

$\tilde{E}$ via Transverse Target Spin Asymmetry and SoLID

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of Regina

JLab Physics with High Luminosity Facilities
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Supported by:



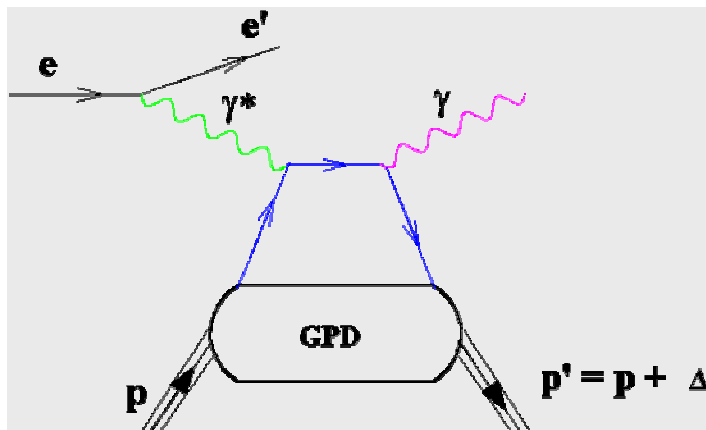
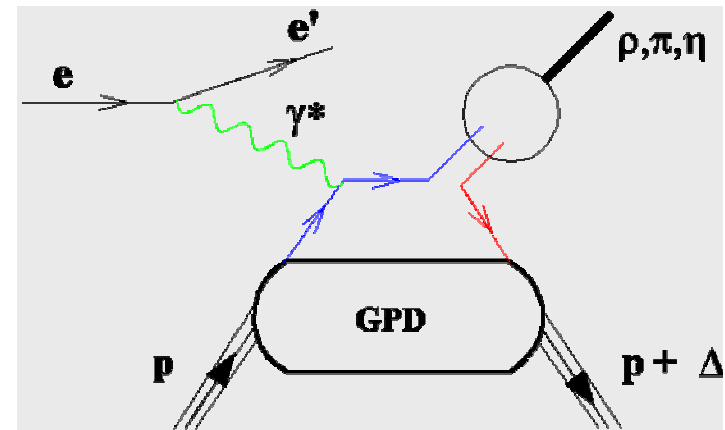
SAPIN-2026-00043

Complementarity of Different Reactions

- **Need a variety of Deep Exclusive Measurements to disentangle the different GPDs.**

Deep Exclusive Meson Production:

- Vector mesons sensitive to spin-average H, E .
- Pseudoscalar mesons sensitive to spin-difference $\tilde{H}, \tilde{E}$.



Deeply Virtual Compton Scattering:

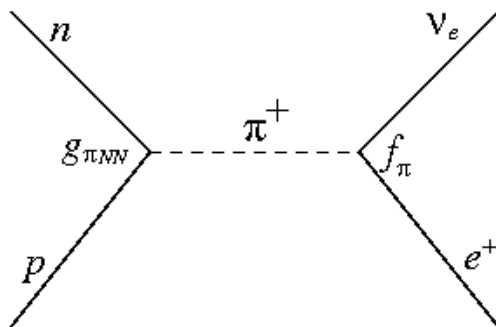
- Sensitive to all four GPDs.

- Additional chiral-odd GPDs ($H_T, E_T, \tilde{H}_T, \tilde{E}_T$) offer a way to access the transversity-dependent quark-content of the nucleon.

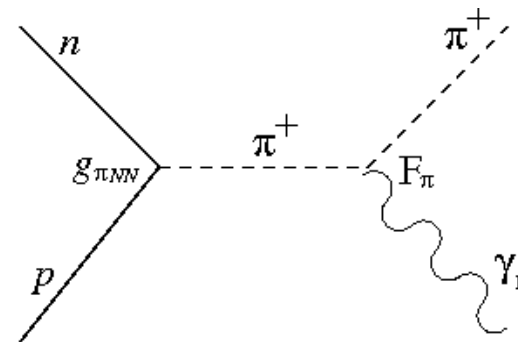
$$\sum_q e_q \int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) = G_P(t)$$

- **$\tilde{E}$ is not related to any already known parton distribution.**
- $G_P(t)$ is highly uncertain because it is negligible at the momentum transfer of β -decay.
 - Due to PCAC, $G_P(t)$ receives contributions from $J^P G = 0^-$ states.
 - $\tilde{E}$ is expected to contain an important pion pole contribution.

Pion pole contribution to $G_P(t)$



Pion pole contribution to meson electroproduction at low $-t$.



A pion pole dominated ansatz is typically assumed:

$$\tilde{E}^{u,d}(x, \xi, t) = F_\pi(t) \frac{\theta(\xi > |x|)}{2\xi} \phi_\pi\left(\frac{x + \xi}{2\xi}\right)$$

where F_π is the pion FF and ϕ_π the pion PDF.

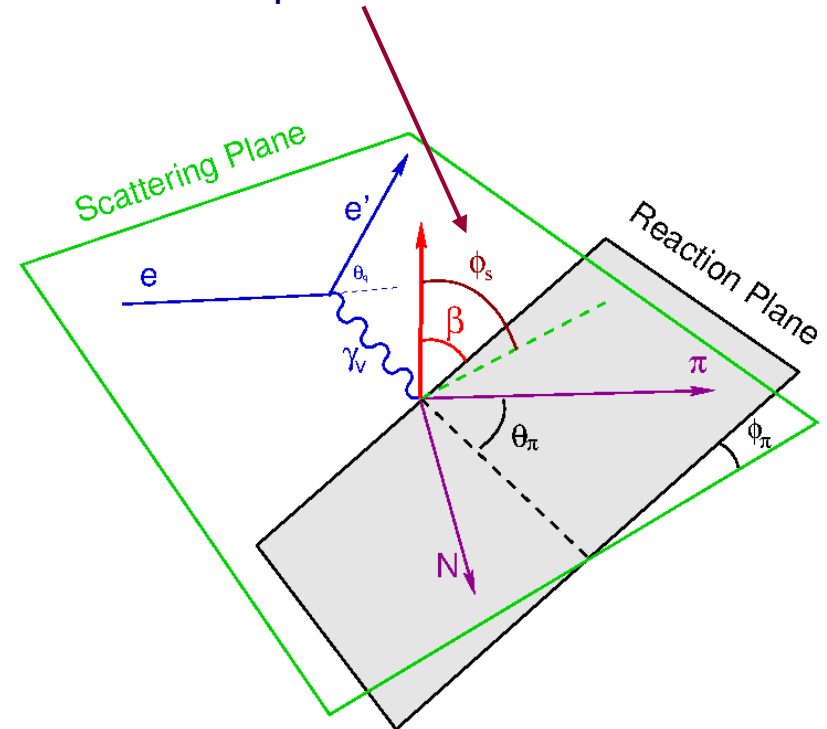
How to determine $\tilde{E}$

- The most sensitive observable to probe $\tilde{E}$ is the transverse single-spin asymmetry in exclusive π production:

$$A_L^\perp = \frac{\left(\int_0^\pi d\beta \frac{d\sigma_L^\pi}{d\beta} - \int_\pi^{2\pi} d\beta \frac{d\sigma_L^\pi}{d\beta} \right)}{\left(\int_0^{2\pi} d\beta \frac{d\sigma_L^\pi}{d\beta} \right)}$$

$$= \frac{\sqrt{-t'}}{2m_p} \frac{\pi\xi\sqrt{1-\xi^2} \operatorname{Im}(\tilde{E}^* \tilde{H})}{(1-\xi^2)\tilde{H}^2 - \frac{t\xi^2}{4m_p} \tilde{E}^2 - 2\xi^2 \operatorname{Re}(\tilde{E}^* \tilde{H})}$$

$d\sigma_\pi^L$ = exclusive π cross section
for longitudinal γ^*
 β = angle between transversely
polarized target vector and the
reaction plane



Refs: A.V. Belitsky, D. Mueller, PLB**513** (2001) 349
L.L. Frankfurt, et al., PRD **60**(1999) 014101

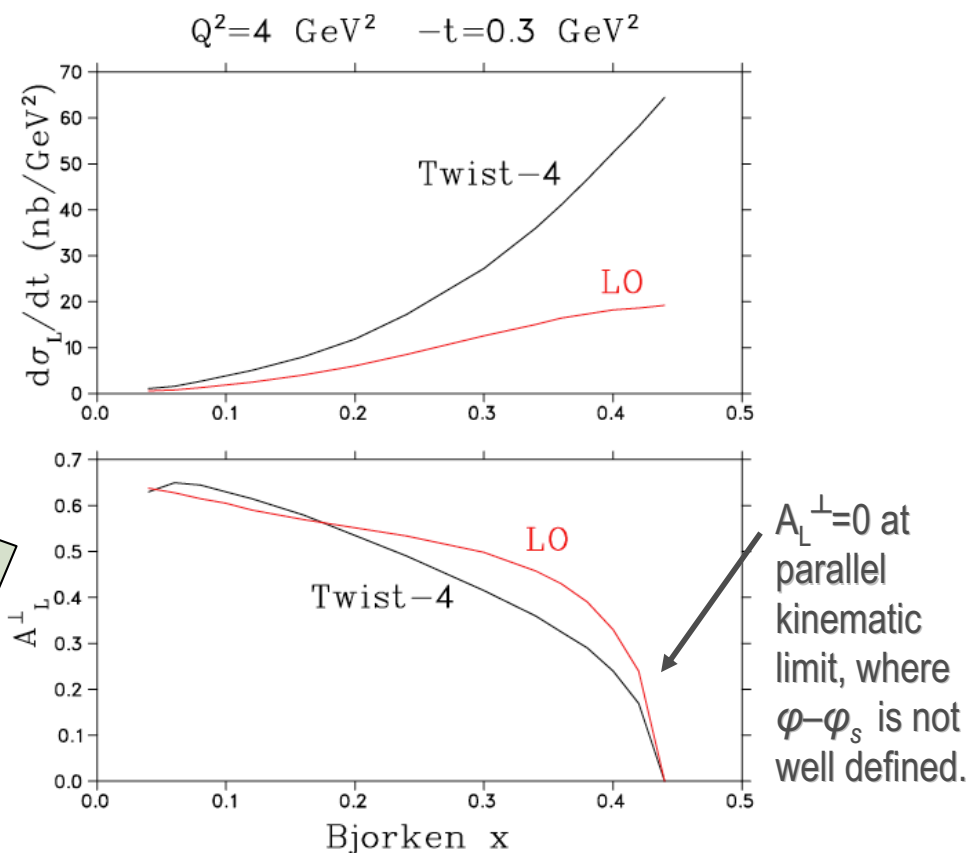
GPD information in $A_L^\perp$ may be particularly clean

- $A_L^\perp$ is expected to display precocious factorization at only $Q^2 \sim 2-4 \text{ GeV}^2$:

- At $Q^2 = 10 \text{ GeV}^2$, Twist-4 effects can be large, but cancel in $A_L^\perp$

(Belitsky & Müller PLB 513(2001)349).

