Nucleon 3-D Structure

II: Nucleon Structure Study: From 1-D to 3-D

- Electron Scattering
- Elastic Scattering: From Factors
    - Surprise: G_E^p @ high Q^2 : proton shape, 2-γ exchange
    - Proton radius puzzle
- Deep-Inelastic Scattering (DIS):
    - Unpolarized Structure Functions -> Parton Distribution Functions
    - Polarized Structure Functions -> Spin Distributions
        - "Spin Crisis/Puzzle", Spin Decompositions
    - Orbital Angular Momentum → Transverse Structure
- Needs to Study 3-D Structure

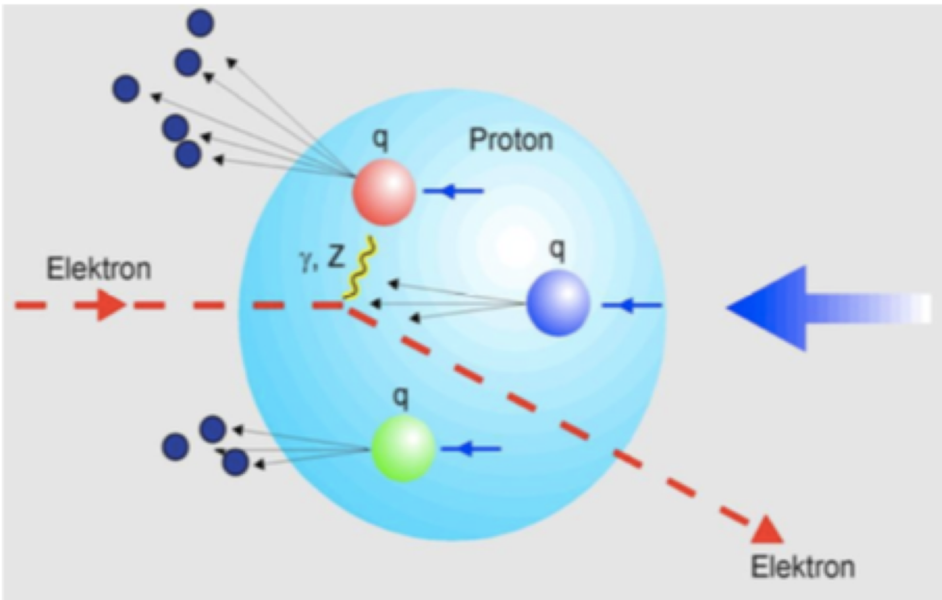
Deep-Inelastic Scattering
Unpolarized Structure Functions

Parton Distribution Functions

How to "see" substructure of a nucleon?

❑ Modern Rutherford experiment – Deep Inelastic Scattering:

SLAC 1968: $e(p) + h(P) \to e'(p') + X$



✧ **Localized probe:**

$$Q^2 = -(p - p')^2 \gg 1\ \text{fm}^{-2}$$

$$\Longrightarrow \quad \frac{1}{Q} \ll 1\ \text{fm}$$

✧ **Two variables:**

$$Q^2 = 4EE' \sin^2(\theta/2)$$

$$x_B = \frac{Q^2}{2m_N\nu}$$

$$\nu = E - E'$$

→ **Discovery of spin ½ quarks, and partonic structure!**

What holds the quarks together?

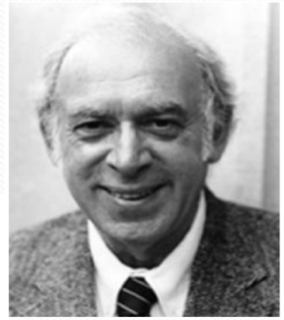
Nobel Prize, 1990

➡ **The birth of QCD (1973)**

– Quark Model + Yang-Mill gauge theory

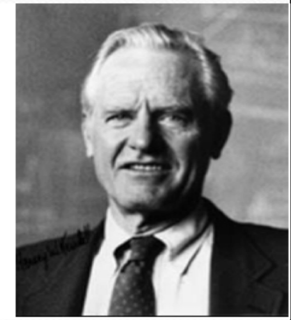
Deep-Inelastic Electron Scattering

Discovery of Quarks (Partons)



J.T. Friedman

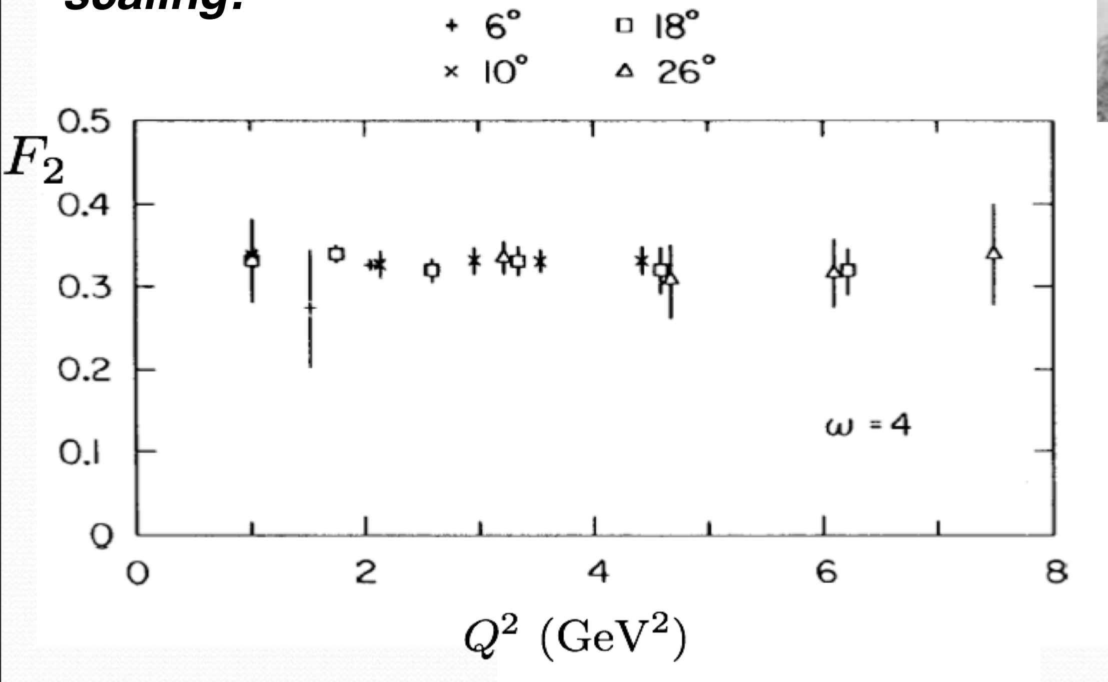
R. Taylor



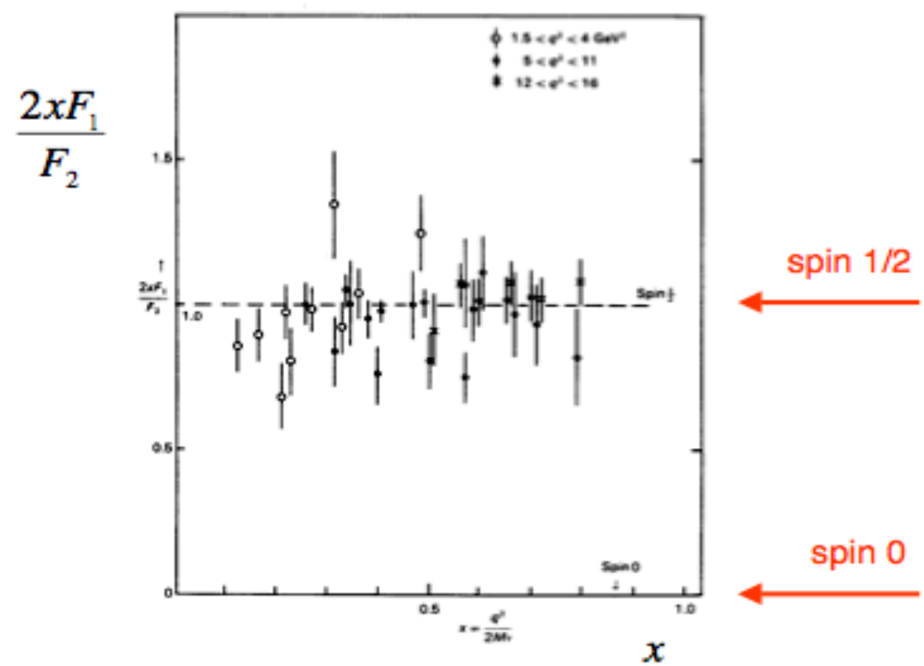
H.W. Kendall

Nobel Prize 1990

Bjorken scaling:



Callan-Gross relation:



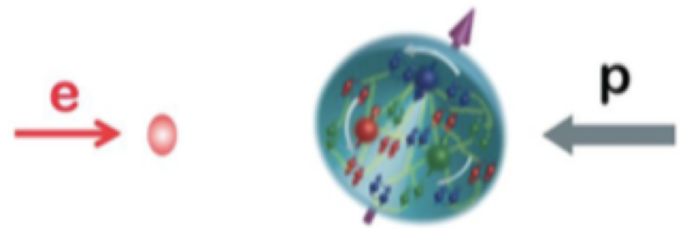
Point particles cannot be further resolved; their measurement does not depend on wavelength, hence Q^2,

Spin-1/2 quarks cannot absorb longitudinally polarized vector bosons and, conversely, spin-0 (scalar) quarks cannot absorb transversely polarized photons.

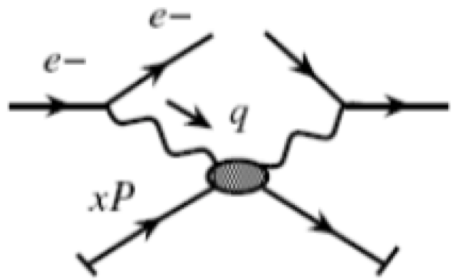
QCD factorization

- The key and a first principle method to relate experimental data to QCD theory

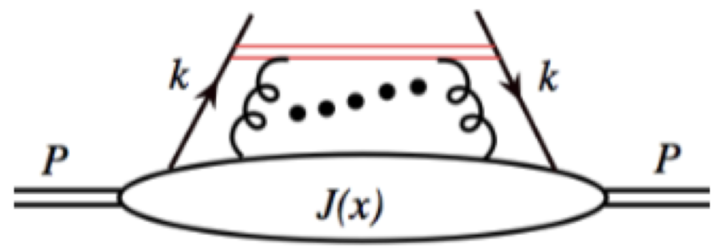
- Electron-hadron:



$\sigma_{\text{tot}}^{\text{DIS}} =$



$\otimes$

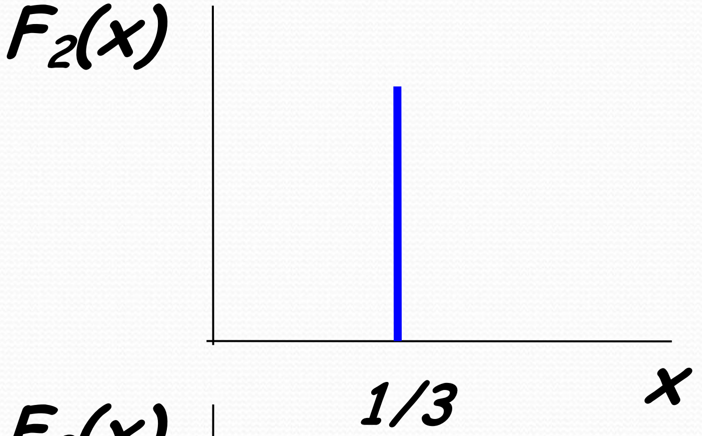


$+ O(\frac{1}{QR})$

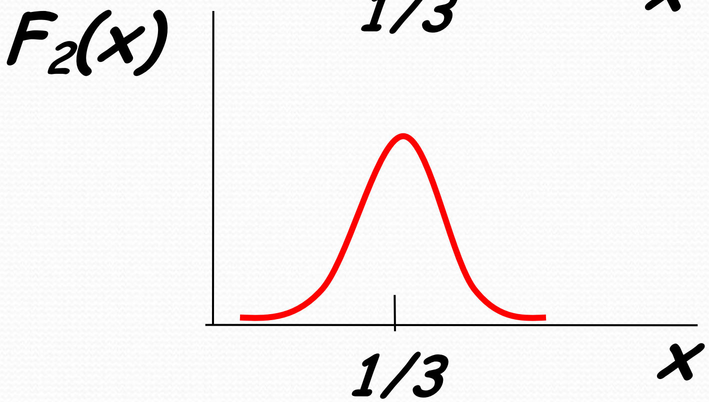
Hard-part Probe	Parton-distribution Structure	Correction Approximation

- PDFs: encoding most nonperturbative information in hadron collision

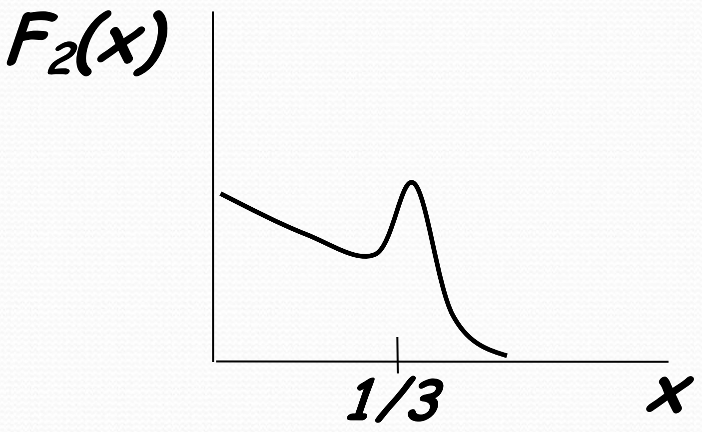
Nucleon Structure



Three quarks with 1/3 of total proton momentum each.



Three quarks with some momentum smearing.

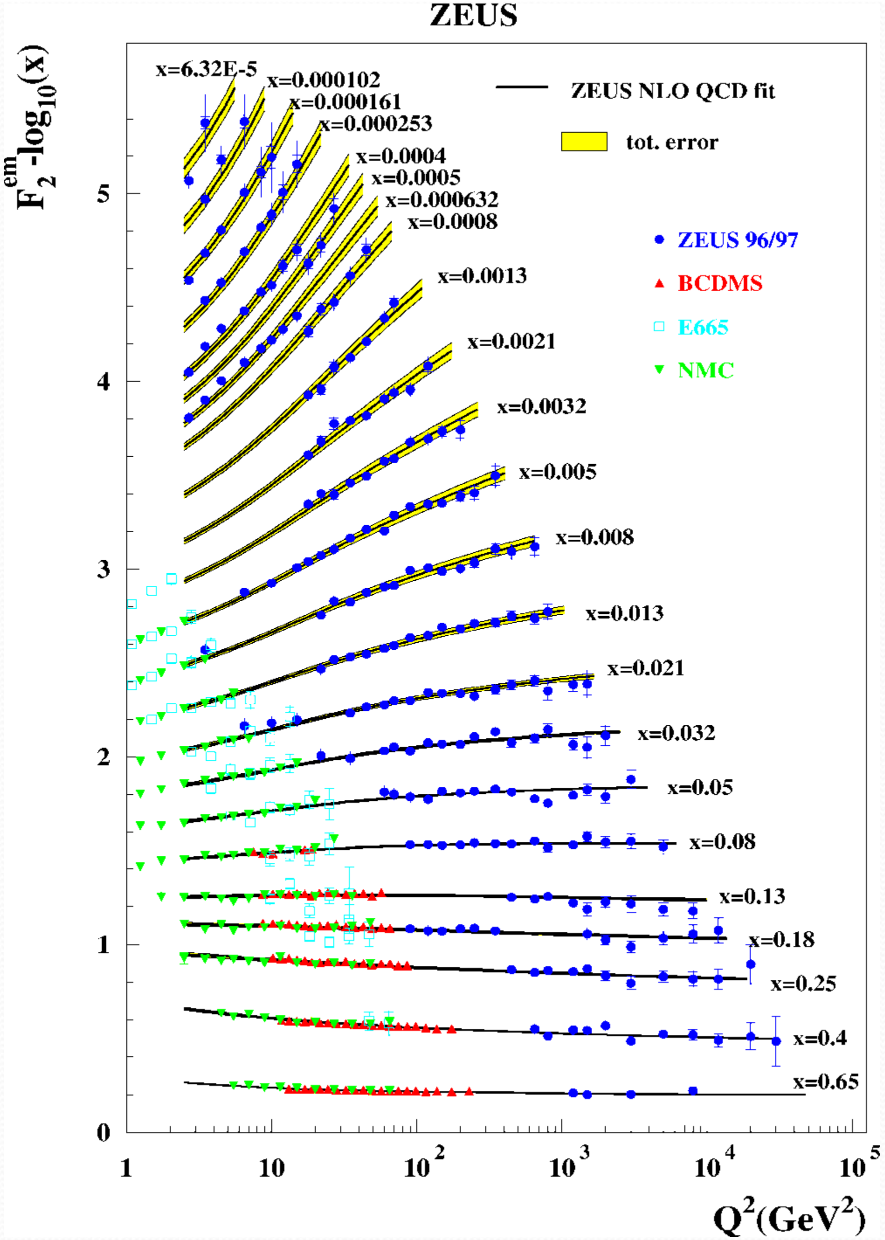


The three quarks radiate gluons to lower momentum fractions x.

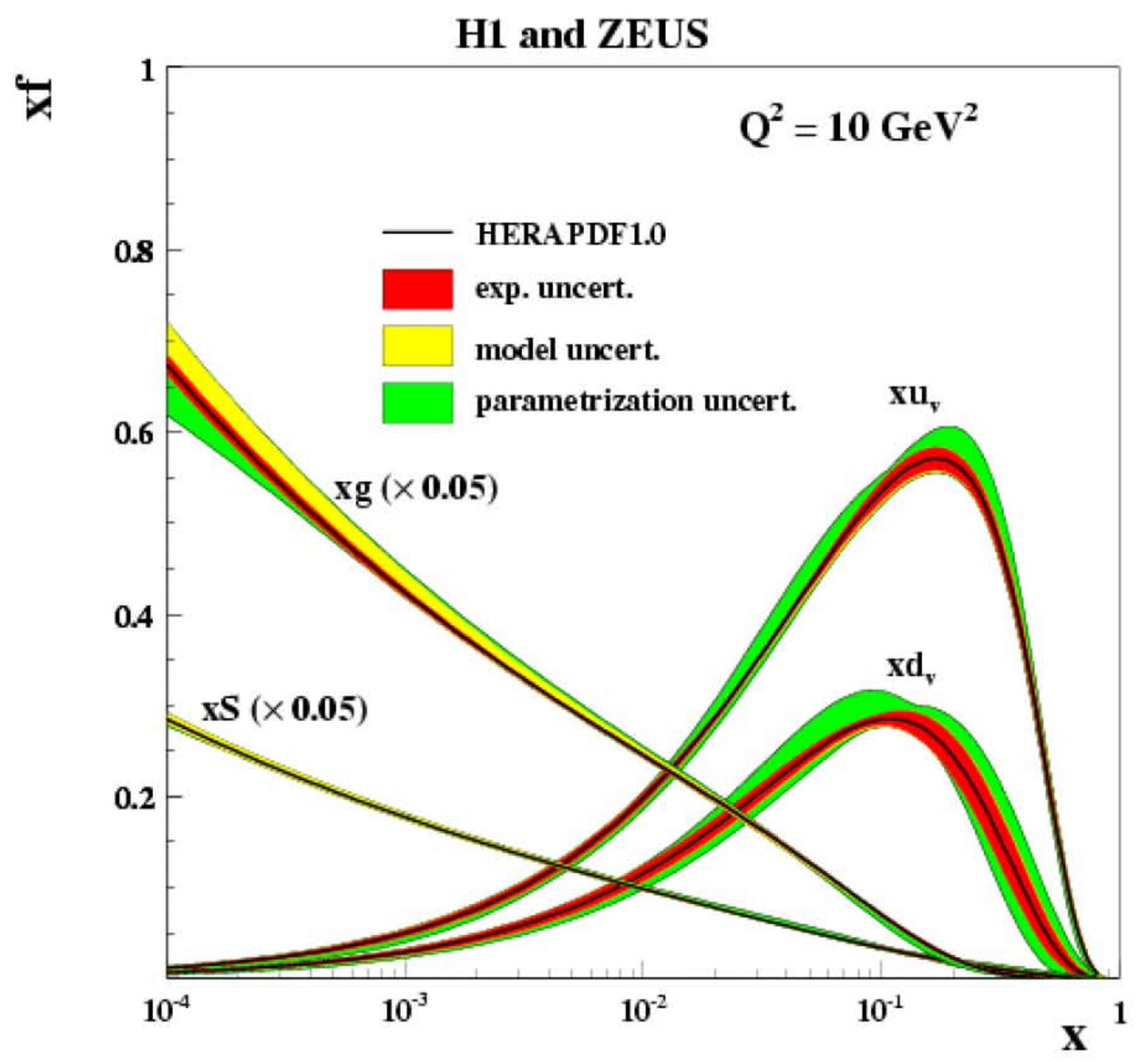
Unpolarized Structure Function F_2

- Bjorken Scaling
- Scaling Violation
- Gluon radiation –
- QCD evolution

  NLO: Next-to-Leading-Order
- One of the best experimental tests of QCD



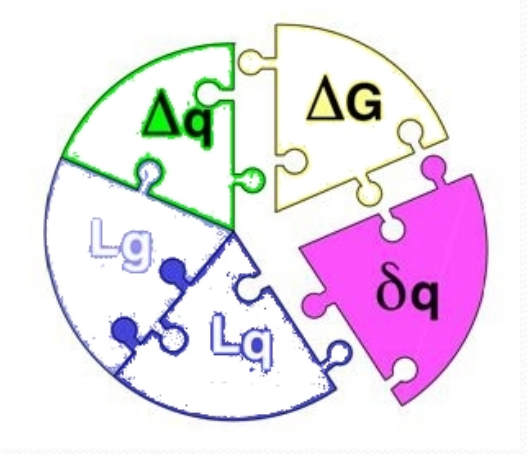
Parton Distribution Functions (CTEQ6)



