SoLID-DEMP Programs
with transversely polarized He3

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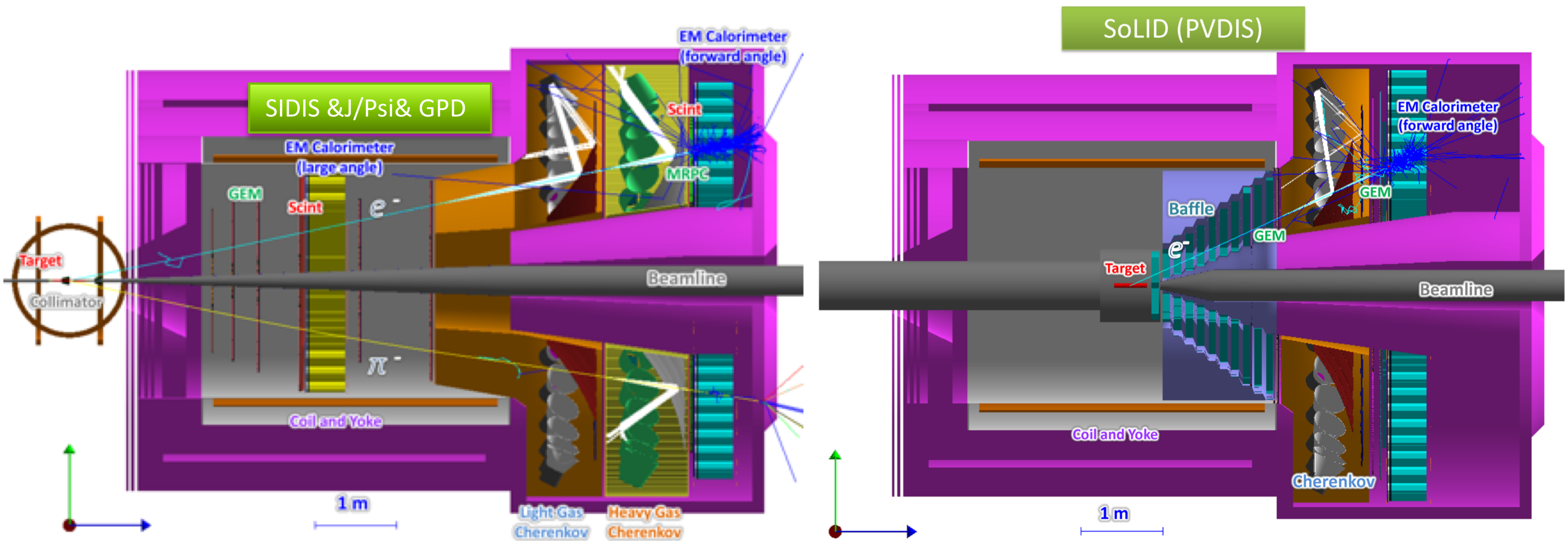
SoLID Overview

- **SoLID: Solenoidal Large Intensity Device**
  - ✓ High Intensity ($10^{37} \sim 10^{39}$ $cm^{-2}s^{-1}$) and,
  - ✓ Large Acceptance
- **SIDIS Programs:**
  - → E12-10-006 (A), SIDIS with Transversely Polarized He3, 90 days
  - → E12-11-007 (A), SIDIS with Longitudinally Polarized He3, 35 days
  - → E12-11-108 (A), SIDIS with Polarized Proton, 120 days
  - → and bonus runs (Ay, Di-Hadron …)
- **Parity Violation Deep Inelastic Scattering (PVDIS):**
  - → E12-10-007 (169 days, A)
  - → EMC with Calcium (proposed and continue developing)
- **J/ψ : Near Threshold Electroproduction of J/ψ at 11 GeV:**
  - → E12-12-006 (60 days, A-),
- **Generalized Parton Distributions (GPDs):**
  - → Time-Like Compton Scattering (TCS) with J/Psi configuration (E12-12-006A)
  - → Deep Exclusive pi- production (DEMP) with polarized He3 target and SIDIS configuration (E12-10-006B)
  - → Other polarized-proton/neutron DVCS & DEMP with polarized targets, Doubly DVCS, etc.

SoLID Overview

- SoLID: **S**o**l**enoidal **L**arge **I**ntensity **D**evice
  - ✓ High Intensity ($10^{37} \sim 10^{39}$ $cm^{-2}s^{-1}$) and,
  - ✓ Large Acceptance

Two Configurations



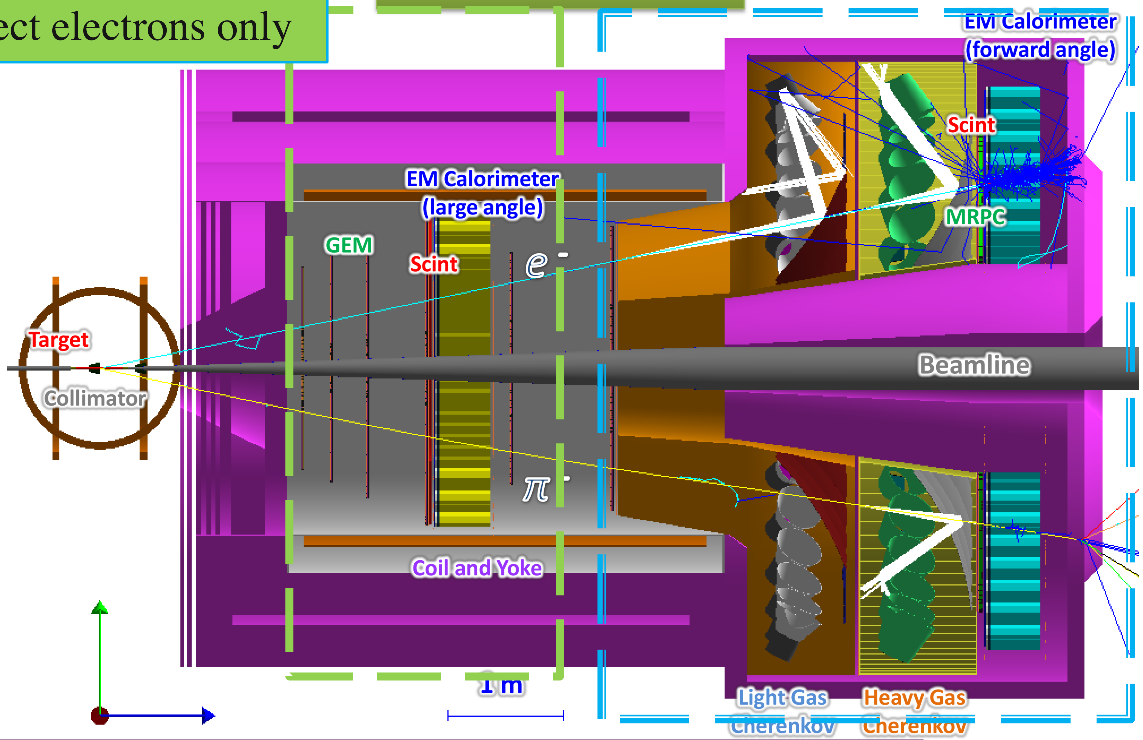
SIDIS uses two polairzed targets
J/psi uses unpolarized targets (plus different triggers)

