Study Generalized Parton Distributions *using SoLID*

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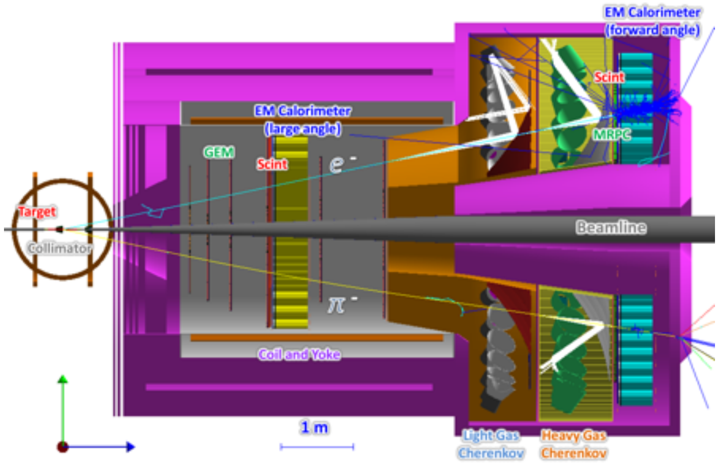
On behalf of the SoLID Collaboration



09/07/2017, INT Workshop, Seattle, WA

Outline:

- Overview of Generalized Parton Distributions
- SoLID and the SIDIS Configuration
- SoLID-DEMP Program with polarized He3
- SoLID-DVCS Program with polarized He3
- SoLID-DDVCS Programs with unpolarized targets

  (see Zhiwen's talk on week#3 for more details on both TCS and DDVCS)

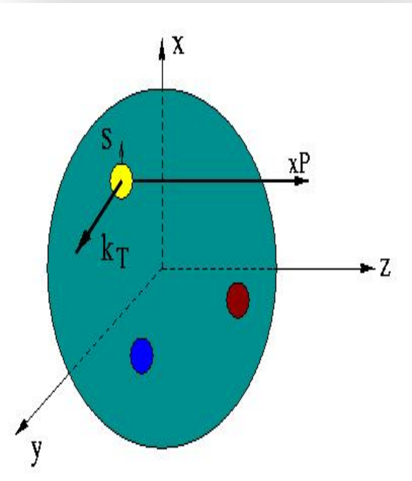
- Future Developments
- Summary

Overview of Generalized Parton Distributions

Physics Overview

$W_p^u(x, k_T, \boldsymbol{r_T})$ Wigner distributions

5D

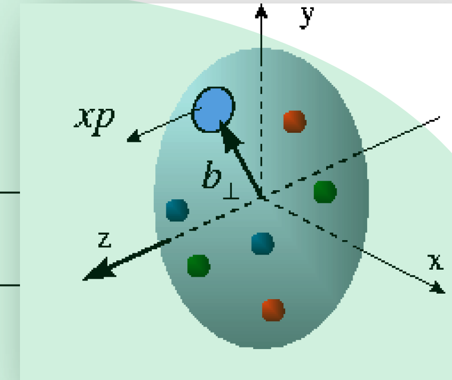


$d^2\boldsymbol{r_T}$

d^2k_T

TMD PDFs
$f_1^u(x, k_T)$, ..
$h_1^u(x, k_T)$

GPDs/IPDs



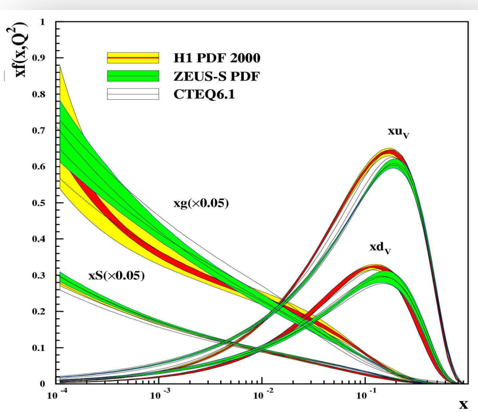
(X. Ji, D. Mueller, A. Radyushkin)

3D

dx & Fourier Transformation

d^2k_T

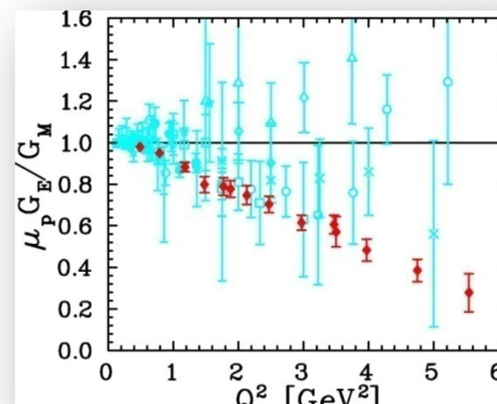
d^2r_T



PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

1D

Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$

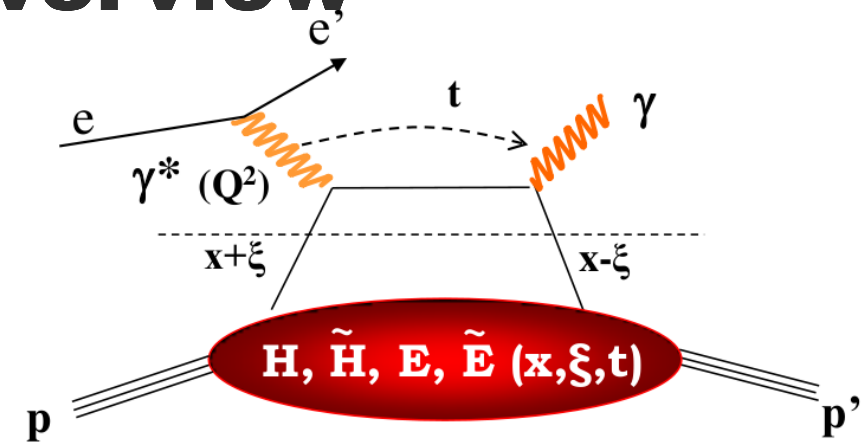


Physics Overview

- **Generalized Parton Distributions (GPD):**
  - Encode Information of the parton distribution in both the transverse plane and longitudinal direction.
  - Eight GPDs for quarks or gluons:

Chiral Even $H^{q/g}, E^{q/g}, \widetilde{H}^{q/g}, \widetilde{E}^{q/g}$

Chiral Odd $H_T^{q/g}, E_T^{q/g}, \widetilde{H}_T^{q/g}, \widetilde{E}_T^{q/g}$



- x → Longitudinal quark momentum fraction (not experimental accessible)
- ξ → Longitudinal momentum transfer. In Bjorken limit: $\xi = x_B/(2-x_B)$
- t → Total squared momentum transfer to the nucleon: $t = (P-P')^2$

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$		$h_1^{\perp}(x,k_T^2)$ Boer-Mulders
	L		$g_1(x,k_T^2)$ Helicity	$h_{1L}^{\perp}(x,k_T^2)$ Long-Transversity
	T	$f_1^{\perp}(x,k_T^2)$ Sivers	$g_{1T}(x,k_T^2)$ Trans-Helicity	$h_1(x,k_T^2)$ Transversity; $h_{1T}^{\perp}(x,k_T^2)$ Pretzelosity

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\widetilde{H}_T + E_T$
	L		$\widetilde{H}$	$\widetilde{E}_T$
	T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

Physics Overview

➢ **Generalized Parton Distributions (GPD):**

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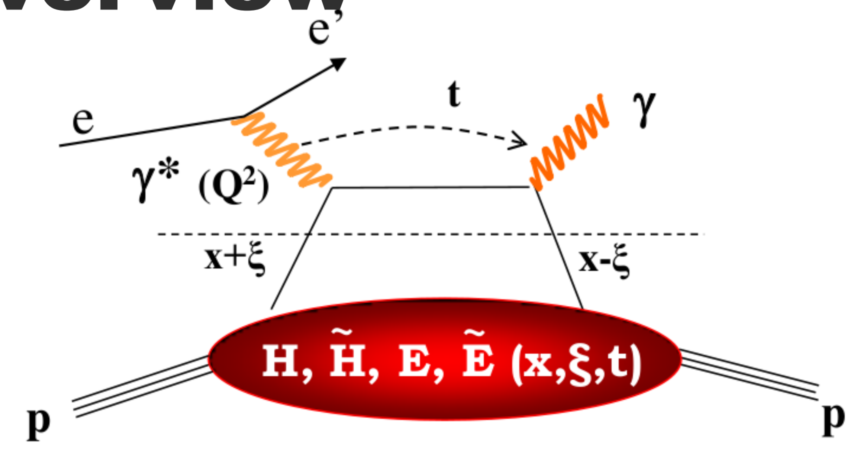


- Connect to FF & PDFs: e.g.

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$

$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

$$\int_{-1}^{1} dx \widetilde{H}^q(x,\xi,t) = g_A^q(t)$$

$$\int_{-1}^{1} dx \widetilde{E}^q(x,\xi,t) = g_P^q(t)$$

$$H^q(x,0,0) = q(x), x > 0$$

$$\widetilde{H}^q(x,0,0) = \Delta q(x), x > 0$$

- Angular Momentum Sum Rule:

✓ Ji's Nucleon Spin Decomposition:

$$\frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

DIS

GPD

✓ Ji's Sum Rule

$$J_{q/g} = \frac{1}{2}\int_{-1}^{+1} dx \cdot x[H^{q/g}(x,\xi,0) + E^{q/g}(x,\xi,0)]$$

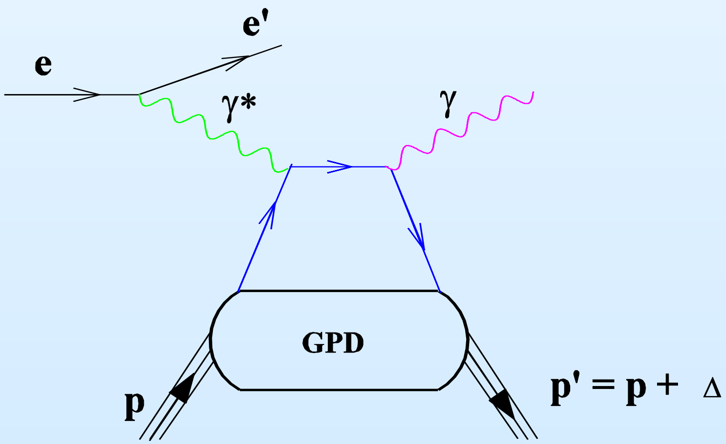
(X. Ji, PRL 78, 610 (1997)

With quark spin measured by DIS, GPD can get access to info of quark's orbital angular momentum

Exclusive Hard Processes

Deeply Virtual Compton Scattering:

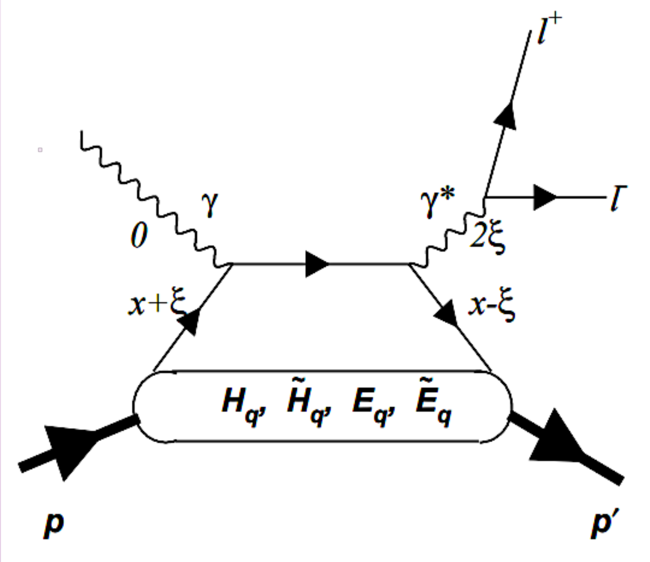
$$e + N \rightarrow e' + N + \gamma$$



- ✓ Sensitive to all four twist-2 GPDs (H, E, $\tilde{H}$ and $\tilde{E}$)
- ✓ Relatively clean
- ✓ Interference with Bethe-Heitler to ”enhance” the signal
- ✓ Measuring the CFF with certain kinematic limitations

Timelike Compton Scattering:

$$\gamma + N \rightarrow N + l^{+} + l^{-}$$

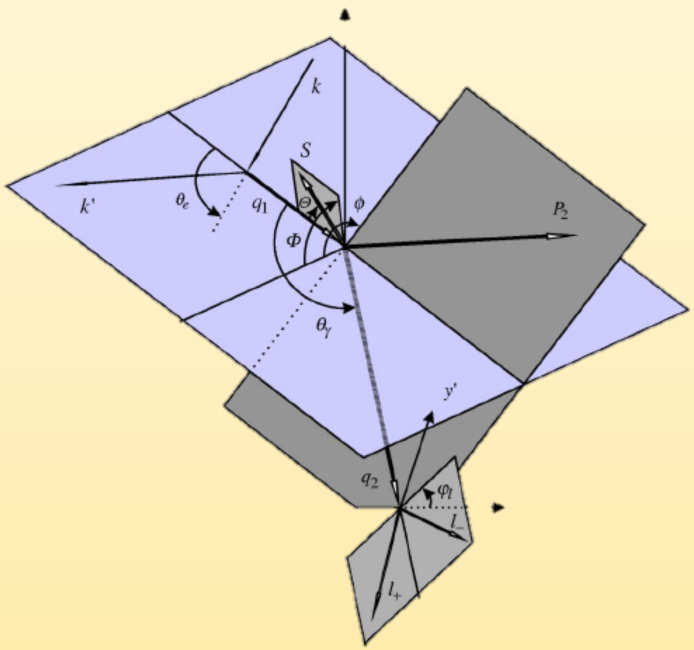


- ✓ Inverse of the space-like DVCS
- ✓ Extract the real part of CFFs
- ✓ Complimental to DVCS

Exclusive Hard Processes

Double-DVCS:

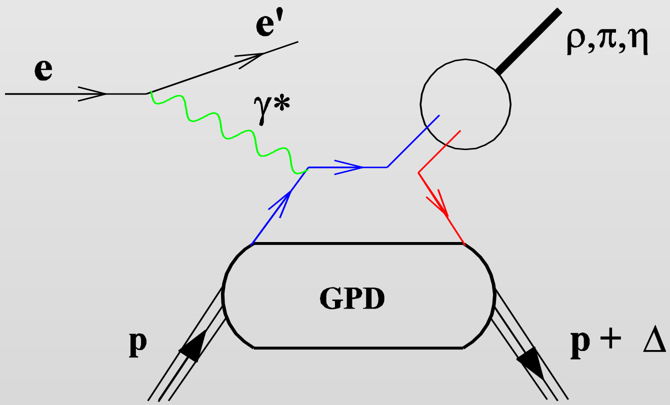
$$e + N \rightarrow e' + N + l^{+} + l^{-}$$



- ✓ A lepton pair in the final state instead of a real photon
- ✓ Can access GPDs ***beyond the x=ξ limit***
- ✓ Rates are extremely limited; Need high luminosity
- ✓ Need dedicated muon detection