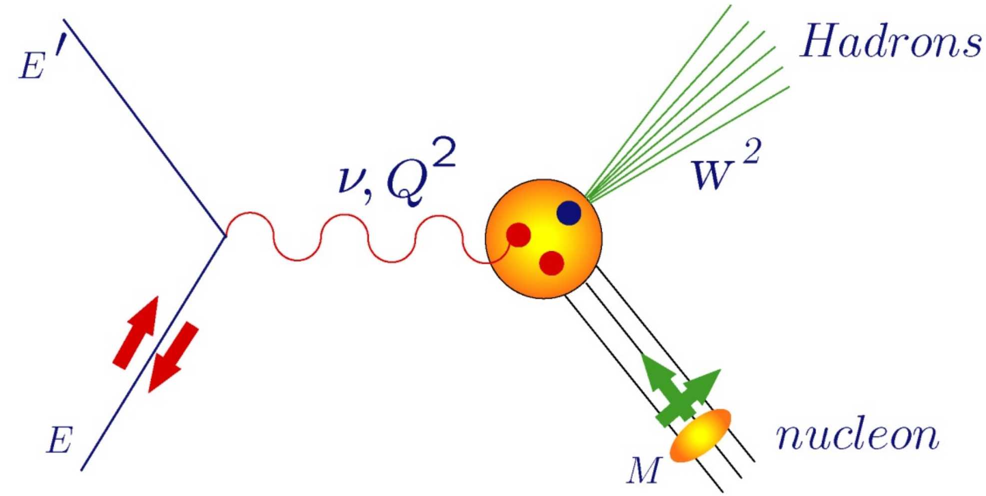
JHEP 1001: 109 (2010)

Polarized Deep-Inelastic Scattering
Polarized Structure Functions

Spin Distributions, “Spin Crisis/Puzzle”
Orbital Angular Momentum



Polarized Deep Inelastic Electron Scattering



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

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

- All information about the nucleon vertex is contained in

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

and

g_1 and g_2 the spin dependent structure functions

Cross Section & Spin Structure Functions

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left[\frac{F_2}{\nu} + 2\frac{F_1}{M}\tan^2\frac{\theta}{2}\right]$$

$$\frac{d^2\sigma}{dE' d\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1 - \frac{Q^2}{\nu}g_2\right]$$

$$\frac{d^2\sigma}{dE' d\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 \sin\theta}{MQ^2}\frac{{E'}^2}{E}\frac{1}{\nu^2}(\nu g_1 + 2E g_2)$$

Quark-Parton Model

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 f_i(x) \qquad g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

$$f_i(x) = q_i^{\uparrow}(x) + q_i^{\downarrow}(x)$$

$$\Delta q_i(x) = q_i^{\uparrow}(x) - q_i^{\downarrow}(x)$$

$q_i(x)$ quark momentum distributions of flavor i

$\uparrow(\downarrow)$ parallel (antiparallel) to the nucleon spin

$F_2 = 2xF_1$ $\qquad g_2 = 0$

$$A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\Sigma\,\Delta q_i(x)}{\Sigma\, f_i(x)}$$

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)

  $\Delta\Sigma = 20-30\%$,   the rest: gluon and quark orbital angular momentum

  $(½)\Delta\Sigma + L_q + \Delta G + L_G = 1/2$

  gauge invariant $(½)\Delta\Sigma + \mathcal{L}_q + J_G = 1/2$

  Bjorken Sum Rule verified to <10% level

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

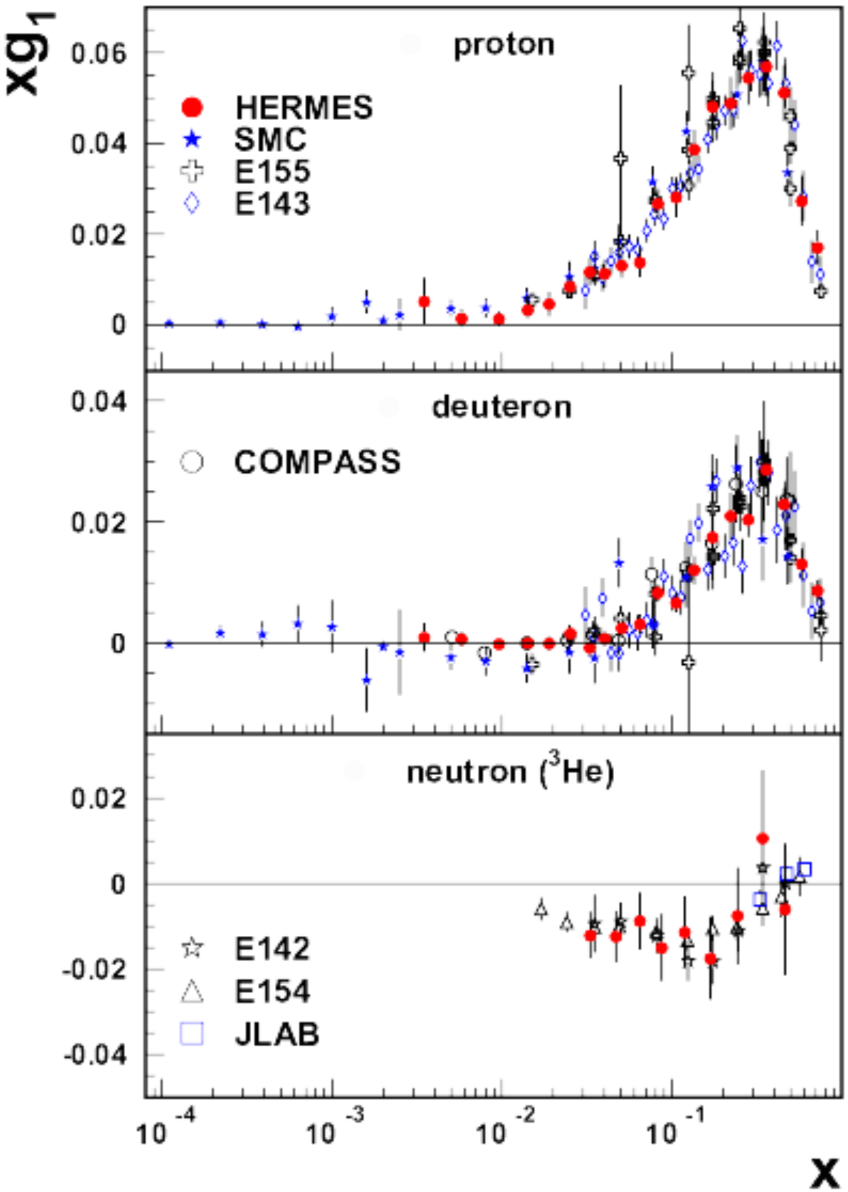
  $\Delta\Sigma \sim 30\%$; ΔG contributes, orbital angular momentum significant

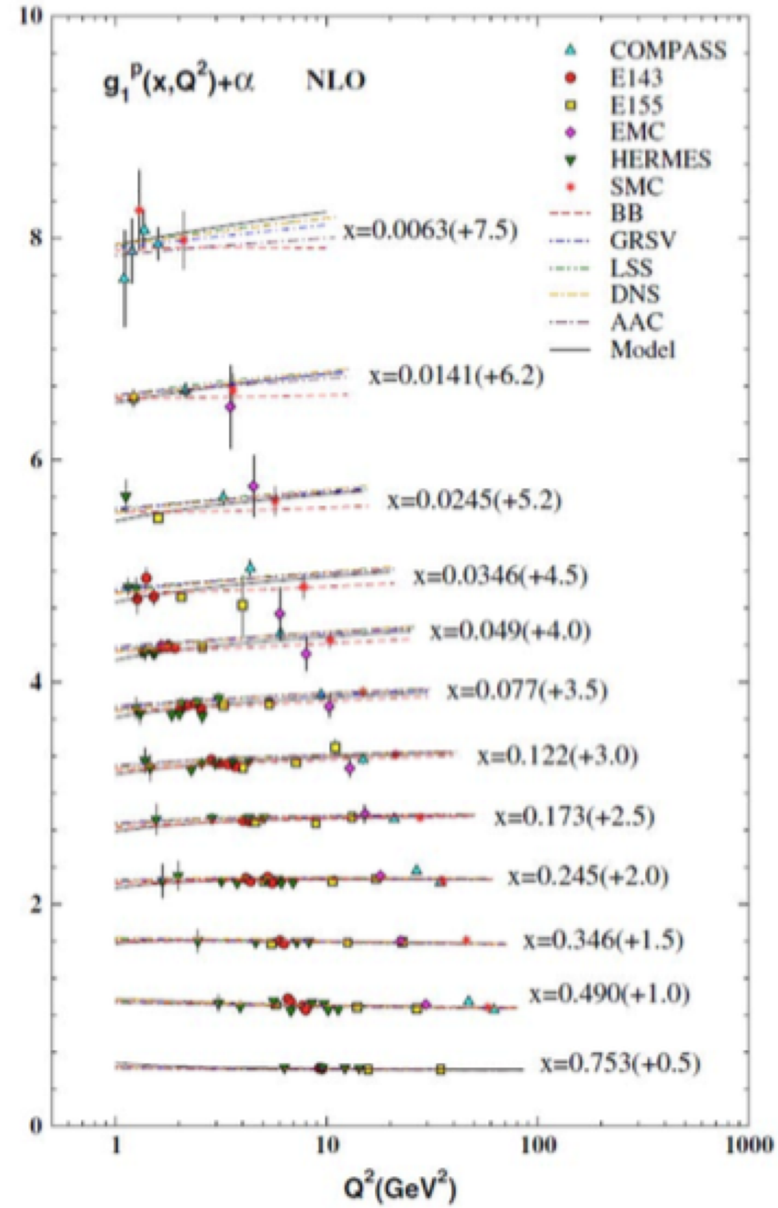
  Needs 3-d structure information to complete the proton spin puzzle

Reviews: Sebastian, Chen, Leader, arXiv:0812.3535, PPNP 63 (2009) 1;

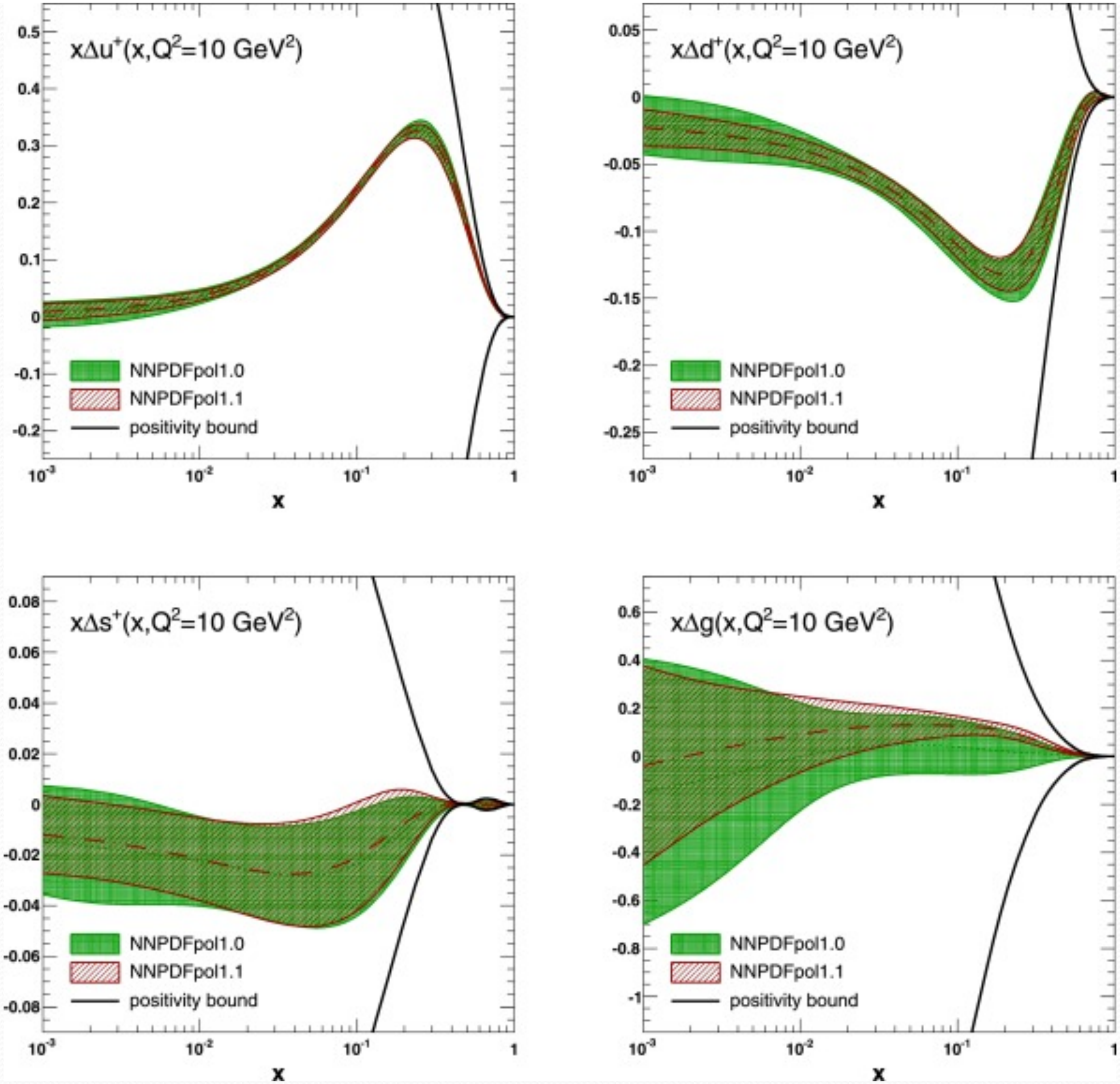
J. P. Chen, arXiv:1001.3898, IJMPE 19 (2010) 1893

Polarized Structure functions



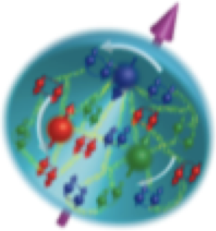


Polarized Parton Distributions



NNPDF, NPB 887, 276 (2014)

Nucleon Spin Decomposition



Proton spin puzzle

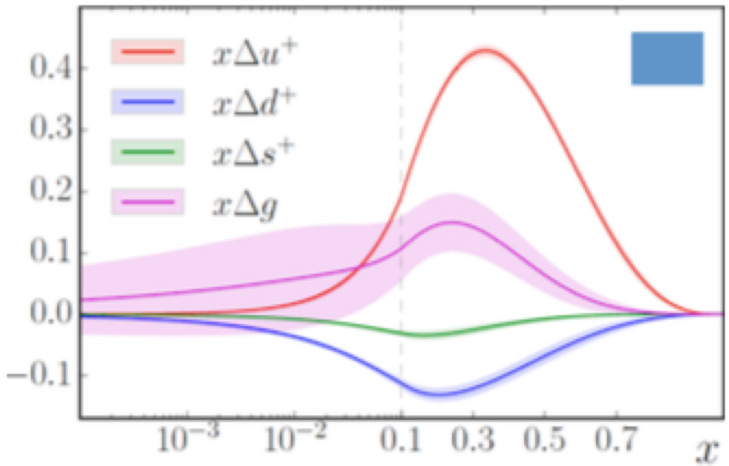
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

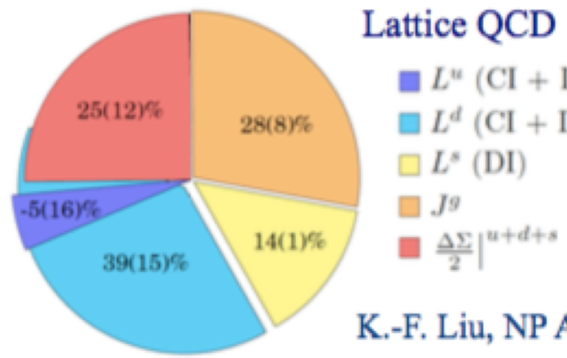
J. Ashman et al., PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



JAM Collaboration, PRD (2016).



K.-F. Liu, NP A928, 99 (2014).

Access to $L_{q/g}$

It is necessary to have transverse information.

Coordinate space: GPDs
Momentum space: TMDs

3D imaging of the nucleon.

Gluon spin: STAR and PHENIX (pp collisions)
Lattice: Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017)

5

Summary

- Electron Scattering to study Nucleon Structure
- Elastic: Form Factors

  charge/current distributions → transverse density

  G_E^p @ large Q^2 surprise, proton radius puzzle

- Deep-Inelastic Scattering

  Precision unpolarized structure functions in large kinematic coverage

  → Parton Distributions, best knowledge on nucleon structure

  best test of QCD

- Spin Structure Study Full of Surprises and Puzzles

  Quark spin only contributes 20-30%, Gluon spin contribution is significant

  Orbital Angular Momentum is important

→ Needs 3-D structure information

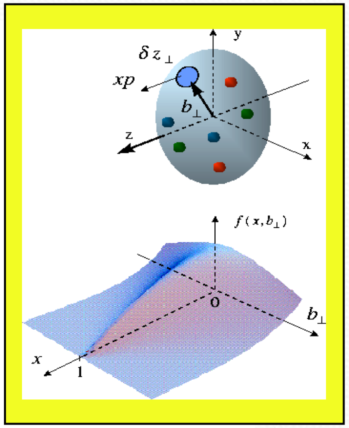
Nucleon 3-D Structure

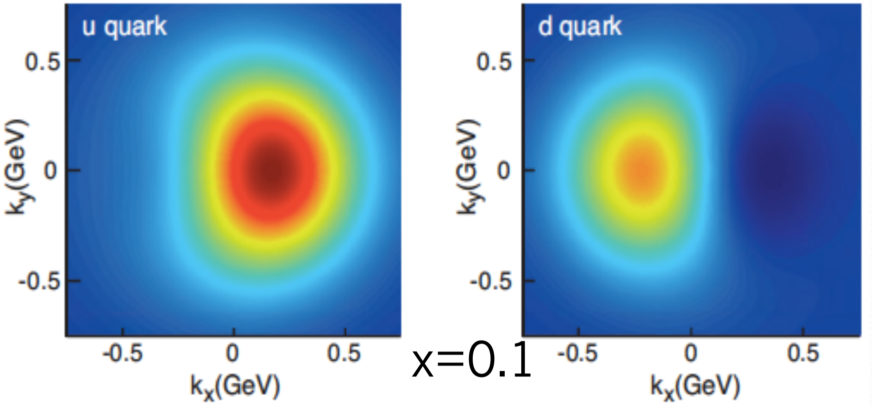
III: 3-d Structure – GPDs and TMDs

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

Weihai HEP School, August 16-25, 2018

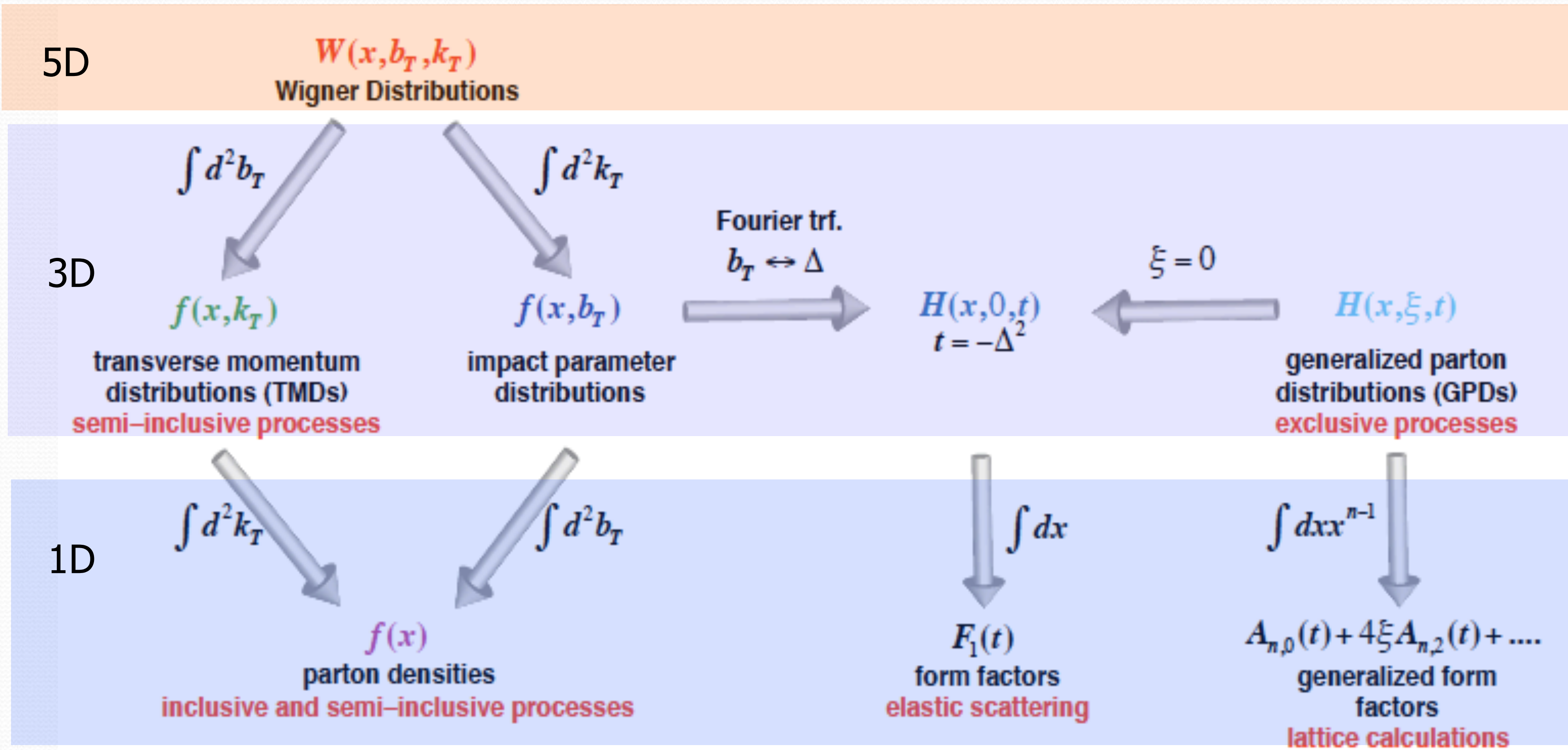
- Unified Picture of Nucleon Structure:
  Wigner Distribution
- GPDs: 3-d (2-d spatial+1-d momentum) distributions
- TMDs:3-d momentum distributions
- Transversity and tensor charge
- Orbital Angular Momentum
- SoLID program
- EIC program





