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Formal Report

Proceedings of RIKEN BNL Research Center Workshop Volume 103

Opportunities for Drell-Yan Physics at RHIC

May 11– 13, 2011

Organizers: Elke Aschenauer (BNL); Les Bland (BNL); Hank Crawford (U. of Berkeley); Yuji Goto (RIKEN/RBRC); Oleg Eyser (UC-Riverside); Zhongbo Kang (BNL/RBRC); Anslem Vossen (U. of Indiana)

RIKEN BNL Research Center

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002 and again in 2007. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of new generations of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consists of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post –doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~100 graduates of which 27 theorists and 14 experimenters have attained tenure positions at major institutions world wide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. In most cases all the talks are made available on the RBRC website. In addition, highlights to each speaker's presentation are collected to form proceedings which can therefore be made available within a short time after the workshop. To date there are one hundred and two proceedings volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S.D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998. The next generation computer in this sequence, QCDCQ (400 Teraflops), will become operational in the summer of 2011.

N. P. Samios, Director
February 2011

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

CONTENTS

Introduction to the workshop:

Drell-Yan (DY) physics gives the unique opportunity to study the parton structure of nucleons in an experimentally and theoretically clean way. With the availability of polarized proton-proton collisions and asymmetric d+Au collisions at the Relativistic Heavy Ion Collider (RHIC), we have the basic (and unique in the world) tools to address several fundamental questions in QCD, including the expected gluon saturation at low partonic momenta and the universality of transverse momentum dependent parton distribution functions. A Drell-Yan program at RHIC is tied closely to the core physics questions of a possible future electron-ion collider, eRHIC. The more than 80 participants of this workshop focused on recent progress in these areas by both theory and experiment, trying to address imminent questions for the near and mid-term future. The talks and discussions were circling around and trying to interconnect between the following topics:

- Theoretical understanding of the transverse structure of the proton and the Sivers function in SIDIS and DY in particular.
- DY in polarized proton collisions: theoretical and experimental challenges.
- Current theoretical understanding of the low-x structure of nuclear matter (low-x PDFs (integrated and un-integrated) and Saturation).
- DY in d+Au collision: What can we learn from asymmetric collisions?
- Future prospects: What can polarized He-3 collisions and p+Au collisions teach us?
- Relation of DY@RHIC to physics at eRHIC.

The Organizers

Opportunities for Drell-Yan Physics at RHIC

	Wednesday 11th of May 2011			
	Title	**Speaker**	**Slides**	**Proceedings**
09:00 - 10:25	Session Chair: Les Bland (BNL)			
09:00	**Welcome**	**Larry McLerran (BNL)**		
09:15	**Introduction: Collinear and TMD factorization for Drell-Yan production**	**George Sterman (Stony Brook)**	pdf	pdf
09:50	**Low-x physics, saturation and forward Drell-Yan production**	**Al Mueller (Columbia)**	pdf	
10:25 - 10:55	Coffee Break			
10:55 - 12:40	Session Chair: Hank Crawford (UC Berkeley Space Science Laboratory)			
10:55	**What semi-inclusive DIS has taught us about TMD's**	**Gunar Schnell (University of the Basque Country and IKERBASQUE)**	pdf	pdf
11:30	**Critique of TMD Phenomenology**	**Mauro Anselmino (University of Torino)**	pdf	pdf
12:05	**Sivers effect: from SIDIS to pp**	**Zhongbo Kang (BNL)**	pdf	pdf
12:40 - 14:00	Lunch			
14:00 - 15:10	Session Chair: Les Bland (BNL)			
14:00	**Gluon densities and di-hadron correlations**	**Bowen Xiao (Penn State University)**	pdf	pdf
14:35	**From DIS to Drell Yan Production through the Color Glass**	**Jamal Jalilian-Marian (Baruch College)**	pdf	pdf
15:10 - 15:40	Coffee Break			
15:40 - 17:25	Session Chair: Hank Crawford (UC Berkeley Space Science Laboratory)			
15:40	**What we can learn with Drell-Yan in proton(deuteron) nucleus collisions**	**Feng Yuan (LBNL)**	ppt	pdf
16:15	**TMD Universality**	**Piet Mulders (VU University Amsterdam)**	pdf, ppt	pdf
16:50	**Gauge Links and TMD Factorization**	**Ted Rogers (VU University Amsterdam)**	pdf	pdf
17:25	End of Session			

	Thursday 12th of May 2011			
	Title	**Speaker**	**Slides**	**Proceedings**
09:00 - 10:45	Session Chair: Oleg Eyser (UC Riverside)			
09:00	**Drell-Yan Production at FNAL-E906**	**Paul Reimer (ANL)**	**pdf pptx**	**pdf pptx**
09:35	**Forthcoming Drell-Yan experiment at COMPASS**	**Oleg Denisov (INFN - Turin)**	**ppt**	**pdf**
10:10	**Other physics opportunities in future Drell-Yan experiments**	**Jen-Chieh Peng (UIUC)**	**pdf**	**pdf**
10:45 - 11:15	Coffee Break			
11:15 - 13:00	Session Chair: Anselm Vossen (Indiana University)			
11:15	**Drell-Yan Production at STAR: Status and Plans**	**Ernst Sichtermann (LBNL)**	**pdf**	**pdf**
11:50	**Drell-Yan Production at PHENIX: Status and Plans**	**Ming Liu (LANL)**	**pdf**	**pdf**
12:25	**AnDY: Status and Plans**	**Les Bland**	**ppt**	**pdf**
13:00 - 14:30	Lunch			
14:30 - 16:15	Session Chair: Oleg Eyser (UC Riverside)			
14:30	**RHIC: present status and plans**	**Wolfram Fischer (BNL)**	**pdf, pptx**	**pdf**
15:05	**Theoretical perspectives on Drell-Yan production measurements**	**Jian-Wei Qiu (BNL)**	**pdf**	**pdf1, pdf2**
15:40	**TMD fracture functions in SIDIS and DY**	**Aram Kotzinian (Torino Uni&INFN and YerPhI)**	**pdf**	**pdf**
16:15 - 16:35	Coffee Break			
16:35 - 17:45	Session Chair: Anselm Vossen (Indiana University)			
16:35	**Discussion of Experimental Opportunities**		**pdf**	
17:45	End of Session			
18:30	Reception and Banquet at the Brookhaven Center			

	Friday 13th of May 2011			
	Title	**Speaker**	**Slides**	**Proceedings**
09:00 - 10:45	Session Chair: Yuji Goto (RIKEN)			
09:00	**Generalized TMDs and Wigner distributions**	**Andreas Metz (Temple University)**	**pdf**	**pdf**
09:35	**Orbital angular momentum**	**Matthias Burkardt (New Mexico State University)**	**pdf**	**pdf**
10:10	**Probing multi-gluon correlations in pp collisions**	**Yuji Koike (Niigata University)**	**ppt**	**pdf**
10:45 - 11:05	Coffee Break			
11:05 - 12:50	Session Chair: Elke-Caroline Aschenauer (BNL)			
11:05	**Gauge links and process dependence in hadronic reactions**	**Leonard Gamberg (Penn State University)**	**pdf**	**pdf**
11:40	**Understanding forward particle production**	**Roman Pasechnik (Uppsala University)**	**pptx**	**pdf**
12:15	**Drell-Yan at forward rapidities**	**Anna Stasto (Penn State/RBRC)**	**pdf**	**pdf**
12:50 :14:00	Lunch			
14:00 - 15:45	Session Chair: Yuji Goto (RIKEN)			
14:00	**Sivers function in SIDIS and pp**	**Alexey Prokudin (JLab)**	**pdf**	**pdf**
14:35	**Transverse physics with e+e-, SIDIS and pp**	**Alessandro Bacchetta (University of Pavia and INFN Pavia)**	**pdf**	**pdf**
15:10	**Photon Pair Production**	**Marc Schlegel (University of Tuebingen)**	**pdf**	**pdf**
15:45 - 16:15	Coffee Break			
16:15 - 17:25	Session Chair: Elke-Caroline Aschenauer (BNL)			
16:15	**Many body QCD: from RHIC (&LHC) to the EIC**	**Raju Venugopalan (BNL)**	**pptx, pdf**	**pdf**
16:50	**Transverse Single Spin Asymmetries for Drell-Yan production**	**John Collins (Penn State University)**	**pdf**	**pdf**
17:25	End of Workshop			

Introduction: Collinear and TMD Factorization for Drell-Yan Production

George Sterman, Stony Brook

This talk describes some general considerations to help set the stage for the workshop. Most of what is included applies to both spin averaged and spin-dependent cross sections. In summary: Factorization in quantum field theory is closely related to classical considerations. Differences between initial- and final-state gauge links are consistent with this factorization. There is a well-developed theory of factorization for Drell-Yan, including transverse momentum (Q_T) dependence. The 'QCD-inclusive' nature of Drell-Yan production maintains the underlying factorization. Nonperturbative effects play an essential role at low Q_T and should be thought of as an integral part of the formalism. The stage is set for a new phenomenology to explore the transverse-momentum dependent and spin-sensitive parton distributions.

I. Drell-Yan Production in the Parton Model

- **The original 'collinear factorization'**
- **In the parton model (1970).**
  Drell and Yan: look for the annihilation of quark pairs into virtual photons of mass Q ... any electroweak boson in NN scattering.

$$\frac{d\sigma_{NN\to\mu\bar{\mu}+X}(Q,p_1,p_2)}{dQ^2 d\ldots} \sim$$

$$\int d\xi_1 d\xi_2 \sum_{a=\mathrm{q}\bar{\mathrm{q}}} \frac{d\sigma^{\mathrm{EW,\,Born}}_{\mathrm{a}\bar{\mathrm{a}}\to\mu\bar{\mu}}(Q,\xi_1 p_1,\xi_2 p_2)}{dQ^2 d\ldots}$$

$$\times(\text{probability to find parton a}(\xi_1)\text{ in }N)$$

$$\times(\text{probability to find parton }\bar{\mathrm{a}}(\xi_2)\text{ in }N)$$

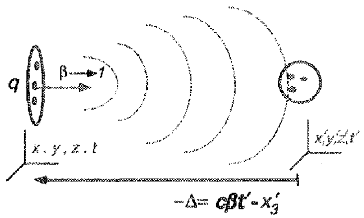
The probabilities are $\phi_{q/N}(\xi_i)$'s from DIS

2. The Physical Basis of Factorization

- **'Collinear factorization' for hadron-hadron scattering for a hard, inclusive process with momentum transfer M to produce final state $F + X$:**

$$
\begin{aligned}
d\sigma_{\mathrm{H_1 H_2}}(p_1, p_2, M) = \\
&\sum_{a,b} \int_0^1 d\xi_a \, d\xi_b d\hat{\sigma}_{ab \to F+X} \left(\xi_a p_1, \xi_b p_2, M, \mu\right) \\
&\times \phi_{a/H_1}(\xi_a, \mu) \, \phi_{b/H_2}(\xi_b, \mu)
\end{aligned}
$$

- **Factorization proofs: justifying the "universality" of the parton distributions.**



field	x frame	x' frame
scalar	$\frac{q}{\lvert\vec{x}\rvert}$	$\frac{q}{(x_T^2+\gamma^2\Delta^2)^{1/2}} \sim \frac{1}{\gamma}$
gauge (0)	$A^0(x) = \frac{q}{\lvert\vec{x}\rvert}$	$A'^0(x') = \frac{-q\gamma}{(x_T^2+\gamma^2\Delta^2)^{1/2}} \sim \gamma^0$
field strength	$E_3(x) = \frac{q}{\lvert\vec{x}\rvert^2}$	$E'_3(x') = \frac{-q\gamma\Delta}{(x_T^2+\gamma^2\Delta^2)^{3/2}} \sim \frac{1}{\gamma^2}$

- **The "gluon field" A'^μ is enhanced, yet is a total derivative:**

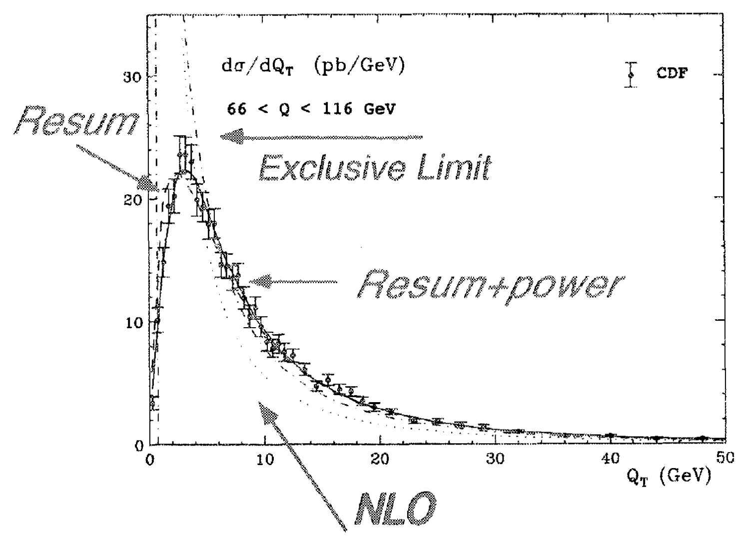
$$A'^\mu = q\frac{\partial}{\partial x'_\mu} \ln\left(\Delta(t', x'_3)\right) + \mathcal{O}(1-\beta) \sim A'^-$$

- **The "large" part of A'^μ can be removed by a gauge transformation!**

4. TMD Factorization for Drell-Yan Production

- Q_T **factorized cross sections: the motivation**
- **Low** Q_T Drell-Yan & Higgs at leading log (LL) $(\alpha_s{}^n \ln^{2n-1} Q_T)$

$$\frac{d\sigma(Q)}{dQ_T} \sim \frac{d}{dQ_T} \exp\left[-\frac{\alpha_s}{\pi} C_F \ln^2\left(\frac{Q}{Q_T}\right)\right]$$
$$(C_F = 4/3)$$



- **Window to nonperturbative distributions:**

$$
\begin{aligned}
E^{\rm soft} &= \frac{1}{2\pi}\int_0^{\mu_I^2}\frac{d^2k_T}{k_T^2}\,A_q(\alpha_s(k_T))\,\ln\left(\frac{Q^2}{k_T^2}\right)\left(e^{i\mathbf{b}\cdot\mathbf{k}_T}-1\right)\\
&\sim -\int_0^{\mu_I^2}\frac{dk_T^2}{k_T^2}\,(\mathbf{b}\cdot\mathbf{k}_T)^2A_q(\alpha_s(k_T))\,\ln\left(\frac{Q^2}{k_T^2}\right)+\cdots\\
&\sim -\,b^2\int dk_T^2\,A_q(\alpha_s(k_T))\,\ln\left(\frac{Q^2}{k_T^2}\right)
\end{aligned}
$$

$\theta(k_T - 1/b) \Rightarrow (e^{i\mathbf{b}\cdot\mathbf{k}_T}-1)$; **in fact, correct to all orders,**

Note the expansion is for b " small enough" only.

6

Low-x physics, saturation and Forward Drell-Yan production

A.H. Mueller*
Columbia University

The idea of saturation; the dipole picture

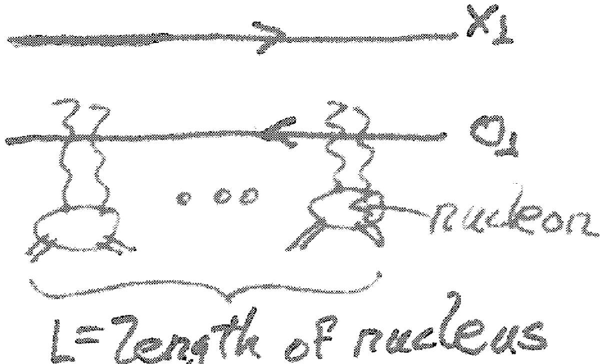
Creating dipoles

Physical processes in Forward deuteron (proton)-nucleus scattering

With F. Dominguez, S. Munier, B. Xiao

The Idea of Saturation; The Dipole Picture

A. Dipole scattering in the McLerran-Venugopalan model?



$$S(x_\perp, L) = e^{-\sigma_{dip}\rho L/2}$$

$$S^2(x_\perp, L) = e^{-L/\lambda}$$

$$\lambda = \frac{1}{\rho\,\sigma_{dip}}$$

One also writes

$$S(x_\perp, L) = e^{-x_\perp^2 \bar{Q}_s^2/4}$$

when $x_\perp > 2/\bar{Q}_s$ strong scatt.

when $x_\perp < 2/\bar{Q}_s$ weak scatt.

$\bar{Q}_s^2$ = quark saturation momentum = $\frac{C_F}{N_c} Q_s^2$

$$Q_s^2 = \frac{4\pi^2 \alpha N_c}{N_c^2 - 1}\,\rho L\, x G_N(x, 1/x_\perp^2)$$

At $x \simeq 10^{-2}$ and $b_\perp \simeq 0$ $Q_s^2 \simeq 1\,\text{GeV}^2$ for large nucleus

The number of gluons per unit area in the nucleus is, when $x_\perp \lesssim 2/Q_s$,

$$\#g/\text{area} \simeq \rho L x G_N = x G_A(x, b_\perp, 1/x_\perp)$$

- The occupation is

$$f_g = \frac{(2\pi)^3}{N_c^2-1}\, x G_A \,\frac{1}{\pi Q_s^2} = \frac{(2\pi)^3}{N_c^2-1}\,\frac{dxG_A}{\underbrace{d^2p_\perp d^2b_\perp}_{\pi Q_s^2}\,\underbrace{dp_z dz}_{1}}$$

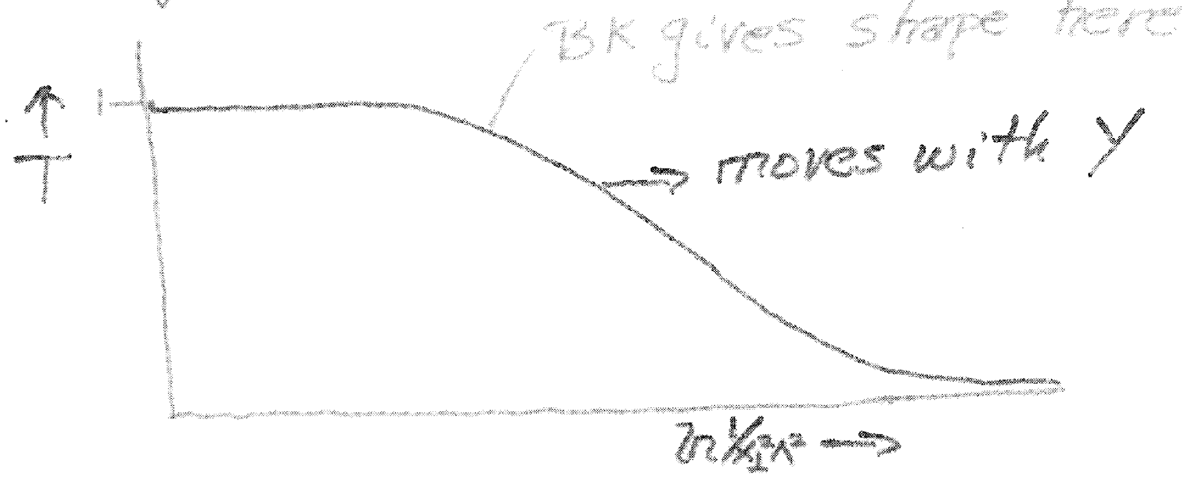
$f_g \simeq 2/\alpha N_c$ at the saturation momentum

. Adding evolution

$$\frac{dT(x_\perp,Y)}{dY} = \frac{\alpha N_c}{2\pi^2}\int d^2z_\perp \frac{x_\perp^2}{z_\perp^2(x_\perp-z_\perp)^2}\Big[\overbrace{T(x_\perp-z_\perp,Y)+T(z_\perp,Y)-T(x_\perp,Y)}^{\text{BFKL}} - \underbrace{T^{(2)}(x_\perp-z_\perp,z_\perp,Y)}_{T(x_\perp-z_\perp,Y)\cdot T(z_\perp,Y)}\Big]$$

is Balitsky-Kovchegov equation.

$T^{(2)}$ Factorizes for large nuclei when Y not too large. In general $T^{(2)}$ Factorizes for large occupancy on an event by event basis.

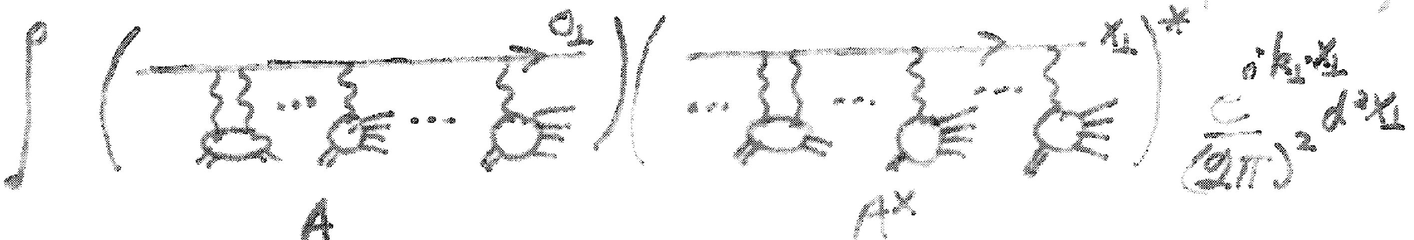


Creating Dipoles

Dipoles of a controllable size occur in $F_L(x,Q^2)$ and in onia, but are hard to build otherwise. However, <u>to some level</u>, they also occur in "easily" accessible processes.

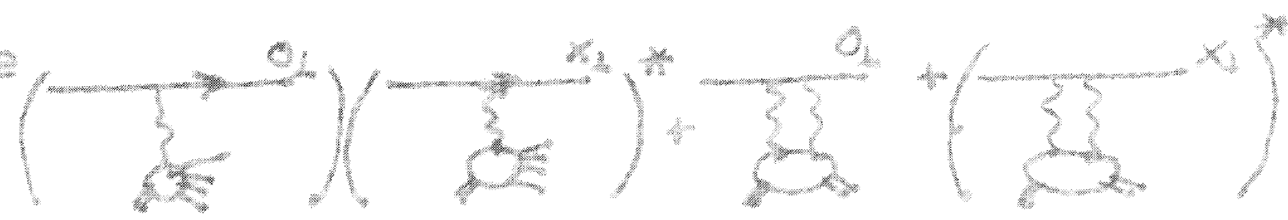
A. $p_\perp$-broadening in MV

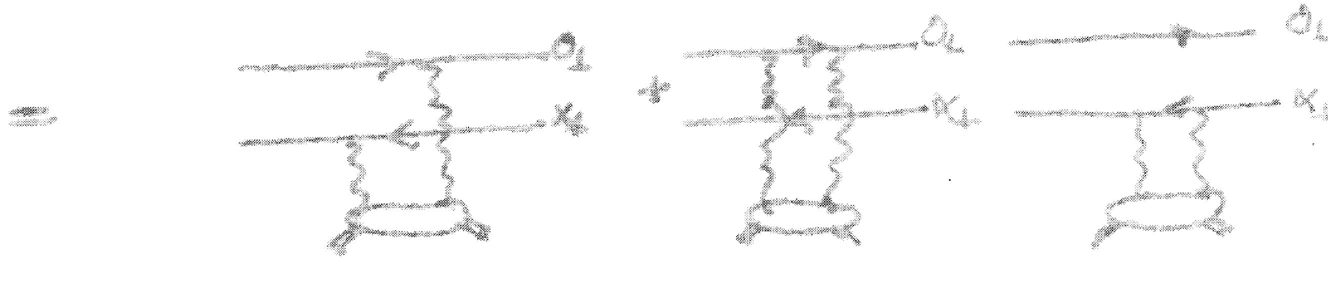
Send quark through nucleus and measure the transverse momentum it picks up.



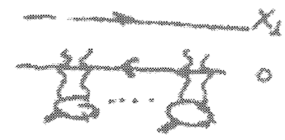
$$= \frac{1}{N}\frac{dN}{d^2k_\perp} = \int \frac{d^2x_\perp}{(2\pi)^2} e^{ik_\perp\cdot x_\perp} A^* A$$

Use





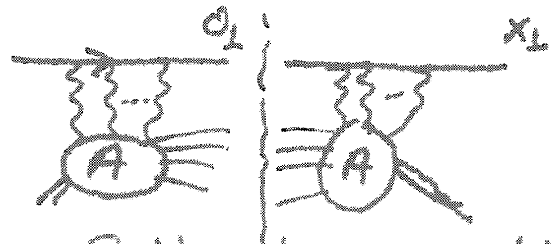
Put in multiple scatterong by Glauber

$$\int S(x_\perp) \frac{d^2x_\perp}{(2\pi)^2} e^{ik_\perp \cdot x_\perp} = \frac{1}{N}\frac{dN}{d^2k_\perp} =$$ 

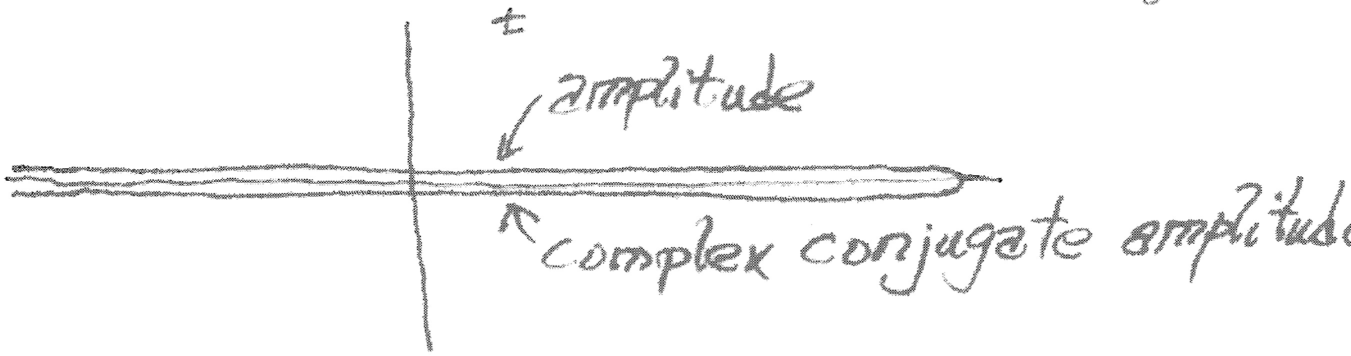
$k_\perp$-broadening given in terms of dipole scattering

2. Bring in evolution

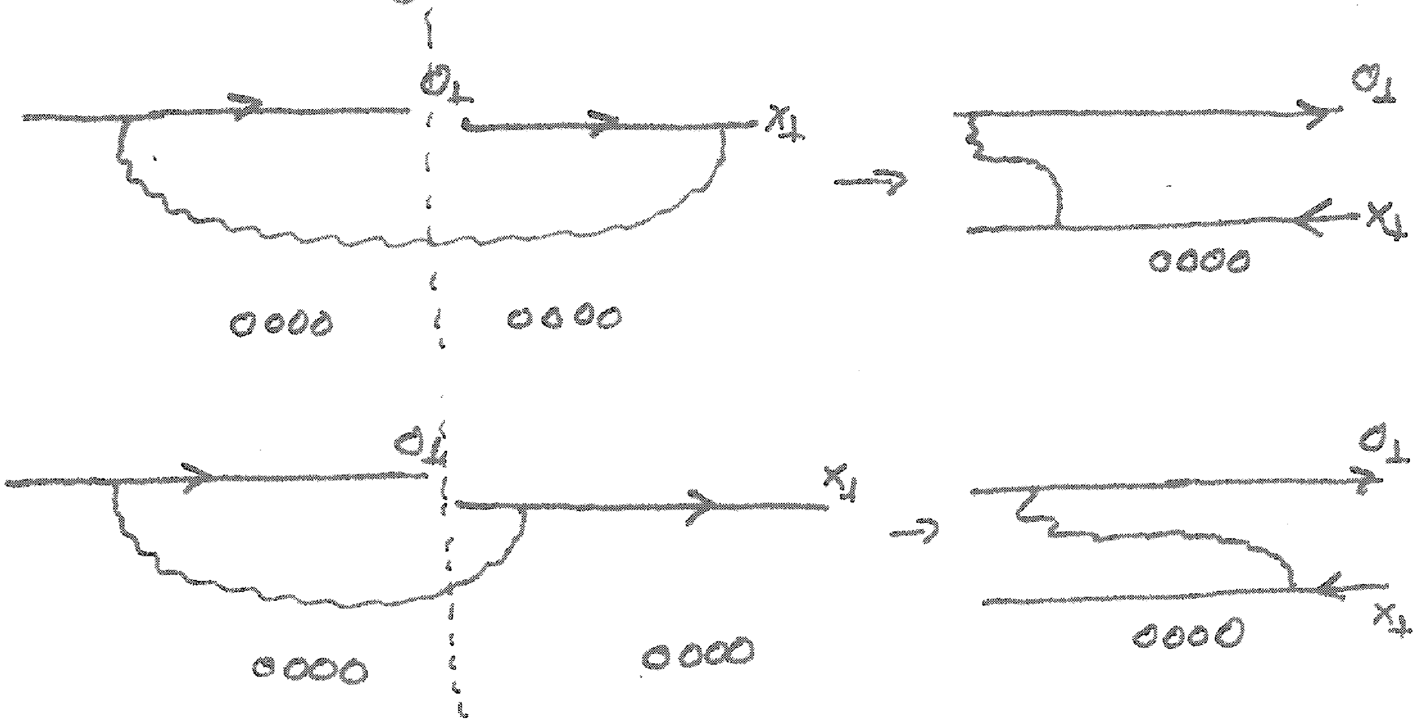
In general

$$\int \frac{d^2k_\perp}{(2\pi)^2} e^{ik_\perp \cdot x_\perp}$$ 

cannot be usefully be written in terms of a time-ordered product. Need two time formalism (or subtle discontinuity)



However, at leading log level one can identify



1-1 correspondence between dipole graphs and the corrections in the original process. OK for $(\alpha N_c Y)^n$ terms (leading logs). Kovchegov Appears to break down at next to leading level.

Should be ok to use dipole picture and BK equation to study $p_\perp$-broadening. But, higher order corrections still an open question.

What semi-inclusive DIS has taught us about TMDs

G. SCHNELL

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IKERBASQUE, Basque Foundation for Science, 48011 Bilbao, Spain

One of the cornerstones of modern hadronic physics is the recognition of the important role of partonic transverse momentum and spin-orbit correlations in the description of the nucleon structure. In semi-inclusive deep-inelastic scattering (DIS) these effects lead to sizable modulations in the azimuthal distribution of hadrons about the virtual-photon direction, which are parameterized in terms of several semi-inclusive structure functions. At leading order in an expansion in M_N/Q, the structure functions are described by transverse-momentum-dependent parton distribution and fragmentation functions (TMDs).

Evidence for TMDs in semi-inclusive DIS were found in the seminal measurement by the HERMES collaboration of pion production off longitudinally polarized protons. All interpretations of these data were hampered by the variety of TMD contributions to this measurement. Two major branches were followed: the interpretation in terms of the Collins fragmentation function and the interpretation as a signal for the naive-T-odd Sivers function. It took a few more years to shed additional light on the true origin of the observed single-spin asymmetries: measurements of similar asymmetries but on transversely polarized protons made it clear that both the Collins function and the Sivers function are non-zero; but the observed asymmetries off longitudinally polarized protons are caused by twist-3 effects.

In the meantime, a wealth of data on TMDs have emerged. Recently the HERMES collaboration completed its analysis of the Sivers modulation using the entire available data set with transversely polarized protons. A manifest signal of non-zero Sivers functions for valence quarks was found, with strong indications that the Sivers distributions for up and down quarks are opposite in sign. This observation is supported by vanishing Sivers modulations measured by the COMPASS collaboration. A surprisingly large signal for positive kaons was found by both collaborations, larger than the one for pions, implying a non-trivial role of sea quarks and/or of the underlying transverse-momentum dependences of the distributions and fragmentation functions.

Besides the Sivers modulation, the HERMES and COMPASS collaborations have data on the Collins effect with tantalizing large signals for π^-. In combination with the results for π^+, which are of opposite sign and smaller in size, it is conjectured that the disfavored Collins fragmentation, i.e., up quarks into π^-, is opposite in sign to and as large as the favored Collins fragmentation, i.e., up quarks into π^+. This can also be concluded when analyzing these data together with data from e^+e^- collision and from semi-inclusive DIS off transversely polarized deuterons.

Sivers, Collins, and transversity are not the only TMDs found to be non-zero. Up to date there are in addition signs for a non-vanishing distribution of longitudinally polarized quarks in transversely polarized nucleons from HERMES and JLAB, for the Boer–Mulders distribution, as well as for several subleading-twist distributions.

Spin-Momentum Structure of the Nucleon

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ + \lambda\gamma^+\gamma_5)\,\Phi\Big] = \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\frac{1}{m}\,f_{1T}^\perp + \lambda\Lambda\,g_1 + \lambda\,S^ik^i\frac{1}{m}\,g_{1T}\Big]$$

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\Big] = \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\frac{1}{m}\,f_{1T}^\perp + s^i\epsilon^{ij}k^j\frac{1}{m}\,h_1^\perp + s^iS^ih_1$$

$$+ s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\,s^ik^i\frac{1}{m}\,h_{1L}^\perp\Big]$$

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helicity

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Twist-[illegible] MDs

Boer-Mulders

Sivers

worm-gear

transversity

Mulders-Tangerman*

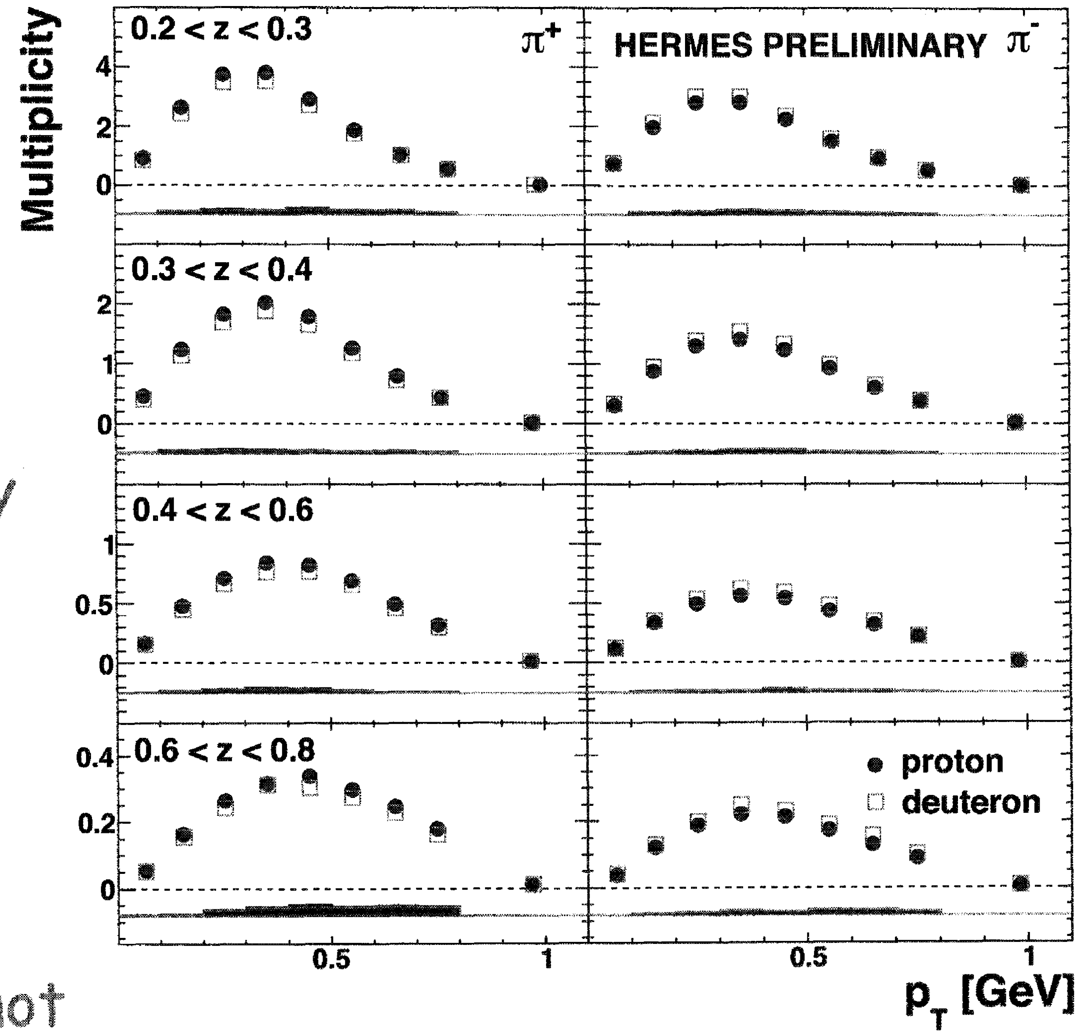
- functions in black survive integration … se momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

*aka Pretzelosity

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Momentum density

- plenty of data available
- but only for integrated version of f_1
- some efforts to get unintegrated gluon density
- spin asymmetries involve unintegrated f_1 in denominator
- need multiplicities and fragmentation functions not only binned in z but also in $P_{h\perp}$



also available for kaons

	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1,\ h_{1T}^{\perp}$

Collins amplitudes COMPASS & HERMES

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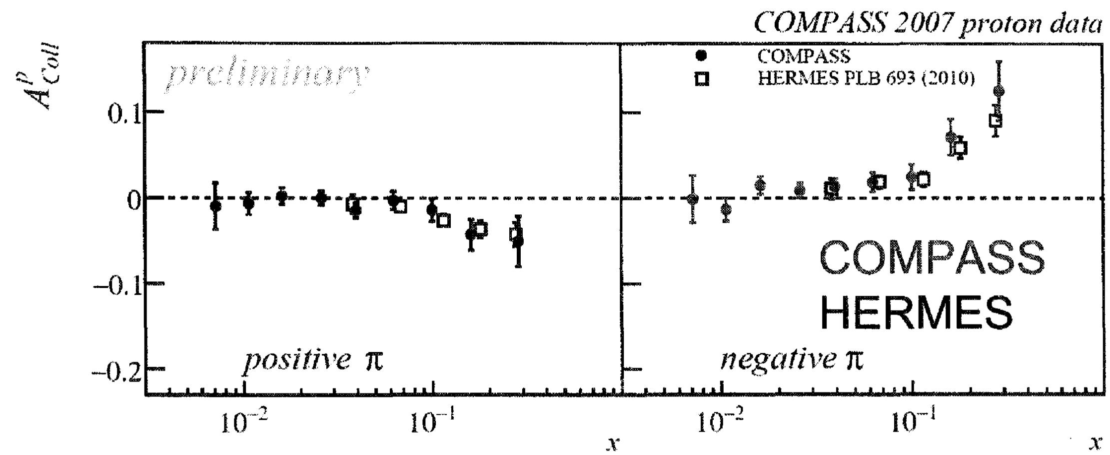
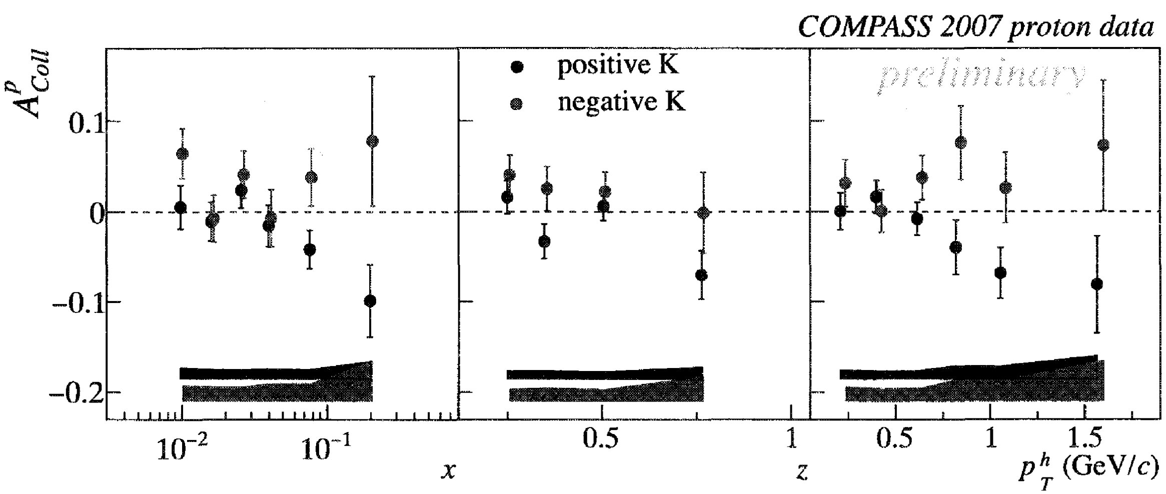
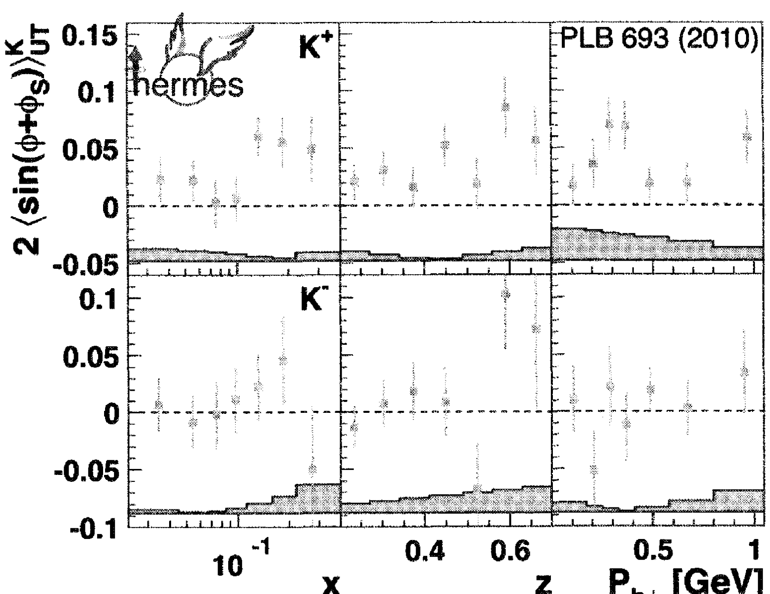
- similar behavior for pions
- similar behavior for K^+
- different trend for K^-
- opposite sign conventions!



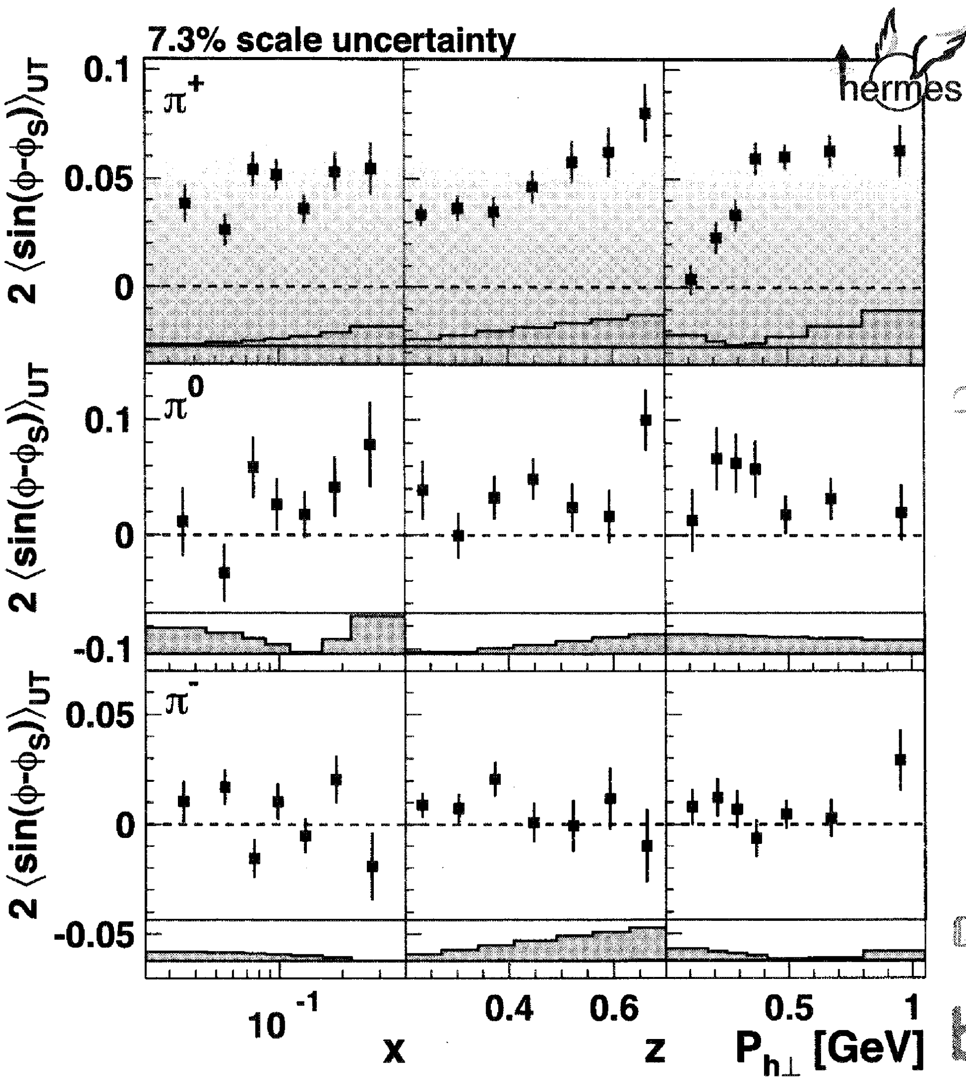




	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1,\ h_{1T}^{\perp}$

Sivers amplitudes for pions

$$2\langle\sin(\phi-\phi_S)\rangle_{\rm UT} = -\frac{\sum_q e_q^2 f_{1\rm T}^{\perp,q}(x,p_T^2)\otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$



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π^+ dominated by u-quark scattering:

$$\simeq -\frac{f_{1\rm T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☞ u-quark Sivers DF < 0

☞ d-quark Sivers DF > 0 (cancelation for π^-)

☞ **u-d cancelation supported by *COMPASS* D data**

Summary

- TMDs provide rich field for studying nucleon structure
- transversity is non-zero and quite sizable
  - can be measured, e.g., via Collins effect or s-p interference in 2-hadron fragmentation
- Sivers and Boer-Mulders effects are also non-zero
  - direct probe of "physics of the QCD gauge links"
- so far no sign of a non-zero Mulders-Tangerman (aka Pretzelosity) distribution
- but first evidence for non-vanishing worm-gear functions
- **great opportunities for measurements in Drell-Yan especially for naive-T-odd TMDs**

Status (critique) of TMD phenomenology

The phenomenological study of TMDs and their extraction from experimental data is reviewed, with attention to possible sources of uncertainties. The role of TMDs in different processes - SIDIS, e+e- and NN inclusive interactions - is discussed. Predictions and suggestions for Drell-Yan measurements are given.

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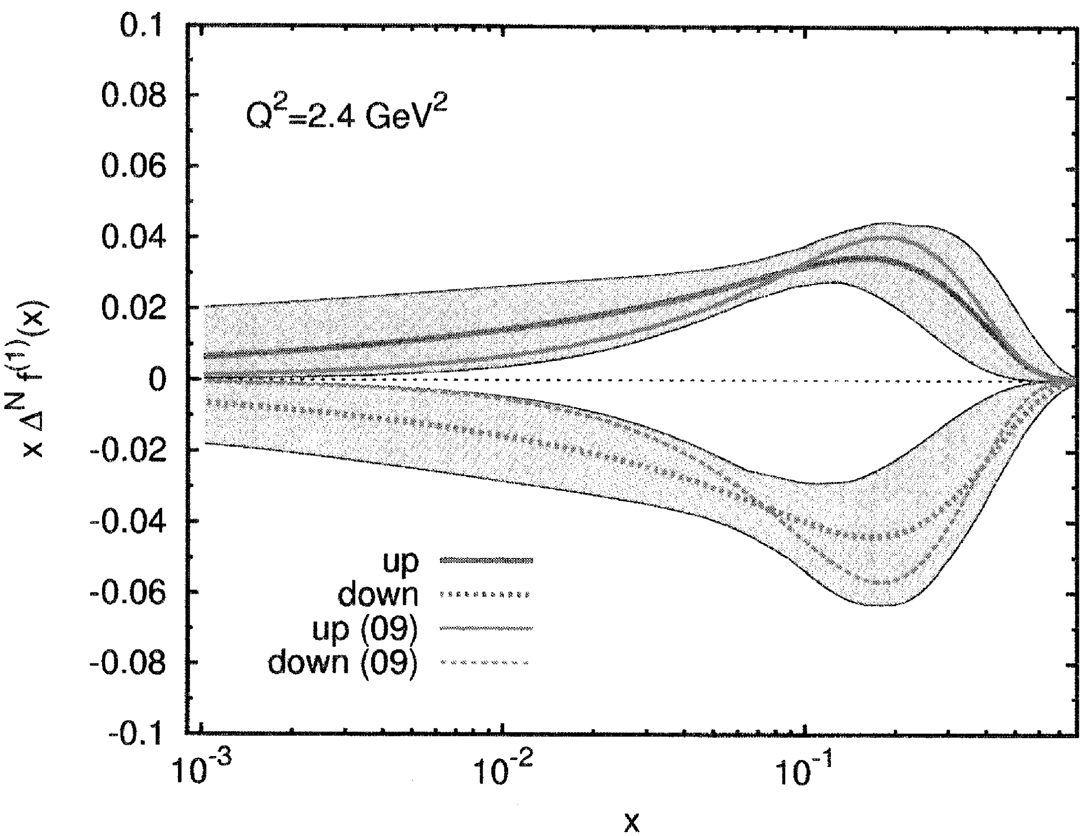
Opportunities for Drell-Yan Physics at RHIC
May 11-13, 2011, RIKEN BNL

Mauro Anselmino, Torino University & INFN

simple Sivers functions for u and d quarks are sufficient to fit the available SIDIS data

large and very small x dependence not constrained by data

talk by A. Prokudin



new and previous extraction of u and d Sivers functions

S. Melis and A. Prokudin, preliminary results

Anselmino et al. Eur. Phys. J. A39,89 (2009)

azimuthal modulations in TFR

(M.A, V. Barone, A. Kotzinian, PL B699 (2011) 108)

cross section for lepto-production of an unpolarized or spinless hadron in the TFR

$$
\begin{aligned}
\frac{\mathrm{d}\sigma^{\mathrm{TFR}}}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}\zeta\,\mathrm{d}^2\boldsymbol{P}_{h\perp}\,\mathrm{d}\phi_S} = \frac{2\alpha_{\mathrm{em}}^2}{Q^2 y} & \left\{ \left(1 - y + \frac{y^2}{2}\right) \right. \\
& \times \sum_a e_a^2 \left[M(x_B, \zeta, \boldsymbol{P}_{h\perp}^2) - |\boldsymbol{S}_\perp| \frac{|\boldsymbol{P}_{h\perp}|}{m_h} M_T^h(x_B, \zeta, \boldsymbol{P}_{h\perp}^2) \sin(\phi_h - \phi_S) \right] \\
& + \lambda_l\, y \left(1 - \frac{y}{2}\right) \sum_a e_a^2 \left[S_\parallel\, \Delta M_L(x_B, \zeta, \boldsymbol{P}_{h\perp}^2) \right. \\
& \left. \left. + |\boldsymbol{S}_\perp| \frac{|\boldsymbol{P}_{h\perp}|}{m_h} \Delta M_T^h(x_B, \zeta, \boldsymbol{P}_{h\perp}^2) \cos(\phi_h - \phi_S) \right] \right\} .
\end{aligned}
$$

possible Sivers-like azimuthal dependence from target fragmentation region

sign mismatch

(Kang, Qiu, Vogelsang, Yuan)

compare

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

as extracted from fitting A_N data, with that obtained by inserting in the the above relation the SIDIS extracted Sivers functions

similar magnitude, but opposite sign!

the same mismatch does not occurr adopting TMD factorization; the reason is that the hard scattering part in higher-twist factorization is negative

Cahn effect in unpolarized D-Y

M. Boglione, S. Melis, arXiv:1103.2084

access to $\langle k_\perp^2 \rangle$

$$\frac{d\sigma^{unp}}{d^4q\,d\Omega'} = \frac{\alpha^2}{6M^2 s}\sum_q e_q^2\, f^q_{a/A}(x_a)\, \bar{f}^q_{b/B}(x_b)\,\frac{e^{-q_T^2/\langle q_T^2\rangle}}{\pi\langle q_T^2\rangle}\left\{(1+\cos^2\theta') + \underbrace{\frac{q_T}{M}\,\frac{\langle k_{\perp a}^2\rangle - \langle k_{\perp b}^2\rangle}{\langle q_T^2\rangle}\sin 2\theta'\cos\phi'}_{\text{Cahn effect}}\right\}$$

$$\langle k_{\perp a}^2\rangle + \langle k_{\perp b}^2\rangle \equiv \langle q_T^2\rangle \qquad \boldsymbol{q}_T = \boldsymbol{k}_{\perp a} + \boldsymbol{k}_{\perp b}$$

$$f_{a/A}(x_a, k_{\perp a}) = f_{a/A}(x_a)\,\frac{e^{-k_{\perp a}^2/\langle k_{\perp a}^2\rangle}}{\pi\langle k_{\perp a}^2\rangle}$$

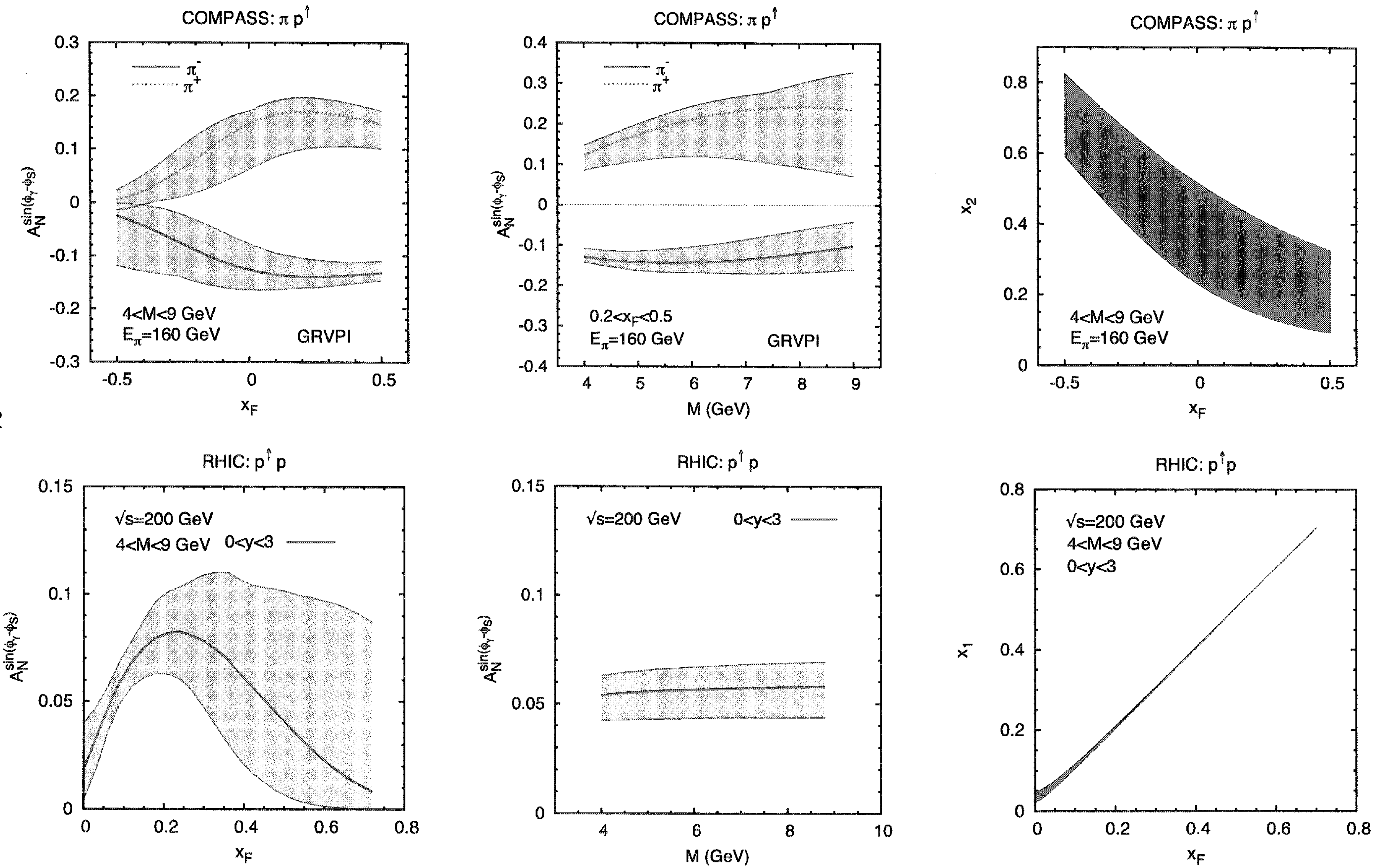
gaussian $k_\perp$ dependence

no effect if $\langle k_{\perp a}^2\rangle = \langle k_{\perp b}^2\rangle$

same conclusion holds for non gaussian distributions

Predictions for A_N

Sivers functions as extracted from SIDIS data, **with opposite sign**



M.A., M. Boglione, U. D'Alesio, S. Melis, F. Murgia, A. Prokudin, e-Print: arXiv:0901.3078

Sivers effect: from SIDIS to pp
- sign change and sign mismatch

Zhongbo Kang

RIKEN BNL Research Center, Brookhaven National Laboratory

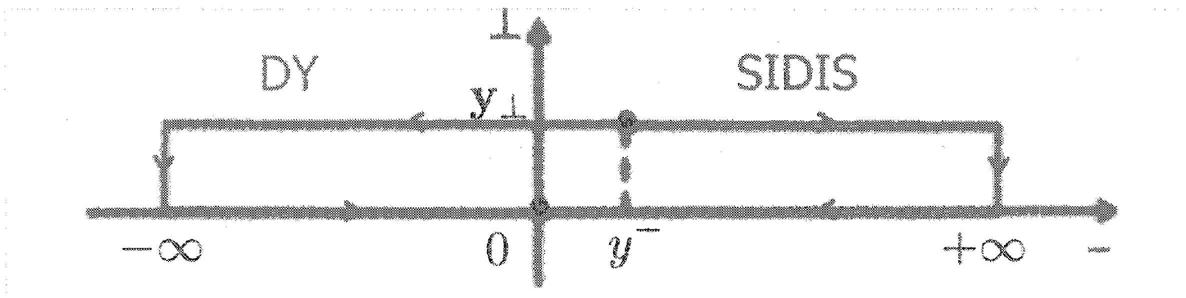
Abstract: The $k_\perp$-moment of a quark's Sivers function is known to be related to the corresponding twist-three quark-gluon correlation function $T_{q,F}(x, x)$. The two functions have been extracted from data for single-spin asymmetries in semi-inclusive deep inelastic scattering and in single-inclusive hadron production in pp collisions, respectively. Performing a consistent comparison of the extracted functions, we find that they show a "sign mismatch": while the magnitude of the functions is roughly consistent, the $k_\perp$-moment of the Sivers function has opposite sign from that of $T_{q,F}(x, x)$, both for up and for down quarks. Barring any inconsistencies in our theoretical understanding of the Sivers functions and their process dependence, the implication of this mismatch is that either, the Sivers effect is not dominantly responsible for the observed single-spin asymmetries in pp collisions or, the current semi-inclusive lepton scattering data do not sufficiently constrain the $k_\perp$-moment of the quark Sivers functions. Both possibilities strengthen the case for further experimental investigations of single-spin asymmetries in high-energy pp and ep scattering.

