SoLID SIDIS Program

Sanghwa Park
(Stony Brook University)
for the SoLID Collaboration

Solenoidal **L**arge **I**ntensity **D**evice

Take full advantage of JLab 12 GeV Upgrade:

A high luminosity (10^{37}-10^{39}) and large acceptance detector with full azimuthal coverage

Rich physics program to address important fundamental questions in nuclear physics:

Nucleon structure and proton mass

Fundamental symmetries

5 highly rated experiments approved + 4 run group experiments

Strong and growing collaboration:

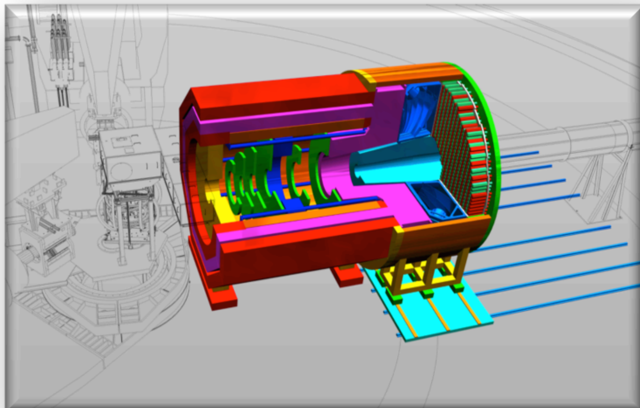
300 collaborators from 72 institutions, 13 countries

Significant international contributions (China, Canada)

Solenoidal Large Intensity Device (SoLID) Physics

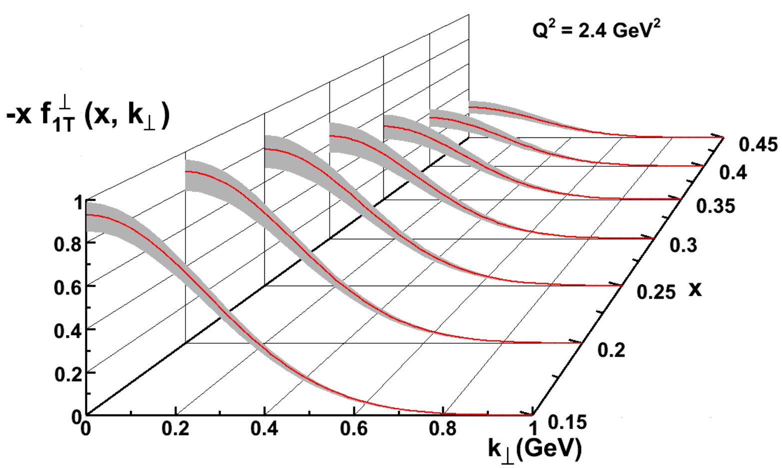
SoLID provides unique capability:

- ✓ high luminosity ($10^{37\text{-}39}$)
- ✓ large acceptance with full ϕ coverage

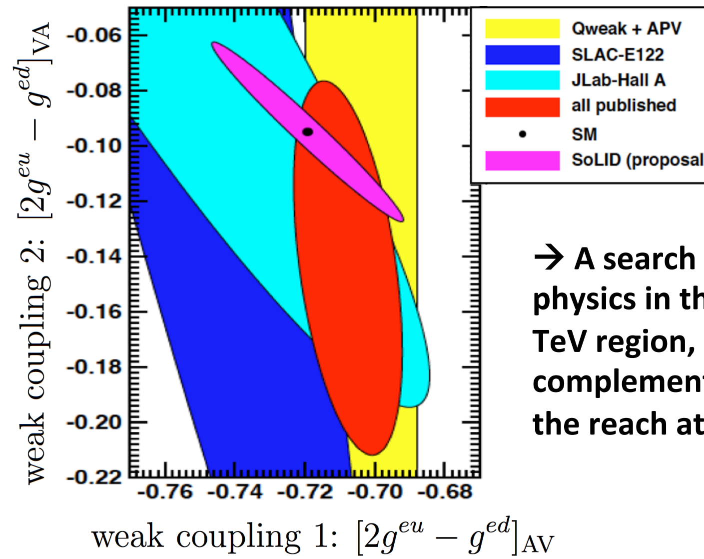


→ multi-purpose program to maximize the 12-GeV science potential

1) Precision in 3D momentum space imaging of the nucleon

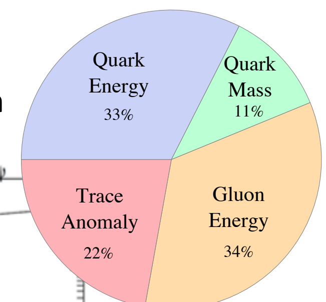


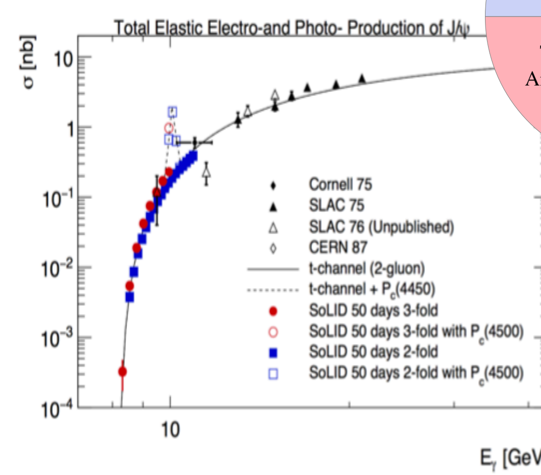
2) Precise determination of the electroweak couplings



→ **A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.**

3) J/ψ production cross section





→ **Constrain the QCD trace anomaly, Proton mass , LHCb charmed pentaquark**

SoLID Physics Program

- **SIDIS program:**

E12-10-006: Single Spin Asymmetry in SIDIS on Transversely Polarized 3He (90 days)

E12-11-007: Single and Double Spin Asymmetries in SIDIS on Longitudinally Polarized 3He (35 days)

E12-11-008: Single Spin Asymmetry in SIDIS on Transversely Polarized Proton (120 days)

+ Run groups: Dihadron (E12-10-006A), Ay (E12-11-108A/E12-10-006A)

- **PVDIS experiments:**

E12-10-007: Parity Violating Asymmetry in DIS with LH2 and LD2 (169 days)

- **J/psi program:**

E12-12-006: Near Threshold Electroproduction of J/psi at 11 GeV (60 days)

+ Run group: Time-Like Compton Scattering (E12-12-006A)

- **GPD program:**

Run group: Deep Exclusive pion production with polarized 3He target and SIDIS configuration (E12-10-006B)

DDVCS on proton (LOI12-12-005), DVMP under development

Leading Twist TMDs

→ Nucleon spin
→ Quark spin

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	$h_{1L}^{\perp}$ = − Worm Gear (Kotzinian-Mulders)
T	$f_{1T}^{\perp}$ = − Sivers	g_{1T} = − Worm Gear	h_1 = − Transversity $h_{1T}^{\perp}$ = − Pretzelosity

SoLID SIDIS Program

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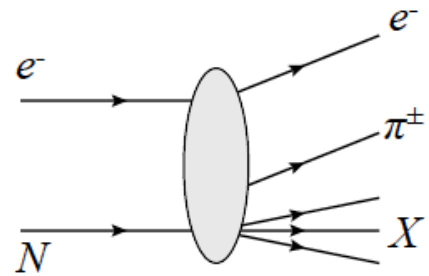
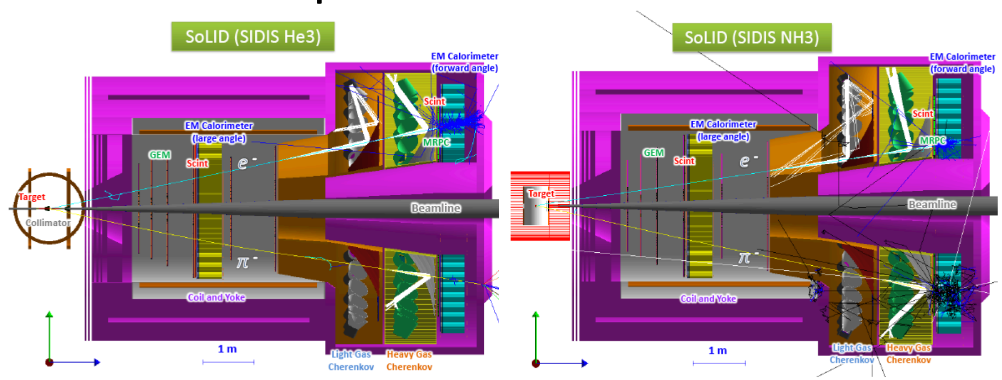


- Highly rated pion SIDIS experiments approved
- 4-dimensional binning with high statistics and well controlled systematics
- Strong collaboration with theorists - impact studies of the SoLID physics

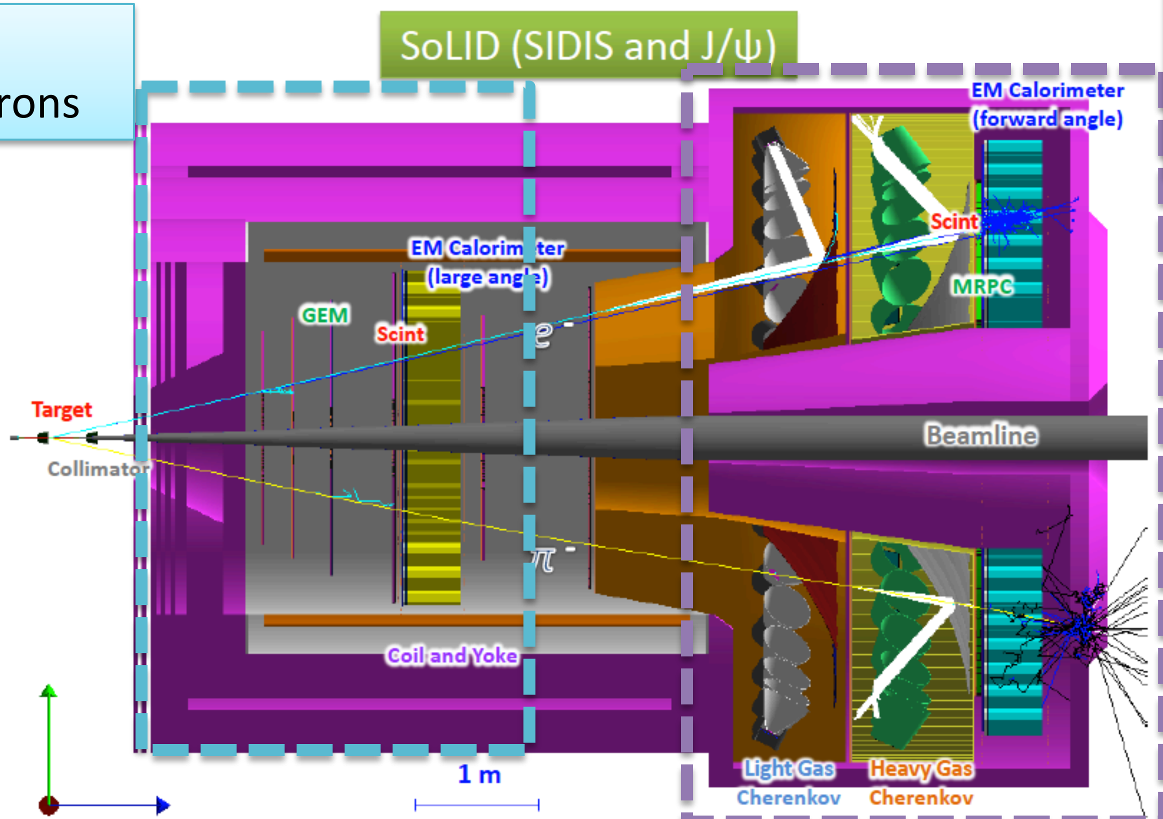


SoLID-SIDIS Configuration

Large-Angle:
Detect electrons

Forward-Angle:
Detect electrons
and hadrons

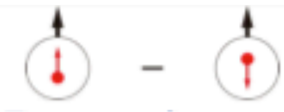
Polarized
3He and NH3
targets



e/π± Coverage: → Forward-Angle: $0 < \phi < 2\pi$, $8° < \theta < 14.8°$, $1 < P < 7$ GeV/c
→ Large-Angle: : $0 < \phi < 2\pi$, $16° < \theta < 24°$, $3.5 < P < 7$ GeV/c (e only)