Unified View of Nucleon Structure

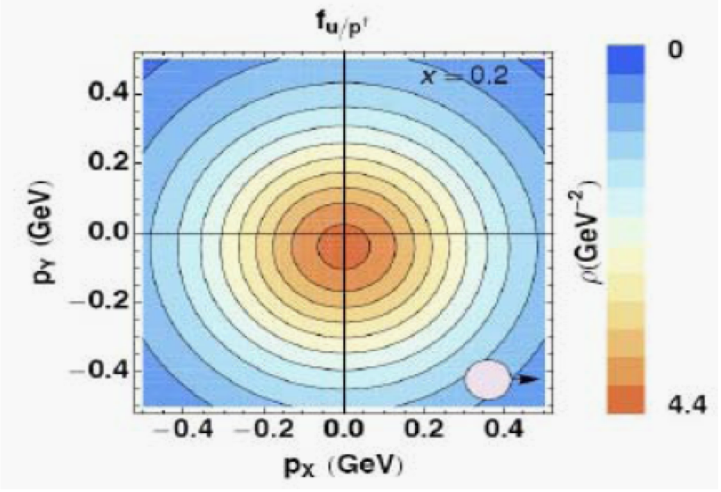
- **Wigner distributions**



3-D Imaging - Two Approaches

TMDs

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

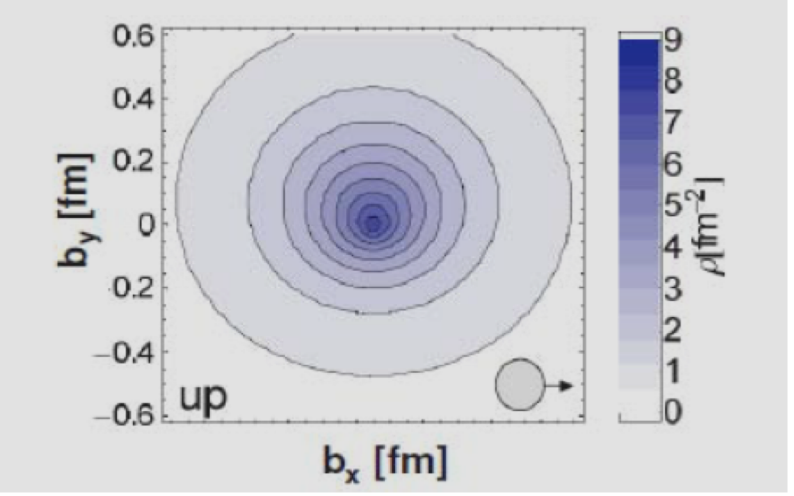


Bacchetta, Conti, Radici

- 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**

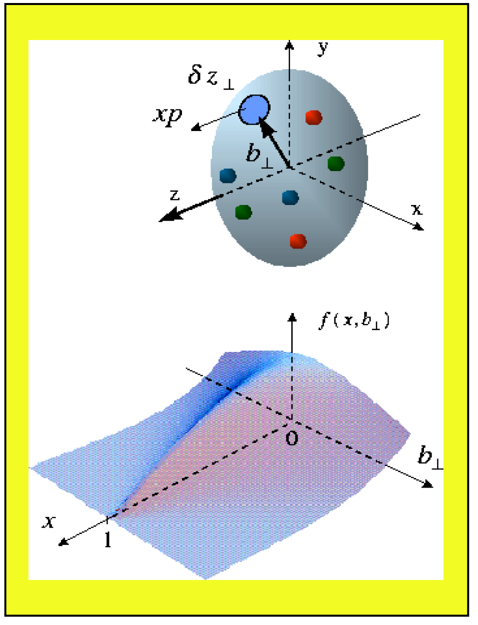


QCDSF collaboration

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

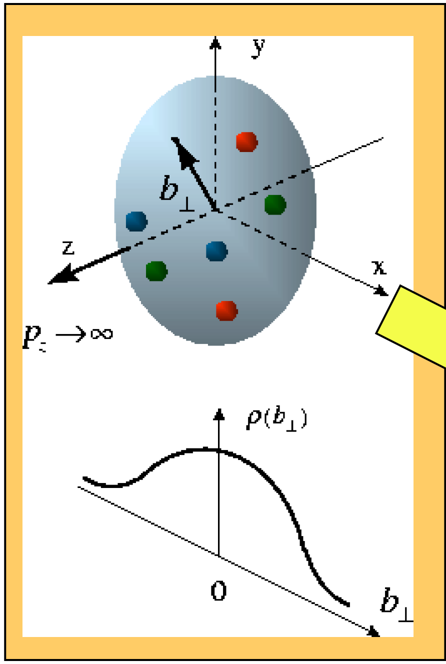
3-D Structure I

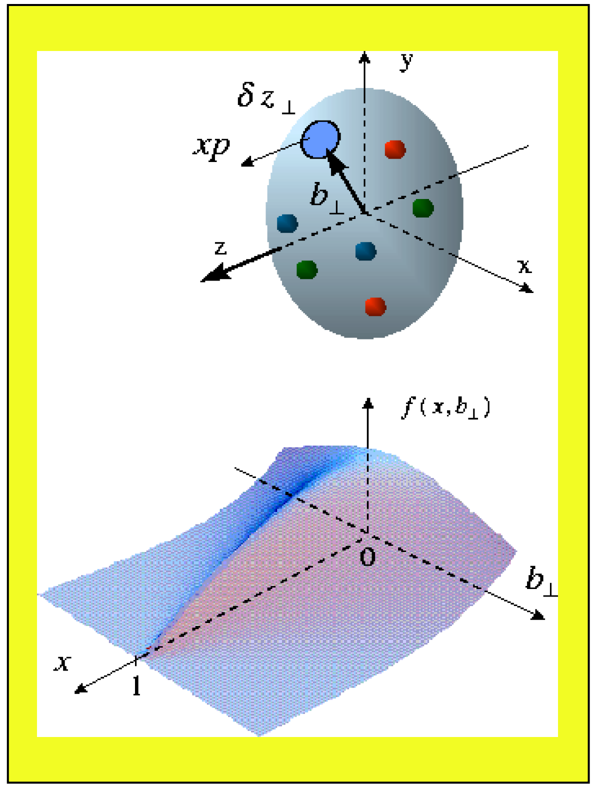
Generalized Parton Distributions

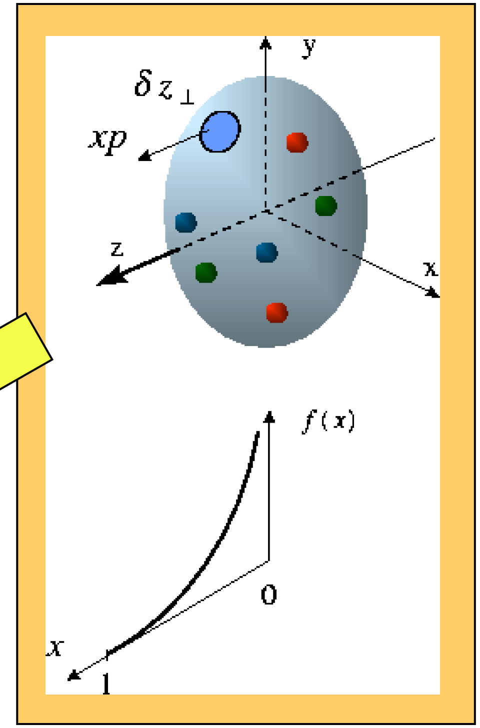


Generalized Parton Distributions (GPDs)

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





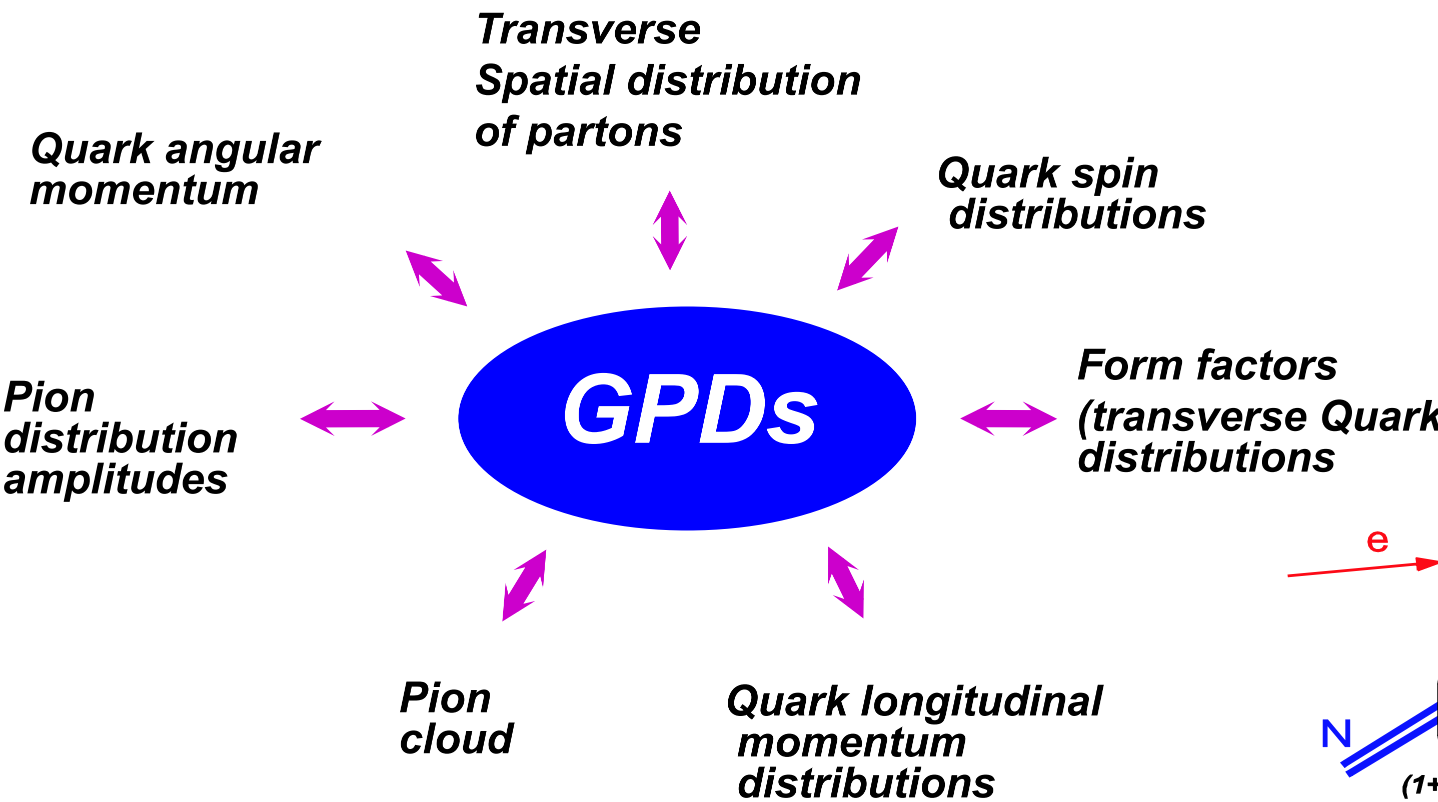


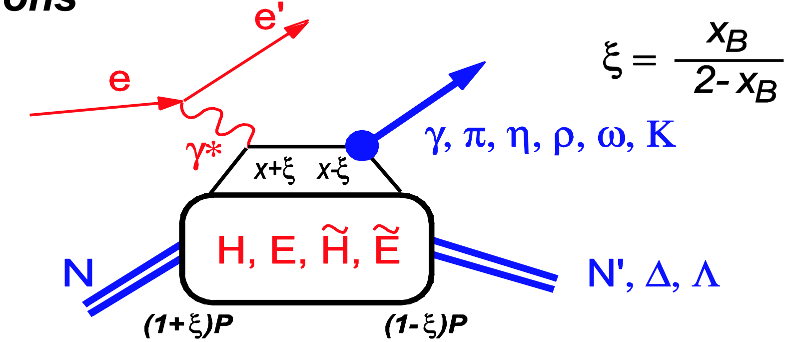
Proton form factors, transverse charge & current densities

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

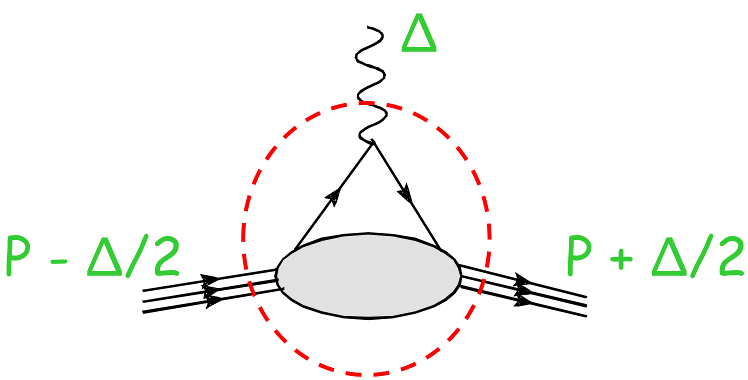
➡ forward limit : ordinary parton distributions

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

$$\boxed{\begin{aligned} \int_{-1}^{1} dx\, H^q(x, \xi, t) &= F_1^q(t) \\ \int_{-1}^{1} dx\, E^q(x, \xi, t) &= F_2^q(t) \\ \int_{-1}^{1} dx\, \tilde{H}^q(x, \xi, t) &= G_A^q(t) \\ \int_{-1}^{1} dx\, \tilde{E}^q(x, \xi, t) &= G_P^q(t) \end{aligned}}$$

Dirac

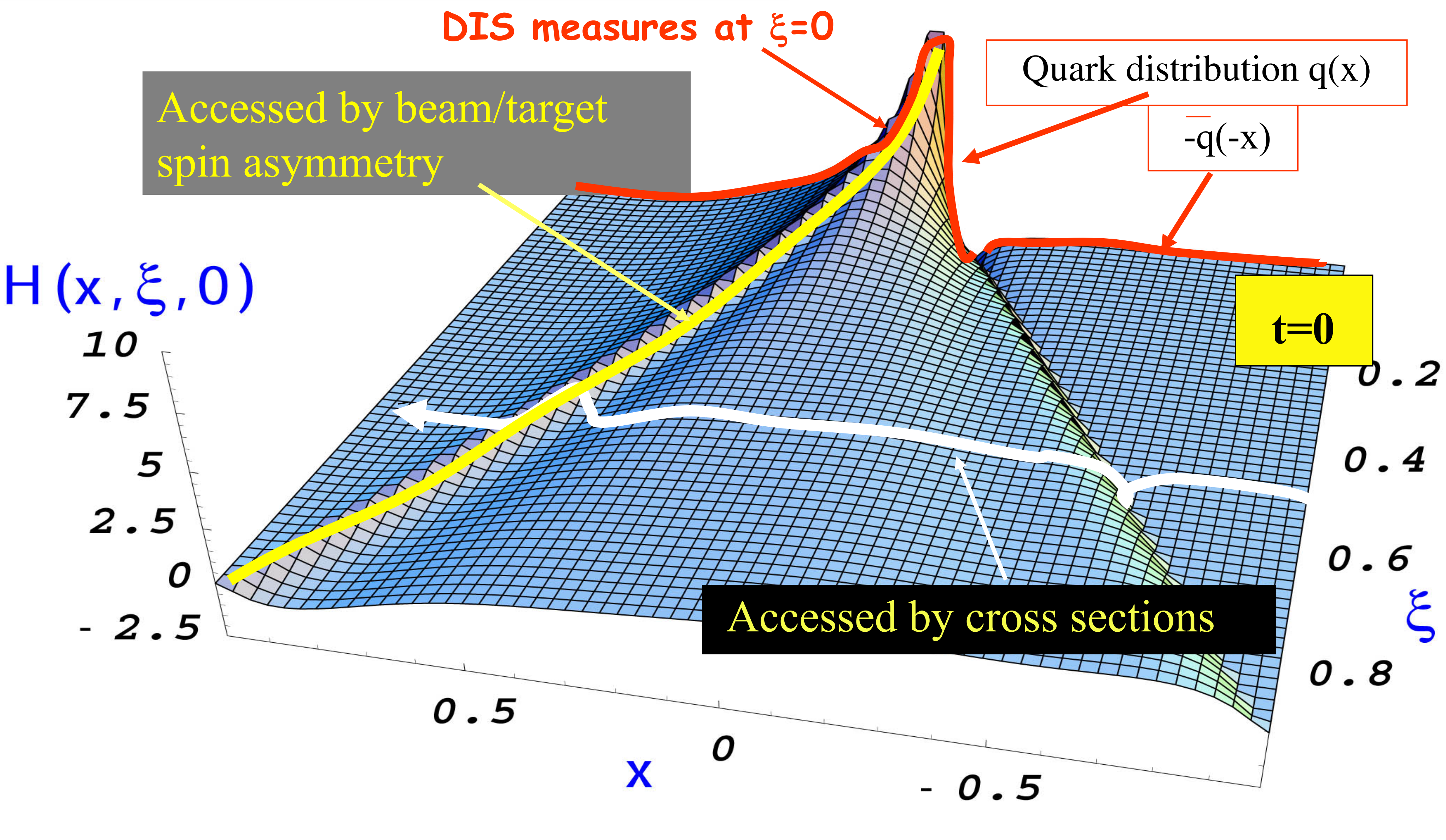
Pauli

axial

pseudo-scalar

Access GPDs through DVCS x-section & asymmetries

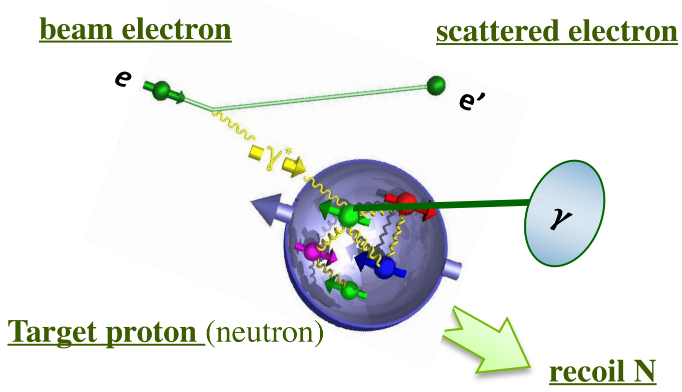
$$T_{DVCS} \propto \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi} - i\pi H(\xi,\xi,t)$$



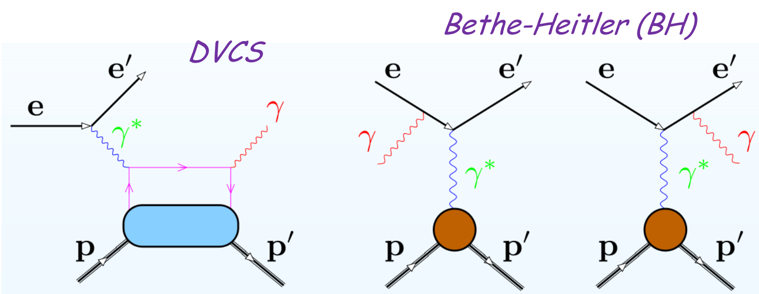
3D Structure of Nucleons

- **Probe GPD using Exclusive Hard Processes**

$$e + N \rightarrow e' + N + \gamma$$



- ✓ Detect the scattered electron, real photon and nucleon
- ✓ Measure chiral-even GPDs (H, E, $\tilde{H}$ and $\tilde{E}$)
- ✓ Interference with Bethe-Heitler （QED Calculatable）



- ✗ DVCS probes all GPD mixed together (actually CFF)
- ✗ Only measure the GPD at ***x=ξ limite***

Observable

- ❖ Absolute Cross Section:

$$\frac{d\sigma}{dQ^2 dx_B dt d\phi} \propto \left|\tau_{DVCS}\right|^2 + I + \left|\tau_{BH}\right|^2$$

Compton Form Factors (CFFs):

$$\tau_{DVCS} \propto \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi \mp i\varepsilon} dx = P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t),$$

- ❖ Asymmetries with polarized target and/or polarized beam:

$$A = \frac{I}{\left|\tau_{DVCS}\right|^2 + I + \left|\tau_{BH}\right|^2} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

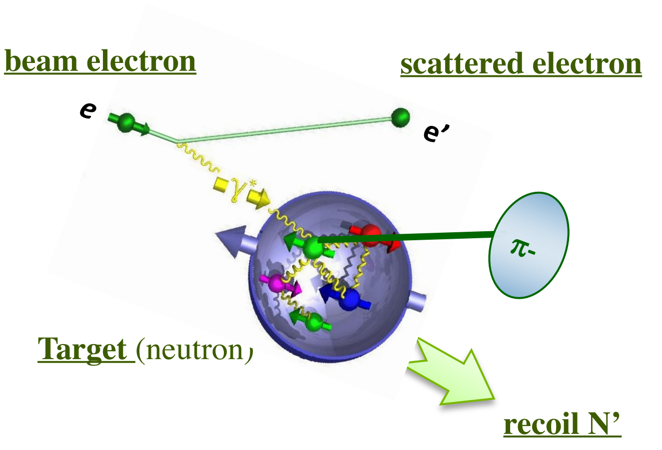
$\sigma^{+/-}$, Beam or/and Target Polarization.

