Exclusive measurements at eRHIC
or
How to access the quark/gluon orbital momenta ?

Antje Bruell
Jlab

New frontiers at RHIC, Oct 30, 2005

Introduction

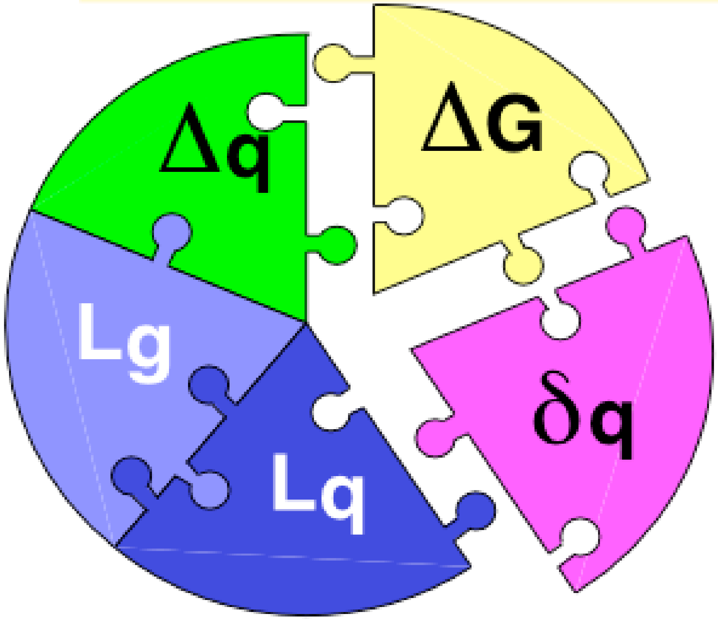
- Nucleons are the basic building blocks of atomic nuclei.
- Their internal structure, arising from the underlying quark and gluon constituents, determines their mass, spin, and interactions.
- These, in turn, determine the fundamental properties of the nuclei and atoms.
- **Nucleon physics represents one of the most important frontiers in modern nuclear physics.**

QCD and the Origin of Mass

u + u + d = proton

mass: 0.003 + 0.003 + 0.006 ≠ 0.938

The Angular Momentum Structure of the Nucleon



Proton Spin

$$\frac{1}{2} = \underbrace{\frac{1}{2}\overbrace{(\Delta u + \Delta d + \Delta s)}^{\sim 30\%} + L_q}_{J_q} + \underbrace{\Delta G + L_g}_{J_g}$$

Δq: well known from DIS & SIDIS

ΔG: first indications from DIS

L_q, L_g: unknown!

The Two Traditional Observables

- Elastic Form Factors
  - Low Q: charge and current distributions.

    High Q: light-cone parton distribution amplitudes, underlying pQCD reaction mechanism,
  - Starting from Hofstadter's work in 1950's
  - Well-measured for some, not so for others
    - Neutron form factors
    - Large Q^2
    - …

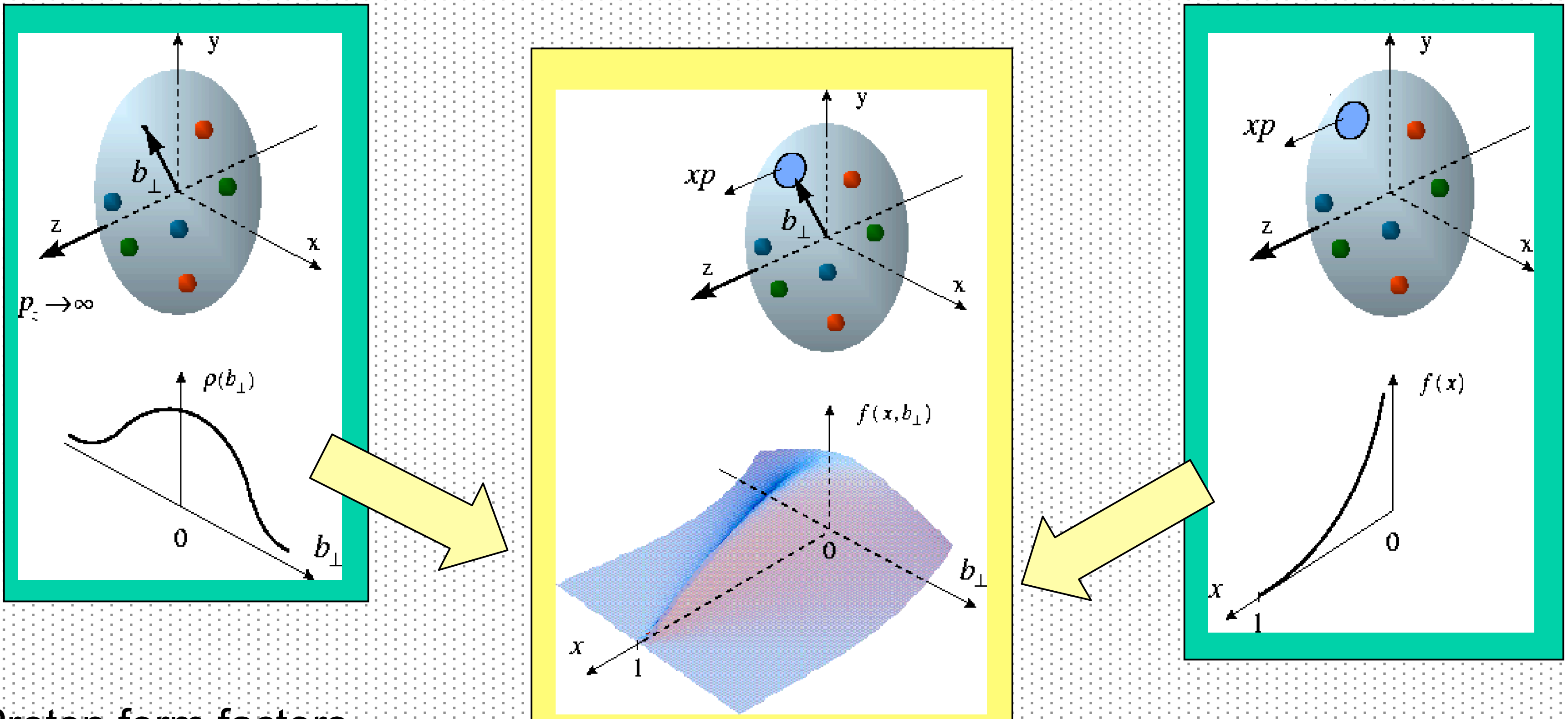
The Two Traditional Observables

- Feynman Parton Distributions
  - Distributions of quarks in momentum space.
  - Starting from Freedman, Kendall and Taylor's DIS experiments at SLAC
  - Well-measured in some kinematics. But some key aspects are missing
    - Parton distributions as x→1
    - Spin-flavor dependence

Beyond form factors and quark distributions – Generalized Parton Distributions (GPDs)

X. Ji, D. Mueller, A. Radyushkin, …

M. Burkardt, … Interpretation in impact parameter space



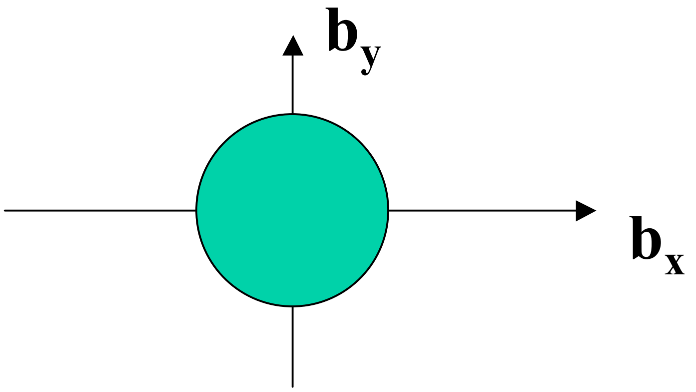
Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Physical Meaning of GPDs at ξ =0

- Form factors can be related to charge densities in the 2D transverse plane in the infinite-momentum frame

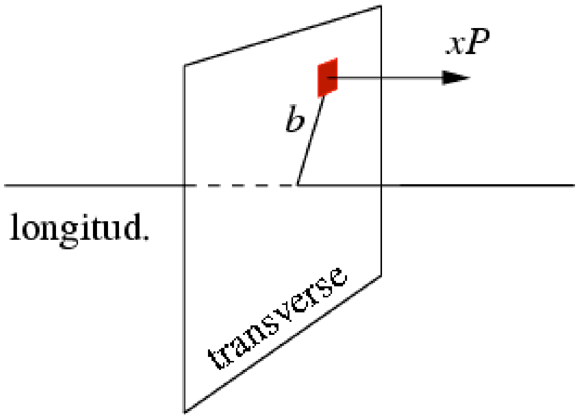


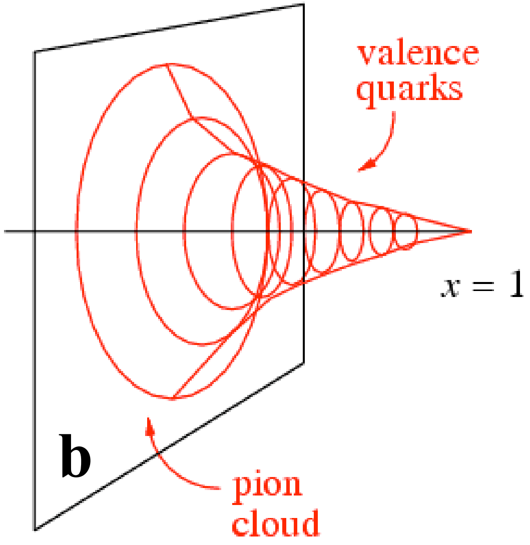
- Feynman parton distribution is a quark density in the longitudinal momentum x,
- The Fourier transformation of a GPD H(x,t, ξ =0) give the density of quarks in the "combined" 2+1 space!

Mixed Coordinate and Momentum “3D” Picture

- Longitudinal Feynman momentum x

  + Transverse-plane coordinates **b** = (b_x, b_y)



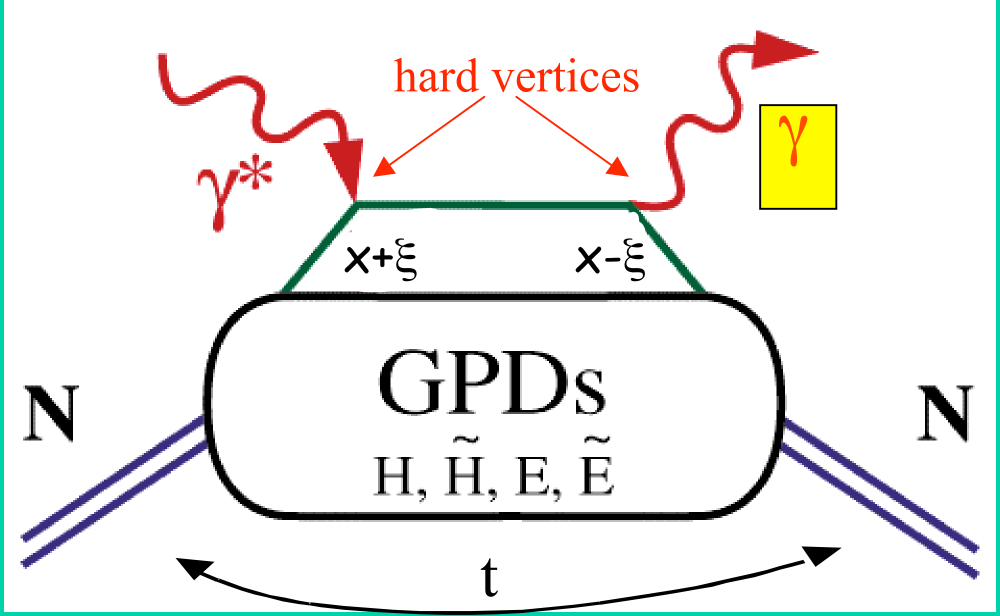


A 3D nucleon

GPDs & Deeply Virtual Exclusive Processes

“handbag” mechanism

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

H(x,ξ,t), E(x,ξ,t), . .

