μCLAS12: electro- and photo-production of muon pairs

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

Proposal PR12-25-001 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 **Motivations and Challenges**: probing the structure of the nucleons with muon pairs

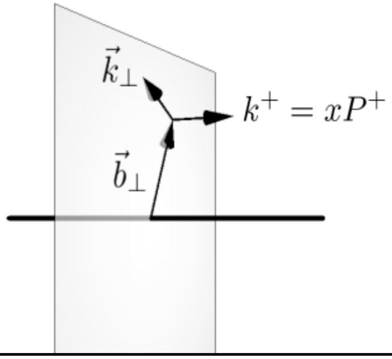
II The µCLAS12 experiment: **Setup and Specifications**

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

Motivations and Challenges

Generalized Parton Distributions

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



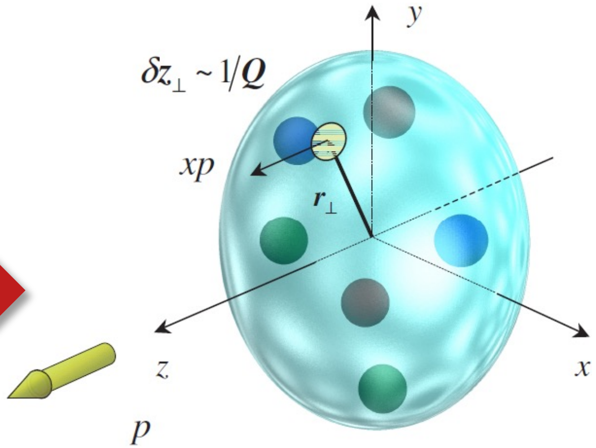
$$\boxed{W(x, \xi, \vec{k}_\perp, \vec{k}_\perp \cdot \Delta_\perp, t)}$$

Generalized **T**ransverse **M**omentum **D**istributions

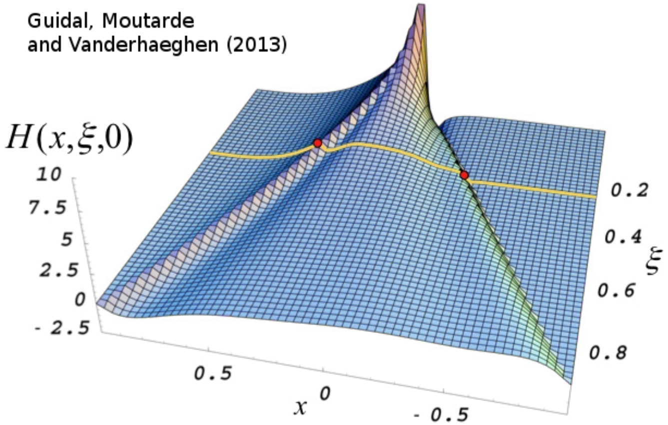
$$\int d^2\vec{k}_\perp$$

Generalized **P**arton **D**istributions

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

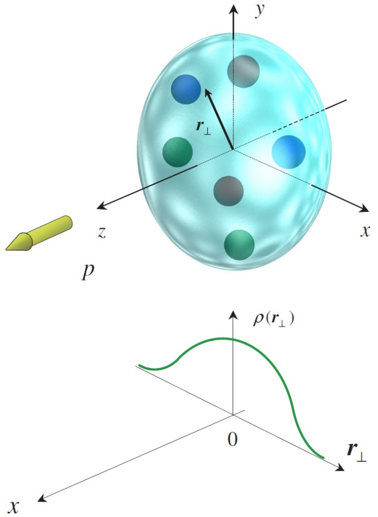


Guidal, Moutarde and Vanderhaeghen (2013)

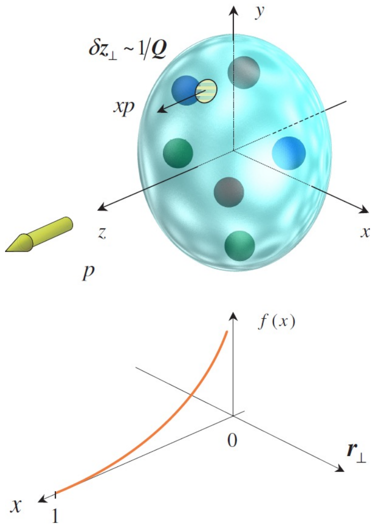


$$\int dx$$

Electro-magnetic **F**orm **F**actors



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



Parton **D**istribution **F**unctions

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

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

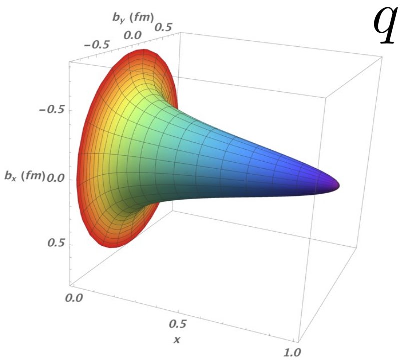
Mass   Spin   Forces

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

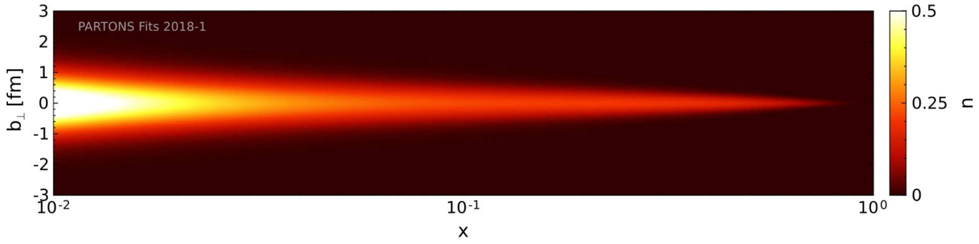
$$\frac{1}{2} = J(0) = \frac{1}{2}(A(0) + B(0)) = \frac{1}{2}\Delta\Sigma + \Delta L$$

Nucleon tomography

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



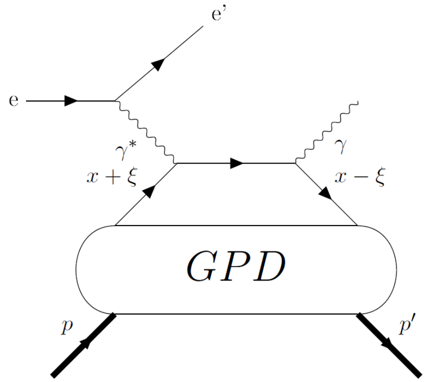
R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95, 011501 (2017)



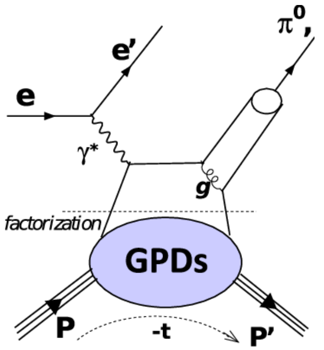
Moutarde, H., Sznajder, P. & Wagner, J. Border and skewness functions from a leading order fit to DVCS data. *Eur. Phys. J. C* **78**, 890 (2018)

… via the experimental measurement of exclusive reactions

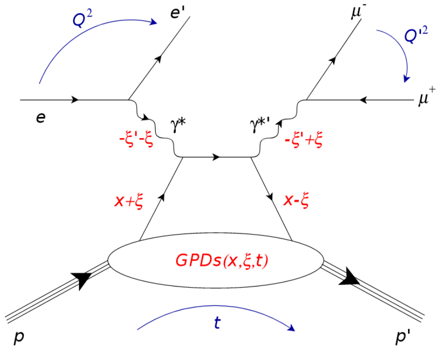
Deeply **V**irtual **C**ompton **S**cattering



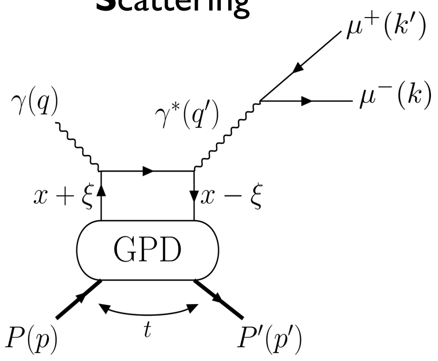
Deeply **V**irtual **M**eson **P**roduction



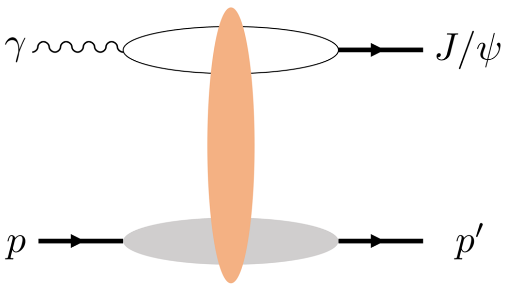
Double DVCS



Timelike **C**ompton **S**cattering



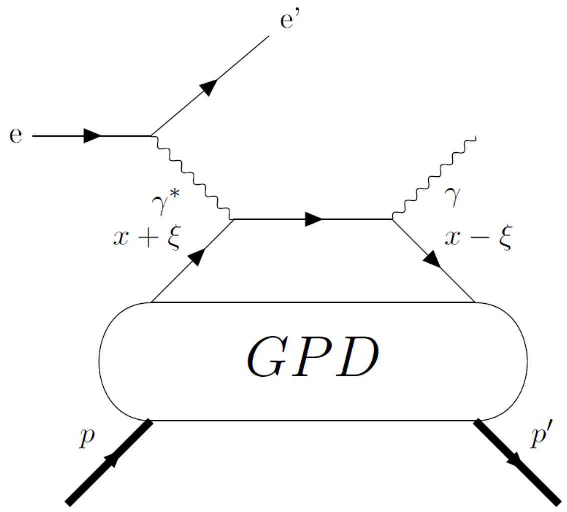
J/ψ Production



The Compton Form Factors: an inverse problem to access GPDs

Deeply Virtual Compton Scattering

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



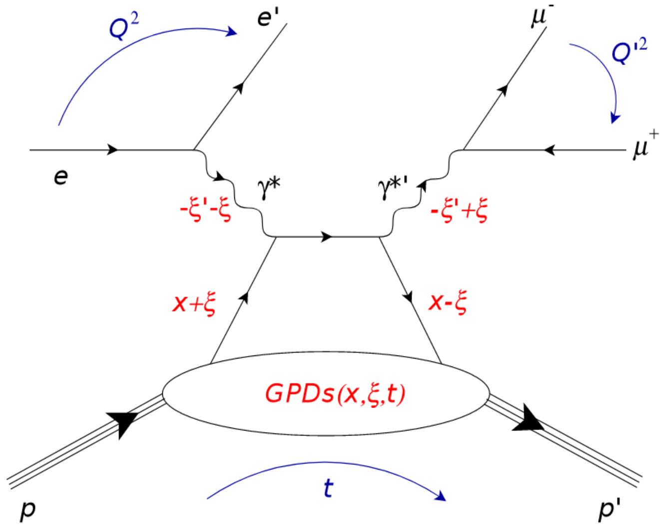
$$\mathcal{H}_{\text{DVCS}}(\xi,t) = \int_{-1}^{1} dx H(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)$$

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

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

Double Deeply Virtual Compton Scattering

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



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

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

The Compton Form Factors: an inverse problem to access GPDs

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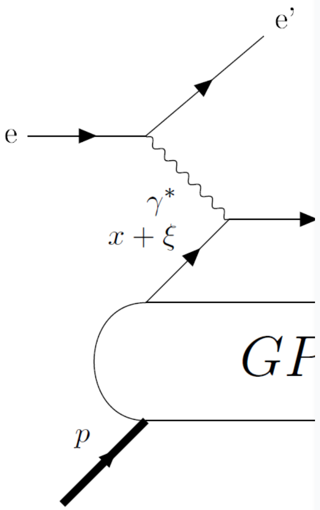
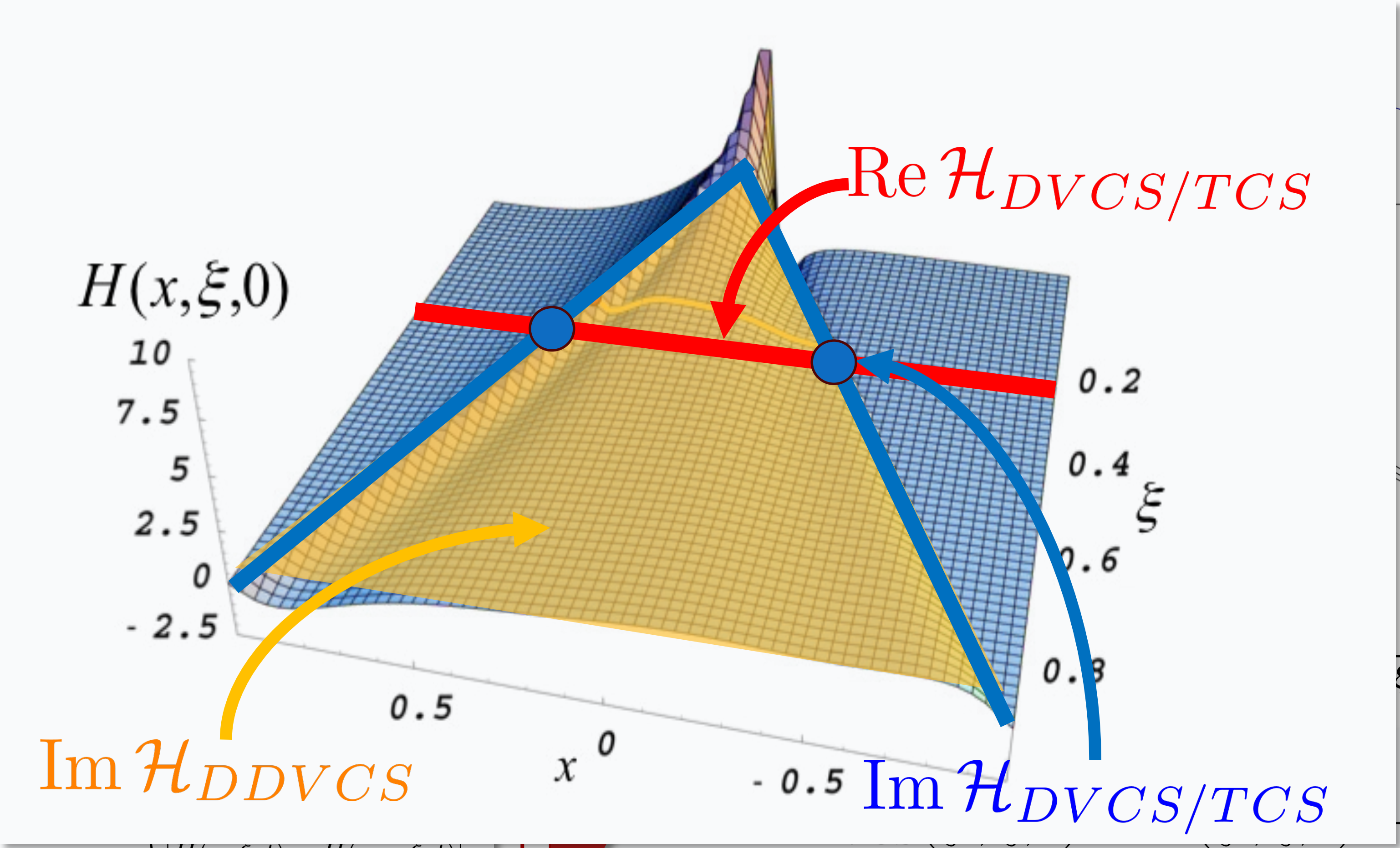




$$\mathcal{H}_{\rm DVCS}(\xi,t) = \int_{-1}^{1} dx H($$

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

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

Double Deeply Virtual Compton Scattering

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

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

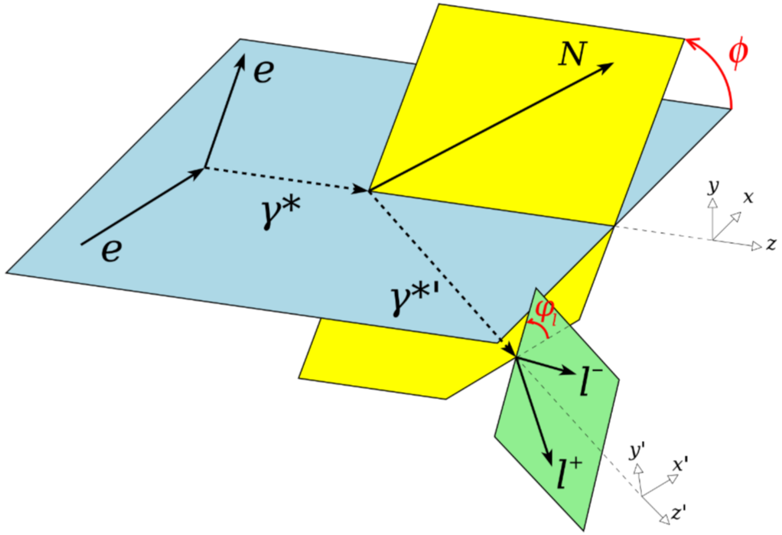
$$H(-\xi',\xi,t)$$

Double Deeply Virtual Compton Scattering (DDVCS)

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

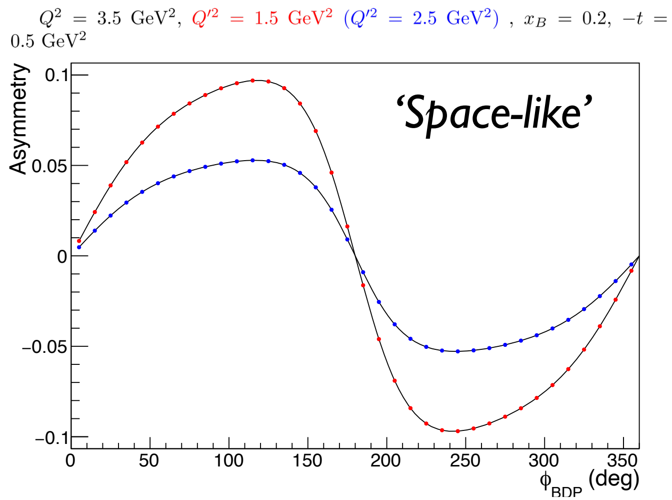
The 5-fold DDVCS cross-section:

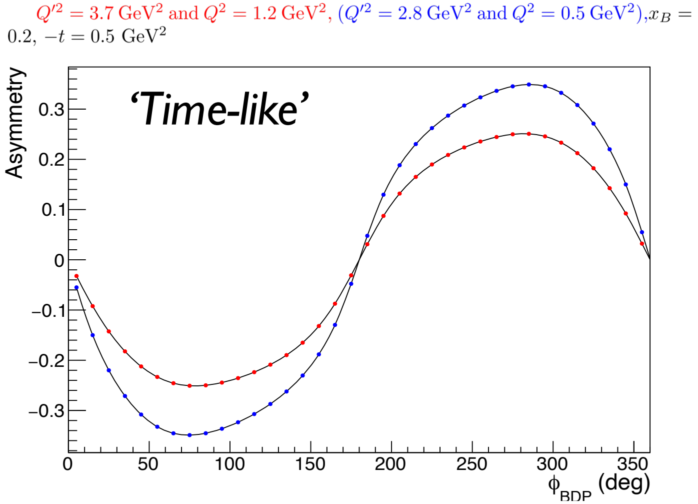
$$\frac{d\sigma^5}{dQ^2 dt dx_B d\phi dQ'^2} = \int_0^{2\pi} d\varphi_l \int_0^{\pi} d\vartheta_l \sin\vartheta_l \frac{d\sigma^7}{dQ^2 dt dx_B d\phi dQ'^2 d\Omega_l}$$
$$= d^5\sigma_{BH1} + d^5\sigma_{BH2} + d^5\sigma_{VCS} + d^5\sigma_{Int_1} + \lambda(d^5\tilde{\sigma}_{VCS} + d^5\tilde{\sigma}_{Int_1})$$



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

Predicted DDVCS BSA



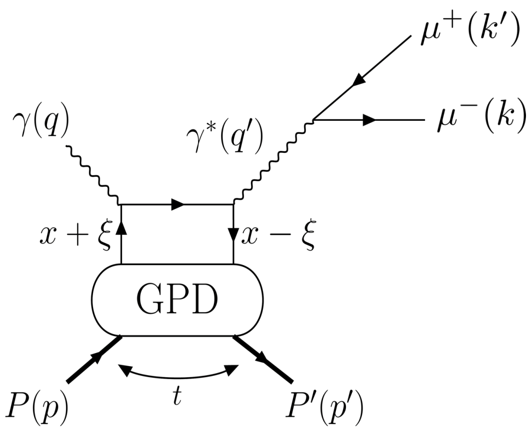


Challenges of DDVCS

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

Timelike Compton Scattering (TCS)

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



The TCS interference cross-section:

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

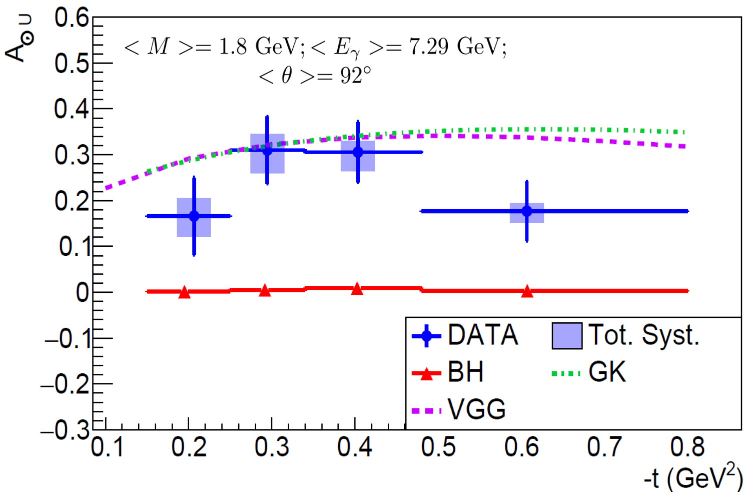
Forward-backward asymmetry:

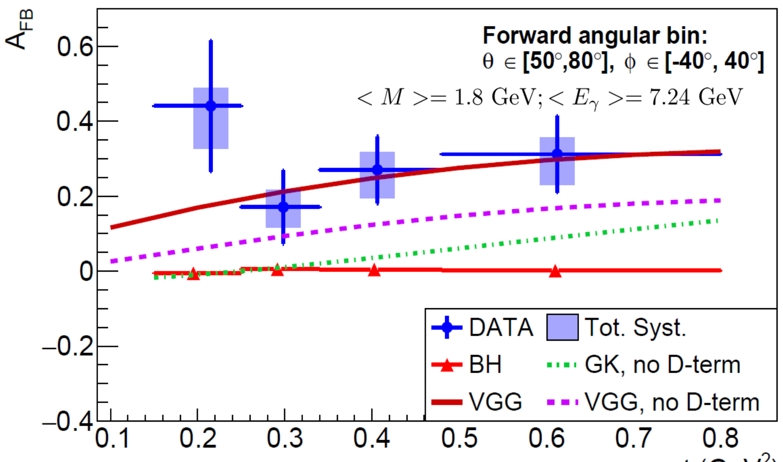
$$A_{FB}(\theta_0,\phi_0) = \frac{d\sigma(\theta_0,\phi_0) - d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}{d\sigma(\theta_0,\phi_0) + d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}$$
$$\propto \frac{\frac{L_0}{L}\cos\phi_0 \frac{(1+\cos^2\theta_0)}{\sin(\theta_0)}\mathrm{Re}\mathcal{H}}{d\sigma_{BH}(\theta_0,\phi_0)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

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



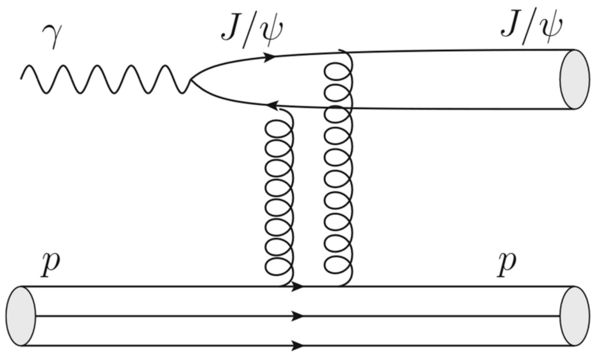


First Measurement of Timelike Compton Scattering, P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)

- 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

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



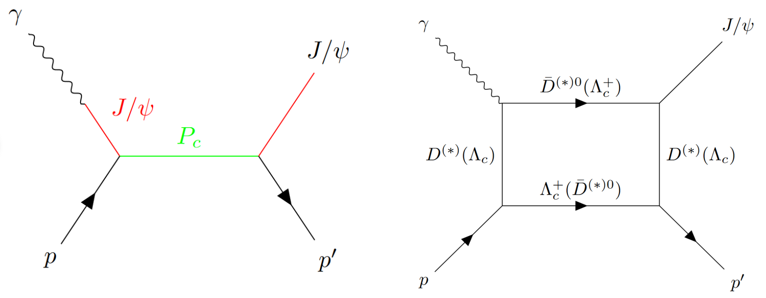
$$\frac{d\sigma}{dt} = \frac{\alpha_{EM} e_Q^2}{4(W^2-M_N^2)^2}\frac{(16\pi\alpha_S)^2}{3M_V^3}|\phi_{NR}(0)|^2|G(t,\xi)|^2$$

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

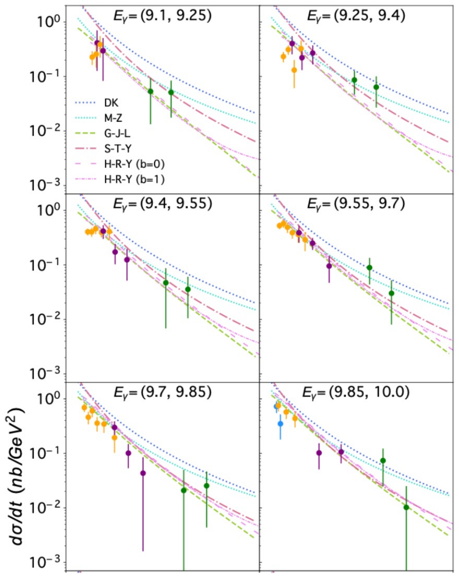
$$\frac{d\sigma}{dt} = \mathcal{N}^2\frac{e^2}{64\pi(s-M_N^2)^2}\frac{[A^g(t)+\eta^2 D^g(t)]^2}{A^{g2}(0)}\cdot\tilde{F}(s)\cdot 8$$

"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

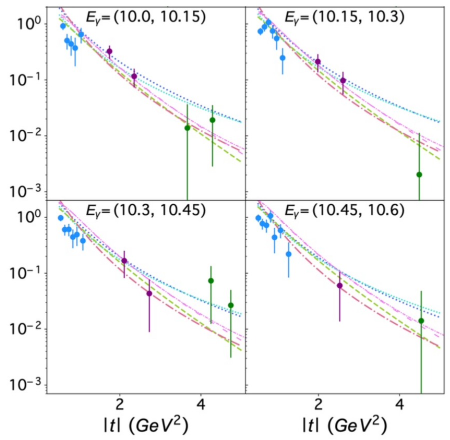
Access to the gluon content of the proton…
… if other contributions can be understood.



