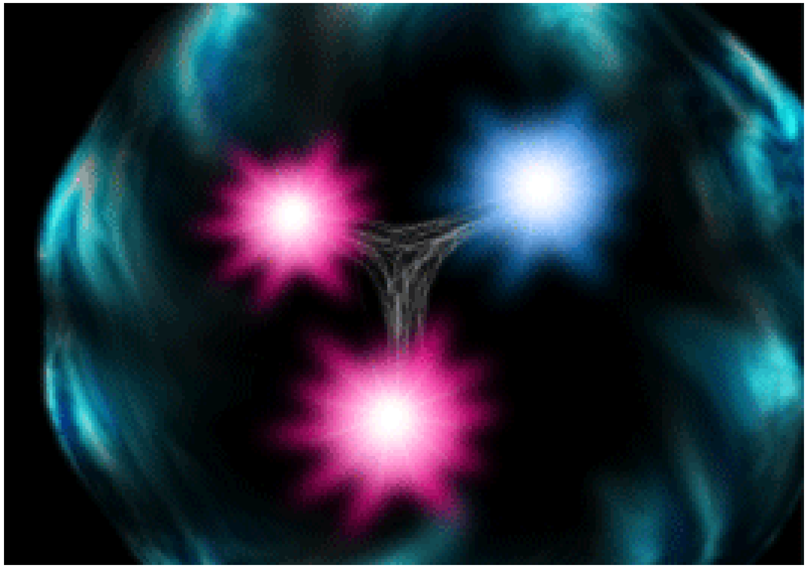
TMDs through SIDIS at EIC

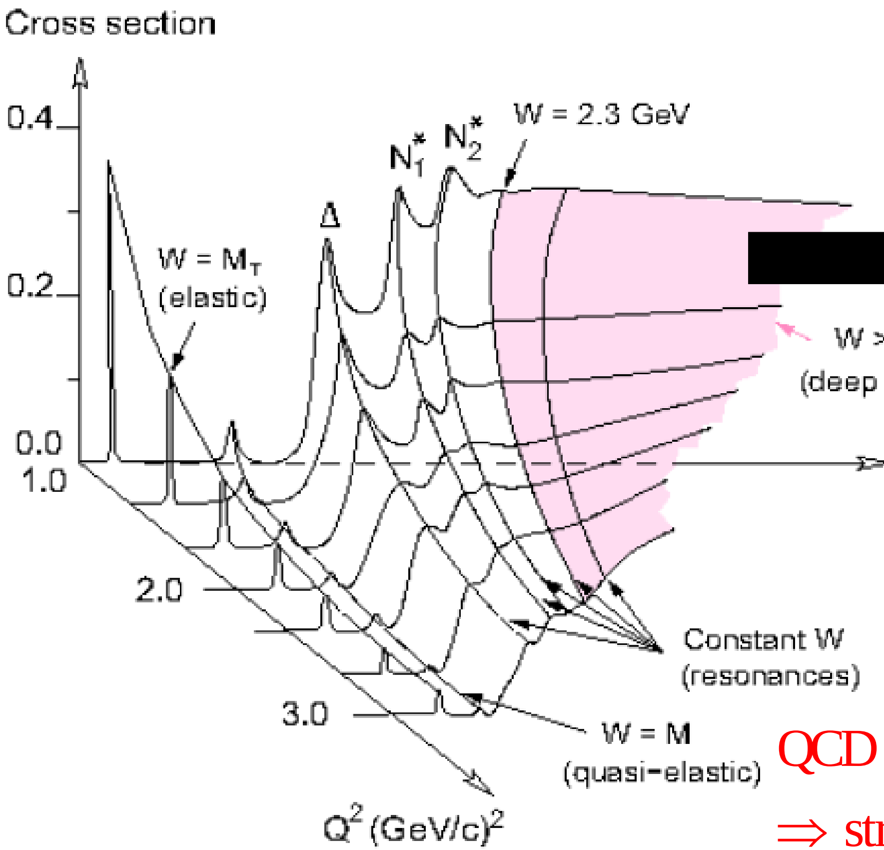
- Introduction
- Accessing TMDs from SIDIS
- Few highlights from simulations
- Summary

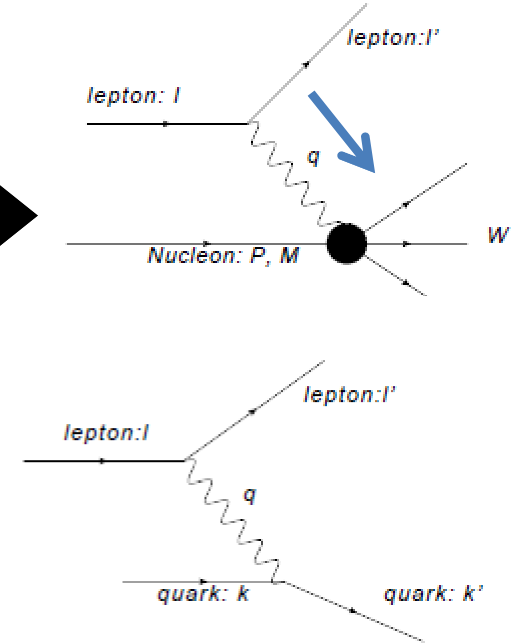


EIC Advisory Committee Meeting,
TJNAF, April 10, 2011

Haiyan Gao
Duke University/TUNL

Lepton Scattering ----- *A powerful tool*





QCD factorization

⇒ structure (non-perturbative) ⊗ hard part (pQCD)

$$Q^2 = -q^2 = -(l - l')^2$$

4-momentum transfer squared: resolution.

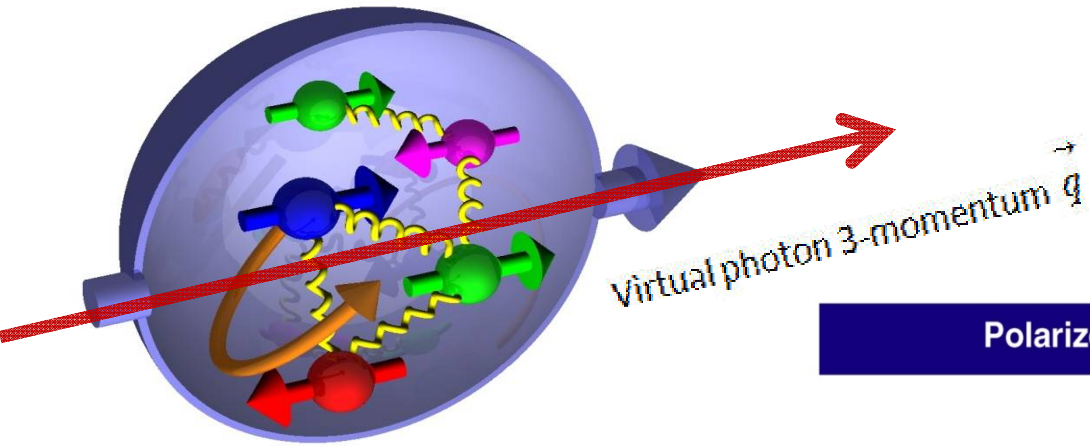
$$\nu = E_l - E_{l'}$$

Energy transfer.

$$x_{Bjorken} = \frac{Q^2}{2m\nu}$$

Longitudinal momentum fraction of parton in the infinite momentum frame.

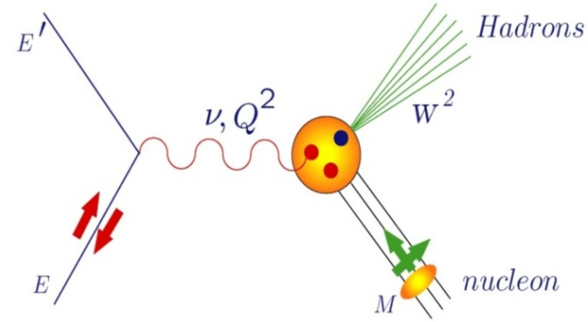
Longitudinal Spin Structure



g_{1L}

Probability for quark polarized in the nucleon spin direction

Polarized Deep Inelastic Electron Scattering



$x = \frac{Q^2}{2M\nu}$ Fraction of nucleon momentum carried by the struck quark

Q^2 = 4-momentum transfer of the virtual photon, ν = energy transfer, θ = scattering angle

- All information about the nucleon vertex is contained in

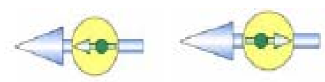
F_2 and F_1 the unpolarized (spin averaged) structure functions,

and

g_1 and g_2 the spin dependent structure functions

Nucleon Spin Structure

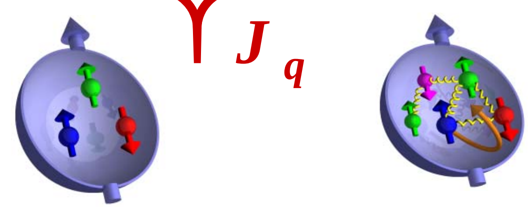
- Understand Nucleon Spin in terms of quarks and gluons (QCD).
  - **Nucleon spin is ½ at all energies, how to divide non trivial (recent developments by Chen *et al.*, Wakamatsu)**



Nucleon's spin
Ji's Sum Rule
(example)

$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + J_g$$

J_q



~30% from quark spin by EMC
1/3 confirmed by more precise data
Gluon intrinsic spin contribution not large

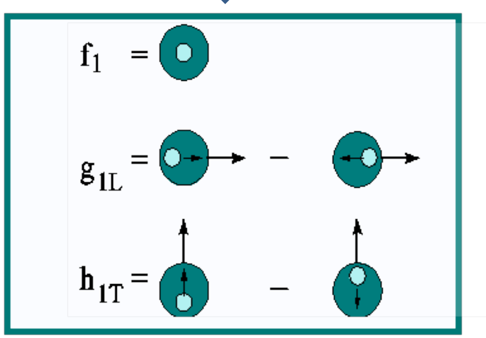
  - Small contribution from quarks and gluons' intrinsic spin
  - Orbital angular momentum of quarks and gluons is important
    - **Understanding of spin-orbit correlations.**

Generalized parton distribution allows for three-dimensional description of nucleon structure (longitudinal momentum, transverse space)

Q: how about quark transverse momentum ?
3-D description in momentum space?