$$\xi = \frac{x_B}{2-x_B}$$

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x), \quad -\bar{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x), \quad \Delta\bar{q}(-x)$$

Form factors (sum rules)

$$\int^1 dx \sum_q \left[H^q(x,\xi,t) \right] = F_1(t) \text{ Dirac f.f.}$$

$$\int^1 dx \sum_q \left[E^q(x,\xi,t) \right] = F_2(t) \text{ Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(\ t), \quad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(\ t)$$

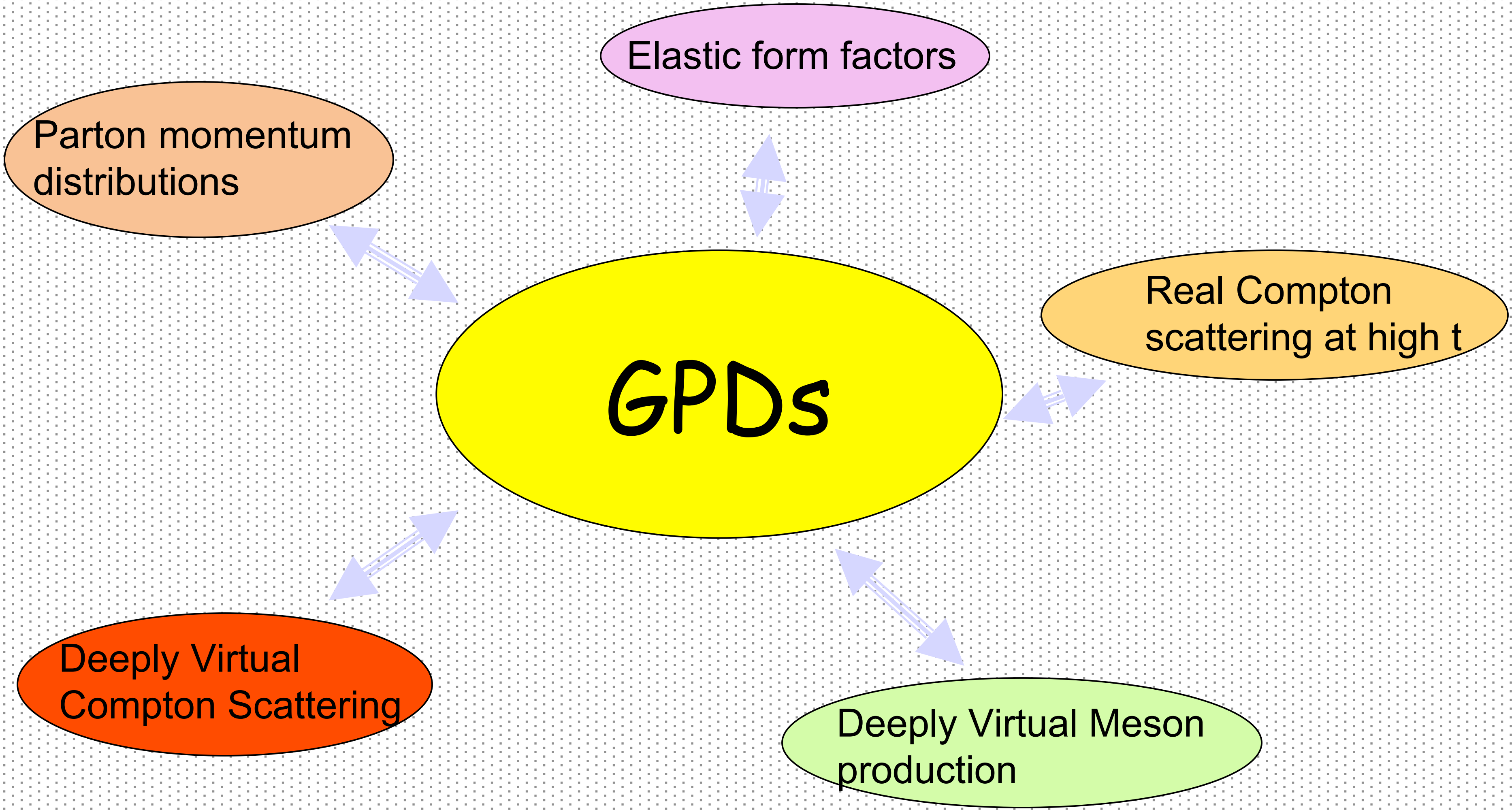
$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

Quark angular momentum (Ji's sum rule)

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

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

A Unified Description of Hadron Structure



Elastic form factors

Parton momentum distributions

GPDs

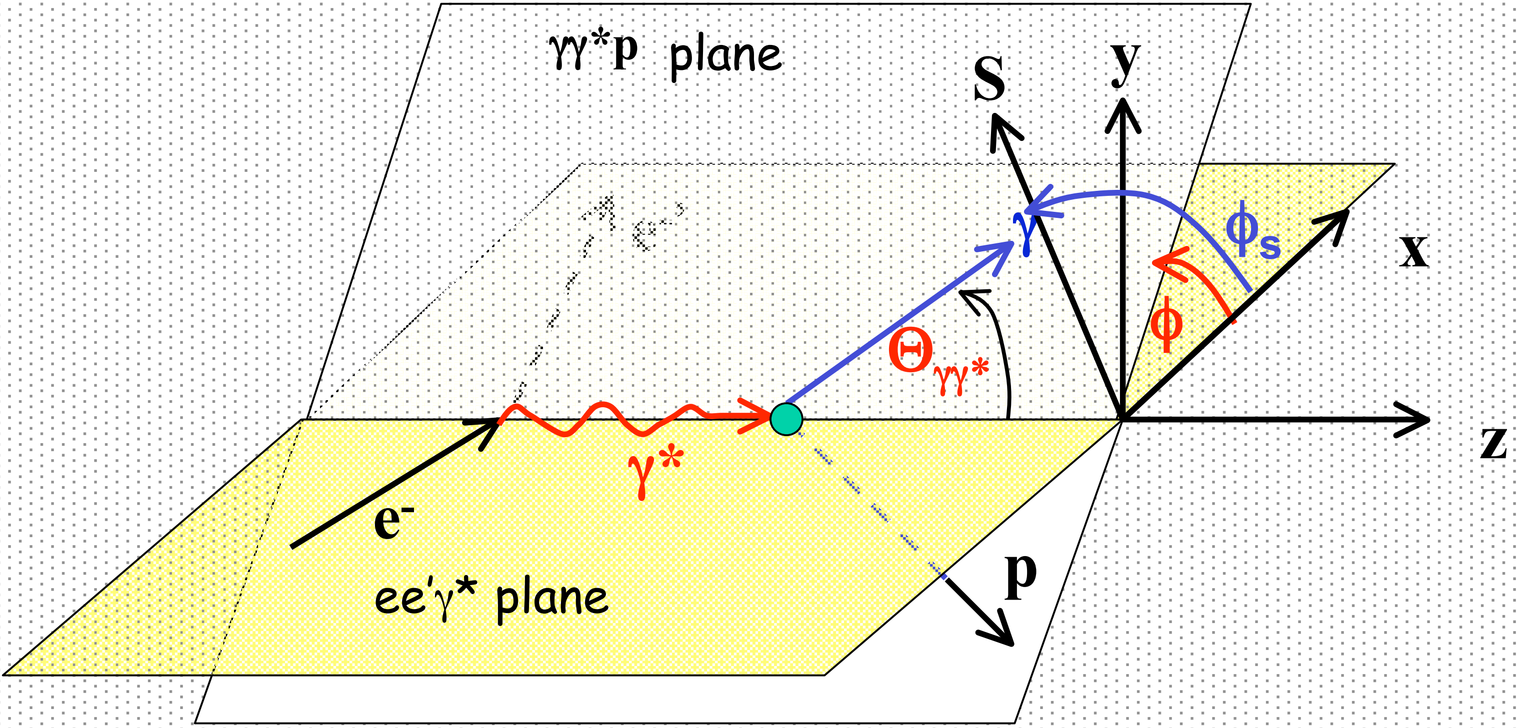
Real Compton scattering at high t

Deeply Virtual Compton Scattering

Deeply Virtual Meson production

DVCS – Kinematics

$ep \longrightarrow ep\gamma$



A_{LU} : Beam Longitudinally polarized, Target Unpolarized

A_{UL} : Beam Unpolarized, Target Longitudinally polarized

A_{UT} : Beam Unpolarized, Target Transversely polarized

Measuring GPDs through polarization

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

Kinematically suppressed

⇒ $H(\xi,t)$

$\xi = x_B/(2-x_B)$

$k = t/4M^2$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi \, \mathrm{Im}\{F_1\tilde{H}+\xi(F_1+F_2)(H+\xi/(1+\xi)E) - .. \}d\phi$$

Kinematically suppressed

⇒ $\tilde{H}(\xi,t)$, $H(\xi,t)$

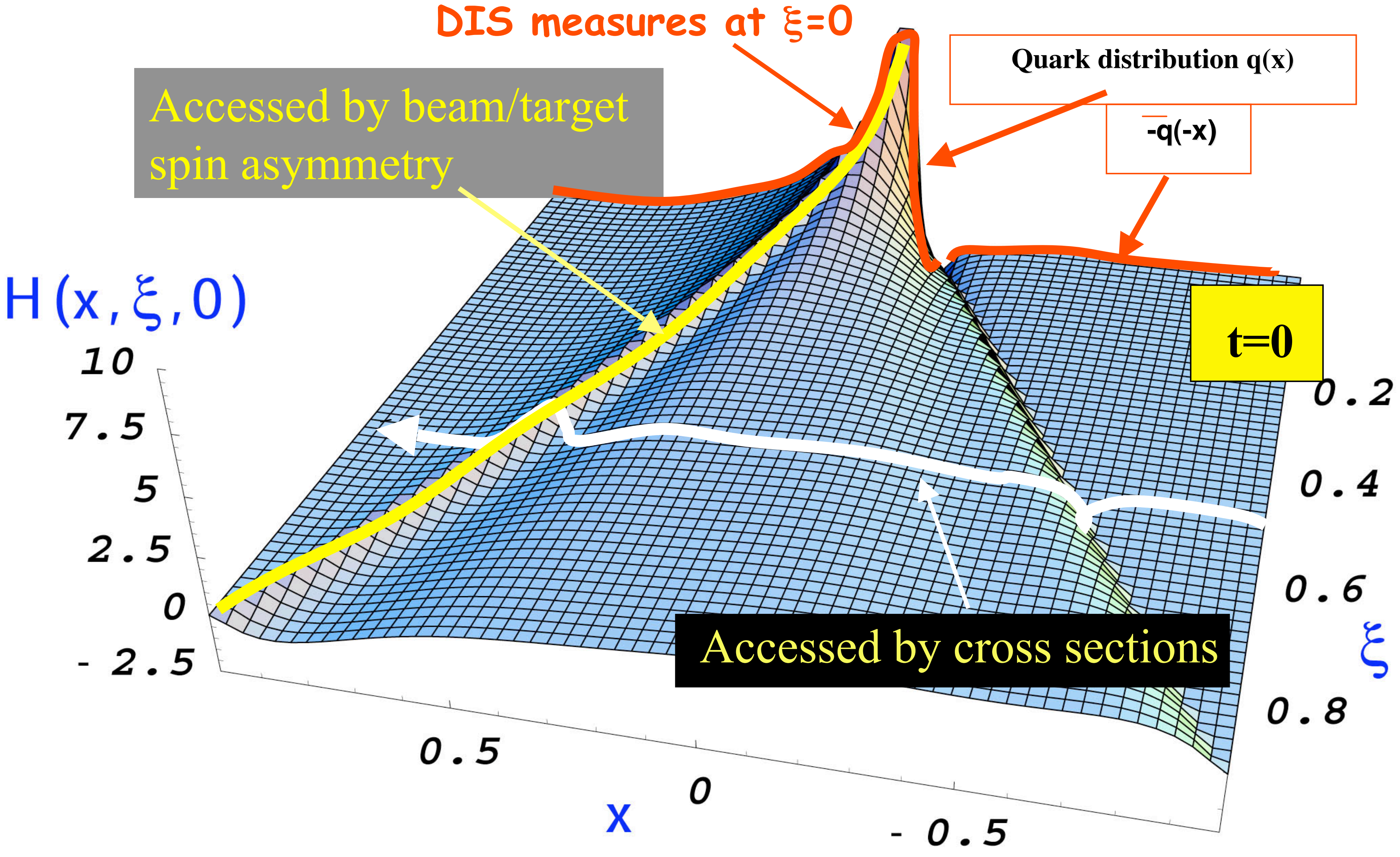
Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \sin\phi \, \mathrm{Im}\{k(F_2 H - F_1 E) + ... \}d\phi$$

