μCLAS12: electro- and photo-production of muon pairs

Double Deeply Virtual Compton Scattering, Timelike Compton Scattering, and J/ψ production

A Proposal to PAC 53 by N. Baltzell, M. Bondi, P. Chatagnon (presenter), R. De Vita, M. Hoballah, V. Kubarovsky, R. Paremuzyan, S. Stepanyan (contact), and the **CLAS Collaboration**

PAC 53, Jefferson Lab, 21st of July 2025

Outline

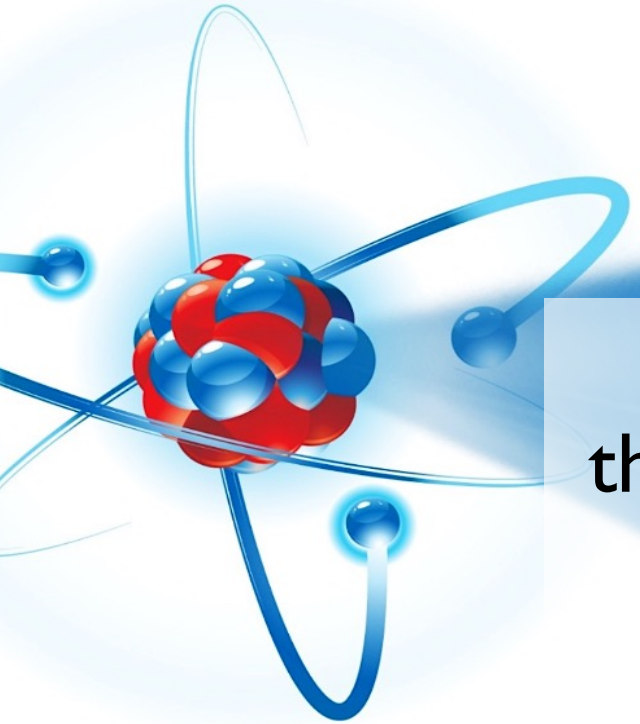
I Probing the structure of the nucleons with muon pairs: Motivations and Challenges

II The μCLAS12 experiment: Setup and Specifications

III Expected results for Double Deeply Virtual Compton Scattering, Timelike Compton Scattering, and J/ψ electroproduction

Physics with muon pairs: Motivations and Challenges

Fundamental properties of the nucleon



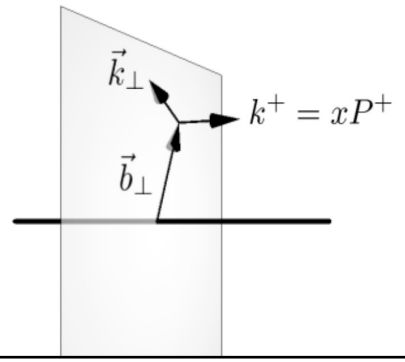
Protons and neutrons are the main building blocks of the visible matter, yet **their fundamental properties are still not fully understood.**

Generalized Parton Distributions

Generalized Parton Distributions

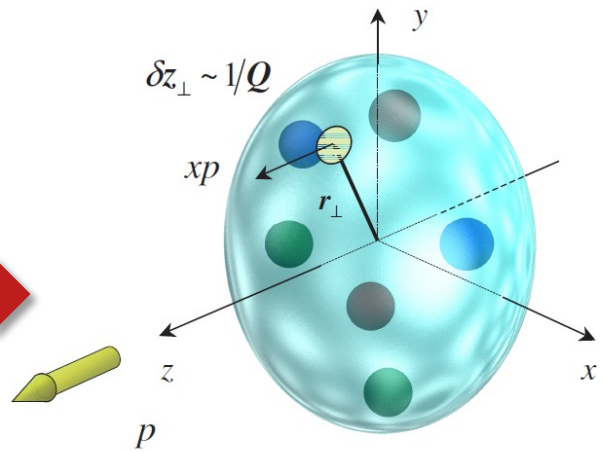
$$H, \tilde{H}, E, \tilde{E}(x, \xi, t)$$

Generalized Transverse Momentum Distributions



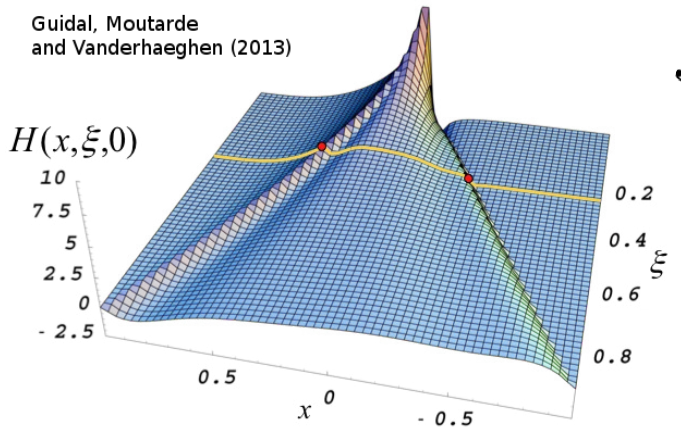
$$W(x, \xi, \vec{k}_\perp, \vec{k}_\perp \cdot \Delta_\perp, t)$$

$\int d^2\vec{k}_\perp$

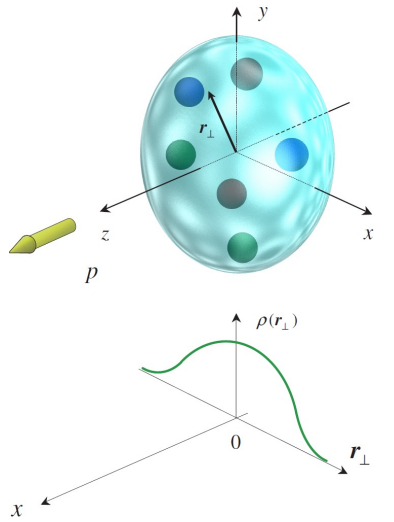


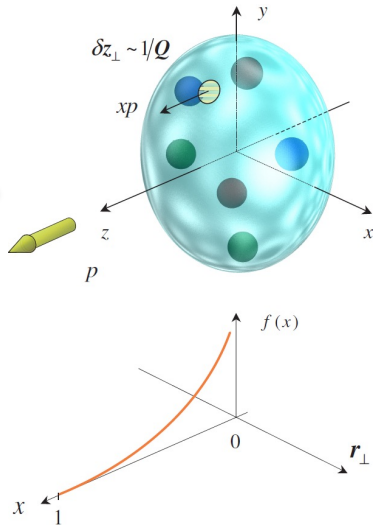
$\int dx$

$\int d^2\vec{b}_\perp$



Electro-magnetic Form Factors





Parton Distribution Functions

Figures in A.V. Belitsky, A.V. Radyushkin, "Unraveling hadron structure with generalized parton distributions", Physics Reports, 2005

Probing the fundamental properties of the nucleon…

Spin, Mass and Forces in the nucleon

→ Moments of GPDs and Gravitational Form Factors

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

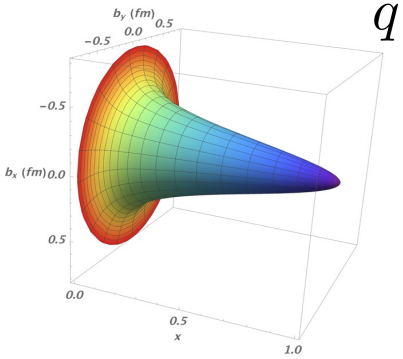
Mass — Spin — Forces

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

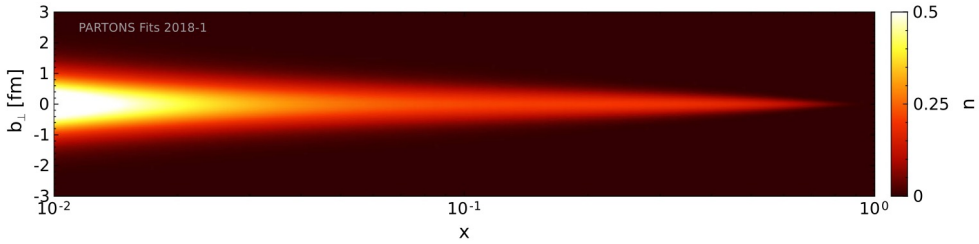
$$\frac{1}{2} = J(0) = \frac{1}{2}(A(0) + B(0)) = \frac{1}{2}\Delta\Sigma + \Delta L$$

Nucleon tomography

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



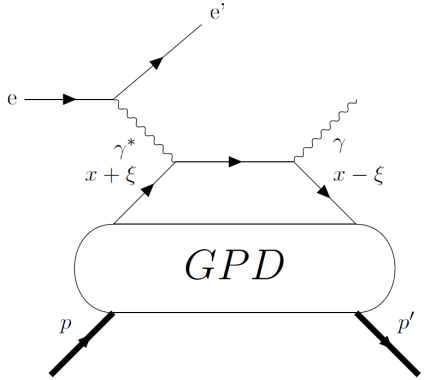
R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95, 011501 (2017)



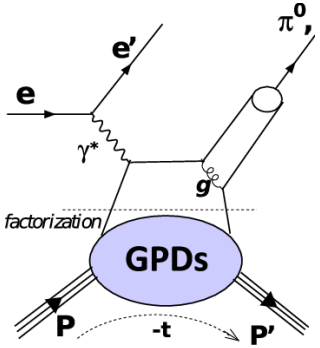
Moutarde, H., Sznajder, P. & Wagner, J. Border and skewness functions from a leading order fit to DVCS data. *Eur. Phys. J. C* **78**, 890 (2018)

… via the experimental measurement of exclusive reactions

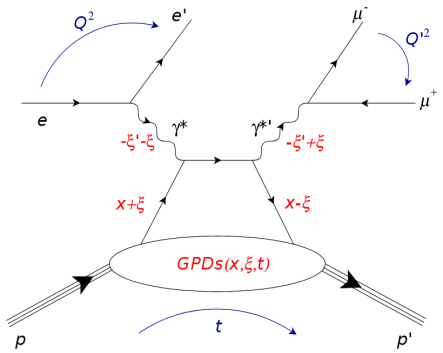
Deeply Virtual Compton Scattering



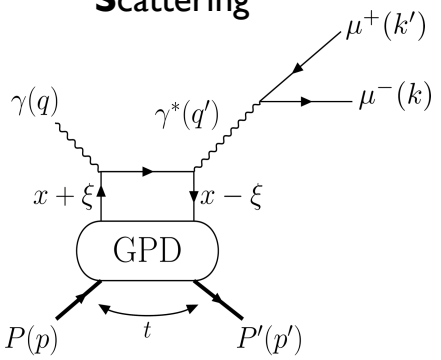
Deeply Virtual Meson Production



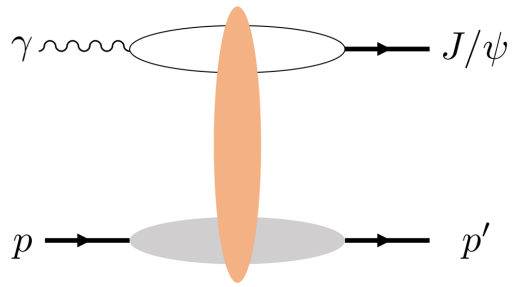
Double DVCS



Timelike Compton Scattering



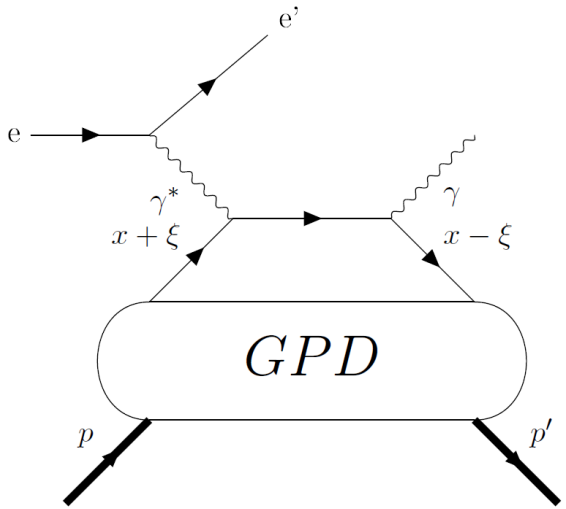
Vector Meson Production



The Compton Form Factors: an inverse problem to access GPDs

Deeply Virtual Compton Scattering

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

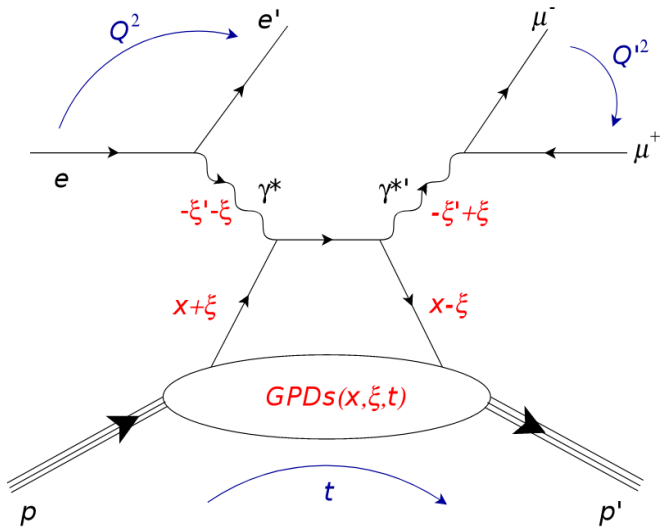


$$\mathcal{H}_{\mathrm{DVCS}}(\xi,t) = \int_{-1}^{1} dx H(x,\xi,t)\left(\frac{1}{\xi-x-i\epsilon} - \frac{1}{\xi+x-i\epsilon}\right)$$

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

Double Deeply Virtual Compton Scattering

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



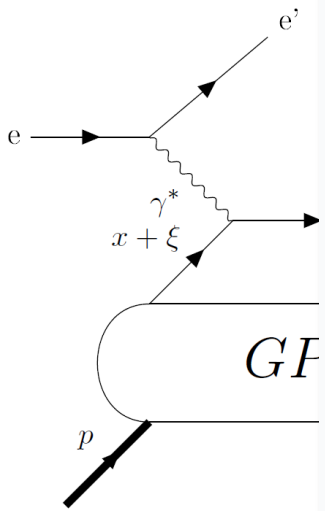
$$\mathcal{H}_{\mathrm{DDVCS}}(\xi',\xi,t) = \int_{-1}^{1} dx H(x,\xi,t)\left(\frac{1}{\xi'-x-i\epsilon} - \frac{1}{\xi'+x-i\epsilon}\right)$$

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

The Compton Form Factors: an inverse problem to access GPDs

Deeply Virtual Compton Scattering

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



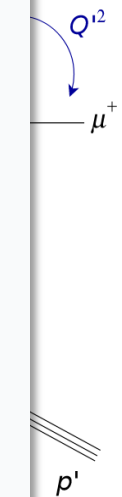
$$\mathcal{H}_{\rm DVCS}(\xi,t) = \int_{-1}^{1} dx H($$

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

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

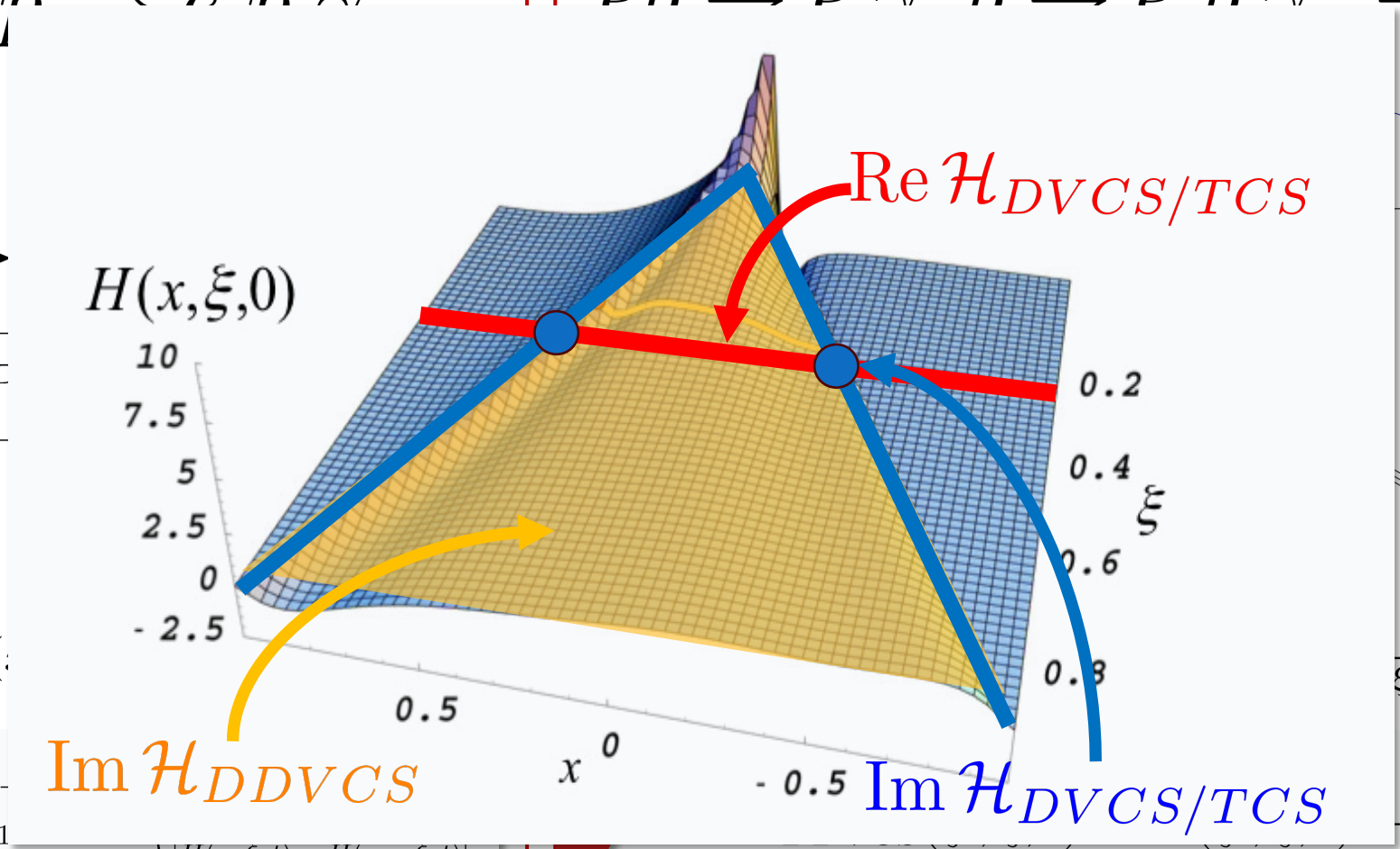
Double Deeply Virtual Compton Scattering