Transverse Momentum-dependent parton distributions (TMDs)

At leading twist 8 total, only 3 TMDs non vanishing upon integrating over transverse momentum of the quark



$$\text{Nucleon tensor charge} = \int_{-1}^{1} h_{1T}\, dx$$

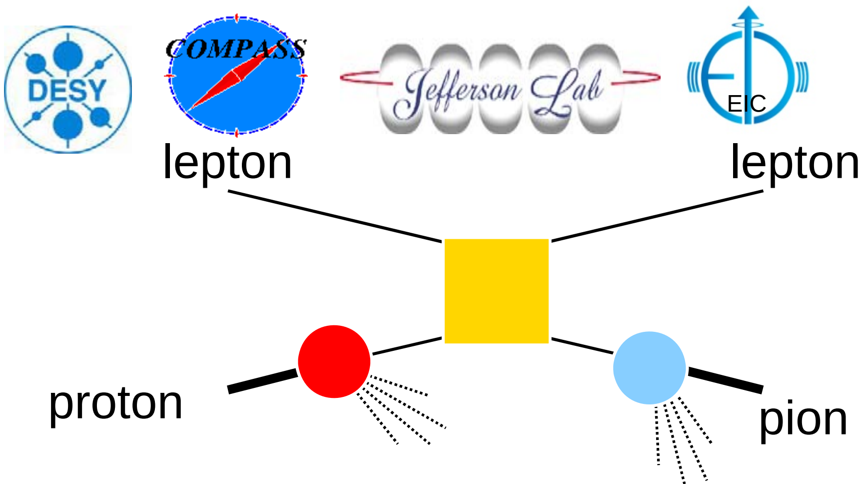
So how to study transversity and other TMDs experimentally?

All Leading Twist TMDs

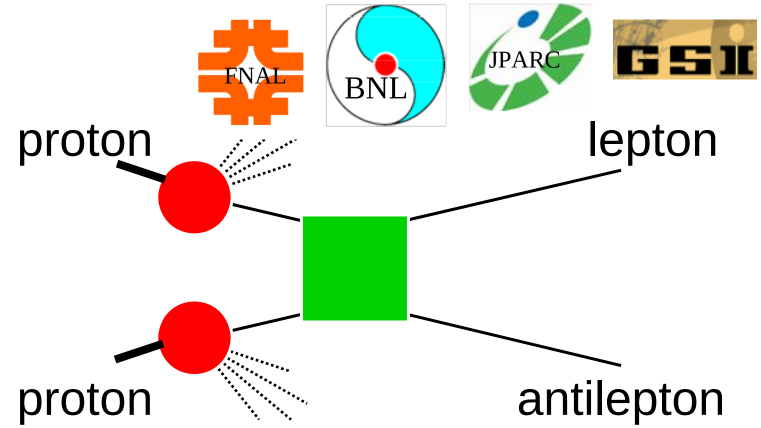
→ Nucleon
→ Quark Spin

Nucleon Polarization		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
	U	$f_1 =$		$h_1^{\perp} =$ − Boer-Mulder
	L		$g_1 =$ − Helicity	$h_{1L}^{\perp} =$ −
	T	$f_{1T}^{\perp} =$ − Sivers	$g_{1T}^{\perp} =$ −	$h_{1T} =$ − Transversity $h_{1T}^{\perp} =$ − Pretzelosity

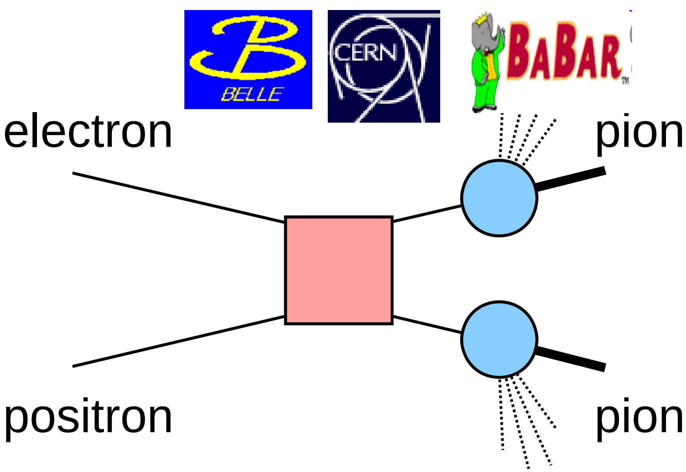
Access TMDs through Hard Processes



SIDIS



Drell-Yan



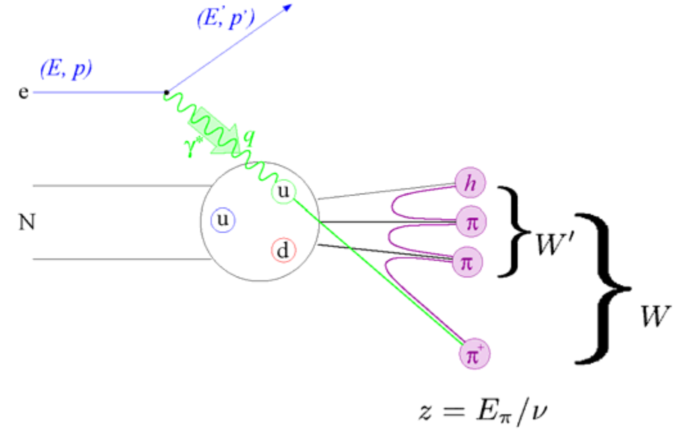
$e^{-}e^{+}$ to pions

- Yellow square: Partonic scattering amplitude
- Light blue circle: Fragmentation amplitude
- Red circle: Distribution amplitude

$$f_{1T}^{\perp q}(SIDIS) = -f_{1T}^{\perp q}(DY)$$

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY})$$

Access Parton Distributions through Semi-Inclusive DIS



$$\frac{d\sigma}{dxdyd\phi_S dzd\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y}{2(1}$$

$$\{F_{UU,T} + \ldots$$
$$+\varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

Unpolarized

$$+S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$
$$+S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+\sin(\phi_h-\phi_S)\cdot(F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$
$$+\varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

Polarized Target

$$+S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$
$$+S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

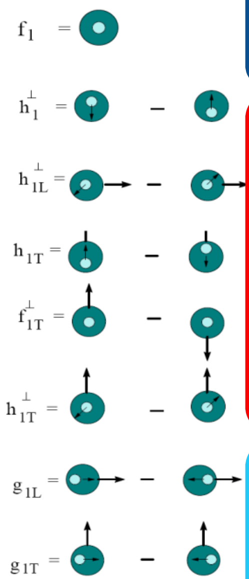
Polarized Beam and Target

Boer-Mulder

Transversity

Sivers

Pretzelosity



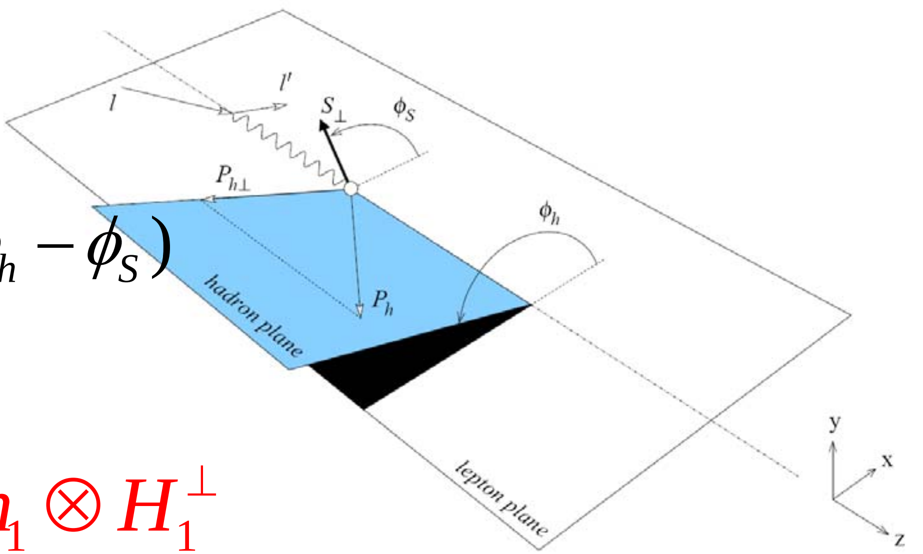
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Separation of Collins, Sivers and pretzelocity effects through angular dependence

$$A_{UT}(\varphi_h^l,\varphi_S^l)=\frac{1}{P}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}$$

$$=A_{UT}^{Collins}\sin(\phi_h+\phi_S)+A_{UT}^{Sivers}\sin(\phi_h-\phi_S)$$

$$+A_{UT}^{Pretzelosity}\sin(3\phi_h-\phi_S)$$



$$A_{UT}^{Collins}\propto\left\langle\sin(\phi_h+\phi_S)\right\rangle_{UT}\propto h_1\otimes H_1^{\perp}$$

$$A_{UT}^{Sivers}\propto\left\langle\sin(\phi_h-\phi_S)\right\rangle_{UT}\propto f_{1T}^{\perp}\otimes D_1$$

