Physics with an Electron-Ion Collider

III: 1-d Structure: Parton Distributions

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

Pre-Workshop Lectures, Hadron-China2018, July 25, 2018

- Deep-Inelastic Scattering:

  Unpolarized Structure Functions → Parton Distribution Functions

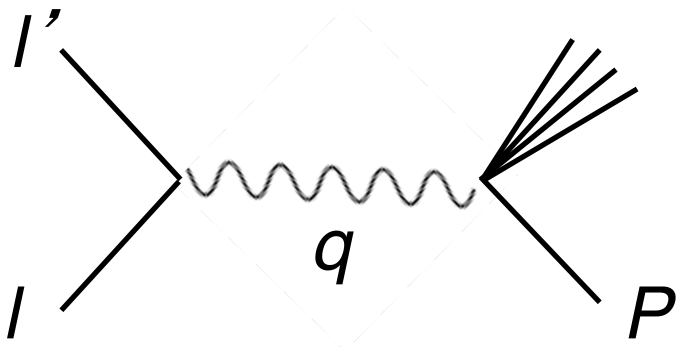
  High-x physics

  Sea asymmetry

Deep-Inelastic Scattering
Unpolarized Nucleon Structure

Parton Distributions:
Flavor Structure: Valence and Sea
Gluons

Inelastic Scattering



Considerably more complex, indeed!

Simplify - consider *inclusive* inelastic scattering,

$$d\sigma \propto \left\langle |\mathcal{M}|^2 \right\rangle = \frac{g_e^4}{q^4} L^{\mu\nu}_{\text{lepton}} W_{\mu\nu\,\text{nucleon}}, \qquad W_{\mu\nu\,\text{nucleon}}(p, q)$$

Again, <u>two</u> (parity-conserving, spin-independent) structure functions:

$$W_1, W_2 \ \ \text{or, alternatively expressed,} \ \ F_1, F_2$$

which may depend on <u>two</u> invariants,

$$Q^2 = -q^2, \qquad x = -\frac{q^2}{2q.p}, \ 0 < x < 1$$

So much for the structure, the physics is in the structure functions.

Elastic scattering off Dirac Protons

Compare:

$$L^{\mu\nu}_{\text{lepton}} = 2\left(k^\mu k'^\nu + k^\nu k'^\mu + g^{\mu\nu}(m^2 - k \cdot k')\right)$$

with:

$$K_{\mu\nu\,\text{nucleon}} = K_1\left(-g_{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) + \frac{K_2}{M^2}\left(p^\mu + \frac{1}{2}q^\mu\right)\left(p^\nu + \frac{1}{2}q^\nu\right)$$

which uses the relations between $K_{1,2}$ and $K_{4,5}$

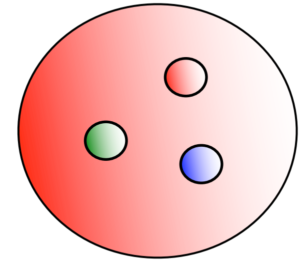
Then, e.g. by substitution of $k' = k\text{-}q$ in L:

$$K_1 = -q^2, \quad K_2 = 4M^2$$

Note, furthermore, that inelastic cross section reduces to the elastic one for:

$$W_{1,2}(q^2, x) = -\frac{K_{1,2}(q^2)}{2Mq^2}\delta(x-1)$$

Elastic scattering off Dirac Partons



Imagine *incoherent* scattering off *Dirac* Partons (quarks) q :

$$W_1^q = \frac{e_q^2}{2m_q}\delta(x_q - 1), \quad W_2^q = -\frac{2m_q e_q^2}{q^2}\delta(x_q - 1) \;\; \text{and} \;\; x_q = -\frac{q^2}{2q\cdot p_q}$$

and, furthermore, suppose that the quarks carry a fraction, z, of the proton momentum

$$p_q = z_q\, p, \quad \text{so that} \;\; x_q = \frac{x}{z_q} \quad (\text{also note} \;\; m_q = z_q M\,!)$$

which uses the relations between $K_{1,2}$ and $K_{4,5}$

Now,

$$MW_1 = M\sum_q \int_0^1 \frac{e_q^2}{2M}\delta(x - z_q)\, f_q(z_q)\, dz_q = \frac{1}{2}\sum_q e_q^2 f_q(x) \equiv F_1(x)$$

$$-\frac{q^2}{2Mx}W_2 = \sum_q \int_0^1 x e_q^2 \delta(x - z_q)\, f_q(z_q)\, dz_q = x\sum_q e_q^2 f_q(x) \equiv F_2(x)$$

Two important *observable* consequences,

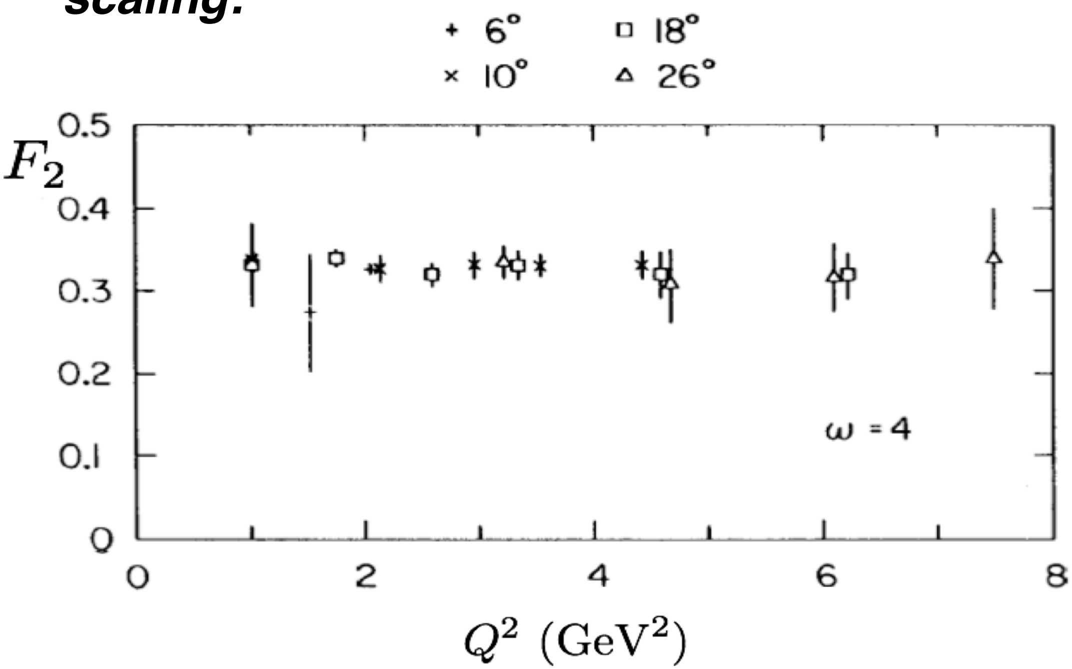
Bjorken scaling: $F_{1,2}(x), \;\; \text{not} \;\; F_{1,2}(x, Q^2)$

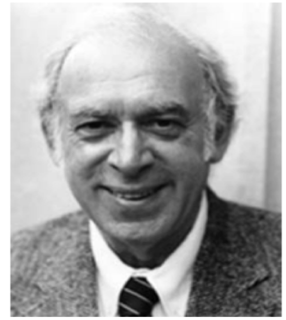
Callan-Gross relation: $F_2 = 2xF_1(x)$

Deep-Inelastic Electron Scattering

Discovery of Quarks (Partons)

Bjorken scaling:





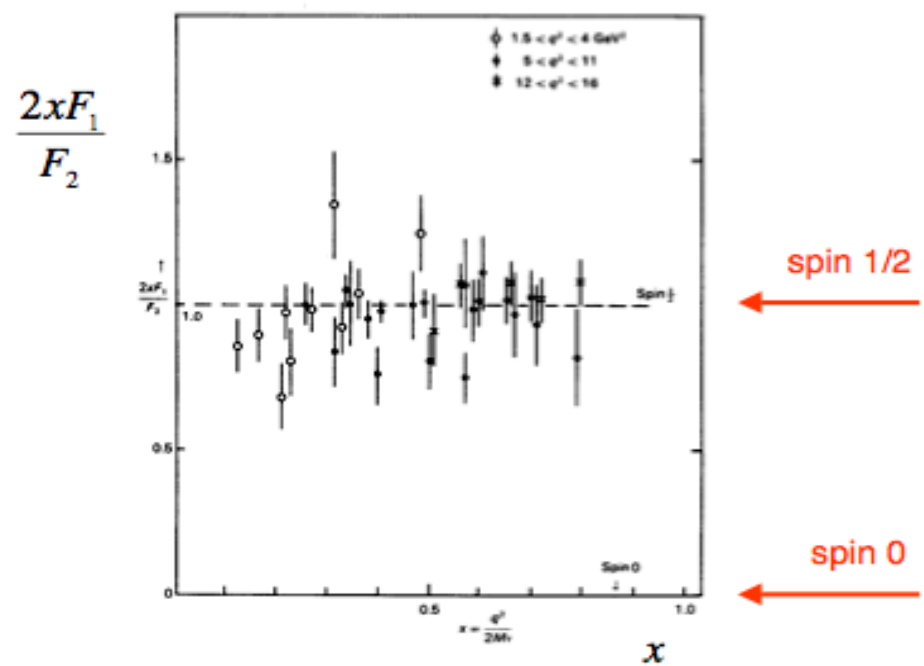
J.T. Friedman

R. Taylor

H.W. Kendall

Nobel Prize 1990

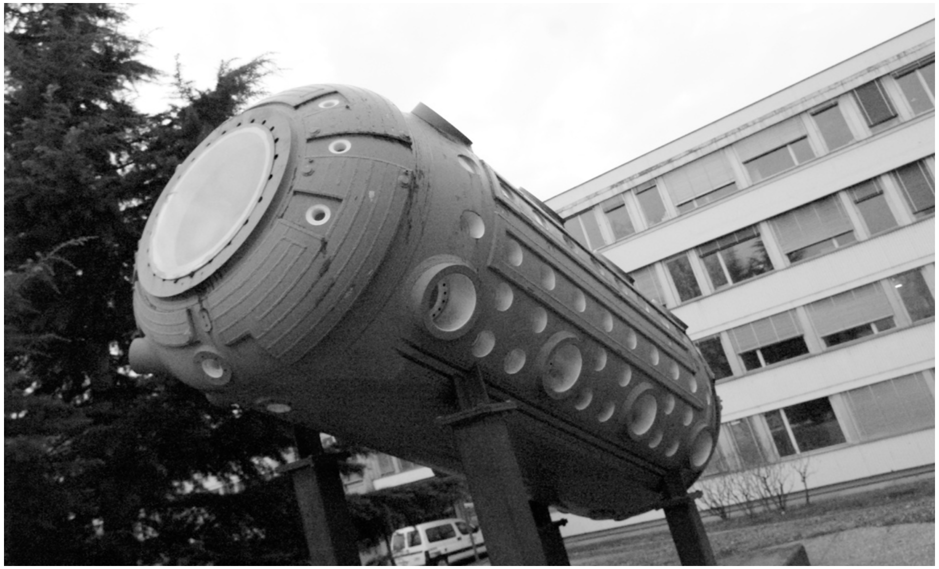
Callan-Gross relation:



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.

Deep-Inelastic Neutrino Scattering

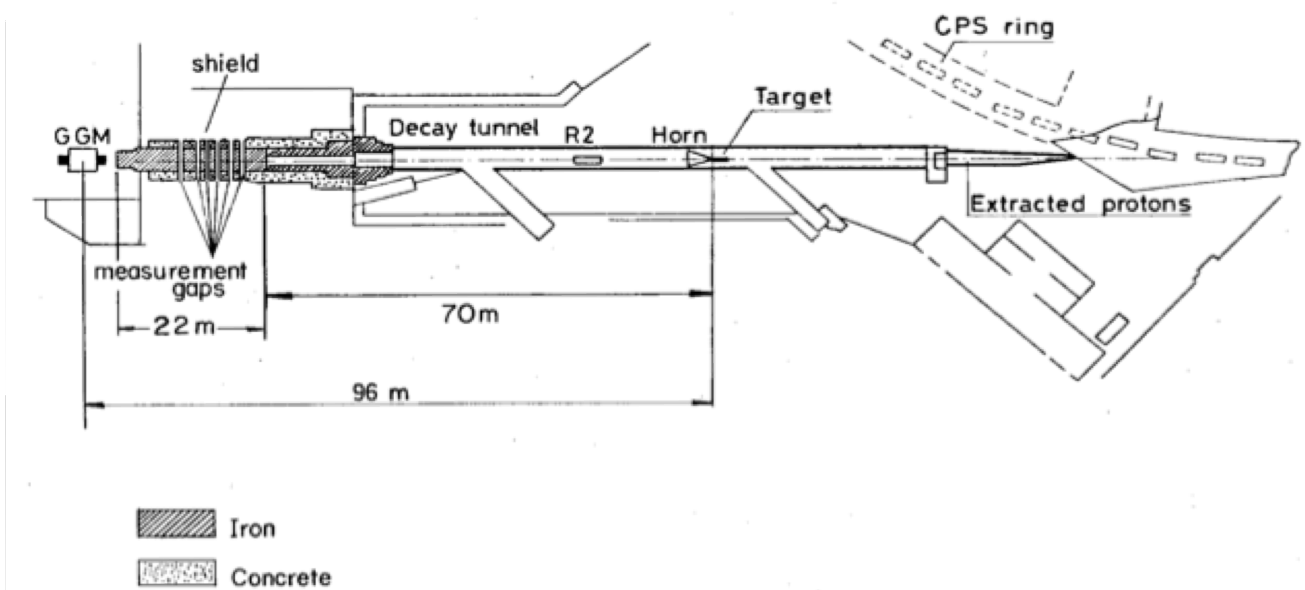


Picture from CERN...

Gargamelle bubble chamber, observation of weak neutral current (1973).

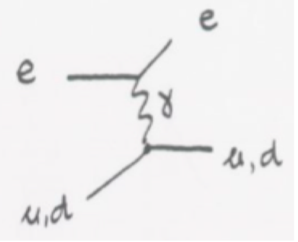
Charged-current DIS!

Nucl.Phys. **B73** (1974) 1
Nucl.Phys. **B85** (1975) 269
Nucl.Phys. **B118** (1977) 218
Phys.Lett. **B74** (1978) 134



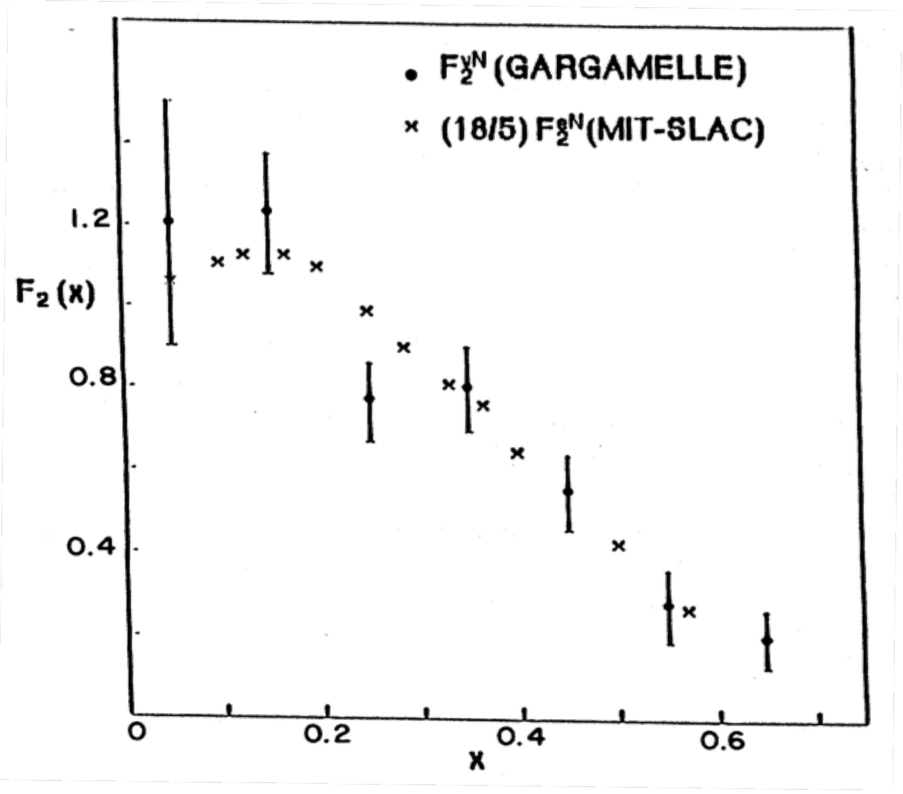
Deep-Inelastic Scattering - Fractional Electric Charges

Neutral-current (photon) DIS:

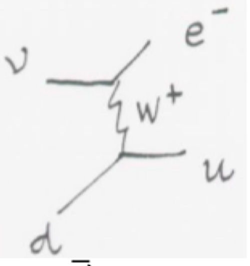


$$F_2 = x \sum e_q^2 (q + \bar{q}), \quad p : uud, \quad n : ddu$$

$$F_2^N = x \, \frac{e_u^2 + e_d^2}{2} \, (u + \bar{u} + d + \bar{d})$$



Charged-current DIS:



$$F_2^{\nu p} = 2x(d + \bar{u}), \quad F_2^{\nu n} = 2x(u + \bar{d})$$

$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

Deep-Inelastic Scattering - Fractional Electric Charges

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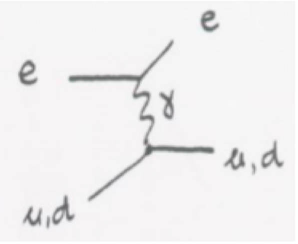

