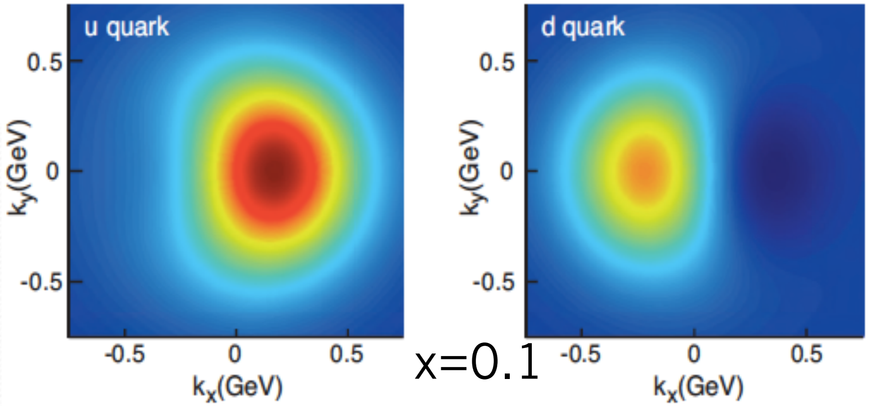
Physics in Electron-Ion Collider Experiments
IV: Nucleon 3-d Structure

Jian-ping Chen (陈剑平), Jefferson Lab, Virginia, USA

Huada School on QCD 2016: QCD in the EIC Era , May 23 – June 3, 2016

- Unified Picture of Nucleon Structure: Wigner Distribution
- GPDs: 3-d (2-d spatial+1-d momentum) distributions
- TMDs:3-d momentum distributions
- Transversity and tensor charge
- SoLID program
- EIC program



Nucleon Spin Structure Study

- 1980s: EMC (CERN) + early SLAC

  quark contribution to proton spin is very small

  $\Delta\Sigma$ = (12+-9+-14)% ! 'spin crisis'

- 1990s: SLAC, SMC (CERN), HERMES (DESY)

  $\Delta\Sigma$ = 20-30%, $$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$ ital angular momentum

  gauge invariant $(\frac{1}{2})\Delta\Sigma + \mathcal{L}q + J_G = 1/2$

  Bjorken Sum Rule verified to <10% level

- 2000s: COMPASS (CERN), HERMES, RHIC-Spin, JLab, … :

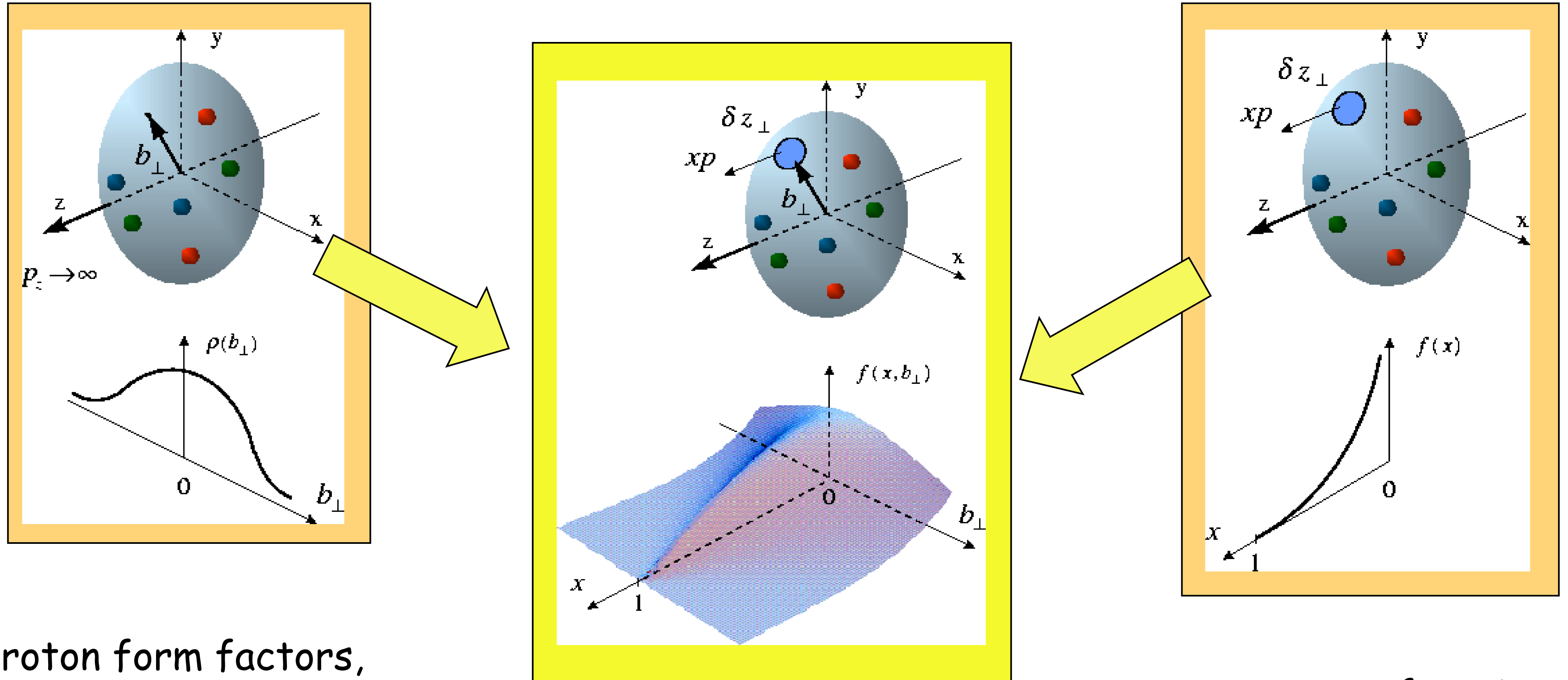
  $\Delta\Sigma$ ~ 30%; ΔG contributes, **orbital angular momentum significant**

  Large-x (valence quark) behavior; Moments and sum rules

  Needs 3-d structure information to complete the proton spin puzzle

Generalized Parton Distributions (GPDs)

X. Ji, D. Mueller, A. Radyushkin (1994-1997)



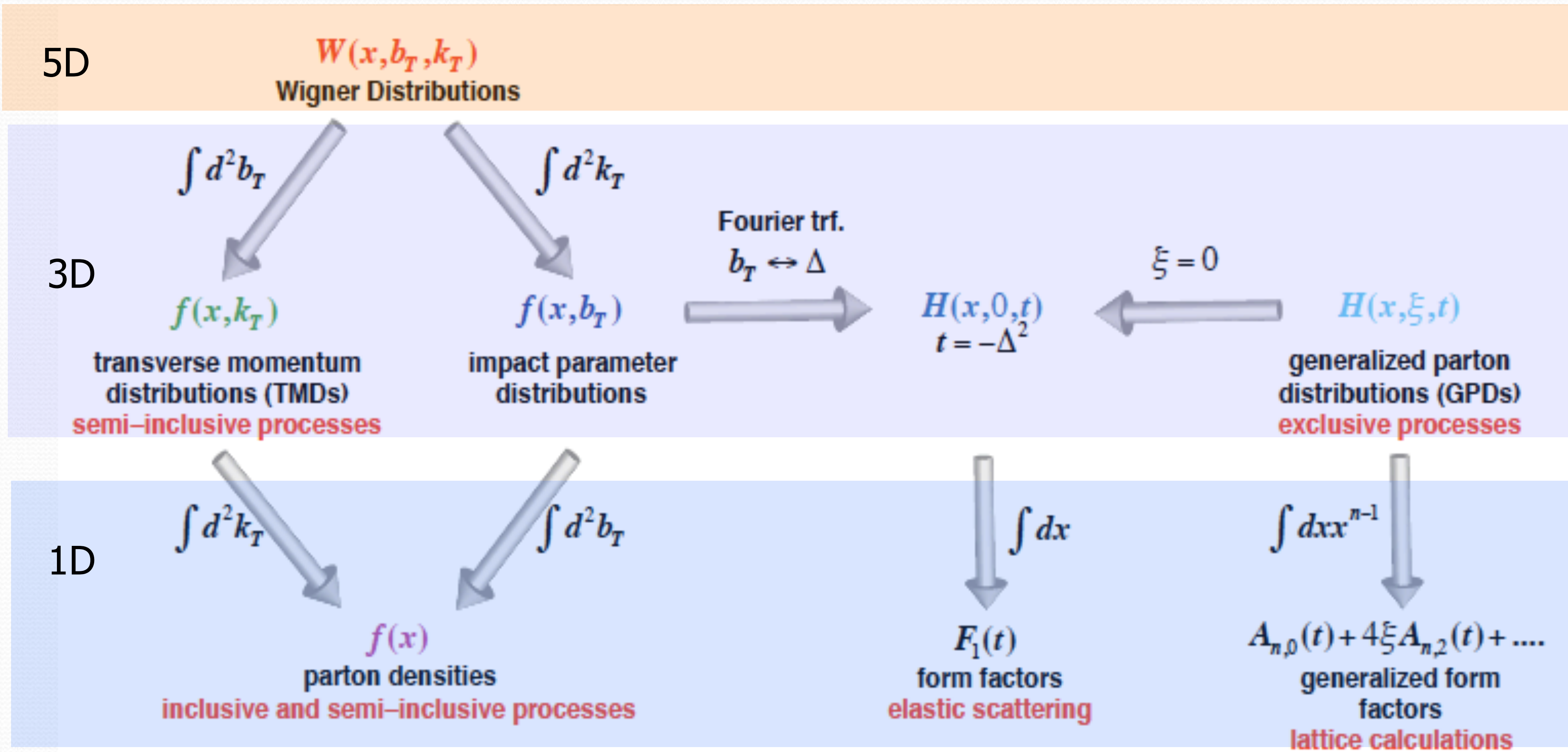
Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

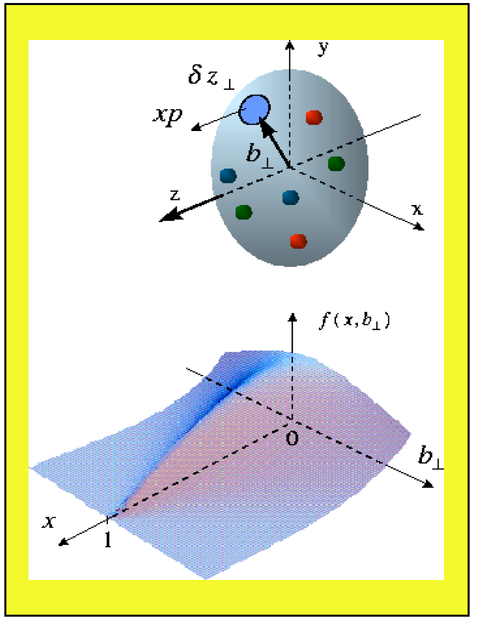
Unified View of Nucleon Structure

- **Wigner distributions**



3-D Structure I

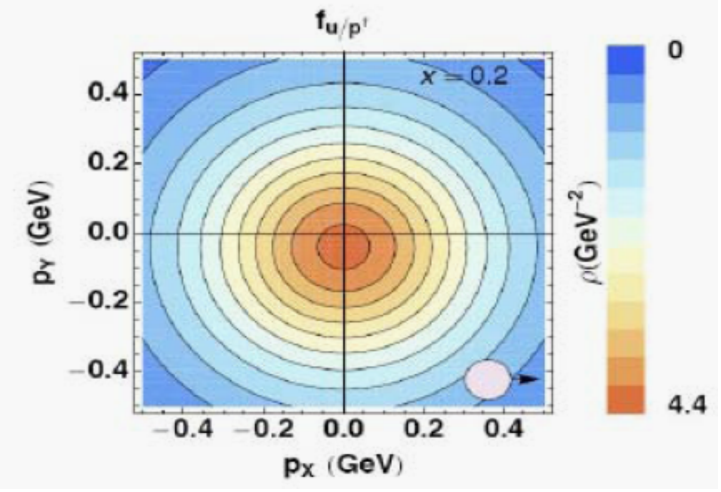
Generalized Parton Distributions



3-D Imaging - Two Approaches

TMDs

2+1 D picture in **momentum space**

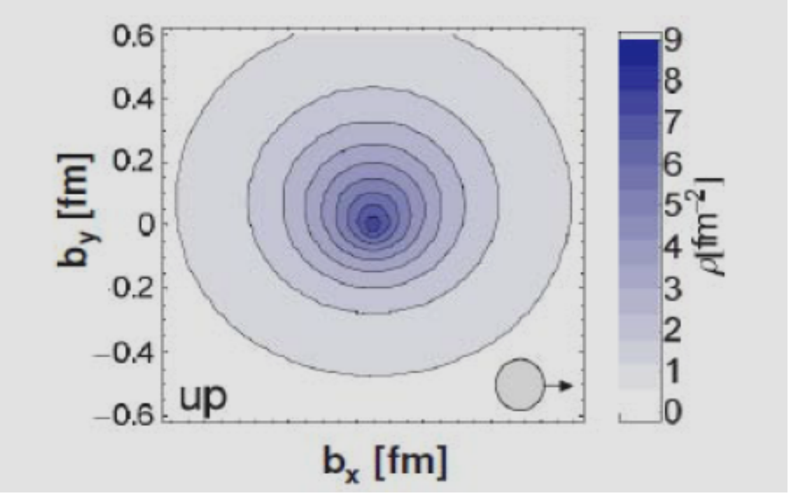


Bacchetta, Conti, Radici

- intrinsic transverse motion
- spin-orbit correlations- relate to OAM
- non-trivial factorization
- accessible in SIDIS (and Drell-Yan)

GPDs

2+1 D picture in **impact-parameter space**

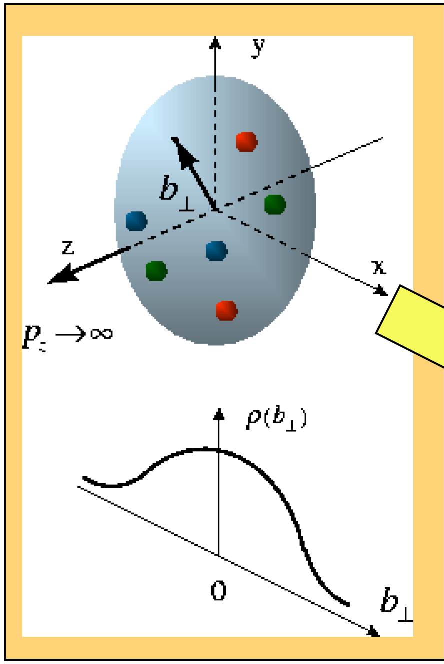


QCDSF collaboration

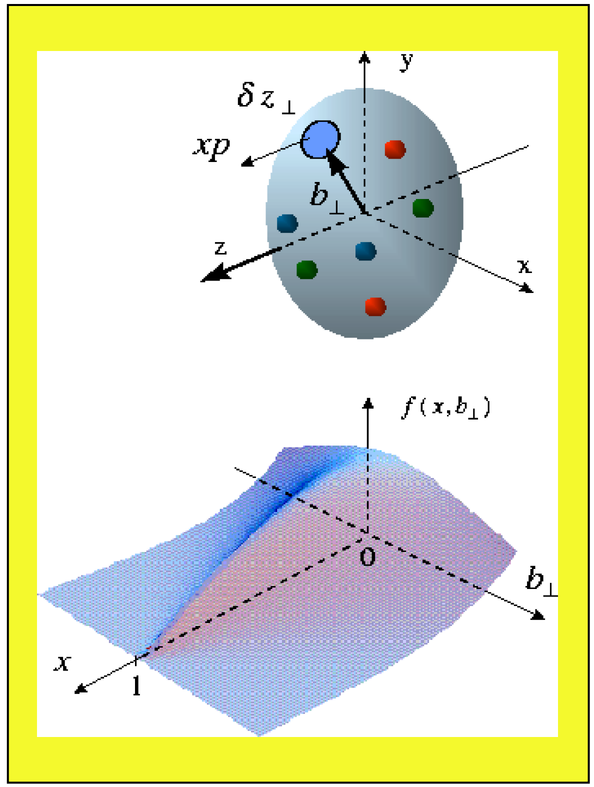
- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- DVCS, exclusive vector-meson production

Generalized Parton Distributions (GPDs)

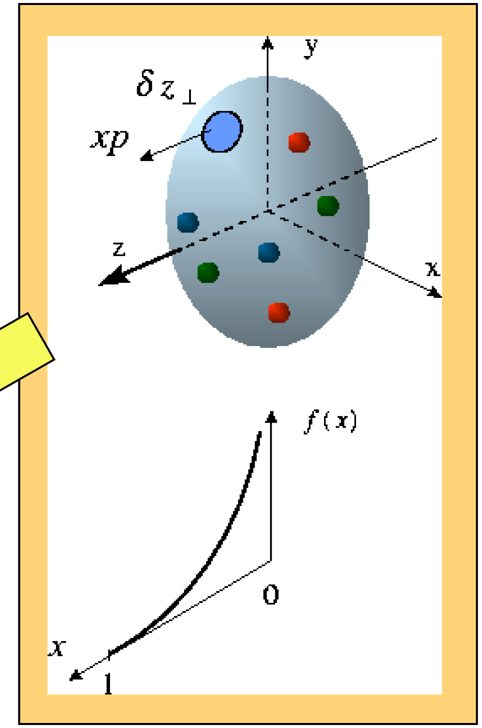
X. Ji, D. Mueller, A. Radyushkin (1994-1997)



Proton form factors, transverse charge & current densities

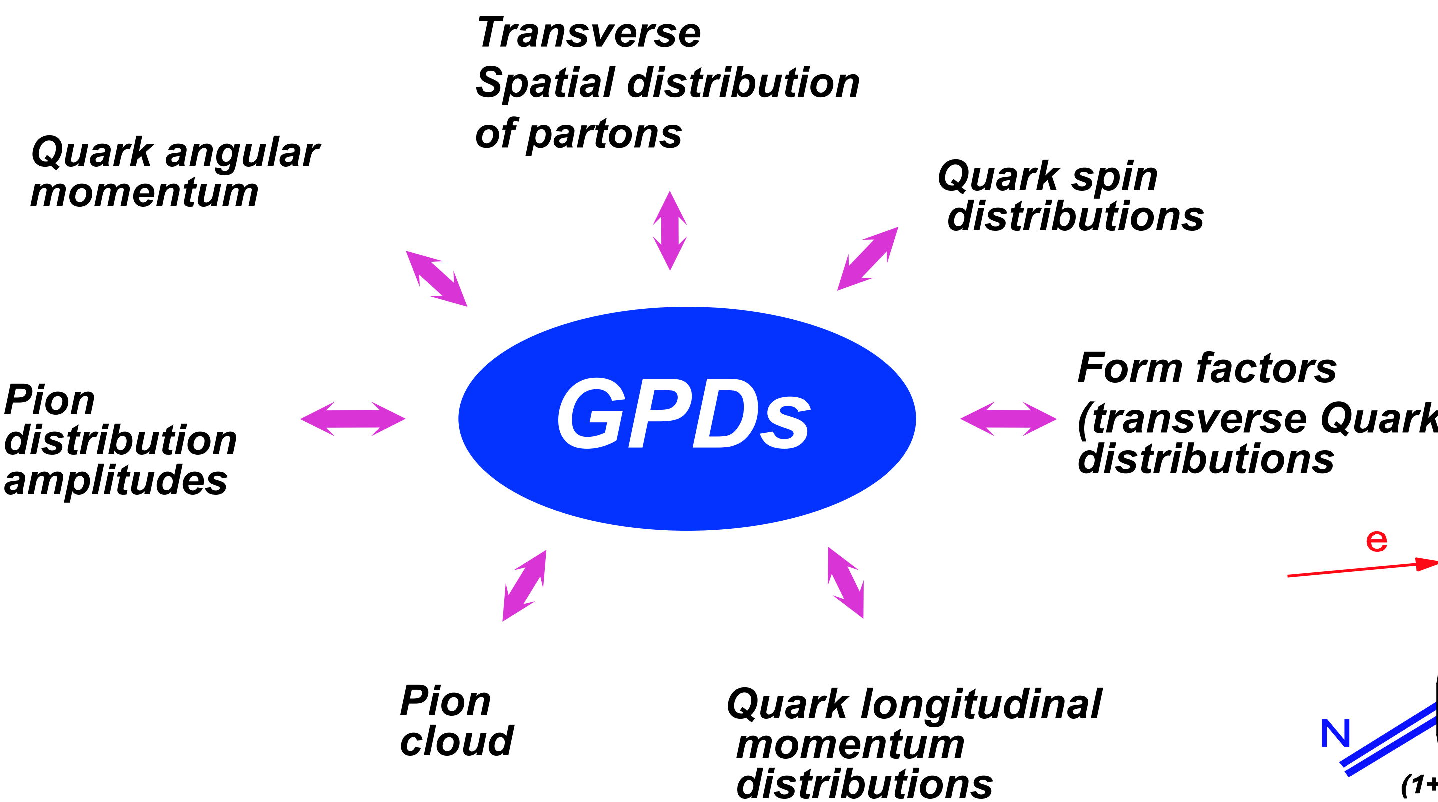


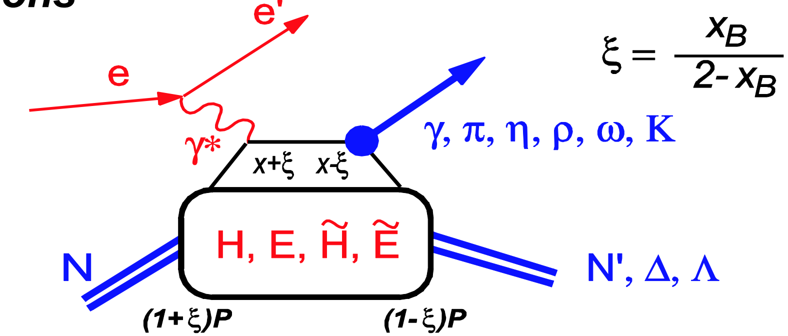
Correlated quark momentum and helicity distributions in transverse space - GPDs



