Jefferson Lab
Exploring the Nature of Matter

GPD Program with the SoLID Spectrometer

Hall A Winter Collaboration meeting, Jan 16 - 17, 2024

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on behalf of the **SoLID Collaboration**

University of Virginia

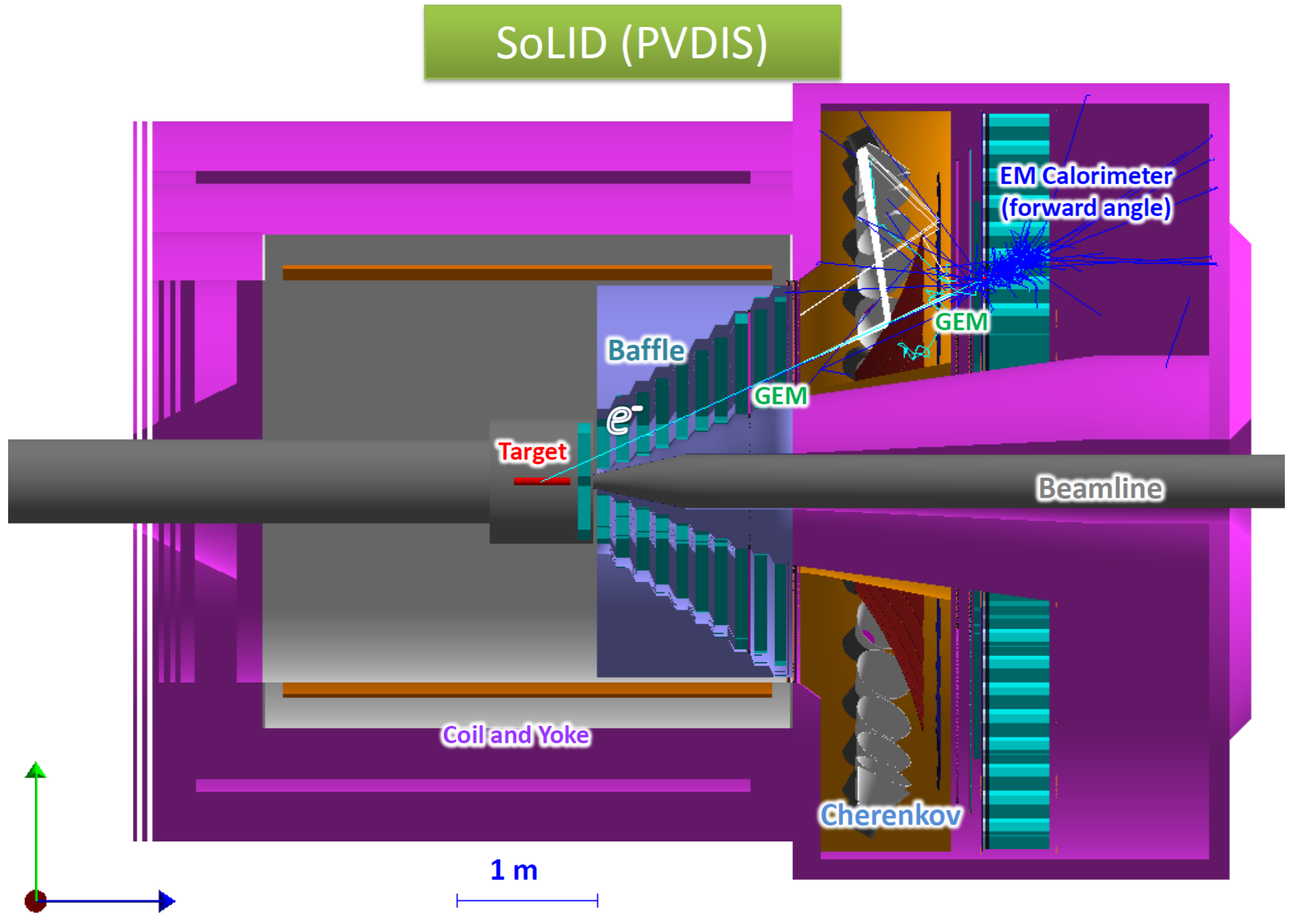
Outline

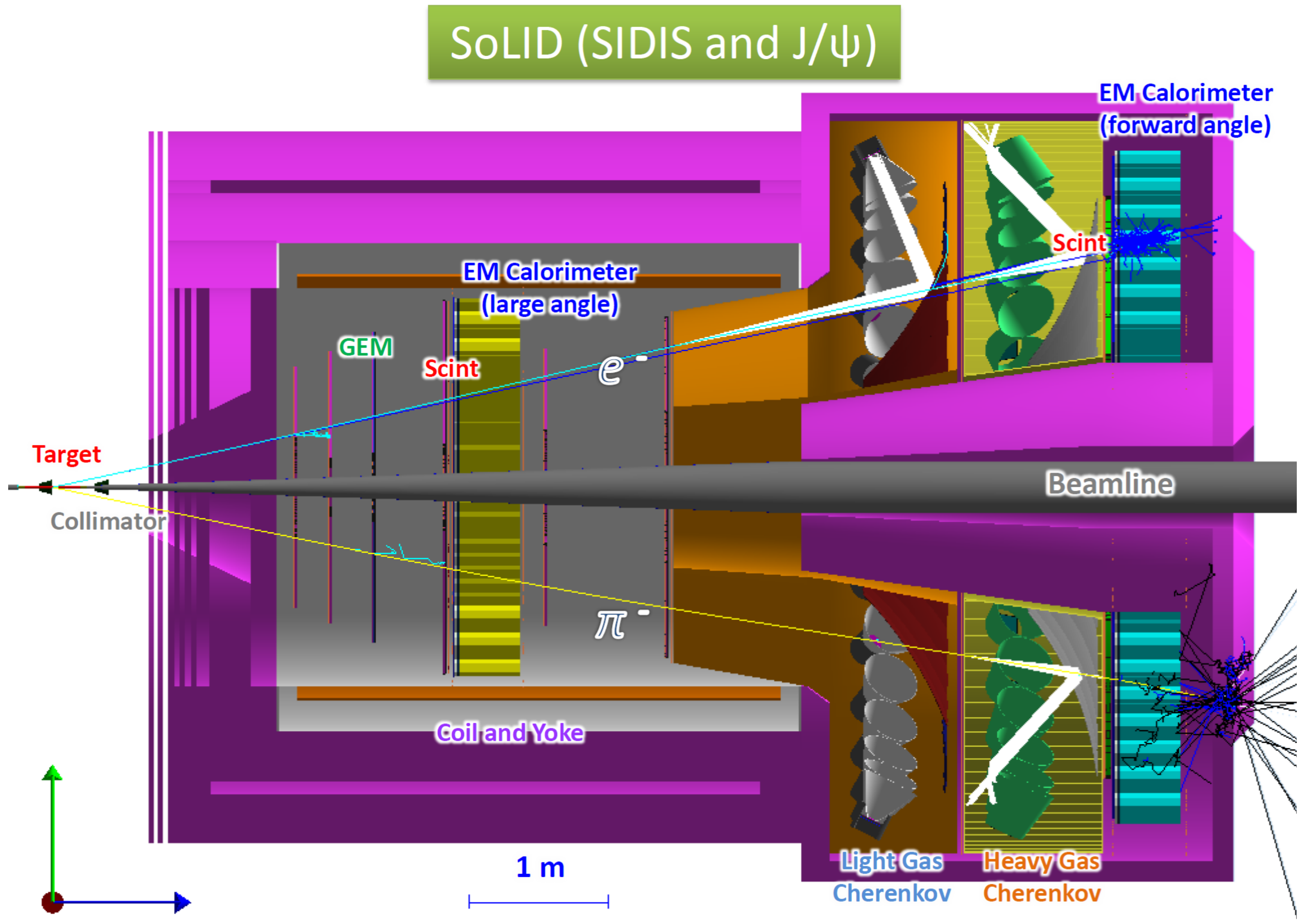
- Overview
- Generalized Parton Distributions
- SoLID GPD Program
- Summary

SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

The SoLID Program

- Full exploration of JLab 12 GeV upgrade with broad physics program
- Capability to handle high luminosity
- Large acceptance with full 2π azimuthal angle coverage, with polar angle coverage: $8^\circ \sim 24^\circ$
- Two major configurations with detectors interchangeable
  - ☑ PVDIS (See Ye Tian's talk)
    - Fundamental symmetries: standard model test and hadron structure
  - ☑ SIDIS and J/ψ (See Sylvester Joosten's talk)
    - Nucleon structure: 3D imaging of the nucleon in momentum space in valence quark region
    - QCD: probe the color field in the nucleon, access to QCD conformal anomaly —J/ψ production at threshold
  - ☐ **GPD program**





Nucleon's Structure Functions

5D

GTMD $F(x, \boldsymbol{\Delta}_T, \boldsymbol{k}_T)$ $\xleftrightarrow{\text{F.T.}}$ **Wigner Distribution** $W_p^u(x, \boldsymbol{k}_T, \boldsymbol{b}_T), \ldots$

GTMD $\xrightarrow{\boldsymbol{\Delta}_T = 0}$ TMD; GTMD $\xrightarrow{\int d^2\boldsymbol{k}_T}$ GPD; Wigner Distribution $\xrightarrow{\int d^2\boldsymbol{k}_T}$ IPD

3D

TMD $f_1^u(x, \boldsymbol{k}_T), h_1^u(x, \boldsymbol{k}_T), \ldots$

GPD $H^u(x, \boldsymbol{\xi}, t), E^u, \tilde{H}^u, \tilde{E}^u \ldots$ $\xleftrightarrow{\text{F.T.}}$ **IPD** $H^u(x, \boldsymbol{\xi}, \boldsymbol{b}_T), E^u, \tilde{H}^u, \tilde{E}^u \ldots$

TMD $\xrightarrow{\int d^2\boldsymbol{k}_T}$ PDF; GPD $\xrightarrow{t = 0}$ PDF; GPD $\xrightarrow{\int dx}$ Form Factors; IPD $\xrightarrow{\int dx}$ Charge Density

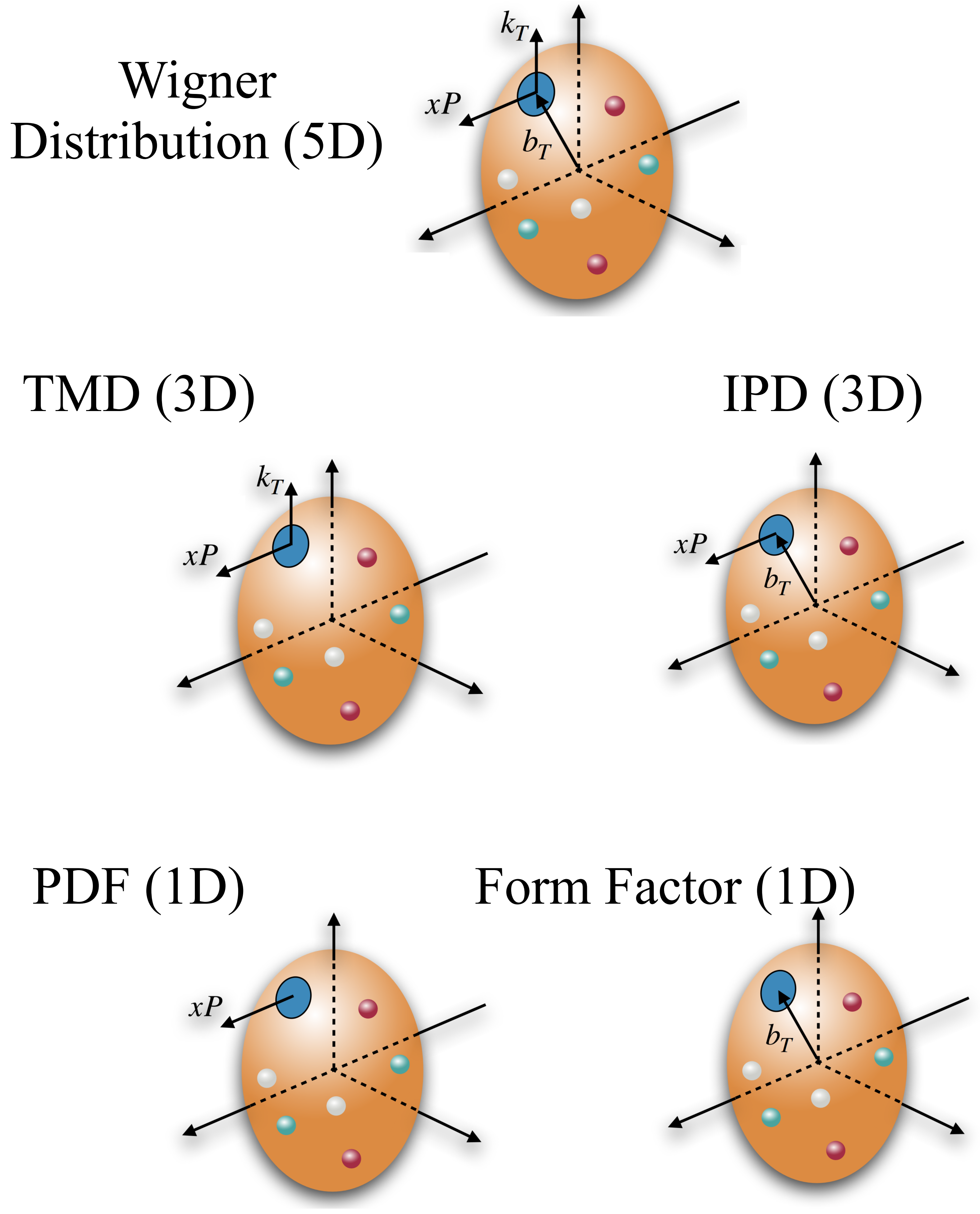
1D

PDF $f_1^u(x), g_1^u(x), h_1^u(x), \ldots$

Form Factors $G_E(Q^2), G_M(Q^2)$ $\xleftrightarrow{\text{F.T.}}$ **Charge Density** $\rho(b_T)$

PDF $\xrightarrow{\int dx}$ Charge; Form Factors $\xrightarrow{t = 0}$ Charge; Charge Density $\xrightarrow{\int db_T}$ Charge

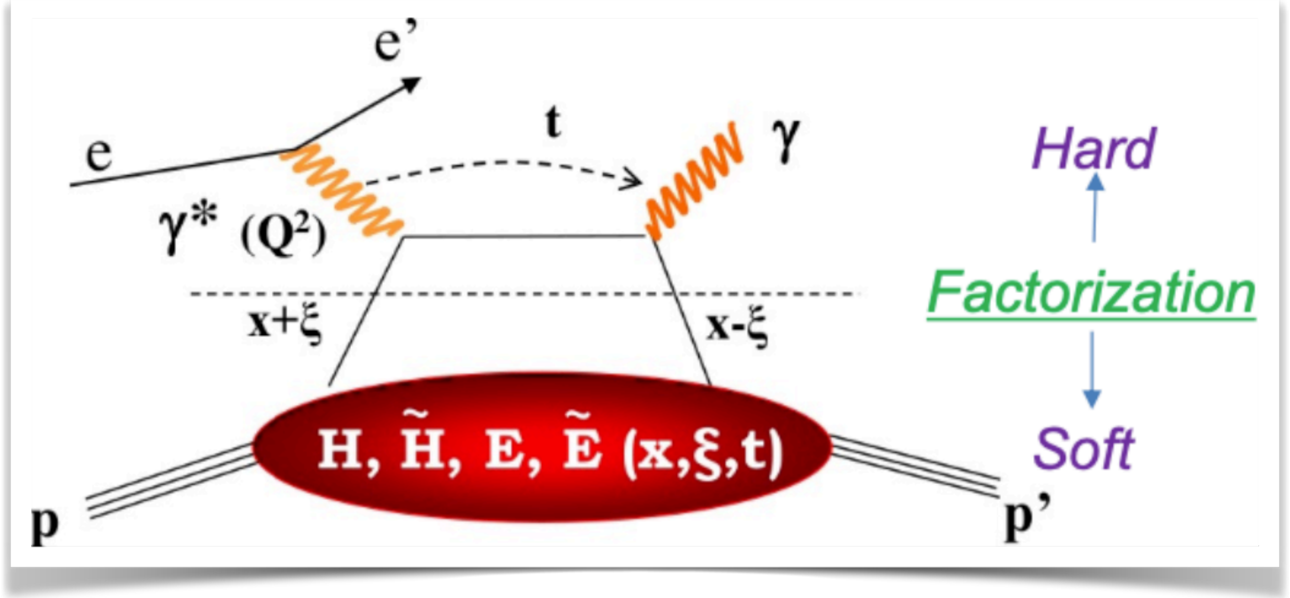
Charge g



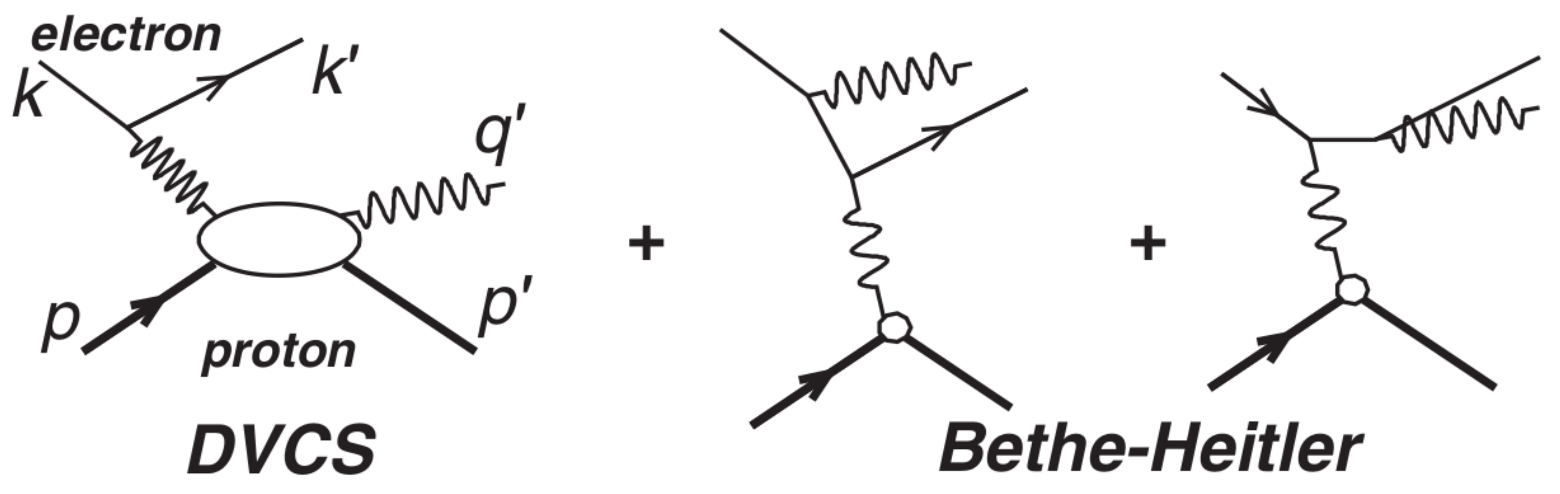
Generalized Parton Distributions

- Correlates 1D longitudinal momentum and 2D transverse position (Fourier Transform)
- GPDs are universal quantities and reflect nucleon structure independently of the probing reaction
- 8 GPDs at leading twist
  - Chiral Even GPDs, helicity of Parton unchanged: $H^{q/g}, E^{q/g}, \tilde{H}^{q/g}, \tilde{E}^{q/g}$,
  - Chiral Odd or transversity GPDs, helicity of Parton flipped: $H_T^{q/g}, E_T^{q/g}, \tilde{H}_T^{q/g}, \tilde{E}_T^{q/g}$
- Access through exclusive processes (DVCS, DVMP, DDVCS, TCS, …), Factorization Theorem

spin	*N no flip*	*N flip*
q no flip	H	E
q flip	$\tilde{H}$	$\tilde{E}$



- Deeply Virtual Compton Scattering (DVCS) is the **Golden Channel** for accessing GPDs



$$\sigma(lp \to l\gamma p) \propto |\tau_{DVCS}|^2 + I + |\tau_{BH}|^2$$

- Access GPDs via Interference Terms

$$I = |\tau_{DVCS}\tau_{BH}^{\star} + \tau_{DVCS}^{\star}\tau_{BH}|^2$$

- DVCS only measures ***Compton Form Factors (CFFs)***

$$\tau_{DVCS} \propto \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi \mp i\epsilon}dx = \underbrace{P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi}dx}_{\mathfrak{Re}(\mathcal{H})} - \underbrace{i\pi H(\pm\xi,\xi,t)}_{\mathfrak{Im}(\mathcal{H})}$$