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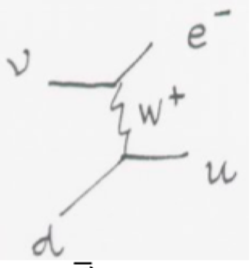
Charged-current DIS:

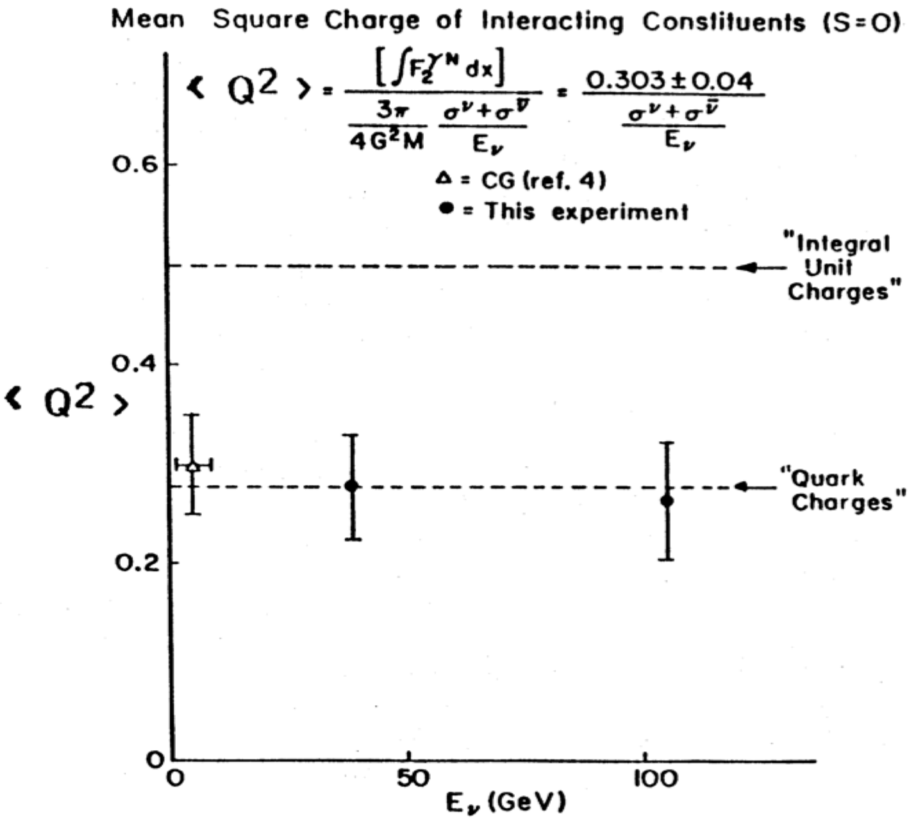


$$F_2^{\nu p} = 2x(d + \bar{u}), \quad F_2^{\nu n} = 2x(u + \bar{d})$$

$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$

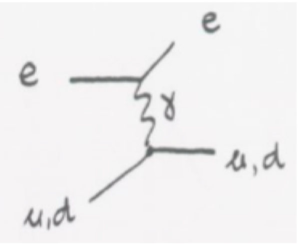
Ratio:

$$\frac{F_2^N}{F_2^{\nu N}} = \frac{1}{2}(e_u^2 + e_d^2) = \frac{5}{18} \simeq 0.28$$



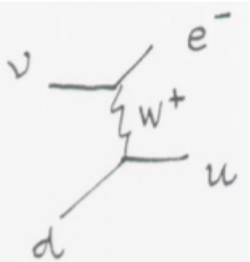
Deep-Inelastic Scattering - Momentum Conservation

Neutral-current (photon) DIS:

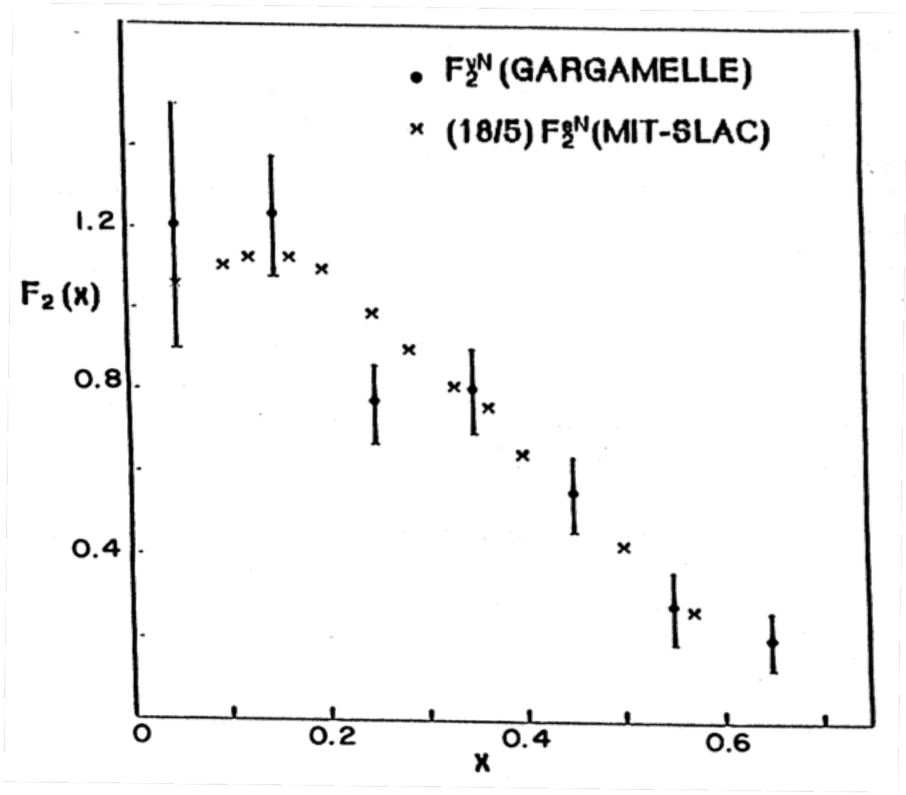


$$F_2^N = x\,\frac{e_u^2 + e_d^2}{2}\,(u + \bar{u} + d + \bar{d})$$

Charged-current DIS:



$$F_2^{\nu N} = x(u + \bar{u} + d + \bar{d})$$



Momentum fraction:

$$\int_0^1 F_2^N\,dx = \frac{e_u^2 + e_d^2}{2}\int_0^1 x(u + \bar{u} + d + \bar{d})$$

Gargamelle: 0.49 +/- 0.07

SLAC: 0.14 +/- 0.05

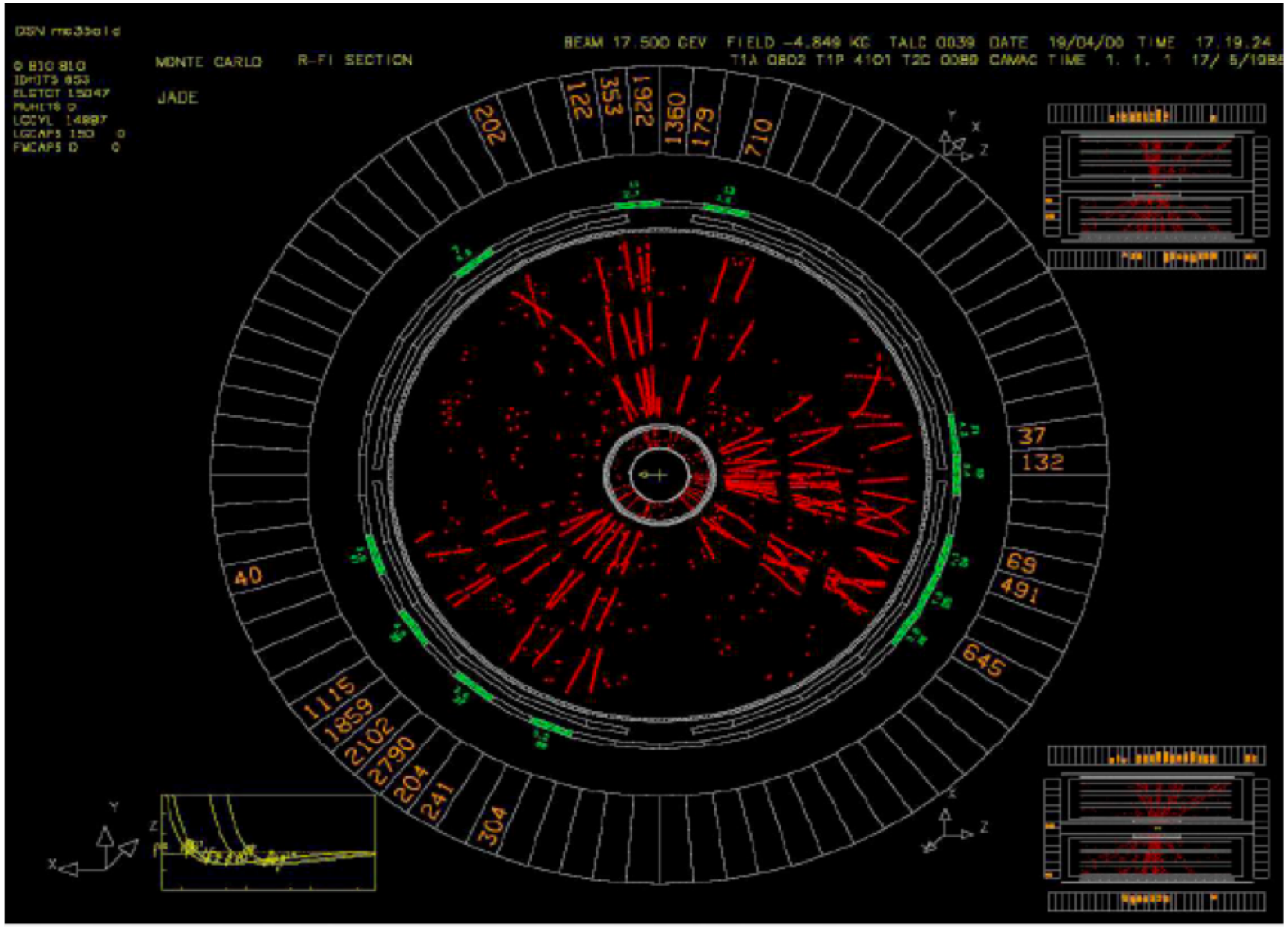
Quarks carry half of the nucleon momentum!

3-jet events at PETRA

Recall the intro on colour:

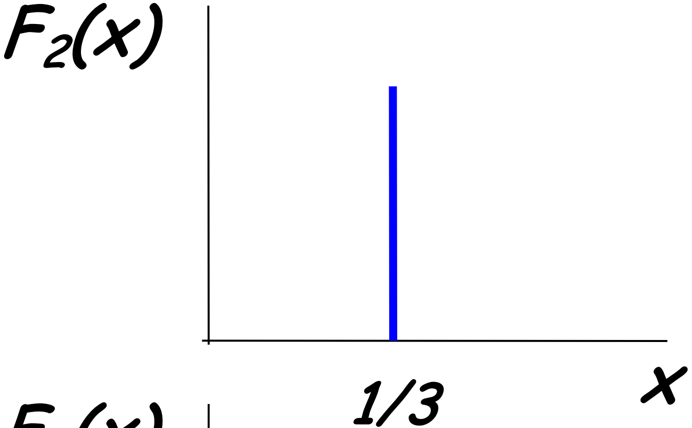
Observation of its higher order process,

marks the discovery of the gluon.

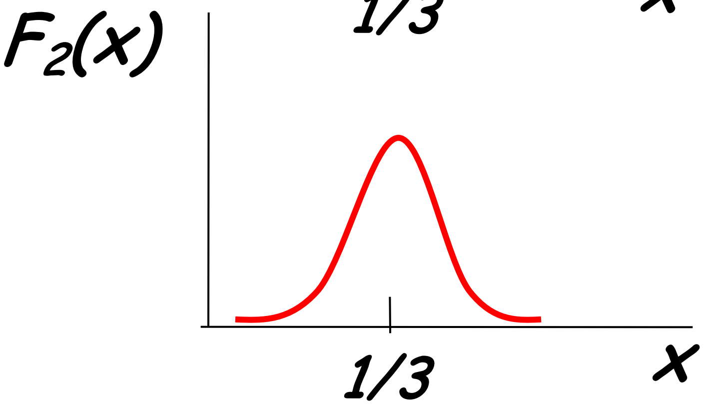


Mom. Conservation: *Gluons carry the other half of the nucleon momentum.*

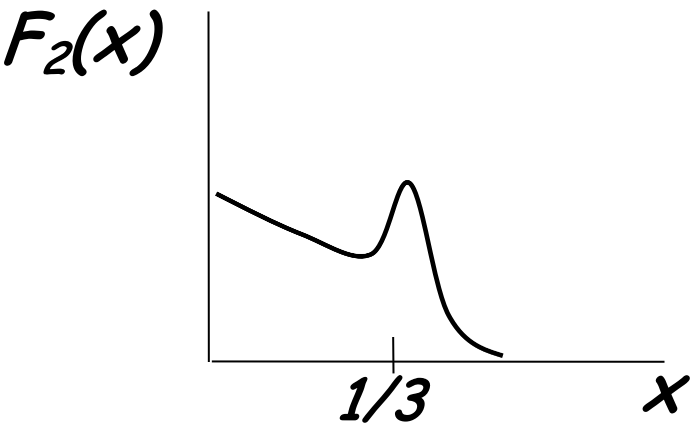
Nucleon Structure



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.

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

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

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

QCD Radiation

Schematically, DGLAP equations:

convolution

$$\frac{dq_f(x,Q^2)}{d\ln Q^2} = \alpha_s \left[q_f \otimes P_{qq} + g \otimes P_{gq} \right]$$

strong coupling constant

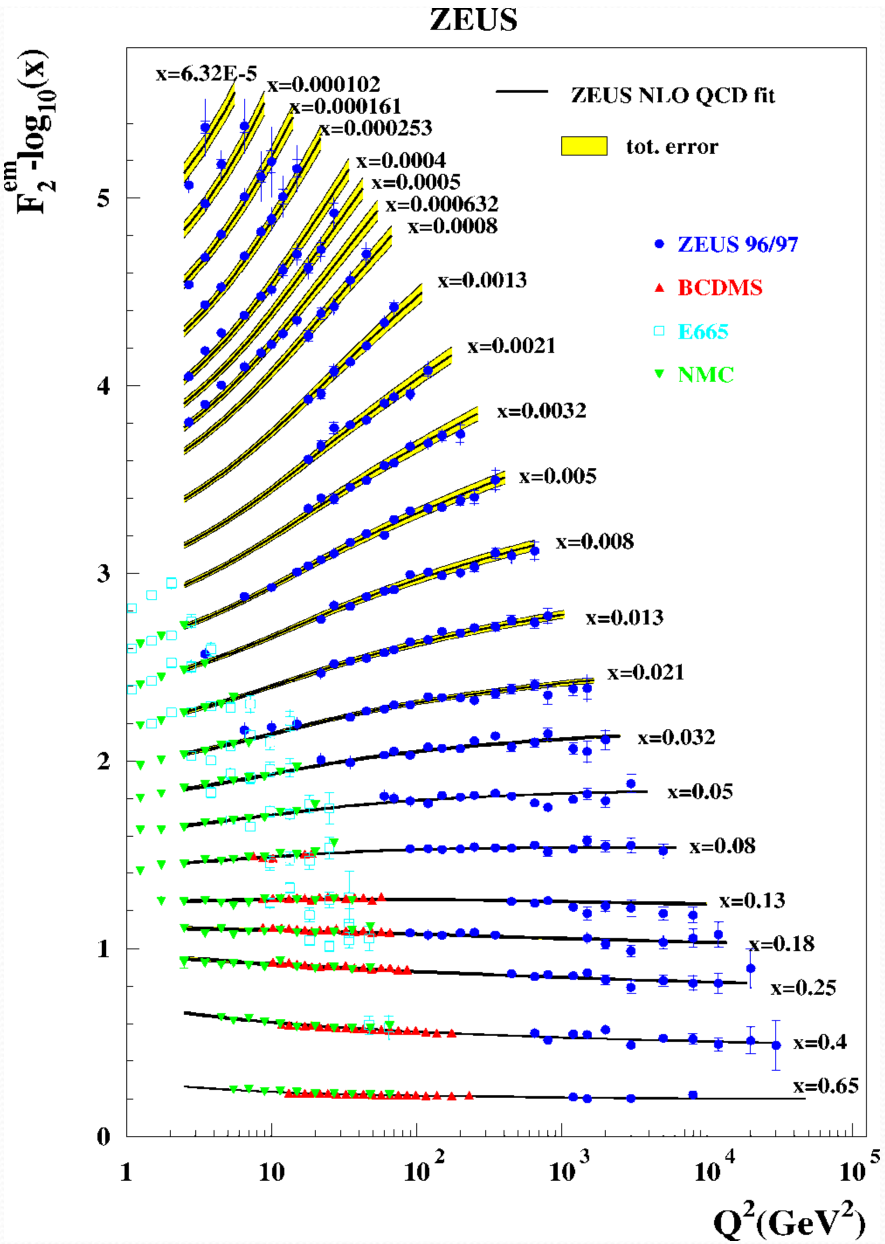
That is, the change of quark distribution *q* with Q^2 is given by the probability that *q* and *g* radiate *q*.

