



μ CLAS12: electro- and photo-production of muon pairs

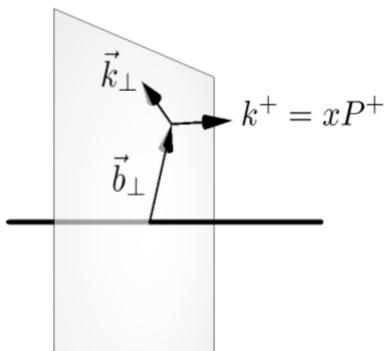
P. Chatagnon, CEA Saclay, France
 μ CLAS12 workshop, 9th of March 2026

Motivations and Challenges

Generalized Parton Distributions...

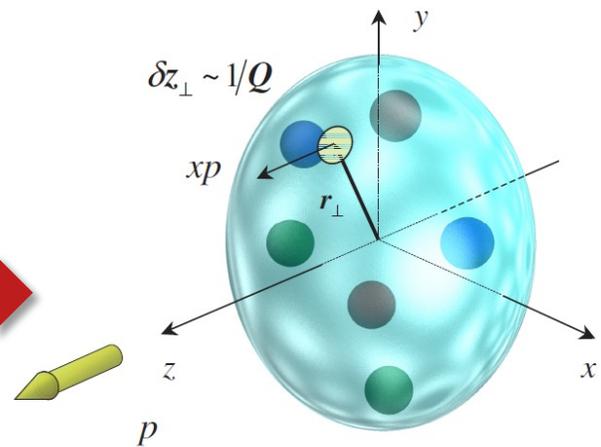
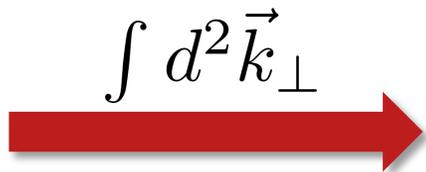
Electro-magnetic Form Factors

Generalized Parton Distributions $H, \tilde{H}, E, \tilde{E}(x, \xi, t)$

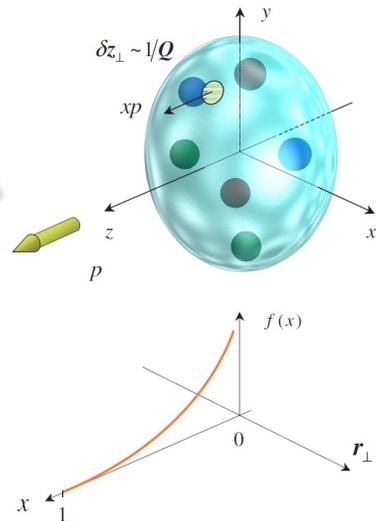
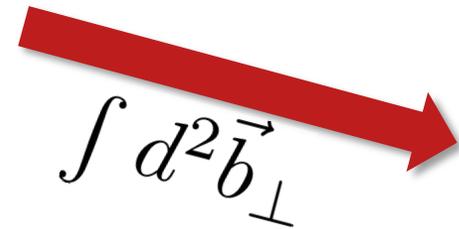
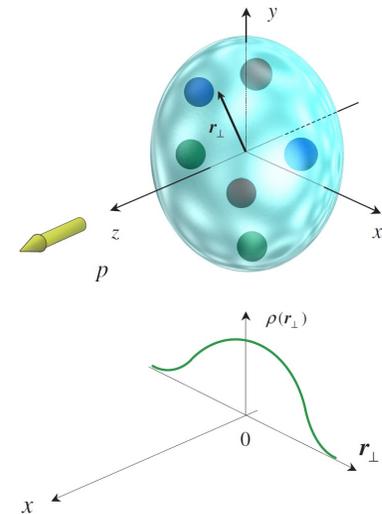
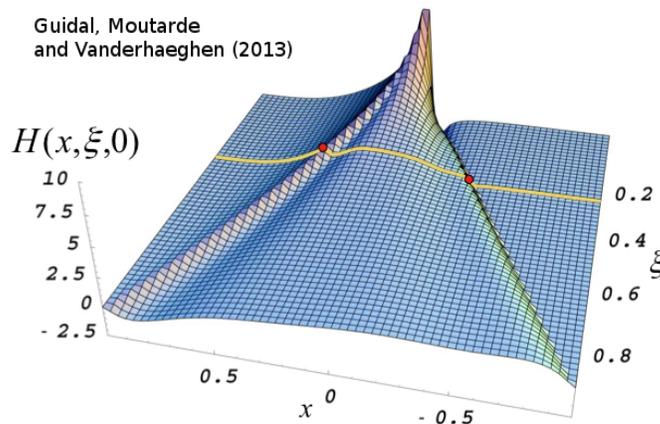


$$W(x, \xi, \vec{k}_\perp, \vec{k}_\perp \cdot \Delta_\perp, t)$$

Generalized Transverse Momentum Distributions



Guidal, Moutarde and Vanderhaeghen (2013)



Parton Distribution Functions

... to probe the fundamental properties of the nucleon

Spin, Mass and Forces in the nucleon

→ Moments of GPDs and Gravitational Form Factors

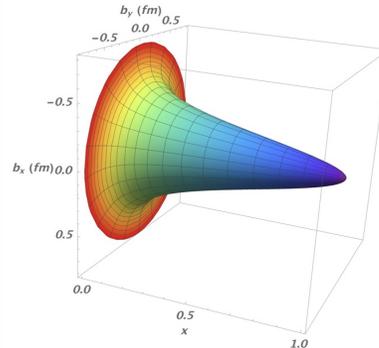
$$\int_{-1}^1 dx x H^q(x, \xi, t) = A^q(t) + \xi^2 D^q(t)$$

Mass \nearrow Spin \nearrow Forces

$$\int_{-1}^1 dx x E^q(x, \xi, t) = B^q(t) - \xi^2 D^q(t)$$

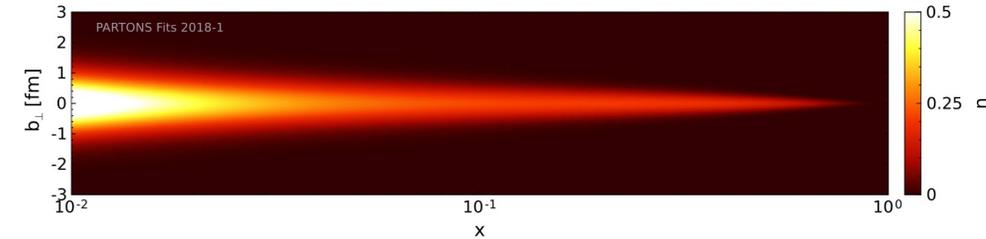
$$\frac{1}{2} = J(0) = \frac{1}{2}(A(0) + B(0)) = \frac{1}{2}\Delta\Sigma + \Delta L$$

Nucleon tomography



R. Dupré, M. Guidal, M. Vanderhaeghen, PRD95, 011501 (2017)

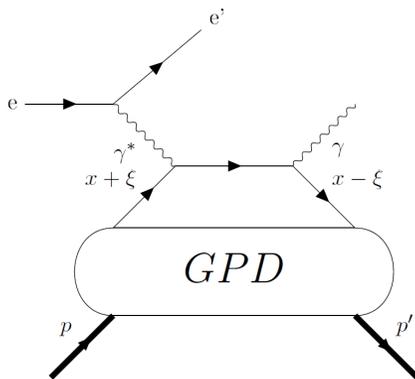
$$q(b_{\perp}, x) = \int_0^{\infty} \frac{d^2\Delta_{\perp}}{(2\pi)^2} e^{\Delta_{\perp} b_{\perp}} H(x, 0, -\Delta_{\perp}^2)$$



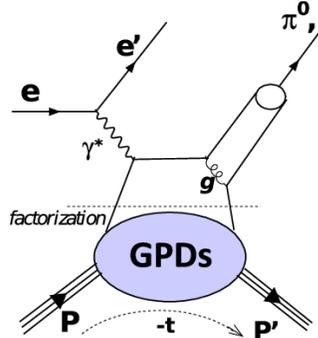
Moutarde, H., Sznajder, P. & Wagner, J. Border and skewness functions from a leading order fit to DVCS data. Eur. Phys. J. C 78, 890 (2018)

