Transverse Spin and TMDs

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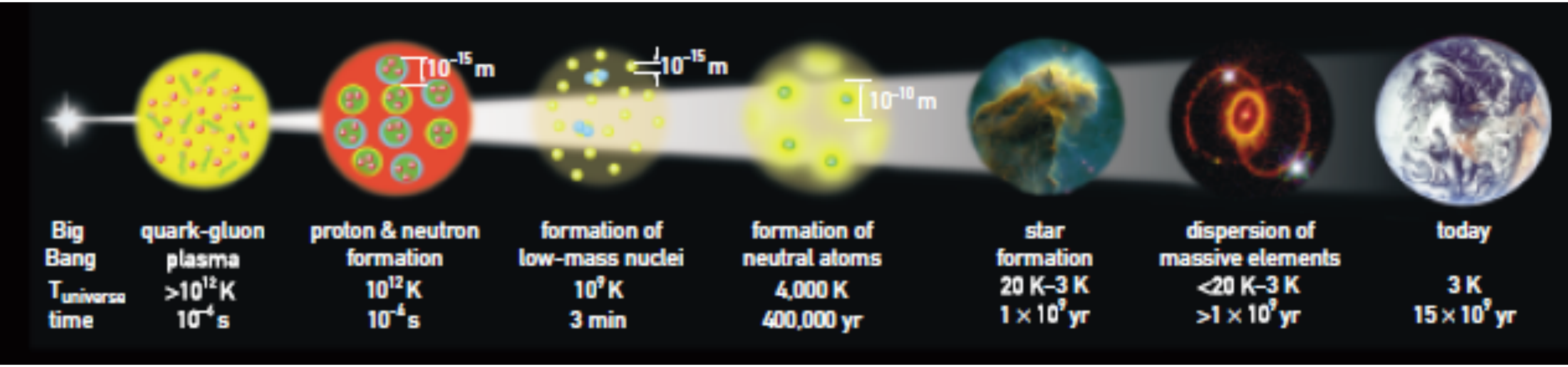
ECT* Dilepton Workshop, Nov. 6-10, 2017

- Introduction
- Spin, Transverse Spin (Transversity), Tensor Charge
- TMDs: Confined Parton Motion in 3D Momentum Space

  Orbital Motion and Orbital Angular Momentum
- Current Status and Future Perspectives
- Summary

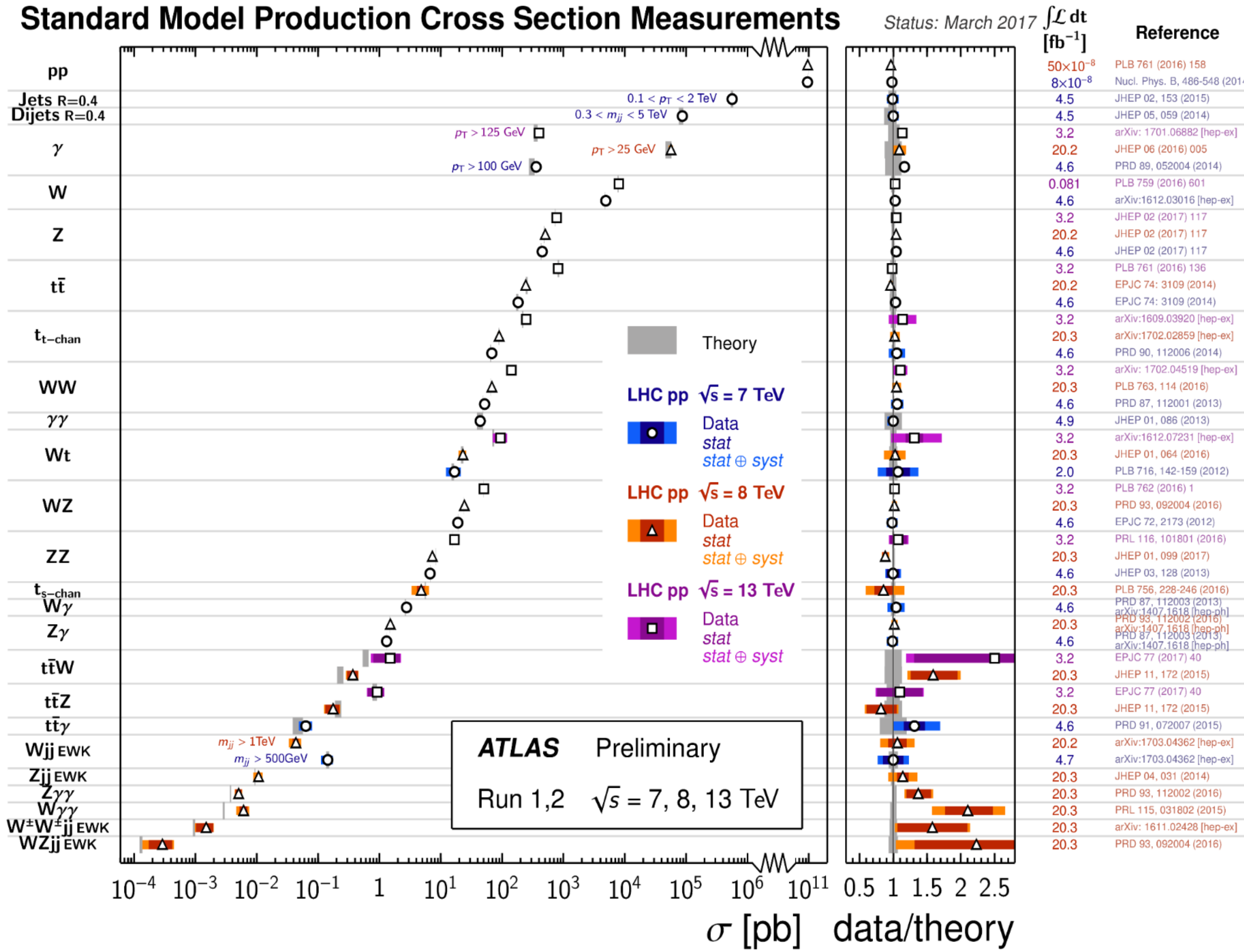
Introduction

Nucleon Structure and Strong Interaction (QCD)



Successes of the Standard Model

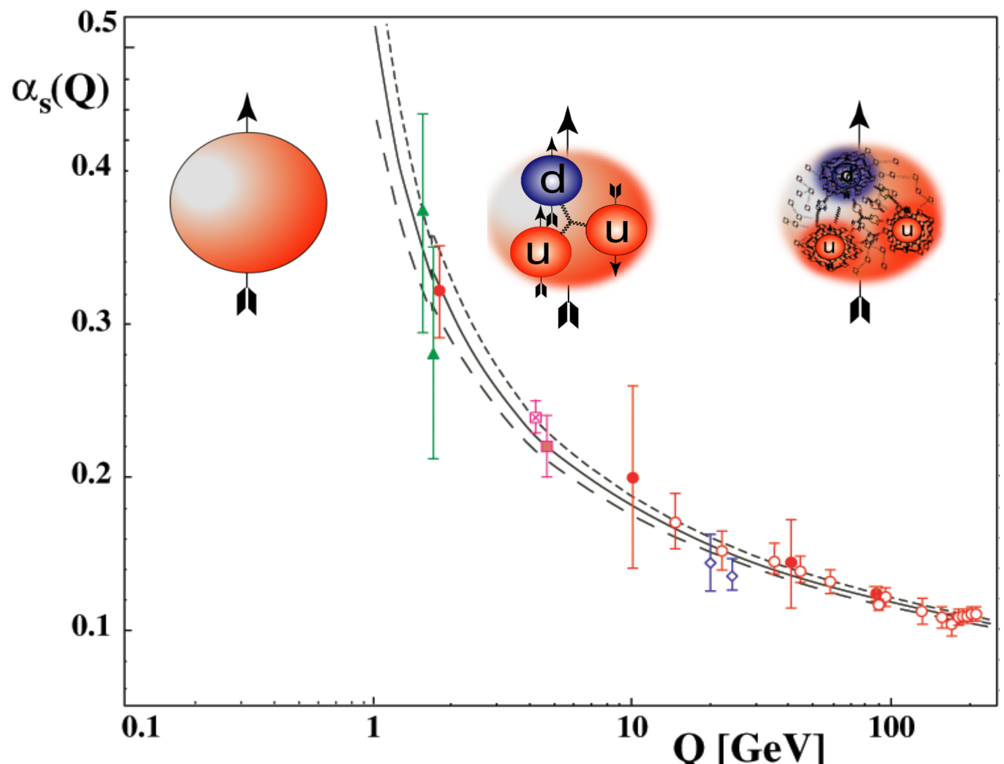
- **EW tested to high precision**
- **LHC:** *Higgs found*
  no evidence of BSM so far!
- **QCD tested at high energy**
  perturbative region
  pQCD works
  over a large range
  for many channels



Last Frontier in SM: QCD in Nonperturbative Region

- *2004 Nobel prize for ``asymptotic freedom''*
- *Non-perturbative regime QCD*
  Confinement ←→ dynamical chiral symmetry breaking ?
- *Nature's only known truly nonperturbative fundamental theory*
- *One of the top 10 challenges for physics!*
- *QCD: Important for discovering new physics beyond SM*
- *QCD vacuum*
- *Nucleon: stable lab to study QCD*

running coupling "constant"



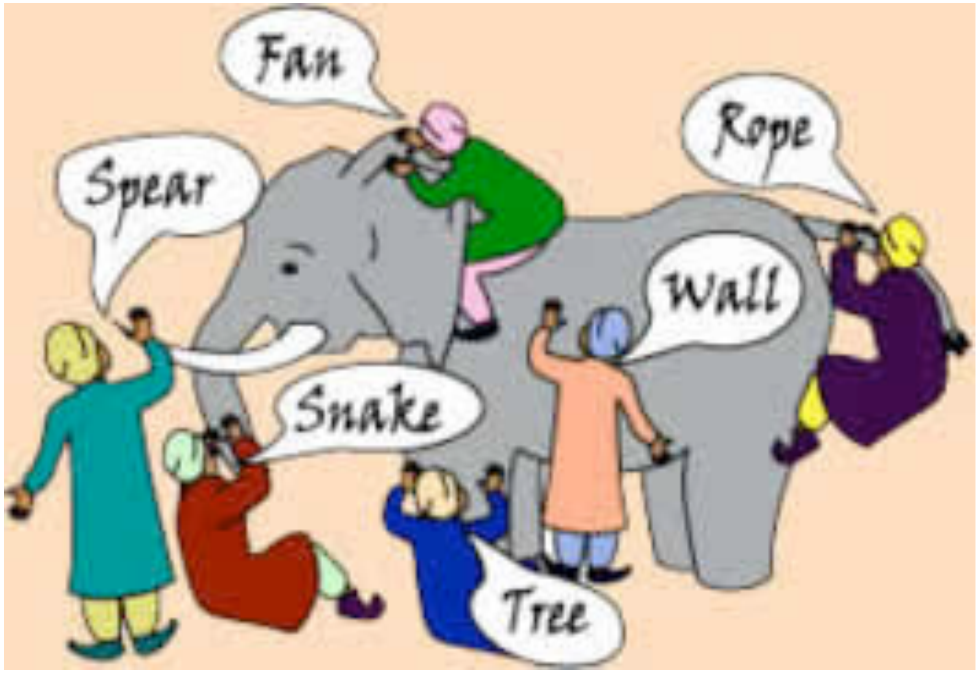
Nucleon Structure Study: Blind Men Touch Elephant

- *With the complexity of non-perturbative QCD, nucleon structure study is very challenging*
- *Precise 1d unpolarized PDF not enough*
- *1d spin shows surprise*
- *precision 3d (or multi-d) structure measurement needed*
- *But even that, it's not enough*

→ Need to ask good questions

→ Need good theory guidance

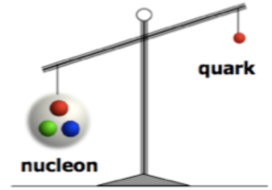
Turn on LIGHTS



Nucleon Structure: A Universe Inside

- Nucleon: proton =(uud) , neutron=(udd) *+ sea quarks + gluons (**QCD vacuum**)*
- Nucleon: ***99% of the visible mass in universe***

➢ **Proton mass "puzzle":**

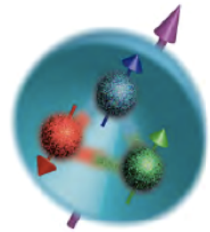


m_q ~ 10 MeV

m_N ~ 1000 MeV

Quarks carry $\sim 1\%$? of proton's mass

How does glue dynamics generate the energy for nucleon mass?



➢ **Proton spin "puzzle":**

Quarks carry $\sim 30\%$ of proton's spin

How does quark and gluon dynamics generate the rest of the proton spin?

➢ **3D structure of nucleon**: **3D in momentum or (2D space +1 in momentum)**

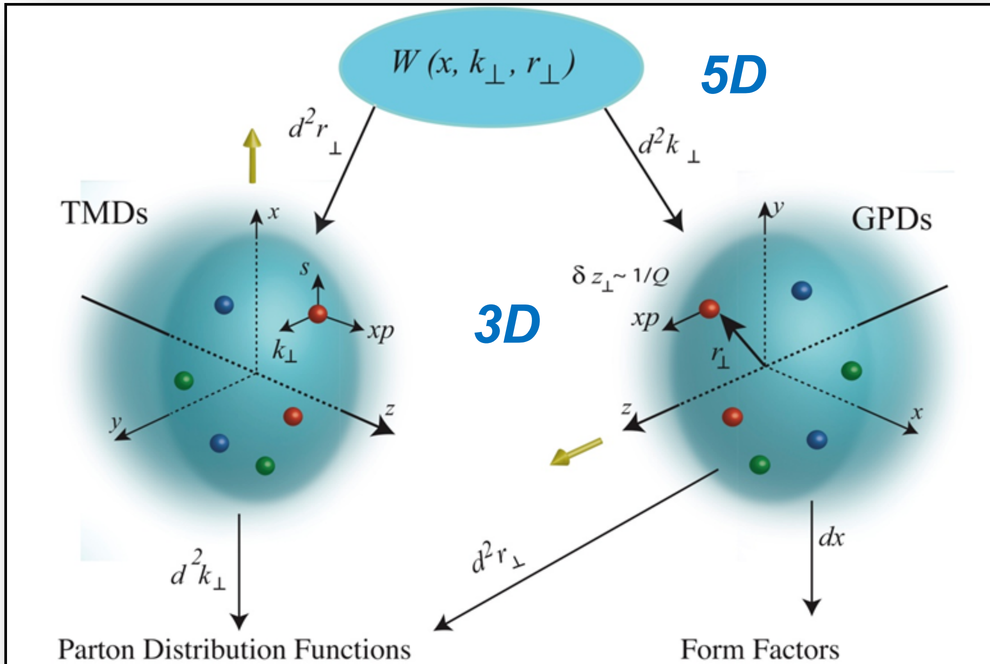
Color Confinement — Asymptotic freedom

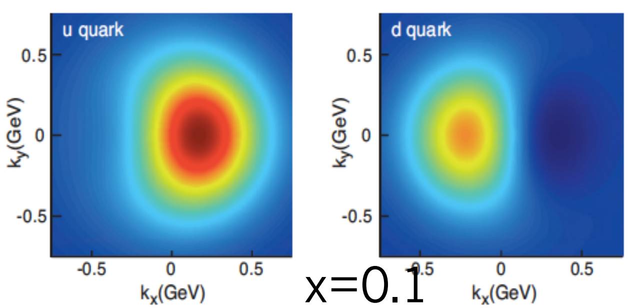
200 MeV (1 fm) — 2 GeV (1/10) — Q (GeV)

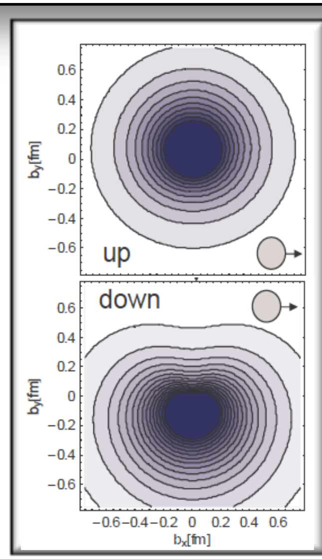
Probing momentum

How does the glue bind quarks and itself into a proton and nuclei?
Can we scan the nucleon to reveal its 3D structure?

