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

Solid Collaboration Meeting, Nov 7-8, 2014

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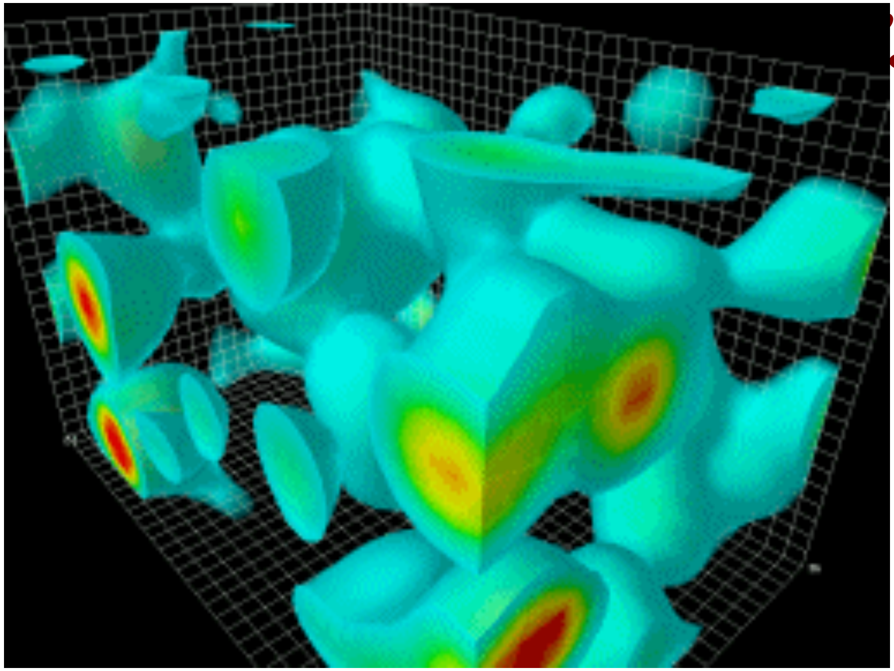
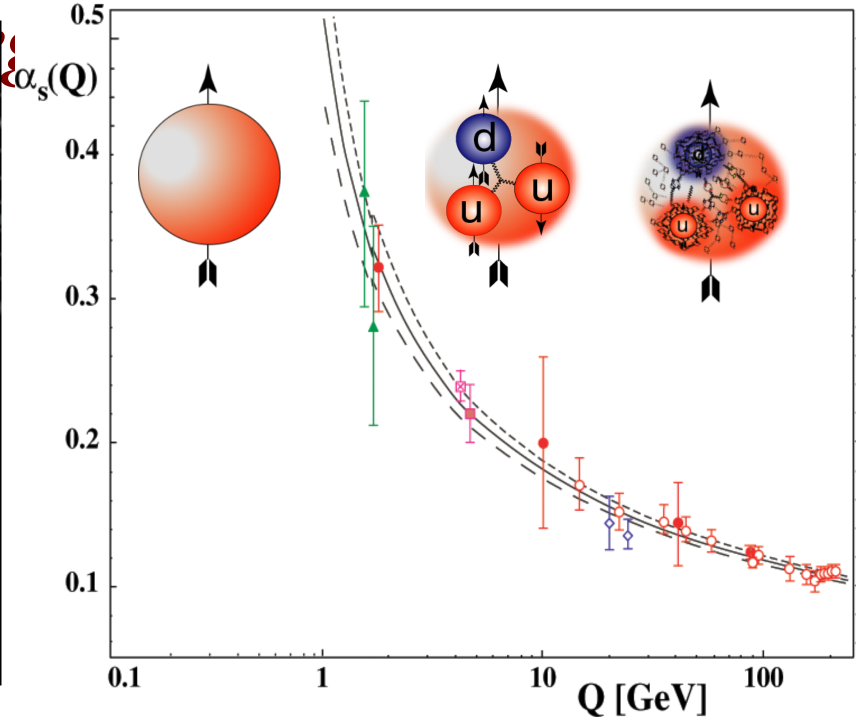
QCD: still unsolved in non-perturbative



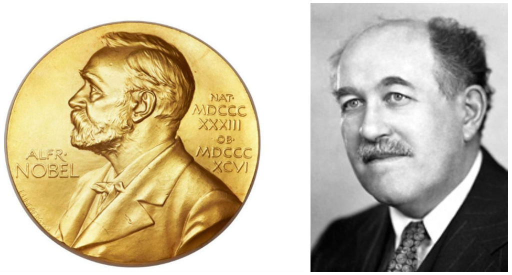


Gauge bosons: gluons (8)

- *2004 Nobel prize for ``asymptotic freedom''*
- *non-perturbative regime QCD ?????*
- *One of the top 10 challenges for physics!*
- *QCD: Important for discovering new physics beyond SM*
- *Nucleon structure is one of the most active areas*

What is inside the proton/neutron?

1933: Proton’s magnetic moment



Nobel Prize
In Physics 1943

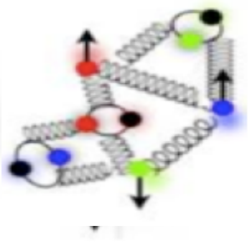
Otto Stern

1960: Elastic e-p scattering

Nobel Prize
In Physics 1961

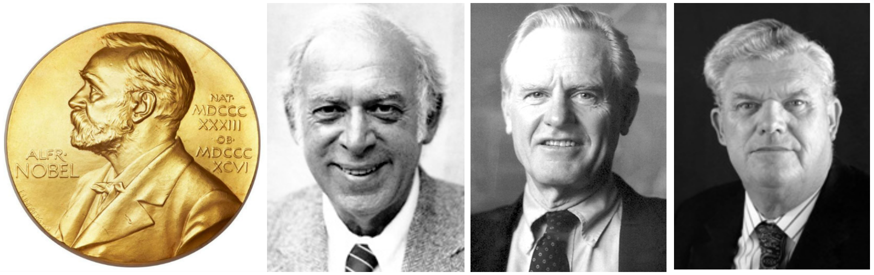
Robert Hofstadter

$g \neq 2$



Form factors $\rightarrow$ Charge distributions

1969: Deep inelastic e-p scattering



Nobel Prize in Physics 1990

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

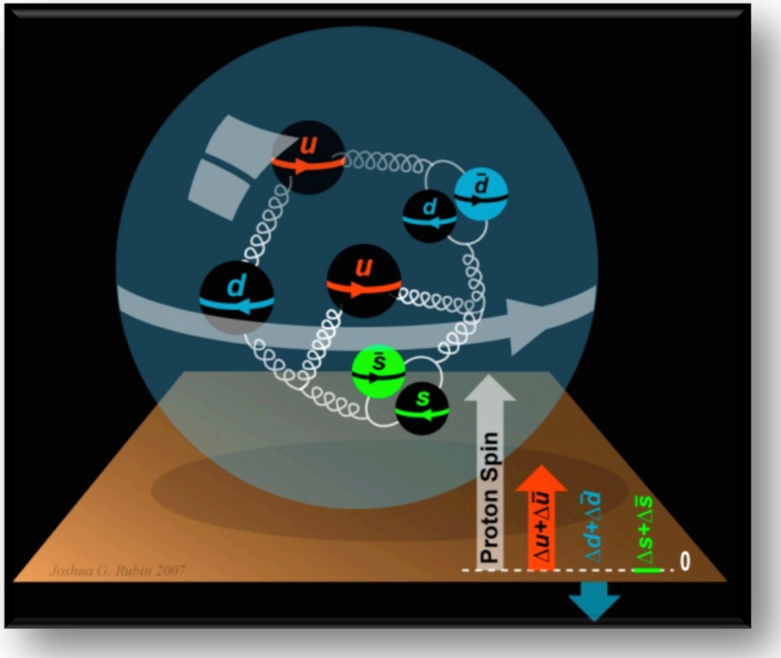
1974: QCD Asymptotic Freedom

Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

slide from Jianwei Qiu

The Incomplete Nucleon: Spin Puzzle



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

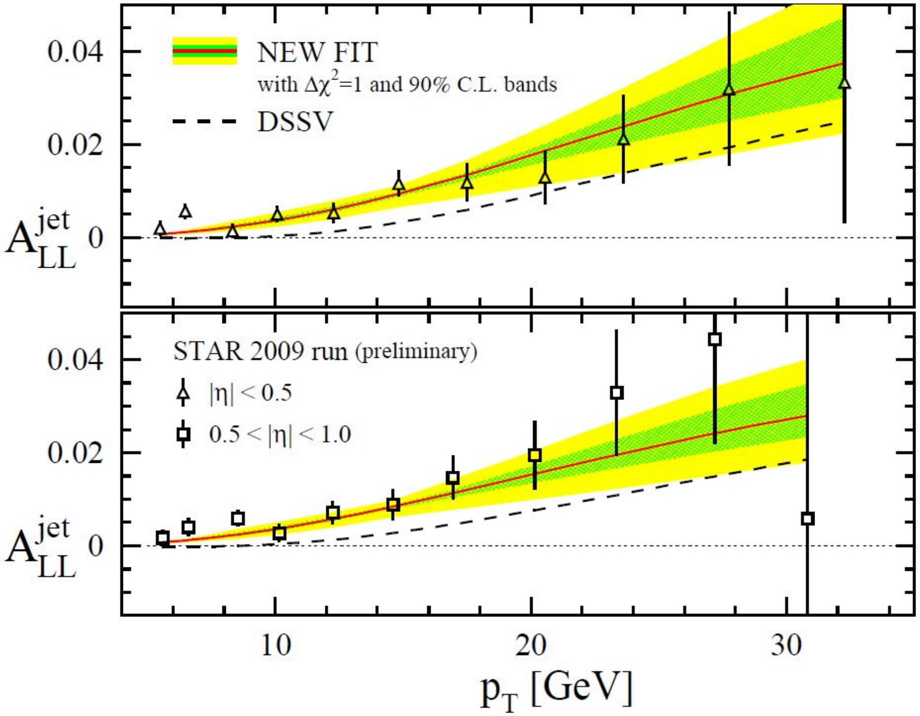
[X. Ji, 1997]

Jaffe-Manohar 1990
Chen *et al*. 2008
Wakamatsu 2009,2010

- DIS → $\Delta\Sigma \cong 0.30$
- RHIC + DIS → Δg not small
- → L_q

Orbital angular momentum of quarks gluons is importan
Understanding of spin-orbit correlation (atomic hydrogen, topological insulator

How to access OAM?

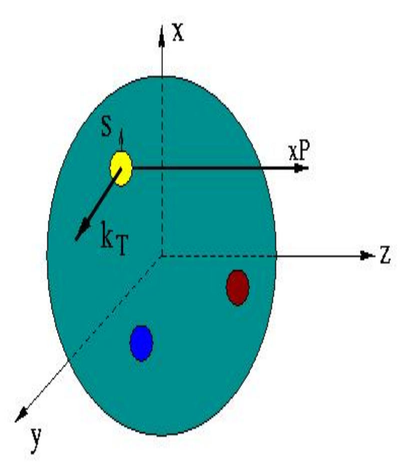


PRL 113, 012001 (2014)

Unified View of Nucleon Structure

$W_p^u(x,k_T,\boldsymbol{r_T})$ Wigner distributions

5D Dist.