Kang, Qiu, Vogelsang, Yuan, arXiv: 1103.1591, PRD 83, 2011
Kang, Prokudin, 2011, in preparation

Time-reversal modified universality of the Sivers function

- Different gauge link for gauge-invariant TMD distribution in SIDIS and DY

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3}\, e^{ixp^+y^- - i\,\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp)\,\boxed{\text{Gauge link}}\,\frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$



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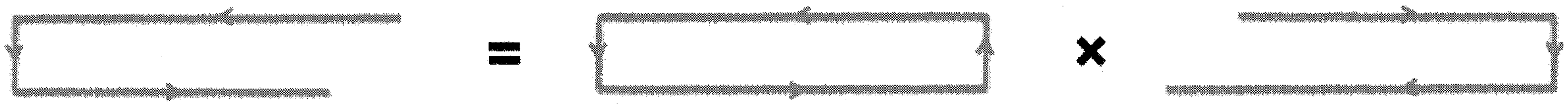
Wilson Loop ~ $\exp\left[-ig\int_\Sigma d\sigma^{\mu\nu}F_{\mu\nu}\right]$ Area is NOT zero



- Parity and time-reversal invariance:

$$\Delta^N f^{\text{SIDIS}}_{q/h^\uparrow}(x,k_\perp) = -\Delta^N f^{\text{DY}}_{q/h^\uparrow}(x,k_\perp)$$

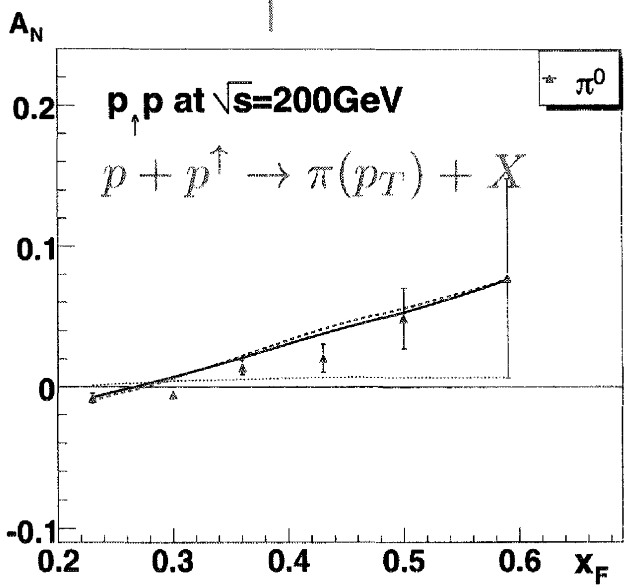
Most critical test for TMD approach to SSA

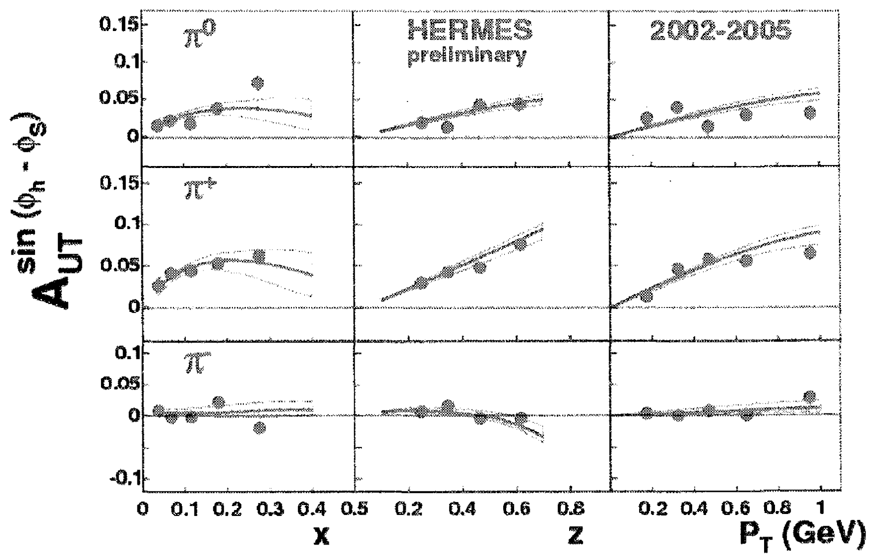
What about the connections?

- Both seem to describe the data well (in their own kinematic region), but what about their connections?
  - At the operator level, ETQS function is related to the first kt-moment of the Sivers function

Boer, Mulders, Pijlman, 2003
Ji, Qiu, Vogelsang, Yuan, 2006

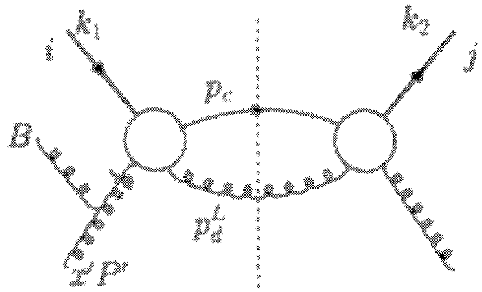
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

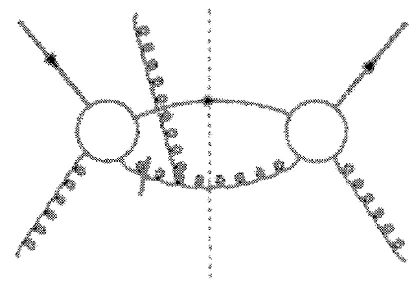




Initial- and final-state interaction in pp collisions

- The dominant channel is qg → qg





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$$H^U_{qg\to qg} = \frac{N_c^2-1}{2N_c^2}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1-\frac{2N_c^2}{N_c^2-1}\frac{\hat{s}\hat{u}}{\hat{t}^2}\right] \xrightarrow{|\hat{t}|\ll\hat{s}\sim|\hat{u}|} \left[\frac{2\hat{s}^2}{\hat{t}^2}\right]$$

$$H^I_{qg\to qg} = \frac{1}{2(N_c^2-1)}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1-N_c^2\frac{\hat{u}^2}{\hat{t}^2}\right] \xrightarrow{|\hat{t}|\ll\hat{s}\sim|\hat{u}|} \left[-\frac{N_c^2}{2(N_c^2-1)}\right]\left[\frac{2\hat{s}^2}{\hat{t}^2}\right]$$

$$H^F_{qg\to qg} = \frac{1}{2N_c^2(N_c^2-1)}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1+2N_c^2\frac{\hat{s}\hat{u}}{\hat{t}^2}\right] \xrightarrow{|\hat{t}|\ll\hat{s}\sim|\hat{u}|} \left[-\frac{1}{N_c^2-1}\right]\left[\frac{2\hat{s}^2}{\hat{t}^2}\right]$$

- Sivers effect in single hadron production is more similar to DY

Directly obtained ETQS function

- ETQS function could be directly obtained from the global fitting of inclusive hadron production in hadronic collisions

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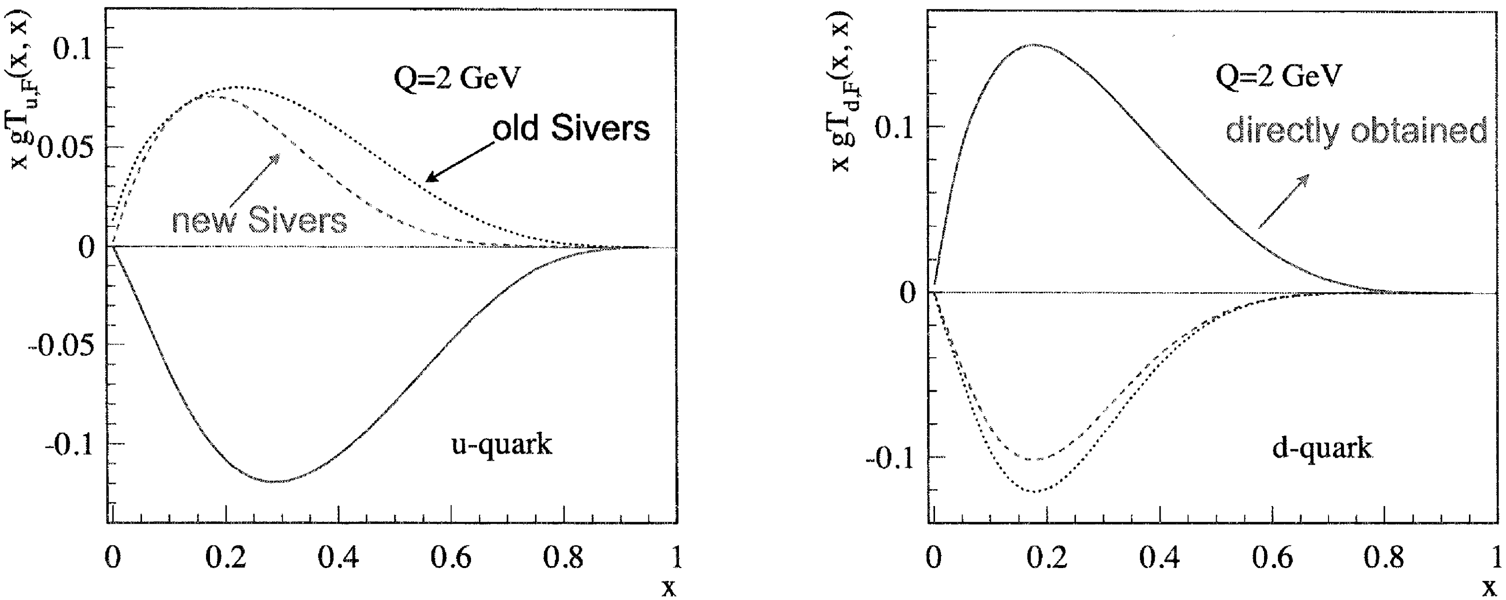
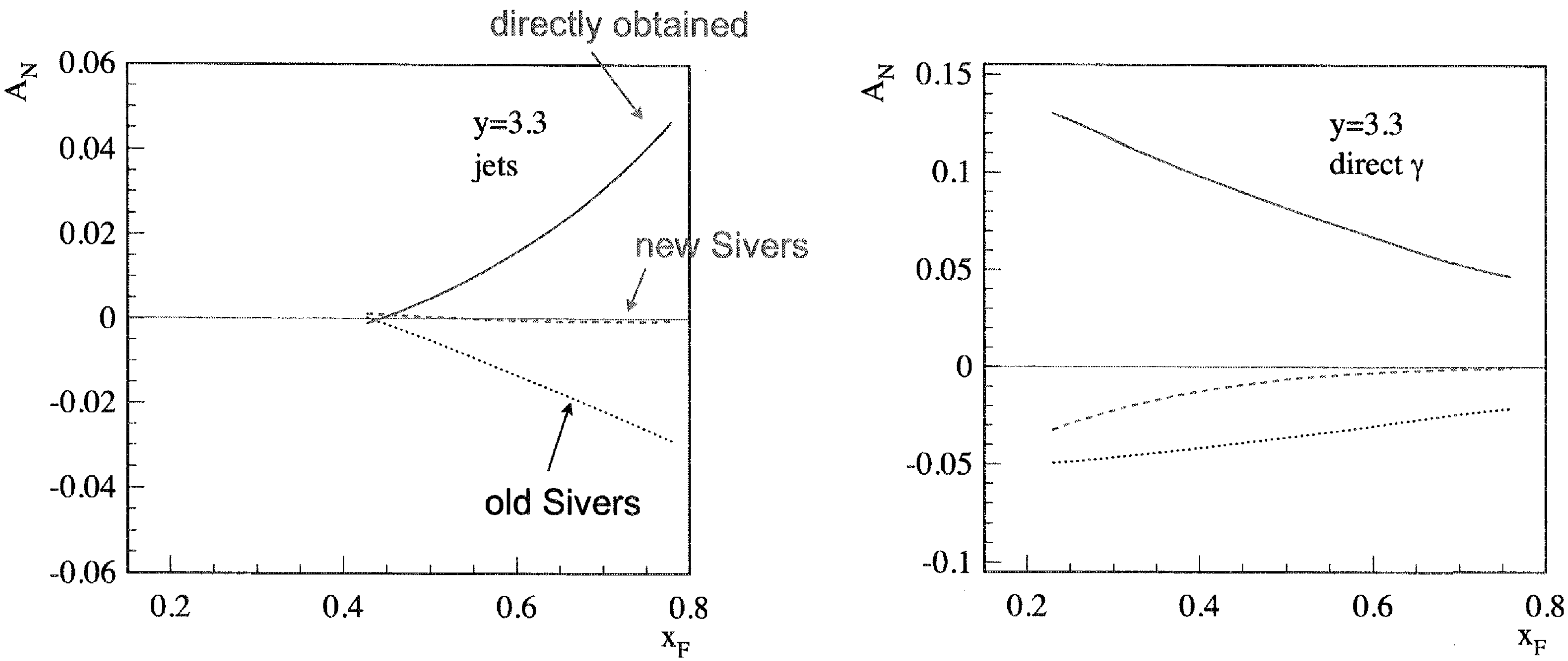


- directly obtained ETQS functions for both u and d quarks are opposite in sign to those indirectly obtained from the kt-moment of the quark Sivers function - "a sign mismatach"

Predictions for jet and direct photon

- at RHIC 200 GeV:



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Gluon Densities and Dihadron correlations

Bo-Wen Xiao, Penn State

- In this talk, a complete calculation of dijet production in various processes is presented. It is well-known that there are two fundamental unintegrated gluon distributions in high density QCD. The first unintegrated gluon distribution, which measures the number density of gluons inside the target nucleus, can be directly measured in DIS dijet production; whereas the second unintegrated gluon distribution, defined as the Fourier transform of the color-dipole amplitude, can be probed in the Drell-Yan-jet correlation in pA collisions. Dijet production cross section in pA collision depends on both gluon distributions through convolutions. We conduct two independent calculations (one is in CGC formalism and the other uses TMD approach.) for all of above processes. We find these two calculation agree perfectly. These calculation has shown important impact on the present RHIC and future EIC and LHeC. In the end, I also present a comprehensive comparison between our numerical results and the forward dihadron production data measured by STAR.

Drell-Yan workshop at BNL, May, 2011

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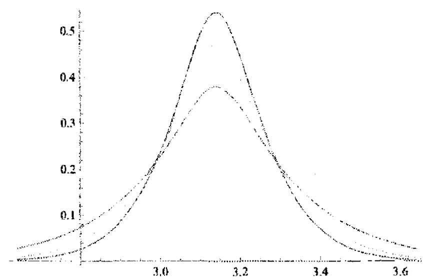
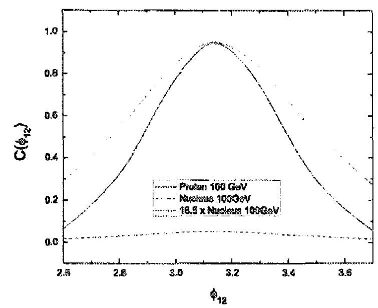
DIS dijet correlation

Azimuthal angle correlation of dijet in DIS probes the WW gluon distributions





Remarks:

- $k_{1\perp} = 5.5$Gev, $k_{2\perp} = 5.0$Gev and $Q_s^2 = 1\,,1.5\,,3$GeV;
- Only away side peak is plotted due to the correlation limit.
- Suppression of away side peak and increase of width at large Q_s^2.
- Dramatic change between ep and eA collisions. $Q^2 = 4\text{GeV}^2$, $z_{h1} = z_{h2} = 0.3$, 2GeV $< p_{1\perp} <$ 3GeV and 1GeV $< p_{2\perp} <$ 2GeV.
- No pedestal.

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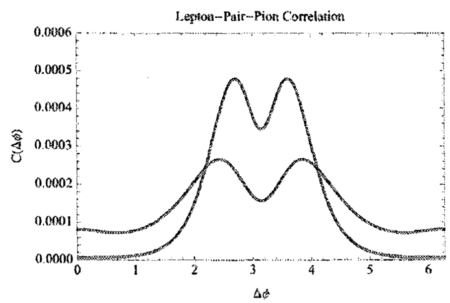
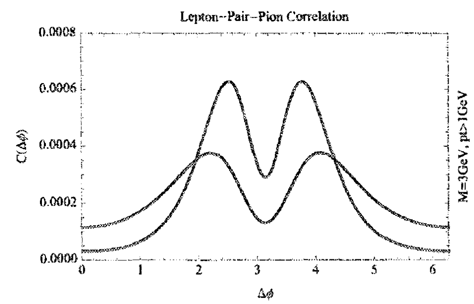
Dilepton Pair + hadron correlation

[F. Dominguez, BX and F. Yuan, in preparation]

Azimuthal angle correlation of γ^*+π^0 at forward rapidity 3.2:





Remarks:

- $p_{1\perp} > 1.5$Gev, $p_{2\perp} > 1.5$Gev and $M^2 = 1\text{GeV}^2$;
- $p_{1\perp} > 1$Gev, $p_{2\perp} > 1$Gev and $M^2 = 9\text{GeV}^2$;
- Suppression of away side peak at central *dAu* collisions.
- Double peak structure on the away side comes from the fact that $xG^{(2)} \propto q_\perp^2$ in the small $q_\perp$ limit.

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Gluon+quark jets correlation

Including all the $qg \to qg$, $gg \to gg$ and $gg \to q\bar{q}$ channels, a lengthy calculation gives

$$
\begin{aligned}
\frac{d\sigma^{(pA\to \text{Dijet}+X)}}{d\mathcal{P}.\mathcal{S}.} &= \sum_q x_1 q(x_1,\mu^2)\frac{\alpha_s^2}{\hat{s}^2}\left[\mathcal{F}_{qg}^{(1)}H_{qg}^{(1)}+\mathcal{F}_{qg}^{(2)}H_{qg}^{(2)}\right] \\
&+x_1 g(x_1,\mu^2)\frac{\alpha_s^2}{\hat{s}^2}\left[\mathcal{F}_{gg}^{(1)}\left(H_{gg\to q\bar{q}}^{(1)}+\frac{1}{2}H_{gg\to gg}^{(1)}\right)\right. \\
&\left.+\mathcal{F}_{gg}^{(2)}\left(H_{gg\to q\bar{q}}^{(2)}+\frac{1}{2}H_{gg\to gg}^{(2)}\right)+\mathcal{F}_{gg}^{(3)}\frac{1}{2}H_{gg\to gg}^{(3)}\right],
\end{aligned}
$$

with the various gluon distributions defined as

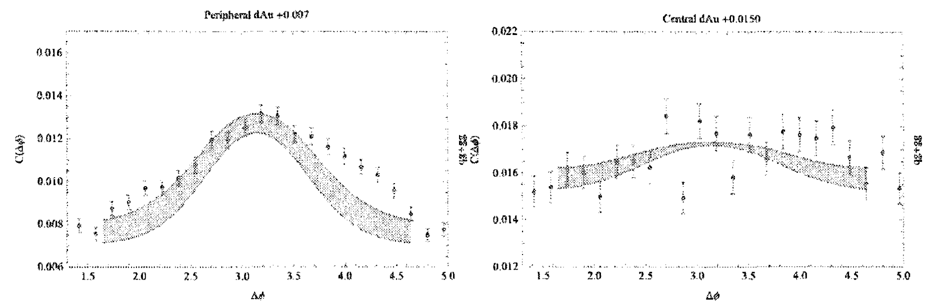
$$
\begin{aligned}
\mathcal{F}_{qg}^{(1)} &= xG^{(2)}(x,q_\perp),\ \mathcal{F}_{qg}^{(2)} = \int xG^{(1)}\otimes F\,, \\
\mathcal{F}_{gg}^{(1)} &= \int xG^{(2)}\otimes F,\ \mathcal{F}_{gg}^{(2)} = -\int \frac{q_{1\perp}\cdot q_{2\perp}}{q_{1\perp}^2}xG^{(2)}\otimes F\,, \\
\mathcal{F}_{gg}^{(3)} &= \int xG^{(1)}(q_1)\otimes F\otimes F\,,
\end{aligned}
$$

where $F=\int\frac{d^2r_\perp}{(2\pi)^2}e^{-iq_\perp\cdot r_\perp}\frac{1}{N_c}\left\langle \text{Tr}U(r_\perp)U^\dagger(0)\right\rangle_{x_g}$.

Remarks: Only the first term was known before.

Comparing to STAR data including both $q+g$ and $g+g$

[A. Stasto, BX, F. Yuan, in preparation]
For away side peak in both peripheral and central dAu collisions:



- Adding a k−factor of 2 to the ratio since the total single inclusive cross section is twice of the data at $\eta = 3.2$.
- Other parameters are kept the same.

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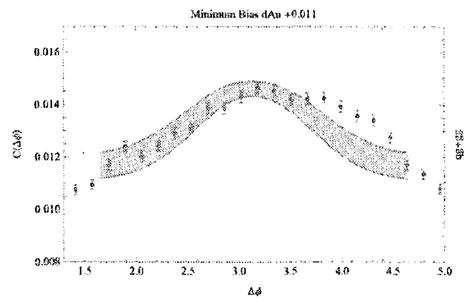
Comparing to STAR data including both $q+g$ and $g+g$

[A. Stasto, BX, F. Yuan, in preparation]
For minimum bias away side peak in *dAu* collisions in $q+g$ channel:



- Adding a $k-$factor of 2 to the ratio since the total single inclusive cross section is twice of the data at $\eta = 3.2$.
- Peripheral $b = 6.8 \pm 1.7$fm with $c(b) = 0.45$ and width $\sigma \simeq 0.99$;
- Central $b = 2.7 \pm 1.3$fm with $c(b) = 0.85$ and width $\sigma \simeq 1.6$;
- Minimum Bias $c(b) = 0.56 \Rightarrow \langle b \rangle = 6$fm and width $\sigma \simeq 1.2$.

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Jamal Jalilian-Marian

Baruch College, New York NY 10010

In the Color Glass Condensate formalism, the amplitudes for quark anti-quark production in DIS and virtual photon (DY) production in proton (deuteron)-nucleus (pA) collisions are related via crossing symmetry. Both production cross sections involve only the dipole (two-point function of Wilson lines) function. Therefore knowledge of the dipole profile gained in DIS structure function studies can be used to predict dilepton production in pA collisions. Lam-Tung relation between the DY structure functions is shown to be sensitive to the high gluon density effects at small x.

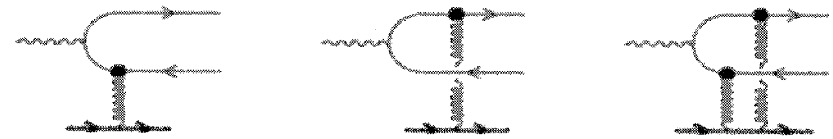
**based on work done in collaboration with F. Gelis*

MV
PRD59 (1999) 094002

DIS at small x

Gelis,Jalilian-Marian
PRD67 (2003) 074019

consider $\gamma^\star \, \mathrm{T} \to \mathrm{q} \, \bar{\mathrm{q}} \, \mathrm{X}$



$$M^\mu(k;q,p) \;=\; \frac{i}{2}\int \frac{d^2 l_t}{(2\pi)^2}\, d^2x_t d^2y_t e^{i l_t\cdot x_t} e^{i(p_t+q_t-k_t-l_t)\cdot y_t}\, \bar{u}(q)\,\Gamma^\mu(k;q,p)\,v(p) \left[V(x_t)\,V^\dagger(y_t) - 1\right]$$

cross section:

averaging over color charges ρ

$$\mathbf{2p_0\,2q_0\,\frac{d\sigma}{d^3q\,d^3p} = \frac{1}{(2\pi)^5}\,\frac{1}{k^-}\,2\pi\delta(k^-p^- - q^-)\,\langle M^\mu M^{\nu\,\star}\rangle\,\epsilon_\mu(k)\epsilon^\star_\nu(k)}$$

to get the DIS total cross section, <u>integrate over quark, anti-quark momenta</u>

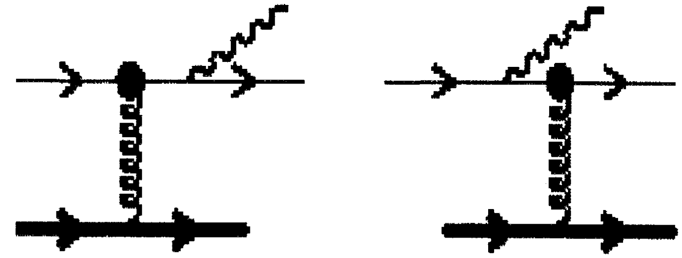
$$\sigma^{\gamma^\star \mathrm{T}\to \mathrm{X}} = \int_0^1 \mathrm{dz} \int \mathrm{d^2x_t d^2y_t}\, |\Psi|^2\, \frac{1}{\mathrm{N_c}}\, \langle \mathrm{Tr}\, [1 - \mathrm{V(x_t)\,V^\dagger(y_t)}] \rangle$$

$\mathbf{T(x_g, r_t, b_t)}$

satisfies the JIMWLK/BK eqs.

dipole cross section $T(x_g, r_t, b_t)$

DY at small x



$\mathbf{q\,T \to q\,\gamma^\star\,X}$

$$\mathbf{M^\mu(p;k,q) = i \int d^2x_t e^{i(q_t+k_t-p_t)\cdot x_t}\, \bar{u}(q)\, \bar{\Gamma}^\mu(k;q,p)\, u(p)\ [V(x_t)-1]}$$

$$= \frac{i}{2}\int \frac{d^2 l_t}{(2\pi)^2}\, d^2x_t d^2y_t e^{il_t\cdot x_t} e^{i(q_t+k_t-p_t-l_t)\cdot y_t}\, \bar{u}(q)\,\Gamma^\mu(-k;q,-p)\,u(p)$$

$$\left[V(x_t)\,V^\dagger(y_t)-1\right]\ V(y_t)$$

extra: unitary matrix

same as DIS

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cross section

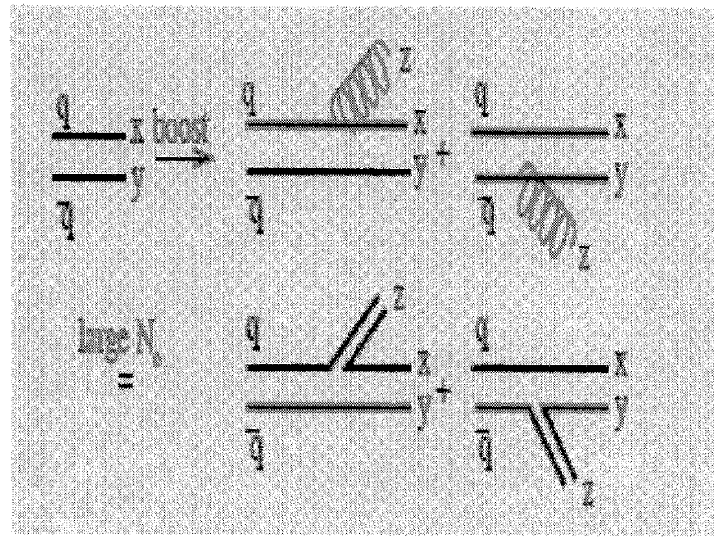
$$\frac{d\sigma}{dz\, d^2k_t\, d\log M^2\, d^2b_t} = \frac{2\alpha_{em}^2}{3\pi}\int \frac{d^2 l_t}{(2\pi)^4}\, d^2r_t e^{il_t\cdot r_t}\, T(x_g,b_t,r_t)\Bigg\{ \left[\frac{1+(1-z)^2}{z}\right] \frac{z^2\, l_t^2}{[k_t^2+(1-z)M^2][(k_t-zl_t)^2+(1-z)M^2]} - z(1-z)M^2\left[\frac{1}{[k_t^2+(1-z)M^2]} - \frac{1}{[(k_t-zl_t)^2+(1-z)M^2]}\right]^2\Bigg\}$$

Gelis,Jalilian-Marian
PRD66 (2002) 094014

Evolution of a dipole (2-point function): BK

$$\frac{d}{dy} < \mathrm{Tr} V_x^\dagger V_y > = -\frac{\bar{\alpha}_s}{2\pi} \int d^2z \, \frac{(x-y)^2}{(x-z)^2 (y-z)^2} \times$$

$$\left[< \mathrm{Tr} V_x^\dagger V_y > - \frac{1}{N_c} < \mathrm{Tr} V_x^\dagger V_z \, \mathrm{Tr} V_z^\dagger V_y > \right]$$



$$\frac{d}{dy} S_4(r, \bar{r} : s) \simeq \frac{d}{dy} [S_2(s - \bar{r}) \, S_2(r - s)] + O(\frac{1}{N_c^2})$$

DIS F2,FL
DY in pA are sensitive to <u>dipoles</u> only

Dijet production probes <u>quadrupoles</u>

A quadrupole *<u>is not</u>* the same as dipole X dipole
AD-JJM, 2011

NLO BK:
B-KW-G-BC (2007-2008)

Dilepton production: k_t integrated

$$\frac{d\sigma^{d(p)\,A\to l^+ l^-\,X}}{d^2b_t\,dM^2\,dx_F} = \frac{\alpha_{em}^2}{6\pi^2}\frac{1}{x_q+x_g}\int_{x_q}^{1} dz \int dr_t^2\,\frac{1-z}{z^2}$$

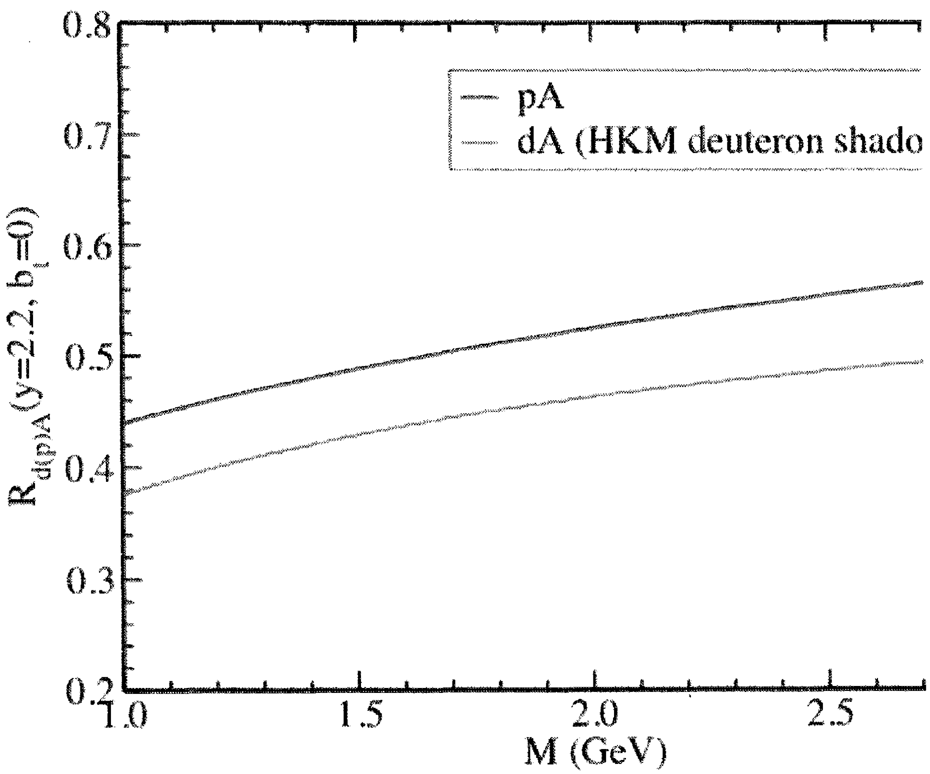
$$F_2^{d(p)}(x_q/z)\,\gamma(x_g,b_t,r_t)$$

$$\left[[1+(1-z)^2]\,K_1^2[\frac{\sqrt{1-z}}{z}Mr_t]\right.$$

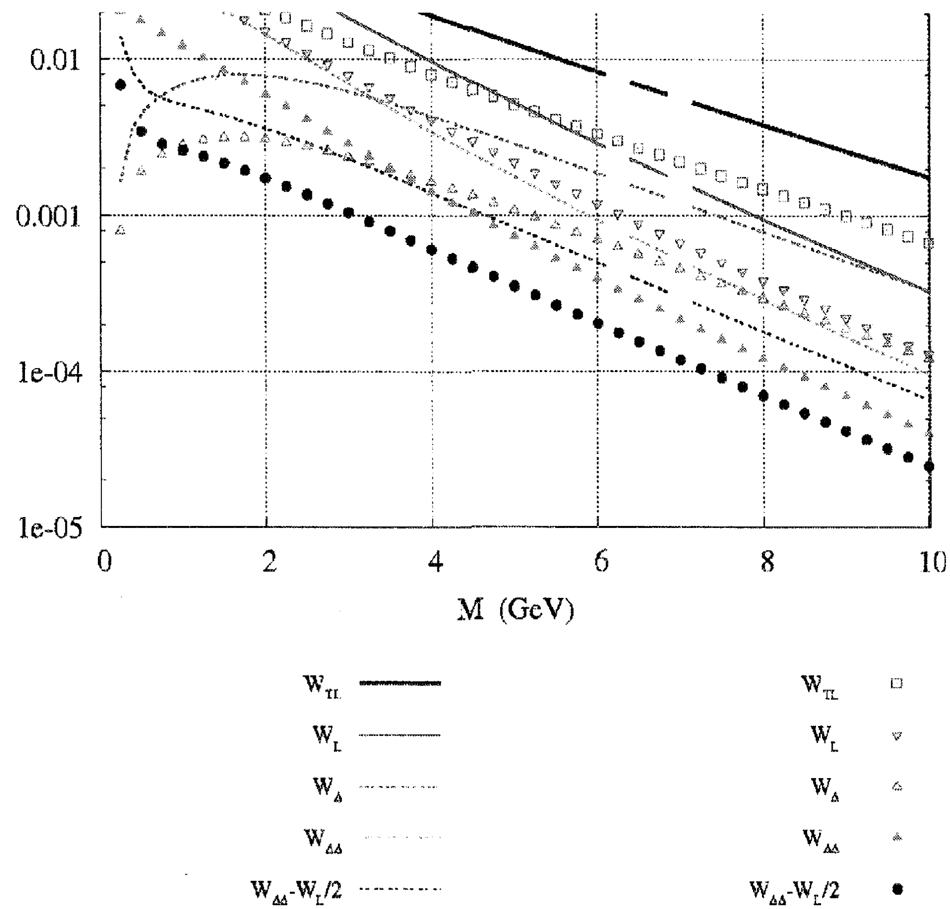
$$\left.+2(1-z)\,K_0^2[\frac{\sqrt{1-z}}{z}Mr_t]\right]$$

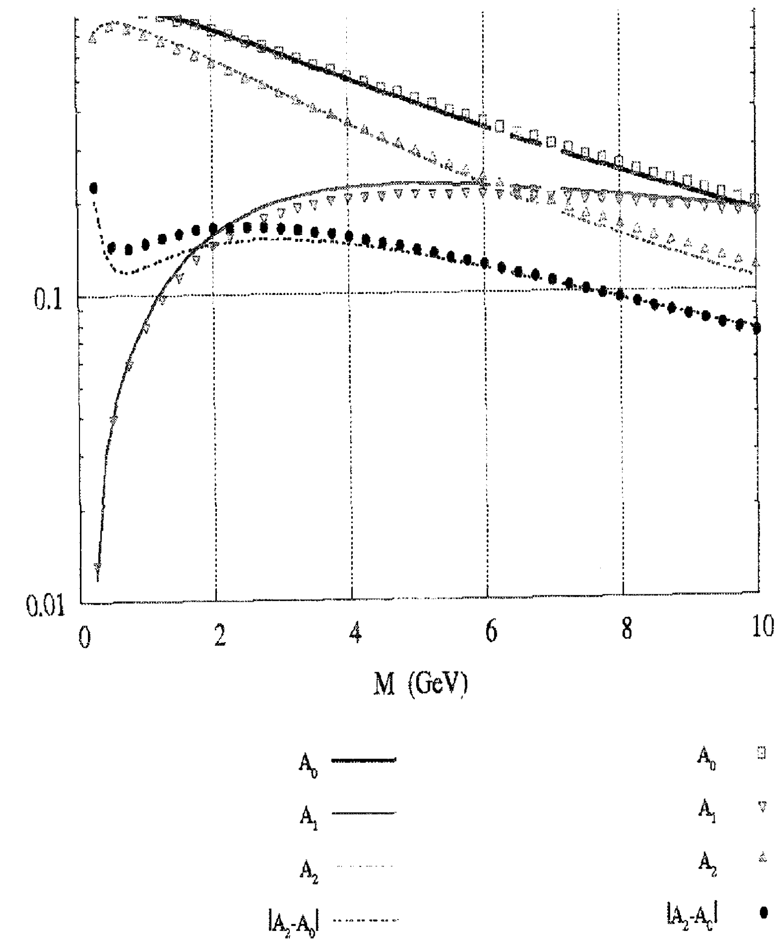
$$x_F \equiv \frac{M}{\sqrt{s}}[e^{y}-e^{-y}]$$

F. Gelis & JJM 02, JJM 04



RHIC: k_t = 3 GeV, y = 2





Lines: (fixed coupling) BK
Points: DHJ

What can we learn with Drell-Yan in p(d)-Nucleus collisions

Feng Yuan
Lawrence Berkeley Lab/RBRC

We argue that the forward Drell-Yan lepton pair production can be used to probe the nontrivial QCD dynamics associated with small-x physics. In particular, the saturation scale Q_s^2 is order of 3-4GeV^2, which is not too small compared to the hard scale: the invariant mass of the lepton pair. We estimate the nuclear suppression factor is less than 0.5 for small transverse momentum lepton pair production, which is unprecedented for Drell-Yan process. In this kinematics, the traditional DGLAP-based shadowing approach is not applicable any more. The Color-Glass-Condensate/Color-dipole approach is more suitable to describe these processes. We further argue that the single spin asymmetries in pp and pA collisions can provide more information on small-x physics, and may shed light on the underlying mechanism for the AN in various processes.

Opportunities for Drell-Yan Physics at RHIC

In p(d) Au Collisions

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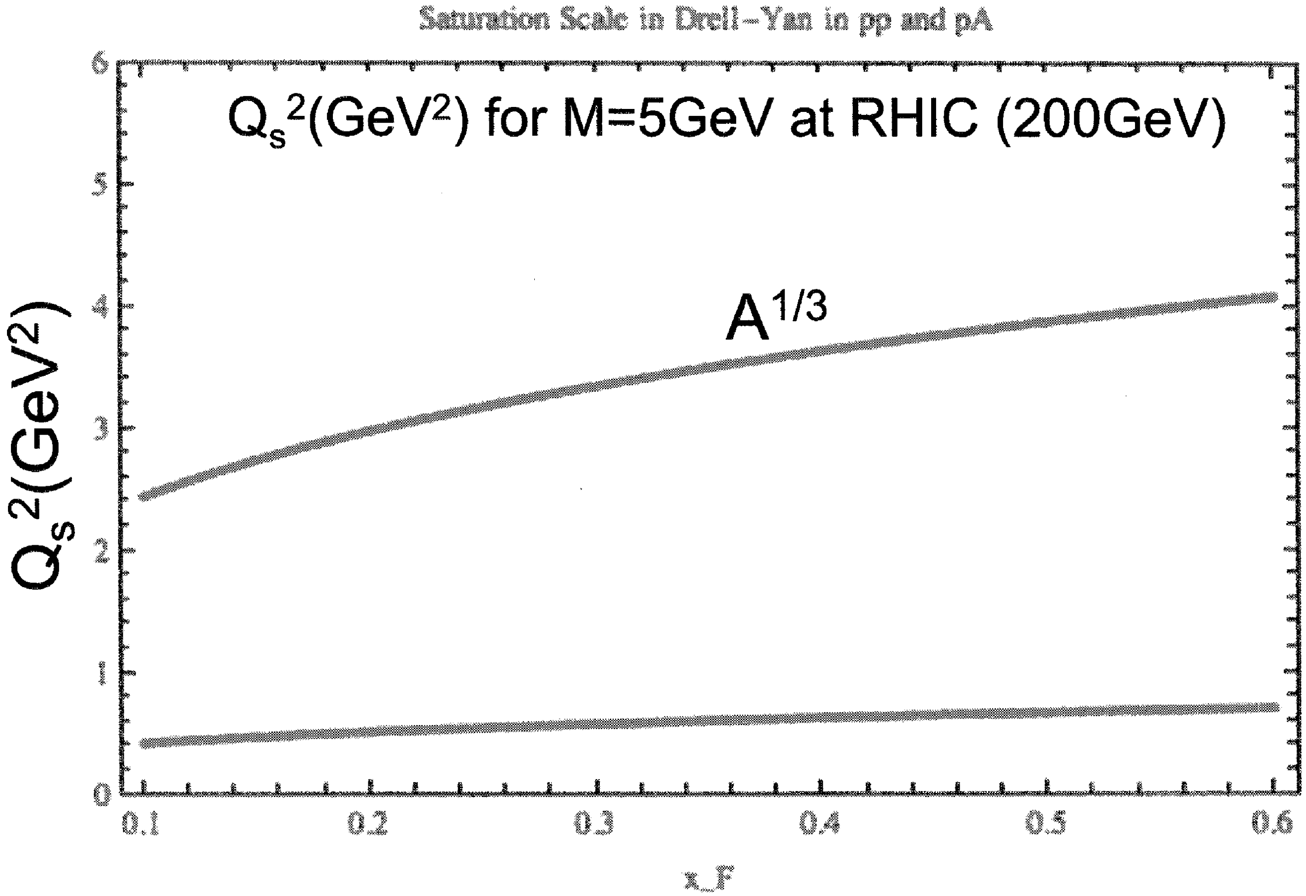
- Inclusive cross section
  - Invariant mass not so large compared to the saturation scale
- Pt dependent observables
  - Directly probe the unintegrated gluon distributions
  - Correlation of DY-hadron
    - *Al's, Bowen's talks*

How relevant is the saturation scale at RHIC



For typical
Range of lepton
Pair mass at
RHIC, Saturation
Is going to
Be important

DGLAP shadowing
Will not be enough

Jamal's talk
Anna's talk

Advantage of Low Pt Drell-Yan

- Direct probe for the transverse momentum dependence of partons
  - Saturation effects explicitly show up in the transverse momentum distribution
- Factorization can be argued for large Q
- Related to the TMD factorization
- Complementary study in SIDIS

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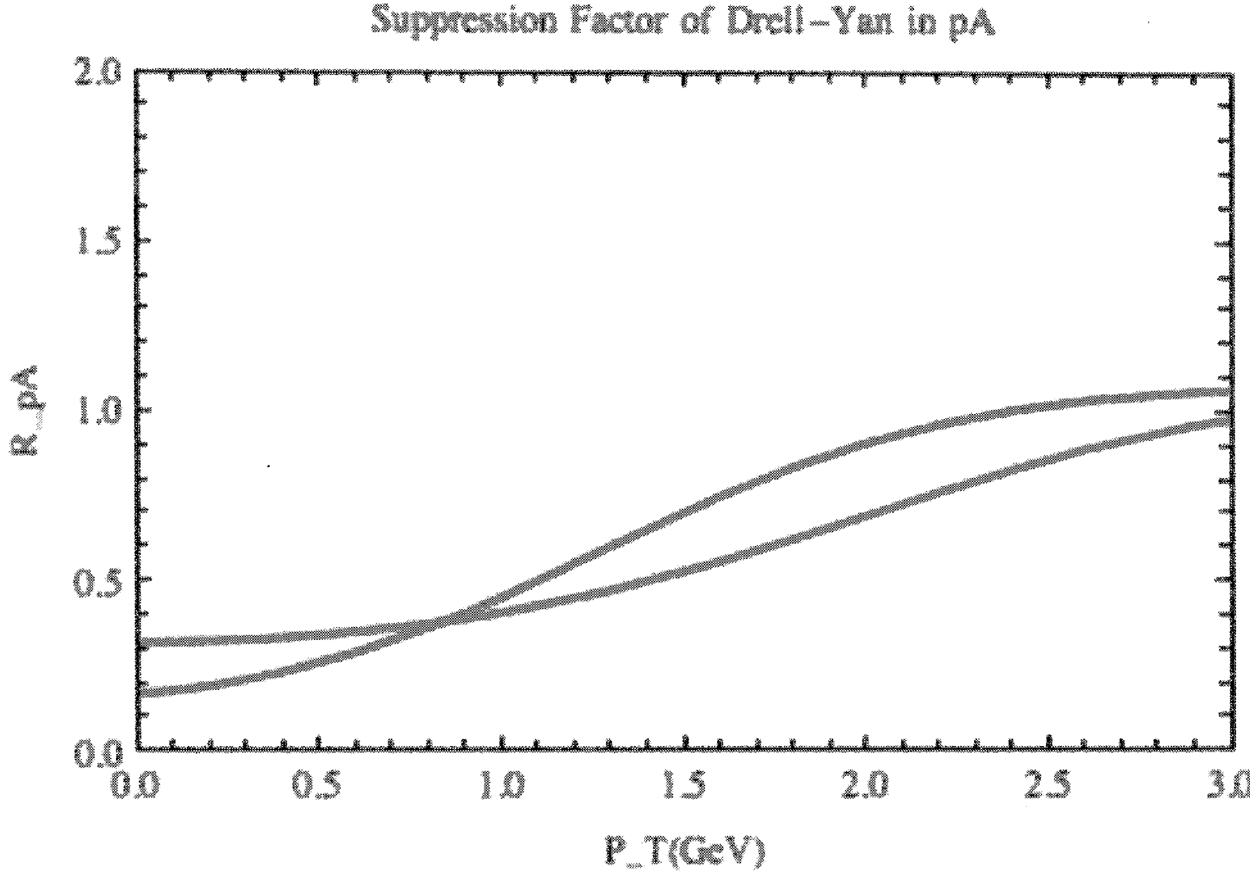
Pt dependence of the Nuclear suppression



$$R_{pA} = \frac{d\sigma^{pA\to\gamma^*}}{A d\sigma^{pp\to\gamma^*}}$$

→ With smearing effects

See also, Guo,Qiu,Zhang, 00

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Pt dependence for A_N

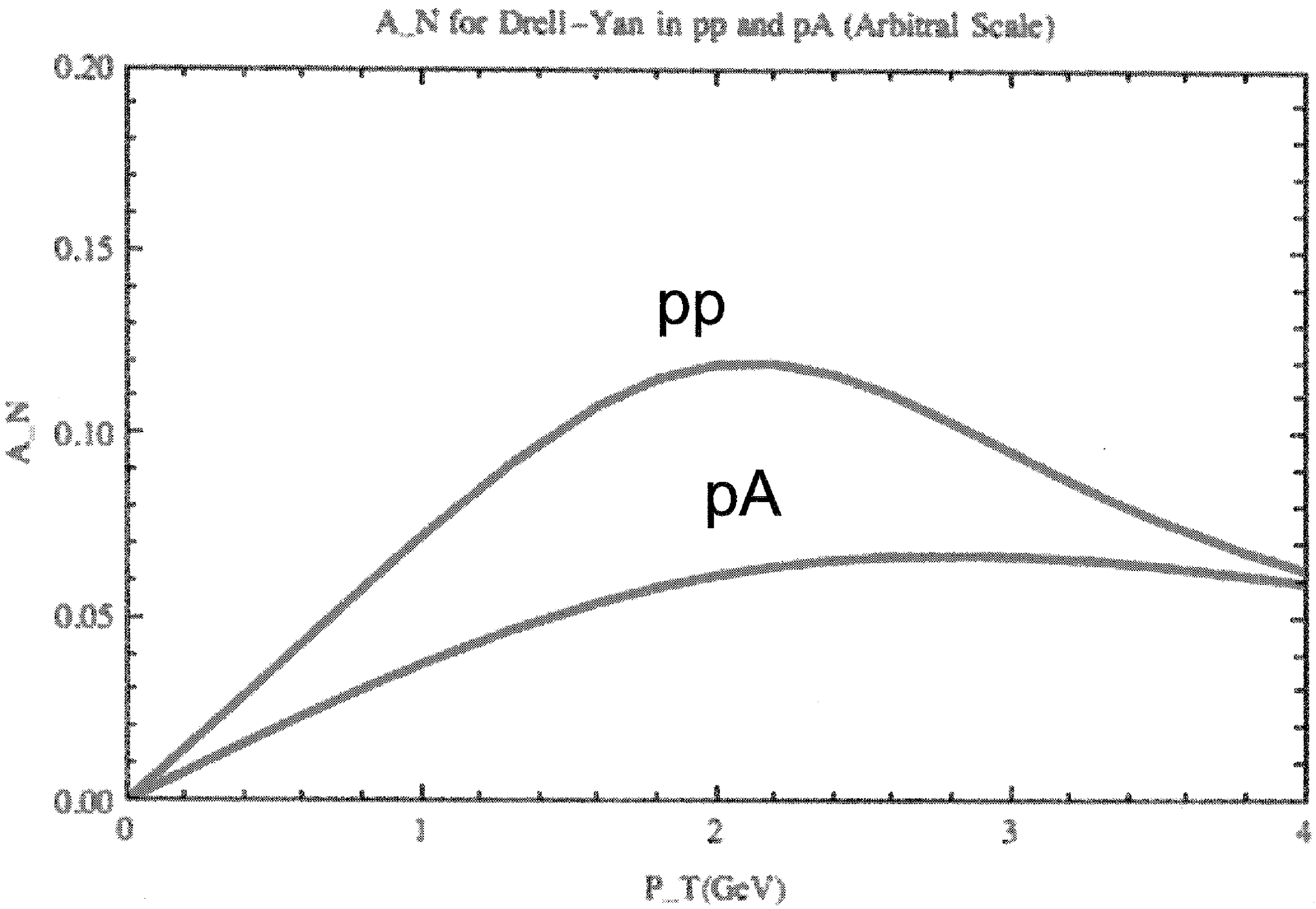


Illustration purpose

Trivial assumption For the Sivers Function

Full calculations Underway

Similar analysis for Pion A_N

TMD Universality

P.J. Mulders
Nikhef and VU University, Amsterdam

The basic idea of PDFs is achieving a factorized description with soft and hard parts, soft parts being portable and hard parts being calculable. In the leading contributions at high energies, the PDFs can be interpreted as probabilities. Beyond the collinear treatment one considers not only the dependence on partonic momentum fractions x, but also the dependence on the transverse momentum p_T of the partons. Experimentally, transverse momentum dependent functions (TMDs) provide a rich phenomenology of azimuthal asymmetries for produced hadrons or jet-jet asymmetries. Furthermore inclusion of transverse momentum dependence provides an explanation for single spin asymmetries.

An important issue is the universality of TMDs, which we study for some characteristic hard processes, where we focus on the pecularities coming from the color flow in the hard part. This color flow in the hard process gives rises to a variety of Wilson lines in the description of the cross section. These give rise to color entanglement, in particular in situations that the color flow is not just a simple transfer of color from initial or final state.

We argue that these Wilson lines can be combined into the appropriate gauge links for TMD correlators in cases where only the transverse momentum of partons in a single (incoming) hadron is relevant (1-parton un-integrated or 1PU processes). Such a situation occurs in single weighted cross sections, which consists of a sum of 1PU processes or if absence of any polarization makes all explicit transverse momentum effects vanish. For 1PU processes one finds TMDs with a complex gauge link structure depending on the color flow of the hard process. In the case of single weighted cross sections the results are the gluonic pole or Qiu-Sterman matrix elements appearing with calculable color factors.

I acknowledge discussions with Maarten Buffing (VU), Ted Rogers (VU) and Mert Aybat (VU and Nikhef). This research is part of the research programme of the Foundation for Fundamental Research of Matter and the National Organisation for Scientific Research (NOW). It is also part of the FP7 EU programme Hadron Physics (No 227431).

Summary of talk given at the Workshop on Opportunities for DY at RHIC, Brookhaven National Laboratory, May 11-13, 2001

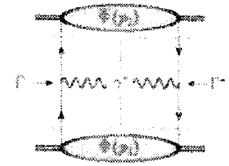
Introduction

- Isolating hard process (factorization)
  - Study of quark and gluon structure of hadrons
  - Account for hadronic physics to study hard process
- Beyond collinear approach
  - Include mismatch of parton momentum p and xP (fraction of hadron momentum)
  - TMDs with novel features
- Operator structure of TMDs
  - Color gauge invariance as guiding principle
  - Appearance of TMDs in hard processes
  - Gauge links in 1-particle un-integrated (1PU) processes

1

Ralston and Soper 79

Example: Drell-Yan process



$$\sum_s u(p_1,s)\,\overline{u}(p_1,s)$$
$$\Rightarrow \Phi(p_1,P_1) \sim (p\!\!/_1 + m) f(p_1)$$

- High energy limits number of soft matrix elements that contribute (twist expansion).
- Expand parton momenta (for DY take e.g. $n = P_2/P_1.P_2$)

$$p = xP^\mu + p_T^\mu + \sigma n^\mu \qquad x = p^+ = p.n \sim 1$$
$$\sim Q \quad \sim M \quad \sim M^2/Q \qquad \sigma = p.P - xM^2 \sim M^2$$

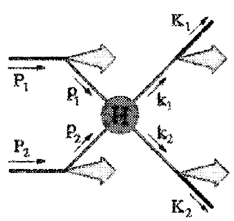
- For meaningful separation of hard and soft, integrate over p.P and look at $\Phi(x,p_T)$. This shows that separation fails beyond 'twist 3'.

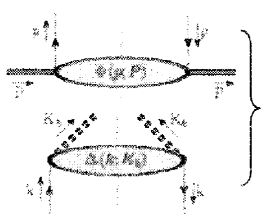
3

PDFs and PFFs

Basic idea of PDFs is to get a full factorized description of high energy scattering processes

$$\hat{\sigma} = |H(p_1,p_2,\ldots)|^2 \quad \text{calculable}$$





defined (!) & portable

$$\sigma(P_1,P_2,\ldots) = \iiint \ldots dp_1 \ldots \Phi_a(p_1,P_1;\mu) \otimes \Phi_b(p_2,P_2;\mu)$$
$$\otimes\, \hat{\sigma}_{ab,c\ldots}(p_1,p_2,\ldots;\mu) \otimes \Delta_c(k_1,K_1;\mu)\ldots.$$

Give a meaning to integration variables!

2

Jaffe (1984), Diehl & Gousset (1998),

Integrated quark correlators: collinear and TMD

- Rather than considering general correlator $\Phi(p,P,\ldots)$, one integrates over p.P = p⁻ (~M_R^2, which is of order M^2)

$$\Phi_{ij}^q(x,p_T;n) = \int \frac{d(\xi.P)\,d^2\xi_T}{(2\pi)^3}\, e^{ip.\xi} \langle P|\overline{\psi}_j(0)\,\psi_i(\xi)|P\rangle_{\xi.n=0} \qquad \text{TMD}$$

lightfront

- and/or p_T (which is of order 1)

$$\Phi_{ij}^q(x;n) = \int \frac{d(\xi.P)}{(2\pi)}\, e^{ip.\xi} \langle P|\overline{\psi}_j(0)\,\psi_i(\xi)|P\rangle_{\xi.n=\xi_T=0} \qquad \text{collinear}$$

lightcone

- The integration over p^- = p.P makes time-ordering automatic. This works for $\Phi(x)$ and $\Phi(x,p_T)$
- This allows the interpretation of soft (squared) matrix elements as forward antiquark-target amplitudes (untruncated!), which satisfy particular analyticity and support properties, etc.

4

Boer & Vogelsang

Relevance of transverse momenta?

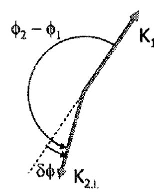
$p_1 \approx x_1 P_1 + p_{1T}$

$p_2 \approx x_2 P_2 + p_{2T}$

- At high energies fractional parton momenta fixed by kinematics (external momenta)

DY $\quad x_1 = p_1.n = \dfrac{p_1.P_2}{P_1.P_2} = \dfrac{q.P_2}{P_1.P_2}$

- Also possible for transverse momenta of partons



pp-scattering

DY $\quad q_T = q - x_1 P_1 - x_2 P_2 = p_{1T} + p_{2T}$

2-particle inclusive hadron-hadron scattering

$$q_T = z_1^{-1} K_1 + z_2^{-1} K_2 - x_1 P_1 - x_2 P_2$$
$$= p_{1T} + p_{2T} - k_{1T} - k_{2T}$$

Second scale!

Care is needed: we need more than one hadron and knowledge of hard process(es)!

