Feasibility Studies for EIC Nucleon Program

Harut Avakian

Jefferson Lab

"Electron-ion colliders"

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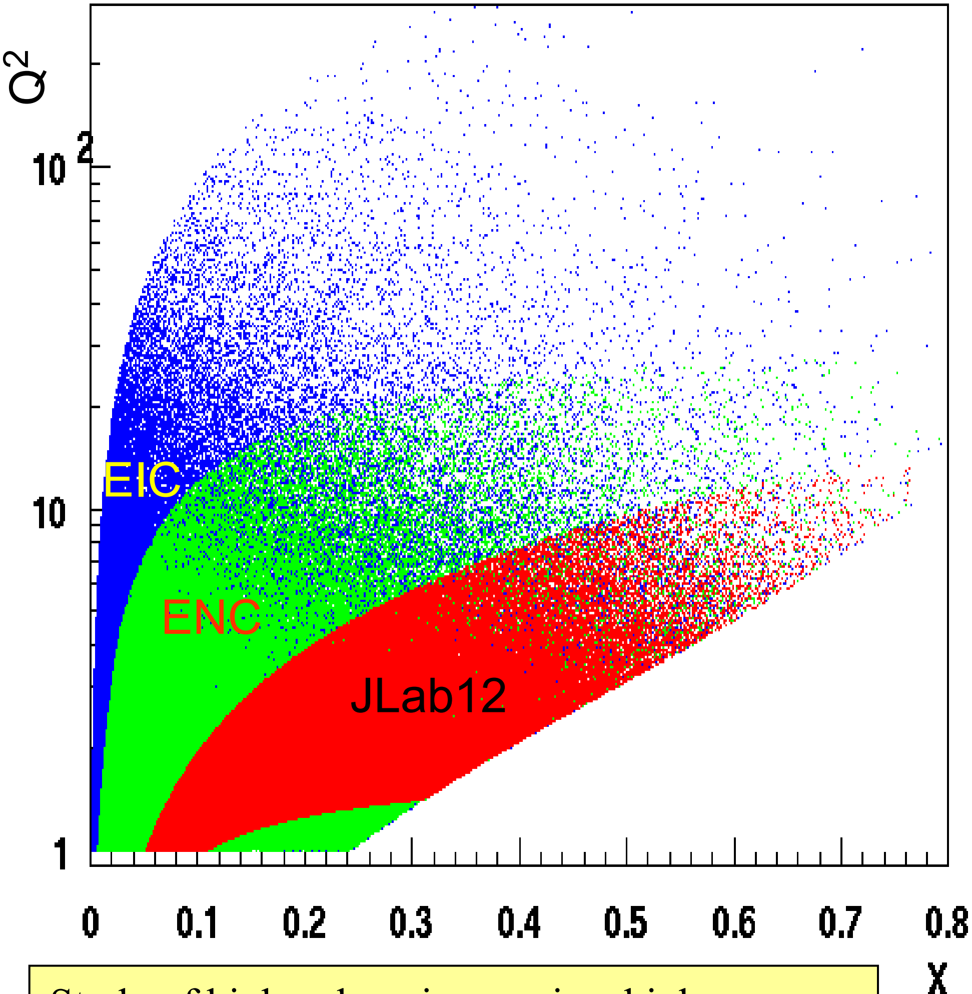
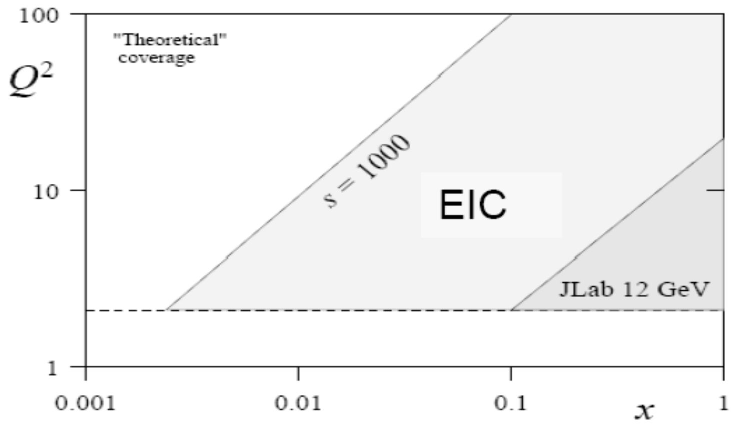
Outline

- Physics motivation
  - TMDs and spin-orbit correlations
    - Accessing TMDs in semi-inclusive DIS
    - Higher twists in SIDIS
  - GPDs and quark-gluon imaging
    - Accessing GPDs in hard exclusive processes
    - Higher twists in hard exclusive processes
- Projections for transverse SSAs at EIC and comparison with JLAB12
- Summary

Electroproduction kinematics: HERA→JLab→EIC





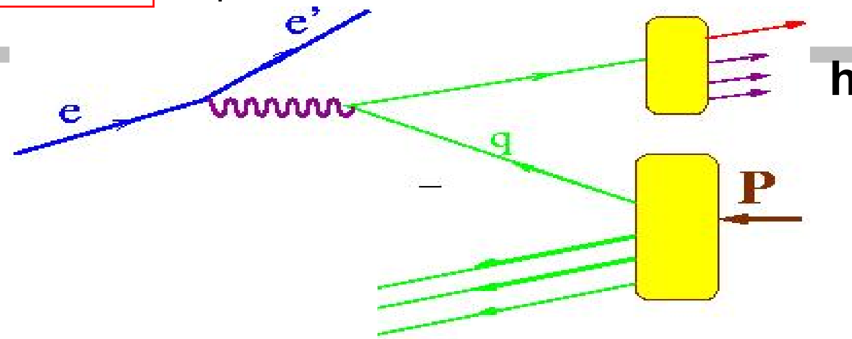
Study of high **x** domain requires high luminosity, low **x** higher energies

collider experiments
H1, ZEUS (EIC)
$10^{-4}<x_B<0.02$ (0.3): gluons (and quarks) in the proton

fixed target experiments
COMPASS, HERMES
→ $0.006/0.02<x_B<0.3$: gluons/valence and sea quarks
JLab/JLab@12GeV
→ $0.1<x_B<0.7$: valence quarks

Single hadron production in hard scattering

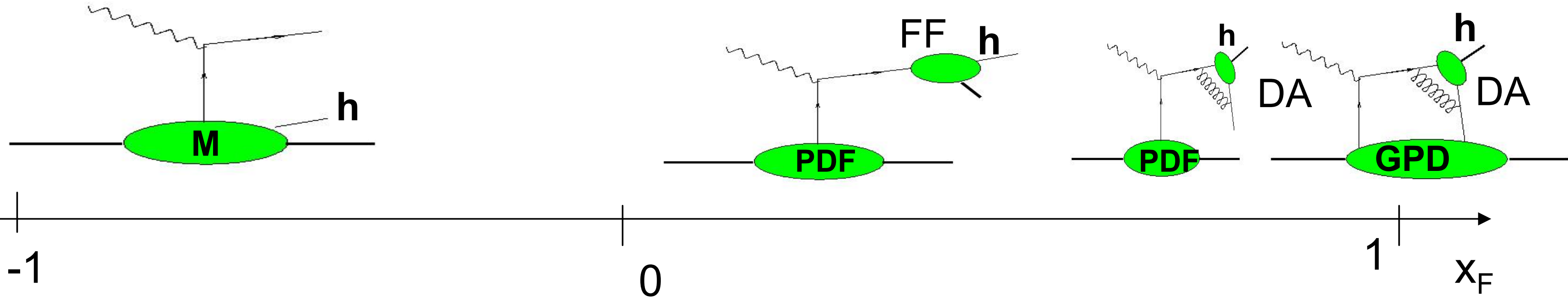
x_F>0 (current fragmentation)



x_F - momentum in the CM frame

Target fragmentation **Current fragmentation**

semi-inclusive **semi-exclusive** **exclusive**



Fracture Functions

k_T-dependent PDFs

Generalized PDFs

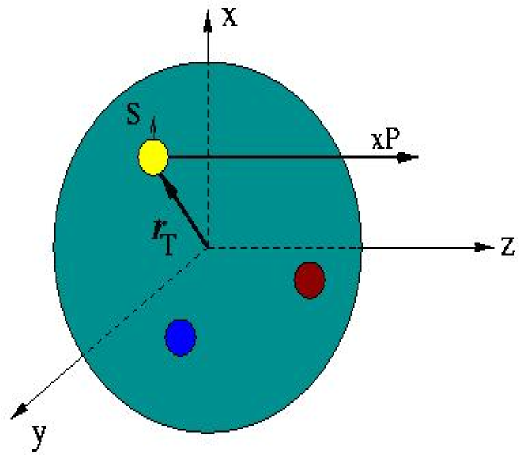
Measurements in different kinematical regions provide complementary information on the complex nucleon structure.

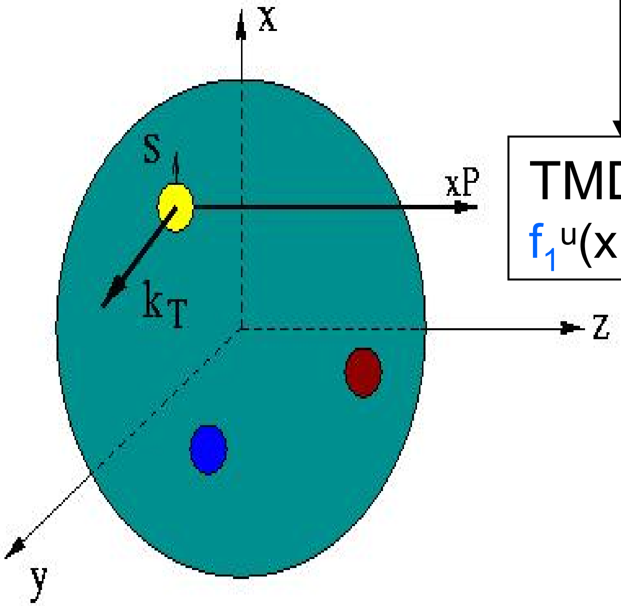
Structure of the Nucleon

$W_p^u(k, r_T)$ "Mother" Wigner distributions

$d^2 r_T$ ↓ / $d^2 k_T$ ↓

GPDs/IPDs





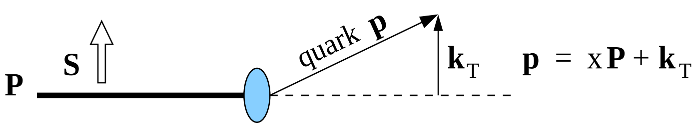
TMD PDFs
$f_1^u(x,k_T)$, .. $h_1^u(x,k_T)$

$d^2 k_T$ ↓

PDFs $f_1^u(x)$, .. $h_1^u(x)$

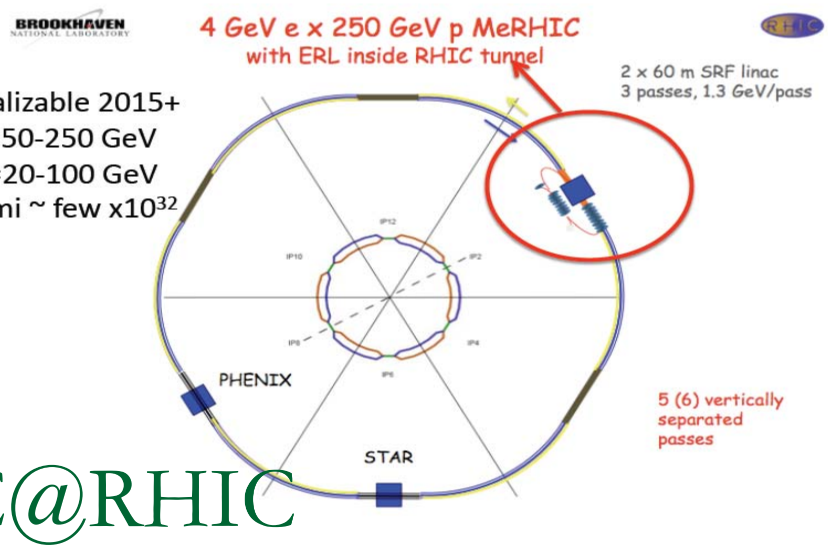
quark polarization

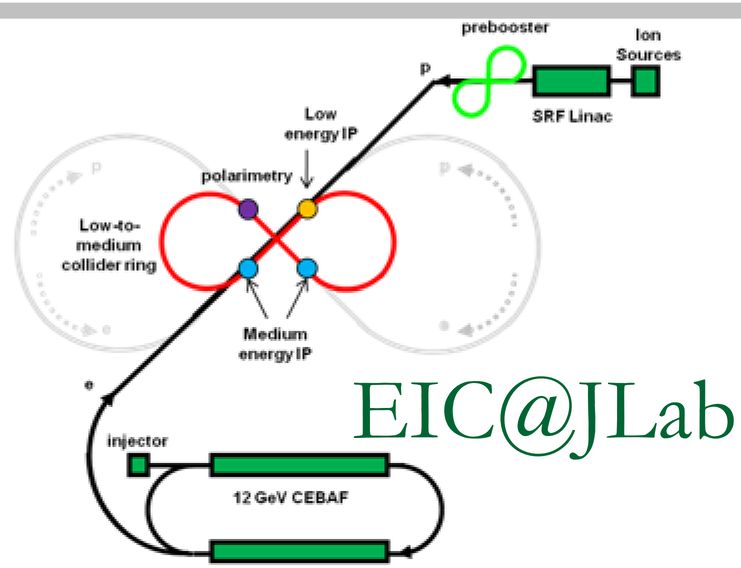
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$



- Gauge invariant definition (Belitsky,Ji,Yuan 2003)
- Universality of k_T-dependent PDFs (Collins,Metz 2003)
- Factorization for small k_T. (Ji,Ma,Yuan 2005)

EIC medium energy





Main Features

EIC@RHIC

- Electron energy: 4-20 GeV
- Proton energy: 50-250 GeV
  - More symmetric kinematics provides better *resolution* and *particle id*
- Luminosity: ~ 10^{33} cm^{-2} s^{-1}
  - in *range* around s ~ 1000-10000 GeV^2
- Polarized electrons and light ions
  - longitudinal and transverse
- Limited R&D needs
- ? interaction regions (detectors)
- 90% of hardware can be reused

EIC@JLab

- Electron energy: 3-11 GeV
- Proton energy: 12-60 GeV
  - More symmetric kinematics provides better *resolution* and *particle id*
- Luminosity: few x 10^{34} cm^{-2} s^{-1}
  - in *range* around s ~ 1000 GeV^2
- Polarized electrons and light ions
  - longitudinal and transverse
- Limited R&D needs
- 3 interaction regions (detectors)
- Potential upgrade with high-energy ring

Current Ideas for EIC

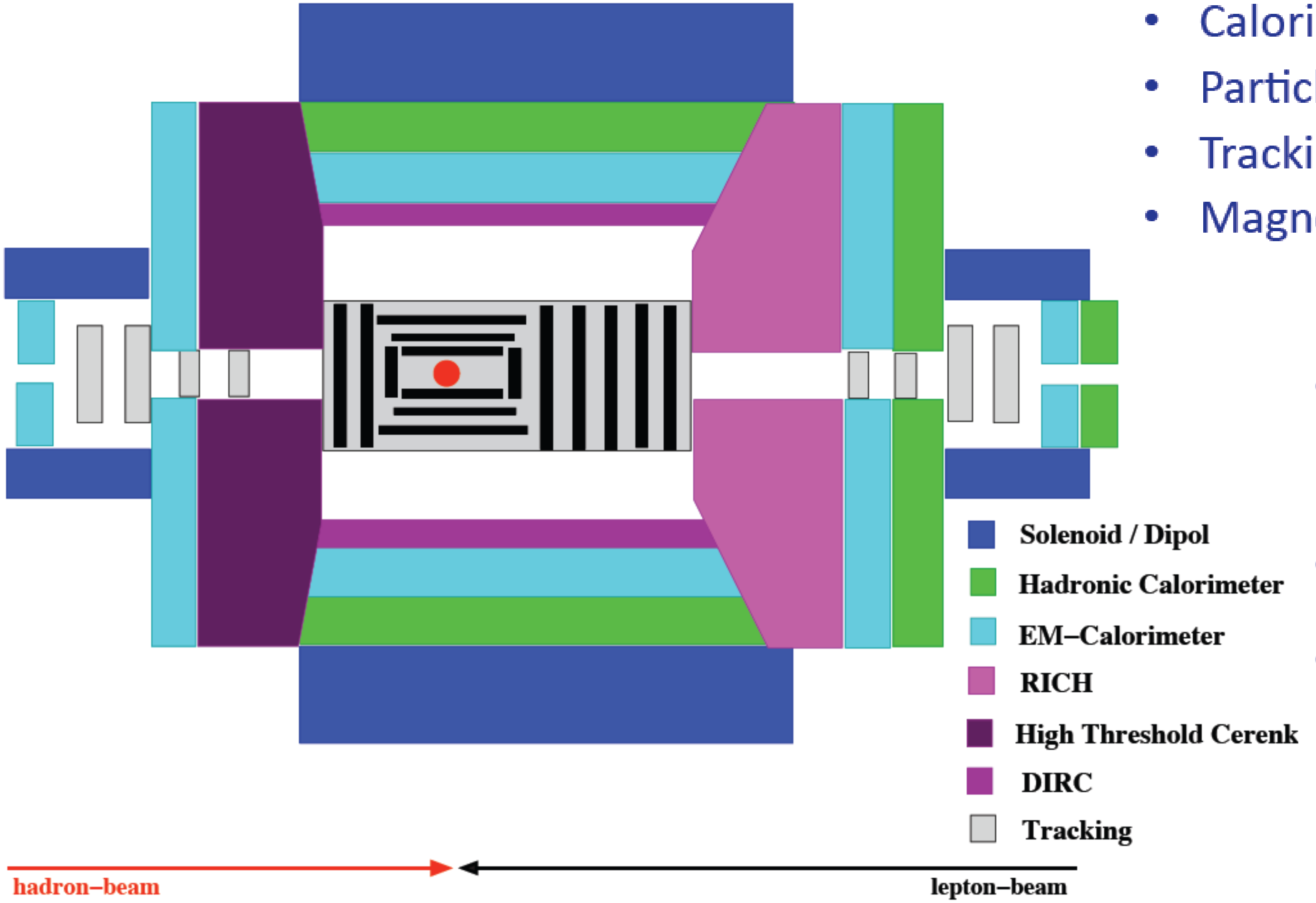
	Energies	s	luminosity
(M)EIC@JLab	Up to 11 x 60	150-2650	Few x 10^{34}
Staged MeRHIC@BNL	Up to 4 x 250	(400-)4000	Close to 10^{33}
Future ELIC@JLab	Up to 11 x 250	11000	Close to 10^{35}
eRHIC@BNL	Up to 20 x 325	26000	Few x 10^{33}

Present focus of interest (in the US) are the (M)EIC and Staged MeRHIC versions, with s up to 2650 and 4000, resp.

Most of the slides are for a "generic" US version of an EIC (5x50 or 4x60):

- polarized beams (longitudinal and transverse, > 70%)
- luminosities of at least 10^{33} (~10^{34} for exclusive processes)
- energies up to 10 x 250, or s = 10000

The Detector

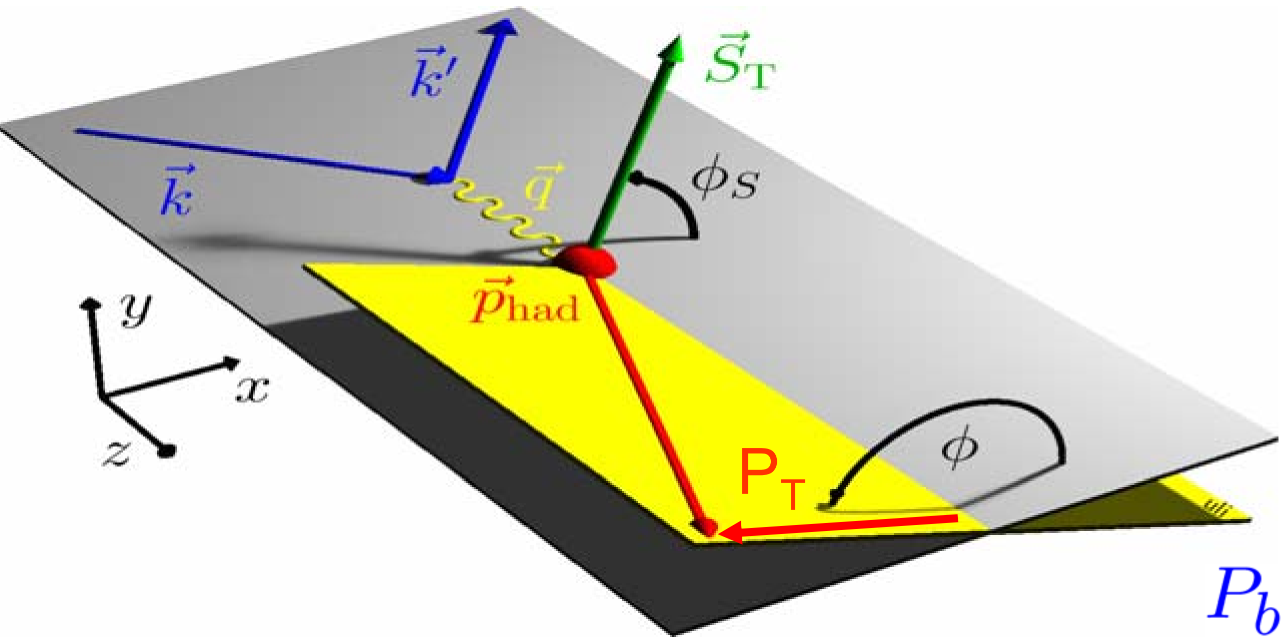


- Calorimetry (EM & Hadronic)
- Particle ID (RICH, TRD ….)
- Tracking (central & forward)
- Magnets

- Tracking, calorimetry for very forward physics (low x, and low Q^2)
  - Diffraction
- Particle ID, spectrometer using beam elements
- Radiation hard, resistence

Wide kinematic coverage and large acceptance would allow studies of hadronization both in the target and current fragmentation regions

SIDIS kinematical plane and observables



$$\nu = (qP)/M$$
$$Q^2 = (k - k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$
$$x_F = p_{||}/|\vec{q}|$$

P_b, P_t

U unpolarized
L long.polarized
T trans.polarized

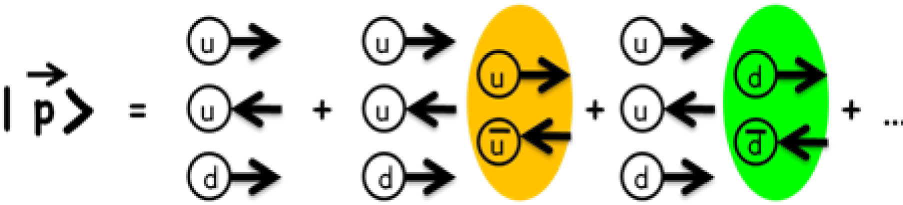
Target polarization **Beam polarization**

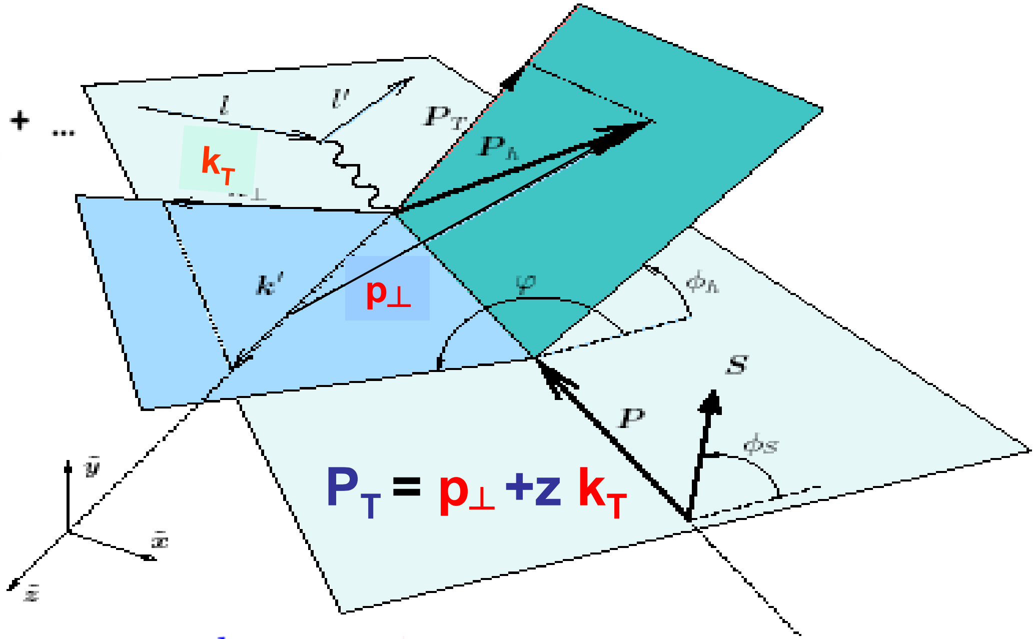
$$\sigma = \sigma_{UU} + P_t \sigma_{UT} \sin(\phi - \phi_S) + P_b P_t \sigma_{LT} \cos(\phi - \phi_S) \ldots$$

$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sigma_{UT}}{\sigma_{UU}} \longrightarrow$$

$\sin(\phi-\phi_S)$ moment of the cross section for unpolarized beam and transverse target

SIDIS: partonic cross sections





$$d\sigma^h \propto \sum f^{H\to q}(x, k_T) \otimes \mathrm{d}\sigma_q(y) \otimes D^{q\to h}(z, p_\perp)$$

↓

$$d\sigma^h \propto \sum f^{H\to q}(x)\mathrm{d}\sigma_q(y) D^{q\to h}(z)$$ ←

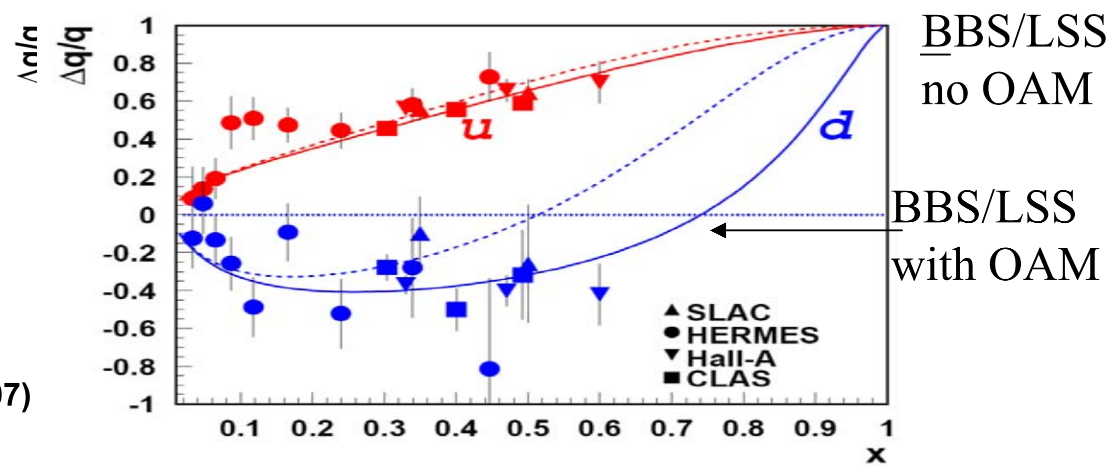
Is this good enough for flavor decomposition?