Similarly, for gluons:

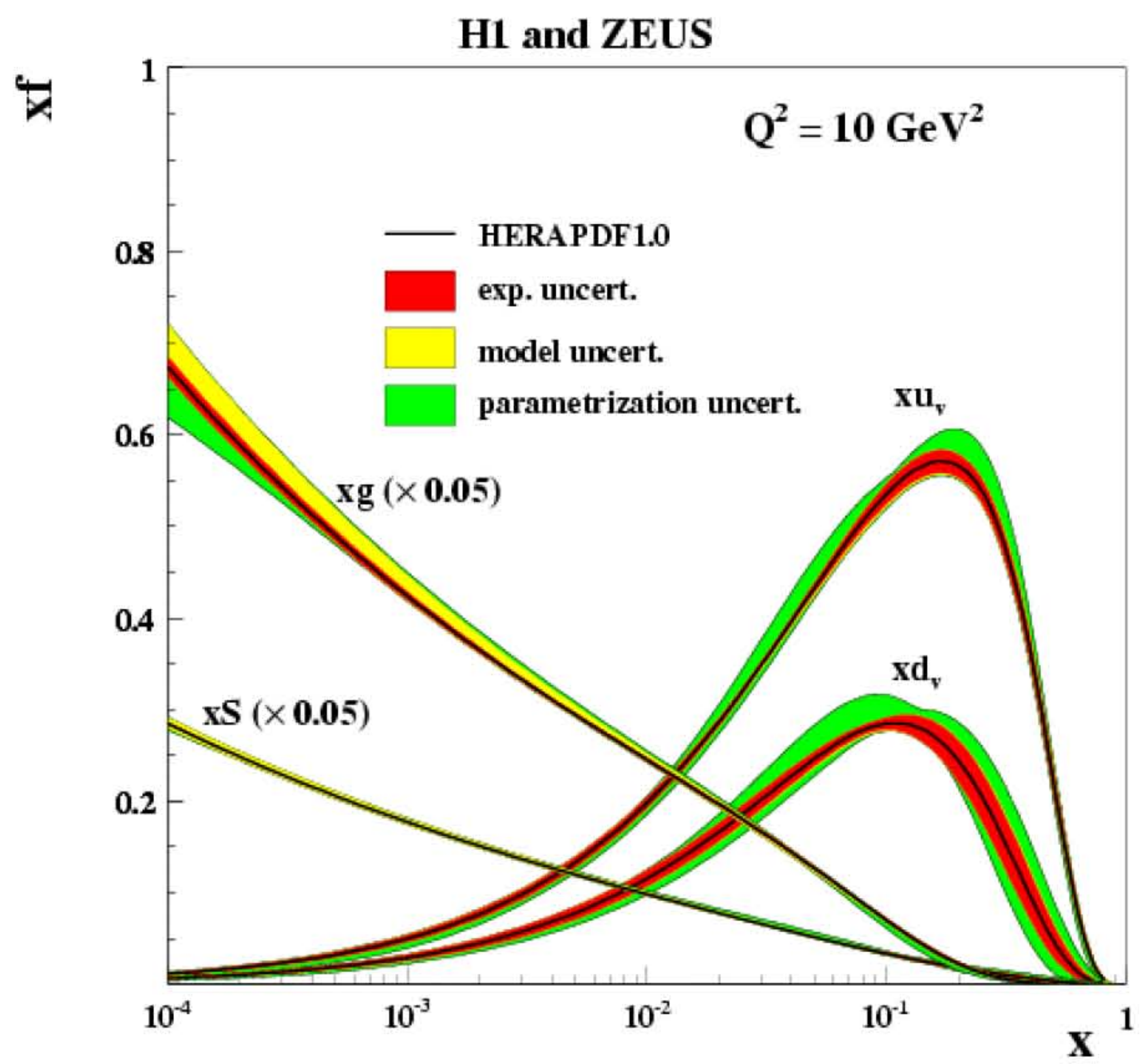
$$\frac{dg(x,Q^2)}{d\ln Q^2} = \alpha_s \left[\sum q_f \otimes P_{qg} + g \otimes P_{gg} \right]$$

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**

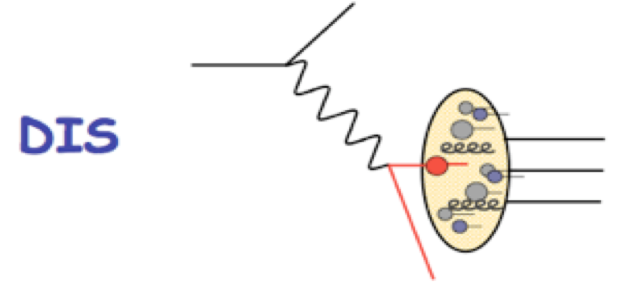


Parton Distribution Functions (CTEQ6)



JHEP 1001: 109 (2010)

Brief Summary:



DIS probe nucleon or nuclear structure,
described in terms of quarks and gluons,

Feynman's parton model - point like partons, which
behave *incoherently* - combined with QCD radiation are remarkably successful in describing DIS cross sections.

QCD evolution allows one to relate quantitatively processes at different scales Q^2,

Parton distributions *f(x)* are intrinsic properties of the nucleon and (thus) process independent.
This is great for RHIC, LHC, and many other areas.

Gluons are a very significant part of the nucleon

Structure Functions at High x

Valence Quark Distributions

Why Are PDFs at High x Important?

- Valence quark dominance: simpler picture
  -- direct comparison with nucleon structure models
  SU(6) symmetry, broken SU(6), di-quark, DSE
- $x \rightarrow 1$ region amenable to pQCD analysis
  -- hadron helicity conservation?
  -- Quark orbital angular momentum
- Clean connection with QCD, via lattice moments
- Input for search for physics BSM at high energy collider
  -- evolution: high x at low $Q^2 \rightarrow$ low x at high Q^2
  -- small uncertainties amplified
  -- example: HERA 'anomaly' (1998)
- Input to nuclear and high energy calculations

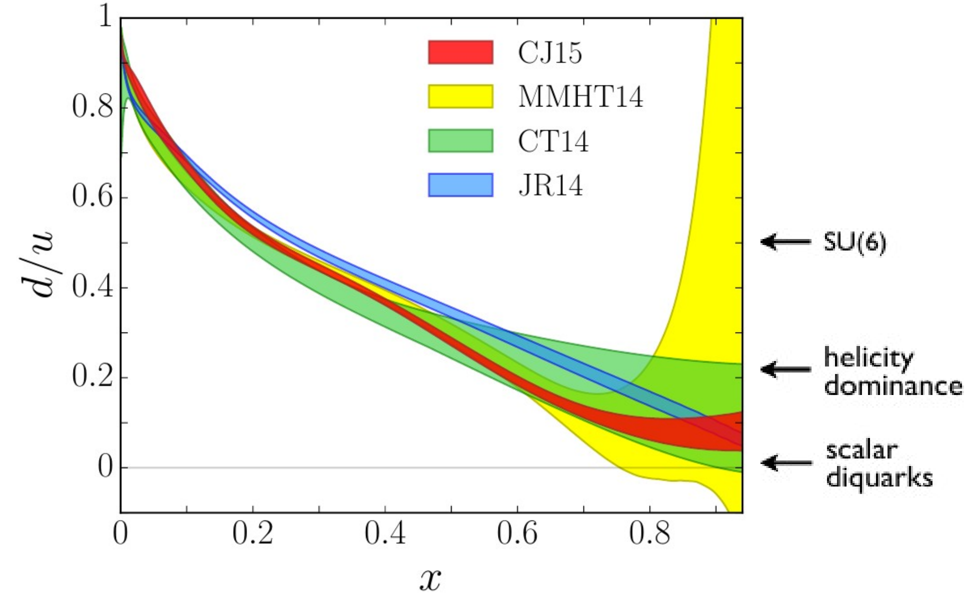
Predictions for High x

Proton Wavefunction (Spin and Flavor Symmetric)

$$\left|p \quad\right\rangle = \frac{1}{\sqrt{2}}\left|u \quad (ud)_{S=0}\right\rangle + \frac{1}{\sqrt{18}}\left|u \quad (ud)_{S=1}\right\rangle - \frac{1}{3}\left|u\downarrow (ud)_{S=1}\right\rangle - \frac{1}{3}\left|d \quad (uu)_{S=1}\right\rangle - \frac{\sqrt{2}}{3}\left|d\downarrow (uu)_{S=1}\right\rangle$$

Nucleon Model	F_2^n/F_2^p	d/u	Δu/u	Δd/d	A_1^n	A_1^p
SU(6)	2/3	1/2	2/3	-1/3	0	5/9
Scalar diquark	1/4	0	1	-1/3	1	1
pQCD	3/7	1/5	1	1	1	1

Hadronic physics output 1: d/u ratio



→ d/u ratio at high x of interest for nonperturbative models of nucleon

→ **CJ15:**

more flexible parametrization

$$d \;\rightarrow\; d + b\, x^c\, u$$

allows finite, nonzero $x = 1$ limit

(standard PDF form gives 0 or ∞ unless $a_2^d = a_2^u$)

MMHT14: fitted deuteron corrections
standard *d* parametrization
→ “UNDERCONSTRAINED”

JR14 (and ABM12):
Similar deuteron corrections
standard *d* ; no lepton/W asym.
→ “OVERCONSTRAINED”

CT14: $\beta_u = \beta_d \implies d/u$ finite
No nuclear corrections

Longstanding issue in proton structure

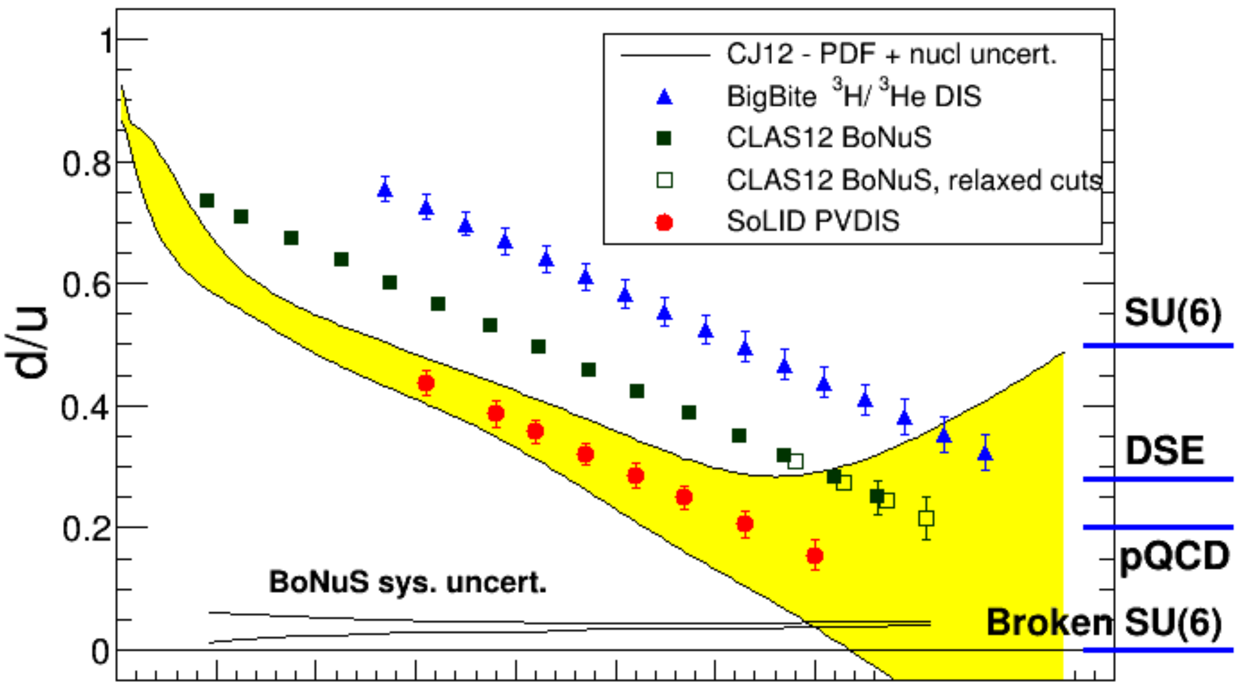
Proton PVDIS: d/u at high x

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}[a(x) + f(y)b(x)]$$

SU(6): d/u~1/2
Broken SU(6): d/u~0
Perturbative QCD: d/u~1/5

$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

Projected 12 GeV d/u extractions



- <u>3 JLab 12 GeV experiments</u>:

- CLAS12 BoNuS spectator tagging
- BigBite – DIS ^{3}H/^{3}He ratio
- **SoLID – PVDIS *ep***

- **The SoLID extraction of *d*/*u* is directly from *ep* DIS:**

  - **No nuclear corrections**
  - **No assumption of charge symmetry**

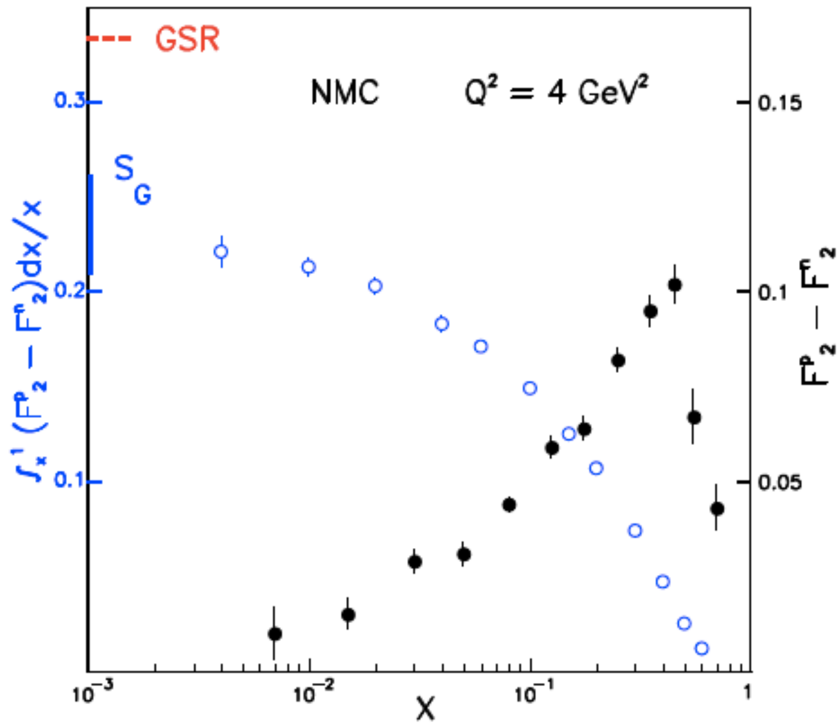
Sea Quark Distributions

Sea Asymmetry (d_bar/u_bar)

Flavor structure of the proton sea

❑ **The proton sea is not SU(3) symmetric!**

Violation of Gottfried sum rule

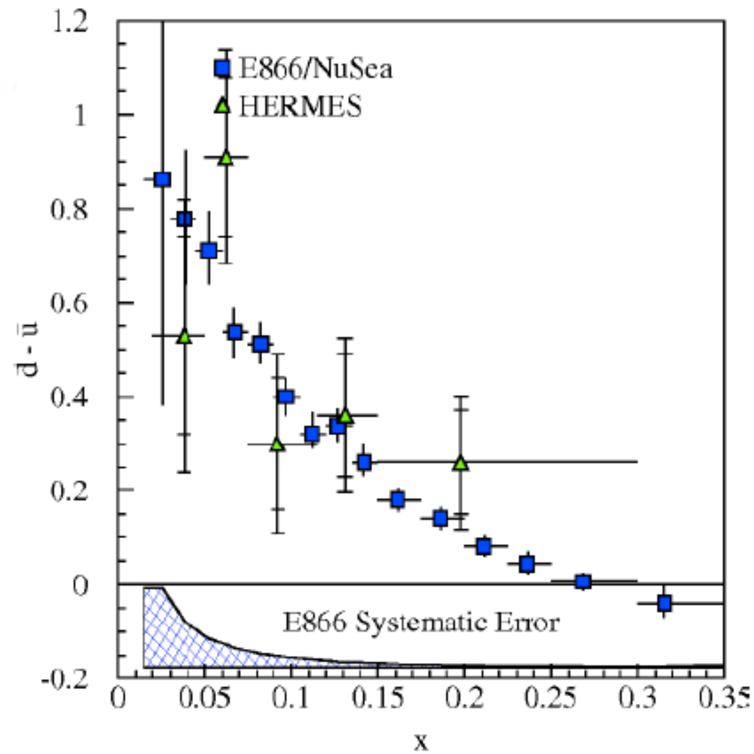


$$S_G = \int_0^1 [(F_2^p(x) - F_2^n(x))/x]\,dx$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\overline{u}_p(x) - \overline{d}_p(x))\ dx$$

$$= \frac{1}{3} \quad (if\ \overline{u}_p = \overline{d}_p) \quad \text{NMC: } S_G = 0.235 \pm 0.026$$

Confirmed by Drell-Yan exp't

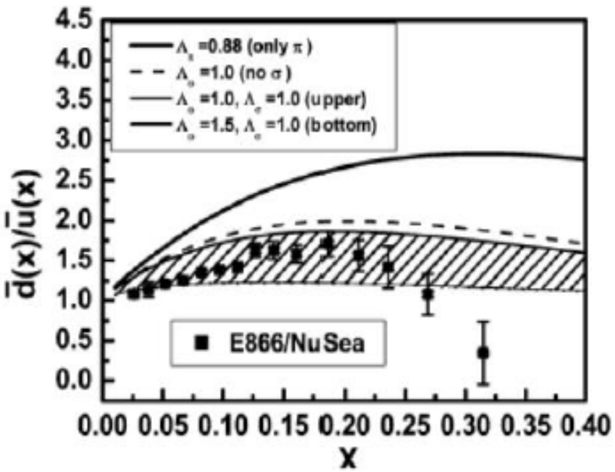


Why $\bar{d}(x) \neq \bar{u}(x)$ ***?***

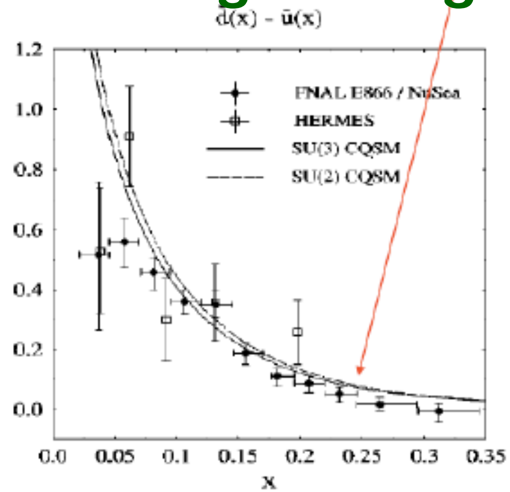
Why does $\bar{d}(x) - \bar{u}(x)$ ***change sign?***

Challenges for $\bar{d}(x) - \bar{u}(x)$

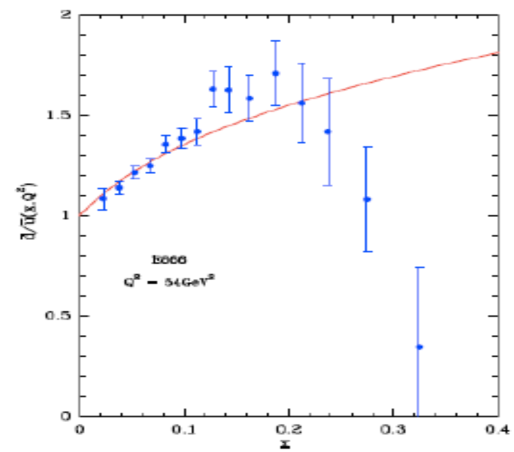
- ❑ All known models predict no sign change!