Nucleon Landscape (Tomography)







- ***Transverse Momentum Dist. (TMD)***
  - ***Confined motion in a nucleon (semi-inclusive DIS, Drell-Yan)***
- ***Generalized Parton Dist. (GPD)***
  - ***Spatial imaging (exclusive DIS)***
- ***Requires***
  - ***High luminosity***
  - ***Polarized beams and targets***
  - ***Sophisticated detector systems***

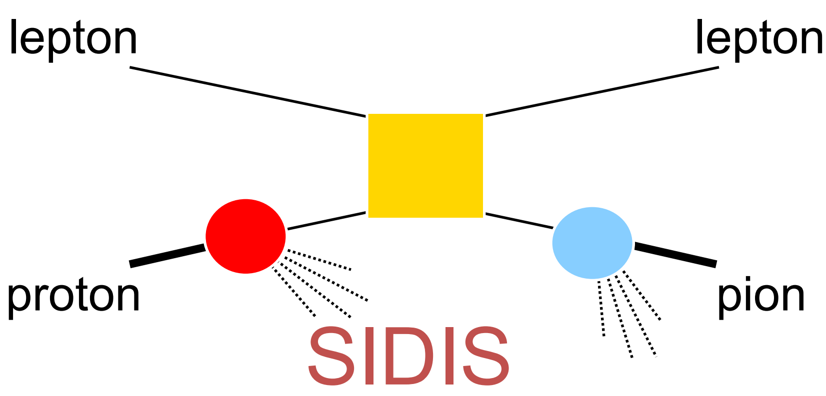
➡ ***Major new capability with JLab @ 12 GeV COMPASS, J-PARC, … and EIC …***

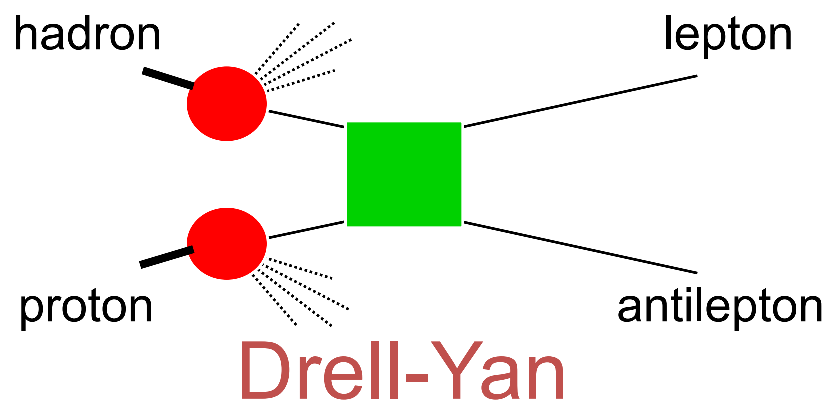
Leading-Twist TMD PDFs

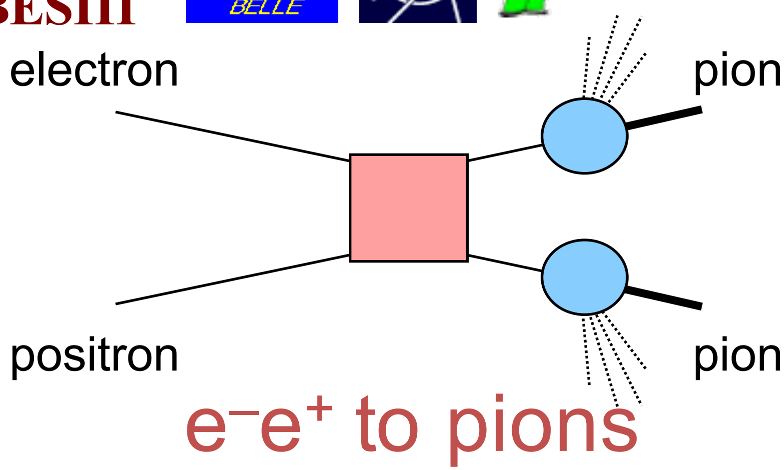
Nucleon Spin
Quark Spin

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







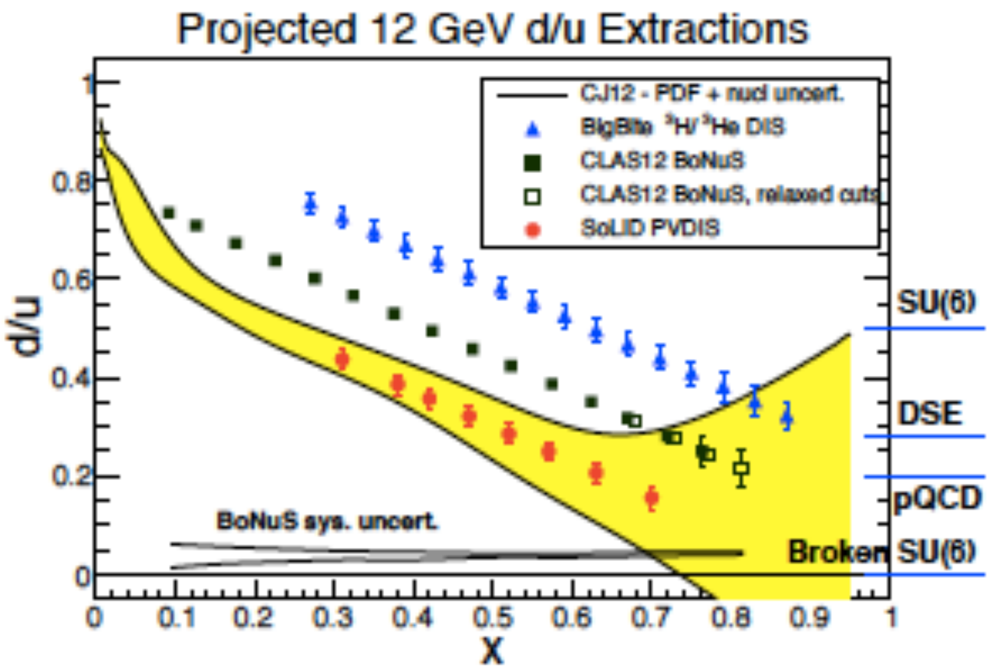
Partonic scattering amplitude

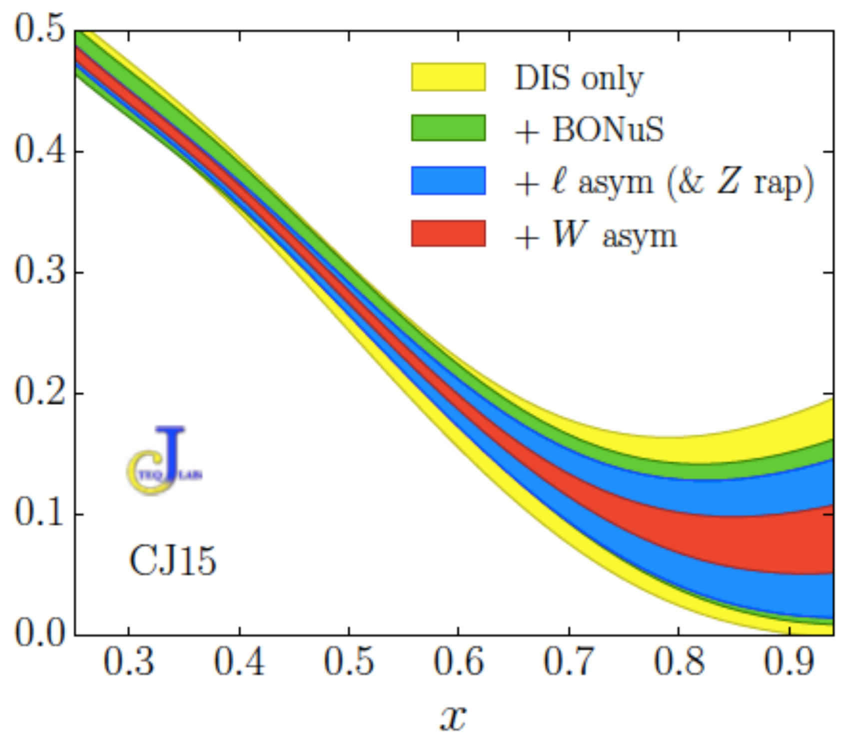
Fragmentation amplitude

Distribution amplitude

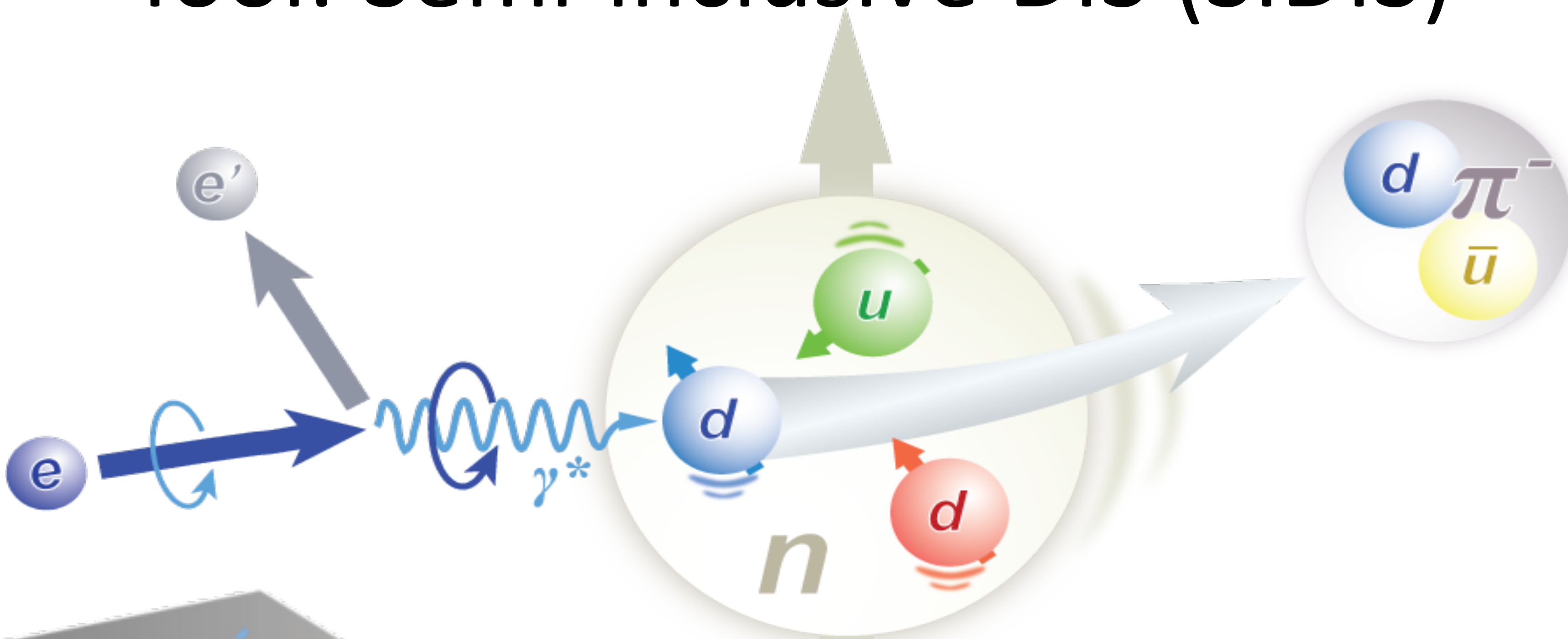
$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

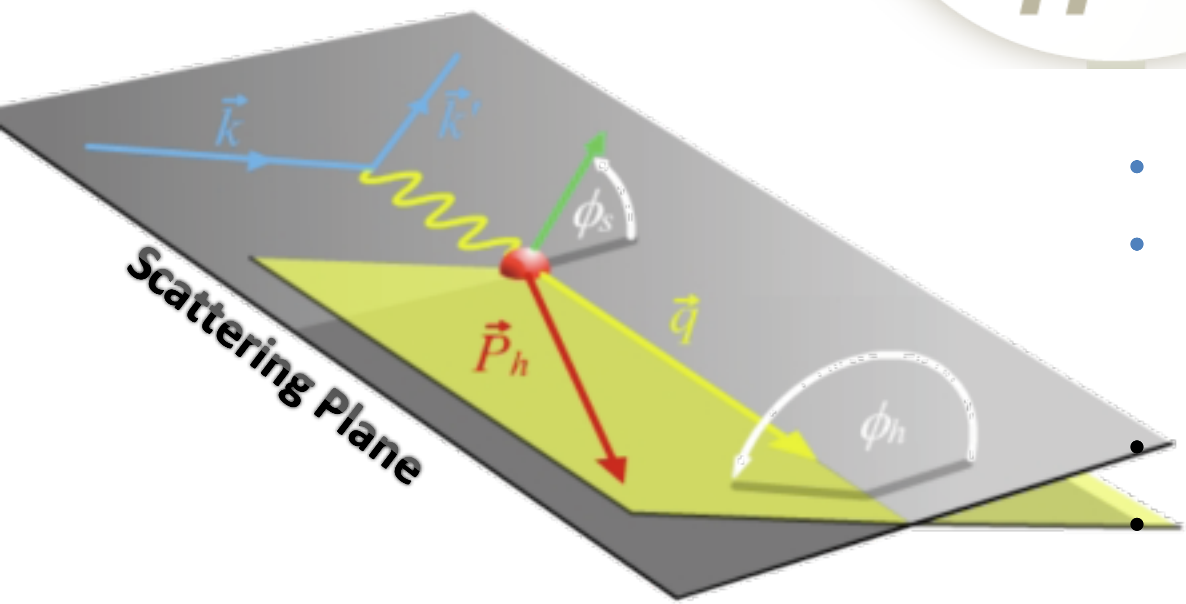
Valence Quark Distributions: d/u@ High-x





Tool: Semi-inclusive DIS (SIDIS)



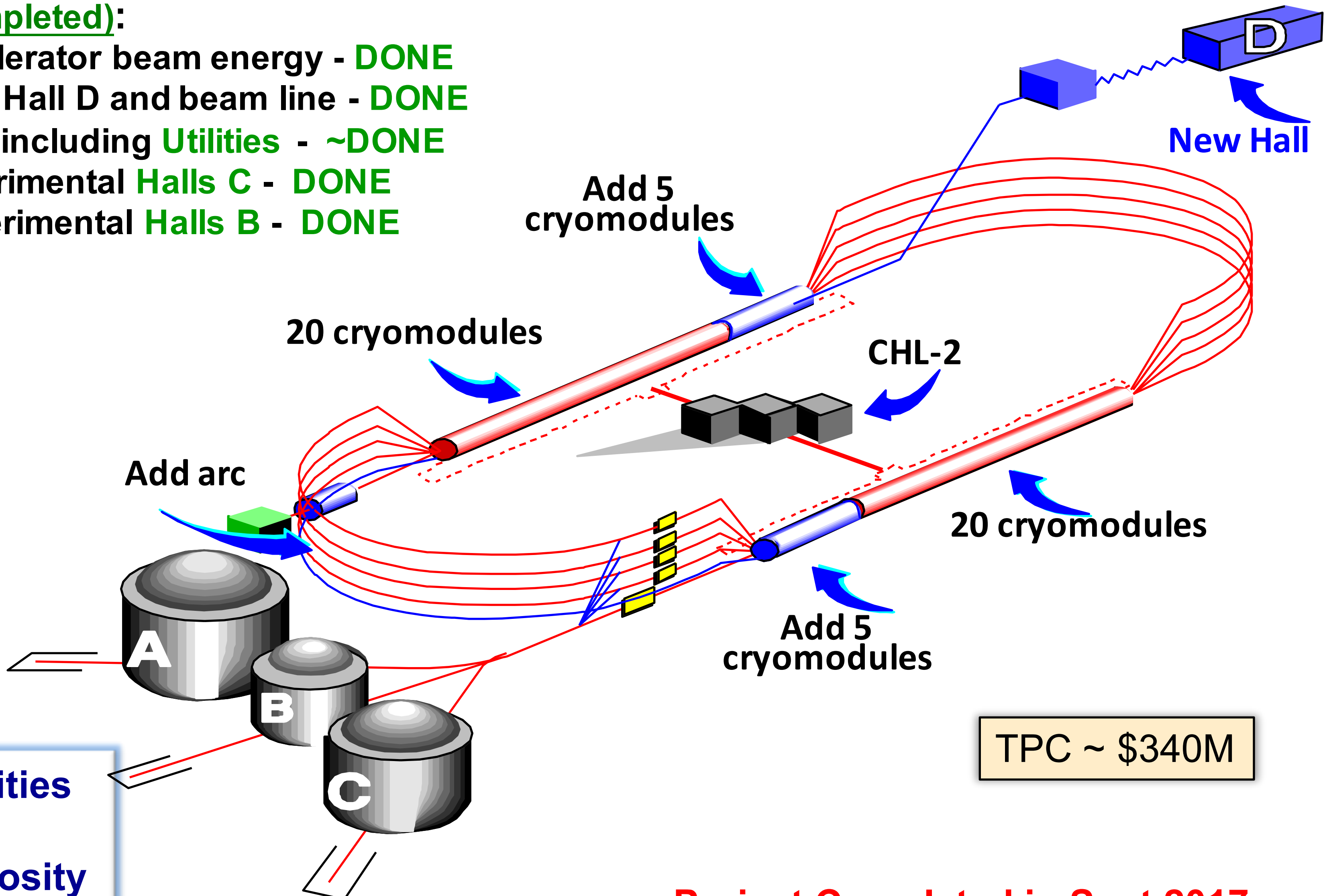


- Gold mine for TMDs
- Access all eight leading-twist TMDs through spin-comb. & azimuthal-modulations
- Tagging quark flavor/kinematics
- Fragmentation functions

