Deep Exclusive π^- Production using a Transversely Polarized ^{3}He Target and the SoLID Spectrometer

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Leading Twist GPD Parameterization

- **GPDs interrelate the longitudinal momentum and transverse spatial structure of partons within a fast moving hadron.**
- **GPDs are universal quantities and reflect nucleon structure independently of the probing reaction.**

- At leading twist–2, four quark chirality conserving GPDs for each quark, gluon type.
- Because quark helicity is conserved in the hard scattering regime, the produced meson acts as helicity filter.
  - Pseudoscalar mesons → $\tilde{H}$ $\tilde{E}$
  - Vector mesons → H E.

$H^{q,g}(x,\xi,t)$ spin avg no hel. flip	$E^{q,g}(x,\xi,t)$ spin avg helicity flip
$\tilde{H}^{q,g}(x,\xi,t)$ spin diff no hel. flip	$\tilde{E}^{q,g}(x,\xi,t)$ spin diff helicity flip

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

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How to determine $\tilde{E}$

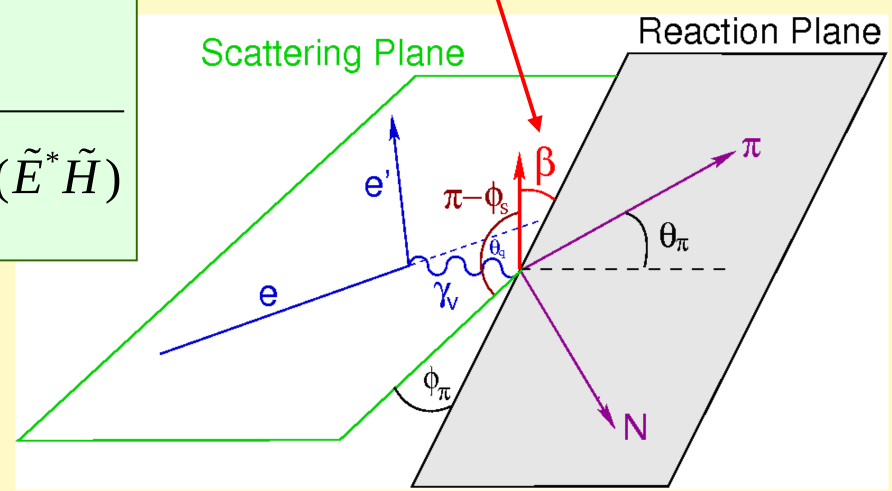
- **GPD $\tilde{E}$ not related to an already known parton distribution.**
- Experimental information on $\tilde{E}$ can provide new nucleon structure info unlikely to be available from any other source.
- The most sensitive observable to probe $\tilde{E}$ is the transverse single-spin asymmetry in exclusive π production:

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

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

$d\sigma_{\pi}^{L}$ = exclusive π cross section for longitudinal γ^*

β =angle between transversely polarized target vector and the reaction plane.



Refs: A.V. Belitsky, D. Mueller, PL**B513** (2001) 349
L.L. Frankfurt, et al., PRD **60**(1999) 014101

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

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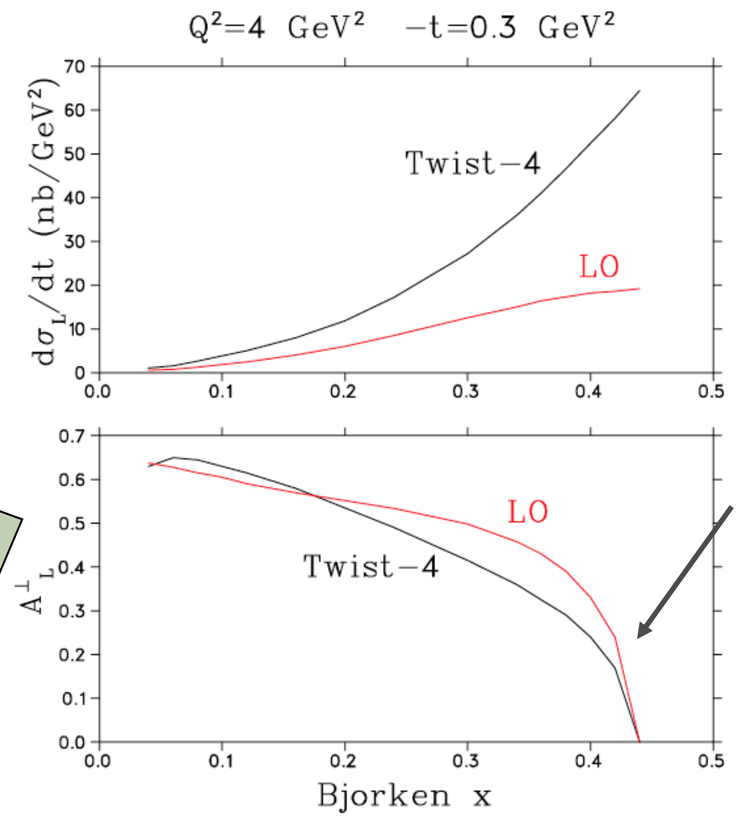
- **$A_L^{\perp}$ is expected to display precocious factorization at only Q^2~2–4 GeV^2:**
  - At Q^2=10 GeV^2, Twist–4 effects can be large, but cancel in $A_L^{\perp}$ (Belitsky & Műller PLB 513(2001)349).
  - At Q^2=4 GeV^2, higher twist effects even larger in σ_L, but still cancel in the asymmetry (CIPANP 2003).



$A_L^{\perp}$=0 at parallel kinematic limit, where φ–φ_s is not well defined.

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.

Transverse Target Single Spin Asymmetry in DEMP

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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

$$\frac{d^3\sigma_{UT}}{dt\,d\phi\,d\phi_s} = -\frac{P_\perp \cos\theta_q}{\sqrt{1-\sin^2\theta_q \sin^2\phi_s}} \begin{pmatrix} \sin\beta\,\mathrm{Im}(d\sigma_{++}^{+-} + \varepsilon d\sigma_{00}^{+-}) \\ +\sin\phi\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}(d\sigma_{+0}^{+-}) \\ +\sin(\phi+\phi_s)\frac{\varepsilon}{2}\mathrm{Im}(d\sigma_{+-}^{+-}) \\ +\sin(2\phi-\phi_s)\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}(d\sigma_{+0}^{-+}) \\ +\sin(3\phi-\phi_s)\frac{\varepsilon}{2}\mathrm{Im}(d\sigma_{+-}^{-+}) \end{pmatrix}$$

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

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

Gives rise to Asymmetry Moments

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

Unseparated sinβ=sin(φ-φ$_s$) Asymmetry Moment

$$A_{UT}^{\sin(\phi-\phi_s)} \sim \frac{d\sigma_{00}^{+-}}{d\sigma_L\binom{++}{00}} \sim \frac{\mathrm{Im}(\tilde{E}^*\tilde{H})}{|\tilde{E}|^2} \text{ where } \tilde{E} \gg \tilde{H}$$

Ref: M. Diehl, S. Sapeta, Eur.Phys.J. C**41**(2005)515.

