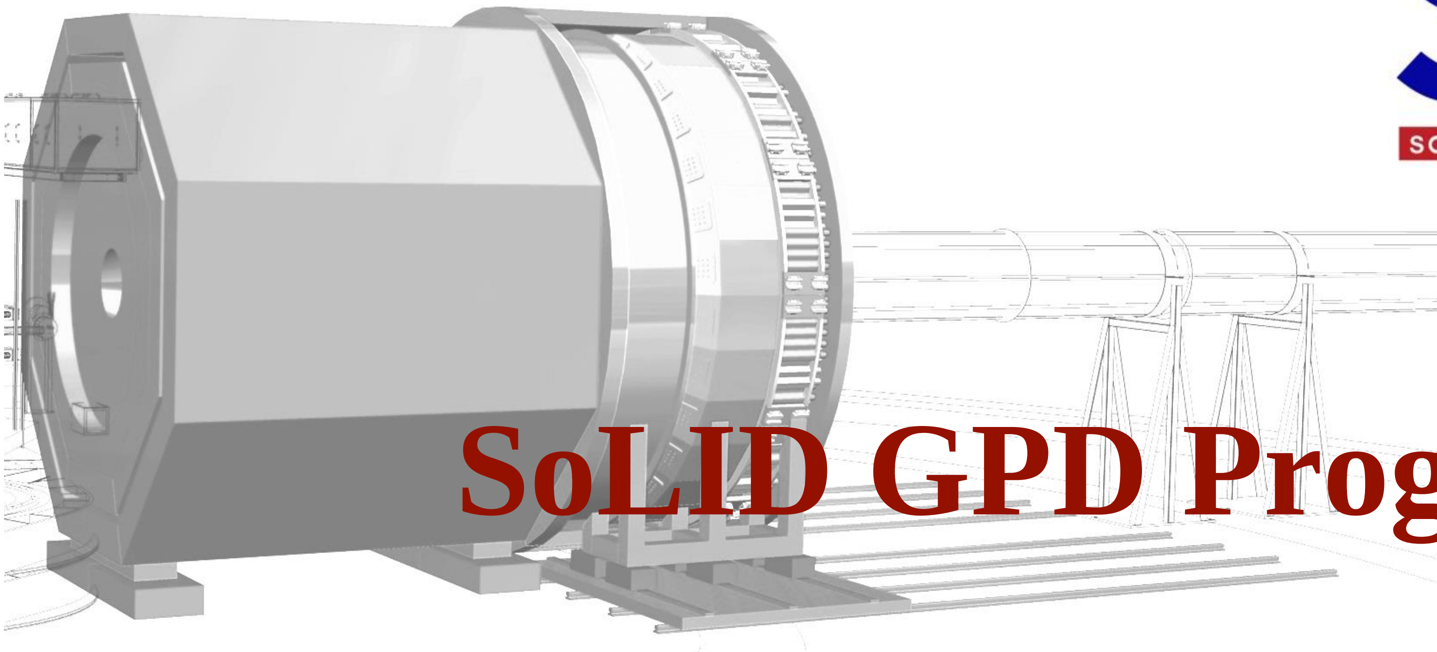


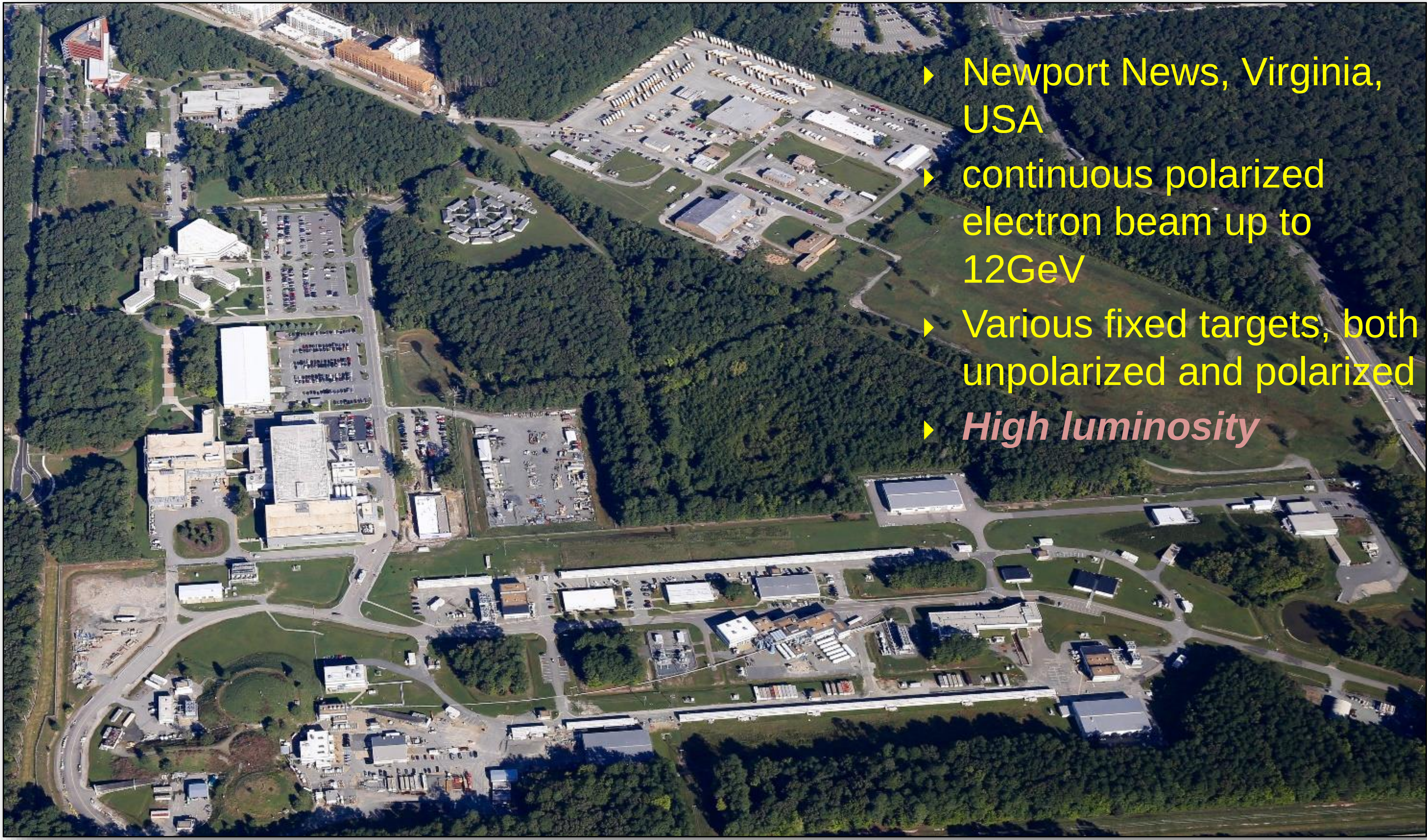
SoLID GPD Program

Zhiwen Zhao

SoLID Collaboration

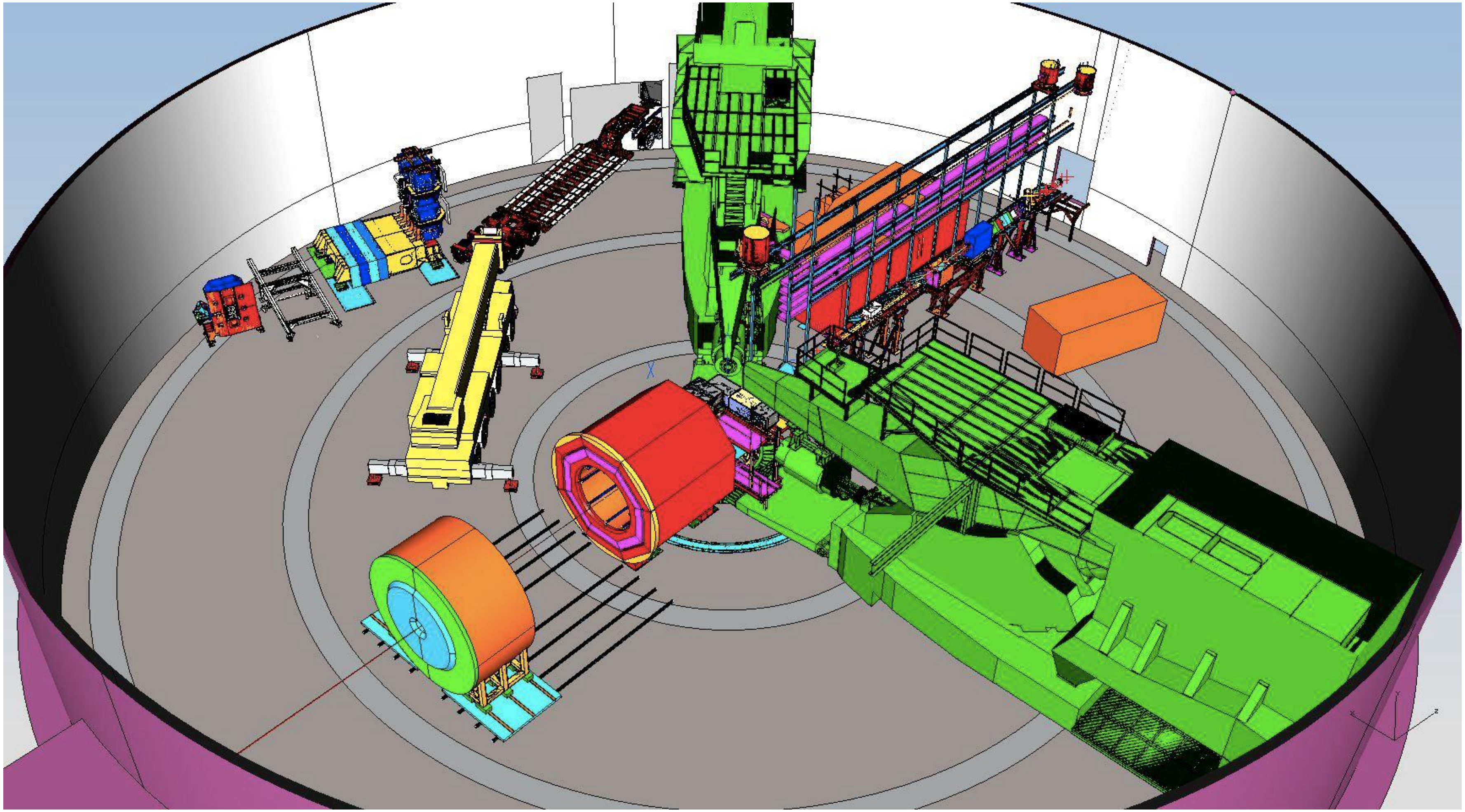
The 12th Workshop on Hadron Physics and Opportunities Worldwide
Dalian, China 2024/08/04-09

Jefferson Lab



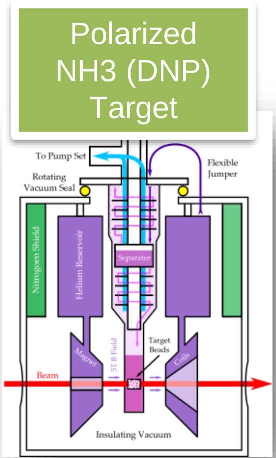
- Newport News, Virginia, USA
- continuous polarized electron beam up to 12GeV
- Various fixed targets, both unpolarized and polarized
- ***High luminosity***

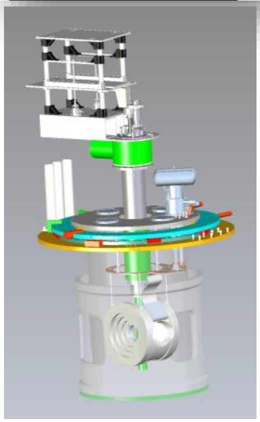
SoLID in Hall A

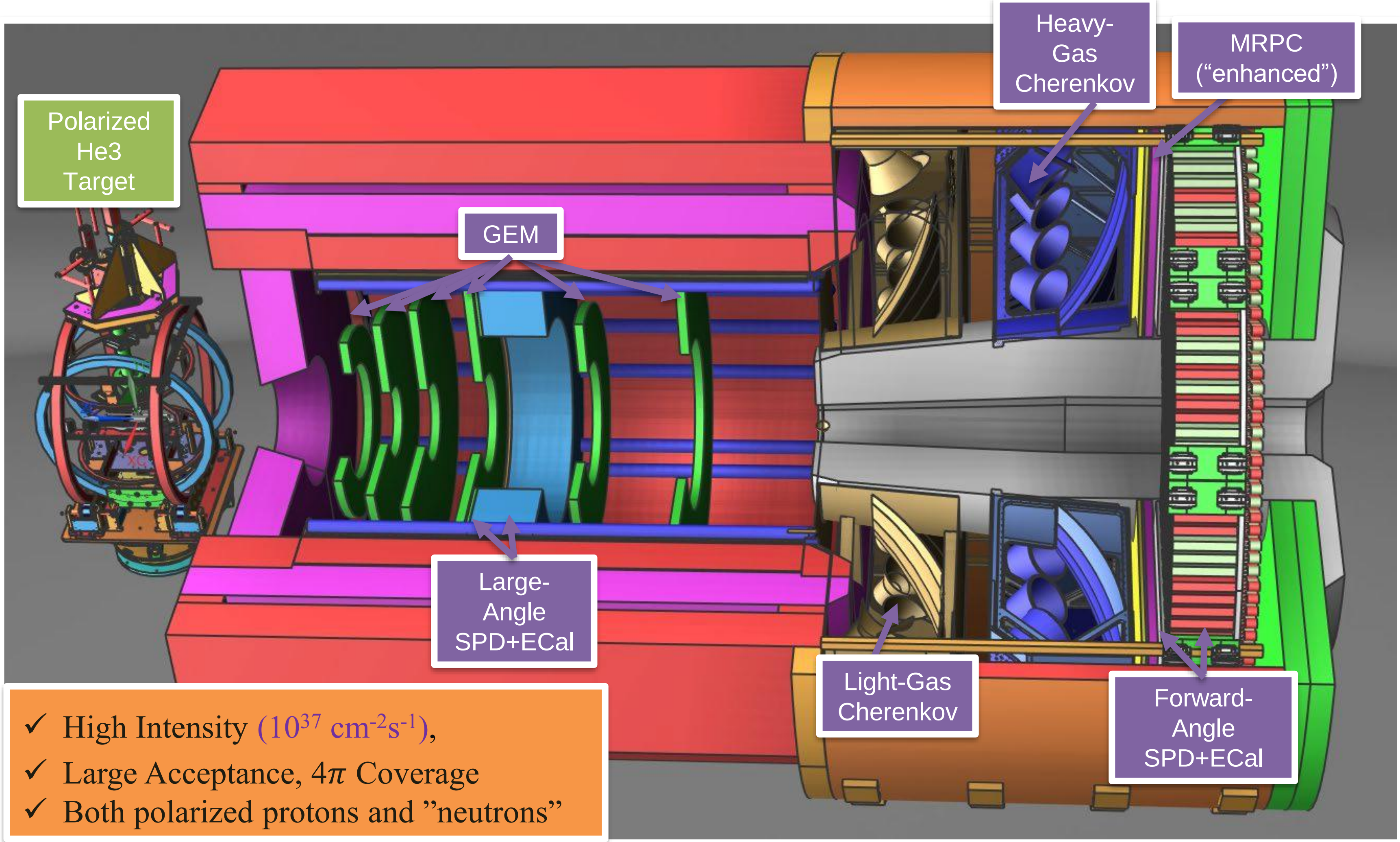


Plan for installing SoLID in Hall A with other equipment moved out of the way.

