06/22/11

A Personal Wish List

~~Theorist's Priorities~~

for RHIC spin & p/d A Programs beyond 2015

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outline & disclaimer

quote from Steve Vigdor's charge for my talk

> "... this should contain the measurements you think it would be most important to make, even if you judge that we do not presently have the luminosity to make them ..."

so, be prepared for some bold ideas along the way

- further improvements of helicity PDFs — "rare probes", A_L with ^{3}He , W+c , Λ
- transverse spin phenomena — transversity from A_{TT} , A_N in DY, ^{3}He
- opportunities in p(d) A — forward correlations , DY, polarization

my humble input for discussions - not meant to be an exhaustive list

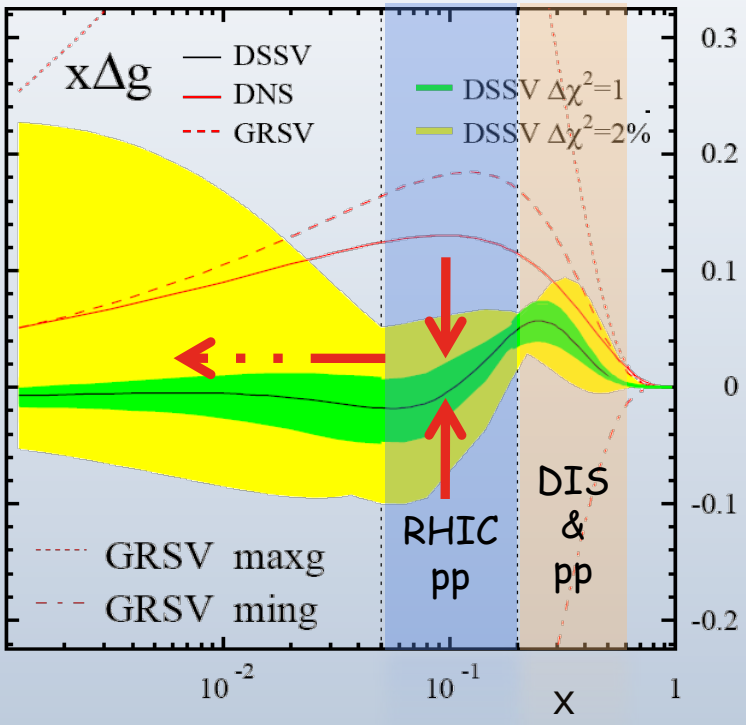
Helicity PDFs in 2015+

Δg – where are we now/in 2015

- inclusive pions & jets remain to be the bread & butter probes
- jet/hadron correlations essential to cover smaller x

straightforward to analyze in global fits

current status: DSSV global fit de Florian, Sassot, MS, Vogelsang



DSSV includes "only" RHIC run6 data

by around 2015 expect to have:

- DSSV 2.0 global analysis based on new world data
- reduced uncertainties on Δg in current x range
- possibility of a node further scrutinized
  "evidence" may become statistically significant or not
- extend x-range towards somewhat lower x
  500 GeV running & particle correlations

full 1st moment (proton spin sum) will have smaller but still significant uncertainties from unmeasured small x region

Δg – where are we now/in 2015 (cont'd)

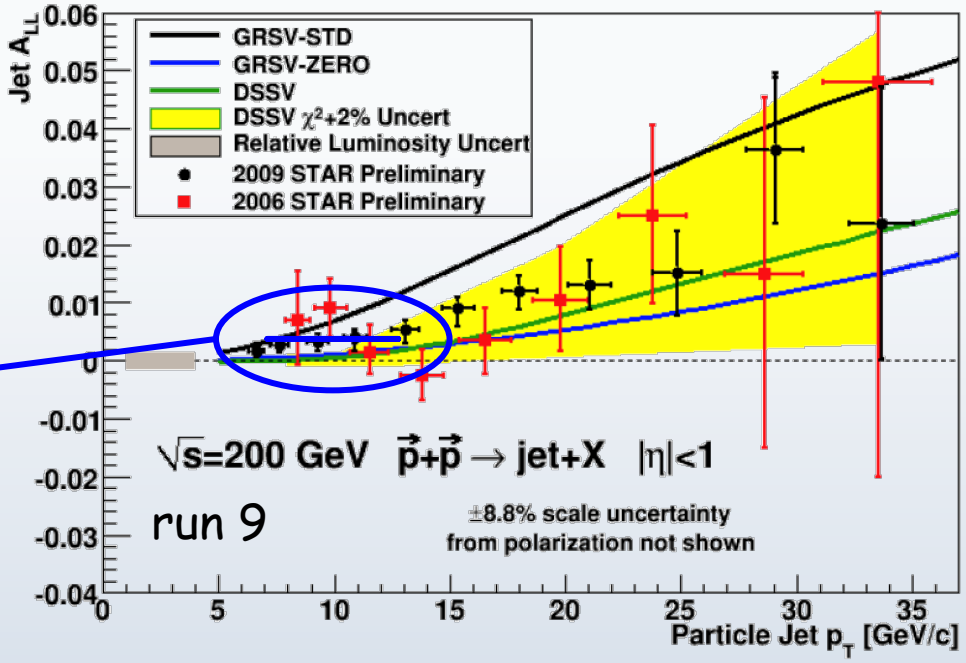
we continuously make progress on Δg: interesting trends in preliminary run-9 data

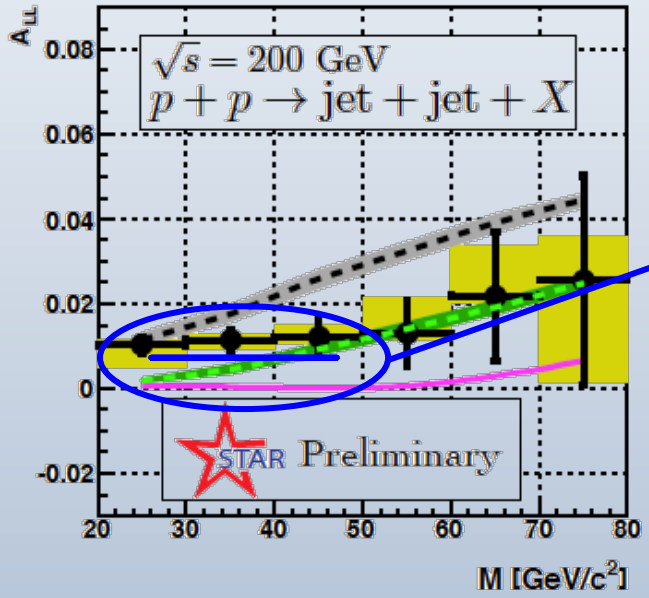
- run 9 data: smaller uncertainties

  better constraint on Δg

  node in Δg might go away ?

  slightly larger polarization ?
  as compared to DSSV analysis





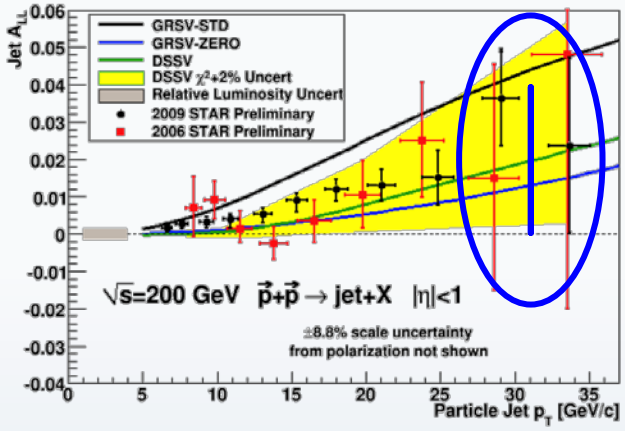
similar trend in di-jets

new data ready to go into
DSSV global analysis once available
(to quantify their impact)

Δg – further improvements from RHIC ?

important to measure A_{LL} precisely
also at large p_T (where gg scattering is small)

- qg scattering -> sign of Δg at large x
- expect rise a large p_T due to large Δq/q at large x (as extracted from DIS)

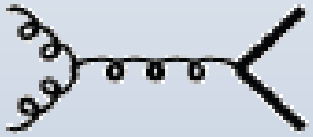


current determinations of Δg from pions and jets is based on the ***same*** partonic hard scattering processes

- with sufficient luminosity we can probe Δg in other, *independent* channels

prompt photons

heavy flavors

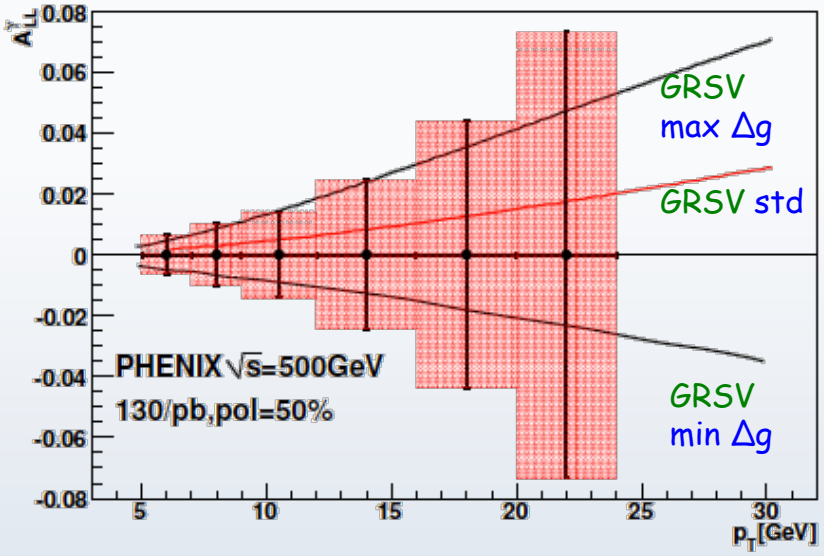


rare probes

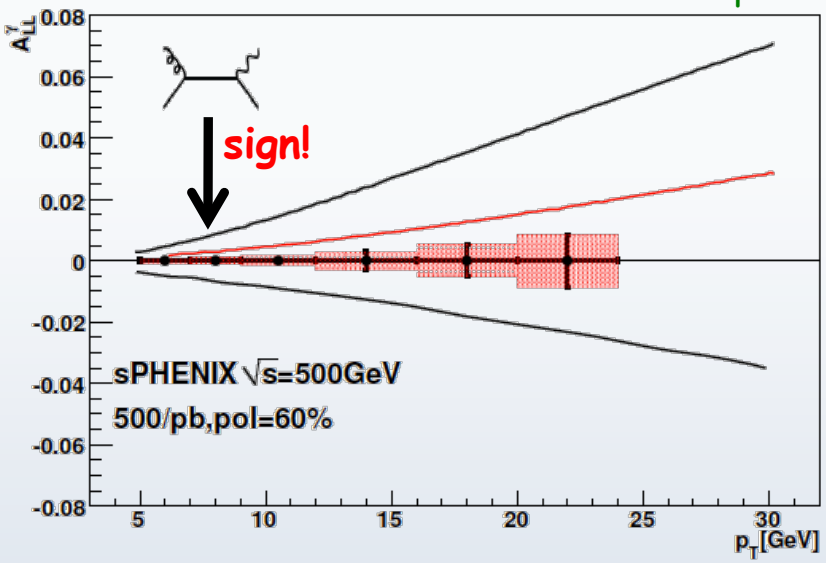
- ✓ much smaller number of subprocesses
- ✓ photons sensitive to sign of Δg
- ✓ different hard scattering dynamics

crucial in understanding spin-dep. QCD hard scattering
test idea of factorization and universality

Δg from prompt photons ?