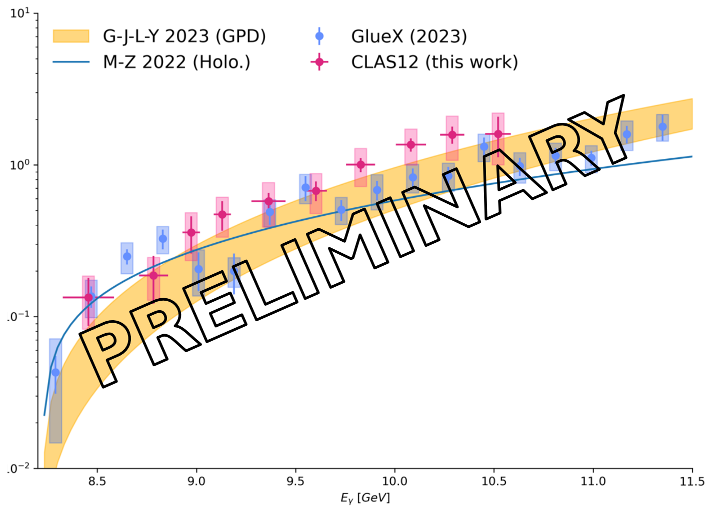
Current experimental status in the e⁺e⁻ final state



"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

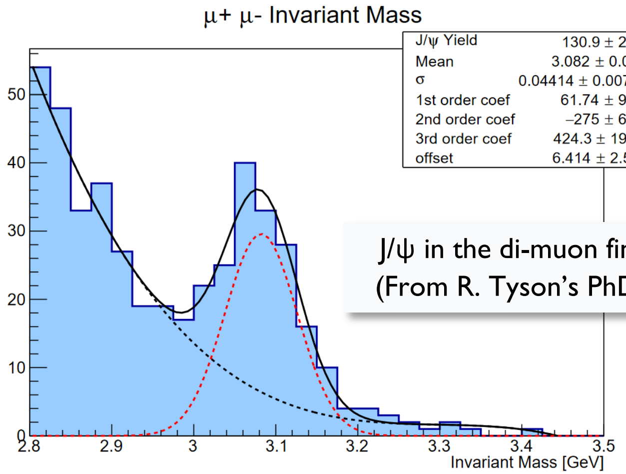


- J/ψ production offers a window to the gluon dynamics in the nucleon, even at JLab energies.
- Requires **large statistics**.

The μCLAS12 setup

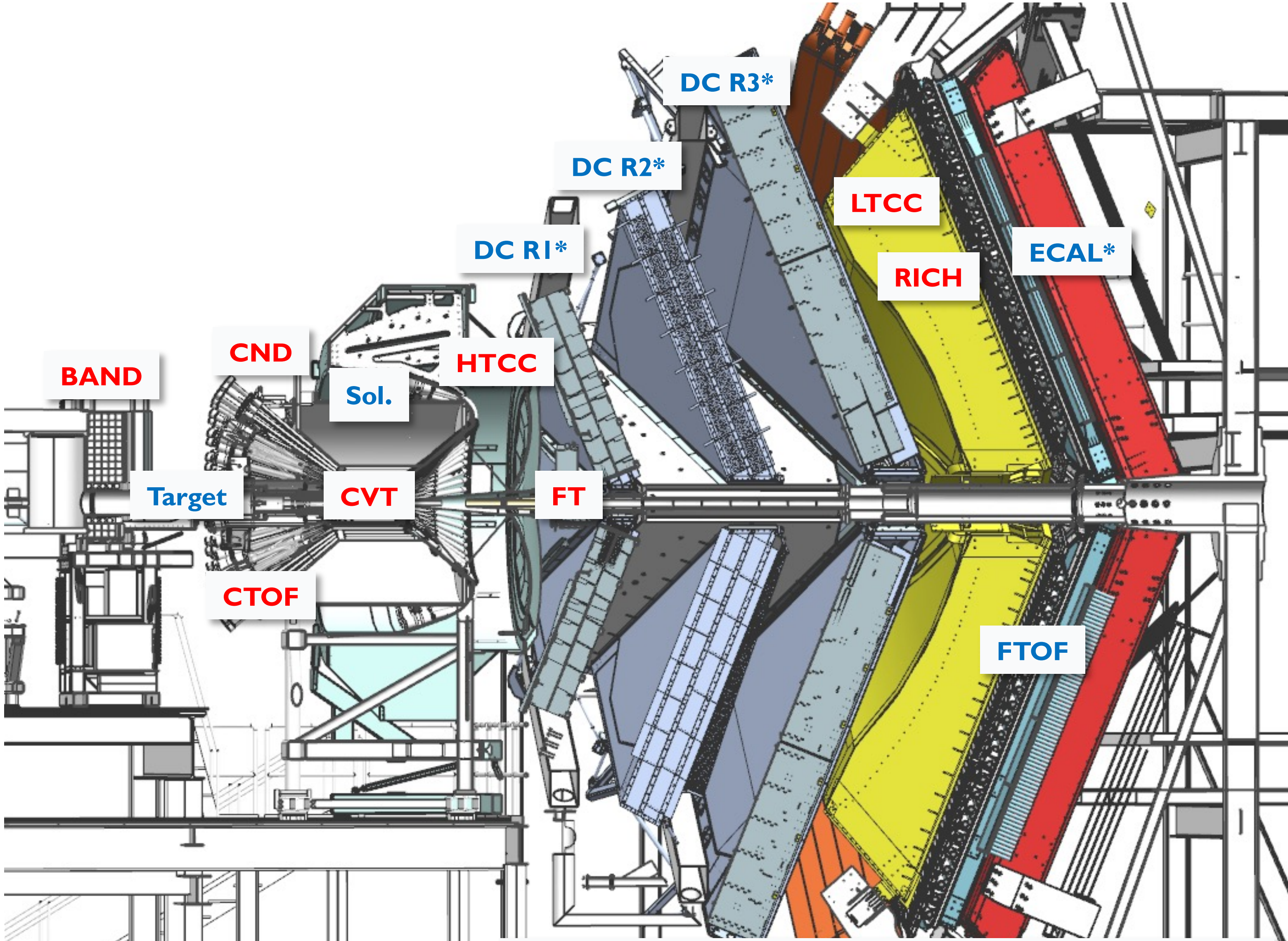
The µCLAS12 configuration

- The µCLAS12 setup will **mostly use existing CLAS12 detectors.**



J/ψ in the di-muon final state (From R. Tyson's PhD thesis)

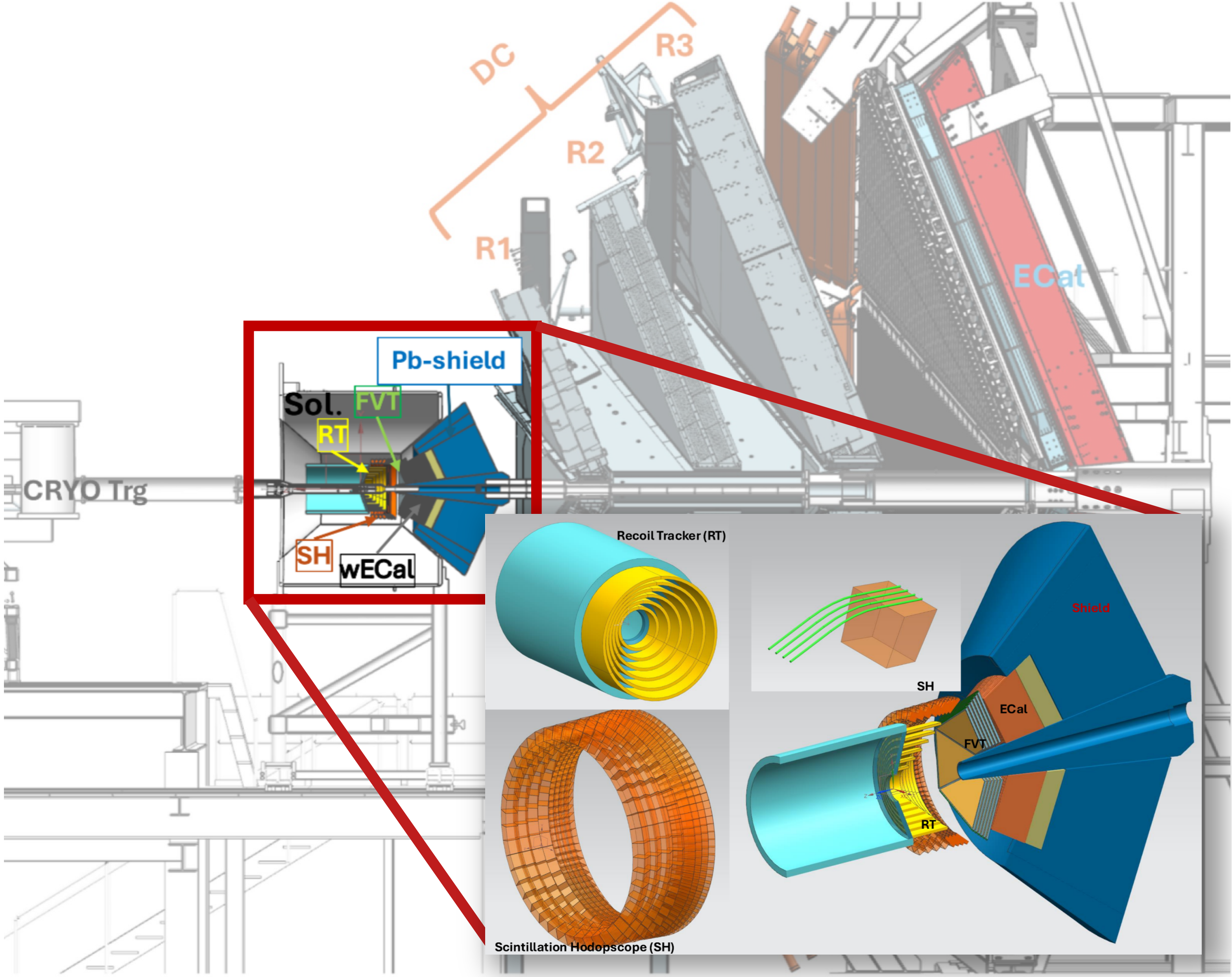
- The CLAS12 FD detector will be effectively used as a muon detector.
- The CTOF, CND, CVT, HTCC, FT, LTCC, RICH and BAND will be removed.



*Detectors used in the current CLAS12 muon identification

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.

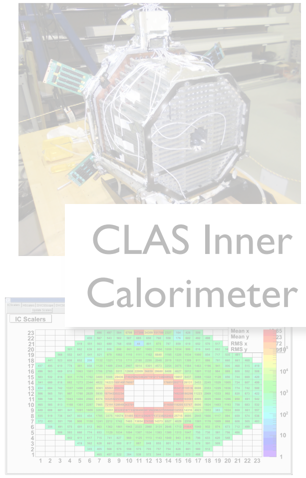


Experimental conditions and beam time request

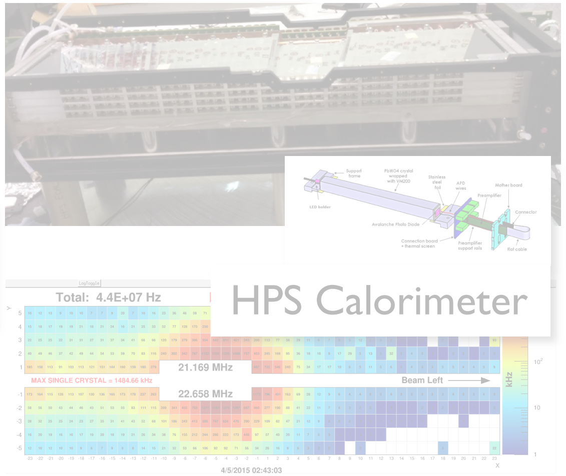
Beam Energy (GeV)	Beam Current (μA)	Beam Requirements	Target Material	Target Length (cm)	Beam time (days)
Commisionning					
11				5	15
Calibration					
11	7.5		Empty target	5	10
11	<1		LH2	5	20
Production					
11	**7.5**	**$>$ 85% longitudinal polarization**	**LH2**	**5**	**200**
Total time					245

The wECAL calorimeter & forward vertex tracker systems

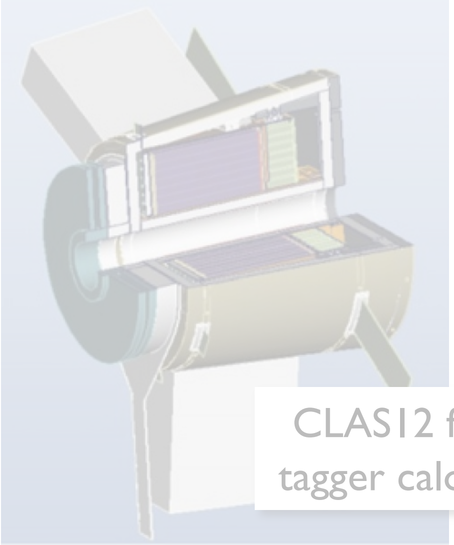
PbWO4 Calorimeters in Hall B

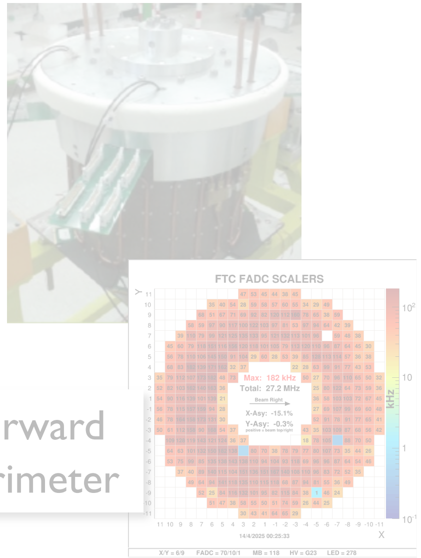


CLAS Inner Calorimeter



HPS Calorimeter

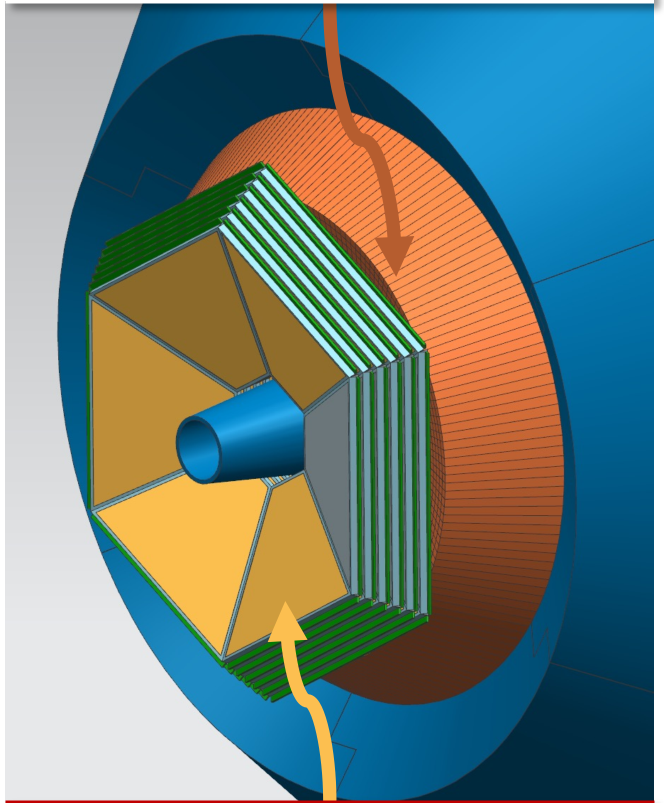




CLAS12 forward tagger calorimeter

wECAL calorimeter

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

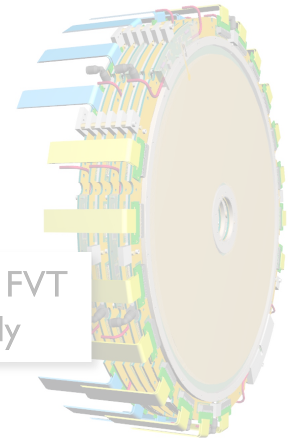


Forward Vertex Tracking

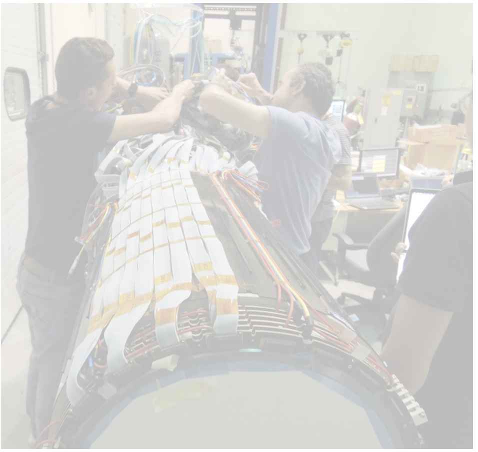
- 6-layer assembly GEM detectors.
- VMM3 readout.
- Expected rates: 500 kHz/cm^2

Forward Vertex Tracker

- Forward tracks reconstructed in the µCLAS12 FD Drift Chambers.
- **No changes to the FD tracking from CLAS12.**
- FVT is used for **vertexing forward-going tracks only.**
- 4 out of 6 layers for track matching.



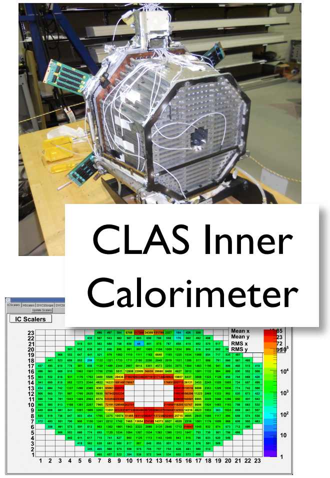
CLAS12 MicroMegas FVT → 6-layer assembly



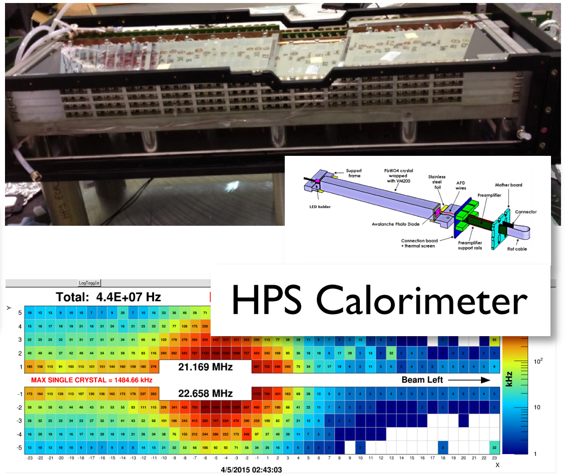
3-layer assembly used in many CLAS12 experiments (eg. Barrel Micromegas)

The wECAL calorimeter & forward vertex tracker systems

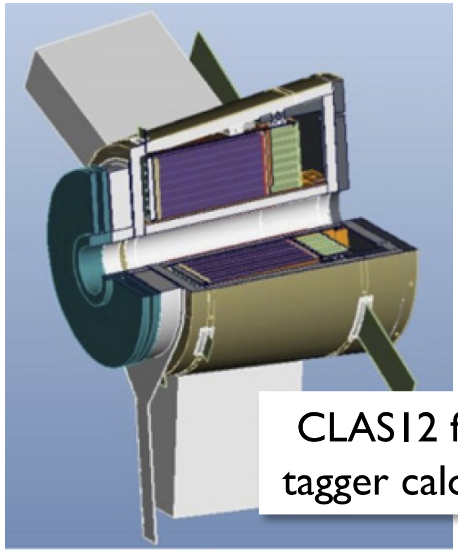
PbWO4 Calorimeters in Hall B

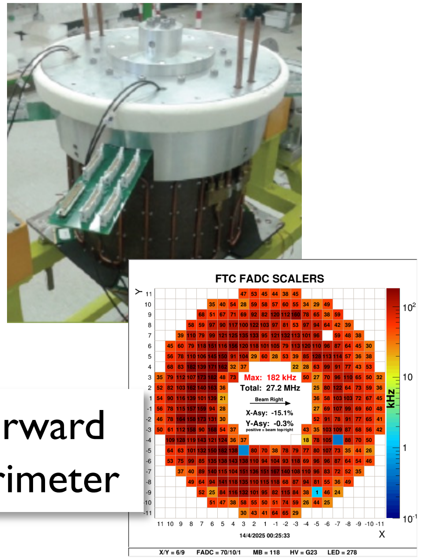


CLAS Inner Calorimeter



HPS Calorimeter





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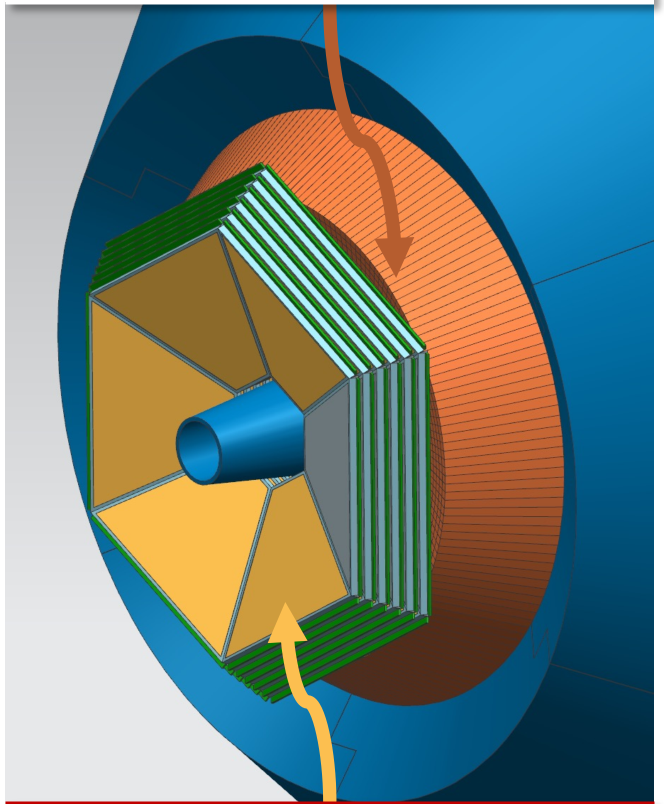

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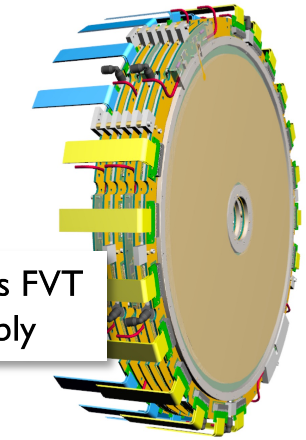
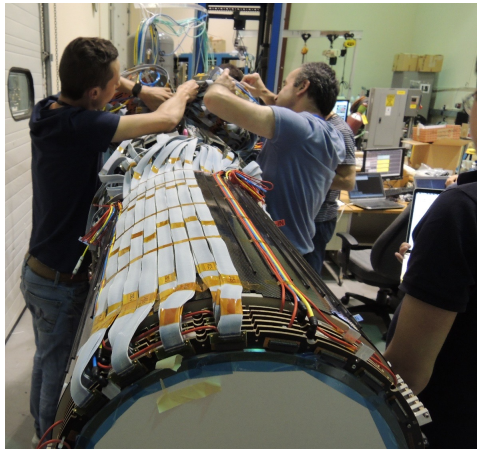
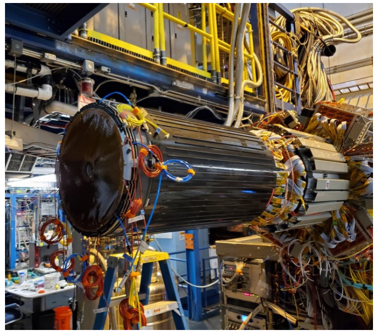


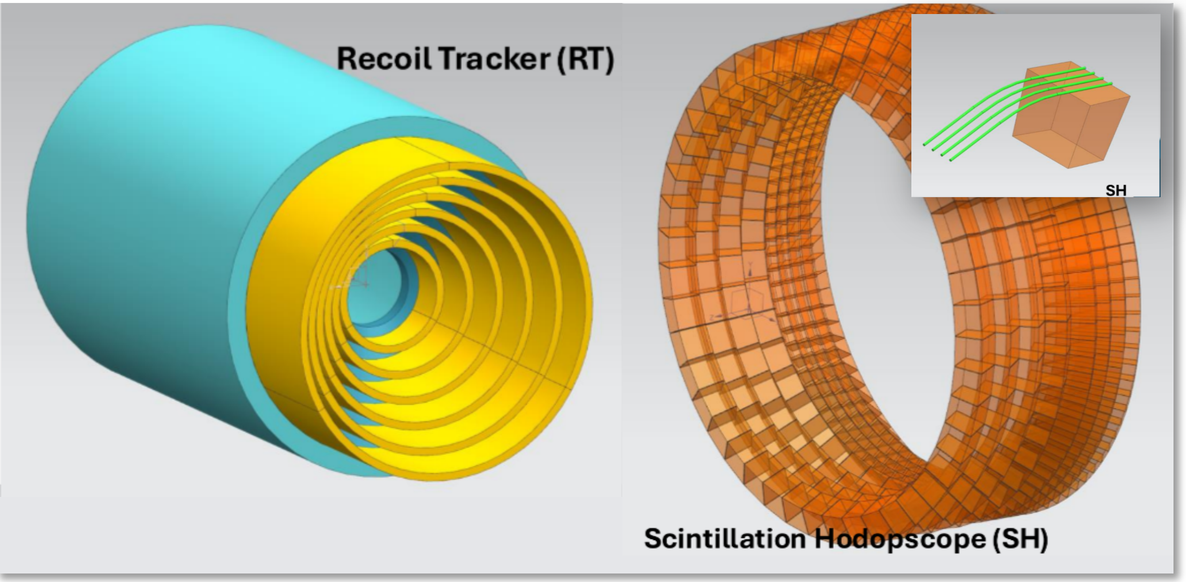
CLAS12 MicroMegas FVT
→ 6-layer assembly

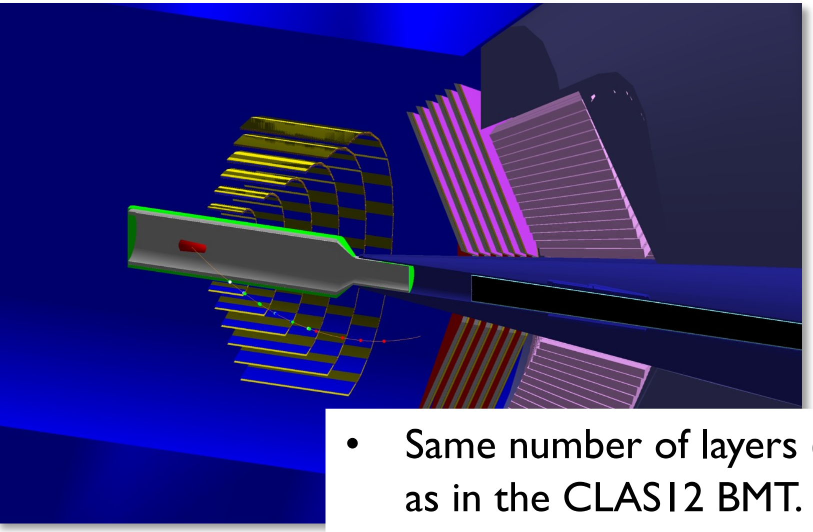




3-layer assembly used in many CLAS12 experiments (eg. Barrel Micromegas)

The Recoil Tracker

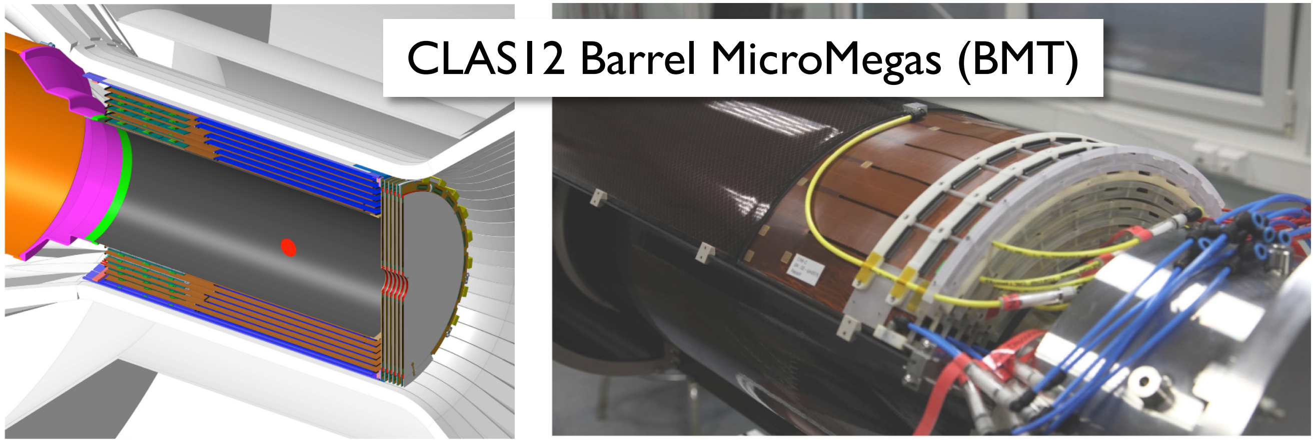




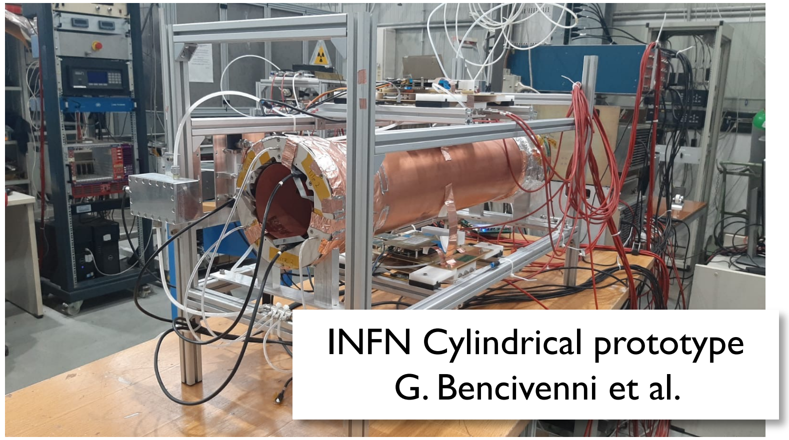
- Same number of layers (6) and 2D-readout as in the CLAS12 BMT.
- First version of the detector **implemented in simulation.**

Cylindrical MPGD in Hall B

Extensive experience in building and operating cylindrical MPGD detectors



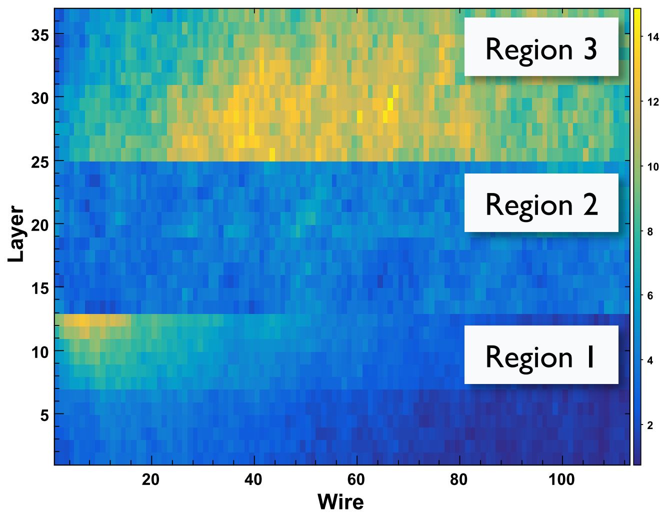
Significant R&D efforts are underway in different labs & at JLAB for high-rate μRWELL detectors (EIC, SoLID, and Hall B LDRD-2507).

