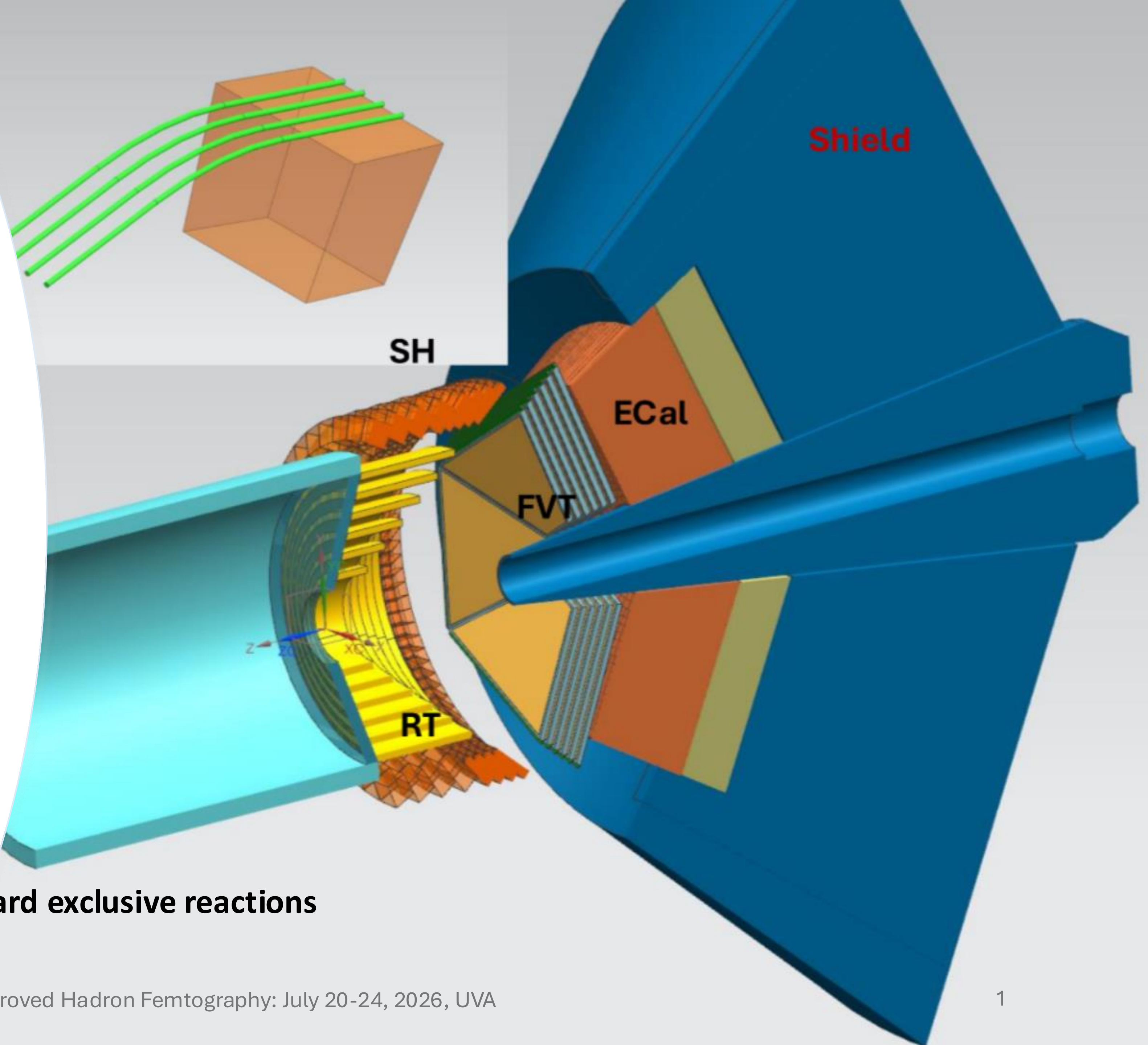
Timelike Compton Scattering and Double Deeply Virtual Compton Scattering in Hall B at JLAB

Rafayel Paremuzyan
Jefferson Lab

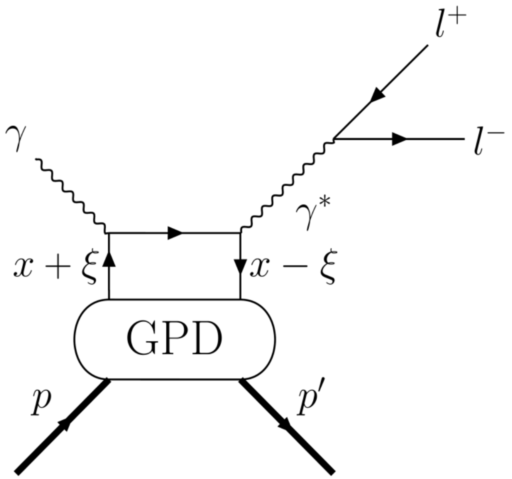


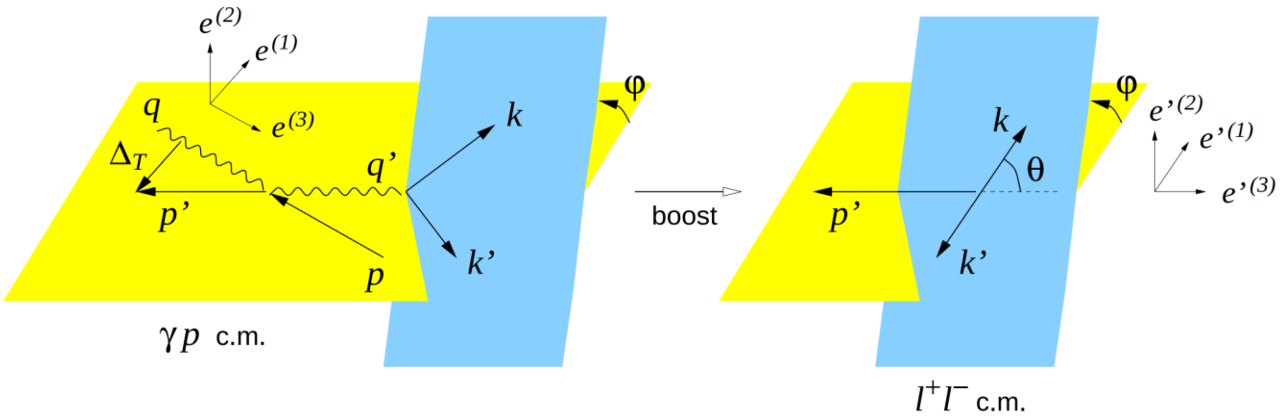
Towards improved hadron femtography with hard exclusive reactions
July 20-24, 2026, University of Virginia

Outline

- Physics motivations
  - TCS
  - What can we learn more with DDVCS
- Current TCS measurements in Hall-B with CLAS12
- The μCLAS12 experimental setup
- The measurement
- Observables and estimations
- Summary

Introduction: Timelike Compton Scattering





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

- TCS – symmetric to DVCS process
- Probes similar CFFs as the DVCS:
  - Direct access to the Re$\mathcal{H}$ and hence **to the D-term**
  - Polarization asymmetry: access to the Im$\mathcal{H}$.
  - Serve as a universality test of GPDs

$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi}=A\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\,\mathcal{H}+\ldots$$

$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi}=-\nu B\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\,\mathcal{H}+\ldots$$

$$A_{\odot U}=\frac{d\sigma^+-d\sigma^-}{d\sigma^++d\sigma^-}$$

Challenges in the extraction of GPDs

Traditional processes to access GPDs experimentally: DVCS, DVMP, TCS

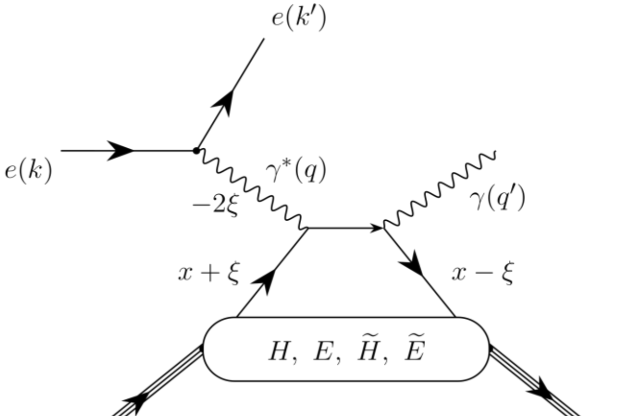
We measure linear combinations of CFFs, while in CFFs the information on x is lost (gets integrated over)

DVCS

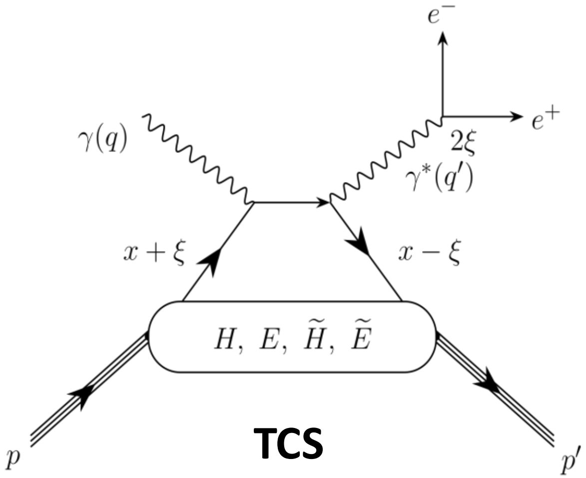
$\mathcal{F} = \{\mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \tilde{\mathcal{E}}\}$ $\qquad F = \{H, E, \tilde{H}, \tilde{E}\}$

$$\mathcal{F}^{\pm}(\xi,t) = \int dx\, F(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} \mp \frac{1}{\xi + x - i\epsilon}\right) = \mathcal{P}\int_{-1}^{1} dx\, \left(\frac{1}{\xi - x} \mp \frac{1}{\xi + x}\right)\sum_q e_q^2 F^q(x,\xi,t) + i\pi \sum_q e_q^2 [F^q(\xi,\xi,t) \mp F^q(-\xi,\xi,t)]$$

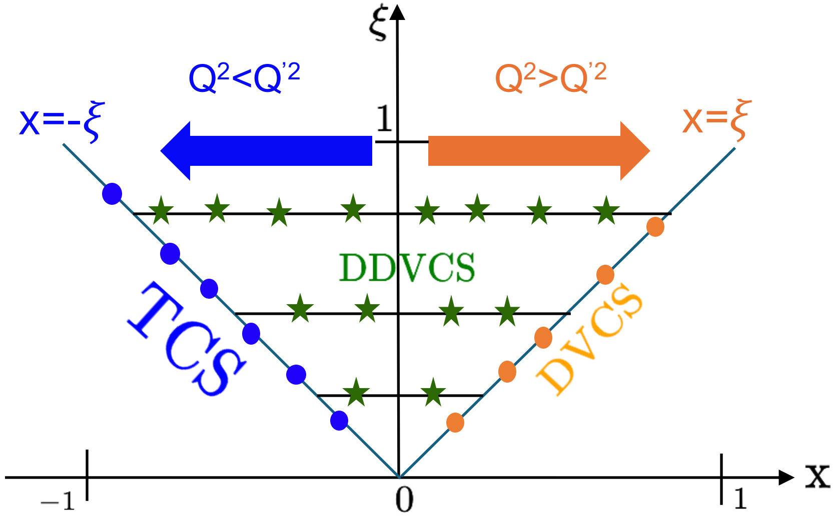
Exception is when one measures Im part of the scattering amplitude, where one can access GPDs at $x=\mp\xi$ line.



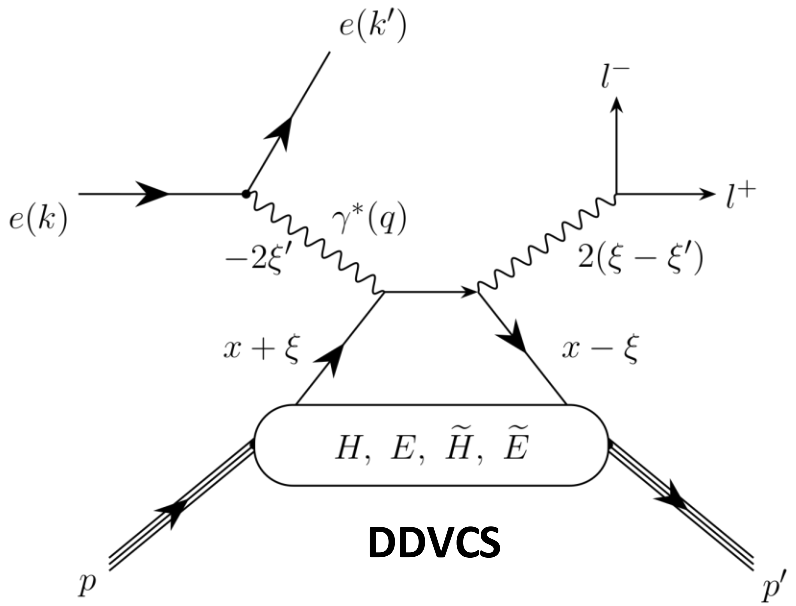
DVCS



TCS



Double Deeply Virtual Compton Scattering: Observable

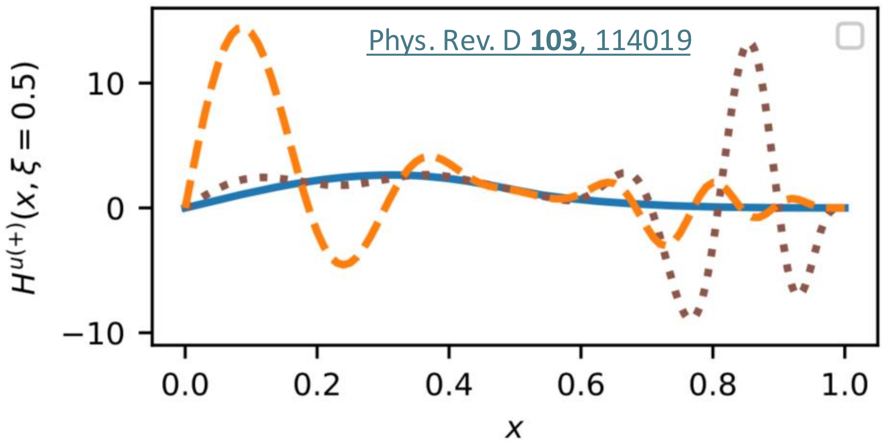


DDVCS

$$\xi = -\xi' \frac{Q^2 + Q'^2}{Q^2 - Q'^2 + t/2}$$

$$\xi' = x_\mathrm{B} \frac{Q^2 - Q'^2 + t/2}{(2 - x_\mathrm{B})\, Q^2 - x_\mathrm{B}\, (Q'^2 - t)}$$

For DVCS/TCS $\xi \approx \mp \xi'$

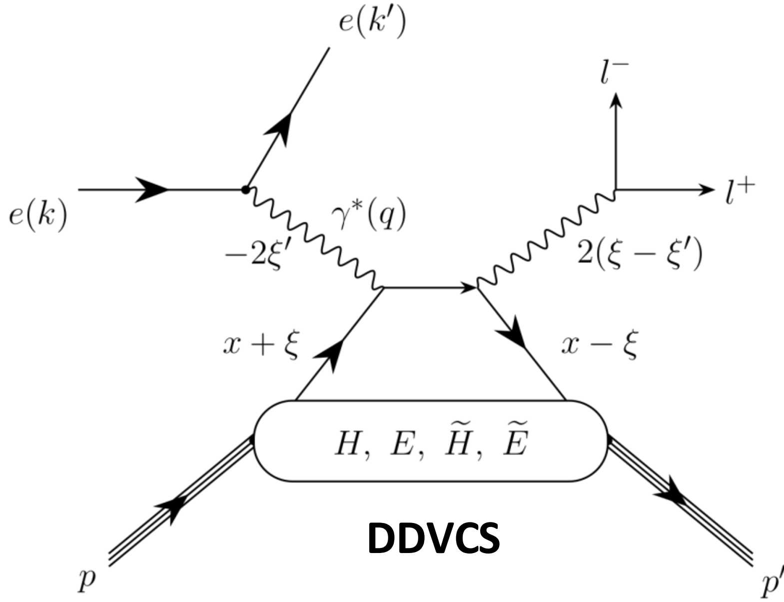


$$\mathcal{F}^{\pm}(\xi', \xi, t) = \mathcal{P} \int dx \left(\frac{1}{\xi' - x} \mp \frac{1}{\xi' + x} \right) \sum_q F^q(x, \xi, t) - i\pi \sum_q \left[F^q(\xi', \xi, t) \mp F^q(-\xi', \xi, t) \right]$$

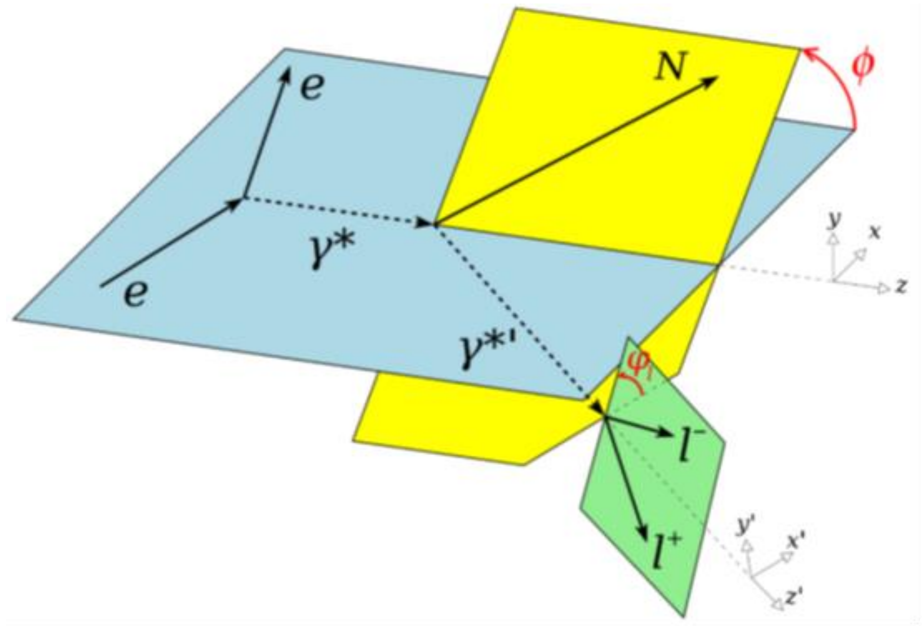
This was realized more than 20 years, ago, however has never been measured, mainly due to very low cross-section compared to DVCS.

DDVCS also will help better constrain shadow GPDs (class of function with null CFF) that will contribute to the solution in the GPD extraction.