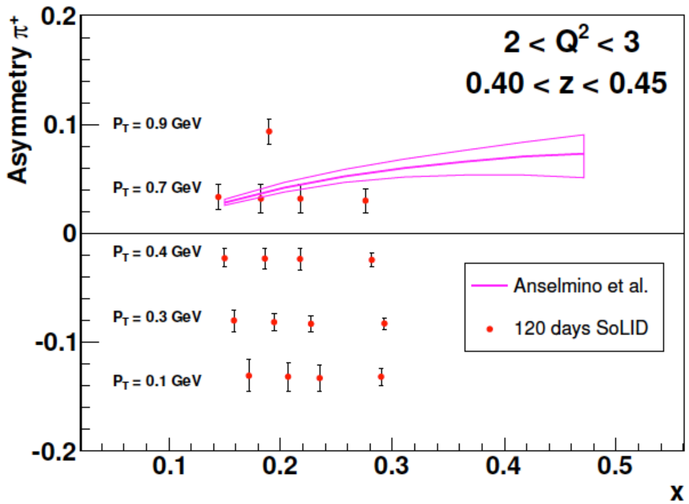
K± Coverage: Same as pions, maximum momentum is limited by TOF time resolution

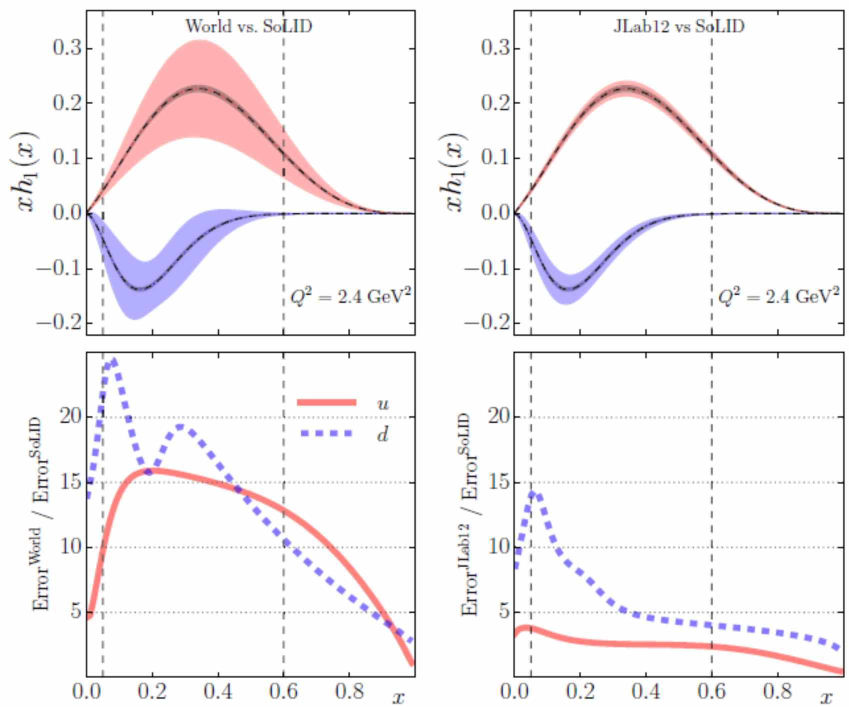
Resolution: $\delta P/P \sim 2\%$, $\theta \sim 0.6$ mrad, $\phi \sim 5$ mrad



Transversity

- One of three parton distribution functions
- Least known due to its chiral odd nature
- Experimentally observed in combination with additional spin dependent final state effects (e.g Collins FF)
- Collins asymmetries ~ Transversity x Collins FF $A_{UT}^{\sin(\phi_h+\phi_S)} \sim h_1(x,k_\perp) \bigotimes H_1^\perp(z,p_\perp)$
- Also Transversity via Interference FF (Dihadron run group experiment)



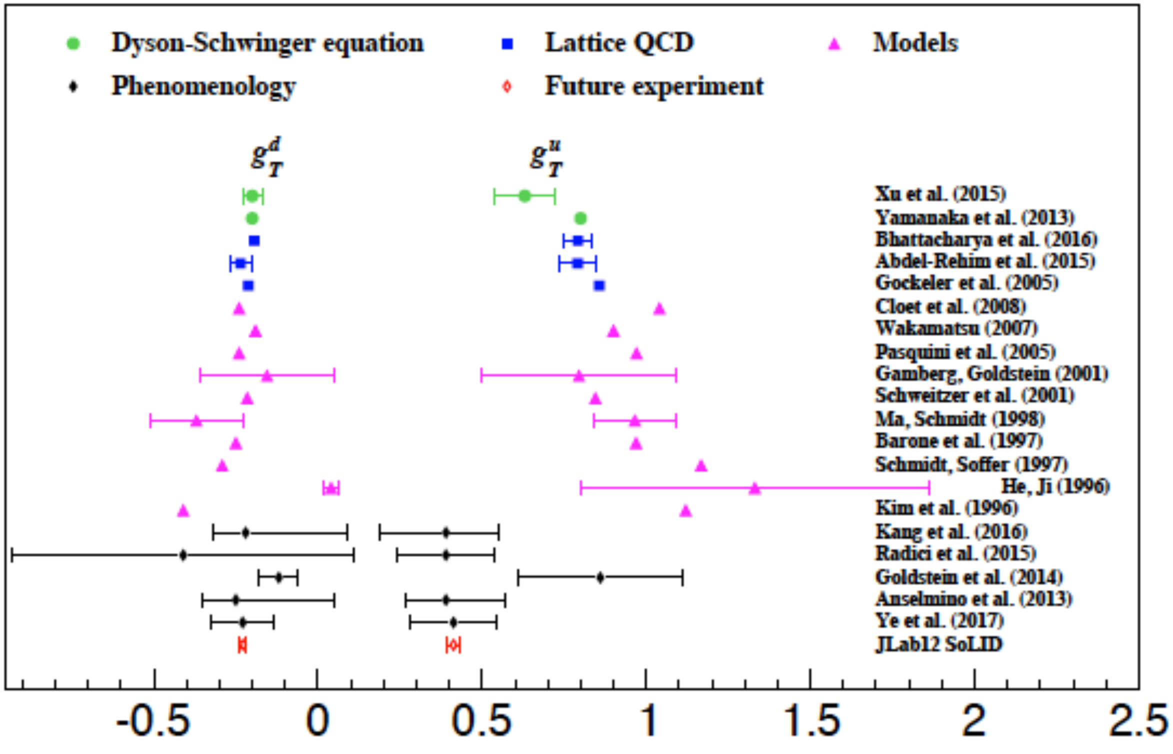


- Impact study with SoLID Collins asymmetries and e+e- data from BELLE and BABAR
- TMD evolution included

Tensor Charge

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = g_T^q\,\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S)$$

- Lowest moment of transversity $\delta_T q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x)\right] \mathrm{d}x$
- Fundamental quantity of nucleon. Valence quark dominant.
- Provide constraints on quark EDMs



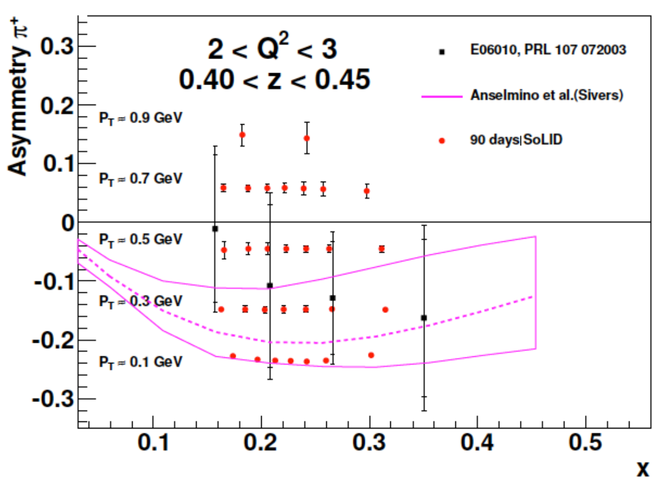
SoLID Impact on Sivers

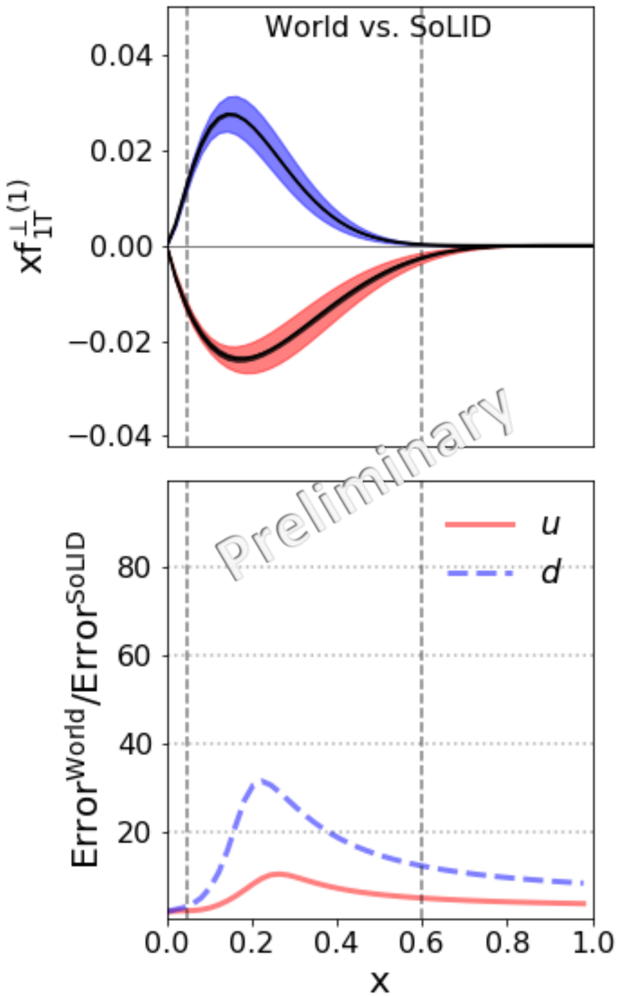
- Sivers distribution

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

- Relates to intrinsic parton motion
→ connected to orbital momentum
- Sivers sign change: Important test for QCD factorization

$$f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x,k_T,Q^2) = -f_{q/h^\uparrow}^{\mathrm{DY}/W^\pm/Z}(x,k_T,Q^2)$$





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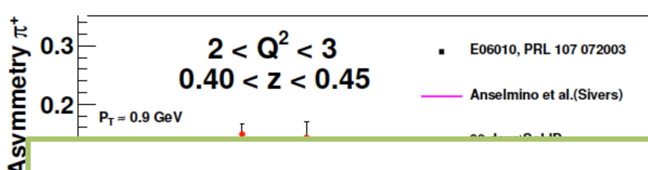
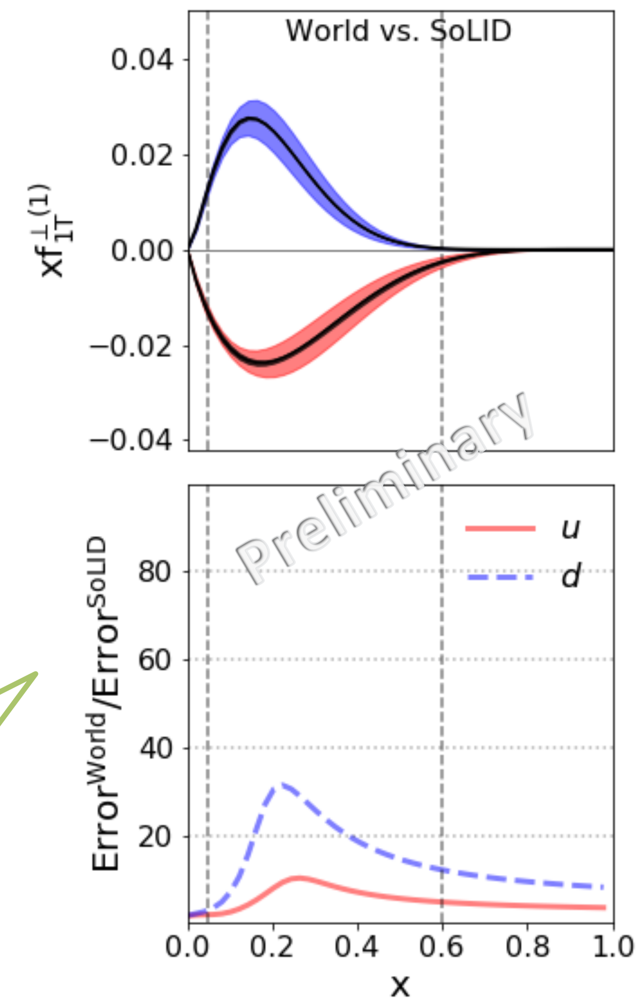


- Monte Carlo method with nested sampling algorithm
- TMD evolution is not included



