Semi-Inclusive DIS and Transverse-Momentum Dependent Parton Distribution Functions

SoLID Collaboration
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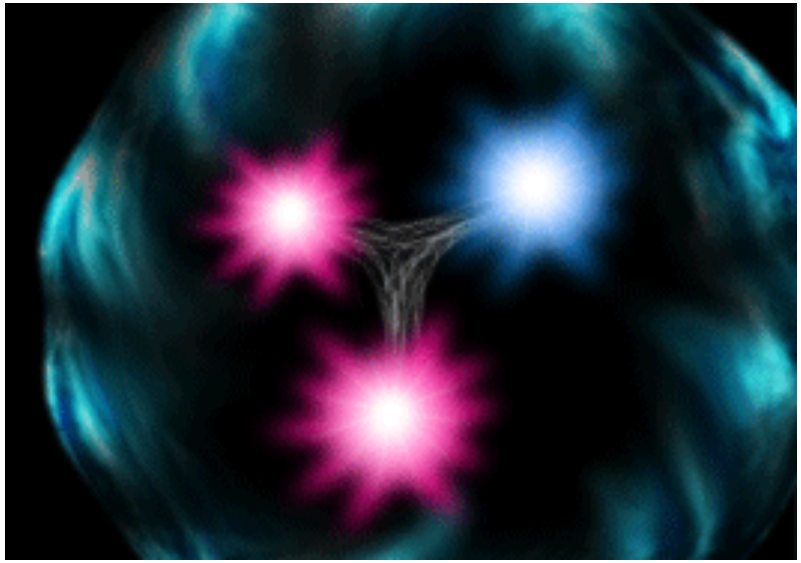
QCD ⟷ *Nucleon Structure*

- **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:**

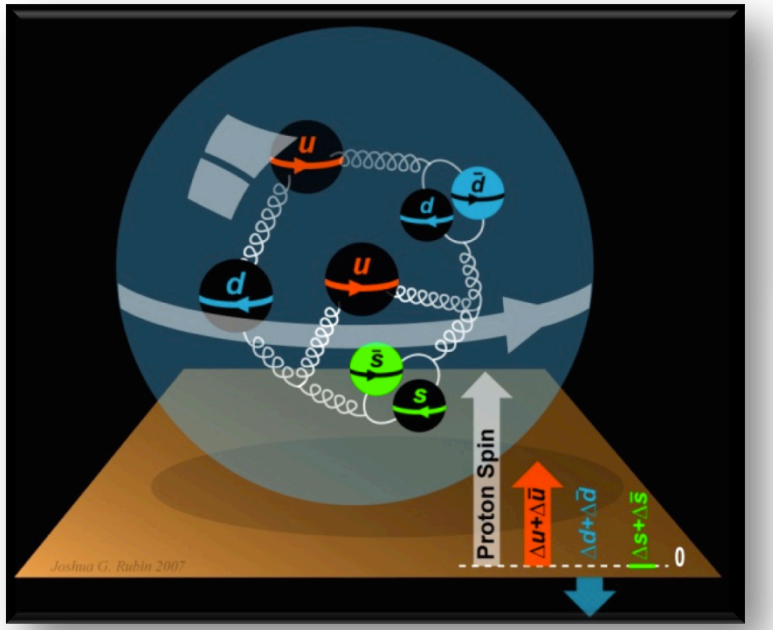
    pQCD, OPE, Lattice QCD, ChPT



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

Spin as an important knob

The Incomplete Nucleon: Spin Puzzle

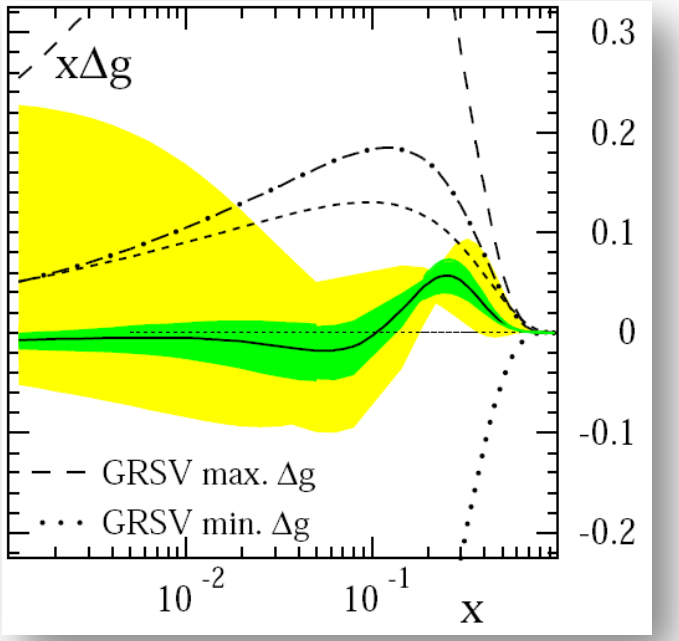


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + J_q(\mu)$$

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

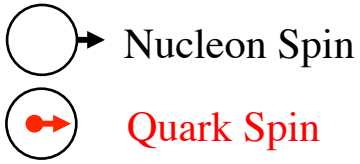
Orbital angular momentum of quarks and gluons is important

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



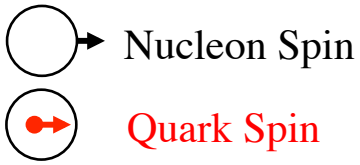
D. de Florian et al., PRL 101 (2008) 072001

Leading-Twist TMD PDFs



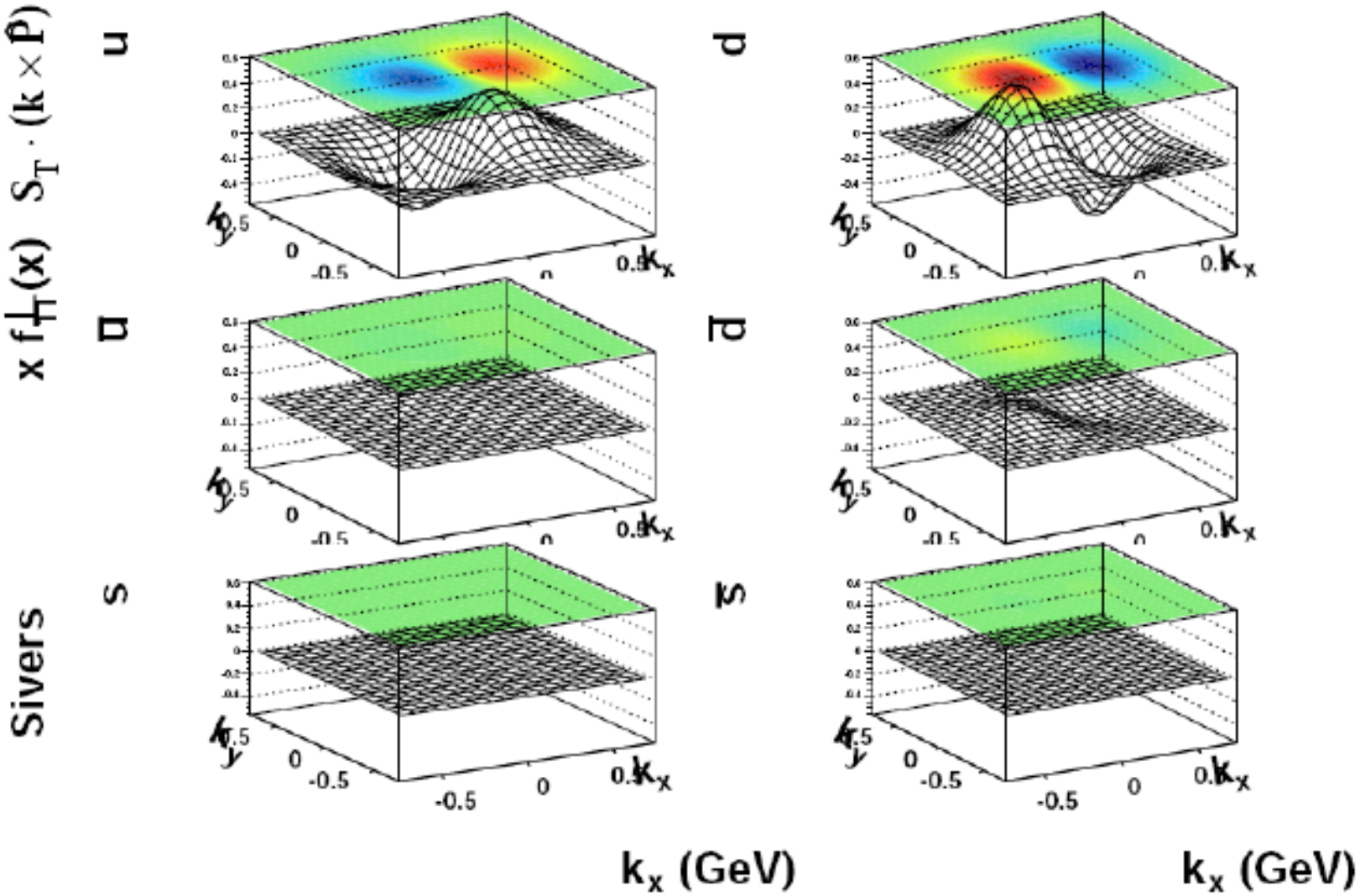
Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1		$h_1^\perp$ **Boer-Mulders**
L		g_1 **Helicity**	$h_{1L}^\perp$ **Long-Transversity**
T	$f_{1T}^\perp$ **Sivers**	g_{1T} **Trans-Helicity**	h_1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

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

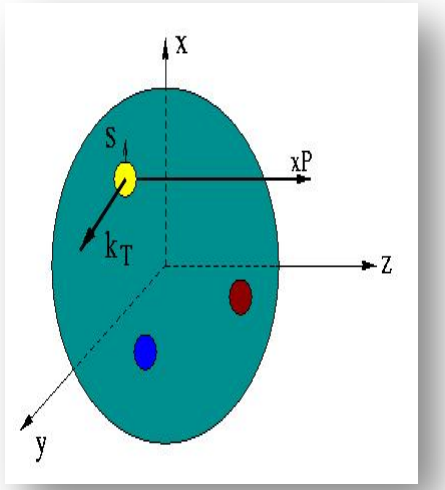
- **TMD PDFs: nucleon structure in 3-D momentum space!** $f_{1T}^{\perp}(x,Q^2,k_T)$ **Sivers as example @ fixed x, Q^2**

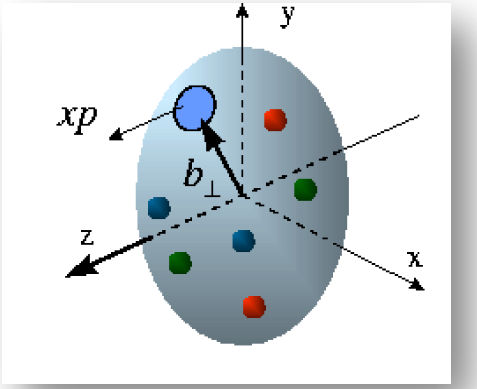


Unified View of Nucleon Structure

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

6D Dist.