Virtual Deep Exclusive Meson Production

$$e + N \rightarrow e' + N' + \pi^{0,\pm}\,(K^{0,\pm}, \eta, \rho, \omega, \dots)$$



- ✓ Vector mesons sensitive to spin-average H, E.
- ✓ Pseudoscalar mesons sensitive to spin-difference , $\tilde{H}$ and $\tilde{E}$.
- ✓ neutron + pseudoscalar DEMP is uniquely sensitive to $\tilde{E}$
- ✓ DEMP is also sensitive to chiral-odd GPDs (H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$)

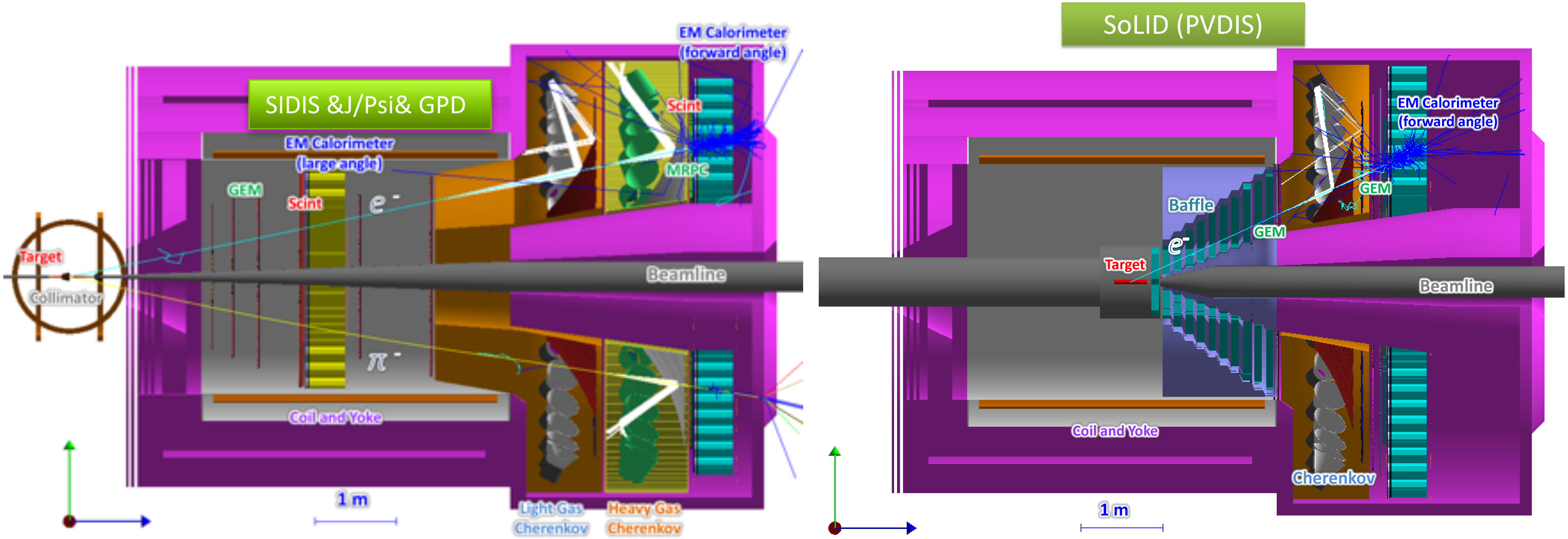
SoLID & SIDIS Configurations

(see Jian-Ping Chen's talk in Week#3)

SoLID Overview

- **SoLID: Solenoidal Large Intensity Device**
  - ✓ High Intensity ($10^{37} \sim 10^{39}$ $cm^{-2}s^{-1}$) and,
  - ✓ Large Acceptance

Two Configurations

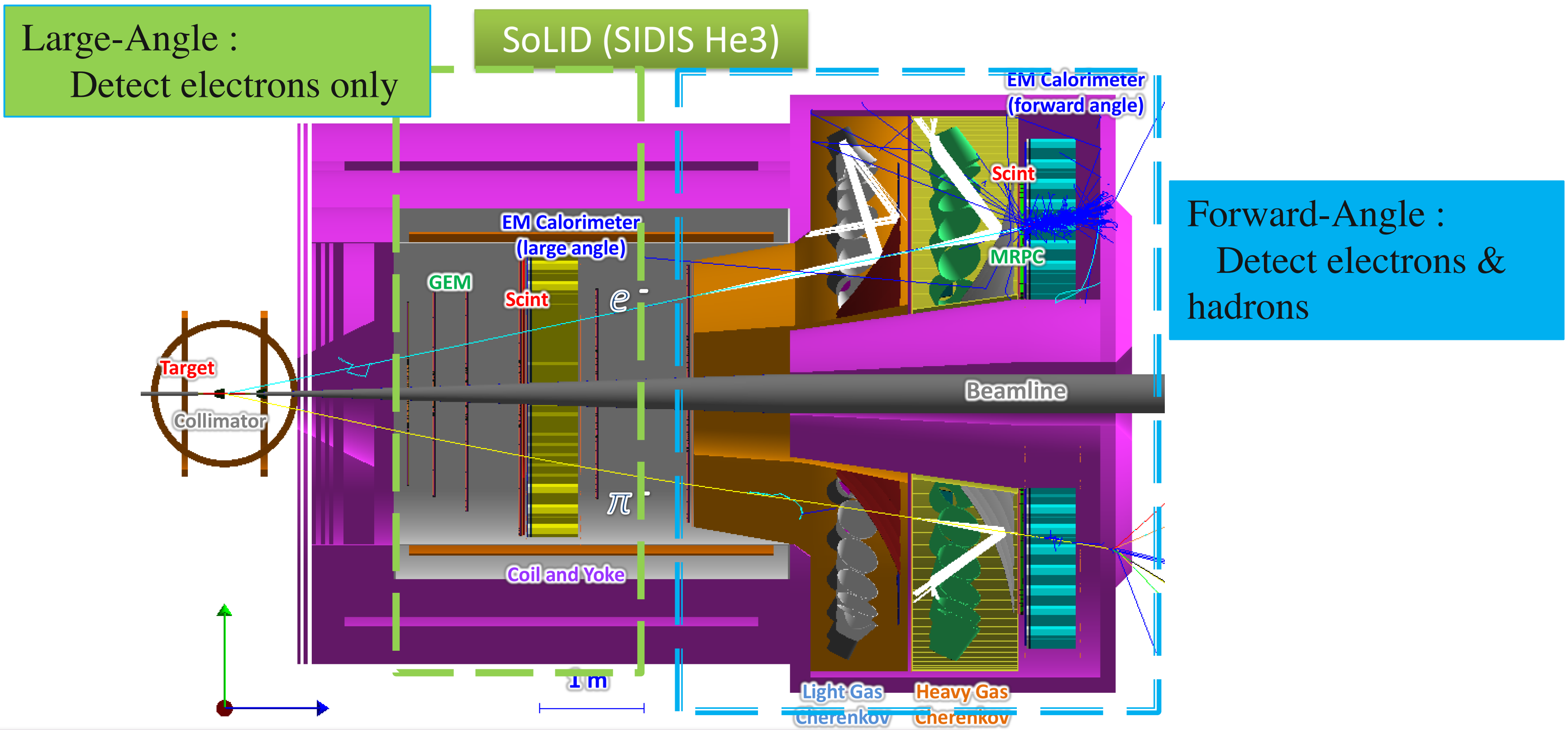


SIDIS uses two polairzed targets
J/psi uses unpolarized targets (plus different triggers)

SoLID Overview

- **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



SIDIS Triggers: Electron + Pion Coincidence

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

Detector Resolutions:

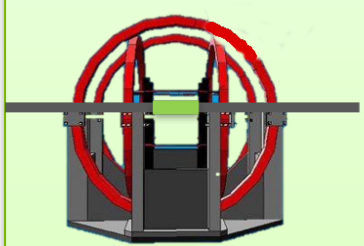
Charged Particle: $\frac{\delta p}{p} = 1.1\sim1.7\%,\ \delta\theta = 1.0\sim1.3mrad, \delta\phi = 1.7\sim5.7mrad$, Vexrex-Z = 0.5~0.9cm

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”



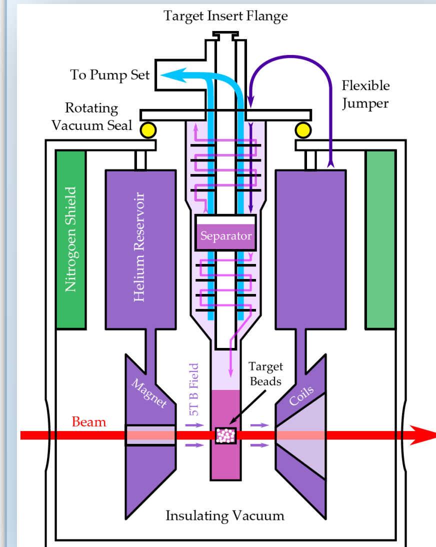
Specification

- ✓ 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/

SoLID-DEMP Programs

with transversely polarized He3

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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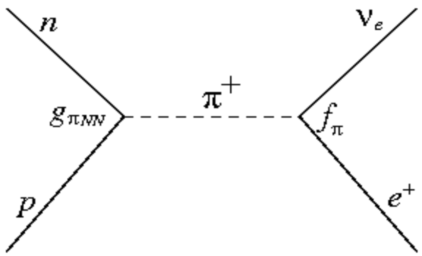
E12-10-006B

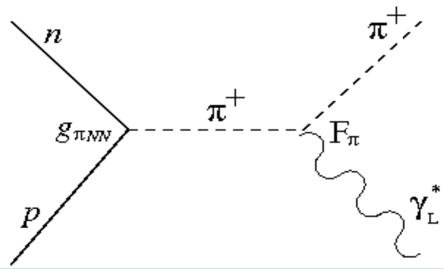
- Probe GPDs with DEMP:
  - GPD-$\tilde{E}$ is not related to any already known parton distribution.

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

  - $G_P(t)$ 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.

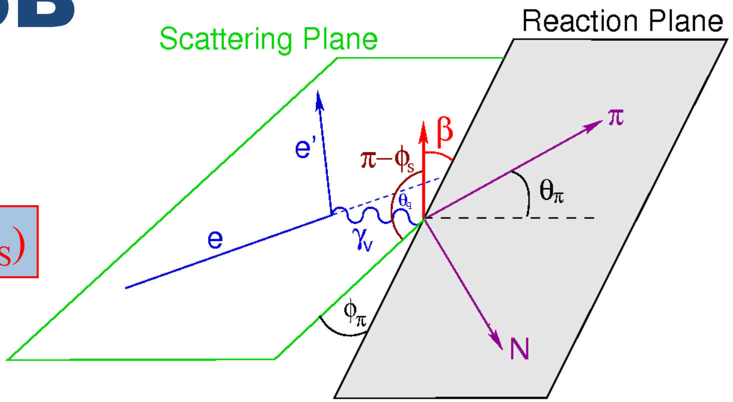
- Additional chiral–odd GPDs ($H_T, E_T, \tilde{H}_T, \tilde{E}_T$) offer a new way to access the transversity-dependent quark content of the nucleon.

E12-10-006B

➢ 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:

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



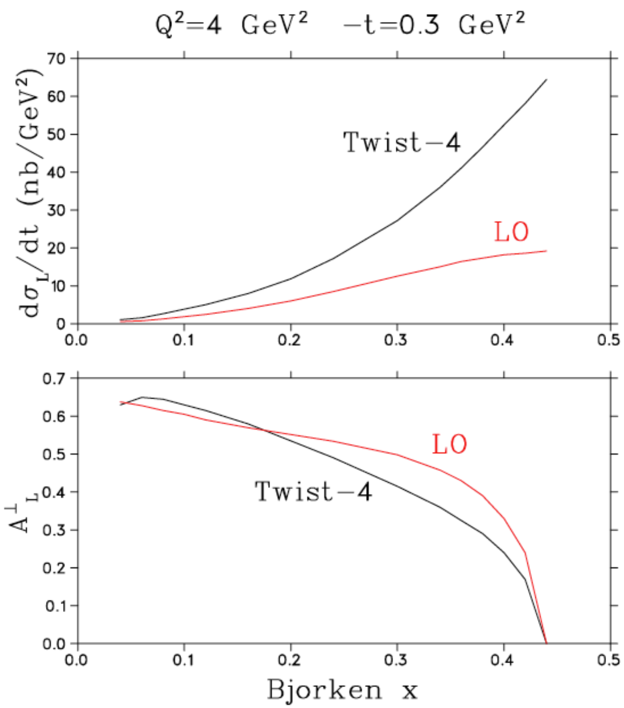
$$A_L^{\perp} = \left(\int_0^{\pi} d\beta \frac{d\sigma_L^{\pi}}{d\beta} - \int_{\pi}^{2\pi} d\beta \frac{d\sigma_L^{\pi}}{d\beta}\right)\left(\int_0^{2\pi} d\beta \frac{d\sigma_L^{\pi}}{d\beta}\right)^{-1}$$

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

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 $\tilde{E}\neq 0$, 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

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

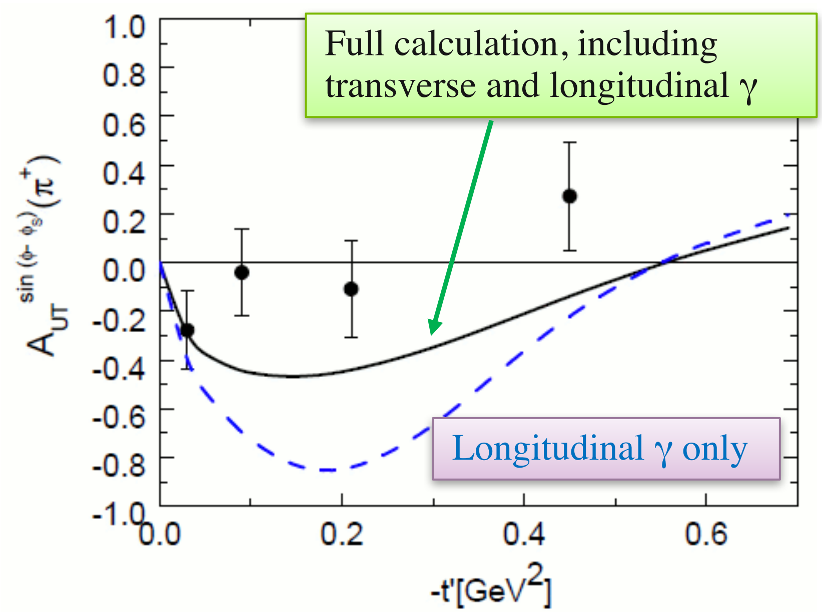
helicities: [pion, neutron, photon, proton]

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

E12-10-006B

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

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



- Exclusive π^+ production by scattering 27.6 GeV positrons or electrons from transverse polarized ^{1}H 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≈0.5 GeV^2 is due to the large contribution from $\tilde{E}$ demanded

