TMD Physics with a Solenoidal Large Intensity Device (SoLID) at 12-GeV Jefferson Lab

4th workshop on Hadron Physics in China and Opportunities in US, July 16-20, 2012

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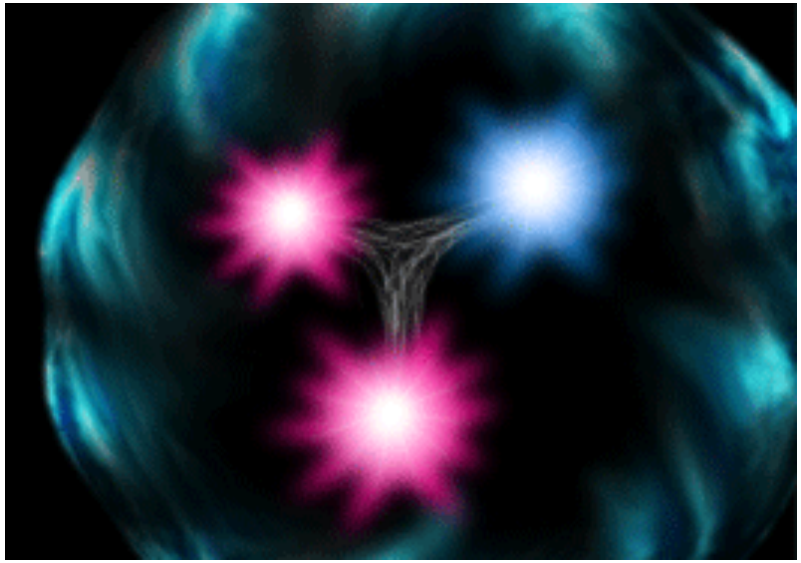
QCD ⟷ Nucleon Structure

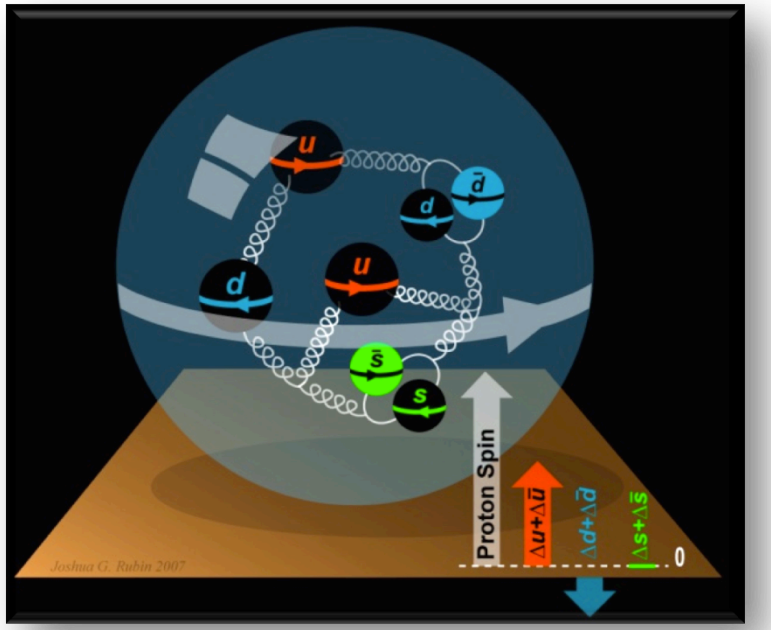
- Strong interaction, running coupling ~1
  - -- QCD: the theory of strong interaction
  - -- asymptotic freedom (2004 Nobel)
    - perturbation calculation works at high energy
  - -- interaction significant at intermediate energy
    - quark-gluon correlations
  - -- confinement
    - interaction strong at low energy
    - coherent hadron
  - -- Chiral symmetry
  - -- theoretical tools:
    - pQCD, OPE, Lattice QCD, ChPT

Spin as an important knob



- *Charge and magnetism (current) distribution*
- *Spin distribution*
- *Quark momentum and flavor distribution*
- *Polarizabilities*
- *Strangeness content*
- *Three-dimensional structure*
- *……*

The Incomplete Nucleon: Spin Puzzle



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$

[X. Ji, 1997]

Jaffe-Manohar 1990

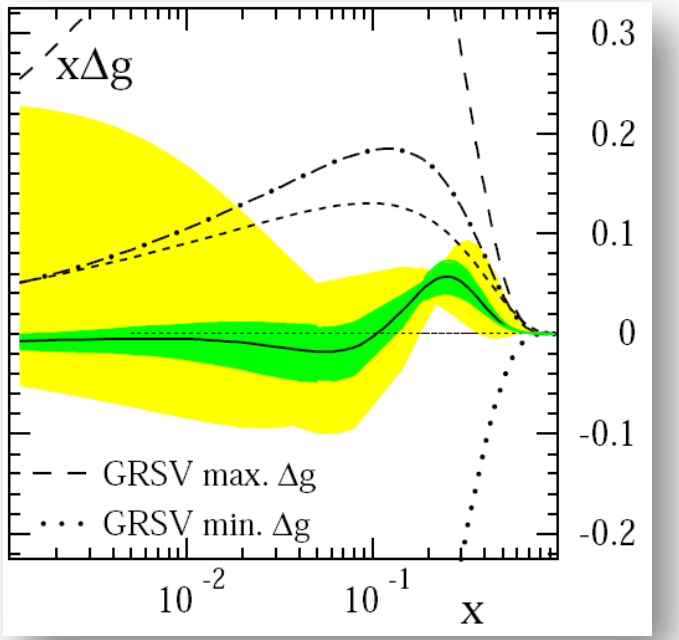
Chen *et al.* 2008

Wakamatsu 2009,2010

- DIS → $\Delta\Sigma \cong 0.25$
- RHIC + DIS → $\Delta g \ll 1$
- → L_q

Orbital angular momentum of quarks and gluons is important

Understanding of spin-orbit correlations (atomic hydrogen, topological insulator…..)

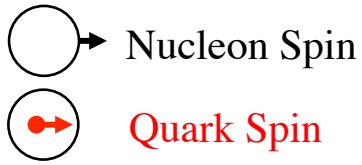


D. de Florian et al., PRL 101 (2008) 072001

Talks by Liu, Chen, Cho, Pak

Go beyond collinear to include transverse momentum

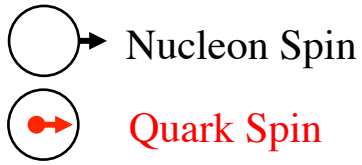
Leading-Twist TMD PDFs



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

F. Yuan's overview, B.Q. Ma's talk last week

Leading-Twist TMD PDFs



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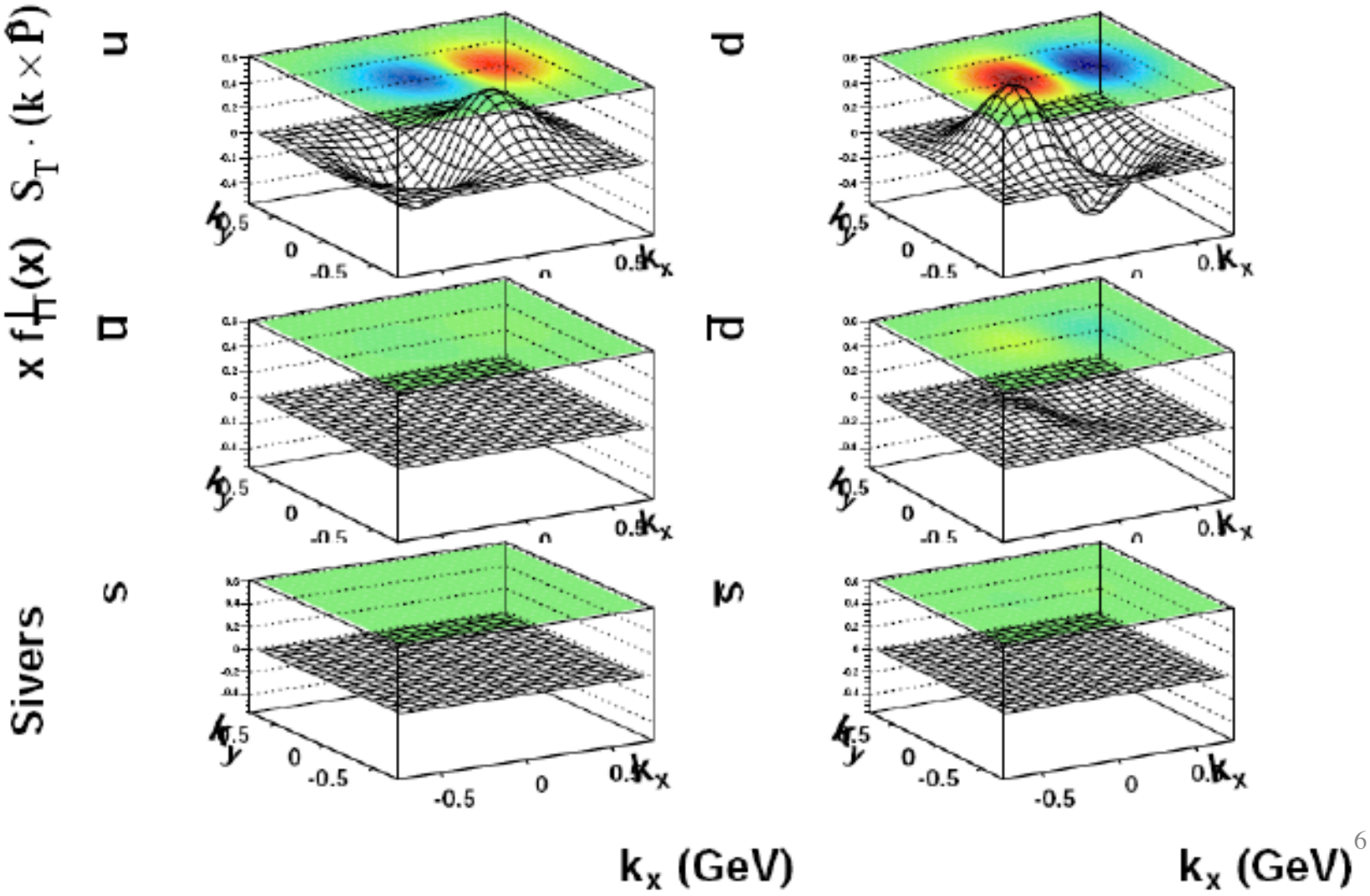
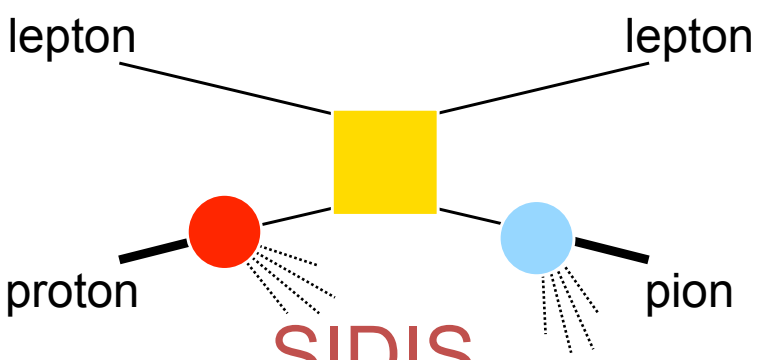
T	$f_{1T}^\perp$ Sivers	g_{1T} Trans-Helicity	h_1 Transversity; $h_{1T}^\perp$ Pretzelosity

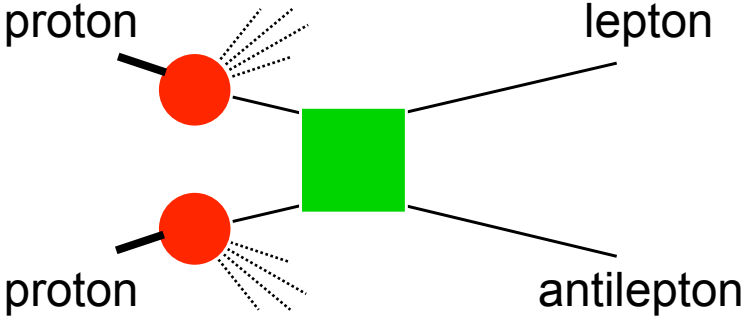
- **TMD PDFs: nucleon structure in 3-D momentum space!** $f_{1T}^{\perp}(x,Q^2,k_T)$ **Sivers as example @ fixed x, Q^2**



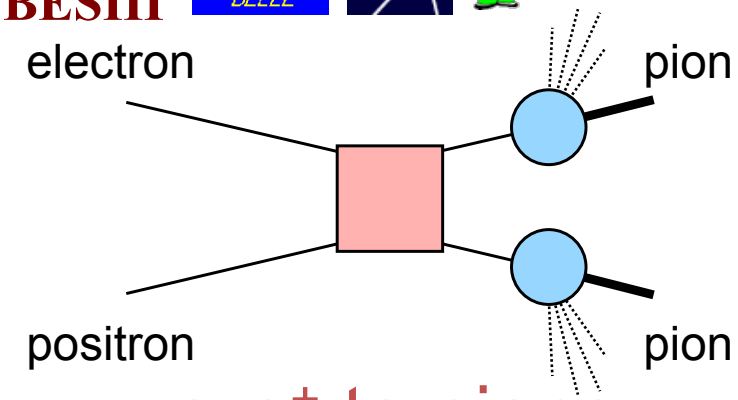
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

