TMD Physics at 12 GeV Jefferson Lab with SoLID

DIS 2016 @ DESY Hamburg, Germany
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(On behalf of SoLID Collaboration)
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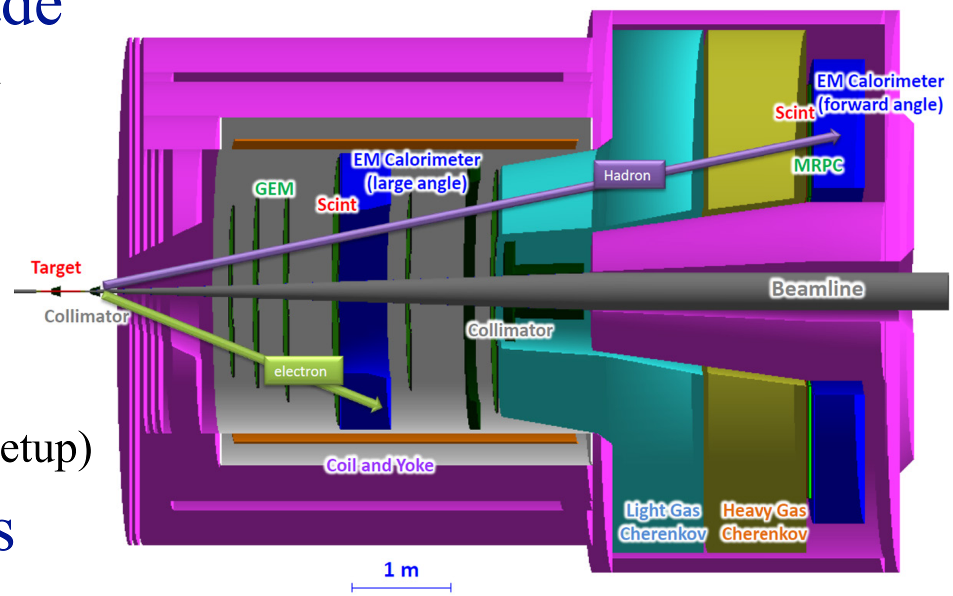
Overview of SoLID

Solenoidal Large Intensity Device



Full exploitation of JLab 12 GeV upgrade

- The capability to handle high luminosity $L \sim 10^{37}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. (for SIDIS)
- Large acceptance with full 2π azimuthal angle coverage.
  Polar angle coverage: 8°~24°.

(SIDIS & J/ψ setup)

Five highly rated approved experiments

- Nucleon structure: three-dimensional imaging of the nucleon in momentum space in valence quark region.
  E12-10-006, E12-11-007, E12-11-008 (SIDIS)
- Fundamental symmetries: new physics in the 10~20 TeV region, complementary to the reach of LHC.
  E12-10-007 (PVDIS)
- QCD: probe the color field in the nucleon, access to QCD conformal anomaly.
  E12-12-006 (J/ψ)

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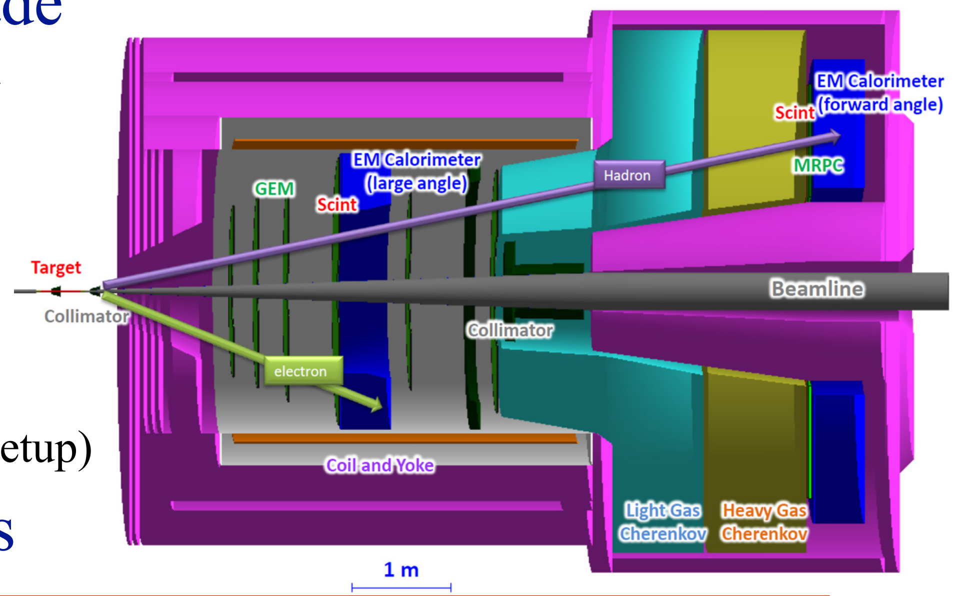

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  E12-12-006 (J/ψ)

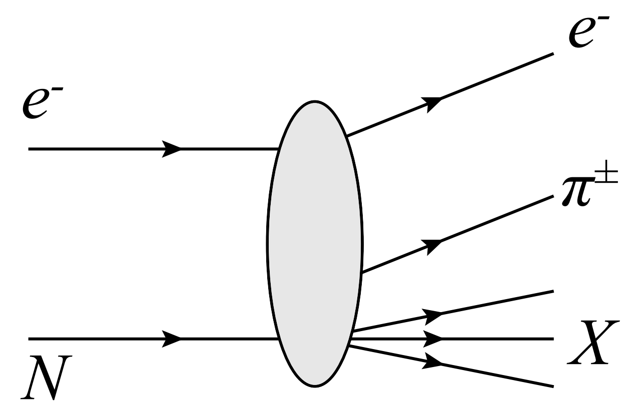
SIDIS @ SoLID

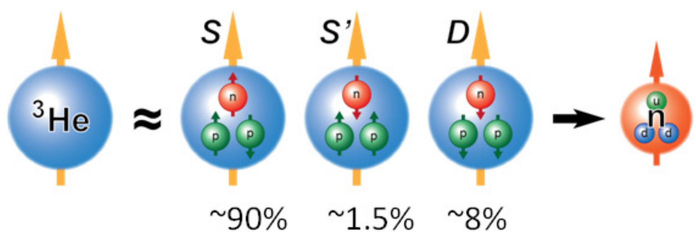
Approved SIDIS experiments 11/8.8 GeV

E12-10-006: Single Spin Asymmetry on Transversely polarized ^{3}He, 90 days.

E12-11-007: Single and Double Spin Asymmetry on Longitudinally polarized ^{3}He, 35 days.

E12-10-008: Single Spin Asymmetry on Transversely polarized proton (NH_3), 120 days.

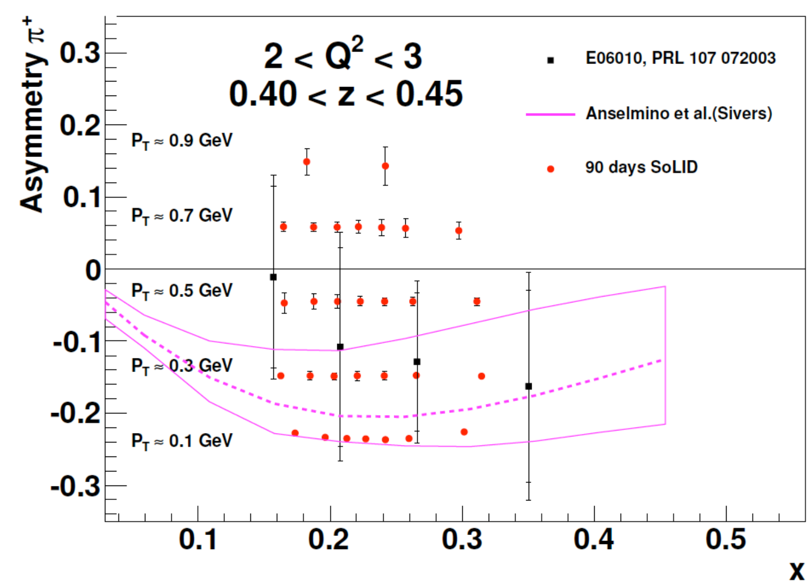




$P_n = 86\%$, $P_p = -2.8\%$

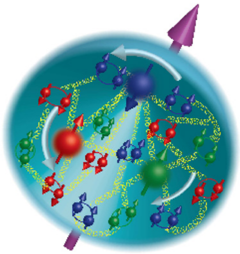
Total about 1400 ^{3}He bins and 650 proton bins in x, z, Q^2, P_T