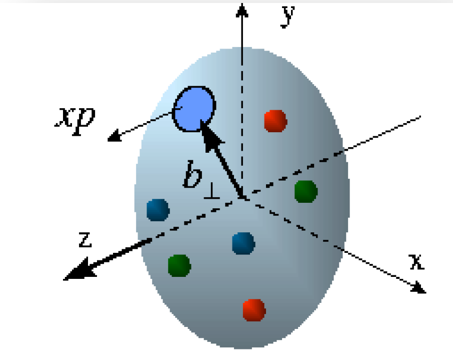


$d^2\boldsymbol{r_T}$

d^2k_T

TMD PDFs
$f_1^u(x,k_T)$, ..
$h_1^u(x,k_T)$

GPDs/IPDs

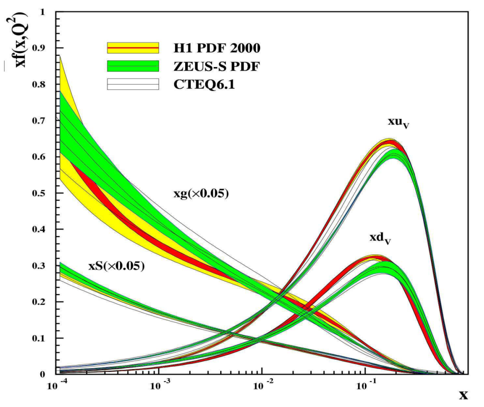


3D imaging

d^2k_T

d^2r_T

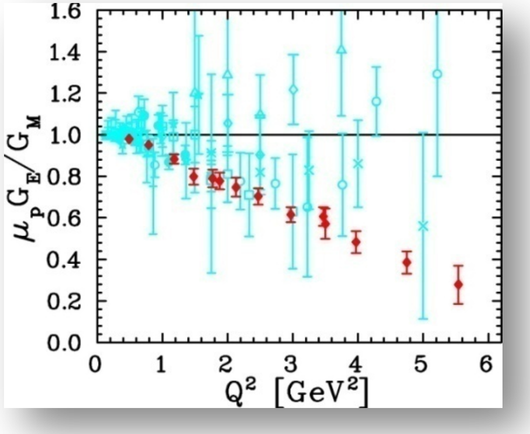
dx &
Fourier Transformation



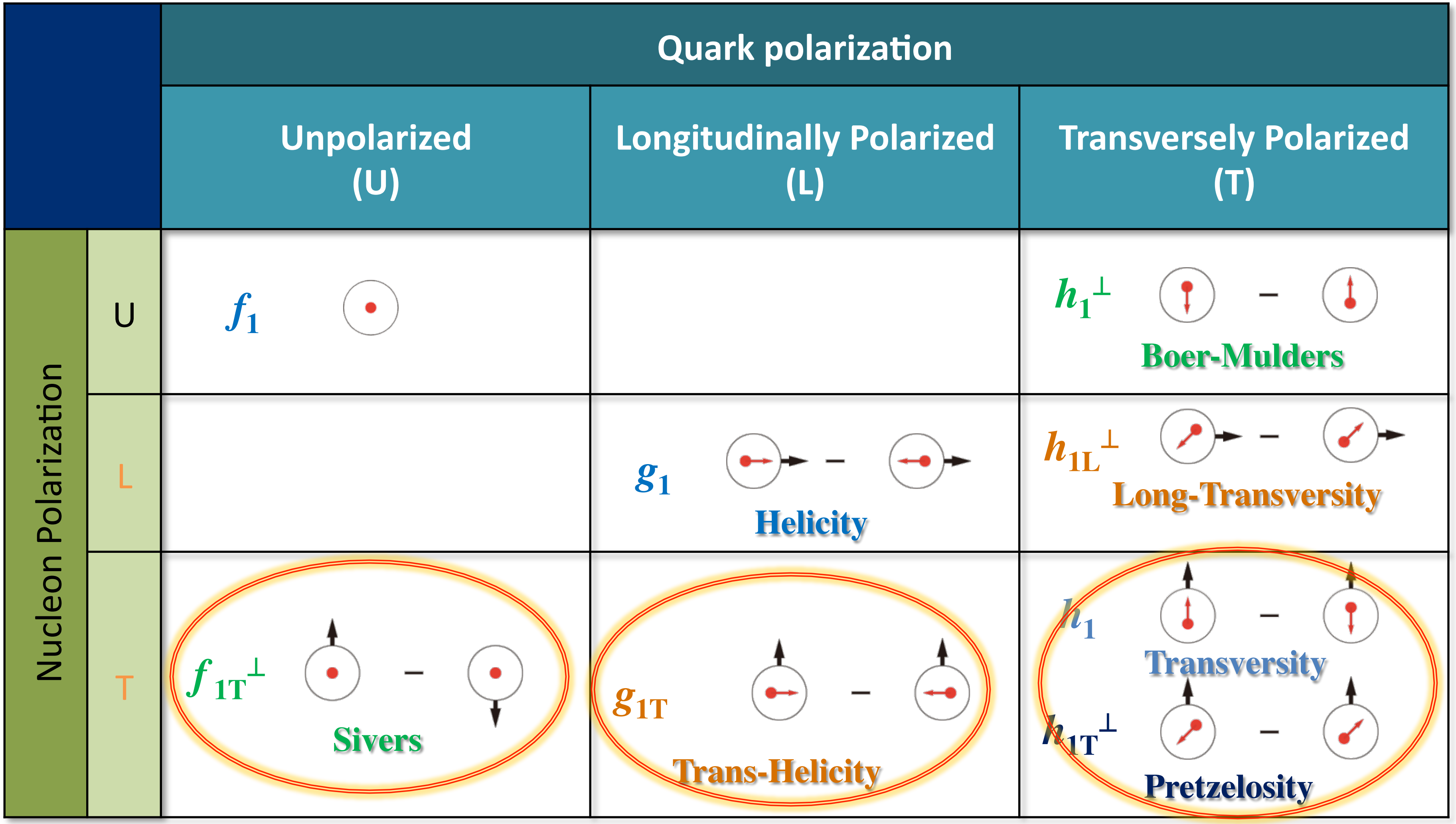
PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

1D

Form
Factors
$G_E(Q^2)$,
$G_M(Q^2)$

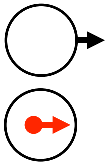


Leading-Twist TMD PDFs



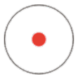
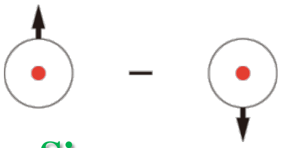
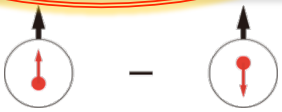
		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1		$h_1^\perp$ − Boer-Mulders
	L		g_1 − Helicity	$h_{1L}^\perp$ − Long-Transversity
	T	$f_{1T}^\perp$ − Sivers	g_{1T} − Trans-Helicity	h_1 − Transversity $h_{1T}^\perp$ − Pretzelosity

Leading-Twist TMD PDFs

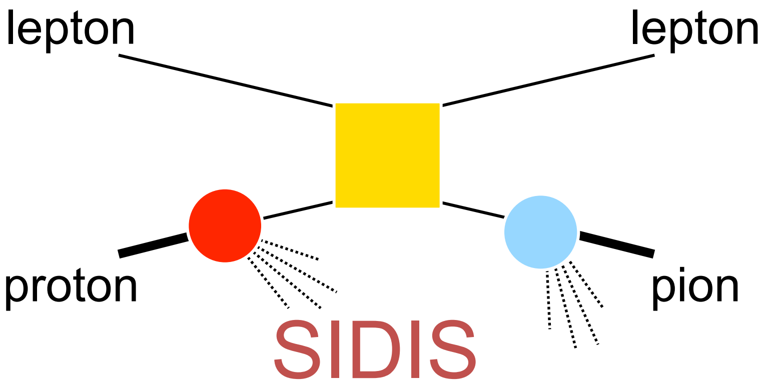


Nucleon Spin

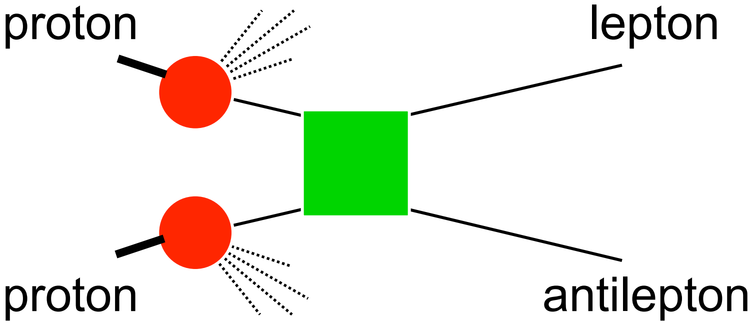
Quark Spin

		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**

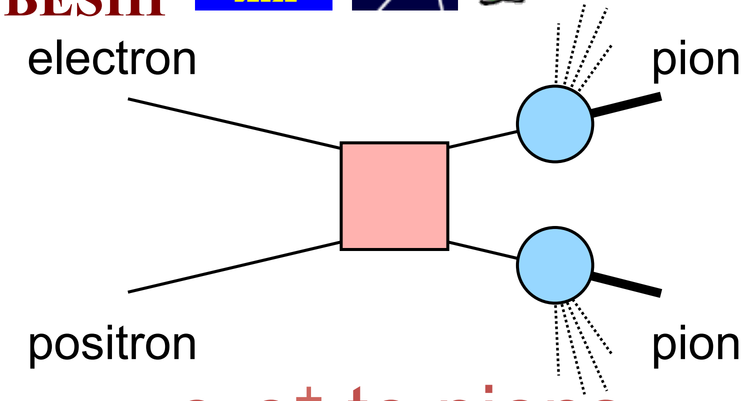
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