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



$$\frac{1}{\xi' - x - i\epsilon} - \frac{1}{\xi' + x - i\epsilon}\Big)$$

$$- H(-\xi',\xi,t)$$

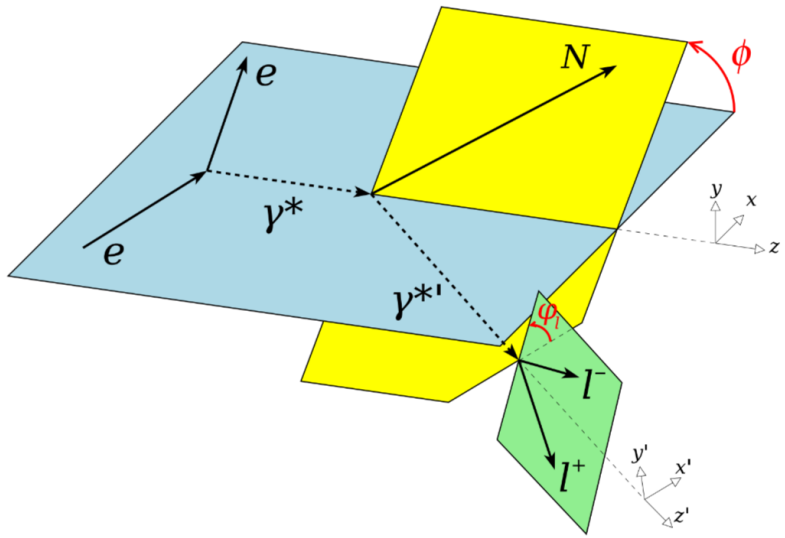


Double Deeply Virtual Compton Scattering (DDVCS)

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

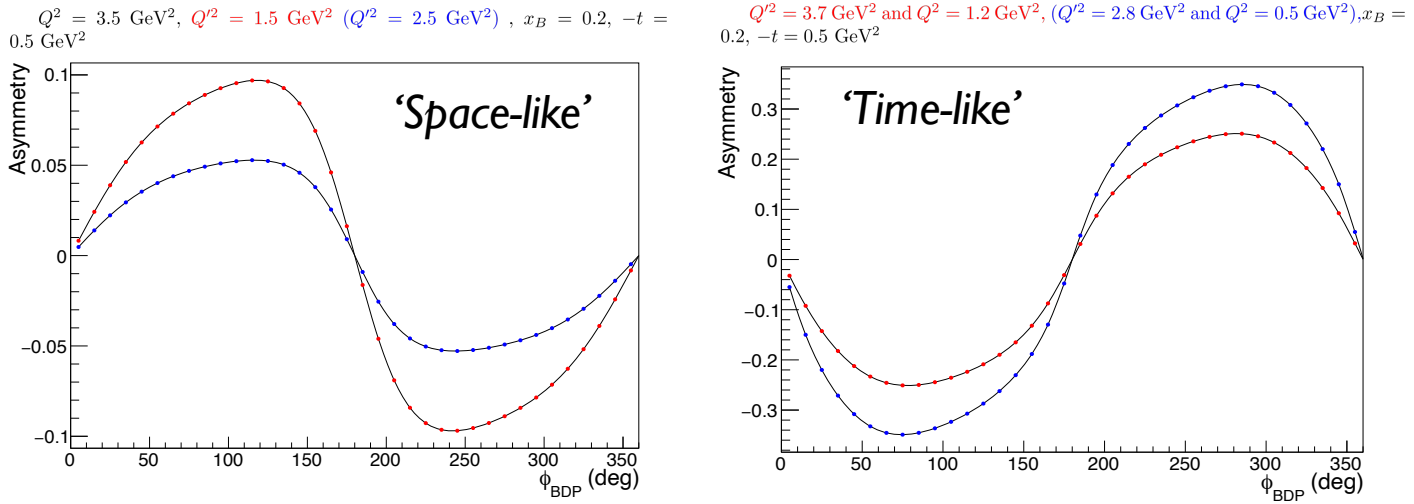
The 5-fold DDVCS cross-section:

$$\frac{d\sigma^5}{dQ^2 dt dx_B d\phi dQ'^2} = \int_0^{2\pi} d\varphi_l \int_0^{\pi} d\vartheta_l \sin\vartheta_l \frac{d\sigma^7}{dQ^2 dt dx_B d\phi dQ'^2 d\Omega_l}$$
$$= d^5\sigma_{BH1} + d^5\sigma_{BH2} + d^5\sigma_{VCS} + d^5\sigma_{Int_1} + \lambda(d^5\tilde{\sigma}_{VCS} + d^5\tilde{\sigma}_{Int_1})$$



$$\Delta\sigma_{LU} \propto \mathrm{Im}[\boldsymbol{F_1\mathcal{H}(\xi',\xi,t)} + \xi'(F_1+F_2)\tilde{\mathcal{H}}(\xi',\xi,t) - \frac{t}{4M^2}F_2\mathcal{E}(\xi',\xi,t)]\sin\phi$$

Projected DDVCS BSA

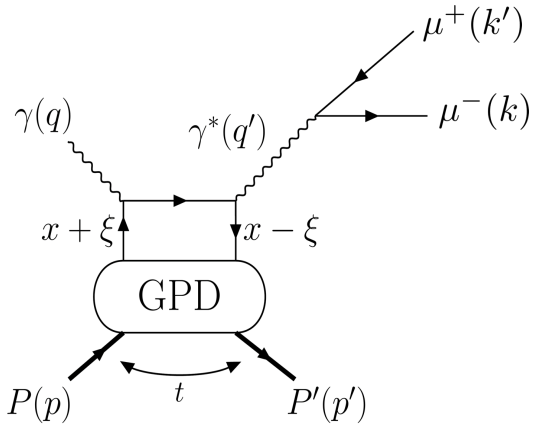


DDVCS Challenges

- **Muon detection** is essential.
- Small cross-section requires **high luminosity** experiment.

Timelike Compton Scattering (TCS)

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



The TCS interference cross-section:

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

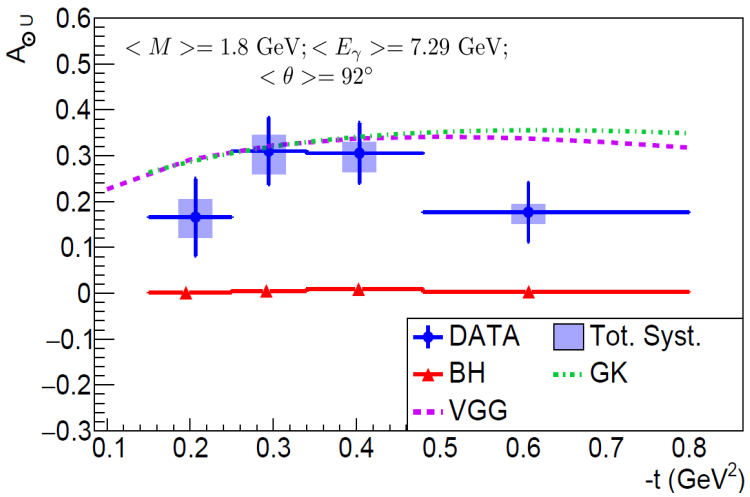
Forward-backward asymmetry:

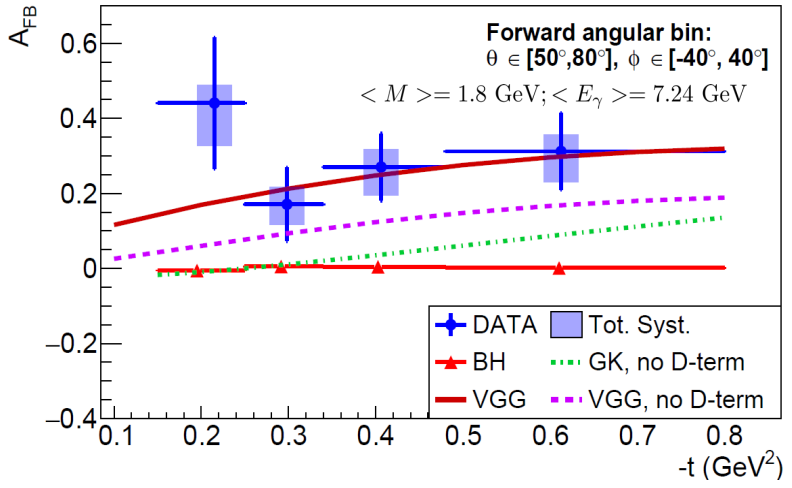
$$A_{FB}(\theta_0,\phi_0) = \frac{d\sigma(\theta_0,\phi_0) - d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}{d\sigma(\theta_0,\phi_0) + d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)} \propto \frac{\frac{L_0}{L}\cos\phi_0 \frac{(1+\cos^2\theta_0)}{\sin(\theta_0)}\mathrm{Re}\mathcal{H}}{d\sigma_{BH}(\theta_0,\phi_0)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

Photon polarization asymmetry:

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

Previous TCS measurement with CLAS12



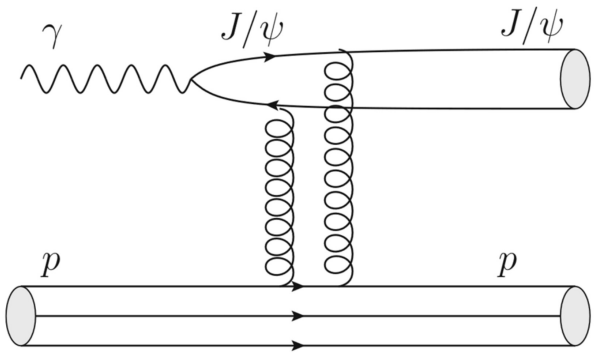


First Measurement of Timelike Compton Scattering. P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)

- 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

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



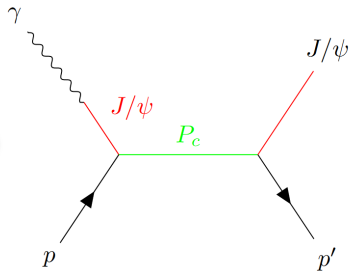
$$\frac{d\sigma}{dt} = \frac{\alpha_{EM} e_Q^2}{4(W^2 - M_N^2)^2} \frac{(16\pi\alpha_S)^2}{3M_V^3} |\phi_{NR}(0)|^2 |G(t,\xi)|^2$$

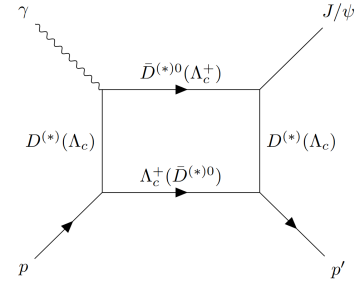
"QCD analysis of near-threshold photon-proton production of heavy quarkonium", Yuxun Guo, Xiangdong Ji, and Yizhuang Liu, Phys. Rev. D 103, 096010, 2021

$$\frac{d\sigma}{dt} = \mathcal{N}^2 \frac{e^2}{64\pi(s - M_N^2)^2} \frac{[A^g(t) + \eta^2 D^g(t)]^2}{A^{g2}(0)} \cdot \tilde{F}(s) \cdot 8$$

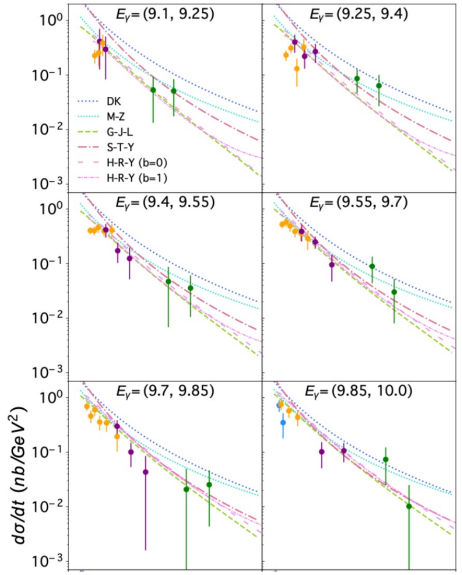
"J/ψ near threshold in holographic QCD: A and D gravitational form factors", Kiminad A. Mamo and Ismail Zahed, Phys. Rev. D 106, 086004, 2022

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

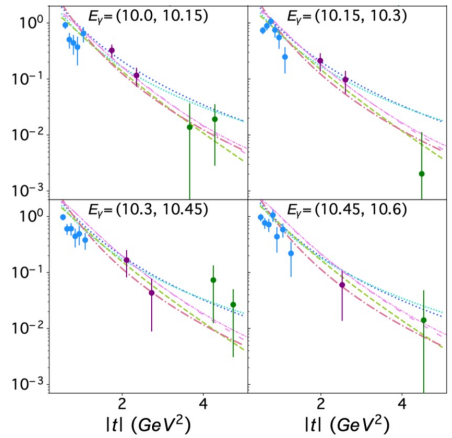




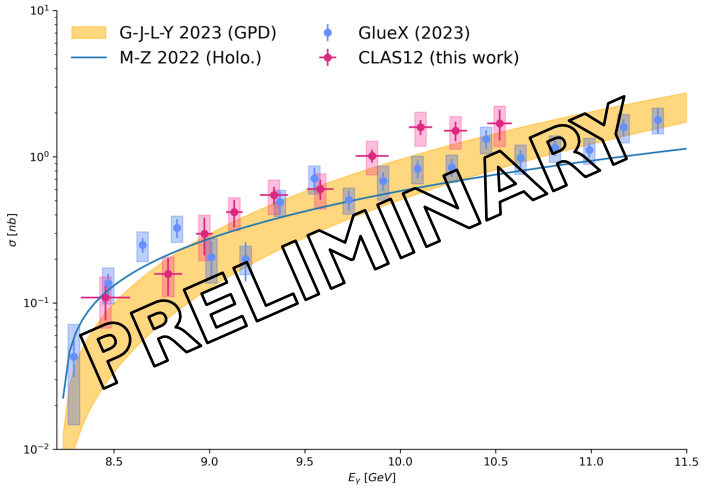
Current experimental status



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



- GlueX results taken from "Measurement of the J/ψ photoproduction cross section", S. Adhikari *et al.* (GlueX Collaboration). Phys. Rev. C 108, 025201, 2023
- Preliminary results from CLAS12, currently under collaboration review

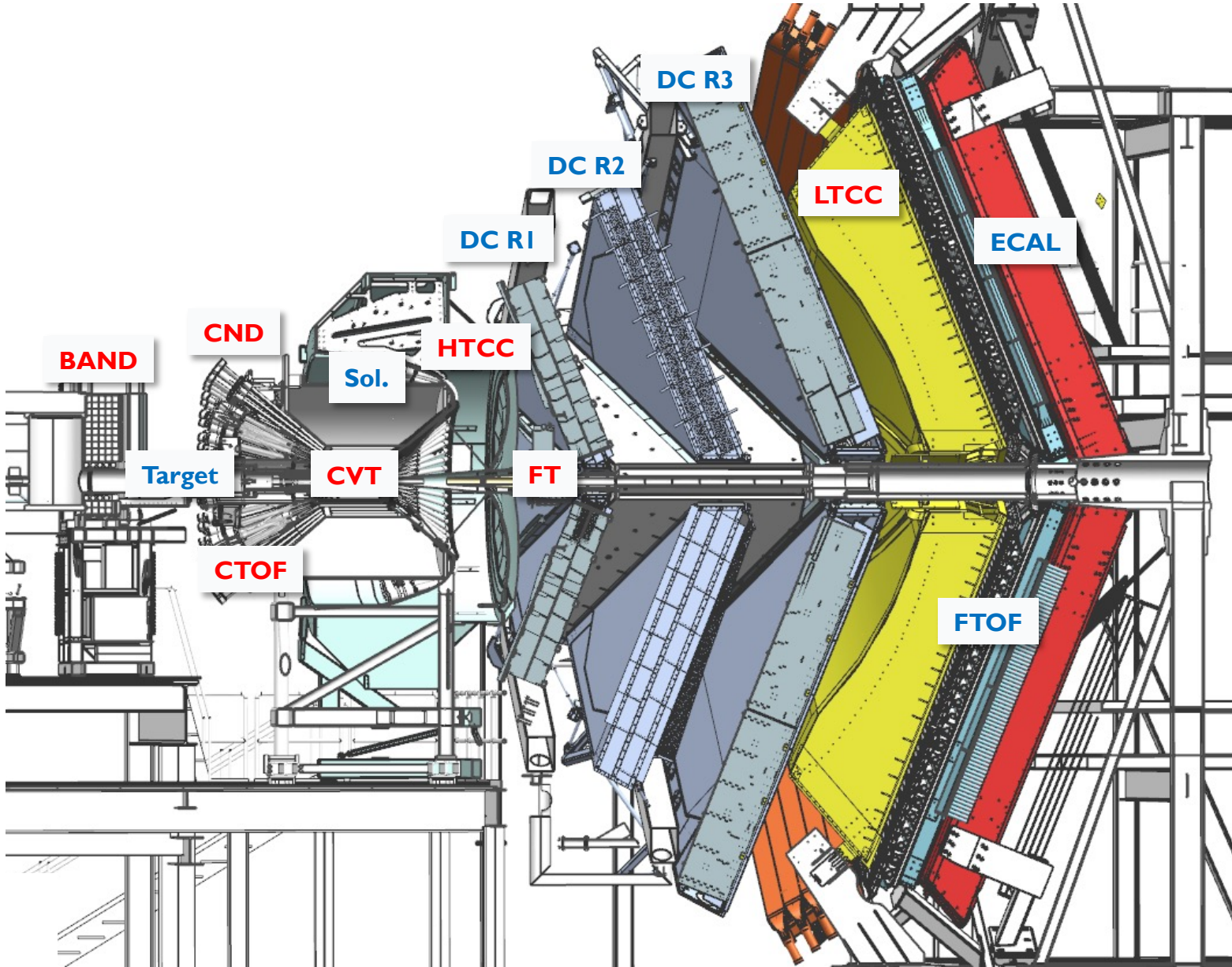


- J/ψ production offers a window to the gluon dynamics in the nucleon, even at JLab energies.
- Requires **large statistics**.