Meson cloud

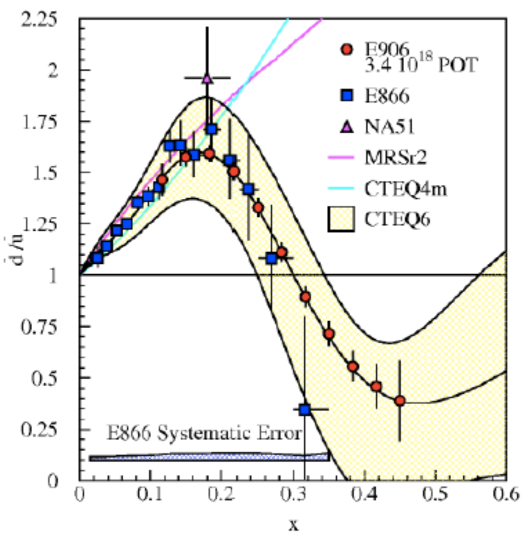


Chiral-quark soliton model

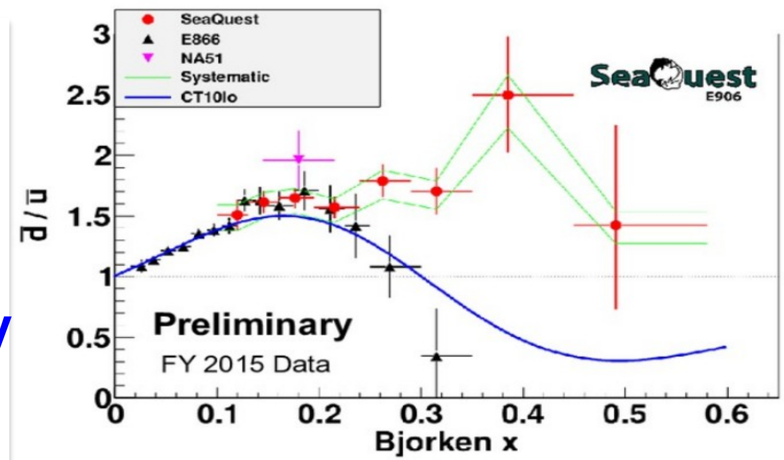


Statistic model

- ❑ Future experiments – E906, …



Preliminary
From
Seaquest



ay 2016

B.Kerns, DNP April 2016

Summary

- Electron Scattering to study Nucleon Structure

- Deep-Inelastic Scattering

    Unpolarized Structure functions → Parton Distributions

    High-x, valance quark distributions, d/u

    Sea distributions: d_bar/u-bar asymmetry

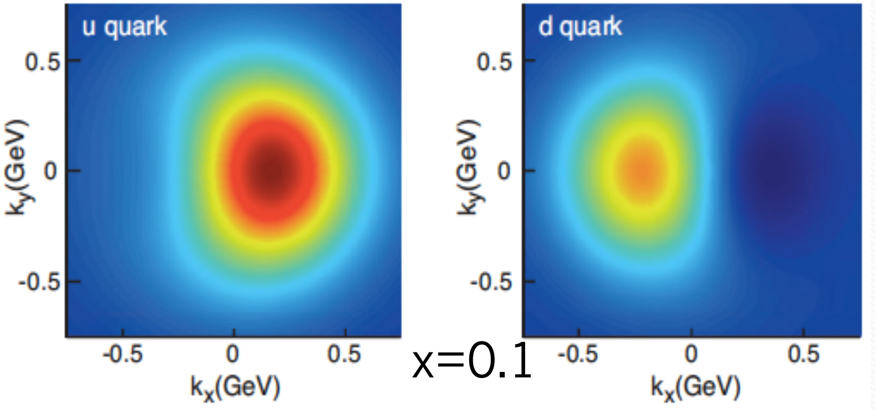
Physics with an Electron-Ion Collider

II: Nucleon 3-d Structure

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

Pre-Workshop Lectures, Hadron-China2018, July 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
- 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)

  $\Delta\Sigma = 20\text{–}30\%$, the rest: gluon and quark orbital angular momentum

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

  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, … :

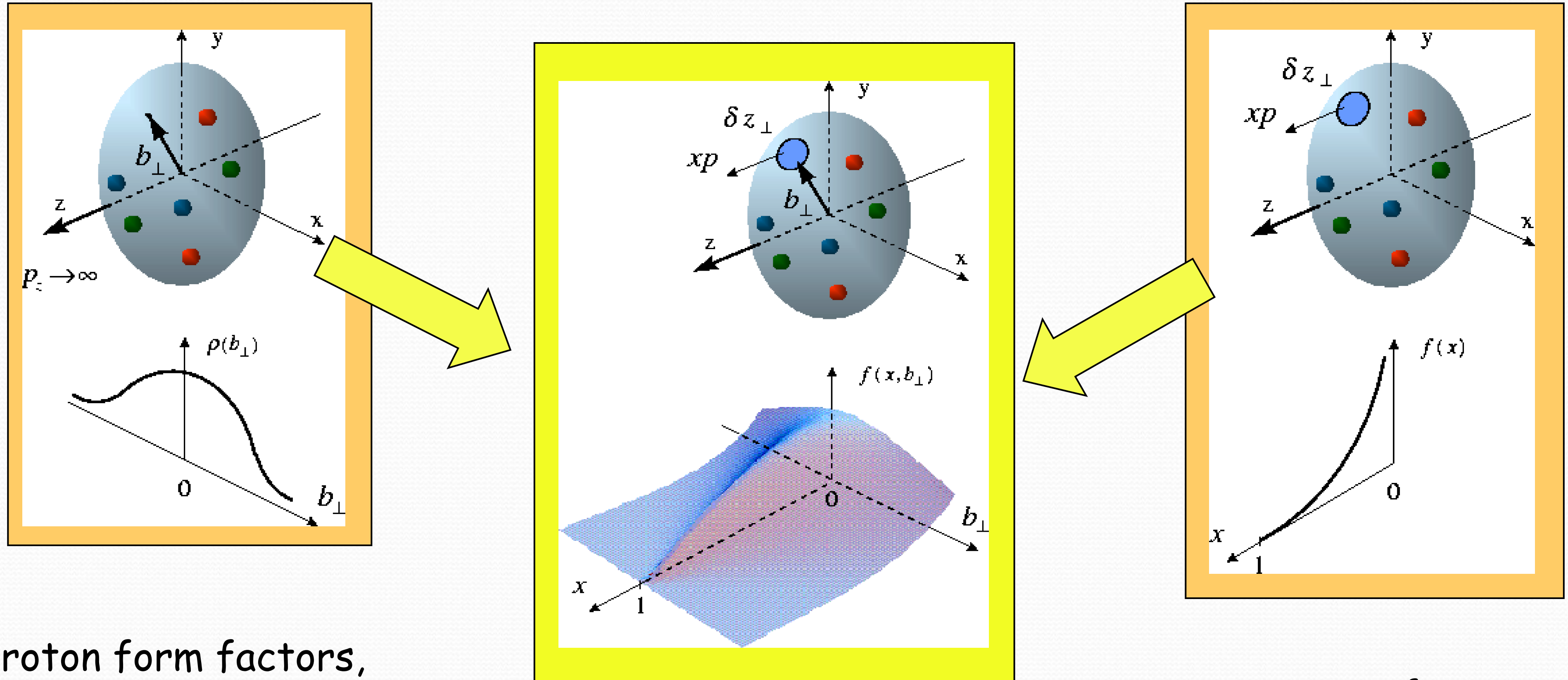
  $\Delta\Sigma \sim 30\%$; ΔG contributes, **orbital angular momentum significant**

  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)



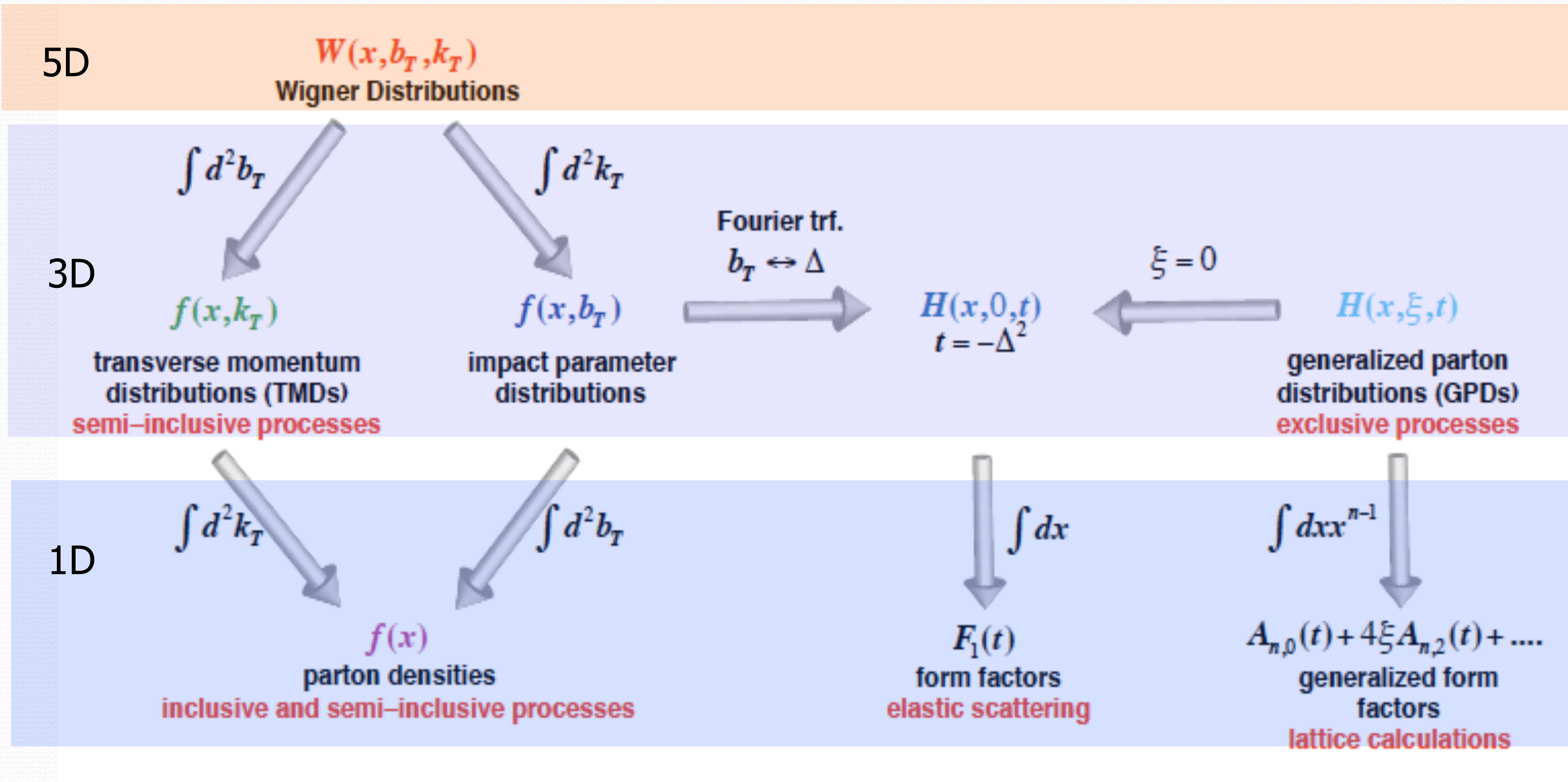
Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