Structure functions, quark longitudinal momentum & helicity distributions

Description of Hadron Structure via Generalized Parton Distributions





H, E - unpolarized, H̃, Ẽ - polarized GPD

The GPDs Define Nucleon Structure

known information on GPDs

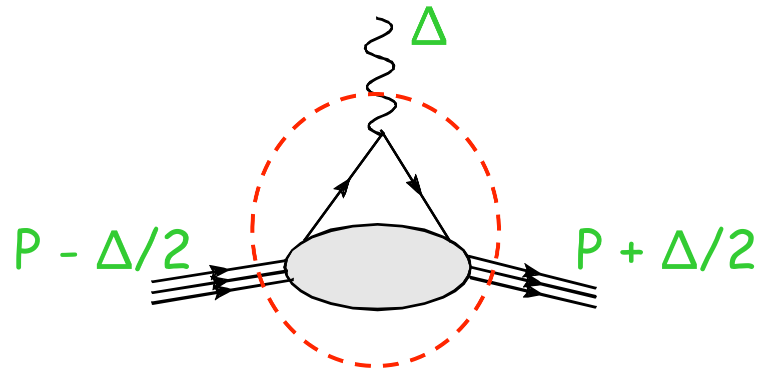
➡ forward limit : ordinary parton distributions

$$H^q(x, \xi = 0, t = 0) \quad = \quad q(x)$$ unpolarized quark distribution

$$\tilde{H}^q(x, \xi = 0, t = 0) \quad = \quad \Delta q(x)$$ polarized quark distribution

$E^q\ ,\ \tilde{E}^q$: do NOT appear in DIS ➡ additional information

➡ first moments : nucleon electroweak form factors



ξ independence : Lorentz invariance

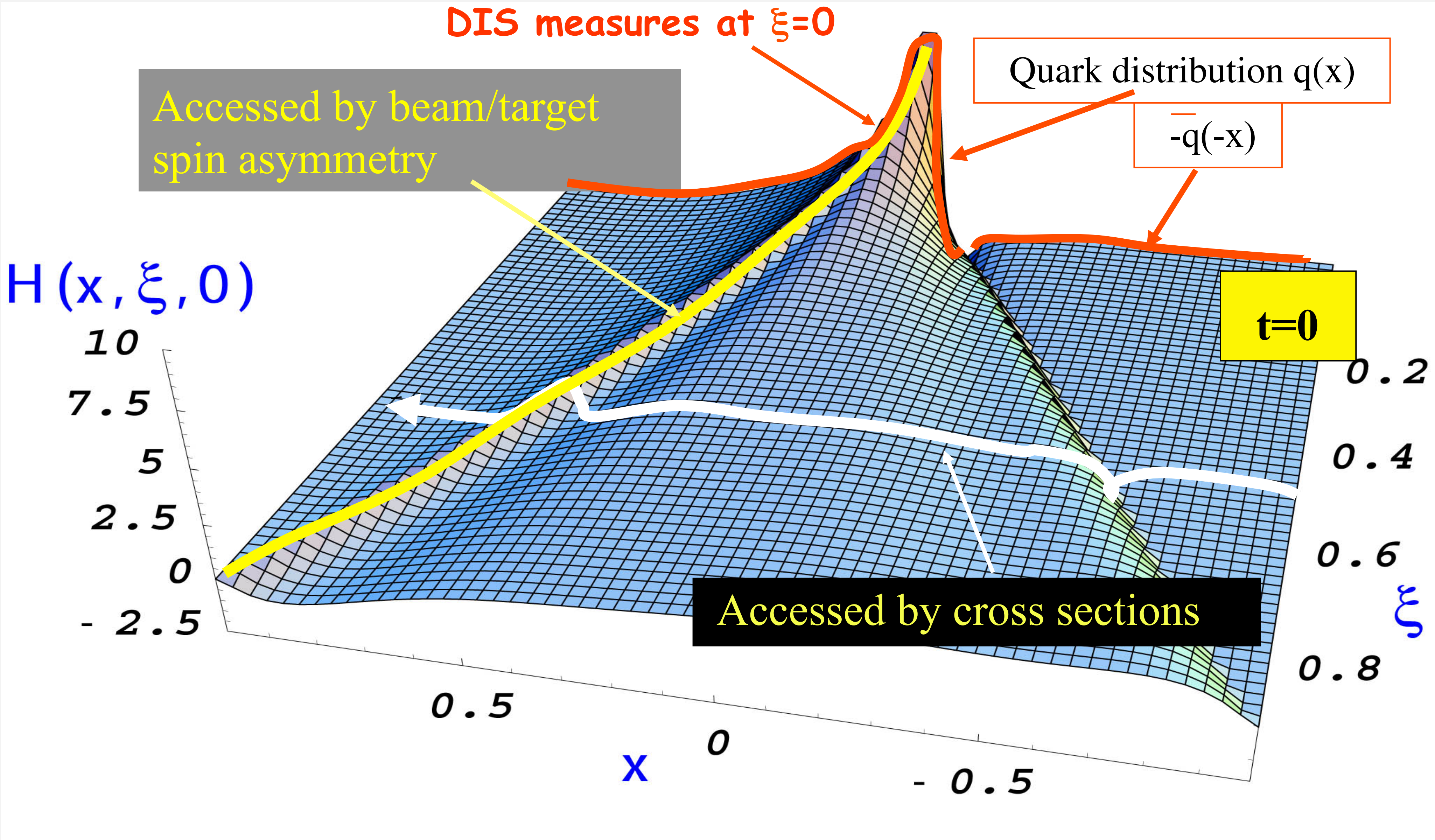
$$\int_{-1}^{1} dx\, H^q(x, \xi, t) \quad = \quad F_1^q(t)$$ Dirac

$$\int_{-1}^{1} dx\, E^q(x, \xi, t) \quad = \quad F_2^q(t)$$ Pauli

$$\int_{-1}^{1} dx\, \tilde{H}^q(x, \xi, t) \quad = \quad G_A^q(t)$$ axial

$$\int_{-1}^{1} dx\, \tilde{E}^q(x, \xi, t) \quad = \quad G_P^q(t)$$ pseudo-scalar

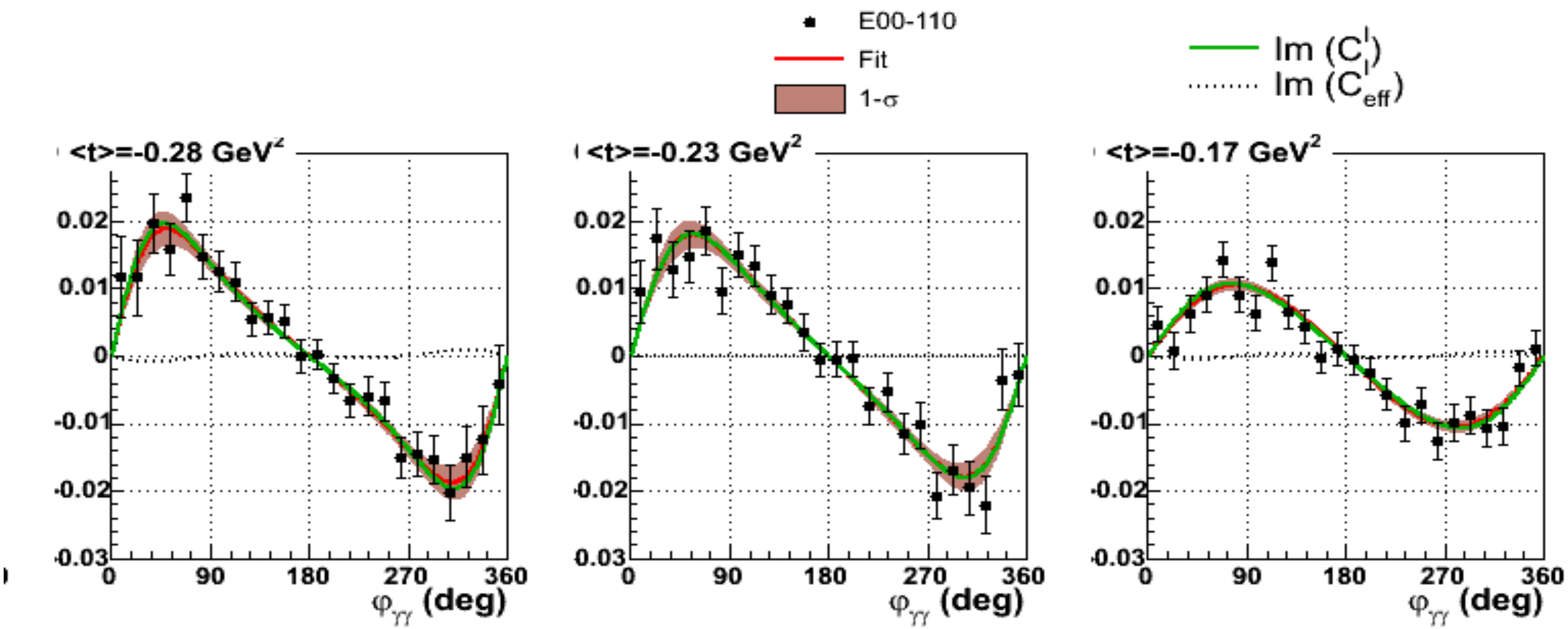
Access GPDs through DVCS x-section & asymmetries



Hall A DVCS Experiment

Handbag Dominance at Modest Q^2

$$\frac{d^4\sigma^+}{dx_B dQ^2 d\varphi\, dt} - \frac{d^4\sigma^-}{dx_B dQ^2 d\varphi\, dt} \quad [\text{nb/GeV}^4]$$



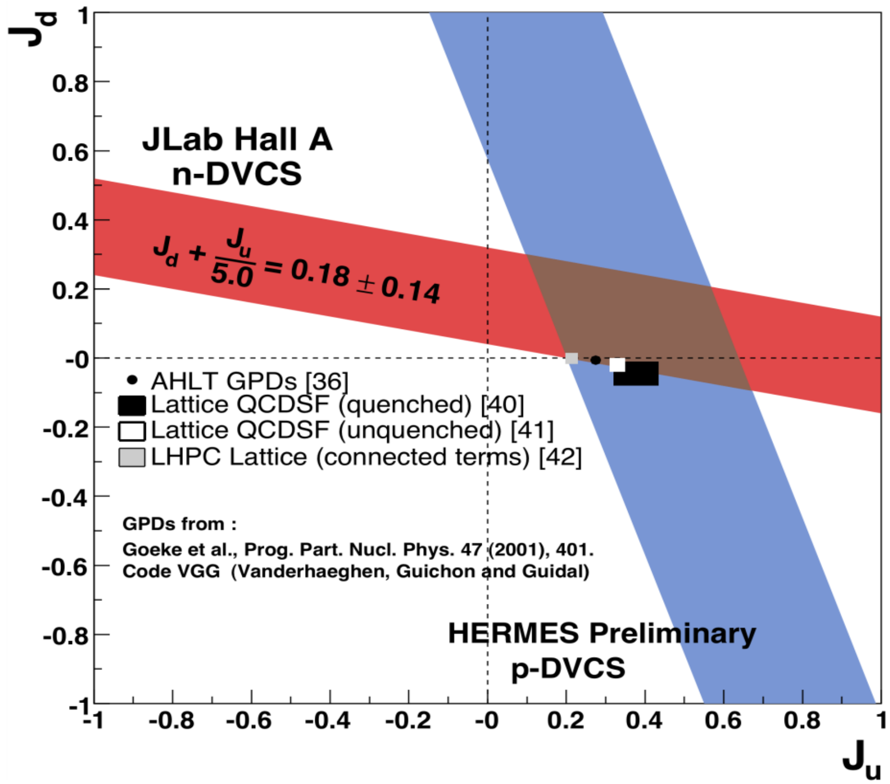
Twist 2 contribution

Twist 3 contribution strongly suppressed

The Twist-2 term can be extracted accurately from the cross-section difference
Dominance of twist-2 ⇒ handbag dominance ⇒ DVCS interpretation

Quark Angular Momentum

$$J^q(t) = \int_{-1}^{+1} dx x[H^q(x,\xi,t) + E^q(x,\xi,t)]$$



→ Access to quark orbital angular momentum

CLAS12 – DVCS/BH Target Asymmetry

$$e\,\vec{p} \longrightarrow ep\gamma$$

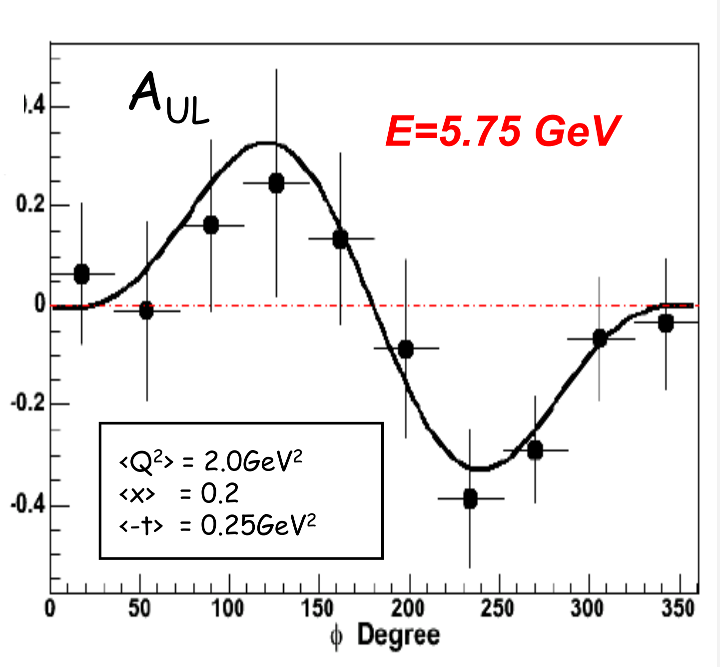
E = 11 GeV

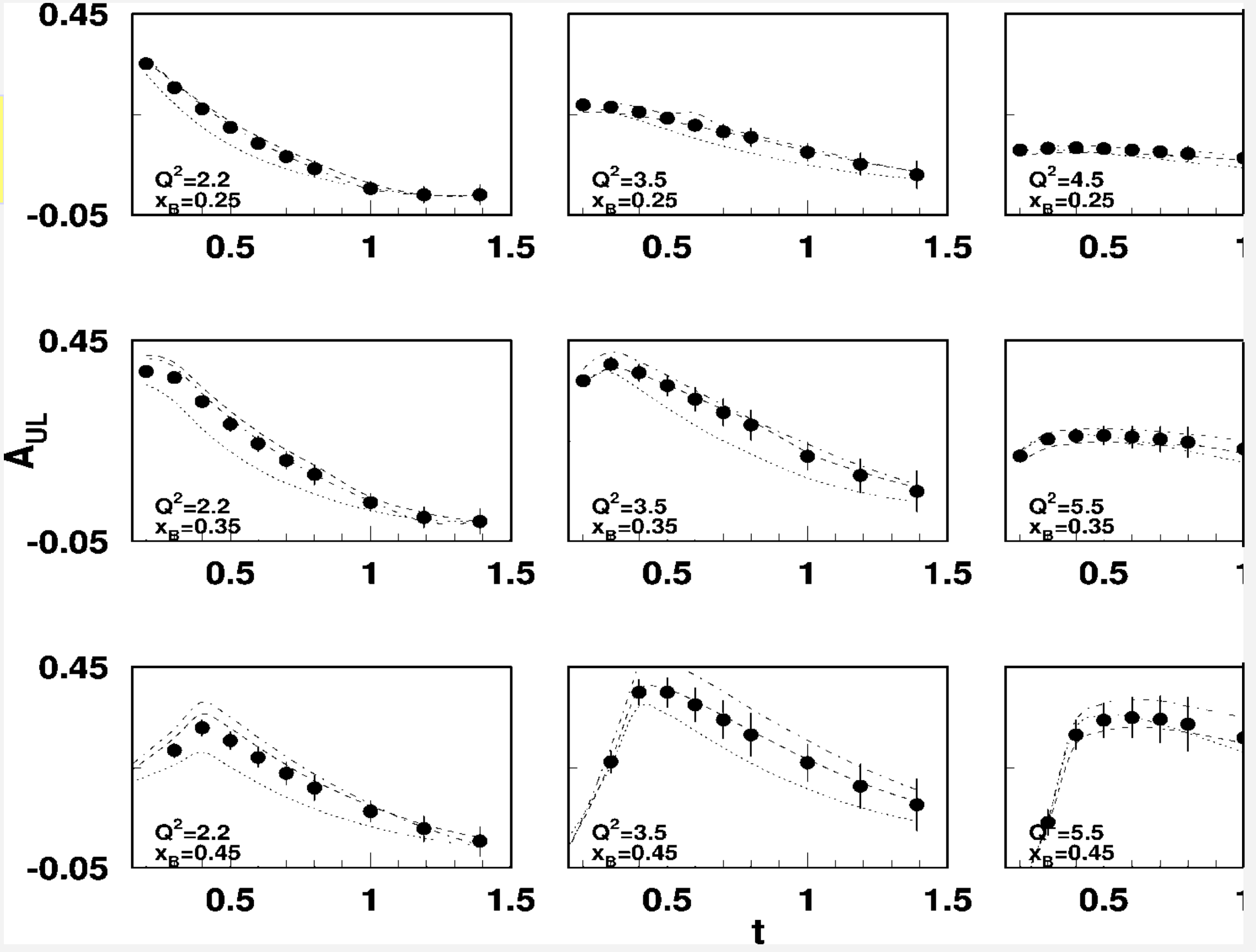
L = 2×10^{35} $cm^{-2}s^{-1}$
T = 1000 hrs
$\Delta Q^2 = 1 GeV^2$
$\Delta x = 0.05$

Longitudinally polarized target

$$\Delta\sigma \sim \sin\phi \, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)H \ldots\}d\phi$$