Physics Motivation

➢ HERMES sin(ϕ_s) Asymmetry Moment

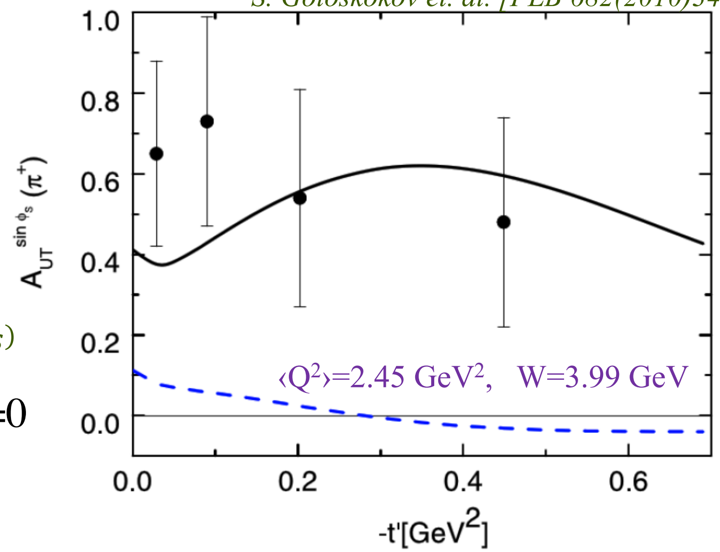
- Only measures the LT interference,

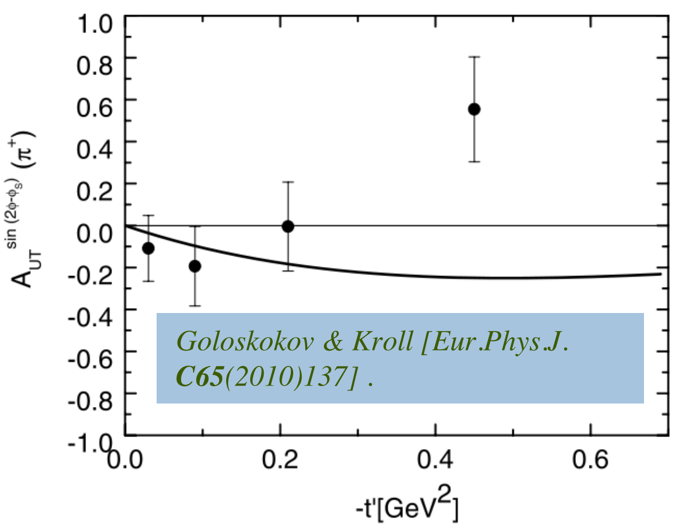
  while $A_{UT}^{\sin(\phi-\phi_S)}$ has contributions from both LT and TT.
- Can provides additional GPD model constraints to aid in the interpretation of the unseparated asymmetry data.

  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.

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





➢ HERMES sin(2ϕ−ϕs) 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.

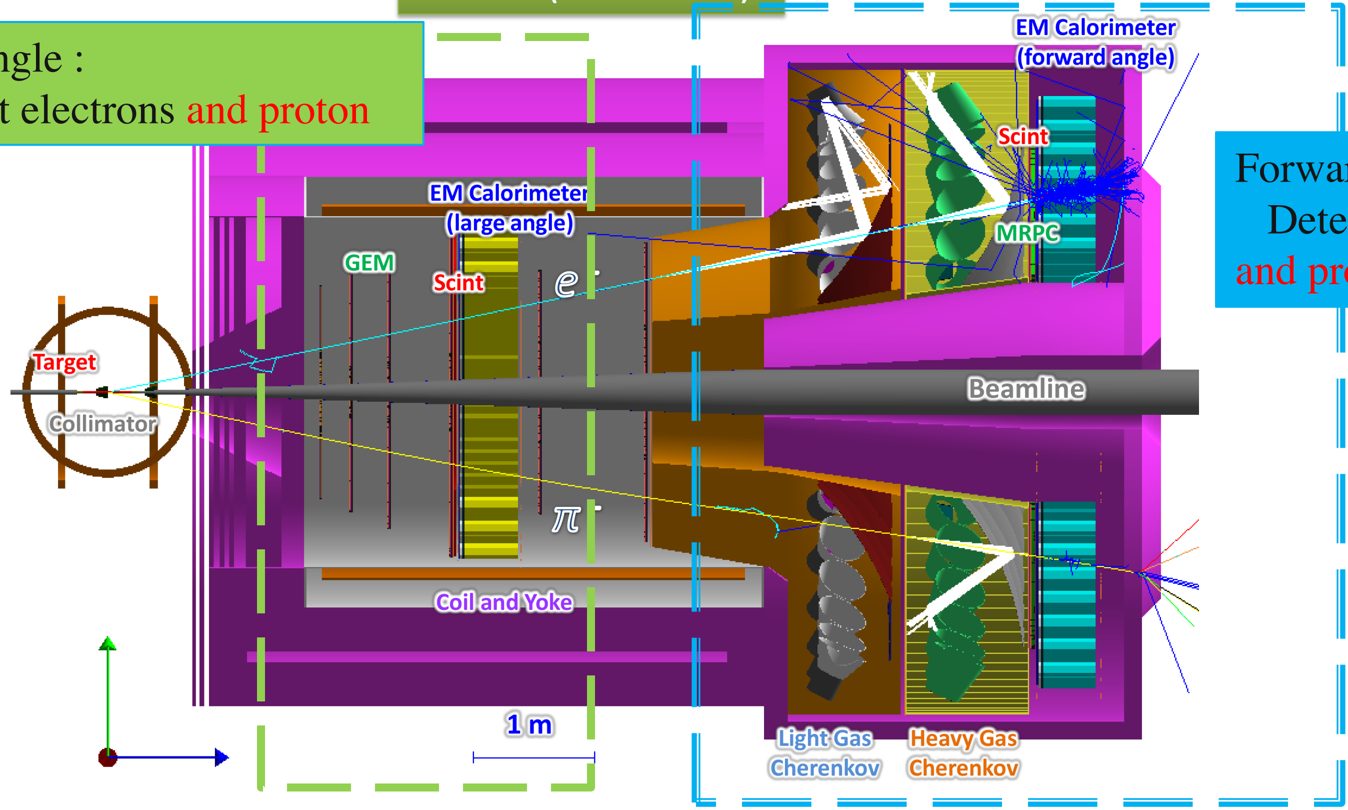
The remaining $\sin(\varphi+\varphi_s)$, $\sin(2\varphi+\varphi_s)$, $\sin(3\varphi-\varphi_s)$ moments are only fed by TT interference and are even smaller.

E12-10-006B

➢ **Experimental Setup:**

Large-Angle :
Detect electrons and proton

Forward-Angle :
Detect electrons, pion and proton



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.

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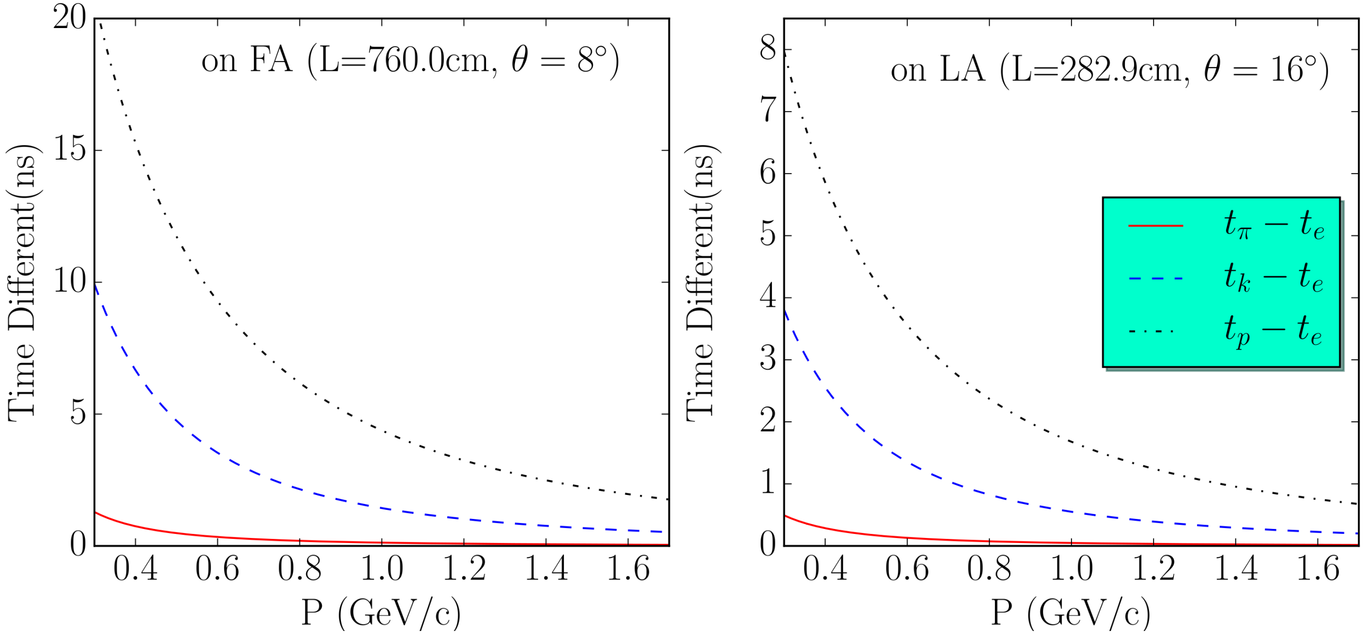
➢ **Recoil Proton Detection: Time of Flight** $^{3}He(e,e'\pi^{-}p)pp_{sp}$

- 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.



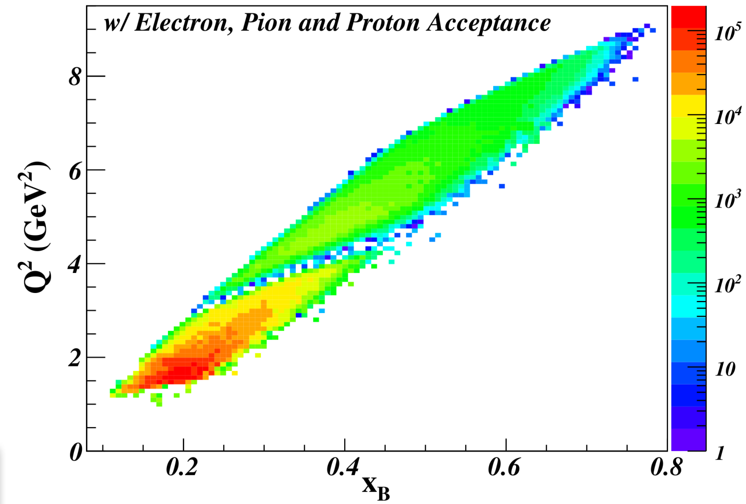
- The currently designed timing resolution is sufficient for proton identification using TOF.
- We also can measure the momenta and angles of the proton via tracking reconstruction, but we currently don't use these info

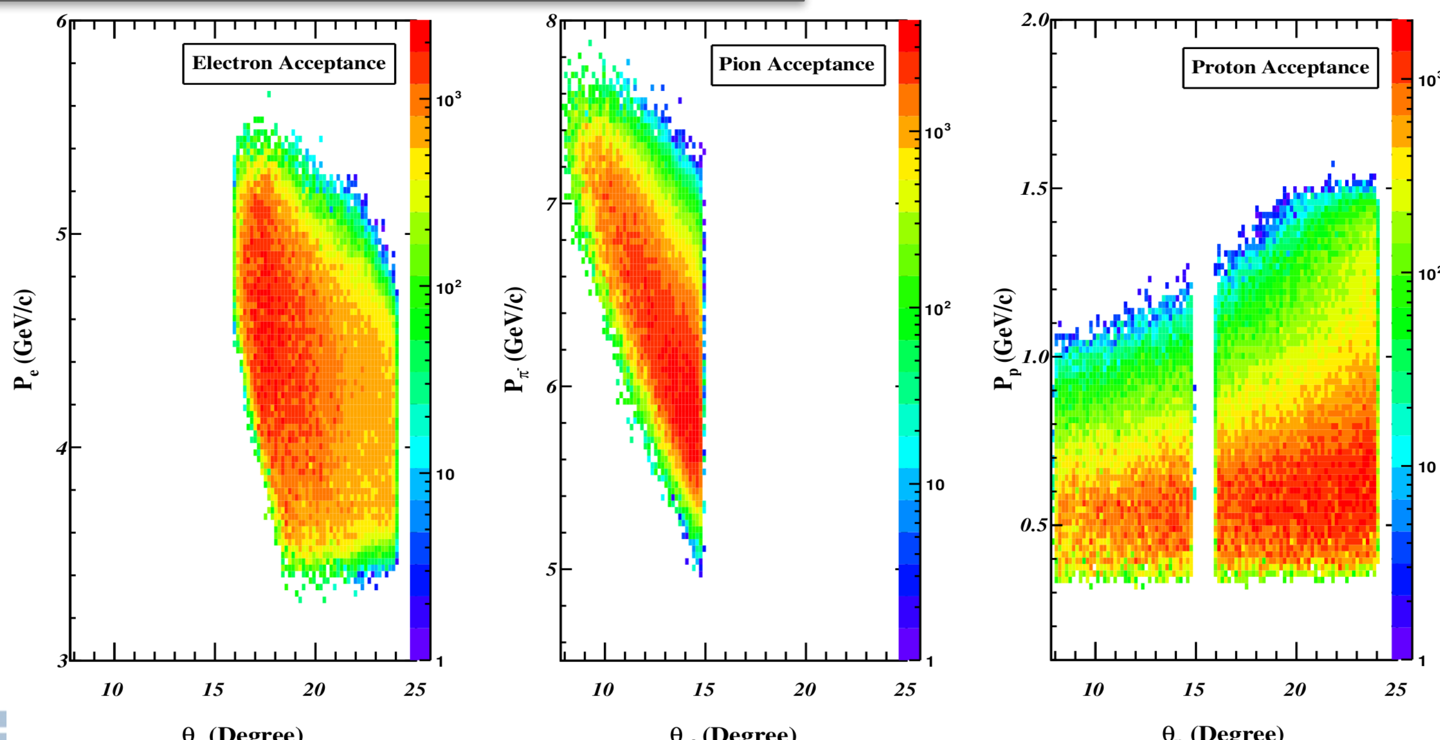
E12-10-006B

➢ **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<ε<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:

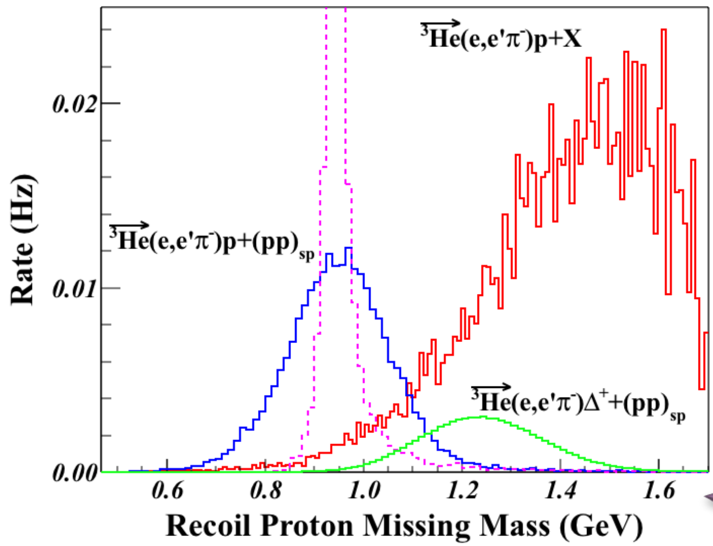
$$M_{miss} = \sqrt{(E_e + m_n - E_{e'} - E_{\pi^-})^2 - (\vec{p}_e - \vec{p}_{e'} - \vec{p}_{\pi^-})^2}$$

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

- **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.