... via the experimental measurement of exclusive reactions

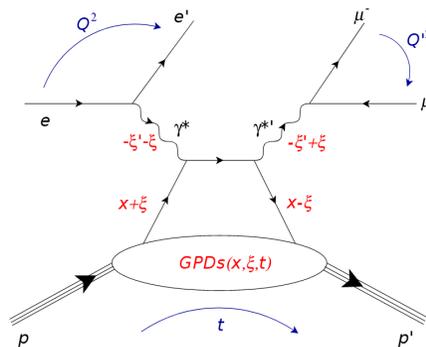
Deeply Virtual Compton Scattering



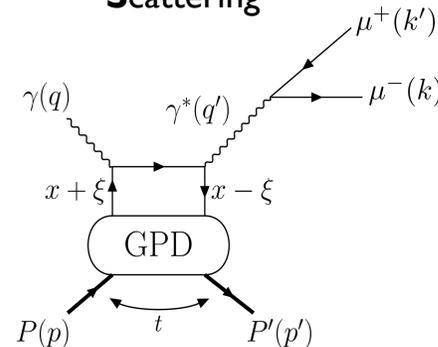
Deeply Virtual Meson Production



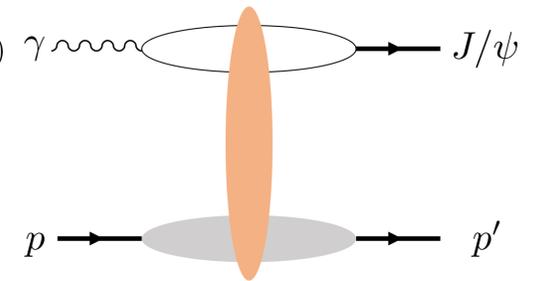
Double DVCS



Timelike Compton Scattering



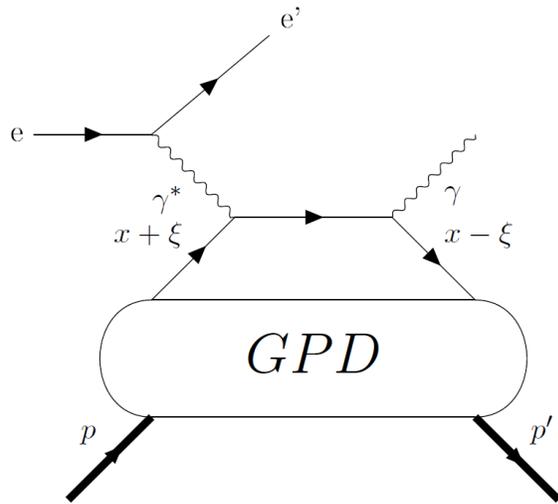
J/psi Production



The Compton Form Factors: an inverse problem to access GPDs

Deeply Virtual Compton Scattering

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



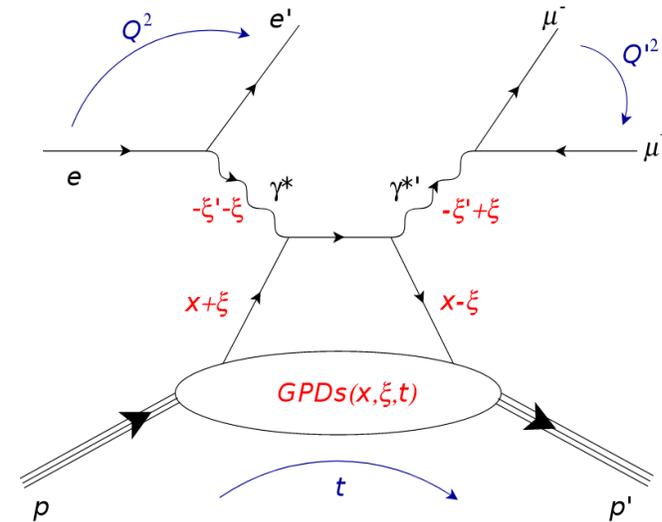
$$\mathcal{H}_{DVCS}(\xi, t) = \int_{-1}^1 dx H(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right)$$

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

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

Double Deeply Virtual Compton Scattering

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

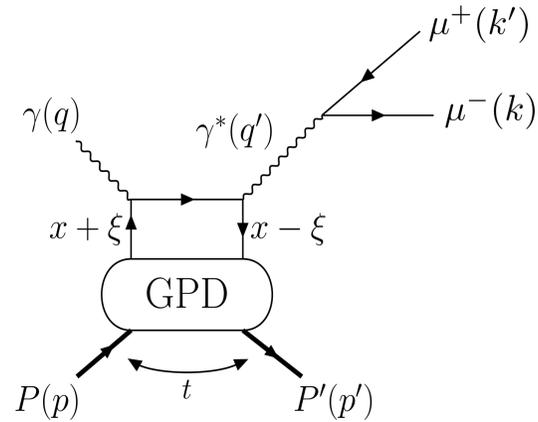


$$\mathcal{H}_{DDVCS}(\xi', \xi, t) = \int_{-1}^1 dx H(x, \xi, t) \left(\frac{1}{\xi' - x - i\epsilon} - \frac{1}{\xi' + x - i\epsilon} \right)$$

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

Timelike Compton Scattering (TCS)

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



The TCS interference cross-section:

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = A \left[\cos(\phi) \frac{1 + \cos^2(\theta)}{\sin(\theta)} \text{Re}\mathcal{H} + \dots \right] - \nu \cdot B \left[\sin(\phi) \frac{1 + \cos^2(\theta)}{\sin(\theta)} \text{Im}\mathcal{H} + \dots \right]$$



Forward-backward asymmetry:

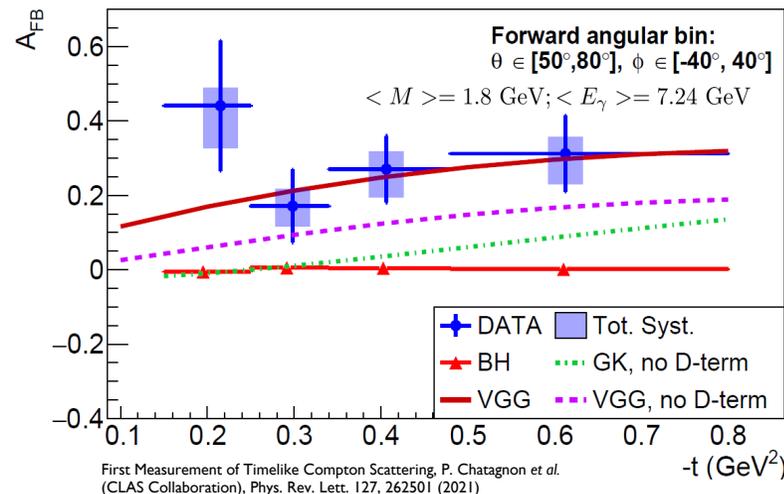
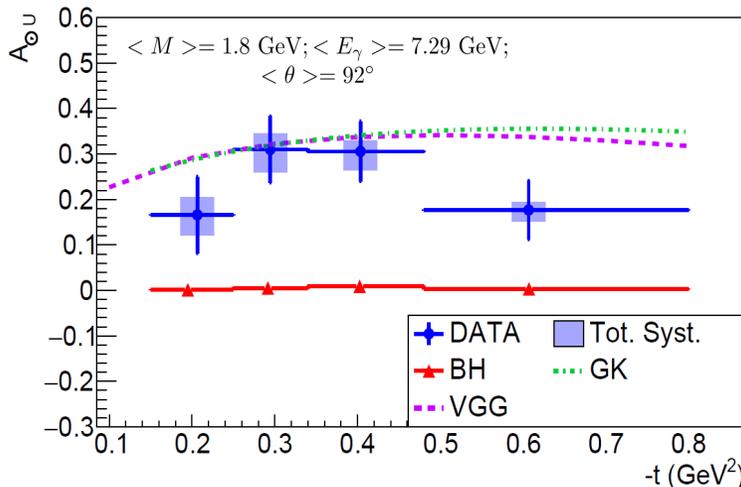
$$A_{FB}(\theta_0, \phi_0) = \frac{d\sigma(\theta_0, \phi_0) - d\sigma(180^\circ - \theta_0, 180^\circ + \phi_0)}{d\sigma(\theta_0, \phi_0) + d\sigma(180^\circ - \theta_0, 180^\circ + \phi_0)}$$

$$\propto \frac{\frac{L_0}{L} \cos \phi_0 \frac{(1 + \cos^2 \theta_0)}{\sin(\theta_0)} \text{Re}\mathcal{H}}{d\sigma_{BH}(\theta_0, \phi_0) + d\sigma_{BH}(180^\circ - \theta_0, 180^\circ + \phi_0)}$$

Photon polarization asymmetry:

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto \frac{\frac{L_0}{L} \sin \phi \frac{(1 + \cos^2 \theta)}{\sin(\theta)} \text{Im}\mathcal{H}}{d\sigma_{BH}}$$

Previous TCS measurement with CLAS12

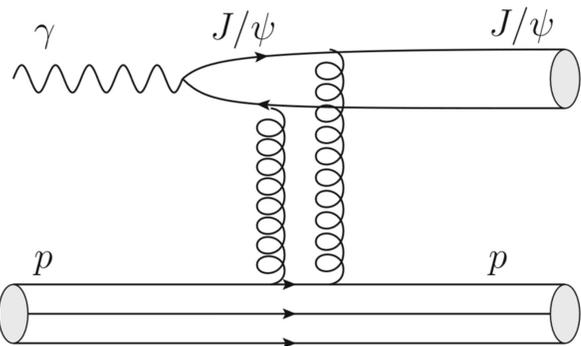


First Measurement of Timelike Compton Scattering, P. Chatagnon et al. (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)

- TCS probes similar CFFs as DVCS.
- **Direct access to the D-term.**
- TCS is measurable with a muon pair in the final state.
- **Recoil proton detection** is needed to ensure exclusivity.

