

# SoLID TCS and DDVCS

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Hi-Lumi workshop

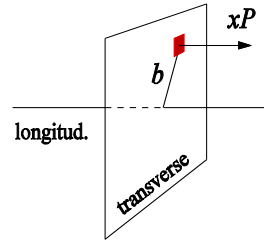
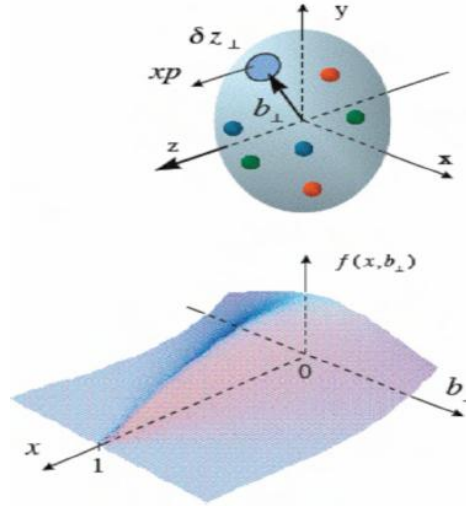
# Outline

- Generalized Parton Distribution and General Compton process
- TCS and SoLID
- DDVCS and SoLID $\mu$
- Summary

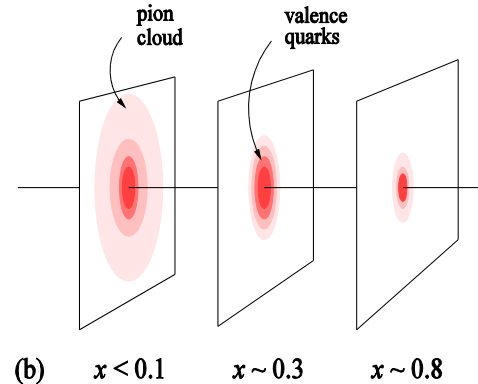
SoLID full and Lite

# Generalized Parton Distribution (GPD)

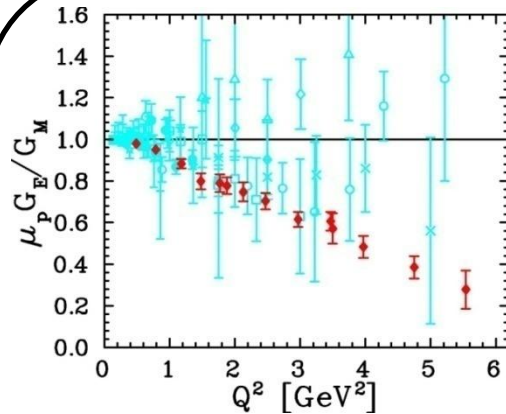
A unified description of partons (quarks and gluons) in the momentum and impact parameter space



(a)

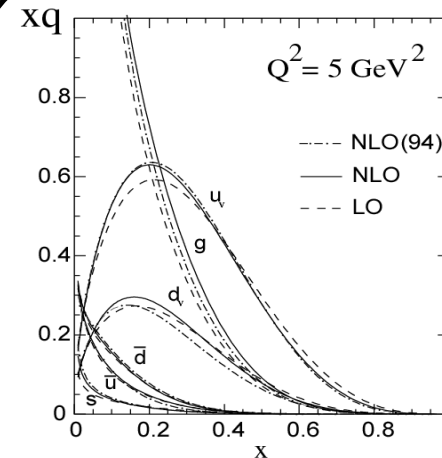
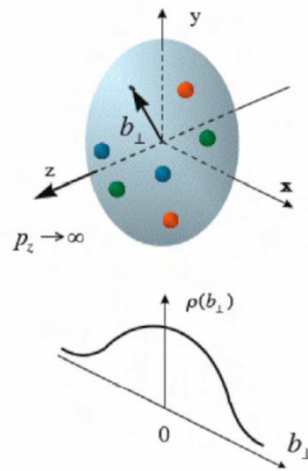


(b)



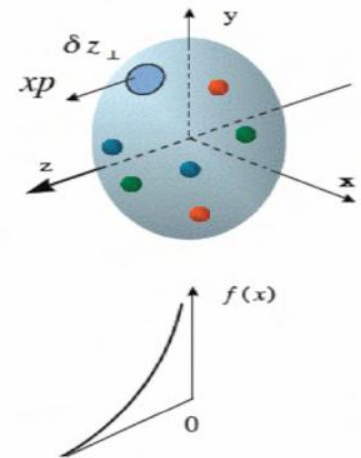
Elastic form factors

Transverse spatial distributions



Parton Distribution Functions

Longitudinal momentum distributions



# Nucleon Structure and GPD

**GPDs** encode **correlations between partons** and contain information about **internal dynamics of hadrons** like **angular momentum** or **distribution of the forces** experienced by quarks and gluons

imaging

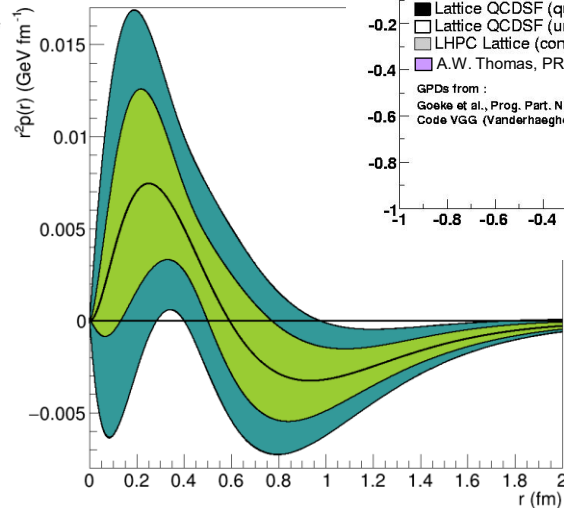
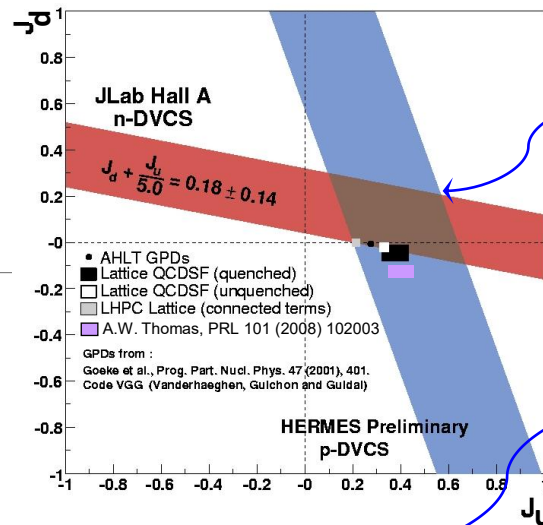
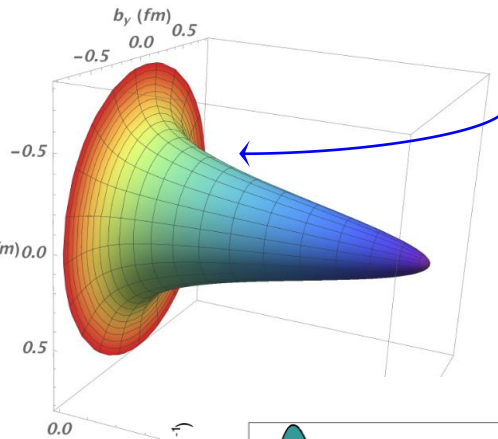
$$\rho_H^q(x, \mathbf{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i\mathbf{b}_\perp \cdot \Delta_\perp} [H^q(x, 0, -\Delta_\perp^2) + H^q(-x, 0, -\Delta_\perp^2)]$$

spin

$$\lim_{t \rightarrow 0} \int_{-1}^1 x [H^q(x, \xi, t) + E^q(x, \xi, t)] dx = J^q$$

gravitational form factor

$$\int_{-1}^1 x \sum_q H^q(x, \xi, t) dx = M_2(t) + \frac{4}{5} \xi^2 d_1(t)$$



The **experimental knowledge** of the  **$\xi$ -dependence** of GPDs at fixed longitudinal momentum fraction is a **crucial step** for unraveling the 3D structure and internal dynamics of the **nucleon**

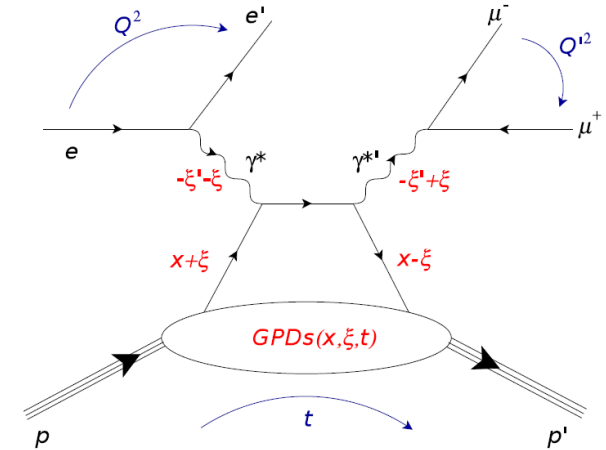
# General Compton Process accessing GPD

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

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

|             |                                                                   |
|-------------|-------------------------------------------------------------------|
| DVCS        | $(\gamma^* \rightarrow \gamma, Q'^2=0, \xi' = \xi)$               |
| Timelike CS | $(\gamma \rightarrow \gamma^*, Q^2=0, \xi' = -\xi)$               |
| Double DVCS | $(\gamma^* \rightarrow \gamma^*, Q^2 Q'^2 \xi' \xi \text{ vary})$ |

Because of the virtuality of the initial and final photon, **DDVCS** allows direct access to GPDs at  $|x| < \xi$ , crucial for modeling and investigation of **nuclear imaging, spin, and internal dynamics**



Compton Form Factor (CFF)

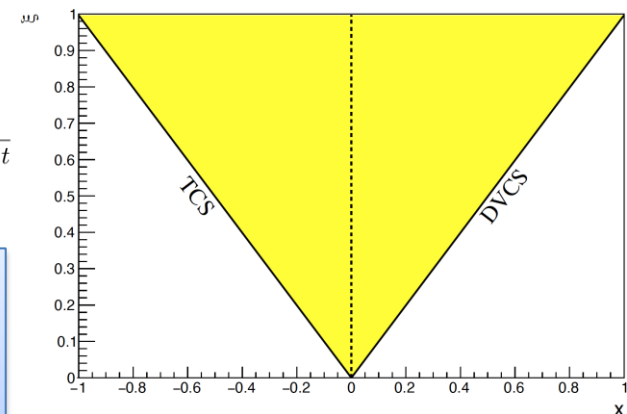
$$\mathcal{F}(\xi', \xi, t) = \mathcal{P} \int_{-1}^1 F_+(x, \xi, t) \left[ \frac{1}{x - \xi'} \pm \frac{1}{x + \xi'} \right] dx - i\pi F_+(\xi', \xi, t)$$

GPD combination

$$F_+(x, \xi, t) = \sum_q \left( \frac{e_q}{e} \right)^2 [F^q(x, \xi, t) \mp F^q(-x, \xi, t)]$$

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

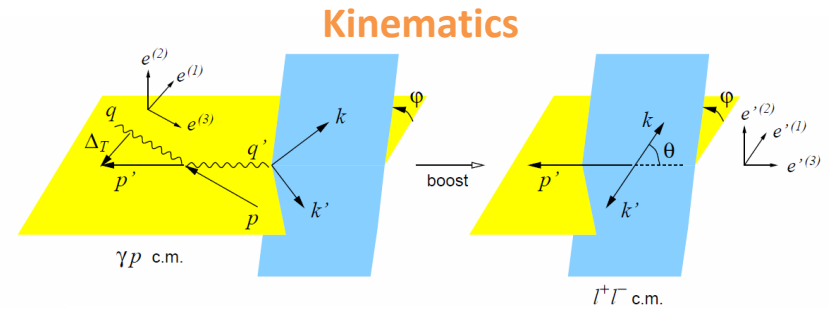
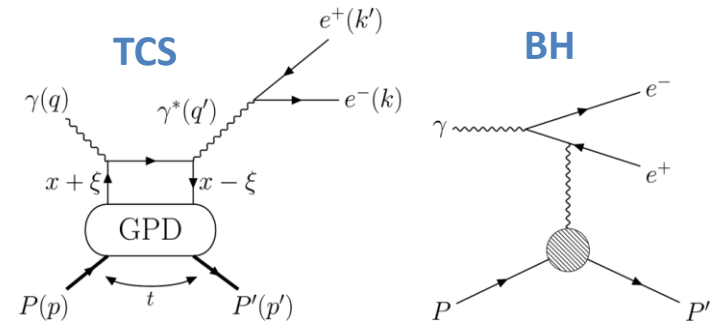
DDVCS following the sign change of  $\xi$  around  $Q'^2=Q^2$ , the imaginary part of  $\mathcal{H}$  and  $\mathcal{E}$  **change sign**, providing a testing ground of **GPD universality**



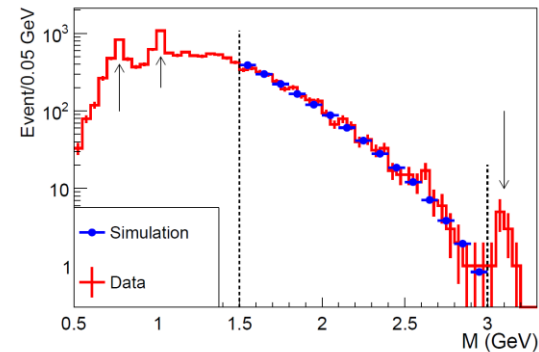
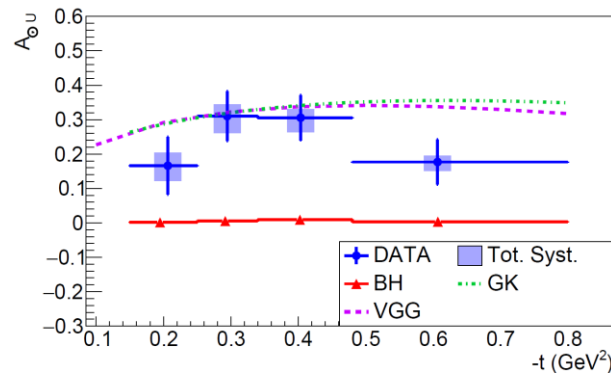
# TCS at JLab

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

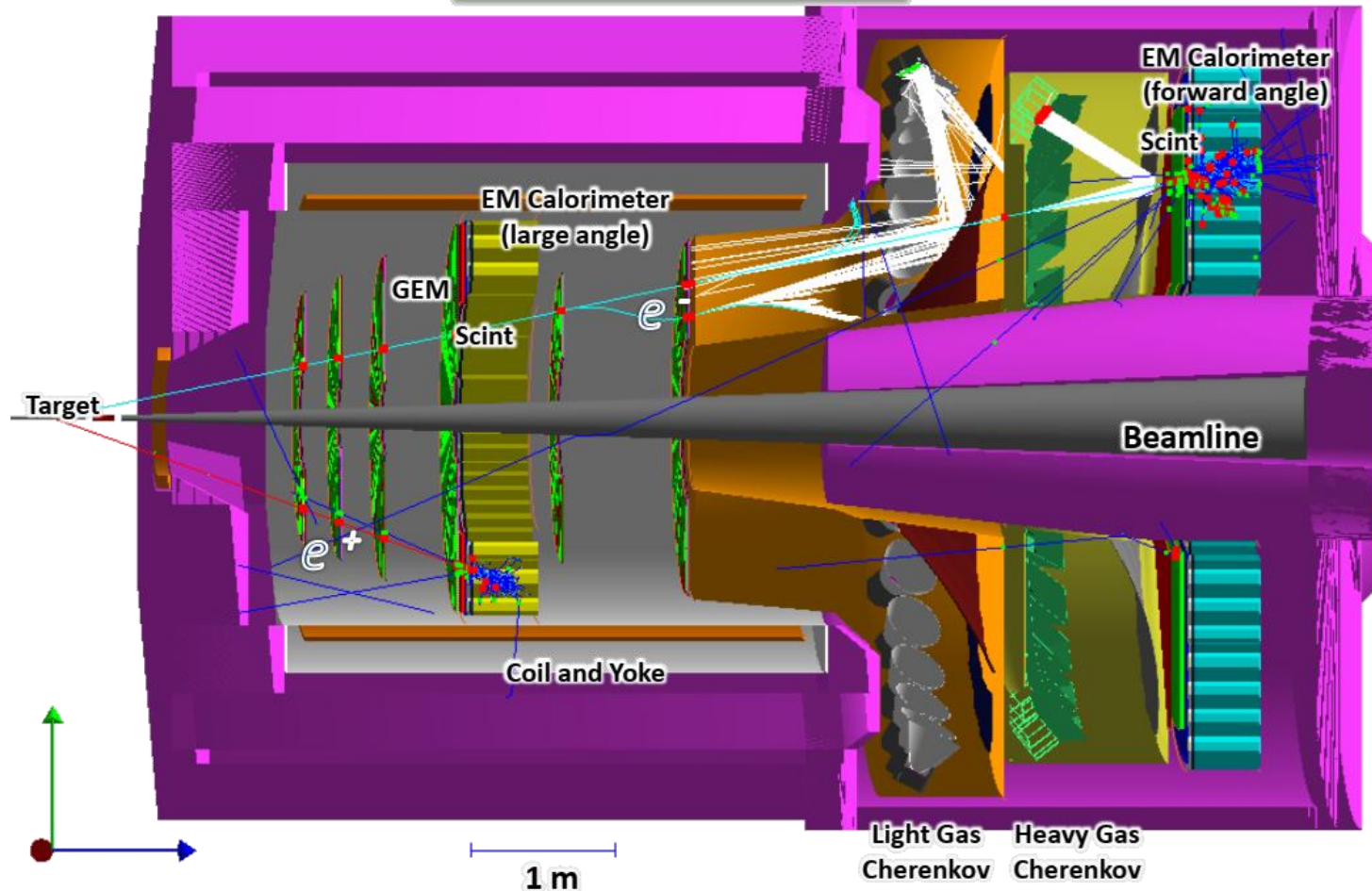
- Motivation
  - Access the same GPDs like DVCS and test universality
  - Access real and imaginary part of GPD H through CFF
  - New observables for global GPD fits
- Status
  - exploration at CLAS 6GeV
  - First result at CLAS12 published at PRL, 127, 262501 (2021) obtain **nonzero** beam polarized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



CLAS12  
result



## SoLID JPsi and TCS

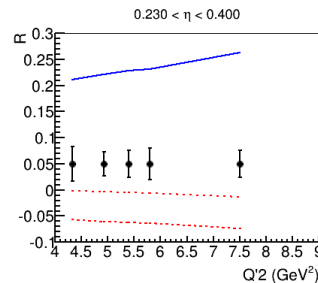
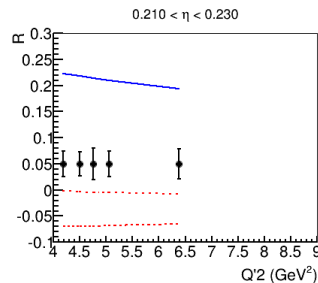
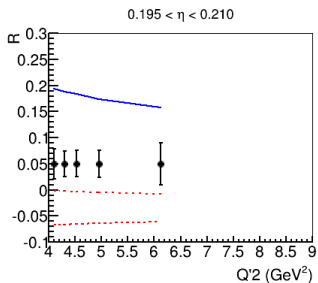
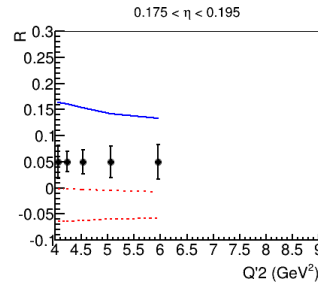
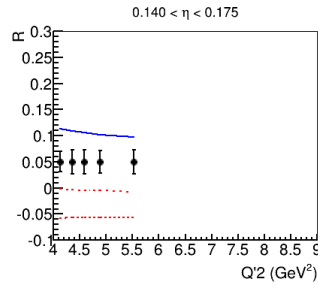
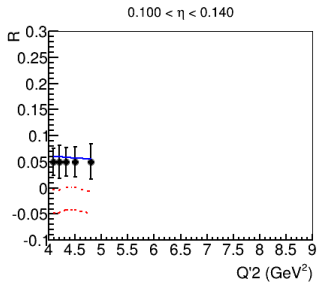
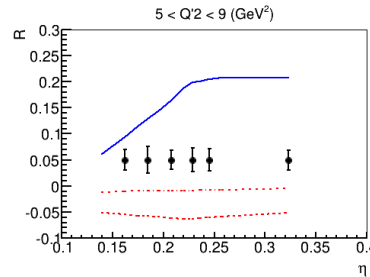
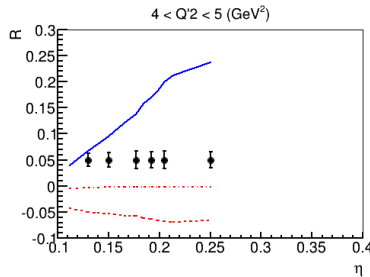
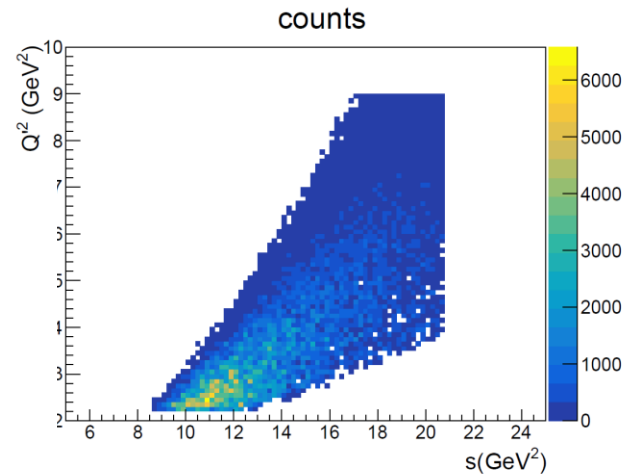
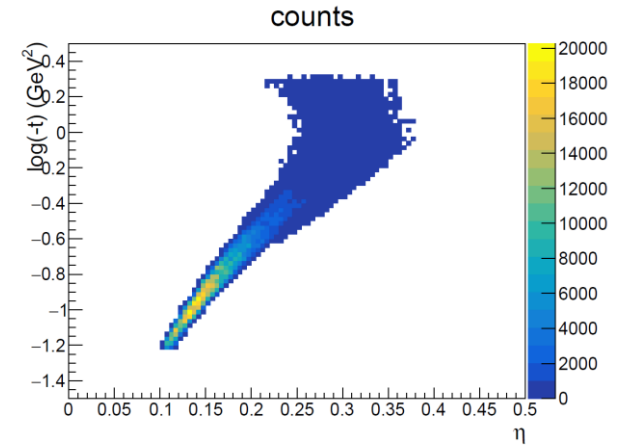