Note: Trento convention used for rest of talk

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HERMES sin(φ–φ$_S$) Asymmetry Moment

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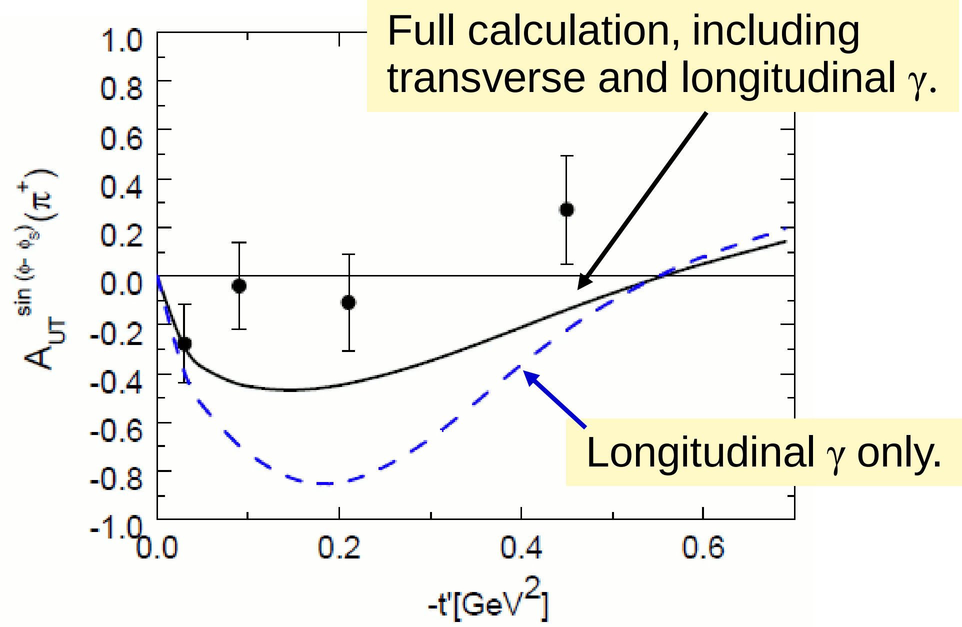
- Exclusive π^+ production by scattering 27.6 GeV positrons or electrons from transverse polarized ^{1}H [PL **B682**(2010)345].
- Analyzed in terms of 6 Fourier amplitudes for φ_π, φ_S.
- $\langle x_B \rangle = 0.13$, $\langle Q^2 \rangle = 2.38$ GeV^2, $\langle -t \rangle = 0.46$ GeV^2.



- **Since there is no L/T separation, $A_{UT}^{\sin(\varphi-\varphi_S)}$ 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.

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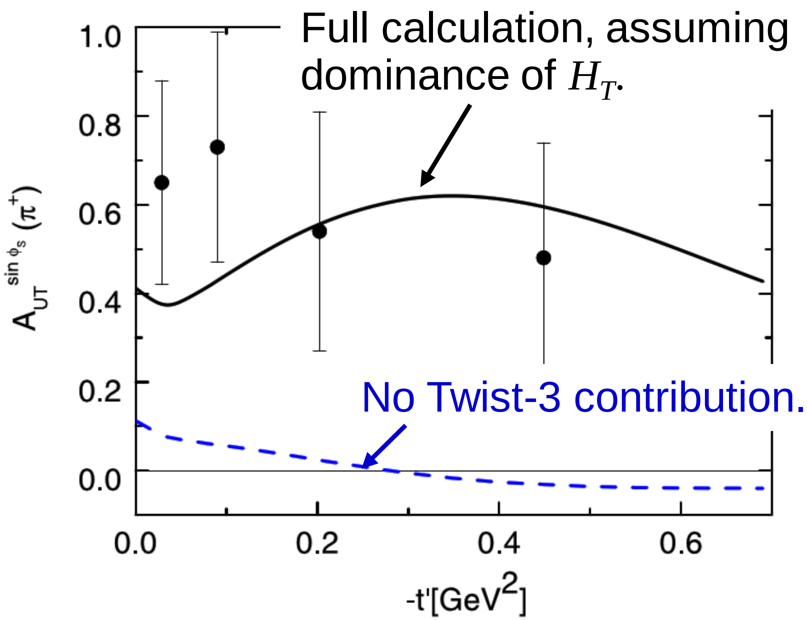
HERMES sin(φ_s) Asymmetry Moment

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



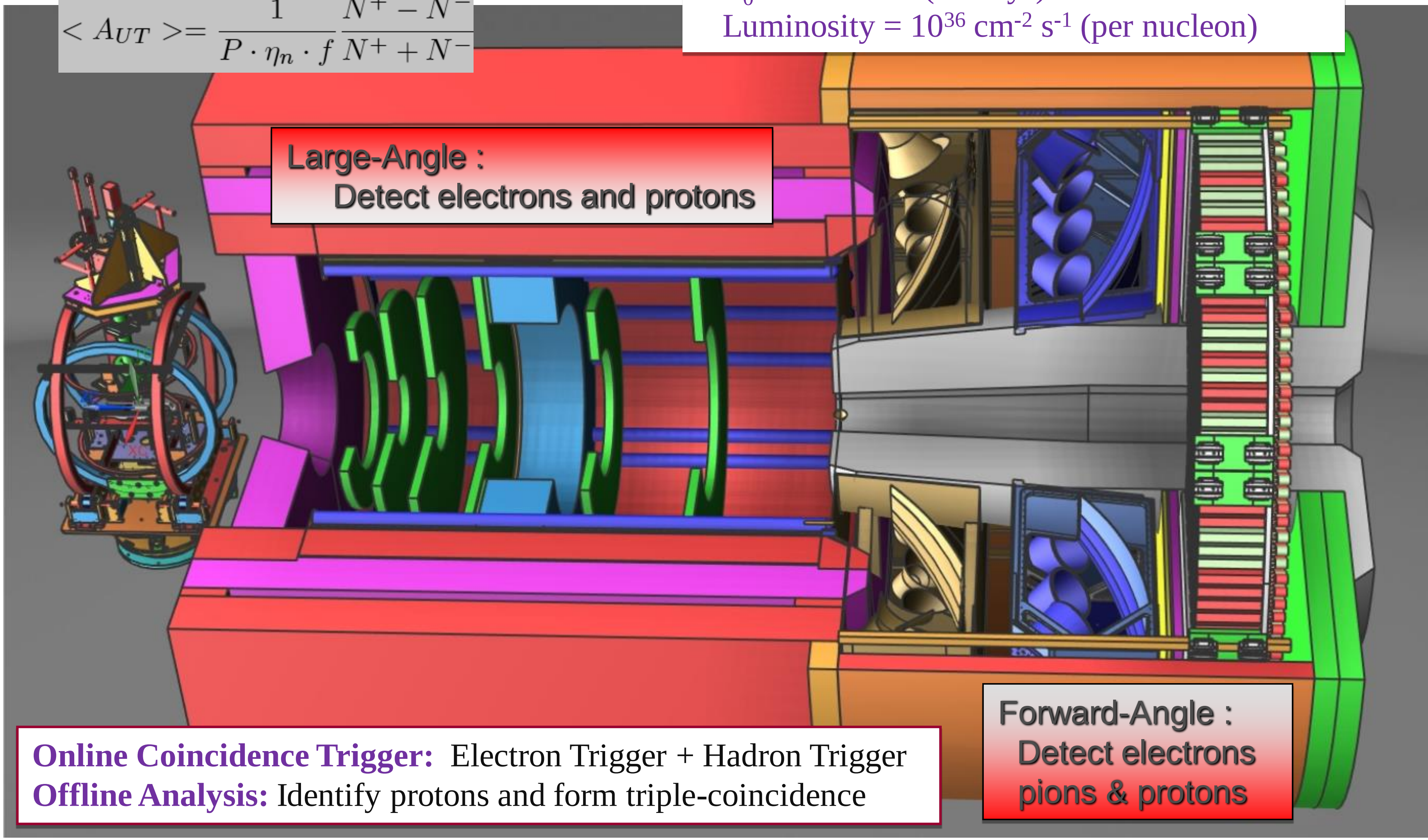
- In contrast to the sin(φ-φ_s) modulation, which has contributions from LL and TT interferences, the sin(φ_S) modulation measures only the LT interference.
- **The HERMES sin(φ_S) modulation is large and nonzero at –*t'*=0, giving the first clear signal for strong contributions from transversely polarized 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.**