- At $Q^2 = 4 \text{ GeV}^2$, higher twist effects even larger in σ_L , but still cancel in the asymmetry (CIPANP 2003).



This relatively low value of Q^2 for the expected onset of precocious scaling is important, because it is experimentally accessible at JLab 12 GeV.

Note: Trento convention used in the rest of the slides

Transverse Target Single Spin Asymmetry in DEMP

Unpolarized Cross section $2\pi \frac{d^2\sigma_{UU}}{dt d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos \phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$

Transversely polarized cross section has additional components

$$\frac{d^3\sigma_{UT}}{dt d\phi d\phi_s} = - \frac{P_\perp \cos \theta_q}{\sqrt{1 - \sin^2 \theta_q \sin^2 \phi_s}}$$

Gives rise to Asymmetry Moments

$$A(\phi, \phi_s) = \frac{d^3\sigma_{UT}(\phi, \phi_s)}{d^2\sigma_{UU}(\phi)} = - \sum_k A_{UT}^{\sin(\mu\phi + \lambda\phi_s)_k} \sin(\mu\phi + \lambda\phi_s)_k$$

$$\left(\begin{aligned} & \sin \beta \operatorname{Im}(d\sigma_{++}^{+-} + \varepsilon d\sigma_{00}^{+-}) \\ & + \sin \phi_s \sqrt{\varepsilon(1+\varepsilon)} \operatorname{Im}(d\sigma_{+0}^{+-}) \\ & + \sin(\phi + \phi_s) \frac{\varepsilon}{2} \operatorname{Im}(d\sigma_{+-}^{+-}) \\ & + \sin(2\phi - \phi_s) \sqrt{\varepsilon(1+\varepsilon)} \operatorname{Im}(d\sigma_{+0}^{-+}) \\ & + \sin(3\phi - \phi_s) \frac{\varepsilon}{2} \operatorname{Im}(d\sigma_{+-}^{-+}) \end{aligned} \right)$$

$\sigma_{mn}^{ij} \rightarrow$ nucleon polarizations $ij = (+1/2, -1/2)$

photon polarizations $mn = (-1, 0, +1)$

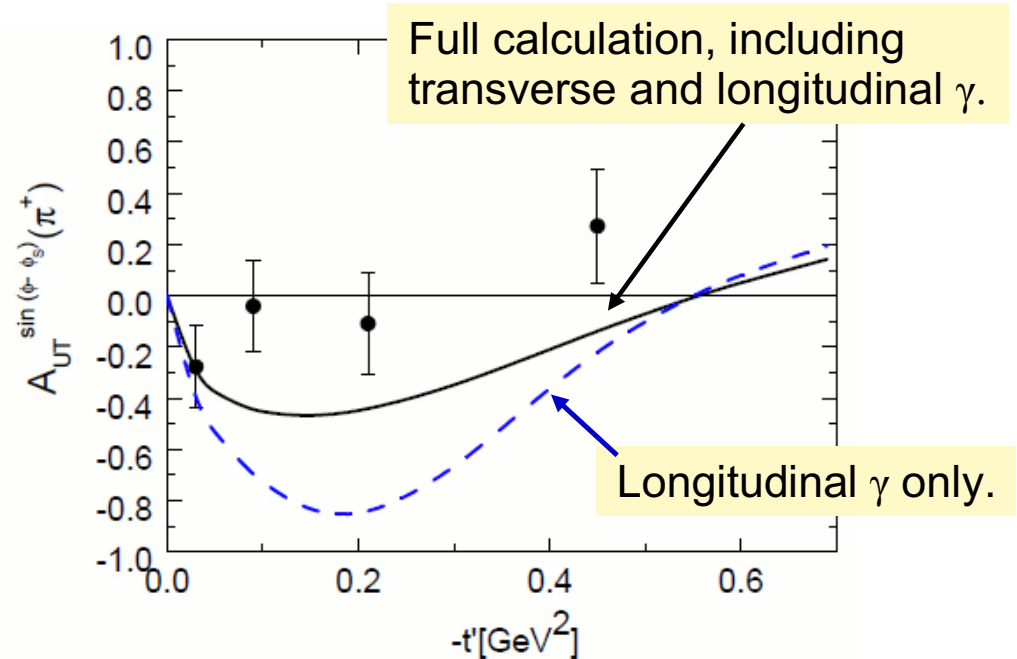
Unseparated $\sin\beta = \sin(\phi - \phi_s)$ Asymmetry Moment

$$A_{UT}^{\sin(\phi - \phi_s)} \sim \frac{d\sigma_{00}^{+-}}{d\sigma_L \left(\begin{smallmatrix} ++ \\ 00 \end{smallmatrix} \right)} \sim \frac{\operatorname{Im}(\tilde{E}^* \tilde{H})}{|\tilde{E}|^2} \text{ where } \tilde{E} \gg \tilde{H}$$

Ref: M. Diehl, S. Sapeta, Eur.Phys.J. C41(2005)515.

HERMES $\sin(\phi-\phi_S)$ Asymmetry Moment

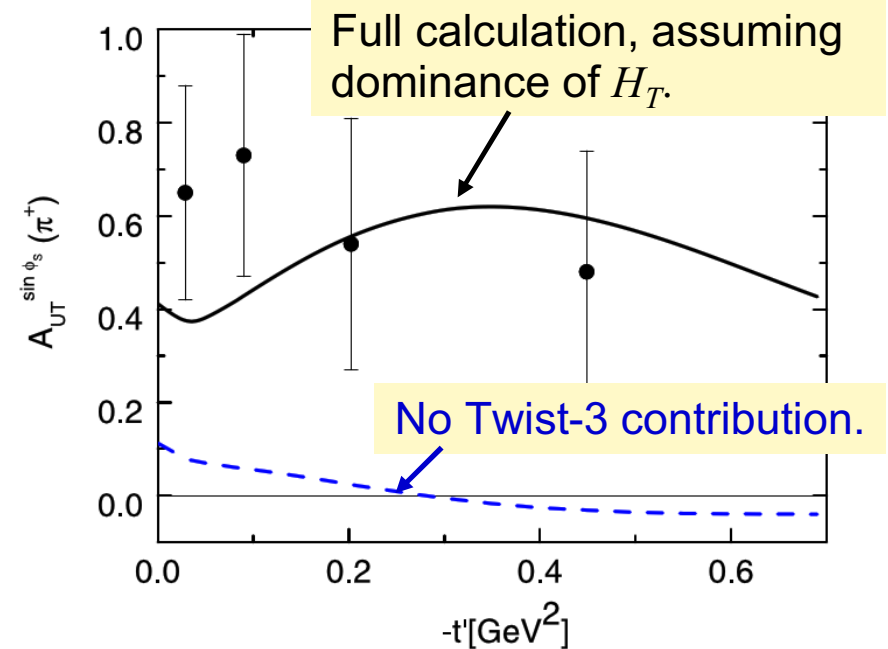
- Exclusive π^+ production by scattering 27.6 GeV positrons or electrons from transverse polarized ^1H [PL B682(2010)345].
- Analyzed in terms of 6 Fourier amplitudes for ϕ_π, ϕ_S .
- $\langle x_B \rangle = 0.13$, $\langle Q^2 \rangle = 2.38 \text{ GeV}^2$, $\langle -t \rangle = 0.46 \text{ GeV}^2$.



- Since there is no L/T separation, $A_{UT}^{\sin(\phi-\phi_S)}$ is diluted by the ratio of the longitudinal cross section to the unseparated cross section.
- Goloskokov and Kroll indicate the HERMES results have significant contributions from transverse photons, as well as from L and T interferences [Eur Phys.J. C65(2010)137].
- Because no factorization theorems exist for exclusive π^+ production by transverse photons, these data cannot be trivially interpreted in terms of GPDs.

HERMES $\sin(\phi_s)$ Asymmetry Moment

- While most of the theoretical interest and the primary motivation of our experiment is the $\sin(\phi - \phi_s)$ asymmetry moment, there is growing interest in the $\sin(\phi_s)$ moment, which may be interpretable in terms of the transversity GPDs.