Kinematically suppressed

⇒ $H(\xi,t)$, $E(\xi,t)$

Access GPDs through x-section & asymmetries



DIS measures at ξ=0

Accessed by beam/target spin asymmetry

Quark distribution q(x)

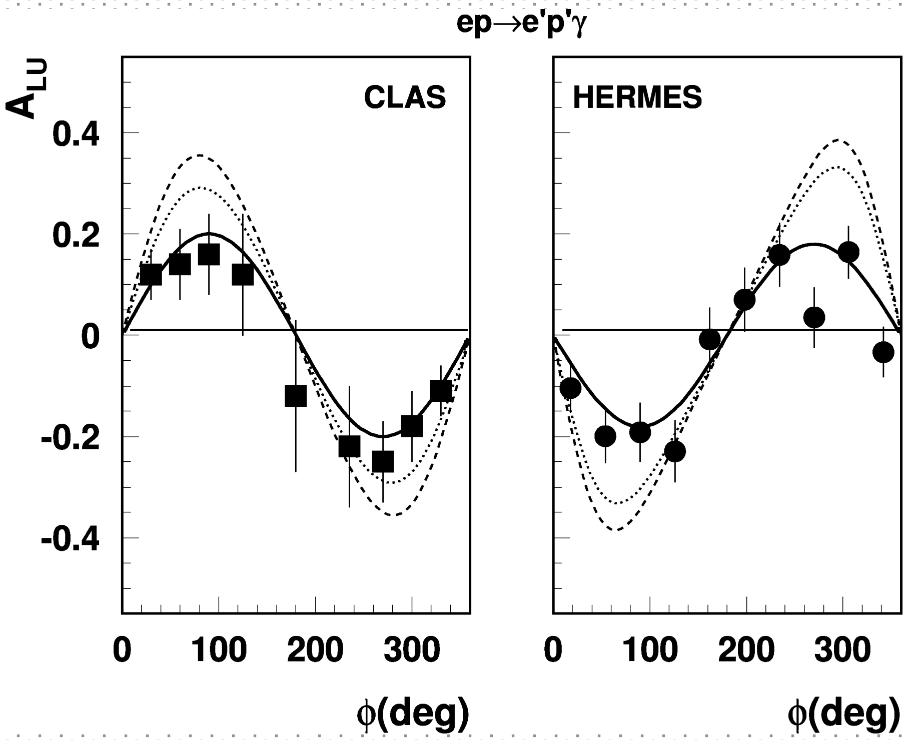
$-\bar{q}(-x)$

t=0

Accessed by cross sections

DVCS interpreted in pQCD at $Q^2 > 1$ GeV^2

Pioneering DVCS experiments

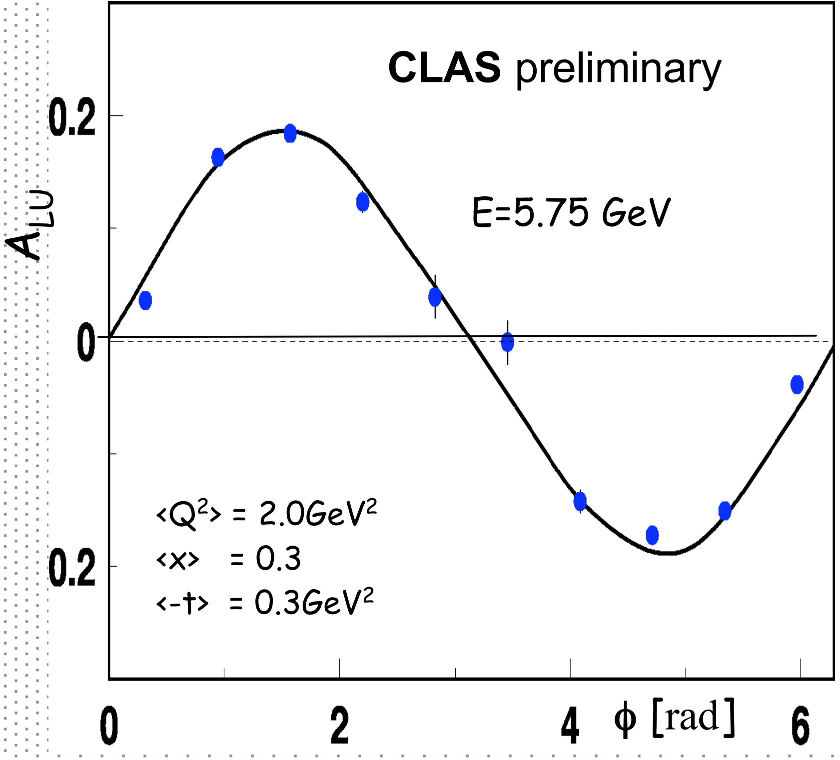


$$A_{UL} = \alpha\underset{\substack{\uparrow\\ \text{twist-2}}}{\sin\phi} + \beta\underset{\substack{\uparrow\\ \text{twist-3}}}{\sin 2\phi}$$

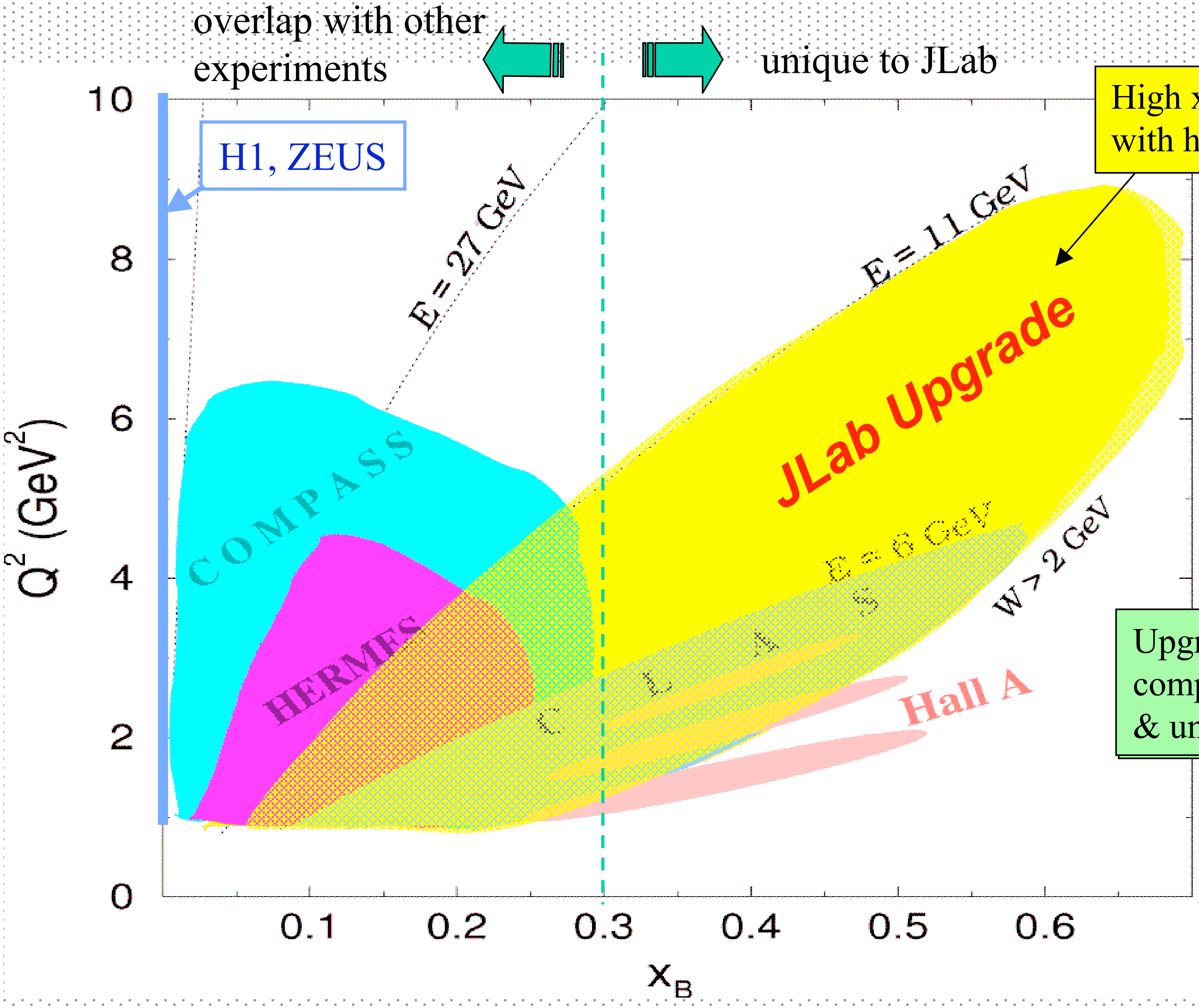
twist-3 contributions are small

First GPD analyses of HERA/CLAS/HERMES data in LO/NLO consistent with α ~ **0.20.**
A. Freund (2003), A. Belitsky et al. (2003)