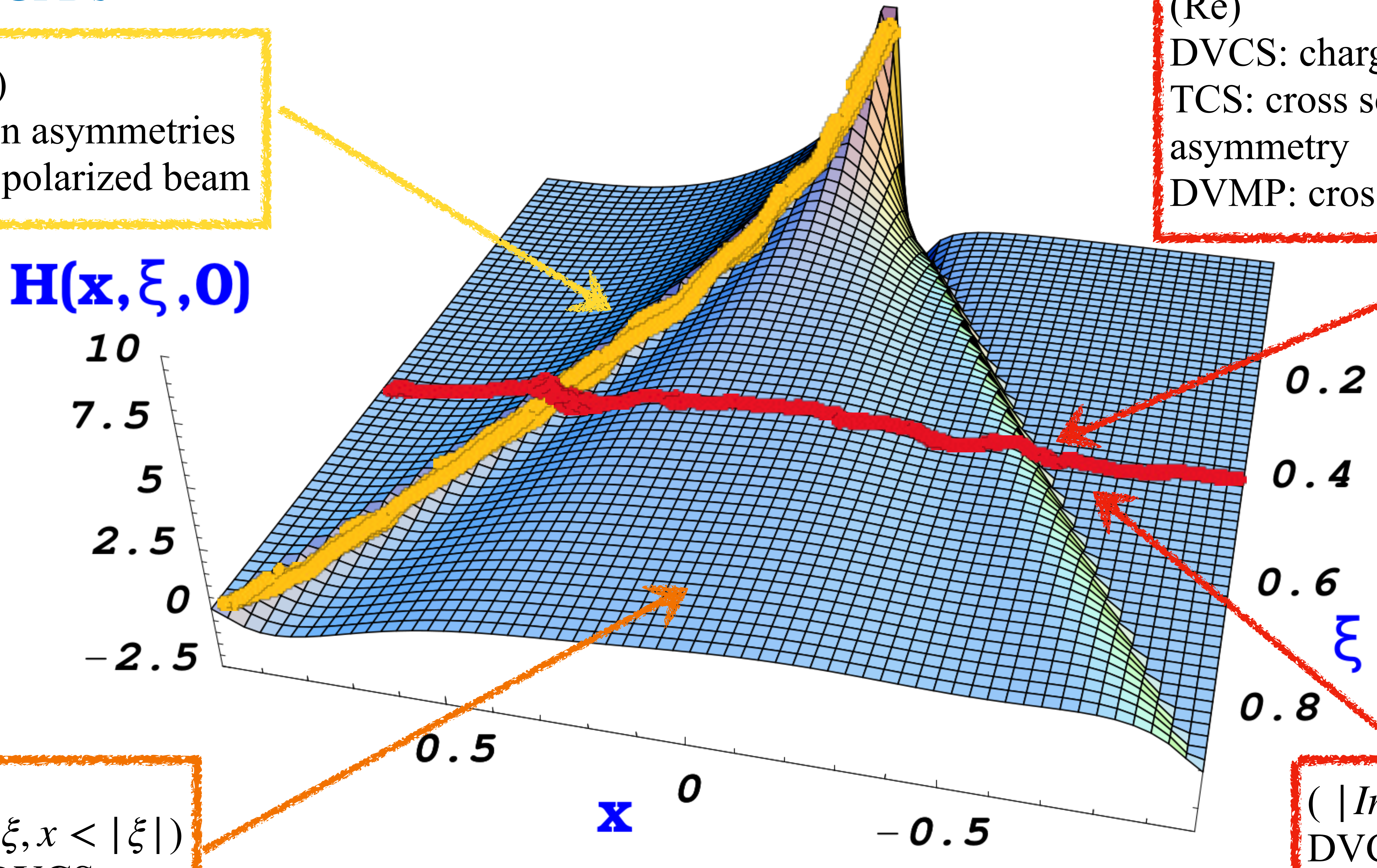
- 8 *CFFs* for $H, E, \tilde{H}, \tilde{E}$

General Compton Processes Accessing GPDs

- Different exclusive processes, different experimental observables, crucial to fully disentangle GPDs

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

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



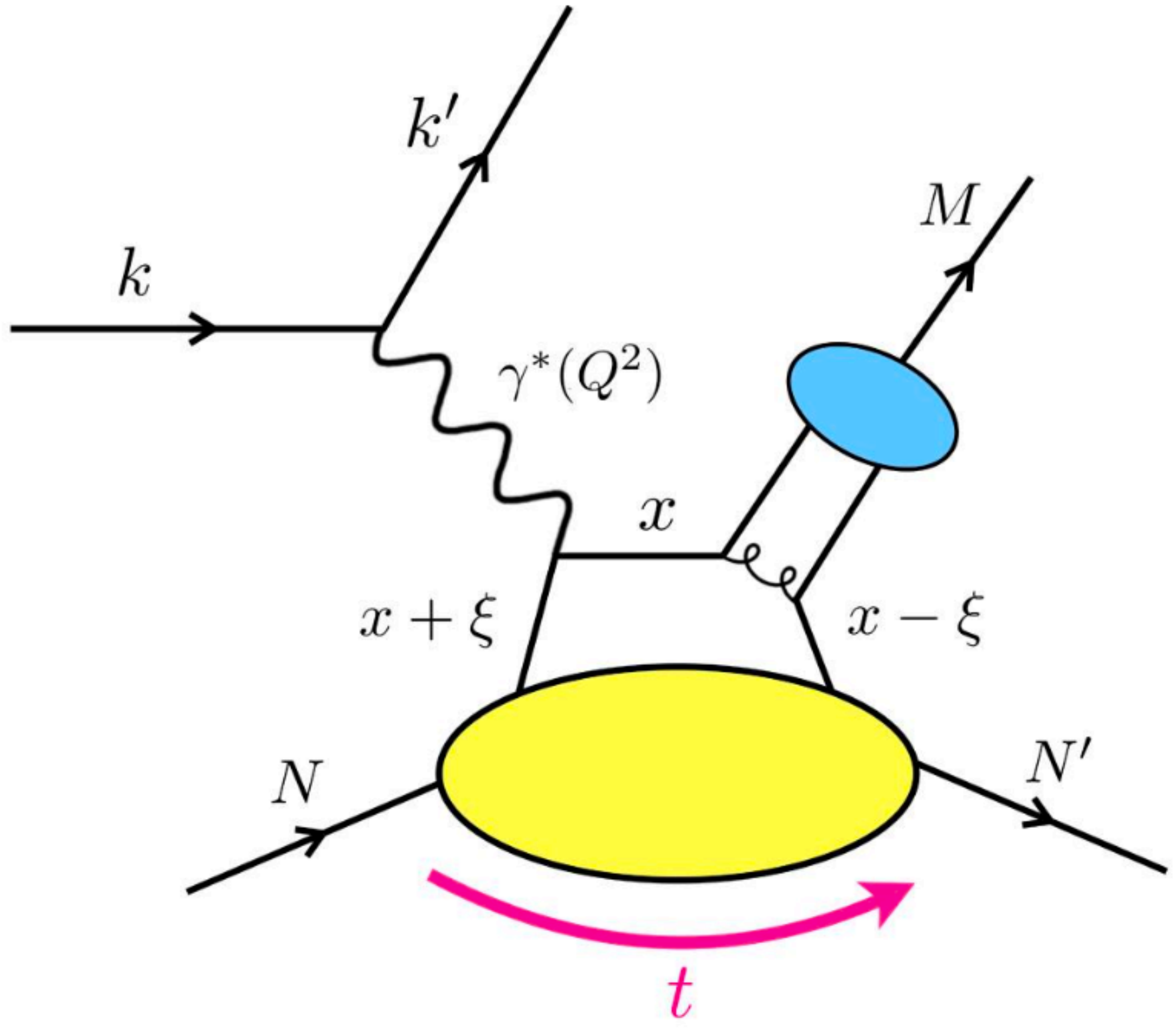
(Im, $x \neq \xi, x < |\xi|$)
Double DVCS

($|Im|^2 + |Re|^2$)
DVCS: cross section
DVMP: cross-section, asymmetries

The SoLID GPD Program

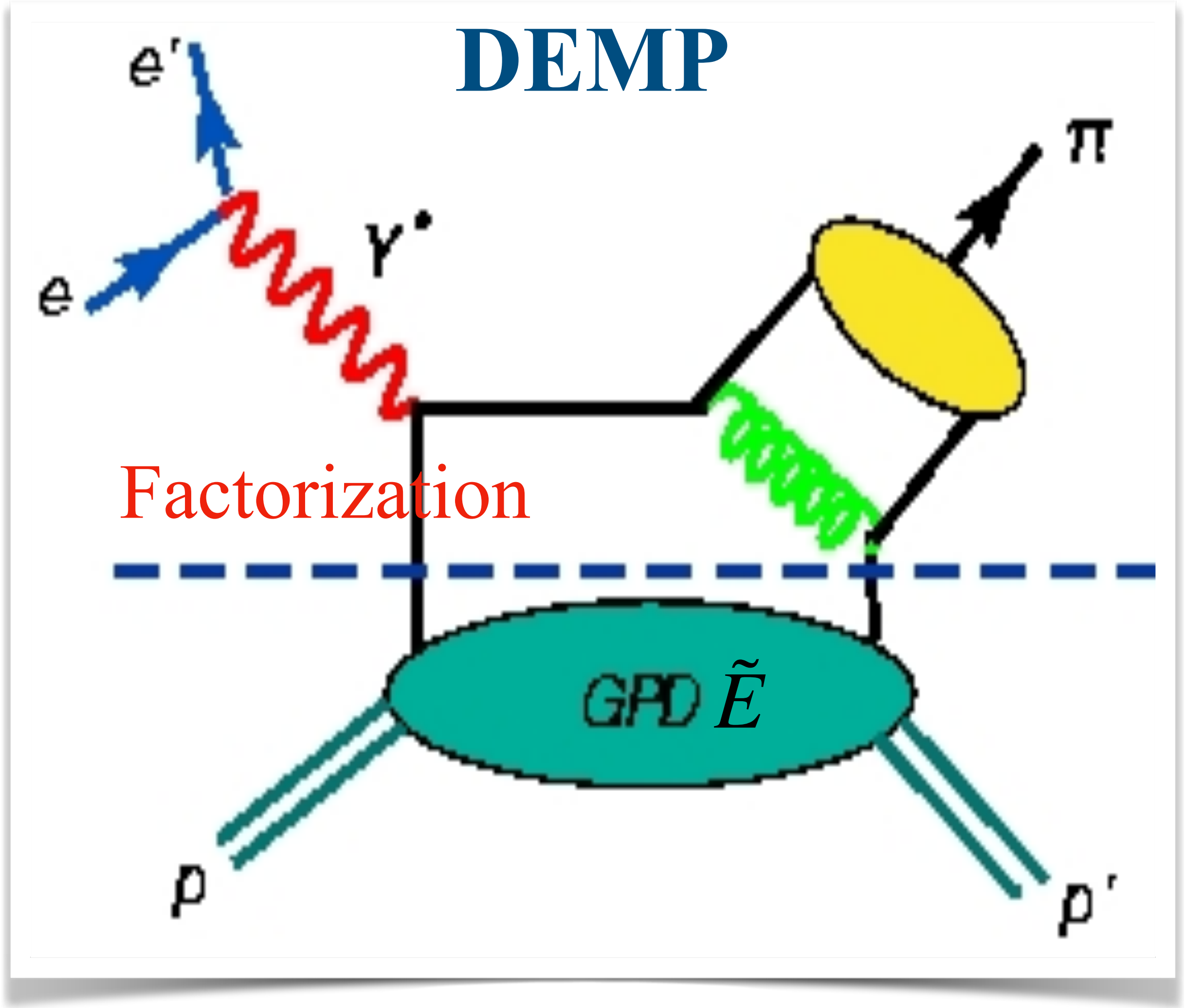
- **Deep Exclusive π^- Production using Transversely Polarized ^3He Target**
  - G.M. Huber, Z. Ahmed, Z. Ye
  - Approved as run group with Transverse Pol. ^3He SIDIS (**E12-10-006B**)
- **Timelike Compton Scattering (TCS) with circularly polarized beam and unpolarized LH2 target**
  - Z.W. Zhao, P. 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 LH2 Target**
  - E. Voter, M. Boer, A. Camsonne, K. Gnanvo, N. Sparveri, Z. Zhao
  - LOI 2015, LOI 2023
- **DVCS on polarized ^3He**
  - Z. Ye (under study)

1. DEMP

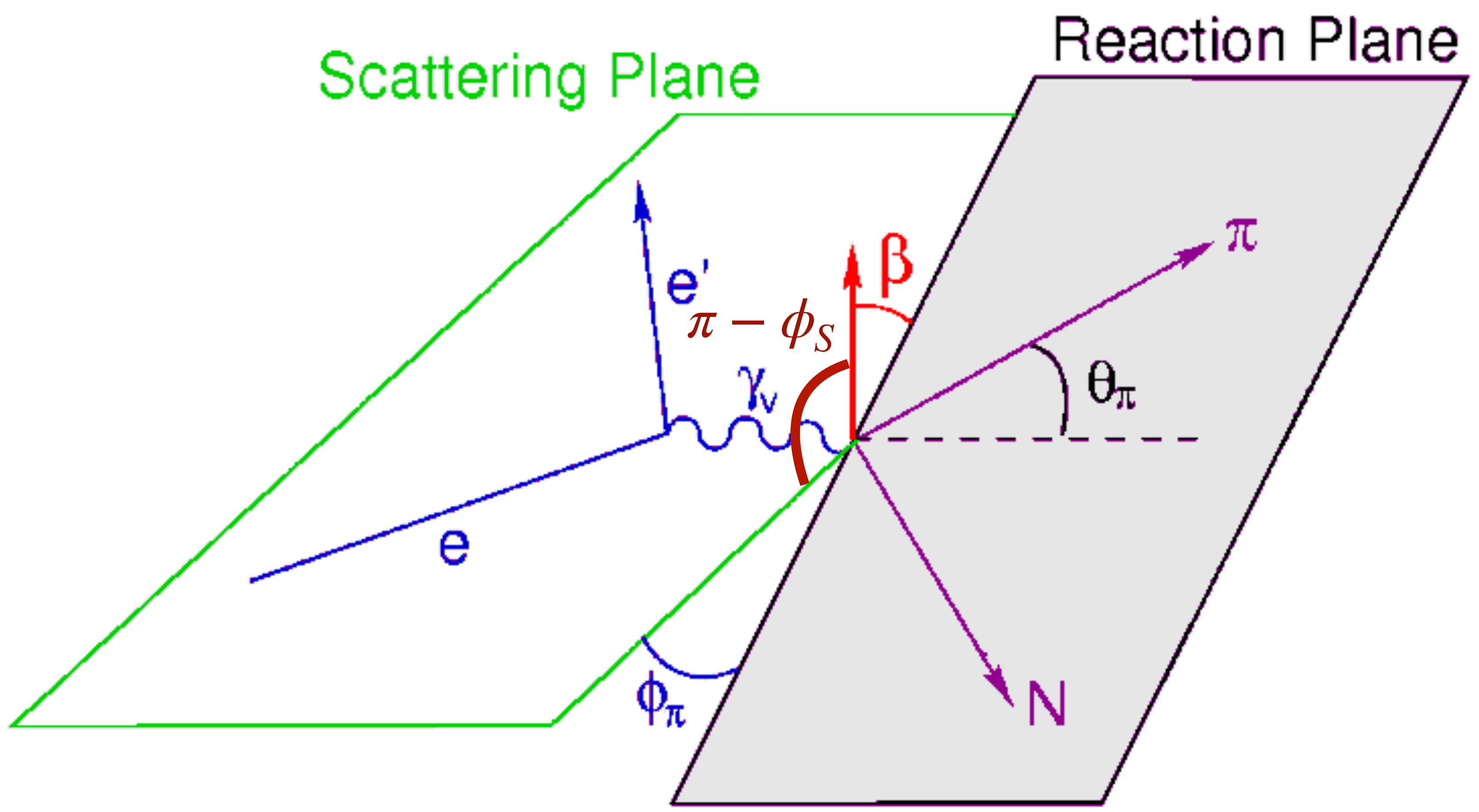


E12-10-006B: Deep Exclusive π^- from Transversely Polarized n

- **Probe GPD $\tilde{E}$ with DEMP**
  - GPD $\tilde{E}$ connects to nucleon Pseudoscalar Form Factor:
  - $\sum_q e_q \int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) = G_p(t)$
  - $G_p(t)$ is poorly known because it is negligible at the momentum transfer of β-decay
  - GPD $\tilde{E}$ is not related to any already known Parton distributions → essentially unknown
  - SOLID experimental measurement can provide new nucleon structure information unlikely to be available from any other sources