SoLID Overview

Large-Angle :
Detect electrons only

SoLID (SIDIS He3)

Forward-Angle :
Detect electrons & hadrons



SIDIS Triggers: Electron + Pion Coincidence

- Electron Trigger: Forward-Angle → LGC + SPD + MRPC + EC
  Large-Angle → SPD + EC
- Pion Trigger: SPD+MRPC+EC

Detector Resolutions:

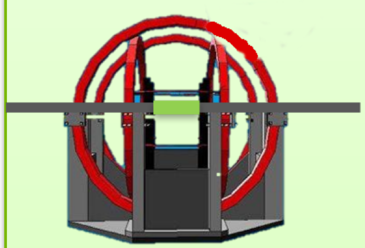
Charged Particle: $\frac{\delta p}{p} = 1.1\sim1.7\%,\ \delta\theta = 1.0\sim1.3mrad, \delta\phi = 1.7\sim5.7mrad$, Vexrex-Z = 0.5~0.9cm

Photons: $\delta x = 1.0\ cm, \delta y = 1.0\ cm, from\ EC\ reconstruction$

$\delta VertexZ = 0.5cm\ (from\ GEM\ tracking\ with\ charged\ particles)$

SoLID Overview

Polarized He3 Targets
"neutron"



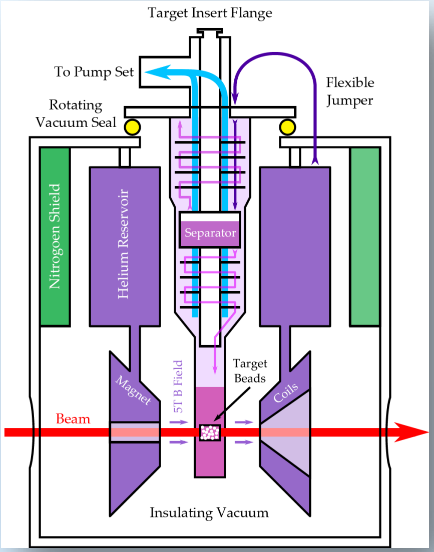
Specification

- ✓ System Size: R=1.83m(outer)
- ✓ Operation Field: 25~30 Gaus
- ✓ Target Length: 40 cm
- ✓ Target Lumi: 10^{36} cm^{-2} s^{-1}
- ✓ Maximum Pol: >70%
- ✓ Pol in Beam: ~60% @ 15uA
- ✓ Dilution: 0.3

- Built in 1998 @ Jlab
- Used by 13 experiments in 6GeV Era
- To be used by >7 approved 12GeV experiments
- Aim to increase the efficiency of flipping polarization.
- Both longitudinally and transversely polarized

http://hallaweb.jlab.org/equipment/targets/polhe3/polhe3_tgt.html

Polarized NH3 Targets
"proton"



Specification

- ✓ System Size: 1.2m(W) x2m(H)
- ✓ Maximum Field: 5 Tesla
- ✓ Target Length: ~3 cm
- ✓ Target Lumi: 10^{35} cm^{-2} s^{-1}
- ✓ Maximum Pol: >90%
- ✓ Pol in Beam: 70%
- ✓ Dilution: ~0.13
- ✓ Operation Temp: 1K

- Many years of developments and application
- The major polarized proton target at JLab
- Used by SLAC E143/E155, and many experiments in Hall-A/B/C at JLab
- Current opening angle for outgoing particles is +/- 17^{o}, and will be +/-25^{o} with new coils

https://userweb.jlab.org/%7Eckeith/Frozen/Frozen.html
http://twist.phys.virginia.edu/

E12-10-006B

- A new run-group proposal aside with the SoLID-SIDIS transversely polarized He3 experiment (E12-10-006)
- Exclusive measurement of π^- production using Polarized He3 ($^3He(e,e'\pi^- p)pp_{sp}$)

$$e + \vec{n} \rightarrow e' + p + \pi^-$$

- Approved by SoLID collaboration and PAC45

A Run-Group Proposal Submitted to PAC 45

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

May 21, 2017

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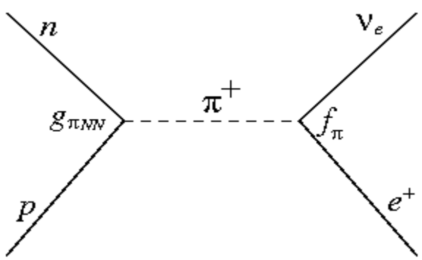
E12-10-006B

➢ Probe GPDs with DEMP:

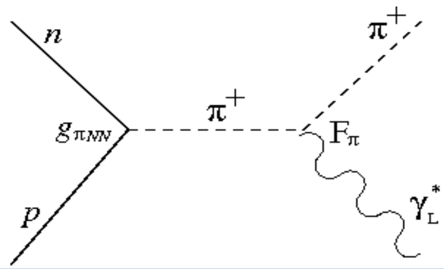
- GPD-$\tilde{E}$ is not related to any already known parton distribution.

$$\sum_q \int_{-1}^{1} dx \tilde{E}^q(x,\xi,t) = G_p(t) \qquad \textit{Pseudoscalar form factor}$$

- $G_P(t)$ is highly uncertain because it is negligible at the momentum transfer of β-decay.
- $G_P(t)$ alone receives contributions from $J^{PG}=0^{--}$ states. These are the quantum numbers of the pion, so GPD-$\tilde{E}$ contains an important pion pole contribution.



Pion pole contribution to $G_P(t)$



Pion pole contribution to meson electroproduction at low –t.

For this reason, 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.