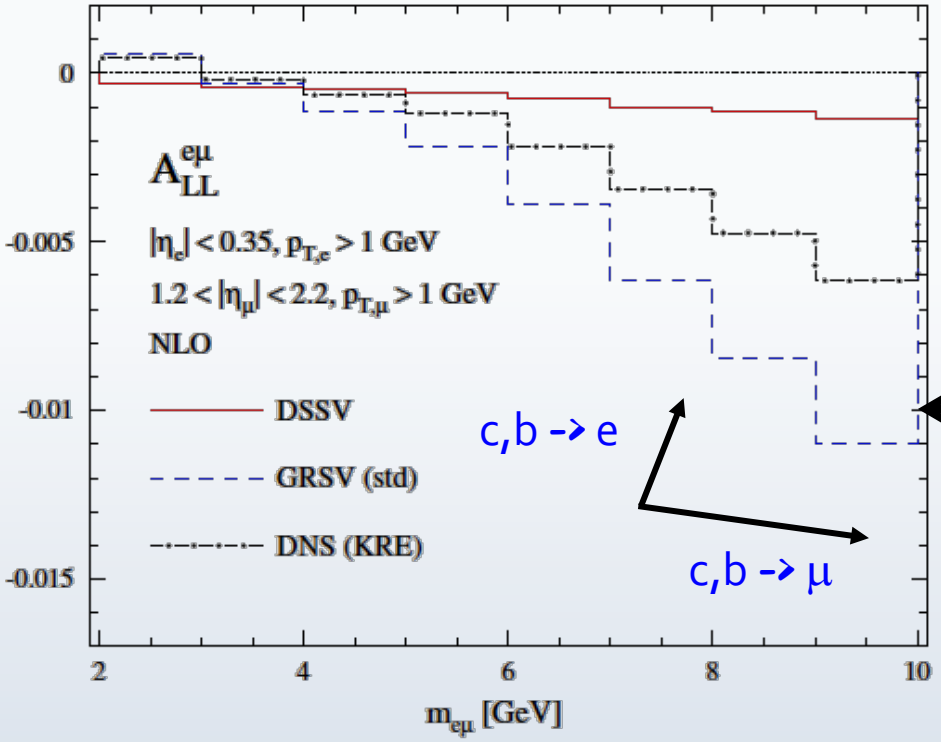
taken from PHENIX decadal plan



still *the* golden channel for Δg in pp measurement should be done

- only probe in pp which provides sensitivity to sign of Δg at small p_T (i.e. small x!)
- requires a significant integrated luminosity **(0.5 ÷ 1 fb^{-1})** to make an impact
- straightforward to include in global QCD analysis; NLO corrections known
- γ-jet correlations would allow for detailed mapping of x dependence

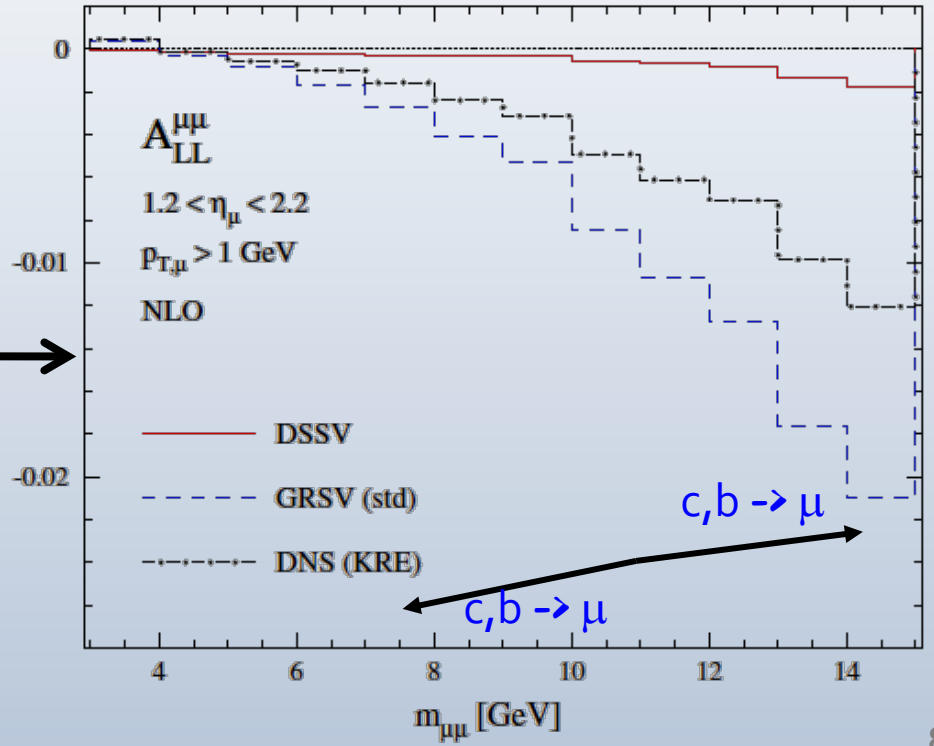
Δg from heavy flavors ?



- correlations most promising
  (recent NLO calculation Riedl, Schafer, MS)
- correlation between A_{LL} and Δg at large enough invariant mass (= larger x)

forward-central e-μ coincidences

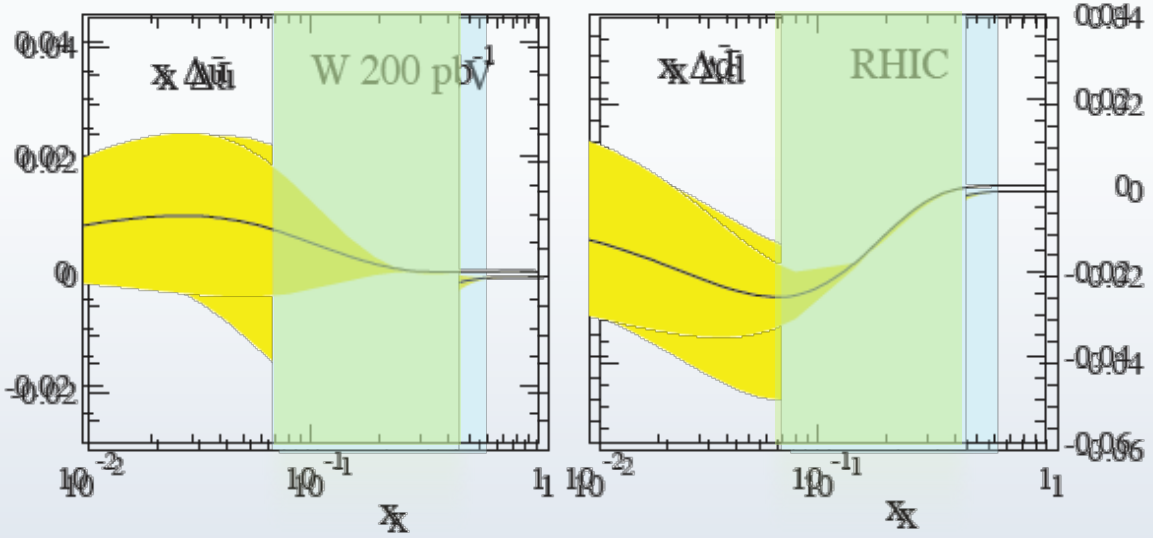
forward-backward μ-μ coincidences



luminosities of a **few hundred pb^{-1}** are required for meaningful measurements at $m_{e\mu,\mu\mu}$ up to 10 ÷ 12 GeV
(less compelling than prompt photons)

Δq's – where are we now/in 2015

W-boson program completed (?) by 2015 – what do we expect to learn?



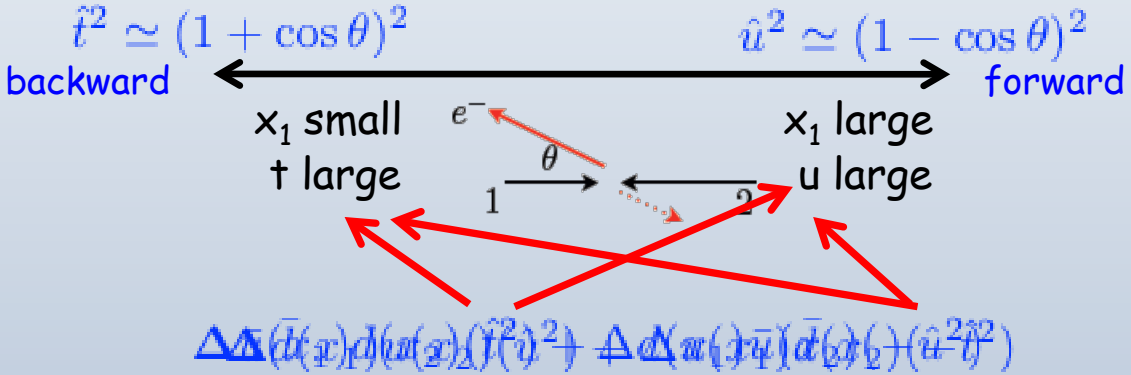
currently impact of RHIC 500 GeV W boson data on global fit

de Florian, Vogelsang

- ✓ reduction of uncertainties for 0.07 < x < 0.4
- ✓ can test consistency of low Q^2 SIDIS data in that x regime

complication:

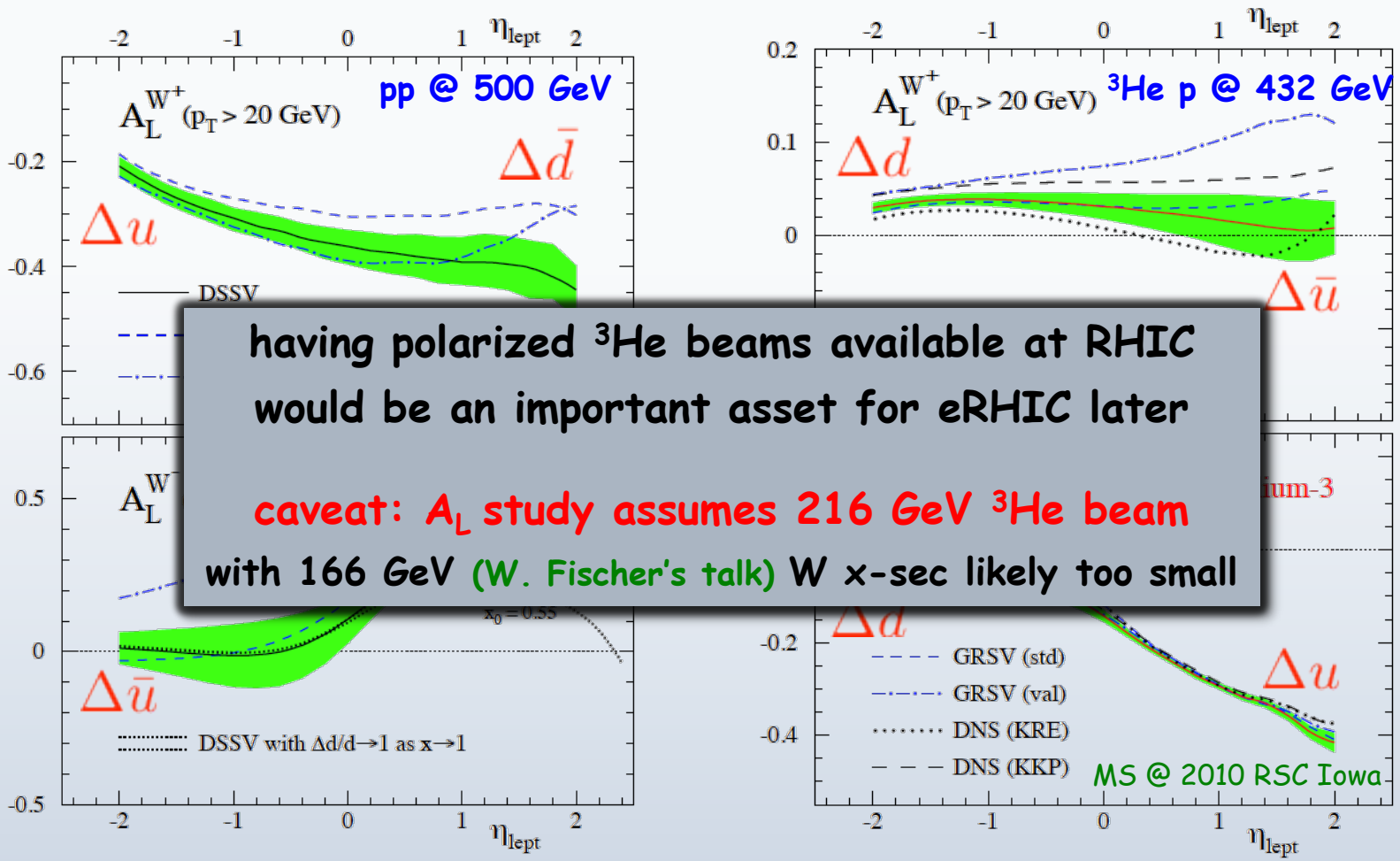
angular and PDF x dependence for decay lepton not always work hand-in-hand



strong sensitivity to $\Delta\bar{d}$

can we flip u <-> d around?

A_L^W: pp vs ^{3}He-p collisions



having polarized ^{3}He beams available at RHIC would be an important asset for eRHIC later

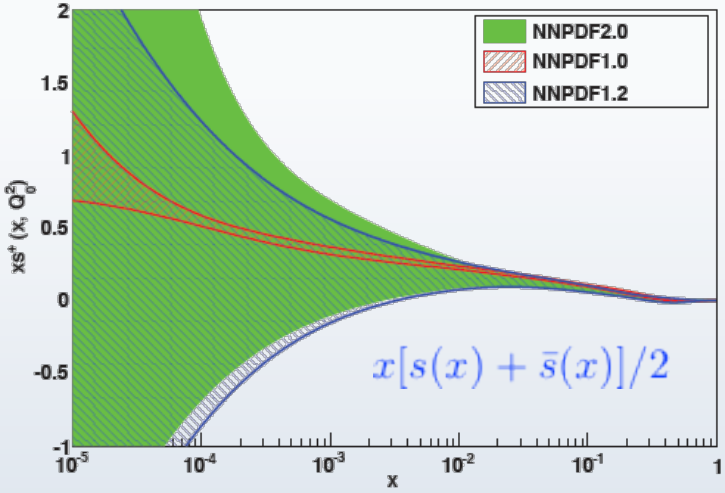
caveat: A_L study assumes 216 GeV ^{3}He beam with 166 GeV (W. Fischer's talk) W x-sec likely too small

- polarized ^{3}He mainly a neutron target: 0.865 n + 2*(-0.027) p but unpol. ^{3}He is n+2p
  → A_L no longer probes $\Delta q/q$ as in pp; but irrelevant "complication" in a global analysis
- like in pp: need significant running time/luminosity O(few hundred pb^{-1}); polarimetry ?

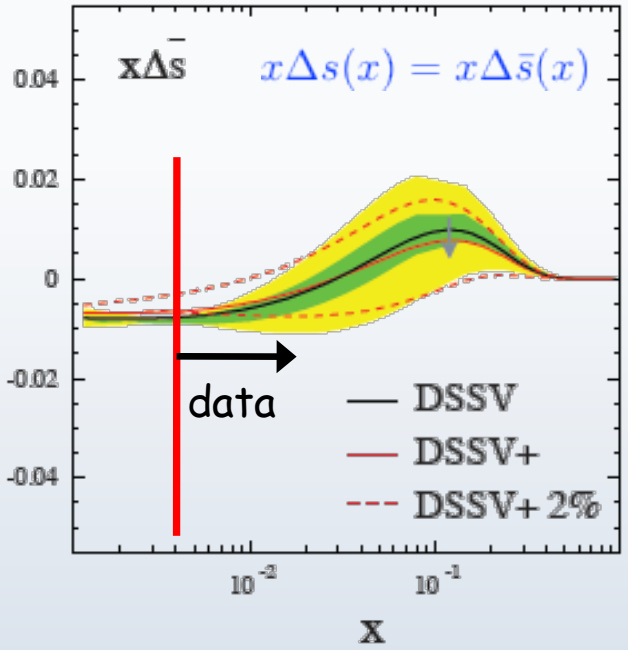
what about Δs at RHIC ?

strangeness is one of the least known quantities in hadronic physics

NNPDF collaboration



DSSV (incl. latest COMPASS data)



- substantial uncertainties
- known issues with HERMES data at large x
- **hot topic:** $s(x) - \bar{s}(x)$

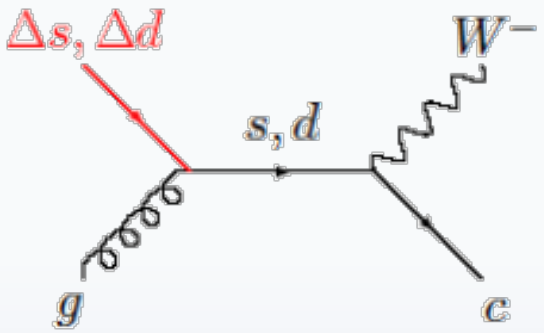
- **surprise:** Δs small & positive from SIDIS data
- but 1st moment is negative and sizable due to "constraint" from hyperon decays (F,D) (assumed SU(3) symmetry debatable M. Savage)
- drives uncertainties on ΔΣ (spin sum)

notoriously difficult to determine in pp collisions
only two options @ RHIC: W+charm and polarized Lambdas

Δs from W+charm production

simple idea:

LO



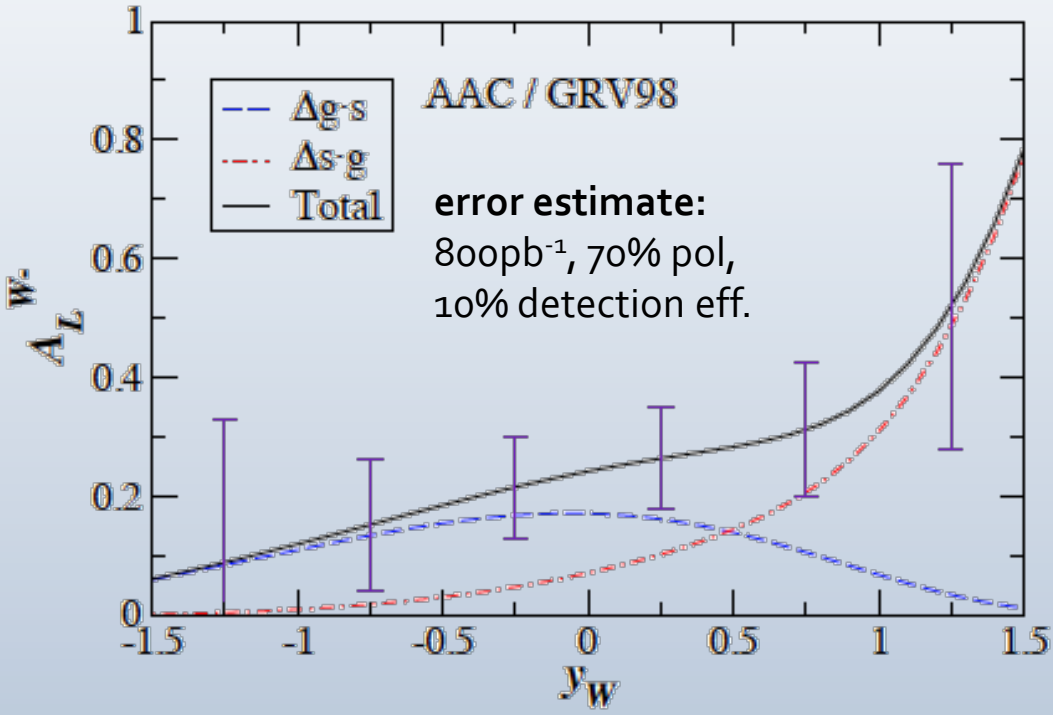
two competing contributions:

Δs' g and s' Δg scattering

$$s' \equiv s\,|V_{cs}|^2 + d\,|V_{cd}|^2$$

any sensitivity to Δs ?

