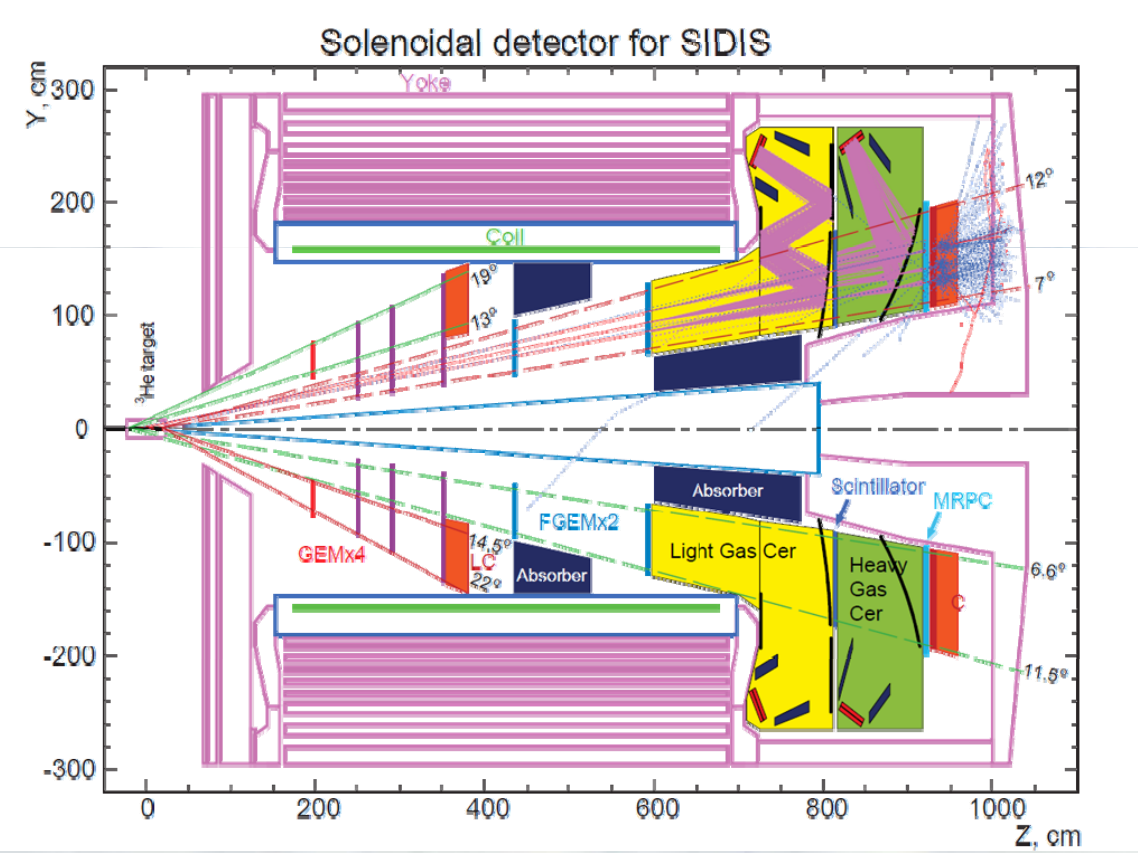
# SIDIS with SoLID Detector

Xin Qian

Caltech



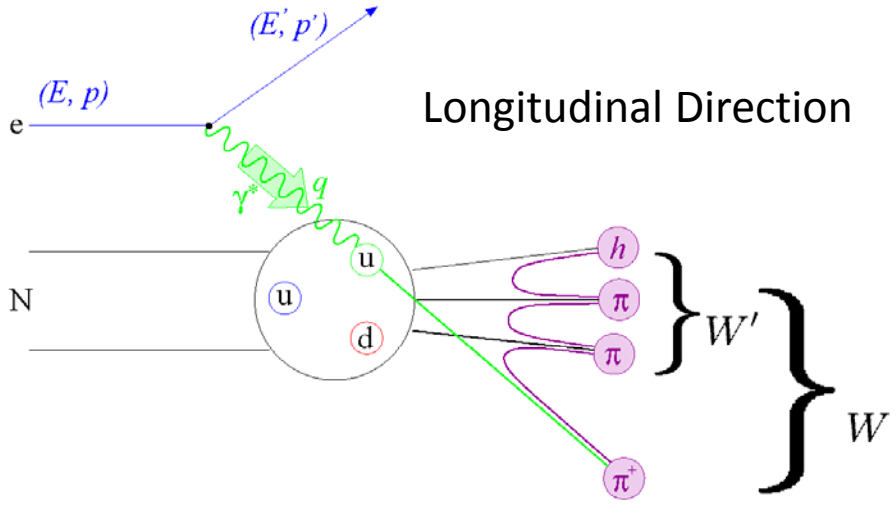
# Current Status of SIDIS with SoLID

- E10-006 (Approved in PAC35 ):
  - Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic Pion Production on a Transversely Polarized $^3$He Target at 8.8 and 11 GeV.
- E11-007 (Approved in PAC 37 ):
  - Asymmetries in Semi-Inclusive Deep-Inelastic Pion production on a Longitudinally Polarized $^3$He Target at 8.8 and 11 GeV.

- PAC Response: "A broad program of high priority physics measurements beyond that of PVDIS program certainly strengthens the case to invest in SoLID"

- White paper: H. Gao et al. Eur. Phys. J. Plus 126:2 (2011)

# Semi-Inclusive Deep Inelastic Scattering




$z = E_\pi / \nu$

W': invariant mass of the residual system

z: energy fraction of the leading hadron with respect to ν

$k_T$ ($P_T$): transverse momentum

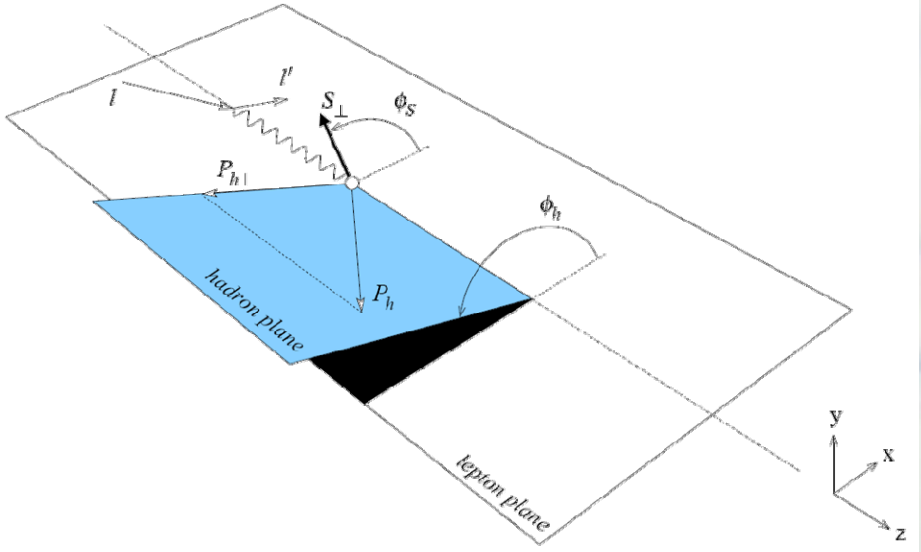
Sensitivity to quark flavors and transverse dynamics, also parton propagation in the cold nuclear matter.

Use E&M interaction to understand "strong force" and "strong material"

Trento Convention:

Three planes: Lepton plane, Spin plane, hadron plane

Two angles: $\phi_h$, $\phi_S$

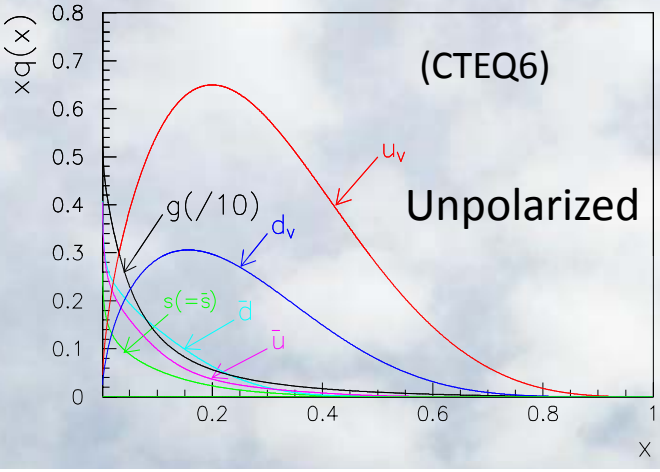


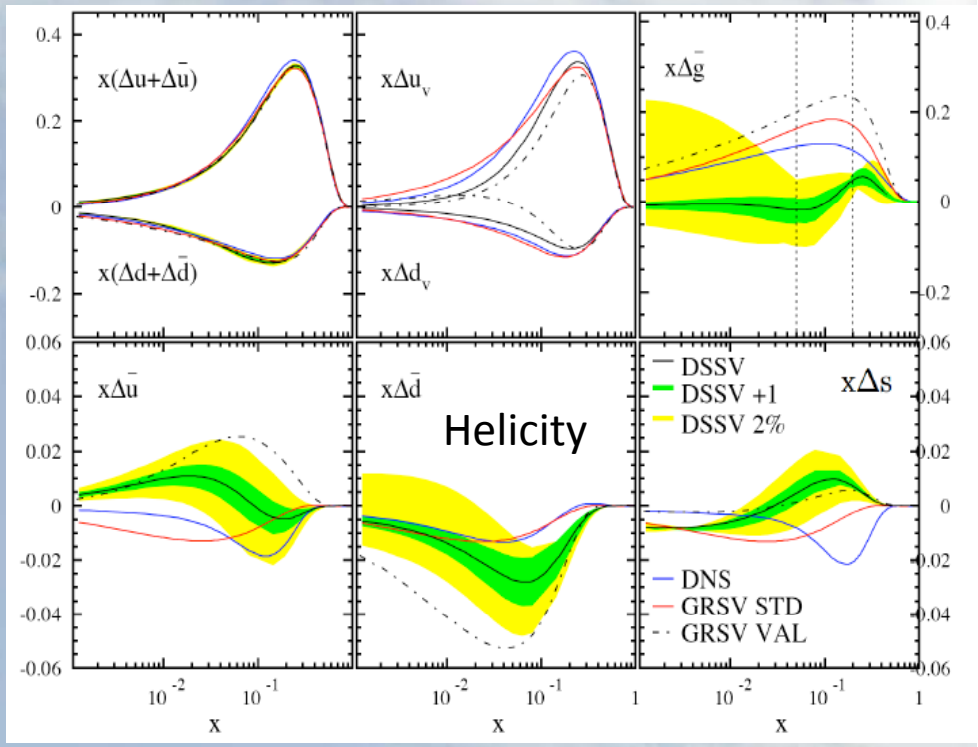
# Leading Twist Transverse Momentum Dependent Parton Distributions (TMDs)

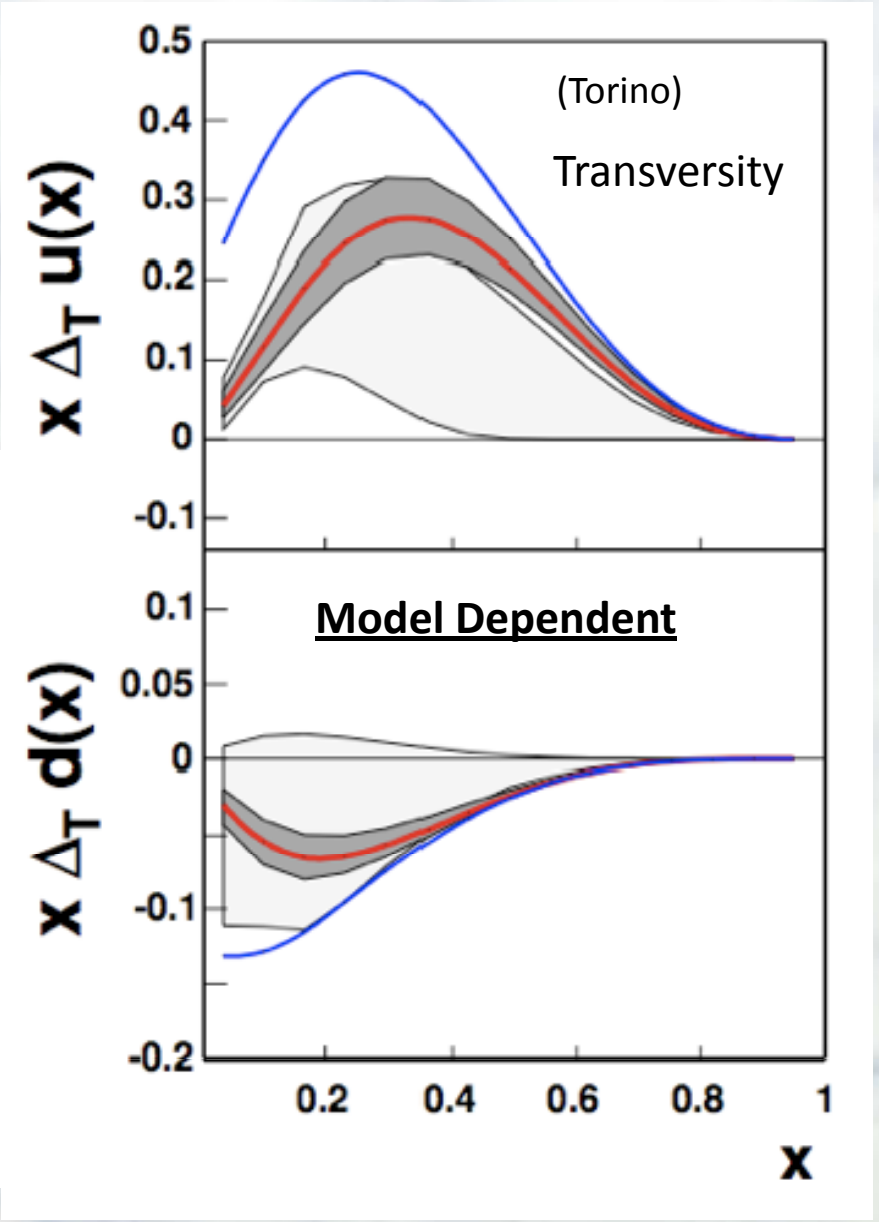
Nucleon Spin
Quark Spin

| Nucleon Polarization | Quark polarization: Un-Polarized | Quark polarization: Longitudinally Polarized | Quark polarization: Transversely Polarized |
|---|---|---|---|
| U | $f_1$ =  | | $h_1^{\perp}$ =  **Boer-Mulder** |
| L | | $g_1$ =  **Helicity** | $h_{1L}^{\perp}$ =  |
| T | $f_{1T}^{\perp}$ =  **Sivers** | $g_{1T}^{\perp}$ =  | $h_{1T}$ =  **Transversity**<br>$h_{1T}^{\perp}$ =  **Pretzelosity** |

# Status of Parton Distributions

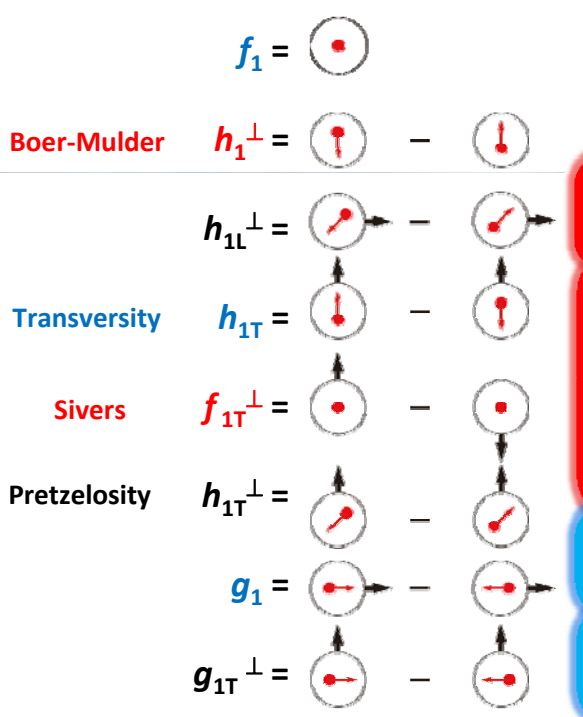


# Access TMDs through SIDIS

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




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

**Unpolarized**

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

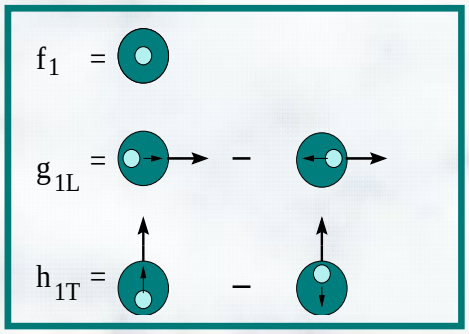
**Polarized Target**

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

**Polarized Beam and Target**

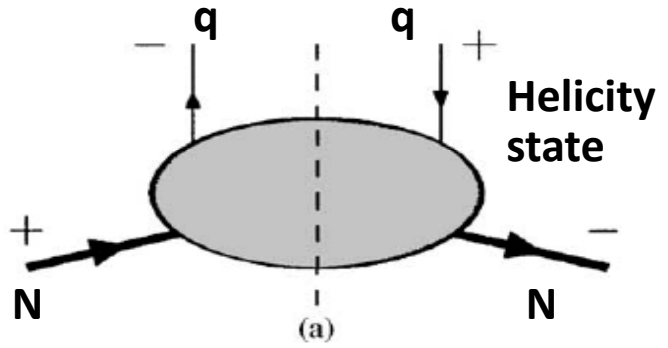
$S_L$, $S_T$: Target Polarization; $\lambda_e$: Beam Polarization