Full GPD analysis needs high statistics and broad coverage



Deeply Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade



overlap with other experiments

unique to JLab

High x_B only reachable with high luminosity

Upgraded JLab has complementary & unique capabilities

CLAS12 – DVCS/BH Beam Asymmetry

E = 11 GeV

$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 H + ..\} d\phi$

Sensitive to GPD H

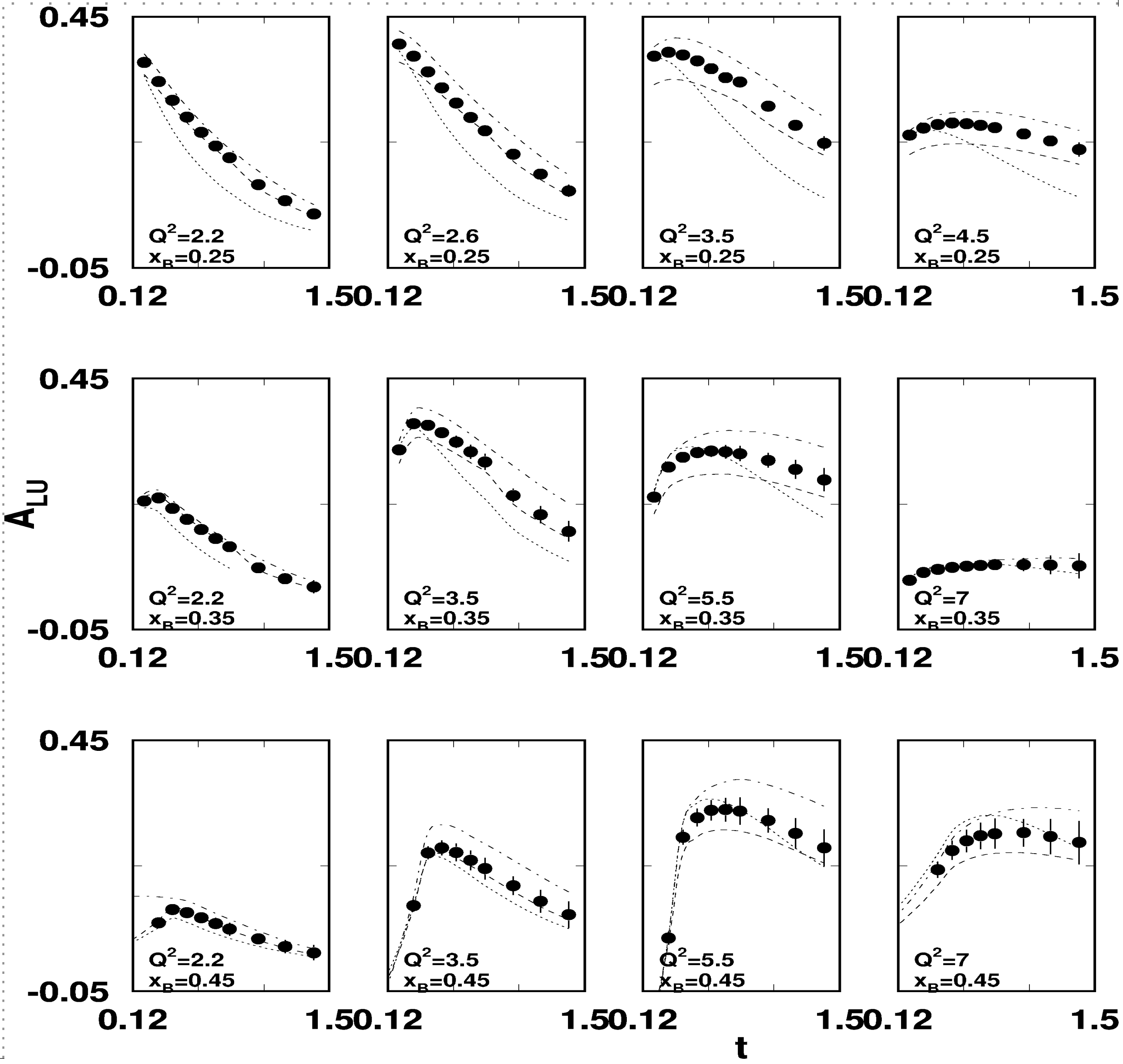
Selected Kinematics

$L = 1 \times 10^{35}$

T = 2000 hrs

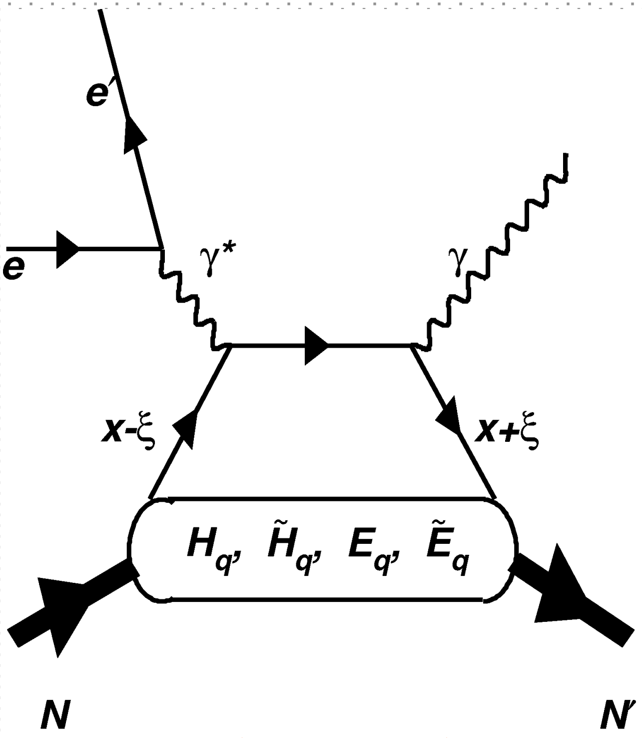
$\Delta Q^2 = 1 \ GeV^2$

$\Delta x = 0.05$

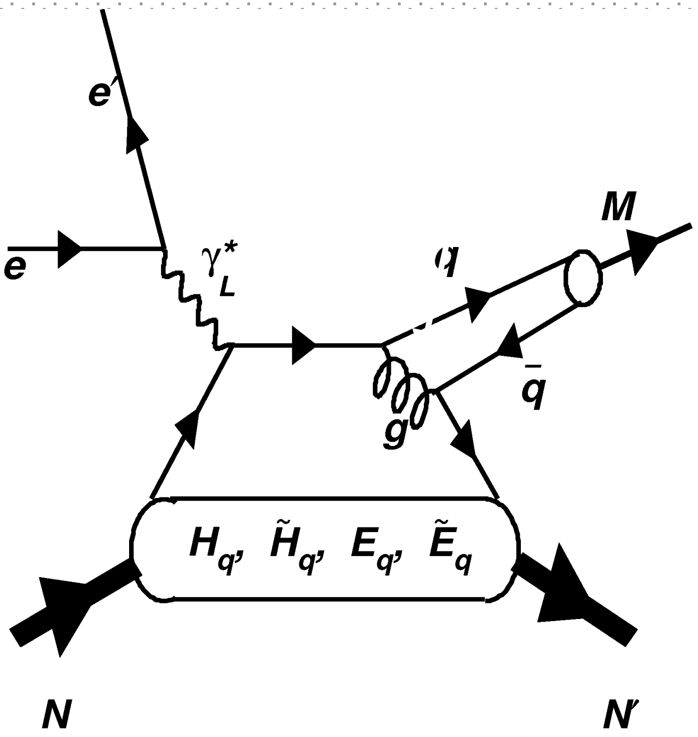


GPDs – Flavour separation

DVCS



DVMP



Photons cannot separate between quark flavours

M = ρ/ω select H, E, for u/d flavours

M = π, η, K select H, E

DVMP needs separation of longitudinal and transverse components

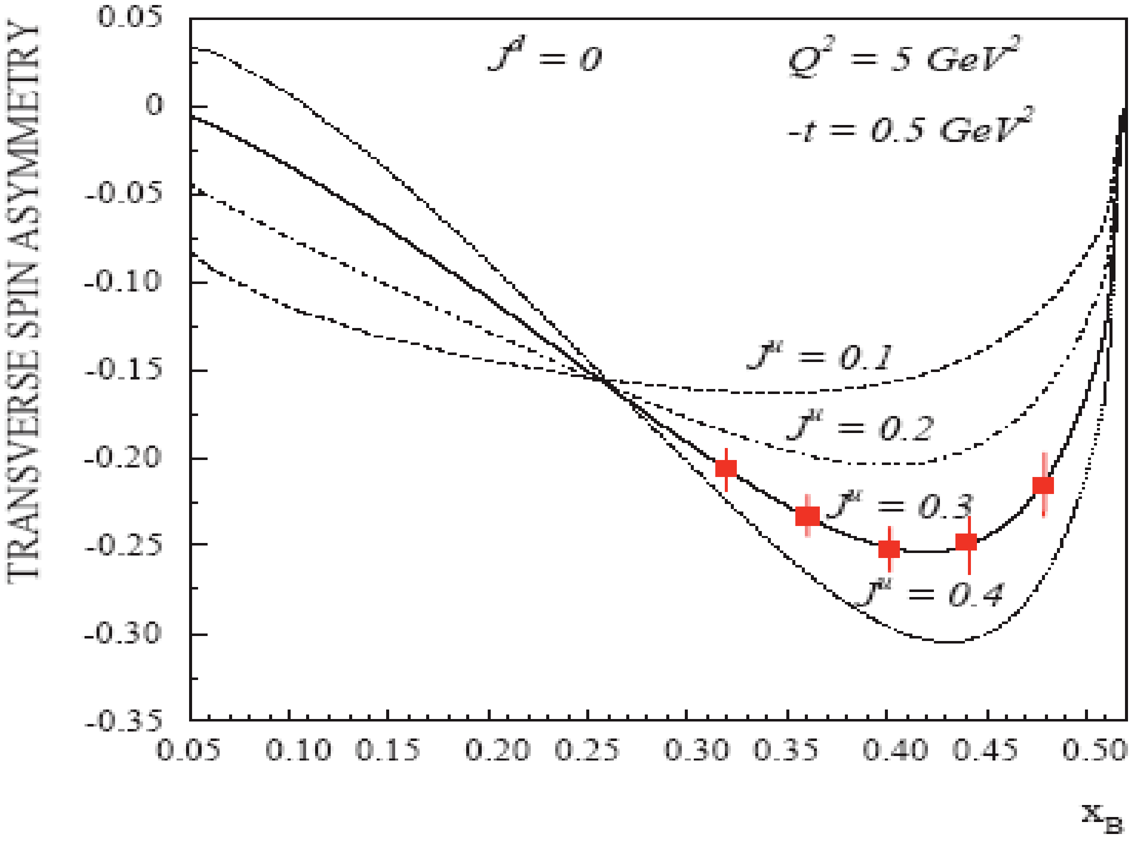
Exclusive ρ^0 production on transverse target

$$A_{UT} = -\frac{2\Delta_\perp(\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

ρ^0 | $A \sim 2H^u + H^d$ | $B \sim 2E^u + E^d$

ρ^+ | $A \sim H^u - H^d$ | $B \sim E^u - E^d$

$\gamma^*_L + p \rightarrow \rho^0_L + p$



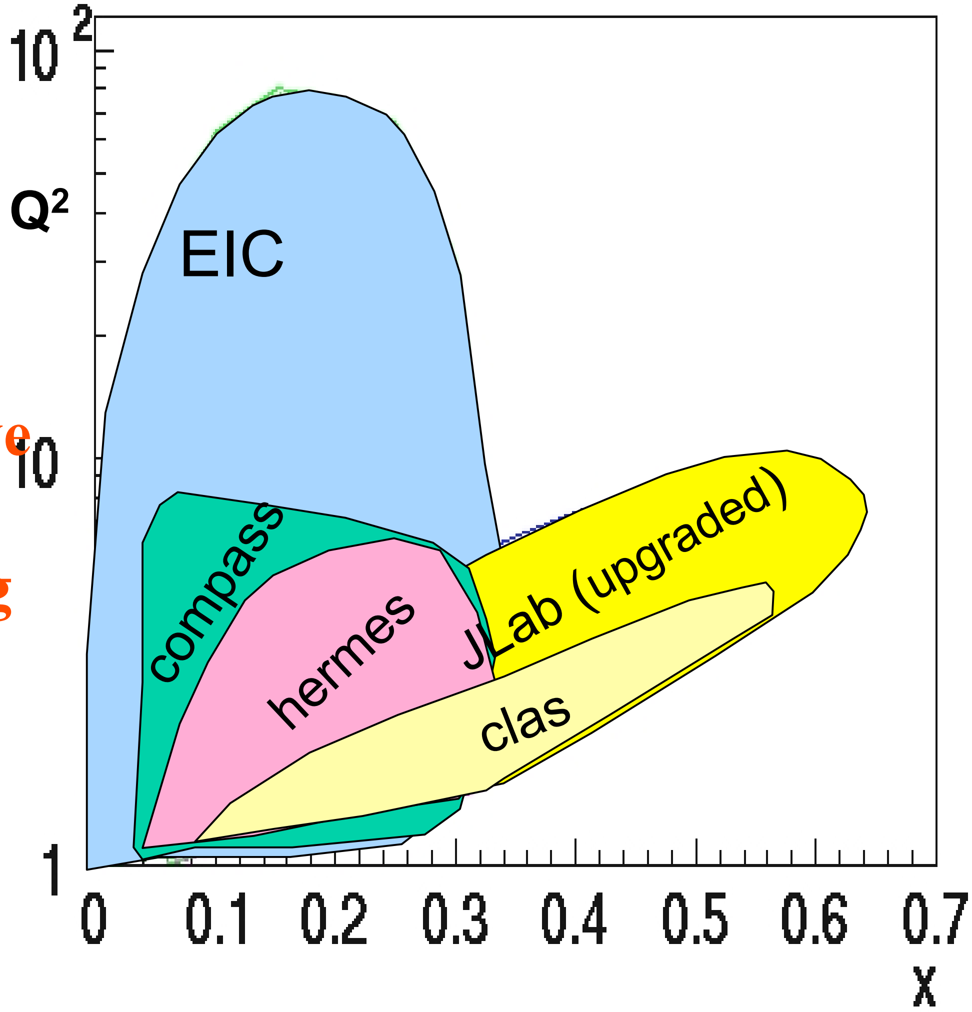
Linear dependence on GPD E (entering Ji's sum rule)