High statistics (example)



Projected data of E12-10-006

Nucleon Spin Decomposition



Proton spin puzzle

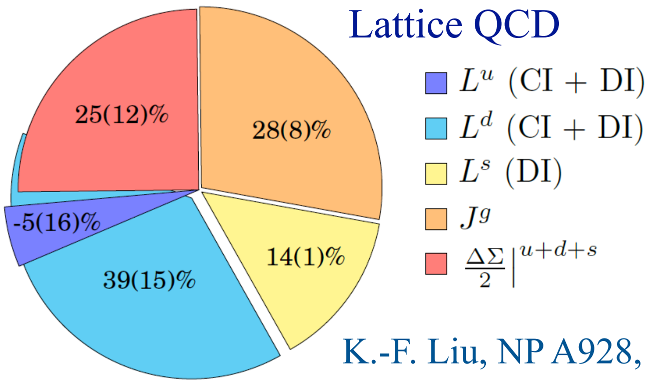
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

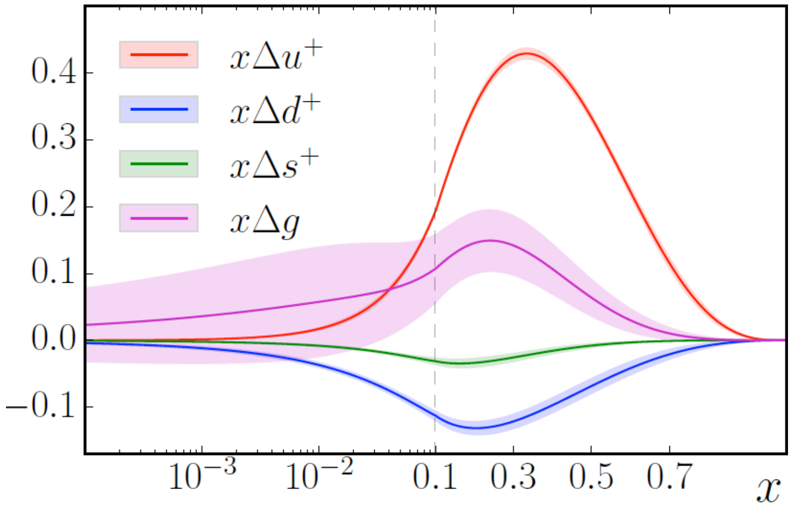
J. Ashman *et al.*, PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



K.-F. Liu, NP A928, 99 (2014).



JAM Collaboration, PR D 93, 074005 (2016).

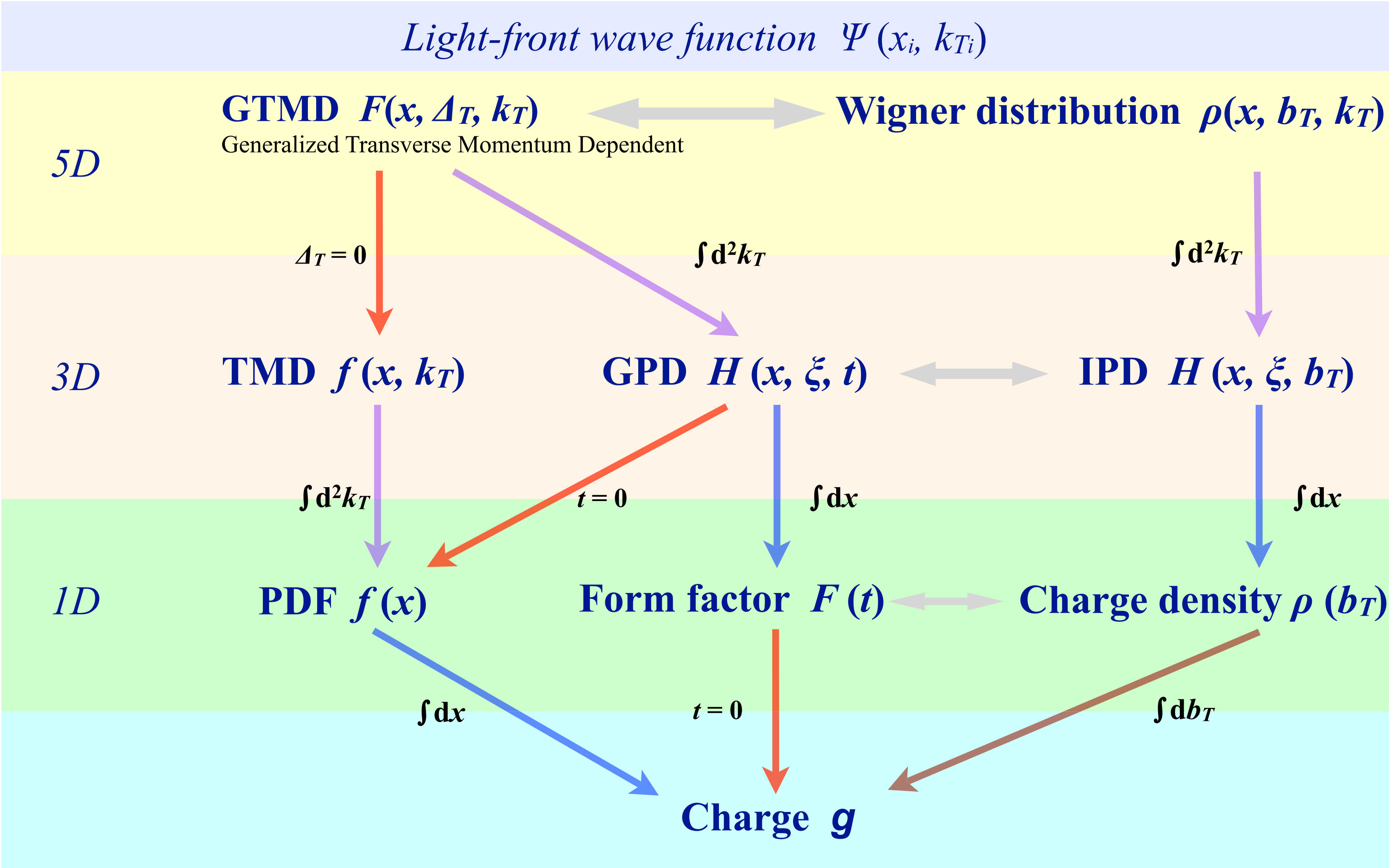
Access to $L_{q/g}$

It is necessary to have transverse information.