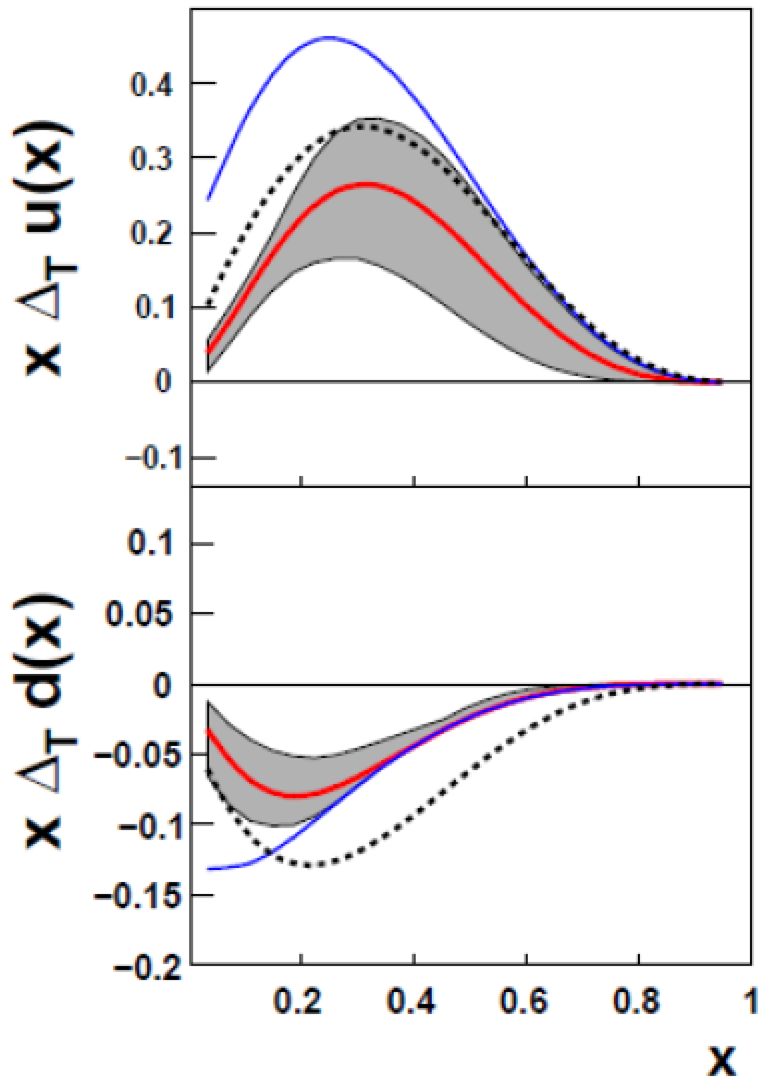
$$A_{UT}^{Pretzelosity}\propto\left\langle\sin(3\phi_h-\phi_S)\right\rangle_{UT}\propto h_{1T}^{\perp}\otimes H_1^{\perp}$$

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

Transversity Distributions

A global fit to the HERMES p, COMPASS d and BELLE e+e- data by the Torino group, Anselmino et al., arXiv:0812.4366



Solid red line : transversity distribution, analysis at Q^2=2.4 $(GeV/c)^2$

Solid blue line: Soffer bound

$|h_{1T}| <= (f_1+g_{1L})/2$

GRV98LO + GRSV98LO

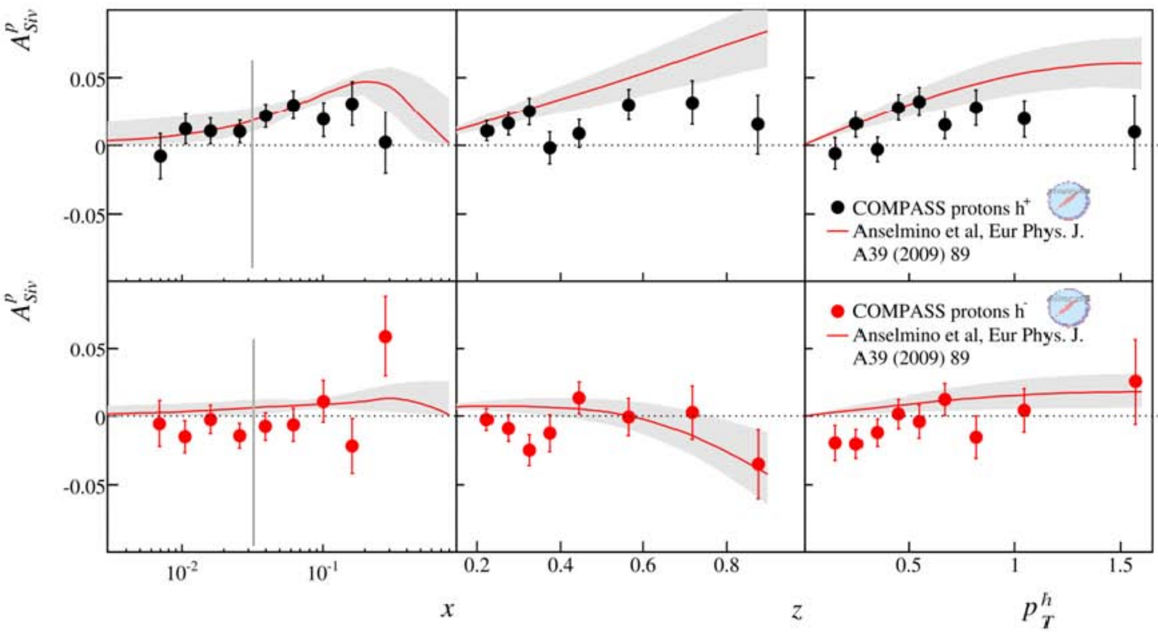
Dashed line: helicity distribution g_{1L}, GRSV98LO

$$\Delta_T = h_{1T}$$

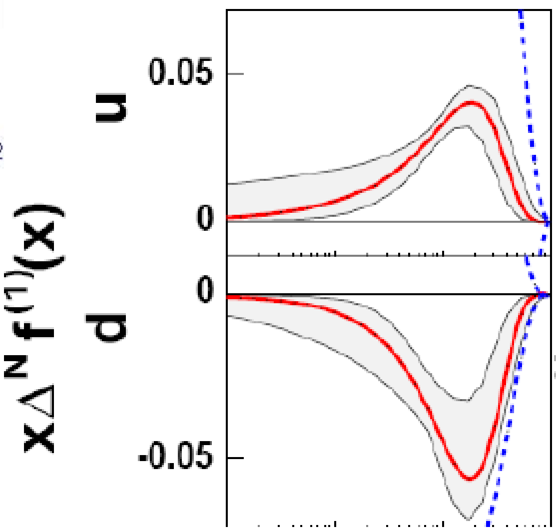
Sivers asymmetry - proton

comparison with theory

… most recent predictions from *M. Anselmino et al.*
based on the fit of HERMES proton and COMPASS deuteron data



Extraction of Sivers fcn (HERMES p, COMPASS d)



Ext: M. Anselmino *et al.*, arXiv:0812.4366

Transversity experiments (JLab HallA)

- Jeffe
  - ❑Si … i-
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    Tr … V
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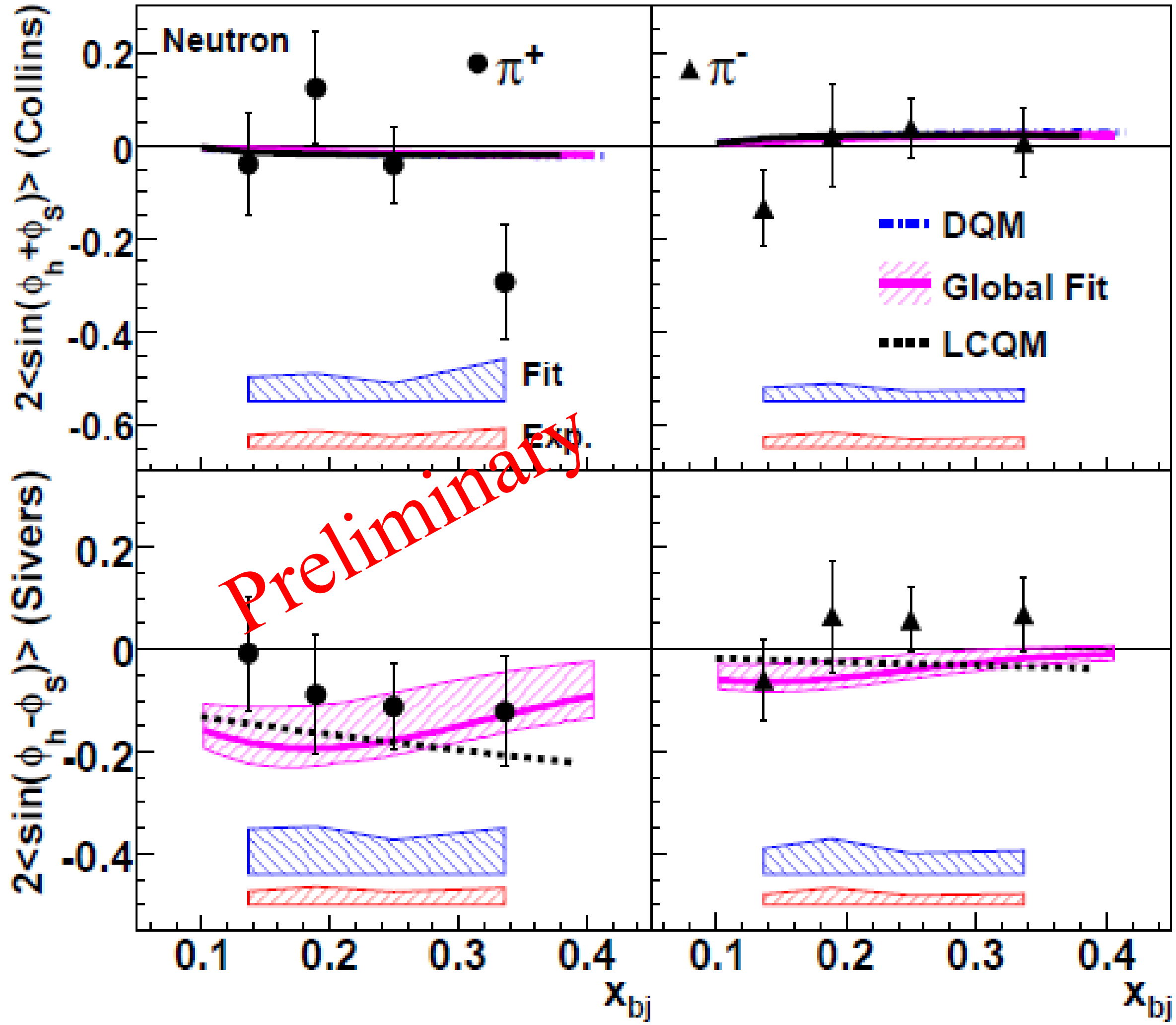
  - ❑*Fi* … ver!
- App … sing
  SoLI … all B
  (EPJ