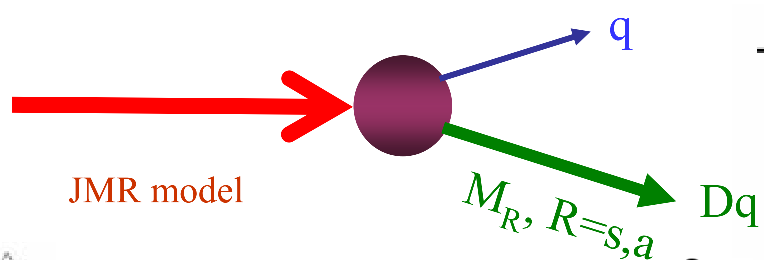
Quark longitudinal polarization

$$u^+(x,k_T) = f_1^u(x,k_T^2) + g_1^u(x,k_T^2)$$

$$u^-(x,k_T) = f_1^u(x,k_T^2) - g_1^u(x,k_T^2)$$

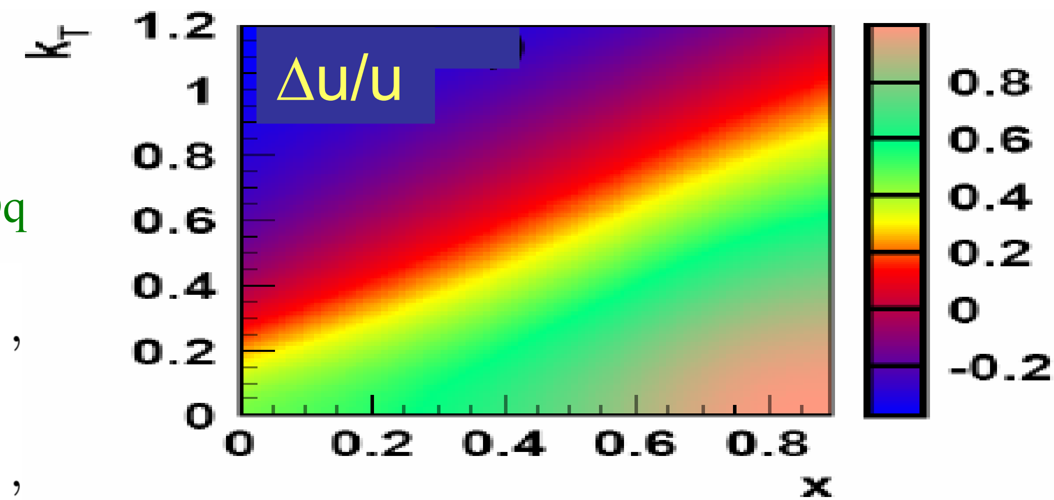
Effect of the orbital motion on the q- may be significant (H.A.,S.Brodsky, A.Deur,F.Yuan 2007)





$$u^+(x,\mathbf{k}_T^2) \propto \frac{(xM+m)^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

$$u^-(x,\mathbf{k}_T^2) \propto \frac{\mathbf{k}_T^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$



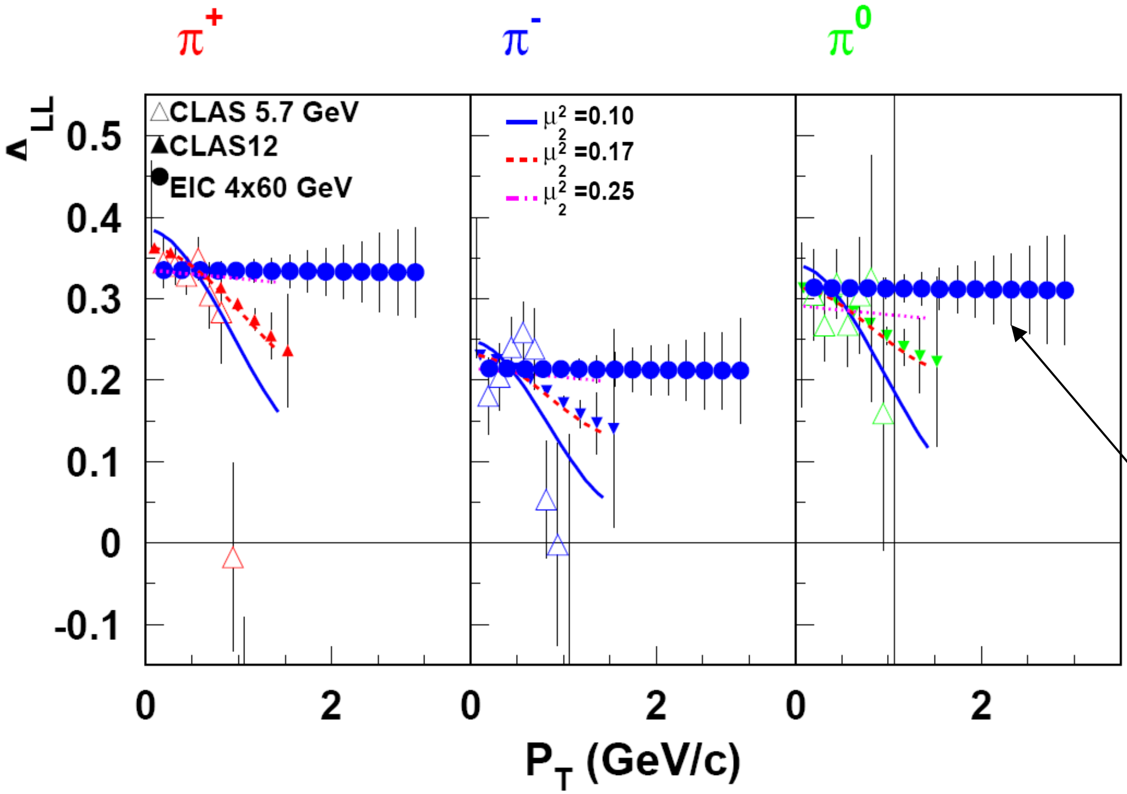
(dipole formfactor), J.Ellis, D-S.Hwang, A.Kotzinian

For given x the sign of the polarization is changing at large k_T

A_1 P_T-dependence in SIDIS

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} \, e^{-z^2 P_T^2 \frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$

M.Anselmino et al
hep-ph/0608048



$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

Perturbative limit calculations available for $g_1^q(x,k_T), f_1(x,k_T)$:

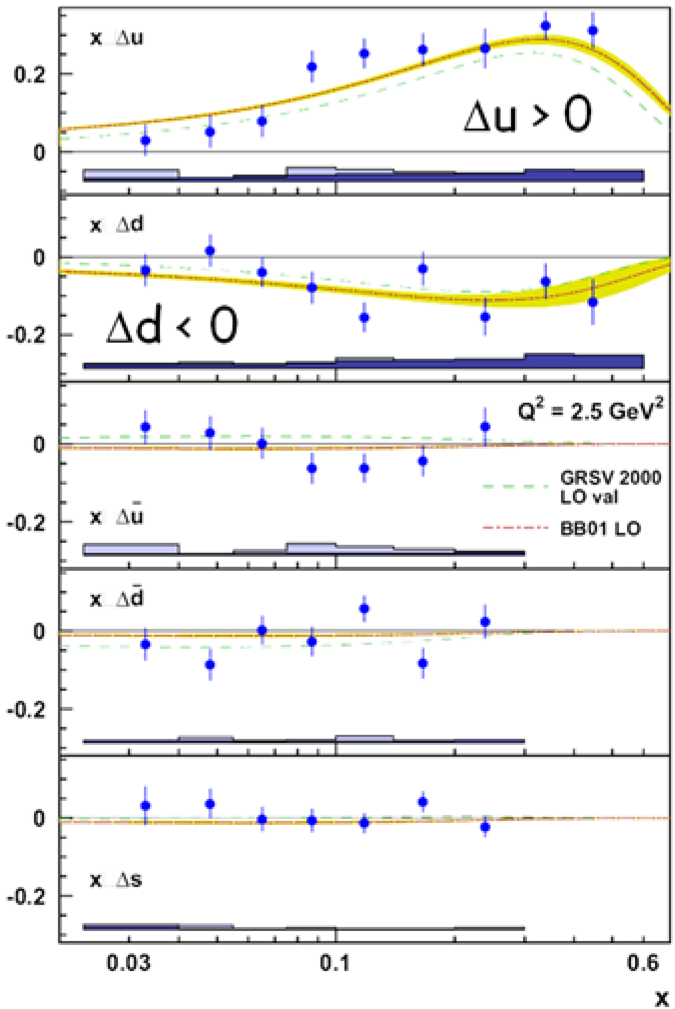
J.Zhou, F.Yuan, Z Liang: arXiv:0909.2238

- **A_{LL} (π) sensitive to difference in k_T distributions for f_1 and g_1**
- **Wide range in P_T allows studies of transition from TMD to perturbative approach**

Flavor Decomposition @ EIC

- **quark polarization $\Delta q(x)$**

→first 5-flavor separation



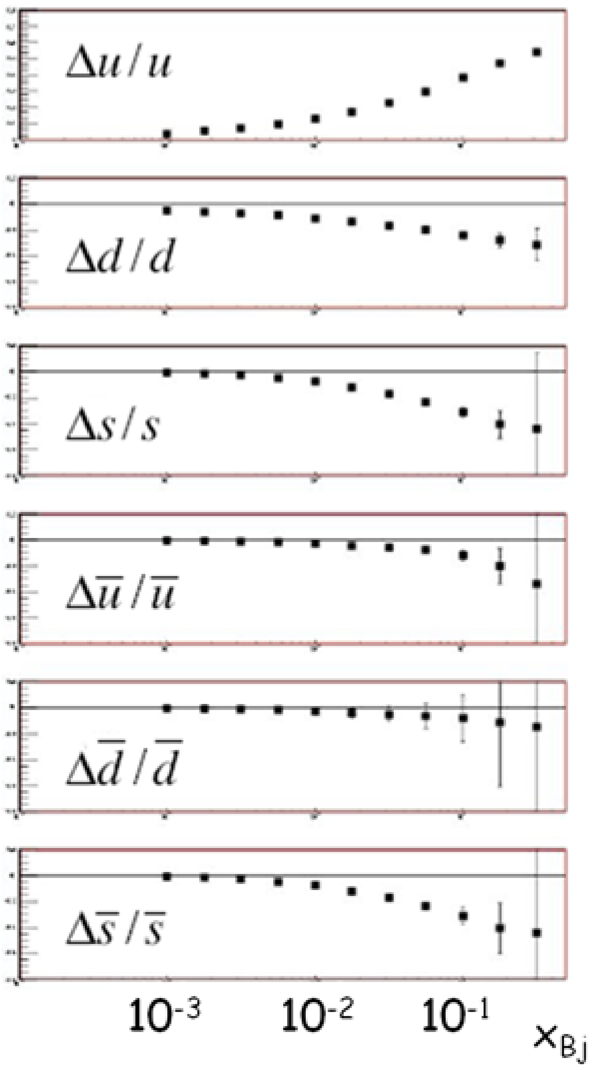
100 days at 10^{33}

Lower x ~ 1/s

5 on 50 → s = 1000

(Ed Kinney, Joe Seele)

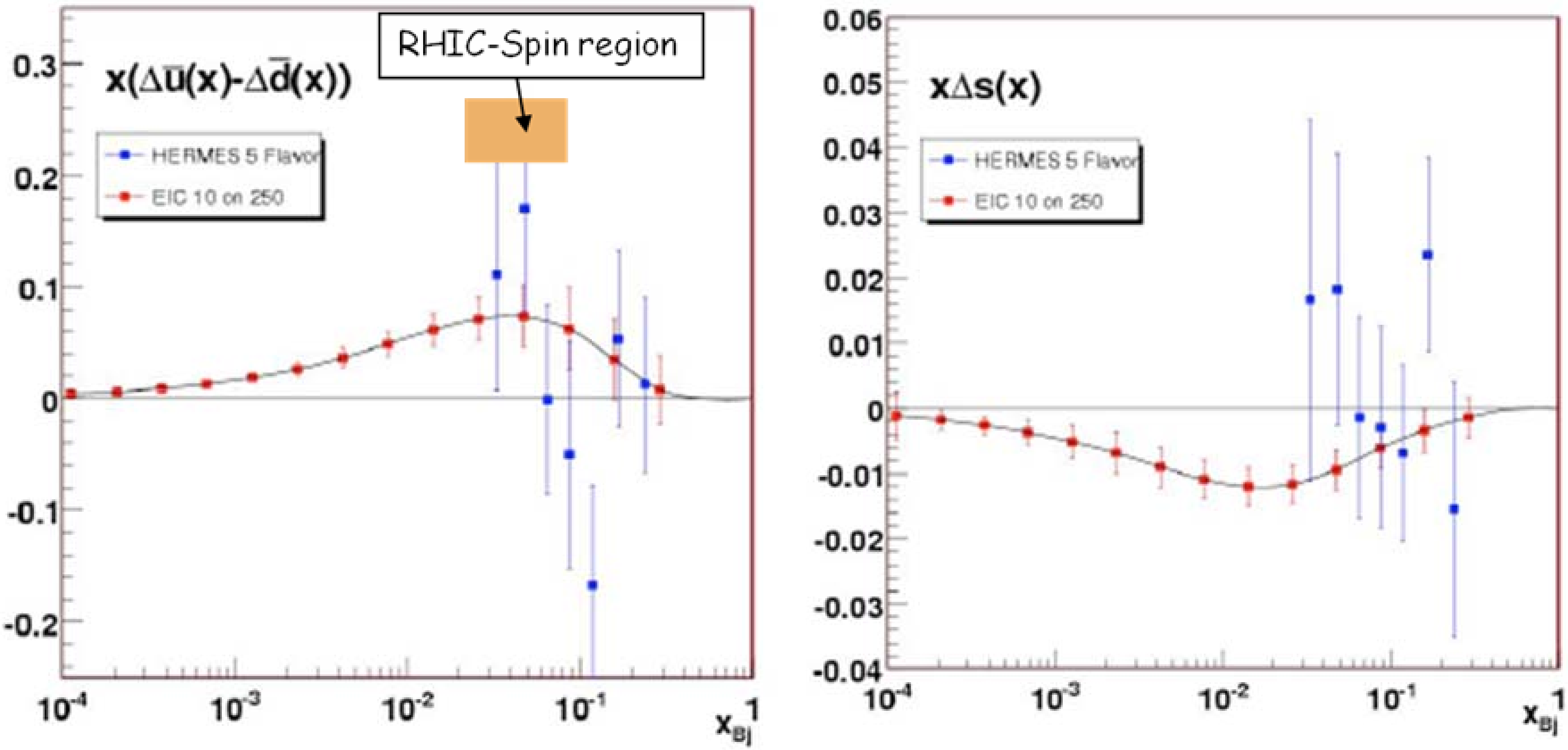
5 on 50 EIC projected data



Precisely image the sea quarks

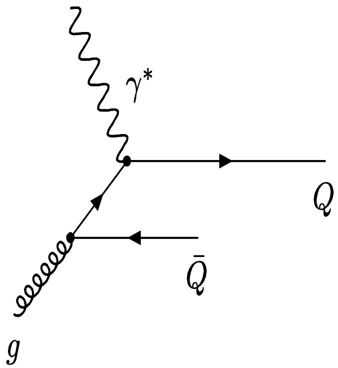
Spin-Flavor Decomposition of the Light Quark Sea

100 days at 10^{33}



Flavor decomposition will be performed using binning in P_T

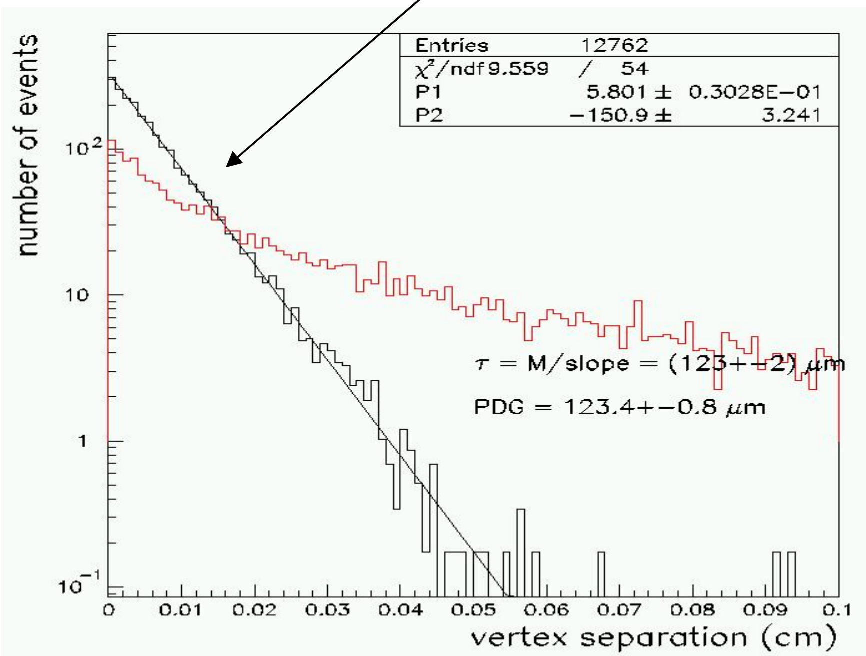
The Gluon Contribution to the Proton Spin

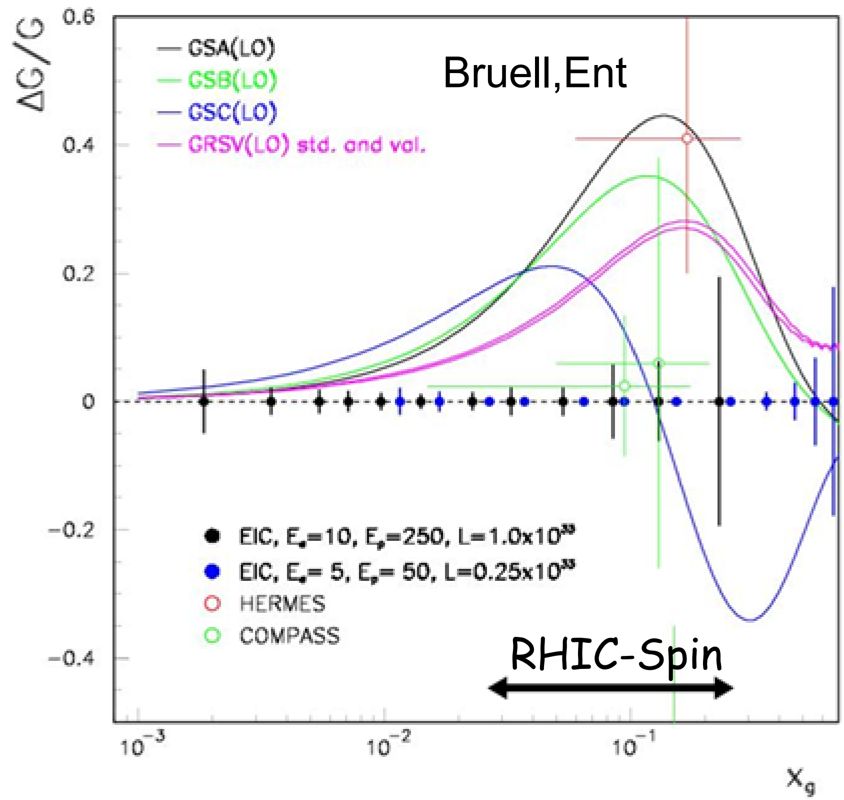


Projected data on $\Delta g/g$ with an EIC, via $\gamma + p \rightarrow D^0 + X$

$K^- + \pi^+$

assuming vertex separation of 100 μm.



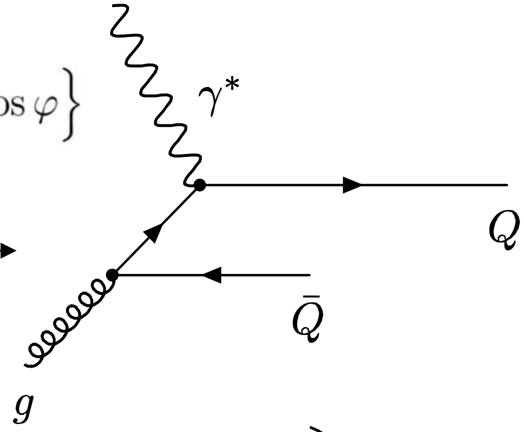


- **Uncertainties in $x\Delta g$ smaller than 0.01**
- **Measure 90% of ΔG (@ Q^2 = 10 GeV^2)**

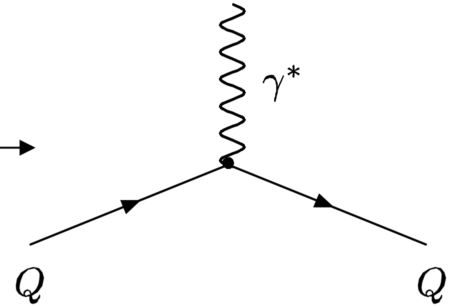
Measuring the charm content of the proton

$$\frac{d^3\sigma_{lN}}{dx\,dQ^2 d\varphi} = \frac{\alpha_{em}^2}{xQ^4}\Big\{ \left[1+(1-y)^2\right] F_2(x,Q^2) - 2xy^2 F_L(x,Q^2) + 4x(1-y)F_A(x,Q^2)\cos 2\varphi + 4x(2-y)\sqrt{2(1-y)}F_I(x,Q^2)\cos\varphi \Big\}$$

Within the FFNS (no heavy quarks), the leading mechanism contributing to F_2, F_L and F_A.



At high Q^2 with heavy quarks (VFNS), there is additional contribution to F_2, but not to F_L and F_A!

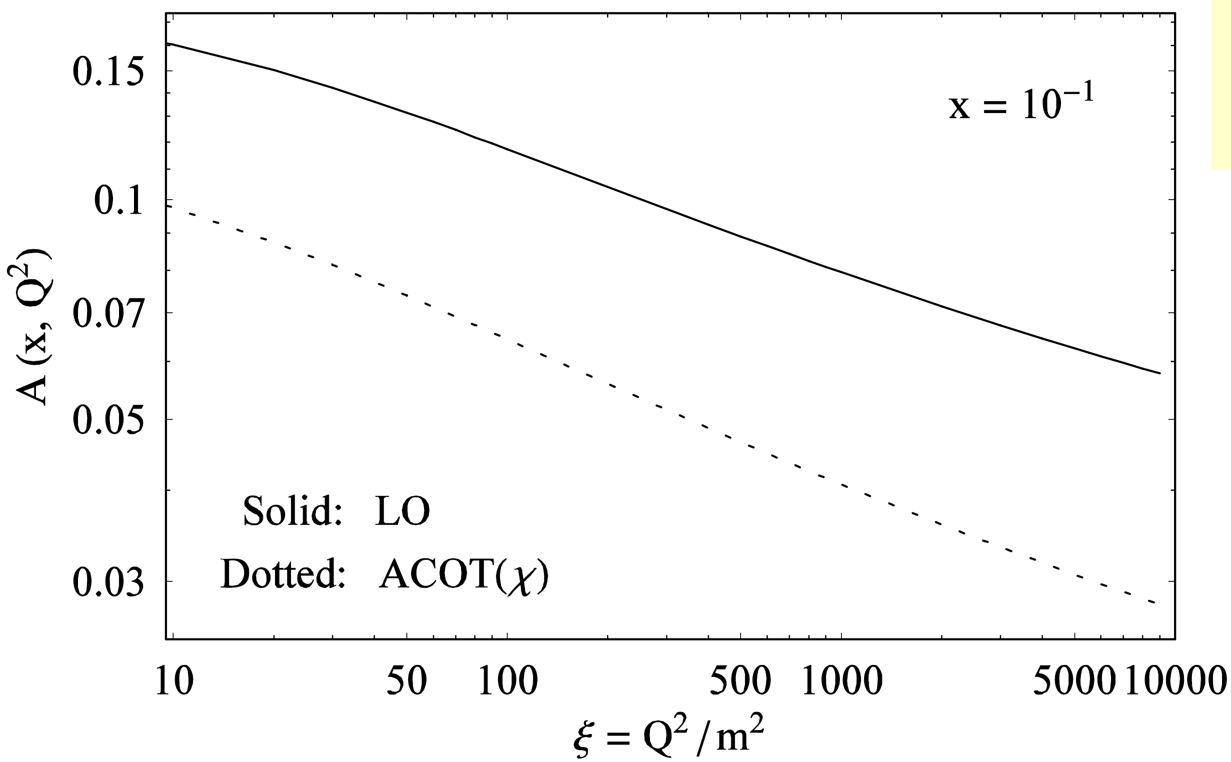


The heavy-quark content of the proton is due to resummation of the mass logarithms of the type $\alpha_s \ln(Q^2/m^2)$ and thus, closely related to behavior of asymptotic perturbative series for high Q^2.

•N.Ya.Ivanov, Nucl. Phys. B 814 (2009), 142

Resummation for $A = 2xF_A / F_2$

$$l(\ell) + N(p) \to l(\ell - q) + Q(p_Q) + X[\overline{Q}](p_X)$$



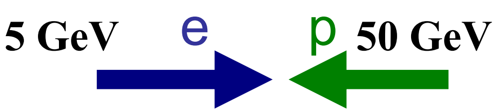
•L.N. Ananikyan, N.Ya. Ivanov,. **Nucl.Phys.B762:256-283,2007**.
N.Ya.Ivanov, Nucl. Phys. B 814 (2009), 142

CTEQ PDFs used for estimates

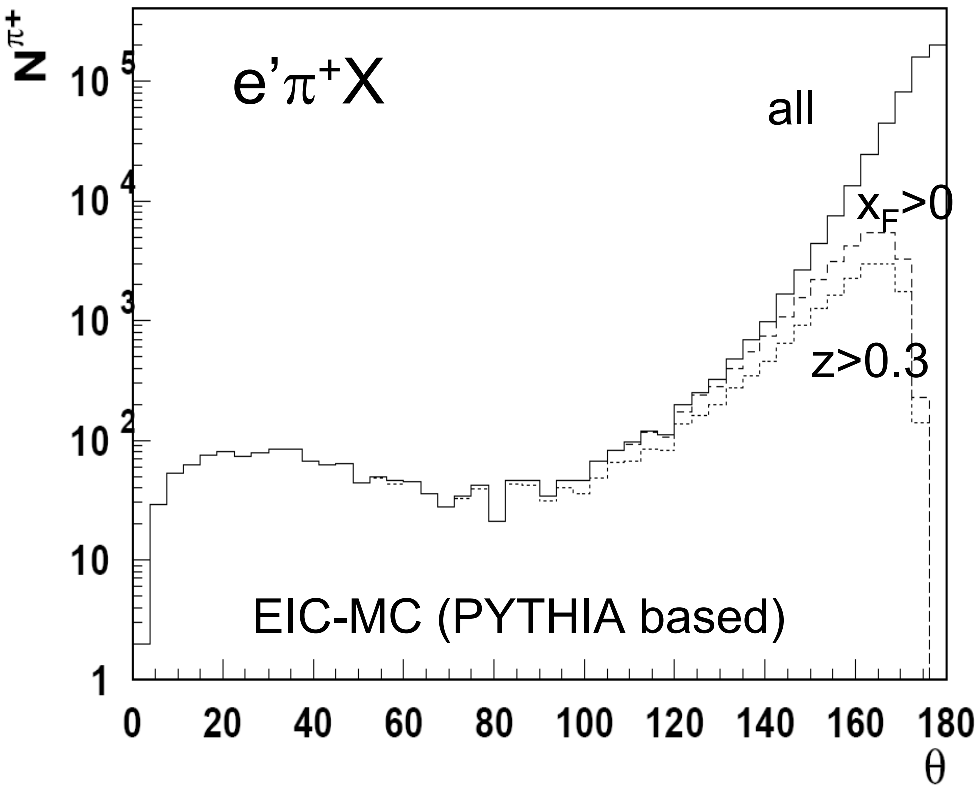
The mass logarithms resummation (or heavy-quark densities) should reduce the pQCD predictions for $R = F_L / F_T$ and $A = 2xF_A / F_2$.
•cos2ϕ moment in charm meson production provides access to charm densities

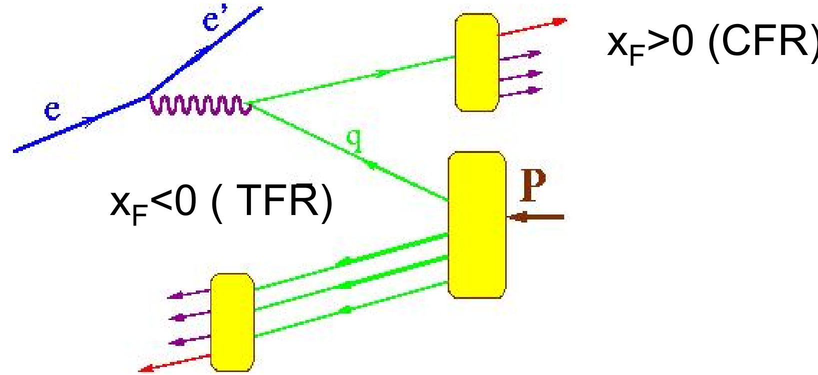
•**N.Ya.Ivanov, Nucl. Phys. B 814 (2009), 142**

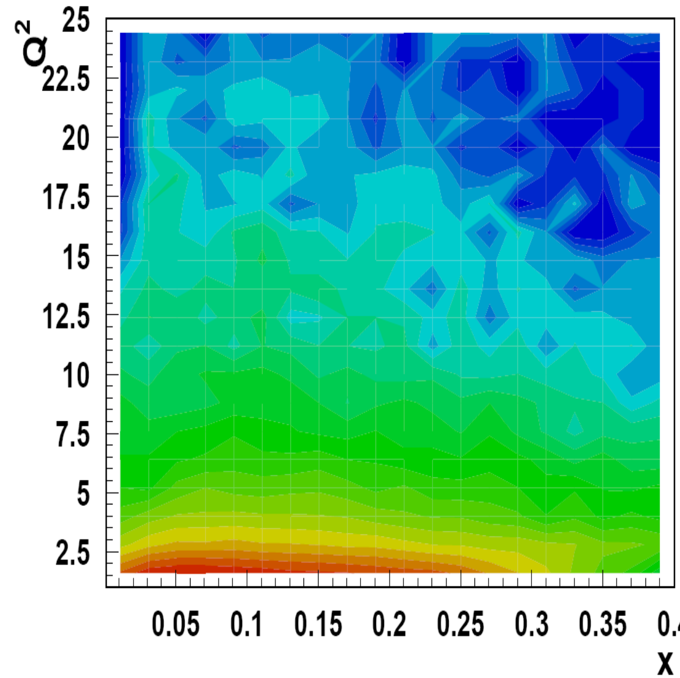
EIC: Kinematics Coverage



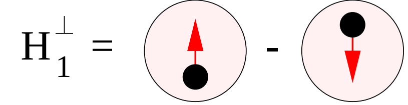
EIC-MC



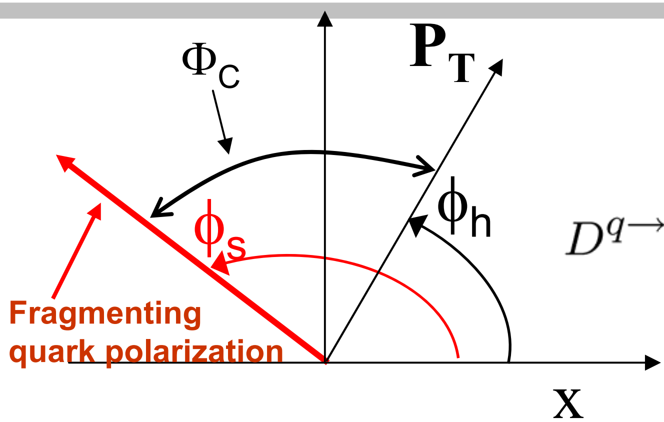




Major part of current particles at large angles in Lab frame (PID at large angles crucial).