SoLID Open Geometry Configuration







- ✓ High Intensity (10^{37} $cm^{-2}s^{-1}$),
- ✓ Large Acceptance, 4π Coverage
- ✓ Both polarized protons and ”neutrons”

https://solid.jlab.org/experiments.html

SoLID (Solenoidal Large Intensity Device)

Full exploitation of JLab 12 GeV upgrade with broad physics program

Lumi ~1e^{39}/cm^2/s (baffled geometry)

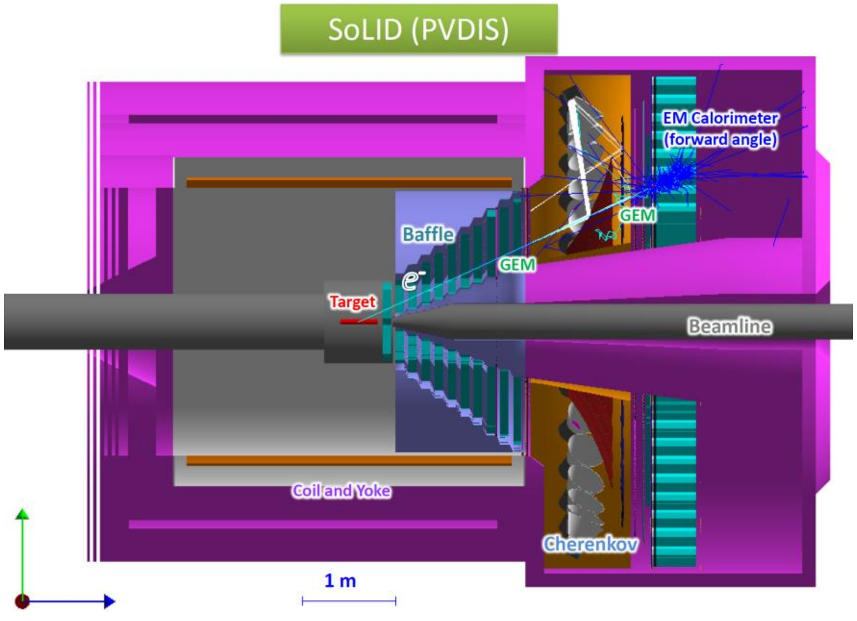
- Standard Model test and hadron structure
  - PVDIS on both deuterium and hydrogen

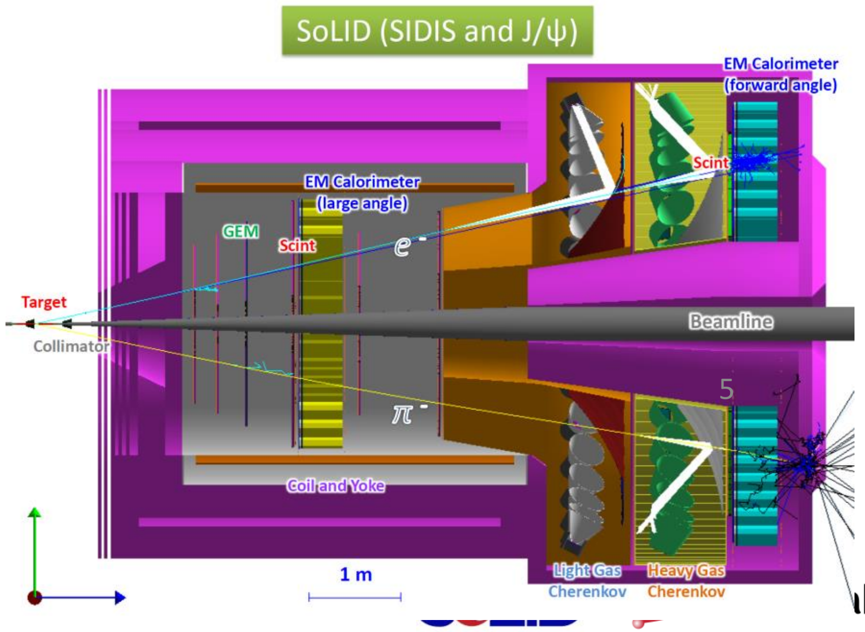
solid.jlab.org

Lumi ~1e^{37}/cm^2/s (open geometry)

- 3D hadron imaging
  - TMD (SIDIS on both neutron and proton)
  - GPD (DEMP,DVCS,TCS,DDVCS)
- proton mass and gluonic interaction
  - J/ψ production at threshold

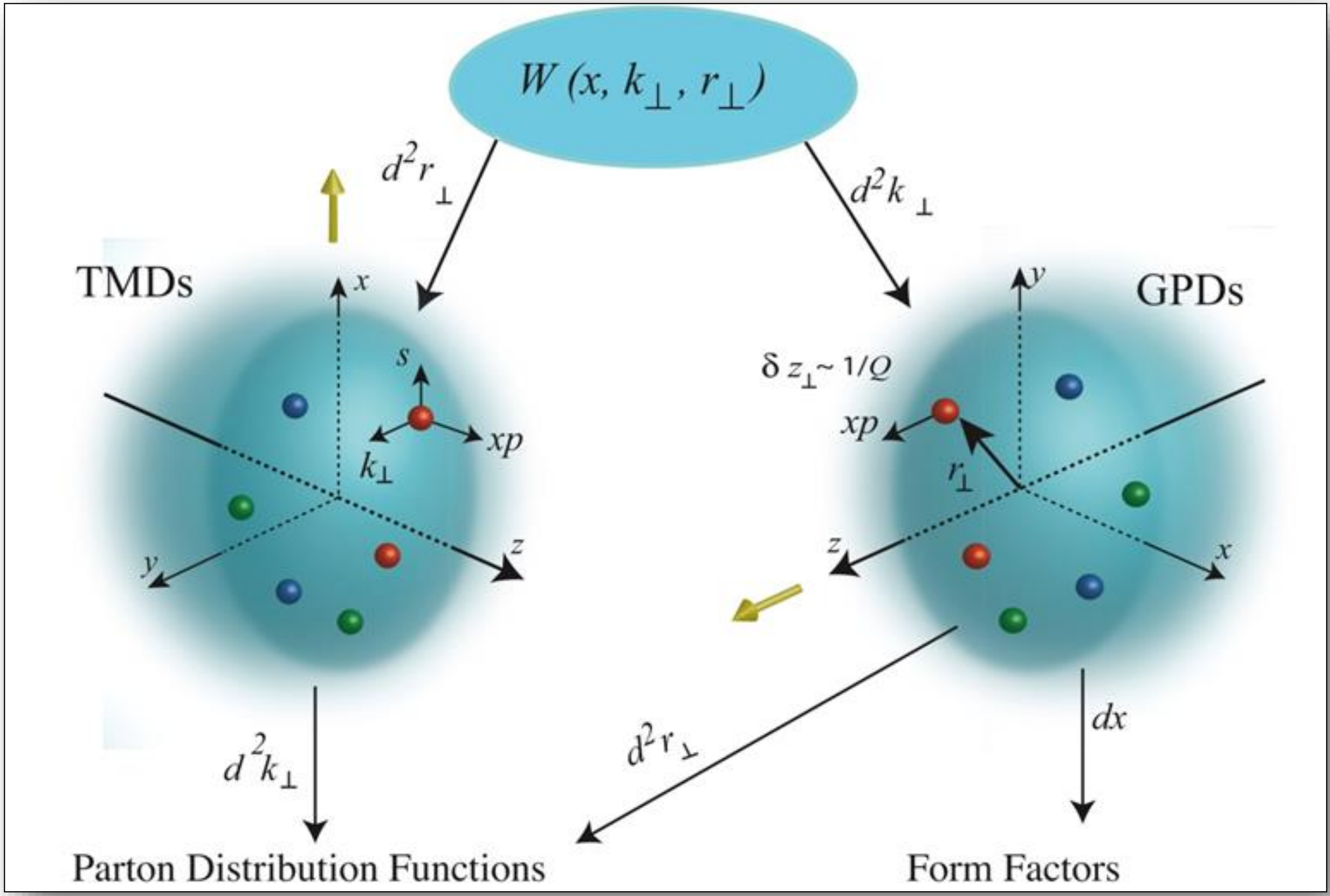
High Luminosity
Large Acceptance





Nucleon Structure from 1D to 3D – orbital motion

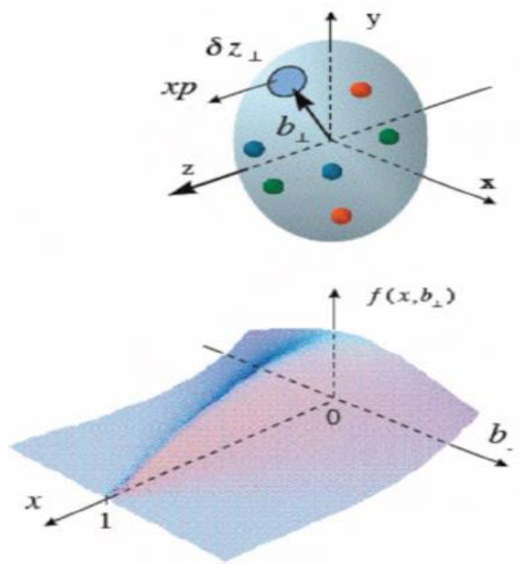
5-D Wigner distribution



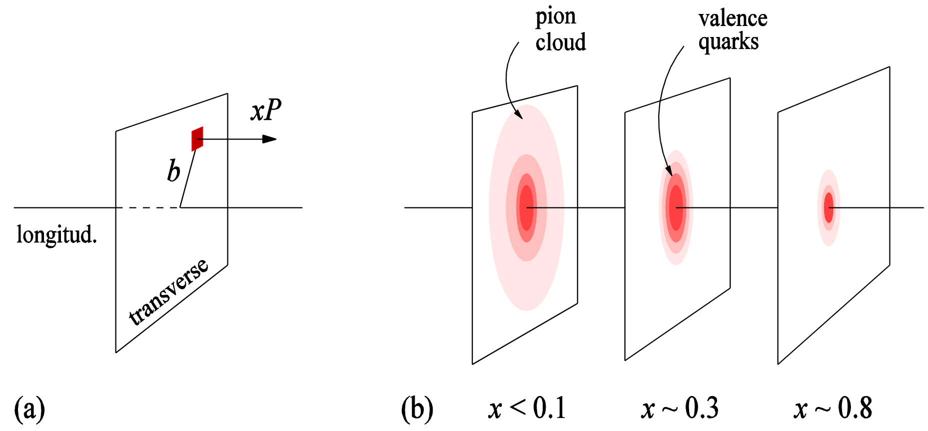
X.D. Ji, PRL91, 062001 (2003);
Belitsky, Ji, Yuan, PRD69,074014 (2004)

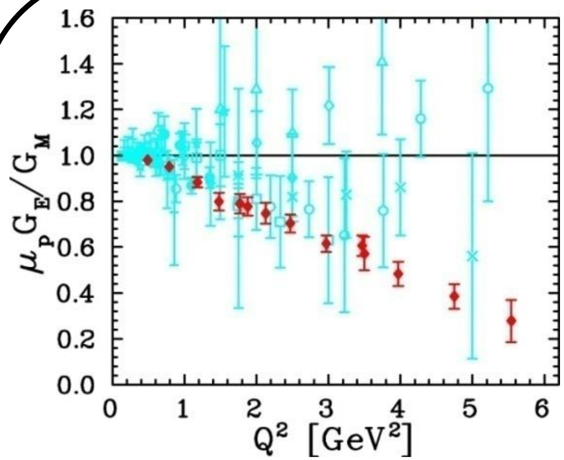
Generalized parton distribution (GPD)
Transverse momentum dependent parton distribution (TMD)
Image from J. Dudek et al., EPJA 48,187 (2012)

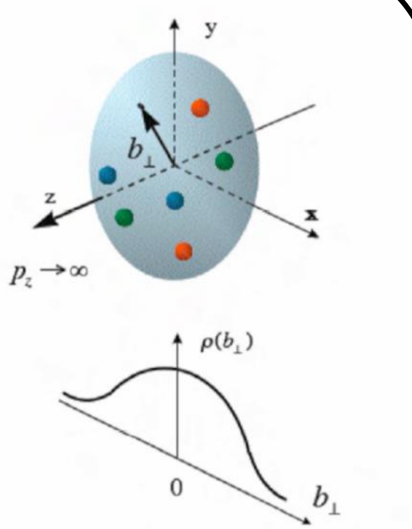
Generalized Parton Distribution (GPD)



A unified descriptions of partons (quarks and gluons) in the momentum and impact parameter space

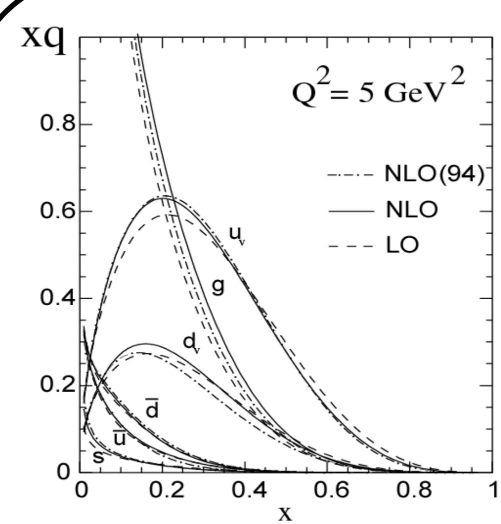


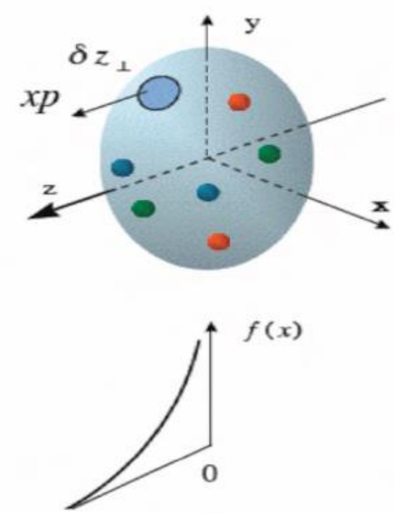




Elastic form factors

Transverse spatial distributions





Parton Distribution Functions

Longitudinal momentum distributions

GPD Parameterization

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 type and gluon.
- 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.**

Compton Scattering:

- Sensitive to all four GPDs.

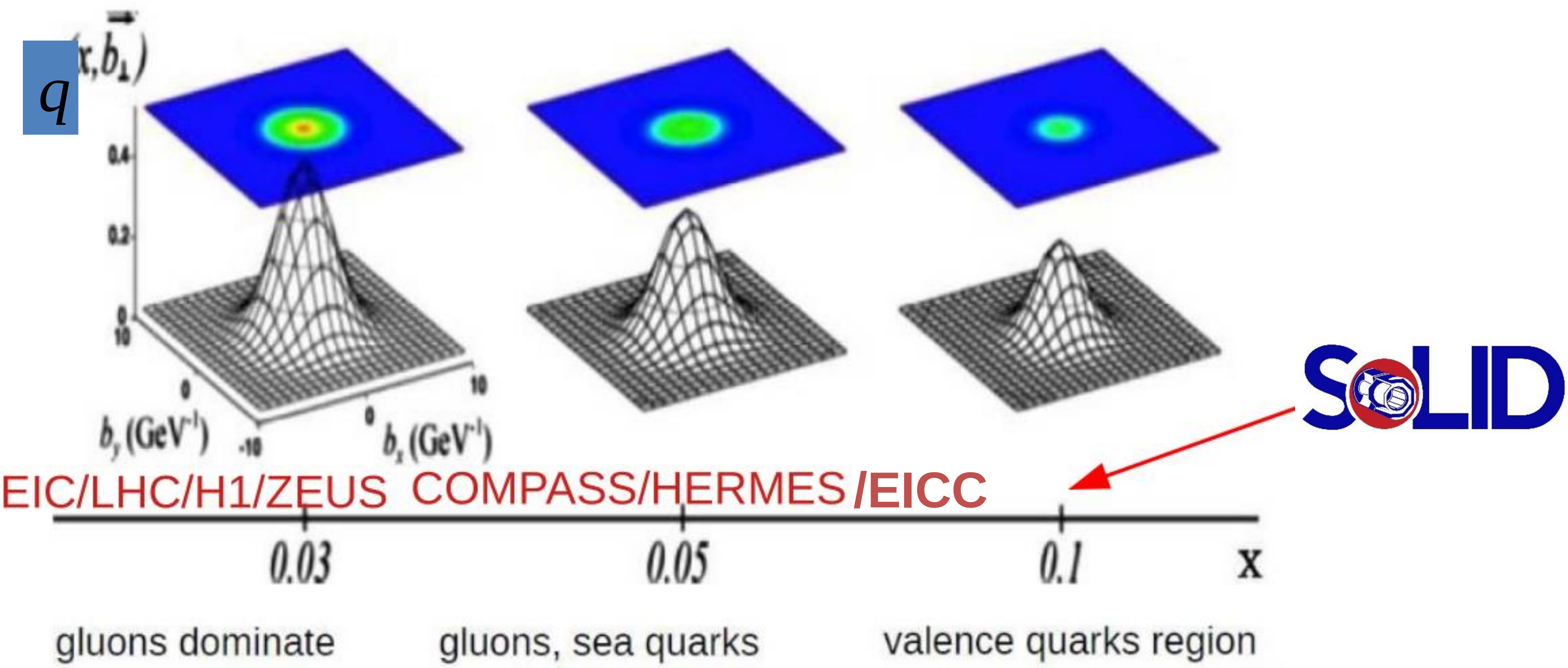
Deep Exclusive Meson Production:

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

Accessible GPD Regions

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

Momentum dependent impact parameter distributions
Quarks and gluons transverse position versus their longitudinal momentum



SoLID GPD Program

A broad array of GPD experiments are 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

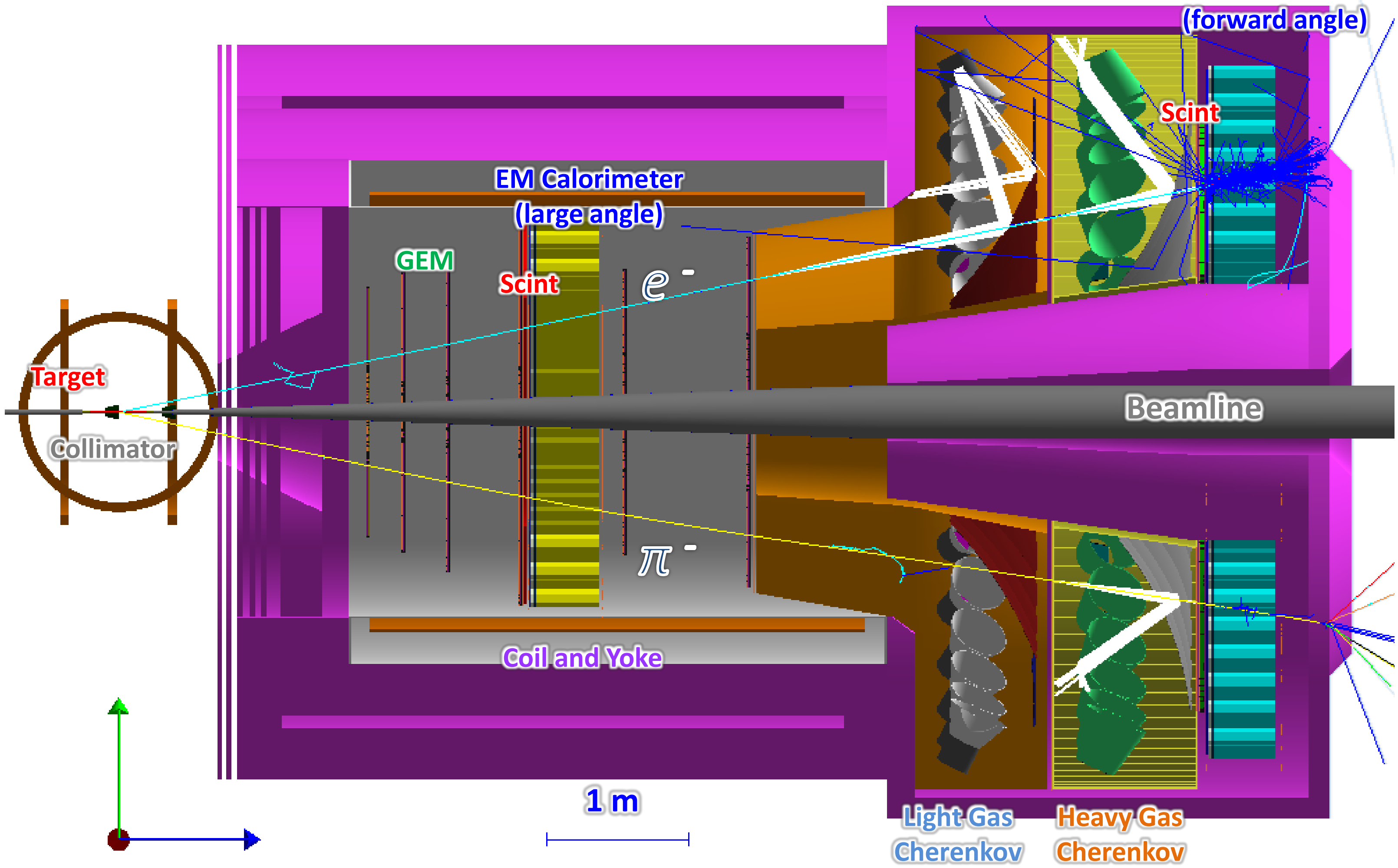
LOI12-23-012 reviewed by PAC51 in 2015, full proposal encouraged, 2023 Update

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)

SoLID SIDIS and DEMP setup



- **E12-10-006:** Single Spin Asymmetries on Transversely polarized ^{3}He @ 90 days, **rating A**
  E12-10-006B: Deep Exclusive π^- from Transversely Polarized n
- **E12-11-007:** Single and Double Spin Asymmetries on longitudinally polarized ^{3}He @ 35 days, **rating A**
- **E12-11-108:** Single Spin Asymmetries on Transversely Polarized Proton @120 days, **rating A**

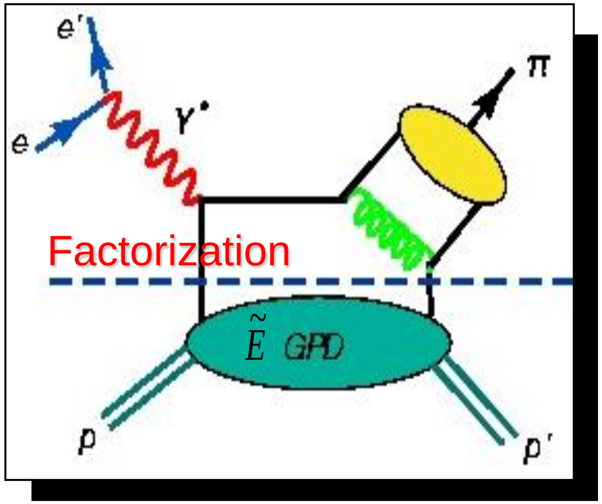
E12-10-006B: Deep Exclusive π⁻ from Transversely Polarized n

Next Generation Study: Polarized GPD $\tilde{E}$ involves a helicity flip:

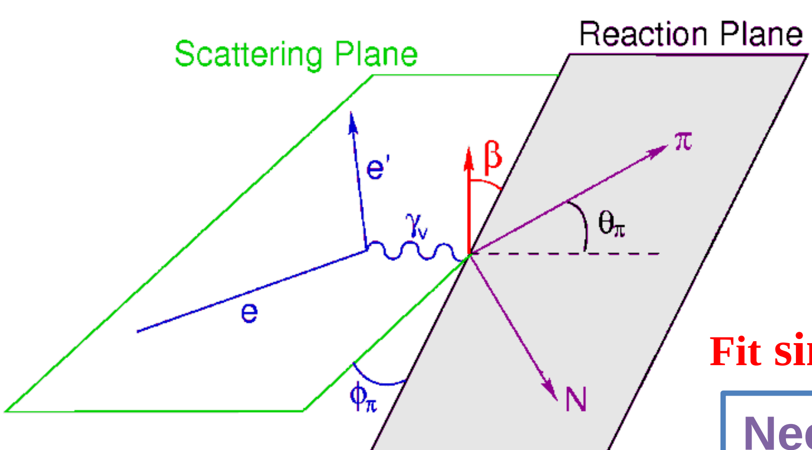
Depends on the spin difference between initial and final quarks.

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

$G_P(t)$ is largely unknown because it is negligible at the momentum transfer of β-decay.



$\tilde{E}$ not related to an already known parton distribution → essentially unknown.
Experimental information can provide new nucleon structure information unlikely to be available from any other source.



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

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

Fit $\sin\beta = \sin(\varphi - \varphi_S)$ dependence.

Need large acceptance

E12-10-006B: Deep Exclusive π⁻ from Transversely Polarized n

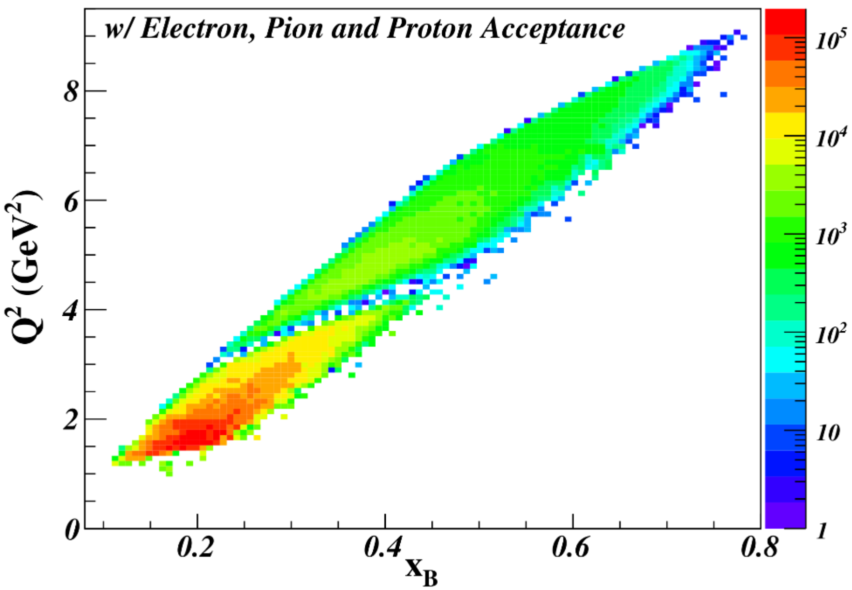
Need high luminosity

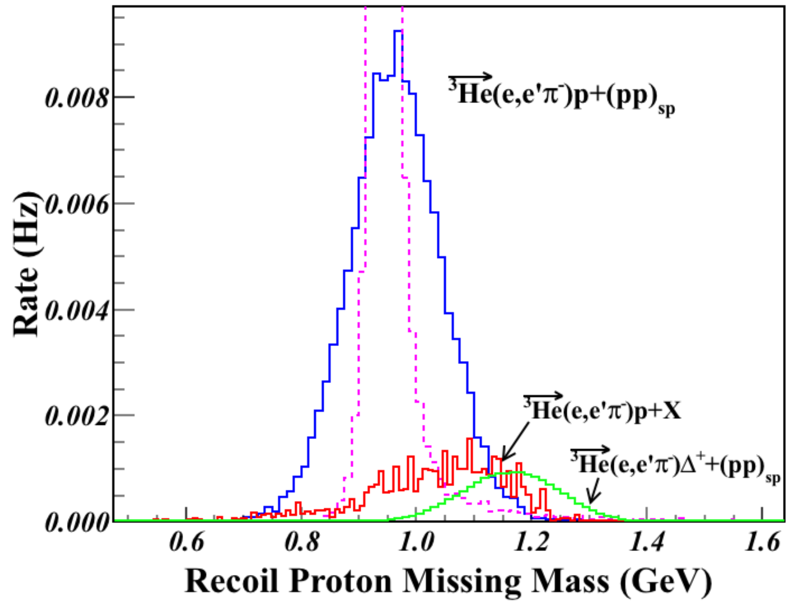
- **Azimuthal modulations of Transverse Single Spin Asymmetry allow access to different GPDs:**
  - $\sin(\beta=\varphi-\varphi_s)$ moment sensitive to helicity-flip GPD
  - $\sin(\varphi_s)$ moment sensitive to transversity GPDs

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

$$\langle A_{UT}\rangle = \frac{1}{P\cdot\eta_n\cdot d}\left(\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}\right)$$

$Q^2>1$ 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



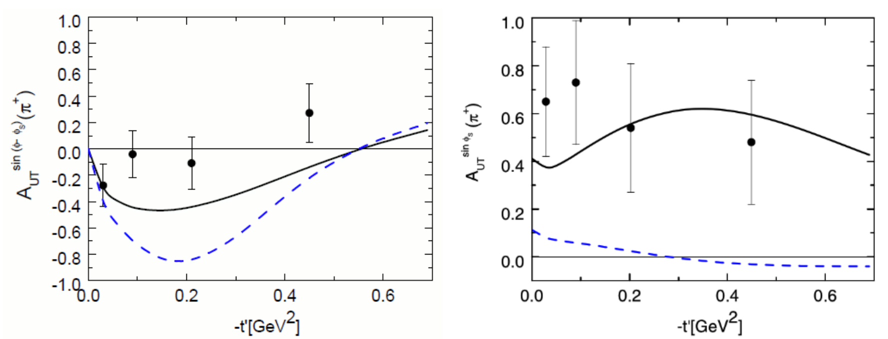


Large kinematic coverage and well controlled background

E12-10-006B: Deep Exclusive π⁻ from Transversely Polarized n

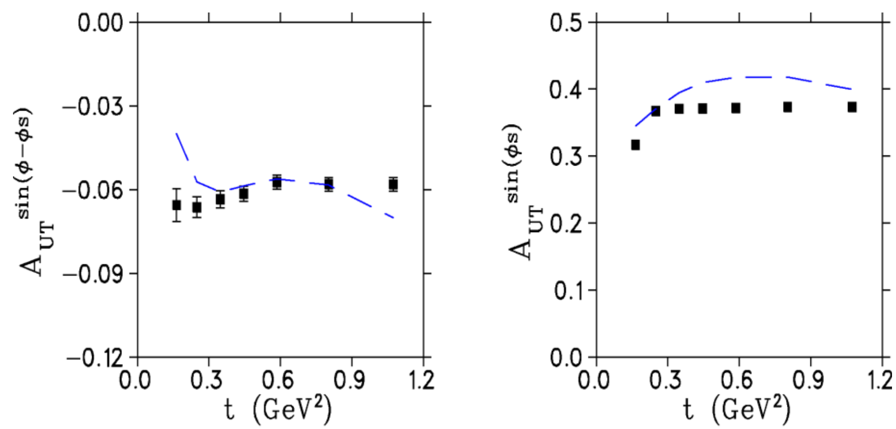
World Data: HERMES

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



SoLID Projected Uncertainties

Proton is tagged to isolate exclusive π^- events



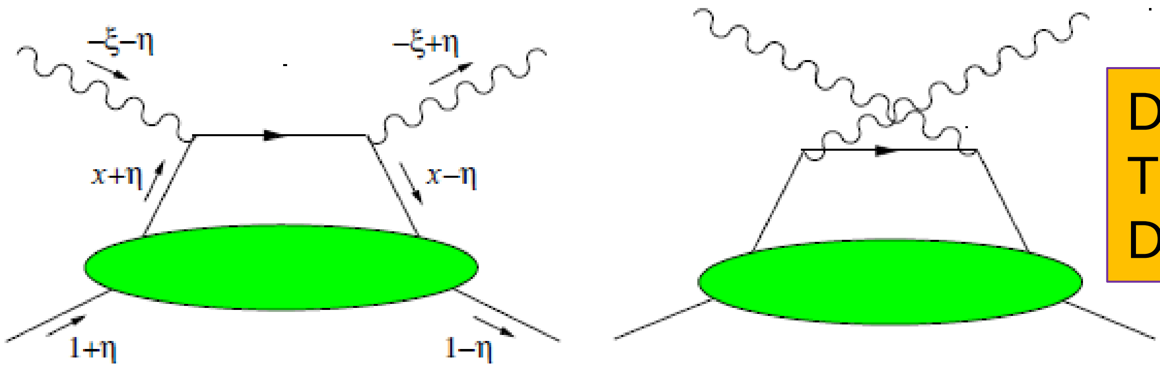
SoLID's large acceptance and high luminosity well-suited to this measurement

World unique, cannot be done anywhere else!

General Compton Process accessing GPD

$$\gamma(q) + p(p) \rightarrow \gamma(q') + p(p')$$

$$Q^2 = -q^2, \quad Q'^2 = q'^2, \quad s = (p+q)^2, \quad t = \Delta^2,$$



Deeply Virtual CS (γ′ → γ)
Timelike CS (γ → γ′)
Double DVCS (γ′ → γ′)

Compton Form Factor (CFF)

$$\mathcal{H}(\xi',\xi,t) = \sum_q e_q^2 \left\{ \mathcal{P}\int_{-1}^{1} dx\, H^q(x,\xi,t)\left[\frac{1}{x-\xi'} + \frac{1}{x+\xi'}\right] - i\pi\left[H^q(\xi',\xi,t) - H^q(-\xi',\xi,t)\right]\right\}$$

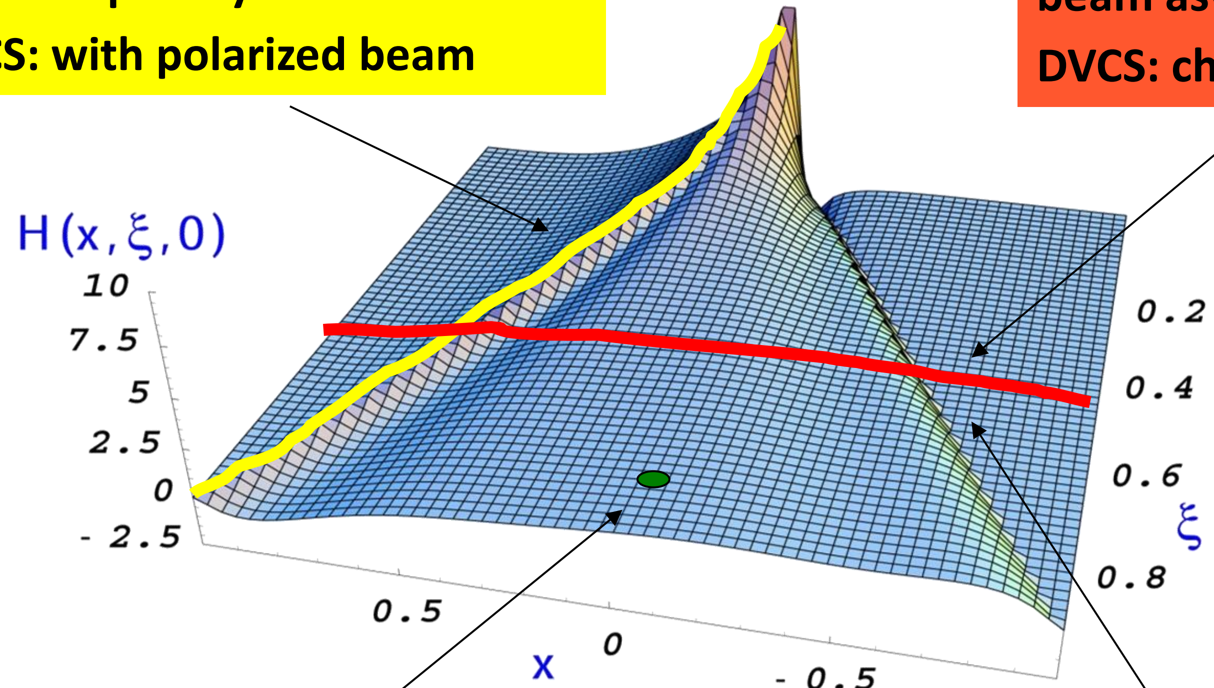
$$\xi' = \frac{Q^2 - Q'^2 + t/2}{2Q^2/x_B - Q^2 - Q'^2 + t} \quad \text{and} \quad \xi = \frac{Q^2 + Q'^2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

E.R. Berger et al. Eur. Phys. J. C 23, 675–689 (2002)

General Compton Process accessing GPD

(Im, x=ξ)
DVCS: spin asymmetries
TCS: with polarized beam

(Re)
TCS: cross section, linear beam asymmetry
DVCS: charge asymmetry



(Im, $x \neq \xi$, $x < |\xi|$)
DDVCS

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

SoLID DVCS

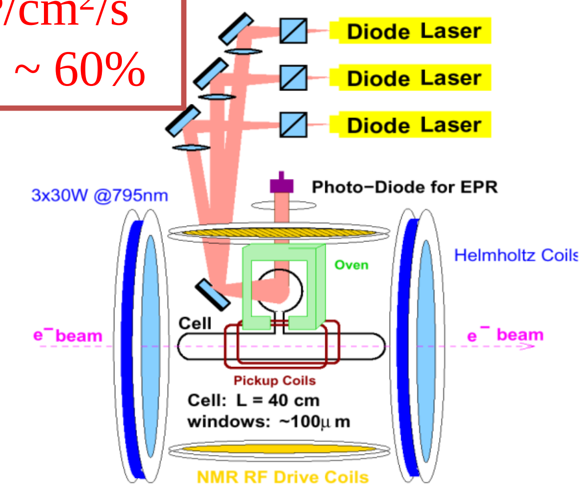
under study

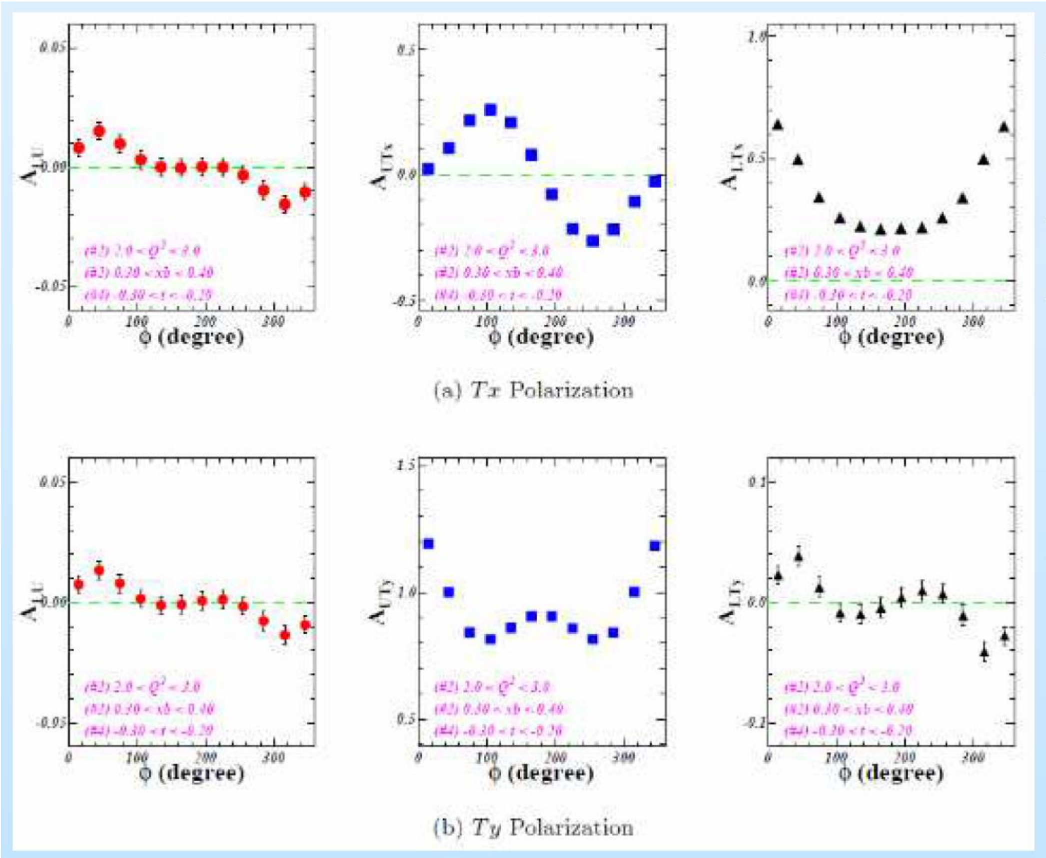
- **Both polarized proton and neutron targets are available**
- **transversely polarized neutron is unique**

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)

polarized ^{3}He target

Pol luminosity $> 10^{36}/cm^2/s$
in-beam polarization $\sim 60\%$



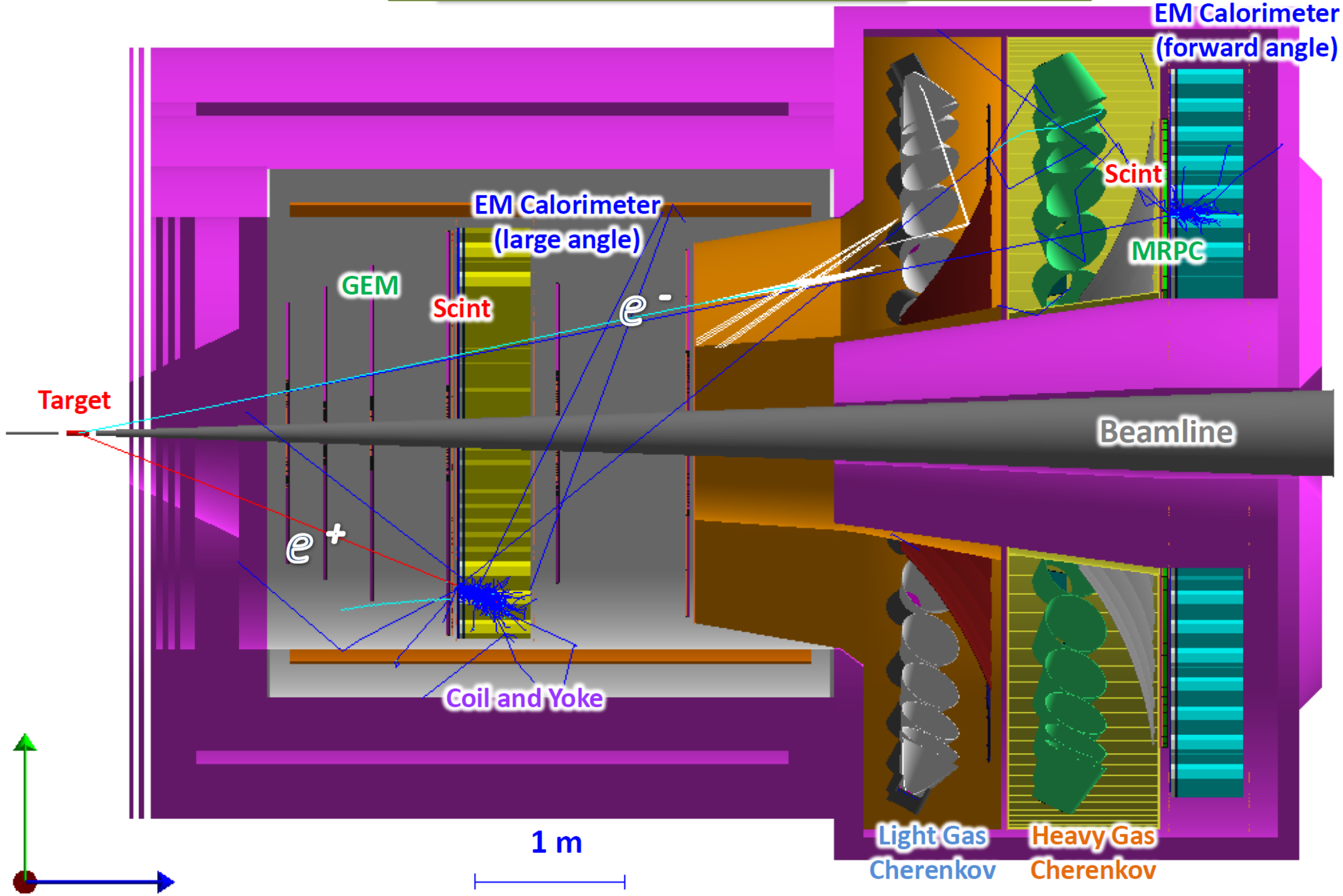


(a) Tx Polarization

(b) Ty Polarization

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

SoLID J/Psi and TCS setup



E12-12-006: Near Threshold J/Psi production on LH2 target 60 days, **rating A**

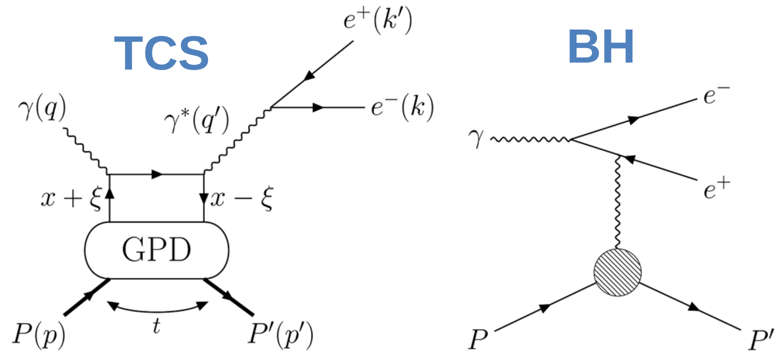
E12-12-006A: TCS with circular polarized beam and LH2 target

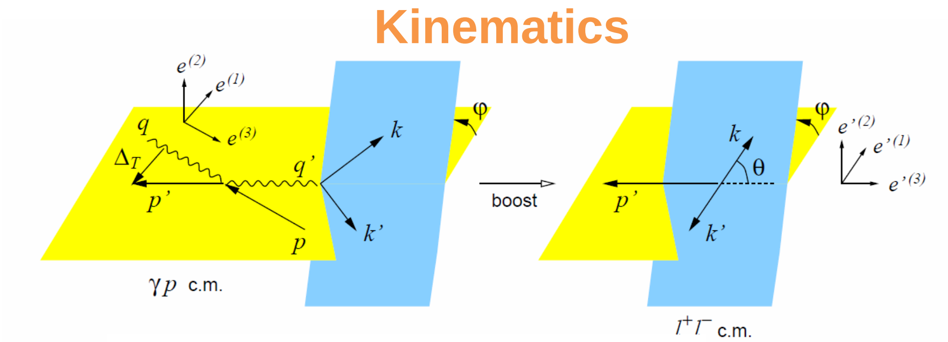
E12-12-006A: TCS with circular polarized beam and LH2 target

sharing beam time with J/psi run using same trigger on decay $e^- e^+$ pair only

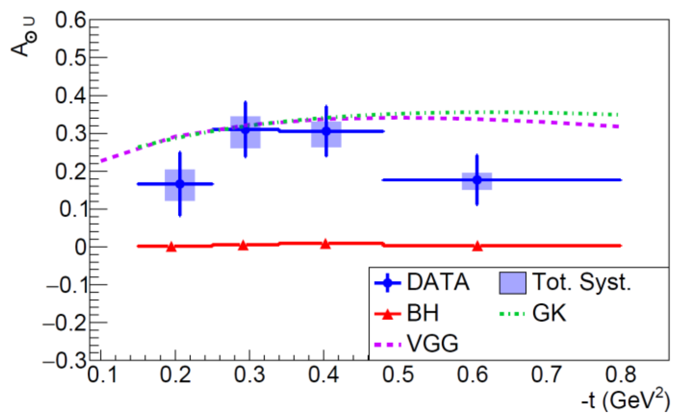
$$\gamma\, p \rightarrow \gamma^*(e^-\, e^+)\, p'$$

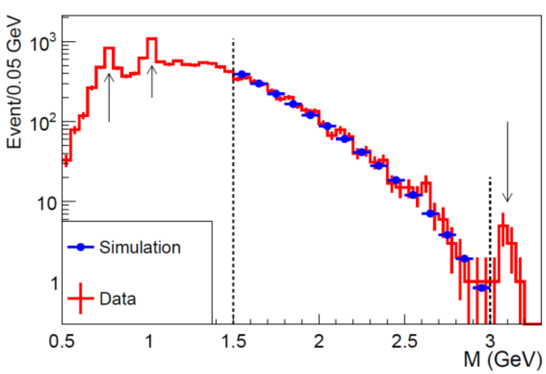
- Motivation
  - Access the same GPDs like DVCS and test universality
  - Access real and immginary part of GPD H through CFF
  - New observables for global GPD fits
- Status
  - exploration at CLAS 6GeV
  - First result at CLAS12 published at PRL, 127, 262501 (2021) obtain **nonzero** beam polarized asymmetry A_{LU} and forward backward asymmetry A_{FB}
  - Limited by low statistics





CLAS12 result

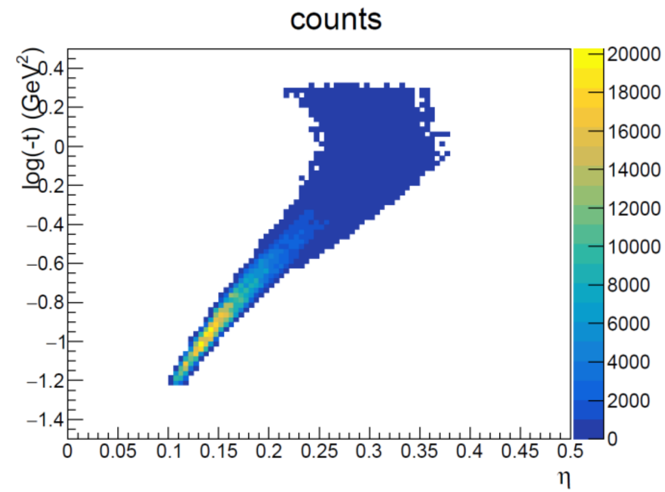


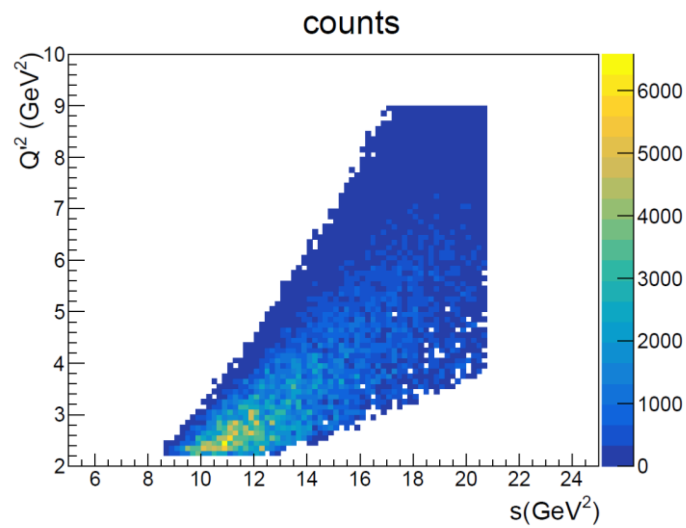


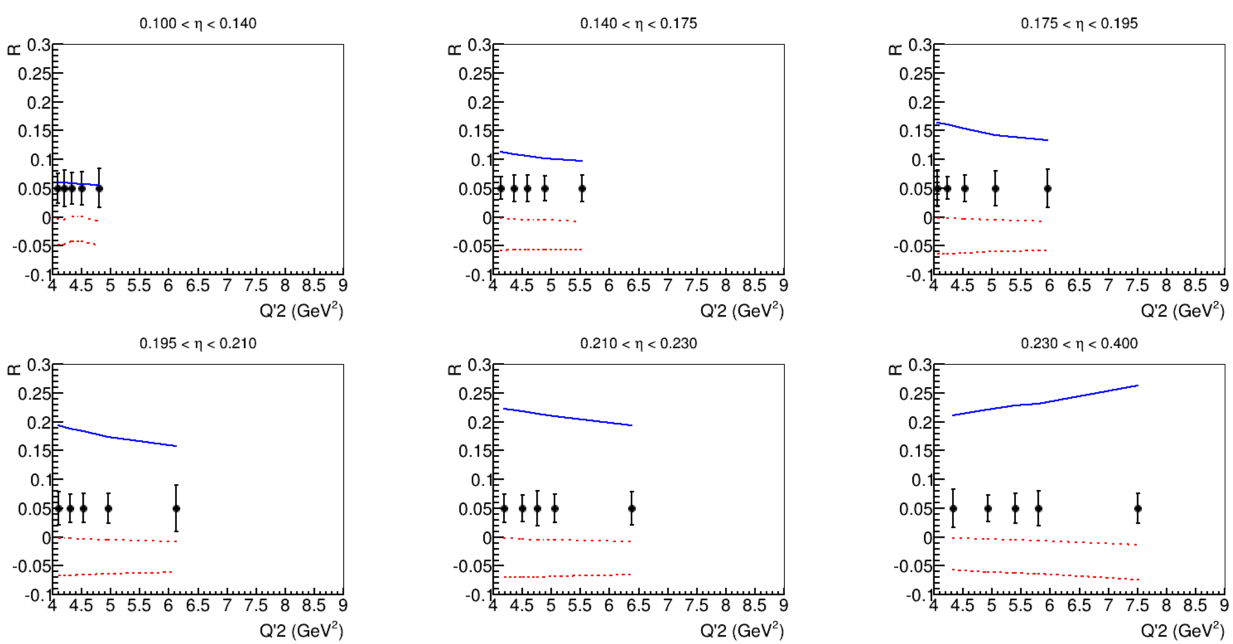
E12-12-006A: TCS with circular polarized beam and LH2 target

- SoLID TCS will have at least 1 order larger statistics than CLAS12 and usher TCS study into precision era with multi-dimensional binning
  - SoLID has 250 times more integrated luminosity than the CLAS12 TCS published result
  - SoLID acceptance to TCS events is about ¼ of CLAS12. But with full azimuthal coverage, (ideal for the forward backward asymmetry)
  - Crosssection measurement (moment)
- SoLID TCS could lead to study of NLO correction

SoLID TCS coverage

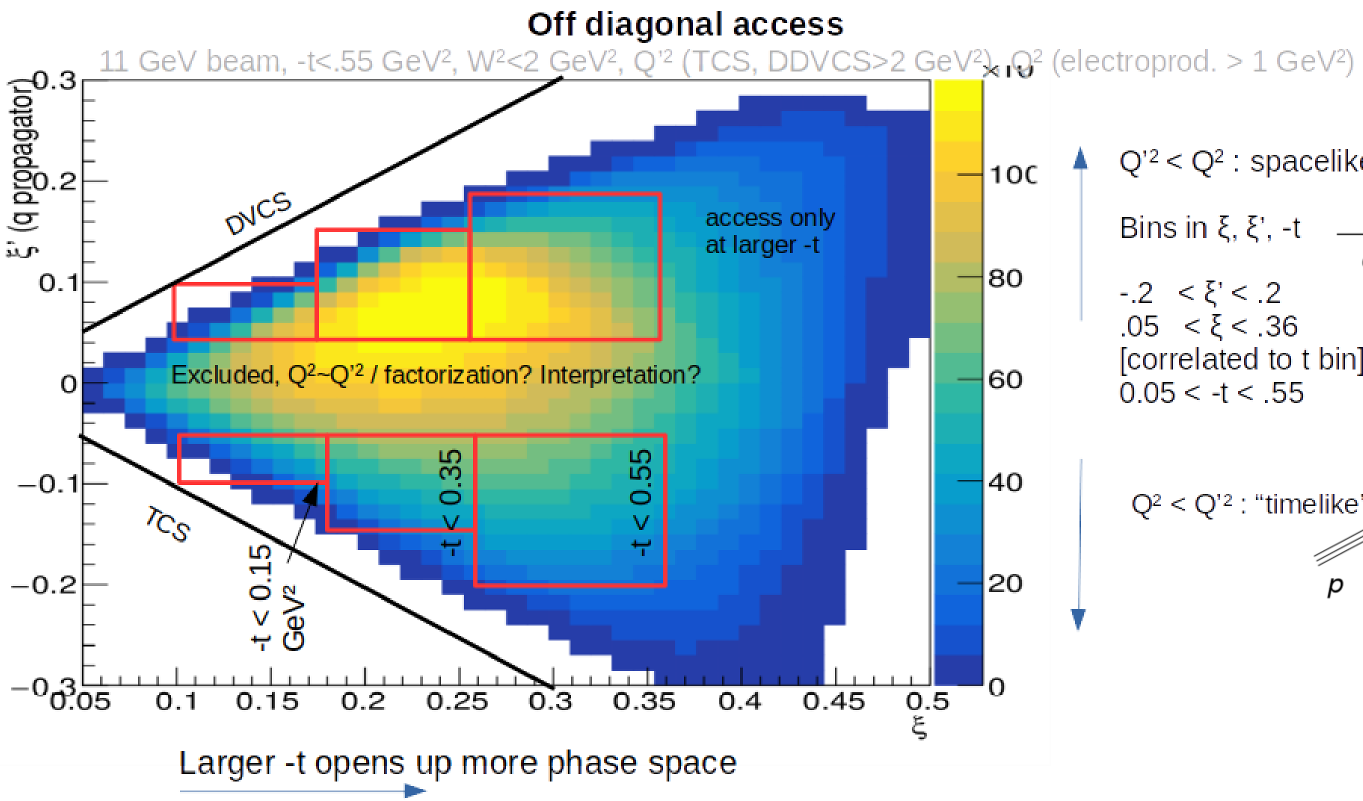


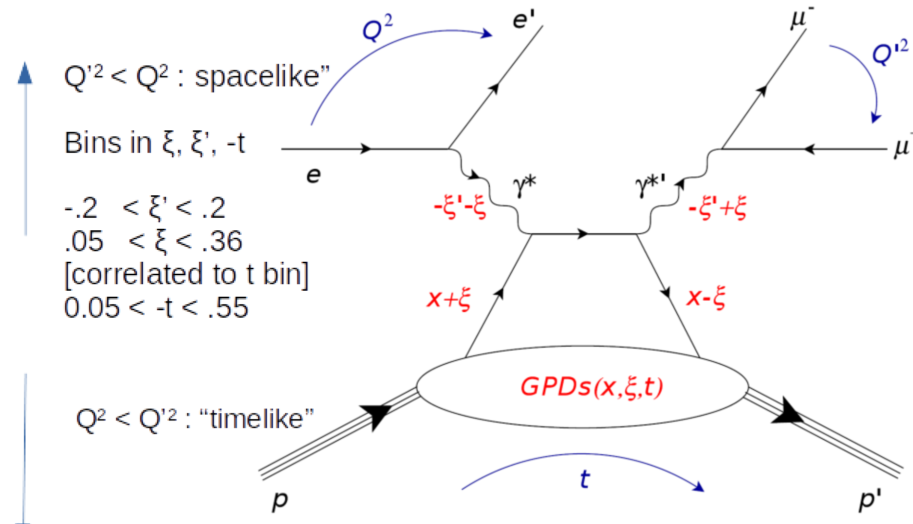


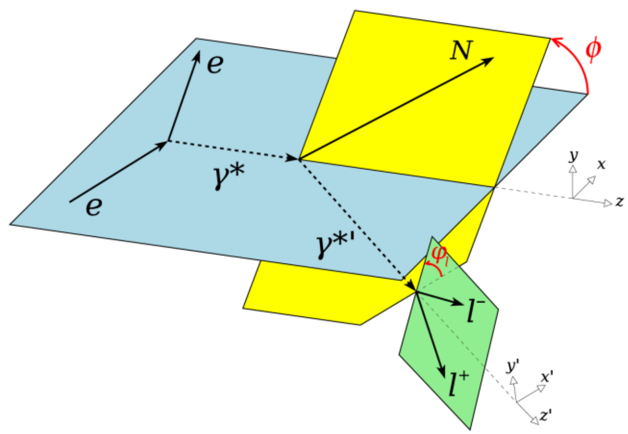


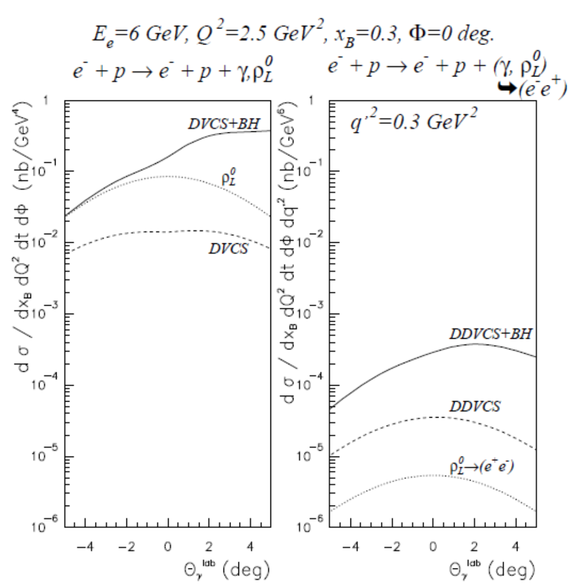
$$R = \frac{2\int_0^{2\pi} d\varphi \cos\varphi \frac{dS}{dQ^2\, dt\, d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ^2\, dt\, d\varphi}}$$

DDVCS with circular polarized beam and LH2 target









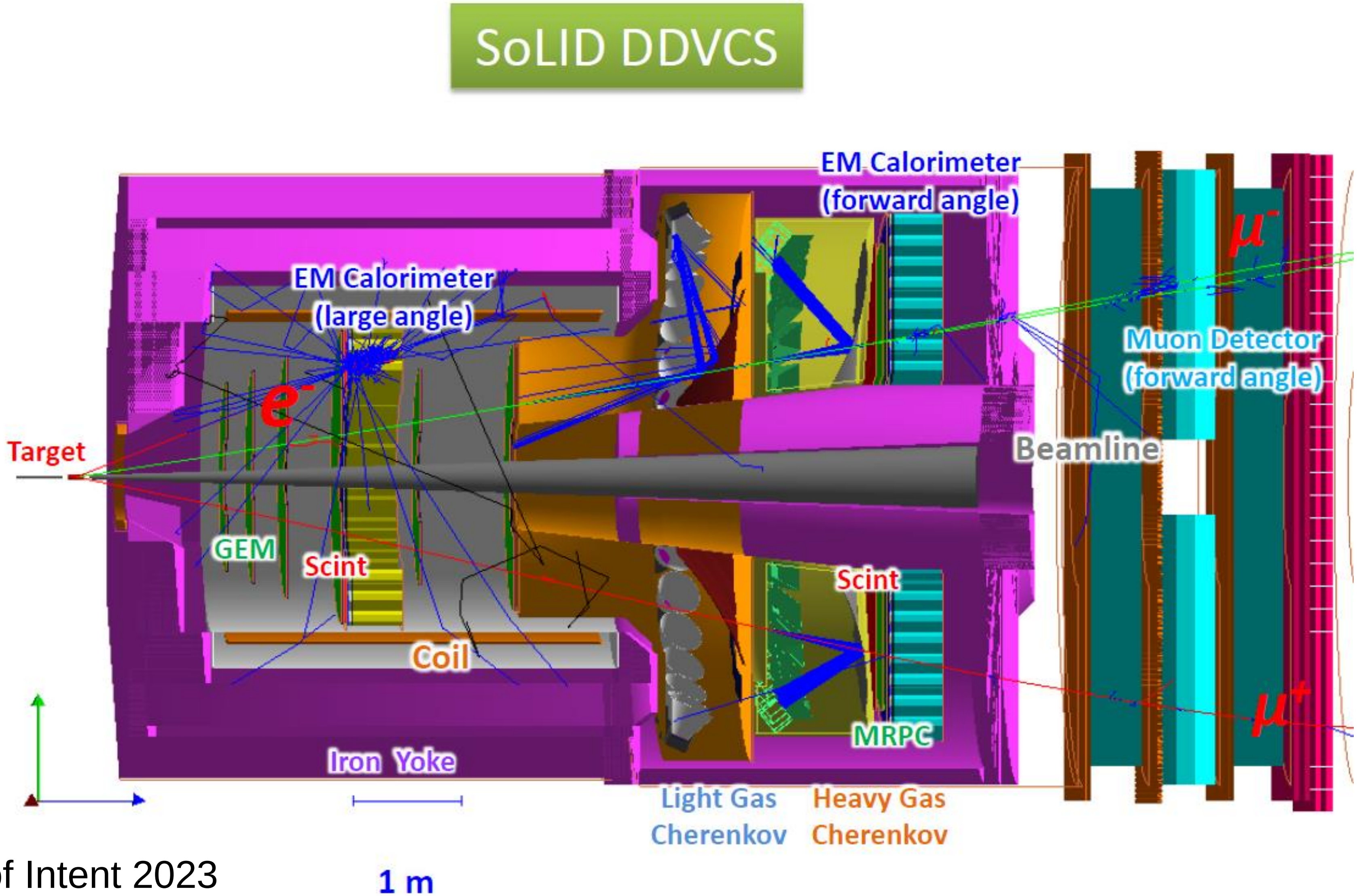
- Small DDVCS crosssection demands high luminosity and large acceptance
- Interference with Beth-Heitler helps construct observable

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

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

SoLID DDVCS Setup

- Based on the J/Psi and TCS setup with forward muon detector added
- Sharing beam time and add muon channels for approved J/Psi and TCS

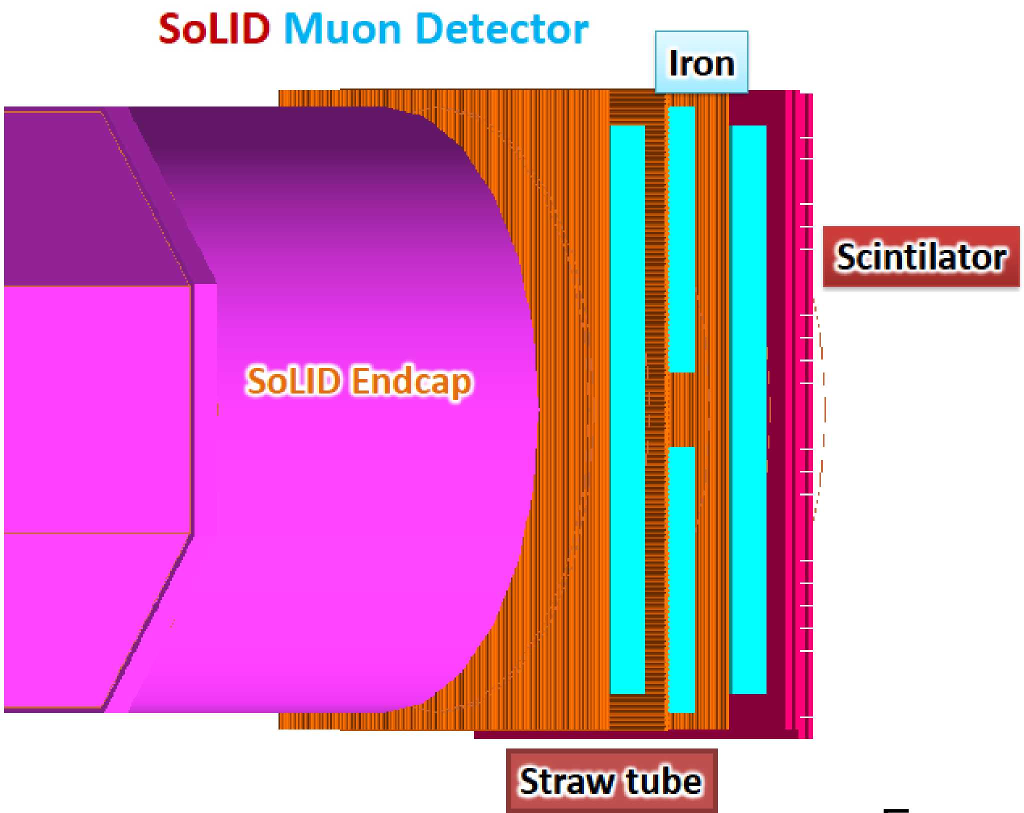


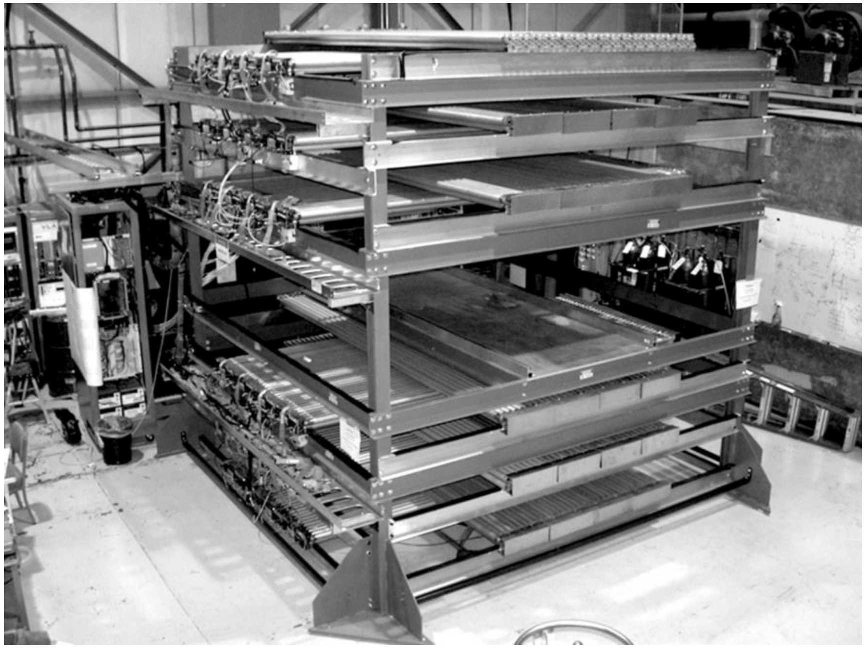
Letter of Intent 2023

Marie Boer, Alexandre Camsonne, Eric Voutier, Zhiwen Zhao

forward angle muon detector

3 layer iron to block charged pions, 3 layer straw tubes for tracking, 2 layer scintillators for trigger

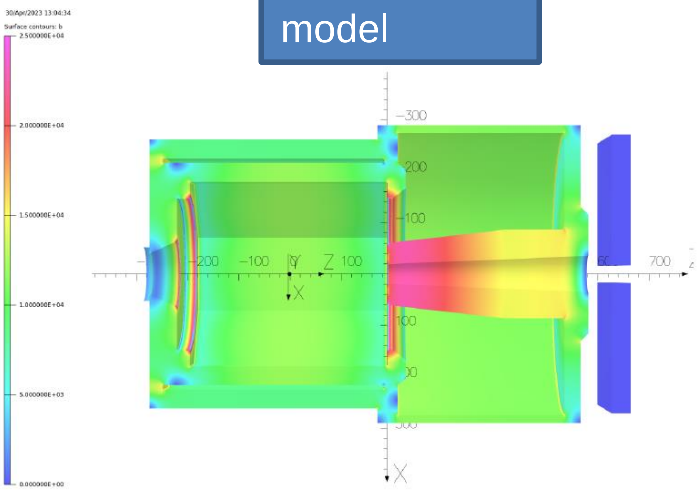




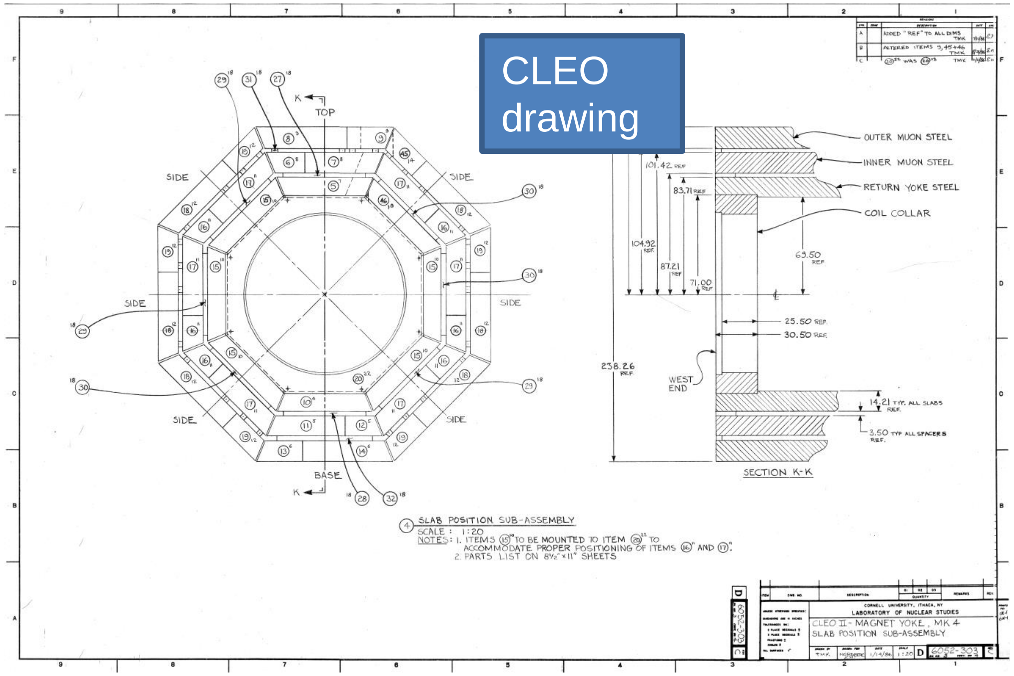
Example of straw tube chambers similar to Seaquest experiment

Iron of forward angle muon detector

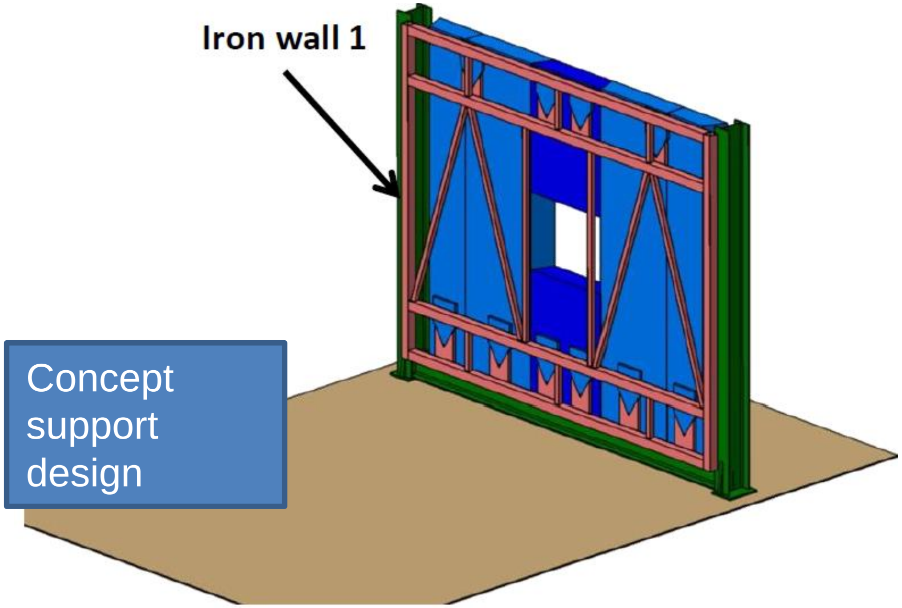
Reuse 6 of 8 CLEO octagon outer layer iron
Each one is about 36x254x533cm
No problem with space
Field (<10G),force(<1N),torque(<2Nm) are small



TOSCA model



CLEO drawing

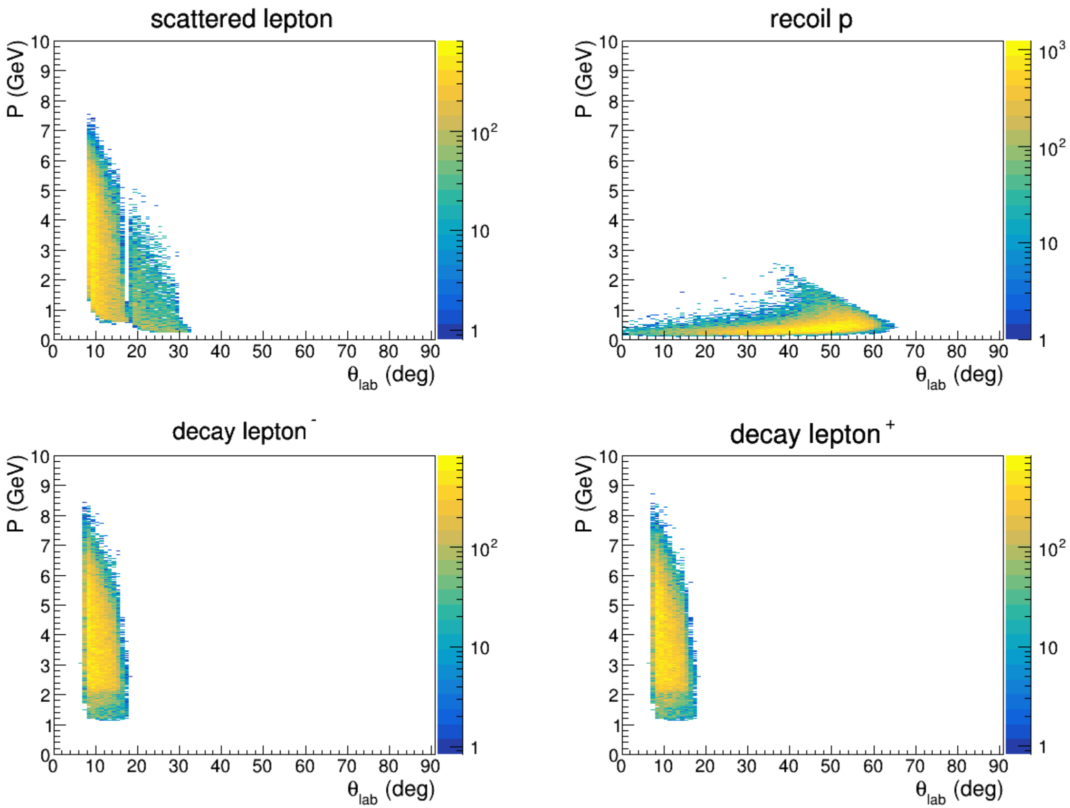


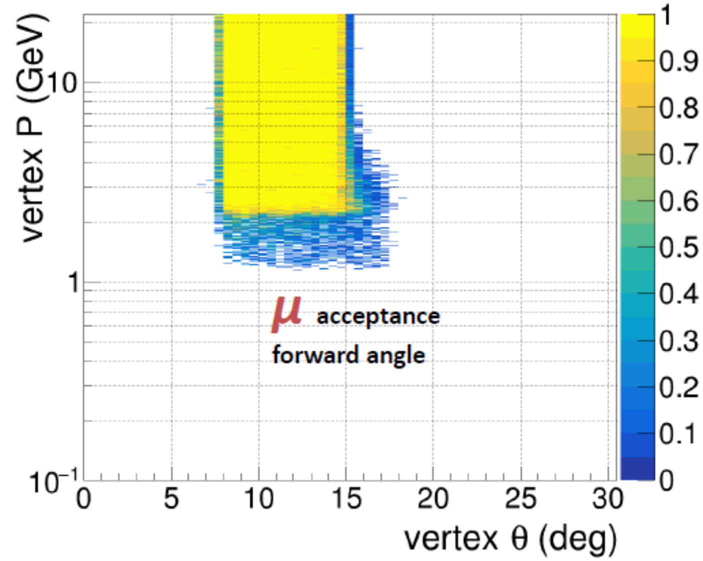
Concept support design

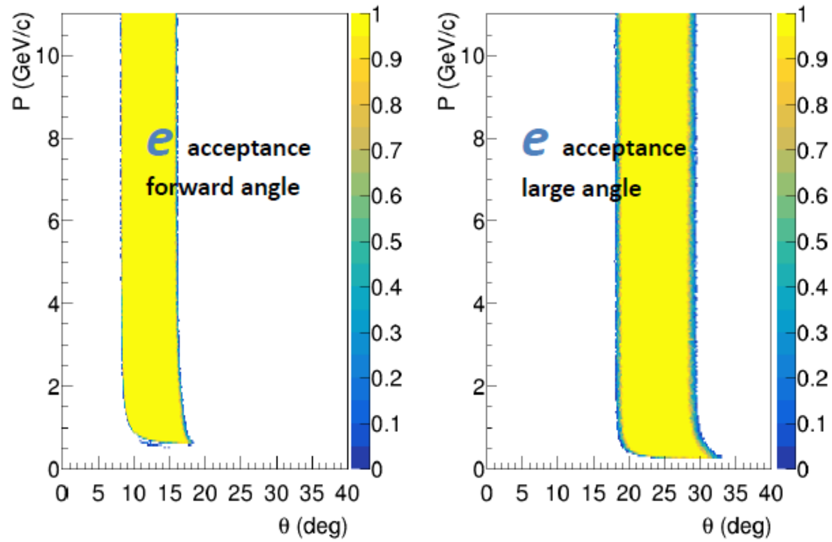
BH acceptance

BH generator grape-dilepton

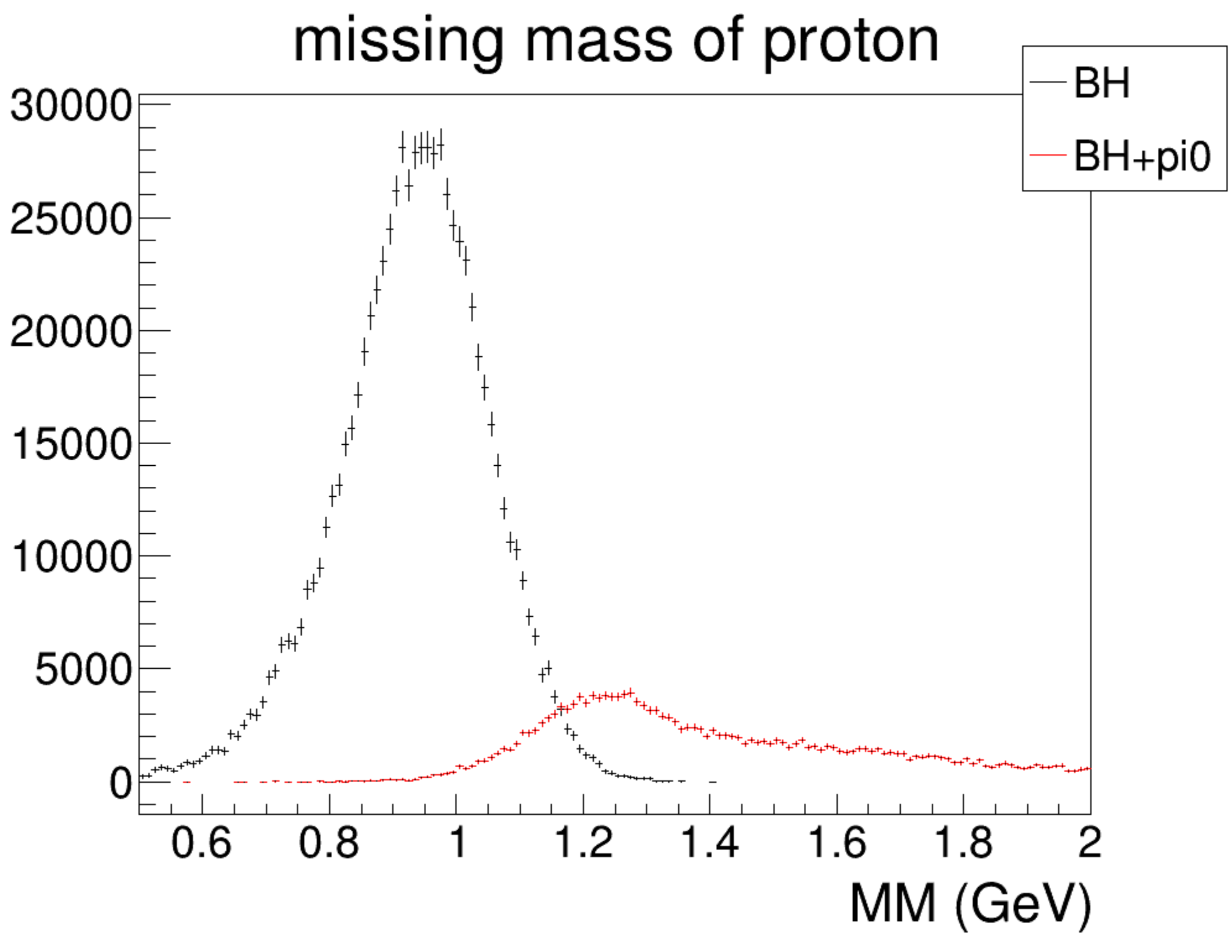
- Muon mom>2GeV is accepted
- Scattered e- and both muons are detected
- recoil proton is not required, but some can still be detected by time of flight







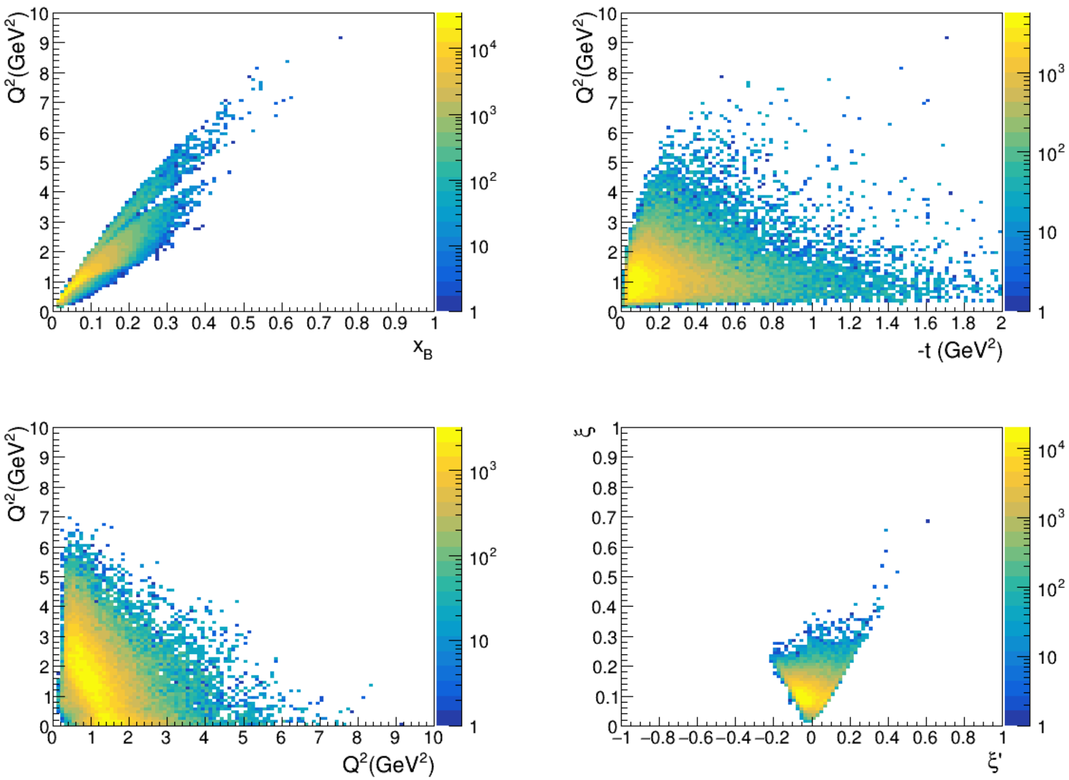
Exclusive cut

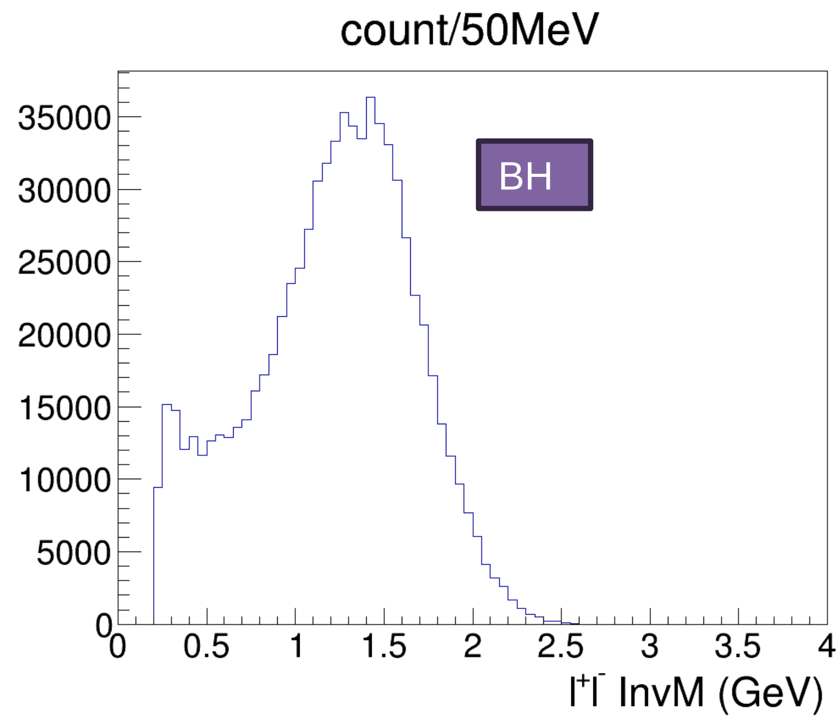


- BH and BH+pi0 from generator grape-dilepton
- Missing mass resolution good enough to separate exclusive events

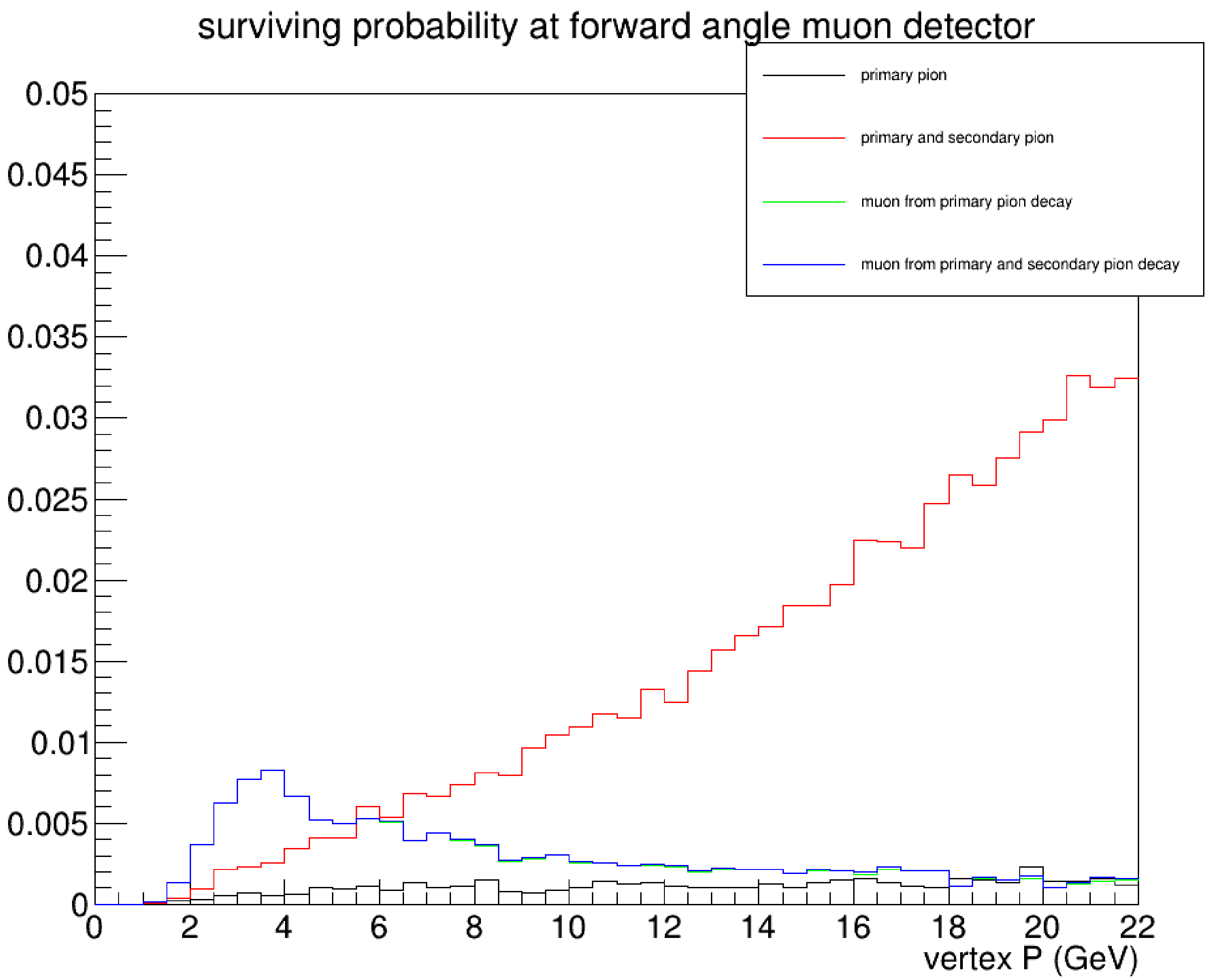
BH kinematics and counts

- 30k events for 2GeV< InvM, 600k events for 1GeV<InvM, 800k events in total
- Enough for ~500bins in 5D with 1000 events per bin





Pion blocking at back of forward angle muon detector



Single pion background at muon detector

- Start from "evgen_bggen" generator based on resonance fit and pythia
- go through full SoLID simulation for pion blocking and muon decay including both primary and secondary particles
- pi-/pi+ rate 9khz, mu-/mu+ rate 26khz, total 70khz
- Two charge particle coincidence rate 70e3*70e3*100ns<1khz

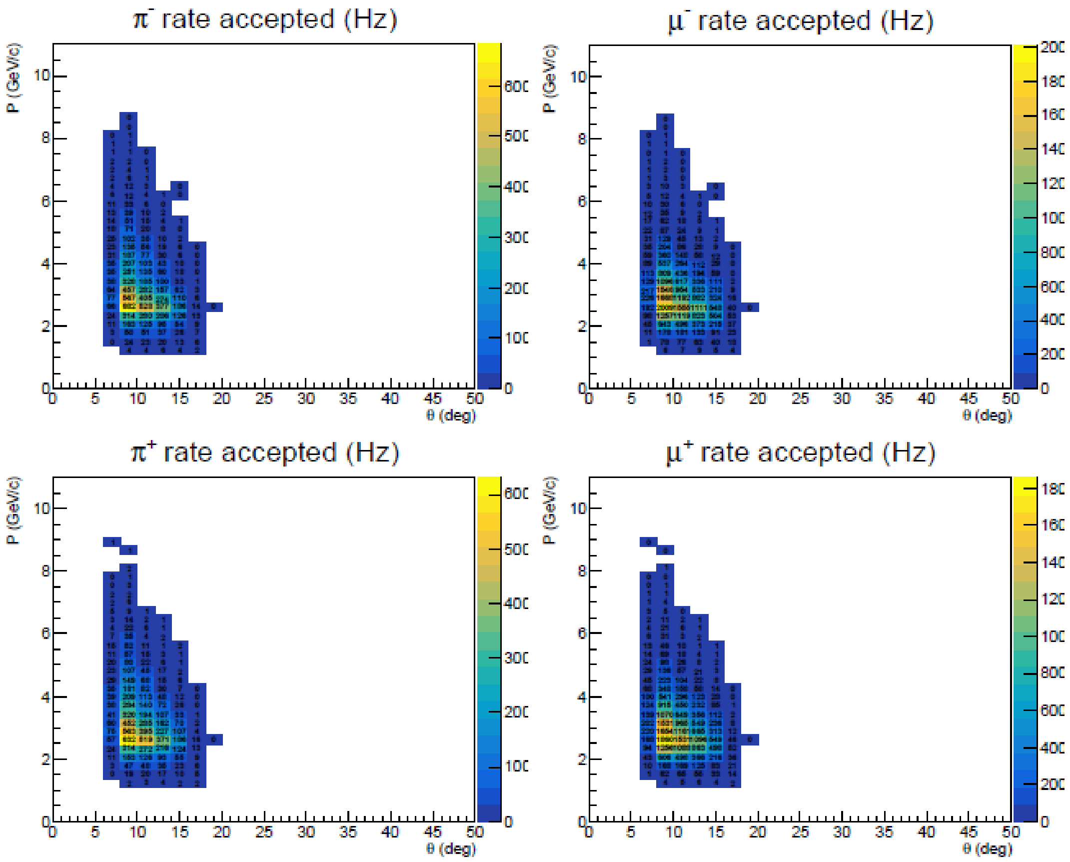
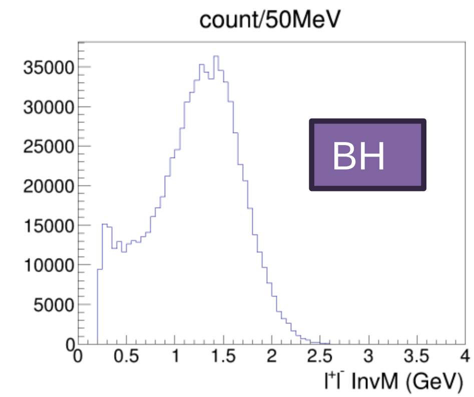


Figure 22: Single particles rate of pion and muon from pion decay at the back of forward angle muon detector. They include both pions directly from target and all secondaries and muons from their decay.

Two pion exclusive background



- Start from “twopeg” generator based on CLAS data fit and extrapolation to 11GeV beam kinematics
- go through full SoLID simulation for pion blocking and muon decay including primary particles only
- Left with counts about 10% of BH counts, mainly from both pions decay into muons.
- Tracking with vertex cut could reduce it further

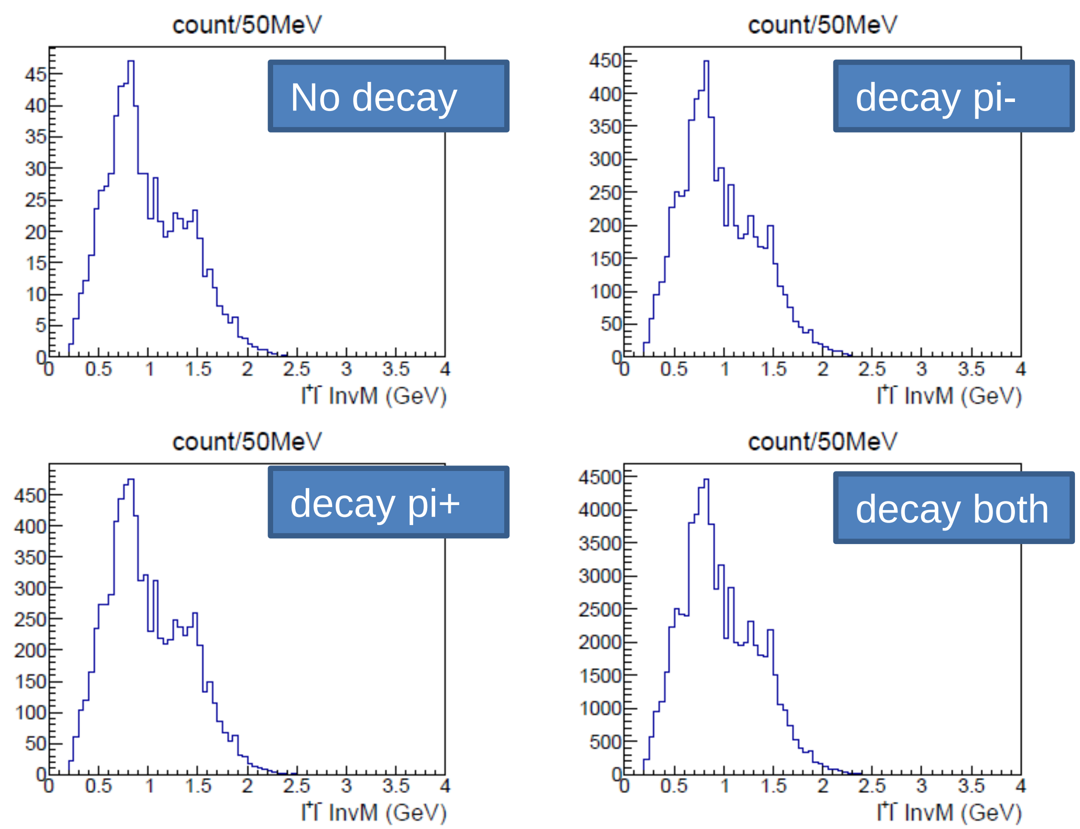
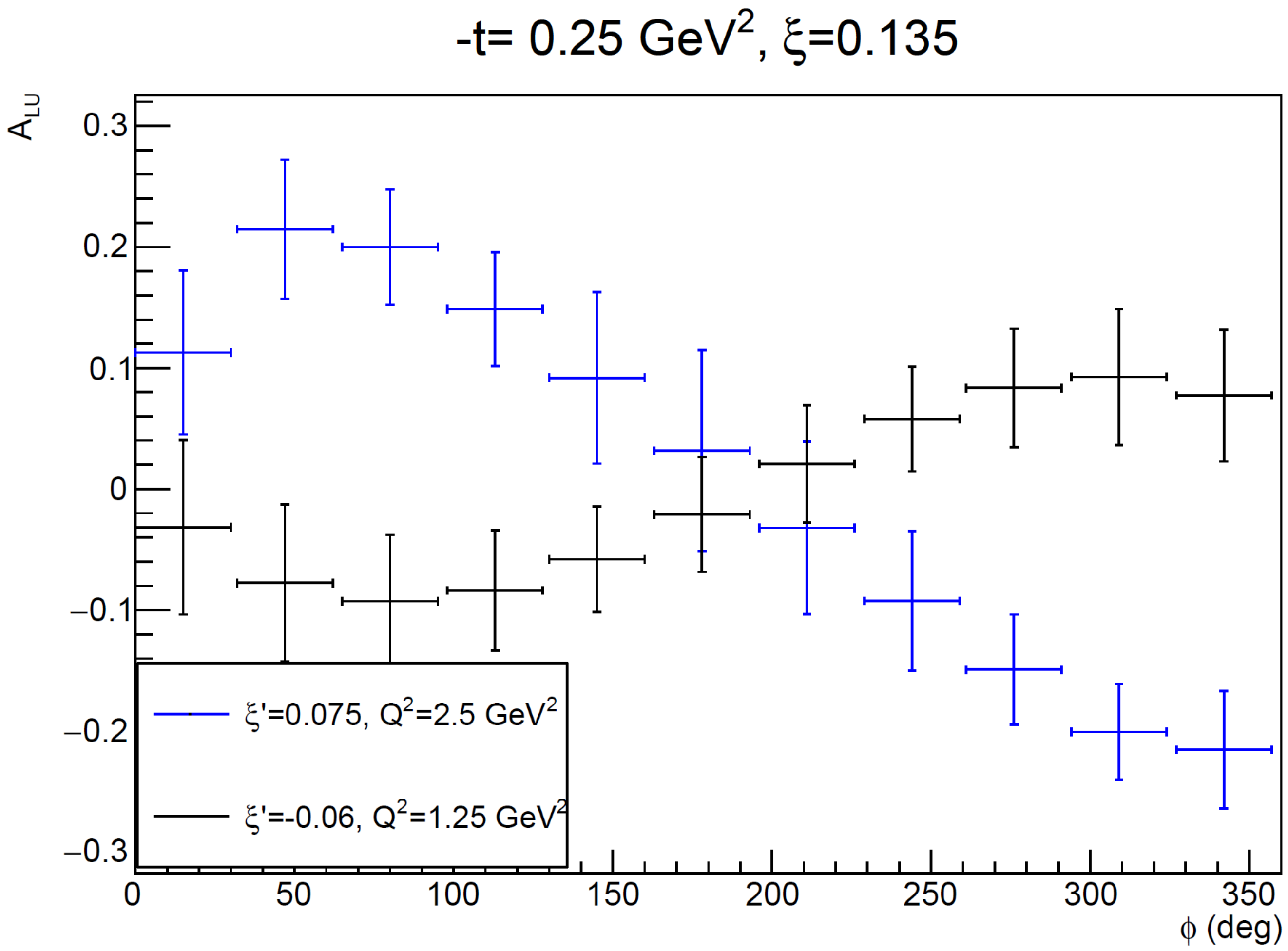


Figure 23: From left to right and top to bottom, the counts from the two pion exclusive channel contamination are shown in 4 cases, neither pion decay, negative pion decays into muon, positive pion decays into muon, and both pions decay.

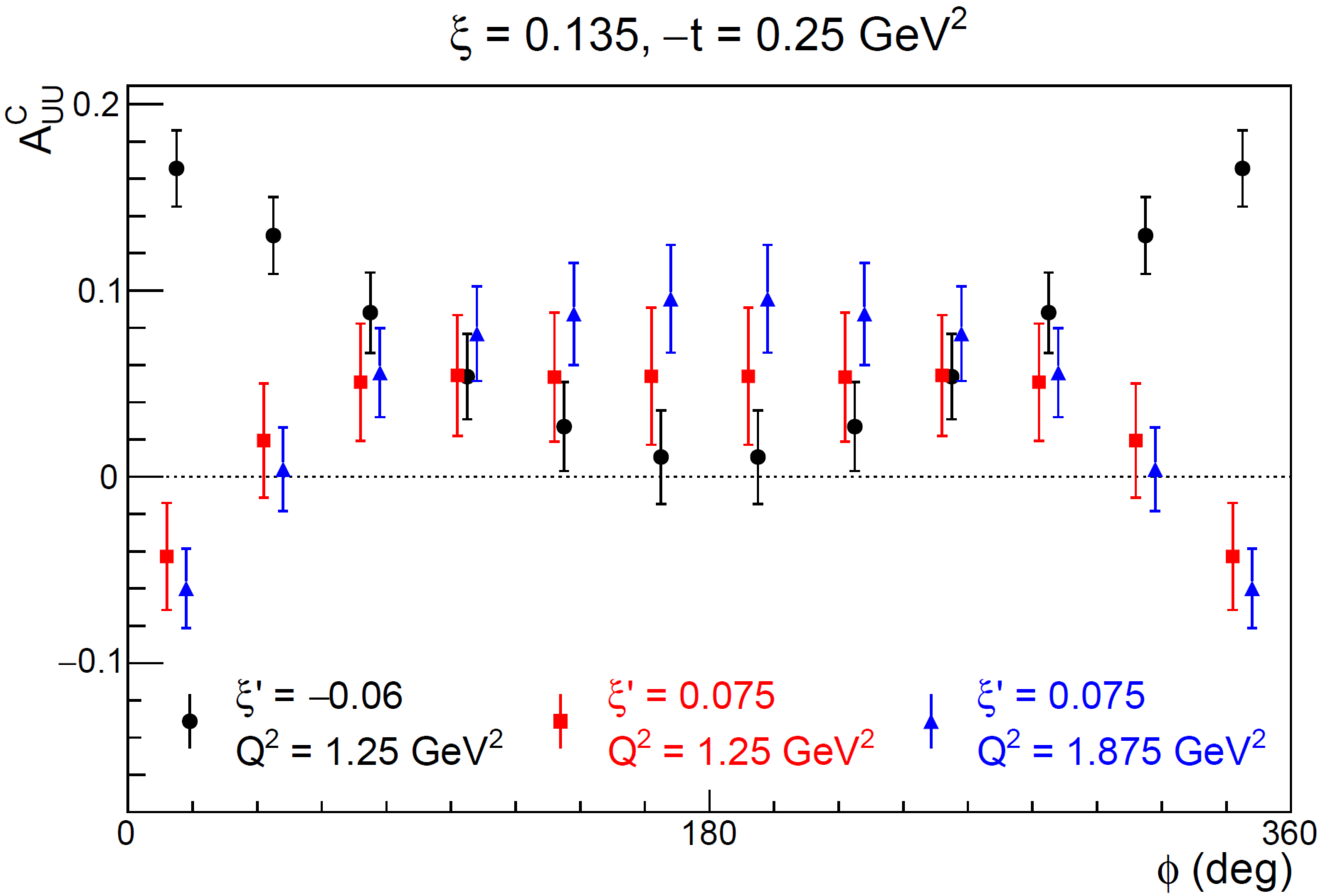
An example of projection with e- beam



$$A^{\pm}_{LU}(\phi) = \frac{1}{\lambda^{\pm}} \frac{d^5\sigma^{\pm}_{+} - d^5\sigma^{\pm}_{-}}{d^5\sigma^{\pm}_{+} + d^5\sigma^{\pm}_{-}} \qquad (15)$$

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

An example of projection with e- and e+ beam



$$A^C_{UU}(\phi) = \frac{(d^5\sigma^+_+ + d^5\sigma^+_-) - (d^5\sigma^-_+ + d^5\sigma^-_-)}{d^5\sigma^+_+ + d^5\sigma^+_- + d^5\sigma^-_+ + d^5\sigma^-_-}$$
$$= \frac{d^5\sigma_{INT_1}}{d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS}}$$

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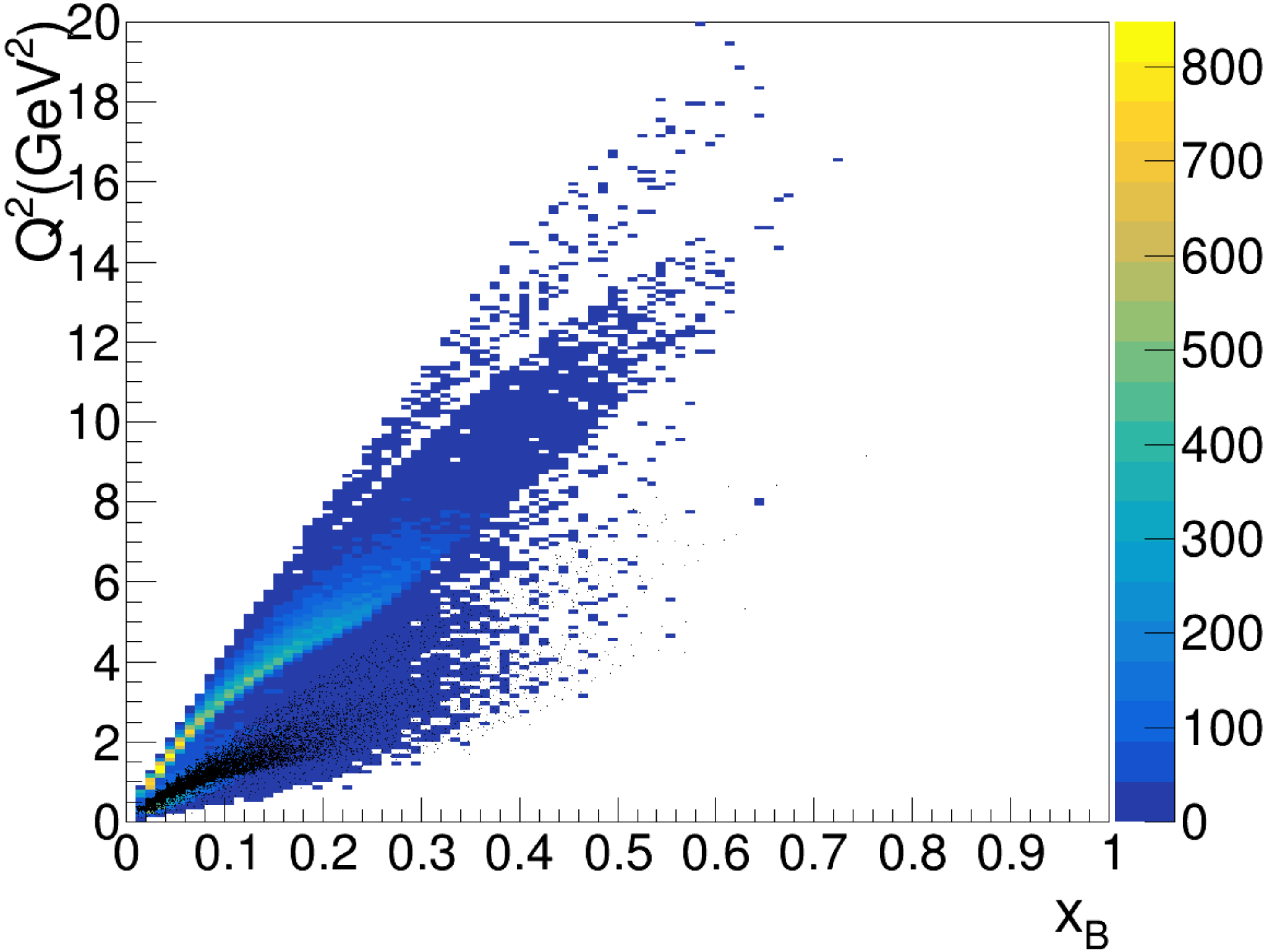
11GeV and 22GeV



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

arXiv:2306.09360

Summary

- SoLID with open geometry has a broad GPD physics program
  - DEMP (approved)
  - DVCS (under study)
  - TCS (approved)
  - DDVCS (under study)
- High luminosity and large acceptance are keys to make those next generation experiments possible with multidimension binning
- More ideas (e.g. deuterium and other nuclei target)

Thank you!

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