X. Qian *et al*, to be submitted to PRL

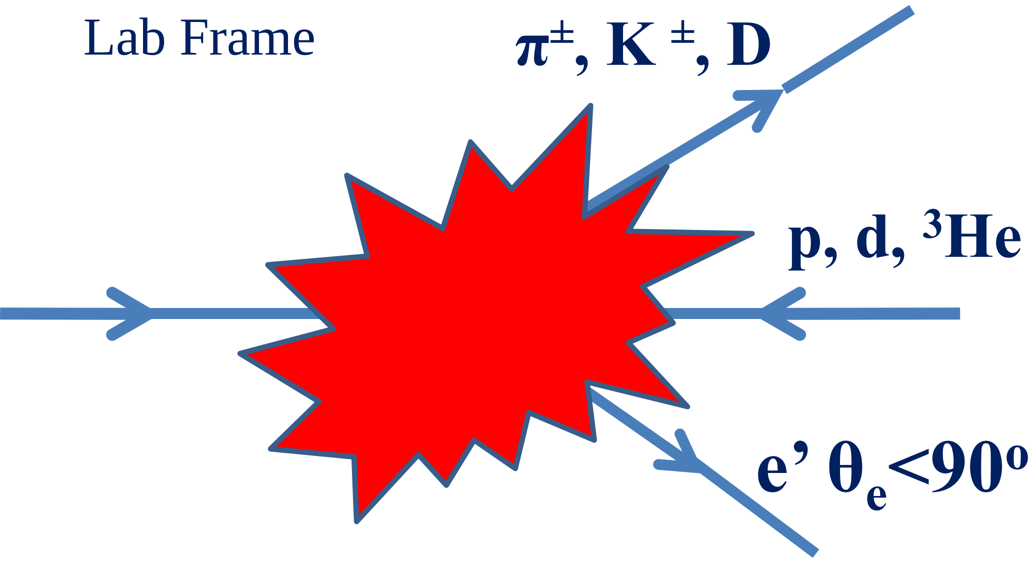
Duke/JLab Workshop on Partonic Transverse Momentum in Hadrons: Quark Spin-Orbit Correlations and Quark-Gluon Interactions, March 2010

Workshop summary paper:
M. Anselmino *et al*. EPJA 47, 35 (2011)

M. Diehl summary of INT program
M. Anselmino *et al*. INT summary paper

SIDIS @ EIC

Lab Frame



$$x = \frac{Q^2}{2P_p \cdot q} \qquad \frac{Q^2}{x \cdot y} = 2P_p \cdot P_e^i \approx s$$

$$y = \frac{P_p \cdot q}{P_p \cdot P_e^i}$$

$$Q^2 = x \cdot y \cdot s$$

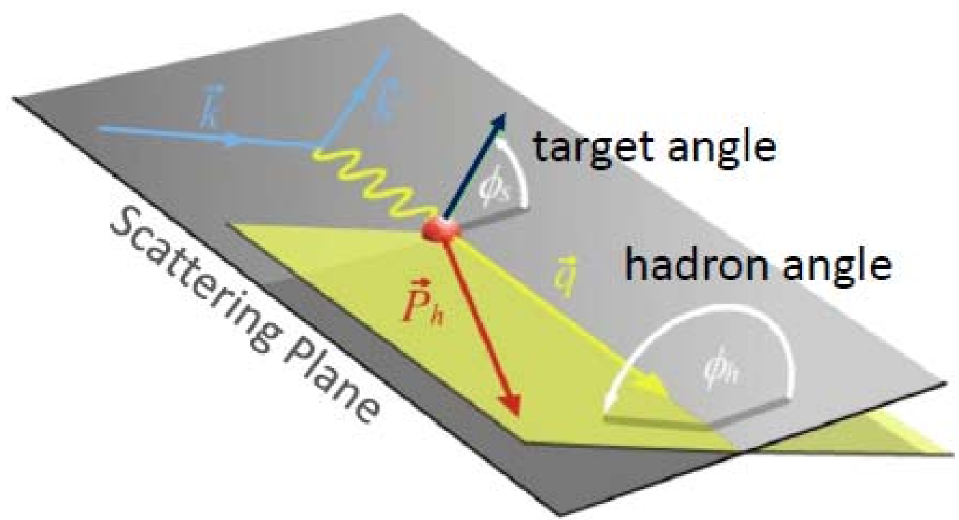
$$z = \frac{P_p \cdot P_h}{P_p \cdot q}$$

(Trento convention)