**E12-12-006:** Near Threshold J/Psi production on LH2 target 60 days, **rating A**  
**E12-12-006A:** TCS with circular polarized beam and LH2 target

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

- sharing beam time with jpsi run by detecting the same final state particles like jpsi photoproduction (eep) but with broader kinematics
- SoLID TCS will have at least 1 order larger statistics than the published CLAS12 result and usher TCS study into precision era with multi-dimensional binning

SoLID TCS coverage



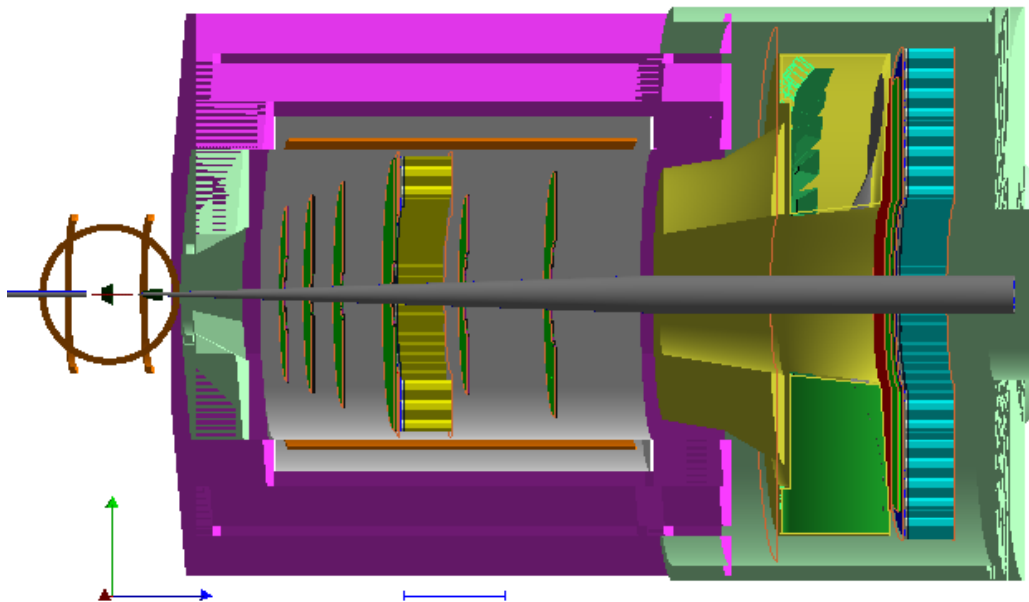
$$R = \frac{2 \int_0^{2\pi} d\varphi \cos \varphi \frac{dS}{dQ^2 dt d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ^2 dt d\varphi}}$$

# SoLID Lite option

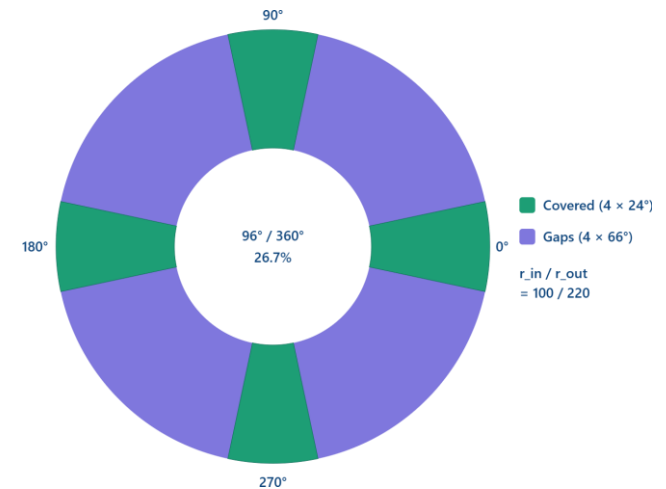
preliminary

- SoLID full with forward angle (FA) and large angle (LA) detectors
- SoLID Lite option (“4seg24degFA+LA”)
  - Works for both Jpsi and SIDIS
  - Reduce FA into 4 segments of 24 deg each while keeping LA full
  - Solenoid magnet using **unmodified CLEO iron (purple)** for JPsi, then add **front piece and others (green)** for SIDIS
  - One Cherenkov with CO<sub>2</sub>, maybe reuse sPHENIX ECAL and others

Two stages of magnet



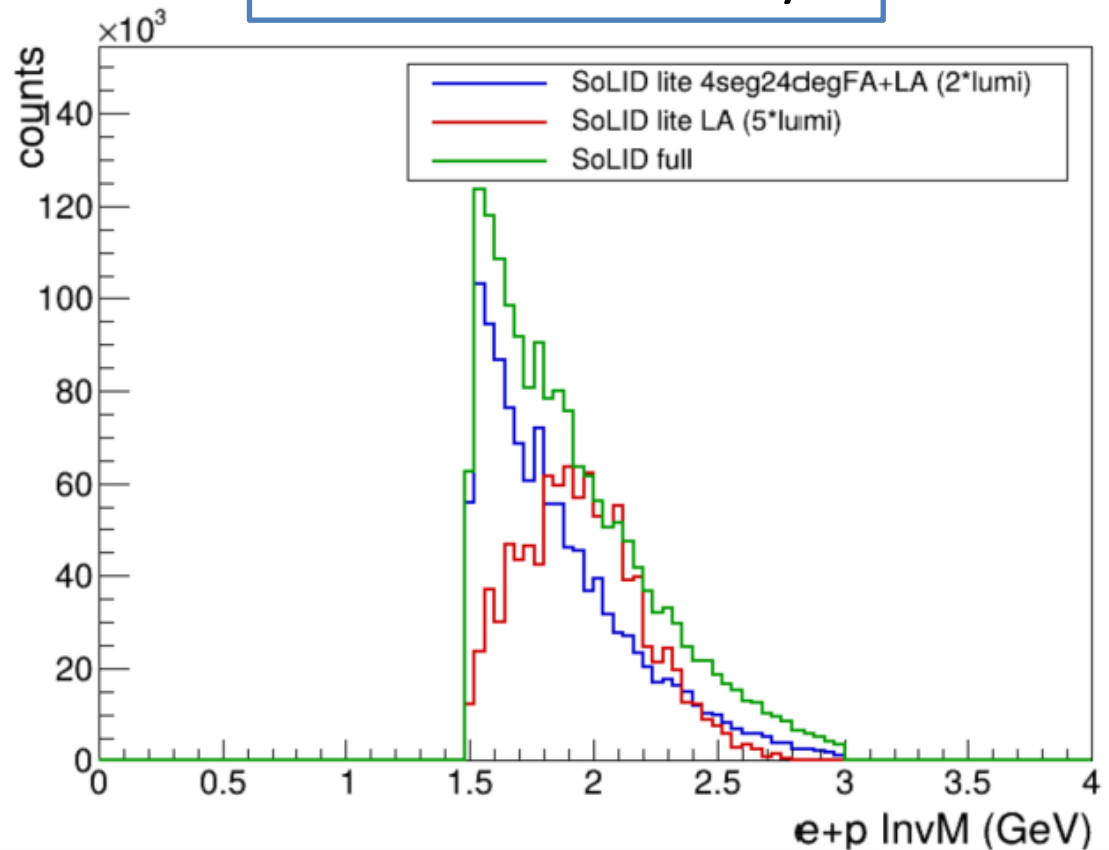
4seg24degFA



# SoLID Lite TCS

- option “4seg24degFA+LA” as good as full
- option “LA” is useful though leads to kinematic coverage loss

BH counts of 50 days

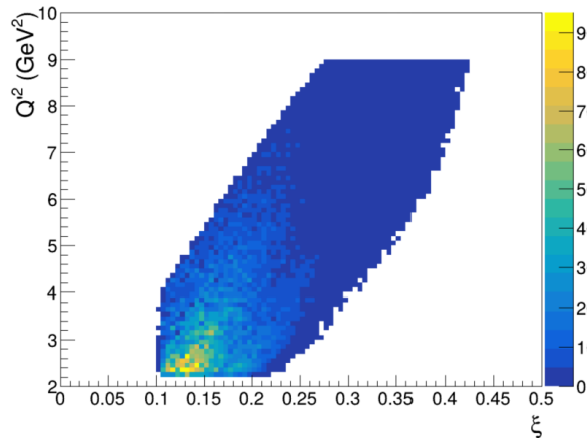


# SoLID Lite TCS

- option “4seg24degFA+LA” is as good as full
- option “LA” is useful though leads to kinematic coverage loss

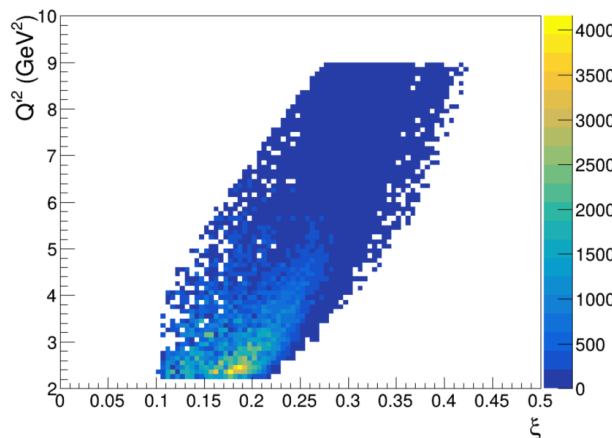
full

counts



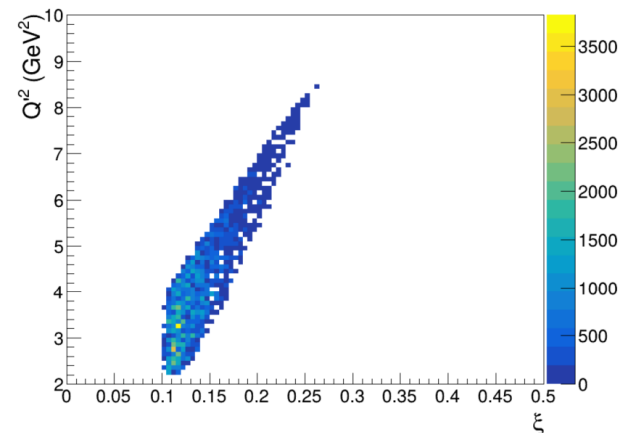
4seg24degFA+LA

counts



LA

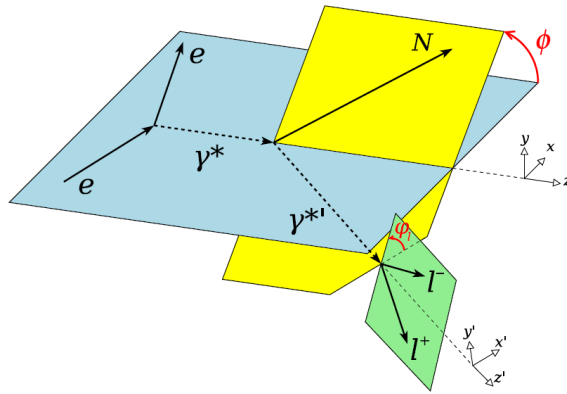
counts



# DDVCS Elementary Cross Section

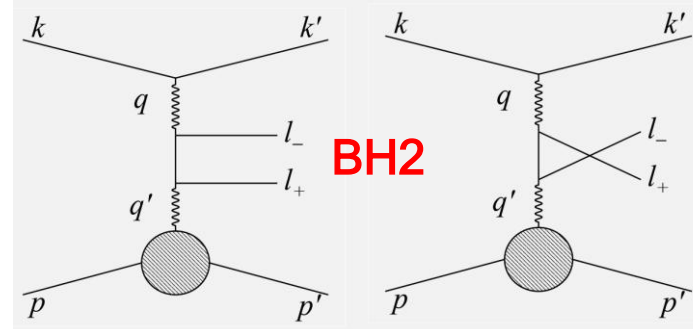
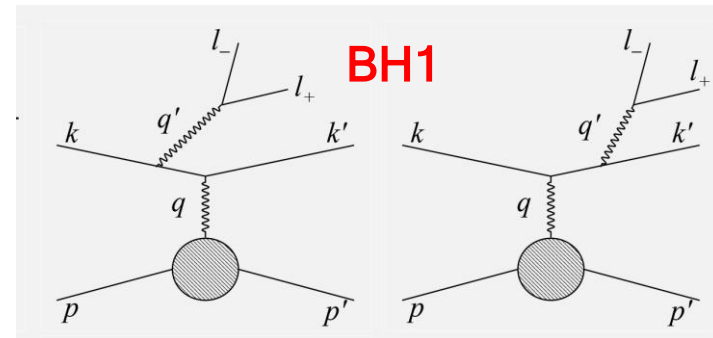
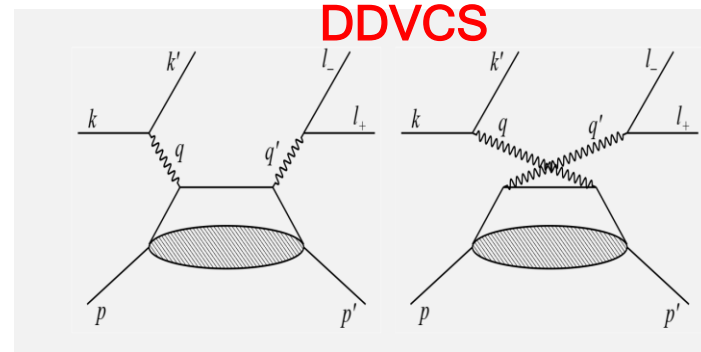
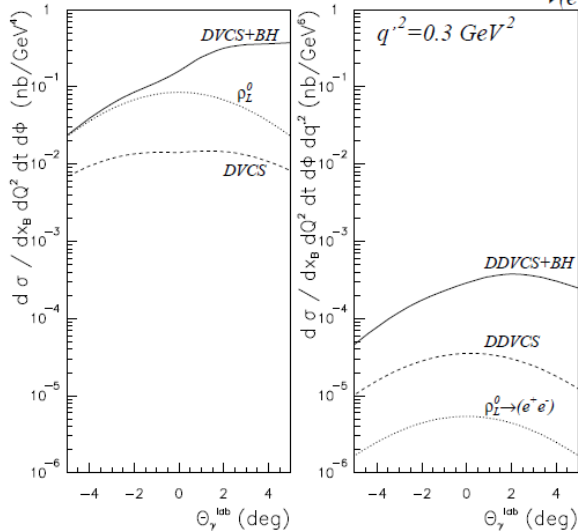
**DDVCS** cross section is about  $\sim 1/100$  of **DVCS**, involves two Bethe-Heitler (BH) processes

$$d^7\sigma_P^e = d^7\sigma_{BH_1} + d^7\sigma_{BH_2} + d^7\sigma_{DDVCS} + P d^7\tilde{\sigma}_{DDVCS} + d^7\sigma_{INT_2} + P d^7\tilde{\sigma}_{INT_2} - e [d^7\sigma_{BH_{12}} + d^7\sigma_{INT_1} + P d^7\tilde{\sigma}_{INT_1}]$$



$$E_e = 6 \text{ GeV}, Q^2 = 2.5 \text{ GeV}^2, x_B = 0.3, \Phi = 0 \text{ deg.}$$

$$e^- + p \rightarrow e^- + p + \gamma, \rho_L^0 \quad e^- + p \rightarrow e^- + p + (\gamma, \rho_L^0) \rightarrow (e^- e^+)$$



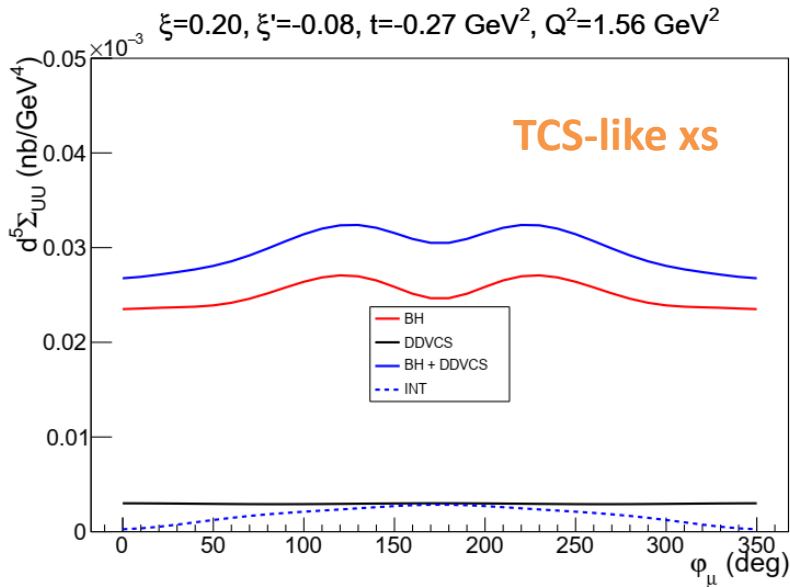
# Integrated Cross Section

**5-fold TCS-like observables** obtained from the **integration** over the **polar angle** of **muon** and the **azimuthal angle** of **initial virtual photon**, also **minimizing** the contribution of the **BH<sub>2</sub>** process

$$\theta_0 = \pi/4$$

$$d^5\Sigma^\lambda(\varphi_\mu) \equiv \frac{d^5\sigma^\lambda(\varphi_\mu)}{dx_B dy dt dQ'^2 d\varphi_\mu} = \int_0^{2\pi} d\phi \int_{\pi/2-\theta_0}^{\pi/2+\theta_0} d\theta_\mu \sin(\theta_\mu) \frac{d^7\sigma^\lambda(\phi, \theta_\mu, \phi_\mu)}{dx_B dy dt d\phi dQ'^2 d\Omega_\mu}$$

$$d^5\Sigma^\lambda = d^5\Sigma_{BH_1} + d^5\Sigma_{BH_2} + d^5\Sigma_{BH_{12}} + d^5\Sigma_{DDVCS} + d^5\Sigma_{\mathcal{I}_1} + d^5\Sigma_{\mathcal{I}_2} + \lambda d^5\tilde{\Sigma}_{\mathcal{I}_2} = d^5\Sigma_{UU} + \lambda d^5\Sigma_{LU}$$



- Our study focuses on using **TCS-like observables** for projection to allow access to both terms above
- DVCS-like observables obtained by integrating over muon phi angle may also be considered as crosscheck