Near-threshold J/ψ production

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



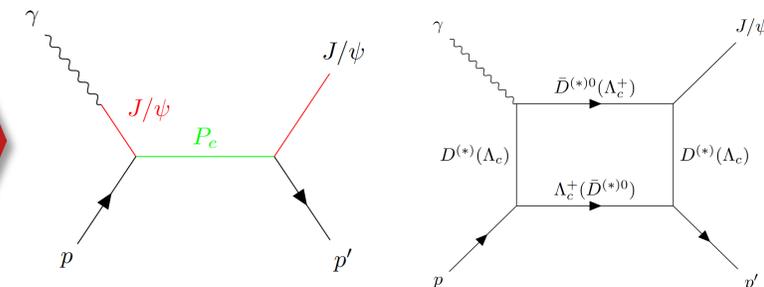
$$\frac{d\sigma}{dt} = \frac{\alpha_{EM} e_Q^2}{4(W^2 - M_N^2)^2} \frac{(16\pi\alpha_S)^2}{3M_V^3} |\phi_{NR}(0)|^2 |G(t, \xi)|^2$$

"QCD analysis of near-threshold photon-proton production of heavy quarkonium",
Yuxun Guo, Xiangdong Ji, and Yizhuang Liu, Phys. Rev. D 103, 096010, 2021

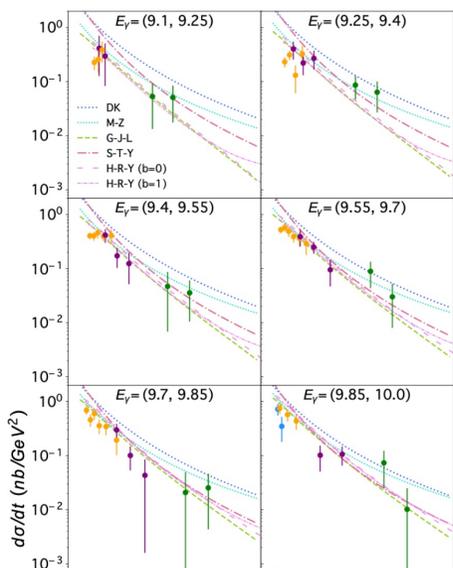
$$\frac{d\sigma}{dt} = \mathcal{N}^2 \frac{e^2}{64\pi(s - M_N^2)^2} \frac{[A^g(t) + \eta^2 D^g(t)]^2}{A^{g^2}(0)} \cdot \tilde{F}(s) \cdot 8$$

" J/ψ near threshold in holographic QCD: A and D gravitational form factors",
Kiminad A. Mamo and Ismail Zahed, Phys. Rev. D 106, 086004, 2022

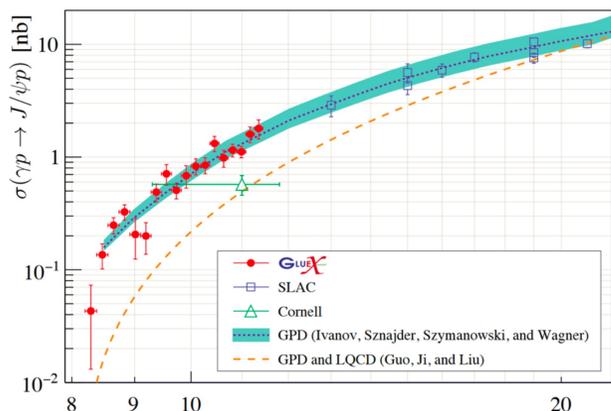
Access to the gluon content of the proton...
... if other contributions can be understood.



Current experimental status in the e^+e^- final state

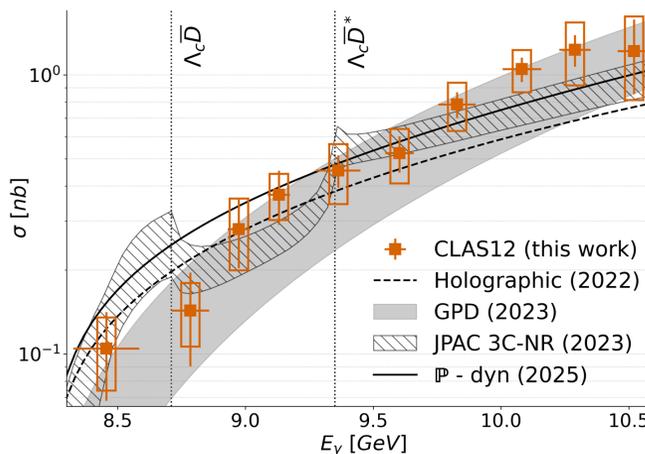


"Determining the gluonic gravitational form factors of the proton". Duran, B., Meziani, Z.E., Joosten, S. et al. Nature 615, 813–816 (2023)



GlueX results taken from S. Adhikari et al. (GlueX Collaboration). Phys. Rev. C 108, 025201, 2023

• Results from CLAS12, just released ! [\(link to the pre-print\)](#)



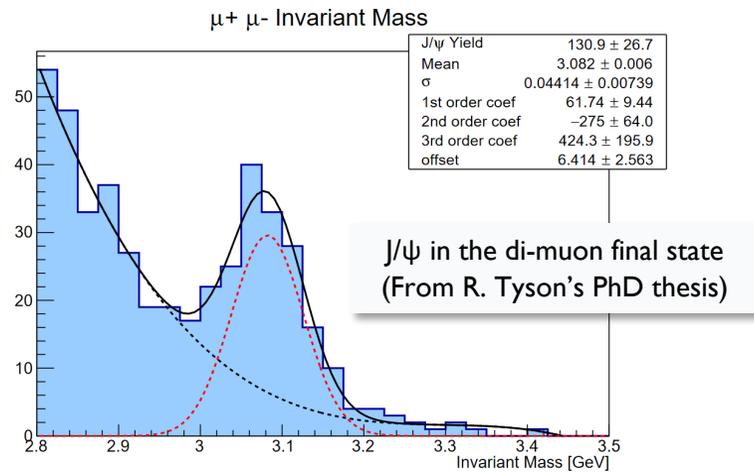
- J/ψ production offers a window to the gluon dynamics in the nucleon, even at JLab energies.
- Requires **large statistics**.



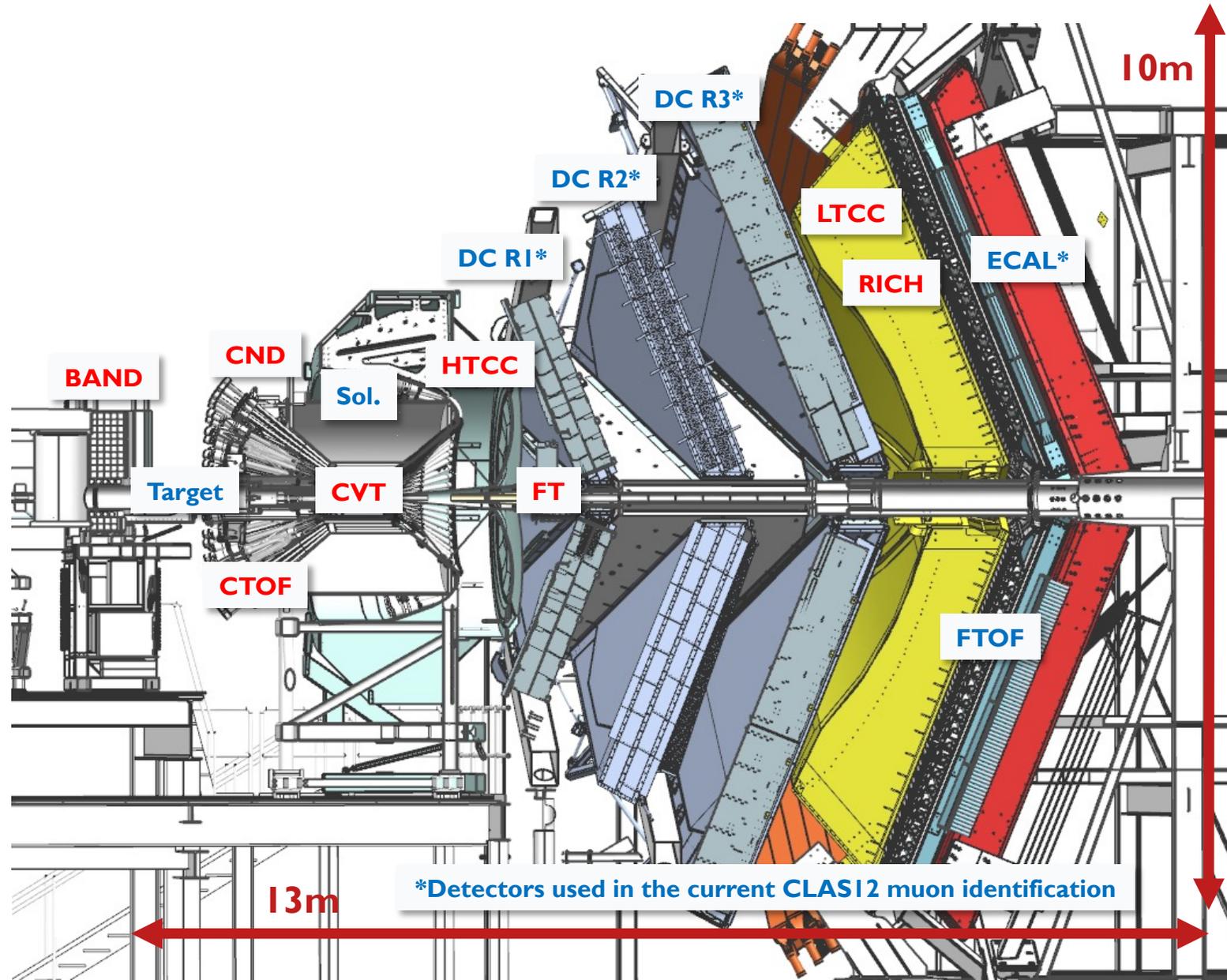
The μ CLAS12 design

From the CLAS12 configuration...