J.P. Ma's talk

Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

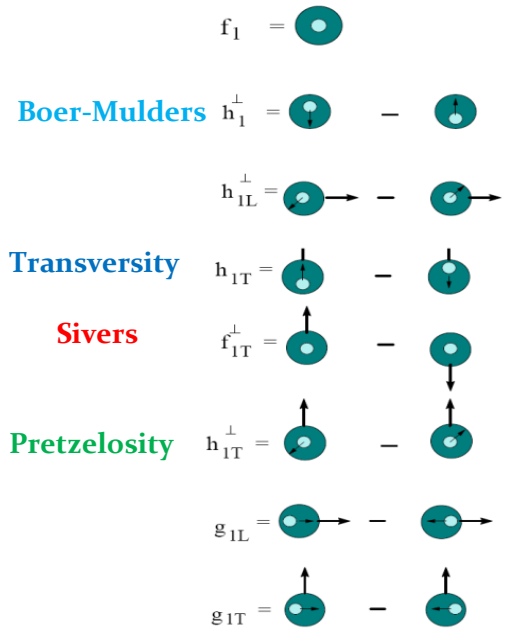
$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

J.W. Qiu et al; and others

Access Parton Distributions through Semi-Inclusive DIS

$$\frac{d\sigma}{dx dy d\phi_S dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$



$$\{F_{UU,T} + \ldots$$
$$+ \varepsilon \cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

Unpolarized

$$+ S_L[\varepsilon \sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$
$$+ S_T[\varepsilon \sin(\phi_h + \phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \sin(\phi_h - \phi_S)\cdot (F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$
$$+ \varepsilon \sin(3\phi_h - \phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

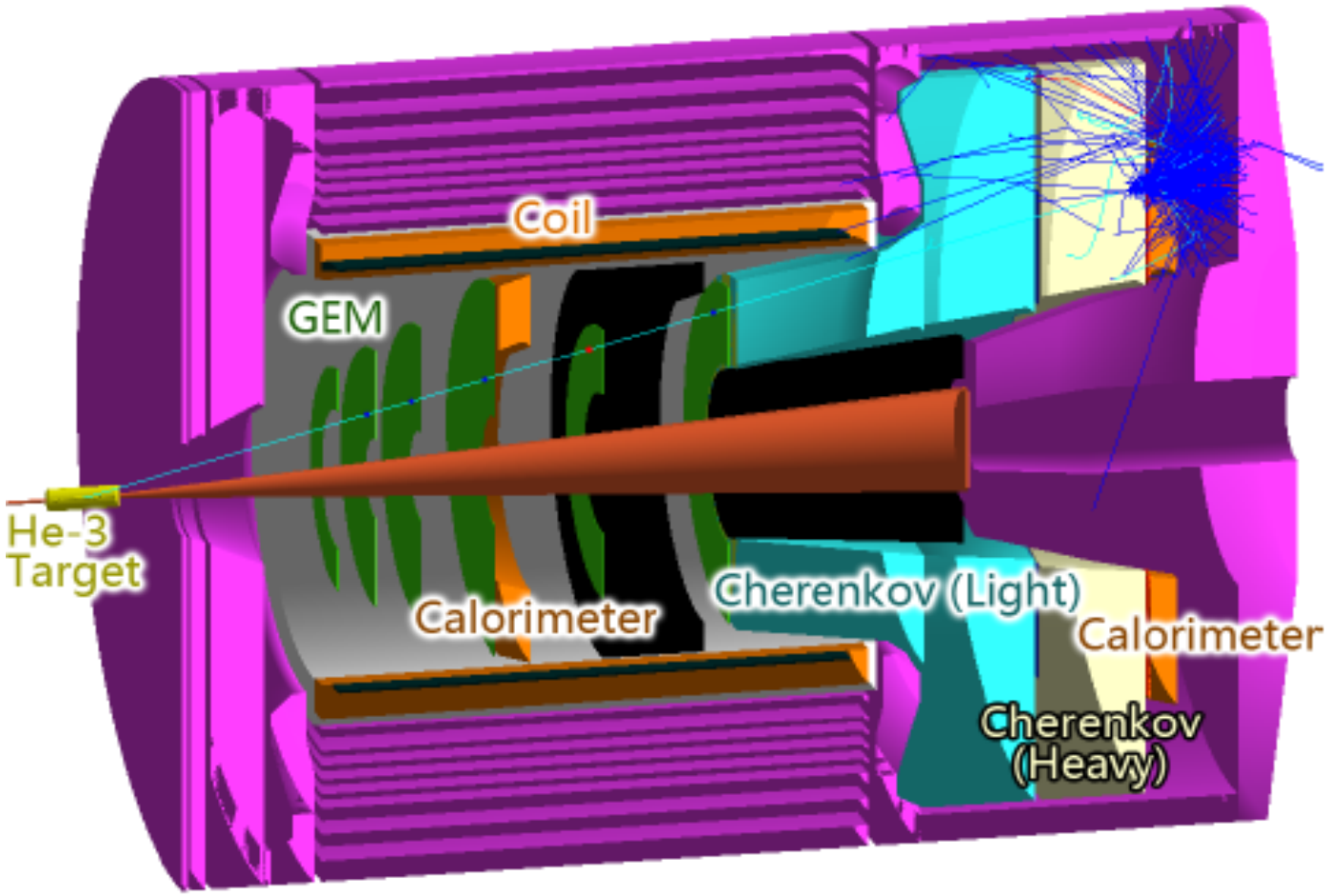
Polarized Target

$$+ S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$
$$+ S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h - \phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

Polarized Beam and Target

S_L, S_T: Target Polarization; λ_e: Beam Polarization

SoLID Spin – International Collaboration



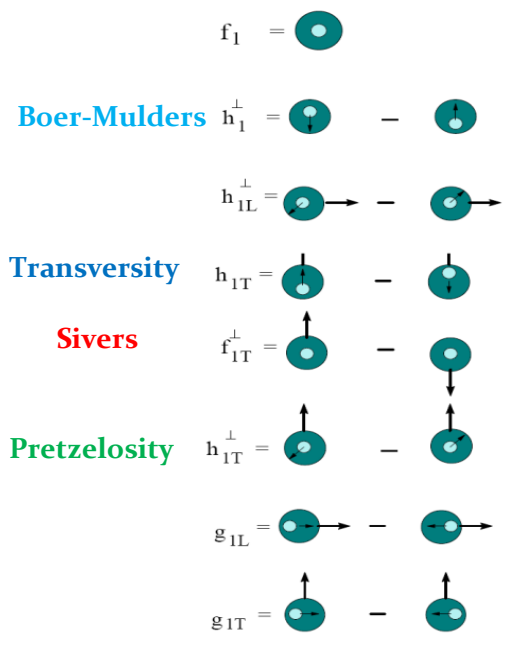
Physicists from US, China, Italy, Israel, South, Korea, Scotland,

What will SoLID ^{3}He (neutron) program do?

$$\frac{d\sigma}{dx dy d\phi_S dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$

$$\{F_{UU,T} + \ldots$$

$$+ \varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$



$$+ S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$

$$+ S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+ \sin(\phi_h-\phi_S)\cdot(F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$

$$+ \varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

Polarized Target

$$+ S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$

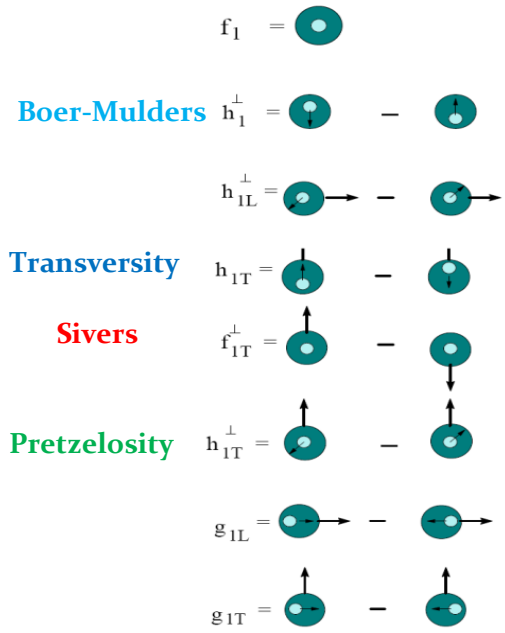
$$+ S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

Polarized Beam and Target

S_L, S_T: Target Polarization; λ_e: Beam Polarization

J.P. Chen's talk

What will SoLID proton (NH_3) program do?



$$\frac{d\sigma}{dx dy d\phi_S dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$

$$\{F_{UU,T} + \ldots$$

$$+ \varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

$$+ S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$

$$+ S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+ \sin(\phi_h-\phi_S)\cdot(F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$

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$$+ S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$

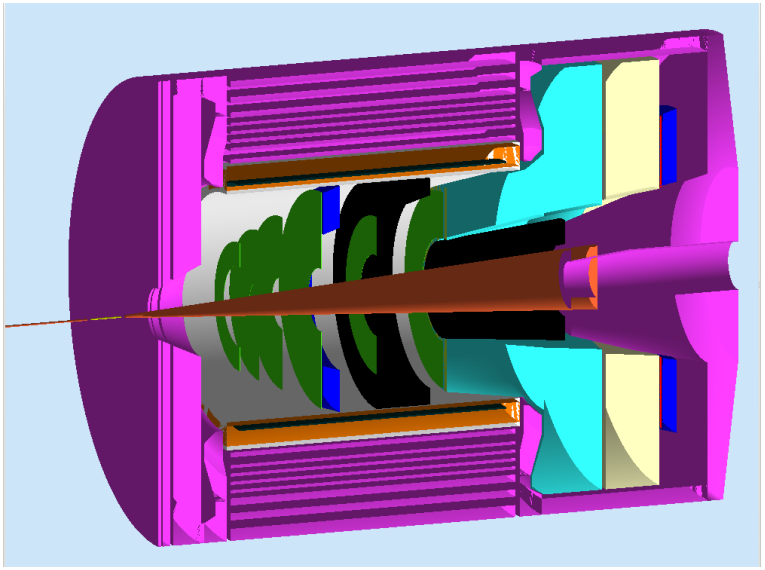
$$+ S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

Transversely Polarized Target

Polarized Beam, Transversely Polarized Target

S_T: Target Polarization; λ_e: Beam Polarization

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

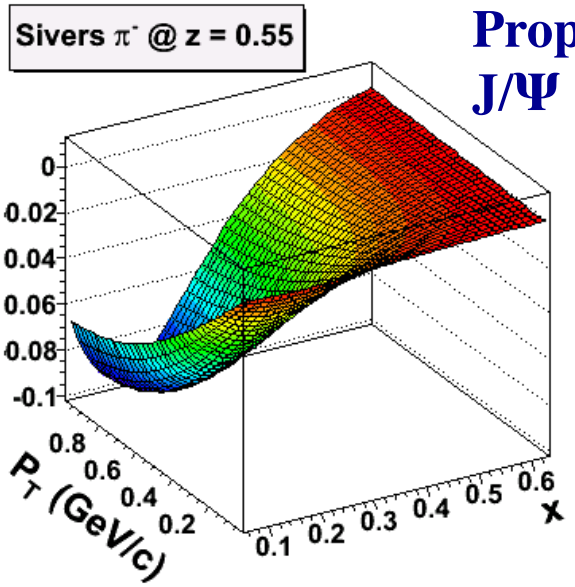


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

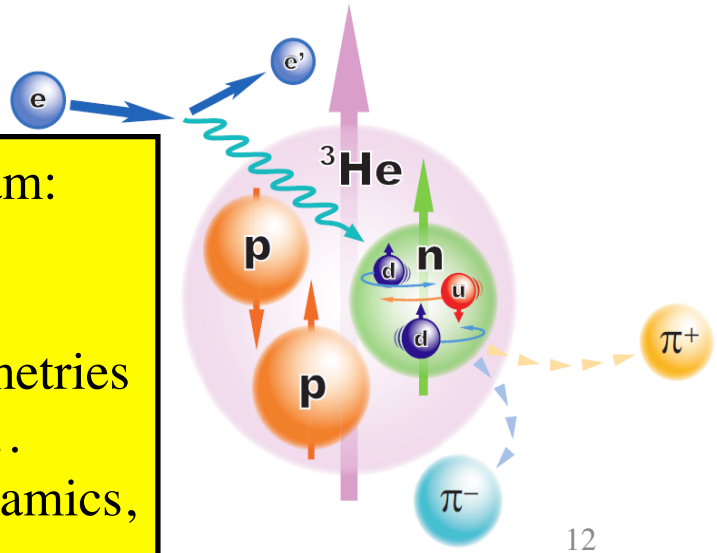
E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**