Measure DEMP with SoLID – Polarized ^{3}He

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

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

Run in parallel with E12-10-006:
- E_0 = 11.0 GeV (48 days)
- Luminosity = 10^{36} cm^{-2} s^{-1} (per nucleon)



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

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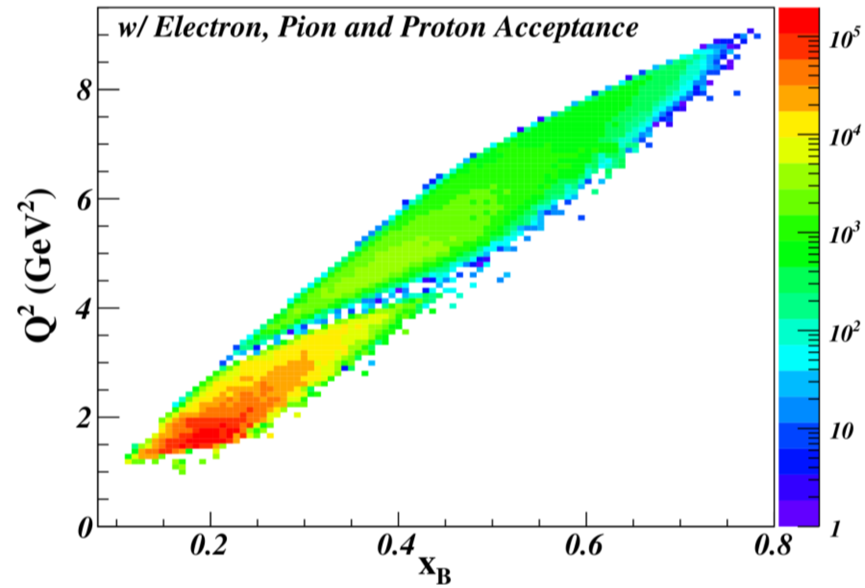
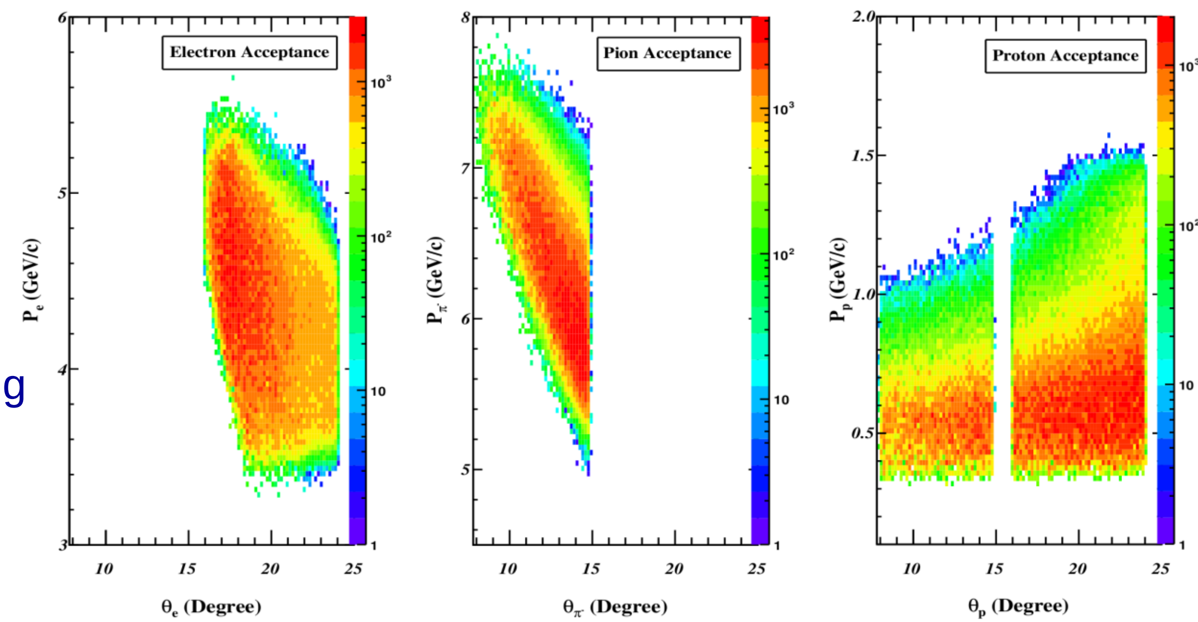
SoLID Acceptance and Projected Rates

Q^2>1 GeV^2 W>2 GeV	Q^2>4 GeV^2 W>2 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 is 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 GeV^2, W>2 GeV, 0.55<ε<0.75 cuts applied.



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Example Cuts to Reduce Background

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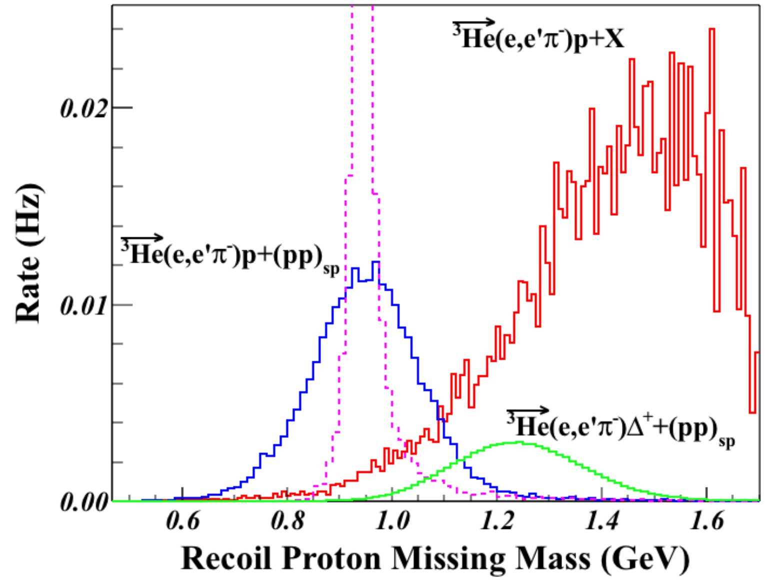
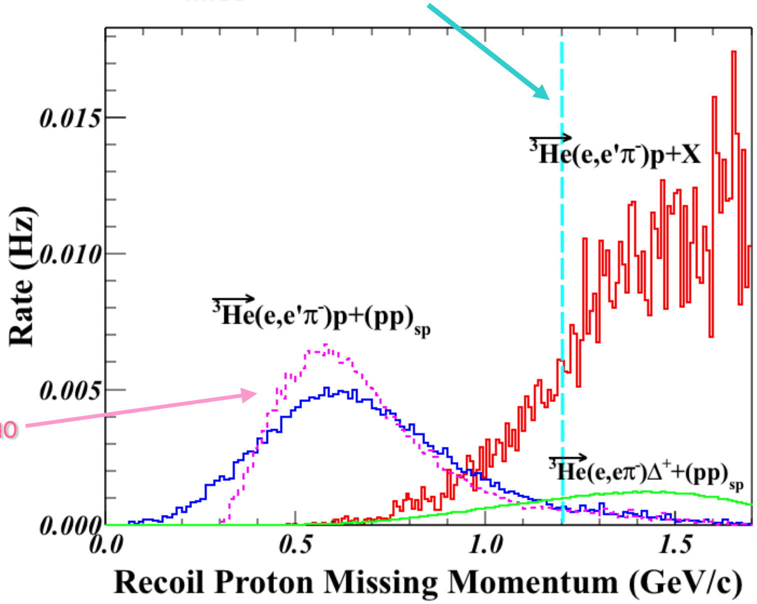
Two different background channels were simulated:

- 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).
- $en\rightarrow\pi^-\Delta^+\rightarrow\pi^-\pi^0p$ where the Δ^+ (polarized) decays with l=1, m=0 angular distribution (more realistic).