Double **D**eeply **V**irtual **C**ompton **S**cattering: Observable



DDVCS



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

$$\frac{d\sigma^5}{dQ^2 dt dx_B d\phi dQ'^2} = d^5\sigma_{BH1} + d^5\sigma_{BH2} + d^5\sigma_{VCS} + d^5\sigma_{Int_1} + \lambda(d^5\tilde{\sigma}_{VCS} + d^5\tilde{\sigma}_{Int_1})$$

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

Observable of interest $A_{LU} = \frac{d\overrightarrow{\sigma}^5 - d\overleftarrow{\sigma}^5}{d\overrightarrow{\sigma}^5 + d\overleftarrow{\sigma}^5}$ In space like and timelike regions

Challenges

- Very low cross-section
  - **Boosting luminosity**
- **Detection of muons**

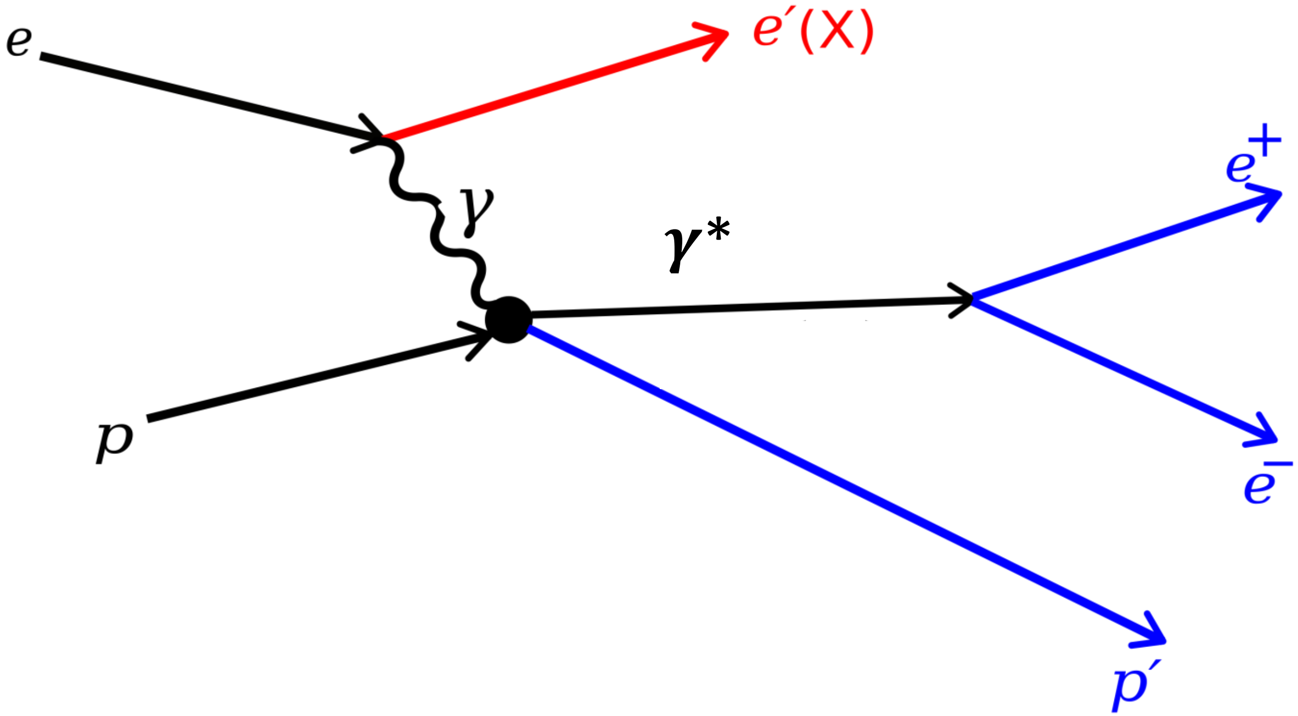
TCS analysis

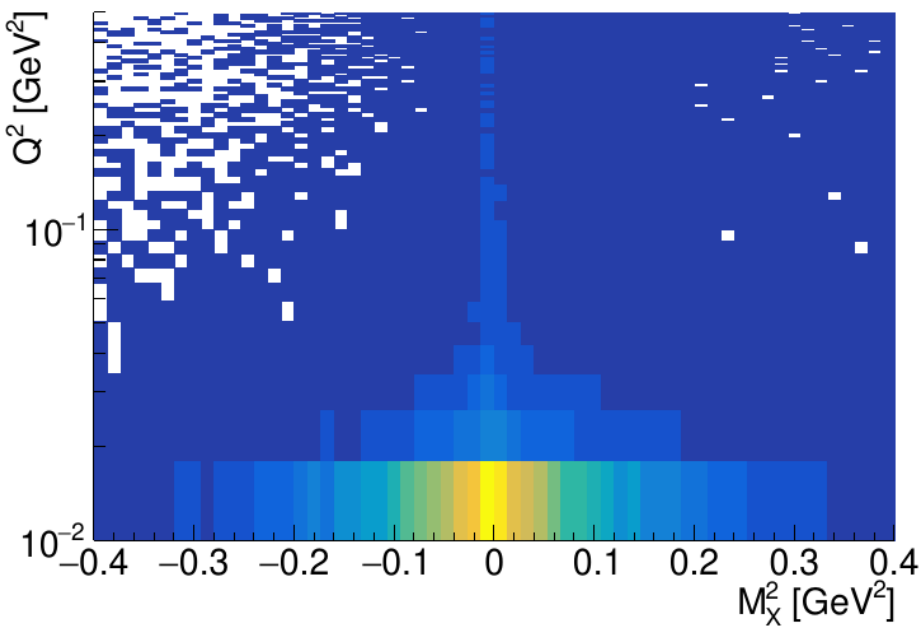
The TCS analysis

- e^-, e^+ and p' are detected in the Forward detector
- Beam scattered electron is not detected but can be identified requiring missing mass to be ≈0.
    - e'(X) = e + p – e^- - e^+ - p'
- Timelike photon or J/ψ identified through the sum of e^- and e^+ four vectors
- Photon is identified as e^- + e^+ + p' - p
- Quasi-real photons have Q^2≈0

$Q^2 = 2*E_b*E_{e'}(1 - \cos\theta_{e'}) \approx 0$

$$|M_X^2| < 0.4\ \mathrm{GeV}^2$$
$$Q^2 < 0.5\ \mathrm{GeV}^2$$

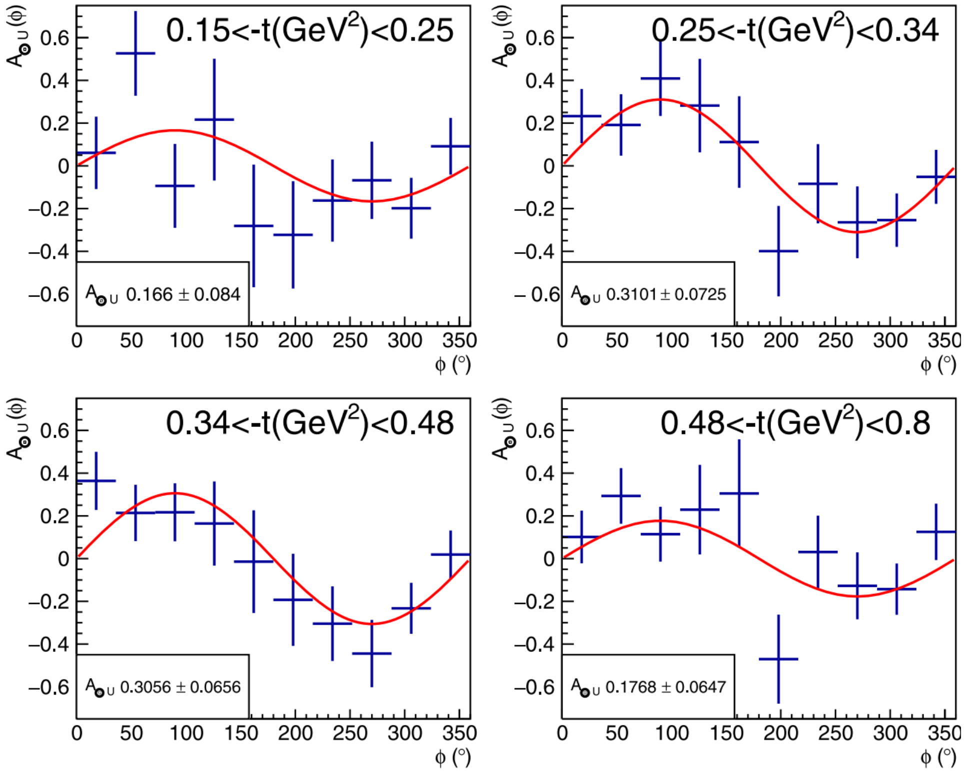




The 1st TCS measurement

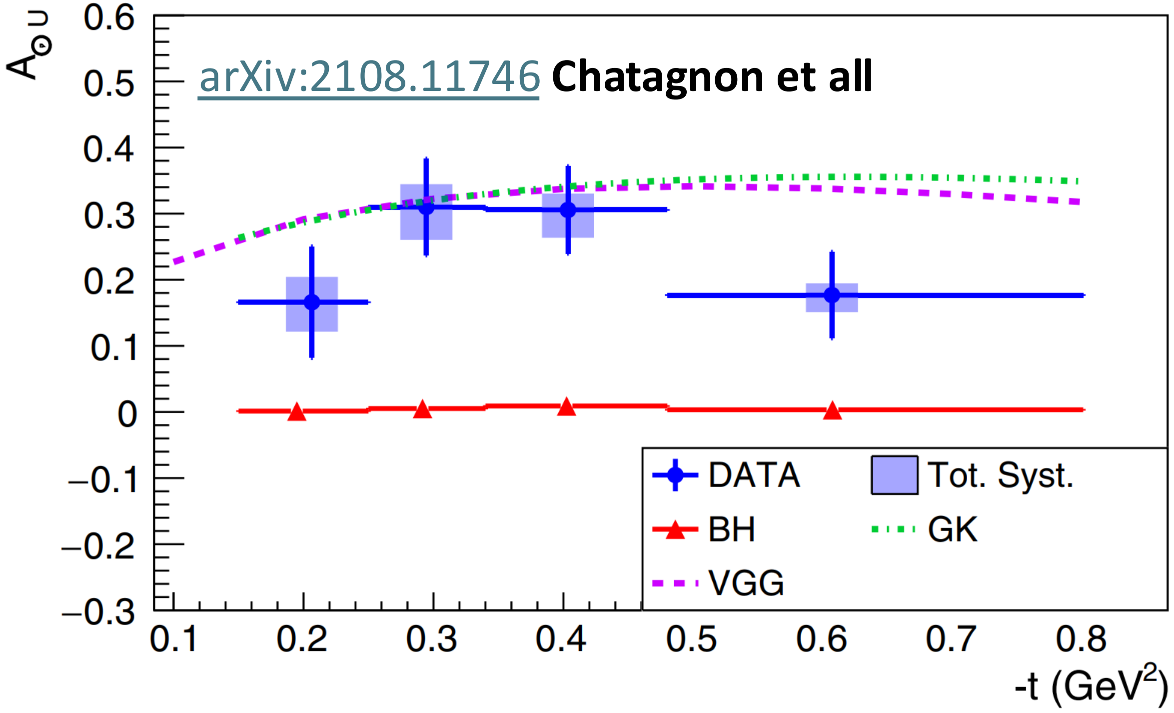
$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

Polarization asymmetry



The polarization asymmetry is measured in 4 –t bins.

$$E_\gamma = 7.29 \pm 1.55 \text{ GeV}$$
$$M = 1.80 \pm 0.26 \text{ GeV}$$

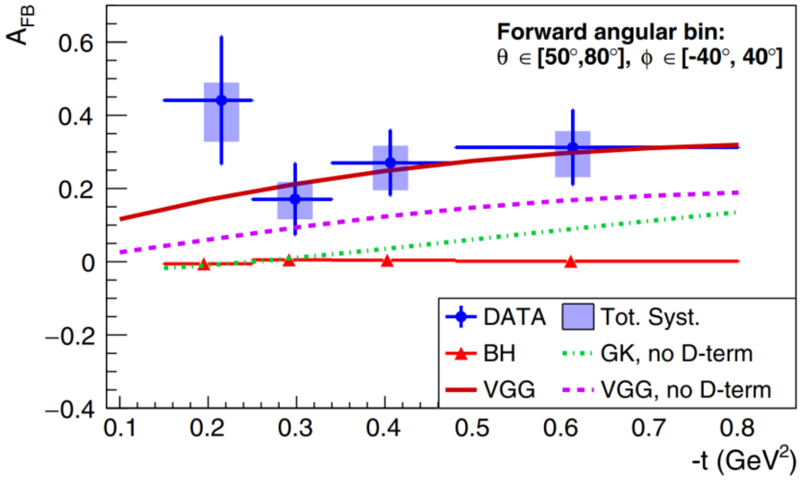


The 1st TCS measurement

Forward Backward asymmetry

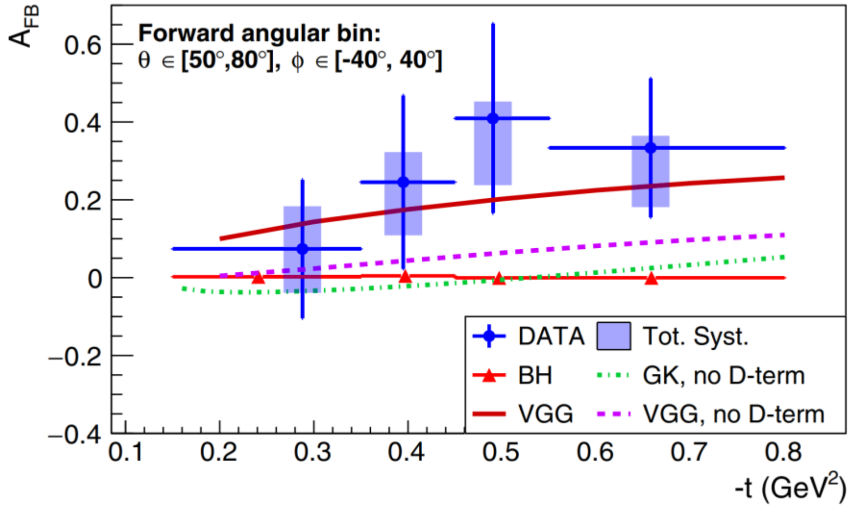
$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta,180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta,180^\circ+\phi)}$$

$$E_\gamma = 7.23 \pm 1.61 \text{ GeV}$$
$$M = 1.81 \pm 0.26 \text{ GeV}$$



$$E_\gamma = 8.13 \pm 1.23 \text{ GeV}$$
$$M = 2.25 \pm 0.20 \text{ GeV}$$

arXiv:2108.11746 **Chatagnon et all**



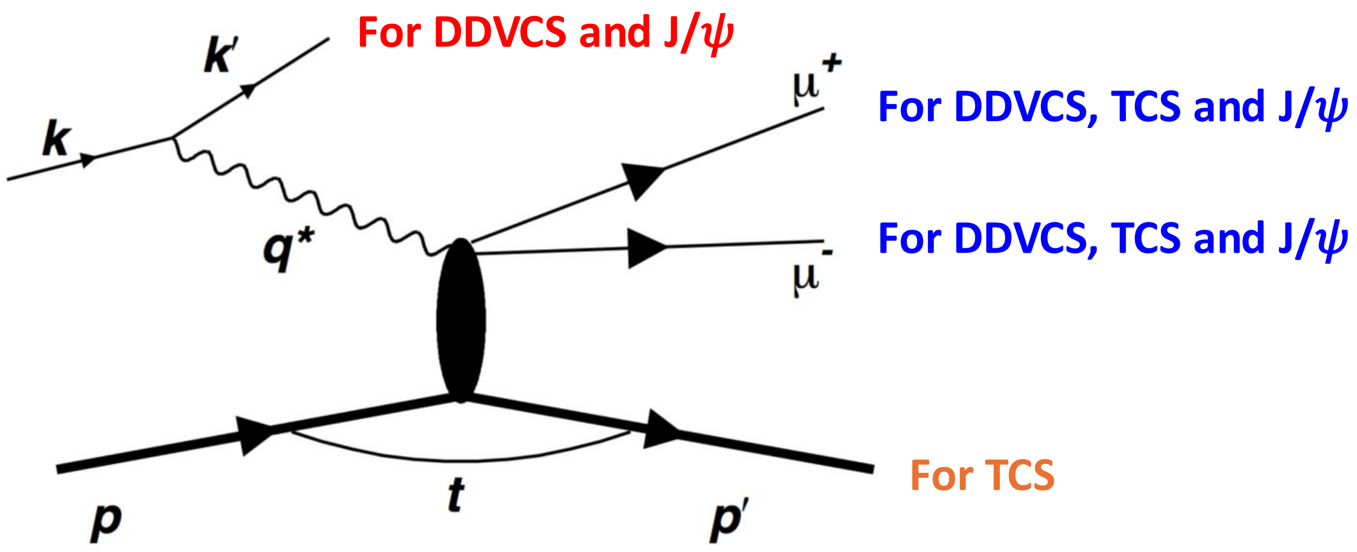
- Since the first TCS publications, track reconstruction efficiency and quality have significantly improved (largely due to AI tools).
- More than twice as much data has already been calibrated and is being analyzed. **K. Gopal** RG-A and **M. Kerr RG-K**
- About half of the approved RG-A beam time has yet to be taken.
- CLAS12 plans to increase luminosity by a factor of two.
- With these improvements, we expect significantly reduced uncertainties and finer binning, which could provide more meaningful input to global GPD extraction efforts.

DDVCS experiment wit μCLAS12

The measurement

The reaction of interest is ep → e′$\mu^-\mu^+$p

- **High Lumi ($10^{37}cm^{-2}s^{-1}$)**
- **Large acceptance**



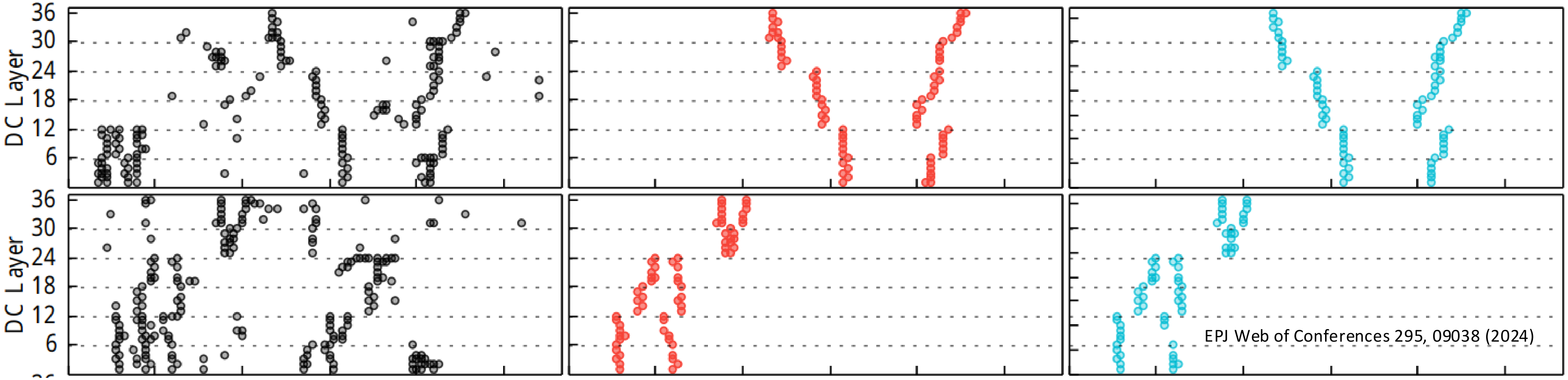
- The timelike photon is identified through the detection of $\mu^-\mu^+$ pair
- We plan to detect at least e′$\mu^-\mu^+$, and the proton kinematics will be deduced from the missing momentum analysis.
- At larger angles (40°-70°) proton will be detected too.

Challenges in increasing the CLAS12 luminosity by x100

- Intolerable Occupancies in detectors : especially in Drift Chambers (DC)
- Detectors pushed beyond operational limit
- Standard CLAS12 electron trigger will be ~ MHz trigger rate
- Backgrounds should be carefully studies

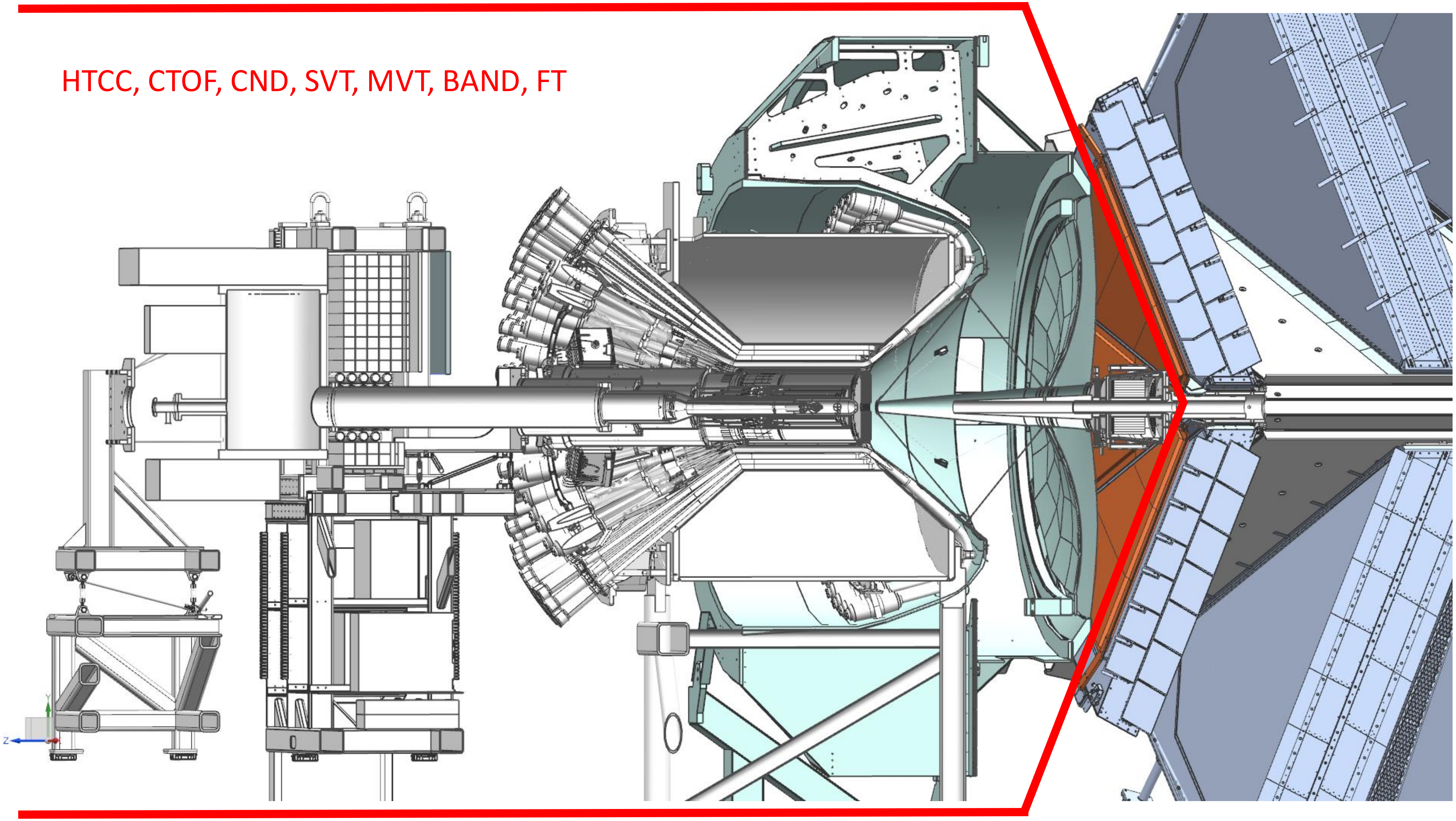
Advance of AI tools allow to significantly reduce the noise in DC; however, AI only cannot handle x100 increase of rates