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



Fit $\sin\beta = \sin(\phi - \phi_S)$ dependence to extract asymmetry

Need large acceptance

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

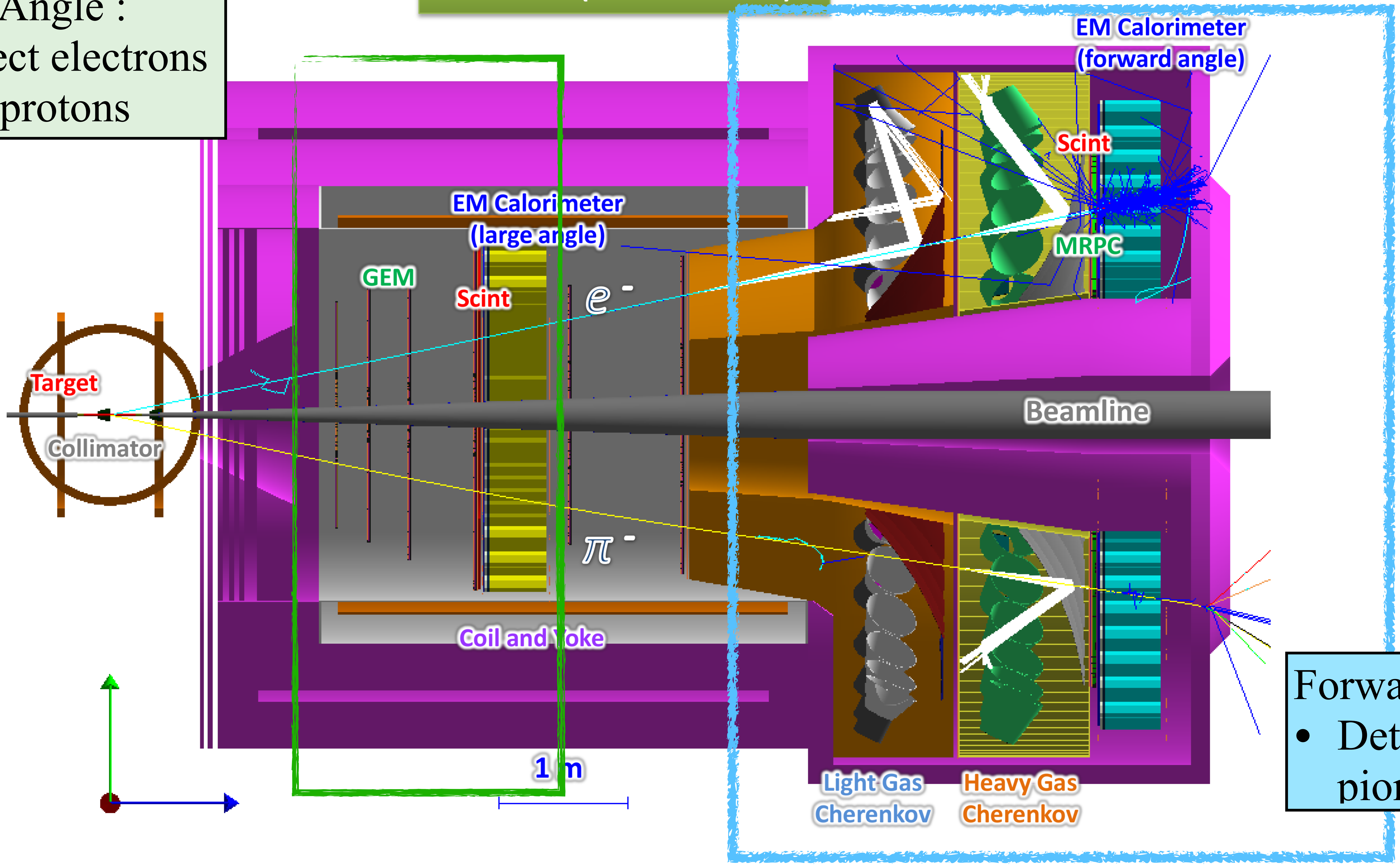
$$= \frac{\sqrt{-t'}}{2m_p} \frac{\pi\xi\sqrt{1-\xi^2} Im(\tilde{E}^* \tilde{H})}{(1-\xi^2)\tilde{H}^2 - \frac{t\xi^2}{4m_p}\tilde{E}^2 - 2\xi^2 Re(\tilde{E}^* \tilde{H})}$$

DEMP — Polarized ^{3}He SIDIS Configuration

- DEMP run in parallel with SIDIS (E12-10006): 11.0 GeV beam, polarized ^{3}He target, 48 days
- Online Coincidence Trigger (SIDIS): Electron trigger + Hadron Trigger (pions)
- Offline analysis: Identify (tag) protons and form triple-coincidence — No effect to SIDIS Experiment

Large-Angle :
- Detect electrons and protons

SoLID (SIDIS He3)



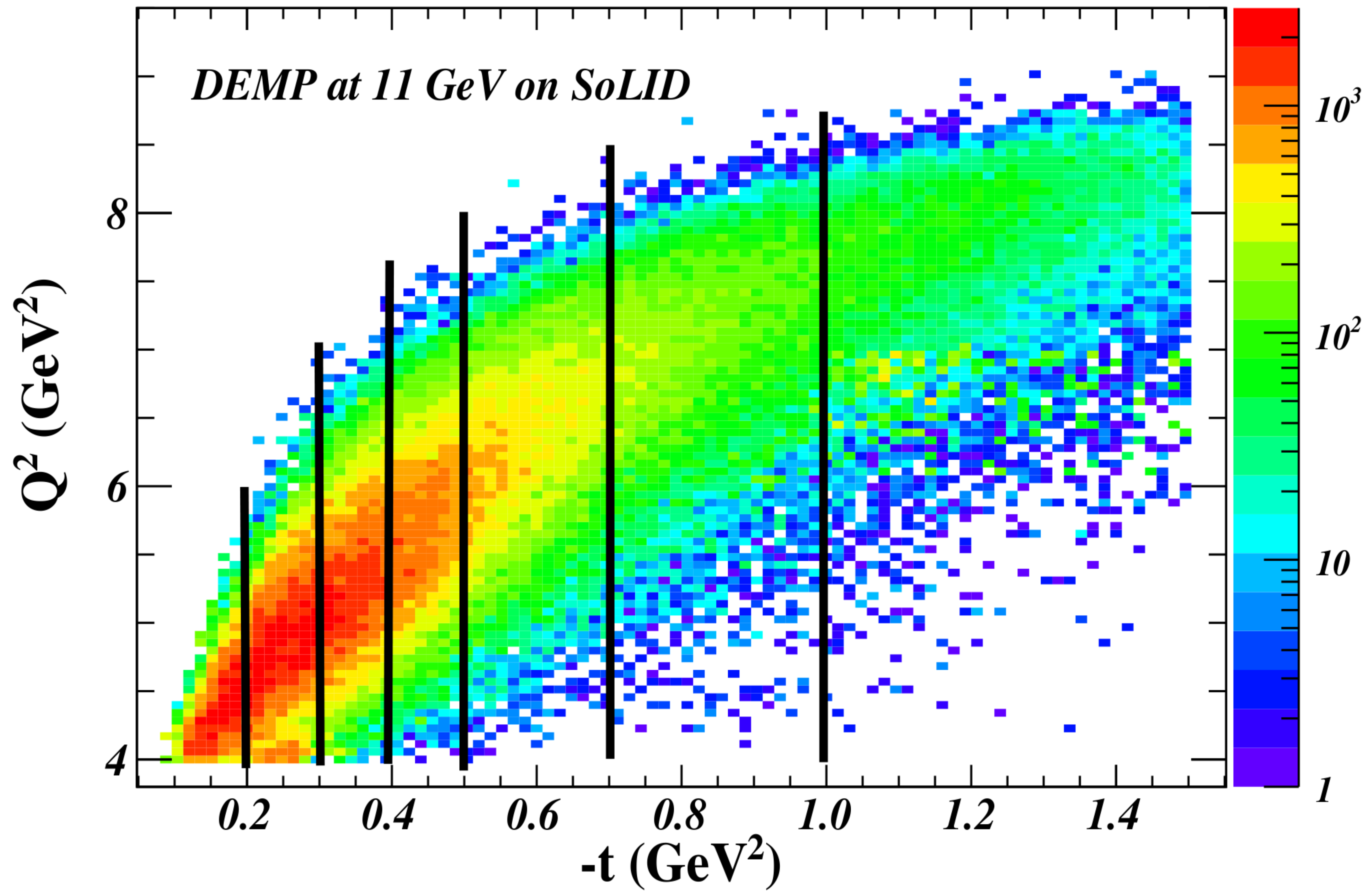
Forward-Angle:
- Detect electrons, pions, protons

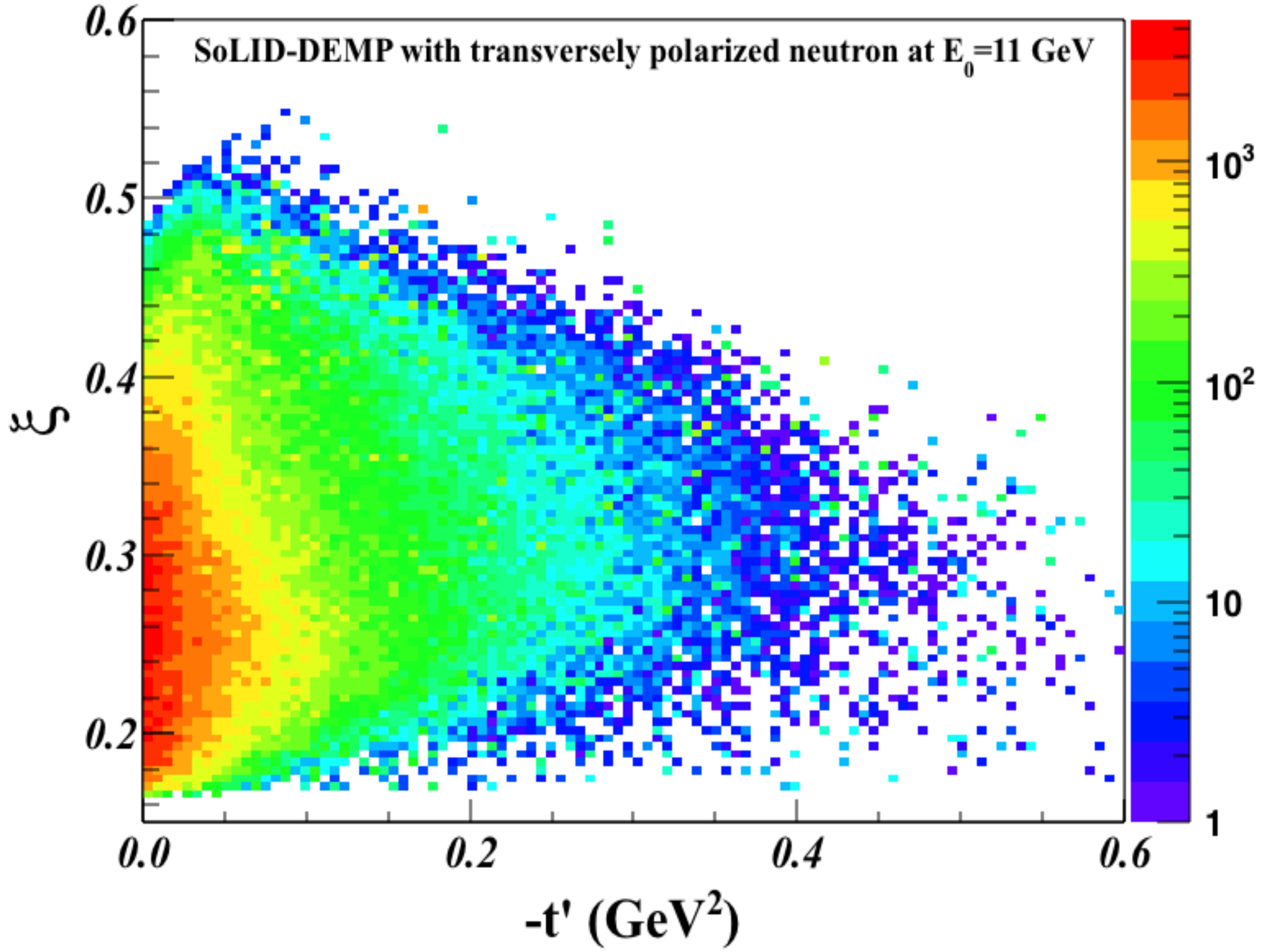
Projected Rates — need high luminosity

$Q^2 > 1$ 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

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

- Data binned into 7 *t*-bins, concentrating on the $Q^2 > 4\text{GeV}^2$ region of greatest physics interest
- HERMES and COMPASS experiments are restricted kinematically to very **small skewness ($\xi < 0.1$)**
- With SoLID, we can measure the skewness dependence of the relevant GPDs over a fairly large range of ξ

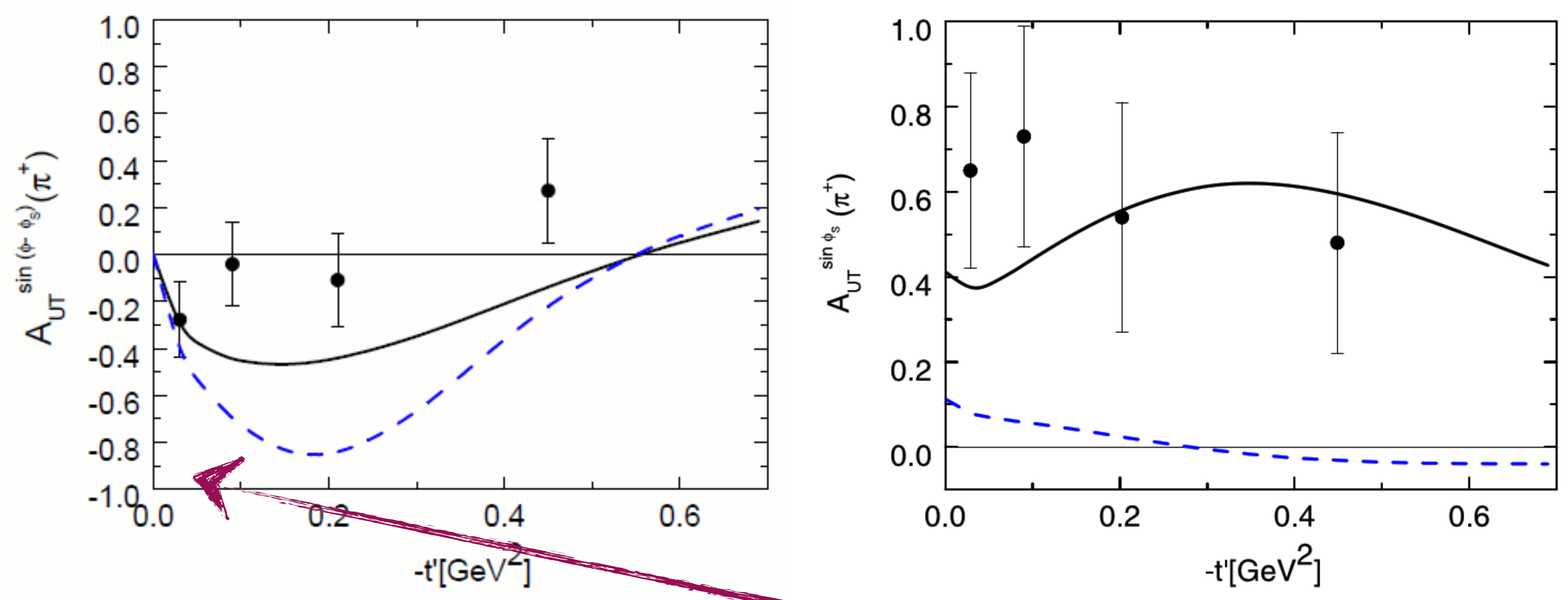




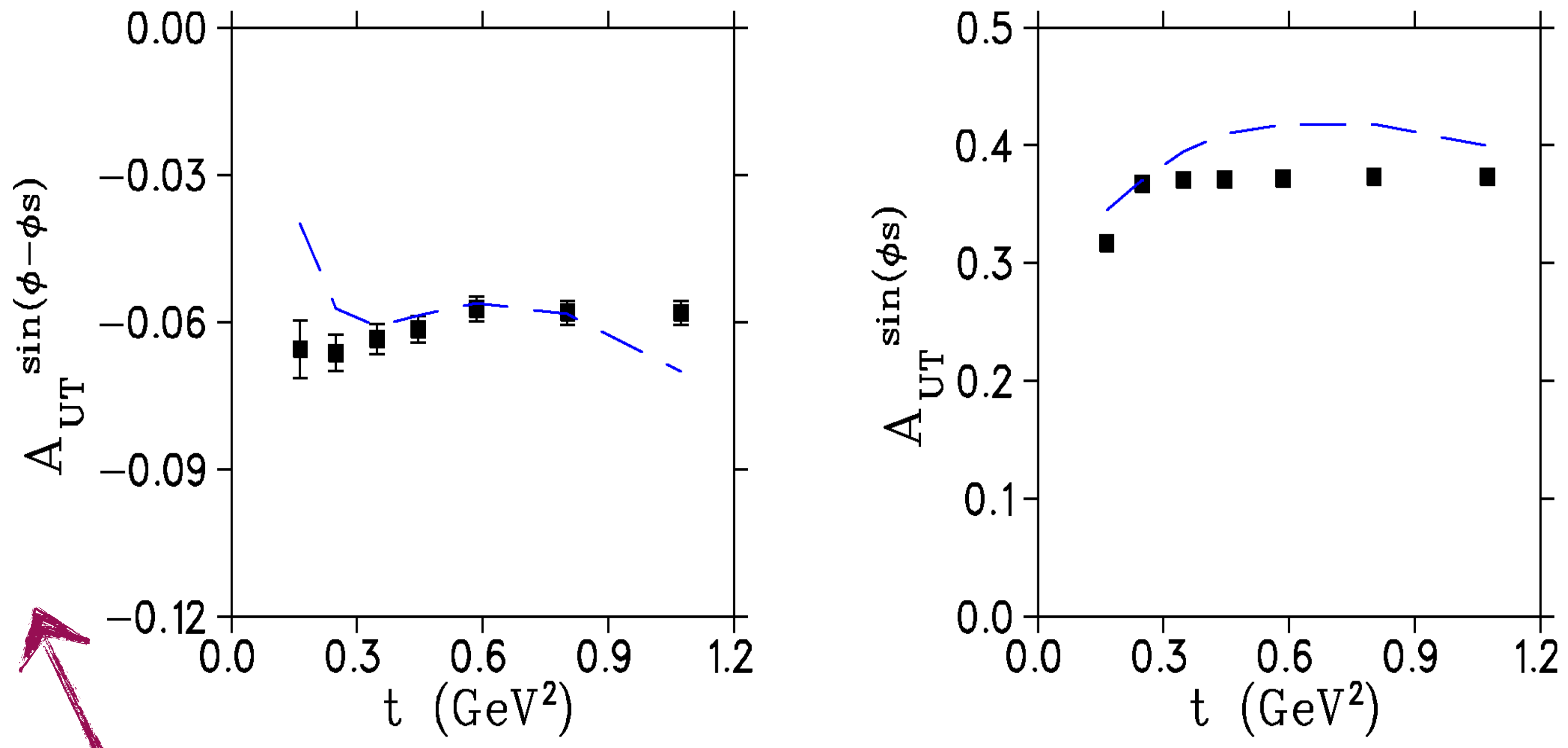
E12-10-006B: Deep Exclusive π^- from Transversely Polarized *n*