Collins mechanism for SSA

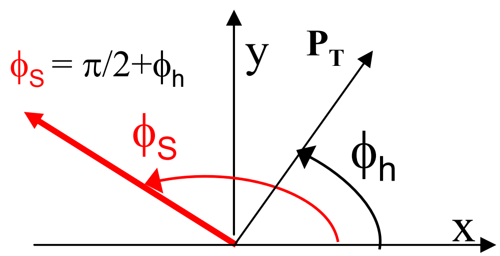


fragmentation of transversely polarized quarks into unpolarized hadrons

$$D^{q\to h}(z,P_T) = D_1^{q\to h}(z,P_T) + H_1^{\perp q\to h}(z,P_T)\times\sin(\underbrace{\phi_h - \phi_s}_{\Phi_C})$$

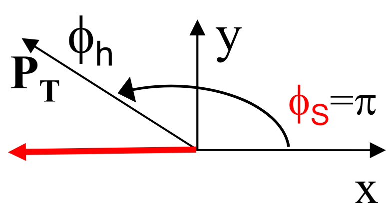
$$h_1 H_1^{\perp} \quad \sin\phi_C$$

$$F_{UU}^{\cos 2\phi}$$



$$h_1^{\perp} H_1^{\perp} \quad \cos 2\phi_h$$

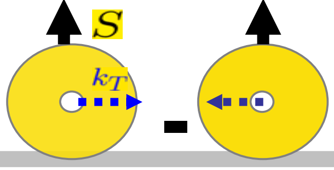
$$F_{LU}^{\sin\phi} \quad F_{UL}^{\sin\phi}$$

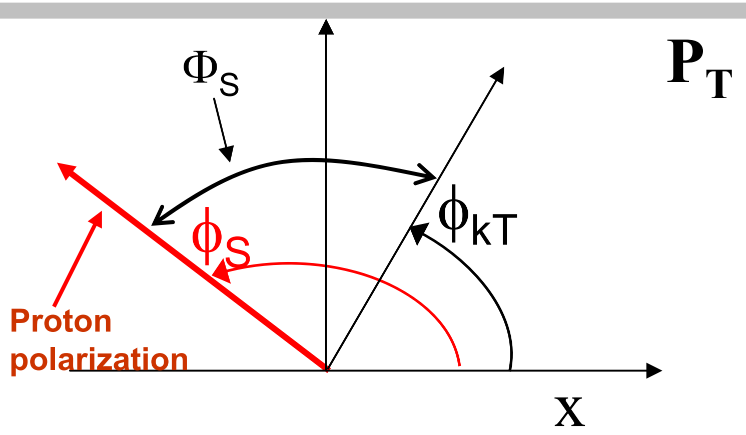


$$eH_1^{\perp}\ ,\ h_L H_1^{\perp} \quad \sin\phi_h$$

HT function related to force on the quark. M.Burkardt (2008)

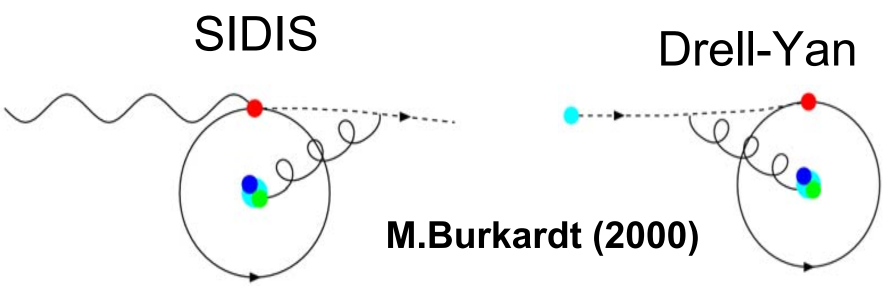
Sivers mechanisms for SSA





Correlation between quark transverse momentum and the proton spin

$$f_{q/p\uparrow}(x, k_T^2) \Rightarrow f_1^q(x, k_T^2) - f_{1T}^{\perp q}(x, k_T^2) \sin \Phi_S$$



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

$$F_{UT}^{\sin(\phi-\phi_S)} \propto f_{1T}^{\perp q} D_1^q$$

$$F_{LU}^{\sin\phi} \propto g^{\perp q} D_1^q$$

$$F_{UL}^{\sin\phi} \propto f_L^{\perp q} D_1^q$$

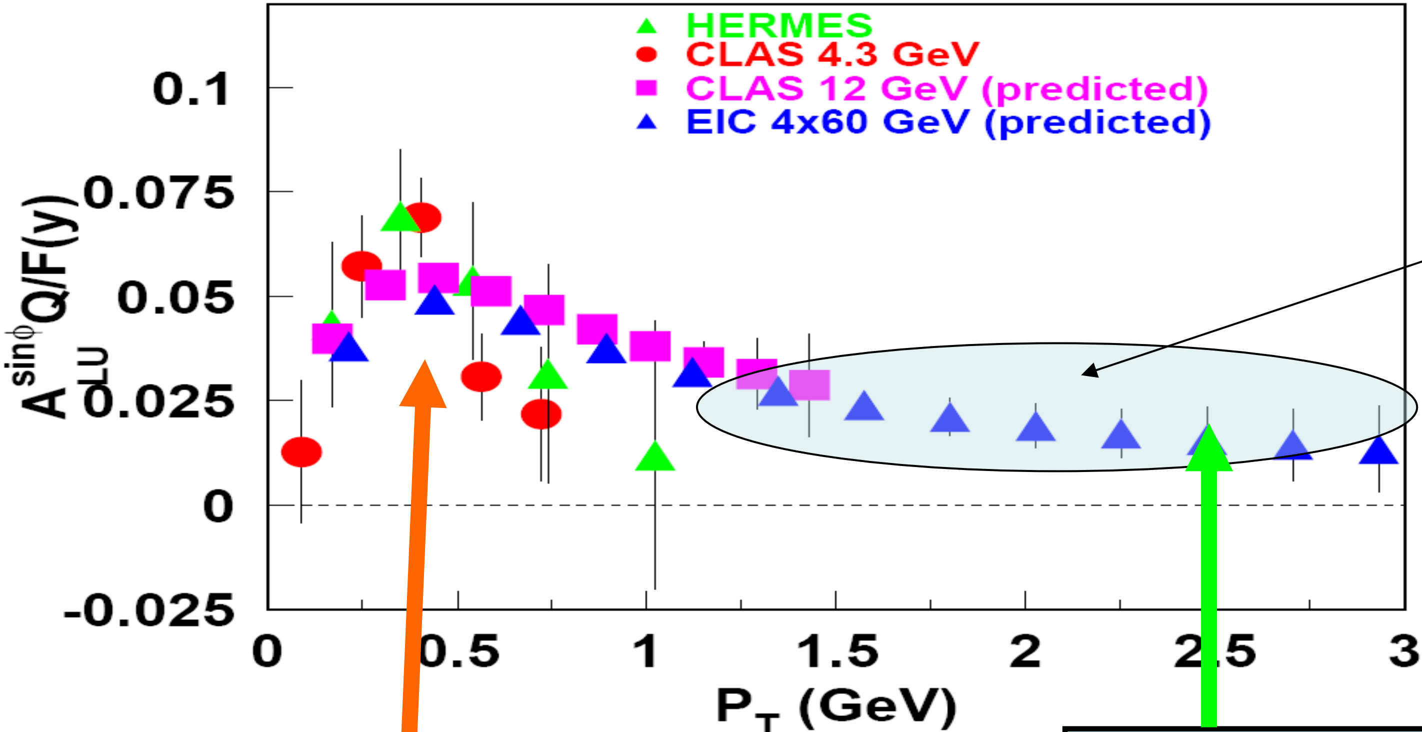
HT asymmetries (T-odd)

No leading twist, provide access to quark-gluon correlations

P_T-dependence of beam SSA

$\sigma^{\sin\phi}_{LU(UL)}$ ~$F_{LU(UL)}$~ 1/Q (Twist-3)

$$A_{LU} \propto g^{\perp}(x) D_1(z)$$



In the perturbative limit $1/P_T$ behavior expected

4x60 100 days, $L=10^{33}cm^{-2}s^{-1}$

Nonperturbative TMD

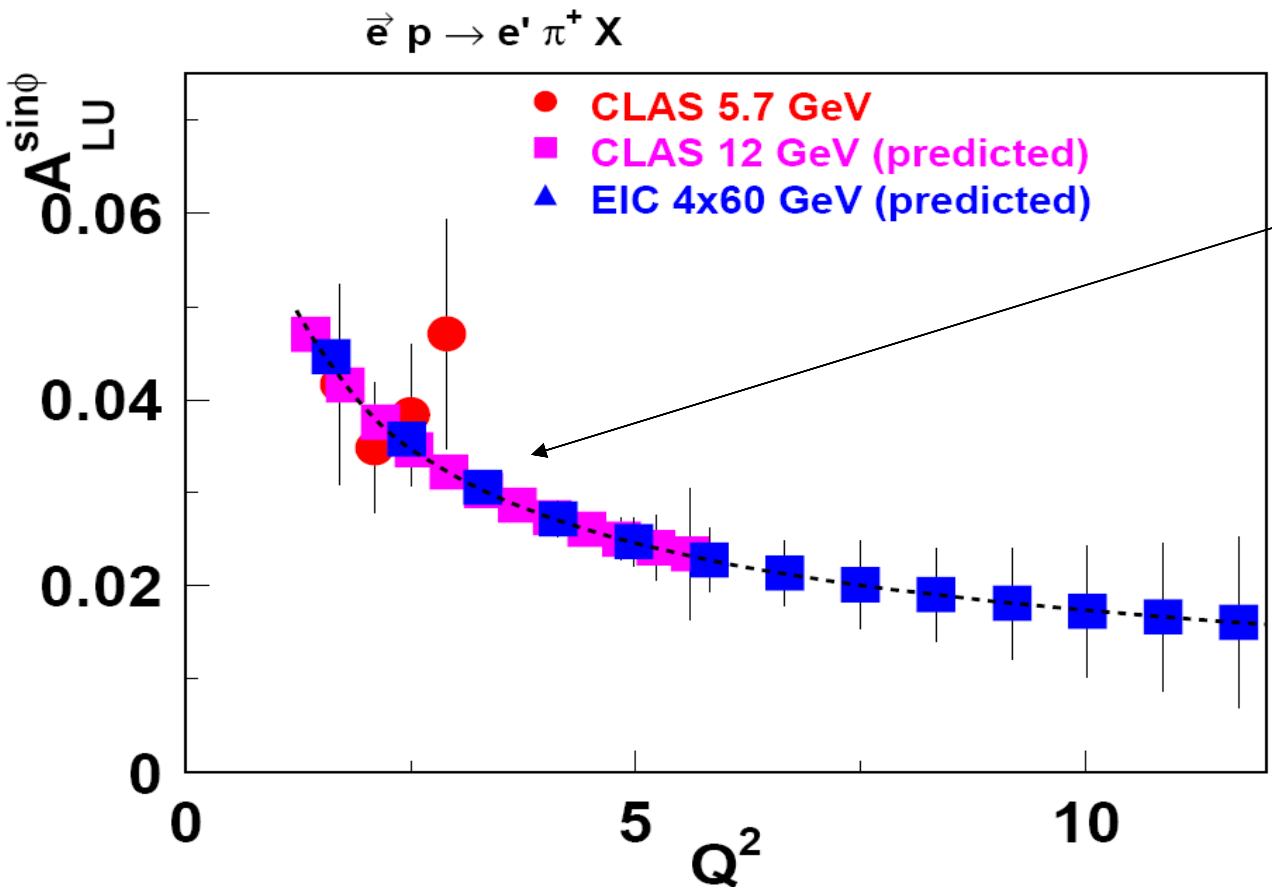
Perturbative region

Study for SSA transition from non-perturbative to perturbative regime.
EIC will significantly increase the P_T range.

Q^2-dependence of beam SSA

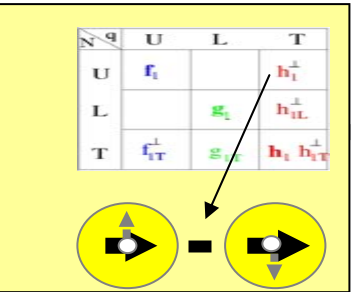
$\sigma^{\sin\phi}_{LU(UL)}$ ~$F_{LU(UL)}$~ 1/Q (Twist-3)

$A_{LU} \propto g^{\perp}(x) D_1(z)$



1/Q behavior expected (fixed x bin)

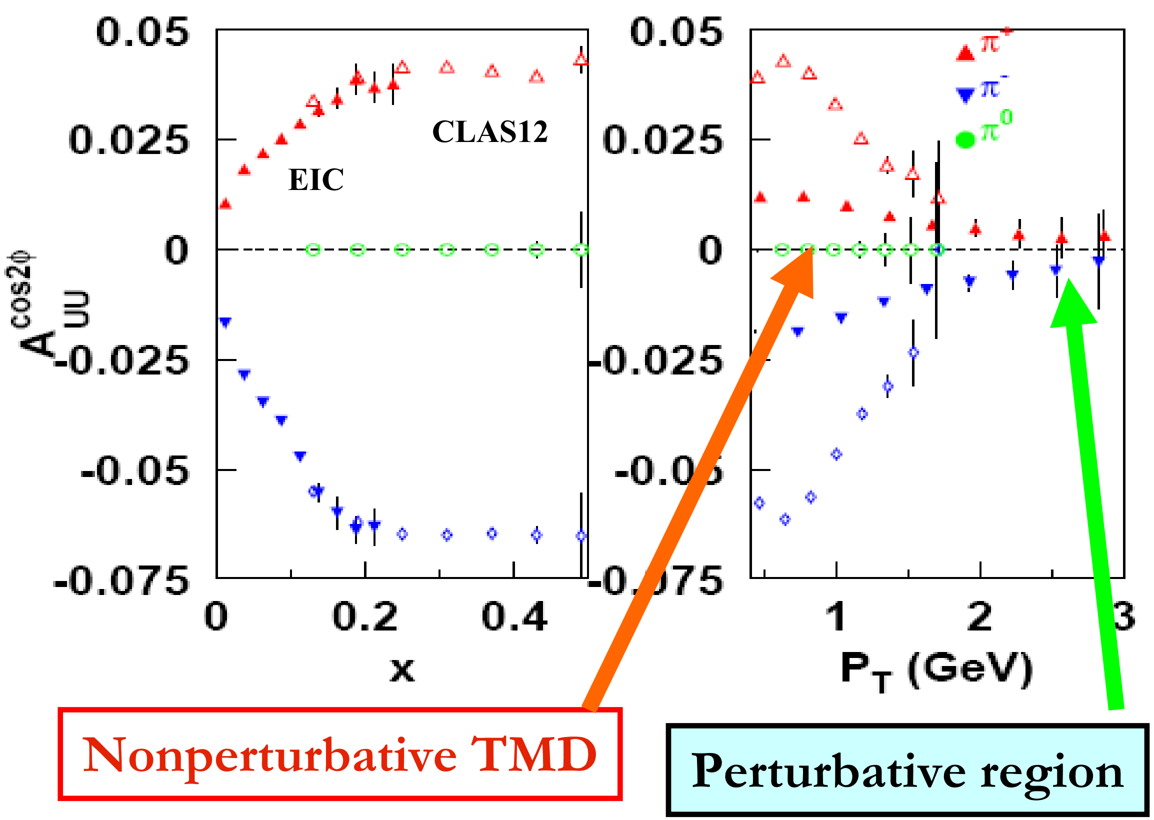
Study for Q^2 dependence of beam SSA allows to check the higher twist nature and access quark-gluon correlations.



Boer-Mulders Asymmetry with CLAS12 & EIC

5-GeV e → ← p 50 GeV

Transversely polarized quarks in the unpolarized nucleon



$\sin(\phi_C) = \cos(2\phi_h)$

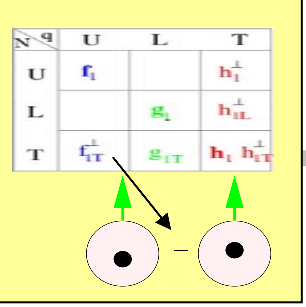
$$A_{UU}^{\cos 2\phi} \propto h_1^\perp H_1^\perp$$

$$\langle \cos 2\phi \rangle |_{P_{h\perp} \gg \Lambda_{QCD}} \propto \frac{1}{P_{h\perp}^2}$$

Perturbative limit calculations available for $f_1(x,k_T), h_1^\perp(x,k_T)$

J.Zhou, F.Yuan, Z Liang: arXiv:0909.2238

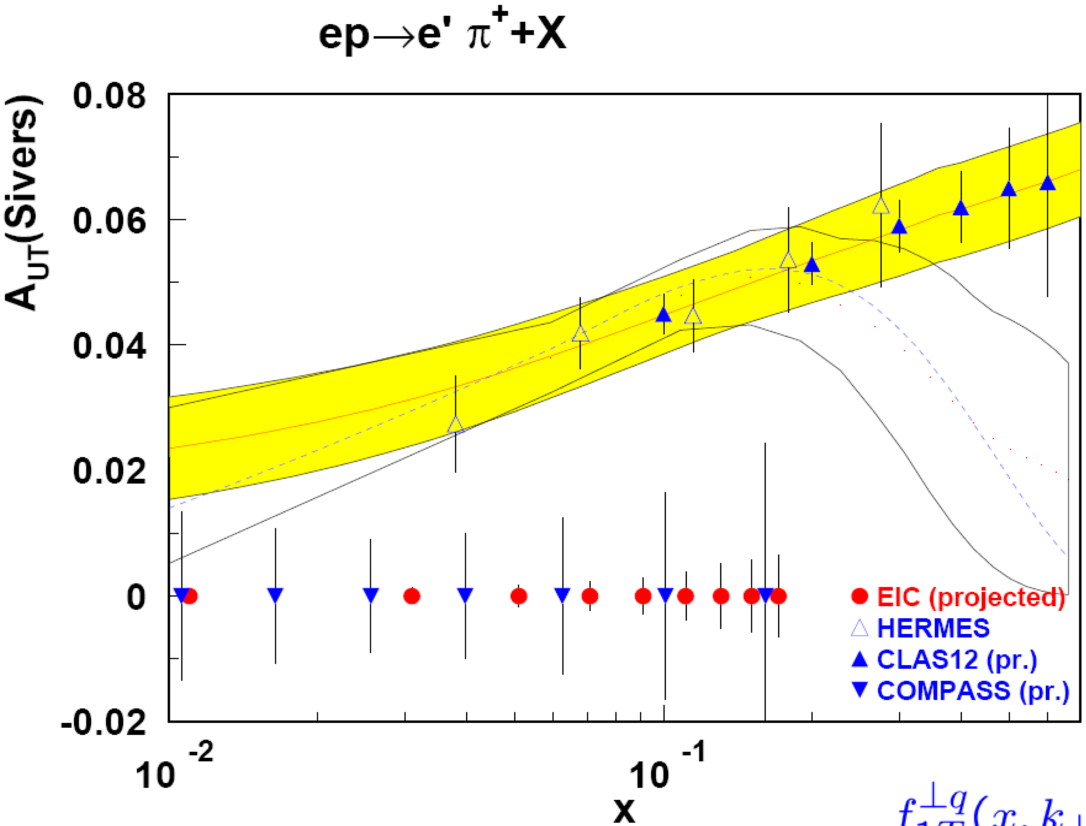
CLAS12 and EIC studies of transition from non-perturbative to perturbative regime will provide complementary info on spin-orbit correlations and test unified theory (Ji et al)



Sivers effect: pion electroproduction

$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

$$q = u, d, s, \bar{u}, \bar{d}, \bar{s}$$



$$f_{1T}^{\perp(1)q}(x) = A_q \frac{\langle p_T \rangle_{unp}}{2M_N} f_1^q(x)$$

GRV98, Kretzer FF (4par)

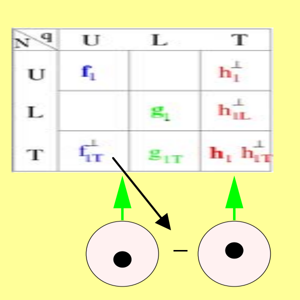
S. Arnold et al
arXiv:0805.2137

M. Anselmino et al
arXiv:0805.2677

GRV98, DSS FF (8par)

$$f_{1T}^{\perp q}(x, k_\perp) \propto N_q x^{\alpha_q}(1-x)^{\beta_q} e^{-k_\perp^2/M_1^2} f_1^q(x, k_\perp)$$

•EIC measurements at small x will pin down sea contributions to Sivers function

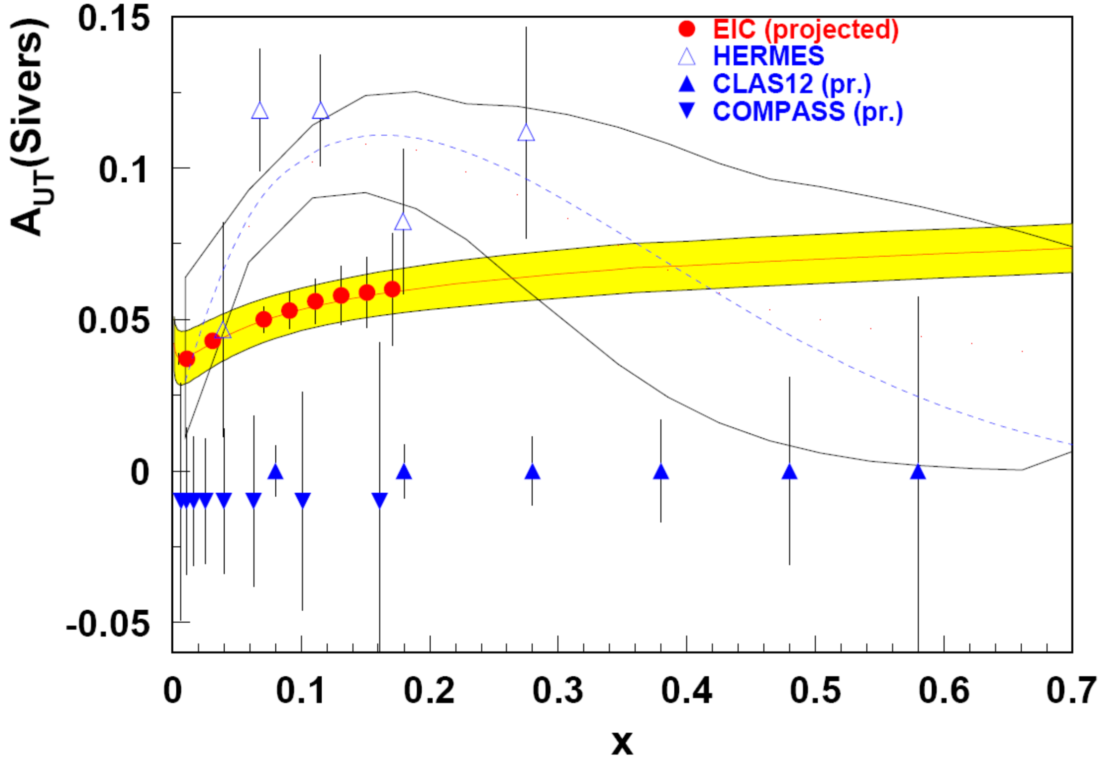


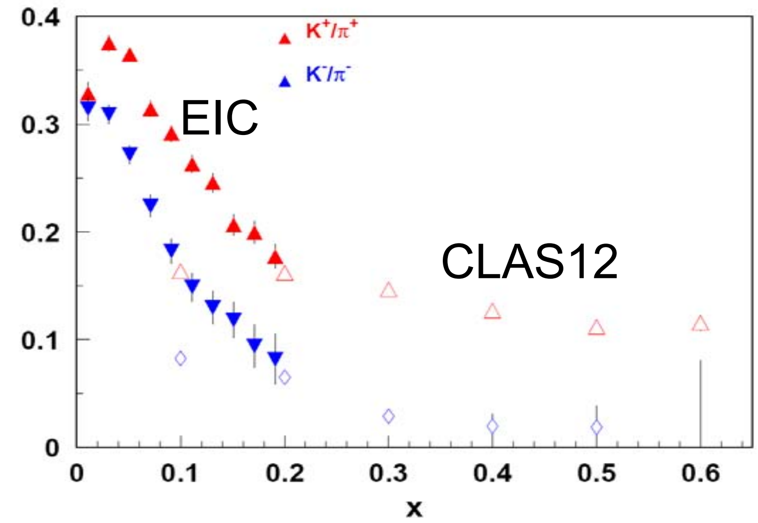
Sivers effect: Kaon electroproduction

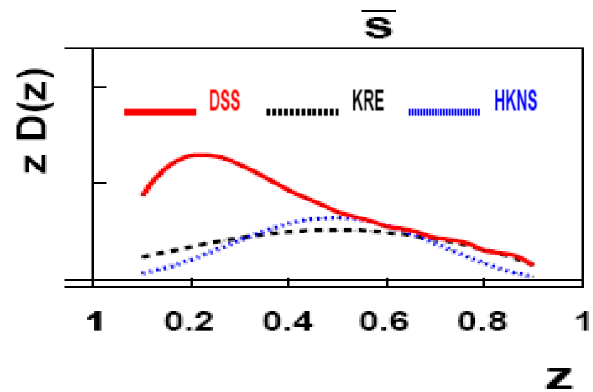
$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

$K^+ \sim u\bar{s}$ $\quad K^- \sim s\bar{u}$

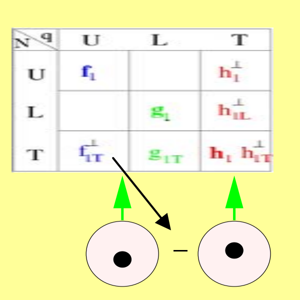
ep→e' K^++X







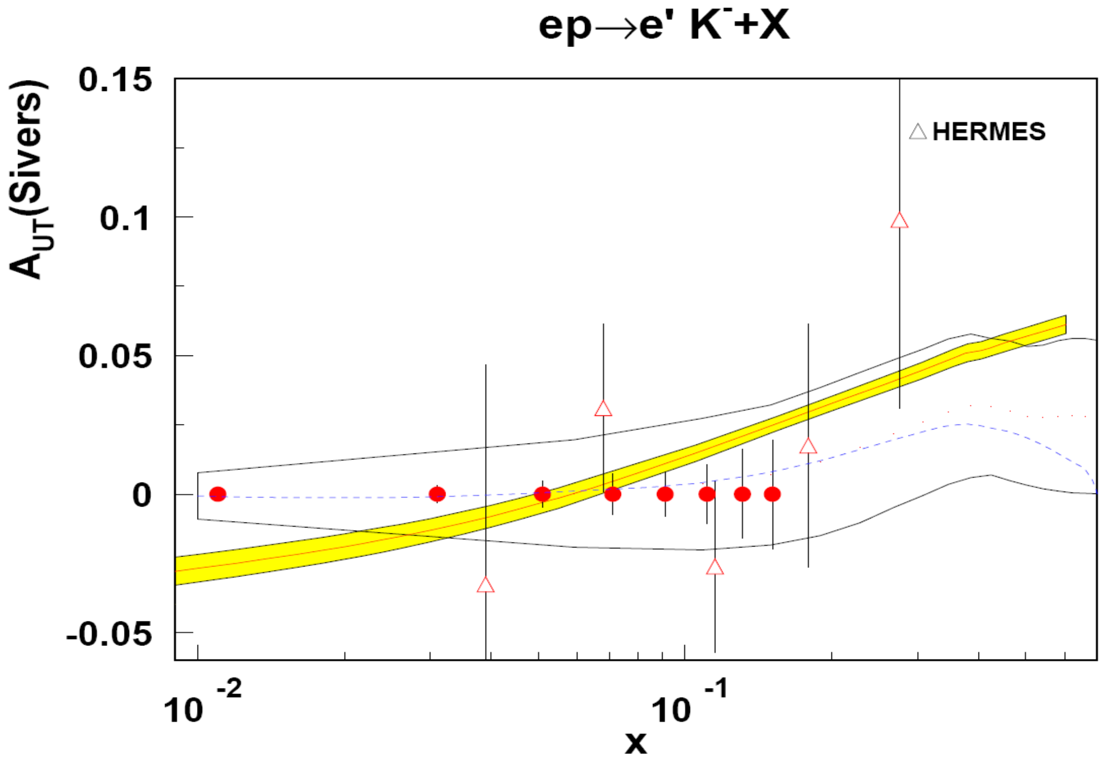
- At small x of EIC Kaon relative rates higher, making it ideal place to study the Sivers asymmetry in Kaon production (in particular K-).
- Combination with CLAS12 data will provide almost complete x-range.



Sivers effect: sea contributions

$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

$$K^- \sim s\bar{u}$$



GRV98, DSS FF

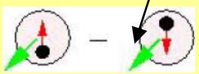
M. Anselmino et al
arXiv:0805.2677

GRV98, Kretzer FF

S. Arnold et al
arXiv:0805.2137

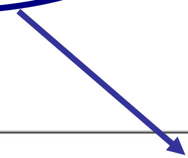
•Negative Kaons most sensitive to sea contributions.
•Biggest uncertainty in experimental measurements (K- suppressed at large x).