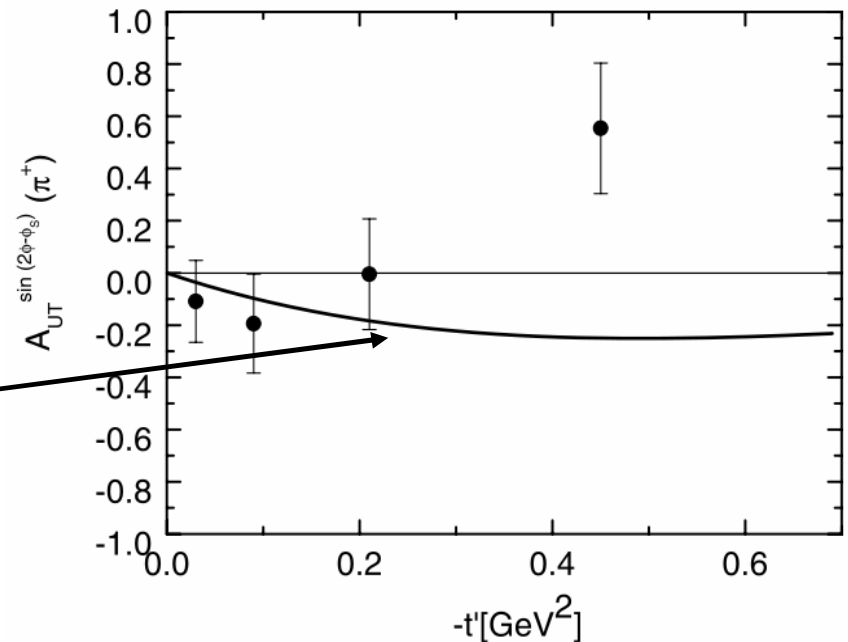


- In contrast to the $\sin(\phi - \phi_s)$ modulation, which has contributions from LL and TT interferences, the $\sin(\phi_s)$ modulation measures only the LT interference.
- **The HERMES $\sin(\phi_s)$ modulation is large and nonzero at $-t'=0$, giving the first clear signal for strong contributions from transversely polarized photons at rather large values of W and Q^2 .**
- **Goloskokov and Kroll calculation [Eur.Phys.J. C65(2010)137] assumes the transversity GPD H_T dominates and that the other three can be neglected.**

HERMES $\sin(2\phi - \phi_s)$ Asymmetry Moment

- $\langle Q^2 \rangle = 2.38 \text{ GeV}^2$, $\langle W \rangle = 3.99 \text{ GeV}$.
- Experimental values and model calculation are both small.

Handbag approach calculation
by Goloskokov & Kroll
[Eur.Phys.J. **C65**(2010)137] .



- **$\sin(2\phi - \phi_s)$ modulation has additional LT interference amplitudes contributing that are not present in $\sin(\phi_s)$.**
 - Improvement to calculation to reproduce sign change would require a more detailed modeling of these smaller amplitudes.
 - This would also improve description of other amplitude moments.
In this sense, different moments provide complementary amplitude term information.
- **The remaining $\sin(\phi + \phi_s)$, $\sin(2\phi + \phi_s)$, $\sin(3\phi - \phi_s)$ moments are only fed by TT interference and are even smaller.**

Measure DEMP with SoLID – Polarized ^3He

$\vec{n}(e, e' \pi^-)p$: with transversely polarized ^3He

$$\langle A_{UT} \rangle = \frac{1}{P \cdot \eta_n \cdot f} \frac{N^+ - N^-}{N^+ + N^-}$$

Run in parallel with E12-10-006:

$E_0 = 11.0 \text{ GeV}$ (48 days)

Luminosity = $10^{36} \text{ cm}^{-2} \text{ s}^{-1}$ (per nucleon)

Spokespersons: GMH, Zhihong Ye

Large-Angle :
Detect electrons and protons

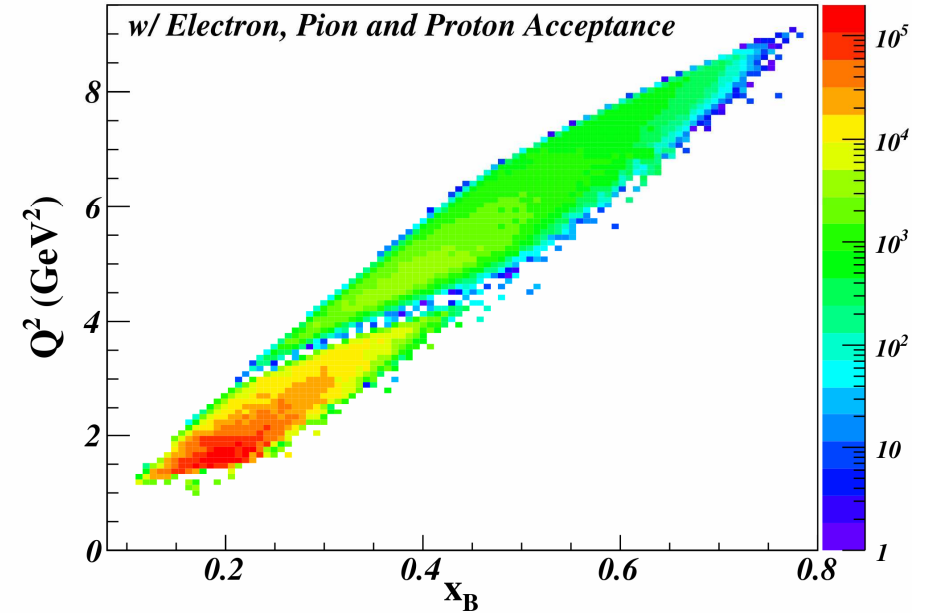
Forward-Angle :
Detect electrons
pions & protons

Online Coincidence Trigger: Electron Trigger + Hadron Trigger
Offline Analysis: Identify protons and form triple-coincidence

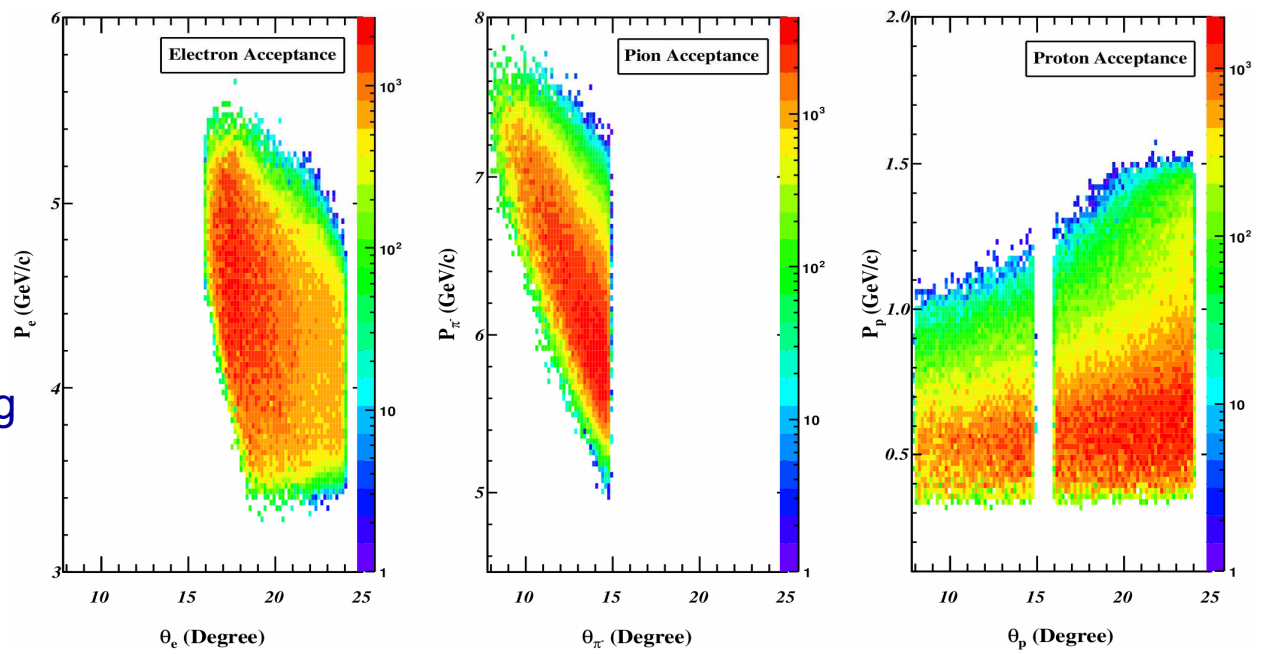
SoLID Acceptance and Projected Rates

$Q^2 > 1 \text{ GeV}^2$ $W > 2 \text{ GeV}$	$Q^2 > 4 \text{ GeV}^2$ $W > 2 \text{ GeV}$
DEMP: $n(e, e' \pi p)$ Triple Coin (Hz)	
4.95	0.40
SIDIS: $n(e, e' \pi^-) X$ Double Coin (Hz)	
1425	35.8

- Event generator based on data from HERMES, Halls B,C with VR Regge+DIS model used as a constraint in unmeasured regions.
- Generator includes electron radiation, multiple scattering and ionization energy loss.
- Every detected particle is smeared in (P, θ, ϕ) with resolution from SoLID tracking studies, and acceptance profiles from SoLID-SIDIS GEMC study applied.