Sensitivity to quark angular momentum

Kinematic coverage of eRHIC (EIC)

Complementary to Jlab@12 GeV

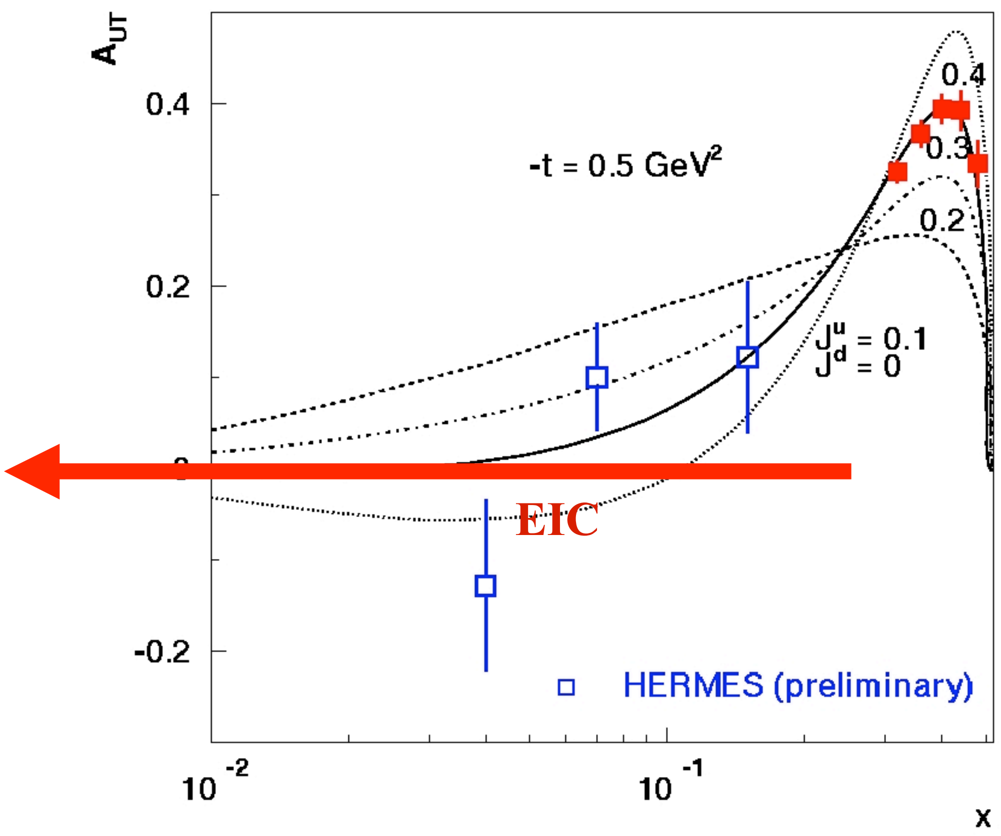
- low x
- high Q^2
  - ➢ **crucial for pQCD interpretation of hard exclusive meson production**
  - ➢ **necessary for understanding of nucleon sea structure**
  - ➢ **contribution to Sum Rules**



Requires large luminosity !

Exclusive ρ^0 production on transverse target

$$A_{UT} = -\frac{2\Delta_\perp(\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$



ρ^0

$A \sim 2H^u + H^d$
$B \sim 2E^u + E^d$

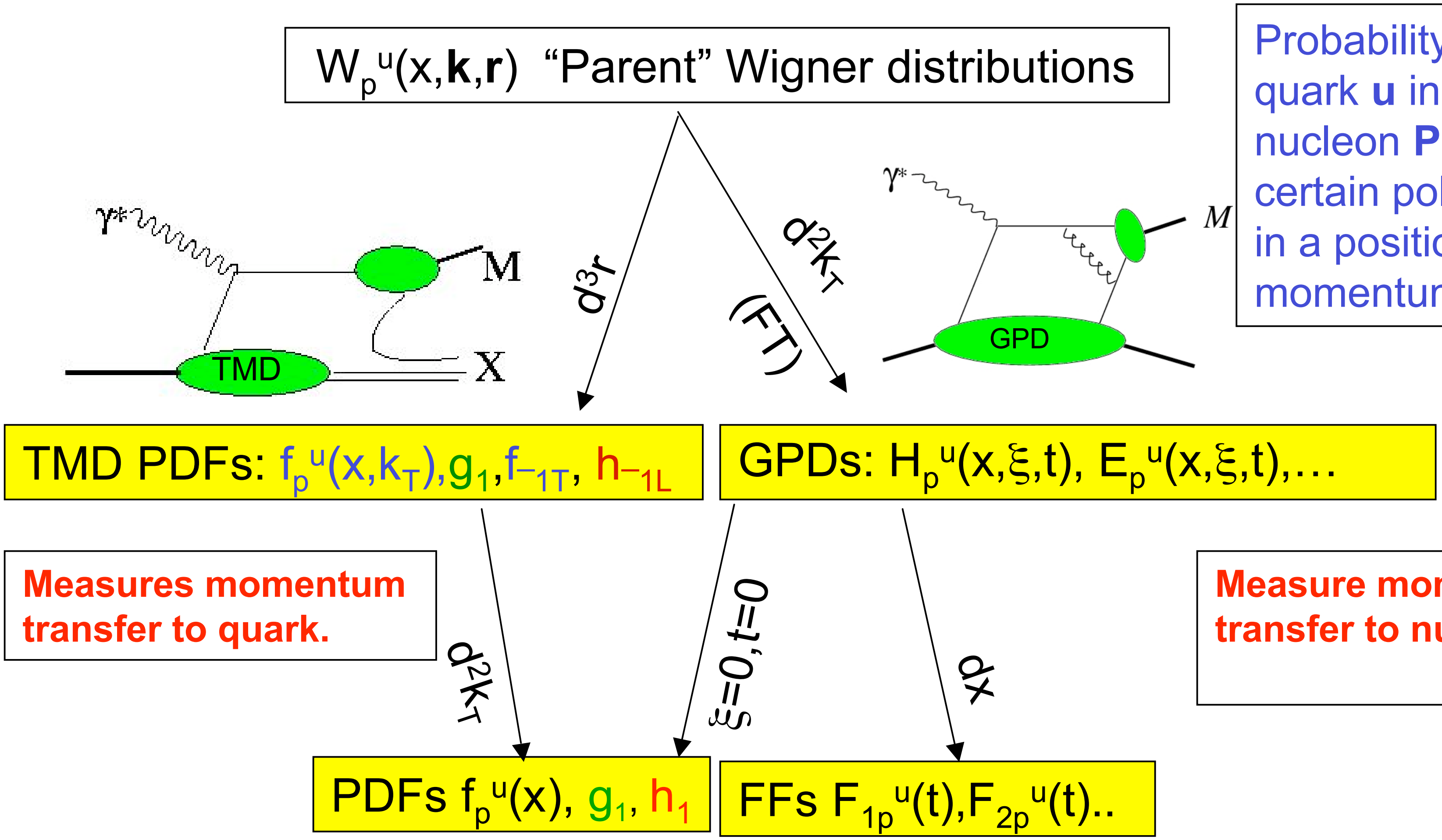
ρ^+

$A \sim H^u - H^d$
$B \sim E^u - E^d$

E^u, E^d needed for angular momentum sum rule.

Higher Q^2 of EIC may be crucial

Transverse Momentum Dependent GPDs (TMDs)



$W_p^u(x,\mathbf{k},\mathbf{r})$ “Parent” Wigner distributions

TMD PDFs: $f_p^u(x,k_T), g_1, f_{-1T}, h_{-1L}$

GPDs: $H_p^u(x,\xi,t)$, $E_p^u(x,\xi,t)$,…

PDFs $f_p^u(x)$, g_1, h_1

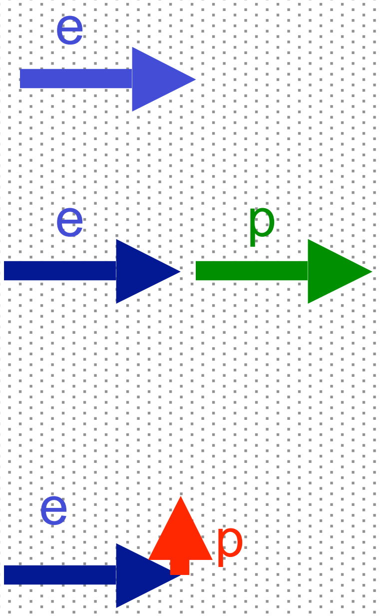
FFs $F_{1p}^u(t)$,$F_{2p}^u(t)$..

Probability to find a quark **u** in a nucleon **P** with a certain polarization in a position **r** and momentum **k**

Measures momentum transfer to quark.

Measure momentum transfer to nucleon.

SIDIS at leading twist



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 $h_{1T}^\perp$

Boer

Mulders

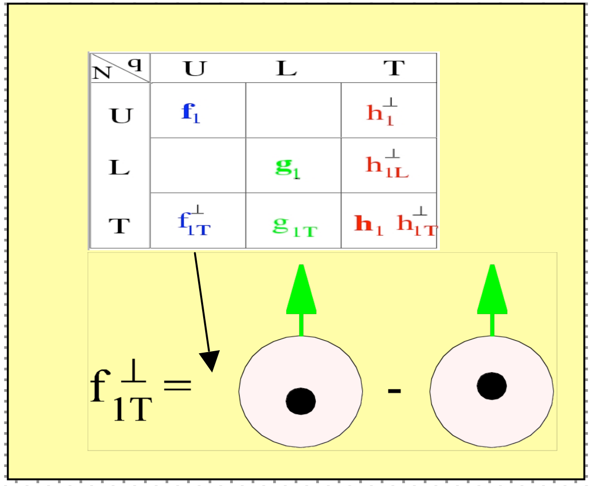
Sivers

transversity

Off-diagonal PDFs vanish if quarks only in s-state! In addition T-odd PDFs require FSI (Brodsky et al., Collins, Ji et al. 2002)

Azimuthal Asymmetry – Sivers Effect

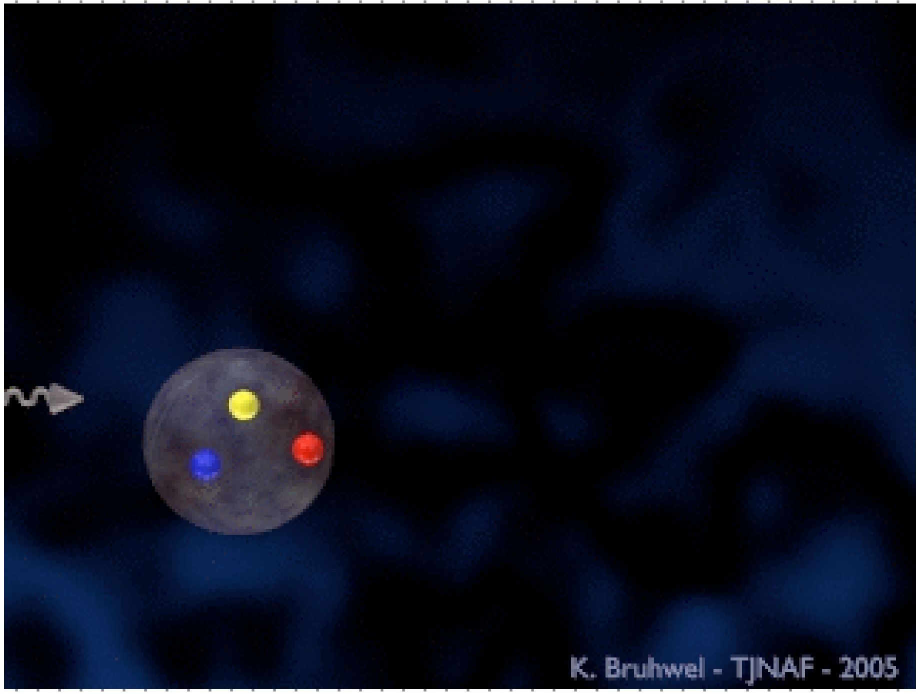
Originates in the quark distribution. It is measured in the azimuthal asymmetry with transverse polarized target.