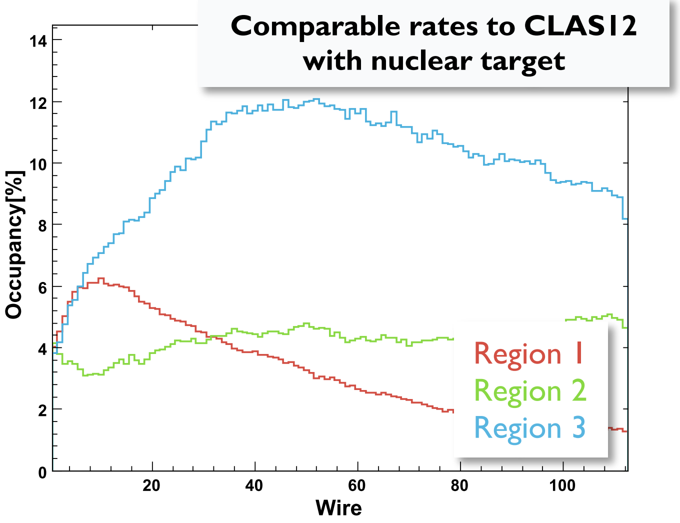


Rates, backgrounds and trigger rate

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

Drift Chambers occupancies

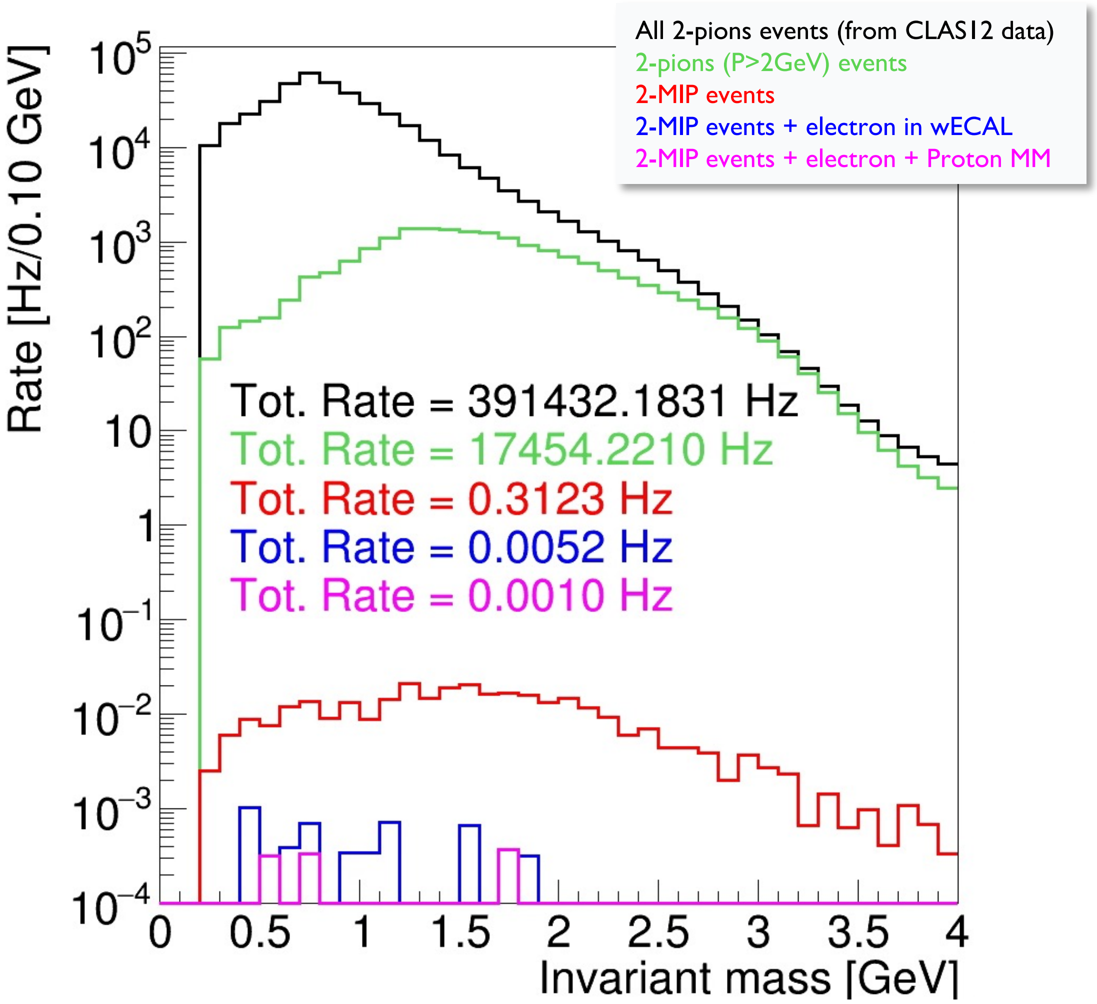




Trigger rate

- **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 from data: 3%
- Inclusive coincidence from MC: 4%

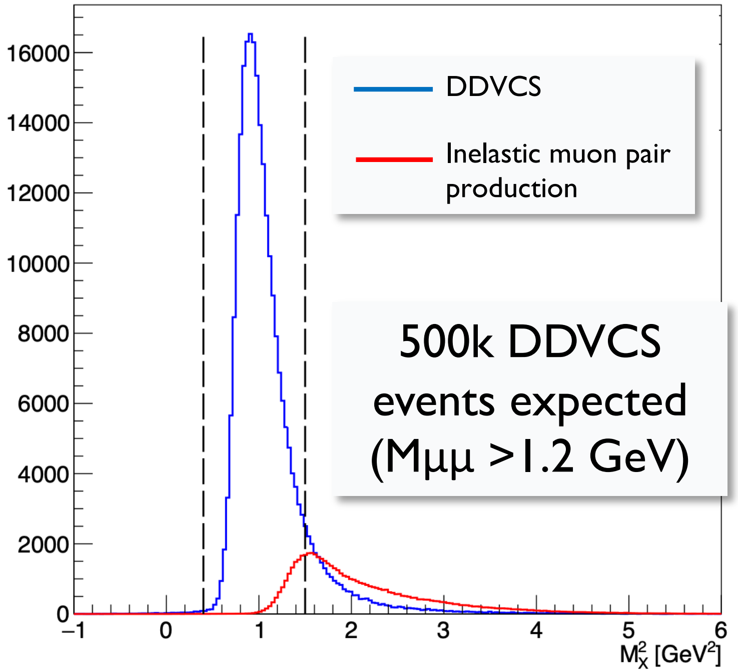
Expected results

Expected results on DDVCS

Analysis strategy

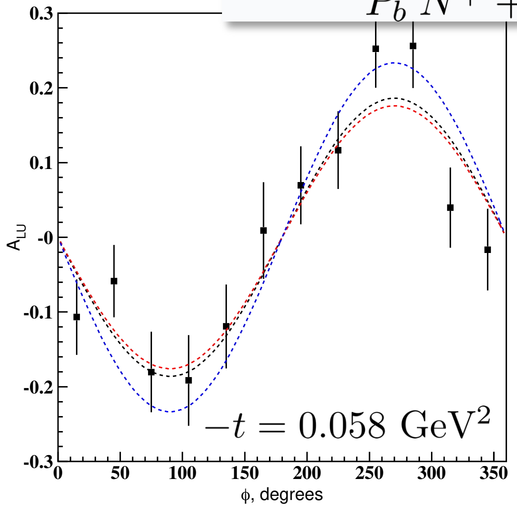
$$ep \to e'\gamma^* p \to e'p'\gamma^* \to \boldsymbol{e'\mu^+\mu^-}(X)$$

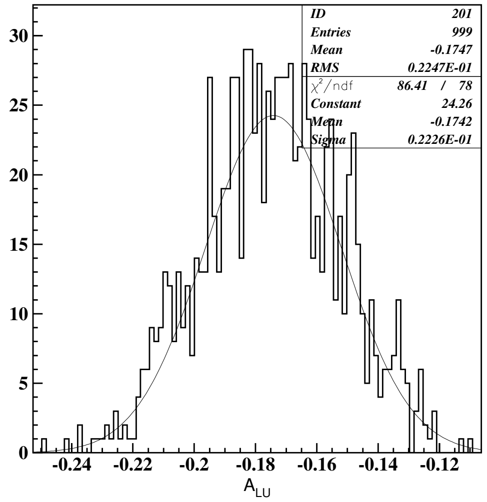
- Electron detected in wECAL.
- Muons in µCLAS12 Forward Detector.
- Missing proton reconstructed from energy-momentum conservation.

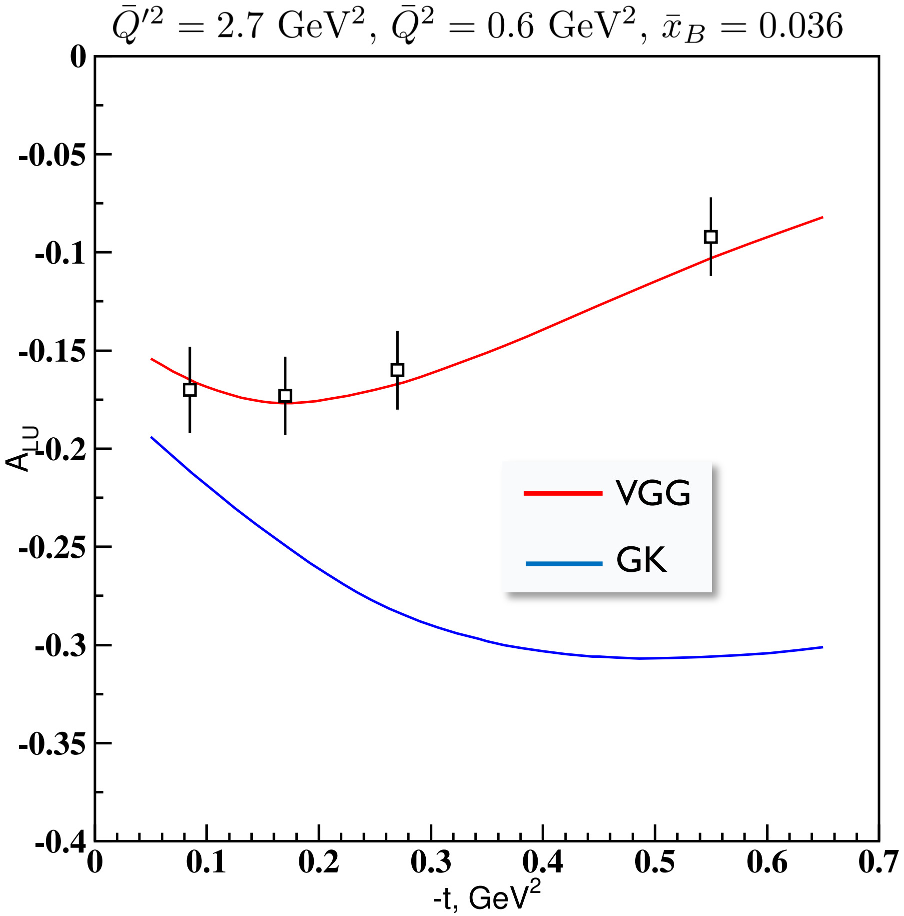


500k DDVCS events expected (Mµµ >1.2 GeV)

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



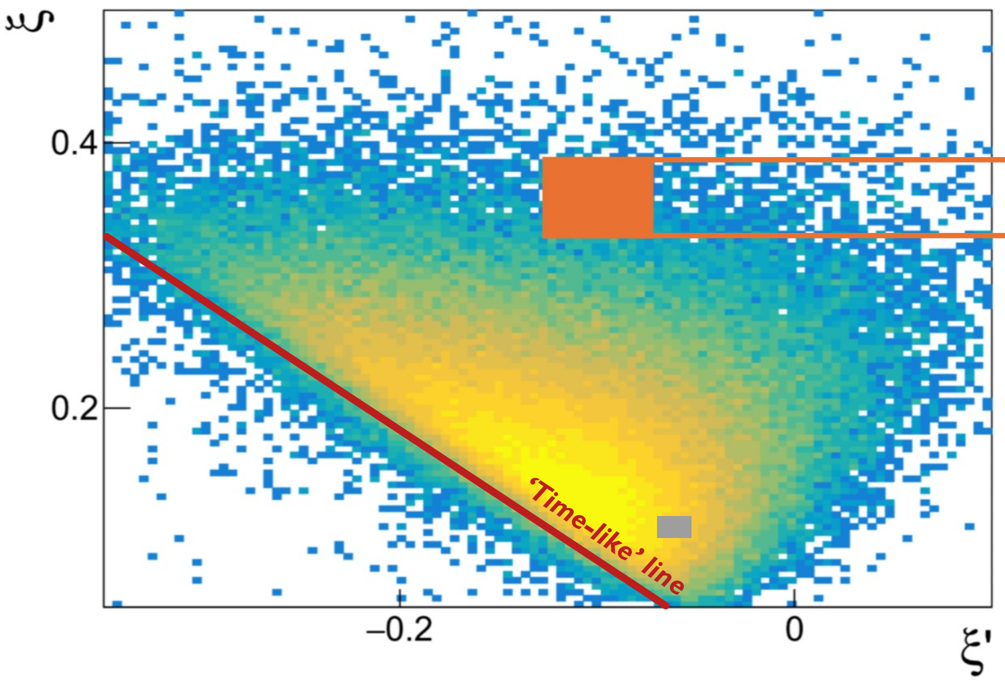


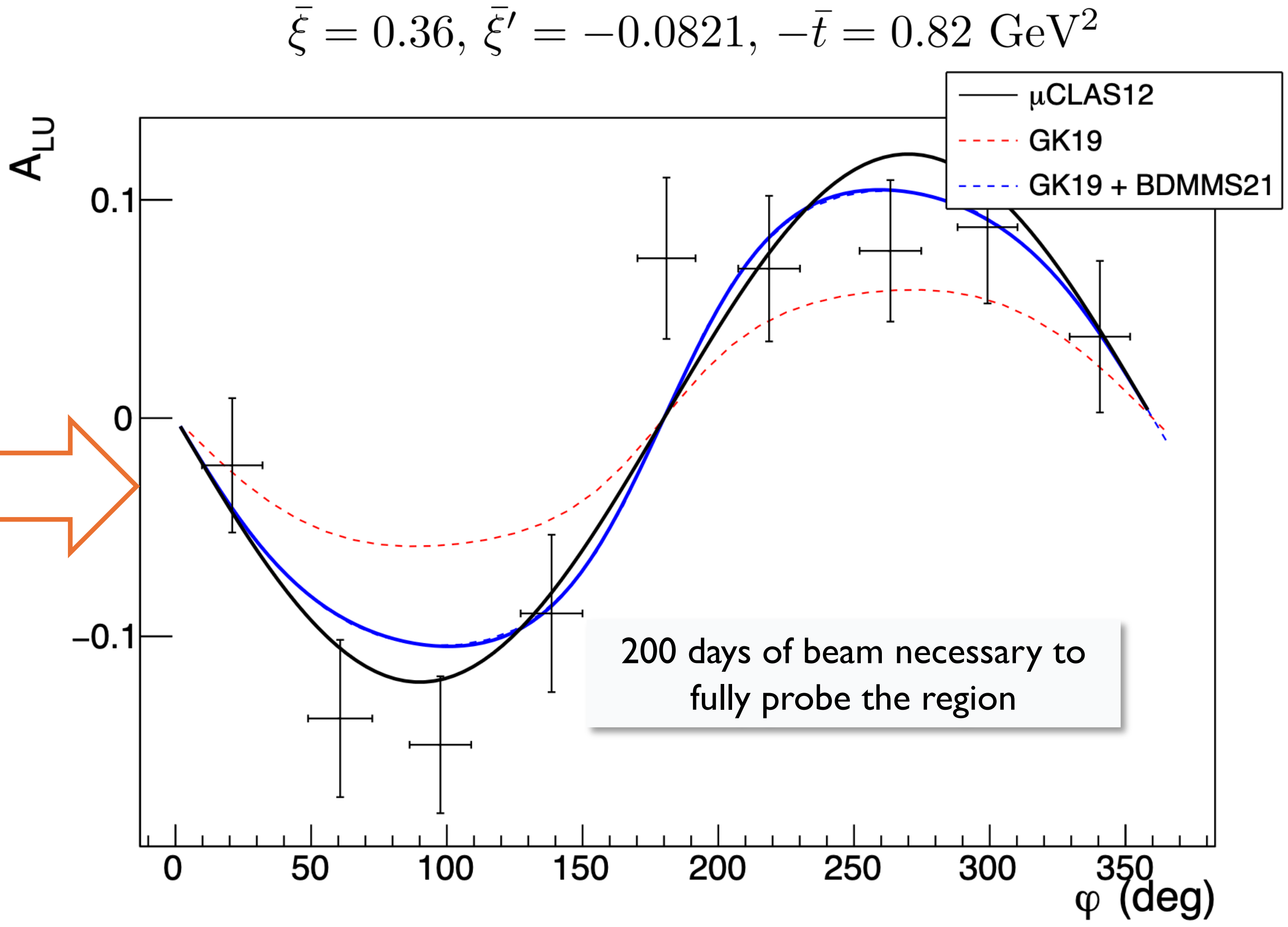


200 days of beam will allow to distinguish model down to the small-t region

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.

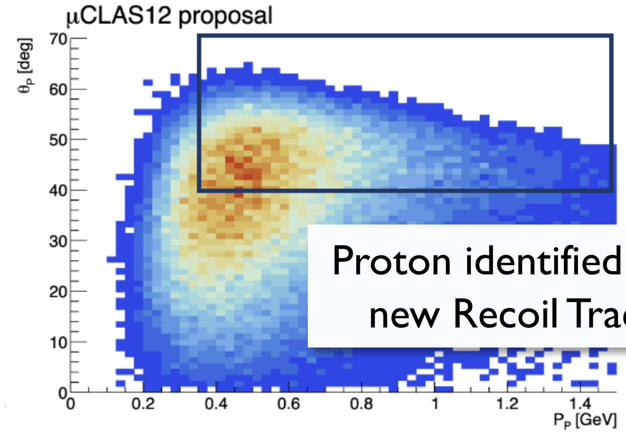




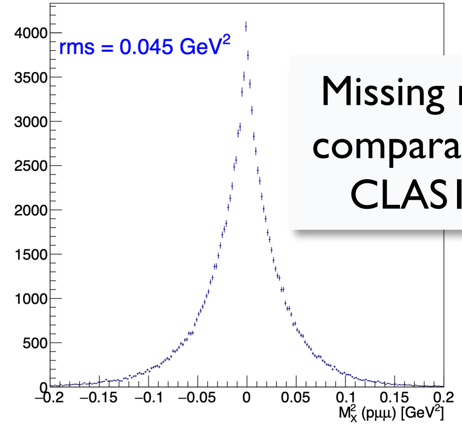
Expected results for TCS

Analysis strategy

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



Proton identified in the new Recoil Tracker

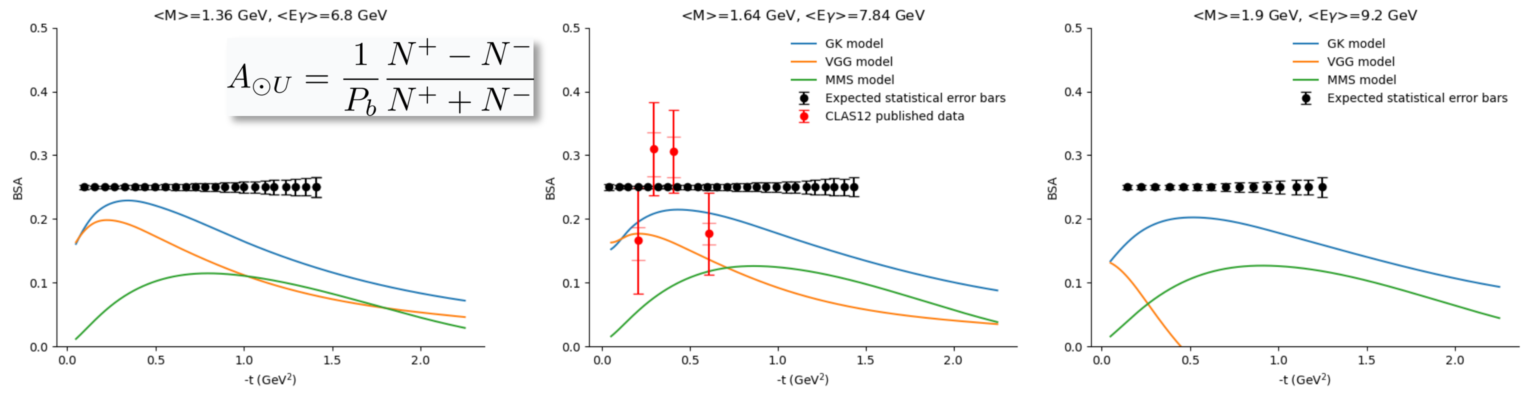


Missing mass resolution comparable to published CLAS12 TCS results

Expected results with 7.7M expected events (Mµµ >1.2 GeV)

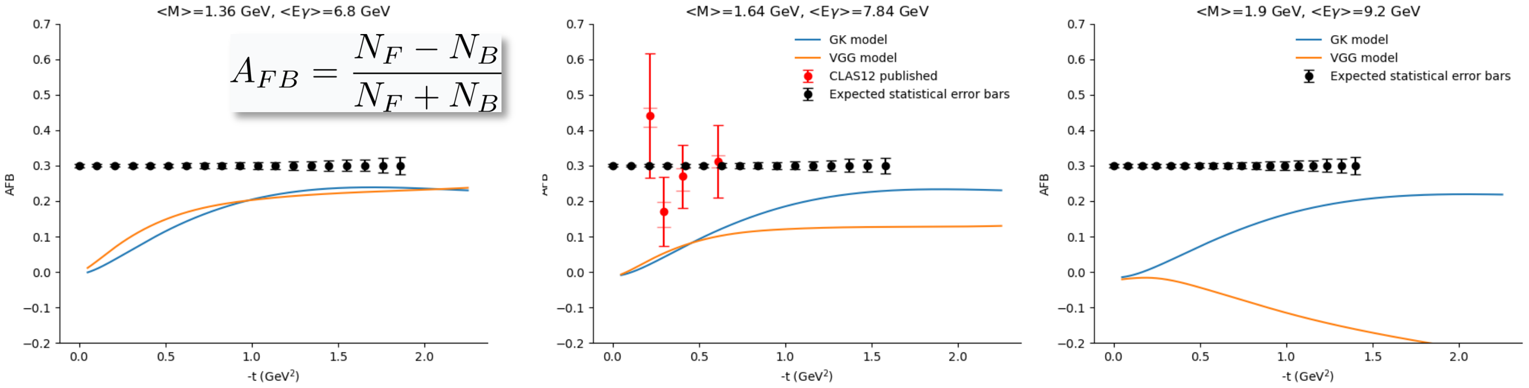
Photon polarization asymmetry

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



Forward-Backward asymmetry

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



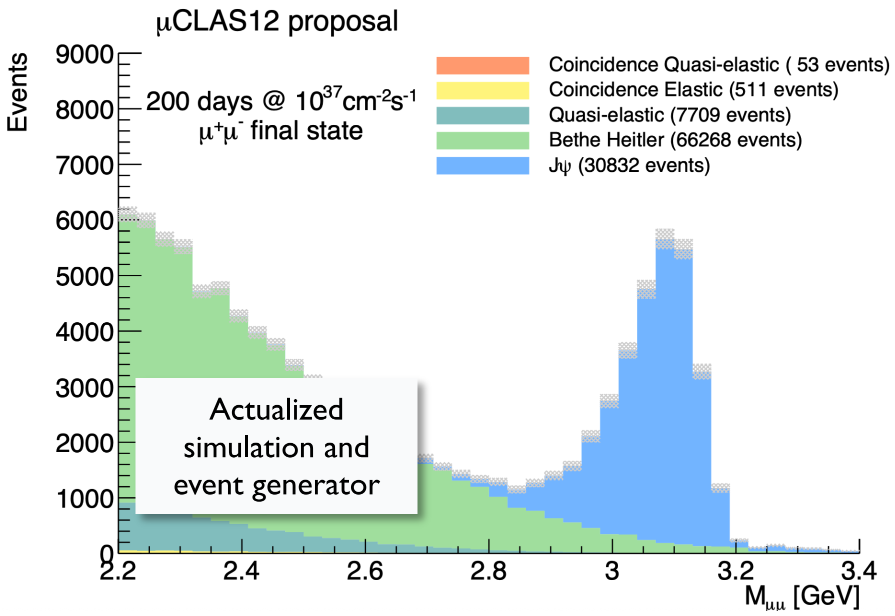
→ First **precision** measurement of TCS

Expected results for J/ψ electro-production

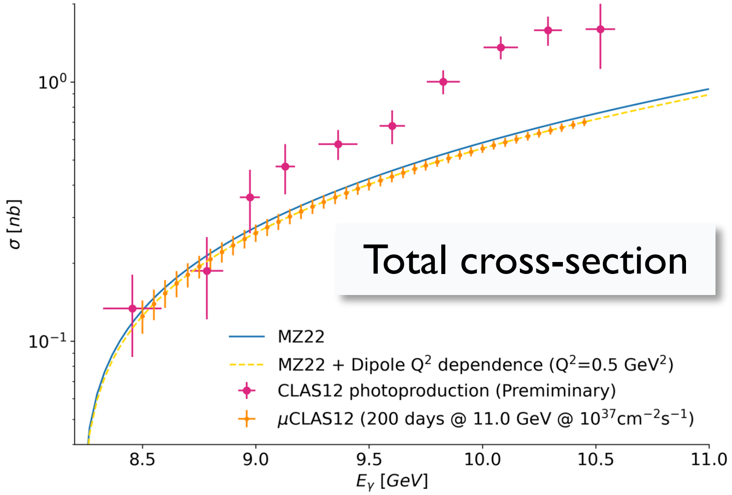
Analysis strategy

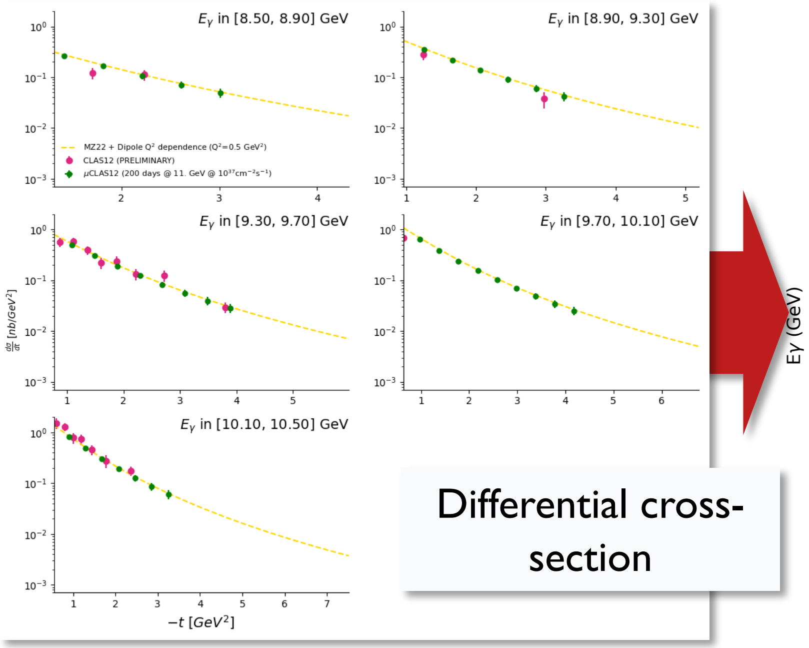
$$ep \to e'\gamma^* p \to e'p'J/\psi$$
$$\to \boldsymbol{e'\mu^+\mu^-}(X)$$

- Electron detected in the wECAL.
- Muons in µCLAS12 Forward Detector.
- Peak in the invariant mass of the $\mu^+\mu^-$ pair.