- A wide $-t$ coverage needed to obtain good understanding of the transverse single spin asymmetry
- SoLID's large acceptance and high luminosity well-suited to this measurement
- ***World unique, cannot be done anywhere else***

World Data: HERMES
Pioneering measurement [PLB 682(2010)345]



SoLID Projected Uncertainties
Proton is tagged to isolate exclusive π^- events

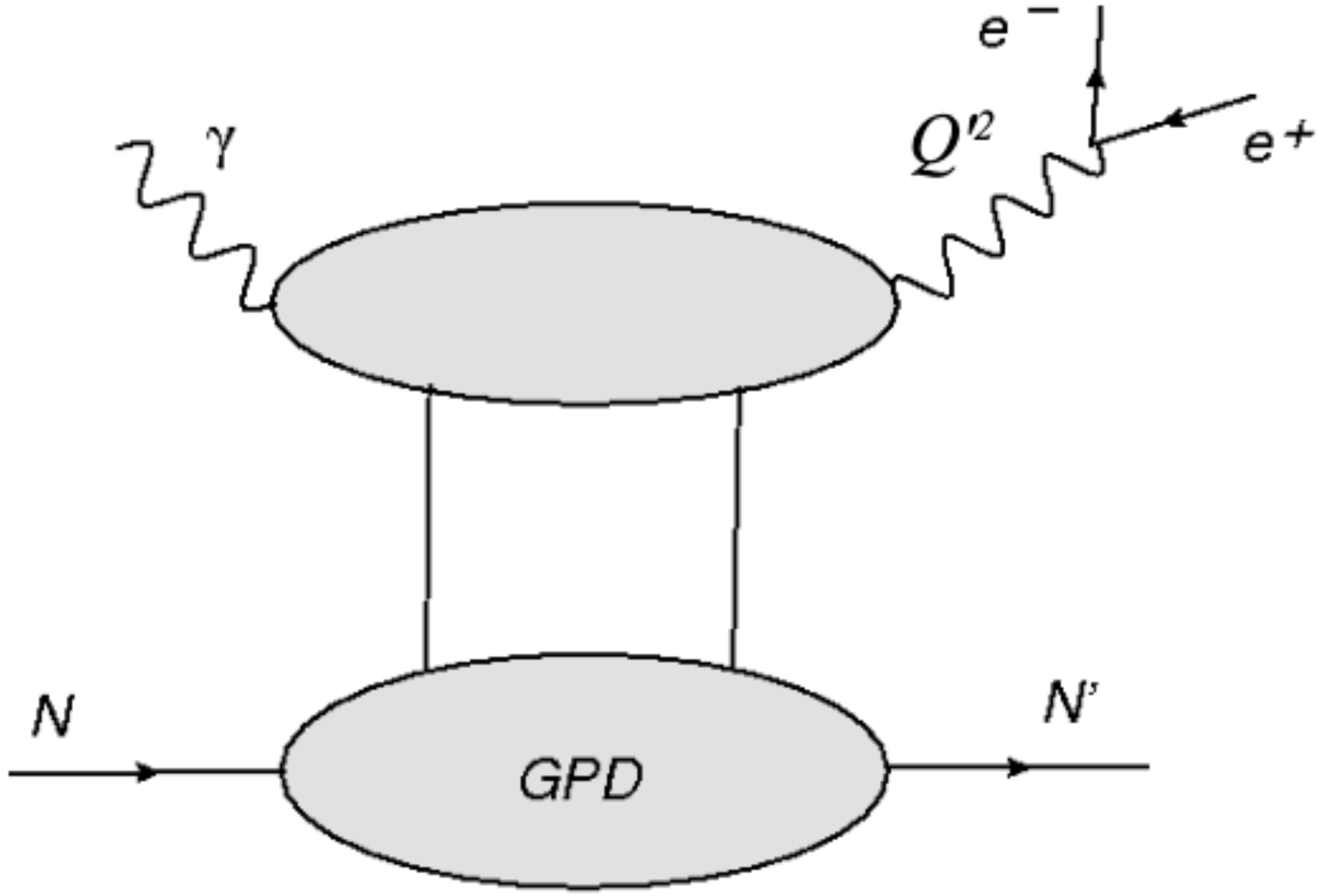


HERMES data &

Solid and dash line: Handbag calculation by Goloskokov and Kroll Eur. Phys. J. C 65, 137 (2010)

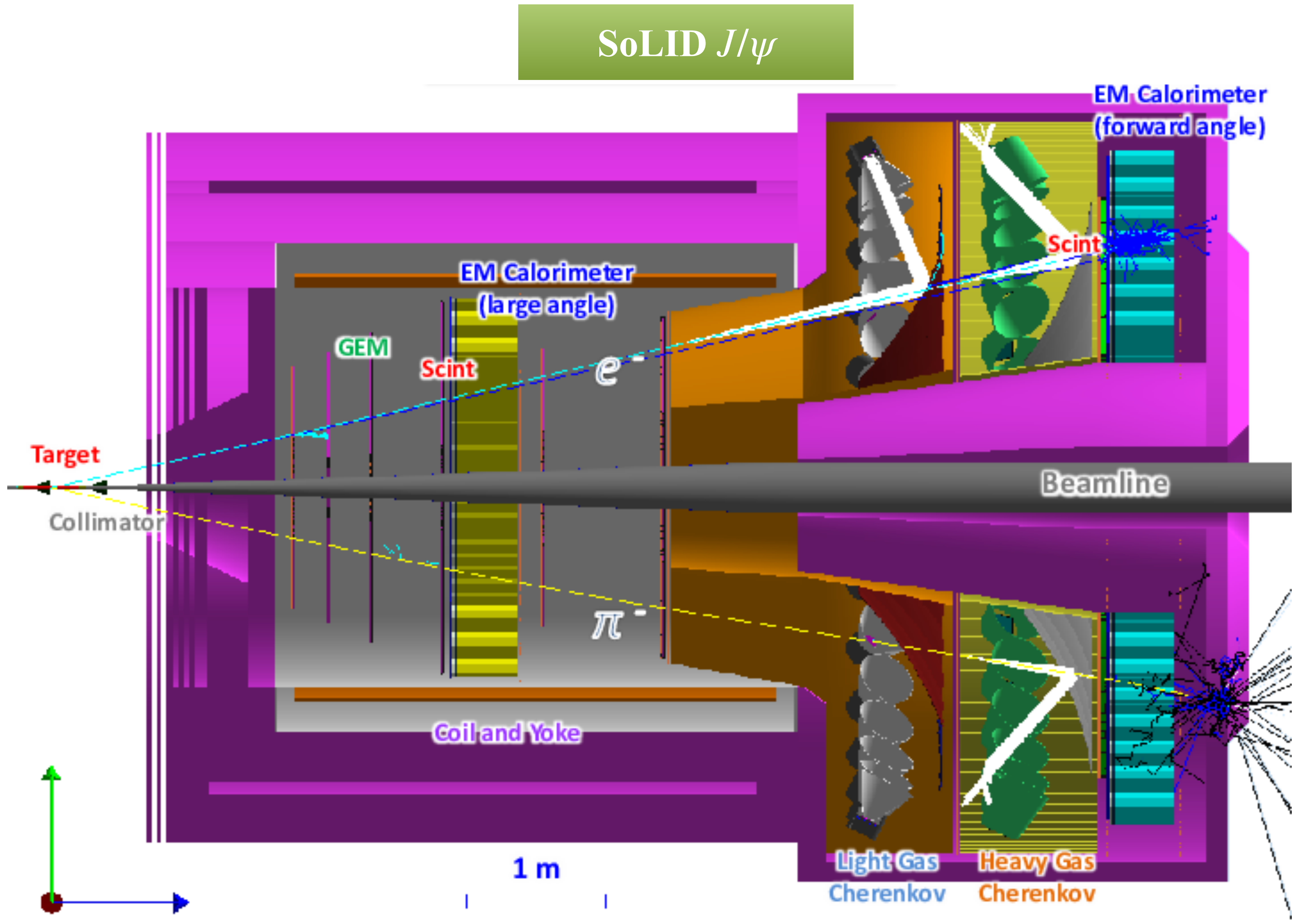
Notice the different axes scale: Significant improvement on uncertainties

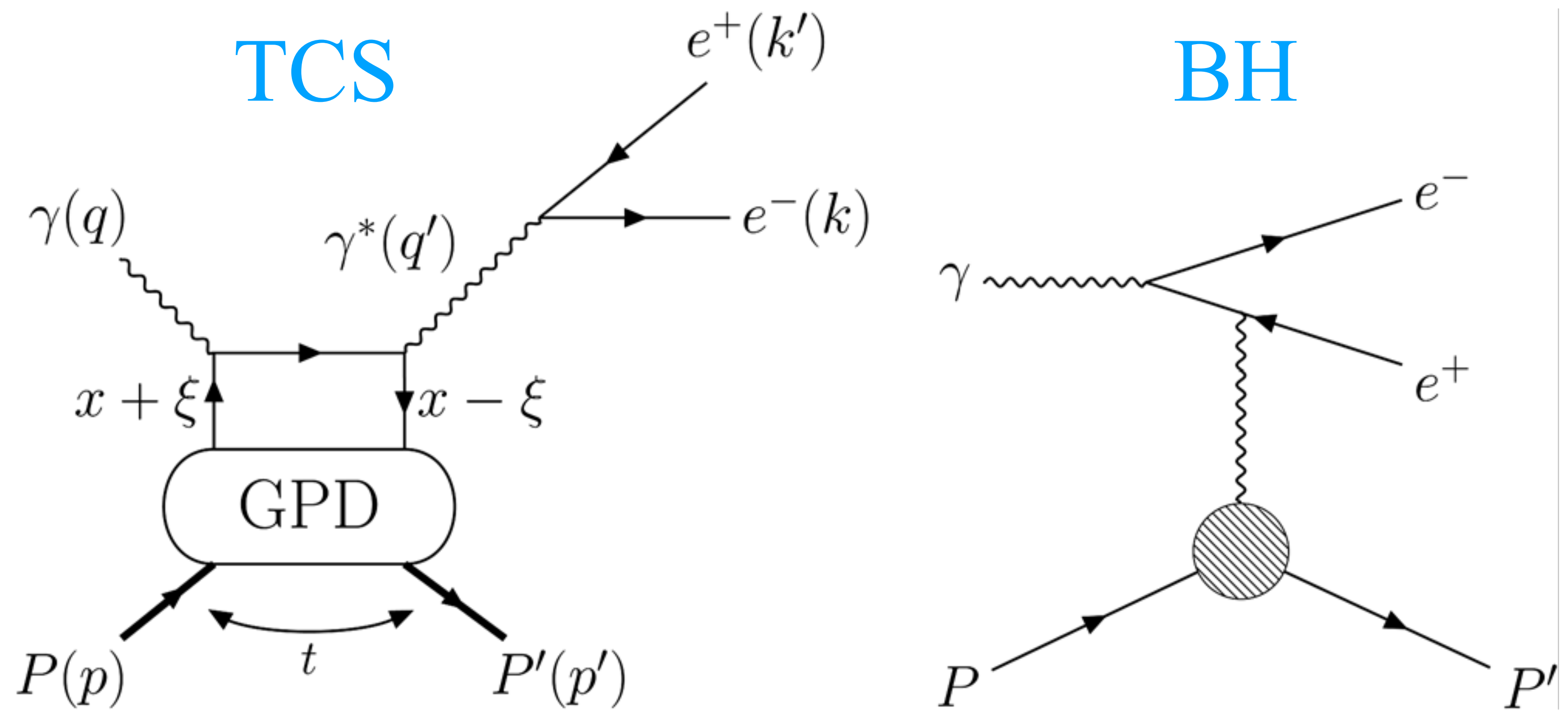
2. TCS



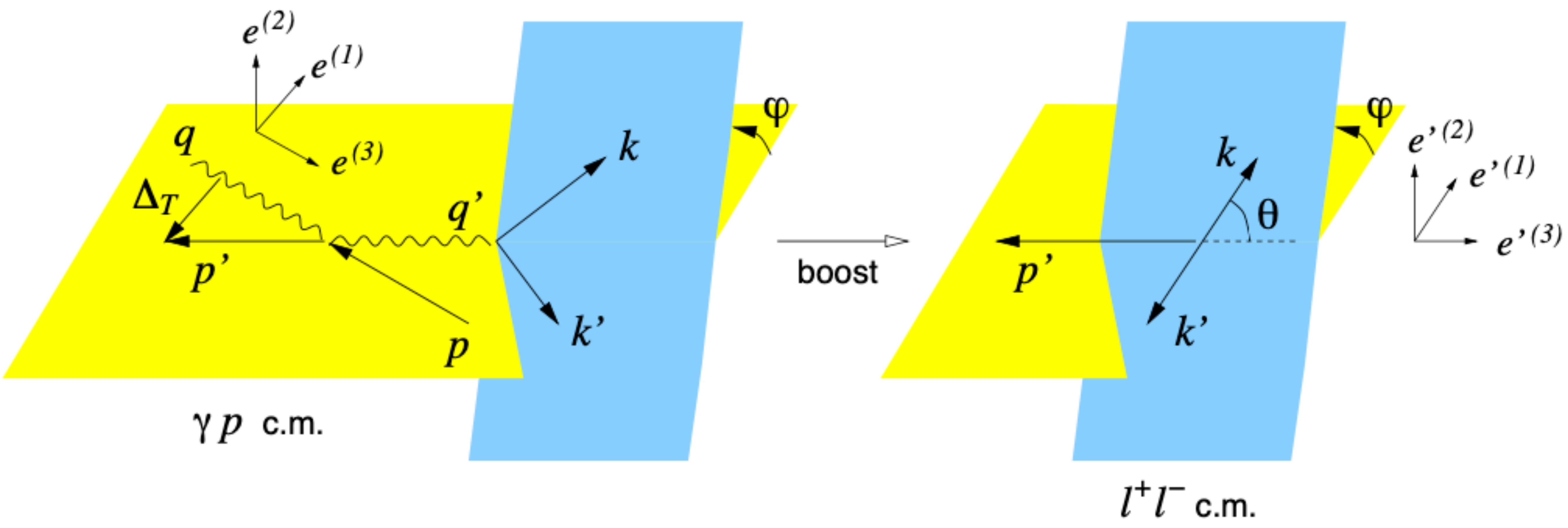
E12-12-006A: TCS with Circular Polarized Beam and LH2 Target

- Approved as run group with SoLID J/ψ (E12-12-006)
- Sharing the beam time and using the same trigger on decay e^-e^+ pair only
- Motivation
  - Access real and imaginary part of GPD H through CFF
  - Access the same GPDs like DVCS and test universality
  - New observables for global GPD fits