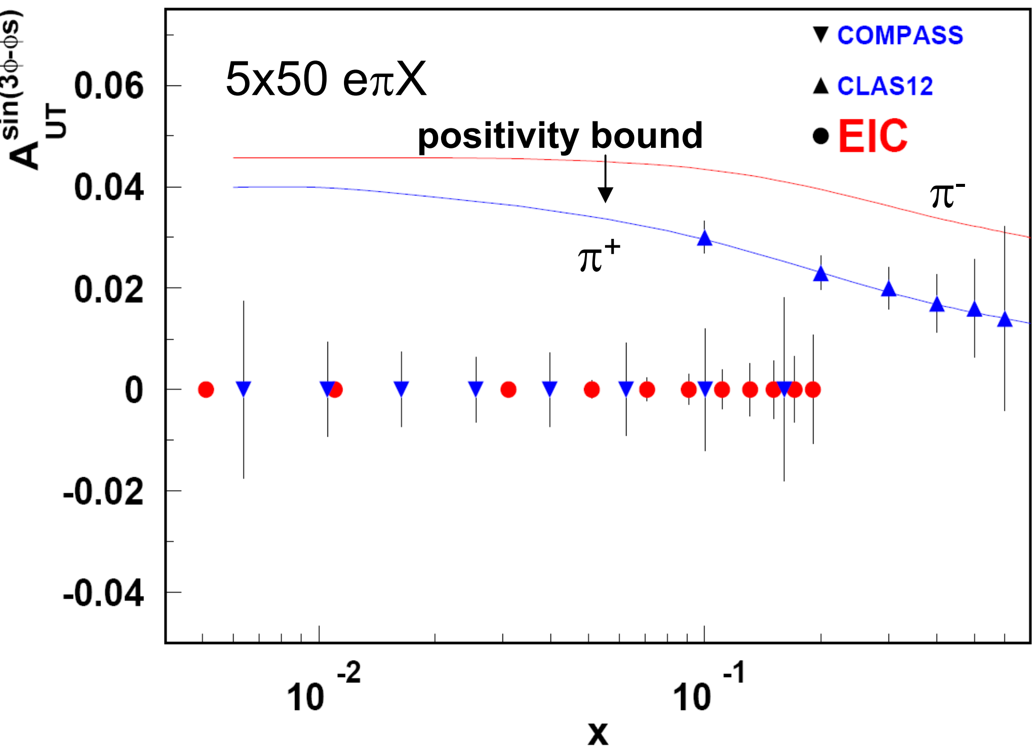
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

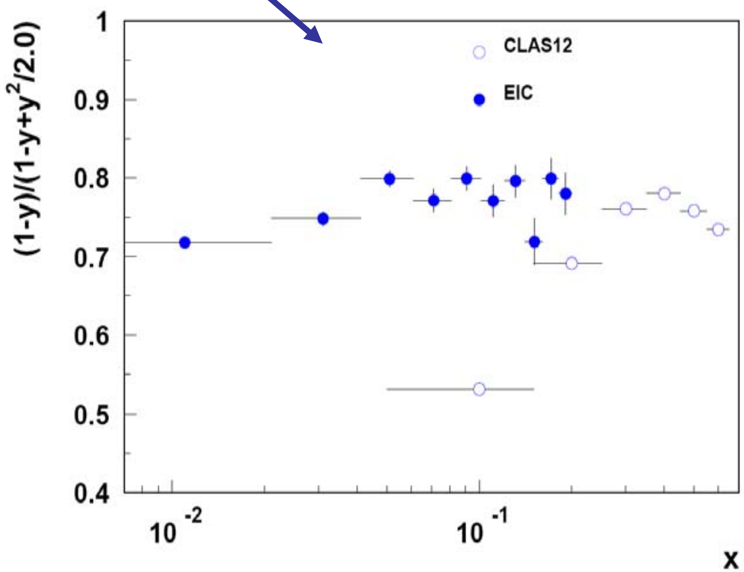


Pretzelosity @ EIC

$$A_{UT}^{\sin(3\phi-\phi_S)} \propto \frac{1-y}{1-y+y^2/2}\,\frac{\sum_q e_q^2 h_{1T}^{\perp(1)q} H_1^{\perp q}}{\sum_q e_q^2 f_1^q D_1^q}$$

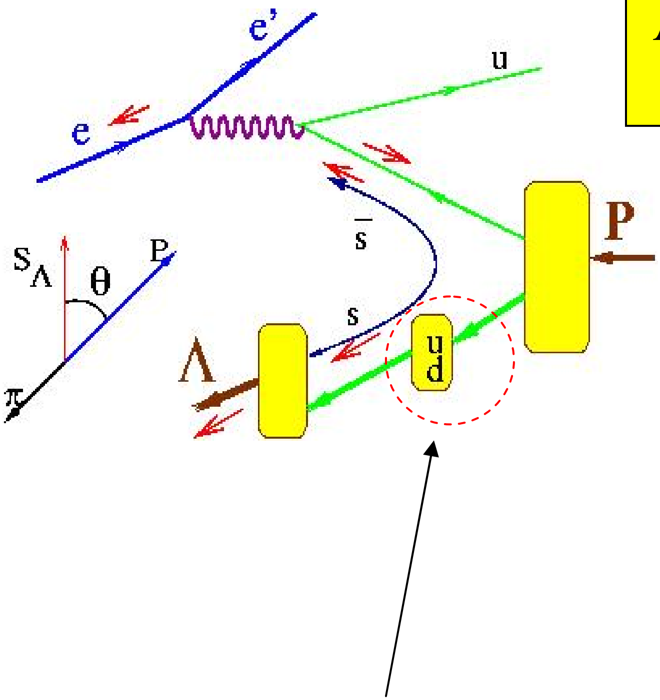






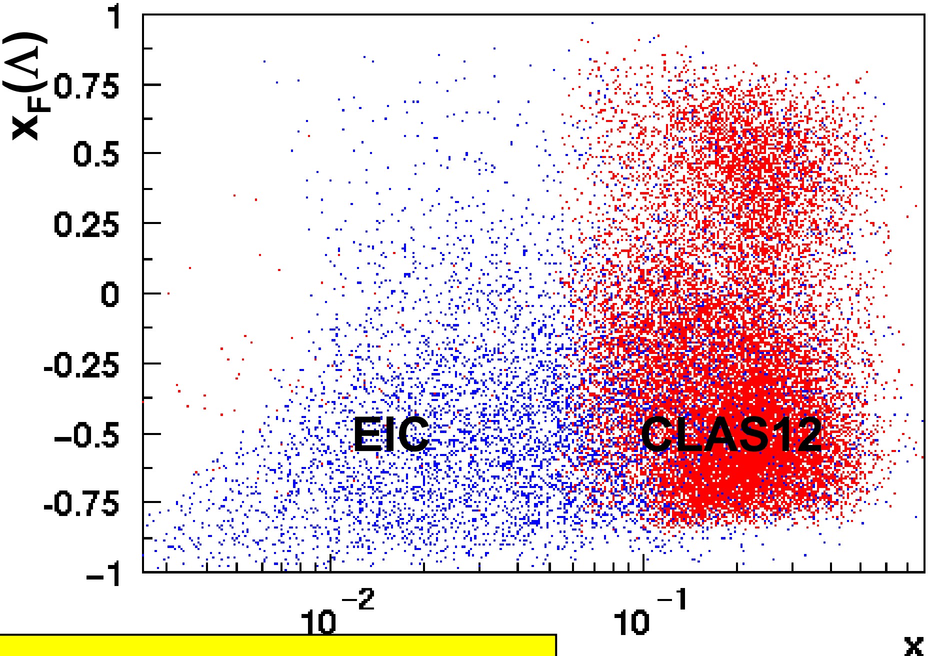
- EIC measurement combined with CLAS12 will provide a complete kinematic range for pretzelosity measurements

Λ polarization in the target fragmentation



Λ polarization in TFR provides information on contribution of strange sea to proton spin

(ud)-diquark is a spin and isospin singlet s-quark carries whole spin of Λ $|\Lambda\rangle = |uds\rangle$

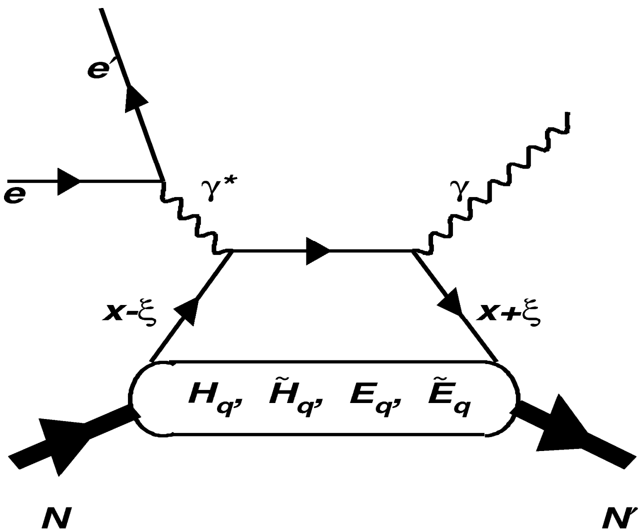


Study polarized diquark fracture functions sensitive to the correlations between struck quark transverse momentum and the diquark spin.

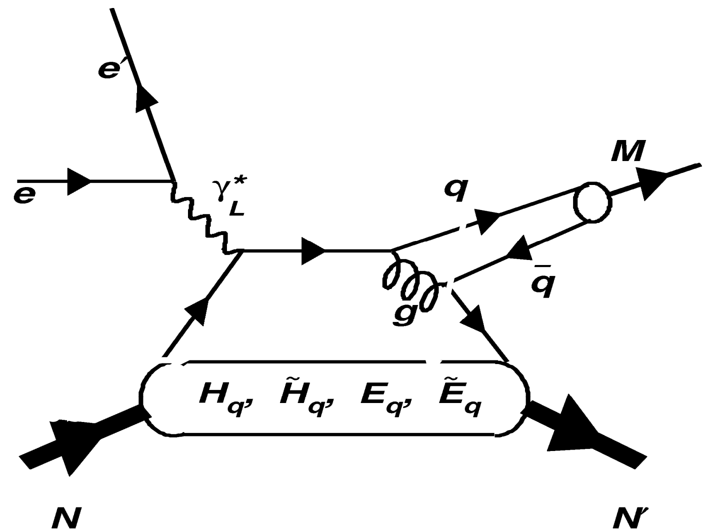
Wide kinematical coverage of EIC would allow studies of hadronization in the target fragmentation region

Hard Exclusive Processes and GPDs

DVCS



DVMP

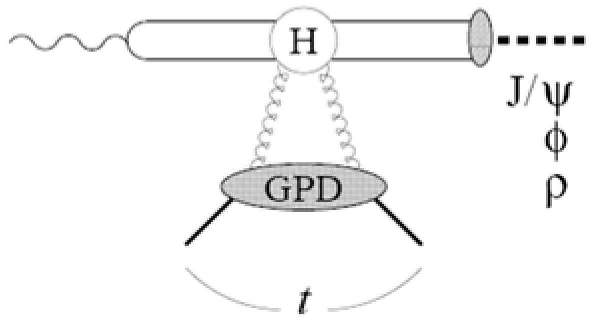


DVCS – for different polarizations of beam and target provide access to different combinations of GPDs H,$\tilde{H}$, E,$\tilde{E}$

DVMP for different mesons is sensitive to flavor contributions (ρ^0/ρ^+/K* select H, E, for u/d flavors, π, η, K select $\tilde{H}$, $\tilde{E}$)

Gluon Imaging with exclusive processes

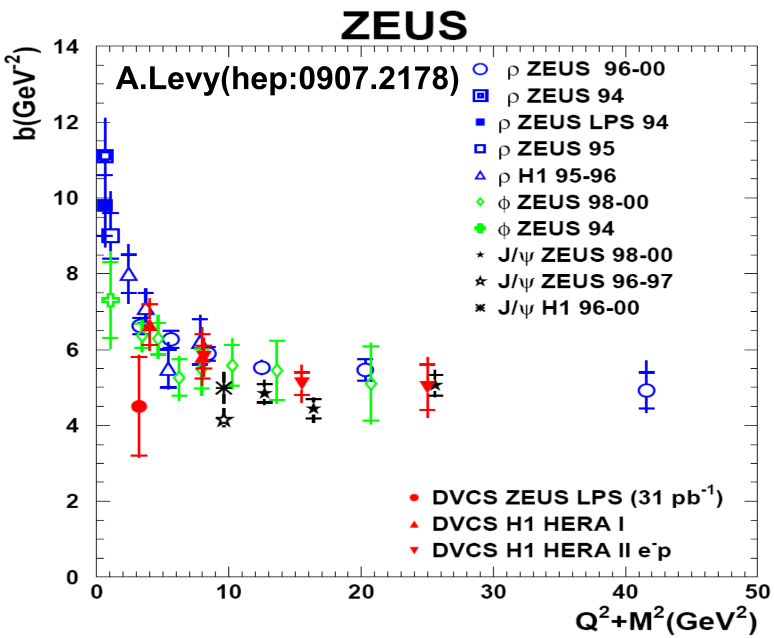
Goal: Transverse gluon imaging of nucleon over wide range of x: 0.001 < x < 0.1



Two-gluon exchange dominant for J/ψ, φ, ρ production at large energies → **sensitive to gluon distribution squared!**

LO factorization ~ color dipole picture
→ access to gluon spatial distribution in nuclei

Fit with $d\sigma/dt = e^{-Bt}$



Measurements at DESY of diffractive channels (J/ψ, φ, ρ, γ) confirmed the applicability of QCD factorization:

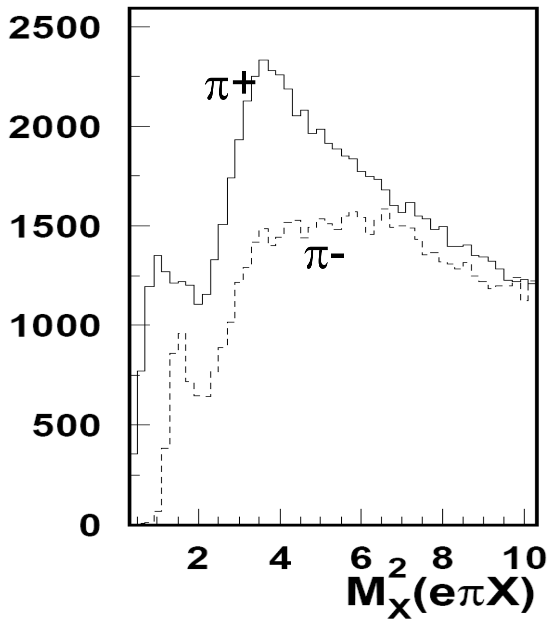
- t-slopes universal at high Q^2
- flavor relations φ:ρ

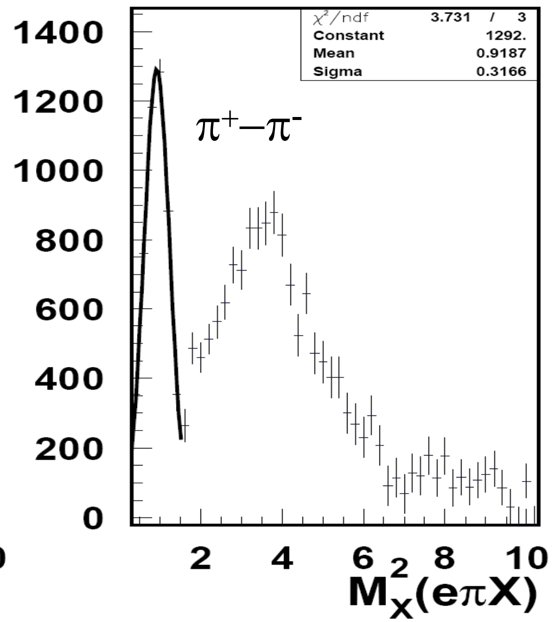
Hard exclusive processes provide access to transverse gluon imaging at EIC!

Quark Imaging with exclusive processes

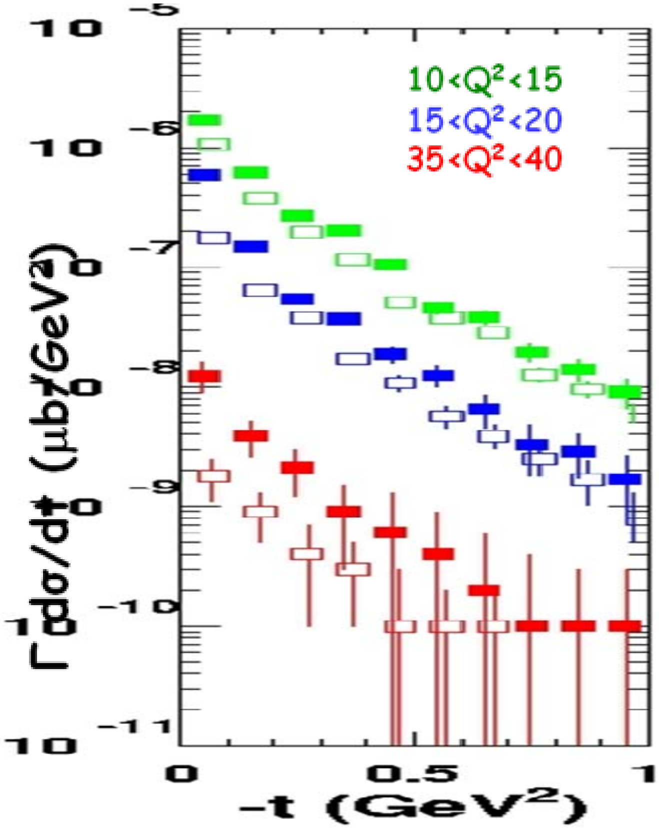
More demanding in luminosity
- Physics closely related to JLab 6/12 GeV
- quark spin/flavor separations
- nucleon/meson structure

Simulation for charged π^+ production, assuming **100 days at a luminosity of 10^{34}, with 5 on 50 GeV (s = 1000)**

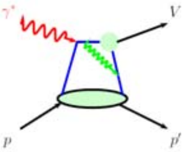




•V. Guzey, Ch. Weiss: Regge model
•T. Horn: π^+ empirical parameterization

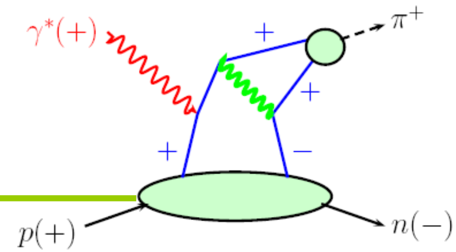


Horn,Bruell,Weiss



SSAs in exclusive pion production

P.Kroll & S. Goloskokov **arXiv:0906.0460**

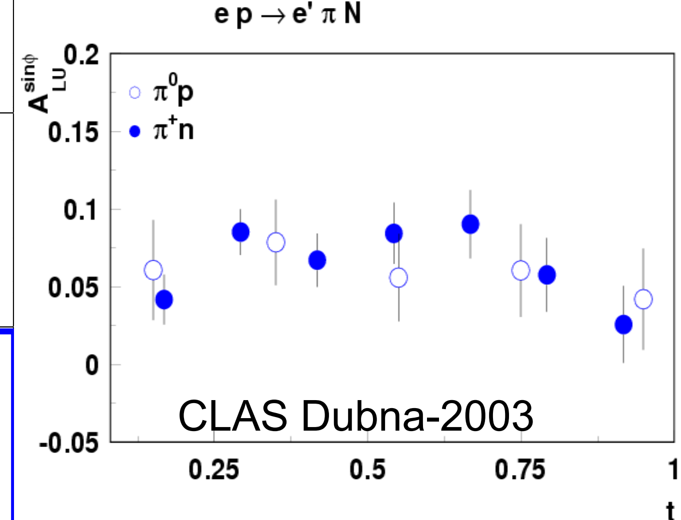


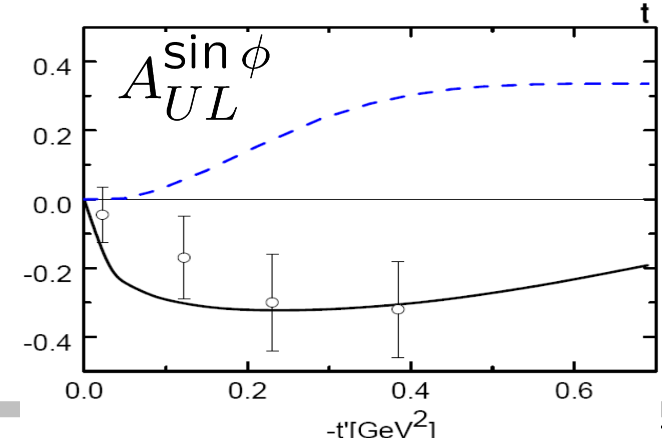
Transverse photon matters

$$\mathcal{M}^{twist-3}_{0-,++} \approx e_0\sqrt{1-\xi^2}\int_{-1}^{+1} d\bar{x}\,\mathcal{H}_{0-,++}[H_T^{(3)}+\ldots]$$

observable	dominant interf. term	amplitudes	low t' behavior
$A_{UT}^{\sin(\phi-\phi_s)}$	LL	$\mathrm{Im}[\mathcal{M}^*_{0-,0+}\mathcal{M}_{0+,0+}]$	$\propto \sqrt{-t'}$
$A_{UT}^{\sin(\phi+\phi_s)}$	TT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,++}]$	$\propto \sqrt{-t'}$
$A_{UT}^{\sin(3\phi-\phi_s)}$	TT	$\mathrm{Im}[\mathcal{M}^*_{0-,-+}\mathcal{M}_{0+,-+}]$	$\propto (-t')^{(3/2)}$
$A_{UT}^{\sin\phi_s}$	LT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,0+}]$	const.
$A_{UL}^{\sin\phi}$	LT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0-,0+}]$	$\propto \sqrt{-t'}$
$A_{LU}^{\sin\phi}$	LT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0-,0+}]$	$\propto \sqrt{-t'}$
$A_{LL}^{\cos\phi}$	LT	$\mathrm{Re}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0-,0+}]$	$\propto \sqrt{-t'}$

$$A_{LU}^{\sin\phi}/A_{UL}^{\sin\phi} \approx \sqrt{(1-\epsilon)/(1+\epsilon)}$$





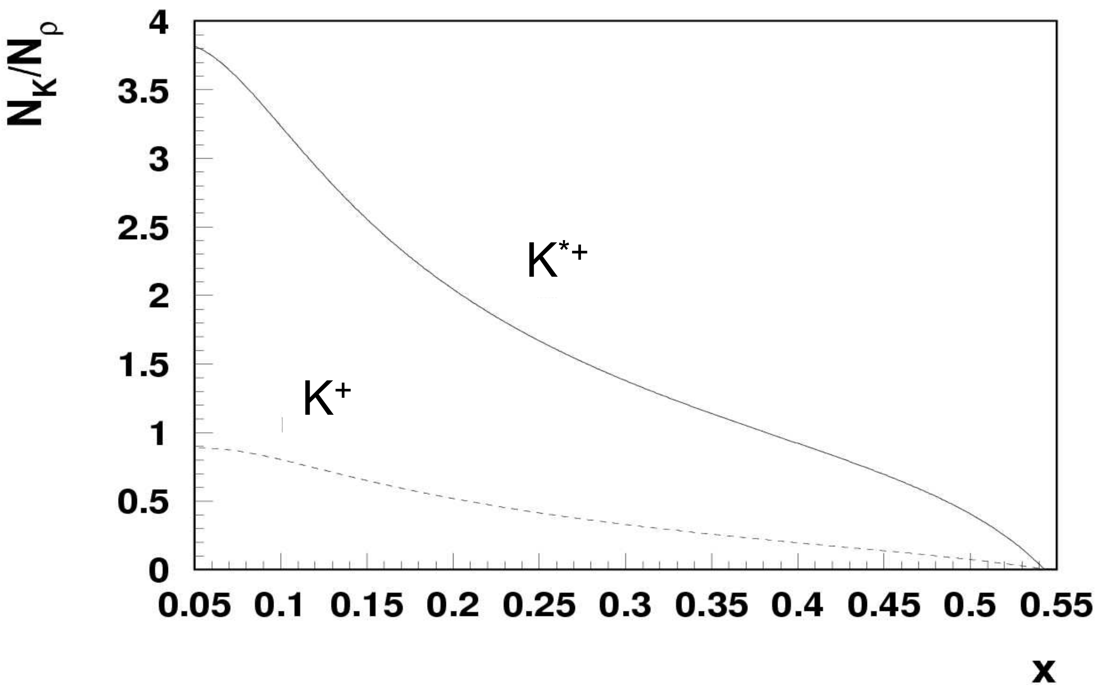
- HT SSAs are expected to be very significant
- EIC can measure Q^2 dependence of HT SSAs significantly extending the range of CLAS12

GPDs from cross section ratios

$$\rho^+ n \propto [2H^u - H^d] - [H^{\bar{u}} - H^{\bar{d}}])$$

$$K^+\Lambda \propto -\frac{1}{\sqrt{6}}(2[2\tilde{H}^u - \tilde{H}^d - \tilde{H}^s] + [2\tilde{H}^{\bar{u}} - \tilde{H}^{\bar{d}} - \tilde{H}^{\bar{s}}])$$

$$K^{*+}\Lambda \propto -\frac{1}{\sqrt{6}}(2[2H^u - H^d - H^s] - [2H^{\bar{u}} - H^{\bar{d}} - H^{\bar{s}}])$$



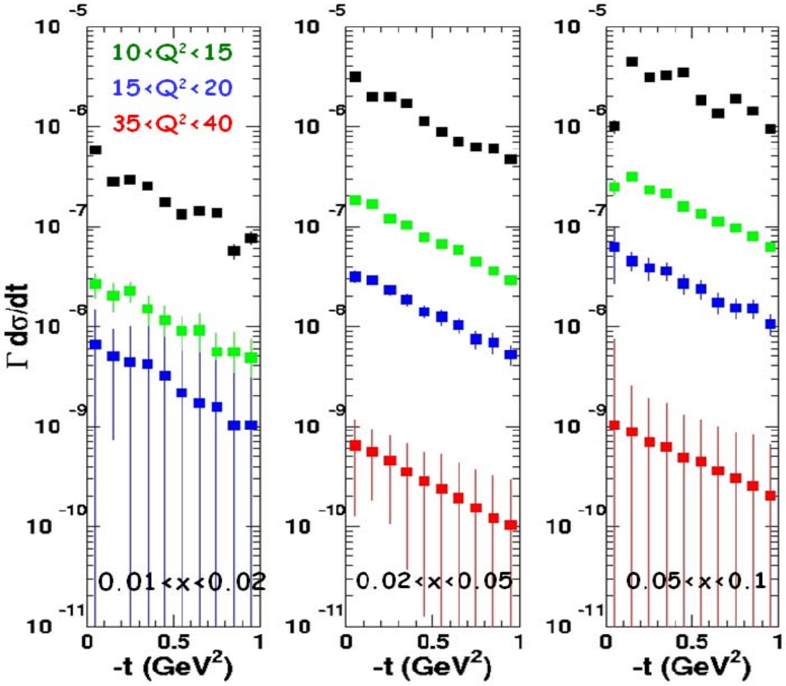
M.Diehl et al. hep-ph/0506171

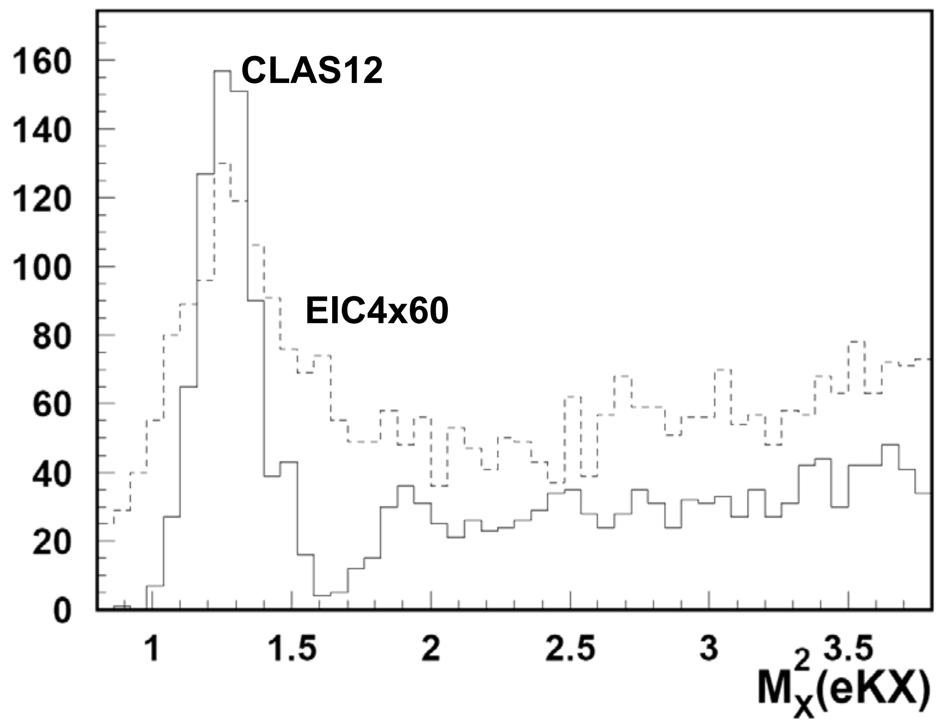
- L/T separation from $K^* \to K\pi$ decay + SCHC

•Study ratio observables: K/K*/ρ+,polarization transfer
•Different final state mesons filter out different combinations of unpolarized (H,E) and polarized (H,E) GPDs.

Quark Imaging with exclusive processes

Rate estimate for KΛ



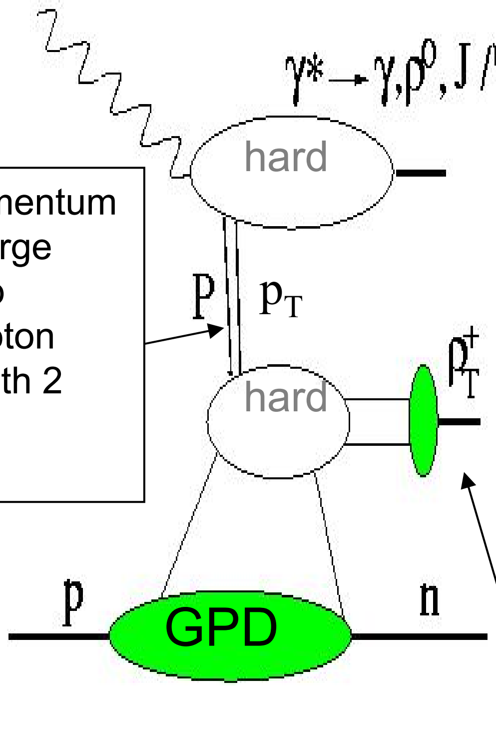


Horn,Cooper

Using an empirical fit to kaon electroproduction data from DESY and JLab assuming **100 days at a luminosity of 10^{34}, with 5 on 50 GeV (s = 1000)**

Need good resolution to identify exclusive events

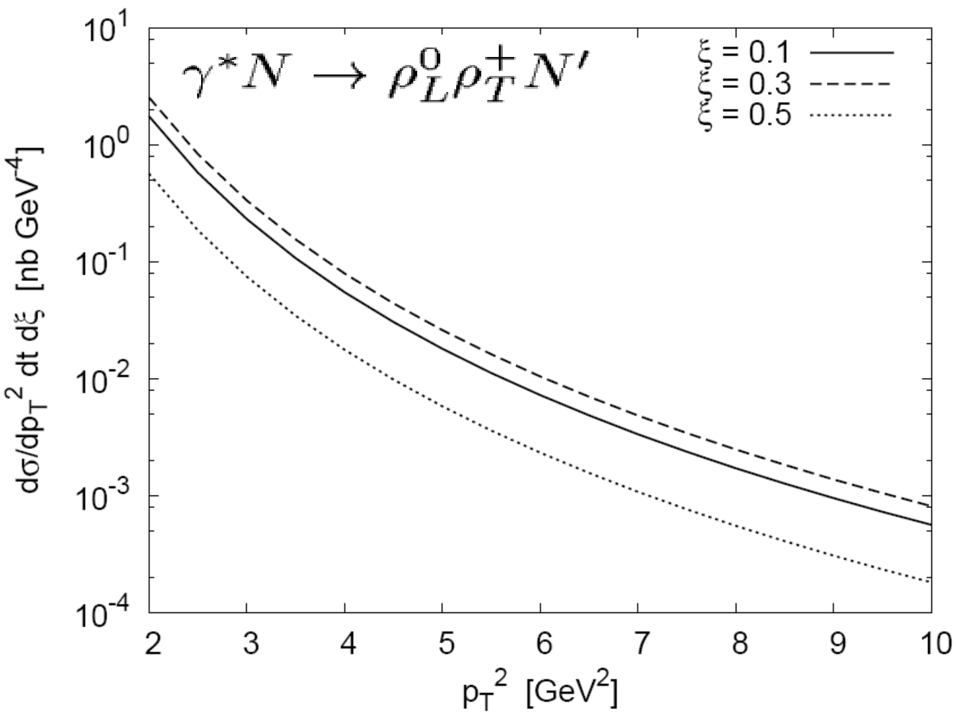
Chiral-odd GPDs with exclusive ρ,ρ+



•Large momentum transfer, large rapidity gap
•Virtual photon replaced with 2 gluons

Smaller rapidity gap ρ+ selects quark antiquark exchange with the nucleon

Long distance part described by GPD H_T



Ivanov et al. Phys.Part.Nucl.35:S67-S70,2004
Enberg et al. Eur.Phys.J.C47:87-94,2006

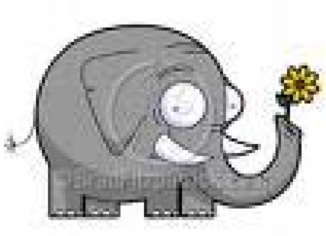
Ratio of $\rho^0_L\rho^+_T n / \rho^0_L\rho^+_L n$ directly related to ratio of GPDs H_T/H

Summary

Studies of semi-inclusive and exclusive processes at EIC

- Provide detailed info on gluon and sea quark spatial imaging of the nucleon
- Measure transverse momentum distributions of partons at small x
- Define quark-gluon correlations using the wide range of Q^2
- Investigate hadronization in target fragmentation

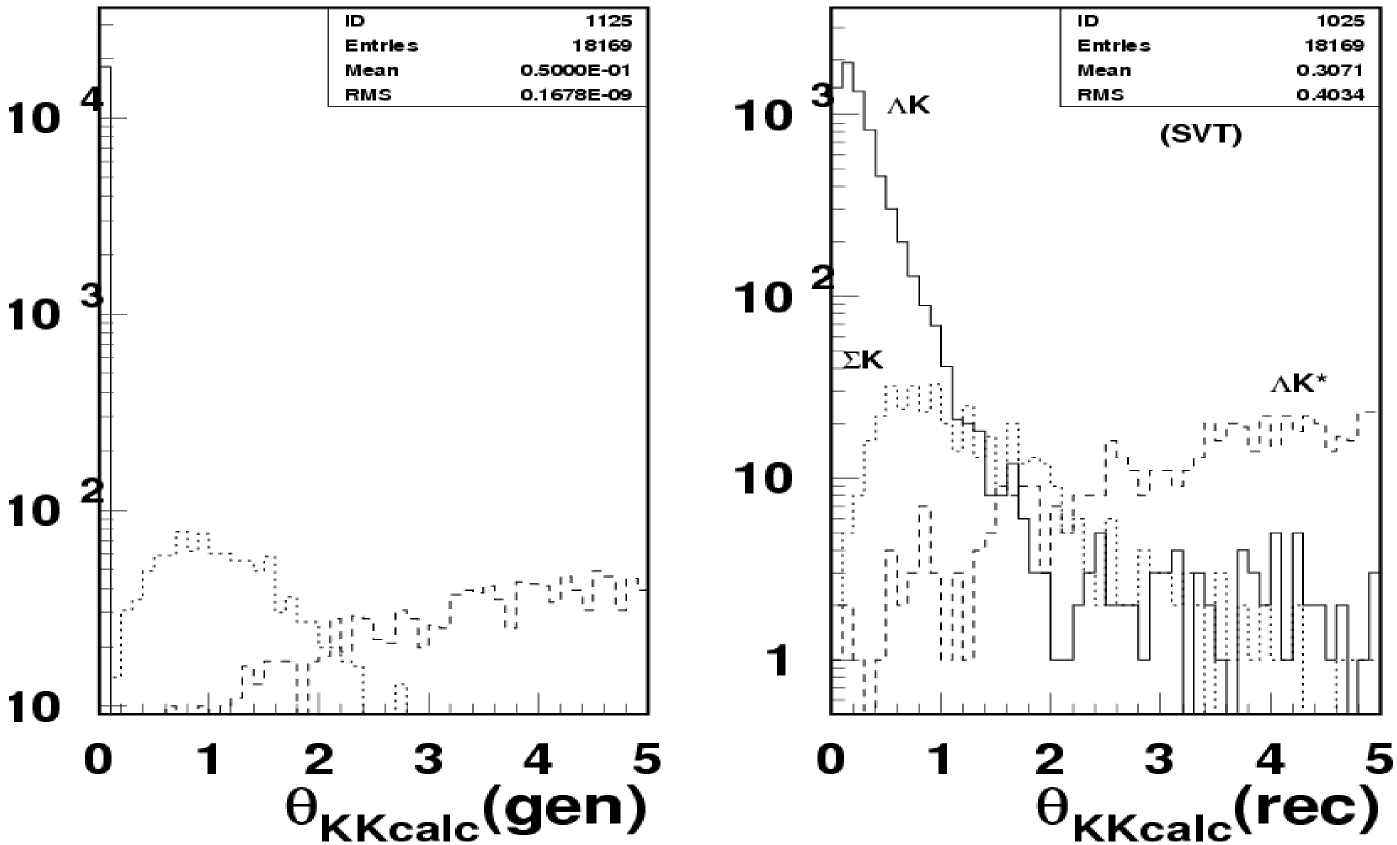
➢**EIC**: ***Measurements related to the spin, spin orbit and quark-gluon correlations (HT) combined with* JLab12 *HERMES,COMPASS, RHIC,BELLE,BABAR,Fermilab,J-PARC,GSI data will help construct a more complete picture about the spin structure of the nucleon* beyond the collinear approximation.**



Thank You!