12 GeV Upgrade Project

<u>Project Scope</u> <u>(completed)</u>:

- Doubling the accelerator beam energy - DONE
- New experimental Hall D and beam line - DONE
- Civil construction including Utilities - ~DONE
- Upgrades to Experimental Halls C - DONE
- Upgrades to Experimental Halls B - DONE



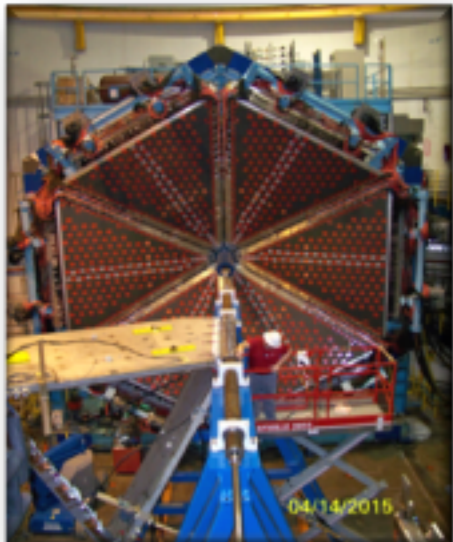
TPC ~ $340M

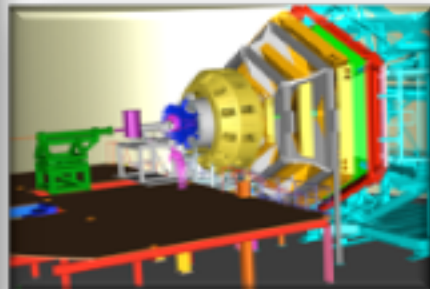
- Enhanced capabilities in existing Halls
- Increase of Luminosity 10^{35} - ~10^{39} $cm^{-2}s^{-1}$

Project Completed in Sept 2017

12 GeV Scientific Capabilities

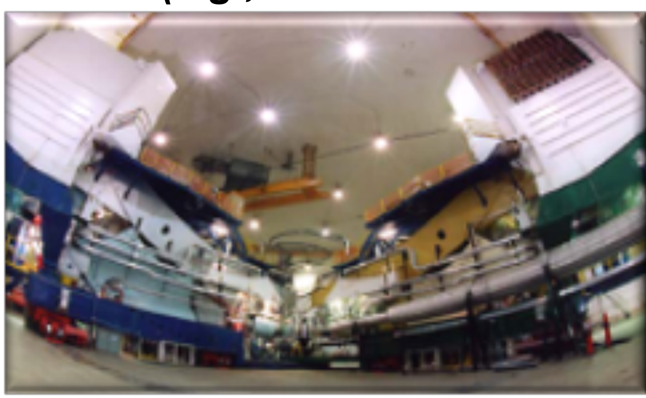
Hall B – understanding nucleon structure via generalized parton distributions

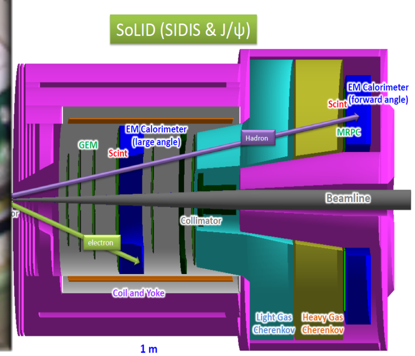




Hall D – exploring origin of confinement by studying exotic mesons

Hall A – form factors, future new experiments (e.g., SoLID and MOLLER)





Hall C – precision determination of valence quark properties in nucleons/nuclei

Why SoLID

- **JLab 6 GeV: precision measurements**

  high luminosity (10^{39}) but small acceptance (HRS/HMS: < 10 msr)

  or large acceptance but low luminosity (CLAS6: 10^{34})

- **JLab 12 GeV upgrade opens up a window of opportunities (DIS, SIDIS, Deep Exclusive Processes) to study valence quark (3-d) structure of the nucleon and other high impact physics (PVDIS, J/ψ, …)**
- **High precision in multi-dimension or rare processes requires very high statistics → large acceptance and high luminosity**
- **CLAS12: luminosity upgrade (one order of magnitude) to 10^{35}**
- **To fully exploit the potential of 12 GeV, taking advantage of the latest technical (detectors, DAQ, simulations, …) development**

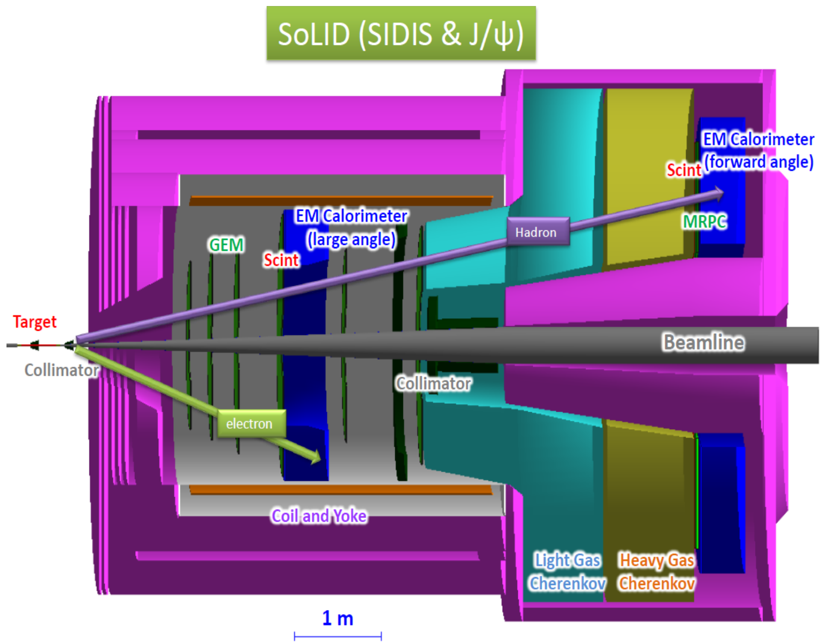
→ **SoLID: large acceptance detector can handle 10^{37} luminosity (no baffles)**

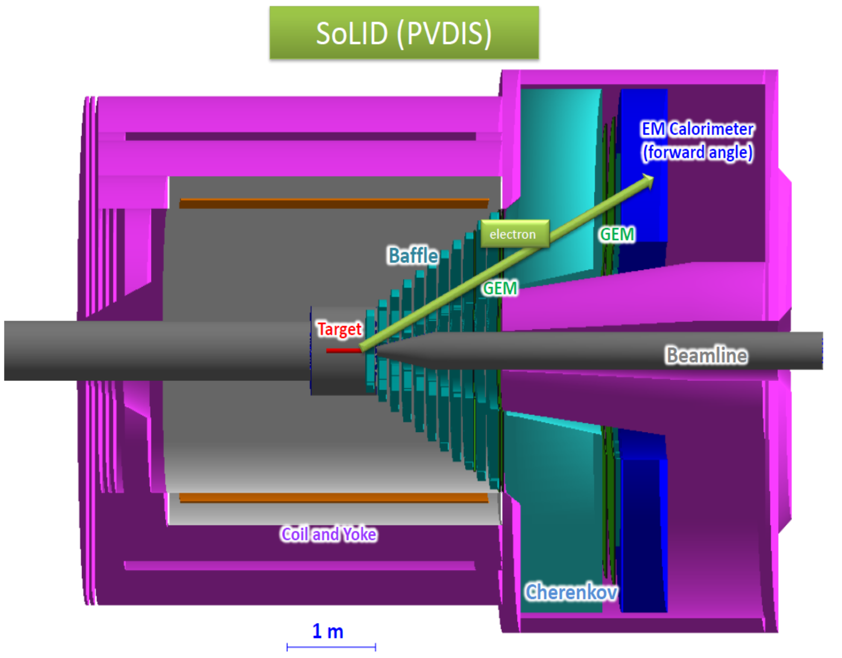
10^{39} with baffles

Overview of SoLID

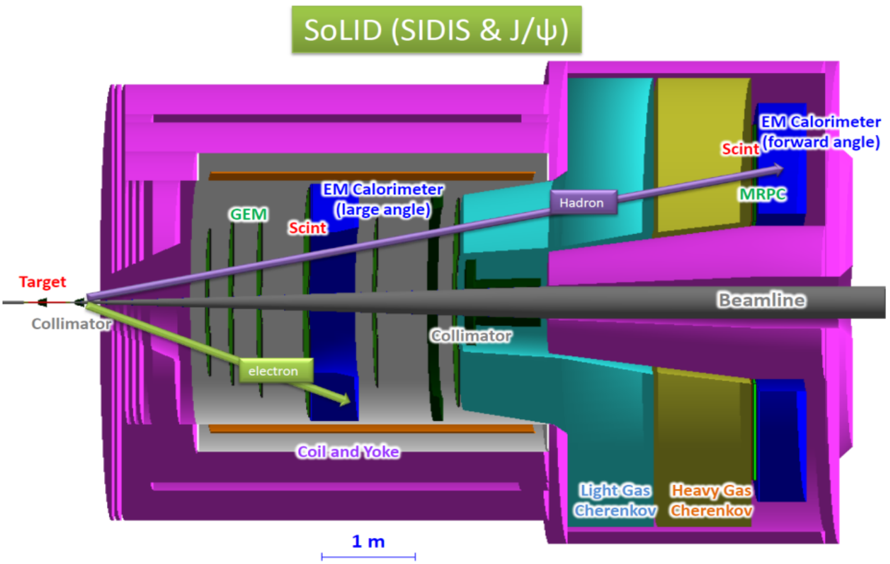
Solenoidal **L**arge **I**ntensity **D**evice

- **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

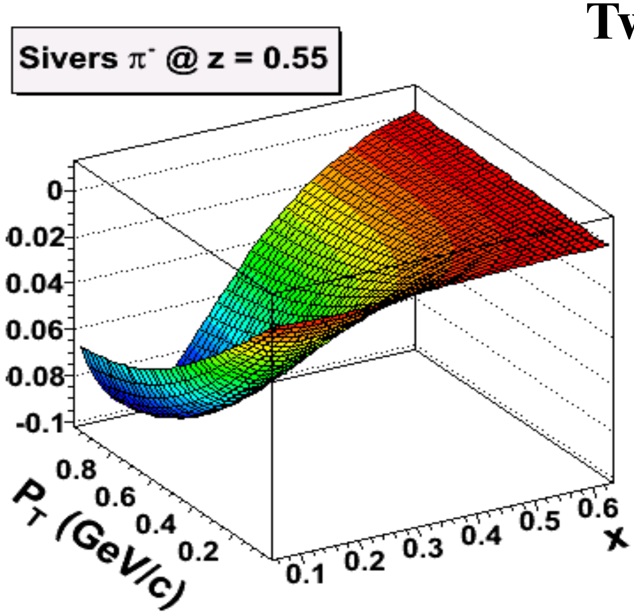


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

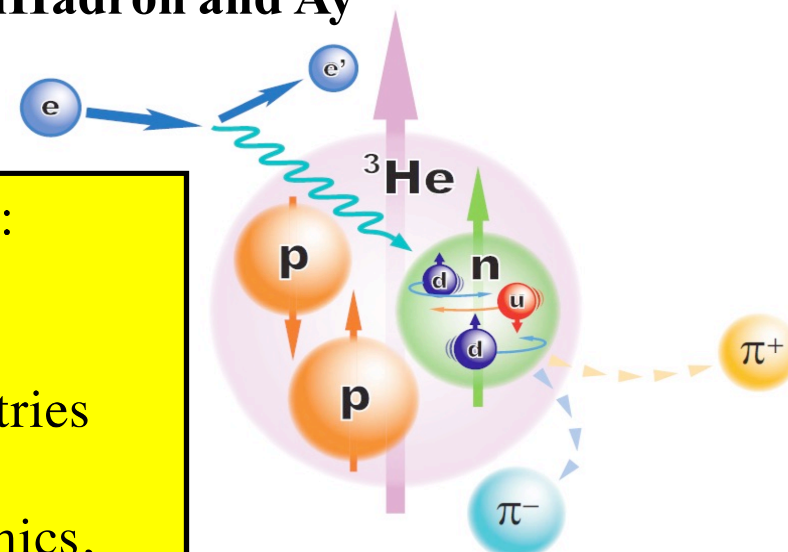
E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

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

Two run group experiments DiHadron and Ay

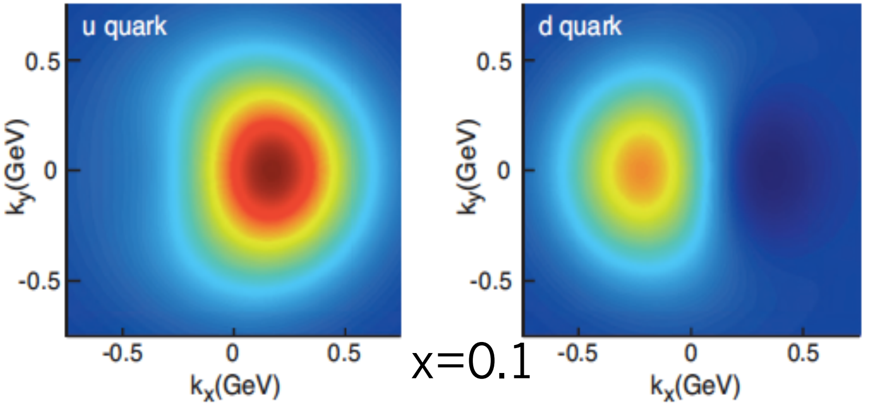


Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→ Lattice QCD, QCD Dynamics, Models.