# Rich Physics in TMDs (Transversity)



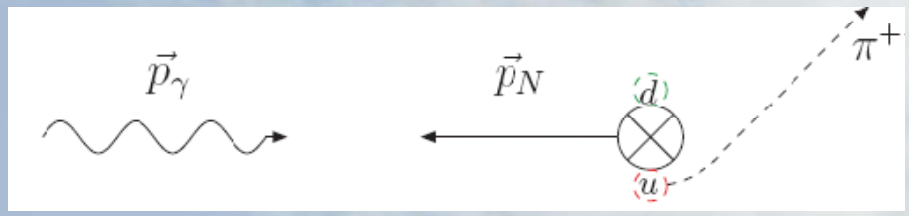

- Some characteristics of transversity
  - $h_{1T} = g_{1L}$ for non-relativistic quarks
  - No gluon transversity in nucleon
  - Chiral-odd → difficult to access in inclusive DIS
  - Soffer's bound
    - $|h_{1T}| <= (f_1+g_{1L})/2$

- *Tensor Charge:*
  - *Integration of transversity over x.*
  - *An important quantity of nucleon.*

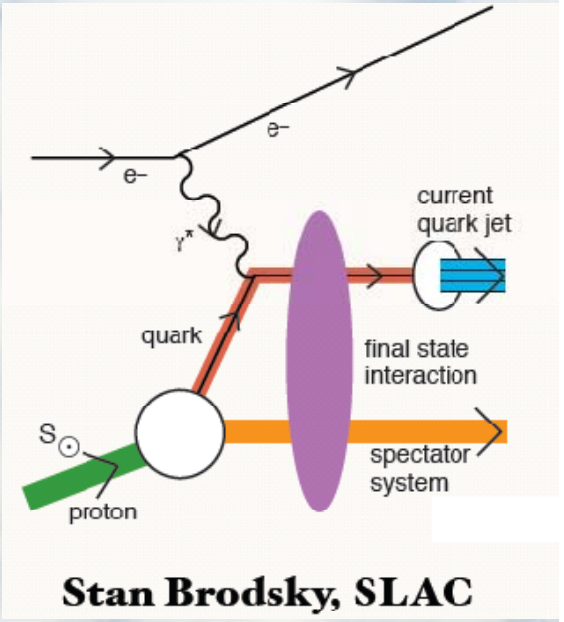


# Rich Physics in TMDs (Sivers Function)

- Correlation between nucleon spin with quark angular momentum ⇨ a new type distribution function
  - Parton orbital angular momentum?
- Matrix element related to anomalous magnetic moment.
- Naive T-odd, also moments
- Close physics relation with twist-3 quark-gluon correlation distribution at high $P_T$




Burkhardt : chromodynamic lensing



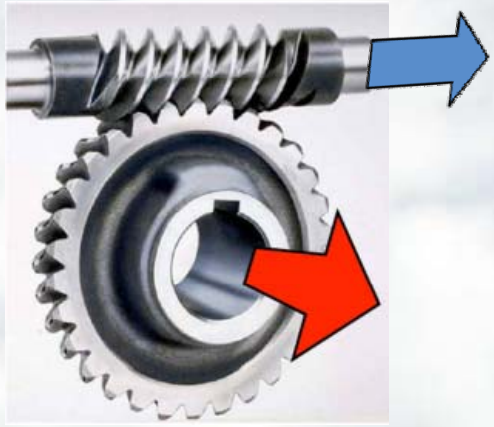

$$f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{D-Y}$$

Important test for Factorization

Final-State-Interaction

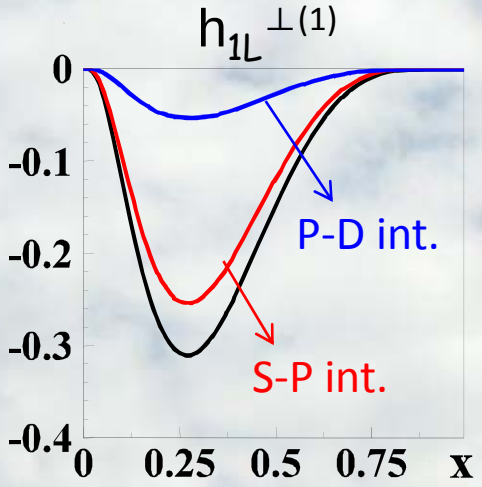
# Rich Physics with TMDs ("Worm-Gear" Functions)

$h_{1L}^{\perp}$ =  $g_{1T}$ = 



**Worm Gear**

- Dominated by real part of interference between L=0 (S) and L=1 (P) states
  - Imaginary part -> BM, Sivers function
- No GPD correspondence
  - Genuine sign of intrinsic transverse motion



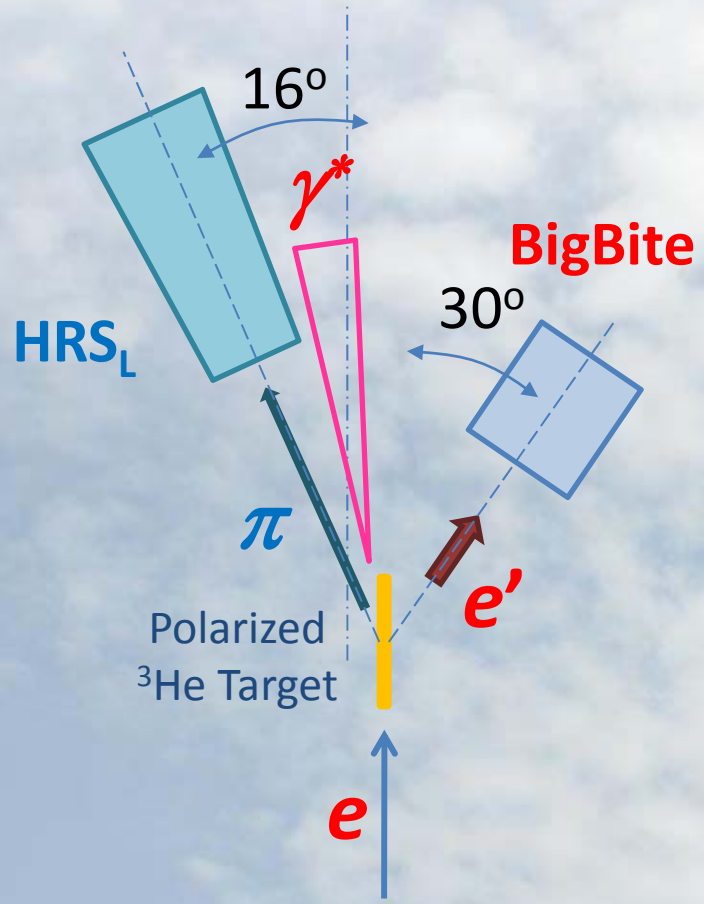

Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

- Lattice QCD -> Dipole Shift in momentum space.
- Model Calculations -> $h_{1L}^{\perp}$ =? $-g_{1T}$
- Connections with Collinear PDFs through WW approximation and LIR.