CLAS12 DC snapshot for 2 different events at standard CLAS12 Luminosity



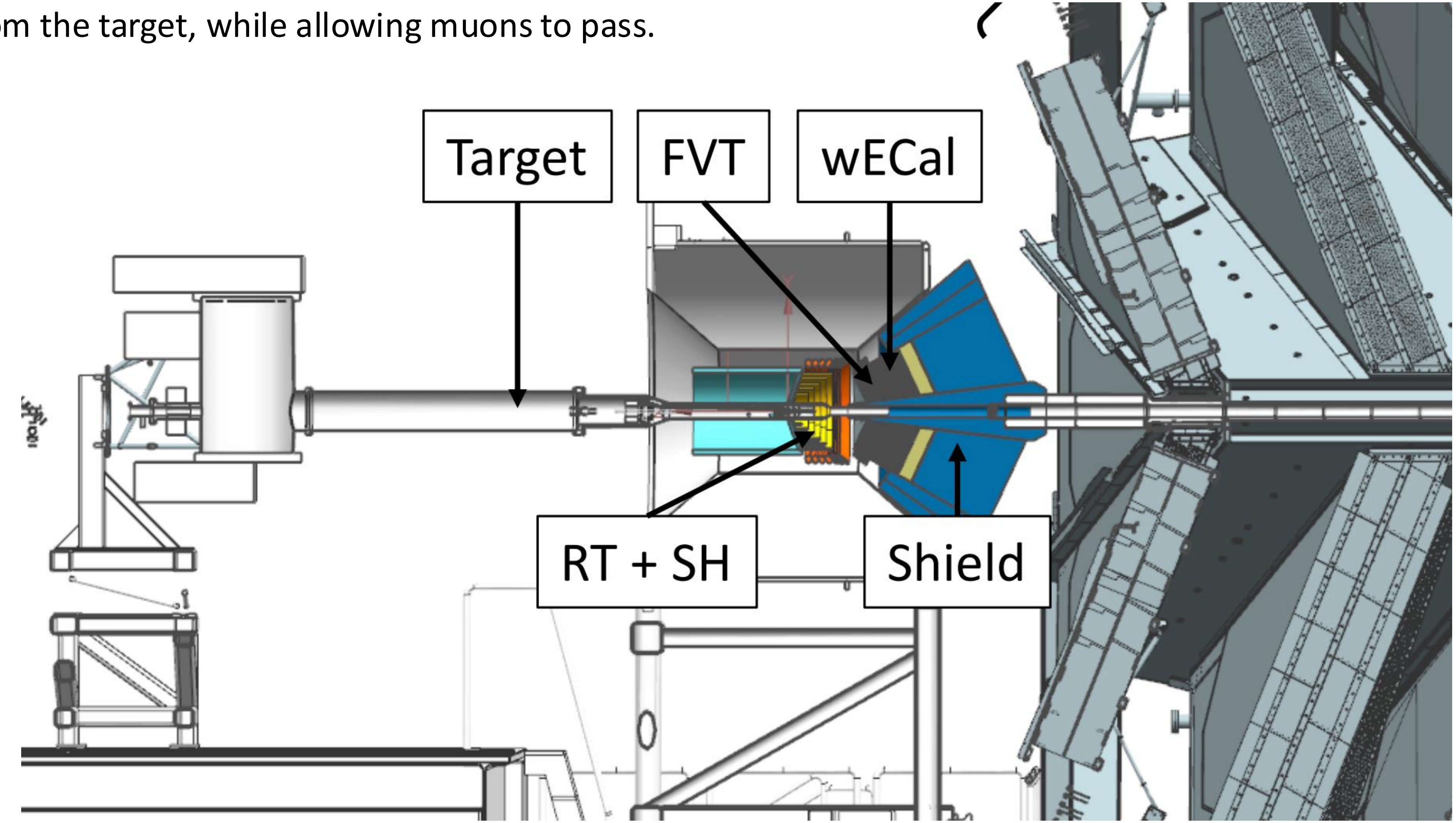
Remove detectors upstream of R1 Drift chambers

HTCC, CTOF, CND, SVT, MVT, BAND, FT

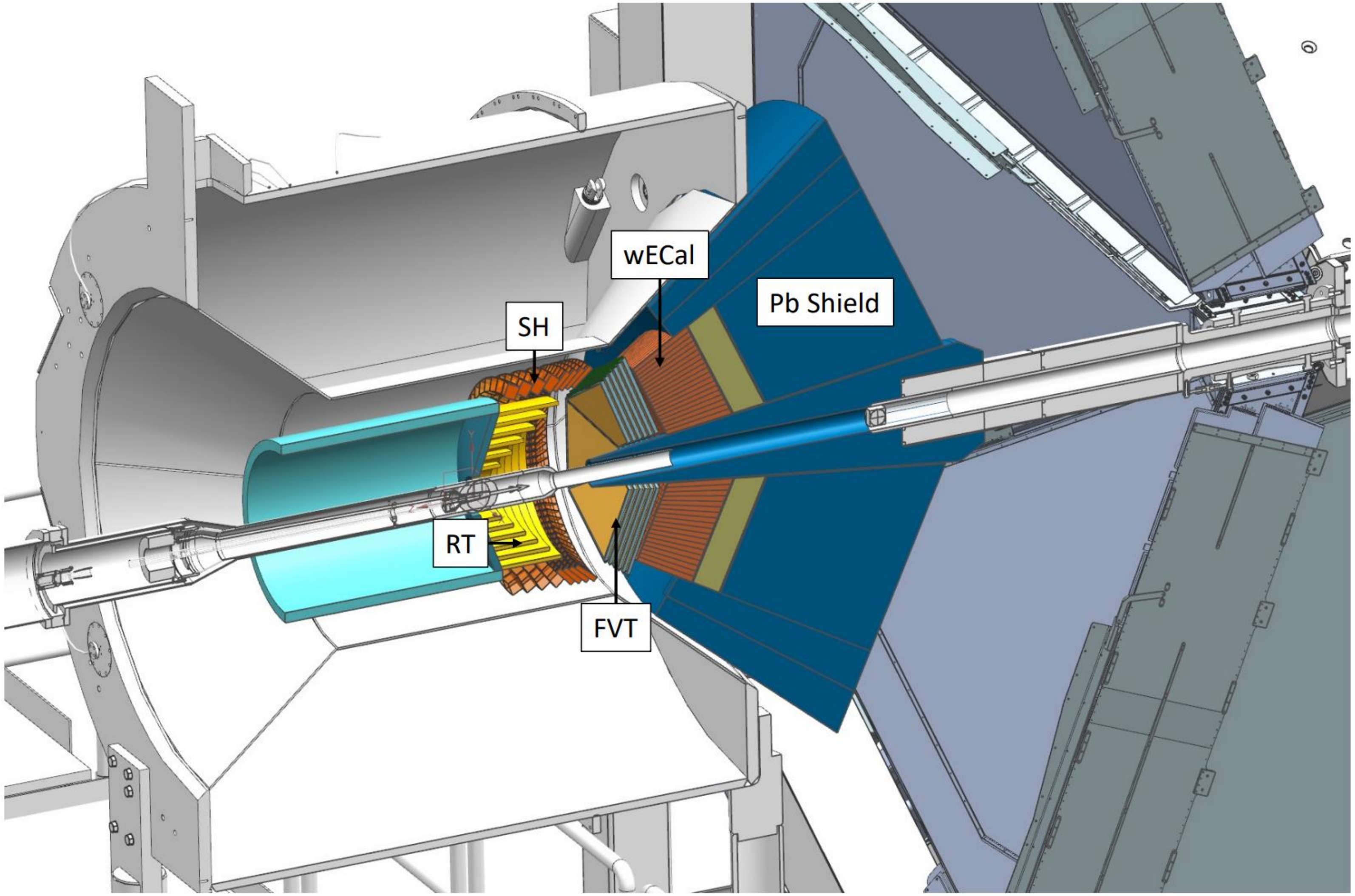


Install new detectors and a Lead shielding

A thick lead shield to strongly suppress all electromagnetic background originating from the target, while allowing muons to pass.



New detectors/components



- Thick Moeller cone covering up to 7°
- 60 cm Lead Shield
- **wECal** 7° to 35° polar angle and 2π in azimuth.
- 6 layers of **F**orward **V**ertex **T**racker: Critical for precise vertex direction and position reconstruction.
- Recoil Detector: 40° to 70°.
  - 6 layers of **R**ecoil **T**racker for the recoil proton reconstruction
  - **S**cintillator **H**odoscope for TOF and pid of the recoil proton.

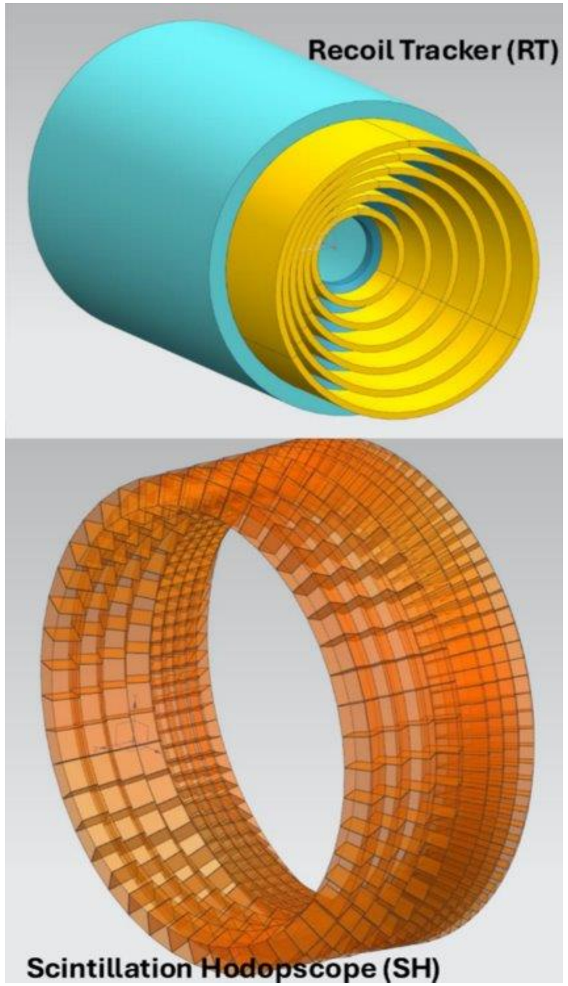
Critical components

- New detector segmentation designed in a way to keep rates/channel under control.
- Details are in backup slides.
  - Drift Chambers DC
  - Forward Vertex Tracker FVT
  - wECal
  - Recoil Tracker (RT)
  - Scintillation Hodoscope (SH)

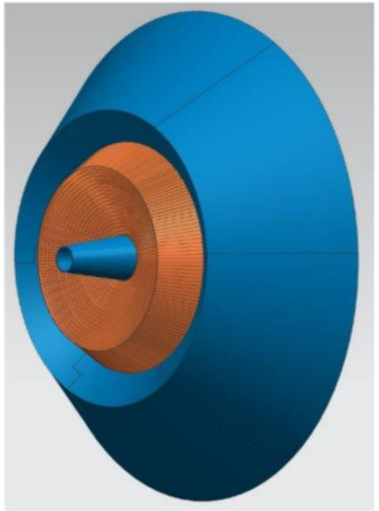
- Trigger

- Ensuring the exclusivity
  - Resolution of critical components.

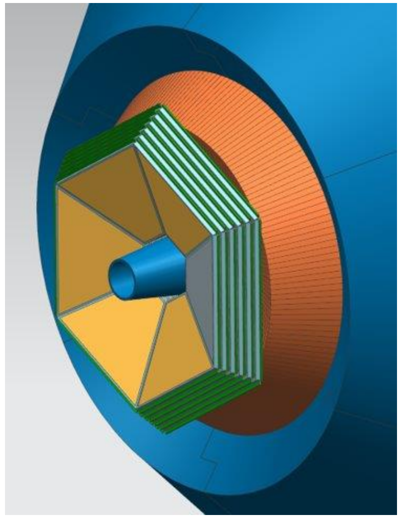
- Control of backgrounds, accidentals



wECal



FVT



Trigger

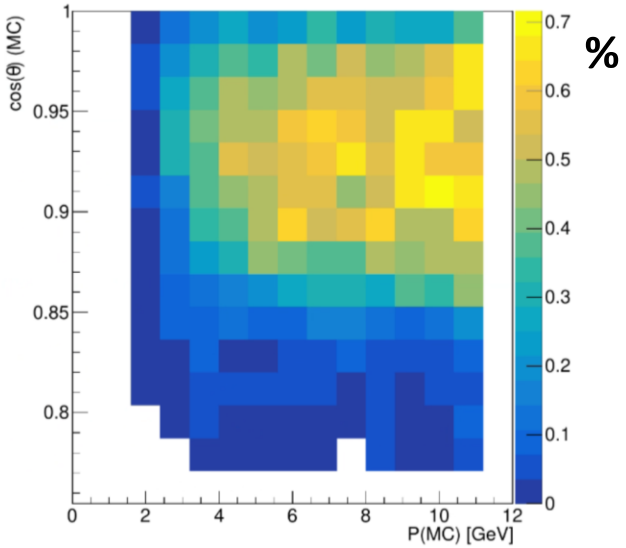
- The trigger "**Single MIP trigger**".
  - MIP energy deposition in Forward Calorimeters (PCal x ECal)
- Allows **simultaneous measurement of DDVCS, TCS and J/ψ**.

- The trigger rate is estimated using collected CLAS12 data.
- CLAS12 has "highly prescaled" trigger (> 10 MeV in fECal)
- Events with at least **1 charged particle and P > 1.5 GeV** are passed through the **μCLAS12 GEMC setup**.
  - **Require MIP signature** (less than 300 MeV energy deposition).
- Only less than 1% of particles pass the shielding.
- Considering the prescale factor and x100 Luminosity increase, we expect 21 KHz. (Well within CLAS12 DAQ limit)

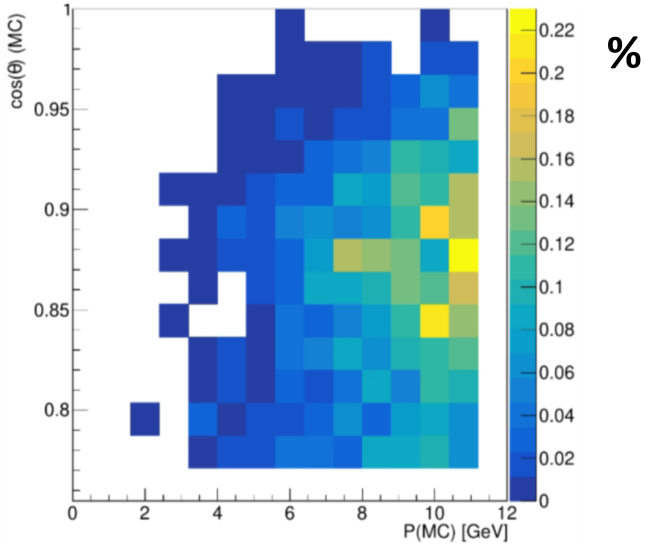
- No increase in data rate is expected, as the number of channels in CLAS12 doesn't increase.
  - New detector channels are compensated with the channels from removed detectors.

Pion suppression

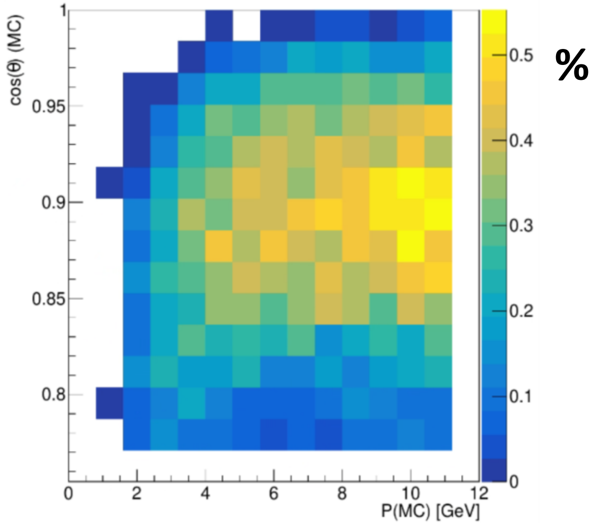
π^+ survives as MIP^+



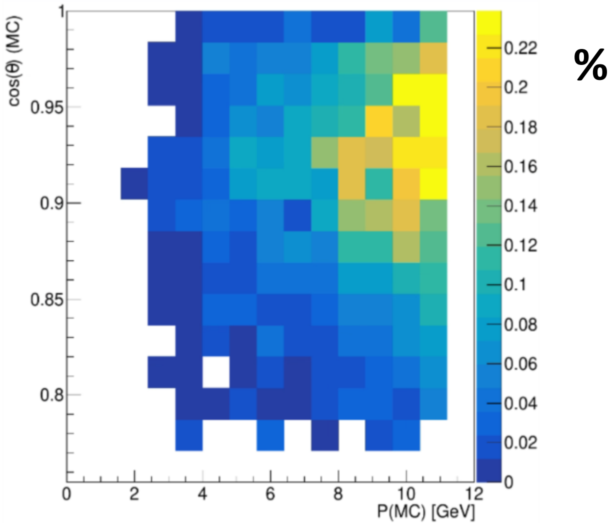
π^+ survives as MIP^-



π^- survives as MIP^-



π^- survives as MIP^+

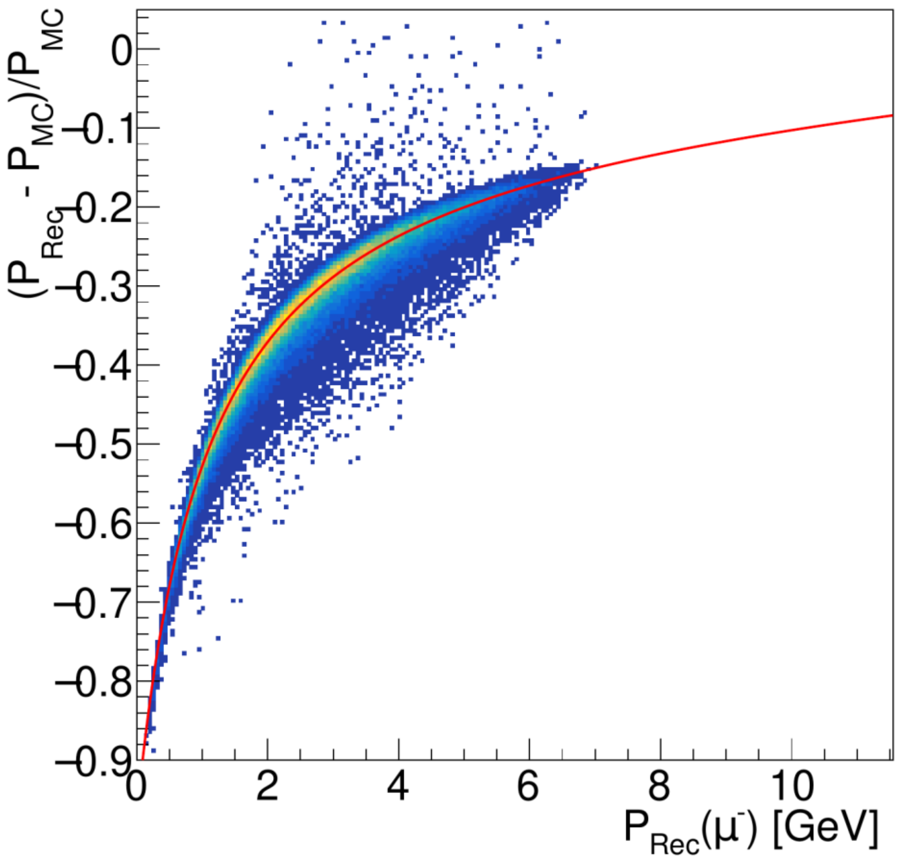


- One of driving factors for choosing the shielding thickness/material was the pion suppression level.
- Multiple shielding thicknesses were studies.
- With 60 cm Lead, the average pion suppression is **over 99%**.

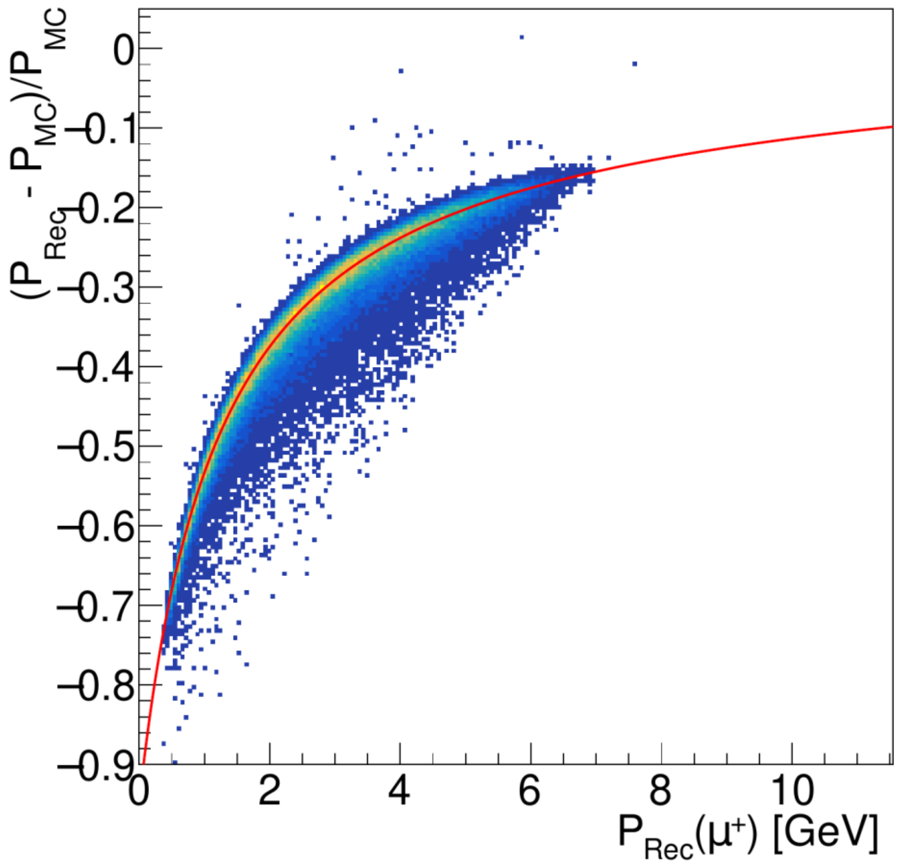
Energy loss

- Up to ~ 1 GeV energy loss in the shielding
- Energy loss is parametrized as a function of momentum
- In the proposal the reconstructed momentum is parametrized with an empirical correction functions
    - Currently an AI model is being developed to predict reconstructed momentum.

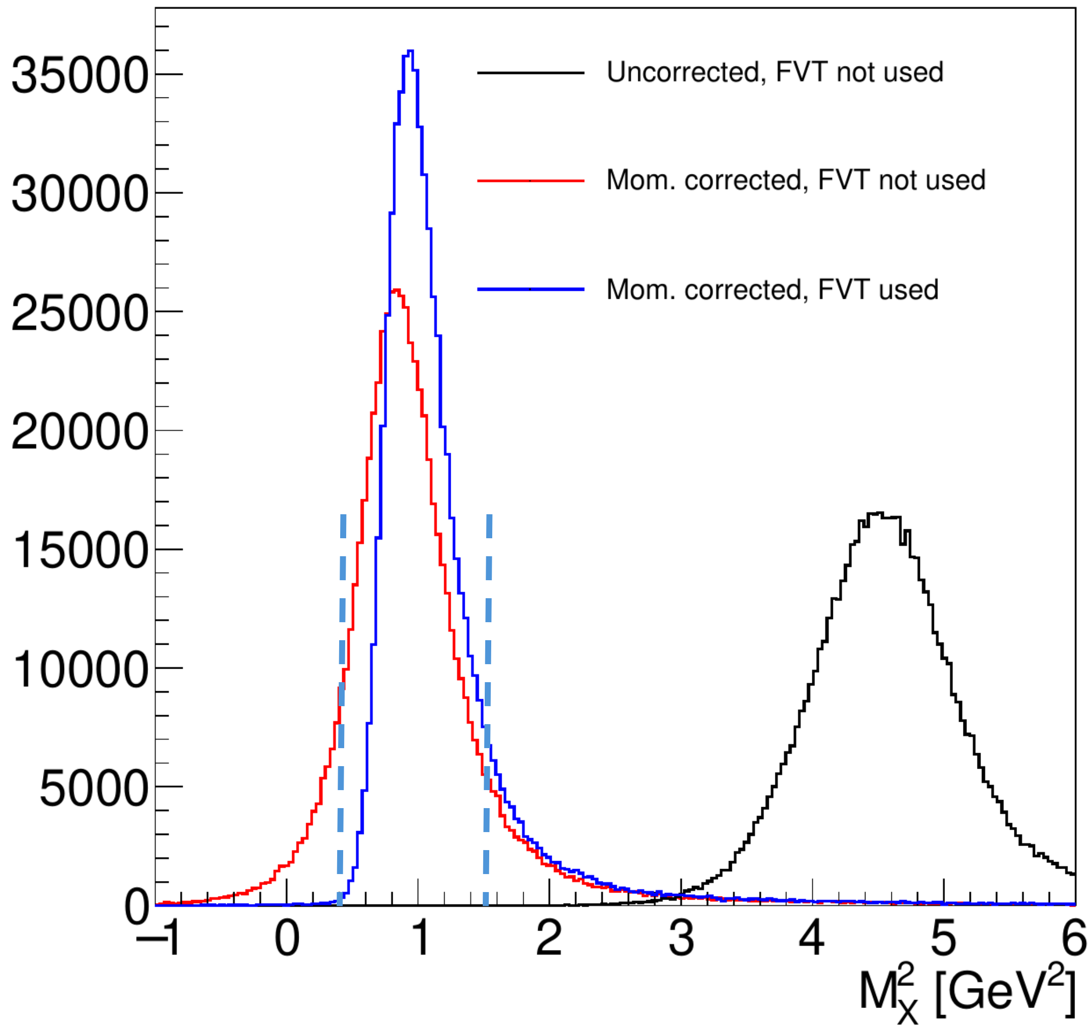
Negative muon



Positive muon



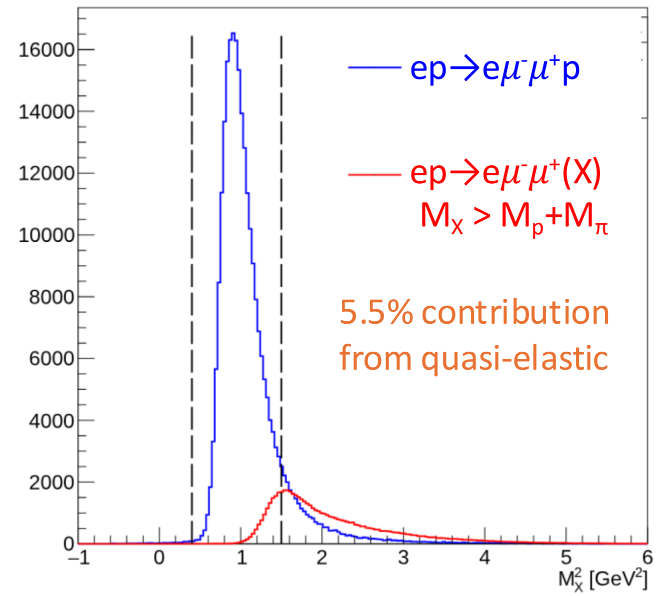
Missing mass reconstruction



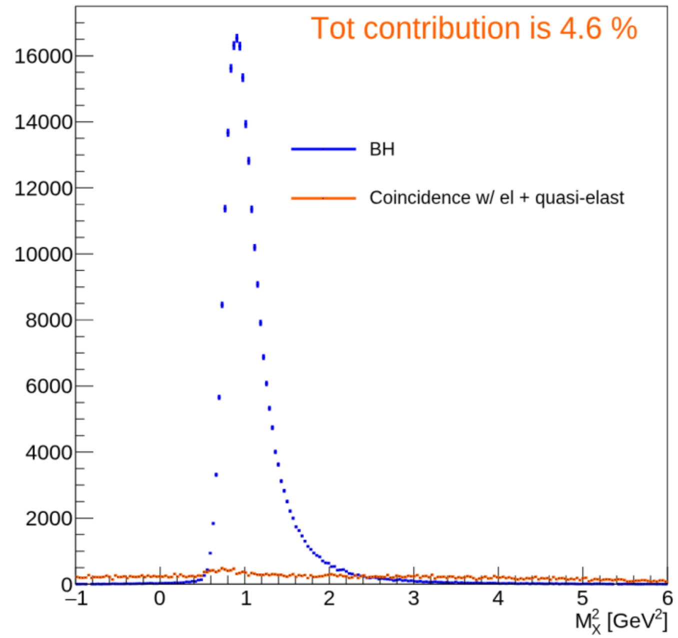
- Momentum correction brings the missing mass close to true value, but the width is high.
- Later using the FVT, the mass resolution significantly gets improved.
- Exclusivity cut: 0.4 GeV^2 < $|M_X{}^2|$ < 1.5 GeV^2
- With AI tools possible further improvement of the missing mass resolution.

Backgrounds

- Quasi elastic muon pair production: ep→e$\mu^-\mu^+$(X)
- GRAPE [*] generates both elastic and quasi-elastic muon pair production:



- Accidentals with inclusive electron
  - ep→$\mu^-\mu^+$(eX) in coincidence with inclusive electron
  - ep→eX



Coincidence is estimated by merging BH and inclusive electron events and sending into GEMC.

[*] Computer Physics Communications Volume 136, Issues 1–2

Backgrounds: pion pairs

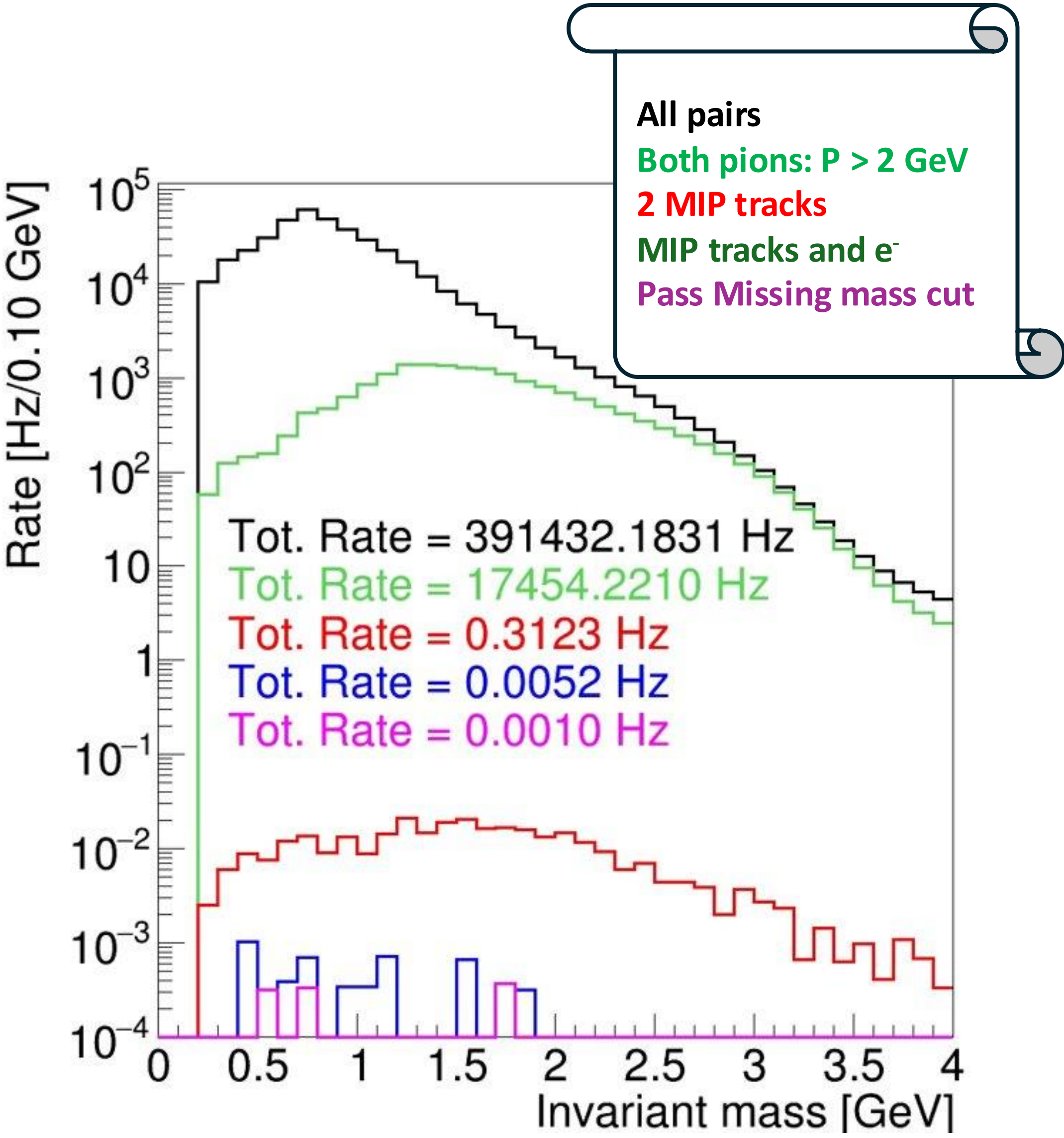
Pion pair production is another source of background too, if both pions survive, they can mimic the ep→e$\mu^-\mu^+$p reaction.

Again, CLAS12 data is used to estimate background from pion pair.

In total **over 1.2B events with pion pairs** are selected and passed through the **μCLAS12 GEMC setup**.

At the end we got three events that can mimic ep→e$\mu^-\mu^+$p reaction, and only one events with M > 1.2 GeV.

This is **1% wrt BH rate** in the M > 1.2 GeV region.



Expected results

All estimations assume:

- **200 days** of running at luminosity $\mathbf{10^{37} cm^{-2} s^{-1}}$.
- Beam energy: **11 GeV**.

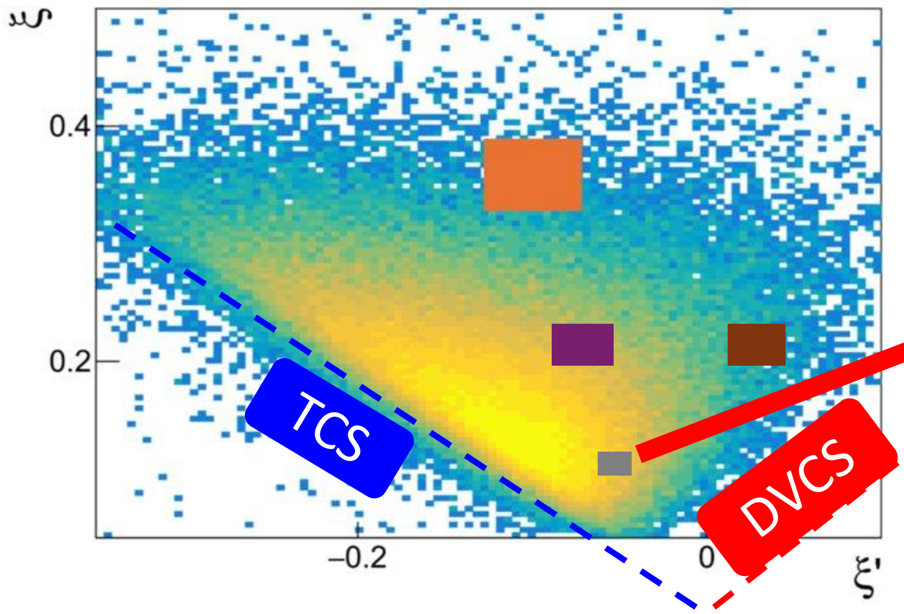
This corresponds to:

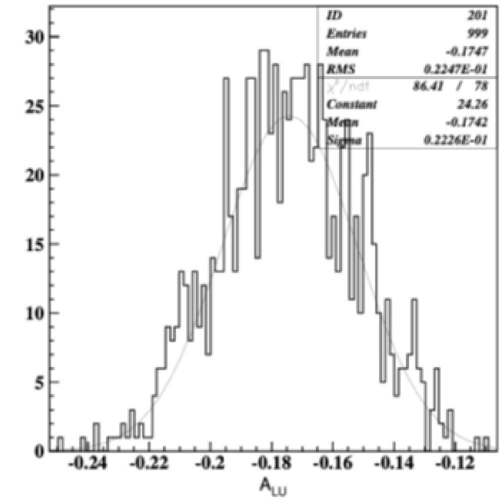
- **7.5 μA** electron beam on **5 cm LH2** target.

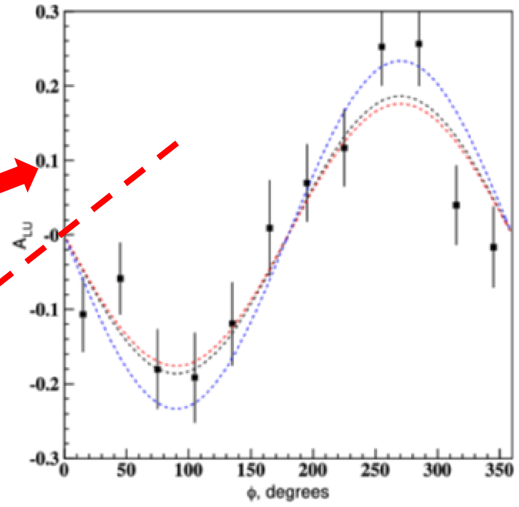
Expected results: t dependence

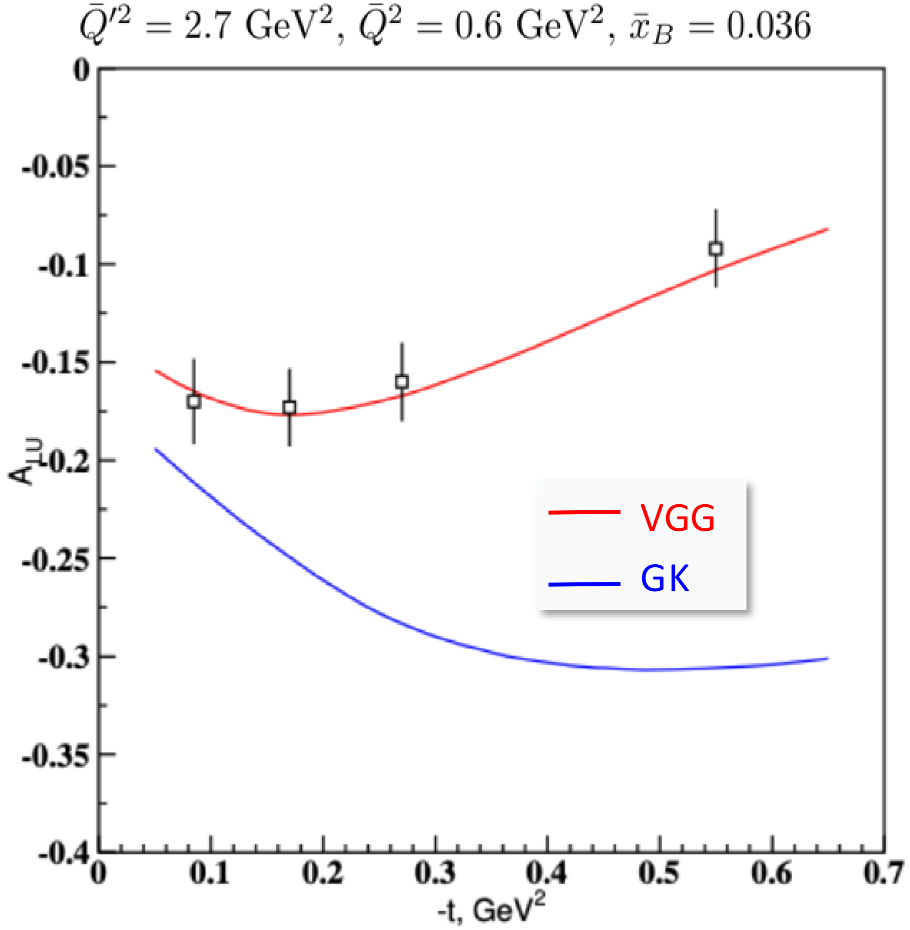
$$A_{LU} = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$

In high stat. region one can study –t dependence.







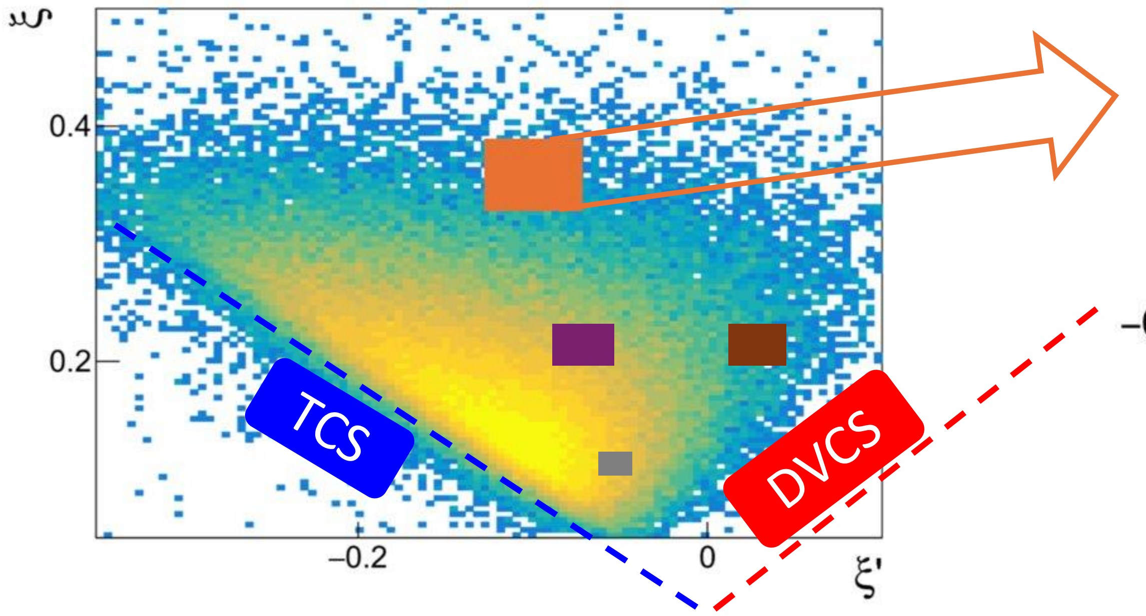


Expected results: Constraining shadow GPDs

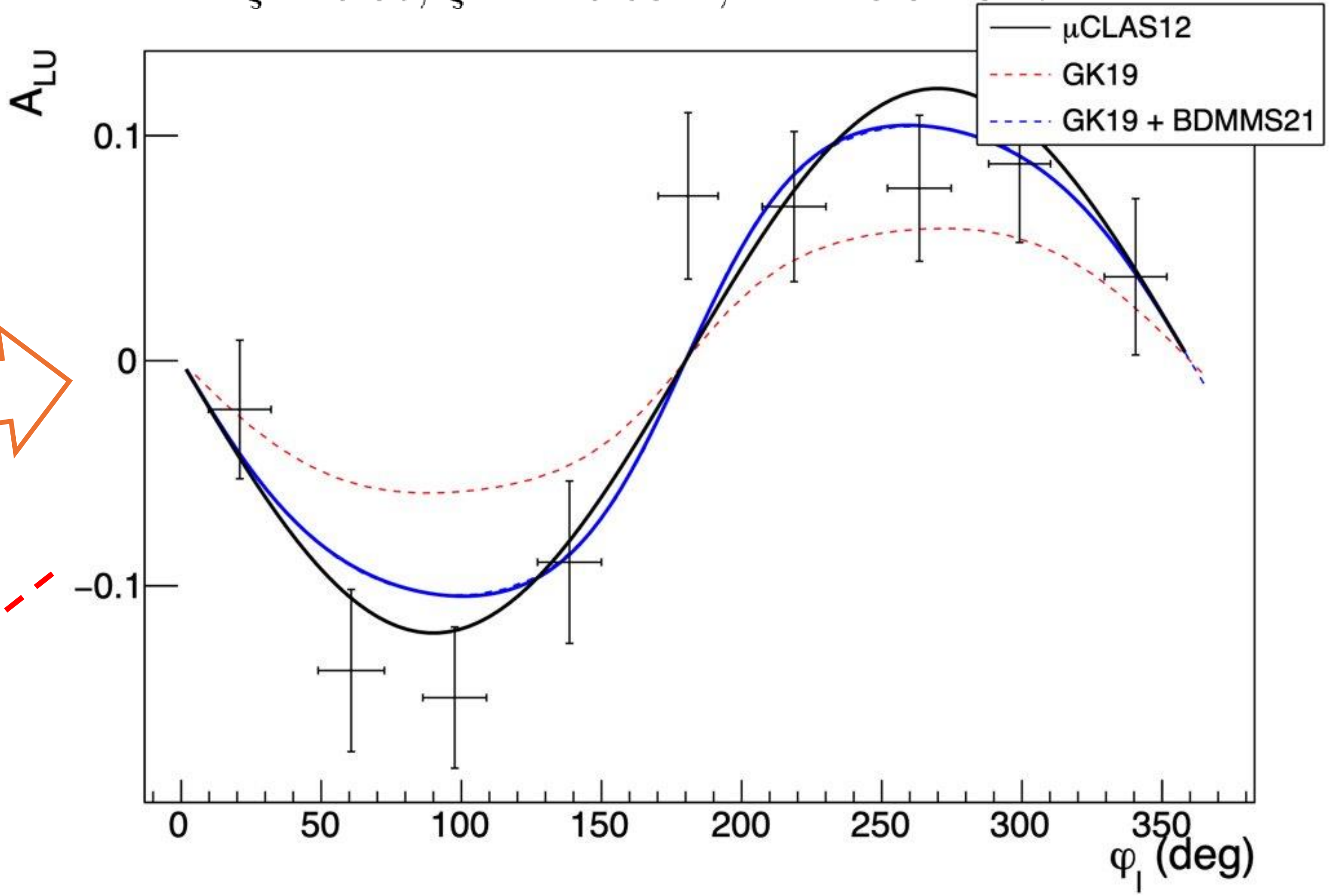
$$A_{LU} = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$

Asymmetries from PARTONS

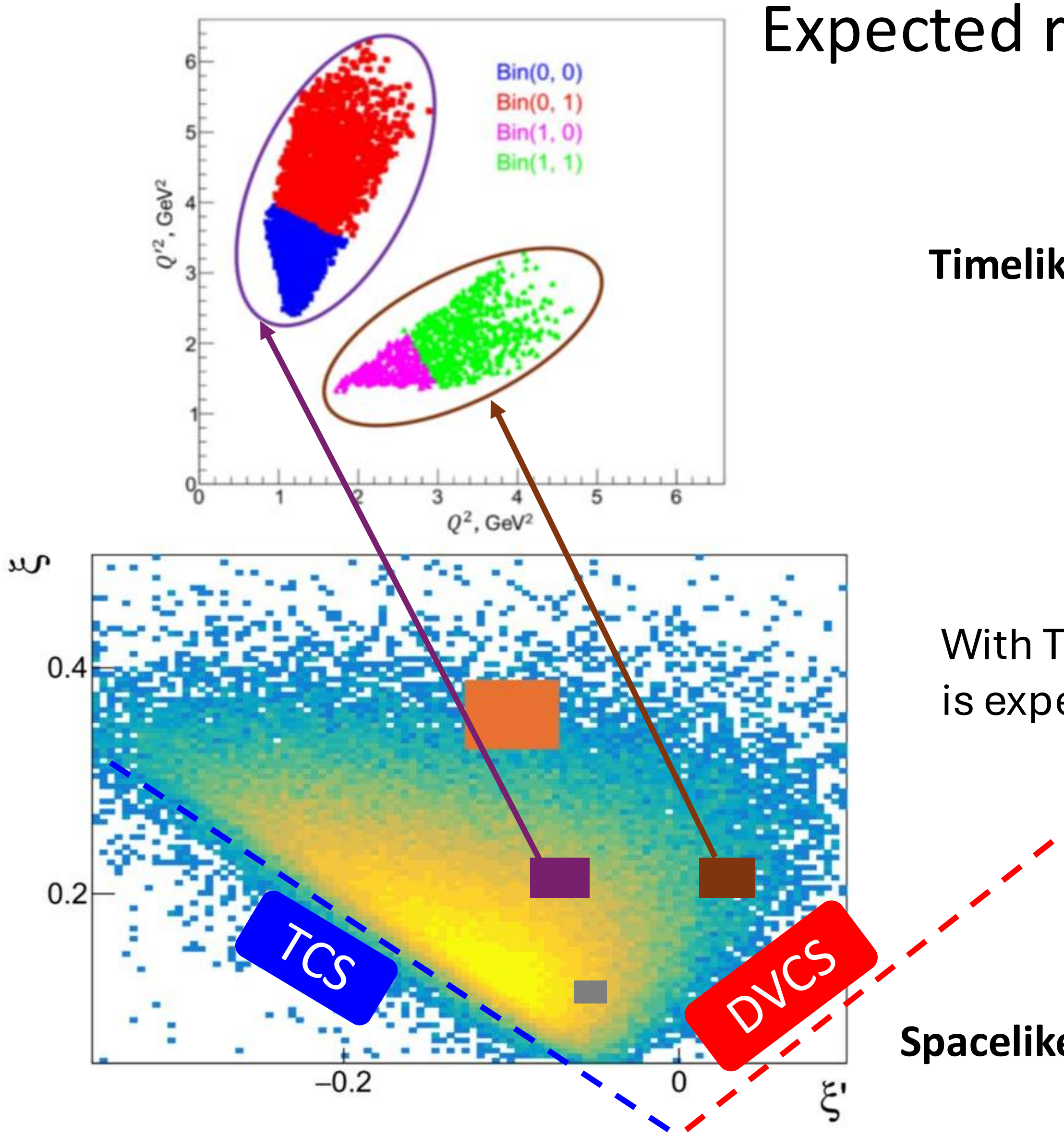
- As DDVCS allows to access GPDs at x≠∓ξ, This measurement will allow to reduce uncertainties coming from shadow GPDs.



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

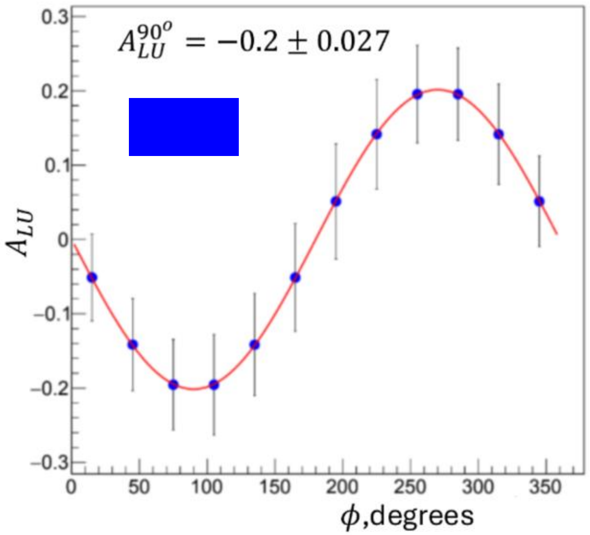


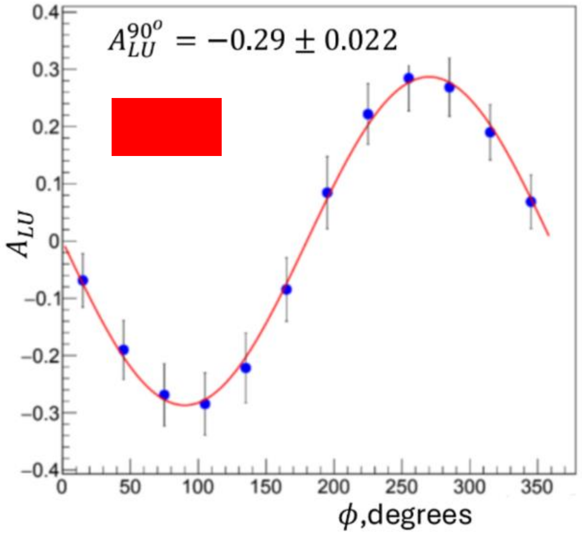
Expected results: timelike vs spacelike regions



VGG predictions

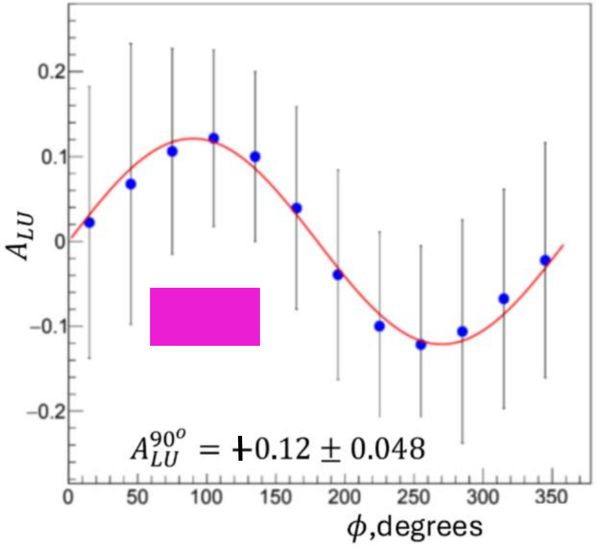
Timelike

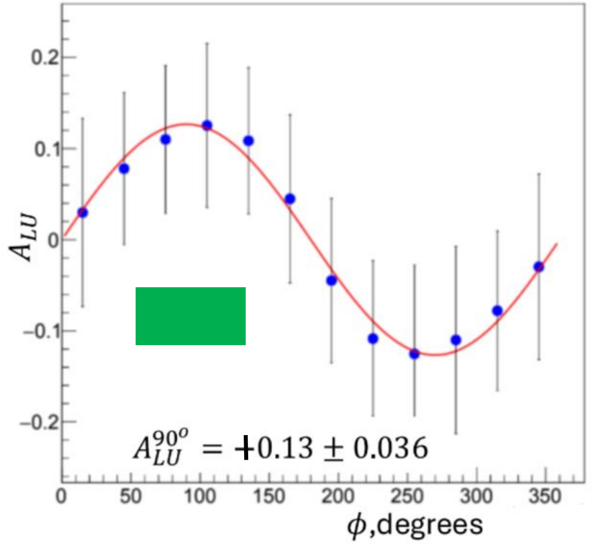




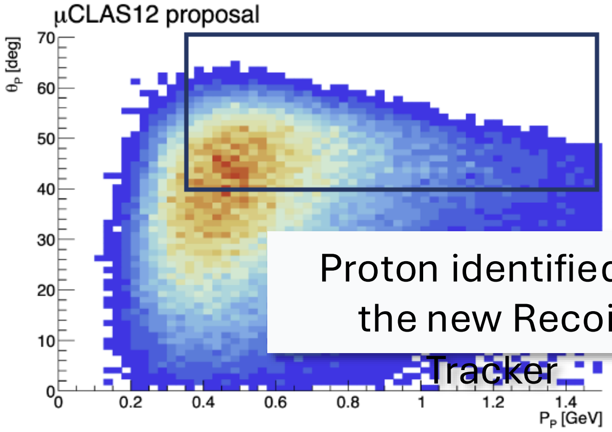
With Timelike → Spacelike transition a change of the sign of the asymmetry is expected.

Spacelike





Expected results: TCS

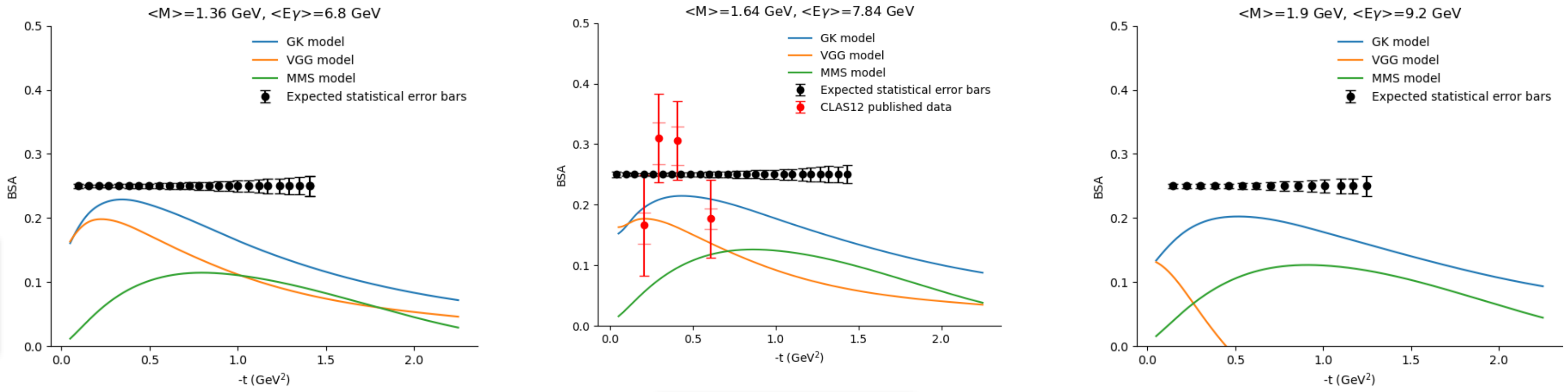


Proton identified in the new Recoil Tracker

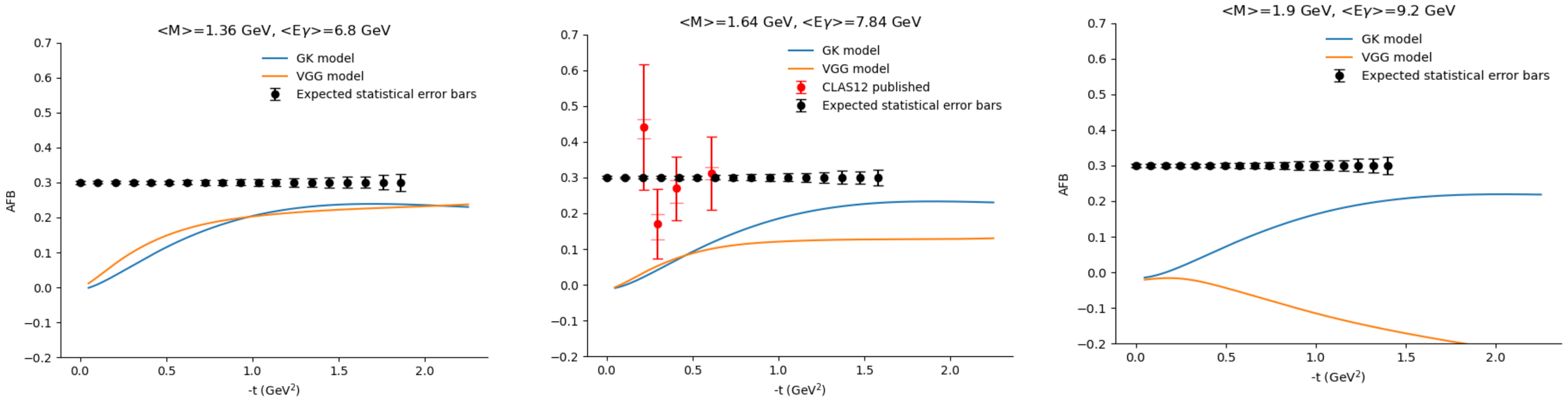
7.7M expected with events M(μμ) >1.2 GeV)

precision measurement of TCS

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



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



Current status of the project

- JLab PAC53 approved the experiment (C1) with an A rating for 200 production + 45 commissioning and calibration days.

- Concise version of the proposal with minor modifications has been submitted to EPJ-A.
  - Got accepted in June arXiv link: arXiv:2605.11690

- Finishing simulation work on optimization of the shield and expected radiation doze

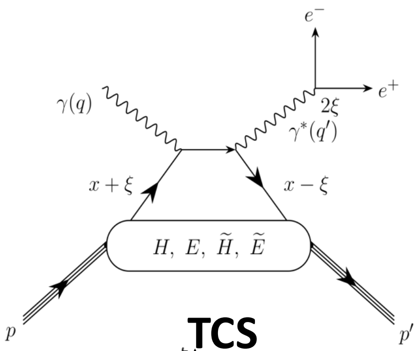
- Then will follow the design work of detectors

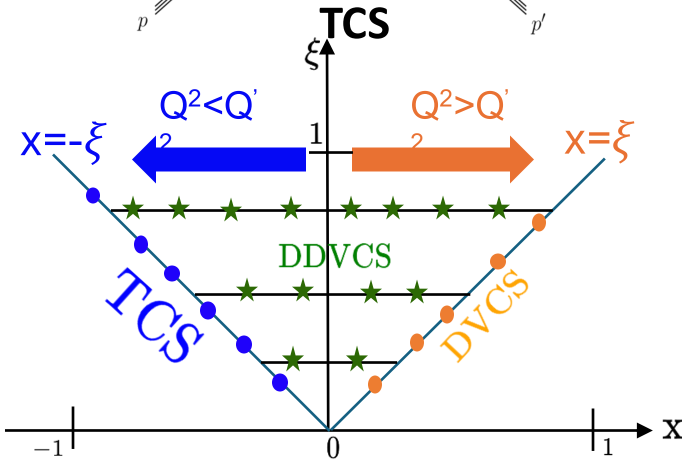
- Thanks to Richard Milner, MIT will lend us 25 crystals by the end of summer, so we can start wCal prototyping in the Fall at JLab.