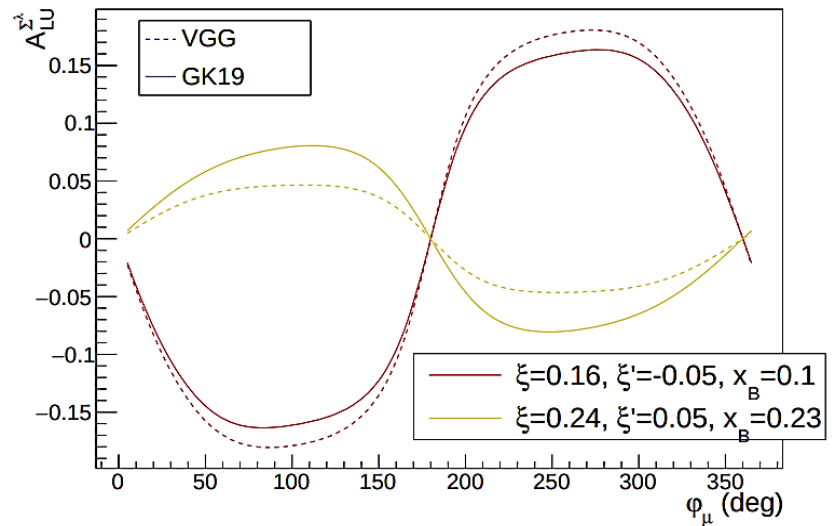
# Beam Spin Asymmetry

$$A_{LU}^{\Sigma^{\lambda}}(\varphi_{\mu}) = \lambda \frac{d^5\Sigma^{+} - d^5\Sigma^{-}}{d^5\Sigma^{+} + d^5\Sigma^{-}} = \frac{\lambda d^5\tilde{\Sigma}_{\mathcal{I}_2}}{d^5\Sigma_{BH_1} + d^5\Sigma_{BH_2} + d^5\Sigma_{BH_{12}} + d^5\Sigma_{DDVCS} + d^5\Sigma_{\mathcal{I}_1} + d^5\Sigma_{\mathcal{I}_2}}$$

$$\propto \Im \left\{ F_1 \mathcal{H} + \xi' (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M_N^2} F_2 \mathcal{E} \right\}$$

- Access to the imaginary part of CFFs
- **BSA** changes sign when transitioning from **DVCS-like region** ( $\xi' > 0, Q^2 > Q'^2$ ) to **TCS-like region** ( $\xi' < 0, Q^2 < Q'^2$ )
- **DDVCS BSAs** are dominated by the CFF  $\mathcal{H}$ , thus providing a measurement of the  $\mathcal{H}$  GPD at  $\xi' \neq \pm \xi$  with similar quality to DVCS

BSA in two regions



# Muon Charge Asymmetry

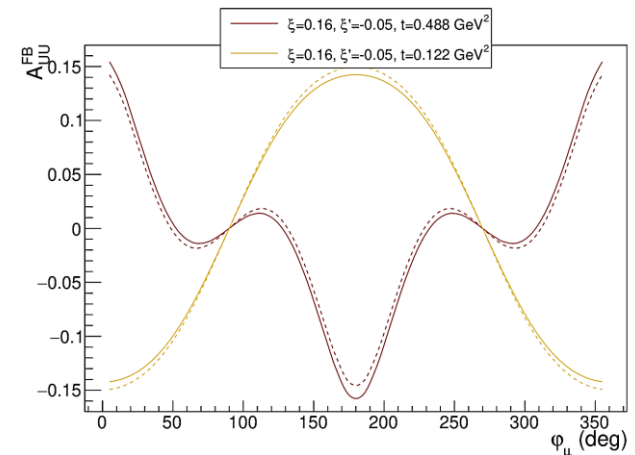
$$A_{UU}^{\mu^\pm}(\varphi_\mu) = \frac{d^5\Sigma_{UU}(\varphi_{\mu^-}) - d^5\Sigma_{UU}(\varphi_{\mu^+})}{d^5\Sigma_{UU}(\varphi_{\mu^-}) + d^5\Sigma_{UU}(\varphi_{\mu^+})}$$

$$= \frac{d^5\Sigma_{BH_{12}} + d^5\Sigma_{\mathcal{I}_2}}{d^5\Sigma_{BH_1} + d^5\Sigma_{BH_2} + d^5\Sigma_{DDVCS} + d^5\Sigma_{\mathcal{I}_1}}$$

$$d^5\Sigma_{\mathcal{I}_2} \propto -\frac{\xi'}{\xi} \Re \left[ F_1 \mathcal{H} + \frac{\xi^2}{\xi'} (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M_N^2} F_2 \mathcal{E} \right]$$

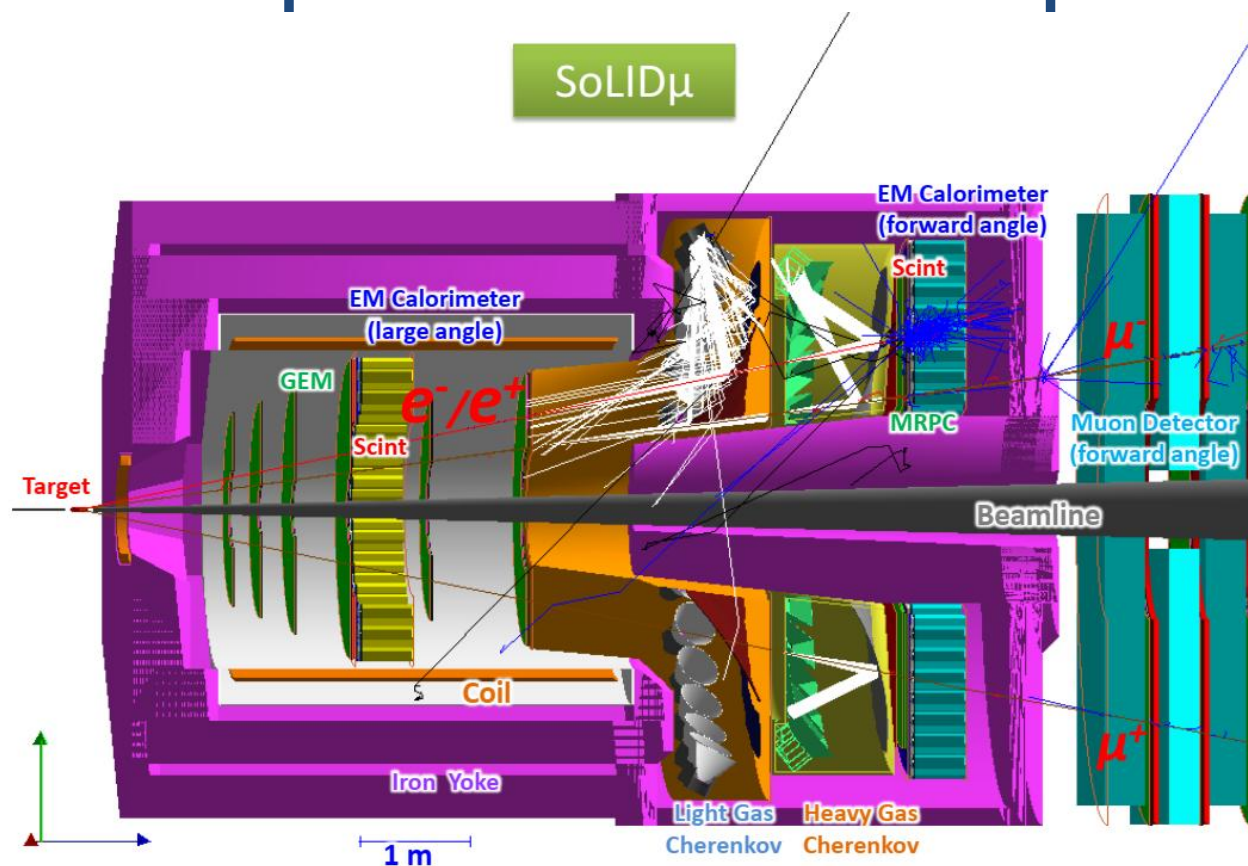
aka Forward Backward Asymmetry

**μCA** in two regions



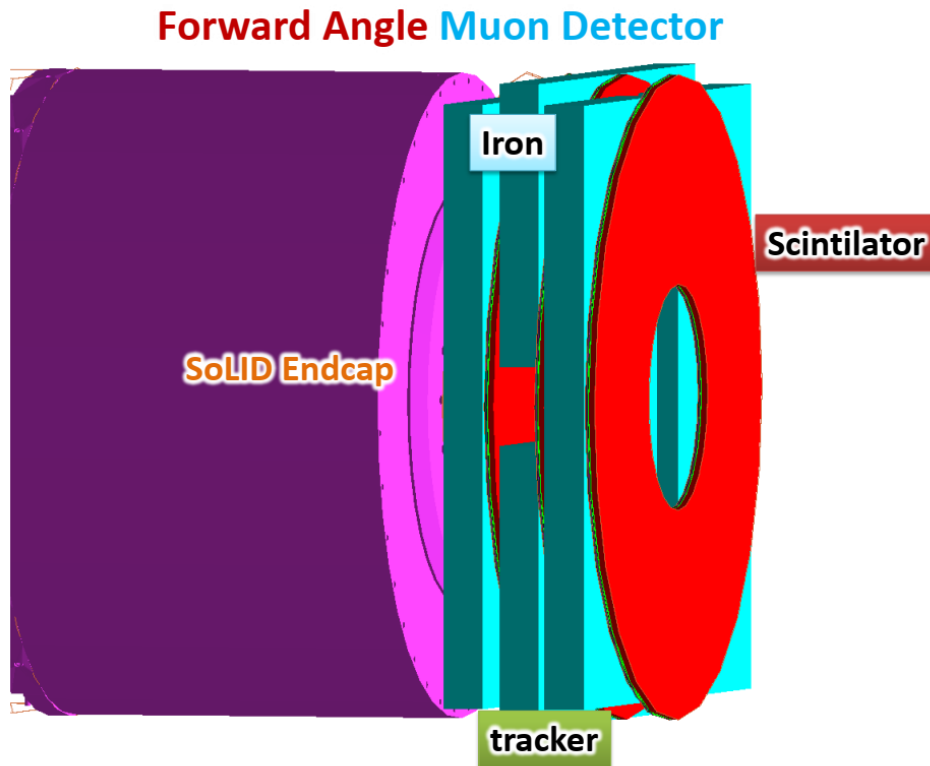
- Access to the real part of CFFs (no dispersion relation has been established)
- **μCA** predicted to have **significant amplitude** and rich **harmonic composition**, like the forward-backward asymmetry of TCS
- **Curvature change** is a highly-discriminating feature for models
- **DDVCS μCA** access a CFF combination **different from BSA**. This feature **distinguishes DDVCS** from DVCS and TCS.

# Experimental Setup



- SoLID can detect  $e^-$ ,  $e^+$ , proton, pion
- Based on SoLID J/Psi and TCS setup ( $1.2e37/cm^2/s$ ) with forward angle muon detector added to form **SoLIDμ spectrometer**
- **Sharing** beam time with approved J/Psi and TCS di-e experiment
- Forward Angle (FA) covers 8.5-16.5deg and Large Angle (LA) covers 18-30deg

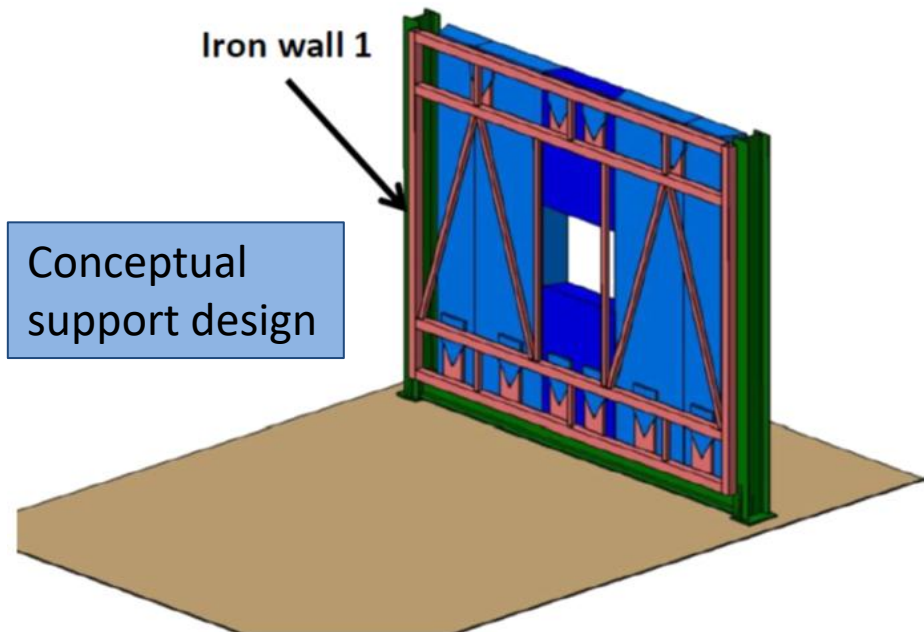
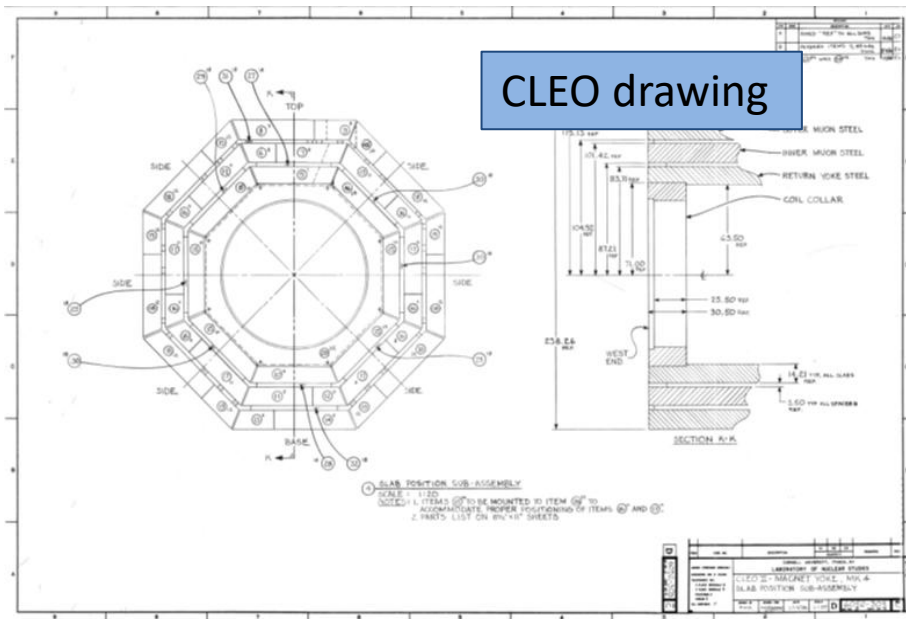
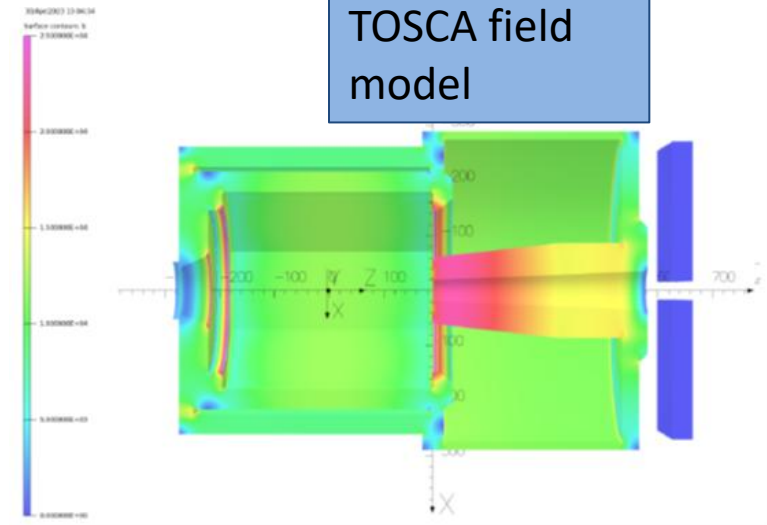
# Forward Angle Muon Detector (FAMD)



- 3 layers of iron+tracker+scintillator ( $R_{in}=1\text{m}$ ,  $R_{out}=3\text{m}$ )
- Iron for pion blocking
- $\mu$ RWell trackers to connect with tracks in SoLID inner GEM trackers
  - track resolution from SoLID inner trackers only
- scintillators for muon PID with pion suppression and trigger

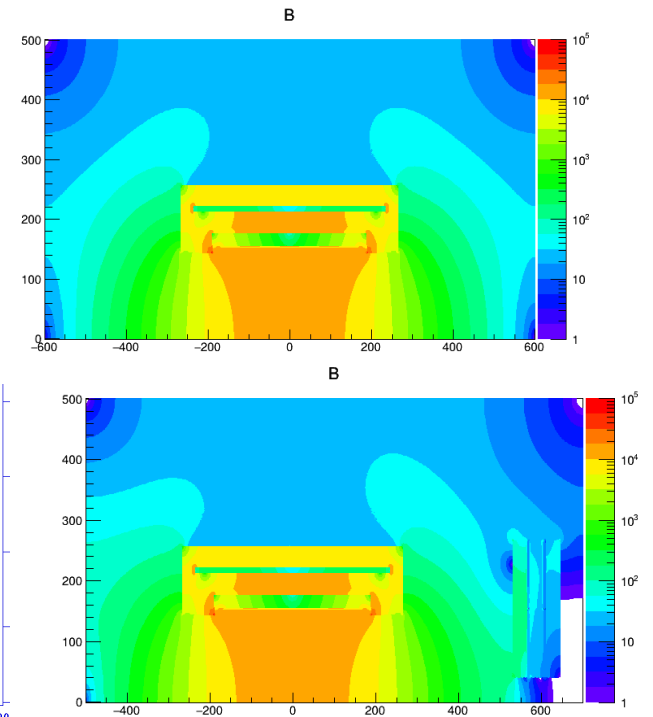
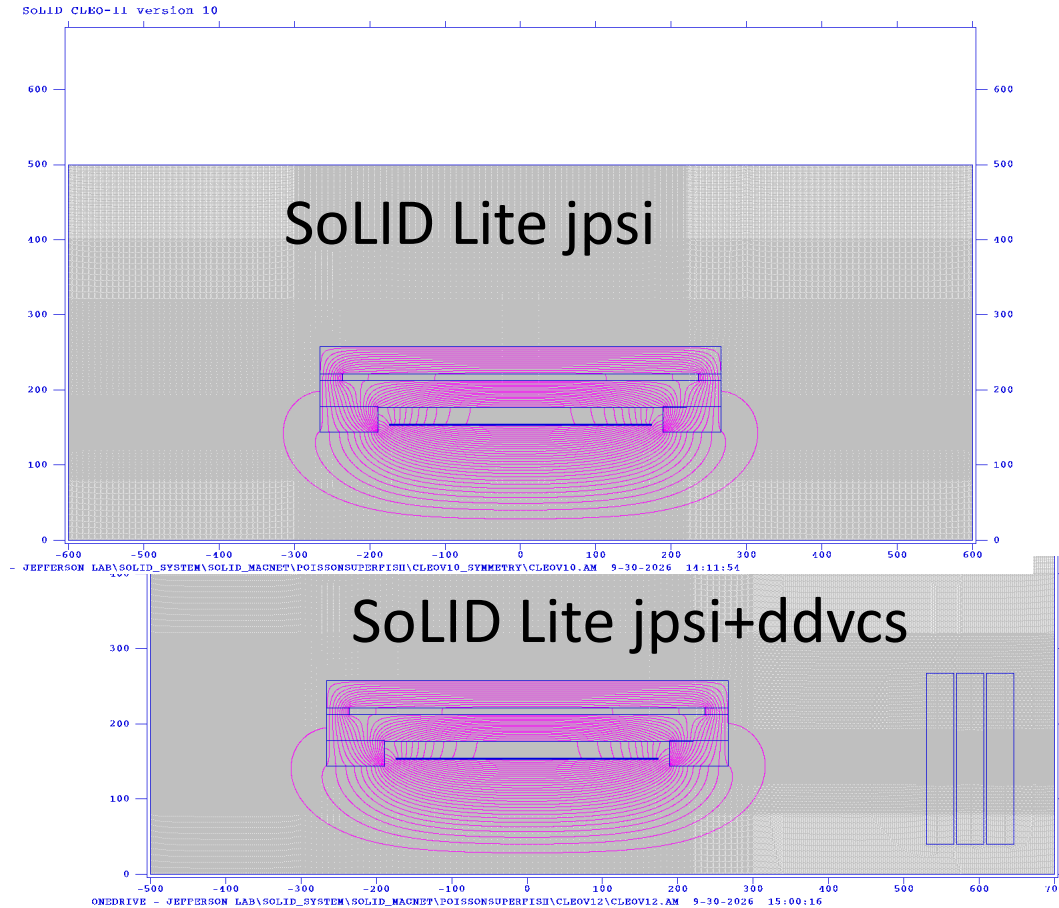
# Iron of FAMD