$\gamma p \to \gamma^\star(e^+e^-)p'$

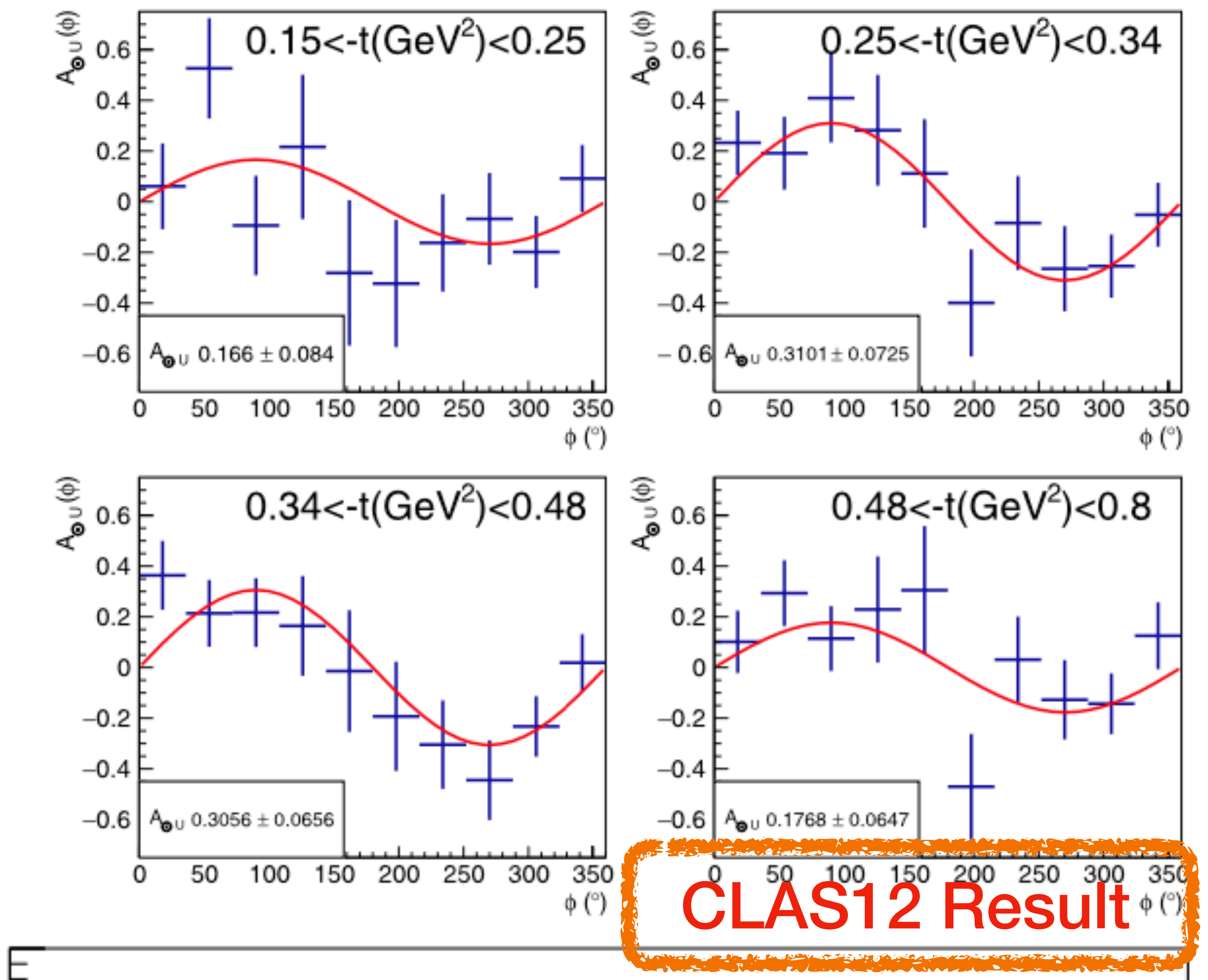


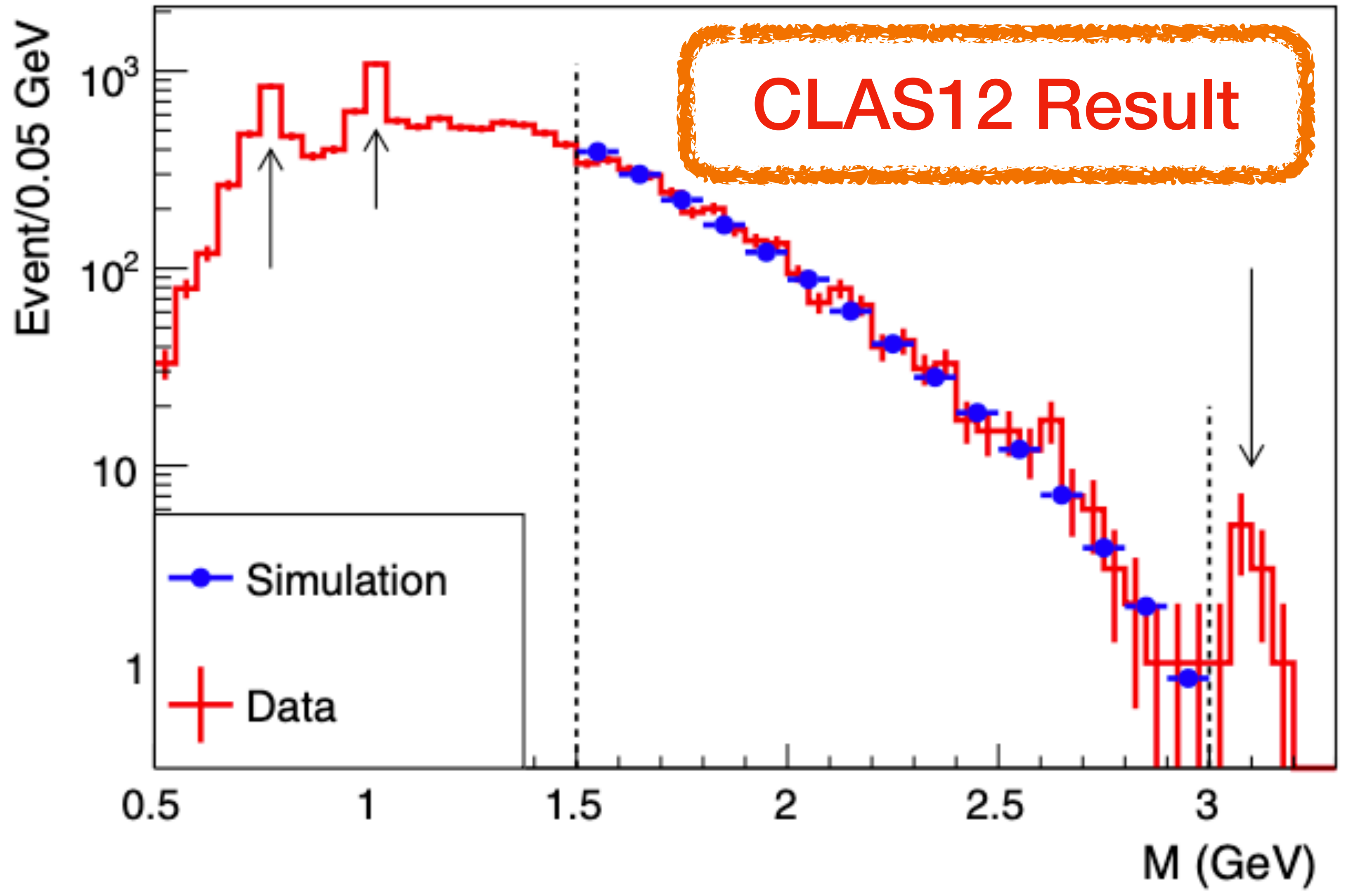
E12-12-006A: TCS with Circular Polarized Beam and LH2 Target

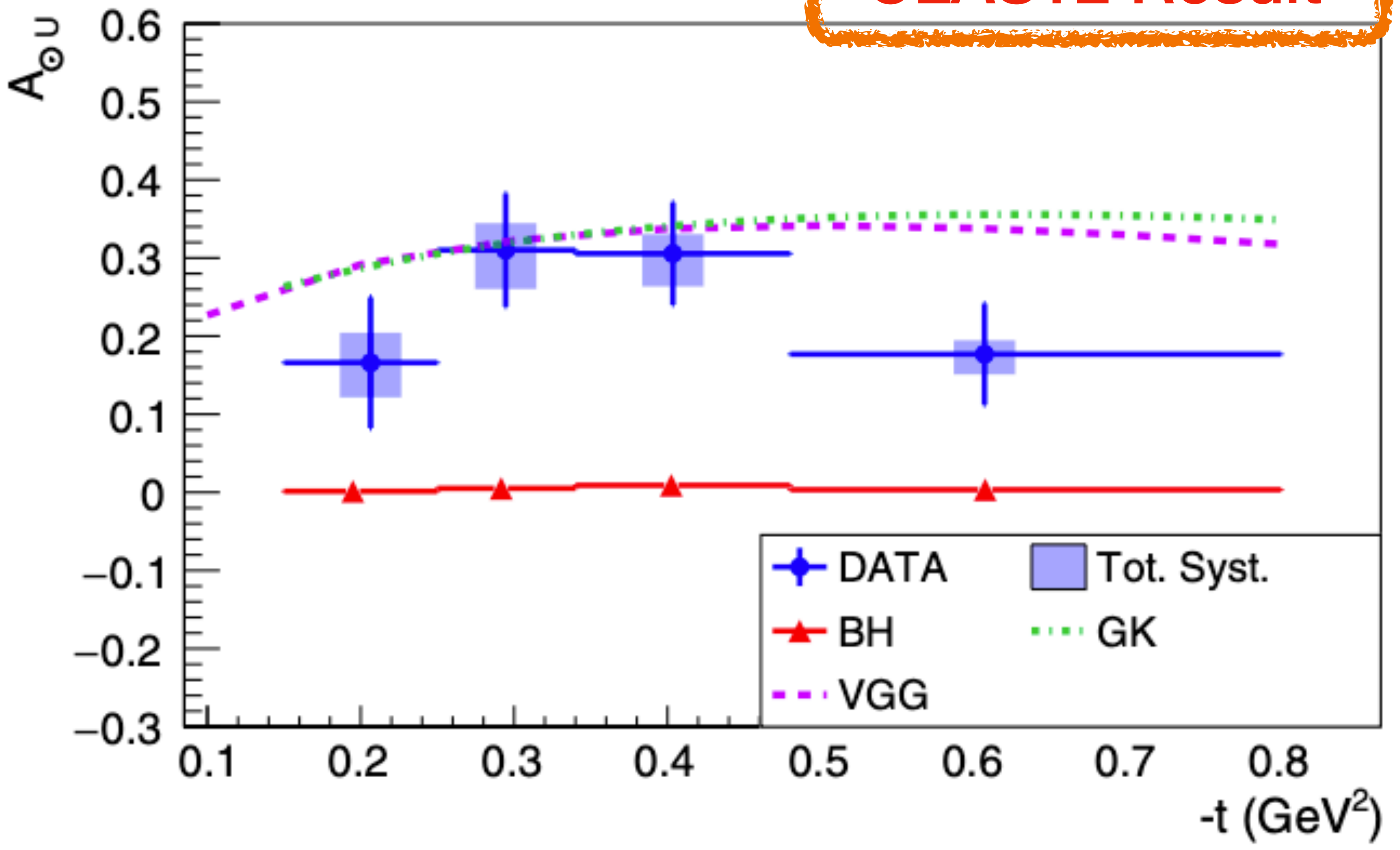
- SoLID extends CLAS12 measurements
- Promising TCS measurement results from CLAS12
  - photon beam polarization asymmetry:

$$A_{\odot U}(-t, E_\gamma, M; \phi) = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-},$$

  - First ever TCS measurement result at CLAS12 published at PRL, 127, 262501(2021) obtained nonzero beam polarization asymmetry $A_{\odot U}$ (GPD universality) and forward-backward asymmetry A_{FB} (access D-term)
  - Limited by low statistics



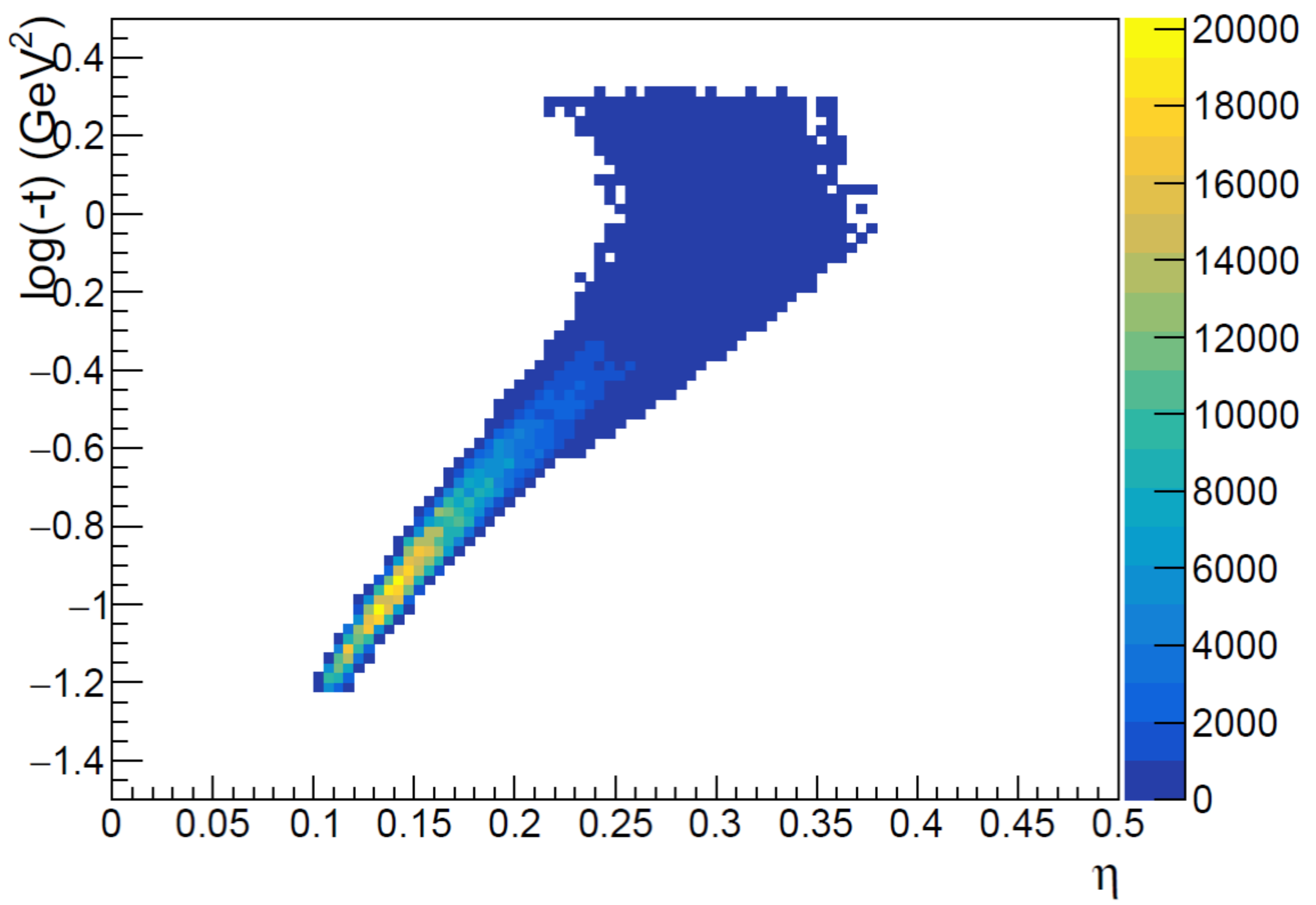


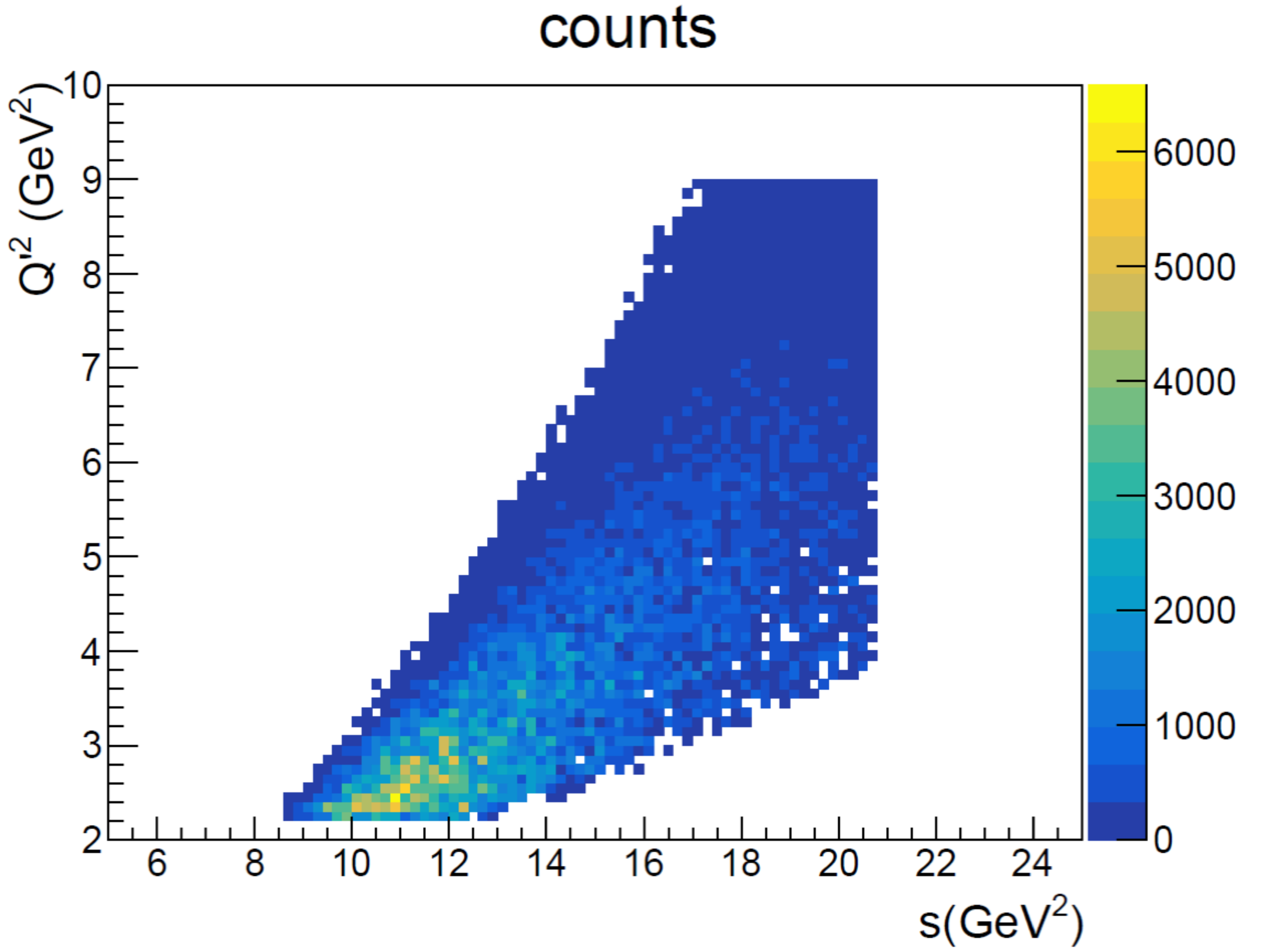


E12-12-006A: TCS with Circular Polarized Beam and LH2 Target

- SoLID TCS will have at least 1 order larger statistics than CLAS12 and usher TCS study into **precision era** with **multi-dimensional binning**
  - 15 cm LH2 target, $3\mu A$ current, $1.2 \times 10^{37}/cm^2/s$ luminosity, 50 + 10 days
  - SoLID TCS has **250 times more integrated luminosity** than the CLAS12 TCS published result
  - SoLID acceptance to TCS events is about 1/4 of CLAS12, but with full azimuthal coverage, (ideal for the forward-backward asymmetry)
  - Cross-section measurement (moment): $R = \dfrac{2\int_0^{2\pi} d\phi \cos\phi \frac{dS}{dQ^2 dt d\phi}}{\int_0^{2\pi} d\phi \frac{dS}{dQ^2 dt d\phi}}$
- ***SoLID TCS could lead to study of NLO correction***

