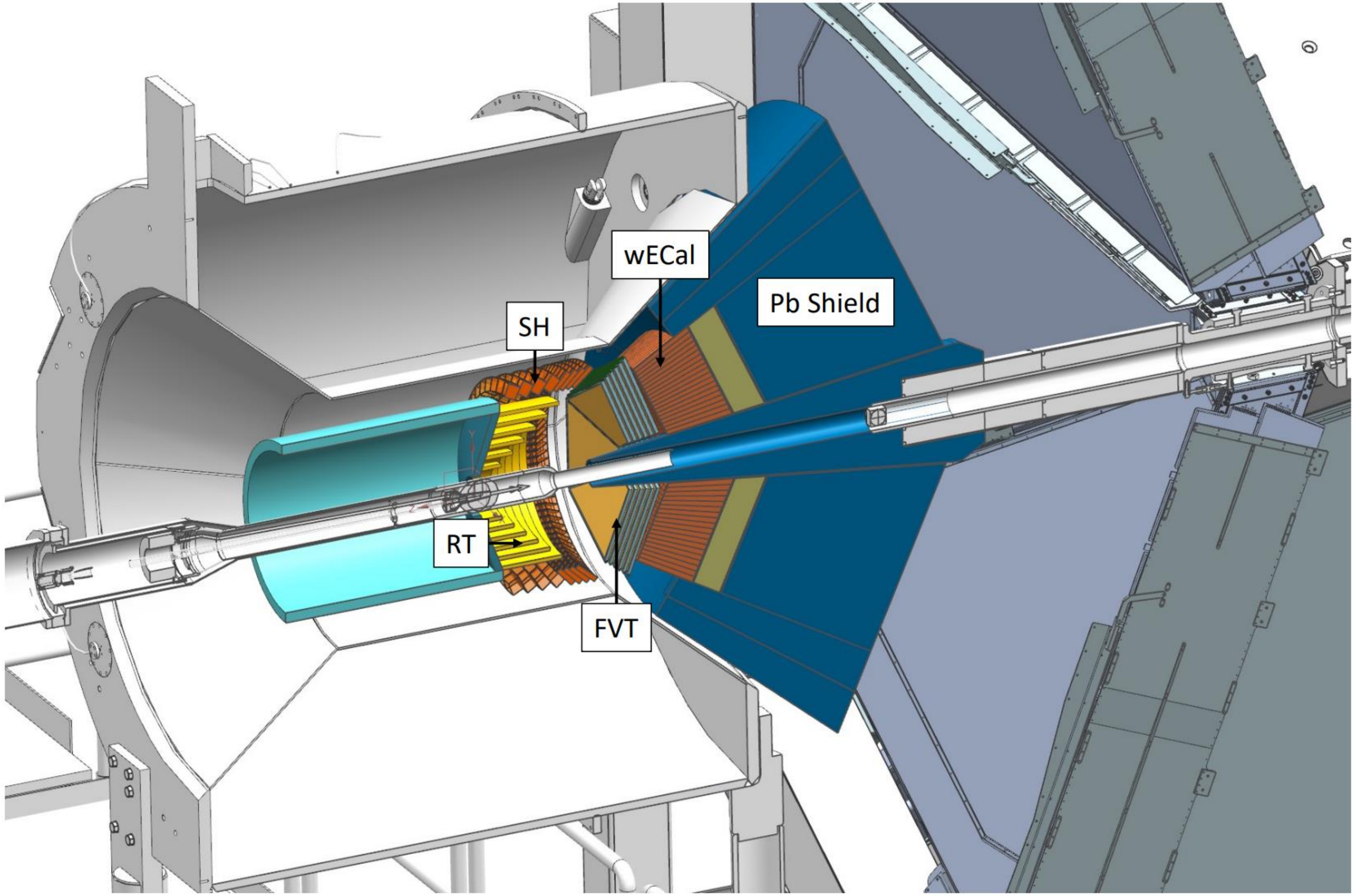
# Update on the $\mu$CLAS12




Rafayel Paremuzyan

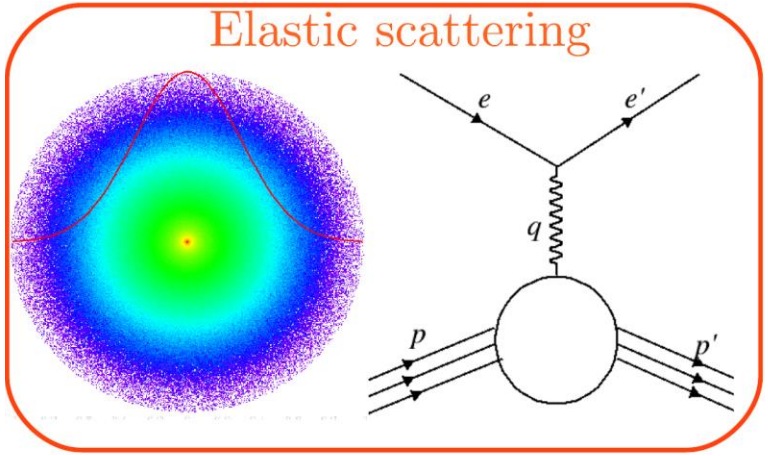
2026 JLUO Annual Meeting, July 23-25, 2026, Jefferson Lab

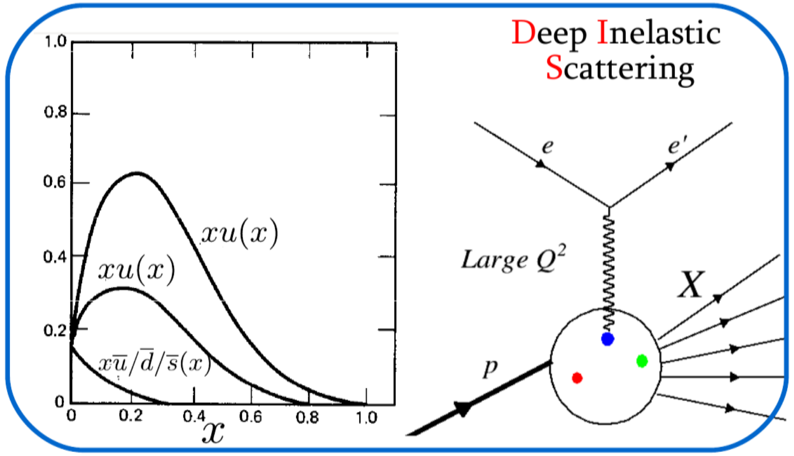
# Outline

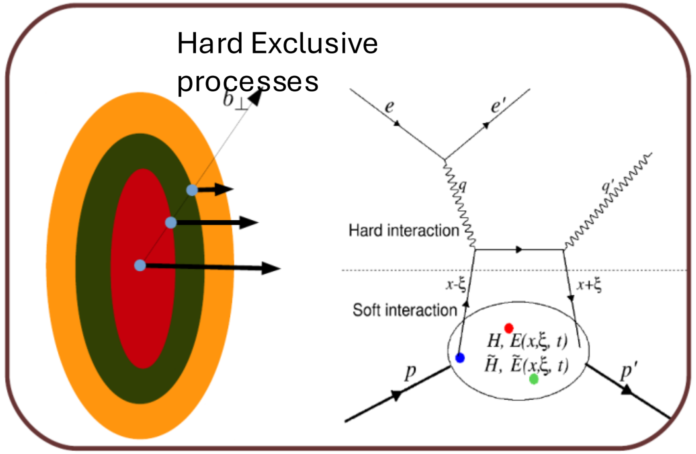
- Physics motivations
  - GPDs and traditional reactions to access GPDs
  - What can we learn more with DDVCS
  - TCS
  - J/$\psi$ production
- The experimental setup
- The measurement
- Observables and estimations
- Summary

# Generalized Parton Distributions

One of flagship experiments at JLab are deep exclusive processes (e.g. DVCS, TCS, DVMP etc), allowing to access **Generalized Parton Distributions** (GPDs).