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



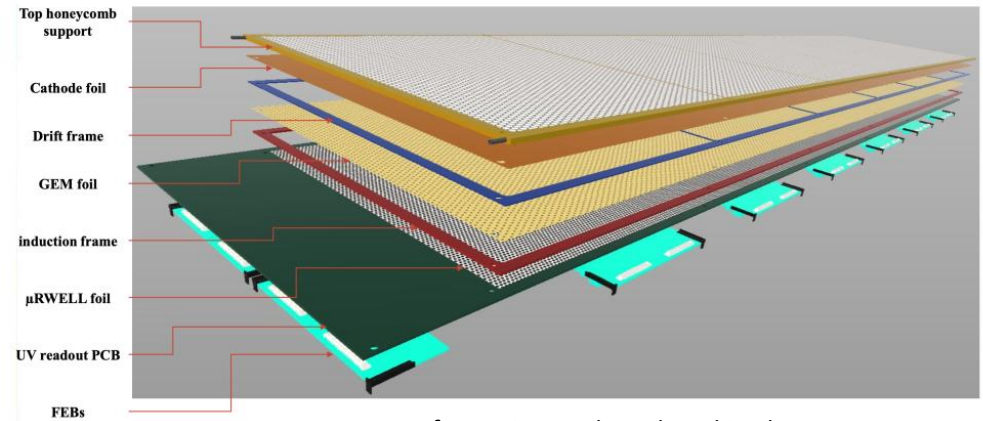
# SoLID lite jpsi+ddvcs

- Muon detector iron effect on field and force on coil are small

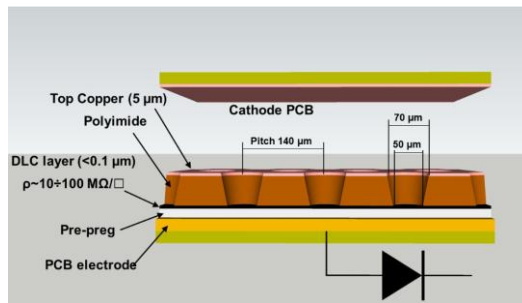


# $\mu$ RWell trackers of FAMD

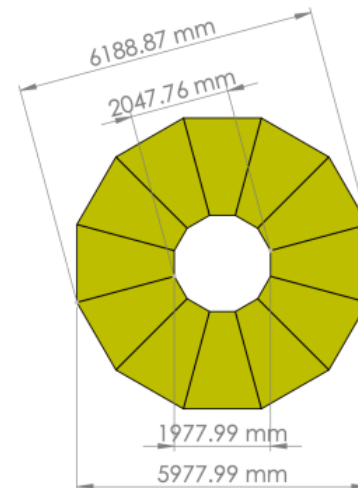
- $\mu$ RWell tracker with good rate capability and lower cost than GEM
- VMM electronics for readout
- 2D UV strips with capacitive charge sharing to have rate 30KHz/cm<sup>2</sup> and position resolution of 1 mm



$\mu$ RWell Detector for EPIC outer barrel tracking layer



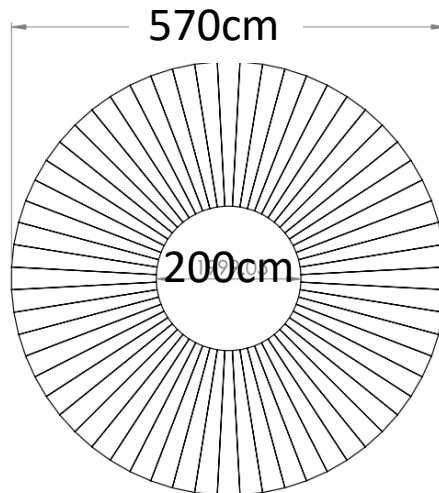
$\mu$ RWell Detector – G. Bencivenni *et al* 2019 *JINST* **14** P05014



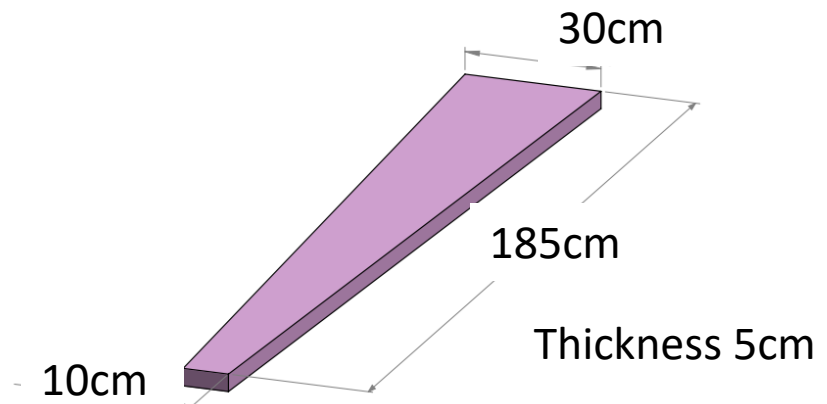
A plane of  $\mu$ RWell detector

# Scintillators of FAMD

- 3 layers of scintillator planes
- Each plane has 60 azimuthal segments
- Readout with light guide and PMTs from both inner and outer radial ends
- Design similar to CLAS12 forward scintillator and SoLID large angle scintillator with similar performance



A plane of scintillator detector



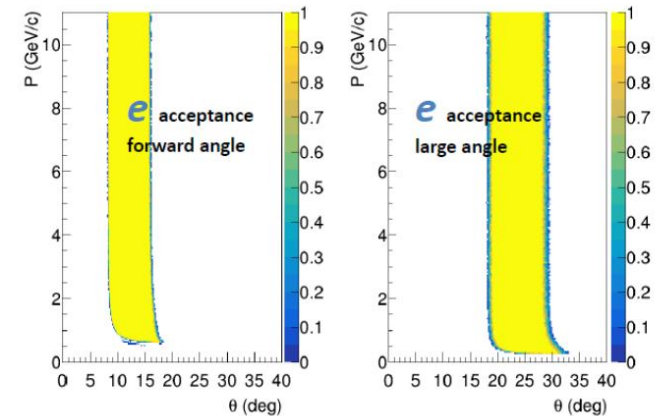
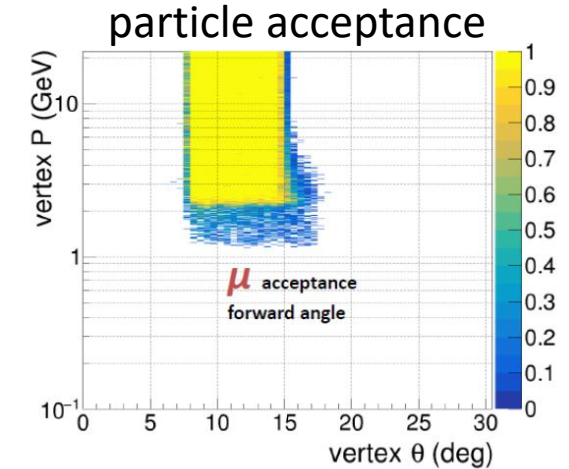
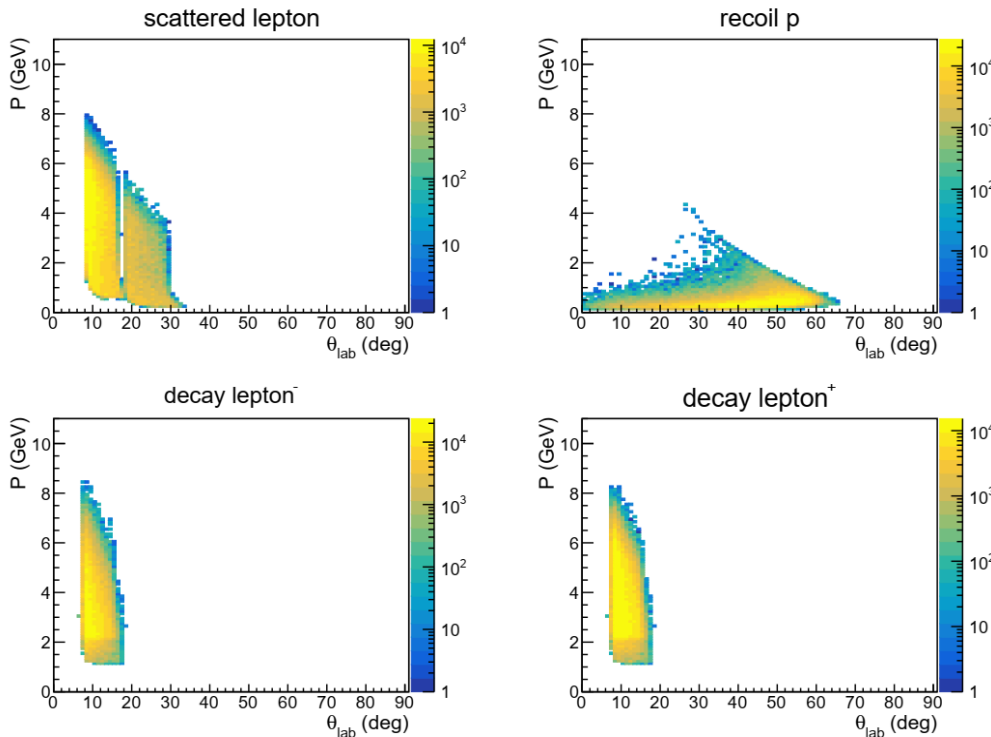
A module of scintillator detector

# Event Acceptance

BH generator "grape-dilepton" used by HERA and verified by CLAS12

- Best topology 3-fold(e+mu+mu): scattered e- at FA+LA, both muons at FA, proton not detected
- Additional topology 4-fold(e+mu+mu+p): recoil proton at FA+LA (clean)

accepted BH 3-fold events

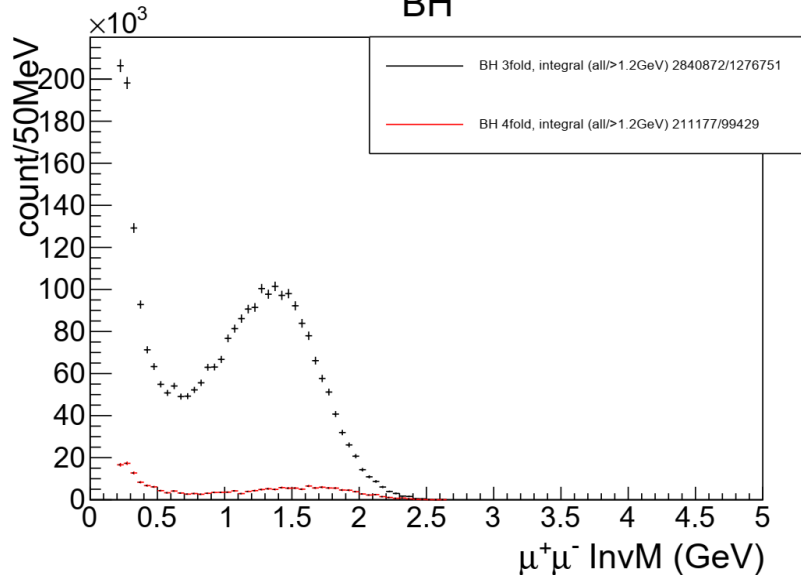


- full azimuthal coverage and large acceptance
- Solenoid field helps control systematics

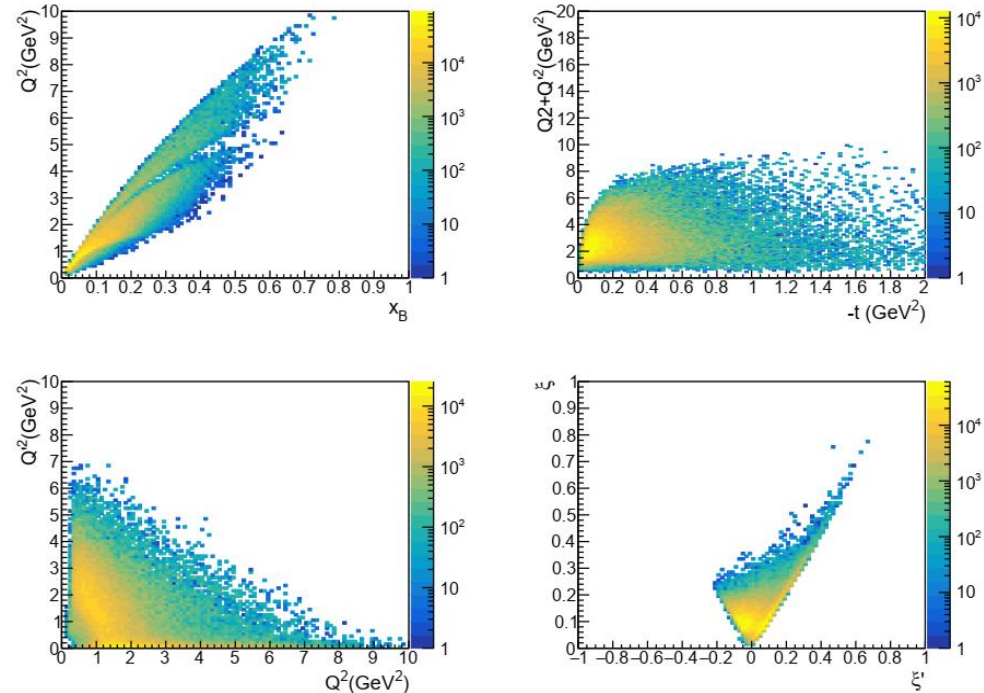
# Event Distribution

- 3-fold BH events covers a large kinematic range
- 0.7 overall detection efficiency
- Enough counts with 1.2e37/cm2/s luminosity and 100 days to have multidimensional binning

BH

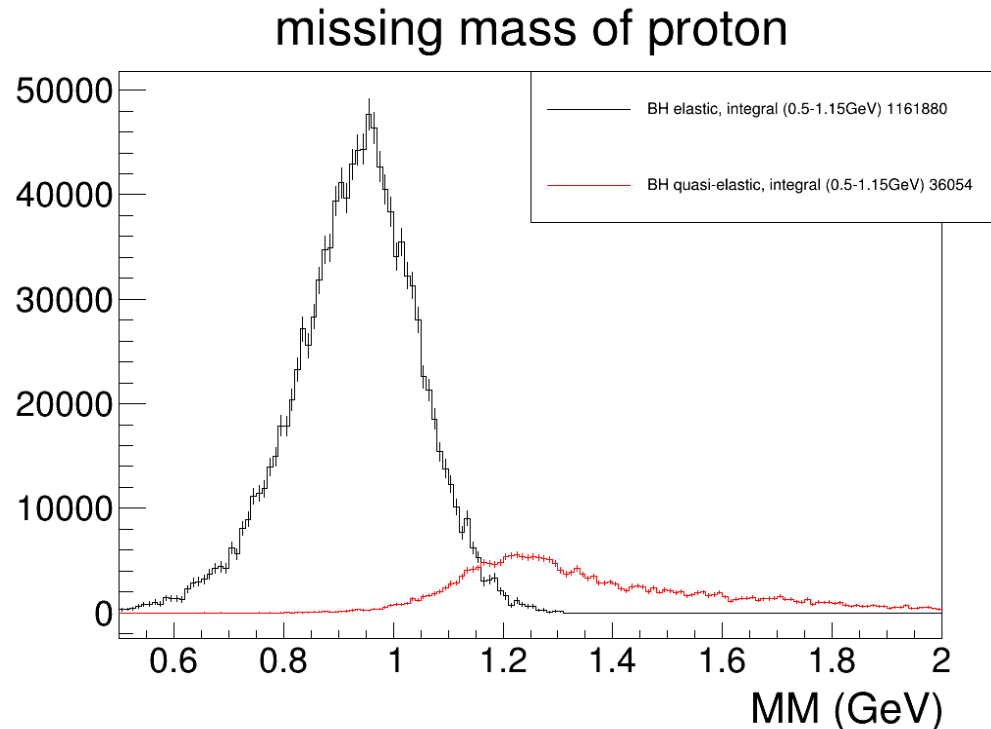


accepted BH 3-fold events

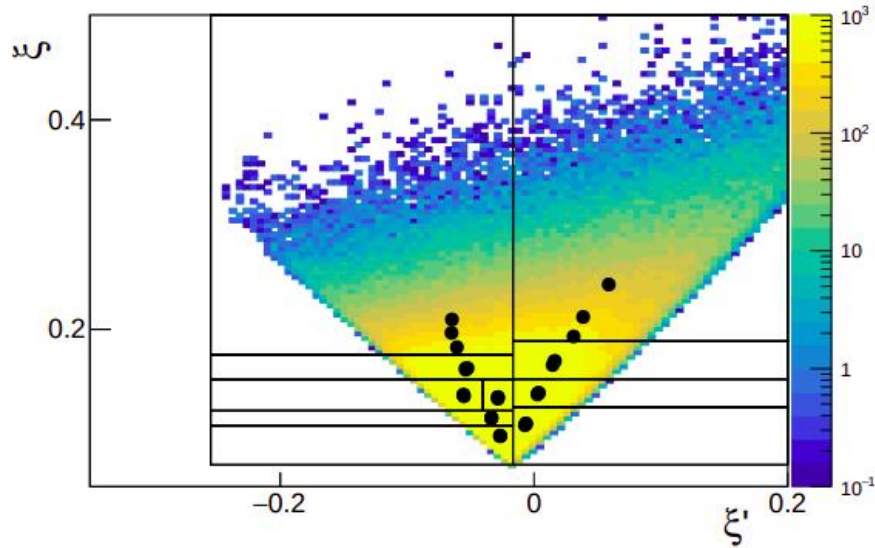


# Exclusivity cut

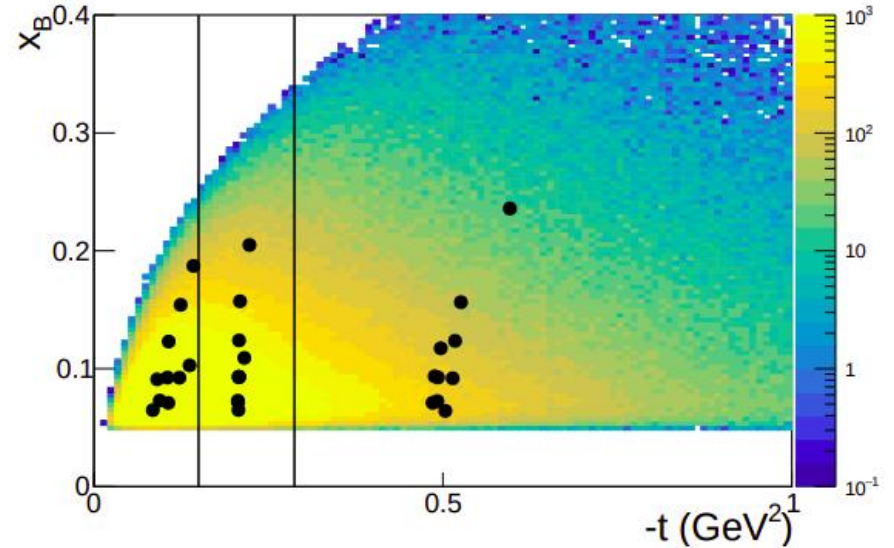
- Both BH with 4 final particles (elastic) and more than 4 particles (quasi-elastic), generated by "grape-dilepton"
- Missing proton mass of 3 fold BH events with resolution from SoLID inner GEM trackers, for resonance free region (muon pair  $\text{InvM} > 1.2 \text{ GeV}$ )
- 3-4% background after cutting  $\text{MM} > 1.15 \text{ GeV}$



# Experimental projection binning



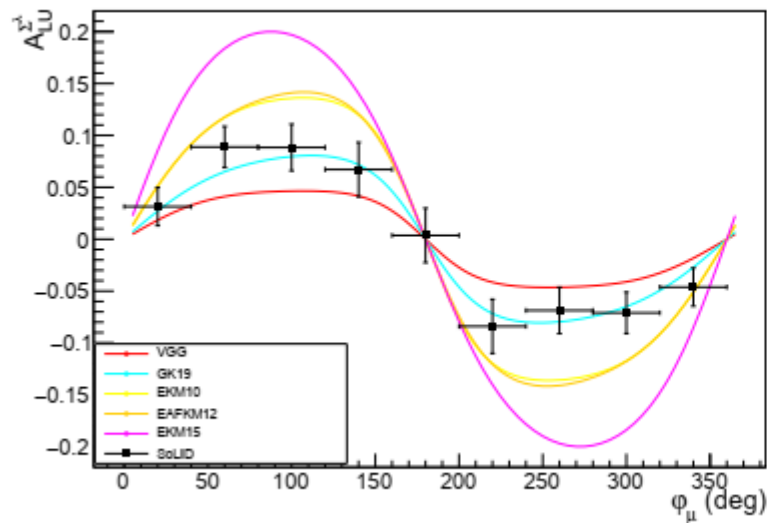
(a)  $(\xi', \xi)$  space.



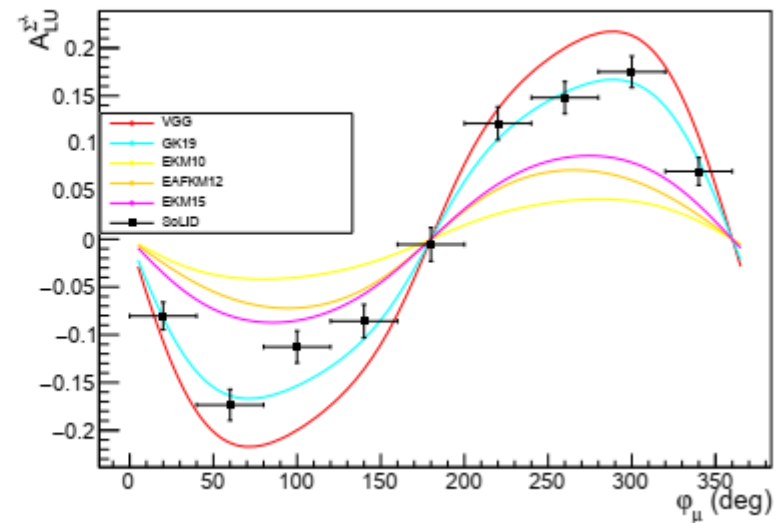
(b)  $(-t, x_B)$  space.