CLAS preliminary



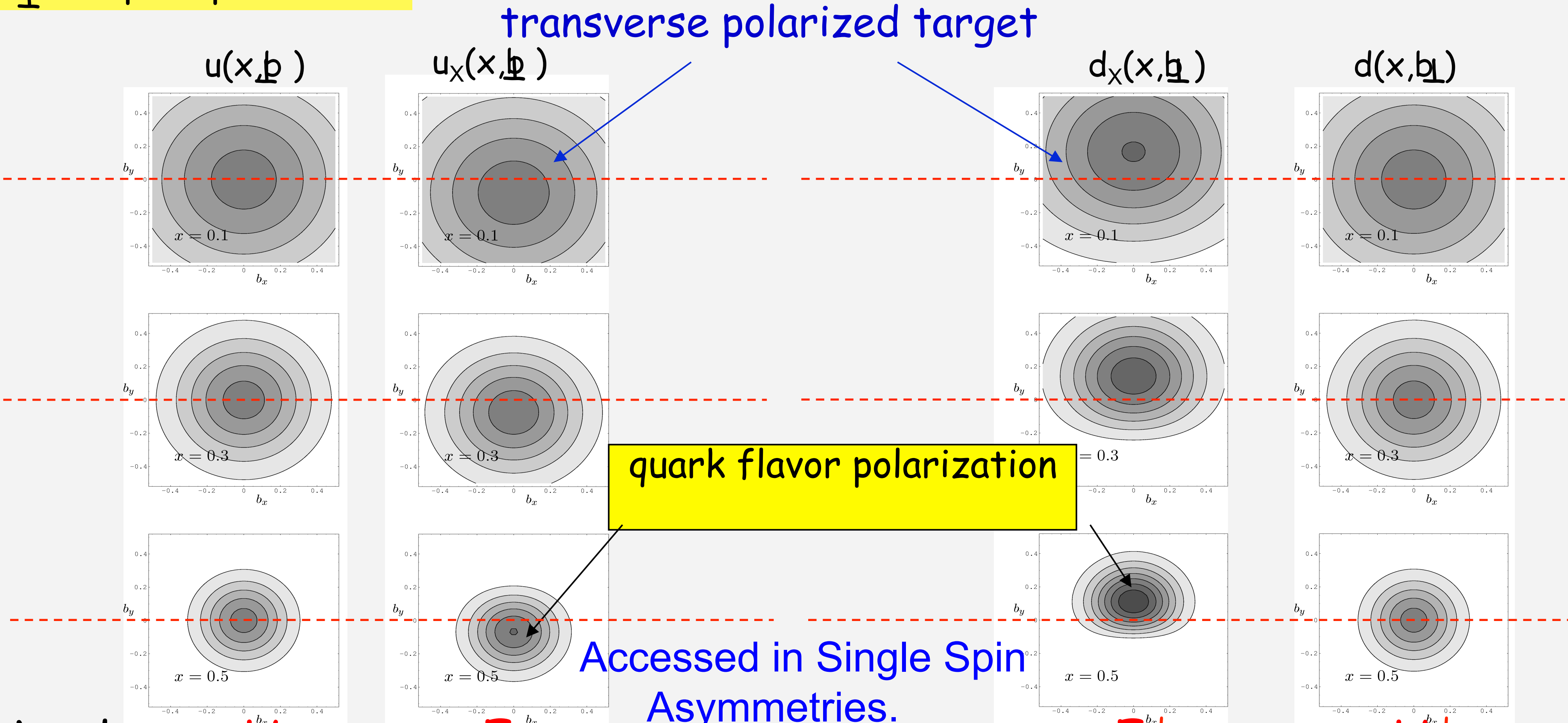


3D Images of the Proton's Quark Content

M. Burkardt PRD 66, 114005 (2002)

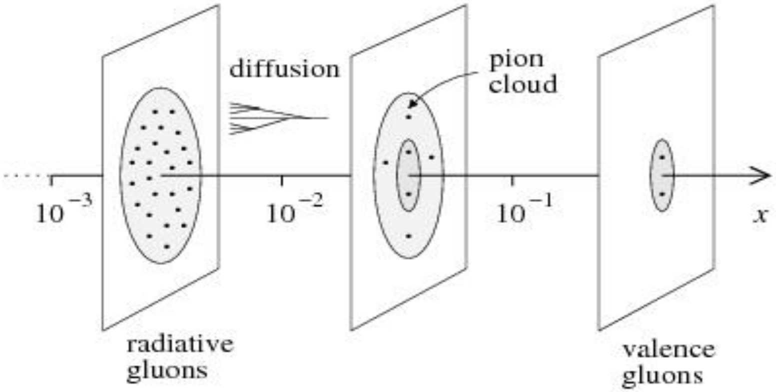
b$_\perp$- Impact parameter

$$q(x,\mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{\Delta}_\perp\cdot\mathbf{b}_\perp} H(x,0,-\mathbf{\Delta}_\perp^2).$$



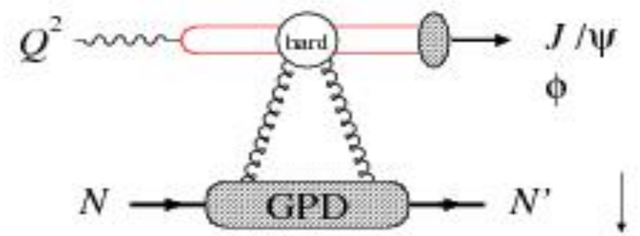
Needs: H^u E^u E^d H^d

Detailed differential images from nucleon's partonic structure



Weiss, Hyde, Horn

EIC: Gluon size from J/Ψ and φ electroproduction (Q^2 > 10 GeV^2)



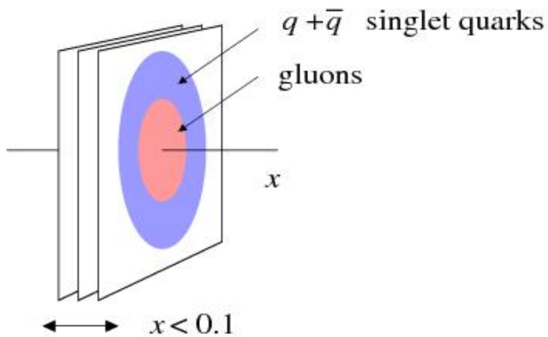
[Transverse distribution derived directly from t dependence]

Hints from HERA:

Area ($q + \bar{q}$) > Area (g)

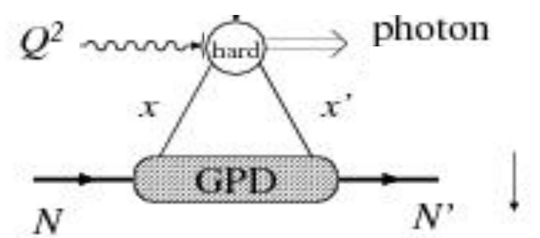
Dynamical models predict difference:

pion cloud, constituent quark picture

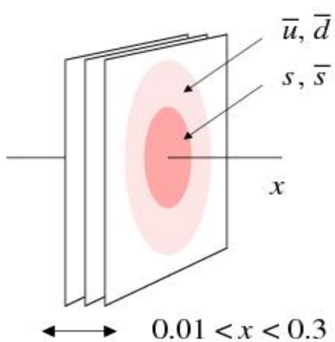


Fazio

EIC: singlet quark size from deeply virtual compton scattering

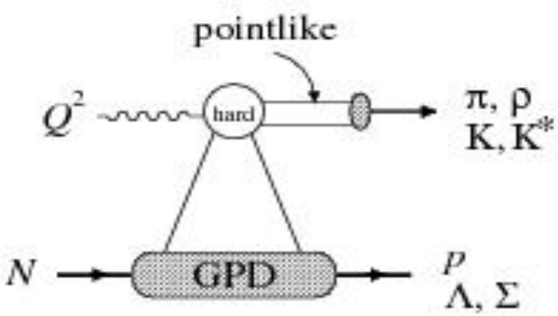


- Q^2 > 10 GeV^2 for factorization
- Statistics hungry at high Q^2!

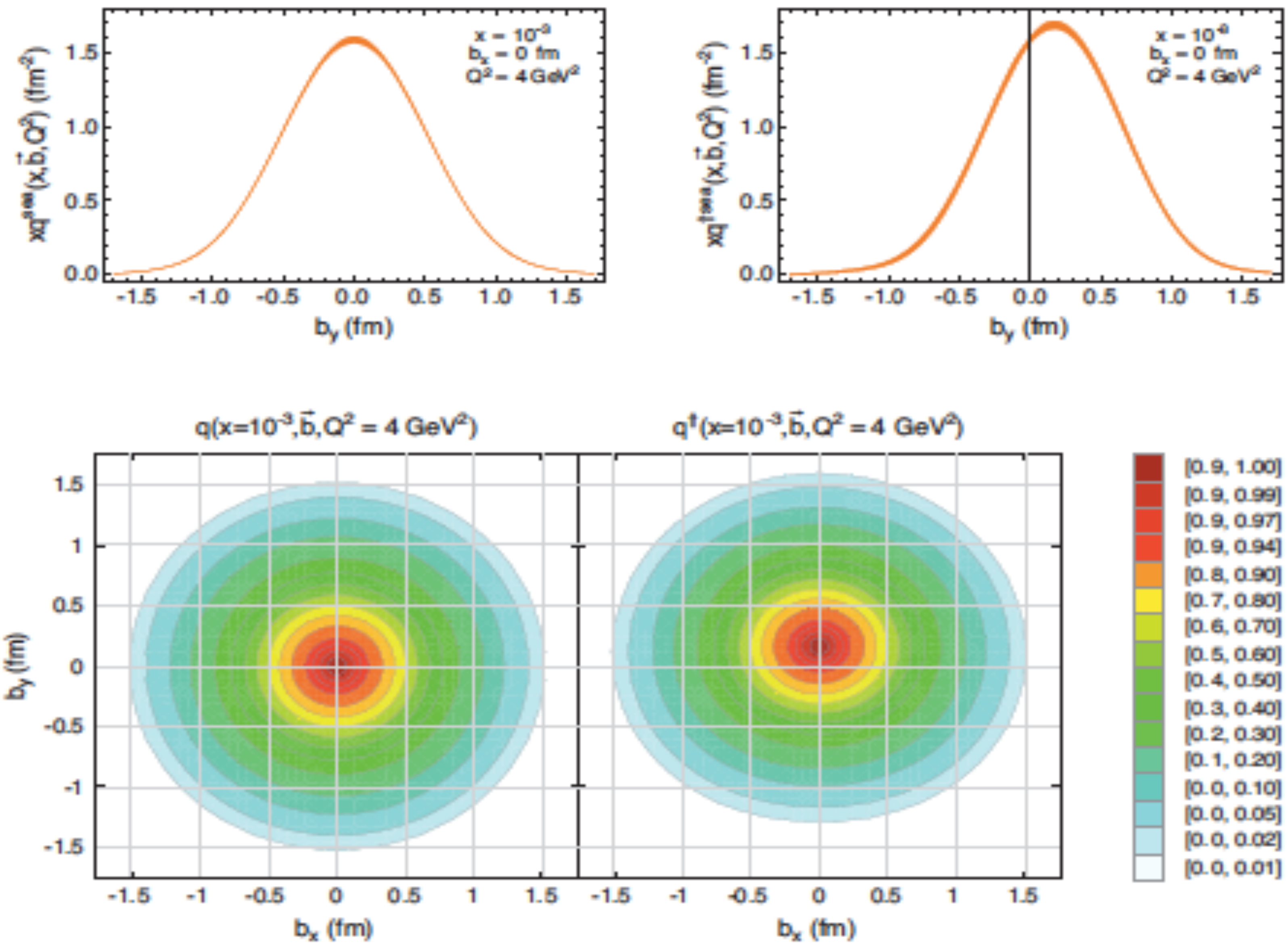


Horn

EIC: strange and non-strange (sea) quark size from π and K production



Polarized DVCS @ EIC



GPD Study at EIC@HIAF

- Unique opportunity for DVMP (pion/Kaon)

  flavor decomposition needs DVMP

  energy reach Q^2 > 5-10 GeV^2, scaling region for exclusive light meson production

  (JLab12 energy not high enough to have clean light meson deep exclusive process)

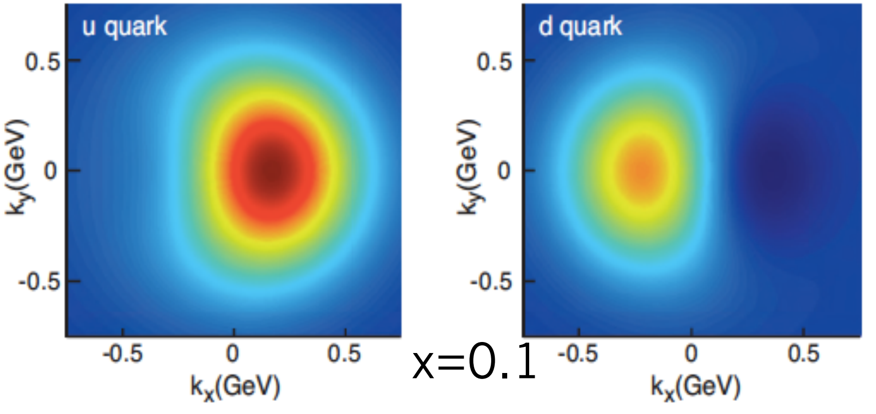
- Significant increase in range for DVCS

  combination of energy and luminosity

- Other opportunities: vector meson, heavy flavors?

3-D Structure II

Transverse Momentum-Dependent Distributions



Leading-Twist TMD PDFs

Nucleon Spin
Quark Spin

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1		$h_1^{\perp}$ – Boer-Mulders
	L		g_1 – Helicity	$h_{1L}^{\perp}$ – Long-Transversity
	T	$f_{1T}^{\perp}$ – Sivers	g_{1T} – Trans-Helicity	h_1 – Transversity $h_{1T}^{\perp}$ – Pretzelosity

TMDs

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 $h_{1T}^\perp$

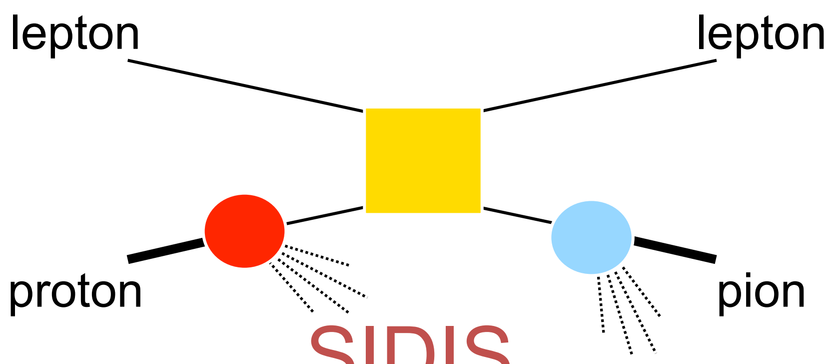
8 functions in total (at leading Twist)

Each represents different aspects of partonic structure

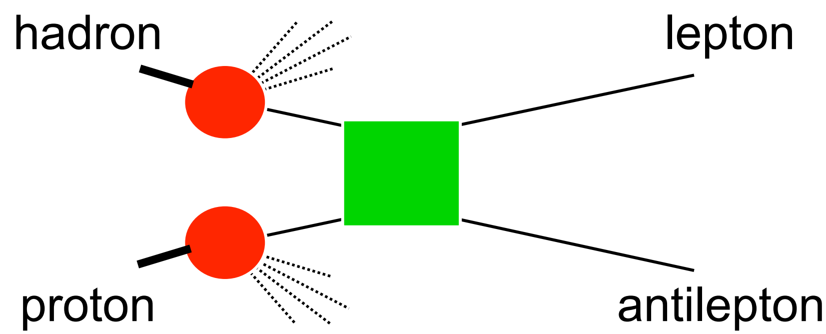
Each function is to be studied

Mulders, Tangerman (1995), Boer, Mulders (1998)

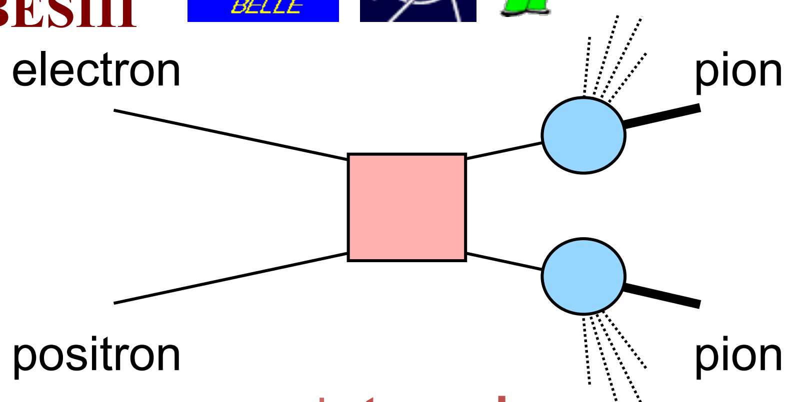
Access TMDs through Hard Processes



SIDIS



Drell-Yan

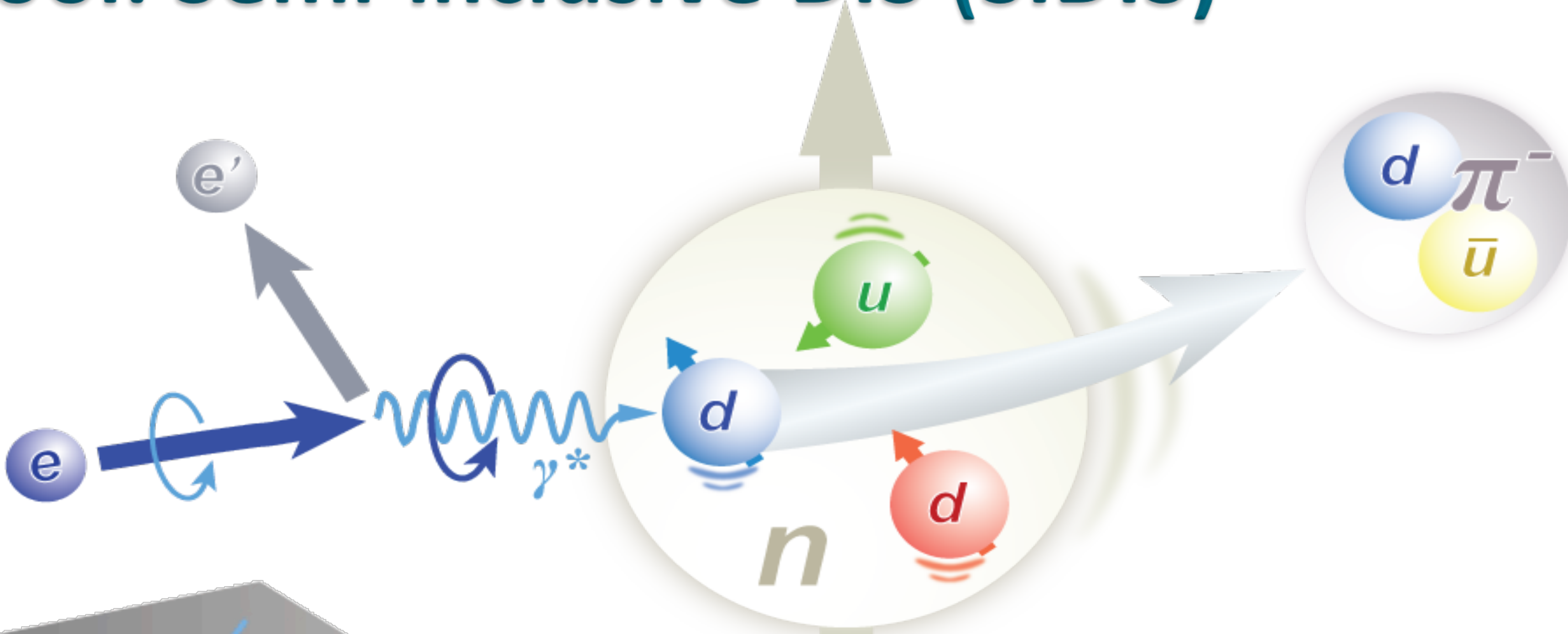


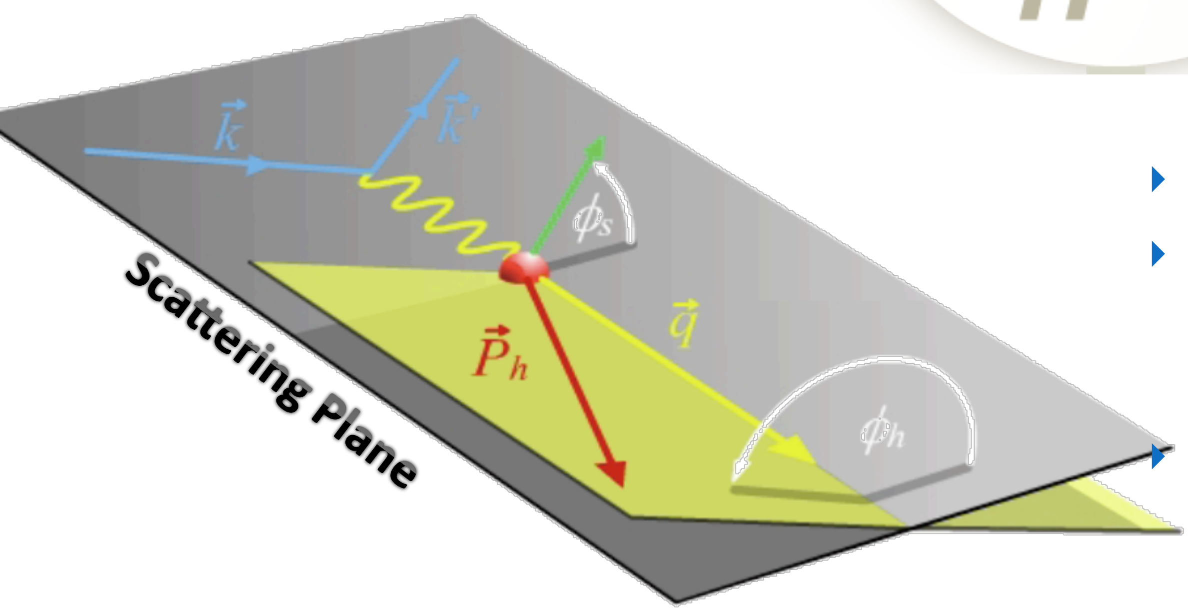
$e^{-}e^{+}$ to pions

- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

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

Tool: Semi-inclusive DIS (SIDIS)