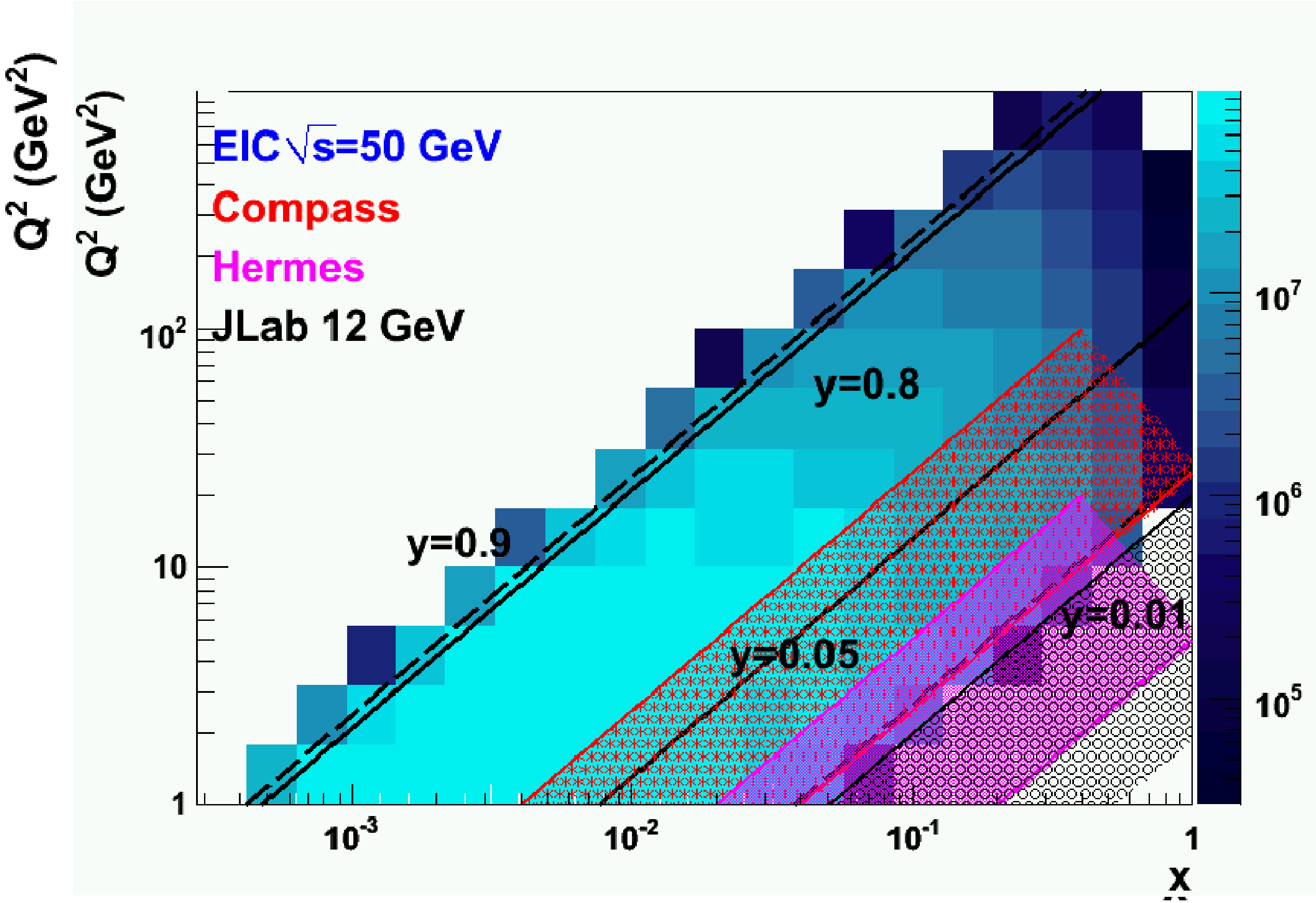
Ion-at-rest (collinear) frame

$\phi_S \quad \phi_h$

$$P_T = \frac{|\vec{p}_h \times \vec{q}|}{|\vec{q}|}$$

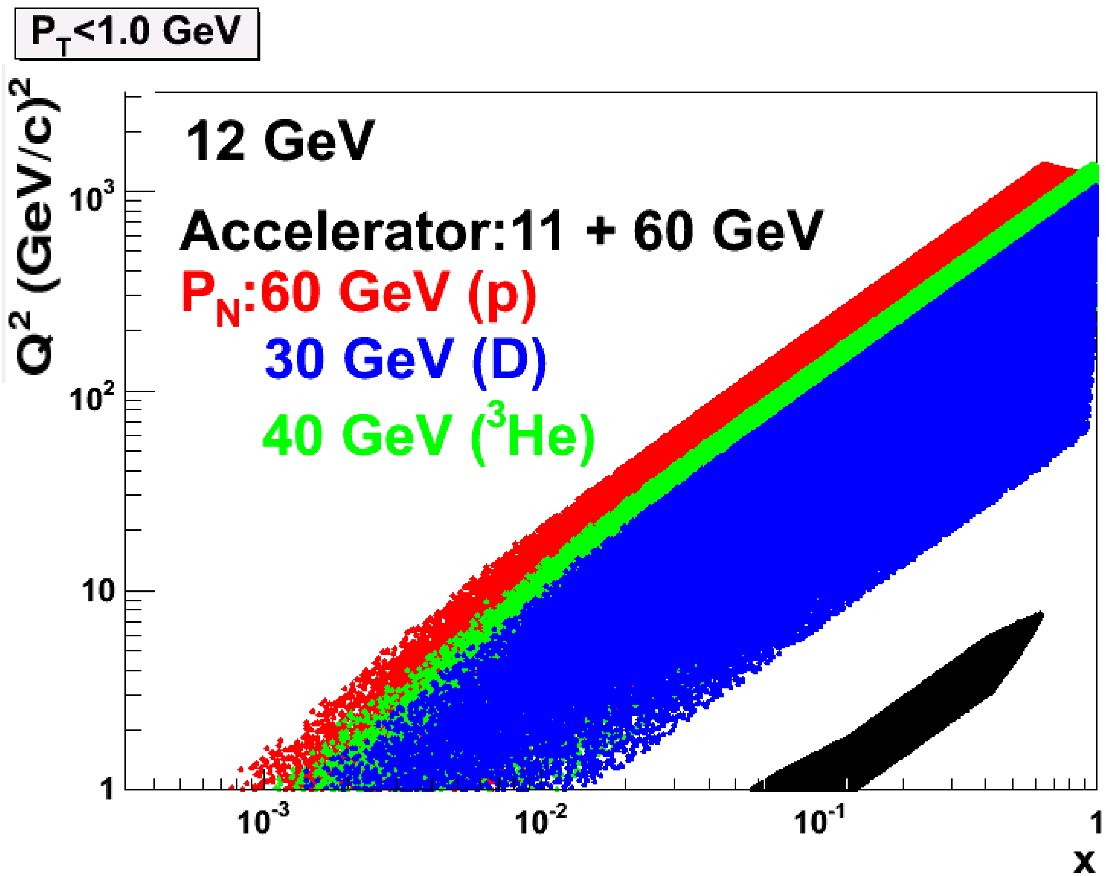


Phase Space Coverage



Note that the coverage of Compass Hermes & Jlab 12 may not be able to do 4D mapping

Study both Proton and Neutron



ion momentum $\propto$ Z

$P_N \propto$ Z/A

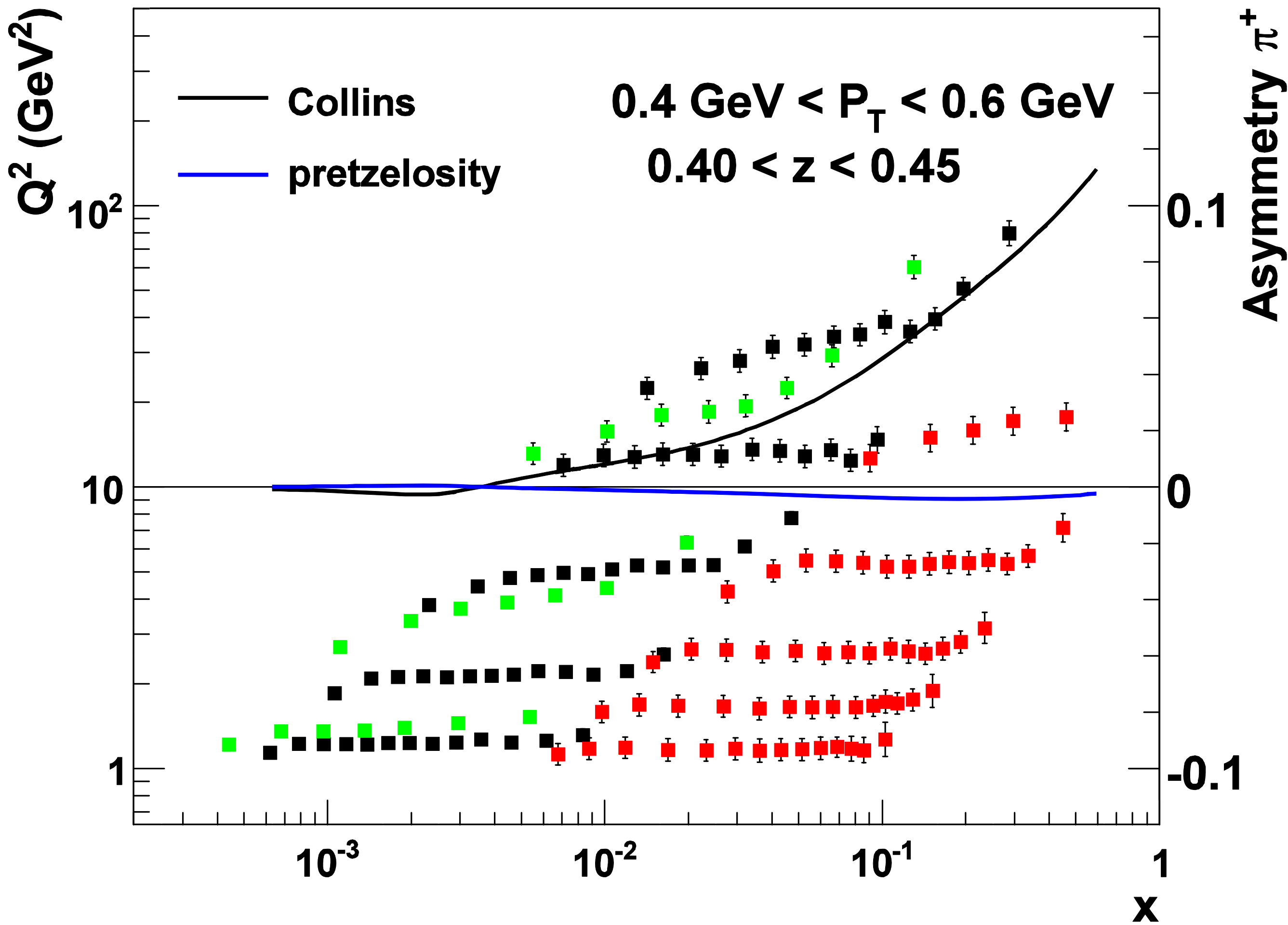
Not weighted by Cross section.

Flavor separation, Combine the data
the lowest achievable x limited by the effective neutron beam and the P_T cut

Projections with Proton (Collins)

- **11 + 60 GeV**
  36 days
  L = 3x10^{34} /cm^2/s
- **11 + 100 GeV**
  36 days
  L = 1x10^{34}/cm^2/s

  2x10^{-3} , Q^2<10 GeV^2
  4x10^{-3} , Q^2>10 GeV^2
- **3 + 20 GeV**
  36 days
  L = 1x10^{34}/cm^2/s
  4x10^{-3} , Q^2<10 GeV^2
  5x10^{-3} , Q^2>10 GeV^2

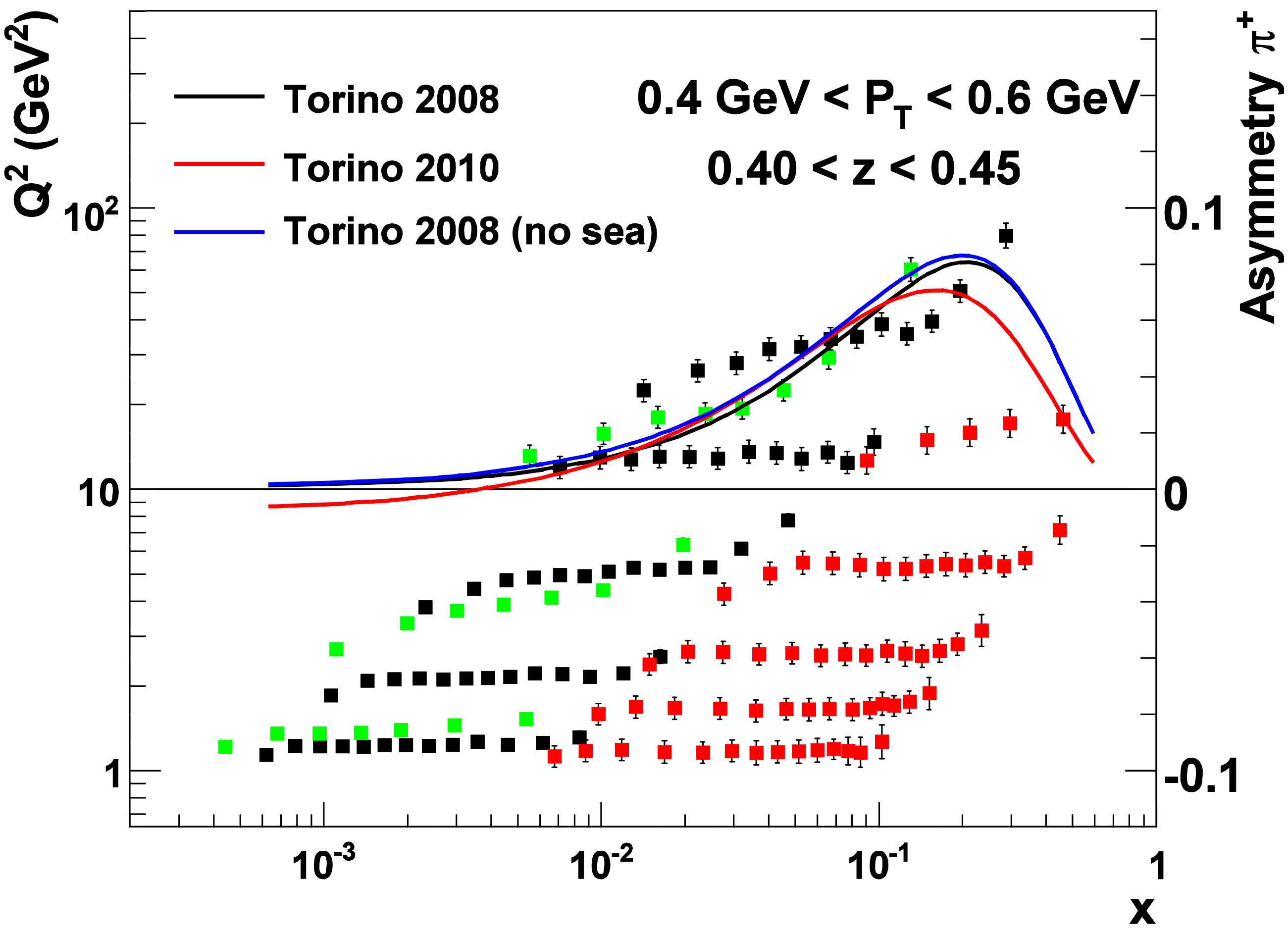


Results on kaons also

Projections with Proton (Sivers)