Sudoh, Yokoya (for 2005 RHIC II workshop)



find:

- Δs contribution enhanced for y_W>1
  probes Δs large x
- extremely rare probe
  cross section of order 1pb
- does not include W decay

neat but VERY hard to do
requires > 1÷2 fb^{-1}

Δs from spin transfer to Λ baryons

idea:
- study helicity transfer to Λ in $\vec{p}p \to \vec{\Lambda}X$ (preferably at forward η where x_1 is large)
- use self-analyzing decay of Λ to determine its polarization
- quark model: Λ spin predominantly carried by s --> **sensitivity to Δs**

s-dominance perhaps as naïve as proton spin in quark model

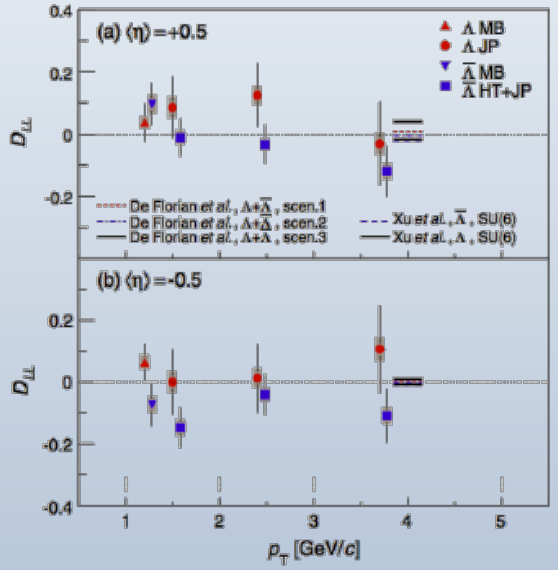
theory prerequisites:
- reliable NLO sets of D_i^{Λ} *and* ΔD_i^{Λ} FFs

DSV: de Florian, MS, Vogelsang

updates needed
don't describe STAR data

AKK: Albino et al.

DSV: de Florian, MS, Vogelsang
sparse data; updates desirable
3 models for ΔD_i considered



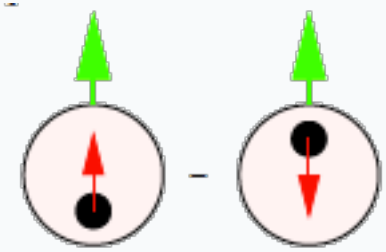
- feed-down from hyperon weak decays; effect on polarization?
- compute helicity-transfer subprocesses at NLO
  difficult – many more processes than pion production; work in progress

the good news: "proof of principle" by STAR

best shot at Δs at RHIC
needs also some theoretical work though

Transverse Spin Program in 2015+

transversity



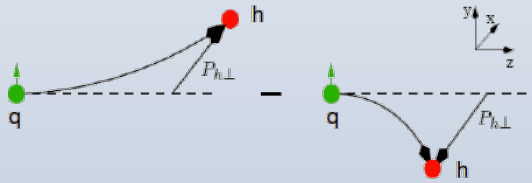
transversity $\delta q(x,Q^2)$ as fundamental as helicity density

- QCD evolution known to NLO: "evolves away" asymptotically Vogelsang; Kumano, Miyama; Koike et al.
- "chiral odd" nature: involves helicity flip -> no gluon transversity Jaffe, Ji; Artru, Mekhfi
- probes relativistic effects in wave function; info on chiral symmetry breaking Collins; Jaffe

what do we know / how to measure:

needs to be paired with another chiral-odd function

- spin transfer (Λ): analyzing power small COMPASS
- 2-hadron FFs : non-zero BELLE, COMPASS, HERMES
- Collins FFs : non-zero & *universal* BELLE, COMPASS, HERMES

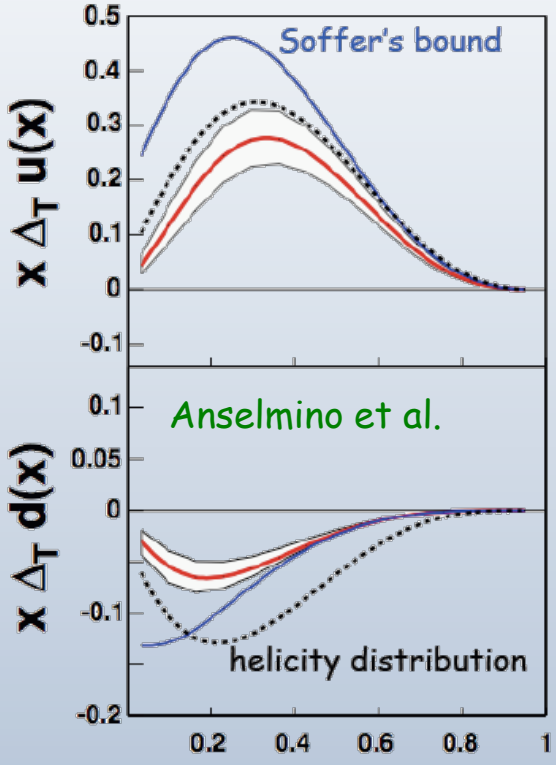


$$s_q \cdot (p_q \times P_T^h)$$

extraction of δq from combined fit: find $\delta u>0$ & $\delta d<0$

present error bars contain many assumptions

transversity for sea quarks?



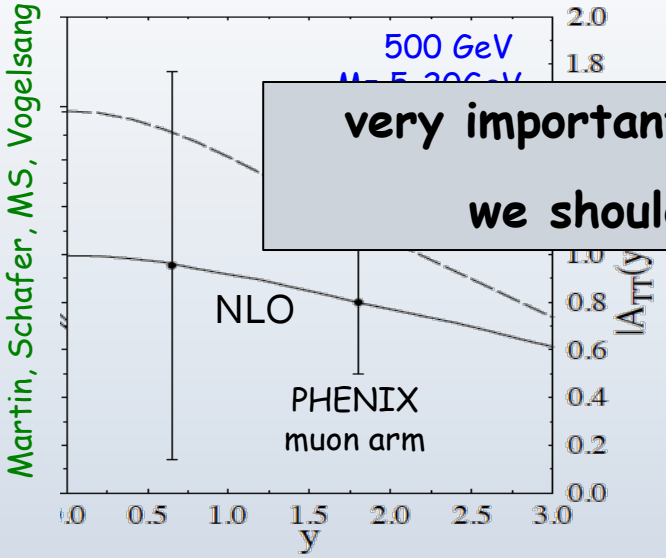
transversity and A_{TT}

we can also pair transversity with itself -> double transverse spin asymmetries A_{TT}

general problem: $A_{TT} = d\delta\sigma/d\sigma$ strongly diluted by gluon contribution to $d\sigma$

"golden channel": Drell Yan **no gluons in LO**

used to "define" δq's:
Ralston, Soper; Ji;
Cortes, Pire, Ralston; Jaffe, Ji; ...



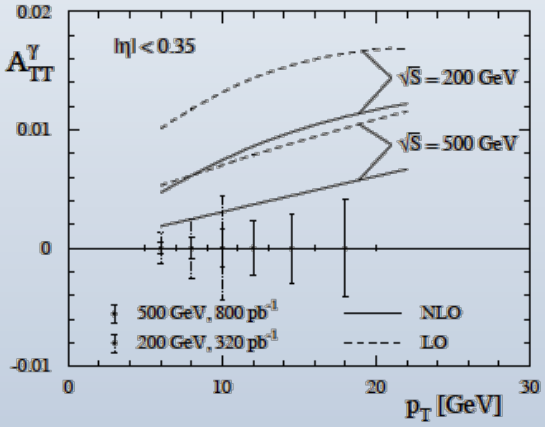
find: A_{TT} at best (upper bound) around 1%

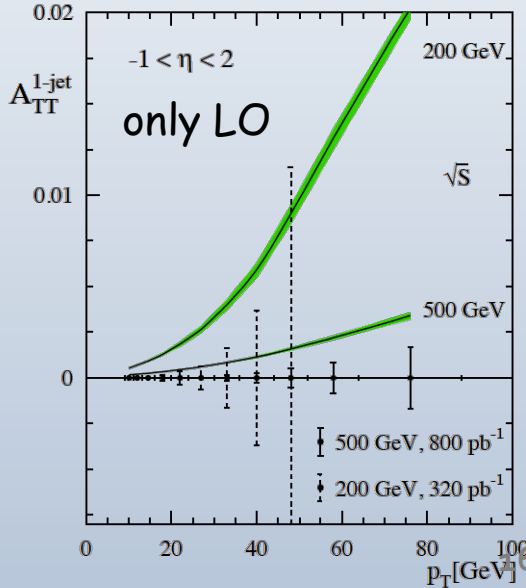
very important but challenging measurements

we should keep them on the radar

ectors / accept.

- doing it in polarized $p\bar{p}$ at GSI more and more remote





photon, hadrons, jets

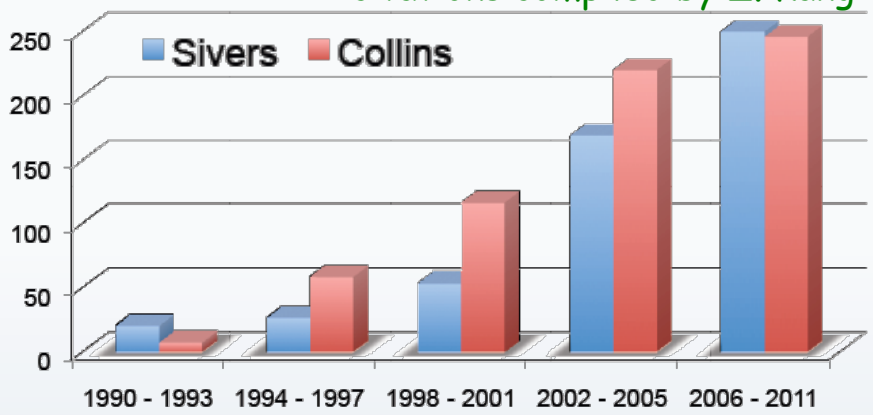
- "selection rule" $|A_{TT}| \ll |A_{LL}|$
  Artru, Mekhfi; Ji; Jaffe, Saito
- upper bounds estimated
  Soffer, MS Vogelsang; Mukherjee, MS, Vogelsang
- never studied: correlations/forward η

single spin asymmetries A_N

considerable activity & excitement

- large asymmetries in ep and pp
- theoretical explanation requires to go beyond collinear approximation or to introduce novel twist-3 parton correlations