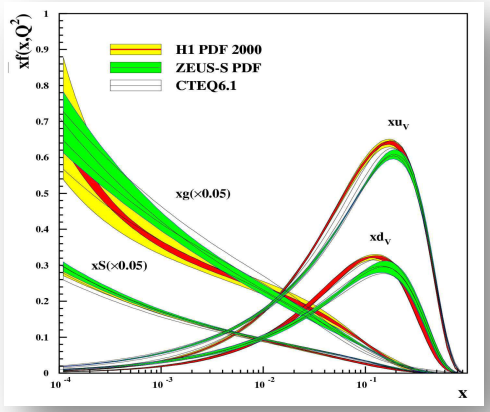
$d^3\boldsymbol{r}$ $d^2k_T\,dr_z$

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

GPDs/IPDs

3D imaging

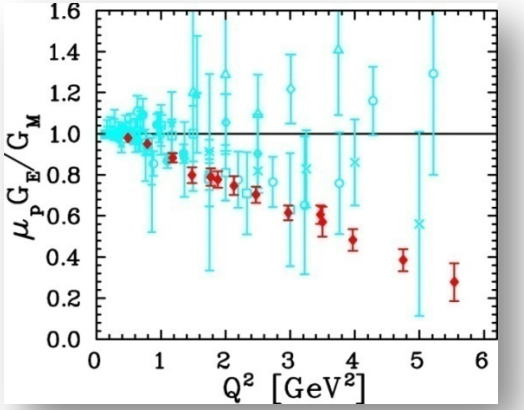
d^2k_T d^2r_T dx & Fourier Transformation



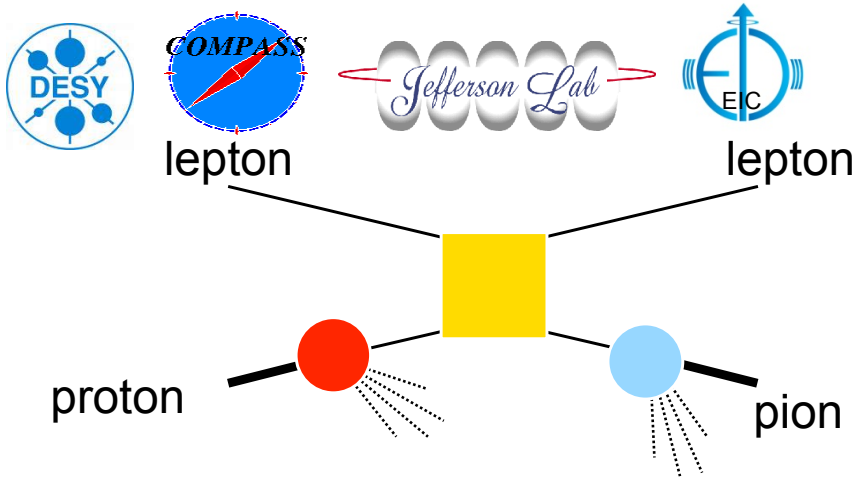
PDFs $f_1^u(x)$, .. $h_1^u(x)$

1D

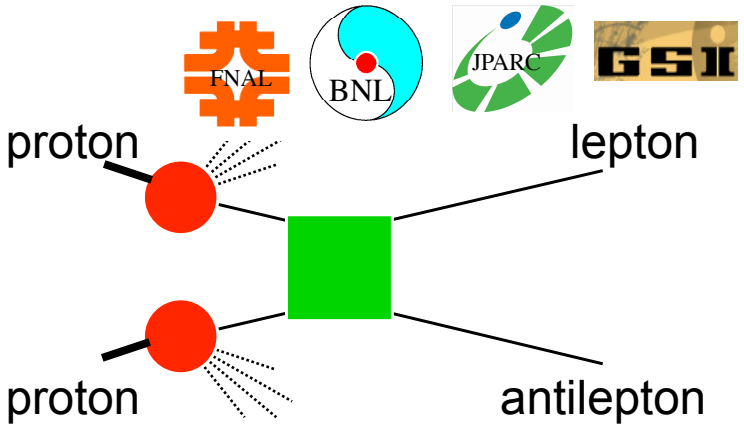
Form Factors $G_E(Q^2)$, $G_M(Q^2)$



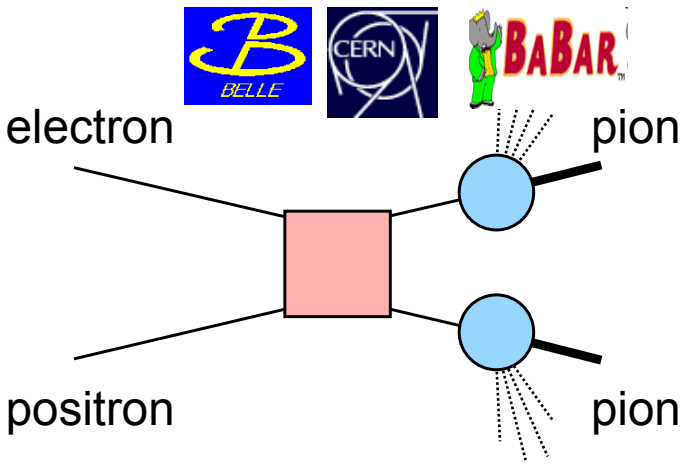
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

Partonic scattering amplitude

Fragmentation amplitude

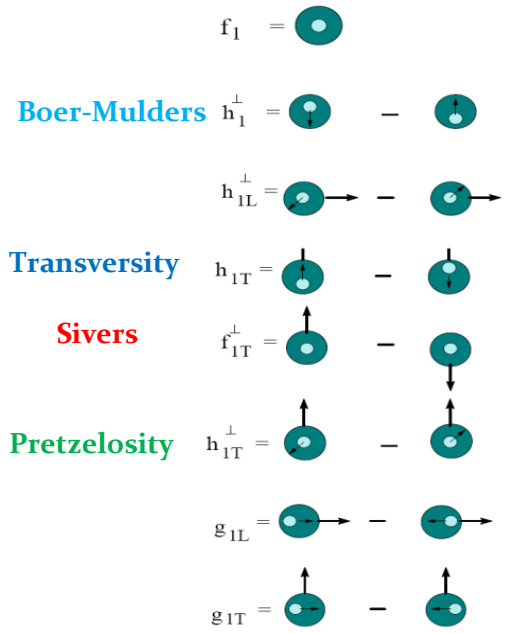
Distribution amplitude

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

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

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

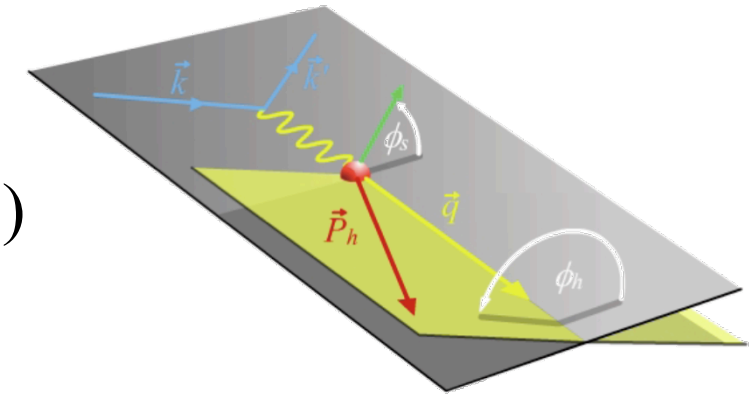
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Example: Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



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

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

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

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

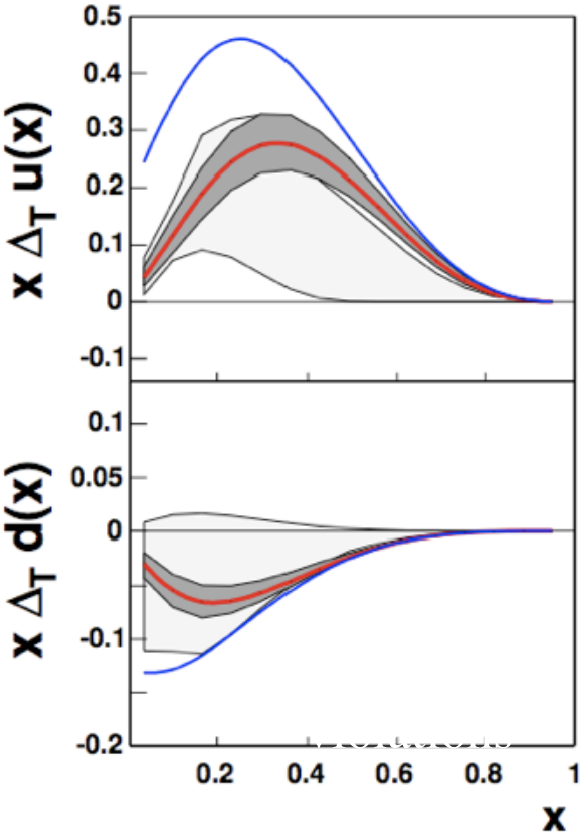
SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

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
  - Fundamental property, benchmark test of Lattice QCD



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

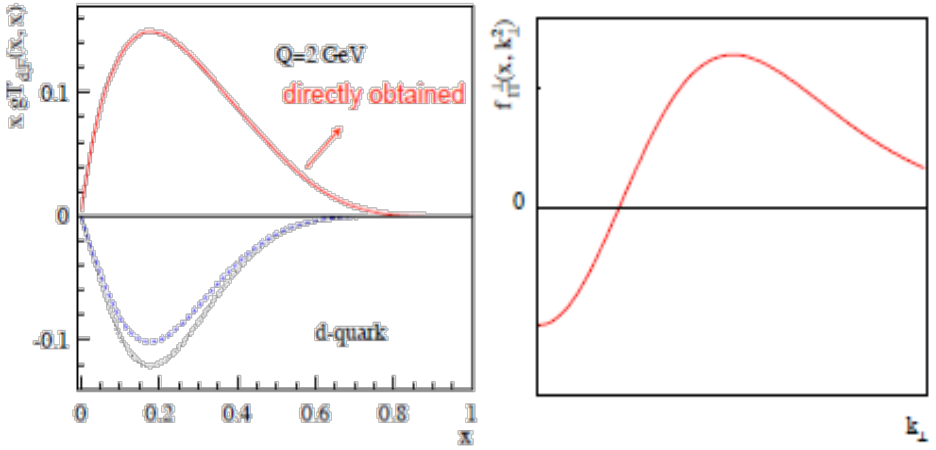
$\Delta_T = h_{1T}$

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
- Recent developments in the evolution of Sivers function