🟨 Partonic scattering amplitude

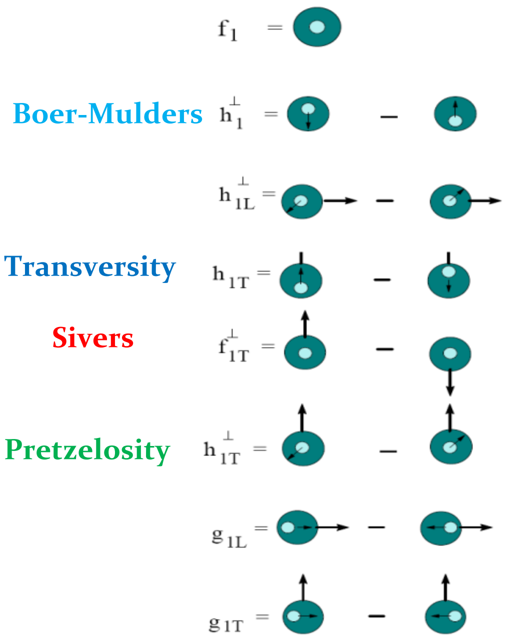
🔵 Fragmentation amplitude

🔴 Distribution amplitude

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

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

Access Parton Distributions through Semi-Inclusive DIS



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

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

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

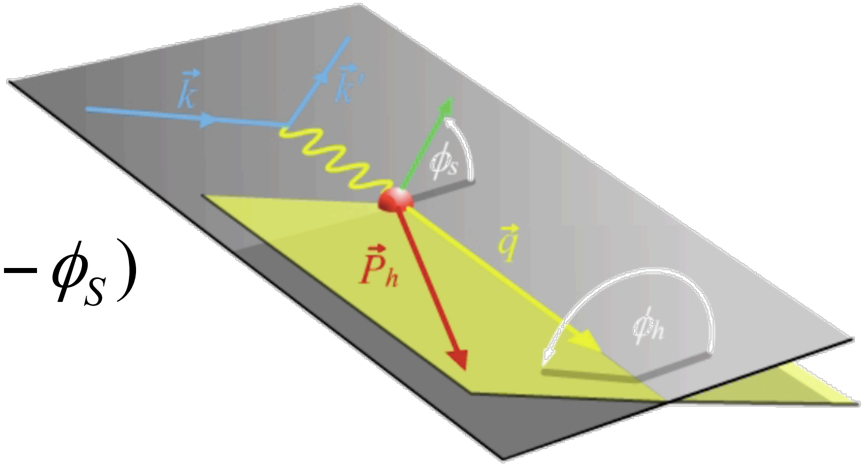
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



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

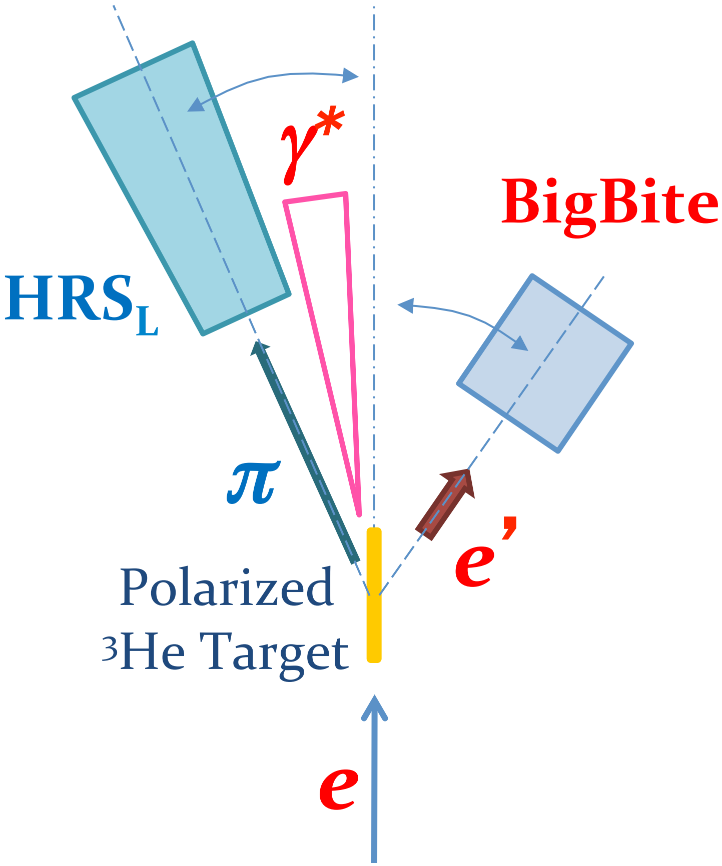
$$A_{UT}^{Sivers}\propto\left\langle\sin(\phi_h-\phi_S)\right\rangle_{UT}\propto f_{1T}^{\perp}\otimes D_1$$

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

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

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.

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



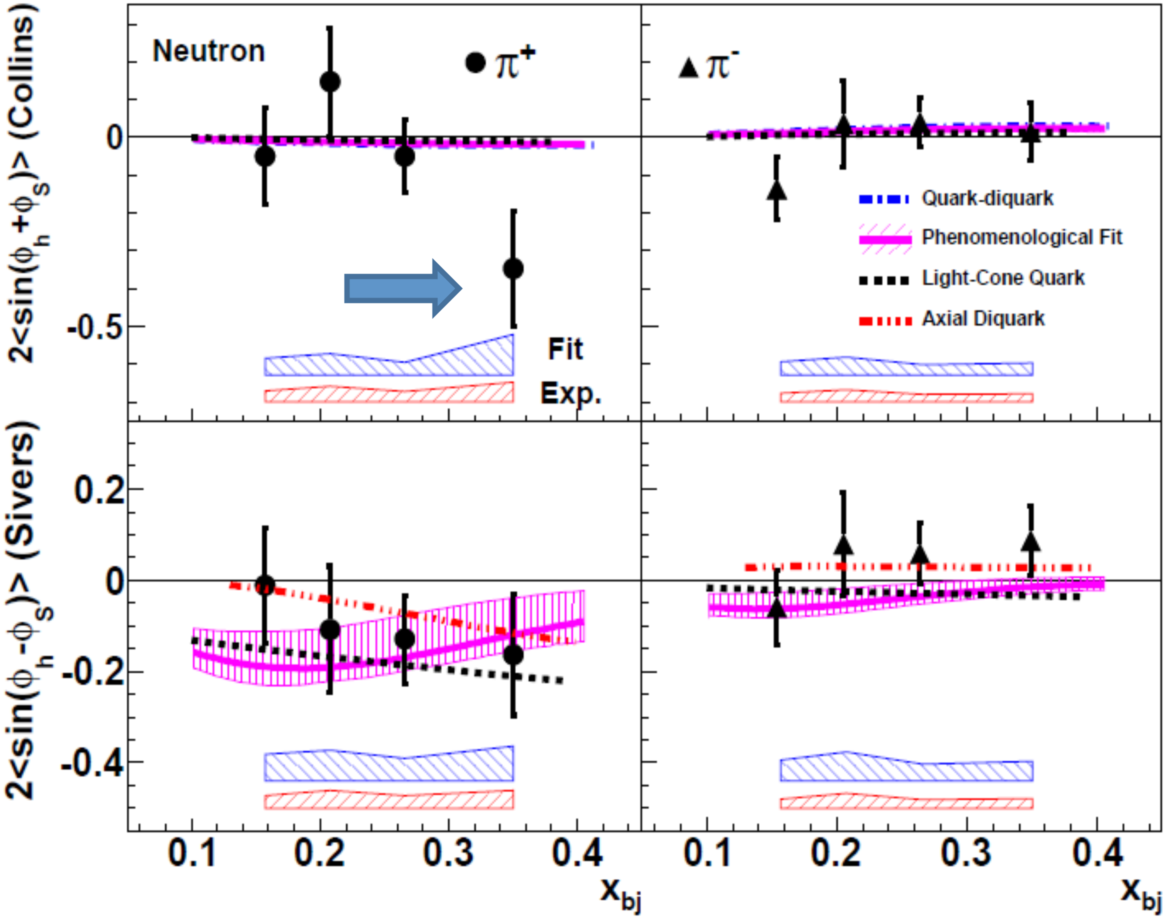
- ***First*** **neutron** data in SIDIS SSA&DSA
  - Similar Q^2 as HERMES experiment
- Disentangle Collins/Sivers effects

- 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° as **electron** arm:
  P_e = 0.6 ~ 2.5 GeV/*c*
- HRSL at 16° 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!**



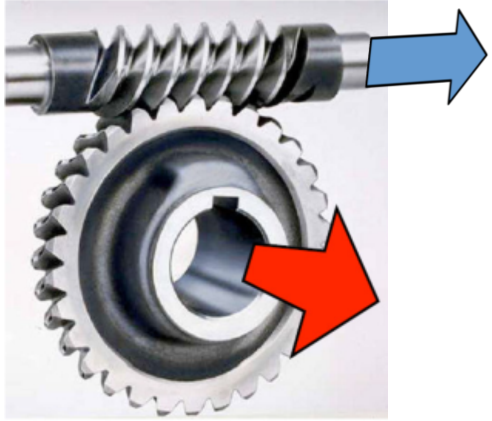
- Negative Sivers π$^+$ Asymmetry
    - Consistent with HERMES/COMPASS
    - **demonstration of negative d quark Sivers function.**

Model (fitting) uncertainties shown in blue band.

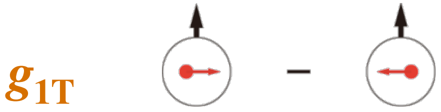
Experimental systematic uncertainties: red band

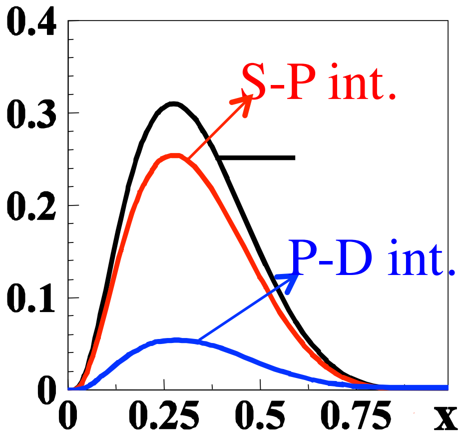
X. Qian *et al*, Phys. Rev. Lett. 107, 072003 (2011)

Double Spin Asymmetry: g_{1T}

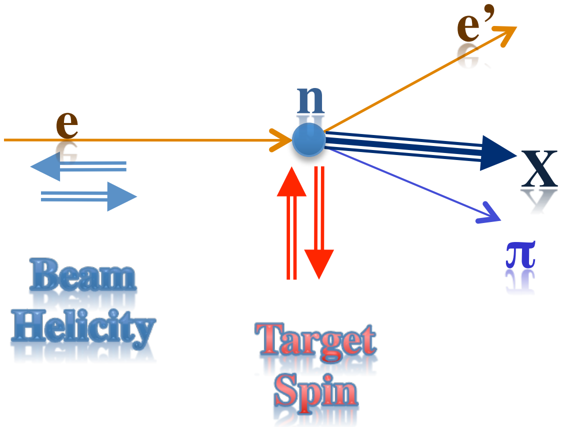


- $A_{LT}^{\cos(\varphi_h-\varphi_s)} \propto g_{1T}^q \otimes D_{1q}^h$
  - Leading twist TMD PDFs
  - T-even, Chiral-even
- Dominated by real part of interference between L=0 (S) and L=1 (P) states
  - Imaginary part -> Sivers effect
- First TMDs in Pioneer Lattice calculation
  - arXiv:0908.1283 [hep-lat],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





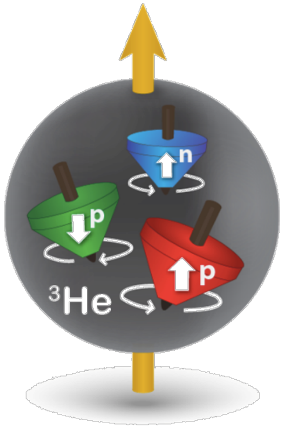
Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