SoLID TCS Coverage



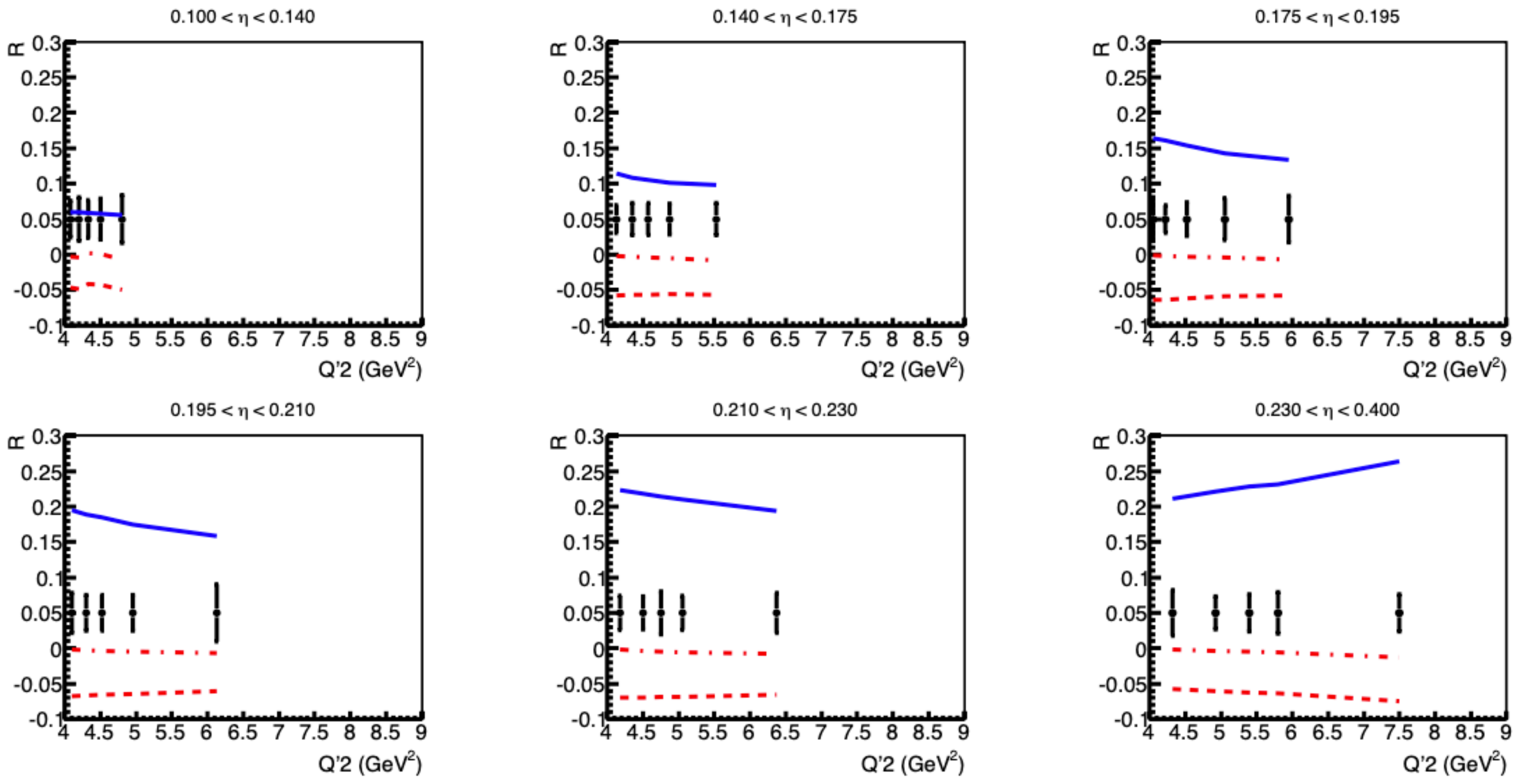


Projected R uncertainties: *cosine moment of the cross section (leading order, leading twist)*

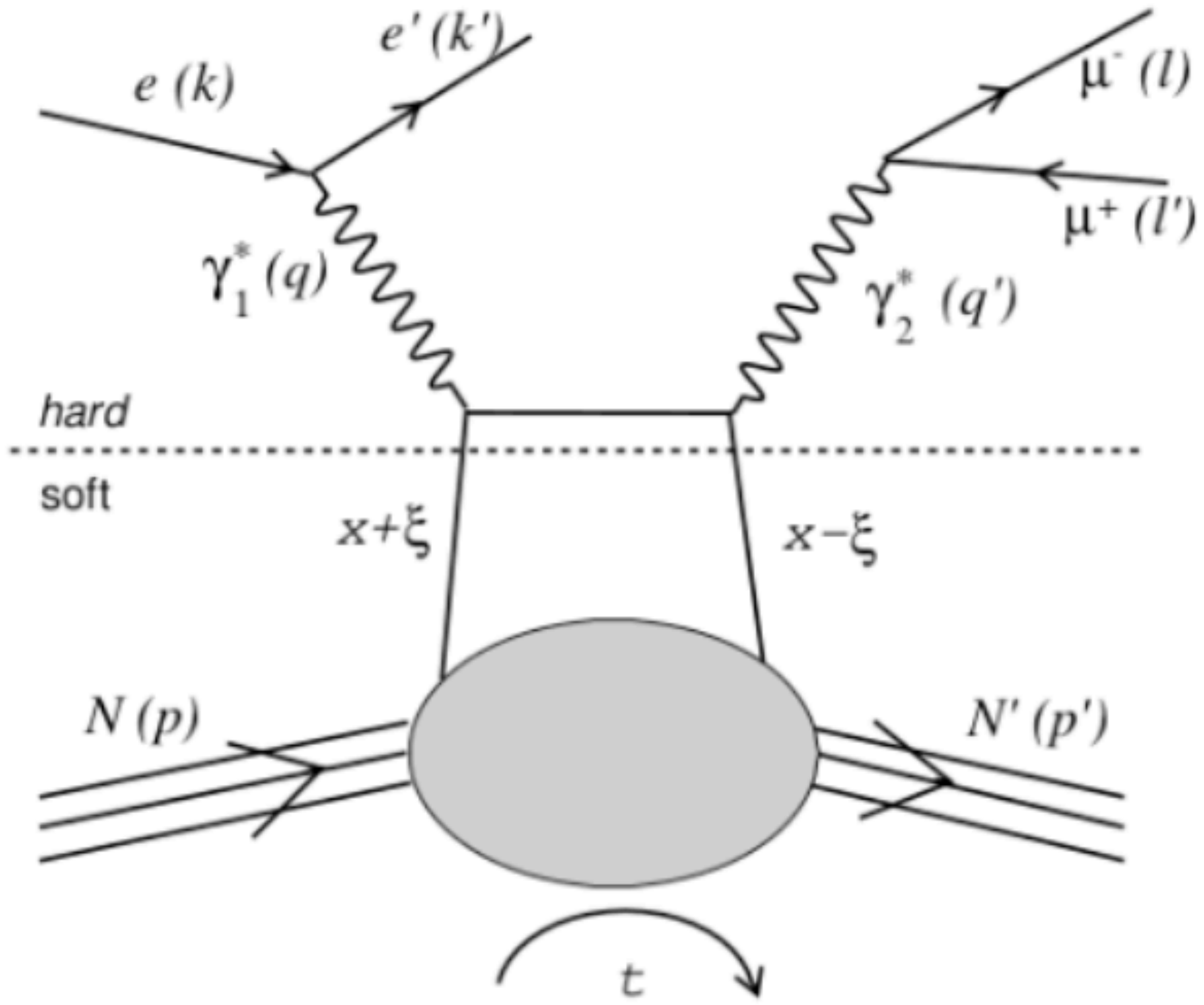
Solid blue line: dual parametrization GPD model

Middle dash line: double distribution with D-term

Bottom dash line: without D-term



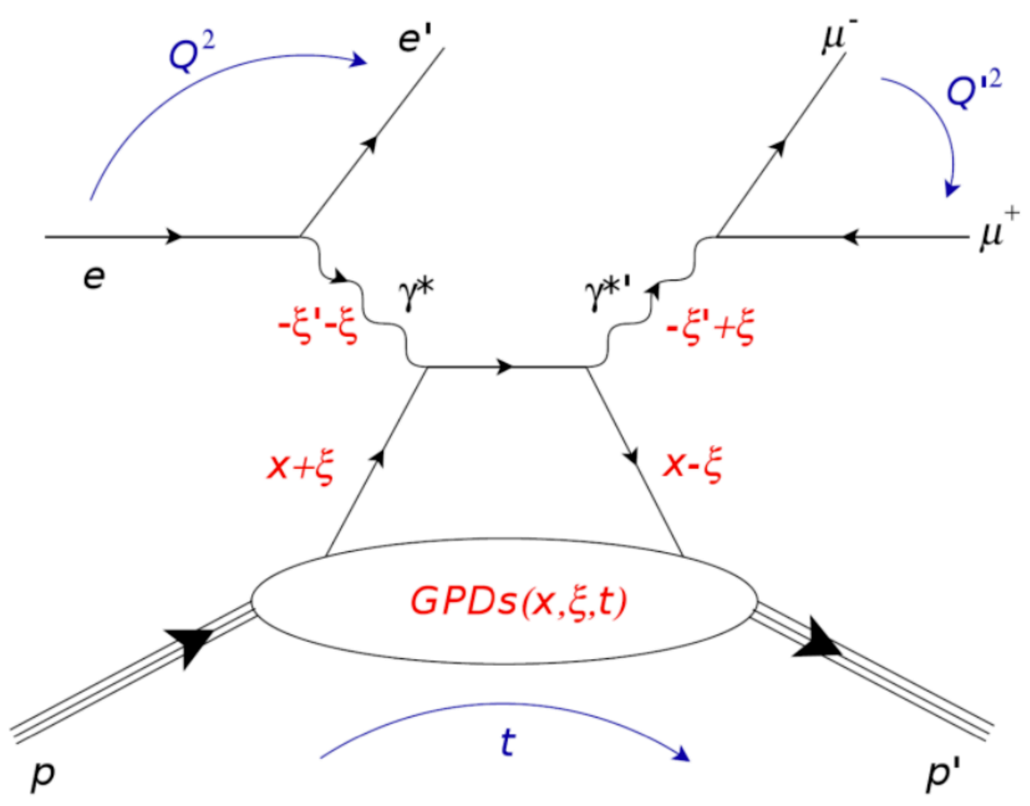
3. DDVCS



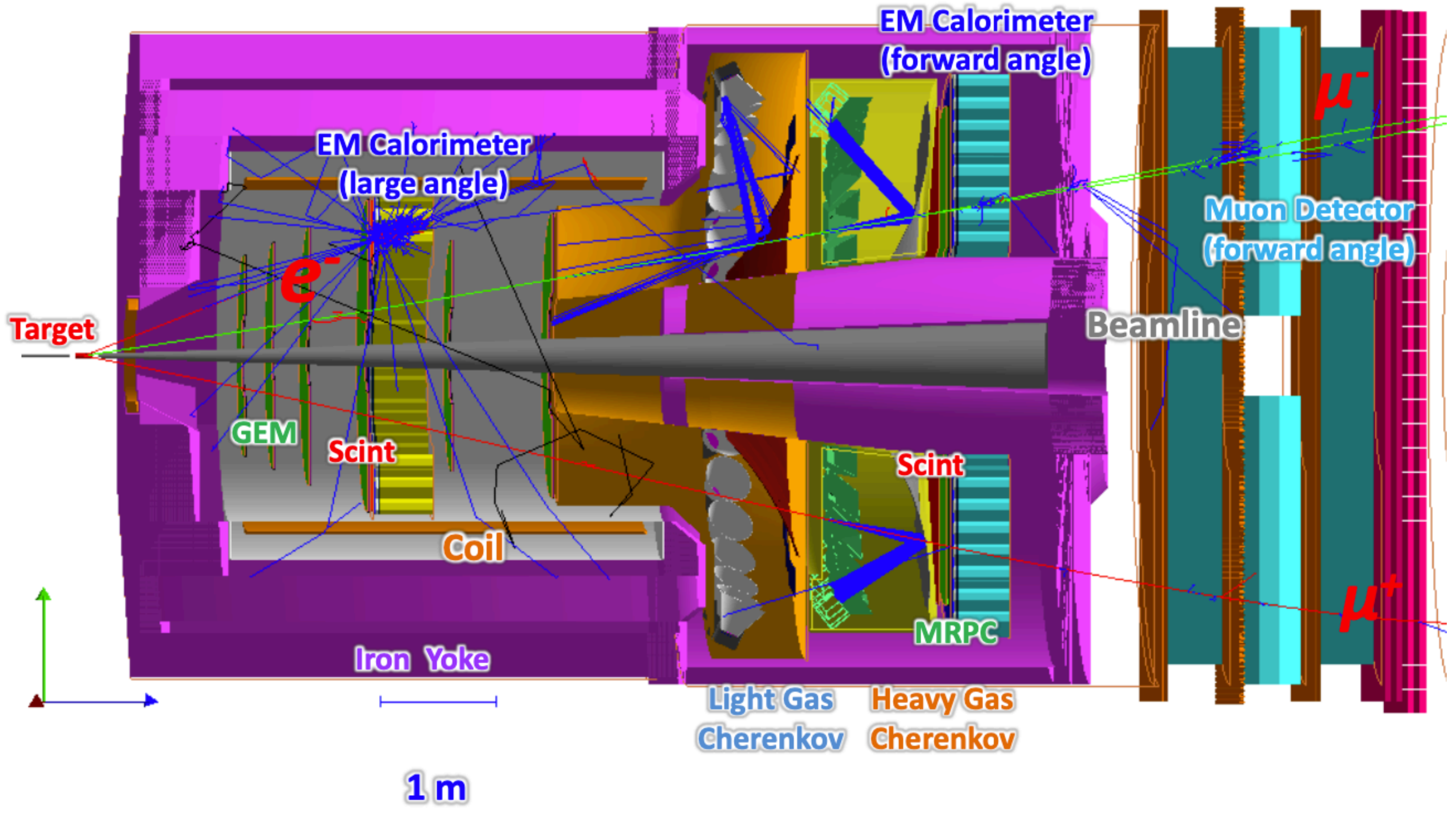
DDVCS with circular polarized beam and LH2 target

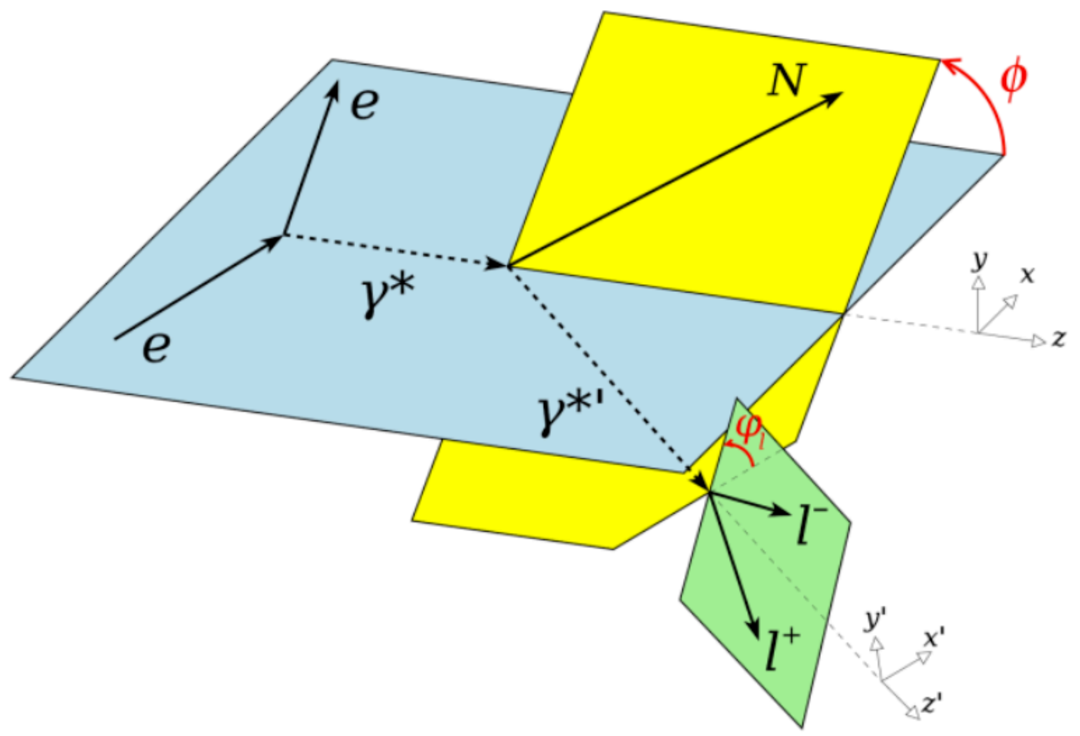
- Under development — **Letter of Intent 2015 and 2023**
- Double Deeply Virtual Compton Scattering explores wide **off-axis kinematic region** of GPDs, beyond DVCS and TCS
- SoLID, with added muon detectors at forward angle, enables DDVCS measurements with both polarized electron and positron beams at 11 GeV
- Share running time and inspect muon channels as well for J/ψ and TCS