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 $h_{1T}^\perp$

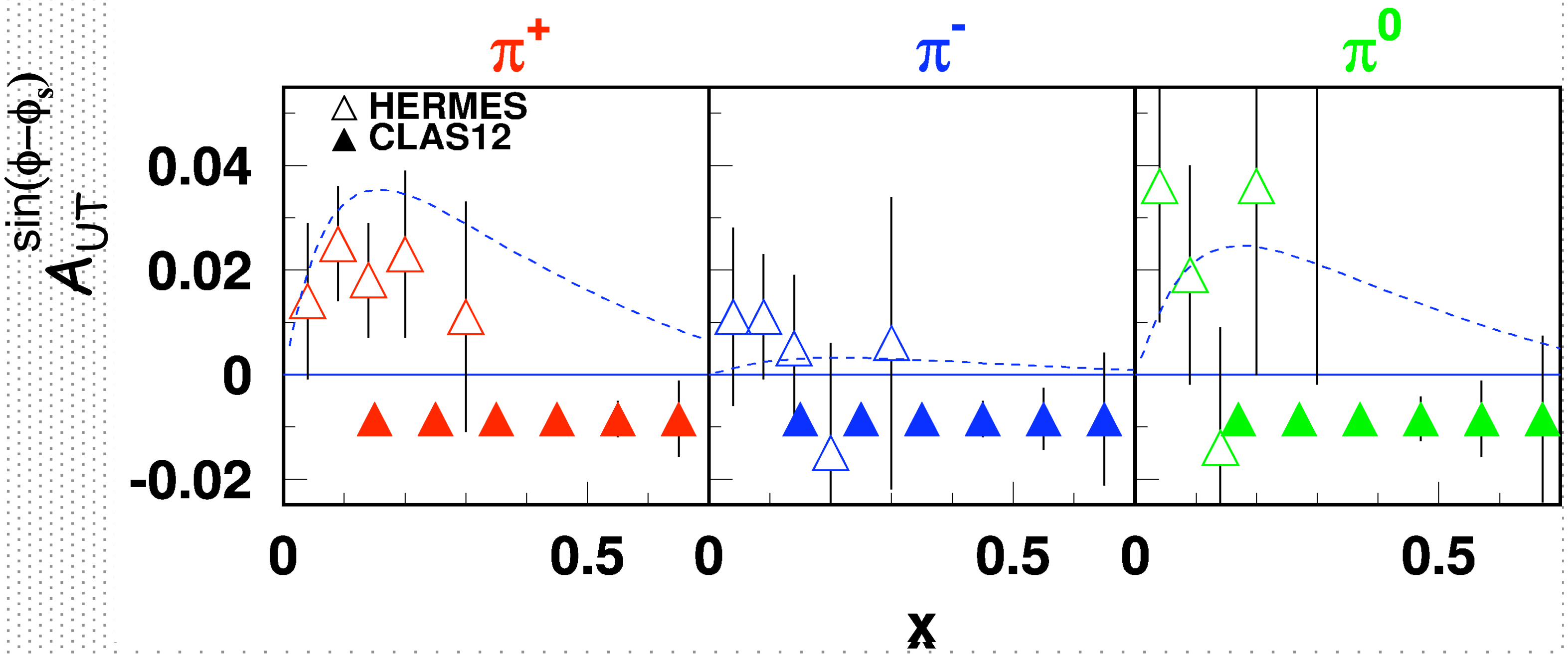
$$A_{UT}^{\sin(\phi-\phi_s)} \sim k f_{1T}^{\perp} D_1$$

Requires: non-trivial phase from the FSI + interference between different helicity states (S. Brodsky)



K. Bruhwel - TJNAF - 2005

SIDIS Azimuthal Asymmetry - Sivers effect



- Probes orbital angular momentum of quarks by measuring the imaginary part of s-p-wave interference in the amplitude.

- Extraction of Sivers function $f_{1T}^{\perp}$ from asymmetry.

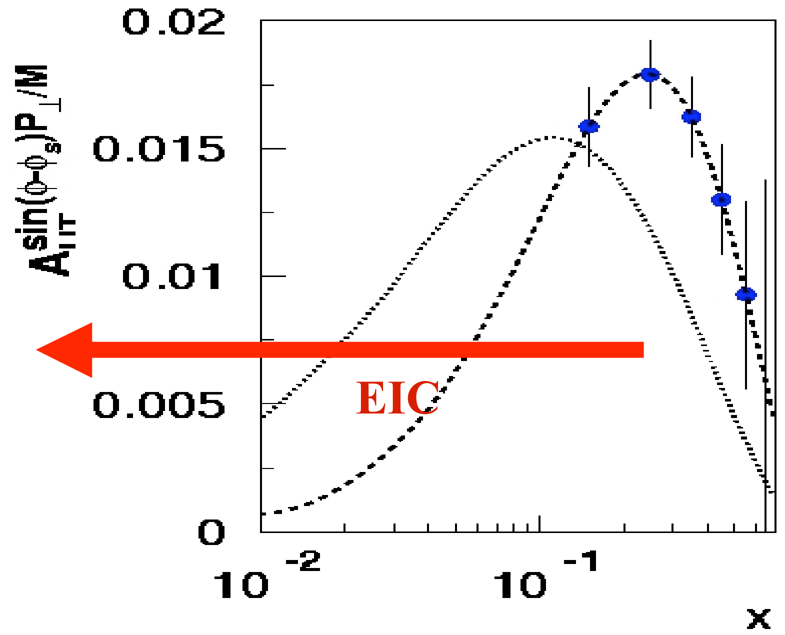
The program of Deeply Exclusive and Semi-Inclusive Experiments at the JLab 12 GeV Upgrade constitutes the next step in the breakthrough experiments to study the internal nucleon structure at a deeper level. It has the potential to revolutionize hadronic physics with electromagnetic probes.

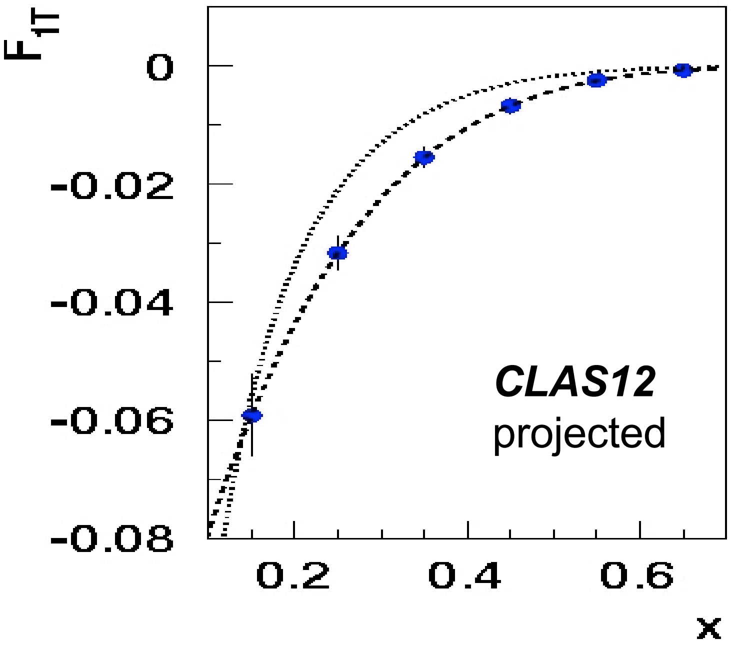
From CLAS12 to EIC: Sivers effect projections

In large Nc limit:
$f_{1T}^{u} = -f_{1T}^{d}$

$F_{1T}=\sum_q e_q^2 f_{1T}^{\perp q}$

Efremov et al
(large x_B behavior of
f_{1T} from GPD E)





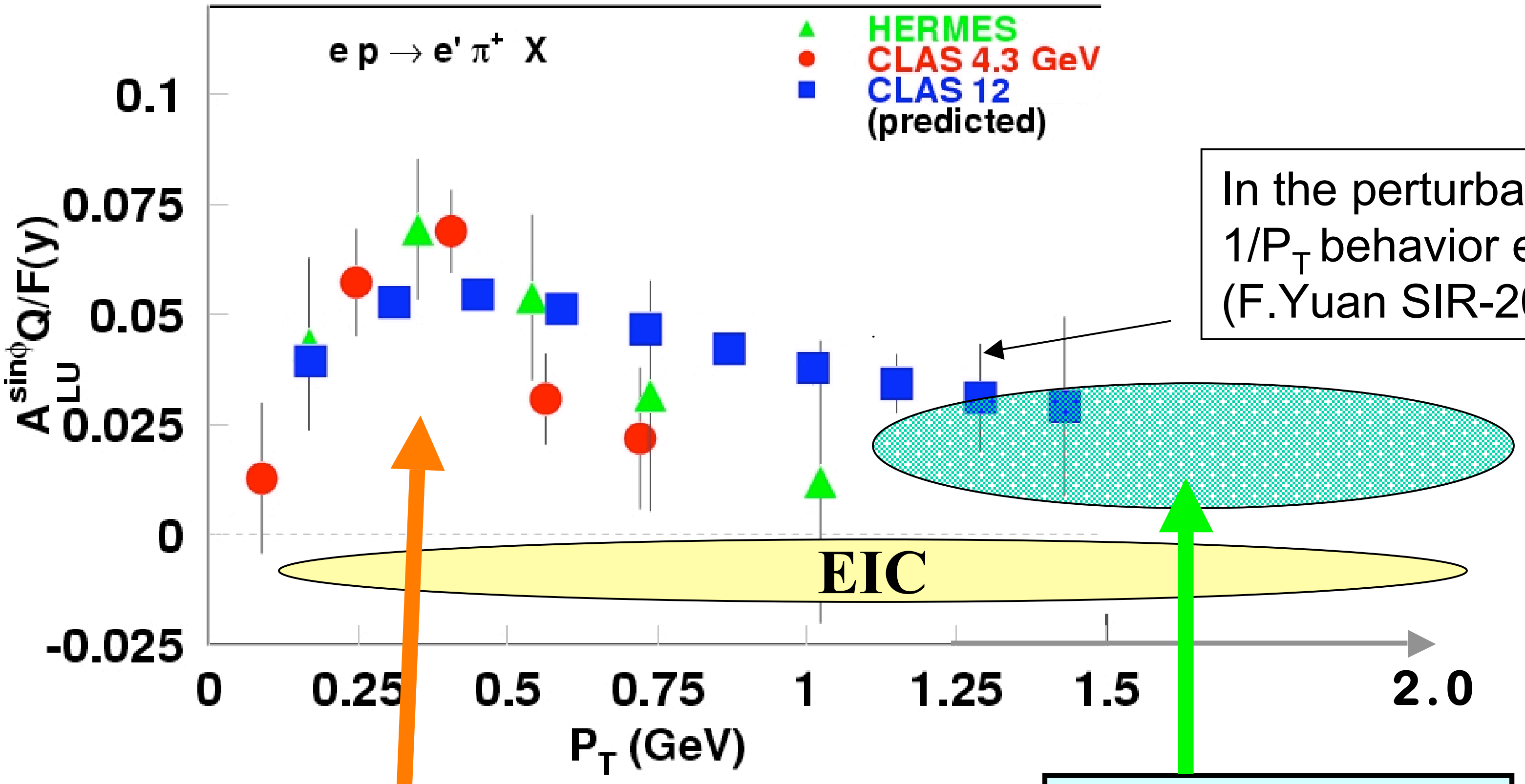
Sivers function extraction from A_{UT} (π^0) does not require information on fragmentation function. It is free of HT and diffractive contributions.