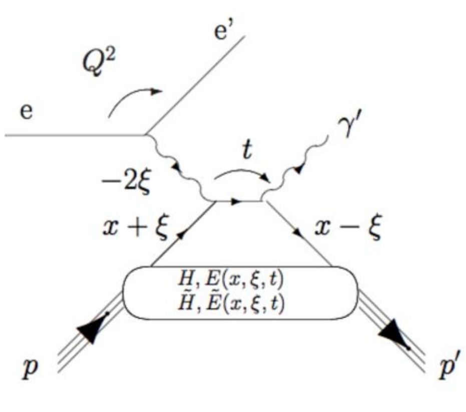


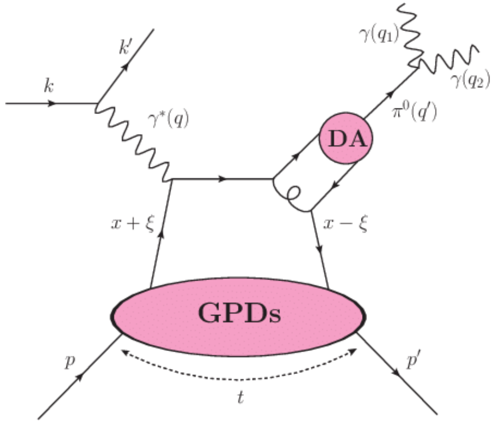




*Hard exclusive reactions experimentally studied at JLab*

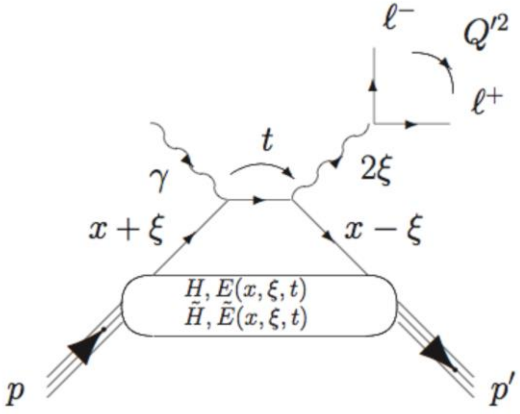
DVCS




DVMP




TCS




- GPDs are hybrid functions that combine aspects of PDFs and Elastic Form Factors.
- 2D spatial + 1D momentum distributions of partons inside the nucleon
- More than a dozen of completed and planned dedicated experiments at JLab.

More details in: Prog.Part.Nucl.Phys. 133 (2023) 104069

# Challenges in the extractioon 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**

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

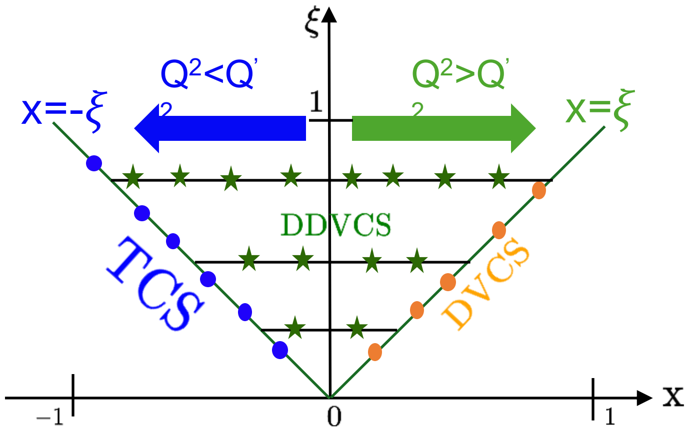
$$\mathcal{F}^{\pm}(\xi,t) = \int dx\, F(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} \mp \frac{1}{\xi + x - i\epsilon}\right) = \mathcal{P}\int_{-1}^{1} dx\left(\frac{1}{\xi - x} \mp \frac{1}{\xi + x}\right)\sum_q e_q^2 F^q(x,\xi,t) + i\pi \sum_q e_q^2 [F^q(\xi,\xi,t) \mp F^q(-\xi,\xi,t)]$$

Exception is when one measures Im part of the scattering amplitude, where one can access GPDs at x=∓ξ line.