Twist expansion of (non-local) correlators

- Dimensional analysis to determine importance of matrix elements (just as for local operators)
- maximize contractions with n to get leading contributions

$$\dim[\overline{\psi}(0)\not{n}\psi(\xi)] = 2$$
$$\dim[F^{n\alpha}(0)F^{n\beta}(\xi)] = 2$$

- 'Good' fermion fields and 'transverse' gauge fields
- and in addition any number of n.A(ξ) = $A^n(x)$ fields (dimension zero!) but in color gauge invariant combinations

dim 0: $\quad i\partial^n \rightarrow iD^n = i\partial^n + gA^n$

dim 1: $\quad i\partial_T^\alpha \rightarrow iD_T^\alpha = i\partial_T^\alpha + gA_T^\alpha$

- Transverse momentum involves 'twist 3'.

Oppertunities of TMDs

- TMD quark correlators (leading part, unpolarized) including T-odd part

$$\Phi^{[\pm]q}(x,p_T) = \left(f_1^q(x,p_T^2) \pm i h_1^{\perp q}(x,p_T^2)\frac{\not{p}_T}{M}\right)\frac{\not{P}}{2}$$

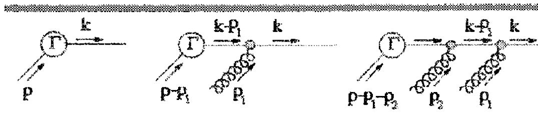
- Interpretation: quark momentum distribution $f_1^q(x,p_T)$ and its transverse spin polarization $h_1^{\perp q}(x,p_T)$ both in an unpolarized hadron
- The function $h_1^{\perp q}(x,p_T)$ is T-odd (momentum-spin correlations!)
- TMD gluon correlators (leading part, unpolarized)

$$\Phi_g^{\mu\nu}(x,p_T) = \frac{1}{2x}\left(-g_T^{\mu\nu} f_1^g(x,p_T^2) + \left(\frac{p_T^\mu p_T^\nu + \frac{1}{2} g_T^{\mu\nu}}{M^2}\right) h_1^{\perp g}(x,p_T^2)\right)$$

- Interpretation: gluon momentum distribution $f_1^g(x,p_T)$ and its linear polarization $h_1^{\perp g}(x,p_T)$ in an unpolarized hadron (both are T-even)

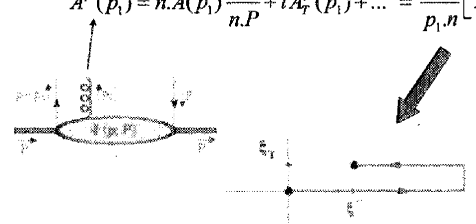
A.V. Belitsky, X.Ji, F. Yuan, NPB 656 (2003) 165
D. Boer, PJM, F. Pijlman, NPB 667 (2003) 201

Gauge link results from leading gluons



Expand gluon fields and reshuffle a bit:

$$A^\mu(p_1) = n.A(p_1)\frac{P^\mu}{n.P} + iA_T^\mu(p_1) + \ldots = \frac{1}{p_1.n}\left[A^n(p_1)\,p_1^\mu + iG_T^{n\mu}(p_1) + \ldots\right]$$



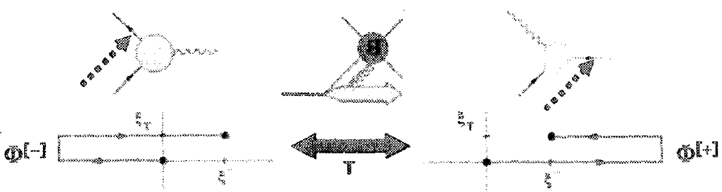
Coupling only to final state partons, the collinear gluons add up to a U_+ gauge link, (with transverse connection from $A_T^\alpha \rightarrow G^{n\alpha}$ reshuffling)

Gauge-invariant definition of TMDs: which gauge links?

$$\Phi_{ij}^{q[C]}(x,p_T;n) = \int \frac{d(\xi.P)d^2\xi_T}{(2\pi)^3} e^{ip.\xi} \langle P|\overline{\psi}_j(0)U_{[0,\xi]}^{[C]}\psi_i(\xi)|P\rangle_{\xi.n=0} \quad \text{TMD}$$

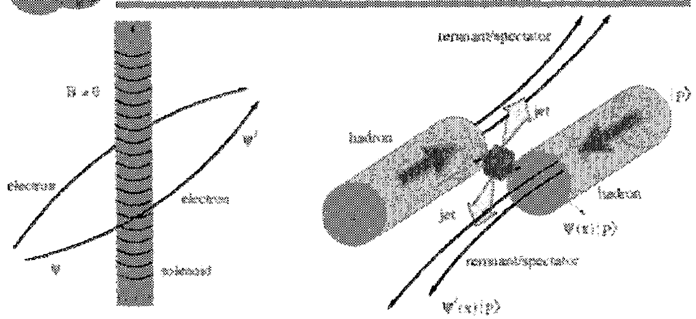
$$\Phi_{ij}^{q}(x;n) = \int \frac{d(\xi.P)}{(2\pi)} e^{ip.\xi} \langle P|\overline{\psi}_j(0)U_{[0,\xi]}^{[n]}\psi_i(\xi)|P\rangle_{\xi.n=\xi_T=0} \quad \text{collinear}$$

- Even simplest links for TMD correlators non-trivial:



These merge into a 'simple' Wilson line in collinear (p_T-integrated) case

Featuring: phases in gauge theories



$$\psi' = P e^{ie\int ds.A}\psi \qquad \psi_i(x)|P\rangle = P e^{-ig\int_x^{x'} ds_\mu A^\mu}\psi_i(x')|P\rangle$$

C Bomhof, PJM, F Pijlman; EPJ C 47 (2006) 147
F Dominguez, B-W Xiao, F Yuan, PRL 106 (2011) 022301

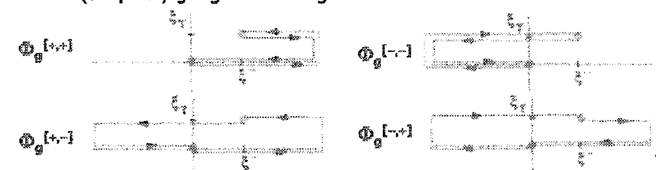
TMD correlators: gluons

$$\Phi_g^{\alpha\beta[C,C']}(x,p_T;n) = \int \frac{d(\xi.P)d^2\xi_T}{(2\pi)^3} e^{ip.\xi} \langle P|U_{[\xi,0]}^{[C]}F^{n\alpha}(0)U_{[0,\xi]}^{[C']}F^{n\beta}(\xi)|P\rangle_{\xi.n=0}$$

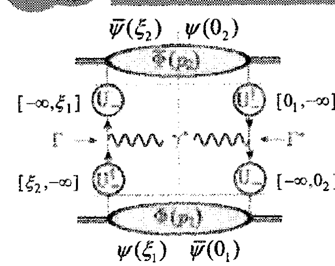
- The most general TMD gluon correlator contains two links, which in general can have different paths.
- Note that standard field displacement involves C = C'

$$F^{\alpha\beta}(\xi) \rightarrow U_{[\eta,\xi]}^{[C]}F^{\alpha\beta}(\xi)U_{[\xi,\eta]}^{[C]}$$

- Basic (simplest) gauge links for gluon TMD correlators:



Gauge invariance for DY



$$U_{[0_1,-\infty]}U_{[-\infty,\xi_1]}U_{[\xi_2,-\infty]}U_{[-\infty,0_2]} = W_{-[0_1,\xi_1]}^{[n]}W_{-[0_2,\xi_2]}^{[n]\dagger} = W_-^{[n]}[p_1]W_-^{[n]\dagger}[p_2]$$

Strategy: transverse moments

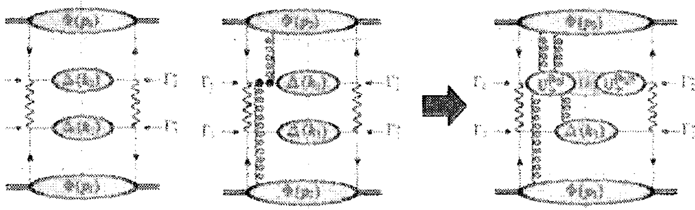
$$d\sigma_{DY} = Tr_c[W_-^{[p_2]}[p_1]\Phi_q(x_1,p_{1T})]Tr_c[\Phi_{\bar{q}}(x_2,p_{2T})W_-^{[p_1]\dagger}[p_2]]\tfrac{1}{N_c}\Gamma\Gamma^*$$
$$= \Phi_q^{[-]}(x_1,p_{1T})\Phi_{\bar{q}}^{[-\dagger]}(x_2,p_{2T})\hat{\sigma}_{q\bar{q}\to\gamma}$$

Employing simple color flow possibilities, e.g. in gg → γγ

J. Qiu, M. Schlegel, W. Vogelsang, ArXiv 1103.3861 (hep-ph)

T.C. Rogers, PJM, PR D81 (2010) 094006

Complications (example: qq → qq)

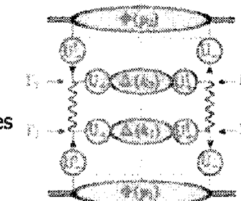


$U_+^{[n]}[p_1,p_2,k_1]$ modifies color flow, spoiling universality (and factorization)

$$U_{-\infty}^{[k](1)}(p,p')...\Gamma...\psi(p)...\psi(p') = \frac{1}{2}\{U_{-\infty}^{[k](1)}(p), U_{+\infty}^{[k](1)}(p')\}...\Gamma...\psi(p)...\psi(p')$$

1-parton unintegrated

- Resummation of all phases spoils universality
- Transverse moments (p_T-weighting) feels entanglement
- Special situations for only one transverse momentum, as in single weighted asymmetries

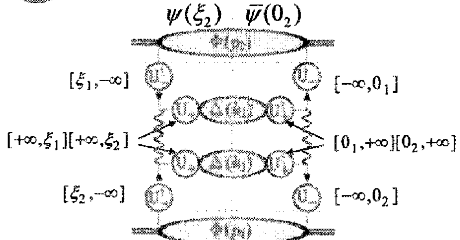


$$\int d^2q_T\, q_T^\alpha ... \int d^2p_{1T} \int d^2p_{2T} ... \delta^2(q_T - p_{1T} - p_{2T})$$
$$= \int d^2p_{1T}\, p_{1T}^\alpha \int d^2p_{2T} ... + \int d^2p_{1T} \int d^2p_{2T}\, p_{2T}^\alpha ...$$

- But: it does produces 'complex' gauge links
- Applications of 1PU is looking for gluon $h_1^{\perp g}$ (linear gluon polarization) using jet or heavy quark production in ep scattering (e.g. EIC), D. Boer, S.J. Brodsky, PJM, C. Pisano, PRL 106 (2011) 132001

M.G.A. Buffing, PJM, in preparation

Color disentanglement for 1PU



Collinear treatment for all-but-one parton (p_1):

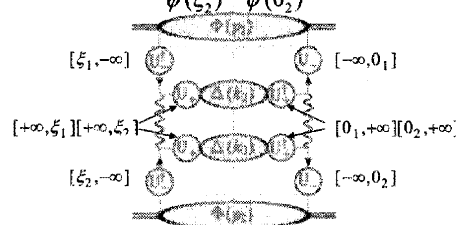
$$\xi_{2t} \rightarrow 0_{2T}$$

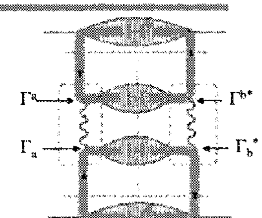
$$\sigma \sim Tr_c[\Phi^{[(\square)+]}(x_1, p_{1T})\Gamma_b^* \Delta(z_1)\Gamma_a]$$
$$\times Tr_c[\Phi(x_2)\Gamma^{b*}\Delta(z_2)\Gamma^a]$$

$$U_{[0_2,+\infty][0_1,+\infty]}U_{[+\infty,\xi_2][+\infty,\xi_1]}U_{[\xi_1,-\infty]}U_{[-\infty,0_1]} = W^{[n]}_{[0_2,\xi_2]}W^{[n]}_{+[0_1,\xi_1]}W^{[n]\dagger}_{-[0_1,\xi_1]} = W^{[n]}[p_2]W^{[n]}_{\square}[p_1]$$
$$U_{[-\infty,0_2]}U_{[0_1,+\infty][0_2,+\infty]}U_{[+\infty,\xi_1][+\infty,\xi_2]}U_{[\xi_2,-\infty]} = U_{[0_1,+\infty]}U_{[+\infty,\xi_1]} = W^{[n]}_{+[0_1,\xi_1]}$$

M.G.A. Buffing, PJM, in preparation

Full color disentanglement? NO!





$$\sigma \not\sim Tr_c[\Phi^{[(\square)+]}(p_1)\Gamma_b^* \Delta^{[(\square)-\dagger]}(k_1)\Gamma_a]$$
$$\times Tr_c[\Phi^{[(\square)+]}(p_2)\Gamma^{b*}\Delta^{[(\square)-\dagger]}(k_2)\Gamma^a]$$

Loop 1: $U_{[0_2,+\infty][0_1,+\infty]}U_{[+\infty,\xi_2][+\infty,\xi_1]}U_{[\xi_1,-\infty]}U_{[-\infty,0_1]} = W^{[n]}_{+[0_2,\xi_2]}W^{[n]}_{+[0_1,\xi_1]}W^{[n]\dagger}_{-[0_1,\xi_1]}$
$= W_+^{[n]}[p_2]W_{\square}^{[n]}[p_1]$

Result for integrated cross section

$$\frac{d\sigma}{d^2 p_{1T}} \sim \sum_{D,abc} \Phi_a^{[C_1(D)]}(x_1, p_{1T})\Phi_b(x_2)\,\hat{\sigma}^{[D]}_{ab\to c\ldots}\,\Delta_c(z_1)\ldots \qquad \text{(1PU)}$$

Collinear cross section

$$\Phi^{[\boxtimes]}(x) = \int d^2 p_T\; \Phi^{[C]}(x, p_T)$$

Gauge link structure becomes irrelevant!

$$\sigma \sim \sum_{abc} \Phi_a(x_1)\Phi_b(x_2)\,\hat{\sigma}_{ab\to c\ldots}\,\Delta_c(z_1)\ldots$$

$$\hat{\sigma}_{ab\to c\ldots} = \sum_D \hat{\sigma}^{[D]}_{ab\to c\ldots} \qquad \text{(partonic cross section)}$$

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APPLICATIONS

Result for single weighted cross section

$$\frac{d\sigma}{d^2 p_{1T}} \sim \sum_{D,abc} \Phi_a^{[C_1(D)]}(x_1, p_{1T})\Phi_b(x_2)\,\hat{\sigma}^{[D]}_{ab\to c\ldots}\,\Delta_c(z_1)\ldots \qquad \text{(1PU)}$$

$$\left\langle p_{1T}^{\alpha}\sigma\right\rangle \sim \sum_{D,abc} \Phi_{\partial\,a}^{\alpha[C(D)]}(x_1)\Phi_b(x_2)\,\hat{\sigma}^{[D]}_{ab\to c\ldots}\,\Delta_c(z_1)\ldots$$

$$\Phi_\partial^{\alpha[C]}(x) = \tilde{\Phi}_\partial^{\alpha[\boxtimes]}(x) + C_G^{[U(C)]}\pi\,\Phi_G^{\alpha[\boxtimes]}(x,x)$$

$$\left\langle p_{1T}^{\alpha}\sigma\right\rangle \sim \sum_{abc} \tilde{\Phi}_{\partial}^{\alpha}(x_1)\Phi_b(x_2)\,\hat{\sigma}_{ab\to c\ldots}\,\Delta_c(z_1)\ldots$$

$\Phi_G(x,x)$ is gluonic pole ($x_1 = 0$) matrix element

T-odd part

$$+\sum_{abc} \pi\Phi_{G\,a}^{\alpha}(x_1,x_1)\Phi_b(x_2)\,\hat{\sigma}_{[a]b\to c\ldots}\,\Delta_c(z_1)\ldots$$

$$\hat{\sigma}_{[a]b\to c\ldots} = \sum_D C_G^{[U(C(D))]}\hat{\sigma}^{[D]}_{ab\to c\ldots} \qquad \text{(gluonic pole cross section)}$$

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APPLICATIONS

Higher p_T moments

- Higher transverse moments

$$\Phi^{[N]\alpha_1\ldots\alpha_N}(x) = \int d^2 p_T\;(p_T^{\alpha_1}\ldots p_T^{\alpha_1} - traces)\,\Phi(x, p_T)$$

- involve yet more functions

$$\tilde{\Phi}_{\partial\partial}^{\alpha\beta}(x),\; \tilde{\Phi}_{\partial G}^{\alpha\beta}(x,x),\; \Phi_{GG}^{\alpha\beta}(x,x,x)$$

- Important application: there are no complications for fragmentation, since the 'extra' functions Δ_G, Δ_{GG}, ... vanish. using the link to 'amplitudes';

L. Gamberg, A. Mukherjee, PJM, PRD 83 (2011) 071503 (R)

- In general, by looking at higher transverse moments at tree-level, one concludes that transverse momentum effects from different initial state hadrons cannot simply factorize.

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SUMMARY

Conclusions

- Color gauge invariance produces a jungle of Wilson lines attached to all parton legs, although the gauge connections themselves have a nicely symmetrized form
- Easy cases are collinear and 1-parton un-integrated (1PU) processes, with in the latter case for the TMD a complex gauge link, depending on the color flow in the tree-level hard process
- Example of 1PU processes are the terms in the sum of contributions to single weighted cross sections
- Single weighted cross sections involve T-even 'normal weighting' and T-odd gluonic pole matrix elements (SSA's)
- Gluonic pole matrix elements in fragmentation correlators vanish, thus treatment of fragmentation TMDs is universal (physical picture: observation of jet direction)
- Furthermore, there is the issue of factorization! (talk Ted Rogers)

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SUMMARY

Gauge Links and TMD-Factorization

Ted Rogers

Vrije Universiteit Amsterdam

I will provide a status overview of transverse momentum dependent factorization theorems, with an emphasis on evolution, universality/non-universality, and the issue of factorization breaking. I will start by reviewing the basic concepts of gauge links and the complications that arise when attempting to define parton correlation functions. I will also describe recent efforts to combine existing implementations of the Collins-Soper-Sterman evolution formalism with fixed scale fits of TMDs. The result is a set of TMD fits in transverse momentum space that include evolution. Emphasis will be placed on the relationship with more standard generalized parton model concepts. I will conclude with a discussion of our future plans to extend TMD phenomenology with evolution.

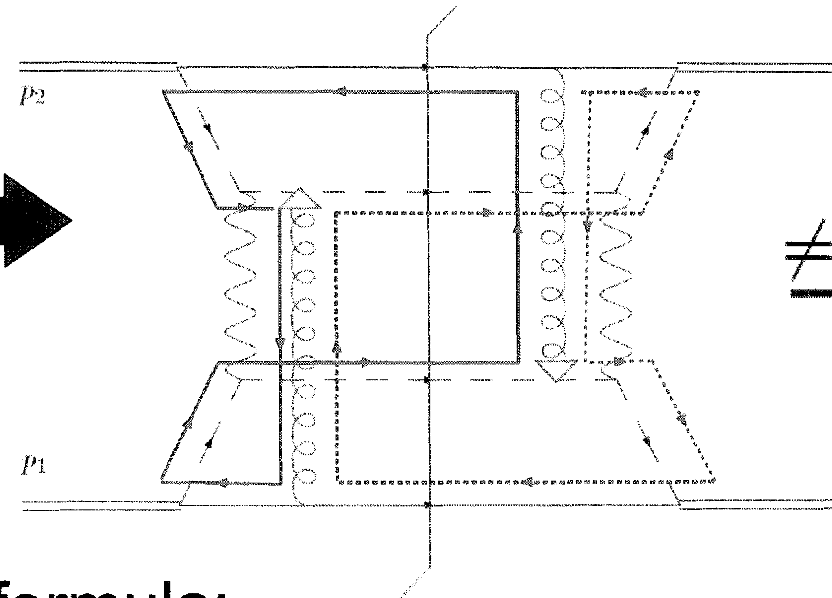
BNL Workshop on Drell-Yan Physics, May 11, 2011

Generalized TMD-factorization breaking:

- Gluons have color.

Actual color structure

Color Entanglement



$\neq 0!$

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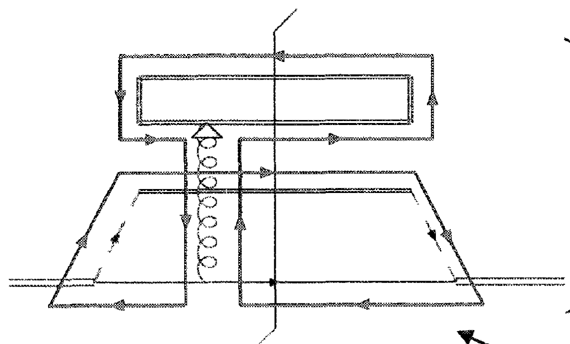
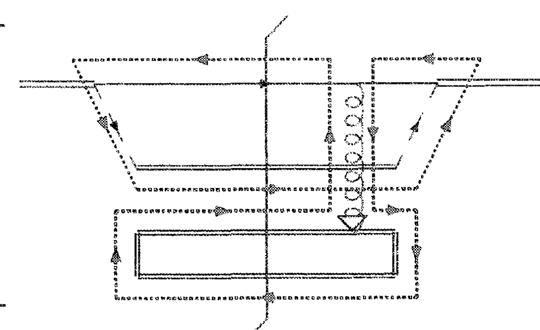
- "generalized" factorization formula:

(TCR, Mulders (2010))

$\mathcal{H}$ x () x () $= 0$

$\mathrm{Tr_C}\,[t^a] = 0$

TMD-Factorization:

- Complications with defining TMDs:
  - Divergences.
  - Wilson lines / gauge links.
  - Universality vs. non-universality.
  - ***Definitions dictated by requirements for factorization!***

- Processes:
  - Semi-Inclusive deep inelastic scattering.
  - Drell-Yan.
  - e^+/e^- annihilation.
  - ~~$p + p \longrightarrow h_1 + h_2 + X$~~ !!

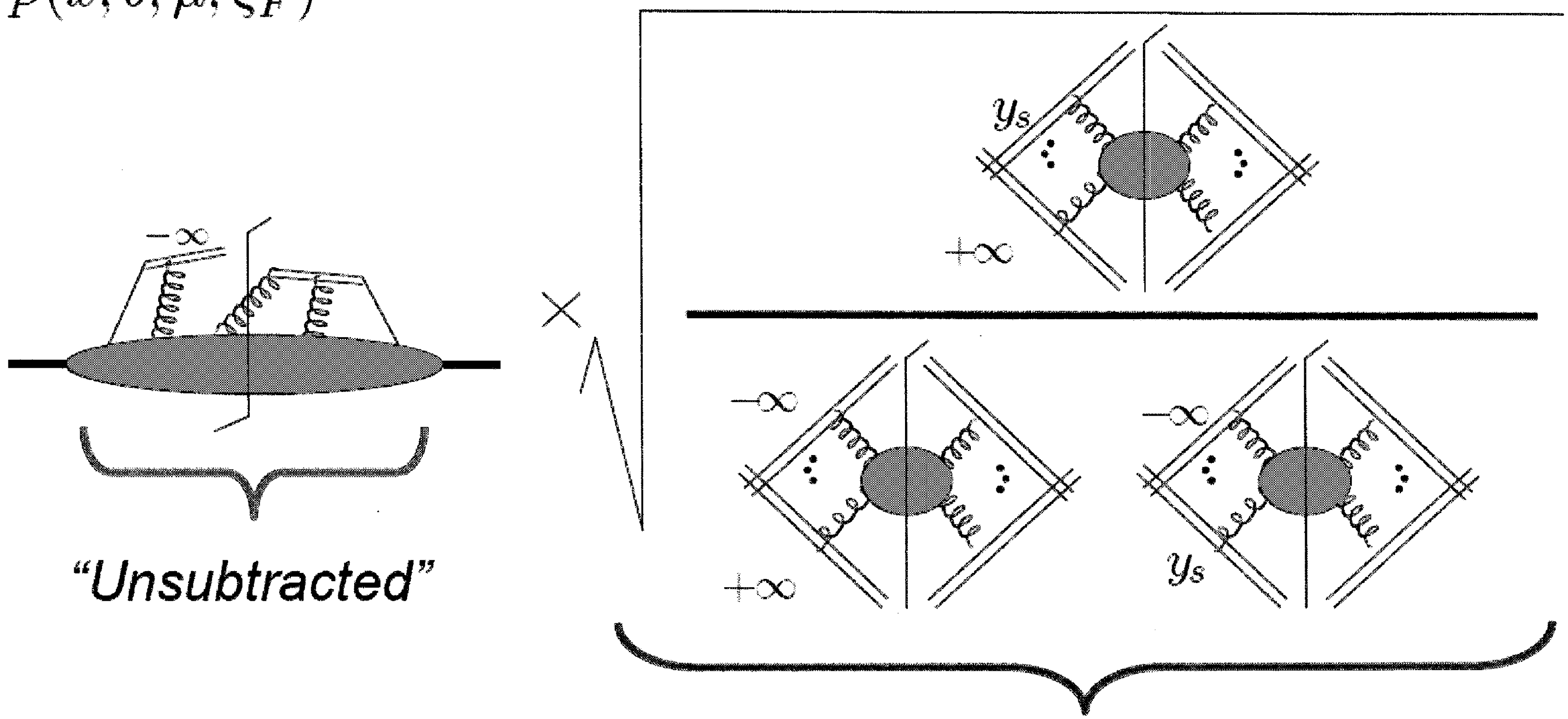
Watch out for sign flips!

- Implementation and TMD phenomenology.
  - Use existing fixed-scale fits / no evolution.
  - Use existing “old fashion” implementation of Collins-Soper-Sterman formalism.
  - ***Full TMD formalism, including evolution.***

    (New Collins Definitions)

TMD PDF, Complete Definition:

$F_{f/P}(x, b; \mu; \zeta_F) =$



Implements Subtractions/Cancellations

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From *Foundations of Perturbative QCD*, J.C. Collins,
(See also, Collins, TMD 2010 Trento Workshop)

<u>*Current Strategy:*</u>

- Use evolution to combine existing fits into unified/global fits that include evolution.

  (S.M. Aybat, TCR (2011))

  – PDFs:
    - Start with DY:

      (Landry et al, (2003); Konychev, Nadolsky (2006)) *(BLNY)*
    - Modify to match to SIDIS:

      (Schweitzer, Teckentrup, Metz (2010)) *(STM)*

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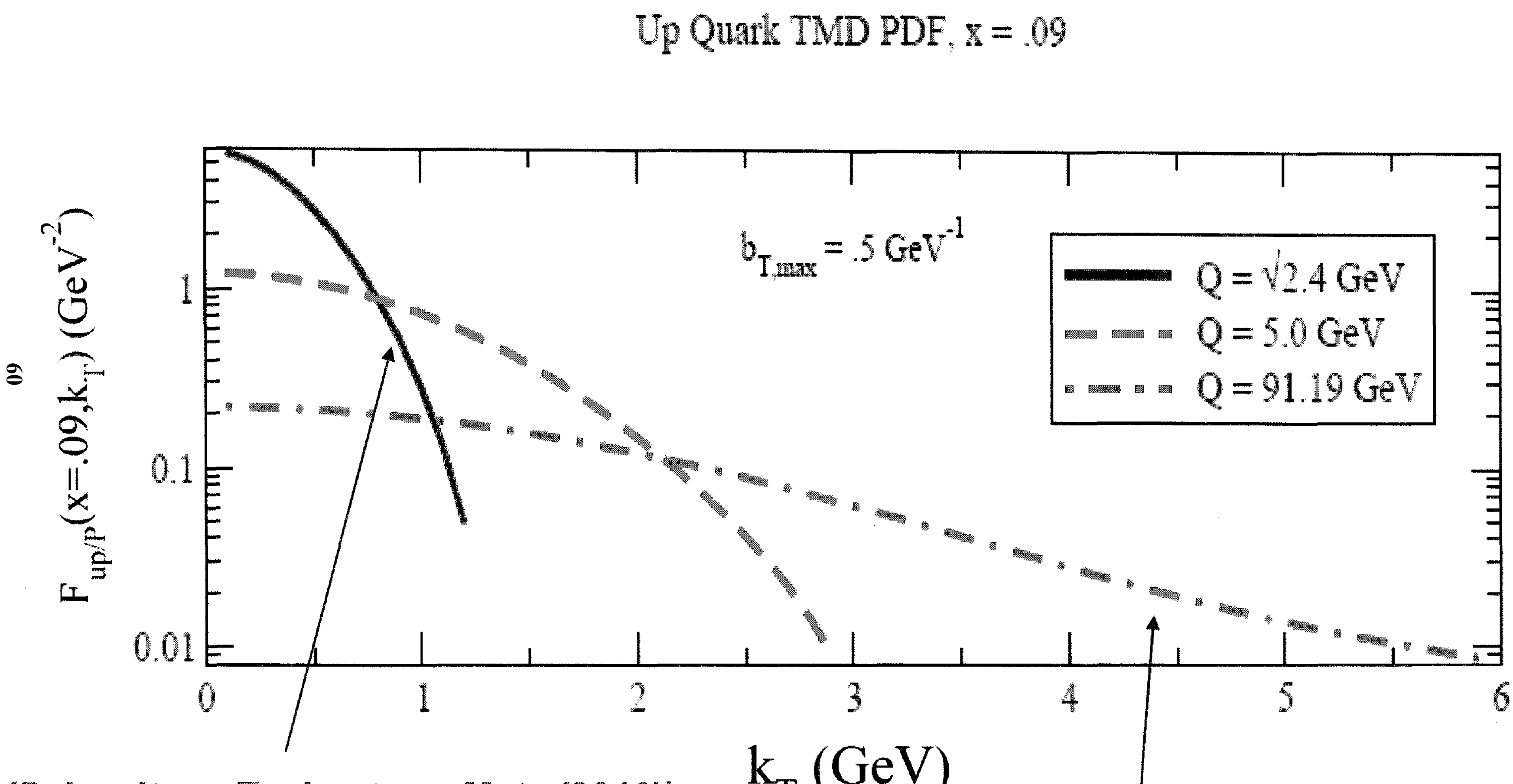
- Can supply explicit, evolved TMD PDF fit.

Evolving TMD PDFs



(Schweitzer, Teckentrup, Metz (2010))

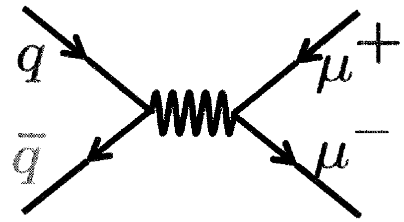
(SIDIS)

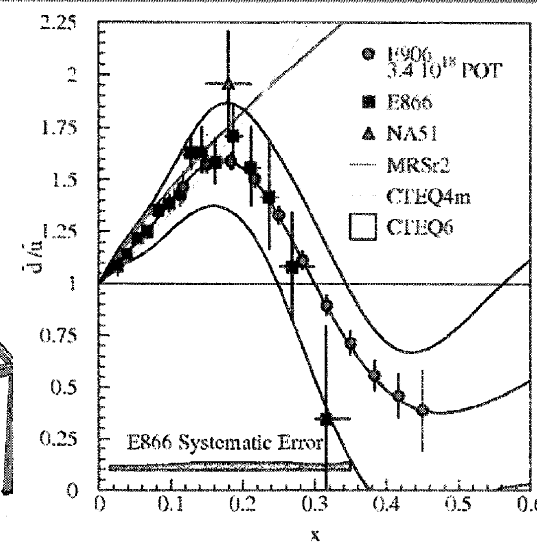
(Landry et al, (2003))

(Drell-Yan)

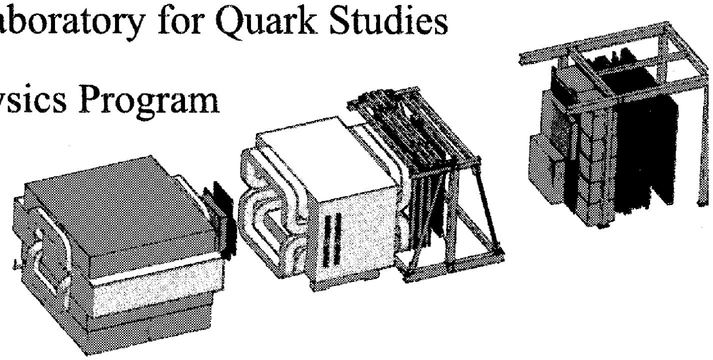
Opportunities with Drell-Yan Scattering at Fermilab

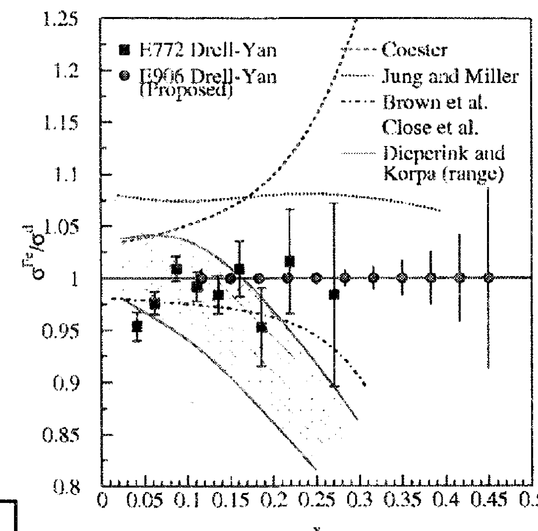
Paul E. Reimer
Physics Division
Argonne National Laboratory



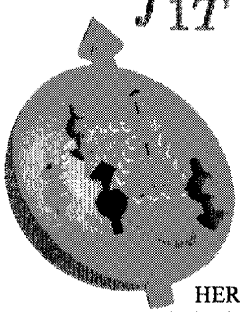


1. The Drell-Yan Process—A Laboratory for Quark Studies
2. Fermilab E-906/SeaQuest Physics Program
   - Sea quark in the proton
   - Sea quarks in the nucleus
   - Angular distributions
3. What can the future hold? Polarized targets or beams?





$$f_{1T}^{\perp}(x,k_T)\Big|_{\rm DIS} = -\, f_{1T}^{\perp}(x,k_T)\Big|_{\rm DY}$$



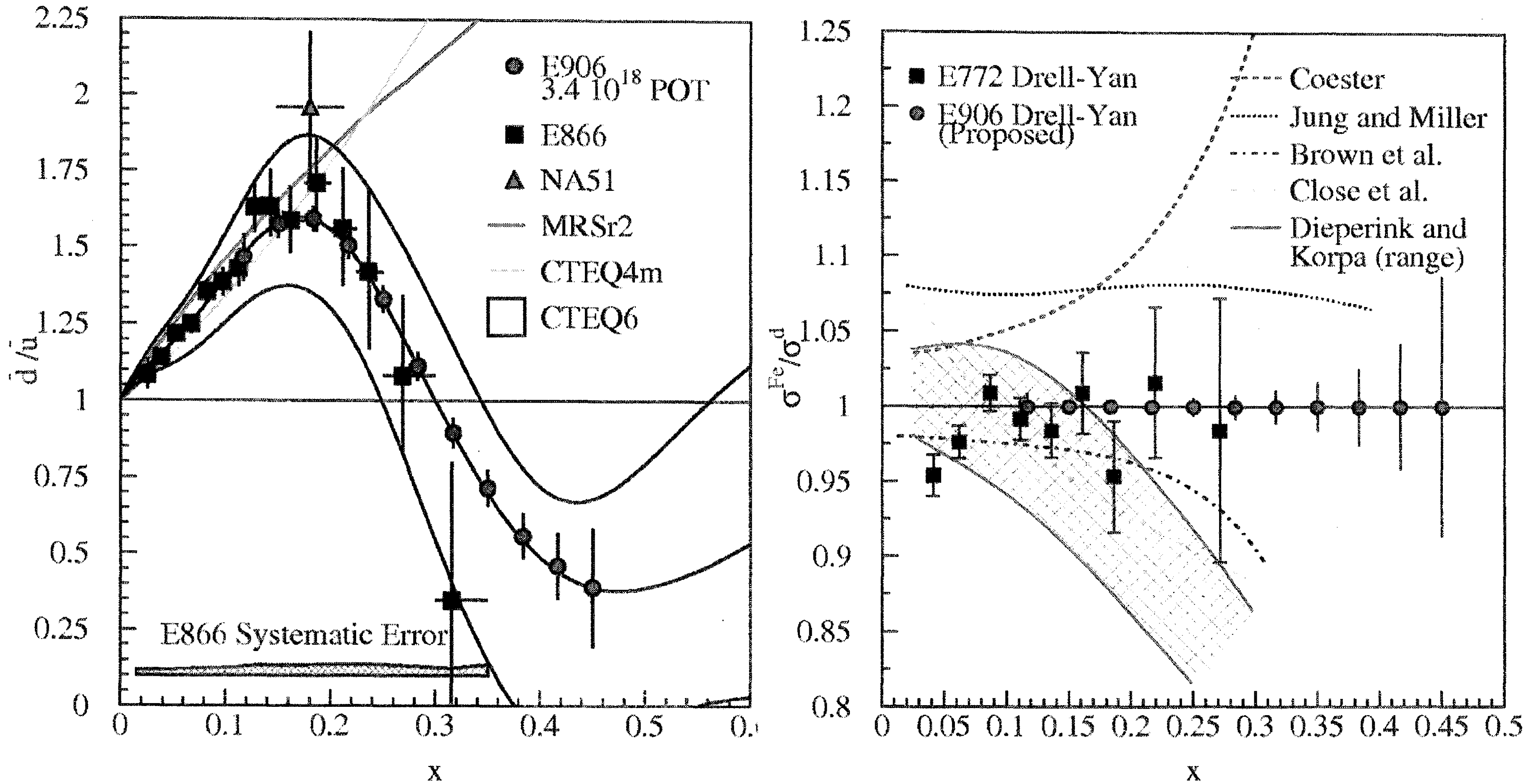
HERMES
U. Elschenbroich

With help from Chiranjib Dutta,
Wolfgang Lorenzon, U. Michigan
and Yuji Goto, RIKEN

This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

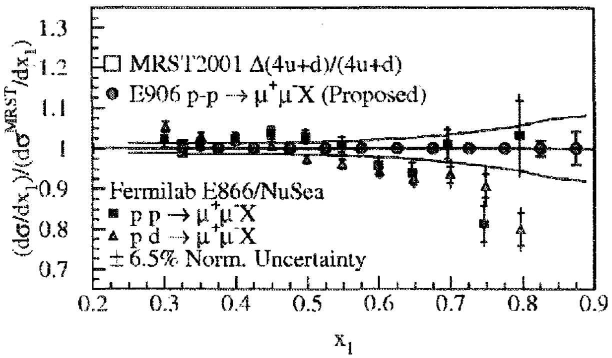
U.S. DEPARTMENT OF ENERGY

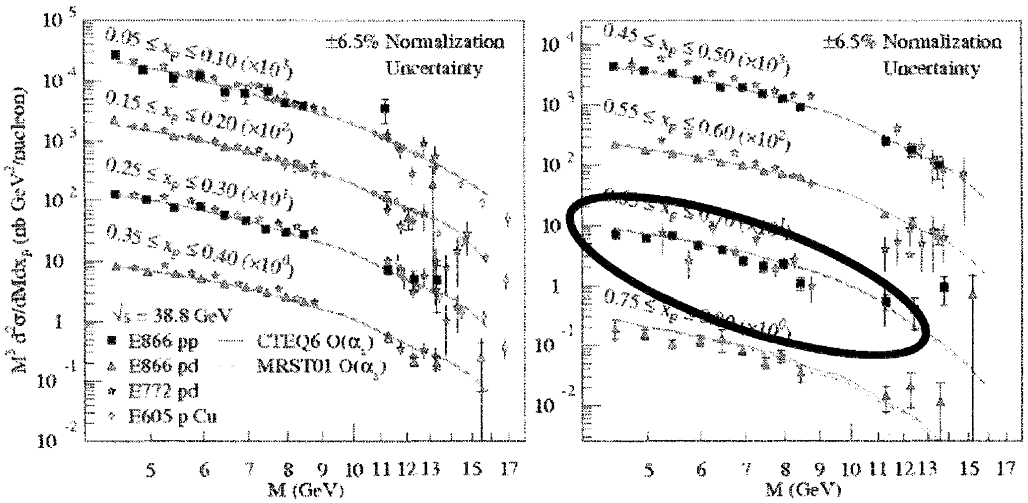
Extracting d-bar/-ubar From Drell-Yan Scattering



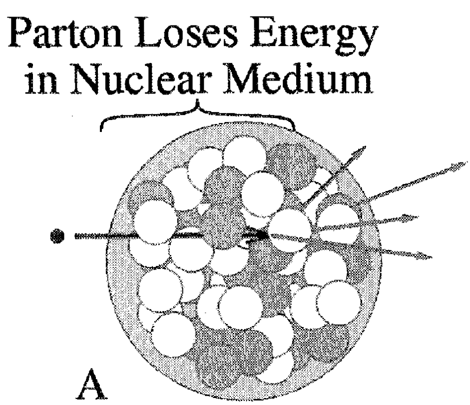
Other Physics from E-906/SeaQuest

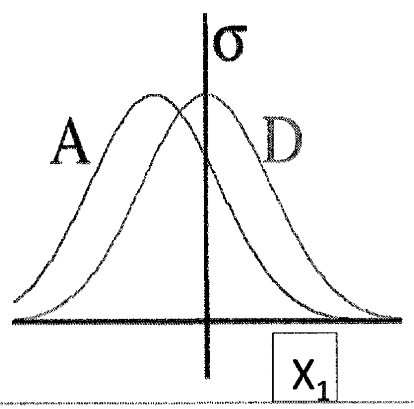
- Absolute High-x_{Bj} Parton Distributions

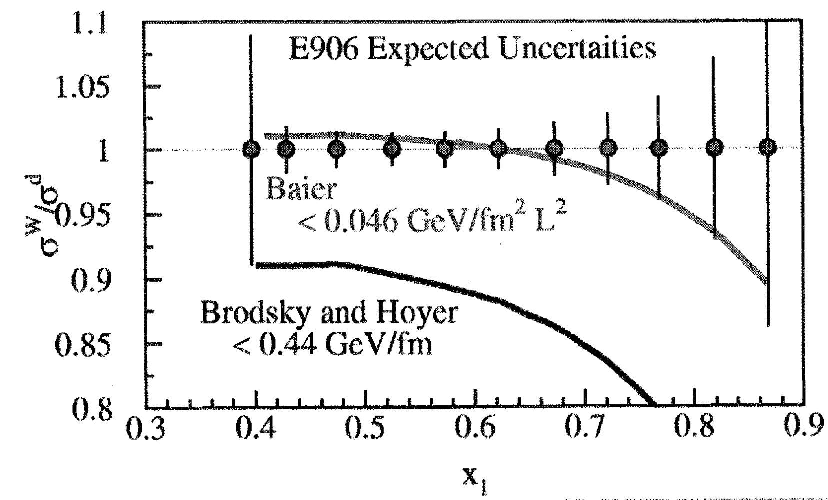




- Partonic Energy Loss in Cold Nuclear Matter

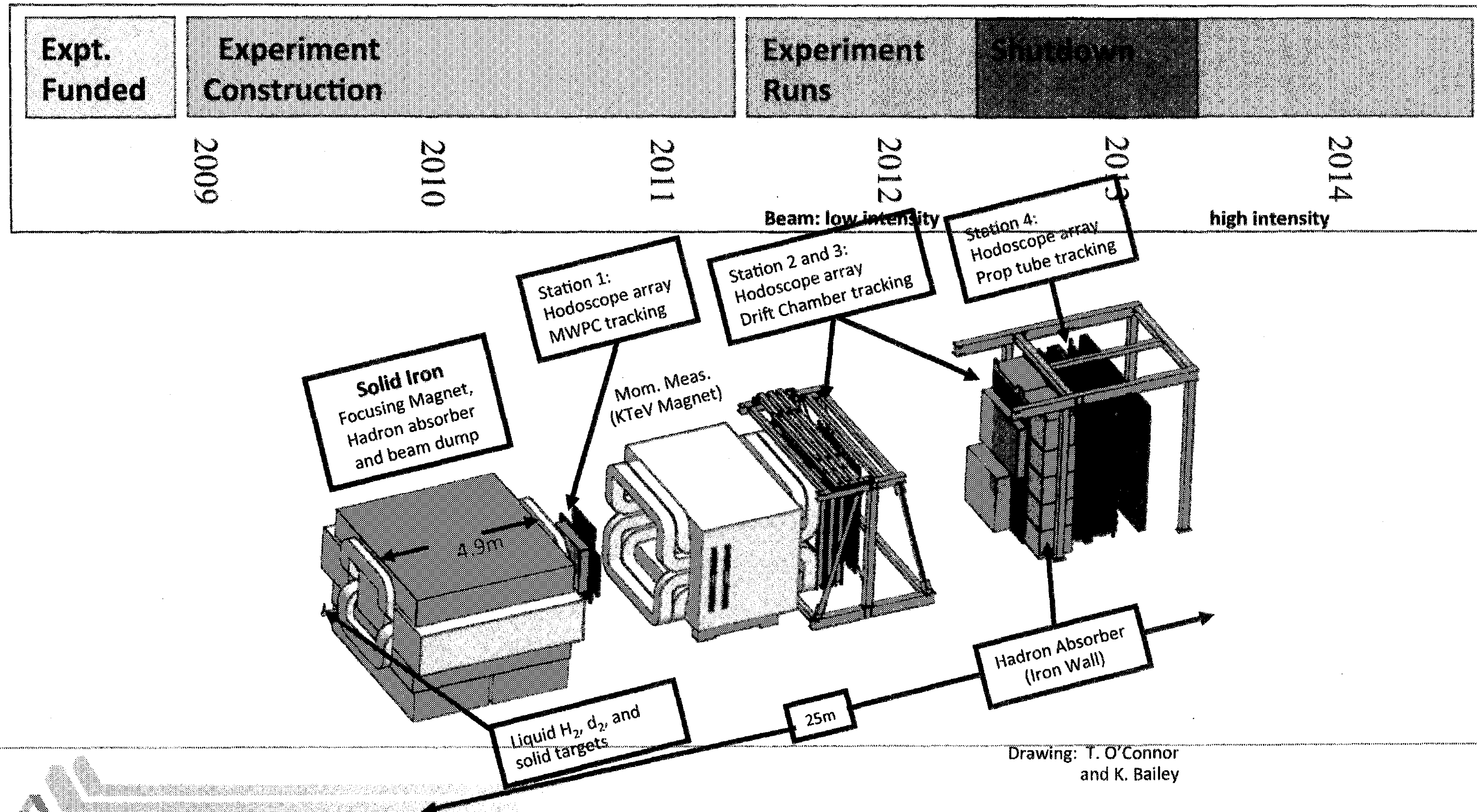






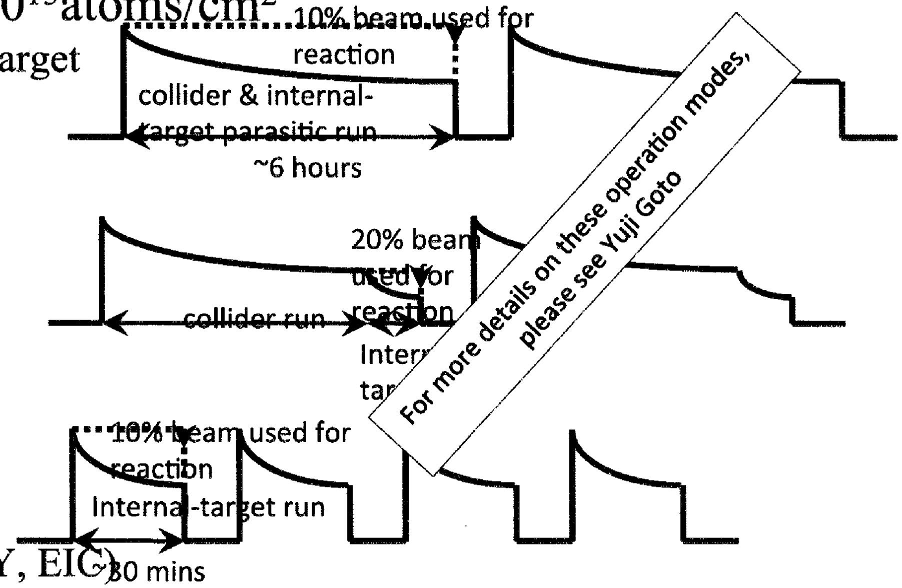
E-906/SeaQuest timeline and plans

- Fermilab PAC approved the experiment in 2001—but experiment was not scheduled due to concerns about "proton economics"
- Fermilab Stage-II Approval granted on 24 December 2008
- Expected first beam in late June 2011

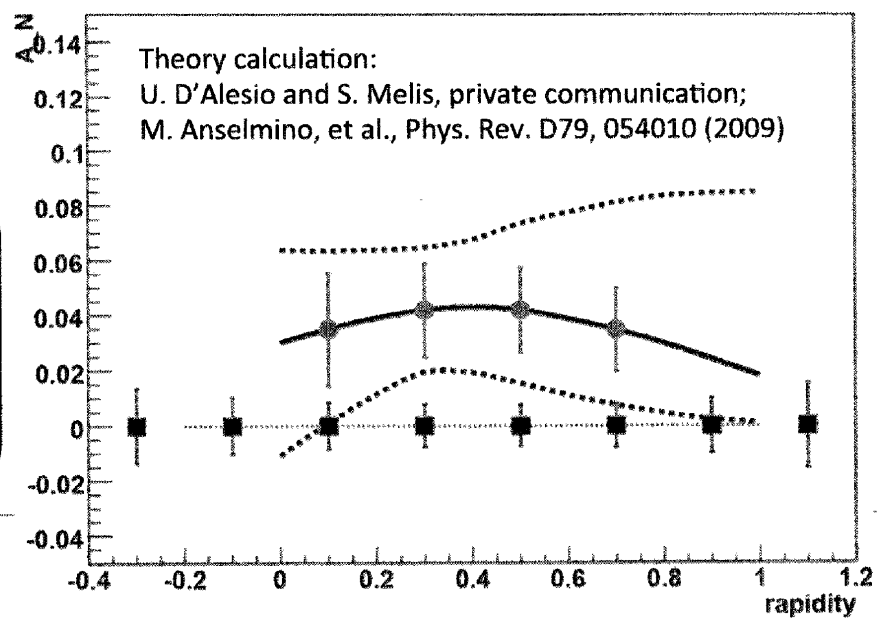


At RHIC?

- Internal Cluster-jet or pellet target 10^{15}atoms/cm^2
  - 50 times thinner than RHIC CNI carbon target
- Operational modes
  - Parasitic
  - End-of-fill (HERMES)
  - Dedicated (in-and-out strike)



- Other questions/obstacles
  - Competition for interaction region (AnDY, EIC)
  - Beam compensation for double dipole spectrometer
  - Beam pipe through spectrometer?

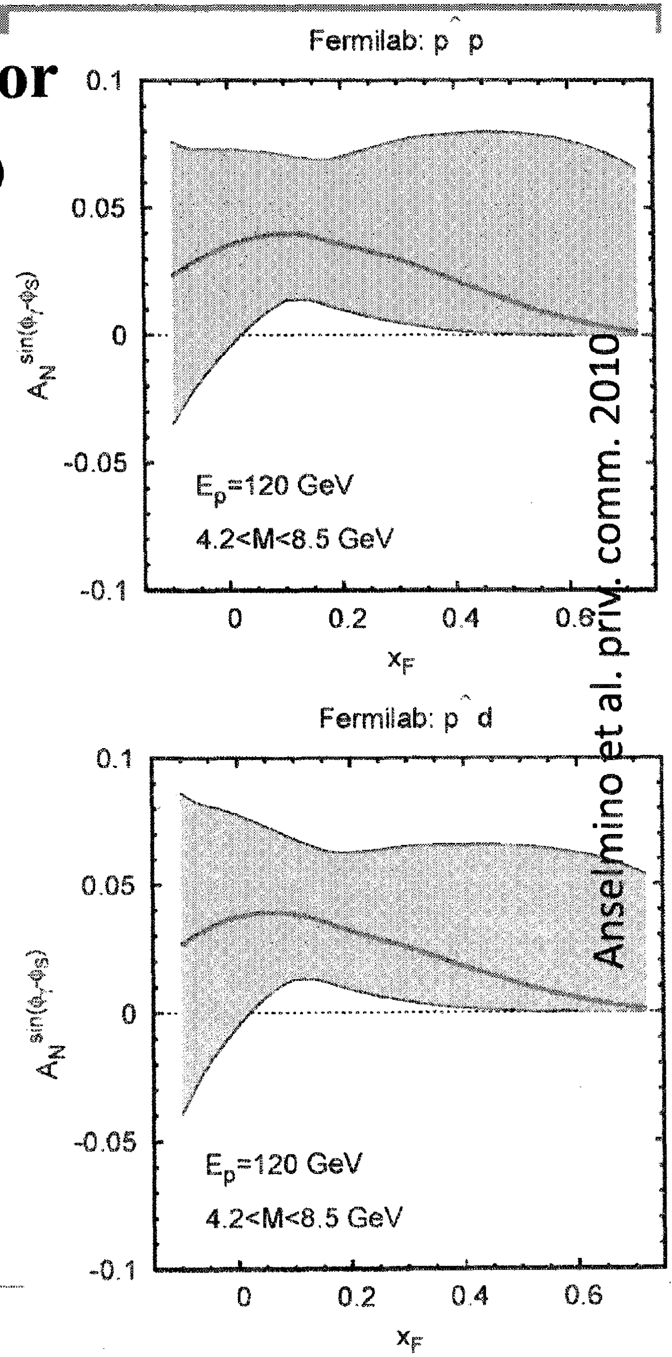


Measure not only the sign of the Sivers but also ***the shape*** of the function

What if
$|f_{1T}^{\perp}|_{DIS} \times |f_{1T}^{\perp}|_{DY} < 0$
but
$|f_{1T}^{\perp}|_{DIS} \neq |f_{1T}^{\perp}|_{DY}$
?

Polarized beam at Fermilab Main Injector

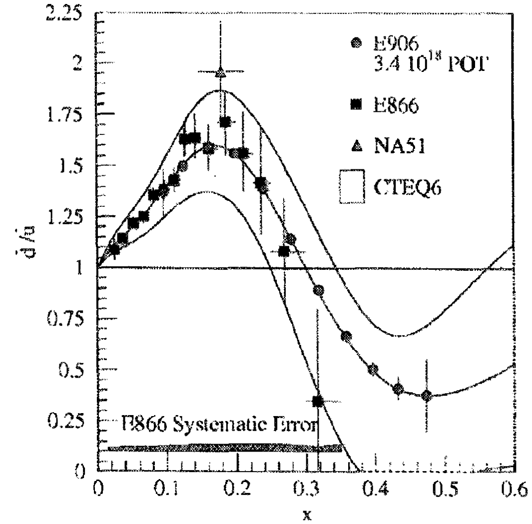
- 1 mA at polarized source delivers 8.1 x 10^{11} p/s (=130 nA)
  - A. Krisch: Spin@Fermi study in 1995
  - Fermilab Main Injector can be polarized (not Tevatron)
  - Revisit study to re-evaluate cost (done in early fall 2011)
  - Feasibility depends on cost (both in $$ and down time of MI)
- Scenarios:
  - SeaQuest liquid H_2 target can take ~5 x 10^{11} p/s (=80 nA)
  - **$\mathcal{L}$ = 1 x 10^{36} /cm²/s** (60% of beam delivered to experiment)
  - **$\mathcal{L}$ = 2 x 10^{35} /cm²/s** (10% of beam delivered to experiment)
- *x*-range:
  - x_1 0.3 – 0.9 (valence quarks)
  - x_2 0.1 – 0.5 (sea quarks)
- Unpolarized SeaQuest
  - luminosity: $\mathcal{L}$ = 3.4 x 10^{35} /cm²/s
  - I_{av} = 1.6 x 10^{11} p/s (=26 nA)
  - N_p= 2.1 x 10^{24} /cm²
  - 2-3 years of running: 3.4 x 10^{18} pot

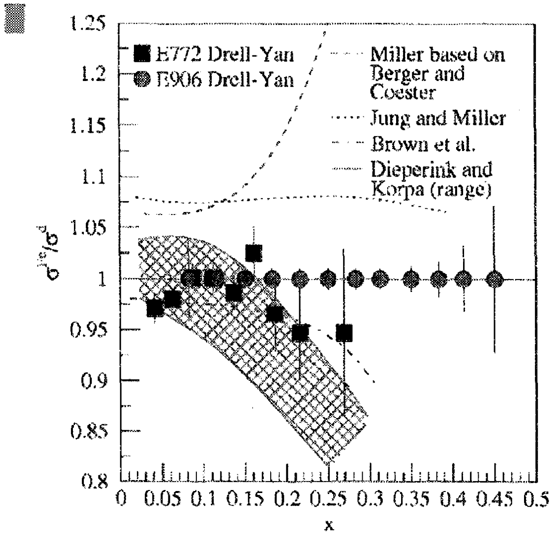


experiment	particles	energy	x_1 or x_2	luminosity	timeline
COMPASS (CERN)	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s}$ = 17.4 GeV	$x_2 = 0.2 - 0.3$ $x_2 \sim 0.05$ (low mass)	$2 \times 10^{33}\ cm^{-2}\ s^{-1}$	>2012
PAX (GSI)	$p^{\uparrow} + p_{par}$	collider $\sqrt{s}$ = 14 GeV	$x_1 = 0.1 - 0.9$	$2 \times 10^{30}\ cm^{-2}\ s^{-1}$	>2017
PANDA (GSI)	$p_{par} + p^{\uparrow}$	15 GeV $\sqrt{s}$ = 5.5 GeV	$x_2 = 0.2 - 0.4$	$2 \times 10^{32}\ cm^{-2}\ s^{-1}$	>2016
J-PARC	$p^{\uparrow} + p$	50 GeV $\sqrt{s}$ = 10 GeV	$x_1 = 0.5 - 0.9$	$1 \times 10^{35}\ cm^{-2}\ s^{-1}$	>2015 ??
NICA (JINR)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 20 GeV	$x_1 = 0.1 - 0.8$	$1 \times 10^{30}\ cm^{-2}\ s^{-1}$	>2014
PHENIX (RHIC)	$p^{\uparrow} + p$	collider $\sqrt{s}$ = 500 GeV	$x_1 = 0.05 - 0.1$	$2 \times 10^{32}\ cm^{-2}\ s^{-1}$	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_1 = 0.25 - 0.4$	$2 \times 10^{33}\ cm^{-2}\ s^{-1}$	>2018
RHIC internal target phase-1	$p^{\uparrow} + p$	250 GeV $\sqrt{s}$ = 22 GeV	$x_1 = 0.25 - 0.4$	$6 \times 10^{34}\ cm^{-2}\ s^{-1}$	>2018
A_NDY RHIC (IP-2)	$p^{\uparrow} + p$	500 GeV $\sqrt{s}$ = 32 GeV	x_1 = ??	?? $cm^{-2}\ s^{-1}$	>2015
SeaQuest (unpol.) (FNAL)	$p + p$	120 GeV $\sqrt{s}$ = 15 GeV	$x_1 = 0.3 - 0.9$	$3.4 \times 10^{35}\ cm^{-2}\ s^{-1}$	>2010
pol. SeaQuest (FNAL)	$p^{\uparrow} + p$	120 GeV $\sqrt{s}$ = 15 GeV	$x_1 = 0.3 - 0.9$	$1 \times 10^{[illegible]}\ cm^{-2}\ s^{-1}$	>??