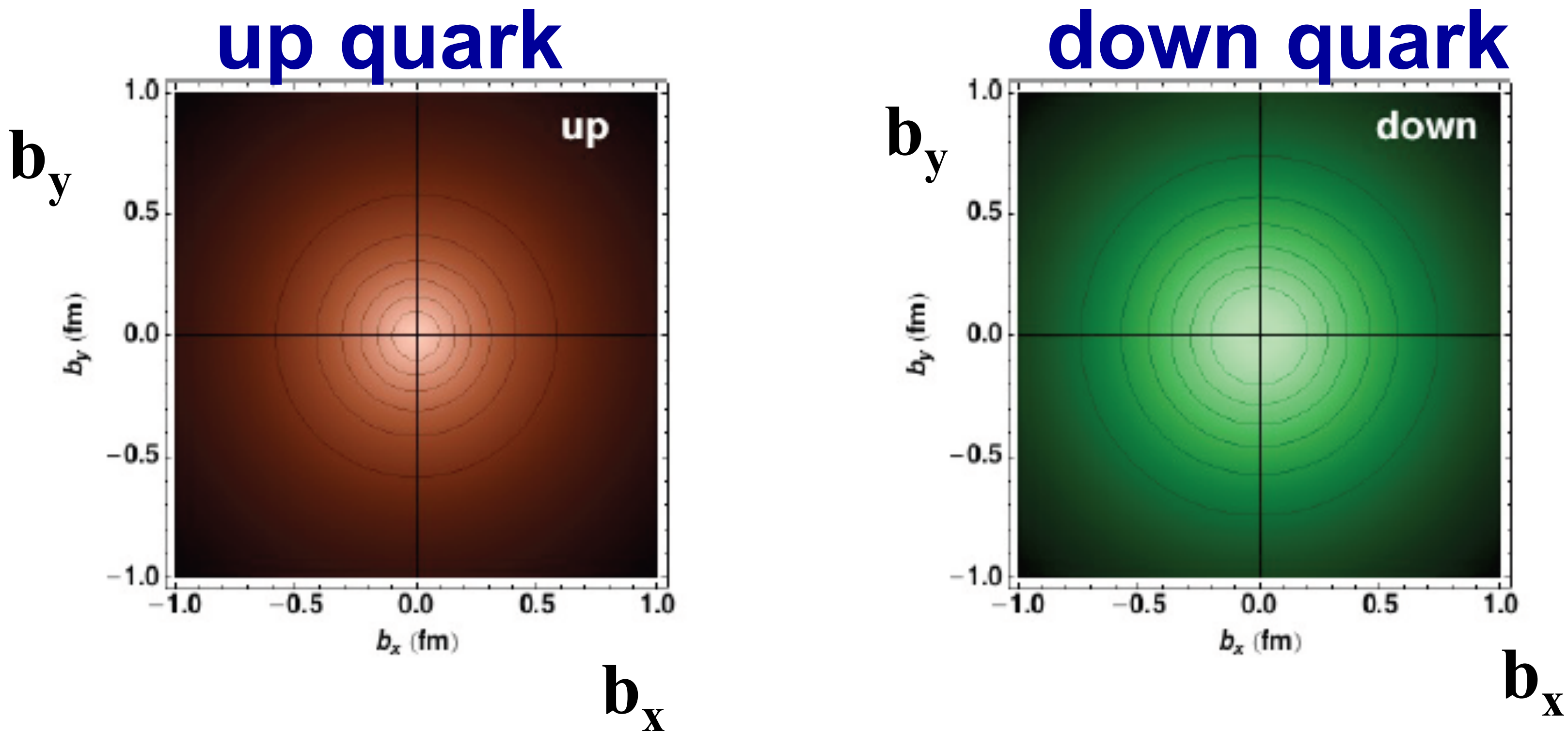
- Gold mine for TMDs
- Access all eight leading-twist TMDs through spin-comb. & azimuthal-modulations
- Tagging quark flavor/kinematics

Unpolarized TMDs
Flavor P_T Dependence

SIDIS Results

From Form Factors to Transverse Densities

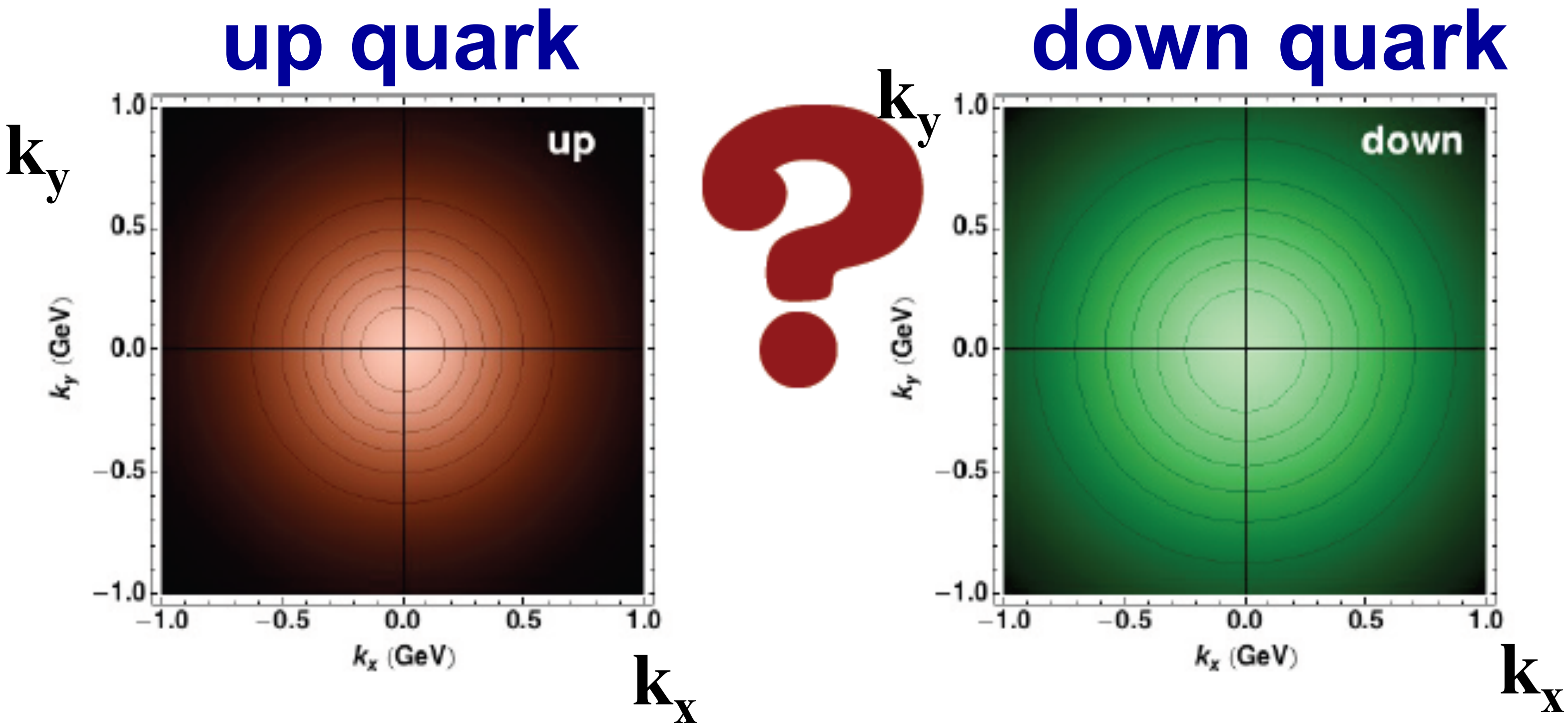
Unpolarized Transverse Densities



Flavor-dependence in form factors can be translated into flavor-dependence of transverse densities

Unpolarized TMD: Flavor P_T Dependence?

Flavor in transverse-momentum space



Is the up distribution wider or narrower than the down?

And the sea?

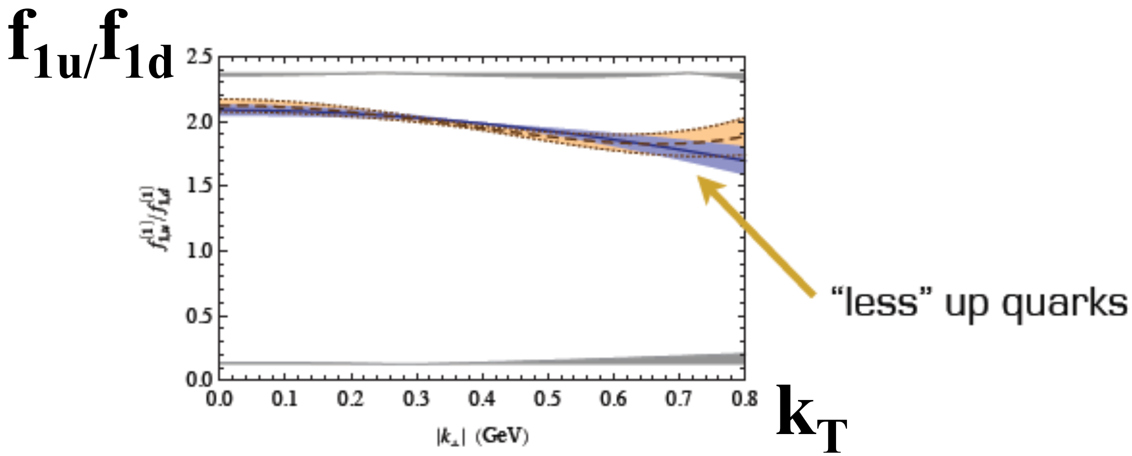
How wide are the distributions?

A. Bacchetta, Seminar @ Jlab, arXiv1309.3507 (2013)

Flavor P_T Dependence from Theory

- **Chiral quark-soliton model (Schweitzer, Strikman, Weiss, JHEP, 1301 (2013)**
  → sea wider tail than valanee

Indications from lattice QCD



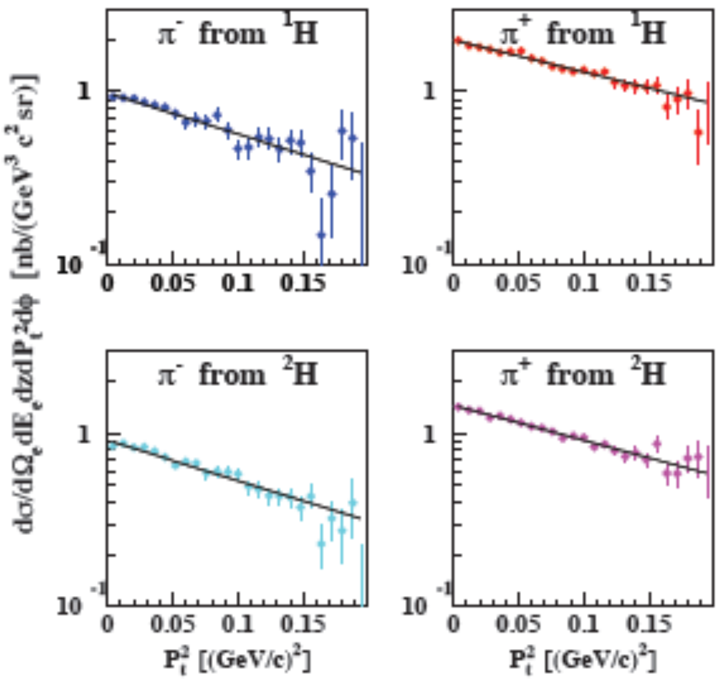
Musch, Hagler, Negele, Schafer, PRD 83 (11)

Pioneering lattice-QCD studies hint at a down distribution being wider than up

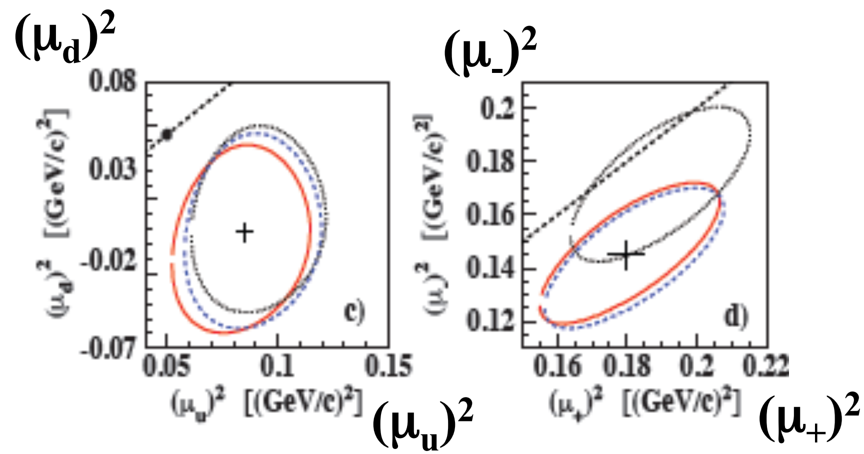
- **Flagmentation model, Matevosyan, Bentz, Cloet, Thomas, PRD85 (2012)**
  → unfavored pion and Kaon wider than favored pion

Flavor P_T Dependence

First indications from experiments



no kaons, no sea,
no *x-z* dependence



Asaturyan et al., E00-108, Hall C, PRC85 (2012)

Conclusion: up is wider than down and favored wider than unfavored

Jefferson Lab

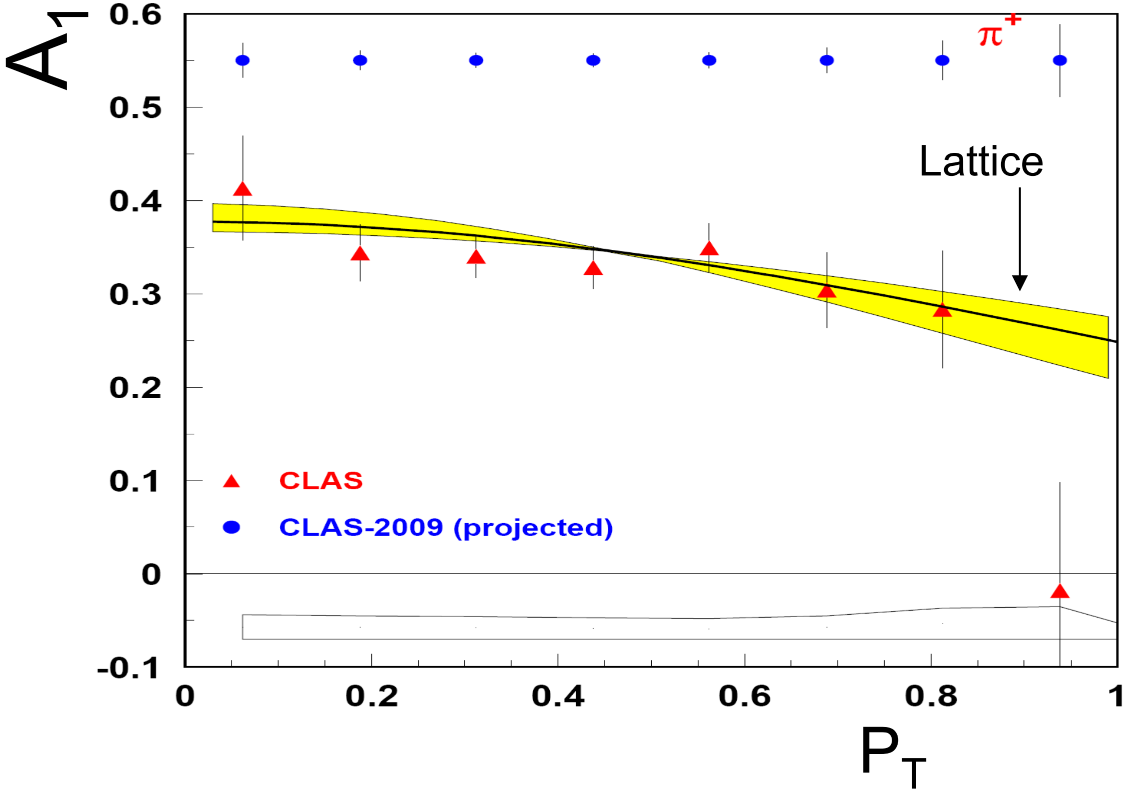
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

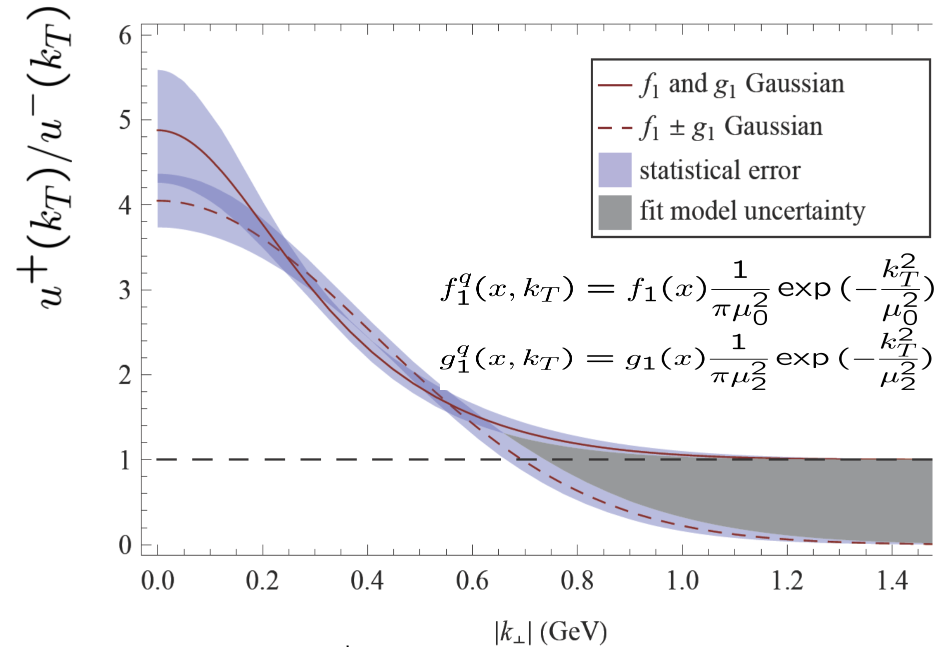
A_1 P_T-dependence

arXiv:1003.4549

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}$$

$$A_1(x,z,P_T) = A_1(x,z)\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle}\exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)$$





B.Musch et al arXiv:1011.1213

$$\mu_2^2/\mu_0^2 = 0.692 \pm 0.039 \pm 0.045$$

CLAS data suggests that width of g_1 is less than the width of f_1

Leading-Twist TMD PDFs

Nucleon Spin
Quark Spin

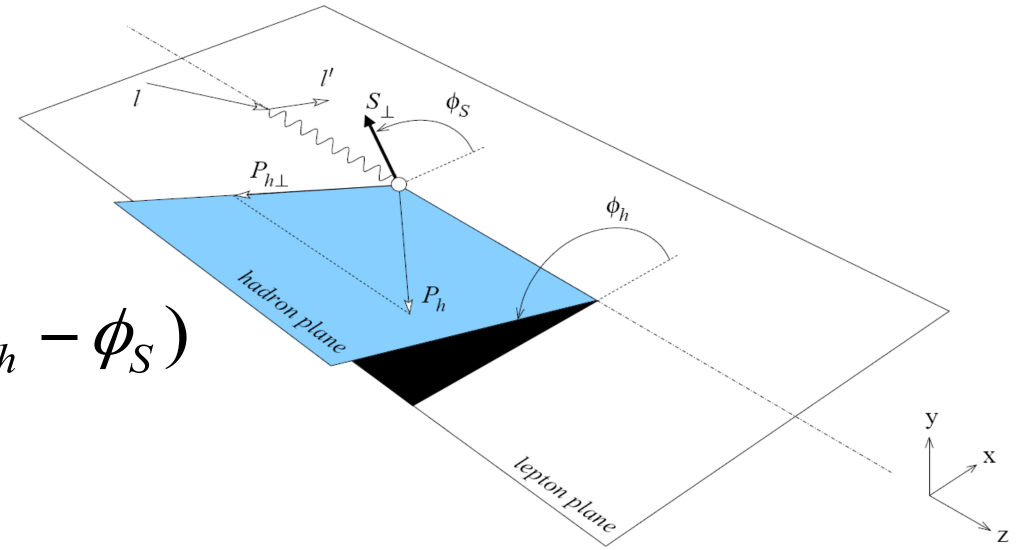
Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1		$h_1^{\perp}$ **Boer-Mulders**
L		g_1 **Helicity**	$h_{1L}^{\perp}$ **Long-Transversity**
T	$f_{1T}^{\perp}$ **Sivers**	g_{1T} **Trans-Helicity**	h_1 **Transversity** $h_{1T}^{\perp}$ **Pretzelosity**

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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