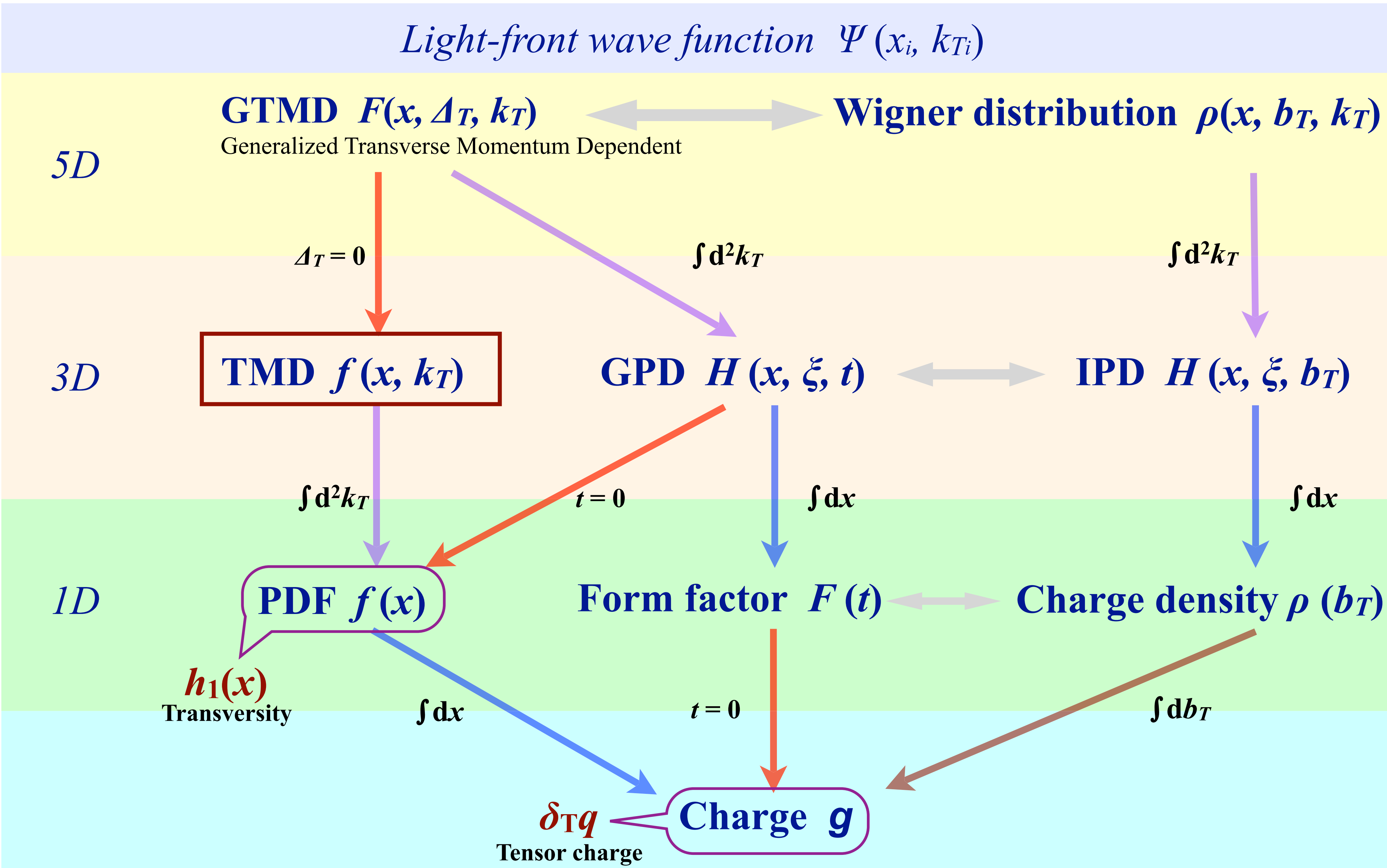
Coordinate space: GPDs
Momentum space: TMDs

3*D* imaging of the nucleon.

Unified View of Nucleon Structure



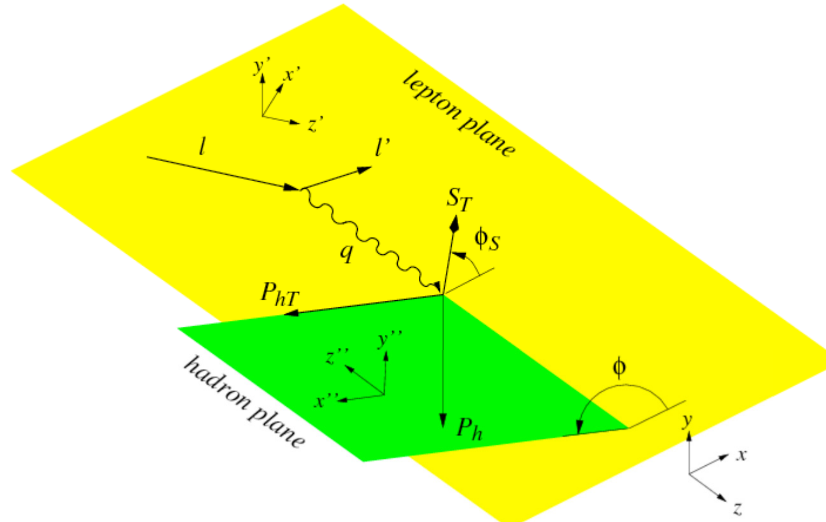
Unified View of Nucleon Structure



Structure Functions

SIDIS differential cross section

18 structure functions $F(x, z, Q^2, P_T)$,
model independent. (one photon exchange approximation)



[Diehl&Sapeta EPJC2005]

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_S} \\
&= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
&\times\Big\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h \\
&+S_L\left[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h+\epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right]+\lambda_e S_L\left[\sqrt{1-\epsilon^2}F_{LL}+\sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\right] \\
&+S_T\Big[\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\sin(\phi_h-\phi_S)+\epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)+\epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\
&\qquad+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big] \\
&+\lambda_e S_T\Big[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\
&\qquad+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}
\end{aligned}
$$

SoLID:
4D bins in (x, z, Q^2, P_T)

In parton model, $F(x, z, Q^2, P_T)$s are expressed as the convolution of TMDs.

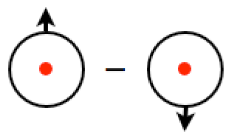
Leading Twist TMDs

		Quark Polarization		
		U	L	T
Nucleon Polarization	U	f_1 unpolarized		$h_1^\perp$ Boer-Mulders
	L		g_{1L} helicity	$h_{1L}^\perp$ longi-transversity (worm-gear)
	T	$f_{1T}^\perp$ Sivers	g_{1T} trans-helicity (worm-gear)	h_1 transversity $h_{1T}^\perp$ pretzelosity

Unpolarized Quark in $p\uparrow$

$$f_{q/p\uparrow}(x,\mathbf{k}_\perp) = f_1^q(x,k_\perp) - f_{1T}^{\perp q}(x,k_\perp)\frac{\hat{\mathbf{P}}\times\mathbf{k}_\perp\cdot\mathbf{S}}{M}$$

Sivers distribution

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

naively time-reversal odd.

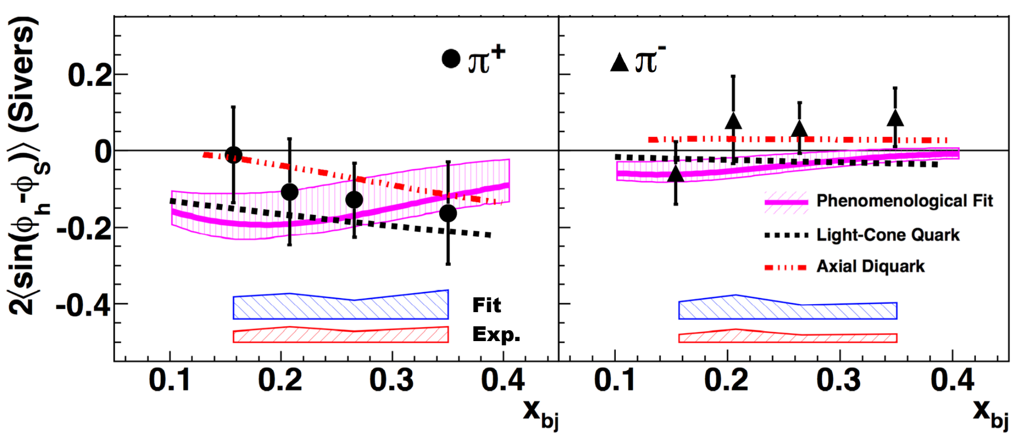
$$f_{1T}^{\perp q}(x,k_\perp)\Big|_{\text{SIDIS}} = -f_{1T}^{\perp q}(x,k_\perp)\Big|_{\text{DY}}$$

Measurement in SIDIS

Single spin asymmetry

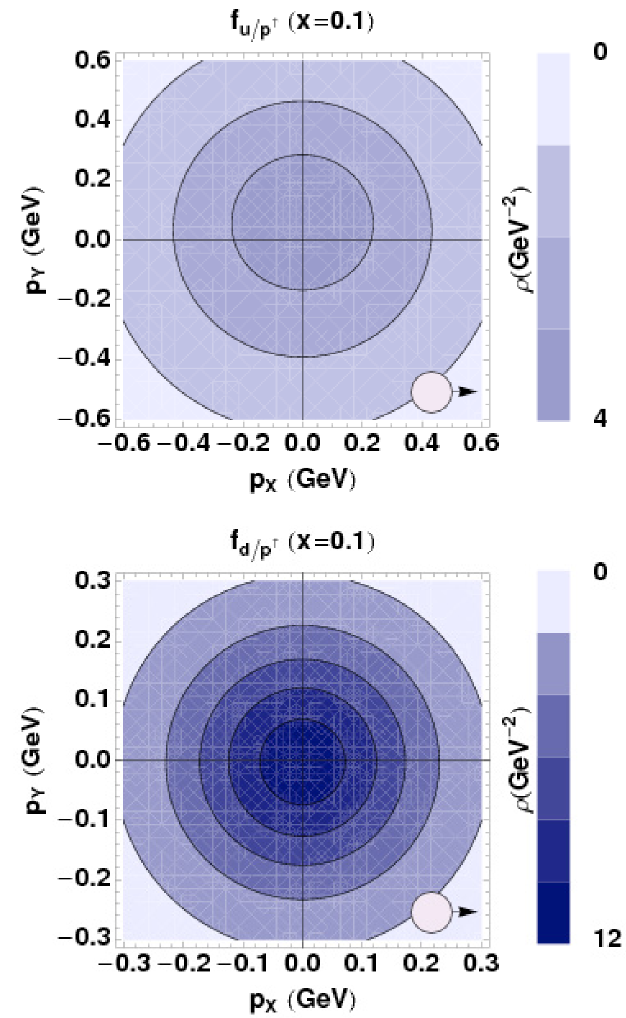
(Sivers asymmetry)

$$A_{UT}^{\sin(\phi_h-\phi_S)} \sim f_{1T}^{\perp}(x,k_\perp)\otimes D_1(z,p_\perp)$$



