PHENIX Spin Program Goals and Upgrades beyond 2015, Including Possible Migration toward eRHIC Capabilities

The 2011 RHIC/AGS Users' Meeting

The RHIC/eRHIC Long Range Plan

Brookhaven National Laboratory

Thanks much for input from my colleagues in PHENIX, in particular
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June 22, 2011

Content

- **Motivation for sPHENIX in p-p, e-p and e-A**

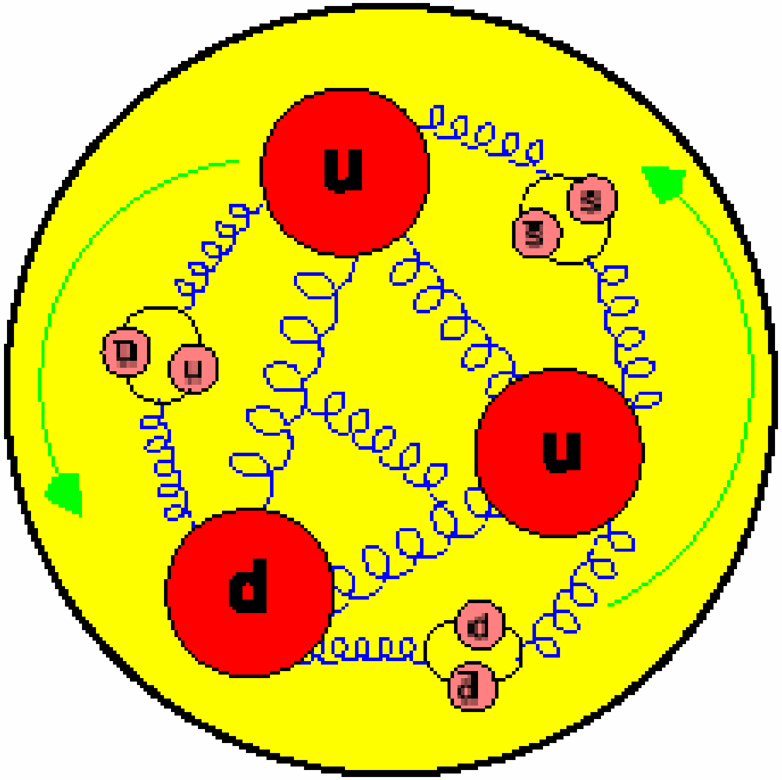
  Precision measurements of the quark and gluon structure of the proton and neutron to quantitatively characterize the fundamental bound state, the nucleon, of the strong interaction and to make connections with related quantum field theory, QCD, ab initio.

- **sPHENIX - Instrumentation**
- **Nucleon Structure: Physics goals for sPHENIX with p-p, e-p and e-A**

  → **helicity structure**
  → **transverse spin structure**
  → **A-dependence of nucleon structure**

The Nucleon as QCD Laboratory

The nucleon is the fundamental bound state of QCD - quarks and gluons are the constituents:



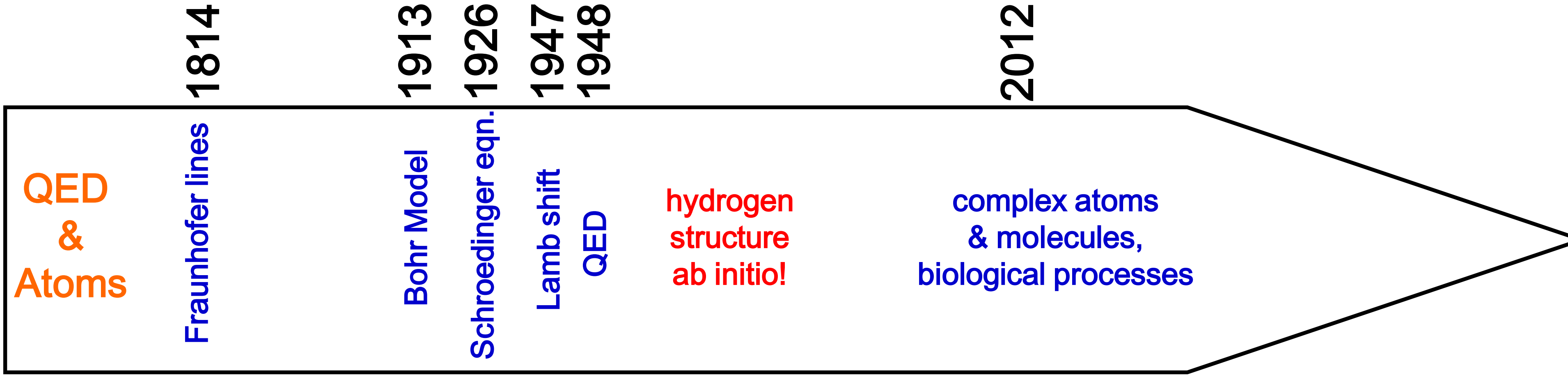
Will it be possible to describe the wave function of the nucleon from first principles QCD ?

Present modest (!) status:

Description of proton in hard scattering processes with parton distribution functions (often model dependent!).

Example EM Force: from Hydrogen Structure to QED to Applications

QED vs QCD



Observation & Models

Precision measurements & contact with fundamental theory

Applications

What Do We Learn at RHIC and EIC
PDFs, TMDs, GPDs …

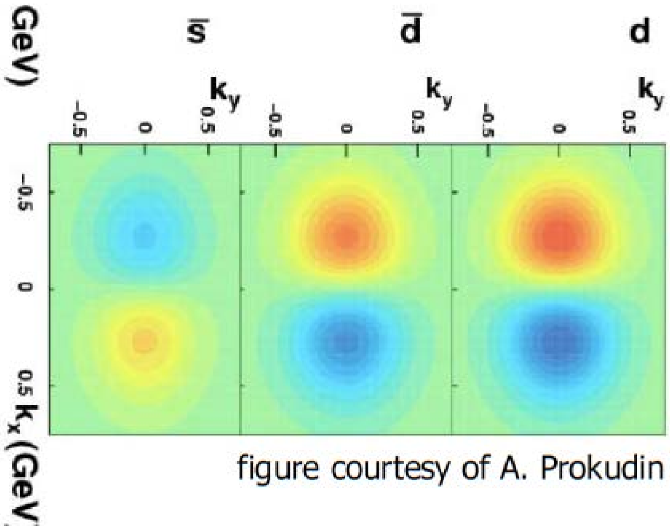
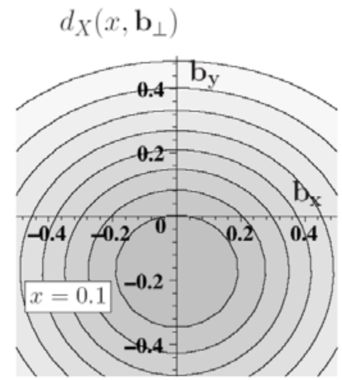


figure courtesy of A. Prokudin



Transverse Momentum Dependent PDF $f(x,k_t)$

3D picture in momentum space
transverse momentum dependent distributions (TMDs)

d^2k_t

PDF $f(x)$

Generalized Parton Distr. $H(x,\xi,t)$

3D picture in coordinate space
generalized parton distribution
→ exclusive reaction eg. DVCS

dx

Form Factors $F_1(Q),F_2(Q)$

From the Qualitative to the Quantitative

Examples:

First measurement of qualitatively new phenomena:

F_2 → established parton structure of the nucleon (SLAC)
g_1 → proton spin crisis (EMC)

Precise measurements and quantitative comparison between experimental observables and ab initio QCD:

F_2 → precise test of Q^2 evolution in QCD at HERA
g_1 → quantify quark spin contribution,
measurement of the Bjorken sum rule
and comparison to OPE/pQCD prediction (SLAC, SMC, Hermes)

Progress continues well after new phenomena are established qualitatively. Increasing precision leads to quantitative understanding and to ab initio tests of the underlying theory.

sPHENIX: Goals in p-p, e-p & e-A

p-p:
- o determine functional form and sign of $\Delta G(x)$ through A_{LL} in γ, γ-jet and jet-jet., $A_{LL}(c,b)$.
- o measure quark and anti-quark helicity distributions in the neutron, A_L in W-production in p-^{3}He collisions.
- o confirm & quantify mechanism for transverse spin asymmetries in hard scattering: A_N(Drell-Yan, γ, jet, γ-jet).
- o determine tensor charge and compare to L-QCD: forward IFF.

e-p:
- o measure $\Delta G(x)$ at small x.
- o test Bjorken sum rule (precision measurement of g_1^p and g_1^n)
- o k_T dependence of TMDs , determine k_T moments and compare to L-QCD.
- o study GPDs in exclusive meson production.

e-A:
- o measure $G_A(x)$ - F_2 Q^2 evolution, F_L, $F_{2,charm}$ - search for for onset of saturation, characterization in “clean” e-A.

Experimental Requirements for p-p and e-p

Beam:

High luminosity proton and ^{3}He beams: 500 – 1500 fb^{-1} on tape
(sofar 60 pb^{-1} longitudinal,10pb^{-1} transverse)