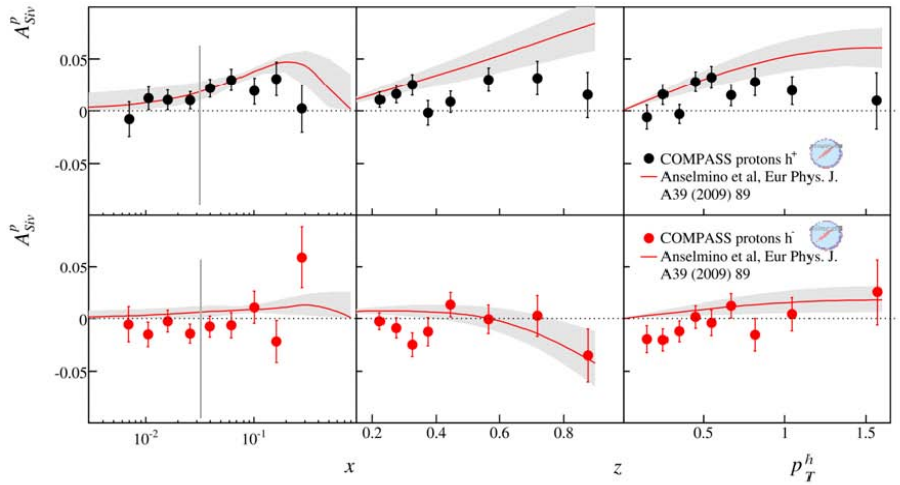
Zhongbo Kang, RBRC/BNL

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

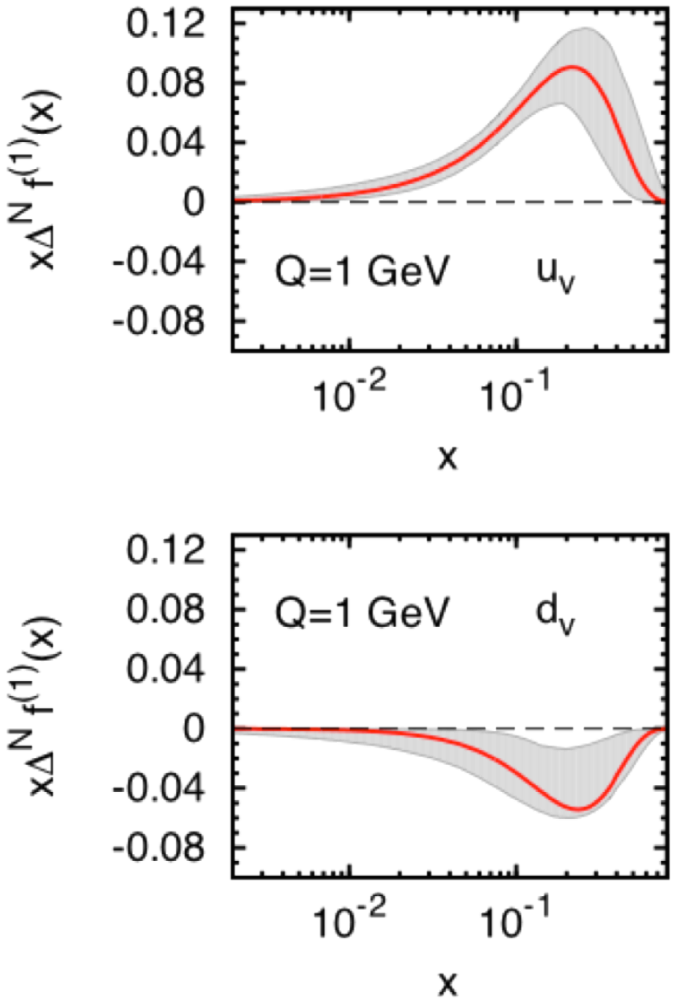
Sivers asymmetry - proton

comparison with theory

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



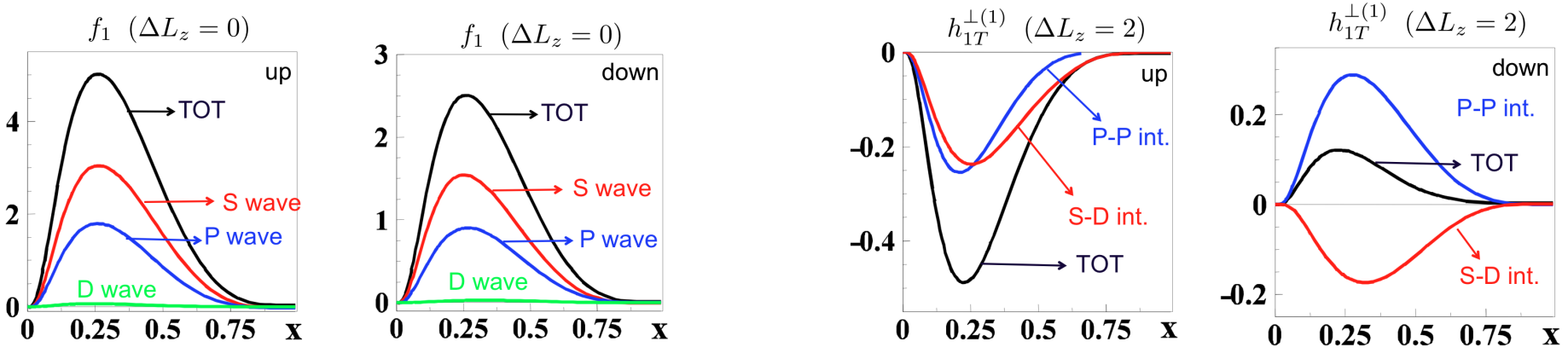
SIVERS FUNCTION - TMD



Older fit shows possibly discrepancy?

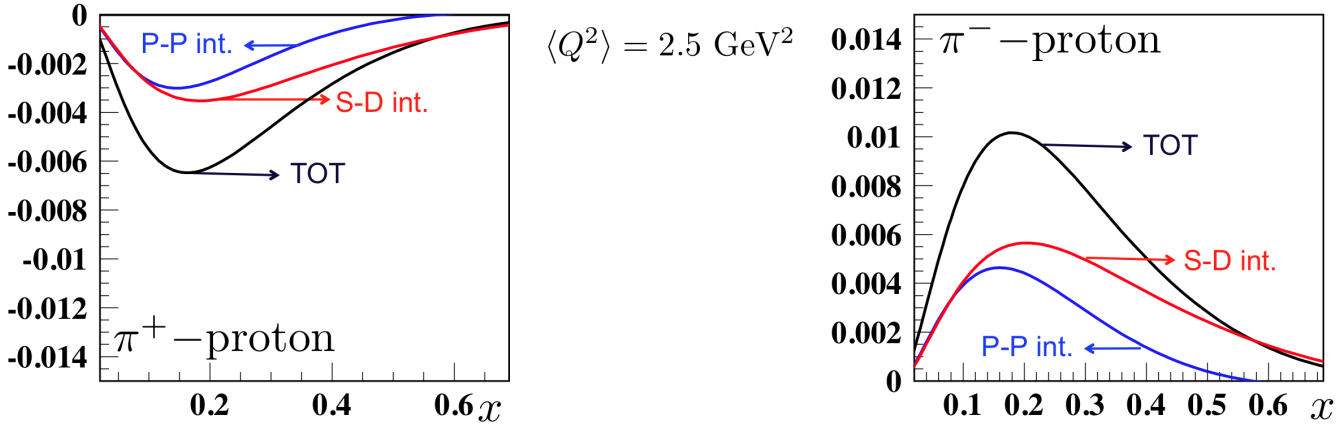
Latest extraction based on HERMES p, COMPASS d and p data by M. Anselmino et al., arXiv:1204.1239 taking into account TMD evolution show consistency between the HERMES and COMPASS data

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



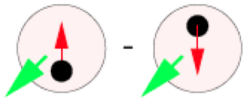
✦ Effects on SIDIS observables

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



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

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]

$\mathcal{L}_z$

chiral even and charge even

$\Delta L_z = 0$

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

chiral odd and charge odd

$|\Delta L_z| = 2$

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'

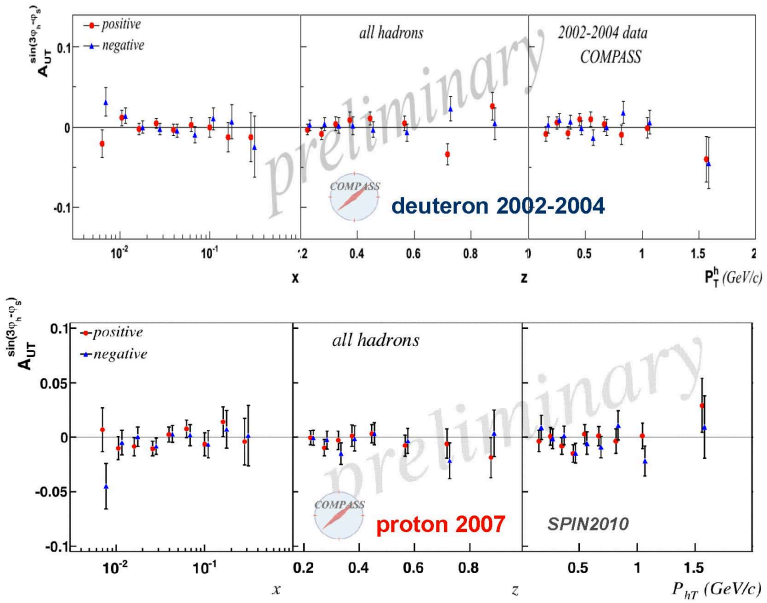
Pretzlosity:

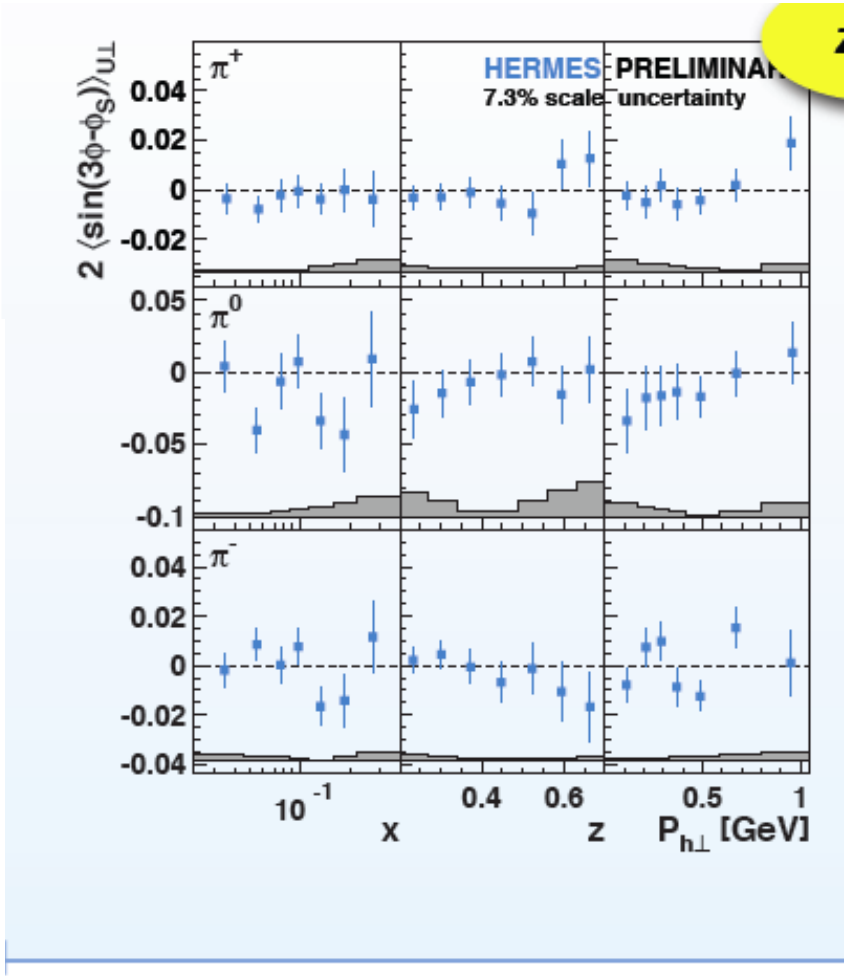
- Relativistic effect of quark
  PRD 78, 114024 (2008)
- (in models) direct measurement of OAM
  PRD 58, 096008 (1998) (more previous slide)
- Expect first non-zero Pretzelosity asymmetries