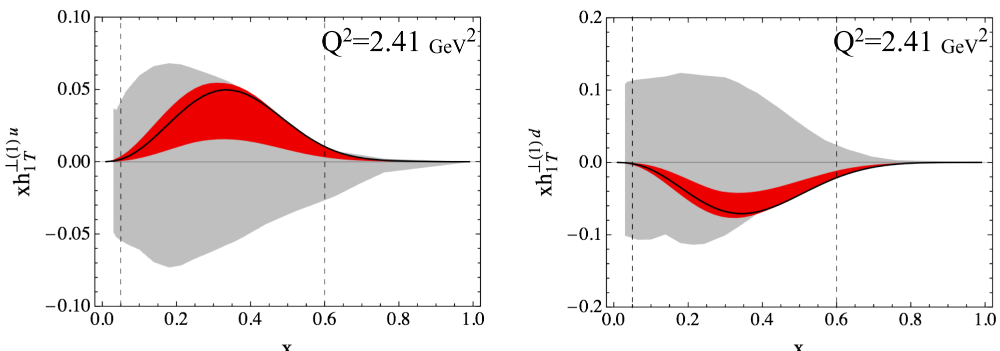
Pretzelosity

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

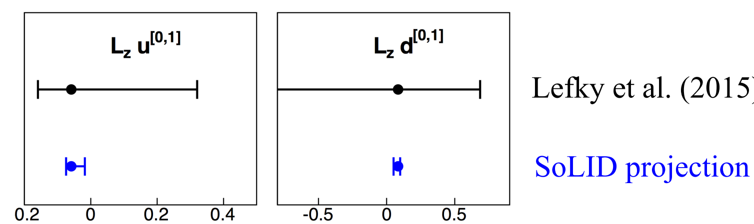
- Measure relativistic effects of quark
- Interference of light-front wave functions differing by ΔL = 2
- Related to OAM (model dependent)

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

Also, Worm-gear: Interference between L=0 and L=1 states

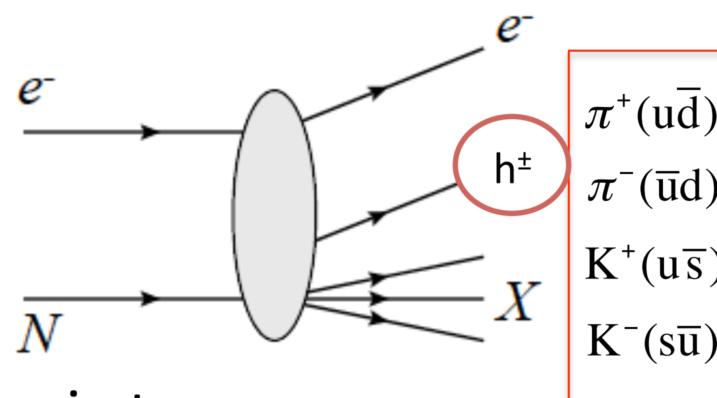


95% C.L.
parametrization by C. Lefky et al., PR D 91, 034010 (2015).
SoLID projection with transversely polarized neutron and proton data.

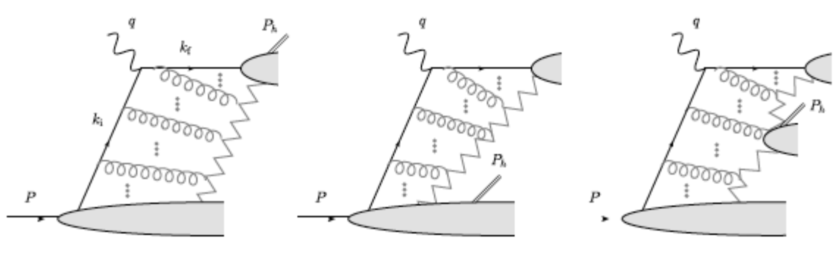


Kaon SIDIS Program

- Provide important input to separate contributions from all light flavors combined with pion measurements
- Unique sensitivity to sea quarks

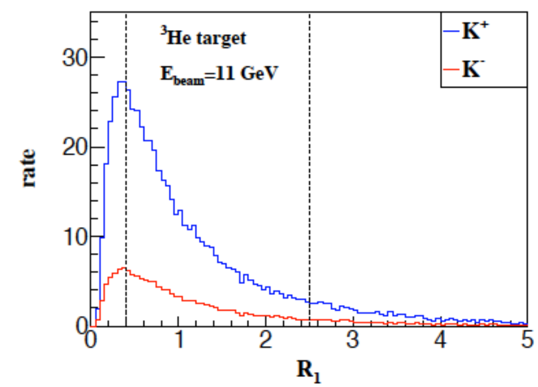


- Recent theory development on a criteria to separate fragmentation regions: [Phys. Lett. 639 B 766, 245 (2017)])



(a) (b) (c)

$$R_1 = \frac{P_h \cdot k_f}{P_h \cdot k_i}$$



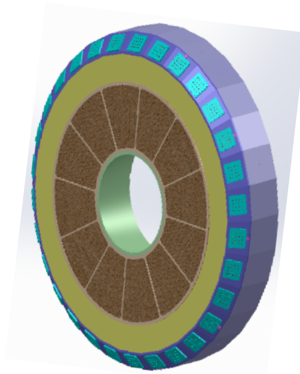
- 20% of data from Current fragmentation region

Kaon SIDIS Program

- New run group proposal submitted to PAC46
- Run in parallel with already approved SoLID experiments with existing experimental setups
- Extract the Kaon Collins, Sivers, and other TMD asymmetries in offline analysis
- K/π separation up to 7 GeV/c with Heavy Gas Cherenkov and MRPC TOF detectors

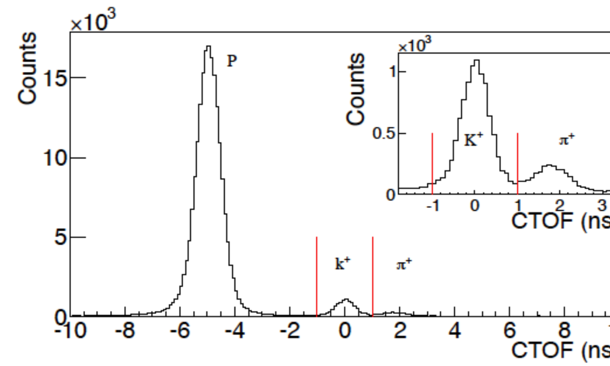
Kaon Identification

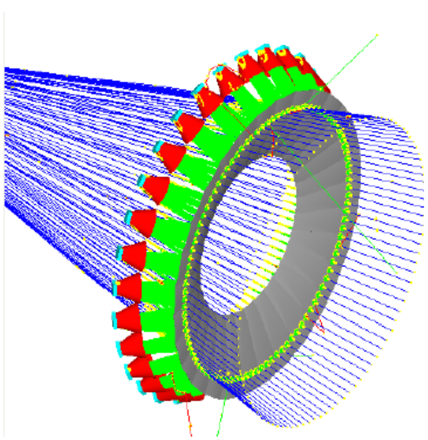
- Combination of the Heavy Gas Cherenkov and MRPC
- Heavy Gas Cherenkov:



U of Regina is producing one sector from their R&D grant

Hall A 6 GeV Transversity experiment →





- The HGC uses C4F8O/C4F10 gas at 1.5 atm under 20 C
- Designed for pi/K separation from 2.2 GeV/c to 7 GeV/c
- During the offline analysis, the veto signals of the HGC can suppress pions and detect kaons
- Preliminary Geant4 simulation study shows that the HGC can suppress pions by 1/100 at 2.5 GeV/c and by 1/400 at 7 GeV/c

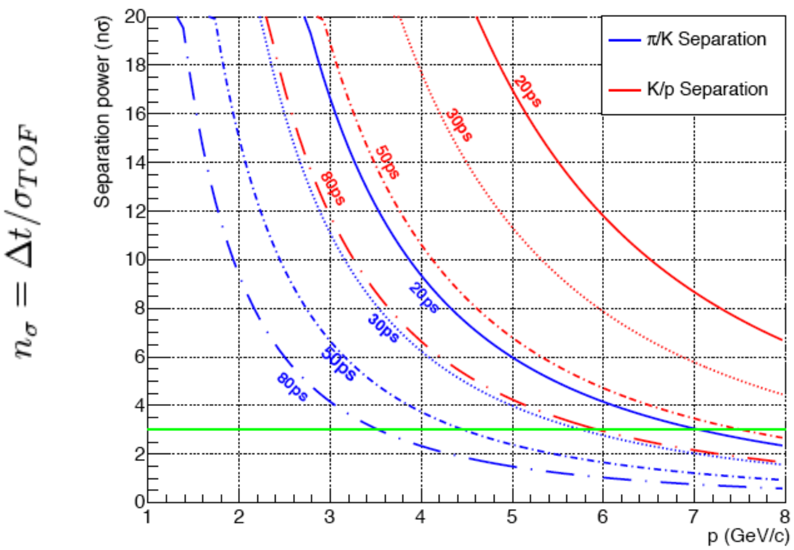
Kaon Identification

- Combination of the Heavy Gas Cherenkov and MRPC
- MRPC Time of Flight (TOF) detector:

The TOF-Beta has been a powerful quantities to perform PID

Particles with same momenta but different masses spend different amount of time when travelling the same distance:

$$\Delta t = t_1 - t_2 \simeq \frac{Lc}{2p^2}(m_1^2 - m_2^2))$$



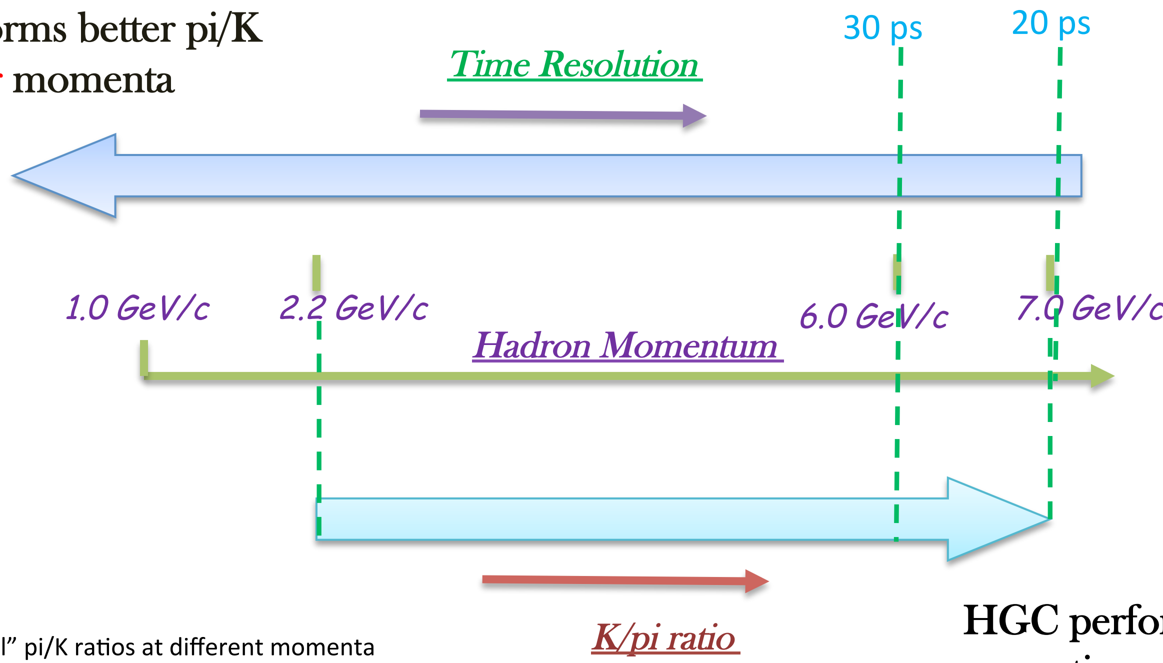
Clean separation of Kaons and protons even with 50 ps time resolution up to 7 GeV/c

pi/K up separation up to 7 GeV/c with 20 ps time resolution and 6 GeV/c with 30 ps time resolution.