Support slides….

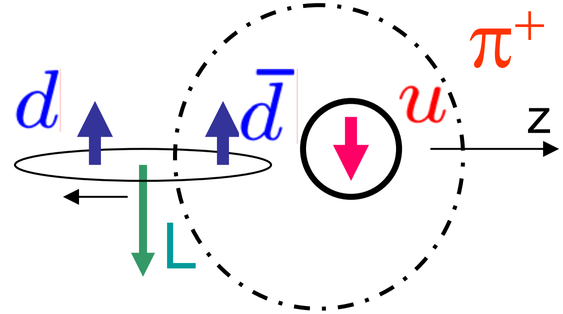
K/K* and Λ/Σ separations



Detection of K+ crucial for separation of different final states (Λ,Σ,K*)

Collins effect

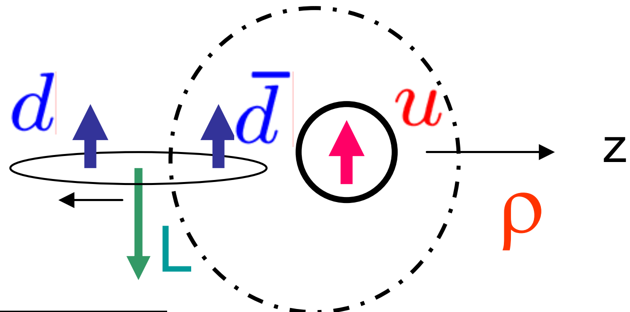
Simple string fragmentation for pions (Artru model)



leading pion out of page

$$h_1 H_1^{\perp u \to \pi}$$

ρ production may produce an opposite sign A_{UT}



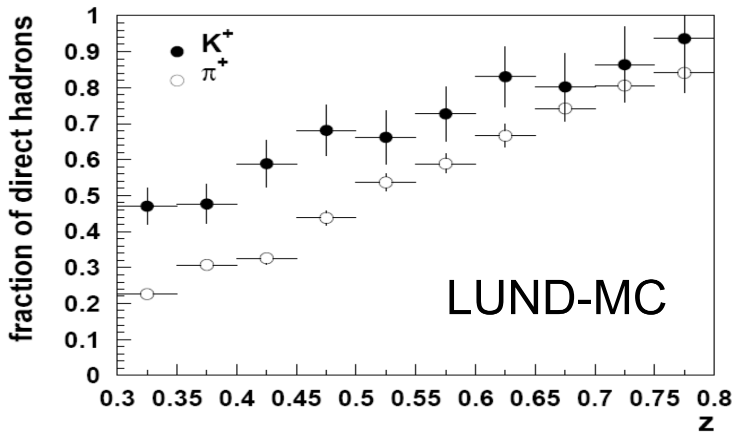
Leading ρ opposite to leading π(into page)

$$H_1^{\perp u \to \rho} \sim -\frac{1}{3} H_1^{\perp u \to \pi}$$

hep-ph/9606390

Fraction of ρ in eπX	% left from eπX asm
20%	~75%
40%	~50%

Fraction of direct kaons may be significantly higher than the fraction of direct pions.



Collins Effect: from asymmetries to distributions

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

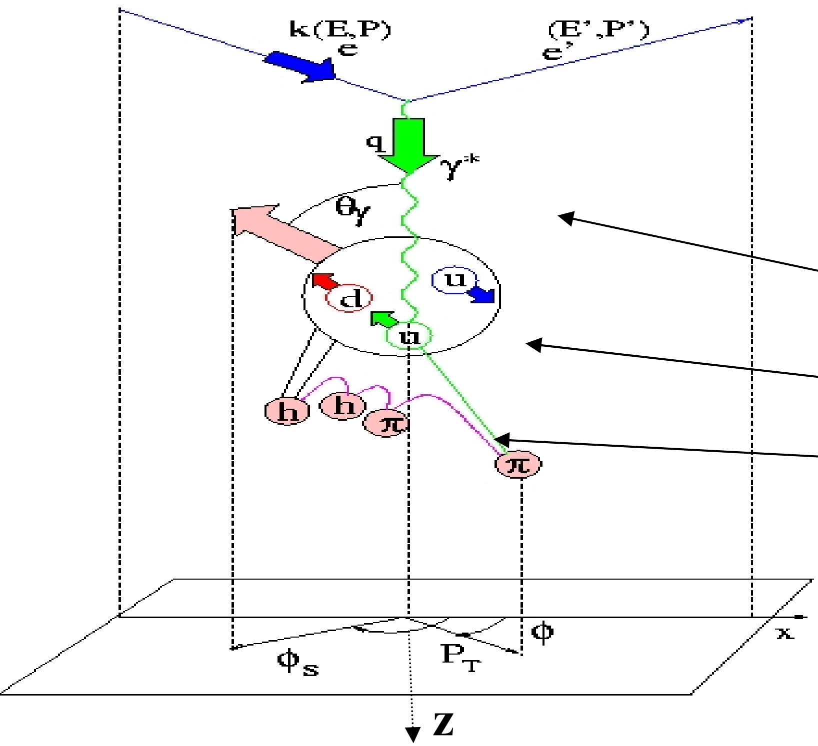
need $H_1^{\perp}$

$$F \equiv \sigma_{UL}^{\sin 2\phi}$$

$$\frac{H_1^{u/K+} - H_1^{u/K-}}{H_1^{u/\pi+} - H_1^{u/\pi-}} = \frac{15}{4} \frac{F_p^{K+} - F_p^{K-}}{3(F_p^{\pi+} - F_p^{\pi-}) + (F_d^{\pi+} - F_d^{\pi-})}$$

Combined analysis of Collins fragmentation asymmetries from proton and deuteron may provide independent to e+e- (BELLE) Information on the underlying Collins function.

SIDIS kinematical plane and observables



Cross section is a function of scale variables ***x,y,z***

$$\nu = (qP)/M$$
$$Q^2 = (k - k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$
$$x_F = p_{||}/|\vec{q}|$$

P_b, P_t

- **U unpolarized**
- **L long.polarized**
- **T trans.polarized**

Beam polarization

Target polarization

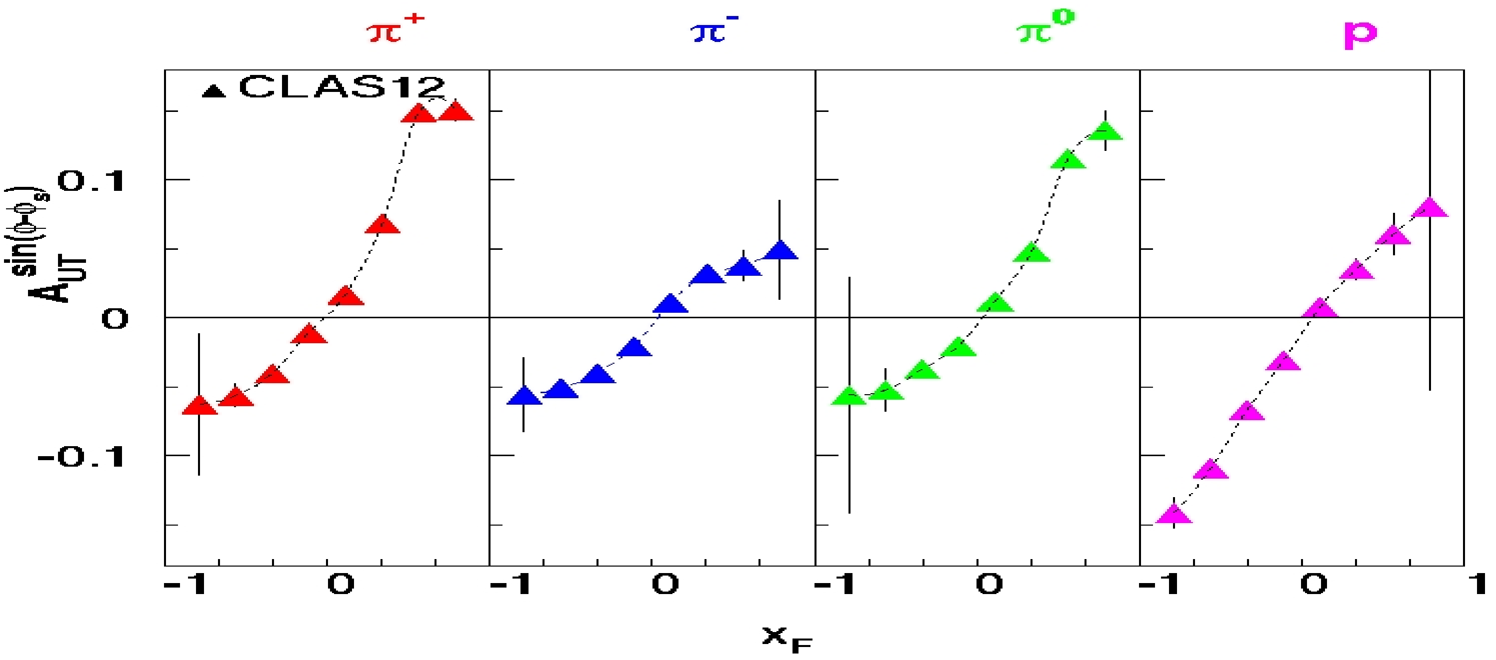
$$\sigma = \sigma_{UU} + P_t \sigma_{UT} \sin(\phi - \phi_S) + P_b P_t \sigma_{LT} \cos(\phi - \phi_S) \ldots$$

$$A_{UT}^{\sin\phi - \phi_S} = \frac{\sigma_{UT}}{\sigma_{UU}}$$

sin2ϕ moment of the cross section for unpolarized beam and long. polarized target

Sivers effect in the target fragmentation

A.Kotzinian



High statistics of CLAS12 will allow studies of kinematic dependences of the Sivers effect in target fragmentation region

Transverse force on the polarized quarks

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	$h, \mathbf{e}$
L	$f_L^{\perp}$	$g_L^{\perp}$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^{\perp}$	$\mathbf{g_T}, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

$$e_2 \equiv \int_0^1 dx x^2 \bar{e}(x)$$

$$F^y(0) = \frac{M^2}{2} e_2$$

Quark polarized in the x-direction with k_T in the y-direction

Force on the active quark right after scattering (t=0)

Interpreting HT (quark-gluon-quark correlations) as force on the quarks (Burkardt hep-ph:0810.3589)

SSA with unpolarized target

quark polarization

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

N/q	U	L	T
U	$f^\perp$	$g^\perp$	h, $\mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{LU}^{\sin\phi} \sim h_1^\perp \frac{E}{z} + x e H_1^\perp$$

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

SSA with unpolarized target

quark polarization

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathsf{LU}}^{\sin\phi} \propto \frac{M_h}{M}\mathbf{f_1}\frac{G^\perp}{z} - \frac{M}{M_h} x g^\perp D_1$$

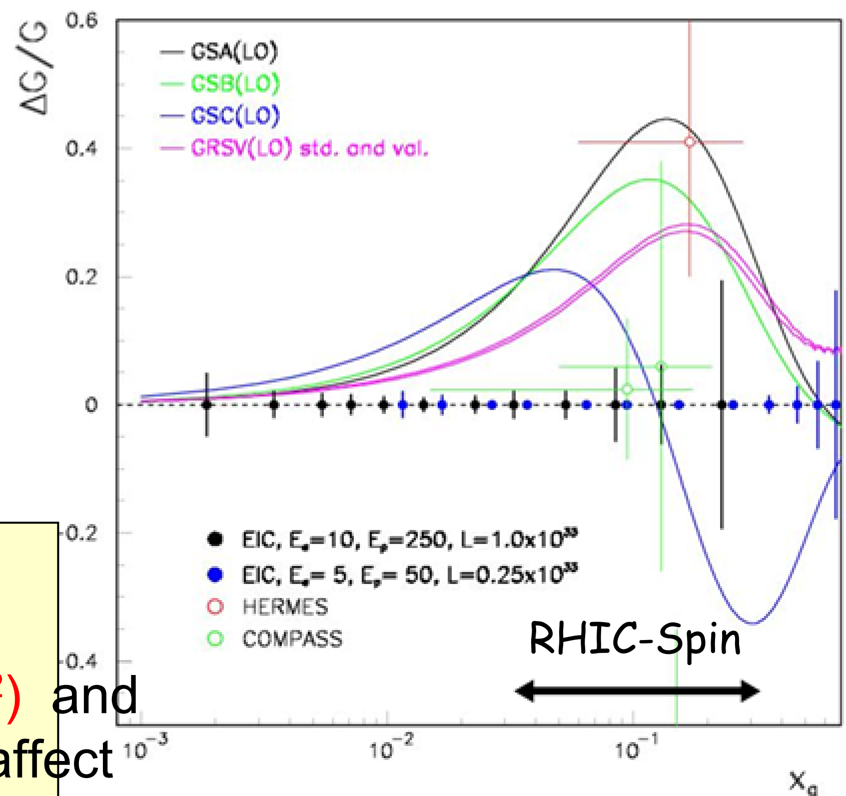
q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

The Gluon Contribution to the Proton Spin

$$\frac{d^3\sigma^{\overset{\rightarrow}{\rightarrow}}}{dxdyd\phi} - \frac{d^3\sigma^{\overset{\leftarrow}{\rightarrow}}}{dxdyd\phi} = \frac{4\alpha^2}{Q^2}\left[\left\{2 - y - \frac{2M^2x^2y^2}{Q^2}\right\}g_1(x,Q^2) - \frac{4M^2x^2y^2}{Q^2}g_2(x,Q^2)\right],$$

Bruell,Ent



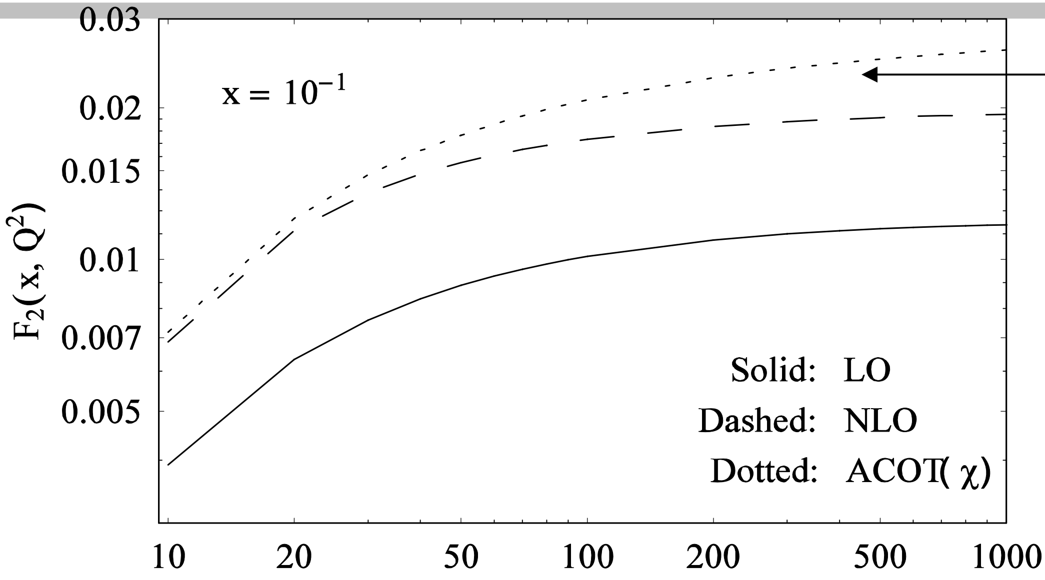
Projected data on $\Delta g/g$ with an EIC, via
$\gamma + p \rightarrow D^0 + X$
$\searrow K^- + \pi^+$
assuming vertex separation of 100 μm.

•Measure 90% of ΔG (@ Q^2 = 10 GeV^2)

Open theoretical problem:
At high Q^2 one should resum the mass logarithms in g_1. Since the signs of $c(x, Q^2)$ and $\Delta c(x, Q^2)$ are opposite, resummation can affect essentially predicted value $\Delta G/G \sim g_1/F_2$.

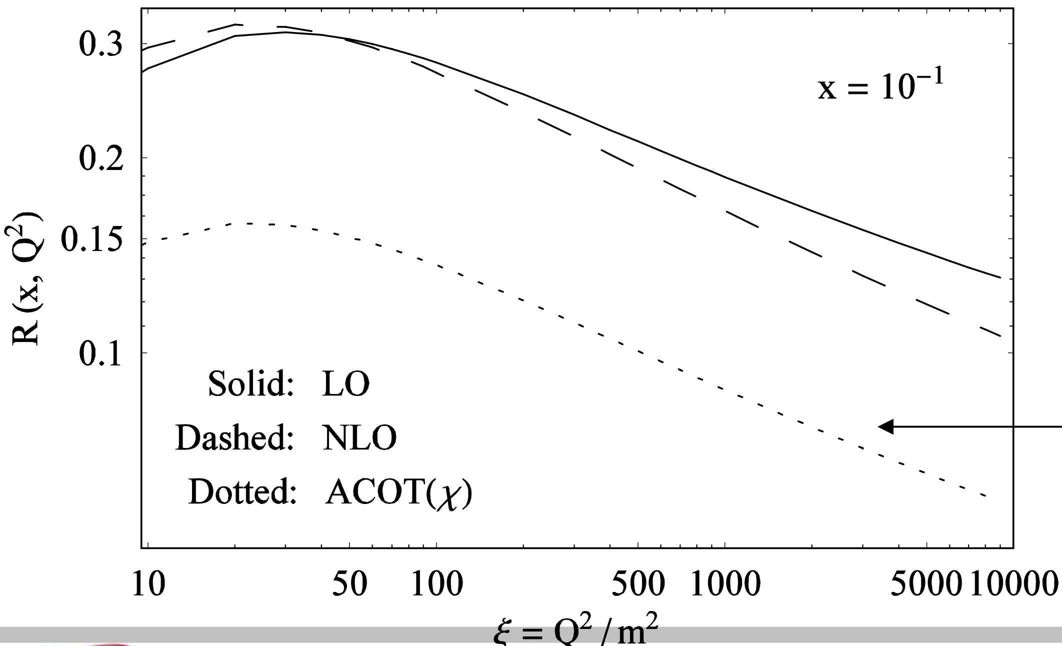
N.Ya. Ivanov e.a., in preparat

pQCD Predictions



Resummation for F_2

For F_2 the NLO and resummation contributions are very close

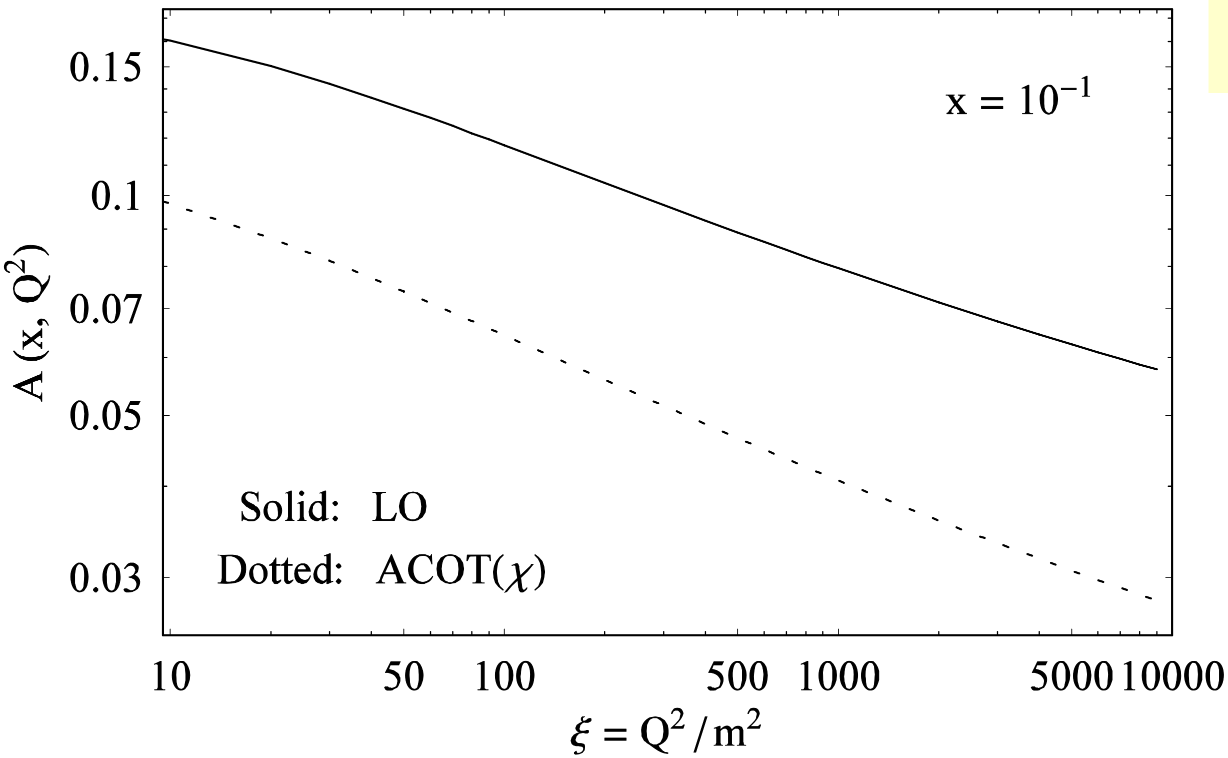


CTEQ PDFs used for estimates

Resummation for $R = F_L / F_2$

- **N.Ya.Ivanov, Nucl. Phys. B 814 (2009), 142**

Resummation for $A = 2xF_A / F_2$

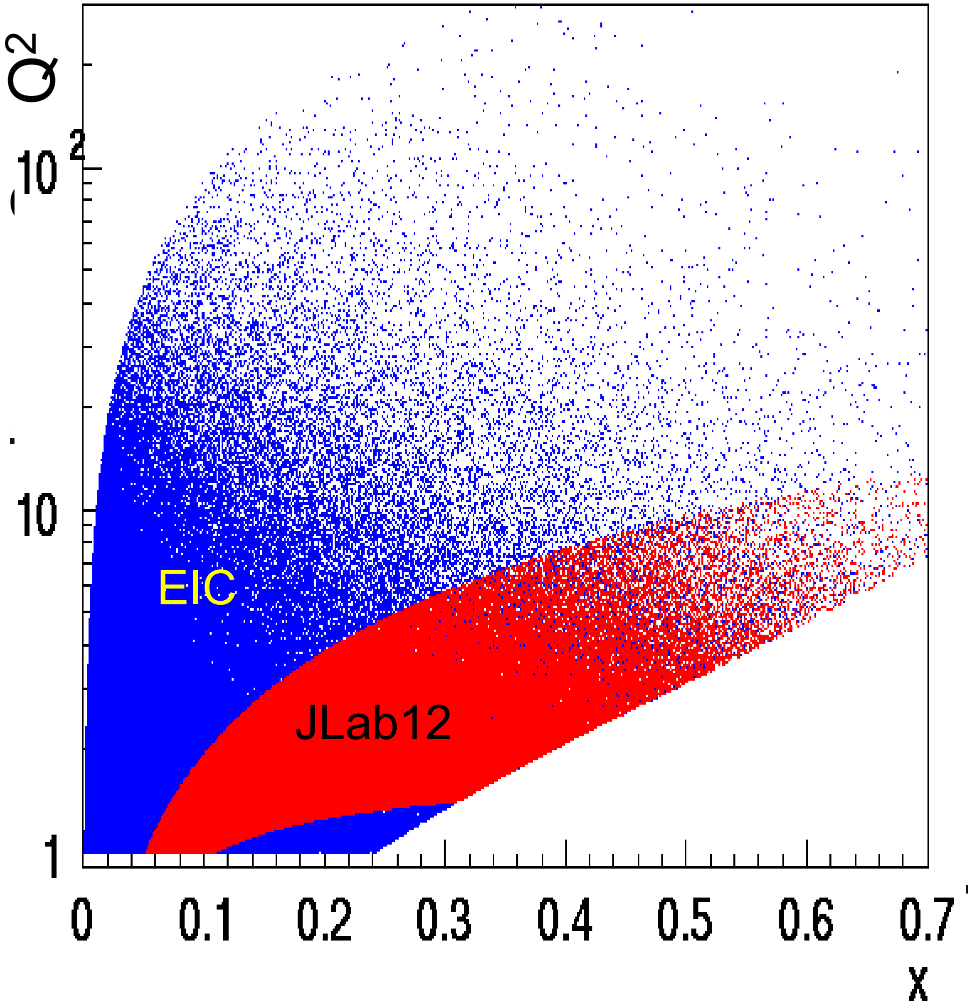


•L.N. Ananikyan, N.Ya. Ivanov,. **Nucl.Phys.B762:256-283,2007**.