International collaboration with 180 Collaborators from 8 countries



Proposals on PVDIS (A), J/Ψ (A$^-$) approved



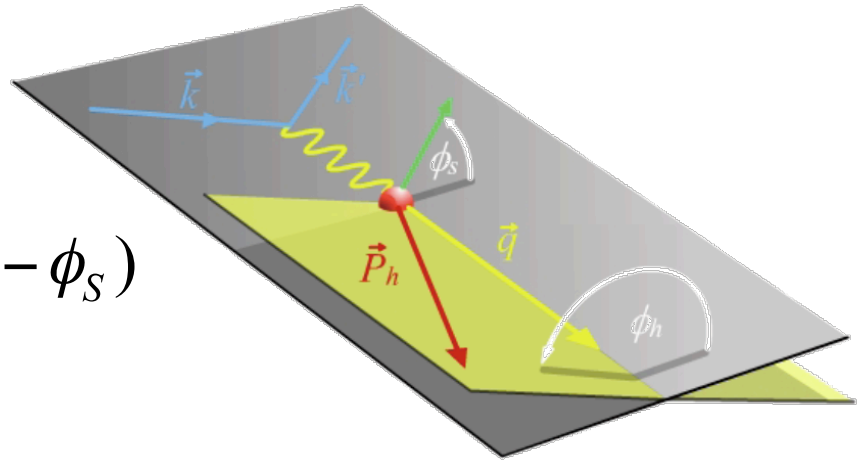
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

SoLID physics I: Separation of Collins, Sivers and pretzelocity effects through angular dependence for n and p

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

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

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



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

Collins frag. Func. from e^+e^- collisions

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

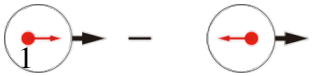
$$A_{UT}^{Pretzelosity} \propto \left\langle \sin(3\phi_h - \phi_S) \right\rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

Transversity

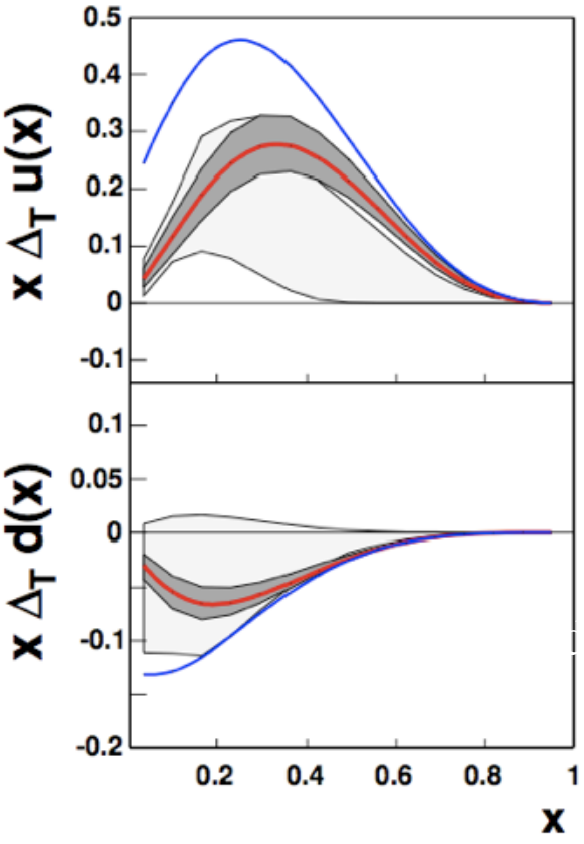
h_{1T} = 

- The third PDFs in addition to f_1  and g_{1L} 
- Lowest moment gives tensor charge

$$\delta q^a = \int_0^1 (h_{1T}^a(x) - h_{1T}^{\bar{a}}(x))dx$$

  - Fundamental property, benchmark test of Lattice QCD

(**Talk by H.X. He**)



A global fit to the HERMES p, COMPASS d and BELLE e+e- data by the Torino group, Anselmino et al., arXiv:0812.4366

Solid red line : transversity distribution, analysis at Q^2=2.4 $(GeV/c)^2$

Solid blue line: Soffer bound
$|h_{1T}| <= (f_1+g_{1L})/2$
GRV98LO + GRSV98LO

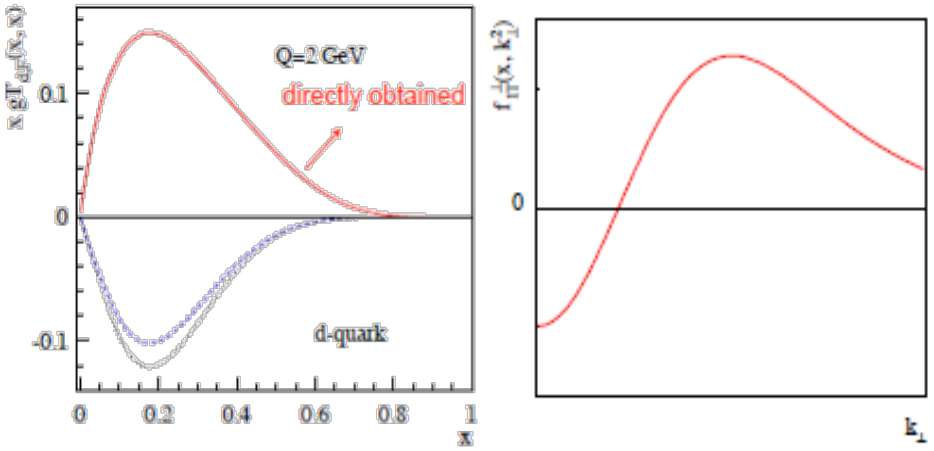
$\Delta_T = h_{1T}$

Dashed line: helicity distribution g_{1L}, GRSV98LO

Sivers Function

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

- Correlation between nucleon spin with quark orbital angular momentum
- Important test for factorization $f_{1T}^{\perp q}\big|_{SIDIS} = -f_{1T}^{\perp q}\big|_{D-Y}$
- **Different sign with twist-3 quark-gluon corr. dis. at high P_T?**
- T-odd final state interaction -> Target SSA (Brodsky et al., and others)
- **Recent developments in the evolution of Sivers function**



Zhongbo Kang, RBRC/BNL

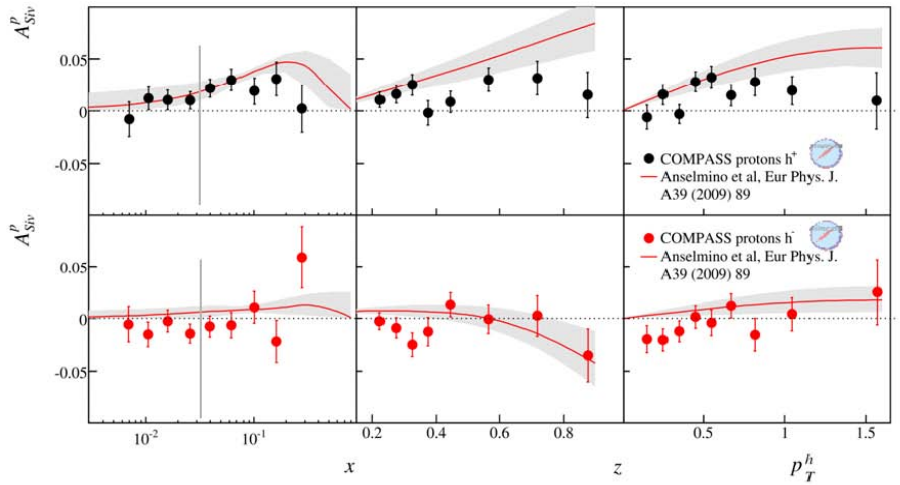
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS}$$

Kang, Qiu, Vogelsang, Yuan (2011), Kang and Qiu (2012)

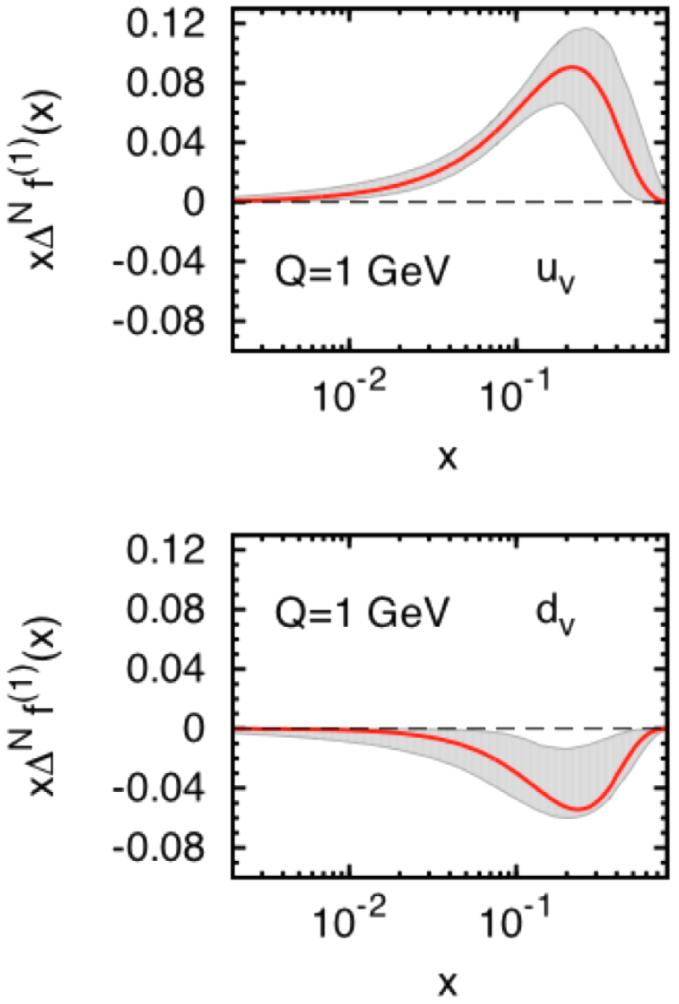
Sivers asymmetry - proton

comparison with theory

... most recent predictions from *M. Anselmino et al.*
based on the fit of HERMES proton and COMPASS deuteron data



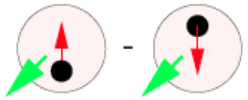
SIVERS FUNCTION - TMD



Older fit shows possibly discrepancy?

Latest extraction based on HERMES p, COMPASS d and p data by M. Anselmino et al., arXiv:1204.1239 taking into account TMD evolution show consistency between the HERMES and COMPASS data

Quark OAM from Pretzelosity

$h_{1T}^{\perp}$ =  "pretzelosity"

model-dependent relation

$$\mathcal{L}_z = -\int \mathrm{d}x \mathrm{d}^2\vec{k}_\perp \frac{k_\perp^2}{2M^2}\, h_{1T}^{\perp}(x, k_\perp^2)$$

first derived in LC-diquark model and bag model

[She, Zhu, Ma, 2009; Avakian, Efremov, Schweitzer, Yuan, 2010]

$\mathcal{L}_z$	$h_{1T}^{\perp}$
chiral even and charge even	chiral odd and charge odd
$\Delta L_z = 0$	$\lvert\Delta L_z\rvert = 2$

no operator identity
relation at level of matrix elements of operators

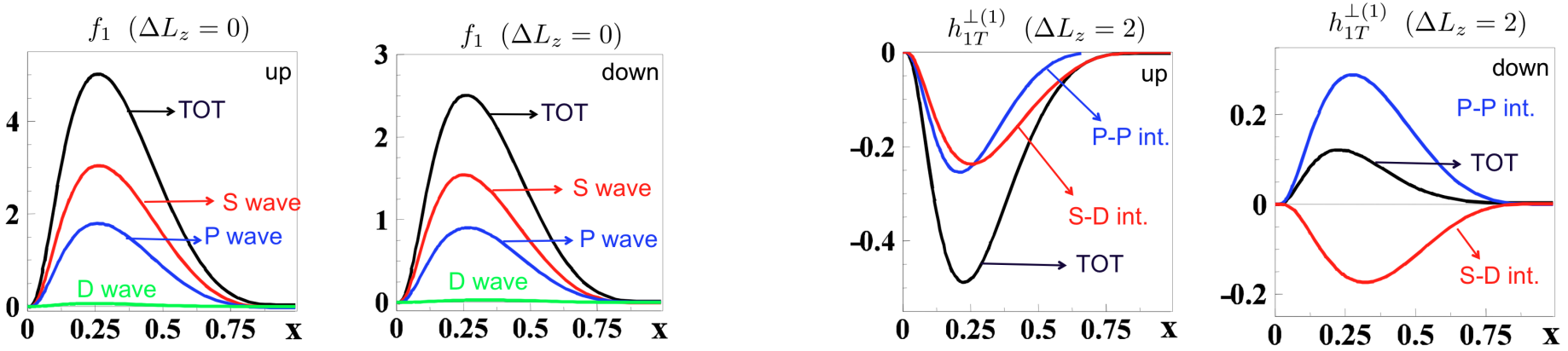
⇩

valid in all quark models with spherical symmetry in the rest frame

[Lorce', BP, PLB (2012)]