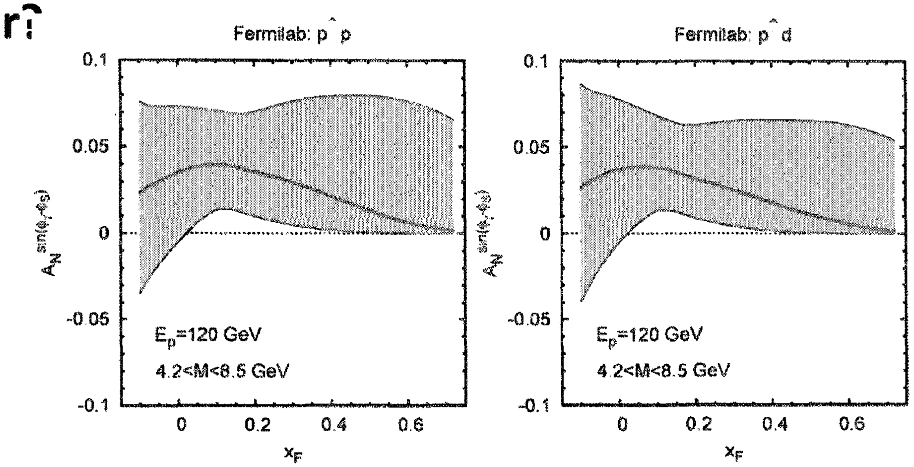
Drell-Yan at Fermilab

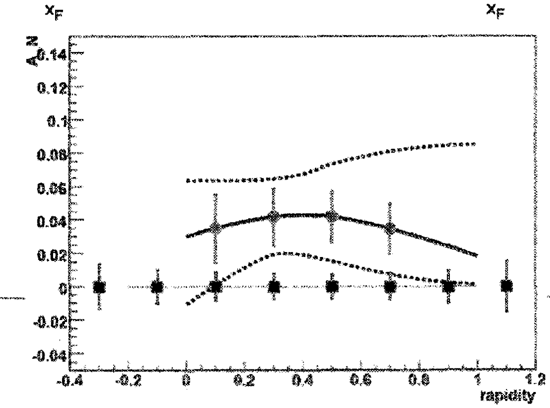
- **What is the structure of the nucleon?**
  - What is d-bar/u-bar?
  - What are the origins of the sea quarks?
  - What is the high-x structure of the proton?





- **What is the structure of nucleonic matter?**
  - Where are the nuclear pions?
  - Is anti-shadowing a valence effect?
- **What is the transverse Structure of the proton?**
  - Polarized beam at Fermilab Main Injector
  - Move apparatus to RHIC or J_PARC





This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

Dr. Oleg Denisov, INFN section of Turin, Italy

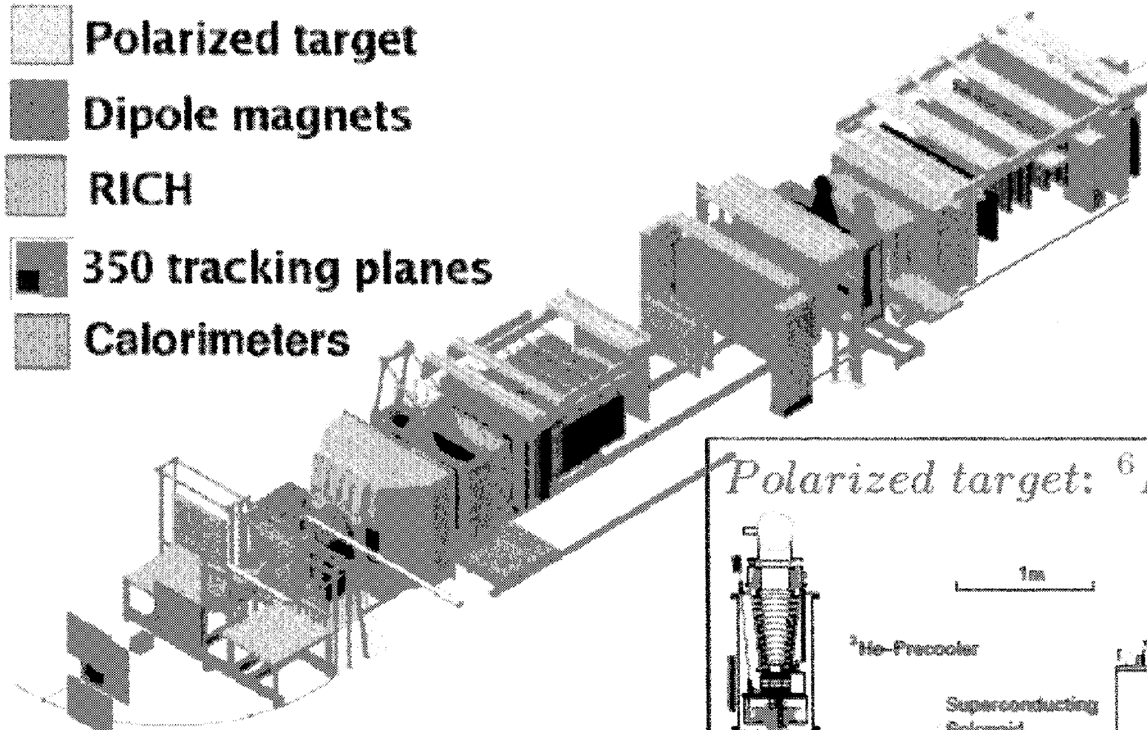
Forthcoming Drell-Yan experiment at COMPASS

The COMPASS experiment at CERN is a universal facility which can operate with both muon and hadron beams as well as with the longitudinally/transversely polarized solid target. The main goal of the experiment is to study the spin structure of the nucleon. The availability of hadron(pion) beam provides an access to the Drell-Yan physics, i.e. to the process where quark(target)-antiquark(beam) pair annihilates electromagnetically with a production of dilepton pair. Study of angular dependencies of the Drell-Yan process cross-section allows us to access parton distribution functions (PDFs) or, more precisely, a convolutions of various PDFs. The possibility to use in a future COMPASS Drell-Yan experiment a transversely polarized target together with negative pion beam will provides us with unique data on transverse momentum dependent (TMD) PDFs.

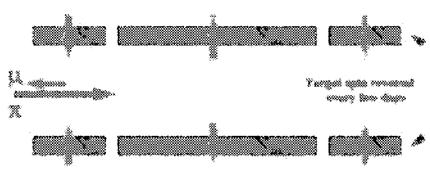
The COMPASS-II proposal [1], which includes the single-polarized Drell-Yan measurements, was submitted to the CERN SPS committee in May 2010, was recommended by SPSC for approval in September 2010 and approved by CERN research board in December 2010. In this presentation the most important features of the Drell-Yan experiment at COMPASS will be discussed. The experimental set-up, its performance including apparatus acceptance and kinematic range coverage as well as projections for the achievable statistical errors on various single-spin-asymmetries will also be reported.

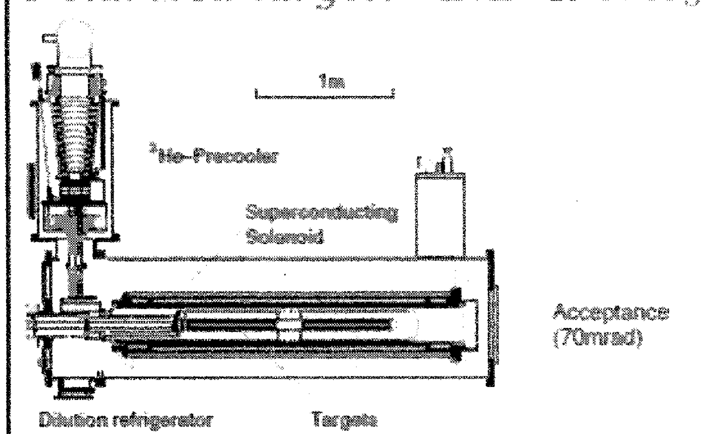
[1] COMPASS Coll., COMPASS-II proposal, CERN-SPSC-2010-014, SPSC-P-340, May 17 2010

COMPASS facility at CERN



μ or π beam





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COMPASS-II (New Physics) a piece of history

- COMPASS is very sophisticated, universal and flexible facility → Physics beyong SIDIS and hadron spectroscopy is possible:
  - Unique COMPASS Polarised Target
  - Both hadron and lepton beams
  - Easy-accessable spectrometer components
- All that all together has generated new physics proposals with COMPASS – DVCS(GPDs) and polarised DY:
  - For the first time these ideas (GPD and DY) were reported at the Villars SPSC meeting in September 2004
  - Since then (DY part) 3 International Workshops (Torino, Dubna, CERN), > 40 COMPASS DY subgroup meetings, 3 Beam Tests, > 20 presentations at the international Conferences….
- The COMPASS-II proposal is submitted to the SPSC on May 17th 2010
- Approved by the CERN research board on December 1st 2010
- April 7th – the Collaboration took a decision to run first the DY program and then DVCS (GPDs) program – we will start in 2013 (beam test) and in 2014 we will have a full year of DY data taking.

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COMPASS-II: a Facility to study QCD

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY

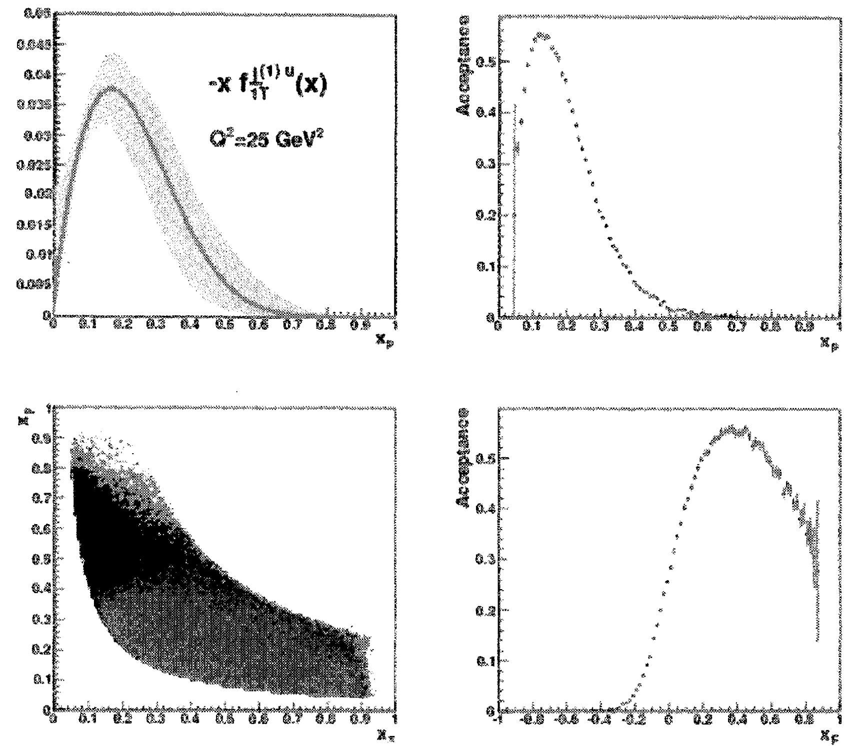
Long Term Plans for at least 5 years (starting in 2012)

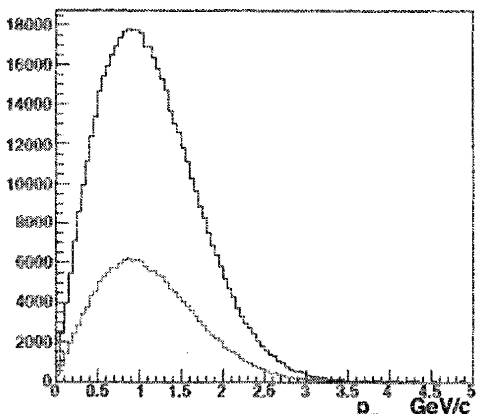
- ✓ Primakoff with π, K beam → Test of Chiral Perturb. theory
- ✓ DVCS & DVMP with μ beams → Transv. Spatial Distrib. with GPDs
- ✓ SIDIS (with GPD prog.) → Strange PDF and Transv. Mom. dep. PDFs
- ✓ Drell-Yan with π beams → Transverse Momentum dependent PDFs

O. Denisov (INFN Torino) - DY, J. Friedrich (TU Munich) - Primakoff, N. d'Hose (CEA Saclay) - GPD
for the COMPASS Collaboration

DY@COMPASS – kinematics - valence quark range
$\pi^- p \rightarrow \mu^- \mu X$ (190 GeV pion beam)

- In our case ($\pi^- p \rightarrow \mu^- \mu X$) contribution from valence quarks is dominant
- In COMPASS kinematics u-ubar dominance
- $\langle P_T \rangle \sim 1$GeV – TMDs induced effects expected to be dominant with respect to the higher QCD corrections





DY@COMPASS projections – Sivers asymmetry

$$\text{(HMR)}: 4. \leq M_{\mu\mu} \leq 9.\ \text{GeV/c}^2$$

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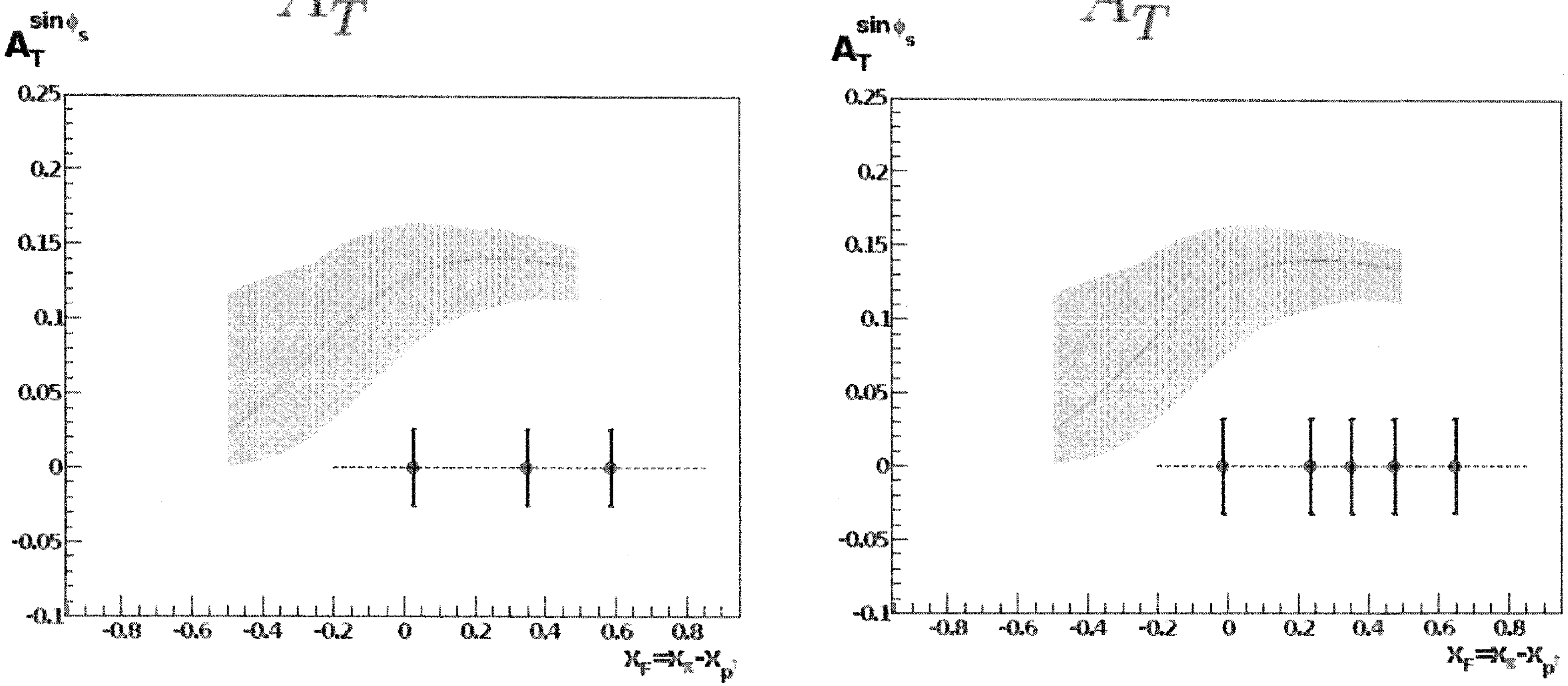
$A_T^{\sin\phi_S}$ $A_T^{\sin\phi_S}$



Other Physics Opportunities in Future Drell-Yan Experiments

Jen-Chieh Peng
University of Illinois at Urbana-Champaign

Workshop on "Opportunities for Drell-Yan Physics at RHIC"
BNL, May 11-13, 2011

Outline

- "Intrinsic sea-quarks" of the nucleons.
- Flavor dependence of the EMC effect.
- Equalities and inequalities in Drell-Yan azimuthal angular distributions.
- Flavor and *x*-dependence of quark intrinsic transverse momentum distributions.
- Drell-Yan and quarkonium duality.

Sea-quark flavor asymmetry and the "intrinsic" quark sea

In the 1980's, Brodsky et al. (BHPS) suggested the existence of "intrinsic" charm

$$|p\rangle = P_{3q}\,|uud\rangle + P_{5q}\,|uudQ\bar{Q}\rangle + \cdots\cdots$$

The $|uudc\bar{c}\rangle$ intrinsic-charm can contribute to charm-production at large x_F

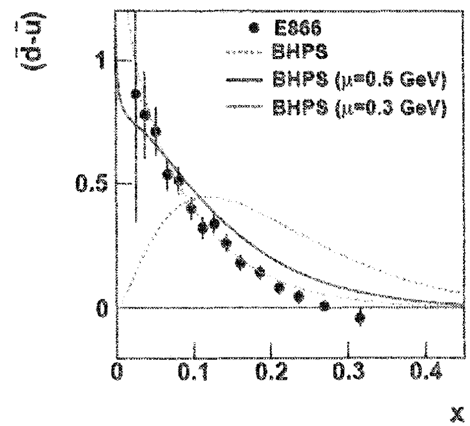
No conclusive experimental evidence for intrinsic-charm so far

Are there experimental evidences for the intrinsic $|uudu\bar{u}\rangle$, $|uudd\bar{d}\rangle$, $|uuds\bar{s}\rangle$ 5-quark states ?

$$(P_{5q}^{uudQ\bar{Q}} \sim 1/m_Q^2)$$

6

Comparison between the $\bar{d}(x) - \bar{u}(x)$ data and the intrinsic 5-q model



E866 data measured at $\langle Q^2 \rangle = 54$ GeV^2

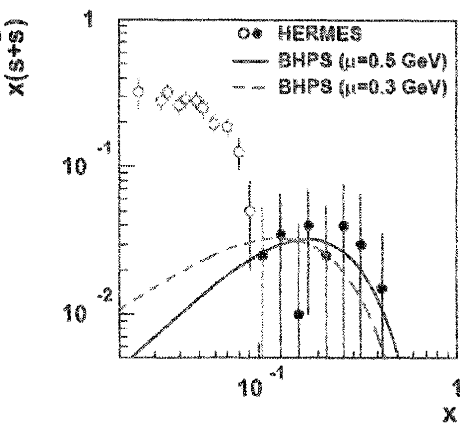
Need to evolve the 5-q model prediction from the initial scale μ to Q^2=54 GeV^2

(W. Chang and JCP arXiv:1102.5631, to appear in PRL)

$$P_5^{uudd\bar{d}} - P_5^{uudu\bar{u}} = \int_0^1 (\bar{d}(x) - \bar{u}(x))\,dx = 0.118$$

8

Comparison between the $s(x)+\bar{s}(x)$ data with the intrinsic 5-q model



$s(x)+\bar{s}(x)$ from HERMES kaon SIDIS data at $\langle Q^2\rangle = 2.5$ GeV^2.

Two distinct shapes in the x distribution:
extrinsic ($g \to s\bar{s}$) and intrinsic $uuds\bar{s}$ sta

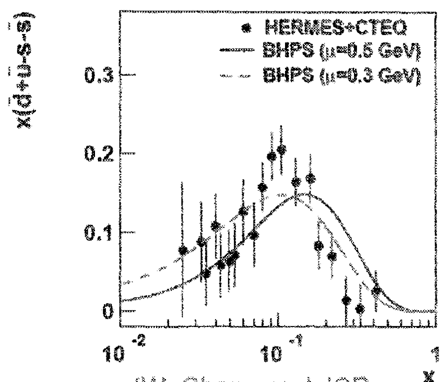
Assume $x > 0.1$ data are from the intrinsic $uuds\bar{s}$ 5-quark state

(W. Chang and JCP arXiv:1102.5631, to appear in PRL)

$P_5^{uuds\bar{s}} = 0.032$

9

Comparison between the $\bar{u}(x)+\bar{d}(x)-s(x)-\bar{s}(x)$ data with the intrinsic 5-q model



(W. Chang and JCP arXiv:1102.5631)

$\bar{d}(x)+\bar{u}(x)$ from CTEQ6.6

$s(x)+\bar{s}(x)$ from HERMES

$$\int_0^1 (\bar{u}(x)+\bar{d}(x)-s(x)-\bar{s}(x))\,dx$$

$$= P_5^{uudd\bar{d}} + P_5^{uudu\bar{u}} - 2P_5^{uuds\bar{s}}$$

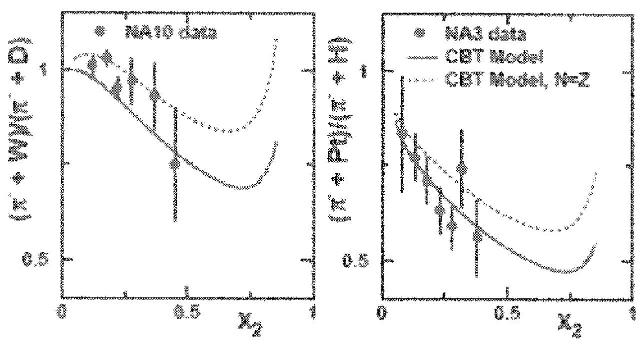
$P_5^{uudd\bar{d}} = 0.248,\ P_5^{uudu\bar{u}} = 0.130,\ P_5^{uuds\bar{s}} = 0.032$

Kaon-induced Drell-Yan could probe strange quark sea

10

Pion-induced Drell-Yan and the flavor-dependent EMC effect

$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

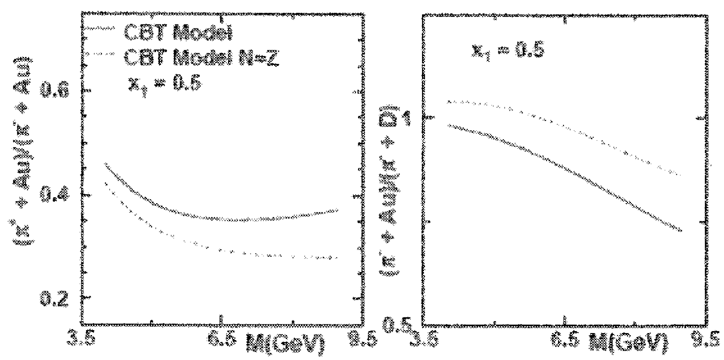


Red (blue) curves correspond to flavor-dependent (independent)

(Dutta, JCP, Cloet, Gaskell, arXiv: 1007.3916)

Pion-induced Drell-Yan and the flavor-dependent EMC effect

$$\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}; \qquad \frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

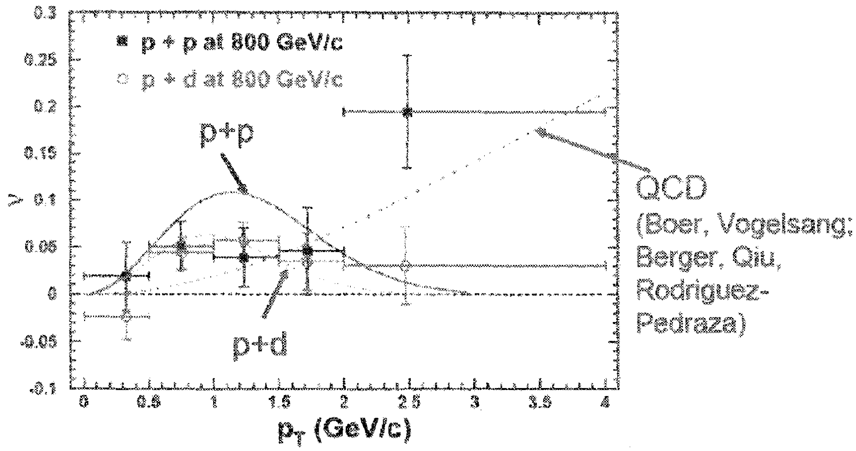


160 GeV pion beam

Future Drell-Yan data with pion beams could provide important new information

Results on cos2Φ Distribution in p+p Drell-Yan

L. Zhu, J.C. Peng, et al., PRL 102 (2009) 182001



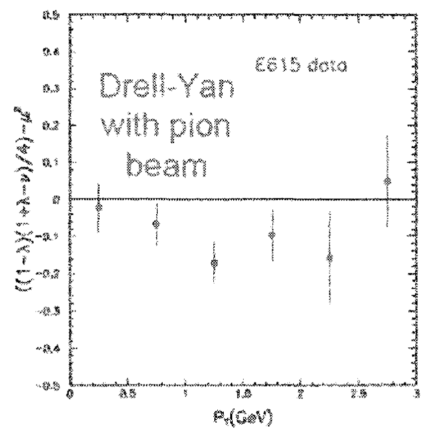
Combined analysis of SIDIS and D-Y by Melis et al.

More data are anticipated from future DY exps.

23

Is the $\mu^2 \le (1-\lambda)(1+\lambda-\nu)/4$ inequality valid?

$(1-\lambda)(1+\lambda-\nu)/4-\mu^2 \ge 0$?



The inequality appears to be violated!

(Teryaev and JCP)

Our knowledge of D-Y azimuthal angular dependence is still incomplete (New Drell-Yan data are essential)

25

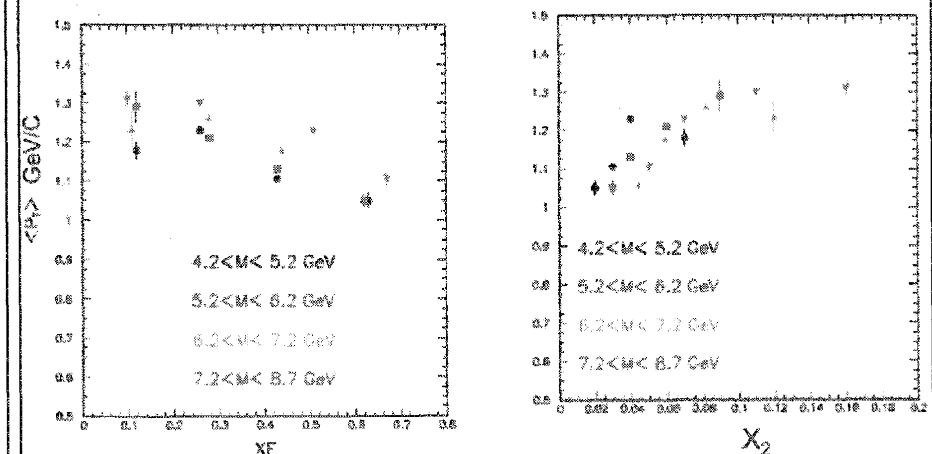
What do we know about the quark and gluon transverse momentum distributions?

- Does the quark k_T distribution depend on x?
- Do valence quarks and sea quarks have different k_T distributions?
- Do u and d quarks have the same k_T distribution?
- Do nucleons and mesons have different quark k_T distribution?
- Do gluons have k_T distribution different from quarks?

- Important for extracting the TMD parton distributior
- Interesting physics in its own right

Possible x-dependent k_T-distributions

E866 p+d D-Y data (800 GeV beam)



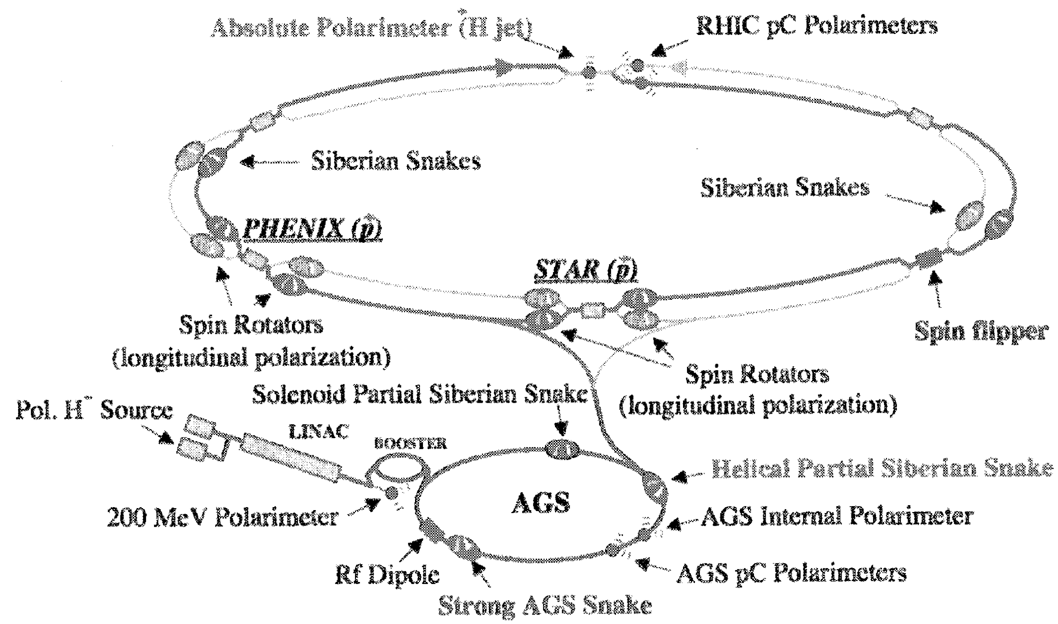
$\langle p_T \rangle$ scale with x_2 ?

Analysis is ongoing. Future data at lower beam energies are essential

Drell-Yan Production at STAR
Status and Plans

Ernst Sichtermann (LBNL)

for the STAR Collaboration



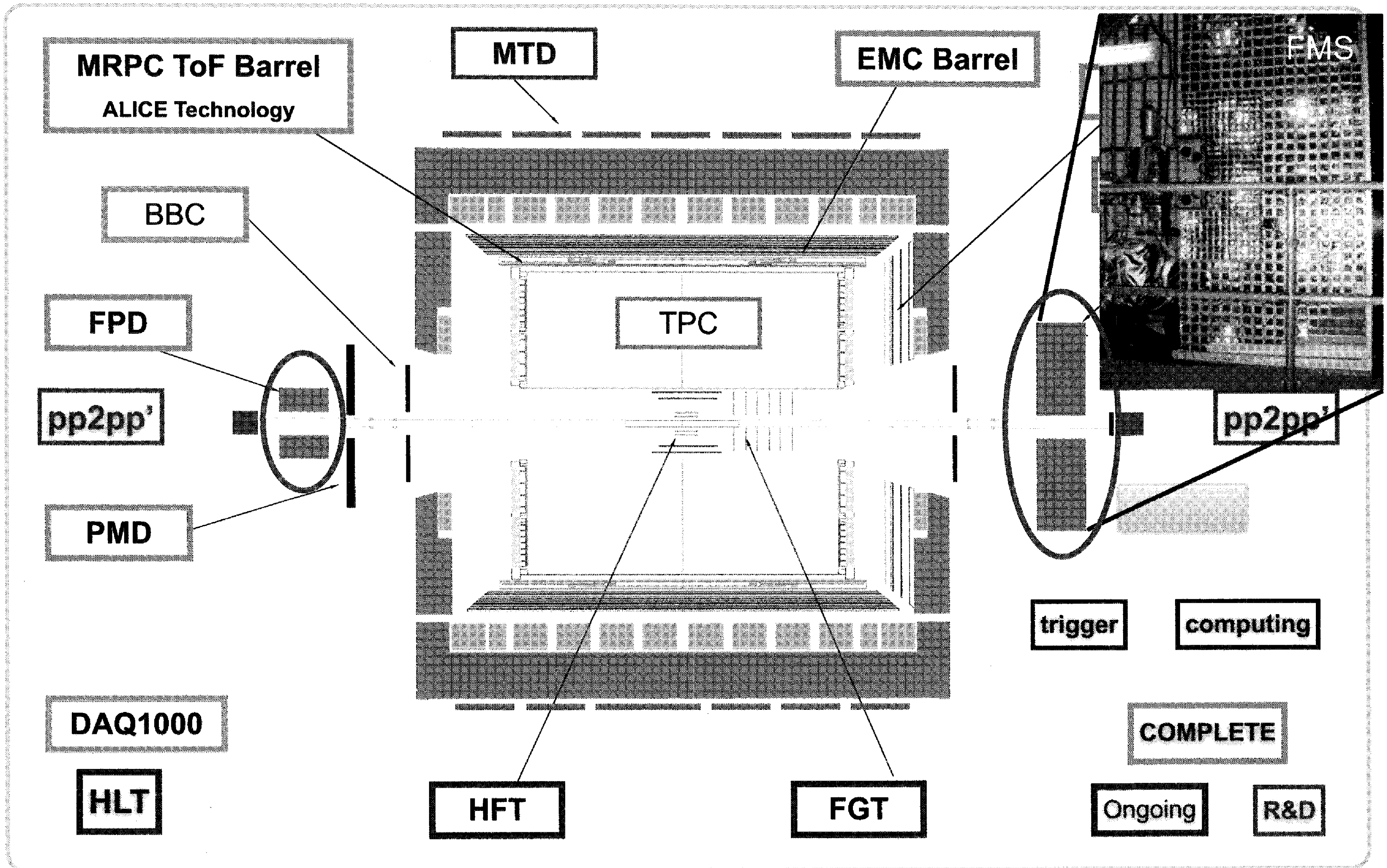
Opportunities for Drell-Yan Physics at RHIC
RIKEN BNL Research Center Workshop
May 11-13, 2011 at Brookhaven National Laboratory

STAR - Summary of Measurement Plan

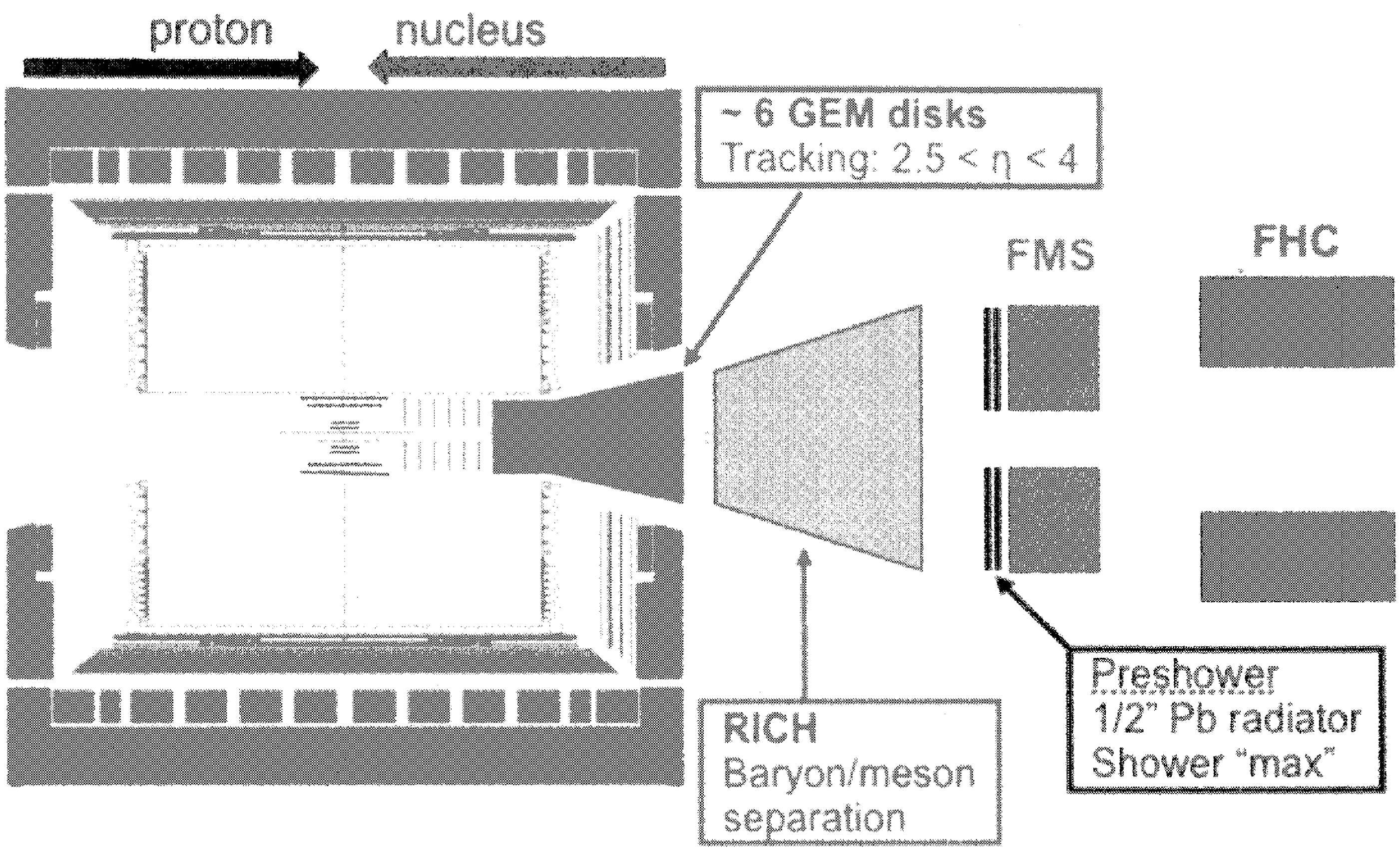
	Near term (Runs 11–13)	Mid-decade (Runs 14–16)	Long term (Runs 17–)
Colliding systems	p+p, A+A	p+p, A+A	p+p, p+A, A+A, e+p, e+A
Upgrades	FGT, FHC, RP, DAQ10K, Trigger	HFT, MTD, Trigger	Forward Instrum, eSTAR, Trigger
(1) Properties of sQGP	Υ, $J/\psi \to ee$, m_{ee}, v_2	Υ, $J/\psi \to \mu\mu$, Charm v_2, R_{CP}, Charm corr, Λ_c/D ratio, μ-atoms	p+A comparison
(2) Mechanism of energy loss	Jets, γ-jet, NPE	Charm, Bottom	Jets in CNM, SIDIS, c/b in CNM
(3) QCD critical point	Fluctuations, correlations, particle ratios	Focused study of critical point region	
(4) Novel symmetries	Azimuthal corr, spectral function	$e-\mu$ corr, $\mu-\mu$ corr	
(5) Exotic particles	Heavy anti-matter, glueballs		
(6) Proton spin structure	W A_L, jet and di-jet A_{LL}, intra-jet corr, $(\Lambda+\bar{\Lambda})$ D_{LL}/D_{TT}		Λ D_{LL}/D_{TT}, polarized DIS, polarized SIDIS
(7) QCD beyond collinear factorization	Forward A_N		Drell-Yan, F-F corr, polarized SIDIS
(8) Properties of initial state			Charm corr, Drell-Yan, J/ψ, F-F corr, Λ, DIS, SIDIS

STAR Decadal Plan, http://www.bnl.gov/npp

STAR Experiment - Forward Calorimeters



A Possible Future Upgrade at STAR

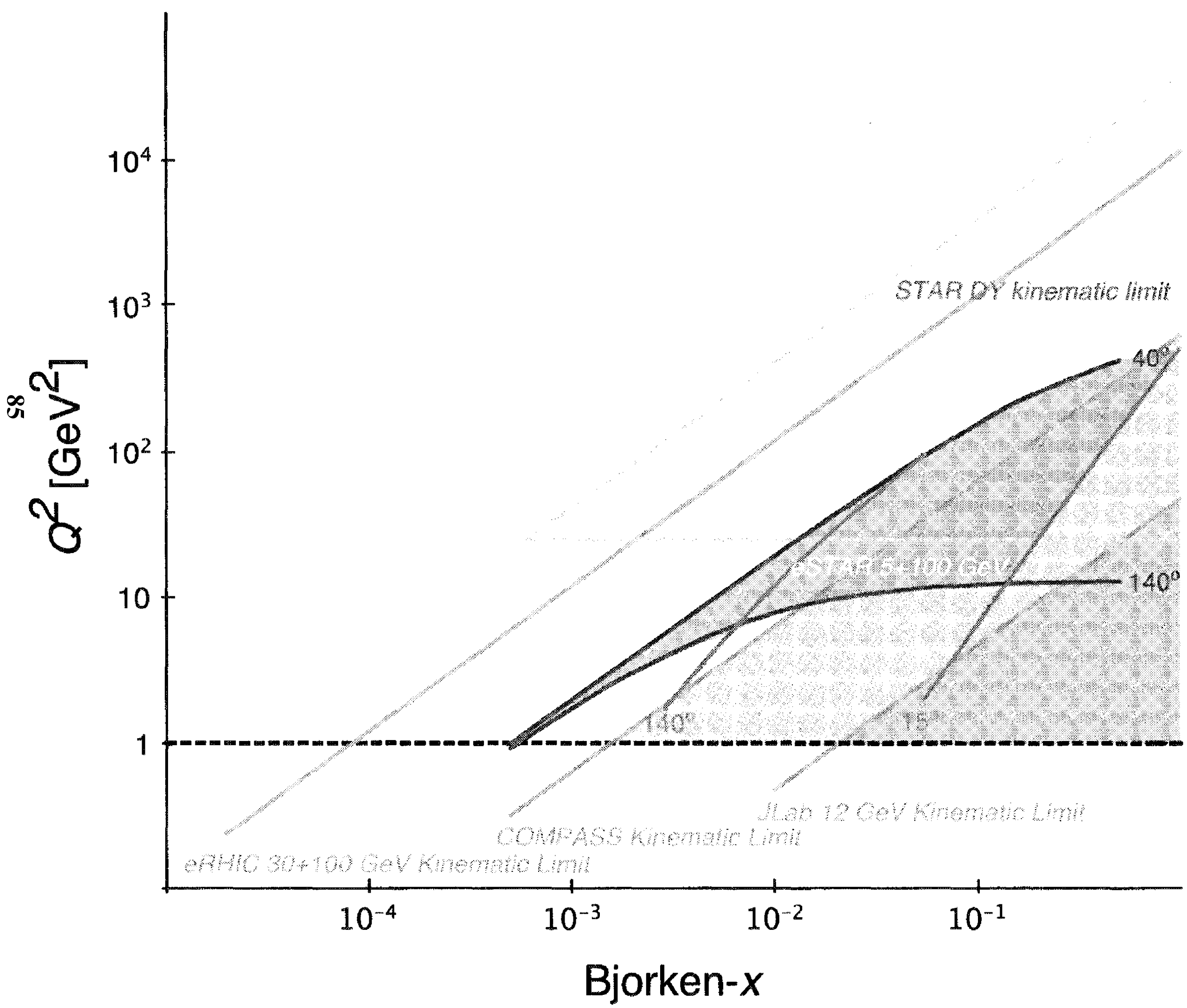


Forward upgrade driven by proton-nucleus and transverse spin physics considerations,

- charged particle tracking,
- electron-hadron and photon-neutral pion separation,
- Baryon meson separation.

Optimizations and full simulations to demonstrate capability are starting.

Drell-Yan, eRHIC, eSTAR



A talk by itself...

Note: this is an *illustration*, not a full simulation.

Here, M > 5 GeV for DY, central-rapidity for eSTAR

Concluding Remarks

STAR has prepared a new decadal plan for 2011-2020, http://www.bnl.gov/npp

Aims to address transverse physics and nuclear structure physics topics via Drell-Yan measurements in the second half of the decade, as part of a broader program that may culminate in an Electron-Ion-Collider,

The Forward Meson Spectrometer is a key part of this program, and has been very successfully commissioned and operated up to $\sqrt{s}$ = 500 GeV,

Anticipate at the level of 150 Drell Yan pairs in the FMS acceptance at $\sqrt{s}$ = 200 GeV, about equal for proton+nucleus and proton+proton collisions, based on RHIC projections,

$\sqrt{s}$ = 500 GeV p+p projected rates are considerably higher, however,
detection at STAR will be considerably more challenging,
p+A collisions are not possible at this energy at RHIC,

Lots of work ahead,

- a number of key aspects are well understood/benchmarked,
- the foreseen upgrade path is evolutionary,
- efforts towards full simulations of measurement capability are starting,
- continued R&D, ...

Thank you!

PHENIX

Los Alamos

Drell-Yan Production at PHENIX Status and Plan

Ming Liu
Los Alamos National Lab
(PHENIX Collaboration)

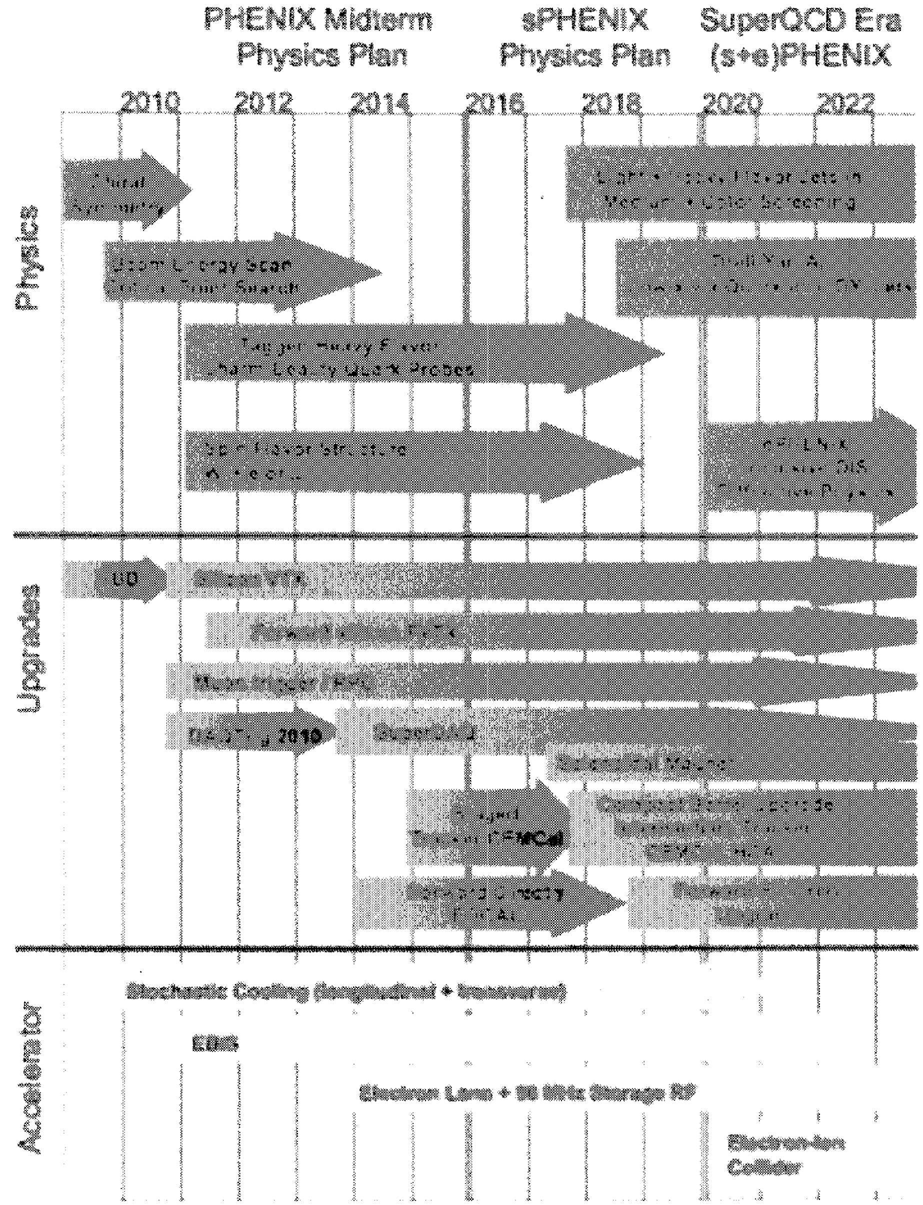
Abstract:

We present the current status and plan for Drell-Yan measurements at PHENIX for next decade. Initial feasibility studies of Drell-Yan production have been carried out with the soon available central and forward vertex upgrade detectors in the dielectron and dimuon channels. Significant luminosity, order of 250 pb^{-1} , is required in order to test and confirm the sign change (or not) in transverse single spin asymmetry (TSSA) in Drell-Yan production in the forward muon arm coverage. In the next five years, PHENIX will carry out Drell-Yan measurements at least to benchmark the cross sections in the PHENIX central electron and forward muon arms covered rapidity ranges from the expected high luminosity longitudinally polarized 500 GeV p+p collisions as well as from transversely polarized 200GeV p+p runs.

Beyond the next 5 years, we have identified new areas of investigation related to the fundamental properties of the sQGP, and to transverse spin physics, that require major new detector capabilities. PHENIX has an ambitious upgrade plan to significantly improve physics capability in the very forward region. The proposed sPHENIX detectors will replace the current PHENIX central magnets with a compact solenoid; in the forward direction, one of the current muon arm (south arm) will be replaced with a new large-acceptance forward spectrometer (η=2~4) with excellent PID for hadrons, electrons, and photons and full jet reconstruction capability. This will enable us for the future eRHIC physics also. Drell-Yan production and asymmetry will be studied in the di-electron channel in a very forward rapidity range that goes beyond the current PHENIX muon arm coverage where significant TSSA A_N is expected. Detailed MC simulation work with sPHENIX is underway to study the experimental sensitivity to TSSA in Drell-Yan production.

The Timeline

- 2011-2018
  - PHENIX w/upgrades
  - VTX/FVTX
- 2018-20XX
  - sPHENIX
  - Also ready for eRHIC physics



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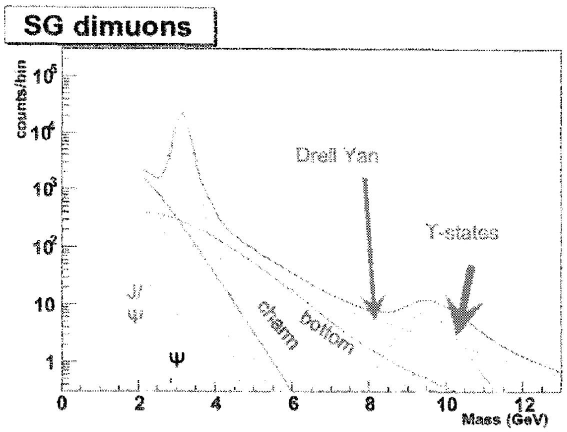
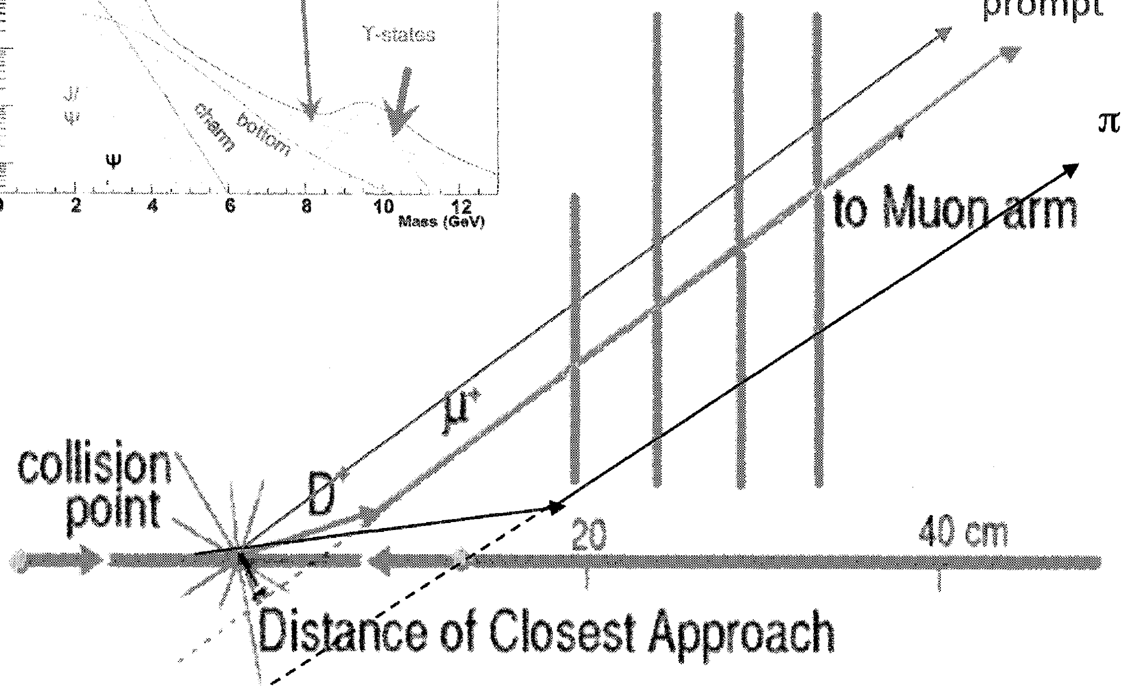
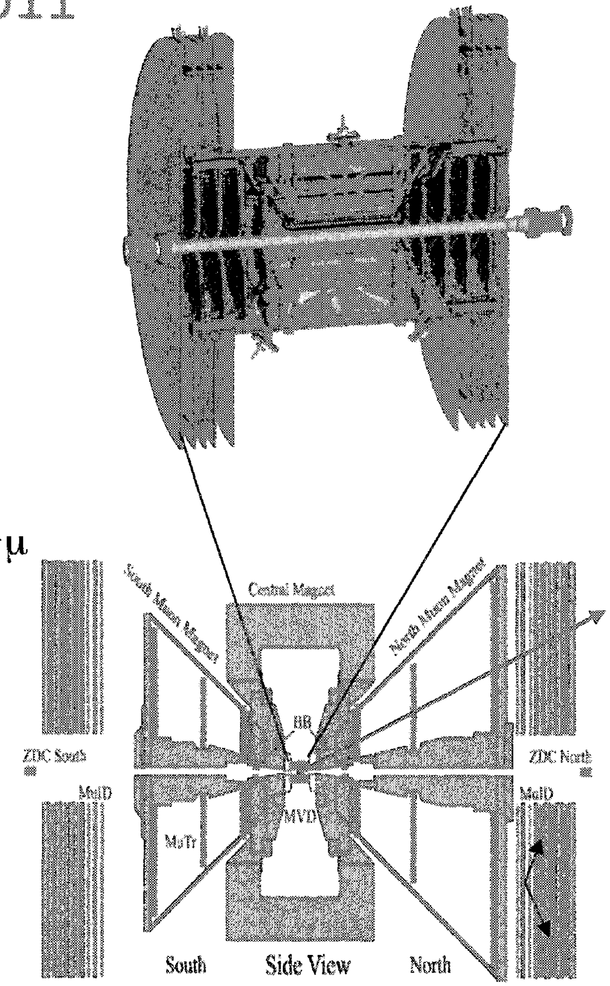
2011-2015: PHENIX Silicon VTX Detectors

– upgrade on going, will be completed in 2011

- Precision Charm/Beauty Measurements
- B→J/ψ, Drell-Yan, ψ'







2018+: sPHENIX Forward Detectors

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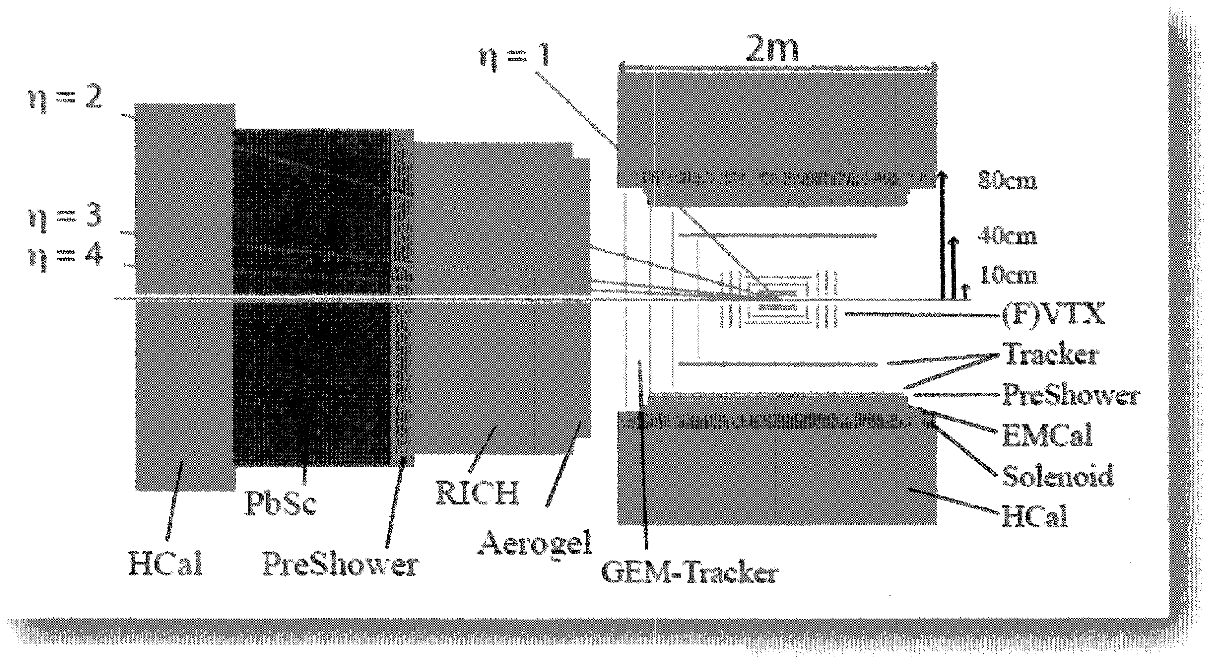
- Optimized for high energy electrons/photons
  - $2 < \eta < 4$
  - e/photon ID
  - Hadron PID
  - eRHIC ready
    - e+p
    - e+A
  - DY via dielectons @ very forward rapidity

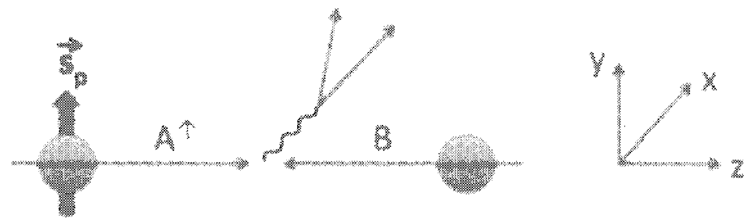


- TRACK has a momentum resolution of $\Delta p/p \approx 2\%$.
- RICH has an electron efficiency of 94% for $p > 10$ GeV/c.
- EMCal has the resolution of the current PHENIX PbGl: $5.95\%/\sqrt{E} + 0.76\%$
- HCAL has the resolution: $50\%/\sqrt{E} + 5\%$ (similar to CMS or LHCb)

Predictions for Drell-Yan process at RHIC

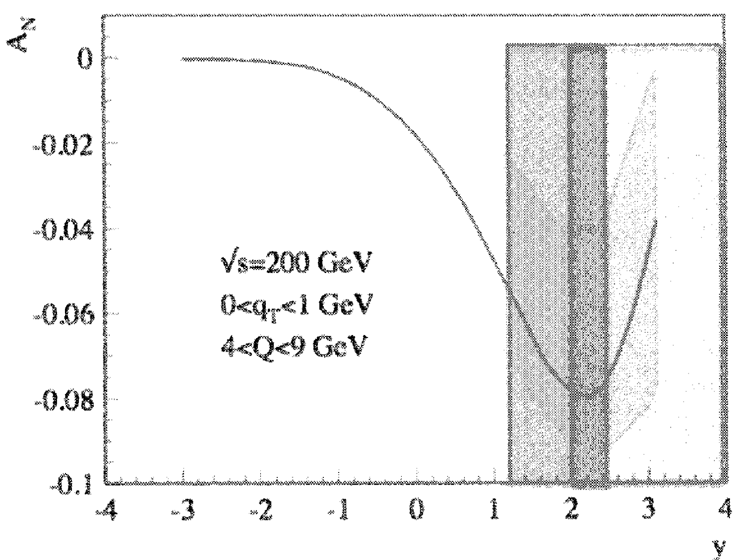
- Reverse the sign of Sivers from SIDIS and make predictions for Drell-Yan production at RHIC

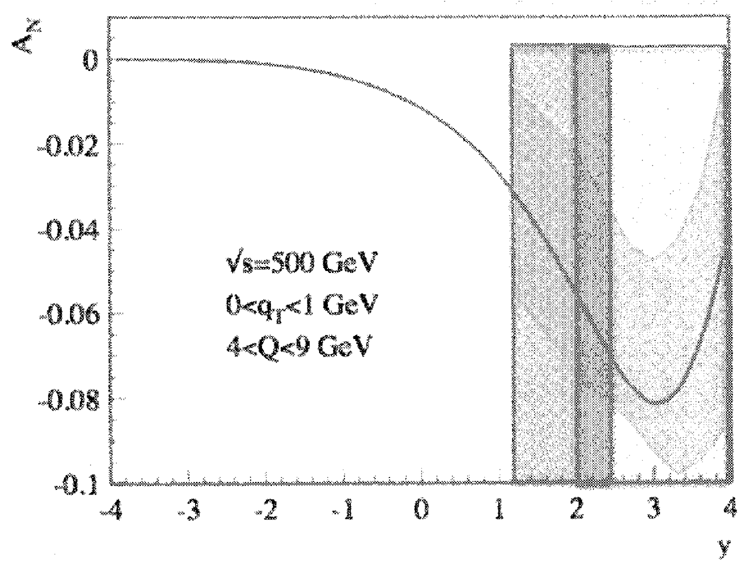
Kang-Qiu, PRD81, 2010



$$A_N \propto \frac{4}{9}\Delta^N u + \frac{1}{9}\Delta^N d < 0$$

- A_N @large rapidities
- PHENIX:
  - -1.2 < y < 2.4
  - -dimuons
- -sPHENIX :
  - -2 < y <4
  - -dielectrons





PHENIX Los Alamos NATIONAL LABORATORY

Summary and Outlook

- Drell-Yan is a powerful tool complimentary to the DIS for exploring parton structures in nucleons and nuclei.
- PHENIX VTX/FVTX upgrades make Drell-Yan measurements possible
  - Central arms via electrons
  - Forward muon arms
  - Some asymmetry measurements (Boer-Mulders alike) possible from upcoming high luminosity longitudinally polarized pp @500GeV

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- Possible Test of Drell-Yan A_N sign change @200GeV and @500GeV after longitudinal W program, likely after 2017 with forward muon arms
  - much improved luminosity needed
- sPHENIX upgrade (2018+)
  - Extend the coverage to very forward rapidity η = 2~4
  - Test sign change in Drell-Yan A_N via di-electrons at very forward rapidity where significant asymmetry expected
- Explore small-x saturation physics at forward rapidity in p(d)A

A_NDY: Status and Plans

L.C. Bland, *Brookhaven National Laboratory*

The motivations for a transverse spin Drell-Yan production (DY) measurement were the focus of this workshop. In brief, the objective is to test the robust theoretical prediction that the sign of the Sivers function will differ between semi-inclusive deep inelastic scattering and DY production. Forward production of low-mass virtual photons from the DY process is also of great interest to the study of parton saturation at low-x, as discussed at this workshop. This contribution describes a proposal to demonstrate the feasibility of detecting the production of low-mass virtual photons in the forward direction at RHIC.