The μCLAS12 setup

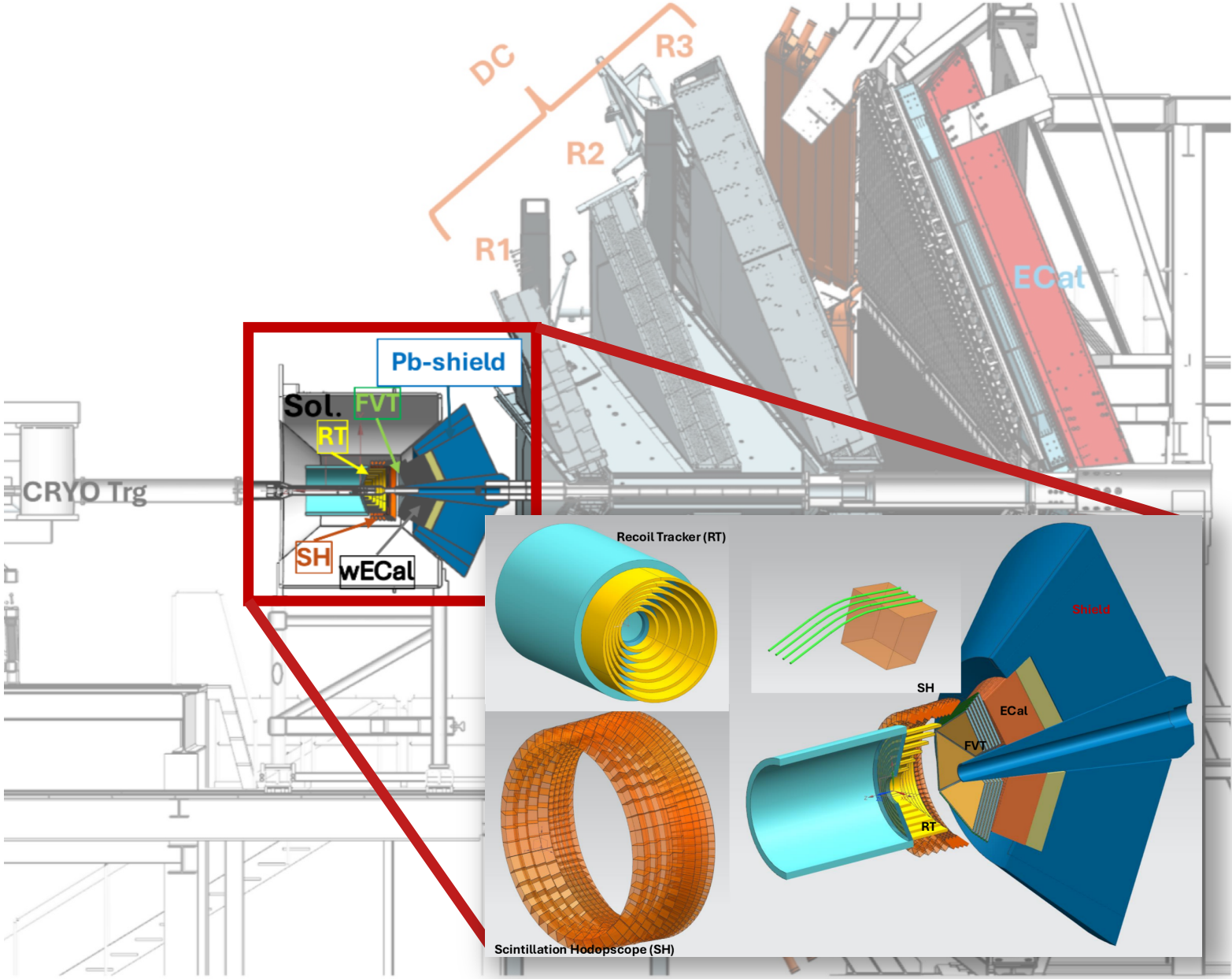
The μCLAS12 configuration

- The μCLAS12 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 and BAND will be removed.



The µCLAS12 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 **µRWELL recoil tracker** surrounds the target to detect recoil proton,
- associated with a **Central Scintillator Hodoscope** for timing.

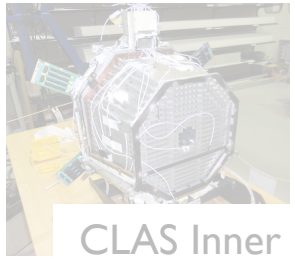


Experimental conditions and beam time request

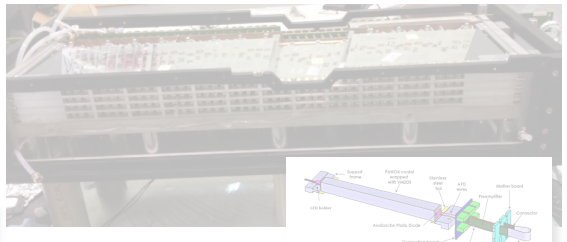
Beam Energy (GeV)	Beam Current (μA)	Beam Requirements	Target Material	Target Length (cm)	Beam time (days)
Commisionning					
11				5	15
Calibration					
11	7.5		Empty target	5	10
11	<1		LH2	5	20
Production					
11	**7.5**	**> 85% longitudinal polarization**	**LH2**	**5**	**200**
Total time					245

The wECAL calorimeter & forward vertex tracker systems

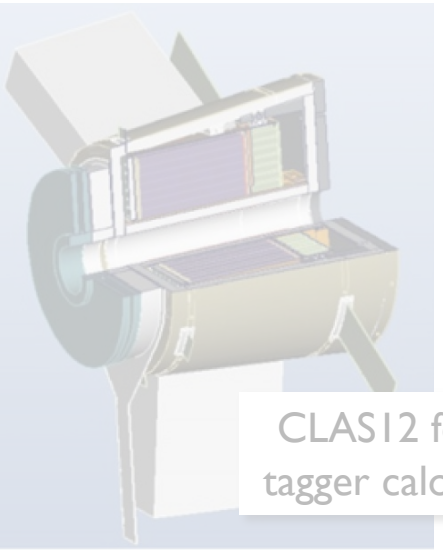
PbWO4 Calorimeters in Hall B



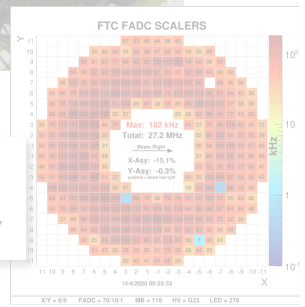
CLAS Inner Calorimeter



HPS Calorimeter

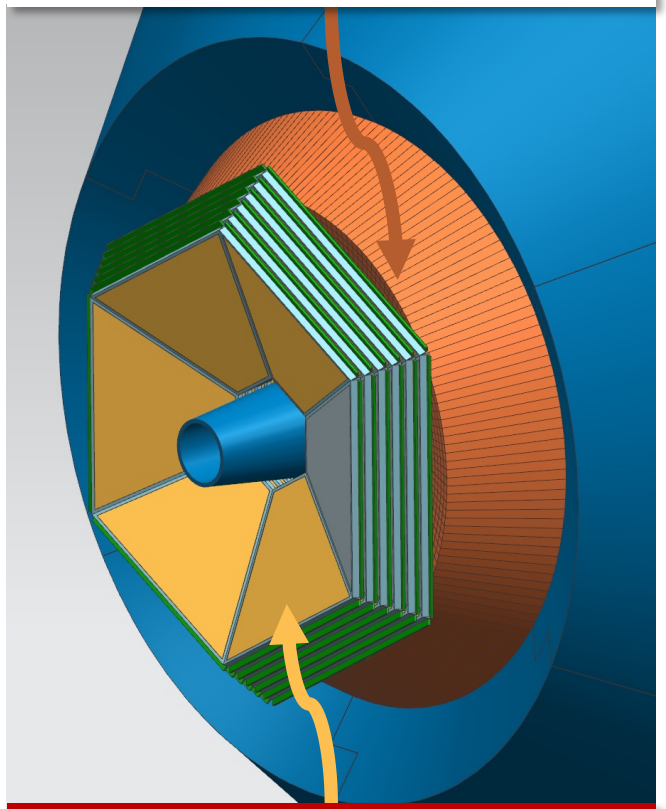


CLAS12 forward tagger calorimeter



wECAL calorimeter

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

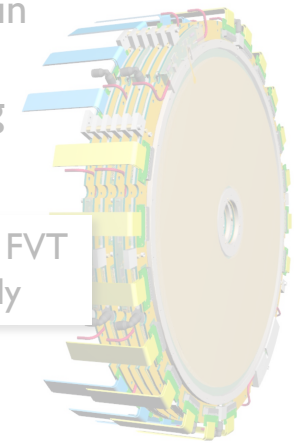


Forward Vertex Tracking

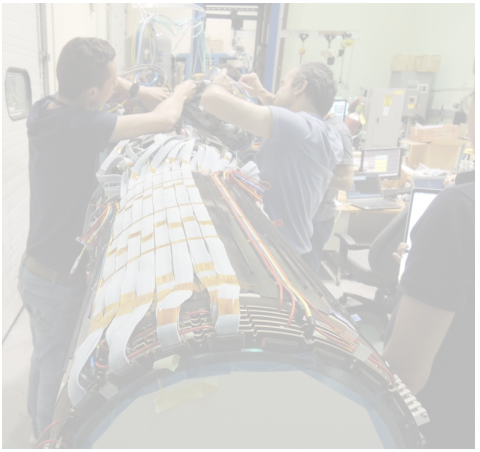
- 6-layer assembly GEM detectors.
- VMM3 readout.
- Expected rates: 500 kHz/cm^2

Forward tracking in Hall B

- FVT is used for **vertexing only.**
- 4 out of 6 layers for track matching.
- Forward tracks reconstructed in the CLAS12 FD DC.
- **No changes to the tracking from CLAS12.**



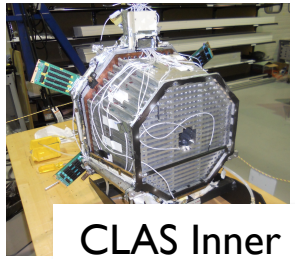
CLAS12 MicroMegas FVT
→ 6-layer assembly



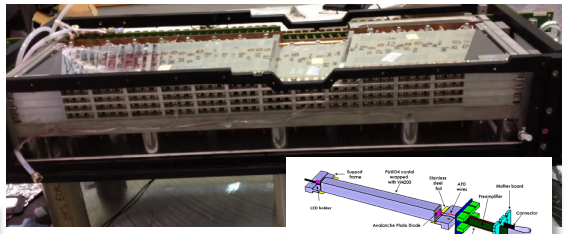
3-layer assembly used in many CLAS12 experiments (eg. Barrel Micromegas)

The wECAL calorimeter & forward vertex tracker systems

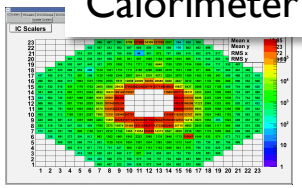
PbWO4 Calorimeters in Hall B

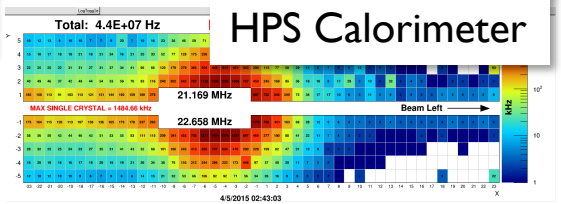


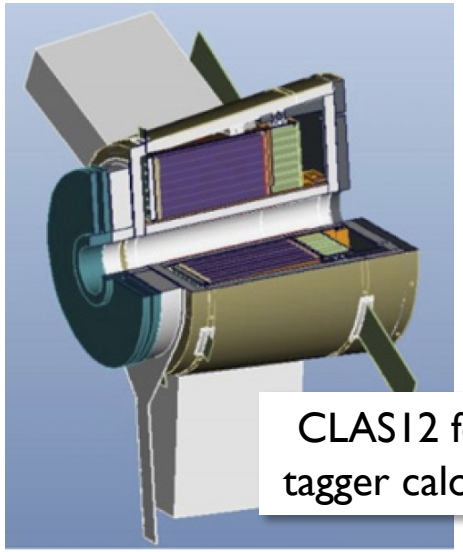
CLAS Inner Calorimeter



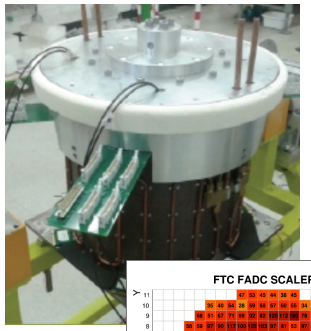
HPS Calorimeter

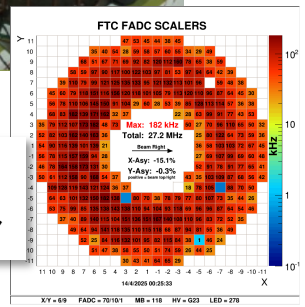






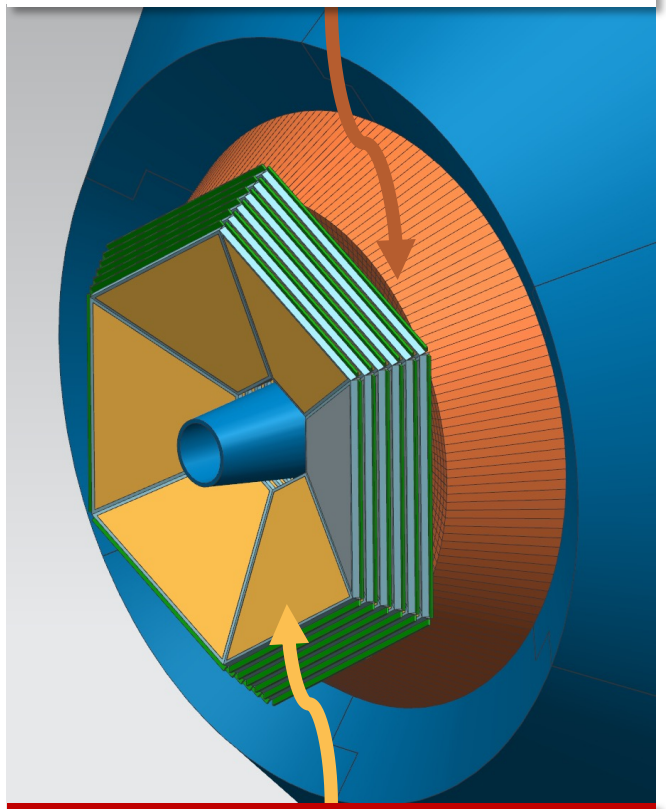
CLAS12 forward tagger calorimeter





wECAL calorimeter

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

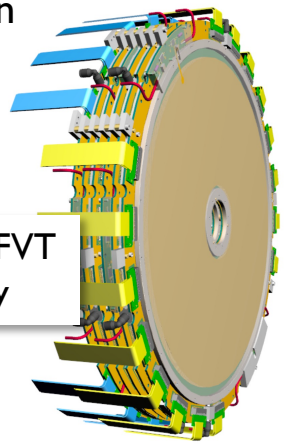


Forward Vertex Tracking

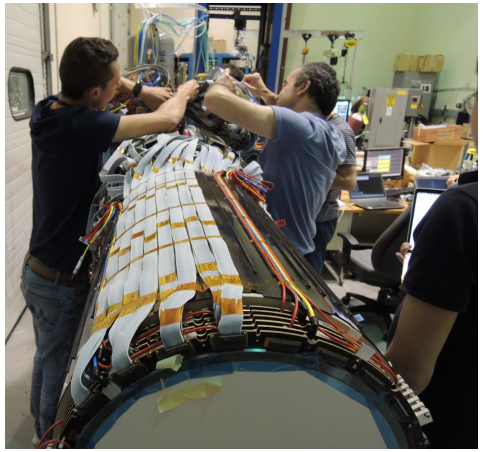
- 6-layer assembly GEM detectors.
- VMM3 readout.
- Expected rates: 500 kHz/cm^2

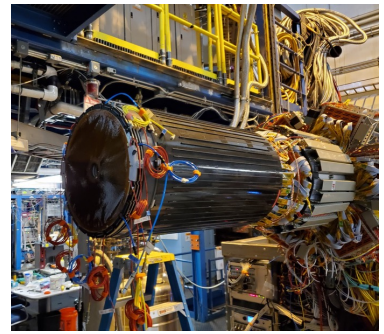
Forward tracking in Hall B

- FVT is used for **vertexing only.**
- 4 out of 6 layers for track matching.
- Forward tracks reconstructed in the CLAS12 FD DC.
- **No changes to the tracking from CLAS12**.



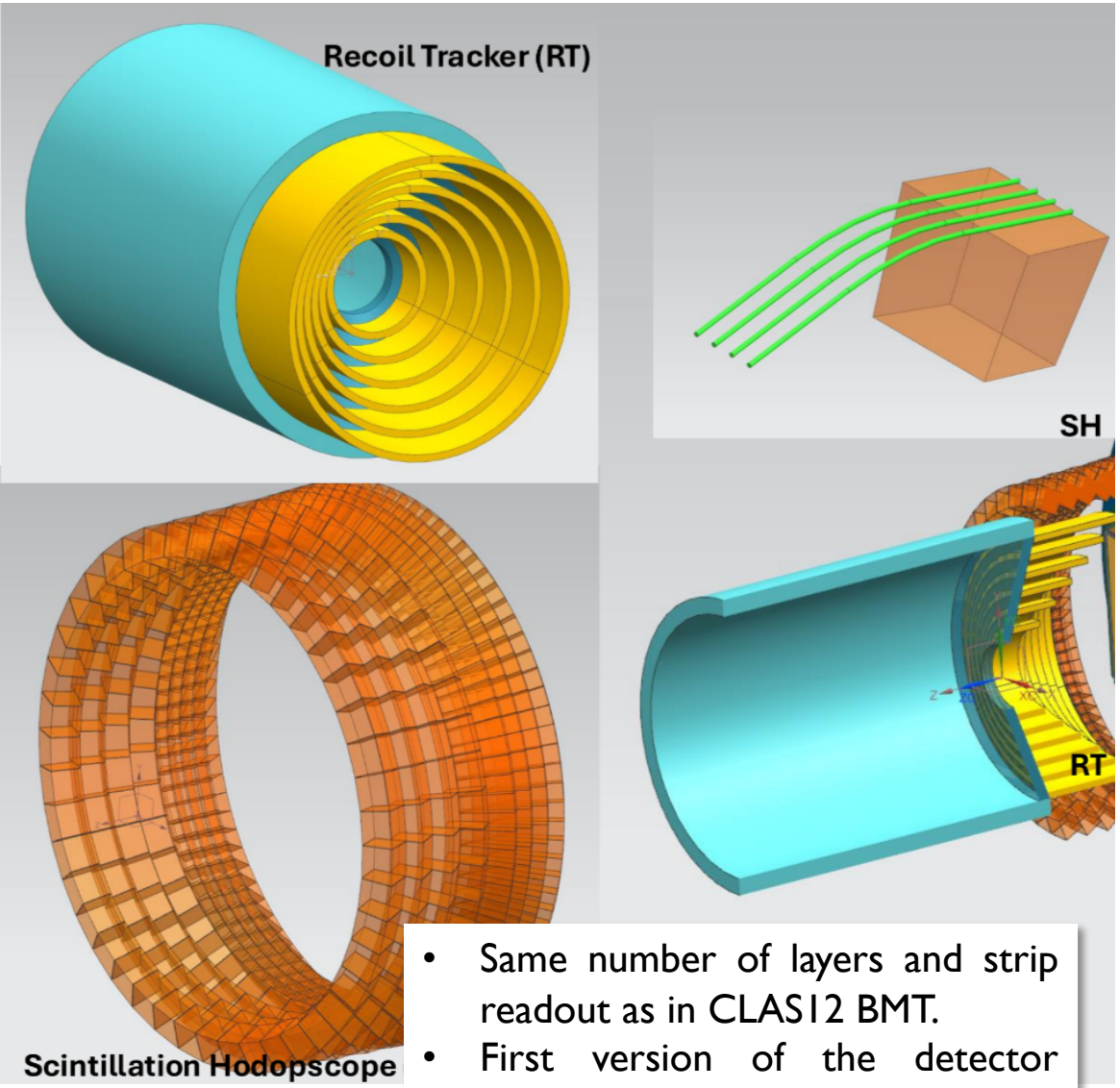
CLAS12 MicroMegas FVT → 6-layer assembly





3-layer assembly used in many CLAS12 experiments (eg. Barrel Micromegas)

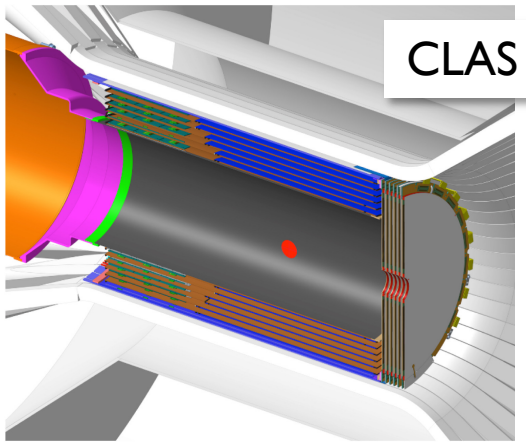
The μRWELL Recoil Tracker



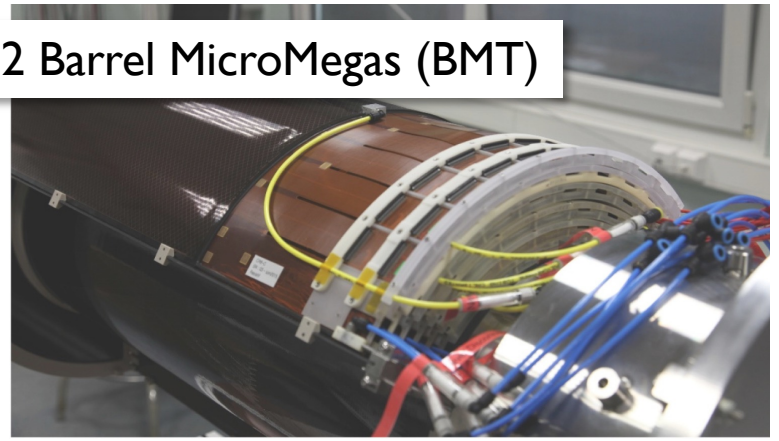
- Same number of layers and strip readout as in CLAS12 BMT.
- First version of the detector implemented in simulation.