citations compiled by Z. Kang

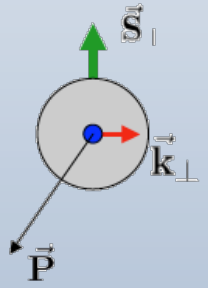


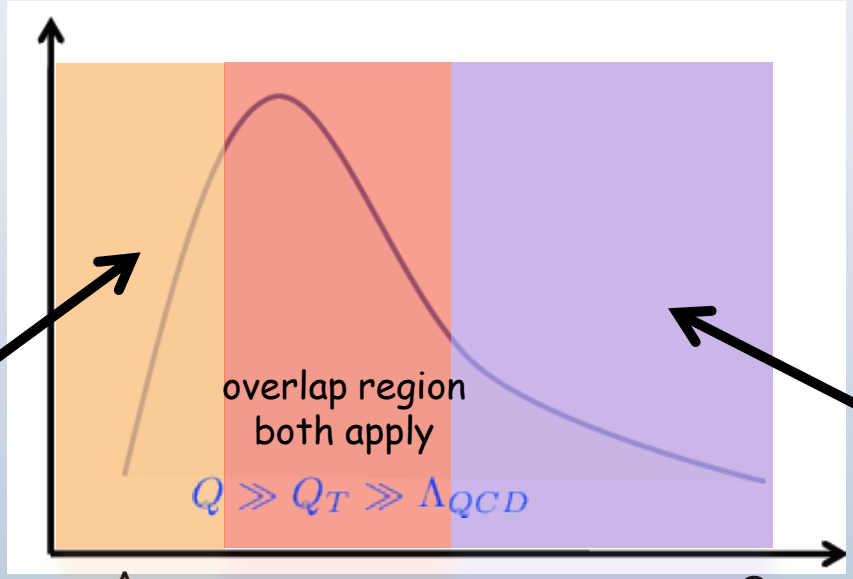
consider, e.g., Drell Yan pairs with q_T

$\Lambda_{QCD} \lesssim q_T \ll Q$

TMD "factorization"

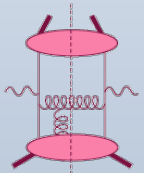
Sivers effect





$Q, Q_T \gg \Lambda_{QCD}$

collinear twist-3 approach



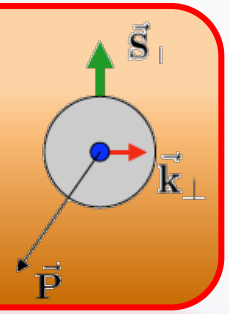
Efremov, Teryaev; Qiu, Sterman

Sivers function and A_N

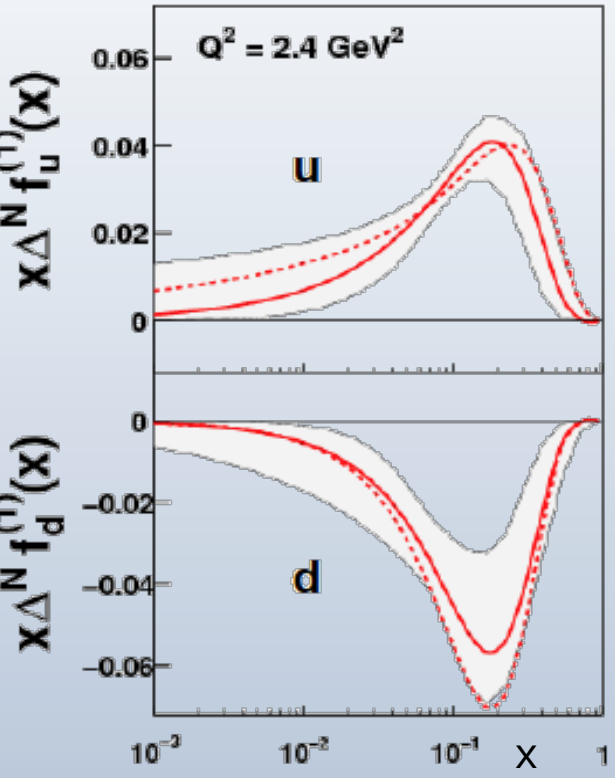
- Sivers fct. encodes physics for small p_T (<<Q) (or p_T differences)
- if p_T is large, it can be treated perturbatively (collinear twist-3 approach)
- no sharp boundary between "intrinsic" and "radiative" p_T --> **matching region**

"Sivers effect"

correlation of transverse spin of proton with k_T of unpolarized quark



Anselmino et al.



find: u and d quark have opposite signs; d larger

- **not a universal function:** non-trivial gauge links

TMD factorization known to work in SIDIS and Drell Yan only but *not* in general pp processes

Ji, Ma, Yuan; …

considerable theory efforts to understand this better

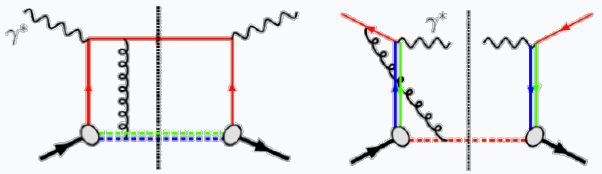
Collins; Belitsky, Ji, Yuan; Boer, Mulders, Pijlman; Mulders, Rogers; Aybat, Rogers; ….

suite of different A_N measurements from RHIC can contribute significantly

sign change & A_N for Drell Yan

- gauge-links have profound physics implication:

Sivers fct. changes sign from SIDIS to Drell Yan

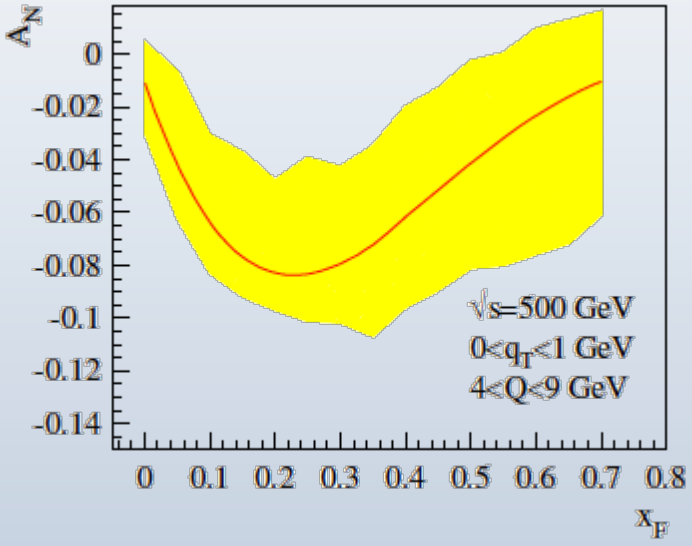


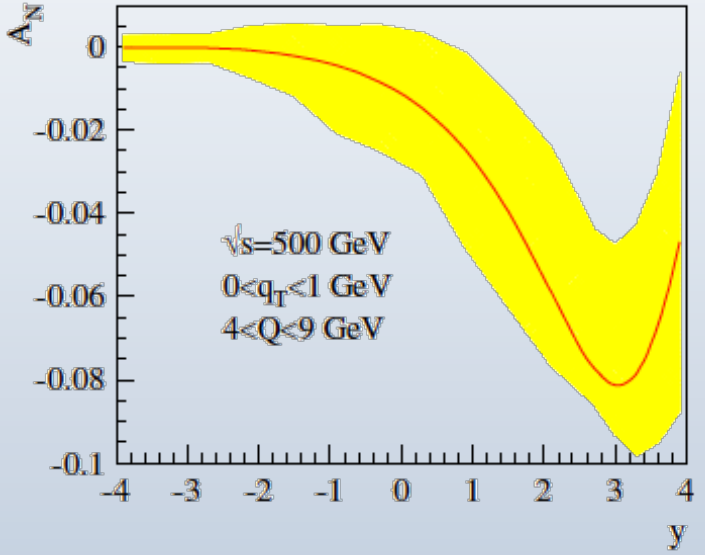
$$f_{1T}^{\perp}|_{DIS} = -f_{1T}^{\perp}|_{DY}$$

"attractive" "repulsive"

critical test for our understanding of TMD's and TMD factorization

expectations for DY Kang, Qiu





- experimental issues: 500 GeV favorable - higher lumi and control of background (HQ decays, etc)
- important first step (analyzing power): AnDY experiment in 2012/13

from sign changes to sign mismatches

- latest twist: "sign mismatch" Kang, Qiu, Vogelsang, Yuan

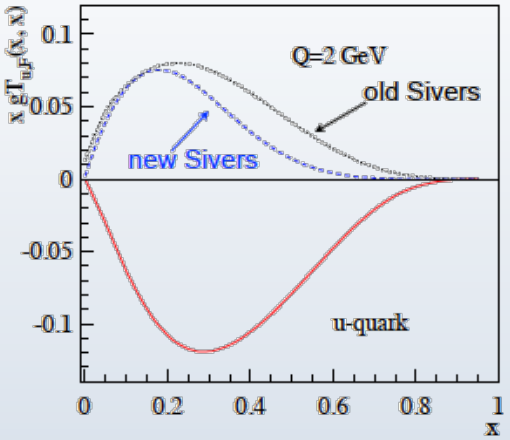
1st k_T moment of Sivers fct and twist-3 analogue related at operator level

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

Boer, Mulders, Pijlman; Ji, Qiu,, Vogelsang, Yuan

both sides have been extracted from data

find: similar magnitude ✓ but wrong sign ✖



inconsistency in formalism?

possible resolutions: (1) data constrain Sivers fct only at low k_T; function has a node

phenomenological studies with more flexible Sivers fct. under way Kang, Prokudin

(2) analysis of $T_{q,F}$ neglects possible final-state contributions to A_N

need data for A_N which are insensitive to fragmentation: photons, jets, DY

- on the bright side: recent progress on evolution for Sivers fct Kang, Xiao, Yuan

crucial for consistent phenomenology – properly related experiments at different scales

A_N in ^{3}He-proton collisions

Sivers fcts. for u and d quarks opposite in sign and slightly larger for d quarks

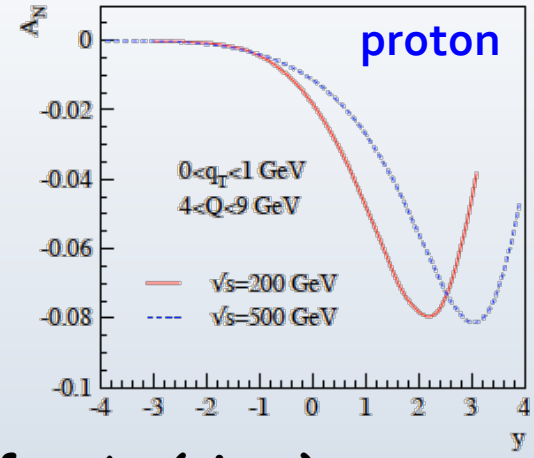
expectations for Drell Yan

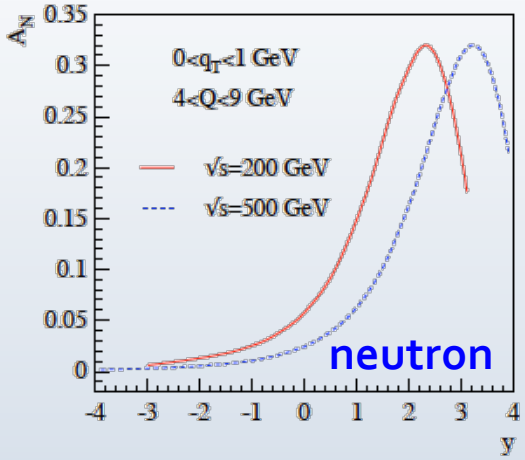
Z. Kang @ 2010 Iowa RSC meeting

- u <-> d isospin rotation leads to different signs for A_N for protons and neutrons
- asymmetries for neutrons are larger (due to electric charges)

caveat:
does not yet include possibility of nodes in Sivers function

^{3}He beam energies !