Transverse Spin and 3-D Structure

Transverse Momentum-Dependent Distributions

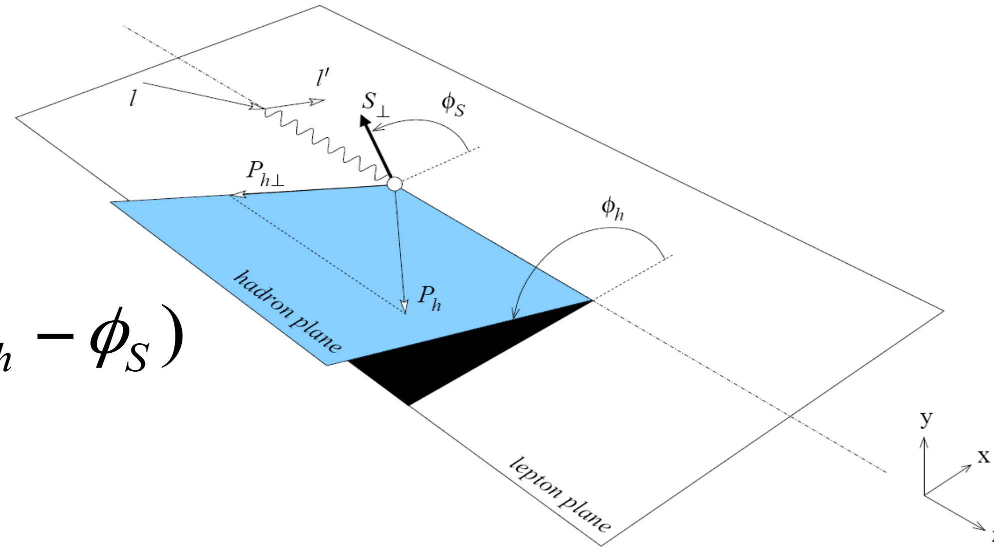


Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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

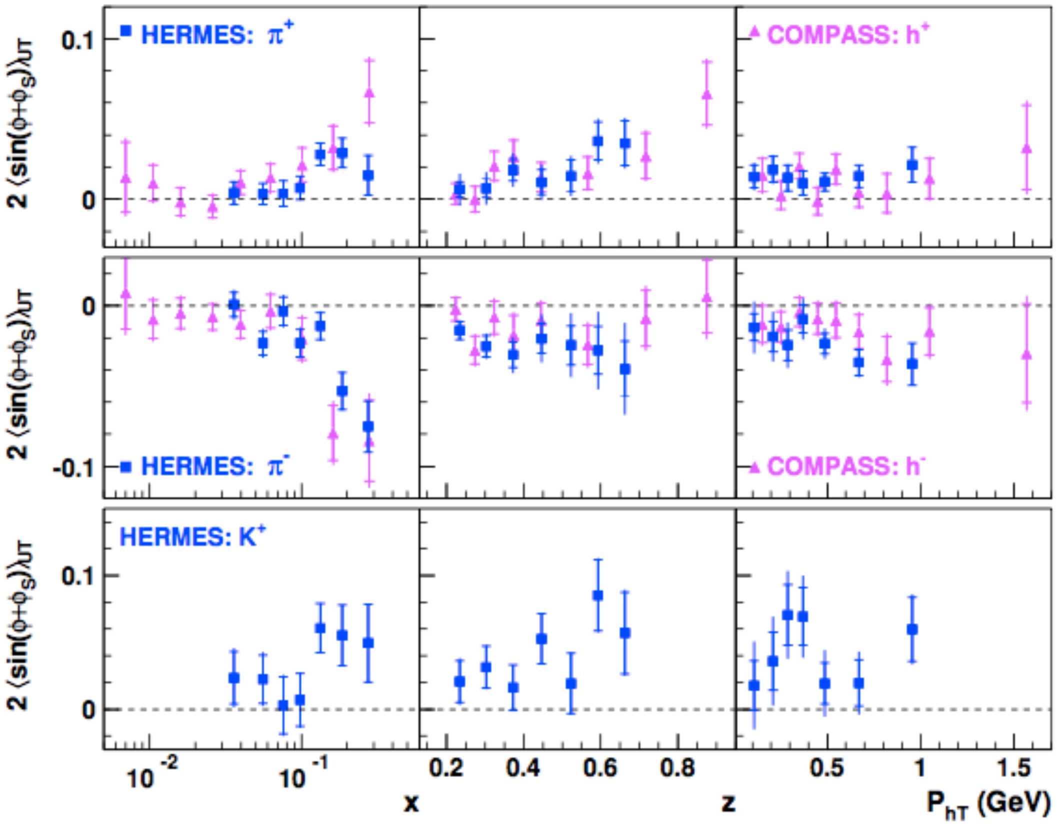


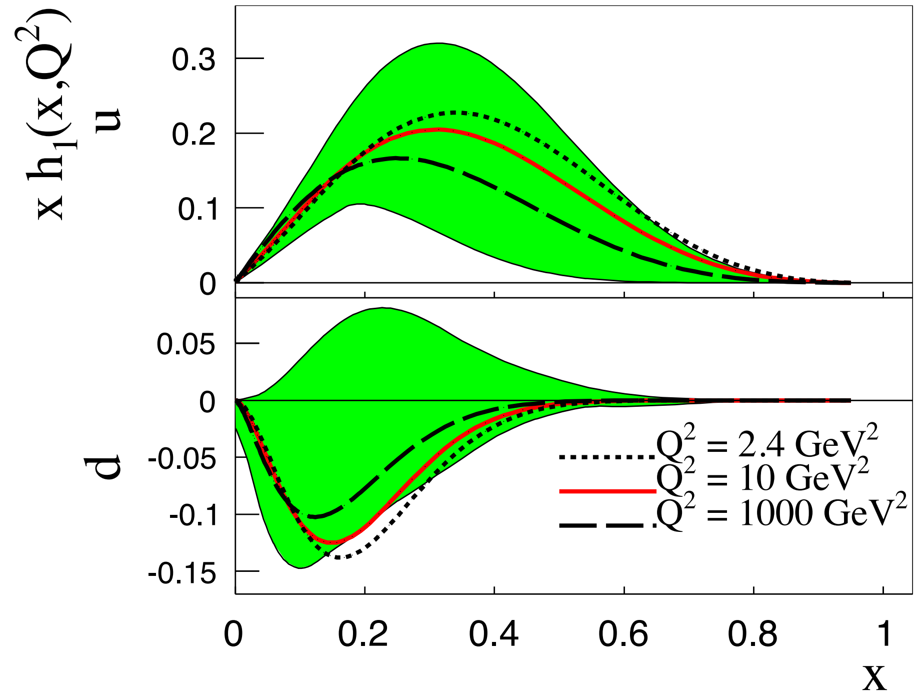
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

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

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

HERMES/COMPASS: *Collin Asymmetries and Extraction of Transversity*



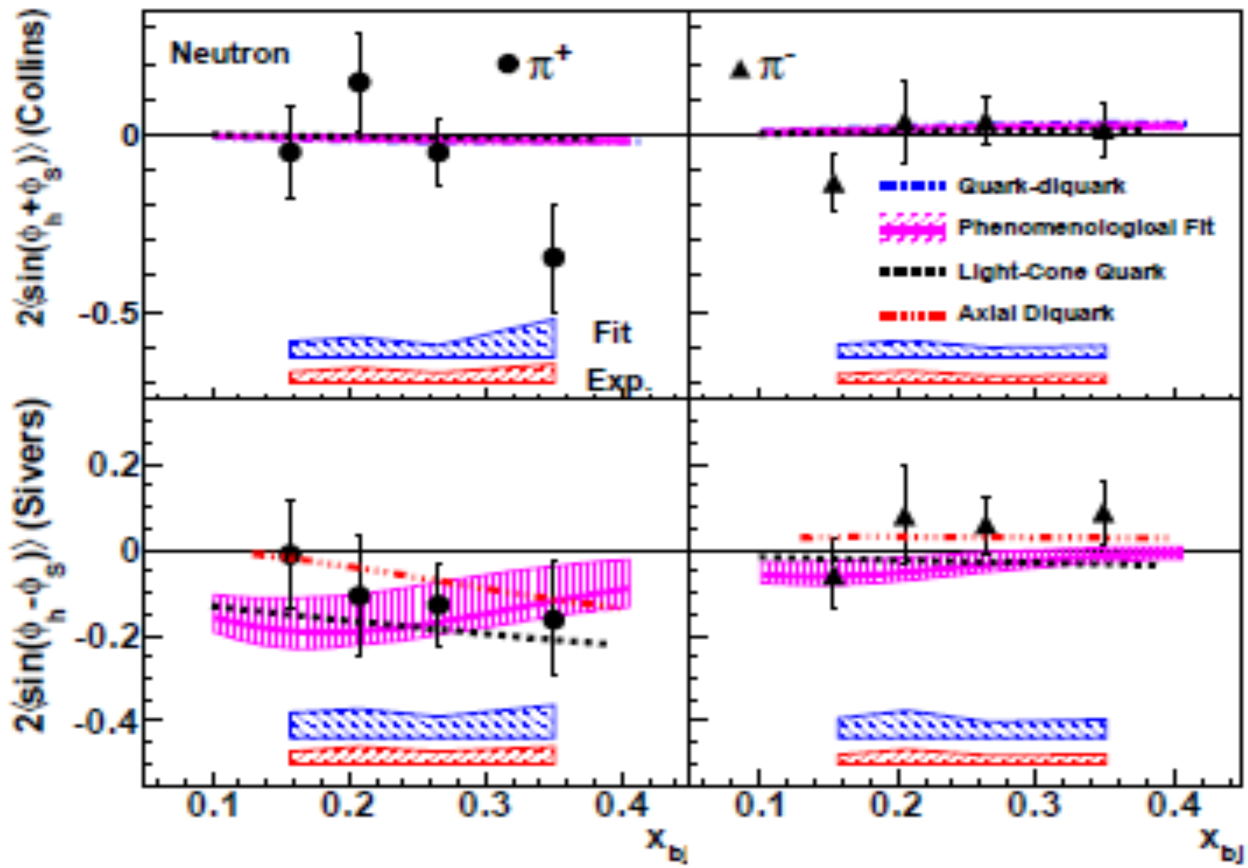


Z. Kang, *et al.*
arXiv:1505.05589 (2015)

^{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+

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

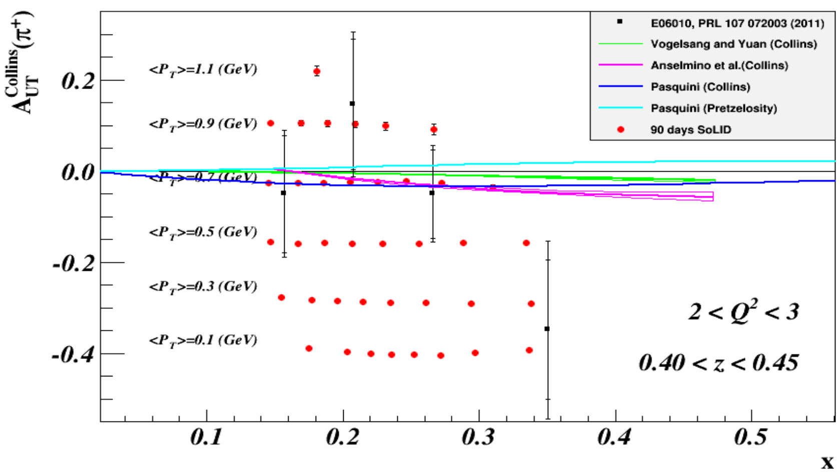
neutron Sivers SSA:
negative for π^+,
Agree with Torino Fit

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

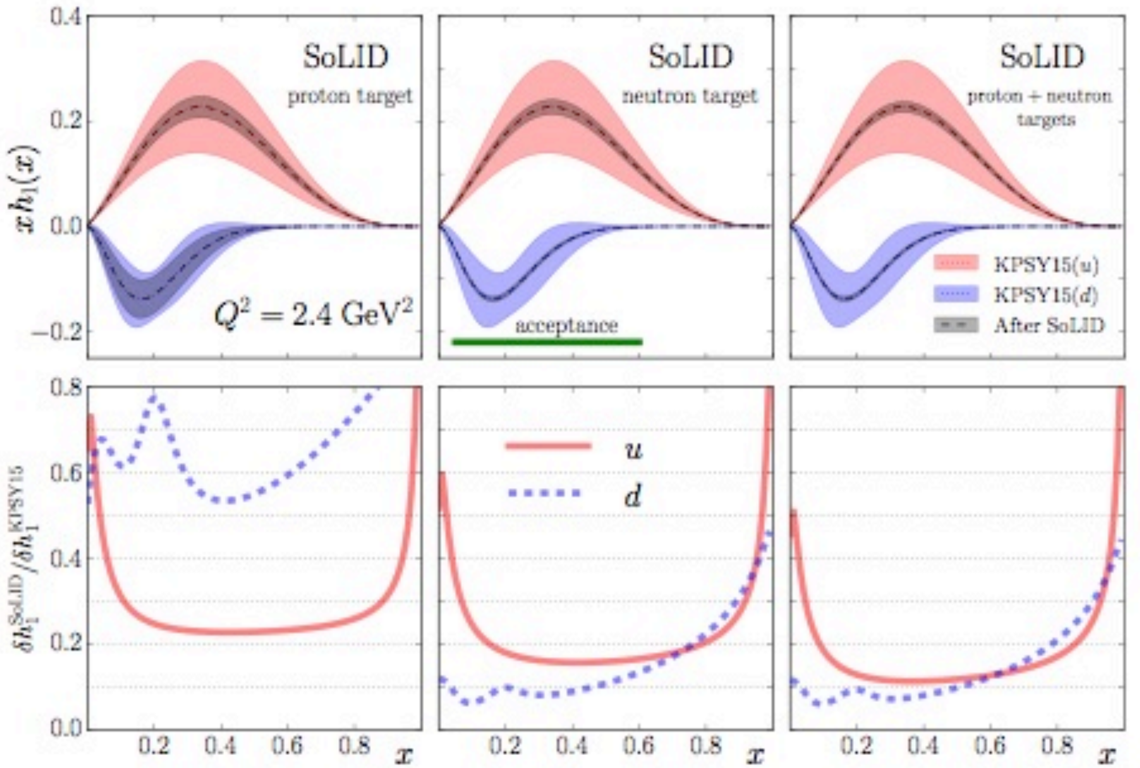
Transversity from SoLID

- Collins Asymmetries ~ Transversity (x) Collin Function
- **Transversity**: chiral-odd, not couple to gluons, **valence behavior**, largely unknown
- Global model fits to experiments (SIDIS and e+e-)
- **SoLID** with **trans polarized n & p** → Precision extraction of u/d quark transversity
- Collaborating with theory group (N. Sato, A. Prokudin, …) on impact study

Collins Asymmetries



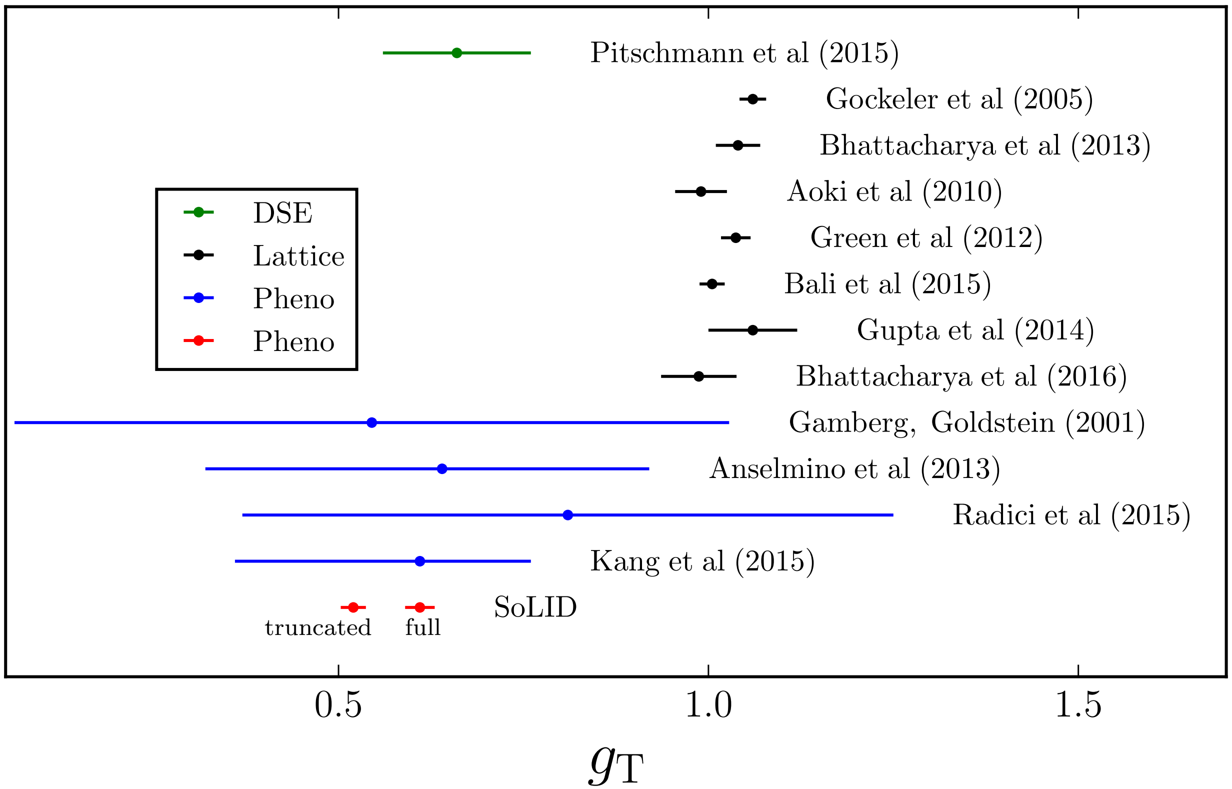
P_T vs. x for one (Q^2, z) bin
Total > 1400 data points