Polarization	Asymmetries	CFFs
Longitudinal Beam	A_{LU}	$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$
Longitudinal Target	A_{UL}	$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \}$ $Im\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$
Long. Beam + Long. Target	A_{LL}	$Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \}$ $Re\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$
Transverse Target	A_{UT}	$Im\{\mathcal{H}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n\}$
Long. Beam +Trans. Targt	A_{LT}	$Re\{\mathcal{H}_p, \mathcal{E}_p\}$ $Re\{\mathcal{H}_n\}$

3D Structure of Nucleons

- Probe GPD using Exclusive Hard Processes

$$e + N \rightarrow e' + N' + \pi^{0,\pm}\ (K^{0,\pm}, \eta, \rho, \omega, \ldots)$$



- ✓ Vector meson production is sensitive to H and E
- ✓ Pseudoscaler meson production is sensitive to $\tilde{H}$ and $\tilde{E}$

  Particularly sensitive to $\tilde{E}$ when using neutron targets
- ✓ DVMP is also uniquely chiral-odd GPDs (H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$)
- ✓ Great complementary to DVCS
- ✗ More difficult to measure; Need high Q^2 and low -t

Observables

- w/ polarized target, the SSA has azimuthal dependence, like SIDIS for TMDs:

$$A(\phi,\phi_s) = \frac{d^3\sigma_{UT}(\phi,\phi_s)}{d^2\sigma_{UU}(\phi)} = -\sum_k A_{UT}^{\sin(\mu\phi+\lambda\phi_s)_k} \sin(\mu\phi+\lambda\phi_s)_k$$

- Different angular modules correspond to diff. GPDs:

$\sin\beta=\sin(\phi-\phi_s)$ Asymmetry Moment

$$A_{UT}^{\sin(\phi-\phi_s)} \sim \frac{d\sigma_{00}^{+-}}{d\sigma_L\binom{++}{00}} \sim \frac{\mathrm{Im}(\tilde{E}^*\tilde{H})}{|\tilde{E}|^2} \text{ where } \tilde{E} \gg \tilde{H}$$

$\sin(\phi_s)$ Asymmetry Moment

$$A_{UT}^{\sin(\phi_S)} \sim \mathrm{Im}[M^*_{0+,++}M_{0-,0+} - M^*_{0-,++}M_{0+,0+}],$$

helicities: [pion, neutron, photon, proton]

$$\mathcal{M}_{0-,++} = e_0\sqrt{1-\xi^2}\int \mathrm{d}x\mathcal{H}_{0-,++}H_T,$$

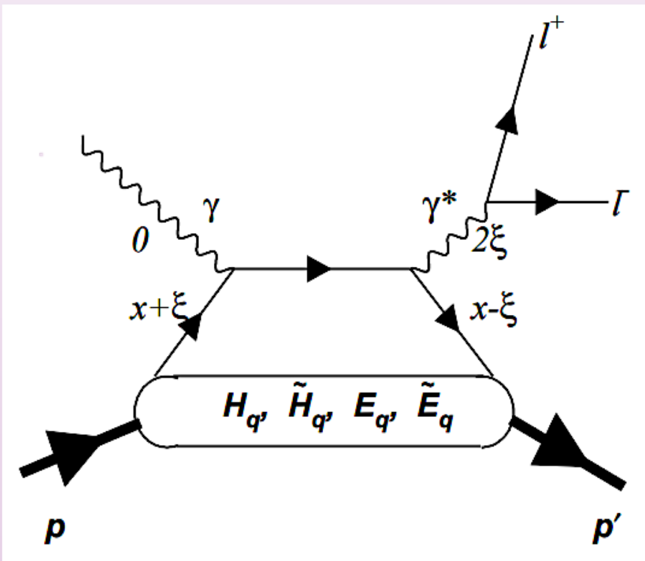
$$\mathcal{M}_{0+,\pm+} = -e_0\frac{\sqrt{t_{\min}-t}}{4m}\int \mathrm{d}x\mathcal{H}_{0-,++}\bar{E}_T.$$

3D Structure of Nucleons

- Probe GPD using Exclusive Hard Processes

Timelike Compton Scattering:

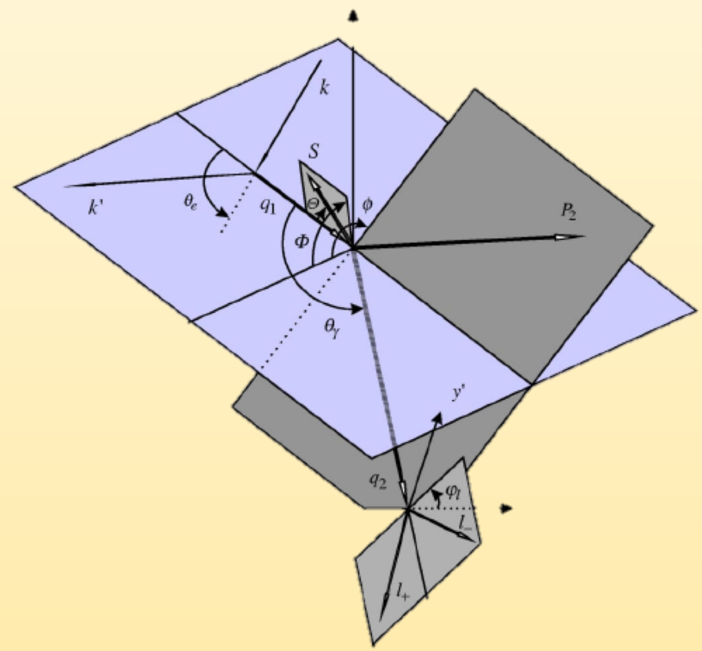
$$\gamma + N \rightarrow N + l^+ + l^-$$



- ✓ Inverse of the space-like DVCS
- ✓ Extract the real part of CFFs
- ✓ Complimental to DVCS

Double-DVCS:

$$e + N \rightarrow e' + N + l^+ + l^-$$

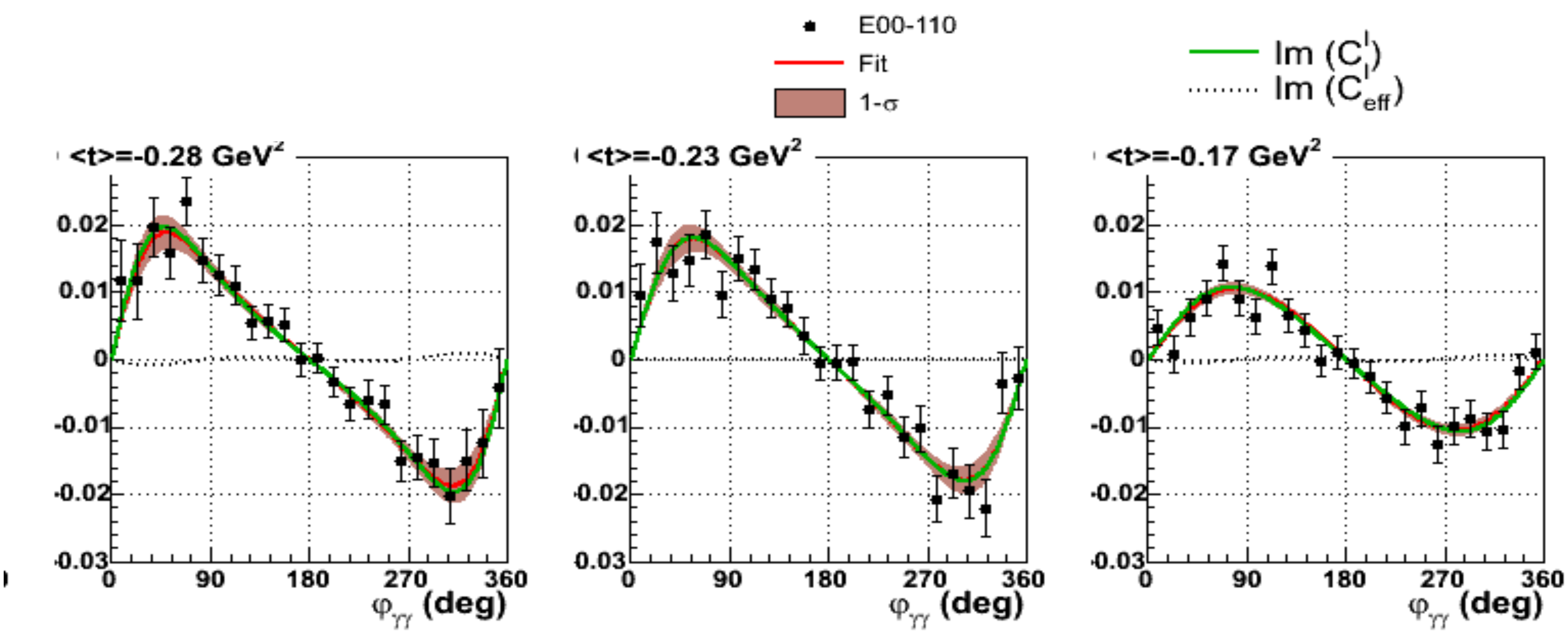


- ✓ A lepton pair in the final state instead of a real photon
- ✓ Can access GPDs ***beyond the x=ξ limit***
- ✓ Rates are extremely limited; Need high luminosity
- ✓ Need dedicated muon detection

Hall A DVCS Experiment

Handbag Dominance at Modest Q^2

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



Twist 2 contribution

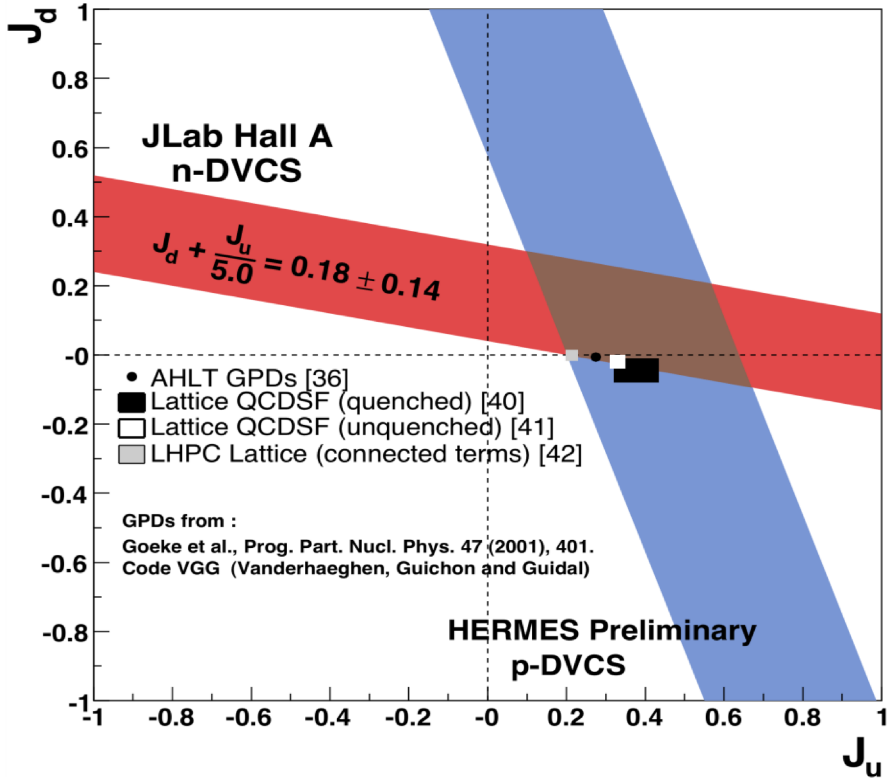
Twist 3 contribution strongly suppressed

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

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

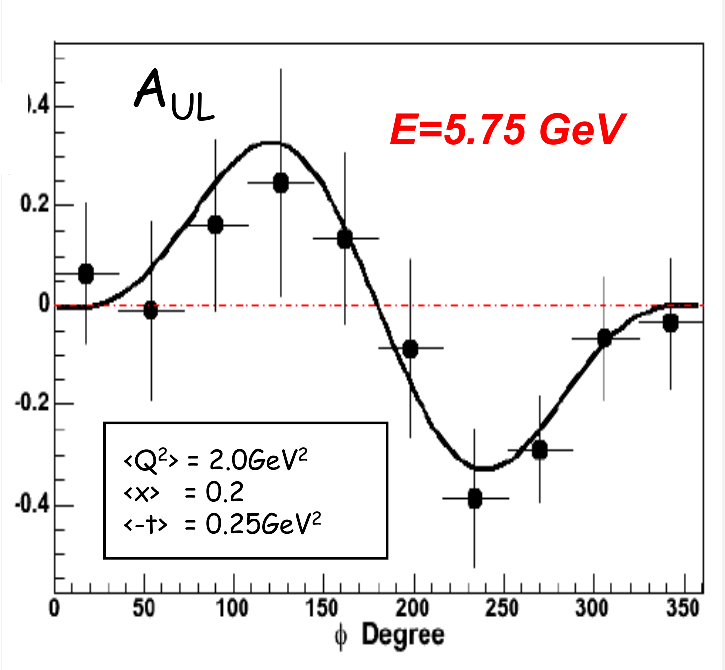
E = 11 GeV

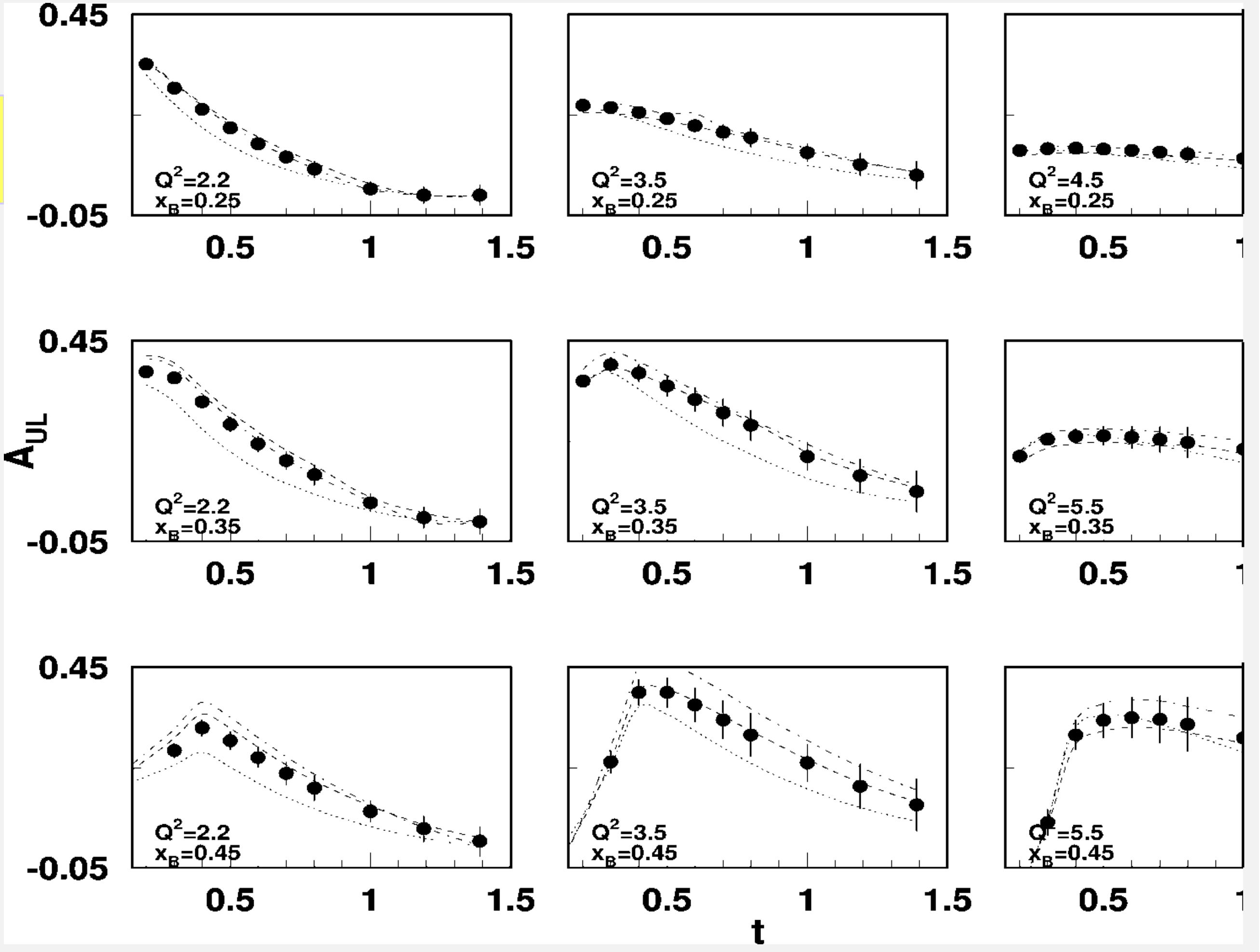
L = 2×10^{35} cm^{-2}s^{-1}
T = 1000 hrs
$\Delta Q^2 = 1$GeV^2
$\Delta x = 0.05$

Longitudinally polarized target

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

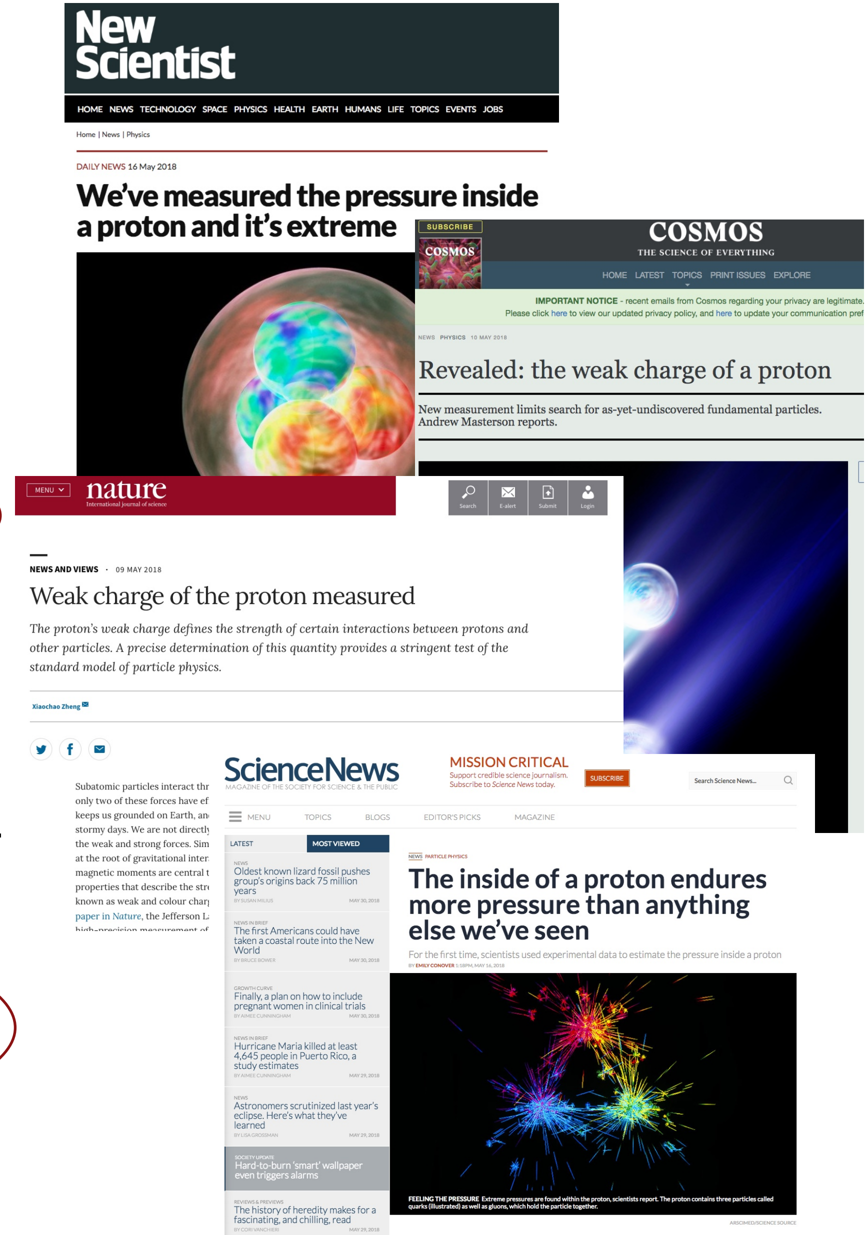
CLAS preliminary





JLab Results Accepted and/or Published in Nature

- *Precision measurement of the weak charge of the proton*, Qweak collaboration,
  Published: Nature 557, 207–211 (2018)
- ***The pressure distribution inside the proton*, Burkert, Elouadrhiri, Girod, Published: Nature 557 (2018) no.7705, 396-399**
- *A per-cent-level determination of the nucleon axial coupling for quantum chromodynamics*, Berkowitz et. al., Published: Nature 558, 91-94 (2018)
- *Ultrafast Nucleons in Asymmetric Nuclei,* M. Duer et. al., CLAS Collaboration, accepted for publication
- ***A glimpse of gluons through deeply virtual compton scattering on the proton*, Dufurne et. al., Published: Nature Communications 8, 1408 (2017)**