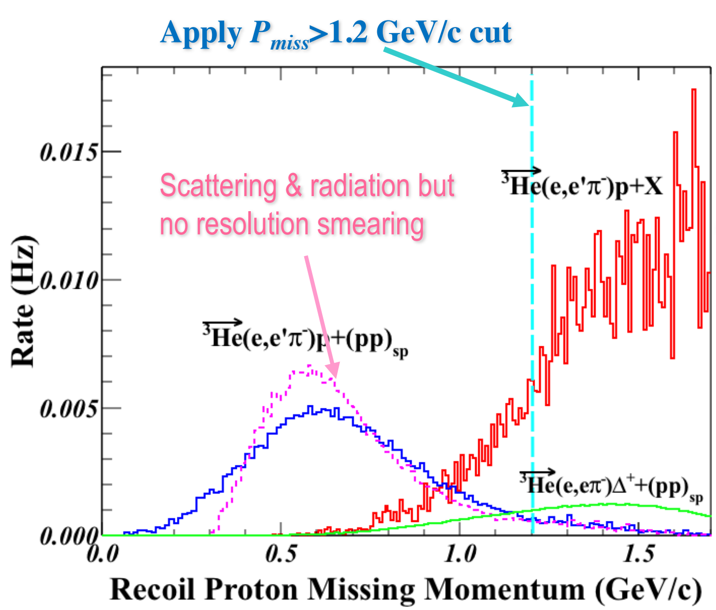
E12-10-006B

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

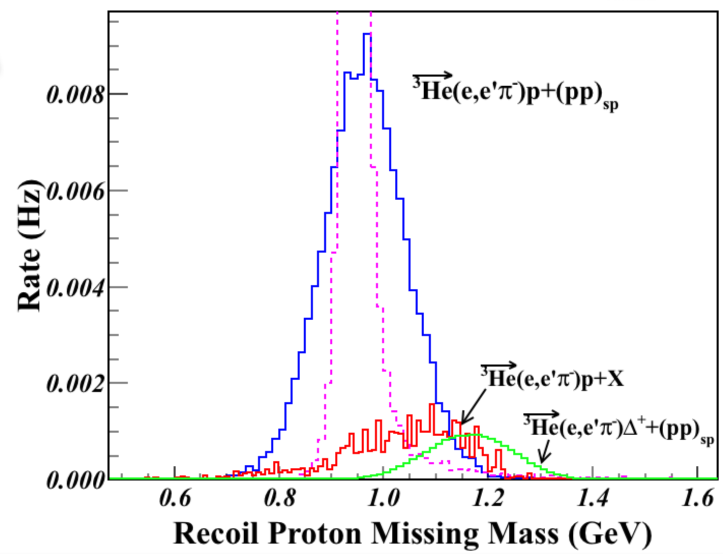


Two different background channels were simulated:

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



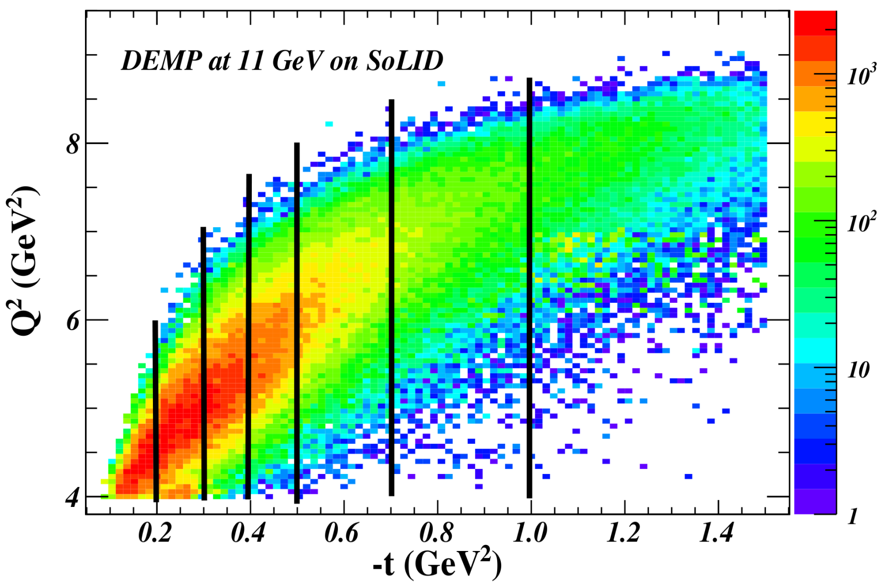
Background remaining after P_{miss} cut

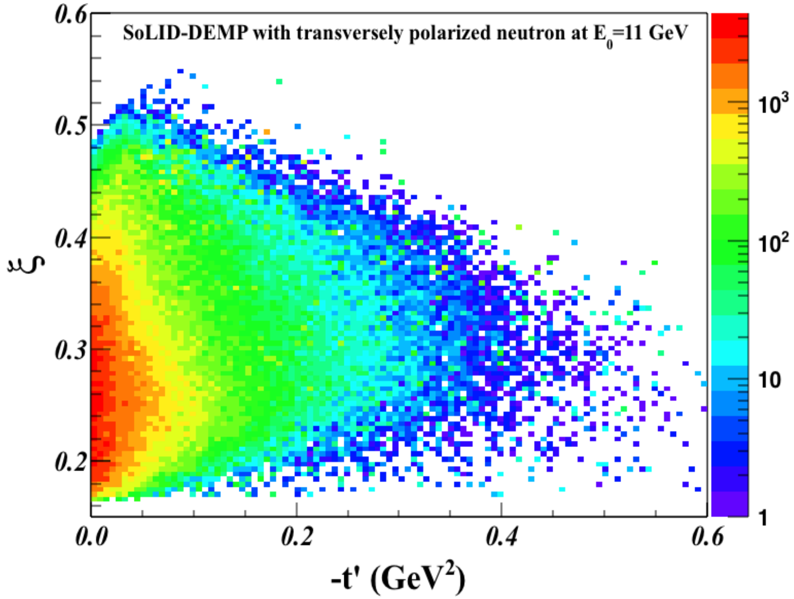


Detector Resolutions were built in; Fermi-Motion, Energy-Loss, FSI etc. were considered

E12-10-006B

➢ 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.

E12-10-006B

➢ 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

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

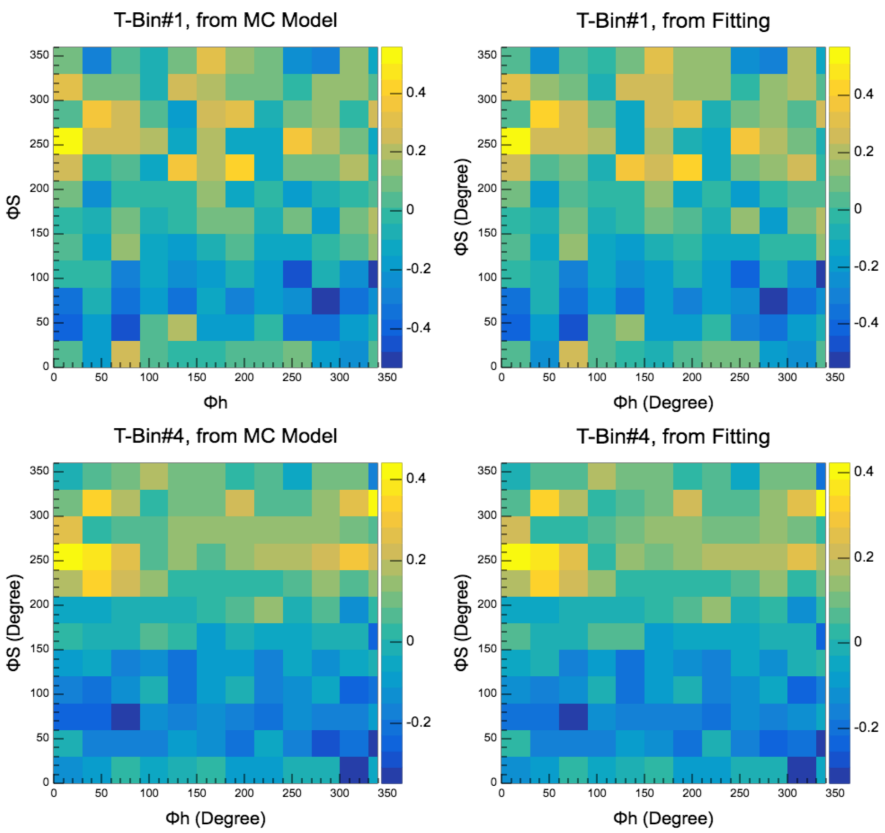
where A_k are the asymmetries that can minimize the likelihood function.

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:



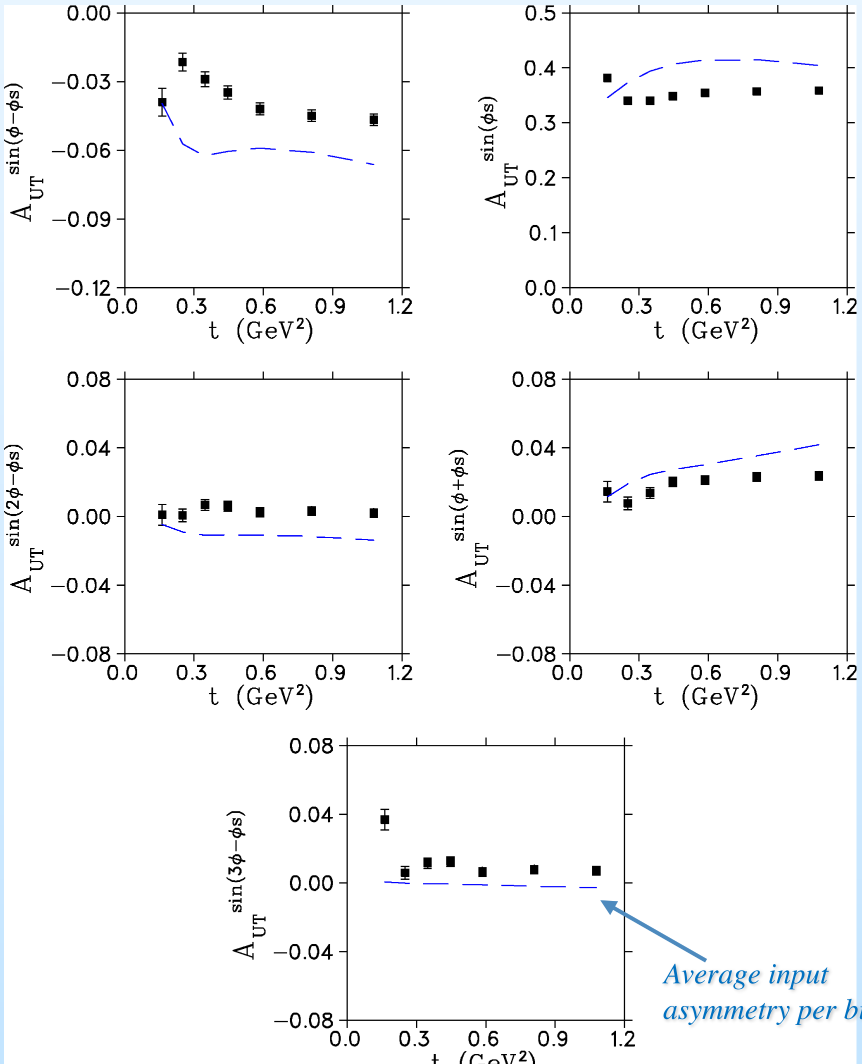
- Same method used by HERMES in their DEMP analysis [PLB 682(2010)345].

E12-10-006B

➢ **Projected Uncertainties**

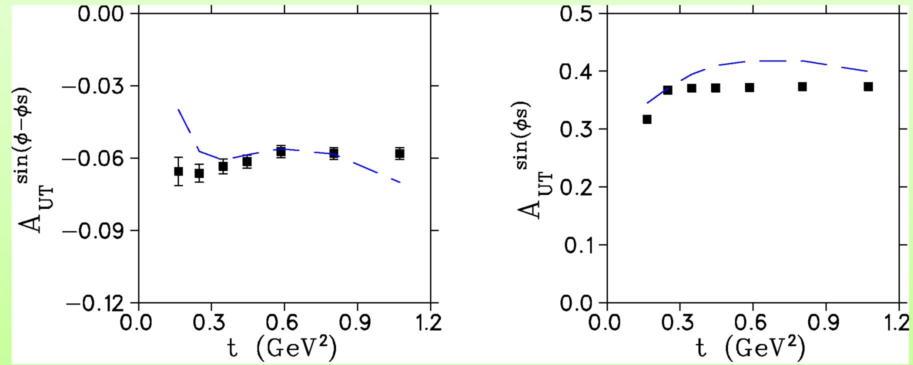
All effects on.

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



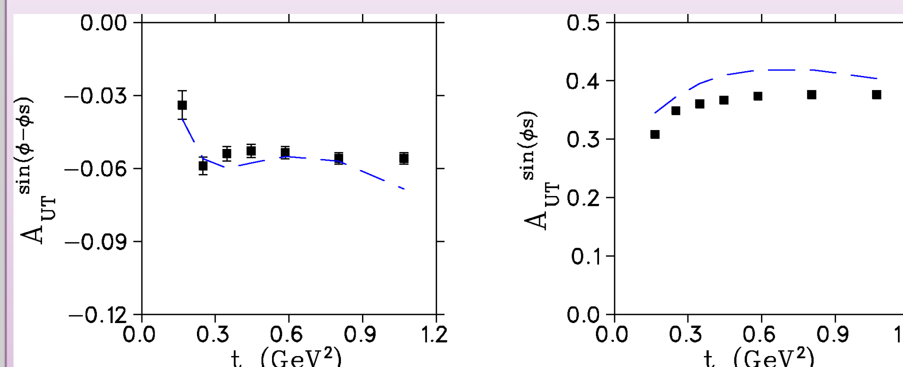
Only Fermi momentum off.