R&D progress from the Chinese collaboration
- Recent cosmic test shows ~27 ps time resolution
- Further improvement in electronics and reconstruction method as well as in-beam test plan

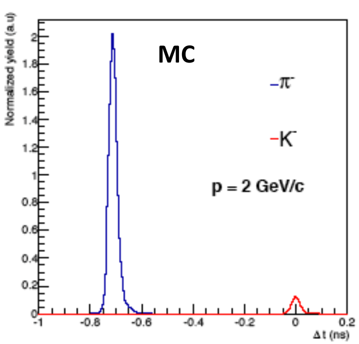
Kaon Identification

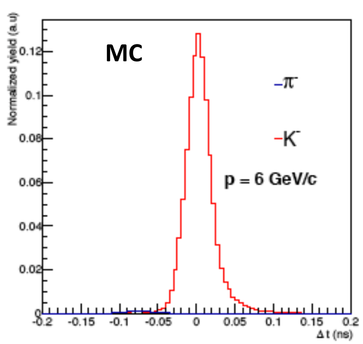
MRPC-TOF performs better pi/K separation at lower momenta



HGC performs better pi/K separation at higher momenta

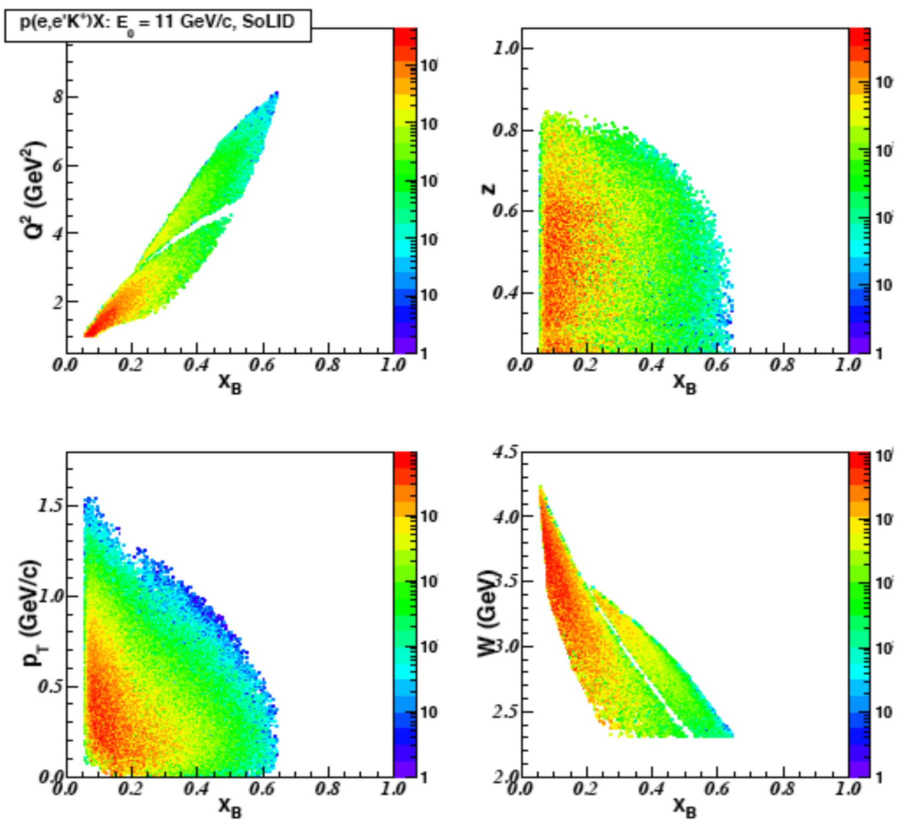
Take into account the "actual" pi/K ratios at different momenta
+ the HGC suppression factors on pions



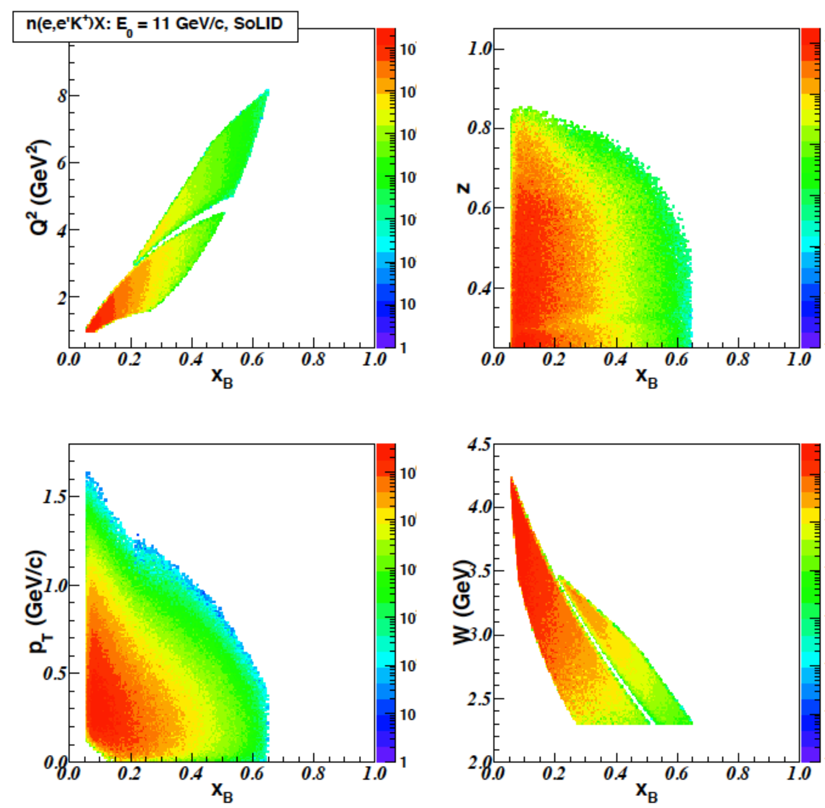


Kinematic Coverage

SoLID-SIDIS with NH3 at 11GeV

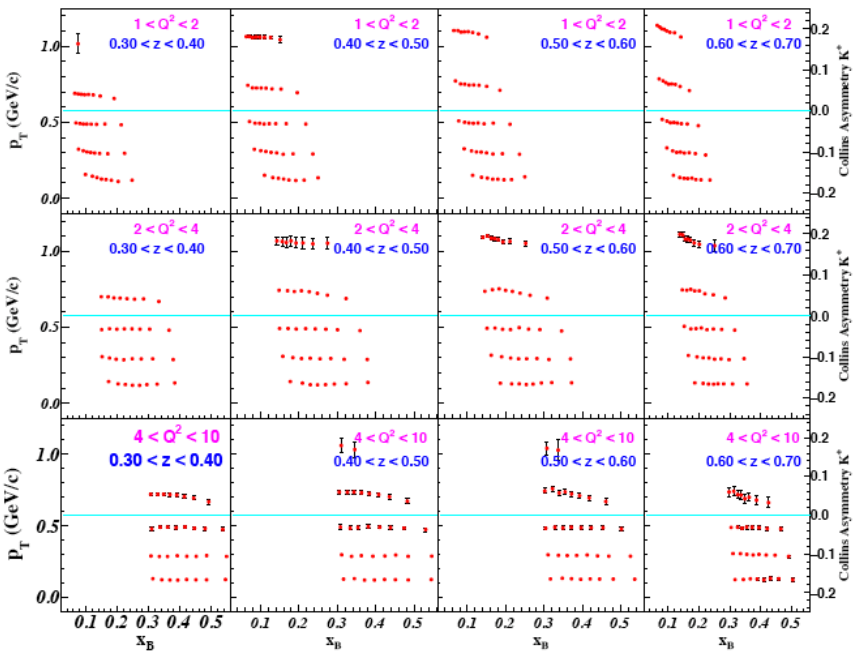


SoLID-SIDIS with He3 at 11GeV

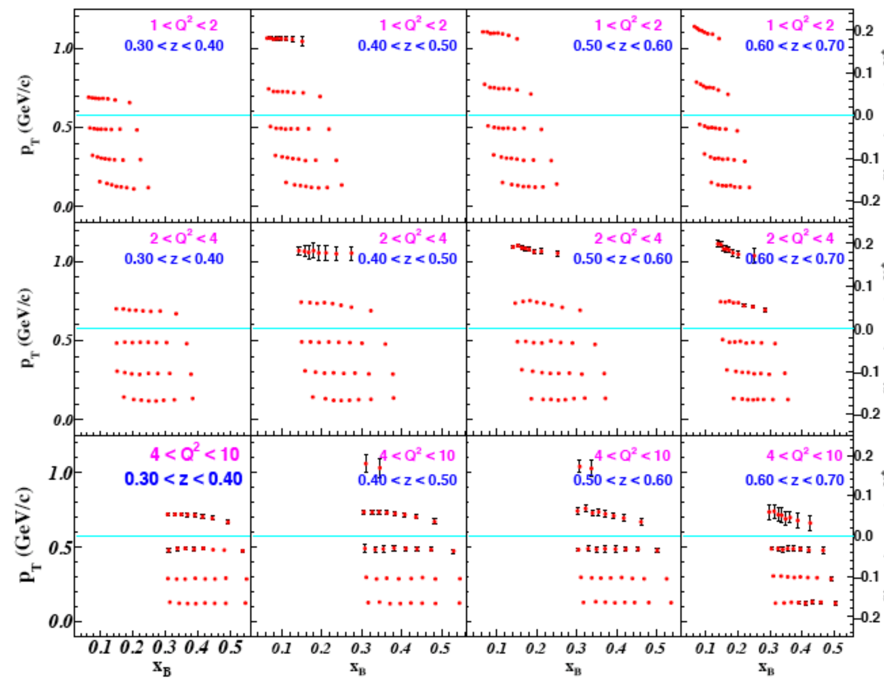


3He Projection

- 4D binning (Q^2, z, pT, x) for He3 setup
- Total 430 bins



(a) $\vec{n}(e, e'K^+)X$



(a) $\vec{n}(e, e'K^+)X$

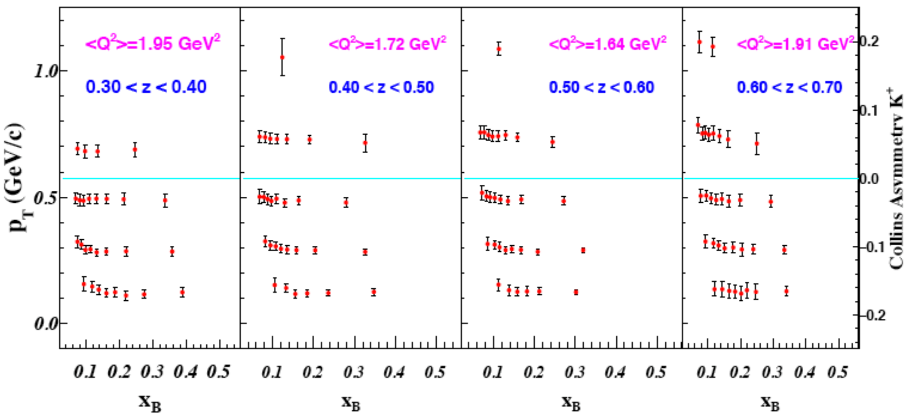
- Kinematic cuts applied:

$Q^2 > 1$ GeV^2, W > 2.3 GeV, W' > 1.6 GeV

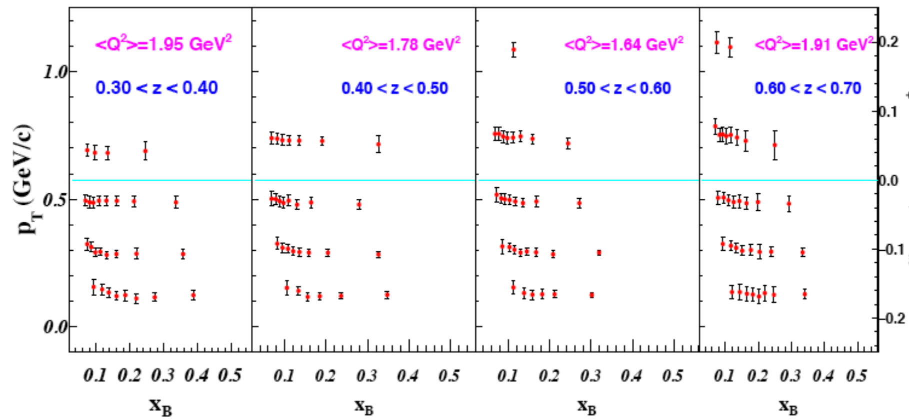
- Total detector efficiency of 85% assumed

NH3 Projection

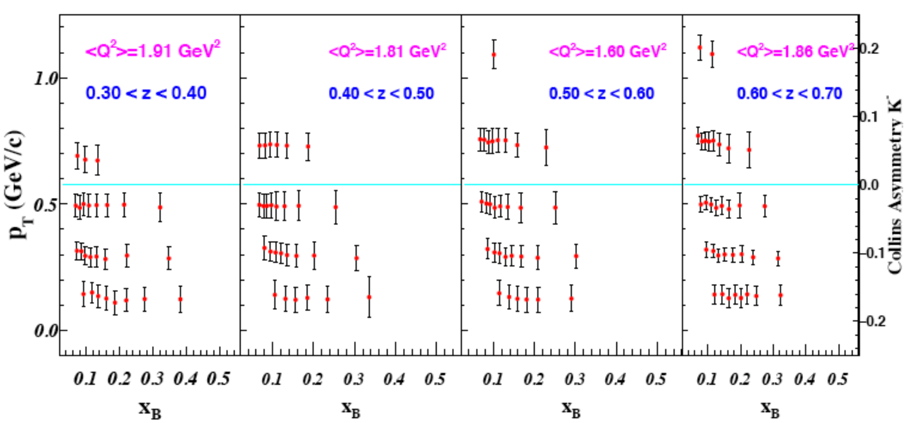
- 3D binning (z, p_T, x), integrated over Q^2
- 120 bins for Sivers and Collins TSA separately