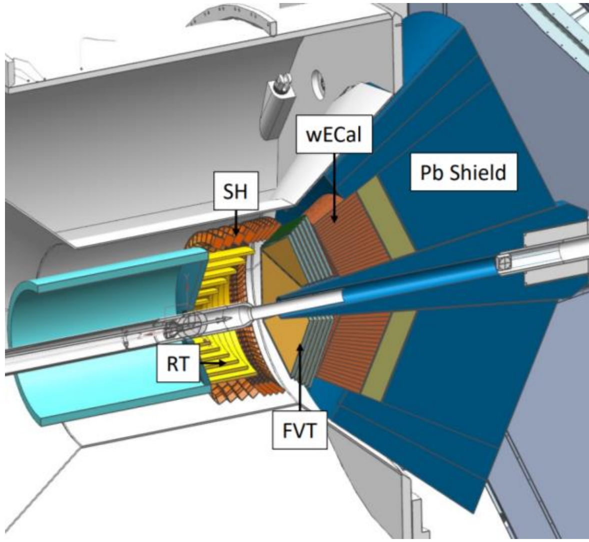
- Dedicated workshop in March of 2026, focused on expanding the physics reach and exploring additional measurement opportunities
  - More details in https://indico.jlab.org/event/1018/

Summary and outlook

- CLAS12 published first TCS data
    - Analysis of larger data set is in progress.
- DDVCS is an important process which allows to access GPDs in a domain inaccessible with DVCS or TCS
- It has not been measured because of the very low cross-section
- μCLAS12 allows to measure **ep→e$^-\mu^-\mu^+$p** process and will be able to take **x100** the standard CLAS12 Luminosity : **10^{37}cm^{-2}s^{-1}**.
- **A** rated experiment: **200 days of production running** will allow precision measurement of DDVCS, TCS and J/ψ in a wide range of kinematics.
- Currently re-evaluating expected rates and dose on detectors, then the design work of detectors will start







Backup

Photoproduction with electron beam

Two photon sources:

Real photons + Virtual photons

Electroproduction cross-section can be expressed as:

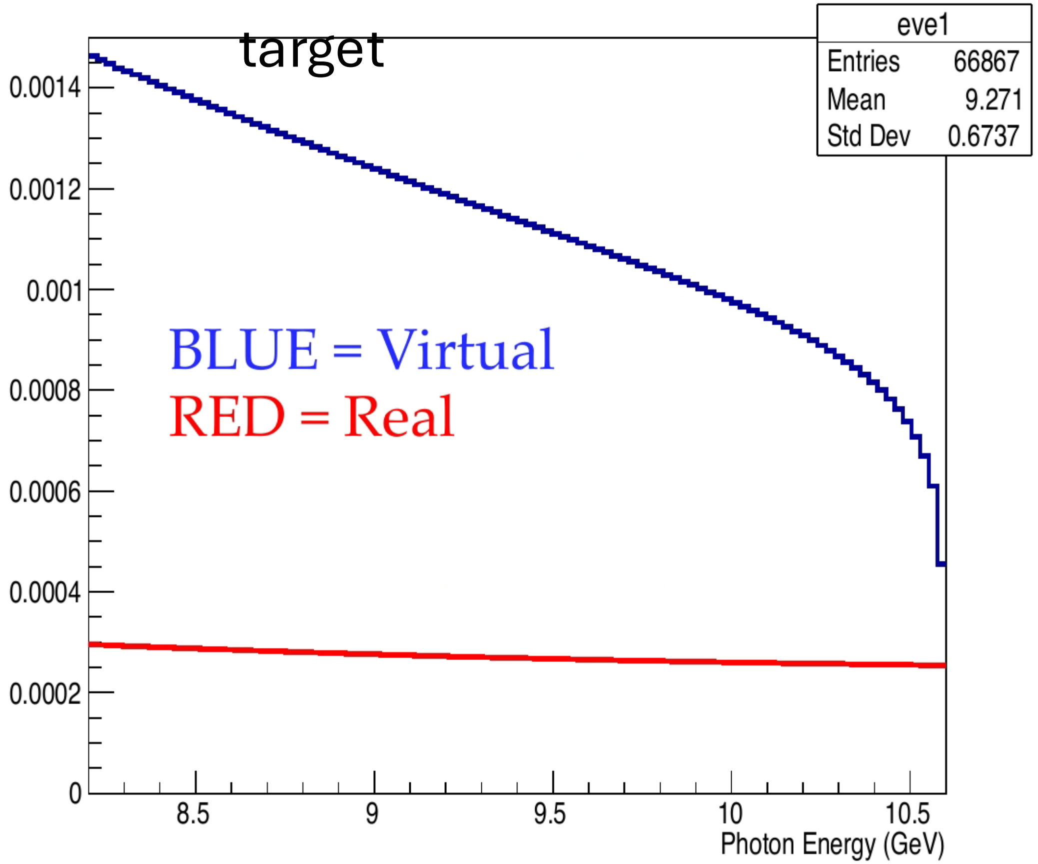
$$\frac{d\sigma}{dt} = \Gamma_\gamma \cdot \frac{d\sigma_\gamma}{dt} + \Gamma_{\gamma*} \cdot \left(\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}\right)$$

Real photon flux Virtual photon flux

At small Q^2, $\boldsymbol{\sigma}_L$ approaches to 0.

$$\frac{d\sigma}{dt} = (\Gamma_\gamma + \Gamma_{\gamma*}) \cdot \frac{d\sigma_\gamma}{dt}$$

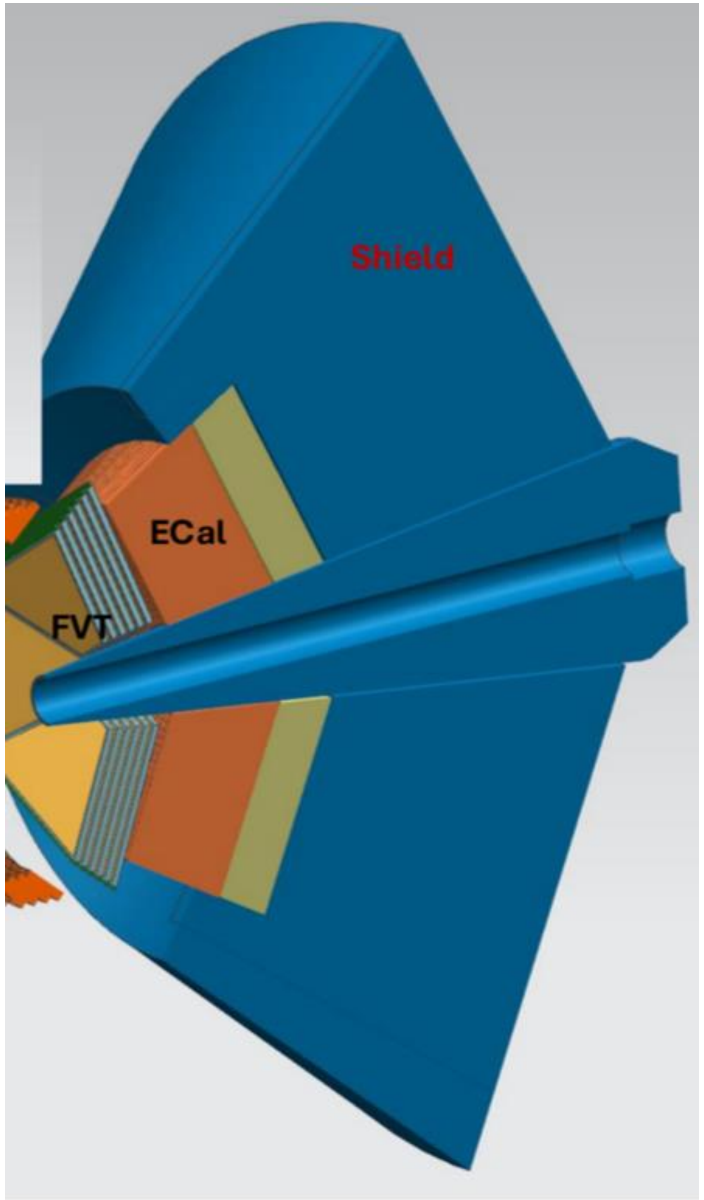
Flux for 5cm LH2 target



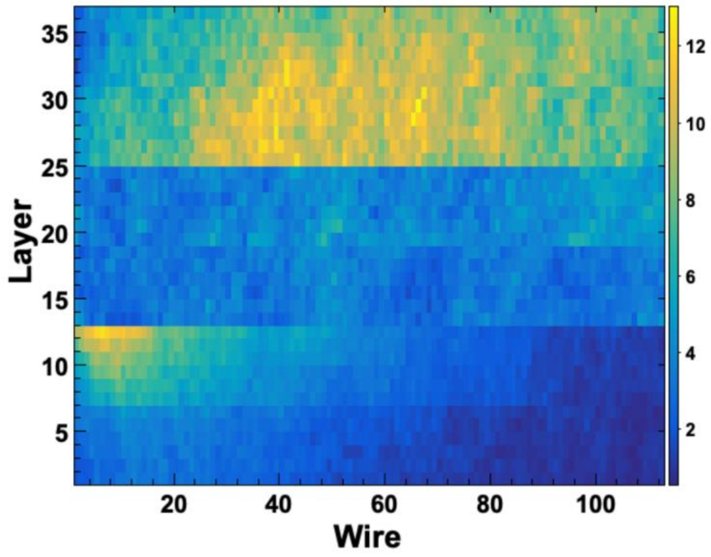
$$n(E_\gamma) = \frac{l}{2 \cdot X_0} \frac{1}{E_\gamma} \cdot \left(\frac{4}{3} - \frac{4}{3}\frac{E_\gamma}{E_b} + \frac{E_\gamma^2}{E_b^2}\right) dE$$ Real photon flux

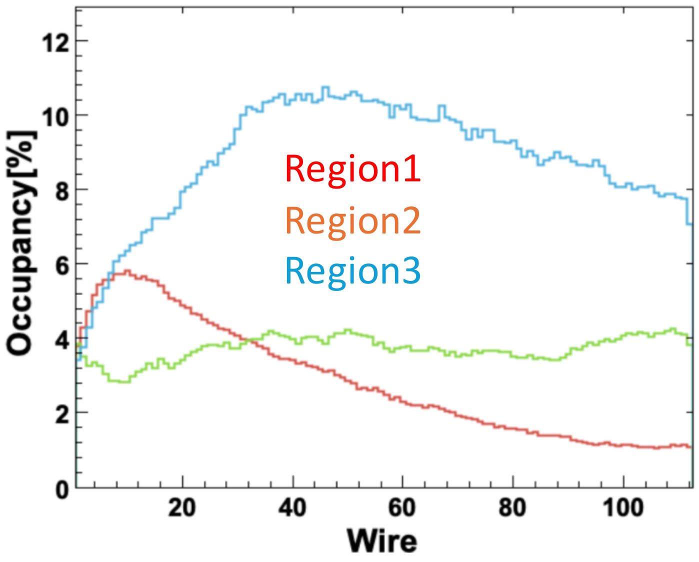
$$\Gamma(E_\gamma) = \frac{1}{E_b} \frac{\alpha}{\pi \cdot x} \cdot \left((1 - x + \frac{x^2}{2}) \cdot log(\frac{Q^2_{max}}{Q^2_{min}}) - (1-x) \right) dE$$ Virtual photon flux

Occupancies in Drift Chambers

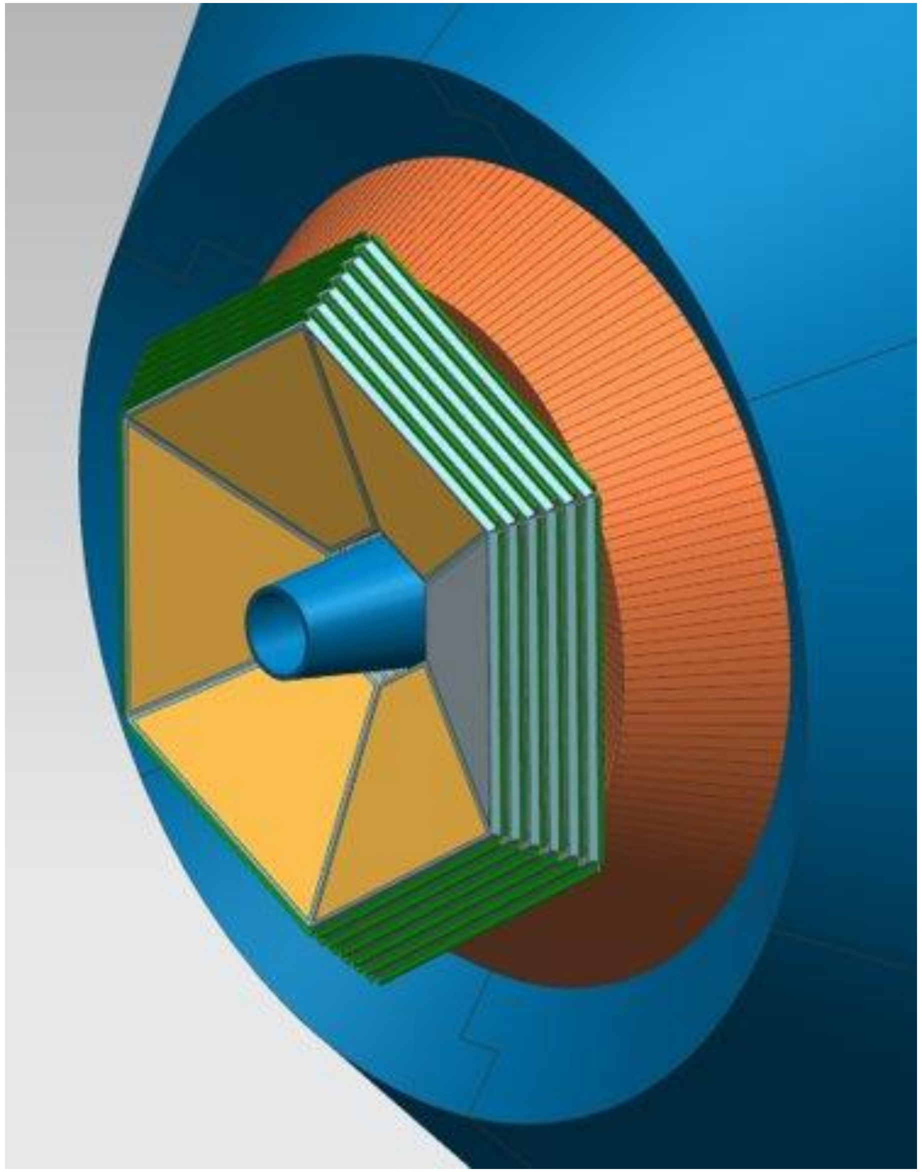


- Thick Moeller cone with the Lead Shielding and the wECal massively suppress the EM background coming from the target.
- These occupancies are comparable with the current CLAS12 occupancies.
    - CLAS12 reached close to 10% with nuclear targets.
- Work continues optimizing shielding and background mitigation to achieve better tracking.

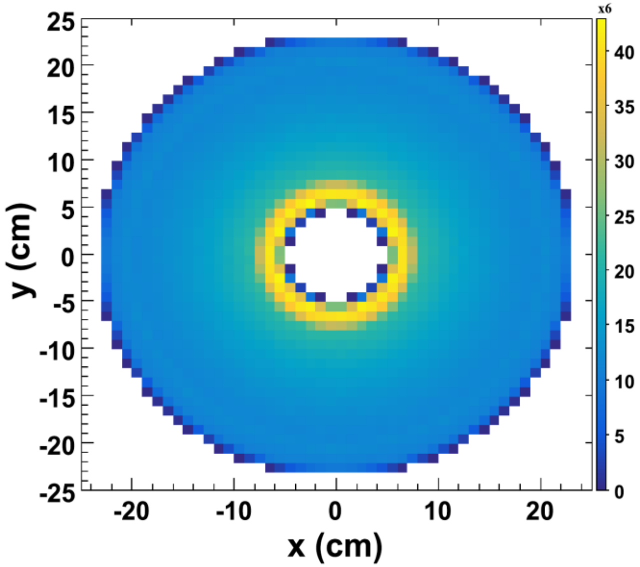


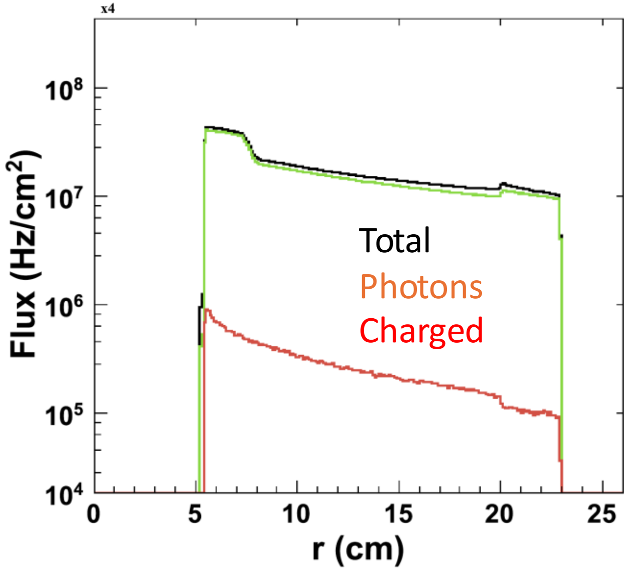


Forward Vertex Tracker



- Muons experience **high energy lose and multiple scattering** inside the shielding material.
- With **just DC, the Vertex (position and angle) reconstruction will be poor**.
- Primary purpose of the FVT is to **precisely reconstruct vertex parameters**.
- 6-layer assembly GEM detectors
  - 40 cm from the target
- VMM3 readout
- Maximum rates is < 1MHz/cm^2 at the very forward region
- Average rate is less than 500 KHz/module





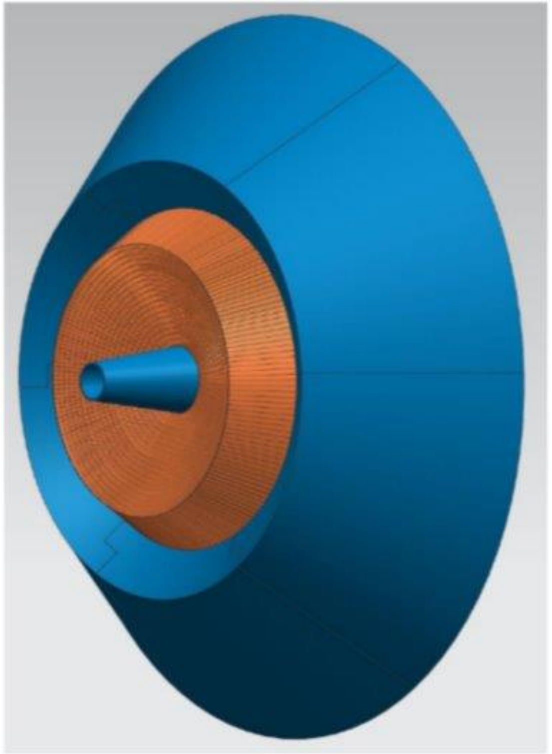
wECal

- 1320 $PbWO_4$ modules, 20 cm long
- 1.3 x 1.3 cm2: Small angles (7° - 12°)
- 1.5 x 1.5 cm2: Large angles (12° - 30°)
- APD readout

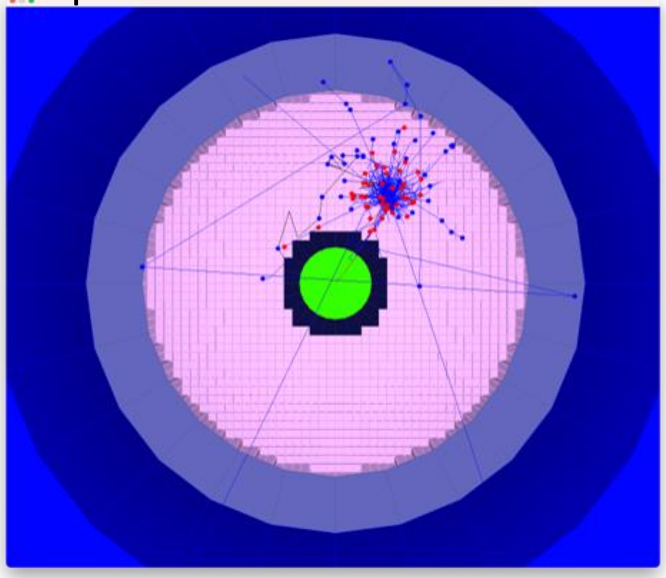
At the 1st ring, rate is less than 2 MHz (per crystal).

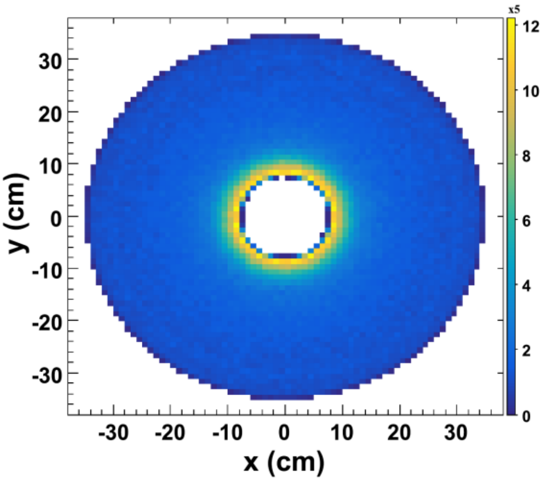
HPS used APD readout and observed comparable rates in hottest crystals.

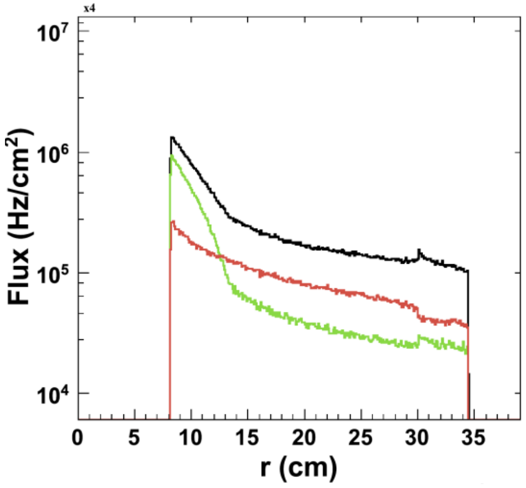
Manageable rate with pulse fitting.