With DDVCS by varying virtualities of incoming and outgoing photons, the -ξ< x < ξ becomes accessible

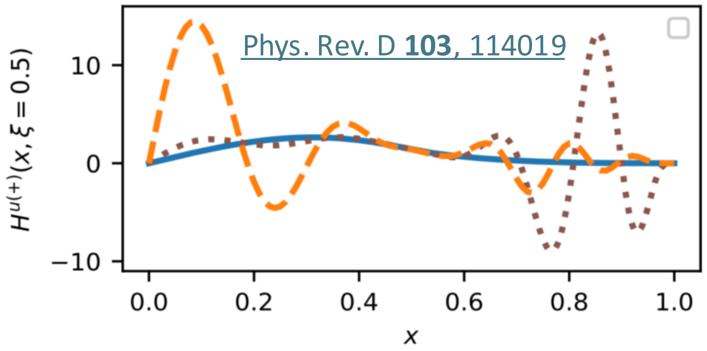
$$\mathcal{H}(\xi'\xi,t) = \int_{-1}^{1} \mathrm{dx}\left(\frac{1}{\xi' - \xi - i\epsilon} - \frac{1}{\xi' + \xi - i\epsilon}\right)\mathrm{H}(\mathrm{x},\xi,\mathrm{t})$$

**DDVCS** $\xi' \to \dfrac{x_B}{2 - x_B}$

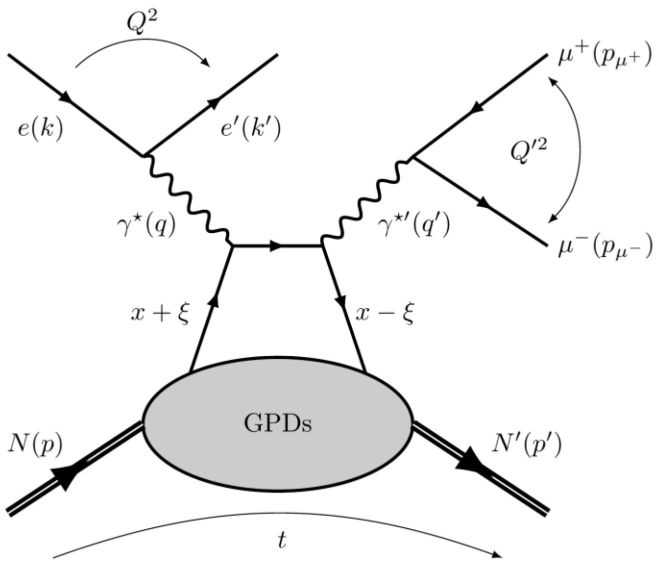


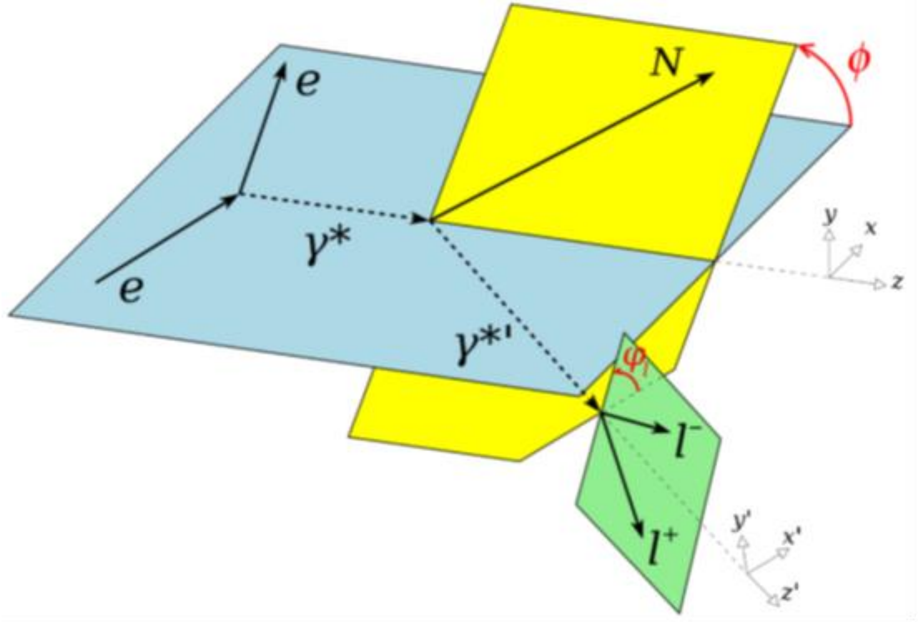

This was realized more than 20 years, ago, however has never been measured, mainly due to very low cross-section compared to DVCS.