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

Tensor Charge from SoLID

- **Tensor charge (0th moment of transversity): fundamental property**
  Lattice QCD, Bound-State QCD (Dyson-Schwinger) , …
- **SoLID** with **trans polarized n & p** → determination of tensor charge



DSE

LQCD

Extractions from existing data

SoLID projections

Tensor Charges

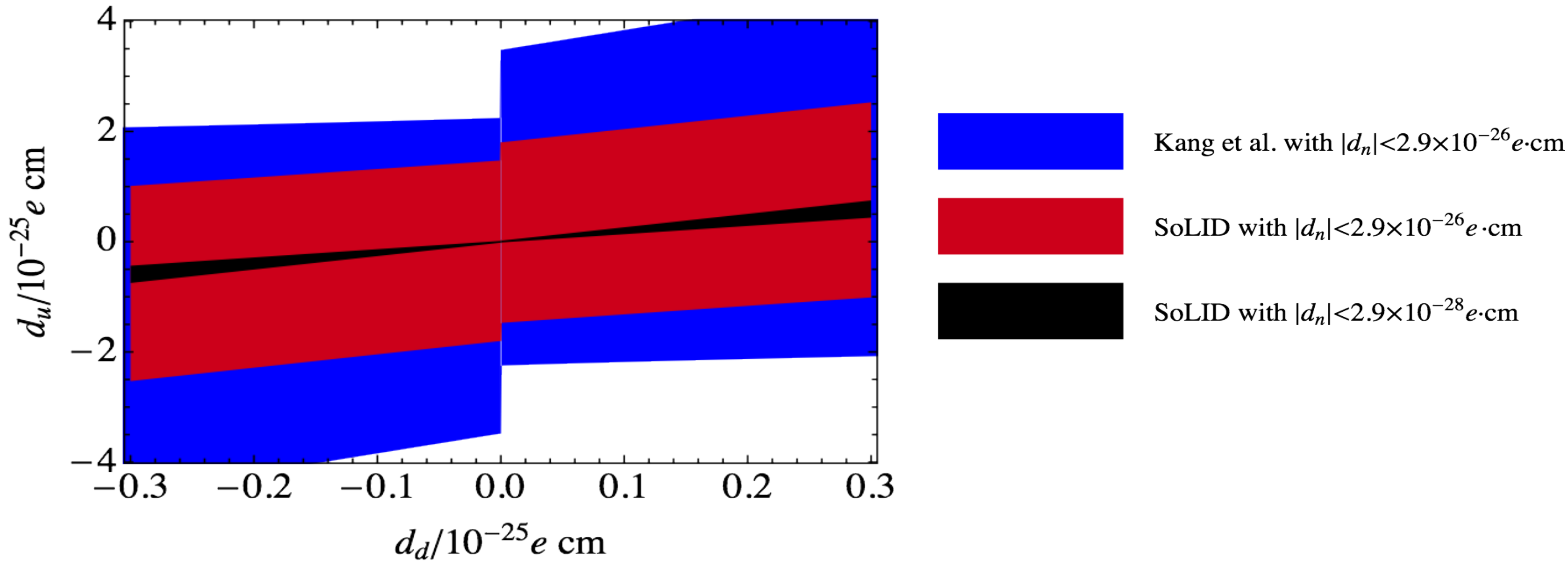
Projections with a model QCD evolutions included

Tensor Charge and Neutron EDM

Electric **D**ipole **M**oment

Tensor charge and EDM

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

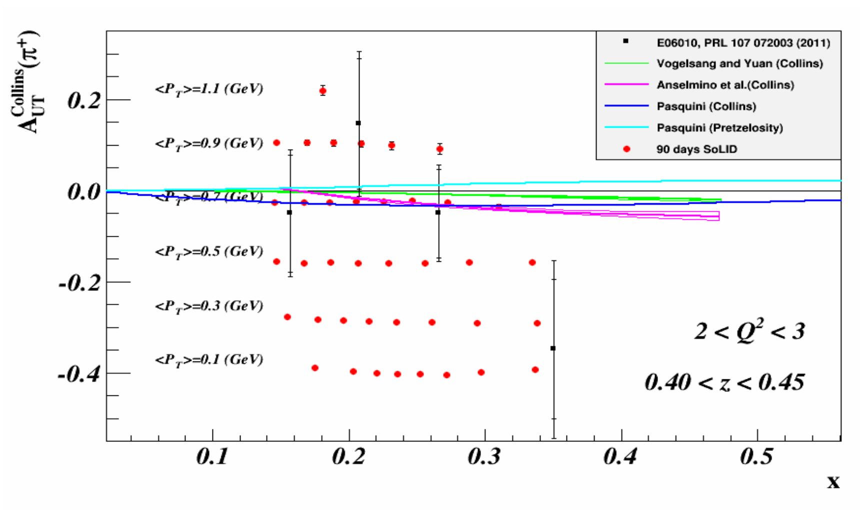


current neutron EDM limit $|d_n| < 2.9 \times 10^{-26} \, e \cdot \mathrm{cm}$

Mapping Sivers Asymmetries with SoLID

- Sivers Asymmetries ~ Sivers Function (x, k_T, Q^2) (x) Fragmentation Function (z, p_T,Q^2)
- Gauge Link/ QCD Final State Interaction
- Transverse Imaging
- QCD evolutions
- **SoLID**: precision multi-d mapping
- Collaborating with theory group: impact study with new approach

Sivers Asymmetries



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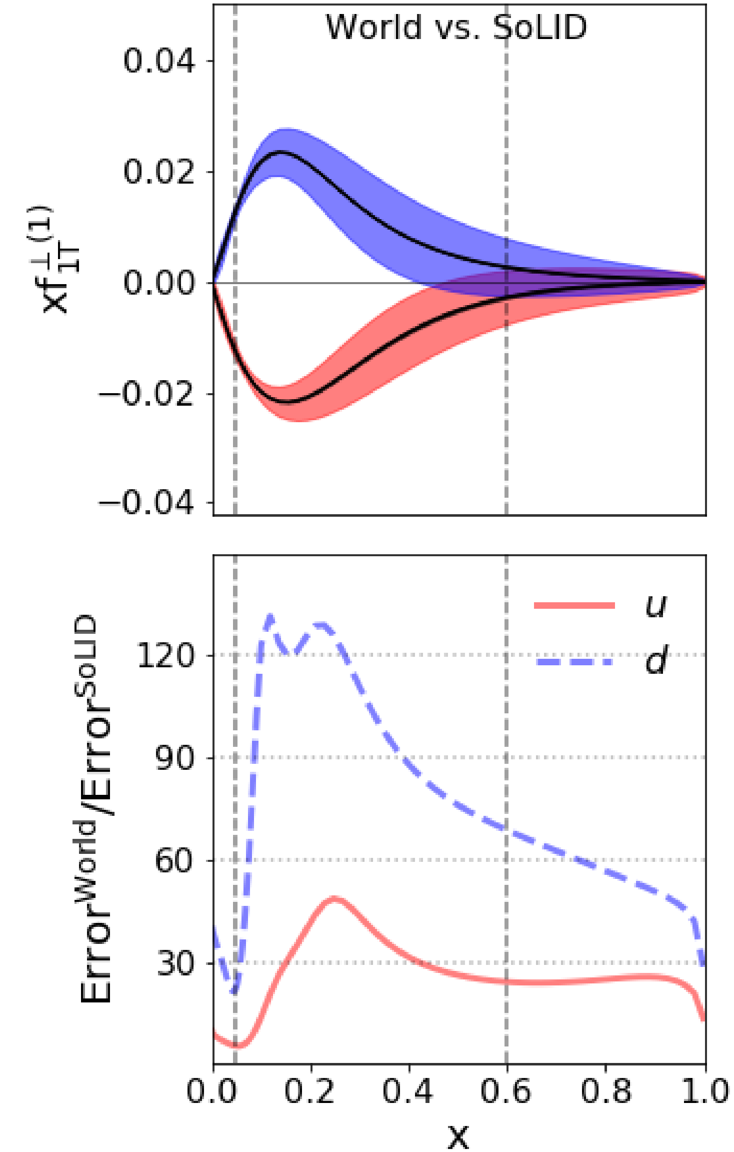
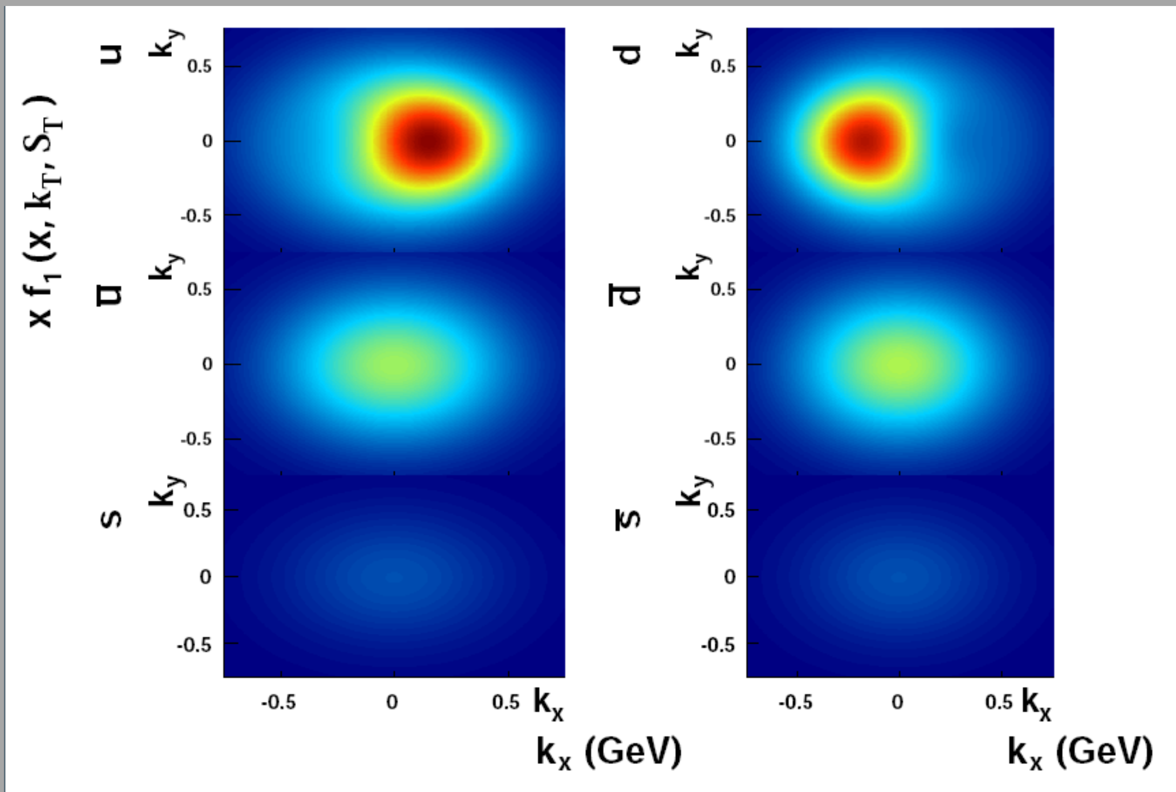


Liu, Sato,… on-going

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:

$$x = 0.1$$

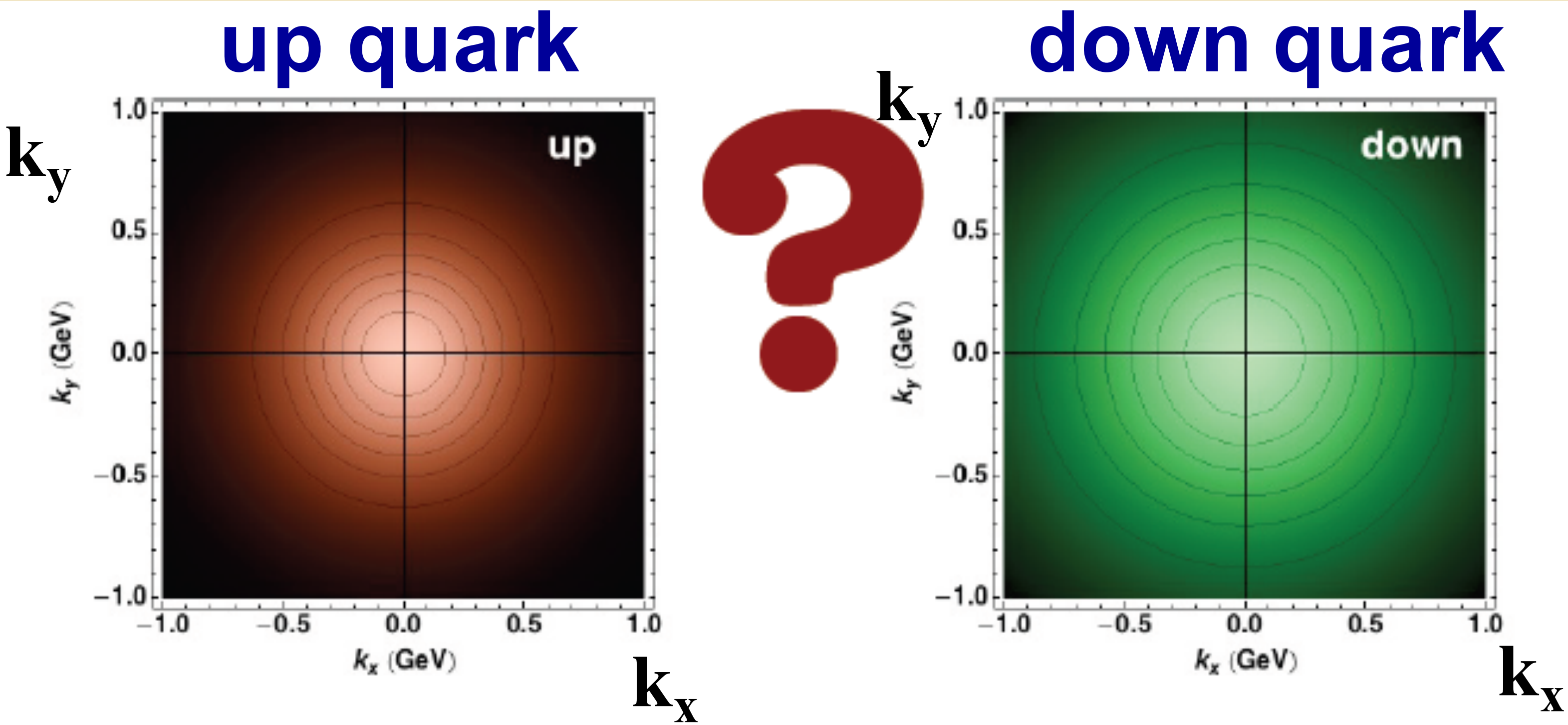
Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

No information on sea quarks

In future we will obtain much clearer picture

Unpolarized TMD: Flavor P_T Dependence?

Flavor in transverse-momentum space



Is the up distribution wider or narrower than the down?

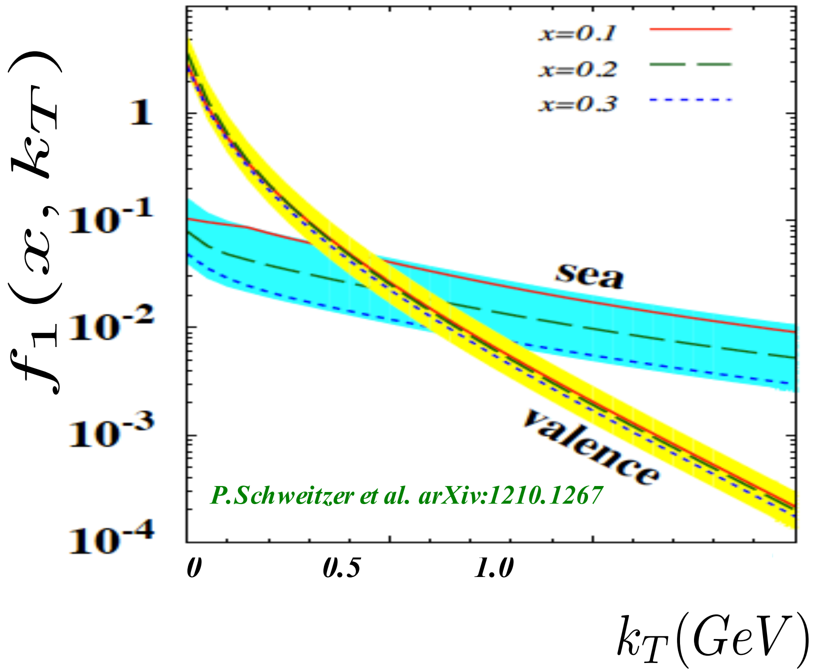
And the sea?