- 100 days would allow for measurements on a five-dimensional grid  $(\xi' \ \xi \ t \ x_B \ \Phi_\mu)$
- Covers both DVCS-like region ( $\xi' > 0, Q^2 > Q'^2$ ) to TCS-like region ( $\xi' < 0, Q^2 < Q'^2$ )

# BSA experimental projections



DVCS-like region



TCS-like region

arXiv:2502.02346

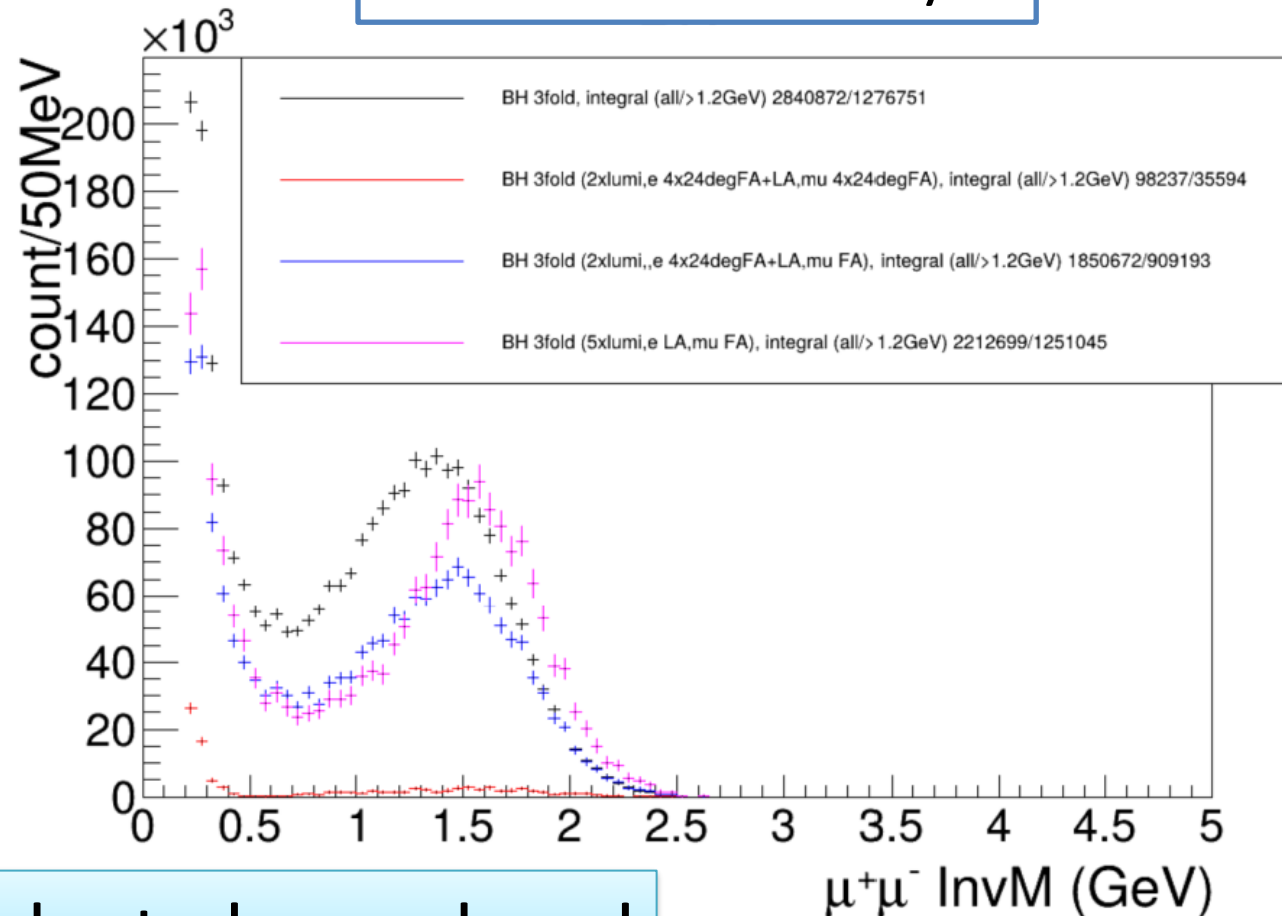
- First time measurement of the BSA sign change between the two regions
- Possibility to constrain GPD models

All projection plots include statistical and polarization errors

# SoLID Lite DDVCS

- option “e 4seg24degFA+ LA, mu FA” is close to full
- option “e LA, mu FA” is very good
- option “mu 4seg24degFA” has too much loss. We need full FA coverage for mu

BH counts of 100 days



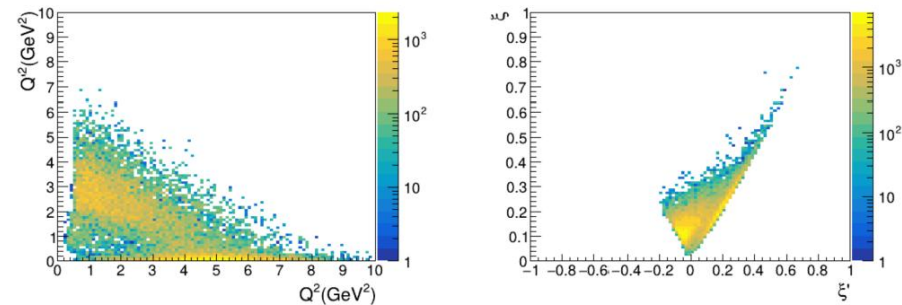
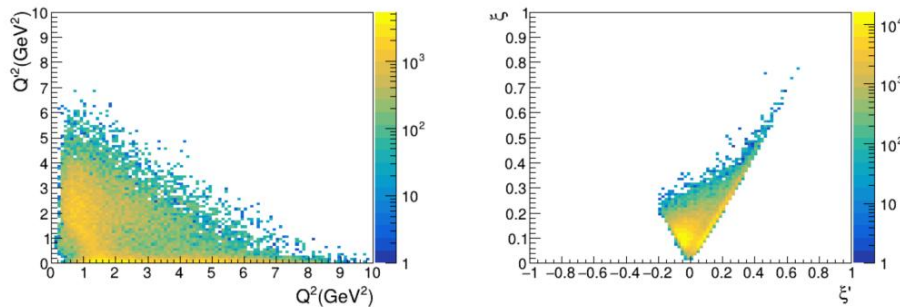
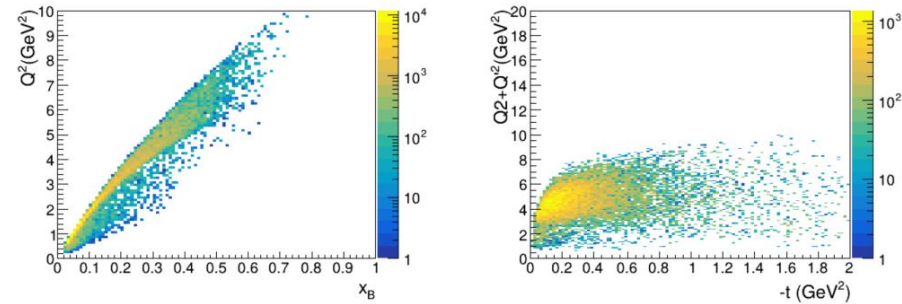
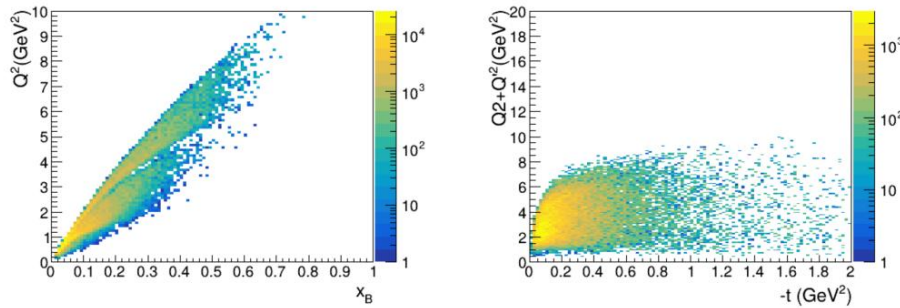
mu at LA will help, to be explored

# SoLID Lite DDVCS

- option “e 4seg24degFA+LA, mu FA” is close to full
- option “e LA, mu FA” is very good

e 4seg24degFA+LA, mu FA

e LA, mu FA



# Summary

- SoLID full/Lite TCS can test GPD universality
- DDVCS needs a forward angle **muon detector** to form **SoLID $\mu$**  spectrometer to measure **DDVCS** in the di-muon channel
- SoLID DDVCS approved in 2025 with 100+10 days (sharing 50+10 days with jpsi)
- SoLID Lite DDVCS is possible but we need to work on muon detector design with cost saving and explore other option like mu at LA
- SoLID dilepton program (jpsi/TCS/DDVCS) has muon and electron together (save beam time, increase statistics, check systematics)

## SoLID DDVCS physics impact

- **first time measurement** of **DDVCS** (mainly BSA and exploratory  $\mu$ CA) over a broad kinematic range
- **first time to access GPD**  $|x| < \xi$  as input for models and global fitting

# Backup

# Proposal to PAC53 PR12-25-010

## Proposal to JLab PAC 53

### Double Deeply Virtual Compton Scattering with SoLID $\mu$ spectrometer

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Garth Huber, Nathan Heinrich, Muhammad Junaid, Vijay Kumar, and Alicia Postuma

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Nilanga Linayage, Huong Thi Nguyen, and Asar Ahmed

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Yi Wang, Junhuai Xu, Zhihong Ye, Haojie Zhang, and Yaopeng Zhang

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\*: Co-spokesperson, †: Contact-spokesperson (camsonne@jlab.org)

## and SoLID Collaboration

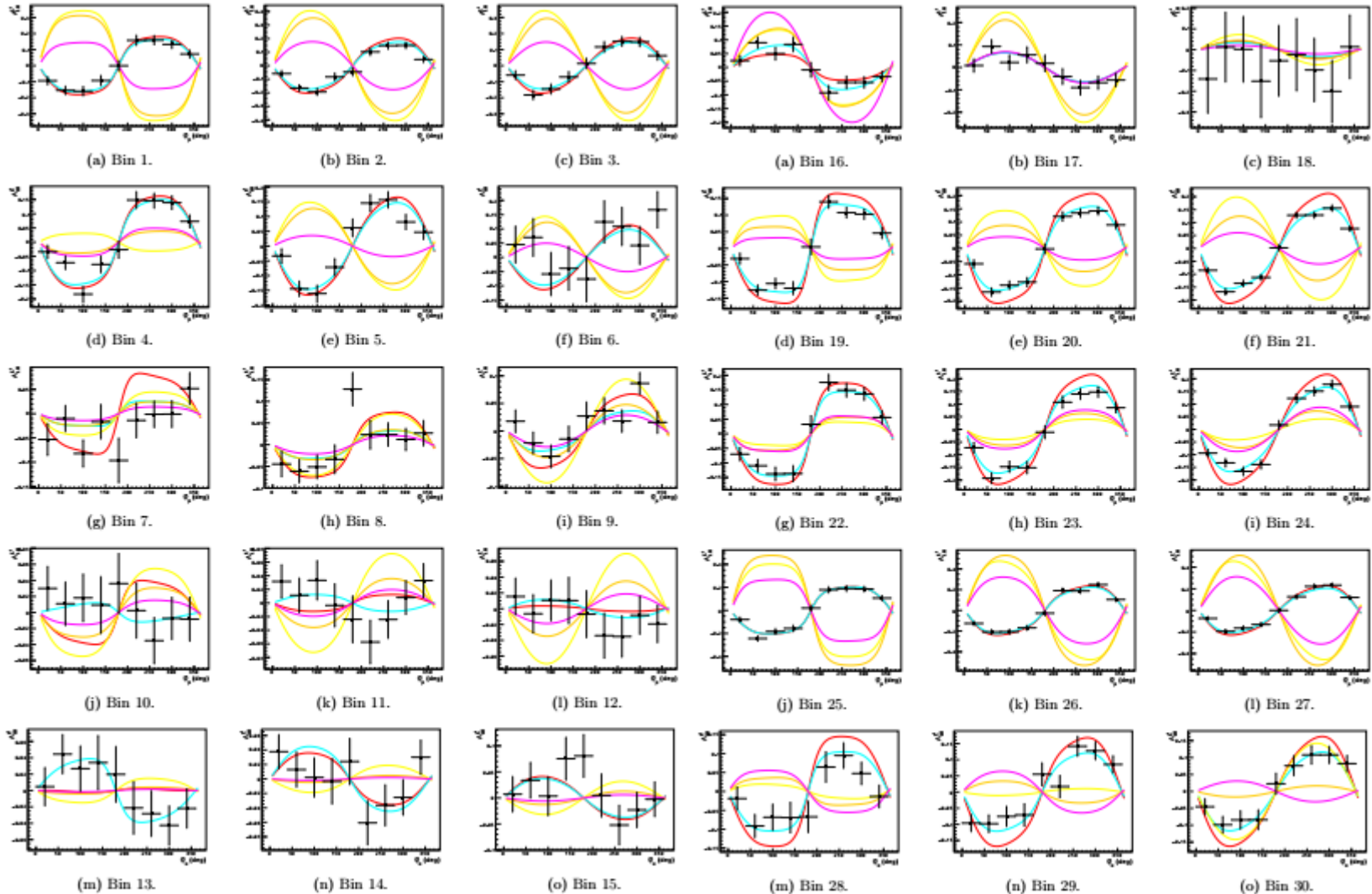
Spokesperson : Juan-Sebastian Alvarado, Alexandre Camsonne, Marie Boer,  
Eric Voutier, Xinzhan Bai, Zhiwen Zhao

# BSA experimental projections

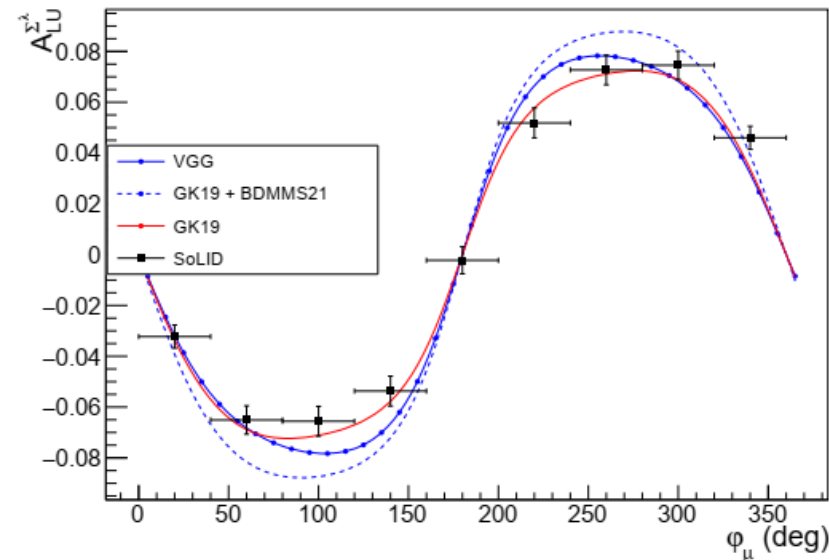
All plots over the entire kinematic range

| Bin | $\xi'$ range             | $\xi$ range           | $t$ range (GeV <sup>2</sup> ) |
|-----|--------------------------|-----------------------|-------------------------------|
| 1   | $-0.255 < \xi' < 0$      | $0.152 < \xi < 0.176$ | $-5.541 < t < -0.287$         |
| 2   |                          |                       | $-0.287 < t < -0.150$         |
| 3   |                          |                       | $-0.150 < t < -0.020$         |
| 4   | $0 < \xi' < 0.512$       | $0.176 < \xi < 0.739$ | $-5.541 < t < -0.287$         |
| 5   |                          |                       | $-0.287 < t < -0.150$         |
| 6   |                          |                       | $-0.150 < t < -0.020$         |
| 7   |                          |                       | $-0.287 < t < -0.150$         |
| 8   | $0 < \xi' < 0.512$       | $0.071 < \xi < 0.126$ | $-5.541 < t < -0.287$         |
| 9   |                          |                       | $-0.287 < t < -0.150$         |
| 10  |                          |                       | $-0.150 < t < -0.020$         |
| 11  |                          |                       | $-0.287 < t < -0.150$         |
| 12  | $0.153 < \xi < 0.189$    | $-5.541 < t < -0.287$ | $-0.287 < t < -0.150$         |
| 13  |                          |                       | $-0.150 < t < -0.020$         |
| 14  |                          |                       | $-0.287 < t < -0.150$         |
| 15  |                          |                       | $-0.150 < t < -0.020$         |
| 16  | $0.189 < \xi < 0.739$    | $-5.541 < t < -0.287$ | $-0.287 < t < -0.150$         |
| 17  |                          |                       | $-0.150 < t < -0.020$         |
| 18  |                          |                       | $-0.287 < t < -0.150$         |
| 19  |                          |                       | $-0.150 < t < -0.020$         |
| 20  | $-0.255 < \xi' < -0.017$ | $0.071 < \xi < 0.108$ | $-5.541 < t < -0.287$         |
| 21  |                          |                       | $-0.287 < t < -0.150$         |
| 22  |                          |                       | $-0.150 < t < -0.020$         |
| 23  |                          |                       | $-0.287 < t < -0.150$         |
| 24  | $-0.395 < \xi' < -0.040$ | $0.122 < \xi < 0.152$ | $-5.541 < t < -0.287$         |
| 25  |                          |                       | $-0.150 < t < -0.020$         |
| 26  |                          |                       | $-0.287 < t < -0.150$         |
| 27  |                          |                       | $-0.150 < t < -0.020$         |
| 28  | $1 < \xi' < -0.017$      | $0.122 < \xi < 0.152$ | $-5.541 < t < -0.287$         |
| 29  |                          |                       | $-0.287 < t < -0.150$         |
| 30  |                          |                       | $-0.150 < t < -0.020$         |
| 31  |                          |                       | $-0.287 < t < -0.150$         |

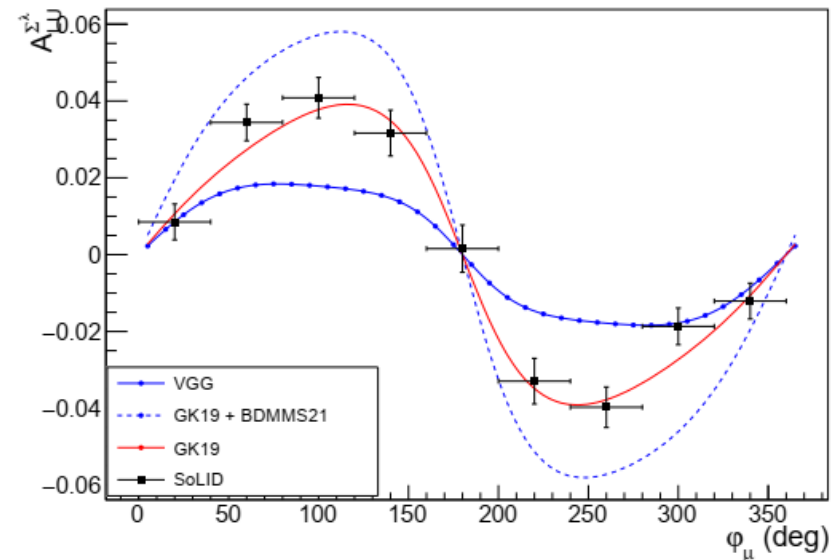
Bin boundaries of the binning scheme shown in Fig. 2



# BSA experimental projections



(a)  $-0.1 < \xi' < -0.04$ .