transversely polarised target

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

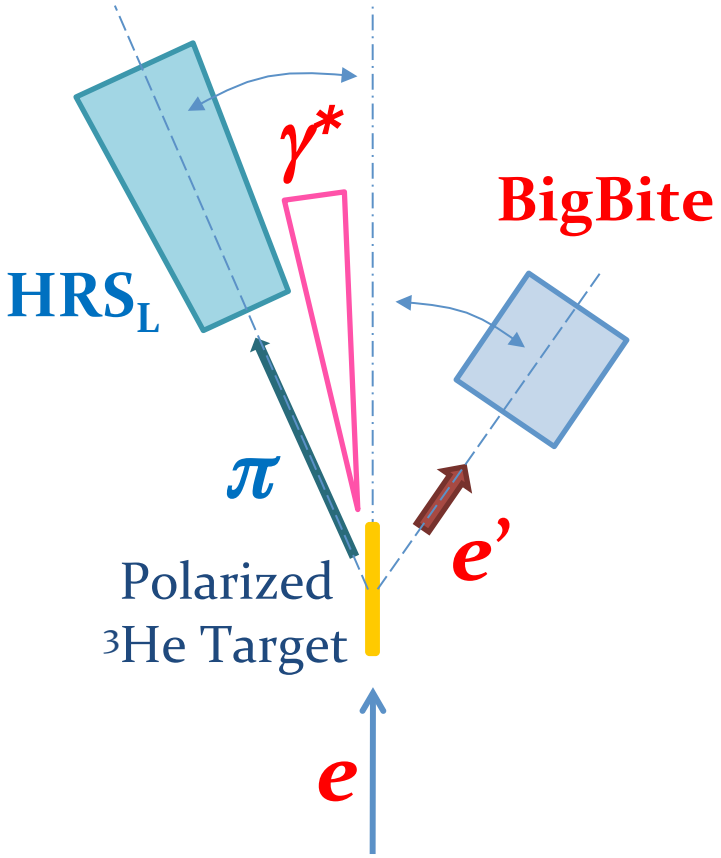
"pretzelosity" PDF
⊗ Collins FF





M. Diefenthaler, EINN 2009

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

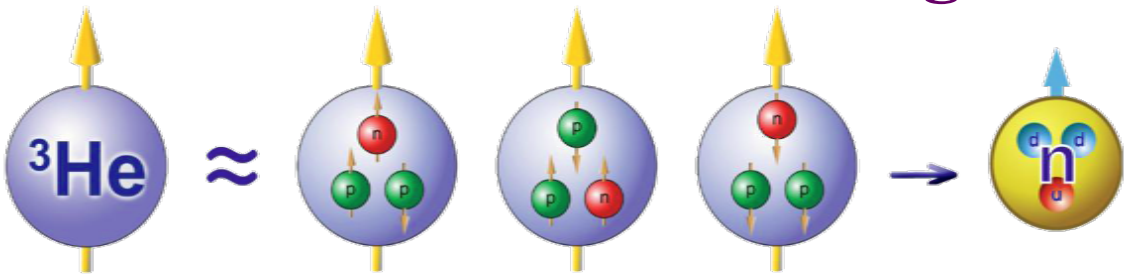


- ***First*** **neutron** data in SIDIS SSA&DSA
  - Similar Q^2 as HERMES experiment
- Disentangle Collins/Sivers effects

- 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)

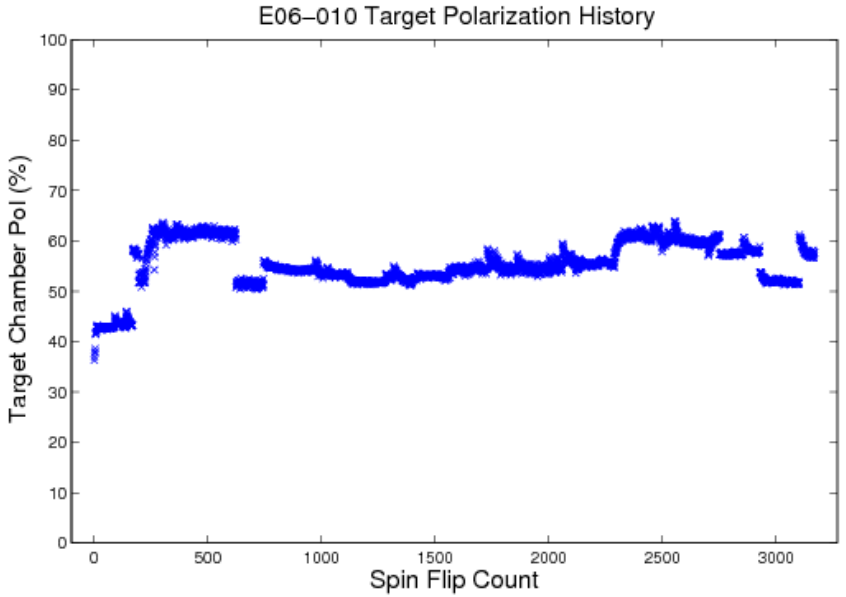
- BigBite at 30^o as **electron** arm:
  P_e = 0.6 ~ 2.5 GeV/c
- HRSL at 16^o as **hadron** arm:
  P_h = 2.35 GeV/c

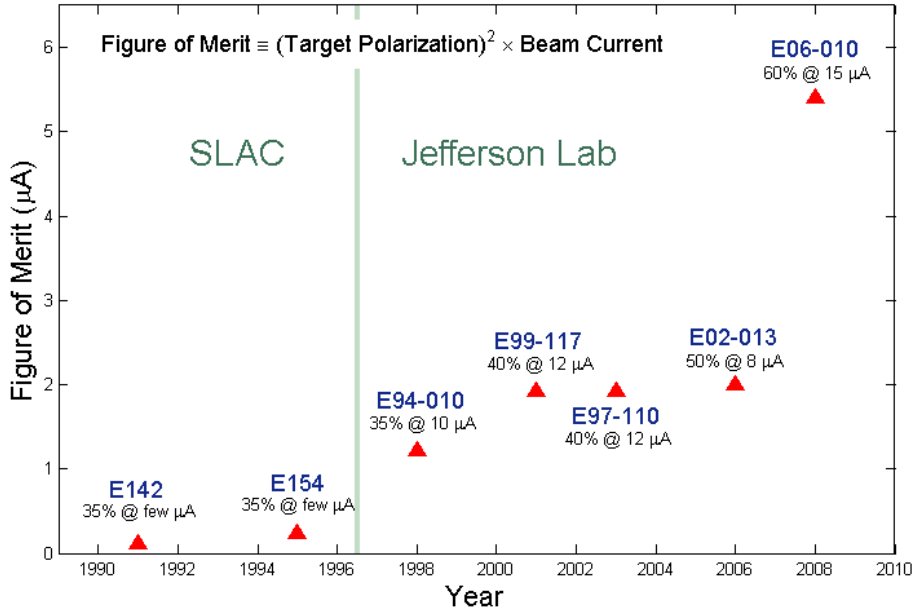
^{3}He Target



Effective Polarized Neutron Target!

- Polarized ^{3}He ran reliably throughout the experiment, and the following three experiments.
- Reached **55%-60%** polarization with 15 μA beam and 20 minute spin flip! **A NEW RECORD!**

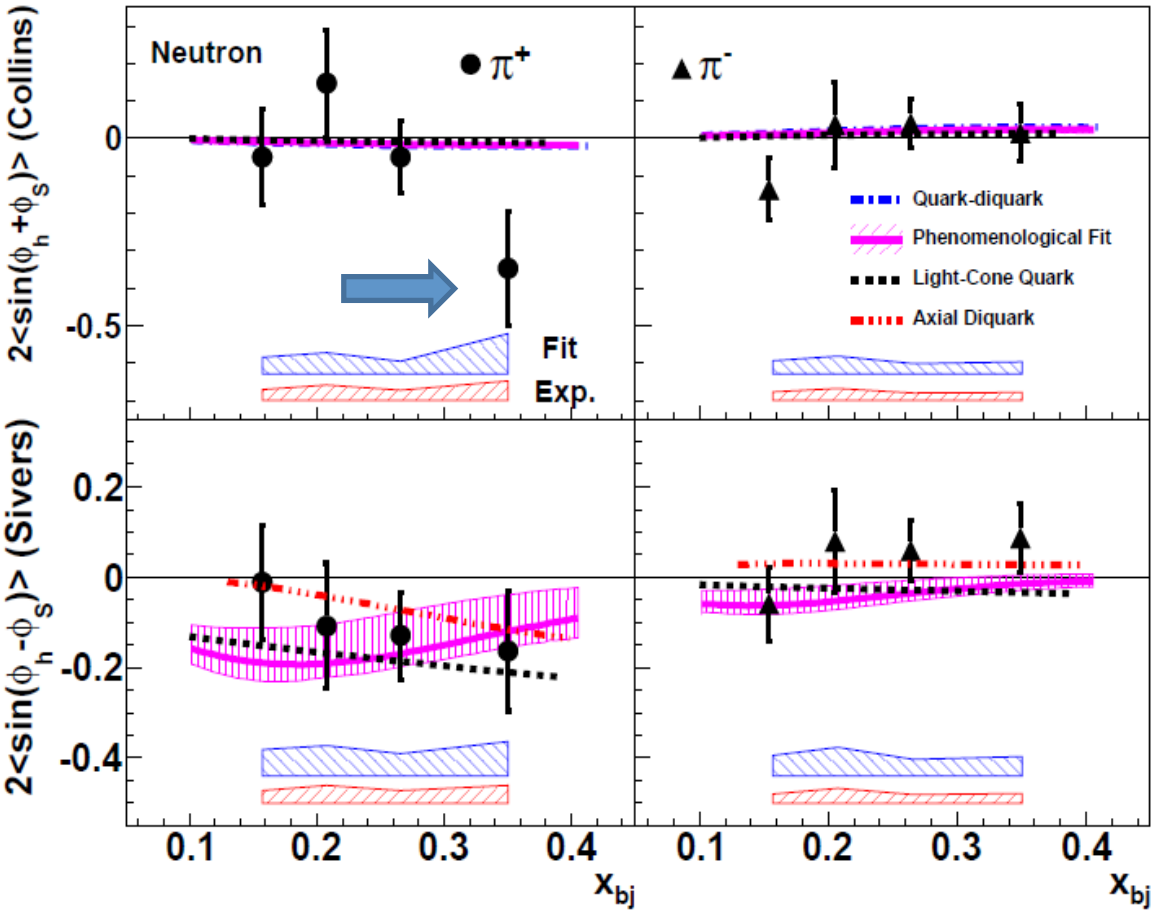




Results on Neutron

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

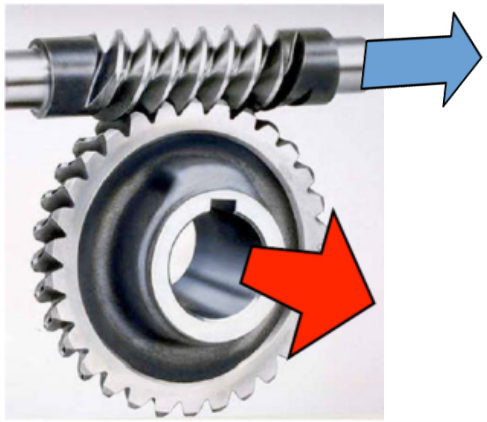
- Negative Sivers π^+ Asymmetry
  - Consistent with HERMES/COMPASS