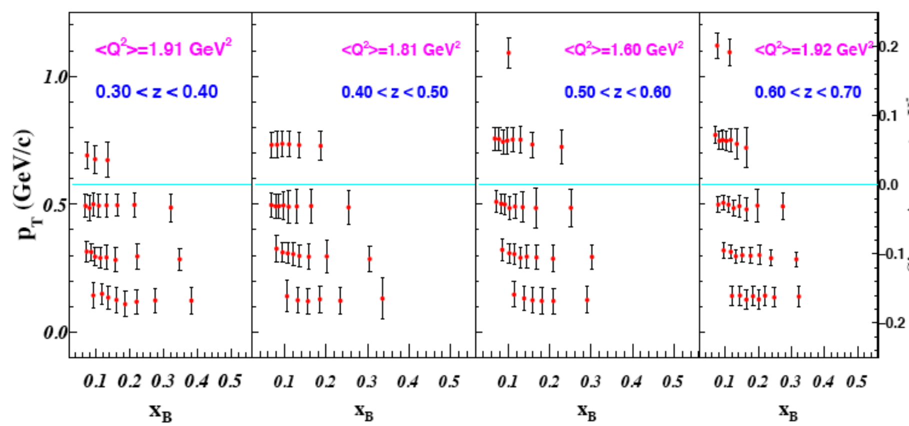
(a) $\vec{p}(e, e'K^+)X$



(a) $\vec{p}(e, e'K^+)X$



(b) $\vec{p}(e, e'K^-)X$



(b) $\vec{p}(e, e'K^-)X$

Summary

- SoLID has Rich, highly rated physics program to address important questions in Nuclear physics
- SIDIS program provides high precision data for 3D imaging of nucleon structure
- New proposal on the Kaon SIDIS measurements has been submitted to PAC46
- Addressed Director's Review Recommendations and updated pre-CDR submitted
- Progress is being made in simulation studies, pre R&D
- Working toward a DOE Science Review

backup

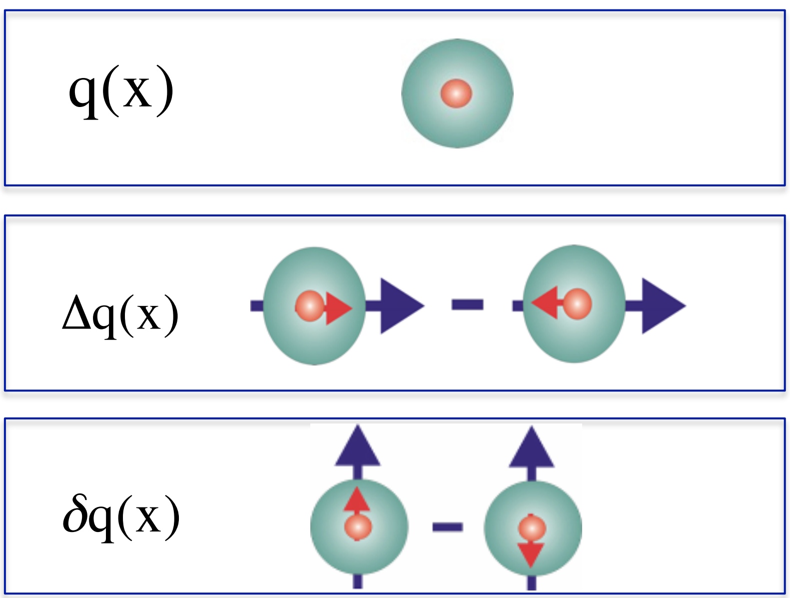
Systematic Budgets

		^{3}He ("n")		NH_3 ("p")	
Sources	Type	Collins ($K^\pm$)	Sivers ($K^\pm$)	Collins ($K^\pm$)	Sivers ($K^\pm$)
Raw Asymmetry	absolute	1.4E-3	1.4E-3	6.5E-3	6.5E-3
Background Subtraction	relative	1.0%	1.0%	2.0%	2.0%
Detector Resolution	relative	<1.0%	<1.0%	<1.0%	<1.0%
Nuclear Effect	relative	4.0% $\sim$ 5.0%	4.0% $\sim$ 5.0%	—-	—
Diffractive Vector Meson	relative	<1.0%	<1.0%	<1.0%	<1.0%
Radiative Correction	relative	2.0 $\sim$ 3.0%	2.0 $\sim$ 3.0%	2.0 $\sim$ 3.0%	2.0 $\sim$ 3.0%
Target Polarization	relative	3.0%+0.5%	3.0%+0.5%	3.0%+0.5%	3.0%+0.5%
Total	relative	6 $\sim$ 7%	6 $\sim$ 7%	4 $\sim$ 5%	4 $\sim$ 5%

- The systematic budgets of the Kaon measurements is almost same as the pion measurements
- Additional 3% due to the pion contamination

From 1D structure of nucleon

Three parton distribution functions unveil the information on the internal structure of hadrons at leading order in a collinear framework

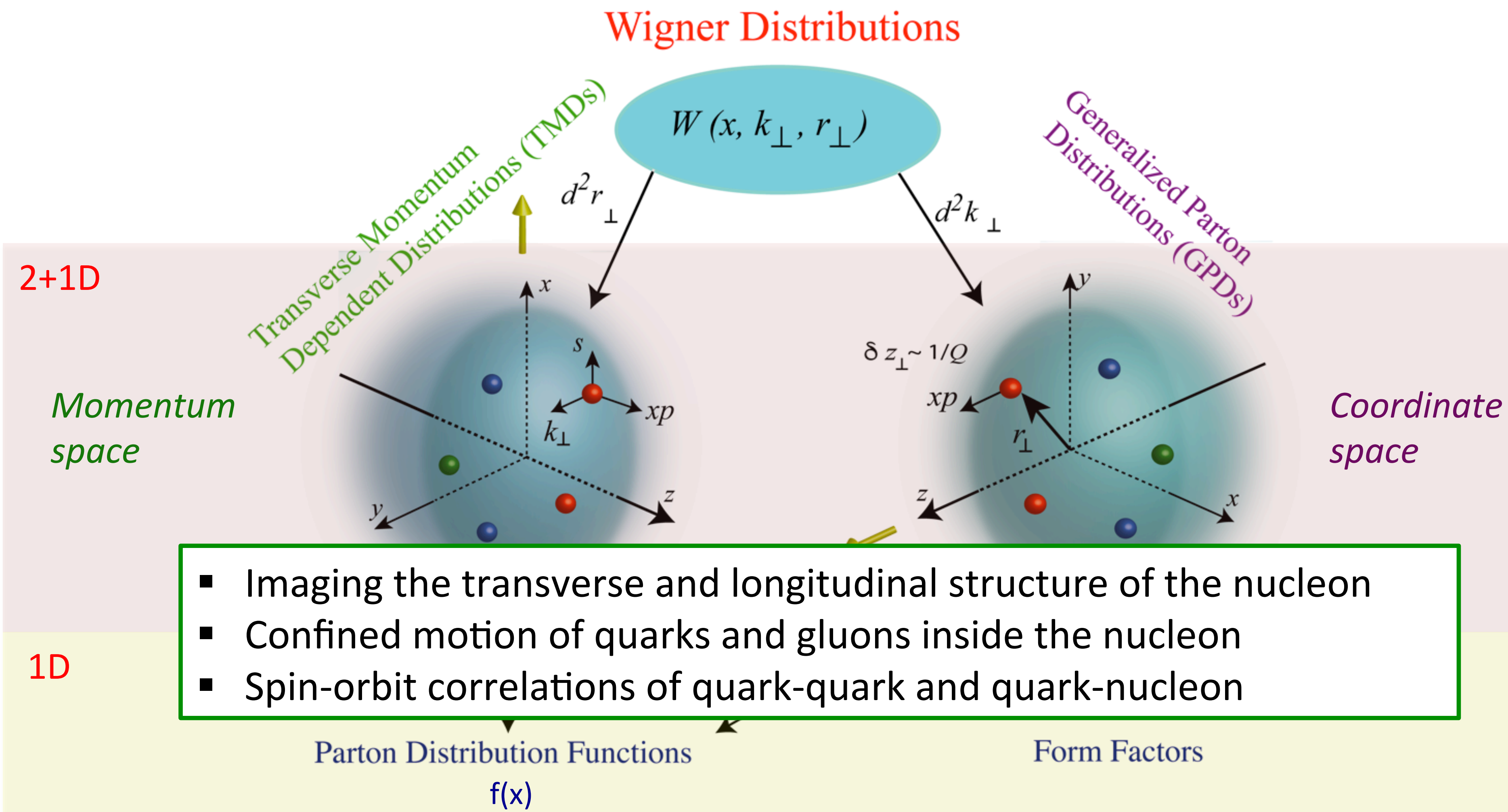


Unpolarized PDFs
quark with a momentum fraction *x* in a nucleon

Helicity PDFs
quark with spin parallel to the nucleon spin in a longitudinally polarized nucleon

Transversity PDFs
quark with spin parallel to the nucleon spin in a transversely polarized nucleon

2+1D Imaging of Nucleon Structure



- Imaging the transverse and longitudinal structure of the nucleon
- Confined motion of quarks and gluons inside the nucleon
- Spin-orbit correlations of quark-quark and quark-nucleon

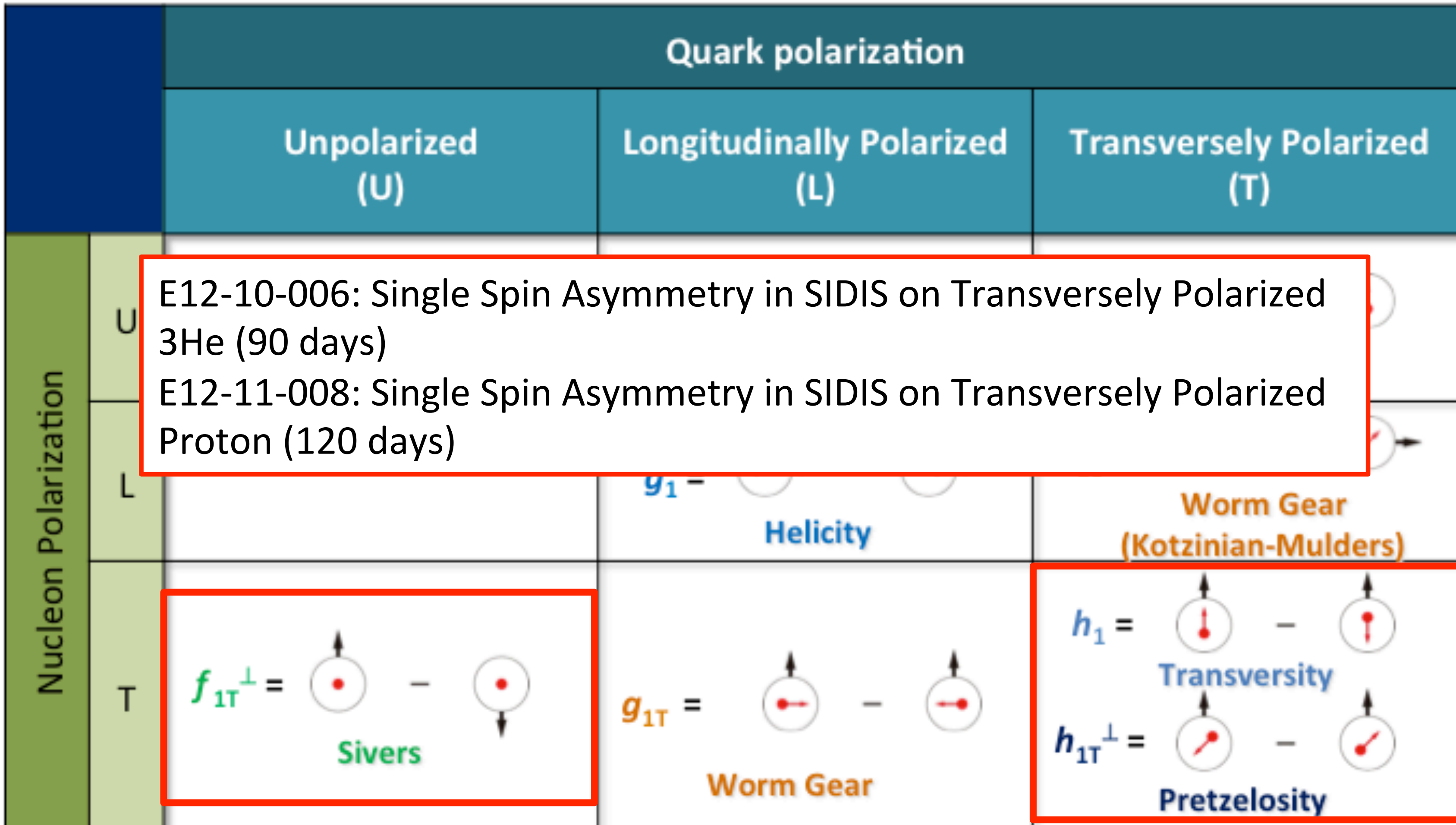
Leading Twist TMDs

→ 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	$h_{1L}^{\perp} =$ − Worm Gear (Kotzinian-Mulders)
	T	$f_{1T}^{\perp} =$ − Sivers	$g_{1T} =$ − Worm Gear	$h_1 =$ − Transversity $h_{1T}^{\perp} =$ − Pretzelosity