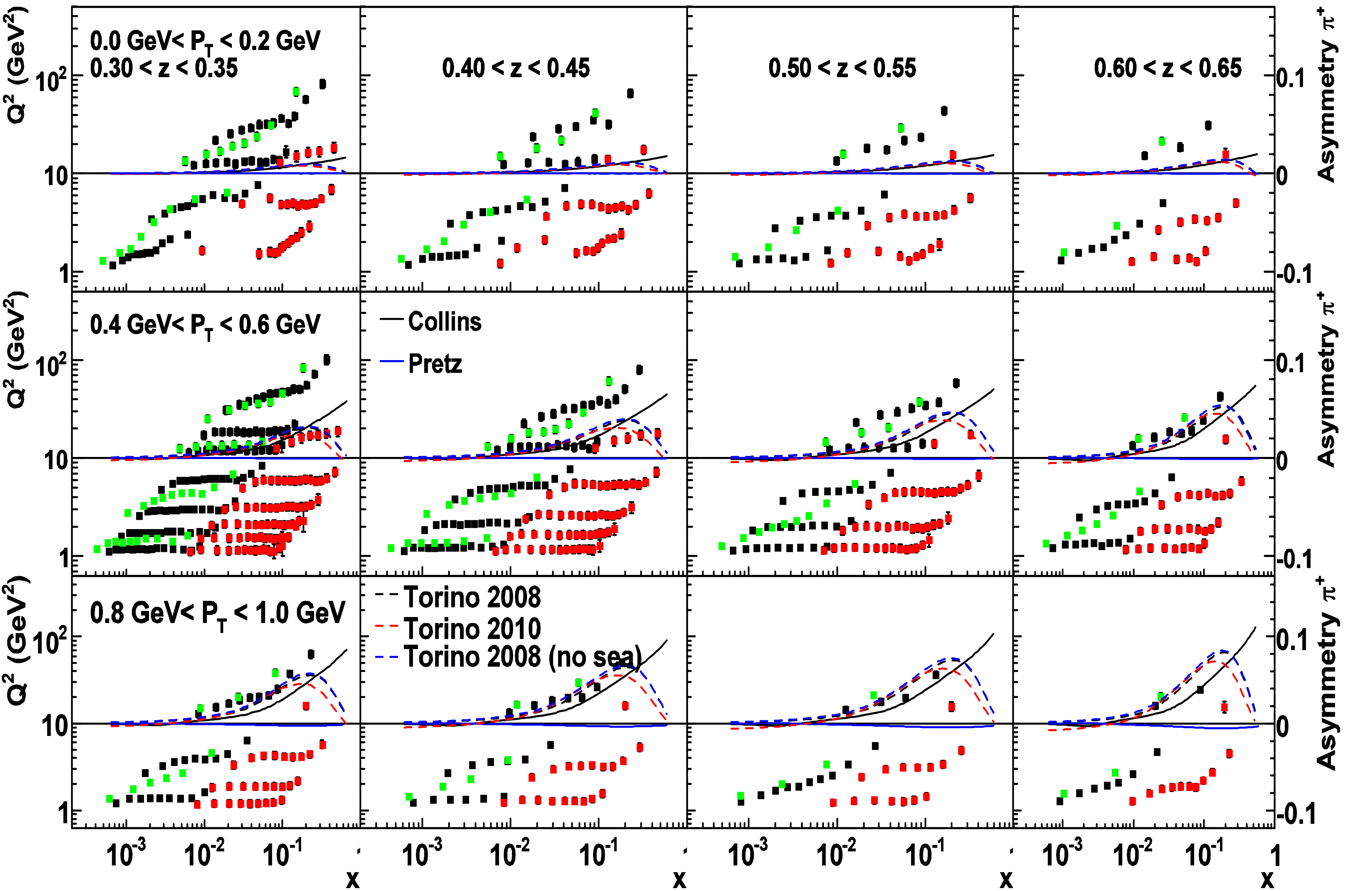
Polarization 70%
Overall efficiency 50%

z: 12 bins 0.2 - 0.8
P_T: 5 bins 0-1 GeV
Also π^-



Results on kaons also

Proton π^+ (z = 0.3-0.7)

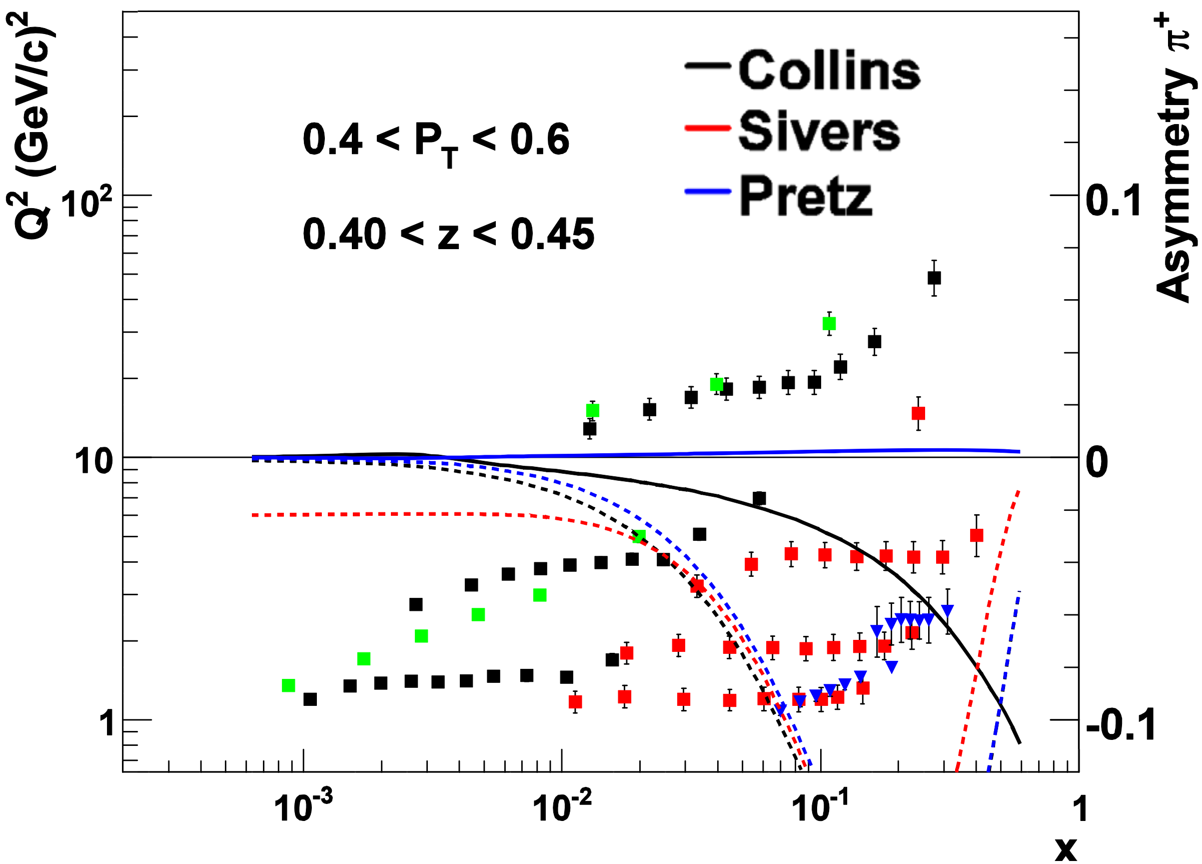


Projections with ^{3}He (neutron)