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



# Double Deeply Virtual Compton Scattering: Observable




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

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

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

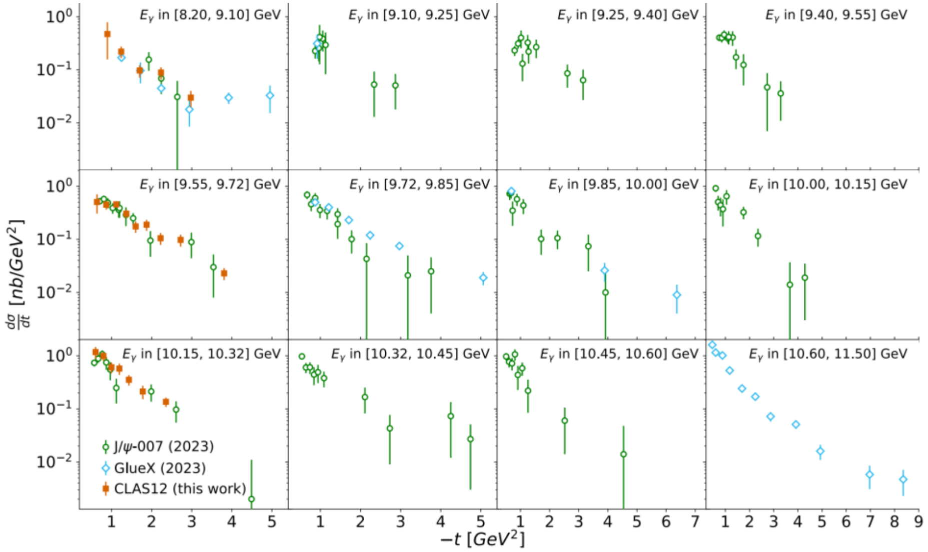
**Observable of interest** $A_{LU} = \dfrac{d\overrightarrow{\sigma}^5 - d\overleftarrow{\sigma}^5}{d\overrightarrow{\sigma}^5 + d\overleftarrow{\sigma}^5}$ In space like and timelike regions

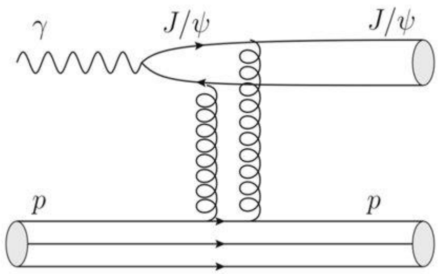
## Challanges

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

# TCS and J/$\psi$ production

While the main objective is the DDVCS measurement, with the same reaction ep → e′$\mu$-$\mu$+p we will be able to do high statistic measurement of TCS and J/$\psi$.