Leading Twist TMDs

→ Nucleon spin
→ Quark spin



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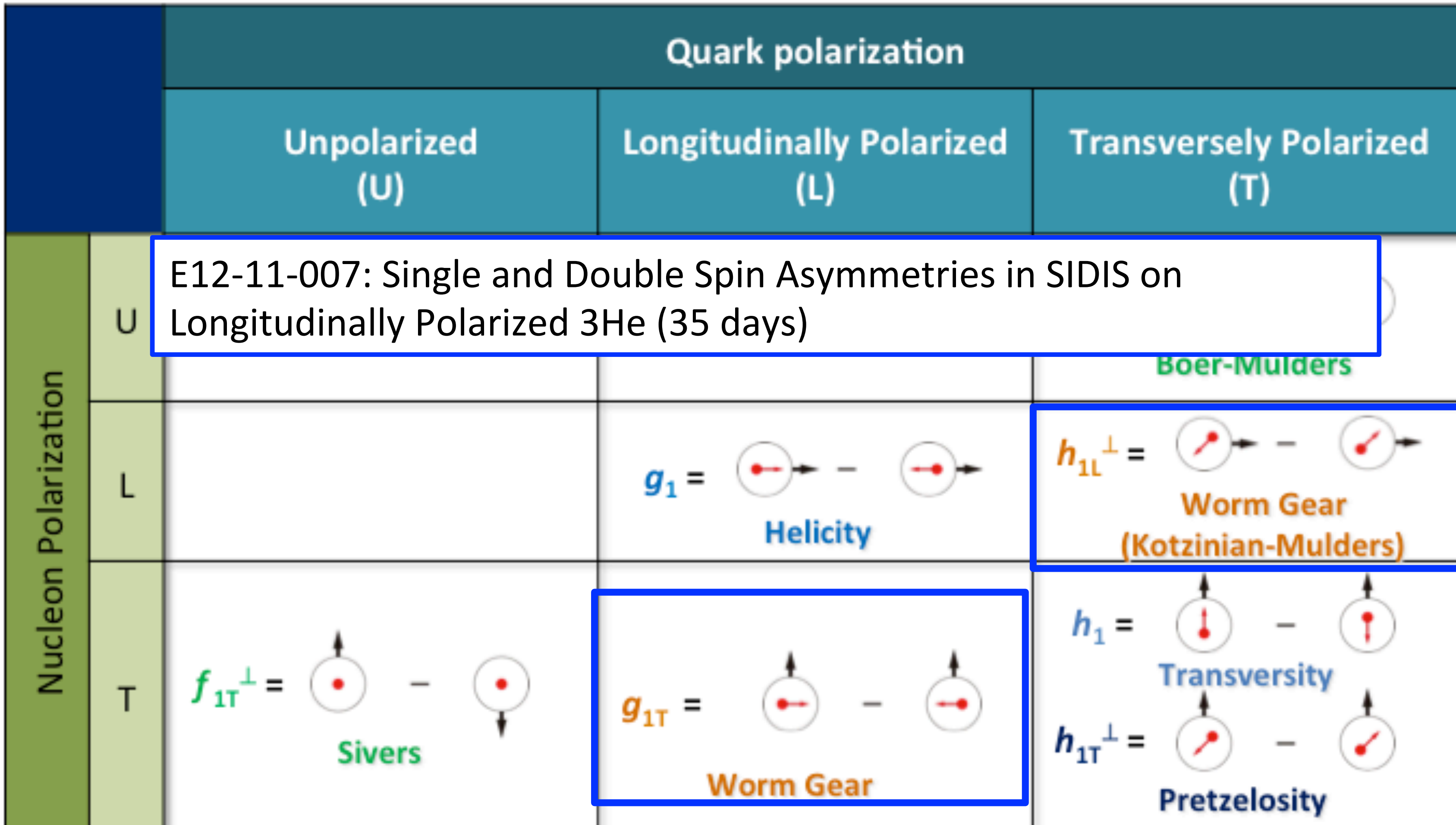
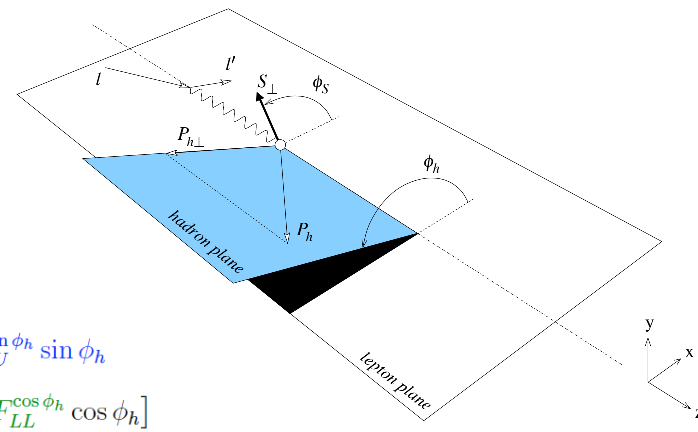
Leading Twist TMDs

→ Nucleon spin
→ Quark spin



Access TMDs with SIDIS

- Access all 8 leading-twist TMDs
- SIDIS differential cross section



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

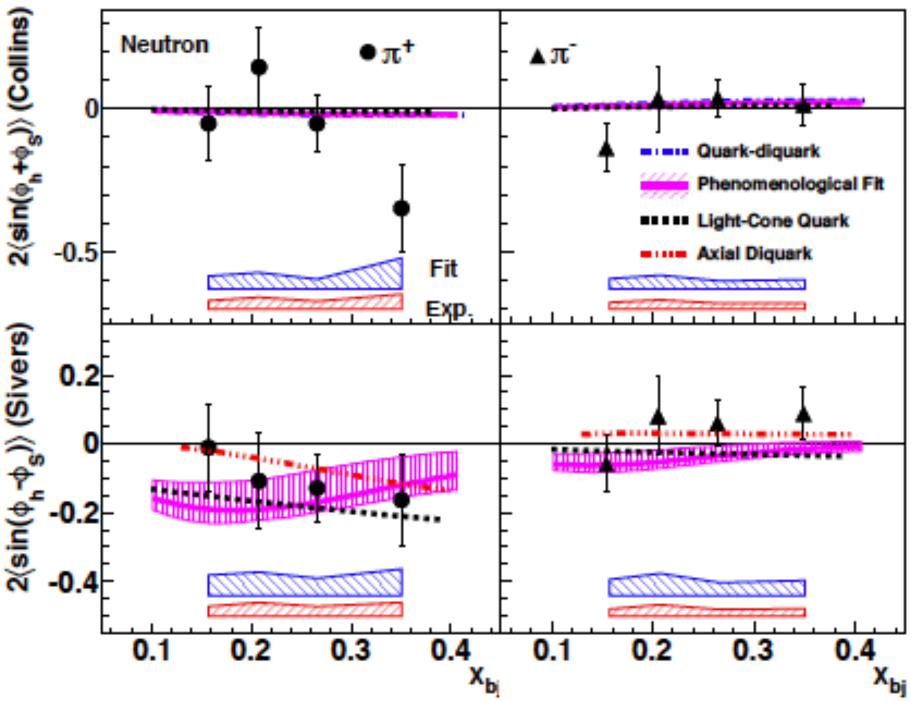
- Target Single Spin Asymmetry

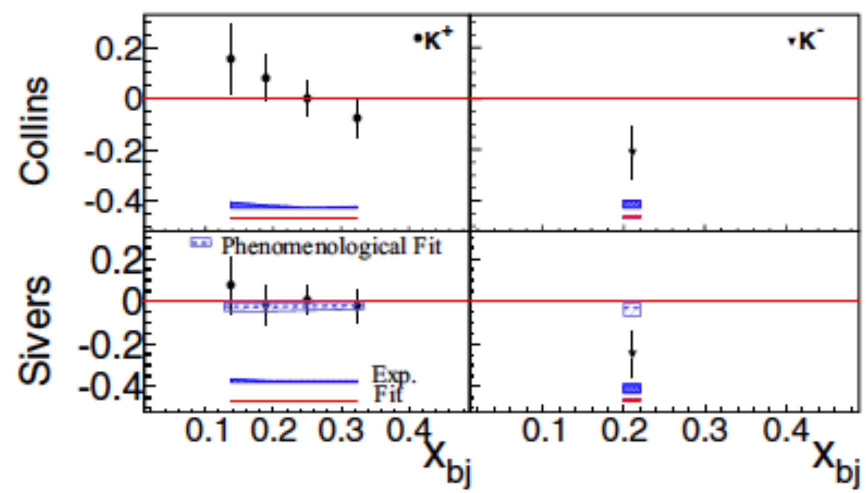
$$A_{UT} = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$$A_{UT} = A_{UT}^{\text{Collins}}\sin(\phi_h+\phi_s) + A_{UT}^{\text{Sivers}}\sin(\phi_h-\phi_s) + A_{UT}^{\text{Pretzelosity}}\sin(3\phi_h-\phi_s) + ..$$

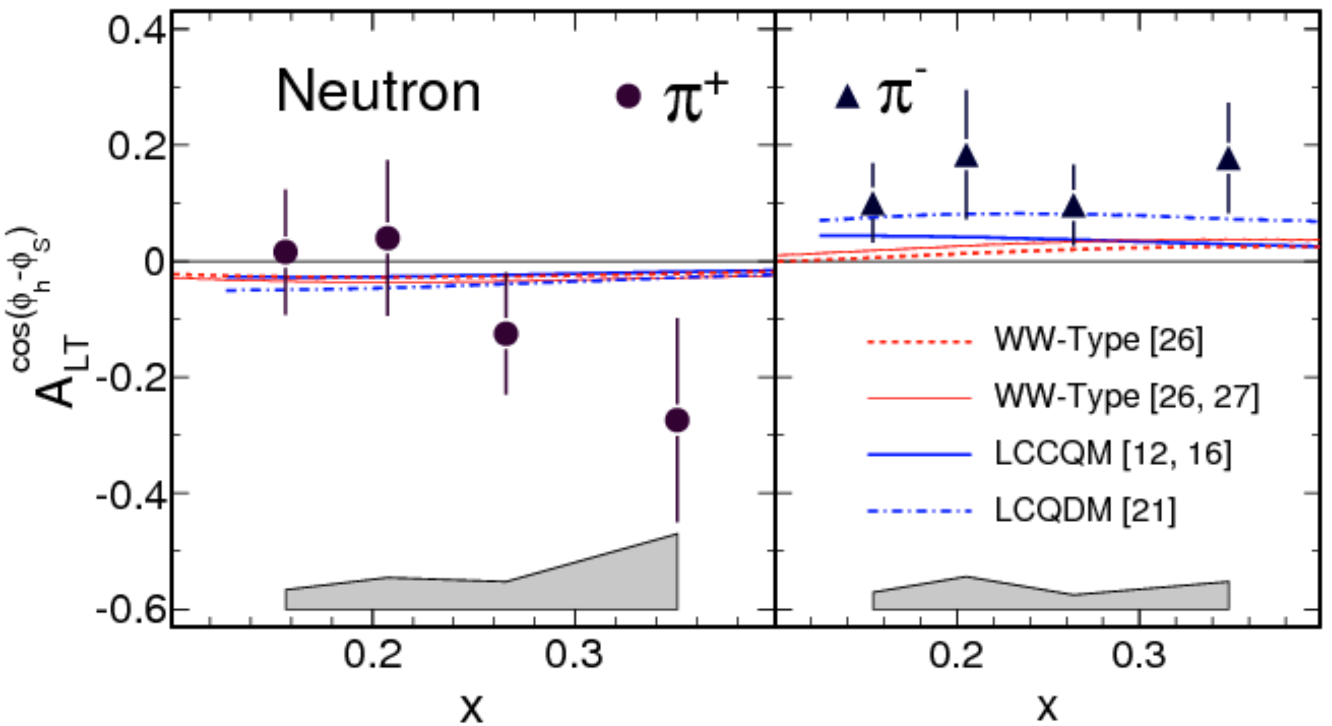
TMDs via SIDIS		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$F_{UU} \propto f_1 \otimes D_1$ Unpolarized		$F_{UU}^{\cos(2\phi_h)} \propto h_1^\perp \otimes H_1^\perp$ Boer-Mulders
	L		$A_{LL} \propto g_1 \otimes D_1$ Helicity	$A_{UL}^{\sin(2\phi_h)} \propto h_{1L}^\perp \otimes H_1^\perp$ Long-Transversity
	T	$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^\perp \otimes D_1$ Sivers	$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T} \otimes D_1$ Trans-Helicity	$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1 \otimes H_1^\perp$ Transversity $A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^\perp \otimes H_1^\perp$ Pretzelosity