- 11 + 60 GeV
  72 days
- 11 + 100 GeV
  72 days
- 12 GeV SoLid

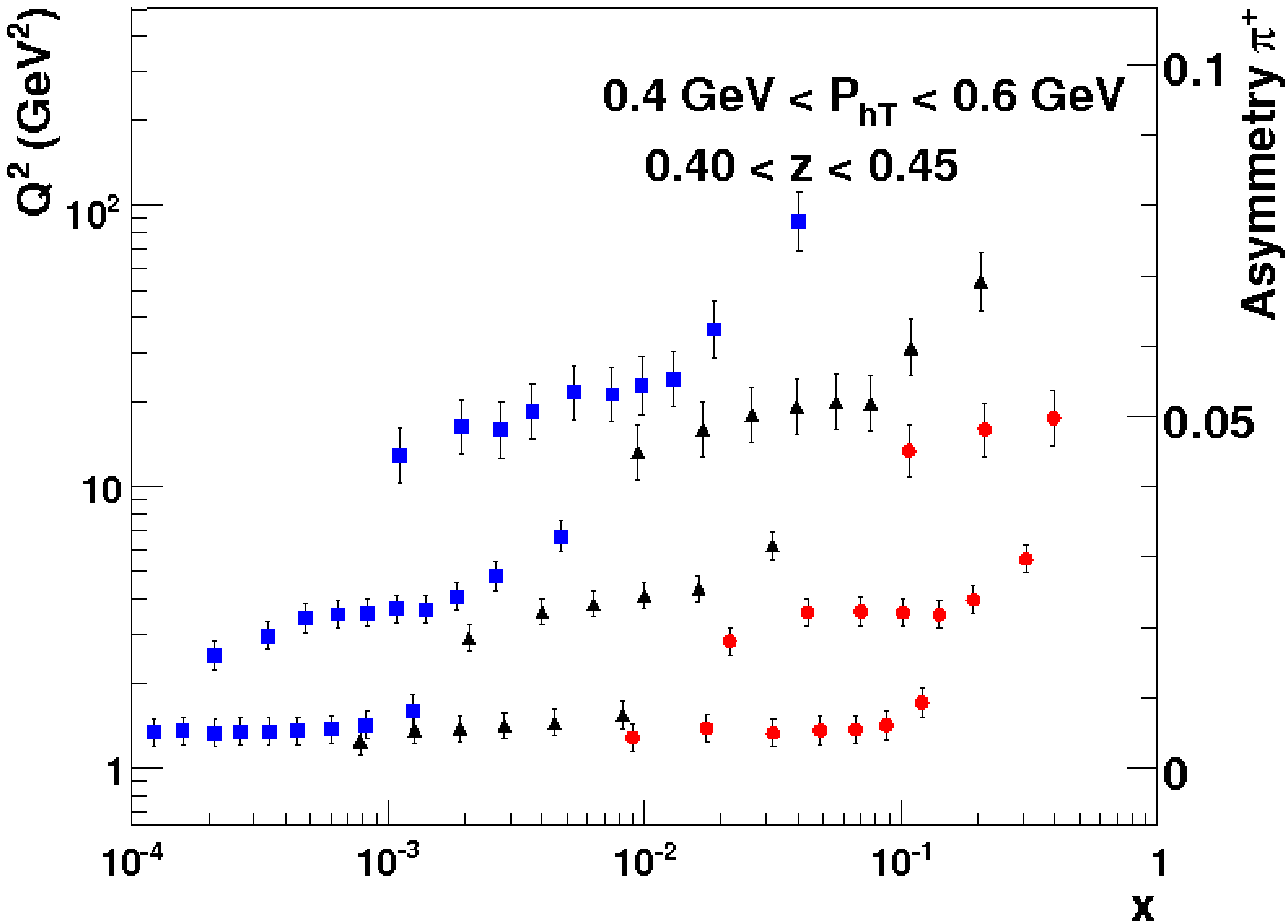
^{3}He: 87% effective polarization

Equal stat. for proton and neutron (combine ^{3}He and D)



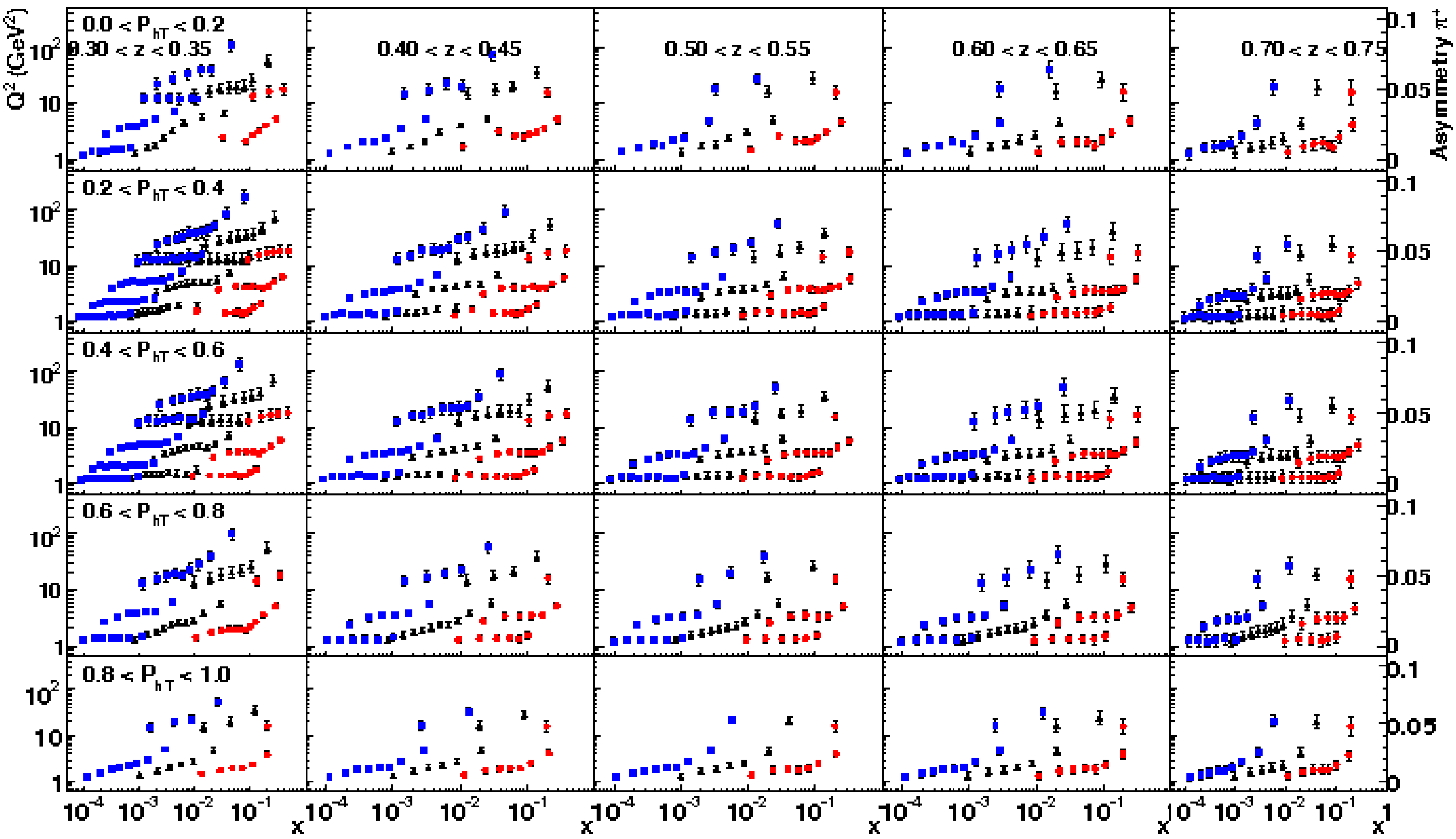
	11 + 60 GeV	11 + 100 GeV	3+20 GeV
P	36 d ($3\times10^{34}/cm^2/s$)	36 d ($1\times10^{34}/cm^2/s$)	36 d ($1\times10^{34}/cm^2/s$)
D	72 d	72 d	72 d
^{3}He	72 d	72 d	72 d

Higher center-of-mass energies



blue: 140 GeV, black 50 GeV, red 15 GeV, integrated lumi: 30 fb^{-1}

Higher center-of-mass energies



sensitivity to sea-quark *Sivers*

[talk by **T. Burton**: week-9]

zoom:

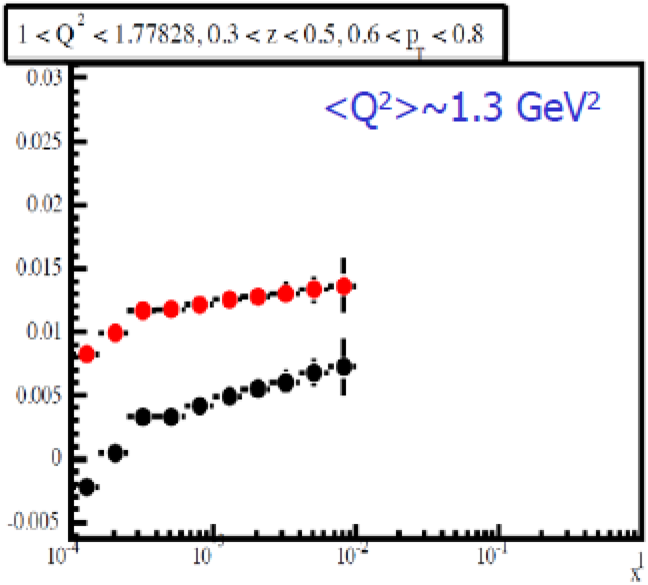
$0.3<z<0.5$

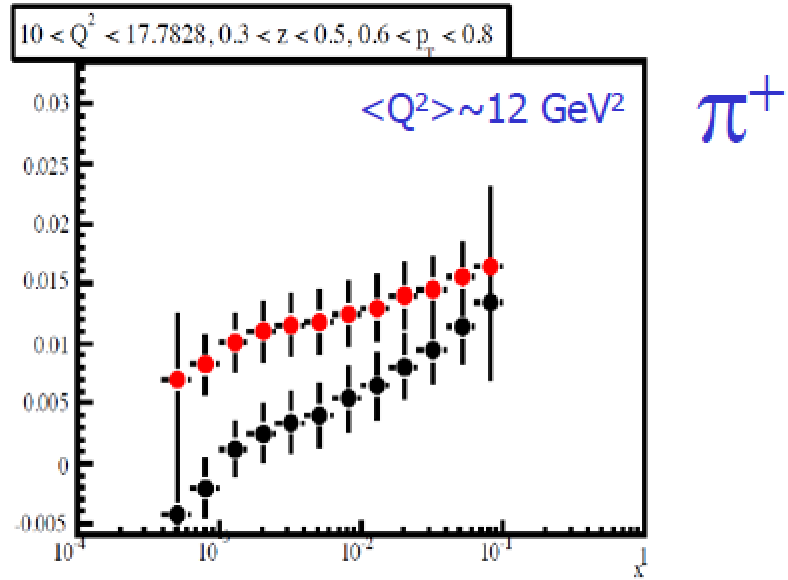
$0.6<P_{hT}<0.8$ GeV

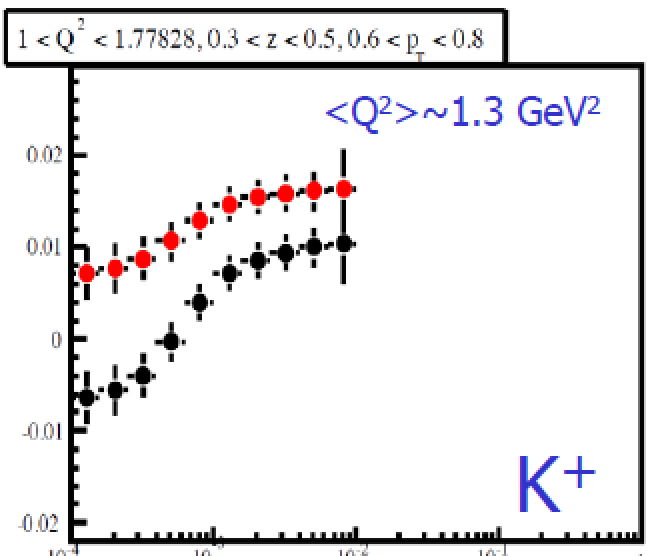
20x250 GeV

20 fb^{-1}

30 days
50% efficiency







- Desire wide kinematic coverage
  - delivered by EIC designs
- High luminosity means:
  - High Q^2 $(x, z, p_{h\perp})$-binning plausible
  - Low Q^2 rapidly systematics-domina

what about the gluon *Sivers* ?