6 GeV JLab E06-010, X. Qian *et al.*, PRL 107, 072003 (2011).

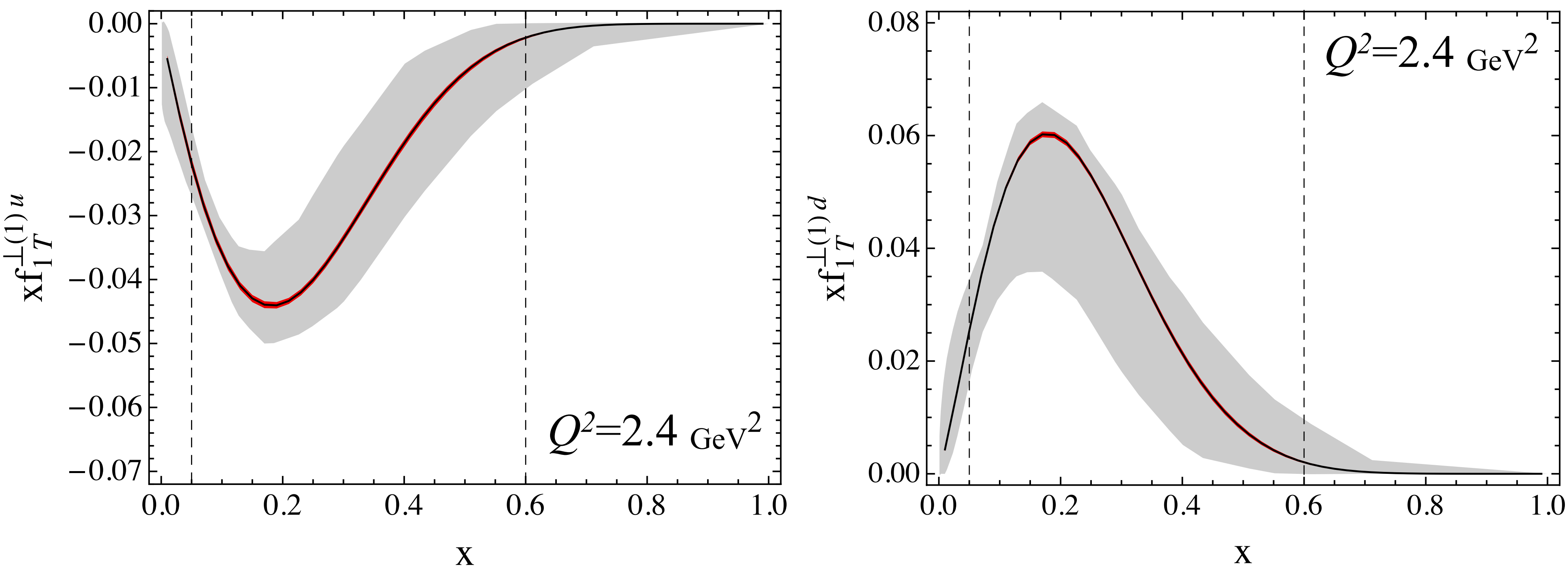
Model Calculation



Bacchetta, Conti, Radici
PR D 78, 074010 (2008).

SoLID Impact on Sivers

$$f_{1T}^{\perp(1)}(x) = \int d^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} f_{1T}^{\perp}(x, k_\perp)$$

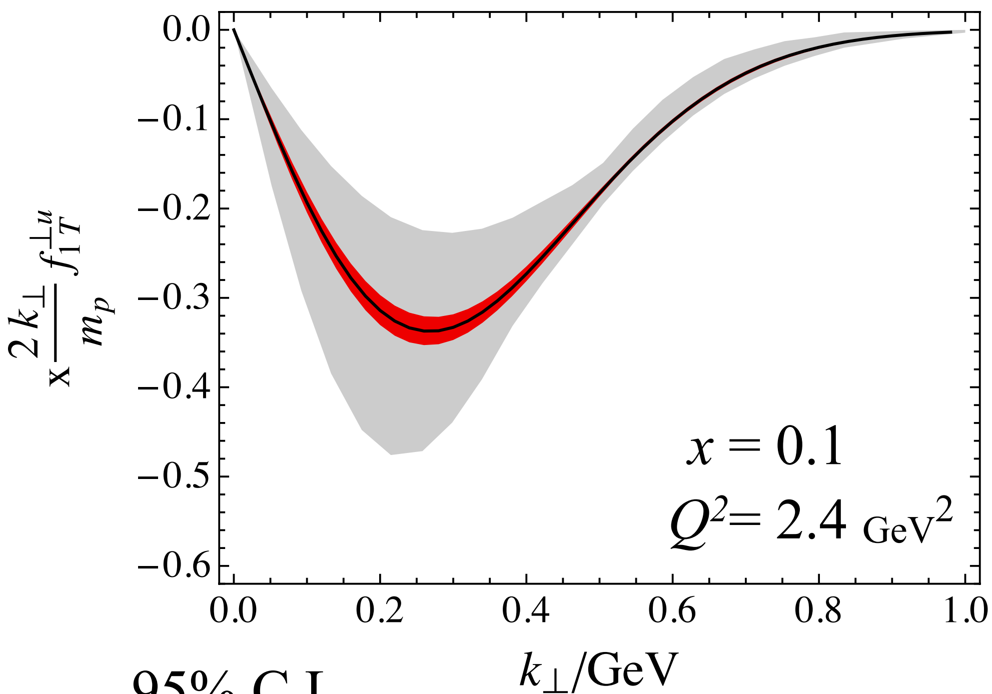


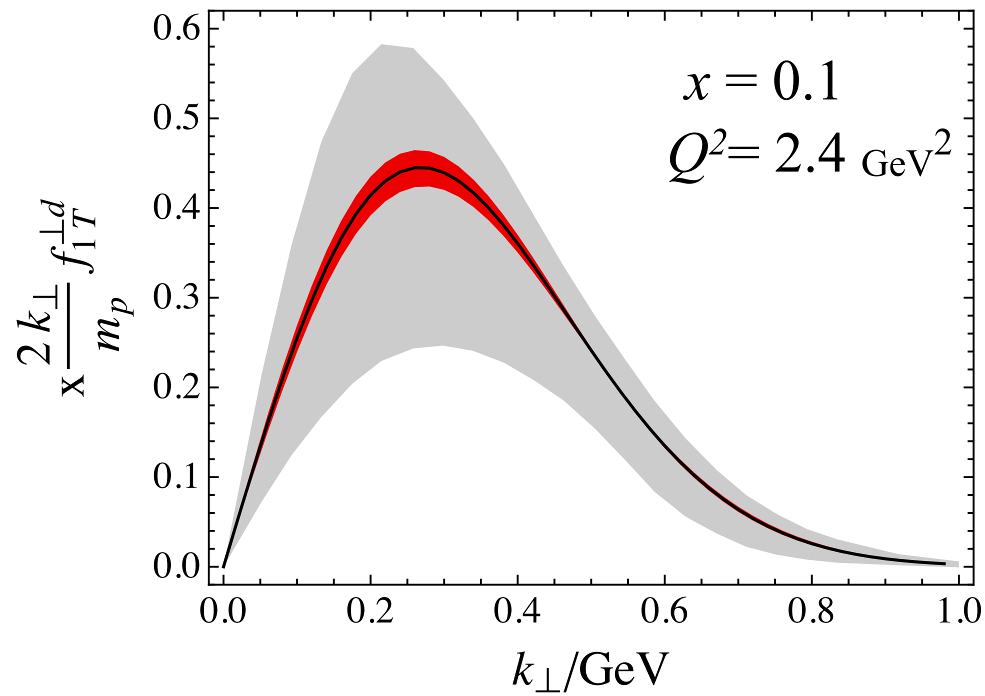
95% C.L.

parametrization by M. Anselmino *et al.*, EPJ A 39, 89 (2009).