- The μ CLAS12 setup will **mostly use existing CLAS12 detectors**.

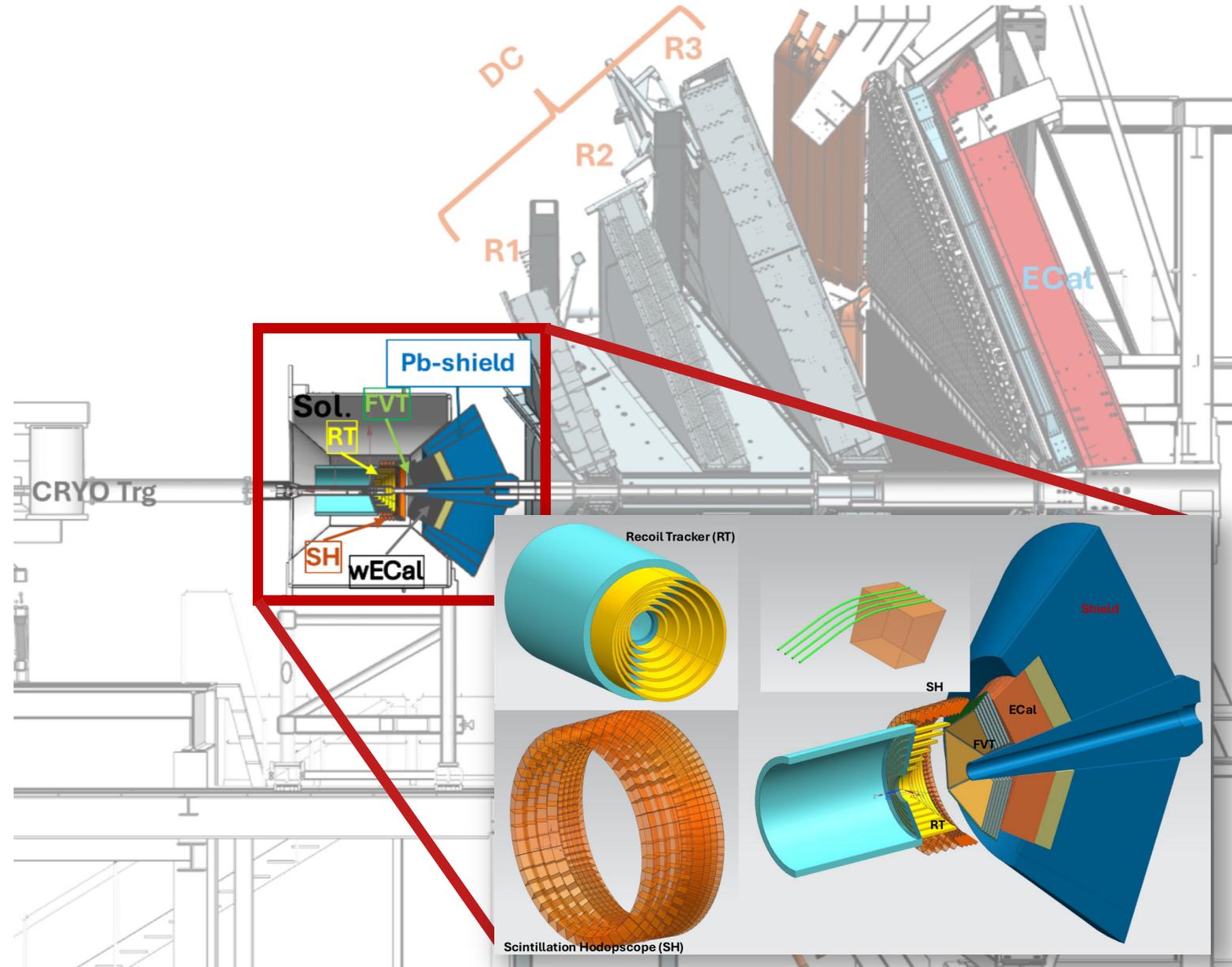


- The CLAS12 FD detector will be effectively used as a muon detector.
- The CTOF, CND, CVT, HTCC, FT, LTCC, RICH and BAND will be removed.



... to the μ CLAS12 configuration

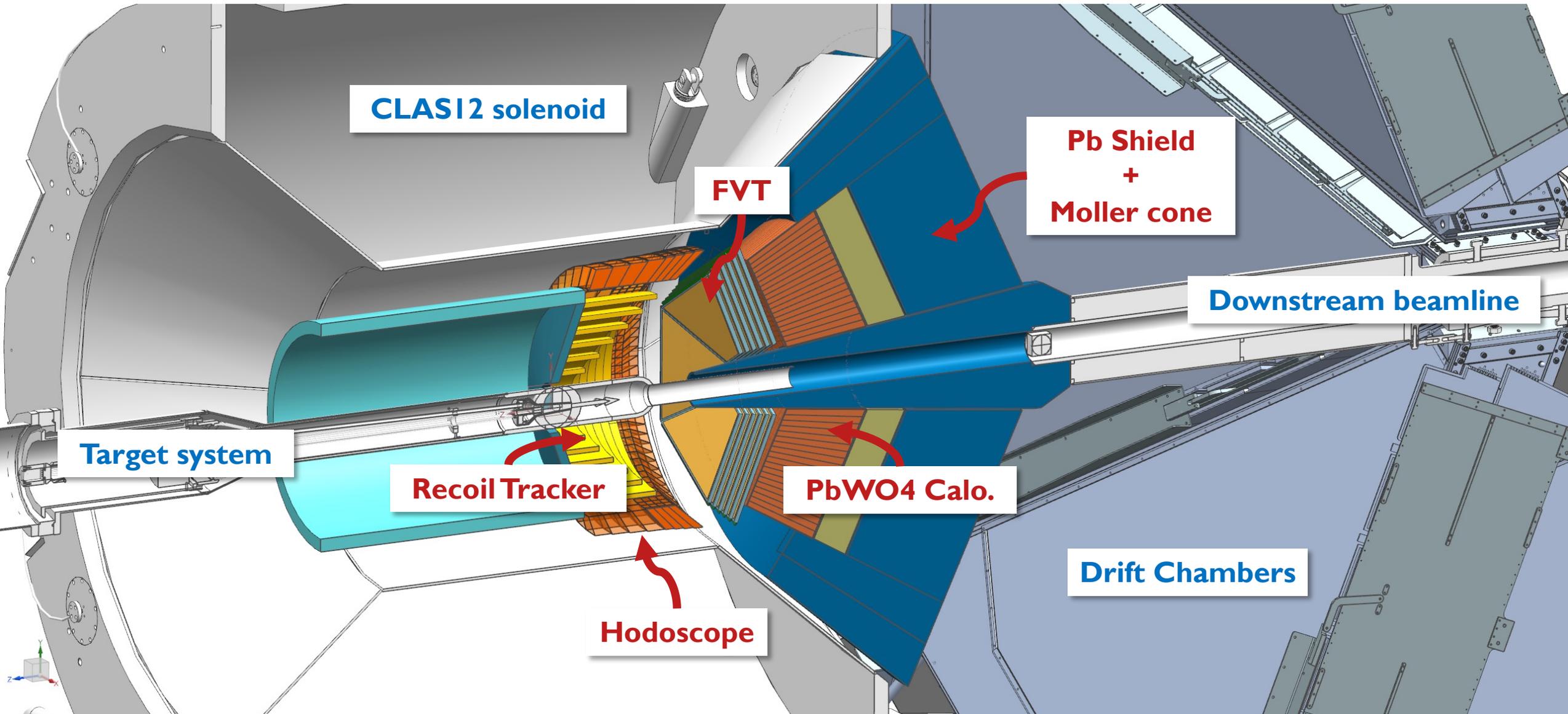
- A **lead shield** to reduce pion background in the FD.
- A **PbWO₄ calorimeter** will identify scattered electron.
- A **GEM Forward Vertex tracker** will be used for vertexing.
- A **recoil tracker** surrounds the target to detect recoil proton,
- associated with a **Central Scintillator Hodoscope** for timing.