How wide are the distributions?

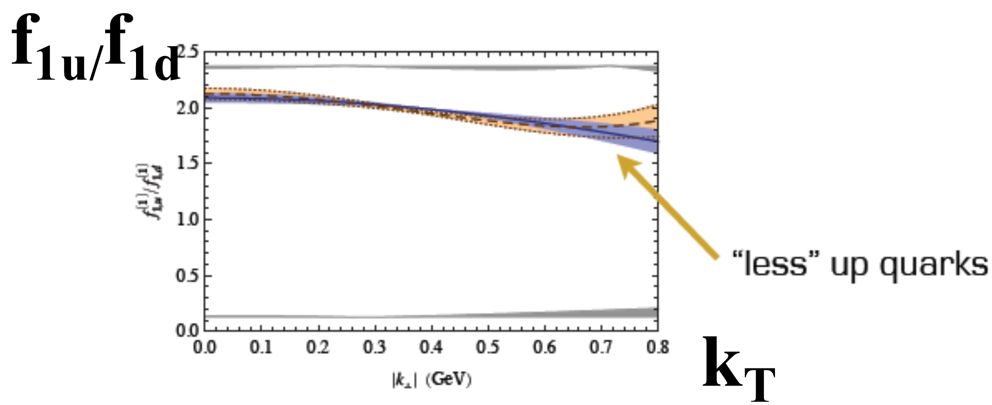
A. Bacchetta, Seminar @ JLab, JHEP 1311 (2013) 194

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



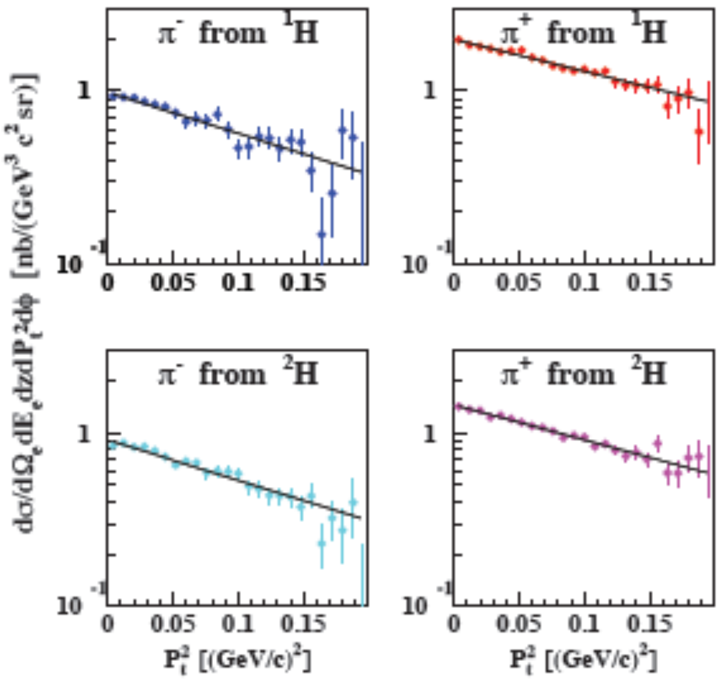
Musch, Hagler, Negele, Schafer, PRD 83 (11)

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

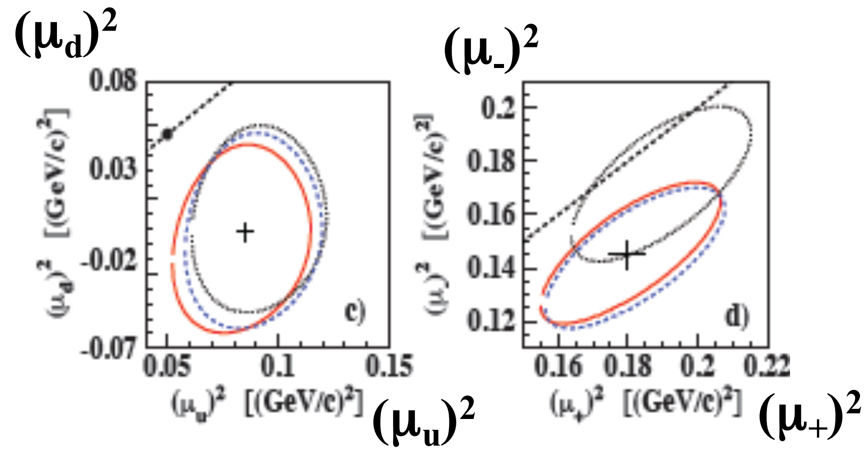
Hall C Results: Flavor P_T Dependence

First indications from experiments



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

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



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

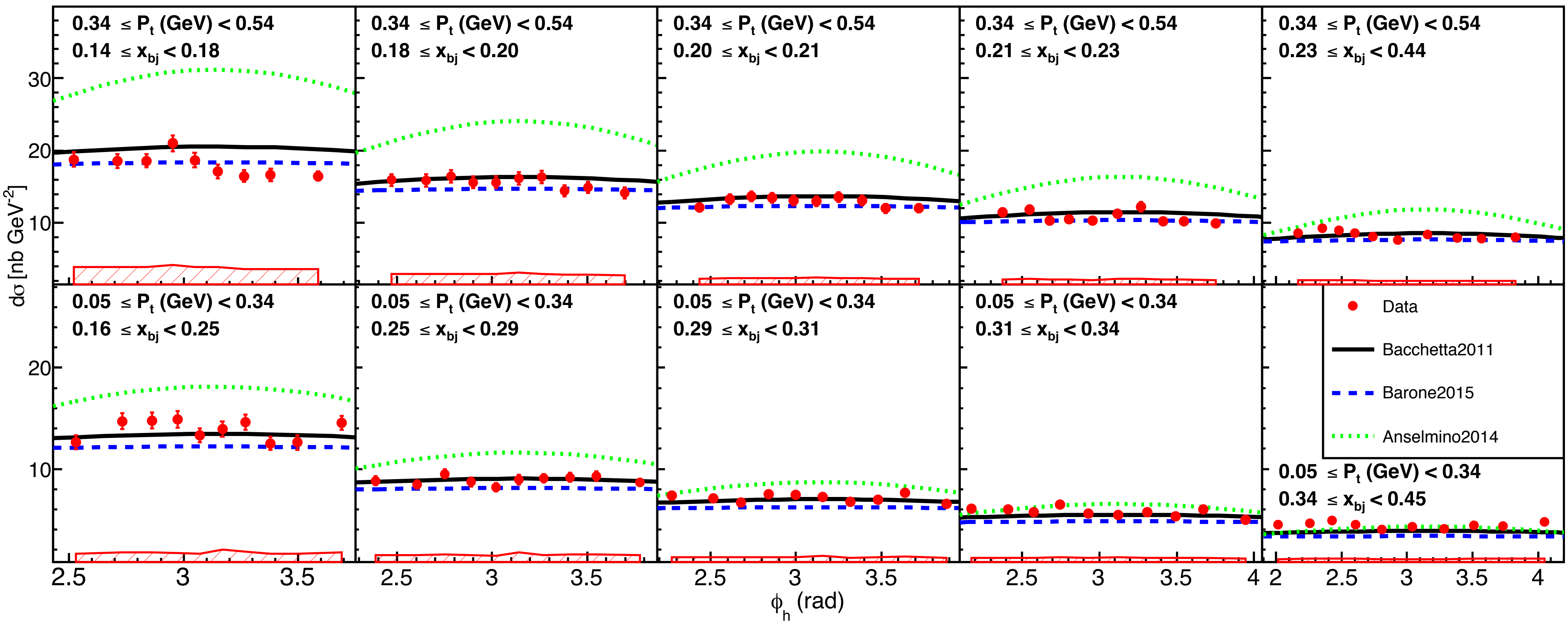
Jefferson Lab

Hall A SIDIS Cross Section Results From E06-010 (Transversity):

pi+ and pi- production on He3

X. Yan *et al.*, Hall A Collaboration, PRC 95, 035209 (2017)

(not enough sensitivity to Boer-Mulders)

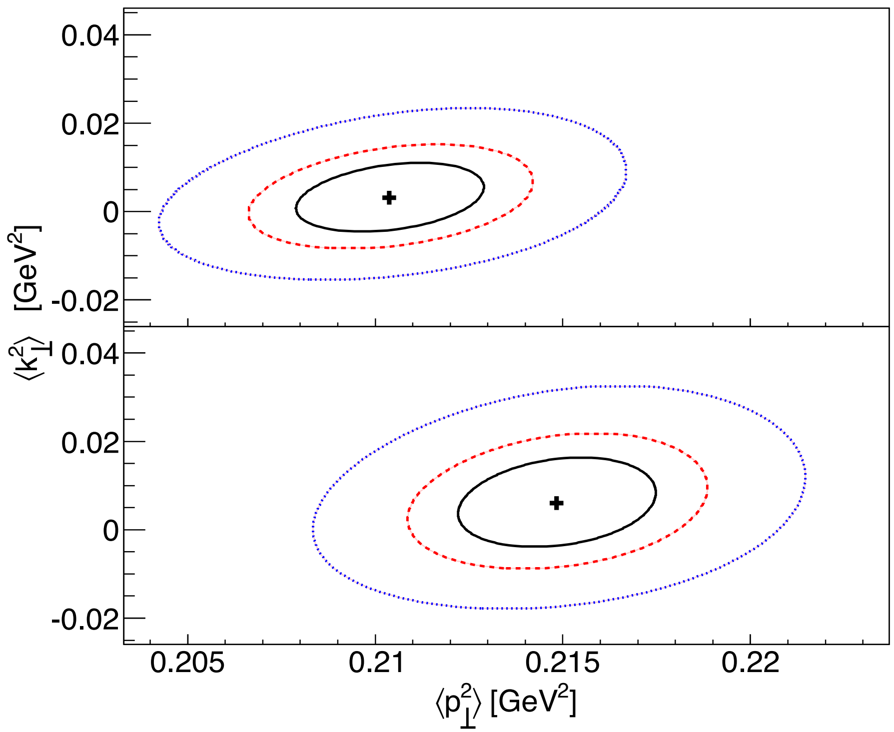


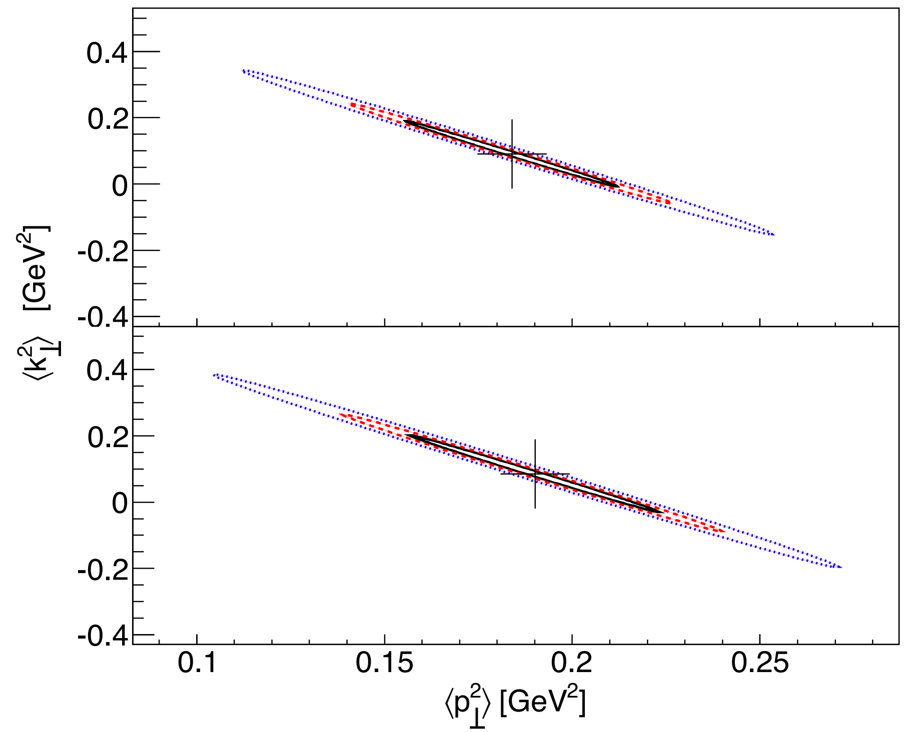
pi+ results Φ_h **(rad)**

Hall A Results: Transverse Momentum dependence

average quark transverse momentum distribution squared
vs. average quark transverse momentum in fragmentation squared

with modulation **no modulation**





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)

X. Chen *et al.* suggested a new one: decompose gauge field into pure and physical

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

- Ji's sum rule:

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

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

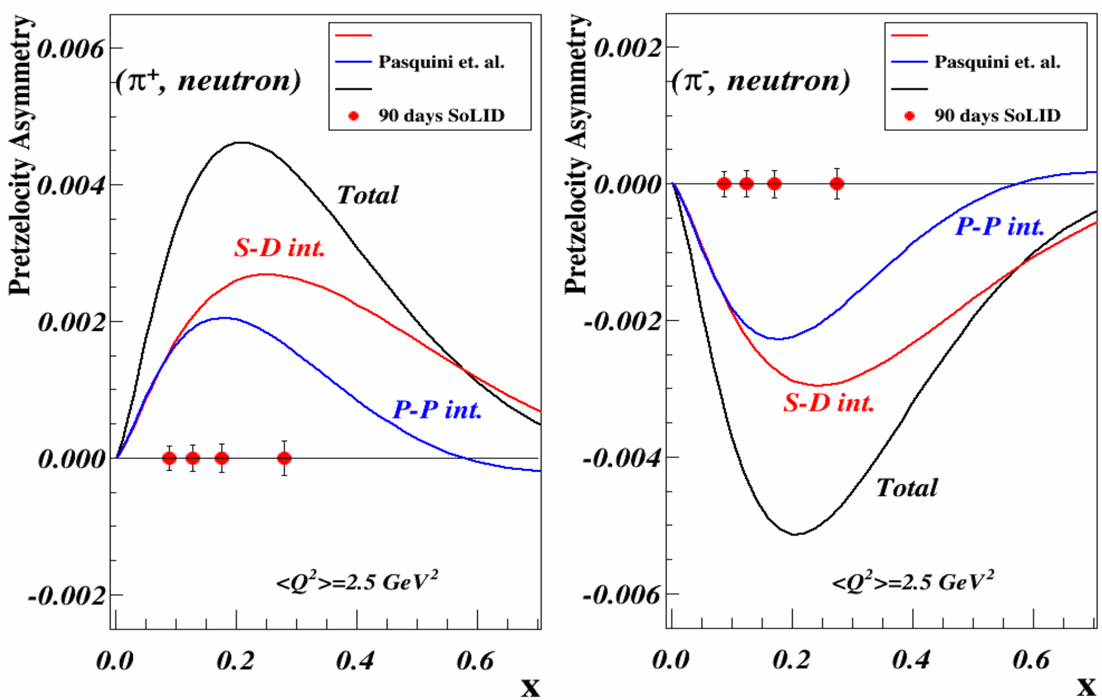
- Parton spin-orbital correlations → transverse momentum

  TMDs provide more direct information

- TMD information related to $\mathcal{L}_q$?