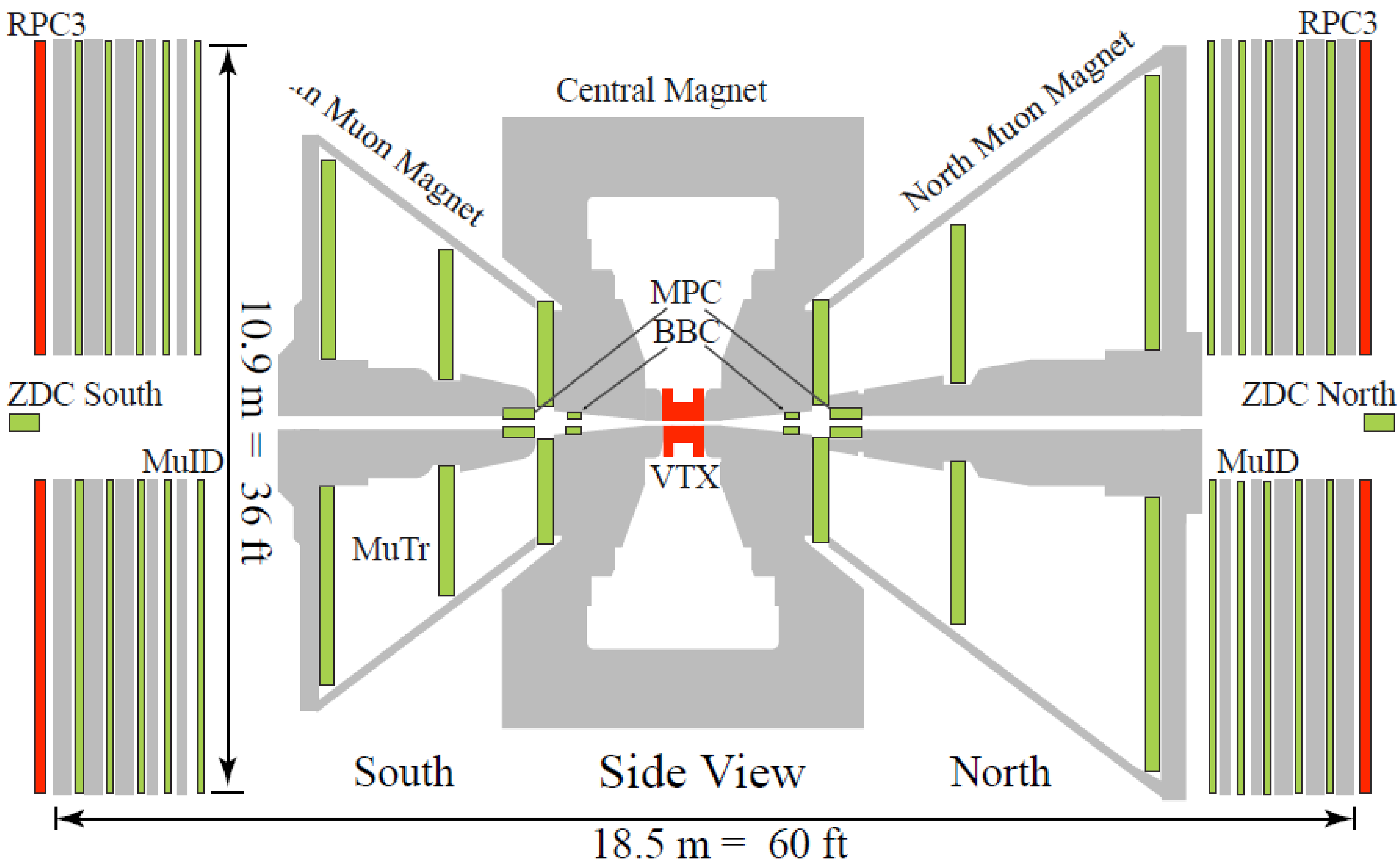
o competing channels require very high luminosity

➔ viability of program depends critically RHIC performance

PHENIX: (and PHENIX upgrades & performance)

photon & electron detection	A_{LL}(γ, γ-jet), A_L(W), A_N(DY, γ, γ-jet)
heavy flavor detection/veto	A_N(DY) , $F_{2,charm}$,A_{LL}(c,b)
jet capability	A_{LL}(jet, jet-γ), A_N(γ, γ-jet)
forward tracking & PID	Tensor charge via IFF
high rate DAQ/rare process triggering	All

Challenge: Upgrade PHENIX and Extend Operational Life Beyond 2015



PHENIX Staging & Upgrade History

Year	Status	Detector	Purpose
2000		Central Arms	Initial installation
2002		South Muon Arm	
2003		North Muon Arm	
2004	Complete	Aerogel	PID, hadron spectra
2005	Complete	TOF-West	PID, hadron spectra
2006	Complete	RXP	Reaction Plane
	Complete	MPC	d-A, A_N, A_{LL} di-hadron
2008	Complete	HBD	PID, low mass di-leptons
2011	Complete	VTX	c-, b-tagging, central tracking
11/12	Active	μ-Trigger	W-physics
2011+	Active	DAQ	Track data volume + luminosity
2012	Active	FVTX	c-, b-tagging

+ Successful experience with staging installation, upgrades and *attracting and leaning on significant resources from outside DOE.*

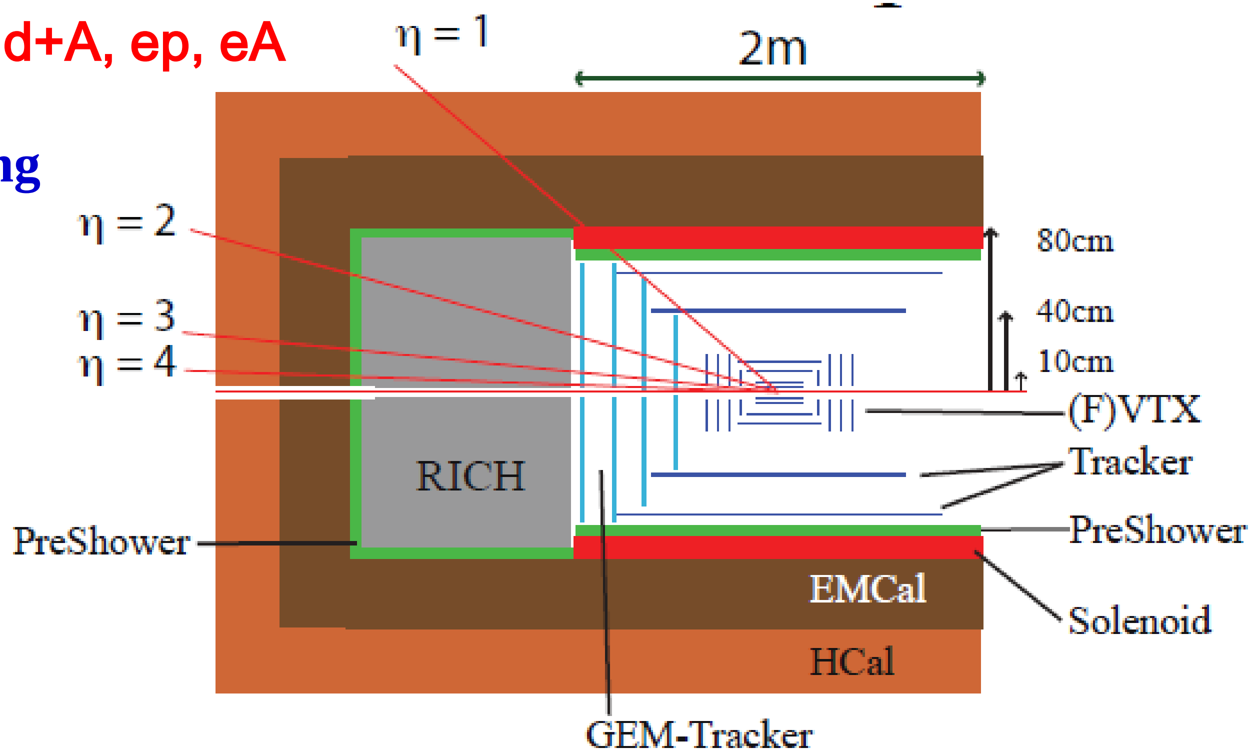
- Need to deal with some aging instrumentation after 15 years of operations

Upgrade of PHENIX Beyond 2015: Strawman ➔ Details TBD

Focus: p+p, d+A, ep, eA

Re-use equipment avoiding end of life issues:

VTX and FVTX
EMC (partially)
DAQ
Infrastructure



Focus on A+A

- **Build incrementally, use process to recruit outside interest & resources**
- **Jets, electrons and photons at mid-rapidity**
- **Gluon saturation physics and spin physics in forward region**
- **First eRHIC detector**

Helicity Structure ➔ Goals

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_Z + \Delta G$$

e/p-p (I) Determine shape and sign of ΔG(x)

p-/^{3}He **(II)** **Measure $\bar{q}(x)$ and q(x) for ^{3}He: best flavor separation!**

e/p-p (III) Improved measurements of ΔΣ and ΔG and therefore total L_z

present ΔΣ = 0.35 ∓ 0.06

➔ ∓ 0.02 (?) (need to quantify goal)

e-p present ΔG = 0.01 ∓ 0.1 + large extrapolation uncertainty

➔ ∓ 0.02 (?) (need to quantify goal)

QCD tests!

(IV) Bjorken sumrule to 2% (need to quantify goal, 5x better than present)

(V) g_1 evolution to 2% (need to quantify goal)

(VI) exclusive production of ρ, J/Psi, explore ability to access L_z

Helicity Structure → Measurements

p-p :	A_{LL}(γ, γ+jet,jet-jet, c,b)
	A_L(W) in p-^{3}He
e-p inclusive:	g_1 (including evolution) for proton and ^{3}He beams
e-p semi inclusive:	A_{LL} for identified charged pions and kaons for proton and ^{3}He beams (limited hadron acceptance)
e-p exclusive :	A_L for pions from exclusive meson/DVCS production for proton and ^{3}He beams (limited hadron acceptance)

Helicity Structure → Needs & Input

→large acceptance detector with hadron pID capabilities, heavy flavor tagging, jet reconstruction, excellent momentum resolution, precision relative luminosity monitors and local polarimeters, Roman pots for n-tagging and for exclusive measurements

Absolute polarimeter:

Local polarimeters:

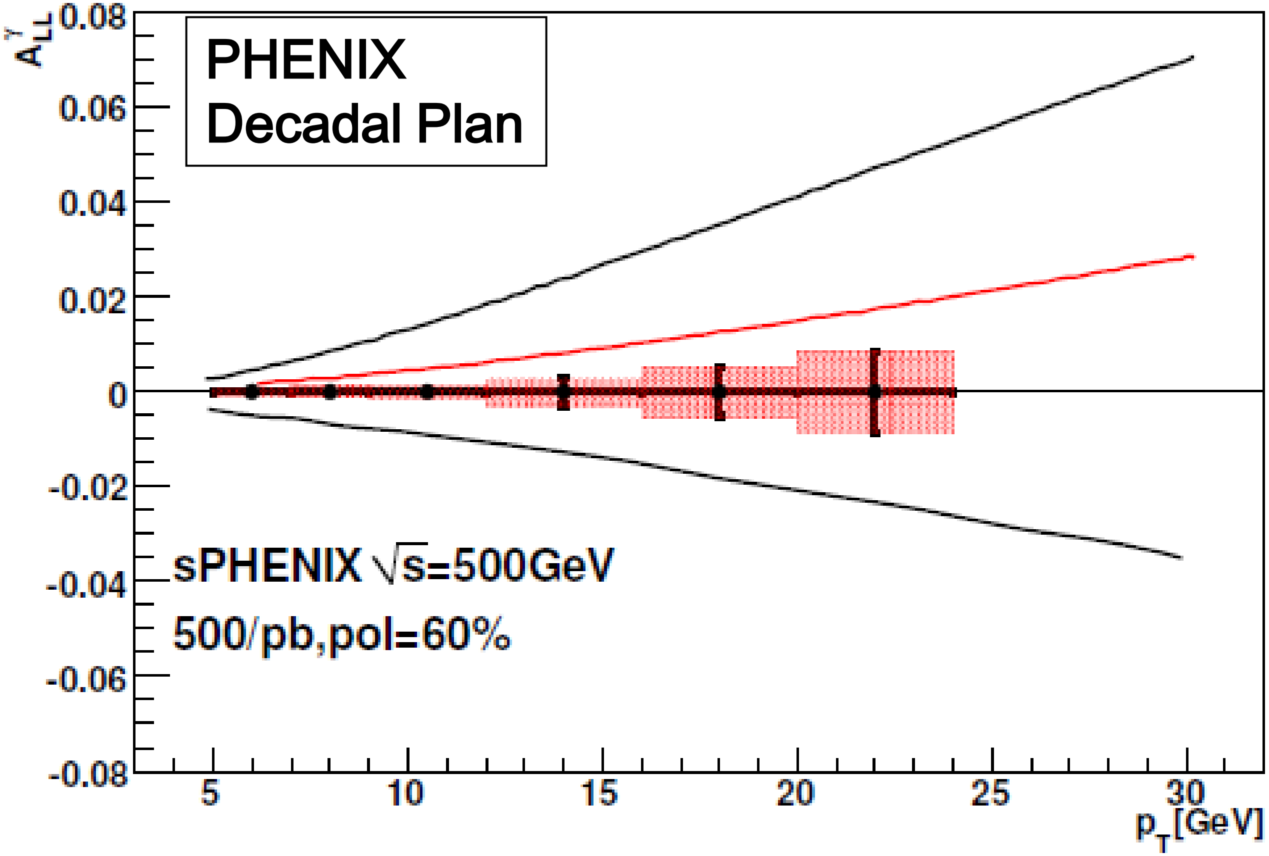
Extrapolation uncertainties:

pQCD framework for PDF extraction: test with cross section
→ normalization (luminosity)

Fragmentation functions:

Control of radiative corrections: all required specs are TBD

A_{LL}^{γ} ,$\sqrt{s}$=500 GeV p-p, $\int L dt$ = 500 pb^{-1}

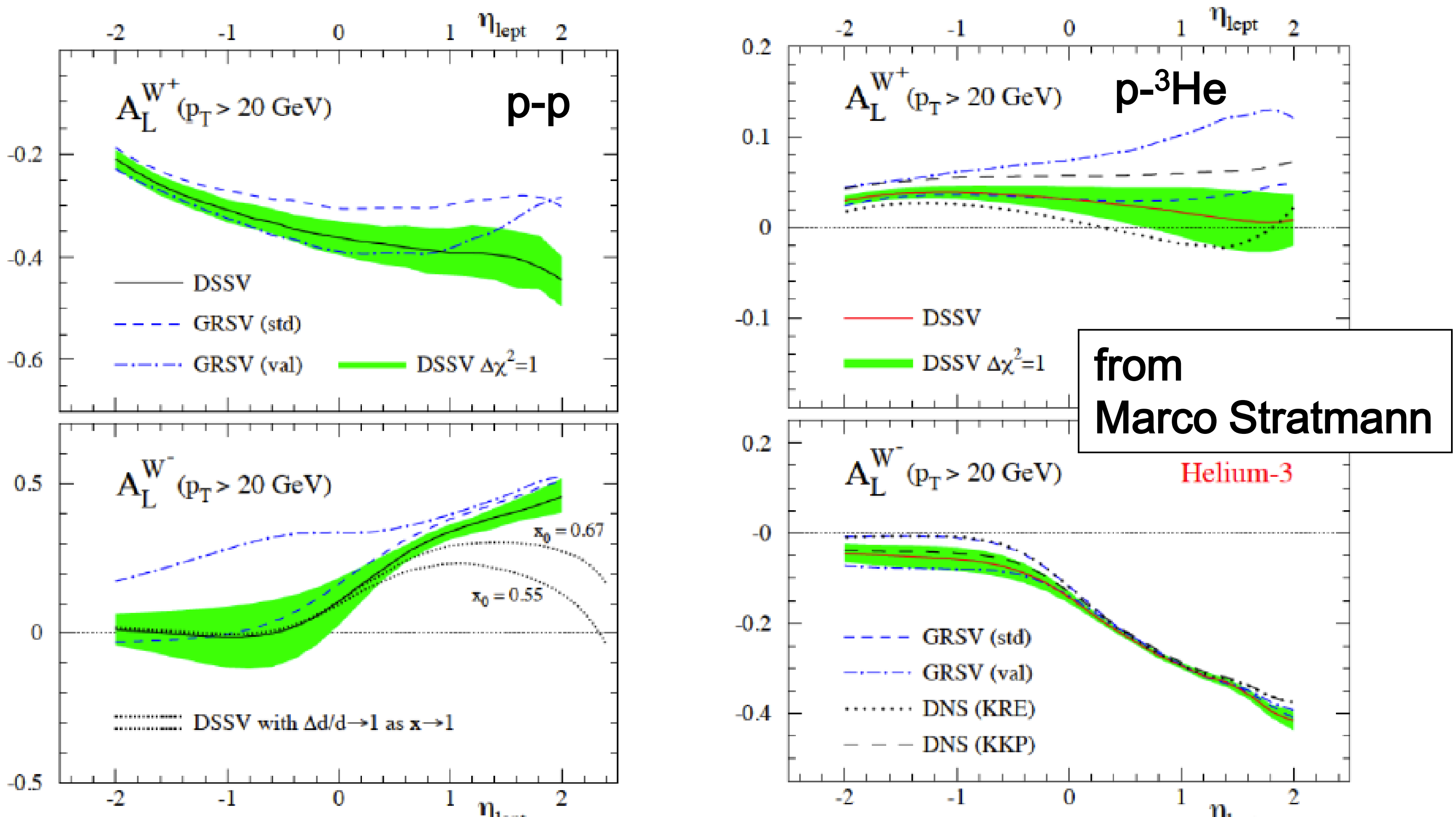


also for γ-jet,
jet-jet heavy flavor

➔QCD analysis to determine ΔG(x)

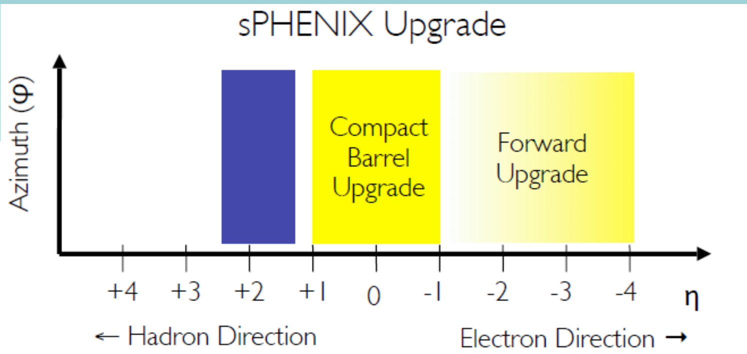
$A_L^{W\to e\nu}$, $\sqrt{s}$=500 GeV p-p and p-^{3}He, $\sqrt{s}$=430 GeV

Not clear what $\sqrt{s}$ we can reach + Roman pots for n-tagging

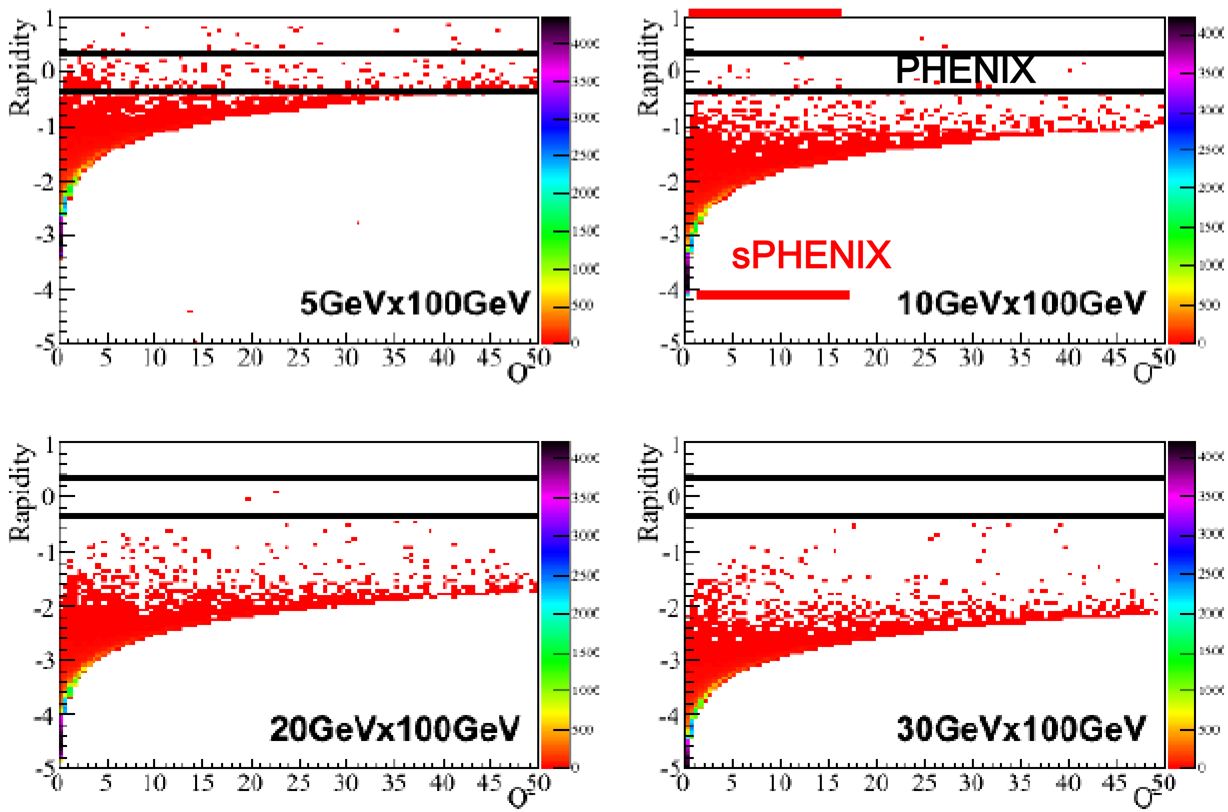


A_L enter QCD analysis. Best sensitivity for u(x), $\overline{u}$(x), d(x) and $\overline{d}$(x)