Cylindrical MPGD in Hall B

Extensive experience in building and operating cylindrical MPGD detectors

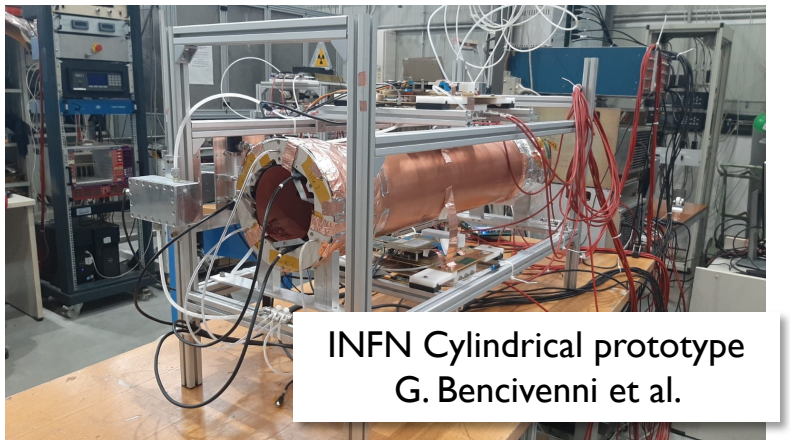


CLAS12 Barrel MicroMegas (BMT)



CLAS12/BoNuS GEM detector

Significant R&D efforts are underway in different labs & at JLAB for high-rate μRWELL detectors (EIC, SoLID, and Hall B LDRD-2507).

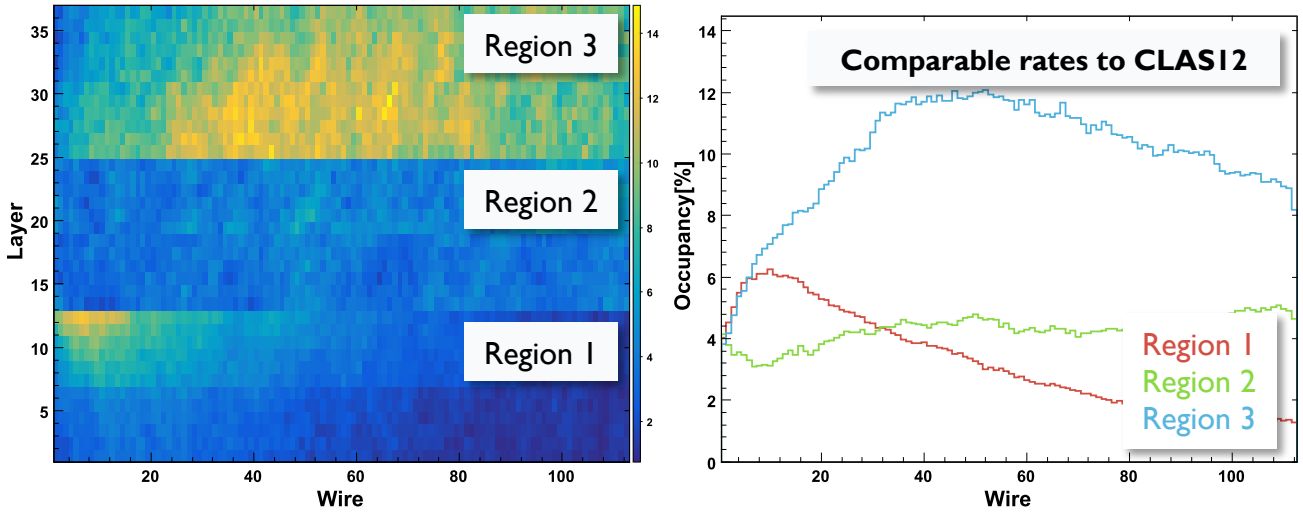


INFN Cylindrical prototype G. Bencivenni et al.

Rates, backgrounds and trigger

The μCLAS12 configuration is **fully implemented** in GEMC, the CLAS12 simulation package.

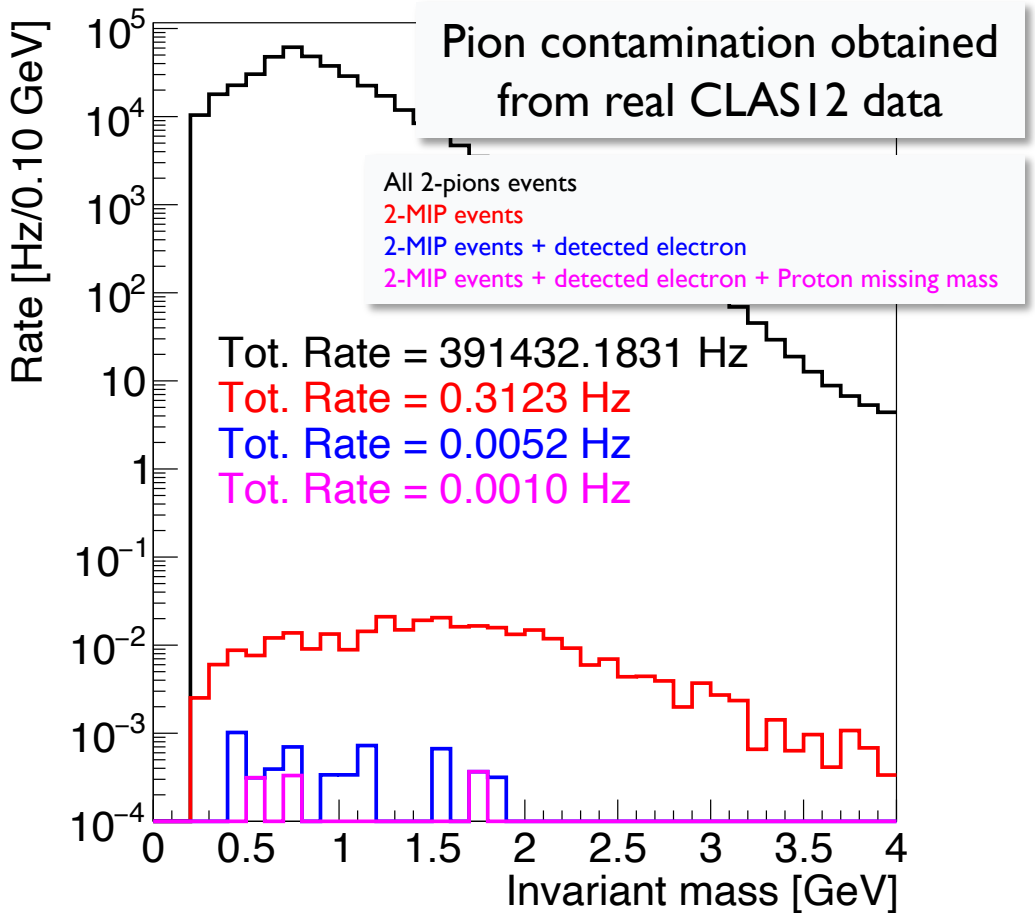
Drift Chambers occupancies



Trigger

- **Single MIP Trigger** rate: **21kHz**.
- Maximum CLAS12 DAQ rate: **30kHz** with >90% live time.
- All proposed physics channels included in the trigger and measured at the same time.

Backgrounds estimation



- Pion contamination: 7%
- Inclusive coincidence: 4%

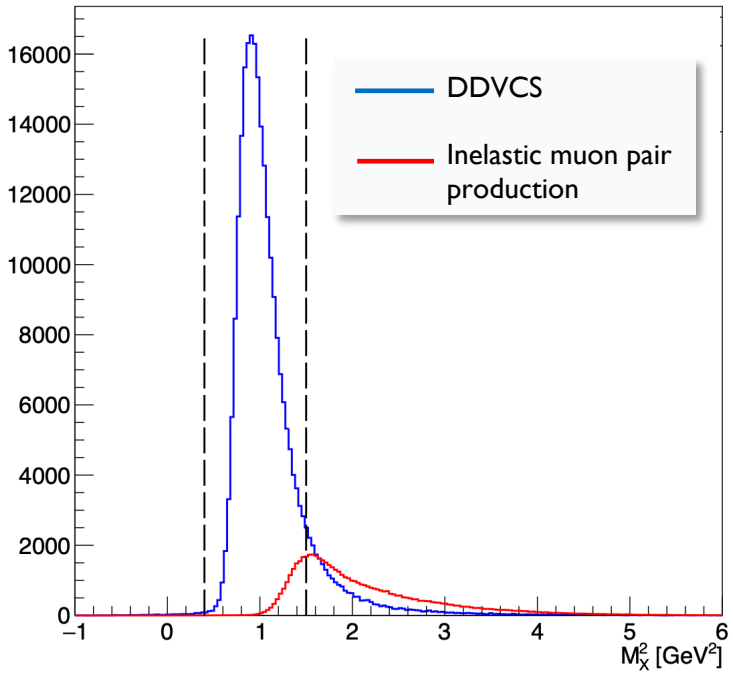
Expected results

Expected results on DDVCS

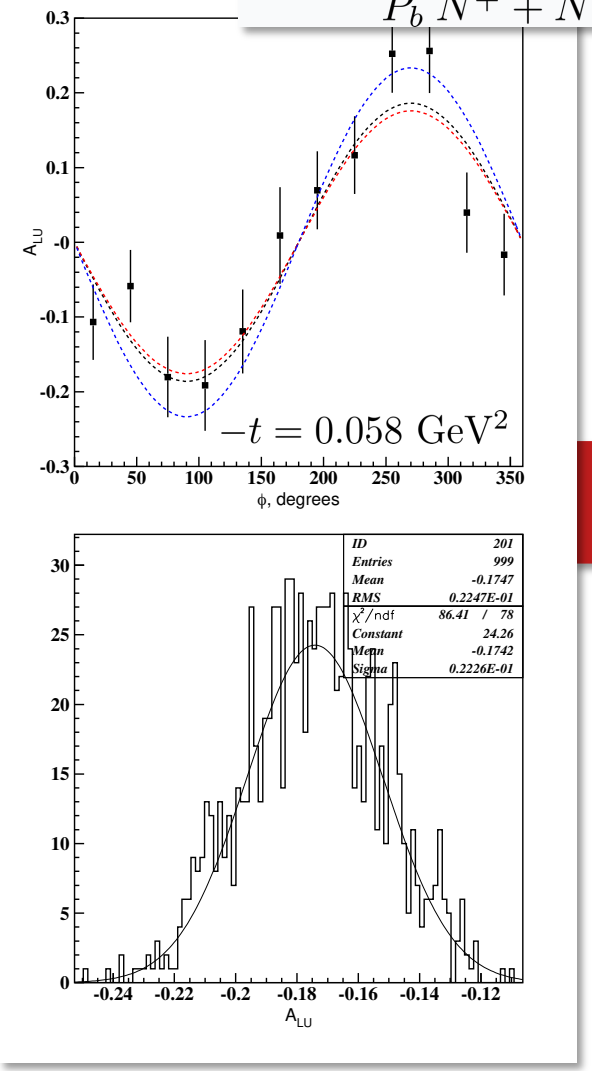
Analysis strategy

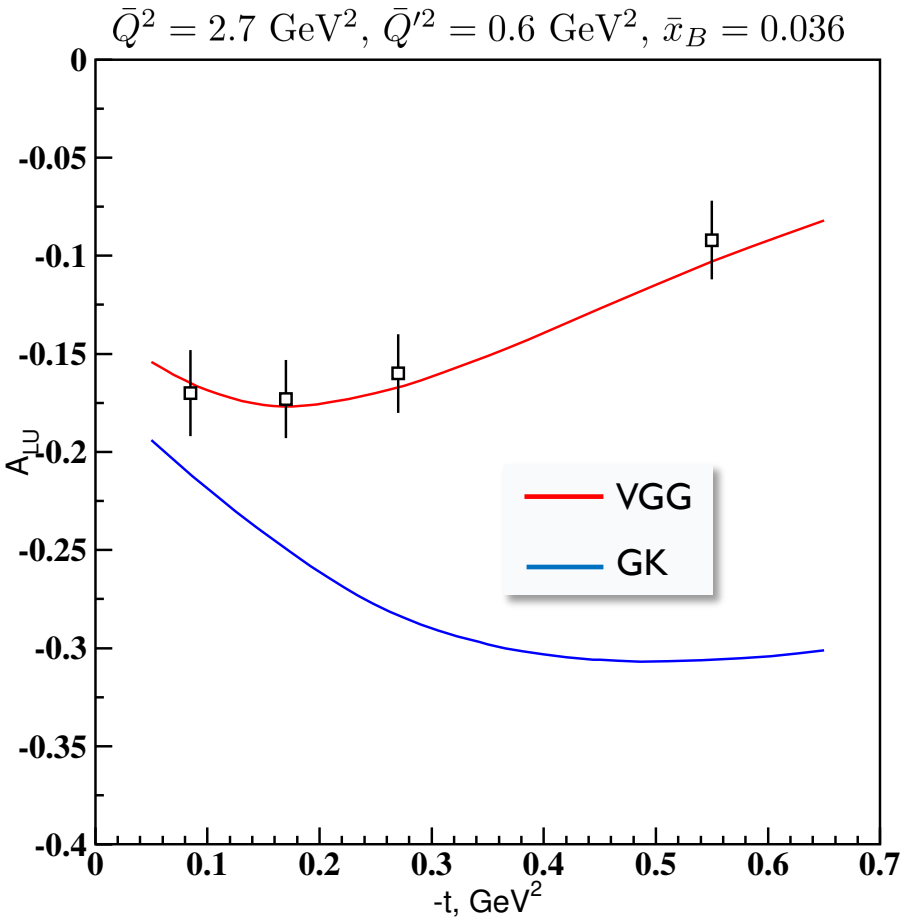
$$ep \to e'\gamma^* p \to e'p'\gamma^* \to e'\mu^+\mu^-(X)$$

- Electron detected in the new PbWO4 calorimeter.
- Muons in μCLAS12.
- Missing proton is reconstructed from energy-momentum conservation.