A_NDY is a proposed experiment at RHIC to measure the analyzing power for forward low-mass Drell-Yan production in transversely polarized proton collisions at $\sqrt{s} = 500$ GeV. This presentation reviewed the status of the project and the plans for completing the measurement in the next two years. The basic measurement is to observe the electron and positron decays of a virtual photon produced with $x_F > 0.1$ and mass $M > 4$ GeV/c^2. The energetic dileptons are to be detected in a lead-glass calorimeter (ECal) mounted in the forward direction at RHIC interaction point 2 (IP2). Discrimination of the dilepton signal from background is accomplished by vetoing hadrons using hadronic calorimetry (HCal) mounted immediately behind the ECal. Further hadron/electron discrimination will be made by the use of segmented scintillator sandwiching a converter. The preshower/converter arrangement also will serve to discriminate photon backgrounds from the dielectrons. Simulations show that a left/right symmetric modular ECal and HCal can be ~30% efficient for the detection of dielectrons from DY production with $x_F > 0.1$ and $M > 4$ GeV/c^2 and can discriminate DY from background. We expect 9400 dielectron events in a 150 pb^{-1} data sample with this modular arrangement. A primary goal of A_NDY is to establish if charge sign discrimination is a requirement for forward dielectron identification for a future forward detector facility at RHIC. Charge sign discrimination in the forward direction is best accomplished using a dipole magnet. A dipole magnet in an interaction region is challenging for a collider.

A primary question addressed during RHIC run 11 is the impact of collisions at IP2 on luminosity and backgrounds at IP6 and IP8. The conclusion from RHIC run 11 is that collisions can be initiated at IP2 without significant impact on IP6 or IP8, and that the integrated luminosity (L_{int}) required for the first transverse spin DY measurement can be delivered in subsequent RHIC runs. Concurrent with the development of IP2 collisions, we recorded >5 pb^{-1} of polarized proton collisions with left/right symmetric modular HCal detectors. This data is expected to provide results for forward jet analyzing power.

The proposal then is to stage an ECal and the final preshower/converter arrangement for RHIC run 12. We propose to record 150 pb^{-1} in RHIC run 12 for transversely polarized proton collisions at $\sqrt{s} = 500$ GeV with this apparatus, with the goal of observing J//ψ, $\Upsilon \to e^+e^-$ and the dilepton continuum between these two signals as a clear benchmark for DY feasibility. A split-dipole magnet and tracking stations would get staged for RHIC run 13. Our plan is to acquire a second data sample with $L_{int} > 150$ pb^{-1} with tracking through the PHOBOS split-dipole field to quantify the role of charge sign discrimination in suppressing backgrounds.

ANDY

"Feasibility Test of Large Rapidity Drell Yan Production at RHIC"

Letter of Intent submitted 24 May 2010

http://www.bnl.gov/npp/docs/pac0610/Crawford_LoI.100524.v1.pdf

PAC presentation:

http://www.bnl.gov/npp/docs/pac0610/aschenauer_DY-collider_june10.pdf

E.C.Aschenauer, A. Bazilevsky, L.C. Bland, K. Drees, C. Folz, Y. Makdisi, A. Ogawa, P. Pile, T.G. Throwe

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C.W. Perkins

University of. California, Berkeley/Space Sciences Laboratory /Stony Brook University

A. Derevshchikov, N. Minaev, D. Morozov, L.V. Nogach

Institute for High Energy Physics, Protvino

G. Igo, S. Trentalange

University of California, Los Angeles

M. Grosse Perdekamp

University of Illinois

M.X. Liu

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H. Avakian

Thomas Jefferson National Accelerator Facility

E.J.Brash

Christopher Newport University and TJNAF

C.F.Perdrisat

College of William and Mary

V. Punjabi

Norfolk State University

Li, Xuan

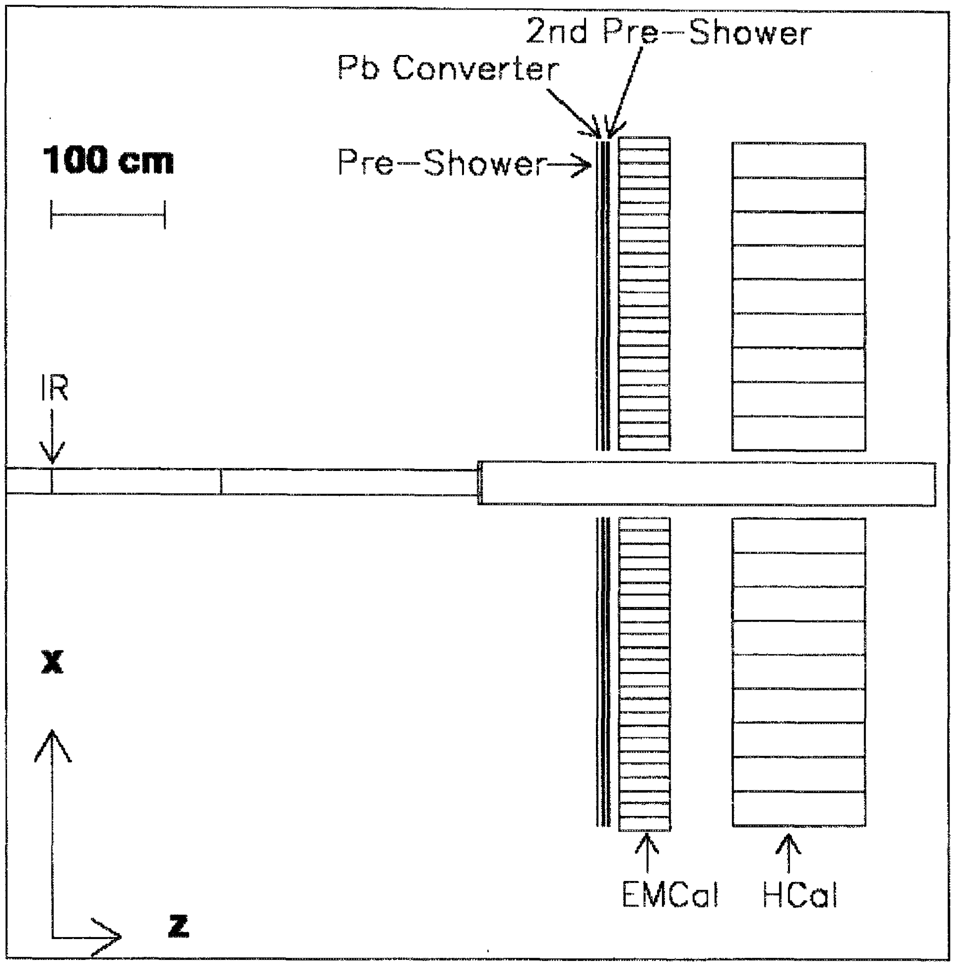
Shandong University, China

Mirko Planinic, Goran Simatovic

University of Zagreb, Croatia

Schematic of detector considered

Run-12 configuration
(PHOBOS split-dipole expected to be in place, but not used)

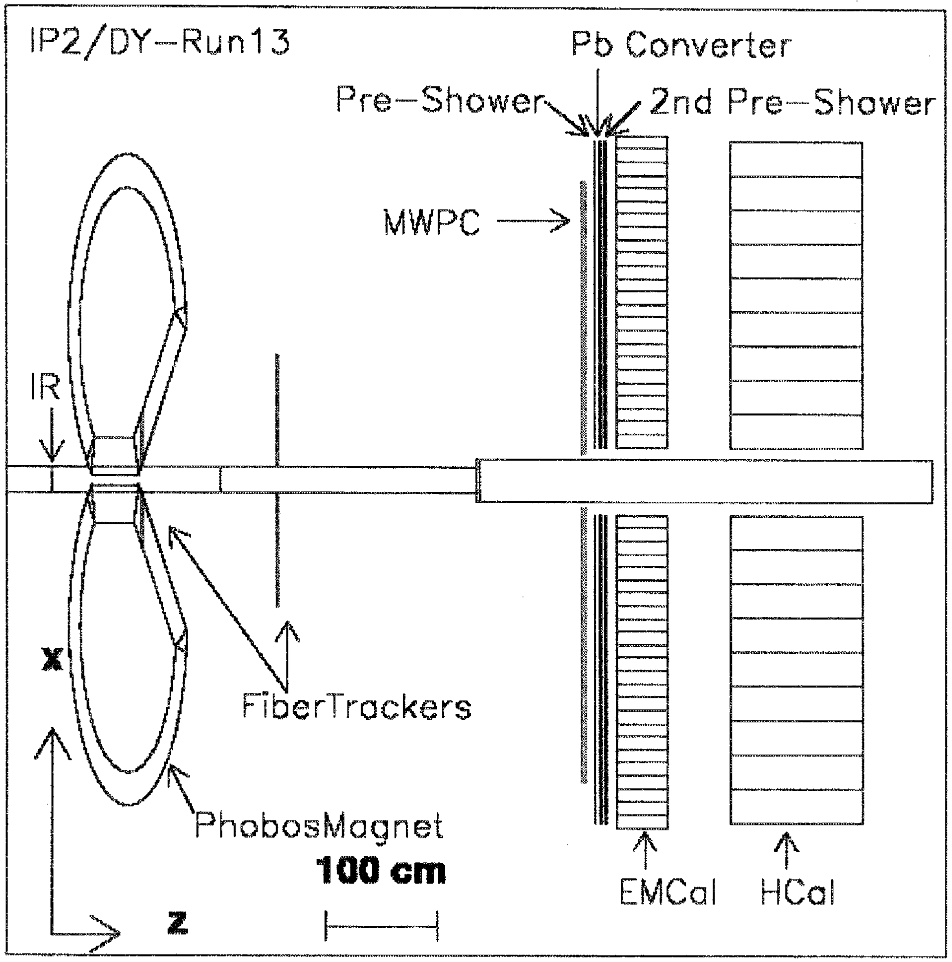


- Hcal is existing 9x12 modules from E864 (NIM406,227)
- EMcal is modeled as only $(3.8cm)^2x(45cm)$ lead glass
- Preshower would require construction

http://www.star.bnl.gov/~akio/ip2/topview2.jpeg

Schematic of detector considered

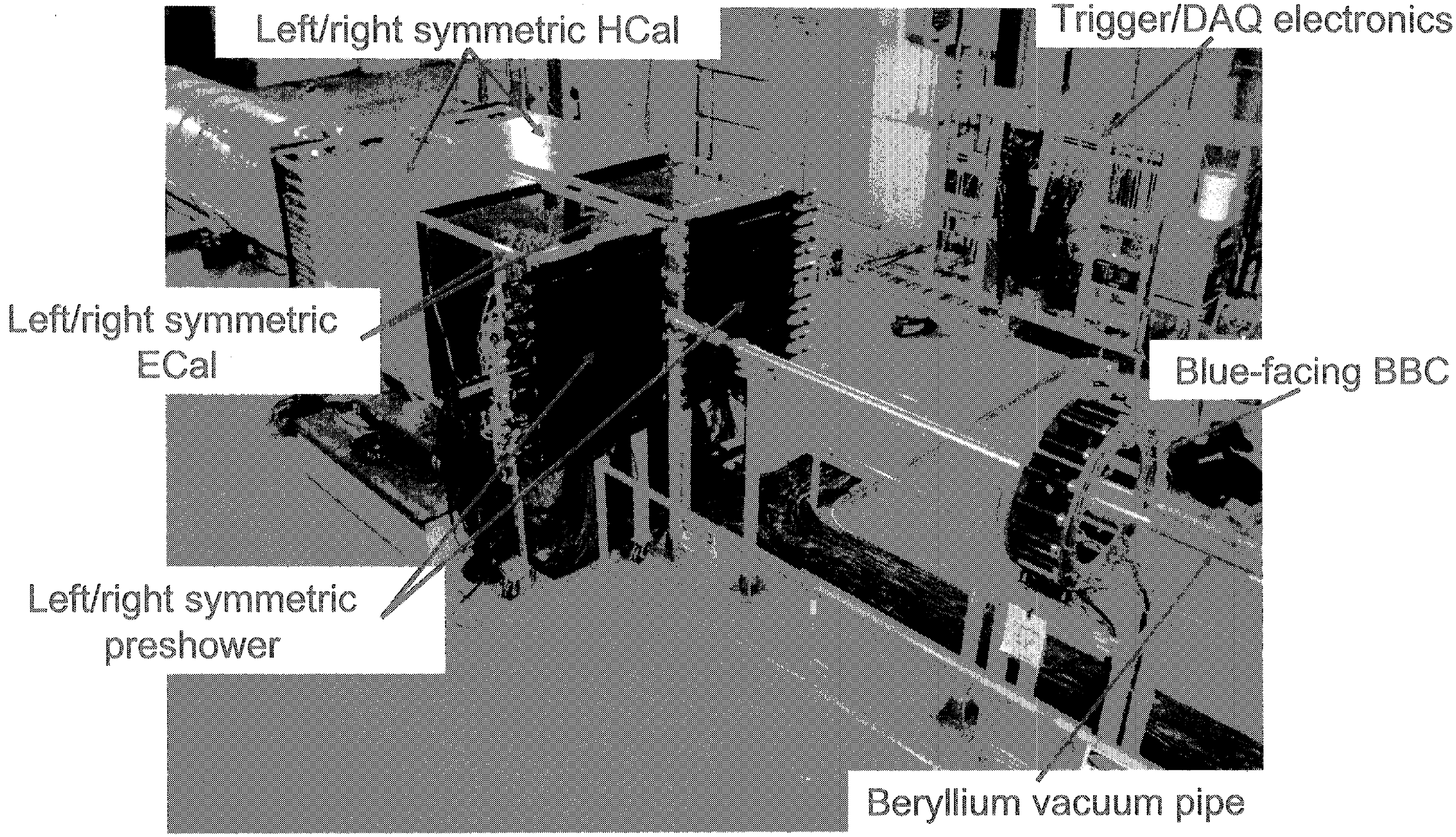
Run-13 configuration
(Uses PHOBOS Split Dipole for charge sign)



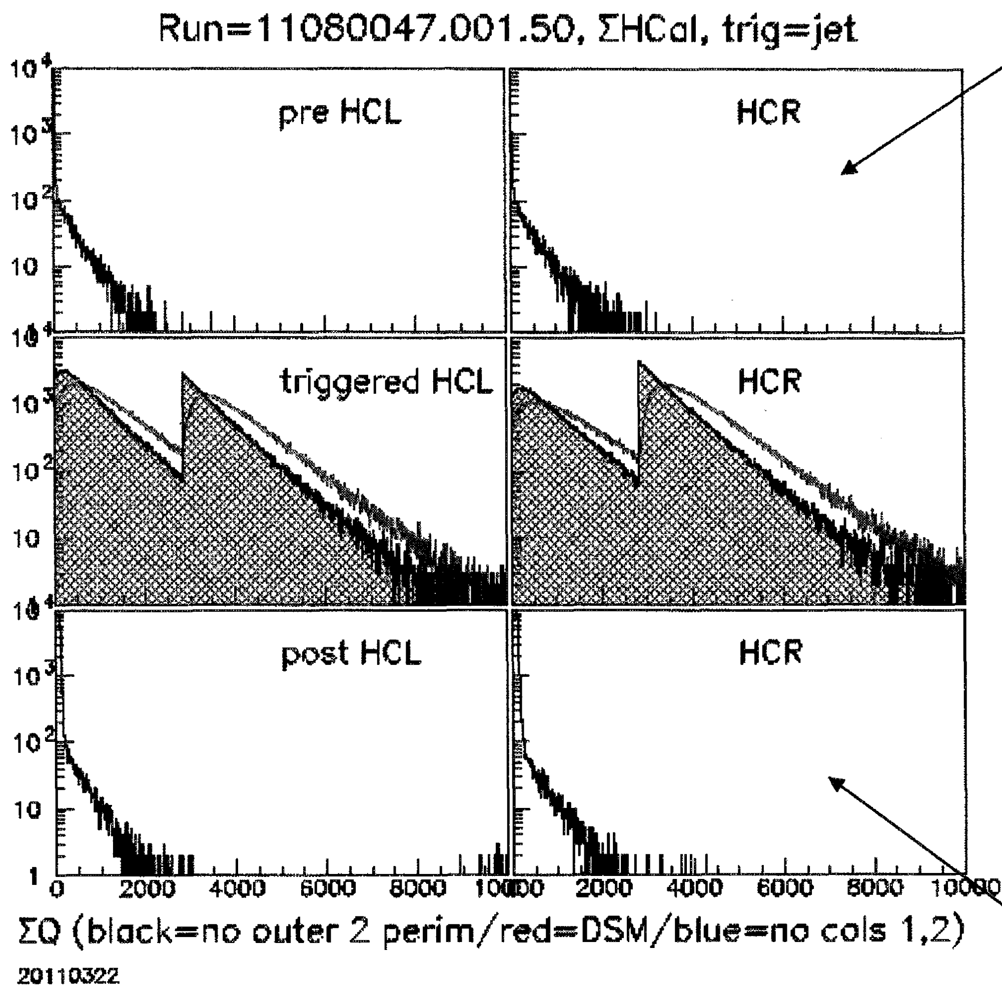
- Hcal is existing 9x12 modules from E864 (NIM406,227)
- EMcal is modeled as only $(3.8\text{cm})^2\text{x}(45\text{cm})$ lead glass
- Preshower would require construction
- PHOBOS split-dipole magnetic field in GEANT model
- Fiber tracker stations and MWPC require construction

http://www.star.bnl.gov/~akio/ip2/topview_run13.jpeg

IP2 in January, 2011



Jet Trigger



Hadron calorimeter is quiet ~107ns before jet event

- Jet trigger sums HCal response excluding outer two perimeters (rather than just two columns closest to beam)
- Definition is consistent with objective of having jet thrust axis centered in hadron calorimeter modules
- HCal energy scale determination from ECal/HCal correlations is underway

Hadron calorimeter is quiet again ~107ns after jet event

RHIC present status and plans

Wolfram Fischer
Brookhaven National Laboratory

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In Run-11 the peak performance in 250 GeV polarized proton operation has significantly increased for both luminosity and polarization, although at a reduced time in store. The RHIC Run-11 is summarized and the main polarized proton upgrades for the next years are presented. d-Au and p-Au operation, a possible energy upgrade, and ^{3}He operation are discussed.

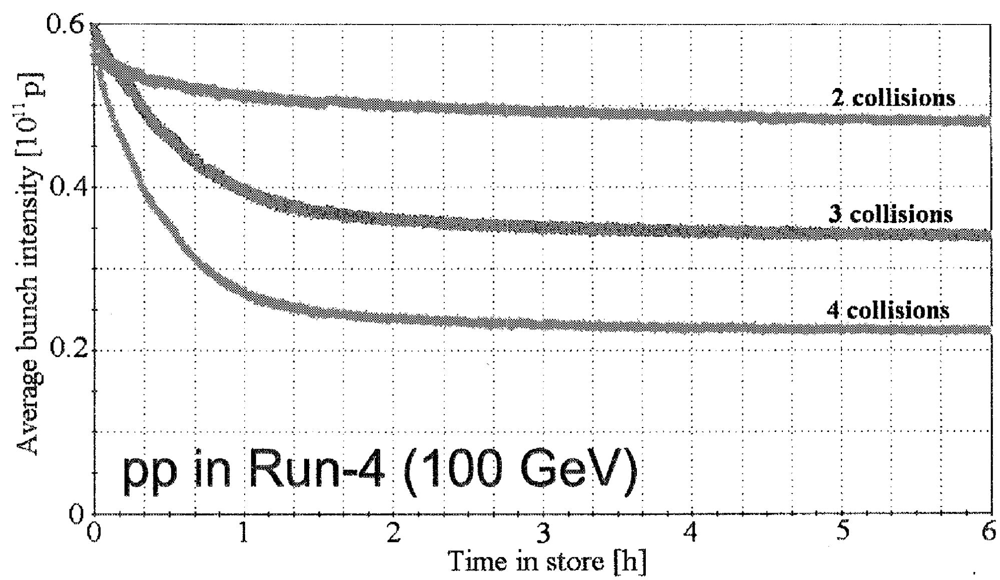
Future operation of A_nDY

- Can reduce β^* at IP2
  - have run with $\beta^* = 2.0$ m previously for BRAHMS
  - $\beta^* = 1.5$ m probably ok, needs to be tested
- Longer stores
  - 10h instead of 8h in Run-11 (depends on luminosity lifetime and store-to-store time)
- Collide earlier in store when conditions are met
  - needs coordination with polarization measurement, PHENIX and STAR
- Electron lenses (see later) if A_nDY runs beyond Run-13
  - increases max beam-beam tune spread, currently $\Delta Q_{max,bb} \approx 0.015$
  - can be used for to increase $\xi \sim N_b/\varepsilon$ and/or number of collisions

Run-11 luminosity at A_nDY:
max ~0.3 pb^{-1}/store

With improvements:
~3x increase,
~10 pb^{-1}/week

[all preliminary]



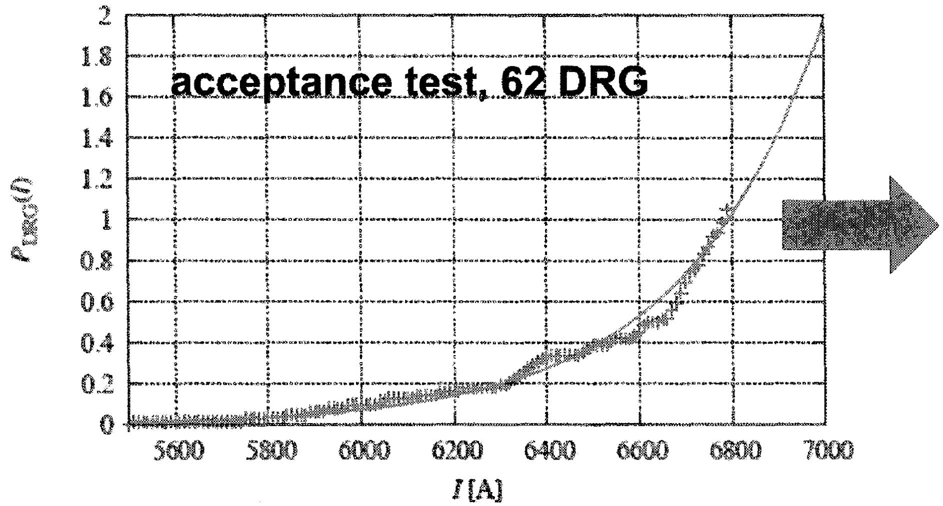
Asymmetric collisions (p-Au)

- p-Au was considered in RHIC design (D. Trbojevic), no operation yet
  100.8 GeV p on 100.0 GeV/nucleon Au ($\gamma_p = \gamma_{Au} = 107.4$)
- **Need to translate DX magnets horizontally by 4.33 cm**
  p are bent stronger than Au^{79+}
- For energy scan need to match Lorentz factor γ of both beams

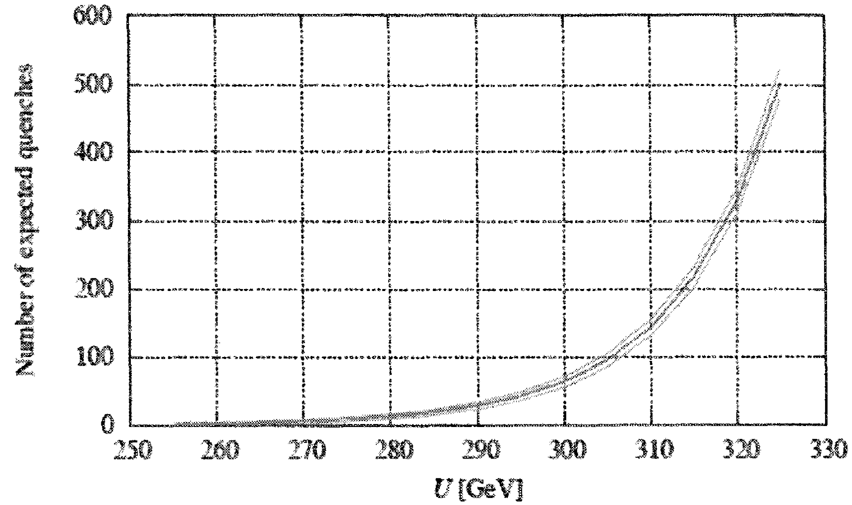
Parameter	unit	p-Au		p-Au	
No of bunches	...	111	111	111	111
Ions/bunch, initial	10^9	100	1.0	200	1.2
Average beam current/ring	mA	139	110	278	132
Stored energy per beam	MJ			0.36	0.42
β^*	m	0.85		0.60	
Hour glass factor	...	1.00		0.91	
Beam-beam parameter ξ/IP	10^{-3}	4.3	1.7	5.2	3.5
Peak luminosity	10^{28} cm^{-2}s^{-1}	30		95	
Average / peak luminosity	%	60		60	
Average store luminosity	10^{28} cm^{-2}s^{-1}	18		57	
Time in store	%	55		55	
Maximum luminosity/week	nb^{-1}			189	
Minimum luminosity/week	nb^{-1}	60			

Energy upgrade – W. MacKay, C-A/AP/422

observed quenches in arc dipoles



estimated # of training quenches



Conclusion:

- 10% increase to 275 GeV (+45% in σ_W) feasible with current magnets
  about 20 DX, 10 other training quenches, more cooling at some current leads
- Requires some hardware upgrades (dump kicker, power supplies)
- Effect on polarization still needs study
- Energies >275 GeV require too many training quenches
  hundreds of arc dipole training quenches alone for 325 GeV

Polarized ^{3}He

[Summary W. MacKay, CAD MAC-05, 09/15/2010]

- Deuterons not good in RHIC — perhaps in a figure-8 ring.

- He^3 looks promising: no real show stoppers.
  - Source: $^3He^{+2}$ OPPIS source — proposal: Milner/Zelenski
    See Anatoli Zelenski's presentation.
  - $|G\gamma|_{\text{max}}$ is higher for He^3:
    - More and Stronger resonances in all rings.
  - ^{3}He polarimeters need to be developed.
  - AGS cold snake may be sufficient at lower field.
    AGS warm snake (fixed field) might be too strong ($\sim$ 14%).
  - AGS injection and extraction spin-matching: not too bad.
    - Booster to AGS may need matching (depends on AGS snakes).
  - RHIC snakes and rotators will work with lower fields.
  - Lower injection rigidity for RHIC should be OK.
    - Injection orbit excursions reduced.

Summary – RHIC performance

- Run-11 p^p^ results:
  $P > 46\%$, $L_{peak} = 150\text{x}10^{30}\text{cm}^{-2}\text{s}^{-1}$, $L_{avg} = 85\text{x}10^{30}\text{cm}^{-2}\text{s}^{-1}$
  (all new records for peak performance, and all within Run-11 projections)
  Integrated luminosity below expectation due to down time
  A_nDY tested, ran with relatively small impact on STAR/PHENIX
- Main hardware upgrades for p^p^ (commissioning planned for Run-13)
  Polarized source: P +5%, intensity +order of magnitude
  Electron lenses : up to 2x more luminosity with source upgrade
- Asymmetric collisions (d-Au and p-Au)
  Expect up 2x more luminosity for future d-Au operation rel. to Run-8
  p-Au possible with change of DX location ($\gamma_p = \gamma_{Au} = 107.4$)
- Limited energy upgrade possible, 10% to 275 GeV protons
  Effect on polarization still needs study, requires hardware upgrades
- Polarized ^{3}He (p-^{3}He, ^{3}He-^{3}He)
  Polarized ^{3}He source R&D has started (with MIT, using EBIS)
  Acceleration and storage in RHIC should be possible
  ^{3}He polarimetry at high (esp. absolute) needs R&D

Theoretical perspectives on Drell-Yan production measurements

Jian-Wei Qiu

Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

I noticed that almost all talks in this workshop addresses the "theoretical perspectives on Drell-Yan production measurements". In this talk, I will list a number of opportunities and challenges associated with Drell-Yan production measurements, and try not to repeat too much what other people have said.

By measuring two leptons, the Drell-Yan process is a hard probe with two natural scales: invariant mass $Q = \sqrt{q^2}$ and total transverse momentum $q_\perp$ of the pair. By measuring Drell-Yan lepton pair at different combinations of these two momentum scales, the measurement can provide rich information on QCD dynamics and colliding hadron's partonic structure. For example, when $q_\perp \ll Q$, the transverse momentum dependent (TMD) factorization formalism should work for the Drell-Yan cross section, and the measurement of Drell-Yan lepton pairs in this kinematic regime probes the TMD parton distributions and dynamics of partons' transverse motion inside a colliding hadron. On the other hand, when $q_\perp \sim Q$ or $q_\perp \gg Q$, the collinear factorization formalism should work better, and the measurement should provide clean information on collinear parton distributions, in particular, the gluon distributions. Exploring the rapidity dependence of the lepton pair can help probe parton densities at very small parton momentum fractions, in particular, in the region where $Q_s \sim q_\perp$. Furthermore, by measuring the angular distribution of the lepton pair in the pair's rest frame, Drell-Yan measurement provides excellent information on the quantum interference of different spin states of the vector boson that decays into the lepton pair.

One of the most important predictions of TMD factorization formalism is the sign change of the Sivers function and the Boer-Mulder function between the SIDIS and Drell-Yan measurement. The sign change is the immediate consequence of the TMD factorization, and the parity and the time-reversal invariance of strong interaction. The test of the sign change is clearly a critical test of the TMD factorization formalism. However, one has to compare the distributions from SIDIS and Drell-Yan at the same momentum fraction x and parton transverse momentum $k_\perp$ in order to have a true test of the sign change. This is because the sign of the spin asymmetries could be different at the different effective value of x or $k_\perp$ if there is a node in either the x-dependence or $k_\perp$ dependence of the TMD distributions.

To test spin asymmetries, it is very important to understand both the numerator and the denominator. The denomenator - the spin averaged Drell-Yan cross section at low $q_\perp$ and large Q requires QCD resummation of large logarithms. For the same kinematics, the resummation is also needed for the numerator - the spin dependent cross section. Theory difficulties exist in controlling lepton angular distributions at low $q_\perp$. If one describes the low $k_\perp$ behavior in terms of TMD parton distributions, it is critical to understand the Q^2 dependence of TMD distributions, which is still lacking.

Test of the predicted strong suppression of Drell-Yan production in the very forward region of dA collisions is exciting. Quantitative comparison between various theory calculations is needed. Verify the predicted sign change of the power correction in low Q region between inclusive Drell-Yan and DIS should be very interesting too. In conclusion, Drell-Yan lepton pair production is one of the oldest hard process proposed to test QCD, and it is still a very good one!

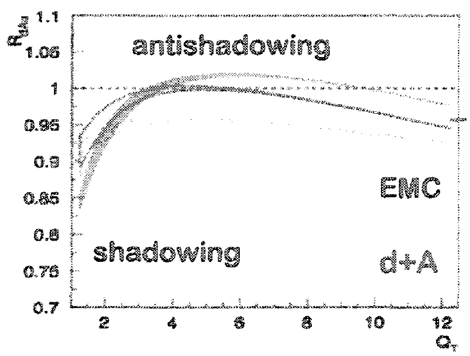
Excellent probe of gluon distribution

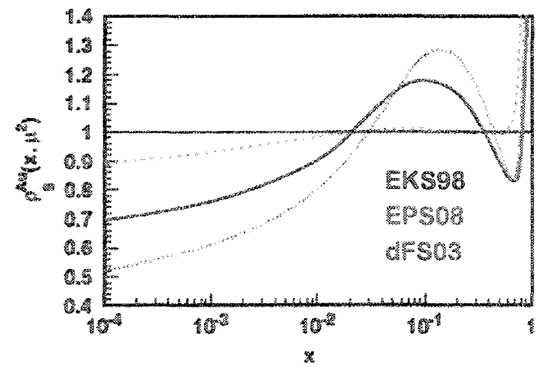
- Nuclear modification factor:

Kang, Qiu, Vogelsang, PRD 2009

$$R_{\rm dAu} \equiv \frac{1}{\langle N_{coll}\rangle}\frac{d^2N^{\rm dAu}/dQ_Tdy}{d^2N^{pp}/dQ_Tdy} \overset{\rm min.bias}{=} \frac{\frac{1}{2A}d^2\sigma^{\rm dAu}/dQ_Tdy}{d^2\sigma^{pp}/dQ_Tdy}$$

- RHIC kinematics – if dominated by single scattering:





– The band is given by κ=1 (top lines) and κ=0 (bottom lines)

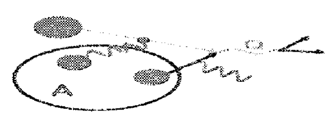
– Ratio follows the feature of gluon distribution if turns off isospin

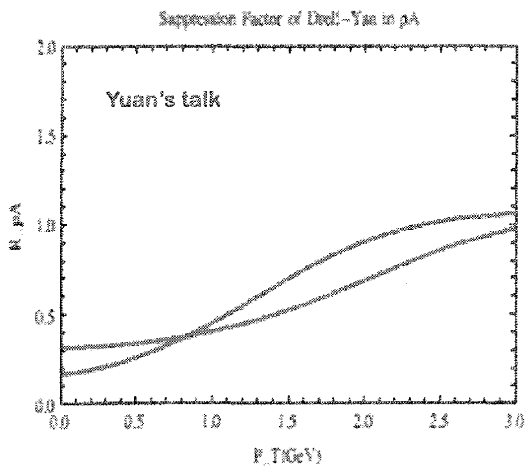
– No suppression if removing isospin effect

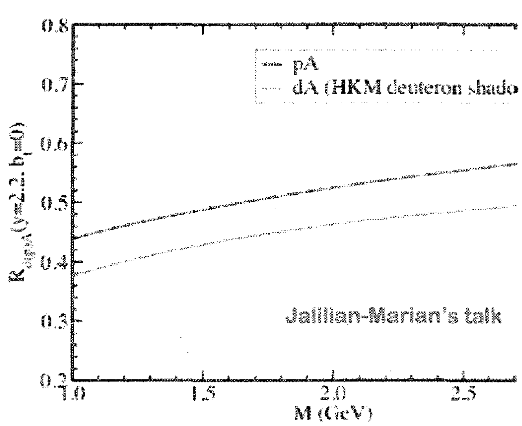
Saturation and CGC physics

- Forward rapidity (y >> 0):

If $Q_T \sim Q_s$, collinear factorization fails





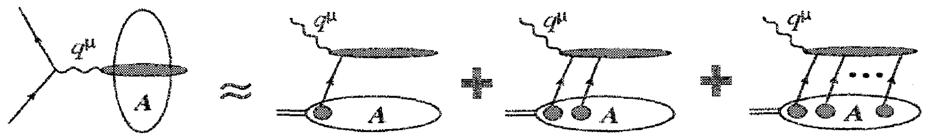


Nuclear shadowing cannot produce such suppression!

Theory challenge: Role of p_T?

Another sign change

- Power correction to DIS – single scale:



$$F_{eA}(x,Q^2) = F_{eA}^{\rm LP}(x,Q^2) + \frac{1}{Q^2}F_{eA}^{\rm NLP}(x,Q^2) + ...$$

Negative - suppression

- Power correction to inclusive DY – single scale:

$$\frac{d\sigma_{pA}}{dQ^2} = \frac{d\sigma_{pA}^{\rm LP}}{dQ^2} + \frac{1}{Q^2}\frac{d\sigma_{pA}^{\rm NLP}}{dQ^2} + ...$$

Positive - enhancement

Compton gives negative contribution in CO factorization

Summary and outlook

- Drell-Yan process is one of the oldest hard process proposed to test QCD – it still a very good one!
- The proof of QCD factorization for Drell-Yan is solid (LP + NLP for collinear, LP for TMD)
- The test of the sign change of the Sivers function is a critical test of TMD factorization!
- Drell-Yan could provide much more than the sign change of Sivers function

Thank you!

TMD fracture functions in SIDIS and DY

Aram Kotzinian

Torino University and INFN, Italy and YerPhI, Armenia

The Fracture Function formalism was introduced by Trentadue and Veneziano in 1994 to describe hadron production in the target fragmentation region (TFR) of SIDIS in collinear configuration.

Recently we generalized this formalism for the spin and transverse momentum dependent fracture functions (see M.Anselmino, V.Barone and A.K., **arXiv:1102.4214; PLB 699 (2011) 108**).

109 In total 16 LO fracture functions are needed to describe spinless hadron production.

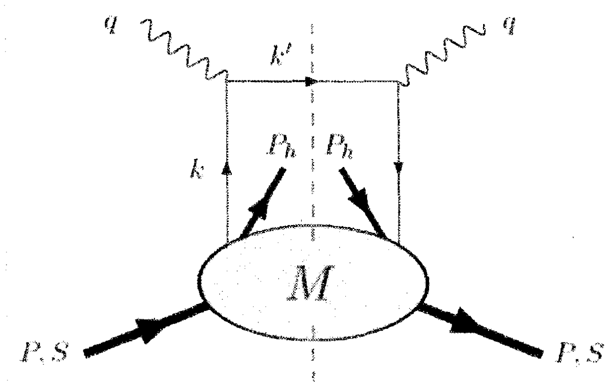
One particle production in the TFR of polarized SIDIS gives access only to 4 k_T-integrated fracture functions.

To study other fracture functions one need to “measure” scattered quark transverse polarization. Collins effect for hadron produced in the current fragmentation region (CFR) allows to access these functions via azimuthal asymmetries measurements in double hadron (one in CFR, another in TFR) production (DSIDIS) process.

Another way to study these fracture functions is to measure the azimuthal asymmetries in the polarized semi-inclusive DY (SIDY) processes when together with high mass lepton pair one spinless hadron is also detected.

The expression for the LO cross sections in polarized DSIDIS and SIDY processes are presented.

Quark correlator



$$\mathcal{M}^{[\Gamma]}(x_B,\vec{k}_\perp,\zeta,\vec{P}_{h\perp}) = \frac{1}{4\zeta}\int\frac{d\xi^+ d^2\xi_\perp}{(2\pi)^6}e^{i(x_B P^-\xi^+ - \vec{k}_\perp\cdot\vec{\xi}_\perp)}\sum_X\int\frac{d^3P_X}{(2\pi)^3 2E_X}\times$$

$$\times\langle P,S|\bar{\psi}(0)\Gamma|P_h,S_h;X\rangle\langle P_h,S_h;X|\psi(\xi^+,0,\vec{\xi}_\perp)|P,S\rangle$$

$$\Gamma = \gamma^-,\ \ \gamma^-\gamma_5,\ \ i\sigma^{i-}\gamma_5$$

STMD Fracture Functions for spinless hadron production

	Quark polarization		
Nucleon Polarization	**U**	**L**	**T**
U	$\hat{M}$	$\frac{\mathbf{k}_T \times \mathbf{P}_T}{m_N m_h} \Delta \hat{M}^{\perp h}$	$\frac{\epsilon_T^{ij} P_T^{\ j}}{m_h} \Delta_T \hat{M}^{h} + \frac{\epsilon_T^{ij} k_T^{\ j}}{m_N} \Delta_T \hat{M}^{\perp}$
L	$\frac{S_L (\mathbf{k}_T \times \mathbf{P}_T)}{m_N m_h} \hat{M}_L^{\perp h}$	$S_L \Delta \hat{M}_L$	$\frac{S_L \mathbf{P}_T}{m_h} \Delta_T \hat{M}_L^{h} + \frac{S_L \mathbf{k}_T}{m_N} \Delta_T \hat{M}_L^{\perp}$
T	$\frac{\mathbf{P}_T \times \mathbf{S}_T}{m_h} \hat{M}_T^{h} +$ $\frac{\mathbf{k}_T \times \mathbf{S}_T}{m_N} \hat{M}_T^{\perp}$	$\frac{\mathbf{P}_T \cdot \mathbf{S}_T}{m_h} \Delta \hat{M}_T^{h} +$ $\frac{\mathbf{k}_T \cdot \mathbf{S}_T}{m_N} \Delta \hat{M}_T^{\perp}$	$\mathbf{S}_T \Delta_T \hat{M}_T +$ $\frac{\mathbf{P}_T (\mathbf{P}_T \cdot \mathbf{S}_T)}{m_h^2} \Delta_T \hat{M}_T^{hh} + \frac{\mathbf{k}_T (\mathbf{k}_T \cdot \mathbf{S}_T)}{m_N^2} \Delta_T \hat{M}_T^{\perp\perp}$ $+ \frac{\mathbf{P}_T (\mathbf{k}_T \cdot \mathbf{S}_T) - \mathbf{k}_T \cdot (\mathbf{P}_T \cdot \mathbf{S}_T)}{m_N m_h} \Delta_T \hat{M}_T^{\perp h}$

LO cross-section in TFR

$$\frac{d\sigma^{\ell(l,\lambda)+N(P_N,S)\to\ell(l')+h(P)+X}(x_F<0)}{dx\,dQ^2\,d\phi_S\,d\zeta\,d^2P_T}=\frac{\alpha^2 x}{yQ^4}\left(1+(1-y)^2\right)\sum_q e_q^2\times$$

$$\times\left[\begin{array}{l} M\left(x,\zeta,P_T^2\right)-S_T\frac{P_T}{m_h}M_T^h\left(x,\zeta,P_T^2\right)\sin(\phi_h-\phi_S)+ \\ \lambda D_{ll}(y)\left(S_L\Delta M_L\left(x,\zeta,P_T^2\right)+S_T\frac{P_T}{m_h}\Delta M_T^h\left(x,\zeta,P_T^2\right)\cos(\phi_h-\phi_S)\right)\end{array}\right]$$

Only 4 terms out of
18 Structure Functions,
2 azimuthal modulations

		Quark polarization		
		U	L	T
Nucleon Polarization	U	$M\left(x,\zeta,P_T^2\right)$		
	L		$\Delta M_L\left(x,\zeta,P_T^2\right)$	
	T	$M_T^h\left(x,\zeta,P_T^2\right)$	$\Delta M_T^h\left(x,\zeta,P_T^2\right)$	

SIDY cross section

$$\frac{d\sigma}{d^4q\,d\Omega\,d\zeta\,d^2P_T} = \frac{\alpha_{em}^2 x_a x_b}{2q^4}\frac{1}{N_c}\sum_q e_q^2 \int d^2\vec{k}_{aT}\,d^2\vec{k}_{bT}\,\delta^{(2)}\left(\vec{q}_T - \vec{k}_{aT} - \vec{k}_{bT}\right)\times$$

$$\times\begin{pmatrix} \left(1+\cos^2\theta\right)\left(\Phi^{q[\gamma^+]}\overline{\mathcal{M}}^{q[\gamma^-]} + \Phi^{q[\gamma^+\gamma_5]}\overline{\mathcal{M}}^{q[\gamma^-\gamma_5]}\right) \\ +\sin^2\theta\begin{pmatrix}\cos 2\phi\left(\delta^{i1}\delta^{j1} - \delta^{i2}\delta^{j2}\right) \\ +\sin 2\phi\left(\delta^{i1}\delta^{j2} + \delta^{i2}\delta^{j1}\right)\end{pmatrix}\Phi^{q[i\sigma^{i+}\gamma_5]}\overline{\mathcal{M}}^{q[i\sigma^{j-}\gamma_5]} \\ +\{\Phi \leftrightarrow \overline{\Phi}, \overline{\mathcal{M}} \leftrightarrow \mathcal{M}\} + \mathcal{O}(1/q) \end{pmatrix}$$

$$= \frac{\alpha_{em}^2 x_a x_b}{2q^4}\begin{pmatrix} \sigma_{UU} + S_{bL}\sigma_{UL} + S_{bT}\sigma_{UT} \\ +S_{aL}\sigma_{LU} + S_{aL}S_{bL}\sigma_{LL} + S_{aL}S_{bT}\sigma_{LT} \\ +S_{aT}\sigma_{TU} + S_{aT}S_{bL}\sigma_{TL} + S_{aT}S_{bT}\sigma_{TT} \end{pmatrix}$$

CONCLUSIONS

- New members appeared in the polarized TMDs family -- 16 LO STMD fracture functions
- For hadron produced in the TFR, only 4 k_T-integrated fracture functions of unpolarized and longitudinally polarized quarks are probed.
  - SSA contains only a Sivers-type modulation $\sin(\phi_h-\phi_S)$ but no Collins-type $\sin(\phi_h+\phi_S)$ or $\sin(3\phi_h-\phi_S)$. The eventual observation of Collins-type asymmetry will indicate that LO factorized approach fails and **long range correlations** between the struck quark polarization and P_T of produced in TFR hadron might be important.
- DSIDIS cross section at LO contains 2 azimuthal independent and 20 azimuthally modulated terms.
- SIDY cross section at LO contains 2 azimuthal independent, 20 lepton azimuth independent and 52 lepton azimuth dependent terms
- The ideal place to test the fracture functions factorization and measure these new nonperturbative objects are JLab12 and EIC facilities with full coverage of phase space and polarized SIDY
- To do
  - Factorization proof (SIDIS, DSIDIS, SIDY).
    - Structure of Wilson lines. SIDIS ←→ DY universality: sign changes of some fracture functions? Higher twist. Polarized hadron production. Phenomenology: parameterizations , simple models. Other processes: $P\uparrow + P \to \pi + X$, $P\uparrow + P \to \pi + jet + X$, ...

What the Drell-Yan measurement can offer us at small-x?

May 12, 2011

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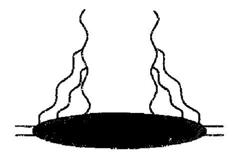
A Tale of Two Gluon Distributions

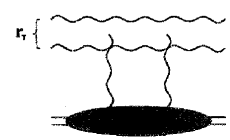
I. Weizsäcker Williams gluon distribution (MV model):

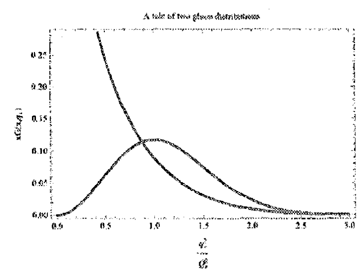
$$xG^{(1)} = \frac{S_\perp}{\pi^2 \alpha_s}\frac{N_c^2-1}{N_c} \Leftarrow$$
$$\times \int \frac{d^2 r_\perp}{(2\pi)^2}\frac{e^{-ik_\perp \cdot r_\perp}}{r_\perp^2}\left(1 - e^{-\frac{r_\perp^2 Q_s^2}{2}}\right)$$



II. Color Dipole gluon distributions:

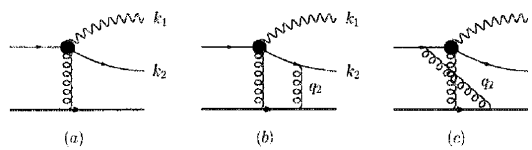
$$xG^{(2)} = \frac{S_\perp N_c}{2\pi^2 \alpha_s} \Leftarrow$$
$$\times \int \frac{d^2 r_\perp}{(2\pi)^2} e^{-ik_\perp \cdot r_\perp} \nabla^2_{r_\perp} N(r_\perp)$$





γ+Jet in pA collisions

The direct photon + jet production in pA collisions. (Drell-Yan Process follows the same factorization.)



Dipole model approach:

$$\frac{d\sigma_{\rm DP}^{pA\to\gamma^* q+X}}{dy_1 dy_2 d^2k_{1\perp} d^2k_{2\perp} d^2b} = \sum_f x_p q_f(x_p,\mu)\frac{\alpha_{e.m.} e_f^2}{2\pi^2}(1-z)\,F_{x_g}(q_\perp)$$
$$\times\left\{\left[1+(1-z)^2\right]\frac{z^2q_\perp^2}{\left[\tilde{P}_\perp^2+\epsilon_M^2\right]\left[(\tilde{P}_\perp+zq_\perp)^2+\epsilon_M^2\right]}\right.$$
$$\left.-z^2(1-z)M^2\left[\frac{1}{\tilde{P}_\perp^2+\epsilon_M^2}-\frac{1}{(\tilde{P}_\perp+zq_\perp)^2+\epsilon_M^2}\right]^2\right\},$$

Remarks:

- Direct photon measurement.
- Correlation.
- In addition, test the BK evolution equation.

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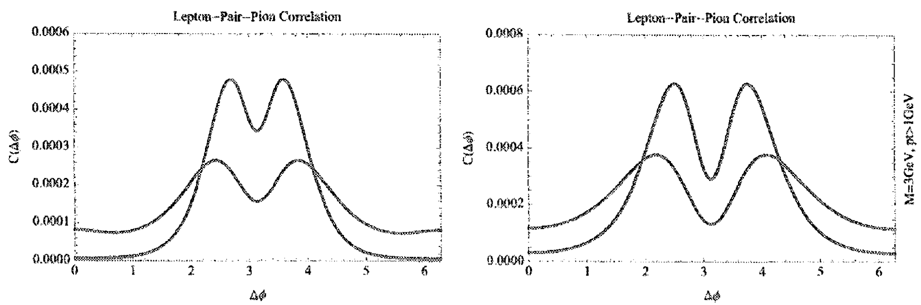
Dilepton Pair + hadron correlation

Azimuthal angle correlation of $\gamma^{*}+\pi^{0}$ at forward rapidity 3.2:



Remarks:

- $p_{1\perp} > 1.5$Gev, $p_{2\perp} > 1.5$Gev and $M^2 = 1\text{GeV}^2$;
- $p_{1\perp} > 1$Gev, $p_{2\perp} > 1$Gev and $M^2 = 9\text{GeV}^2$;
- Suppression of away side peak at central dAu collisions.
- The unique double peak structure on the away side comes from the fact that $xG^{(2)} \propto q_{\perp}^{2}$ in the small $q_{\perp}$ limit.
- To avoid the contamination of ρ and J/Ψ, better choice of kinematical region. Low Mass M^2 vs high mass?

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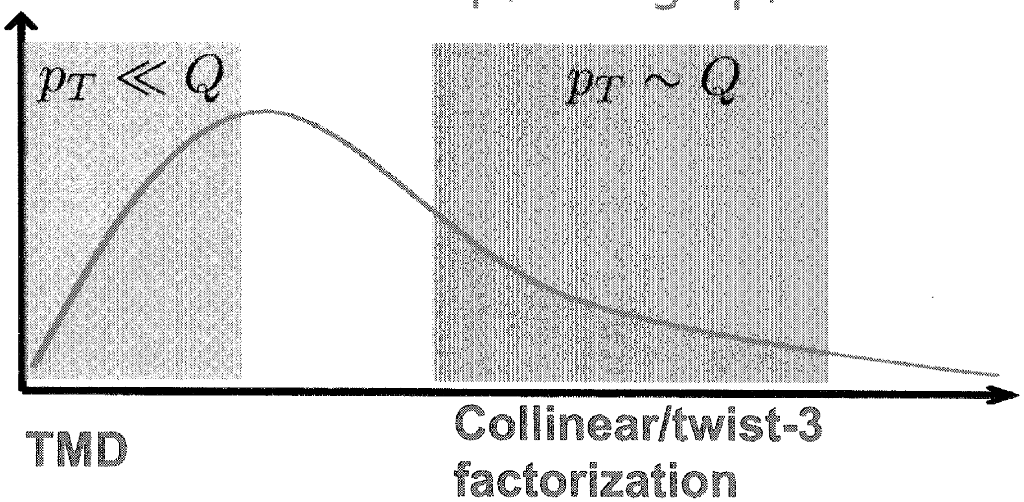
Questions?