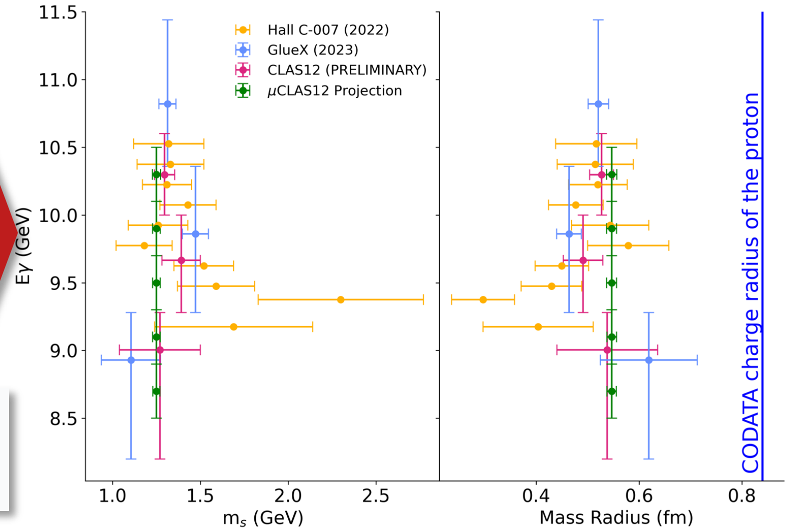
Projected results with 30k expected events





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

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



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 and reconstruction** framework.
- Rates, trigger rates, background rates and expected number of events are based on realistic simulation and existing CLAS12 data.

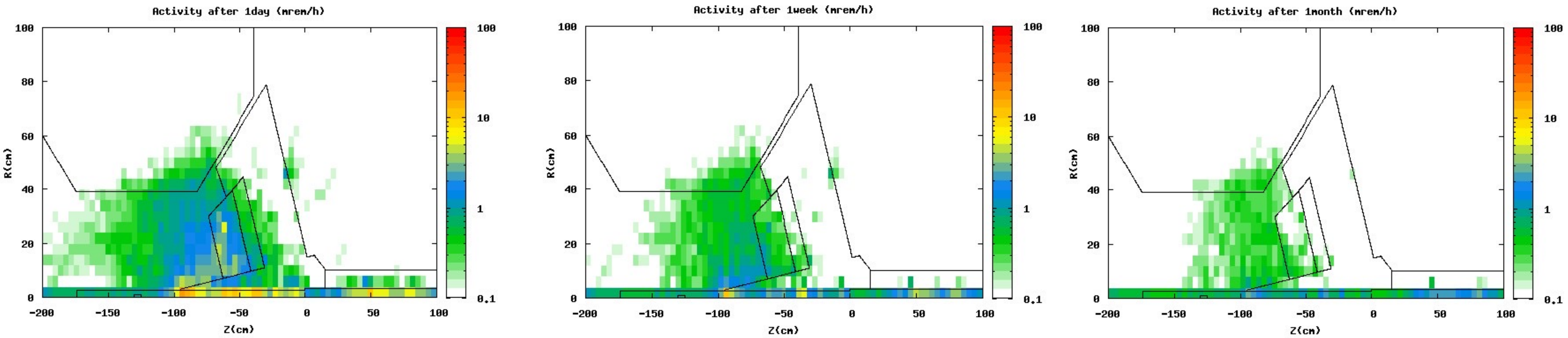
Beam Energy (GeV)	Beam Current (μA)	Beam Requirements	Target Material	Target Length (cm)	Beam time (days)
Production					
11	**7.5**	$>$ **85% longitudinal polarization**	**LH2**	**5**	**200**
Total time					245

Back-up

Back-up: Activation and Neutron radiation

Activation of the setup and decommissioning

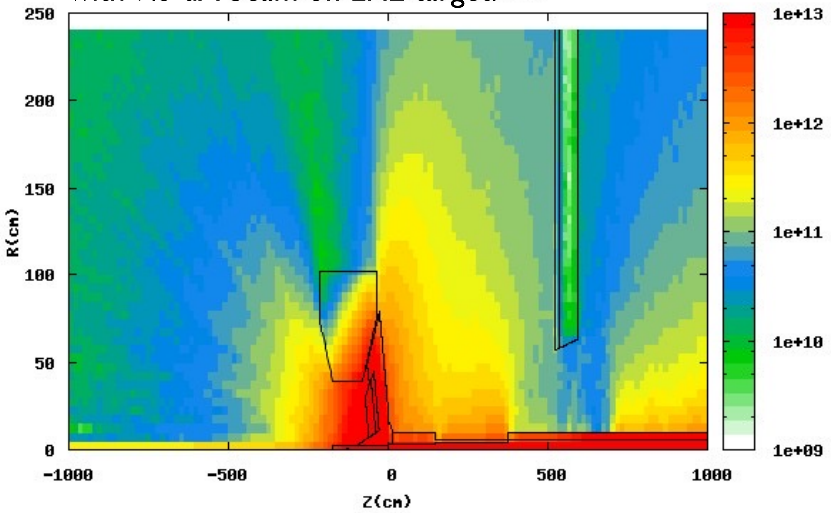
- The accumulated dose and activation after 200 days of running at a luminosity of $10^{37} cm^{-2} sec^{-1}$.
- 1 day after the beam is off, the activation of the shield components is less than 1 mrem/h.
- 1 week after the beam is off, the activation of all components beside the target is less than 1 mrem/h (well below current Hall A and C values)
- This experiment will dump 15 W of beam power in the target, while nominal runs in A or C, have 100s of Watts.
- **Note:** The experiment cannot run the whole 200 days in one year; it is highly likely it will require three separate approximately 80-day runs per year to complete it



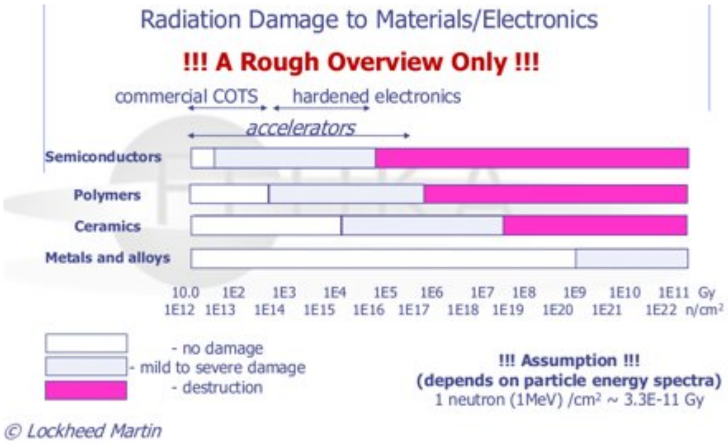
Radiation studies from Lorenzo Zana, JLAB Radiation Control Group

Neutron radiation

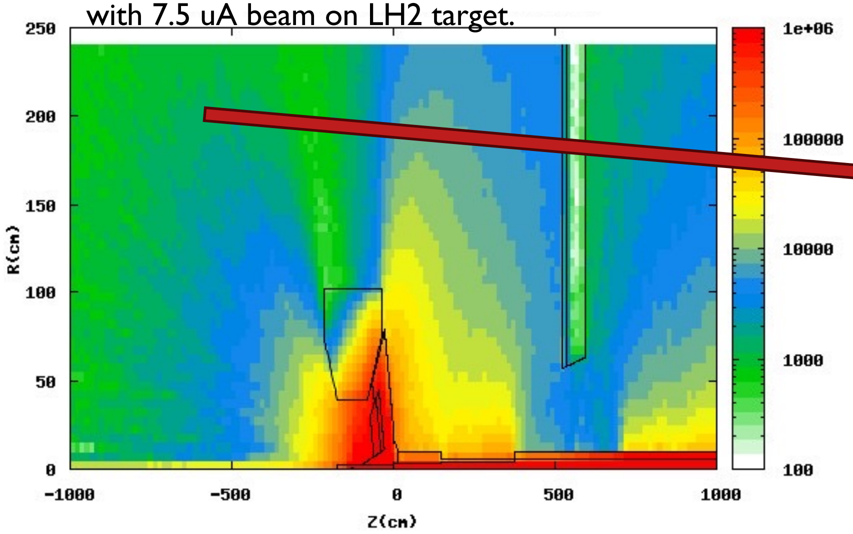
1 MeV equivalent neutron fluence in Si [sm^{-2} 200 days] with 7.5 uA beam on LH2 target.



The accumulated dose in the wECal and tracker electronics region is less than 2×10^{12} n/cm^2, close to but below the levels that cause damage to the semiconductors.

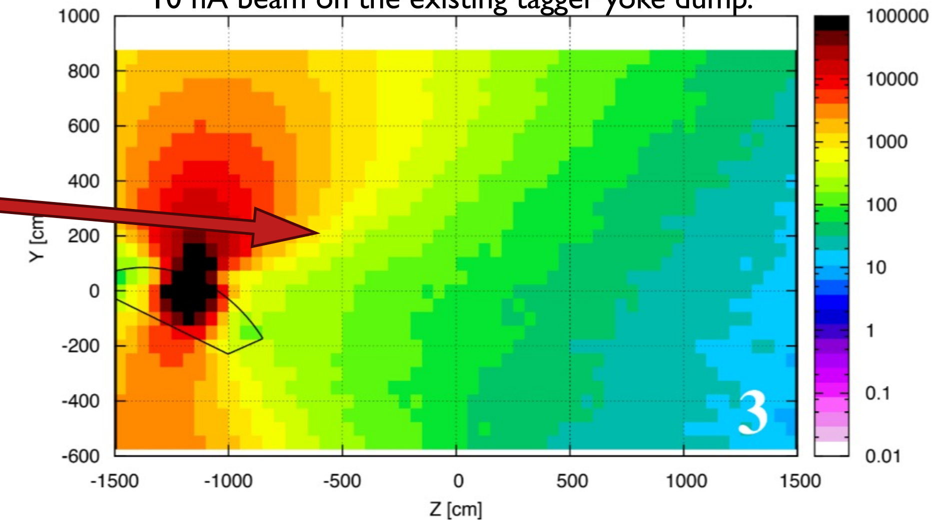


1 MeV equivalent neutron fluence in Si [sm^{-2} s^{-1}] with 7.5 uA beam on LH2 target.



The dose in the region of concern for electronics is the same order as in the current operations of CLAS12.

1 MeV equivalent neutron fluence in Si [sm^{-2} s^{-1}] with 10 nA beam on the existing tagger yoke dump.



Radiation studies from Lorenzo Zana, JLAB Radiation Control Group

Back-up: Beam dump and target

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 require increasing the Hall B power limit **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.

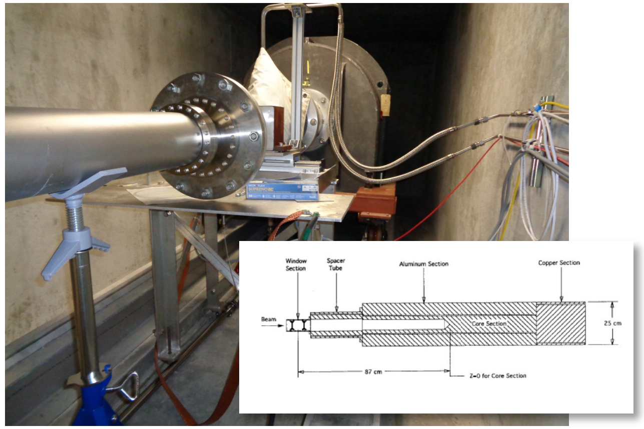
Beam dump upgrade

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.

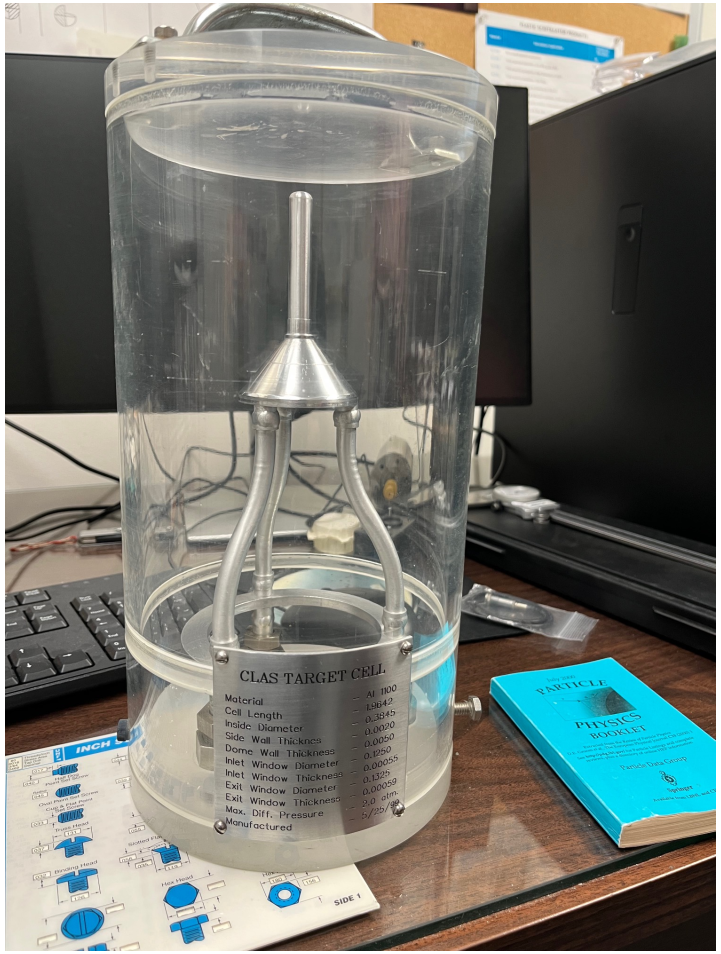


Hall B Cryo-target

All Aluminum cells used in CLAS electron scattering experiments:

- Single cell for CLAS/e1, a 5 cm long, 10 mm ID, and 15 μm thick entrance and exit windows.
- Dual cell, LD_2-LH_2, for CLAS/e5 with similar characteristics.

CLAS/e1

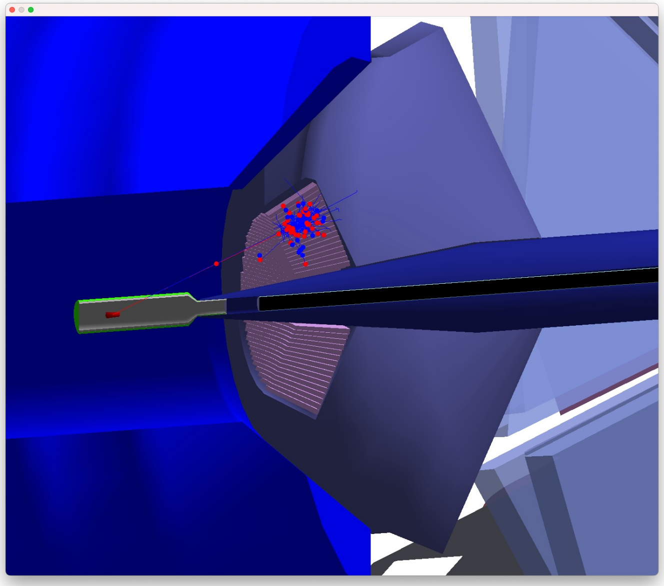


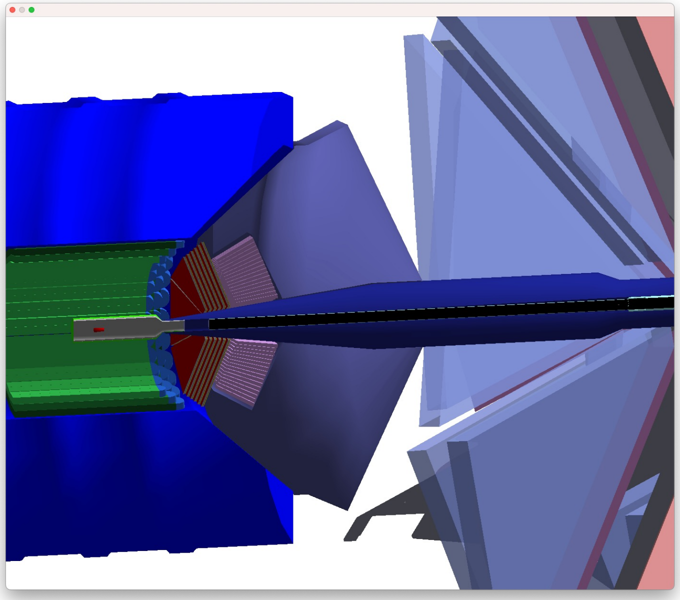
CLAS/e5

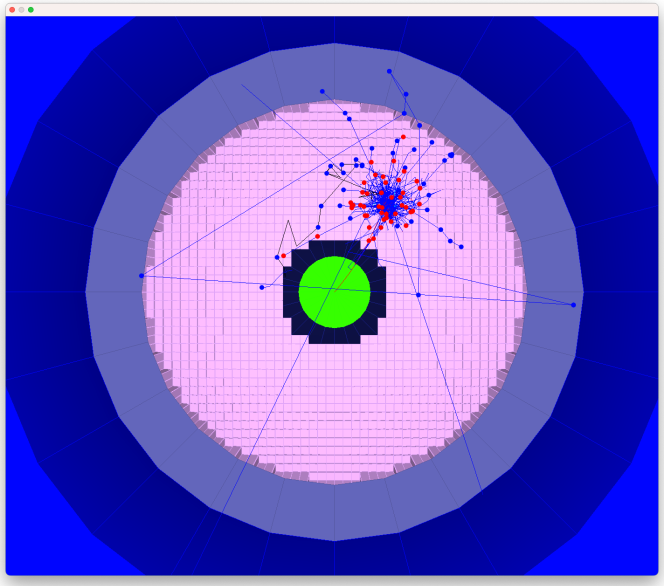
Back-up: wECAL

wECAL in GEMC

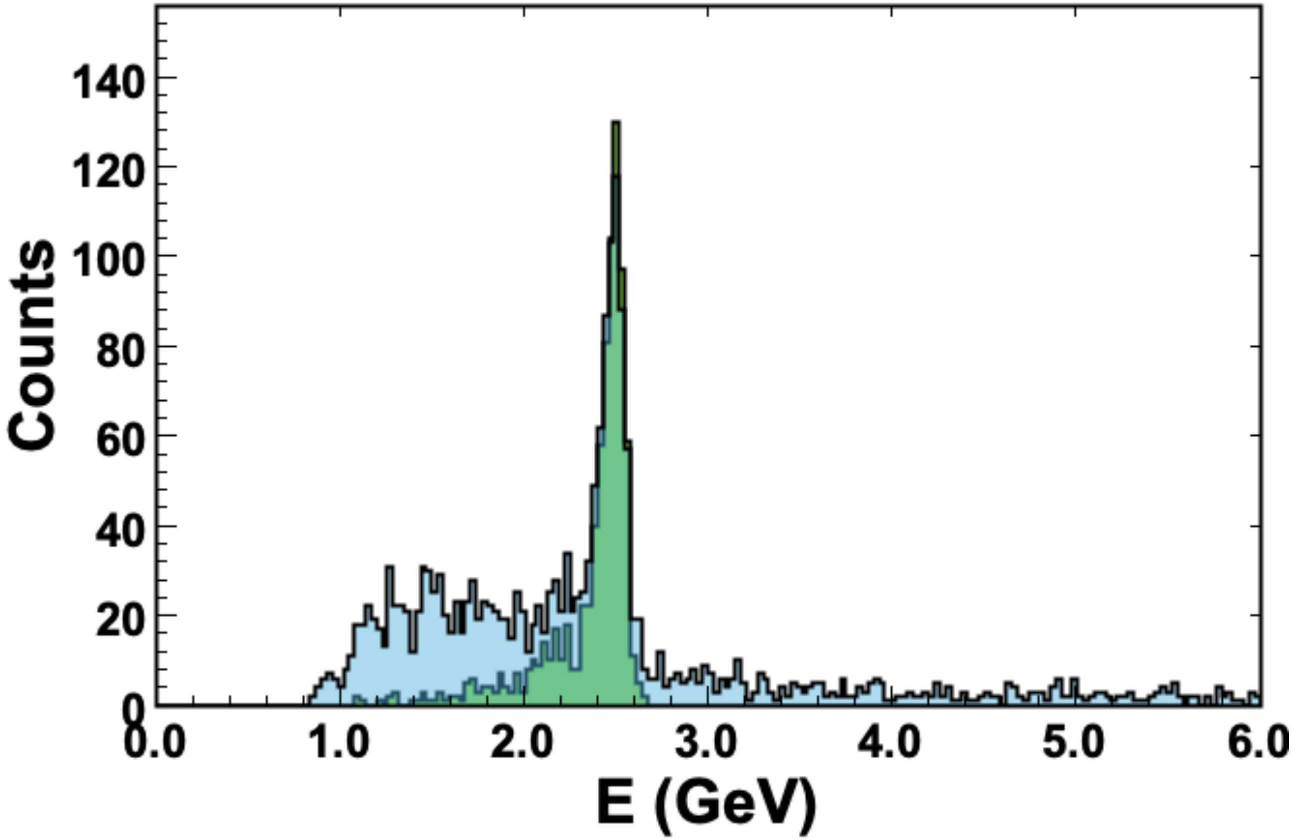
- Fully implemented in the CLAS12 GEANT4 model
  - Trapezoidal crystals with APD readout
  - Digitized signal includes fluctuations in scintillation light, APD QE and noise, preamplifier noise
- Reconstruction implemented in the CLAS12 framework
  - Clustering
  - Energy leakage correction







Electrons in wECAL

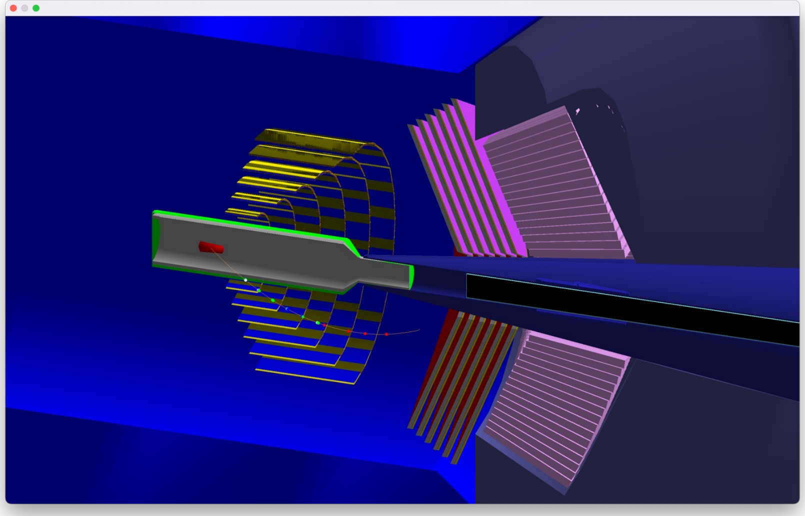


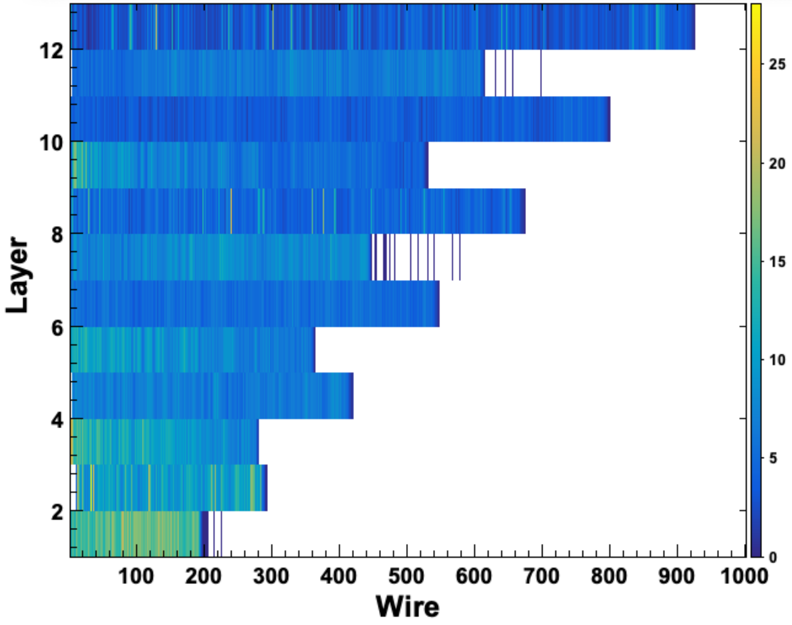
- 2.5 GeV electron between 8 and 29 deg (to avoid calorimeter edges)
- Comparison of pure signal and signal with bg (10^{37} luminosity in 100 ns window)
- Clusters with seed > 0.5 GeV and size>4, hit threshold 30 MeV