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)

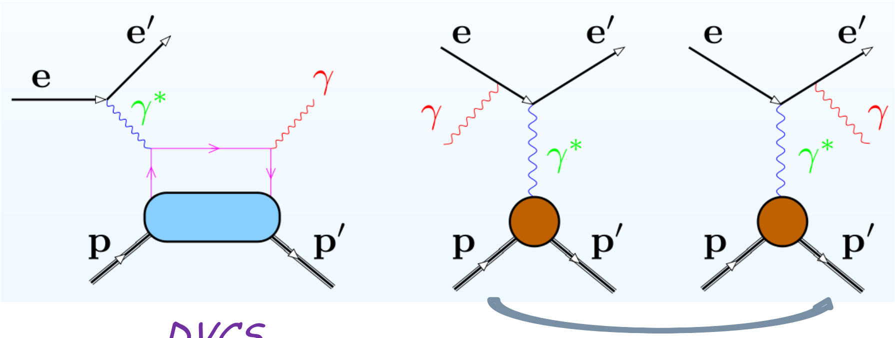
SoLID-DVCS Programs

with polarized He3

SoLID-DVCS with Polarized He3

- Deeply Virtual Compton Scattering (DVCS): $e + N \rightarrow e' + N + \gamma$

$$\frac{d\sigma}{dQ^2 dx_B dt d\phi} \propto |\tau_{DVCS}|^2 + I + |\tau_{BH}|^2$$



DVCS

Bethe-Heitler (BH)

◆ Interference-Term:

$$I = \left|\tau_{DVCS}\tau^*_{BH} + \tau^*_{DVCS}\tau_{BH}\right|^2$$

$\tau_{BH} \propto$ from Nucleon FF, F_1 & F_2

◆ Compton Form Factors (CFFs): Re(H) Im(H)

$$\tau_{DVCS} \propto \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi \mp i\varepsilon} dx = P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t),$$

(8 CFFs for $H, E, \widetilde{H}, \widetilde{E}$)

Access GPDs via DVCS by measuring the Φ dependence of DVCS & Interference Terms

◆ In the asymmetry:

$$A = \frac{I}{|\tau_{DVCS}|^2 + I + |\tau_{BH}|^2} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$\sigma^{+/-}$, Beam or/and Target Polarization.

SoLID-DVCS with Polarized He3

- DVCS with polarized electron beam and targets:

Polarization	Asymmetries	CFFs
Longitudinal Beam	A_{LU}	$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_p, \mathcal{E}_n\}$
Longitudinal Target	A_{UL}	$Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ $Im\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$
Long. Beam + Long. Target	A_{LL}	$Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ $Re\{\mathcal{H}_n, \mathcal{E}_n, \tilde{\mathcal{E}}_n\}$
Transverse Target	A_{UT}	$Im\{\mathcal{H}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n, \boxed{\mathcal{E}_n}\}$
Long. Beam +Trans.Targt	A_{LT}	$Re\{\mathcal{H}_p, \mathcal{E}_n\}$ $Re\{\mathcal{H}_n, \boxed{\mathcal{E}_n}\}$

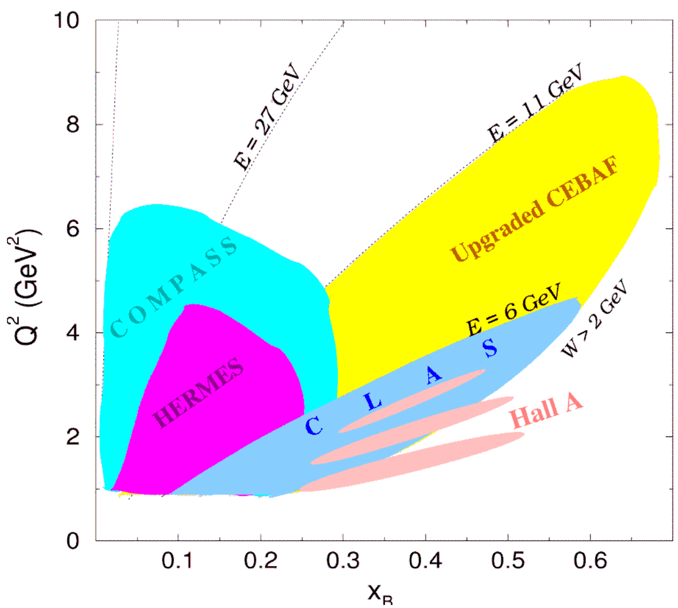
Suppressed at t→0 where F_1^n→0 but should be sensitive at large t

- In addition to measuring the absolute DVCS cross sections, extracting all kinds asymmetries on proton and neutron is also essential to decouple different GPDs and perform flavor decomposition.

32

SoLID-DVCS with Polarized He3

- DVCS with polarized electron beam and targets:



Approved 12GeV DVCS experiments:

- E12-06-114 (Hall-A)
  unpol. proton, absolute XS & BSA, limited coverage
- E12-13-010 (Hall-C)
  unpol. proton, absolute XS &π^0, limited coverage.
- E12-06-119 (Hall-B)
  longi. pol proton (DNP), BSA, TSA, wide coverage
- C12-12-010 (Hall-B) conditional approved
  trans. pol. proton (HDice), TSA,BSA, wide coverage
- E-12-11-003 (Hall-B)
  unpol. neutron, BSA
- PR12-15-004 (Hall-B): c2 from PAC43
  long. pol. Deuteron ("neutron"), TSA, BSA

No polarized neutron-DVCS experiment has been done or fully approved at Jlab!

GPDs study needs neutron data, e.g. flavor decomposition!

SoLID can bring:

- ✓ Transversely polarized neutron-DVCS (He3, with E12-10-006 SIDIS setup)
- ✓ Longitudinally polarized neutron-DVCS (He3, with E12-11-007 SIDIS setup)
- ✓ Transversely polarized proton-DVCS (DNP, with E1211-108 SIDIS setup)
- ✓ Longitudinally polarized proton-DVCS (DNP)

SoLID-DVCS with Polarized He3

- This program was initialized in 2015 and a LOI was only submitted to SoLID collaboration.
- Projected results look very promising, but need further study on the background issues.

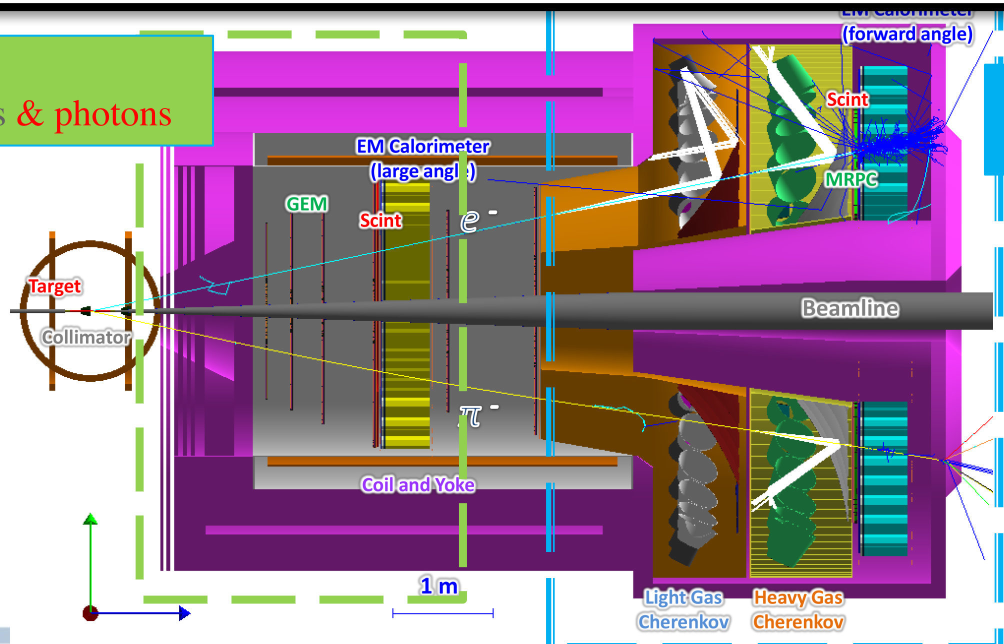
$$e + \vec{n} \rightarrow e' + n + \gamma$$

An Measurement of Deeply Virtual Compton Scattering with Transversely Polarized Neutron using the SoLID Spectrometer

A new letter of intent to Jefferson Lab PAC43

Alexandre Camsonne[1], Haiyan Gao[2], Carlos Muñoz Camacho[3], Gu Chao[4], Kondo Gnanvo[4], Nilanga Liyanage[4], Marie Boer[3], Zhihong Ye[2], Zhiwen Zhao[2], and and the Hall A SoLID collaboration[1]

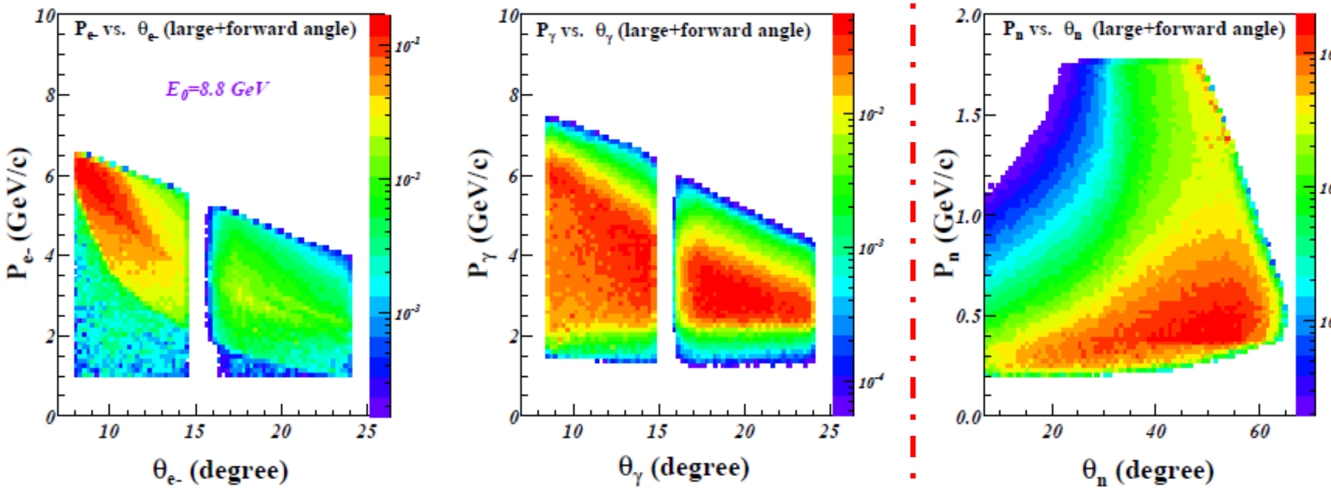
Large-Angle :
Detect electrons & photons



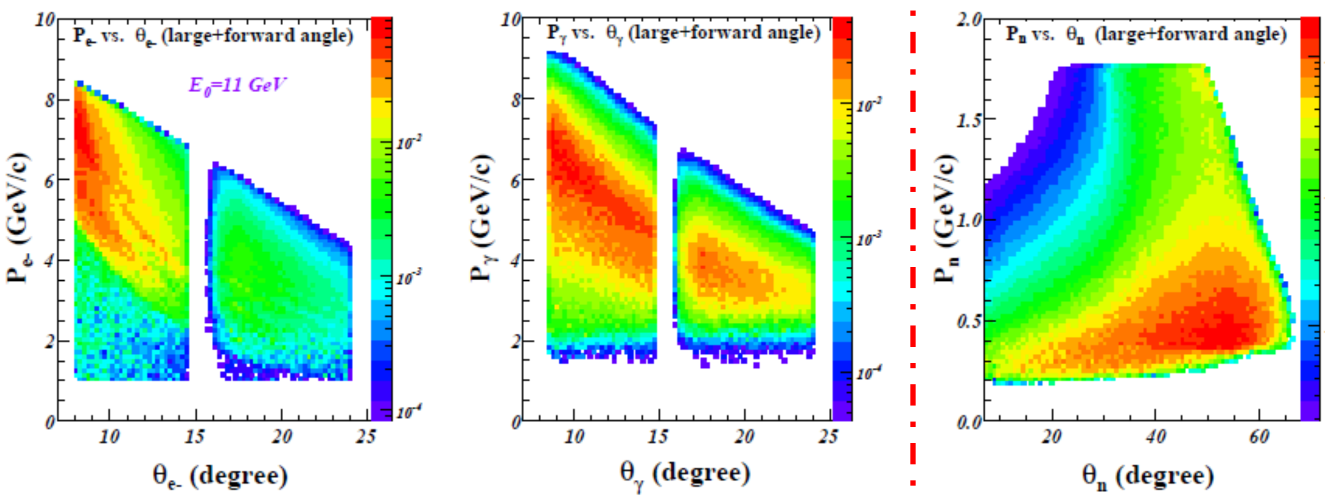
Forward-Angle :
Detect electrons & photons

SoLID-DVCS with Polarized He3

- Acceptance



(a) E_{beam}=8.8 GeV



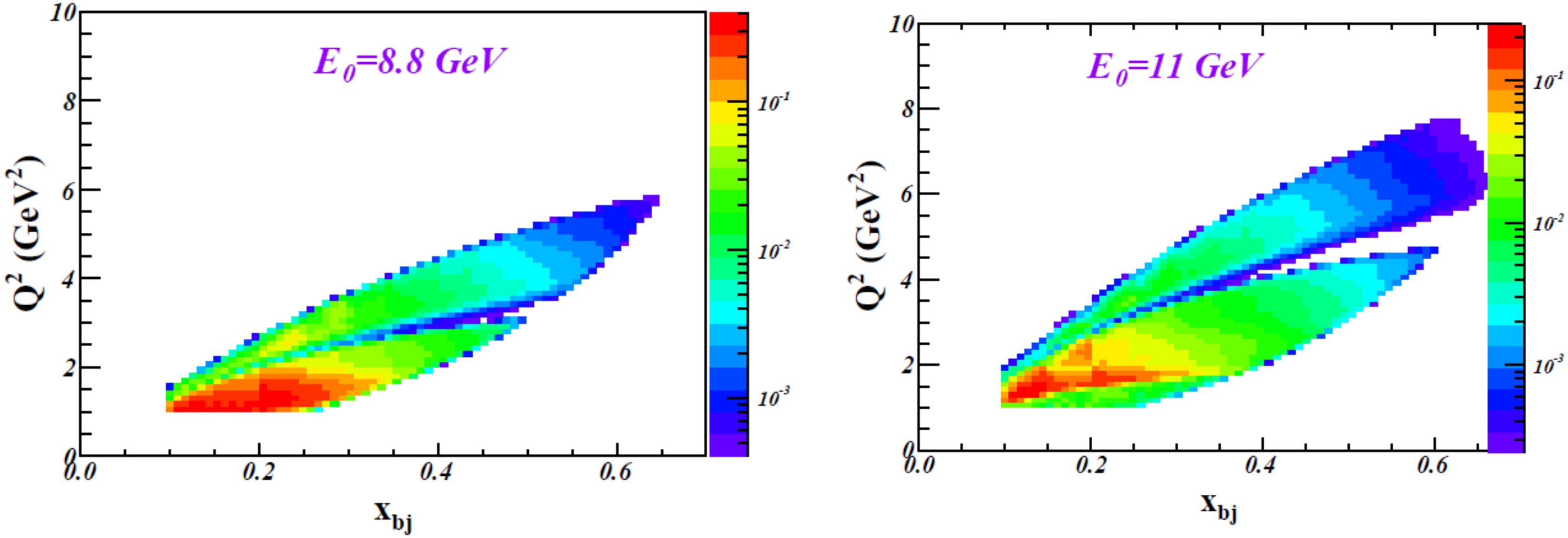
(b) E_{beam}=11 GeV

Recoil neutrons:
(1) at large angles
(2) P~0.4GeV/c

It will be difficult to detect neutrons

SoLID-DVCS with Polarized He3

- Kinematic Coverage



- Integrated Rate:

✓Single γ-rate from Background ~ 120KHz

✓The (e+γ) accidental coincidence rate reduced to ~100Hz

E_0	8.8 GeV	11 GeV
Single Rates (Hz)		
e- (FAEC)	64.78	36.17
e- (LAEC)	2.57	1.70
γ (FAEC)	45.37	40.54
γ (LAEC)	31.05	28.83
Coincidence Rates (Hz)		
e-(FAEC)+γ(FAEC+LAEC)	36.06	20.50
e-(LAEC)+γ(FAEC+LAEC)	1.46	1.00

Based on VGG Model

SoLID-DVCS with Polarized He3

- Asymmetry Binning and Projection
  - ✓ 21 days on E0=8.8GeV, 48 days on E0=11GeV
  - ✓ 4D Binning:

$$\begin{aligned}
Q^2[6] &= \{1.0, 1.5, 2.0, 3.0, 4.5, 7.0\}, \quad (5\ bins) \\
x_{bj}[6] &= \{0.1, 0.2, 0.3, 0.4, 0.5, 0.7\}, \quad (5\ bins) \\
t[7] &= \{-2.0, -0.7, -0.5, -0.4, -0.3, -0.2, -0.1\}, \quad (6\ bins) \\
\phi[13] &= \{0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, 360\}, \quad (12\ bins)
\end{aligned}$$

$$N = (\sum_{i \in bin} \sigma_i^{avg} \cdot A_i^{e+\gamma}) \cdot PSF/N_{gen} \cdot T_{8.8(11GeV)} \cdot L \cdot \epsilon_{eff},$$

  - ✓ Asymmetries:

$$A_{BS} = \frac{N^+ - N^-}{N^+ + N^-} \frac{1}{P_e} \qquad \delta A_{BS} = \frac{1}{\sqrt{N}} \frac{\sqrt{1-(P_e A_{BS})^2}}{P_e},$$

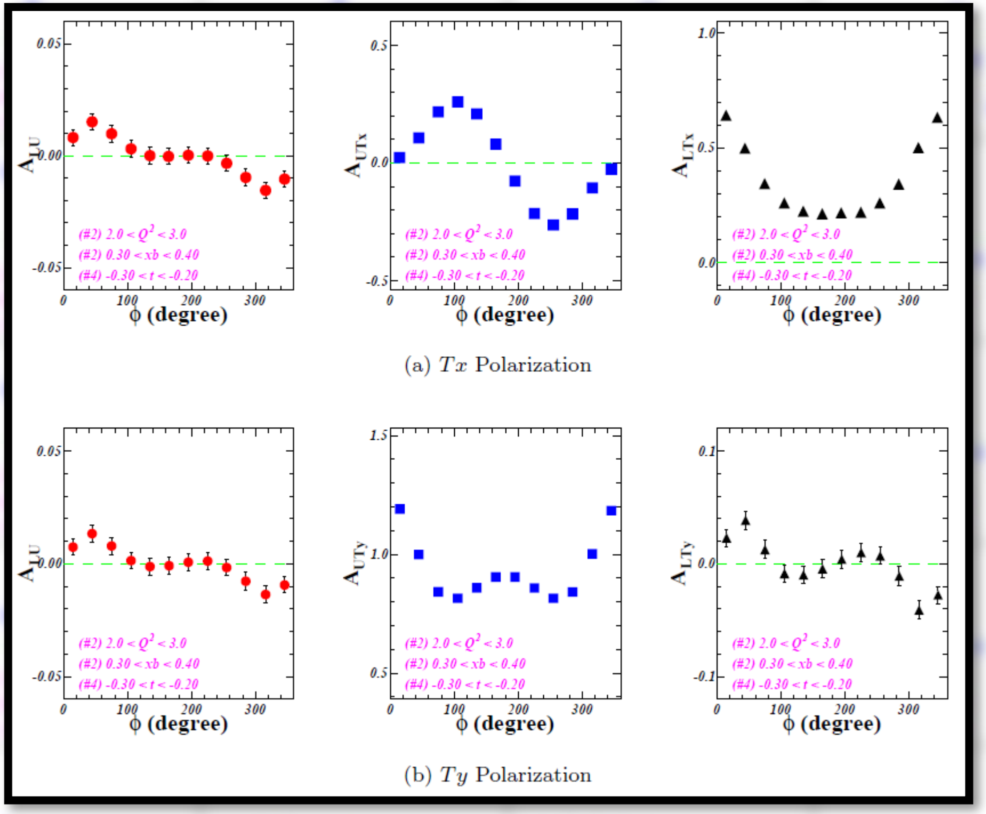
$$A_{TS} = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \frac{1}{f P_T P_n}, \qquad \delta A_{TS} = \frac{1}{\sqrt{N}} \frac{\sqrt{1-(f P_T P_n A_{BS})^2}}{f P_T P_n},$$

$$A_{DS} = \frac{(N^{+\uparrow} + N^{-\downarrow}) - (N^{+\downarrow} + N^{-\uparrow})}{N^{+\uparrow} + N^{+\downarrow} + N^{-\uparrow} + N^{-\downarrow}} \frac{1}{f P_T P_n P_e}, \qquad \delta A_{DS} = \frac{1}{\sqrt{N}} \frac{\sqrt{1-(f P_T P_n P_e A_{BS})^2}}{f P_T P_n P_e}$$

SoLID-DVCS with Polarized He3

- Asymmetry Projection:

21 days on E0=8.8GeV, 48 days on E0=11GeV (approved for SIDIS); Bins match CLAS12's projections



(a) Tx Polarization

(b) Ty Polarization

SoLID-DVCS with Polarized He3

➢Background Study with Missing Mass Reconstruction: $e+n \to e'+n+\gamma$

- Main background if not detecting recoil neutrons: (n+γ) from π^0 decay

$$e+n \to e+n'+\pi^0, \pi^0 \to \gamma+\gamma$$

- Missing Mass Reconstruction: detect electron and photons (angles, momentum/energy)

  The spectrum resolution is limited by the Electromagnetic Calorimeters' (ECs) resolution (~5%)

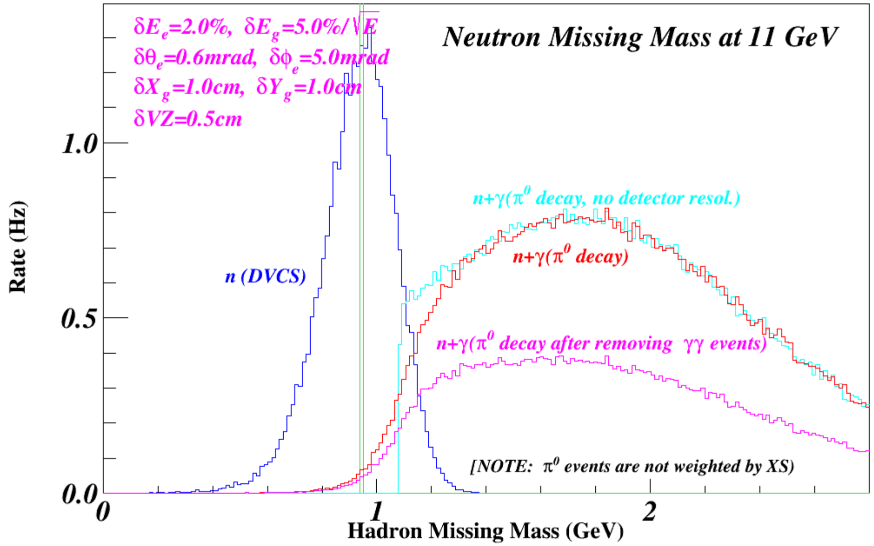
- Background Subtraction: ECs can detect partial π^0 decay events

$$N_{\pi^0}^{Total} = \frac{N_{\pi^0}^{MC-Total}}{N_{\pi^0}^{MC-Accept}} N_{\pi^0}^{Detect}$$

$N_{\pi^0}^{Total}$ ($N_{\pi^0}^{Detect}$) →Total real pi0 events (detected by SoLID)

$N_{\pi^0}^{MC-Total}$ ($N_{\pi^0}^{MC-Accept}$) →Total MC pi0 events (within SoLID acceptance)

(Same method applied in CLAS12's DVCS proposals)



- Pi0 background was generated uniformly
- Need to find a neutron-pi0 model
- Also learn from the recent Hall-A DVCS results and the new 12GeV DVCS data).
- And other background and nuclear effect studies like what we did in the DEMP proposal

SoLID-DDVCS Programs *with unpolarized targets*

For Time-like Compton Scattering, see Zhiwen's talk on week#3

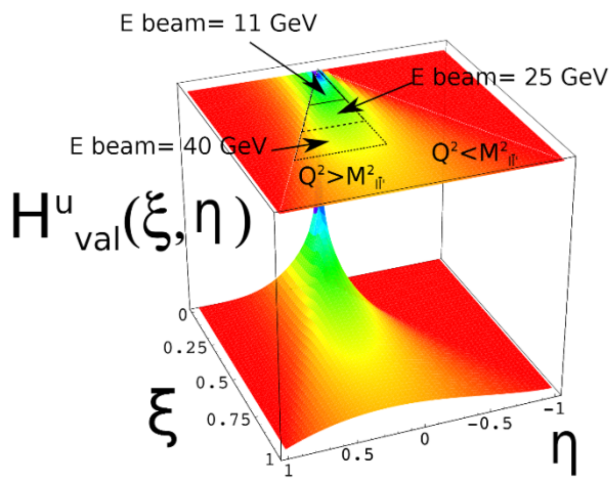
SoLID-DDVCS Programs (LOI)

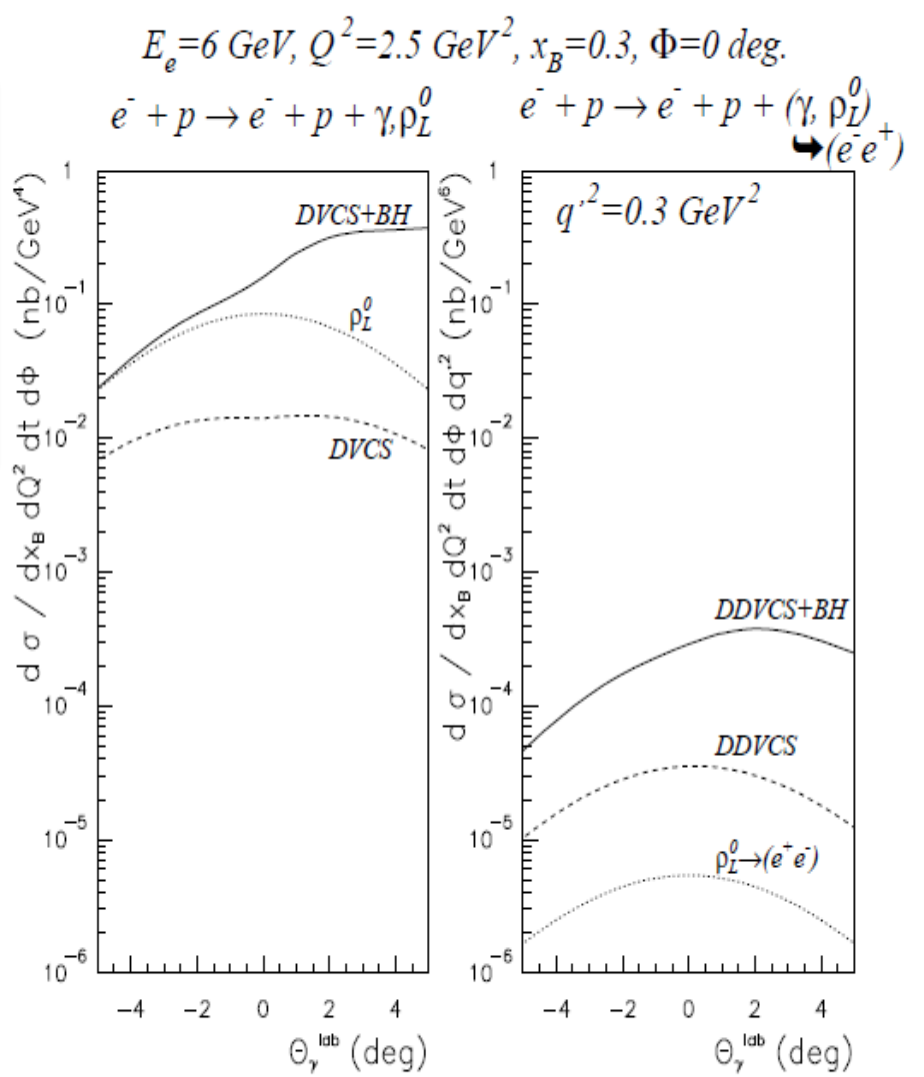
➢ Double-DVCS: (see Zhiwen's talk on week#3)

Guidal& Vanderhaegen:arXiv:hep-ph/0208275v1 (2002)
Belitsky&Radyushkin: arXiv:hep-ph/0504030v3 (2005)

$$\gamma^* + N \to \gamma^* + N \to (l^+ + l^-) + N$$

- Measure GPD beyond the the kinematic limit of DVCS $(x = \xi)$
- Kinematical range increases with beam energy (larger dilepton mass)
- Experimentally it is more practical to detect (μ^+, μ^-) pairs
- Rates are about 100 to 1000 smaller than DVCS





SoLID-DDVCS Programs (LOI)

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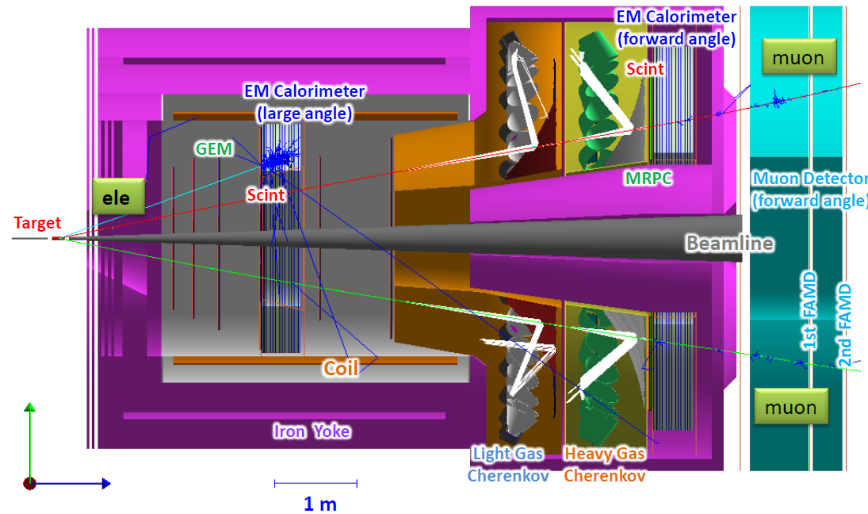
$$\gamma^* + N \to \gamma^* + N \to (l^+ + l^-) + N$$