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

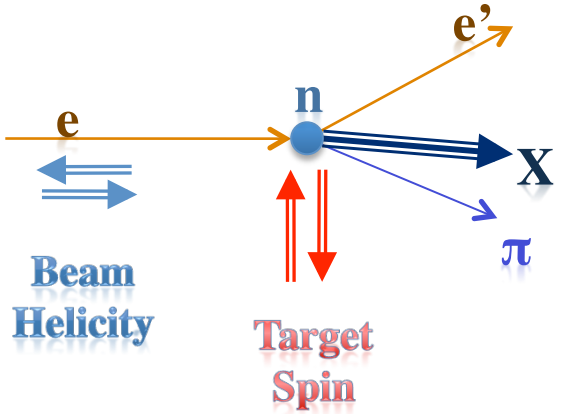
Model (fitting) uncertainties shown in blue band.
Experimental systematic uncertainties: red band
X. Qian *et al*, Phys. Rev. Lett. 107, 072003 (2011)

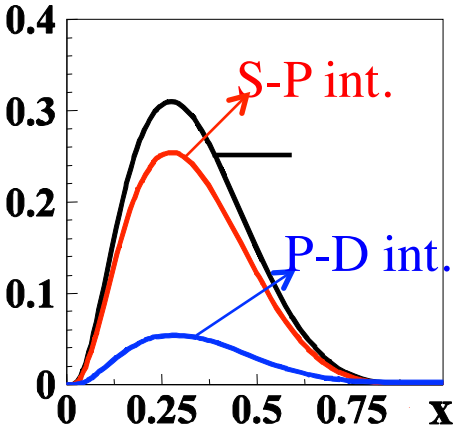
Double Spin Asymmetry: g_{1T}



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

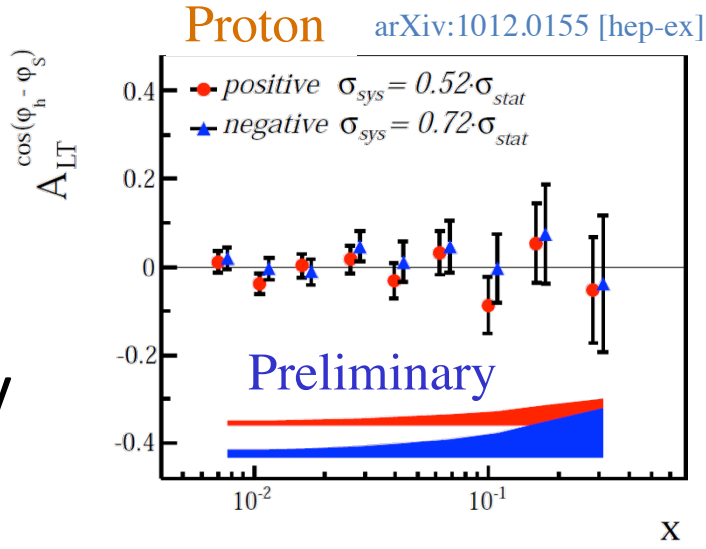


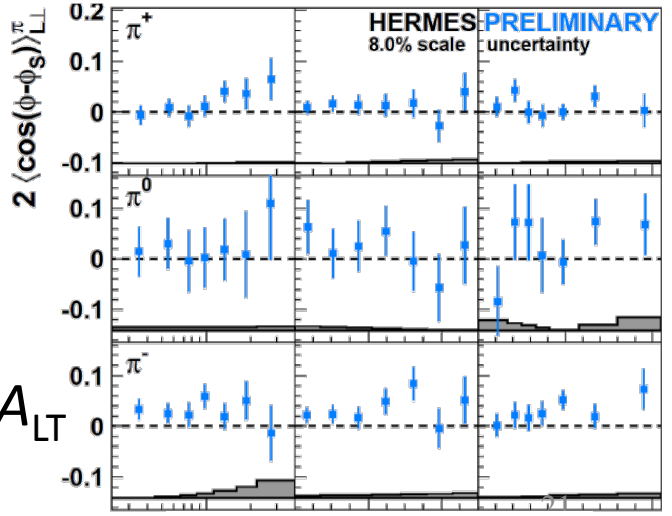


Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

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}



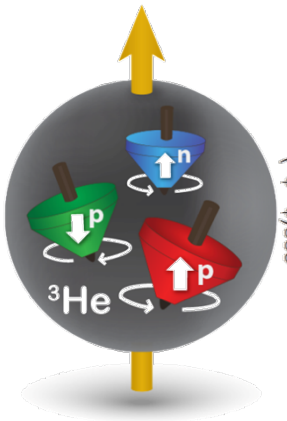


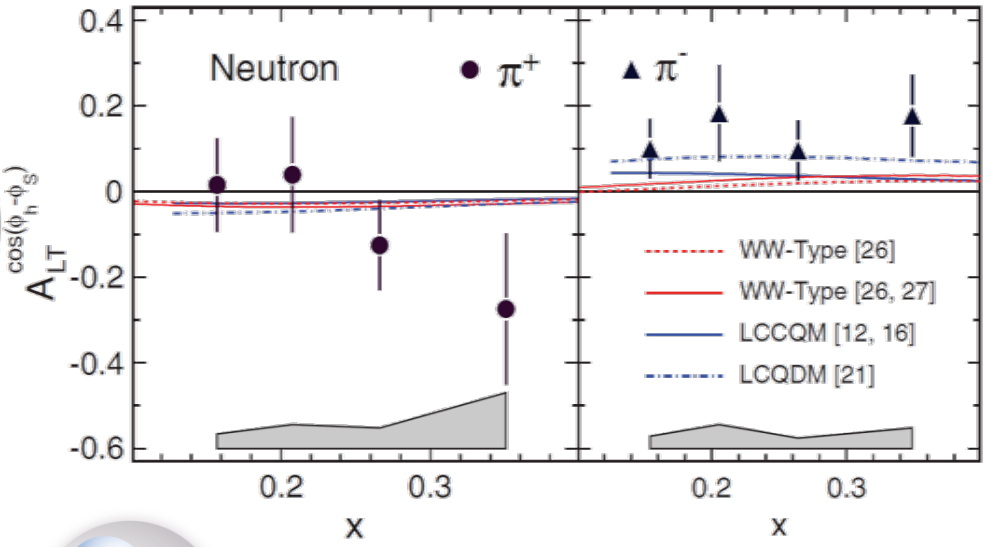
arXiv:1107.4227 [hep-ex]

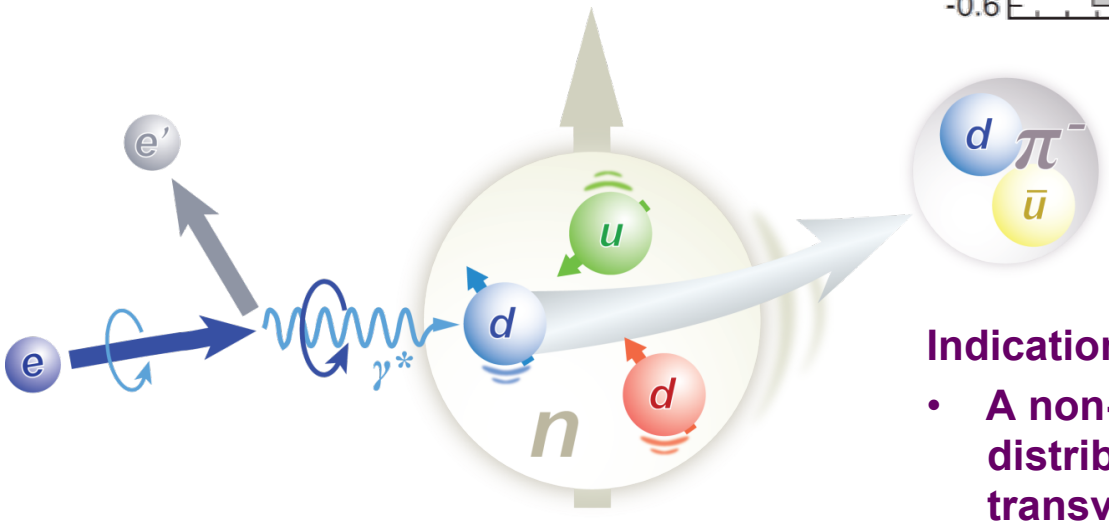
New Observable Reveals Interesting Behaviors of Quarks

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

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







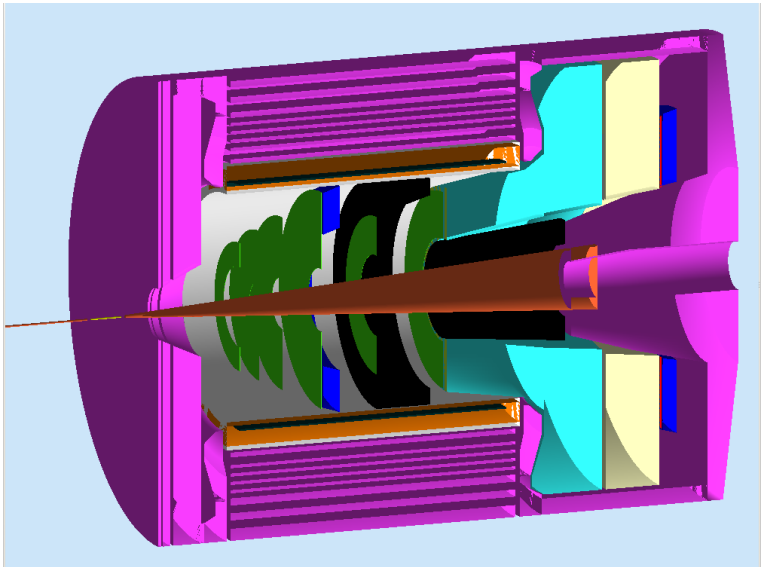
First measurement of A_{LT}
beam-target double-spin asymmetry

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

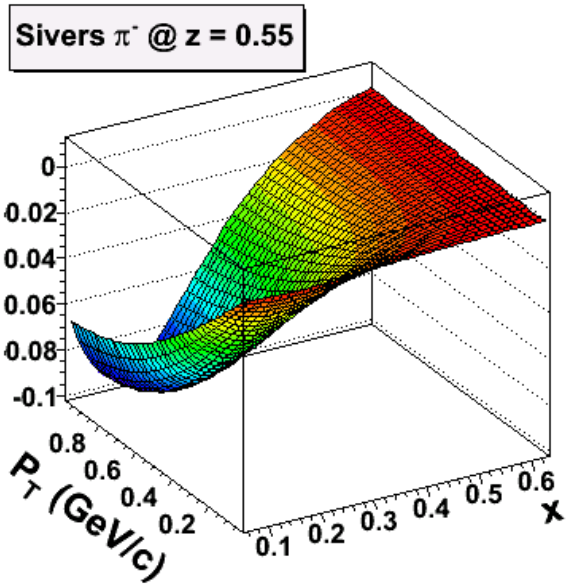


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

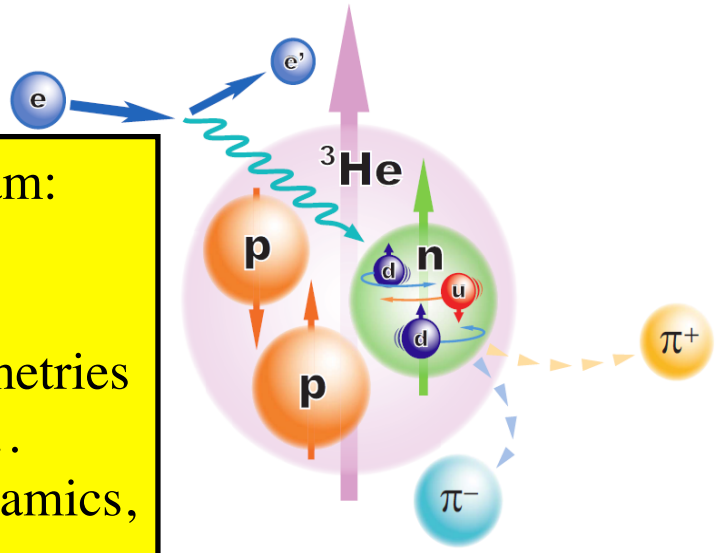
E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days, **rating A**