Back-up: Recoil tracker

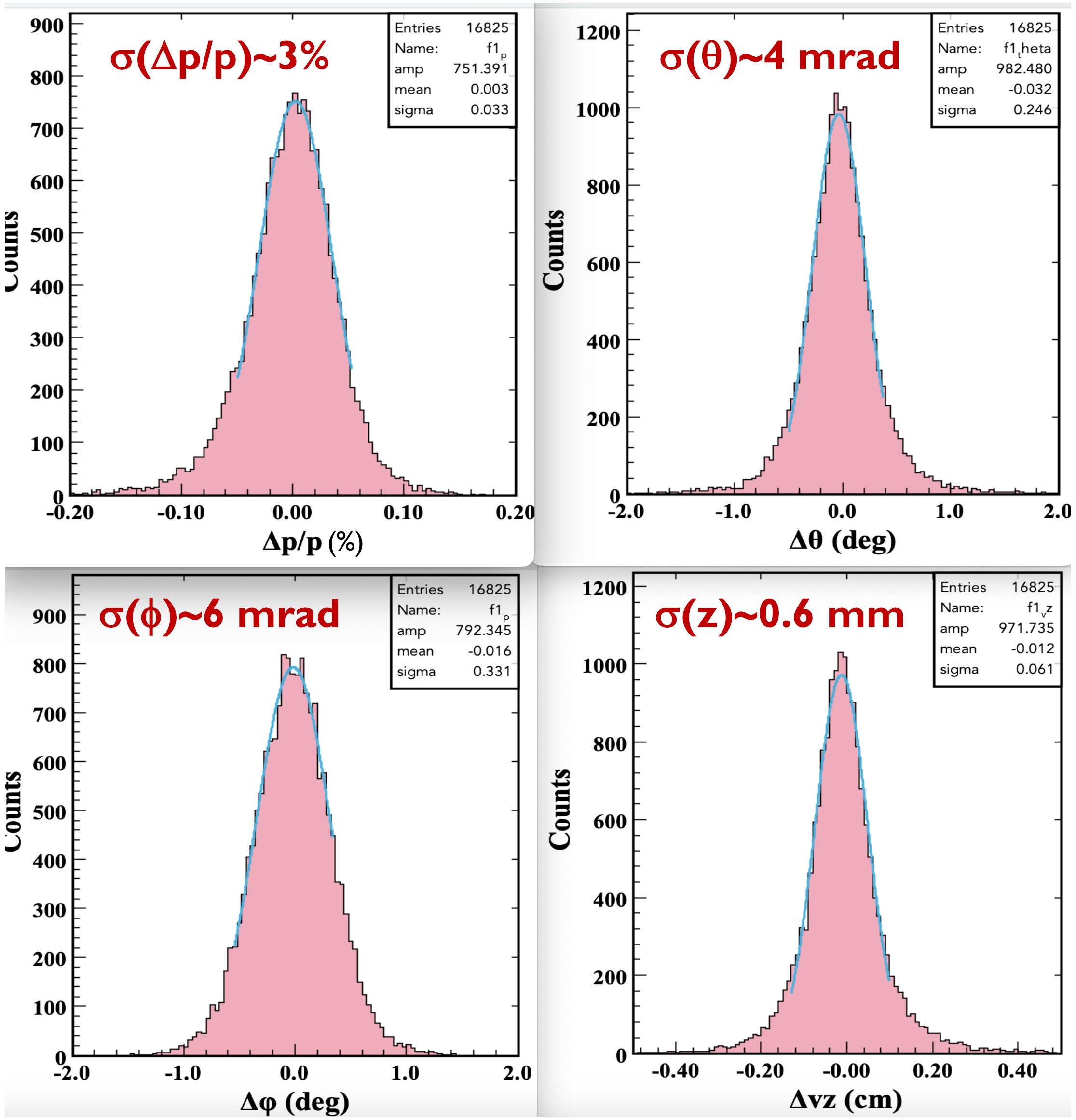
Recoil tracker simulation and occupancy

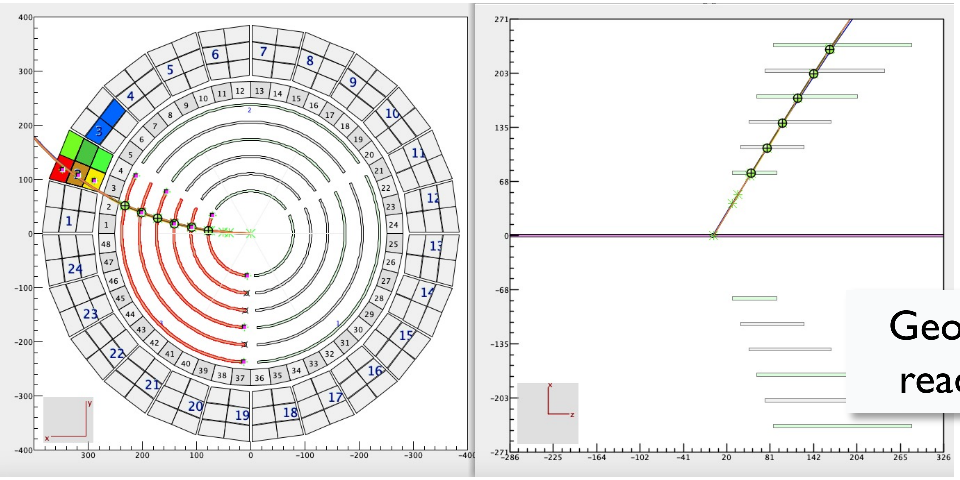
- Implemented in the CLAS12 GEANT4 model
  - 6 regions x 3 sectors of uRWell detectors
  - Dual readout with strips along and at fixed z (arcs), inspired by the layout of the existing CLAS12 central uMegas tracker
  - Digitized signal from energy deposited in the gas layer, including fluctuations in the number of electron-ion pairs and diffusion
- Background simulations
  - Occupancy estimated in a 100 ns window with a minimal energy threshold (one primary electron-ion pair)
  - Maximum occupancy in the innermost detector with average ~15% (~5% in the outermost)
  - "Effective" occupancy affecting track reconstruction can be easily reduced by a factor of several with timing cuts and a higher threshold



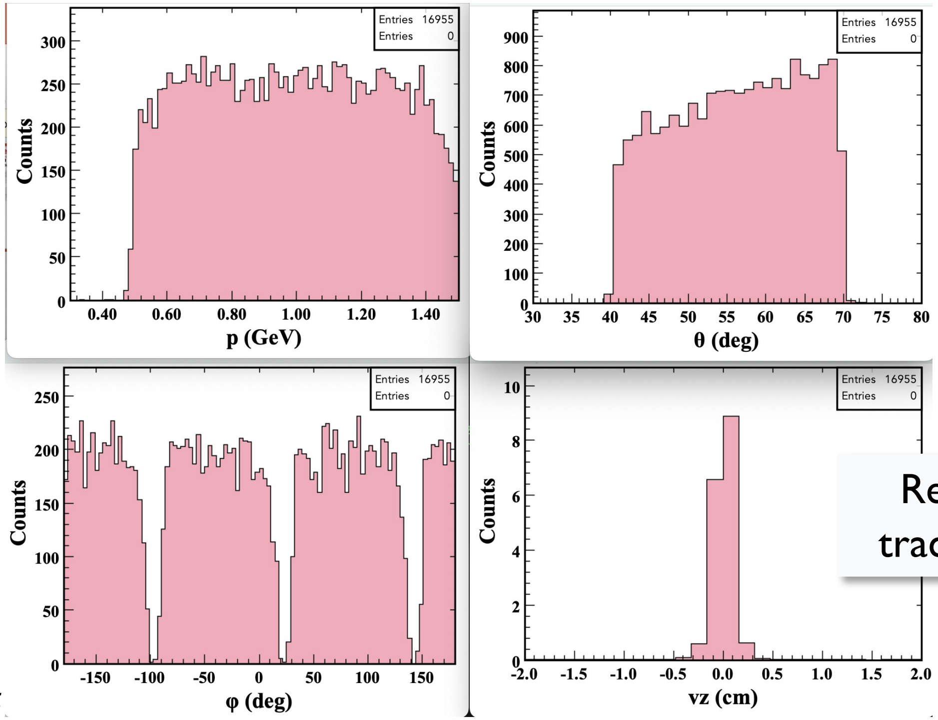


Recoil tracker reconstruction





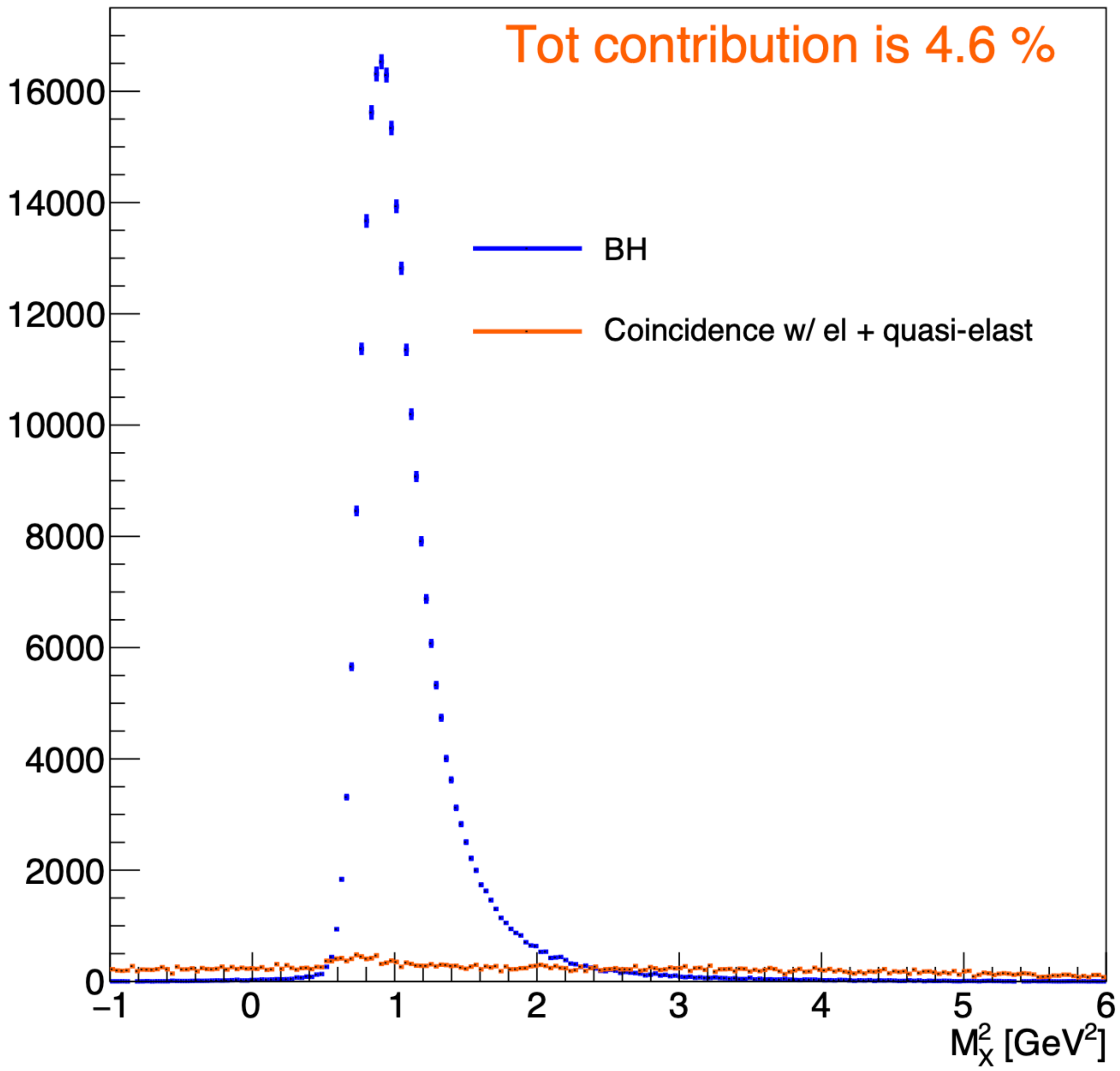
Geometry in ced read from sqlite



Reconstructed track parameters

Back-up: Backgrounds

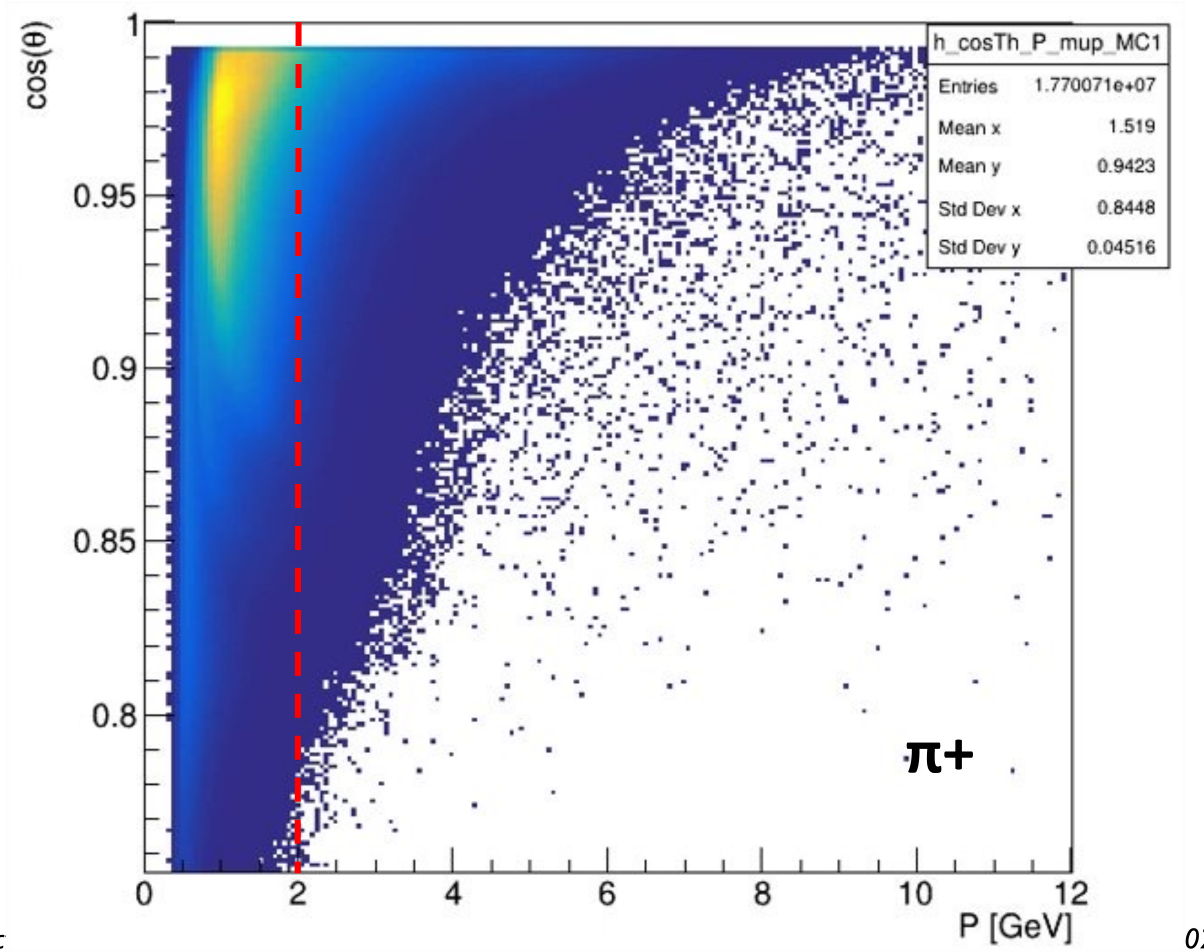
Coincidence rates

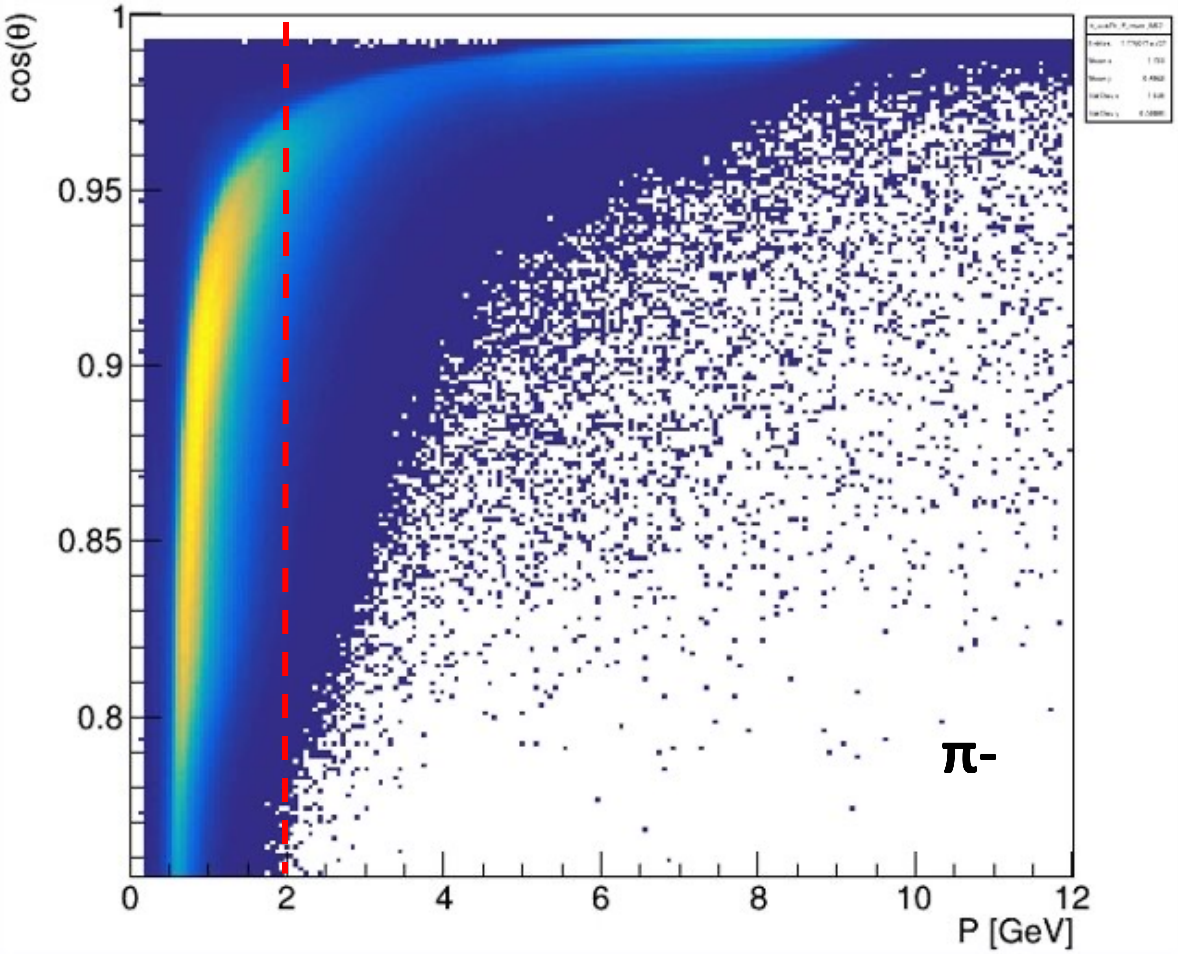


Pion Background 1

Kinematic distributions from CLAS12 RG-A

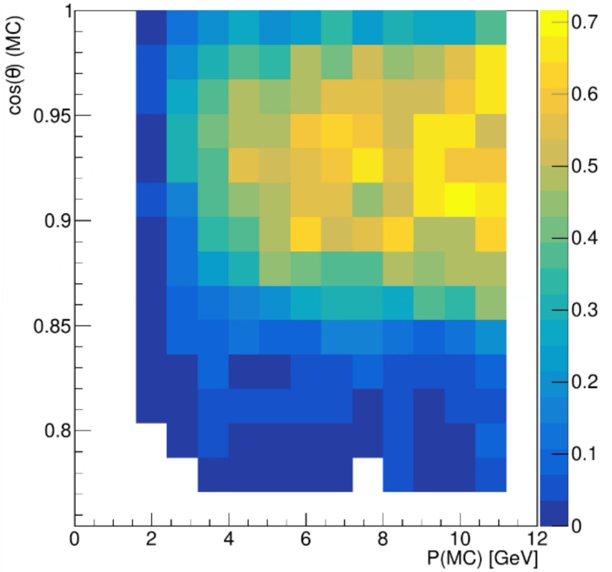
- Majority of pions are below 2 GeV. Under 2 GeV, MIPs lose almost all their energy and don't get reconstructed.
- In addition, lower momenta and high cos_theta has several times lower survival probability than high momenta.
- Effective survival probability is roughly 0.23%-0.3%





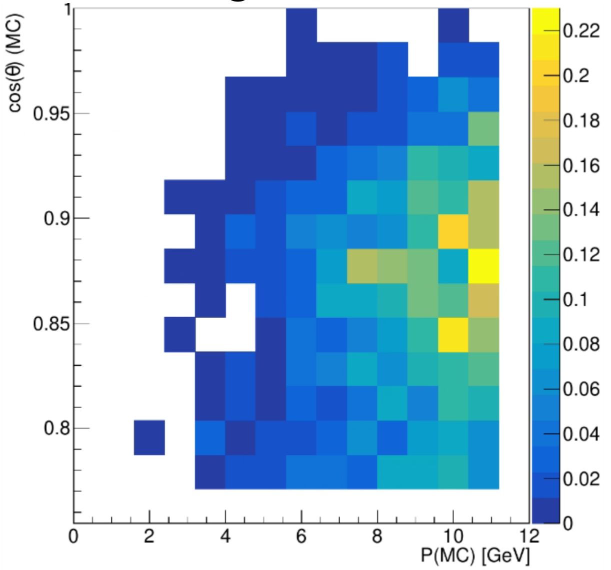
Pion survival rates

Positive MIP



a)

Negative MIP

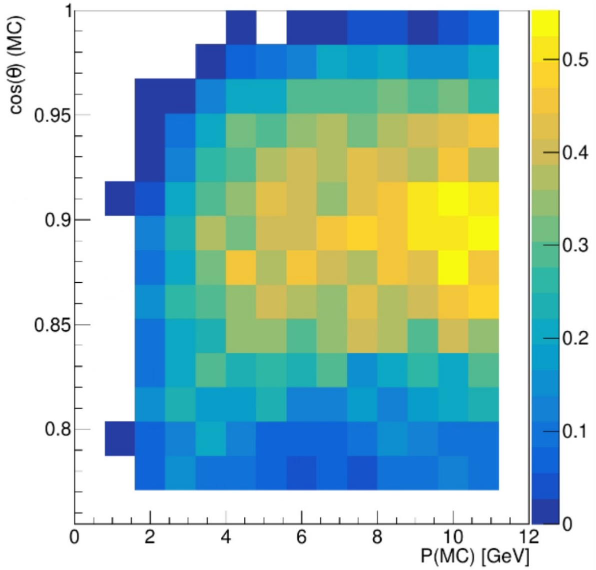


b)

π^+ survival rates

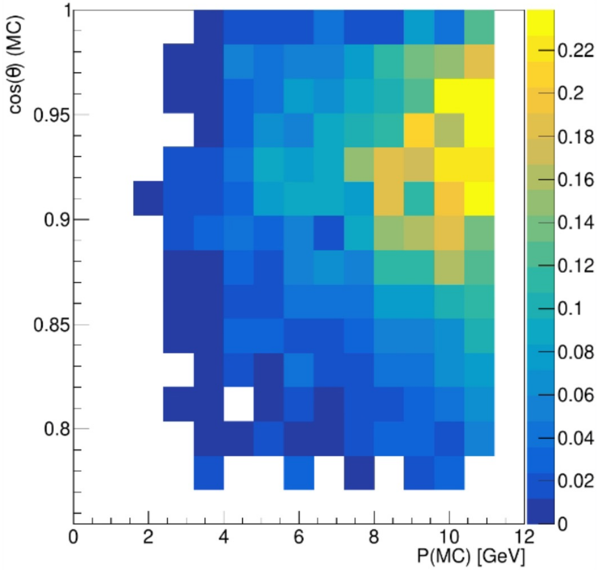
π^- survival rates

Positive MIP



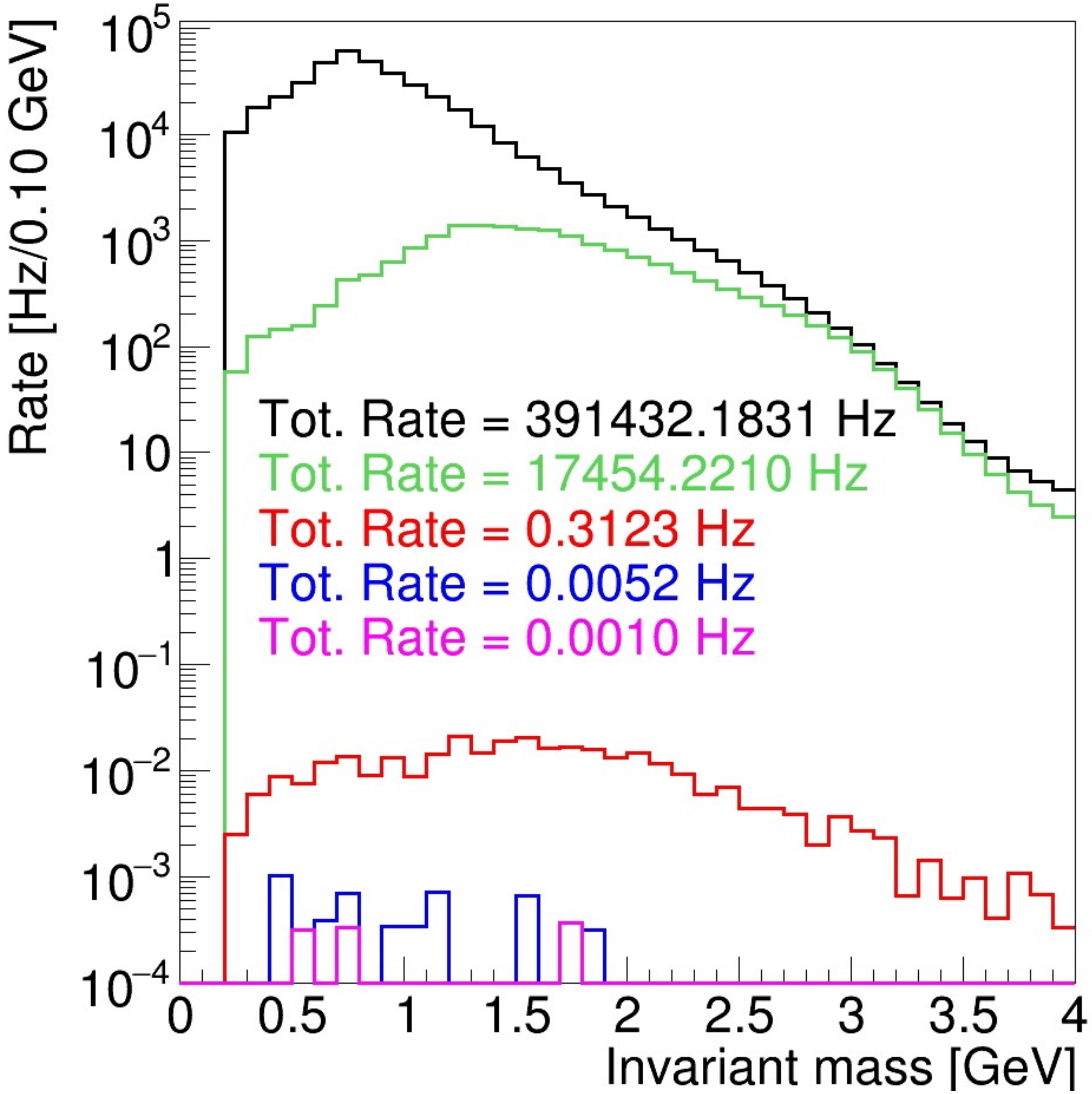
a)

Negative MIP



b)

Pion Background 2

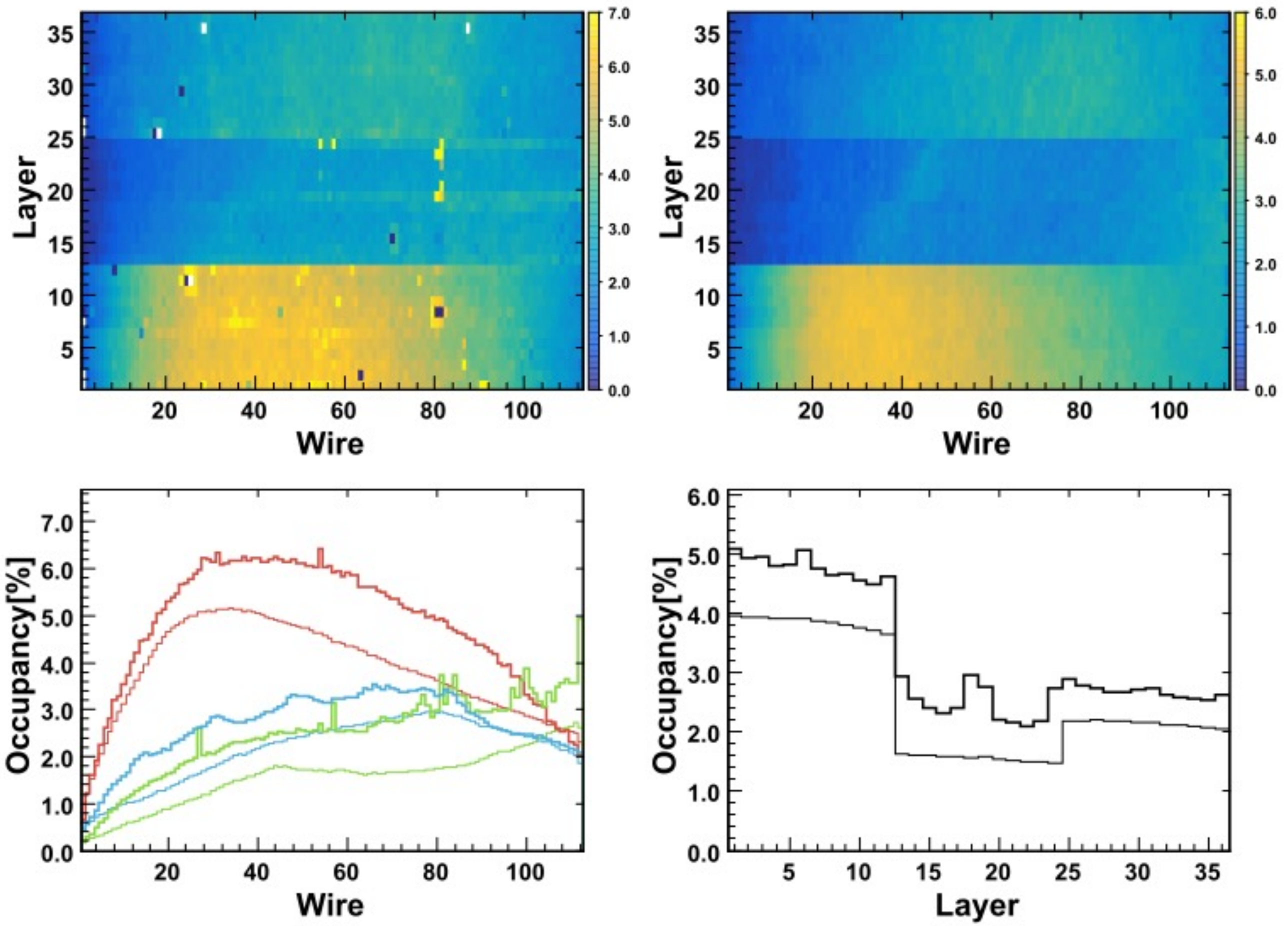


The green histogram has both pions momenta greater than 2 GeV.