CTEQ PDFs used for estimates

The mass logarithms resummation (or heavy-quark densities) should reduce the pQCD predictions for $R = F_L / F_T$ and $A = 2xF_A / F_2$.
cos2ϕ moment in charm meson production provides access to charm densities

Hard Scattering Processes: Kinematics Coverage

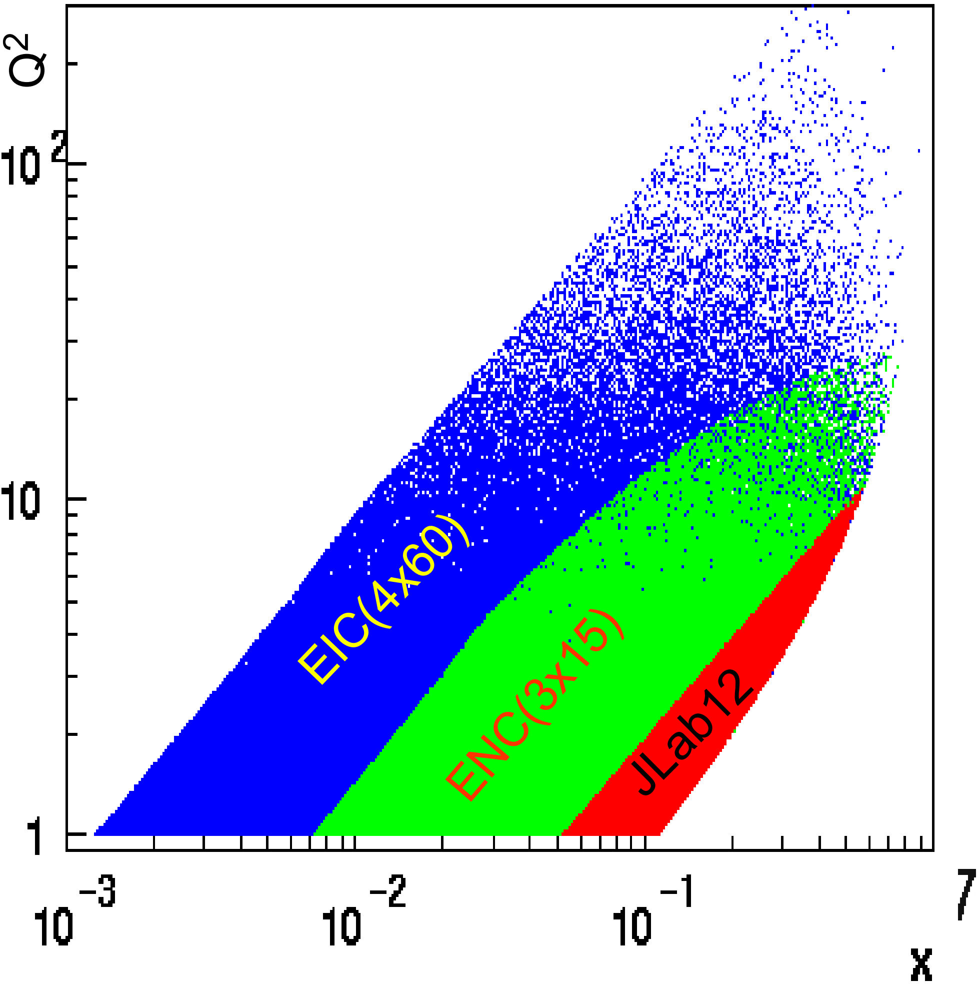


collider experiments
H1, ZEUS (EIC)
$10^{-4}<x_B<0.02$ (0.3): gluons (and quarks)
in the proton

fixed target experiments
COMPASS, HERMES
→ $0.006/0.02<x_B<0.3$: gluons/valence and sea quarks
JLab/JLab@12GeV
→ $0.1<x_B<0.7$: valence quarks

Study of high **x** domain requires high luminosity, low **x** higher energies

Hard Scattering Processes: Kinematics Coverage



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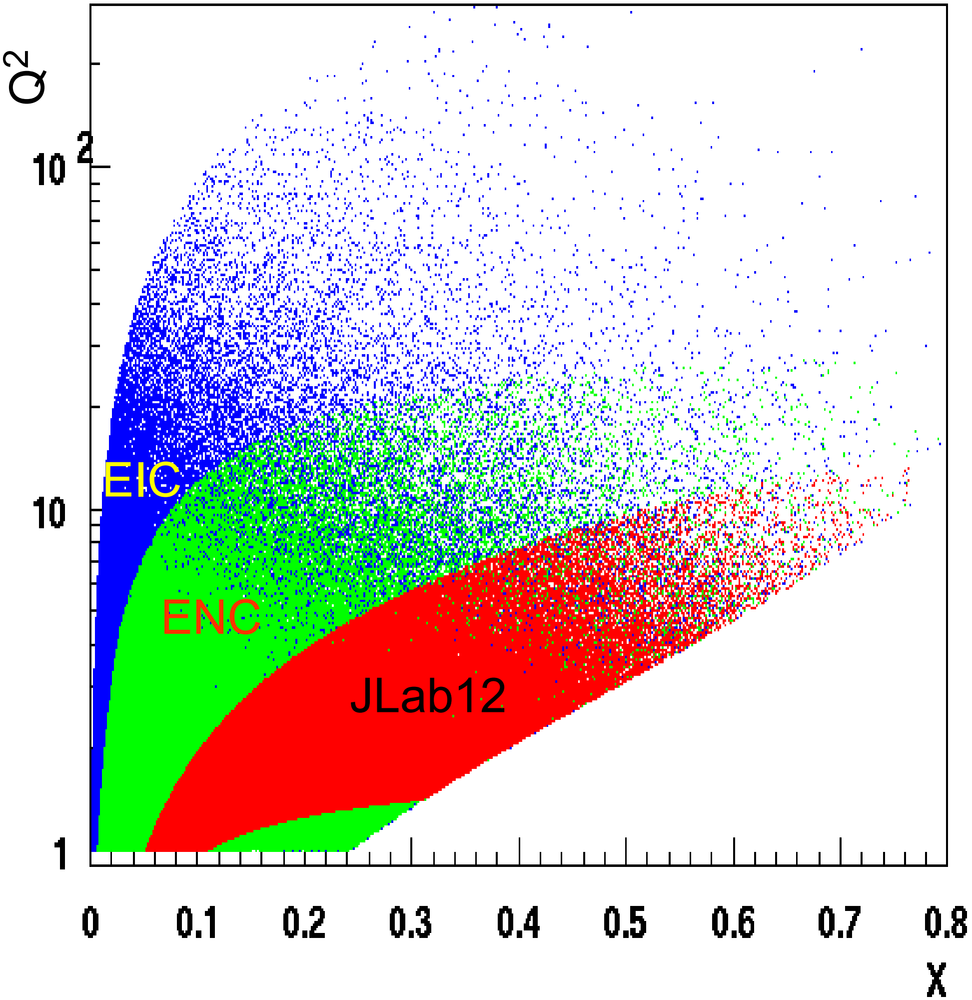
Hard Scattering Processes: Kinematics Coverage



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Study of high **x** domain requires high luminosity, low **x** higher energies

hep:arXiv-09092238

$$q(x,k_\perp)|_{k_\perp \gg \Lambda_{\rm QCD}} = \frac{1}{(k_\perp^2)^n}\int \frac{dx'}{x'} f_i(x') \times \mathcal{H}_{q/i}(x;x') \ , \qquad (23$$

where $q(x,k_\perp)$ represents the TMD quark distribution we are interested, f_i represents the in tegrated quark distribution for the $k_\perp$-even TMDs, and higher twist quark-gluon correlatio function for the $k_\perp$-odd TMDs. For the latter case, x' should be understood as two variable for the twist-three quark-gluon correlation functions as we discussed in the last section. Th overall power behavior $1/(k_\perp^2)^n$ can be analyzed by the power counting rule [48]. The har coefficient $\mathcal{H}_{q/i}(x;x')$ is calculated from perturbative QCD. In this paper, we will show th one-gluon radiation contribution to this hard coefficient.

The $k_\perp$-even TMD quark distribution functions, $f_1(x,k_\perp)$, $g_{1L}(x,k_\perp)$, and $h_1(x,k_\perp$ be calculated from the associated integrated quark distributions [23][3]. For the non-s contributions, they are expressed as [23],

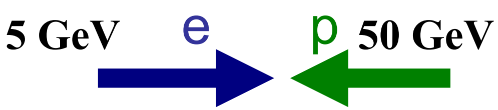
$$f_1(x_B,k_\perp) = \frac{\alpha_s}{2\pi^2}\frac{1}{\vec{k}_\perp^2}C_F\int\frac{dx}{x}f_1(x)\left[\frac{1+\xi^2}{(1-\xi)_+}+\delta(1-\xi)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2}-1\right)\right],$$

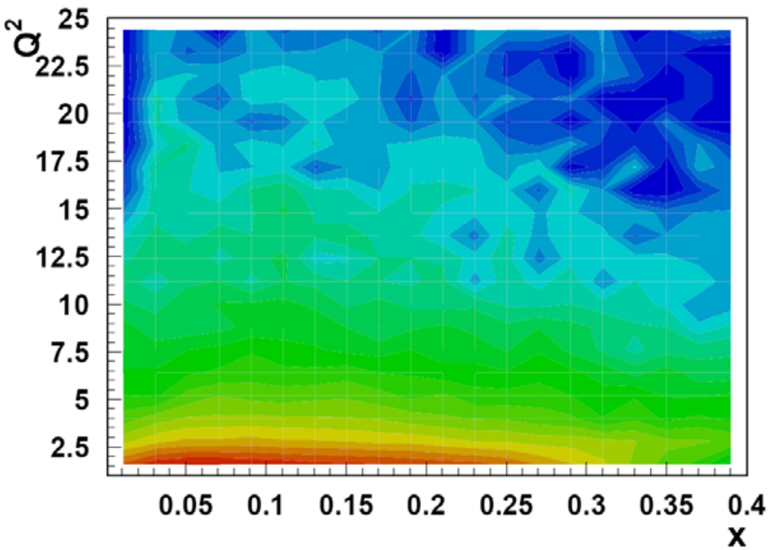
$$g_{1L}(x_B,k_\perp) = \frac{\alpha_s}{2\pi^2}\frac{1}{\vec{k}_\perp^2}C_F\int\frac{dx}{x}g_{1L}(x)\left[\frac{1+\xi^2}{(1-\xi)_+}+\delta(1-\xi)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2}-1\right)\right],$$

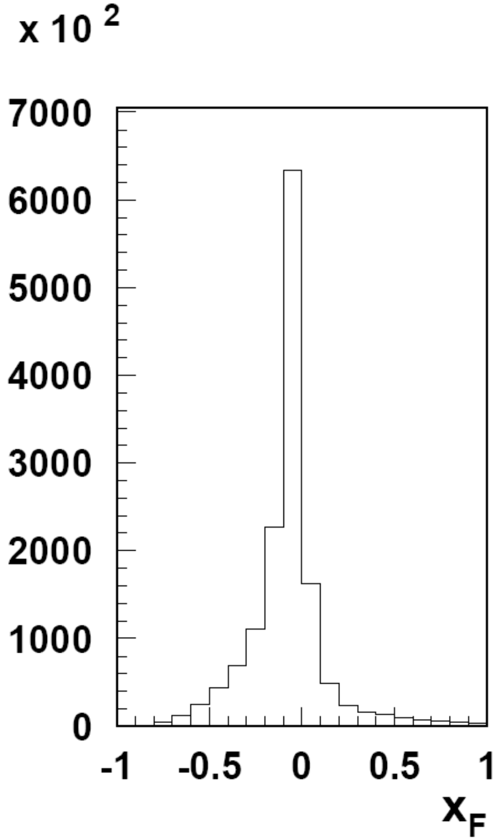
$$h_1(x_B,k_\perp) = \frac{\alpha_s}{2\pi^2}\frac{1}{\vec{k}_\perp^2}C_F\int\frac{dx}{x}f_1(x)\left[\frac{2\xi}{(1-\xi)_+}+\delta(1-\xi)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2}-1\right)\right],$$

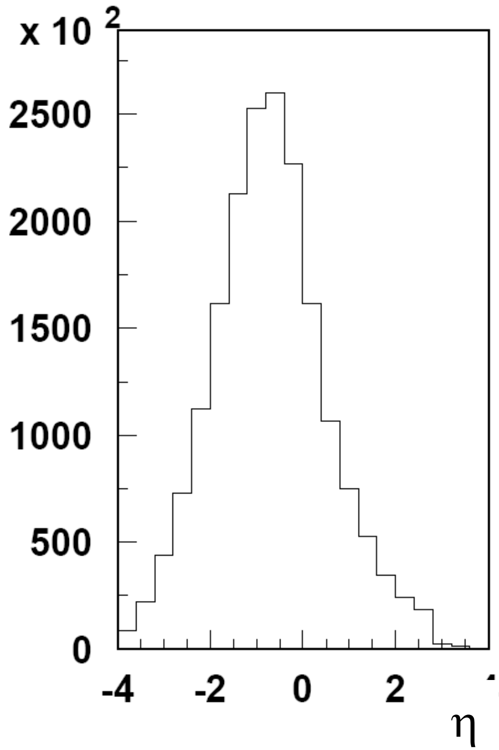
where the color factor $C_F = (N_c^2-1)/2N_c$ with $N_c = 3$, $\xi = x_B/x$ and $\zeta^2 = (2v\cdot P)^2/v^2$.

Hard Scattering Processes: Kinematics Coverage



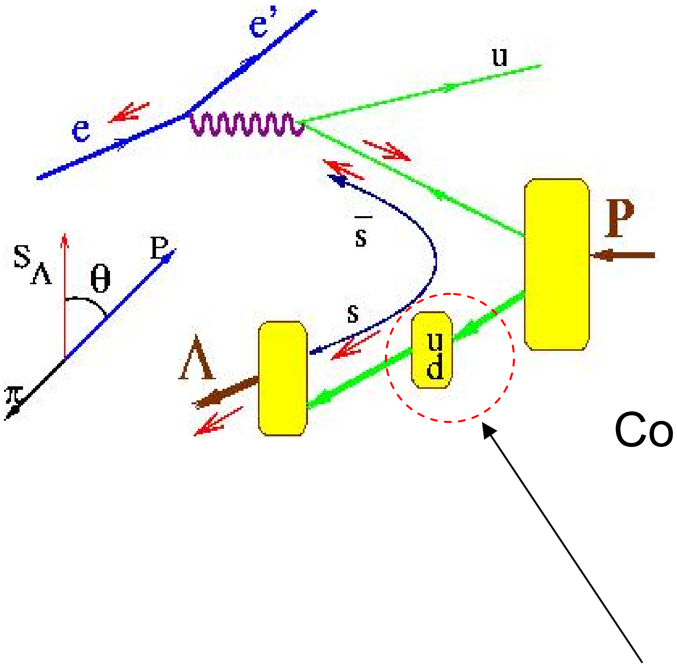






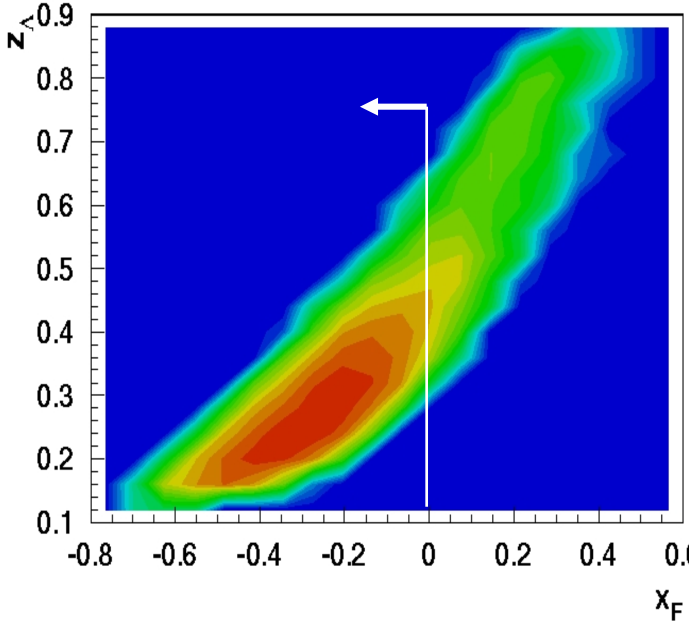
Study of high **x** domain requires high luminosity, low **x** higher energies

Λ polarization in the target fragmentation



Λ polarization in TFR provides information on contribution of strange sea to proton spin

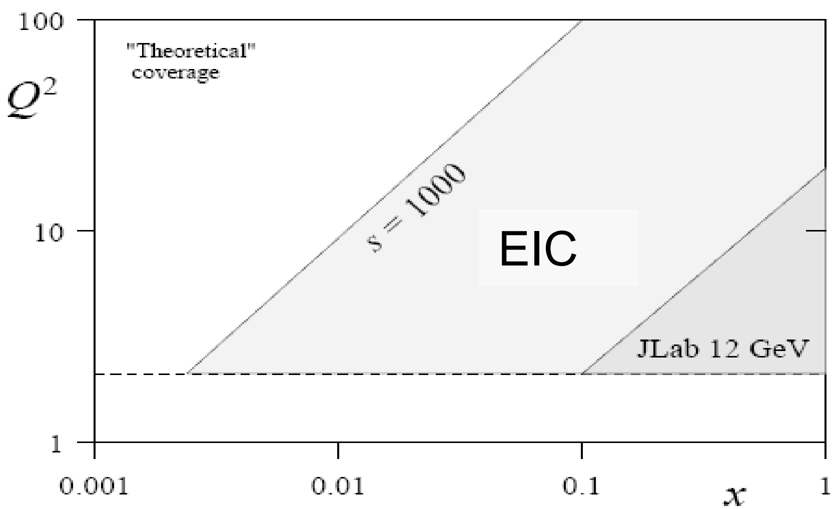
Compare x_F with eic!

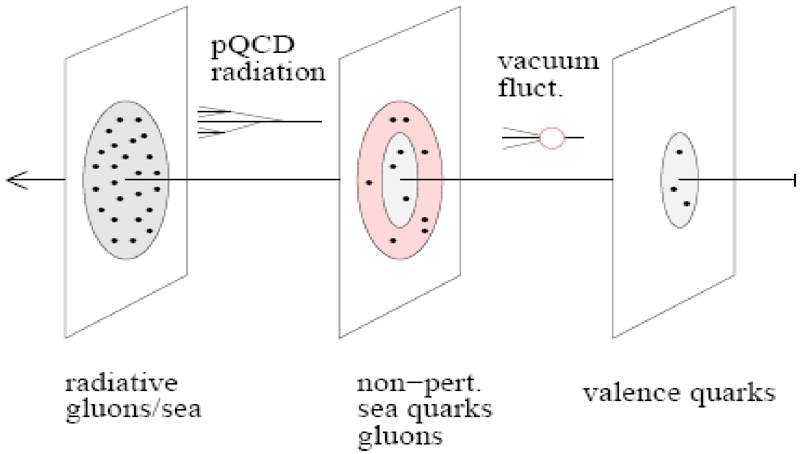


Study polarized diquark fracture functions sensitive to the correlations between struck quark transverse momentum and the diquark spin.

Wide kinematical coverage of EIC would allows studies of hadronization in the target fragmentation region

Structure of nucleon: HERA→JLab→EIC



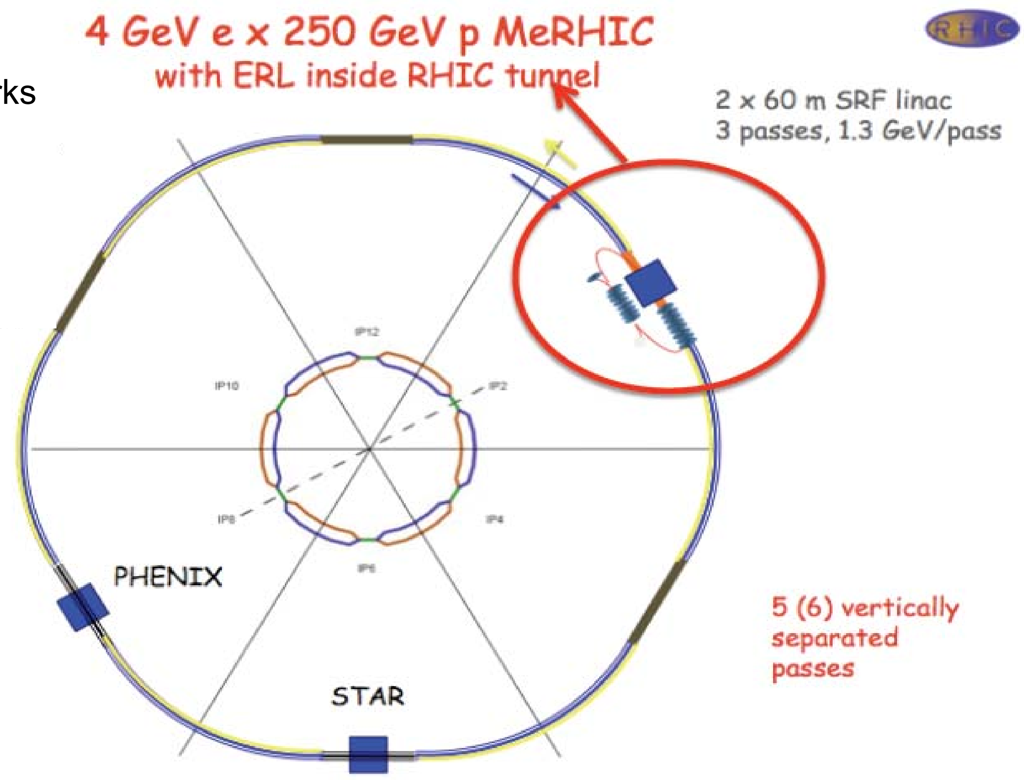


- JLab 12 GeV: Valence quark spin/flavor/spatial distributions
- EIC@JLab: Gluons and sea quark spin/flavor/spatial distributions
  - → multiparticle dynamics
  - → role of gluons in structure
  - → non–pert. QCD vacuum, meson cloud
- High–energy collider (HERA): small–x gluons
  - → perturbative QCD radiation
  - → high parton densities, "saturation"

EIC@RHIC – an overview

Science highlights

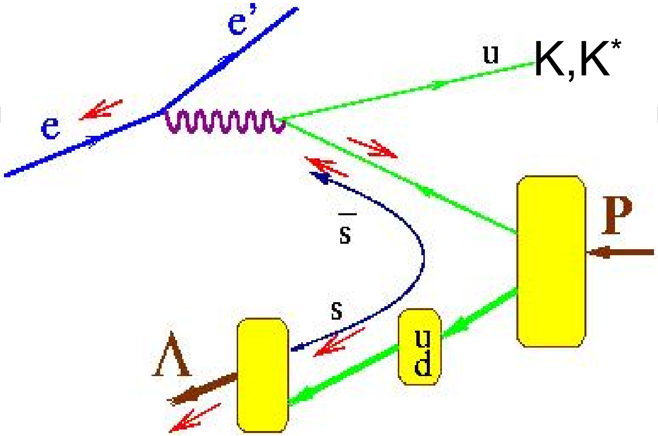
- Transverse imaging of gluons and sea quarks
- Nucleon spin (quark/gluon orbital motion)
- Nuclei in QCD (quark/gluon structure)
- QCD vacuum in hadron structure and creation



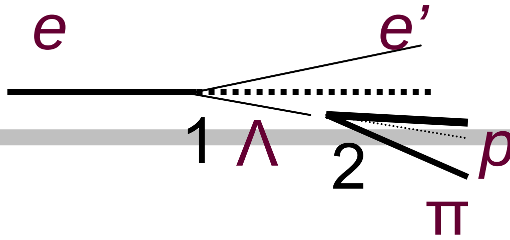
V.N. Litvinenko, DIS 2009, Madrid, April 28 2009

Main Features

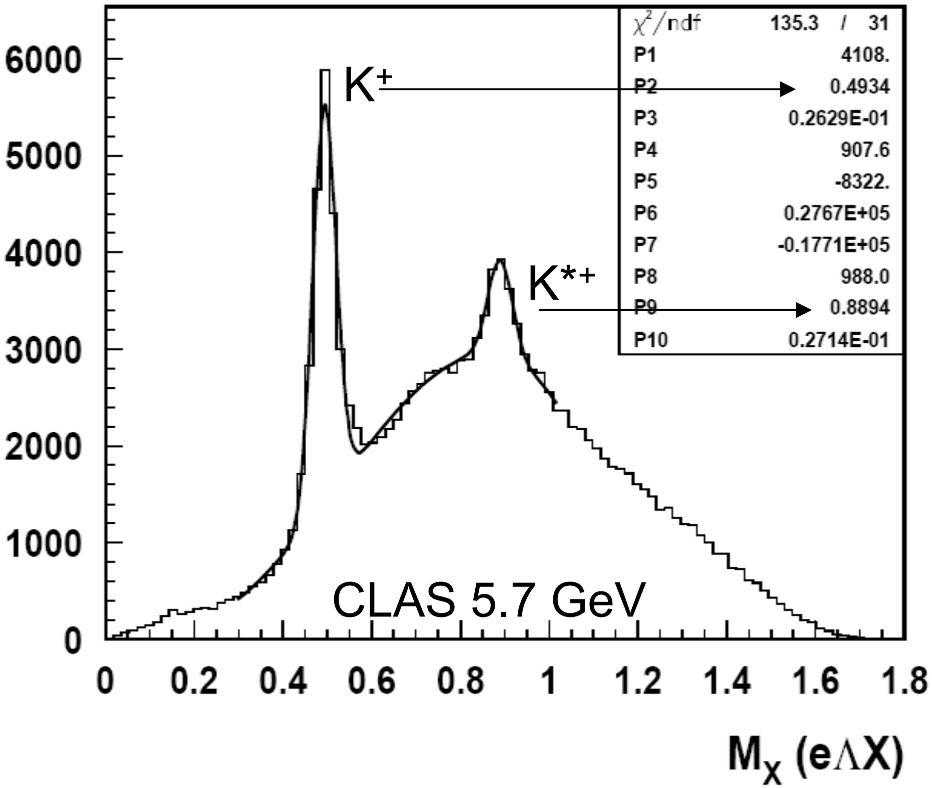
- Electron energy: 4-20 GeV
- Proton energy: 50-250 GeV
  - More symmetric kinematics provides better *resolution* and *particle id*
- Luminosity: few x 10^{32} cm^{-2} s^{-1}
  - in *range* around s ~ 1000-10000 GeV^2
- Polarized electrons and light ions
  - longitudinal and transverse
- Limited R&D needs
- ? interaction regions (detectors)
- 90% of hardware can be reused

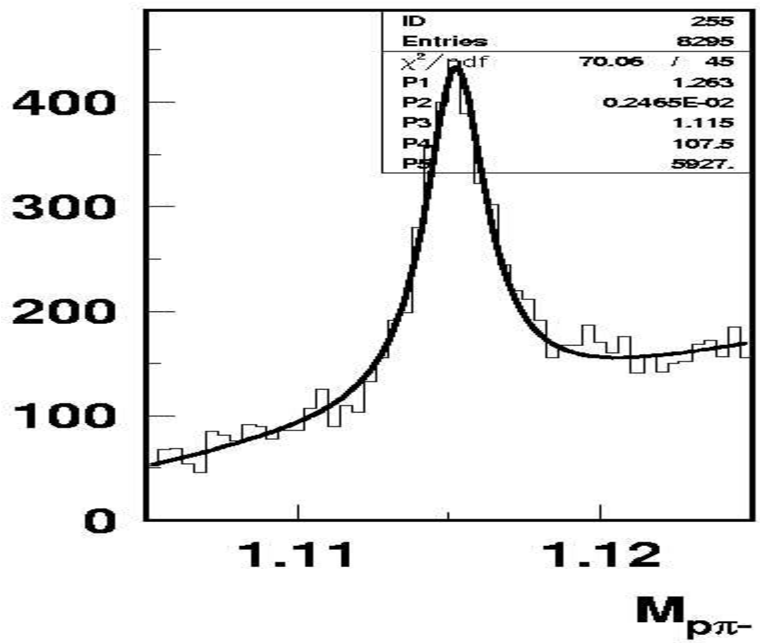


Λ production



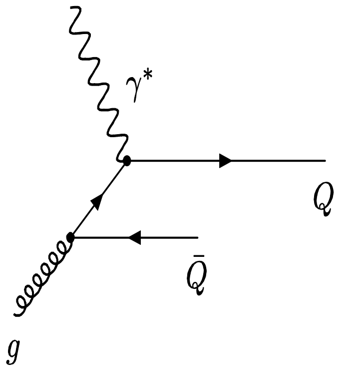
(ud)-diquark is a spin and isospin singlet s-quark carries whole spin of Λ $|\Lambda\rangle = |uds\rangle$



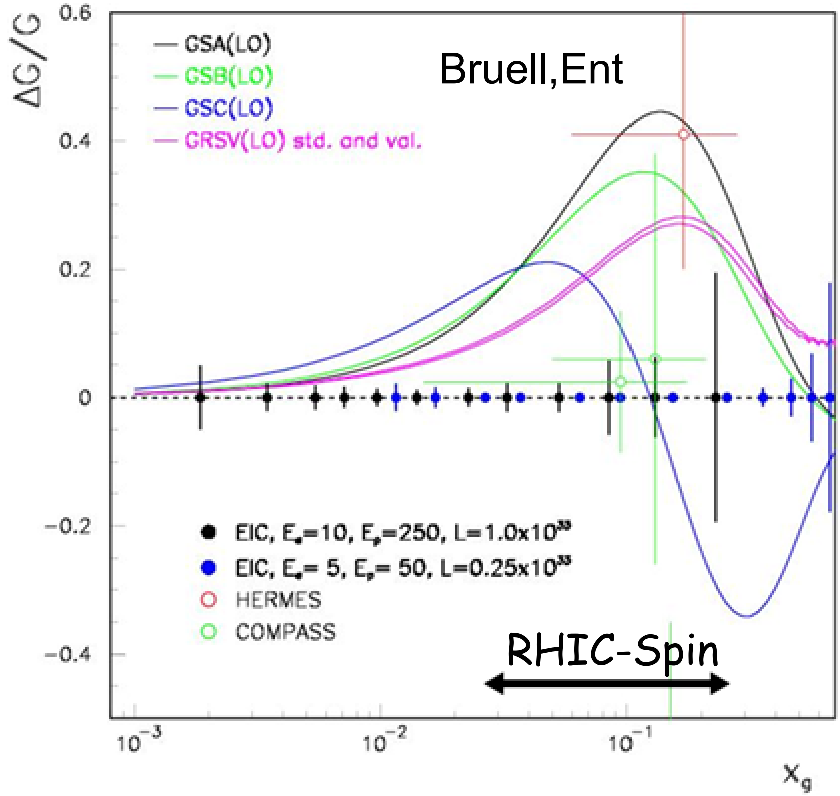


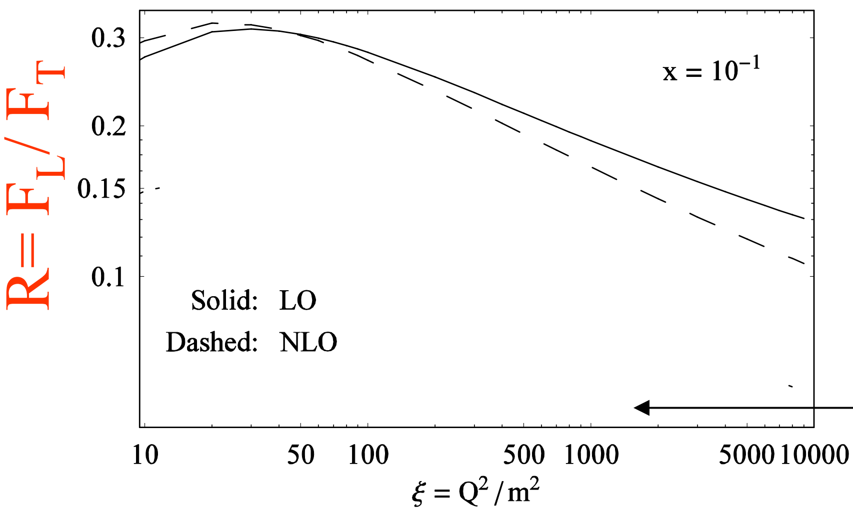
The Gluon Contribution to the Proton Spin

$$\frac{d^3\sigma_{lN}}{dx\,dQ^2 d\varphi} = \frac{\alpha_{em}^2}{xQ^4}\left\{ \left[1+(1-y)^2\right] F_2(x,Q^2) - 2xy^2 F_L(x,Q^2) \right.$$



Projected data on $\Delta g/g$ with an EIC, via $\gamma + p \rightarrow D^0 + X$
$\hookrightarrow K^- + \pi^+$
assuming vertex separation of 100 μm.