sPHENIX e-p Acceptance for Inclusive Electron

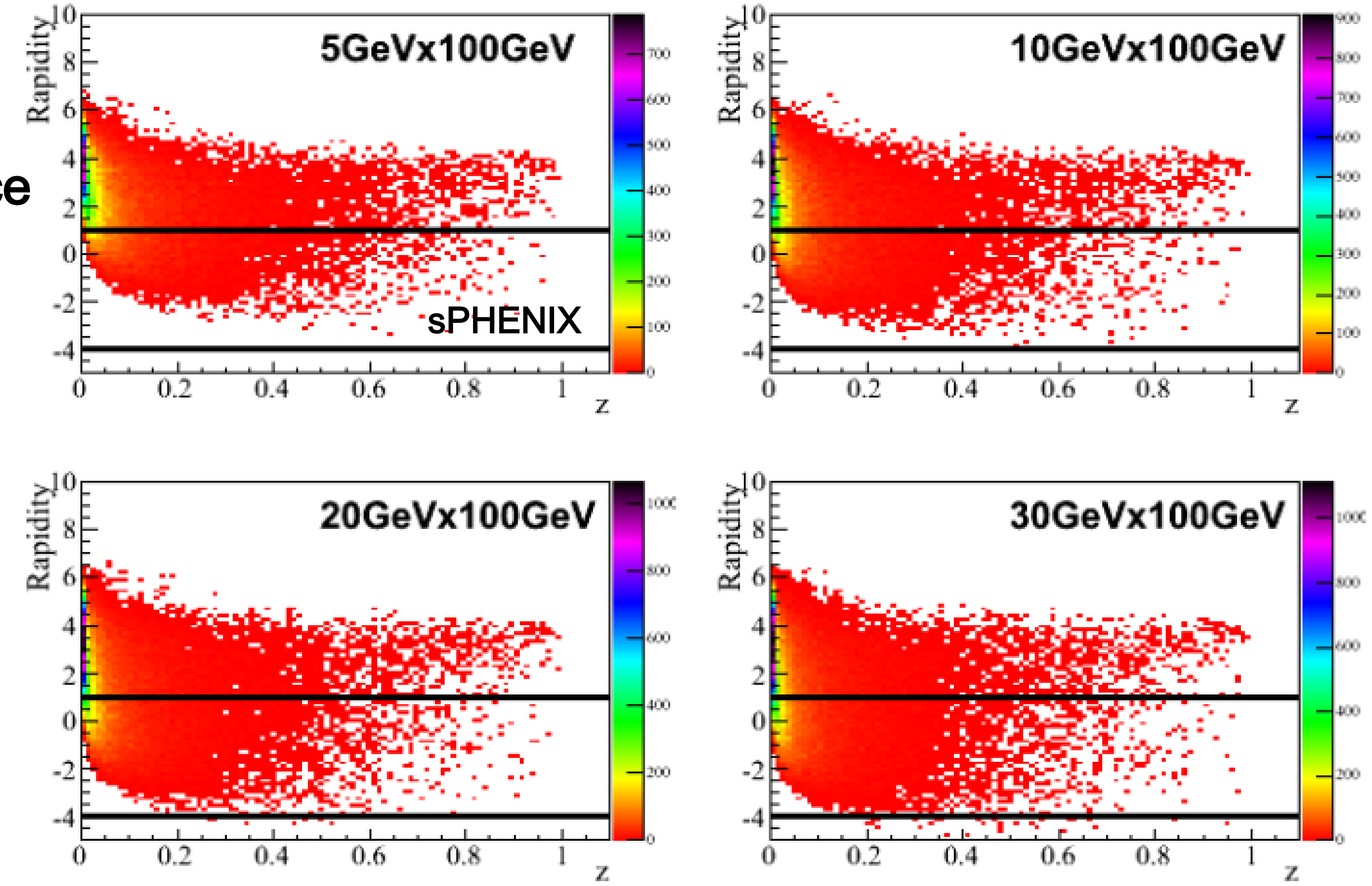


sPHENIX acceptance close to HERA like detector at low x and low Q^2 [➔ $\Delta G(x)$, $G_A(x)$ & saturation physics]



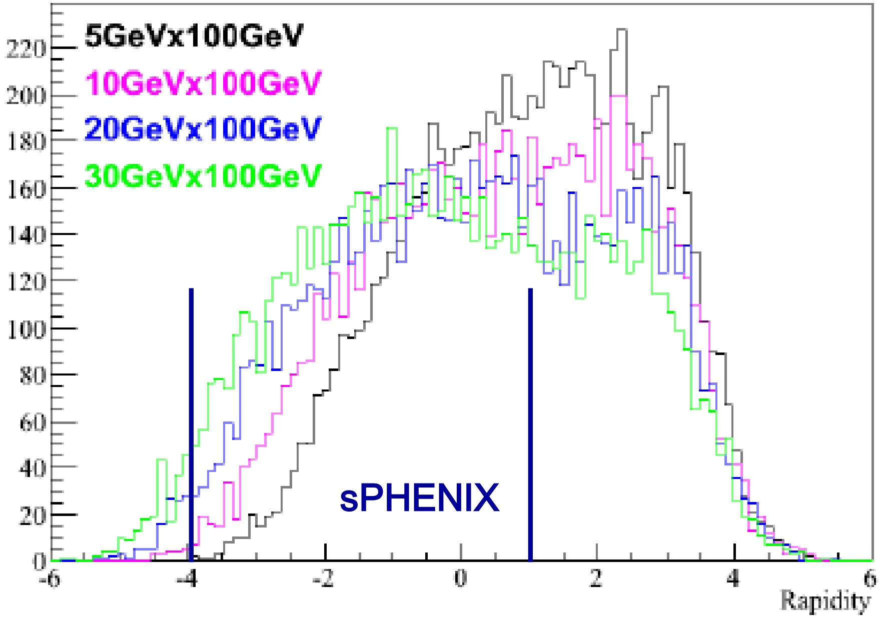
sPHENIX Acceptance for Hadrons in SIDIS

sPHENIX has limited acceptance for hadrons in SIDIS [➔ Δq(x), TMDs]



$z=2E_h/\sqrt{s}$

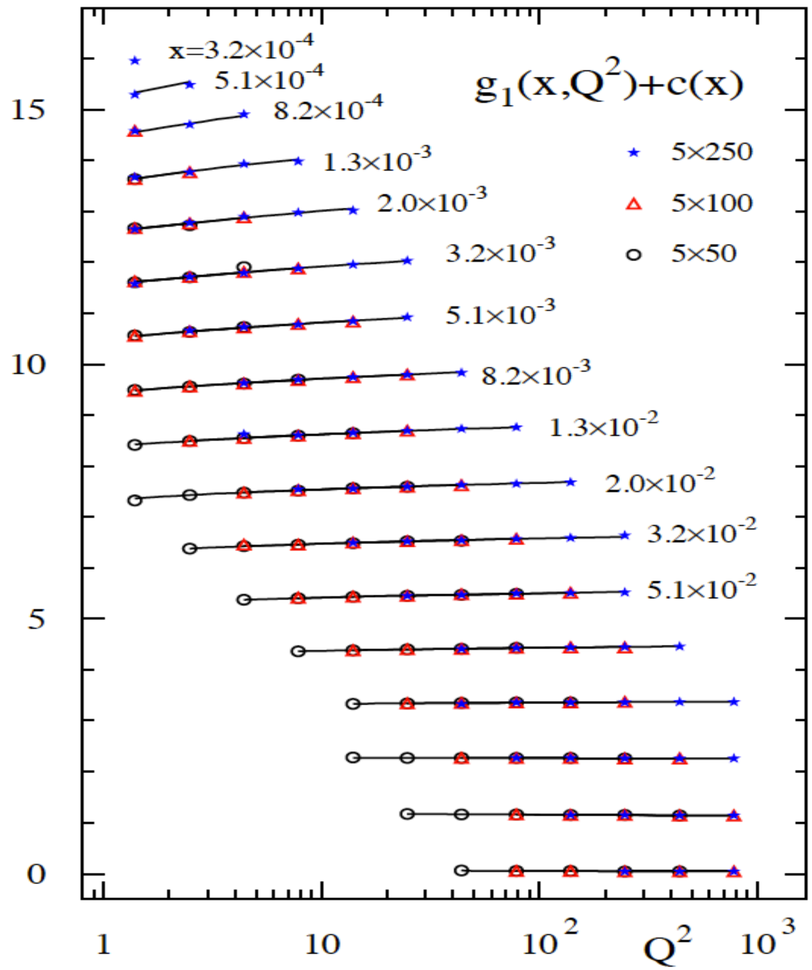
sPHENIX e-p Acceptance for Exclusive ρ^0



sPHENIX has
limited acceptance
for pions from the decay
of exclusive mesons [➔ GPDs]