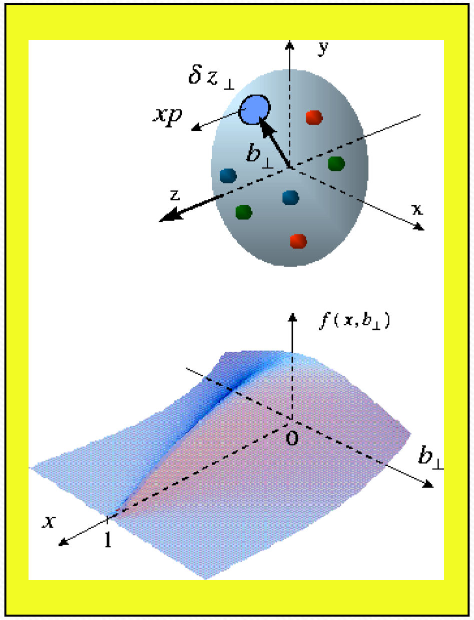
Unified View of Nucleon Structure

❑ **Wigner distributions**



3-D Structure I

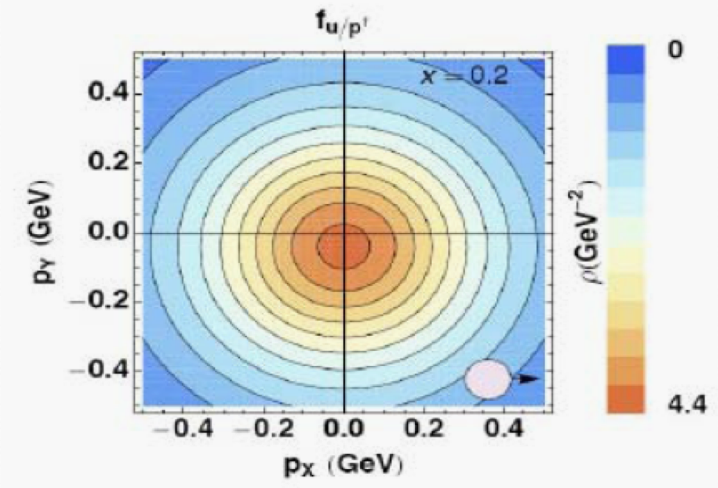
Generalized Parton Distributions



3-D Imaging - Two Approaches

TMDs

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

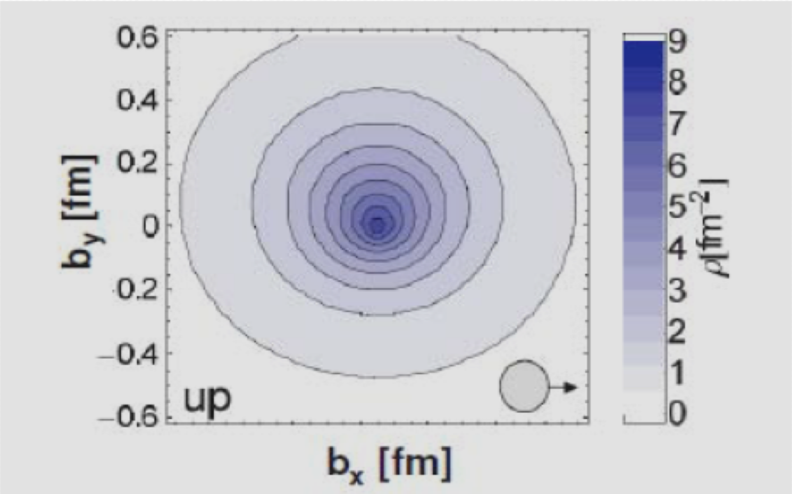


Bacchetta, Conti, Radici

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

GPDs

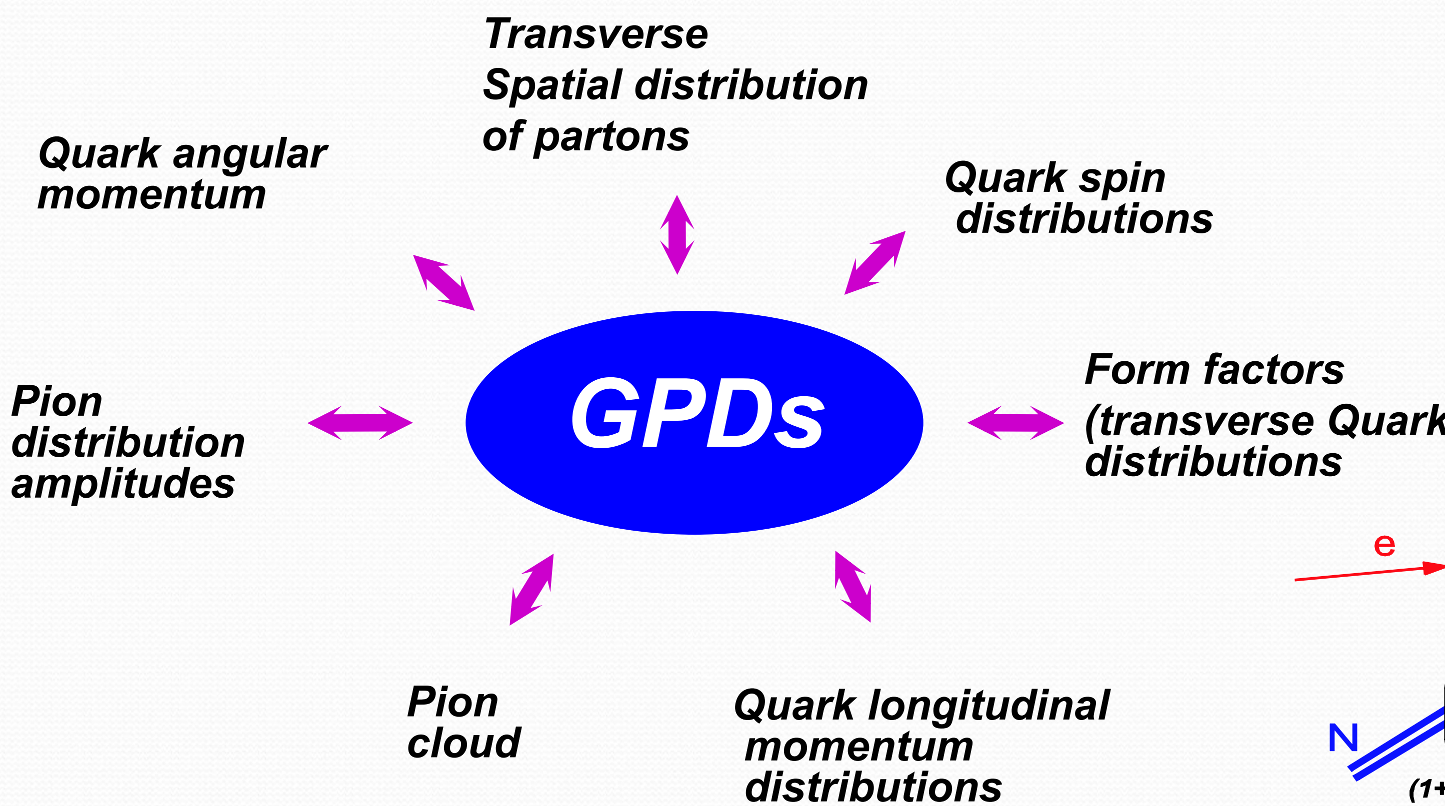
2+1 D picture in **impact-parameter space**

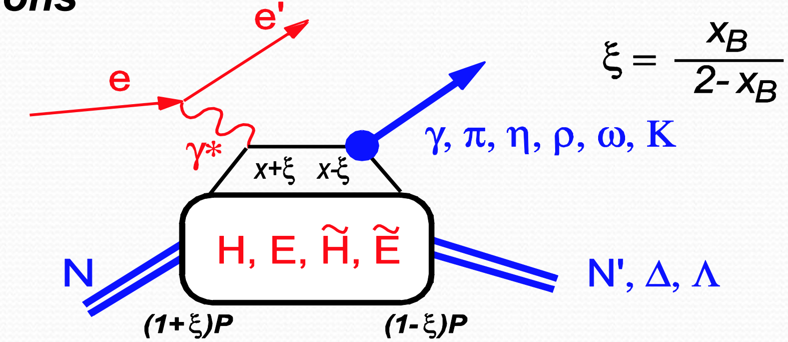


QCDSF collaboration

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

Description of Hadron Structure via Generalized Parton Distributions





H, E - unpolarized, $\tilde{H}$, $\tilde{E}$ - polarized GPD

The GPDs Define Nucleon Structure

known information on GPDs

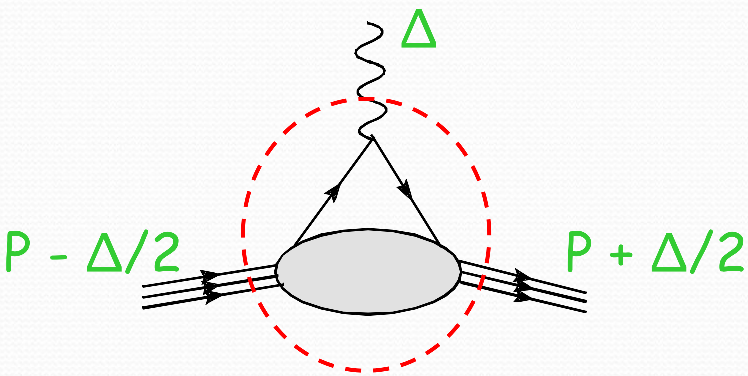
- forward limit : ordinary parton distributions

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

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

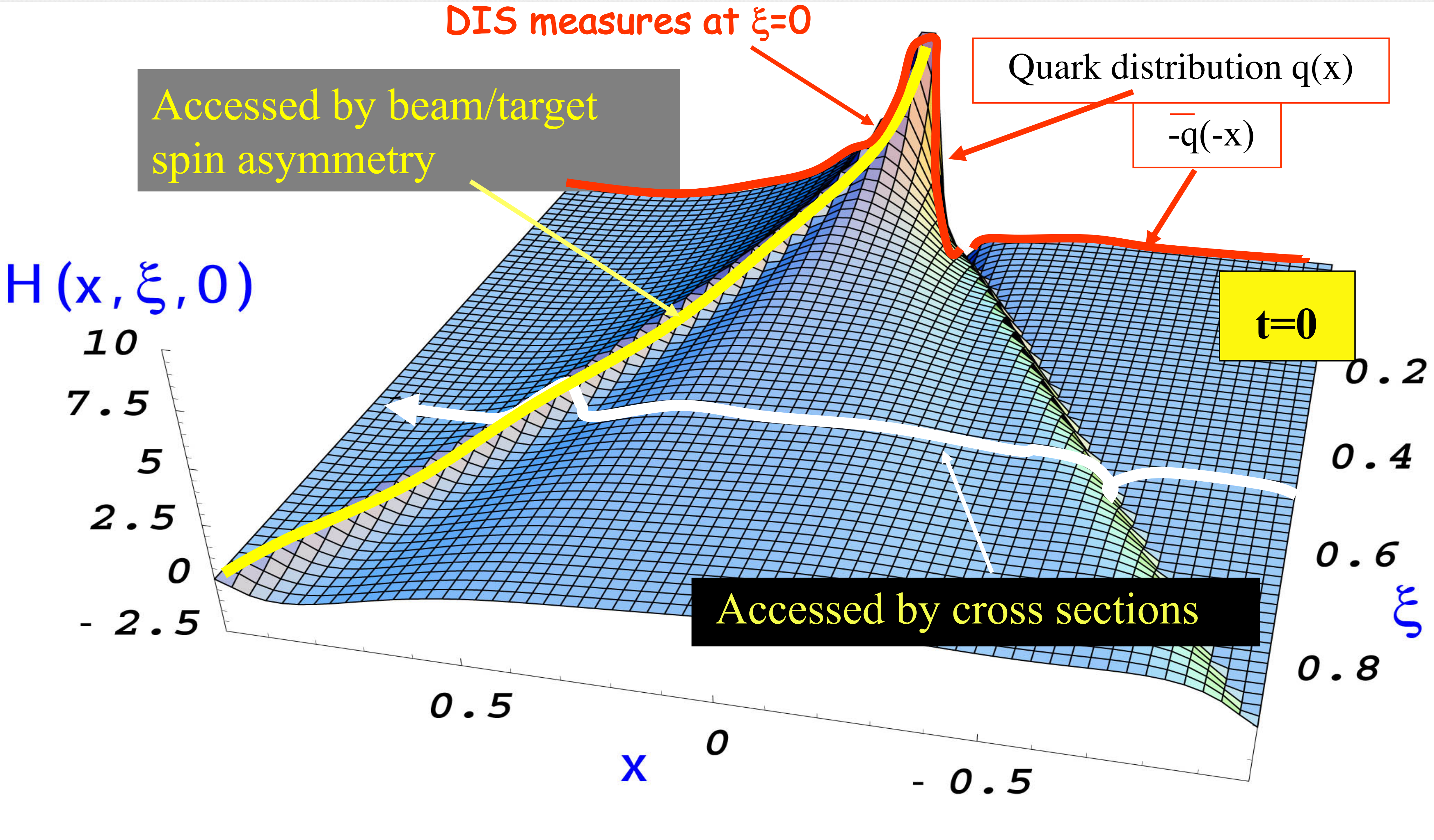
$$\int_{-1}^{1} dx\, H^q(x, \xi, t) = F_1^q(t)$$ Dirac

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

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

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

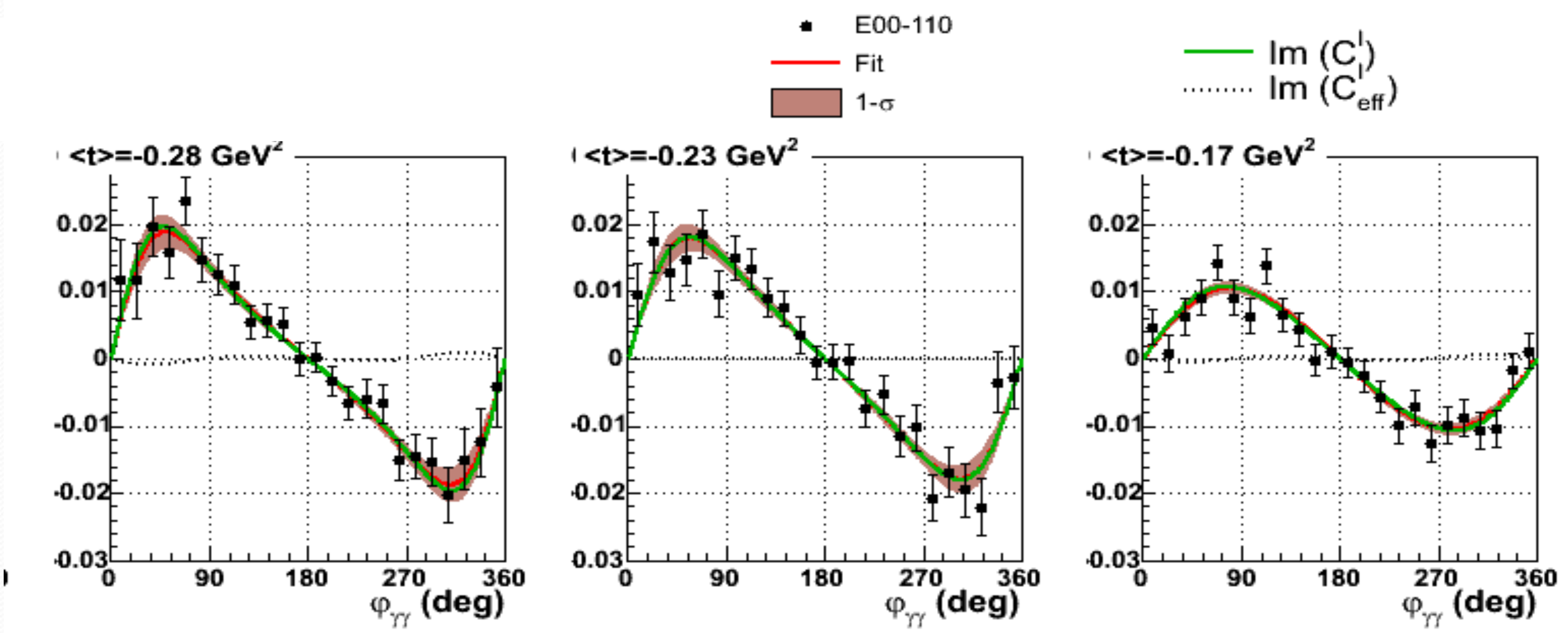
Access GPDs through DVCS x-section & asymmetries



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

3D Images of the Proton's Quark Content

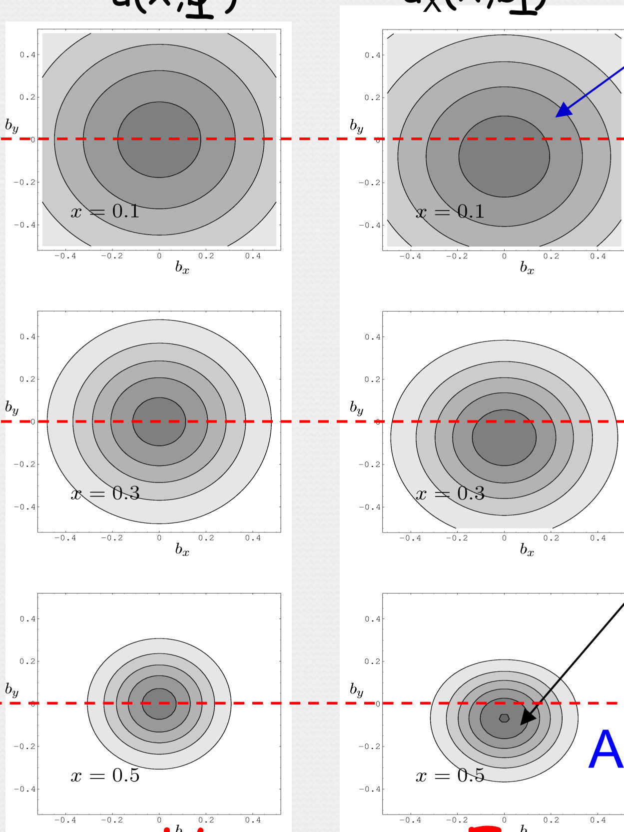
M. Burkardt PRD 66, 114005 (2002)

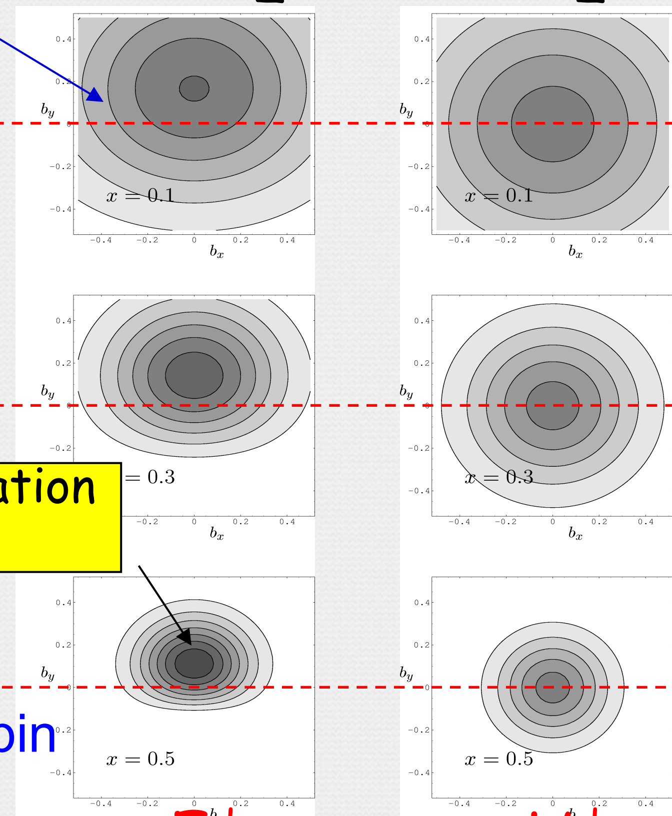
$$q(x,\mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{\Delta}_\perp\cdot\mathbf{b}_\perp} H(x,0,-\mathbf{\Delta}_\perp^2).$$

$b_\perp$- Impact parameter

transverse polarized target

$u(x,b_\perp)$ $u_X(x,b_\perp)$ $d_X(x,b_\perp)$ $d(x,b_\perp)$



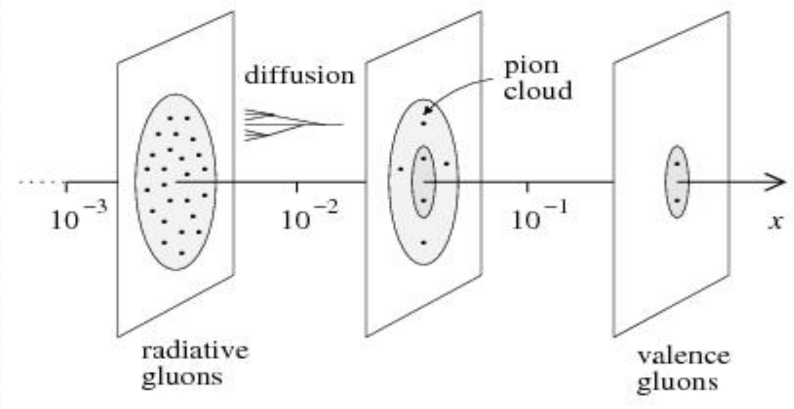


quark flavor polarization

Accessed in Single Spin Asymmetries.