SoLID projection with transversely polarized neutron and proton data.

Quark Transverse Momentum in $p\uparrow$





95% C.L.

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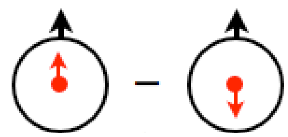
SoLID projection with transversely polarized neutron and proton data.

$$\langle \mathbf{k}_\perp \rangle = -M \int \mathrm{d}x\, f_{1T}^{\perp(1)}(x)\, (\mathbf{S} \times \hat{\mathbf{P}})$$

	$\langle k_\perp \rangle^u$	$\langle k_\perp \rangle^d$
parametrization (grey)	96^{+60}_{-28} MeV	-113^{+45}_{-51} MeV
SoLID projection (red)	$96^{+2.8}_{-2.4}$ MeV	$-113^{+1.3}_{-1.7}$ MeV

Transverse Spin Structure

Transversity

h_1  (Collinear & TMD)

A transverse counter part to the longitudinal spin structure: helicity g_{1L}

They are NOT the same due to relativity.

Chiral-odd

Unique for the quarks.
No mixing with gluons.
Simpler evolution effect.

NOT accessible via inclusive DIS process.
Must couple to another chiral-odd function.
(*e.g.* Collins function $H_1^{\perp}$)

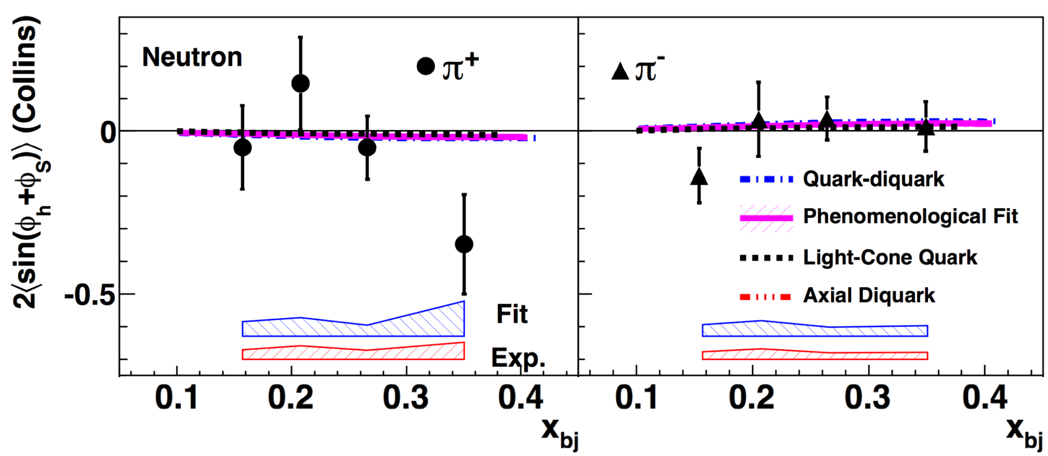
Measured via
SIDIS (E12-10-006, E12-11-008), Drell-Yan
Di-hadron (approved as run group with E12-10-006)

Measurement in SIDIS

Single spin asymmetry
(Collins asymmetry)

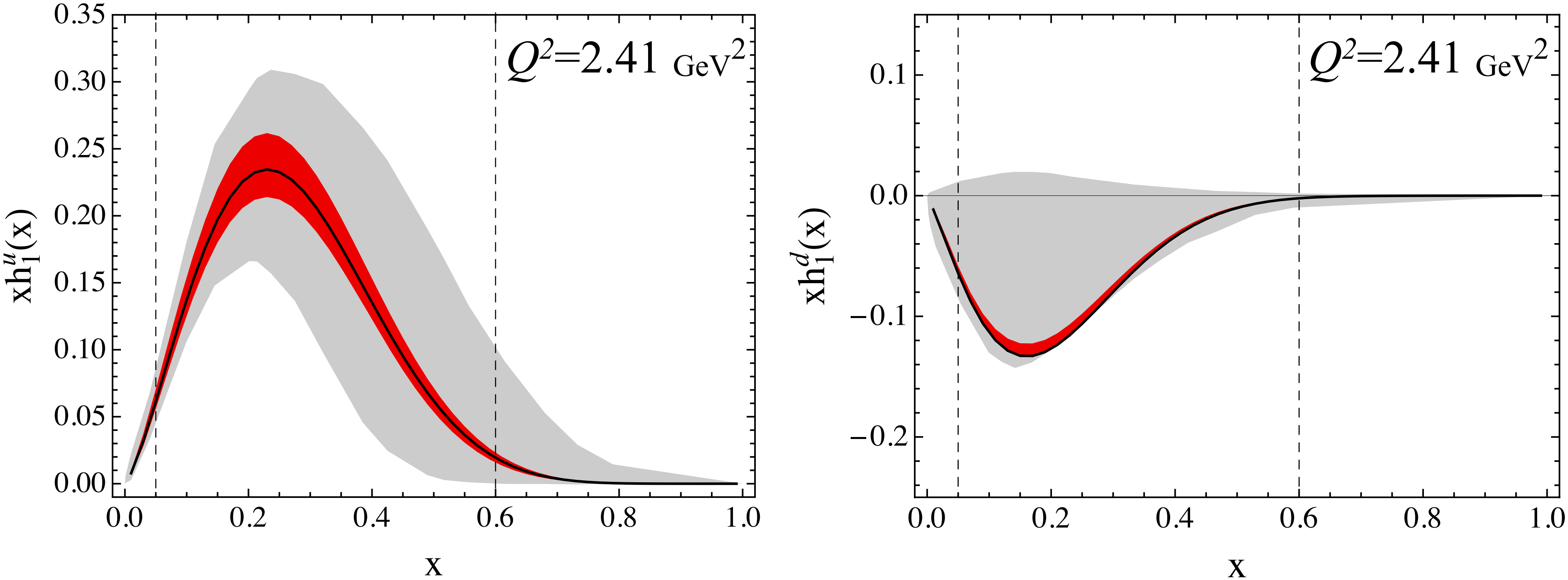
$$A_{UT}^{\sin(\phi_h+\phi_S)} \sim h_1(x,k_\perp) \bigotimes H_1^{\perp}(z,p_\perp)$$