A_{UT} (π^0) on proton and neutron will allow flavor decomposition w/o info on FF.

P_T-dependence of beam SSA

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

$$A_{LU} \propto g^{\perp(1)}(x) D_1(z)$$



In the perturbative limit
$1/P_T$ behavior expected
(F.Yuan SIR-2005)

Nonperturbative TMD

Perturbative region

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

Experimental Requirements

- High luminosity
- Beam and target polarisation
- Detection of the scattered proton (Roman pots)
- Hermetic detector ?
- Particle identification
- Neutron detection ?
- **realistic simulations are just beginning**

Summary

- Understanding the structure of the nucleon requires measurements of the Generalised Parton Distributions **over the full x range and at high Q**

- Measurements of both DVCS and exclusive meson production at EIC wi allow the determination of the quark and gluon orbital momenta

- Single spin asymmetries in semi-inclusive scattering provide an alternative approach to orbital momenta (connection ?)

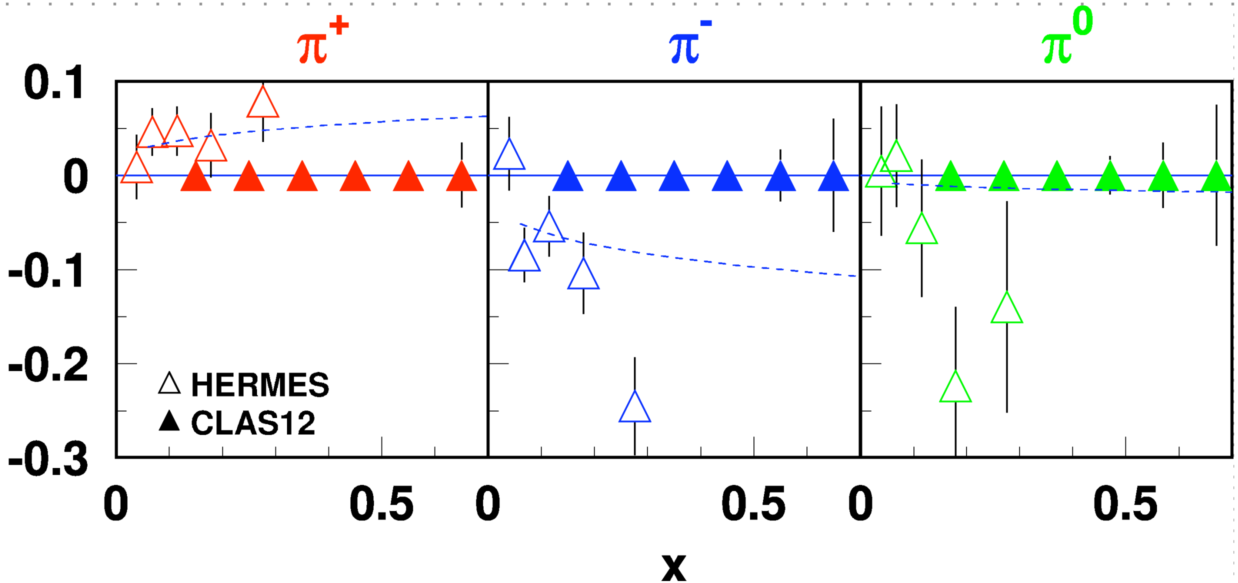
- Jlab@12 GeV will address these questions in the valence region and at moderate Q^2

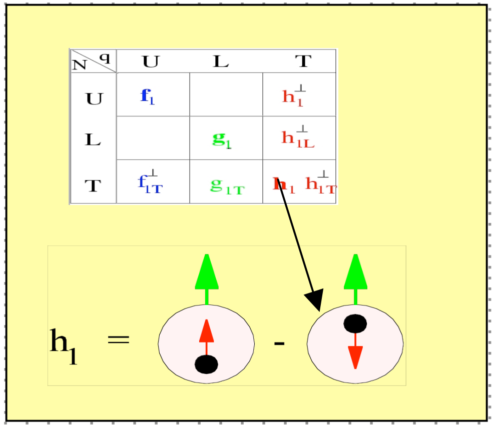
- **but** the definite answer will require the additional coverage of low x an the access to sufficiently high values of Q^2

- **accessible only at a future polarised Electron Ion Collider with very high luminosity**

Additional slides

Azimuthal Asymmetry - Collins Effect

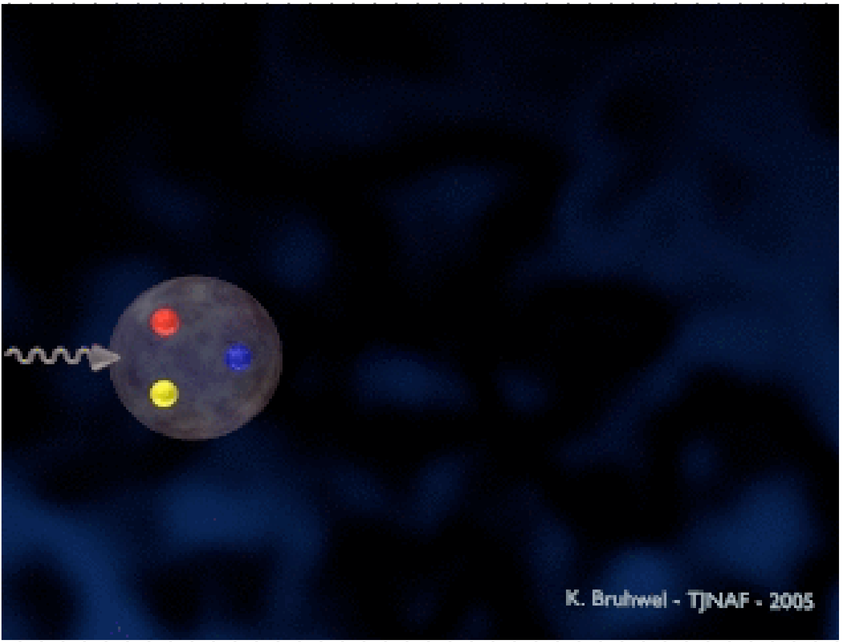




N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

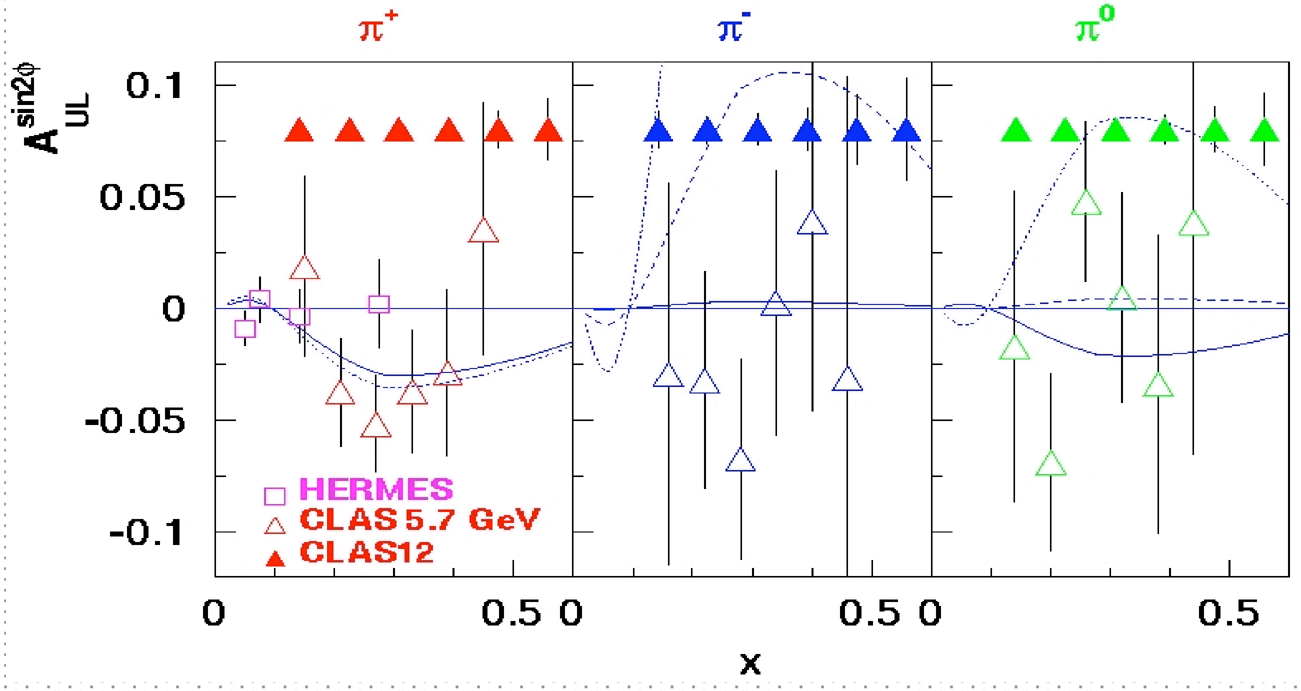
$$\sigma_{UT}^{\sin(\phi+\phi_s)} \sim k\, h_1\, H_1^\perp$$

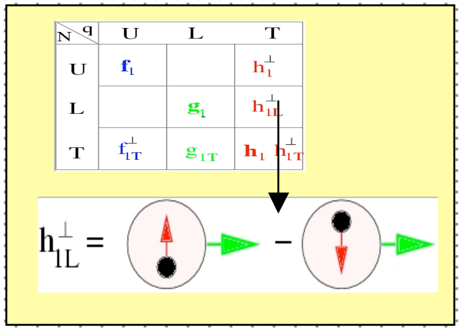
- Access to transversity distribution and fragmentation of polarized quarks.