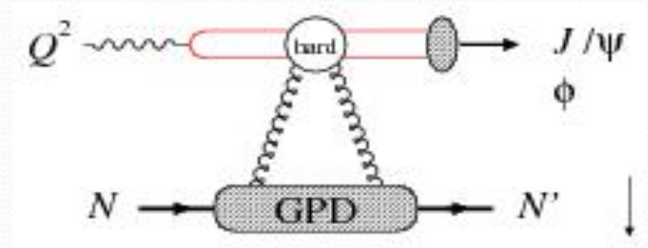
Needs: H^u E^u E^d H^d

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)



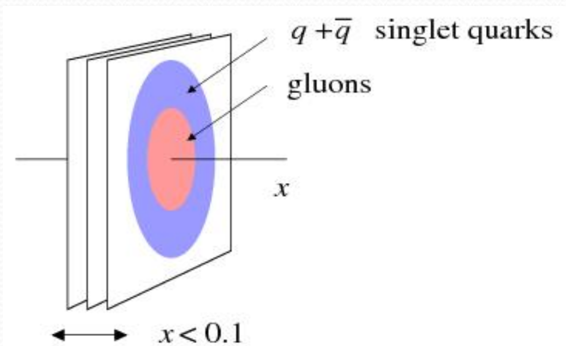
[Transverse distribution derived directly from t dependence]

Hints from HERA:

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

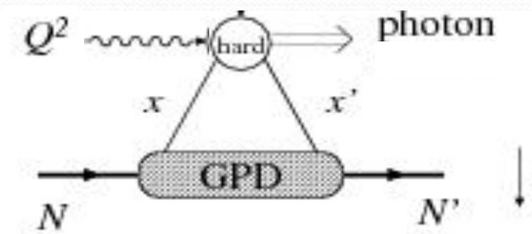
Dynamical models predict difference:

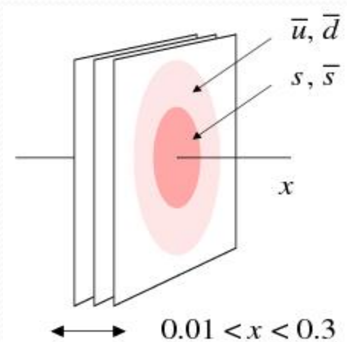
pion cloud, constituent quark picture



Fazio

EIC: singlet quark size from deeply virtual compton scattering

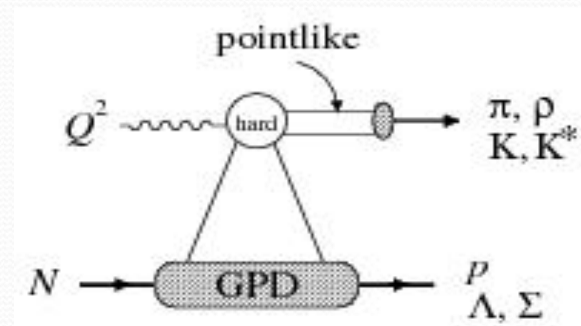




- Q^2 > 10 GeV^2 for factorization
- Statistics hungry at high Q^2!

Horn

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



GPD Study at EIC@HIAF

- Unique opportunity for DVMP (pion/Kaon)

  flavor decomposition needs DVMP

  energy reach $Q^2 > 5\text{-}10\ GeV^2$, scaling region for exclusive light meson production

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

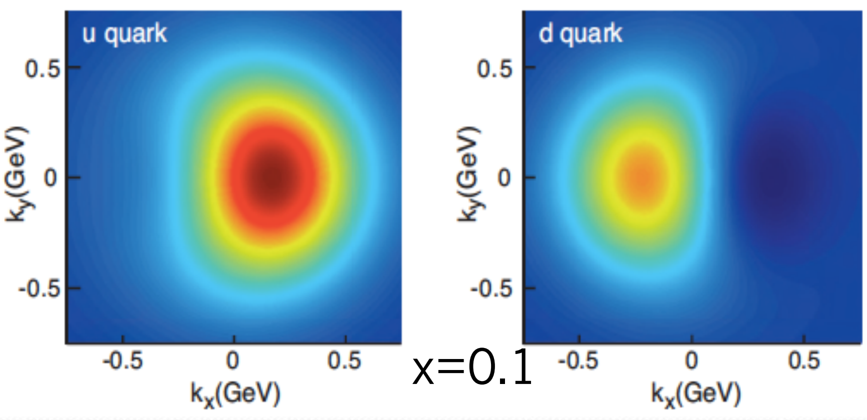
- Significant increase in range for DVCS

  combination of energy and luminosity

- Other opportunities: vector meson, heavy flavors?

3-D Structure II

Transverse Momentum-Dependent Distributions

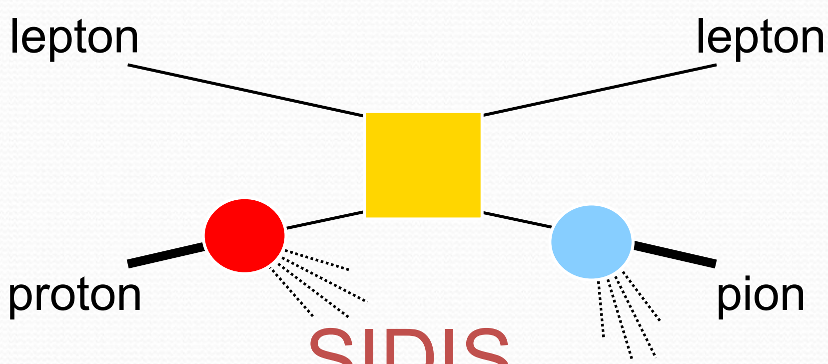


Leading-Twist TMD PDFs

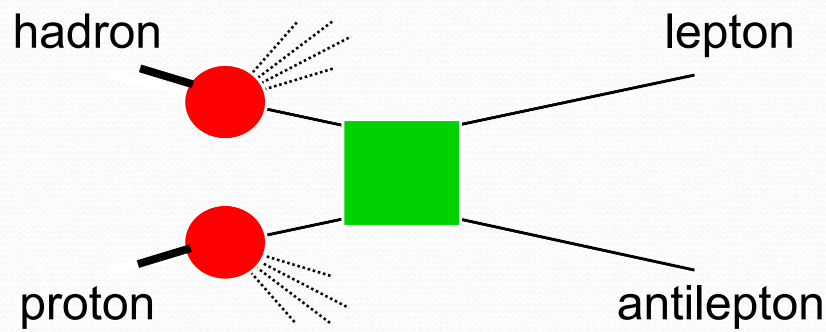
Nucleon Spin
Quark Spin

		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

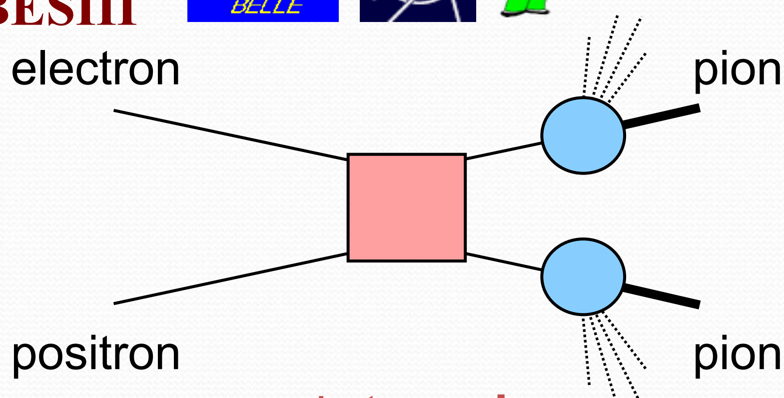
Access TMDs through Hard Processes



SIDIS



Drell-Yan

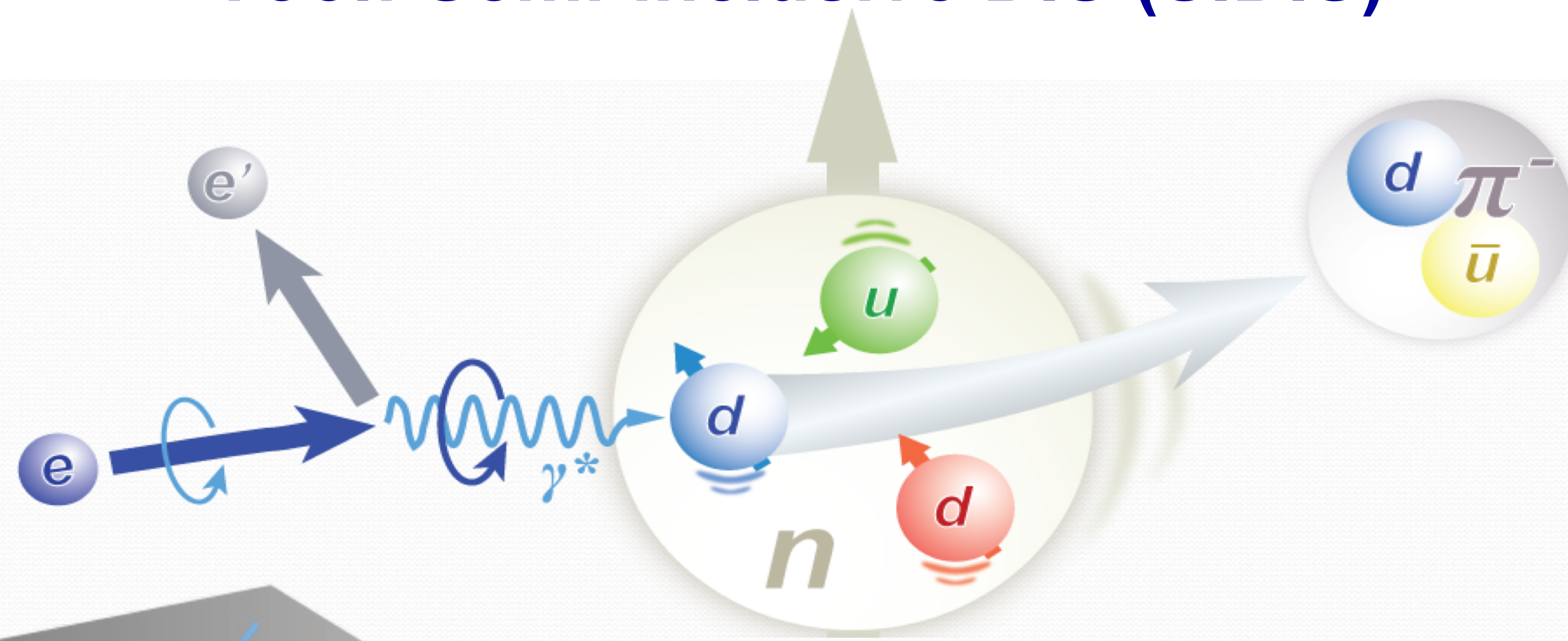


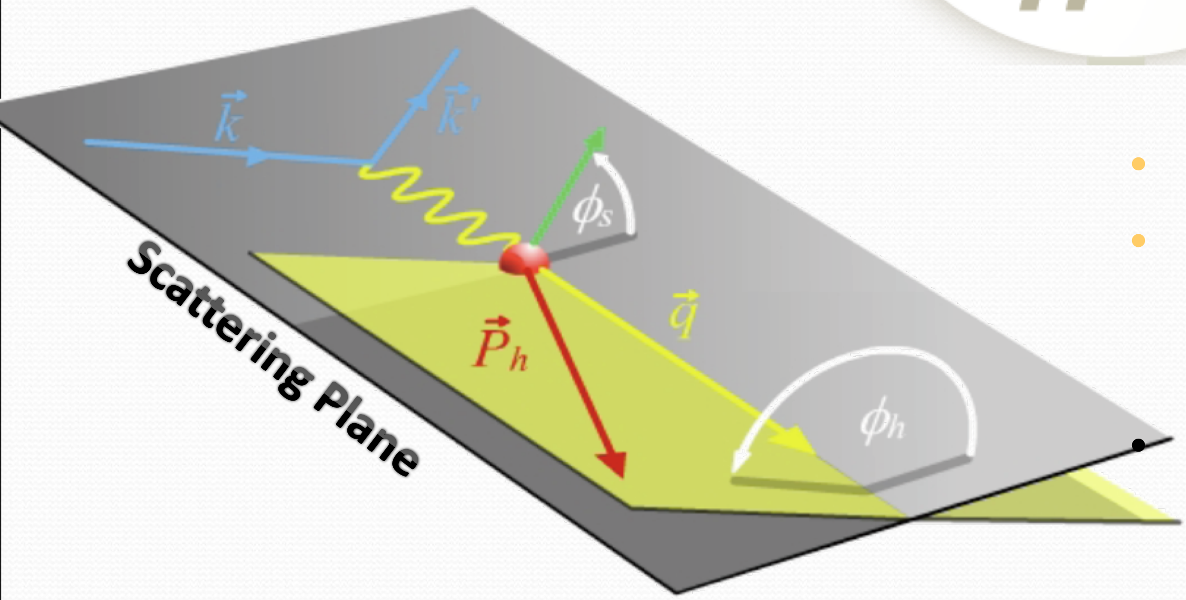
e^-e^+ to pions

- 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

Leading-Twist TMD PDFs

Nucleon Spin

Quark Spin

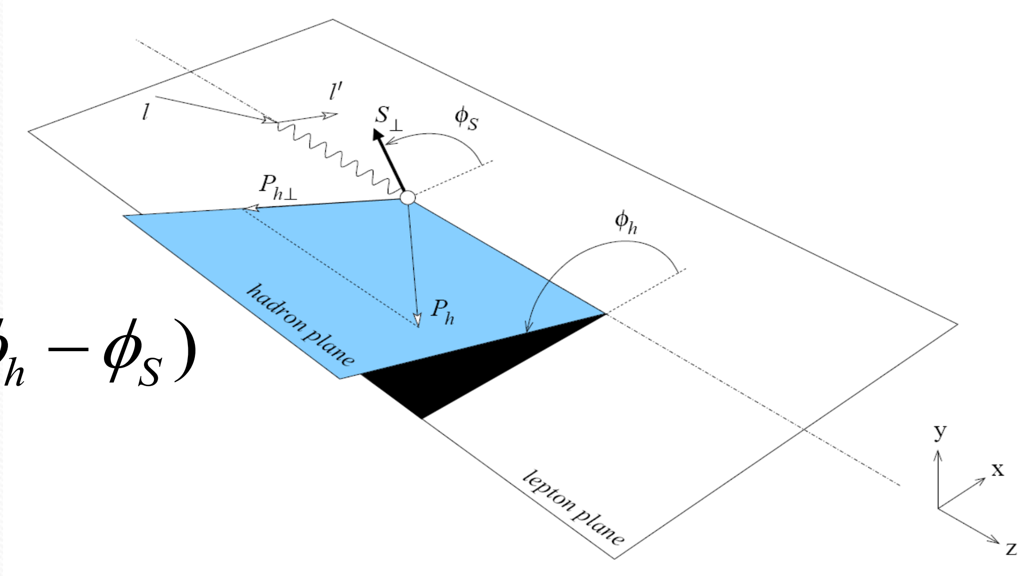
Nucleon Polarization		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
	U	f_1		$h_1^\perp$ – Boer-Mulders
	L		g_1 – Helicity	$h_{1L}^\perp$ – Long-Transversity
	T	$f_{1T}^\perp$ – Sivers	g_{1T} – Trans-Helicity	h_1 – Transversity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

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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