$H_1^{\perp}(z,p_\perp)$ Collins fragmentation function



6 GeV JLab E06-010, X. Qian *et al.*, PRL 107, 072003 (2011).

SoLID Impact on Transversity

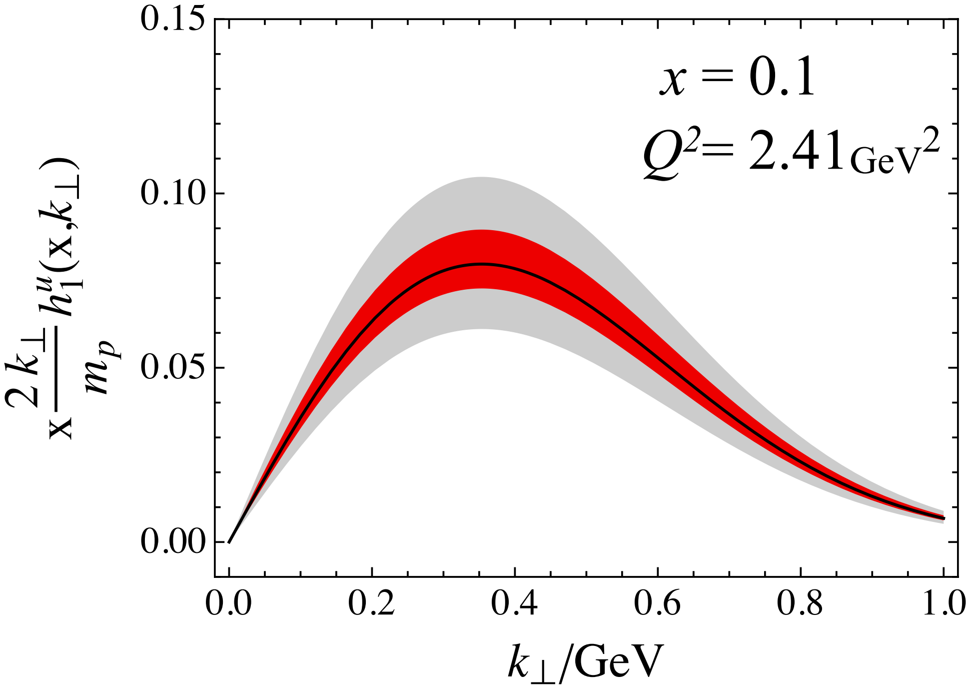


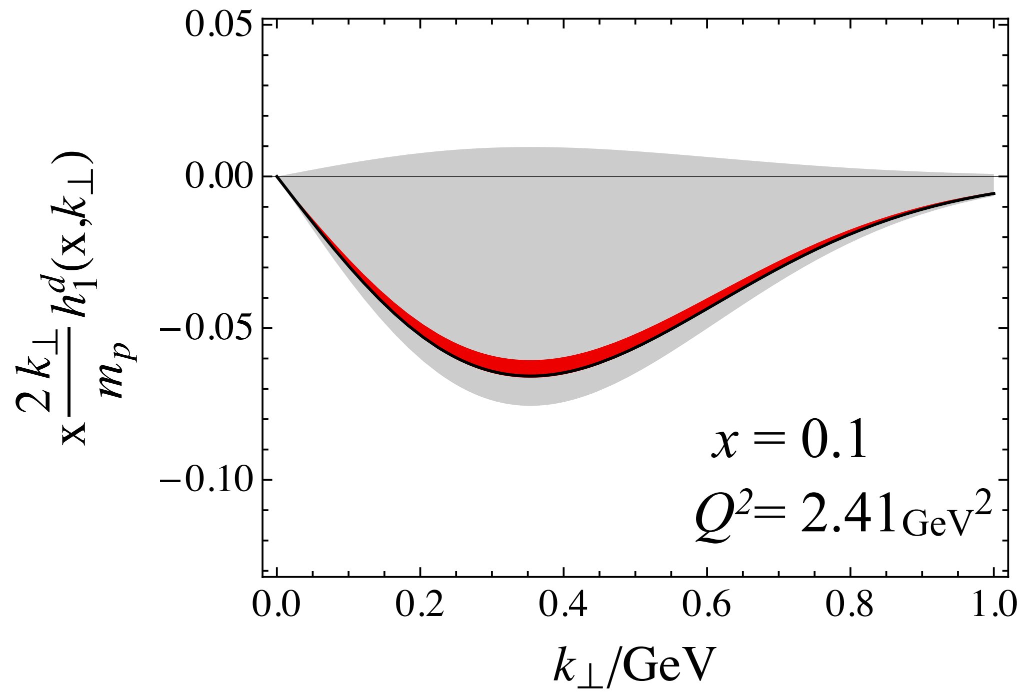
95% C.L.

parametrization by M. Anselmino *et al.*, PR D 87, 094019 (2013).

SoLID projection with transversely polarized neutron and proton data.

SoLID Impact on Transversity TMD





95% C.L.

parametrization by M. Anselmino *et al.*, PR D 87, 094019 (2013).

SoLID projection with transversely polarized neutron and proton data.

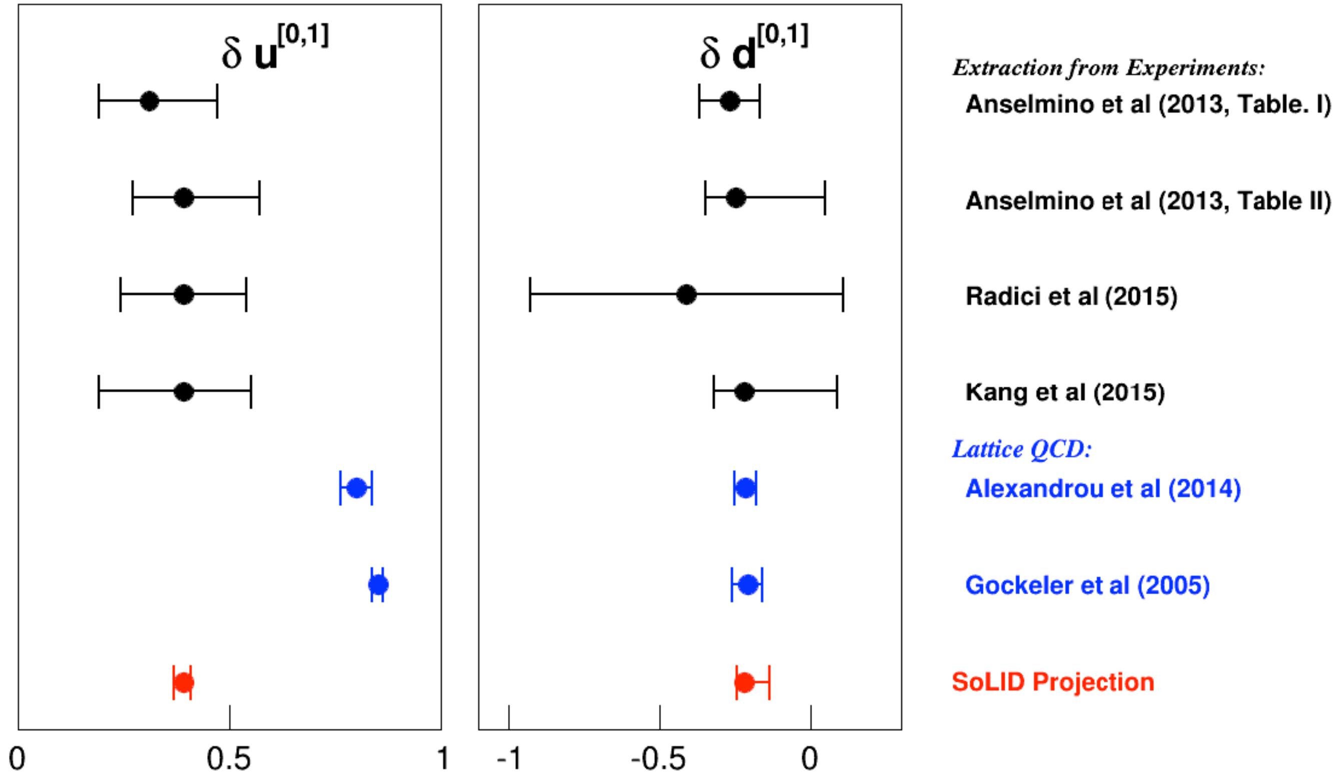
Tensor Charge

Definition

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = \delta_T q \bar{u}(P,S) i\sigma^{\mu\nu} u(P,S) \qquad \delta_T q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x)\right] \mathrm{d}x$$

A fundamental QCD quantity. Matrix element of local operators.
Moment of transversity distribution. Valence quark dominant.
Calculable in lattice QCD.