Helicity Structure → g_1 at EIC

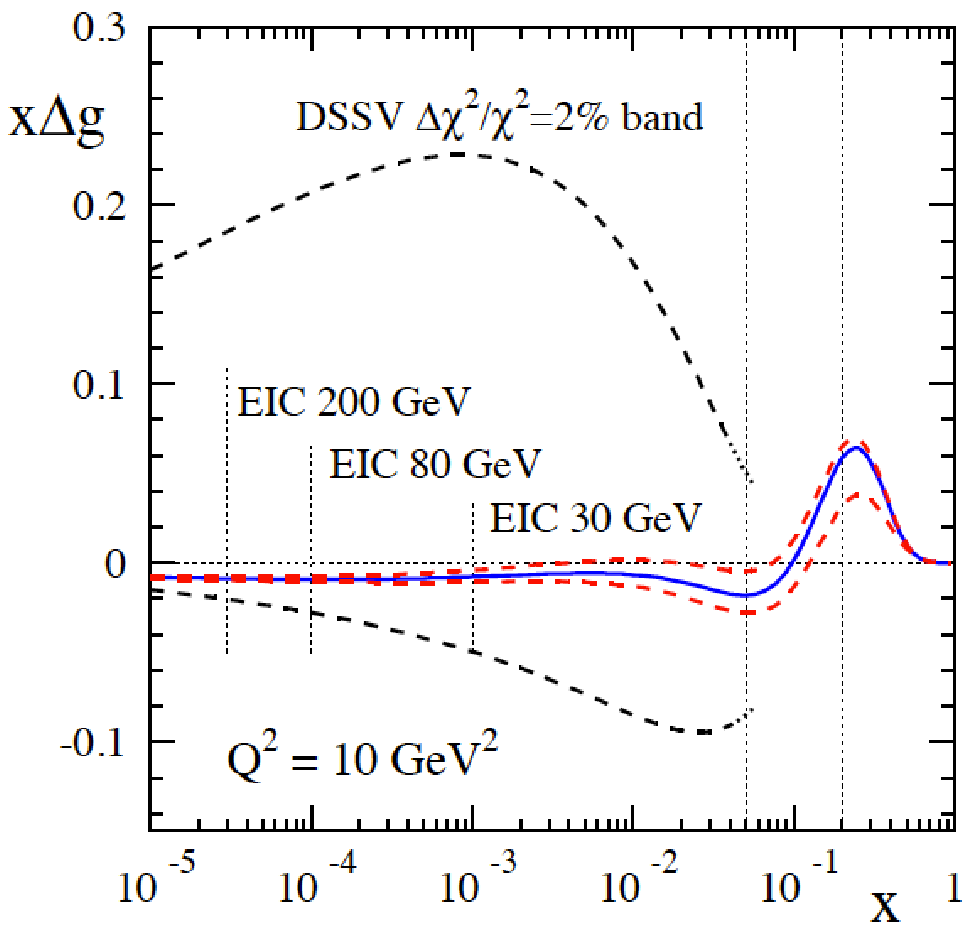
Awaits studies for sPHENIX, shown are results for a HERA like detector. sPHENIX has similar acceptance for small x & Q^2.



[Aschenauer, Stratmann]

e-p Sensitivities for ΔG(x)

(Stratmann, Sassot)



Can evaluate ΔG(x) to x ~ 0.0001

Evaluate $\int \Delta G(x)\,dx$ to ~ 10%

➔ $L_z = ½ - \Delta G – 1/2\Delta\Sigma$

can be evaluated to ~10%

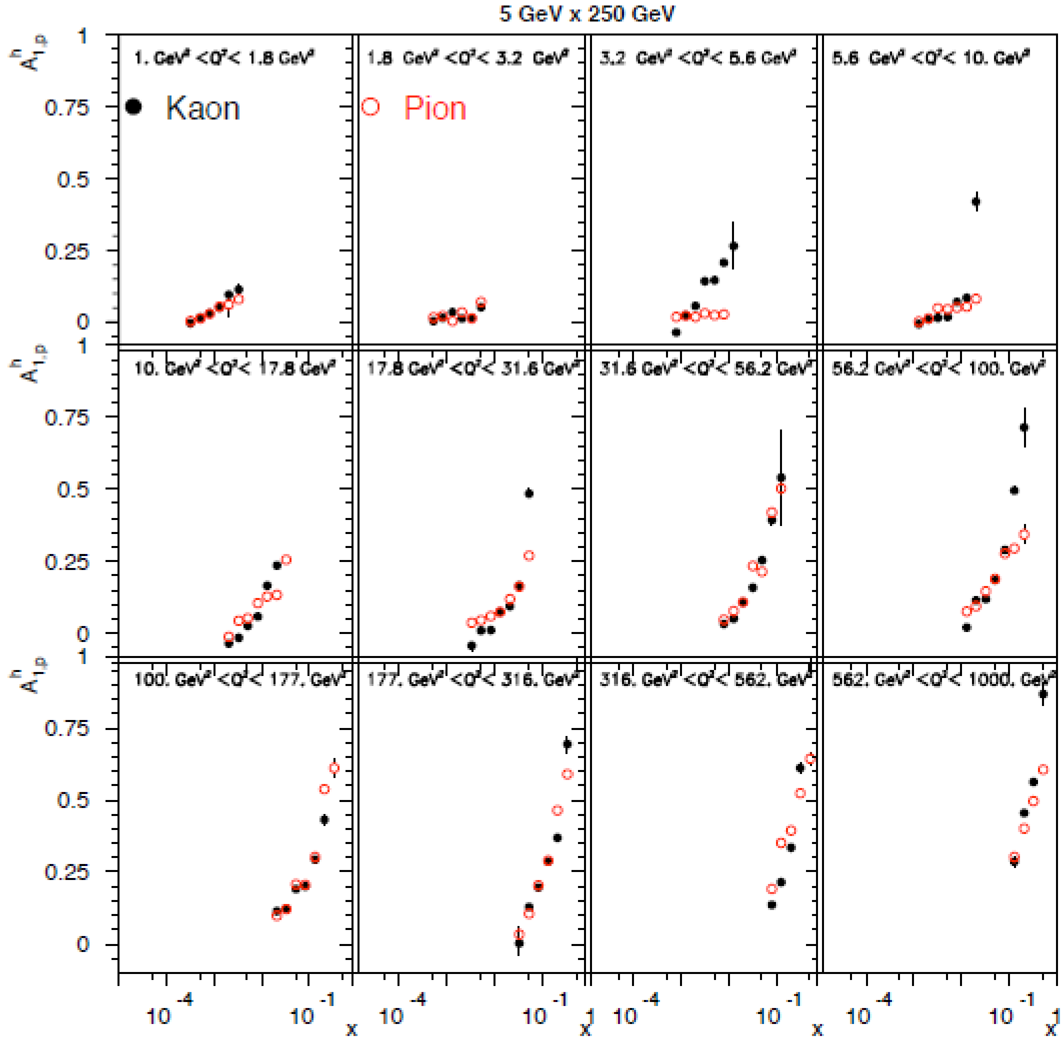
Helicity Structure → SIDIS at EIC

A_{LL} **for semi inclusive Hadronen**

(Elke Aschenhauer
Marco Stratmann)

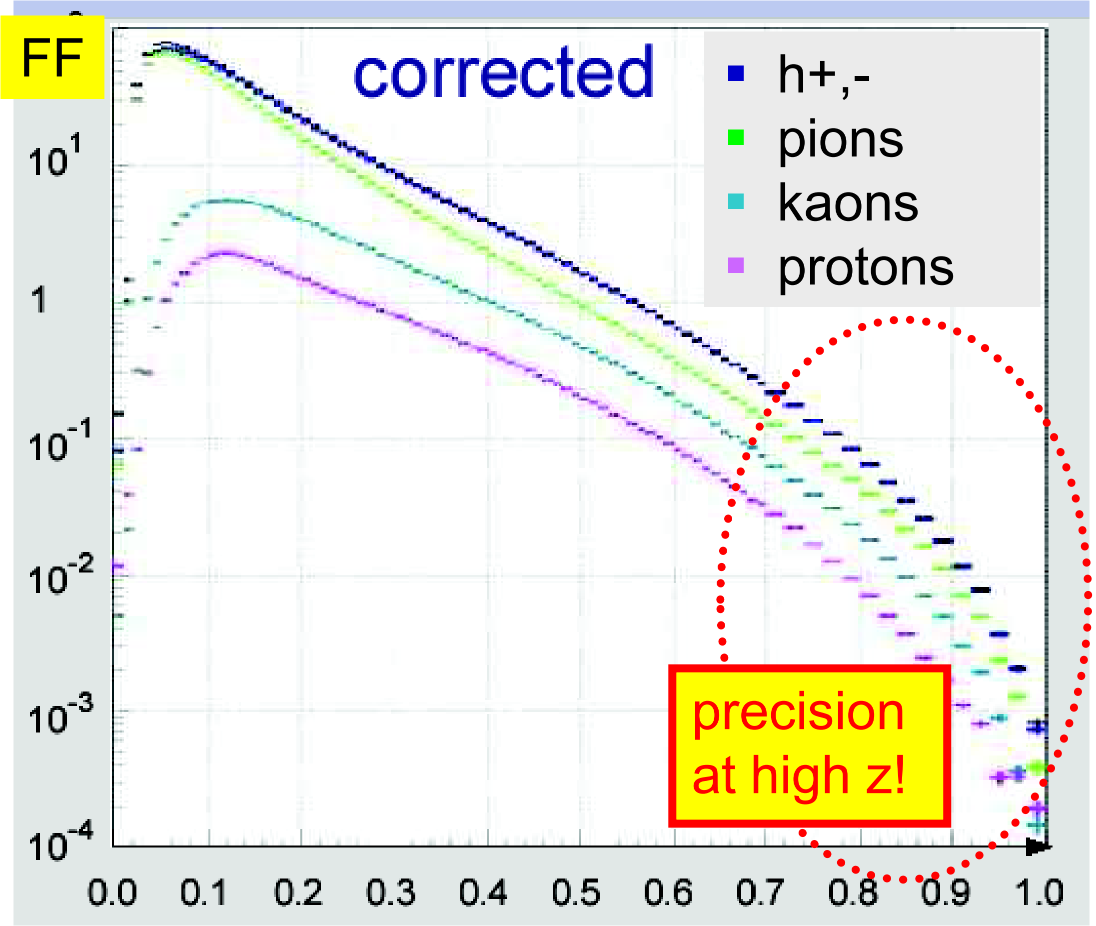
Excellent statistical resolution for all quark and anti-quark helicity cistributions. However, need to evaluate with sPHENIX detector!

Fragmentation functions?



Possible Solution: Precision FF Information from e^+e^- in Belle

Belle: Charged $h^{+/-}$, pions, kaons, protons



$$z = \frac{E^h}{\sqrt{s}/2}$$

Belle sensitivities for identified charged hadron multiplicities (Monte Carlo projections)

√s=10.52 GeV

Inclusive hadrons
Pions
Kaons
Protons

Goal: late 2011 (RIKEN/Indiana/Illinois)

Generalized Parton Distributions to Access Orbital Angular Momentum …

GPDs H^u, H^d, E^u, E^d provide access to total quark contribution to proton angular momentum in exclusive processes $l + N \rightarrow l' + N + \gamma$

Proton spin sum $\frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q + J_g$

J_q (= $\frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q$)

$$J^q = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

Need to evaluate impact of sPHENIX detector!

Transverse Spin -> TMD Distributions: Transversity, Sivers, Boer-Mulders

Transversity : Correlation between transverse proton spin and quark spin $h_{1T,q}(x)$

S_p– S_q

Sivers : Correlation between transverse proton spin and quark transverse momentum $\bar{f}_{1T}^{\perp q}(x, k_\perp^2)$

S_p– $k_{T,q}$ (L_q?)