TMDs: Access Quark Orbital Angular Momentum

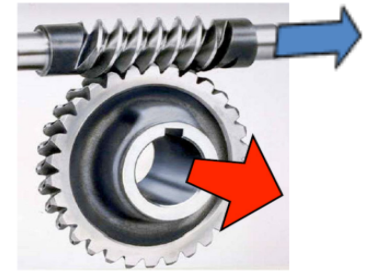
- TMDs : Correlations of transverse motion with quark spin and orbital motion
- **Without OAM, off-diagonal TMDs=0,**
  no direct model-independent relation to the OAM in spin sum rule yet
- Sivers Function: QCD lensing effects
- In a large class of models, such as light-cone quark models
  Pretzelosity: 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

Asymmetry A_{LT} Result

E06-010 Collaboration, J. Huang et al., **PRL. 108, 052001 (2012).**



Worm-Gear
Trans helicity

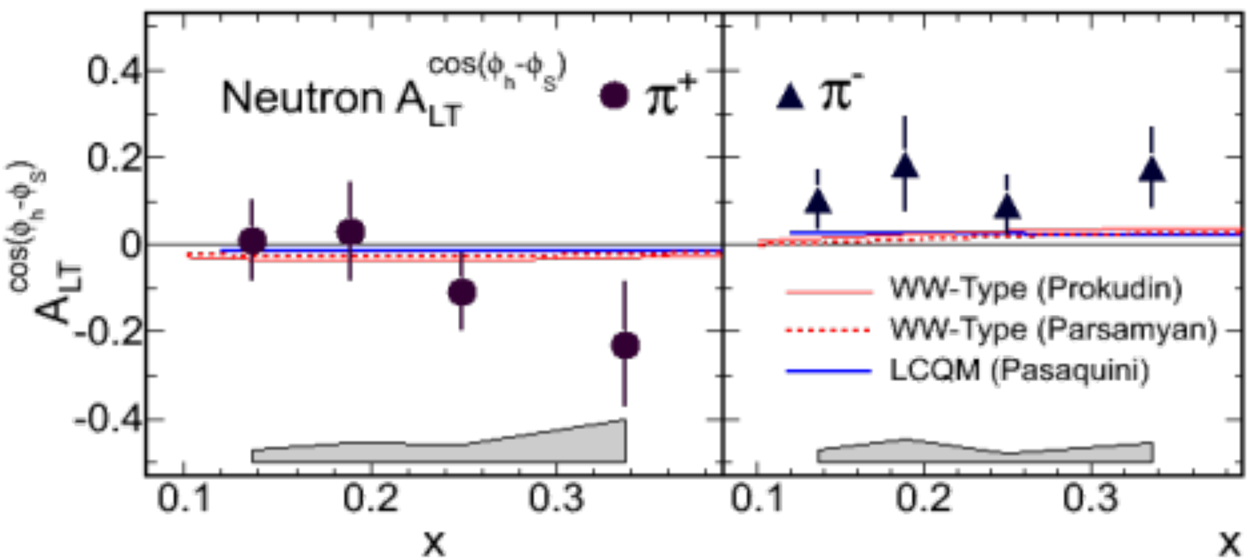
To leading twist:

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

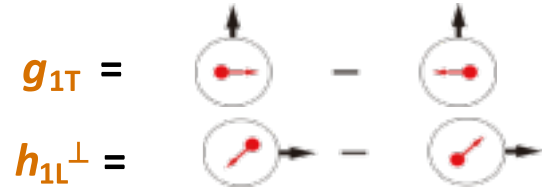
Dominated by L=0 (S) and L=1 (P) interference

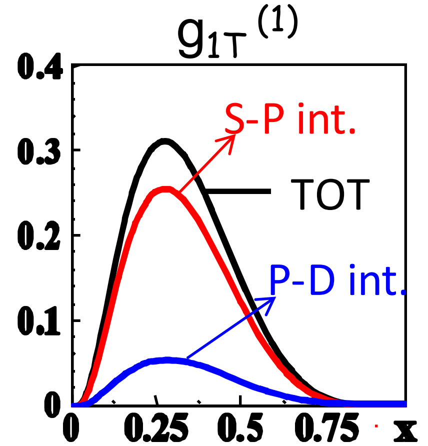
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

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



Worm-gear Functions

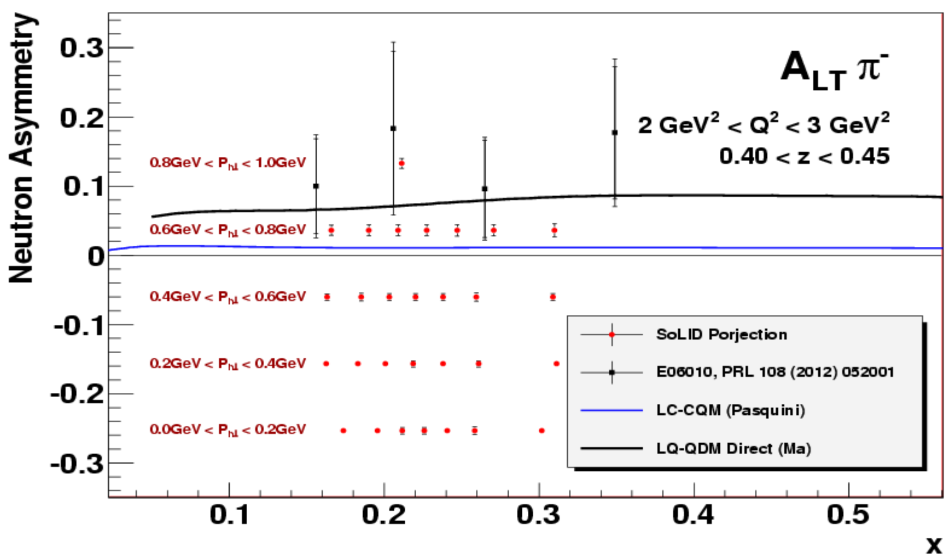


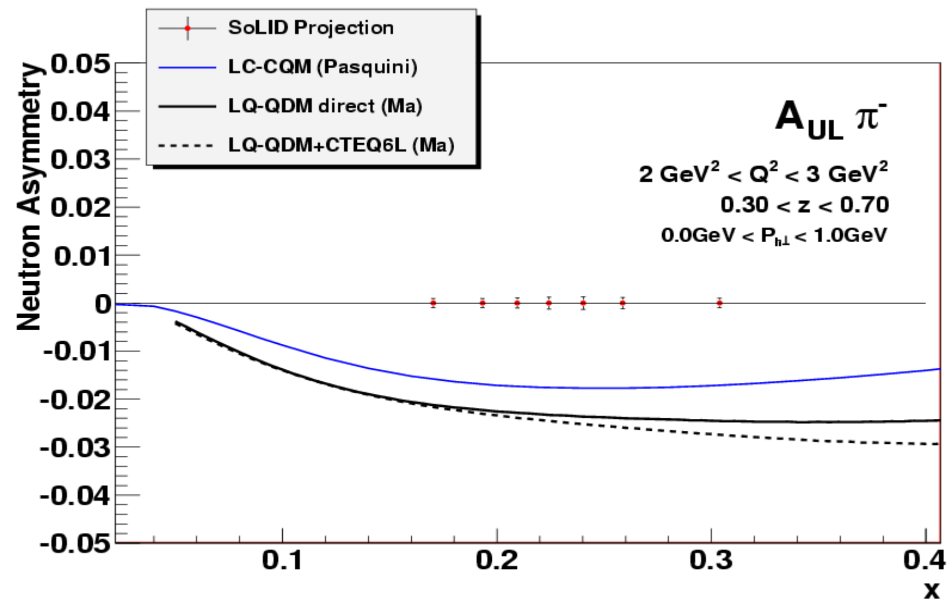


Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

- 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)

Neutron Projections,





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

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

Yoshitaka Hatta

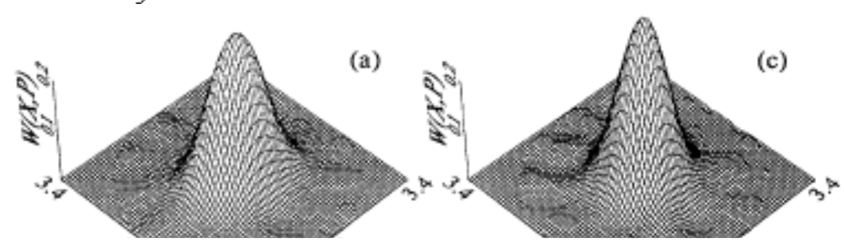
Wigner distribution: Is it measurable?

In quantum optics, yes!

VOLUME 70, NUMBER 9 PHYSICAL REVIEW LETTERS 1 MARCH 1993

Measurement of the Wigner Distribution and the Density Matrix of a Light Mode Using Optical Homodyne Tomography: Application to Squeezed States and the Vacuum

D. T. Smithey, M. Beck, and M. G. Raymer
Department of Physics and Chemical Physics Institute, U
A. Faridani
Department of Mathematics, Oregon State Uni
(Received 16 Novembe



What about in QCD? Go to small-x!

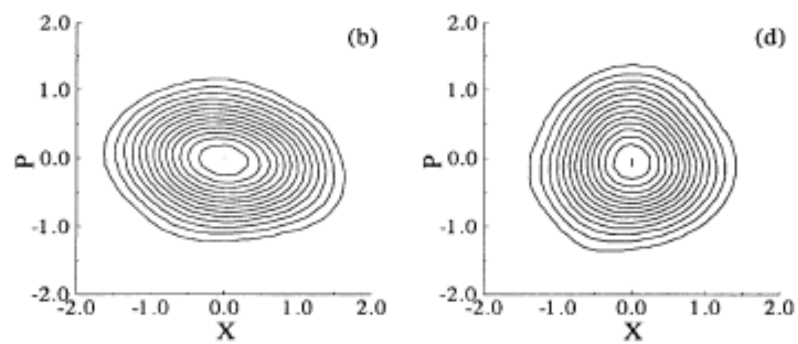
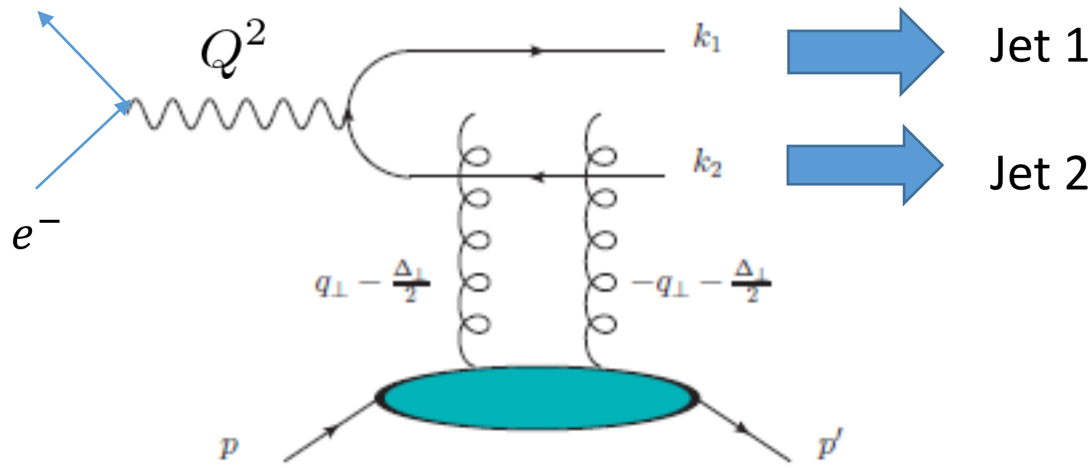


FIG. 1. Measured Wigner distributions for (a),(b) a squeezed state and (c),(d) a vacuum state, viewed in 3D and as contour plots, with equal numbers of constant-height contours. Squeezing of the noise distribution is clearly seen in (b).

Probing Wigner (GTMD) in diffractive dijet production

YH, Xiao, Yuan (2016)



$$\vec{\Delta}_\perp = -(\vec{k}_{1\perp} + \vec{k}_{2\perp})$$

$$\vec{P}_\perp = \frac{1}{2}(\vec{k}_{2\perp} - \vec{k}_{1\perp})$$

Fourier transform of $S(\vec{r}_\perp, \vec{b}_\perp)$

$$\frac{d\sigma^{\gamma_T^* A \to q\bar{q}X}}{dy_1 d^2k_{1\perp} dy_2 d^2k_{2\perp}} \propto z(1-z)[z^2 + (1-z)^2] \int d^2q_\perp d^2q'_\perp S(q_\perp, \Delta_\perp) S(q'_\perp, \Delta_\perp) \times \left[\frac{\vec{P}_\perp}{P_\perp^2 + \epsilon^2} - \frac{\vec{P}_\perp - \vec{q}_\perp}{(P_\perp - q_\perp)^2 + \epsilon^2}\right] \cdot \left[\frac{\vec{P}_\perp}{P_\perp^2 + \epsilon^2} - \frac{\vec{P}_\perp - \vec{q}'_\perp}{(P_\perp - q'_\perp)^2 + \epsilon^2}\right]$$

$$\sim d\sigma_0 + 2\cos 2(\phi_P - \phi_\Delta) d\tilde{\sigma}$$

Summary

- TMDs:
  - transverse imaging
  - QCD dynamics, access quark orbital angular momentum
- Exploratory study from HERMES(p), COMPASS (d,p) and JLab 6 GeV (n)
- **SoLID-**TMD Program
  - multi-dimensional mapping in the valence region with ultimate precision
  - Transversity/Tensor Charge, Sivers, Other TMDs → Orbital Motion

→ Understanding nucleon 3-d structure, study QCD dynamics, quark orbital angular momentum and more

Detailed information on SoLID: SoLID whitepaper: arXiv:1409.7741; and http://hallaweb.jlab.org/12GeV/SoLID/

EIC will continue the study for sea quarks and gluons

Dilepton Production with e and γ Beams

J/ψ Threshold Production: Proton Mass Puzzle?
TSC and DDVCS: GPDs

Dilepton Production with SoLID

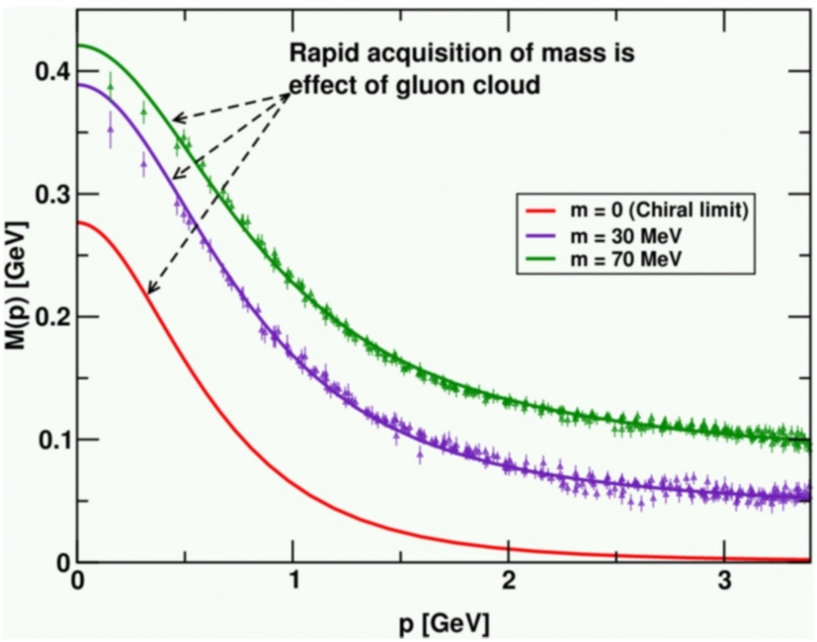
- ***J/ψ threshold Production***
  QCD Dynamics, Proton Mass, Charm-Pentaquark

- ***Timelike Compton Scattering (Run-group Proposal)***
  Study GPDs, Universality

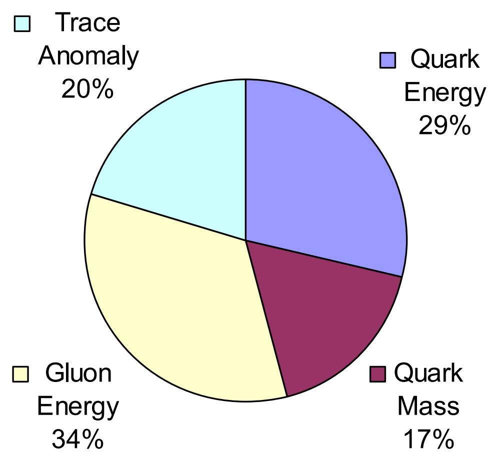
- ***Double DVCS (Letter-Of-Intent)***
  GPD beyond $x=\xi$