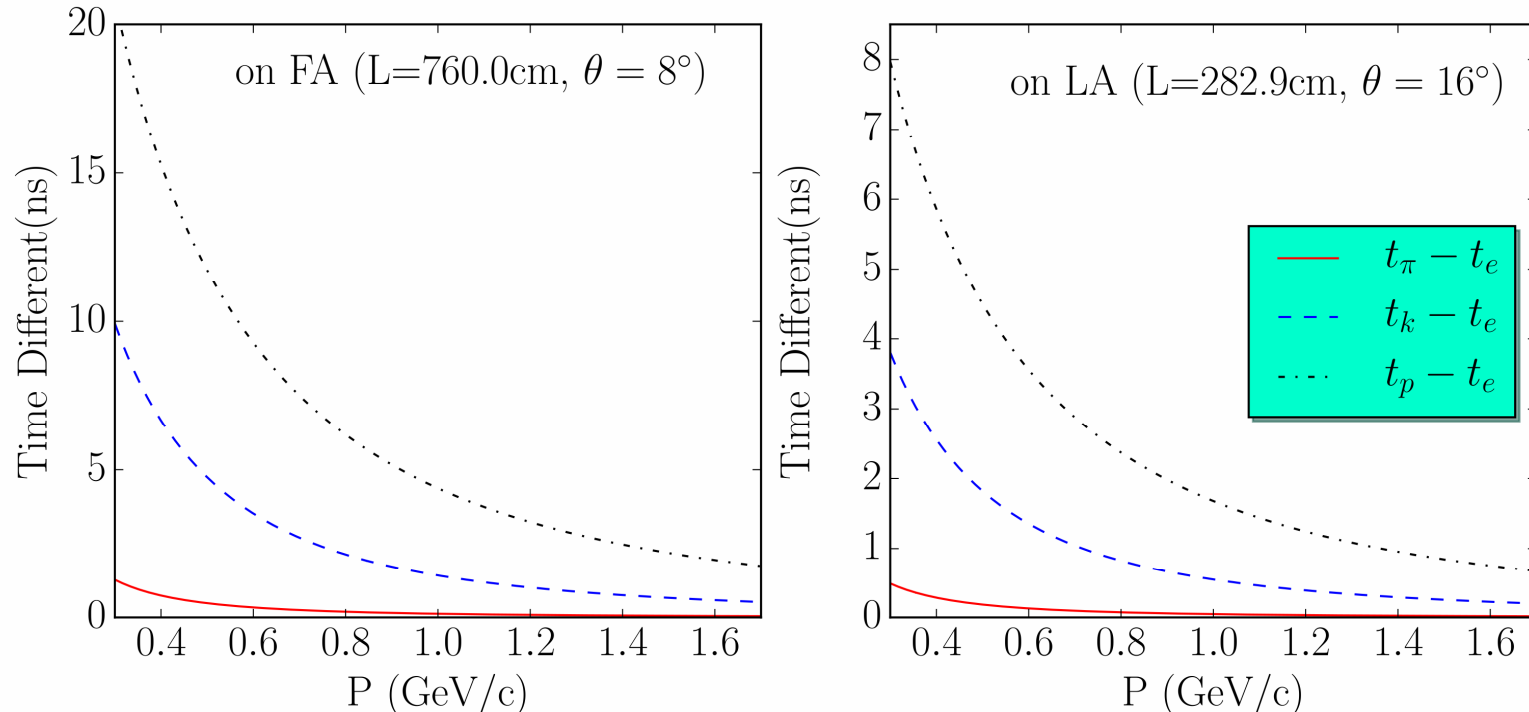
$Q^2 > 4 \text{ GeV}^2$, $W > 2 \text{ GeV}$, $0.55 < \epsilon < 0.75$ cuts applied.



Recoil Particle Detection: Time of Flight

$${}^3\text{He}(e, e' \pi^- p) pp_{sp}$$

- Want $>5\sigma$ timing resolution to identify protons from other charged particles



- **SoLID Timing Detector Specs:**

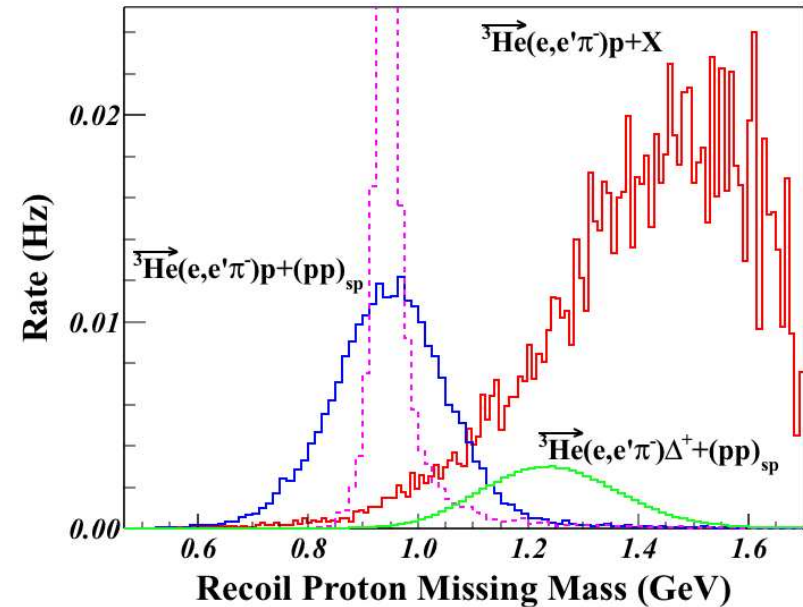
- MRPC & FASPC at Forward-Angle: cover $8^\circ \sim 14.8^\circ$, >3 ns separation.
- LASPD at Large-Angle: cover $14^\circ \sim 24^\circ$, >1 ns separation.

- The currently designed timing resolution is sufficient for proton identification using TOF.

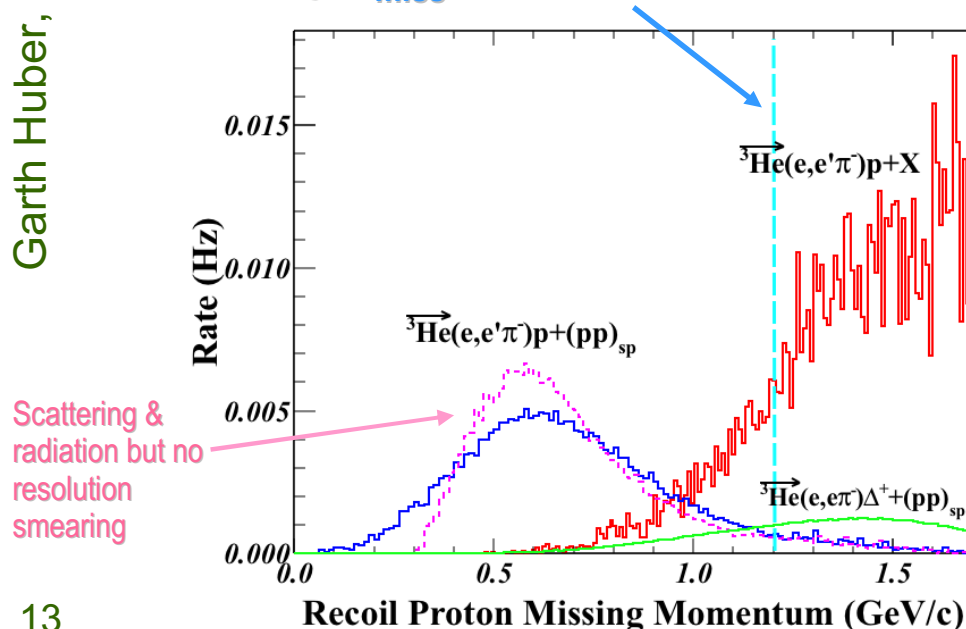
Example Cuts to Reduce Background

Two different background channels were simulated:

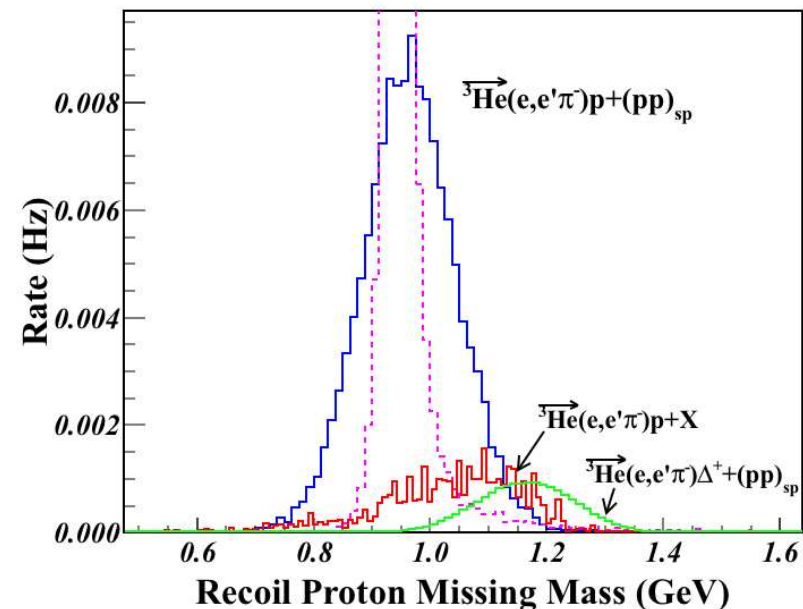
- SoLID–SIDIS generator $p(e, e' \pi^-)X$ and $n(e, e' \pi^-)X$, where we assume all X fragments contain a proton (over-estimate).
- $en \rightarrow \pi^- \Delta^+ \rightarrow \pi^- \pi^0 p$ where the Δ^+ (polarized) decays with $l=1, m=0$ angular distribution (more realistic).