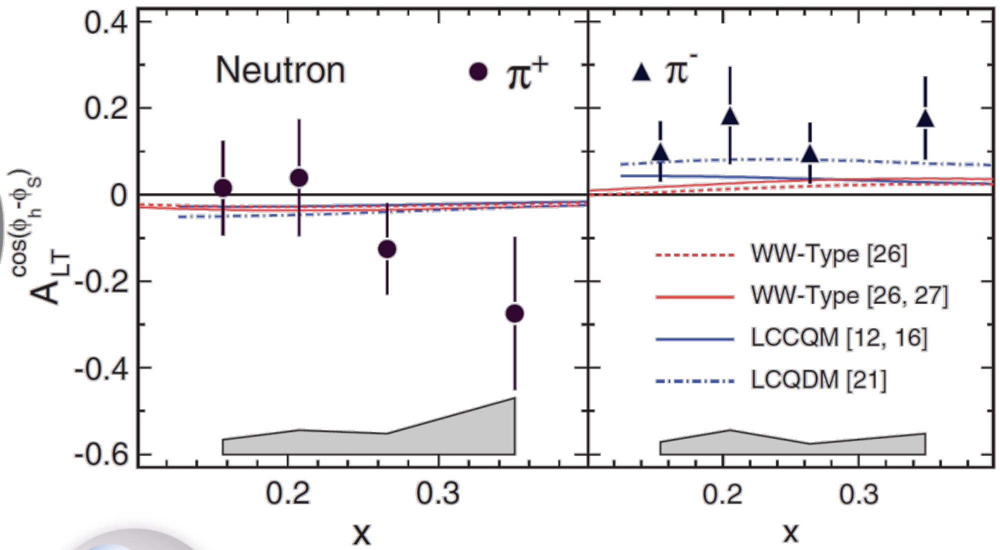


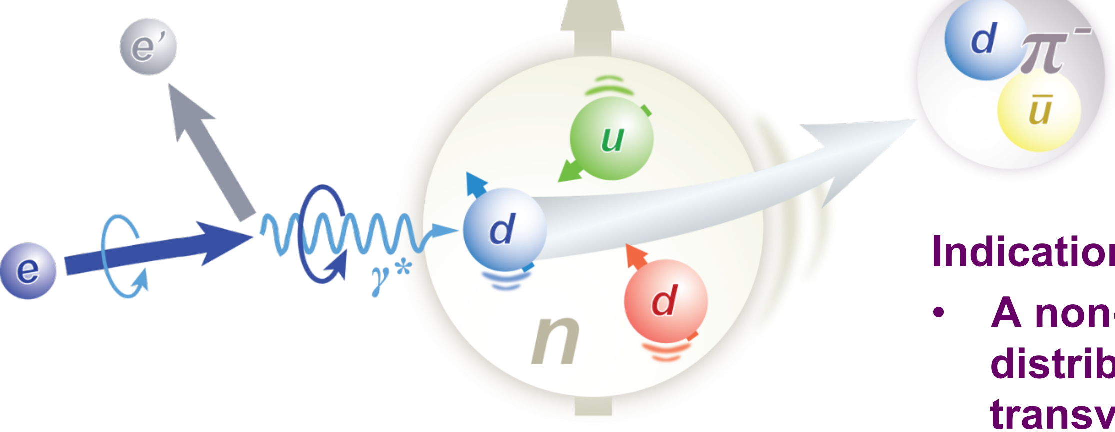
New Observable Reveals Interesting Behaviors of Quarks

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

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







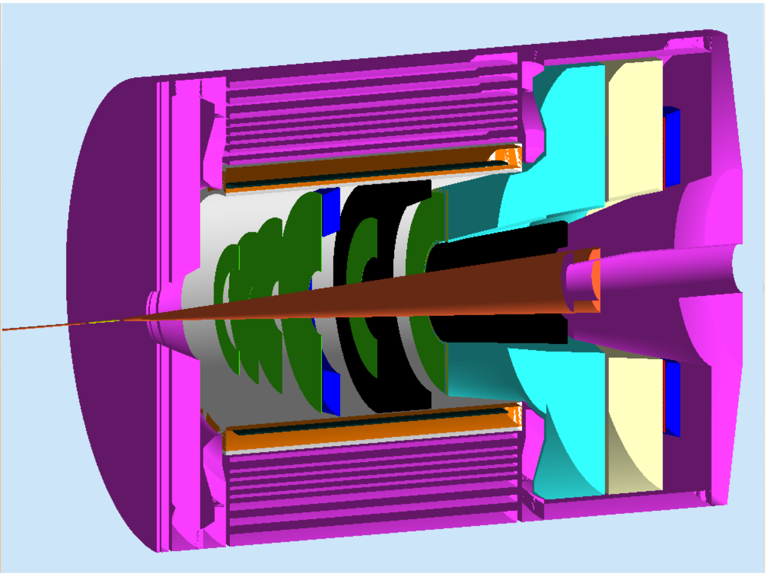
First measurement of A_{LT}
beam-target double-spin asymmetry

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)

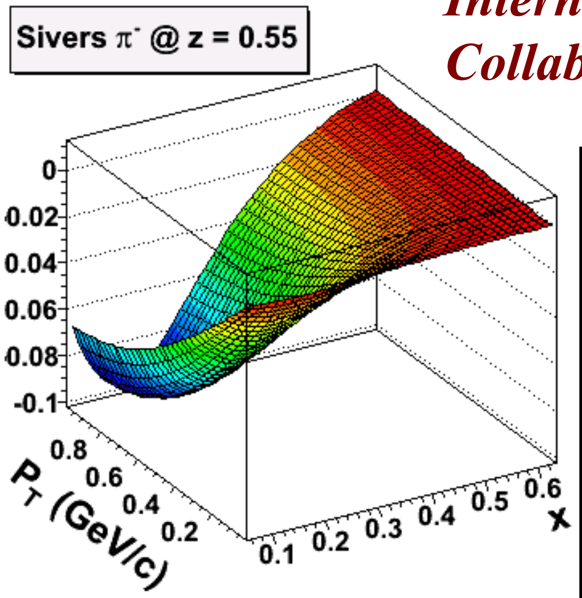
SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV



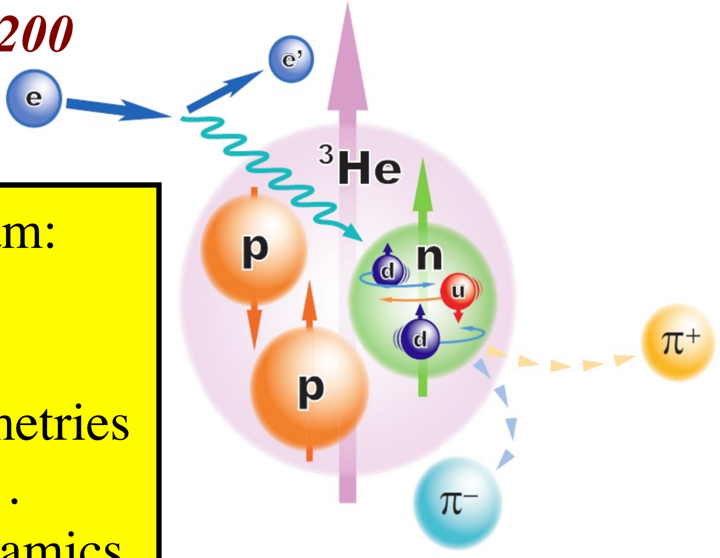
E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

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 200 Collaborators from 11 countries



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 200 collaborators, 50+ institutions, 11 countries, strong overlap with PVDIS Collaboration

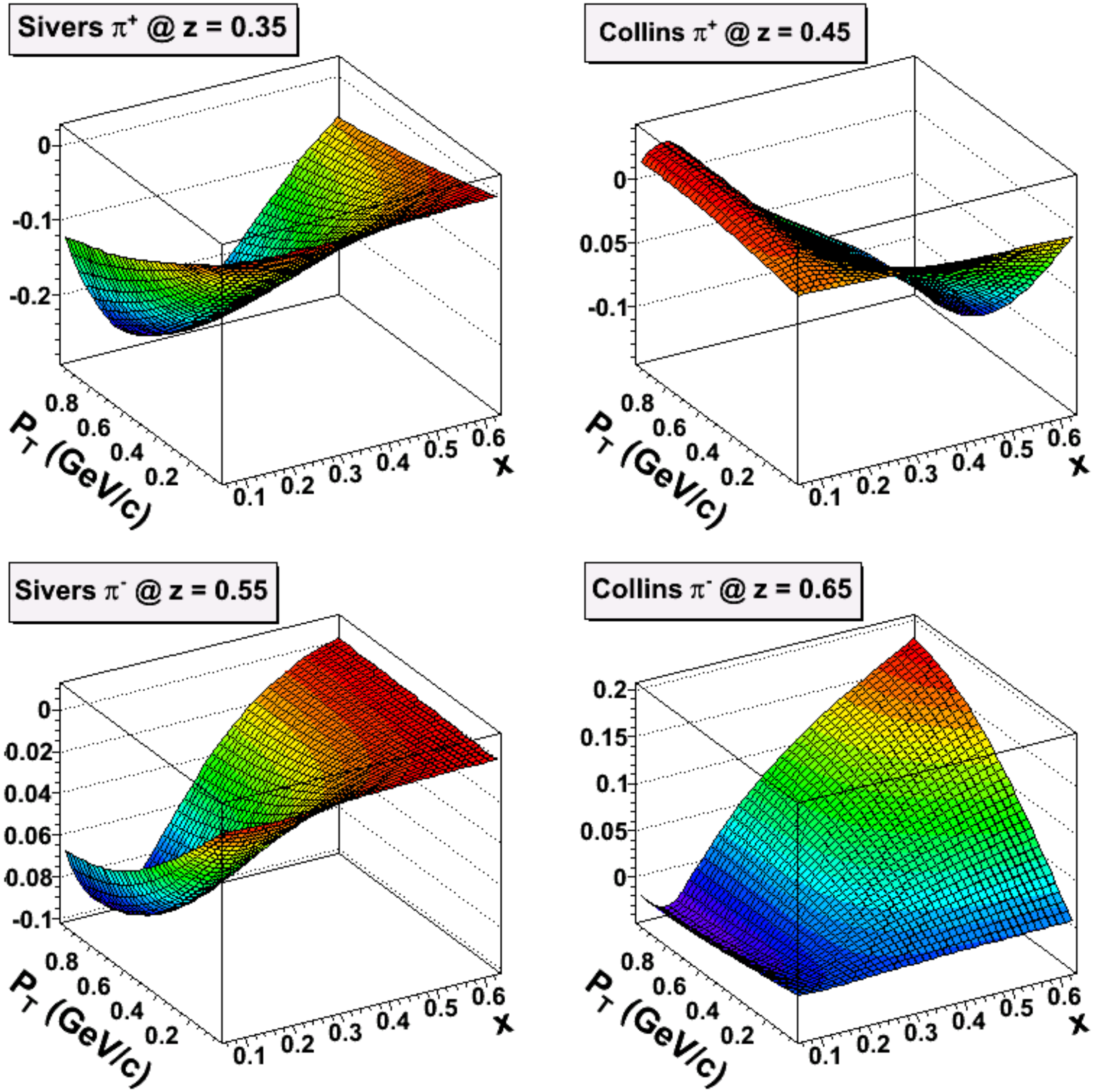
3-D neutron π^+/π^- Collins/Sivers Asymmetries at Q^2=2.0 GeV^2

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

Multi-dimensional nature.