$$A_{LU} = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$

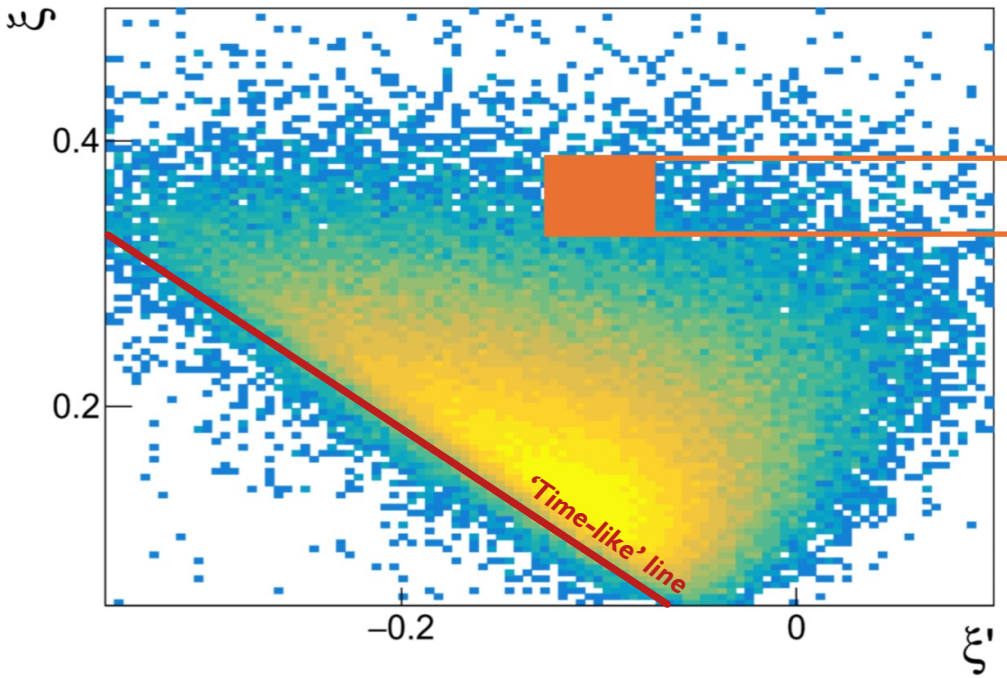




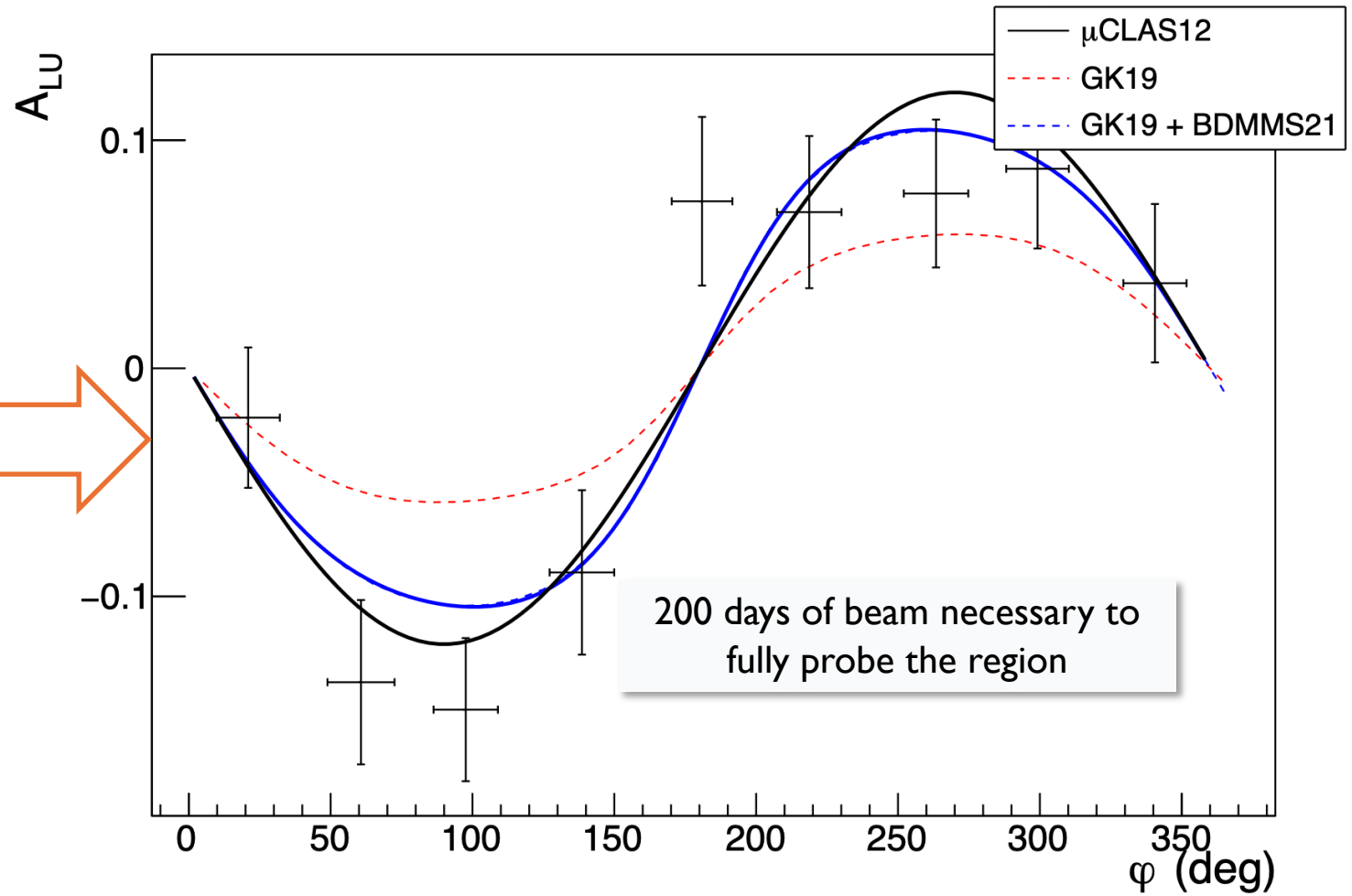
200 days of beam will allow to distinguish model down to the small-t region

Impact on Shadow GPDs

- Shadow GPDs manifest in the DVCS/TCS CFFs inverse problem.
- Because DDVCS allows to **access the ξ≠ξ' region**, this measurement will greatly **reduce model uncertainty** arising from these shadow GPDs.



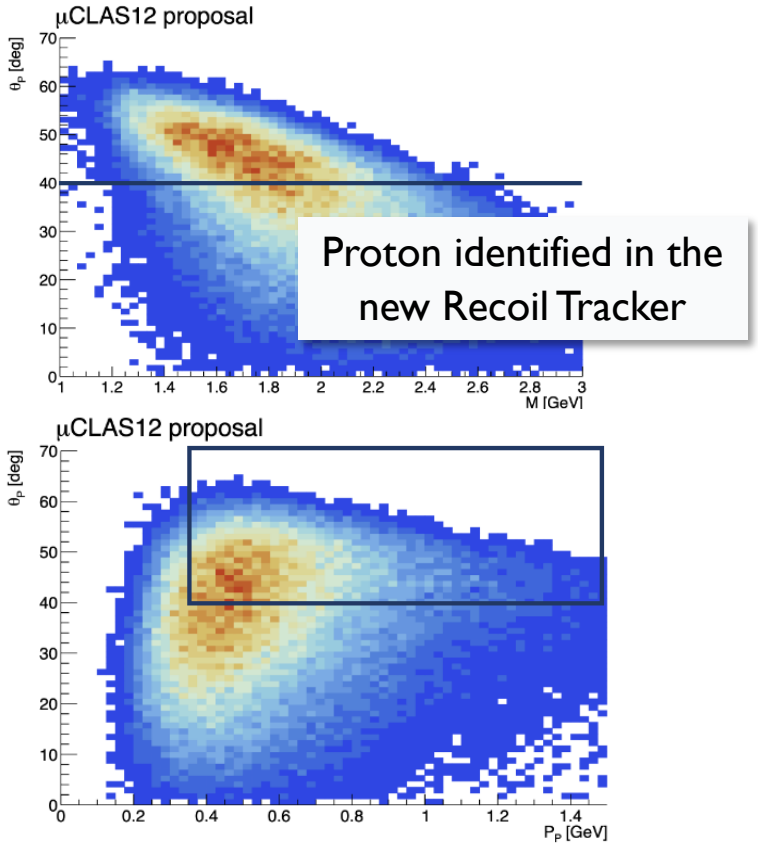
$$\bar{\xi} = 0.36,\ \bar{\xi}' = -0.0821,\ -\bar{t} = 0.82\ \mathrm{GeV}^2$$



Expected results for TCS

Analysis strategy

$$ep \to (e')\gamma p \to (e')p'\gamma^* \to (X)\boldsymbol{p'\mu^+\mu^-}$$

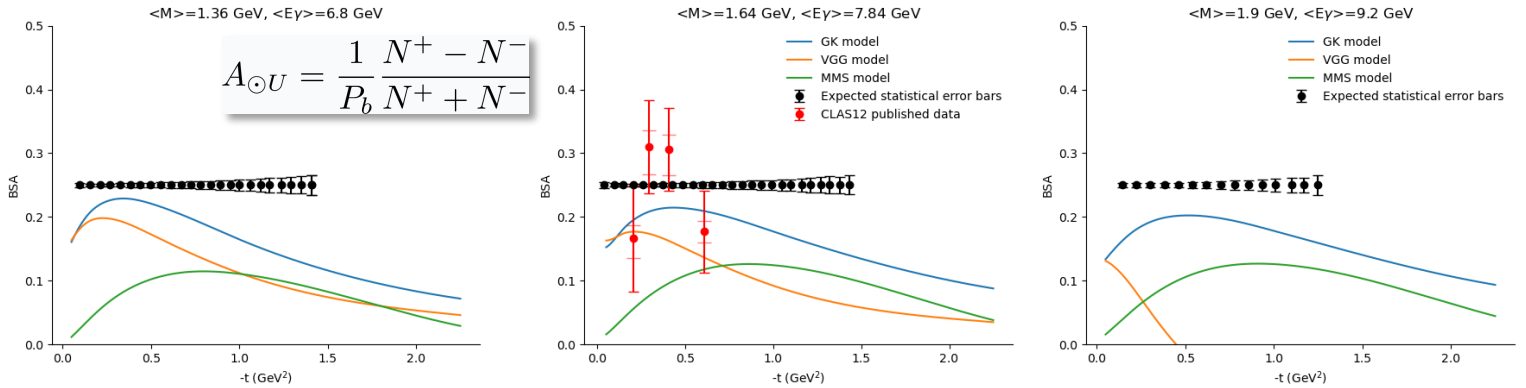


Proton identified in the new Recoil Tracker

Expected results with 7.7M expected events

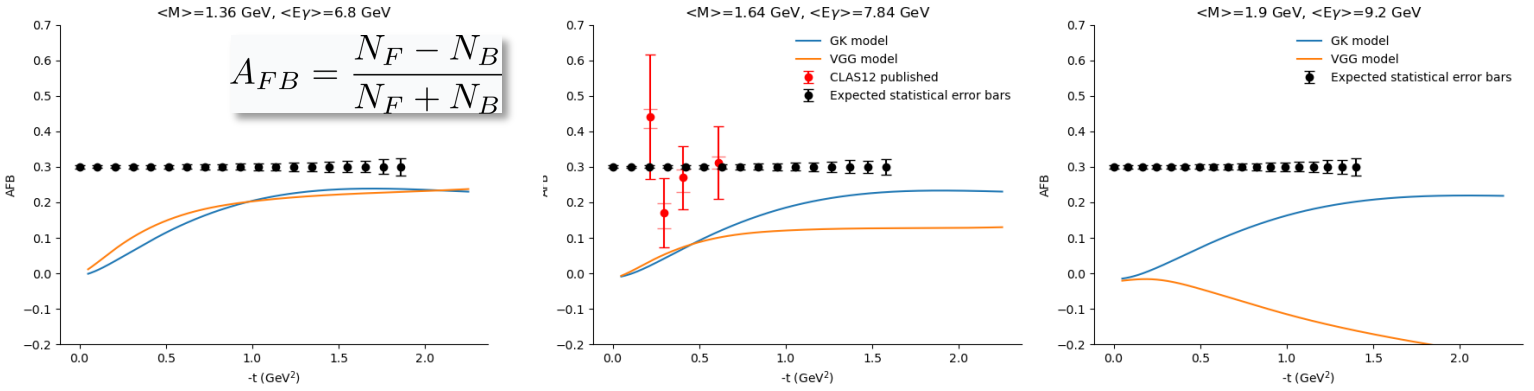
Photon polarization asymmetry

$$A_{\odot U} = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$



Forward-Backward asymmetry

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



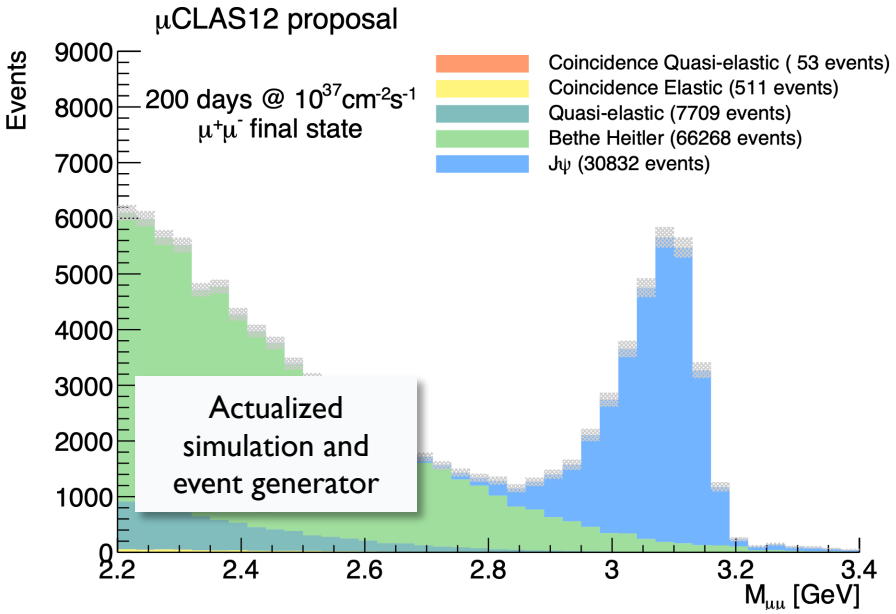
→ **First precision measurement of TCS**

Expected results for J/ψ electro-production

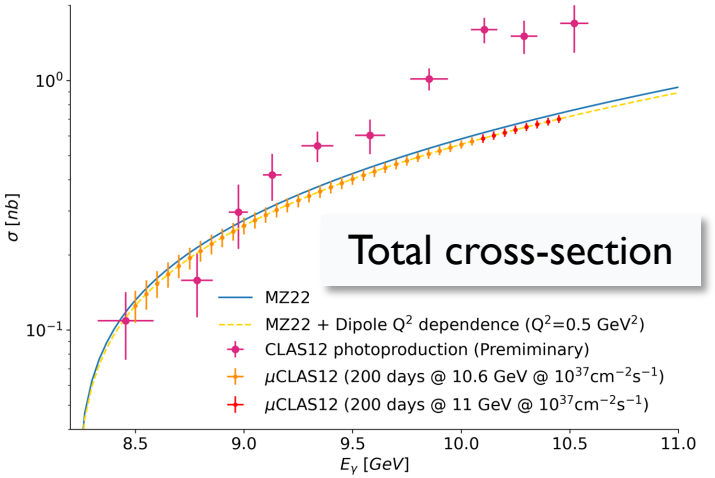
Analysis strategy

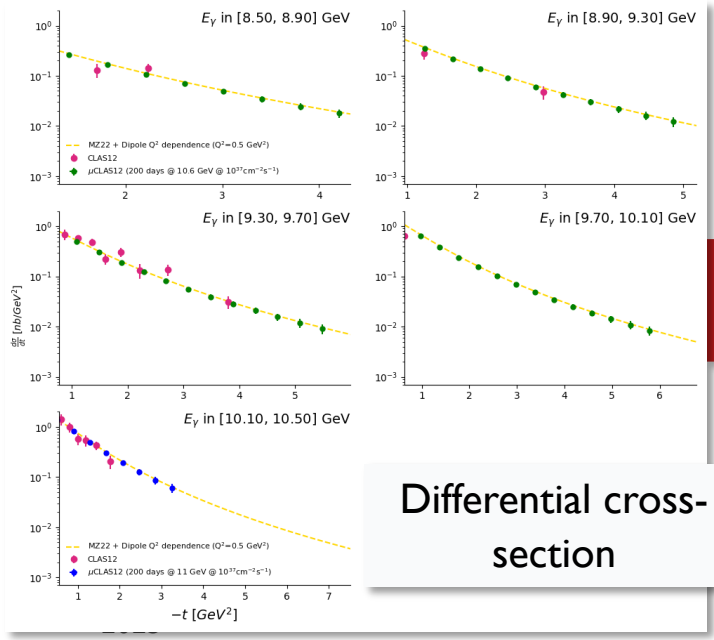
$$ep \rightarrow e'\gamma^* p \rightarrow e'p'J/\psi$$
$$\rightarrow \boldsymbol{e'\mu^+\mu^-}(X)$$

- Electron detected in the wECAL.
- Muons in μCLAS12.
- Peak in the invariant mass of the muon pair.



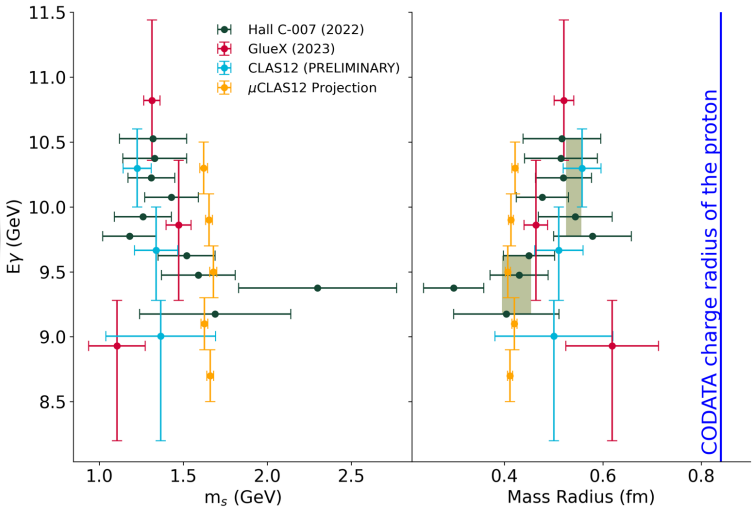
Projected results with 30k expected events





- 10 times more events than the current largest J/ψ sample at JLab.
- ¾ of the expected SoLID J/ψ rate.
- Energy reach limited by the wECAL threshold.

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}|_0 \cdot \frac{1}{(1-t/m_S^2)^4} \qquad \sqrt{\langle r_m^2 \rangle} = \frac{\sqrt{12}}{ms}$$



D. E. Kharzeev, "Mass radius of the proton", PRD (2021)

Key takeaways

- The μCLAS12 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 μCLAS12 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 technologies have already been demonstrated in Hall B or at JLab.

- μCLAS12 has been **fully implemented in CLAS12 simulation** framework.
- Rates, trigger rates, pion background rates and expected number of events are based on realistic simulation and existing CLAS12 data.

Beam Energy (GeV)	Beam Current (μA)	Beam Requirements	Target Material	Target Length (cm)	Beam time (days)
Production					
11	**7.5**	**$>85\%$ longitudinal polarization**	**LH2**	**5**	**200**
Total time					245

Back-up

Addressing the increased beam current in Hall B

Environmental assessment

- The current EA-1534 has a **total operating limit of 2 MW** for CEBAF operations.
- Both Hall A and C have a respective1MW limit.
- The proposed experiment will Hall B power **from 27.5 kW to 82.5 kW**, with **no significantly effect on the total** limit.
- To date, four EA assessments have been conducted (1987, 1997, 2002, and 2007) to support the experimental program.
- It is expected that EA updates will be done in the future, for example, for positron running.

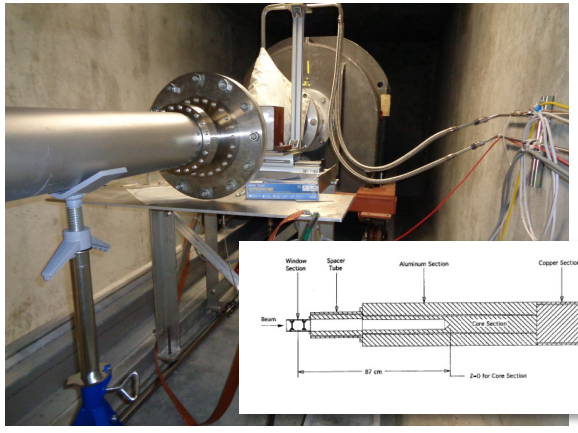
Beam dump upgrade

Phase-I upgrade: 5 kW to 10 kW – Completed

The Faraday cup and the retractable, water-cooled Copper dump are relocated to the end of the downstream tunnel.