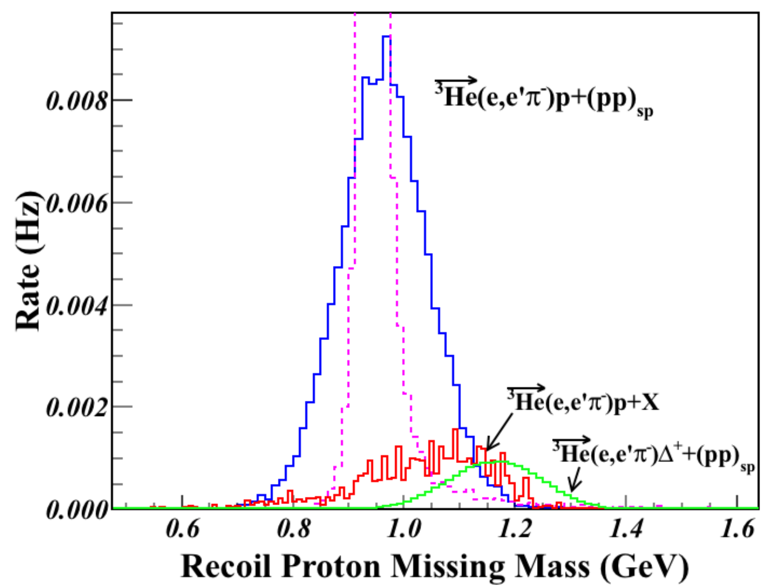


Apply P_{miss}>1.2 GeV/c cut



Scattering & radiation but no resolution smearing

Background remaining after P_{miss} cut



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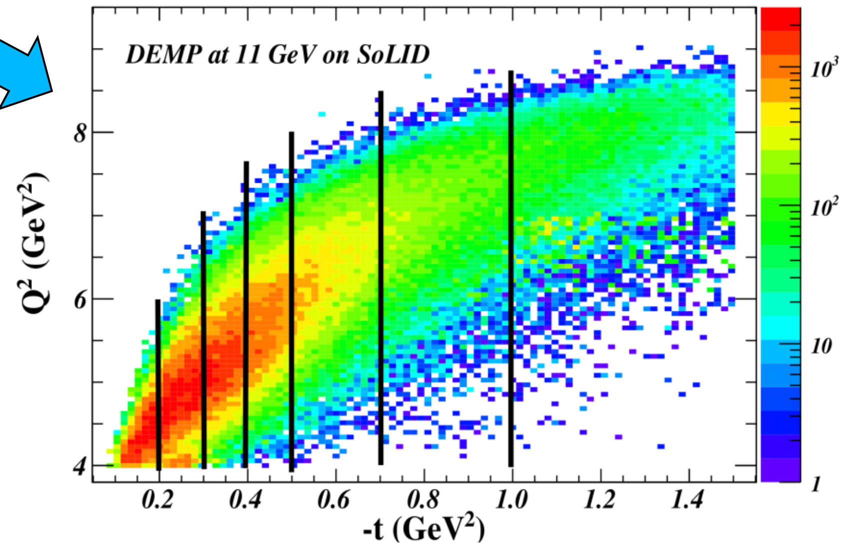
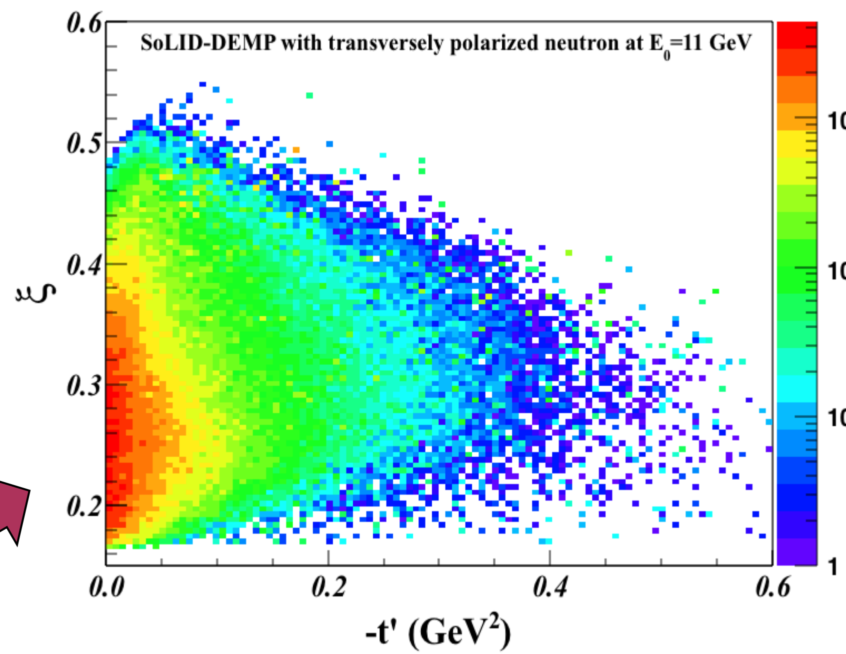
Kinematic Coverage and Binning

- **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 (ξ<0.1).
- **With SoLID, we can measure the skewness dependence of the relevant GPDs over a fairly large range of ξ.**





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E12–10–006B Projected Uncertainties

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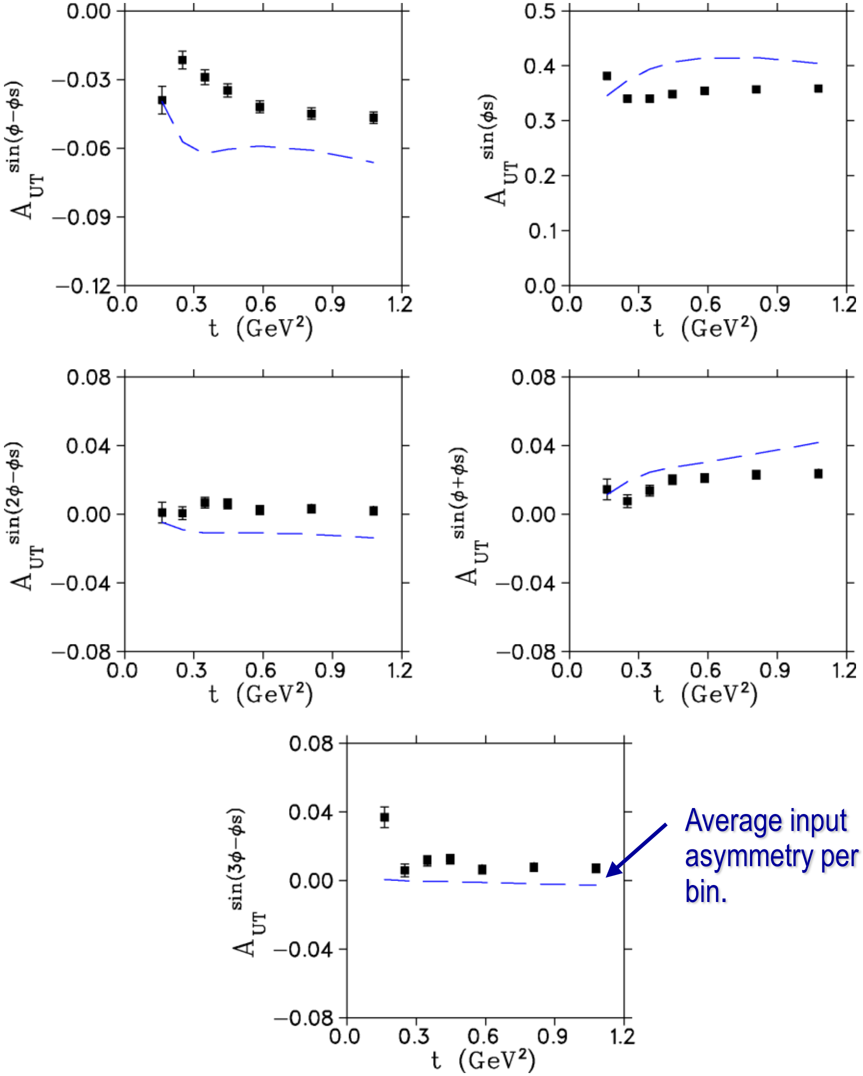
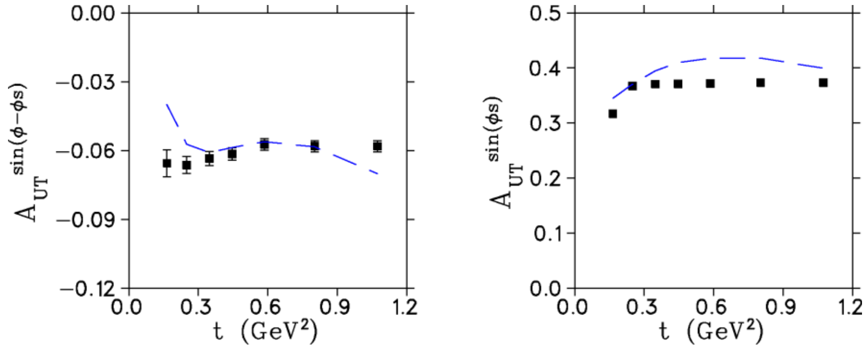
All effects on.