With 0.3% survival probability the rate of Red histogram would be estimated as 17K*0.003*0.003 = 0.16 Hz, which is comparable with the rate we got from GEANT4 (0.3123 Hz)

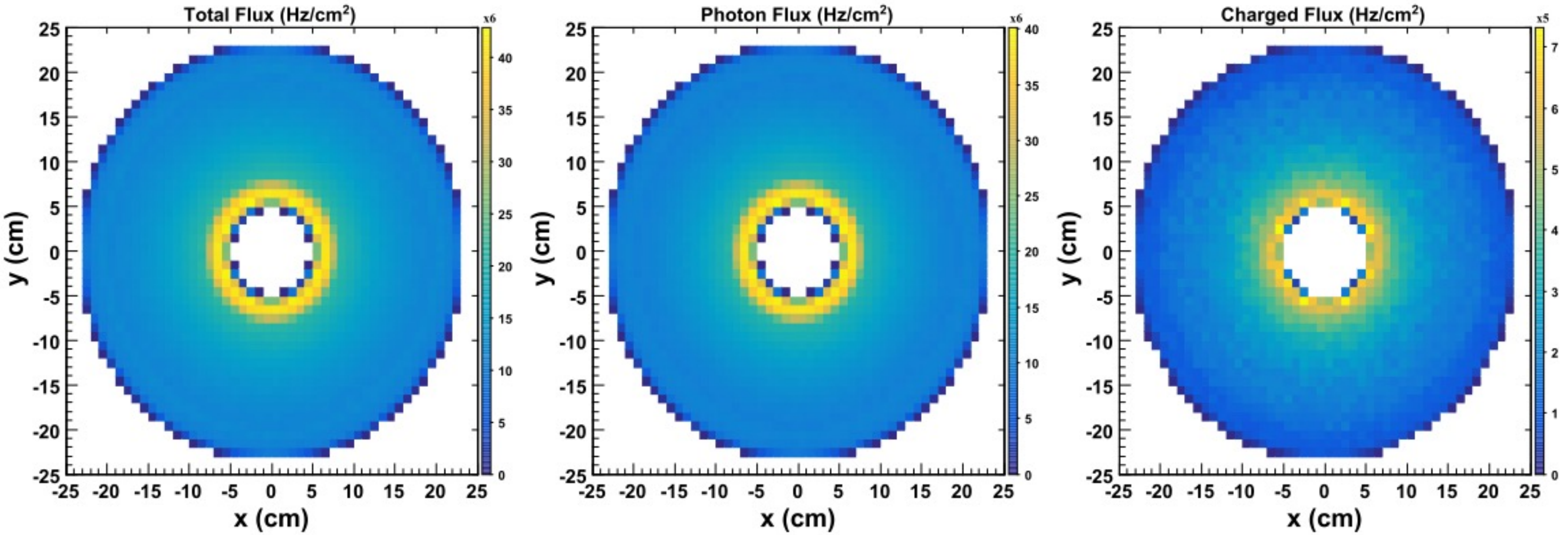
Back-up: Rates

Rates in subsystems: validation of DC simulation in CLAS12



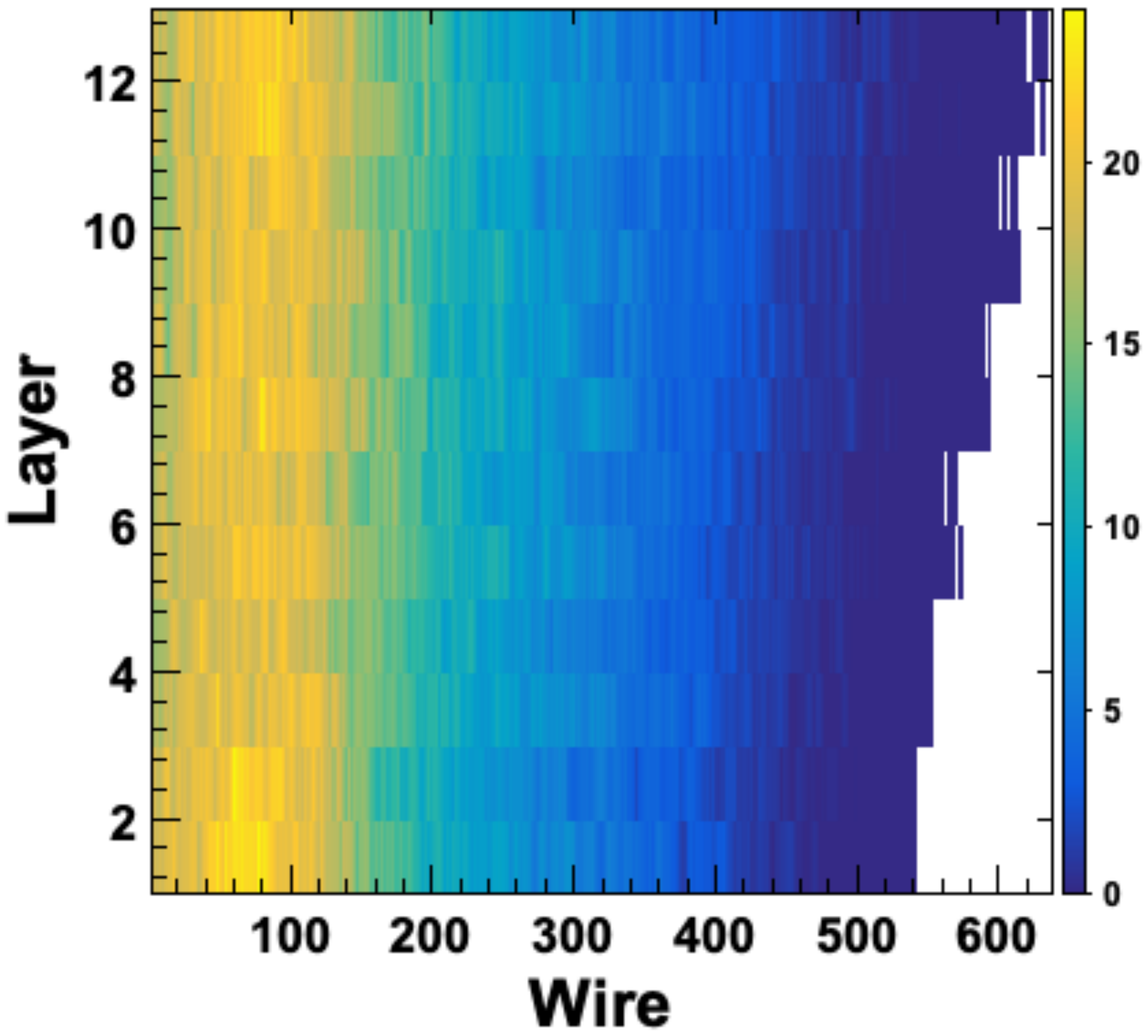
Drift chamber (DC) occupancies measured from CLAS12 data during the RG-A run and simulated using GEMC. Top row: 2D distributions of wire occupancy versus DC layer and wire number, shown for experimental data (left) and Monte Carlo simulation (right). Bottom row: Integrated occupancies per wire (left) and per layer (right), with darker lines representing data and lighter lines representing simulation.

Rates in subsystems: FVT



Rates of particles at a luminosity of 10^{37} cm^{-2}s^{-1} crossing the scoring plane located 40 cm downstream from the target center. Left: total particle rate; middle: rate of photons; and right: rate of charged particles only.

Rates in subsystems: FVT

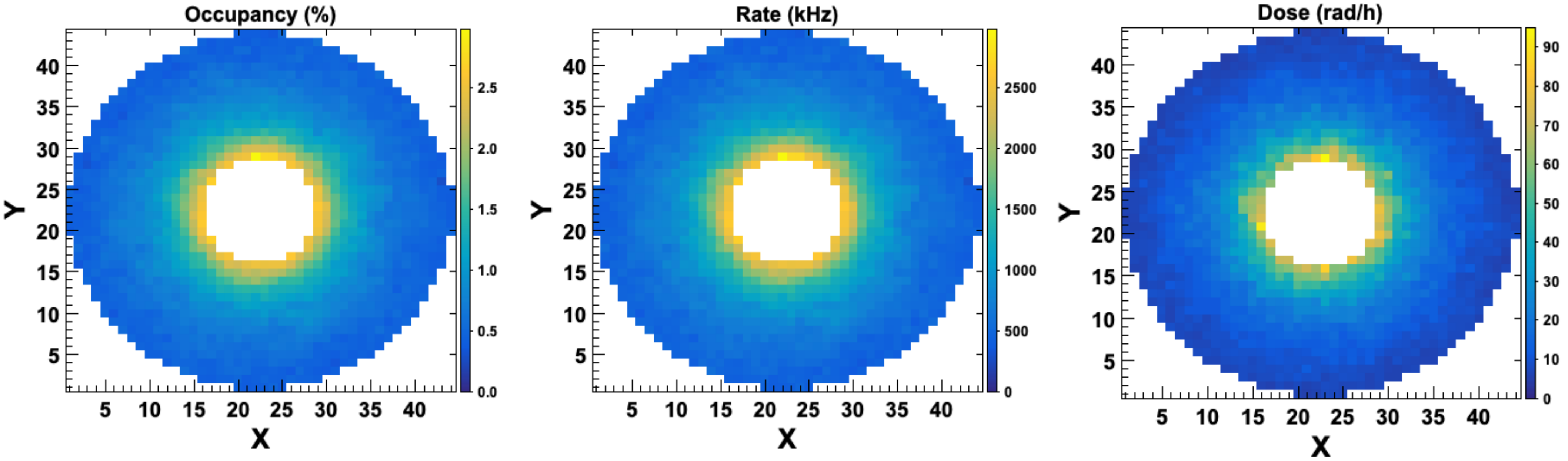


- Plot showing the occupancy in one sector within a 100 ns window. The maximum of ~20% corresponds to a rate per strip of 2 MHz. The average is about 8% i.e. 800kHz. Done with a threshold on the energy seen by the strip of 25 eV which gives a cluster size of 2-3. Accounting for the cluster size, the hit rates mentioned above correspond to a cluster rate of 1MHz (max) and 400 kHz (average).

- Coincidence with muon track to reduce the integration window by a factor 5

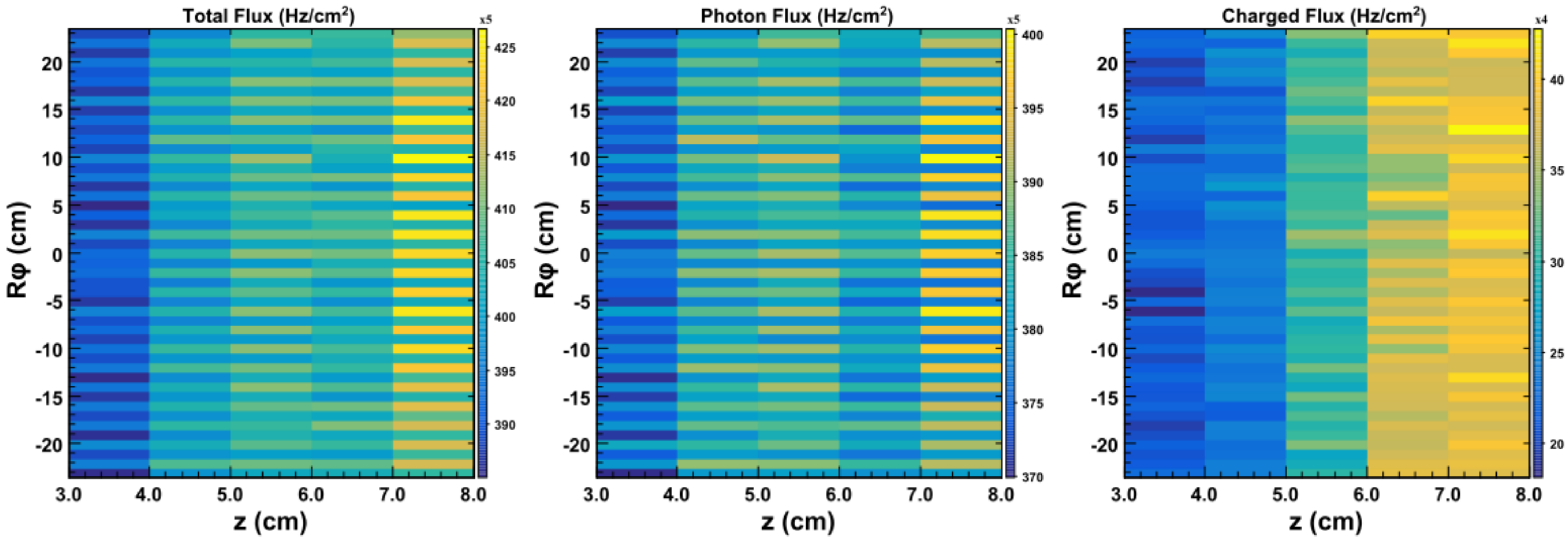
- SBS max occupancy: 50%

Rates in subsystems: wECAL



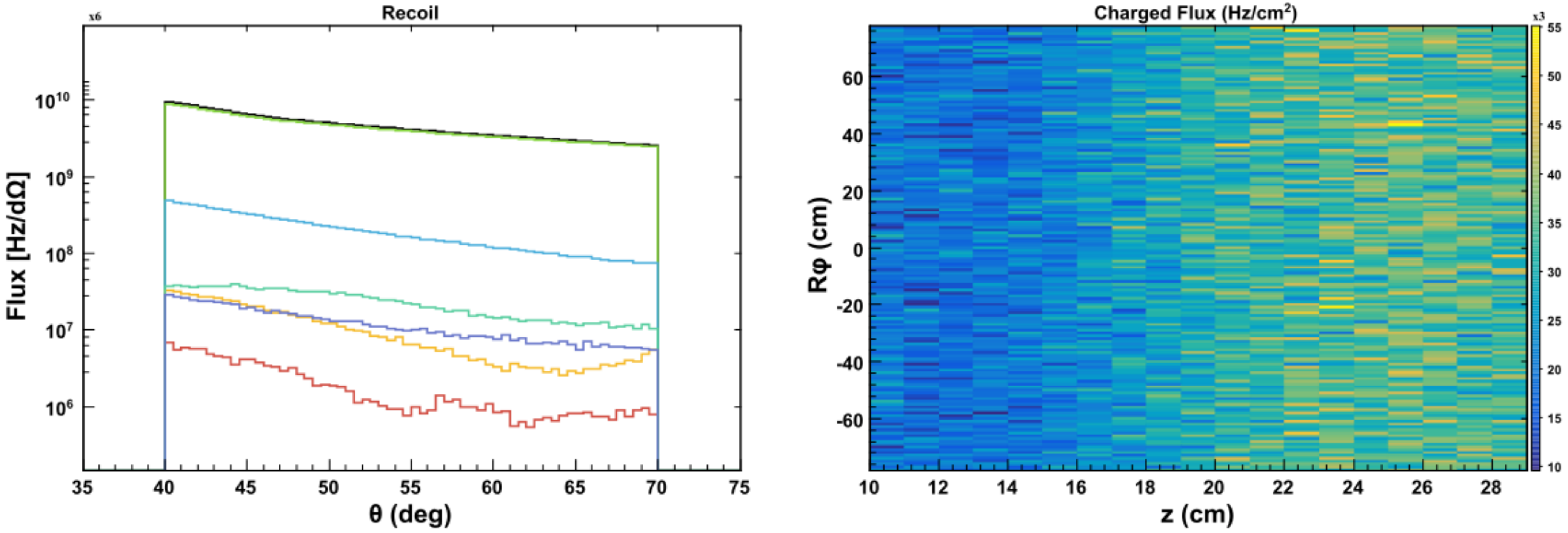
- Occupancy and rates for deposited energy >20 MeV
- Estimated dose for 200 days <5x10^5 rad = 5000 Gy

Rates in subsystems: Recoil tracker



Rates of particles at the cylindrical scoring plane located at a 7.5 cm radius from the beam axis, at a luminosity of 10^{37} cm^{-2}s^{-1}. Left: Rates for different particle types as a function of polar angle, applying a 10 keV energy threshold. Right: Azimuthal and longitudinal (z) distribution of rates for photons and charged particles.

Rates in subsystems: Recoil hodoscope



Rates of particles at the cylindrical scoring plane located at a 25 cm radius from the beam axis, at a luminosity of 10^{37} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Left: Rates for different particle types as a function of polar angle. Color lines are: black is the total rate, green - photons, blue - neutrons, yellow - protons, cyan - pions, red - electrons. Right: Azimuthal and longitudinal (z) distribution of rates for charged particles.

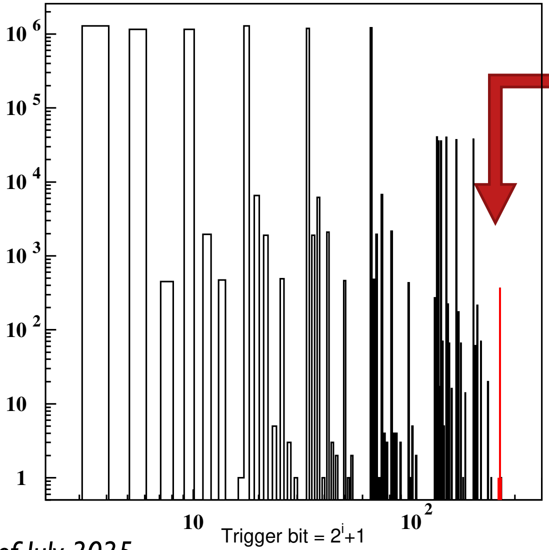
Back-up: Trigger

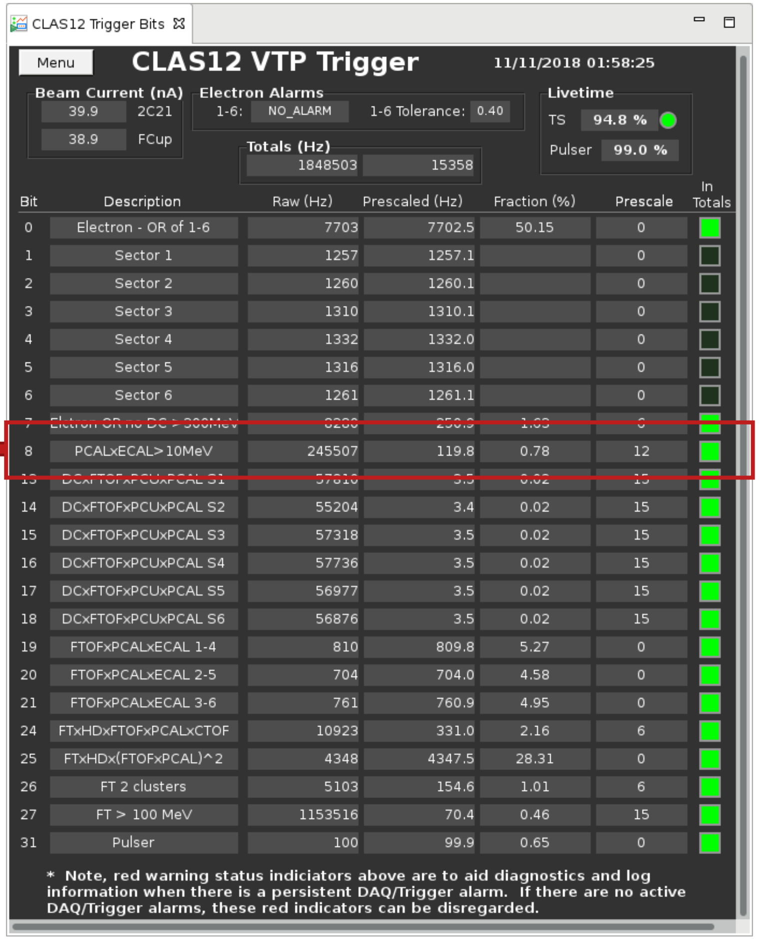
Trigger : Single MIP trigger rate from the CLAS12 RG-A data

- Multiple trigger configurations have been used for RG-A data taking. Highly prescaled (1:2049) trigger bit 8 (TB8) counts hits in fECal with energy > 10 MeV.
- Any particle: $e^{\pm}, n, p, \gamma, h^{\pm}$ that reaches the calorimeter and deposits > 10 MeV energy will activate TB8.
- μCLAS12 will use a single charge particle trigger with 10 MeV to 400 MeV energy deposition in the calorimeter. The RG-A TB8 is well well-suited to estimate a single MIP trigger rate for μCLAS12.

- We analyzed RG-A data corresponding to about $53{\times}10^{37}$ cm^{-2} integrated luminosity, using events acquired with TB8.
- We found a total of 53000 events with at least one negatively or positively charged particle that had 10 MeV to 400 MeV energy deposition in fECal.

- The mCLAS12 MC studies show that less than 1% of those will penetrate through the Pb shield.
- This corresponds to 10 Hz at 10^{37} cm^{-2} sec^{-1} luminosity.
- Accounting for the prescale factor of TB8, we will end up with 20.5 kHz trigger rate for mCLAS12.