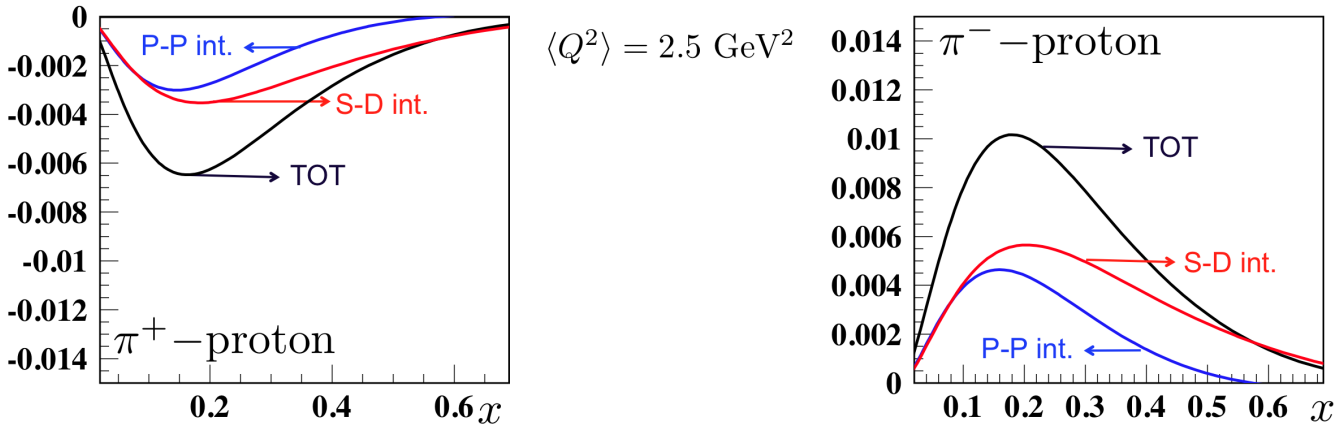
☞ see talk by C. Lorce'

✦ Orbital angular momentum content of TMDs (light-cone constituent quark model)



✦ Effects on SIDIS observables

$$A_{UT}^{\sin(3\phi-\phi_S)} \sim \frac{h_{1T}^{\perp} \otimes H_1}{f_1 \otimes D_1}$$



Boffi, Efremov, BP, Schweitzer, PRD79(2009)

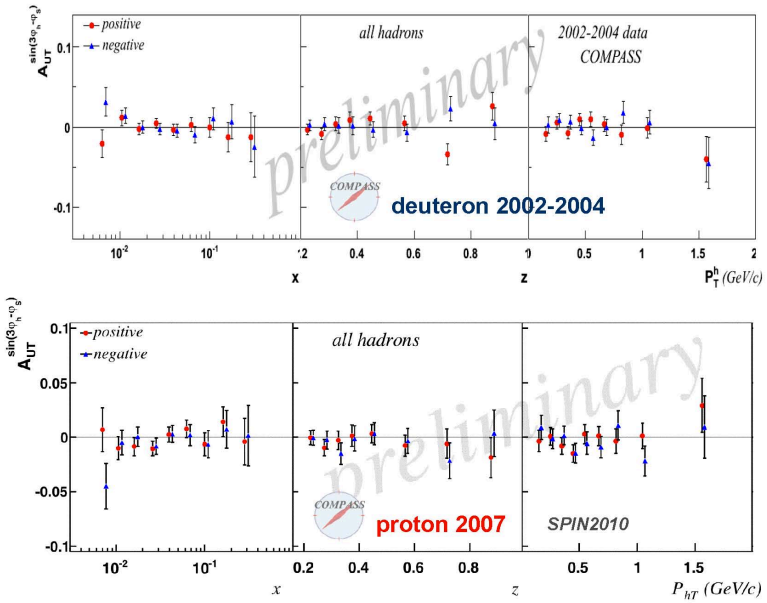
Pretzlosity:

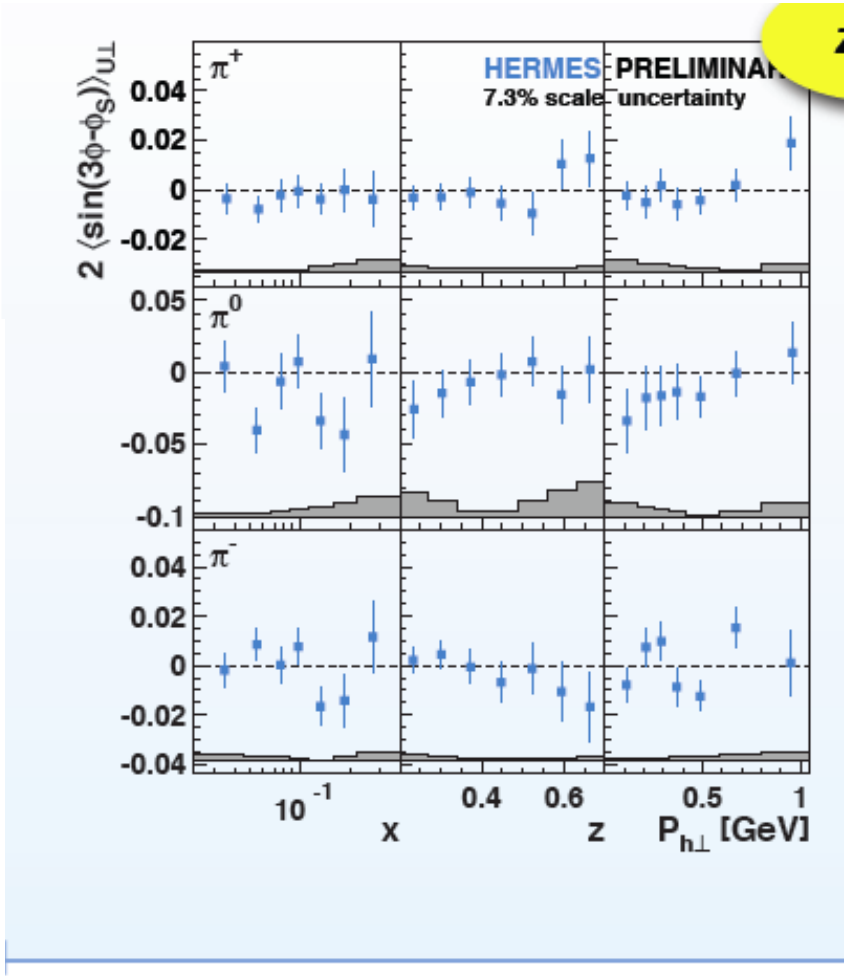
- Relativistic effect of quark
  PRD 78, 114024 (2008)
- (in models) direct measurement of OAM
  PRD 58, 096008 (1998) (more previous slide)
- Expect first non-zero Pretzelosity asymmetries

transversely polarised target

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

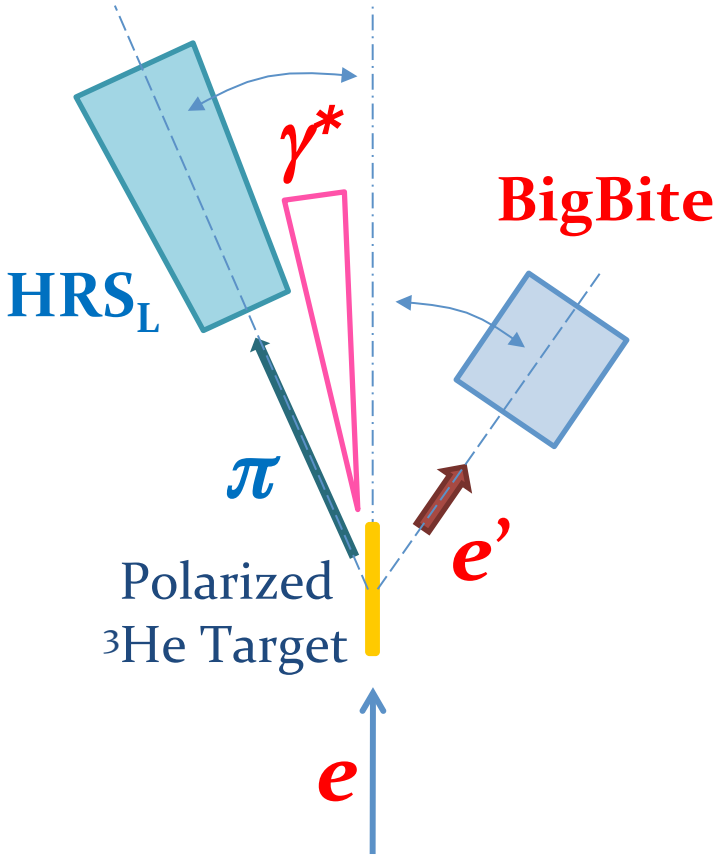
"pretzelosity" PDF
⊗ Collins FF





M. Diefenthaler, EINN 2009

E06-010: neutron $A_{(U/L)T}(\pi^+K^+, \pi^-K^-)$



- ***First*** **neutron** data in SIDIS SSA&DSA
  - Similar Q^2 as HERMES experiment
- Disentangle Collins/Sivers effects

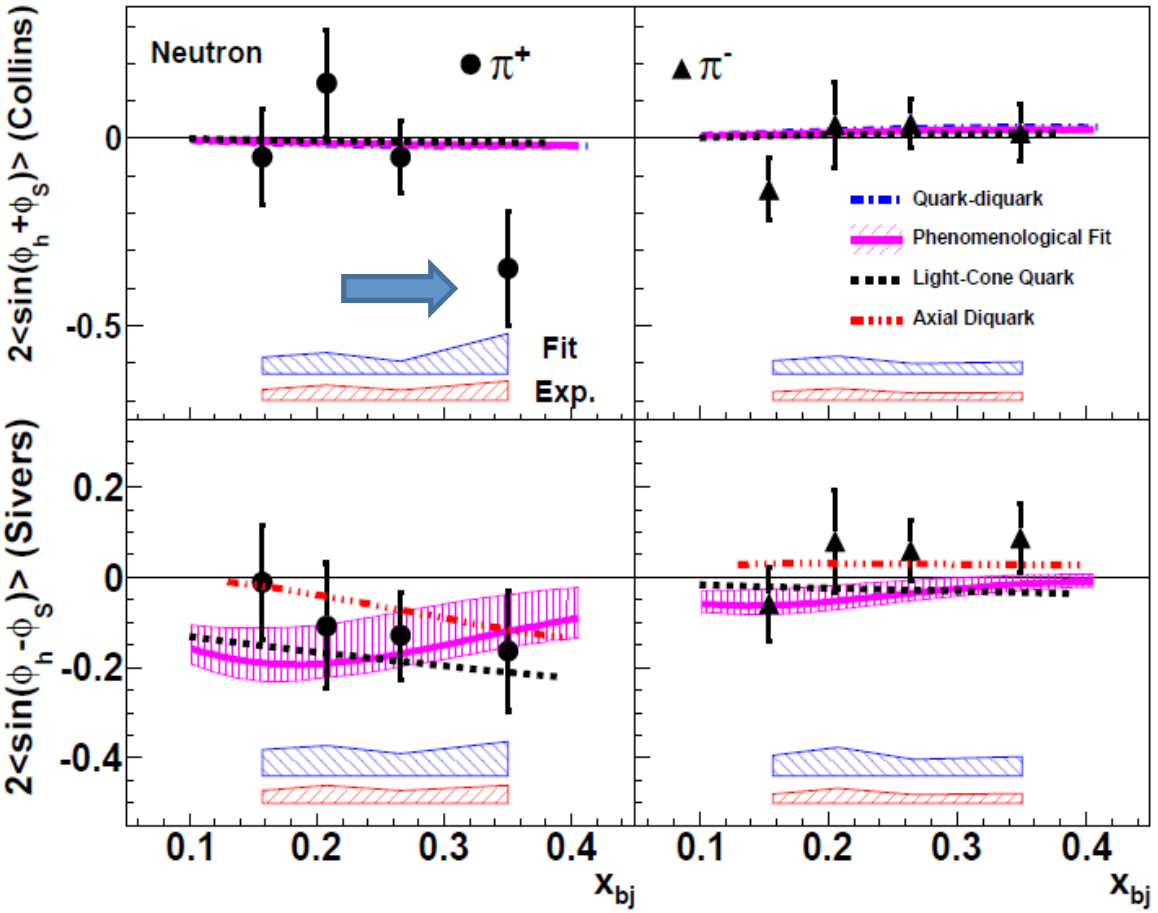
- Electron beam: ***E*** = 5.9 GeV
- High luminosity L ~ 10^{36} $cm^{-2}s^{-1}$
  - 40 cm transversely polarized ^{3}He target
  - Average beam current 12 uA (max: 15 uA as in proposal)

- BigBite at 30^o as **electron** arm:
  P_e = 0.6 ~ 2.5 GeV/c
- HRSL at 16^o as **hadron** arm:
  P_h = 2.35 GeV/c

Results on Neutron

- Sizable Collins π^+ asymmetries at x=0.34?
  - Sign of violation of Soffer's inequality?
  - **Data are limited by stat. Needs more precise data!**

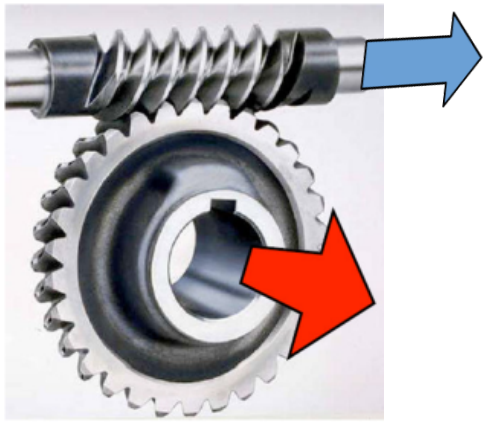
- Negative Sivers π^+ Asymmetry
  - Consistent with HERMES/COMPASS