# Current Status on Transversity

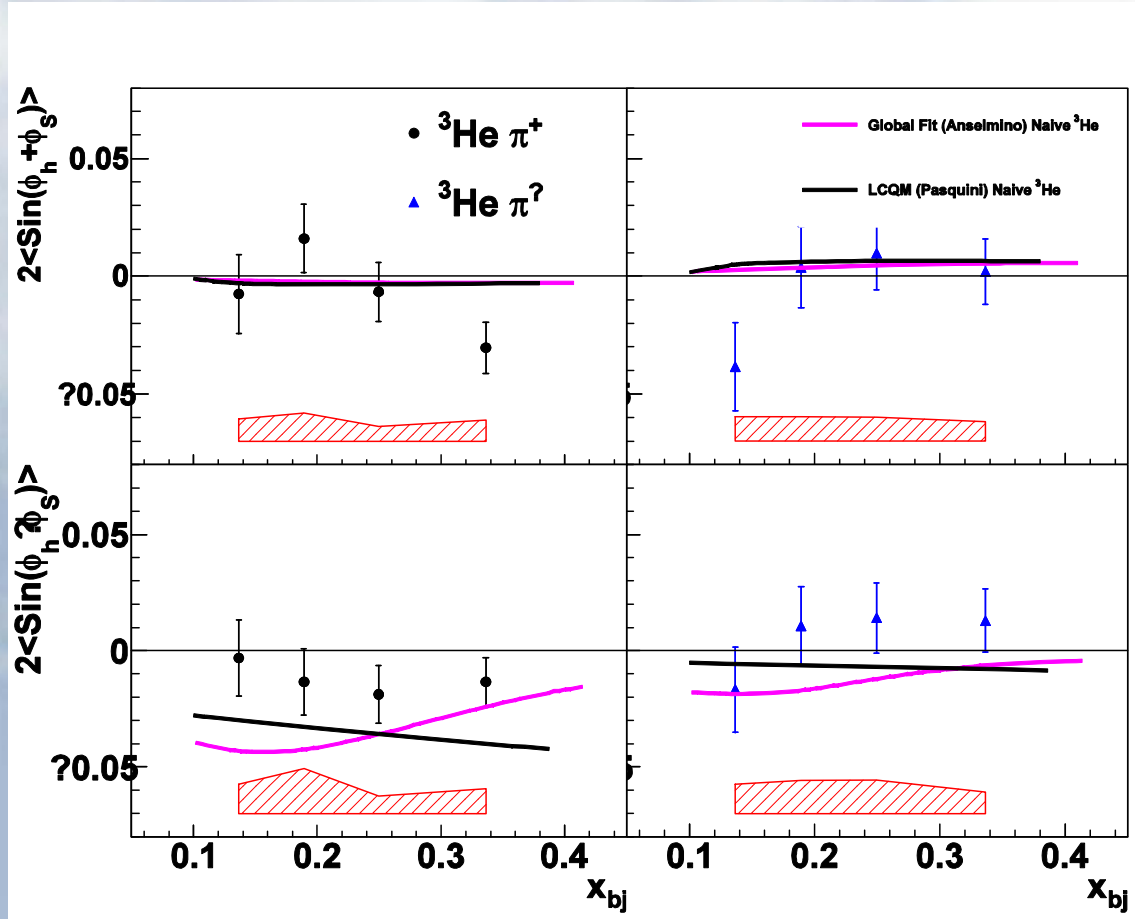
- Collins Asymmetries
  - sizable for proton (HERMES and COMPASS)
    Large at high x, large for $\pi^-$ ($\pi^-$ and $\pi^+$ has opposite sign)
    Unfavored Collins fragmentation as large as favored (opposite sign)
    Also see Belle's data.
  - consistent with 0 for deuteron (COMPASS)
- Sivers Asymmetries
  - non-zero for $\pi^+$ from proton (HERMES), consistent with COMPASS results at high $Q^2$?
  - consistent with zero for $\pi^-$ from proton and for $\pi^+$ and $\pi^-$ from deuteron
  - similar for $K^+$
- Very active theoretical and experimental study
  - **RHIC-spin, JLab (Hall A 6 GeV, CLAS12, HallA/C 12 GeV), Belle, FAIR (PAX) Future EIC**
  - Global Fits/models by Anselmino *et al.*, *Yuan et al.* and …

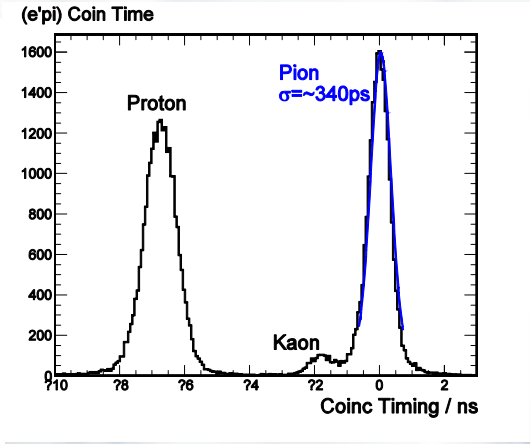
# E06-010 Experimental Setup

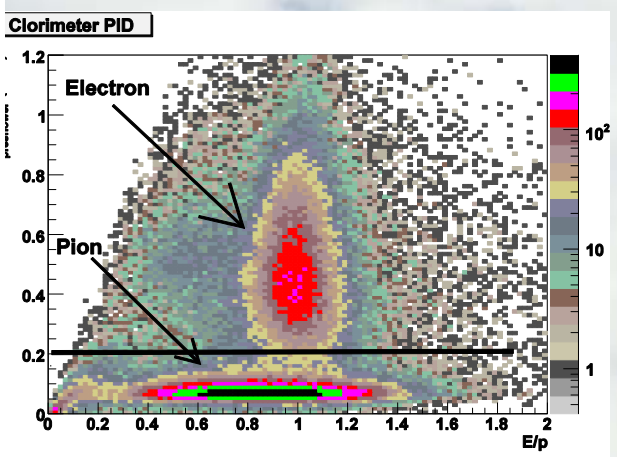



- Electron beam: E = 5.9 GeV
- 40 cm polarized $^3$He target
- BigBite at 30° to detect electron:
  - $P_e$ = 0.7 ~ 2.2 GeV/c
- $HRS_L$ at 16° to detect hadron:
  - $P_h$ = 2.35 GeV/c
- Measure Collins and Sivers asymmetries in valence range:
  - $x_B$ = 0.1 ~ 0.4

# Preliminary Results



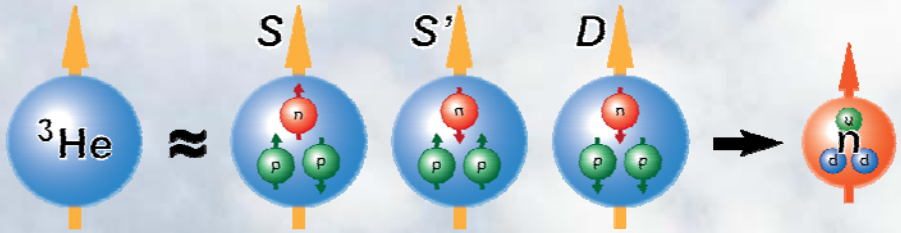




Finalizing the analysis on neutron. Submit the papers this spring! **Also $A_{LT}$!**

# SoLID Setup for SIDIS on $^3$He

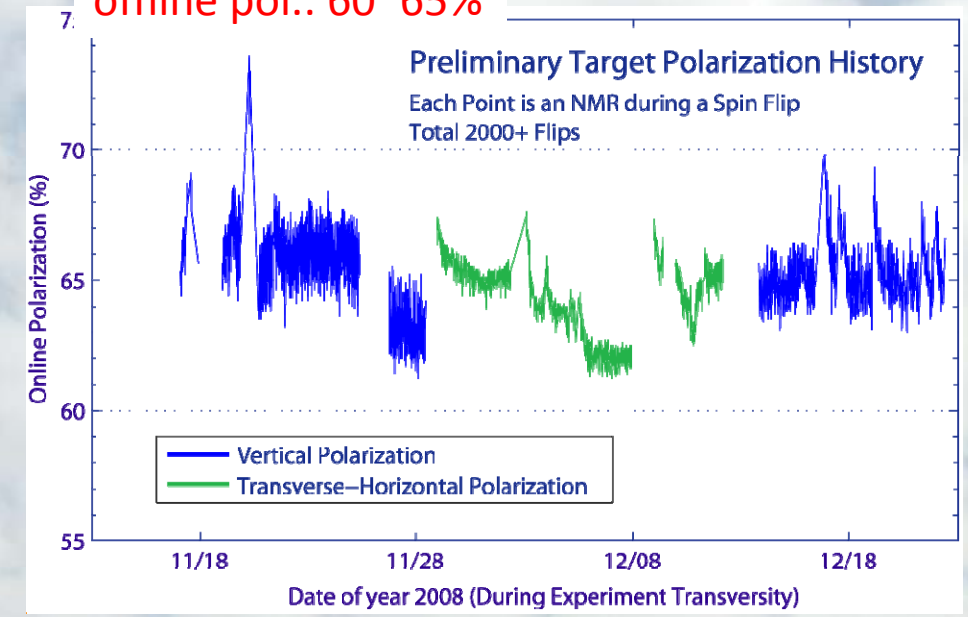
- Together with a high luminosity polarized $^3$He target.
  - Effective neutron target and the highest luminosity of polarized target.
- Large acceptance -> 4-D binning.
  - Observable depends on x, $Q^2$, z and $P_T$.
- Full azimuthal angular coverage -> smalller systematic uncertainties in SSA measurement and separation of different terms.
- Fixed-target experiment -> large-x (valence) physics