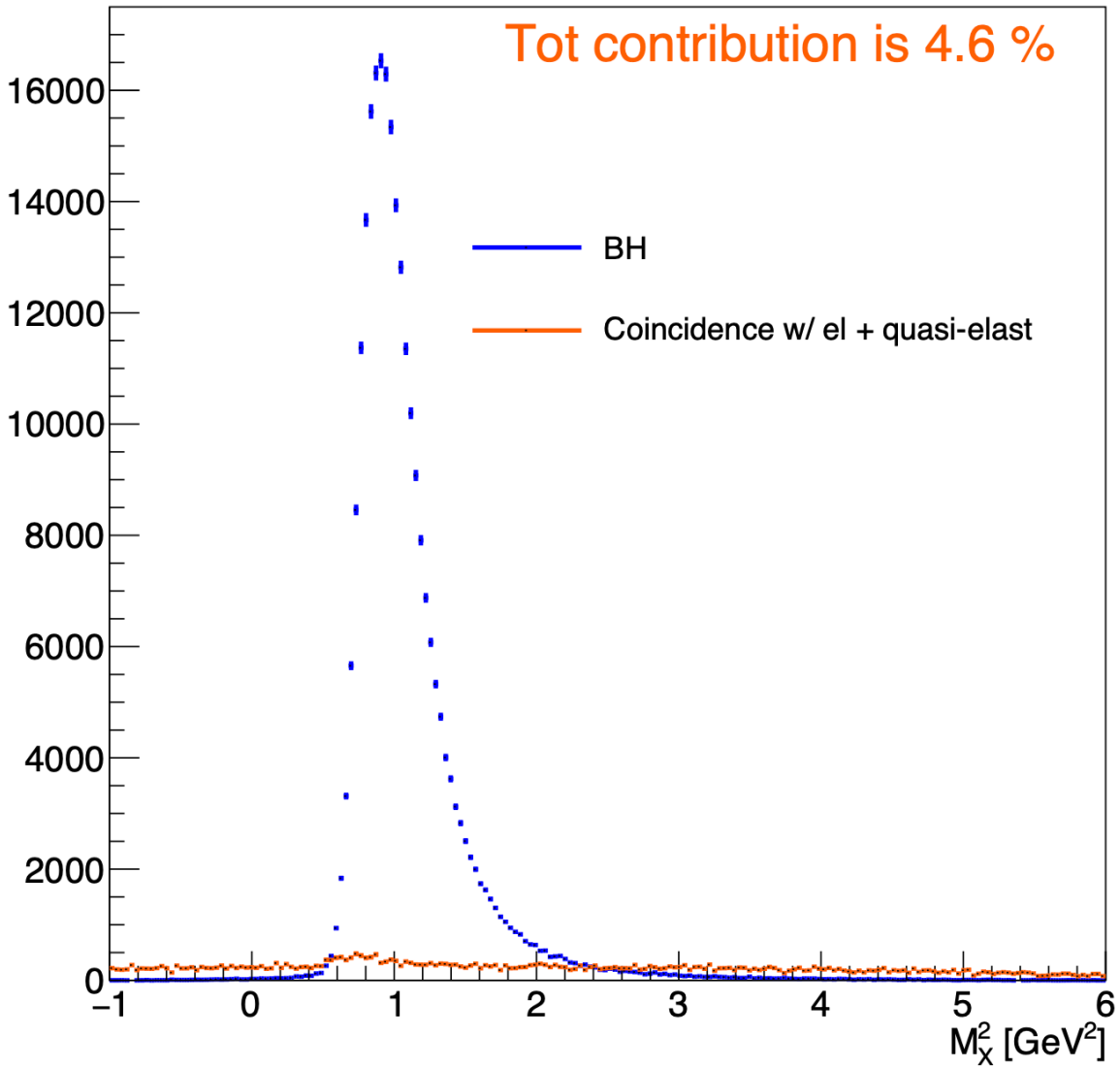
Phase II upgrade: 10 kW to 100 kW
(required for the approved experiment C12-20-002)

- Replace the existing water-cooled retractable Copper dump with a new, high-power dump with closed-loop cooling.
- Preliminary design, similar to the Hall D electron dump exists.