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



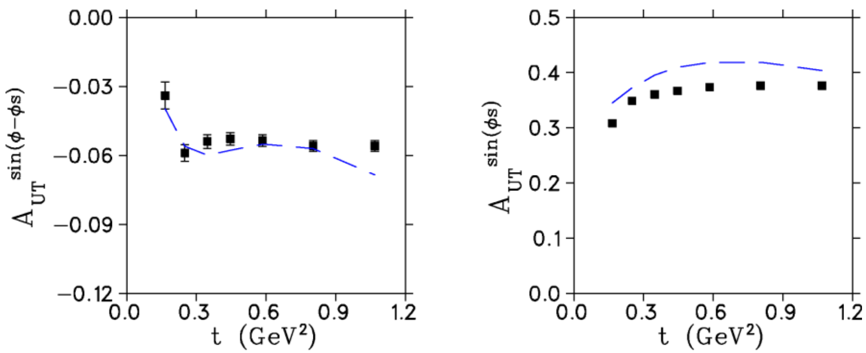
Only Fermi momentum off.

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



All effects off.

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



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Summary

- $A_{UT}^{\sin(\varphi-\varphi_s)}$ 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^2~2-4 GeV^2, while scaling is not expected until Q^2>10 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.
- **High luminosity and good acceptance capabilities of SoLID make it well–suited for this measurement. It is the only feasible manner to access the wide –*t* range needed to fully understand the asymmetries.**
- **SoLID measurement is also important preparatory work for EIC.**

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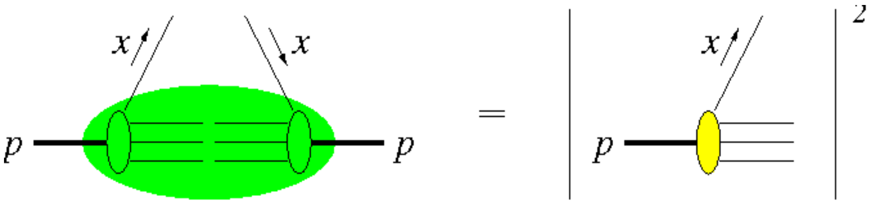
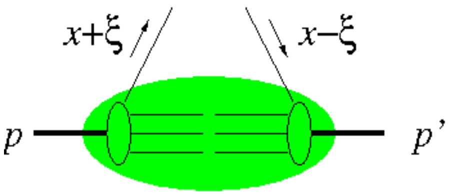
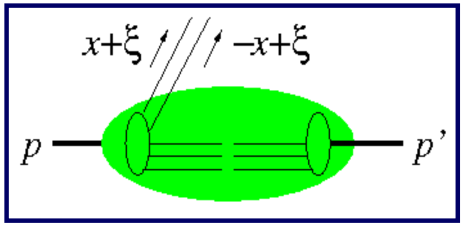
GPDs in Deep Exclusive Meson Production

PDFs : **probability of finding a parton with longitudinal momentum fraction x and specified polarization in fast moving hadron.**



GPDs : **interference between partons with $x+\xi$ and $x-\xi$, interrelating longitudinal momentum & transverse spatial structure of partons within fast moving hadron.**





A special kinematic regime is probed in Deep Exclusive Meson Production, where the initial hadron emits $q\bar{q}$ or gg pair.

- No counterpart in usual PDFs.
- Since GPDs correlate different parton configurations in the hadron at quantum mechanical level,
  - GPDs determined in this regime carry information about $q\bar{q}$ and gg-components in the hadron wavefunction.

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Spin–Flip GPD $\tilde{E}$

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

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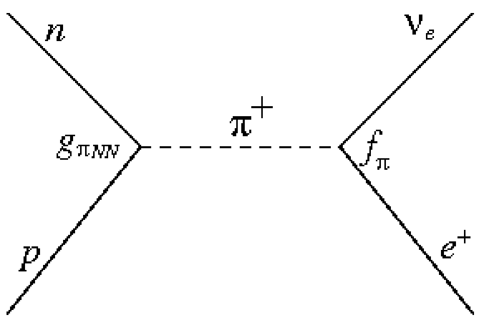
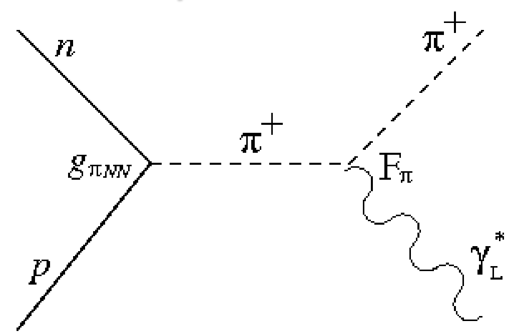
- **$\tilde{E}$ is not related to any already known parton distribution.**
- *$G_P(t)$ is highly uncertain because it is negligible at the momentum transfer of β-decay.*
  - *Due to PCAC, $G_P(t)$ receives contributions from $J^{PG}=0^{--}$ states.*
  - *$\tilde{E}$ is expected to contain an important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