Apply $P_{miss} > 1.2$ GeV/c cut

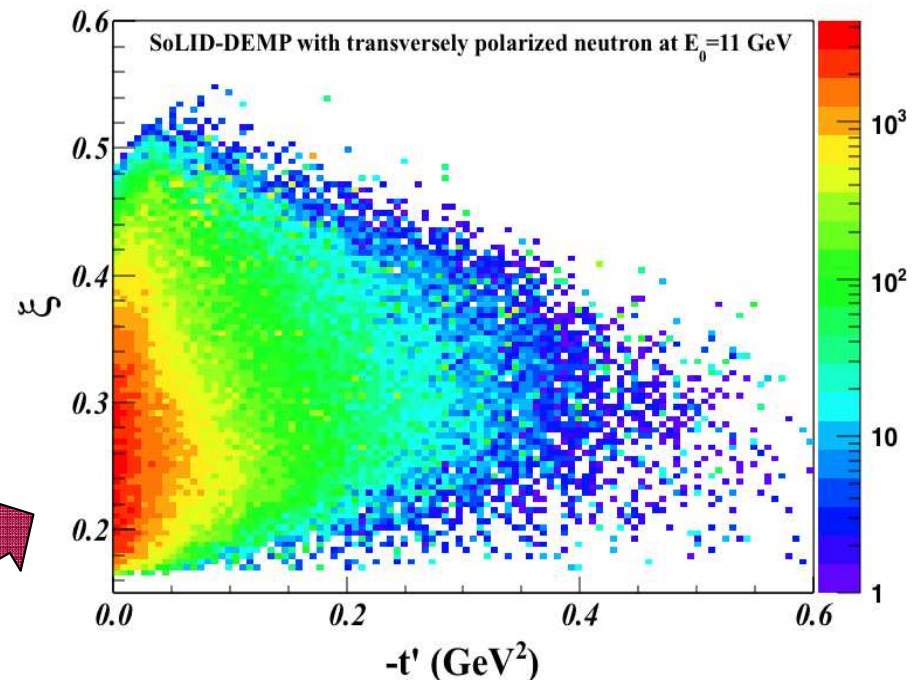
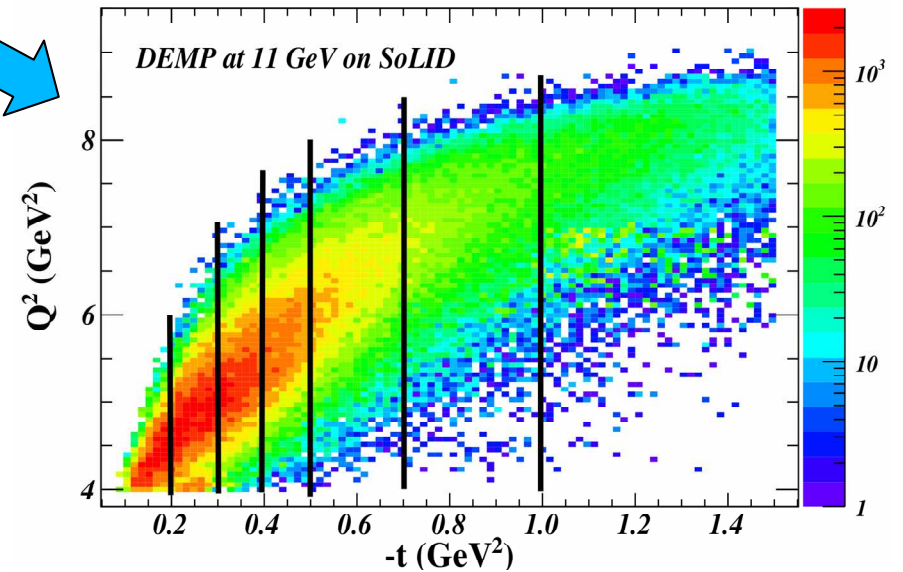


Background remaining after P_{miss} cut



Kinematic Coverage and Binning

- We binned the simulated data in 7 t -bins.
- In actual data analysis, we will consider alternate binning.
- All JLab data cover a range of Q^2 , x_{Bj} values.
 - x_{Bj} fixes the skewness (ξ).
 - Q^2 and x_{Bj} are correlated. In fact, we have an almost linear dependence of Q^2 on x_{Bj} .
- HERMES and COMPASS experiments are restricted kinematically to very small skewness ($\xi < 0.1$).
- With SoLID, we can measure the skewness dependence of the relevant GPDs over a fairly large range of ξ .



Asymmetry Moment Modeling

- Event generator incorporates A_{UT} moments calculated by Goloskokov and Kroll for kinematics of this experiment.

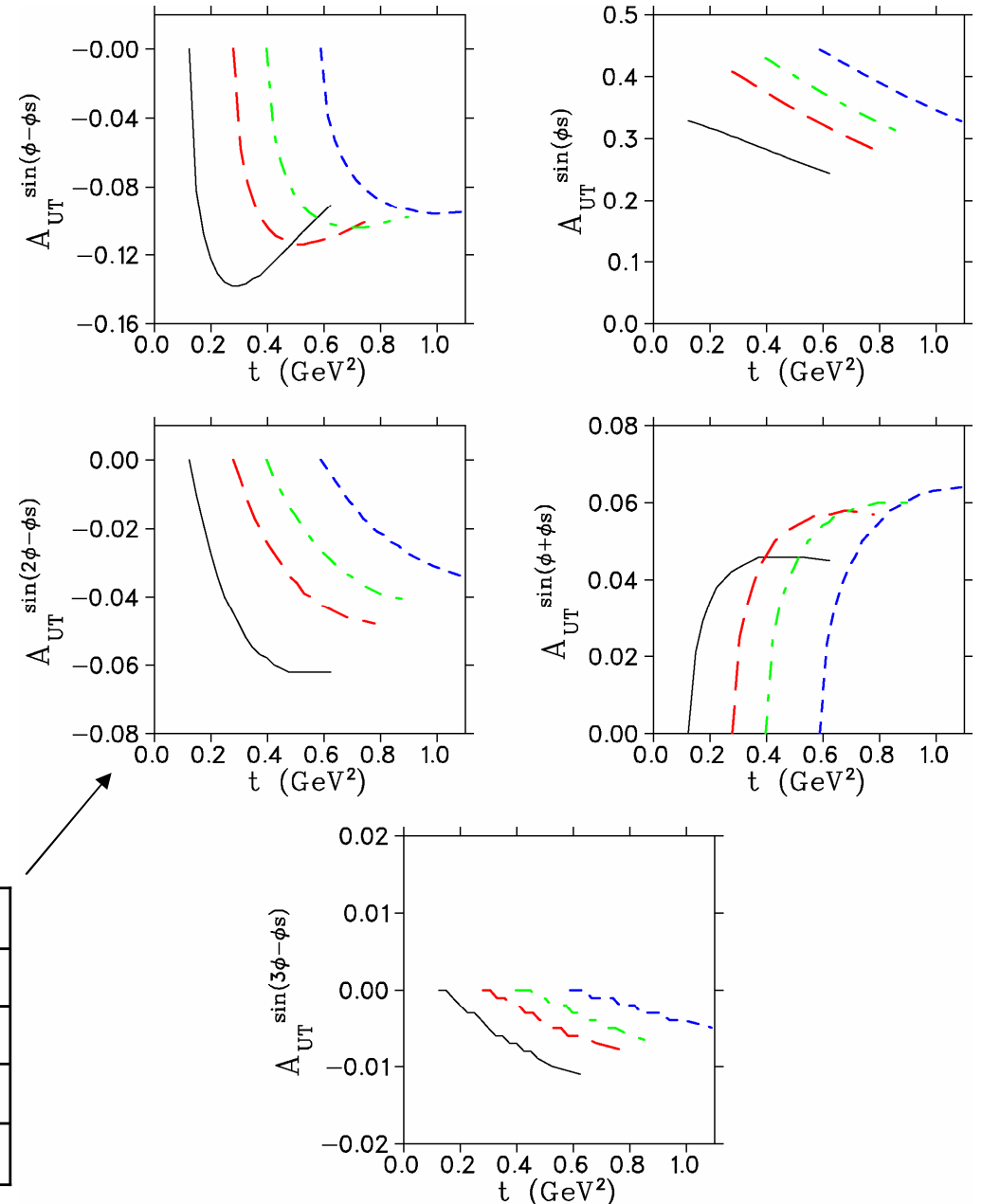
- CompPhysComm 208(2025)109444

- Moments from GK handbag approach for π^- from neutron:

- Eur.Phys.J. C65(2010)137.

- Eur.Phys.J. A47(2011)112.

- Simulated data for target polarization up and down are subjected to same $Q^2 > 4 \text{ GeV}^2$, $W > 2 \text{ GeV}$, $0.55 < \epsilon < 0.75$ cuts.



Q^2	W
4.11	3.17
5.14	2.80
6.05	2.72
6.89	2.56

Unbinned Maximum Likelihood (UML)

- **Same method used by HERMES in their DEMP analysis** [PLB 682(2010)345].
- Instead of dividing the data into (ϕ, ϕ_s) bins to extract the asymmetry moments, UML takes advantage of full statistics of the data, obtains much better results when statistics are limited.

1. Construct probability density function

$$f_{\uparrow\downarrow}(\phi, \phi_s; A_k) = \frac{1}{C_{\uparrow\downarrow}} \left(1 \pm \frac{|P_T|}{\sqrt{1 - \sin^2(\theta_q) \sin^2(\phi_s)}} \times \sum_{k=1}^5 A_k \sin(\mu\phi + \lambda\phi_s) \right)$$

where A_k are the asymmetries that can minimize the likelihood function.