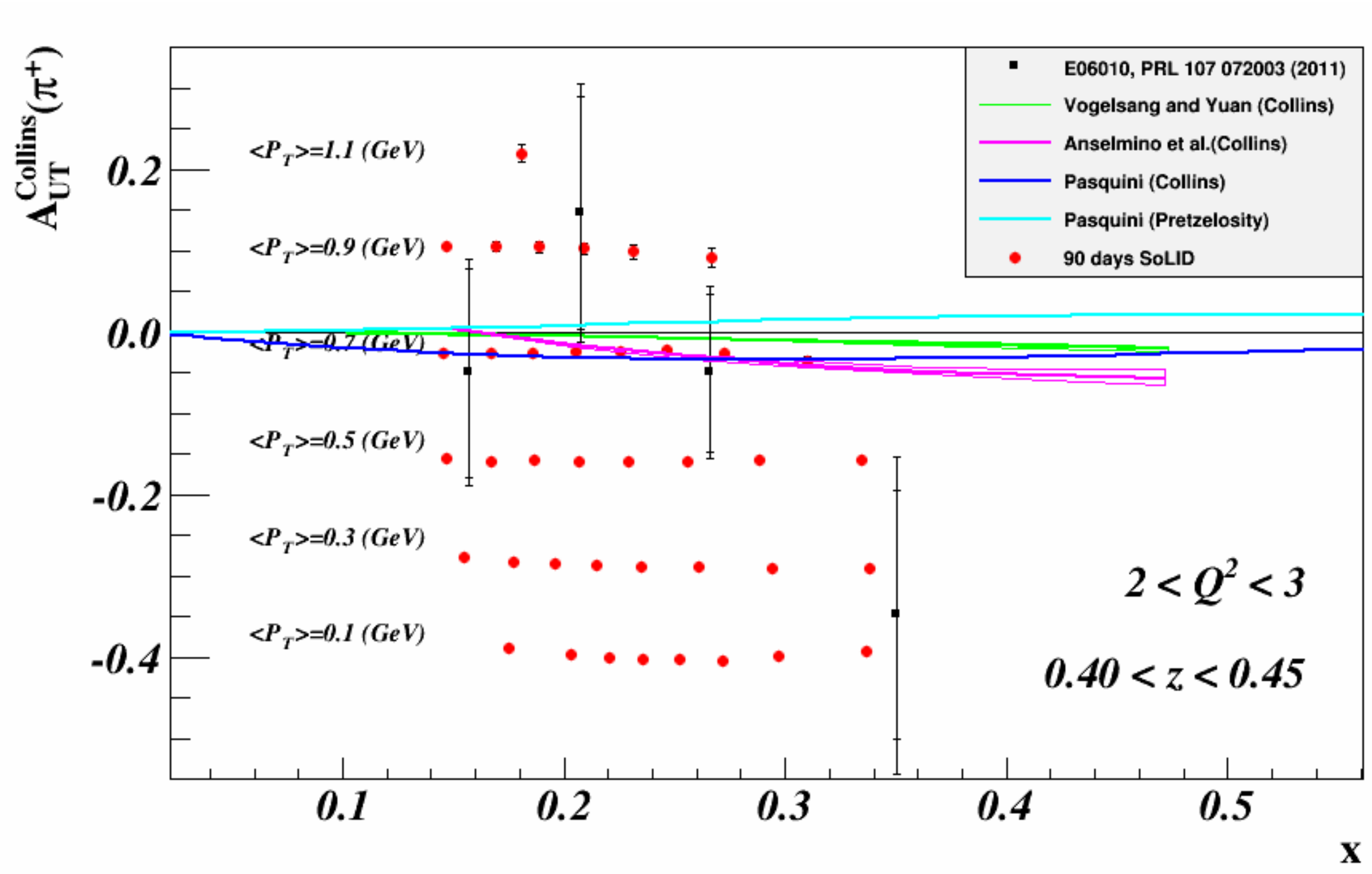
Targets: ^{3}He (neutron), and H/D (factorization)

Detect: positive pion and negative pions!



Torino 2008

Projected Data (E12-10-006)

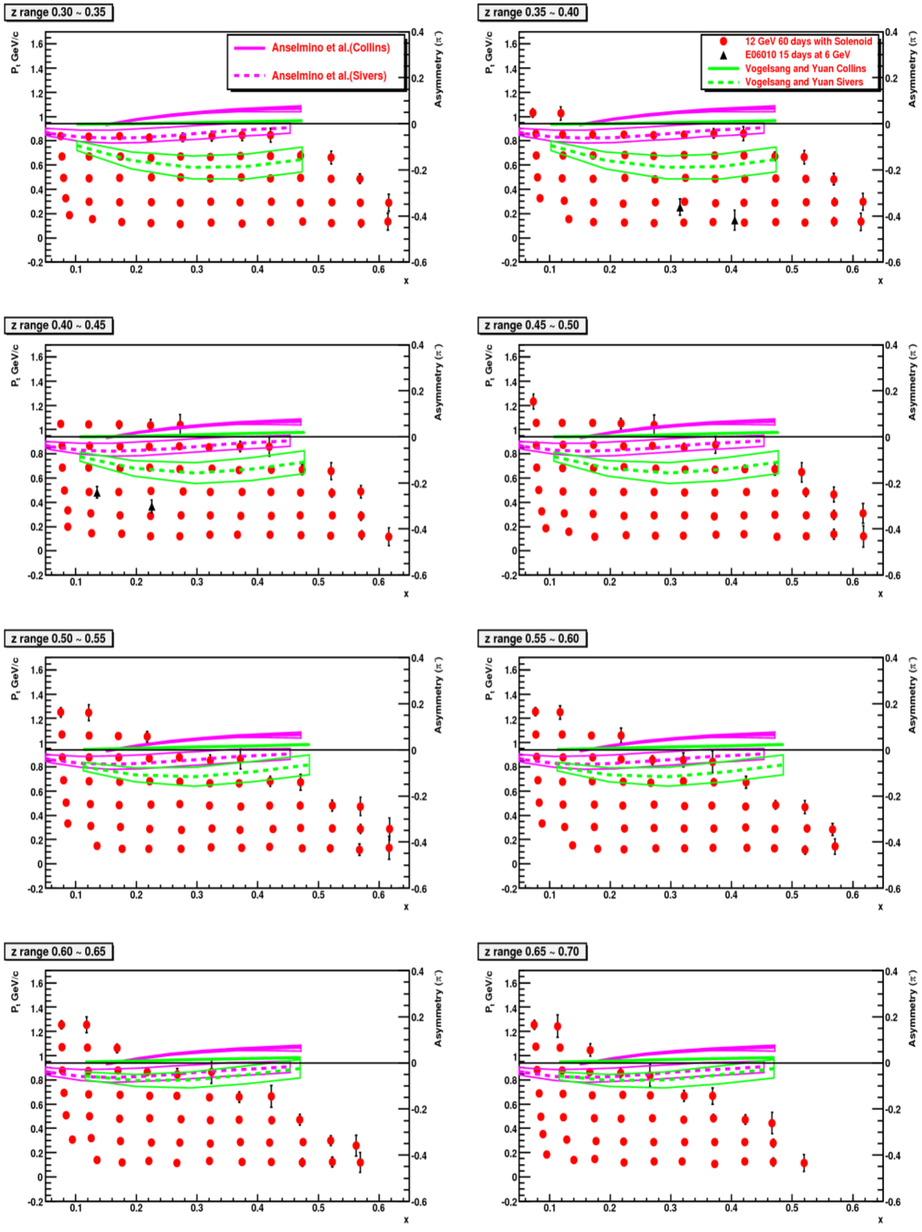


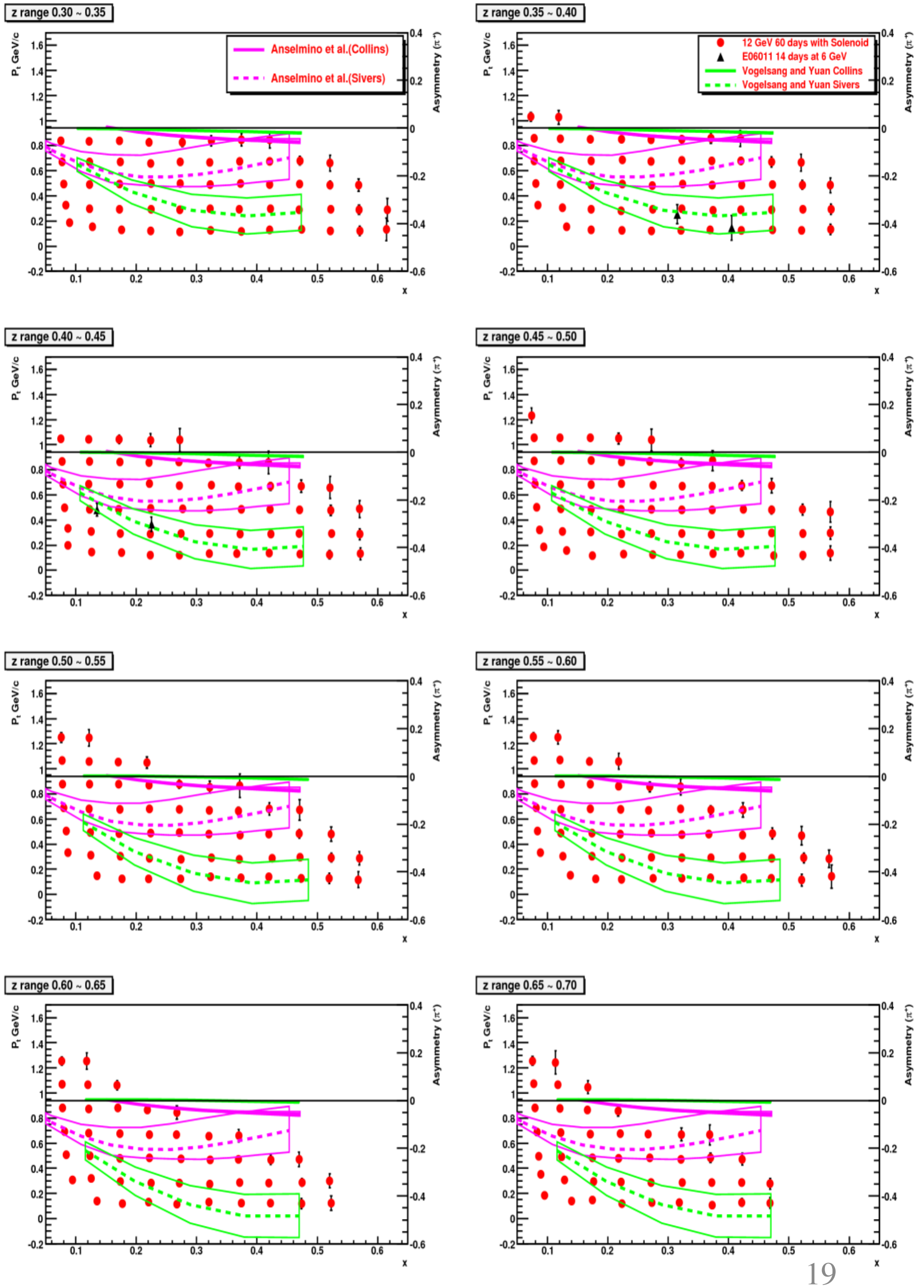
- z ranges from 0.3 ~ 0.7, only one z and Q^2 bin of 11/8.8 GeV is shown here. π^+ projections are shown, similar to the π^- .