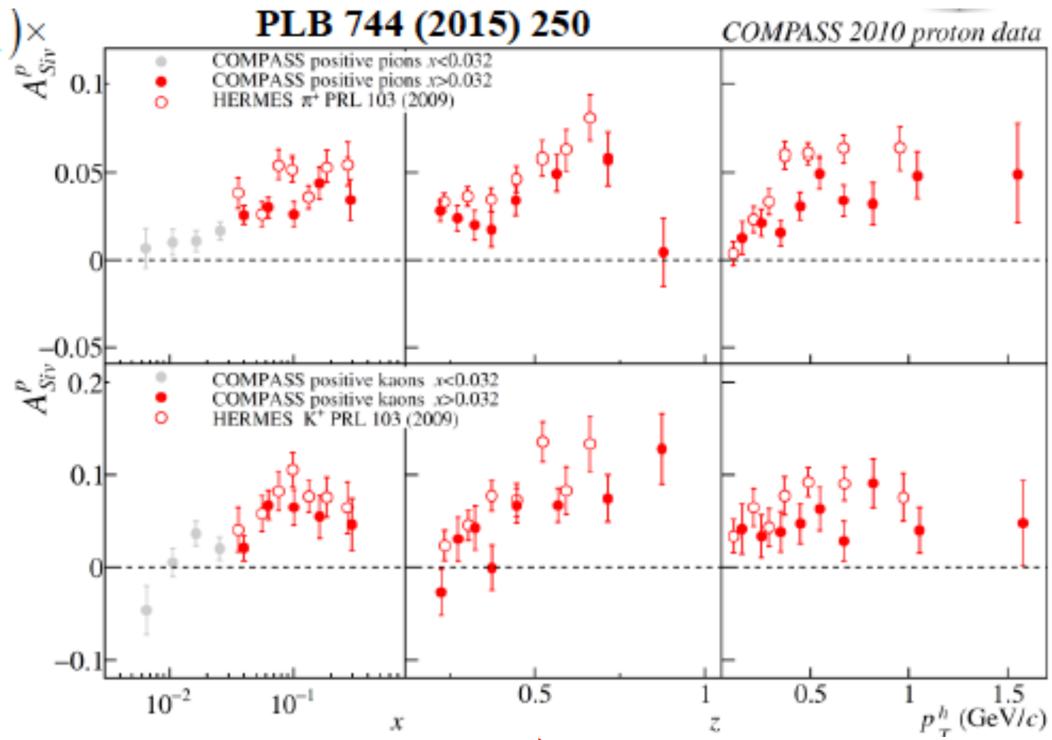


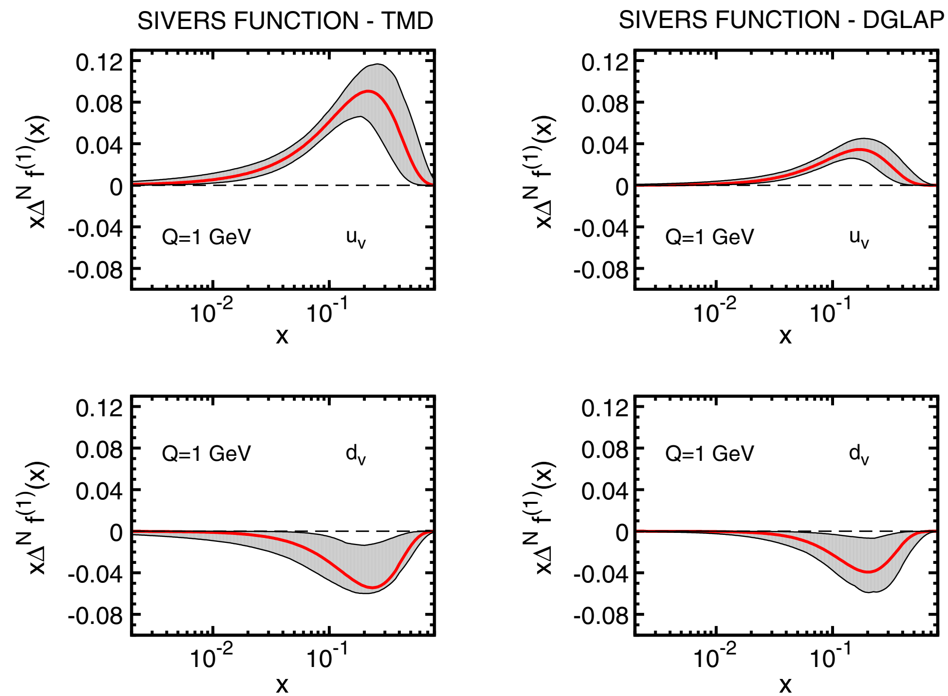
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

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

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

COMPASS/HERMES: *Sivers Asymmetries and Extraction of Sivers Function*





Also other TMDs.

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 $h_{1T}^{\perp}$

M. Anselmino, M. Boglione, and S. Melis
Phys. Rev. D 86, 014028 (2012)

JLab 6 GeV Experiment E06-010

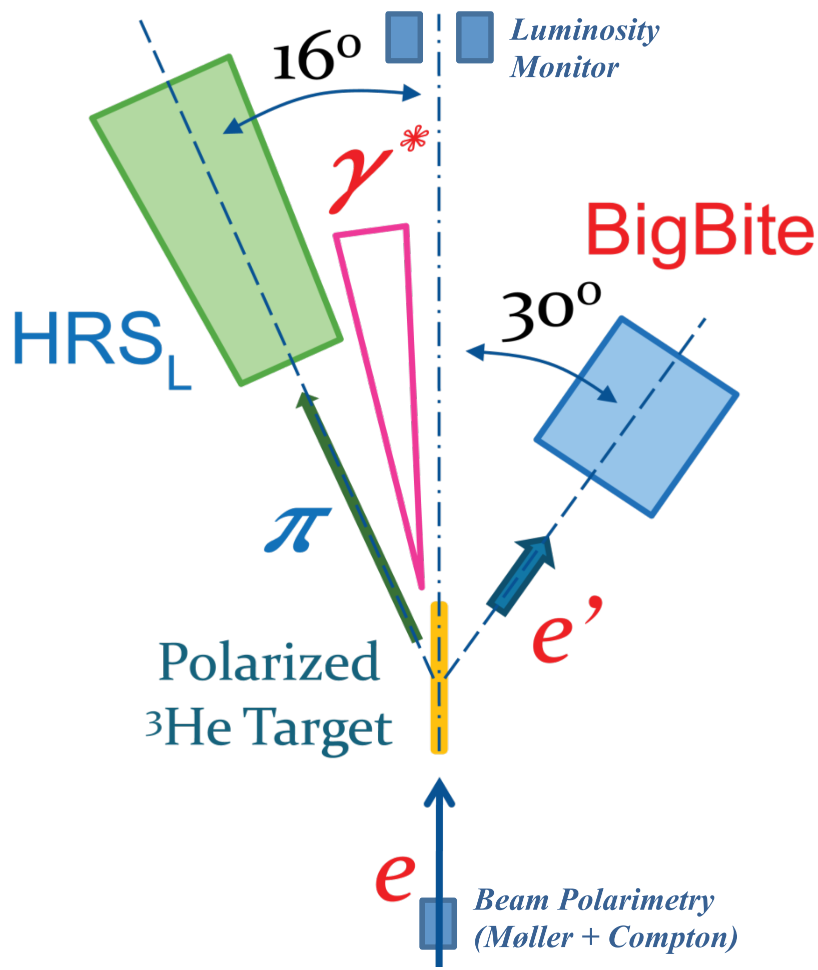
$$^3He^{\uparrow}(\vec{e}, e'\pi^{\pm})X$$

$$^3He^{\uparrow}(\vec{e}, e'K^{\pm})X$$

- **First measurement on n (^{3}He)**
- Transversely Polarized ^{3}He Target
- Polarized Electron Beam, 5.9 GeV

- **Results published in 7 PRL/PRC papers:**

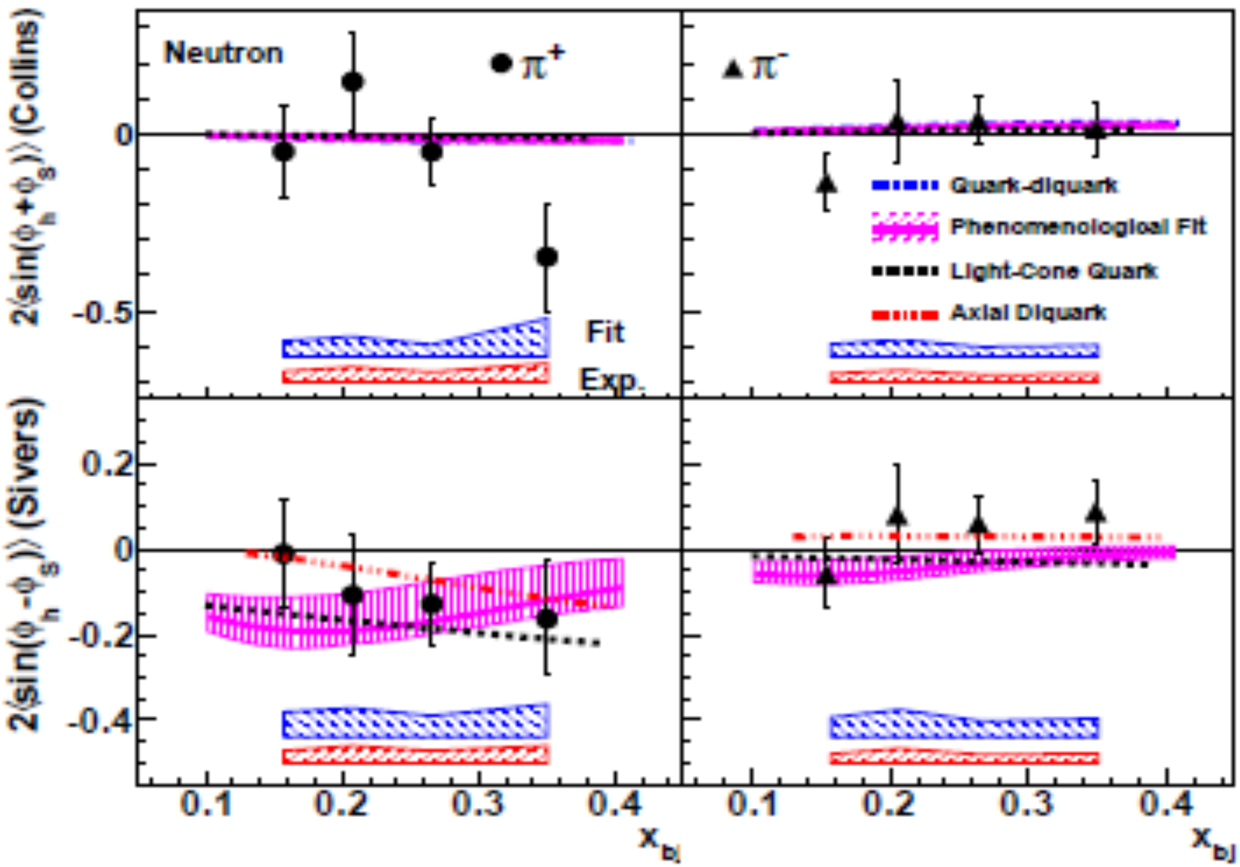
✓ π^{+-} Collins/Sivers asymmetries: PRL 107:072003(2011)
✓ π^{+-} worm-gear asymmetries: PRL 108, 052001 (2012)
✓ π^{+-} pretzelosity asymmetries: PRC 90 5, 055209(2014)
✓ K^{+-} Collins/Sivers asymmetries:PRC 90 5, 05520 (2014)
✓ Inclusive hadron SSA: PRC 89, 042201 (2014)
✓ Inclusive electron SSA: PRL 113, 022502 (2014)
✓ Inclusive hadron DSA: PRC 92, 015207 (2015)



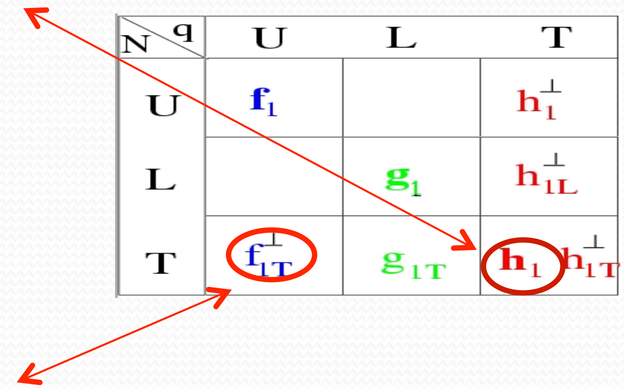
^{3}He (n) Target Single-Spin Asymmetry in SIDIS

E06-010 collaboration, X. Qian at al., **PRL 107:072003(2011)**

$$n^{\uparrow}(e,e'h), h = \pi^+, \pi^-$$



neutron Collins SSA small
Non-zero at highest x for π+

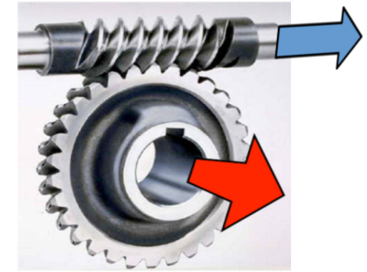


neutron Sivers SSA:
negative for π+,
Agree with Torino Fit

Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties

Asymmetry A_{LT} Result

J. Huang et al., **PRL. 108, 052001 (2012).**



Worm-Gear
Trans helicity

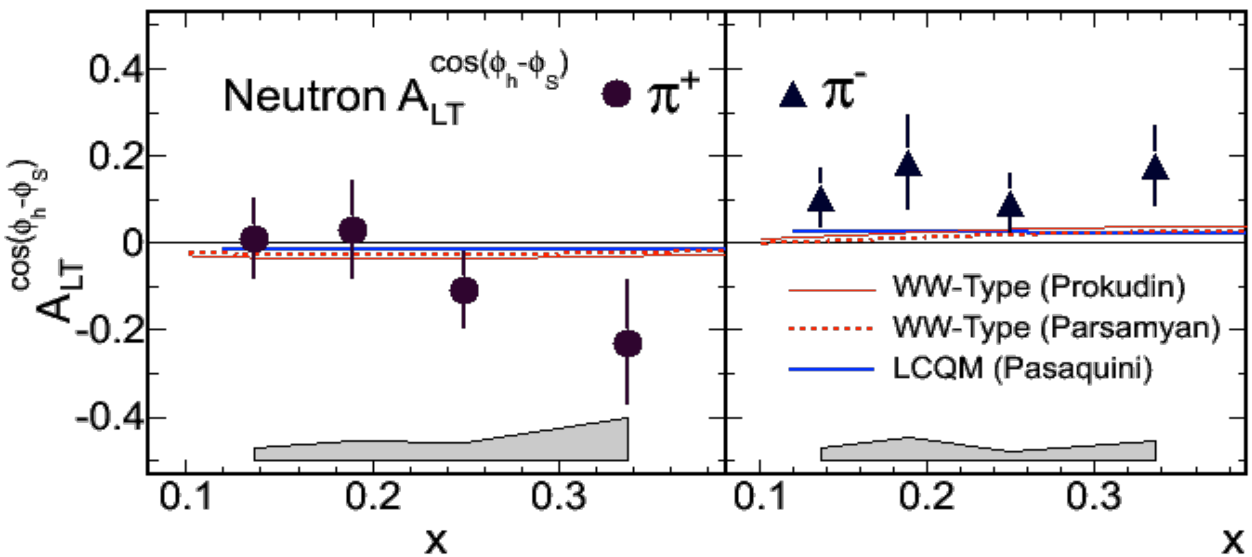
To leading twist:

$$A_{\mathrm{LT}}^{\cos(\phi_h-\phi_s)} \propto F_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

Dominated by L=0 (S) and L=1 (P) interference

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 $h_{1T}^{\perp}$

- **neutron A_{LT} : Positive for π-**
- **Consist w/ model in signs, suggest larger asymmetry**



Status of Transversity/TMD Study

- Large single spin asymmetry in *pp->πX (*Fermi, RHIC-spin)

- Collins Asymmetries

  - sizable for the *proton* (HERMES and COMPASS)

    large at high *x*, π^- and $\pi+$ has opposite sign

    unfavored Collins fragmentation as large as favored (opposite sign)?

  - consistent with 0 for the *deuteron* (COMPASS)

- Sivers Asymmetries

  - non-zero for π^+ from *proton*, HERMES and COMPASS data, Q^2 dependence
  - large for *K^+* ?

- Collins fragmentation functions from Belle/BaBar
- Global Fits/models
- Very active theoretical and experimental efforts

  JLab , RHIC-spin, COMPASS, Belle/BaBar, J-PARC, EIC, …

- First neutron measurement from Hall A 6 GeV (E06-010)
- SoLID with polarized n and p at JLab 12 GeV

  Unprecedented precision with high luminosity and large acceptance

Planned TMD Studies with JLab 12/SoLID

Transverse Spin (Transversity) and Tensor Charge TMDs

Precision Study of TMDs: JLab 12 GeV, EIC

- Explorations: HERMES, COMPASS, RHIC-spin, JLab6,…
- From exploration to precision study

  JLab12: valence region; EIC: sea and gluons
- Transversity: fundamental *PDF*s, tensor charge
- *TMD*s: 3-d momentum structure of the nucleon

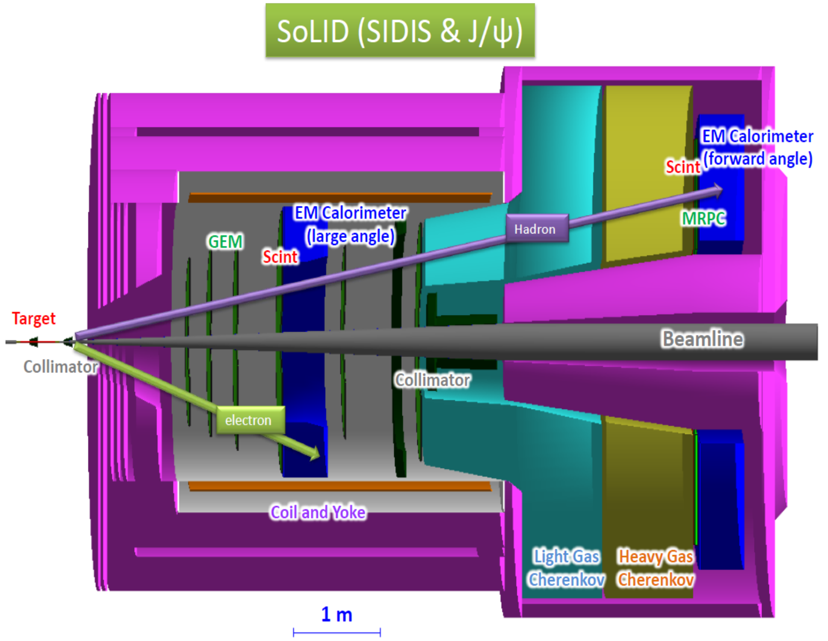
  → information on quark orbital angular momentum

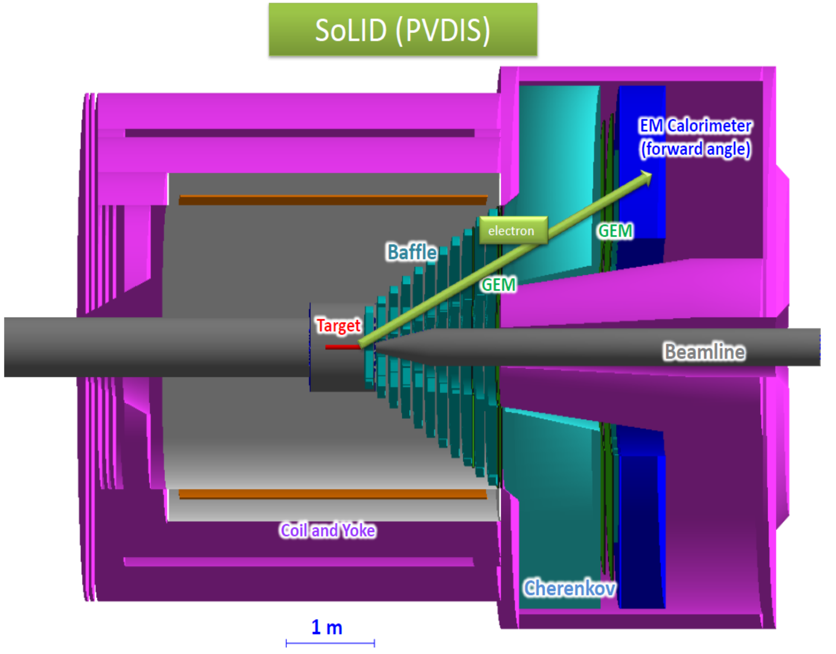
  → information on QCD dynamics
- Multi-dimensional mapping of *TMD*s
- Precision → high statistics
  - high luminosity and large acceptance