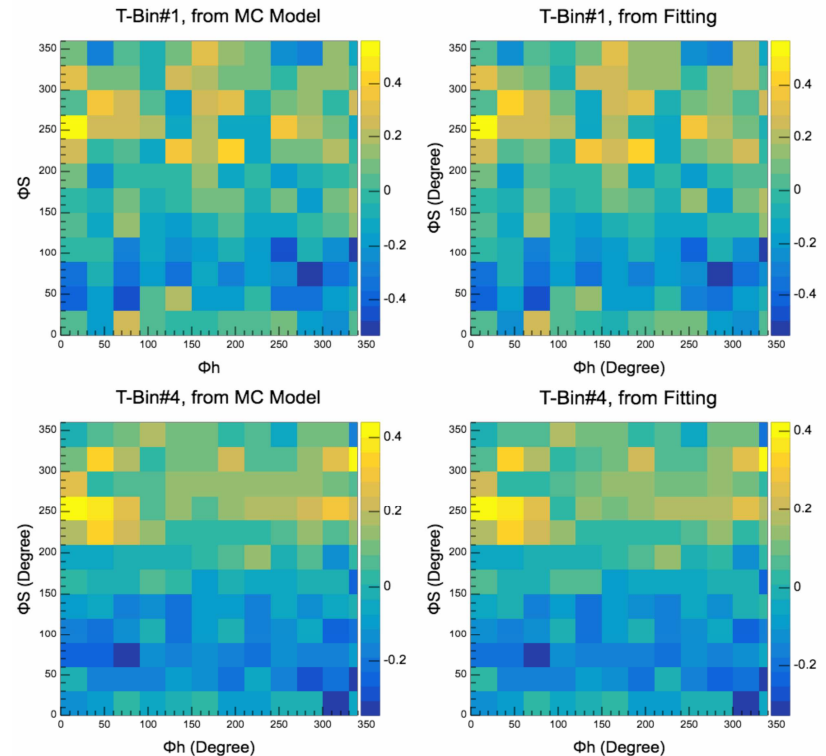
2. Minimize negative log-likelihood function:

$$-\ln L(A_k) = -\ln L_{\uparrow}(A_k) - \ln L_{\downarrow}(A_k)$$

$$= \sum_{l=1}^{N_{MC}^{\uparrow}} \left[w_l^{\uparrow} \cdot \ln f_{\uparrow}(\phi_l, \phi_{s,l}; A_k) \right] - \sum_{m=1}^{N_{MC}^{\downarrow}} \left[w_m^{\downarrow} \cdot \ln f_{\downarrow}(\phi_m, \phi_{s,m}; A_k) \right]$$

where w_l, w_m are MC event weights based on cross section & acceptance.

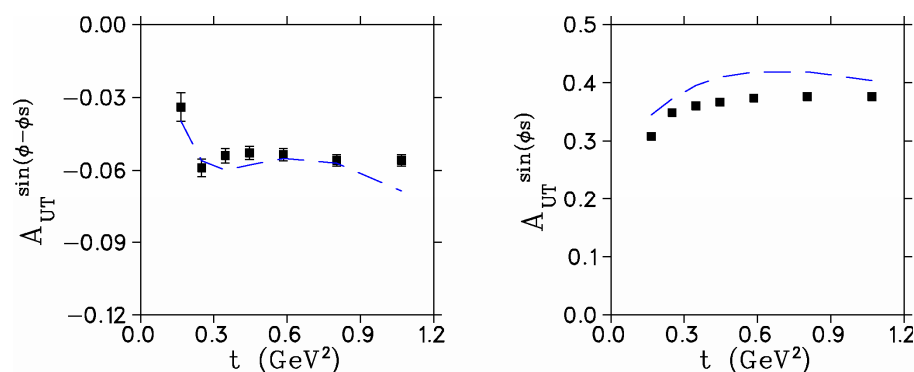
3. As an illustration, reconstruct azimuthal modulations & compare:



E12-10-006B Projected Uncertainties

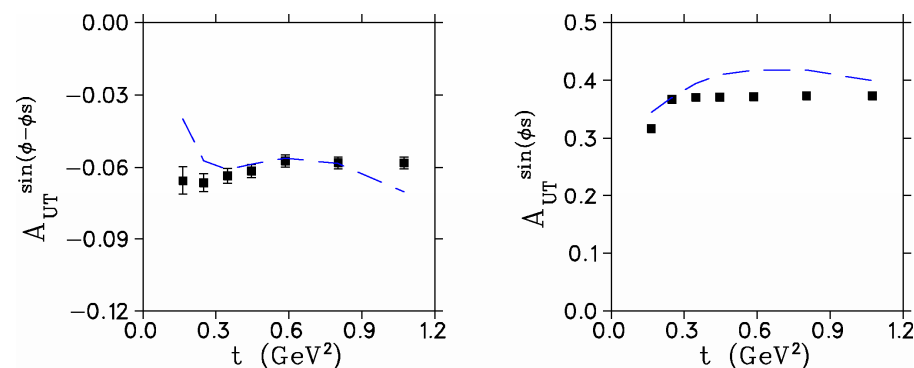
All effects off.

- Agreement between input and output fit values is very good. Validates the Unbinned Maximum Likelihood analysis procedure.



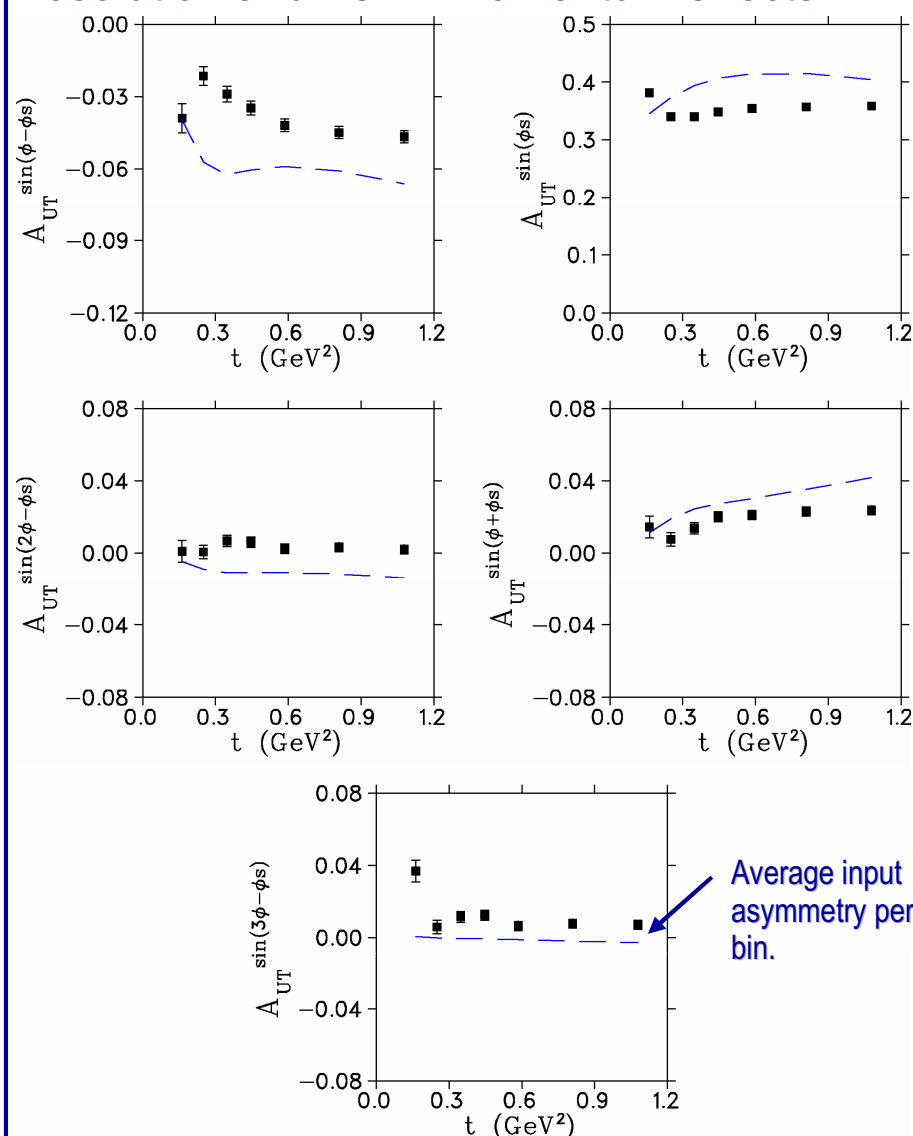
Only Fermi momentum off.

Includes all scattering, energy loss, resolution effects. Similar to where proton resolution is good enough to correct for Fermi momentum effects.



All effects on.

Includes all scattering, energy loss, resolution and Fermi momentum effects.



$\tilde{E}$ SoLID Lite Requirements

■ Offline Triple Coincidence:

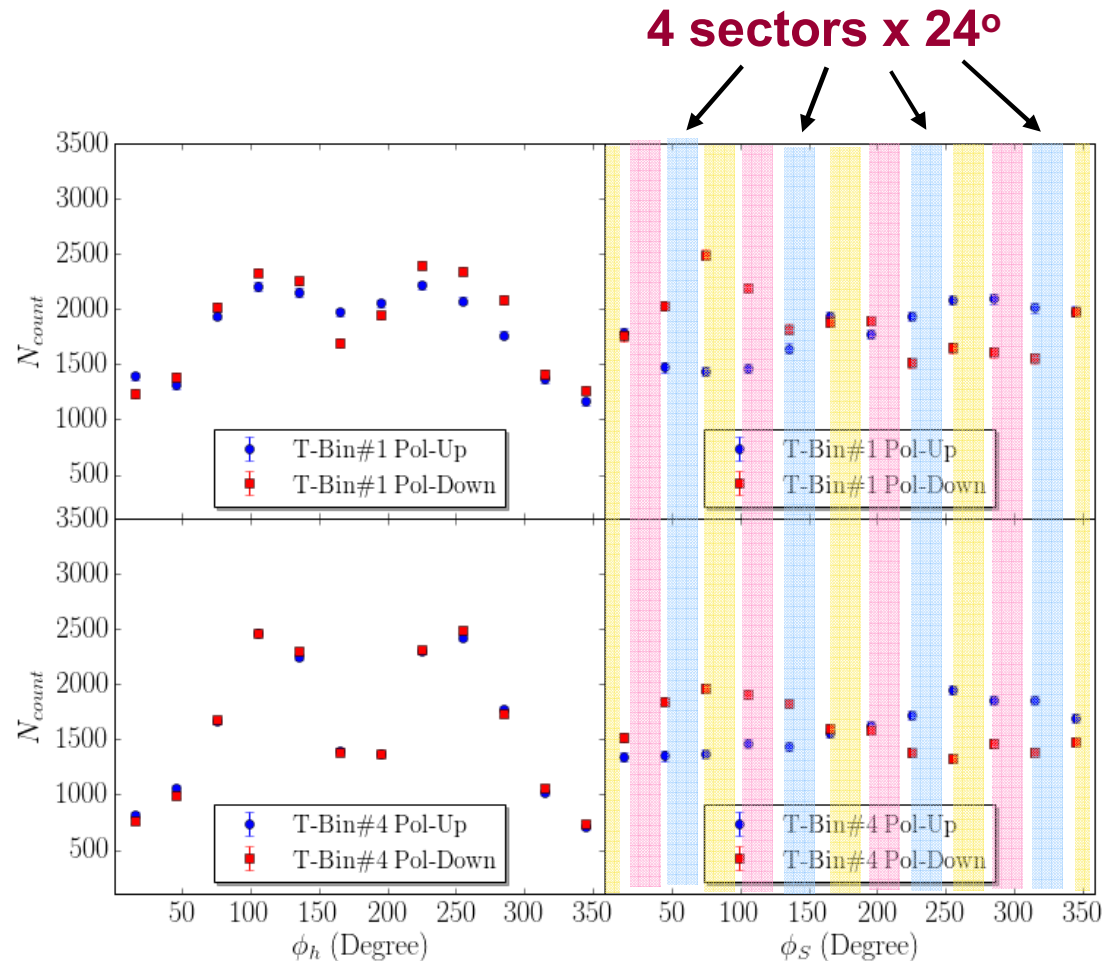
- $e'(LA) \pi^-(FA)$
 $p(FA+LA)$

■ Recoil PID:

- Need sufficient TOF resolution to separate protons from $\pi^\pm$ (FA+LA)

■ Azimuthal coverage:

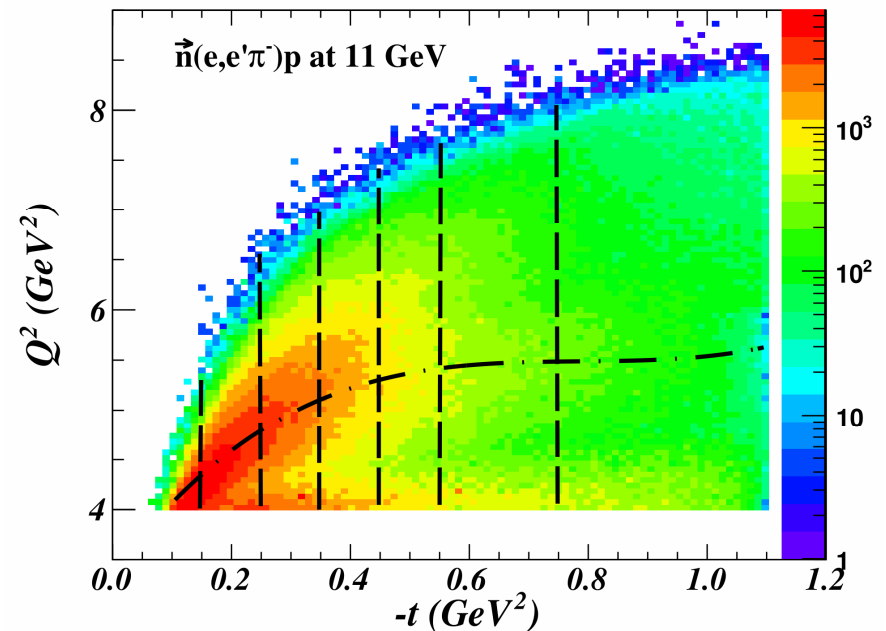
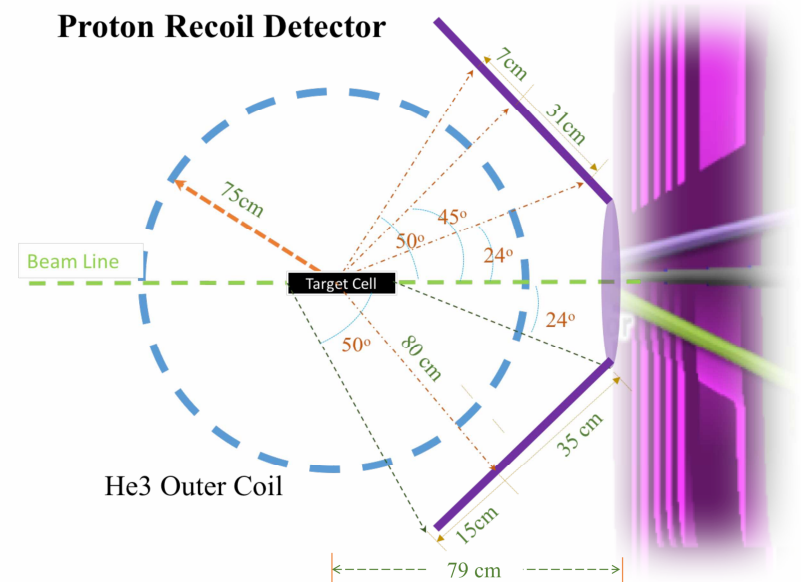
- Separate $\sin(\varphi - \varphi_s)$ moment (Amplitude ~ -0.04)
- From dominant $\sin(\varphi_s)$ moment (Amplitude $\sim +0.35$) and lesser $\sin(2\varphi - \varphi_s)$ moment (Amplitude $\sim +0.01$)
- SoLID Lite sectors are **slices of constant φ_s** , compensated with target polarization at $+60^\circ$ (pink) and -60° (blue) in addition to vertical $\pm 90^\circ$ (yellow)
- **Reduced φ coverage** (hadron production azimuth) can be offset by higher luminosity planned by SIDIS



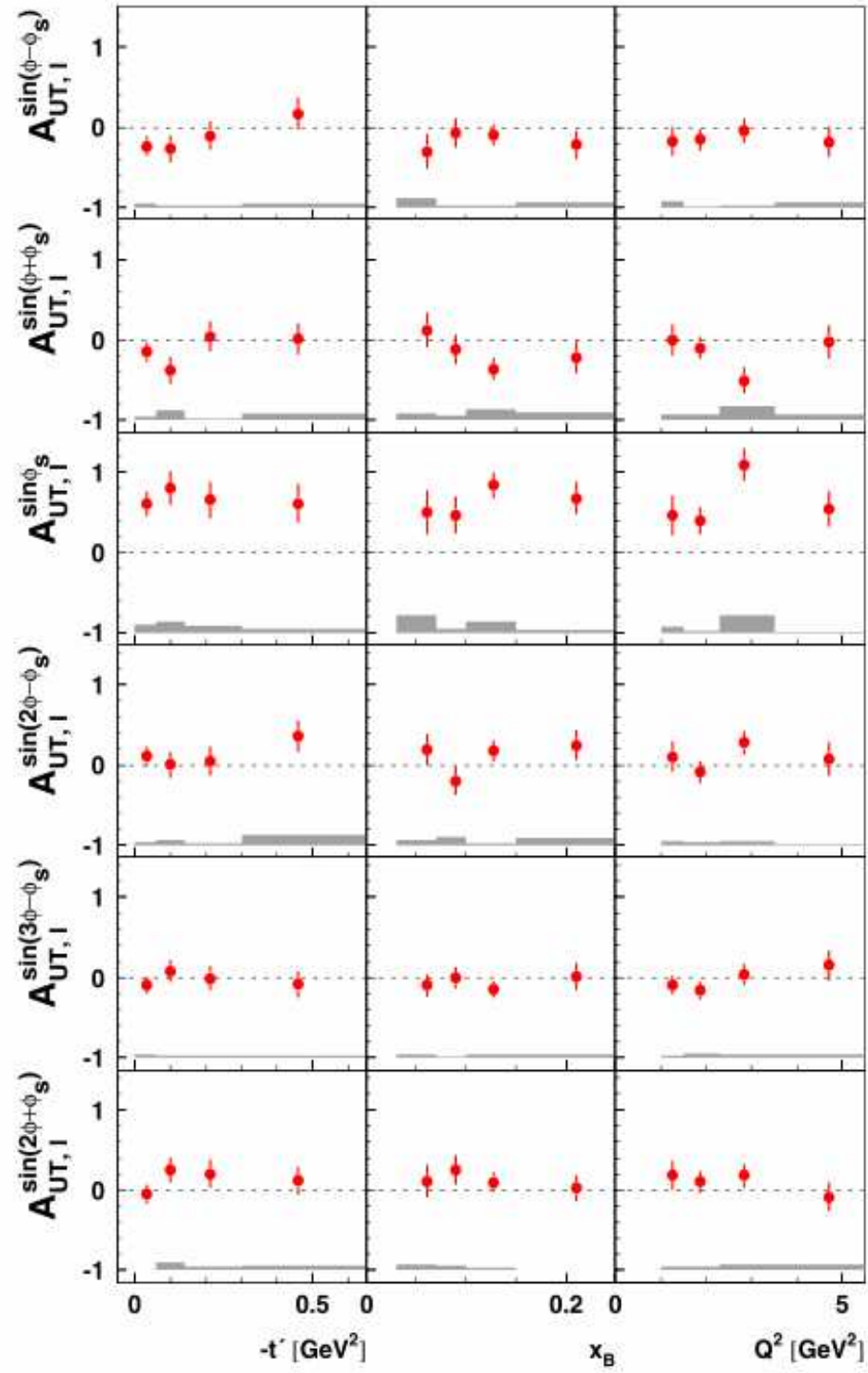
- Expected yield as function of φ , φ_s for t -bins:
#1 (0.05–0.20) #4 (0.40–0.50)
- Dropoff on edges of φ distribution, since q not aligned with solenoid axis.
- Critical feature: φ dropoff same for tgt pol up, down.