Proton Mass

Mass Generation

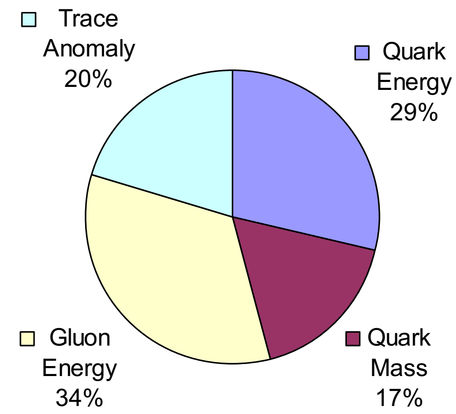


Mass Decomposition



Theoretical Developments

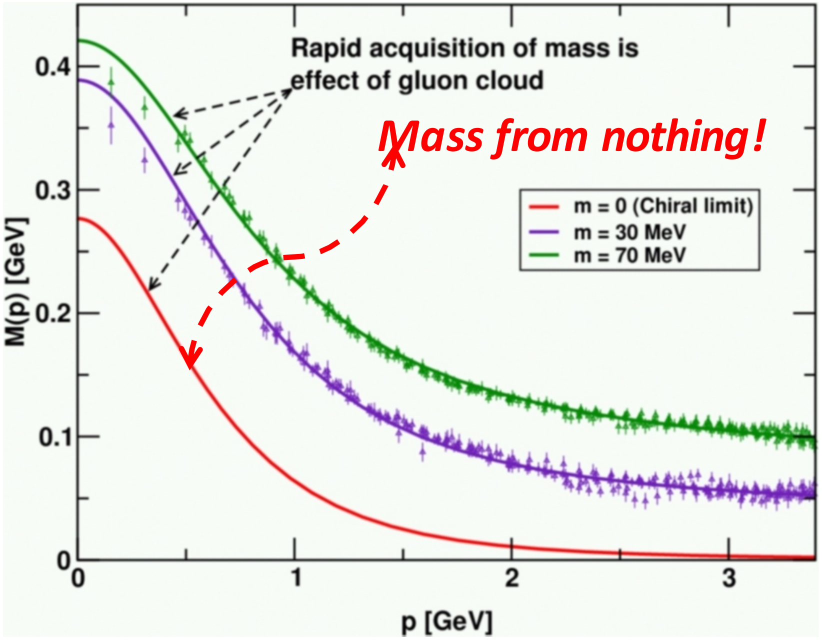
- **Dynamical Chiral Symmetry Breaking <-> Confinement**
  - **Responsible for ~99%(?) of the nucleon mass**
  - **Higgs mechanism is (almost) irrelevant to light quarks**
  - **Understand proton mass (energy structure) can provide clue**



Proton Mass Decomposition

- **Energy Momentum Tensor, $T^{\mu\nu}$**
  - **Invariant: $m^2 = E^2 - P^2 \sim \text{Trace} \langle p | (T^{\mu\nu}) | p \rangle$**
  - **Rest Frame: $m = E \sim \langle p | T^{00} | p \rangle$**

- **Recent development in theory**
  - **Lattice QCD**
  - **Bound State QCD: Dyson-Schwinger**
  - **Ads/CFT: Holographic QCD**
  - **……**



Proton Mass Generation

Decomposition – Sum Rules

❑ Roles of quarks and gluons?

✧ **QCD energy-momentum tensor:**

$$T^{\mu\nu} = \overline{T^{\mu\nu}} + \widehat{T^{\mu\nu}}$$

Traceless term: $\overline{T^{\mu\nu}} \equiv T^{\mu\nu} - \frac{1}{4} g^{\mu\nu} T^{\alpha}_{\alpha}$

Trace term: $\widehat{T^{\mu\nu}} \equiv \frac{1}{4} g^{\mu\nu} T^{\alpha}_{\alpha}$

Vacuum expectation breaks chiral symmetry

with $T^{\alpha}_{\alpha} = \frac{\beta(g)}{2g} F^{\mu\nu,a} F^{a}_{\mu\nu} + \sum_{q=u,d,s} m_q (1+\gamma_m) \overline{\psi}_q \psi_q$

QCD trace anomaly $\beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$

✧ **Invariant hadron mass (in any frame):**

$\langle p| T^{\mu\nu} |p\rangle \propto p^\mu p^\nu$ ➡ $\langle p| T^{\mu\nu} |p\rangle (g_{\mu\nu}) \propto p^\mu p^\nu (g_{\mu\nu}) = m^2$

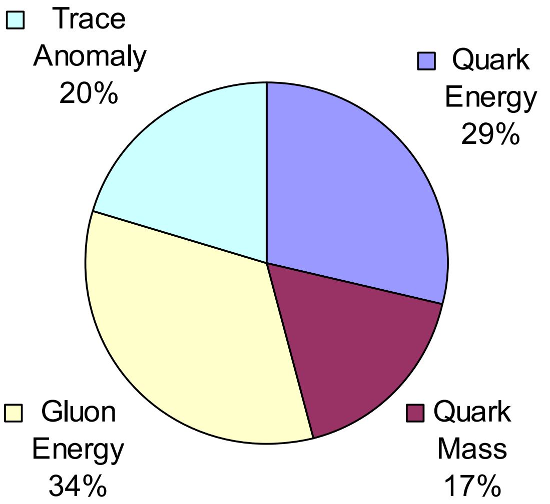
$m^2 \propto \langle p| T^{\alpha}_{\alpha} |p\rangle$ ➡ $\frac{\beta(g)}{2g} \langle p| F^2 |p\rangle$

➡ **At the chiral limit, the entire mass is from gluons!**

Proton Mass: QCD energy

X. Ji, PRL741071(1995)

- One can calculate the proton mass through the expectation value of the QCD Hamiltonian,



$$H_{\mathrm{QCD}} = H_q + H_m + H_g + H_a .$$

$$H_q = \int d^3\vec{x}\ \bar{\psi}(-i\mathbf{D}\cdot\alpha)\psi,$$ ← ***Quark energy***

$$H_m = \int d^3\vec{x}\ \bar{\psi}m\psi,$$ ← ***Quark mass***

$$H_g = \int d^3\vec{x}\ \frac{1}{2}(\mathbf{E}^2 + \mathbf{B}^2),$$ ← ***Gluon energy***

$$H_a = \int d^3\vec{x}\ \frac{9\alpha_s}{16\pi}(\mathbf{E}^2 - \mathbf{B}^2).$$ ← ***Trace anomaly (Dark Energy)***

Relating to Measurements

- **Traceless part** at rest frame becomes ***quark kinetic energy and gluon energy***
  can be extracted from **parton distribution functions**
  scheme and scale dependent

- ***Quark mass*****:** u and d quark contribution obtain from **pi-nucleon sigma term**
  s quark from **Chiral Purturbation Theory for baryon octet**
  or LQCD, …

- *Trace Anomaly*: **analogous to the cosmological constant (dark energy)!**
  J/ψ threshold production may provide access?

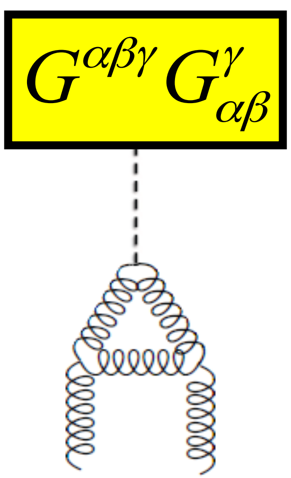
SoLID-J/ψ: Study Non-Perturbative Gluons

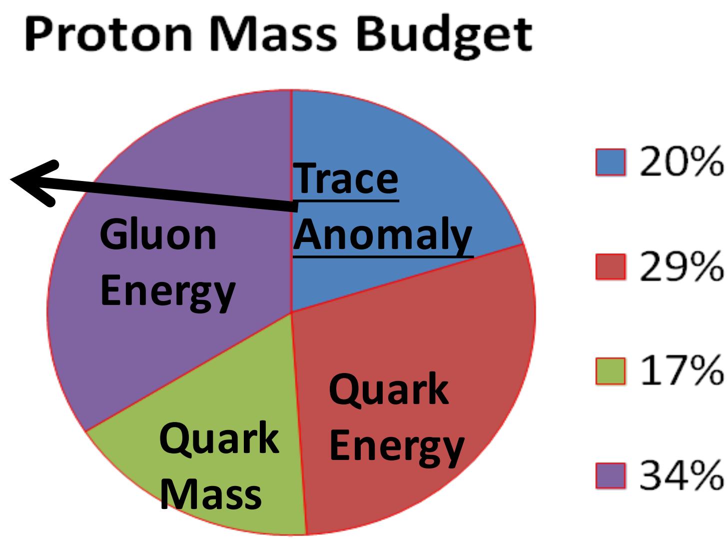
J/ψ: ideal probe of non-perturbative gluon

The high luminosity & large acceptance capability of SoLID enables a unique "precision" measurement near threshold

- **Shed light on the low energy J/ψ-nucleon interaction (color Van der Waals force)**
- **Shed light on the 'conformal anomaly' an important piece in the proton mass budget:**

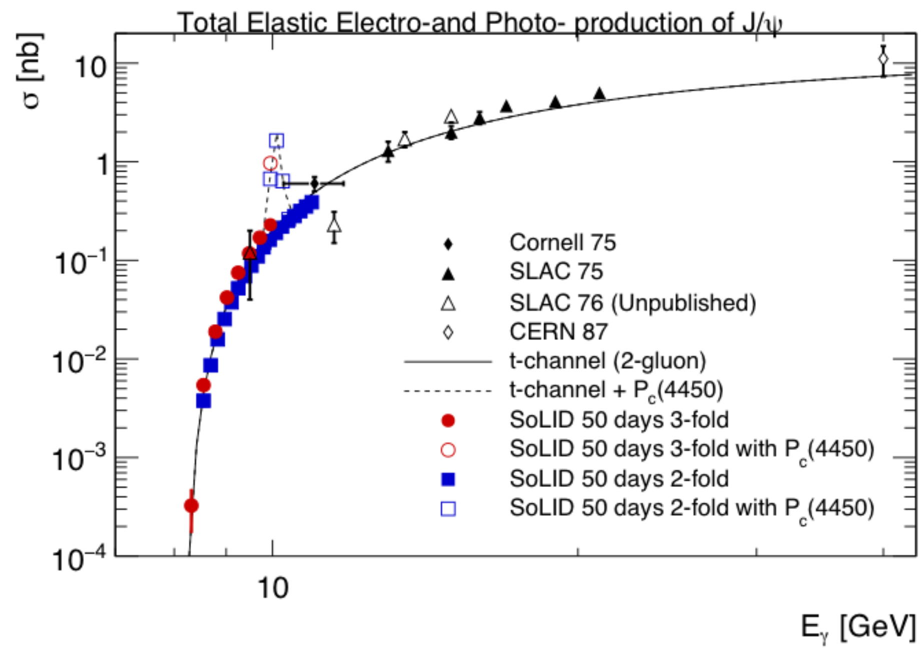
Models relate J/ψ enhancement to trace anomaly





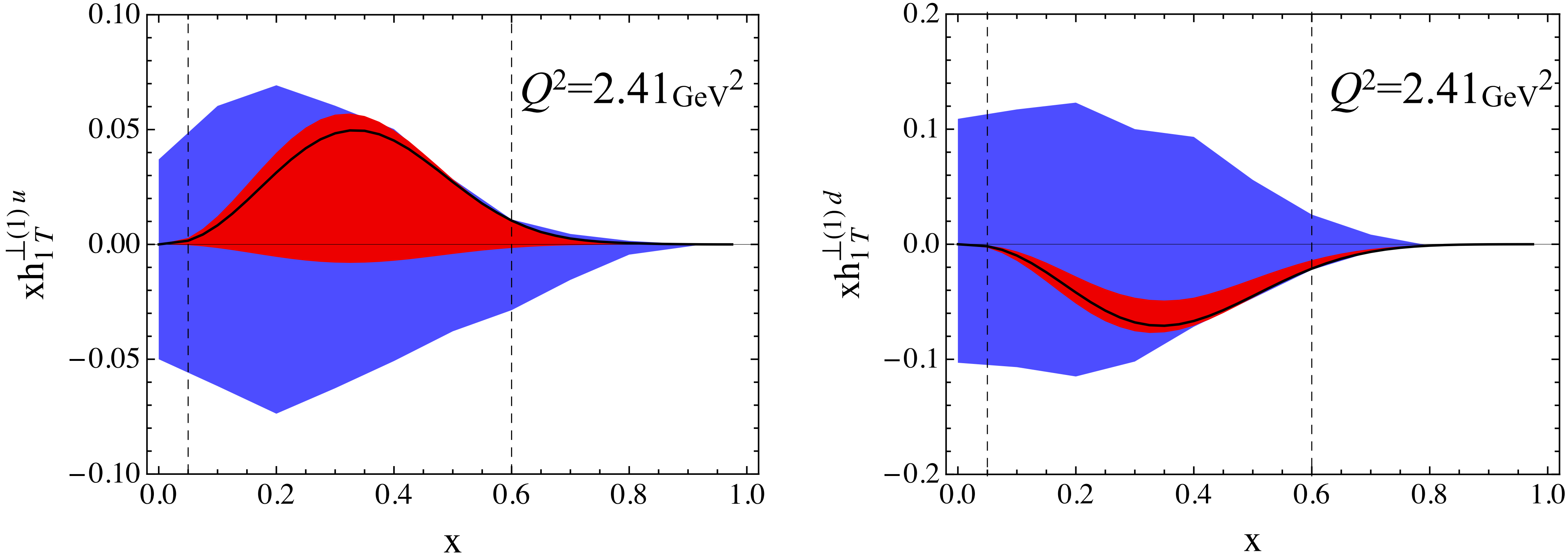
X. Ji PRL 74 1071 (1995)

$$\gamma^* + N \rightarrow N + J/\psi$$



Backup

SoLID Impact on Pretzelosity



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

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

95% C.L.

Duke UNIVERSITY

by Tianbo Liu (Duke & DKU)

昆山杜克大学 DUKE KUNSHAN UNIVERSITY

Angular Momentum (1)

T. Liu

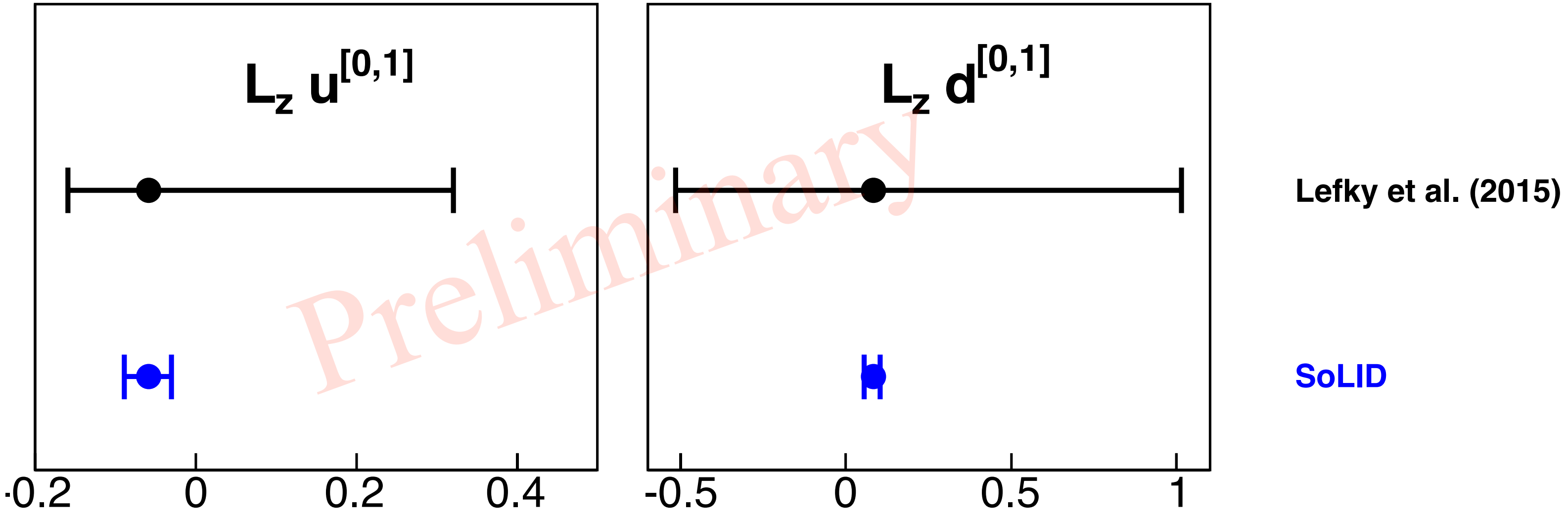
OAM and pretzelosity:

model dependent

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

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

SoLID impact:



Angular Momentum

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: