The SoLID GPD Program

Garth Huber University of Regina

On behalf of the SoLID Collaboration

SOLENOIDAL LARGE INTENSITY DEVICE

Supported by:
NSERC CRSNG
SAPIN-2021-00026

Towards Improved Hadron Femtography with Hard Exclusive Reactions
ECT* Workshop, Trento, Italy
August 5, 2024

SoLID @ 12 GeV JLab: the QCD Intensity Frontier

SoLID will ***maximize*** the science return of the 12-GeV CEBAF upgrade by **combining...**

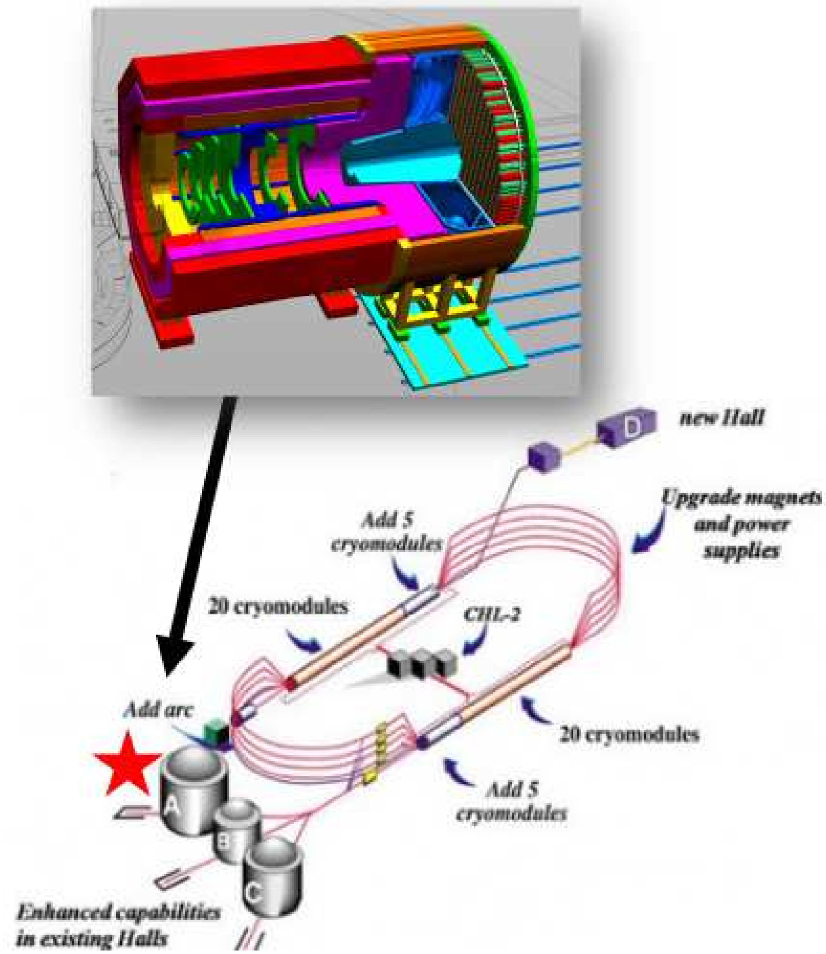
High Luminosity
$10^{37\text{-}39}$ /cm^2/s
[>100x CLAS12][>1000x EIC]

+

Large Acceptance
Full azimuthal ϕ coverage

Research at **SoLID** will have the ***unique*** capability to **explore** the QCD landscape while **complementing** the research of other key facilities

- **Precision lepto-quark couplings** at unique mass and sensitivity scales
- 3D momentum imaging of a relativistic strongly interacting confined system (nucleon spin)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (proton mass)



Synergizing with the pillars of EIC science (proton spin and mass) through high-luminosity valence quark tomography and precision J/ψ production near threshold

The SoLID GPD Program

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- **2015 SoLID Director's Review recommendation:**

  "The SoLID Collaboration should investigate the feasibility of carrying out a competitive GPD program. Such a program would seem particularly well suited to their open geometry and high luminosity"

- **A broad array of GPD experiments are now planned:**
  - **DVCS on polarized ^{3}He**
    - *Z. Ye (under study)*
  - **Timelike Compton Scattering (TCS)** with circularly polarized beam and unpolarized LH_2 target
    - *Z.W. Zhao, M. Boer, P. Nadel-Turonski, J. Zhang*
    - *Approved as run group with J/ψ (E12-12-006A)*
  - **Double Deeply Virtual Compton Scattering (DDVCS)** in di–lepton channel on unpolarized LH_2 target
    - *E. Voutier, M. Boer, A. Camsonne, K. Gnanvo, N. Sparveri, Z. Zhao*
    - *LOI12-23-012 reviewed by PAC51, full proposal encouraged*
  - **Deep Exclusive π^- Production using Transversely Polarized ^{3}He Target**
    - *G.M. Huber, Z. Ahmed, Z. Ye*
    - *Approved as run group with Transverse Pol. ^{3}He SIDIS (E12-10-006B)*

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Leading Twist GPD Parameterization

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- **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 a helicity filter.

$H^{q,g}(x,\xi,t)$ 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

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

Deeply Virtual Compton Scattering:
- Sensitive to all four GPDs.

Deep Exclusive Meson Production:
- Vector mesons sensitive to spin–average H, E.
- Pseudoscalar sensitive to spin–difference $\tilde{H}$, $\tilde{E}$.

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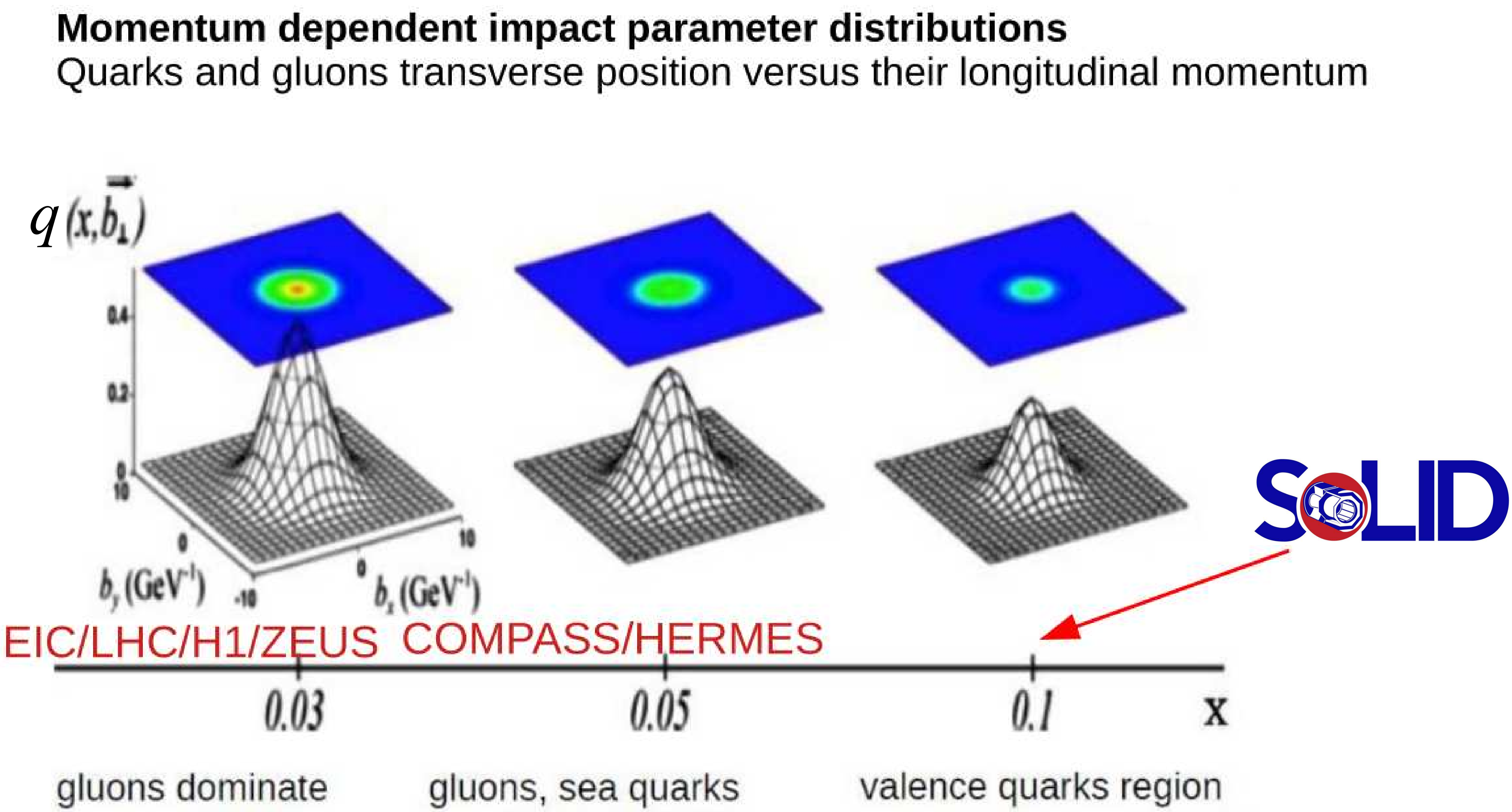
Accessible GPD Regions

- One of the interpretations of GPDS: tomographic imaging of the nucleon
- Other: spin, angular momenta correlation, “pressure”, etc



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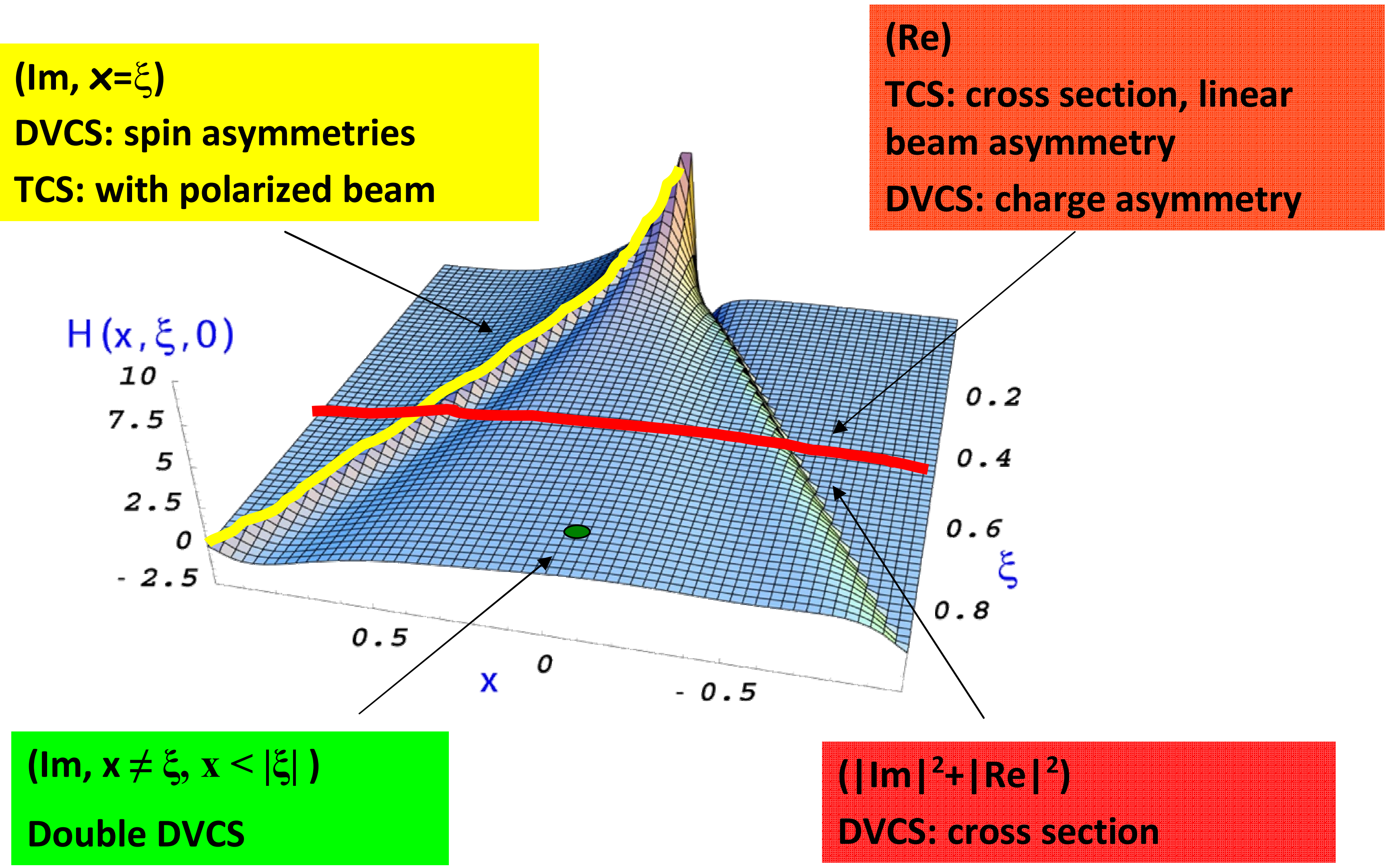
Marie Boer, Va Tech

Compton Processes Accessing GPDs



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SoLID DVCS Study

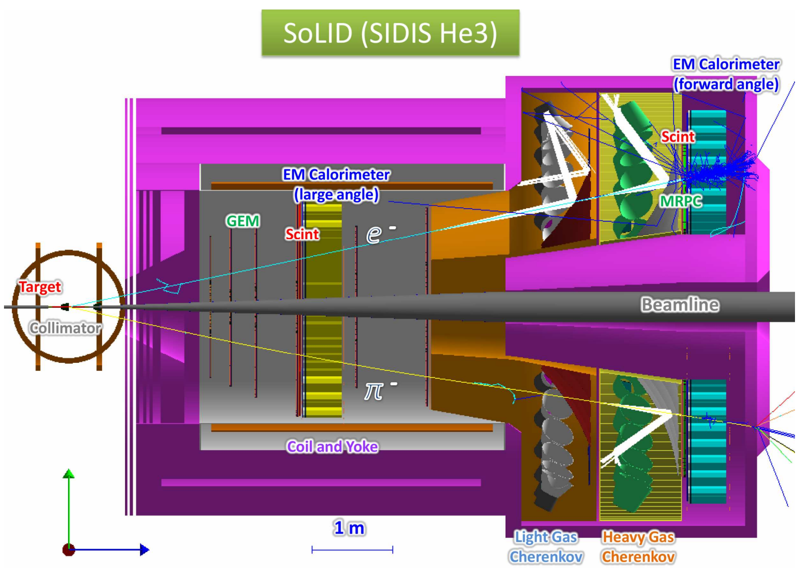
➢ DVCS with polarized electron beam and targets:

- GPD study needs both proton neutron data (flavor decomposition), and all types of observables (GPD disentangling)
- Approved 12GeV polarized DVCS experiments:

✓ E12-06-119 (Hall-B): longi. pol proton (DNP), BSA, TSA
✓ C12-12-010 (Hall-B): trans. pol. proton (DNO), TSA,BSA

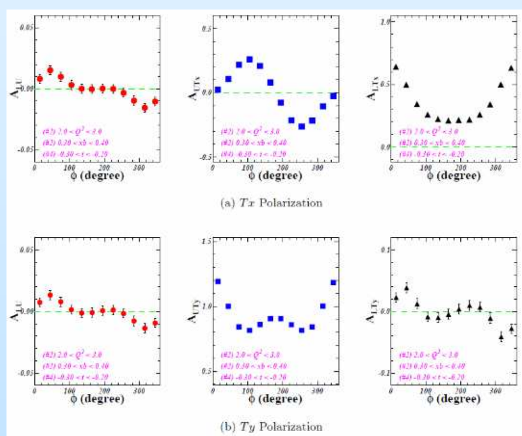
▪ NO polarized neutron-DVCS experiment has been done or proposed at JLab, and SoLID is currently the only place that can do such measurements.
(only done at HERMES with poor accuracy and limited coverage)

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



Transversely polarized neutron DVCS:

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



(a) Tx Polarization

(b) Ty Polarization

✓ Measurements of BSA, TSA and DSA
✓ Wide kinematic coverage
✓ 4-dimensional binning on Q2, -t, xB and phi (>500 bins)
✓ **To do#1:** Extract CFF distributions with using PARTON fitting toolkit (arXiv:1512.06174)

- **SoLID can bring a whole set of polarized DVCS data:**

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

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SoLID DVCS Study

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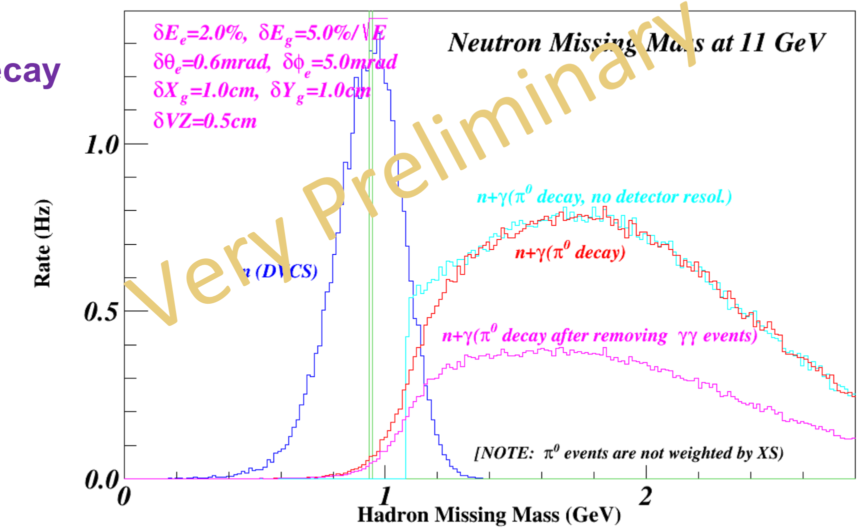
➢ Exclusivity and Backgrounds:

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

- ✓ Missing Mass Reconstruction after detecting electrons and photons (angles, momentum/energy).
- ✓ The spectrum resolution is limited by the EC resolution (~5%)
- ✓ Background Subtraction: ECs can detect partial π^0 decay events by reconstruction two-photons events



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

$N_{\pi^0}^{Total}$ ($N_{\pi^0}^{Detect}$) → Detected **π⁰** events which are mixed into the MM spectrum

$N_{\pi^0}^{MC-Total}$ ($N_{\pi^0}^{MC-Accept}$) → All **π⁰** events in the entire from simulation

To Do #2:

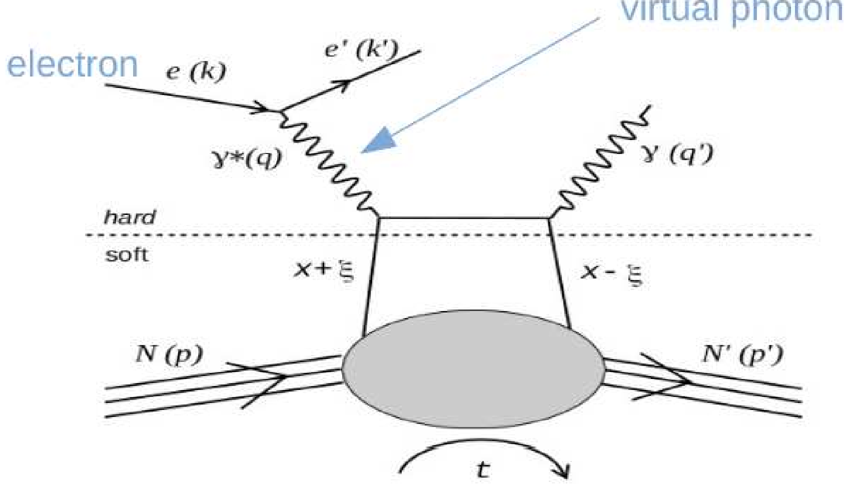
- ➢ Evaluate other background
- ➢ Evaluate systematic uncertainties
- ➢ Study nuclear effects, energy loss (combined with nDEMP works)

To Do #3:

- ➢ Evaluate π^0 background. Current found two generators:
  - (1) from Prof. Simonetta Liuti
  - (2) HEPGEN++ provided by Valery Kubarovsky
- ➢ Learn from the new Hall-A 12GeV-DVCS data.

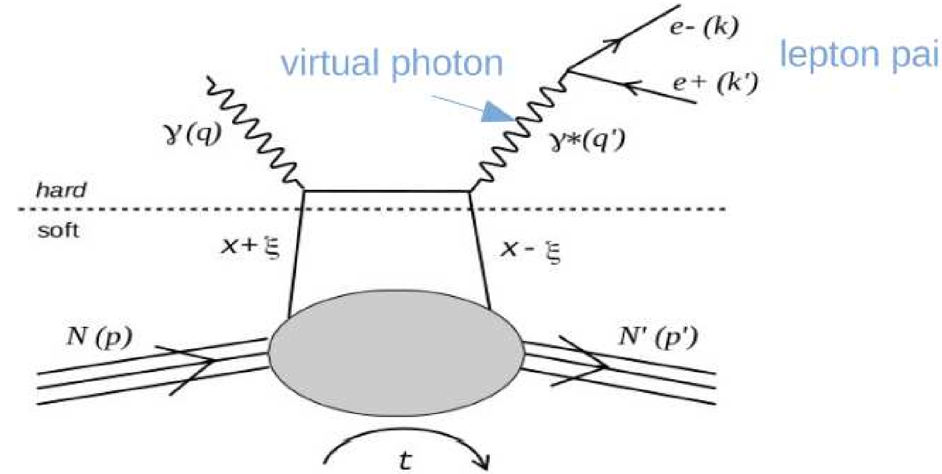
Complementarity of DVCS and TCS

Initial lepton beam / spacelike photon



Deeply Virtual Compton Scattering (DVCS)

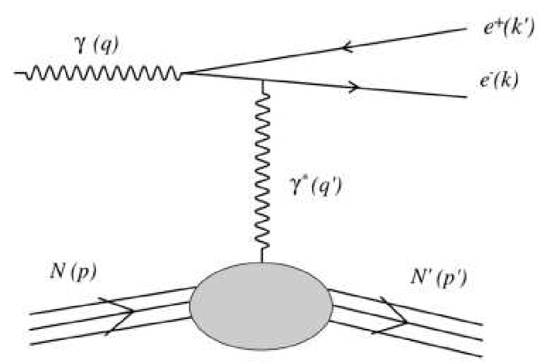
Final lepton pair / timelike photon



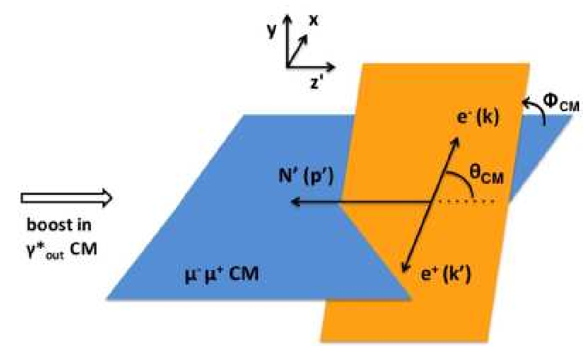
Timelike Compton Scattering (TCS)

Interference with "BH"
Harmonics in φ ($φ_S$)

Measuring cross section, beam/target spin asymmetries...



BH interferes with TCS



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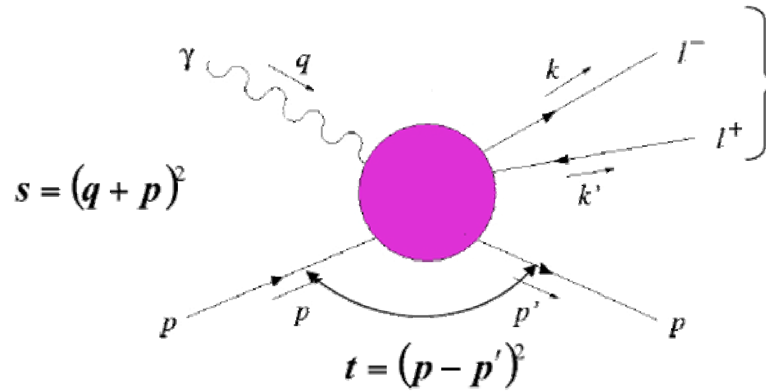
SoLID TCS (E12–12–006A)

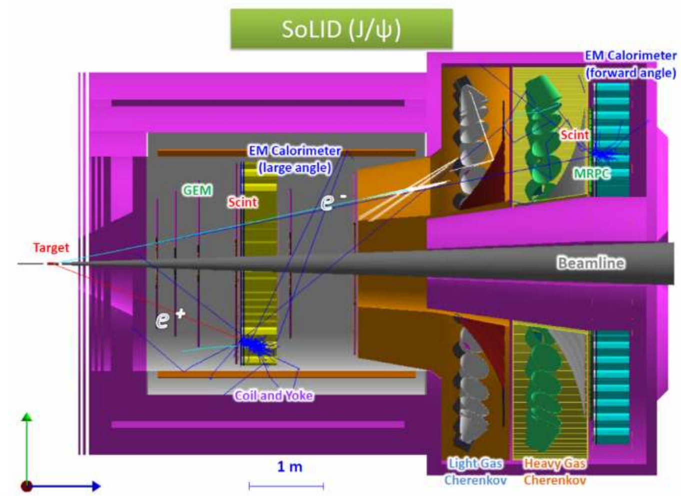
- Unpolarized data access to real part of CFFs, sensitive to D-term in GPD parametrization with observables cross section ratio (R) and forward backward asymmetry (A_{FB})
- Circularly polarized data access to imaginary part of CFFs with BSA (similar to DVCS) to study GPD universality

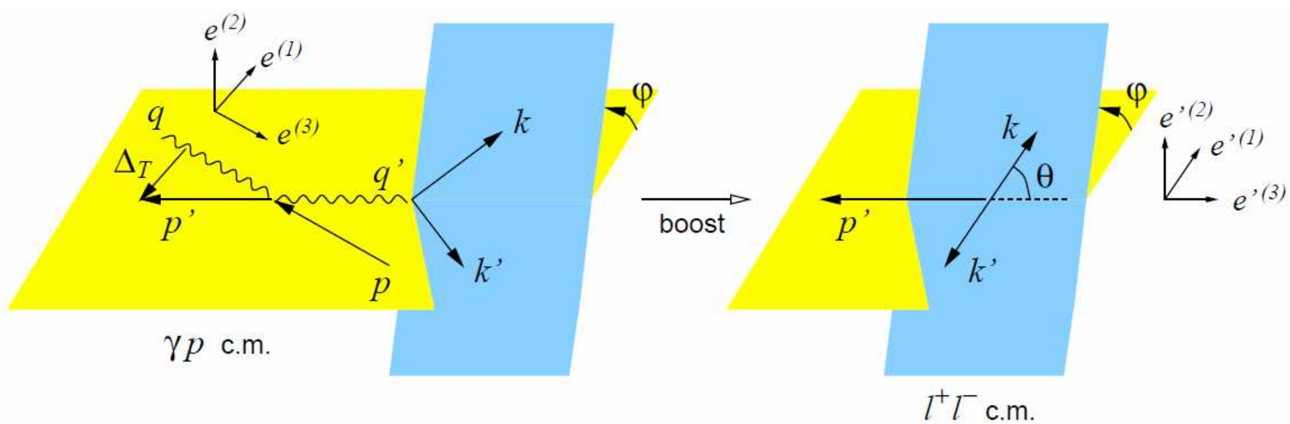


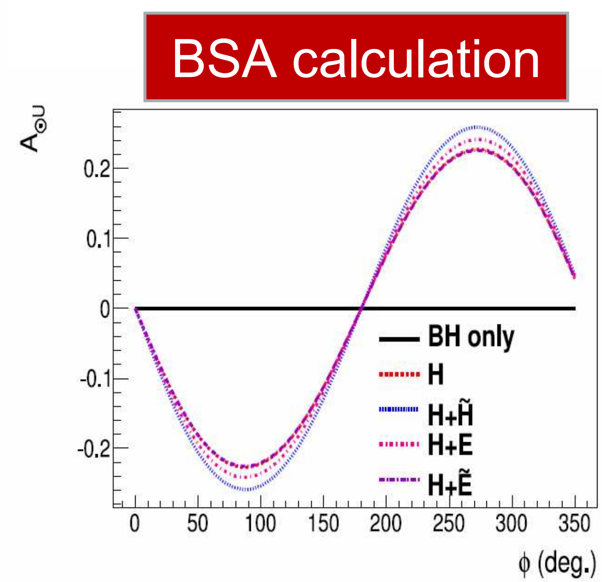
Hard scale

$$Q'^2 = M^2_{l^+l^-} = (k + k')^2$$

$$\eta = \frac{Q'^2}{2s - Q'^2}$$







$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ - \theta, 180^\circ + \phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ - \theta, 180^\circ + \phi)}$$

Zhiwen Zhao, Duke

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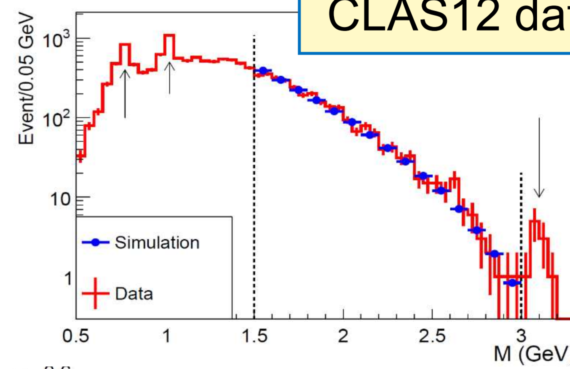
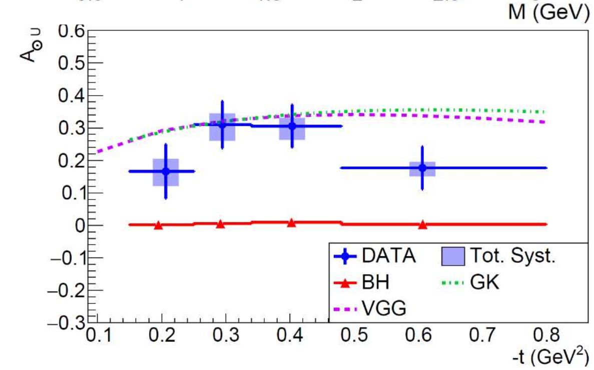
SoLID TCS Impact

15cm LH2 target, 3μA current, 1.2x10^{37}/cm^2/s luminosity for 50+10 days

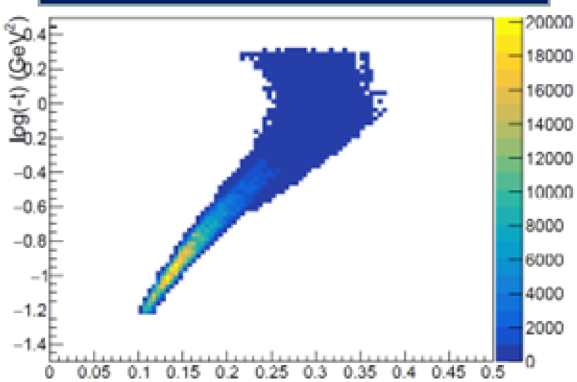
- SoLID TCS will have at least 1 order of magnitude larger statistics than CLAS12 and usher TCS study into precision era with multi–dimensional binning
  - 250x more integrated luminosity, but ¼ CLAS12 acceptance
  - Full azimuthal coverage ideal for forward–backward asymmetry
- SoLID TCS could lead to study of NLO correction

CLAS12 data

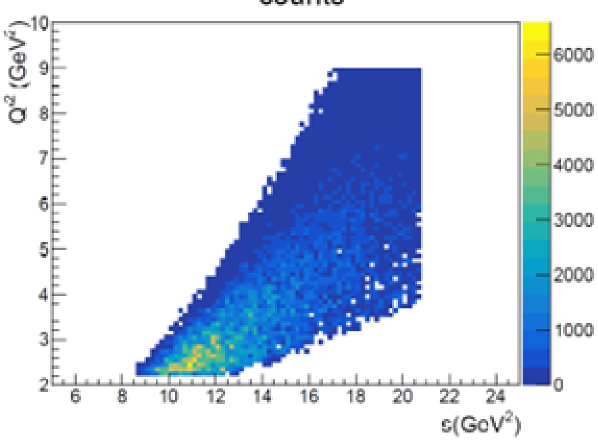




Kinematic coverage

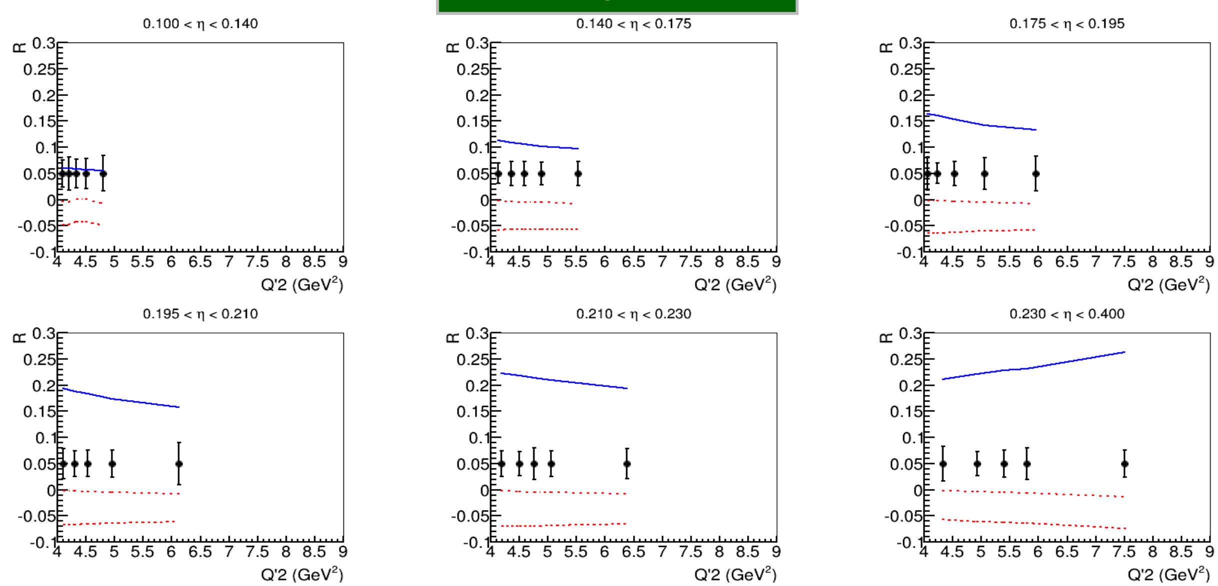


counts



$$R = \frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ^2\, dt\, d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ^2\, dt\, d\varphi}}$$

R projection



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Double DVCS with SoLID

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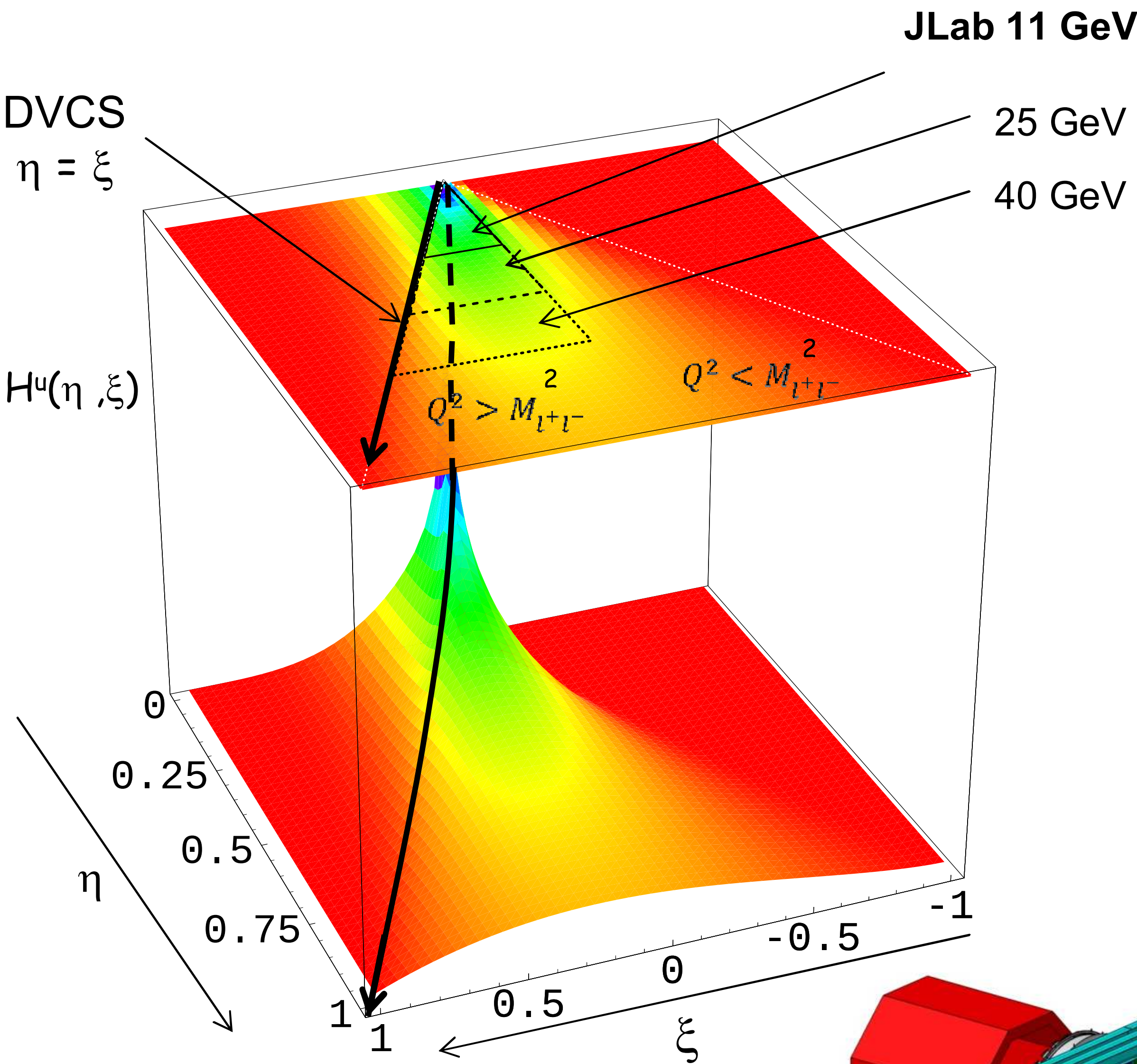
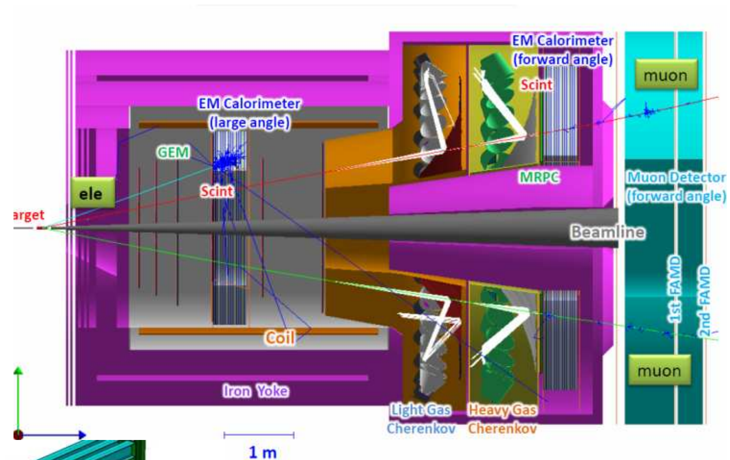
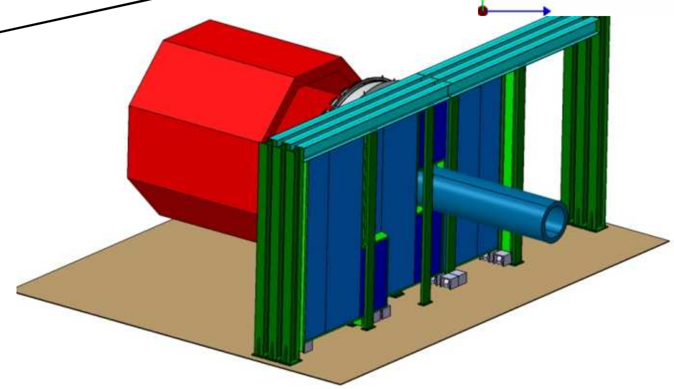


- DVCS only probes h=x line
- Example with model of GPD H for up quark
- JLab : $Q^2>0$
- Kinematical range increases with beam energy (larger dilepton mass)

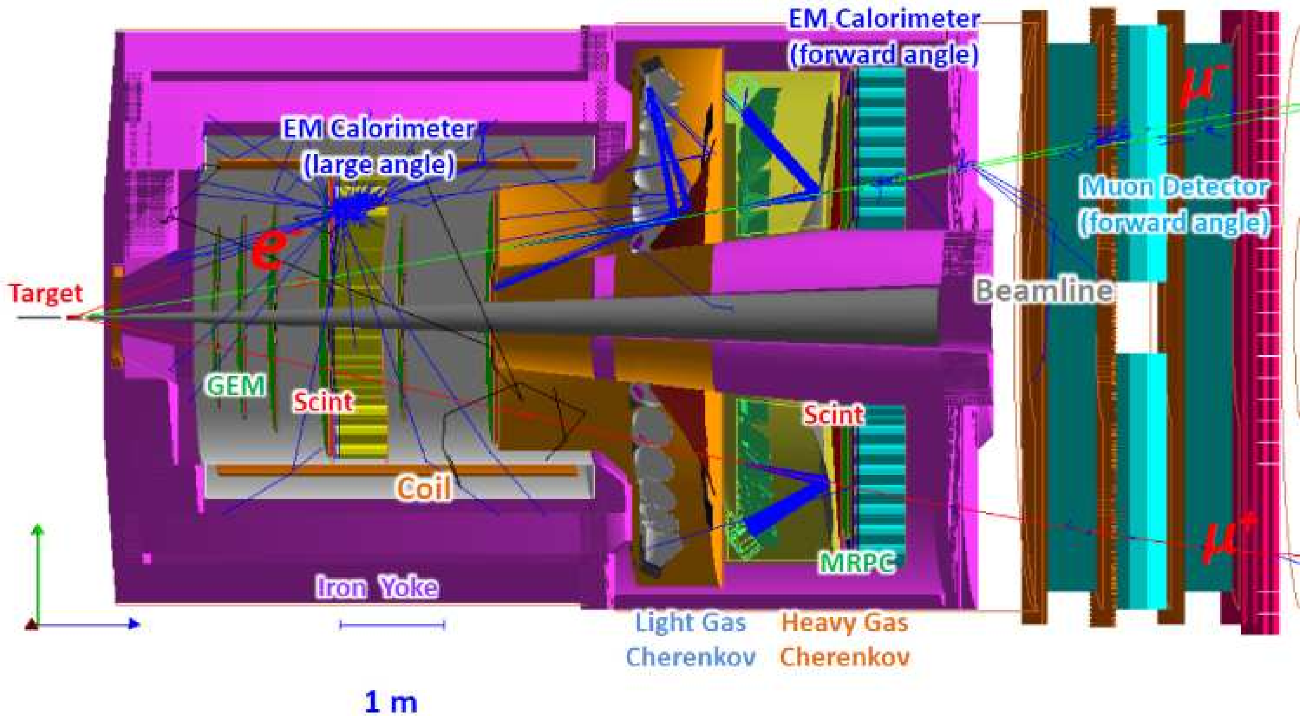




Alexandre Camsonne, JLab

SoLID Double DVCS Setup

SoLID DDVCS



- Solenoidal configuration ideal for high luminosity
- Based on J/ψ and TCS setup with forward muon detector added
- 2023 LOI

Marie Boer, Alexandre Camsonne, Eric Voutier, Zhiwen Zhao

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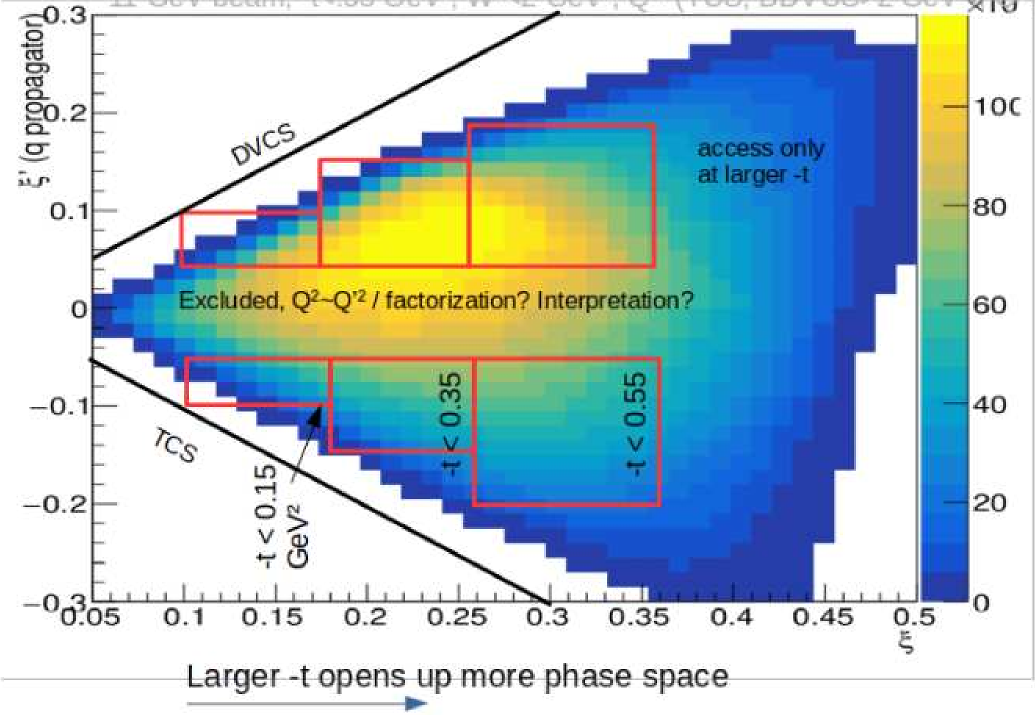
DDVCS with Circularly Polarized Beam

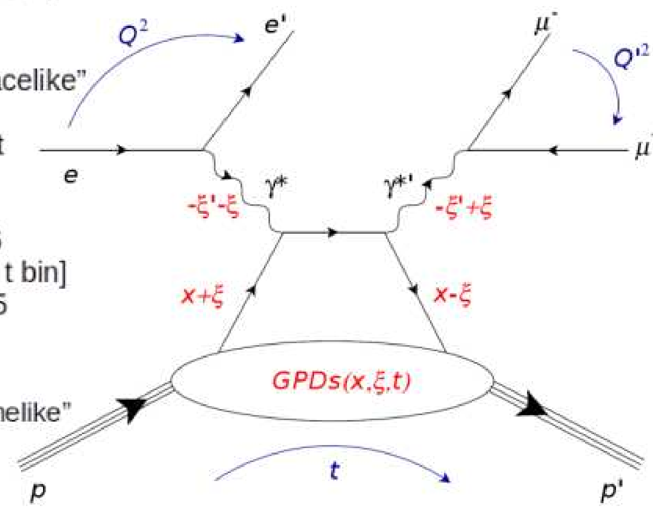


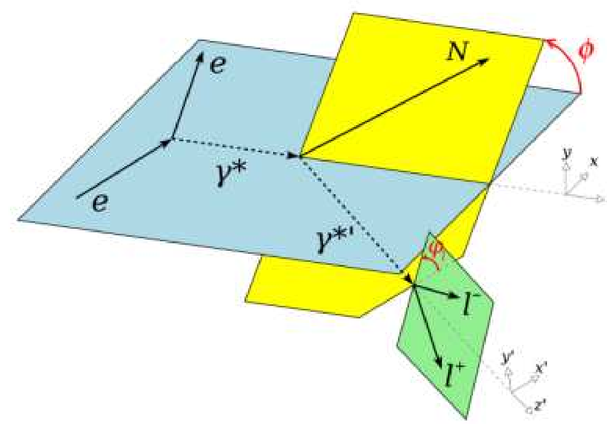
Q'² < Q² : spacelike"

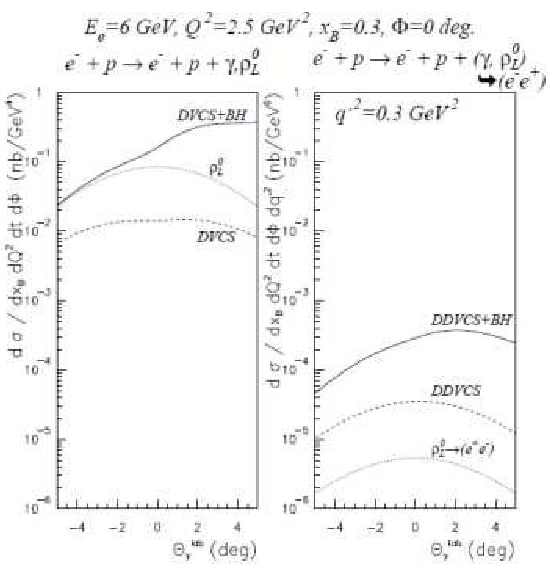
Bins in ξ, ξ', -t

-.2 < ξ' < .2
.05 < ξ < .36
[correlated to t bin]
0.05 < -t < .55

Q² < Q'² : "timelike"







- Small DDVCS crosssection demands high luminosity and large acceptance
- Interference with Beth-Heitler helps construct observable

$$\xi' = \frac{Q^2 - Q'^2 + t/2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

$$\xi = \frac{Q^2 + Q'^2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

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SoLID DDVCS Projections

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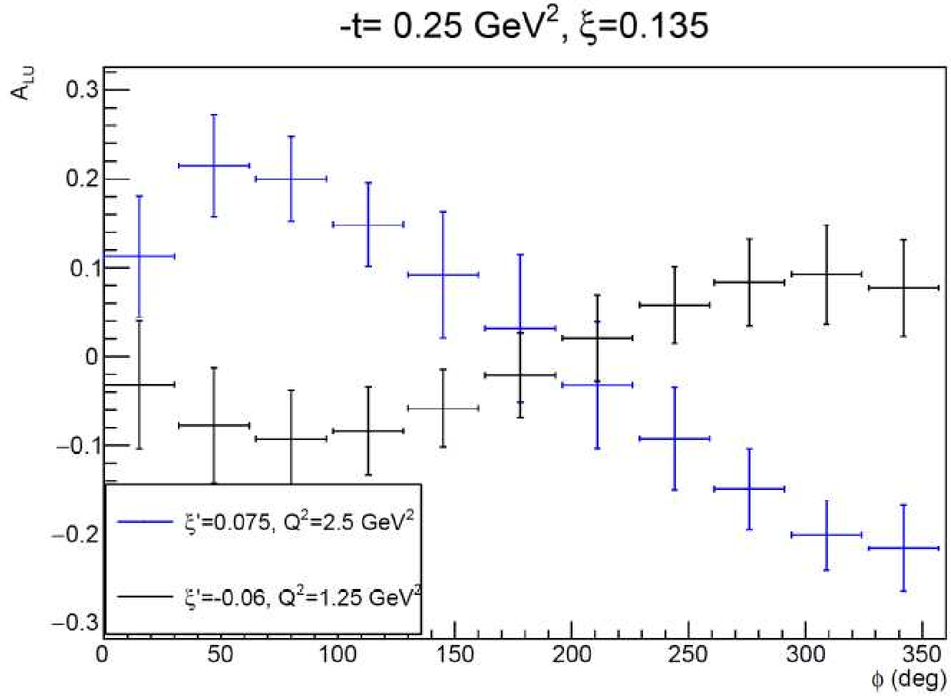
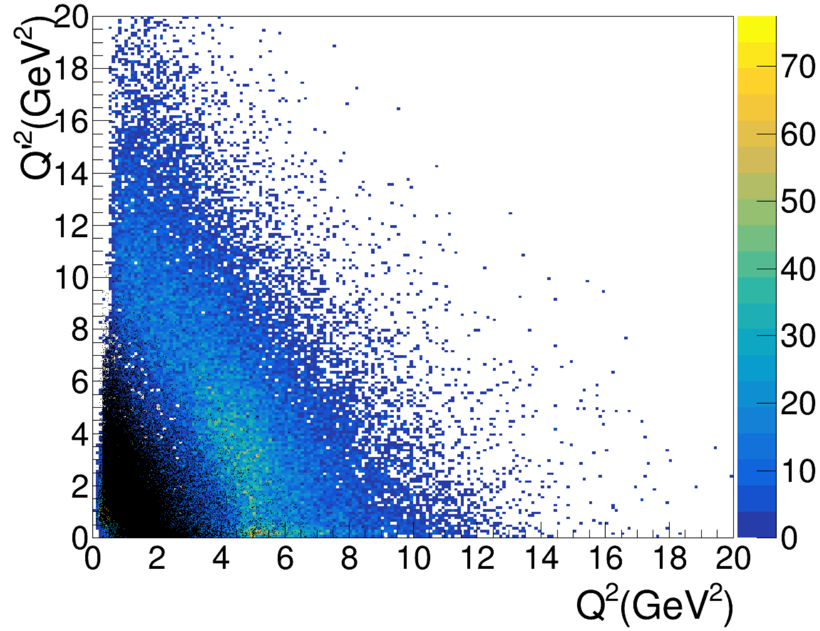
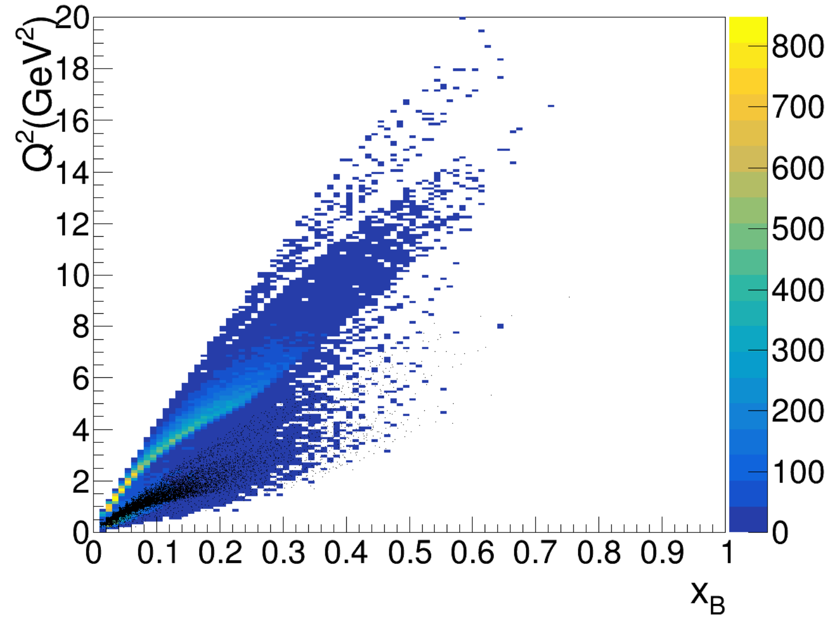
11 GeV Beam Asymmetry Projection



$$A_{LU}^{\pm}(\phi) = \frac{1}{\lambda^{\pm}} \frac{d^5\sigma_{+}^{\pm} - d^5\sigma_{-}^{\pm}}{d^5\sigma_{+}^{\pm} + d^5\sigma_{-}^{\pm}}$$

$$= \frac{d^5\widetilde{\sigma}_{DDVCS} \mp d^5\widetilde{\sigma}^{\mathrm{INT1}}}{d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} \mp d^5\sigma_{INT_1}}$$





22 GeV (colored) has ~10% event rate of 11 GeV (black) but much larger kinematic coverage

Marie Boer, Alexandre Camsonne, Eric Voutier, Zhiwen Zhao

Exclusive π^- from Transversely Polarized Neutron

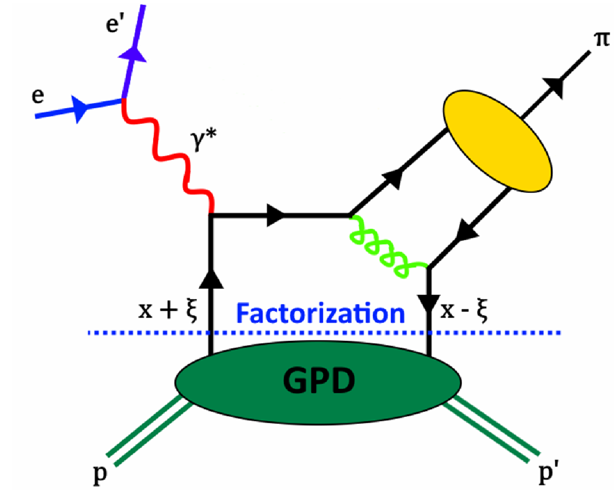
University of Regina

Polarized GPD $\tilde{E}$ via Deep Exclusive π Production

- *GPD $\tilde{E}$ involves a helicity flip*

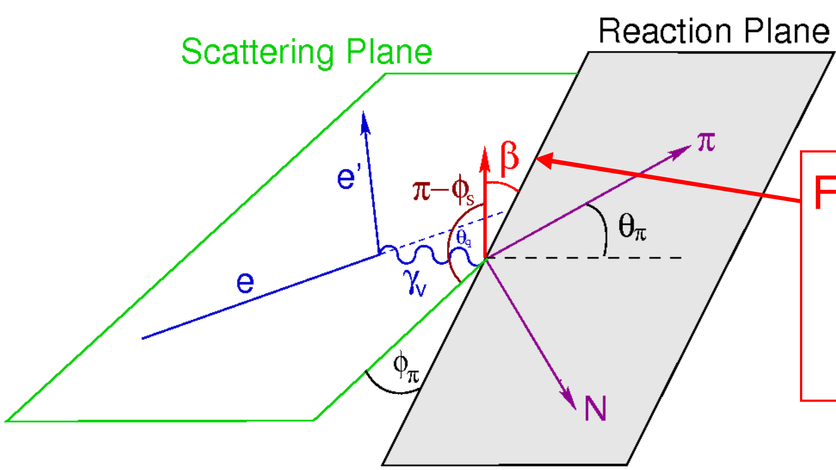
$$\sum_q e_q \int_{-1}^{+1} dx\, \tilde{E}^q(x,\xi,t) = G_P(t)$$

- *$G_P(t)$ is highly uncertain because it is negligible at momentum transfer of β–decay*
- *GPD $\tilde{E}$ not related to an already known parton distribution $\rightarrow$ Essentially unknown*
- *Experimental data can provide new nucleon structure information 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:

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



Fit sinβ=sin(φ−φ$_S$) dependence to extract asymmetry.

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

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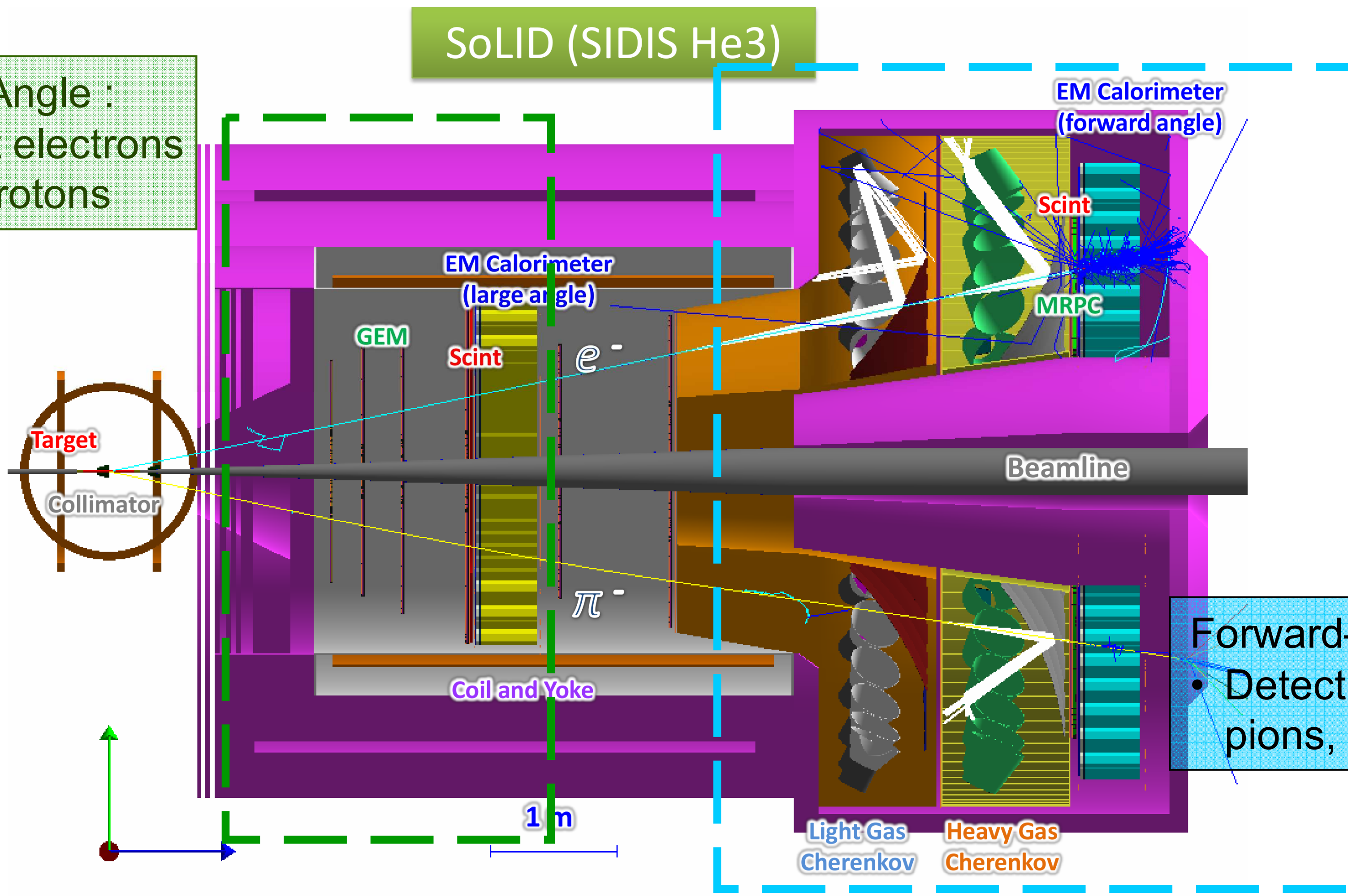
SoLID – Polarized ^{3}He SIDIS Configuration

Run in parallel with E12–10–006: E_0 = 11.0 GeV (48 days)
Online Coincidence Trigger: Electron Trigger + Hadron Trigger (pions)
Offline Analysis: Identify (tag) protons and form triple–coincidence
SoLID's Large Acceptance, Full Azimuthal Coverage,
High Luminosity Capability are Essential for this Measurement!

Large–Angle :
- Detect electrons and protons



Forward–Angle :
- Detect electrons, pions, protons

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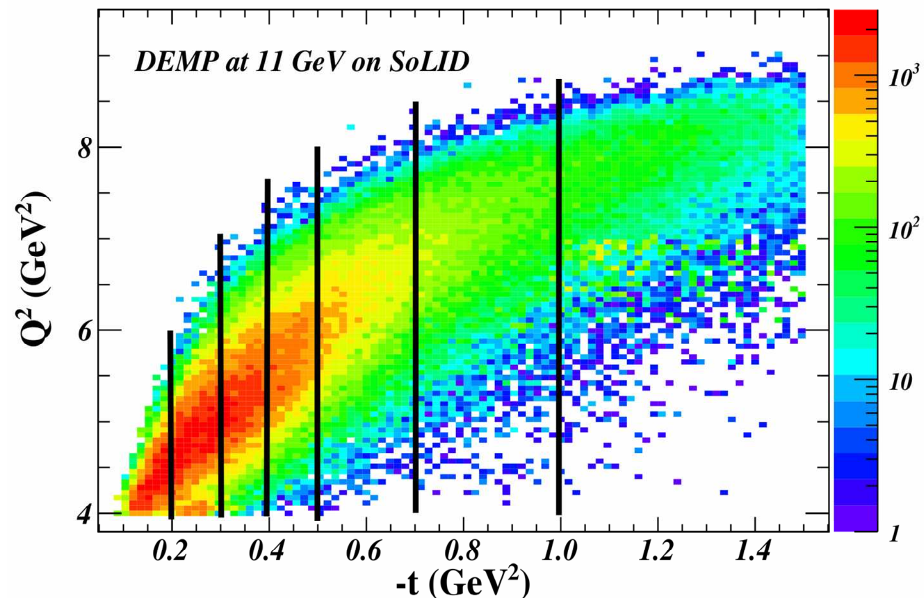
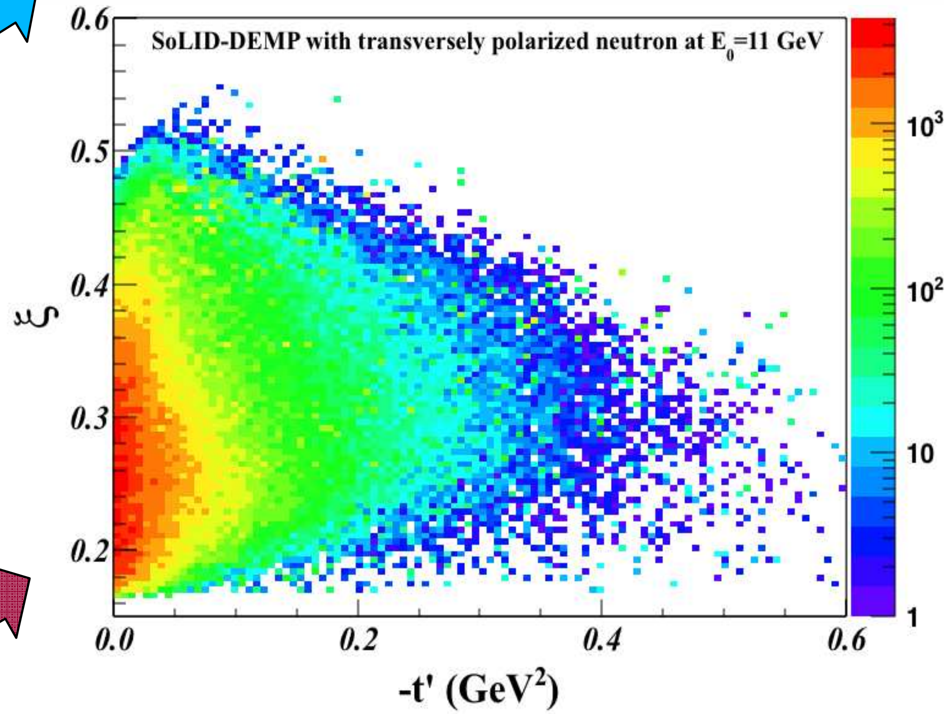
E12–10–006B Kinematic Coverage

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 based on data from HERMES, Halls B,C with VR Regge+DIS model used as constraint in unmeasured regions.
- Data divided in 7 t–bins concentrating on the Q^2>4 GeV^2 region of greatest physics interest.
- Pioneering HERMES data at: $\langle Q^2\rangle$=2.38 GeV^2, $\langle x_B\rangle$=0.13, $\langle -t\rangle$=0.46 GeV^2, small skewness ξ<0.1.
- **With SoLID, we can measure skewness dependence of the relevant GPDs over a fairly large range of ξ.**





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Example Cuts to Reduce Inclusive Background

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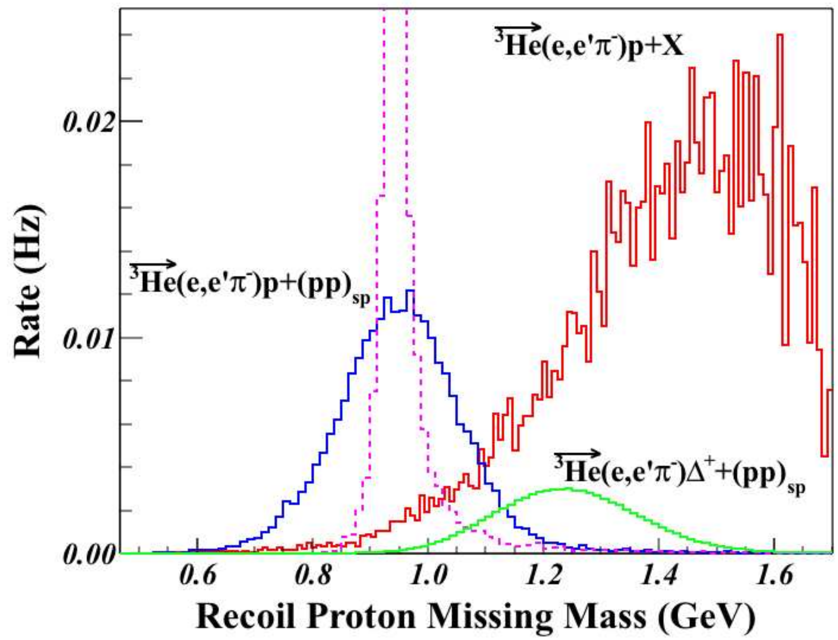
Two different background channels were simulated:

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

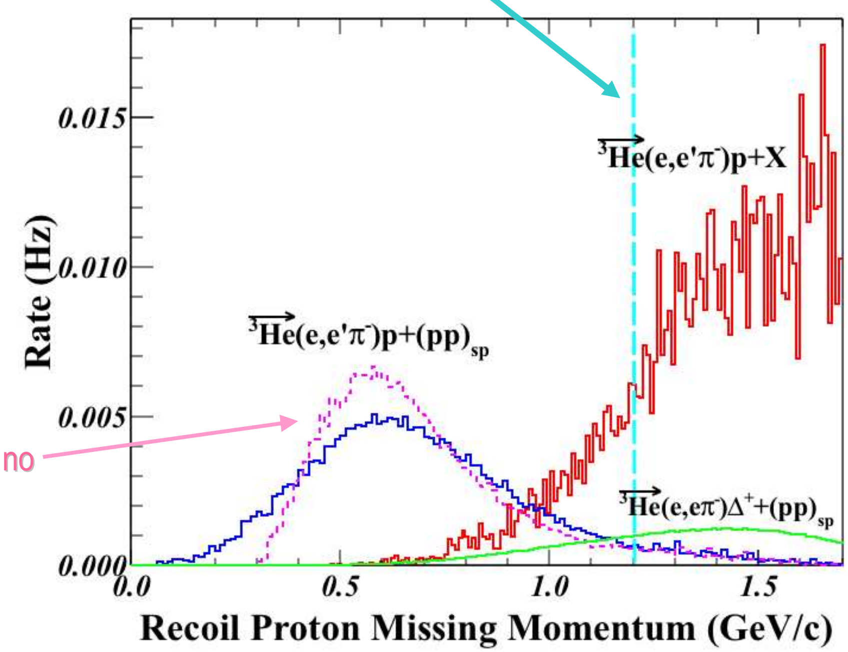


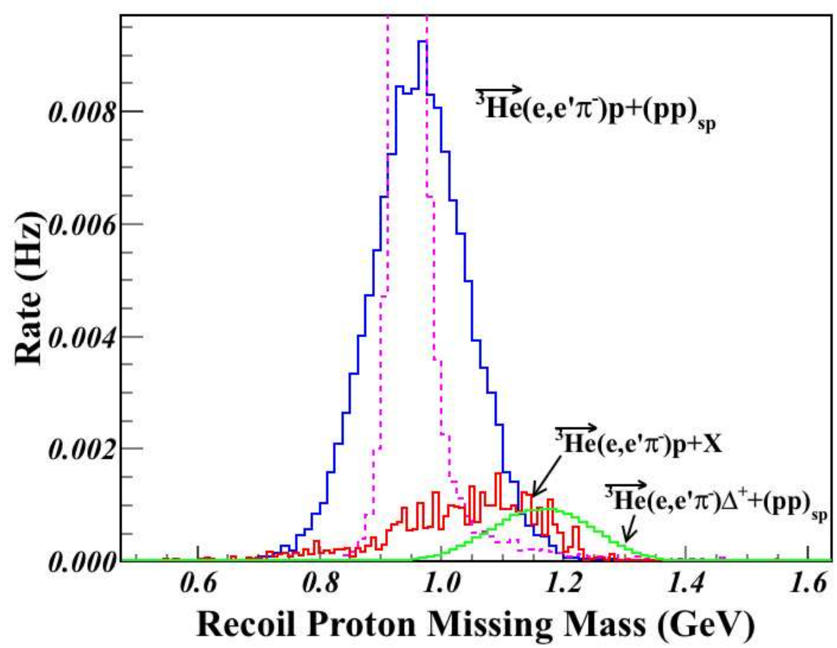
Apply P_{miss}>1.2 GeV/c cut

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

Background remaining after P_{miss} cut

Scattering & radiation but no resolution smearing





Unbinned Maximum Likelihood (UML)

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- **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.

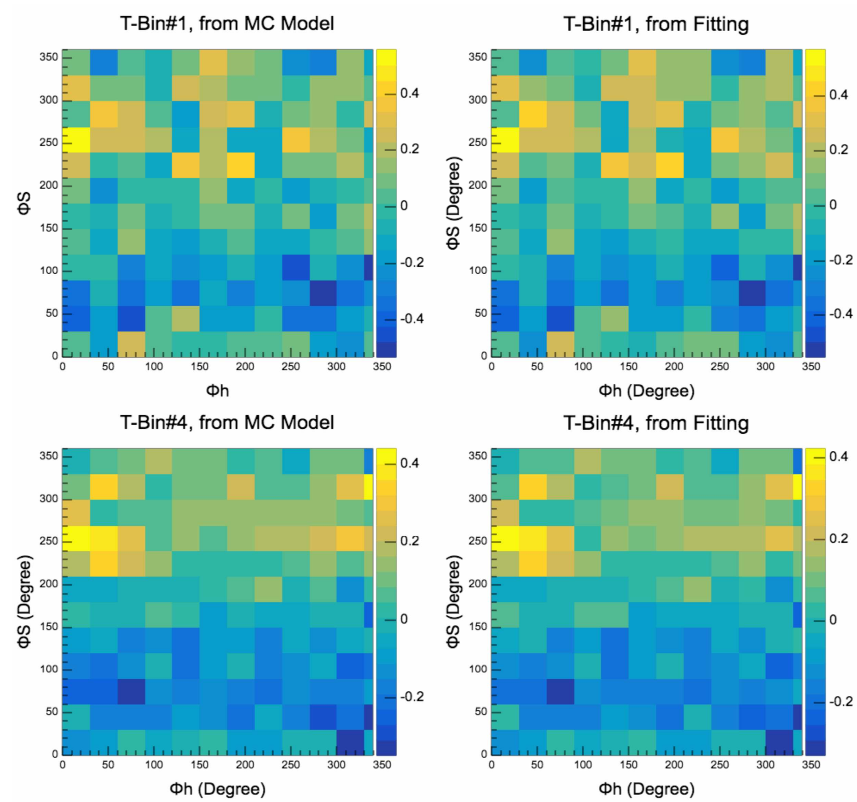
2. Minimize negative log-likelihood function:

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

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

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

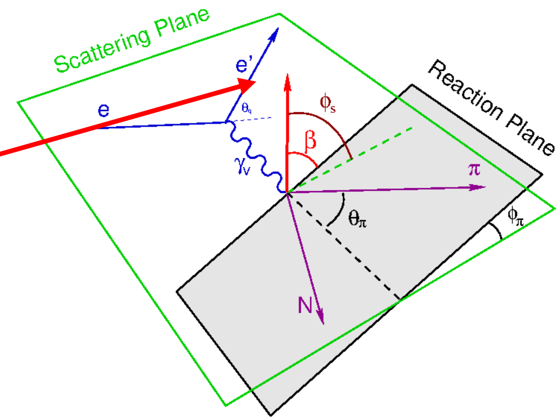
3. As an illustration, reconstruct azimuthal modulations & compare:



E12–10–006B Projected Data

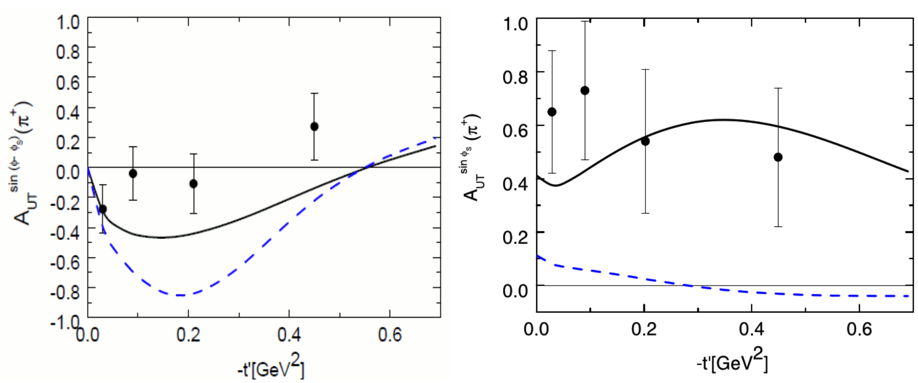
University of Regina

- **Azimuthal modulations of Transverse Single Spin Asymmetry allow access to different GPDs:**
  - $\sin(\beta=\varphi-\varphi_s)$ moment sensitive to helicity-flip GPD $\tilde{E}$
  - $\sin(\varphi_s)$ moment sensitive to transversity GPDs



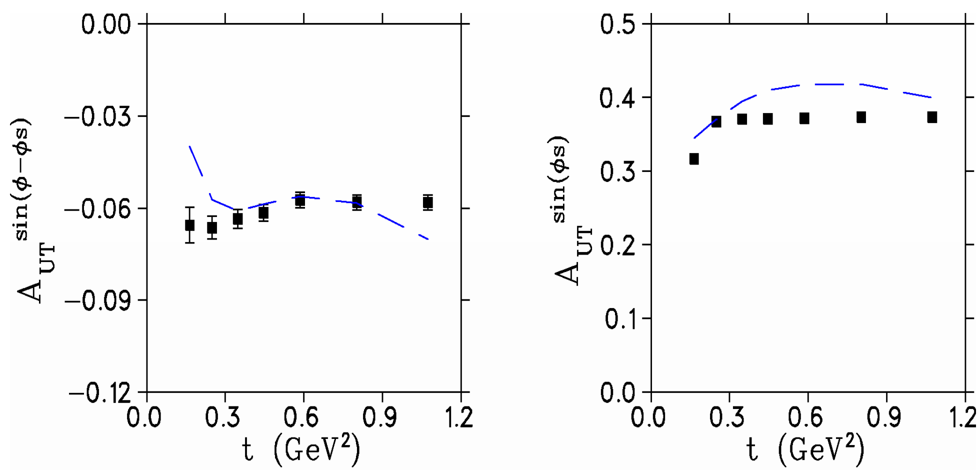
World Data: HERMES

Pioneering measurement [PLB **682**(2010)345]



SoLID Projected Uncertainties

Proton is tagged to isolate exclusive π^- events



SoLID's large acceptance and high luminosity essential to this measurement

- **Dramatically better statistics, at higher Q^2 and x_B, with broader –*t* coverage than pioneering HERMES measurement**
- **World unique, cannot be done anywhere else!**

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Summary

- SoLID's Large Acceptance and High Luminosity capabilities are key to measuring GPDs using deep exclusive processes
- Multi–dimension binning with high statistics
- SoLID has a broad exclusive physics program for GPD measurements:
  - DVCS on polarized ^{3}He — under study
  - TCS — approved, *J/ψ* run group *(E12-12-006A)*
  - DDVCS — LOI12-23-012 reviewed by PAC51, full proposal planned for next PAC
  - DEMP — approved, SIDIS run group *(E12-10-006B)*
  - More ideas under study (e.g. deuterium and other nuclear targets)
- ***Collaborators welcome!***

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