Overview of SoLID

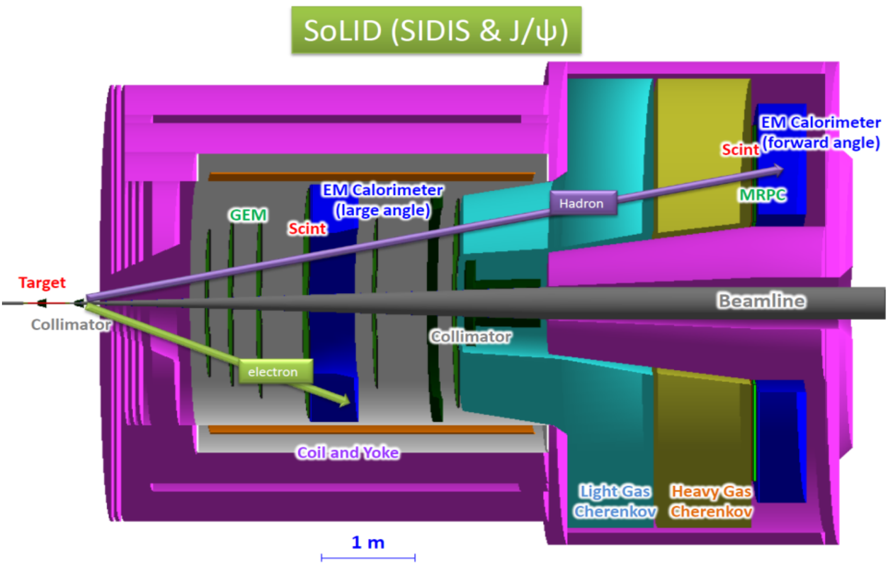
Solenoidal **L**arge **I**ntensity **D**evice

- **Full exploitation of JLab 12 GeV Upgrade**
  → A **Large Acceptance** Detector **AND** Can Handle **High Luminosity** (10^{37}-10^{39})
  Take advantage of latest development in detectors , data acquisitions and simulations
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-*x* region and threshold J/ψ
- **5 highly rated experiments approved**
  Three SIDIS experiments, one PVDIS, one J/ψ production (+ 3 run group experiments)
- **Strong collaboration** (250+ collaborators from 70+ institutes, 13 countries)
  Significant international contributions (Chinese collaboration)





SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV

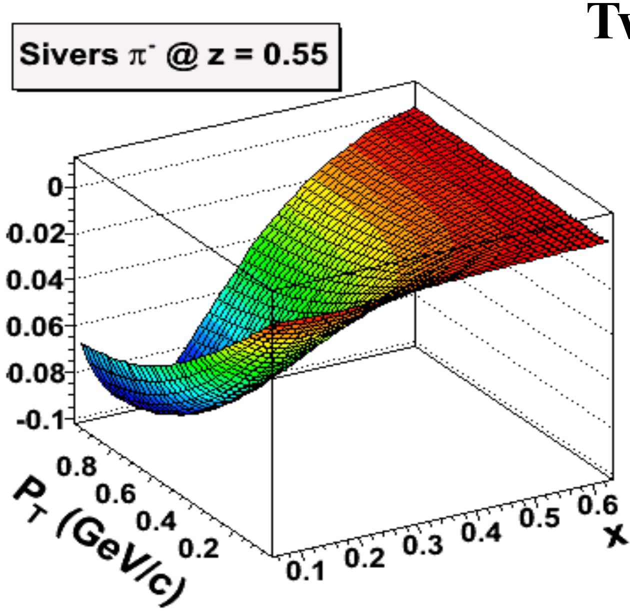


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

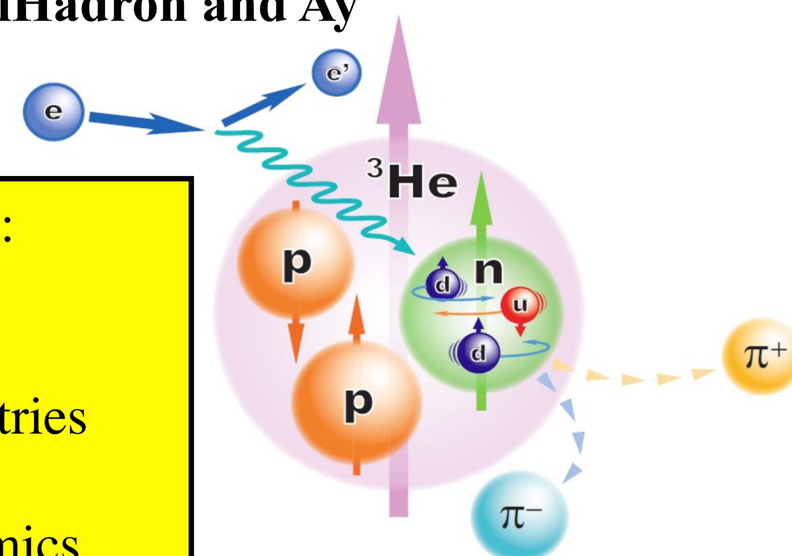
E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton, **rating A**

Two run group experiments DiHadron and Ay



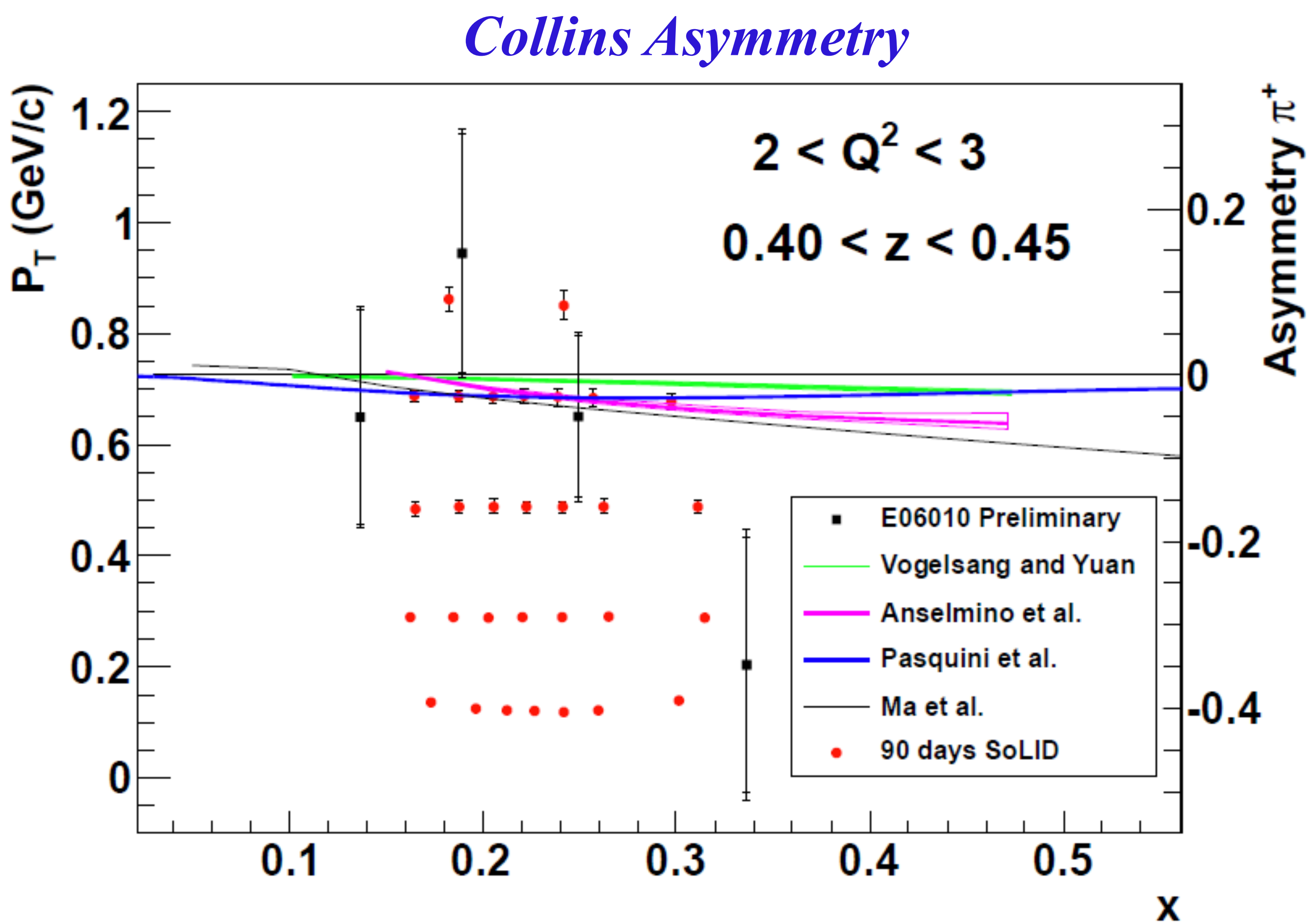
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.



E12-10-006/E12-11-108, Both Approved with "A" Rating

Mapping of Collins(Sivers) Asymmetries with SoLID

- Both π+ and π-
- Precision Map in region
  x(0.05-0.65)
  z(0.3-0.7)
  Q^2(1-8)
  P_T(0-1.6)
- <10% d quark tensor charge



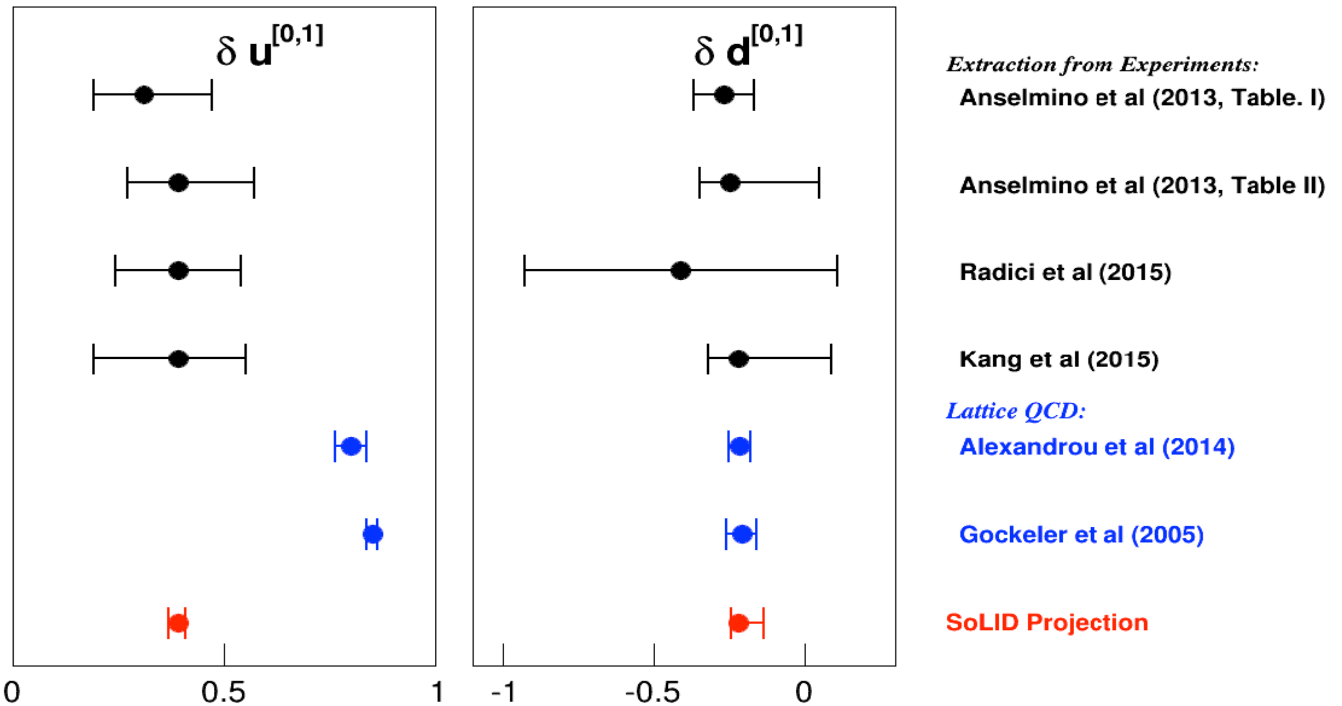
Tensor Charge

Definition

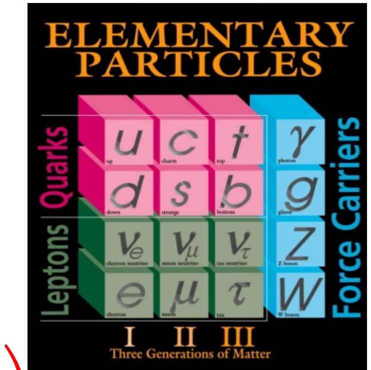
$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = \delta_T q\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S) \quad \delta_T q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x)\right] \mathrm{d}x$$

A fundamental QCD quantity. Matrix element of local operators.
Moment of transversity distribution. Valence quark dominant.
Calculable in lattice QCD.

SoLID impact



CP violation in the Standard Model



- Flavor changing weak current

Cabibbo-Kobayashi-Maskawa (CKM) Matrix

$$J^{\mu} = \begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix} \frac{\gamma_{\mu}(1-\gamma^{5})}{2} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Mass eigenstates

- 3 mixing angles and 1 complex phase δ_{CKM}
  - $\delta_{CKM} \neq 0$, CP violation

- **The θ term in QCD lagrangian**

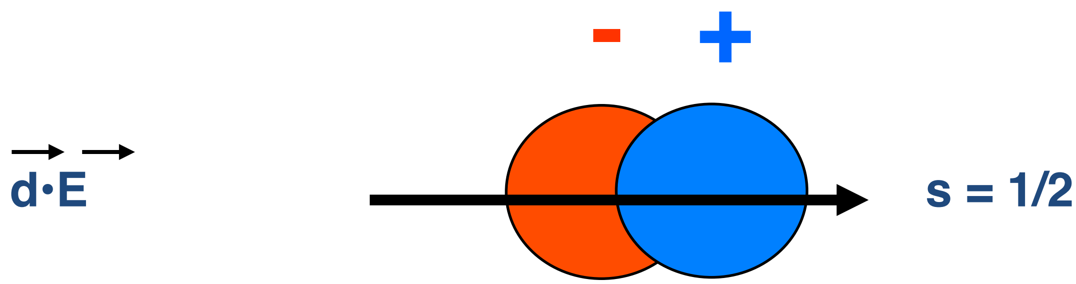
$$L_{QCD} = -\frac{1}{4} G^{\alpha}_{\mu\nu} G^{\alpha\mu\nu} - \sum_{n} \bar{\psi}_{n} [i\gamma^{\mu}\partial_{\mu} + g\gamma^{\mu} G^{\alpha}_{\mu} T^{\alpha} + m_{n}] \psi_{n} + \theta \frac{g^{2}}{32\pi^{2}} G^{\alpha\mu\nu} \tilde{G}^{\alpha}_{\mu\nu}$$

- If $\theta \neq 0$, $G^{\alpha\mu\nu}\tilde{G}^{\alpha}_{\mu\nu}$ violates P & T

$$\tilde{G}^{\alpha}_{\mu\nu} \equiv \frac{1}{2} \varepsilon_{\mu\nu\rho\sigma} G^{\alpha\rho\sigma}$$

Neutron Electric Dipole Moment (EDM)

Current limit (10^{-26} θ) e.cm , next generation of experiments aim at (10^{-28} θ) e.cm



- If neutron possesses EDM, in an electric field, Hamiltonian $H = -d_n \vec{\sigma} \bullet \vec{E}$
  - – changes sign under T (P) symmetry operation
- d_n is more sensitive to θ than to δ_{CKM}
- Neutron EDM ~ O(10^{-16} θ) e.cm (various model predictions)

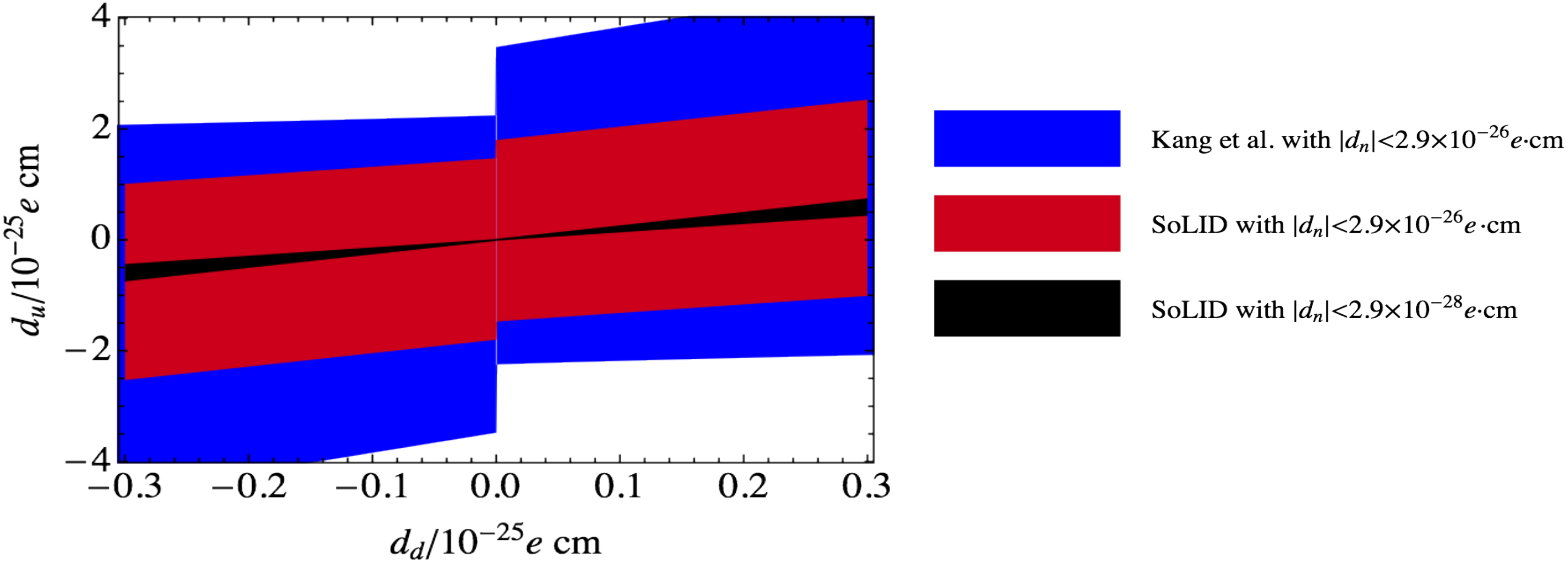
Quark EDM appears only at the three-loop level