Boer/Mulders: Correlation between transverse quark spin and quark transverse momentum $h_1^{\perp q}(x, k_\perp^2)$

S_q-- $k_{T,q}$ (L_q?)

Transverse Spin → Goals

Tensor Charge $\sum_q \int dx\left[h_{1T,q}(x) - \bar{h}_{1T,q}(x)\right]$ L-QCD prediction exist

p-p (I) Confirm theoretical understanding of large transverse spin asymmetries in hard scattering

e/p-p (II) Precise measurements of $h_{1T,q}$ (transversity) and $f^{\perp}_{1T,q}$ (Sivers) as function of x (high x first in p-p forward measurements !).

e/p-p (III) Tensor charge

e-p (IV) h_{1T} evolution

} (Lattice) QCD tests!

experimental goals for precision TBD

Transverse Spin → Measurements

p-p:

A_N for Drell-Yan, γ-jet, W, → Sivers sign change
A_N for jet, γ (forward) → Sivers at large x
A_N for di-hadron interference fragmentation IFF

e-p semi inclusive:

A_{UT} Sivers, Boer-Mulders, Collins and IFF asymmetries with proton and ^{3}He beams

→Full acceptance detector with hadron pID capabilities, excellent momentum resolution, relative luminosity monitors and local polarimeters

Transverse Spin → Needs & Input

Absolute polarimeter:

Local polarimeters:

Extrapolation uncertainties (tensor charge):

pQCD framework for PDF extraction:

Fragmentation functions:

Control of radiative corrections:

Requirements to be determined!

A_N Drell-Yan: Competition

Dedicated Drell-Yan experiment is planned (runs 12 & 13) at IP-2 in parallel to longitudinal W-measurements in STAR and PHENIX.

Drelll-Yan + GPD physics from 2013.

Drell-Yan physics proposals pending.

Drell-Yan + J/ψ physics from 2014.

Drell-Yan physics from 2020 (PANDA).

New Developments as discussed by Les Bland at PAC meeting

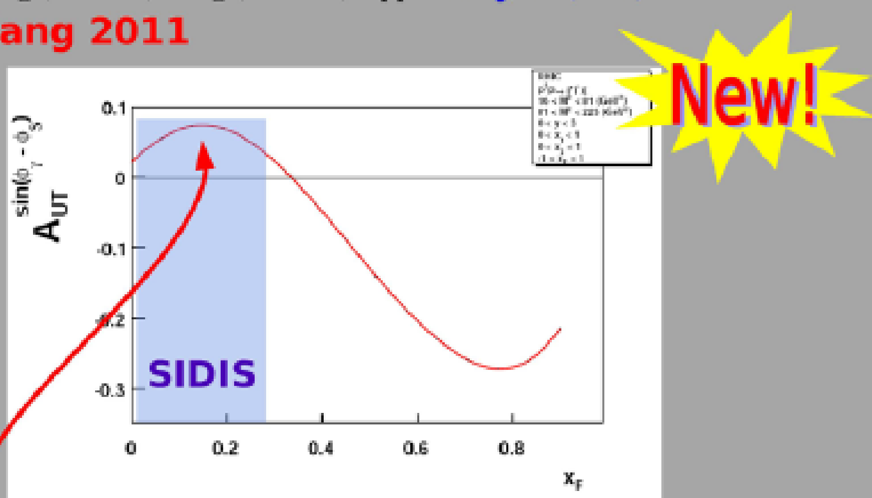
- *SIDIS and RHIC pion production do not overlap in momentum fraction (x)*
- *Attempts to describe both results in a sign "mismatch" conclusion [Kang, Qiu, Vogelsang, Yuan PRD83 (2011) 094001 and arXiv:1103.1591]*
- *Essential to test predicted sign change for DY in same kinematics as SIDIS*

Drell Yan

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

AP, Kang 2011

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



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

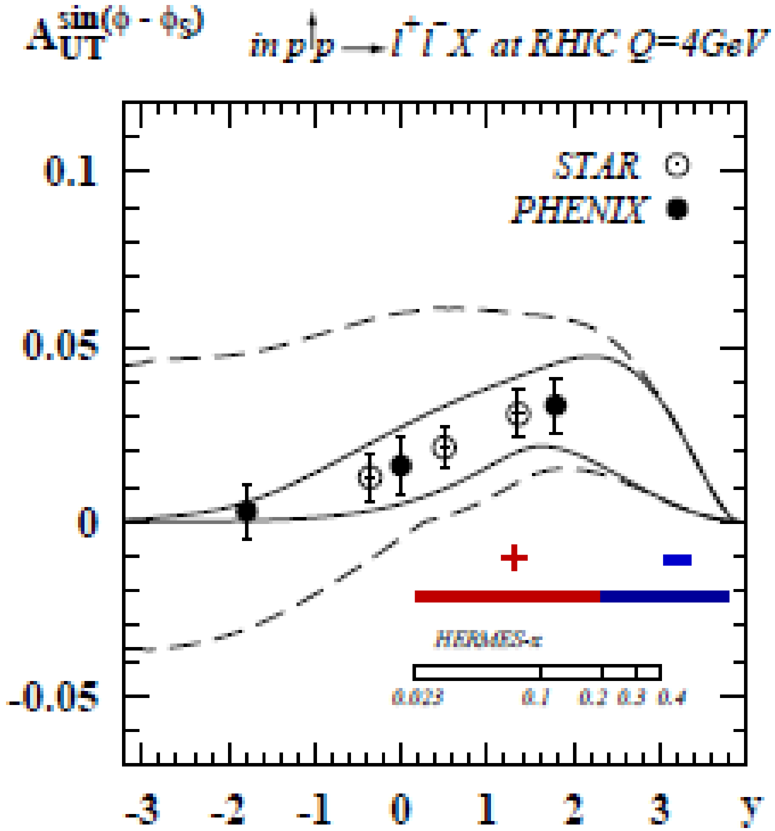
Alexei Prokudin - Sivers function from SIDIS and PP

Combined analysis of SIDIS and RHIC pion production leads to the conclusion that the u-quark Sivers function has a node at x~0.4

A. Prokudin, Z.B. Kang "Opportunities for Drell-Yan Physics at RHIC" workshop (May, 2011)

A_N Drell-Yan in STAR and PHENIX

J. Collins et al. Phys.Rev.D73:094023,2006



$\sqrt{s}$ = 200 GeV, $\int$Ldt = 125 pb^{-1}

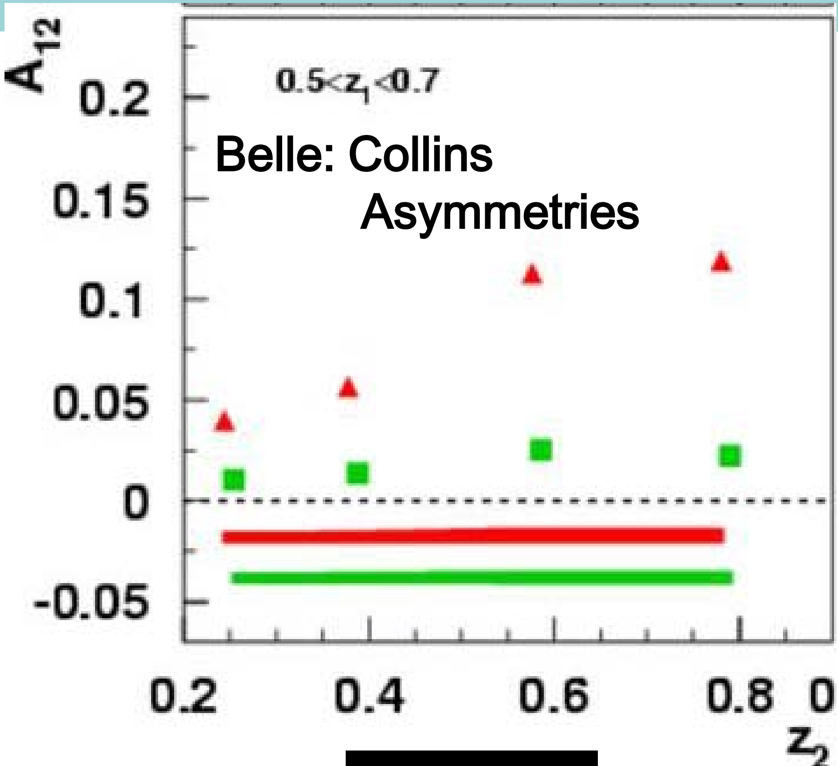
Projection for AN based on Sivers function obtained from HERMES SIDIS data

Dashed line represents uncertainty from choice of sea-quark Sivers distributions.

Measurement over wide rapidity range in sPHENIX aims to disen-tangle x-dependence + contributions from sea.

Compare Drell-Yan with other Sivers Observables A_N for jets, photons, Ws in sPHENIX !

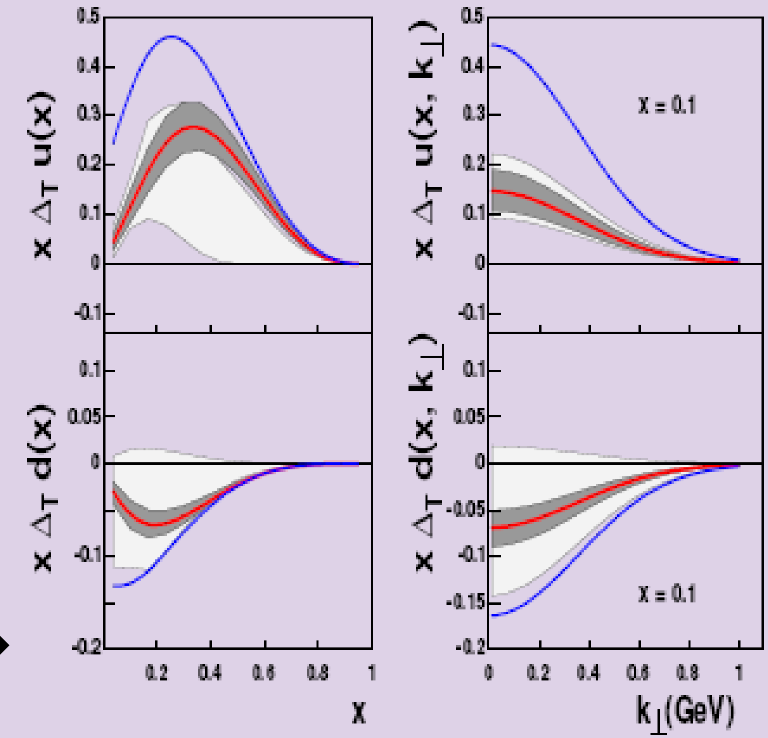
Status of Extraction of Quark Transversity Dis. and the Tensor Charge SIDIS+e⁺e⁻