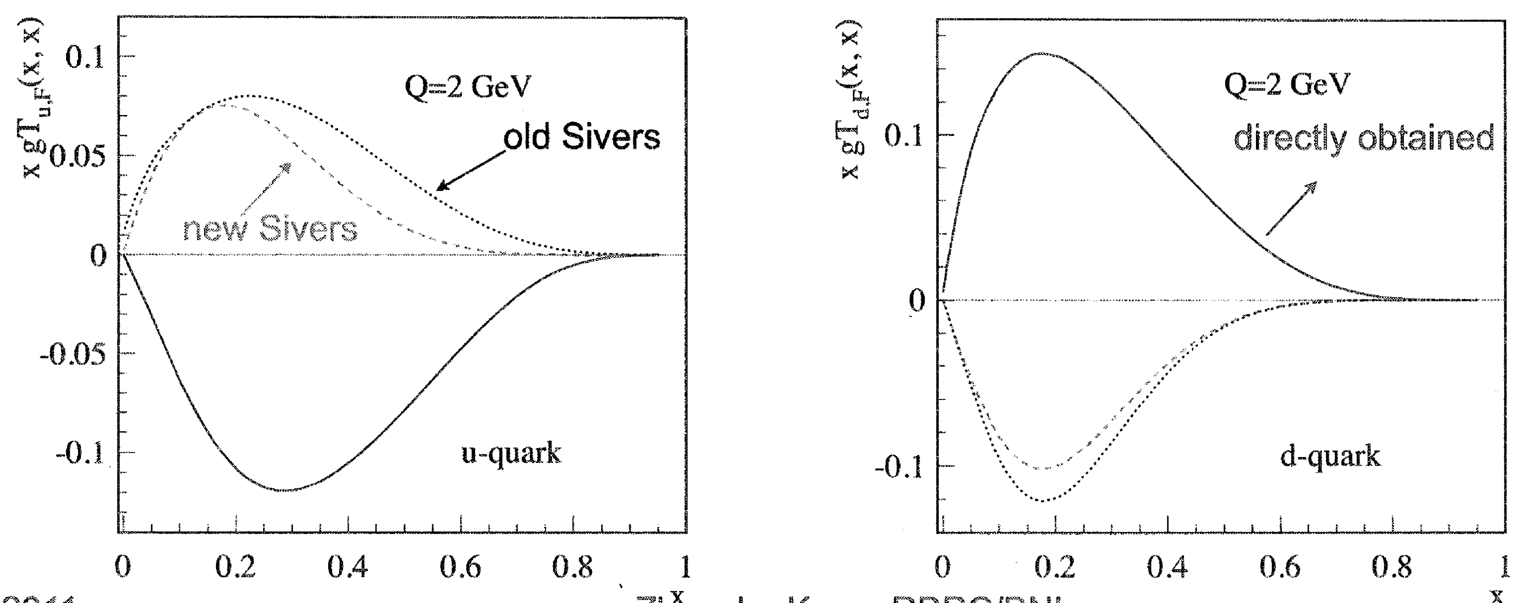
- What is the theoretical uncertainties of DY A_N predictions?
  - How do they affect our goal of checking the sign change?
- What is the real impact of the measurement of sign change?
  - Is this issue only relevant to spin physics? How should be convey to outside community?
  - If we have sign change, what is the contribution we have made?
  - If we have not sign change, what does this mean? Is this really a big deal?

“Sign mismatch” between SIDIS and pp

- Transition from low p_T to high p_T

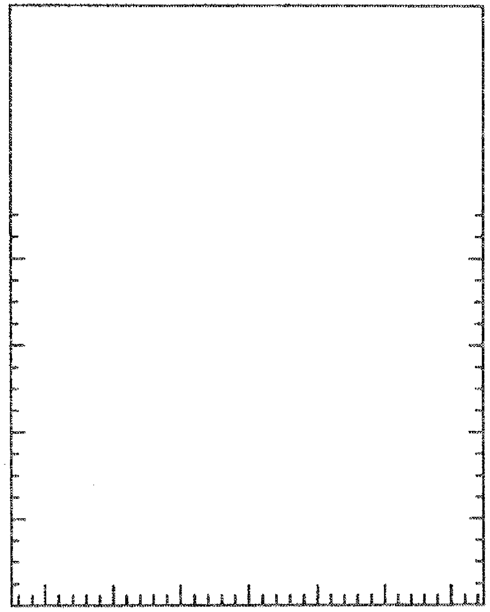


- Need to determine the sign and constrain $T_F(x,x)$



Dijet asymmetry measurement

- The theory prediction here is using $T_F(x, x)$ from the first kt-moment of Sivers function from SIDIS



- Also the problem of factorization breaking

- What is the impact of DY on small-x physics?

- What to blame if
  - No sign change
  - if we see a sign change but different magnitude/shape?

- What can we learn from Collider vs. fixed Target?

- What measurements are needed in the future?
- (or what analysis should be done on existing data?)
- What do we need to learn from current DY experiments (Compass, AnDY, E906) for the future

Still open: Jen-Chieh at 2010 DY workshop in Santa Fe

- Is there a Boer-Mulders sign change?
- Boer-Mulders different in protons and pions?
- Flavor dependence of DY?
- k_t dependence:
  - x dependence?
  - flavor dependence?
  - difference between nucleons and mesons?
  - gluon/quark differences?

Generalized TMDs and Wigner Distributions

(A. Metz, Department of Physics, Temple University, Philadelphia, PA 19122)

ABSTRACT: The first complete parameterization of Generalized TMDs (GTMDs) for a spin-$\frac{1}{2}$ target is presented. The Fourier transform of GTMDs has a strong similarity to Wigner distributions, which are the quantum mechanical analogues of classical phase space distributions.

Many nontrivial relations between GPDs and TMDs have been found in simple spectator models. Since GTMDs contain the GPDs and the TMDs in certain limits, one can use them in order to study the status of the nontrivial GPD-TMD relations. Such an analysis reveals that none of those relations can be promoted to a model-independent status. The talk also briefly addresses more recent developments on the GTMD field as well as some potential further applications of these objects.

In collaboration with: K. Goeke, S. Meißner, M. Schlegel
(hep-ph/0703176 ; arXiv:0805.3165 ; arXiv:0906.5323)

Parameterization of GTMDs

- GTMD-correlator

$$W^{[\Gamma]} = \frac{1}{2}\int \frac{dz^-}{2\pi}\,\frac{d^2\vec{z}_T}{(2\pi)^2}\, e^{ik\cdot z}\,\langle p' \,|\, \bar{\psi}\Big(-\frac{z}{2}\Big)\,\Gamma\,\mathcal{W}_{GTMD}\,\psi\Big(\frac{z}{2}\Big)\,|\, p\rangle\Big|_{z^+=0}$$

$\longrightarrow$ $W^{[\Gamma]}$ appears, e.g., in handbag diagram of DVCS

- Projection onto GPDs and TMDs

$$\begin{aligned} F^{[\Gamma]} &= \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ik\cdot z}\,\langle p' \,|\, \bar{\psi}\Big(-\frac{z}{2}\Big)\,\Gamma\,\mathcal{W}_{GPD}\,\psi\Big(\frac{z}{2}\Big)\,|\, p\rangle\Big|_{z^+=z_T=0} \\ &= \int d^2\vec{k}_T\, W^{[\Gamma]} \end{aligned}$$

$$\begin{aligned} \Phi^{[\Gamma]} &= \frac{1}{2}\int \frac{dz^-}{2\pi}\,\frac{d^2\vec{z}_T}{(2\pi)^2}\, e^{ik\cdot z}\,\langle p \,|\, \bar{\psi}\Big(-\frac{z}{2}\Big)\,\Gamma\,\mathcal{W}_{TMD}\,\psi\Big(\frac{z}{2}\Big)\,|\, p\rangle\Big|_{z^+=0} \\ &= W^{[\Gamma]}\Big|_{\Delta=0} \end{aligned}$$

$\longrightarrow$ GPDs and TMDs appear as certain limits of GTMDs (mother distributions)

- Parameterization of GTMD-correlator **(Meißner, Metz, Schlegel, 2009)**
  - Use constraints from hermiticity and parity
  - Eliminate redundant terms by means of Gordon identities, etc.

$$\det \begin{pmatrix} g^{\alpha\mu} & g^{\beta\mu} & g^{\gamma\mu} & g^{\delta\mu} & g^{\varepsilon\mu} \\ g^{\alpha\nu} & g^{\beta\nu} & g^{\gamma\nu} & g^{\delta\nu} & g^{\varepsilon\nu} \\ g^{\alpha\rho} & g^{\beta\rho} & g^{\gamma\rho} & g^{\delta\rho} & g^{\varepsilon\rho} \\ g^{\alpha\sigma} & g^{\beta\sigma} & g^{\gamma\sigma} & g^{\delta\sigma} & g^{\varepsilon\sigma} \\ g^{\alpha\tau} & g^{\beta\tau} & g^{\gamma\tau} & g^{\delta\tau} & g^{\varepsilon\tau} \end{pmatrix} = 0$$

  - Example

$$W^{[\gamma^+]} = \frac{1}{2M}\,\bar{u}(p')\left[\boldsymbol{F}_{1,1} + \frac{i\sigma^{i+}k_T^i}{P^+}\,\boldsymbol{F}_{1,2} + \frac{i\sigma^{i+}\Delta_T^i}{P^+}\,\boldsymbol{F}_{1,3} + \frac{i\sigma^{ij}k_T^i\Delta_T^j}{M^2}\,\boldsymbol{F}_{1,4}\right]u(p)$$

$\longrightarrow$ GTMDs are complex functions: $F_{1,n} = F_{1,n}^e + iF_{1,n}^o$

  - Parameterization for all twists
  - By-product: first full classification of GPDs beyond leading twist
  - Relations between GPDs/TMDs and GTMDs worked out
  - Leading twist GTMDs computed in scalar diquark model

Wigner distributions

- Phase-space distribution in classical mechanics $\rho(\vec{k}, \vec{r})$
- Phase-space distribution in quantum mechanics (Wigner distribution) $W(\vec{k}, \vec{r})$
  - Relation to probability density in position and momentum space

$$|\psi(\vec{r})|^2 = \int d^3\vec{k}\, W(\vec{k}, \vec{r}) \qquad |\psi(\vec{k})|^2 = \int d^3\vec{r}\, W(\vec{k}, \vec{r})$$

- Fourier transform of GTMDs ($\xi = 0$) (Ji, 2003 / Belitsky, Ji, Yuan, 2003)

$$\mathrm{WD}(x, \vec{k}_T, \vec{b}_T) \simeq \int d^2\vec{\Delta}_T\, e^{-i\vec{\Delta}_T\cdot\vec{b}_T}\, \mathrm{GTMD}(x, \vec{k}_T, \vec{\Delta}_T)$$

  - Relation with GPDs and TMDs

$$\mathrm{GPD}(x, \vec{b}_T) \simeq \int d^2\vec{k}_T\, \mathrm{WD}(x, \vec{k}_T, \vec{b}_T) \qquad \mathrm{TMD}(x, \vec{k}_T) \simeq \int d^2\vec{b}_T\, \mathrm{WD}(x, \vec{k}_T, \vec{b}_T)$$

  - No handle on longitudinal position of parton
  - $\vec{b}_T$ and $\vec{k}_T$ are not Fourier conjugate variables

Relations/Analogies between GPDs and TMDs

- Relations of first type

$$f_1^{q/g} \leftrightarrow \mathcal{H}^{q/g} \qquad g_{1L}^{q/g} \leftrightarrow \tilde{\mathcal{H}}^{q/g}$$

$$\left(h_{1T}^q + \frac{\vec{k}_T^2}{2M^2}\, h_{1T}^{\perp q}\right) \leftrightarrow \left(\mathcal{H}_T^q - \frac{\vec{b}_T^2}{M^2}\, \Delta\tilde{\mathcal{H}}_T^q\right)$$

- Relations of second type

$$f_{1T}^{\perp q/g} \leftrightarrow -\left(\mathcal{E}^{q/g}\right)' \qquad h_1^{\perp q} \leftrightarrow -\left(\mathcal{E}_T^q + 2\tilde{\mathcal{H}}_T^q\right)'$$

$$\left(h_{1T}^g + \frac{\vec{k}_T^2}{2M^2}\, h_{1T}^{\perp g}\right) \leftrightarrow -2\left(\mathcal{H}_T^g - \frac{\vec{b}_T^2}{M^2}\, \Delta\tilde{\mathcal{H}}_T^g\right)'$$

- Relations of third type

$$h_{1T}^{\perp q} \leftrightarrow 2\left(\tilde{\mathcal{H}}_T^q\right)'' \qquad h_1^{\perp g} \leftrightarrow 2\left(\mathcal{E}_T^g + 2\tilde{\mathcal{H}}_T^g\right)''$$

- Relation of fourth type

$$h_{1T}^{\perp g} \leftrightarrow -4\left(\tilde{\mathcal{H}}_T^g\right)'''$$

Summary

- Classification of Generalized TMDs (and Wigner distributions) for nucleon exists
- GTMD analysis can be applied to study potential nontrivial GPD-TMD relations
- Various quantitative nontrivial GPD-TMD relations in simple spectator models
- GTMD analysis: none of those relations can have model-independent status (analysis also for subleading twist)
- Additional developments and further applications

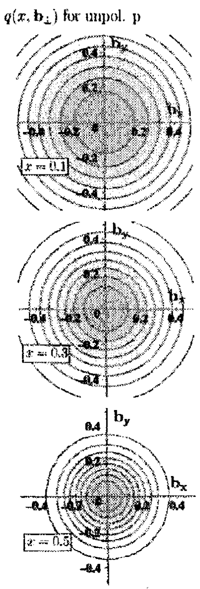
Orbital Angular Momentum

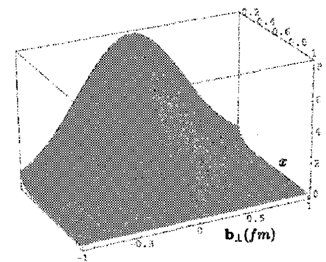
Matthias Burkardt

New Mexico State University

May 13, 2011

Impact parameter dependent quark distributions 5

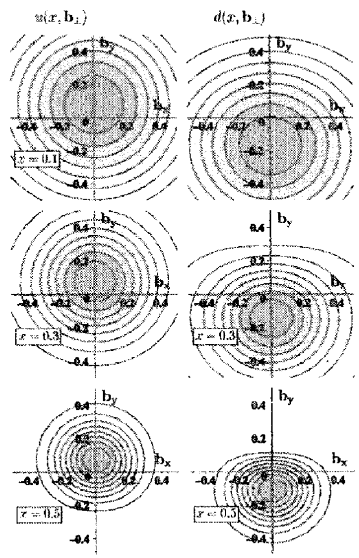




- x = momentum fraction of the quark
- $\vec{b} = \perp$ distance of quark from $\perp$ center of momentum
- small x: large 'meson cloud'
- larger x: compact 'valence core'
- $x \to 1$: active quark becomes center of momentum

$\hookrightarrow$ $\vec{b}_\perp \to 0$ (narrow distribution)

Impact parameter dependent quark distributions 7



proton polarized in $+\hat{x}$ direction

$$q(x,\mathbf{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} H_q(x,0,-\Delta_\perp^2) e^{-i\mathbf{b}_\perp\cdot\Delta_\perp}$$

$$-\frac{1}{2M}\frac{\partial}{\partial b_y}\int \frac{d^2\Delta_\perp}{(2\pi)^2} E_q(x,0,-\Delta_\perp^2) e^{-i\mathbf{b}_\perp\cdot\Delta_\perp}$$

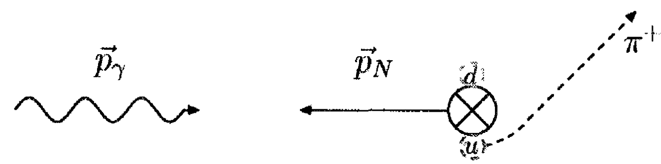
sign & magnitude of the average shift

model-independently related to p/n anomalous magnetic moments:

$$\langle b_y^q \rangle \equiv \int dx \int d^2 b_\perp q(x,\mathbf{b}_\perp) b_y$$

$$= \frac{1}{2M}\int dx E_q(x,0,0) = \frac{\kappa_q}{2M}$$

example: $\gamma p \to X$



- u, d distributions in $\perp$ polarized proton have left-right asymmetry in $\perp$ position space (T-even!); sign 'determined' by κ_u & κ_d
- attractive FSI deflects active quark towards the CoM

$\hookrightarrow$ FSI translates position space distortion (before the quark is knocked out) in $+\hat{y}$-direction into momentum asymmetry that favors $-\hat{y}$ direction → 'chromodynamic lensing'

$\Rightarrow$ $\kappa_p\,, \kappa_n \quad \longleftrightarrow \quad$ sign of SSA!!!!!!!! (MB,2004)

- confirmed by HERMES p data; consistent with vanishing isoscalar Sivers (COMPASS)

Angular Momentum Carried by Quarks 14

relate to impact parameter dependent quark distributions $q(x, \mathbf{b}_\perp)$

- Thus $J_q^x = m_N \int dx\, x r^y q(x, \mathbf{r}_\perp)$ with $b^y = r^y - \frac{1}{2m_N}$, where $q(x, \mathbf{r}_\perp)$ is distribution relative to CoM of whole nucleon
- recall: $q(x, \mathbf{b}_\perp)$ for nucleon polarized in $+\hat{x}$ direction

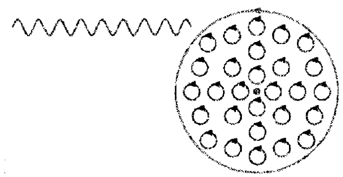
$$\begin{aligned} q(x, \mathbf{b}_\perp) &= \int \frac{d^2\Delta_\perp}{(2\pi)^2} H_q(x, 0, -\Delta_\perp^2) e^{-i\mathbf{b}_\perp \cdot \Delta_\perp} \\ &\quad - \frac{1}{2M_N} \frac{\partial}{\partial b_y} \int \frac{d^2\Delta_\perp}{(2\pi)^2} E_q(x, 0, -\Delta_\perp^2) e^{-i\mathbf{b}_\perp \cdot \Delta_\perp} \end{aligned}$$

$$\begin{aligned} \Rightarrow J_q^x &= M_N \int dx\, x r^y q(x, \mathbf{r}_\perp) = \int dx\, x \left(m_N b^y + \frac{1}{2} \right) q(x, \mathbf{r}_\perp) \\ &= \frac{1}{2} \int dx\, x \left[H(x, 0, 0) + E(x, 0, 0) \right] \end{aligned}$$

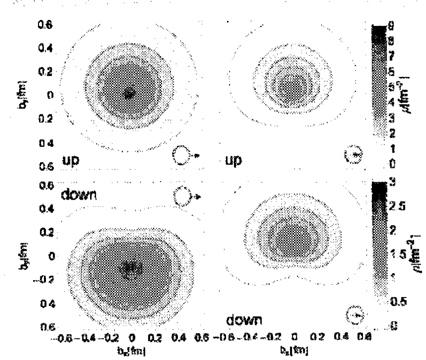
- X.Ji (1996): rotational invariance $\Rightarrow$ apply to all components of $\vec{J}$
- partonic interpretation exists only for $\perp$ components!

Sign of Boer-Mulders Function 15

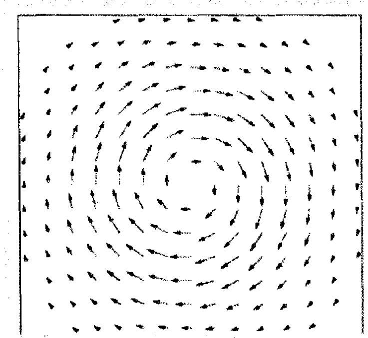
q with polarization ⊙



lattice calculations (QCDSF)



unpolarized target



- transversity distribution in unpol. target described by chirally odd GPD $\bar{E}_T$
- $\bar{E}_T > 0$ for both u & d quarks
- connection $h_1^\perp(x, \mathbf{k}_\perp) \leftrightarrow \bar{E}_T$ similar to $f_{1T}^\perp(x, \mathbf{k}_\perp) \leftrightarrow E$.

$\hookrightarrow$ $h_1^\perp(x, \mathbf{k}_\perp) < 0$ for $u/p, d/p, u/\pi, \bar{d}/\pi, ..$

Probing multi-gluon correlations in pp collisions

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Abstract:

· We derived the contribution of the 3-gluon correlation functions to the polarized cross section for $p^{\uparrow}p \to DX$, $p^{\uparrow}p \to \gamma X$ and $p^{\uparrow}p \to \ell^{+}\ell^{-}X$.

· There are two independent twist-3 three-gluon correlation functions in the polarized nucleon due to the different color contractions; $O(x_1, x_2)$ and $N(x_1, x_2)$.

· SSA occurs as a pole contribution which is written in terms of four independent functions $O(x, x)$, $N(x, x)$, $O(x, 0)$ and $N(x, 0)$.

- Numerical calculation for $p^{\uparrow}p \to DX$ and $p^{\uparrow}p \to \gamma X$.

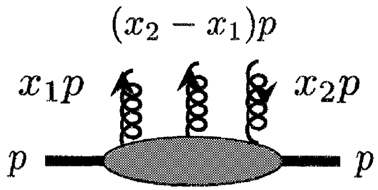
· Rising behavior of A_N for $p^{\uparrow}p \to DX$ at $x_F > 0$ as in the case of the SGP contribution from the quark-gluon correlation function for $p^{\uparrow}p \to \pi X$.

· For $p^{\uparrow}p \to \gamma X$, $A_N \simeq 0$ at $x_F > 0$ regardless of the magnitude of the 3-gluon correlation functions.

· A_N at $x_F < 0$ is sensitive to small-x behavior of 3-gluon correlation function for the two processes.

$\star$ Two processes are useful to get costraint on magnitude and shape of 3-gluon correlation functions.

⋆ Twist-3 "three-gluon" correlation functions



cf. Beppu-Koike-Tanaka-Yoshida (PRD 82('10)054005)

See also, Belitsky-Ji-Lu-Osborne, PRD63,094012(2001)
Braun-Manashov-Pirnay, PRD80,114002(2009).

- Hermiticity, PT-invariance, Permutation symmetry

$$O^{\alpha\beta\gamma}(x_1,x_2) = -g i^3 \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle pS | d^{bca} F_b^{\beta n}(0) F_c^{\gamma n}(\mu n) F_a^{\alpha n}(\lambda n) | pS \rangle$$

$$= 2iM_N \left[O(x_1,x_2) g^{\alpha\beta} \epsilon^{\gamma p n S} + O(x_2, x_2 - x_1) g^{\beta\gamma} \epsilon^{\alpha p n S} + O(x_1, x_1 - x_2) g^{\gamma\alpha} \epsilon^{\beta p n S} \right]$$

$$N^{\alpha\beta\gamma}(x_1,x_2) = -g i^3 \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle pS | i f^{bca} F_b^{\beta n}(0) F_c^{\gamma n}(\mu n) F_a^{\alpha n}(\lambda n) | pS \rangle$$

$$= 2iM_N \left[N(x_1,x_2) g^{\alpha\beta} \epsilon^{\gamma p n S} - N(x_2, x_2 - x_1) g^{\beta\gamma} \epsilon^{\alpha p n S} - N(x_1, x_1 - x_2) g^{\gamma\alpha} \epsilon^{\beta p n S} \right].$$

$F_a^{\alpha n} \equiv F_a^{\alpha\mu} n_\mu$ $\qquad$ n: lightlike vector satisfying $p \cdot n = 1$.

$\epsilon^{\gamma p n S} \equiv \epsilon^{\gamma\mu\nu\lambda} p_\mu n_\nu S_\lambda$ etc.

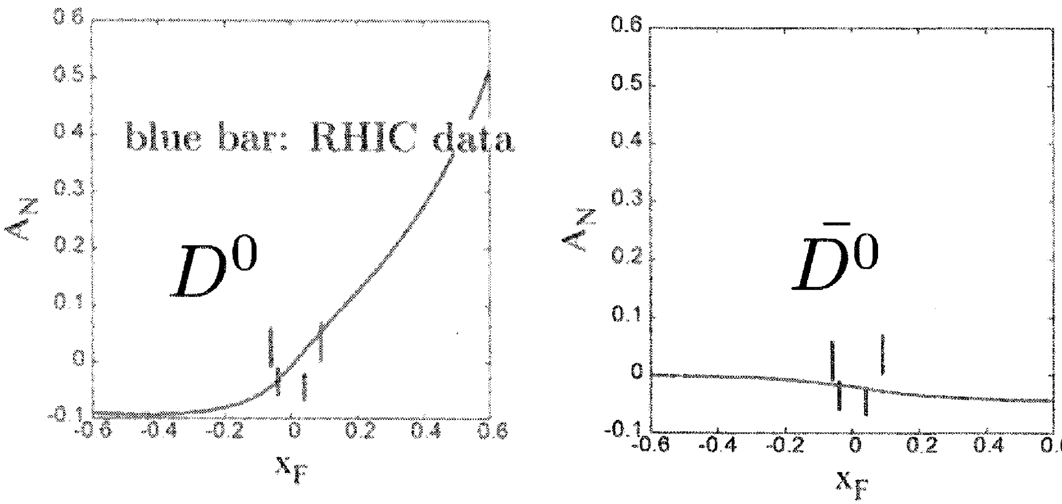
- Only two independent scalar functions due to the different color structures:

$$O(x_1,x_2) = O(x_2,x_1), \qquad O(x_1,x_2) = O(-x_1,-x_2),$$

$$N(x_1,x_2) = N(x_2,x_1), \qquad N(x_1,x_2) = -N(-x_1,-x_2).$$

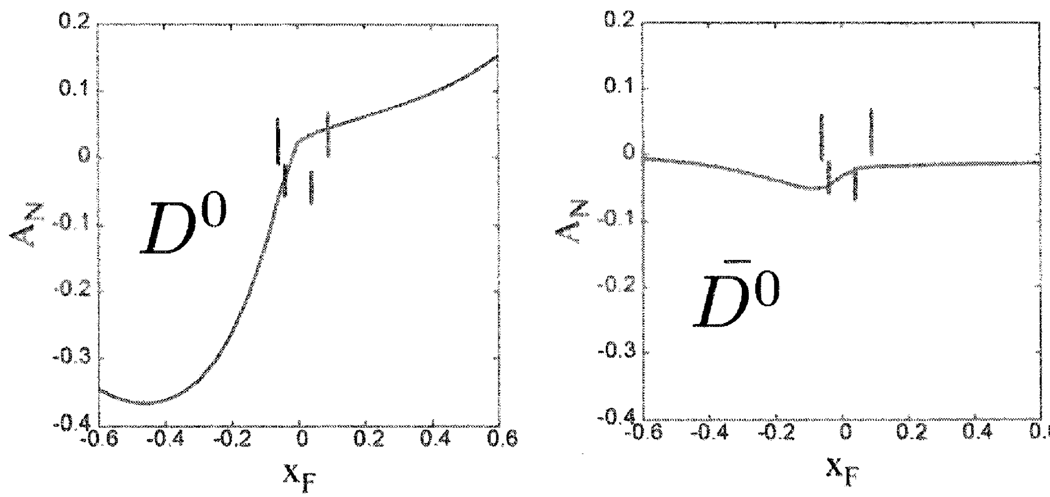
Model 1:
$O(x,x) = 0.002xG(x)$

@ $\sqrt{S} = 200$ GeV, $P_T = 2$ GeV



· Change of relative signs between $\{O(x,x), O(x,0)\}$ and $\{N(x,x), N(x,0)\}$ gives opposite prediction for D and $\bar{D}$ mesons.

Model 2:
$O(x,x) = \frac{1}{4} \times 0.002\sqrt{x}G(x)$



· A_N at $x_F < 0$ strongly depends on the small-x behavior of 3-gluon correlation function.

⋆ Three-gluon contribution to the direct photon production: $p^\uparrow(p)+p(p)\to\gamma(q)+X$.

(YK, S.Yoshida, in preparation)

$$E_\gamma\frac{d\sigma}{d^3q} = \frac{4\alpha_{em}\alpha_s M_N\pi}{S}\sum_a\int\frac{dx'}{x'}f_a(x')\int\frac{dx}{x}\delta(\hat{s}+\hat{t}+\hat{u})\epsilon^{qpnS_\perp}\frac{1}{\hat{u}}$$
$$\times\left[\delta_a\left(\frac{d}{dx}O(x,x)-\frac{2O(x,x)}{x}+\frac{d}{dx}O(x,0)-\frac{2O(x,0)}{x}\right)\right.$$
$$\left.-\frac{d}{dx}N(x,x)+\frac{2N(x,x)}{x}+\frac{d}{dx}N(x,0)-\frac{2N(x,0)}{x}\right]\left(\frac{1}{N}\left(\frac{\hat{s}}{\hat{u}}+\frac{\hat{u}}{\hat{s}}\right)\right)$$

$\delta_a=1$ for a =quark, $\delta_a=-1$ for a =anti-quark.

$\hat{s}=(xp+x'p')^2$, $\hat{t}=(xp-q)^2$, $\hat{u}=(x'p'-q)^2$

↑ The same as twist-2 cross section (also from master formula!)

· This differs form the previous study (X. Ji, Phys.lett.B289 ('92)137).

· Contribute in the combination of $O(x,x)+O(x,0)$ and $N(x,x)-N(x,0)$ as in $m_c\to 0$ for $p^\uparrow p\to DX$.

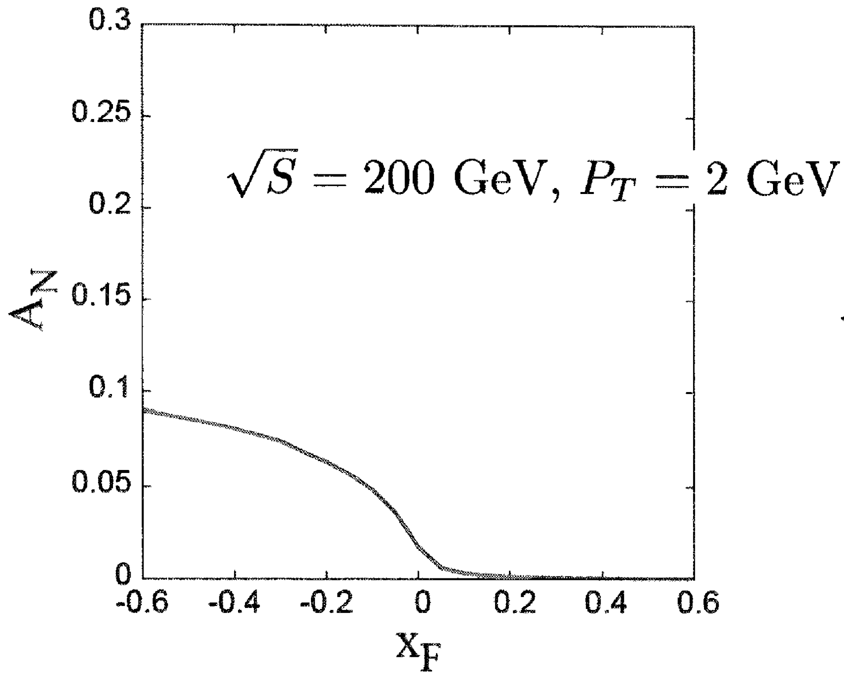
· $O(x,x)+O(x,0)=-(N(x,x)-N(x,0))\to$ quarks in the unpolarized nucleon are active. → Large A_N^γ.

· $O(x,x)+O(x,0)=N(x,x)-N(x,0)\to$ quarks in the unpolarized nucleon are NOT active. → Small A_N^γ.

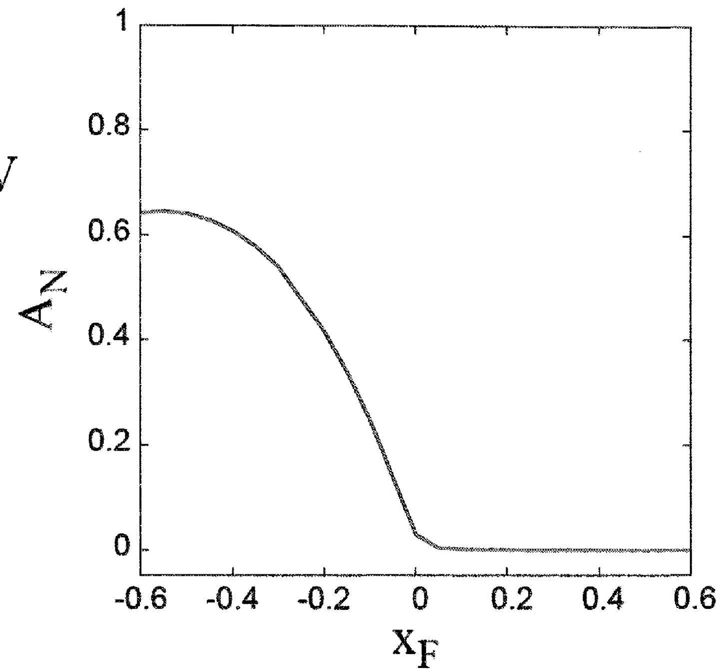
Change sign for N as $N(x,x) \to -N(x,x)$ and $N(x,0) \to -N(x,0)$.

$\to$ Quark contribution from the unpolarized nucleon is active, while anti-quark contribution is cancelled.

Model 1': $O(x,x) = 0.002 \times xG(x)$
$O(x,x) = O(x,0) = -N(x,x) = N(x,0)$



Model 2': $O(x,x) = 0.0005\sqrt{x}G(x)$
$O(x,x) = O(x,0) = -N(x,x) = N(x,0)$



· $A_N \sim 0$ at $x_F > 0$ regardless of magnitude of the 3-gluon correlation functions.

· Behavior at $x_F < 0$ is sensitive to small x behavior similarly to $pp \to DX$.

⋆ Three-gluon contribution to $p^{\uparrow}p \to \gamma^* X$.   (YK, S.Yoshida, in preparation)

$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} = \frac{2\pi M_N \alpha_{em}^2 \alpha_s}{3\pi S Q^2} \int \frac{dx}{x} \int \frac{dx'}{x'} \delta(\hat{s} + \hat{t} + \hat{u} - Q^2) \epsilon^{qpnS_\perp} \frac{1}{\hat{u}} \sum_a e_a^2 f_a(x')$$

$$\times \Big[\delta_a \Big(\frac{d}{dx} O(x,x) - \frac{2O(x,x)}{x} \Big) \hat{\sigma}_1 + \Big(\frac{d}{dx} O(x,0) - \frac{2O(x,0)}{x} \Big) \hat{\sigma}_2 + \frac{O(x,x)}{x} \hat{\sigma}_3 + \frac{O(x,0)}{x} \hat{\sigma}_4$$

$$- \Big(\frac{d}{dx} N(x,x) - \frac{2N(x,x)}{x} \Big) \hat{\sigma}_1 + \Big(\frac{d}{dx} N(x,0) - \frac{2N(x,0)}{x} \Big) \hat{\sigma}_2 - \frac{N(x,x)}{x} \hat{\sigma}_3 + \frac{N(x,0)}{x} \hat{\sigma}_4 \Big]$$

$$\hat{\sigma}_1 = \frac{2}{N} \Big(\frac{\hat{u}}{\hat{s}} + \frac{\hat{s}}{\hat{u}} + \frac{2Q^2 \hat{t}}{\hat{s}\hat{u}} \Big) \qquad \hat{\sigma}_3 = -\frac{1}{N} \frac{4Q^2 (Q^2 + \hat{t})}{\hat{s}\hat{u}}$$

$$\hat{\sigma}_2 = \frac{2}{N} \Big(\frac{\hat{u}}{\hat{s}} + \frac{\hat{s}}{\hat{u}} + \frac{4Q^2 \hat{t}}{\hat{s}\hat{u}} \Big) \qquad \hat{\sigma}_4 = -\frac{1}{N} \frac{4Q^2 (3Q^2 + \hat{t})}{\hat{s}\hat{u}}$$

· At $Q^2 \neq 0$, hard cross sections for $\{O(x,x), N(x,x)\}$ differ from those for $\{O(x,0), N(x,0)\}$ as in $ep^{\uparrow} \to eDX$.

· As $Q^2 \to 0$, this agrees with the result for the direct-photon production.

· Sum of the above result and that from the quark-gluon correlation functions gives the complete twist-3 cross section for Drell-Yan and direct-photon processes.

For q-g correlations, see
SGP: Ji-Qiu-Vogelsang-Yuan, PRD73('06), YK-Tanaka,PLB646('07)
Hard pole+SFP: Kanazawa-YK,arXiv:1105.1036 [hep-ph]

13 May 2011

Gauge Links & Process dependence in Hadronic Reactions

Leonard Gamberg Penn State University

Phys.Lett. B696 2011 w/ Zhongbo Kang ***BNL***

We study the single transverse spin asymmetries in the single inclusive particle production within the framework of the generalized parton model (GPM). By carefully analyzing the initial- and final-state interactions, we include the process-dependence of the Sivers functions into the GPM formalism. The modified GPM formalism has a close connection with the collinear twist-3 approach. Within the new formalism, we make predictions for inclusive π^0 and direct photon productions at RHIC energies. Also we consider the Sivers asymmetry from the cross section for $p^\uparrow p \longrightarrow h_1 \, \mathrm{jet} \, X$ (w/ D'lesio, Murgia & Pisano). We find the predictions are opposite to those in the conventional GPM approach.

Spin Dependent Cross Section in GPM $pp \to \pi X$

$$f_{q/A^\uparrow}(x, \vec{k}_T) = f_{q/A}(x, k_T^2) \; + \; \tfrac{1}{2}\Delta^N f_{q/A^\uparrow}(x, k_T^2)\vec{S}\cdot(\hat{P}\times\vec{k}_T)$$

A_N is defined by the ratio $\quad A_N \equiv E_h \dfrac{d\Delta\sigma}{d^3P_h} \Big/ E_h \dfrac{d\sigma}{d^3P_h}.$

$$E_h\frac{d\Delta\sigma}{d^3P_h} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int\frac{dx_a}{x_a}d^2k_{aT}\Delta^N f_{a/A}(x_a, k_{aT})\frac{1}{2}S_A\cdot(\hat{P}_A\times\hat{k}_{aT})\int\frac{dx_b}{x_b}d^2k_{bT}f_{b/B}(x_b, k_{bT})$$
$$\times\int\frac{dz_c}{z_c^2}D_{h/c}(z_c)H^U_{ab\to c}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u}),$$

GPM Anselmino et al.

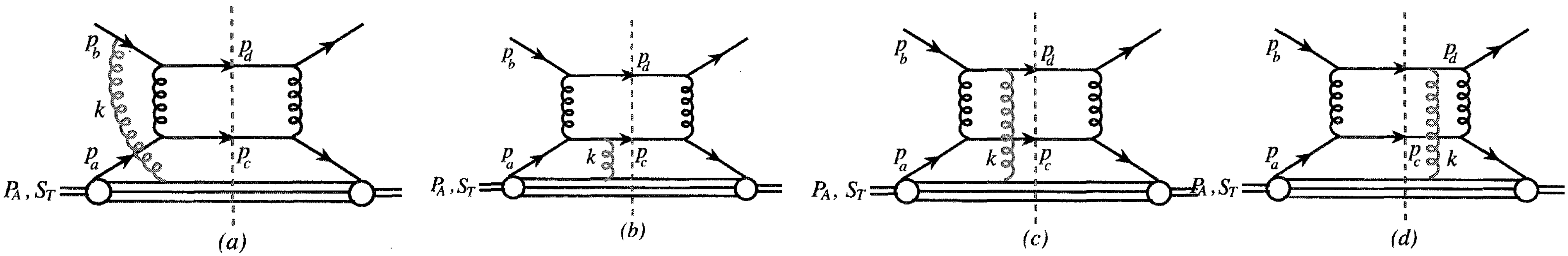
$$E_h\frac{d\Delta\sigma}{d^3P_h} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int\frac{dx_a}{x_a}d^2k_{aT}\Delta^N f^{ab\to c}_{a/A}(x_a, k_{aT})\frac{1}{2}S_A\cdot(\hat{P}_A\times\hat{k}_{aT})\int\frac{dx_b}{x_b}d^2k_{bT}f_{b/B}(x_b, k_{bT})$$
$$\times\int\frac{dz_c}{z_c^2}D_{h/c}(z_c)H^U_{ab\to c}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u}),$$

GPM w/color
LG & Z. Kang
Phys.Lett. B696 2011

process-dependent Sivers function denoted as $\Delta^N f^{ab\to c}_{a/A}(x_a, k_{aT})$

how to get it ?

One gluon exchange approx for ISI and FSI $qq' \to qq'$

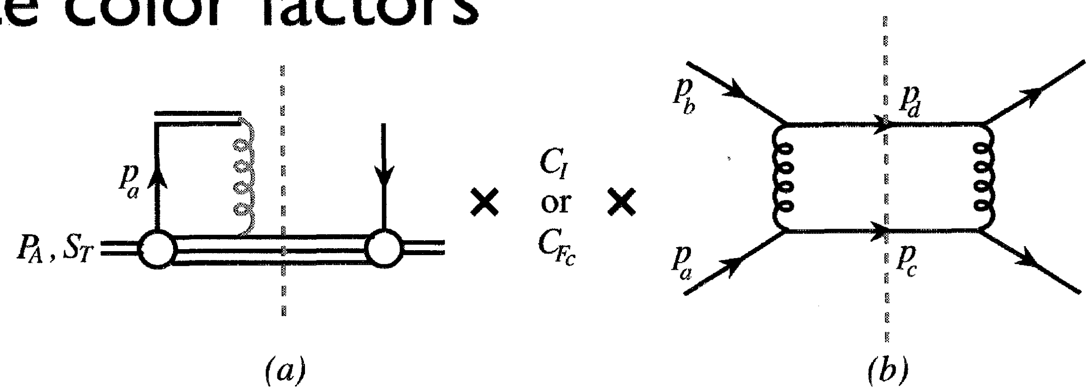


interaction w/unobserved particle "d" vanishes after summing over both cuts

$$\left[\frac{-g}{-k^+ - i\epsilon} T^a\right] \qquad \left[\frac{g}{-k^+ + i\epsilon} T^a\right]$$

$$C_I = -\frac{1}{2N_c^2}, \qquad C_{F_c} = -\frac{1}{4N_c^2},$$

calculate color factors

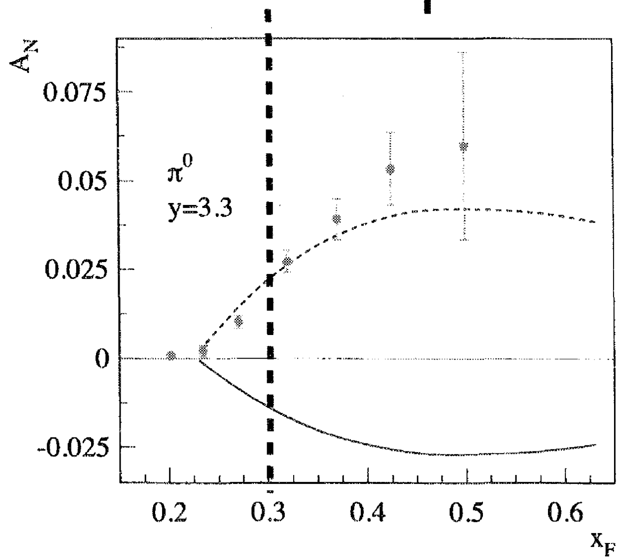


Note unpolarized color factor

$$C_u = \frac{N_c^2 - 1}{4N_c^2}$$

Based on old parameterization

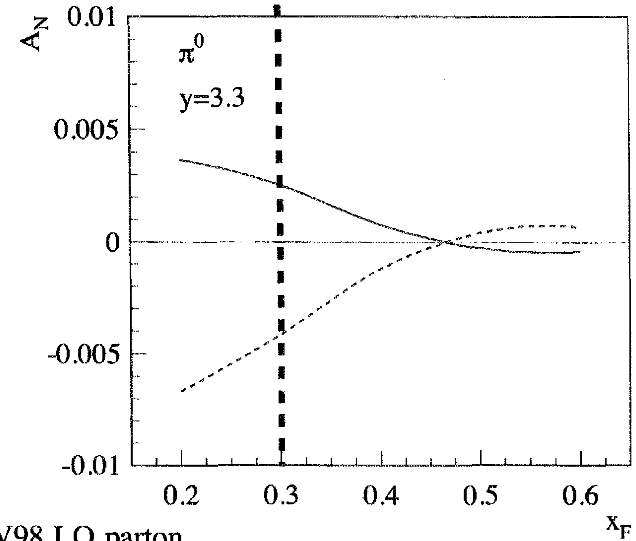
Based on new parameterization



We use GRV98 LO parton

the old Sivers function from [4], and Kretzer fragmentation function [5].

$$pp \to \pi X$$



We use GRV98 LO parton

, the latest Sivers function from [2], and DSS fragmentation function [3].

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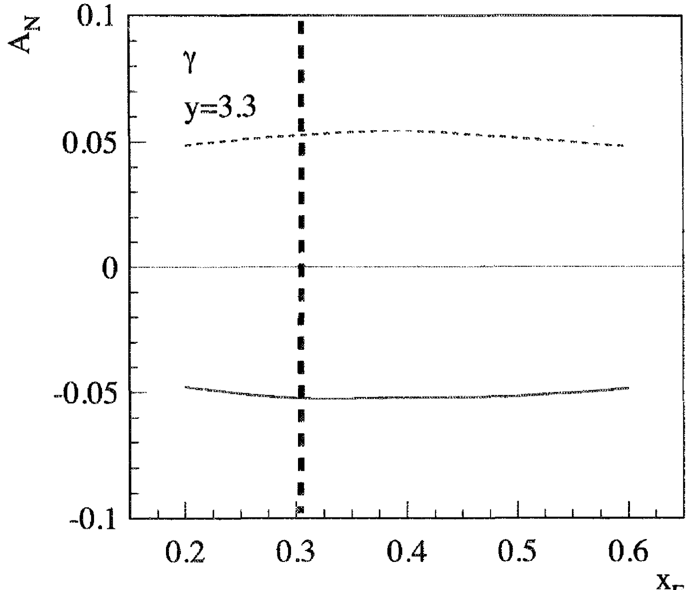
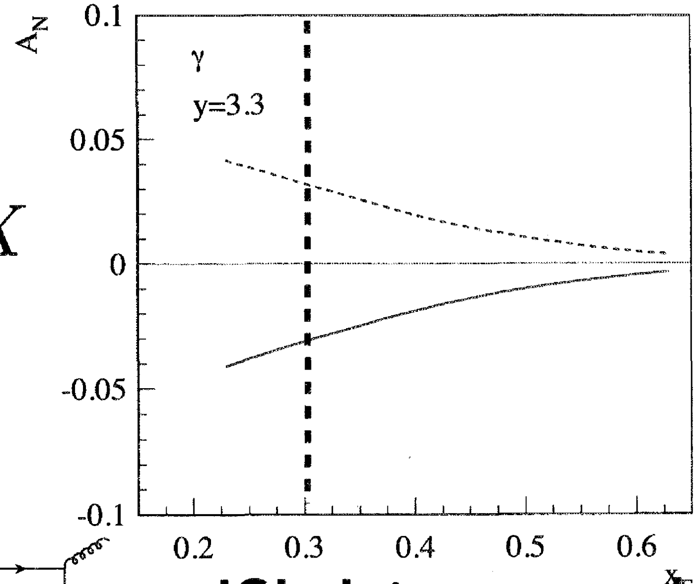
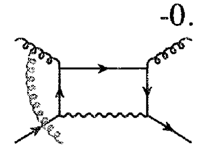


$$pp \to \gamma X$$

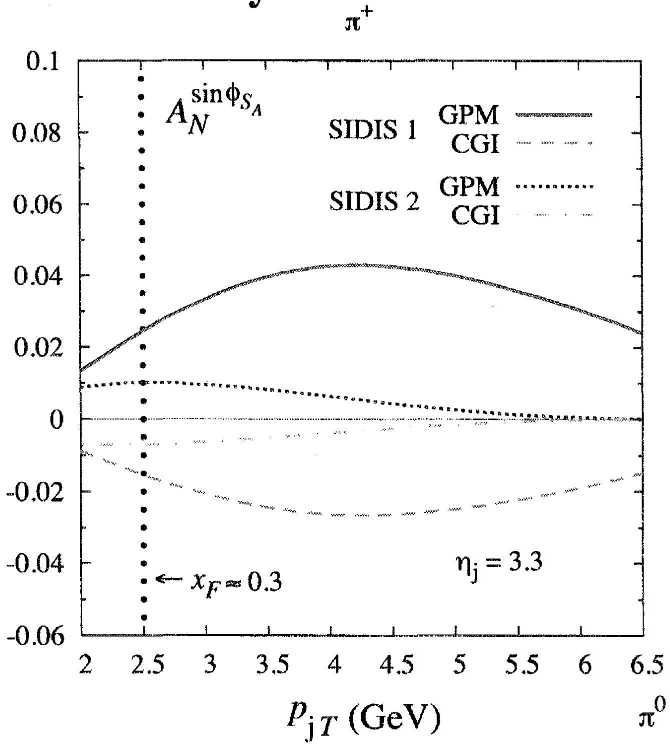


$$H^{\rm Inc}_{qg\to\gamma q} = -\frac{N_c}{N_c^2-1}e_q^2\left[-\frac{\hat{t}}{\hat{s}}-\frac{\hat{s}}{\hat{t}}\right]$$

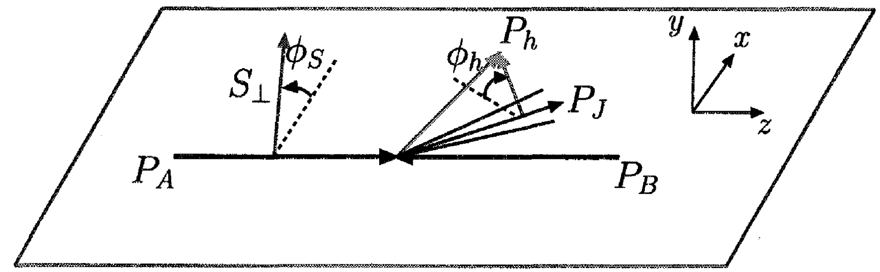


ISI drives result

Azimuthal asymmetries for hadron distributions inside a jet in hadronic collisions

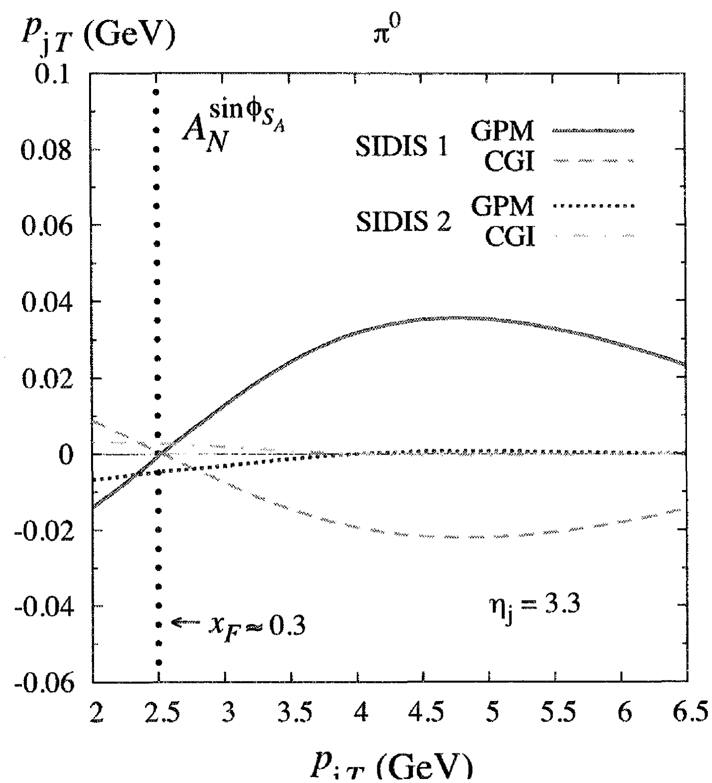


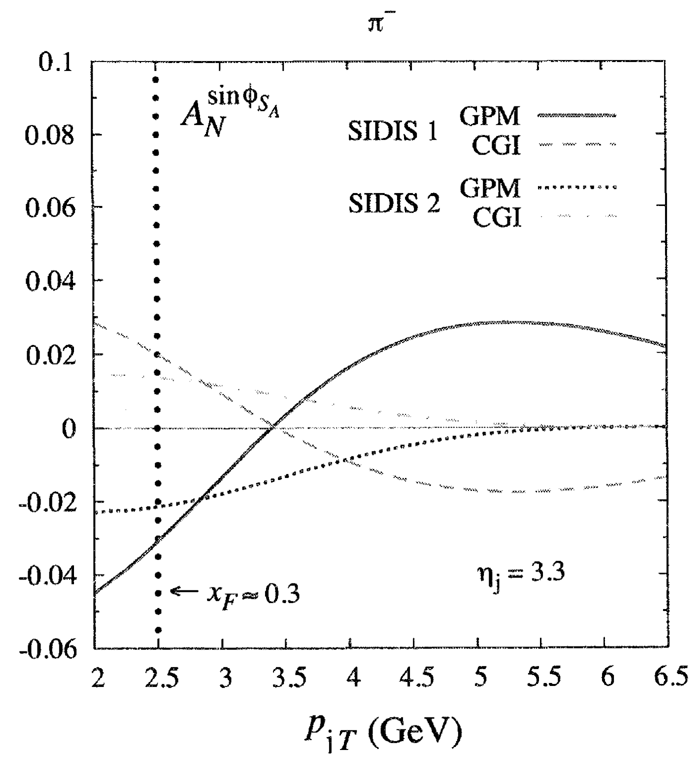
$$\sqrt{s} = 200\,\mathrm{GeV}$$



$$x_F = \frac{2P_T}{\sqrt{s}} \sinh(\eta)$$

(w/ D'lesio, Murgia & Pisano)





Implementing a k_T expansion collinear twist three expression emerges

$$E_h \frac{d\Delta\sigma}{d^3P_h} = \frac{\alpha_s^2}{s} \sum_{abc} \int \frac{dz_c}{z_c^2} D_{h/c}(z_c) \frac{\epsilon^{P_h S_T n \bar{n}}}{z_c \tilde{u}} \frac{1}{x} \left(T_F(x,x) - x\frac{d}{dx} T_F(x,x)\right)$$
$$\times \int \frac{dx_b}{x_b} f_{b/B}(x_b) \int H^{\mathrm{Inc}}_{ab\to c}(\tilde{s},\tilde{t},\tilde{u}) \frac{1}{x_b s + T/z_c}$$

same as Kouvaris, Qiu, Vogelsang, and Yuan PRD 2006

- Twist 3 and twist 2 approach connection

  we have another term ....comes from $H^{\mathrm{Inc}}_{ab\to c}(\hat{s},\hat{t},\hat{u})$

Conclusions

- Generalize GPM w/ color--can then perform global analysis
- Elephant in the room is break down of factorization for these processes
- Appears to be connection between generalized parton model at twist 3 and twist 3 approach
- Estimate mismatch-investigating LG Z. Kang
- TMD fact. is assumed in both GPM and GGPM is this a reasonable pheno. approximation?
- Direct photon driven by same ISI factor as in DY

UPPSALA
UNIVERSITET

Understanding forward particle production

Roman Pasechnik

Uppsala University, THEP group

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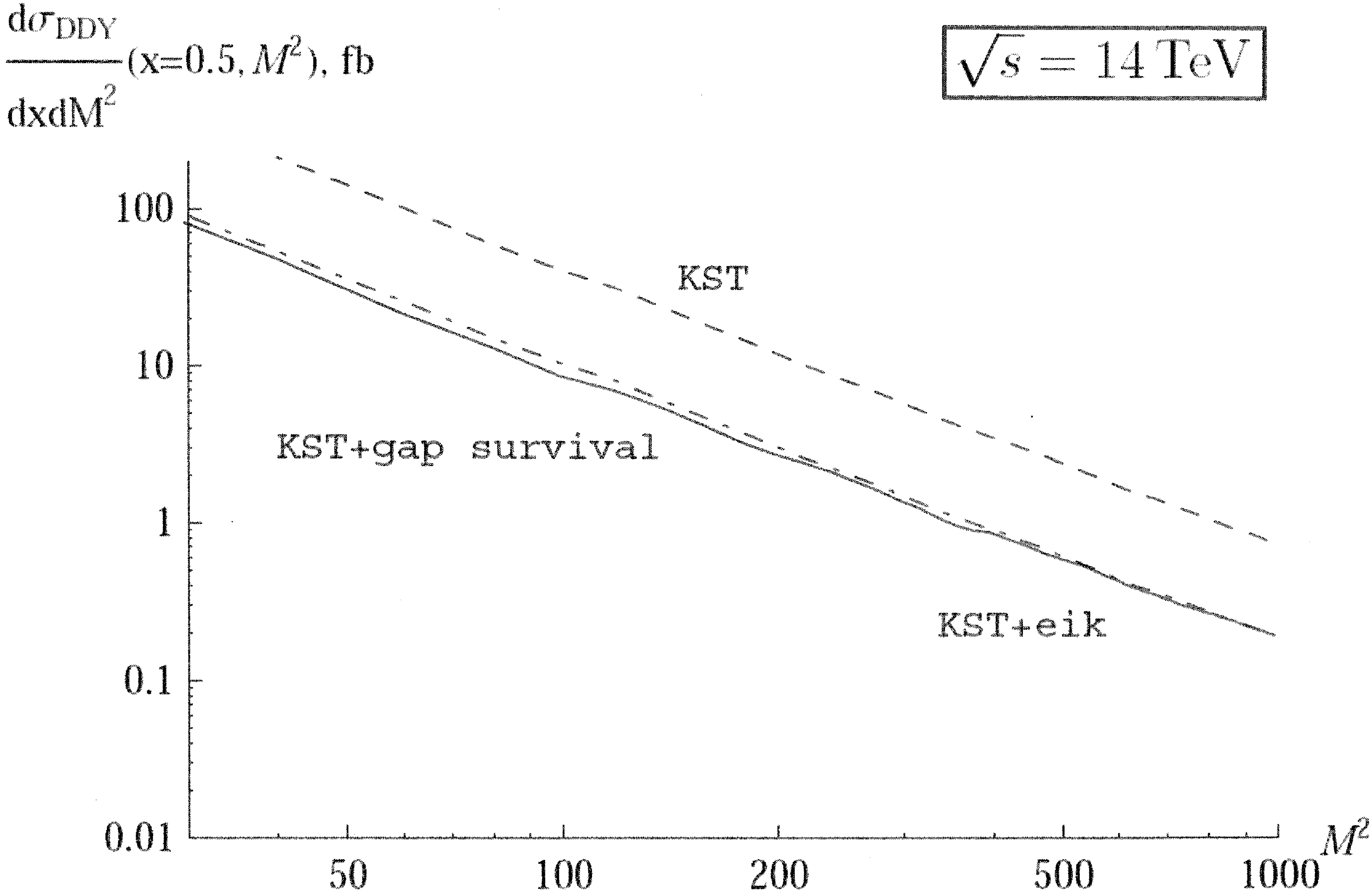
In collaboration with
B. Kopeliovich
(USM, Chile)

Opportunities for Drell-Yan Physics at RHIC
May 13th, 2011

We will talk about...