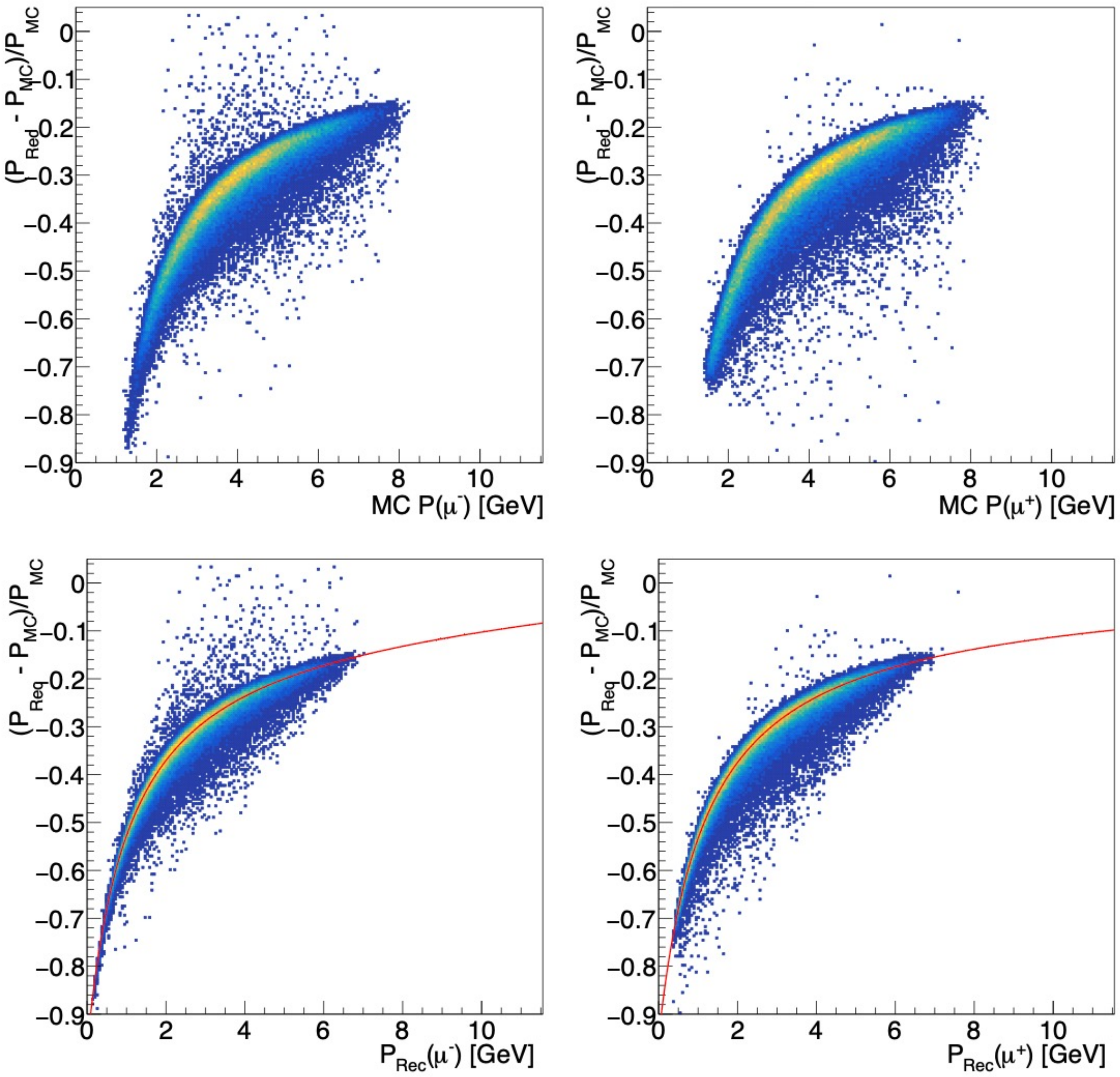


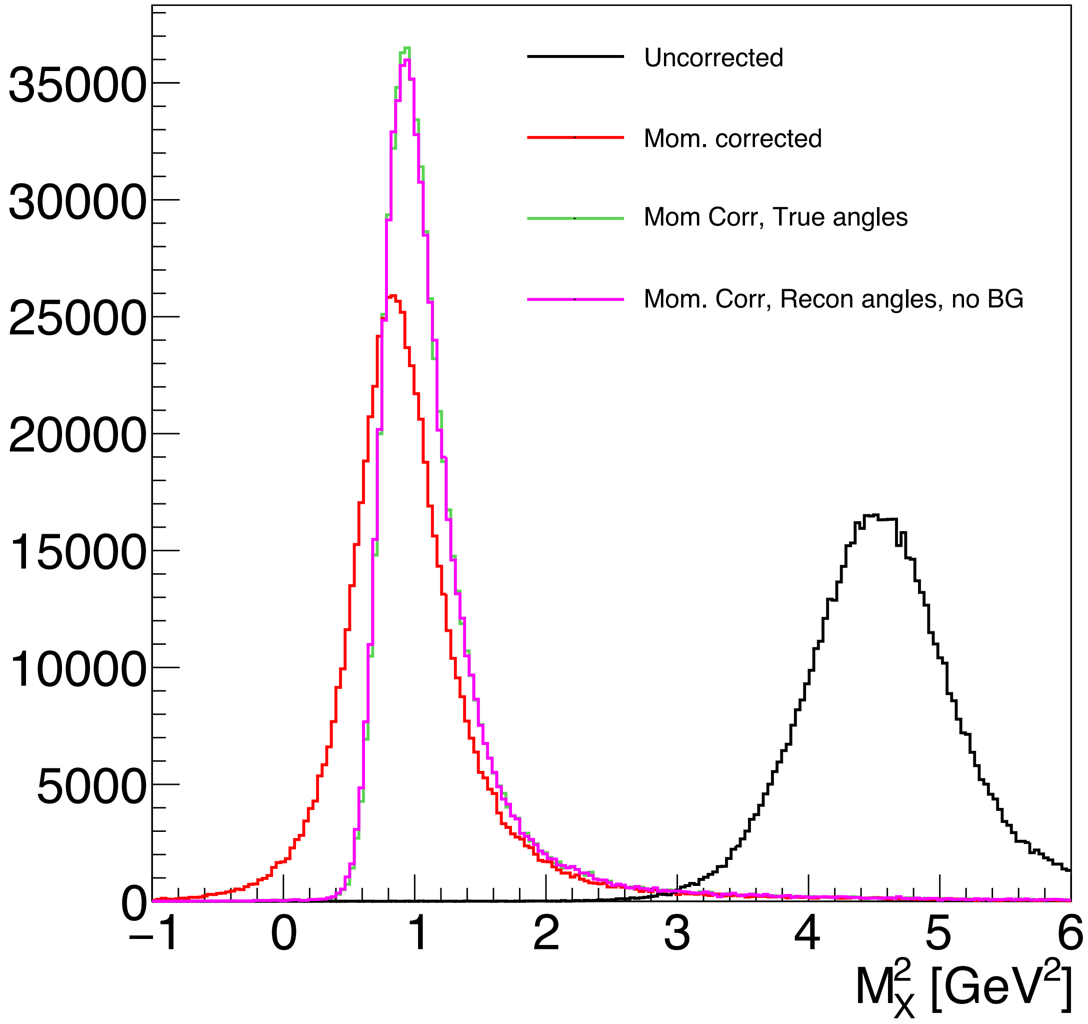
Bit	Description	Raw (Hz)	Prescaled (Hz)	Fraction (%)	Prescale	In Totals
0	Electron - OR of 1-6	7703	7702.5	50.15	0	
1	Sector 1	1257	1257.1		0	
2	Sector 2	1260	1260.1		0	
3	Sector 3	1310	1310.1		0	
4	Sector 4	1332	1332.0		0	
5	Sector 5	1316	1316.0		0	
6	Sector 6	1261	1261.1		0	
7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
8	PCALxECAL>10MeV	245507	119.8	0.78	12	
13	DCxFTOFxPCUxPCAL S1	[illegible]	3.5	0.02	15	
14	DCxFTOFxPCUxPCAL S2	55204	3.4	0.02	15	
15	DCxFTOFxPCUxPCAL S3	57318	3.5	0.02	15	
16	DCxFTOFxPCUxPCAL S4	57736	3.5	0.02	15	
17	DCxFTOFxPCUxPCAL S5	56977	3.5	0.02	15	
18	DCxFTOFxPCUxPCAL S6	56876	3.5	0.02	15	
19	FTOFxPCALxECAL 1-4	810	809.8	5.27	0	
20	FTOFxPCALxECAL 2-5	704	704.0	4.58	0	
21	FTOFxPCALxECAL 3-6	761	760.9	4.95	0	
24	FTxHDxFTOFxPCALxCTOF	10923	331.0	2.16	6	
25	FTxHDx(FTOFxPCAL)^2	4348	4347.5	28.31	0	
26	FT 2 clusters	5103	154.6	1.01	6	
27	FT > 100 MeV	1153516	70.4	0.46	15	
31	Pulser	100	99.9	0.65	0	

* Note, red warning status indiciators above are to aid diagnostics and log information when there is a persistent DAQ/Trigger alarm. If there are no active DAQ/Trigger alarms, these red indicators can be disregarded.

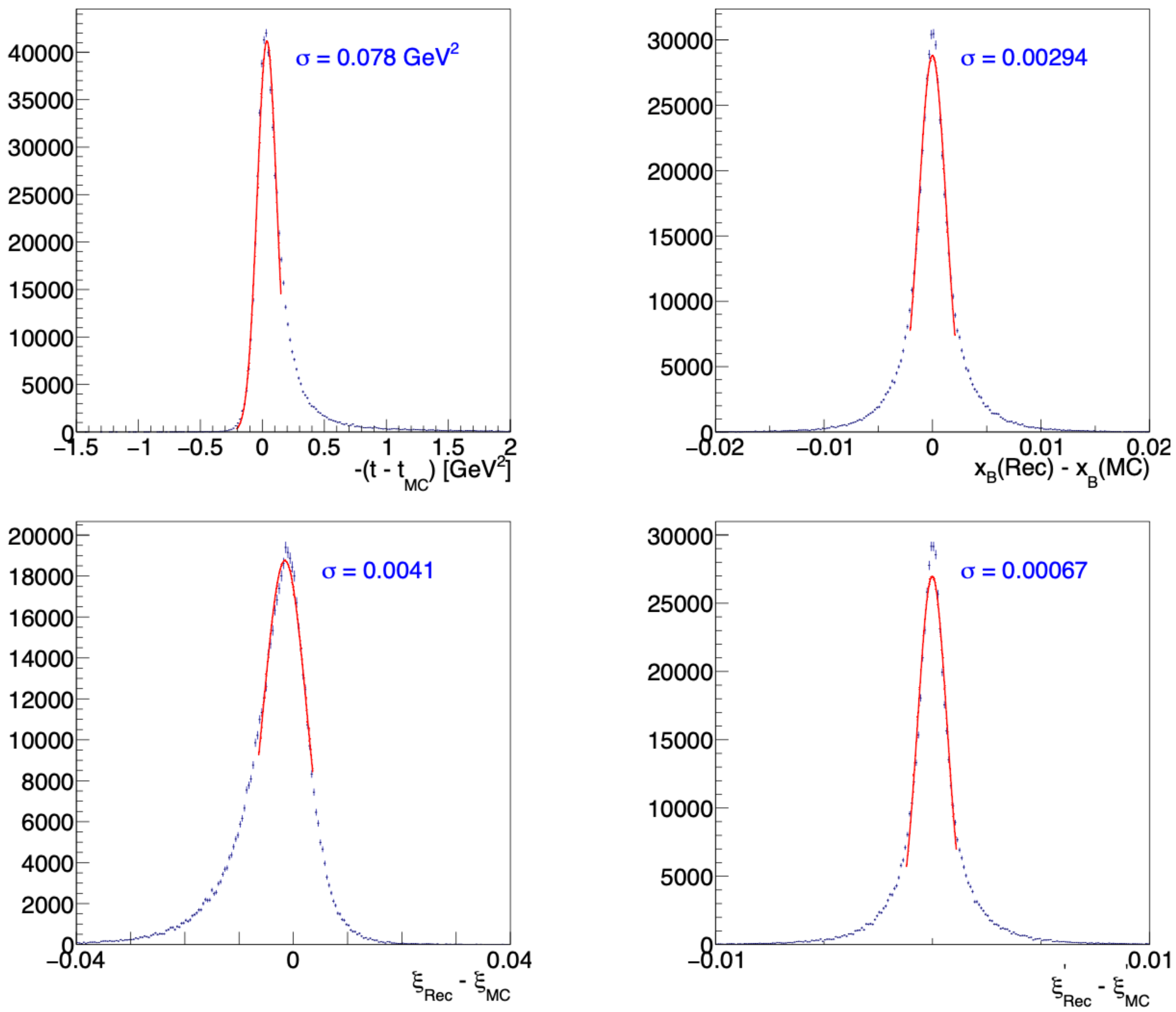
Back-up: Resolutions

Muon momentum corrections

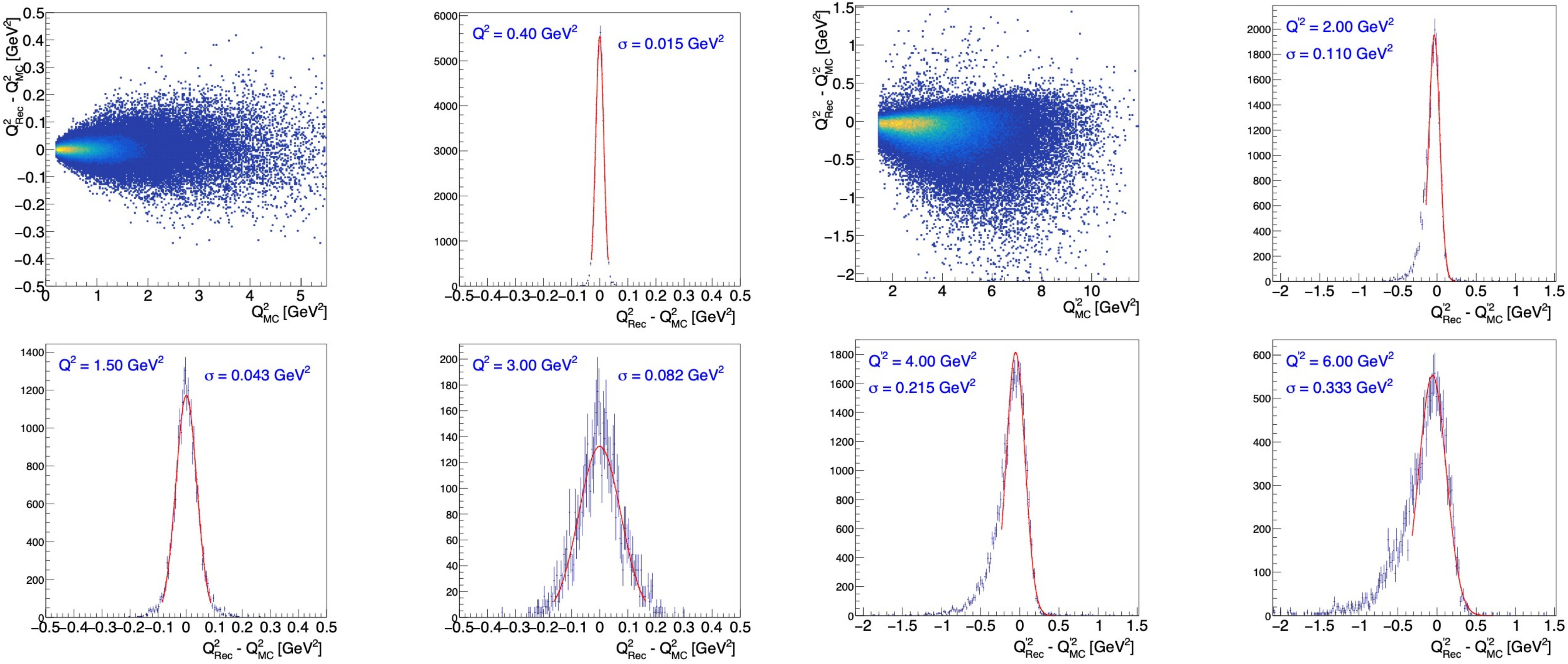




Resolutions: kinematic variables

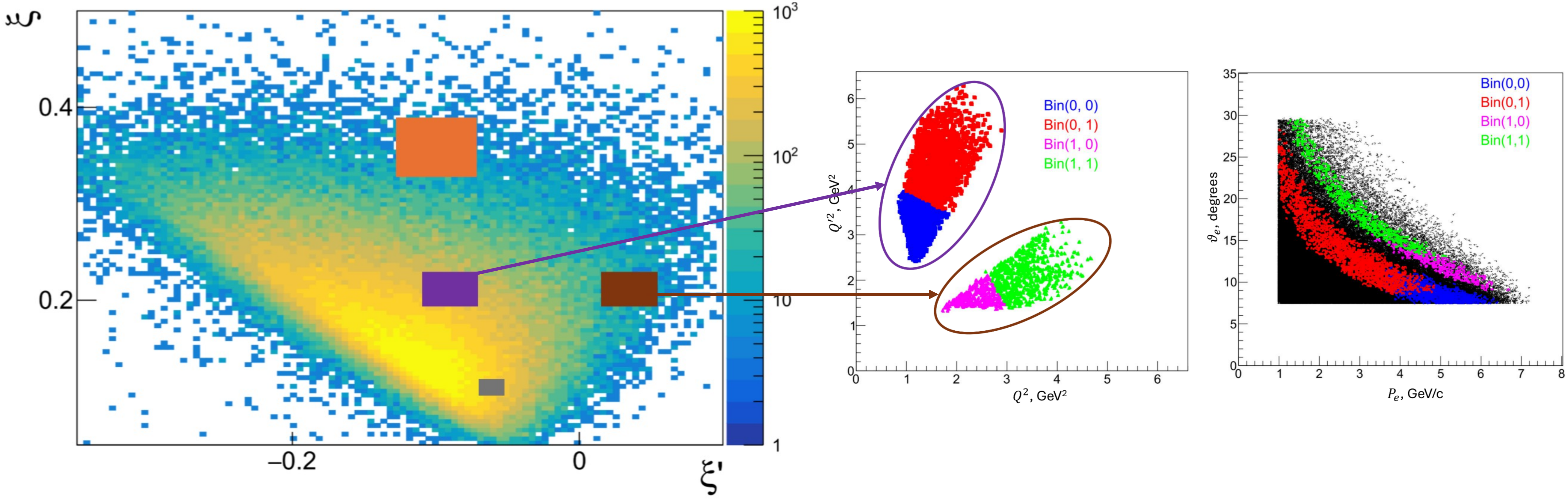


Resolutions: virtualities

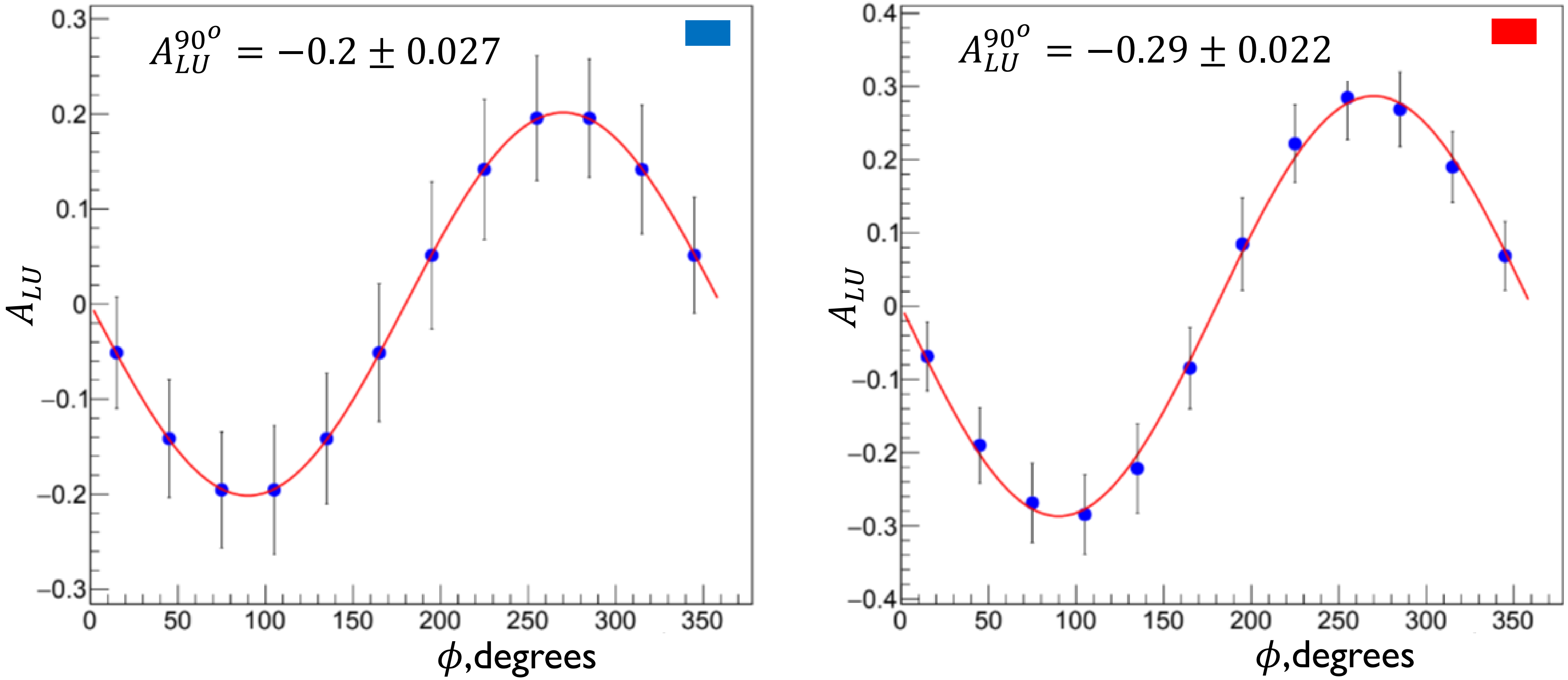


Back-up: Expected results DDVCS

More on DDVCS: Binning

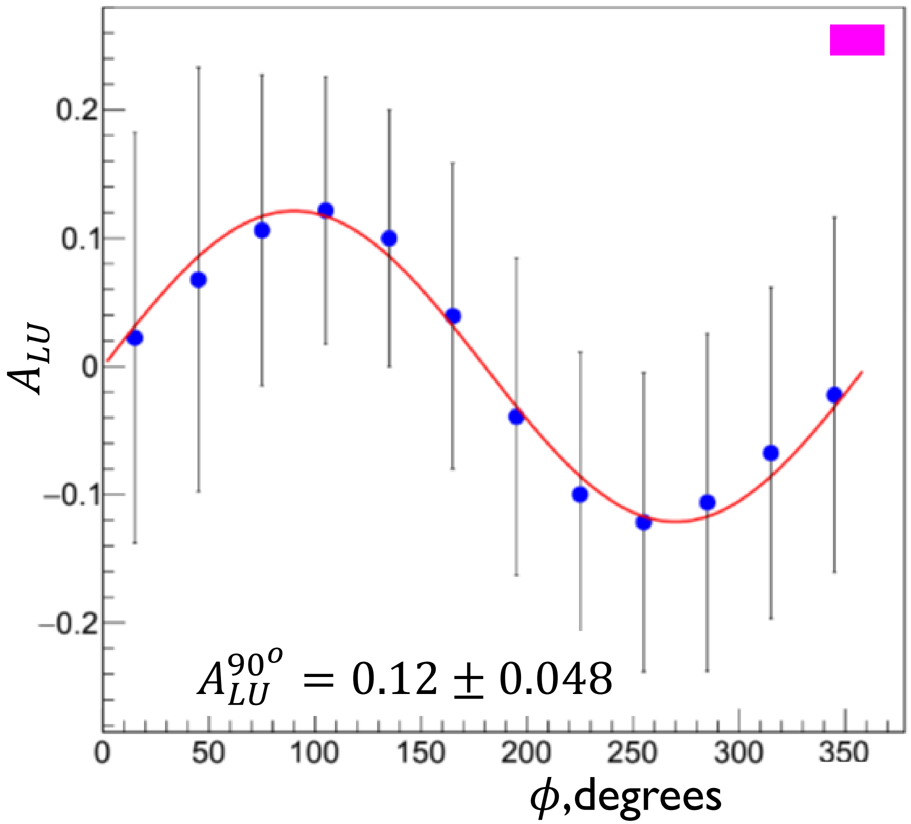


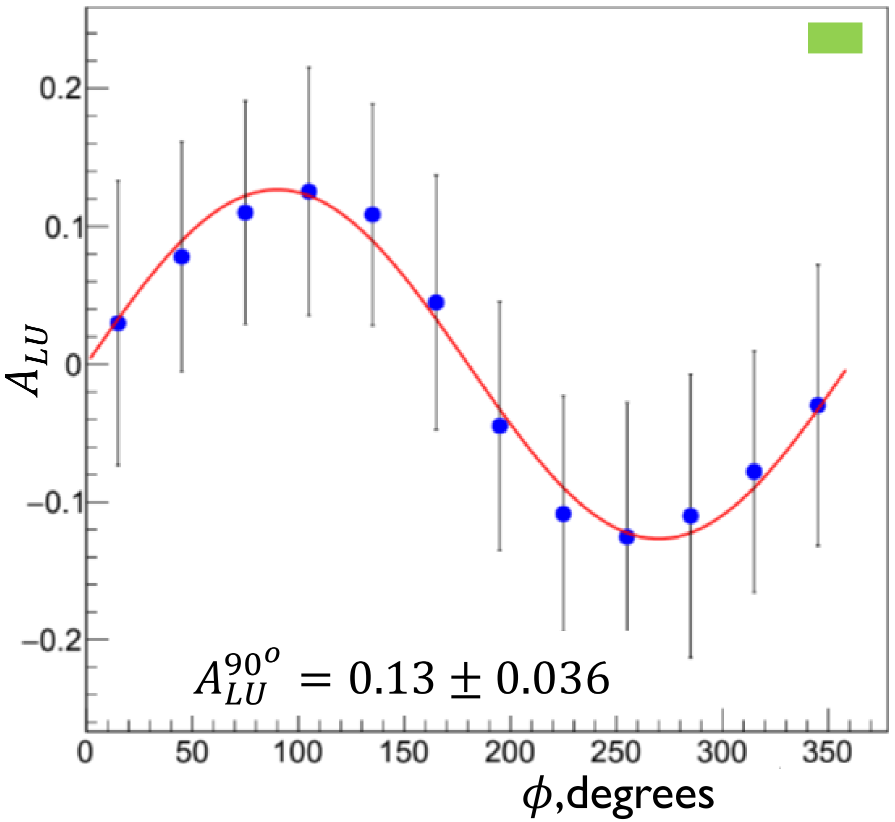
More on DDVCS: error bars on BSA 1



Time-like region: on the left - $\bar{Q}^2 = 1.24$ GeV^2, $\bar{Q}'^2 = 3.3$ GeV^2, $\bar{x}_B = 0.11$, and $-\bar{t} = 0.33$ GeV^2; on the right - $\bar{Q}^2 = 1.63$ GeV^2, $\bar{Q}'^2 = 4.55$ GeV^2, $\bar{x}_B = 0.1$, and $-\bar{t} = 0.34$ GeV^2.

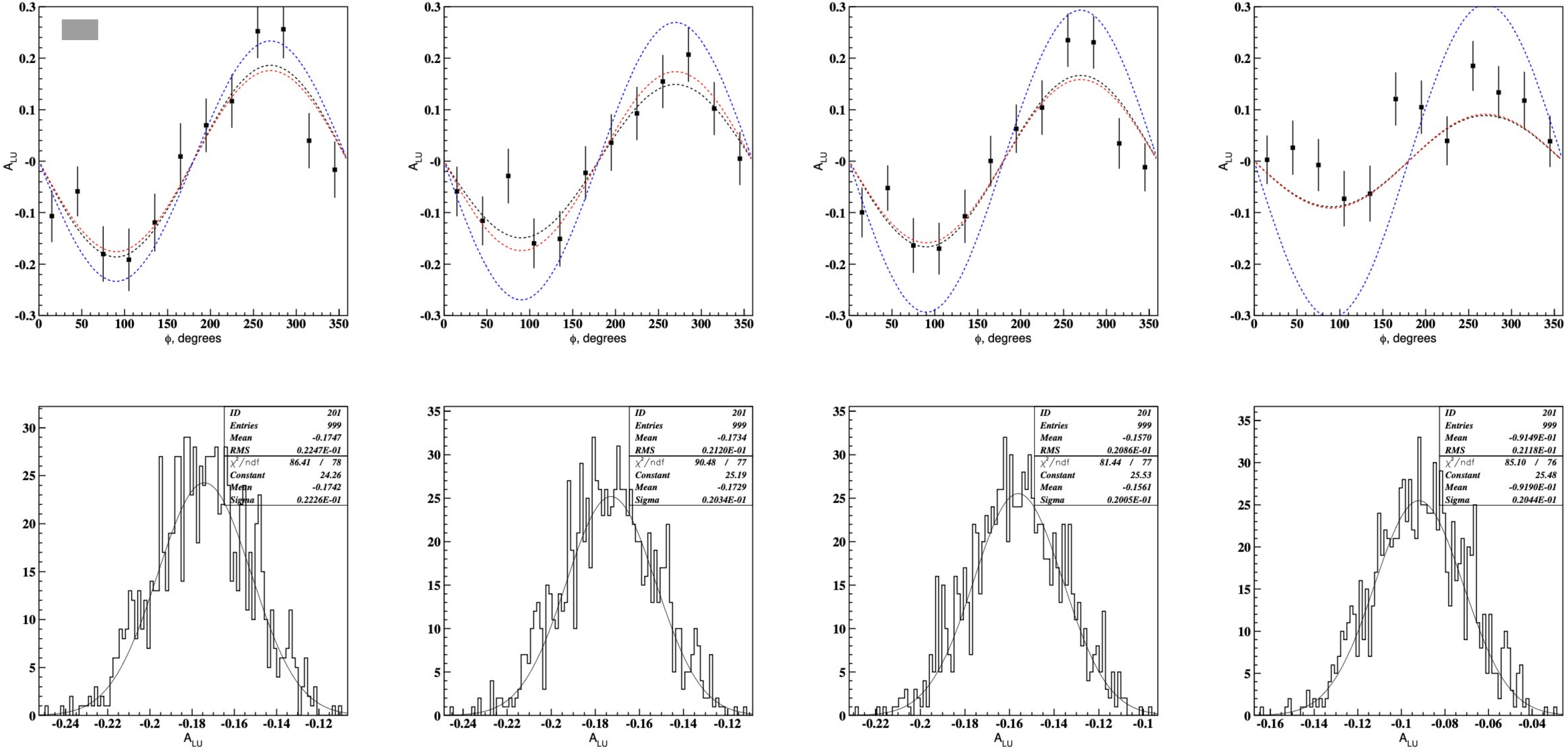
More on DDVCS: error bars on BSA 2





Space-like region: on the left - $\bar{Q}^2 = 2.4$ GeV^2, $\bar{Q}'^2 = 1.64$ GeV^2, $\bar{x}_B = 0.21$, and $-\bar{t} = 0.33$ GeV^2; on the right - $\bar{Q}^2 = 3.38$ GeV^2, $\bar{Q}'^2 = 2.14$ GeV^2, $\bar{x}_B = 0.21$, and $-\bar{t} = 0.34$ GeV^2.