Running conditions & beam time

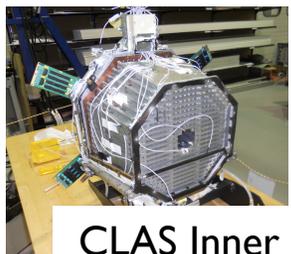
Beam Energy (GeV)	Beam Current (μ A)	Beam Requirements	Target Material	Target Length (cm)	Beam time (days)
Commisionning					
11				5	15
Calibration					
11	7.5		Empty target	5	10
11	<1		LH2	5	20
Production					
11	7.5	> 85% longitudinal polarization	LH2	5	200
Total time					245

μ CLAS12 subsystems overview

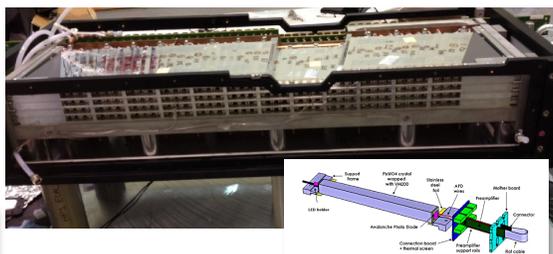


The wECAL calorimeter

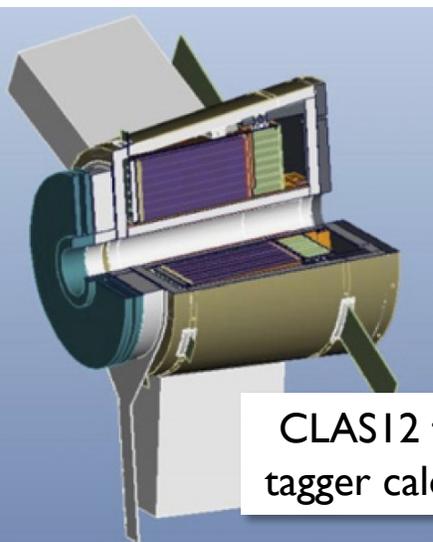
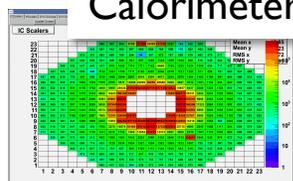
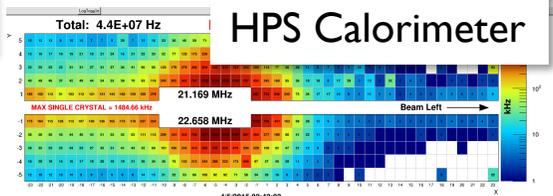
PbWO4 Calorimeters in Hall B



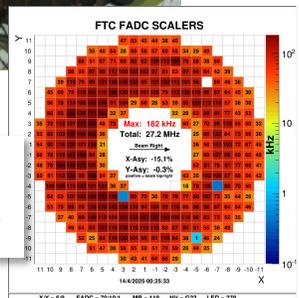
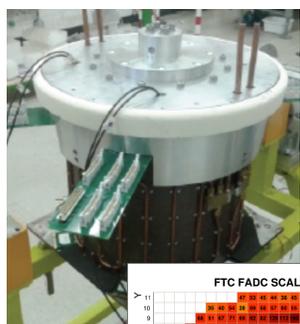
CLAS Inner Calorimeter



HPS Calorimeter

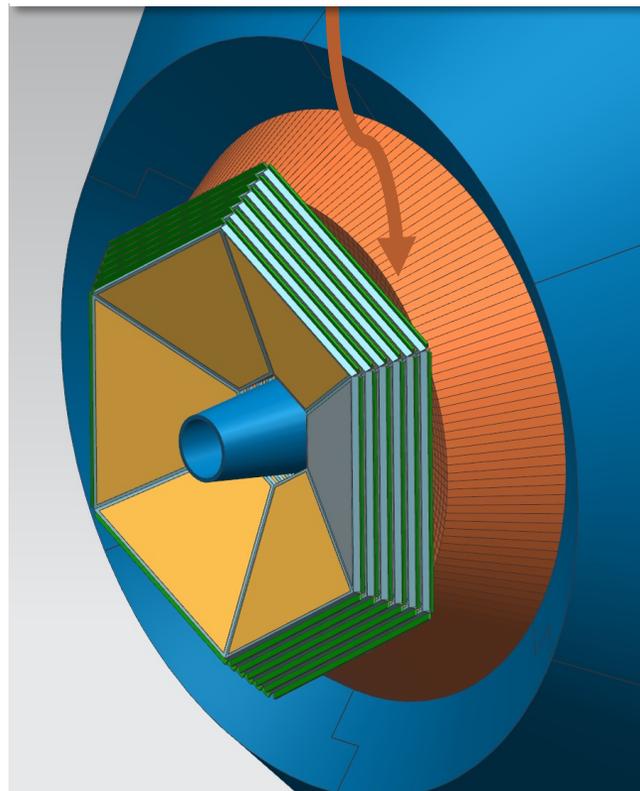


CLAS12 forward tagger calorimeter



wECAL calorimeter

- wECal design based on the existing CLAS12 FTCal.
- APD readout (used in CLAS12 FT & HPS)
- **Same MC and recon software as FT**
- Expected rates: 2 MHz (~HPS calo.)

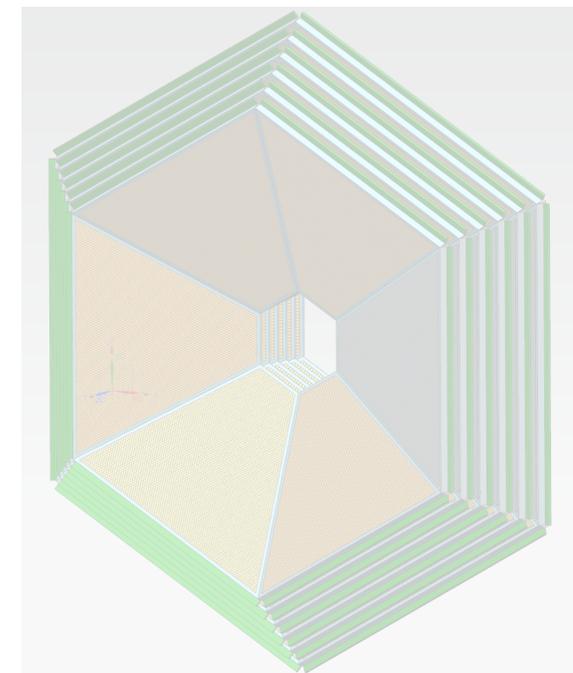


Forward Vertex Tracking

- 6-layer assembly GEM detectors.
- VMM3 readout.
- Expected rates: 500 kHz/cm²

Forward Vertex Tracker

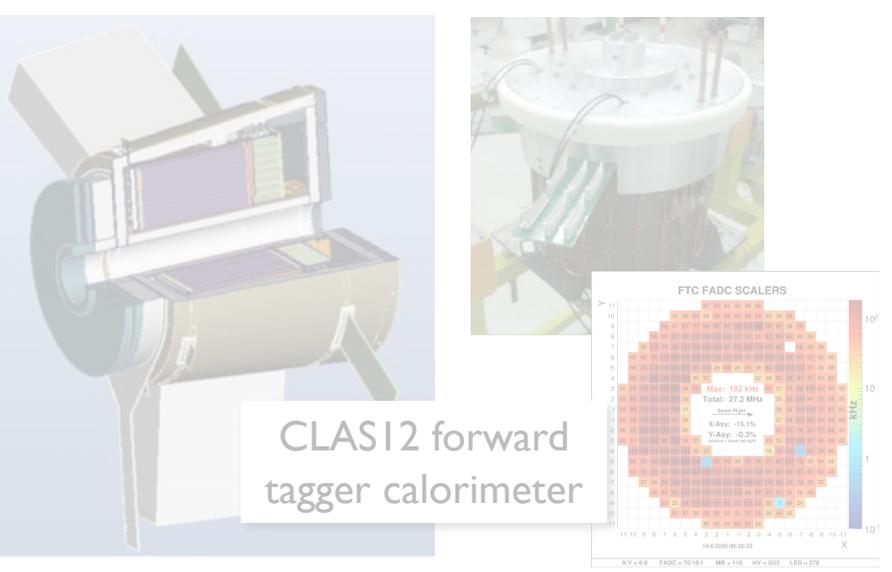
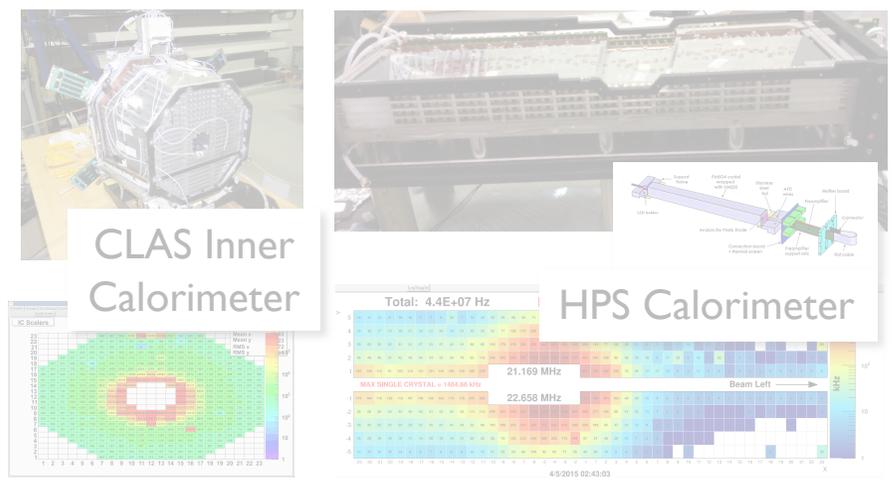
- Forward tracks reconstructed in the μ CLAS12 FD Drift Chambers.
- **No changes to the FD tracking from CLAS12.**
- FVT is used for **vertexing forward-going tracks only.**



- 2D stereo readout
- Position resolution better than 100 μ m.