- Color neutralization and soft physics in diffractive DIS
- Sudakov suppression and elastic scattering
- Drell-Yan at high energies: diffractive vs inclusive
- Large and small dipoles
- Eikonalization of the elastic amplitude and gap survival
- Summary

Gap survival vs. eikonalization



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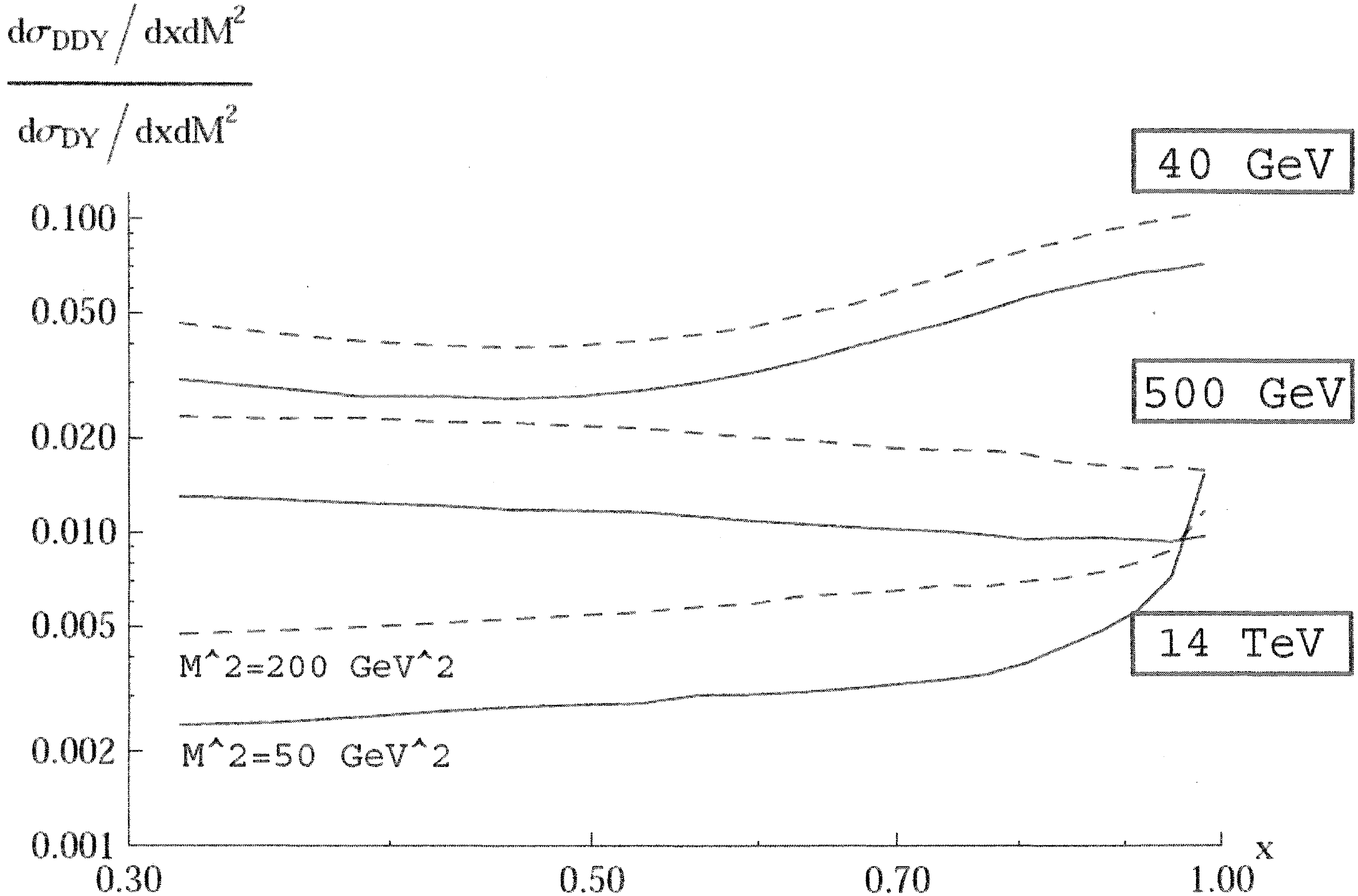
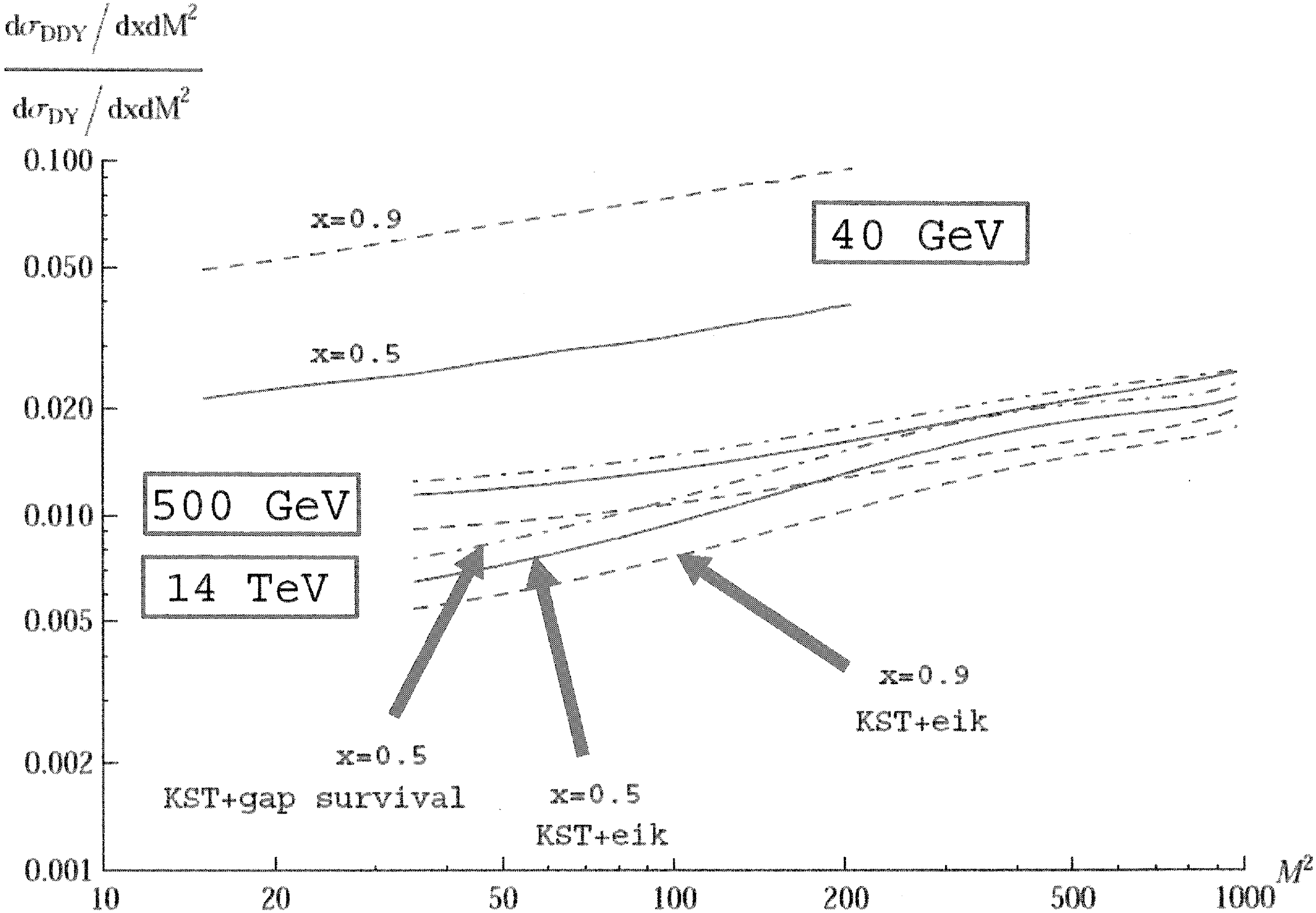
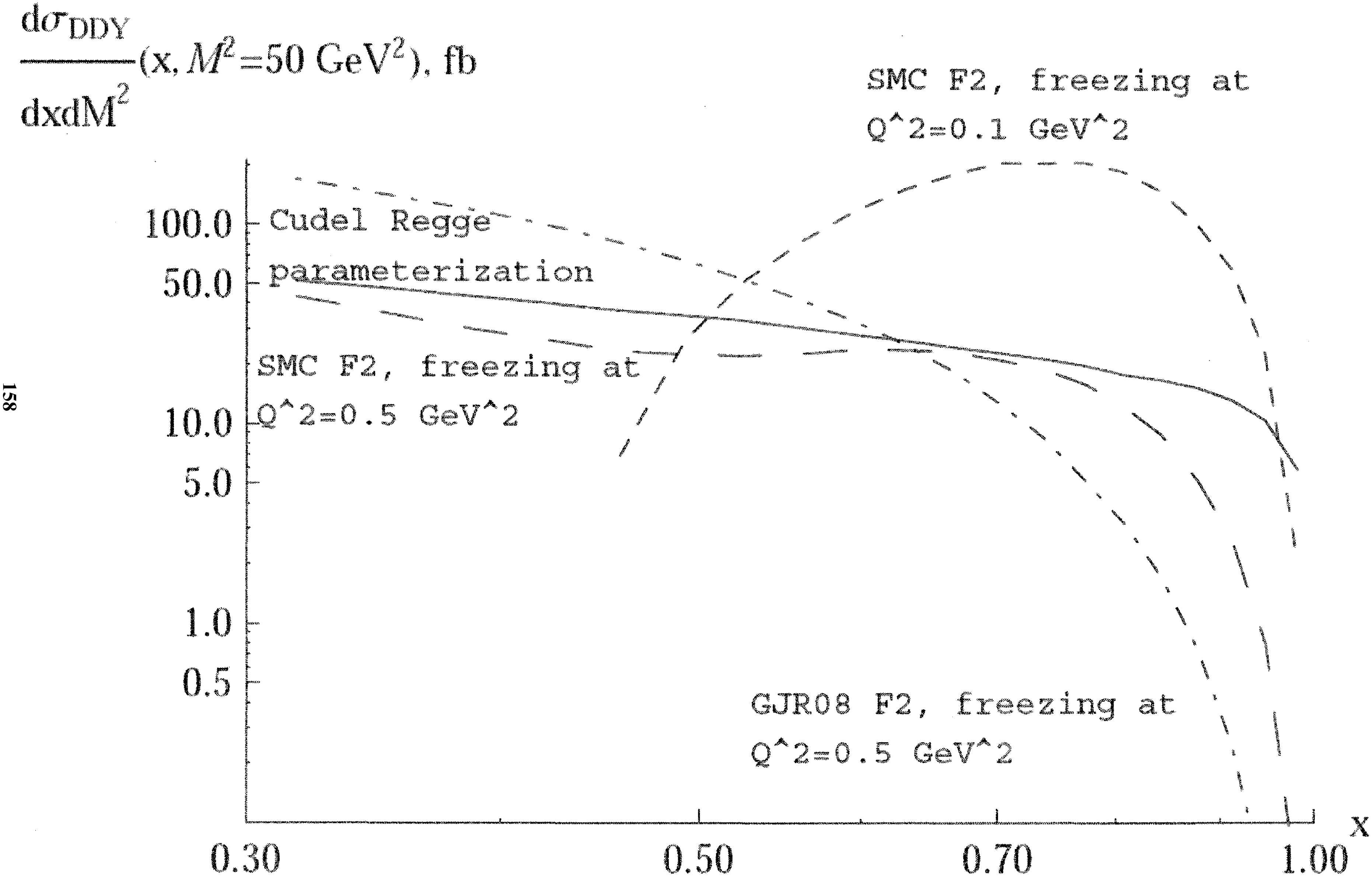
Diffractive vs. inclusive DY



Diffractive vs. inclusive DY



Theory uncertainties



Conclusions

- A quark **cannot radiate** photon diffractively in the forward direction
- A hadron can radiate photon diffractively in the forward direction because of the transverse motion of quarks
- The ratio diffractive/inclusive DY cross sections falls with energy and rises with photon dilepton mass due to **the saturated shape** of the dipole cross section
- Hard and soft interactions contribute to the DDY on the same footing, which is the dramatic breakdown of the QCD factorisation
- Main features of Drell-Yan diffraction are valid for other Abelian processes
- Experimental measurements of DDY would allow to probe directly the dipole cross section **at large separations**, as well as the proton structure function at soft and semihard scales, and large x
- DDY is a good playground for diffractive production of heavy flavors

Drell-Yan at forward rapidities

Anna M. Staśto

May 16, 2011

We analyze the Drell-Yan lepton pair production at forward rapidity at the Large Hadron Collider. Using the dipole framework for the computation of the cross section we find a a significant suppression in comparison to the collinear factorization formula due to saturation effects in the dipole cross section. We develop a twist expansion in powers of $Q_s(x_2)/M$ where Q_s is the saturation scale and M the invariant mass of the produced lepton pair. For the nominal LHC energy the leading twist description is sufficient down to masses of 6 GeV. Below that value the higher twist terms give a significant contribution. We perform the analysis for Tevatron and LHC energies.

In collaboration with K. Golec-Biernat and E.Lewandowska

Dipole model for Drell-Yan

Drell-Yan in the dipole model at small x

$$\frac{d^2\sigma^{DY}_{T,L}}{dM^2\, dx_F} = \frac{\alpha_{em}}{6\pi M^2} \frac{1}{x_1 + x_2} \sum_f \int_{x_1}^{1} \frac{dz}{z} F_2^f\left(\frac{x_1}{z}, M^2\right) \sigma^f_{T,L}(qp \to \gamma^* X)\,.$$

Structure function of the incoming projectile

z Fraction of the energy of the quark taken by the photon

Radiation of the photon from the fast quark

r Photon - quark transverse separation

$$\sigma^f_{T,L}(qp \to \gamma^* X) = \int d^2r\, W^f_{T,L}(z, r, M^2, m_f)\, \sigma_{qq}(x_2, zr)\ ,$$

$$W_T^f = \frac{\alpha_{em}}{\pi^2} \left\{ \left[1 + (1-z)^2\right] \eta^2 K_1^2(\eta r) + m_f^2\, z^4 K_0^2(\eta r) \right\}\ ,$$

$$W_L^f = \frac{2\alpha_{em}}{\pi^2} M^2 (1-z)^2 K_0^2(\eta r)$$

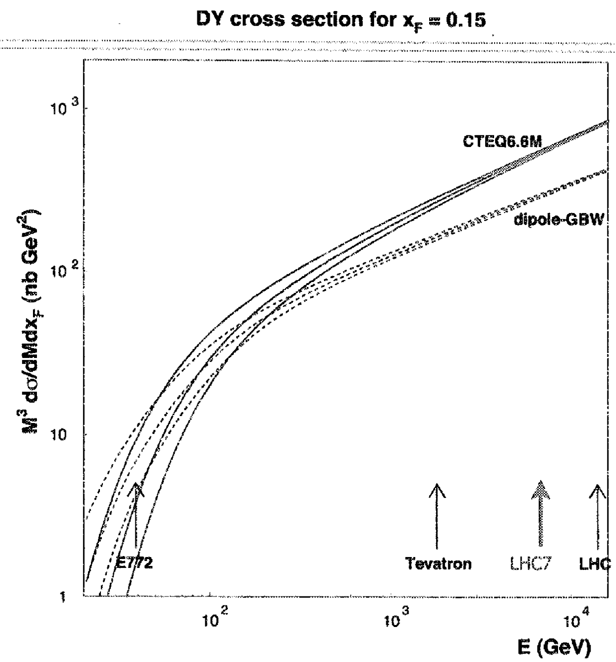
$$\eta^2 = (1-z)M^2 + z^2 m_f^2$$

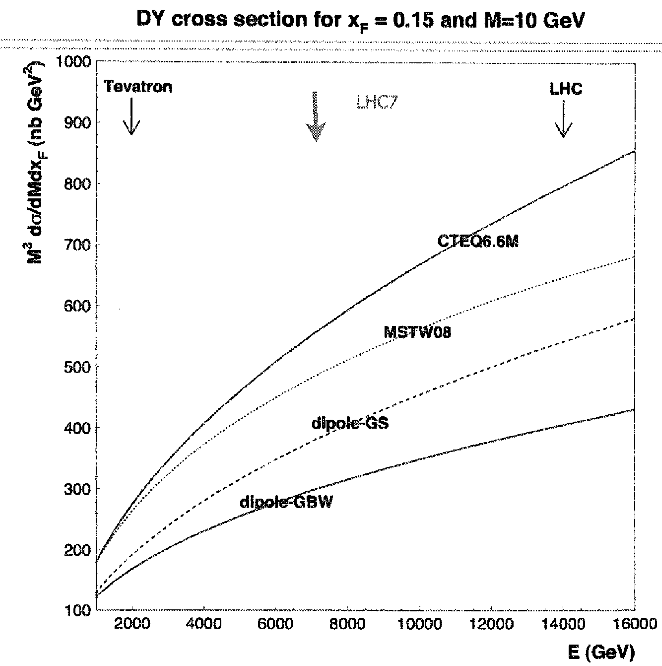
As an example use the Golec Biernat and Wusthoff formula

$$\sigma_{qq}(x, r) = \sigma_0 \left\{1 - \exp(-r^2 Q_s^2(x)/4)\right\}\,.$$

We will also use other models.

Predictions for LHC





Dilepton mass $M = 6, 8, 10$ GeV

dipole-GS (Golec-Sapeta)
DGLAP included

Large differences between collinear approaches

$x_2 \simeq 3 \cdot 10^{-6} - 10^{-5}$ typical values probed at energies 14-7 TeV

$y \sim 5 - 6$ range of rapidities

Dipole predictions systematically lower than the collinear calculations.

Twist expansion for Drell-Yan

It is more complicated than in DIS, because of the convolution with the structure function of the forward projectile.

$$\frac{d^2\sigma_T^{DY}}{dM^2\,dx_F} = \frac{\alpha_{em}^2\sigma_0}{6\pi^2M^2}\frac{1}{x_1+x_2}\int_{c-i\infty}^{c+i\infty}\frac{d\gamma}{2\pi i}G(\gamma)\widetilde{H}_T(\gamma)\left(\frac{Q_s^2(x_2)}{4M^2}\right)^{\gamma}$$

$$\times \int_{x_1}^{1}\frac{dz}{z}\,F_2\!\left(\frac{x_1}{z},M^2\right)[1+(1-z)^2]\left(\frac{z^2}{1-z}\right)^{\gamma}$$

Cannot directly perform integral over z (fraction of the light-cone momentum of the initial quark carried away by the photon), since it is weighted by the structure function of the projectile.

Two methods: fully analytical in terms of expansion in (1-x1). Semi-analytical with exact results for twist contributions

Twist expansion: explicit

Twist 2: contribution from $\gamma = 1$

$$\frac{d^2\sigma_T^{DY(\tau=2)}}{dM^2\,dx_F} = \Delta_{T,2}^{(0)} + \Delta_{T,2}^{(k>0)}$$

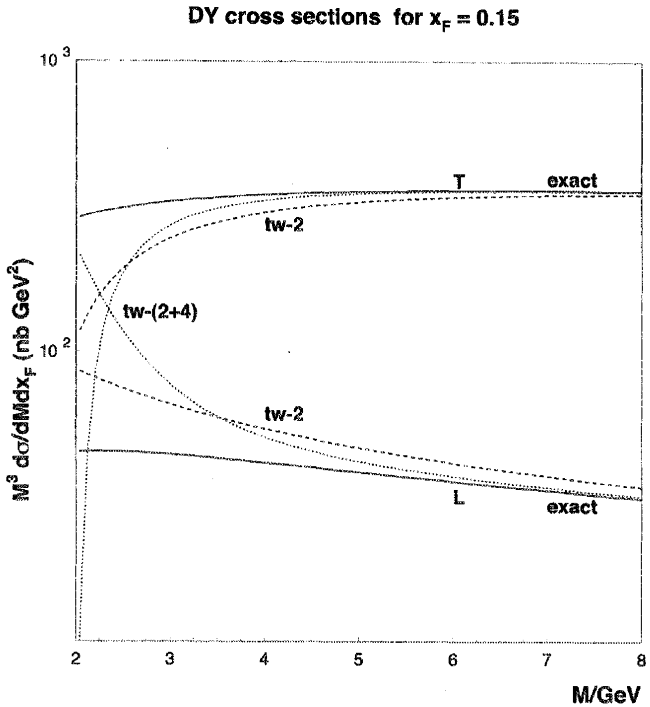
$$\Delta_{T,2}^{(0)} = \frac{\alpha_{em}^2\sigma_0}{6\pi^2M^2}\frac{F_2(x_1,M^2)}{x_1+x_2}\times 2\frac{Q_s^2(x_2)}{4M^2}\left[\frac{4}{3}\gamma_E - 1 + \frac{2}{3}\psi(\frac{5}{2}) - \frac{2}{3}\ln\frac{Q_s^2(x_2)}{4M^2(1-x_1)}\right]$$

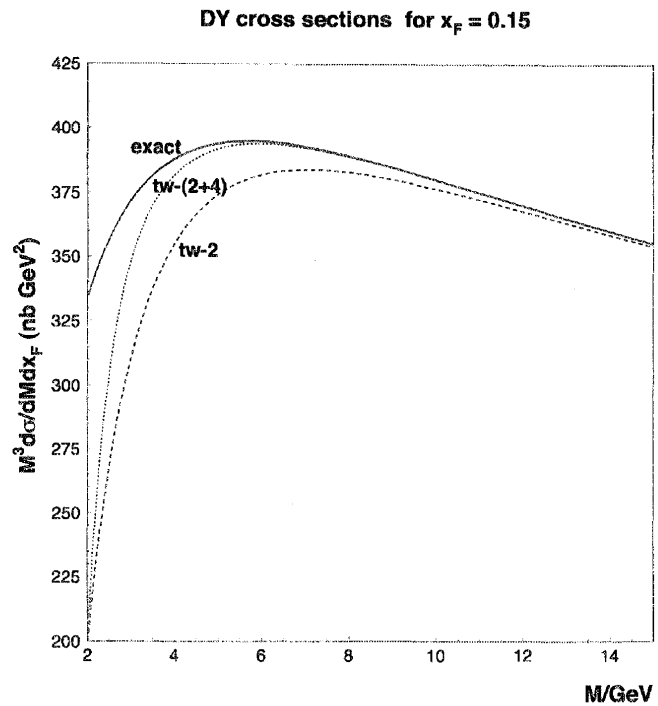
$$\Delta_{T,2}^{(k>0)} = \frac{\alpha_{em}^2\sigma_0}{6\pi^2M^2}\frac{1}{x_1+x_2}\times\frac{4}{3}\left(\frac{Q_s^2(x_2)}{4M^2}\right)\int_{x_1}^1 dz\,\frac{zF_2(\frac{x_1}{z},M^2)(1+(1-z)^2) - F_2(x_1,M^2)}{1-z}$$

First term contains the contribution from the double pole in the Mellin space (hence the logarithm). The result is exact twist 2 contribution.

Note the integrals over z over the structure function of the projectile.

Twist expansion for DY: results





$\sqrt{s} = 14$ TeV

- Twist expansion divergent for M<4.
- For higher masses M>6 twist 2 sufficient.
- For longitudinal twist 2 overestimates, for transverse part underestimates the exact result.
- The sum is better approximated by twist expansion.

Workshop on opportunities for DY at RHIC

BNL May 10 - 13

Sivers function from SIDIS,PP and DY

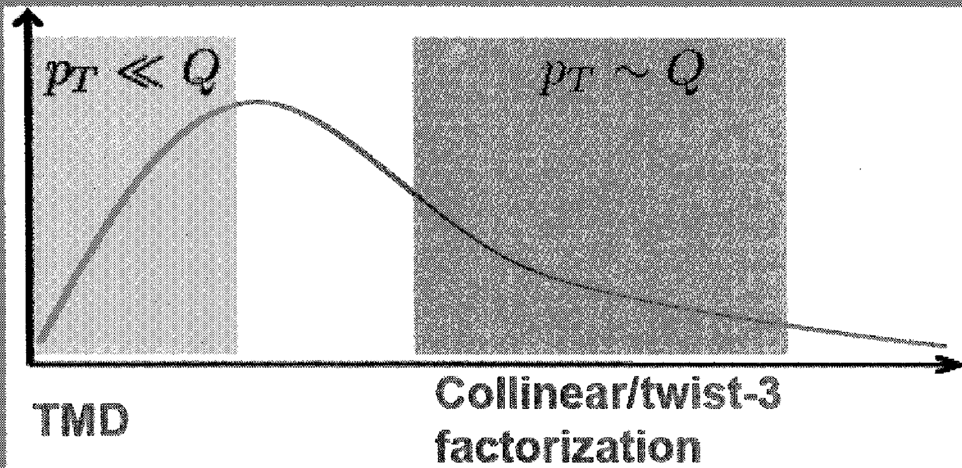
Alexei Prokudin
Jefferson Laboratory

Zhongbo Kang
RIKEN BNL

We analysed Sivers function using TMD factorization (SIDIS data) and twist-3 formalism (PP data). We find that Sivers function for u quark exibits a node at $x \sim 0.4$. Prediction for Drell Yan experiments at RHIC are given and the region of xF which is resemblant to SIDIS kinematical region is found to be xF from 0 to 0.2. The measuremets of predicted sign change of Sivers function is of extreme importance for our understanding of color gauge invariance of QCD.

TMD and Collinear factorizations

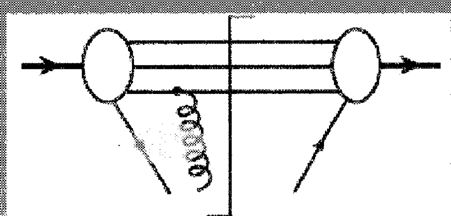
Both factorizations are consistent in the overlap region



Talks of John Collins, Piet Mulders, Ted Rogers, Jian-Wei Qui, Alessandro Bacchetta

Relation of multyparton correlations and moments of TMDs

$$\int d^2 p_T \frac{p_T^2}{M} f_{1T}^{\perp}(x, p_T^2) + \mathbf{UVCT}(\mu^2) = T_F(x, x, \mu^2) \qquad f_{1T}^{\perp(1)} \equiv \int d^2 p_T \frac{p_T^2}{2M^2} f_{1T}^{\perp}(x, p_T^2)$$



Sivers function is related to TF, but counterterm matters!

Talks of John Collins, Piet Mulders, Ted Rogers, Jian-Wei Qui

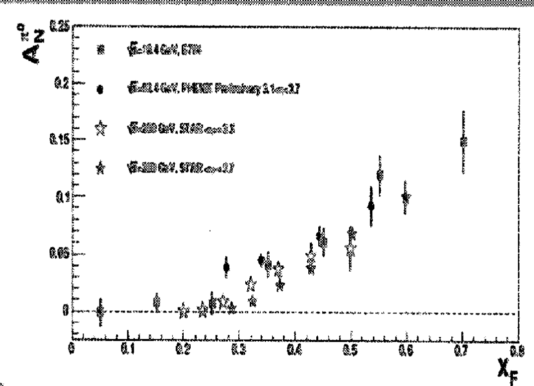
Alexei Prokudin – Sivers function from SIDIS and PP

Data analysis

Proton Proton

$$A(p_A, s_\uparrow) + B(p_B) \to \pi(p) + X$$

$$A(\ell, \vec{s}) \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$



Only one scale P_T

Collinear analysis:

Kouvaris, Qiu, Vogelsang, Yuan (2006)

Kanazava, Koike (2010)

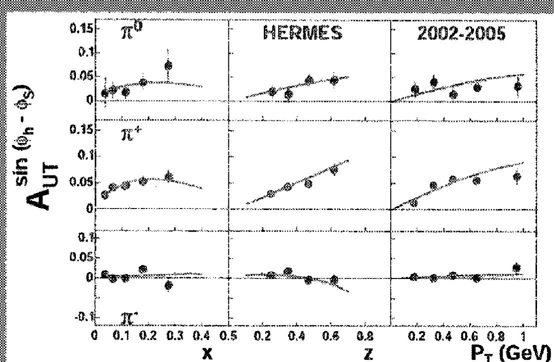
TMD analysis:

Anselmino et al (2006)

SIDIS

$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

$$d\sigma^\uparrow - d\sigma^\downarrow \propto \underbrace{f_{1T}^{\perp} \otimes D_1 \sin(\phi_h - \phi_S)}_{\text{Sivers effect}}$$



Two scales P_T, Q

$$\Lambda^2_{QCD} < P^2_{h\perp} \ll Q^2$$

TMD analysis: Anselmino et al (2008); Collins et al (2007) ; Vogelsang, Yuan (2006)

Alexei Prokudin – Sivers function from SIDIS and PP

Parametrization

$$\mathbf{f_{1T}^{\perp q} \propto x^{\alpha_q}(1-x)^{\beta_q}(1-\eta_q x)}$$

as in De Florian, Sassot, Stratmann, Vogelsang (2009)

$\mathbf{1 - \eta_q x}$ has a node if $\mathbf{\eta_q > 0}$

SIDIS: HERMES, COMPASS data $\pi^{\pm}, \mathbf{K}^{\pm}$

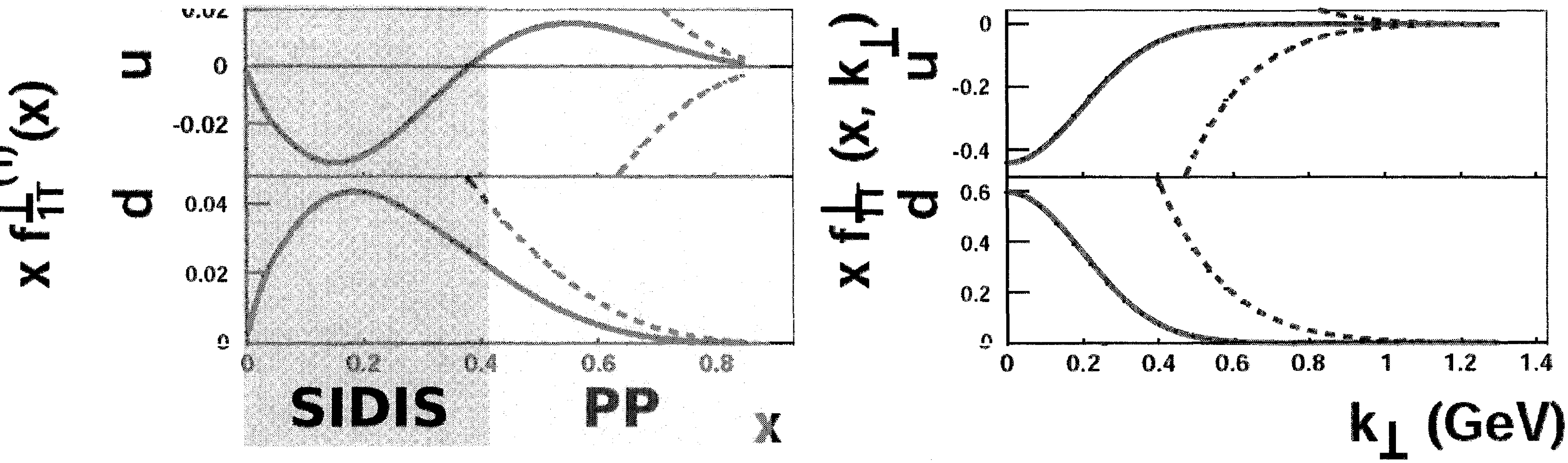
$$\mathbf{A_{UT}^{\sin(\Phi_h - \Phi_S)} \sim f_{1T}^{\perp} \otimes \sigma \otimes D_1}$$

PP: STAR data π^{0}

$$\mathbf{A_N \sim T_F \otimes \sigma \otimes D_1}$$

using PDF GRV98 and FF DSSV

Results: Sivers function



Sivers function has a node!

$$x_{node} \sim 0.4$$

Alexei Prokudin – Sivers function from SIDIS and PP

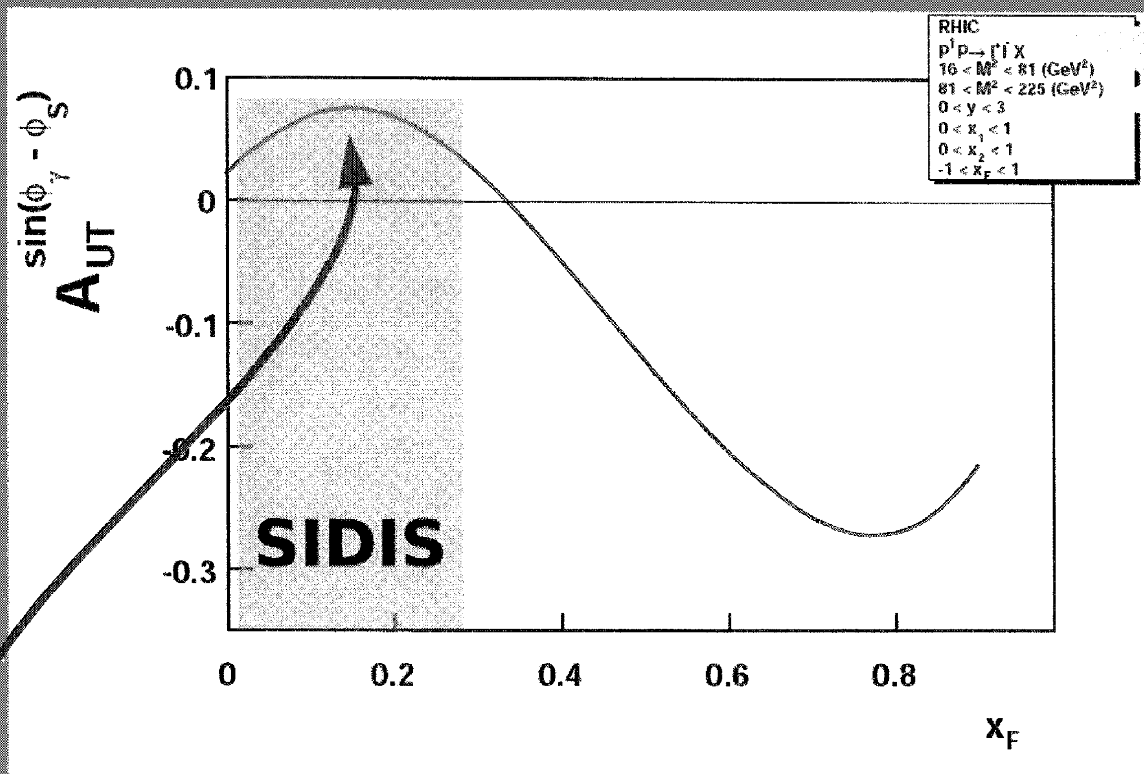
Drell Yan

$$A_N = \frac{\sum_q f_{1T}^{\perp q}(x_1, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}{\sum_q f_1^q(x_1, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}$$

Analysis at LO in hadronic cm frame
Kang, AP (2011)

AP, Kang 2011

New!



To measure in order to check $-f_{1T}^{\perp}|_{DY} = f_{1T}^{\perp}|_{SIDIS}$

Alexei Prokudin – Sivers function from SIDIS and PP

Alessandro Bacchetta
Università di Pavia and INFN Pavia

TRANSVERSE PHYSICS WITH SIDIS, e^+e^- & pp

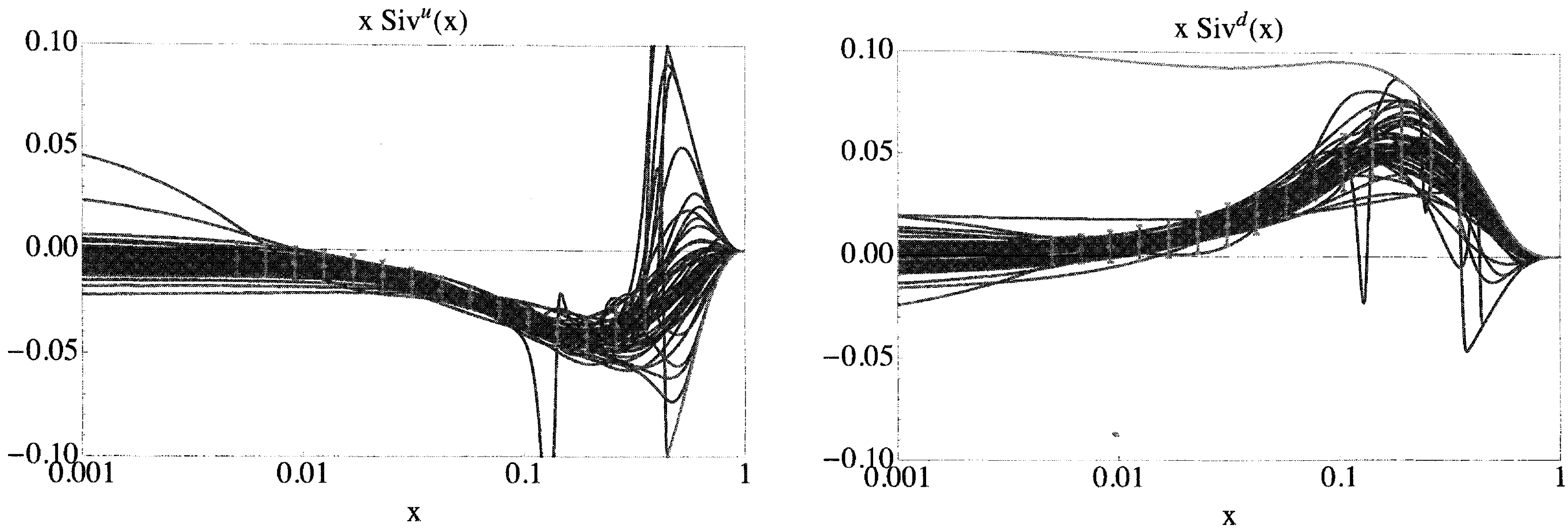
Two different topics are discussed:
1. TMD opportunities in Drell-Yan
2. Accessing transversity with dihadron fragmentation functions

Concerning the first topic, the relevance of the sign change of the Sivers function is discussed. A simple implementation of neural-network fits is discussed as a method to critically assess the current knowledge of the Sivers function, with particular emphasis on the presence of poles.

A few other crucial questions on TMDs that can be addressed in Drell-Yan experiments are mentioned: the knowledge of unpolarized TMDs, their x dependence, their transverse-momentum shape, and their flavor dependence.

Concerning the second topic, the results of the first extraction of the transversity distribution function based on collinear factorization is discussed. The results are derived from experimental measurements in SIDIS and e^+e^- annihilation. A comparison with the transversity extracted in TMD factorization is shown.

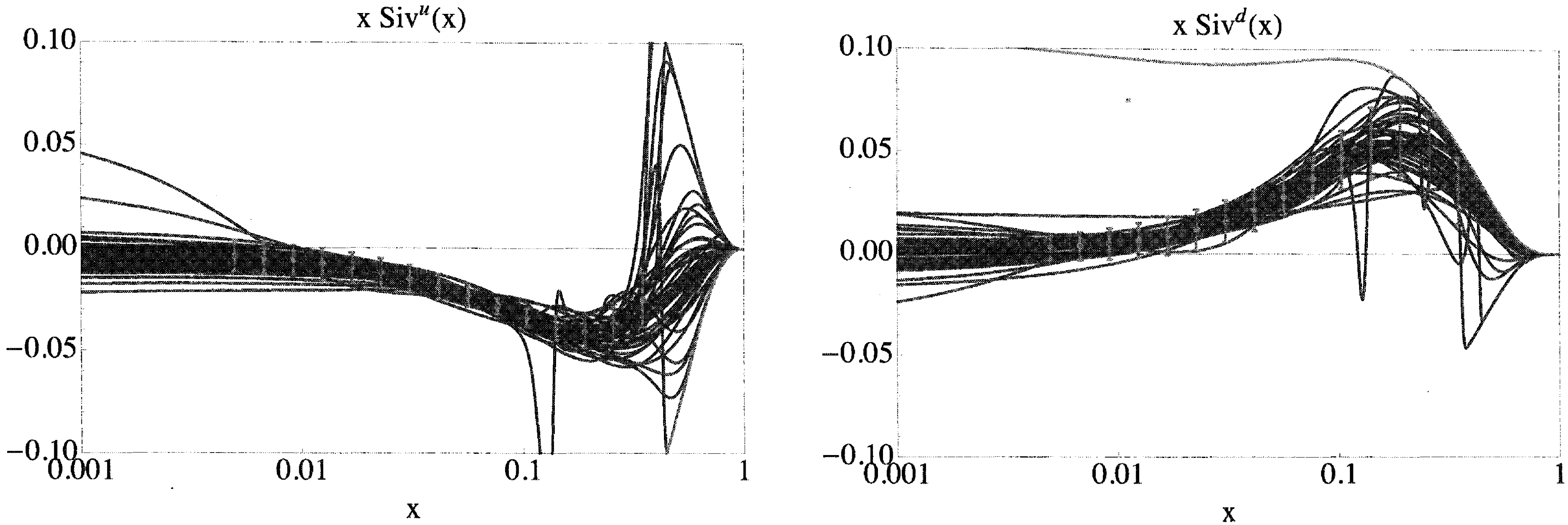
"Toy" neural-network fit



All curves have χ^2<1.6

Friday, 13 May 2011

"Toy" neural-network fit



All curves have χ^2<1.6

Neural-network fits are the best tools to avoid **biased functional forms**

BLNY fit

Landry, Brock, Nadolsky, Yuan, PRD67 (03)

Experiment	Reference	Reaction	$\sqrt{S}$ (GeV)	δN_{exp}
R209	[14]	$p + p \rightarrow \mu^+\mu^- + X$	62	10%
E605	[15]	$p + Cu \rightarrow \mu^+\mu^- + X$	38.8	15%
E288	[16]	$p + Cu \rightarrow \mu^+\mu^- + X$	27.4	25%
CDF-Z (Run-0)	[17]	$p + \bar{p} \rightarrow Z + X$	1800	–
DØ -Z (Run-1)	[18]	$p + \bar{p} \rightarrow Z + X$	1800	4.3%
CDF-Z (Run-1)	[19]	$p + \bar{p} \rightarrow Z + X$	1800	3.9%

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D-Y (including Z production) is the most important source of information for unpolarized TMDs

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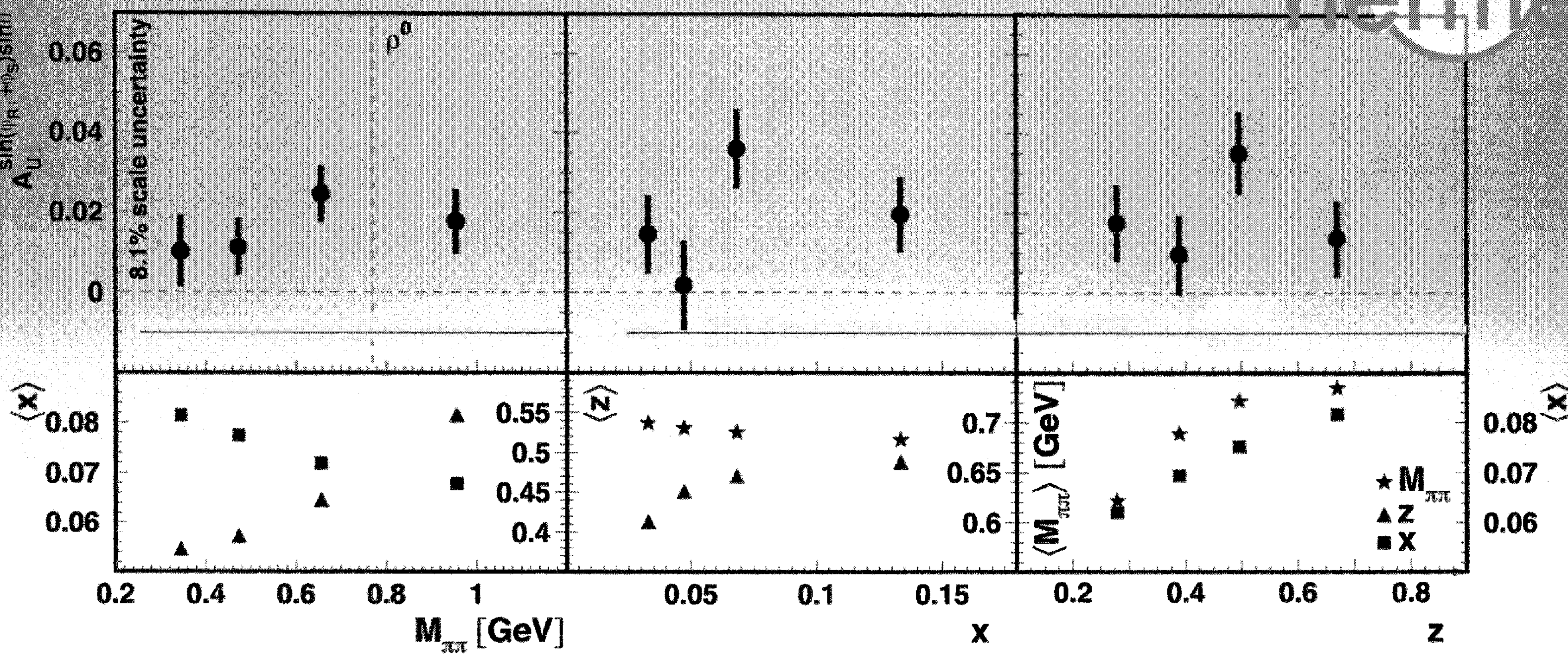
CDF-Z (Run-0)	[17]	$p + \bar{p} \to Z + X$	1800	[illegible]
DØ -Z (Run-1)	[18]	$p + \bar{p} \to Z + X$	1800	4.3%
CDF-Z (Run-1)	[19]	$p + \bar{p} \to Z + X$	1800	3.9%

AnDY

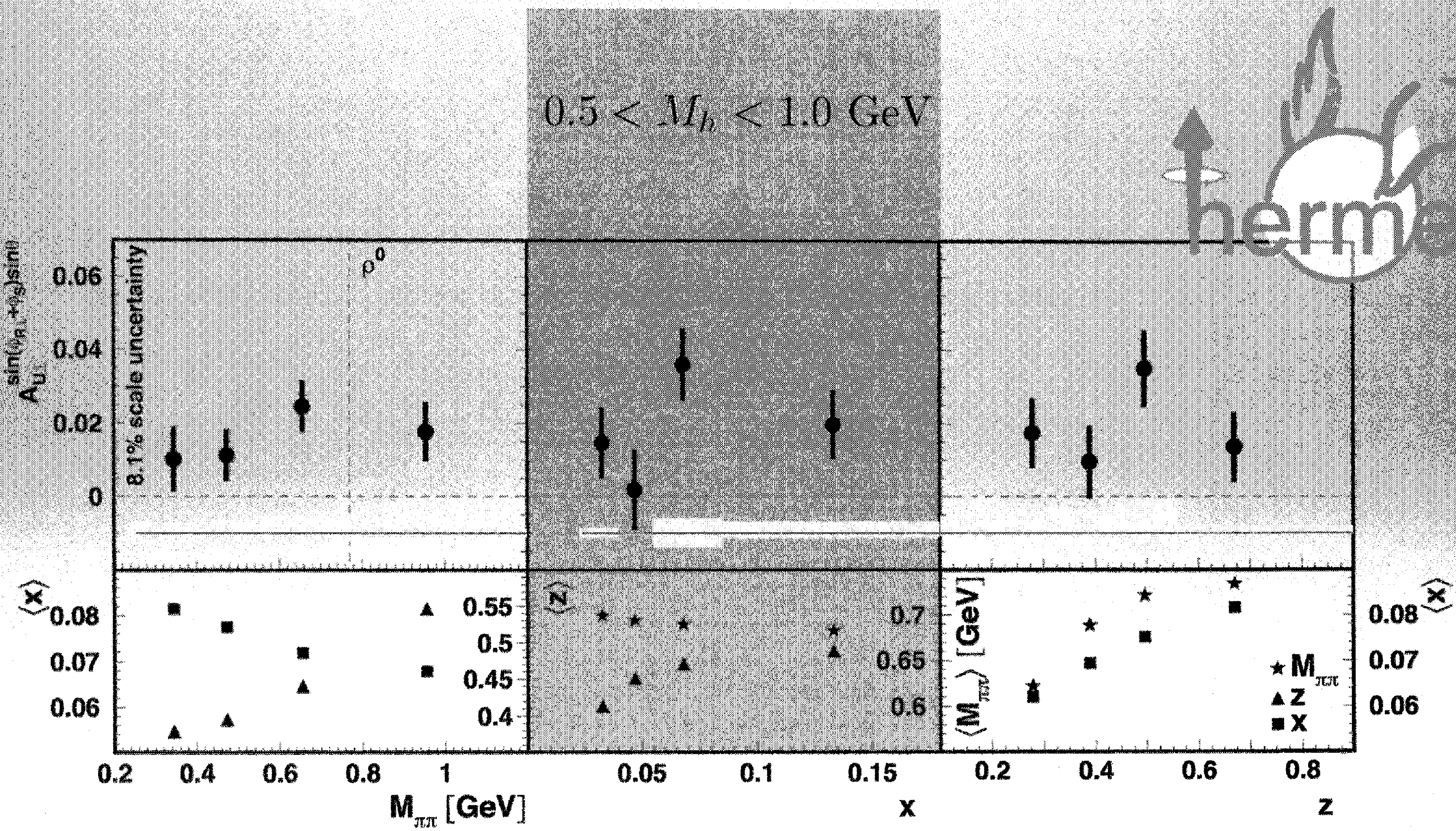
D-Y (including Z production) is the most important source of information for unpolarized TMDs

HERMES data



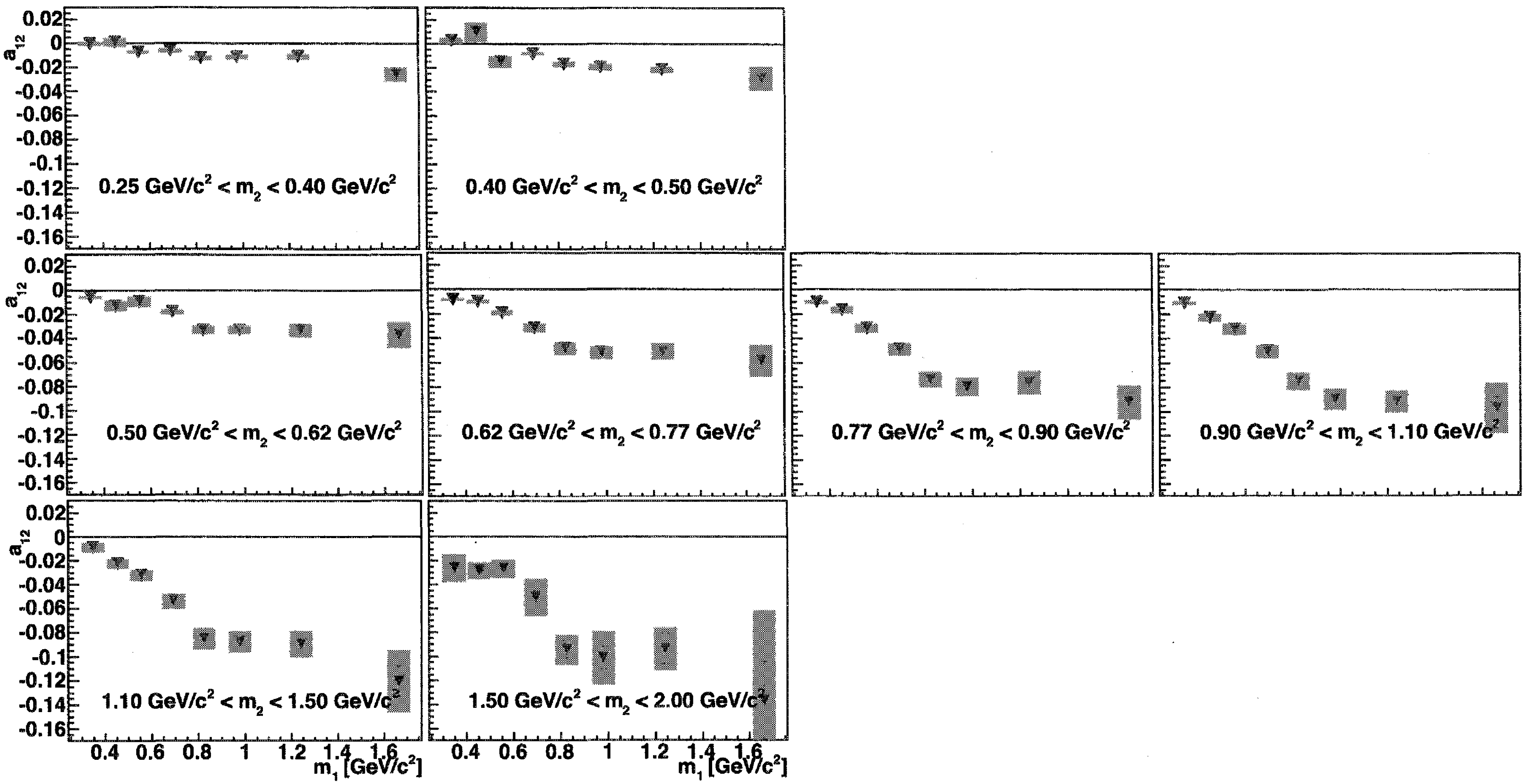
8.1% scale uncertainty
ρ^0
$A_U^{\sin(\phi_R+\phi_S)\sin\theta}$
0.06
0.04
0.02
0
$\langle x \rangle$
0.08
0.07
0.06
0.55
0.5
0.45
0.4
$\langle z \rangle$
0.7
0.65
0.6
$\langle M_{\pi\pi} \rangle$ [GeV]
$M_{\pi\pi}$
z
x
0.2 0.4 0.6 0.8 1
$M_{\pi\pi}$ [GeV]
0.05 0.1 0.15
x
0.2 0.4 0.6 0.8
z

HERMES data



0.5 < M_h < 1.0 GeV
8.1% scale uncertainty
ρ^0
0.06
0.04
0.02
0
0.08
0.07
0.06
0.55
0.5
0.45
0.4
0.7
0.65
0.6
$\langle x \rangle$
$\langle z \rangle$
$\langle M_{\pi\pi} \rangle$ [GeV]
0.2
0.4
0.6
0.8
1
0.05
0.1
0.15
$M_{\pi\pi}$ [GeV]
x
z
$M_{\pi\pi}$
z
x

BELLE data



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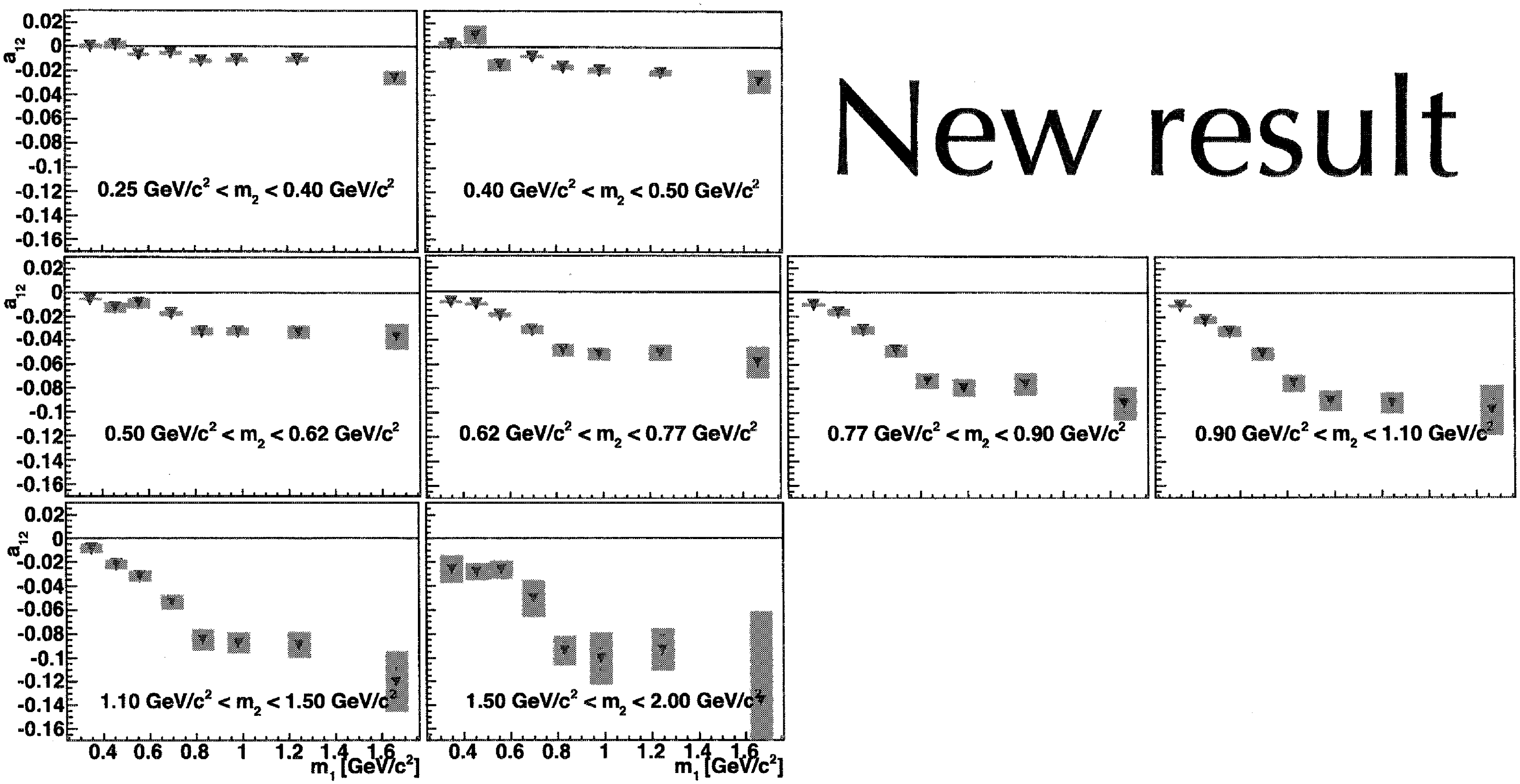
Vossen, Seidl et al. (Belle), arXiv:1104.2425 [hep-ex]