- 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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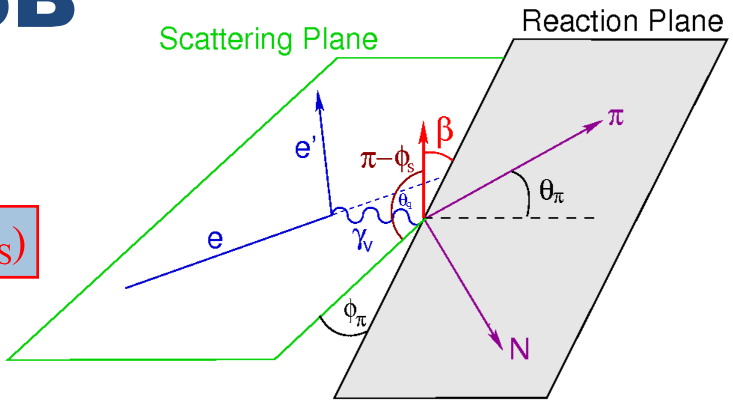
➢ How to Probe $\tilde{E}$ with DEMP:

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

$\beta=(\varphi-\varphi_S)$



$$A_L^{\perp} = \left(\int_0^{\pi} d\beta \frac{d\sigma_L^{\pi}}{d\beta} - \int_{\pi}^{2\pi} d\beta \frac{d\sigma_L^{\pi}}{d\beta}\right)\left(\int_0^{2\pi} d\beta \frac{d\sigma_L^{\pi}}{d\beta}\right)^{-1}$$

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

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

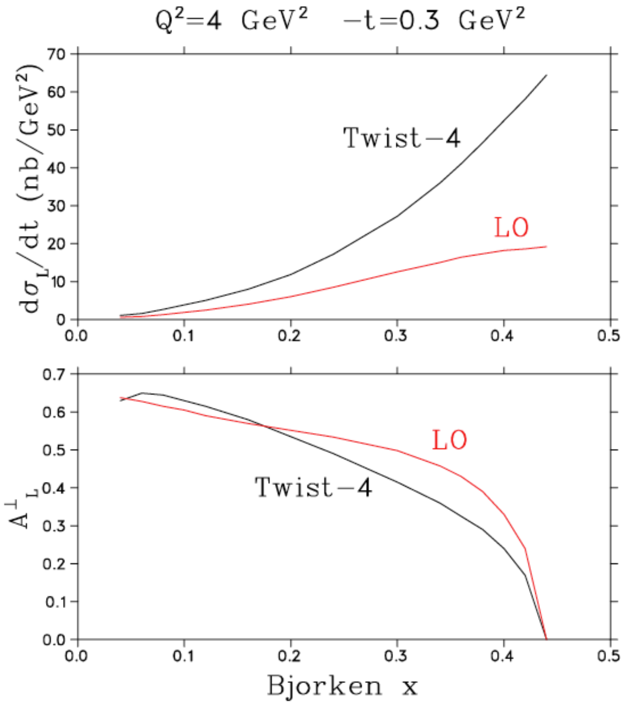
- Frankfurt et al. have shown $A_L^{\perp}$ vanishes if $\tilde{E}$ is zero. If $\tilde{E}\neq0$, the asymmetry will produce a sinβ dependence.

  (PRD 60(1999)014010)

- $A_L^{\perp}$ is expected to display precocious factorization even 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).*



Because of requiring the virtual photon to be longitudinally polarized, it has not yet been possible to perform an experiment to directly measure $A_L^{\perp}$

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- Experimental Observables w/o LT Separation

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

- 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

$$d\sigma_{UT}(\phi,\phi_s)=\sum_k d\sigma_{UT_k}(\phi,\phi_s)=-\frac{P_\perp\cos\theta_q}{\sqrt{1-\sin^2\theta_q\sin^2\phi_s}}\Big[\sin\beta\,\mathrm{Im}(\sigma_{++}^{+-}+\epsilon\sigma_{00}^{+-})$$
$$+\sin\phi_s\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Im}(\sigma_{+0}^{+-})$$
$$+\sin(\phi+\phi_s)\,\frac{\epsilon}{2}\,\mathrm{Im}(\sigma_{+-}^{+-})$$
$$+\sin(2\phi-\phi_s)\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Im}(\sigma_{+0}^{-+})$$
$$+\sin(3\phi-\phi_s)\,\frac{\epsilon}{2}\,\mathrm{Im}(\sigma_{+-}^{-+})\Big],$$

$\sigma_{mn}^{ij}\rightarrow$ 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

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

sin(ϕ$_s$) Asymmetry Moment

$$A_{UT}^{\sin(\phi_S)}\sim\mathrm{Im}[M_{0+++}^*M_{0-0+}-M_{0-++}^*M_{0+0+}],$$

helicities: [pion, neutron, photon, proton]

$$\mathcal{M}_{0-,++}=e_0\sqrt{1-\xi^2}\int dx\,\mathcal{H}_{0-,++}H_T,$$
$$\mathcal{M}_{0+,\pm+}=-e_0\frac{\sqrt{t_{\min}-t}}{4m}\int dx\,\mathcal{H}_{0-,++}\bar{E}_T.$$

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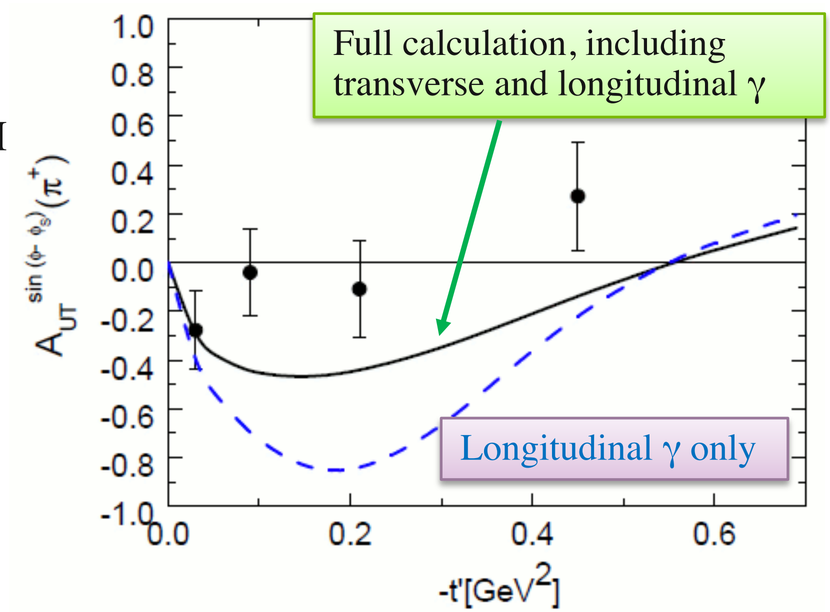
➢ HERMES sin(□=□-□$_s$) Asymmetry Moment