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

X. Qian et al in PRL 107, 072003

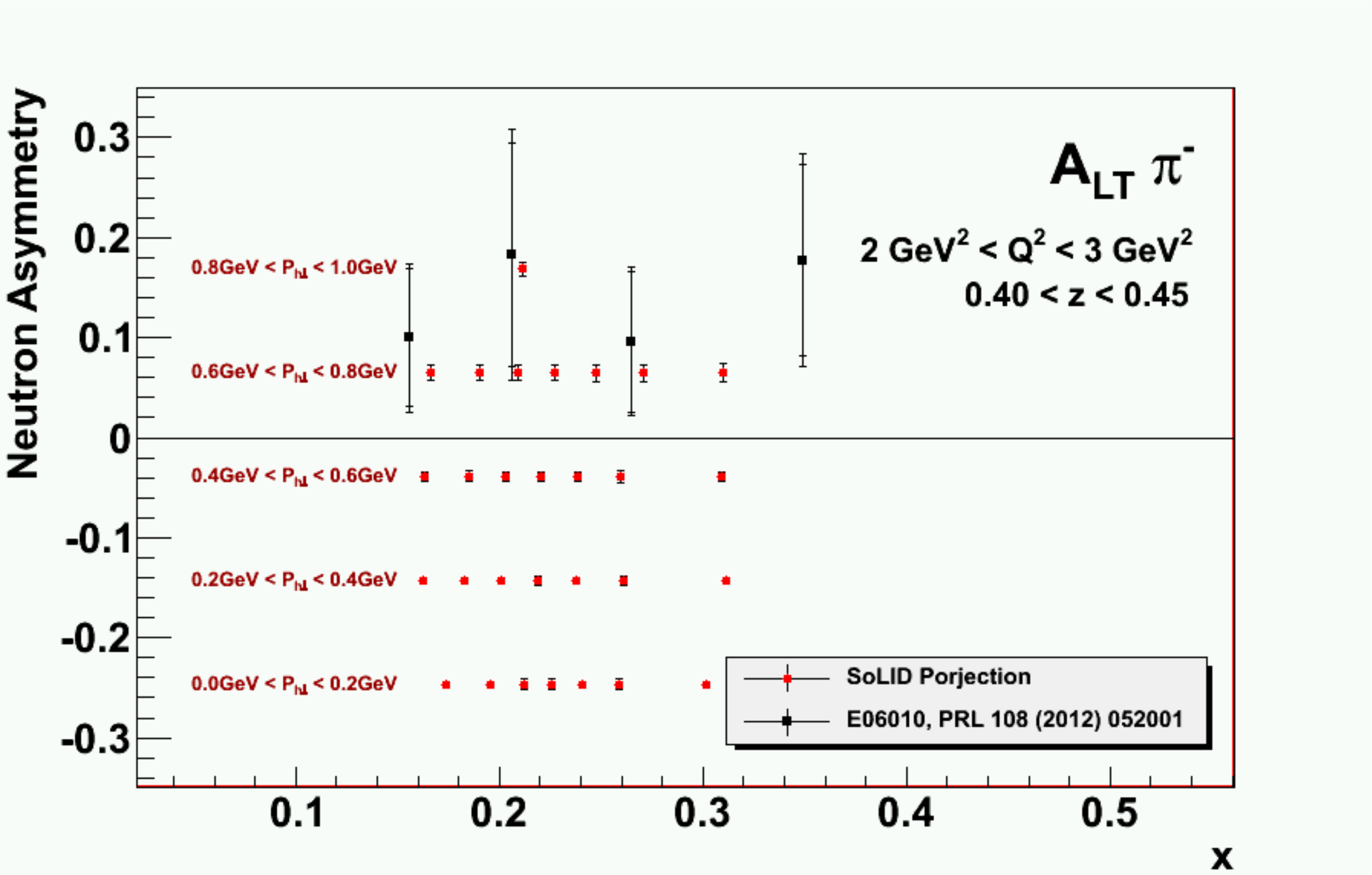
Power of SOLID (example)





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^-

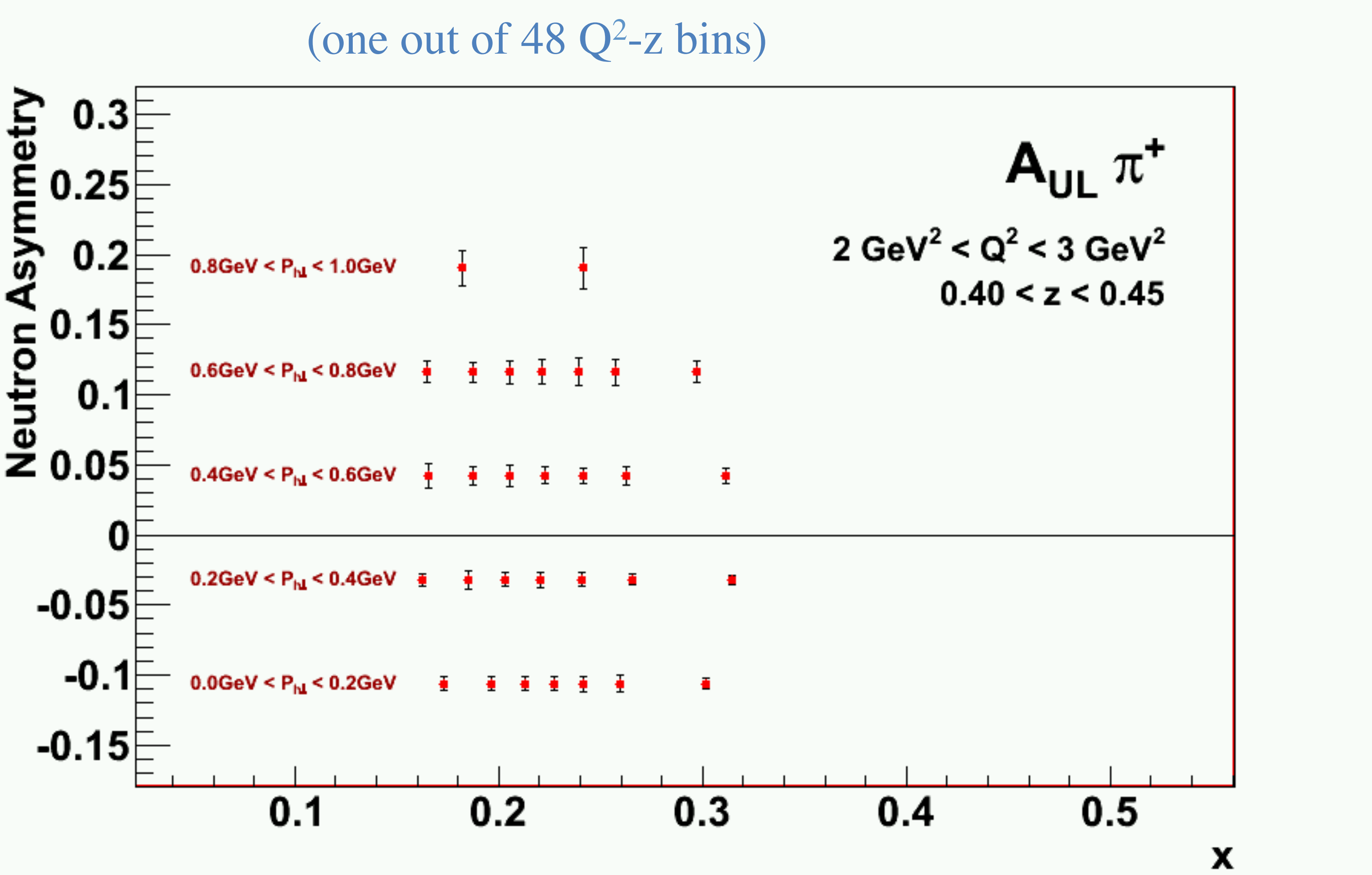


E12-11-007 spokespersons: J.P. Chen, J. Huang, Yi Qiang, W.B. Yan (USTC)
E06010 Results, J. Huang et al., PRL108, 052001 (2012)

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

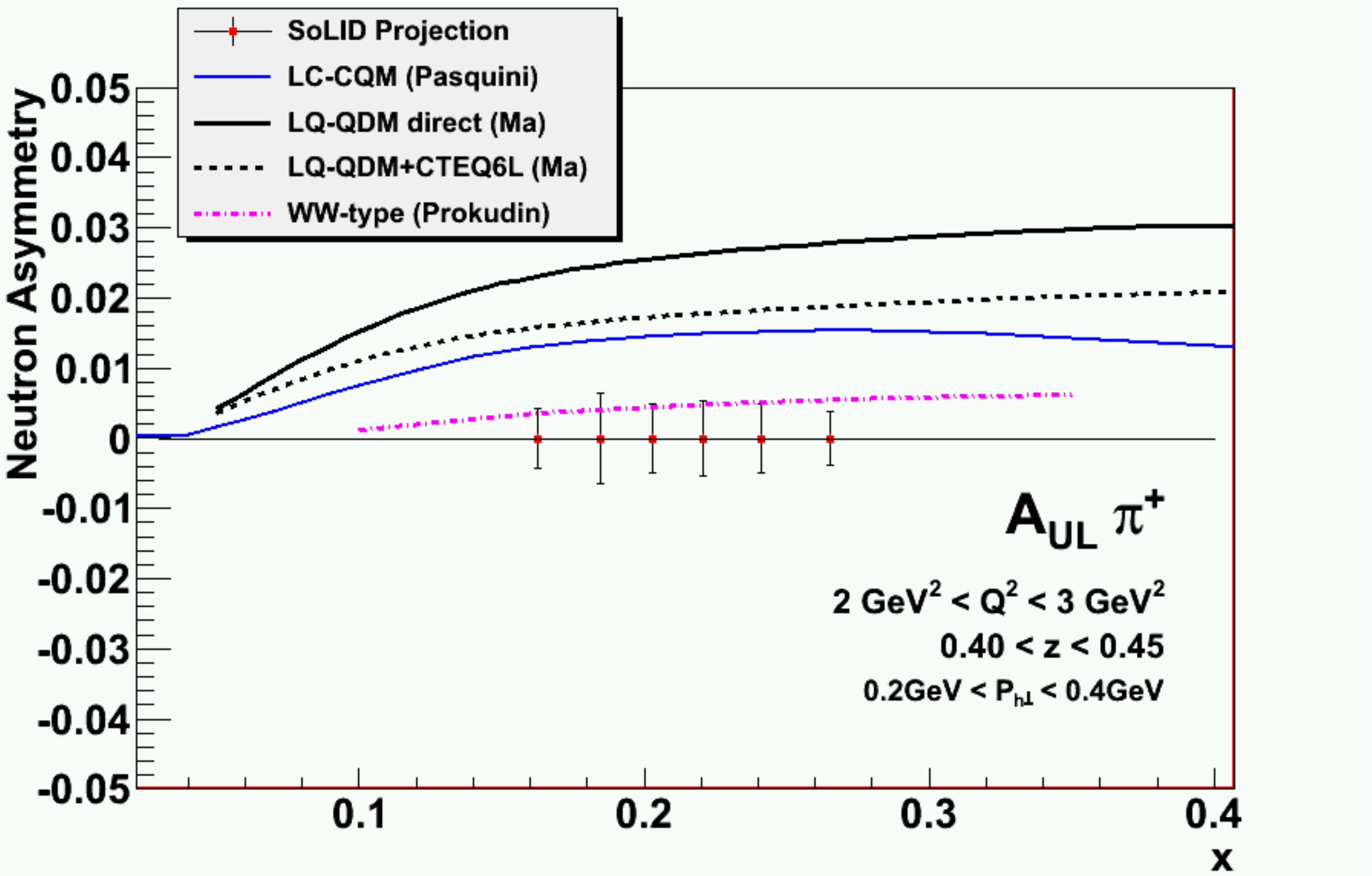
- Projection of a single Q^2-z bin for π^+

