



# Report from the $\mu$ CLAS12 workshop

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CLAS Collaboration meeting, 10<sup>th</sup> of March 2026

# Outline

I The  $\mu$ CLAS12 design

II Brief overview of the physics program

III Summary of the workshop

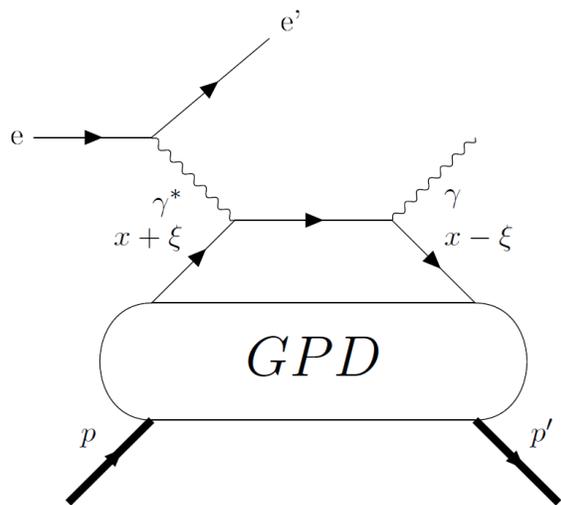


# The $\mu$ CLAS12 design

# Double DVCS to access the full GPD phase space

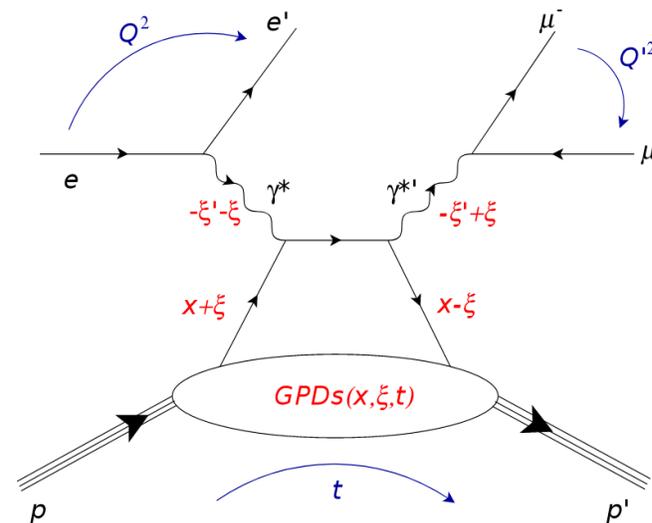
## Deeply Virtual Compton Scattering

$$ep \rightarrow e' \gamma^* p \rightarrow e' p' \gamma$$



## Double Deeply Virtual Compton Scattering

$$ep \rightarrow e' \gamma^* p \rightarrow e' p' \gamma^* \rightarrow e' \mu^+ \mu^- p'$$



$$\mathcal{H}_{DVCS}(\xi, t) = \int_{-1}^1 dx H(x, \xi, t) \left( \frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right)$$

$$\text{Im} \mathcal{H}_{DVCS}(\xi, t) = H(\xi, \xi, t) - H(-\xi, \xi, t)$$

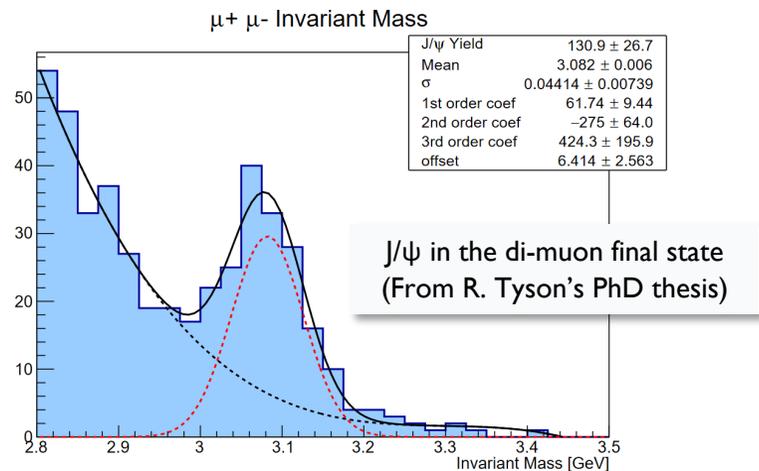
$$\text{Re} \mathcal{H}_{DVCS}(\xi, t) = \mathcal{P} \int_{-1}^1 dx \left( \frac{1}{\xi - x} - \frac{1}{\xi + x} \right) [H(x, \xi, t) - H(-x, \xi, t)]$$

$$\mathcal{H}_{DDVCS}(\xi', \xi, t) = \int_{-1}^1 dx H(x, \xi, t) \left( \frac{1}{\xi' - x - i\epsilon} - \frac{1}{\xi' + x - i\epsilon} \right)$$

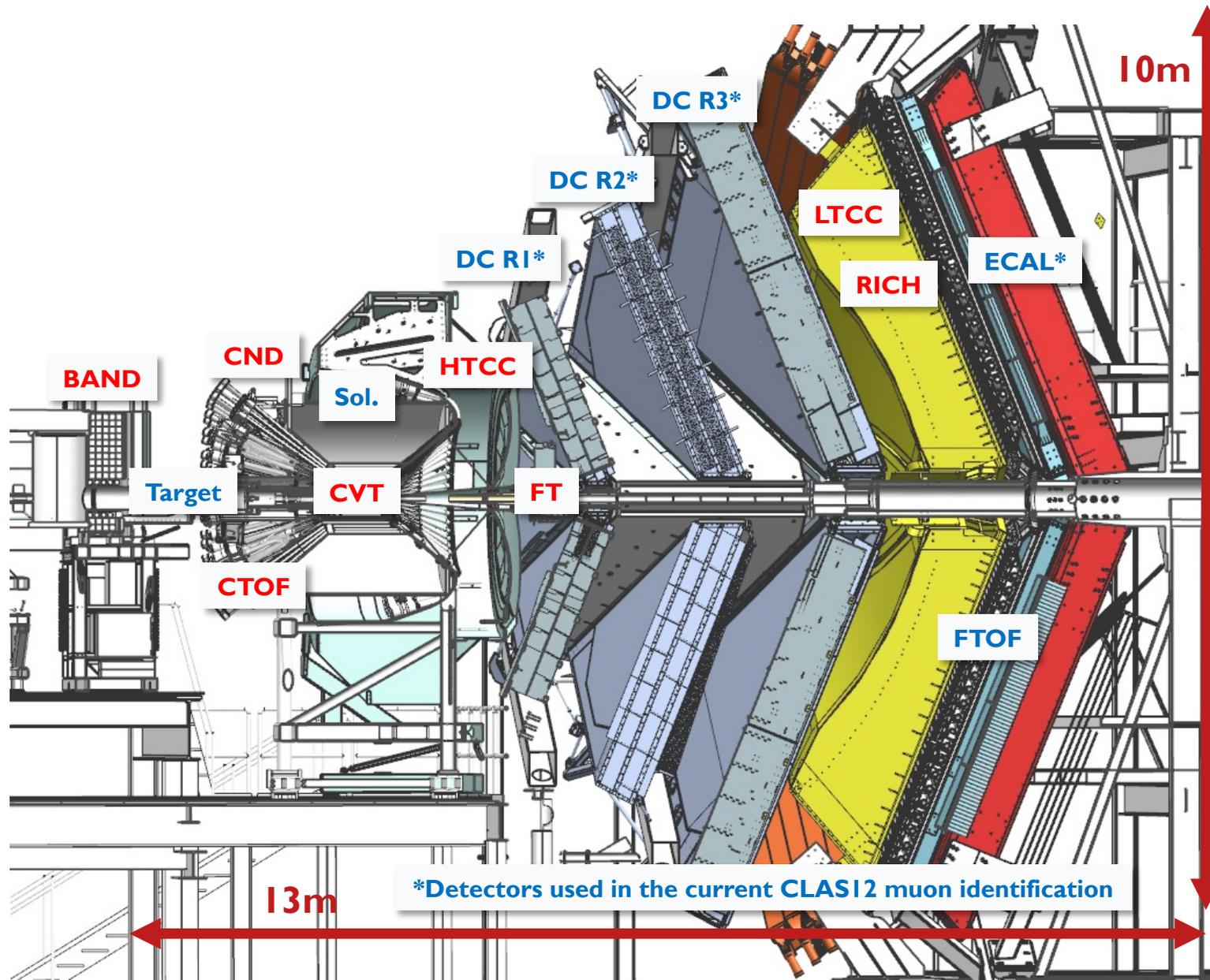
$$\text{Im} \mathcal{H}_{DDVCS}(\xi', \xi, t) \propto H(\xi', \xi, t) - H(-\xi', \xi, t)$$

# From the CLAS12 configuration...

- The  $\mu$ CLAS12 setup will **mostly use existing CLAS12 detectors**.

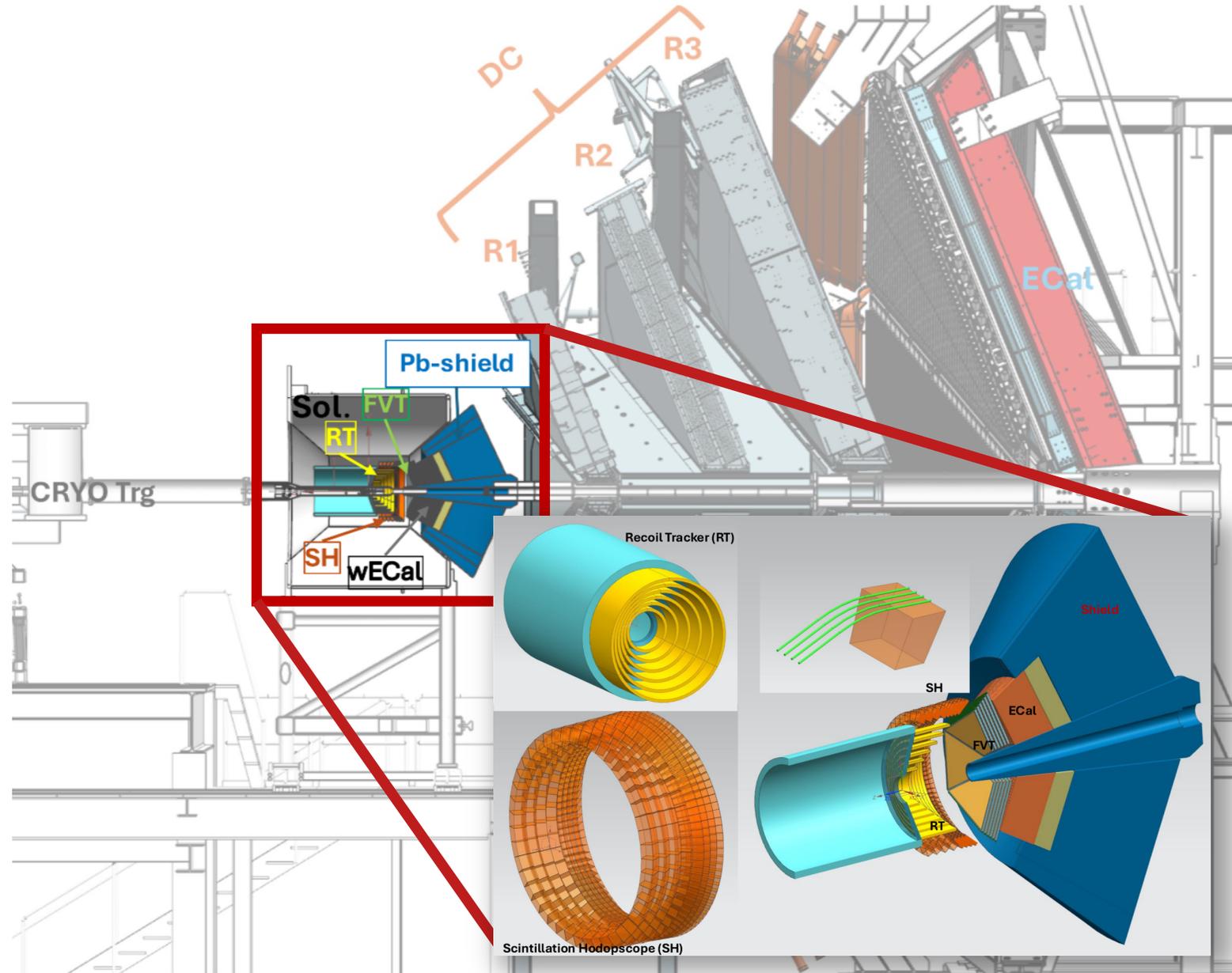


- The CLAS12 FD detector will be effectively used as a muon detector.
- The CTOF, CND, CVT, HTCC, FT, LTCC, RICH and BAND will be removed.

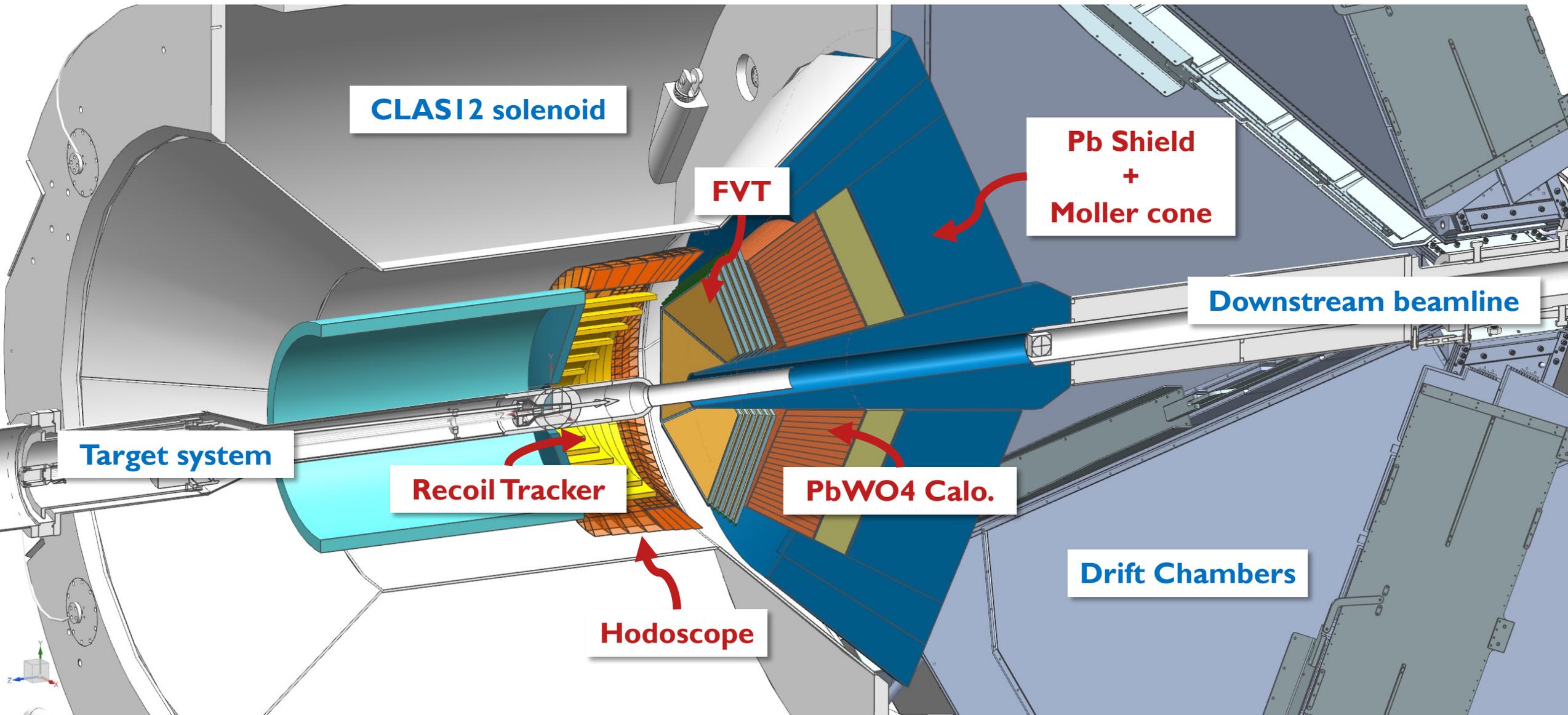


# ... to the $\mu$ CLAS12 configuration

- A **lead shield** to reduce pion background in the FD.
- A **PbWO<sub>4</sub> calorimeter** will identify scattered electron.
- A **GEM Forward Vertex tracker** will be used for vertexing.
- A **recoil tracker** surrounds the target to detect recoil proton,
- associated with a **Central Scintillator Hodoscope** for timing.



# $\mu$ CLAS12 subsystems overview



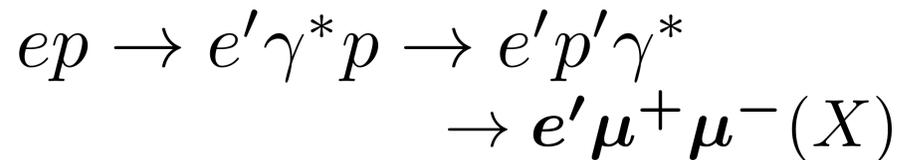
# Running conditions & beam time

| Beam Energy (GeV) | Beam Current ( $\mu$ A) | Beam Requirements                         | Target Material | Target Length (cm) | Beam time (days) |
|-------------------|-------------------------|---|-----------------|--------------------|------------------|
| Commisionning     |                         |   |                 |                    |                  |
| 11                |                         |   |                 | 5                  | 15               |
| Calibration       |                         |   |                 |                    |                  |
| 11                | 7.5                     |   | Empty target    | 5                  | 10               |
| 11                | <1                      |   | LH2             | 5                  | 20               |
| Production        |                         |   |                 |                    |                  |
| <b>11</b>         | <b>7.5</b>              | <b>&gt; 85% longitudinal polarization</b> | <b>LH2</b>      | <b>5</b>           | <b>200</b>       |
| Total time        |                         |   |                 |                    | 245              |

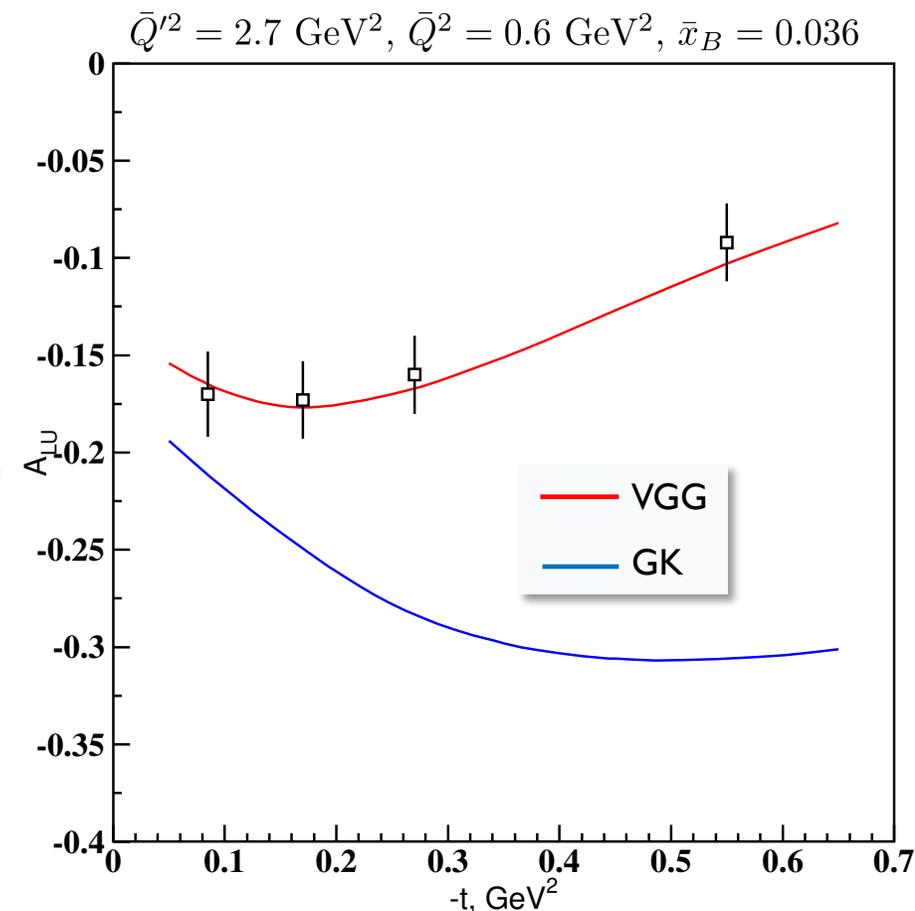
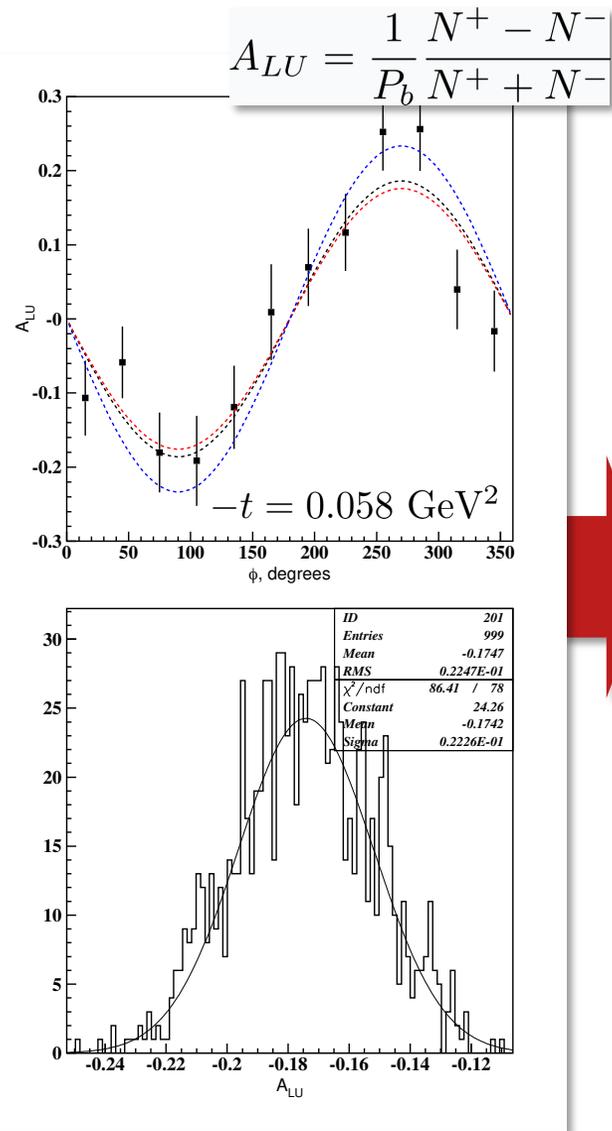
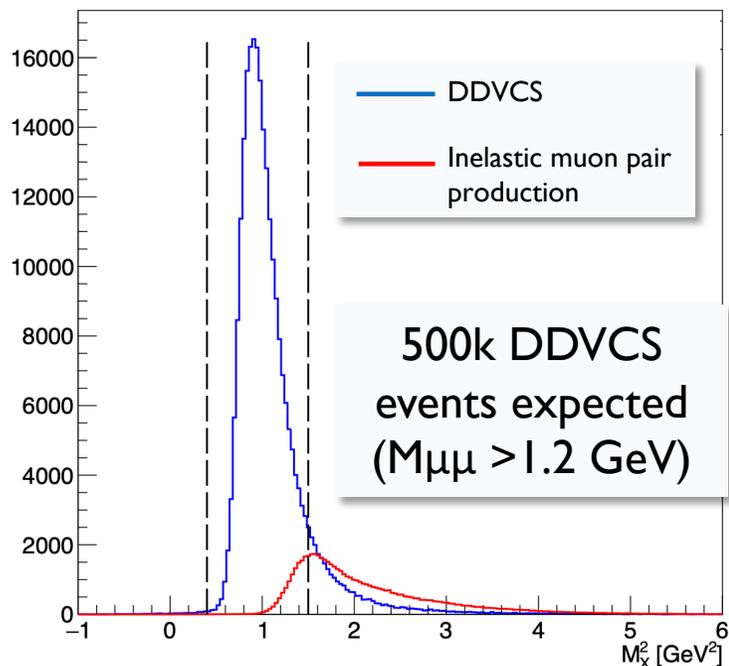
# Proposed measurements and Expected result

# Expected results on DDVCS

## Analysis strategy



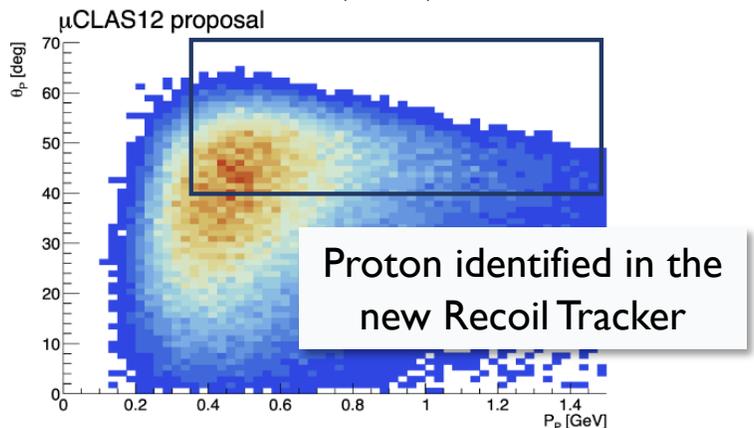
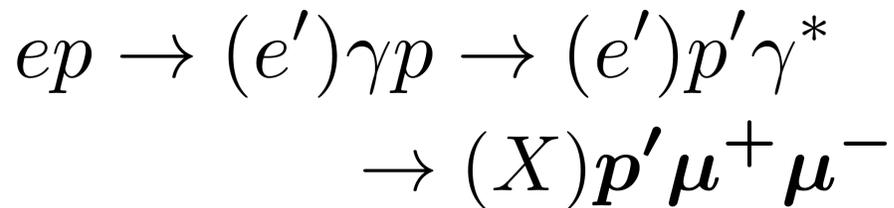
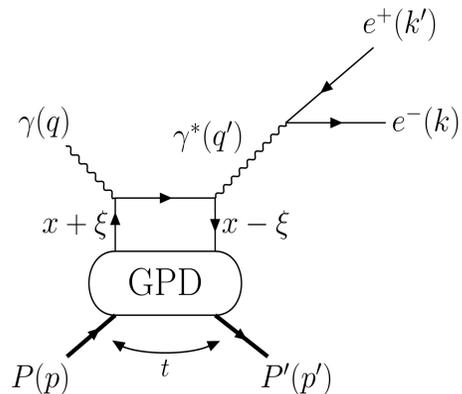
- Electron detected in wECAL.
- Muons in  $\mu$ CLAS12 Forward Detector.
- Missing proton reconstructed from energy-momentum conservation.



200 days of beam will allow to distinguish model down to the small-t region

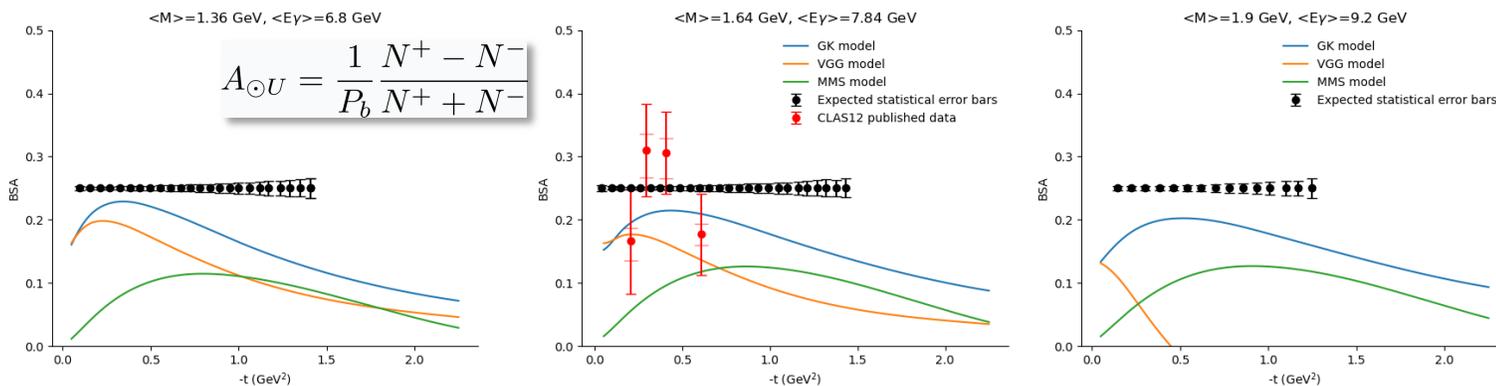
# Expected results for Timelike Compton Scattering

## TCS with $\mu$ CLAS12

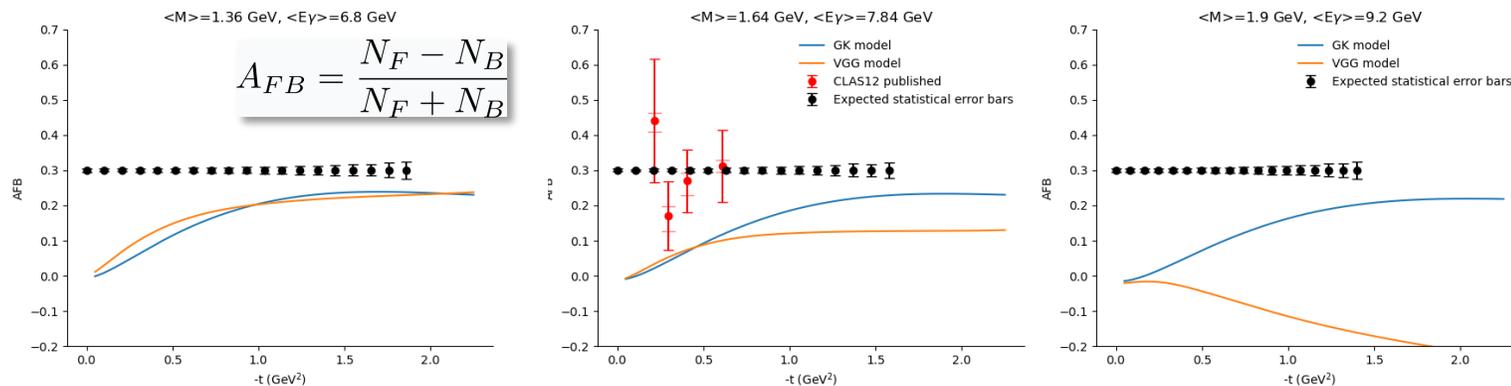


## Expected results with 7.7M expected events ( $M_{\mu\mu} > 1.2$ GeV)

### Photon polarization asymmetry



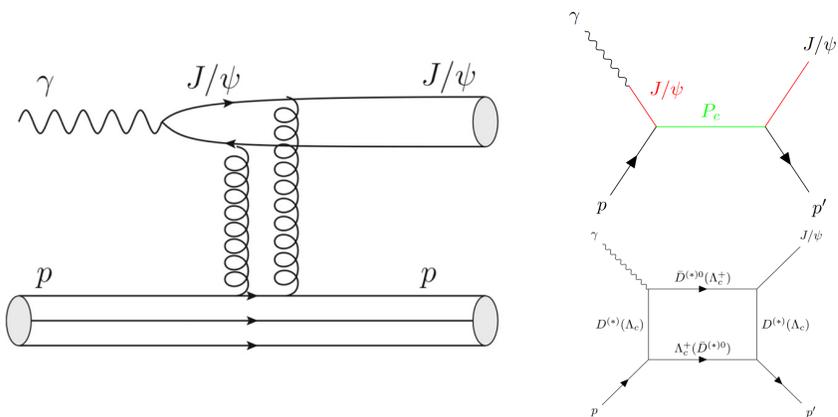
### Forward-Backward asymmetry



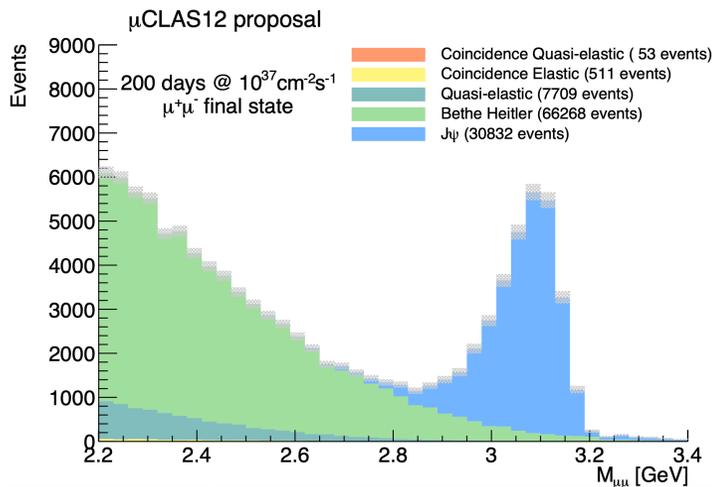
→ First **precision** measurement of TCS

# Expected results for $J/\psi$ electro-production

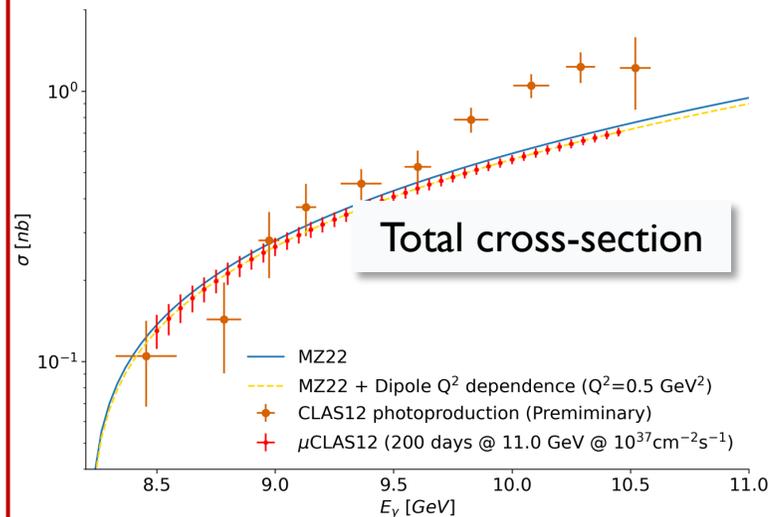
## Analysis strategy



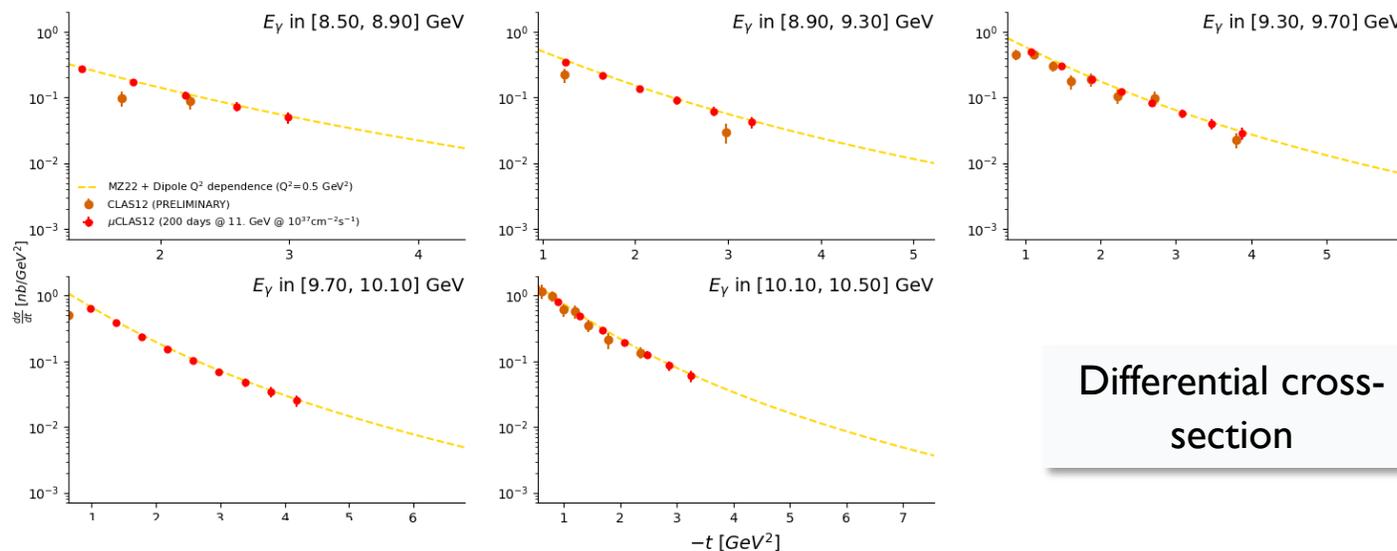
$$ep \rightarrow e' \gamma^* p \rightarrow e' p' J/\psi \rightarrow e' \mu^+ \mu^- (X)$$



## Projected results with 30k expected events



- 10 times more events than the current largest  $J/\psi$  sample at JLab.
- $\frac{3}{4}$  of the expected SoLID  $J/\psi$  rate.
- Energy reach limited by the wECAL threshold.



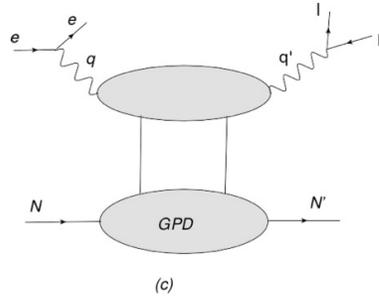


# Overview of workshop

# Double DVCS Theory – Jakub Wagner (NCBJ Warsaw)

Double DVCS

LO



(c) Double Deeply Virtual Compton Scattering (DDVCS):  $\gamma N \rightarrow l^+ l^- N'$

$$\gamma^*(q_{in})N(p) \rightarrow \gamma^*(q_{out})N'(p')$$

Variables, describing the processes of interest in this generalized Bjorken limit, are the **scaling variable  $\xi$**  and **skewness  $\eta > 0$** :

$$\xi = -\frac{q_{out}^2 + q_{in}^2}{q_{out}^2 - q_{in}^2} \eta, \quad \eta = \frac{q_{out}^2 - q_{in}^2}{(p + p') \cdot (q_{in} + q_{out})}$$

- DDVCS:  $q_{in}^2 < 0, \quad q_{out}^2 > 0, \quad \eta \neq \xi$
- DVCS:  $q_{in}^2 < 0, \quad q_{out}^2 = 0, \quad \eta = \xi > 0$
- TCS:  $q_{in}^2 = 0, \quad q_{out}^2 > 0, \quad \eta = -\xi > 0$

• DVCS vs TCS

$$DVCS T^q = -e_q^2 \frac{1}{x + \eta - i\epsilon} - (x \rightarrow -x) = (TCS T^q)^*$$

$$DVCS \tilde{T}^q = -e_q^2 \frac{1}{x + \eta - i\epsilon} + (x \rightarrow -x) = -(TCS \tilde{T}^q)^*$$

$$DVCS Re(\mathcal{H}) \sim P \int \frac{1}{x \pm \eta} H^q(x, \eta, t), \quad DVCS Im(\mathcal{H}) \sim i\pi H^q(\pm\eta, \eta, t)$$

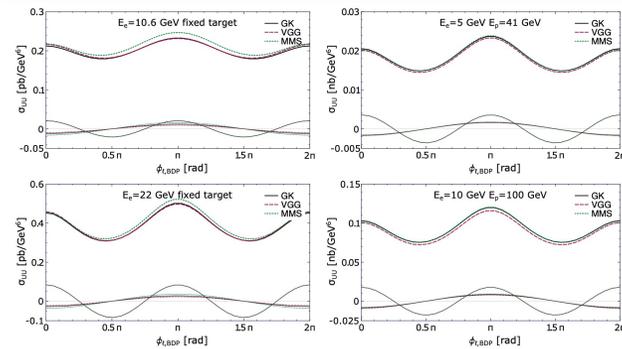
• DDVCS

$$DDVCS T^q = -e_q^2 \frac{1}{x + \xi - i\epsilon} - (x \rightarrow -x)$$

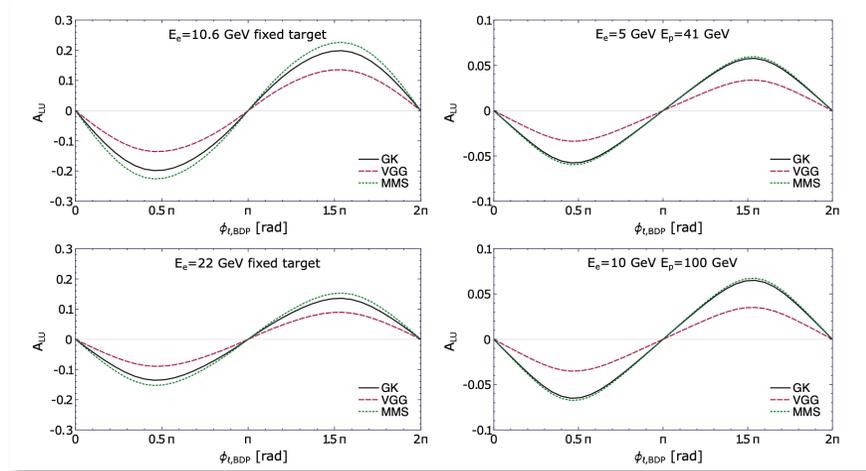
$$DDVCS Re(\mathcal{H}) \sim P \int \frac{1}{x \pm \xi} H^q(x, \eta, t), \quad DVCS Im(\mathcal{H}) \sim i\pi H^q(\pm\xi, \eta, t)$$

DDVCS can provide unique information, but is very challenging experimentally. But recent measurement of TCS should also make us more optimistic about DDVCS!

**We need muon detection!**

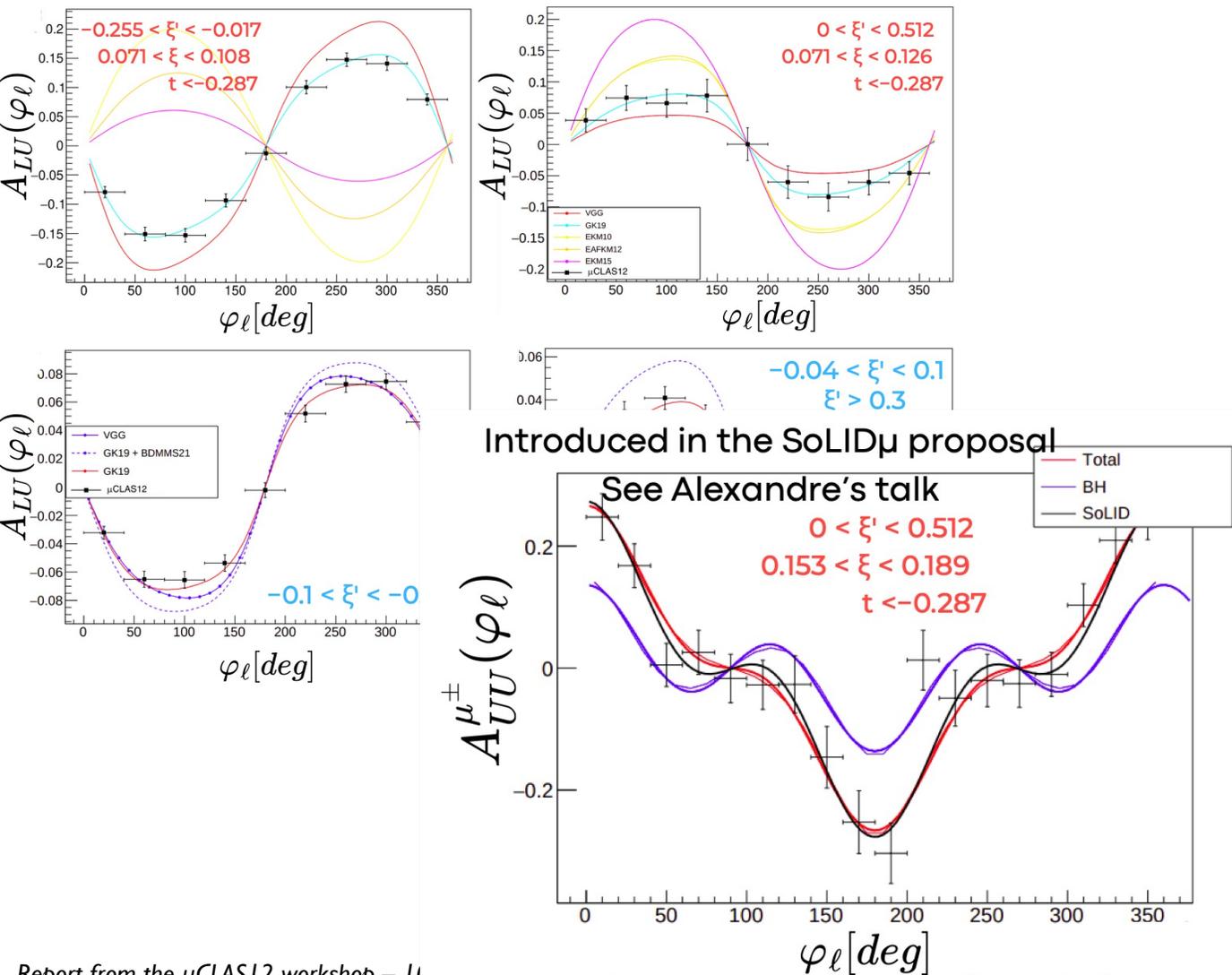


| JLab12, JLab20+ |   | EIC 5x41, EIC 10x100 |                        |                                    |                                    |
|-----------------|---|----------------------|------------------------|------------------------------------|------------------------------------|
| Experiment      | Beam energies [GeV]                       | y                    | t  [GeV <sup>2</sup> ] | Q <sup>2</sup> [GeV <sup>2</sup> ] | Q <sup>2</sup> [GeV <sup>2</sup> ] |
| JLab12          | E <sub>e</sub> = 10.6, E <sub>p</sub> = M | 0.5                  | 0.2                    | 0.6                                | 2.5                                |
| JLab20+         | E <sub>e</sub> = 22, E <sub>p</sub> = M   | 0.3                  | 0.2                    | 0.6                                | 2.5                                |
| EIC             | E <sub>e</sub> = 5, E <sub>p</sub> = 41   | 0.15                 | 0.1                    | 0.6                                | 2.5                                |
| EIC             | E <sub>e</sub> = 10, E <sub>p</sub> = 100 | 0.15                 | 0.1                    | 0.6                                | 2.5                                |

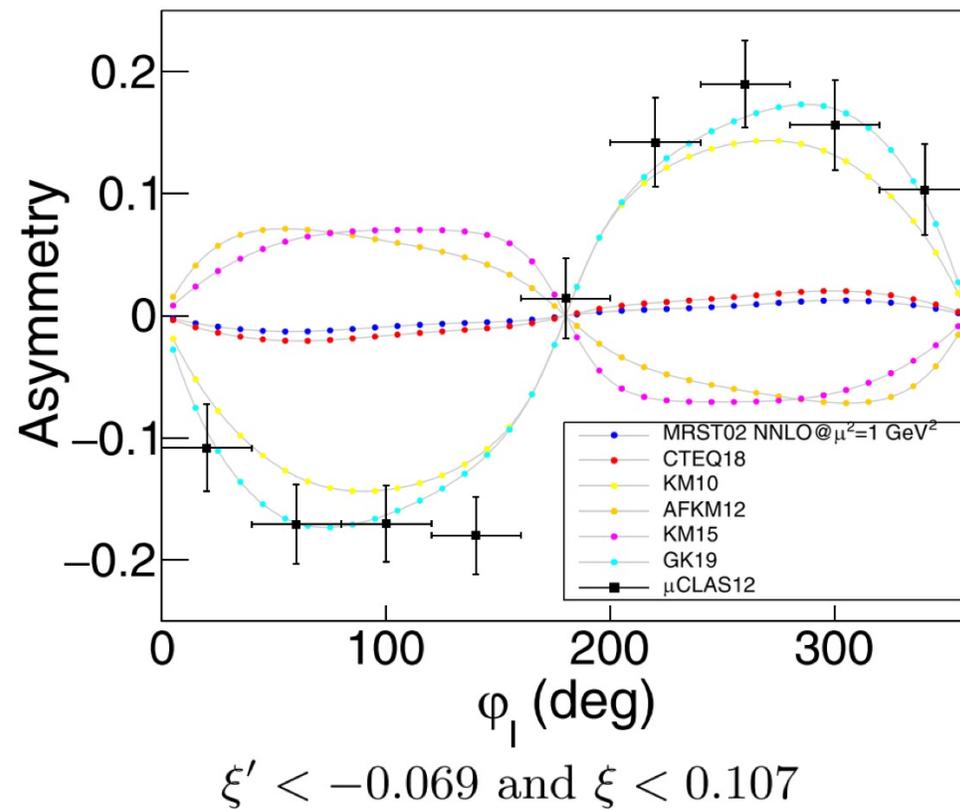


# Double DVCS Phenomenology – Sebastian Alvarado (IJCLab Orsay)

## BSA projections



## TSA PROJECTIONS



Proposal for polarized target, need to be studied better (polarized target cannot handle large currents)

# Double DVCS Phenomenology – Derek Glazier (Glasgow)

## EPIC LOW- $Q^2$ TAGGER - DESIGN

### Tagger Design

- Two tagger stations covering different energy ranges.
- Tracker consisting of 4 layers of Timepix4 detectors.
- Detector layer consisting of tiled Timepix4 ASICs using TSV.
- SPIDR4 readout.

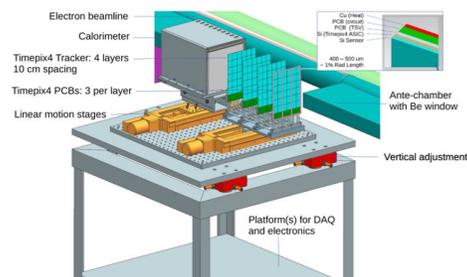


Figure 4: CAD model of a tagger station

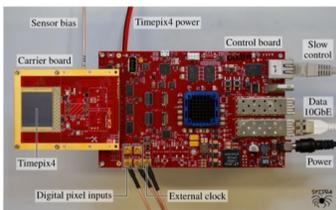
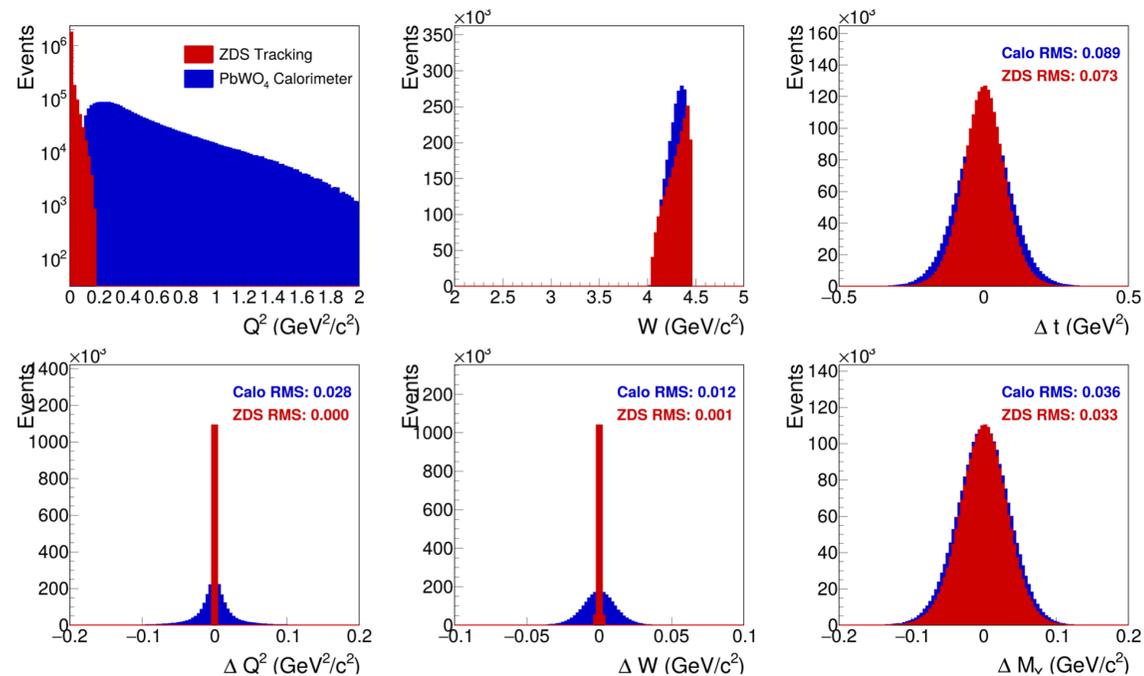


Figure 3: SPIDR4 readout - K. Heijhoff et al 2022

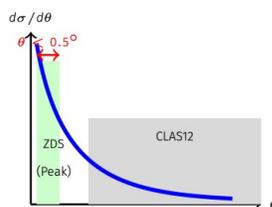
## PHYSICS PERFORMANCE: ZDS VS. PBWO<sub>4</sub> CALORIMETER



## THE CASE FOR A ZERO-DEGREE SPECTROMETER (ZDS)

### The "Missing" Physics at $10^{37} \text{ cm}^{-2}\text{s}^{-1}$

- Peak Photon Flux:** Photoproduction cross-sections peak at  $\theta \approx 0^\circ$  and  $Q^2 \rightarrow 0$ .
- Geometric Blind Spot:** In the baseline  $\mu$ CLAS12, these electrons never exit the beam pipe or are lost in the first magnets.
- CLAS12 Gap:** There is a forward hole in CLAS12 of around  $0.5^\circ$ . May be able to detect  $e^-$  after this...



### ZDS: Transforming the Reach

- Direct Tagging:** Detects electrons in the critical  $\theta < 0.5^\circ$  range.
- Kinematic Certainty:** Directly measuring  $E_{e'}$  provides a precise  $E_\gamma$  for every event, removing missing-momentum ambiguity.
- Polarisation** Measuring scattering plane gives transverse/linearly polarised photons - more physics.

- Range:**  $0.5 < E_{e'} < 3.5 \text{ GeV}$ .
- Impact:** High-resolution tagging enables precise GPD studies through TCS and  $J/\psi$ .

# Deuterium target with $\mu$ CLAS12 – Richard Tyson (Glasgow)



## Deuteron GPDs

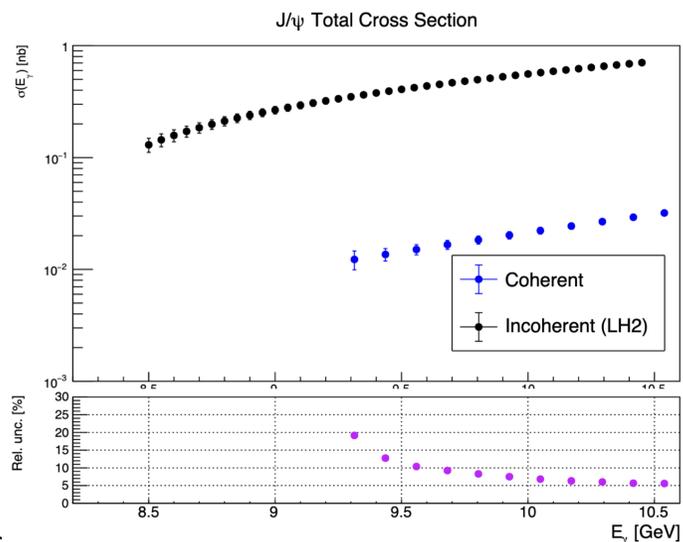
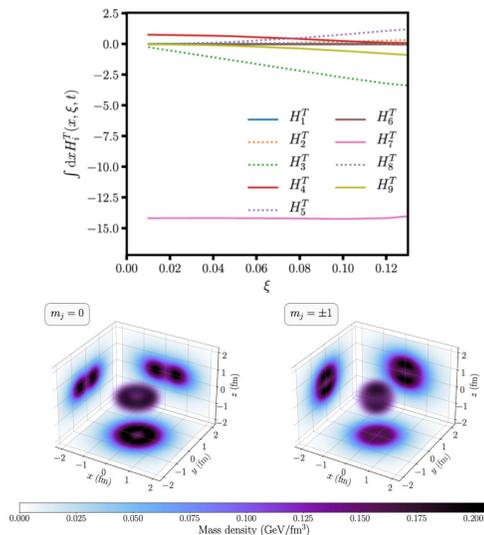
Growing body of work on deuteron GPDs.

In particular, descriptions of deuteron Energy Momentum Tensor and Mechanical Form Factors.

This includes work in holographic QCD formalism that is fairly successful for proton gluon GFFs.

9 leading-twist quark GPDs, and harder to isolate individual GPDs  $\Rightarrow$  no well defined observables (as far as I can tell)

*Phys. Rev. D* **98**, 074020 (2020)  
*Phys. Rev. D* **99**, 094035 (2019)  
*Phys. Rev. D* **100**, 036003 (2019)  
*EPJC* **79**, 476 (2019)  
*EPJC* **85** 361, (2025)  
 arXiv 2602.18298 (2026)



## Neutron Strategy

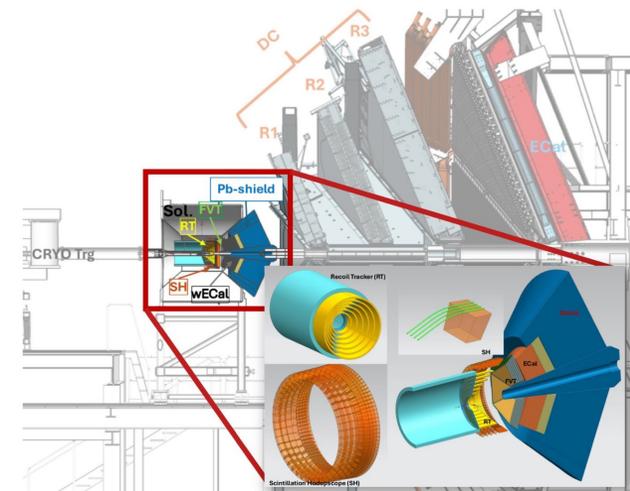
### Active Detection

Expect background rates in pre-shielding wECAL to be too high to accurately distinguish neutrons.

Possible with exclusivity to restrict neutron candidates? Good enough timing?

Otherwise, have to verify neutron efficiency in forward ECAL (behind shielding).

Will look into detailed simulations when available.



Aim is to submit Letter of Intent to this year's PAC.

Several questions relating to the measurements:

- Simulate neutron channels to understand neutron detection strategy
- Simulate coherent channels to confirm deuteron detection and resolution on exclusivity variables

# Charmonia spectroscopy with $\mu$ CLAS12 – Alessandro Pilloni (Messina)

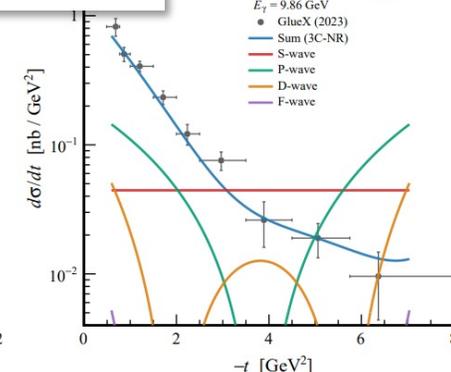
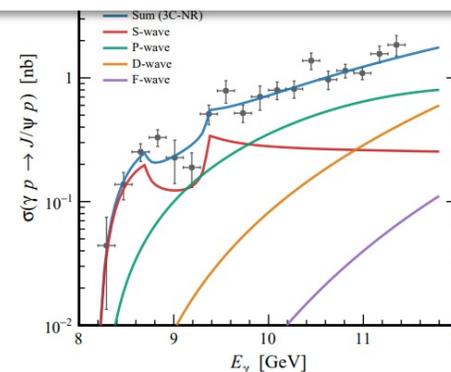
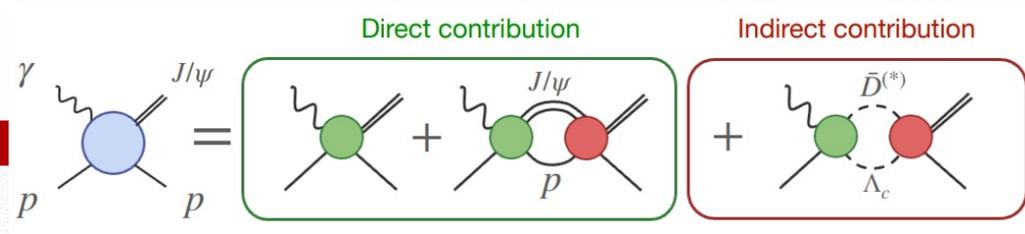
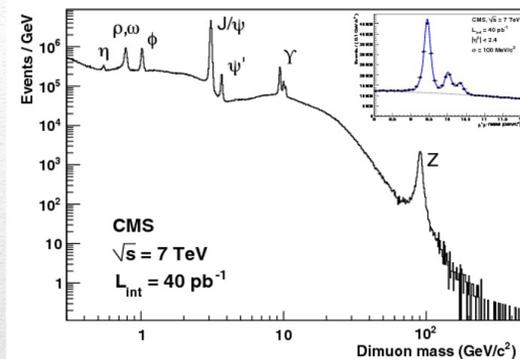
## Spectroscopy with muons?

### Pros:

- Cleaner than electrons
- Better signal/bkg
- Increase in luminosity with new run
- Peculiar signatures

### Cons:

- Radiative/leptonic decays, small BR

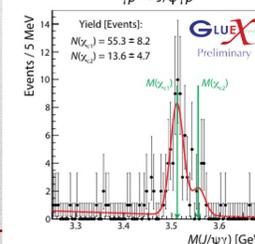
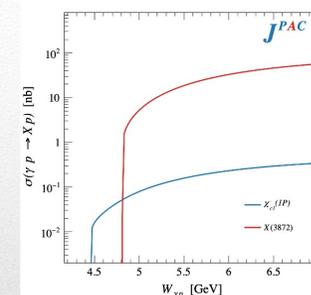


## $\chi_{c1}$ photoproduction

Preliminary results from GlueX suggest that vector meson exchange underestimate the cross section

Possible contribution from  $C = -3$ -gluon exchange (Odderon-like)

Needs further measurement and theory modeling,  $t$  and  $Q^2$  dependence to be explored



### Light sector unfeasible

$$\frac{BR(\phi \rightarrow \mu^+ \mu^-)}{BR(\phi \rightarrow K^+ K^-)} = 5.7 \times 10^{-4}$$

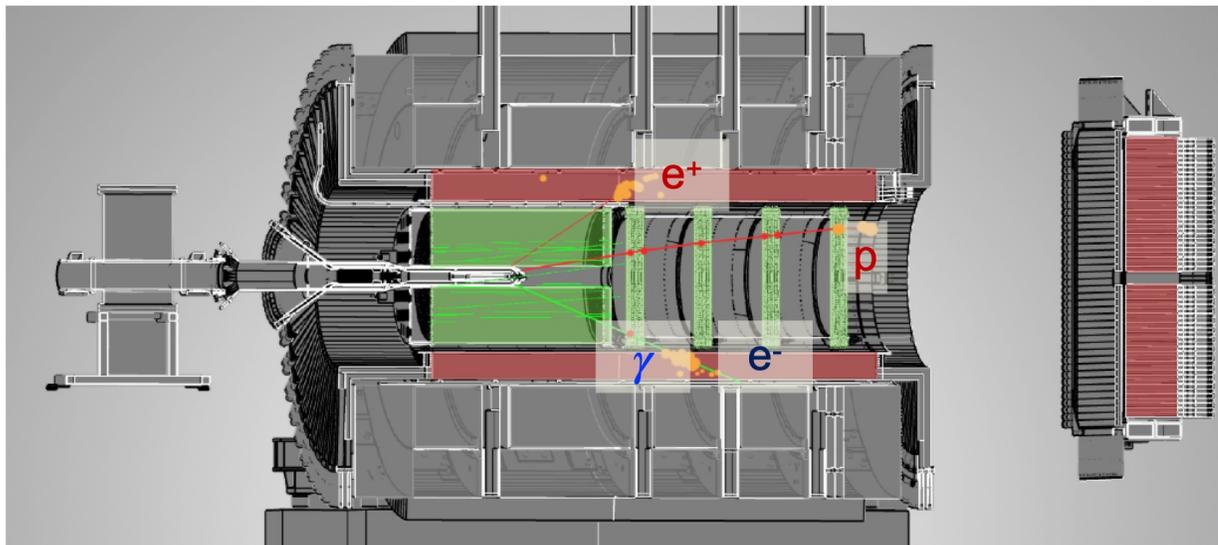
### Charmonium promising

$$\frac{BR(J/\psi \rightarrow \mu^+ \mu^-)}{BR(J/\psi \rightarrow had)} = 7\%$$

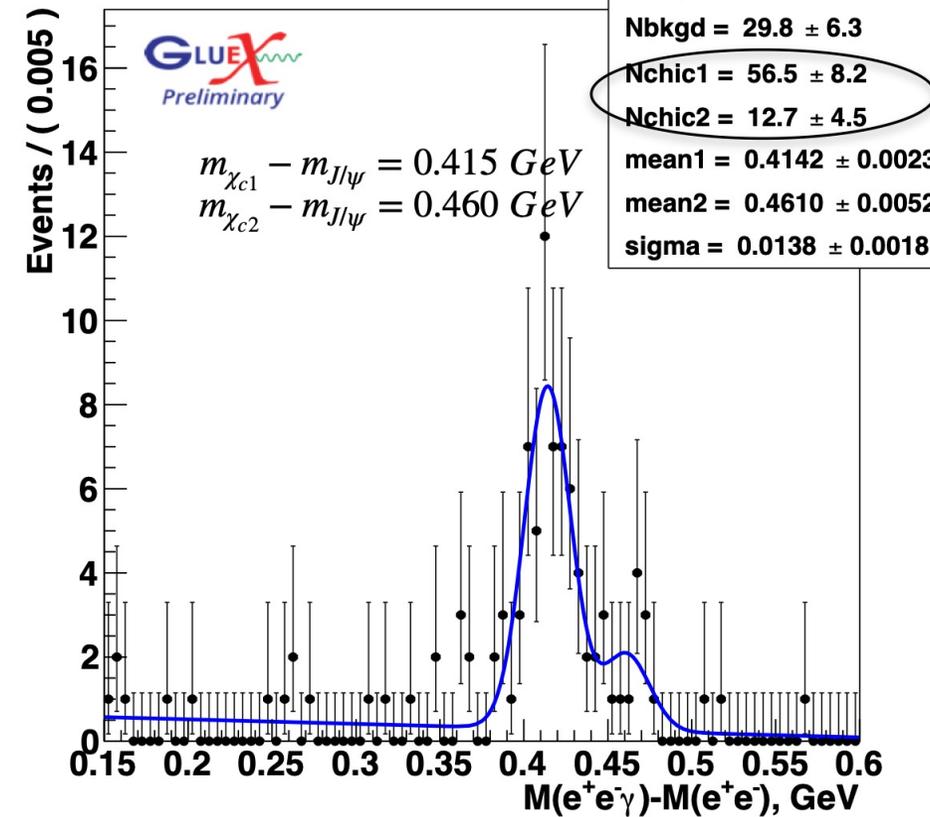
# $\chi_c$ measurements with GlueX – Lubomir Pentchev (JLab)

$$\gamma p \rightarrow \chi_c p \rightarrow J/\psi \gamma p \rightarrow e^+ e^- \gamma p \text{ exclusive}$$

$$\gamma p \rightarrow \chi_c p \rightarrow (J/\psi \gamma) p \rightarrow (e^+ e^- \gamma) p$$

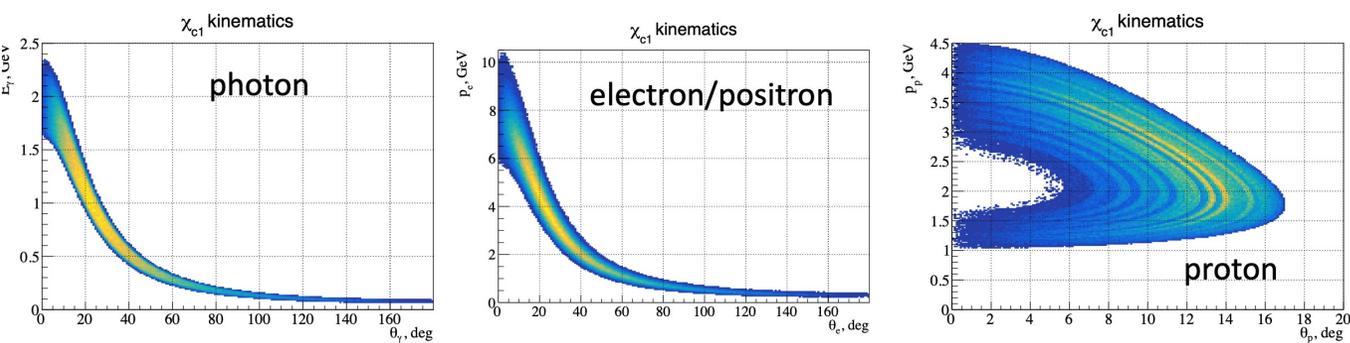


$\chi_{c1,2}$



$$m_{\chi_{c1}} - m_{J/\psi} = 0.415 \text{ GeV}$$

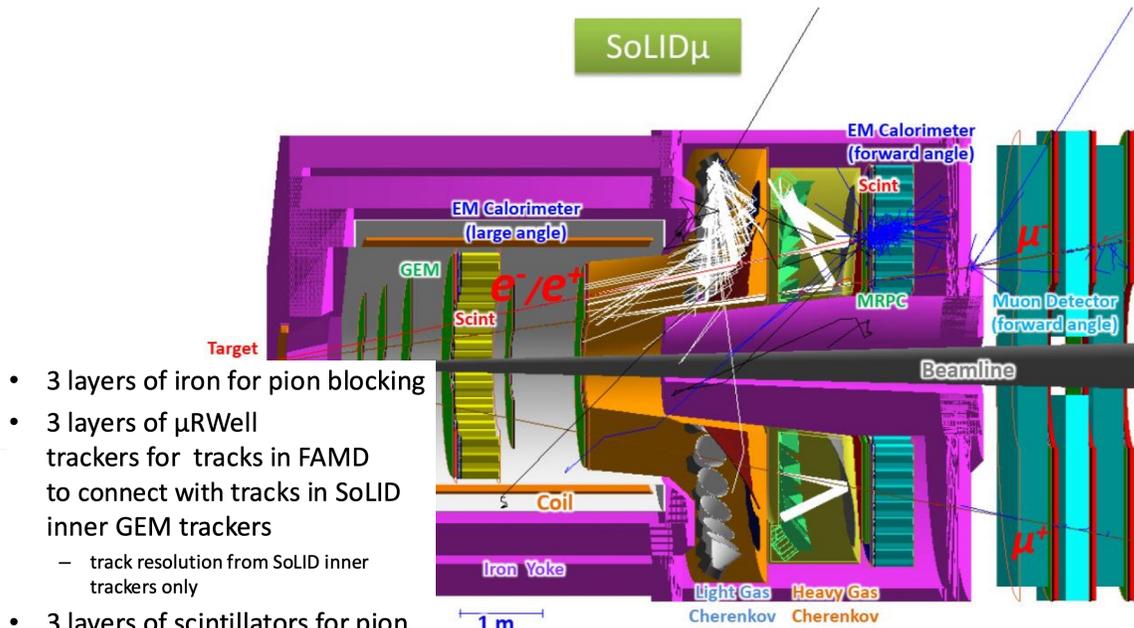
$$m_{\chi_{c2}} - m_{J/\psi} = 0.460 \text{ GeV}$$



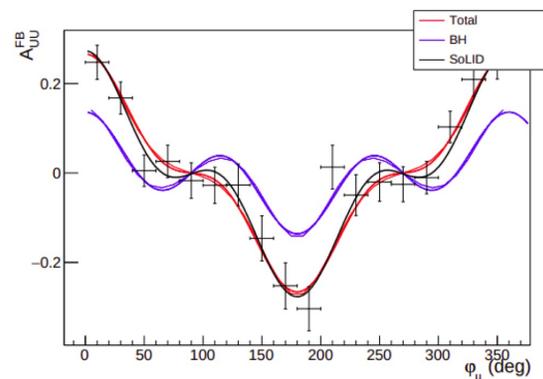
MC simulations

- $\chi_{c1}(3511)$  and  $\chi_{c2}(3556)$ ,  $1^{++}$  and  $2^{++}$  ( $1P$ ),  
 $E_{\gamma}^{thr} = 10.1 \text{ GeV}$

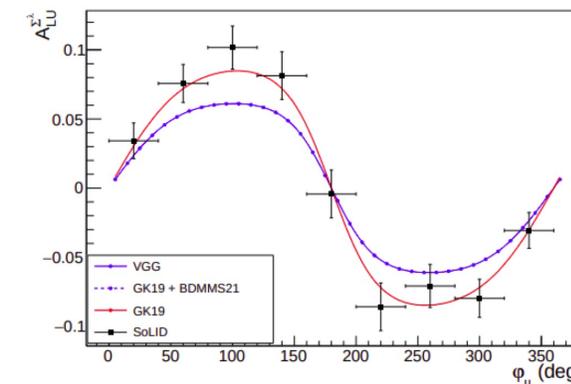
# Double DVCS with the SoLID experiment – Alexandre Camsonne (Jlab)



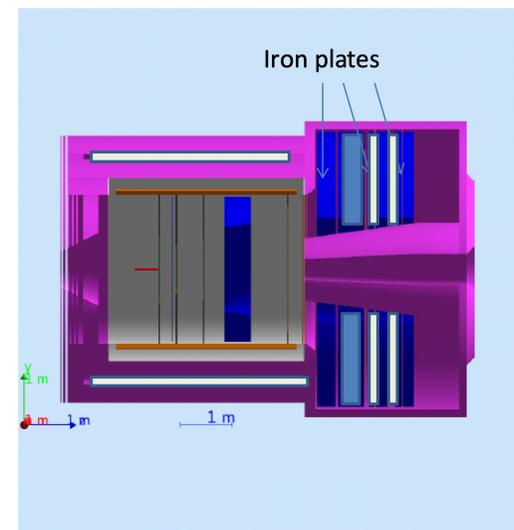
- 3 layers of iron for pion blocking
- 3 layers of  $\mu$ RWell trackers for tracks in FAMD to connect with tracks in SoLID inner GEM trackers
  - track resolution from SoLID inner trackers only
- 3 layers of scintillators for pion suppression and muon PID. And last layer for trigger



(a)  $\mu$ CA and the components entering the  $\cos \varphi_\mu$  moment.



## Possible future dedicated setup



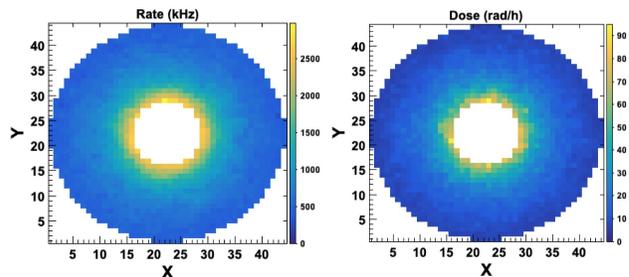
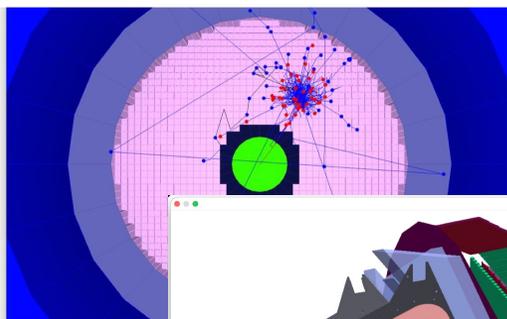
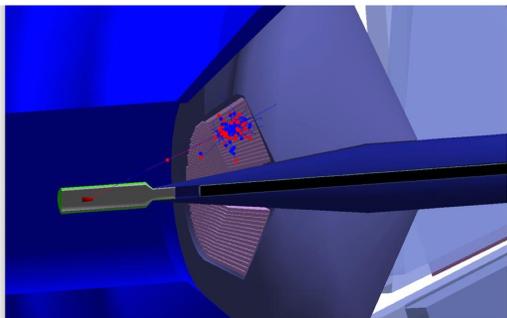
- Target moved 2m from Jpsi position inside and switch to 45 cm target
- Iron plate from 3<sup>rd</sup> layer yoke in front and behind calorimeter
- Remove Gas Cerenkov
- Try to reach  $10^{38} \text{ cm}^{-2}\text{s}^{-1}$
- 10 uA on 45 cm target

| 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              |

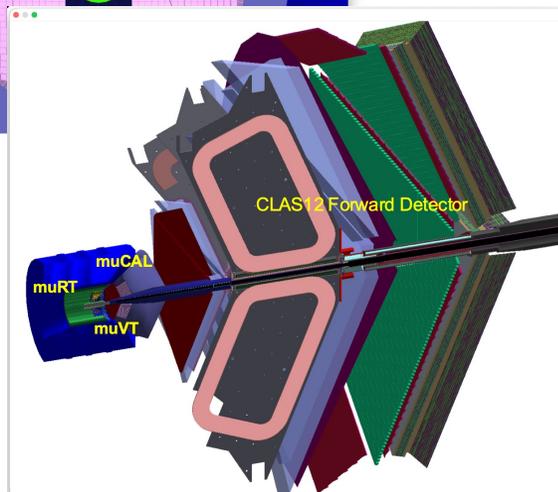
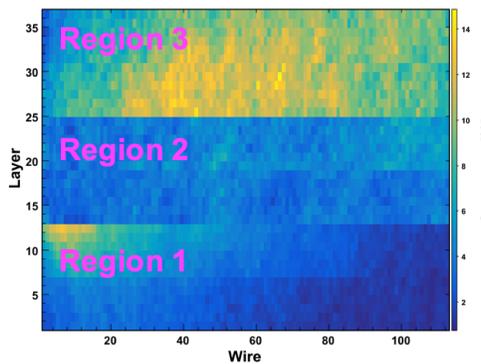
# $\mu$ CLAS12 simulation and reconstruction software – Raffaella De Vita (JLab)

## Background studies: muCAL

- Fully implemented in the CLAS12 GEANT4 model
  - Trapezoidal crystals with APD readout
  - Digitized signal includes fluctuations in scintillation light, APD QE and noise, preamplifier noise
  - Estimated dose for 200 days  $<5 \times 10^5$  rad = 5000 Gy



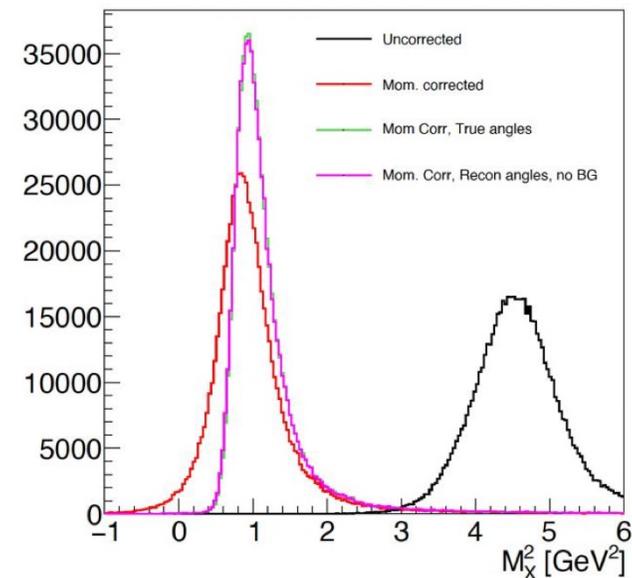
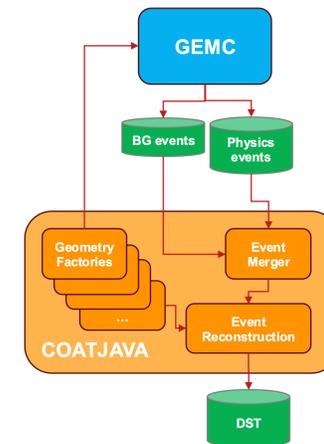
### Drift Chambers Occupancy



GEMC rendering of the  $\mu$ CLAS12 setup

## muCLAS12 in reconstruction

- New detectors' reconstruction implemented in CLAS12 reconstruction framework, COATJAVA
  - Detector geometry
  - Low-level reconstruction, from "raw" data to hits and clusters
  - Track reconstruction
  - Event building
- Status
  - Tested on simulations of single particles and full physics events
  - First studies with simulated background
  - Still a lot to be done but software is operational!



# Summary

- The  $\mu$ CLAS12 experiment will provide the unique opportunity to measure **Double Deeply Virtual Compton Scattering** and access the full kinematic dependence of Generalized Parton Distributions.
- Large statistics **TCS and  $J/\psi$  production** will also be measured, at the same time.
  
- Yesterday workshop was a success !
- **9 talks:**
  - 4 online – 5 in-person
  - 3 theory/phenomenology – 3 new measurements – 3 on  $\mu$ CLAS12/SoLID
- Peak online attendance: **38**
- 30+ people in the room → **Peak attendance 60+ !**
- Plenty of discussions, new ideas, one LOI at this year PAC
- Great coffee and cakes
  
- We are working to **publish the proposal in EPJA**.
- We are meeting bi-weekly on Thursday at 10am ET ([wiki](#), [mailing list](#)).