# Hall A Pol. $^3$He Target

- 

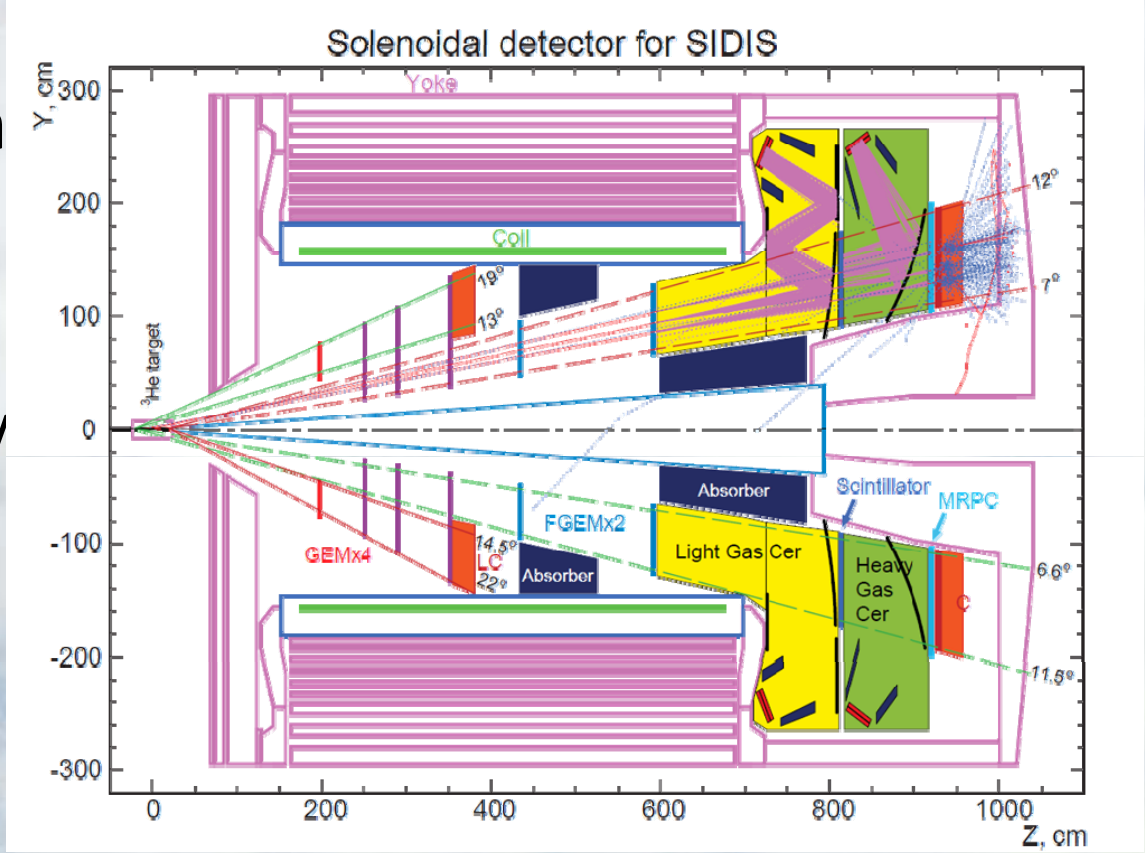

- Assuming achieved performance
- Supports both long. & trans. spin
- High polarization
- Frequent spin flip

offline pol.: 60~65%



# SoLID Setup for SIDIS on $^3$He

- Shared device with PVDIS:
  - GEM Tracker
  - Light Gas Cerenkov
  - Calorimeter
- Shared R&D in
  - GEM
  - Light collection in magnetic field.
  - Fast DAQ
  - New Calorimeter System

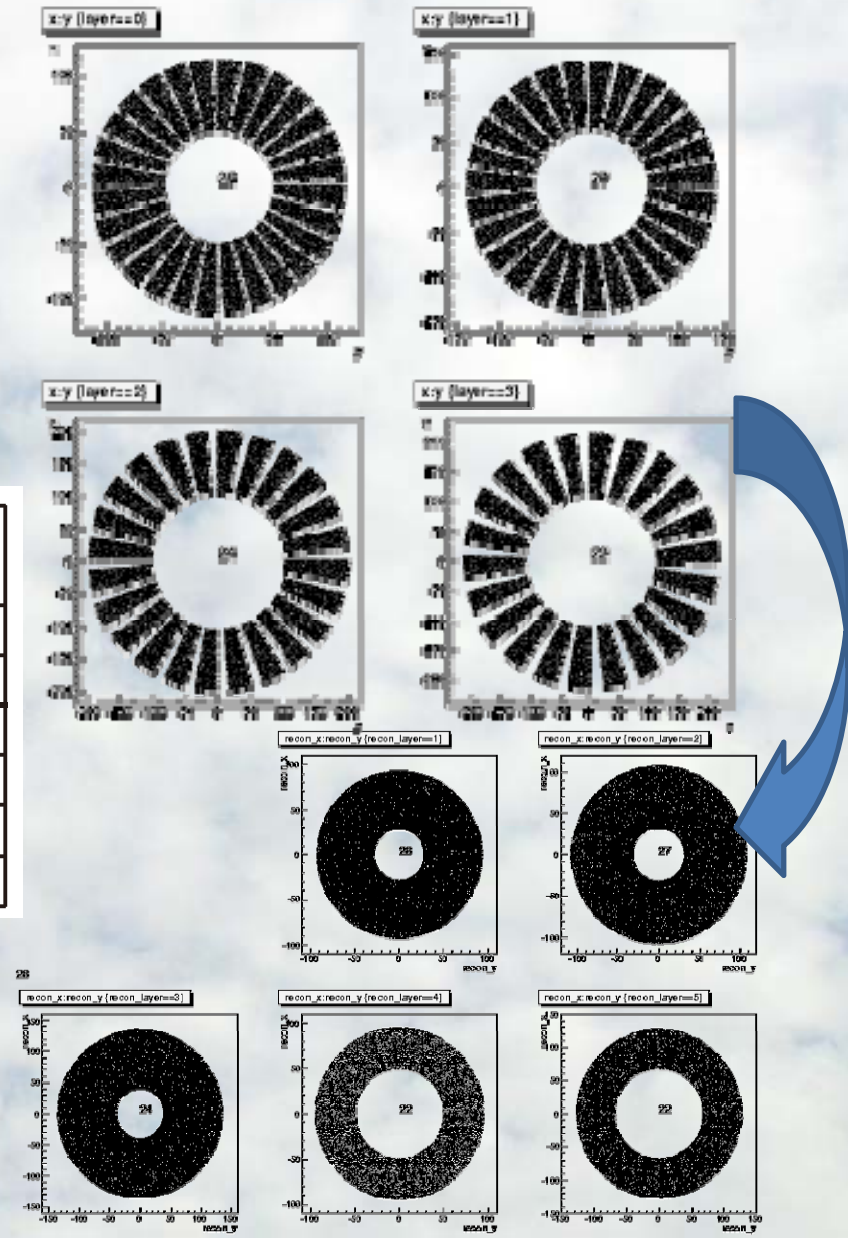



Additional devices of MRPC, scintillator plane, heavy gas Cerenkov which provide us the capability in hadron detection.

# Tracking with GEM detectors As an Example

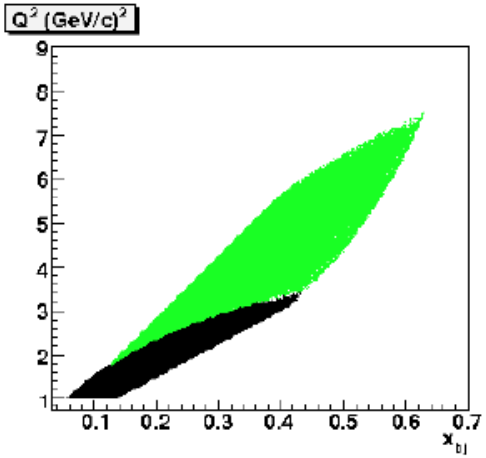
- 5 planes reconfigured from PVDIS GEM detectors (23 $m^2$ , gaps for baffles)
- Total surface for this experiment ~ 18 $m^2$
- Need to build the first plane 1.15 $m^2$
- Electronics will be shared