(one out of 48 Q^2-z bins)



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

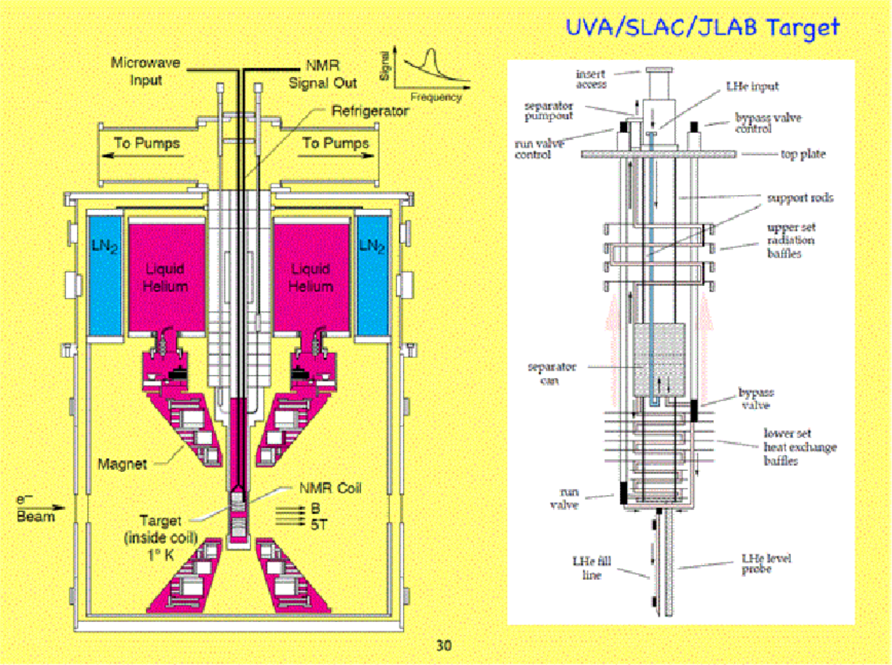
- Projection of a single Q^2-z-PT bin for π^+ (no existing measurement) And compared to model predictions for SoLID kinematics



Experiment E12-11-108:

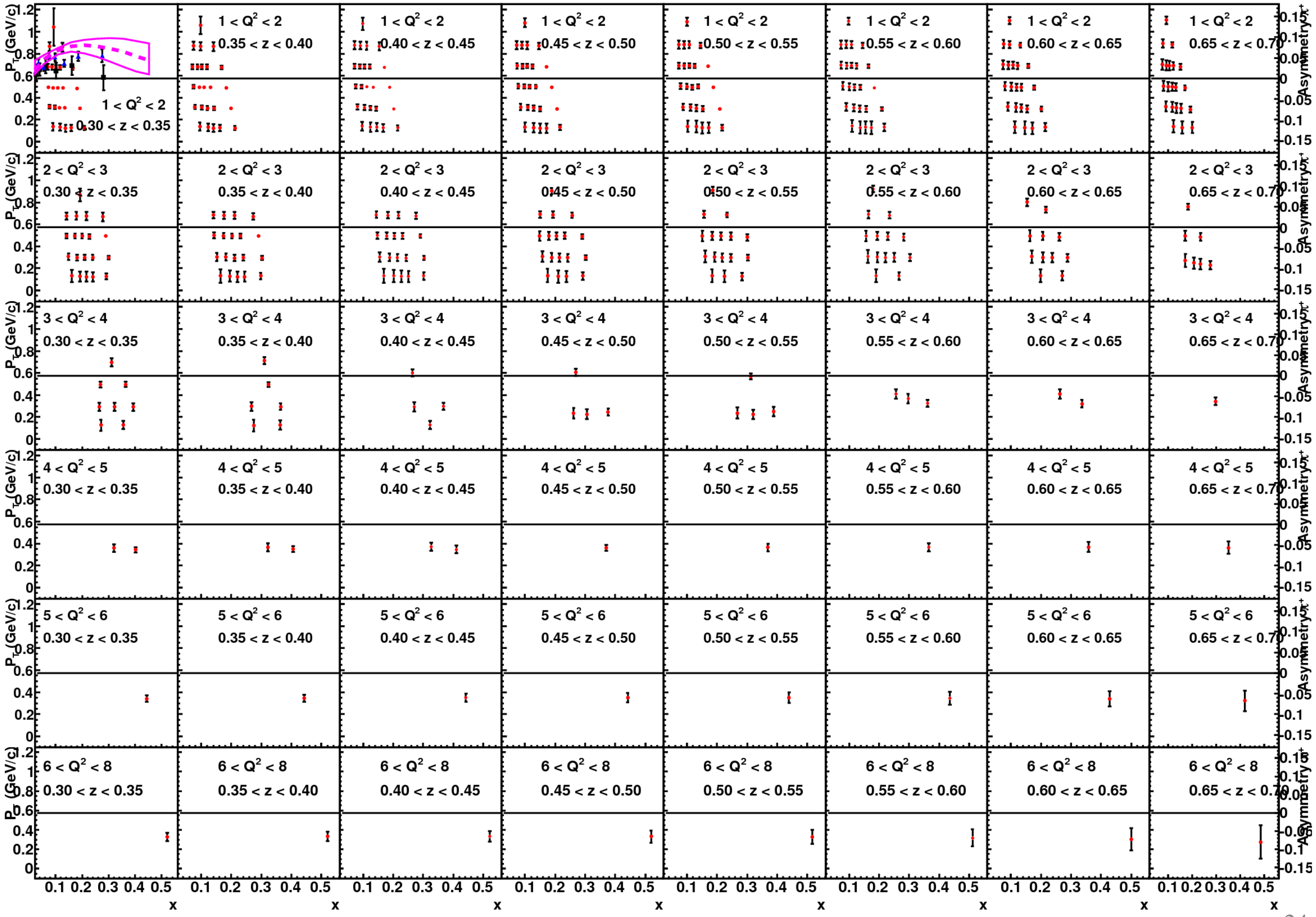
Target Single Spin Asymmetry in SIDIS *(e, eπ^±)* Reaction on a Transversely Polarized Proton Target and SoLID

- 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.)

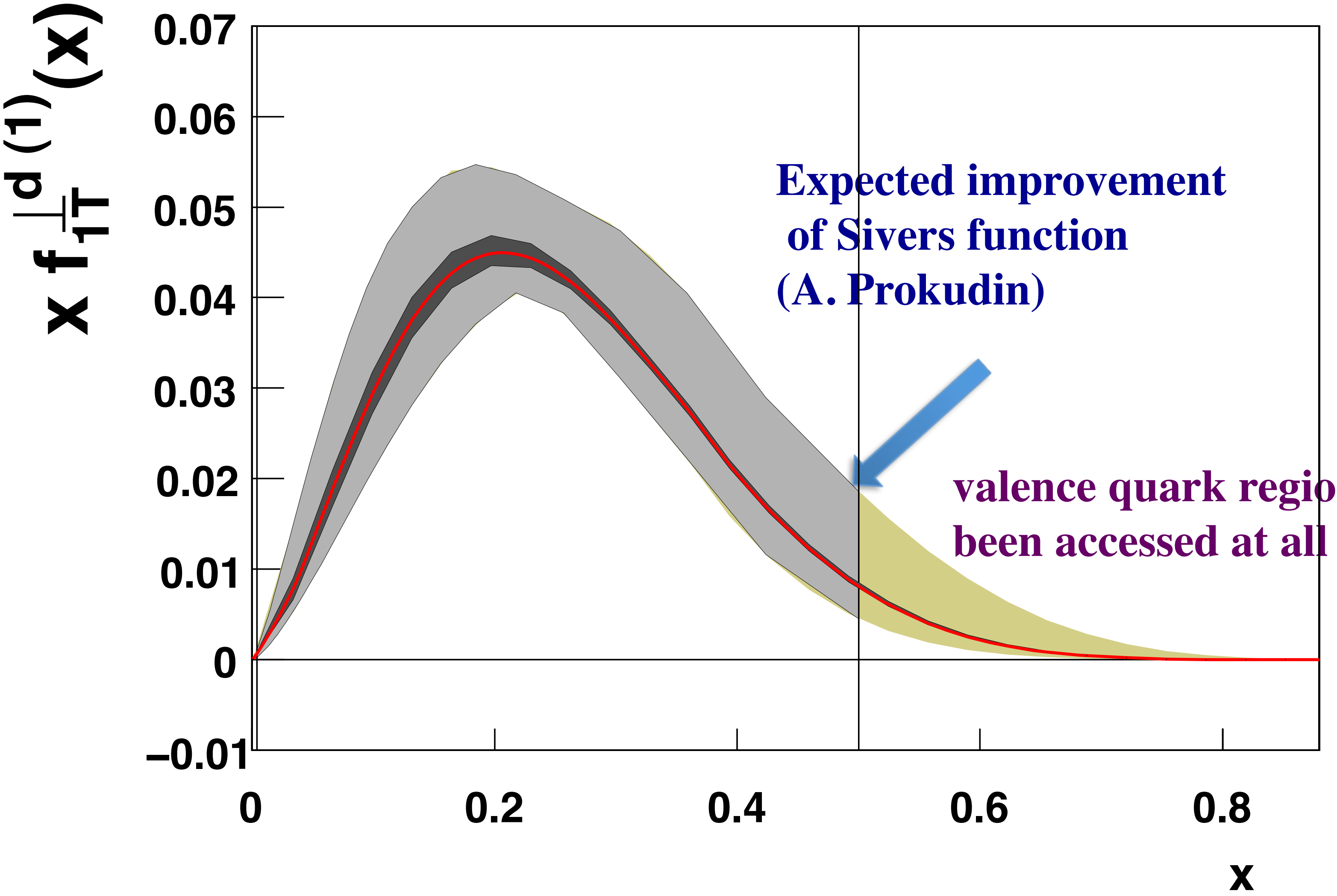


Spokespersons: K. Allada (Jlab), J. P. Chen (Jlab), Haiyan Gao (Contact), Xiaomei Li (CIAE), Z-E. Meziani (Temple)

Proton 4-D Projection



Projected measurements in 1-D (x)



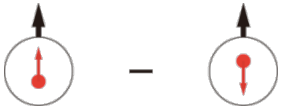
Expected improvement of Sivers function (A. Prokudin)

valence quark region has not been accessed at all so far

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.