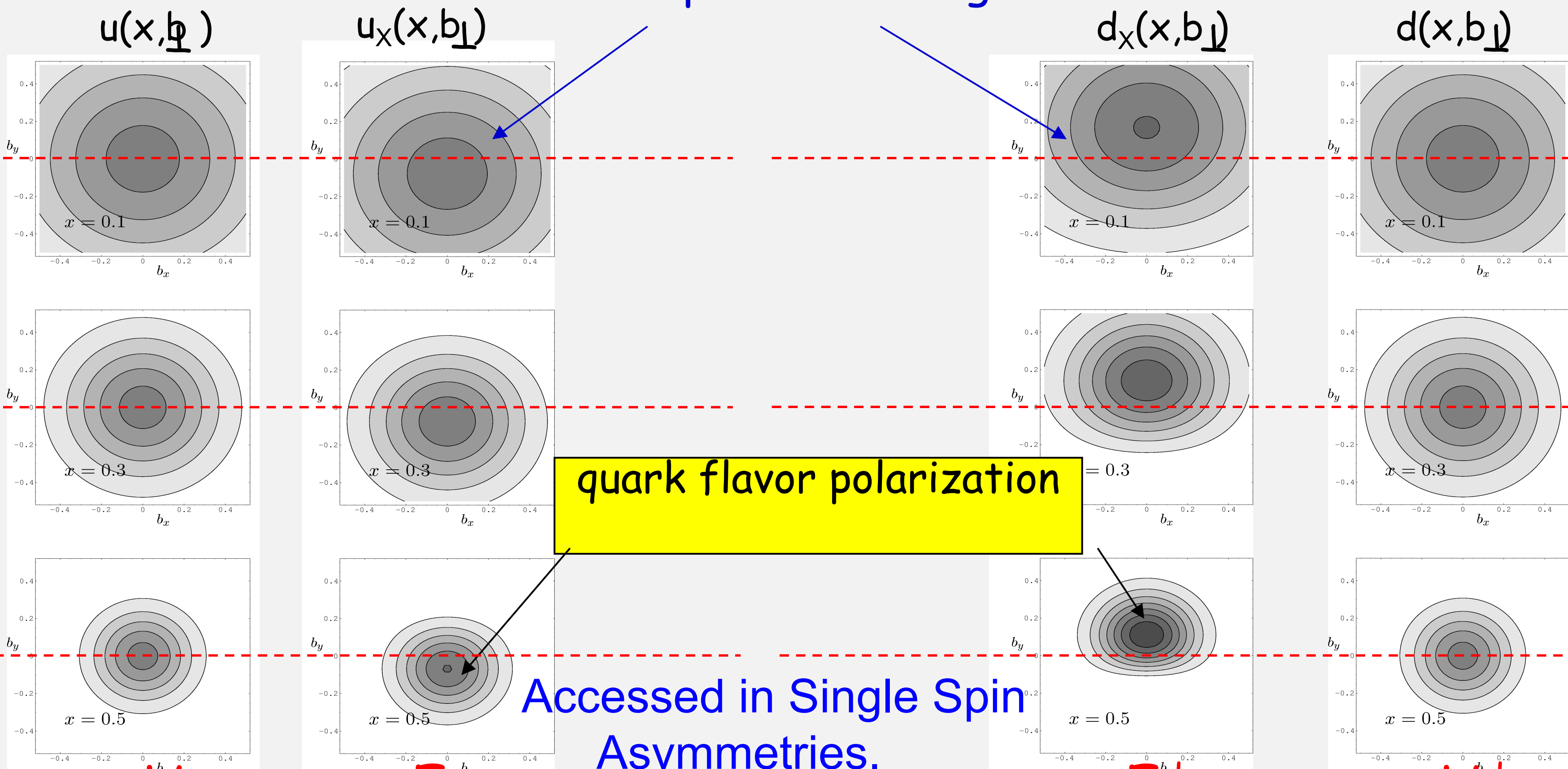
3D Images of the Proton's Quark Content

M. Burkardt PRD 66, 114005 (2002)

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

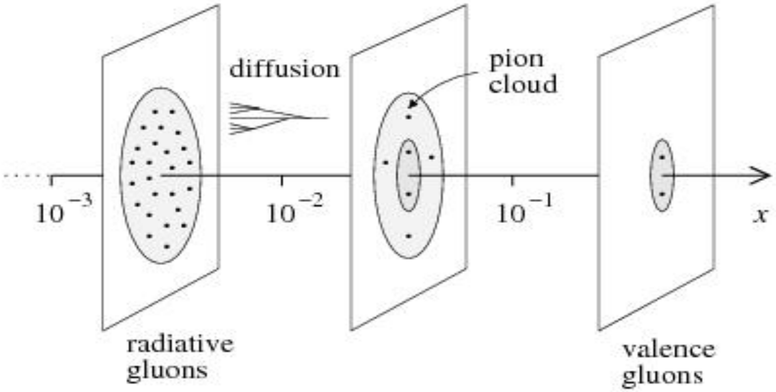
$\mathbf{b}_\perp$- Impact parameter

transverse polarized target



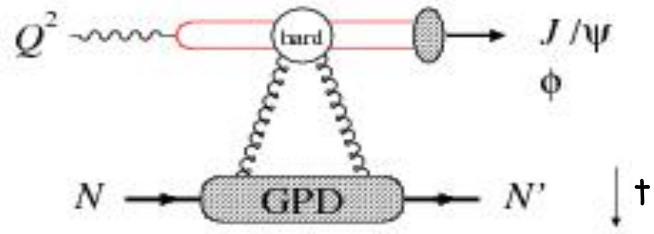
Needs: H^u E^u E^d H^d

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)



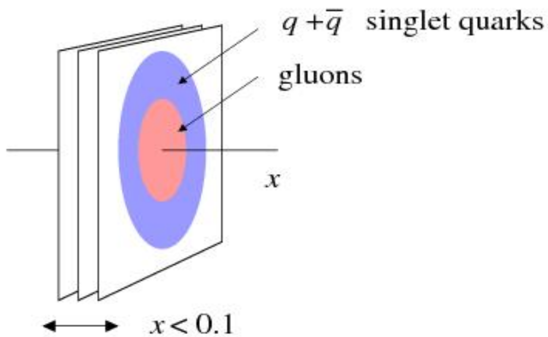
[Transverse distribution derived directly from t dependence]

Hints from HERA:

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

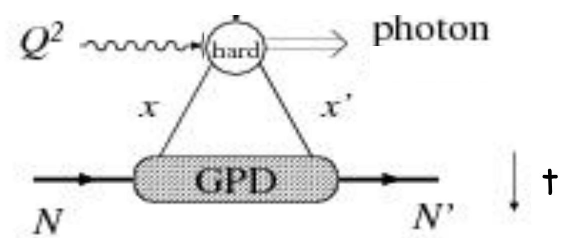
Dynamical models predict difference:

pion cloud, constituent quark picture

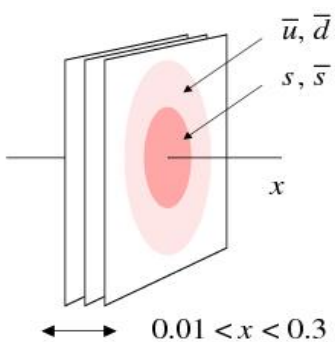


Fazio

EIC: singlet quark size from deeply virtual compton scattering

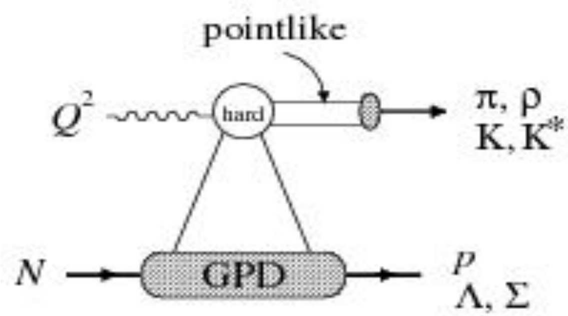


- Q^2 > 10 GeV^2 for factorization
- Statistics hungry at high Q^2!

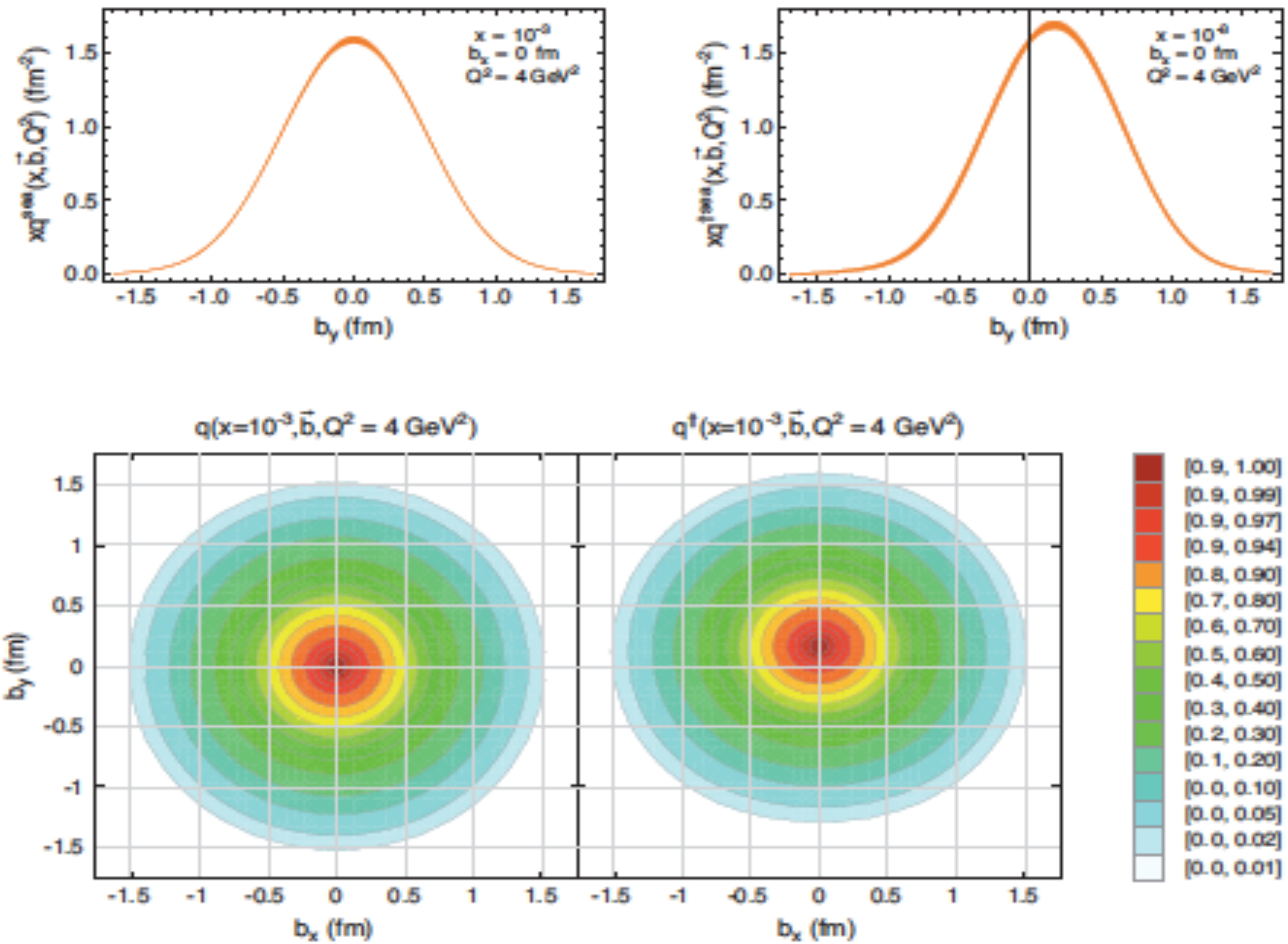


Horn

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)

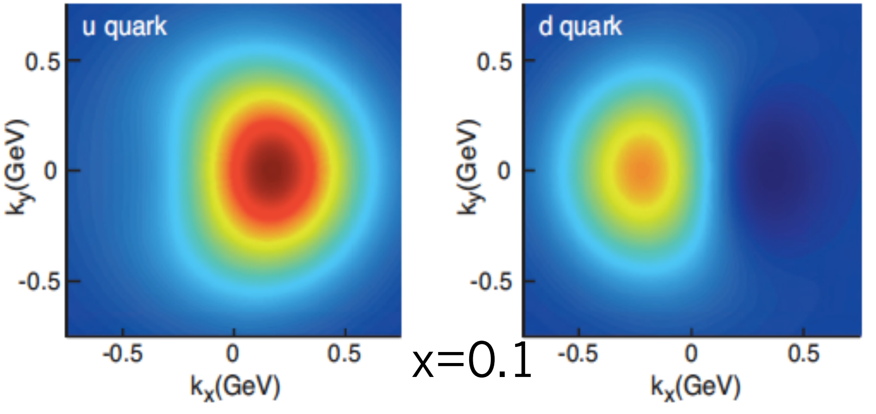
- Significant increase in range for DVCS

  combination of energy and polarized luminosity

- Other opportunities: vector meson, heavy flavors?

3-D Structure II

Transverse Momentum-Dependent Distributions



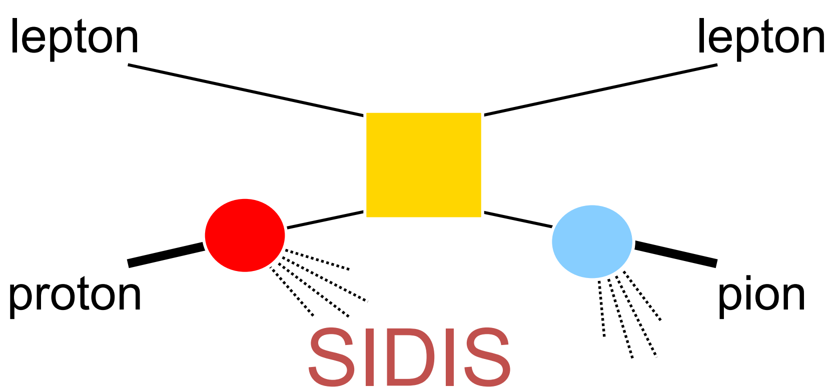
Leading-Twist TMD PDFs

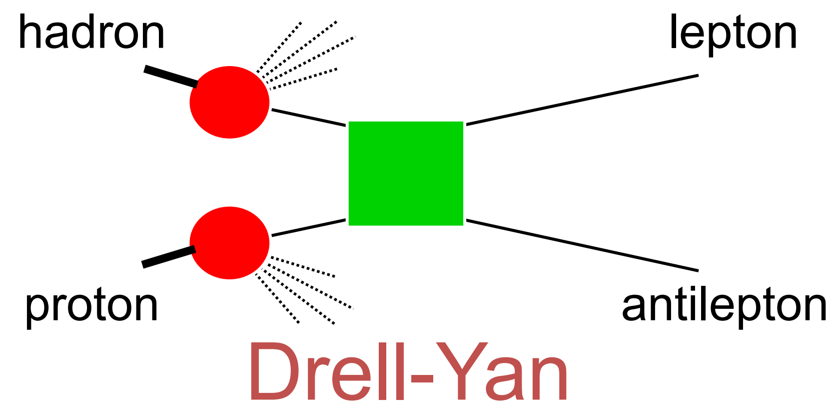
Nucleon Spin

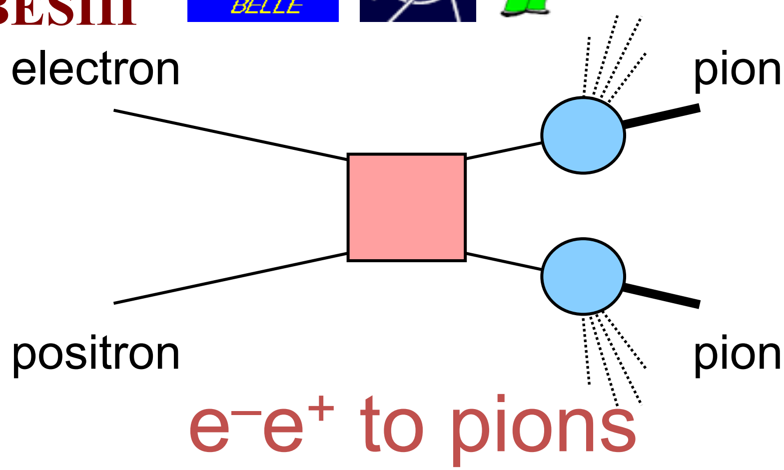
Quark Spin

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

Access TMDs through Hard Processes







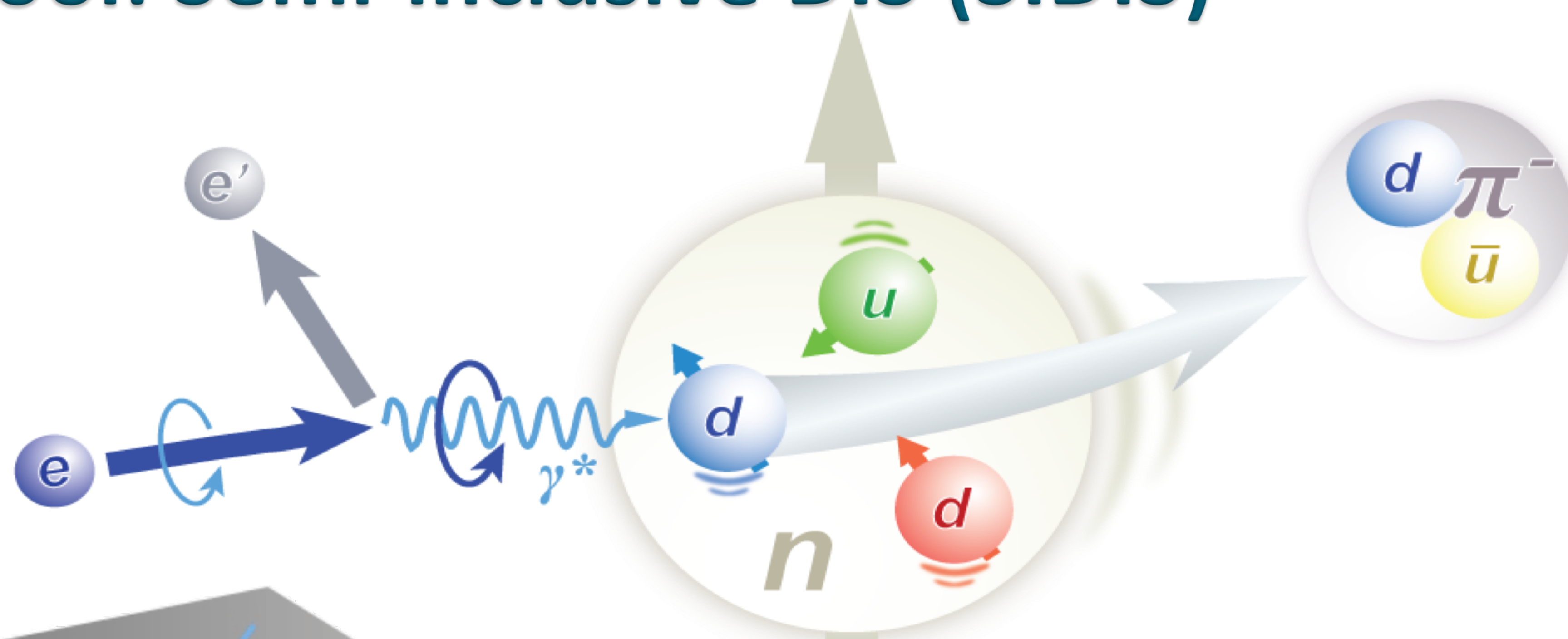
Partonic scattering amplitude

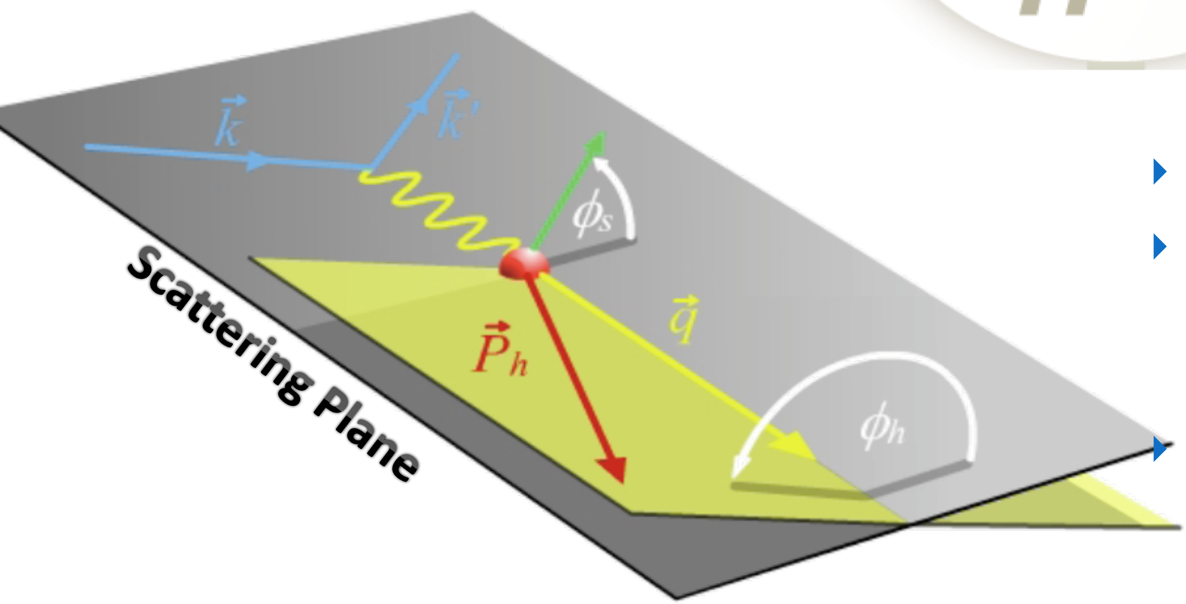
Fragmentation amplitude

Distribution amplitude

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

Tool: Semi-inclusive DIS (SIDIS)