Tensor Charge and Neutron EDM

Electric Dipole Moment

Tensor charge and EDM

$$d_n = \delta_T u \, d_u + \delta_T d \, d_d + \delta_T s \, d_s$$



current neutron EDM limit $|d_n| < 2.9 \times 10^{-26} \, e \cdot \text{cm}$

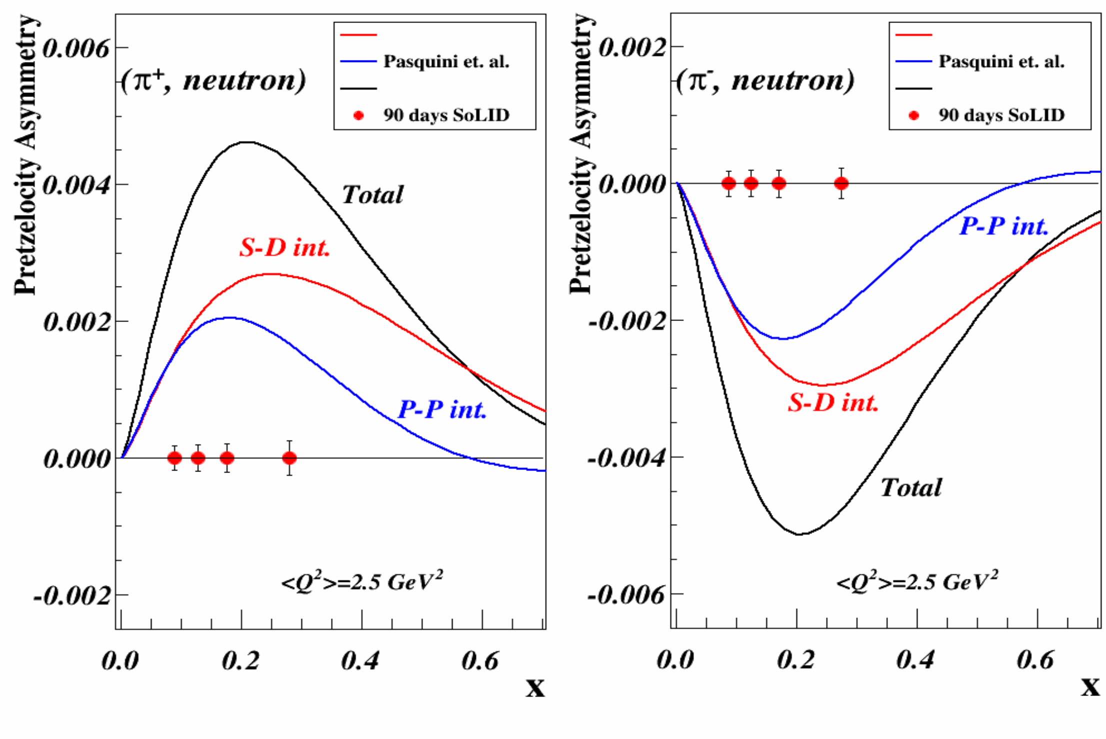
TMDs and Orbital Angular Momentum

Pretzelosity ($\Delta L=2$), Worm-Gear ($\Delta L=1$),

Sivers: Related to GPD E through Lensing Function

TMDs: Access Quark Orbital Angular Momentum

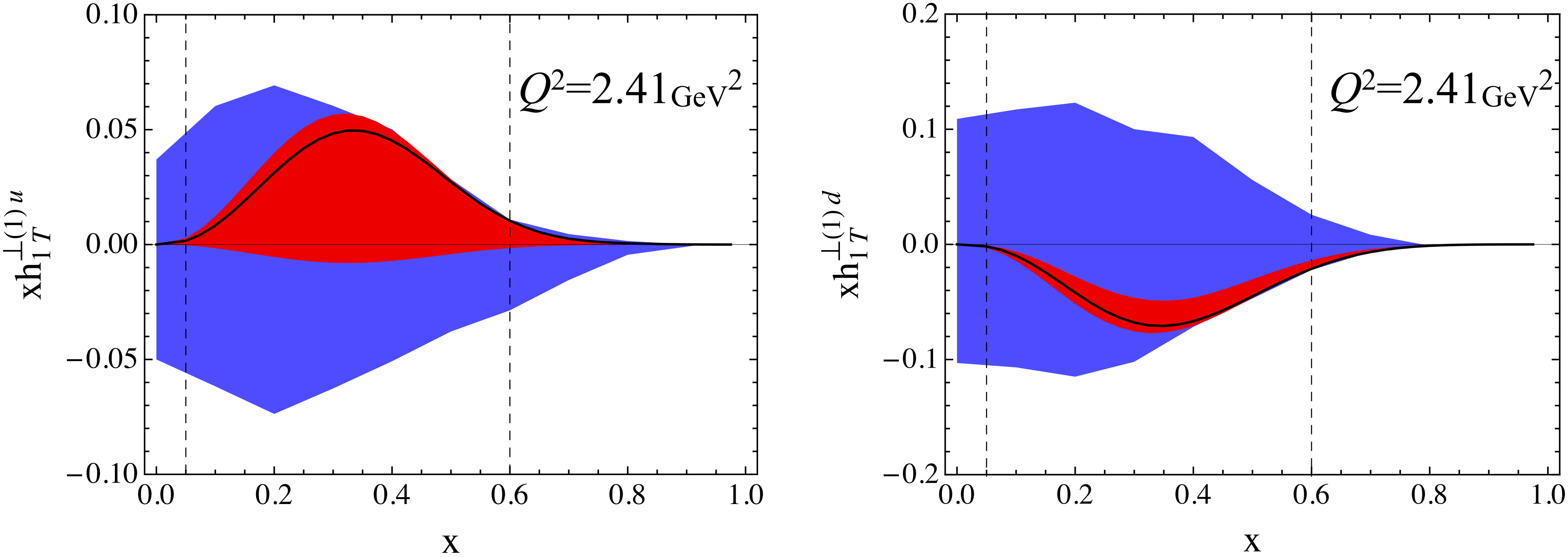
- TMDs : Correlations of transverse motion with quark spin and orbital motion
- **Without OAM, off-diagonal TMDs=0**,
  no direct model-independent relation to the OAM in spin sum rule yet
- Sivers Function: QCD lensing effects
- In a large class of models, such as light-cone quark models
  Pretzelosity: ΔL=2 (L=0 and L=2 interference , L=1 and -1 interference)
  Worm-Gear: ΔL=1 (L=0 and L=1 interference)
- **SoLID with trans polarized n/p → quantitative knowledge of OAM**



SoLID Projections 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 $h_{1T}^{\perp}$

SoLID Impact on Pretzelosity



C. Lefky *et al.*, PR D 91, 034010 (2015).

SoLID transversely polarized ^{3}He, E12-10-006.

95% C.L.

by Tianbo Liu (Duke & DKU)

Duke UNIVERSITY

昆山杜克大学 DUKE KUNSHAN UNIVERSITY

Angular Momentum (1)

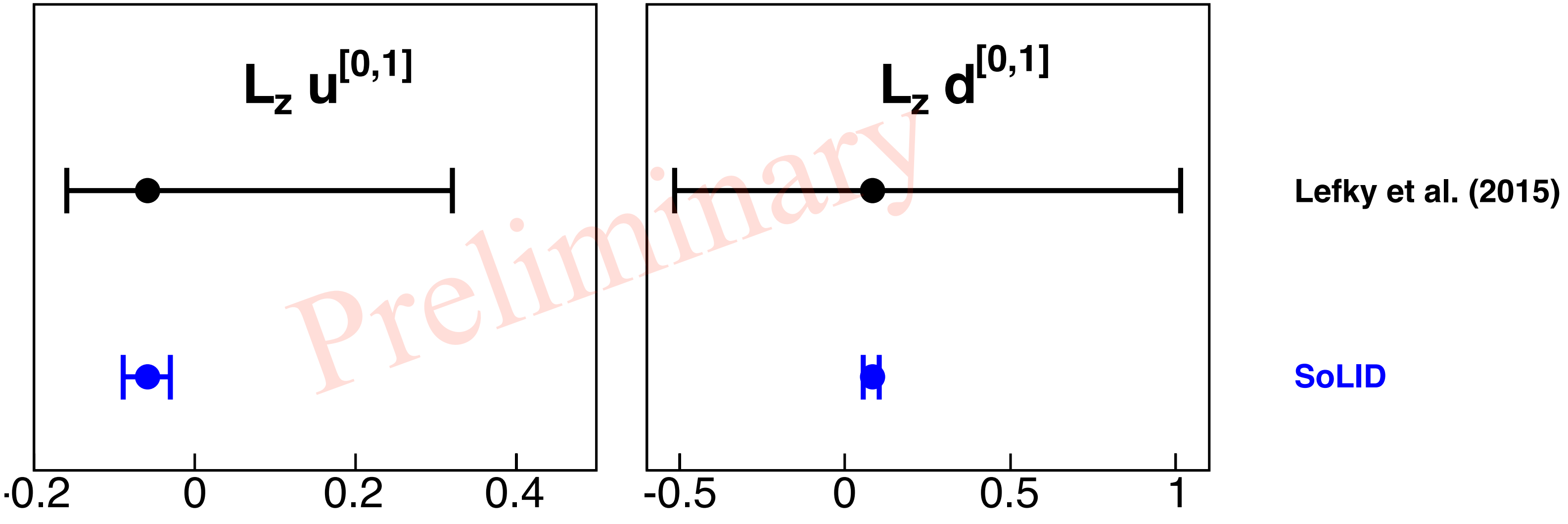
OAM and pretzelosity:

model dependent

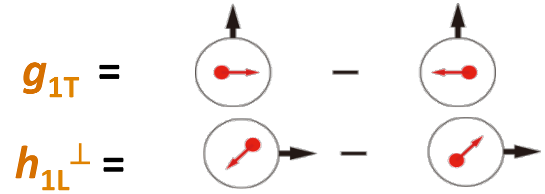
$$L_z = -\int d\,x\,d^2\,k_\perp\,\frac{k_\perp{}^2}{2\,M_p^2}\,h_{1T}^\perp\left(x, k_\perp{}^2\right)$$

J. She *et al.*, PR D 79, 058008 (2009).

SoLID impact:

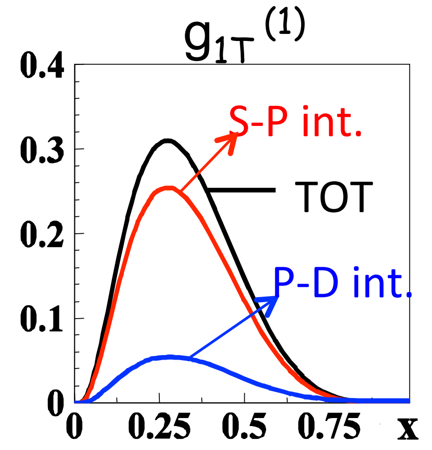


Worm-gear Functions



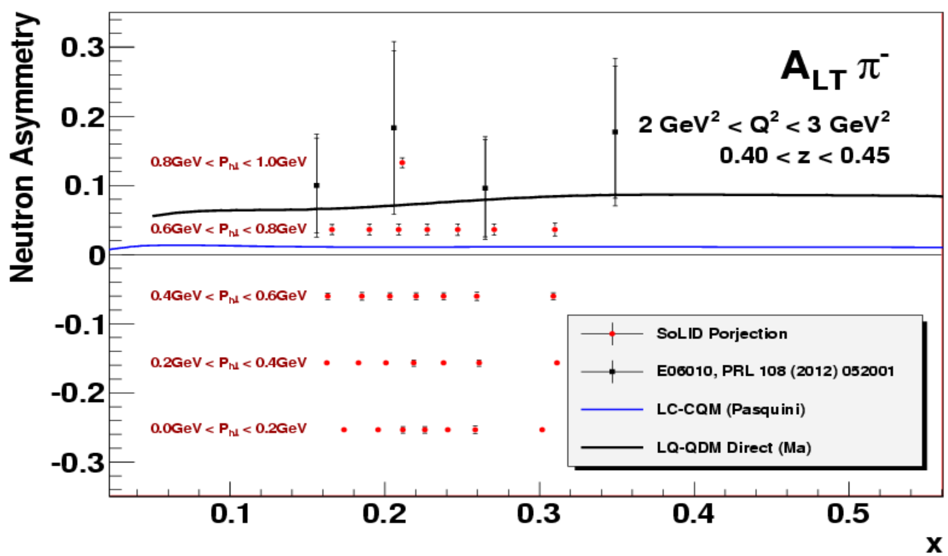
- Dominated by real part of interference between **L=0 (S) and L=1 (P) states**
- No GPD correspondence
- Exploratory lattice QCD calculation:
  Ph. Hägler et al, EPL 88, 61001 (2009)

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 $h_{1T}^{\perp}$

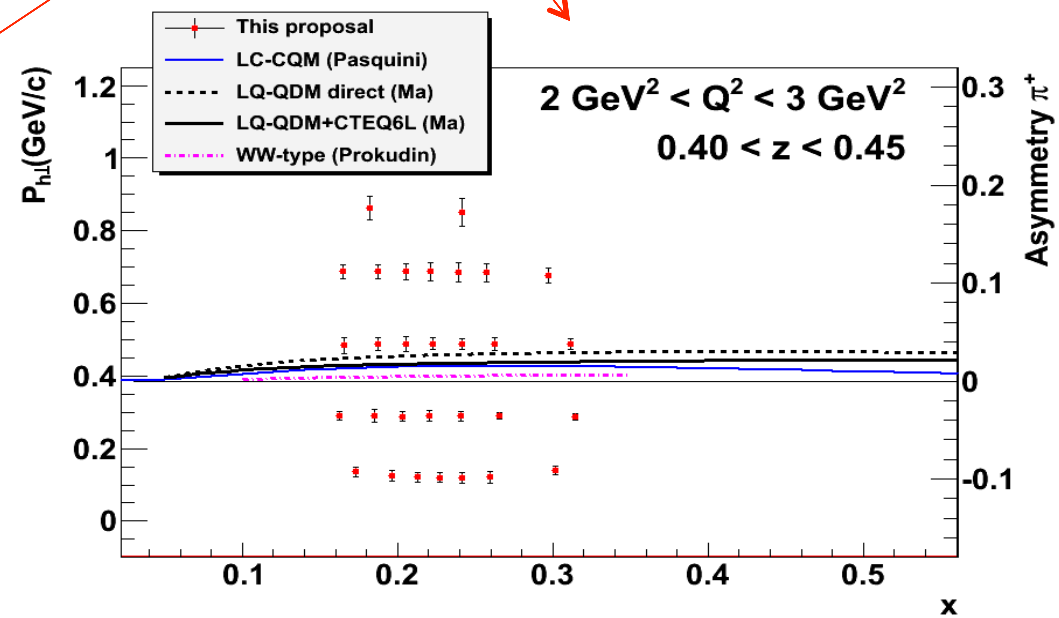


Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

Neutron Projections,



$$A_{LT} \sim g_{1T}(x) D_1(z)$$



$$A_{UL} \sim h_{1L}^{\perp}(x) \otimes H^{\perp}{}_1(z)$$

Angular Momentum (2)

Sivers and GPD E:

model dependent

$$f_{1T}^{\perp(0)}(x, Q_0^2) = -L(\mathrm{x})\, E\left(x, 0, 0, Q_0^2\right)$$

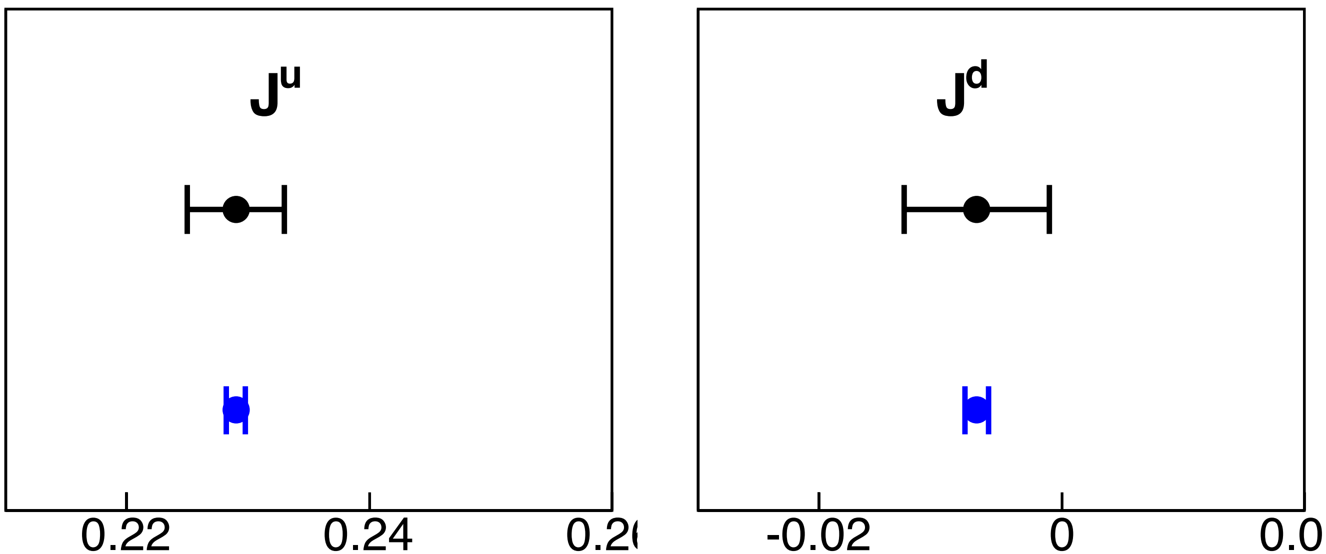
$$L(\mathrm{x}) = \frac{\mathrm{K}}{(1-x)^{\eta}}$$ lensing function

A. Bacchetta *et al.*, PR L 107, 212001 (2011).

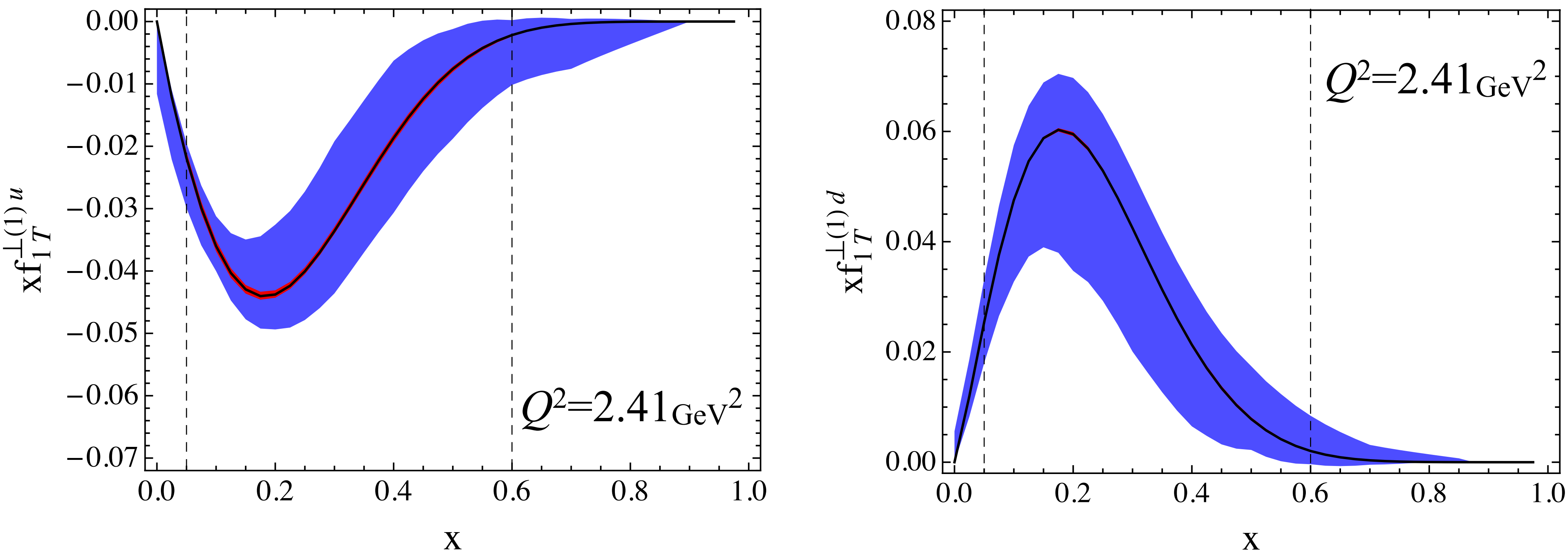
K and η are fixed by anomalous magnetic moments κ^p and κ^n.

$$J = \frac{1}{2}\int dx\, x\,[\, H(x,0,0) + E(x,0,0)\,]$$

SoLID:



SoLID Impact on Sivers

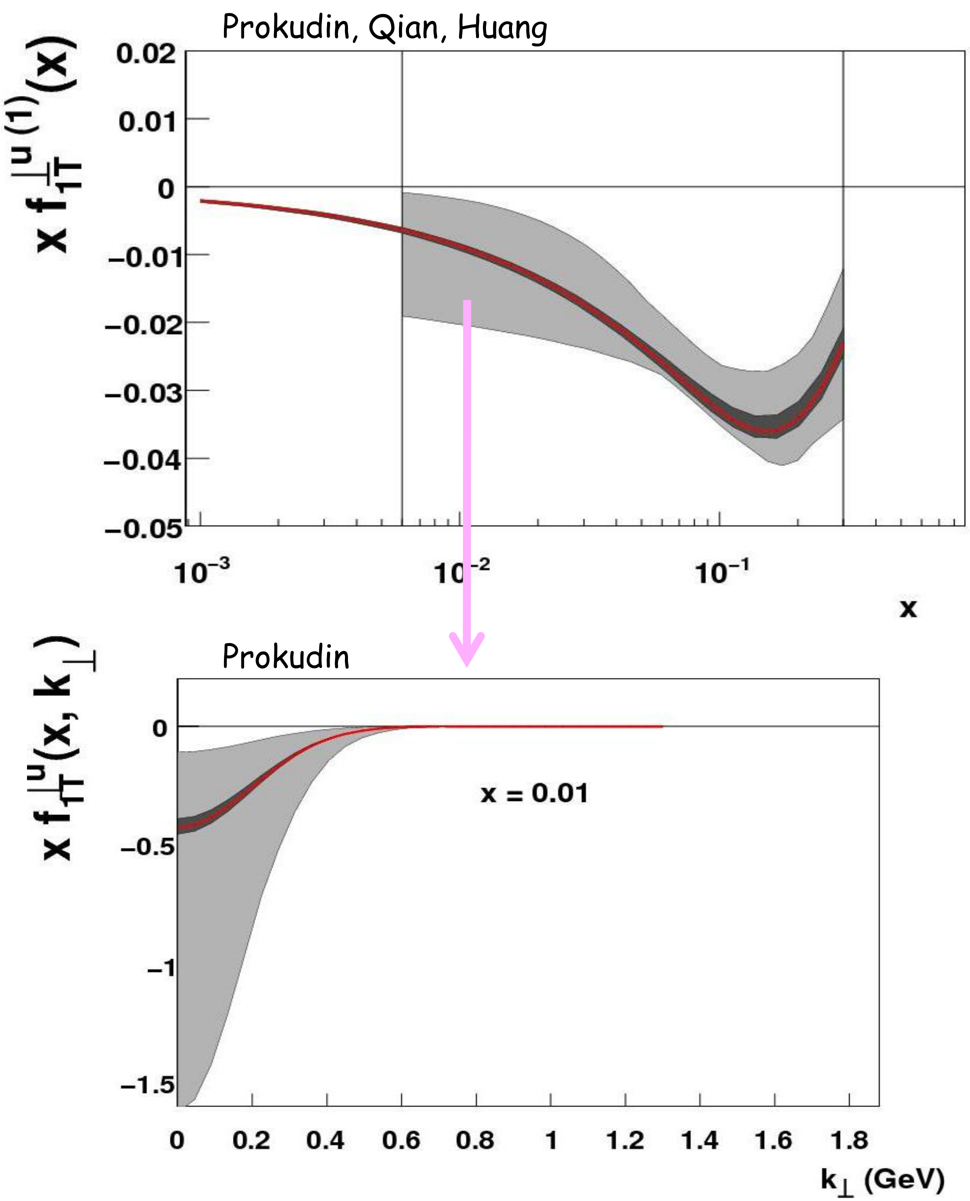


M. Anselmino *et al.,* EPJ A39, 89 (2009).

SoLID transversely polarized ^{3}He, E12-10-006.
(sea quark contribution fixed)

95% C.L.