Guidal& Vanderhaegen:arXiv:hep-ph/0208275v1 (2002)
Belitsky&Radyushkin: arXiv:hep-ph/0504030v3 (2005)

SoLID (DDVCS, JPsi/TCS)



- Measure GPD beyond the the kinematic limit of DVCS ($x = \xi$)
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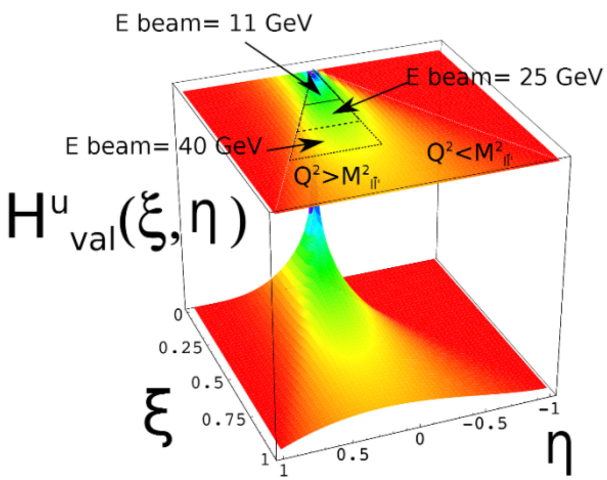
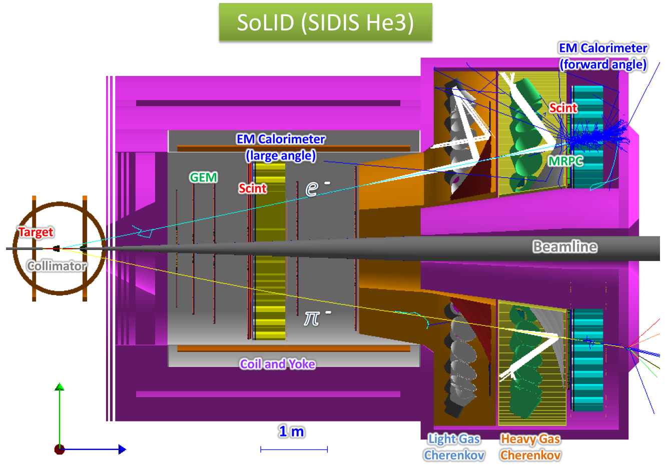


- A parasitic run with the J/psi configuration was studied (a LOI was submitted to PAC43)
- 60 days with J/psi setup at 10^{37} cm^{-2}s^{-1}
- Adding the ion chambers for muon detections.
- A upgraded luminosity of 10^{38} cm^{-2}s^{-1}or higher is more feasible to have enough statistics for multiple-dimension binning study.

- A similar effort to measure DDVCS with CLAS12 is also under developments with major upgrade to the Forward detectors (a LOI was submitted to PAC45)

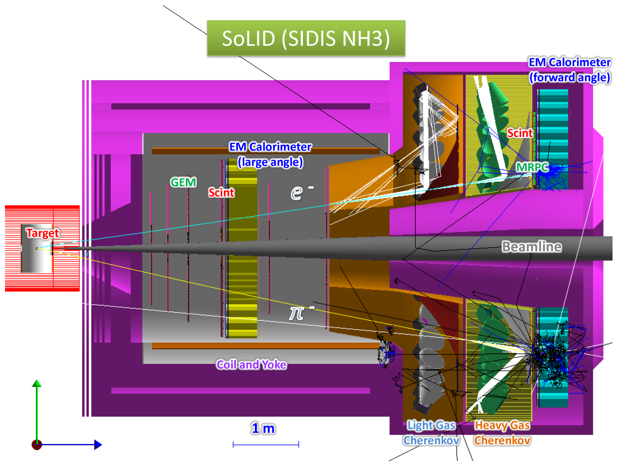
Future Developments

Future GPD Programs



➢ with Polarized He3

- ❑ Finish the DVCS proposal after studying the background
- ❑ DEMP measurement of more negative charged meson production, such as K^-, ρ^-, etc.
  - ✓ Experimentally these data will be collected together with the π^- reaction (E12-10-006B)
- ❑ DEMP measurements of neutral pseudoscalar and vector meson production, such as π^0, ρ^0, ω, etc.
  - ✗ Will have to detect decayed photons (SoLID ECs are not designed for high resolution energy measurements)
  - ✗ It is more difficult to tag recoil neutron (need a recoil detectors to tag other two protons



➢ with Polarized NH3

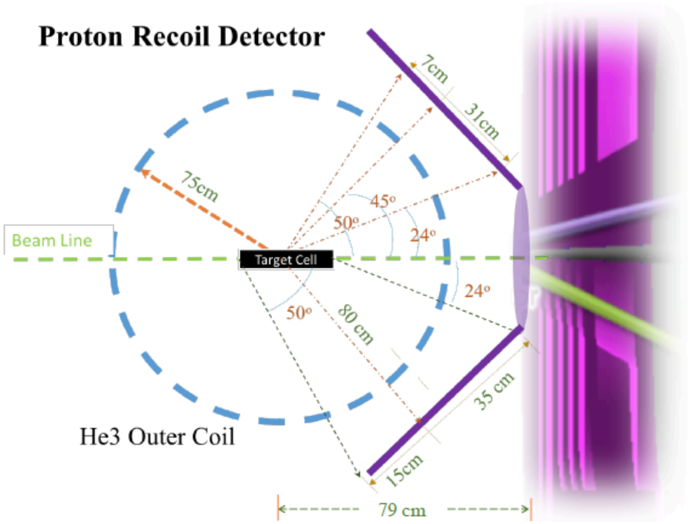
- ❑ DVCS with polarized proton
- ❑ DEMP measurements of neutral pseudoscaler and vector meson production, such as π^0, ρ^0, ω, etc.
  - ✗ Again, SoLID-EC could be a limitations,
  - • Instead, we can try to precisely measure protons
- ❑ DEMP measurement of more positive charged meson production, such as K+, ρ^+, etc.
  - ✗ Also have to deal with recoil neutrons

Future GPD Programs

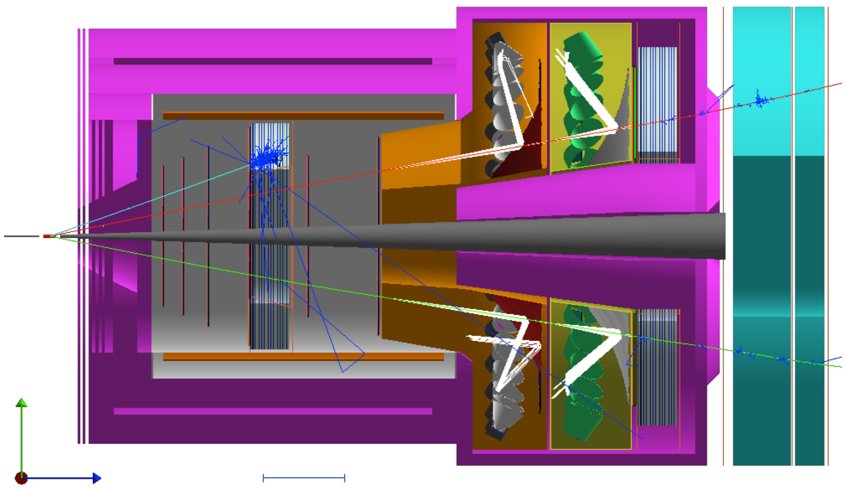
➢ **Maximize the power of SoLID for GPDs:**

- ✓ A dedicated configuration for GPD Programs (or optimize the SIDIS configuration)
- ✓ Improve the EC energy resolution for photon energy measurement
- ✓ Add a large angle proton detector:

> ✓ Cover angles of 24° to 50°
> 2π on the azimuthal angle
> ✓ Inner Radius=32 cm
> Outer Radis = 67 cm
> Detector Length = 50 cm
> ✓ Distance from Target = 79cm
> (far end touches the magnet)



- ✓ Add a Central Recoil Detector for recoil protons and spectator protons (for neutron identification)
- ✓ For DDVCS, add muon detectors and/or major reconfiguration of the SIDIS/Jpsi configuration.



Summary

Summary

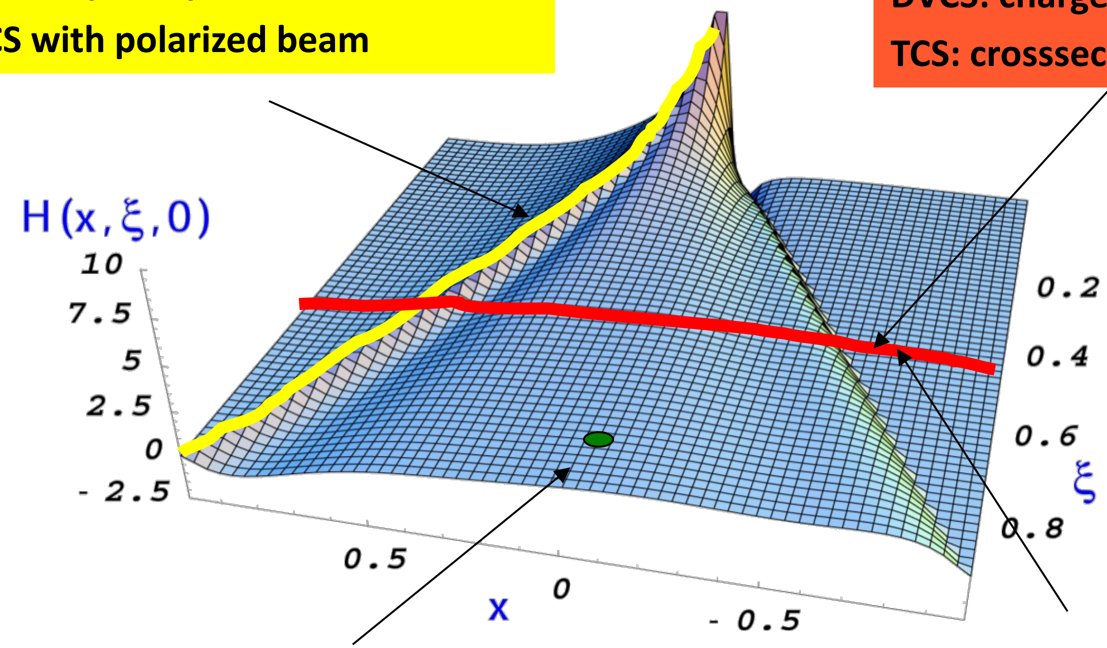
- GPDs provide unique information on the transverse spatial distributions; They connects to form factors and parton distribution function; They can also help us to understand the composition of nucleon spin
- Exclusive reactions, such as DVCS, DEMP, TCS and DDVCS can get access to GPDs
- SoLID has the unique features of high luminosity and wide coverage which are essential for measuring the GPD with exclusive channels.
  - SoLID-SIDIS configurations with the polarized He3 (“neutron”) and NH3 (“proton”) will provide many experimental observables to study GPDs
  - The approved SoLID-DEMP experiment with polarized He3 can help us to determine the GPD-$\tilde{E}$ that are unlikely to be probed elsewhere, and provide new data with great improvement in uncertainties and kinematic coverage compare with HEMES; It is also sensitive to the transversity GPDs.
  - The SoLID-DVCS measurement with polarized He3 target is the missing piece of the Jlab 12GeV DVCS program.
  - The approved TCS can provide complementary study to the DVCS.
  - Other GPD programs, such as DDVCS, more DEMP measurements, are under development.
- Future optimization and upgrade to the SIDIS configuration will maximize the power of studying GPDs with SoLID.

Backup Slides

Exclusive Hard Processes

(Im, $x=\xi$)
DVCS: spin asymmetries
TCS with polarized beam

(Re)
DVCS: charge asymmetry
TCS: crosssection, lin beam asymmetry



(Im, $x \neq \xi$, $x < |\xi|$)
Double DVCS

($|Im|^2+|Re|^2$)
DVCS: cross section

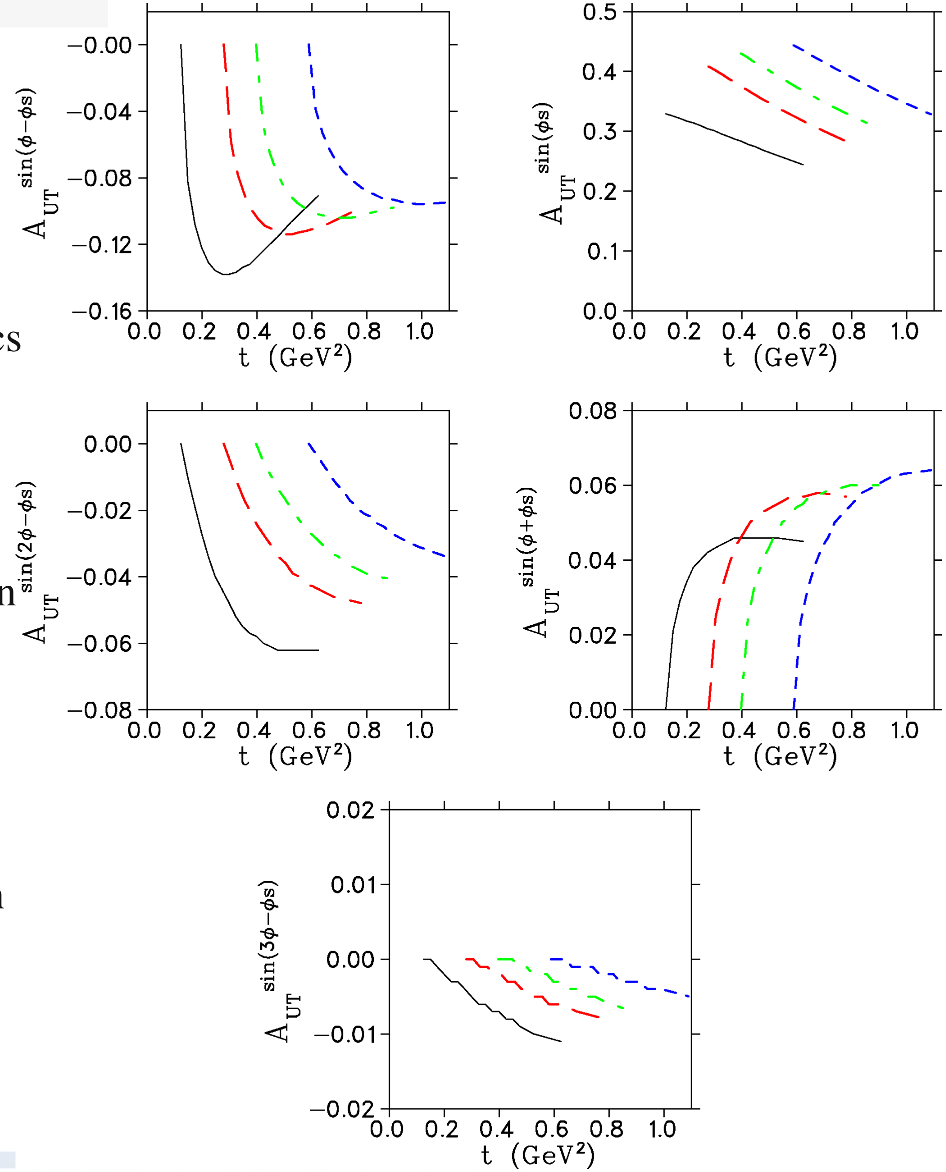
E12-10-006B

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

➢ Modeling Diluted Asymmetry with SoLID

- Event generator is based on data from HERMES, Halls B, C with VR Regge+DIS model used as a constraint in unmeasured regions.
- Event generator incorporates A_{UT} moments calculated by Goloskokov and Kroll for kinematics of this experiment. GK handbag approach for $\pi^{+/-}$ from neutron:

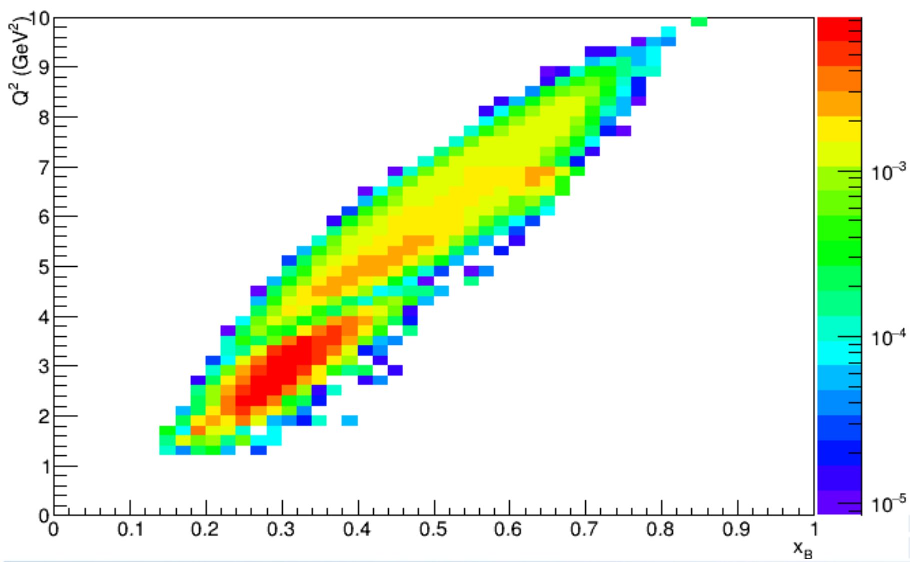
  Eur.Phys.J. C65(2010)137, Eur.Phys.J. A47(2011)112.
- Simulated data for target polarization up and down are subjected to same Q^2>4 GeV^2, W>2 GeV, 0.55<ε<0.75 cuts.
- Generator includes electron radiation, multiple scattering and ionization energy loss.
- Every detected particle is smeared in (P,θ,ϕ) with resolution from SoLID tracking studies, and acceptance profiles from SoLID-SIDIS GEMC study applied.

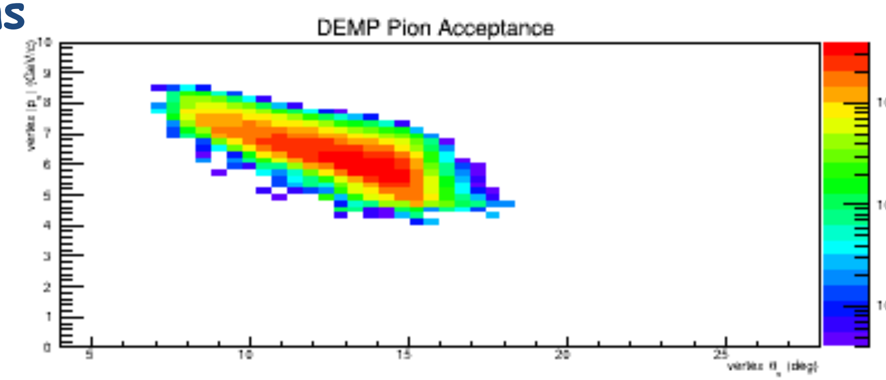


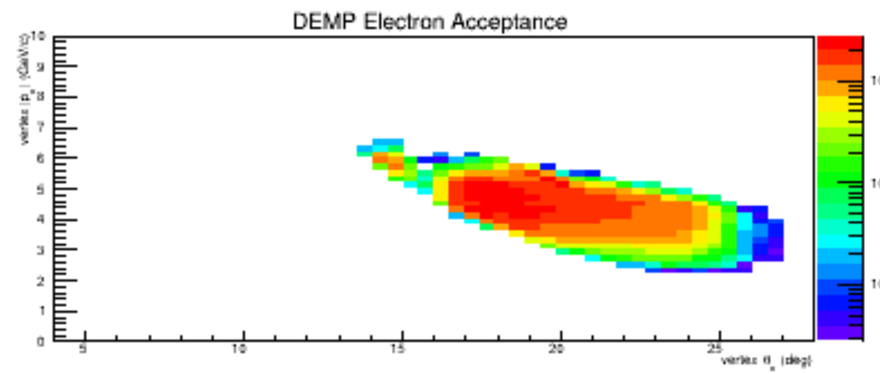
E12-10-006B

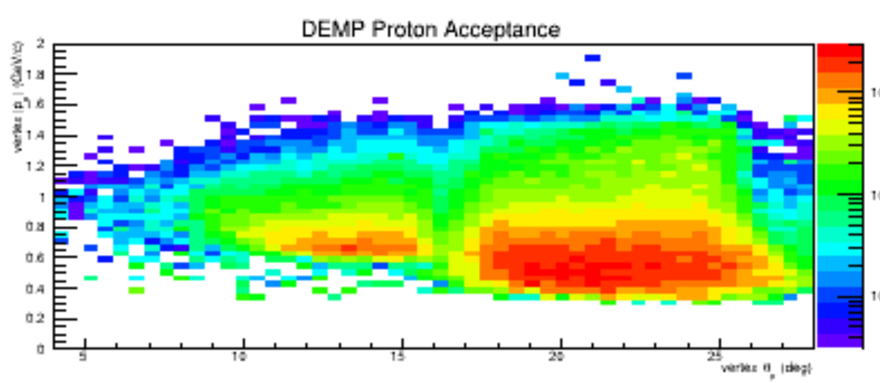
➢ Similar Results from GEMC Simulations

- As requested in last year's TAC review, we performed a 2nd set of simulations to better model the lowest momentum recoil protons.
- GEMC flux tree used to see if a particle hits a specific detector.
- Good agreement with 1st set of simulations.
- Detected proton momentum shifted upward slightly, ~300-350 MeV/c, partly due to change in plotting variables.









E12-10-006B

➢ 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 $\sin(\phi-\phi_s)$ moment, and about -0.04 on the $\sin(\phi_s)$ 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.

E12-10-006B

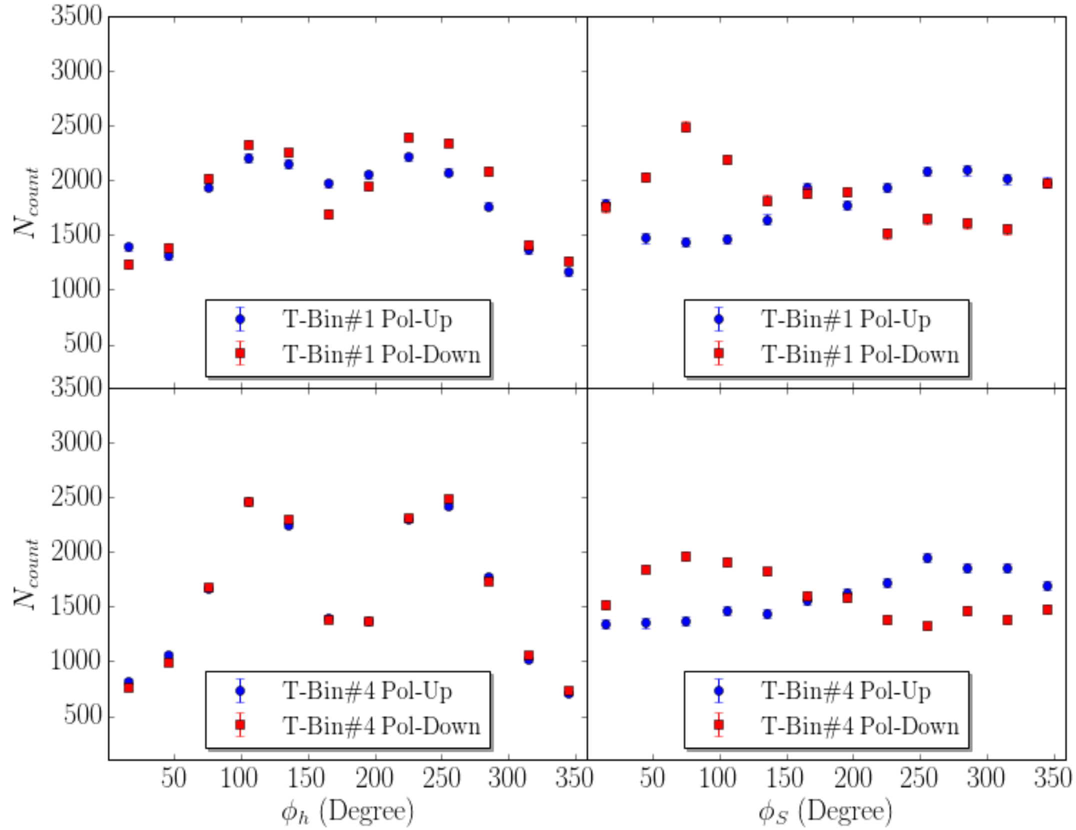
➢ Final State Interaction (FSI) Effects

- 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.

E12-10-006B

➢ 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.

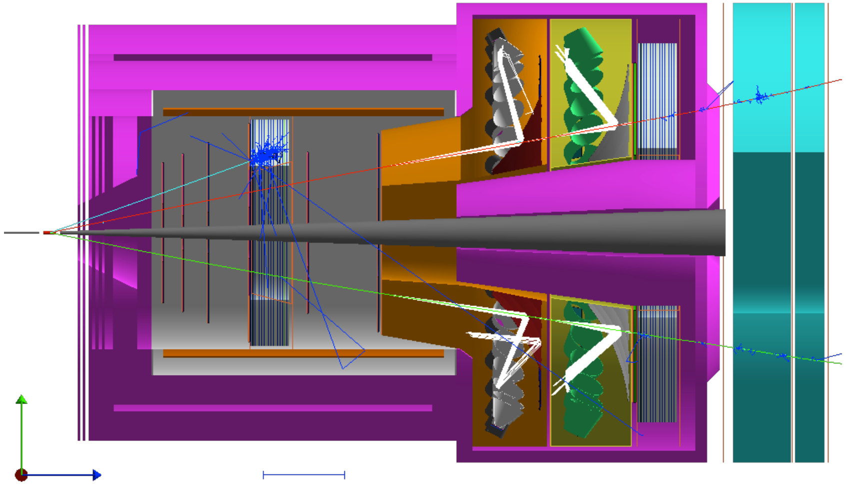


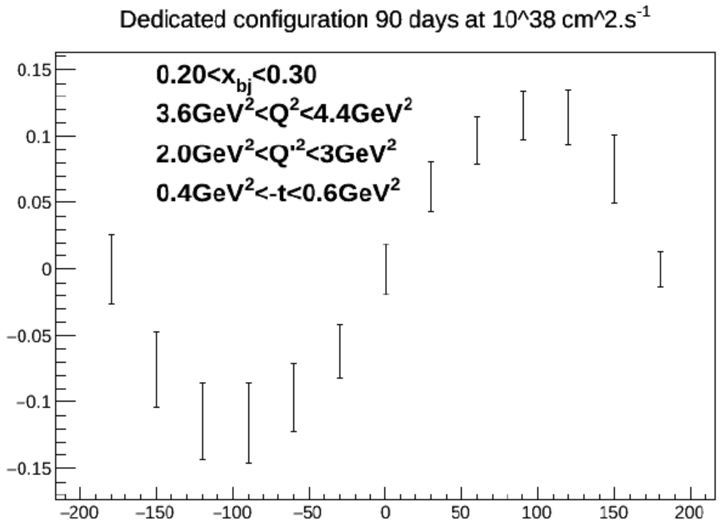
- **UML analysis shows that sufficient statistics are obtained over full (ϕ,ϕ_s) plane to extract asymmetry moments with small errors.**

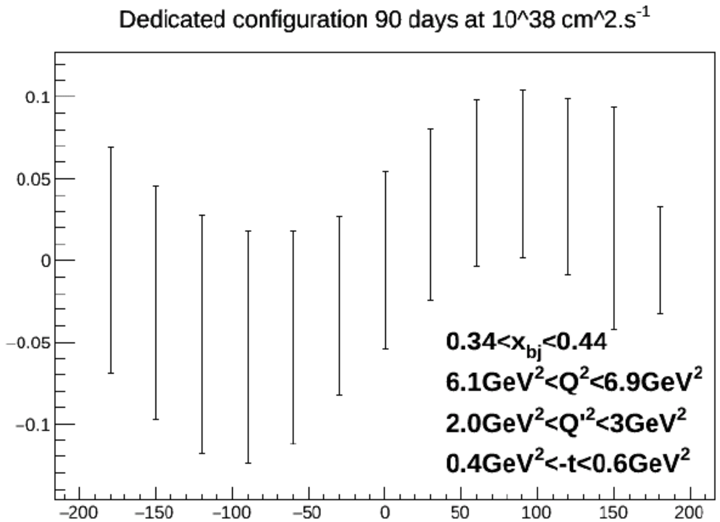
SoLID-DDVCS Programs

➢ Double-DVCS: (see Zhiwen's talk on week#3)

- A parasitic run with the J/psi configuration was studied (a LOI was submitted to PAC43)
- Counts of 60 days with J/psi setup at 10^{37} cm^{-2}s^{-1}
- Adding the ion chambers for muon detections.
- A upgraded luminosity of 10^{38} cm^{-2}s^{-1}or higher is more feasible to have enough statistics for multiple-dimension binning study.







- A similar effort to measure DDVCS with CLAS12 is also under developments with major upgrade to the Forward detectors (lead by Stephan Stephanyan and a LOI submitted to PAC45)

Future GPD Programs

➢ **A Recoil Detector for polarized targets:**

✓ Add a Central Recoil Detector for recoil protons and spectator protons (for neutron identification)

An ideal recoil detector is like:

1. Polarize the He3 gas outside the target region
2. Circulate the polarized gas through the recoil detector installed on the target pivet
3. Remove the target cell at the center and use silicon tracker as the container
4. The recoil detector detects both the recoil protons and the spectator protons

A Recoil Detector with a Polarized He3 Target