- **demonstration of negative d quark Sivers function.**

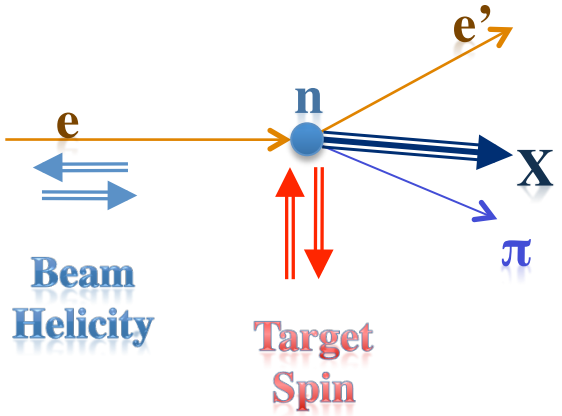
Model (fitting) uncertainties shown in blue band.
Experimental systematic uncertainties: red band
X. Qian *et al*, Phys. Rev. Lett. 107, 072003 (2011)

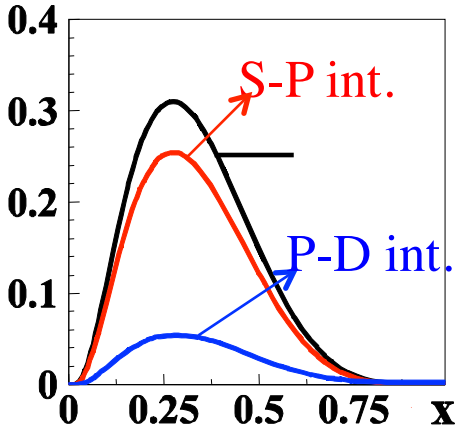
Double Spin Asymmetry: g_{1T}



- $A_{\mathrm{LT}}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$
  - Leading twist TMD PDFs
  - T-even, Chiral-even
- Dominated by real part of interference between L=0 (S) and L=1 (P) states
  - Imaginary part -> Sivers effect
- First TMDs in Pioneer Lattice calculation
  - arXiv:0908.1283 [hep-lat], Europhys.Lett.88:61001,2009
  - arXiv:1011.1213 [hep-lat] , Phys.Rev.D83:094507,2011

g_{1T} 

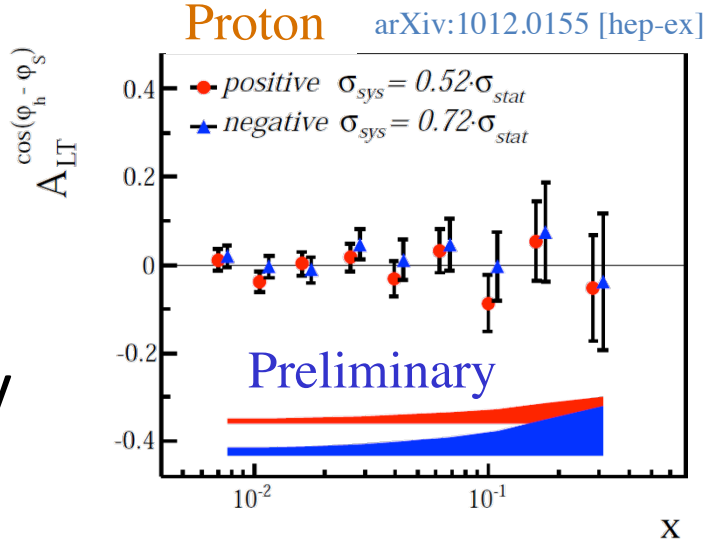


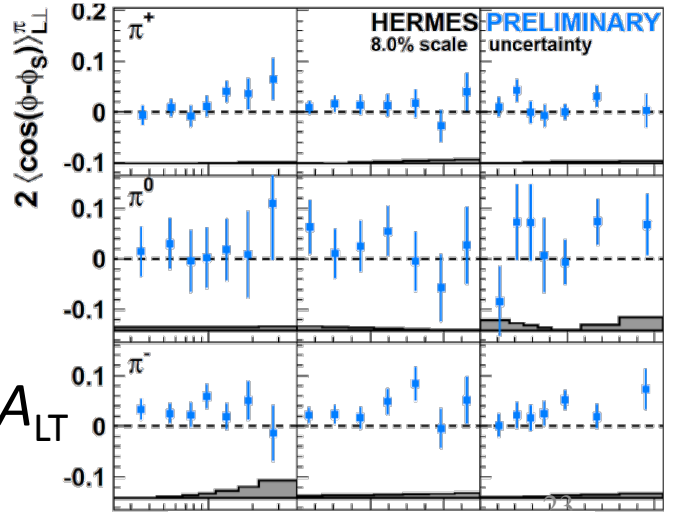


Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

Existing A_{LT} Results are preliminary

- No measurement until 2002
- Preliminary COMPASS results
  - A_{LT} on proton and deuteron
  - Fixed beam helicity (μ beam)
  - Low x, small predicted asymmetry
- Preliminary HERMES results
  - A_{LT} on proton
- New measurement needed
  - Different target for flavor decomposition
  - Higher precision at valence region
  - Double spin reversal to cleanly separate A_{LT}



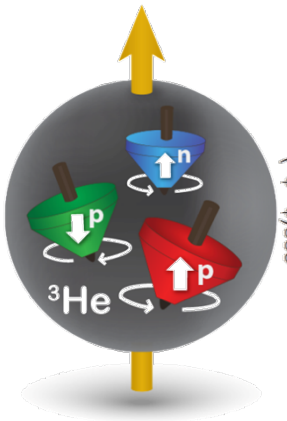


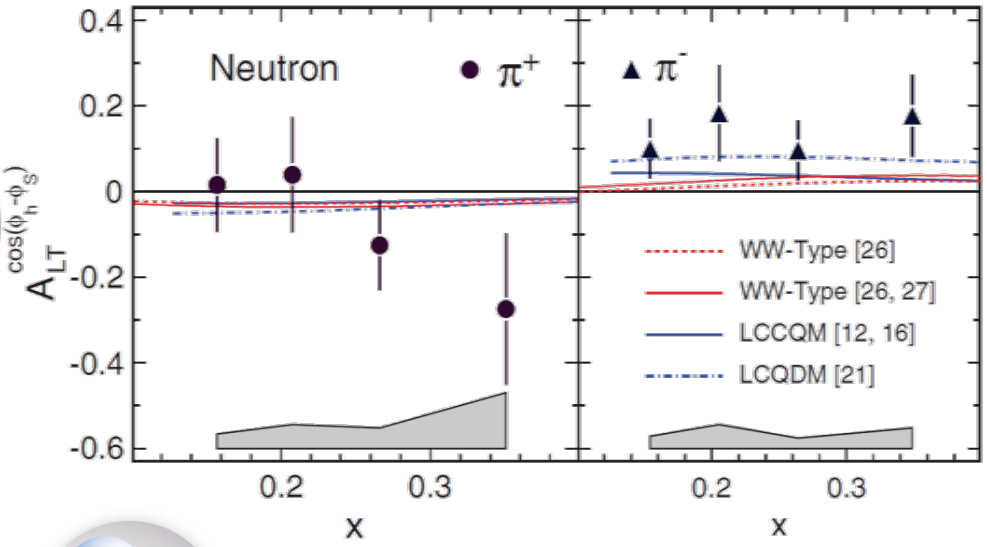
arXiv:1107.4227 [hep-ex]

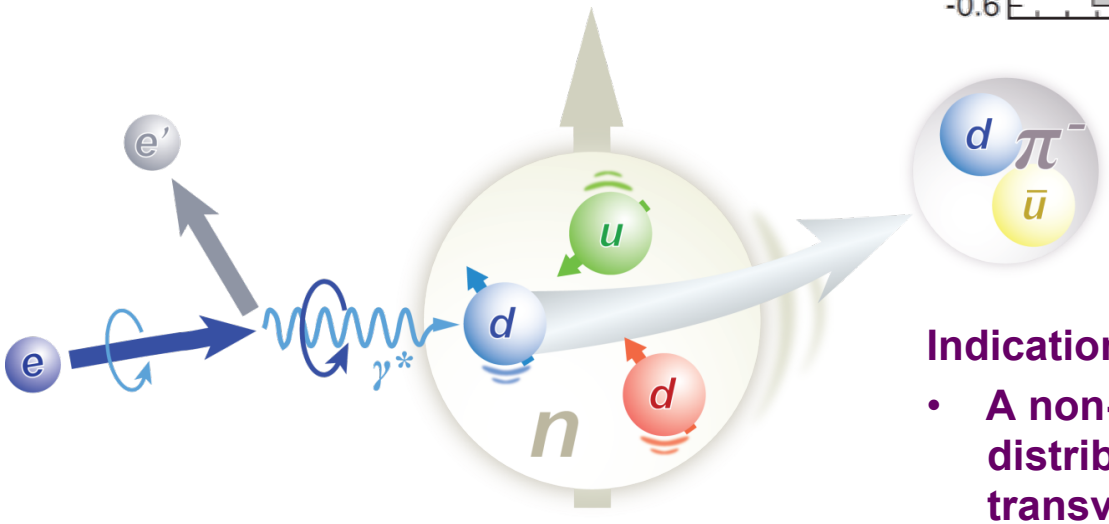
New Observable Reveals Interesting Behaviors of Quarks

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

Target:
polarized ^{3}He => polarized neutron







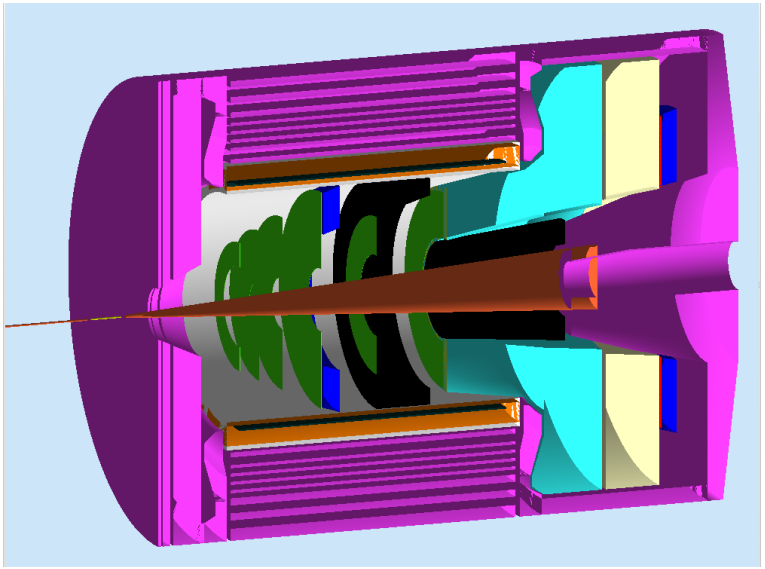
First measurement of A_{LT}
beam-target double-spin asymmetry

Indications:

- **A non-vanishing quark "transversal helicity" distribution, reveals alignment of quark spin transverse to neutron spin direction**
- **Quark orbital motions**

J. Huang et al., PRL108, 052001 (2012)

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

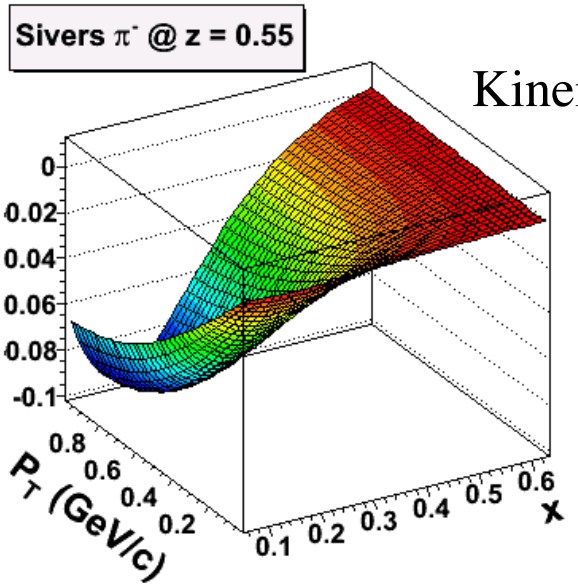


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days, **rating A**

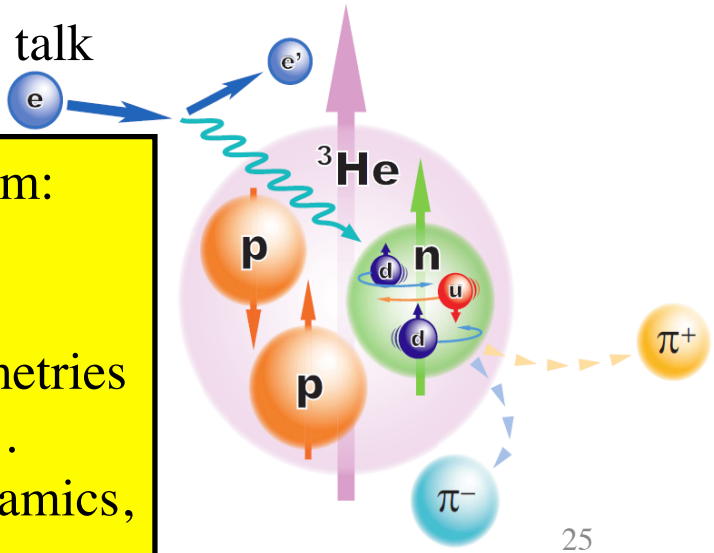
E12-11-108: Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**

International collaboration with 180 Collaborators from 8 countries



Kinematic coverage: M. Huang's talk

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



Experiment E12-10-006

Nucleon Transversity at 11 GeV Using a Polarized ^{3}He Target and SOLid in Hall A