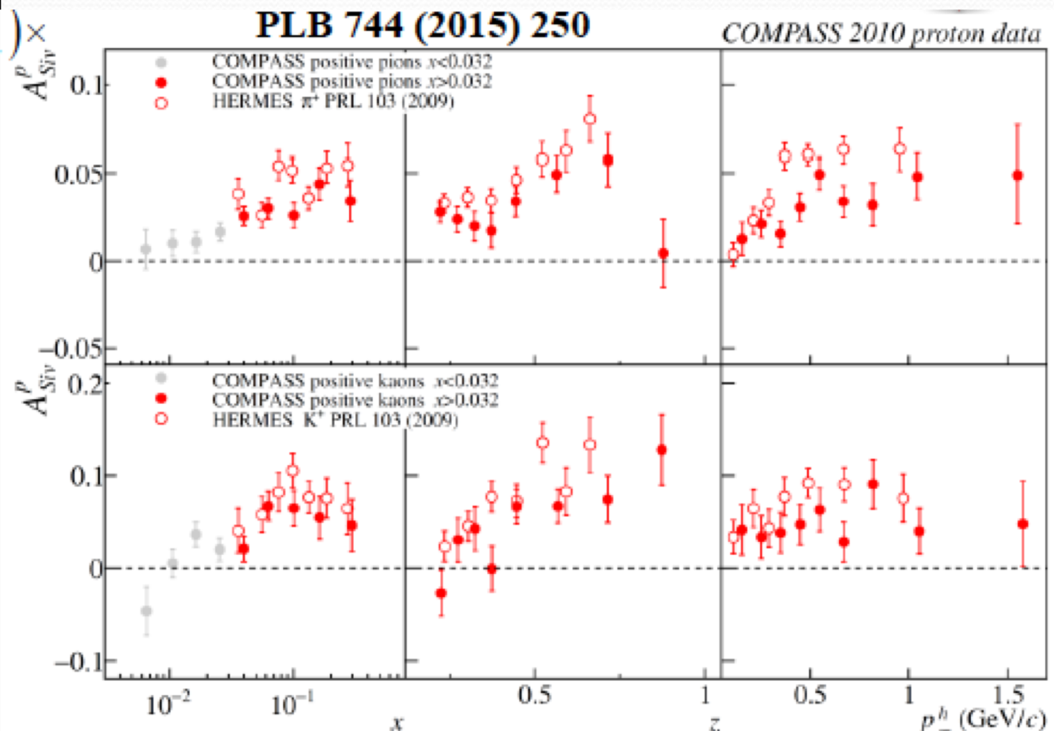


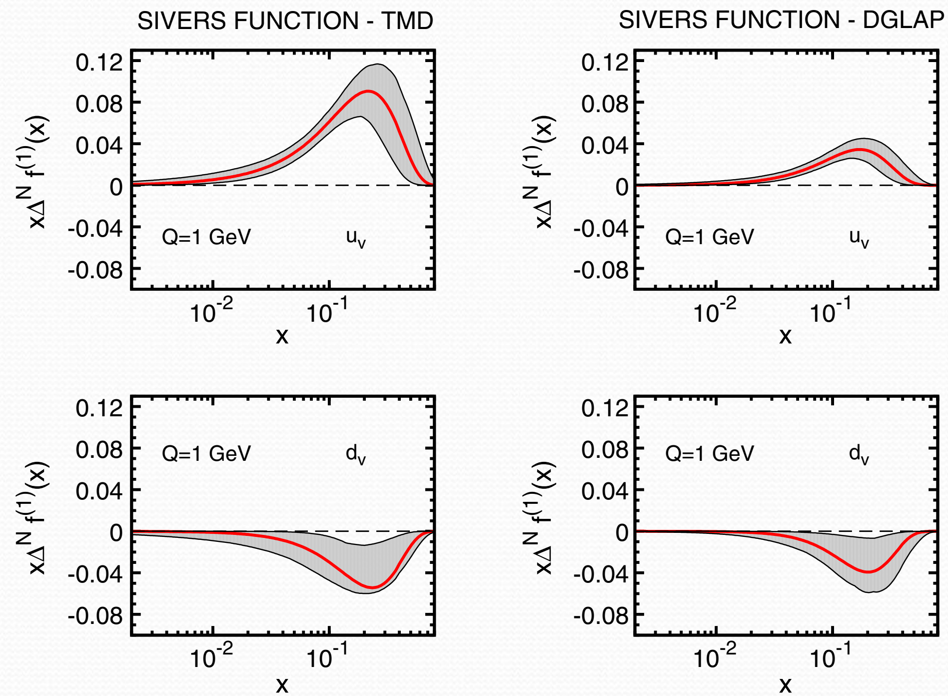
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

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

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

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

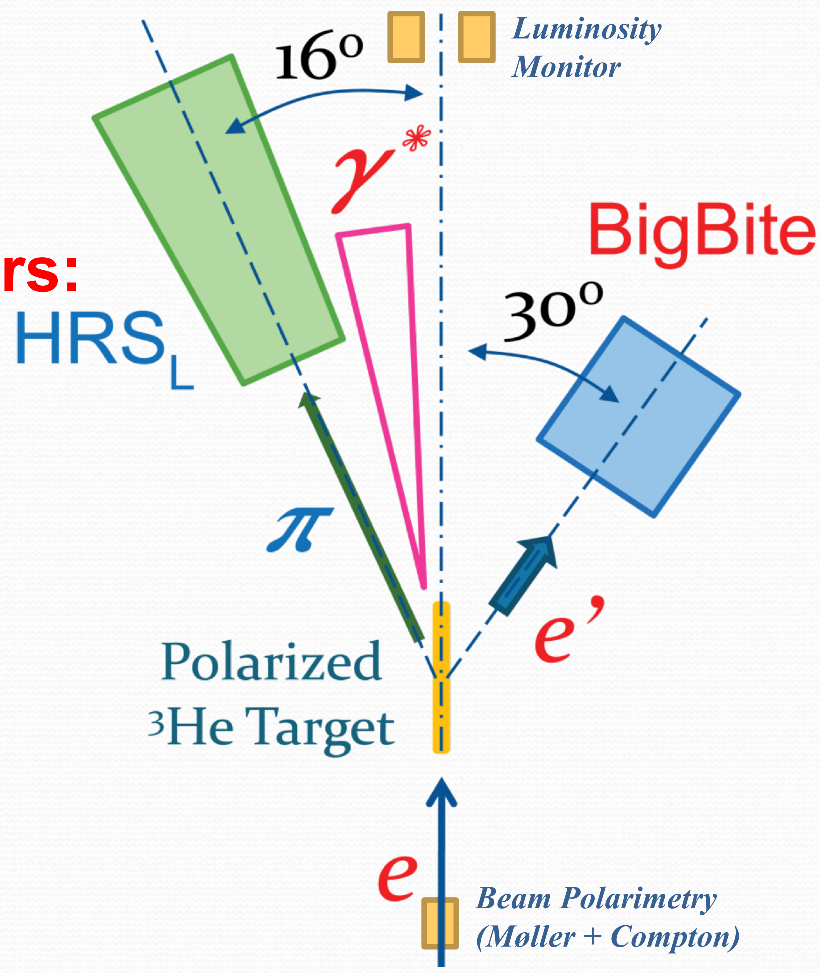
$$^{3}He^{\uparrow}(\vec{e},e'\pi^{\pm})X$$

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

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

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

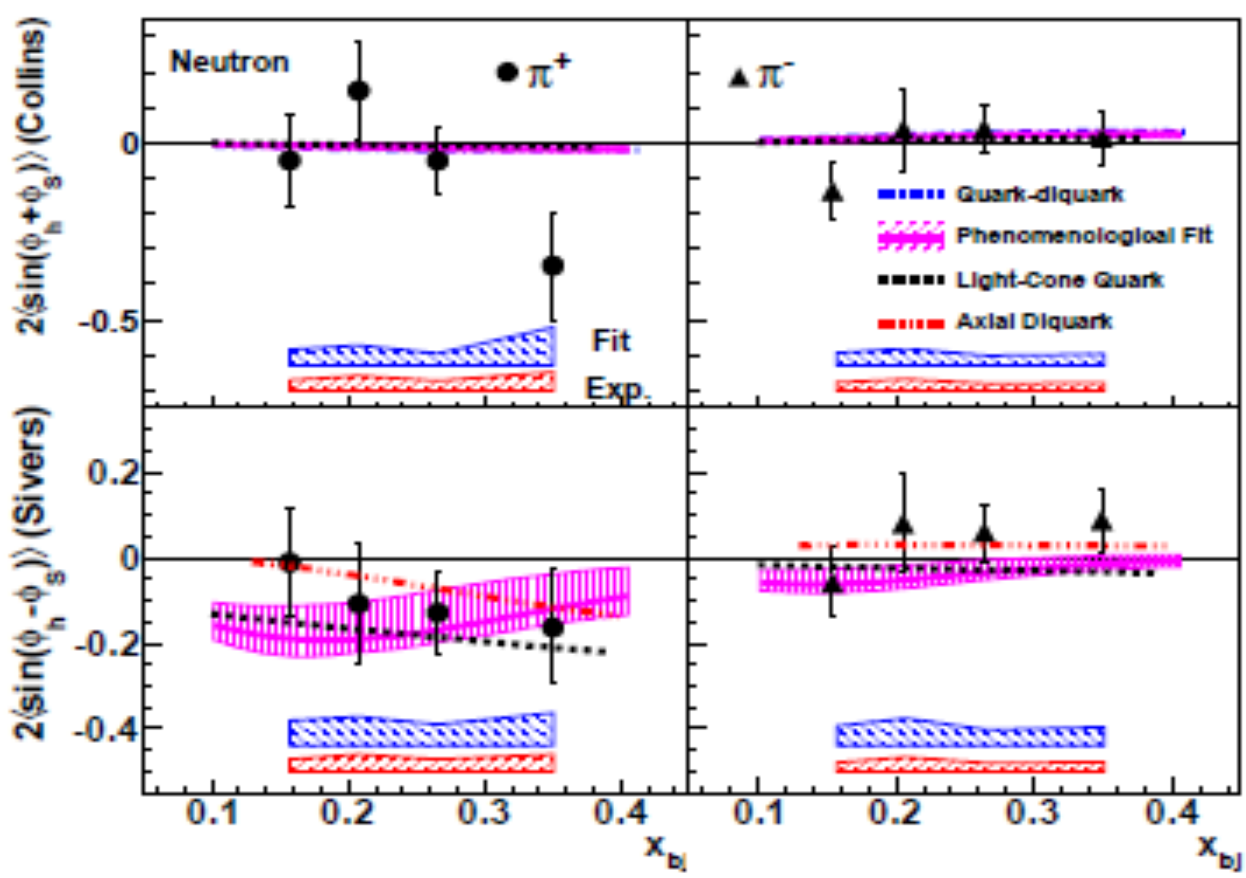
✓ π^{+-} Collins/Sivers asymmetries: PRL 107:072003(2011)
✓ π^{+-} worm-gear asymmetries: PRL 108, 052001 (2012)
✓ π^{+-} pretzelosity asymmetries: PRC 90 5, 055209(2014)
✓ K^{+-} Collins/Sivers asymmetries:PRC 90 5, 05520 (2014)
✓ Inclusive hadron SSA: PRC 89, 042201 (2014)
✓ Inclusive electron SSA: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

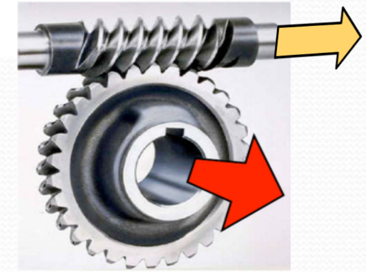
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

neutron 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

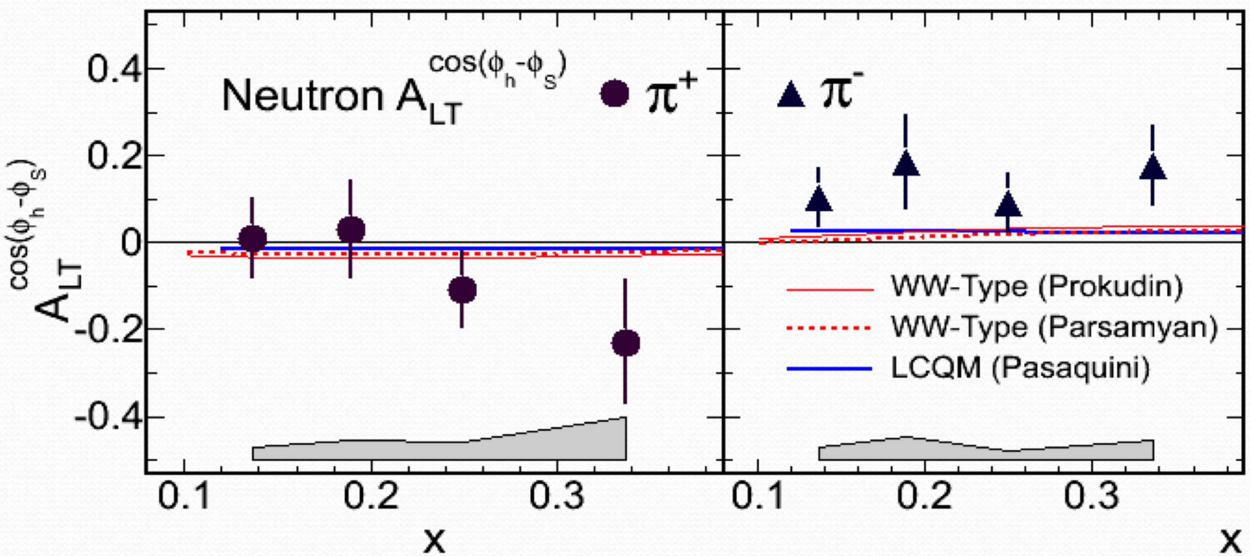
To leading twist:

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

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

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

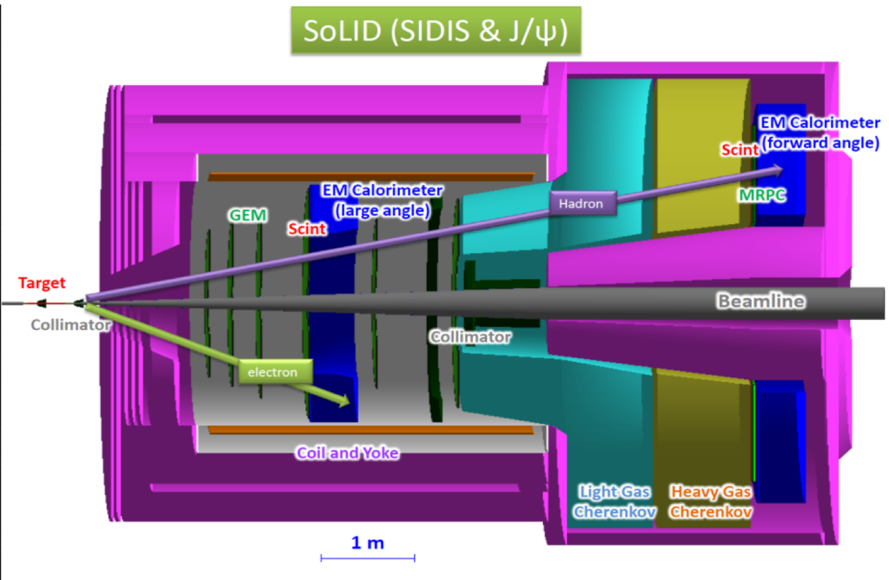
- **neutron A_{LT} : Positive for π-**
- **Consist w/ model in signs, suggest larger asymmetry**



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

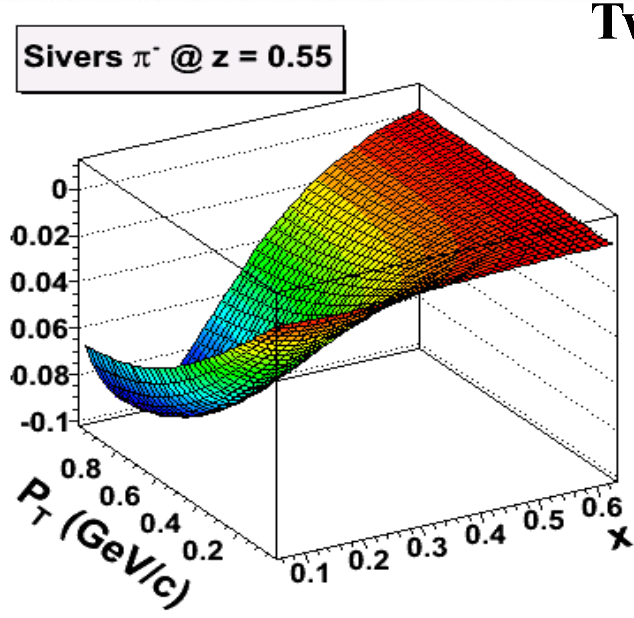


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

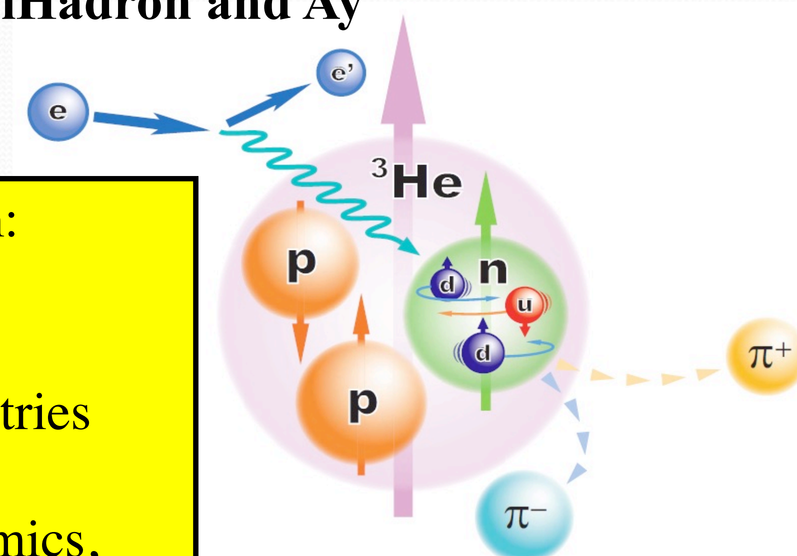
E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