$$e^- p \to e^- \gamma^\star (\mu^- \mu^+) p'$$



SoLID DDVCS

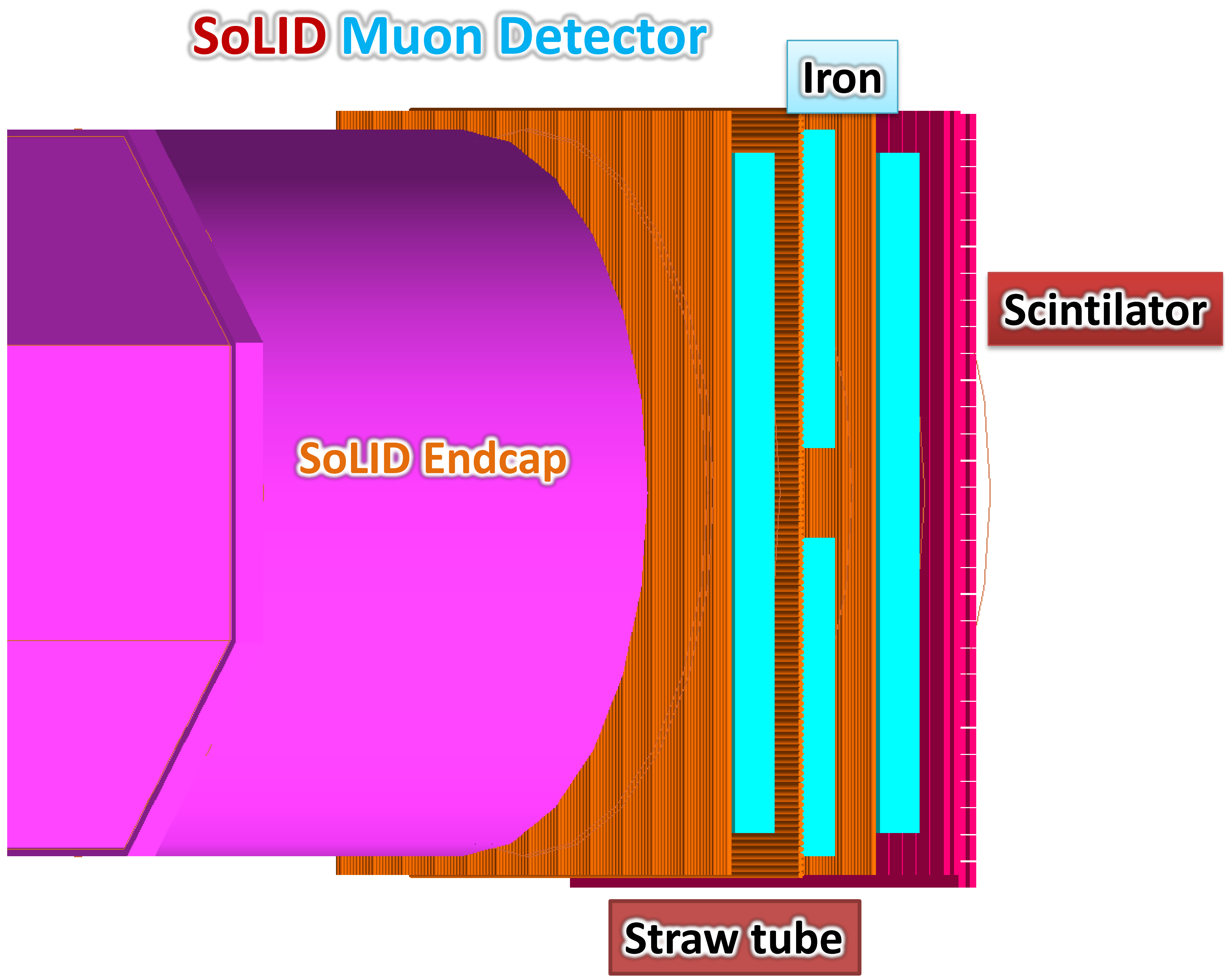


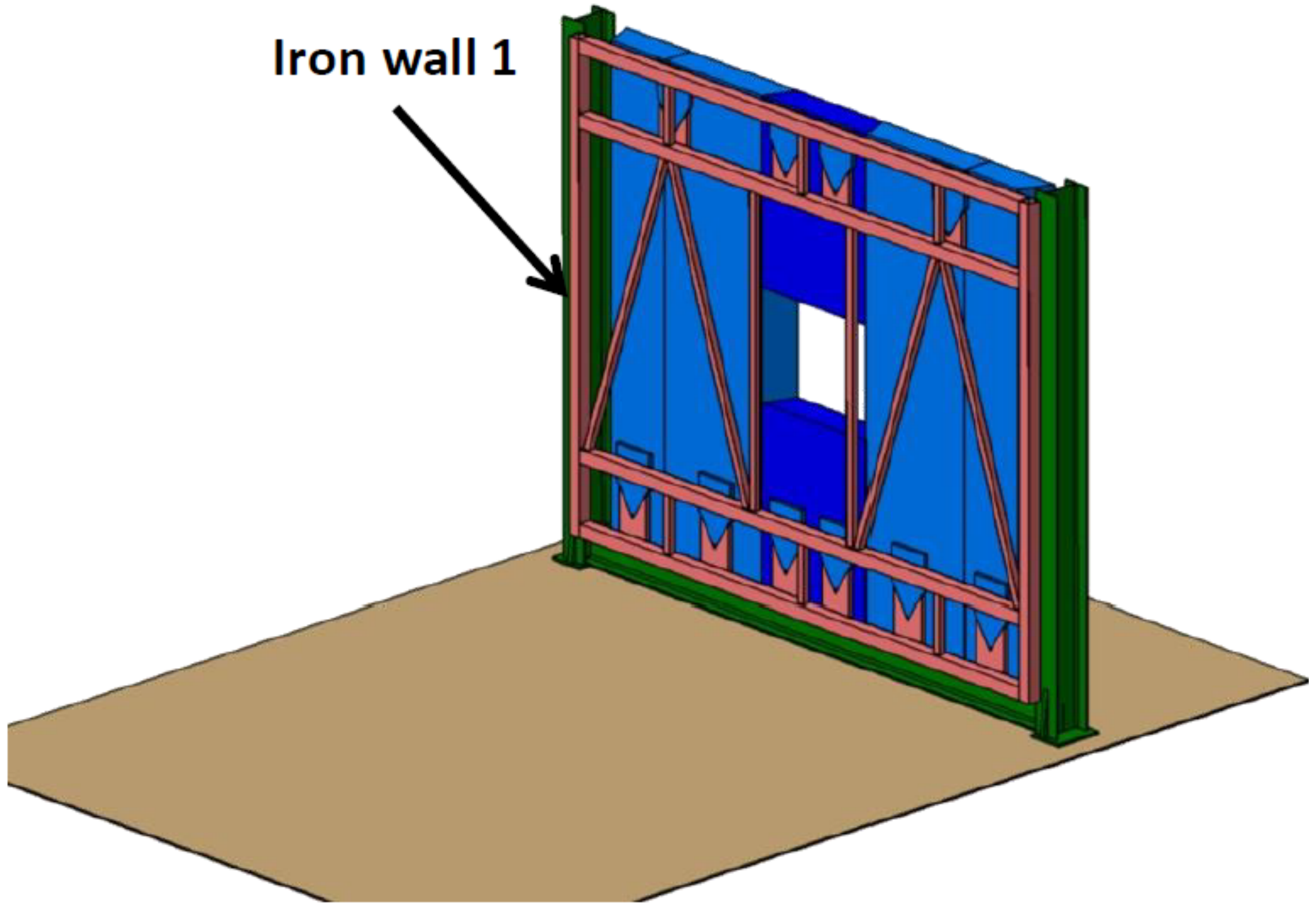


EPJA 57, 240 (2021)

SoLID Muon Detector

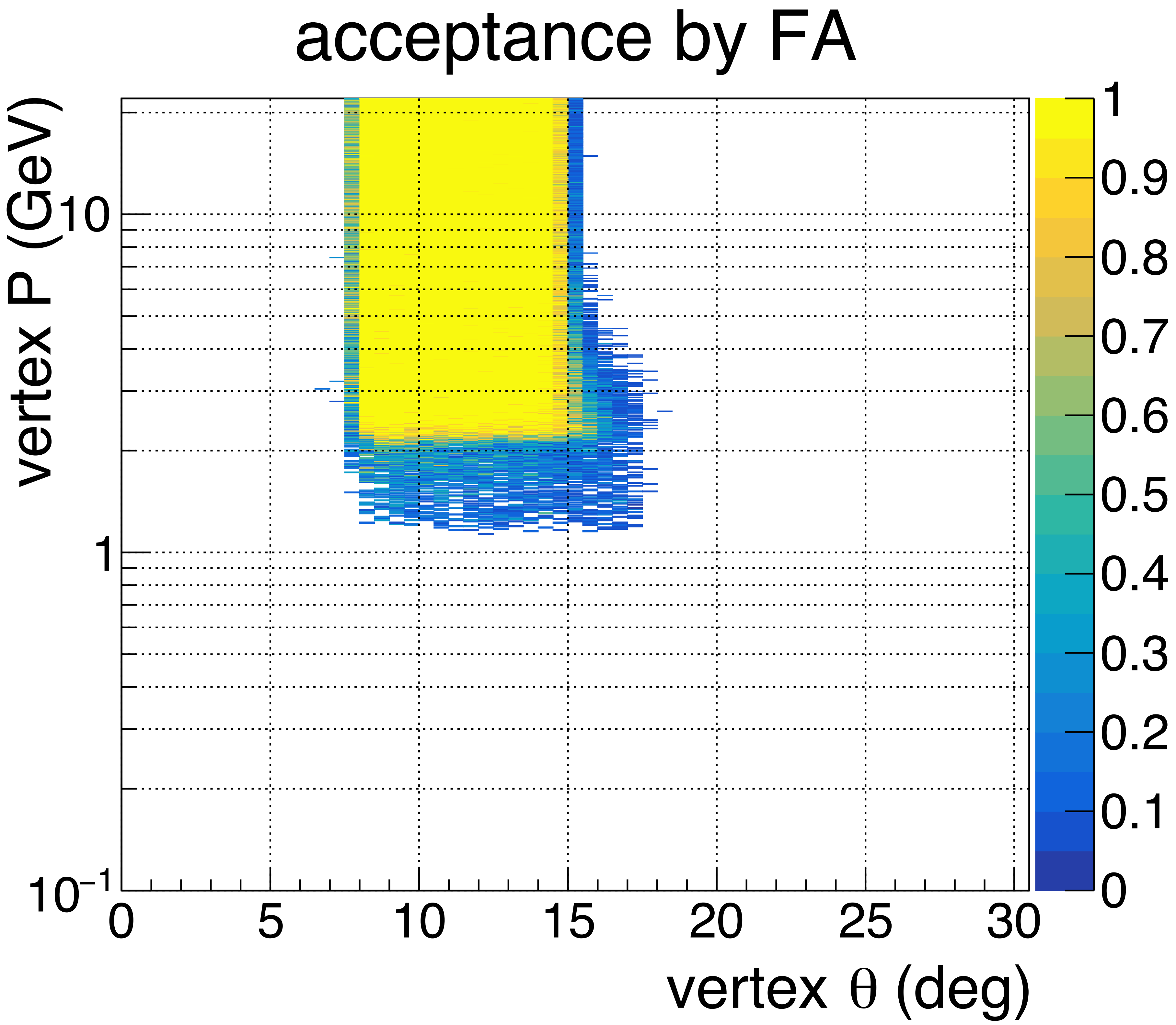
- Di-muon channel: $e^- p \rightarrow e^- \gamma^\star(\mu^- \mu^+) p'$
- SoLID J/ψ configuration + muon detector (iron plate + scintillator)
- Iron plate to block pion, straw tube for tracking, and scintillator for trigger