6 GeV results

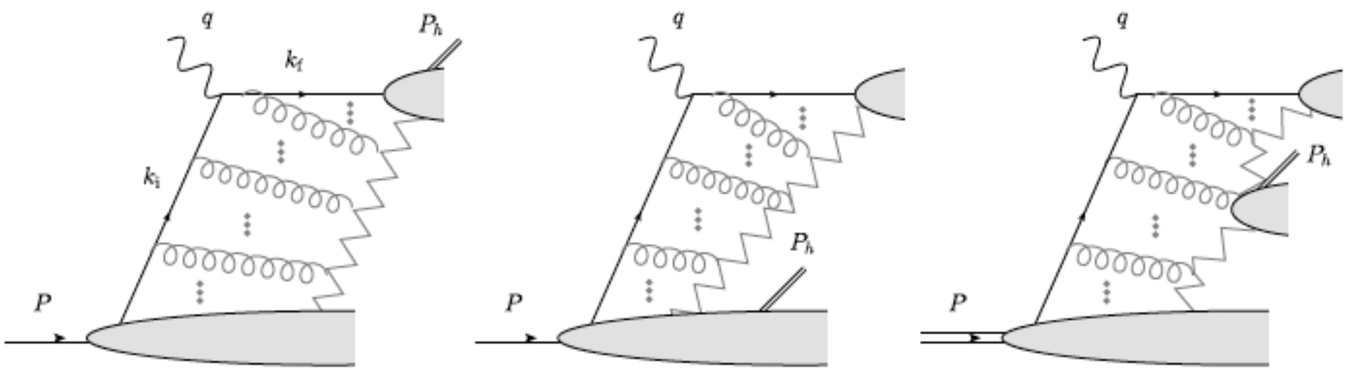




6 GeV result



Neutron
π+
π-
$A_{LT}^{\cos(\phi_h-\phi_S)}$
0.4
0.2
0
-0.2
-0.4
-0.6
0.2
0.3
x
WW-Type [26]
WW-Type [26, 27]
LCCQM [12, 16]
LCQDM [21]

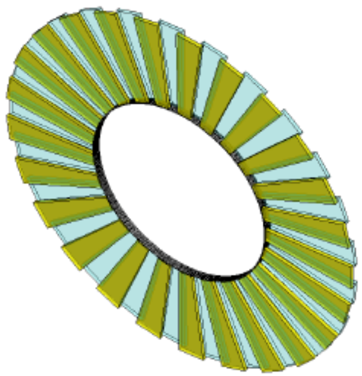


criteria

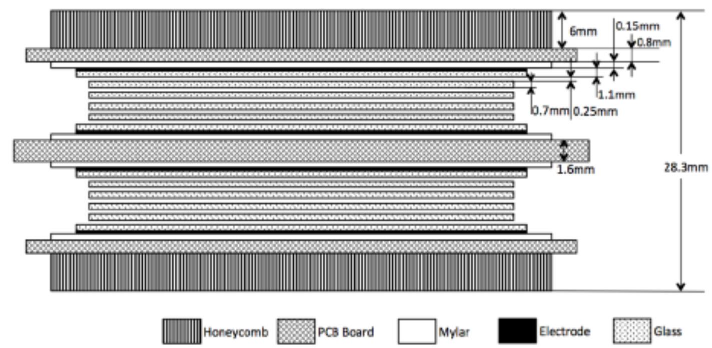
Kaon Identification

➢ Multiple-gaps Resistant-Plate Chamber (MRPC):

- ❖ The SoLID TOF detector is the MRPC (50 super-modules w/ 3MRPC modules for each super-module)
- ❖ Each MRPC contains 10 gas gaps (0.25mm each gas layer + 0.7mm each glass)
- ❖ Maximum rate capability – 50 KHz/cm^2.

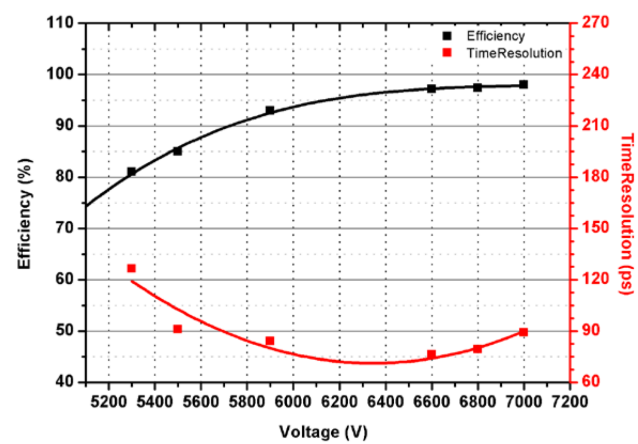


(a) The layout of the MRPC



(b) The structure of the MRPC prototype

- ❖ The MRPC prototype built by Tsinghua University had 50 ps resolution with 95% efficiency with cosmic ray.
- ❖ The beam-test during G2p experiment showed 80 ps resolution with 94% efficiency at 15 KHz/cm^2.



Physics Projection

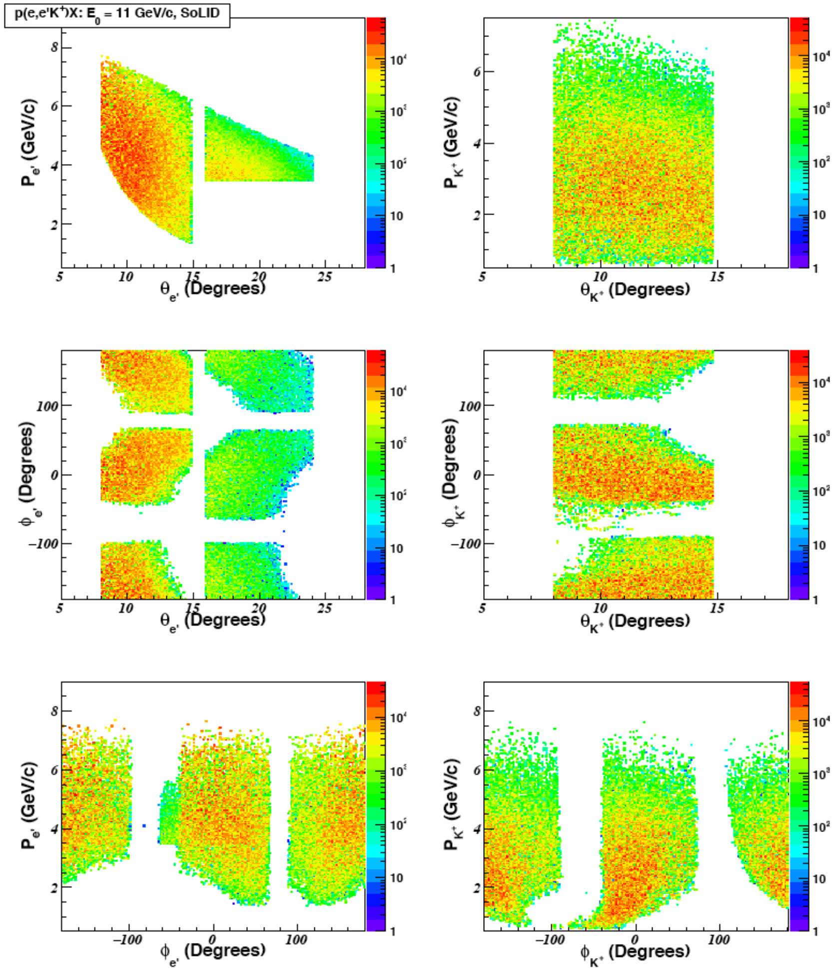
- Monte-Carlo Simulation

- Use the conventional SIDIS event generator used for SoLID, but with improved models for Kaons
- Generate events uniformly in a phase-space larger than the SoLID acceptance
- Use Geant4-GEMC to obtain the acceptance of electrons and kaons in SoLID
- Built in polarization, detector efficiency, approved beam-time, target lumonisities, etc., from the approved pion experiments.

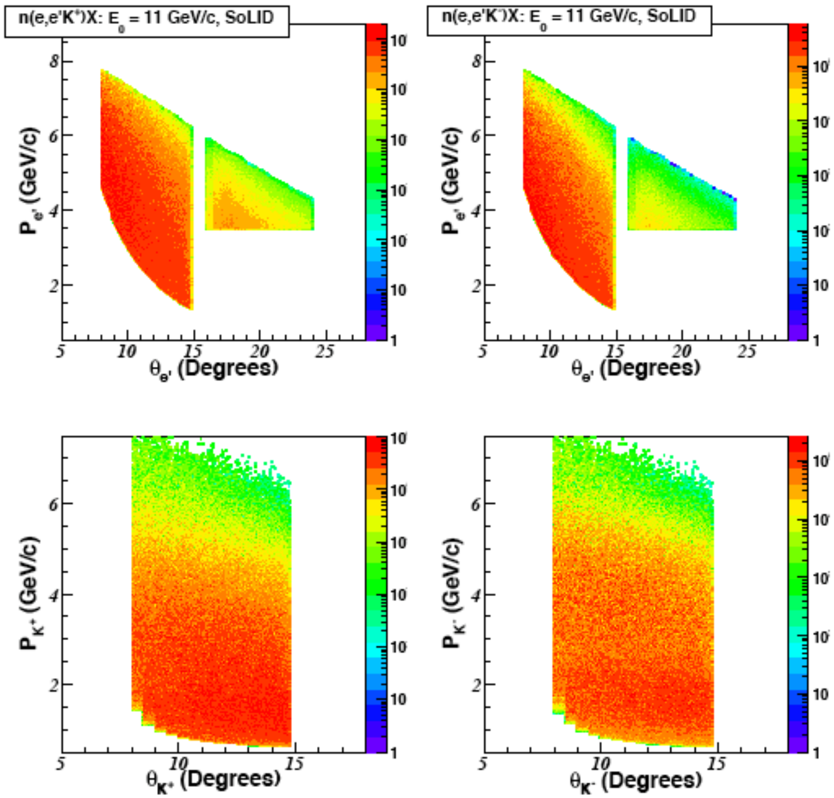
SoLID-SIDIS Coincident Rates (Hz)				
Polarized Target	^{3}He ("n")		NH_3 ("p")	
Beam Energy	8.8 GeV	11 GeV	8.8 GeV	11 GeV
e-(FAEC+LAEC)+K^+(FAEC)	359.3	575.6	4.9	10.4
e-(LAEC+LAEC)+K^-(FAEC)	83.2	144.1	0.93	2.7
e-(FAEC+LAEC)+π^+(FAEC)	1555.0	2185.9	20.3	37.4
e-(LAEC+LAEC)+π^-(FAEC)	1012.5	1449.6	10.2	20.7