Back-up: backgrounds and rates

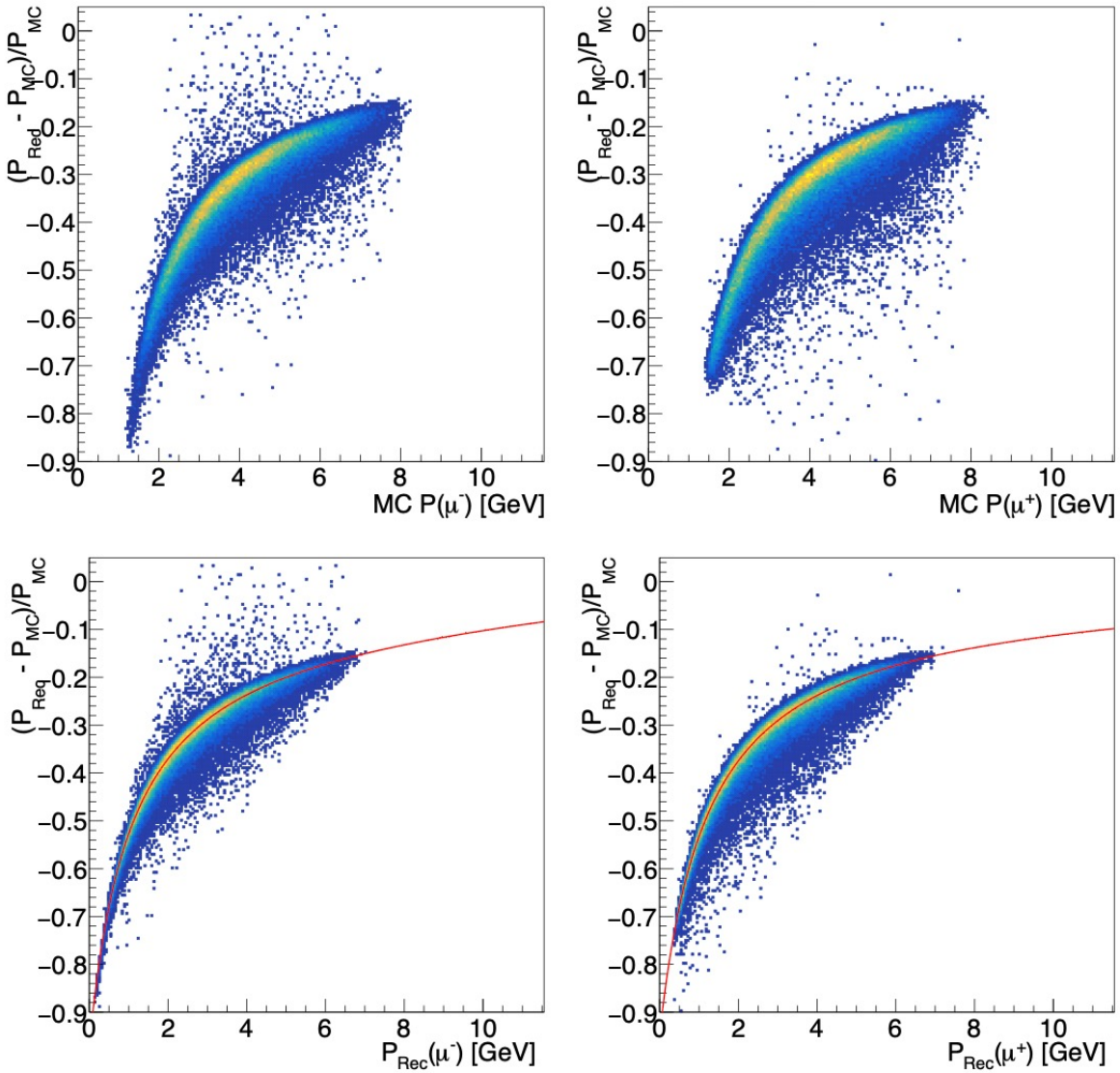
Coincidence rates

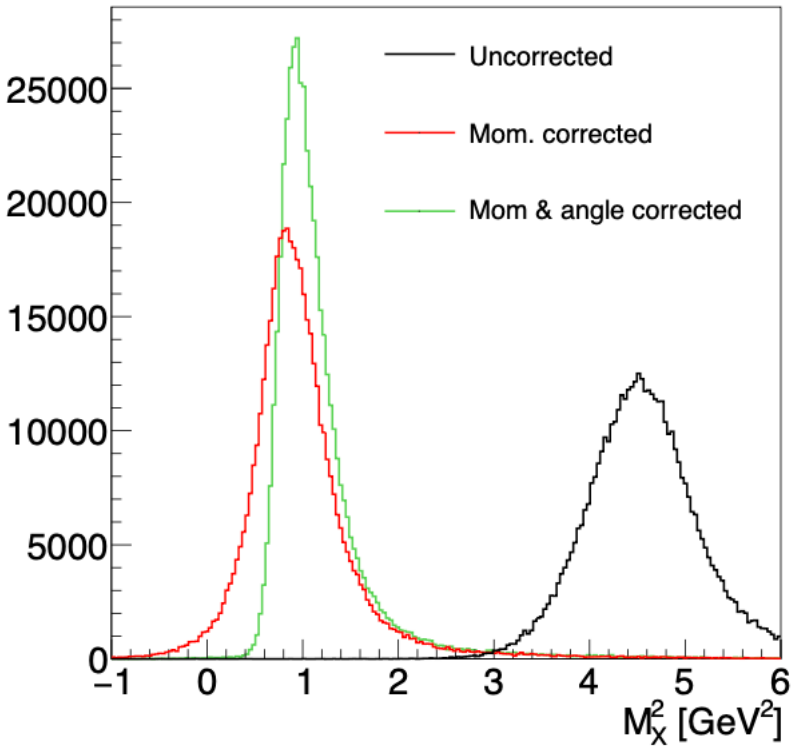


Rates

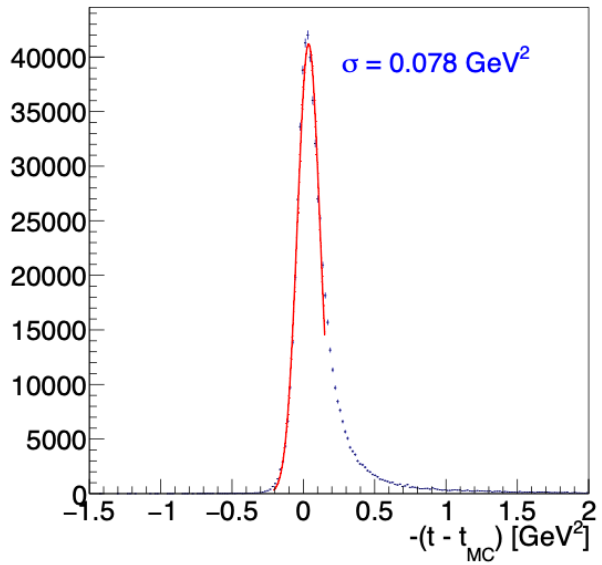
Back-up: simulations

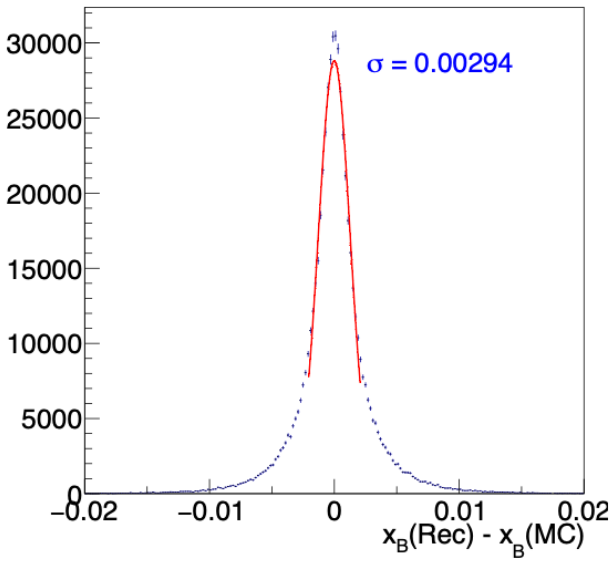
Muon momentum corrections

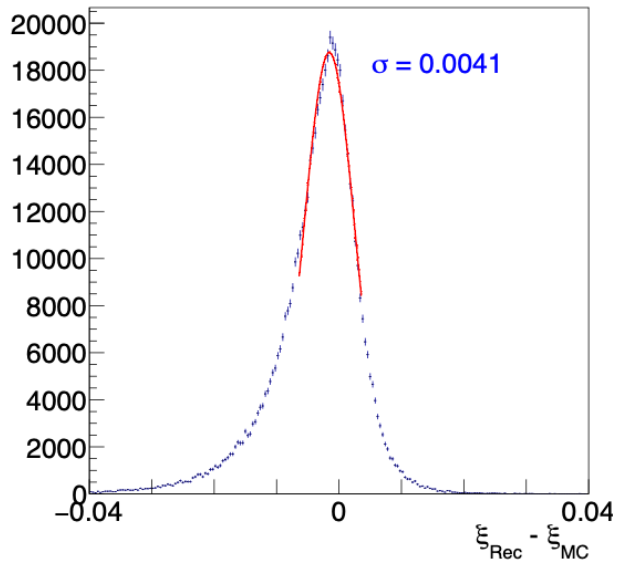


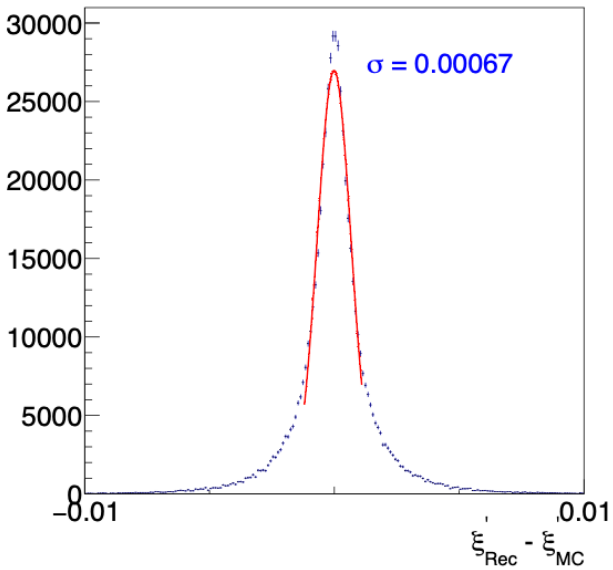


Resolutions: kinematic variables

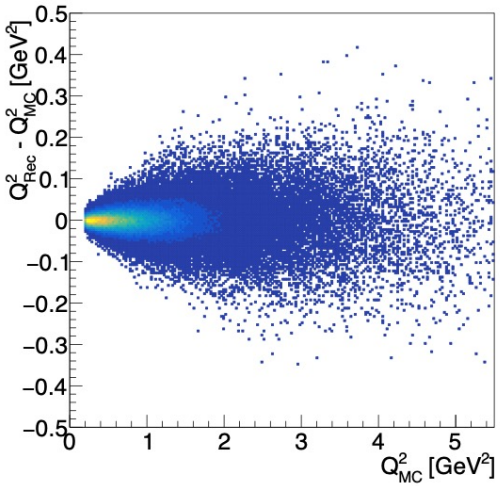


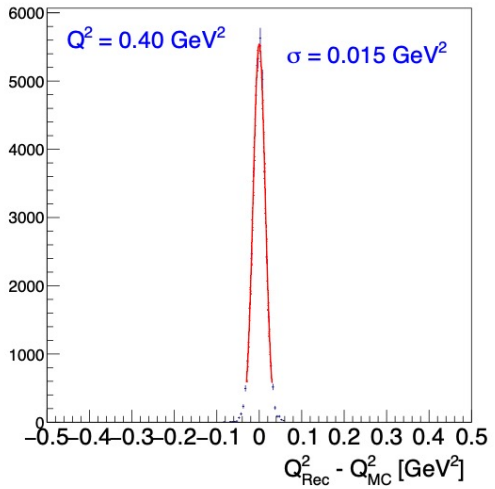


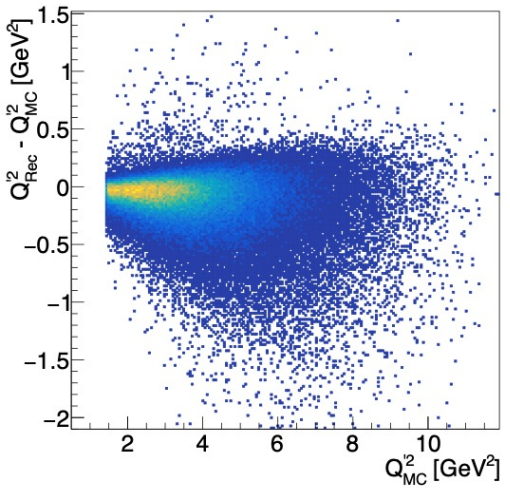


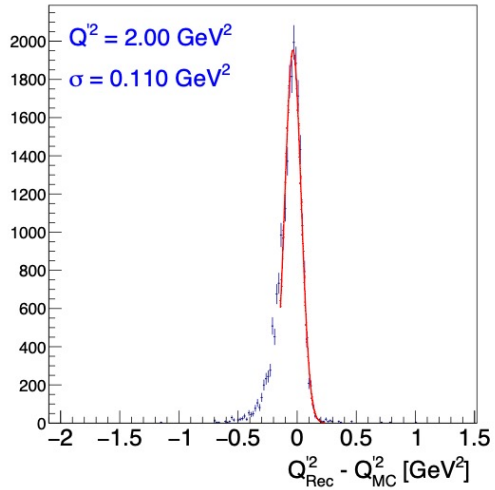


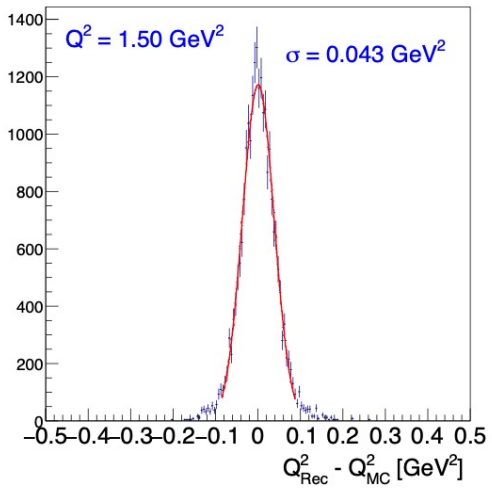
Resolutions: virtualities

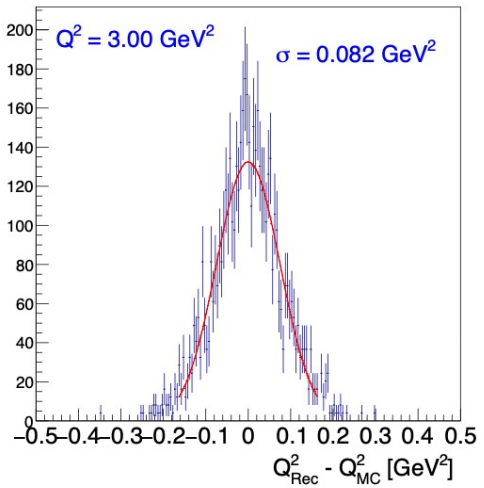


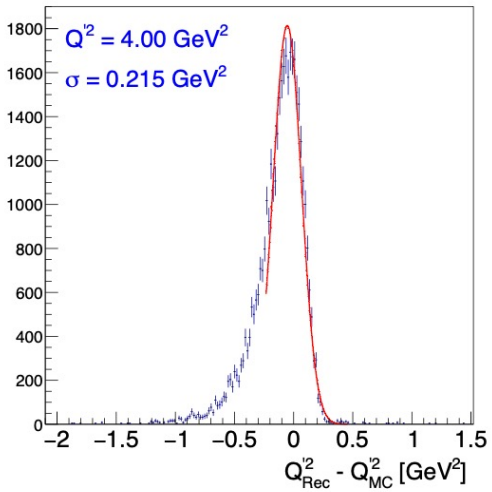


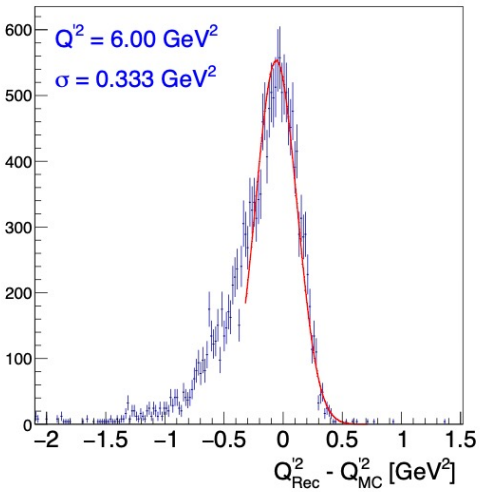








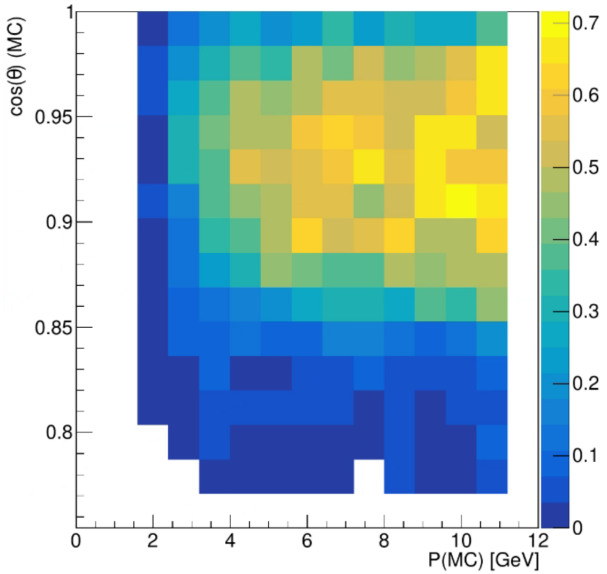




Pion survival rates

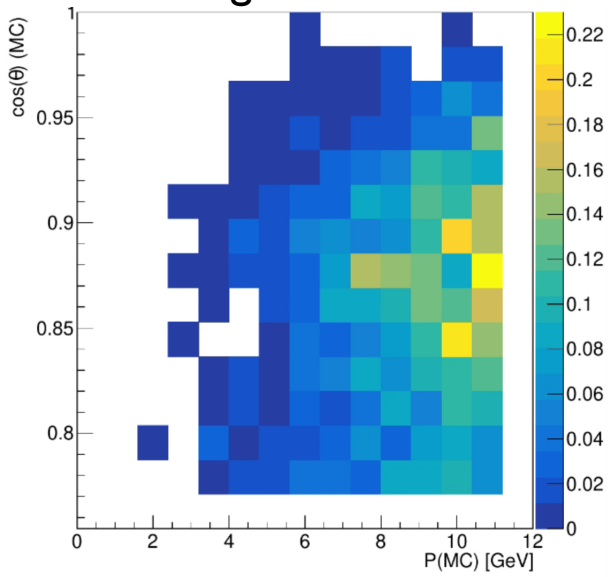
π^+ survival rates

Positive MIP



a)

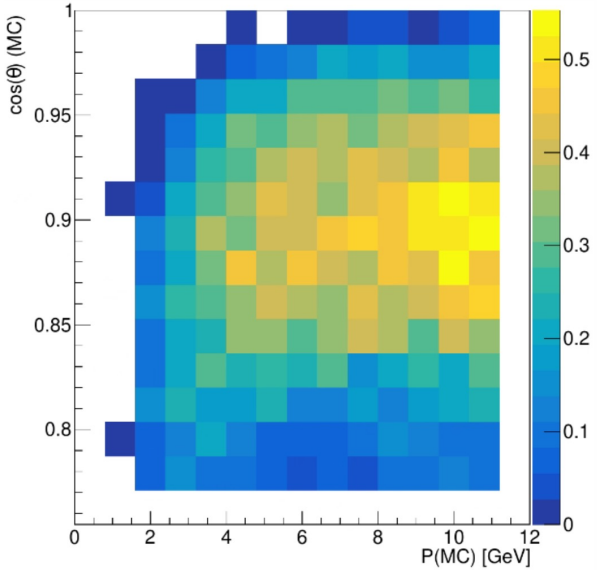
Negative MIP



b)

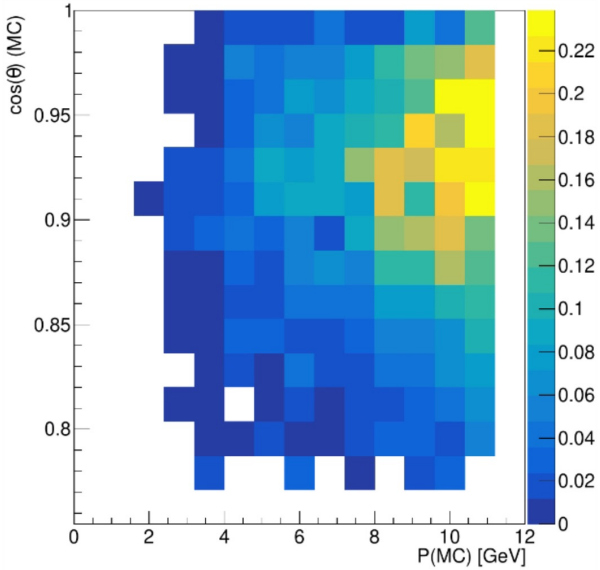
π^- survival rates

Positive MIP



a)

Negative MIP

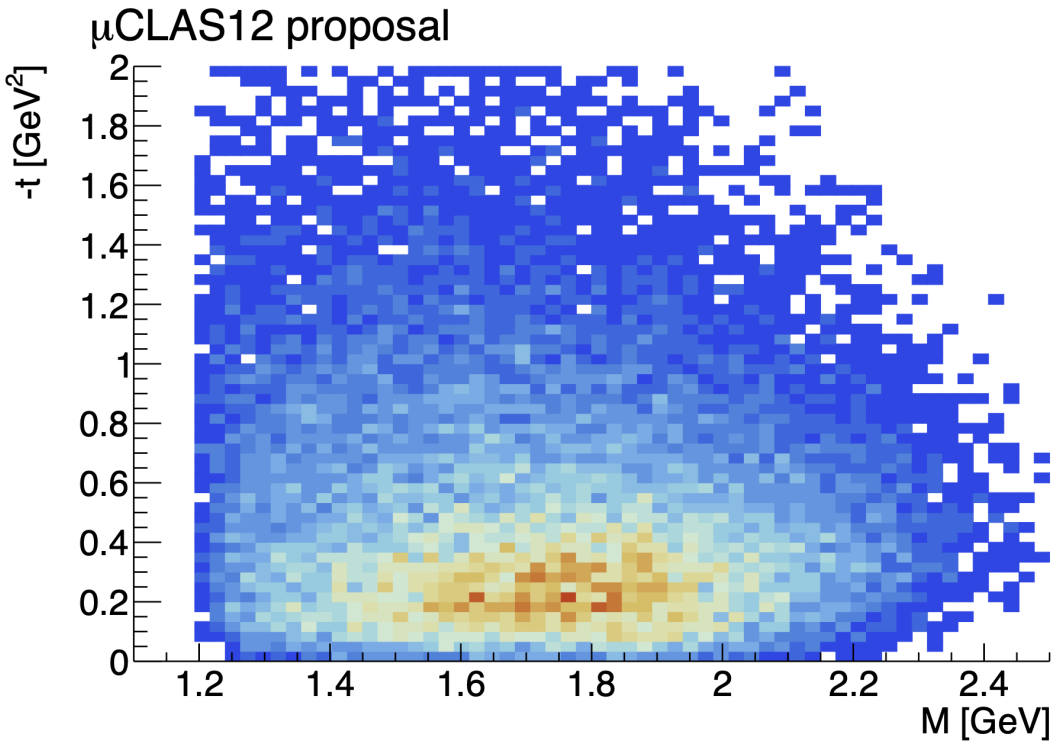


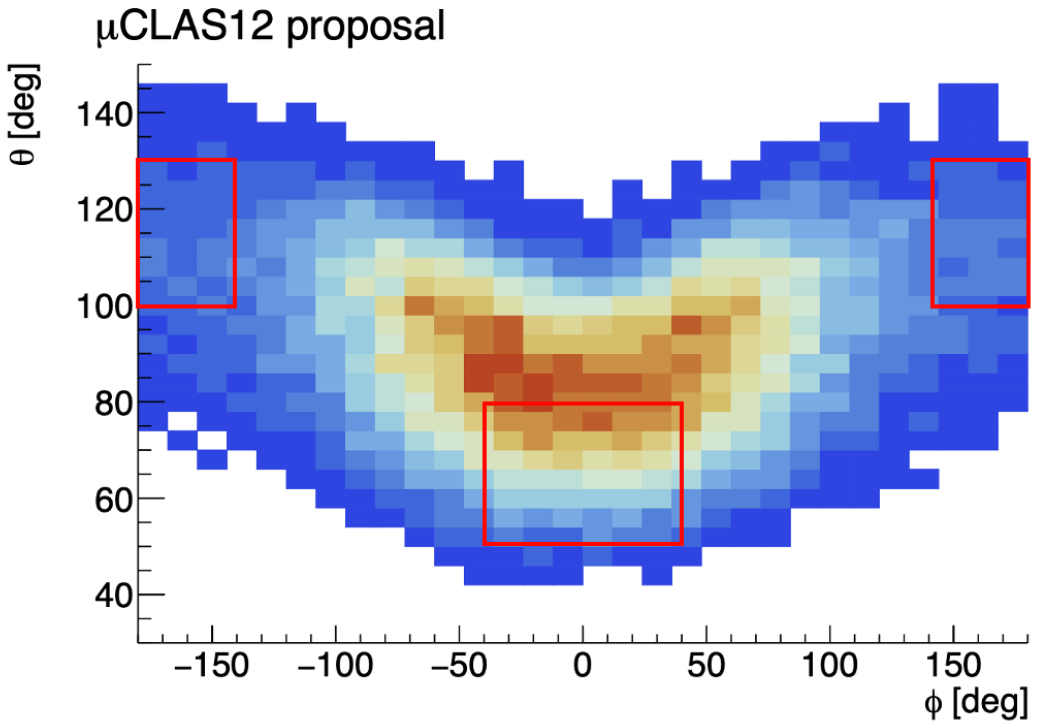
b)

Back-up: expected results

More on Timelike Compton Scattering: kinematic coverage

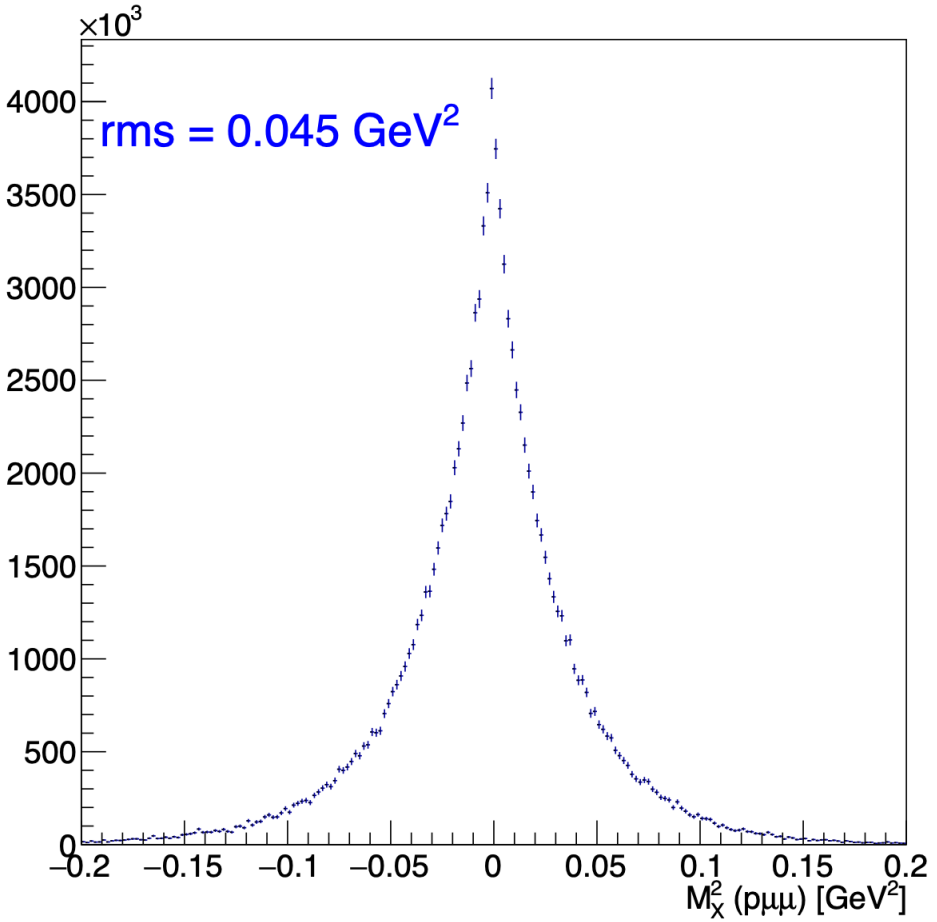
$$ep \to (e')p'\mu^+\mu^-$$



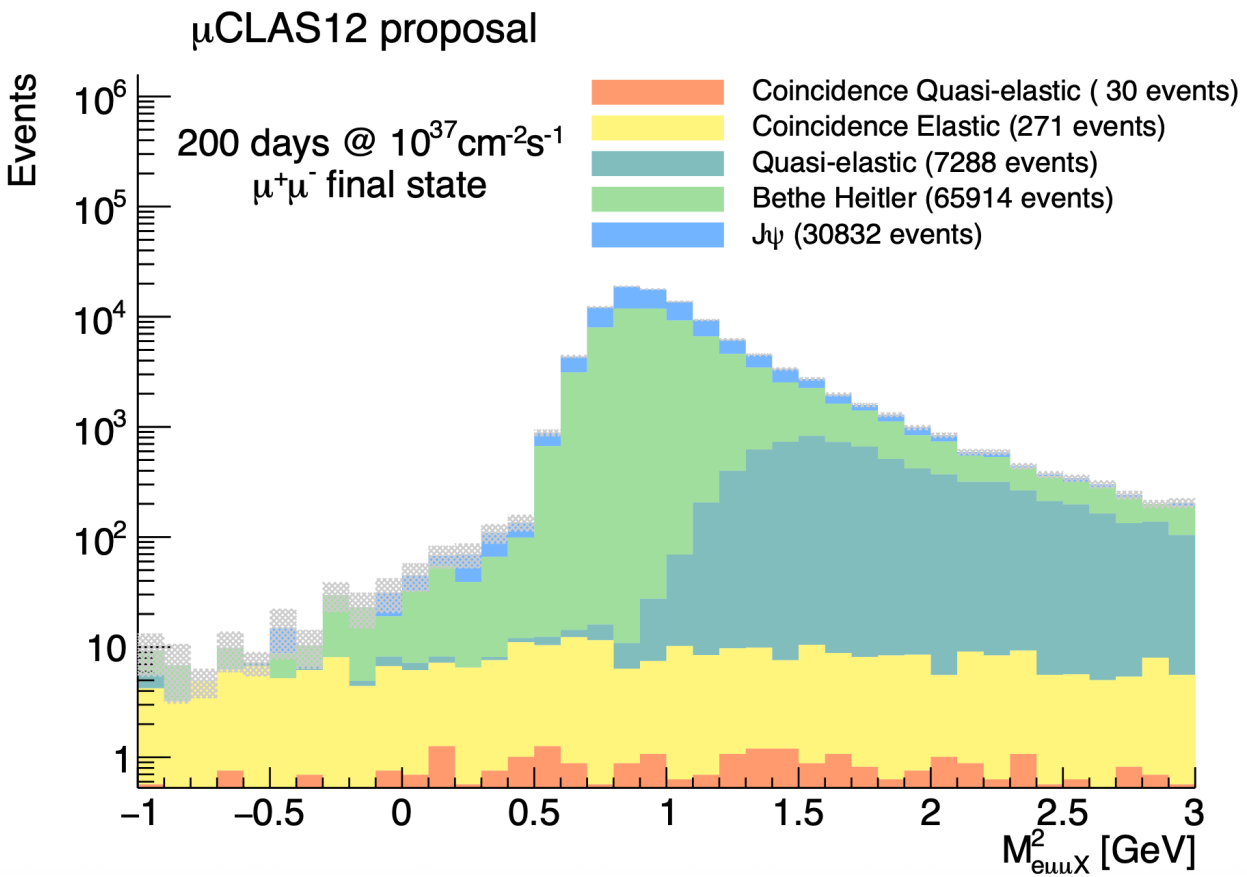


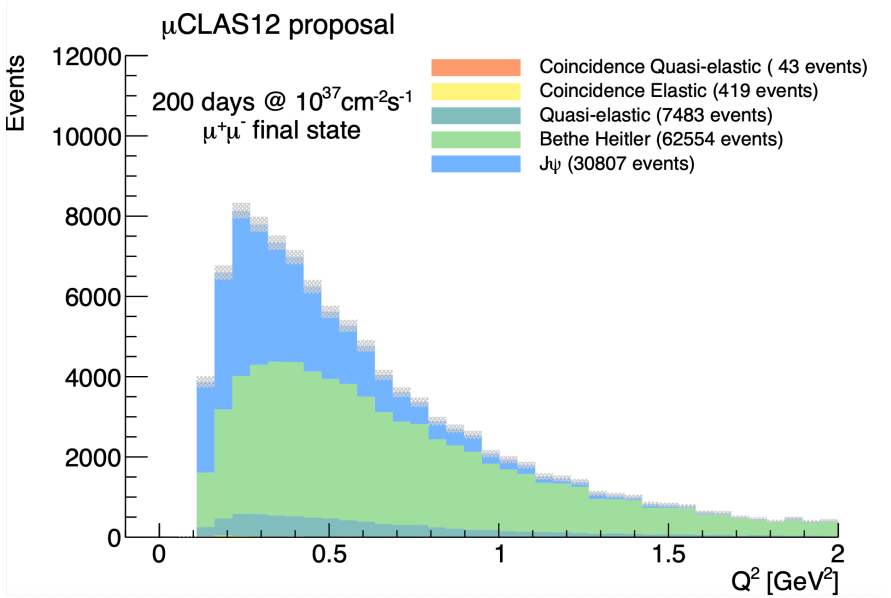
More on Timelike Compton Scattering: missing mass