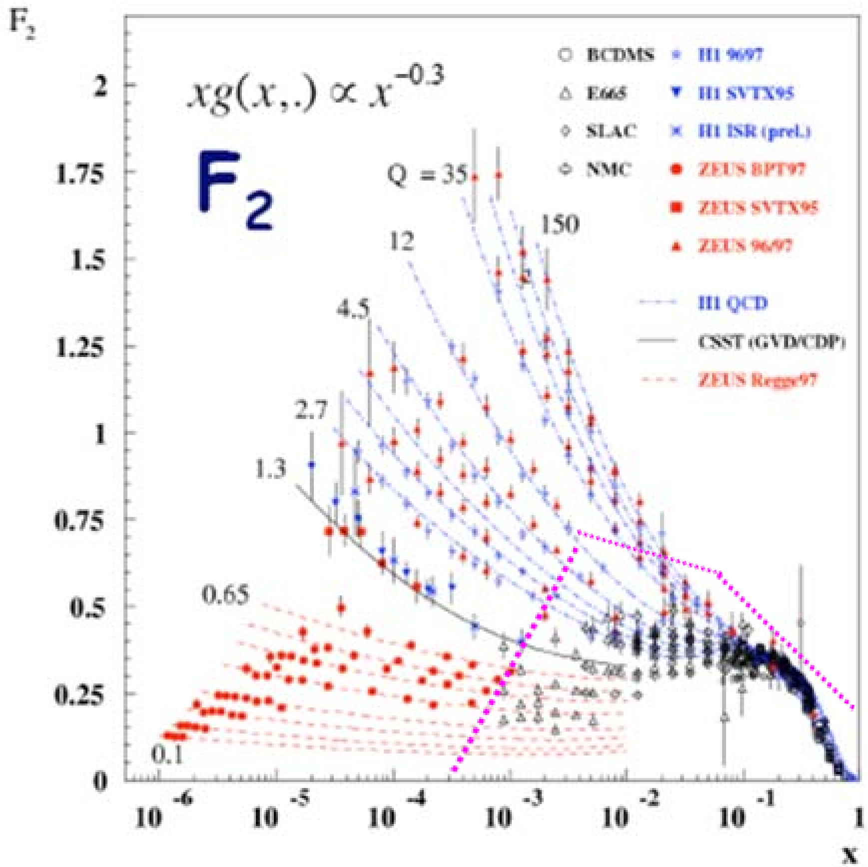


- *Uncertainties in $x\Delta g$ smaller than 0.01*
- *Measure 90% of ΔG (@ Q^2 = 10 GeV^2)*

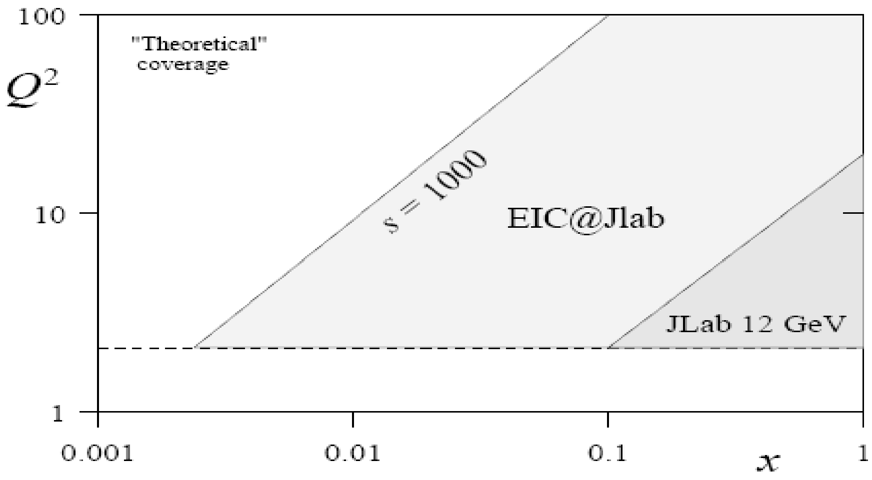
Resummation for $R = F_L / F_T$

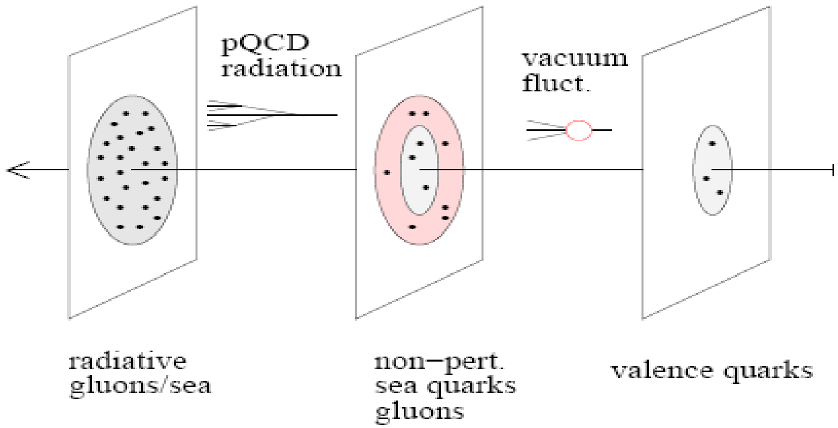
- **N.Ya.Ivanov, Nucl. Phys. B 814 (2009), 142**

HERA legacy



Access rising distributions with staged EIC



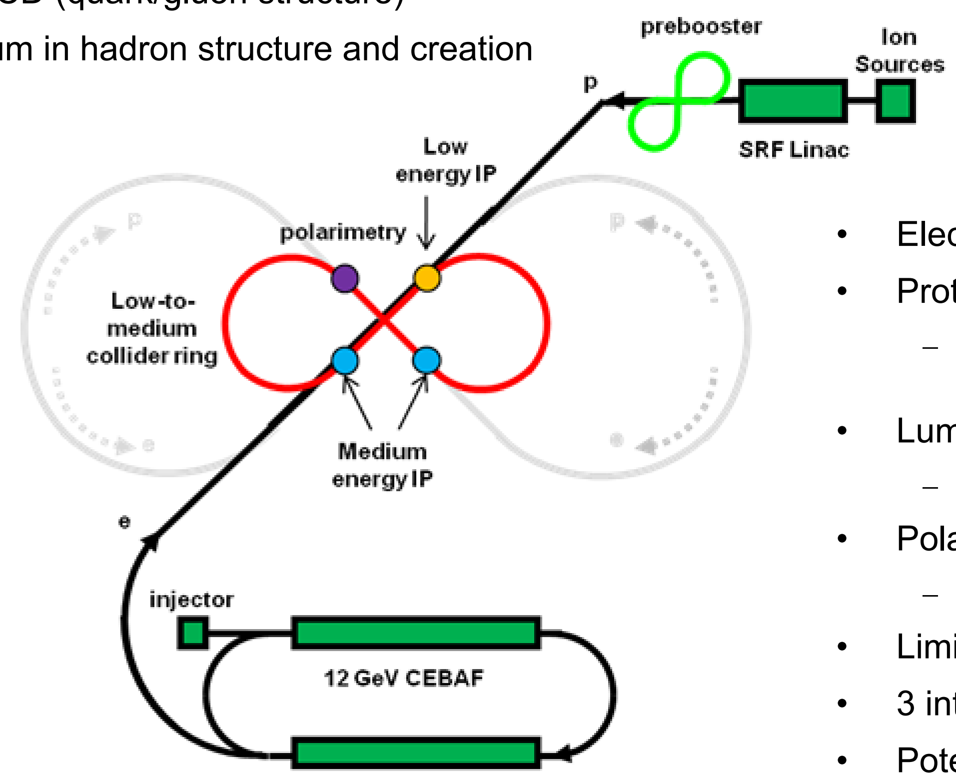


Need to study glue at the highest density.

EIC@JLab – an overview

Science highlights

- Transverse imaging of gluons and sea quarks
- Nucleon spin (quark/gluon orbital motion)
- Nuclei in QCD (quark/gluon structure)
- QCD vacuum in hadron structure and creation



Main Features

- Electron energy: 3-11 GeV
- Proton energy: 12-60 GeV
  - More symmetric kinematics provides better *resolution* and *particle id*
- Luminosity: few x 10^{34} cm^{-2} s^{-1}
  - in *range* around s ~ 1000 GeV^2
- Polarized electrons and light ions
  - longitudinal and transverse
- Limited R&D needs
- 3 interaction regions (detectors)
- Potential upgrade with high-energy ring

Comparison with directly measured $\Delta G/G$ at $Q^2 = 3$ GeV^2

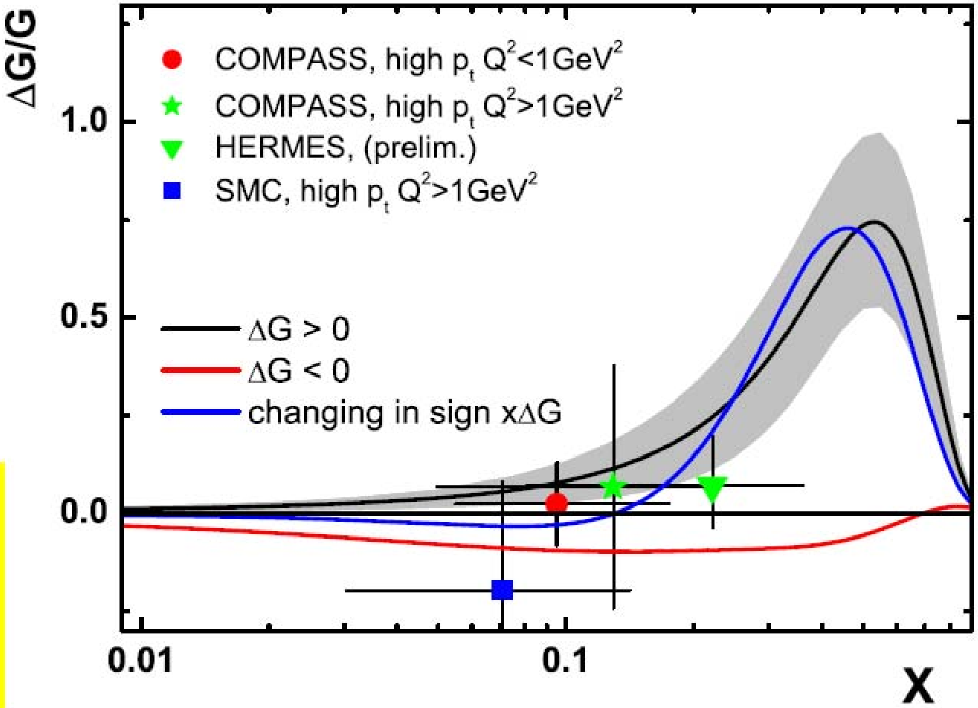
MRST'02 unpolarized gluon density is used for G(x)

The error band corresponds to statistic and systematic errors of ΔG

The error bars of the experimental points represent the total errors

The most precise value of $\Delta G/G$, the *COMPASS* one, is well consistent with any of the polarized gluon densities determined in our analysis

The high p_t measurements cannot also distinguish between different solutions for ΔG



What E_{cm} and Luminosity are needed for hard Processes?

Both BNL and JLab have emphasized staging ideas for an EIC as their immediate priority:

- MeRHIC: $400 < s < 4000$, L close to 10^{33}
- (M)EIC : $100 < s < 2600$, L few times 10^{34}

Processes requiring most luminosity are:

deep exclusive pion and kaon (!) electroproduction

large p_T semi-inclusive DIS

Processes driving to a center-of-mass energy of 30-50 are: jet production

(to map quark transverse momentum?)

factorization? ($E_{cm} > 40$?)

But, deep exclusive charged meson production drives more symmetric energies and E_{cm} of 10-30

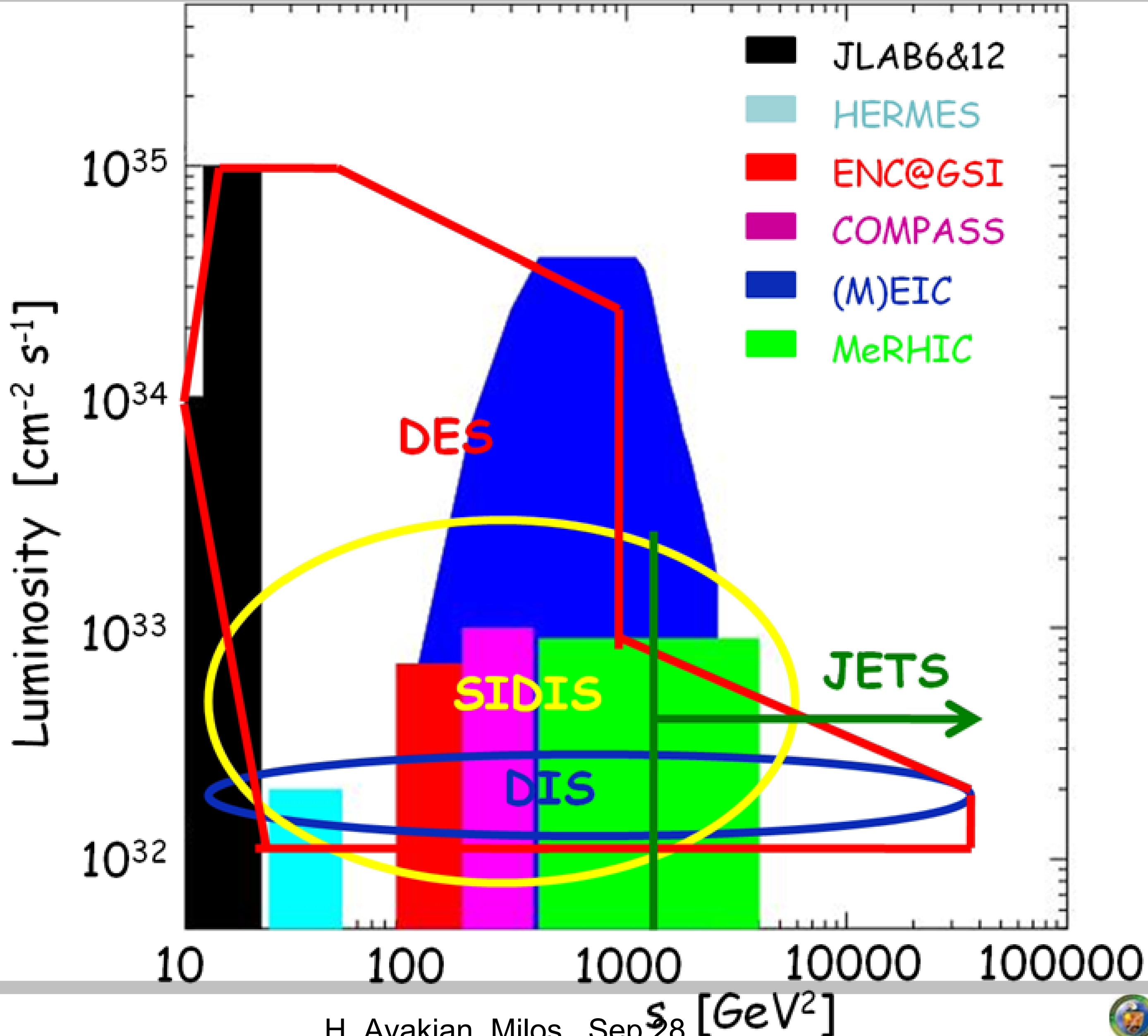
The EIC **will** indeed allow a unique **GPD & TMD** program

Optimization of such EIC requires more work.

What E_{cm} and Luminosity are needed for Semi-Inclusive DIS Processes?

•Find that 100 days of measurements with a luminosity of 10^{33} is in general sufficient (for $p_T < 1$ GeV)
• Useful to include lower-energies to improved data quality at larger x values (~ 0.1)
• Include higher energies (E_{cm} = 30-50) to access jets (and diffraction)
• but, for SIDIS need multiple conditions: Longitudinal, Transverse, ^{1}H, ^{2}H, ^{3}He, heavy A, low, high E_{cm}
→10^{33} really seems minimum
→ full program requires (*n times 100 days*)
• simulations at large p_T were done assuming 10^{35} luminosity
→ Likely needs more than 10^{33} luminosity

science/luminosity matrix for EIC



The approach is based on following observations:

- The ratios $R = F_L / F_T$ and $A = 2xF_A / F_2$ in heavy-quark leptoproduction are perturbatively stable within the FFNS.
- The quantities F_L / F_T and $2xF_A / F_2$ are sensitive to resummation of the mass logarithms of the type $\alpha_s \ln(Q^2 / m^2)$ within the VFNS.

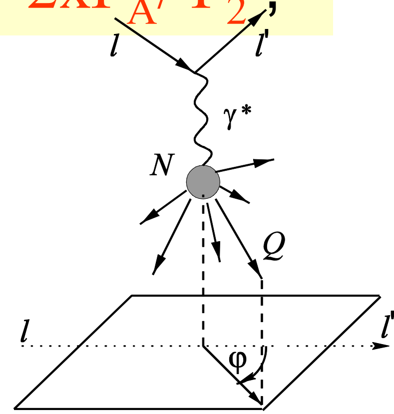
These facts together imply that (future) high-Q^2 data on the ratios $R = F_L / F_T$ and $A = 2xF_A / F_2$ will make it possible to probe the heavy-quark densities in the nucleon, and thus to compare the convergence of perturbative series within the FFNS and VFNS.

Remember that, within the VFNS, the heavy-quark content of the proton is due to resummation of the mass logarithms of the type
$\alpha_s \ln(Q^2 / m^2)$ and, for this reason, closely related to behavior of asymptotic perturbative series for high Q^2.

How to measure the charm content of the proton?

VFNS vs. FFNS: What series is more efficient?

We propose two clean experimental ways to determine the heavy quark densities in the proton: using the Callan-Gross ratio $R=F_L/F_T$ and azimuthal $\cos 2\varphi$ asymmetry, $A=2xF_A/F_2$, in DIS:



$$l(\ell)+N(p)\rightarrow l(\ell-q)+Q(p_Q)+X[\overline{Q}](p_X)$$

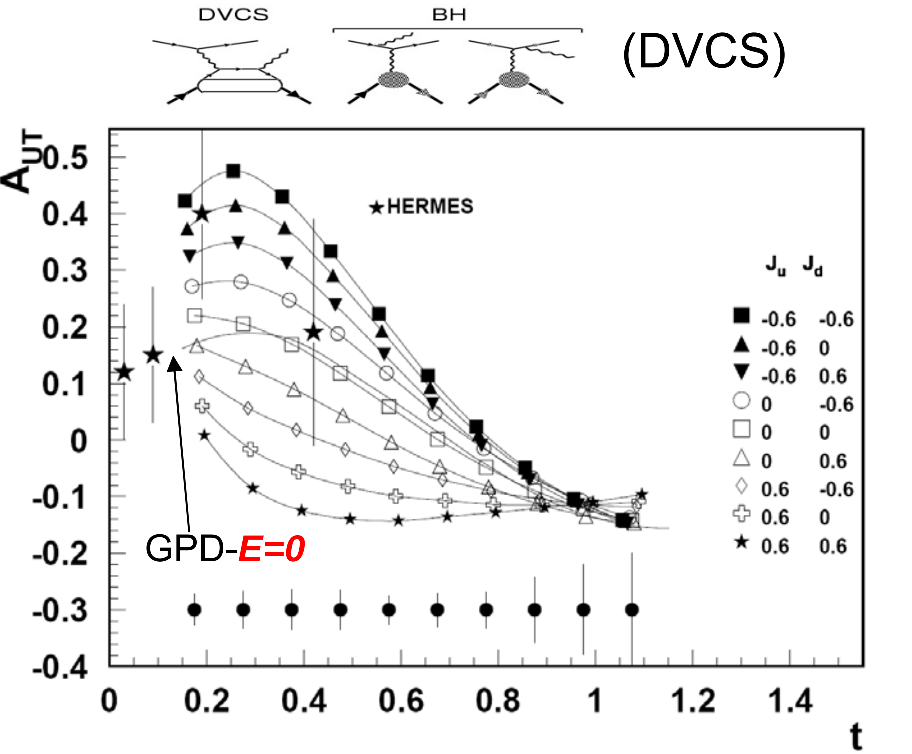
Corresponding cross section is:

$$\frac{\mathrm{d}^3\sigma_{lN}}{\mathrm{d}x\,\mathrm{d}Q^2\mathrm{d}\varphi}=\frac{\alpha_{em}^2}{xQ^4}\Big\{\left[1+(1-y)^2\right]F_2(x,Q^2)-2xy^2F_L(x,Q^2)$$
$$+4x(1-y)F_A(x,Q^2)\cos 2\varphi+4x(2-y)\sqrt{2(1-y)}F_I(x,Q^2)\cos\varphi\Big\}$$

where $F_2(x,Q^2)=2x(F_T+F_L)$ and x, y, Q^2 are usual DIS observables

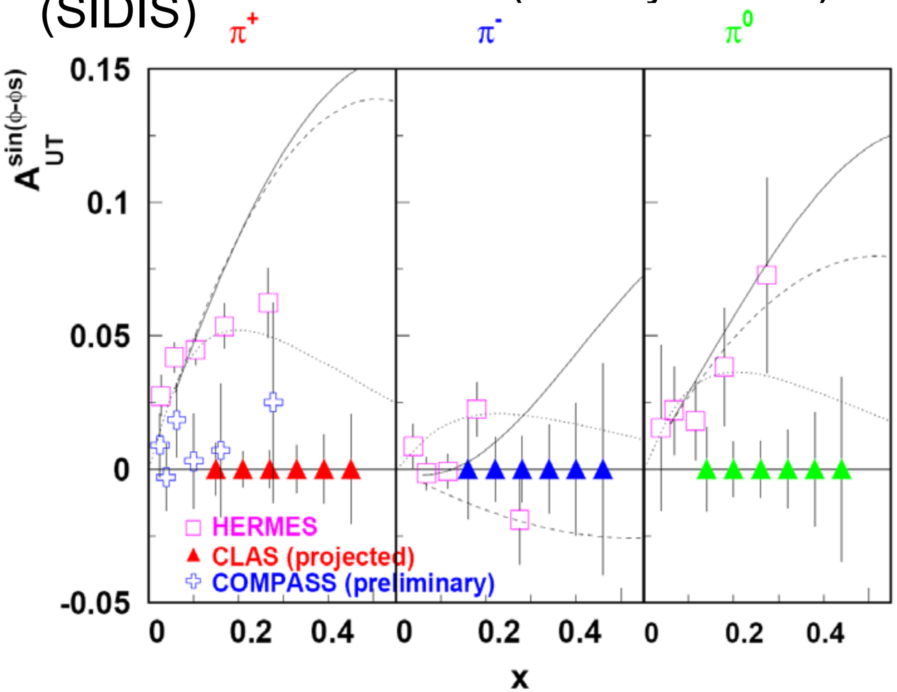
Measurement of Sivers function and GPD-E

(DVCS)



(SIDIS)

CLAS6 (25 days-2011)



DVCS Transverse asymmetry (function of momentum transfer to proton) is large and has strong sensitivity to GPD-***E***

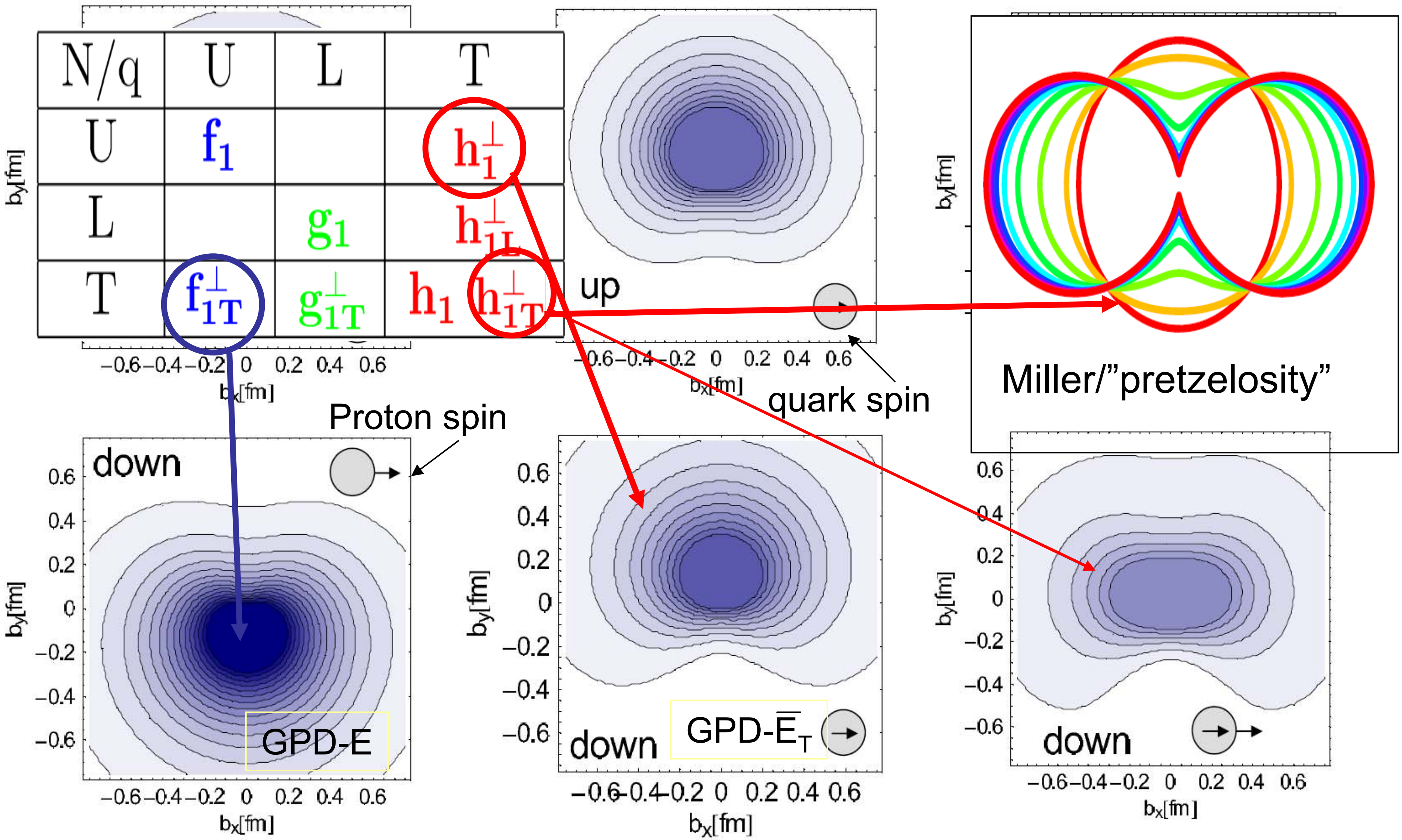
CLAS will provide a measurements of Sivers asymmetry at large x, where the effect is large and models unconstrained by previous measurements.

$$\int d^2\vec{k}_T \vec{k}_T^2 f_{1T}^{\perp}(x,\vec{k}_T^2) = -e_s e_q \frac{(1-x)}{4\pi} \int d^2\vec{b}_T (E(x,\vec{b}_T^2))'$$

Meissner, Metz & Goeke (2007)

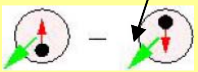
Spin densities from Lattice (QCDSF and UKQCD Collaborations)

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$



Pretzelosity

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



$$h_{1T}^\perp / f_1 \sim (1-x)^2$$

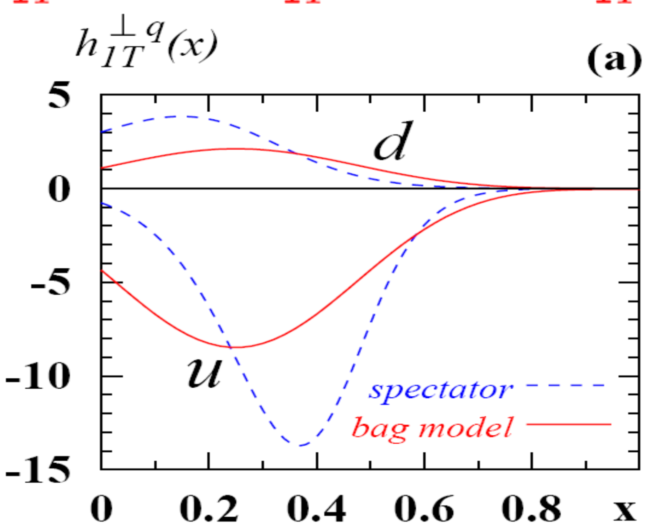
Transversely polarized quarks in transversely polarized proton

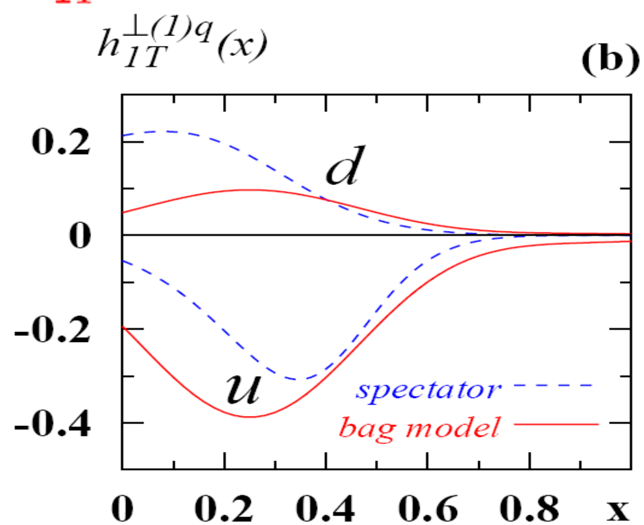
$$\left|\frac{k_\perp^2}{2M_N^2} h_{1T}^{\perp q}(x,k_\perp)\right| \leq \frac{1}{2}\left(f_1^q(x,k_\perp) - g_1^q(x,k_\perp)\right) \leq f_1^q(x,k_\perp)$$

positivity conditions

$$|h_{1T}^{\perp(1)u}(x) - h_{1T}^{\perp(1)d}(x)| \ll |h_{1T}^{\perp(1)u}(x) + h_{1T}^{\perp(1)d}(x)|$$

Large N_c





P. Schweitzer
F. Yuan

•The difference between transversity and helicity distributions is measure of relativistic effects!

$$g_1^q(x,k_\perp) - h_1^q(x,k_\perp) = \frac{k_\perp^2}{2M_N^2} h_{1T}^{\perp q}(x,k_\perp)$$

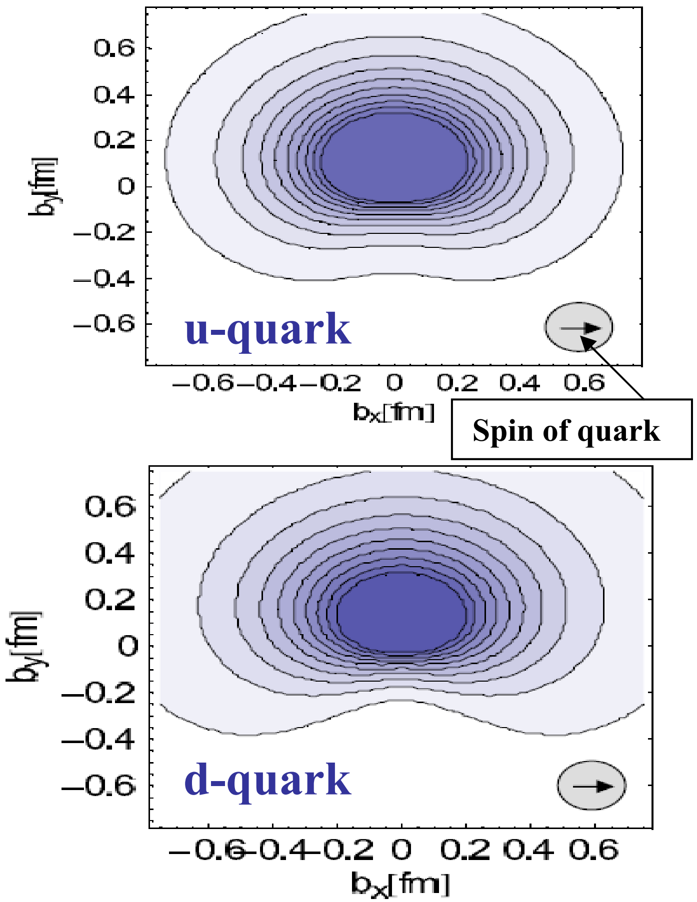
Chiral-odd GPDs

First introduced : $H_T, \tilde{H}_T$ X.Ji, P.Hoodbhoy 1987

$$H_T(x,0,0) = h_1(x)$$

$H_T, \tilde{H}_T, E_T, \tilde{E}_T$ M.Diehl 2001

P.Haegler GPD2006(QCDSF)



$2\tilde{H}_T + E_T$ **describe the sideways shift in distribution of transversely polarized quarks in the unpolarized proton** (Diehl,Haegler 2005)

First model calculations of $2\tilde{H}_T + E_T$ indicate large sideways shift (B.Pasquini et al. 2005)

Transverse shift (conjugate to transverse momentum) is due to spin-orbit interactions in quark wave functions

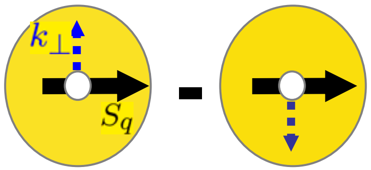
$$\kappa_T^q = \int dx[2\tilde{H}_T(x,0,0) + E_T(x,0,0)]$$

Transverse spin-flavor dipole moment κ_T^q from GPDs related to Boer-Mulders PDF describing transversely polarized quarks in unpolarized target (Burkardt 2005)

Lattice (QCDSF/UKQCD) and GPD model calculations confirm large transverse shift!