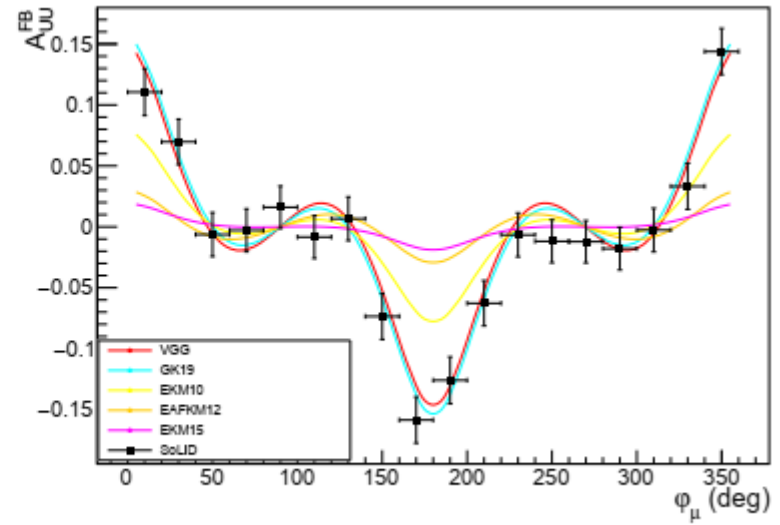
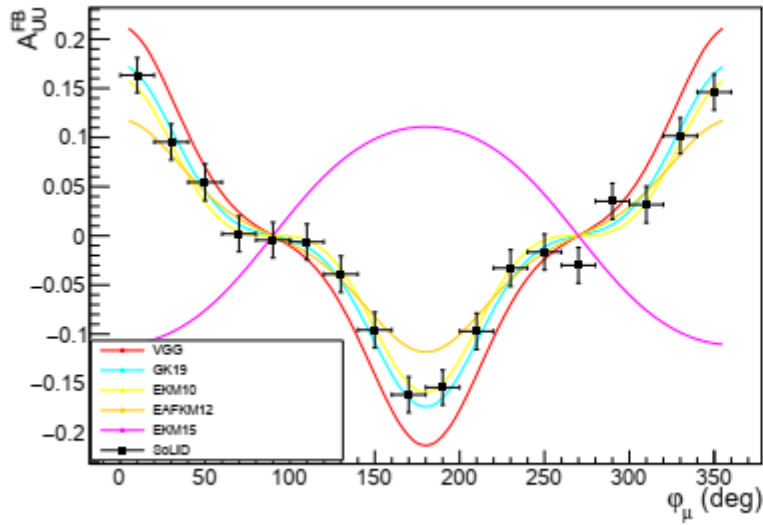


(b)  $-0.04 < \xi' < 0.1$ .

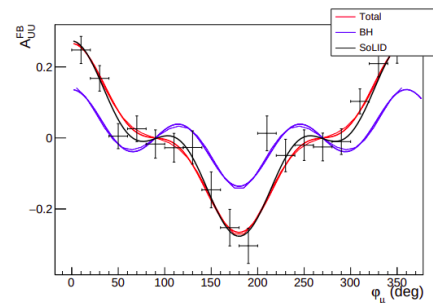
Figure 26: Projected exploratory TCS-like BSA measurements sensitive to shadow GPDs in the  $0.3 < \xi < 0.4$  region.

**First time exploratory measurement of BSA constraining shadow GPD models** (a class of functions with null CFF and forward limit contributing to GPD solutions in the deconvolution problem)

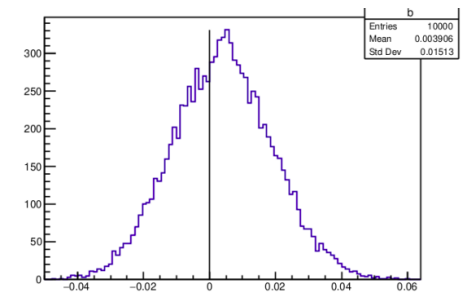
# $\mu$ CA experimental projections



First time exploratory measurement of  $\mu$ CA to access the CFF real part with curvature change



(a)  $\mu$ CA and the components entering the  $\cos \varphi_\mu$  mo-



(b) Distribution of the  $\cos \varphi_\mu$  moment of the  $\mu$ CA

$$A_{UU}^{\mu\pm}(\varphi_\mu) = a_0 + a_1 \cos(\varphi) + a_3 \cos(3\varphi).$$

- known BH contribution is small in certain regions and can be subtracted
- $\mu$ CA has contributions from  $\cos(\phi)$  and  $\cos(3\phi)$  modulations
- $\cos(\phi)$  component can be extracted from fitting

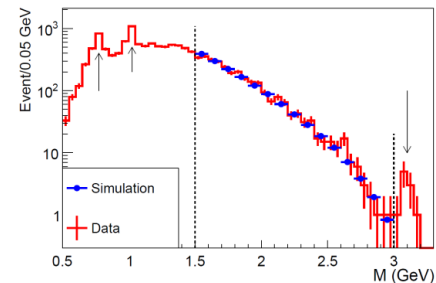
# Systematic effects

BSA systematics originates mainly from electron beam polarization, electron detection efficiency, and muon detection efficiency

$$A_{LU}^{\Sigma\lambda} = \frac{1}{\lambda} \frac{Y_+ - Y_-}{Y_+ + Y_-} \quad Y_{\pm}(\varphi_{\mu}) = \frac{1}{Q_{\pm}} \frac{1}{\Delta\Omega_e(\varphi_{\mu}) \Delta\theta_{\mu}(\varphi_{\mu})} \int_0^{2\pi} d\phi \int_{\pi/4}^{3\pi/4} d\theta_{\mu} \sin(\theta_{\mu}) \frac{N_{\pm}(\varphi_{\mu}, \phi, \theta_{\mu})}{\epsilon_e(\phi) \epsilon_{\mu}(\varphi_{\mu}, \theta_{\mu})}$$

$$Y_{\pm}(\varphi_{\mu}) \equiv \sum_{i=1}^{N_{\phi}} \sum_{j=1}^{N_{\theta_{\mu}}} \frac{n_{\pm}^{ij}}{\epsilon_e^i \epsilon_{\mu}^j} \quad \delta A_{LU}^{\Sigma\lambda} = \sqrt{\left[A_{LU}^{\Sigma\lambda}\right]^2 \left(\frac{\delta\lambda}{\lambda}\right)^2 + \frac{1}{2\lambda^2} \frac{1}{N_{\phi}} \left(\frac{\delta\epsilon_e}{\epsilon_e}\right)^2 + \frac{1}{2\lambda^2} \frac{1}{N_{\theta_{\mu}}} \left(\frac{\delta\epsilon_{\mu}}{\epsilon_{\mu}}\right)^2} \quad \lambda = 0.85 \rightarrow 0.04$$

*Bin independence hypothesis*  $(N_{\phi}, N_{\theta_{\mu}})$  are the kinematic dependent number of bins, typically (20,10)



CLAS12 BH di-e data  
and sim comparison

## Control systematics through reference channels

- SoLID will have crosssection measurement before this experiment
- For e- detection, use inclusive DIS and elastic measurements
- For muon detection, use both resonance and resonance free region and cross check both di-e and di-mu channels
- Pion channel measurement are also taken at the same time

# Beam time request

| Beam Energy (GeV)          | Beam Current (uA) | Beam Requirements | Target Material | Target Thickness (cm) | Beam time (days) |
|----------------------------|-------------------|-------------------|-----------------|-----------------------|------------------|
| 11                         | 3                 | polarized (>85%)  | LH2             | 15                    |                  |
| Run Group Calibration time |                   |                   |                 |                       | 10               |
| Run Group Production time  |                   |                   |                 |                       | 50               |
| Requested Production time  |                   |                   |                 |                       | 50               |
| Total Time                 |                   |                   |                 |                       | 110              |

- Main trigger on di-muon to take DDVCS, J/psi and TCS di-mu data at the same time
- Independent di-e trigger for approved J/psi and TCS di-e data taking at the same time
- **Comprehensive program including muons and electrons within same runs.** It can also help cross check systematics

# 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.

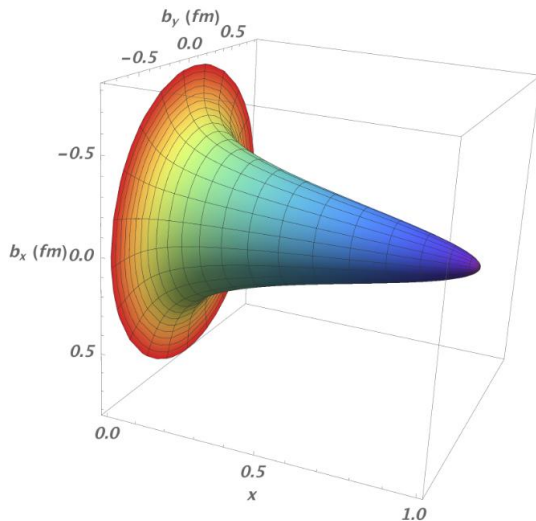
## Deep Exclusive Meson Production:

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

# Nucleon Femtography

M. Burkardt PRD 62 (2000) 071503. M. Diehl EPJC 25 (2002) 223 A.V. Belitsky, D. Müller, NPA 711 (2002) 118c J.P. Ralston; B. Pire PRD 66 (2002) 111501

$$\rho_H^q(x, \mathbf{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i\mathbf{b}_\perp \cdot \Delta_\perp} [H^q(x, 0, -\Delta_\perp^2) + H^q(-x, 0, -\Delta_\perp^2)]$$



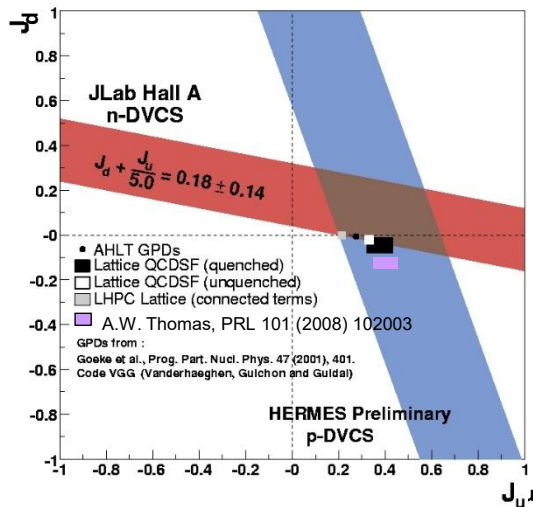
- The **transverse densities** of partons in nucleons and nuclei is related to the transverse momentum transfer ( $-\Delta_\perp^2$ ) dependence of GPDs at **zero-skewness**.
- **DVCS** and **TCS** cannot map out **zero-skewness GPDs** over the **full physics phase space**.

The **experimental knowledge** of the  **$\xi$ -dependence** of GPDs at fixed longitudinal momentum fraction allows to **control** the **zero-skewness extrapolation** required for **nucleon imaging**.

R. Dupré, M. Guidal, M. Vanderhaeghen, PRD 95 (2017) 011501

# Nucleon Spin

$$\lim_{t \rightarrow 0} \int_{-1}^1 x [H^q(x, \xi, t) + E^q(x, \xi, t)] dx = J^q$$

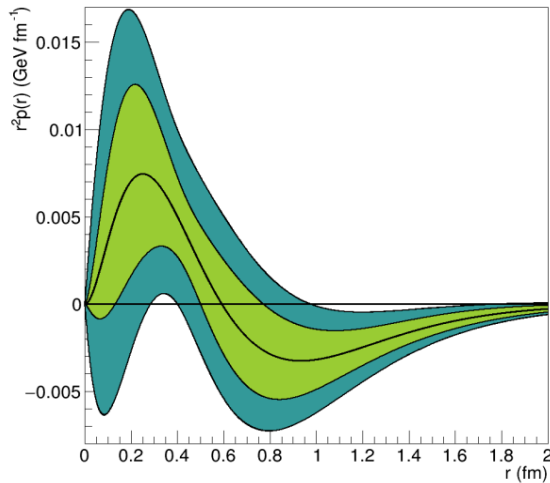


- The **total angular momentum of partons** inside the nucleon can be inferred from the  $J_i$  sum rule which involves the **forward limit** of the **first Mellin moment** of partons helicity conserving GPDs.
- **DVCS** and **TCS** cannot access GPDs at  $x \neq \xi$  over the **full physics phase space**.

The **experimental knowledge** of the  **$\xi$ -dependence** of GPDs at fixed longitudinal momentum fraction is a **mandatory step** for unraveling the **nucleon spin**.

# Nucleon Forces

$$\int_{-1}^1 x \sum_q H^q(x, \xi, t) dx = M_2(t) + \frac{4}{5} \xi^2 d_1(t)$$



- The **skewness dependence** of the **first Mellin moment** of the GPD  $H$  provides an access to the **gravitational form factors** of the energy momentum tensor of the nucleon.
- **$e^\pm$ -DVCS** and **TCS** offers another path via **dispersion relations**.

The  **$\xi$ -dependence** of GPDs reveals the **internal dynamics** of the nucleon.

V. Burkert, L. Elouadrhiri, F.-X. Girod, Nat. 557 (2018) 396; arXiv:2104.02031

# Integrated Cross Section

**5-fold observables** obtained from the **integration over** the **polar angle** of the **muon** and the **azimuthal angle of initial virtual photon or final virtual photon** are required, also **minimizing** the contribution of the **BH<sub>2</sub>** process

**DVCS-like xs**  
(integral of  $\phi_\mu$ )

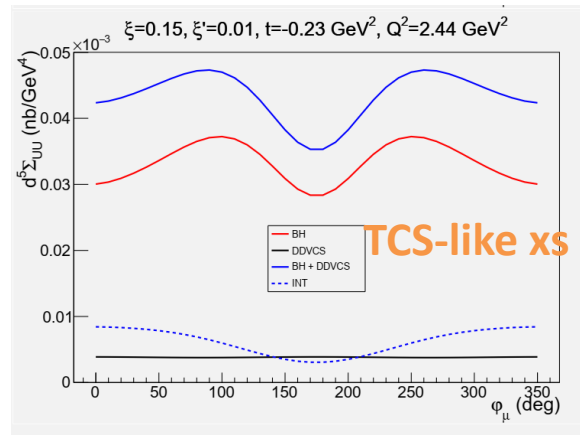
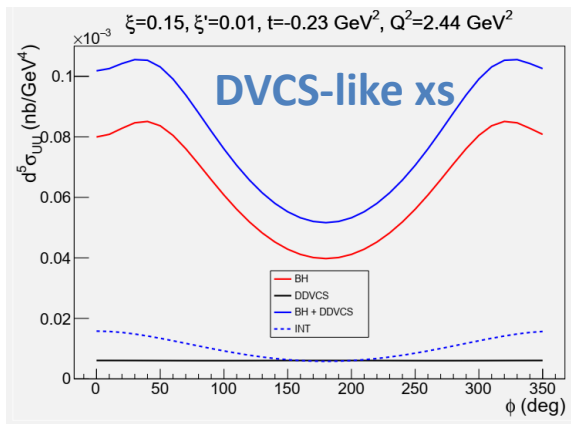
$$d^5\sigma^\lambda(\phi) \equiv \frac{d^5\sigma^\lambda(\phi)}{dx_B dy dt dQ'^2 d\phi} = \int_0^{2\pi} d\varphi_\mu \int_{\pi/2-\theta_0}^{\pi/2+\theta_0} d\theta_\mu \sin(\theta_\mu) \frac{d^7\sigma^\lambda(\phi, \theta_\mu, \phi_\mu)}{dx_B dy dt d\phi dQ'^2 d\Omega_\mu}$$

$$d^5\sigma^\lambda = d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} + d^5\sigma_{\mathcal{I}_1} + \lambda d^5\tilde{\sigma}_{\mathcal{I}_1} = d^5\sigma_{UU} + \lambda d^5\sigma_{LU}$$

**TCS-like xs**  
(integral over  $\phi$ )

$$d^5\Sigma^\lambda(\varphi_\mu) \equiv \frac{d^5\sigma^\lambda(\varphi_\mu)}{dx_B dy dt dQ'^2 d\varphi_\mu} = \int_0^{2\pi} d\phi \int_{\pi/2-\theta_0}^{\pi/2+\theta_0} d\theta_\mu \sin(\theta_\mu) \frac{d^7\sigma^\lambda(\phi, \theta_\mu, \phi_\mu)}{dx_B dy dt d\phi dQ'^2 d\Omega_\mu}$$

$$d^5\Sigma^\lambda = d^5\Sigma_{BH_1} + d^5\Sigma_{BH_2} + d^5\Sigma_{BH_{12}} + d^5\Sigma_{DDVCS} + d^5\Sigma_{\mathcal{I}_1} + d^5\Sigma_{\mathcal{I}_2} + \lambda d^5\tilde{\Sigma}_{\mathcal{I}_2} = d^5\Sigma_{UU} + \lambda d^5\Sigma_{LU}$$



Our study focuses on  
using **TCS-like xs** for  
projection

# Muon Charge Asymmetry

aka Forward Backward Asymmetry

$$A_{UU}^{FB}(\varphi_\mu) = \frac{d^5\Sigma_{UU}(\varphi_{\mu-}) - d^5\Sigma_{UU}(\varphi_{\mu-} + \pi)}{d^5\Sigma_{UU}(\varphi_{\mu-}) + d^5\Sigma_{UU}(\varphi_{\mu-} + \pi)} = \frac{d^5\Sigma_{UU}(\varphi_{\mu-}) - d^5\Sigma_{UU}(\varphi_{\mu+})}{d^5\Sigma_{UU}(\varphi_{\mu-}) + d^5\Sigma_{UU}(\varphi_{\mu+})} = A_{UU}^{\mu\pm}(\varphi_\mu)$$

$$\begin{aligned} d^5\Sigma_{UU}(\varphi_{\mu-} + \pi) &= \int_0^{2\pi} d\phi \int_{\pi/2-\theta_0}^{\pi/2+\theta_0} d\theta_{\mu-} \sin(\theta_{\mu-}) \frac{d^7\sigma^0(\phi, \pi - \theta_{\mu-}, \varphi_{\mu-} + \pi)}{dx_B dy dt d\phi dQ'^2 d\Omega_{\mu-}} \\ &= \int_0^{2\pi} d\phi \int_{\pi/2-\theta_0}^{\pi/2+\theta_0} d\theta_{\mu+} \sin(\theta_{\mu+}) \frac{d^7\sigma^0(\phi, \theta_{\mu+}, \varphi_{\mu+})}{dx_B dy dt d\phi dQ'^2 d\Omega_{\mu+}} = d^5\Sigma_{UU}(\varphi_{\mu+}) \end{aligned}$$

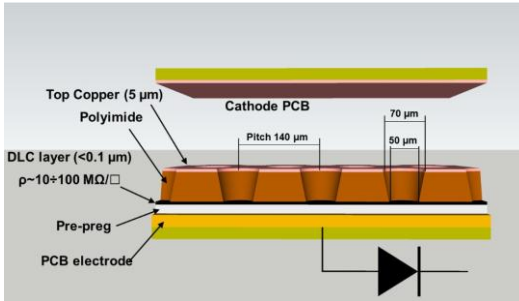
$$A_{UU}^{\mu\pm}(\varphi_\mu) = \frac{d^5\Sigma_{BH_{12}} + d^5\Sigma_{\mathcal{I}_2}}{d^5\Sigma_{BH_1} + d^5\Sigma_{BH_2} + d^5\Sigma_{DDVCS} + d^5\Sigma_{\mathcal{I}_1}}$$

$$d^5\Sigma_{\mathcal{I}_2} \propto -\frac{\xi'}{\xi} \Re \left[ F_1 \mathcal{H} + \frac{\xi^2}{\xi'} (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M_N^2} F_2 \mathcal{E} \right]$$

- Access to the real part of CFFs (no existing dispersion relation)
- **μCA** predicted to have **significant amplitude** and rich **harmonic composition**, like the forward-backward asymmetry of TCS
- **Curvature change** is a highly-discriminating feature for models
- **DDVCS μCA** access a CFF combination **different** from **BSA**. This feature **distinguishes DDVCS** from DVCS and TCS.