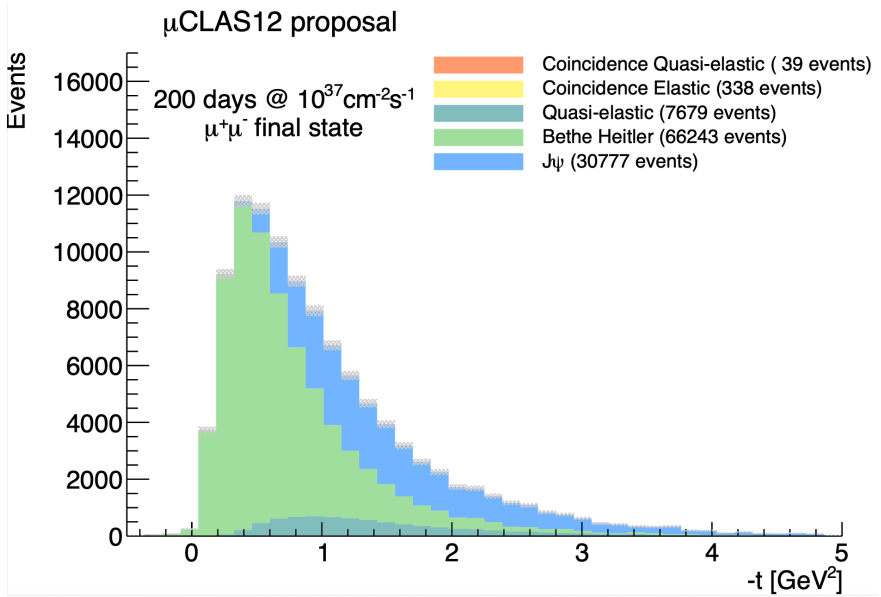
$$ep \to (e')p'\mu^+\mu^-$$



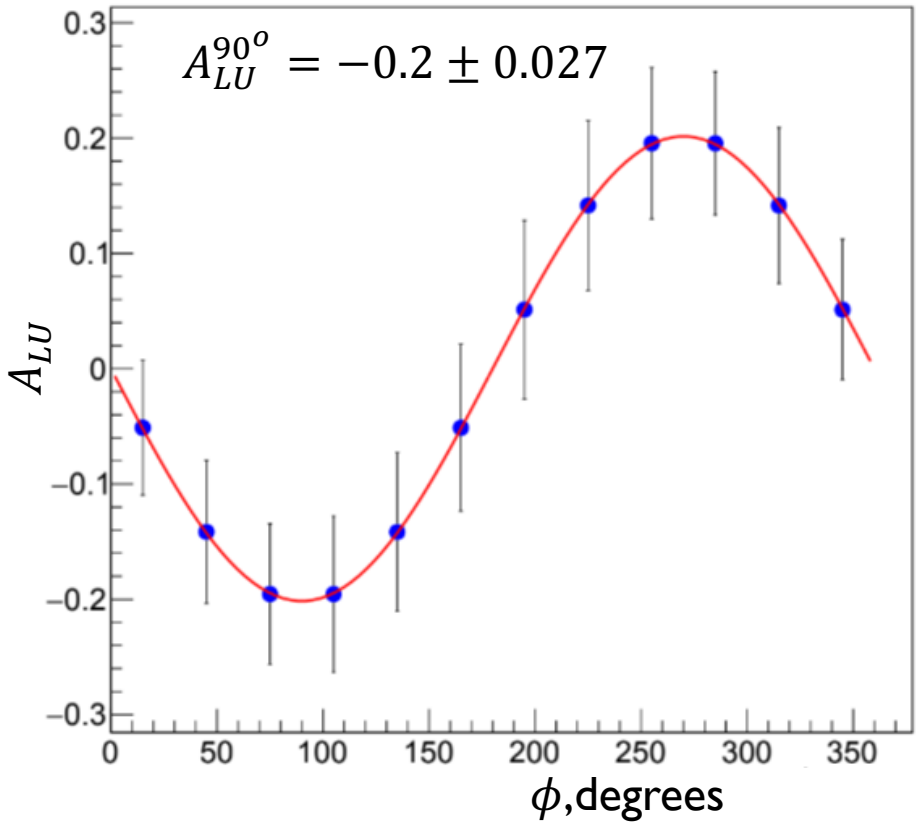
More on J/ψ electro-production: kinematic and missing mass

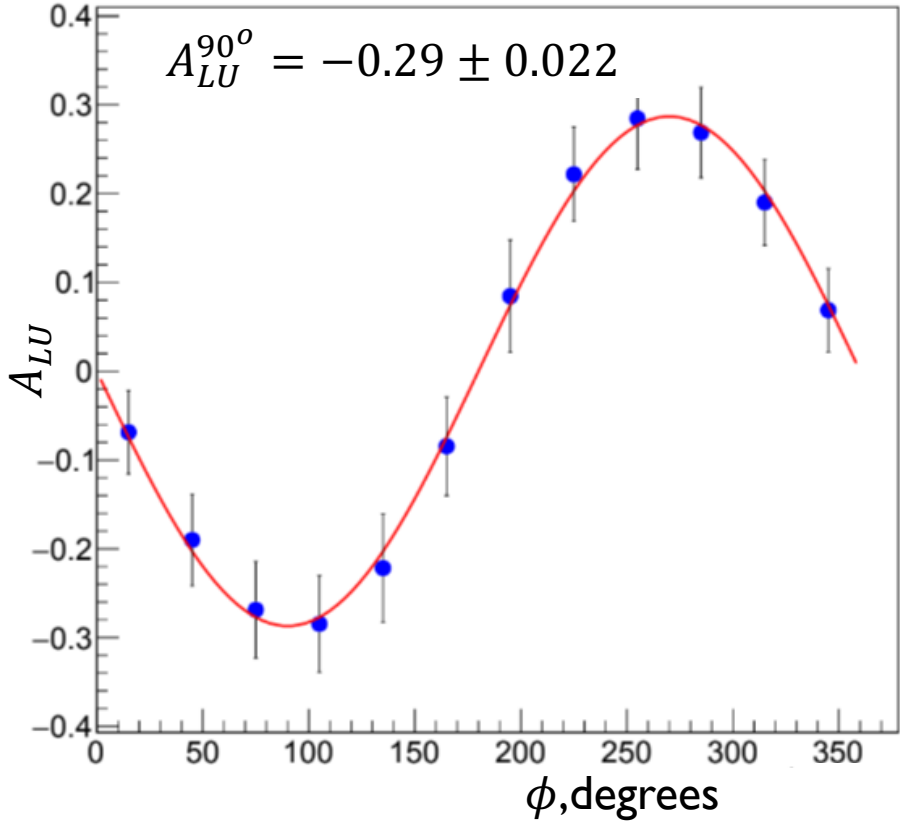




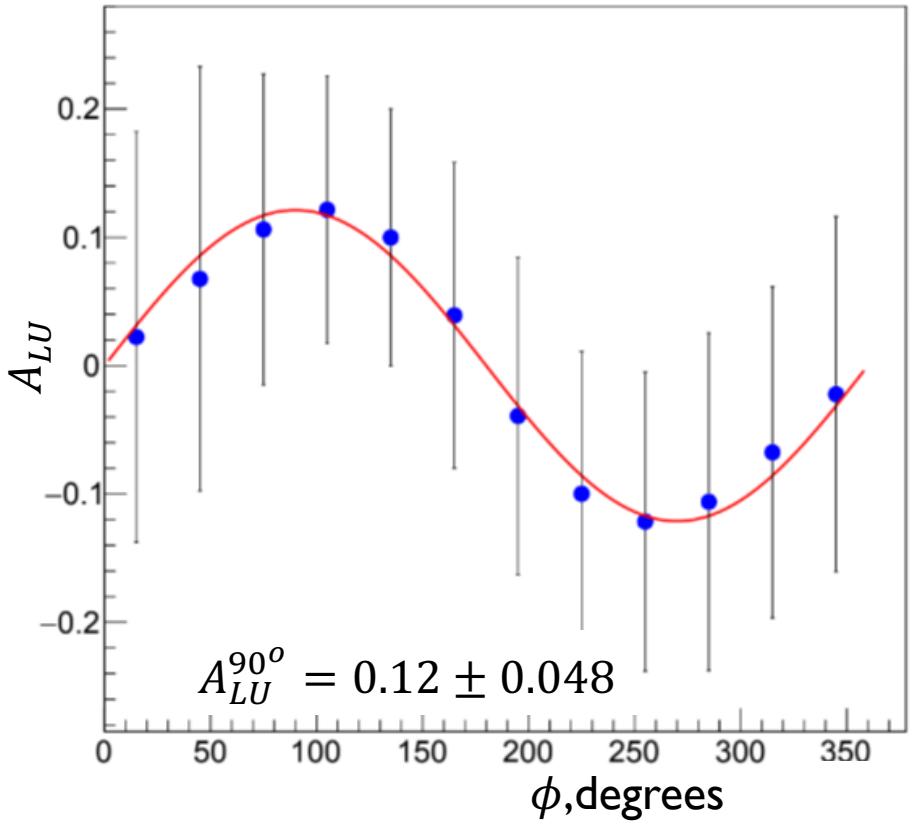


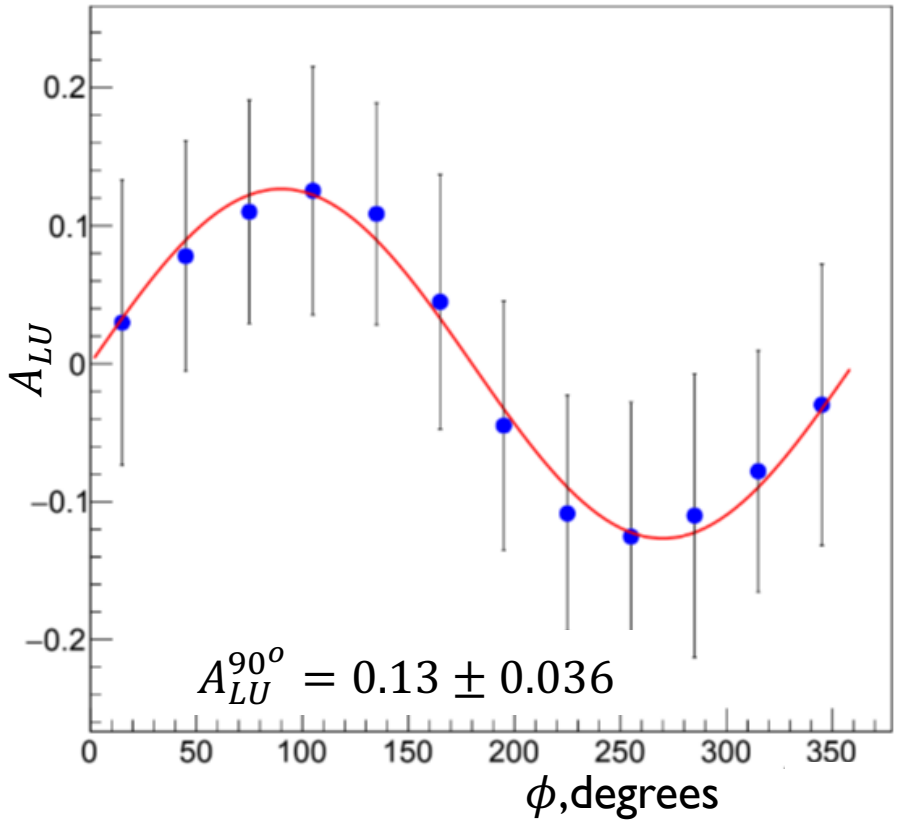
More on DDVCS: error bars on BSA I



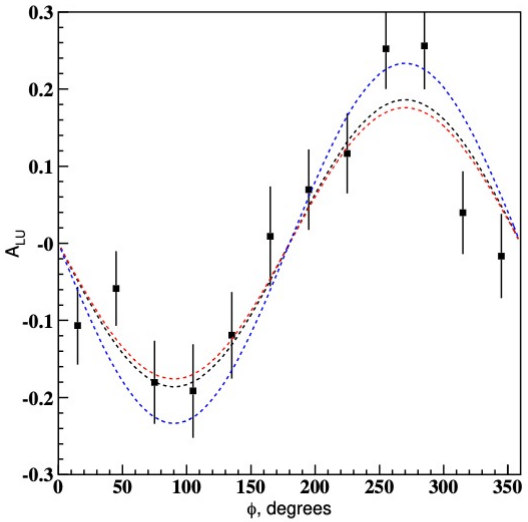


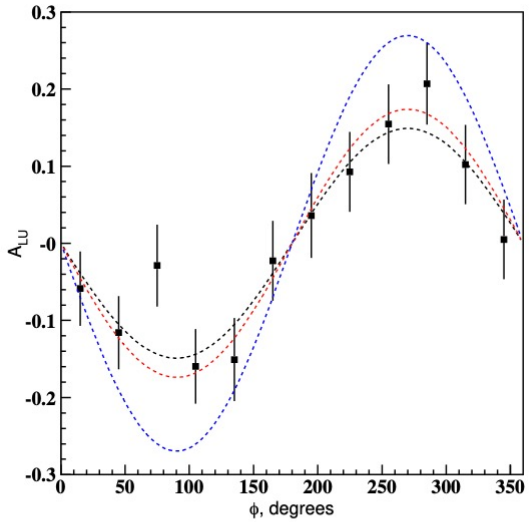
More on DDVCS: error bars on BSA 2

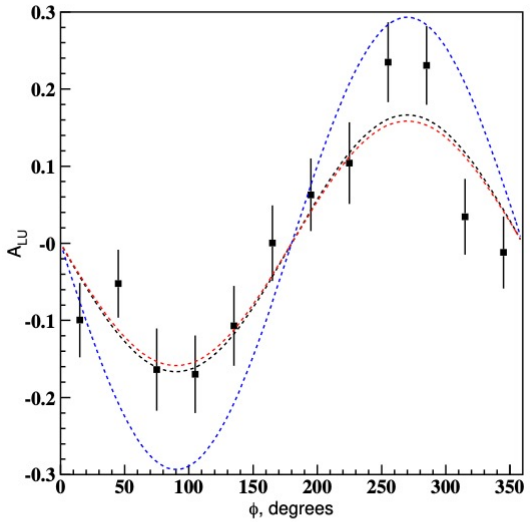


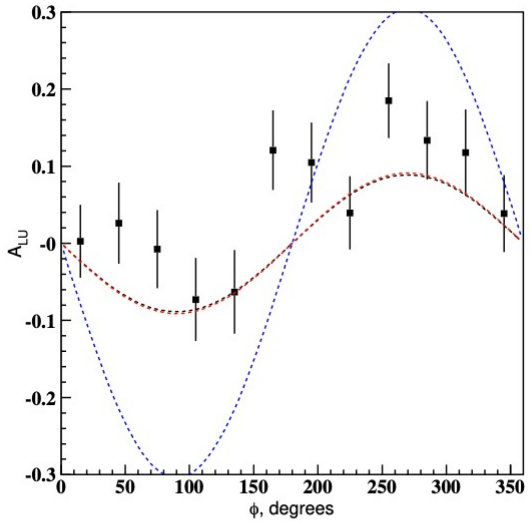


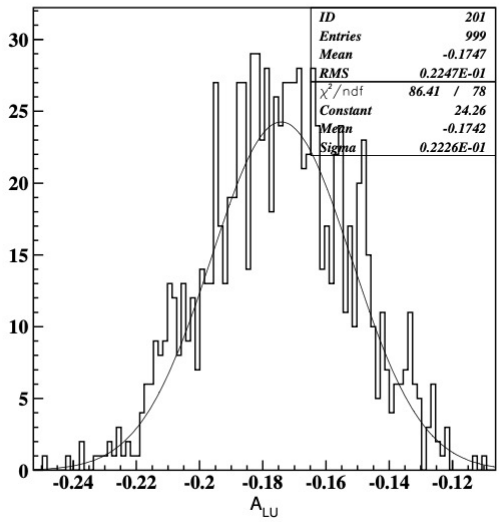
More on DDVCS: error bars on BSA 3

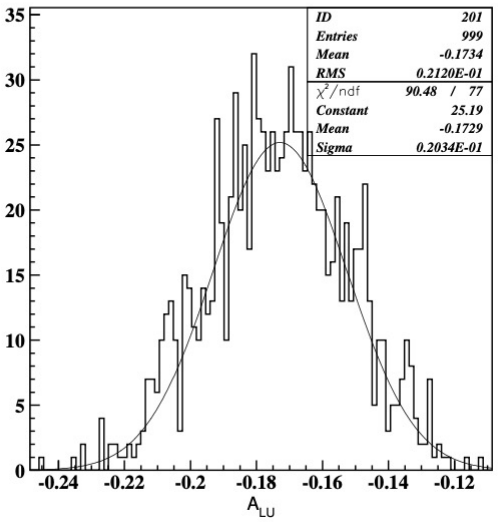


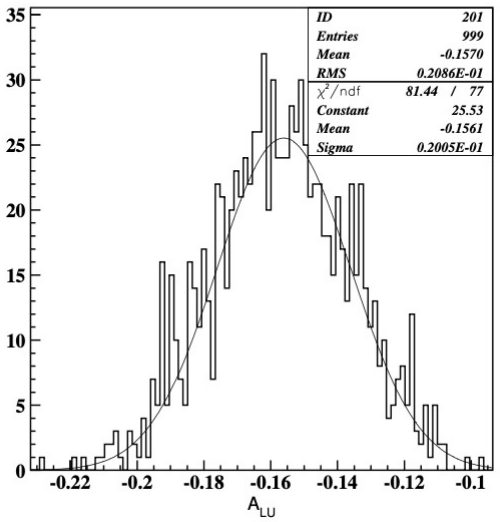


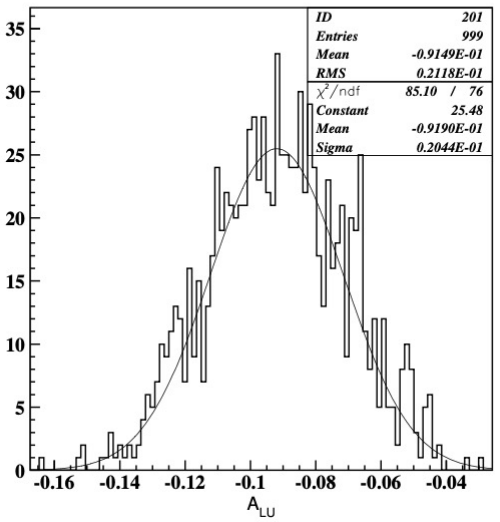












Back-up: systematics