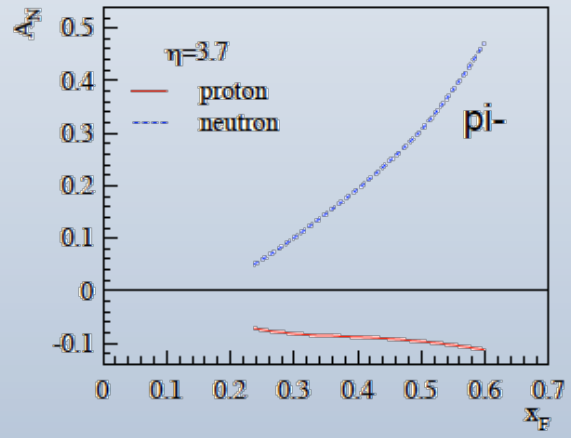




expectations for A_N (pions)

- similar effect for $\pi^{\pm}$ (π^0 unchanged)

this time computed within twist-3 formalism
here, effect due to favored/unfavored fragmentation



3He: helpful input for understanding of transverse spin phenomena

Proton/Deuteron-Heavy Ion Scattering

key physics objectives for p(d)+A in a nutshell

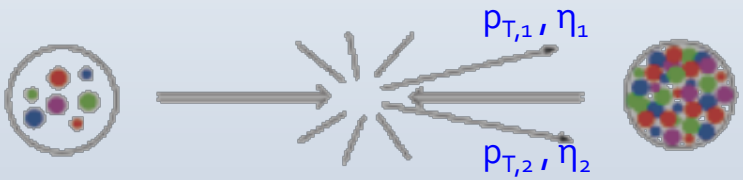
"usual" argument: p(d)+A needed to "calibrate" understanding of A+A results

detailed questions:

- what is the nature of the initial state in heavy ion collisions ?
- how important is saturation and what is the dependence of Q_s on A (and x) ?
- where do factorization and nuclear PDFs work ?

merits of p(d)+A collisions:

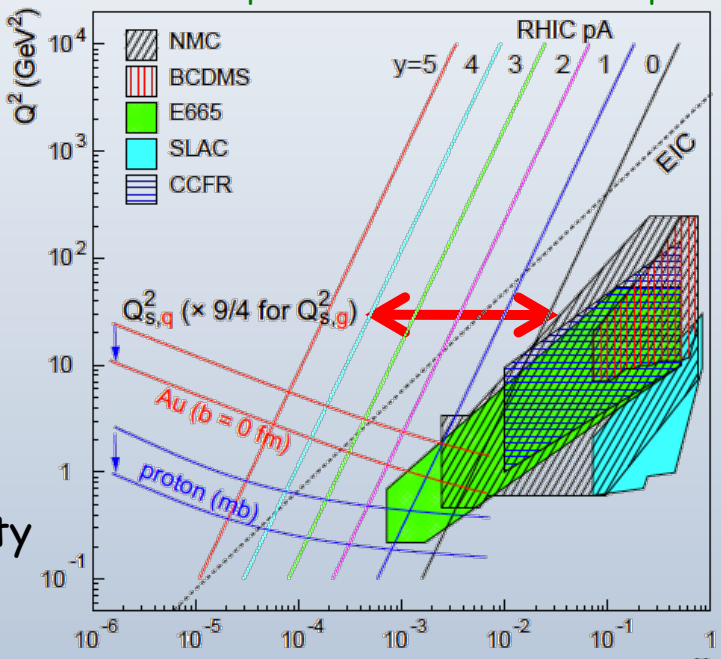
best probe: correlations at forward rapidity



$$x_A = \frac{p_{T,1}e^{\eta_1} + p_{T,2}e^{\eta_2}}{\sqrt{S}} \simeq 10^{-3}$$

- can go in/out of saturation region by changing rapidity
- can test dependence of Q_s on A ("oompf factor")

adapted from STAR's decadal plan

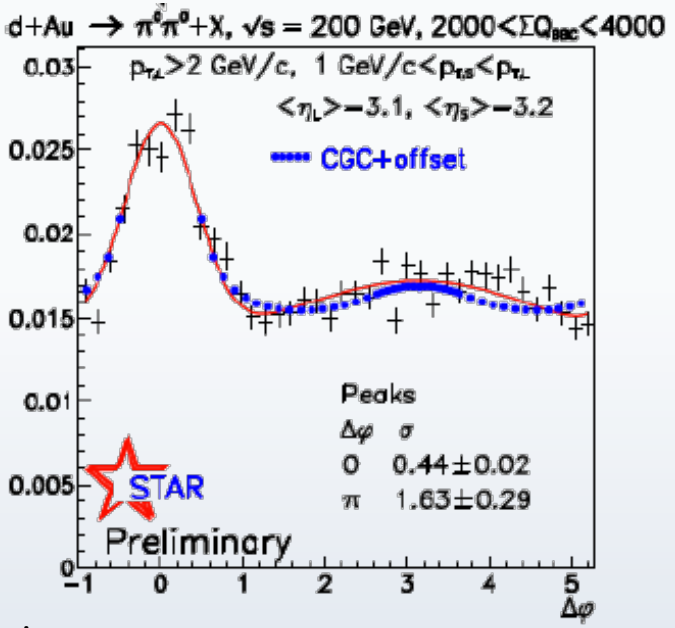


why pA and not dA?

strongest hint for saturation at RHIC:

- away-side peak for forward di-hadron correlations disappears/broadens in central dAu collisions

PHENIX, arXiv:1105.5112
STAR, prel.



- naturally explained within CGC: Albacete, Marquet; …

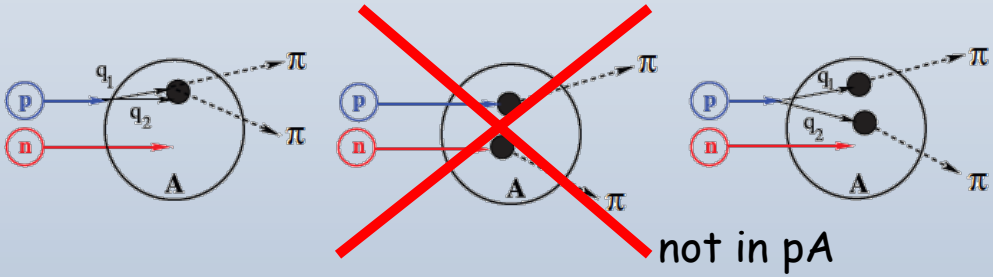
away-side randomized by strong color fields
multiple rescattering controlled by Q_s

however, jet correlations probe not only universal "dipoles"
but also "quadrupoles" -> need to do better Dumitru, Jalilian-Marian; Dominguez et al.

potential caveat for interpretation:

- contributions from multi-parton interactions can be important at forward rapidities

Strikman, Vogelsang



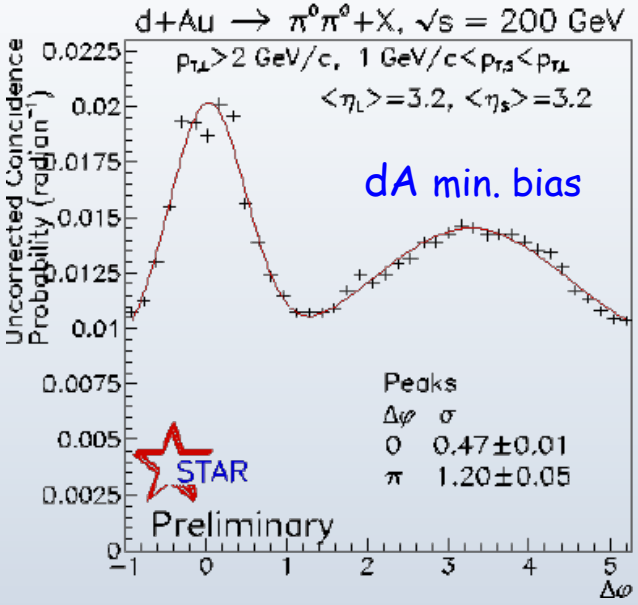
--> MPI affect the "pedestral level"

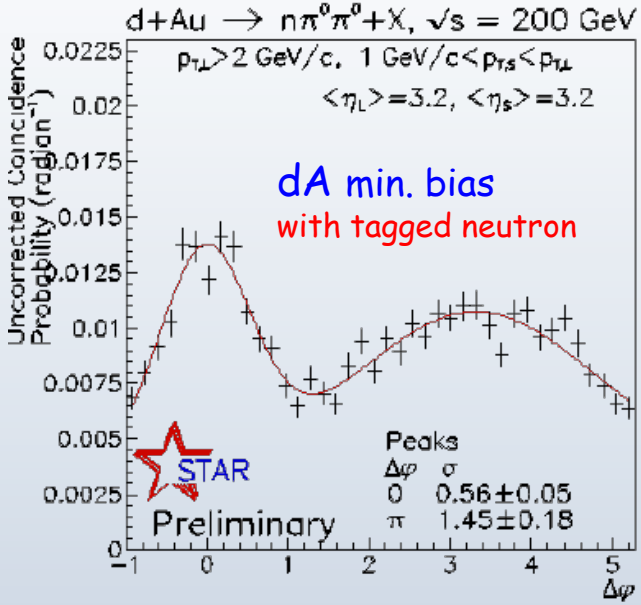
can be further scrutinized by comparing dA and pA

why pA and not dA? – cont'd

BUT do we really need pA collisions to clarify role of MPI?