Enhanced Proton Recoil Detection

- A Proton Recoil Detector covering angles 24° to 50° would allow data over a wider range of $-t$ to be acquired
- A document on using the sPHENIX MVTX detector with SoLID was submitted in January 2026 by GMH, W.B. Li, R. Montgomery, Z. Ye, Z. Zhao
- Recoil detector would allow Tagged DIS (TDIS) measurements to be added to the SoLID program, with promising simulations of $H(e, e'p_{\text{recoil}})X$ and $D(e, e'p_{\text{recoil}})X$ coverage



- $A_{UT}^{\sin(\varphi-\varphi_s)}$ transverse single–spin asymmetry in exclusive π production is particularly sensitive to the spin–flip GPD $\tilde{E}$. Factorization studies indicate precocious scaling to set in at moderate $Q^2 \sim 2\text{--}4 \text{ GeV}^2$, while scaling is not expected until $Q^2 > 10 \text{ GeV}^2$ for absolute cross section.
- $A_{UT}^{\sin(\varphi_s)}$ asymmetry can also be extracted from same data, providing powerful additional GPD–model constraints and insight into the role of transverse photon contributions at small $-t$, and over wide range of ξ .
- **SoLID Lite measurement will need $\pm 60^\circ$ target field running in addition to $\pm 90^\circ$ to compensate for holes φ_s FA coverage, as well as higher beam current planned by SIDIS measurement**
- **SoLID Lite uncertainties require dedicated study, probably 2x worse than SoLID experiment**



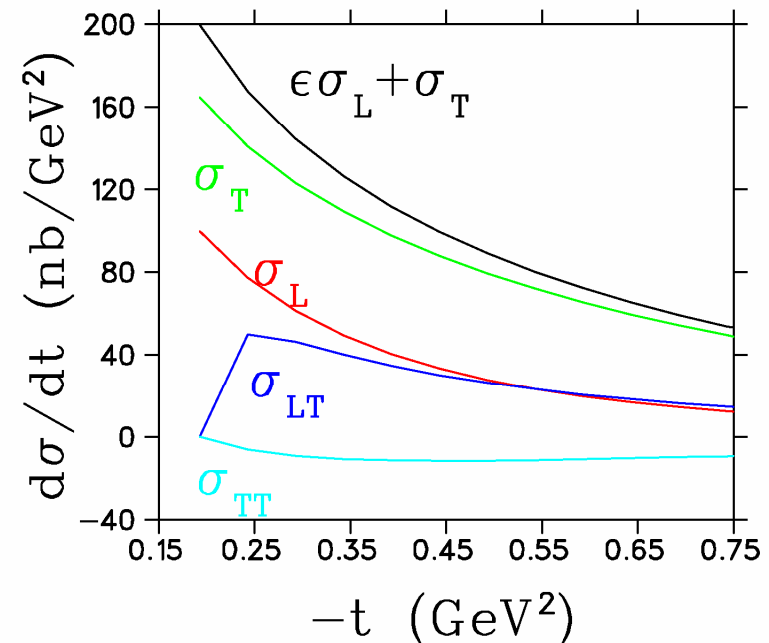
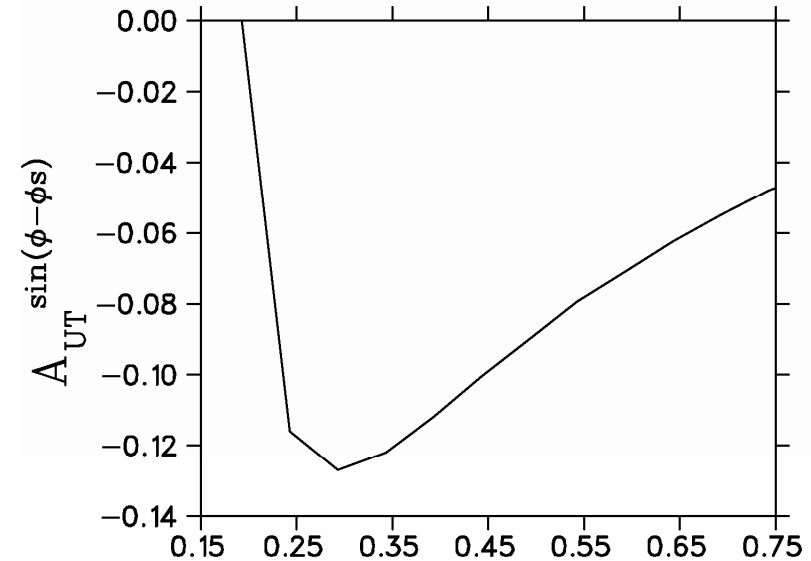
Separated versus Unseparated Expts

- Our reaction of interest is $\vec{n}(e, e' \pi^-) p$ from the neutron in transversely polarized ^3He .
- It has not yet been possible to perform an experiment to measure $A_L^\perp$.
 - Conflicting experimental requirements of transversely polarized target, high luminosity, L–T separation and closely controlled systematic uncertainties make this an exceptionally challenging observable to measure.
- The most closely related measurement, of the transverse single-spin asymmetry in $\vec{p}(e, e' \pi^+) n$, without an L–T separation, was published by HERMES in 2010.
 - Significant GPD information was obtained.
 - Our proposed SoLID measurements will be a significant advance over the HERMES data in terms of kinematic coverage and statistical precision.

Asymmetry Dilution with SoLID

- **Calculation of cross section components and $\sin(\beta=\phi-\phi_s)$ asymmetry moment in handbag approach by Goloskokov & Kroll for our kinematics.**
 - Although their calculation tends to underestimate σ_L values measured by JLab F π -2, their model is in reasonable agreement with unseparated $d\sigma/dt$.
- Similar level of $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry dilution as observed by HERMES is expected in SoLID measurement.
- **SoLID measurement at higher Q^2 than HERMES, will cover a wide range of $-t$ (and ξ) with good statistical precision.**

$Q^2=4.0 \text{ GeV}^2$ $W=2.8 \text{ GeV}$ $\epsilon=0.35$



Missing Mass and Missing Momentum

- **Conservative estimates:**

- Although we will detect the recoil proton to separate the exclusive channel events, in this analysis we do not assume that the proton momentum resolution is sufficiently good to provide an additional constraint.
- Thus, we compute the missing mass and momentum as if the proton were not detected:

$$M_{miss} = \sqrt{(E_e + m_n - E_{e'} - E_{\pi^-})^2 - (\vec{p}_e - \vec{p}_{e'} - \vec{p}_{\pi^-})^2}$$
$$p_{miss} = \left| \vec{p}_e - \vec{p}_{e'} - \vec{p}_{\pi^-} \right|$$

- **Of course, in the actual analysis, we will try to reconstruct the proton momentum as accurately as possible.**
- If the resolution is sufficiently good, this would allow additional background discrimination, as well as the effect of Fermi momentum to be removed from the asymmetry moments on an event-by-event basis.

Fermi Momentum Effects

- If the recoil proton momentum resolution is sufficiently good, it will be possible to correct for Fermi momentum on an event-by-event basis.
- For the purposes of the proposal, we take the more conservative view that the resolution is not good enough, even though the removal of the Fermi momentum effect would simplify the physics interpretation of our data.
- To estimate the impact of Fermi momentum, we ran the generator in a variety of configurations and repeated our analysis:
 - Multiple scattering, energy loss, radiation effects ON/OFF.
 - Fermi momentum ON/OFF.
- The effect of Fermi momentum is about -0.02 on the $\sin(\varphi - \varphi_s)$ moment, and about -0.04 on the $\sin(\varphi_s)$ moment.
- We hope this estimate of Fermi momentum effects at an early stage will encourage theorists to calculate them for a timely and correct utilization of our proposed data, as suggested in last year's Theory review.
- 2017 Theory review appeared to be satisfied with this response.

SoLID Systematic Uncertainties

- Detector–wide, DEMP measurement shares the same systematic uncertainties with SIDIS experiments

Sources	Relative Value
Beam Polarization	2%
Target Polarization	3%
Acceptance	3%
Other Contamination	< 5%
Radiation Correction	1%

- Other sources of uncertainties are still under estimation.

Final State Interaction (FSI) Effects

- To estimate FSI effects, we used an empirical (phase–shift) parameterization of π^-N differential cross sections.
- Based on this model, and the fact that there are only two proton spectators in the final state to interact with, we anticipate about 1% of events will suffer FSI interactions. The FSI fraction is weakly dependent on Q^2 , rising to about 1.2% for $Q^2 > 5 \text{ GeV}^2$ events. Of these, a large fraction of FSI events are scattered outside the triple-coincidence acceptance, reducing the FSI fraction to $\sim 0.4\%$. This will be further reduced by analysis cuts such as $P_{\text{miss}} < 1.2 \text{ GeV}/c$.
- Over the longer term, we will consult with theoretical groups for a more definitive FSI effect study.
 - e.g. Del Dotto, Kaptari, Pace, Salme and Scopetta recent study of FSI effects in SIDIS from a transversely polarized ^3He target [arXiv:1704.06182] showed that extracted Sivers and Collins asymmetries are basically independent of FSI. A similar calculation for DEMP, after this proposal is accepted, would be a natural extension of their work.