PKU., CalState-LA, CIAE, W&M, Duke, FIU, Hampton, Huangshan U., Cagliari U. and INFN, Huazhong Univ. of Sci. and Tech., INFN-Bari and U. of Bari, INFN-Frascati, INFN-Pavia,Torino U. and INFN, JLab, JSI (Slovenia), Lanzhou U, LBNL, Longwood U, LANL, MIT, Miss. State, New Mexico, ODU, Penn State at Berks, Rutgers, Seoul Nat. U., St. Mary's, Shandong U., Syracuse, Tel aviv, Temple, Tsinghua U, UConn, Glasgow, UIUC, Kentucky, Maryland, UMass, New Hampshire, USTC, UVa

and the Hall A Collaboration

Strong theory support, Over 180 collaborators, 40 institutions, 8 countries, strong overlap with PVDIS Collaboration

Approved by JLab PAC35

E12-10-006

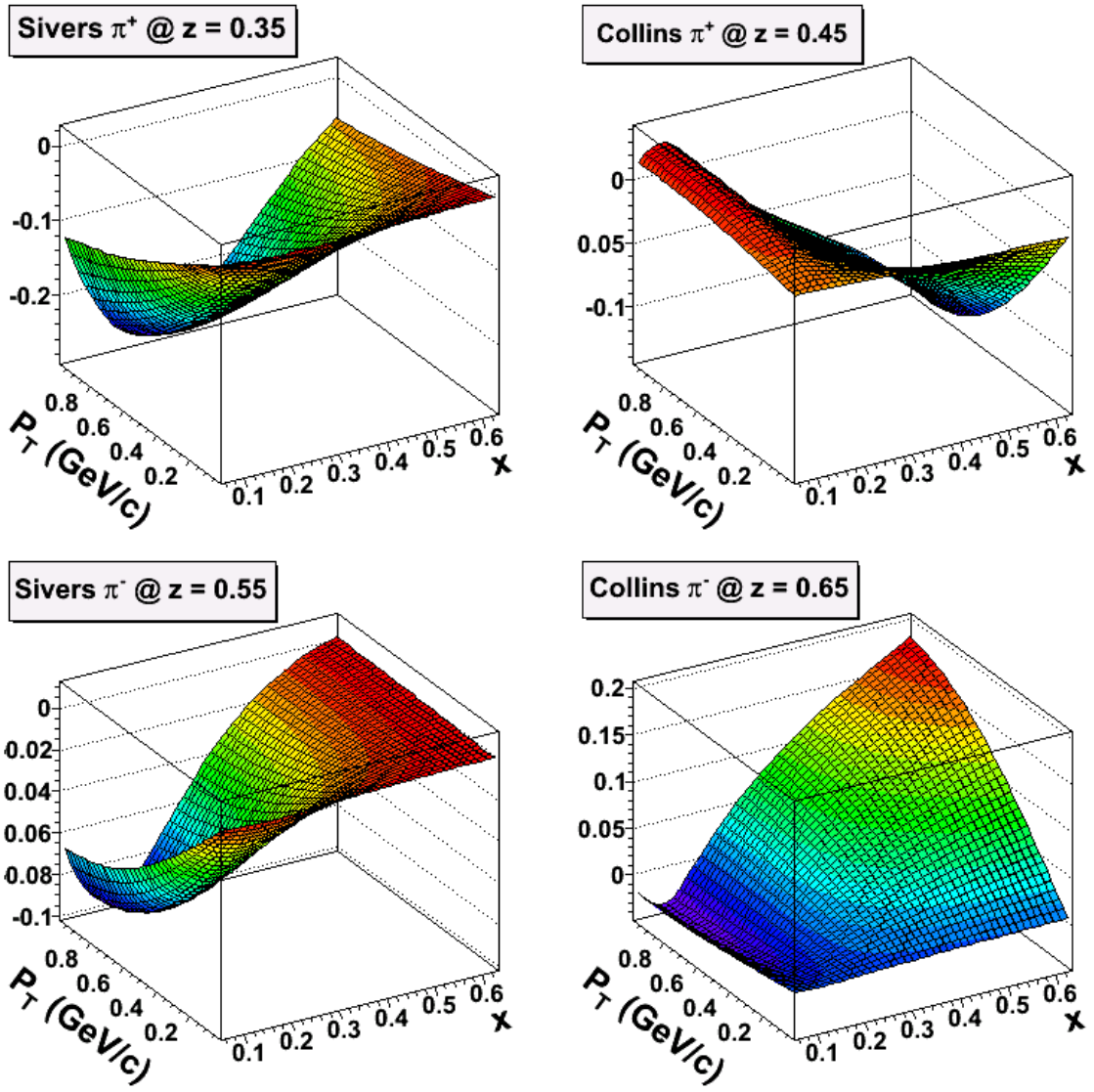
3-D neutron π^+/π^- Collins/Sivers Asymmetries at Q^2=2.0 GeV^2

Collins/Sivers asymmetries vs. x and transverse momentum P_T at different z at fixed Q^2.

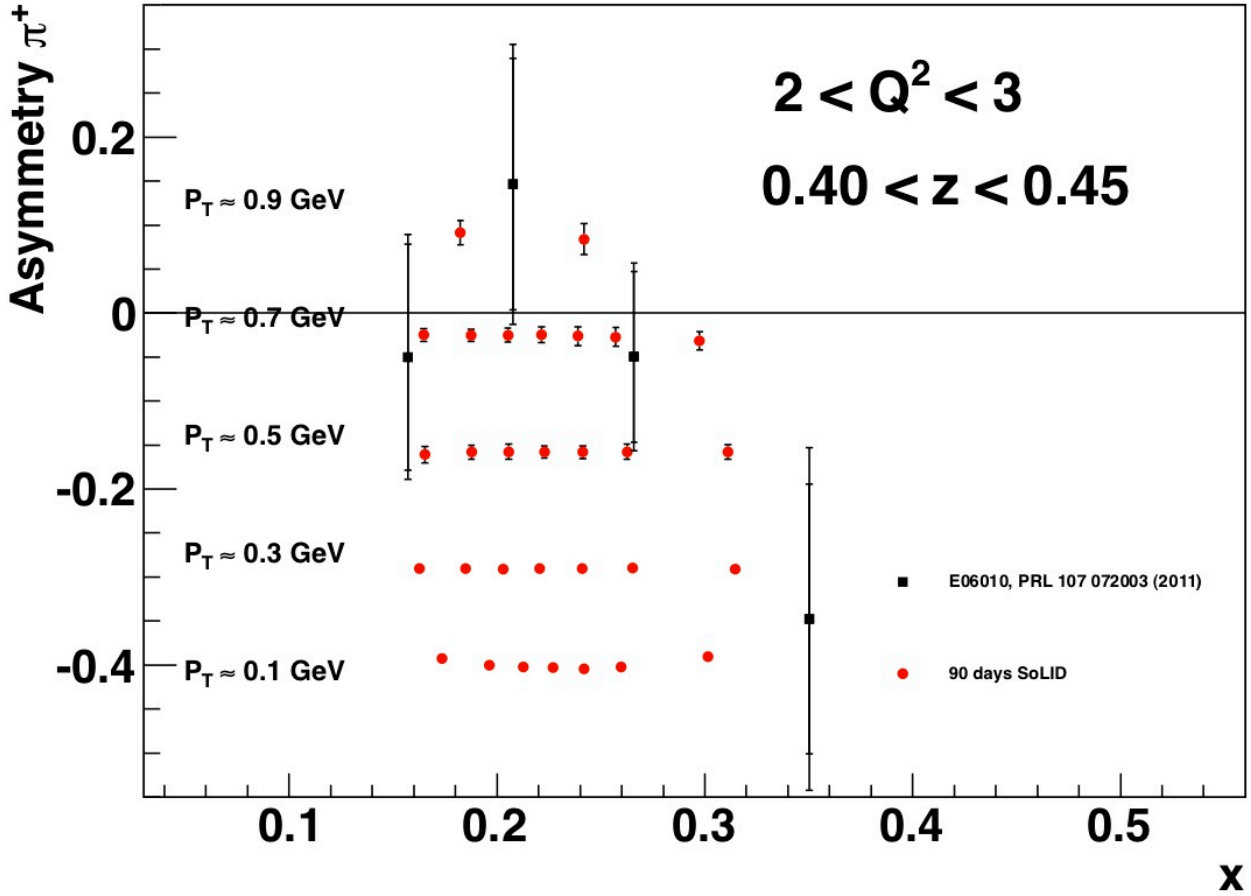
Multi-dimensional nature.

Targets: proton and neutron

Detect: positive pion and negative pions!



Projected Data (E12-10-006)