STAR has obtained 1st "pA" results from tagged forward neutrons in dA collisions:





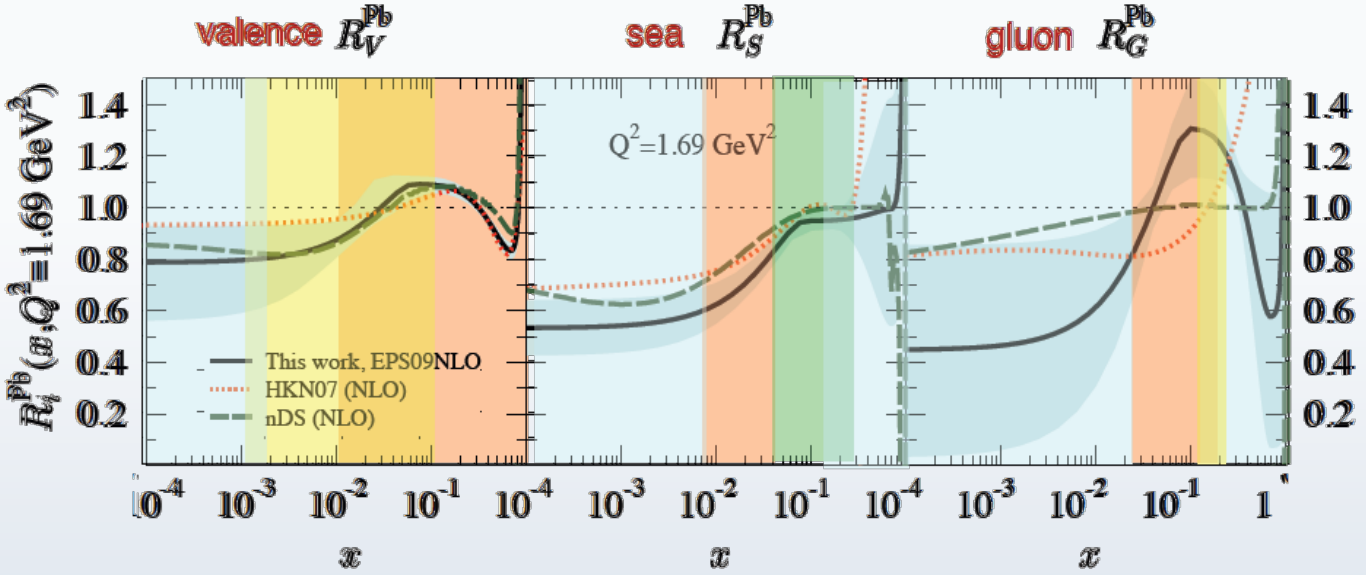
C. Perkins (DIS2011)

H. Caines (QM 2011)

can we turn tagged neutrons in dA into a surrogate for pA collisions ?

factorization and nuclear PDFs

current status of NLO fits: taken from Eskola, Paukkunen, Salgado



DIS data
DY data
sum rules
assumptions

assume:

factorization holds
all nuclear effects
absorbed into R_i^A

$$f_i^A(x) = R_i^A(x) f_i^p(x)$$

- we don't know much about gluons in nuclei (and very little about sea quarks)
- fits based on e-m probes (DIS & DY) – no final-state medium effects to worry about
  factorization dictates the use of standard partonic cross sections and DGLAP evolution of nPDFs

nPDFs happily applied to predict

- $R_{p(d)A}$ for QCD processes (hadrons, jets, HQs,J/Ψ, …)
- and even for R_{AA}

final-state/medium effects ?
factorization at all ?
centrality dependence ?

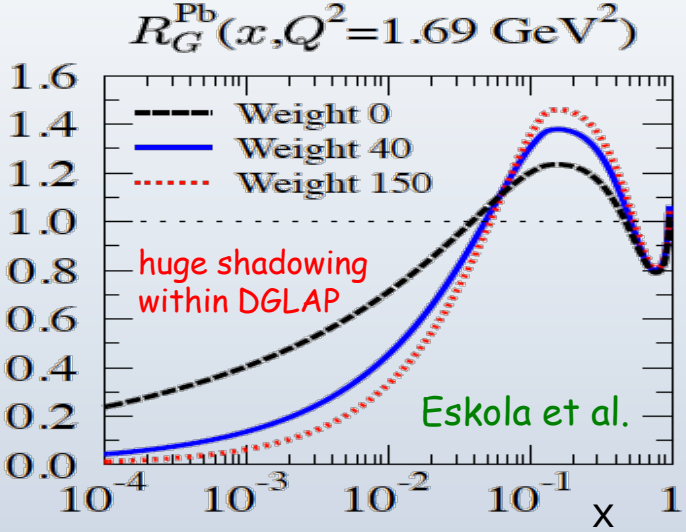
we need to *carefully* map out the range of applicability

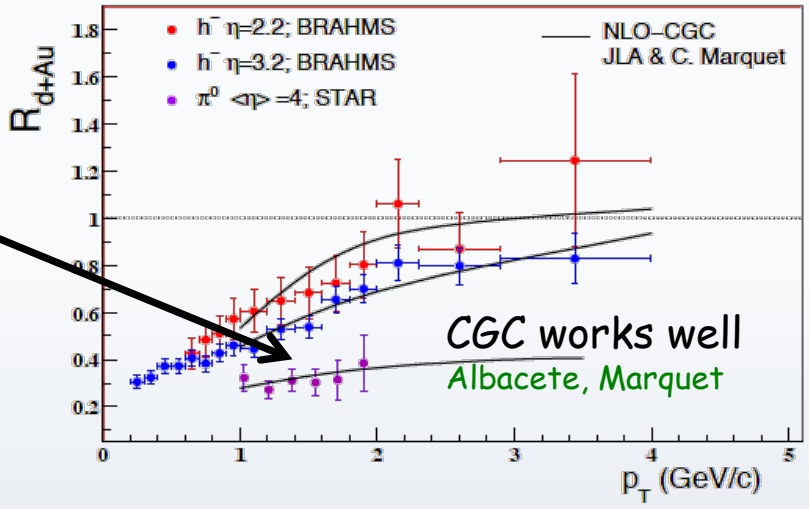
1st signs for trouble ?

single-hadrons in dAu at forward rapidity:

small R_{dAu} at forward rapidities
indicates strong suppression of gluons

need humongous shadowing of gluon PDF to describe data





required shadowing would be much (?) less if final-state/energy loss effects are relevant

pQCD does not work well at small p_T and large η (e.g. pp data at η=4 not used in any fits)

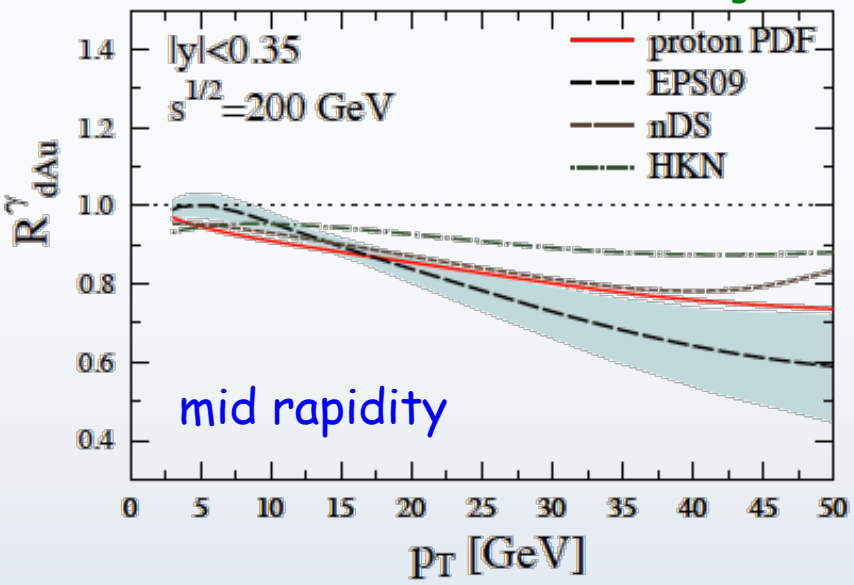
general issue for forward physics at RHIC

recall: *CGC* has Q_s as additional semi-hard scale

to unambiguously demonstrate breakdown of DGLAP based framework we should "keep" clean e-m probes (γ's & DY) high up on the agenda

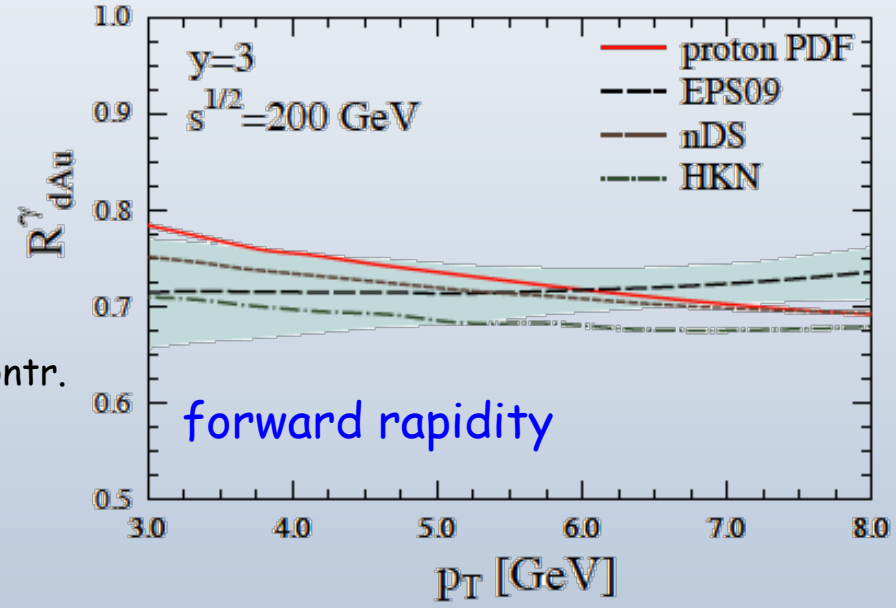
prompt photons in p(d) A

from Arleo, Eskola, Paukkunen, Salgado



- sensitivity to nPDFs at fairly large x
  anti-shadowing/EMC region
- need to isolate nuclear from "isospin" effects
  γ's couple to u-quarks and $u_p(x) > u_{Au}(x)$

impact on global fits of nPDFs



- probes gluon in saturation regime ($x \approx 10^{-3}$)
- here "isospin" effect from deuteron !
  vanishes for pA collisions at forward rapidities
- complications: photon isolation/fragmentation contr.
- also: forward photon-jet correlations
  free of complication of 4-pt fcts in CGC formalism