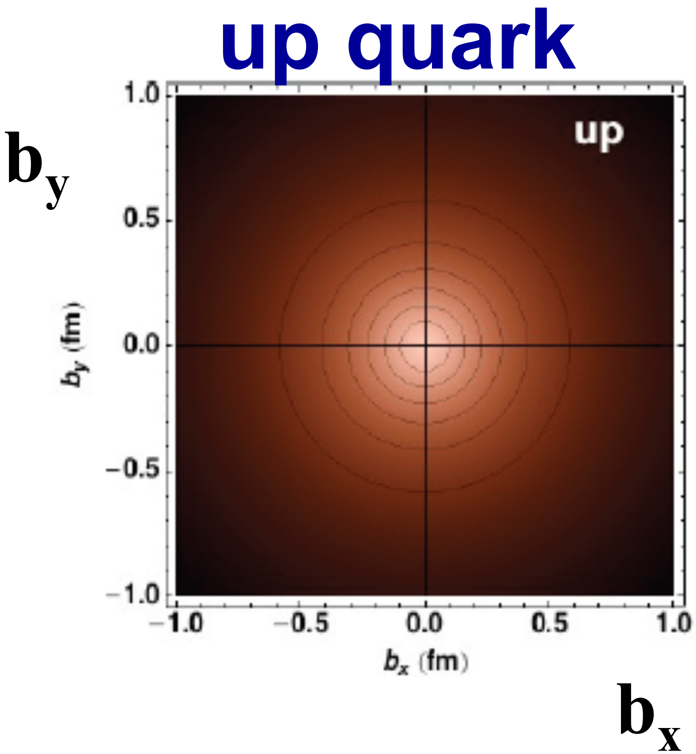
- Gold mine for TMDs
- Access all eight leading-twist TMDs through spin-comb. & azimuthal-modulations
- Tagging quark flavor/kinematics

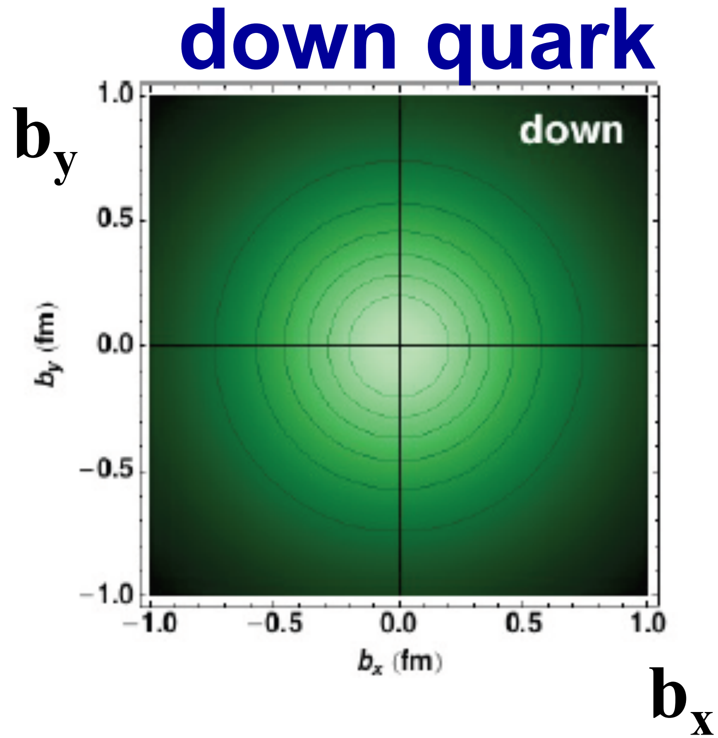
Unpolarized TMDs
Flavor P_T Dependence

SIDIS Results

From Form Factors to Transverse Densities

Unpolarized Transverse Densities

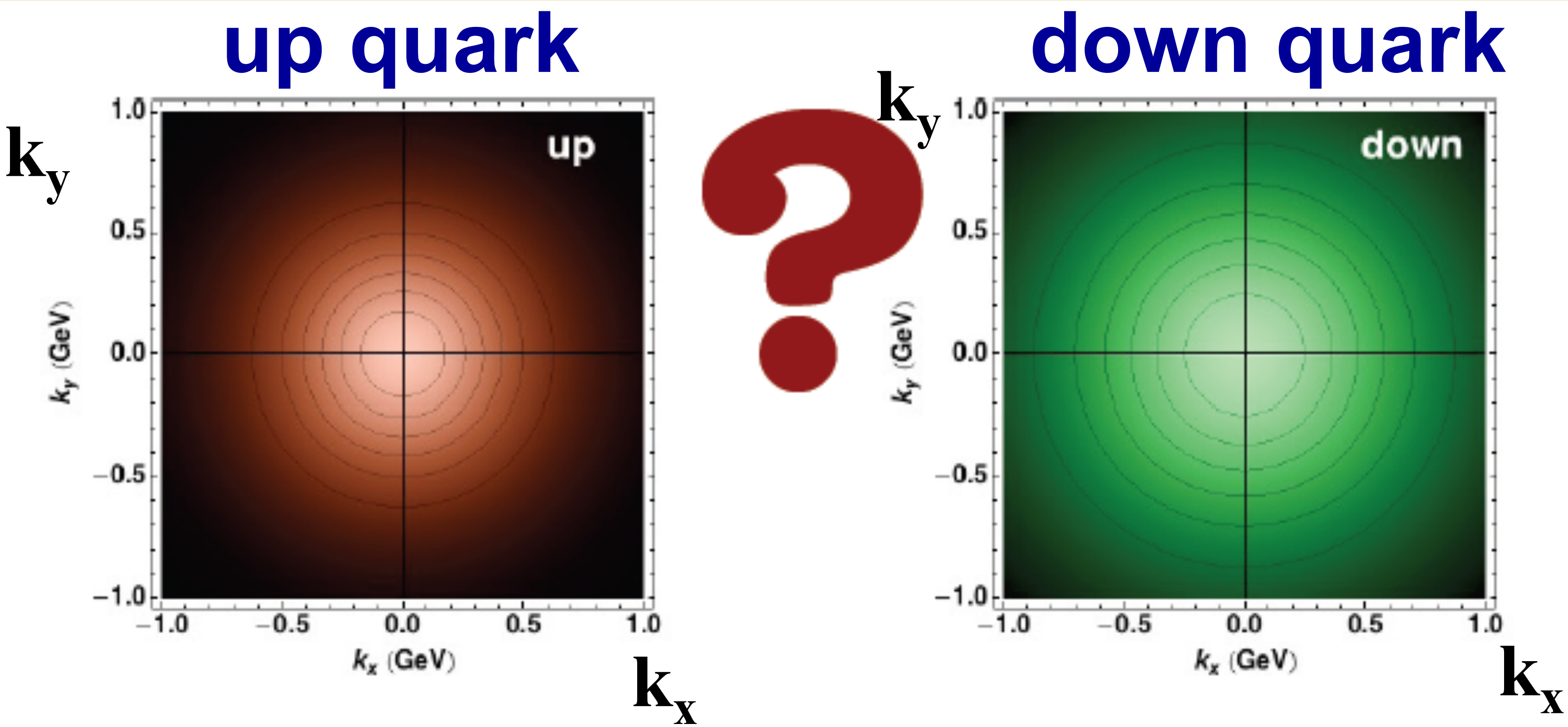




Flavor-dependence in form factors can be translated into flavor-dependence of transverse densities

Unpolarized TMD: Flavor P_T Dependence?

Flavor in transverse-momentum space



Is the up distribution wider or narrower than the down?

And the sea?

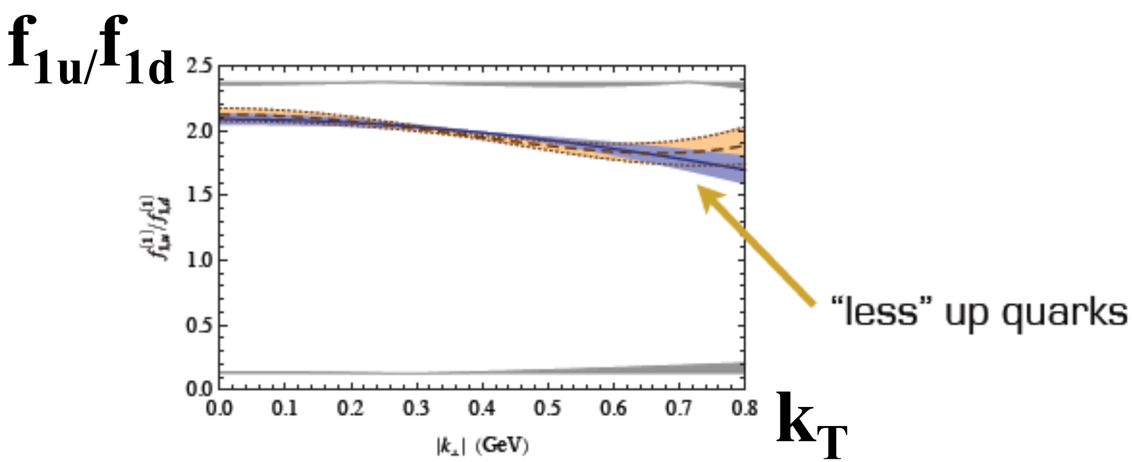
How wide are the distributions?

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



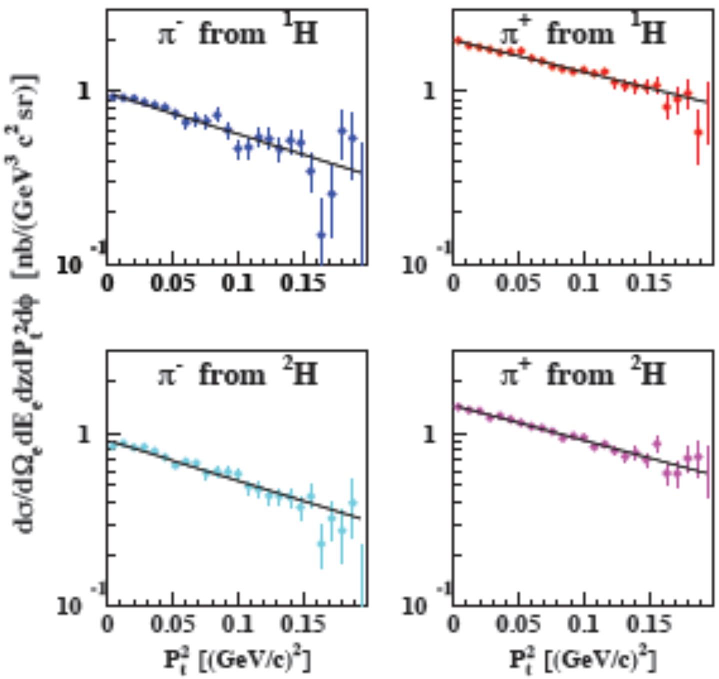
Musch, Hagler, Negele, Schafer, PRD 83 (11)

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

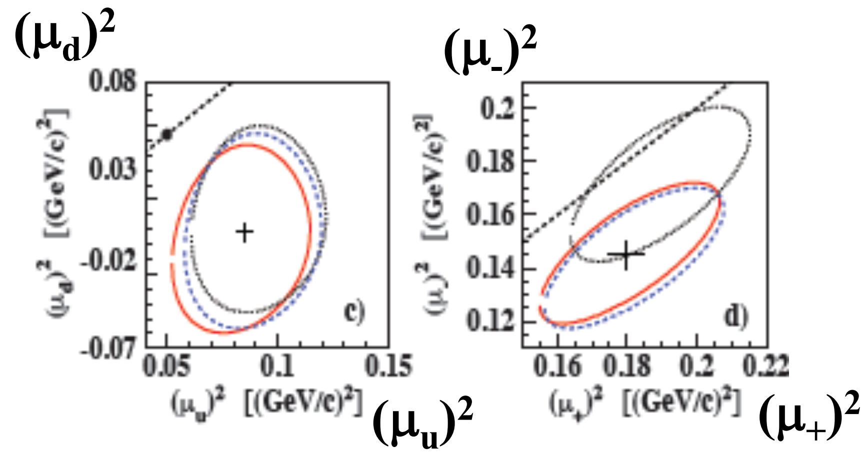
- Flagmentation model, Matevosyan, Bentz, Cloet, Thomas, PRD85 (2012)
  → unfavored pion and Kaon wider than favored pion

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

Leading-Twist TMD PDFs

Nucleon Spin

Quark Spin

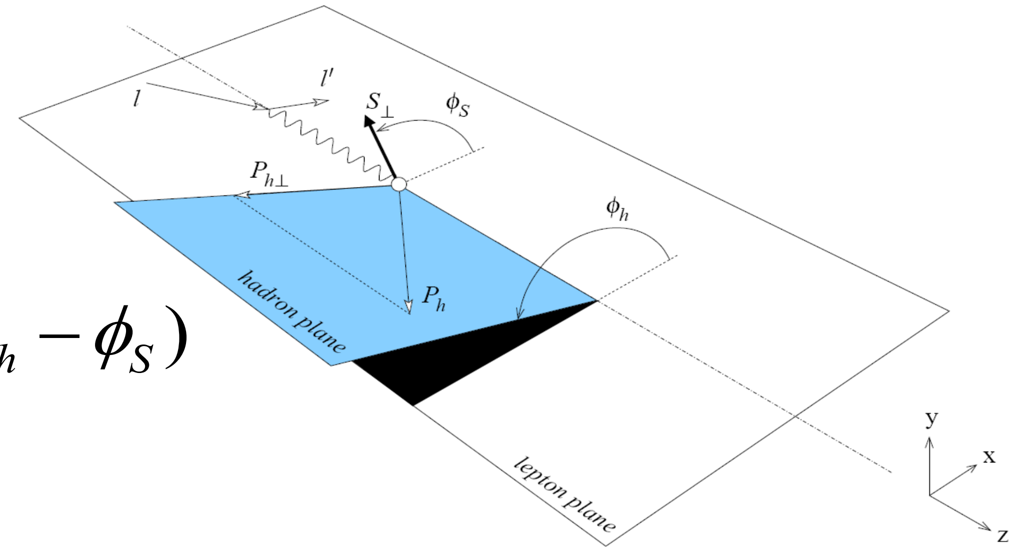
Nucleon Polarization	Quark polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^\perp$ Long-Transversity
T	$f_{1T}^\perp$ Sivers	g_{1T} Trans-Helicity	h_1 Transversity $h_{1T}^\perp$ Pretzelosity

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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

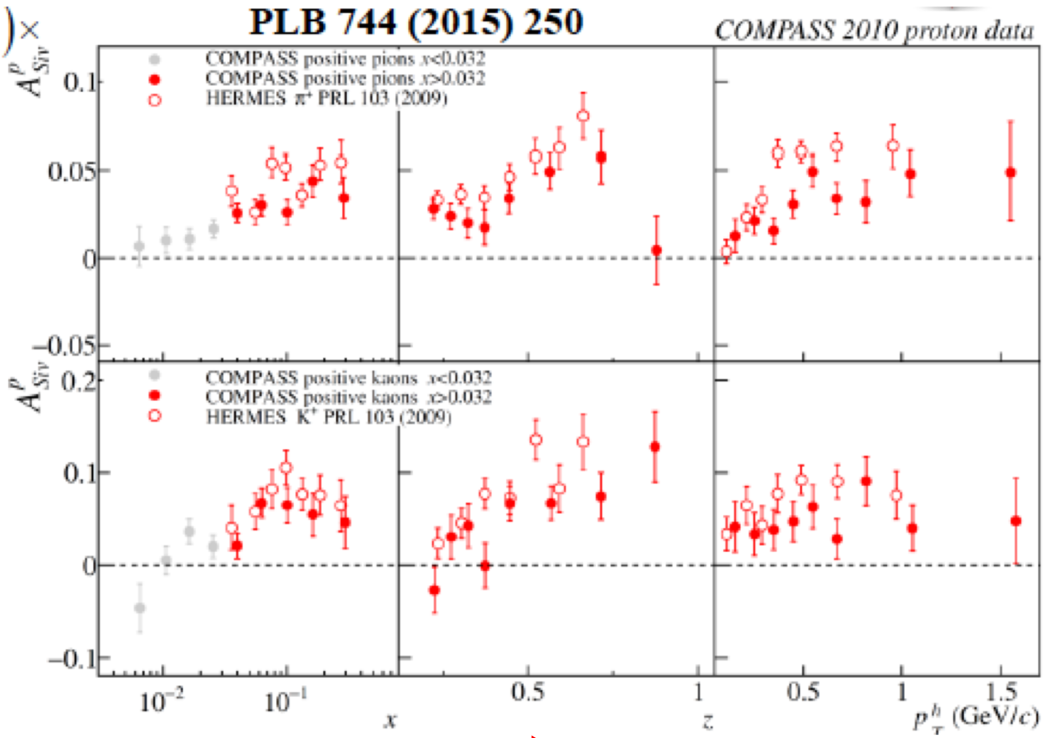


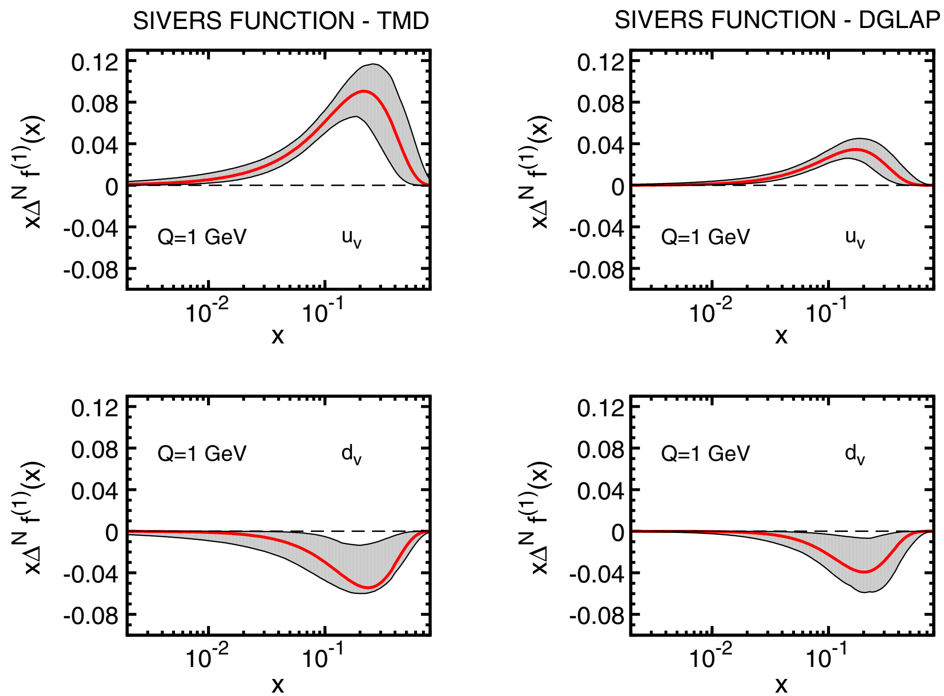
$$A_{UT}^{Collins}\propto\left\langle\sin(\phi_h+\phi_S)\right\rangle_{UT}\propto h_1\otimes H_1^{\perp}$$

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

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

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

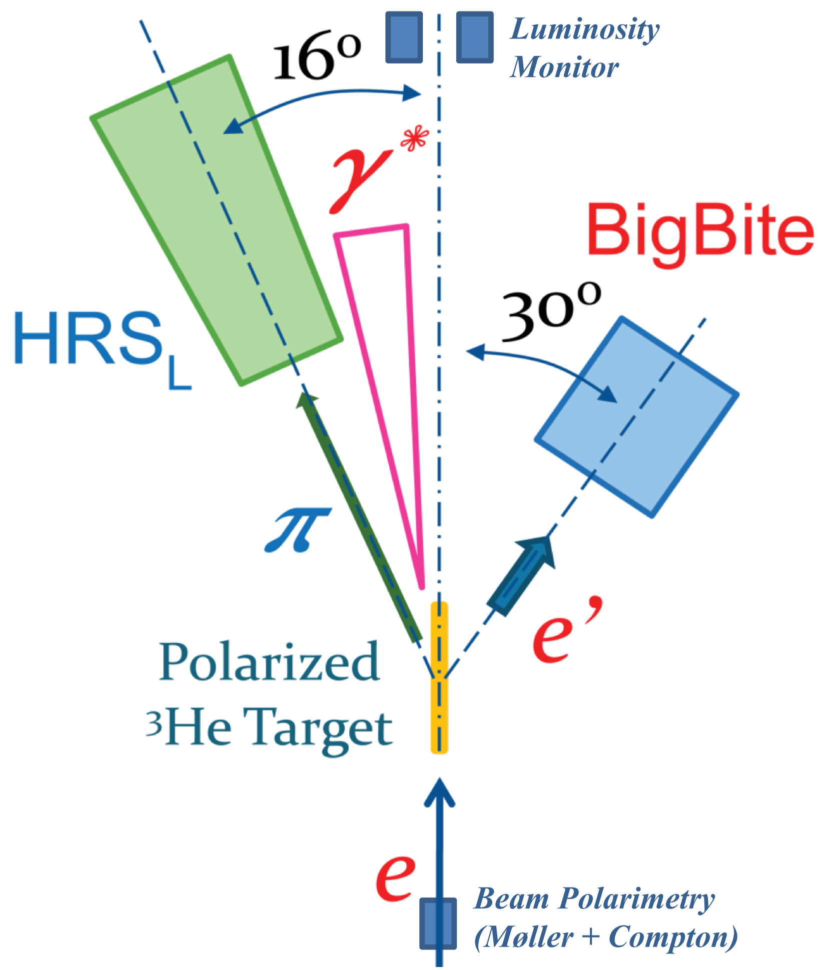
$$^3He^{\uparrow}(\vec{e}, e'\pi^{\pm})X$$