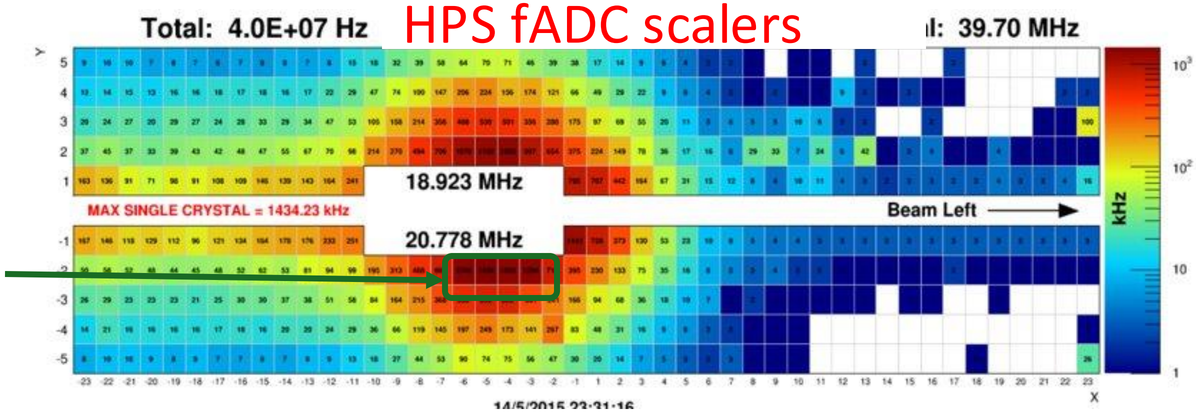
Implementation in GEANT4





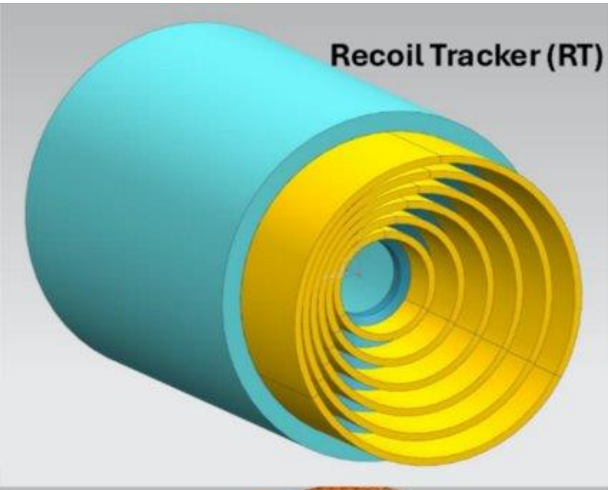


HPS fADC scalers

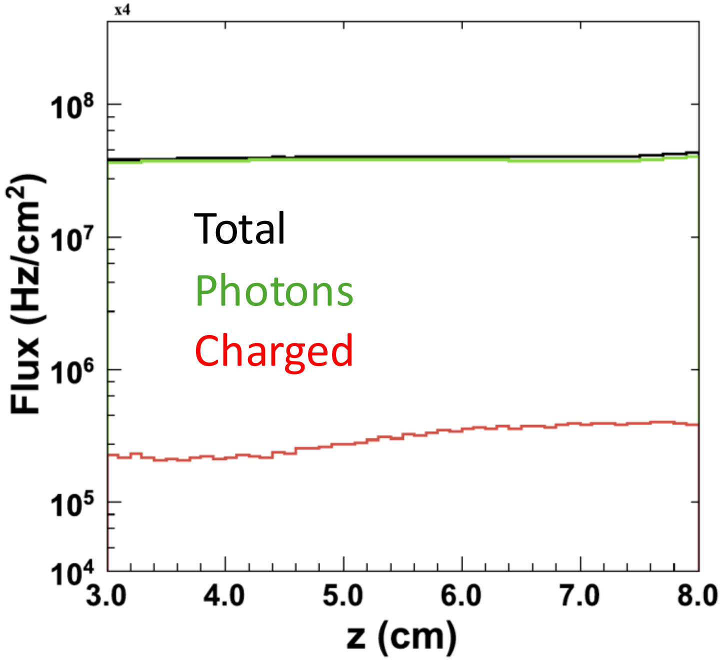


≈1.5 MHz

RD : Recoil Tracker + Scintillation Hodoscope

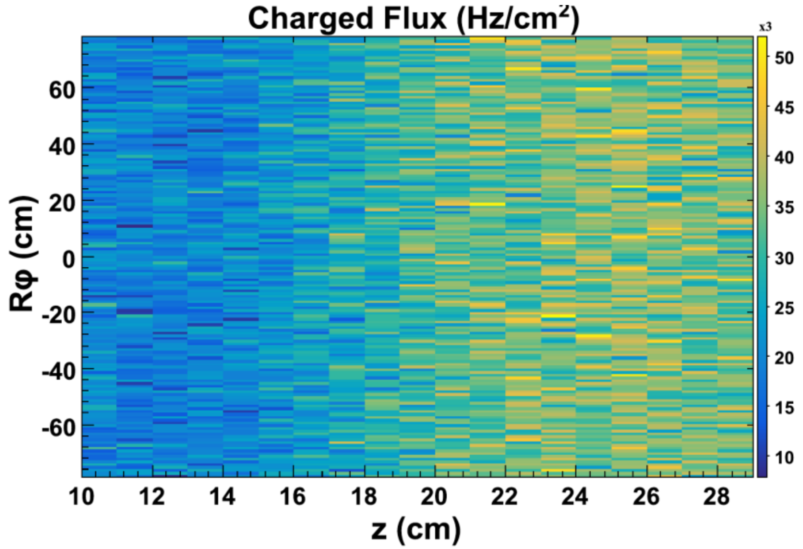


- 6 concentric cylindrical µRWELL layers
    - R = 8 cm (1st layer) and 23.5 (6th layer)
- Each layer is divided into three identical sectors
- Coverage : 40˚ to 70˚
- Total rate < 250 KHz/cm^2.

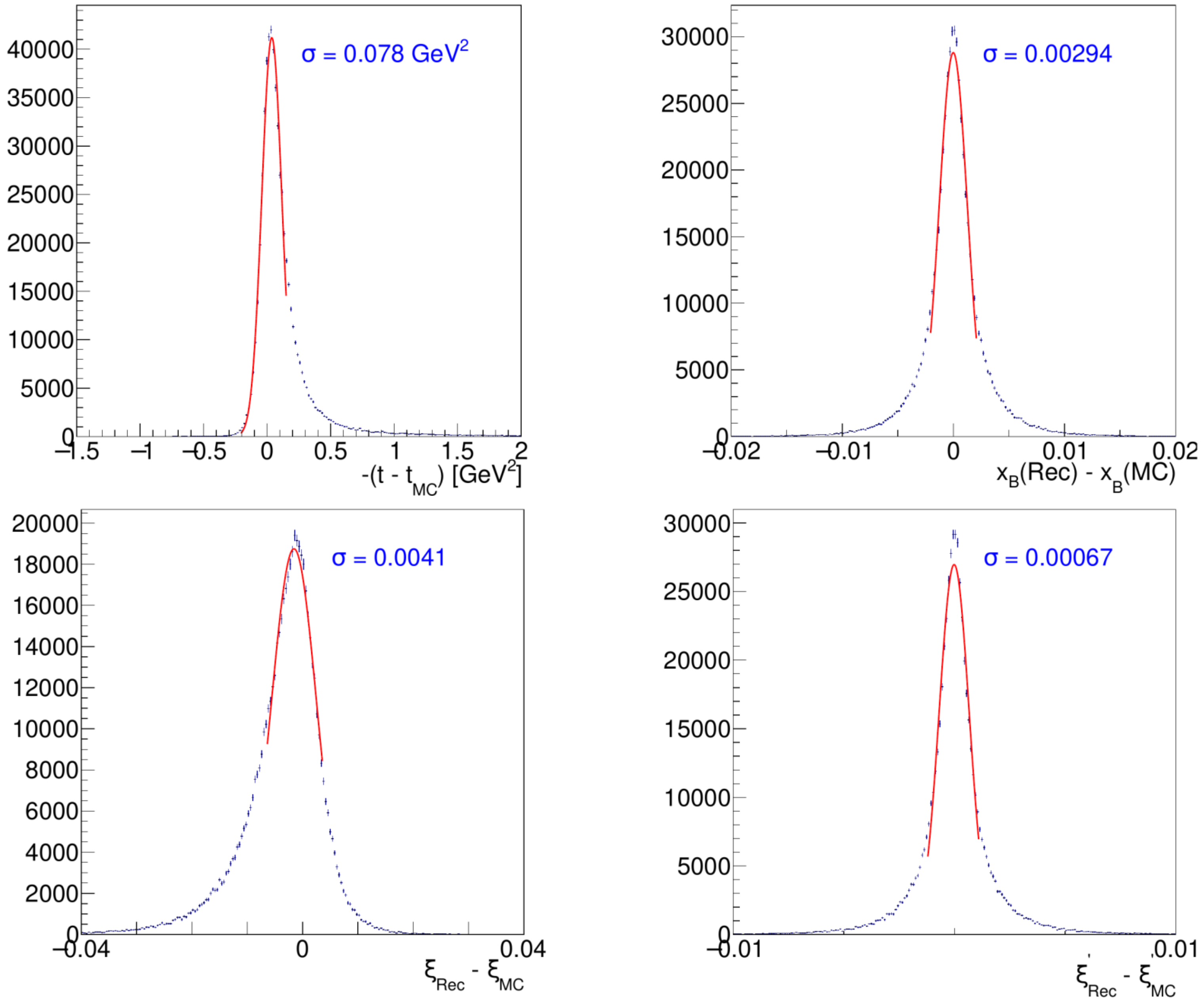


Scintilliation Hodoscope **SC**

- 540 truncated pyramidal modules arranged in concentric rings around the beam line
- (40° - 50°) 2x2 cm^2 tiles
- (50° - 70°) 4x4 cm^2 tiles
- At forward angles the charged particle rate is under 50 KHz/cm2 → per crystal rate is under **200 KHz**.