PR12-11-108: Single and Double Spin Asymmetries on Transverse Proton (conditionally approved)

International collaboration with 180 Collaborators from 8 countries



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



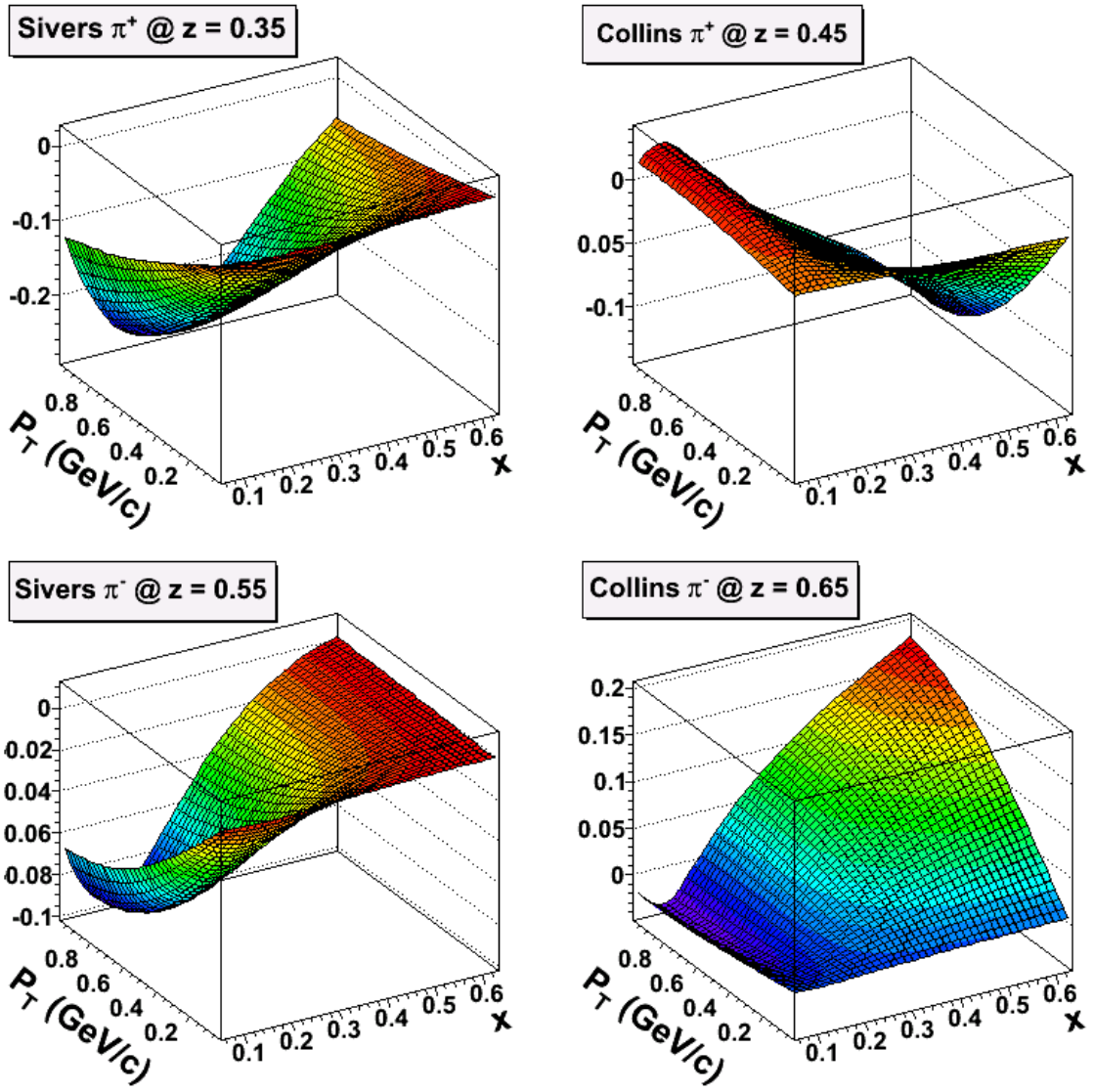
3-D neutron π^+/π^- Collins/Sivers Asymmetries at Q^2=2.0 GeV^2

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

Multi-dimensional nature.

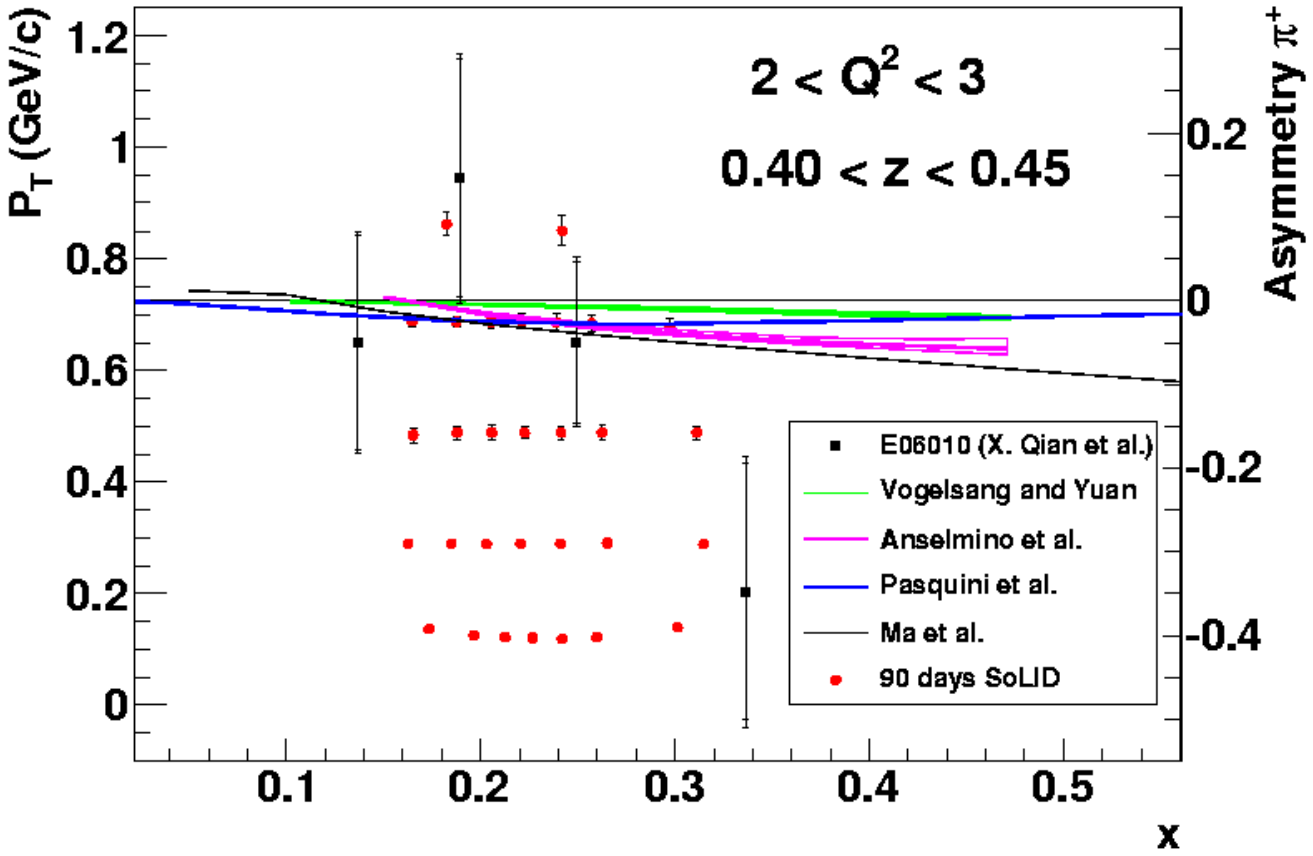
Targets: proton and neutron

Detect: positive pion and negative pions!



Torino 2008

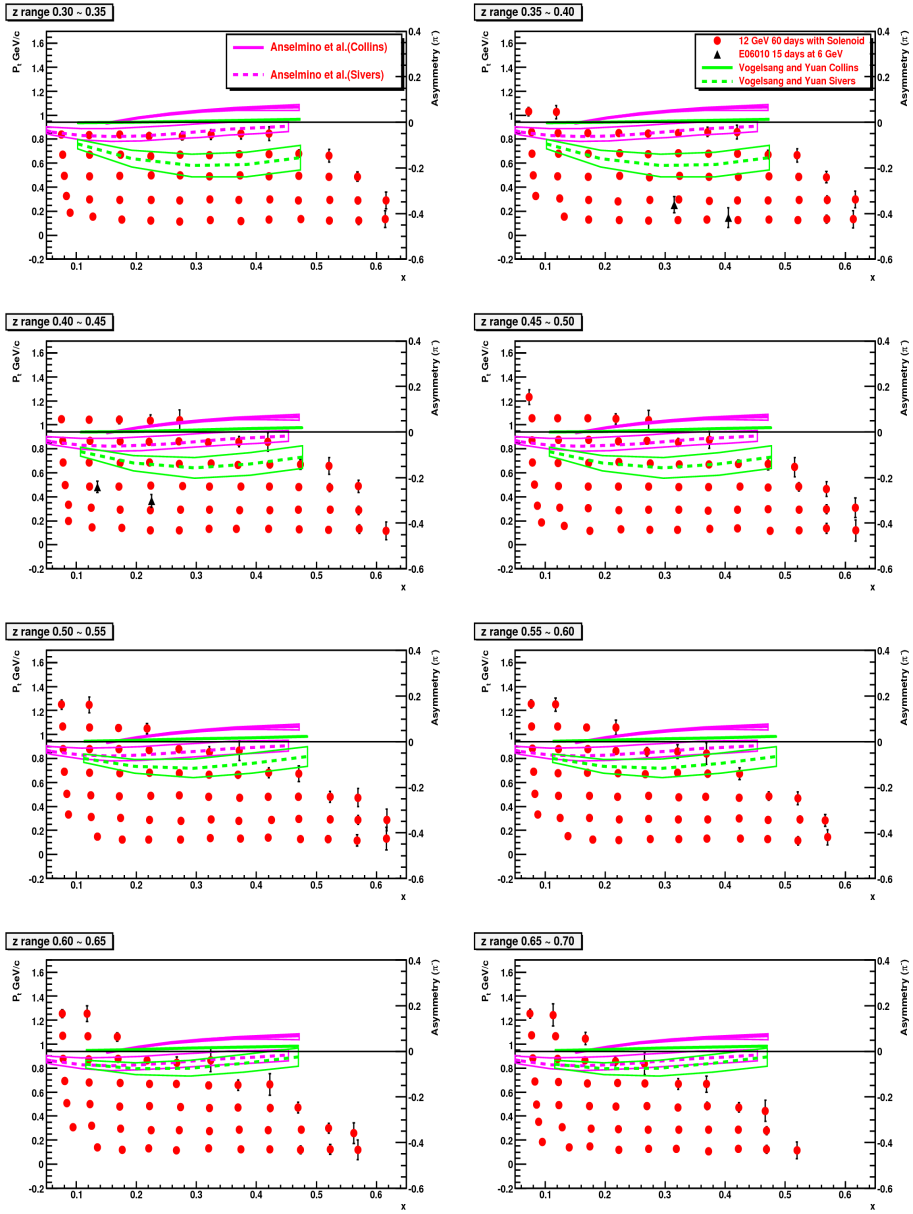
Projected Data (E12-10-006)