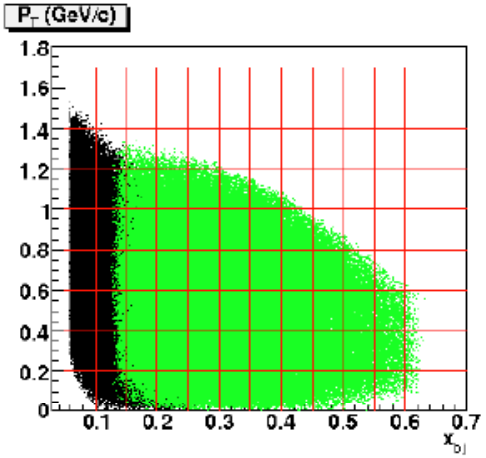
| | $R_{min}$ (cm) | $R_{max}$ (cm) | z (cm) | Status | PVDIS configuration (cm) |
|---|---|---|---|---|---|
| Chamber1 | 46 | 76 | 197 | New | N/A |
| Chamber2 | 28 | 93 | 250 | PVDIS C1 | 50-115 |
| Chamber3 | 31.5 | 107.5 | 290 | PVDIS C2 | 64-140 |
| Chamber4 | 39 | 135 | 352 | PVDIS C3 | 104-200 |
| Chamber5 | 49 | 95 | 435 | PVDIS C4 | 109-215 |
| Chamber6 | 67 | 127 | 592 | PVDIS C4 | 109-215 |

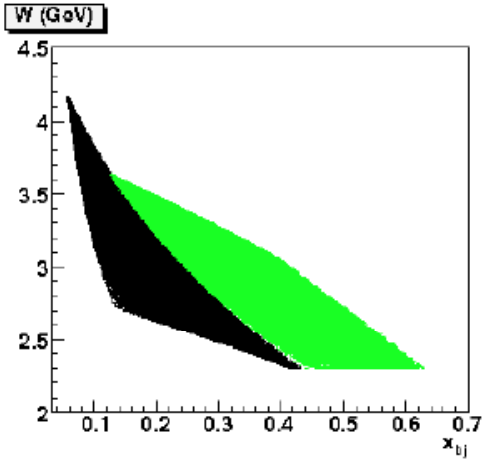


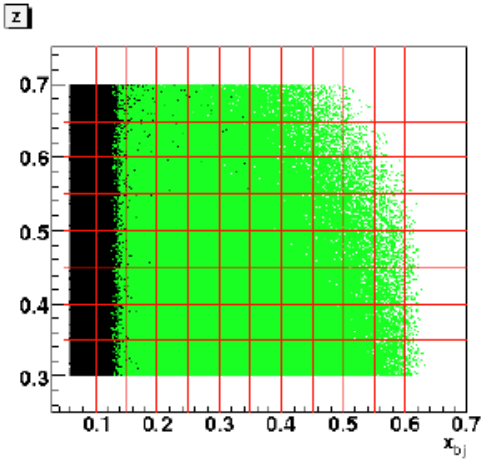
# Kinematic Coverage

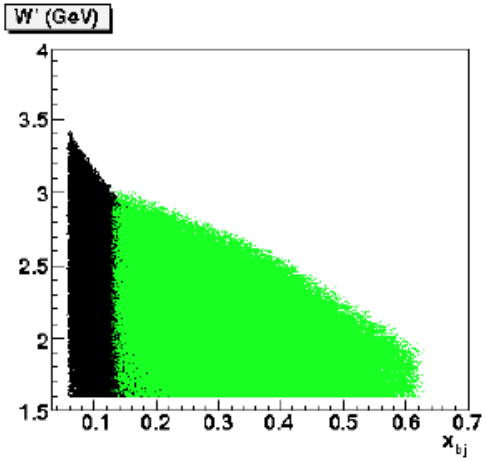
- Precision 4-D ($x$, $Q^2$, $p_T$ and $z$) mapping of Collins, Sivers and pretzelosity.
- **Coverage with 11 GeV beam**
  - Black: forward angle
  - **Green: large angle**
- $x_B$: 0.05 ~ 0.6
  - Majority of valence quark region for tensor charge
- $Q^2$: 1 ~ 7.5 $(GeV/c)^2$
- $P_T$: 0 ~ 1.5 GeV/$c$
- W: 2.3 ~ 4 GeV
- z: 0.3 ~ 0.7
- $M_m$: 1.6~ 3.3 GeV

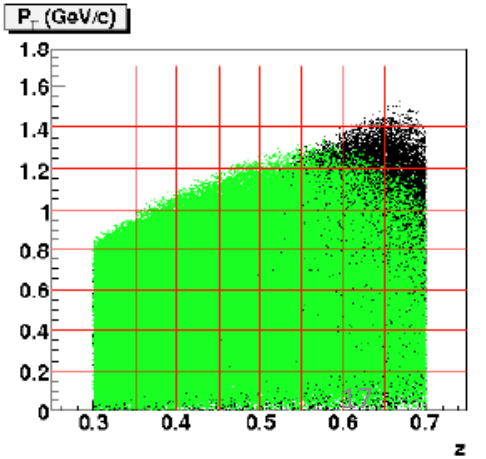


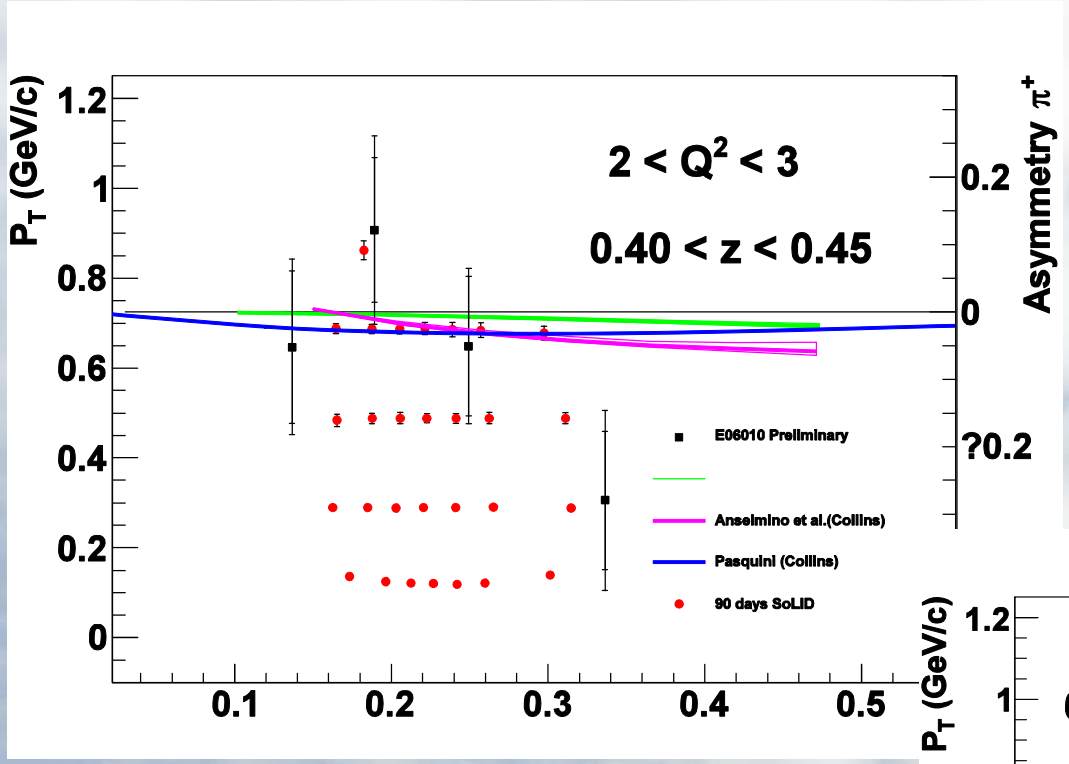



# Projections on Collins/Sivers Asymmetry (90 Days)

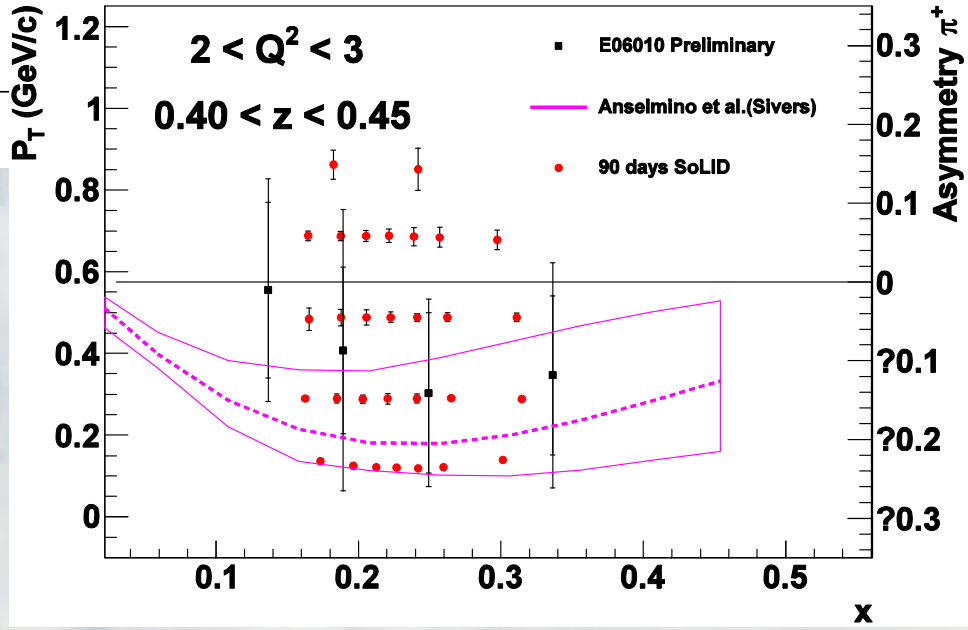



Black points: E06-010 SSA preliminary @ 6 GeV Kinematics.