+ HERMES, & COMPASS data
➔ first extraction of δq(x) :

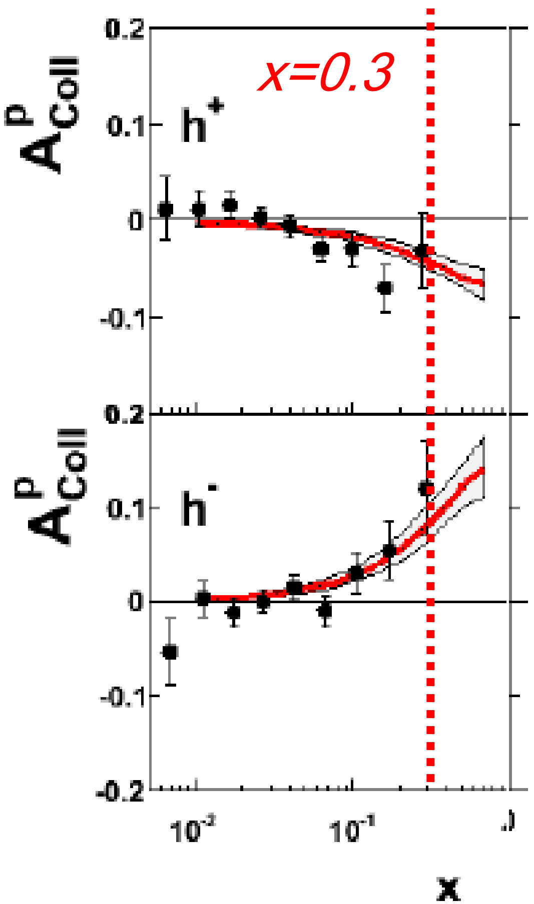
Anselmino, Prokudin et al.
Phys. Rev. D75:05032, 2007
Nucl. Phys. Proc. Suppl. 191, 2009

Extraction of Transversity & Collins FF including errors !



Comparison of HERMES + Belle Based Prediction for COMPASS to Data

Preliminary COMPASS Collins Asymmetries for Proton Target vs predictions from Anselmino, Prokudin et al.



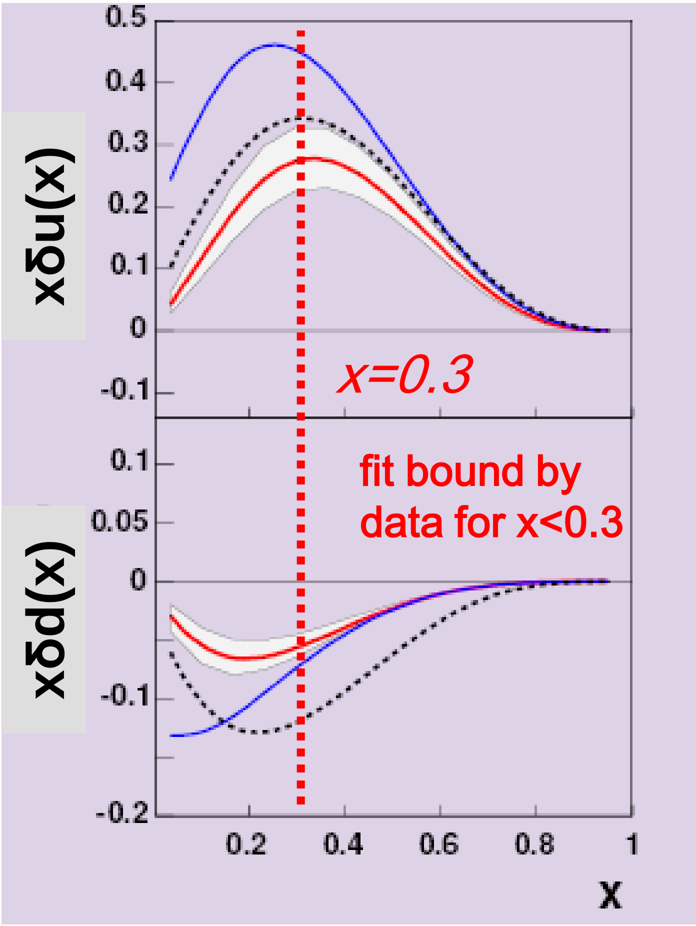
Good agreement of COMPASS proton data with preditions from fit to HERMES, COMPASS-d +Belle. Important cross check as COMPASS is at higher Q^2!

However, no data at x > 0.3 …

➔$h_{1T,q}(x)$ not bound at large x

➔uncertainty in tensor charge

About 40% of Tensor Charge = $\Sigma_{q=u,d}\int_0^1 h_{1T,}q(x)dx$ Bound by Data ➔ Extrapolation to Large x Important



Prokudin et al. at Ferrara

$\int h_{1T,u}(x)dx = +0.59^{+0.14}_{-0.13}$

$\int h_{1T,d}(x)dx = -0.20^{+0.05}_{0.07}$ at Q^2=0.8 GeV^2

Example for lattice QCD calculation

(M. Gockeler et al, Phys. Lett. B 627, 2005)

$\int h_{1T,u}(x)dx = +0.86 +/- 0.02$

$\int h_{1T,d}(x)dx = -0.22 +/- 0.05$ at Q^2=0.8 GeV^2

Can nucleon structure be described ab initio QCD with the help Lattice QCD?

sPHENIX contribution:
constrain tensor charge by measuring transversity at medium and high x!

Transversity ➔ Collins A_{UT} *at EIC*

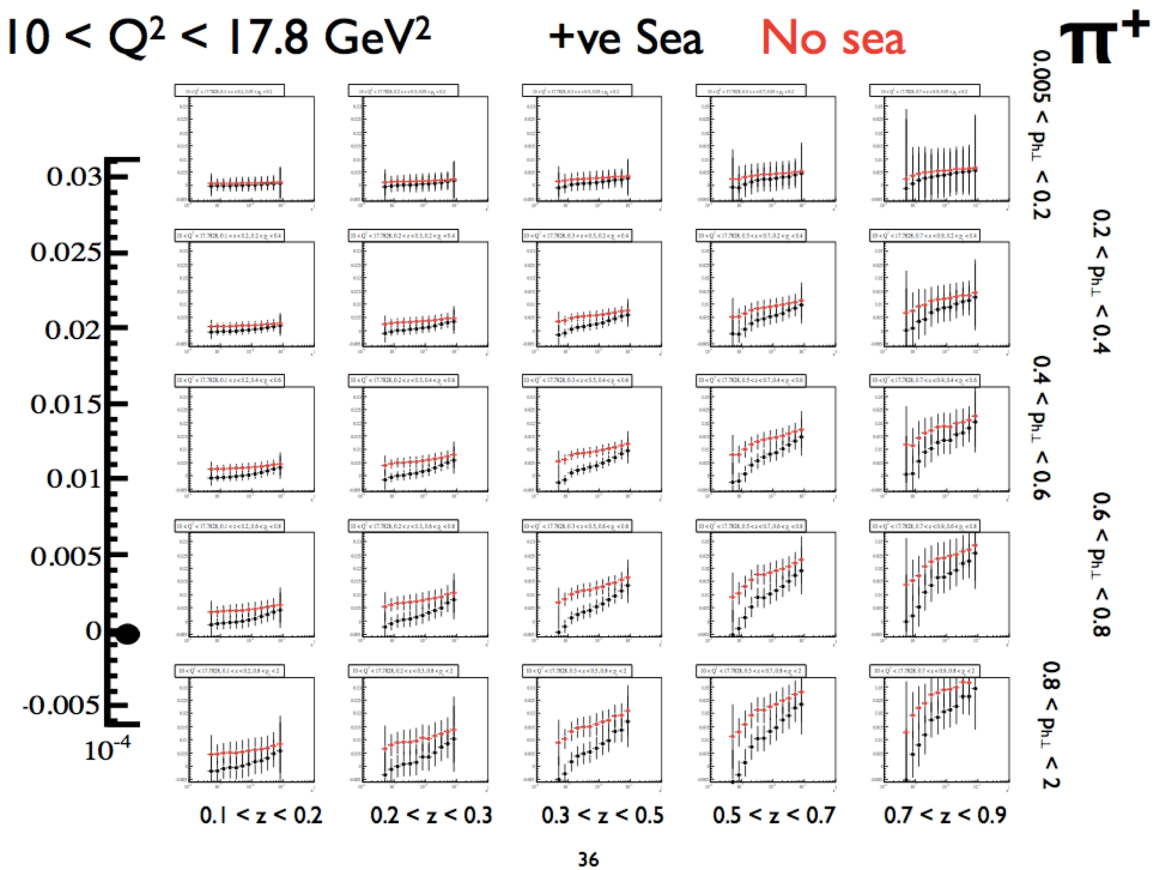
Excellent statistical resolution over a large region in Q^2 !

[Thomas Burton]

A_{UT} ~ Transversity(x) x Collins(z)

Study with sPHENIX required.

However, extraction relies on assumptions and alternative possibiities exist!