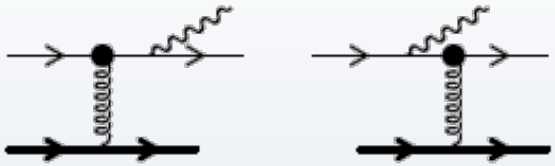
Jalilian-Marian; Gelis, Jalilian-Marian

Drell-Yan in p(d) A

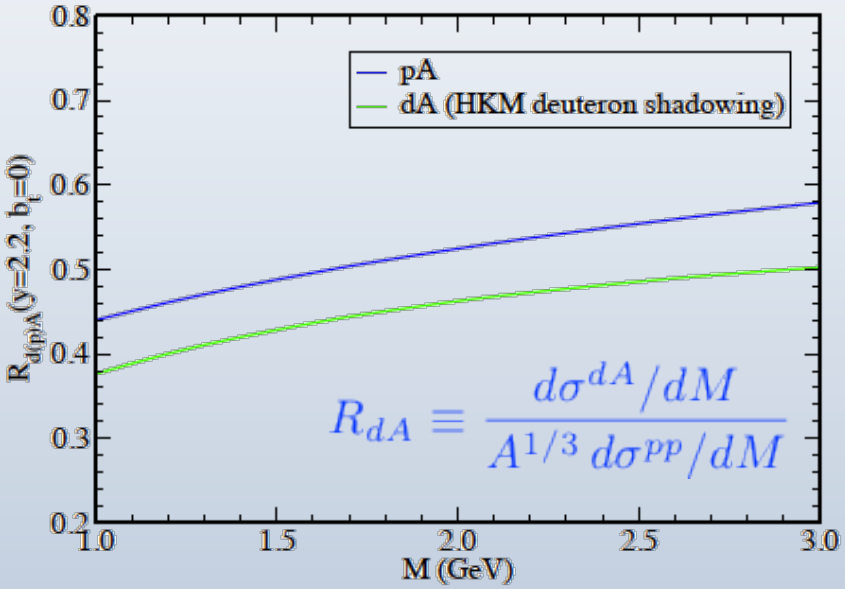
unfortunately, only very limited number of expectations available …

in CGC framework: no equivalent to "LO" qq annihilation, starts with "bremsstrahlung"

Jalilian-Marian;
Gelis, Jalilian-Marian



- should work for forward lepton pairs with M ≈ Q_s, large x quarks in p(d), and small x gluons in the nucleus
- only dipoles contribute ✓



in TMD framework: Yuan (DY workshop); Marquet, Xiao, Yuan

for low p_T pairs can apply TMD factorization

- calculate *universal* $q(x,k_T)$ based on dipole model
- find (small x):

$$xq(x,k_T)|_{k_T\to 0} \propto N_c/4/\pi^4$$
$$xq(x,k_T)|_{k_T\gg Q_s^2} \propto Q_s^2/k_T^2$$

TMD's at small x contain info on Q_S

(reproduces McLerran, Venugopalan result from 1998)

exp. requirement (background) M > 4 GeV
can we really reach into saturation regime with DY ?

a case for polarized pA ?

polarized protons are a unique capability of RHIC – we should exploit it as much as possible

not many studies yet: need to look into single spin asymmetries A_N

A_N at forward rapidities can be a unique link between spin and saturation physics

find scaling relation between A_N in pp and pA: Kang, Yuan, arXiv:1106.1375

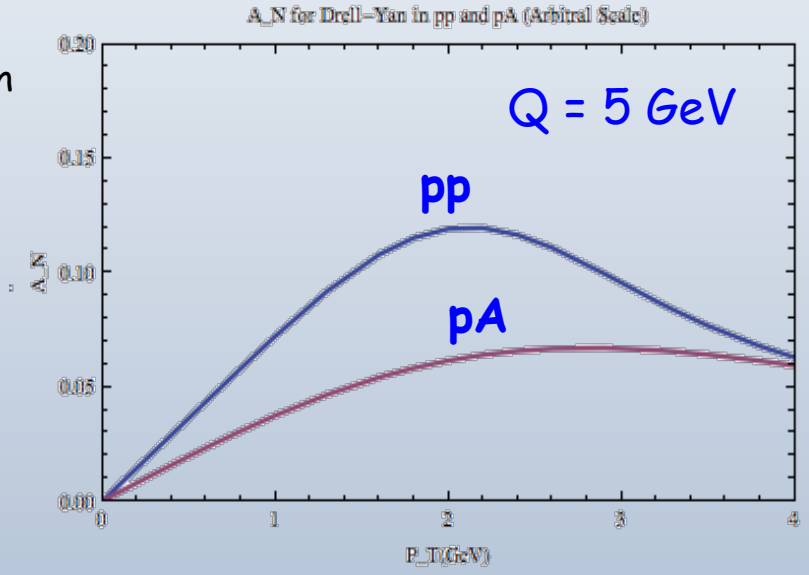
$$\left.\frac{A_N^{pA\to hX}}{A_N^{pp\to hX}}\right|_{P_{h,T}^2\ll Q_s^2} \approx \frac{Q_{s,p}^2}{Q_{s,A}^2} e^{P_{h,T}^2\delta^2/Q_{s,p}^4}$$

$P_{h,T}$ -> 0 limit of A_N depends on Q_S

$$\left.\frac{A_N^{pA\to hX}}{A_N^{pp\to hX}}\right|_{P_{h,T}^2\gg Q_s^2} \approx 1$$

Q_S drops out for large $P_{h,T}$

prel. num. study for Drell-Yan
F. Yuan @ BNL DY workshop



do we learn something beyond what can be done in unpolarized pA ?

AA and pA program @ LHC

CERN-PH-TH/2011-119
LHC-Project-Report-1181

Proton-Nucleus Collisions at the LHC:
Scientific Opportunities and Requirements

physics agenda has it all

1st run might already happen in 2012

can a RHIC p(d)A program in 2015+ still be relevant?

what they don't have:

- so far only Pb ions – no A dependence
- perhaps RHIC energy range/variability more interesting
- no polarization for protons

Other Opportunities

(no time to discuss in detail)

QCD resummations

if there happens to be a pp program at lower energies (reference for energy scan)

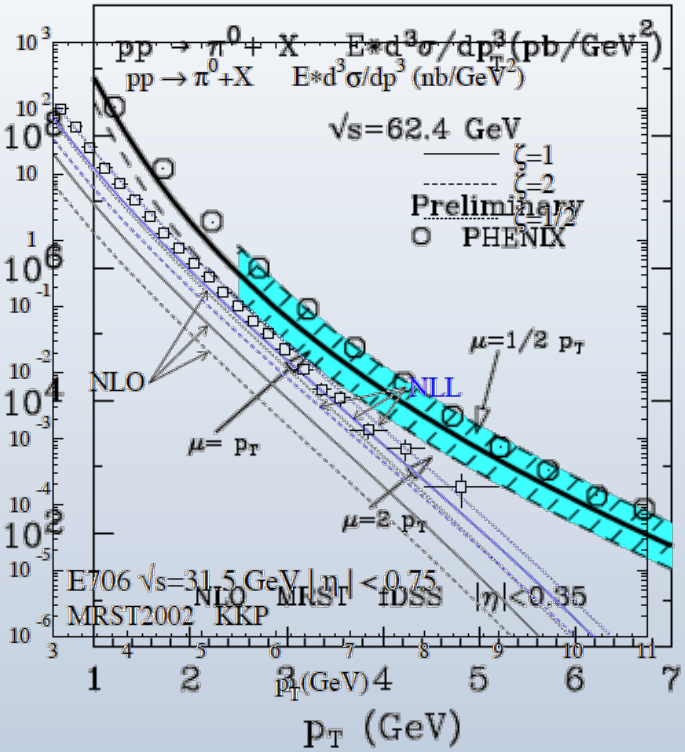
- opportunity to study relevance of QCD threshold resummations

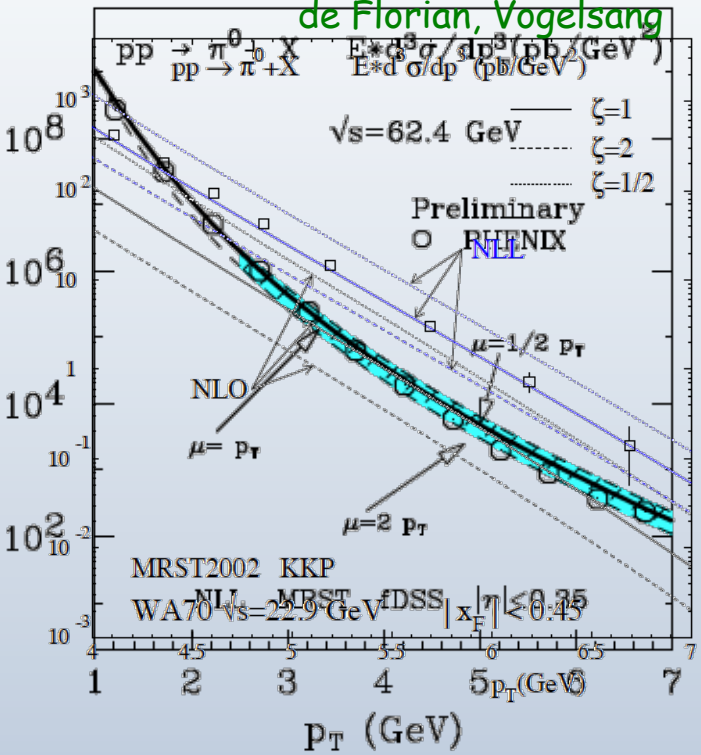
NLL resummations lead to a better decription of PHENIX π^0 data at 62.4 GeV

how far down in energy does it work ?

de Florian, Vogelsang, Wagner

de Florian, Vogelsang





Summary / Conclusions

no conclusions yet – talk meant to be an input for discussions

two finals thoughts, though …

on spin

most measurements require a substantial amount (> 2yrs) of running

correlations with photons, A_L with ^3He , A_N for Drell Yan, A_{TT}, …

unlikely that we can do all: either set priorities (e.g. Drell Yan)
or (?) let one experiment do longitudinal and the other transverse spin

also, certain things like Δg at small x clearly require an EIC

on p(d)+A

possible p+Pb running at the LHC will likely determine future directions