SoLID impact



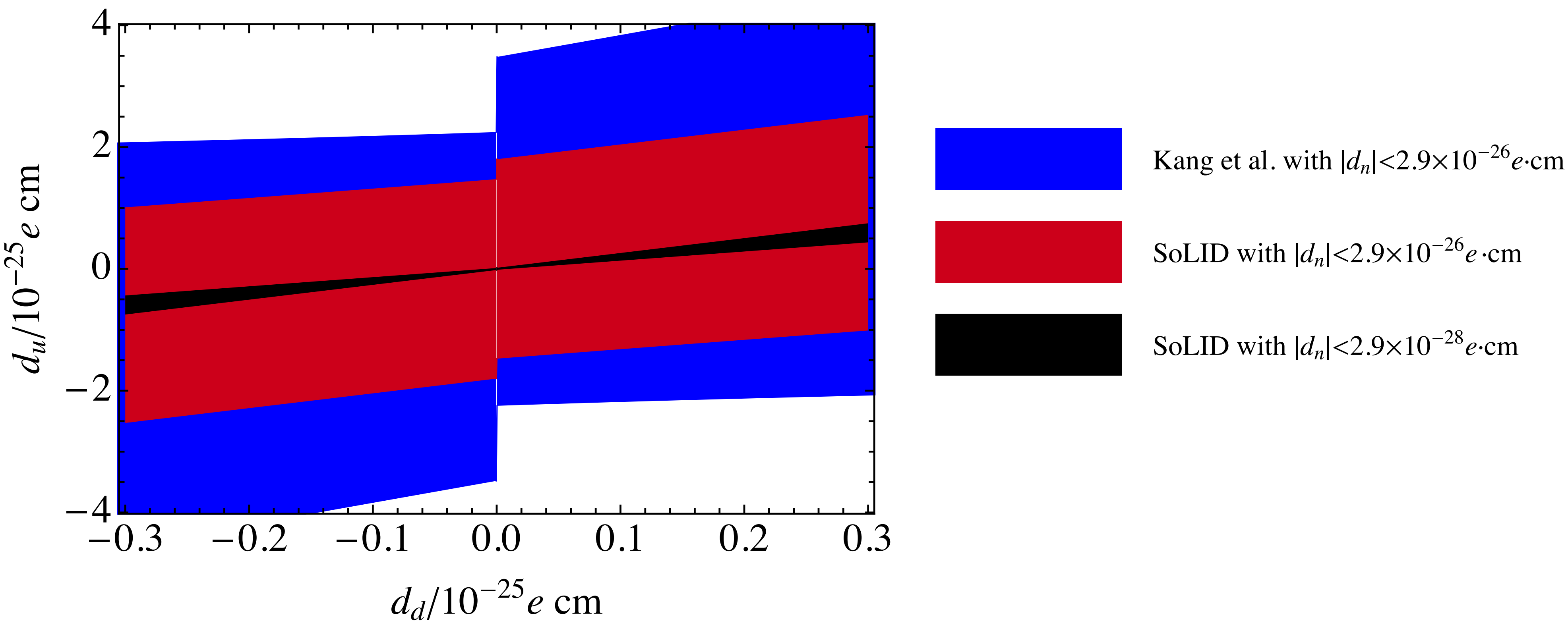
SoLID projection by A. Prokudin, N. Sato, K. Allada, and Z. Ye (on-going).

Tensor Charge and Neutron EDM

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

Tensor charge and EDM

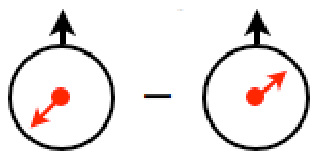
$$d_n = \delta_T u\, d_u + \delta_T d\, d_d + \delta_T s\, d_s$$



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

Pretzelosity

Pretzelosity distribution

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

Chiral-odd. NO gluon analogy.
Interference of light-front wave functions differing by $\Delta L = 2$.
Measuring the difference between helicity and transversity, and hence relativistic effects. (spherically symmetric models)

Relation to OAM (canonical)

$$L_z^q = -\int \mathrm{d}x\mathrm{d}^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int \mathrm{d}x h_{1T}^{\perp(1)q}(x)$$ (model dependent)

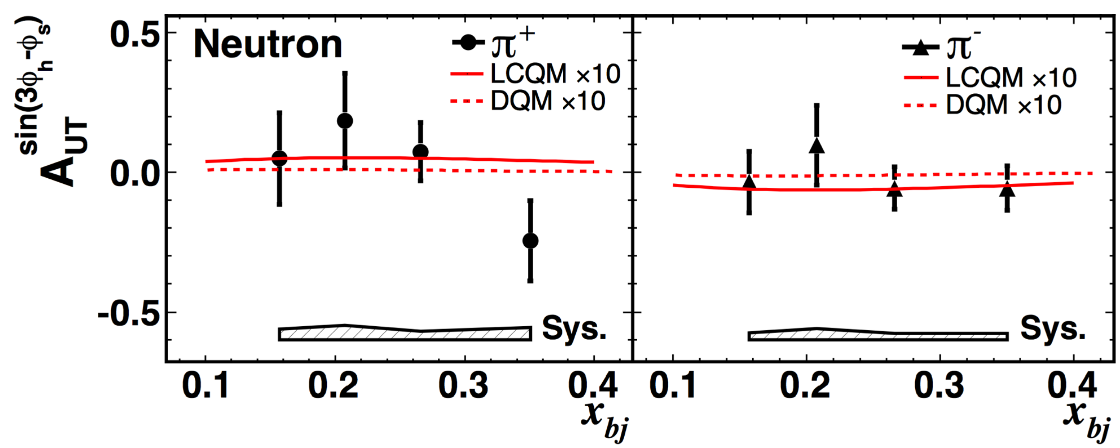
Measurement in SIDIS

Single spin asymmetry

$$A_{UT}^{\sin(3\phi_h - \phi_S)} \sim h_{1T}^{\perp}(x, k_\perp) \otimes H_1^{\perp}(z, p_\perp)$$

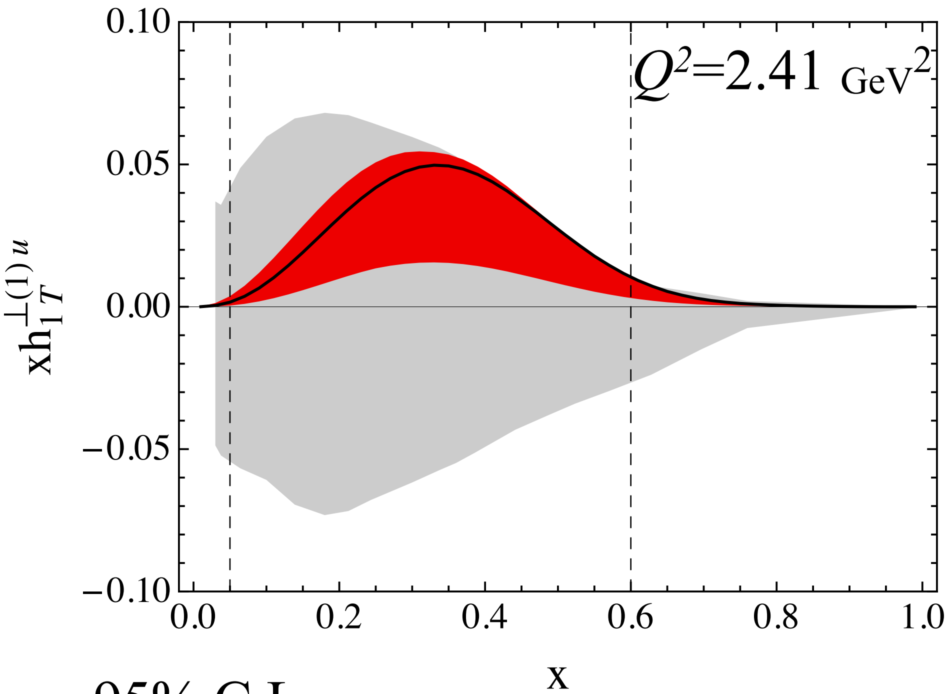
A global fit to 175 data from COMPASS, HERMES, and JLab found comparable with null signal hypothesis at 72% C.L..

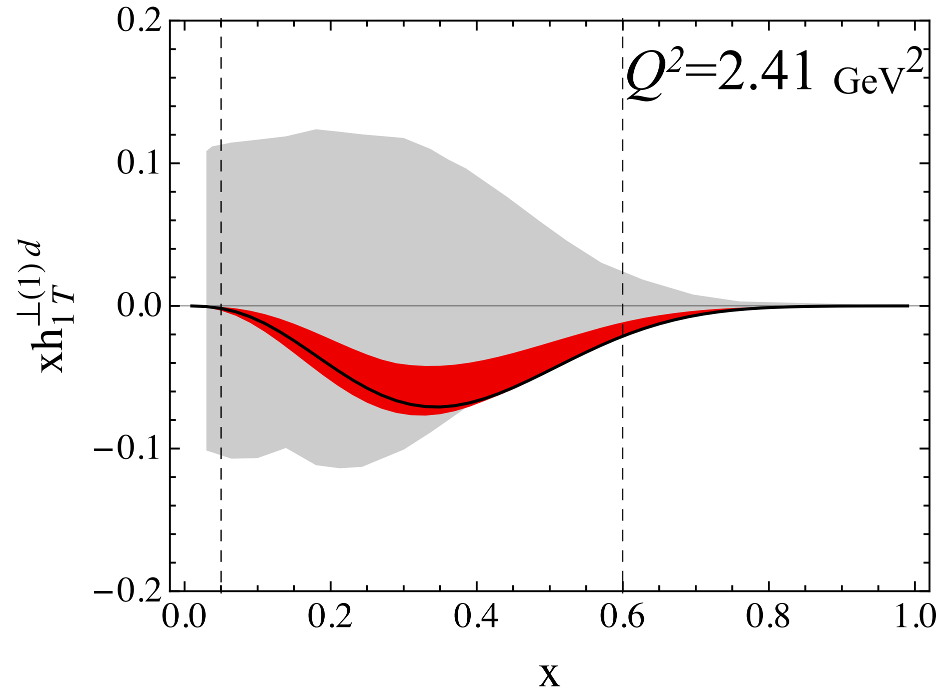
C. Lefky, A. Prokudin, PR D 91, 034010 (2015).