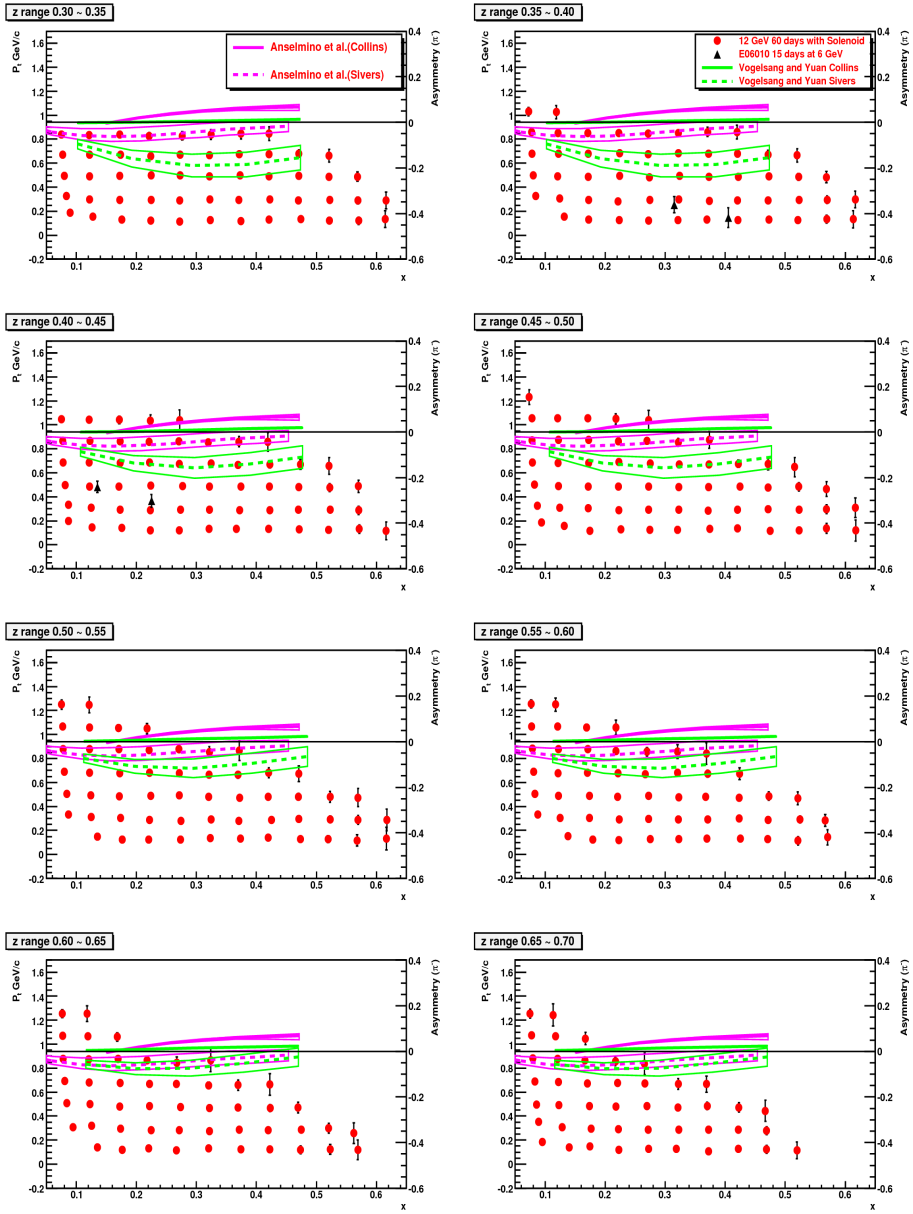


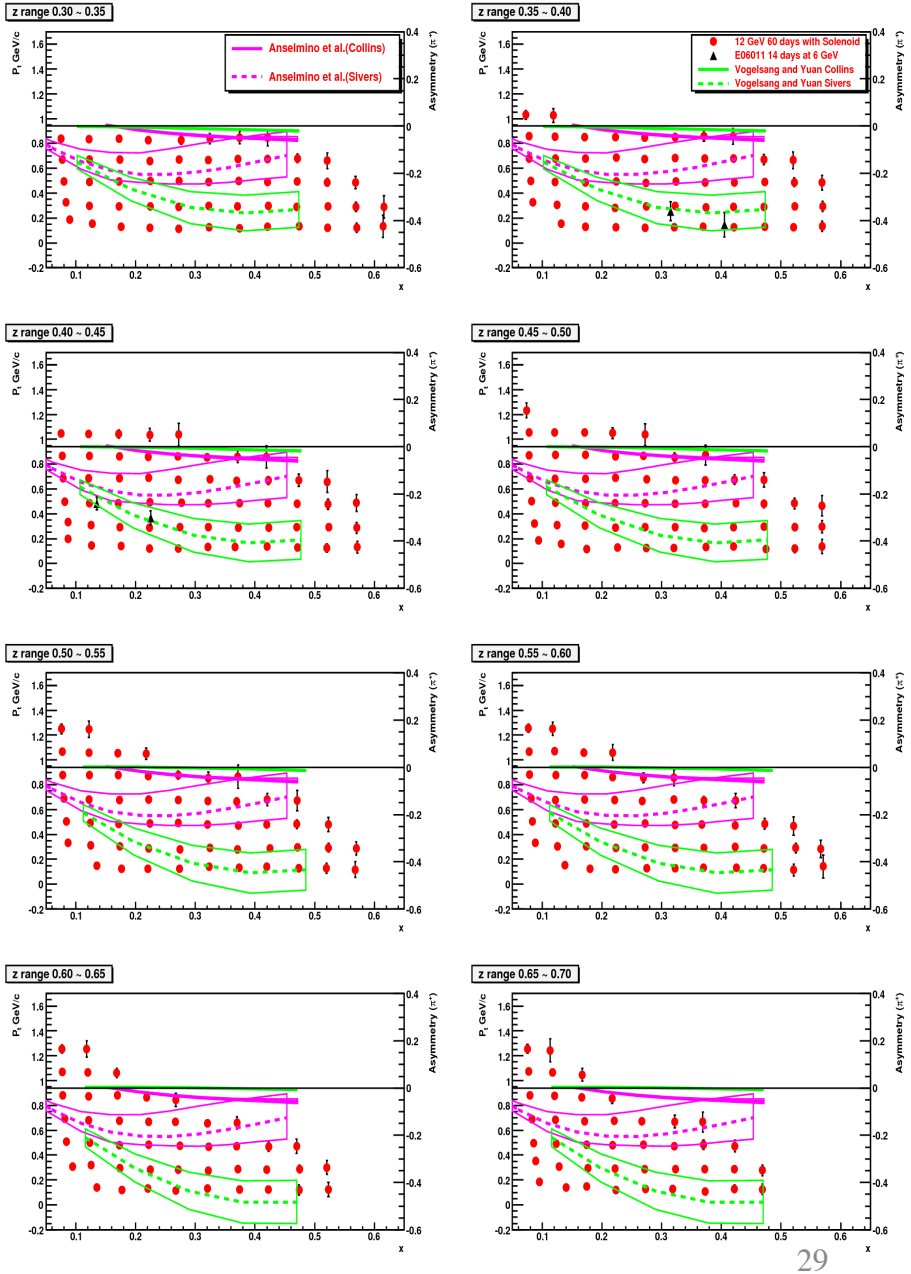
- Total 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.
- z ranges from 0.3 ~ 0.7, only one z and Q^2 bin of 11/8.8 GeV is shown here. π^+ projections are shown, similar to the π^- .

E12-10-006 Spokespersons: Chen, Gao (contact), Jiang, Qian and Peng

X. Qian et al in PRL 107, 072003

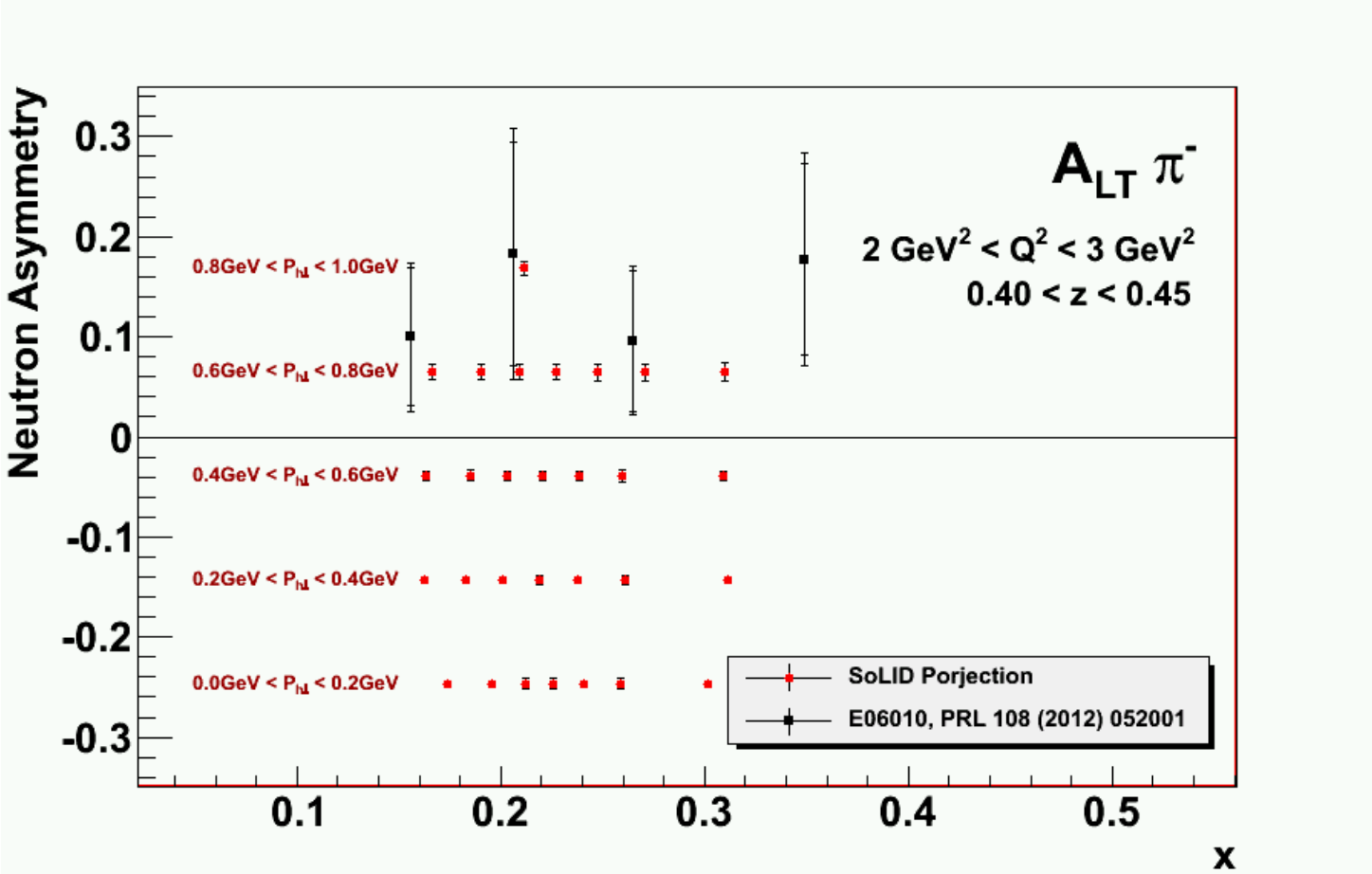
Power of SOLID (example)





SoLID E12-11-007 Projection for A_{LT} (Partial)

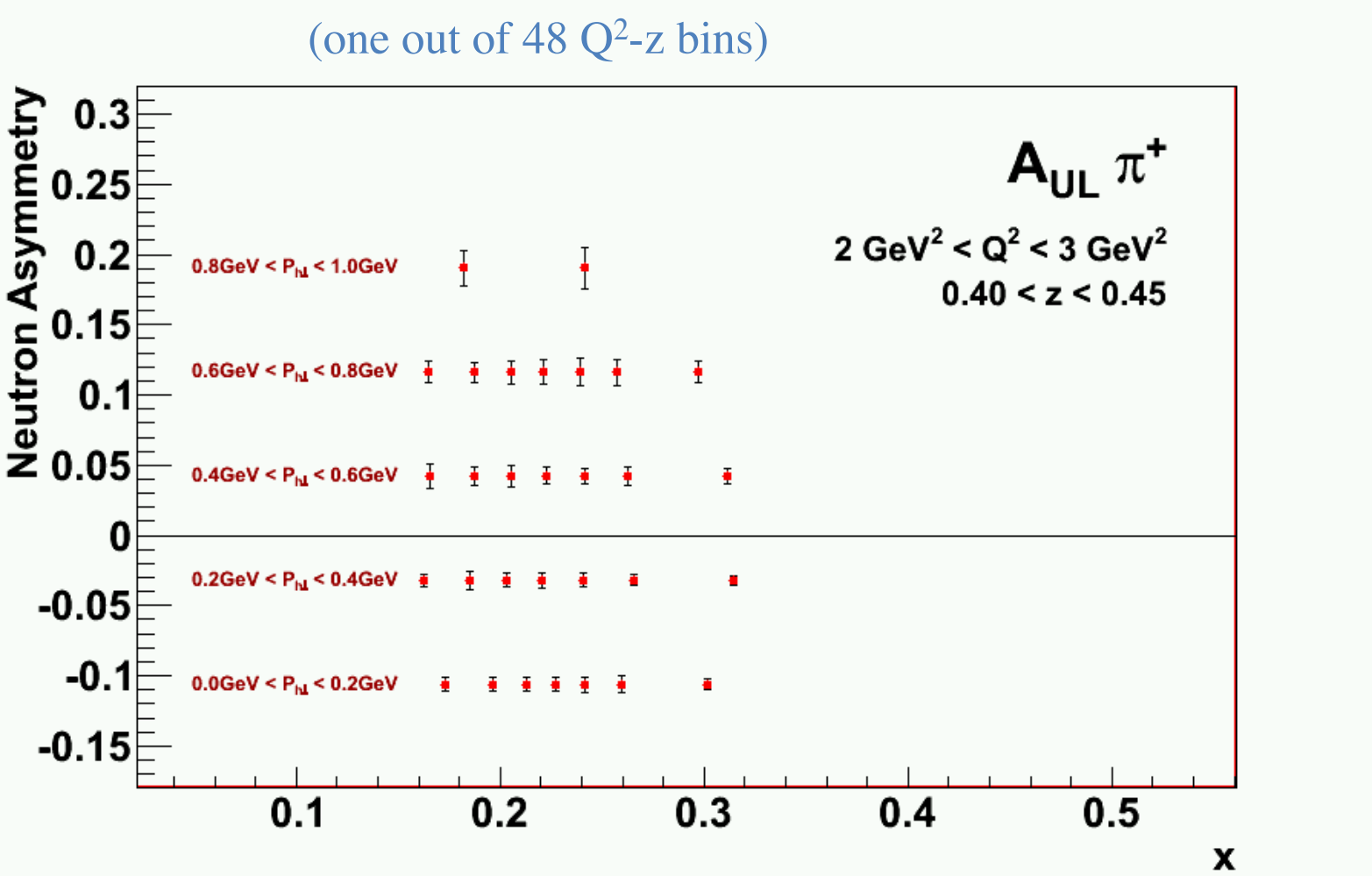
- E12-11-007 and E12-10-006:
  Neutron A_{LT} Projection of one out of 48 Q^2-z bins for π^-



E12-11-007 spokespersons: J.P. Chen, J. Huang, Yi Qiang, W.B. Yan (USTC)
E06010 Results, J. Huang et al., PRL108, 052001 (2012)

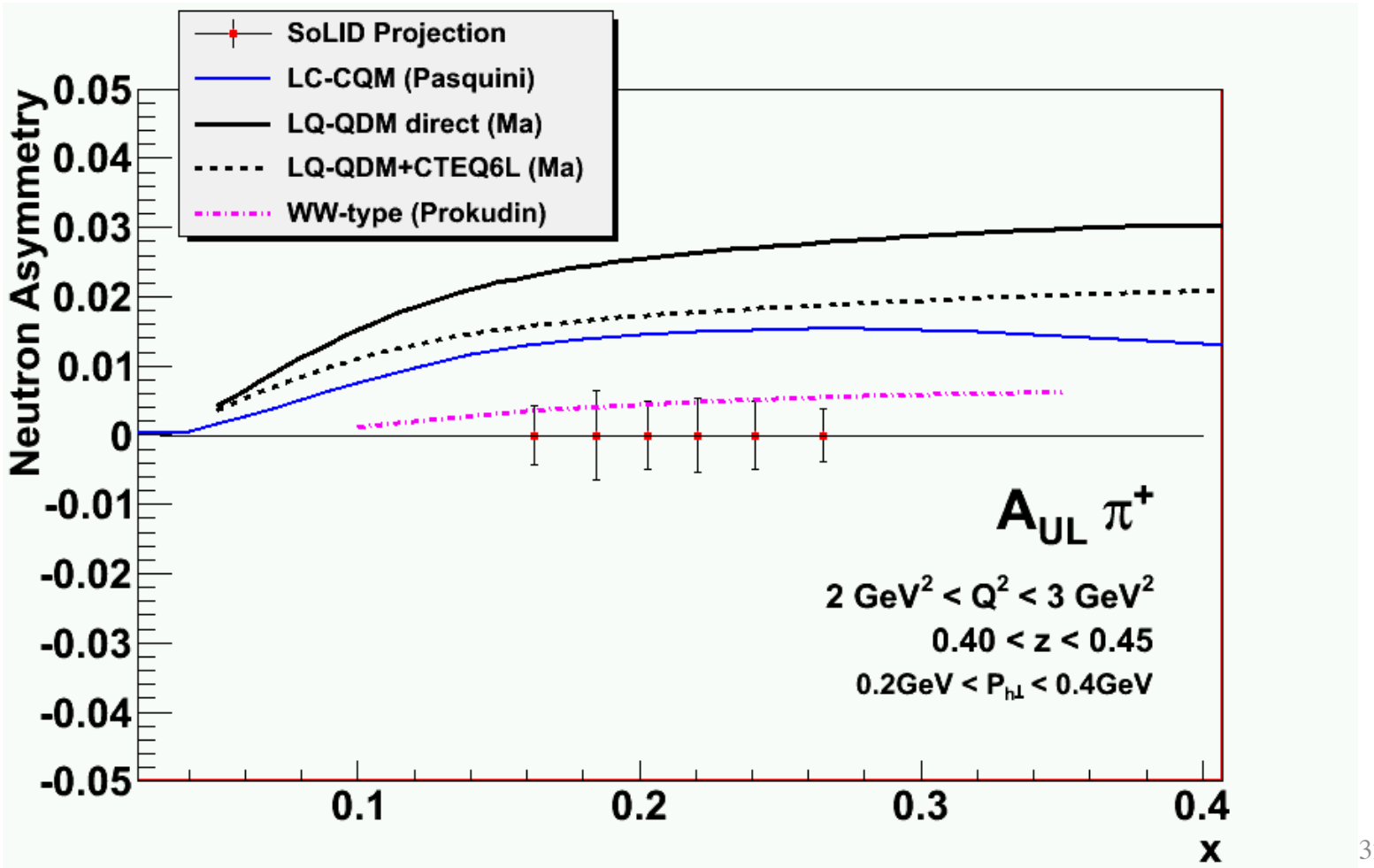
SoLID E12-11-007 Projection/A_{UL} (Partial)