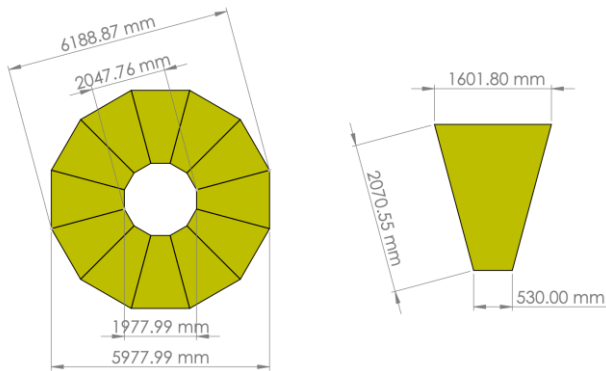
$$A_{UU}^{\mu\pm}(\varphi_\mu) = a_0 + a_1 \cos(\varphi) + a_3 \cos(3\varphi), \quad \frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = -\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau\sqrt{1-\tau}} \frac{L_0}{L} [\cos(\phi) \frac{1+\cos^2(\theta)}{\sin(\theta)} \text{Re}\tilde{M}^{--} - \cos(2\phi) \sqrt{2} \cos(\theta) \text{Re}\tilde{M}^{0-} + \cos(3\phi) \sin(\theta) \text{Re}\tilde{M}^{+-} + O(\frac{1}{Q'})], \quad 42$$

# Muon Detector Tracker

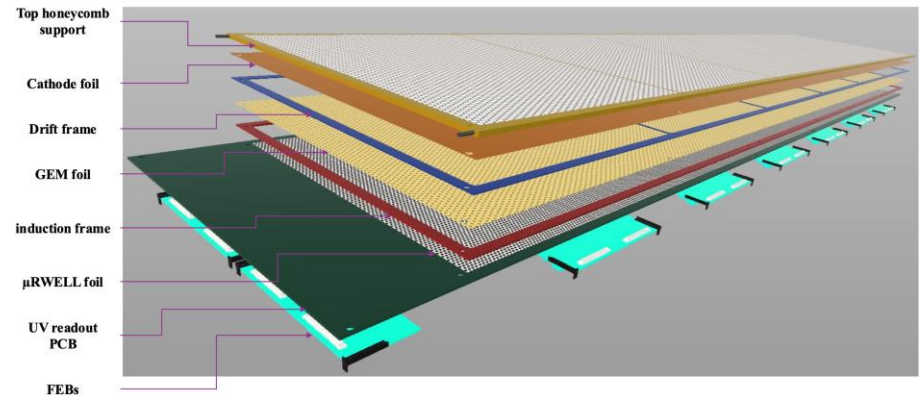


- Utilize  $\mu$ RWELL detectors for muon tracking layers
  - Current  $\mu$ RWELL detector rate capability –  $\sim 200 \text{ KHz/cm}^2$  (High-rate version in development –  $10 \text{ MHz/cm}^2$ )
  - Discharge resistant thanks to integrated DLC layers – a huge improvement on electronics stability – less interruption on DAQ during running
  - No spacers needed compared with GEM detectors – no dead area
- A similar technology adopted by EIC
  - Our muon detector unit would be roughly in the same size as EIC prototypes
  - Total cost (3 complete layers covering a total of  $75 \text{ m}^2$ ) around 900K

$\mu$ RWELL Detector – G. Bencivenni *et al* 2019 *JINST* **14** P05014



A plane of  $\mu$ RWELL detectors for muon detection



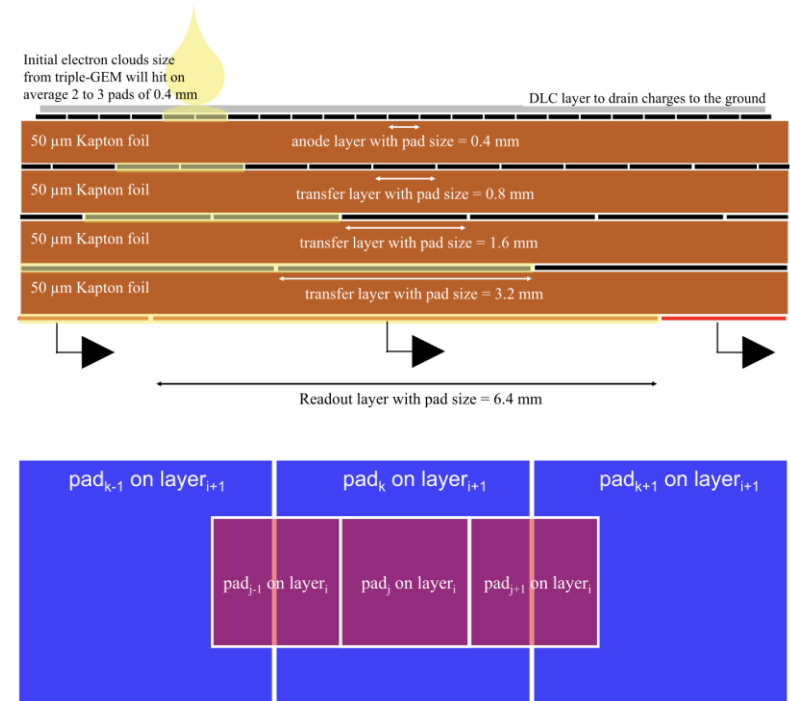
$\mu$ RWELL Detector for EPIC outer barrel tracking layer

# Muon Detector Tracker

- Use **capacitive charge sharing** technique to reduce total readout channels while maintain the **same space resolution**
- Works for all readout patterns – strip, pad, zigzag, ...

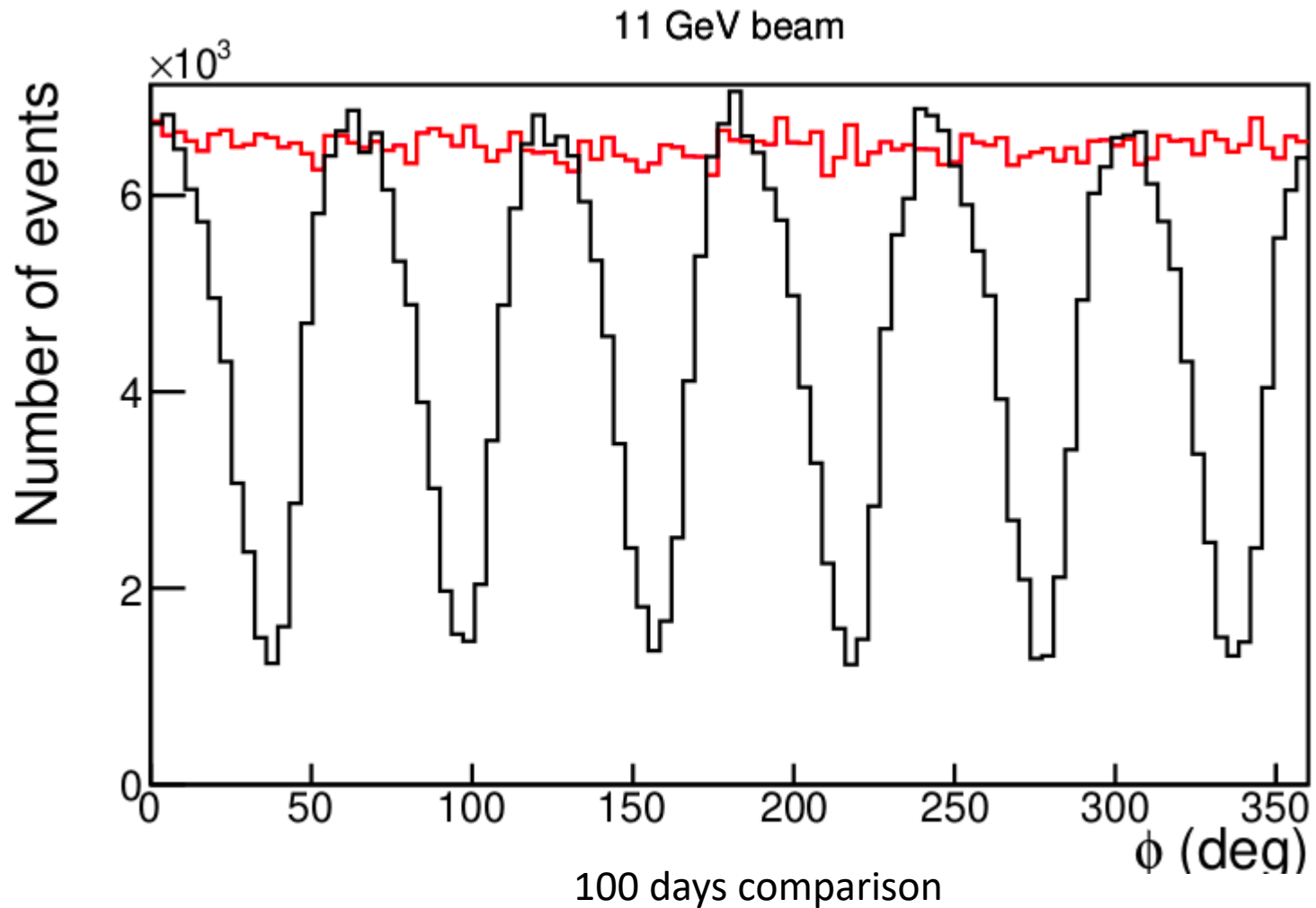
With Capacitive charge sharing:

- Space resolution : 1 mm
- Total readout channel can be reduced to around 22K for all 3 layers combined
- Detector rate will be determined by the final readout strip width, larger strip width leads to lower detector rate capability
- For 22K readout channels, 1 mm space resolution, with capacitive charge sharing technique – **rate capability:  $\sim 30 \text{ KHz/cm}^2$**  (assume 300 ns signal integral time)

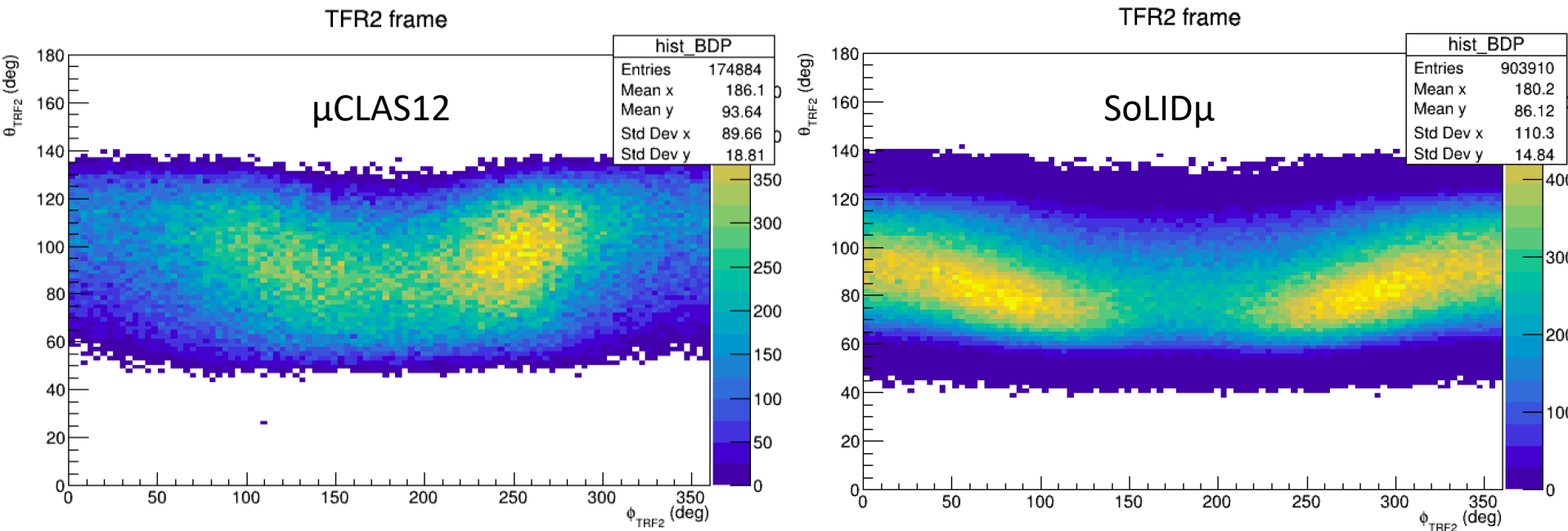


Concept for capacitive charge sharing – K. Gnanvo *et al*, *Nuclear Inst. and Methods in Physics Research, A* 1047 (2023) 167782

# SoLID $\mu$ vs $\mu$ CLAS12

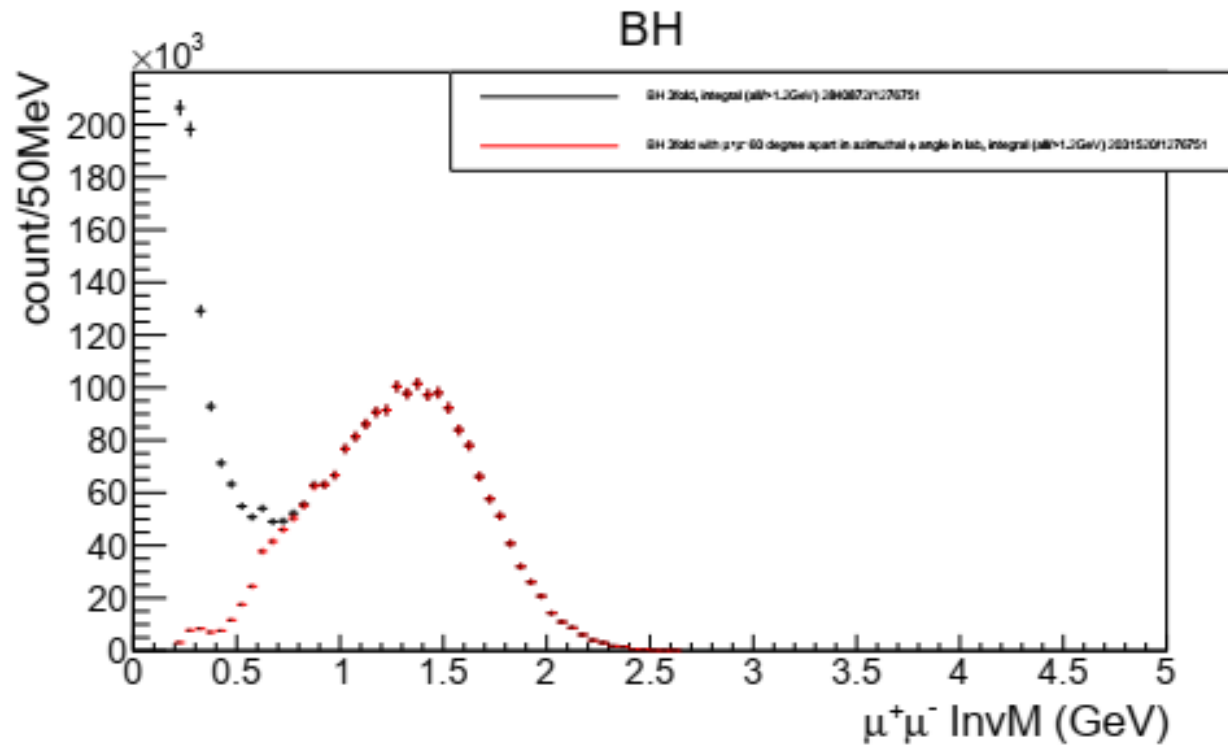


# SoLID $\mu$ vs $\mu$ CLAS12



- Angles in the muon center-of-mass frame
- Larger coverage with SoLID $\mu$

# BH and trigger



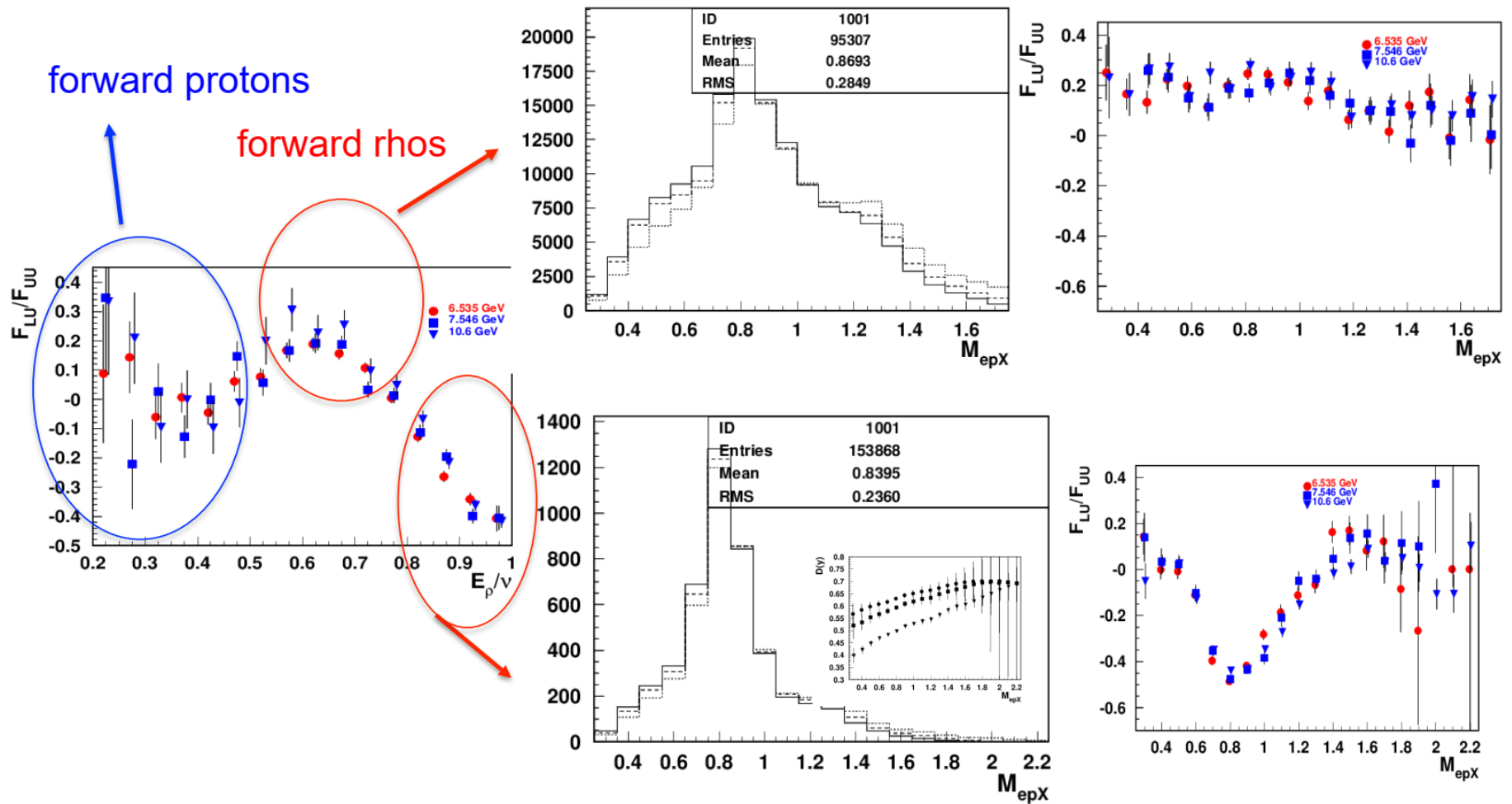
# Systematic effects

- Systematics of the measurements will be controlled via **simulations** and the measurement of **reference processes**. The **solenoidal field** and the **symmetrical configuration** of SoLID $\mu$  offer further cross-checks
- **Muon solid angle** : extensive simulations based on the **SoLID $\mu$  GEANT4 model** ( $\delta\Delta\theta_\mu/\Delta\theta_\mu \sim 3\%$ )
- **Electron detection efficiency** : measurement of **DIS** and **elastic** electron **scattering** ( $\delta\epsilon_e/\epsilon_e \sim 7\%$ )
- **Muon detection efficiency** : measurement of **Bethe-Heitler** and comparison of the  $e^\pm$  and  $\mu^\pm$  **decay** of specific meson ( $\phi, J/\Psi$ ) ( $\delta\epsilon_\mu/\epsilon_\mu \sim 15\%$ )

# Background asymmetry

- signal channel asymmetry  $A_s=0.1$  and rate  $R_s$
- background channel asymmetry  $A_b=0.5$  and rate  $R_b$
- Background/signal rate  $R_b/R_s=0.05$  with error  $ER=0.01$
- Rel\_Error of  $A_s = (A_s - A_b) / (1 - R_b/R_s)^2 * ER / A_s$   
 $= (0.1 - 0.5) / (1 - 0.05)^2 * 0.01 / 0.1 = -0.045$
- With those conservative assumptions, background only give about 5% error on signal asymmetry

# Exclusive $\pi^+\pi^-$ : missing mass dependence



Rhos dominate both exclusive dihadron samples, contributing differently depending on  $z$