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

Two run group experiments DiHadron and Ay

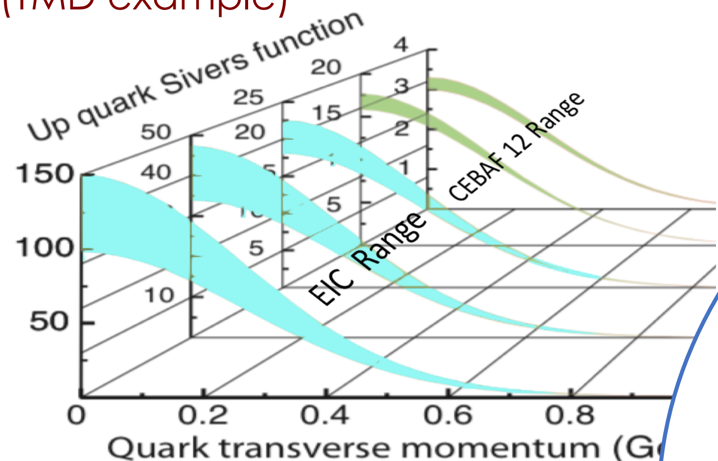


Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

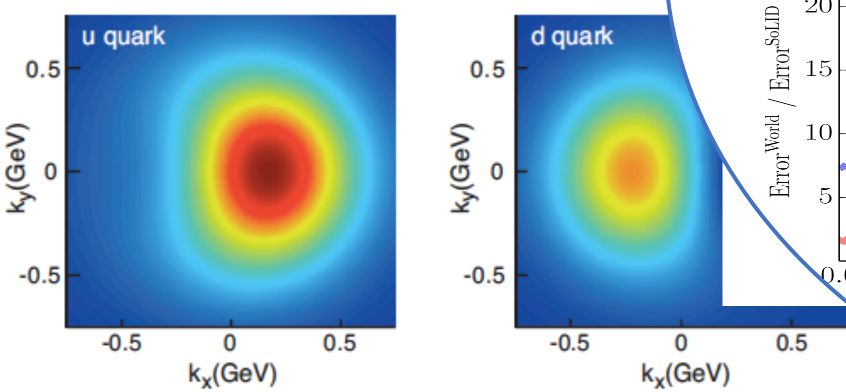


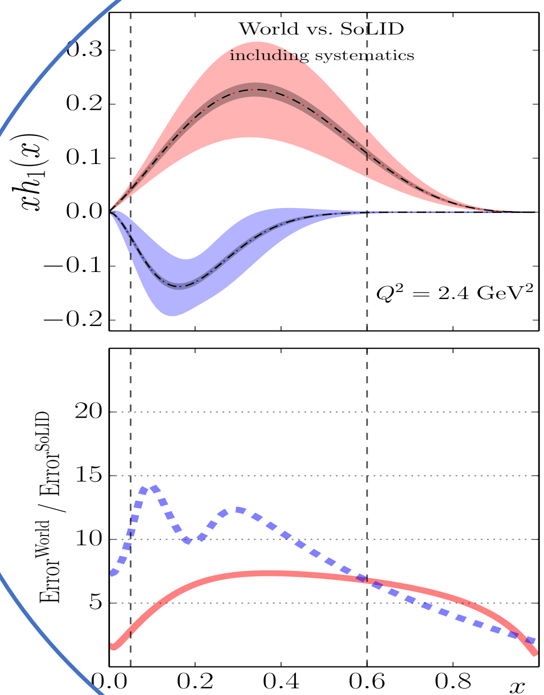
SoLID and EIC: full imaging of nucleons and study QCD

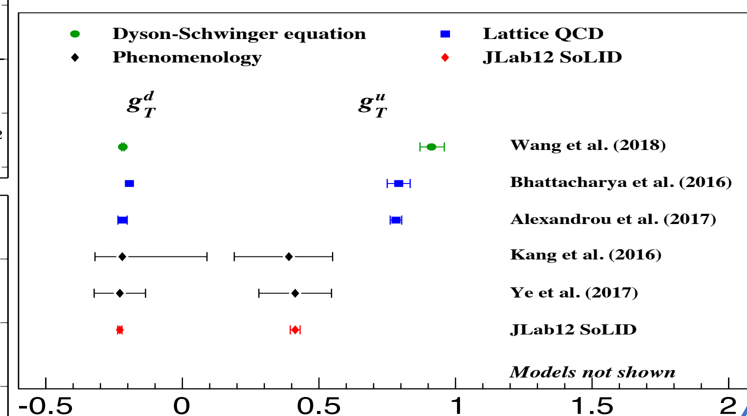
(TMD example)



Polarized Quark 3D Momentum distributions

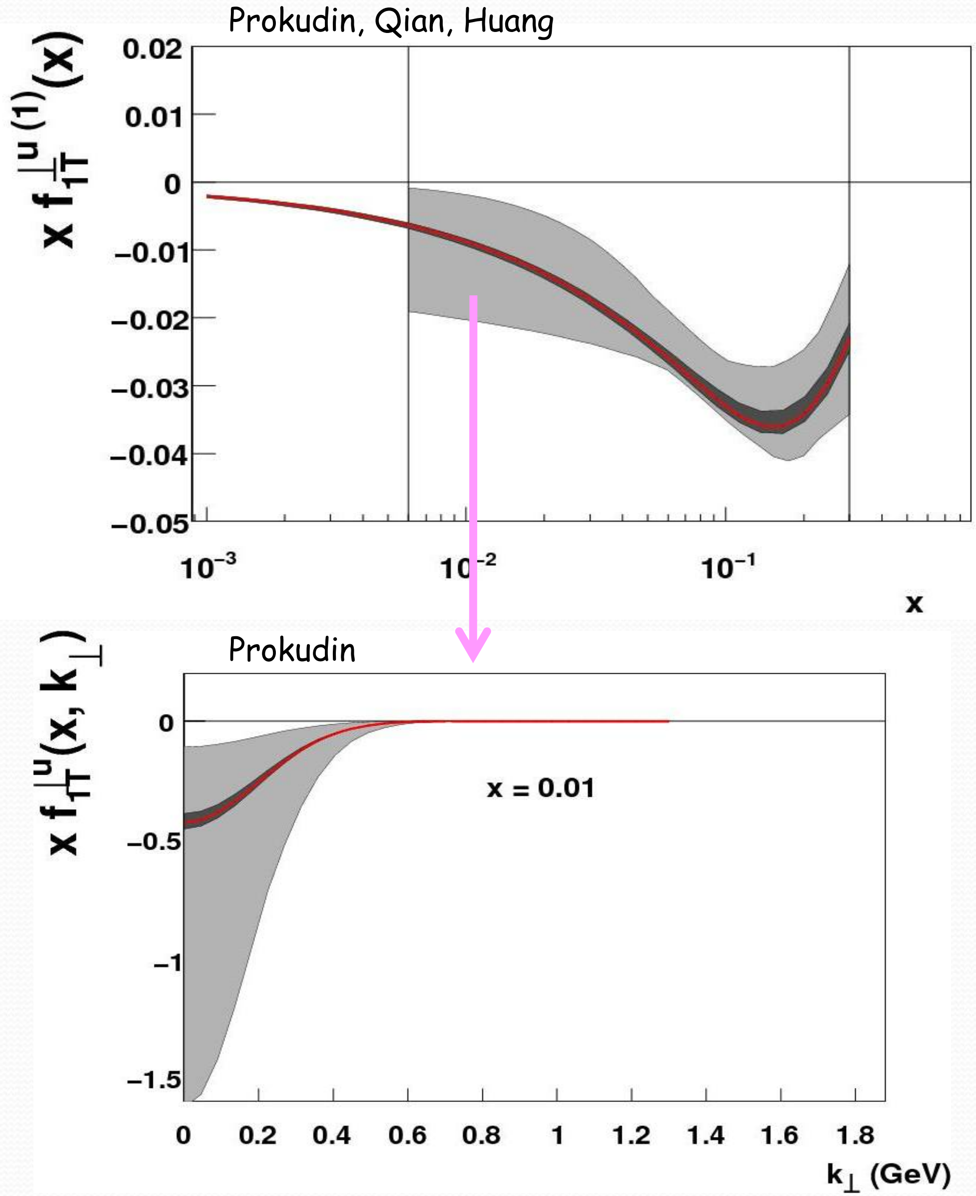






Transversity: valence quark effect

Image the Transverse Momentum of the Quarks



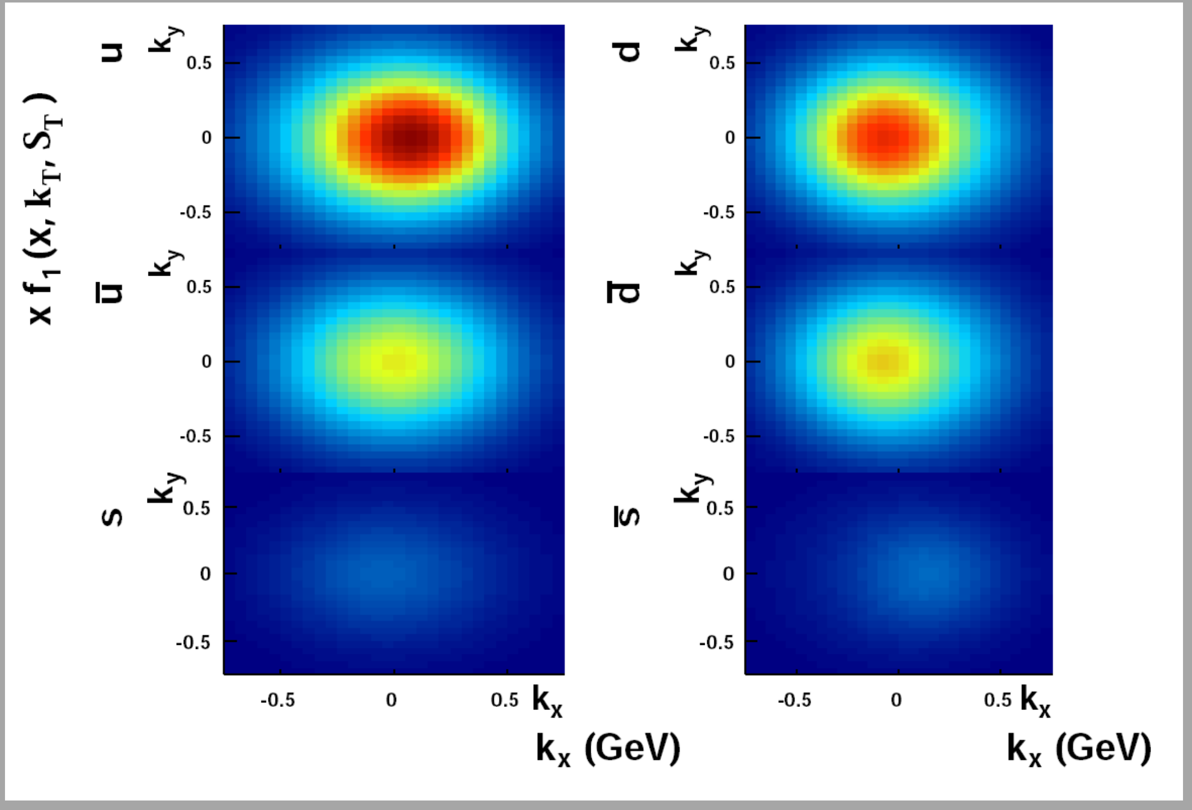
Only a small subset of the (x,Q^2) landscape has been mapped here.

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:

$x = 0.1$

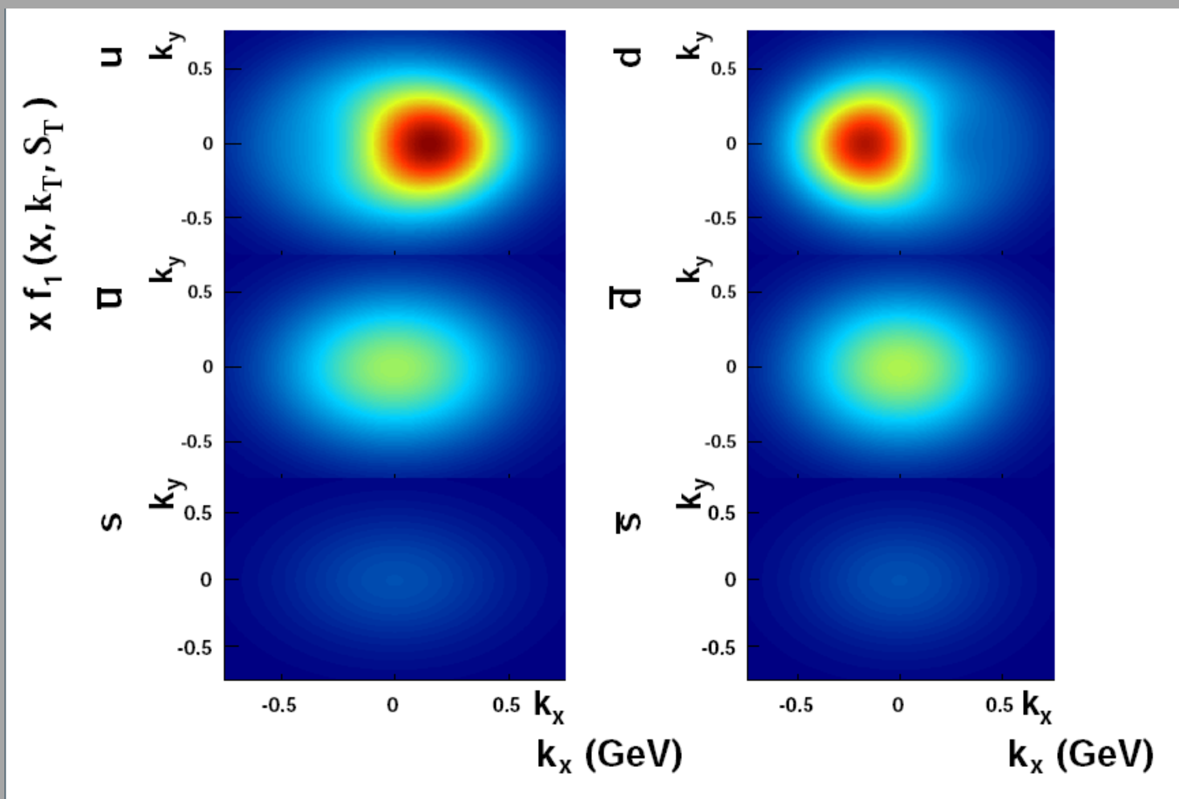
Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

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:

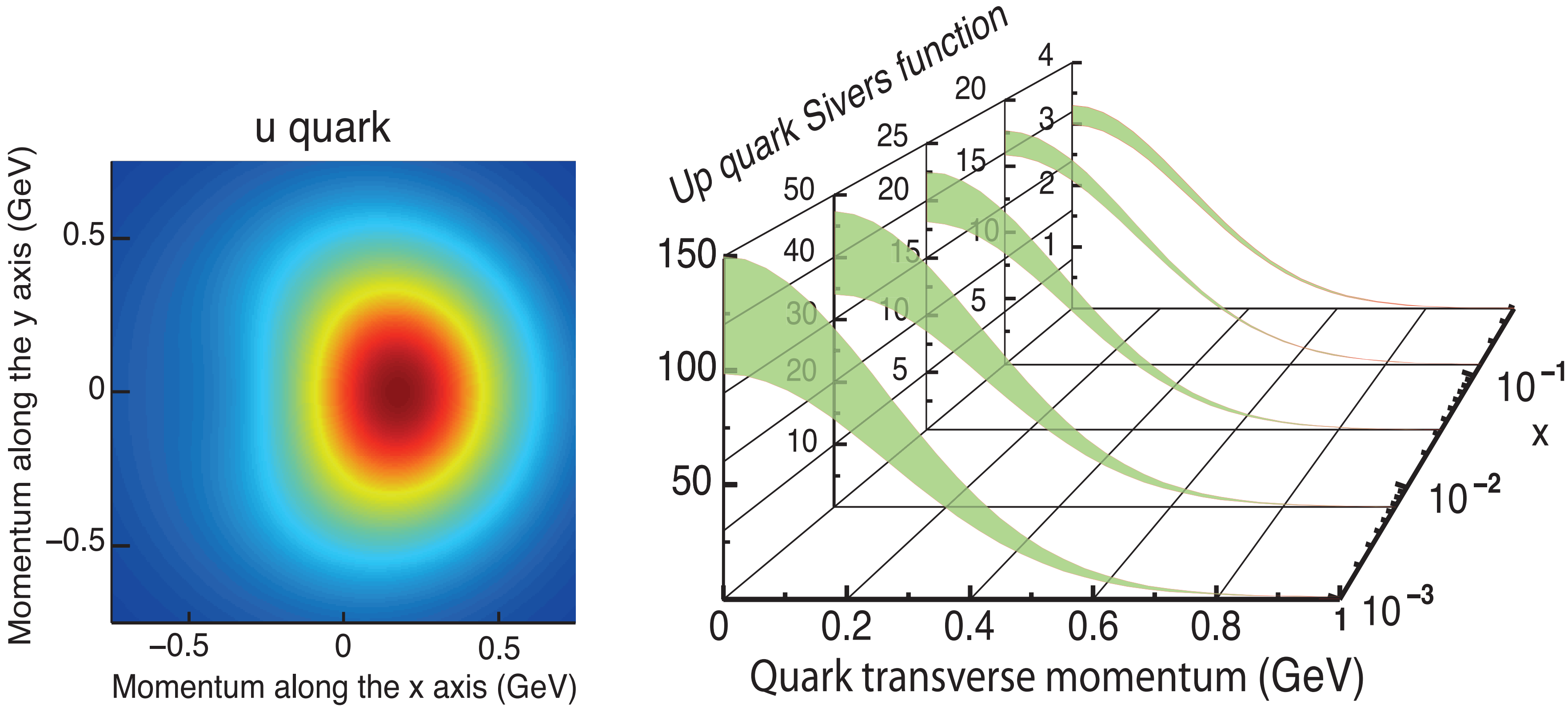
$$x = 0.1$$

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 Imaging in 3-d momentum space



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
  - 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 of JLab and EIC program

  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?