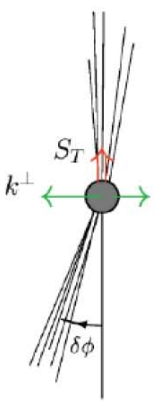
essentially nothing known → might be (very) large:

- positivity bound: $$f_{1T}^{\perp,g}(x,p_T^2)\frac{p_T}{M_p} \le f_1^g(x,p_T^2)$$

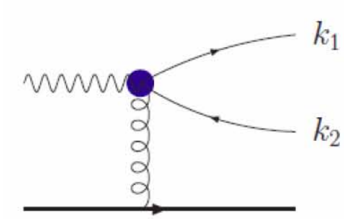
as for quark Sivers, further bounds might be derived

- Burkardt-SR: $$\sum_{a=q,\bar{q},g}\langle p_T^a\rangle = 0 \;\rightarrow\; \sum_{a=q,\bar{q},g}\int dx\; f_{1T}^{\perp(1),a}(x) = 0$$

ways to measure the gluon *Sivers* :



- DIS dijet (dihadron): $\gamma_T^* A \rightarrow q(k_1) + \bar{q}(k_2) + X$



- heavy quark / quarkonium production (*J/Ψ, D*):
  imbalance between q and q-bar probes gluon TMDs

[talk by C. Pisano: week-2, W. Xiao: week-5]

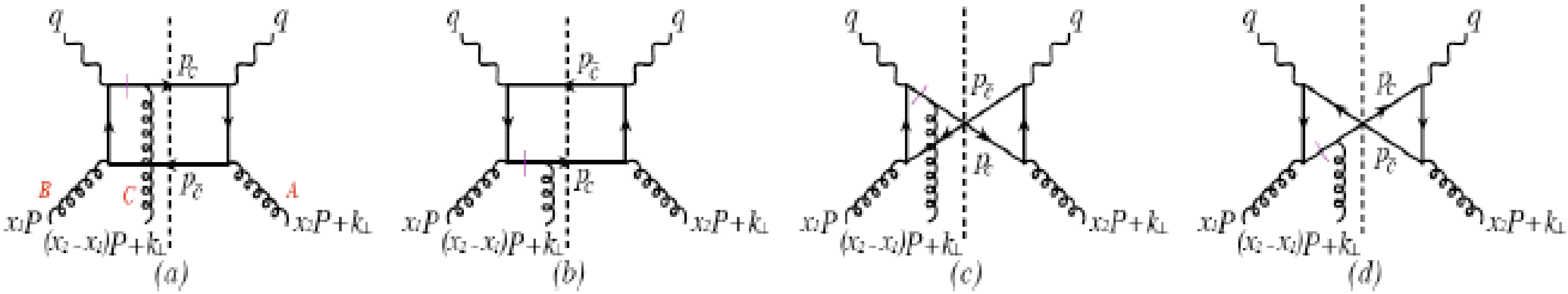
→ *inclusive* heavy flavour prod. probes the integrated gluon distr.
or gluon correlation (twist-3)

[talk by K. Tanaka: week-9]

Delia Hasch talk @ INT

D-meson Production at EIC

- Dominated by tri-gluon subprocesses (Kang Qiu PRD 2008)

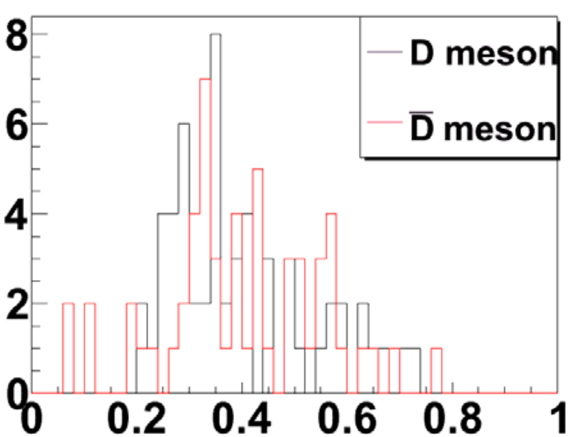


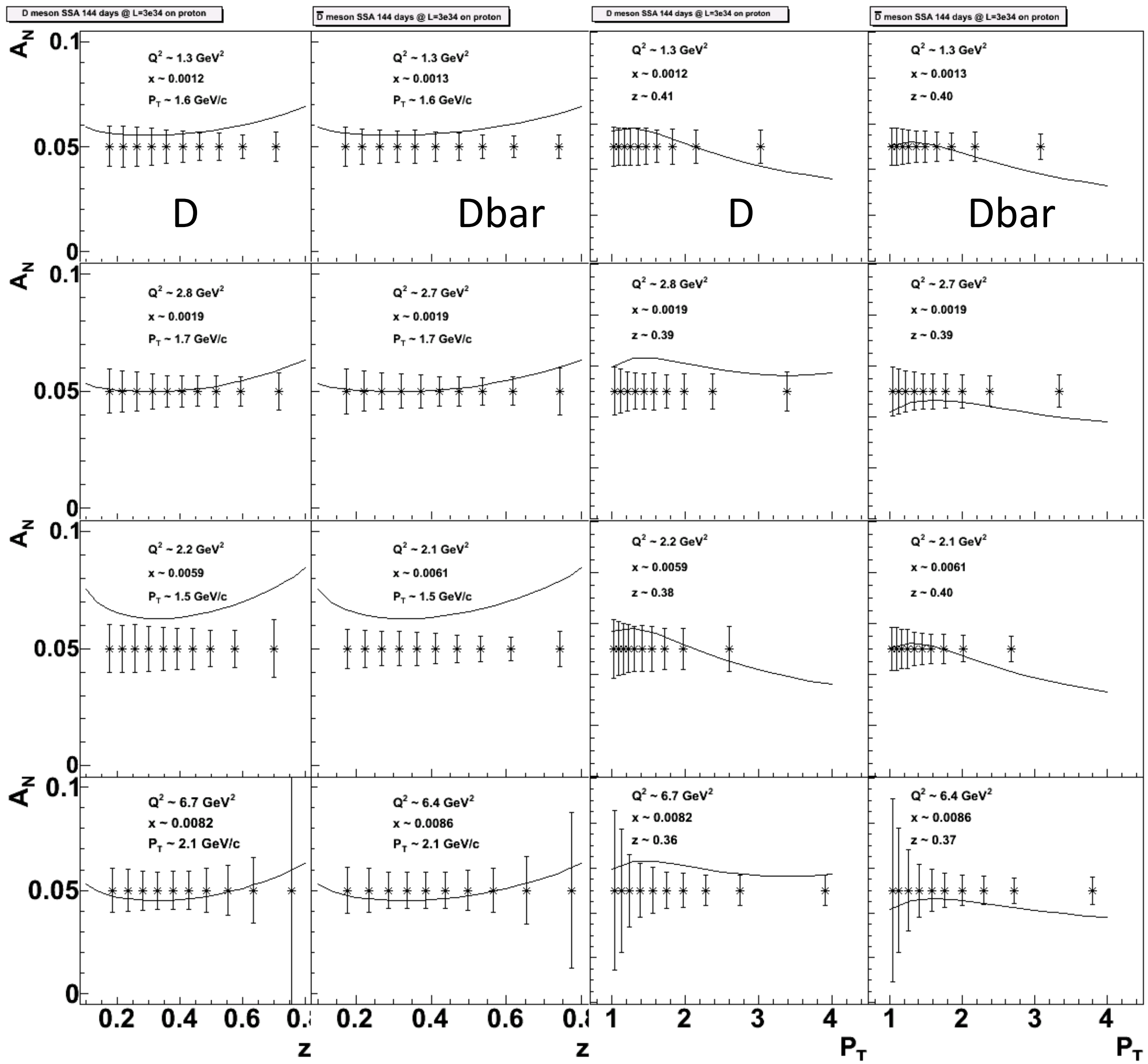
  - Four tri-gluon distributions (Kang, Koike, Tanaka)
  - Closely related to gluon Sivers function
  - Intrinsic charm is not important at large P_T
- Single transverse Spin Asymmetries
  - Twist-3 effect, fall off as $1/P_T$
  - Proportional to tri-gluon functions
  - Any small SSA is discovery of tri-gluon distribution functions.
  - Differentiate different tri-gluon functions with D-meson and Dbar-meson

X. Qian

144 Days @ L = 3×10^{34} on Proton

10 GeV > Momentum > 0.6 GeV
Polar angle > 10 degree
0.9 > y > 0.05; Q^2>1GeV^2,
P_T > 1GeV; z > 0.15
Include decay of kaon and pion
Additional 60% efficiency
80% polarization
Sqrt(2) for angular separation.
Dilution factor due to other processes and accidental pion and kaons.
2x2 bins in x and Q^2.





Calculations from Z. B. Kang

Summary

- **Frontiers in nucleon structure go beyond collinear, 1-D picture**
  - **three-dimensional imaging of the nucleon through GPDs, revealing hidden aspects of its internal dynamics**
  - **TMDs**
    - **Three-dimensional description of nucleon in momentum space**
    - **Direct link with orbital motion (orbital angular momentum)**
    - **Transverse motion: spin-orbit correlations, multi-parton correlations, dynamics of confinement and QCD**
- **EIC - ideal machine for the next frontier of QCD**
  - **From valence quark region to sea quark region**
  - **Gluon TMDs ……**

I like to thank Elke Aschenauer, Tom Burton, Markus Diehl, Delia Hasch, Min Huang, and X. Qian for their help

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