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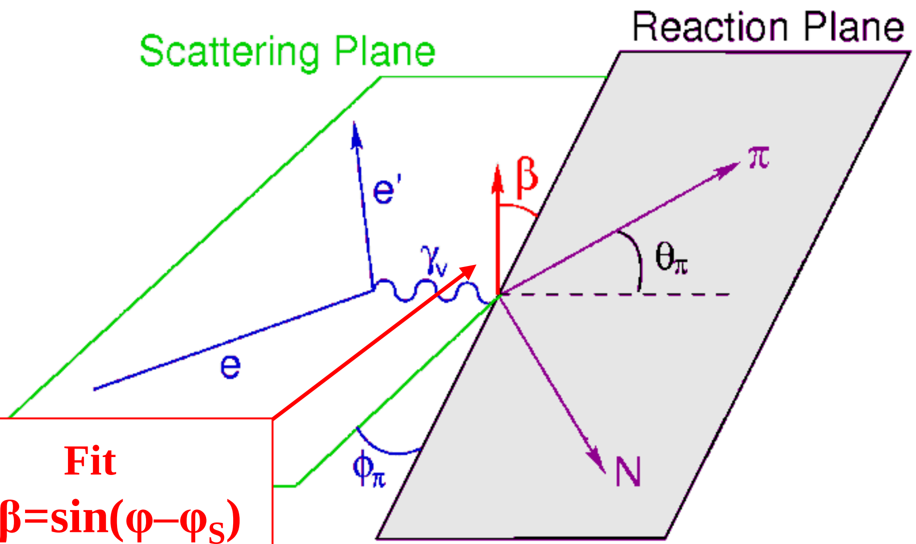
Exclusive π^- from Transversely Polarized Neutron

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

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



Fit sinβ=sin(φ–φ$_S$) dependence.

$$A_\perp = \frac{\int_0^\pi d\beta \frac{d\sigma_L^{\pi^-}}{d\beta} - \int_\pi^{2\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta}}{\int_0^{2\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta}}$$

$d\sigma^{\pi}{}_L$ → exclusive cross section for longitudinal γ*

$\beta=\varphi-\varphi_S$ → angle between polarized target and reaction plane

These experimental measurements can provide new nucleon structure information unlikely to be available from any other source.

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HERMES $\sin(2\varphi-\varphi_s)$ Asymmetry Moment

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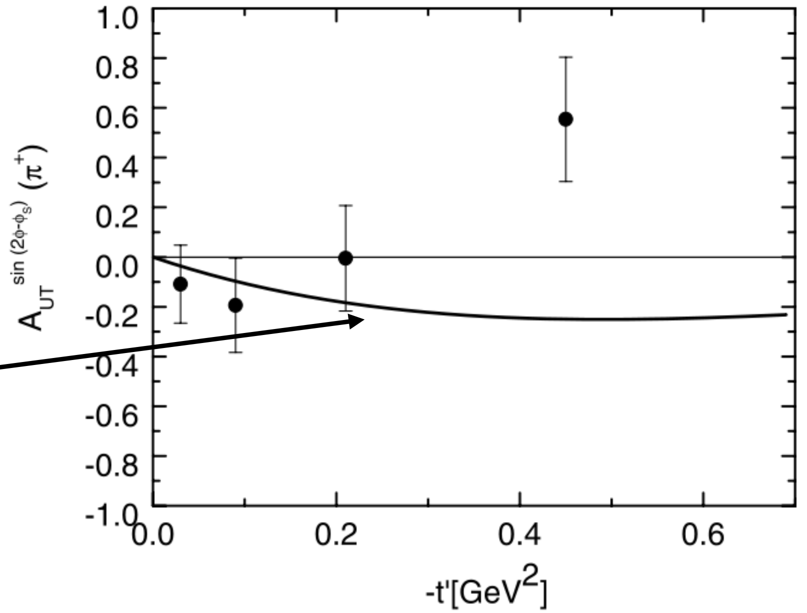
- $\langle Q^2\rangle$=2.38 GeV^2, $\langle W\rangle$=3.99 GeV.
- Experimental values and model calculation are both small.

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



- **$\sin(2\varphi-\varphi_S)$ modulation has additional LT interference amplitudes contributing that are not present in $\sin(\varphi_s)$.**
  - 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 $\sin(\varphi+\varphi_s)$, $\sin(2\varphi+\varphi_s)$, $\sin(3\varphi-\varphi_s)$ moments are only fed by TT interference and are even smaller.**

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Separated versus Unseparated Expts

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- **Our reaction of interest is $\vec{n}(e,e'\pi^-)p$ from the neutron in transversely polarized ^{3}He.**
- **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.

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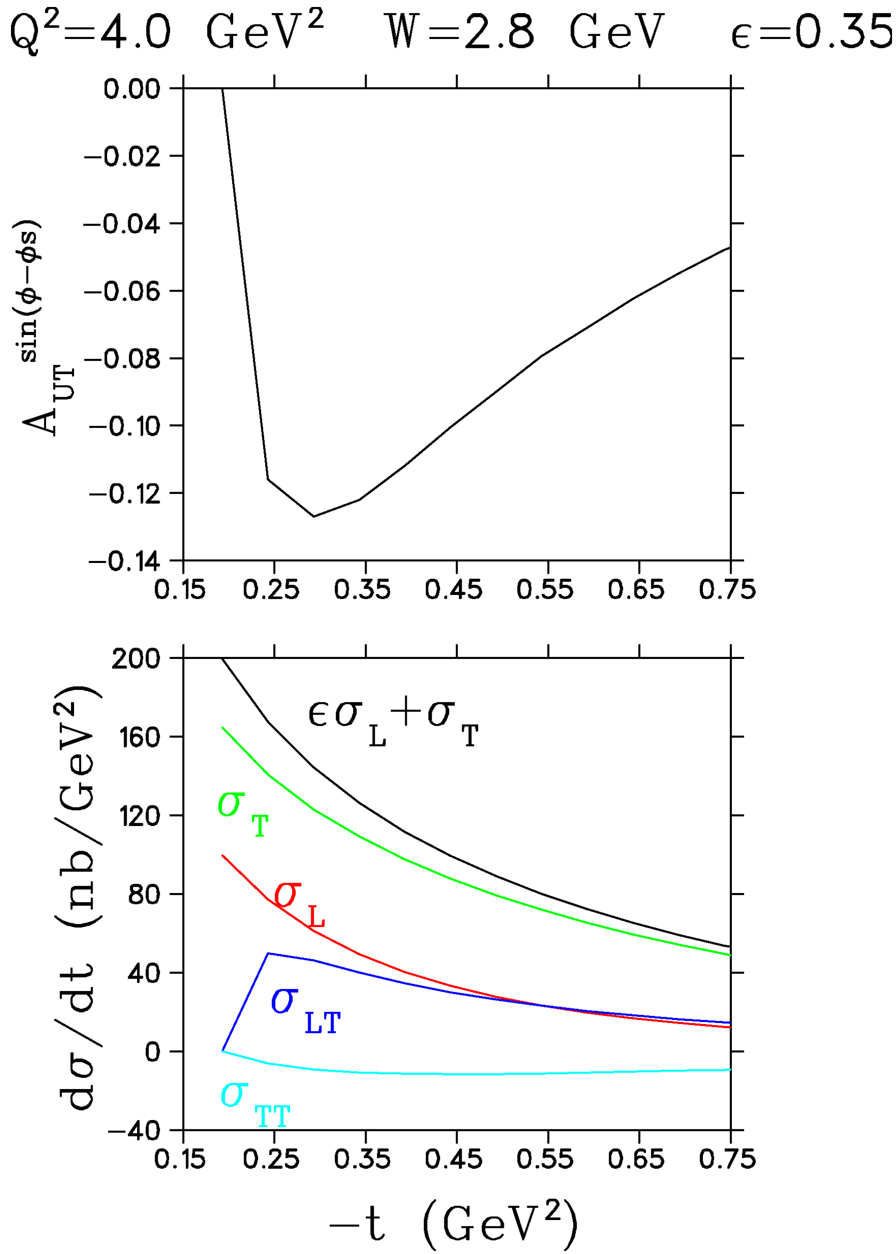
Asymmetry Dilution with SoLID

- **Calculation of cross section components and $\sin(\beta=\varphi-\varphi_s)$ asymmetry moment in handbag approach by Goloskokov & Kroll for our kinematics.**
  - Although their calculation tends to underestimate σ_L values measured by JLab Fπ–2, their model is in reasonable agreement with unseparated dσ/dt.
- Similar level of $A_{UT}^{\sin(\varphi-\varphi s)}$ 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.**



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Complementarity of Hall C and SoLID Expts

SHMS+HMS:

- HMS detects scattered e'.