Transversity

h_{1T} =



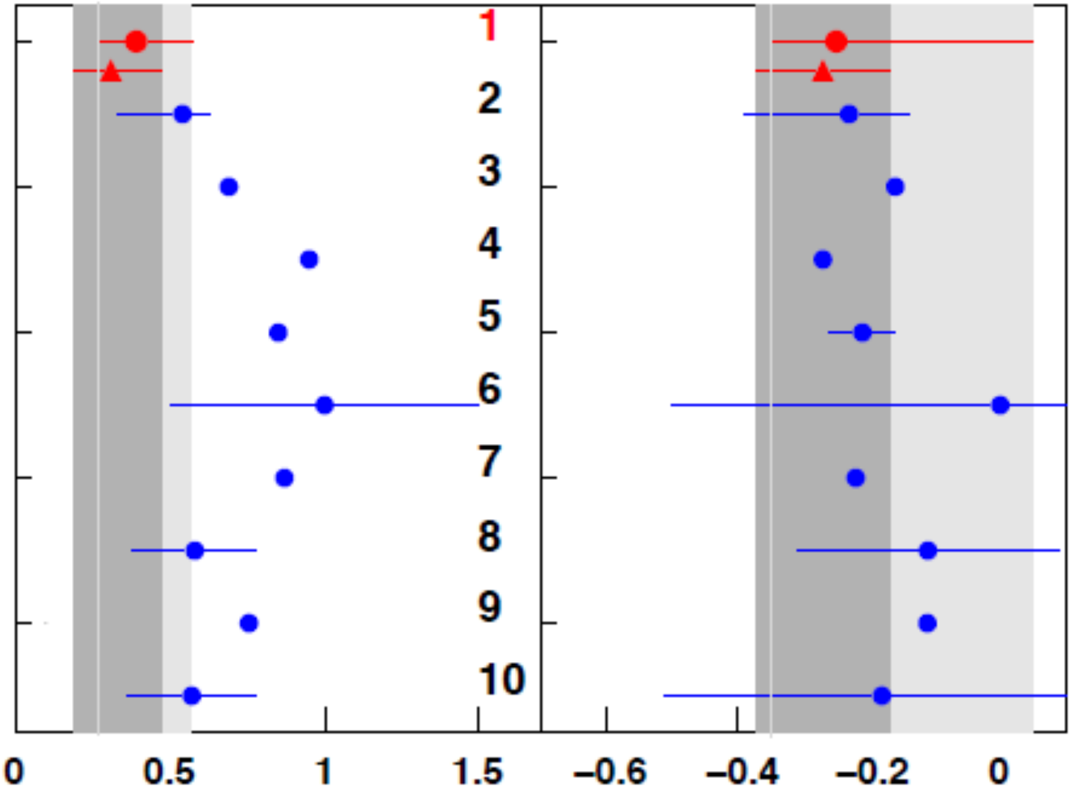
- Lowest moment gives tensor charge

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

  - Fundamental property, benchmark test of Lattice QCD

● $\delta u = 0.39^{+0.18}_{-0.12}$ ● $\delta d = -0.25^{+0.30}_{-0.10}$

▲ $\delta u = 0.31^{+0.16}_{-0.12}$ ▲ $\delta d = -0.27^{+0.10}_{-0.10}$

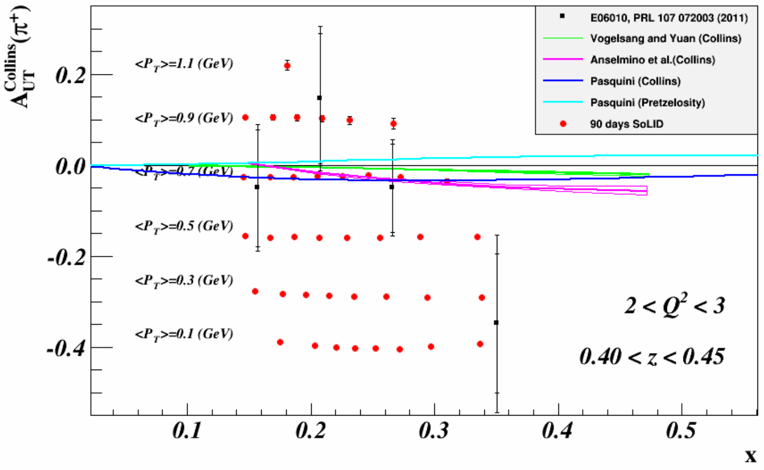


arXiv:1303.3822

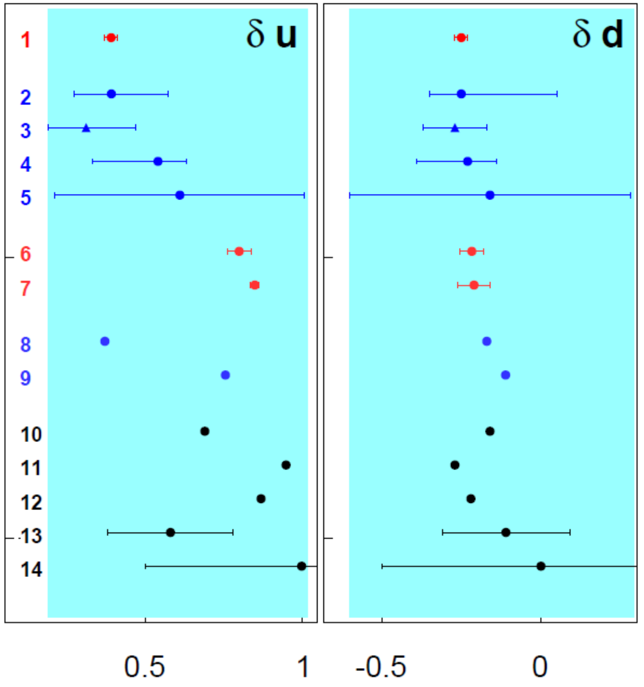
Transversity and Tensor Charge

- Collins Asymmetries ~ Transversity (x) Collin Function
- **Transversity**: chiral-odd, not couple to gluons, **valence behavior**, largely unknown
- **Tensor charge (0th moment of transversity): fundamental property**
  Lattice QCD, Bound-State QCD (Dyson-Schwinger) , Light-cone Quark Models, …
- Global model fits to experiments (SIDIS and e+e-)
- SoLID with **trans polarized n & p** → determination of tensor charges for **d & u**

Collins Asymmetries



Tensor Charges



1 - 12 GeV SoLID (projection)

Extractions from experiments:

2,3 - Anselmino et al, Phys.Rev. D87 (201

4 - Anselmino et al, Nucl. Phys. Proc. Su

5 - Bacchetta, Courtoy, Radici, JHEP 130

Lattice QCD:

6 - Alexandrou et al, PoS(LATTICE 2014)

7 - Gockeler et al, Phys. Lett. B (2005)

DSE:

8 - Pitschmann et al, (2014)

9 - Hecht, Roberts and Schmidt, Phys. Re

Models:

10 - Cloet, Bentz and Thomas, Phys. Lett

11 - Wakamatsu, Phys. Lett. B (2007)

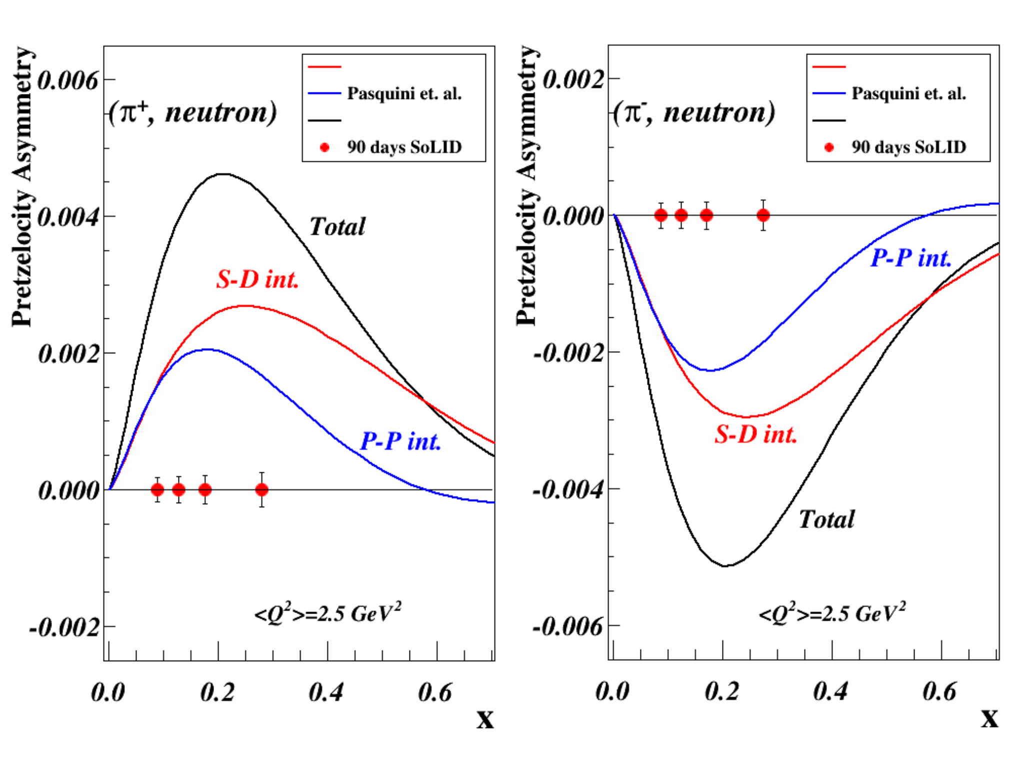
12 - Pasquini et al, Phys. Rev. D (2007)

13 - Gamberg and Goldstein, Phys. Rev.

14 - He and Ji, Phys. Rev. D (1995)

TMDs: 3-d Structure, Quark Orbital Motion

- 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**



Summary

- **Frontiers in nucleon structure go beyond collinear, 1-D picture**
  - **TMDs**
    - **Three-dimensional description of nucleon in momentum space**
    - **Quantitative information about orbital motion (orbital angular momentum)**
    - **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**

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