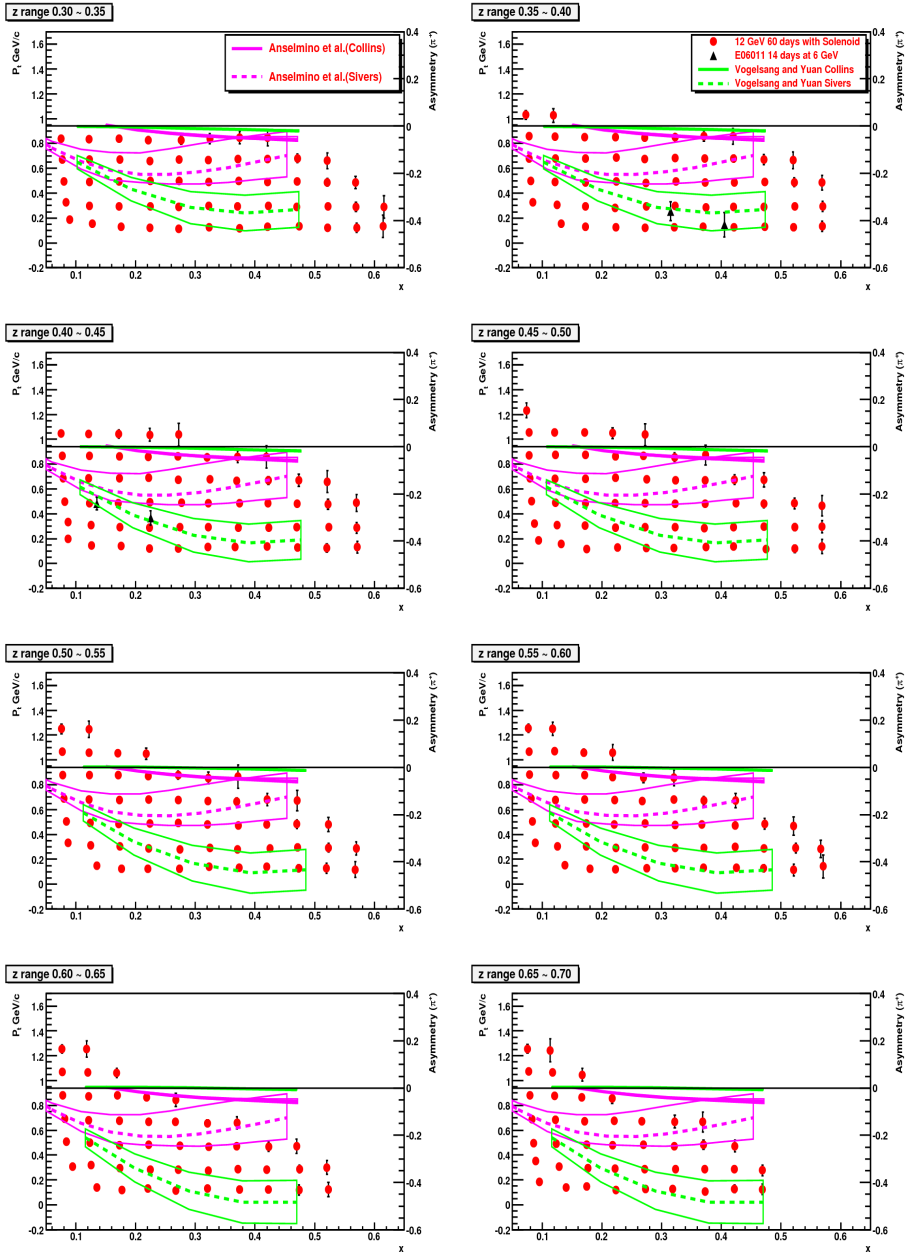


- Total 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.
- z ranges from 0.3 ~ 0.7, only one z and Q^2 bin of 11/8.8 GeV is shown here. π^+ projections are shown, similar to the π^- .

X. Qian et al in PRL 107, 072003

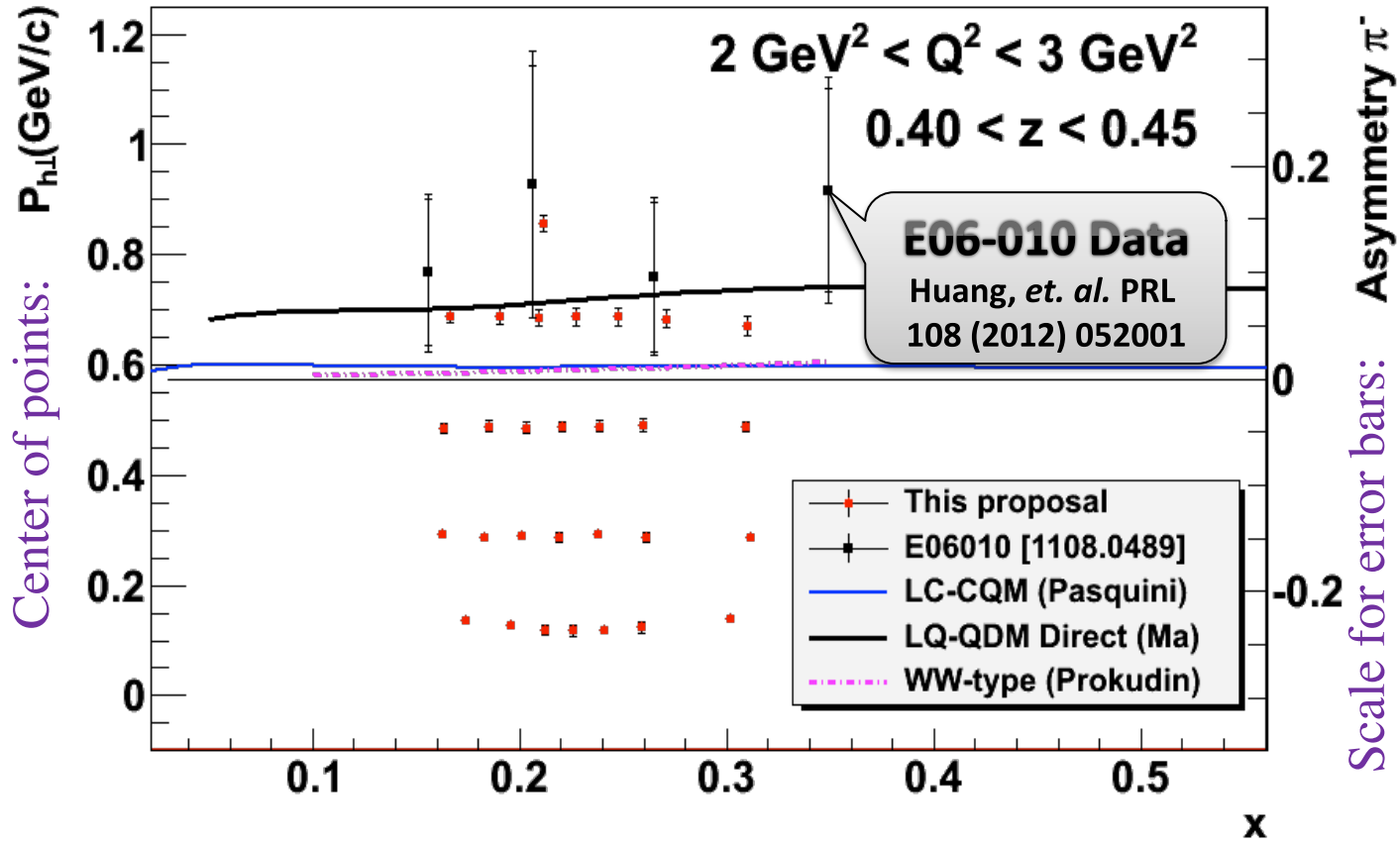
Power of SOLID (example)





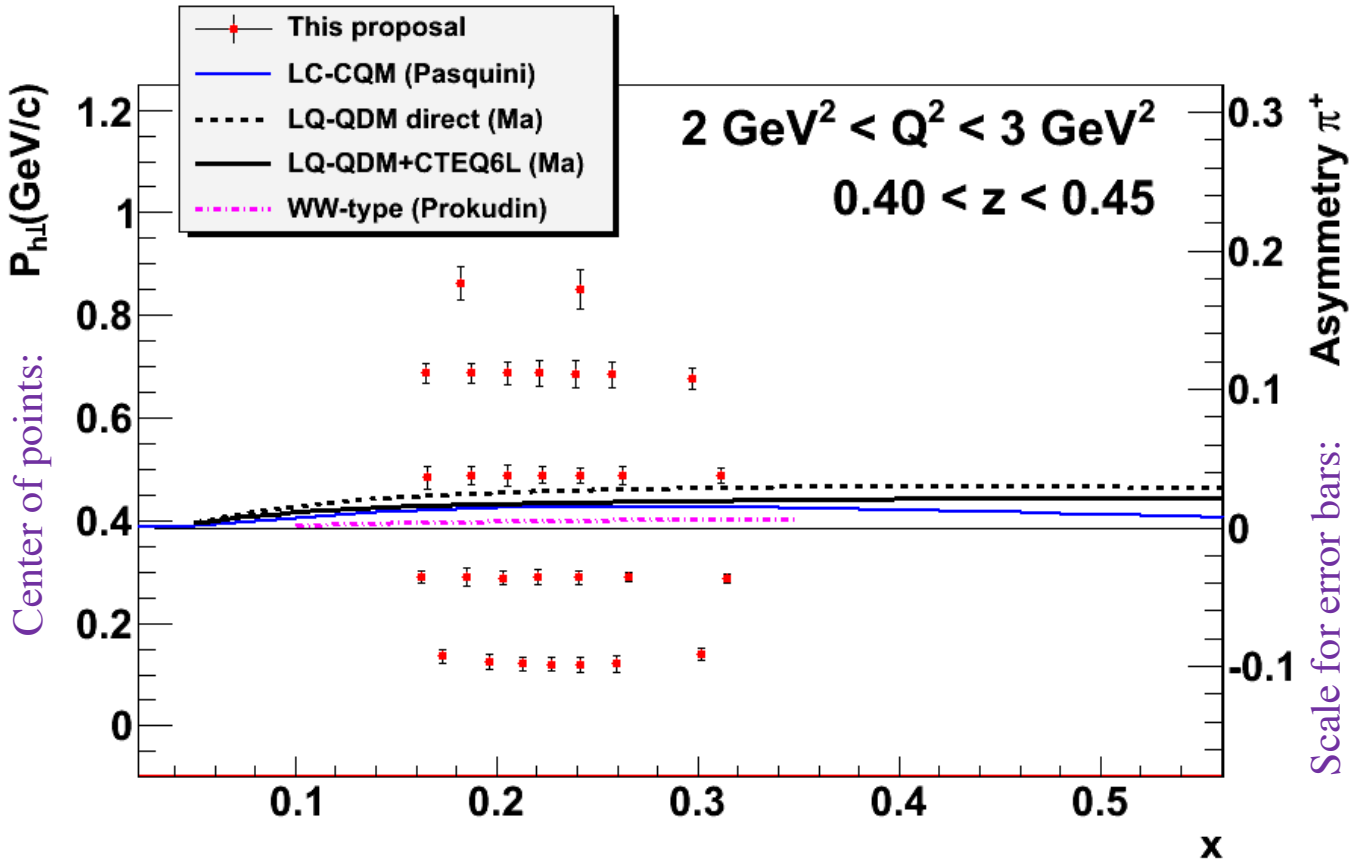
SoLID Data Projection for A_{LT} (Partial)