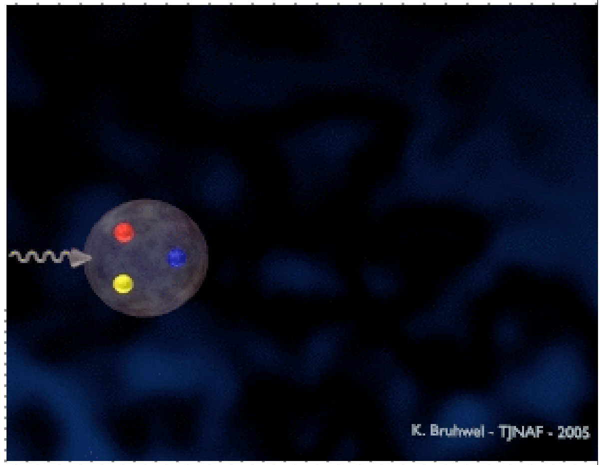
K. Bruhwel - TJNAF - 2005

Collins Effect and Kotzinian-Mulders Asymmetry





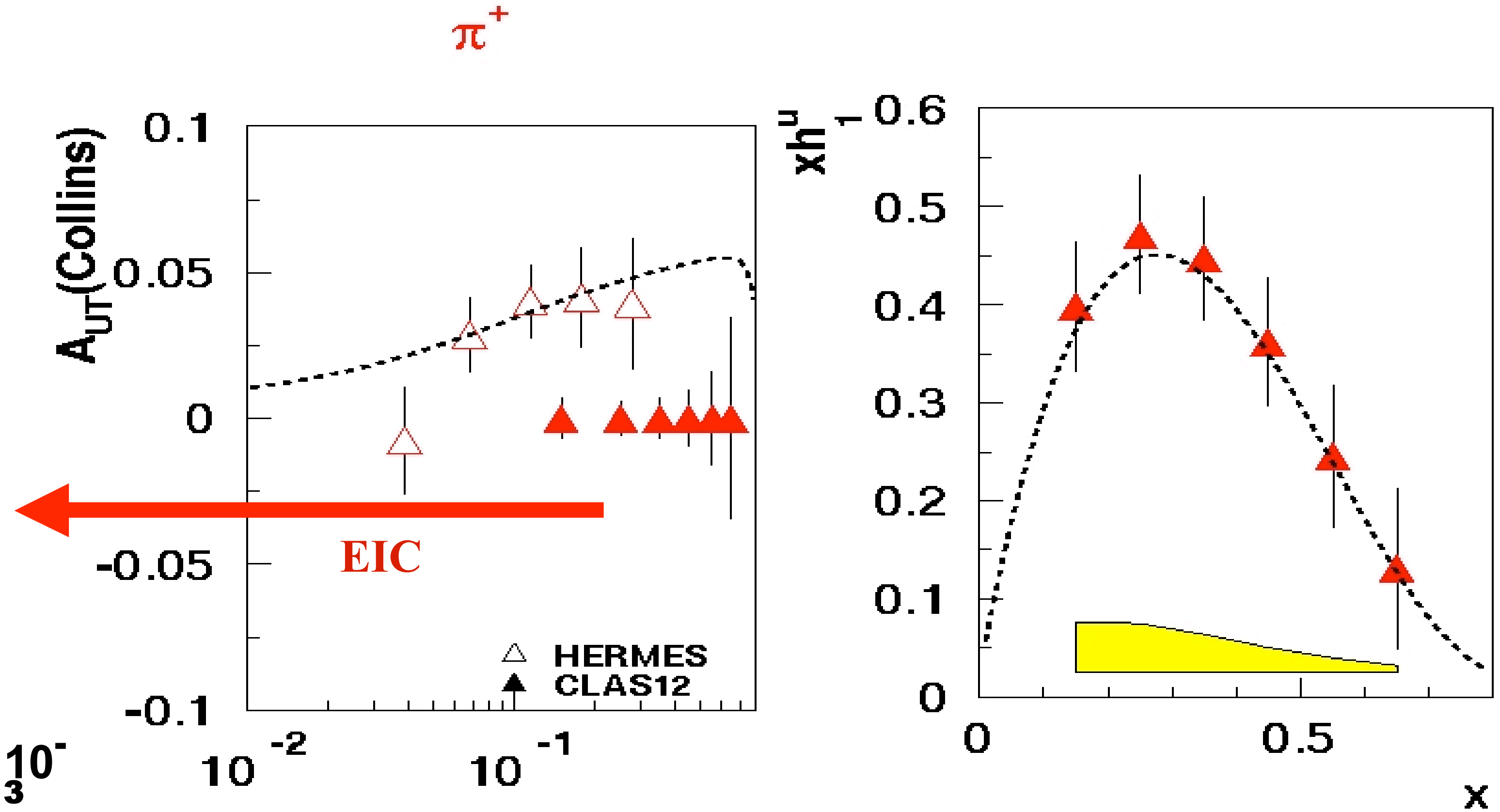
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$



$$\sigma_{UL}^{KM} \sim k\, h_{1L}^{\perp} H_1^{\perp}$$

Measures the Collins fragmentation with longitudinally polarized target. Access to the real part of s-p wave interference amplitudes.

From CLAS12 to EIC: Transversity projections

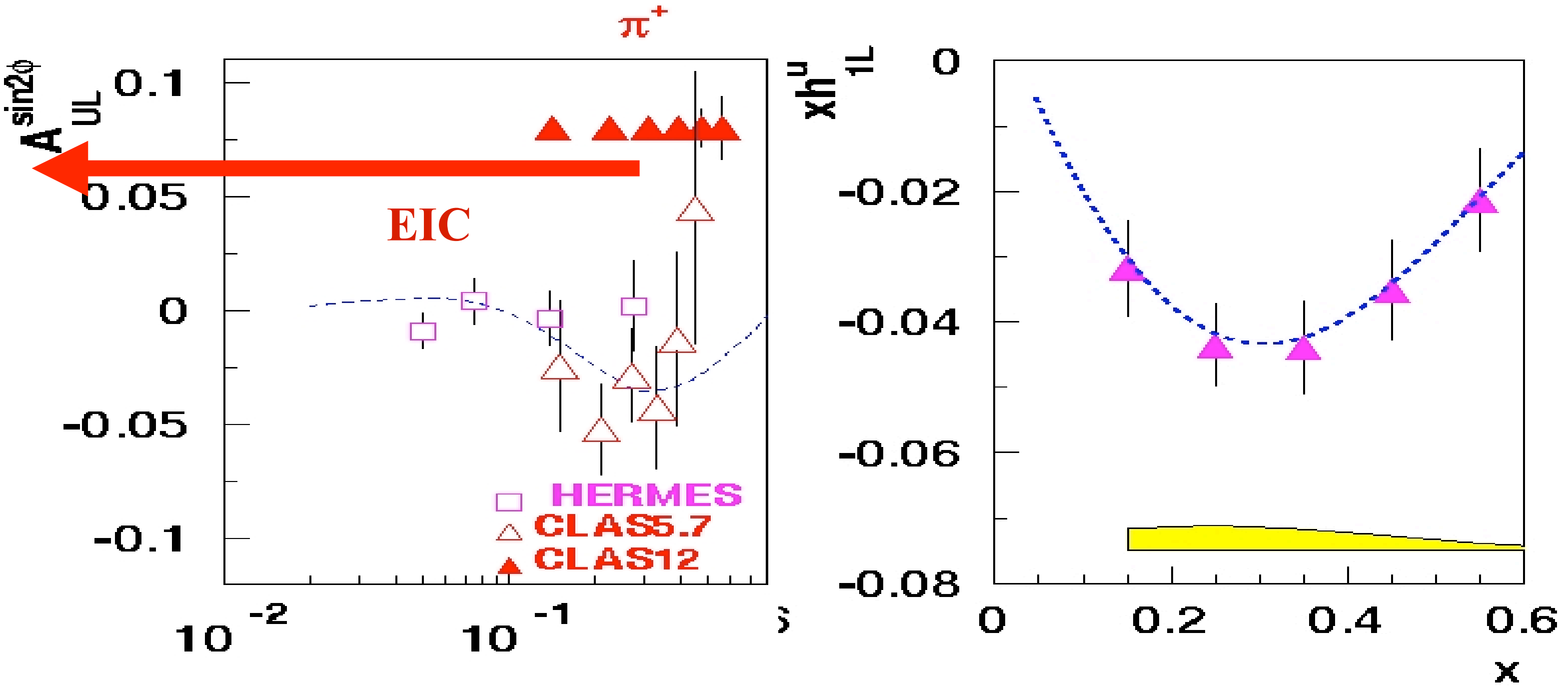


Simultaneous measurement of, exclusive ρ,ρ+,ω with a transversely polarized target

The background from vector mesons very different for CLAS12 and EIC.

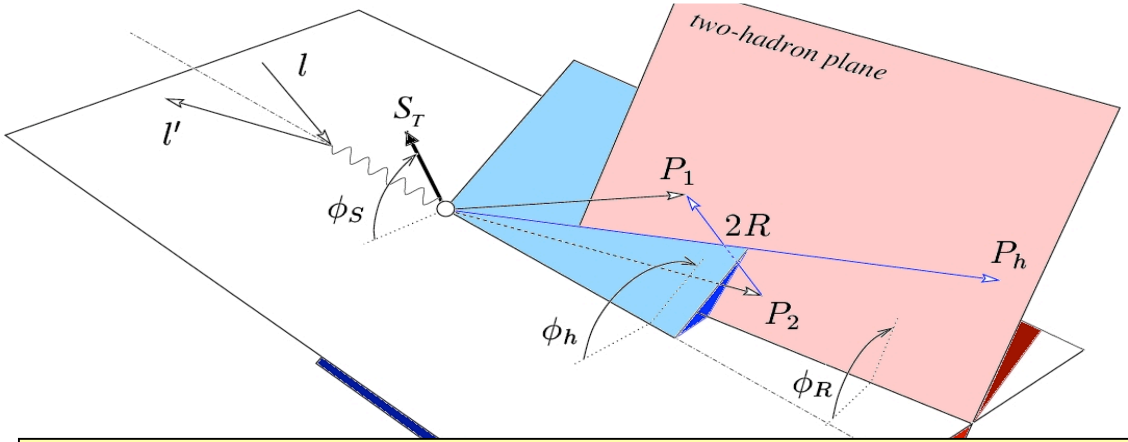
From CLAS12 to EIC: Mulders TMD projections

$$\sigma_{UL}^{KM} \sim (1-y)h_{1L}^{\perp}H_1^{\perp}$$



Simultaneous measurement of, exclusive ρ,ρ+,ω with a longitudinally polarized target important to control the background.

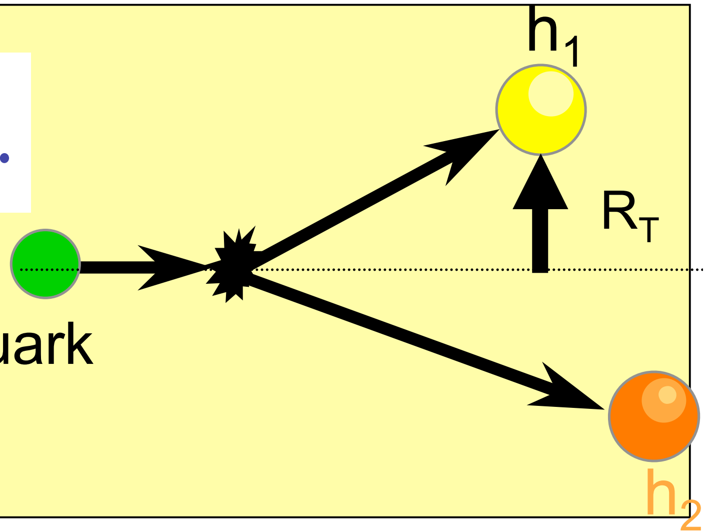
Transversity in double pion production



The angular distribution of two hadrons is sensitive to the spin of the quark

$$A_{UT} \infty \sin(\varphi_R + \varphi_S) h_1 H_1^{\perp R} + \dots$$

"Collinear" dihadron fragmentation described by two functions at leading twist:
$D_1(z, \cos\theta_R, M\pi\pi), H_1^R(z, \cos\theta_R, M\pi\pi)$



Collins et al,
Ji, Jaffe et al,
Radici et al.

relative transverse momentum of the two hadrons replaces the P_T in single-pion production (No transverse momentum of the pair center of mass involved)

Dihadron production provides an alternative, "background free" access to transversity