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

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

- **Results published in 8 PRL/PRC papers:**

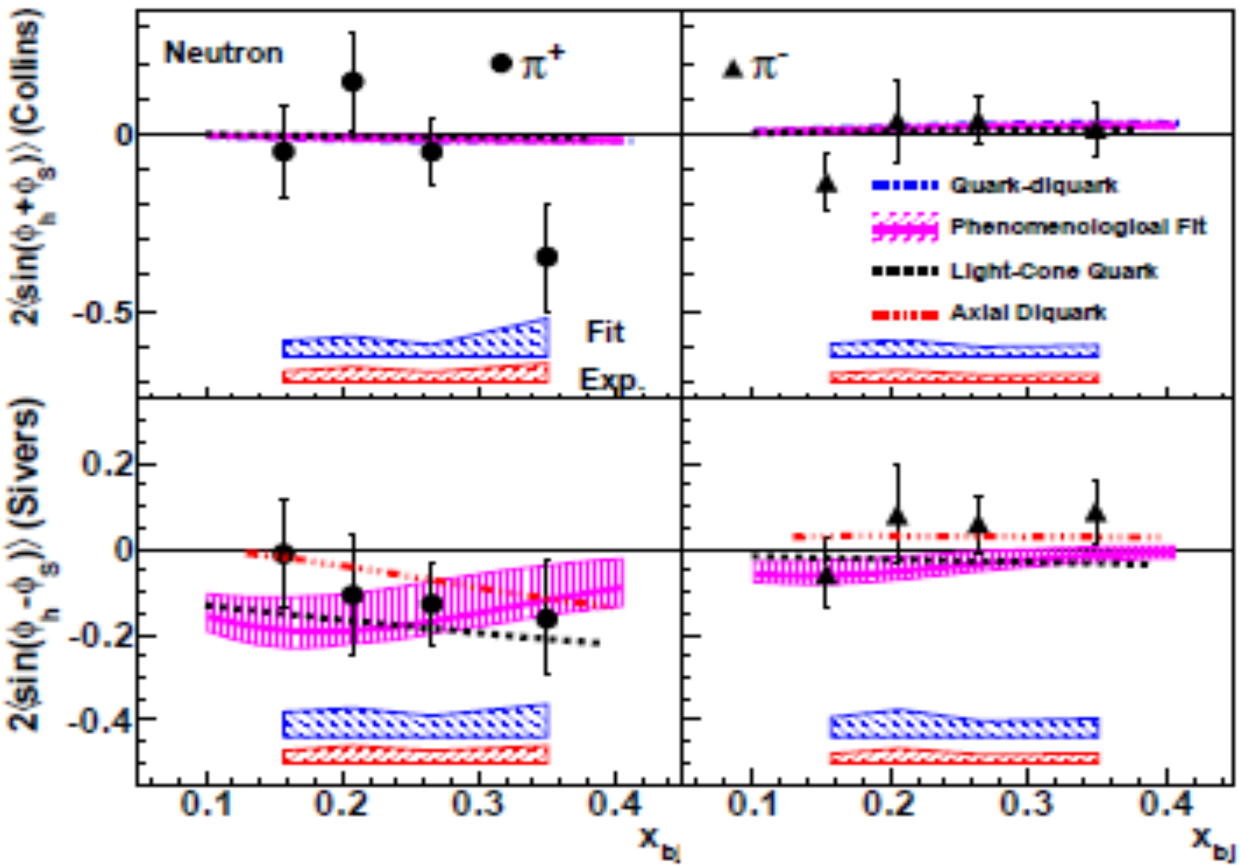
✓ **π^{+-} Collins/Sivers asymmetries: PRL 107:072003(2011)**
✓ **π^{+-} worm-gear asymmetries: PRL 108, 052001 (2012)**
✓ **π^{+-} pretzelosity asymmetries: PRC 90 5, 055209(2014)**
✓ **K^{+-} Collins/Sivers asymmetries:PRC 90 5, 05520 (2014)**
✓ **Inclusive hadron SSA: PRC 89, 042201 (2014)**
✓ **Inclusive electron SSA: PRL 113, 022502 (2014)**
✓ **Inclusive hadron DSA: PRC 92, 015207 (2015)**
✓ **π^{+-} SIDIS cross sections: PRC 95, 035209 (2017)**



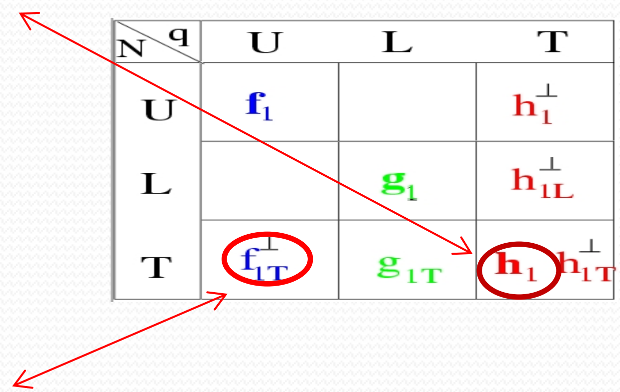
^{3}He (n) Target Single-Spin Asymmetry in SIDIS

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

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 π^+ 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

TMD Study "Milestones"

- First large single spin asymmetry in $pp \to \pi X$ (Fermi, 1970s)
- Non-zero Collins/Sivers Asymmetries (HERMES; COMPASS)
- Collins fragmentation functions (Belle)

- Twist-3: (Qiu-Sterman, 1991)
- TMD and SIDIS/Drell-Yan formalism: (Boer & Mulders, 1998)

- Sivers not power suppressed:
  - QCD final state interaction (Brodsky, Hwang & Schmidt, 2002)
  - Gauge Link: (Blitsky, Ji &Yuan; Collins, 2002; …)

- TMD factorization: (Ji, Yuan& Ma (2004); Collins (2011), …)
  - sign change for Sivers between SIDIS and Drell-Yan
  - factorization break in processes involving more than 2 hadrons
  - P_T dependence: TMD and Co-linear regions, overlap region

- Global analysis/ extraction of TMDs: (Anselmino et al., 2005, Kang et al, 2015 …)

- TMD Evolutions (Collins, 2011, Aybat, Prokudin & Rogers, …, on-going)

  …..

Planned TMD Studies with JLab 12/SoLID

Transverse Spin (Transversity) and Tensor Charge TMDs

Precision Study of TMDs: JLab 12 GeV, EIC

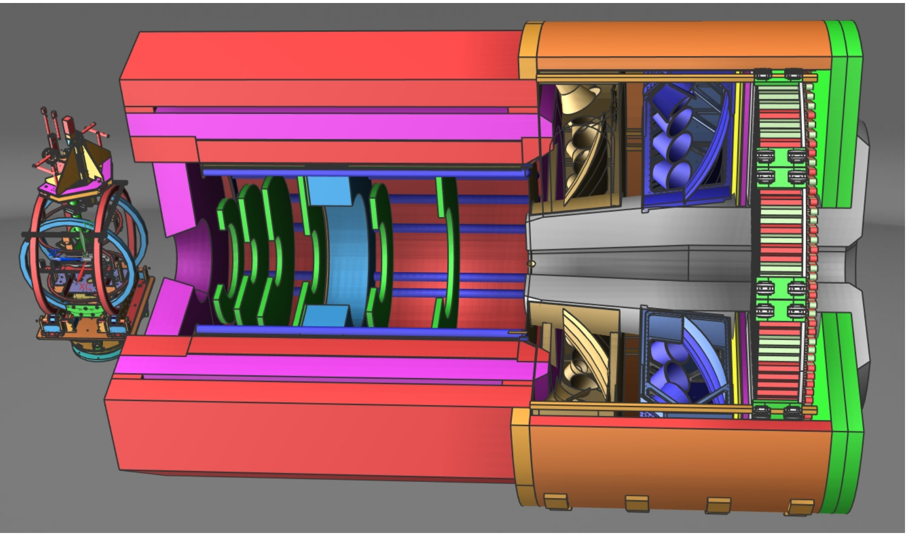
- Explorations: HERMES, COMPASS, RHIC-spin, JLab6,…
- From exploration to precision study

  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

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

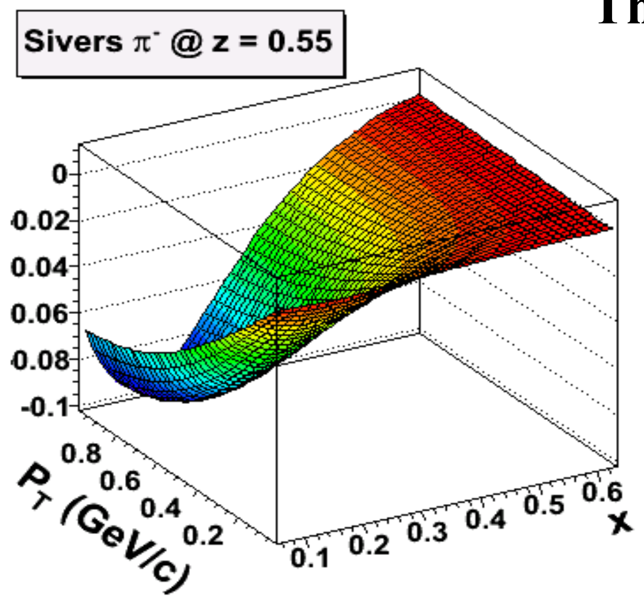


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

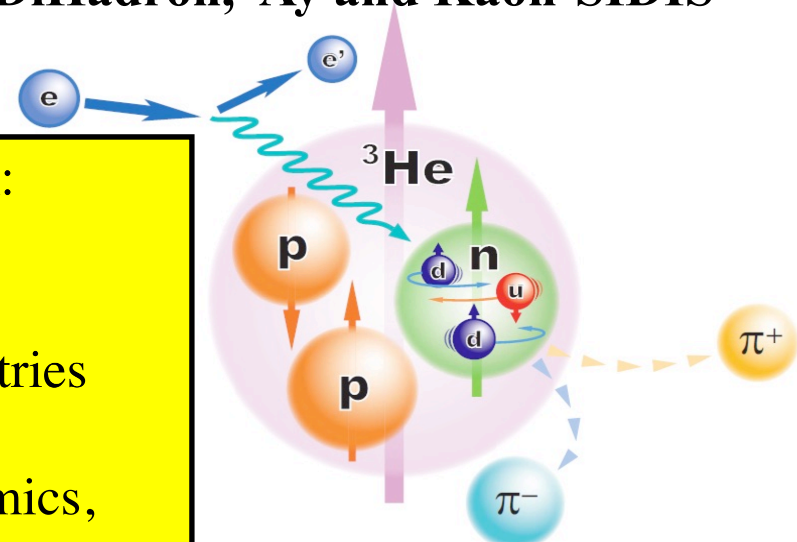
E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

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

Three run group experiments DiHadron, Ay and Kaon-SIDIS



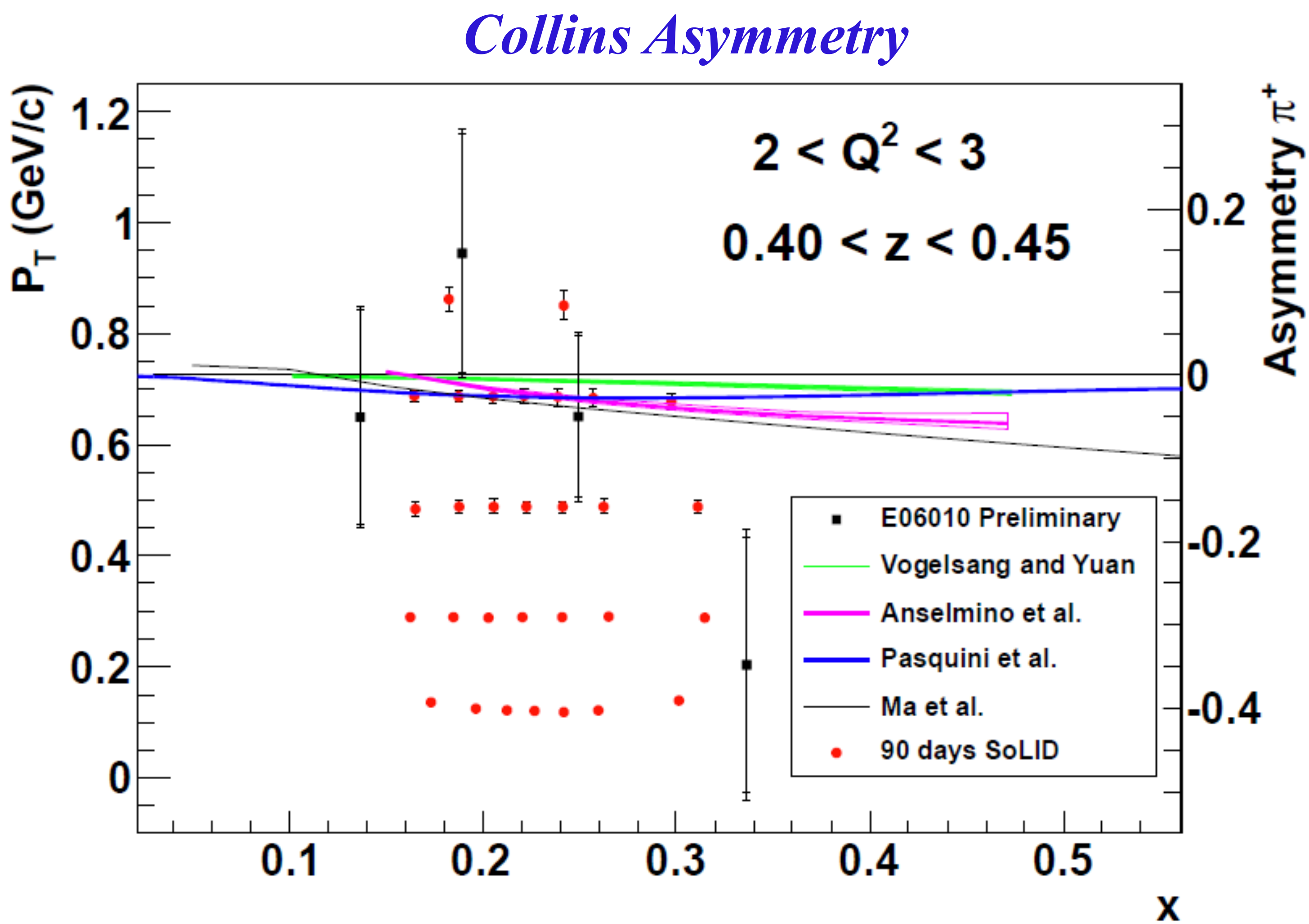
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Quark Orbital Angular Momentum, Imaging in 3-D momentum space.



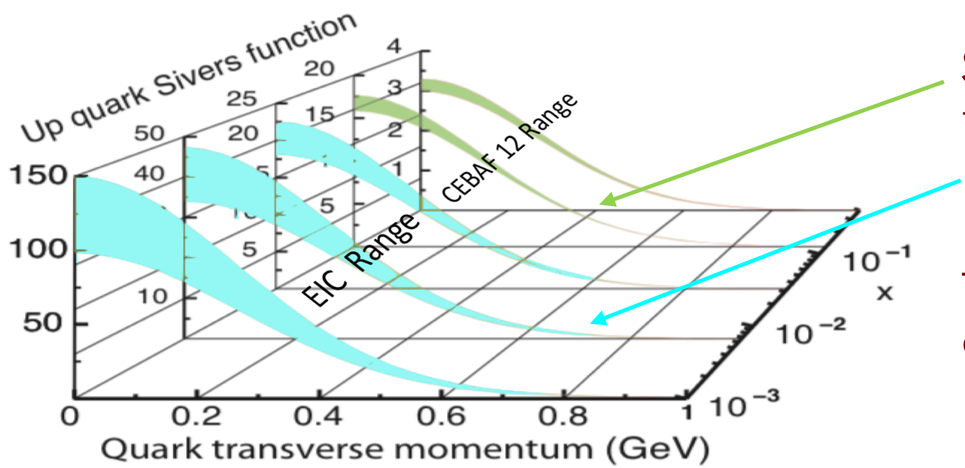
E12-10-006/E12-11-108, Both Approved with "A" Rating

Mapping of Collins(Sivers) Asymmetries with SoLID

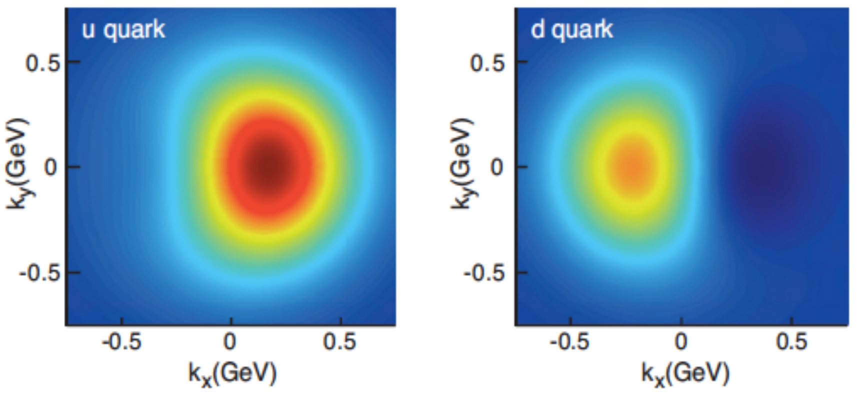
- Both π+ and π-
- Precision Map in region
  x(0.05-0.65)
  z(0.3-0.7)
  Q^2(1-8)
  P_T(0-1.6)
- <10% d quark tensor charge



SoLID and EIC: full imaging of nucleons and study QCD



Polarized Quark 3D Momentum distributions



SoLID - high precision extraction of Sivers function in the valence quark region
– complementary to EIC Sivers measurement

Transversity distribution (valence quark dominant) and tensor charge – unique SoLID contribution

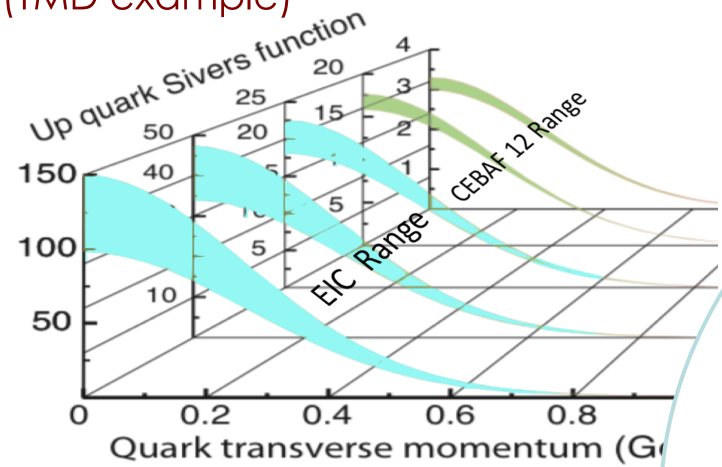
$$g_T^q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x)\right] dx$$

1. A fundamental QCD quantity
2. Matrix element of local operators
3. Calculable in lattice QCD.
4. Connects to quark electric dipole moment

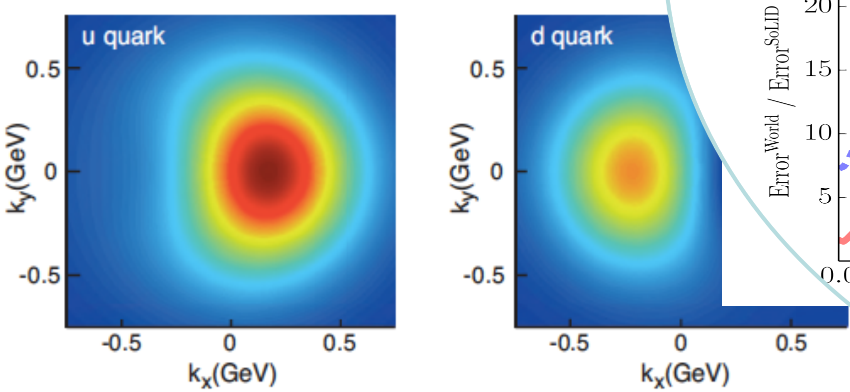
and sensitive to new physics beyond SM

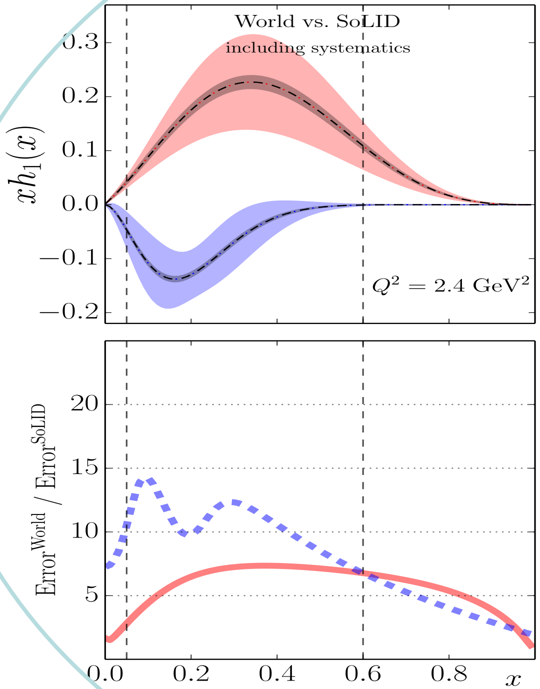
SoLID and EIC: full imaging of nucleons and study QCD

(TMD example)