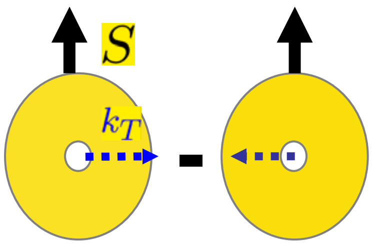
TMDs in SIDIS at leading twist

$$f_{q/p}(x,k_\perp^2)=\frac{1}{2}[f_1^q(x,k_\perp^2)-h_1^{\perp q}(x,k_\perp^2)\frac{(\hat{P}\times k_\perp)\cdot S_q}{M}]$$



Correlation between the transverse momentum and transverse spin of quarks

$$f_{q/p\uparrow}(x,k_T^2)=\frac{1}{2}[f_1^q(x,k_T^2)-f_{1T}^{\perp q}(x,k_T^2)\frac{(\hat{P}\times k_T)\cdot S}{M}]$$



Correlation between the quark transverse momentum and transverse spin of the proton

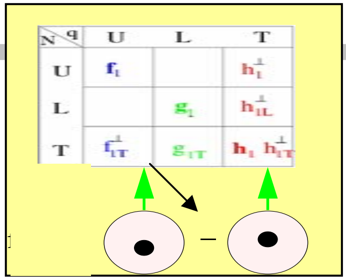
$$f_{1T}^{\perp q}(SIDIS)=-f_{1T}^{\perp q}(DY)$$

Collins (2002)

$$\int d^2\vec{k}_T\vec{k}_T^2 f_{1T}^{\perp}(x,\vec{k}_T^2)=-e_s e_q\frac{(1-x)}{4\pi}\int d^2\vec{b}_T(E(x,\vec{b}_T^2))'$$

Meissner, Metz & Goeke (2007)

TMDs and spin-orbit correlations



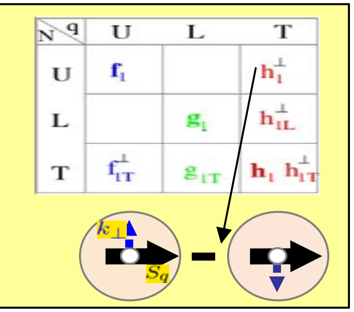
Unpolarized quarks

$$\sigma_{UU} \sim (1-y+y^2/2) f_1 D_1$$

$$f_{1T}^{\perp} \sim (1-x)^4 \qquad \sigma_{UT}^{sin(\phi-\phi_S)} \sim (1-y+y^2/2) f_{1T}^{\perp} D_1$$

QCD large-x limit,
Brodsky & Yuan (2006)

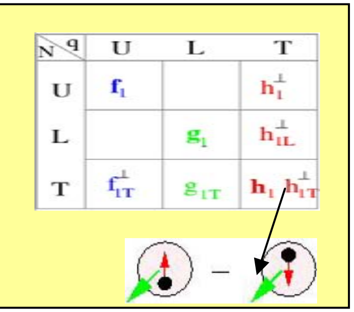
$$\sim \frac{1}{P_T^3}$$ (perturbative limit)



$$h_1^{\perp} \sim (1-x)^4 \qquad \sigma_{UU}^{cos2\phi} \sim (1-y) h_1^{\perp} H_1^{\perp}$$

$$\sim \frac{1}{P_T^4}$$

Transversely polarized quarks



Pretzelosity

$$h_{1T}^{\perp} \sim (1-x)^5 \qquad \sigma_{UT}^{sin(3\phi-\phi_S)} \sim (1-y) h_{1T}^{\perp} H_1^{\perp}$$

$$\sim \frac{1}{P_T^5}$$

TMDs: QCD based predictions

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Large-x limit

Brodsky & Yuan (2006)

Burkardt (2007)

$f_{1T}^\perp \sim (1-x)^4$ $g_{1T}^\perp \sim (1-x)^4$ $h_1 \sim (1-x)^3$ $h_{1T}^\perp \sim (1-x)^5$

Large-Nc limit (Pobilitsa)

$f_1^{\perp u} > 0, f_1^{\perp d} > 0$ $h_1^{\perp u} < 0, h_1^{\perp d} < 0$

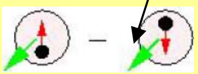
Do not change sign (isoscalar)

$f_{1T}^{\perp u} < 0, f_{1T}^{\perp d} > 0$

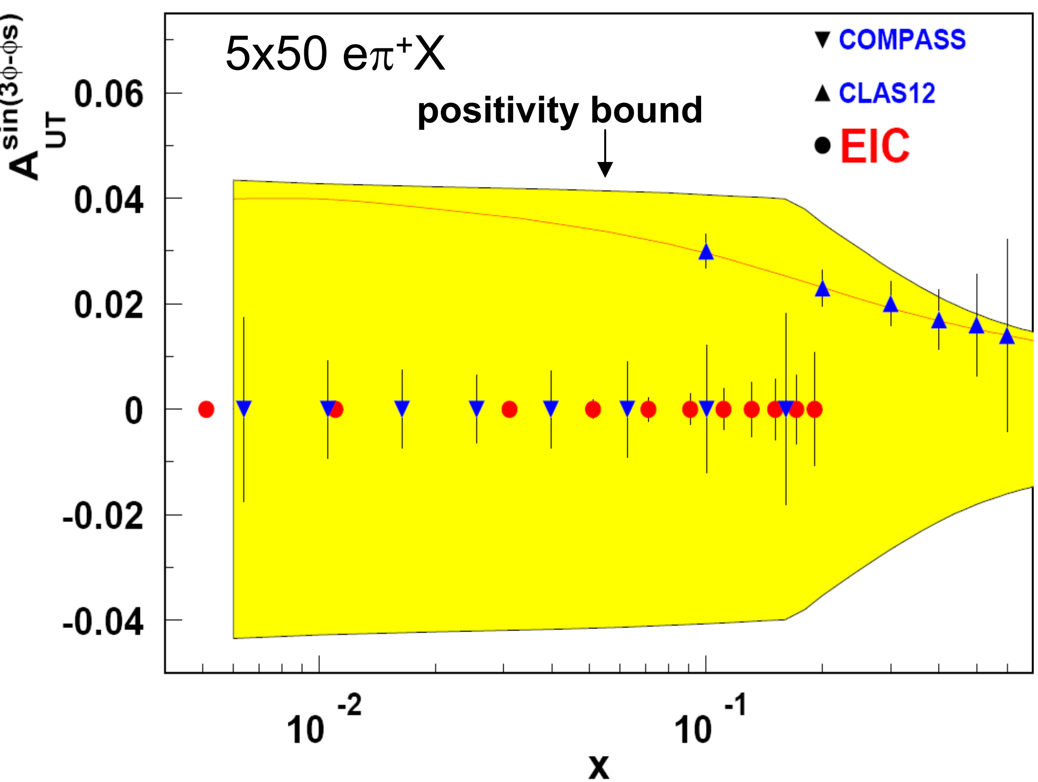
All others change sign
u→d (isovector)

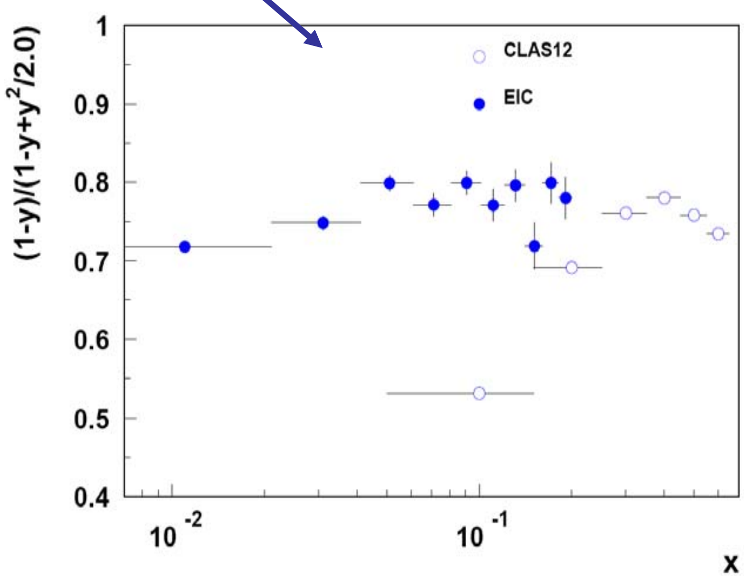
Pretzelosity @ EIC

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$



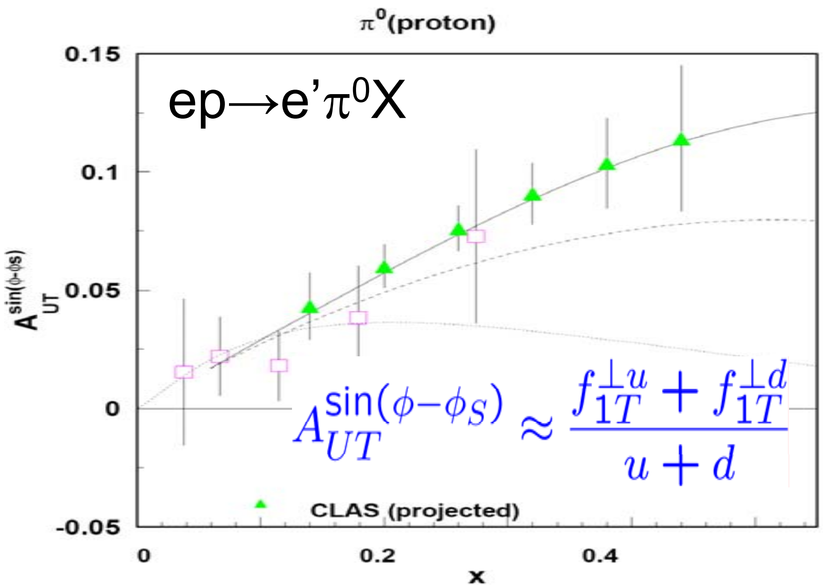
$$A_{UT}^{\sin(3\phi-\phi_S)} \propto \frac{1-y}{1-y+y^2/2}\frac{\sum_q e_q^2 h_{1T}^{\perp(1)q} H_1^{\perp q}}{\sum_q e_q^2 f_1^q D_1^q}$$

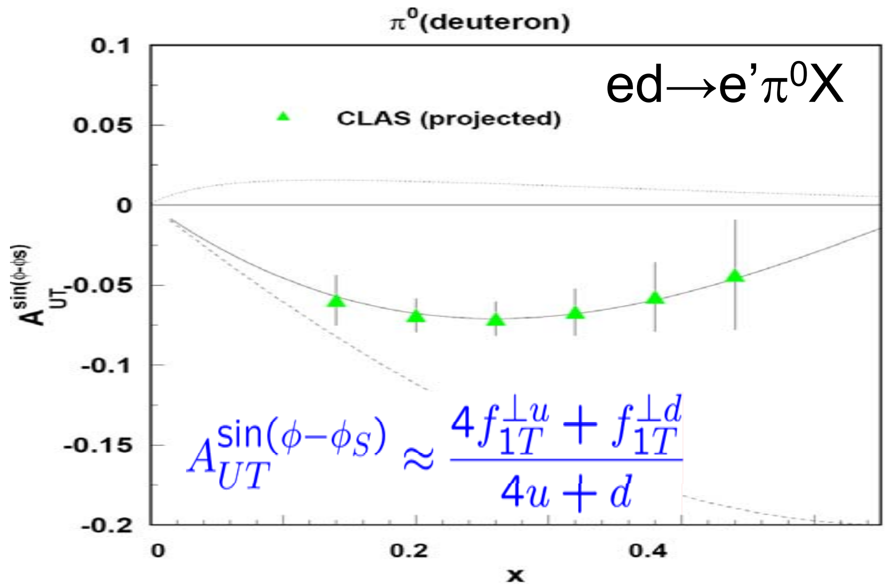




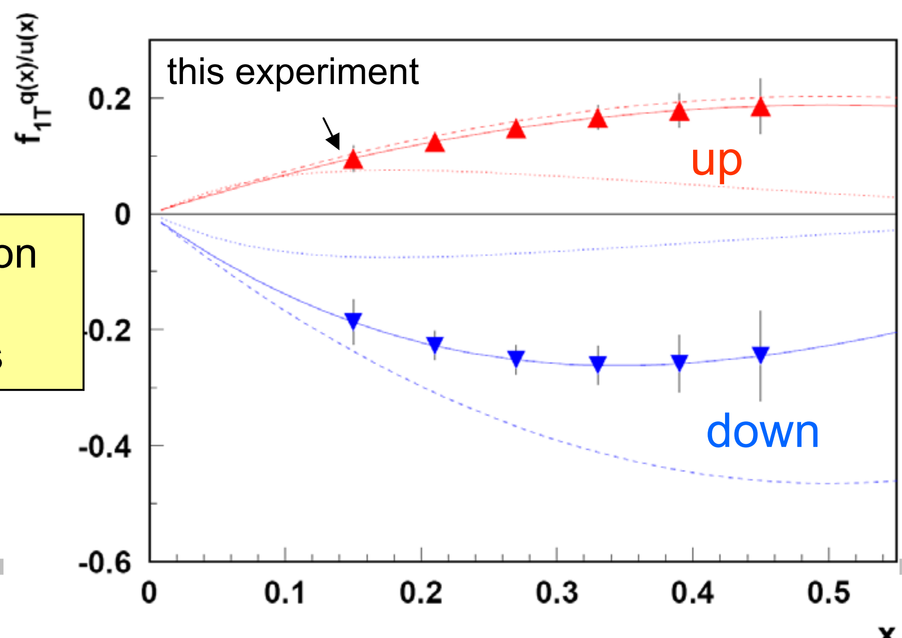
- EIC measurement combined with CLAS12 will provide a complete kinematic range for pretzelosity measurements

Sivers effect on π^0: extracting the Sivers function



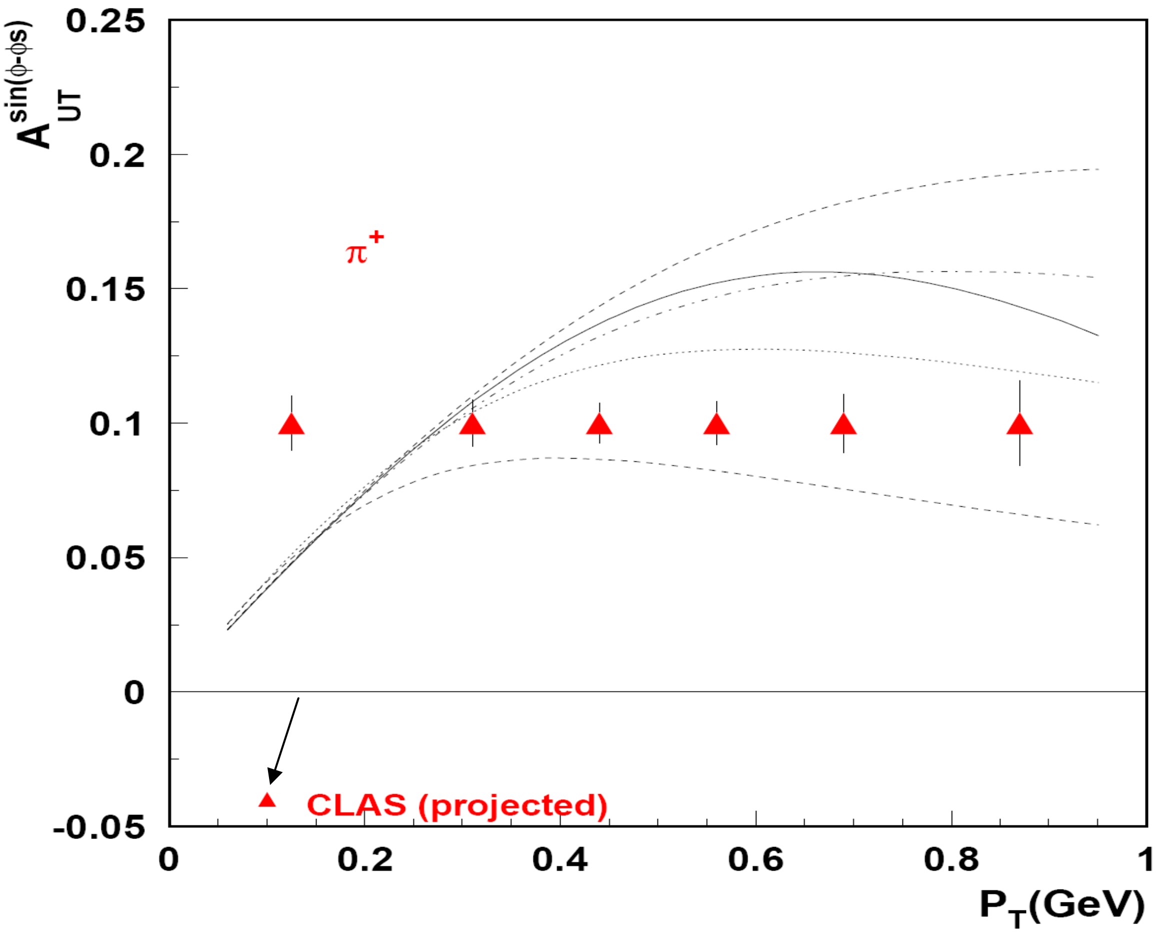


$\pi^+ + \pi^-$ or π^0 A_{UT} for proton doesn't depend on fragmentation functions



Sivers asymmetry measurements on deuteron and proton target allow model independent extraction of Sivers function for u and d quarks at large x

Sivers effect: P_T-dependence

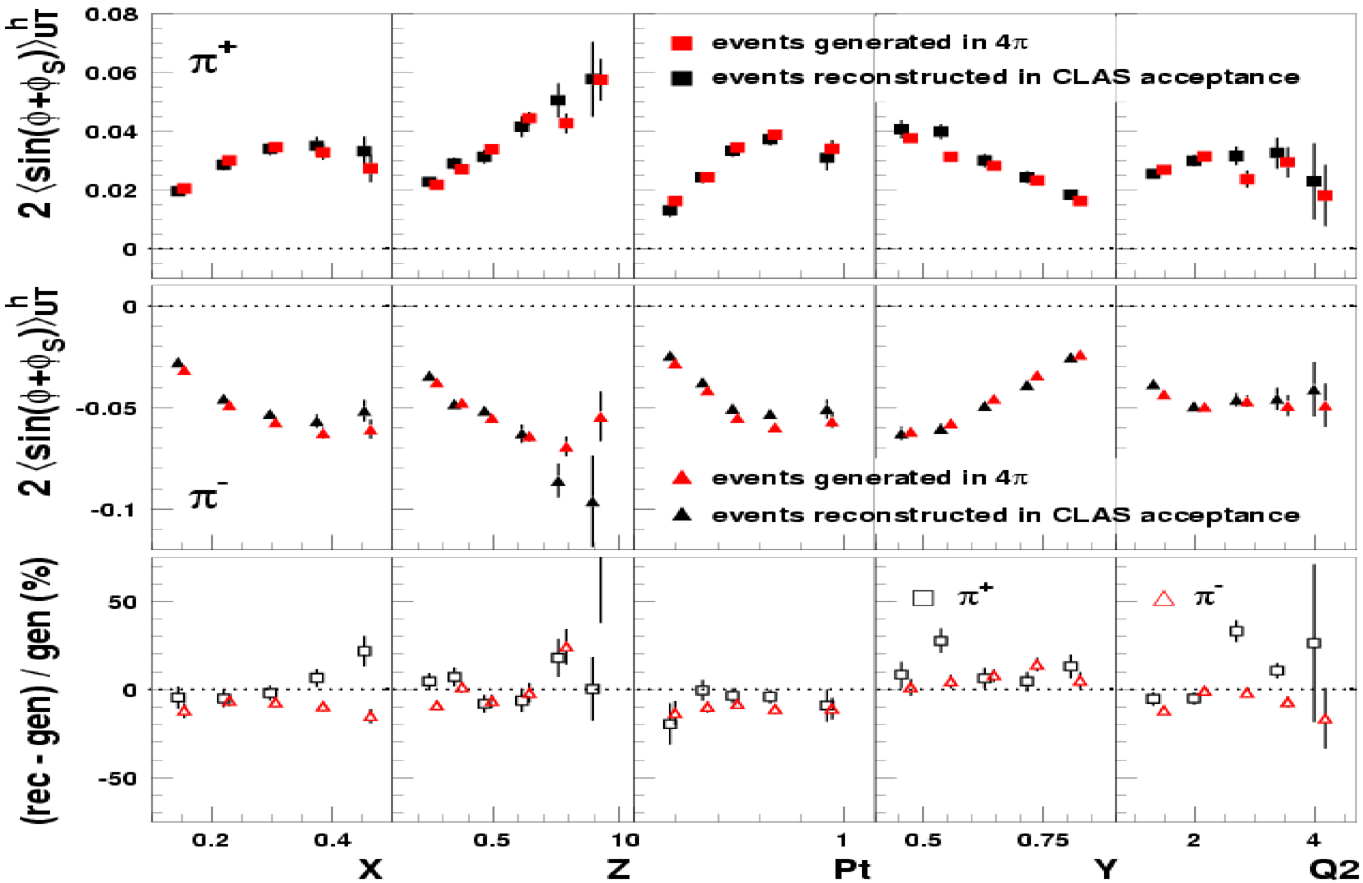


Model calculations
Yuan & Vogelsang,
Schweizer & Efremov

$$A_{UT} \sim \frac{P_T}{P_T^2 + M^2(1-x)}$$

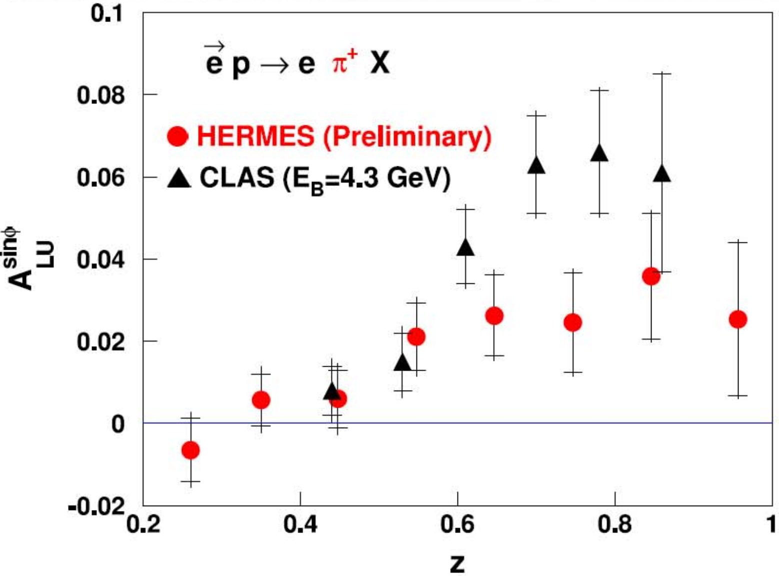
P_T-dependence at large P_T crucial (not accessible at Hall-A/C).

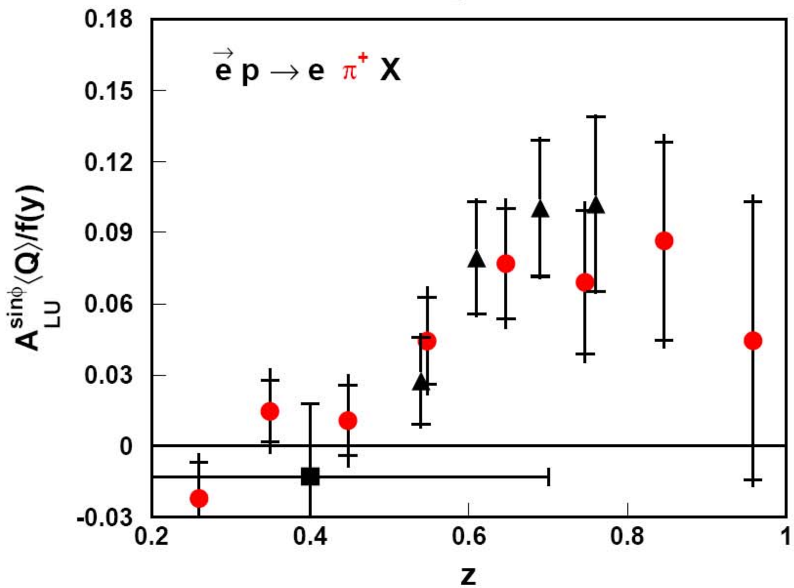
Acceptance corrections for A_{UT}



Esimated acceptance corrections for CLAS using HERMES analysis chain (GMCtrans)

Comparisons with CLAS Results





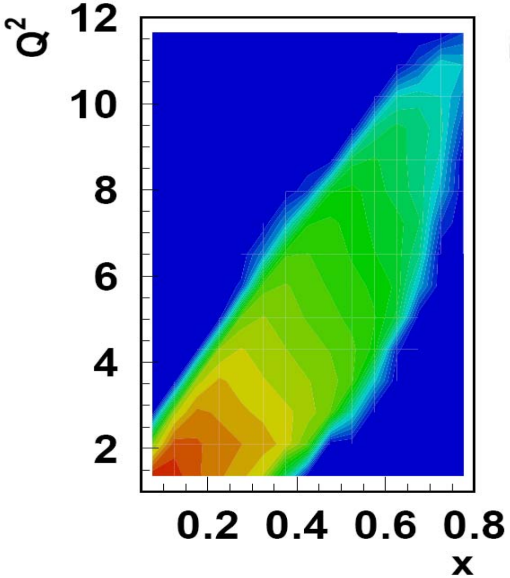
- not so good agreement at high z?
- have to correct for different y range at CLAS and HERMES:

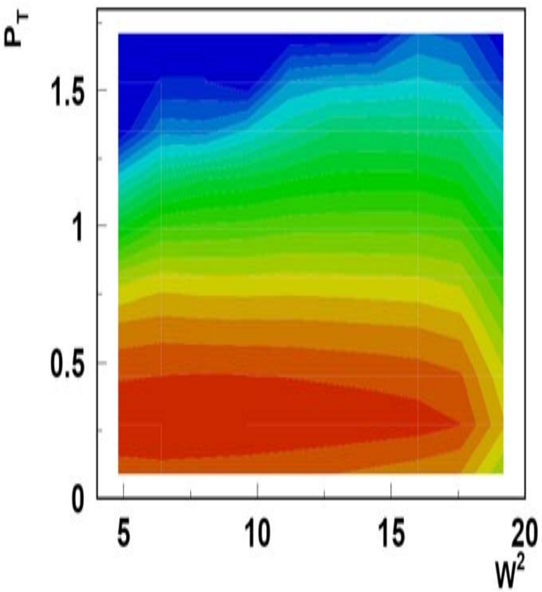
$$\left\langle \sin\phi \right\rangle_{LU} \propto f(y) \equiv \frac{2y\sqrt{(1-y)}}{1-y+y^2/2}$$

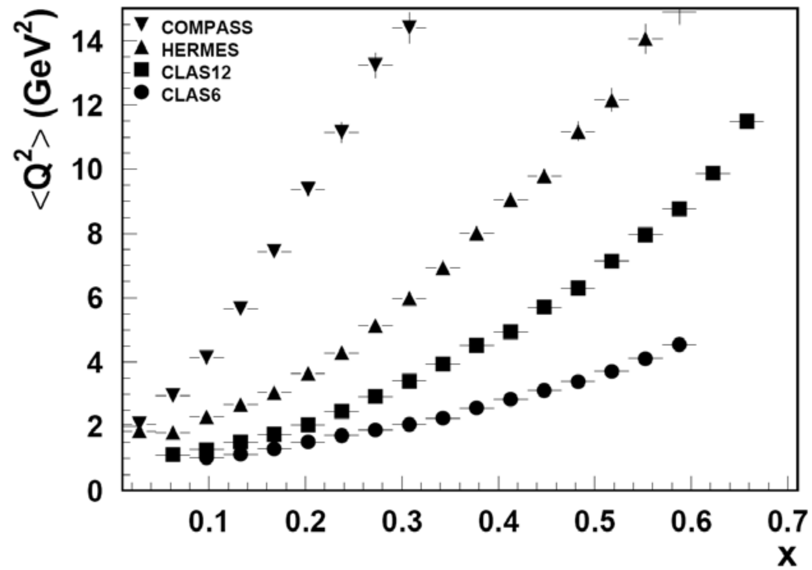
strong suppression at HERMES for high z compared to CLAS

$\Rightarrow$ rescaling of amplitudes leads to good agreement

CLAS12: Kinematical coverage







SIDIS kinematics

$Q^2 > 1 GeV^2$
$W^2 > 4 GeV^2 (10)$
$y < 0.85$
$M_X > 2 GeV$

$x = 0.3 \rightarrow Q^2 = \sim 2 GeV^2$ (CLAS),
$\sim 5 GeV^2$ (HERMES)
$\sim 15 GeV^2$ (COMPASS)

Large Q^2 accessible with CLAS12 are important for separation of HT contributions

SIDIS transverse SSA