S. Goloskokov et. al. [PLB 682(2010)345]

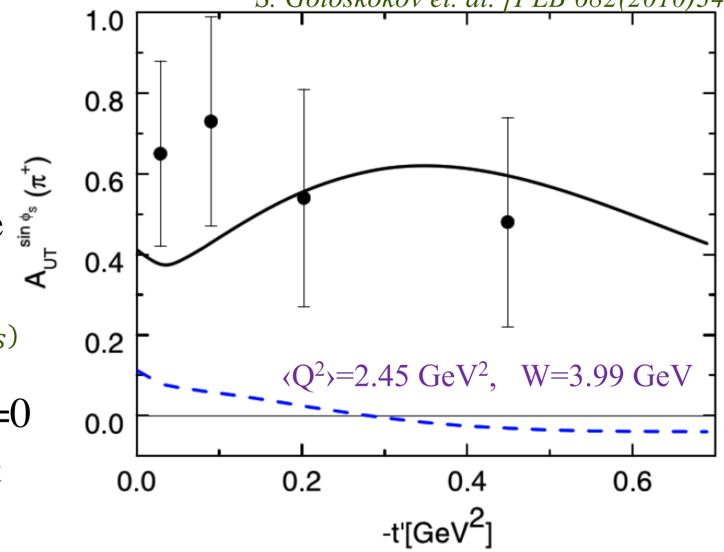
- Exclusive π^+ production by scattering 27.6 GeV positrons or electrons from transverse polarized ^1H without L/T separation.
- Analyzed in terms of 6 Fourier amplitudes for ϕ_π, ϕ_s.
- $\langle x_B \rangle = 0.13$, $\langle Q2 \rangle = 2.38$ GeV^2, $\langle -t \rangle = 0.46$ GeV^2



- 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)*.
- The HERMES data are consistent with GPD models based on the dominance of $\tilde{E}$ over $\tilde{H}$ at low –t.
- The sign crossing in the model curve at $-t \approx 0.5$ GeV^2 is due to the large contribution from $\tilde{E}$ demanded

Physics Motivation

S. Goloskokov et. al. [PLB 682(2010)345]



➢ HERMES $\sin(\phi_s)$ Asymmetry Moment

- Only measures the LT interference,

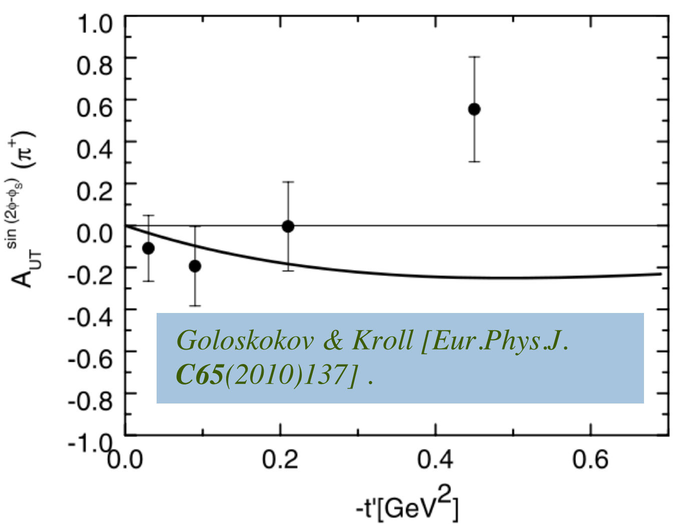
  while $A_{UT}^{\sin(\phi-\phi_S)}$ has contributions from both LT and TT.

- Can provides additional GPD model constraints to aid in the interpretation of the unseparated asymmetry data.

  Any DEMP pion model needs to describe both $A_{UT}^{\sin(\phi_S)}$ and $A_{UT}^{\sin(\phi-\phi_S)}$

- HERMES data shows large asymmetries do not vanish at -t=0

  Indicating strong contribution from transversely polarized photons at rather large W and Q^2.



*Goloskokov & Kroll [Eur.Phys.J. **C65**(2010)137] .*

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

- $\sin(2\phi-\phi_S)$ modulation has additional LT interference amplitudes contributing that are not present in $\sin(\phi_s)$.
- Can also improve description of other amplitude moments.
- 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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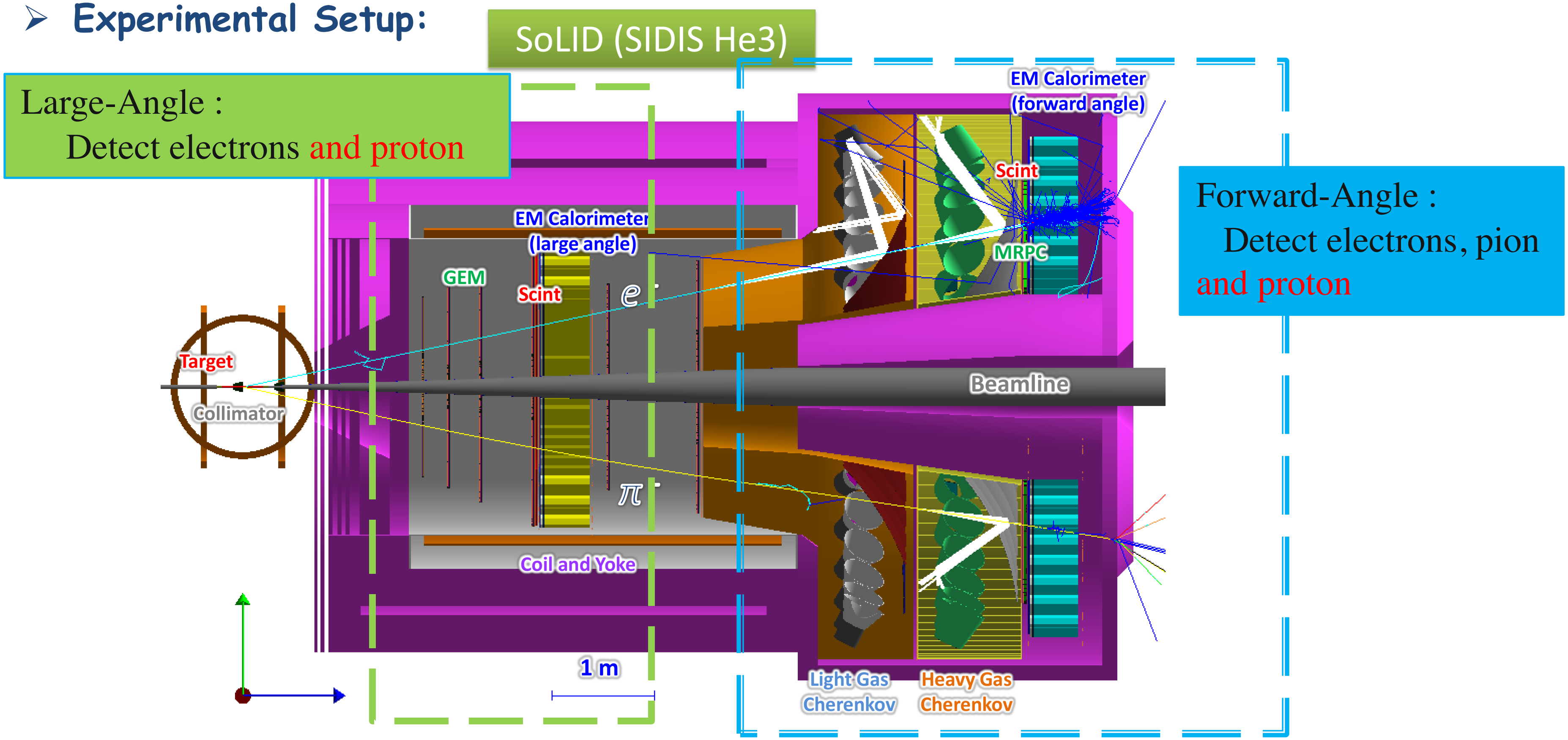
➢ Experimental Setup:



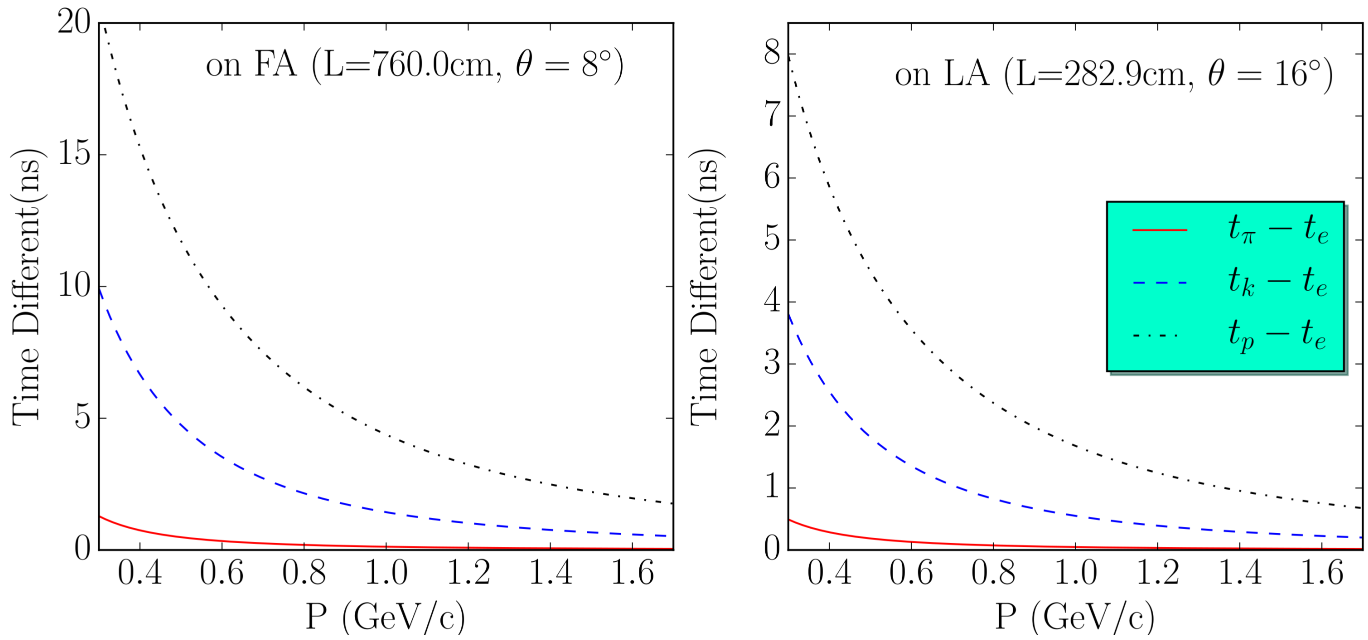
Exclusive Mearsurement based on SIDIS Setup: $^{3}He(e,e'\pi^{-}p)pp_{sp}$

- During online data taken, share the same trigger events with SIDIS
- During offline analysis, identify knocked-out protons via TOF (don't need to precisely measure their momenta and angles)
- Reconstructed Missing mass and Missing Momenta of knocked-out protons to further suppress background.

E12-10-006B

- **Recoil Proton Detection: Time of Flight** $^{3}He(e,e'\pi^{-}p)pp_{sp}$

  - Need >5σ timing resolution to identify protons from other charged particles
  - **Existing SoLID Timing Detectors:**
    - MRPC & FASPC at Forward-Angle: cover 8°~14.8°, >3 ns separation.
    - LASPD at Large-Angle: cover 14°~24°, >1 ns separation.



  - The currently designed timing resolution is sufficient for proton identification using TOF.
  - We also can measure the momenta and angles of the proton via tracking reconstruction, but we currently don't use these info

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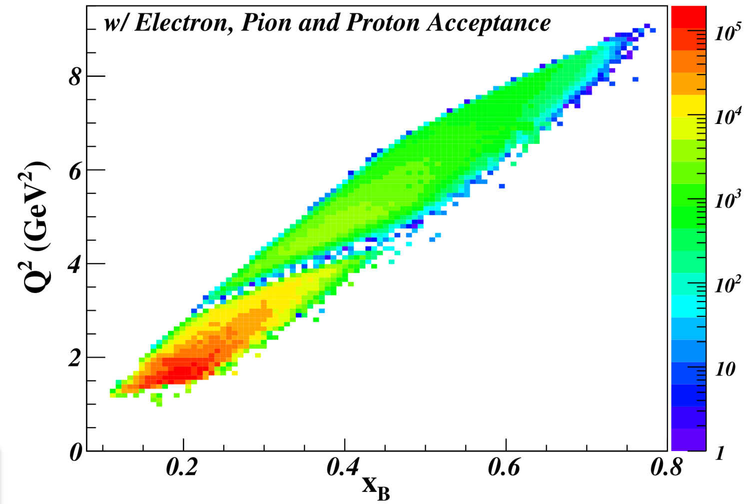
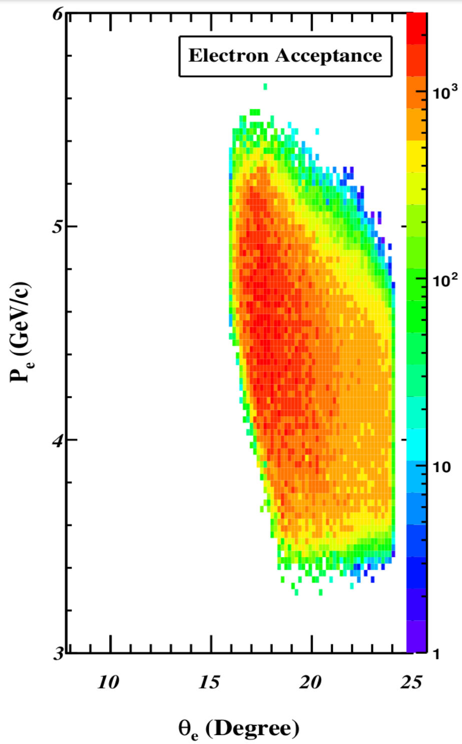
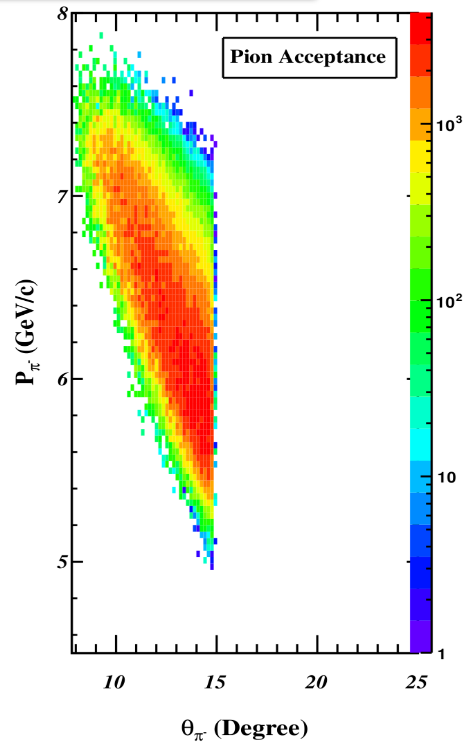
➢ Acceptance and Projected Rates