  SHMS detects forward, high momentum π.
- **Expected small systematic uncertainties to give reliable L/T separations.**
- Good missing mass resolution to isolate exclusive final state.
- Multiple SHMS angle settings to obtain complete azimuthal coverage up to 4^o from q-vector.
- **It is not possible to have complete azimuthal coverage at larger –*t*, where $A_L^\perp$ is largest.**
- **PR12-12-005 by GH, D. Dutta, D. Gaskell, W. Hersman** based on next generation polarized ^{3}He target (e.g. UNH).

SoLID:

- Complete azimuthal coverage (for π) up to $\theta=24^o$.
- **High luminosity, particle ID and vertex resolution capabilities well matched to the experiment.**
- L/T separation is not possible, the $\sin(\varphi-\varphi_s)$ asymmetry moment is "diluted" by LL, TT contributions.
- **The measurement is valuable as it is the only practical way to obtain $A_{UT}^{\sin(\varphi-\varphi_s)}$ over a wide kinematic range.**
- We will also measure $A_{UT}^{\sin(\varphi_s)}$ and its companion moments, as was done by HERMES.
- **Provides vital GPD information not easily available in any other experiment prior to EIC.**

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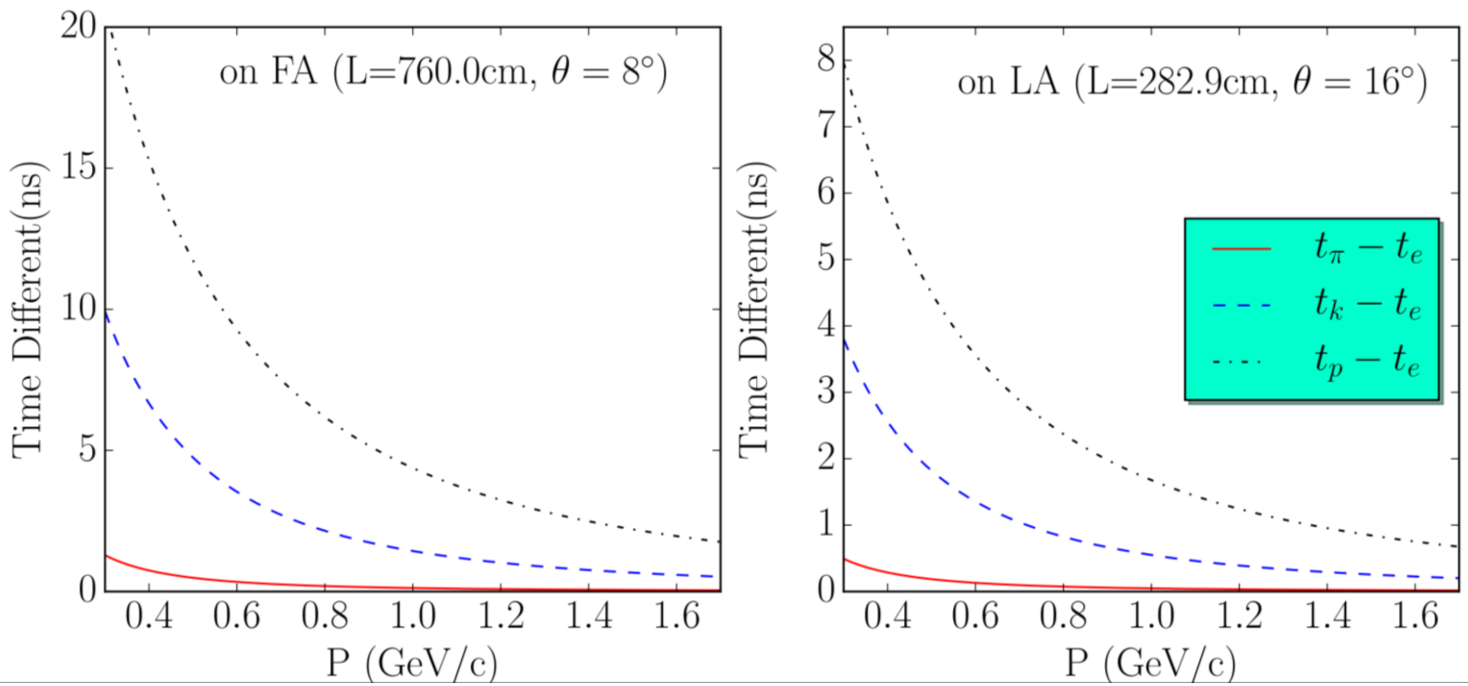
Recoil Particle Detection: Time of Flight

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

- Need >5σ timing resolution to identify protons from other charged particles



- **Exisiting SoLID Timing Detectors:**
  - MRPC & FASPC at Forward-Angle: cover 8º~14.8º, >3 ns separation.
  - LASPD at Large-Angle: cover 14º~24º, >1 ns separation.
- The currently designed timing resolution is sufficient for proton identification using TOF.

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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.

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Asymmetry Moment Modeling

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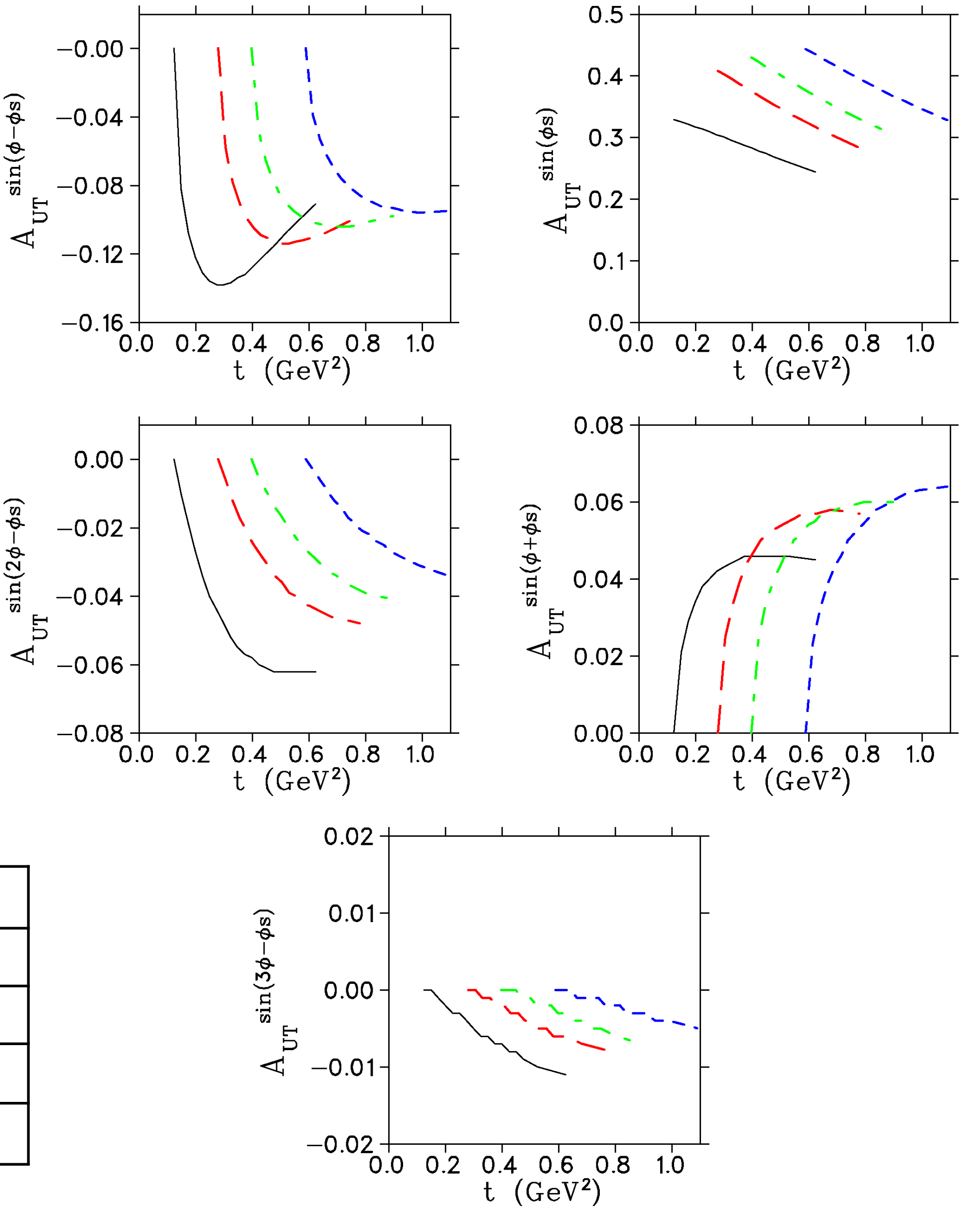
- **Event generator incorporates A_{UT} moments calculated by Goloskokov and Kroll for kinematics of this experiment.**
- GK handbag approach for π□ from neutron:
  - Eur.Phys.J. C**65**(2010)137.
  - Eur.Phys.J. A**47**(2011)112.
- **Simulated data for target polarization up and down are subjected to same *Q*²>4 GeV², *W*>2 GeV, 0.55<ε<0.75 cuts.**