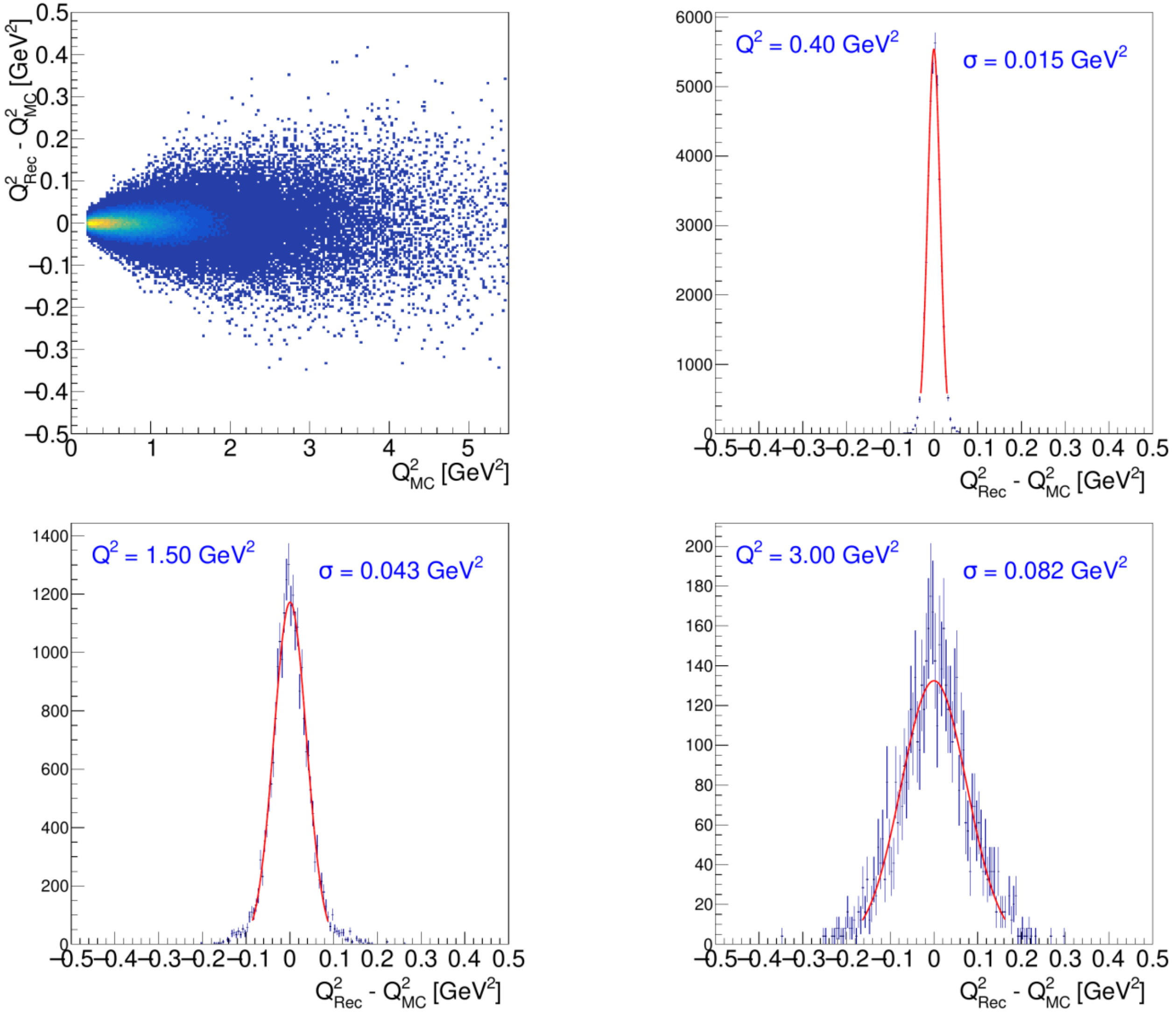


Resolutions: Kinematic variables

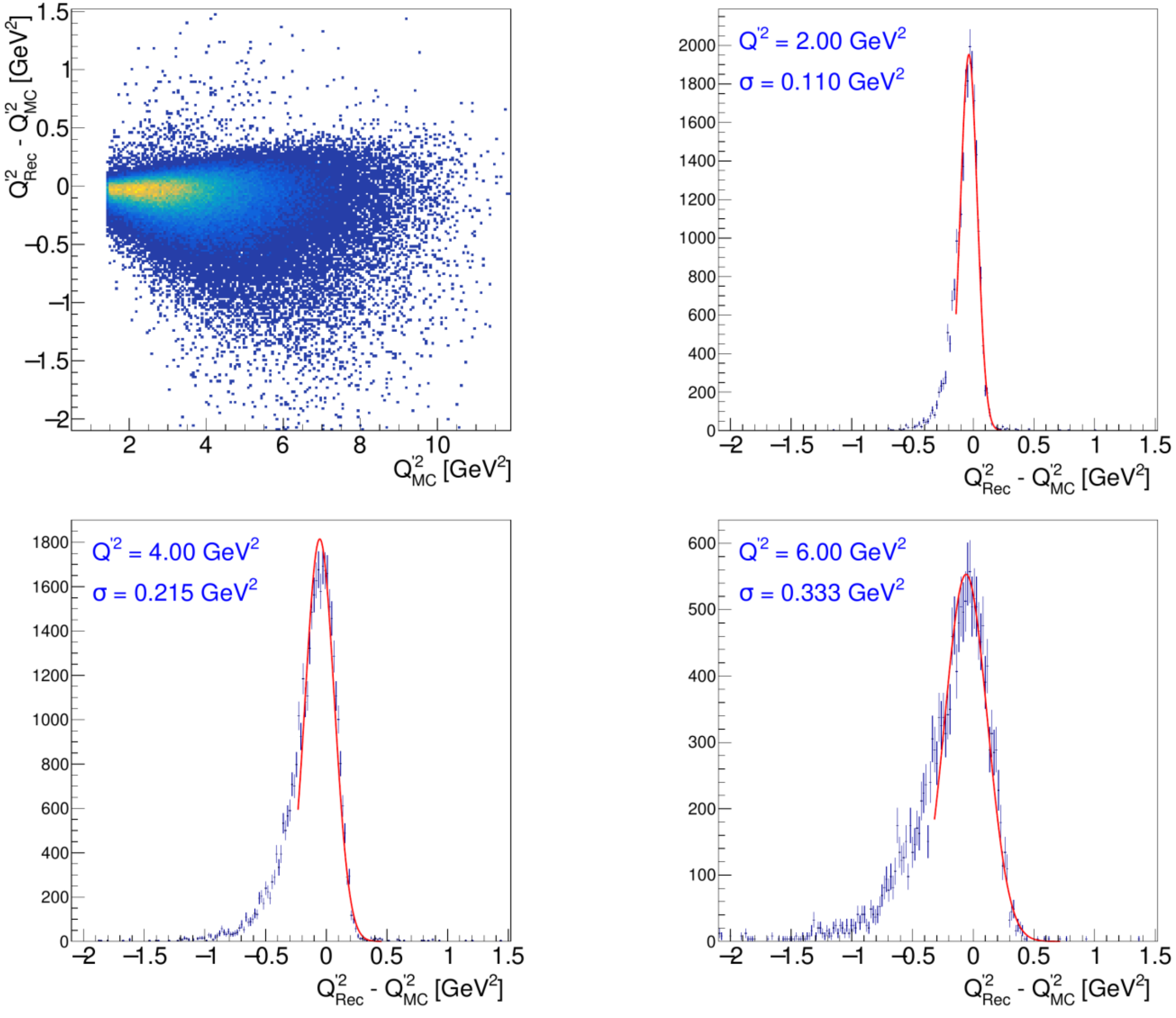


Resolutions: Virtualities

Q^2



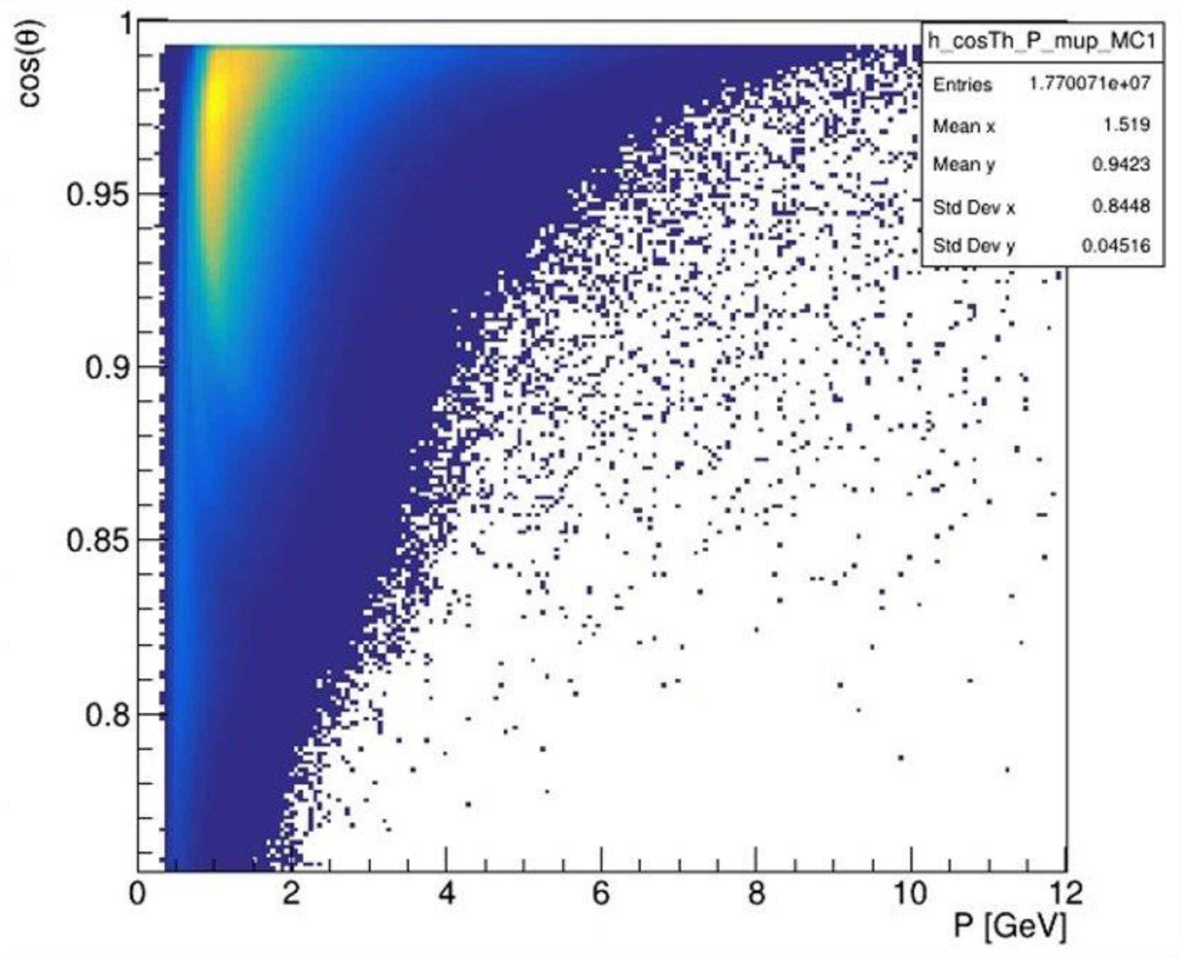
Q'^2

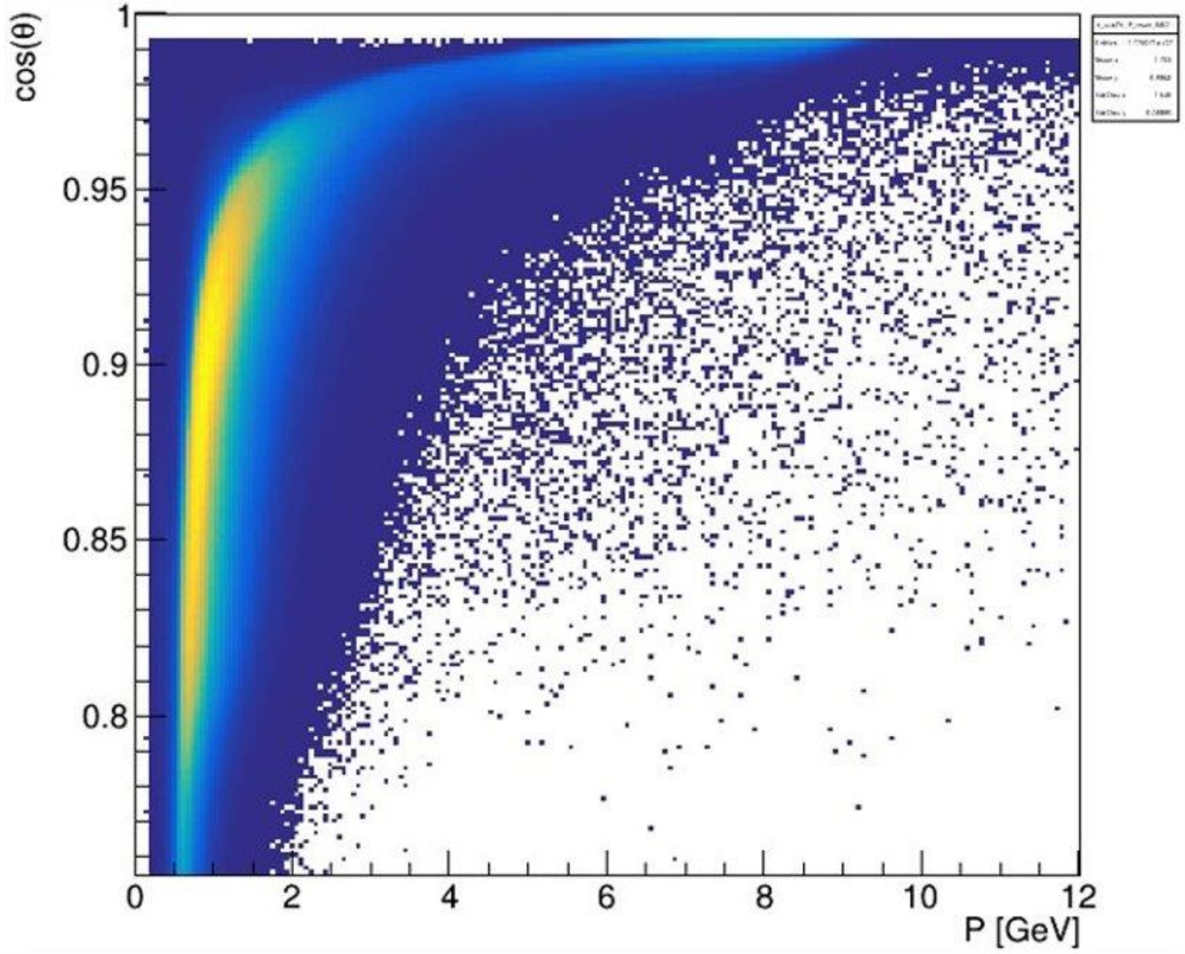


Pion background

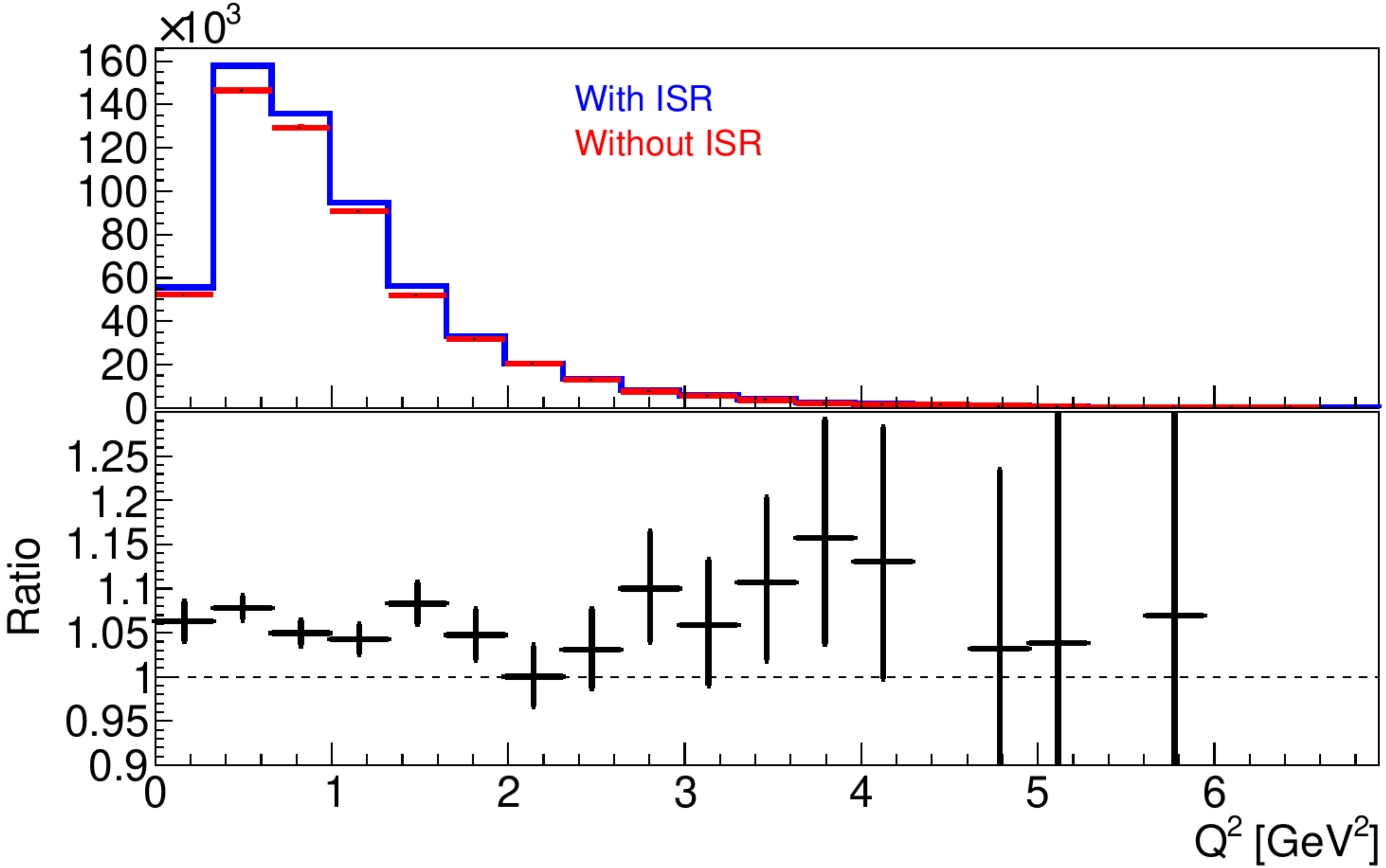
Kinematic distributions from CLAS12 RG-A

- 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%



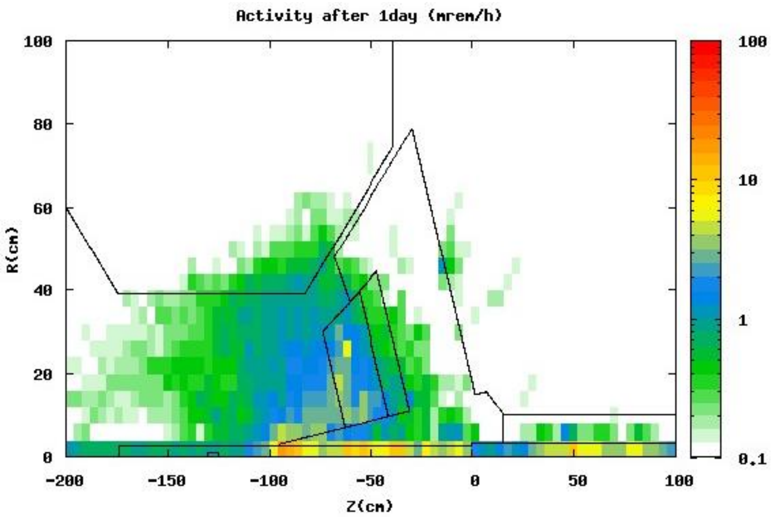


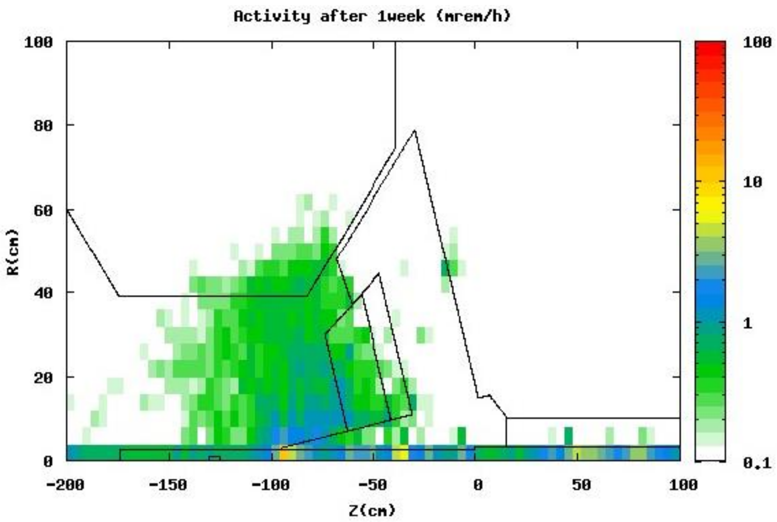
Initial state radiation

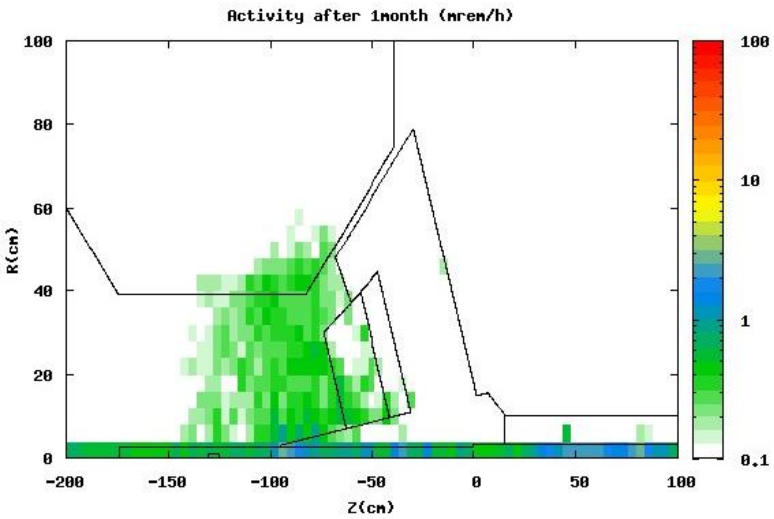


Activation of the setup and decommissioning

- 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

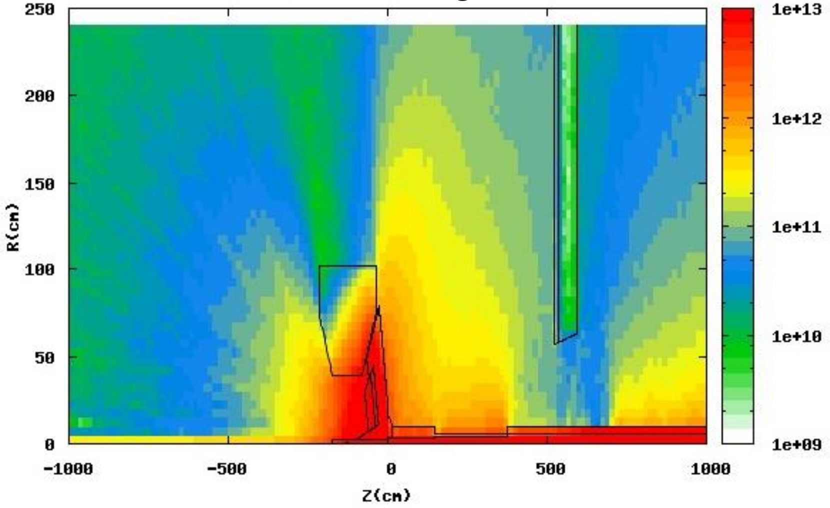




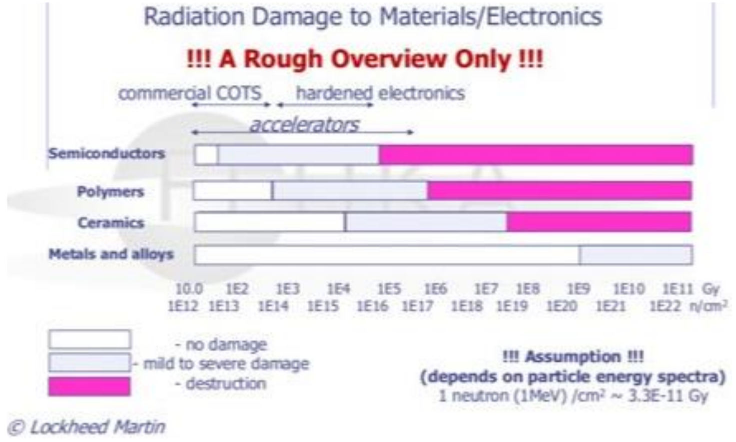


Neutron Radiation

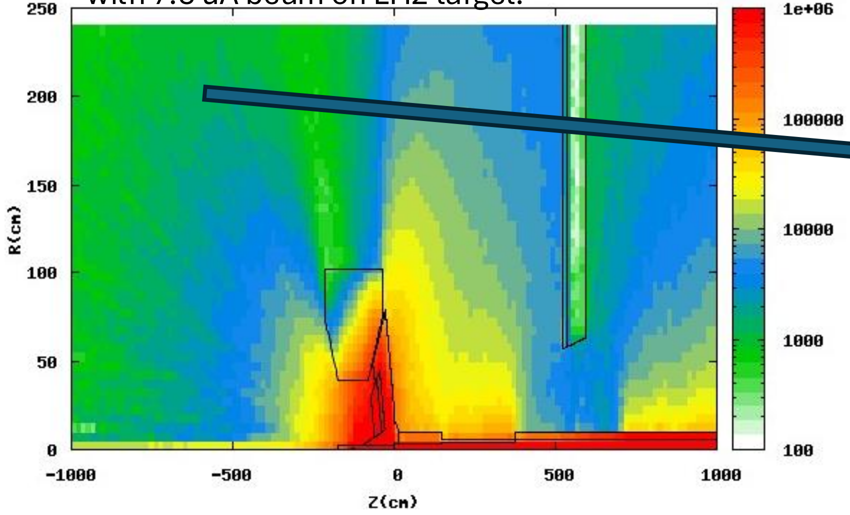
1 MeV equivalent neutron fluence in Si [sm^{-2} 200 days] with 7.5 uA beam on LH2 target.



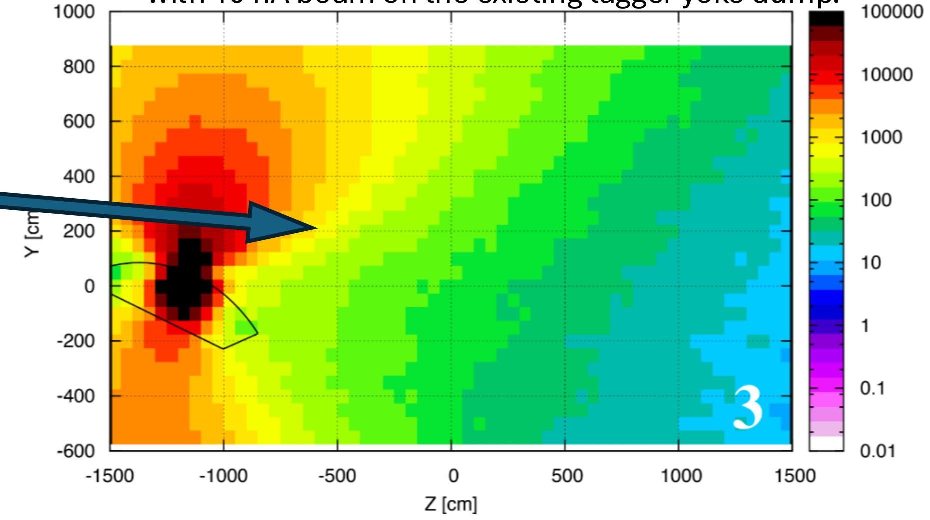
The accumulated dose in the wECal and tracker electronics region is less than 2×10^{12} n/cm^2, close to but below the levels that cause damage to the semiconductors.



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



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



Summary of awarded beam time

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

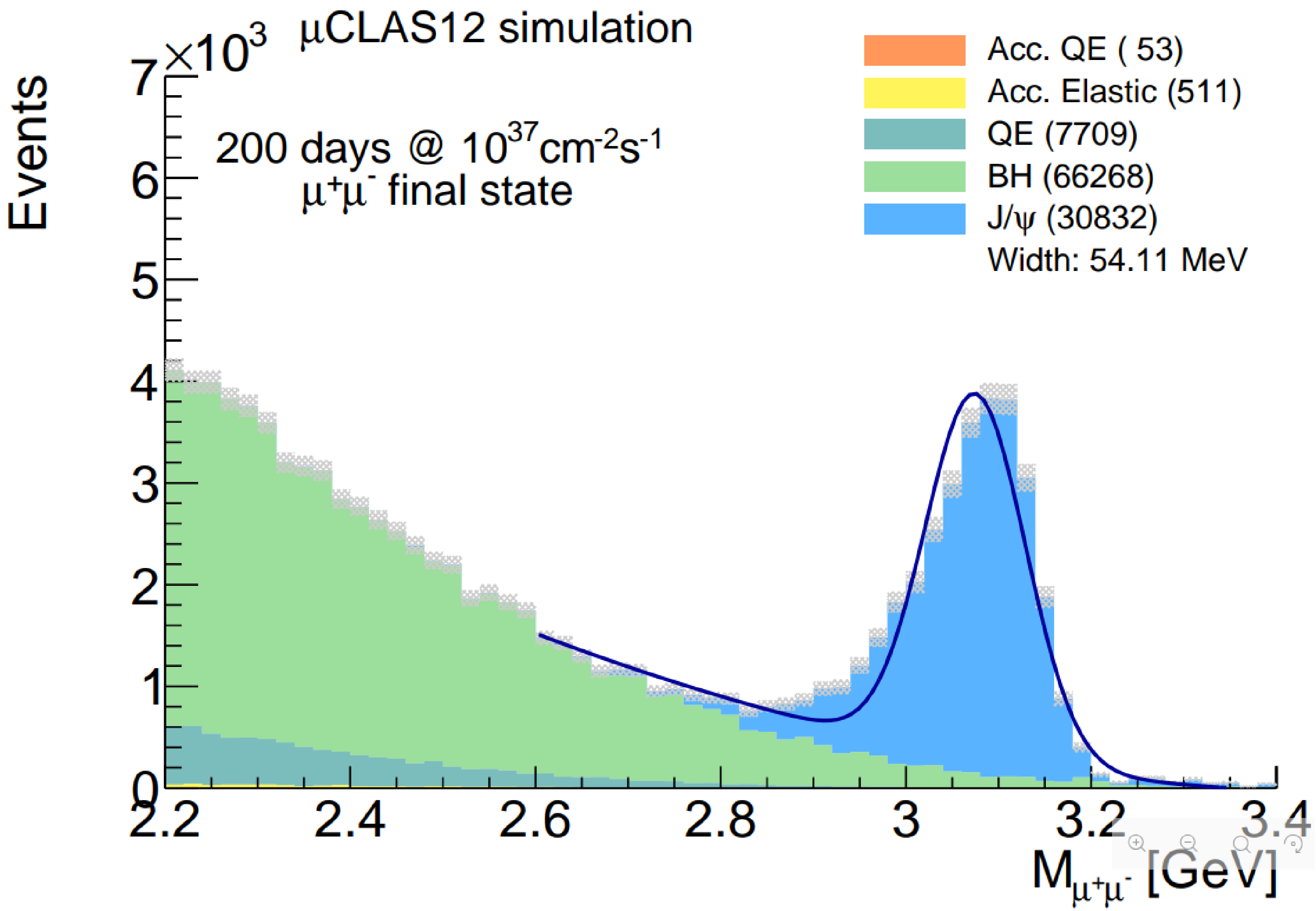
Systematics

DDVCS BSA	Systematics
Beam polarization uncertainty	3 %
Background asymmetry	< 6
Radiative effects	< 5%
Total	**< 8.5 %**

J/ψ cross section	Systematics
Acummulated charge	1.5 %
Normalization	< 10 %
Radiative effects	< 5%
Total	**< 11.3 %**

TCS BSA	Systematics
Beam polarization uncertainty	3 %
Background asymmetry	< 6 %
Radiative effects	< 5%
Total	**< 8.5 %**

TCS FBA	Systematics
Radiative effects	5 %
Normalization	< 10 %
Total	**< 11.2 %**


μCLAS12 simulation
$\times 10^3$
Events
200 days @ 10^{37}cm^{-2}s^{-1}
$\mu^+\mu^-$ final state
Acc. QE (53)
Acc. Elastic (511)
QE (7709)
BH (66268)
J/ψ (30832)
Width: 54.11 MeV
0
1
2
3
4
5
6
7
2.2
2.4
2.6
2.8
3
3.2
3.4
$M_{\mu^+\mu^-}$ [GeV]