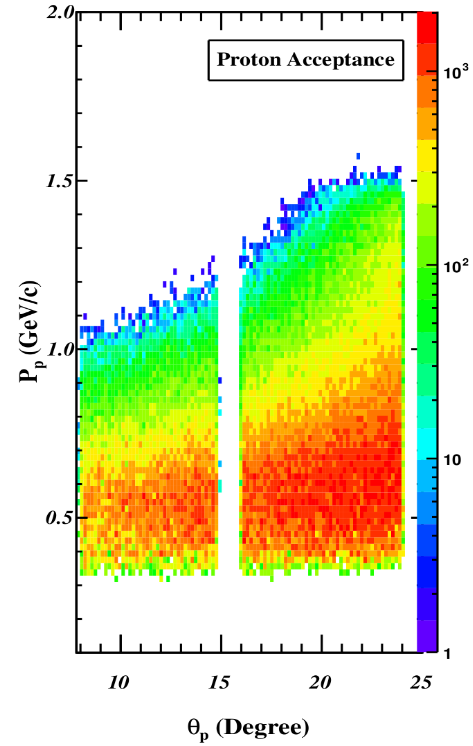
$Q^2>1$ GeV^2 $W>2$ GeV	$Q^2>4$ GeV^2 $W>2$ GeV
DEMP: $n(e,e'\pi^- p)$ Triple Coin (Hz)	
4.95	0.40
SIDIS: $n(e,e'\pi^-)X$ Double Coin (Hz)	
1425	35.8

$Q^2>4$ GeV^2, $W>2$ GeV, $0.55<\varepsilon<0.75$ cuts applied.









E12-10-006B

➢ Background Study via Missing Mass and Missing Momentum

- **We have been very conservative in our estimations.**
- The main background comes from the SIDIS channel where the target fragments may contain protons; In our study, we assume all target fragments contain protons
- We compute the missing mass and momentum as if the proton were not detected:

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

$$P_{miss} = |\vec{p}_e - \vec{p}_{e'} - \vec{p}_{\pi^-}|$$

- **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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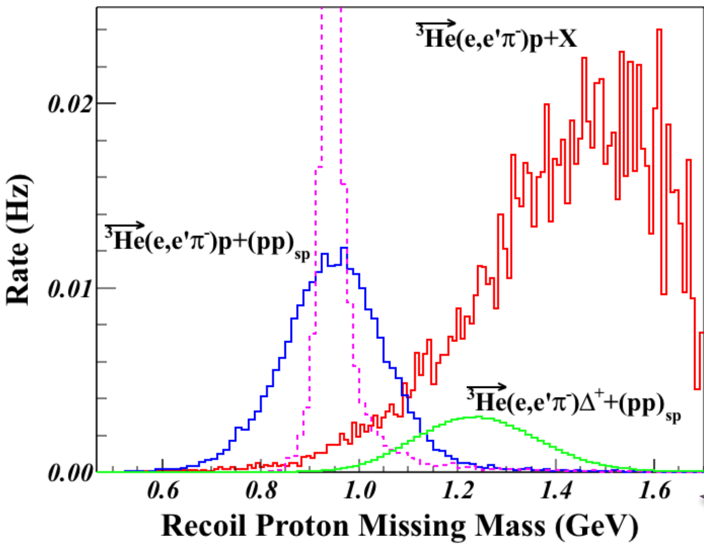
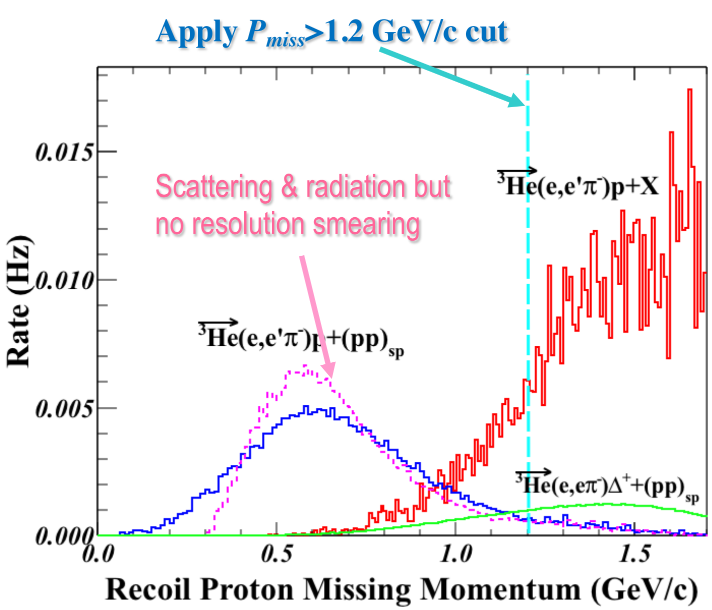
➢ Background Study via Missing Mass and Missing Momentum

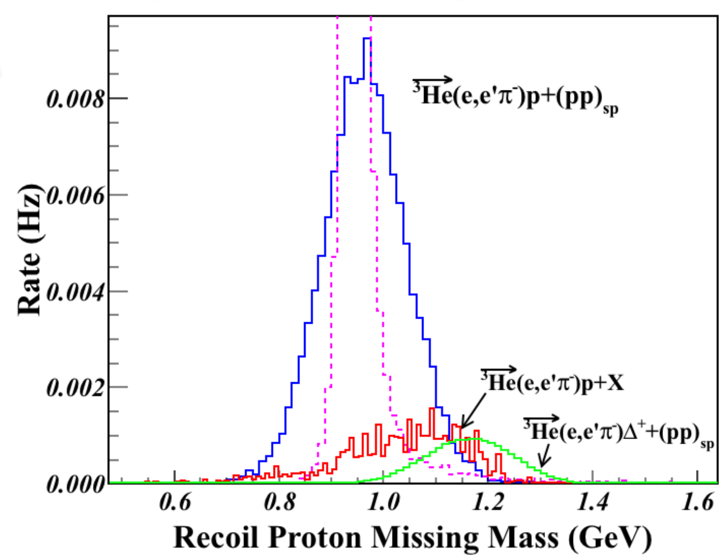


Two different background channels were simulated:

- ✓ 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).