6 GeV JLab E06-010, Y. Zhang *et al.*, PR C 90, 055209 (2014).

SoLID Impact on Pretzelosity





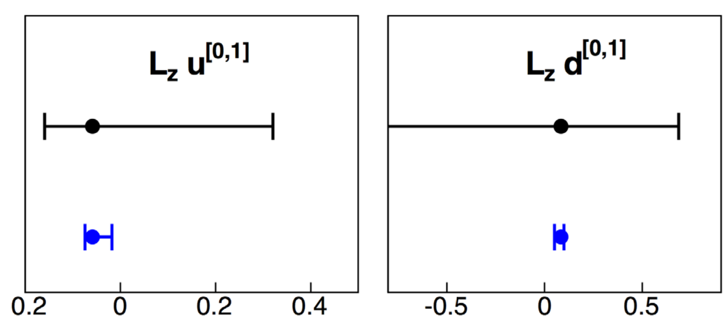
95% C.L.

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

SoLID projection with transversely polarized neutron and proton data.

OAM:

$$L_z^q = -\int \mathrm{d}x\mathrm{d}^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int \mathrm{d}x h_{1T}^{\perp(1)q}(x)$$



Lefky *et al.* (2015)

SoLID projection

Summary

- Lepton scattering is a powerful tool to probe the internal structure of the nucleon.
- Unprecedented precision with high luminosity and large acceptance at JLab 12-GeV with SoLID.
- SoLID-SIDIS program: multi-dimensional mapping in valence quark region with ultimate precision.
- TMD: transverse imaging of the nucleon, access to orbital angular momentum.
- Tensor charge and neutron EDM, constraint on new physics.

Thank you!

Backup

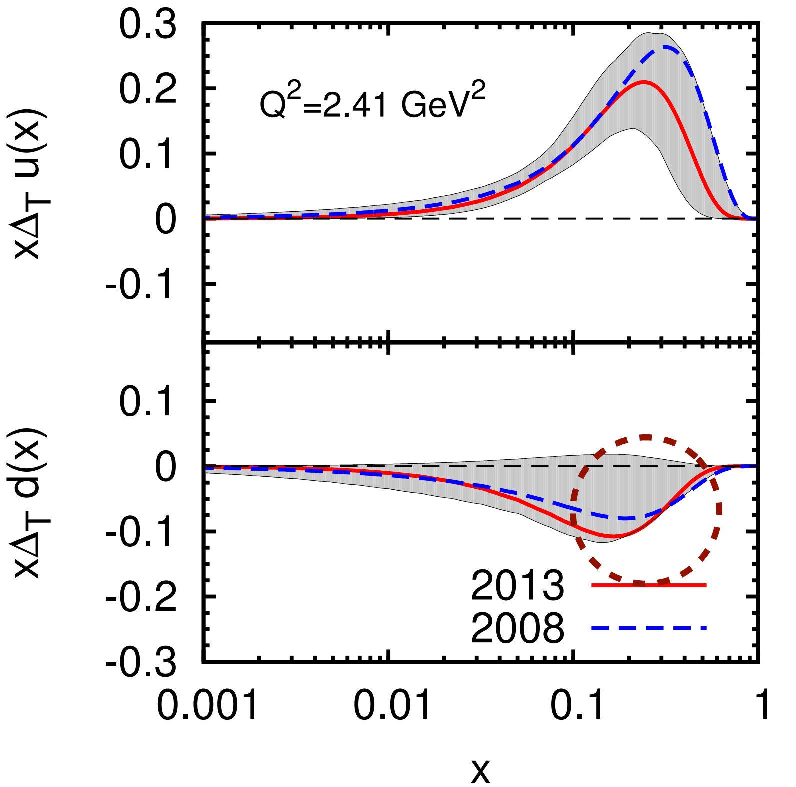
Soffer's Inequality

Soffer's bound

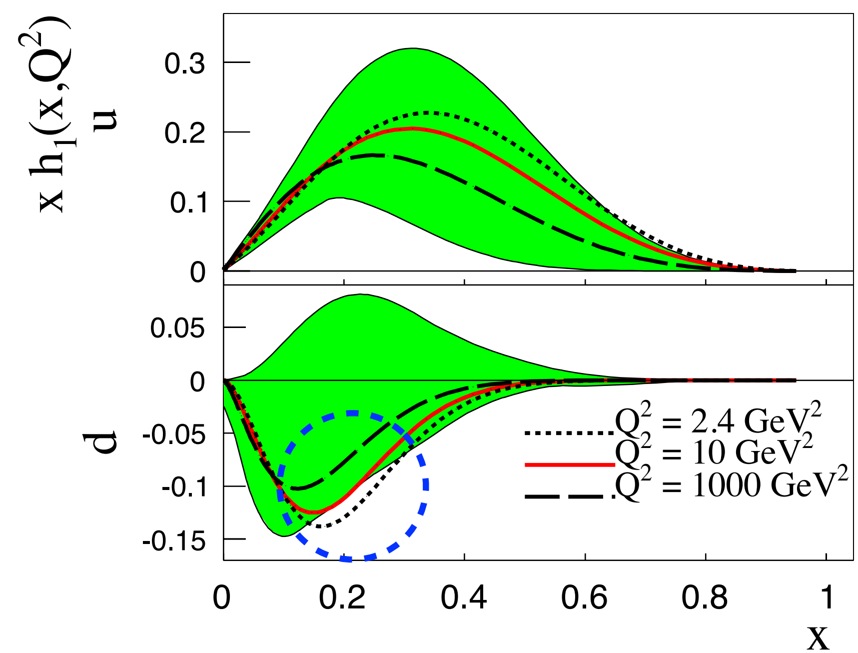
$$|h_1(x)| \leq \frac{1}{2}\left[f_1(x) + g_{1L}(x)\right]$$

Derived by using the positivity constraint on the forward scattering helicity amplitude.

Global fits of transversity



M. Anselmino *et al.*, PR D 87, 094019 (2013).



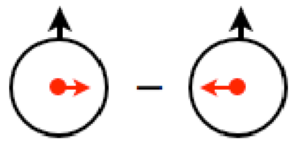
Z.-B. Kang *et al.*, PR D 93, 014009 (2016).

Test Soffer's inequality @ SoLID

What Else in SIDIS @ SoLID

Worm-gears

g_{1T}



Trans-helicity (worm-gear).
Interference of light-front wave functions differing by $\Delta L = 1$.

Measured by DSA $A_{LT}^{\cos(\phi_h - \phi_S)} \sim g_{1T}(x, k_\perp) \bigotimes D_1(z, p_\perp)$

(The other worm-gear from $A_{UL}^{\sin 2\phi_h} \sim h_{1L}^\perp(x, k_\perp) \bigotimes H_1^\perp(z, p_\perp)$.)

Subleading twist effect

Beam spin asymmetry $A_{LU}^{\sin\phi_h}$ from twist-3 TMDs.

Other subleading twist asymmetries, *e.g.* $A_{UT}^{\sin(2\phi_h - \phi_S)}, \quad A_{UT}^{\sin\phi_S}, \quad A_{LT}^{\cos\phi_S} \quad \cdots$

Unpolarized process

Multiplicity or differential cross section.

Cahn effect $f_1 \otimes D_1$ Boer-Mulders effect $h_1^\perp \otimes H_1^\perp$