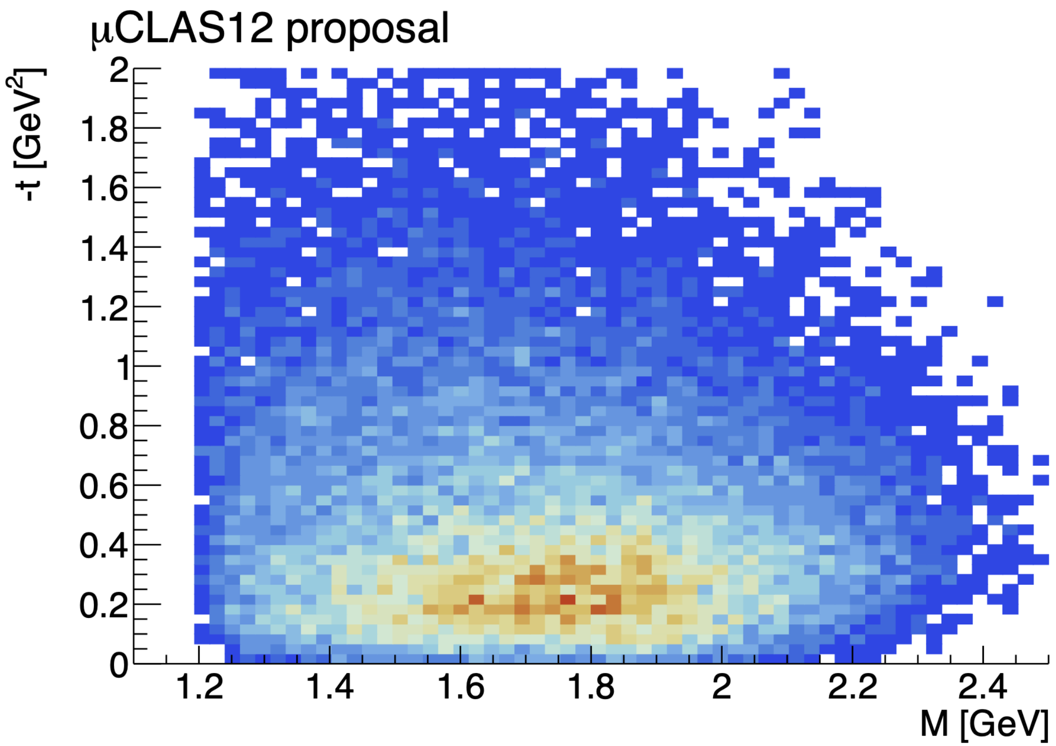
More on DDVCS: error bars on BSA 3

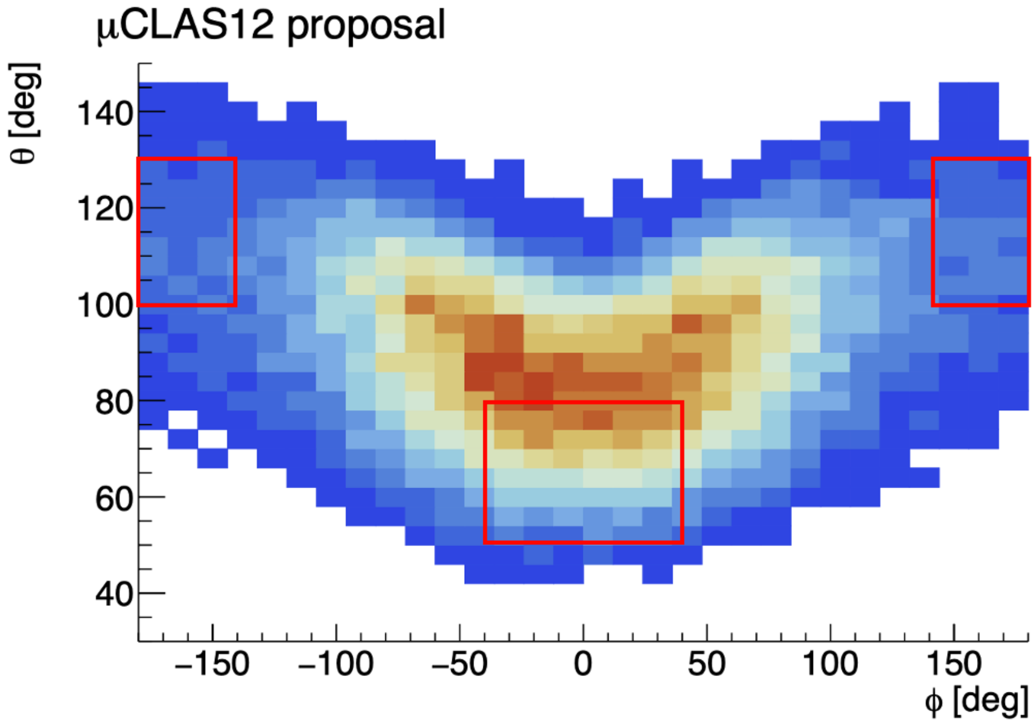


Back-up: Expected results TCS

More on Timelike Compton Scattering: kinematic coverage

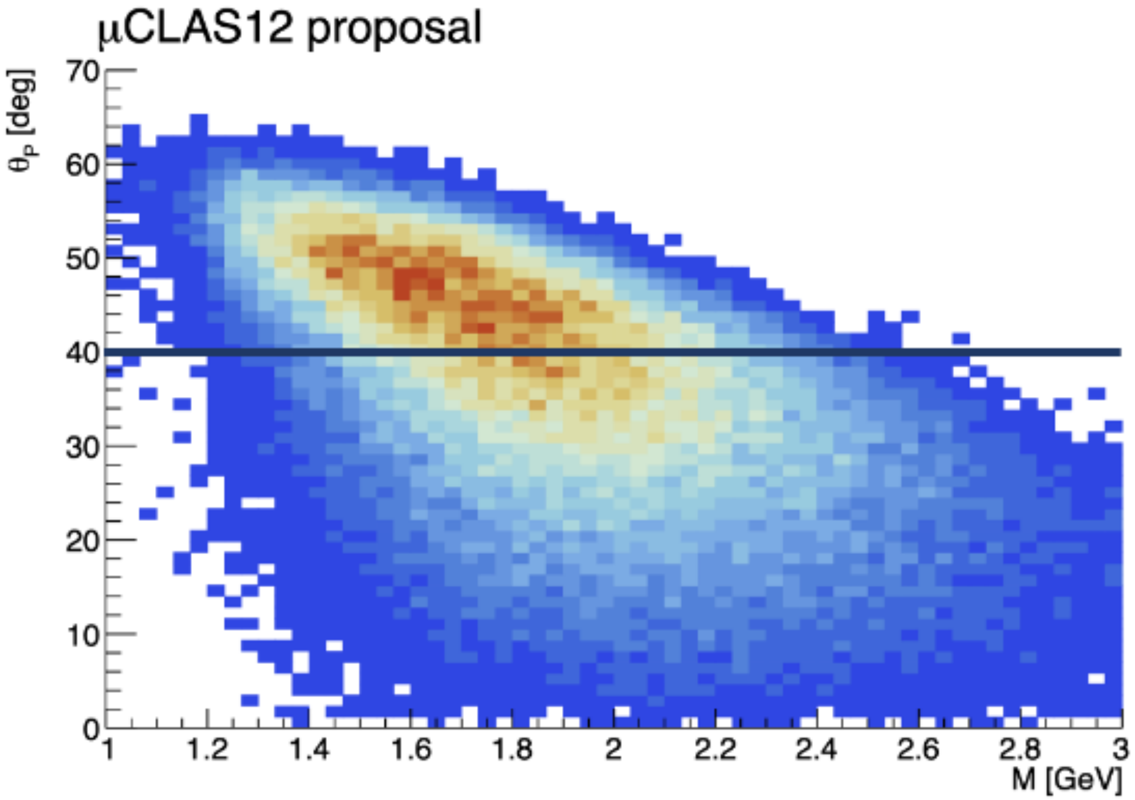
$$ep \rightarrow (e')p'\mu^+\mu^-$$

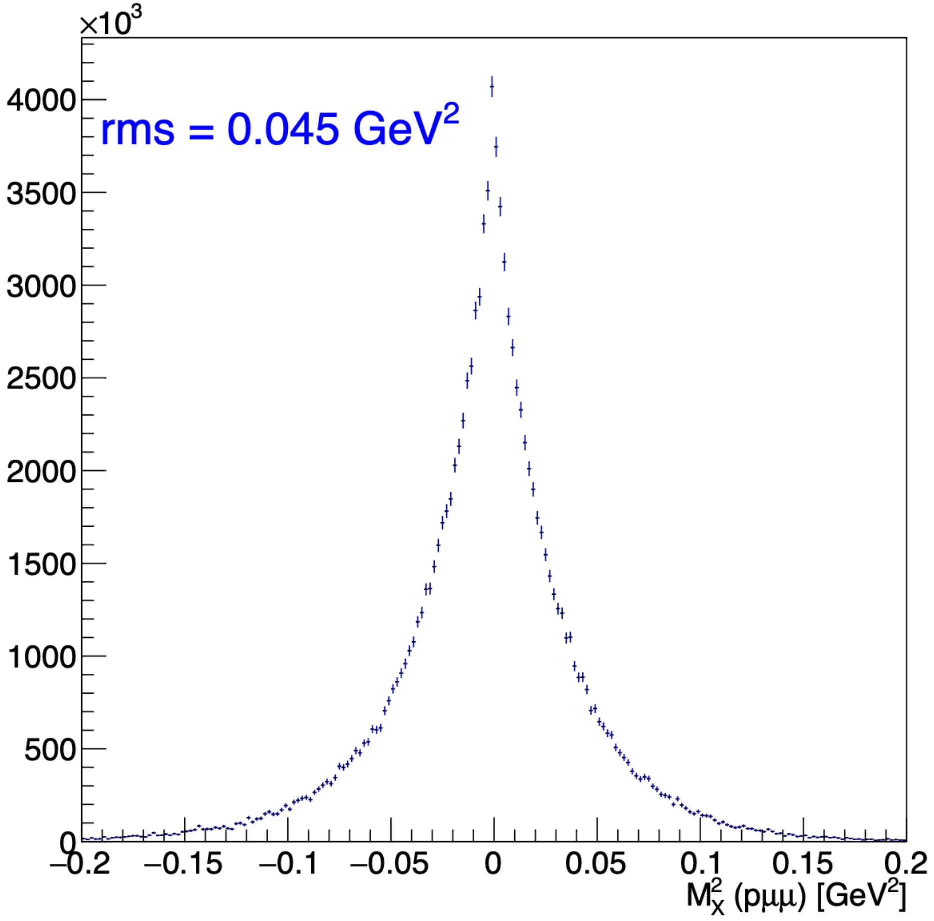




More on Timelike Compton Scattering: missing mass and invariant mass

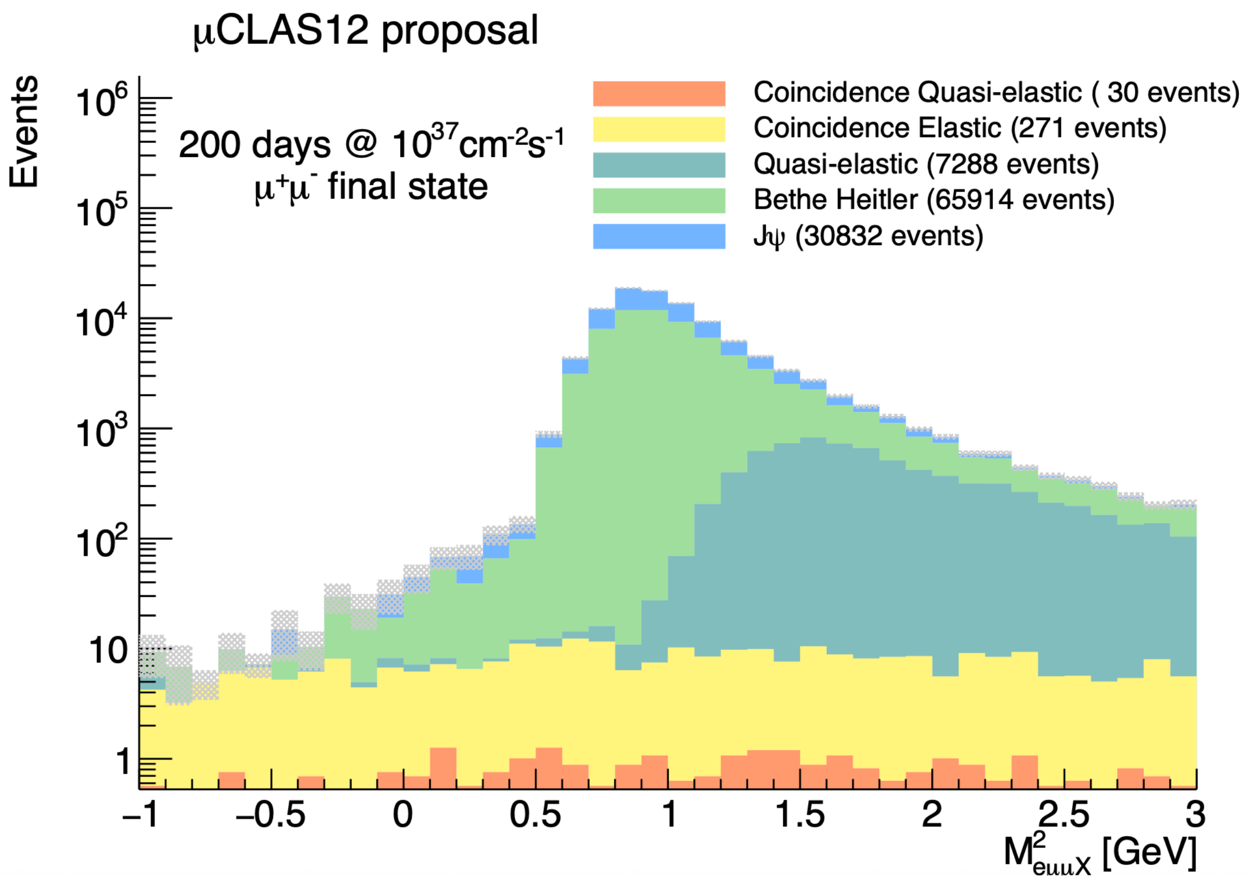
$$ep \to (e')p'\mu^+\mu^-$$

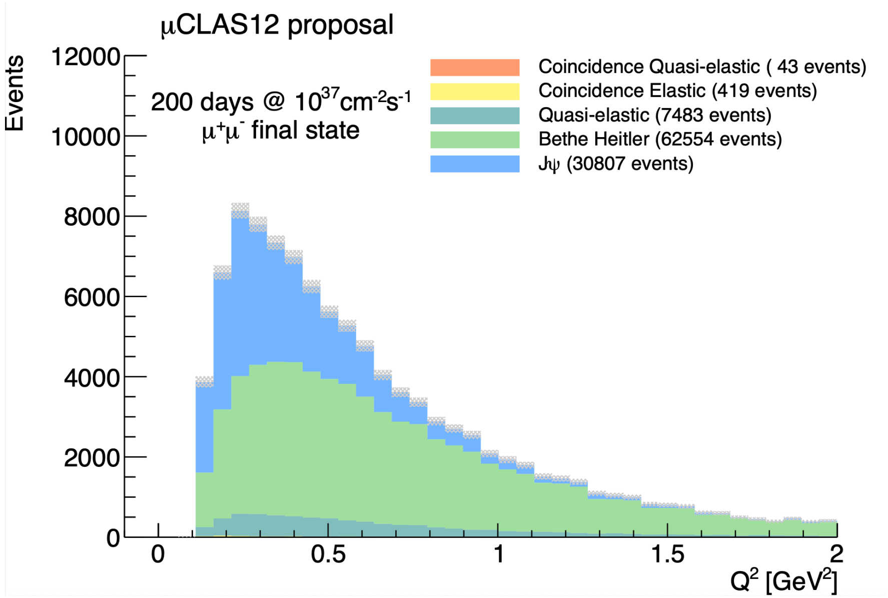


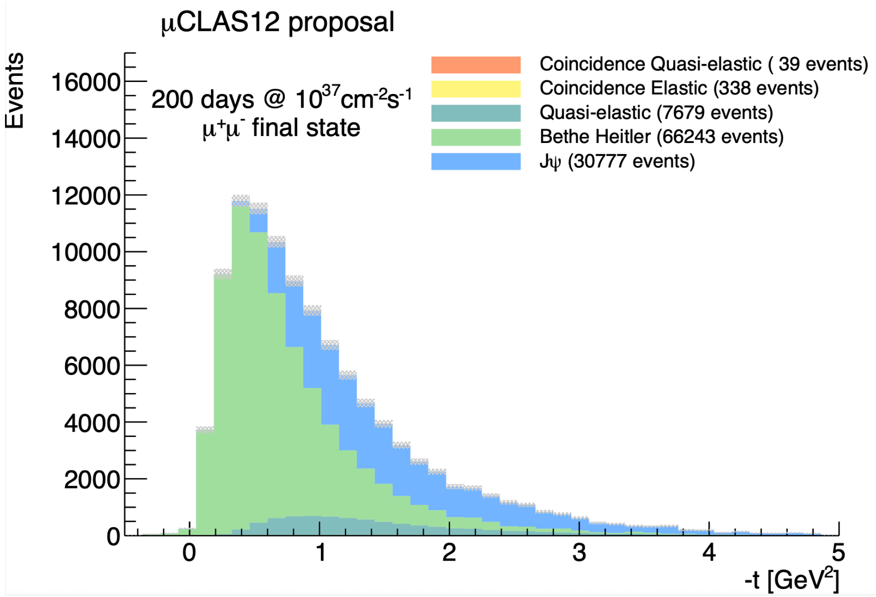


Back-up: Expected results J/ψ

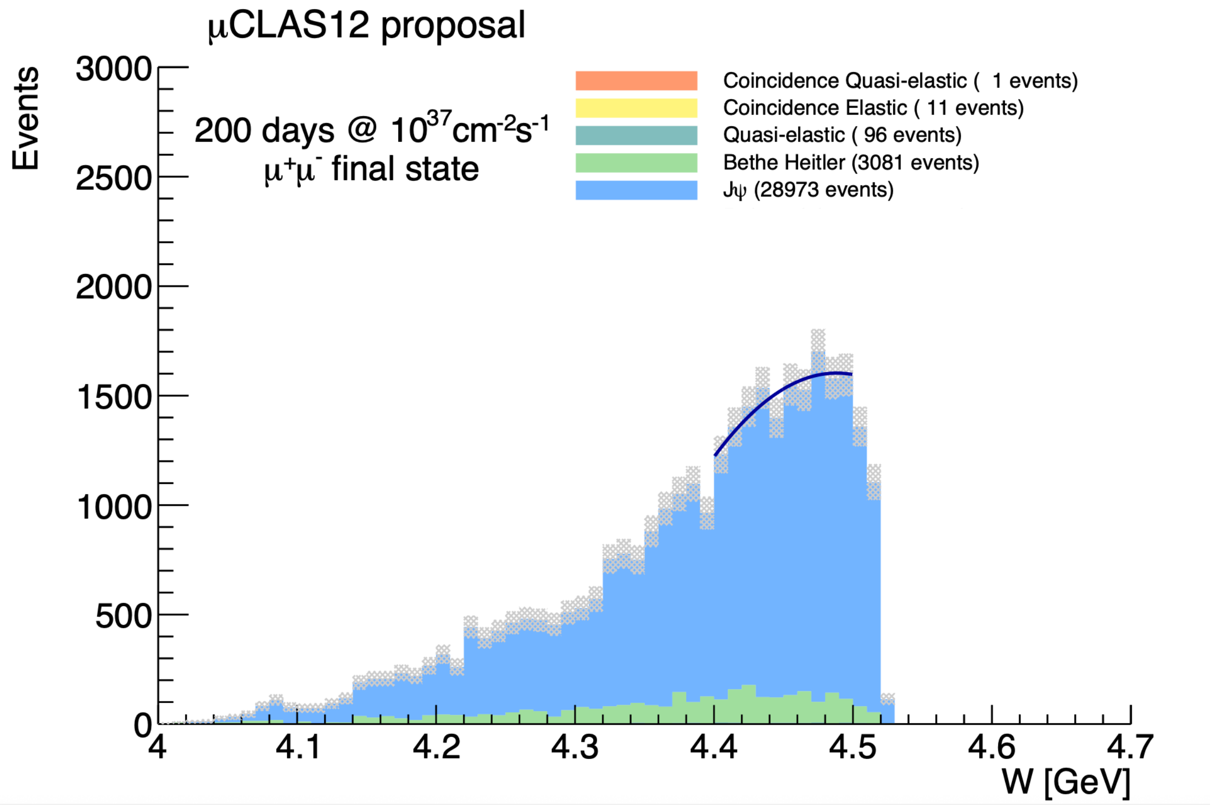
More on J/ψ electro-production: kinematic and missing mass

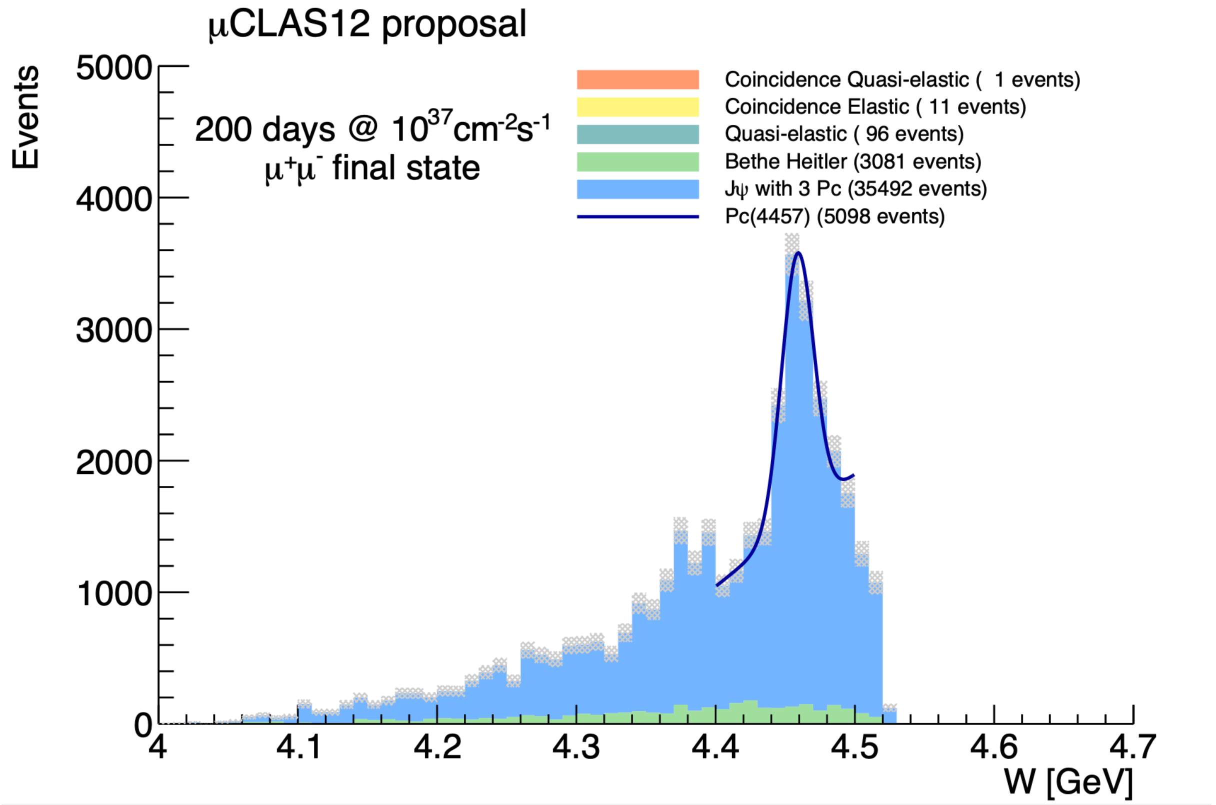






More on J/ψ electro-production: Pentaquark





Back-up: Systematics

Systematics budget

DDVCS BSA	Systematics
Beam polarization	< 3%
Background assymetry	< 6% (18% bg, 30% uncertainty)
Radiative effects	< 5%
Total	< 8.5%

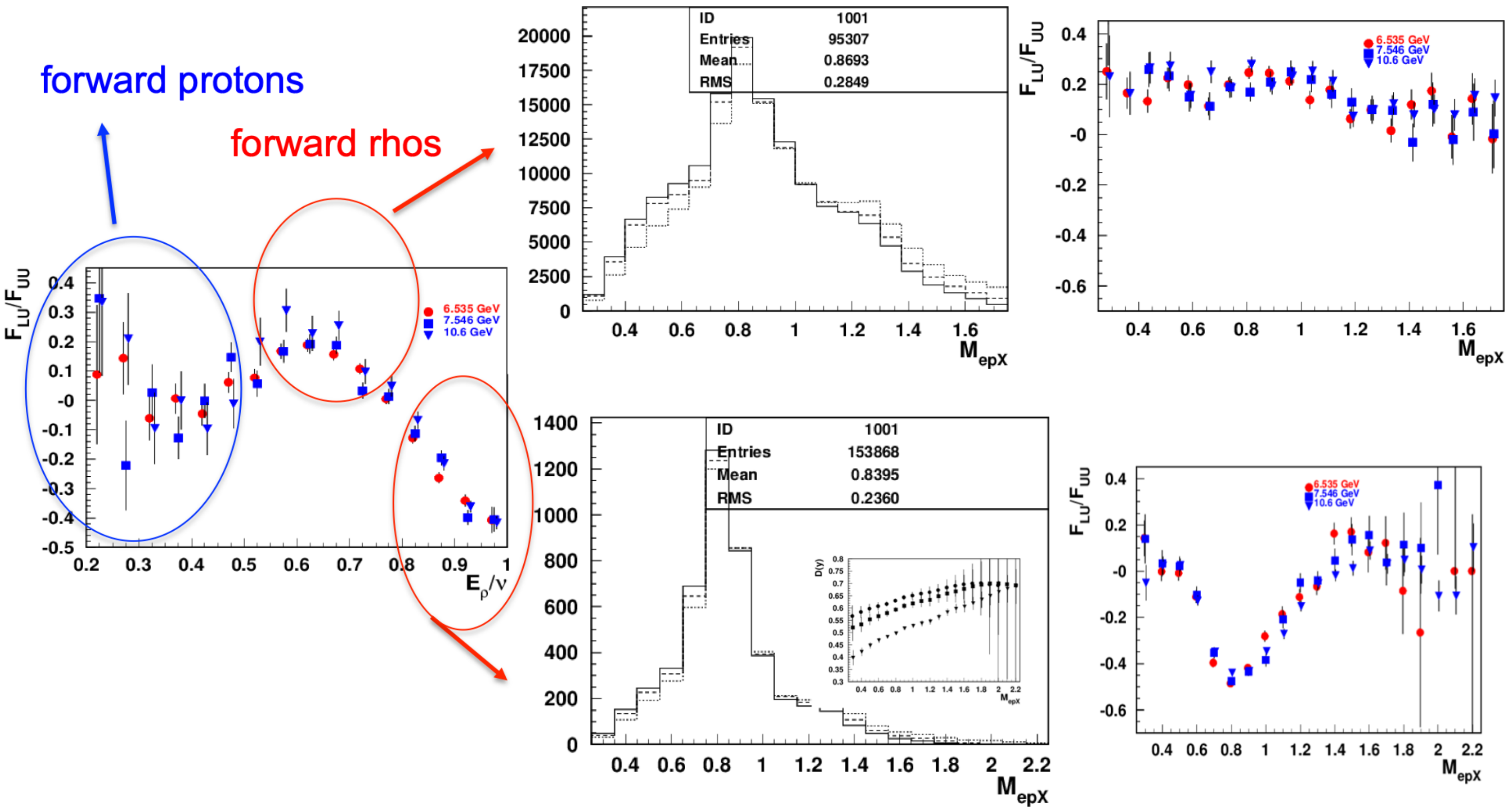
TCS BSA	Systematics
Beam polarization	< 3%
Background assymetry	< 6% (18% bg, 30% uncertainty)
Radiative effects	< 5%
Total	< 8.5%

J/ψ Cross-section	Systematics
Accumulated charge	1.5%
Radiative effects	5% (from CLAS12 J/ψ analysis)
Normalization	< 10% (currently 20% with CLAS12)
Total	< 11.5%

TCS AFB	Systematics
Radiative effects	< 5%
Normalization	< 10% (currently 20% with CLAS12)
Total	< 11.2%

Double pion assymetry

Exclusive π+π−: missing mass dependence



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

Jefferson Lab H. Avakian, COMAP, April 30 4