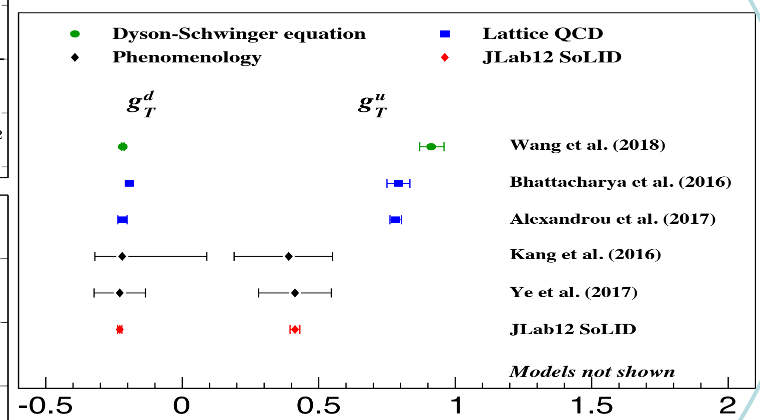


Polarized Quark 3D Momentum distributions





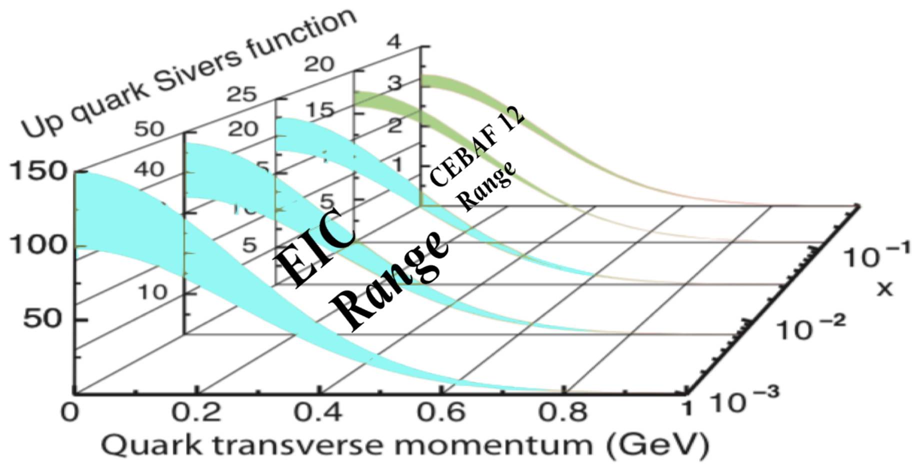
Tensor Charge



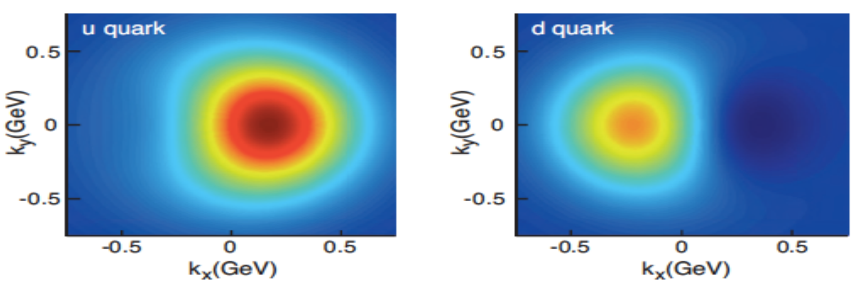
Transversity: valence quark effect

Z. Ye *et al.*, PLB 767, 91 (2017)

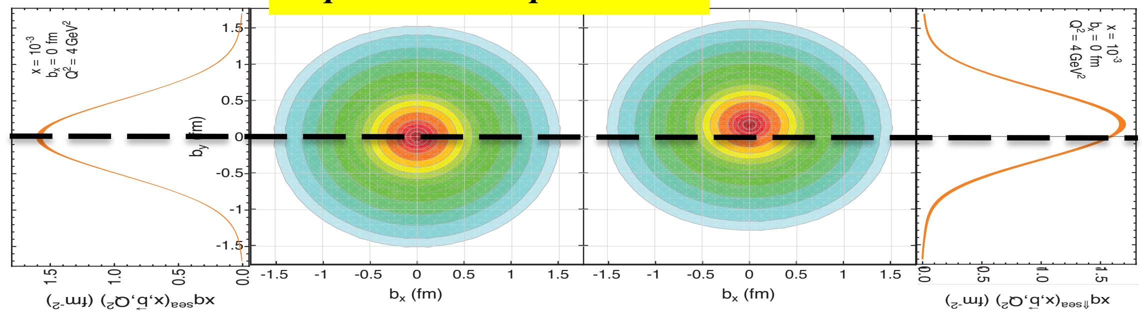
EIC Science: Imaging quarks and gluons in nucleons



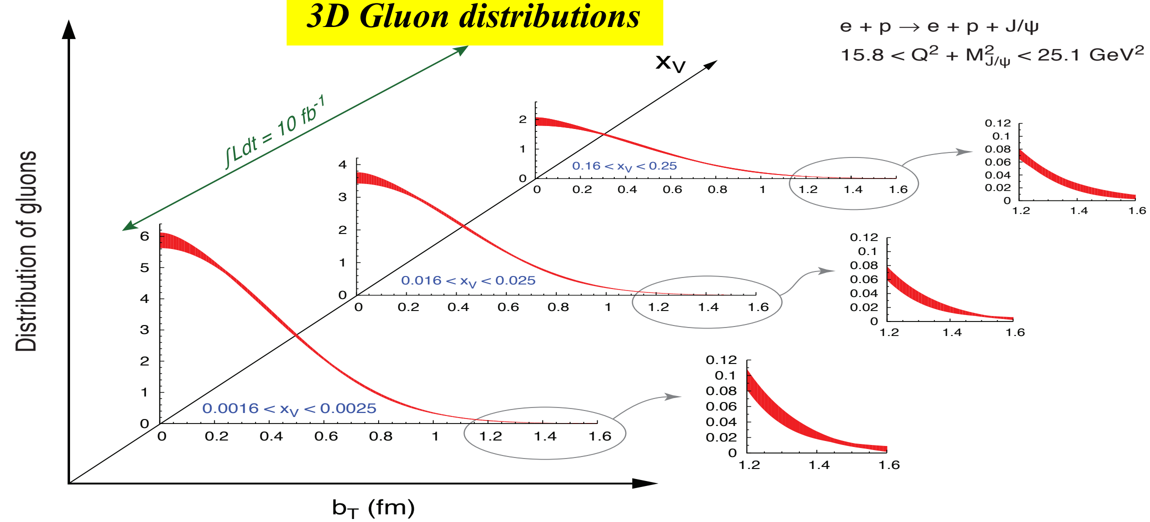
Polarized Quark 3D Momentum distributions



3D Sea Quark distributions unpolarized and polarized



3D Gluon distributions



TMDs and Orbital Angular Momentum

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

Sivers: Related to GPD E through Lensing Function

Quark Orbital Angular Momentum

Nucleon spin ½ = ½ ΔΣ + L_q + J_g Ji (gauge invariant)

= ½ ΔΣ + $\mathcal{L}_q + \Delta G + \mathcal{L}_g$ Jeffe-Manohar (light-cone)

- Spin Puzzle: missing piece, orbital angular momentum (OAM)
- Indirect evidence → OAM is significant
- Lattice Calculation: u and d cancellation?

  disconnected diagrams
- Ji's sum rule:

$$J_{q,g} = \frac{1}{2}\int dx\,x\,(H_{q,g}(x,0,0) + E_{q,g}(x,0,0)) \;,$$

measure GPDs to access the total angular momentum

needs GPD E (and H) be measured in all x at fixed ξ

DVCS only access GPDs @ x=ξ ridge

experimentally difficult to measure GDPs at all x with fixed ξ, if not impossible

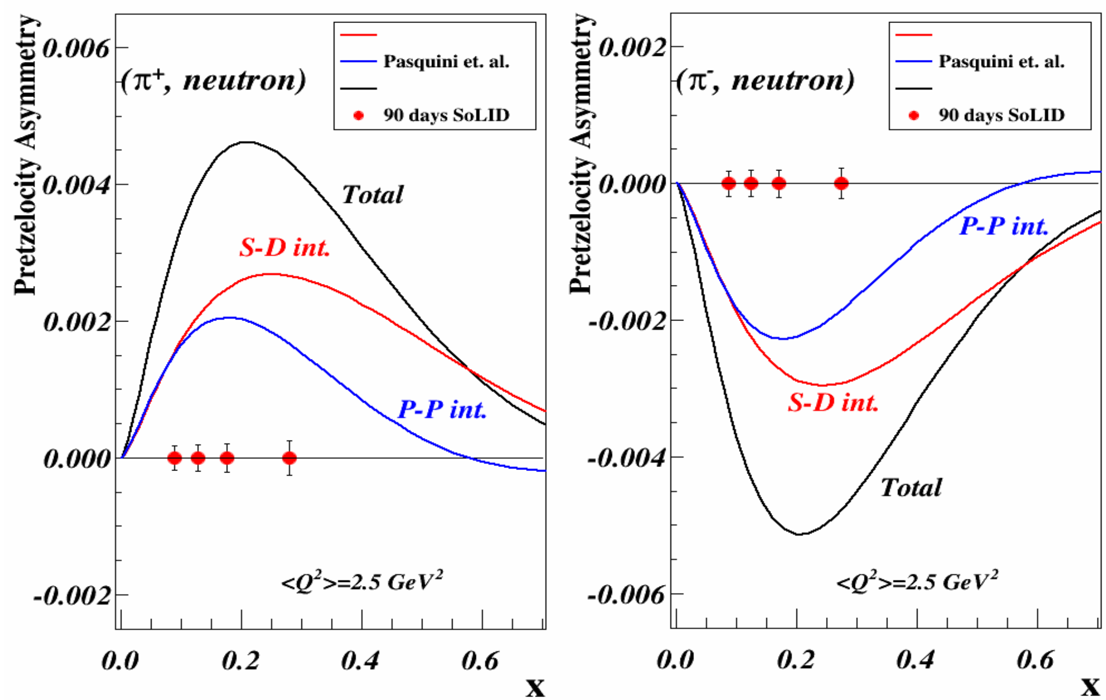
DDVCS?

OAM and Parton Distributions

- How best to access/measure quark orbital angular momentum?
  Extensively discussed in the last decade or so
  X. Ji, et al., arXiv:1202.2843; 1207.5221
  " Thus a partonic picture of the orbital contribution to the nucleon helicity necessarily involves parton's transverse momentum. In other words, TMD parton distributions are the right objects for physical measurements and interpretation. "
- Transversely polarized nucleon: $$J_q = \frac{1}{2}\sum_i \int dx x \left[q_i(x) + E_i(x,0,0)\right] ,$$
- Longitudinally polarized nucleon: related to Twist-3 GPDs (more difficult?)
- Intuitive definition: L= r x p → can be defined in Wigner Distributions
  $$L(x) = \int (\vec{b}_\perp \times \vec{k}_\perp) W(x, \vec{b}_\perp, \vec{k}_\perp) d^2\vec{b}_\perp d^2\vec{k}_\perp ,$$
  access through both TMDs and GPDs
  possible direct measurement of Wigner distributions? J. Qiu, S. Liuti,
  Gluon Wigner distribution: Hatta, et al.,… (2017)
- Parton spin-orbital correlations → transverse momentum
  TMDs provide direct information
- TMD information related to $\mathbf{L_q}$ and /or $\mathcal{L}_q$?

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 $h_{1T}^\perp$

Angular Momentum (1)

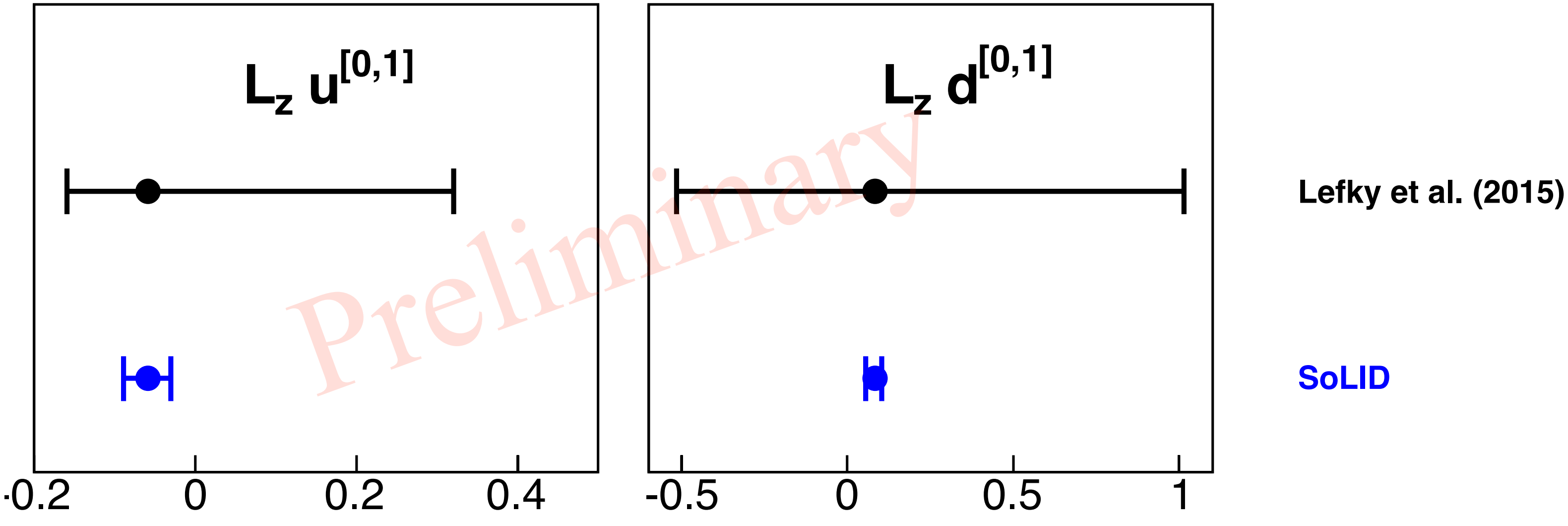
OAM and pretzelosity:

model dependent

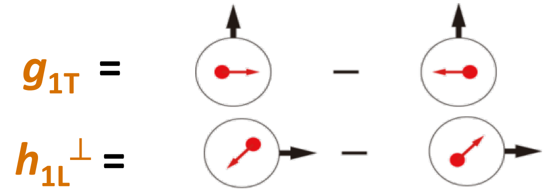
$$L_z = -\int d\,x\,d^2\,k_\perp\,\frac{k_\perp{}^2}{2\,M_p^2}\,h_{1T}^\perp\left(x, k_\perp{}^2\right)$$

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

SoLID impact:

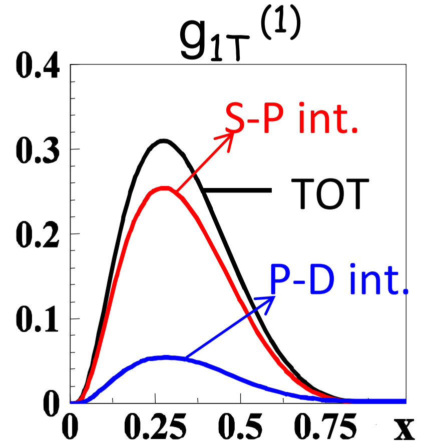


Worm-gear Functions



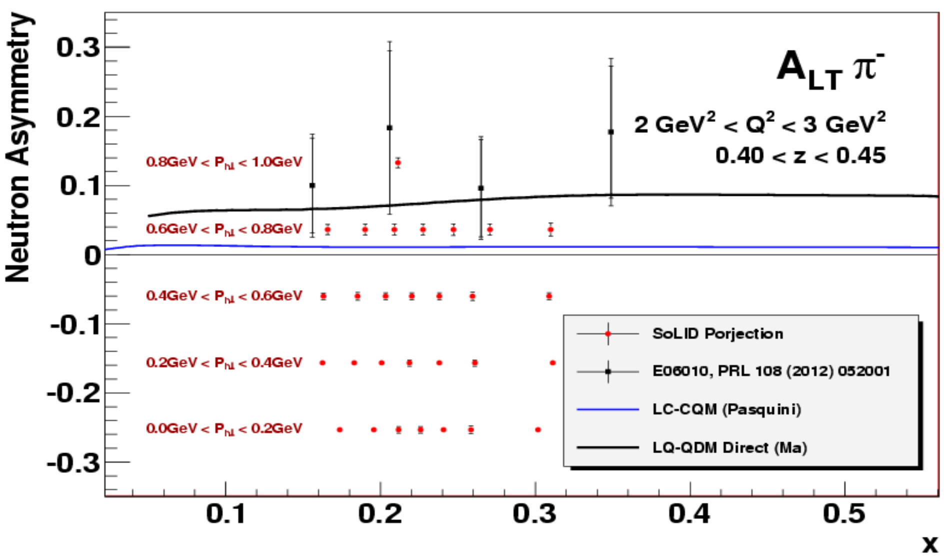
- Dominated by real part of interference between **L=0 (S) and L=1 (P) states**
- No GPD correspondence
- Exploratory lattice QCD calculation:
  Ph. Hägler et al, EPL 88, 61001 (2009)

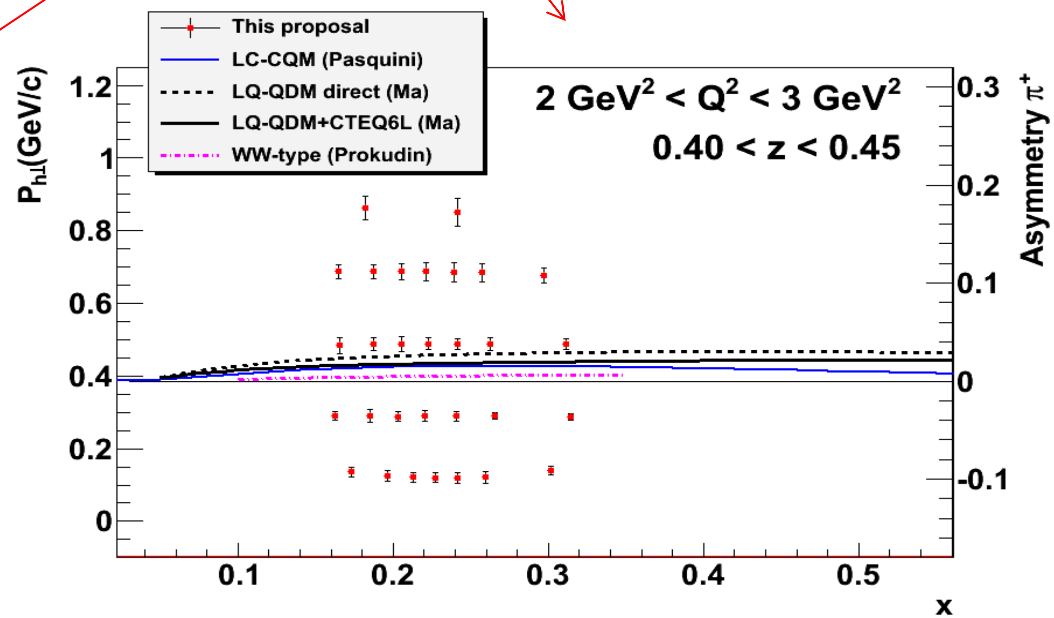
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



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

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

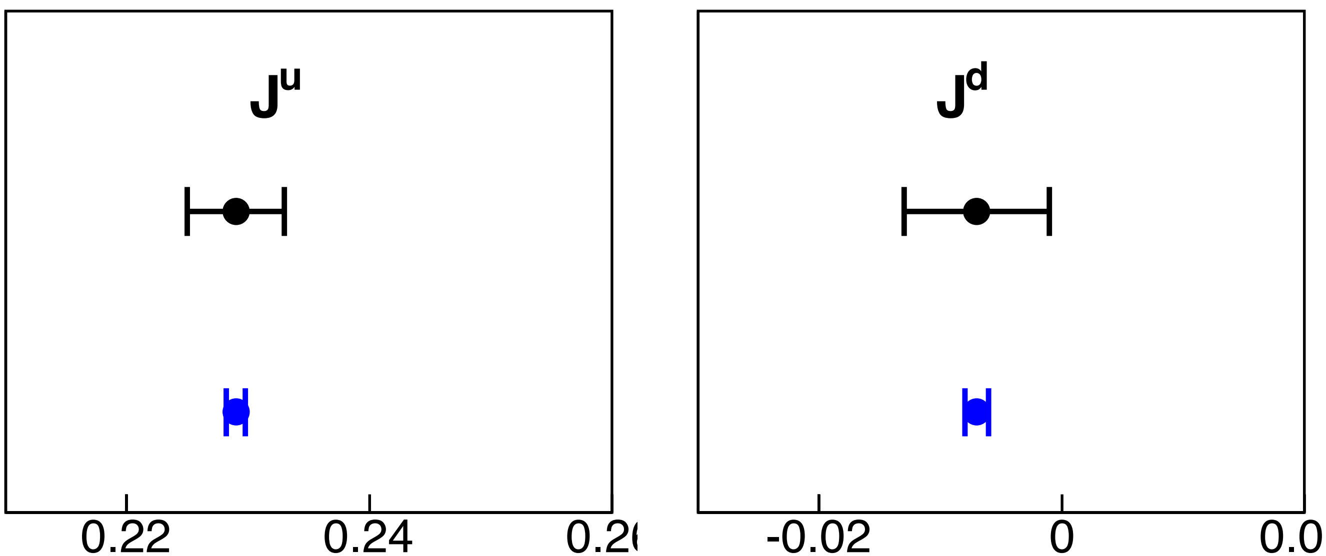
$$L(\mathrm{x}) = \frac{\mathrm{K}}{(1-x)^{\eta}}$$ lensing function

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:



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

  \+ three 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

- JLab Highlights: Valance Structure

  Precision EM form factors, proton radius

  Nucleon spin-flavor structure (unpolarized and polarizd)

  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?

Homework

- Why electron (lepton) beam is a “clean” probe to study nucleon structure?
- What is the nucleon “spin crisis/puzzle” and what do we know now?
- What do 1-d and 3-d nucleon structure mean?
- What are the main scientific goals of energy upgraded JLab and planned US Electron-Ion Collider?