The forward vertex tracker

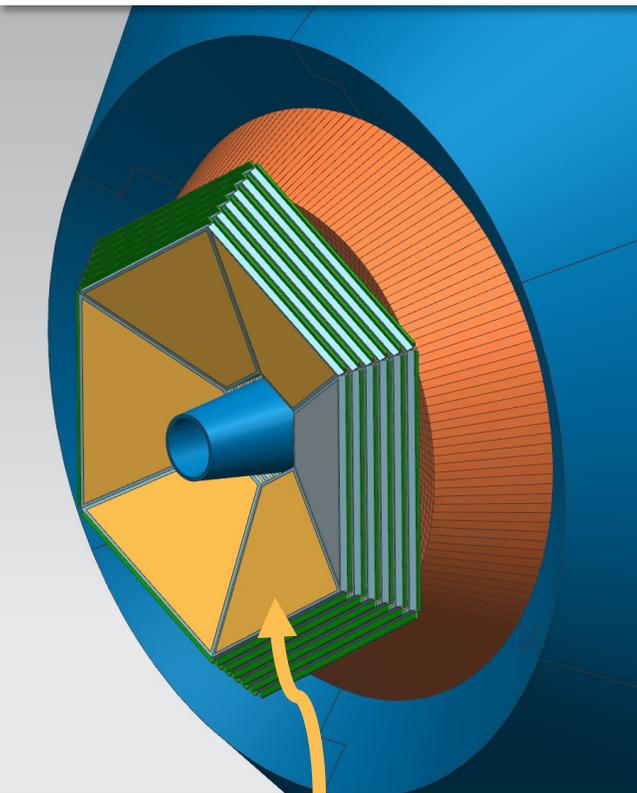
PbWO4 Calorimeters in Hall B



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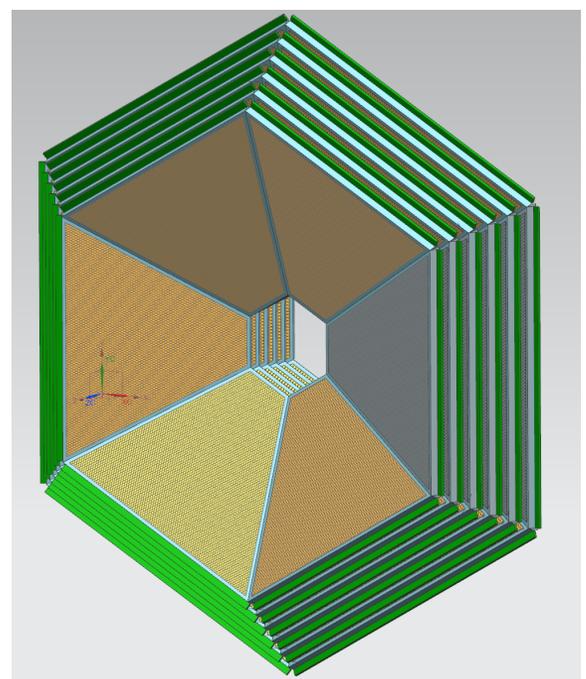


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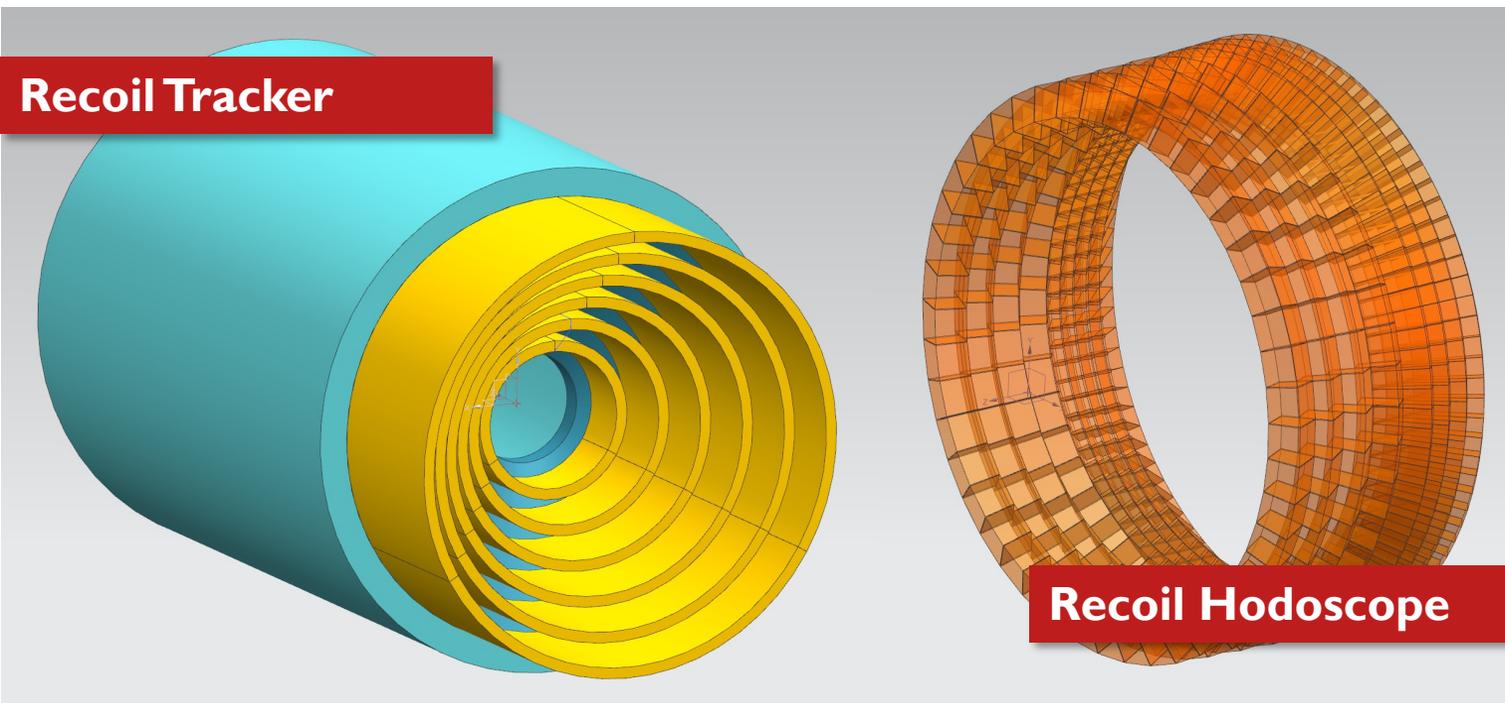
Forward Vertex Tracker

- Forward tracks reconstructed in the μ CLAS12 FD Drift Chambers.
- No changes to the FD tracking from CLAS12.**
- FVT is used for **vertexing forward-going tracks only.**



- 2D stereo readout/1200 ch./modules
- Position resolution better than 100 μ m.

The Recoil Detector: tracker & hodoscope



Recoil Tracker

- 6 regions x 3 sectors
- Dual readout with strips along and at fixed z (arcs)
- 500 μ m pitch
- Inspired by the layout of the existing CLAS12 BMT

Recoil Hodoscope

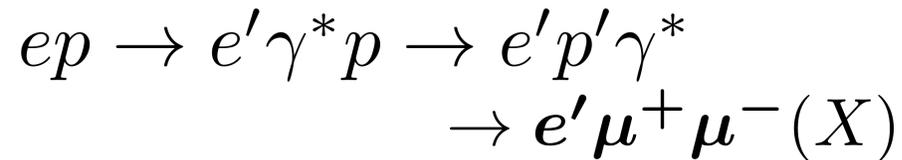
- 540 truncated pyramidal modules
- 2x2 and 4x4 cm²
- Readout using SiPMs 2m away, using light fibers