Background remaining after P_{miss} cut



Detector Resolutions were built in; Fermi-Motion, Energy-Loss, FSI etc. were considered

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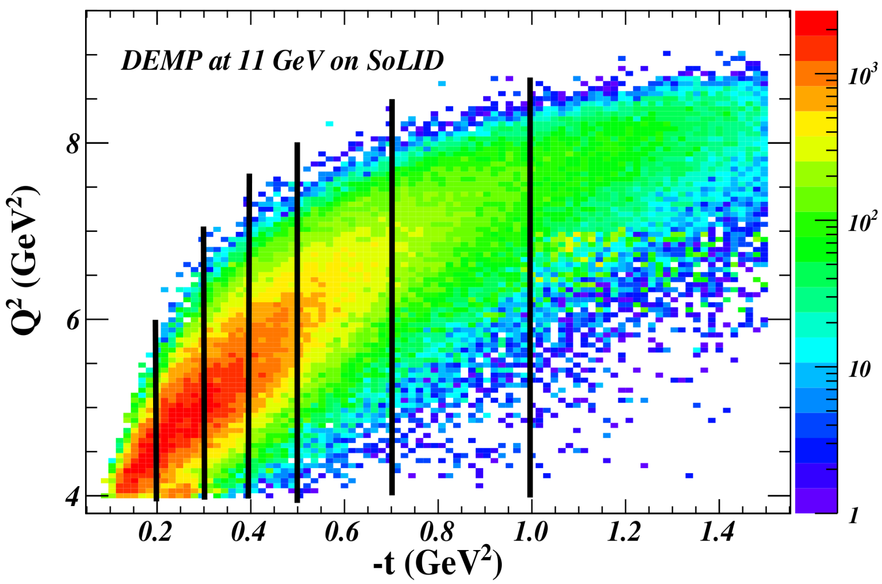
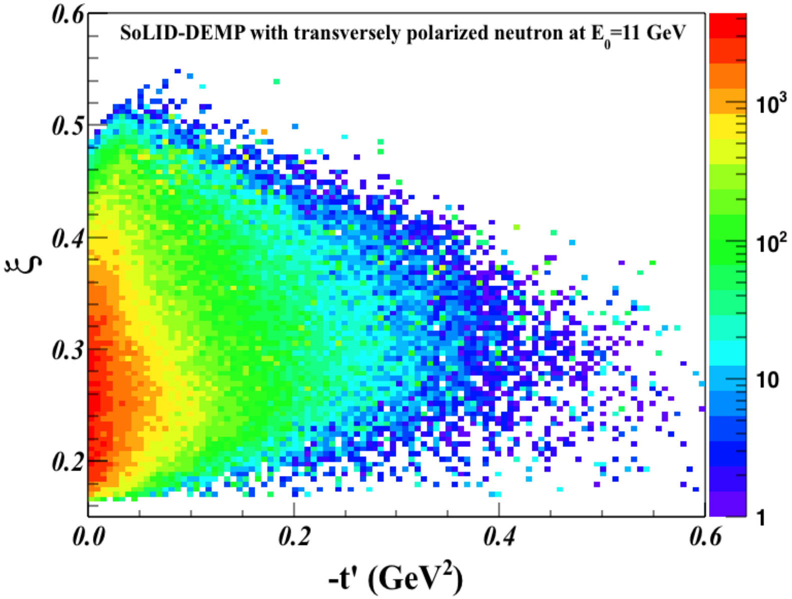
- **Kinematic Coverage and Binning**





- For this proposal, we only binned the 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).
- We can measure the skewness dependence of the relevant GPDs over a fairly large range of ξ.

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➢ Unbinned Maximum Likelihood (UML) Method

- 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.

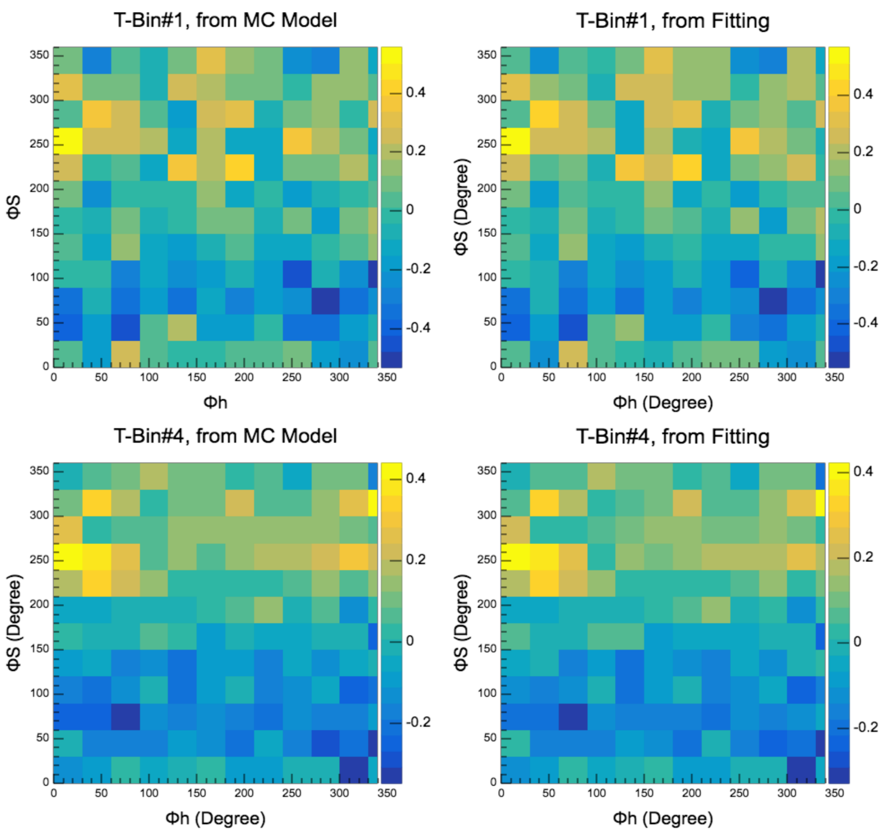
2) Minimize negative log-likelihood function:

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

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

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

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



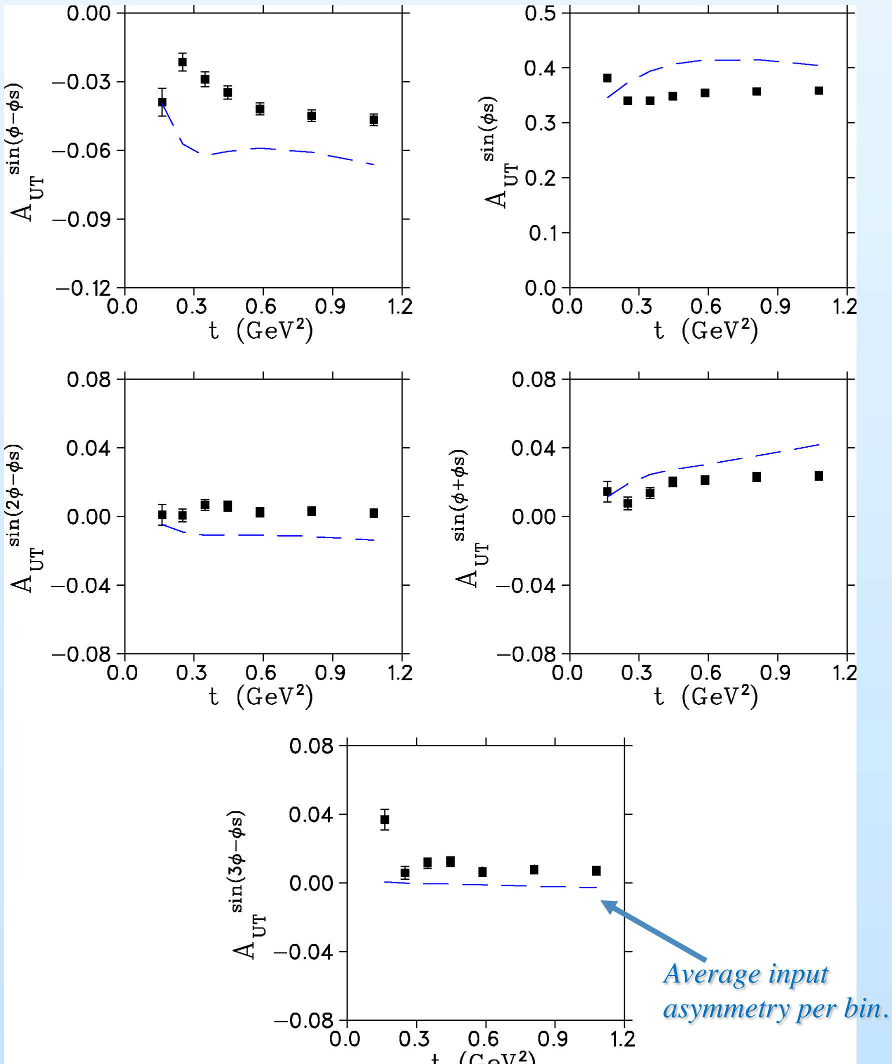
- Same method used by HERMES in their DEMP analysis [PLB 682(2010)345].

E12-10-006B

➢ **Projected Uncertainties**

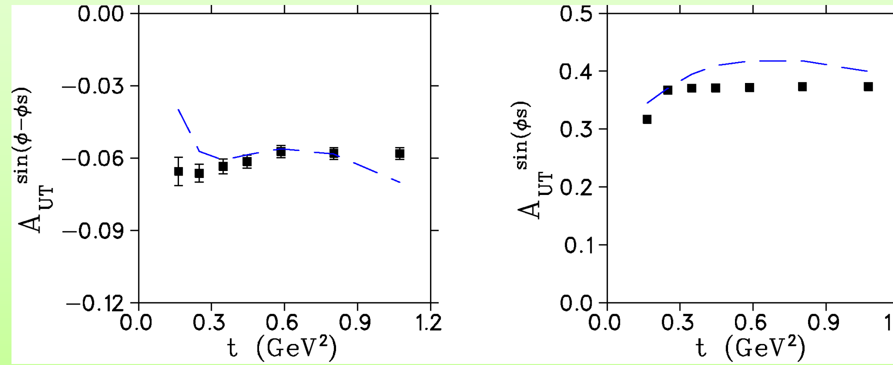
All effects on.

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



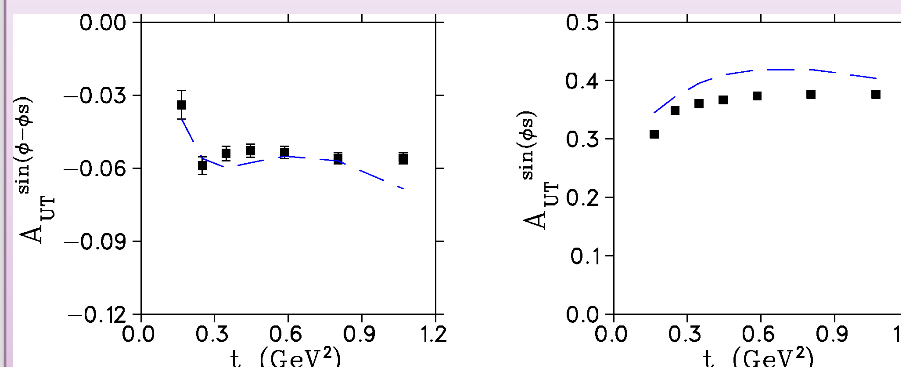
Only Fermi momentum off.

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 UML procedure.



E12-10-006B

➢ Summary

- $A_{UT}^{\sin(\phi-\phi_s)}$ transverse single-spin asymmetry in exclusive π production is particularly sensitive to the spin-flip GPD.
- $A_{UT}^{\sin(\phi_s)}$ asymmetry can also be extracted, 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.
- E12-10-006B shares the same SoLID-SIDIS experimental setup and will look for e-π^--p triple coincidence events.
- We used a sophisticated UML analysis to extract the asymmetries from simulated data in a realistic manner, just as was used in the pioneering HERMES data. The projected data are expected to be a considerable advance over HERMES in kinematic coverage and statistical precision.
- SoLID-DEMP measurement is also important preparatory work for future EIC.

The SoLID review committee identifies the SoLID-DEMP as the forth flagship experiment, in addition to the baseline programs (SIDIS, PVDIS, J/psi)