Collins Extraction of Transversity: Model Dependence from Transverse Momentum Dependences!

$$A_{UT}^{Collins} = \frac{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp \delta q(x,k_\perp) \frac{d(\Delta\sigma)}{dy} H_{1,q}^{\perp}(z,p_\perp) \sin(\phi_S + \phi + \phi_h) \sin(\phi_S + \phi_h)}{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp q(x,k_\perp) \frac{d(\Delta\sigma)}{dy} D_q^h(z,p_\perp)}$$

transversity, Collins FF, quark pdf, hadron FF

$k_\perp$ transverse quark momentum in nucleon

$p_\perp$ transverse hadron momentum in fragmentation

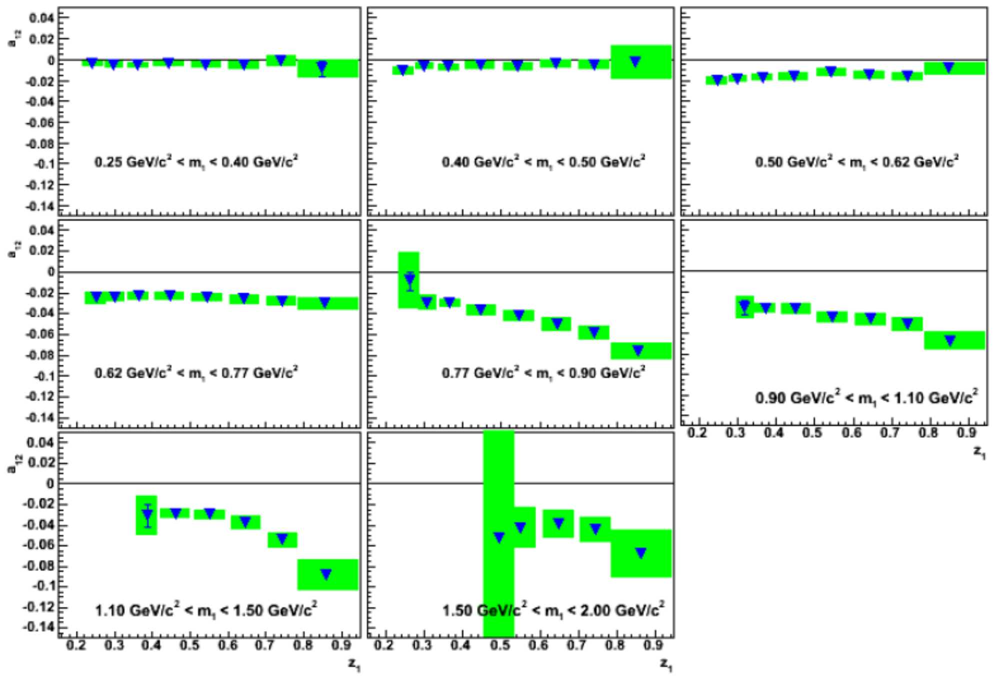
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk Phys. Rev. D75:05032,2007

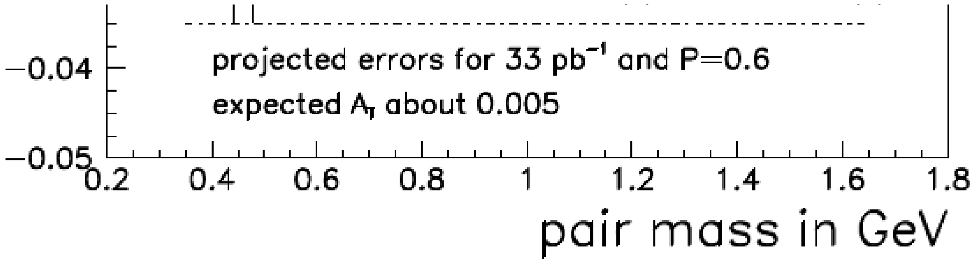
The transverse momentum dependencies are unknown and difficult to obtain experimentally!

IFF will provide alternative route of access independent of knowledge of transverse momentum dependencies.

sPHENIX IFF in p-p

Belle IFF asymmetries vs z for diff. $m_{h1,h2}$





PHENIX IFF results and projections for midrapidity for 30 pb-1

s-PHENIX offers forward measurements with good PID, larger analyzing power and higher statistics

Potentially best access to transversity & tensor charge, quantitative study will be needed.

Belle IFF results have been submitted to PRL.

A-Dependence of Nucleon Structure → Goals

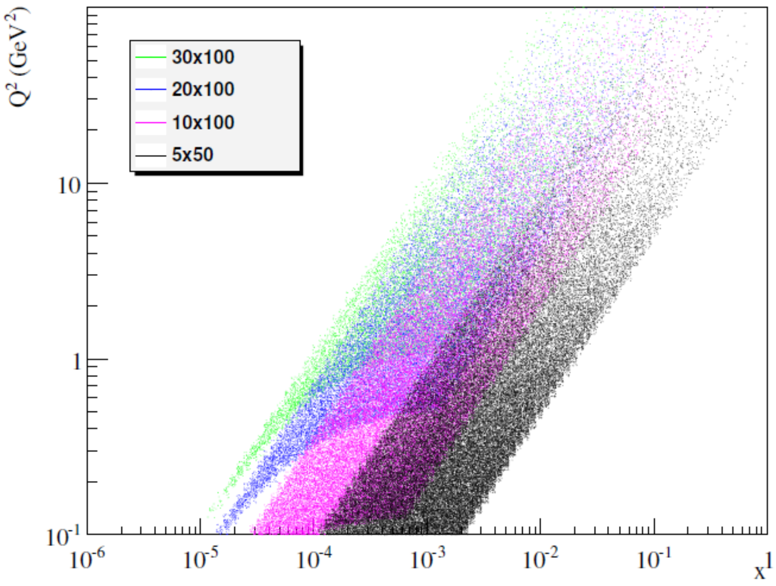
e-A (I) Measure $G_A(x)$ and quantify initial state for HI collisions at RHIC.

e-A (II) Search for onset of gluon saturation and verify CGC framework as an effective field theory at high field strengths in QCD.

Q: can we determine color configurations $W(\rho)$ and use the JIMWLK evolution to evolve them to LHC energies?

A-Dependence of Nucleon Structure ➔ Measurements

e-p Inclusive:



F_2^A, F_L^A, $F_{2,c}^A$

sPHENIX has good acceptance at low x, Q2 were we will be looking for deviations from DGLAP evolution: e.g. scan A at fixed kinematics.

A-Dependence of Nucleon Structure → Measurements

e-p exclusive:

Diffractive J/ψ production

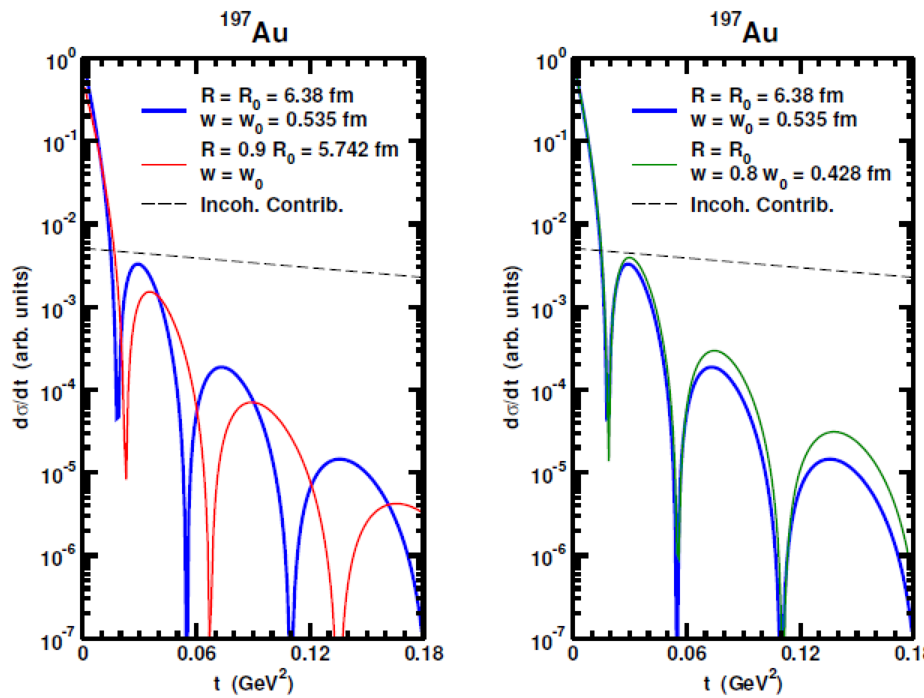
sPHENIX has good acceptance for mesons in exclusive production.

Diffraction patterns for vector mesons for Au.

Blue: gluon density scales with Woods-Saxon charge Density

Red/left: 10% smaller radius

Green/right: 20% smaller width.



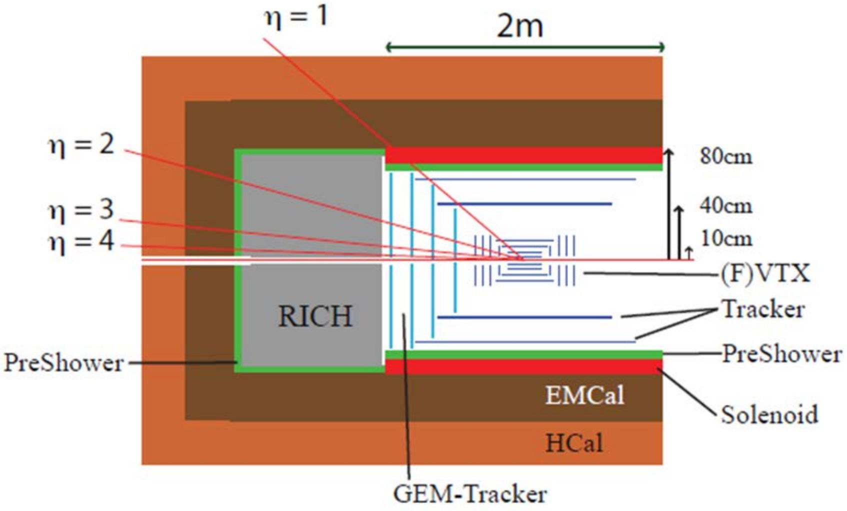
Summary

- In combination with high luminosity, high polarization proton beams sPHENIX offers an interesting physics program in p-p and e-A collisions.
- Precision measurements with clean theoretical interpretation will become possible:

  Saturation physics, helicity decomposition, Bjorken sumrule survey of the Sivers function, tensor charge and tests of QCD evlolution of g_1 and h_{1T}.
- Significant effort and care will be needed to meet the experimental and theoretical challenges: high luminosity + polarization, high performance detector, precision polarimetery, tools for the clean pdf extraction.

The PHENIX Decadal Upgrade Detector

Build incrementally



What is new:

- **2-3T solenoid (R = 60-100 cm)**
- **Preshower detector**
- **Barrel EMCal (maybe new)** } **$20M**
- **Hadronic Calorimetry** } **$8-10M**
- **Additional tracking layers of Si at ~ 40cm** } **$5-7M**
- **Forward Arm with RICH and GEM tracker** } **$10M**

Other

- **Forward magnet**
- **Completion of HCAL**
- **N Spectrometer arm**

} **$10-15M**

All cost estimates include overhead and contingency

Total Project Cost $53-62M

- **Approx ½ replacement cost of existing $130M PHENIX detector**
- **DOE contribution estimated to be 60% of total $32-37M**
- **Forward detector is key for eRHIC physics (part of eRHIC project?)**