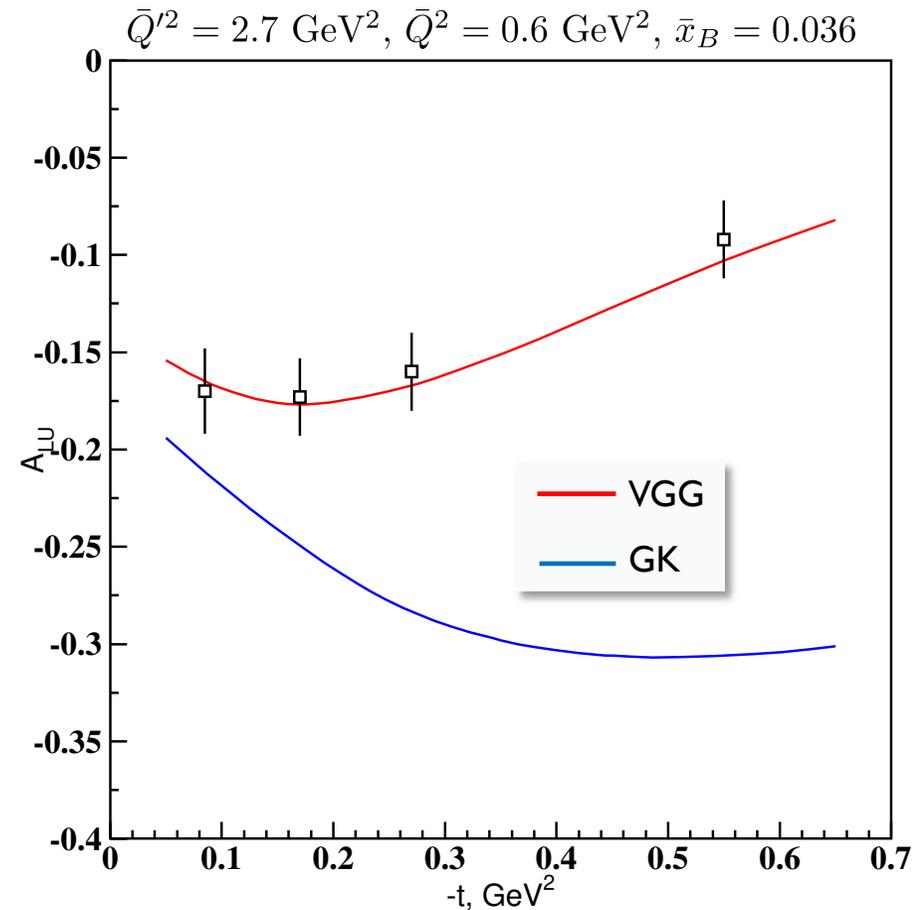
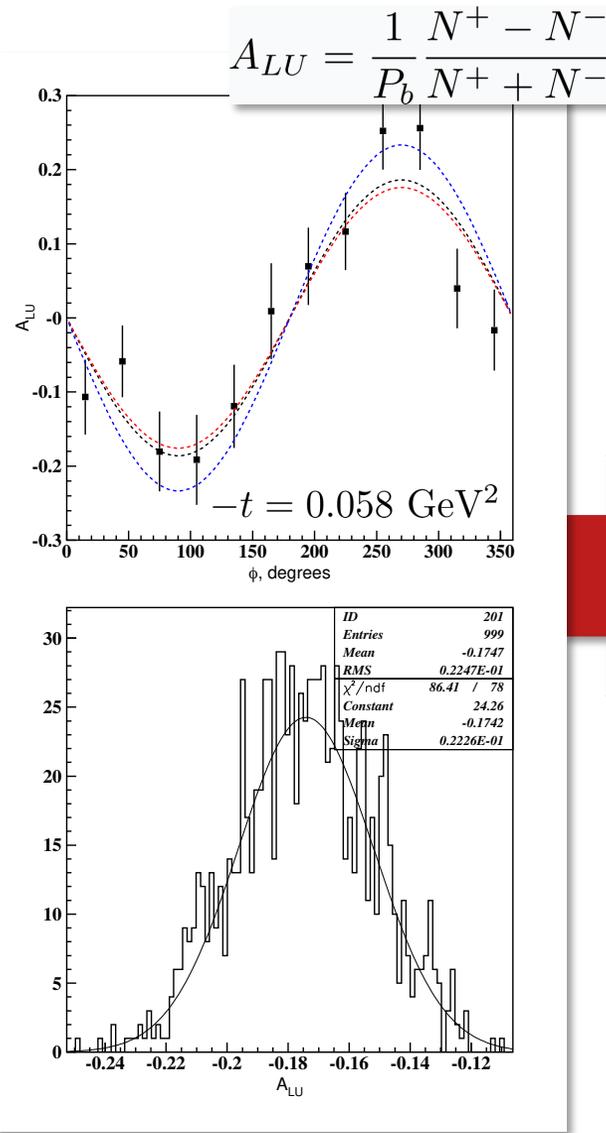
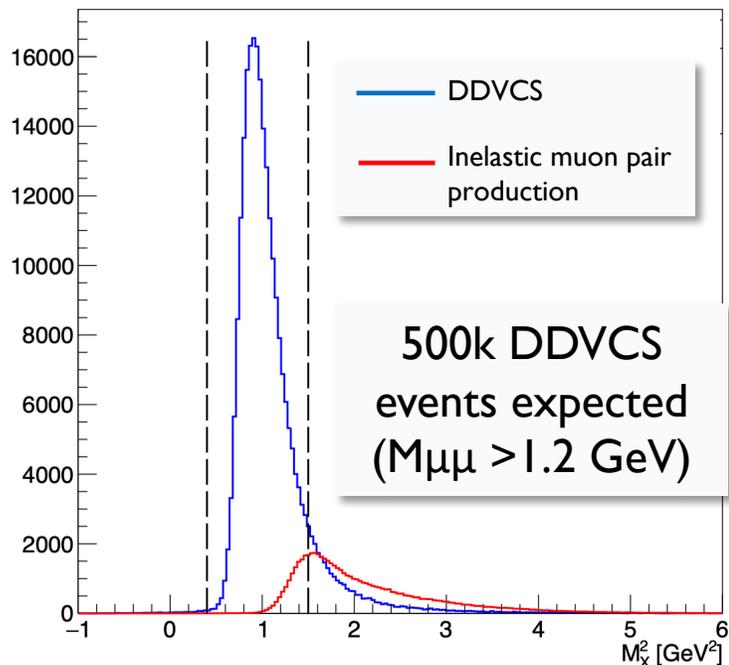
Overview of the expected results

Expected results on DDVCS

Analysis strategy



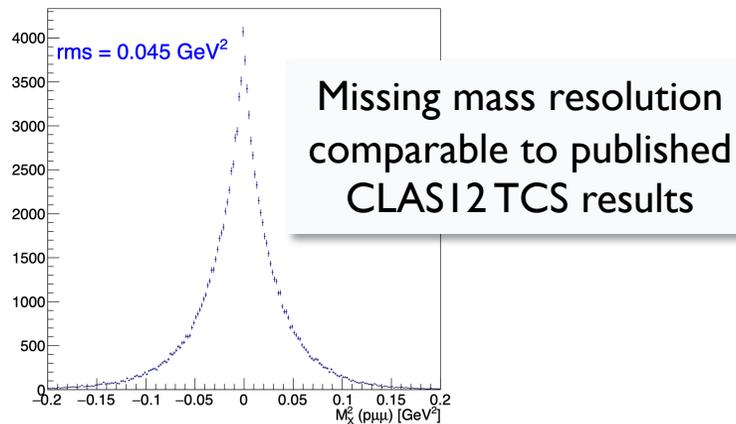
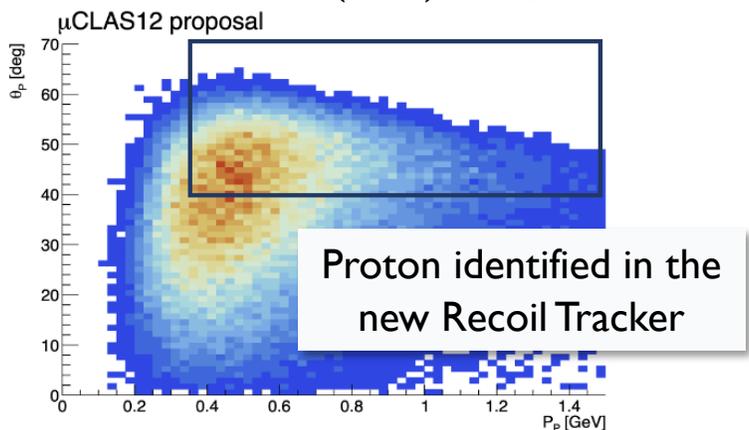
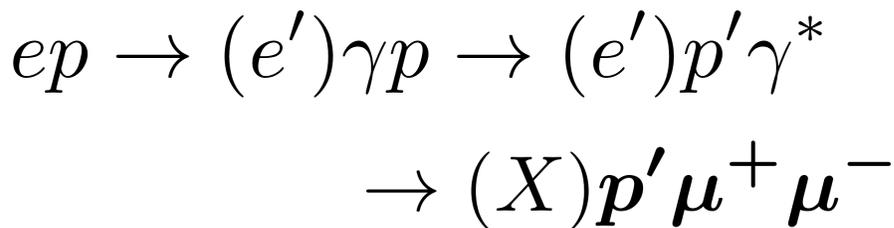
- Electron detected in wECAL.
- Muons in μ CLAS12 Forward Detector.
- Missing proton reconstructed from energy-momentum conservation.