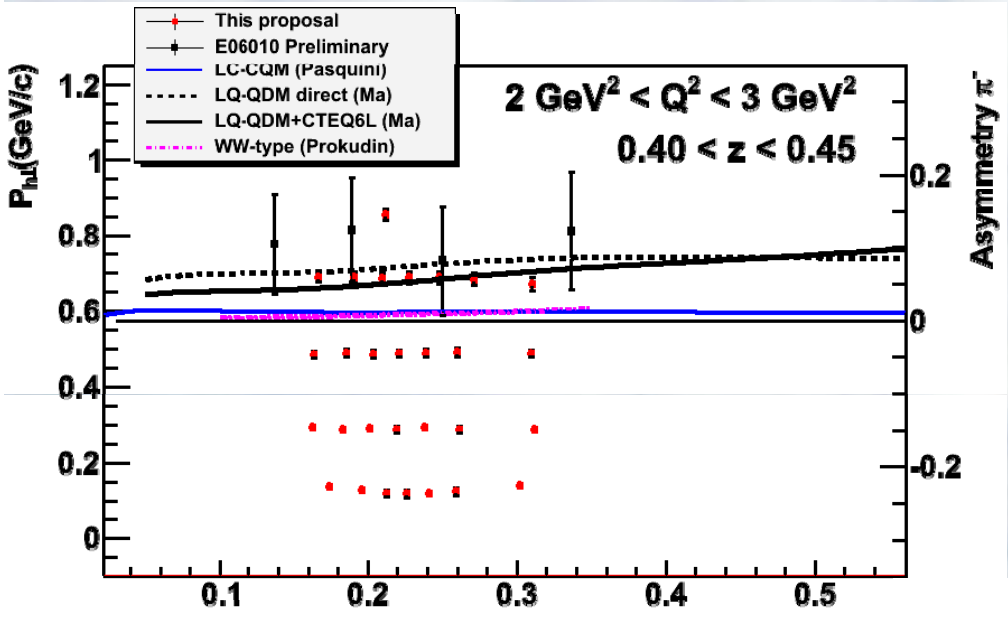
Similar precision for Pretzlosity terms.

Similar plots for longitudinal case.

One of the major goals: Transversity Distribution!



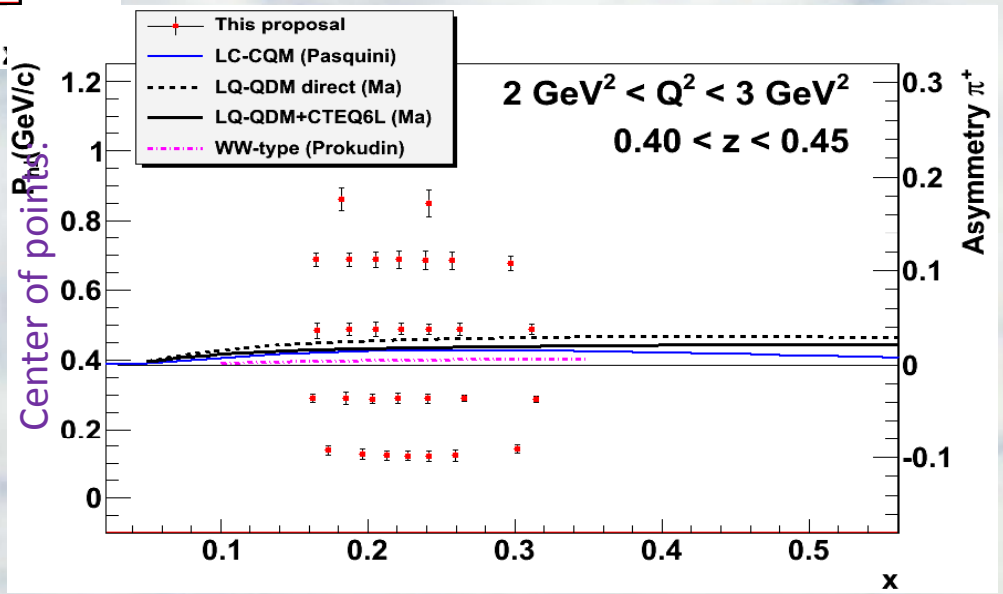
# Longitudinal Target Polarization (35 days)



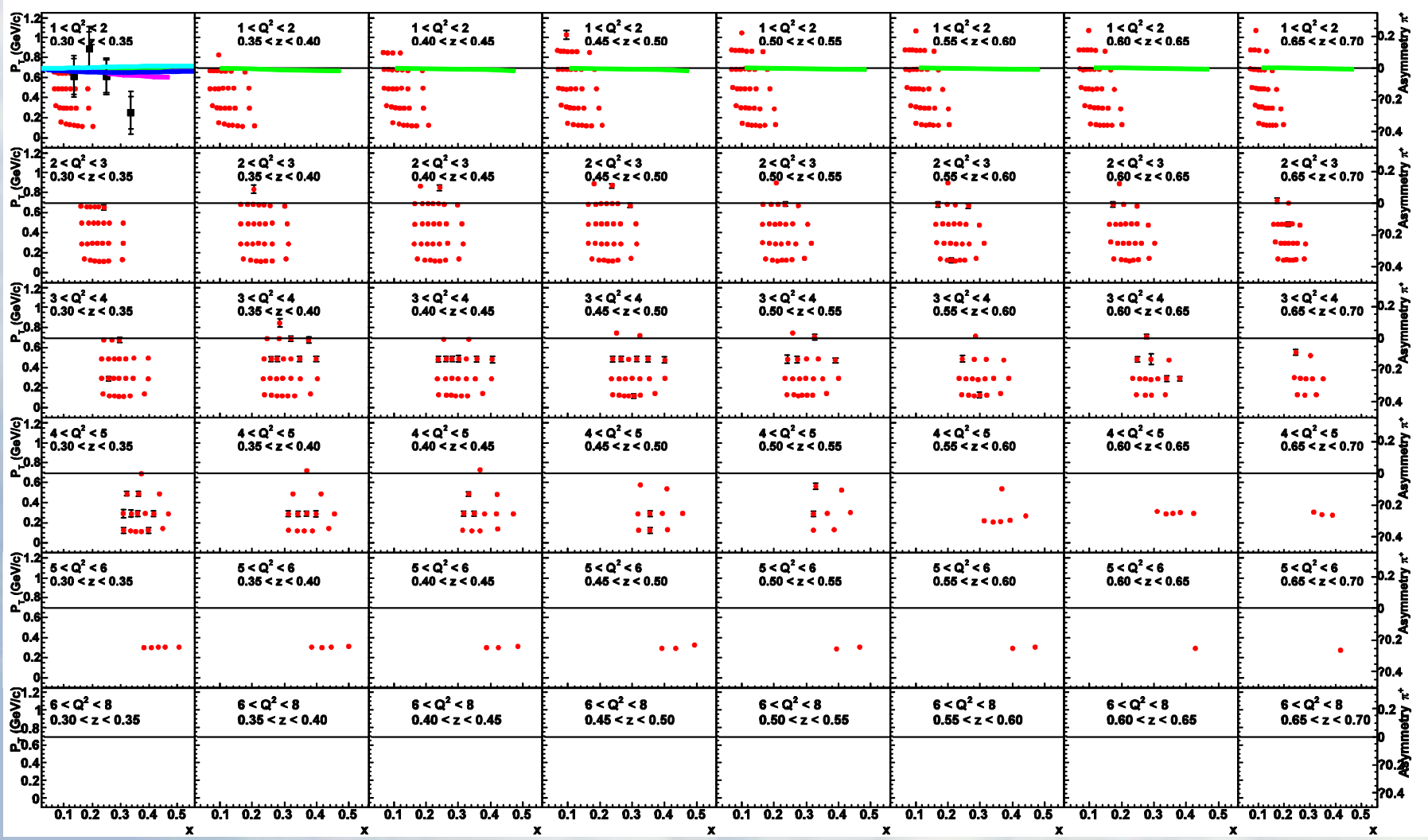

- $A_{LT}$, Strong theory supports
- 4 sets of predictions calculated for this proposal
- 6 GeV data from E06-010