- Projection of a single Q^2-z bin for π^+



SoLID E12-11-007 Projection/A_{UL} (Partial)

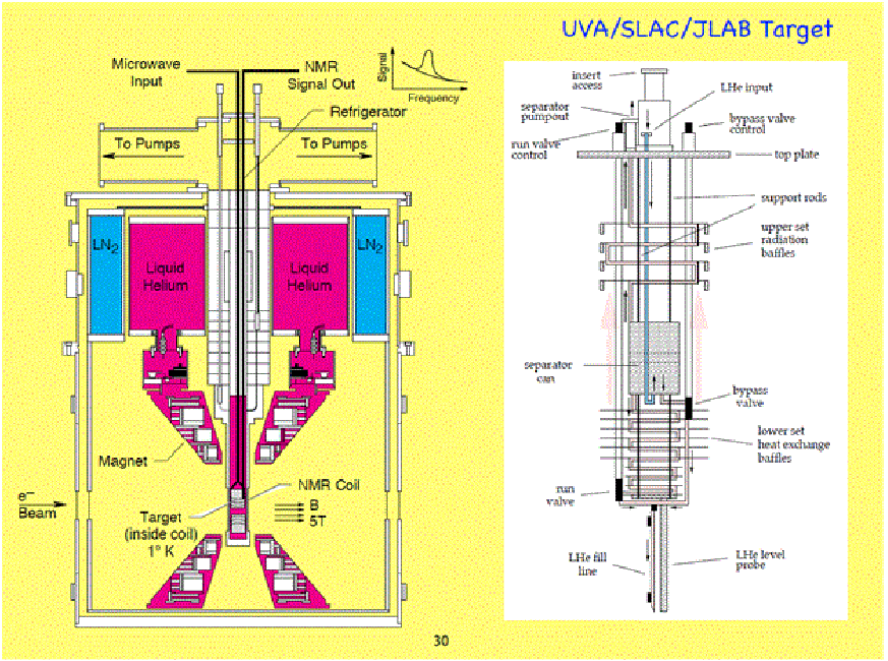
- Projection of a single Q^2-z-PT bin for π^+ (no existing measurement) And compared to model predictions for SoLID kinematics



Experiment E12-11-108:

Target Single Spin Asymmetry in SIDIS *(e, eπ±)* Reaction on a Transversely Polarized Proton Target and SoLID

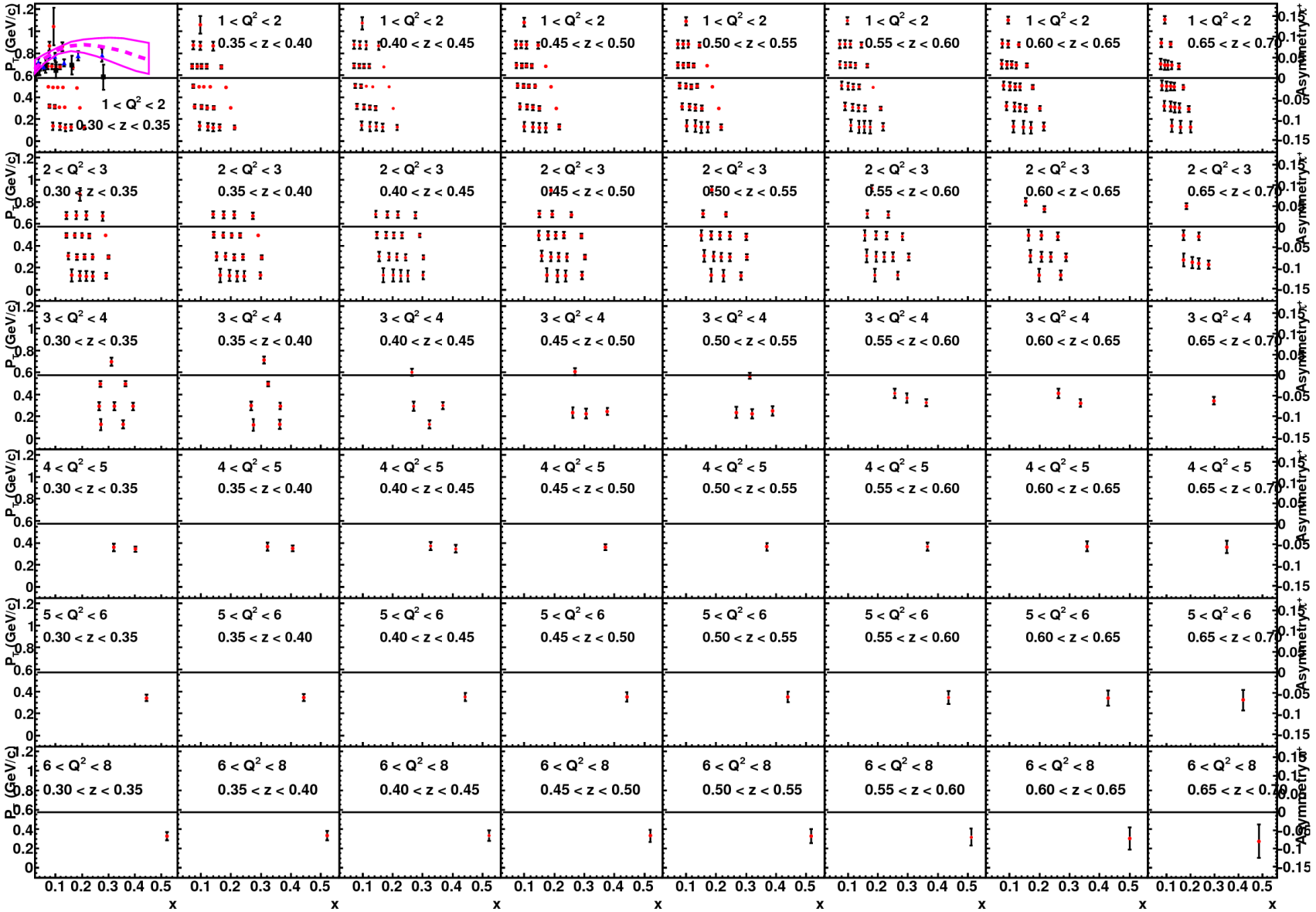
- Measure SSA in SIDIS using transversely polarized proton target
  - Use similar detector setup as that of two approved ^{3}He SoLID expts.
  - Use JLab/UVa polarized NH_3 target with upgraded design of the magnet
  - Target spin-flip every two hours with average in-beam polarization of 70%
  - Two Beam energies: 11 GeV and 8.8 GeV
  - Polarized luminosity with 100nA current: 10^{35} $cm^{-2}s^{-1}$
  - Beamline chicane to transport beam through 5T target magnetic field (already used for g2p expt.)



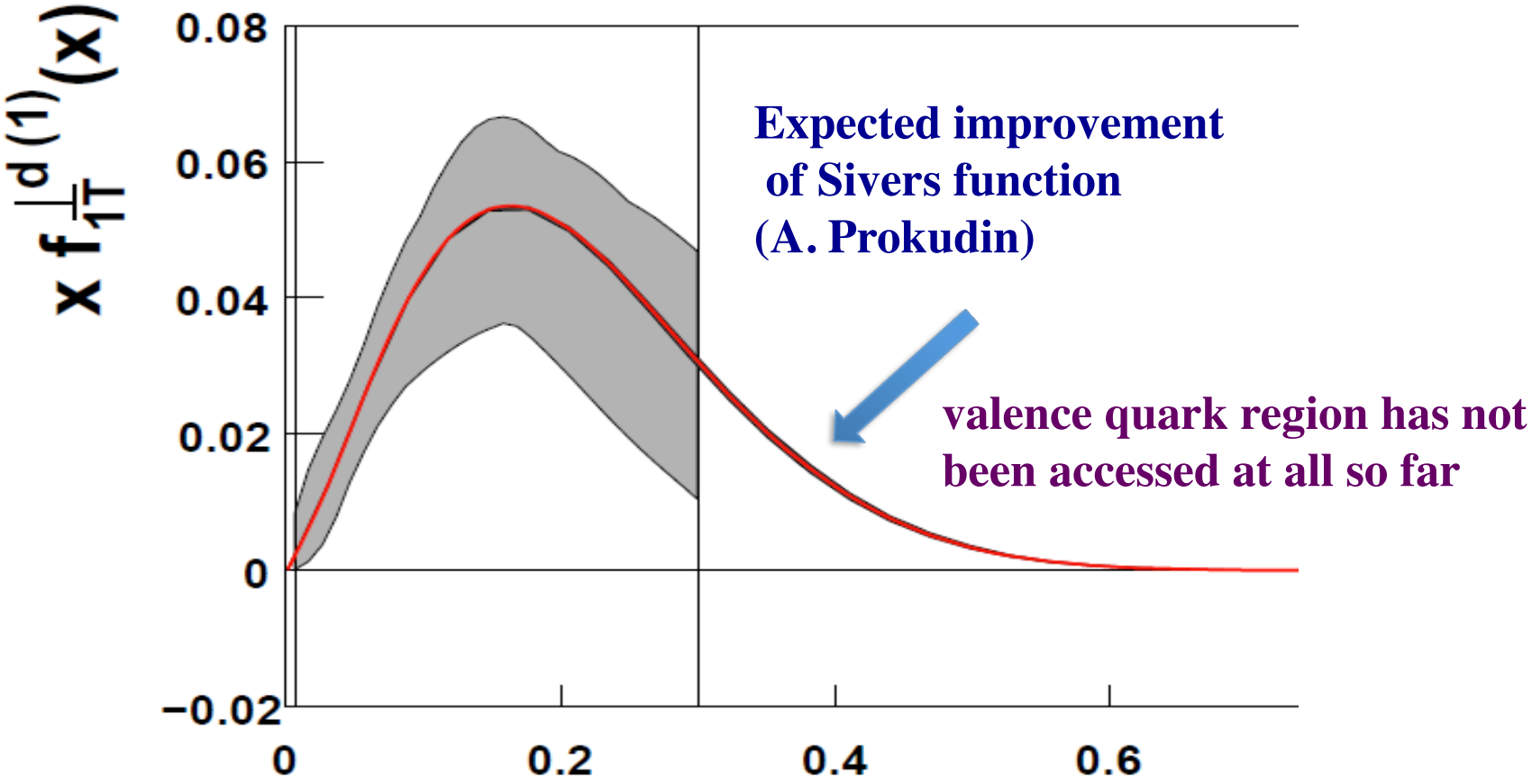
Spokespersons: K. Allada (Jlab), J. P. Chen (Jlab), Haiyan Gao (Contact), Xiaomei Li (CIAE), Z-E. Meziani (Temple)

PAC39: approved with A rating

Proton 4-D Projection



Projected measurements in 1-D (x)



Assumption: We know the k_T dependence, Q^2 evolution of TMDs. Also knowledge on TMFF → project onto 1-D in x to illustrate the power of SoLID-^{3}He. (A similar impact plot on tensor charge soon, stay tuned)

Summary

- **Frontiers in nucleon structure go beyond collinear, 1-D picture**
  - **TMDs**
    - **Three-dimensional description of nucleon in momentum space**
    - **Direct link with orbital motion (orbital angular momentum)**
      - **Quantitative investigation of impact of SoLID measurement on quark OAM is ongoing (Duke and Pavia)**
    - **Transverse motion: spin-orbit correlations, multi-parton correlations, dynamics of confinement and QCD**
    - **10% quark tensor charge from both SSA data from SoLID provides excellent test of LQCD predictions**
- **JLab 12-GeV upgrade will provide excellent opportunities to map out the 3-dimensional structure of the nucleon through TMDs and GPDs**
- **SoLID will just do that!**

Thanks to B. Pasquini, A. Prokudin, J. P. Chen, J. Huang, and X. Qian, Y. Qiang, and others in the SoLID collaboration
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