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

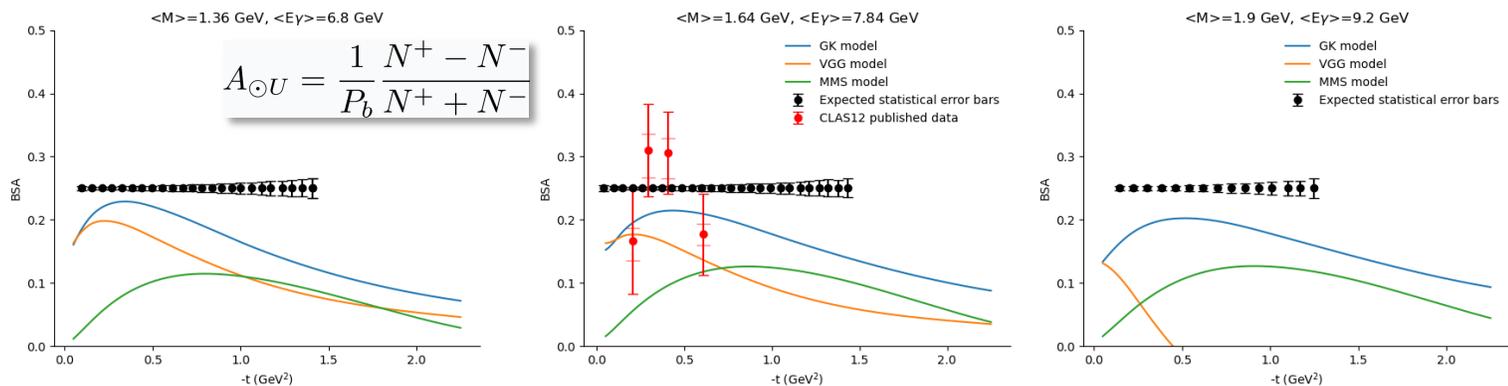
Expected results for TCS

Analysis strategy

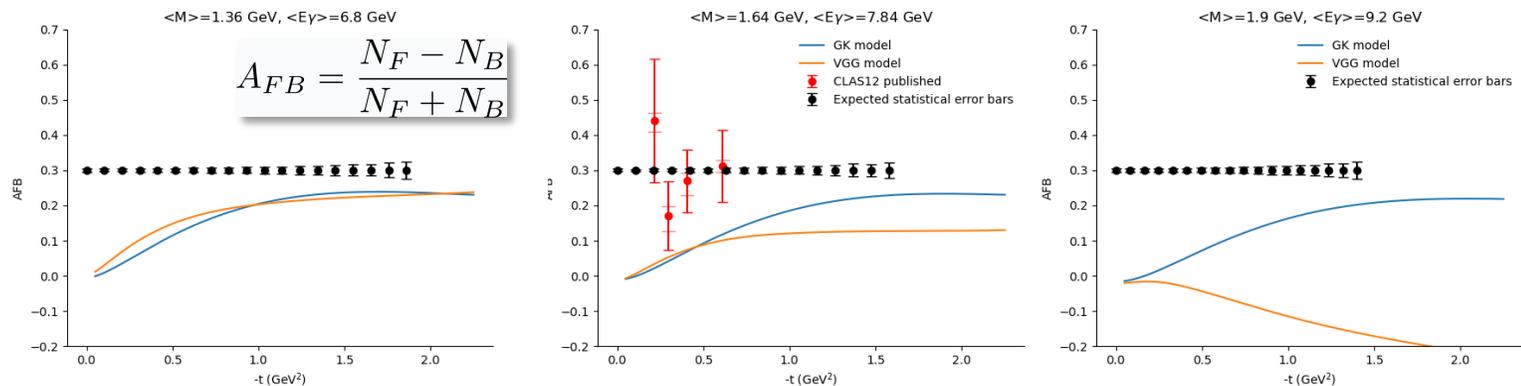


Expected results with 7.7M expected events ($M_{\mu\mu} > 1.2$ GeV)

Photon polarization asymmetry



Forward-Backward asymmetry



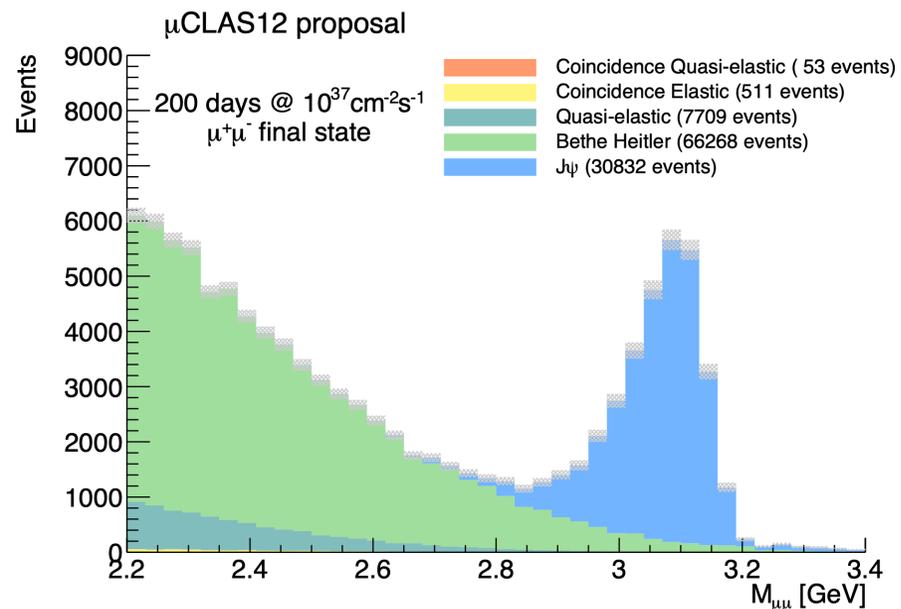
→ First **precision** measurement of TCS

Expected results for J/ψ electro-production

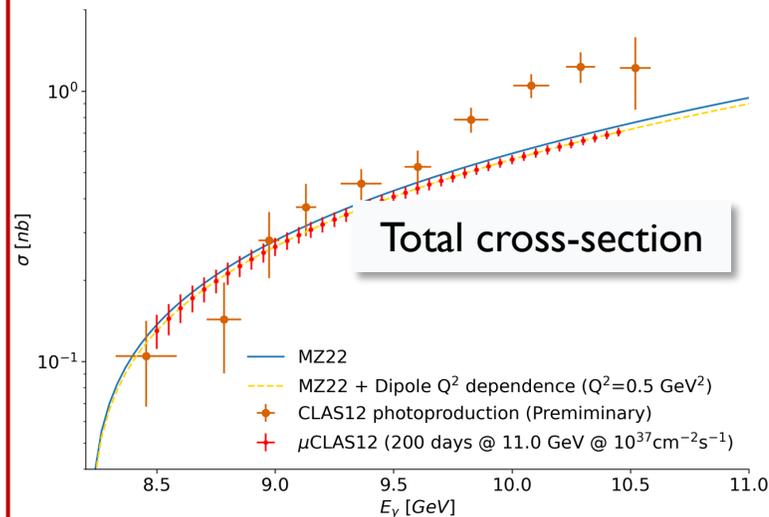
Analysis strategy

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

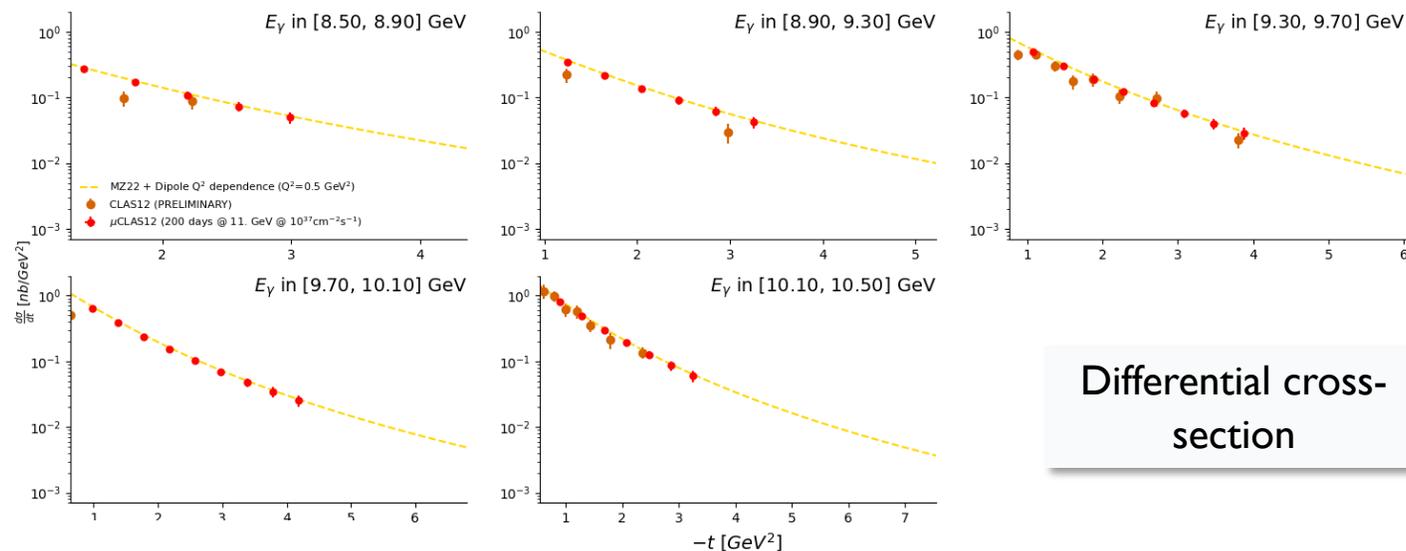
- Electron detected in the wECAL.
- Muons in μ CLAS12 Forward Detector.
- Peak in the invariant mass of the $\mu^+ \mu^-$ pair.



Projected results with 30k expected events



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



Key takeaways

- The μ 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/ψ production** will also be measured, at the same time.
- The μ CLAS12 setup will **use most of the existing CLAS12 detector package** with the **additions of shielding, calorimeter and tracking** in front of the Forward Detector.
- All the planned detector are based on technologies that have already been demonstrated at JLab.
- μ CLAS12 has been **implemented in CLAS12 simulation and reconstruction** framework.
- Rates, trigger rates, background rates and expected number of events are based on realistic simulation and existing CLAS12 data.
- μ CLAS12 is **approved by the 2025 JLab Program Advisory Committee**.
- We are working to finalize the design and specifications, and publish the proposal in EPJA.