Acceptance and Kinematic Coverage

SoLID-SIDIS with NH3 at 11GeV

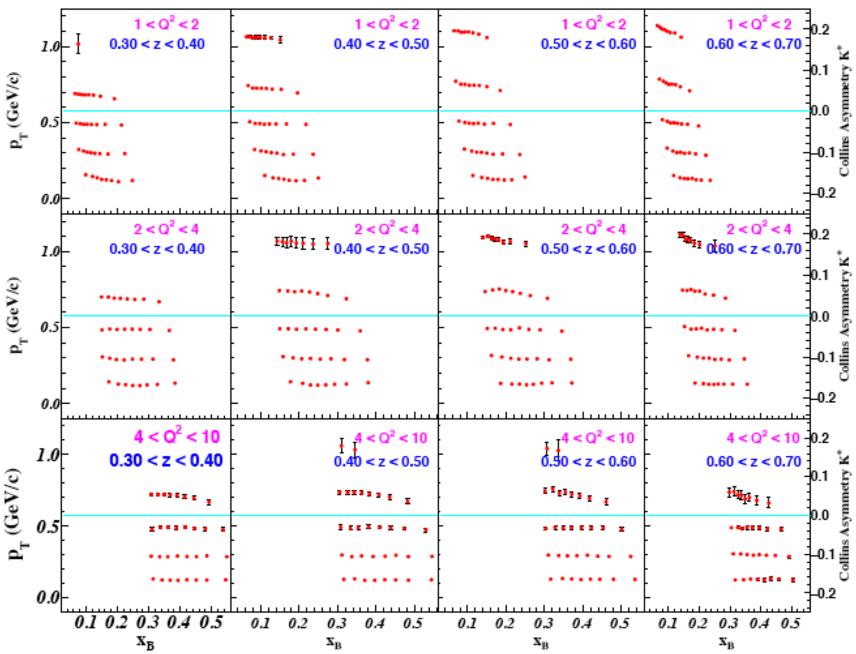


SoLID-SIDIS with He3 at 11GeV

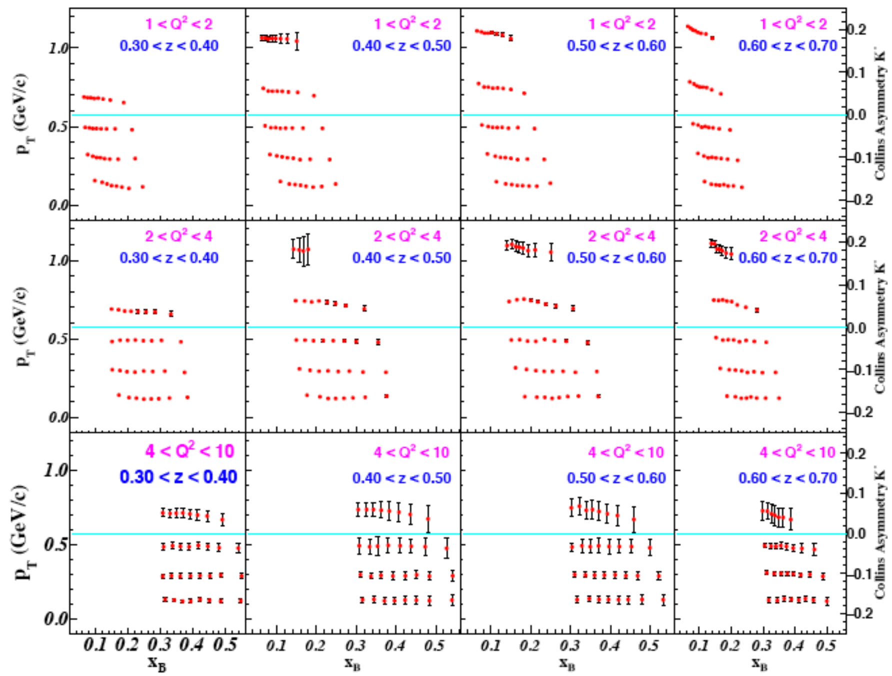


3He Projection - Collins

- 4D binning (Q^2, z, pT, x) for He3 setup
- Total 430 bins



(a) $\vec{n}(e, e'K^+)X$



(b) $\vec{n}(e, e'K^-)X$

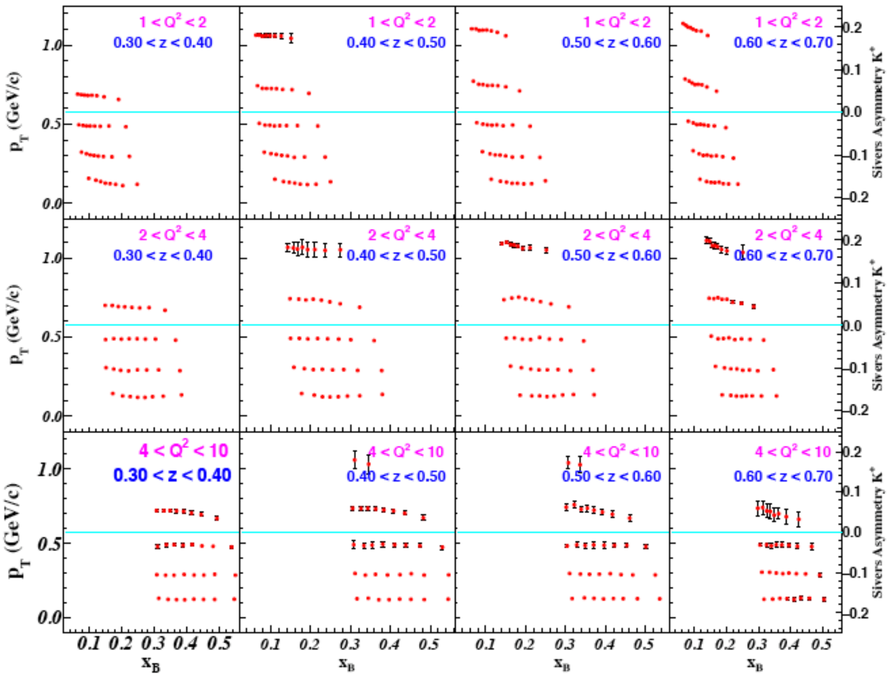
- Kinematic cuts applied:

$Q^2 > 1$ GeV^2, W > 2.3 GeV, W' > 1.6 GeV, $0.3 < z < 0.7$

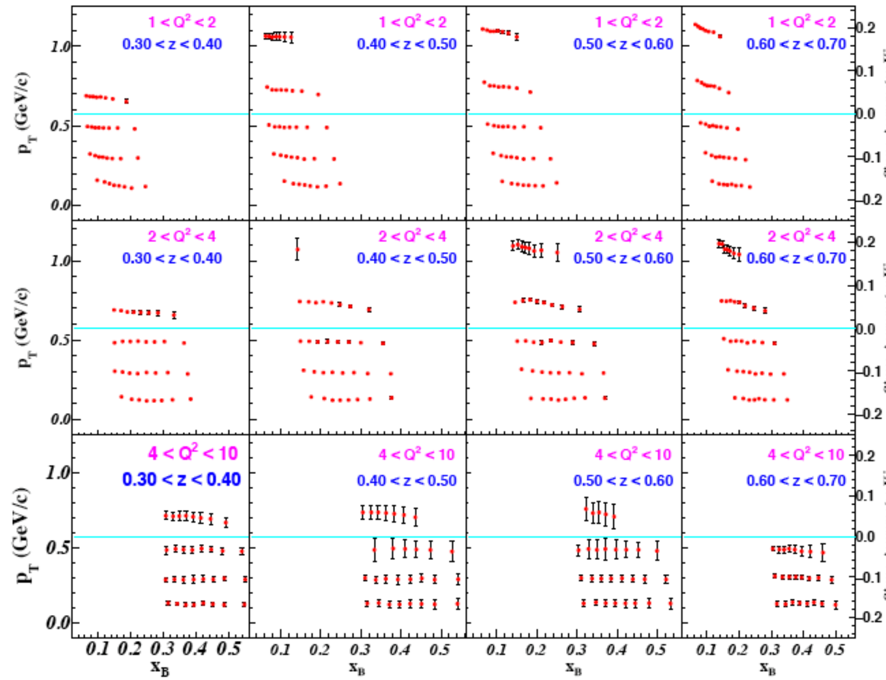
- Total detector efficiency of 85% assumed

3He Projection - Sivers

- 4D binning for He3 setup
- Total 430 bins



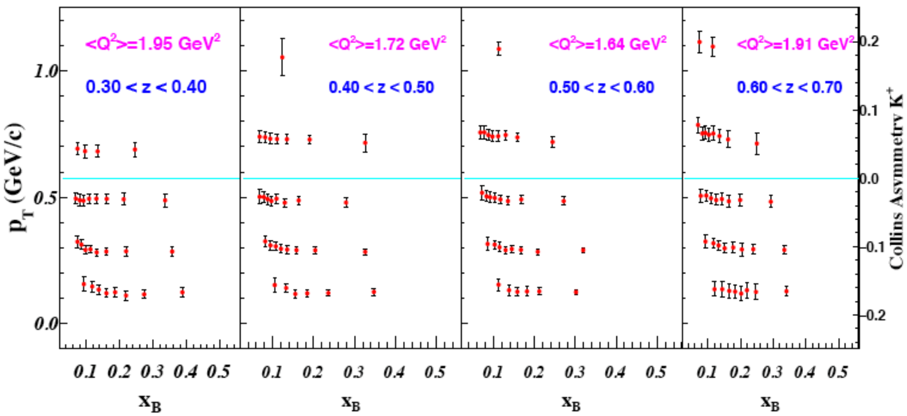
(a) $\vec{n}(e, e'K^{+})$X



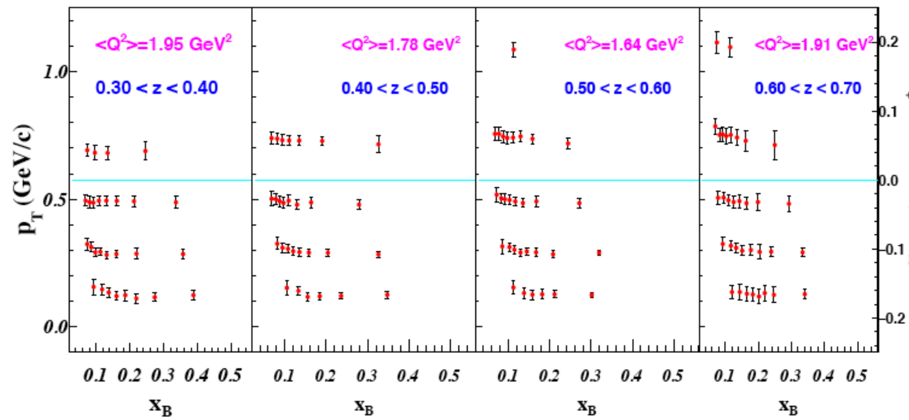
(b) $\vec{n}(e, e'K^{-})$X

NH3 Projection

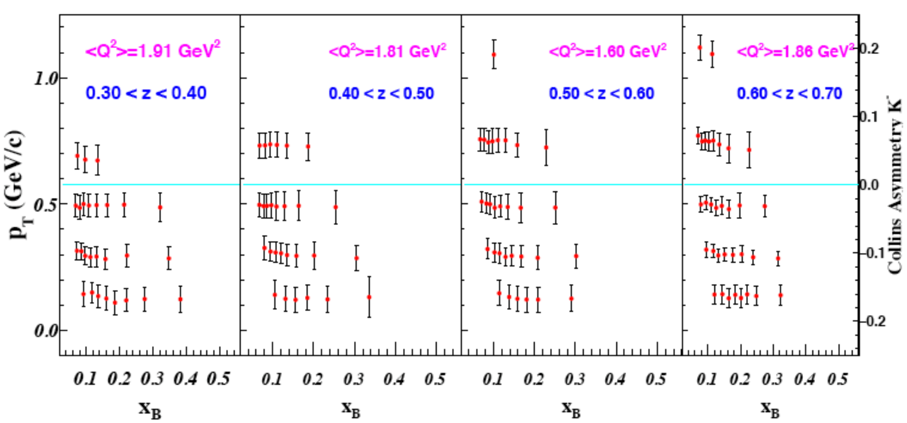
- 3D binning (z, p_T, x), integrated over Q^2
- 120 bins for Sivers and Collins TSA separately



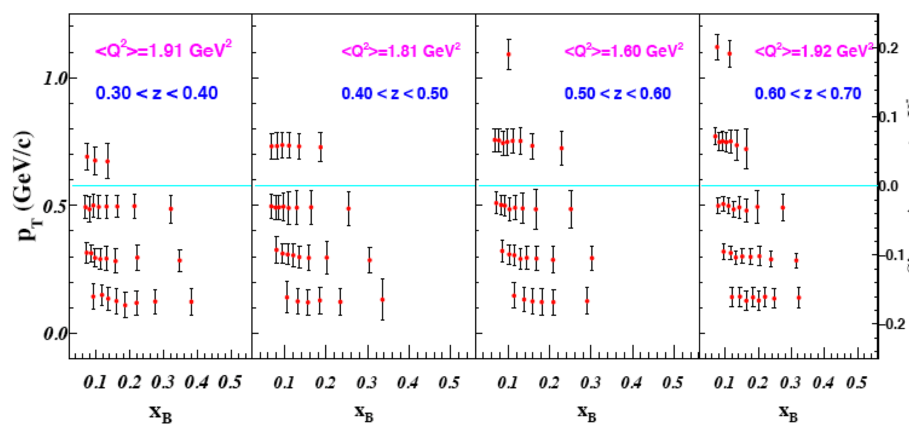
(a) $\vec{p}(e, e'K^+)X$



(a) $\vec{p}(e, e'K^+)X$



(b) $\vec{p}(e, e'K^-)X$



(b) $\vec{p}(e, e'K^-)X$