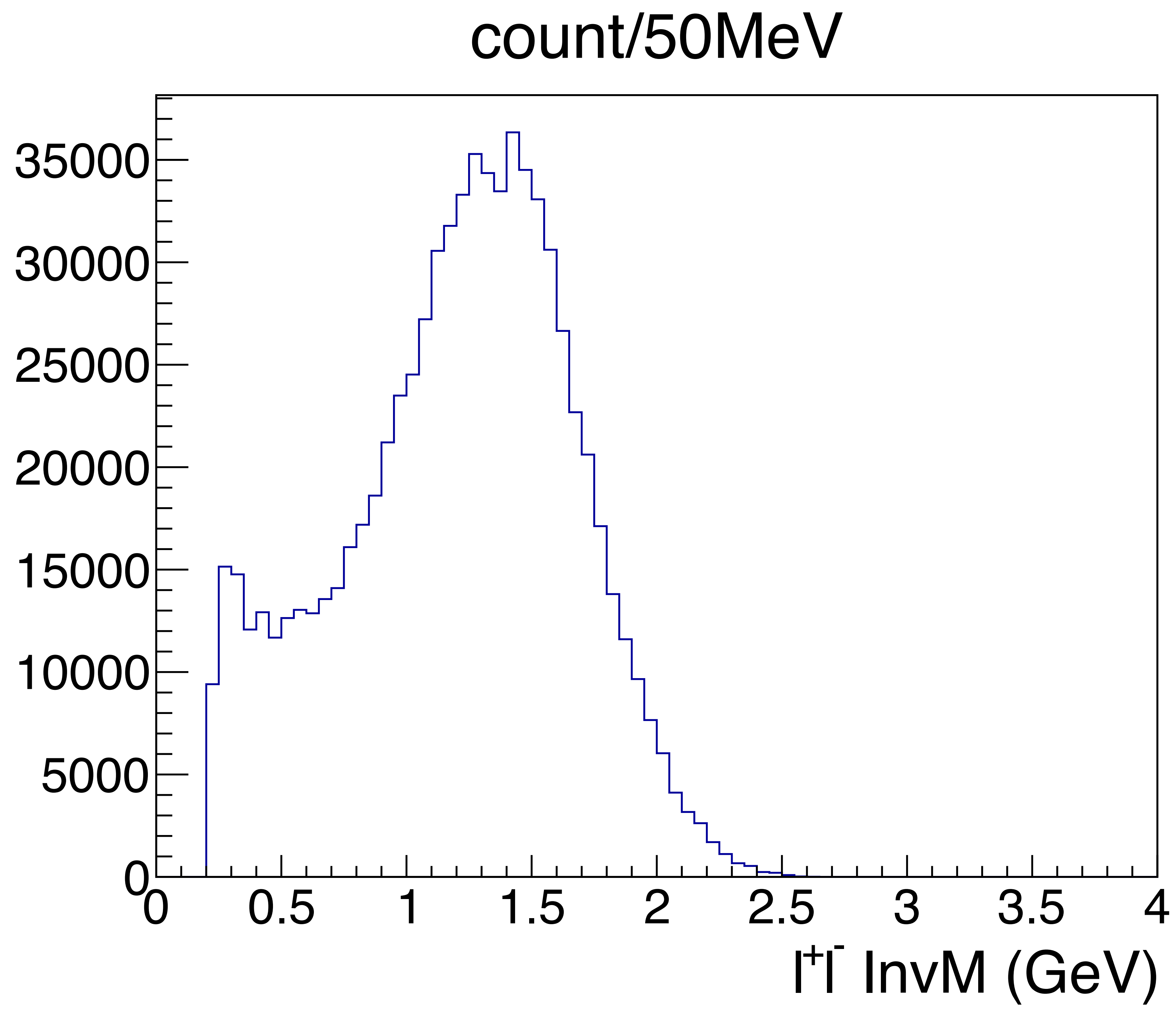


SoLID collaboration LOI 2023

DDVCS with circular polarized beam and LH2 target



μ **acceptance forward angle**

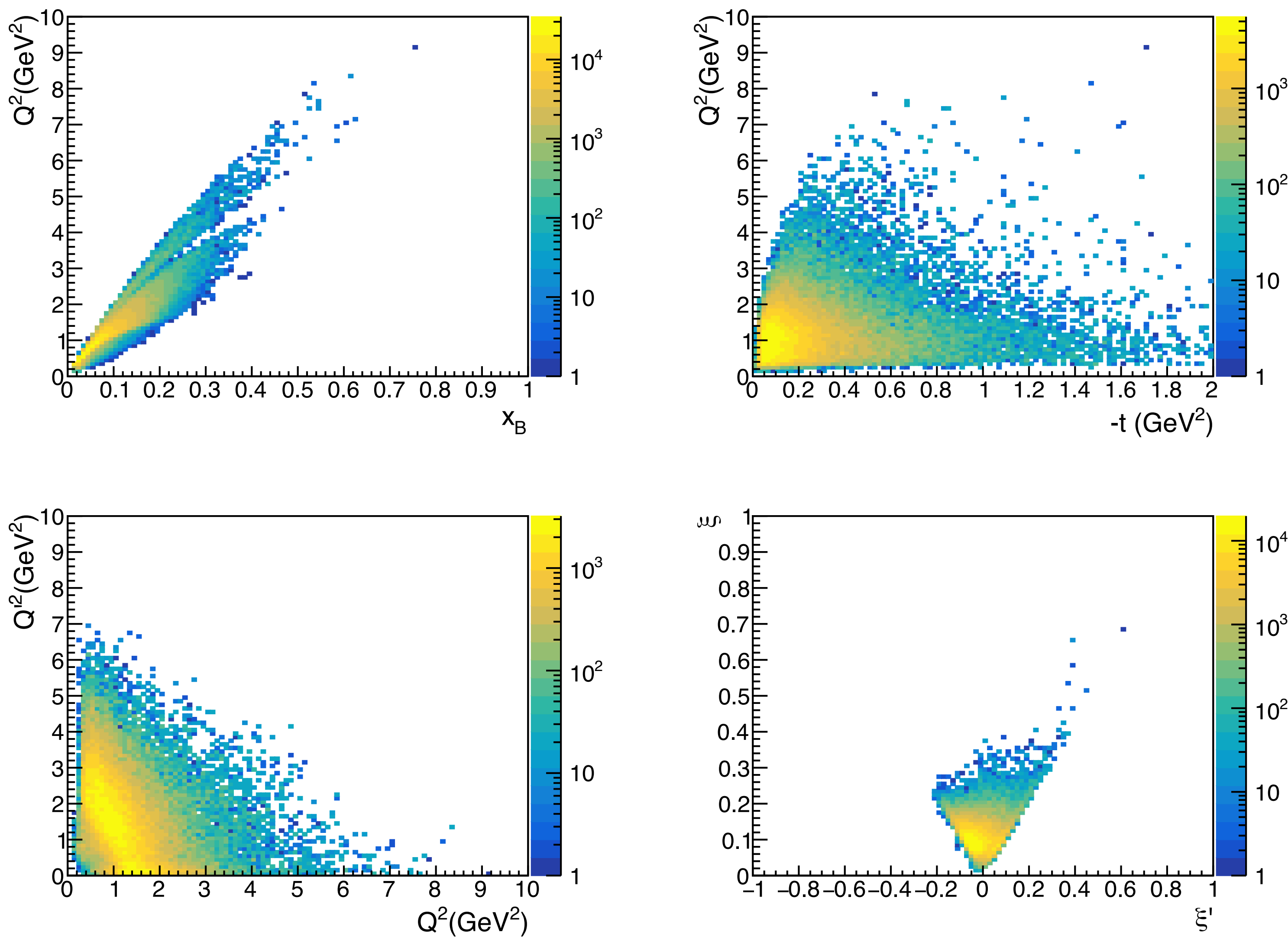


Total expected BH muon pairs detected for the run time

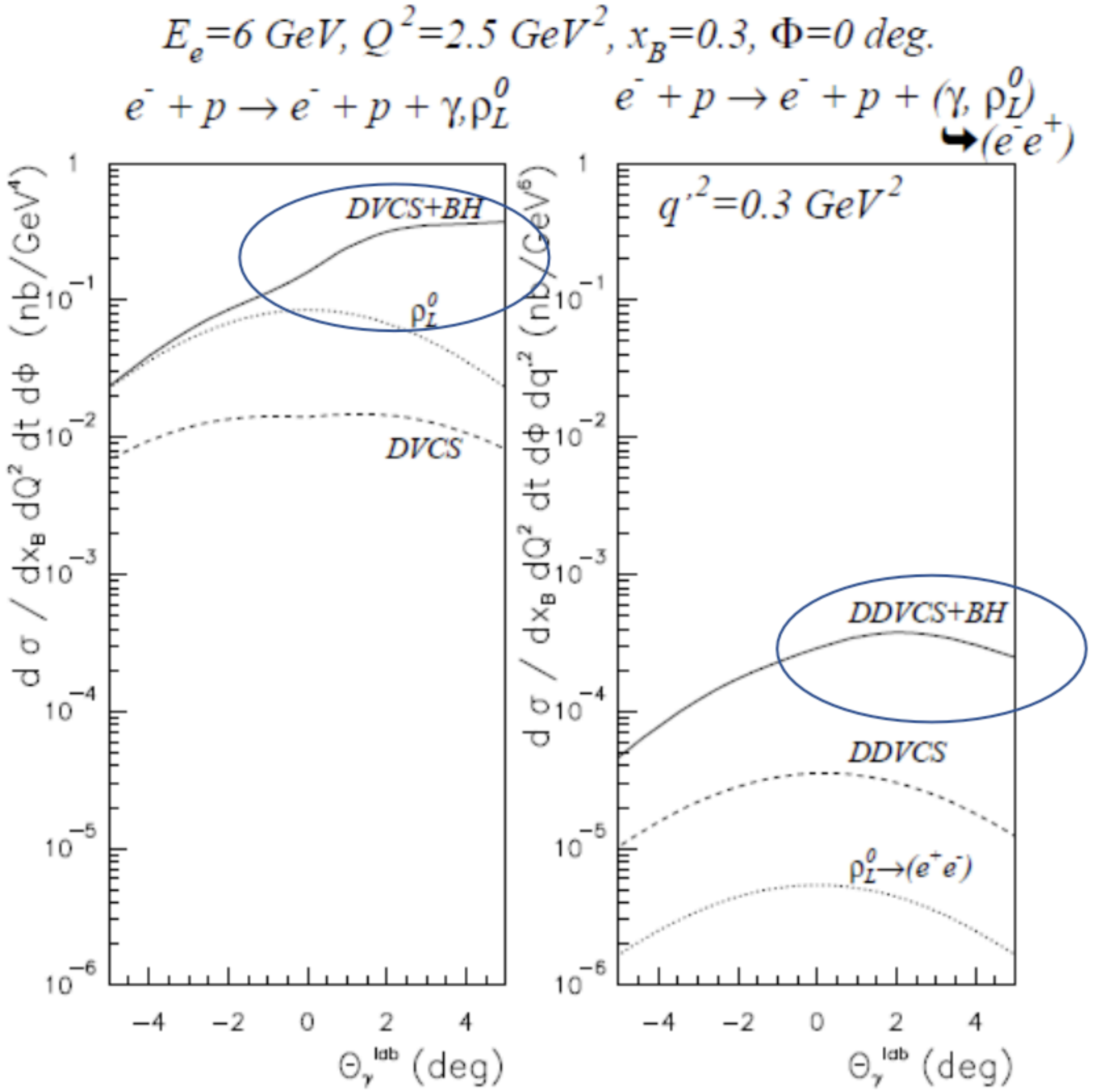
SoLID collaboration LOI 2023

DDVCS with circular polarized beam and LH2 target

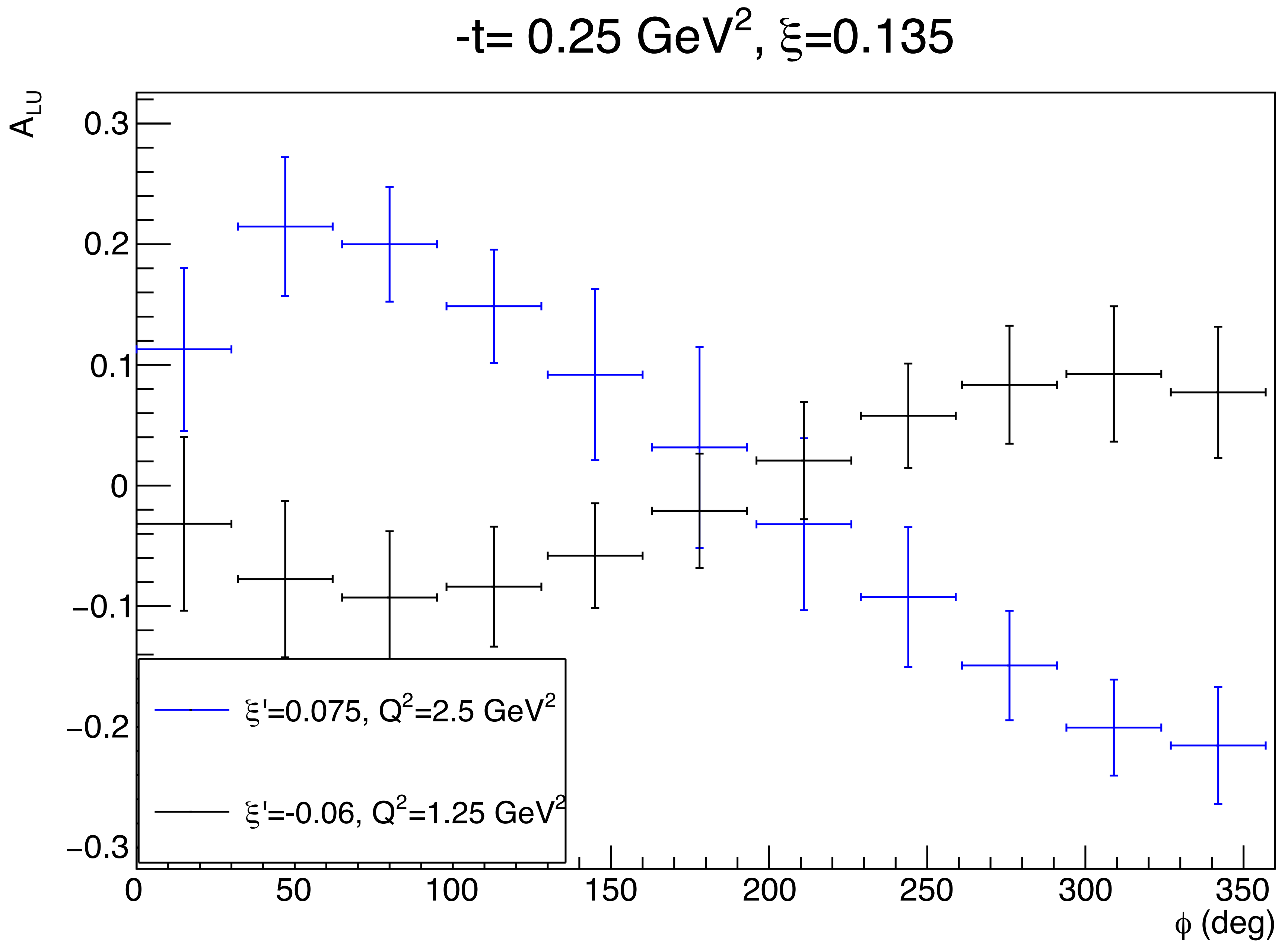
- Kinematics coverage



- Extremely low cross section



- Projected BSA results



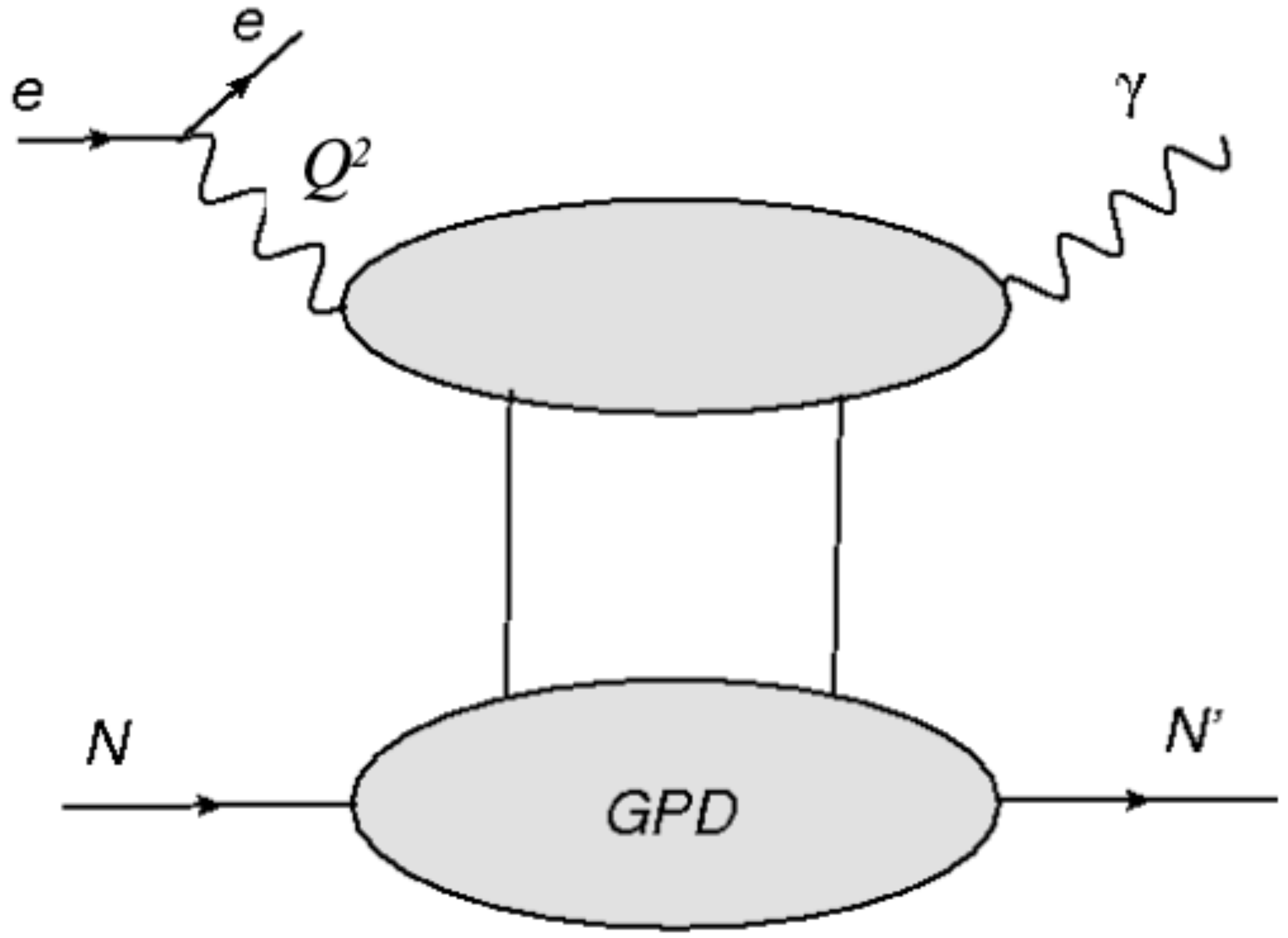
- *VGG model*
- *Order of $\sim 0.1pb = 10^{-36}cm^2$, about 100 to 1000 smaller than DVCS*
- *Interference term enhanced by BH*

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

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

SoLID collaboration LOI 2023

4. DVCS



DVCS with Polarized Electron Beam and Target

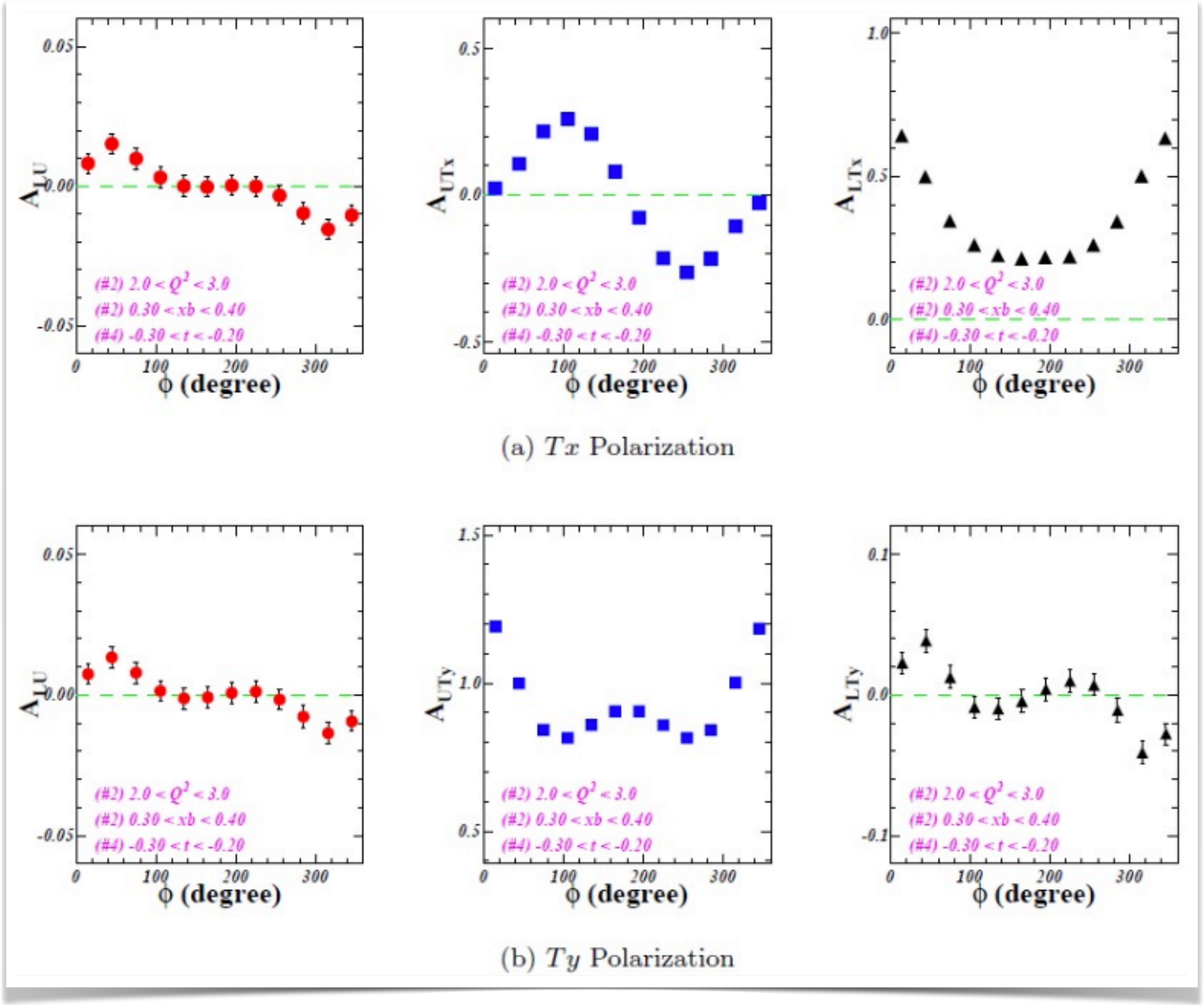
- Approved 12 GeV polarized DVCS experiments (***Hall B & C***)
  - Mostly with **proton** targets
- GPD study needs both proton and neutron data (flavor decomposition, …), and all types of observables (GPD disentangling, …)
- SoLID is the unique place for a DVCS experiment on **neutron** targets
  - **He3: transversely and longitudinally polarized neutron target**
  - **NH3: transversely polarized proton target**
- **Currently still under study — no proposal yet**

Approved 12GeV DVCS experiments:

- E12-16-010B (Hall-B): unpol. proton, XS
- E12-11-003 (Hall-B): unpol. Deuteron, BSA
- E12-06-119 (Hall-B): long-pol proton, BSA, TSA,
- C12-12-010 (Hall-B): *conditional approved*, trans. pol. Proton, TSA,BSA
- C12-15-004 (Hall-B): *conditional approved*, long. pol. Deuteron, TSA, BSA
- E12-06-114 (Hall-A&C): unpol. proton, XS & BSA, limited coverage
- E12-13-010 (Hall-C): unpol. proton, XS,
- E12-15-001 (Hall-C): proton, XS
- ***LOI:*** nDVCS w/ TDIS setup (Hall-A), tagged neutron, XS

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}	$Re\{\mathcal{H}_p, \mathcal{E}_p\}$ $Re\{\mathcal{H}_n\}$

Polarization variables for GPD study



(a) Tx Polarization

(b) Ty Polarization

SoLID DVCS with Polarized He3
Projection: one (Q^2, x, t) bin out of 1000+ bins

Zhihong Ye, Tsinghua University

Summary

- SoLID spectrometer's High Luminosity and Large Acceptance are key to GPD measurements using exclusive processes
- Multi-dimensional binning with high statistics
- SoLID has a broad exclusive physics program for GPD measurements:
  - DEMP — approved, SIDIS run group experiment
  - DVCS — under study
  - TCS — approved, J/ψ run group experiment
  - DDVCS — under study, add muon detector to SIDIS configuration
- More ideas (e.g. deuterium and other nuclear targets)

SoLID Collaboration

- 270+ collaborators, 70+ institutions from 13 countries
- Active development and validation of the design and physics programs
- Strong theory support

Backup Slides

Generalized Parton Distributions

- GPDs connects to nucleon elastic form factors through model-independent sum rules

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

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

Dirac and Pauli FF : t-dependence fairly well-known

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

Axial FF : t-dependence poorly known

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

Pseudoscalar FF : very poorly known