- 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 Projection/A_{UL} (Partial)

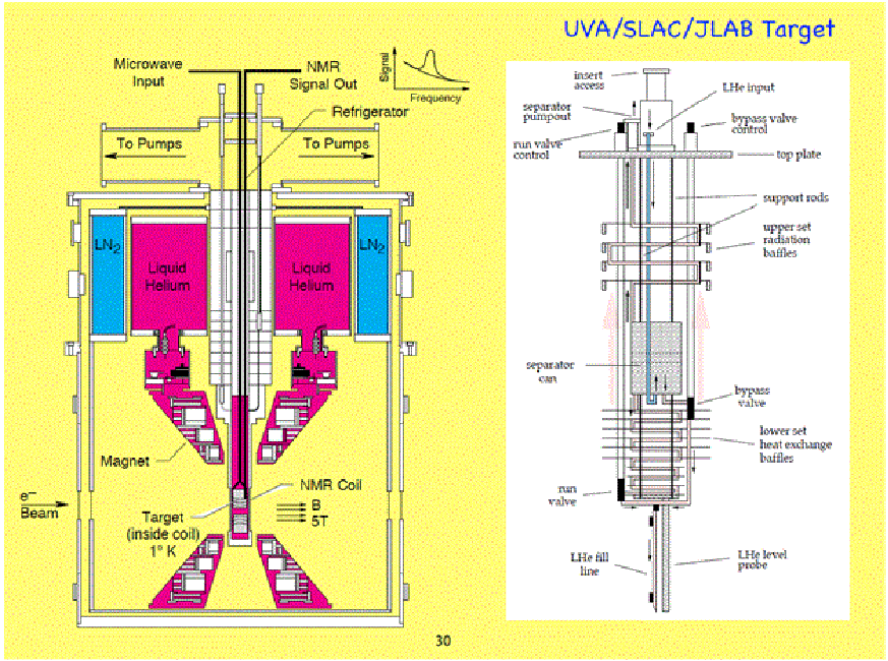
- Projection of a single Q^2-z bin for π^+



Proposal PR12-11-108:

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

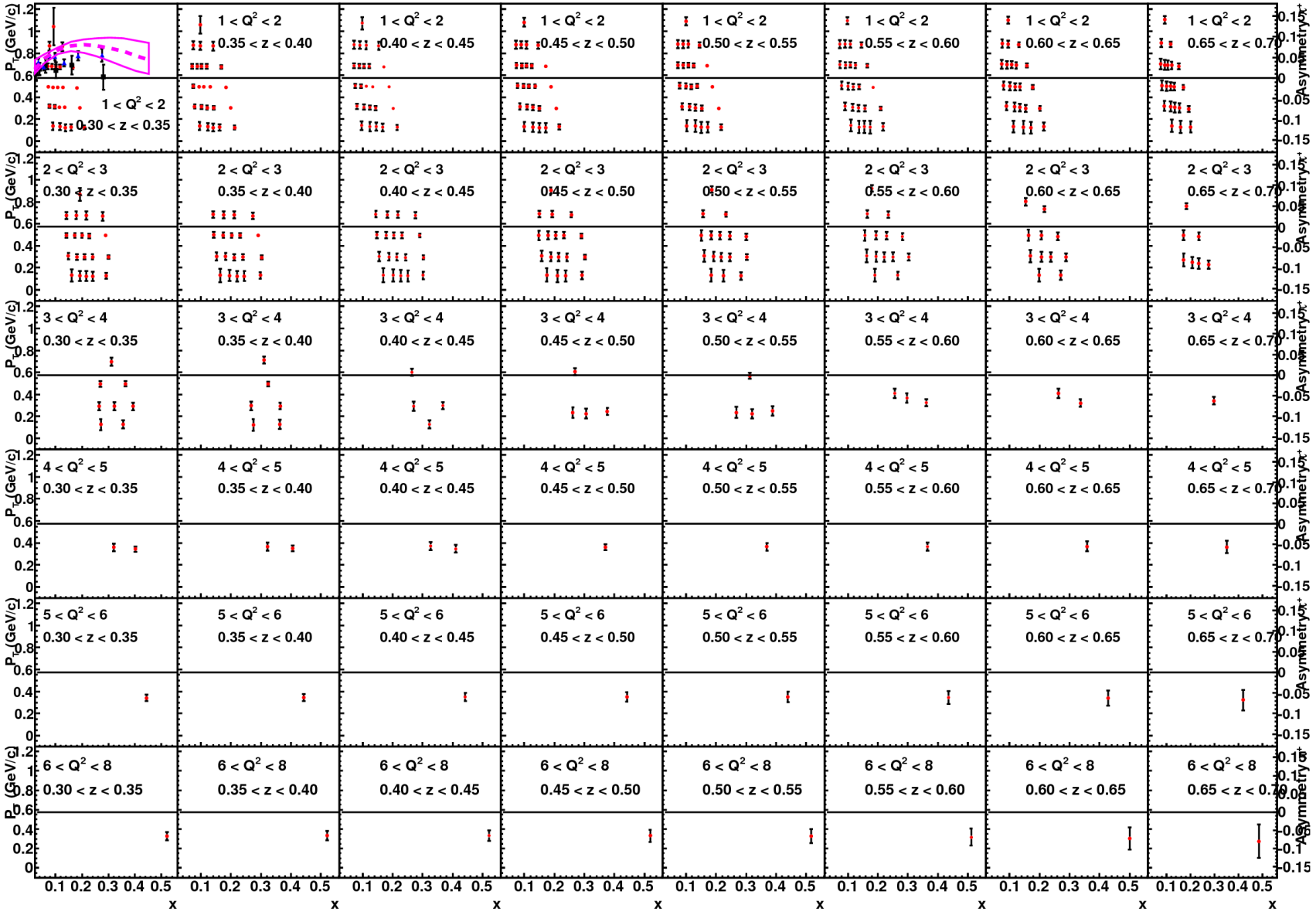
- Measure SSA in SIDIS using transversely polarized proton target
  - Use similar detector setup as that of two approved ^{3}He SoLID expts.
  - Use JLab/UVa polarized NH_3 target with upgraded design of the magnet
  - Target spin-flip every two hours with average in-beam polarization of 70%
  - Two 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 designed for g2p expt.)



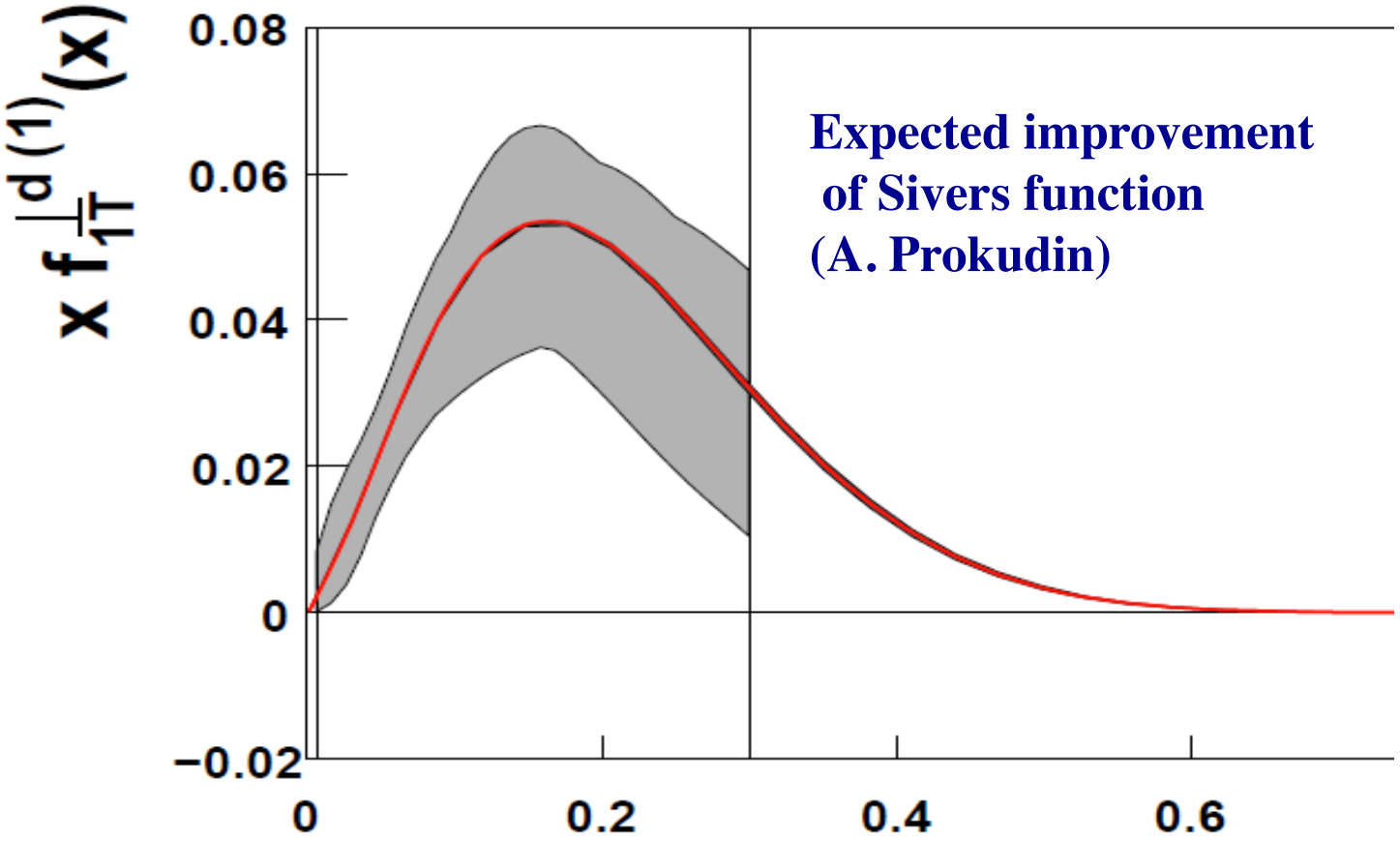
Spokespersons: K. Allada (Jlab), J. P. Chen (Jlab), Haiyan Gao (Contact), Xiaomei Li (CIAE), Z-E. Meziani (Temple)

PAC38: Conditionally approved, update submitted to PAC39

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.

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)**
    - **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, J. P. Chen, J. Huang, and X. Qian and others in the SoLID collaboration
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