E11-007 in PAC 37

$A_{UL}$, and also $A_{LL}$



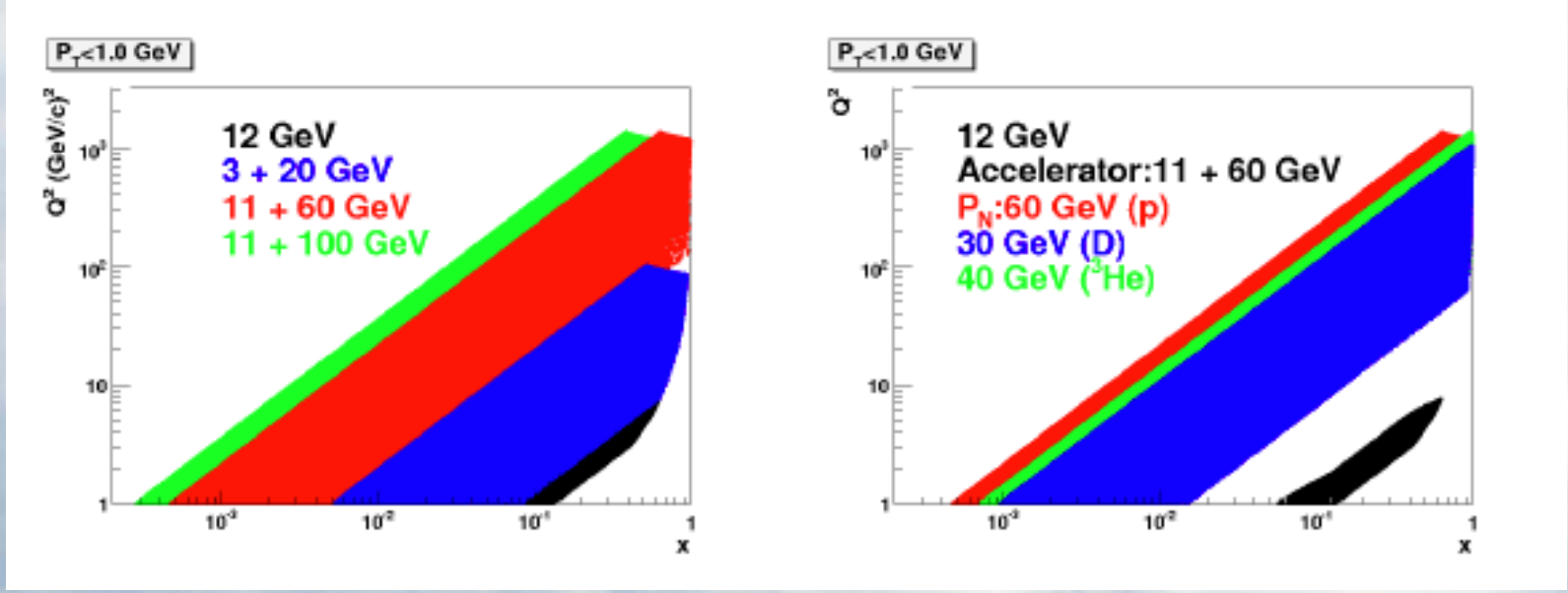
# 4-D Mapping of SSA




Mostly limited to low $P_T$, Ultimate 4-D precision for valence quark TMDs. Acceptance at low and high z to study target fragmentation and exclusive channels.

# Bright Future for TMDs

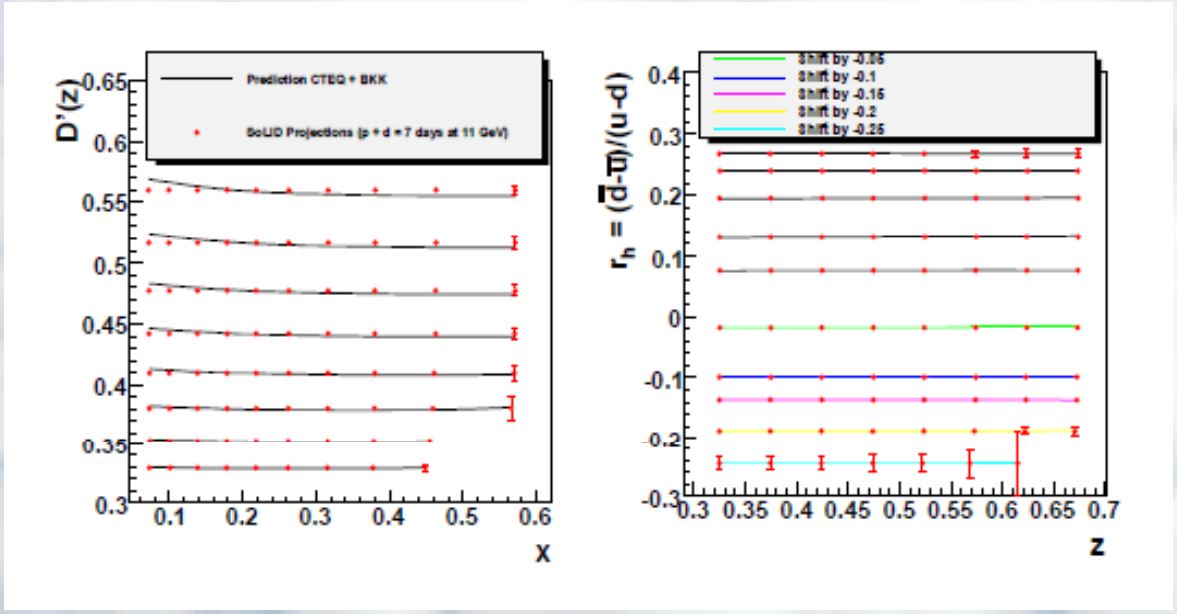
- Golden channel of Electron-Ion Collider



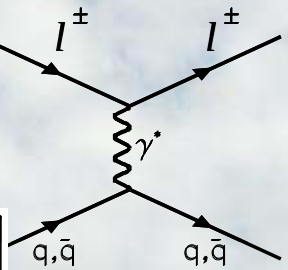

- Sea quark TMDs
- Gluon Sivers? What happened at very low x? SIDIS vs. dipole model
- Test Collins-Soper Evolution for high vs. low $Q^2$ at large x.

# Also Factorization Test of SIDIS

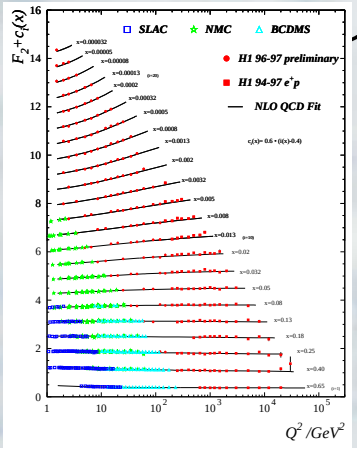
- Factorization test in Collinear picture at exact kinematics from hydrogen, deuterium and $^3$He
- Proton, Deuteron, and $^3$He are Essential for possible nuclear correction.

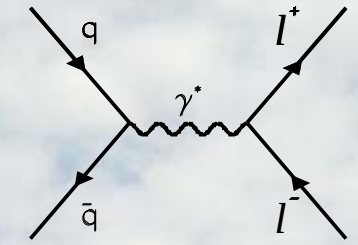


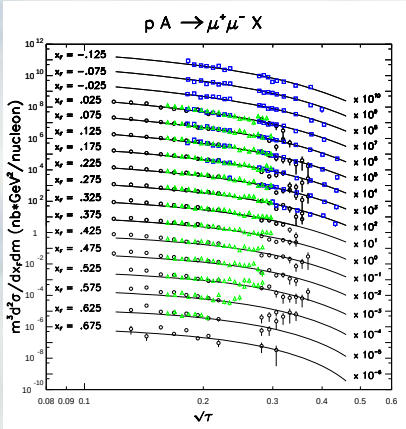

DIS




Drell-Yan



# Future Possibilities

- Transverse Proton Target on TSSA?
- Nuclear Target -> Parton Propagation/Hadronization mechanism in the cold nuclear medium
- PVRES in both inclusive and SIDIS channel
  - MAID model in the weak sector?
  - Potential importance to neutrino community.
- Other ideas?

# Summary

- SIDIS is a powerful tool to study Parton dynamics in the amplitude level (TMDs)
  - Spin-OAM correlation, flavor dependence etc.
- SoLID is an ideal device to study SIDIS
  - High luminosity, large acceptance and full azimuthal coverage
  - Will provide ultimate precision (4-D) of SSA, at high-x (valence), low $Q^2$ region, which is crucial input to global analysis.
- Integrated Effort in SoLID R&D with PVDIS!