# Cost

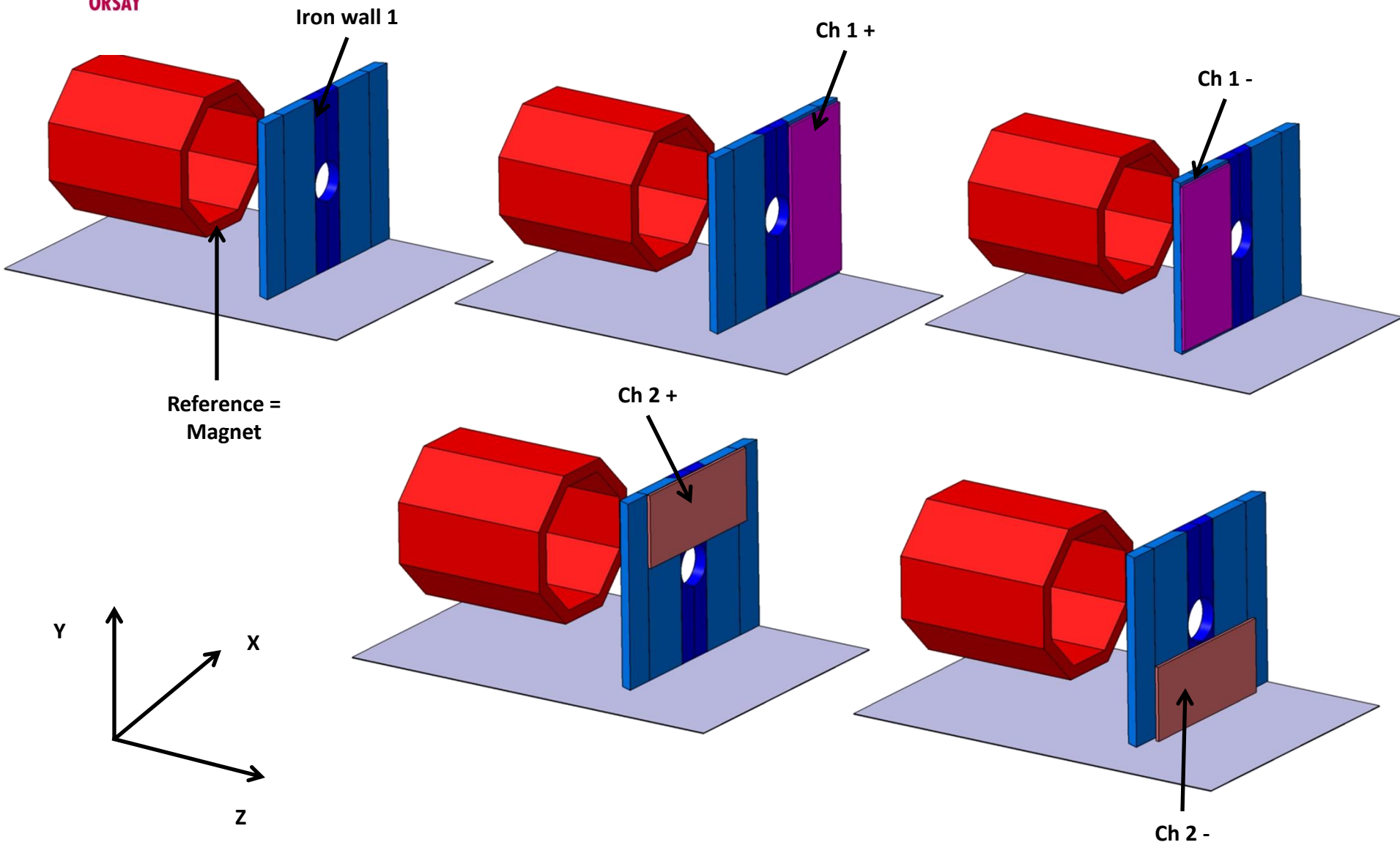
| System              | Item             | Cost (K\$) |
|---------------------|------------------|------------|
| Tracker planes      | uRWell           | 900        |
|                     | VMM readout      | 300        |
|                     | HV               | 10         |
|                     | Mechanical       | 100        |
| Scintillator planes | Scint. materials | 640        |
|                     | light guide      | 180        |
|                     | PMT+base         | 180        |
|                     | FADC             | 500        |
|                     | HV               | 150        |
|                     | Mechanical       | 100        |
| Iron planes         | Mechanical       | 200        |
| Total               |                  | 3,260      |

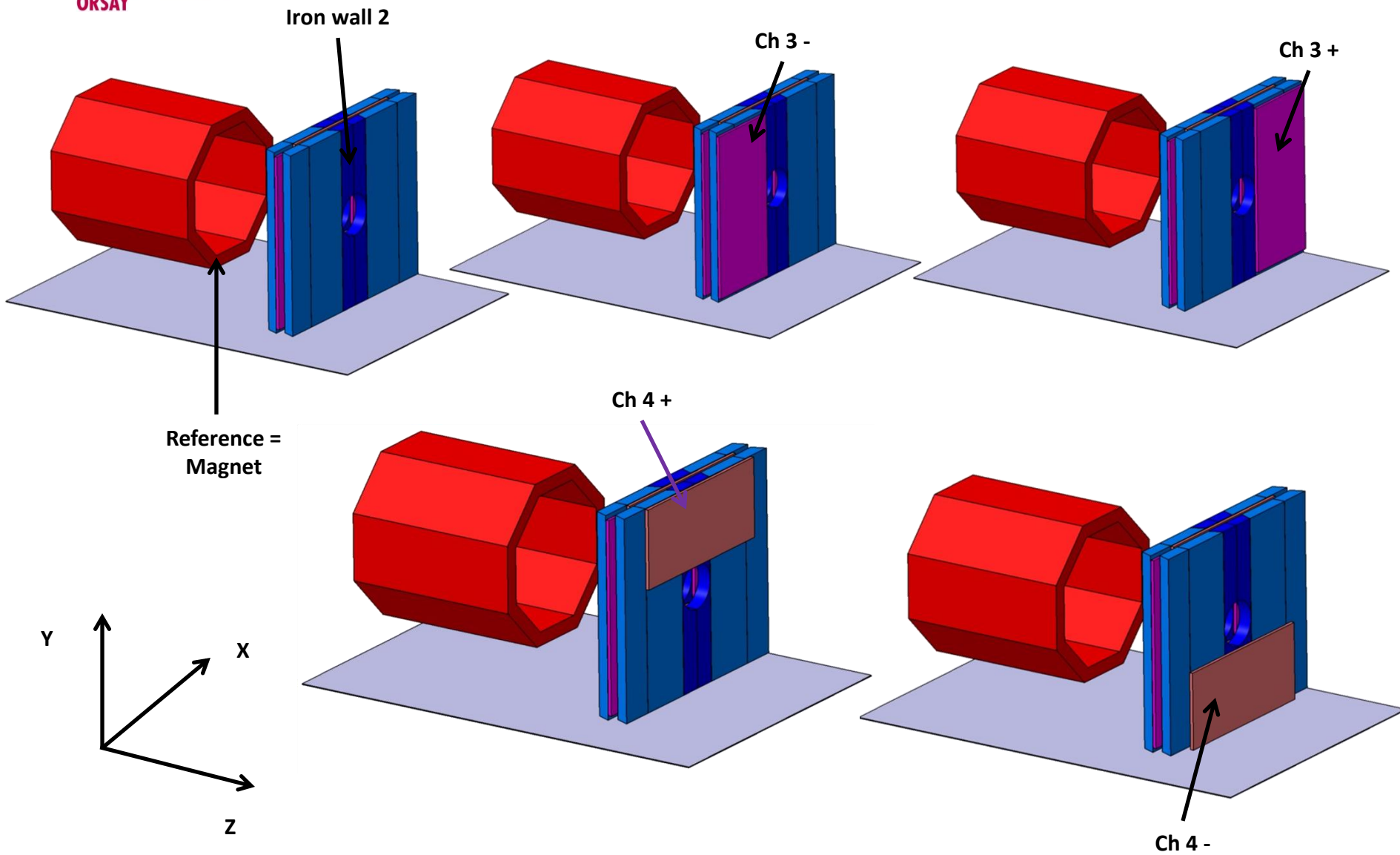
Table 1: Cost estimation of the forward angle muon detector and related hardware.

# Binning

| Bin | $\xi'$ range             | $\xi$ range           | $t$ range (GeV <sup>2</sup> ) |
|-----|--------------------------|-----------------------|-------------------------------|
| 1   | $-0.255 < \xi' < 0$      | $0.152 < \xi < 0.176$ | $-5.541 < t < -0.287$         |
| 2   |                          |                       | $-0.287 < t < -0.150$         |
| 3   |                          |                       | $-0.150 < t < -0.020$         |
| 4   |                          | $0.176 < \xi < 0.739$ | $-5.541 < t < -0.287$         |
| 5   |                          |                       | $-0.287 < t < -0.150$         |
| 6   |                          |                       | $-0.150 < t < -0.020$         |
| 7   | $0 < \xi' < 0.512$       | $0.071 < \xi < 0.126$ | $-5.541 < t < -0.287$         |
| 8   |                          |                       | $-0.287 < t < -0.150$         |
| 9   |                          |                       | $-0.150 < t < -0.020$         |
| 10  |                          | $0.126 < \xi < 0.153$ | $-5.541 < t < -0.287$         |
| 11  |                          |                       | $-0.287 < t < -0.150$         |
| 12  |                          |                       | $-0.150 < t < -0.020$         |
| 13  |                          | $0.153 < \xi < 0.189$ | $-5.541 < t < -0.287$         |
| 14  |                          |                       | $-0.287 < t < -0.150$         |
| 15  |                          |                       | $-0.150 < t < -0.020$         |
| 16  |                          | $0.189 < \xi < 0.739$ | $-5.541 < t < -0.287$         |
| 17  |                          |                       | $-0.287 < t < -0.150$         |
| 18  |                          |                       | $-0.150 < t < -0.020$         |
| 19  | $-0.255 < \xi' < -0.017$ | $0.071 < \xi < 0.108$ | $-5.541 < t < -0.287$         |
| 20  |                          |                       | $-0.287 < t < -0.150$         |
| 21  |                          |                       | $-0.150 < t < -0.020$         |
| 22  |                          | $0.108 < \xi < 0.122$ | $-5.541 < t < -0.287$         |
| 23  |                          |                       | $-0.287 < t < -0.150$         |
| 24  |                          |                       | $-0.150 < t < -0.020$         |
| 25  | $-0.255 < \xi' < -0.040$ | $0.122 < \xi < 0.152$ | $-5.541 < t < -0.287$         |
| 26  |                          |                       | $-0.287 < t < -0.150$         |
| 27  |                          |                       | $-0.150 < t < -0.020$         |
| 28  | $-0.040 < \xi' < -0.017$ | $0.122 < \xi < 0.152$ | $-5.541 < t < -0.287$         |
| 29  |                          |                       | $-0.287 < t < -0.150$         |
| 30  |                          |                       | $-0.150 < t < -0.020$         |

Table 2: Bin boundaries of the binning scheme shown in Fig. [24](#).

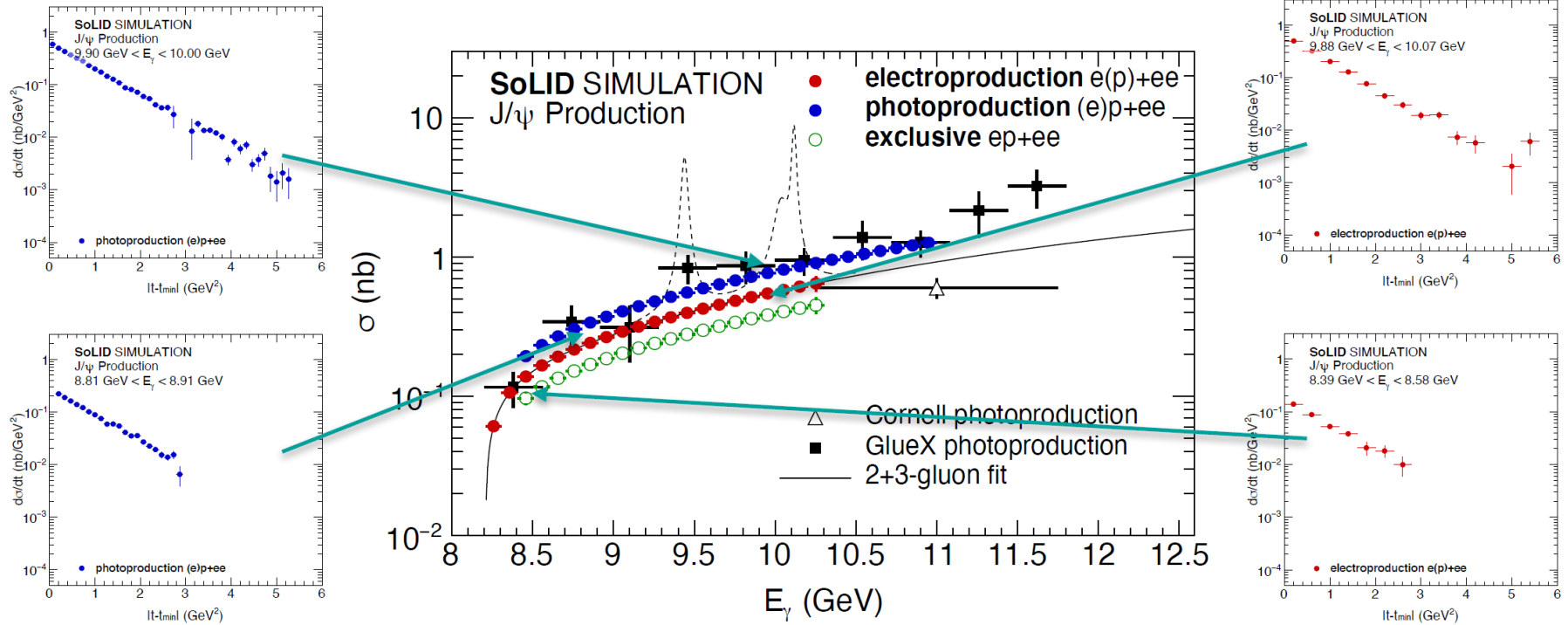




**Most precise measurement near threshold**

# SOLID-J/Ψ PROJECTIONS

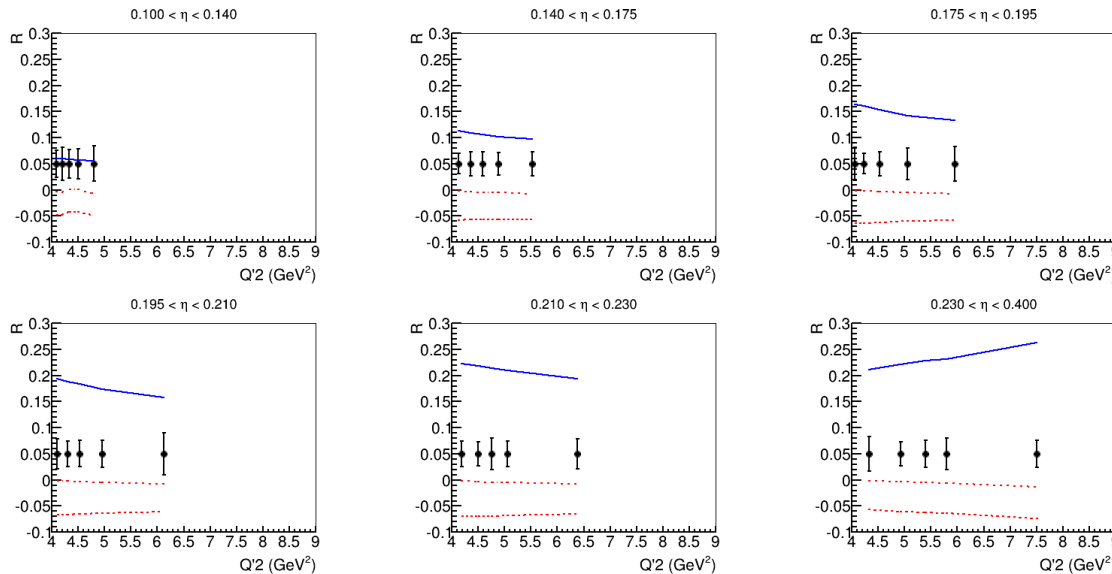
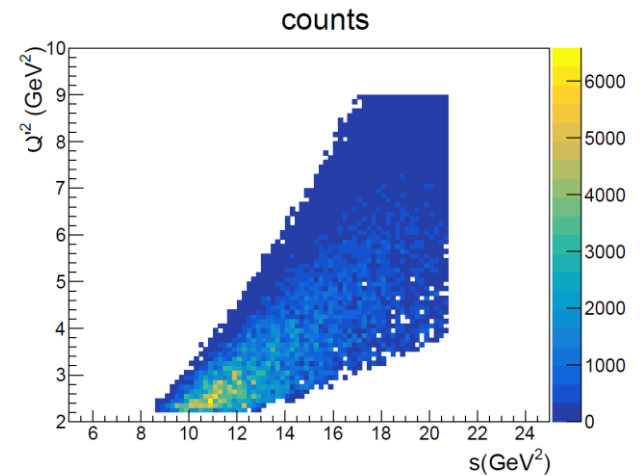
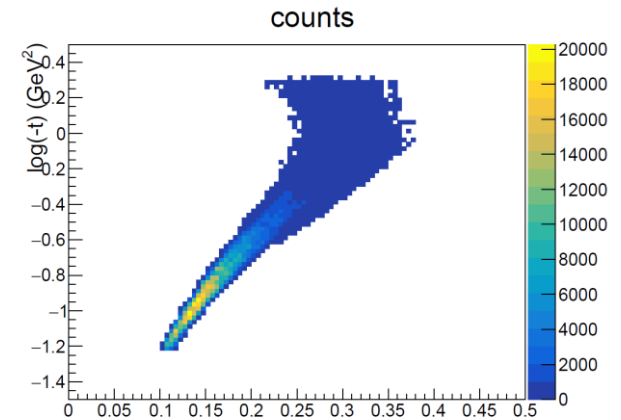
Precision at high  $t$  crucial for extrapolations to the forward limit  
(exponential, dipole, triple, ...)



# 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



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

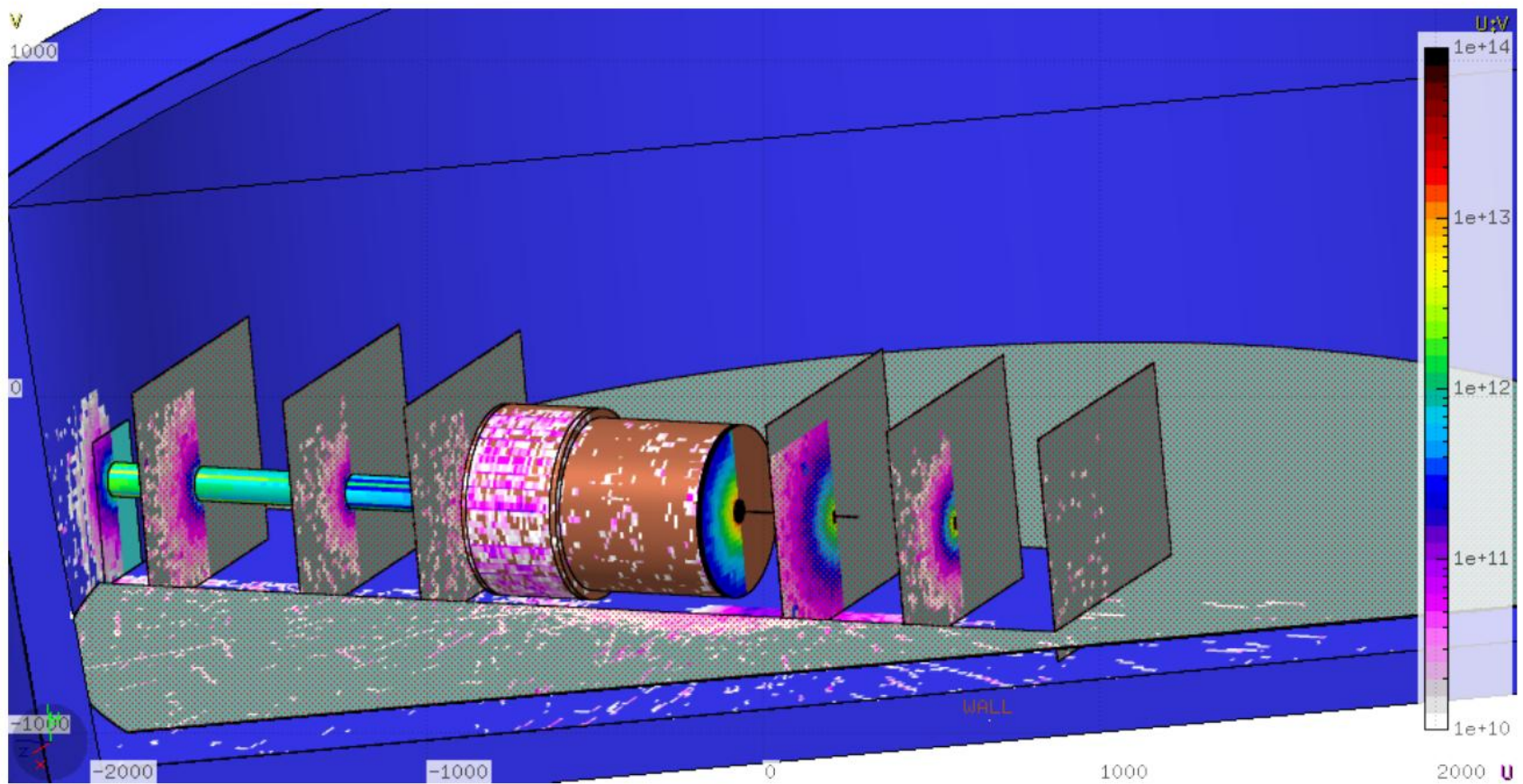


Figure 151: Estimate of radiation damage in the Hall with the SoLID spectrometer and the  $J/\Psi$  configuration with a 15cm Liquid Hydrogen target. The leading part of radiation present in the Hall for the SoLID spectrometer is originating from the target area and the closer surface of the magnet. In this plot, we show the 1MeV neutron equivalent flux per  $cm^2$  on the volume surfaces estimated for 60 days of continuous running with a beam current of  $3\mu A$  (This is the expected beam-time with the  $J/\Psi$  configuration). In order to better show the behavior of the radiation leaking, different planes of observation have been inserted (see Fig. 149a for reference of the position of each plane). The Color scale is different than in the previous cases in order to enhance the details in the desired region.