BELLE data

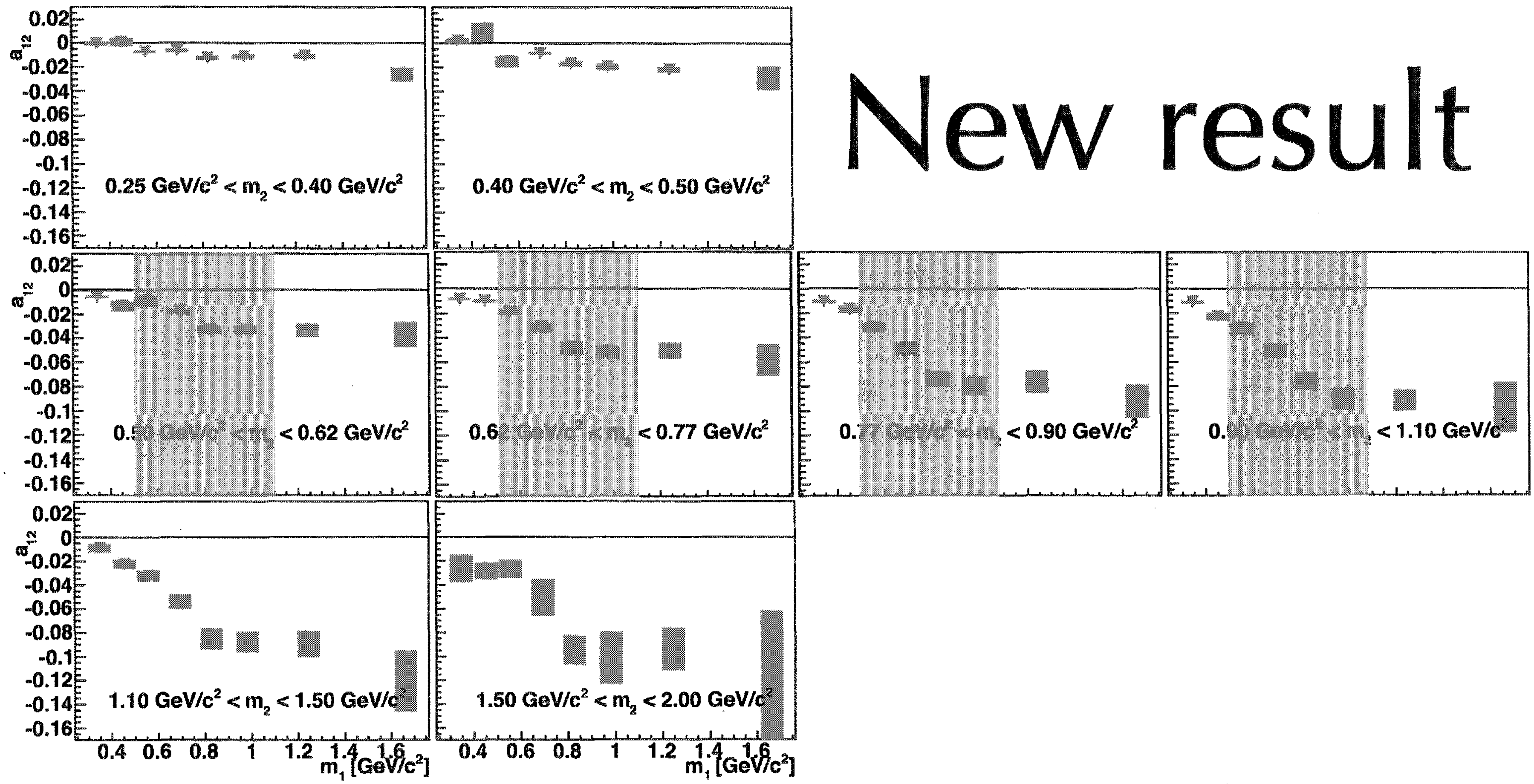


New result

Vossen, Seidl et al. (Belle), arXiv:1104.2425 [hep-ex]

BELLE data

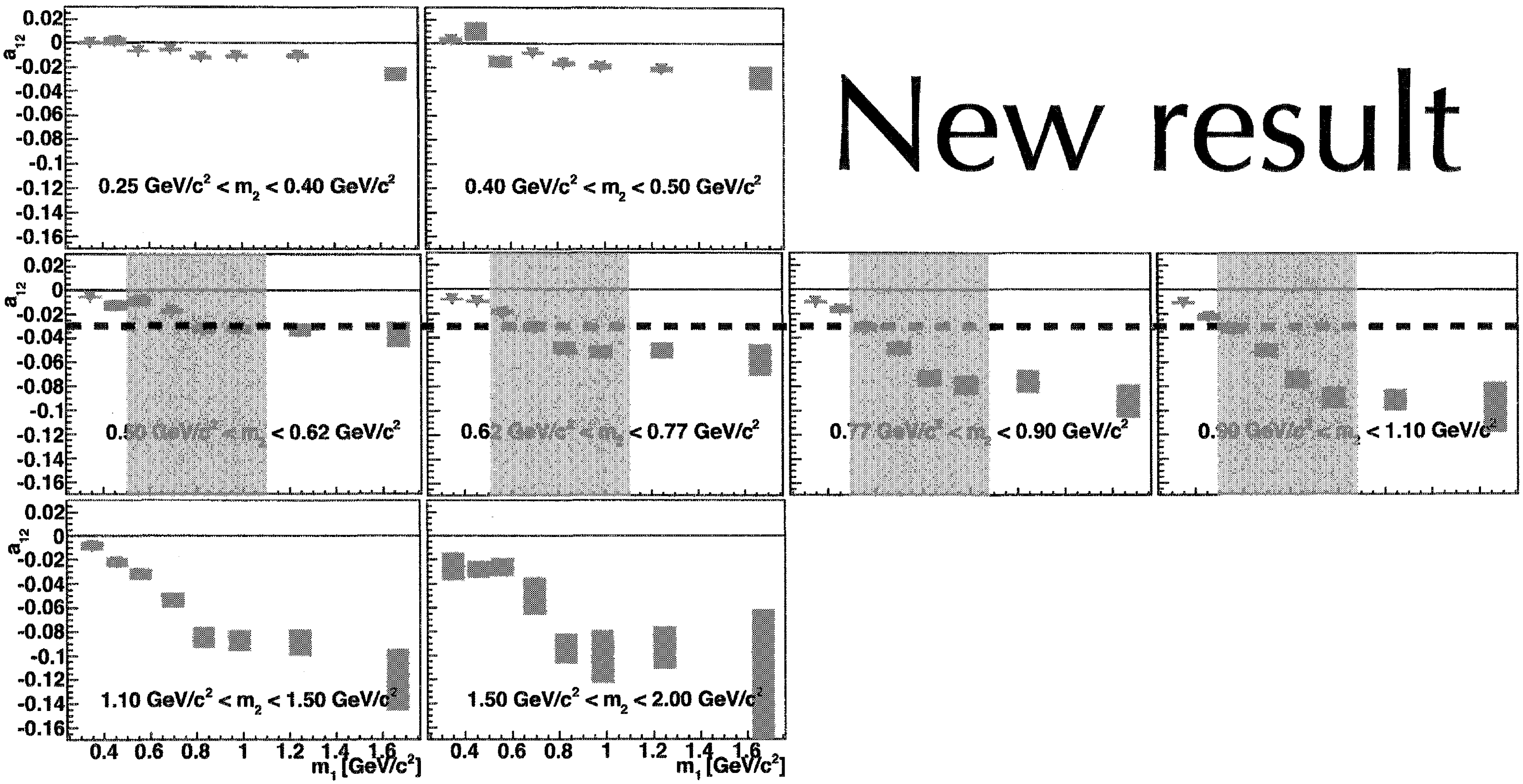
New result



Vossen, Seidl et al. (Belle), arXiv:1104.2425 [hep-ex]

BELLE data

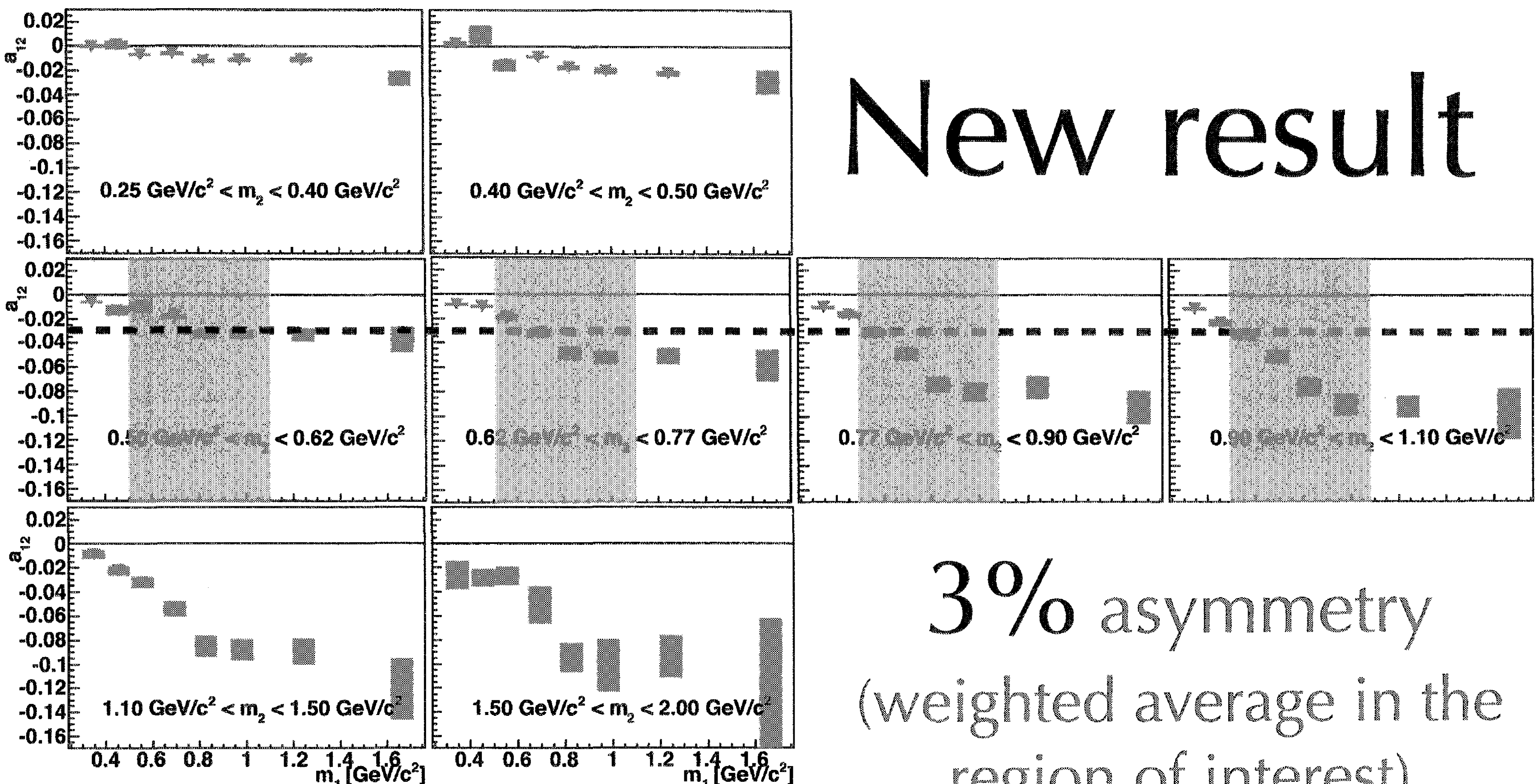
New result



185

Vossen, Seidl et al. (Belle), arXiv:1104.2425 [hep-ex]

BELLE data



New result

3% asymmetry

(weighted average in the region of interest)

Vossen, Seidl et al. (Belle), arXiv:1104.2425 [hep-ex]

Simplified expressions

SIDIS

$$A_{DIS}(x) \approx -\langle C_y \rangle \, \frac{(h_1^{u_v}(x) - h_1^{d_v}(x)/4)}{(f_1^{u+\bar{u}}(x) + f_1^{d+\bar{d}}(x)/4)} \, \frac{n_u^{\uparrow}}{n_u}$$

187

e^+e^-

$$A_{e+e-} \approx \frac{-\langle \sin^2 \theta_2 \rangle}{\langle 1 + \cos^2 \theta_2 \rangle} \, \frac{\langle \sin\theta \rangle \, \langle \sin\bar{\theta} \rangle \, 5 \, (n_u^{\uparrow})^2}{5\, n_u^2 + n_s^2 + 4\, n_c^2}$$

Simplified expressions

DIS

$$\frac{n_u^{\uparrow}}{n_u} = \frac{\iint \frac{|\boldsymbol{R}|}{M_h} H_{1,u}^{\sphericalangle}(z, M_h^2)}{\iint D_{1,u}(z, M_h^2)}$$

$$A_{DIS}(x) \approx -\langle C_y \rangle \, \frac{(h_1^{u_v}(x) - h_1^{d_v}(x)/4)}{(f_1^{u+\bar{u}}(x) + f_1^{d+\bar{d}}(x)/4)} \, \frac{n_u^{\uparrow}}{n_u}$$

e⁺e⁻

$$A_{e+e-} \approx \frac{-\langle \sin^2\theta_2 \rangle}{\langle 1 + \cos^2\theta_2 \rangle} \, \frac{\langle \sin\theta \rangle \, \langle \sin\bar{\theta} \rangle \, 5\,(n_u^{\uparrow})^2}{5\,n_u^2 + n_s^2 + 4\,n_c^2}$$

Simplified expressions

SIDIS

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e^+e^-

From BELLE: $\frac{n_u^{\uparrow}}{n_u} = 25\%$

$$A_{e+e-} \approx \frac{-\langle \sin^2 \theta_2 \rangle}{\langle 1 + \cos^2 \theta_2 \rangle} \, \frac{\langle \sin \theta \rangle \, \langle \sin \bar{\theta} \rangle \, 5 \, (n_u^{\uparrow})^2}{5 \, n_u^2 + n_s^2 + 4 \, n_c^2}$$

Simplified expressions

SIDIS

$$\frac{n_u^\uparrow}{n_u} = \frac{\iint \frac{|\boldsymbol{R}|}{M_h} H_{1,u}^{\sphericalangle}(z, M_h^2)}{\iint D_{1,u}(z, M_h^2)}$$

$$A_{DIS}(x) \approx -\langle C_y \rangle \frac{(h_1^{u_v}(x) - h_1^{d_v}(x)/4)}{(f_1^{u+\bar{u}}(x) + f_1^{d+\bar{d}}(x)/4)} \frac{n_u^\uparrow}{n_u}$$

e^+e^-

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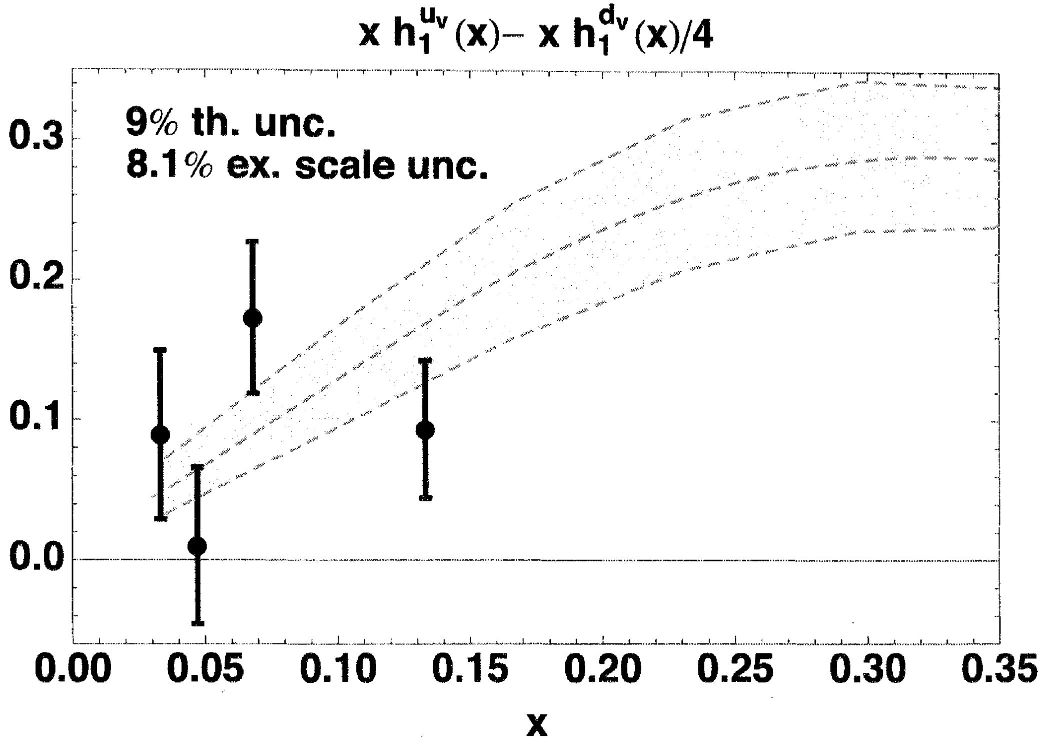
$$A_{e+e-} \approx \frac{-\langle \sin^2 \theta_2 \rangle}{\langle 1 + \cos^2 \theta_2 \rangle} \frac{\langle \sin \theta \rangle \langle \sin \bar{\theta} \rangle \, 5\, (n_u^\uparrow)^2}{5\, n_u^2 + n_s^2 + 4\, n_c^2}$$

First glimpses at transversity



Not in disagreement with Anselmino et al.

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Photon Pair Production

Marc Schlegel

Institute for Theoretical Physics
University of Tuebingen

in collaboration with Jianwei Qiu & Werner Vogelsang

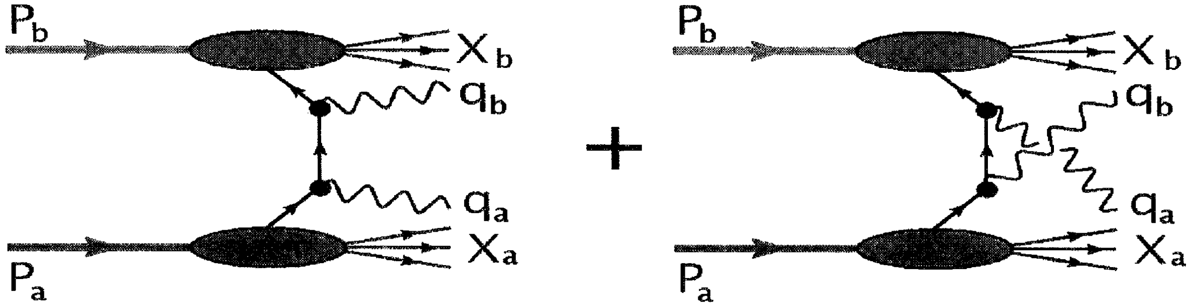
arXiv:1103.3861

Summary:

The photon pair production process in proton collision is discussed as a complementary process to the Drell-Yan process in the context of TMD-factorization. It is argued that gluon TMDs can be extracted from photon pair production at RHIC. Estimates are given for the gluonic Boer-Mulders and Sivers effects.

Photon Pairs from $q\bar{q}$-channel

Parton model tree-level at $O(\alpha_s^0)$ → quark-TMDs!



Only relevant at very small q_T: $\Lambda_{QCD} \sim q_T \ll Q$

$$\left(\frac{d\sigma}{d^4q\, d\Omega}\right) \propto \int d^2k_{aT} \int d^2k_{bT}\, \delta^{(2)}(\vec{k}_{aT} + \vec{k}_{bT} - \vec{q}_T)\, \mathrm{Tr}\Big[\Phi(x_a, \vec{k}_{aT})\, H(x_a, x_b, q_a, q_b)\, \bar{\Phi}(x_b, \vec{k}_{bT})\, H^\dagger\Big] + \mathcal{O}(\tfrac{M}{Q})$$

k_T - correlator:

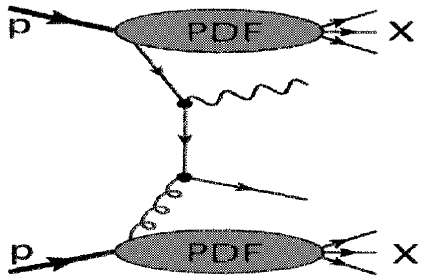
$$\Phi_{ij}(x, \vec{k}_T) = \int \frac{dz^- d^2z_T}{(2\pi)^2}\, e^{ik\cdot z} \langle P, S|\, \bar{q}_j(0)\, \mathcal{W}^{?/DY}[0\,;\, z]\, q_j(z)\, |P, S\rangle\Big|_{z^+=0}$$

<u>Main result of the TMD tree-level formalism:</u>

$$\left(\frac{d^6\sigma^{hh\to\gamma\gamma X}}{dy\, dQ^2\, d^2q_T\, d\Omega}\right)(\Lambda \sim q_T \ll Q) = \frac{2}{\sin^2\theta}\left(\frac{d\sigma^{hh\to l^+l^- X}}{dy\, dQ^2\, d^2q_T\, d\Omega}\right)(\Lambda \sim q_T \ll Q\, |\, e_q \to e_q^2)$$

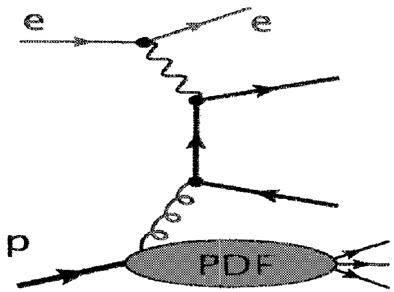
Gluon TMDs in photon pair production

<u>Gluon TMDs in pp-collisions with colored final state:</u>



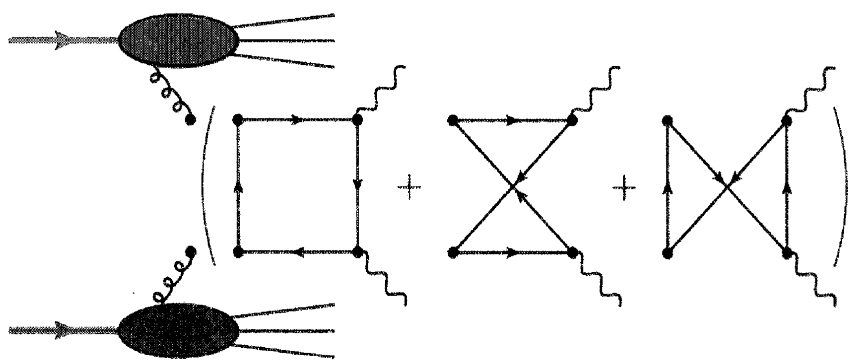
TMD-Factorization (?)

<u>Gluon TMDs in Heavy-quark production in ep-collisions:</u>



Wait for EIC

Feature of photon pair production → direct sensitivity to gluon TMDs at O($_s^2$)



- No colored final state
- Box diagrams finite
- Potentially large gluon distributions
- New Observables, e.g. Cos(4ϕ)

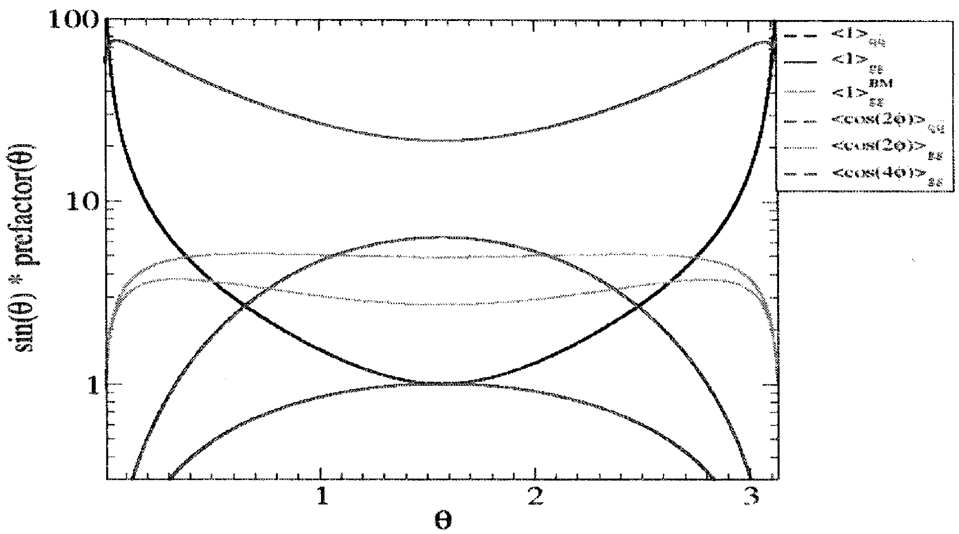
Unpolarized Cross Section

Six structures for the unpolarized cross section ($q_T << Q$)

$$\frac{d\sigma_{UU}}{d^4q\, d\Omega} \sim \left(\frac{2}{\sin^2\theta}\right)\Big((1+\cos^2\theta)[f_1^q \otimes f_1^{\bar{q}}] + \cos(2\phi)\sin(2\theta)[h_1^{\perp q} \otimes h_1^{\perp \bar{q}}]\Big)$$

$$+\left(\frac{\alpha_s}{2\pi}\right)^2\Big(\mathcal{F}_1[f_1^g \otimes f_1^g] + \mathcal{F}_2[h_1^{\perp g} \otimes h_1^{\perp g}] + \cos(2\phi)\mathcal{F}_3[h_1^{\perp g} \otimes f_1^g + f_1^g \otimes h_1^{\perp g}] + \cos(4\phi)\mathcal{F}_4[h_1^{\perp g} \otimes h_1^{\perp g}]\Big)$$

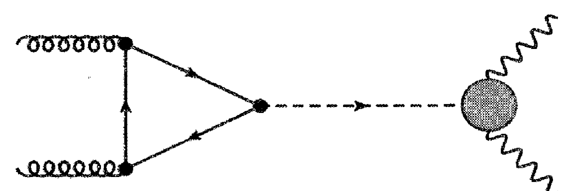
$\mathcal{F}_i$: non-trivial functions of sin(θ) and cos(θ) (Logarithms)



- $q\bar{q}$ singular for θ → 0, π
  - → p_T (or θ)-cuts for each photon
- cos(4ϕ) induced by gluon BM- functions,
  - → no corresponding quark / DY term.
- powerful in combination with DY
  - → even gluon TMD f_1 unknown.
- cos(2ϕ) determines sign of gluon BM-function.
- Same angular structure found in collinear resummation formulas for higher qT.
  (Balazs et al., Catani & Grazzini)

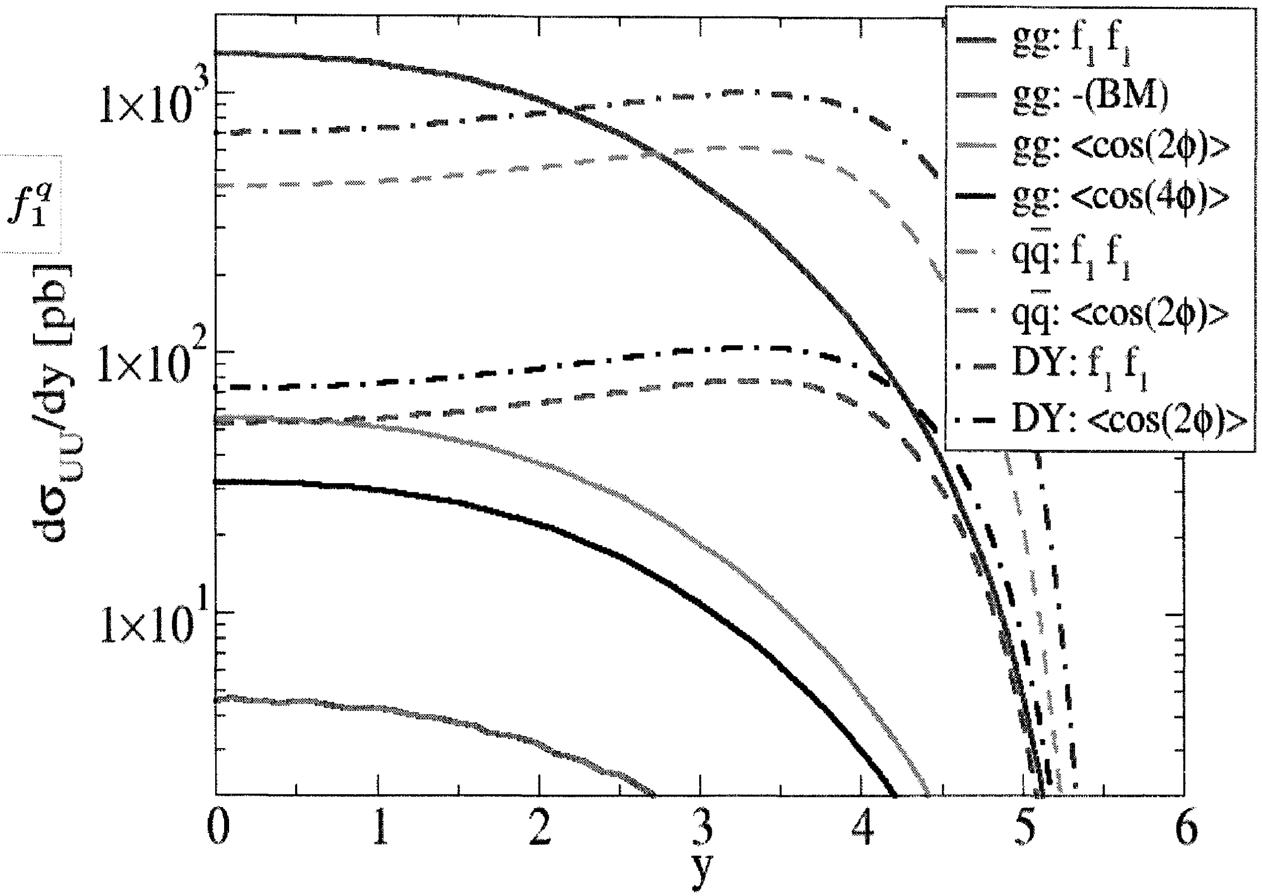
LHC: Diphotons → main channel for Higgs-Prod.

→ Background process: diphotons via quark-box
→ gluon TMD (unpol., BM) feasible



(Maximal) Gluonic BM-effect at RHIC

Estimates at RHIC ($S^{1/2}$ = 500 GeV) → Gluon (and Quark!) TMDs unknown at RHIC energy



<u>Saturation of Positivity bounds:</u>

$$|h_1^{\perp,g}| \leq \frac{2M^2}{k_T^2} f_1^g \qquad |h_1^{\perp}, q| \leq \frac{M}{k_T} f_1^q$$

<u>Gaussian Ansatz:</u>

$$f_1^{q/g}(x, k_T^2) = f_1^{q/g}(x)\, e^{-k_T^2/\langle k_{T,q/g}^2\rangle}$$

<u>Further assumption:</u>

$$\langle k_{T,q}^2\rangle = \langle k_{T,g}^2\rangle = 0.5\,\mathrm{GeV}^2$$

<u>P_T-cut for photons:</u>

$$p_T^\gamma > 1\,\mathrm{GeV}$$

- Gluons at midrapidity, quarks at large rapidity
- BM-contribution to ϕ-indep. CS small
- <cos(4ϕ)> ≤ 1% (depend. on saturation)

Gluonic Sivers-effect at RHIC

Four structures for the ϕ-indep. transv. Single-Spin Asymmetry

$$\frac{\mathrm{d}\sigma_{\mathrm{TU}}}{\mathrm{d}^4 q\,\mathrm{d}\Omega} \sim S_T \sin\phi_S \Big[\frac{2}{\sin^2\theta}(1+\cos^2\theta)\,[f_{1T}^{\perp,q}\otimes f_1^{\bar{q}}] + \Big(\frac{\alpha_s}{2\pi}\Big)^2 \Big(\mathcal{F}_1\,[f_{1T}^{\perp,g}\otimes f_1^g] + \mathcal{F}_2\,[h_1^g\otimes h_1^{\perp,g}] + \mathcal{F}_2\,[h_{1T}^{\perp,g}\otimes h_1^{\perp,g}]\Big)\Big] + \ldots$$

Positivity bounds:

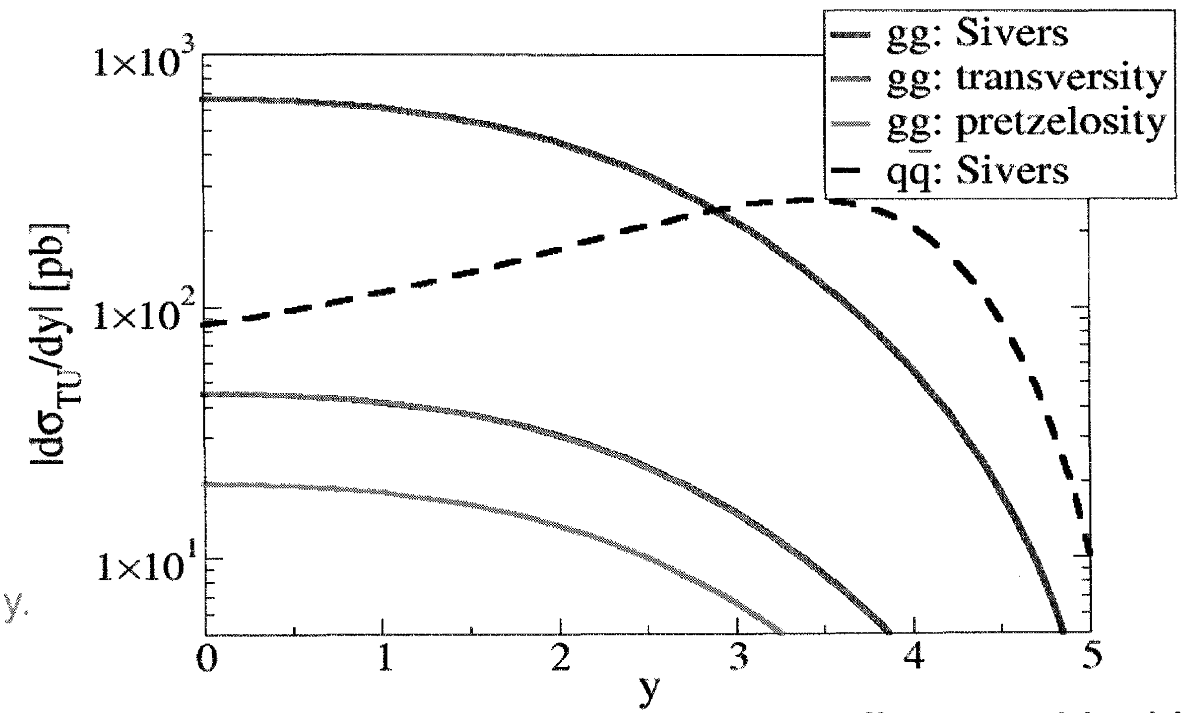
$$|f_{1T}^{\perp,q/g}| \leq \frac{M}{k_T}\, f_1^{q/g}$$

$$|h_1^g| \leq \frac{M}{k_T}\, f_1^g \qquad |h_{1T}^{\perp,g}| \leq \frac{2M^3}{k_T^3}\, f_1^g$$

Flavor cancellation:

$$f_{1T}^{\perp,u} \sim -f_{1T}^{\perp,d}$$

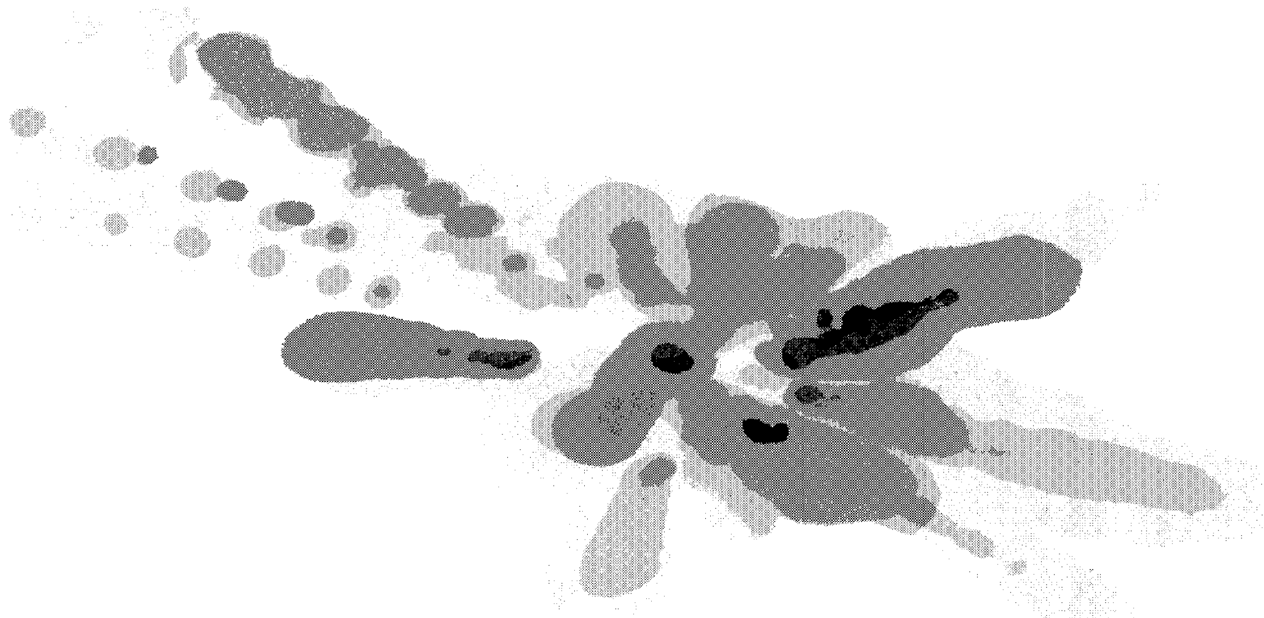
$\rightarrow$ pos. pound given by u-quark only.



- Sign of Sivers function not predicted by positivity $\rightarrow$ quark and gluon effects could add.
- Gluonic effects at midrapidity, quark effects at large rapidities.
- Effects by gluon transversity / pretzelosity small.

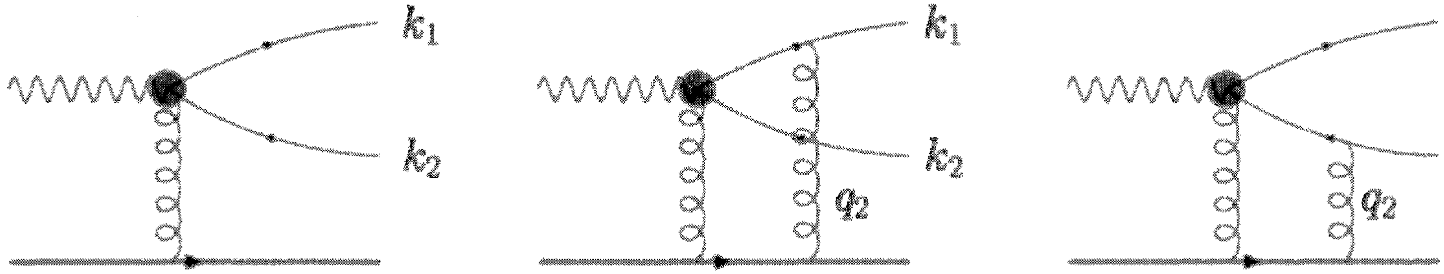
Many body QCD: from RHIC (& LHC) to the EIC

Raju Venugopalan
Brookhaven National Laboratory



BNL Drell-Yan workshop, May 11-13, 2011

Semi-inclusive DIS: quadrupole evolution



Dominguez,Marquet,Xiao,Yuan (2011)

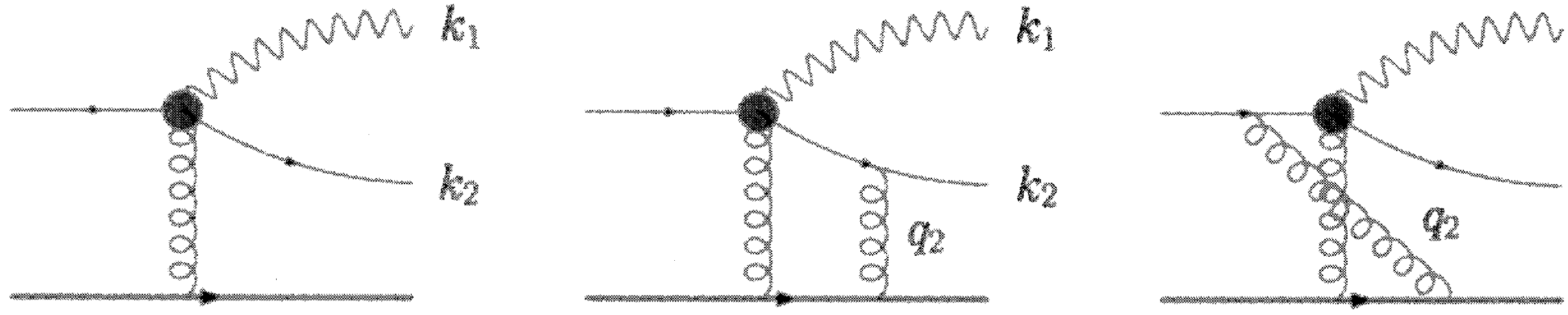
$$\frac{d\sigma^{\gamma^*_{\mathrm{T,L}} A \to q\bar{q}X}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x}\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})} e^{ik_{2\perp}\cdot(y-\bar{y})} \left[1 + Q(x,y;\bar{y},\bar{x}) - D(x,y) - D(\bar{y},\bar{x})\right]$$

$$D(x,y) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_y^\dagger)\rangle_Y \qquad Q(x,y;\bar{y},\bar{x}) = \frac{1}{N_c}\langle \mathrm{Tr}(V_x V_{\bar{x}}^\dagger V_{\bar{y}} V_y^\dagger)\rangle_Y$$

Cannot be further simplified a priori even in the large N_c limit

(See talks by Mueller, Xiao, Jalilian-Marian)

Universality: Di-jets in p/d-A collisions



Jalilian-Marian, Kovchegov (2004)
Marquet (2007)
Dominguez,Marquet,Xiao,Yuan (2011)

$$\frac{d\sigma^{qA\to qgX}}{d^3k_1 d^3k_2} \propto \int_{x,y,\bar{x},\bar{y}} e^{ik_{1\perp}\cdot(x-\bar{x})} e^{ik_{2\perp}\cdot(y-\bar{y})} \left[S_6(x,y,\bar{x},\bar{y}) - S_4(x,y,v) - \ldots\right]$$

$$S_6 \Rightarrow \frac{N_c}{2\,C_F}\left\langle Q(x,y\,\bar{y},\bar{x})D(y,\bar{y}) - \frac{D(x,\bar{x})}{N_c}\right\rangle \qquad S_4 \Rightarrow \frac{N_c}{2\,C_F}\left\langle D(x,y)D(\bar{y},\bar{x}) - \frac{D(x,\bar{x})}{N_c}\right\rangle$$

Fundamental ingredients are the universal dipoles and quadrupoles

B-JIMWLK hierarchy: Langevin realization

Numerical evaluation of Wilson line correlators on 2+1-D lattices:

$$\left\langle \mathcal{O}[U] \right\rangle_Y = \int D[U]\, W_Y[U]\, \mathcal{O}[U] \longrightarrow \frac{1}{N} \sum_{U \epsilon W} \mathcal{O}[U]$$

Langevin eqn:

Gaussian random variable

$$\partial_Y [V_x]_{ij} = [V_x i t^a]_{ij} \left[\int d^2 y\, [\mathcal{E}^{ab}_{xy}]_k\, [\xi^b_y]_k + \sigma^a_x \right]$$

$$\mathcal{E}^{ab}_{xy} = \left(\frac{\alpha_S}{\pi^2}\right)^{1/2} \frac{(x-y)_k}{(x-y)^2} \left[1 - U^\dagger_x U_y\right]^{ab}$$

"square root" of JIMWLK kernel

$$\sigma^a_x = -i \left(\frac{\alpha_S}{2\pi^2} \int d^2 z \frac{1}{(x-z)^2} \mathrm{Tr}(T^a\, U^\dagger_x U_z) \right)$$

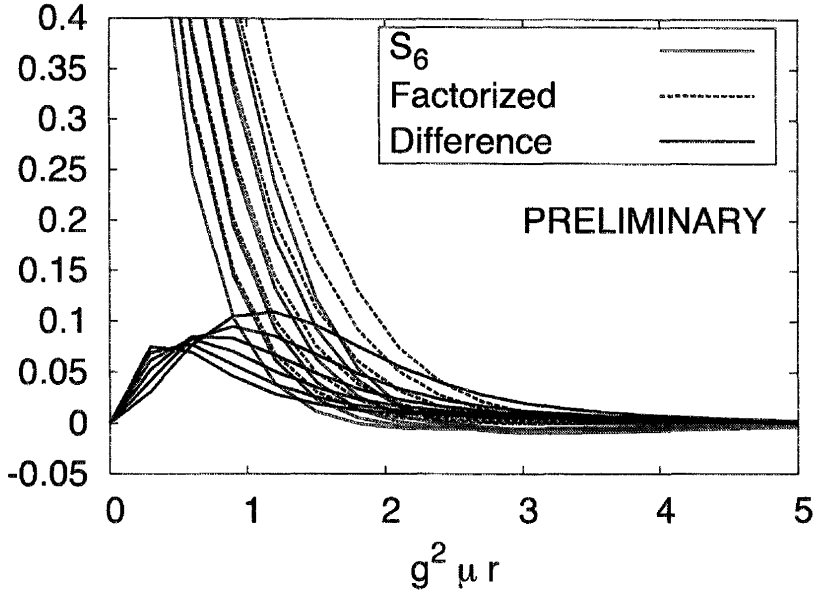
"drag"

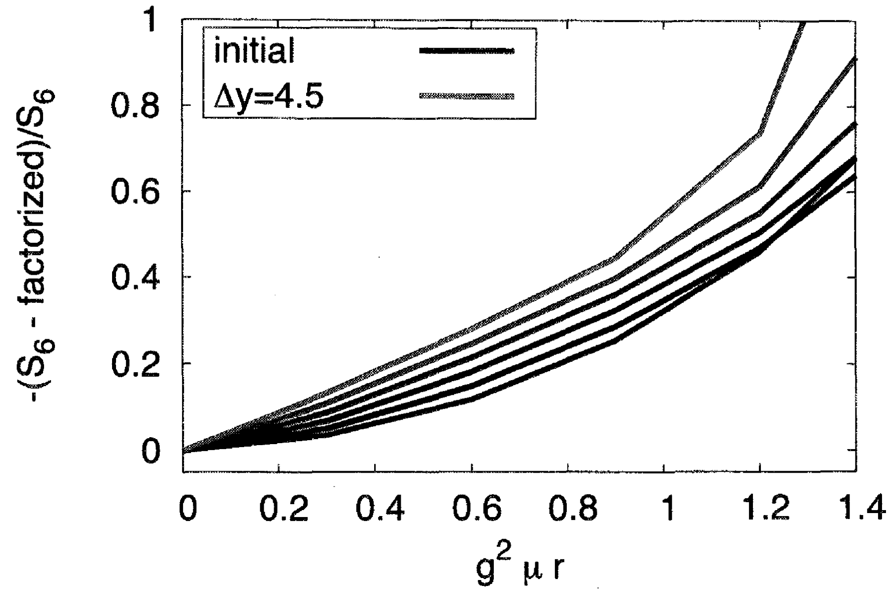
- ❑ **Initial conditions for V's from the MV model**
- ❑ **Daughter dipole prescription for running coupling**

Numerical results-IV

Lappi,Schenke,RV

How about the quantity S_6 containing quadrupoles that appear in di-hadron correlations ?





Violations large for large r and for large Y
(i.e., when saturation effects are important) – confirming analytical estimates

Outlook - I

- The JIMWLK hierarchy contains non-trivial "many body" correlations -these are now being explored using numerical and analytical techniques

- It is likely that they could be inferred (given sufficient precision) from experiments thereby providing key insight into QCD many body dynamics in the Regge-Gribov limit

- There are many open questions that hopefully will be resolved in the next decade, such as i) NLL corrections, ii) matching to OPE based analyses at larger x and Q^2

Transverse Single Spin Asymmetries for Drell-Yan production

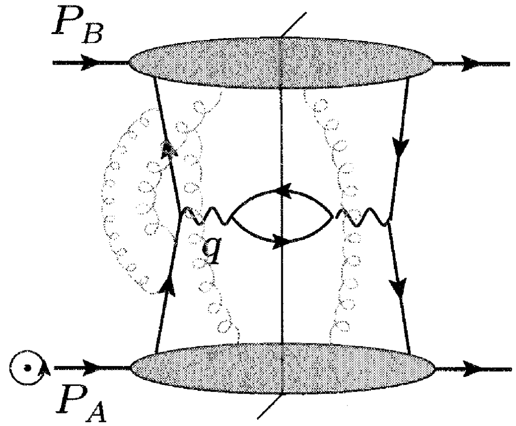
John Collins
Penn State University

Abstract

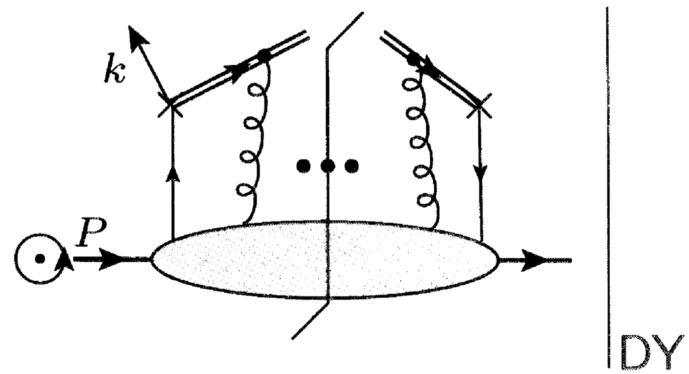
I review the arguments for the importance of measuring transverse single spin asymmetries for the Drell-Yan process. On the theory side, key elements of factorization are Wilson lines in the definition of parton densities; these correspond to partonic color flows relative to a hard scattering. The appropriate choice of the Wilson line directions manifests itself in a testable way in the predicted change in sign of Sivers function between SIDIS and DY.

If experiments find that this prediction fails, and this finding survives close scrutiny, we would have to reconsider our understanding of QCD hard scattering.

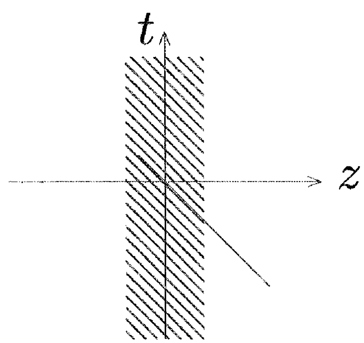
Drell-Yan has different pdfs

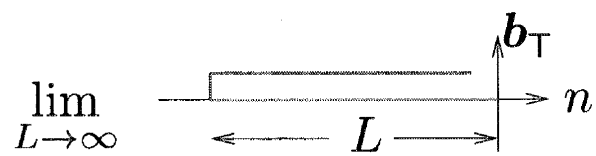


$\Longrightarrow$



with past-pointing WLs:





(Need cancellation of f.s.i.; *inclusive* Drell-Yan only.)
(Proof of TMD factorization — JCC's "Foundations of perturbative QCD".)

Experimentally accessible consequence of WL: Sign change of Sivers function

Relate pdfs in SIDIS and DY by TP transformation

Changes:

- Wilson lines:

  Future-pointing for SIDIS pdfs $\overset{TP}{\Longleftrightarrow}$ past-pointing for DY pdfs

- States:

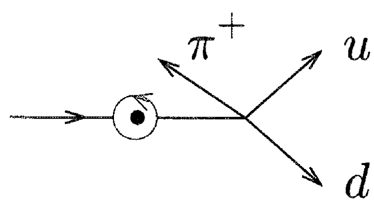
$$|\mathbf{P}, \boldsymbol{s}_\mathrm{T}\rangle \quad \overset{P}{\Longleftrightarrow} \quad |-\mathbf{P}, \boldsymbol{s}_\mathrm{T}\rangle \quad \overset{T}{\Longleftrightarrow} \quad |\mathbf{P}, -\boldsymbol{s}_\mathrm{T}\rangle$$

- Hence for pdfs:
  - normal pdf_DY = normal pdf_DIS
  - But $\text{Sivers}_\mathrm{DY} = -\text{Sivers}_\mathrm{DIS}$

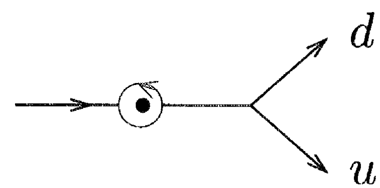
Prediction for DY

To have a prediction, $x_{\textit{in polarized proton}}$ *must be in Hermes region*

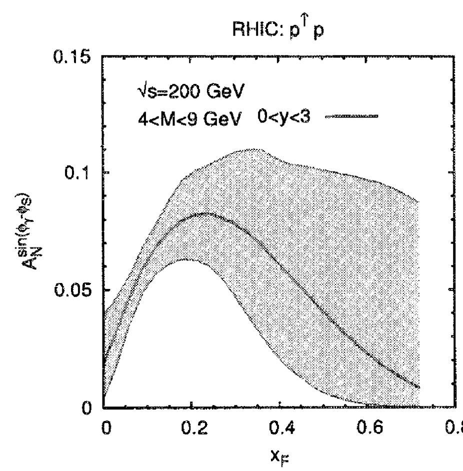
SIDIS



DY



Prediction *w/o (CSS) evolution for TMDs*



(Anselmino et al. Phys.Rev. D79 (2009) 054010)

For $\mathrm{d}\sigma\,/\,\mathrm{d}q\,\mathrm{d}\Omega$: distribution $\propto \sin(\phi_q - \phi_s)(1+\cos^2\theta)$ + Boer-Mulders term

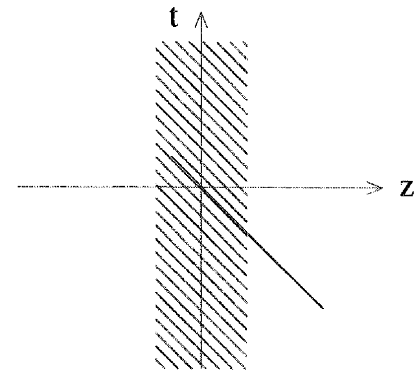
Reliability of theoretical framework

QCD

Kinematic approximations

Disentangle gluons into Wilson lines

Cancellation of spectator interactions



factorization

TMD, incl. Sivers

Cancellation of soft ints.

Collinear factorization

Any problems with Sivers function impact issues critical to all kinds of factorization.

(Unpolarized) factorization survived many tests, so probability of failure is low.

Wilson lines encode space-time locations of color flow relative to hard scattering.

Conclusions

- Sivers function gives stress test of our understanding of QCD parton dynamics in hard scattering, especially of space-time locations of color flows

  (Key issues were hidden until recently!)

- SSA in Drell-Yan is clean test case with predictions deduced from SIDIS data and unpolarized Drell-Yan

  But remember CSS evolution (or equivalent) in making predictions.

- Disquieting data for $p^{\uparrow} p \to \pi X$

- But than $p^{\uparrow} p \to \pi X$ is harder for theory than Drell-Yan

Opportunities for Drell-Yan Physics at RHIC – List of Participants

Title	First Name	Last Name	Affiliation	
Dr.	Kensuke	Okada	Brookhaven National Laboratory	
Dr.	Atsushi	Taketani	RIKEN	
	Thomas	Burton	Brookhaven National Laboratory	
	Larisa	Nogach	IHEP, Protvino	
Dr.	Marco	Contalbrigo	INFN Ferrara	
Dr.	Akio	Ogawa	Brookhaven National Laboratory	
Dr.	Yasuyuki	Akiba	RIKEN	
Dr.	Ernst	Sichtermann	Lawrence Berkeley National Laboratory	
Dr.	Achim	Franz	Brookhaven National Laboratory	
Dr.	John	Haggerty	Brookhaven National Laboratory	
Dr.	Paul	Reimer	Argonne National Laboratory	
Dr.	Alexey	Prokudin	Thomas Jefferson National Accelerator Facility	
	Len	Eun	Lawrence Berkeley National Laboratory	
Dr.	Thomas	Ludlam	Brookhaven National Laboratory	
Dr.	James	Dunlop	Brookhaven National Laboratory	
Dr.	Matt	Lamont	Brookhaven National Laboratory	
	Fabio	Dominguez	Columbia University	
Dr.	Francesca	Giordano	University of Illinois	
Dr.	Angelo	Maggiora	INFN	
Dr.	Oleg	Denisov	INFN - Turin section	
Dr.	Itaru	Nakagawa	RIKEN/RBRC	
Prof.	Donald	Crabb	University of Virginia	
Dr.	Dmitri	Smirnov	Brookhaven National Laboratory	
	Ralf	Seidl	RIKEN	
Dr.	Anna	Stasto	riken bnl	
Dr.	Ming	Liu	Los Alamos National Laboratory	
Dr.	Michael	Tannenbaum	Brookhaven National Laboratory	
	Oleg	Tsai	UCLA	
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May 11 – 13, 2011

Li Keran

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Through collision
Generate new states of matter.
T.D. Lee

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