Image the Transverse Momentum of the Quarks



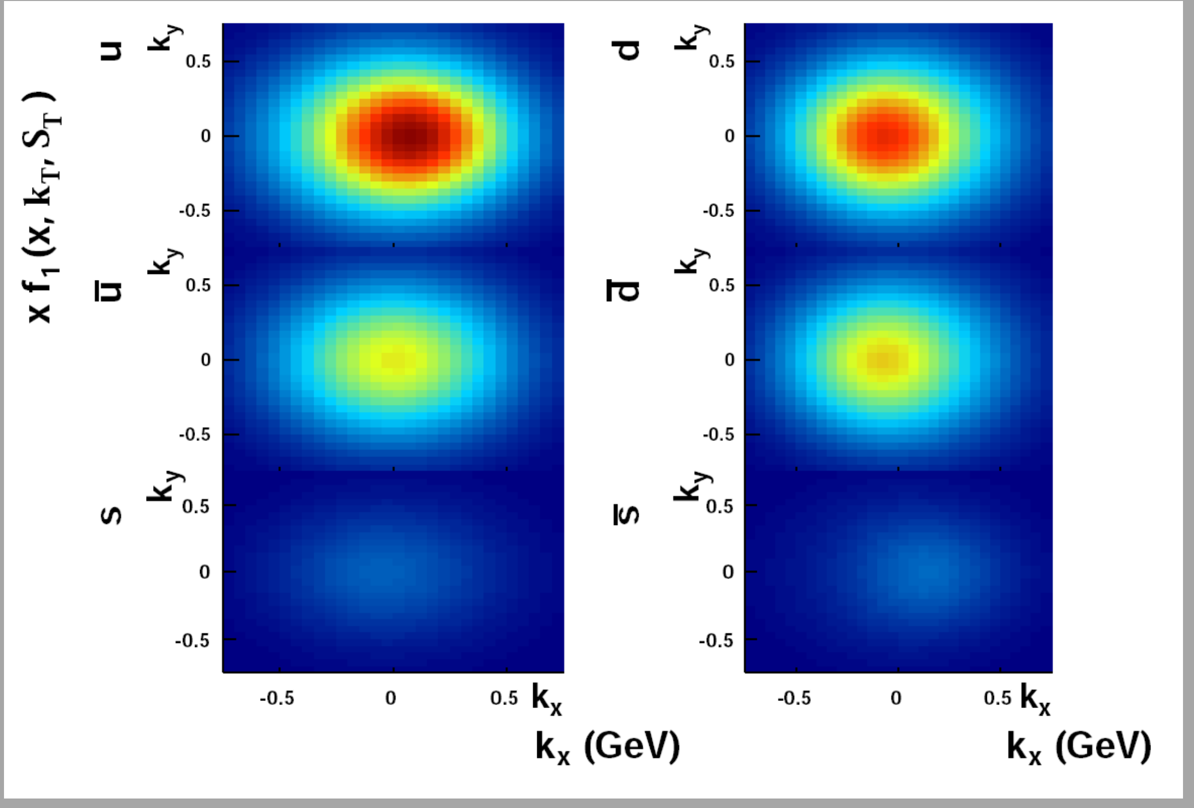
Only a small subset of the (x,Q^2) landscape has been mapped here.

An EIC with good luminosity & high transverse polarization is the optimal tool to to study this!

Exact k_T distribution presently essentially unknown!

What do we learn from 3D distributions?

$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_{T1}}}{M}$$



The slice is at:

$x = 0.1$

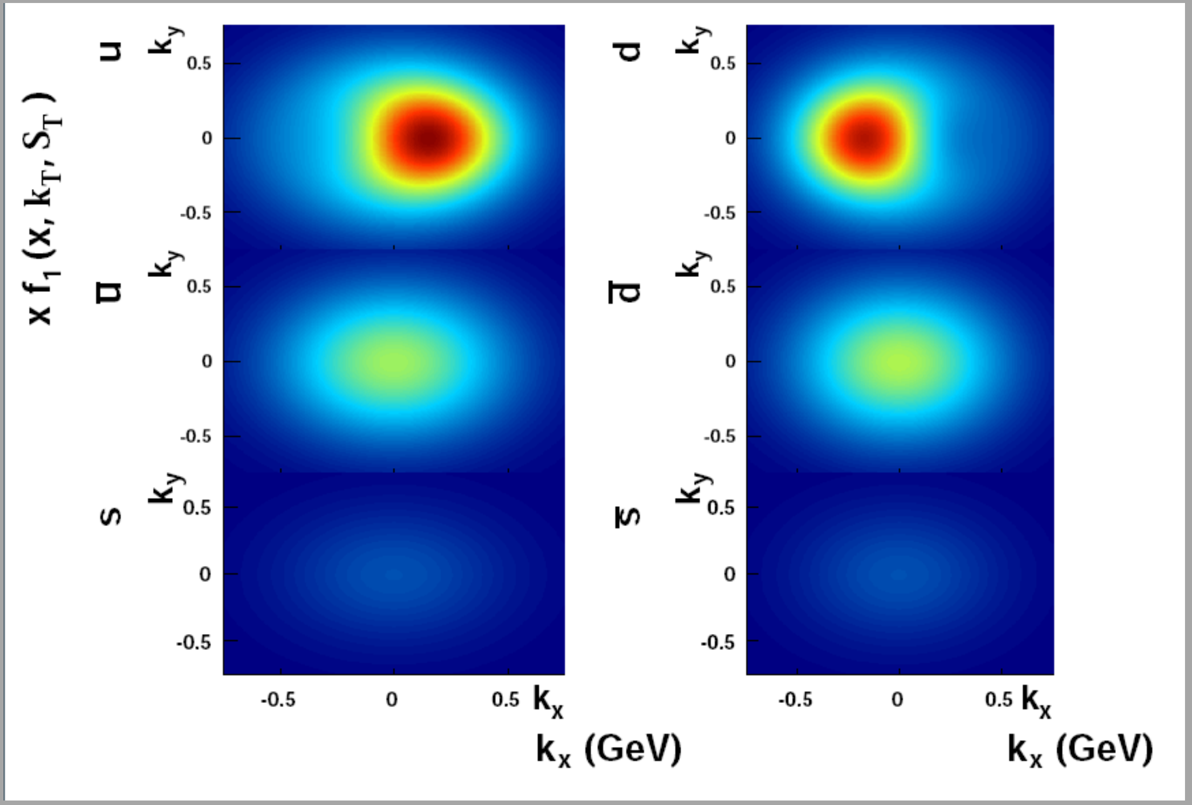
Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

No information on sea quarks

Picture is still quite uncertain

What do we learn from 3D distributions?

$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_{T1}}}{M}$$



The slice is at:

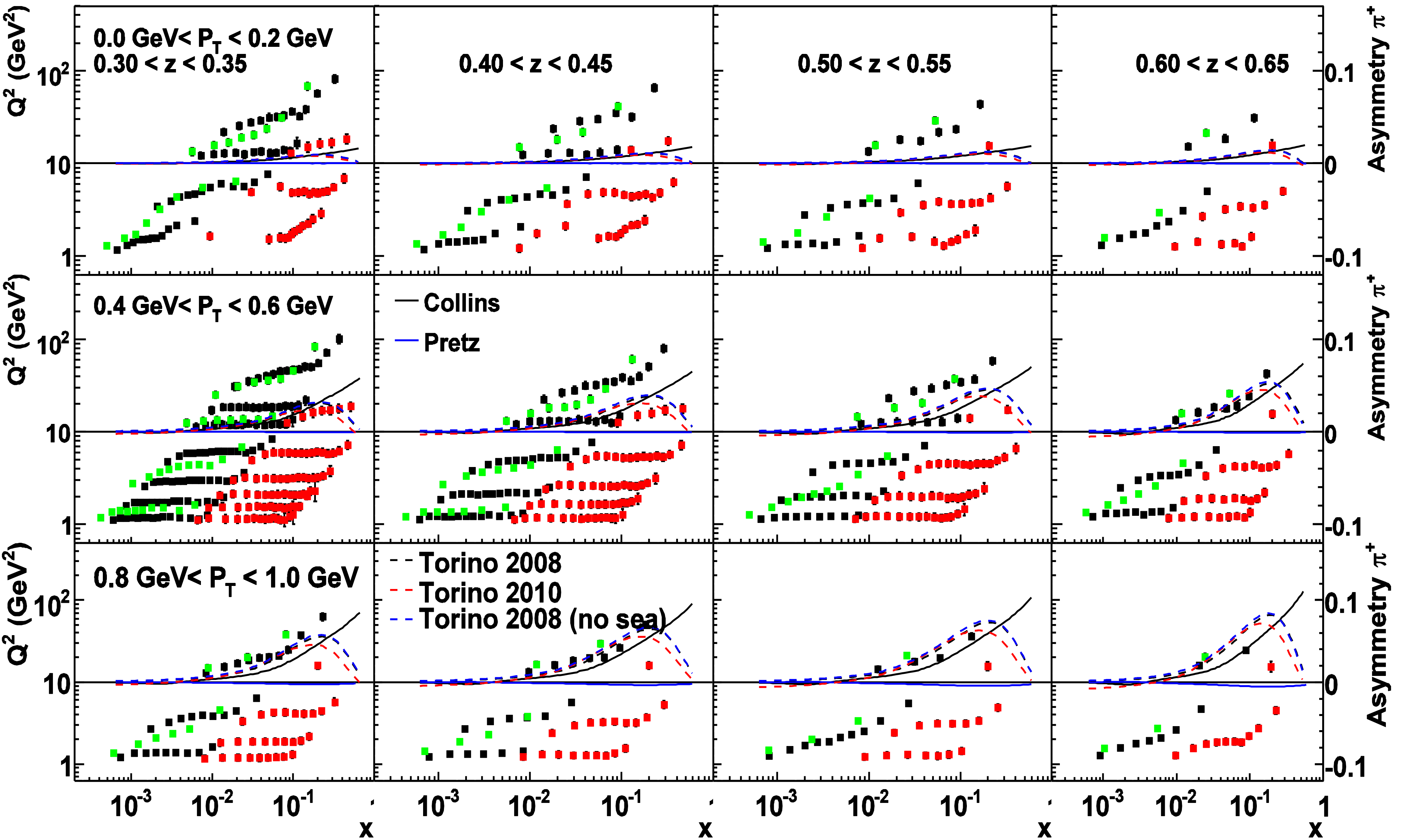
$$x = 0.1$$

Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

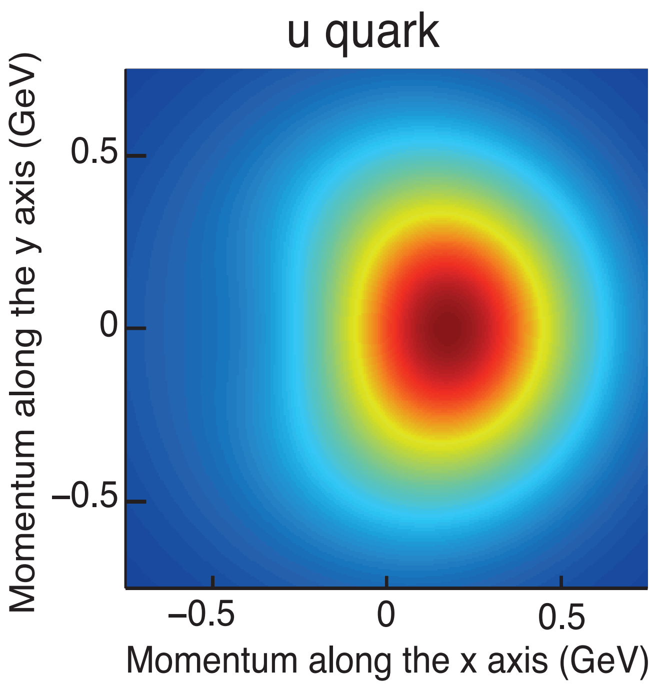
No information on sea quarks

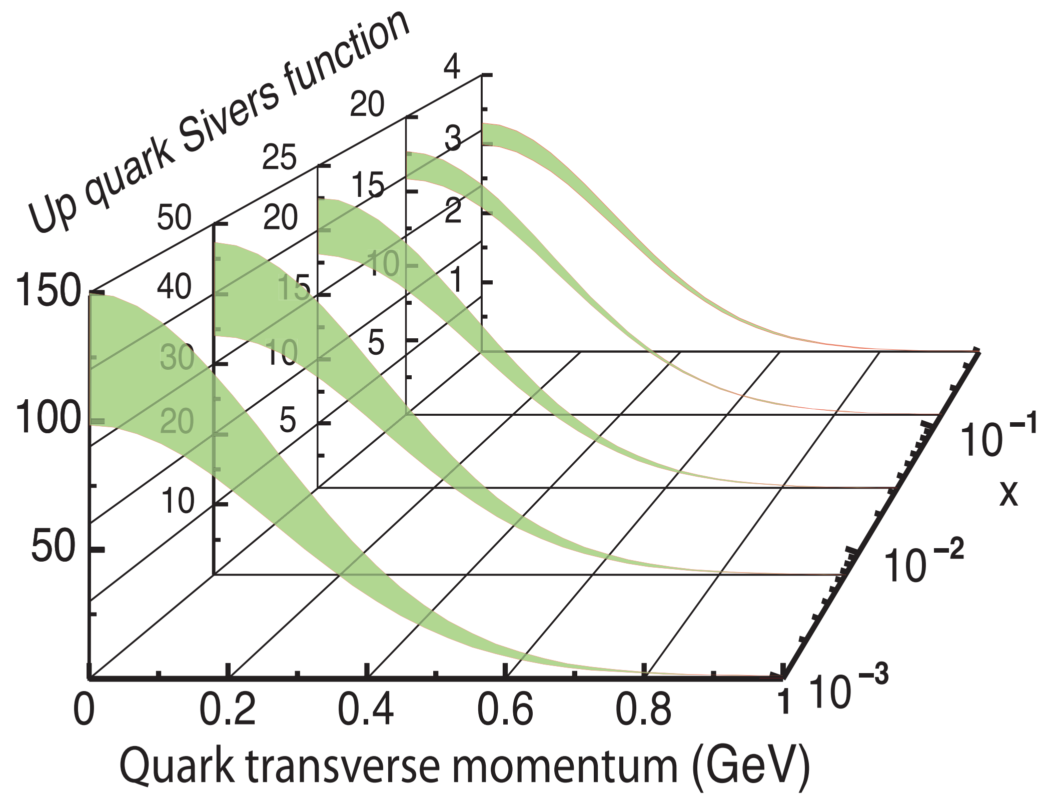
In future we will obtain much clearer picture

EIC (11x60) Projection: p(e,e’π⁺) (Sivers/Collins)

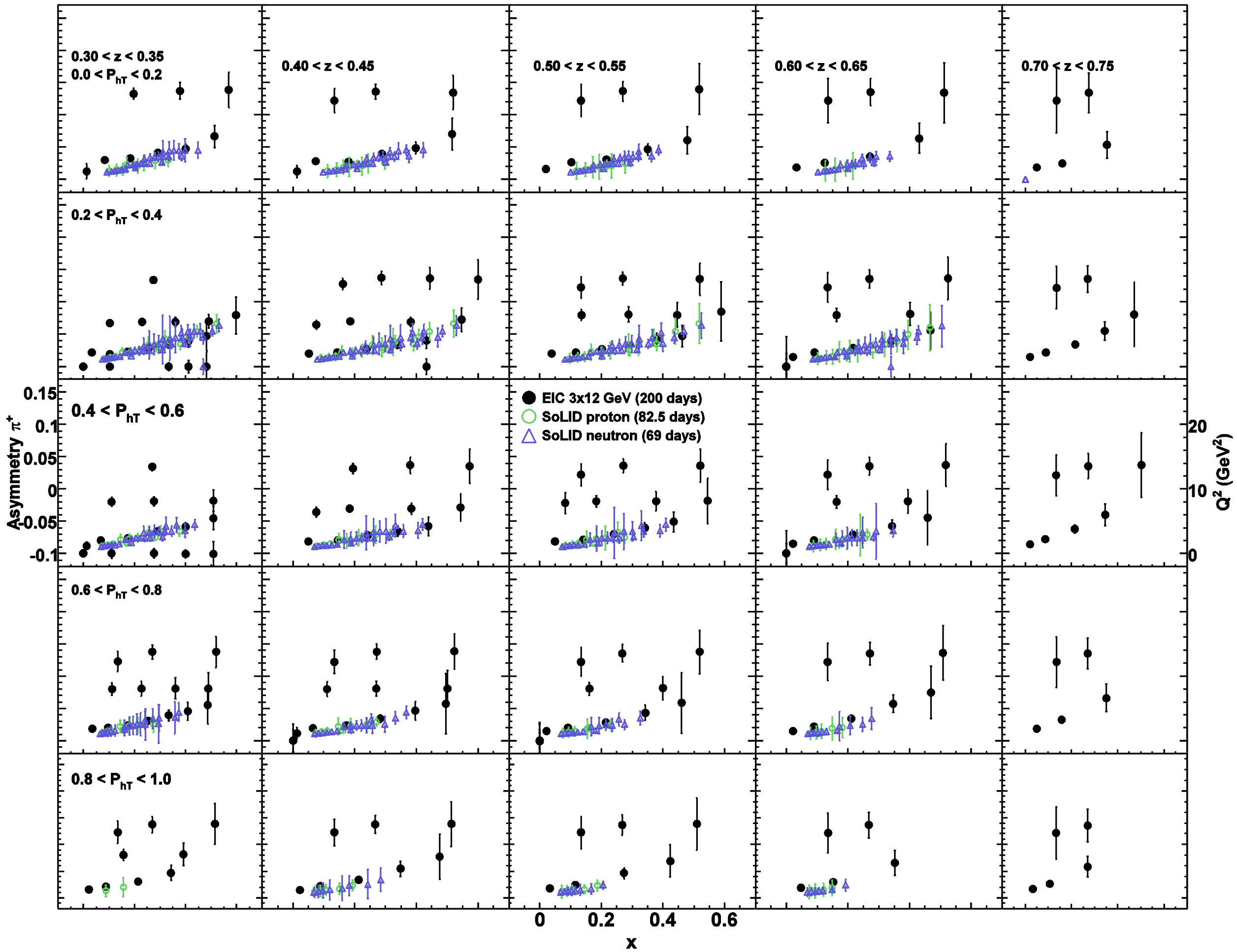


Imaging in 3-d momentum space





EIC@HIAF Projections for SIDIS Asymmetry π^+



EIC@HIAF reach high precision similar to SoLID at lower x, higher Q2 region

Green (Blue) Points: SoLID projections for polarized NH_3 ($^3He/n$) target
Luminosity: 10^{35} (10^{36}) ($1/cm^2/s$); Time: 120 (90) days

Black points: EIC@HIAF projections for 3 GeV e and 12 GeV p
Luminosity: 4 x 10^{32} $/cm^2/s$; Time: 200 days

Summary on TMD Program

- Exploratory results from 6 GeV neutron experiment
- **Unprecedented precision *multi-d* mapping of SSA in valence quark region with SoLID at 12 GeV JLab**
- Both polarized n (^{3}He) and polarized proton

  Three “A” rated experiments approved

  + two run-group experiments

- Combining with the world data (fragmentation functions)
  - extract transversity for both *u* and *d* quarks
  - determine tensor charges -> LQCD, EDMs
  - learn quark orbital motion and QCD dynamics
  - 3-d imaging
- Global efforts (experimentalists and theorists), global analysis
  - much better understanding of 3-d nucleon structure and QCD
- **Long-term future: EIC to map sea and gluon SSAs**

Summary

- Nucleon Structure Study: Discoveries and Surprises

  Understand strong interaction/nucleon structure: remains a challenge

- Highlights

  Precision EM form factors, proton radius

  Nucleon spin-flavor structure (unpolarized and polarizd, valence, sea)

  3-d Structure: GPDs

  3-d Structure: TMDs, SoLID program

- EIC opens up a new window to study/understand nucleon structure, especially the sea quarks and gluons

  Exciting new opportunities → lead to breakthroughs?