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



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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

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

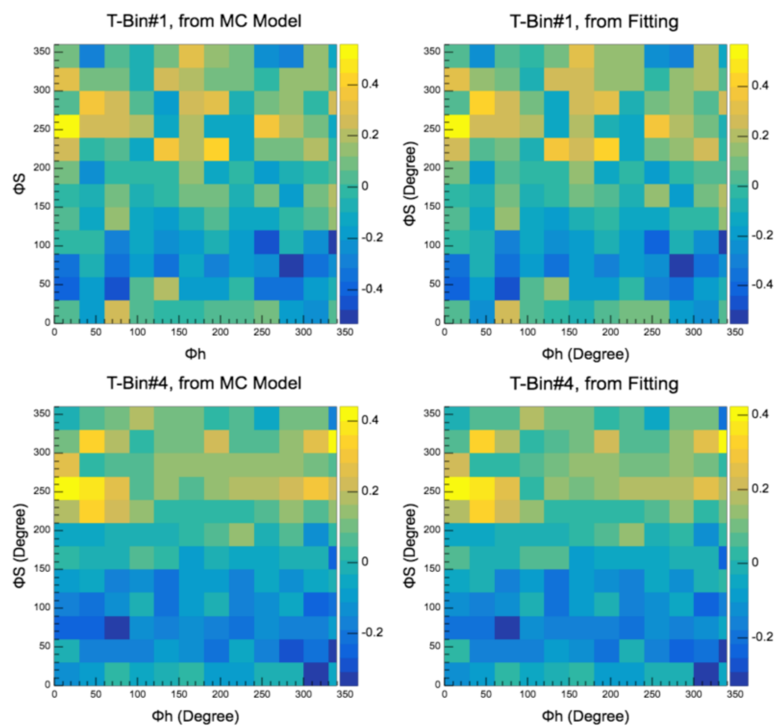
where A_k are the asymmetries that can minimize the likelihood function.

2. Minimize negative log-likelihood function:

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

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

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



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Fermi Momentum Effects

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- **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.

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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.

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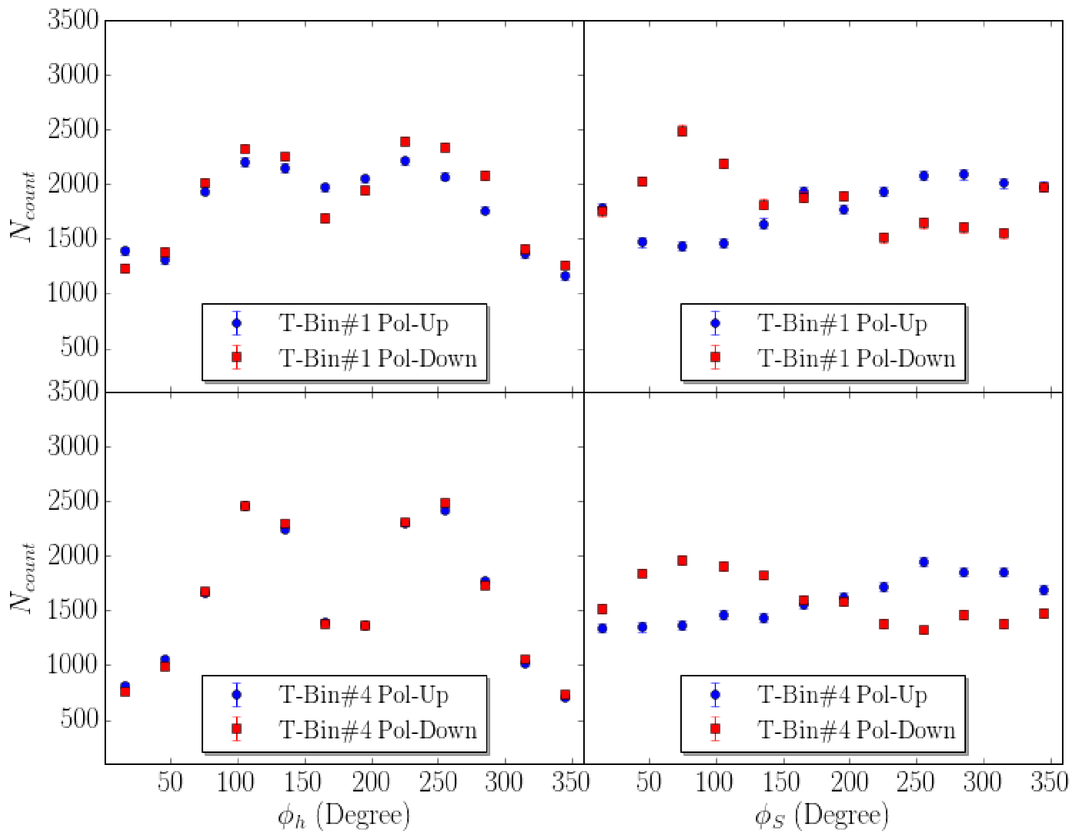
Acceptance Effects vs. (φ, φ_s)

- Expected yield as function of φ, φ_s for *t*–bins:
  - #1 (0.05–0.20)
  - #4 (0.40–0.50)
- Acceptance fairly uniform in φ_s.
- Some drop off on edges of φ distribution, since *q* is not aligned with the solenoid axis.
  - Critical feature is that φ drop off is same for target pol. up, down.



- **UML analysis shows that sufficient statistics are obtained over full (φ,φ_s) plane to extract asymmetry moments with small errors.**

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Final State Interaction (FSI) Effects

- To estimate FSI effects, we used an empirical (phase–shift) parameterization of $\pi^{-}N$ 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 GeV^2 events. Of these, a large fraction of FSI events are scattered outside the triple-coincidence acceptance, reducing the FSI fraction to ~0.4%. This will be further reduced by analysis cuts such as P_{miss}<1.2 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 ^{3}He 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.

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