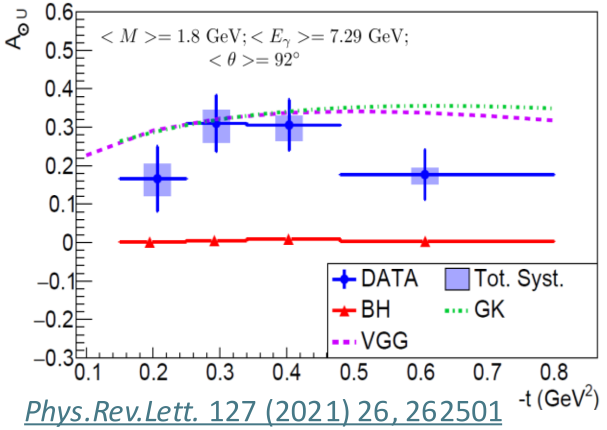


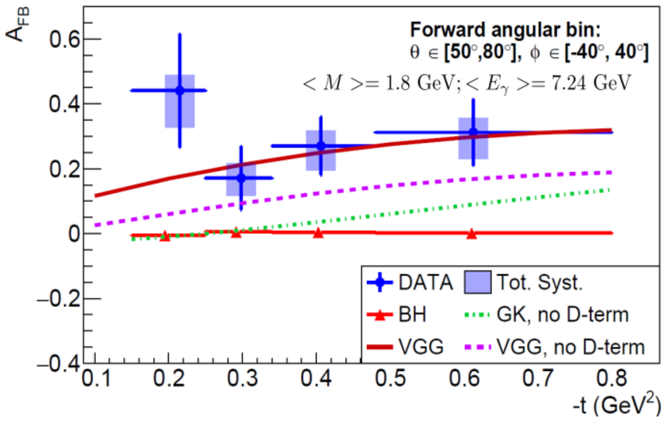




- With measurement of the t dependence of j/$\psi$ one can access GFFs of proton..
- Then one can extract mechanical properties of the nucleon.
- With x100 high luminosity, cross-section measurements can be significantly improved.

## Timelike Compton Scattering

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



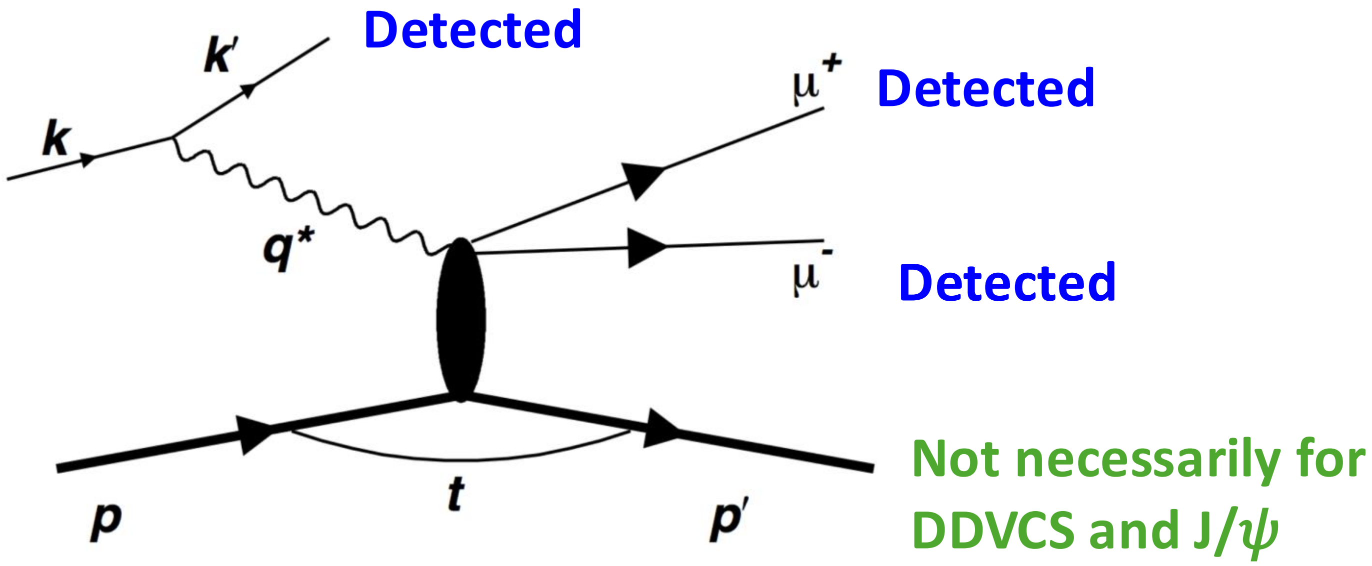

Phys.Rev.Lett. 127 (2021) 26, 262501

- TCS probes similar CFFs as DVCS.
- Direct access to the D-term.
- TCS is measurable with a muon pair in the final state.
- Current uncertainties are large: they don't significantly help with GPD extraction efforts.
- Can serve as a universality test of GPDs
- **Recoil proton detection** is needed to ensure exclusivity.

# The proposed measurement

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

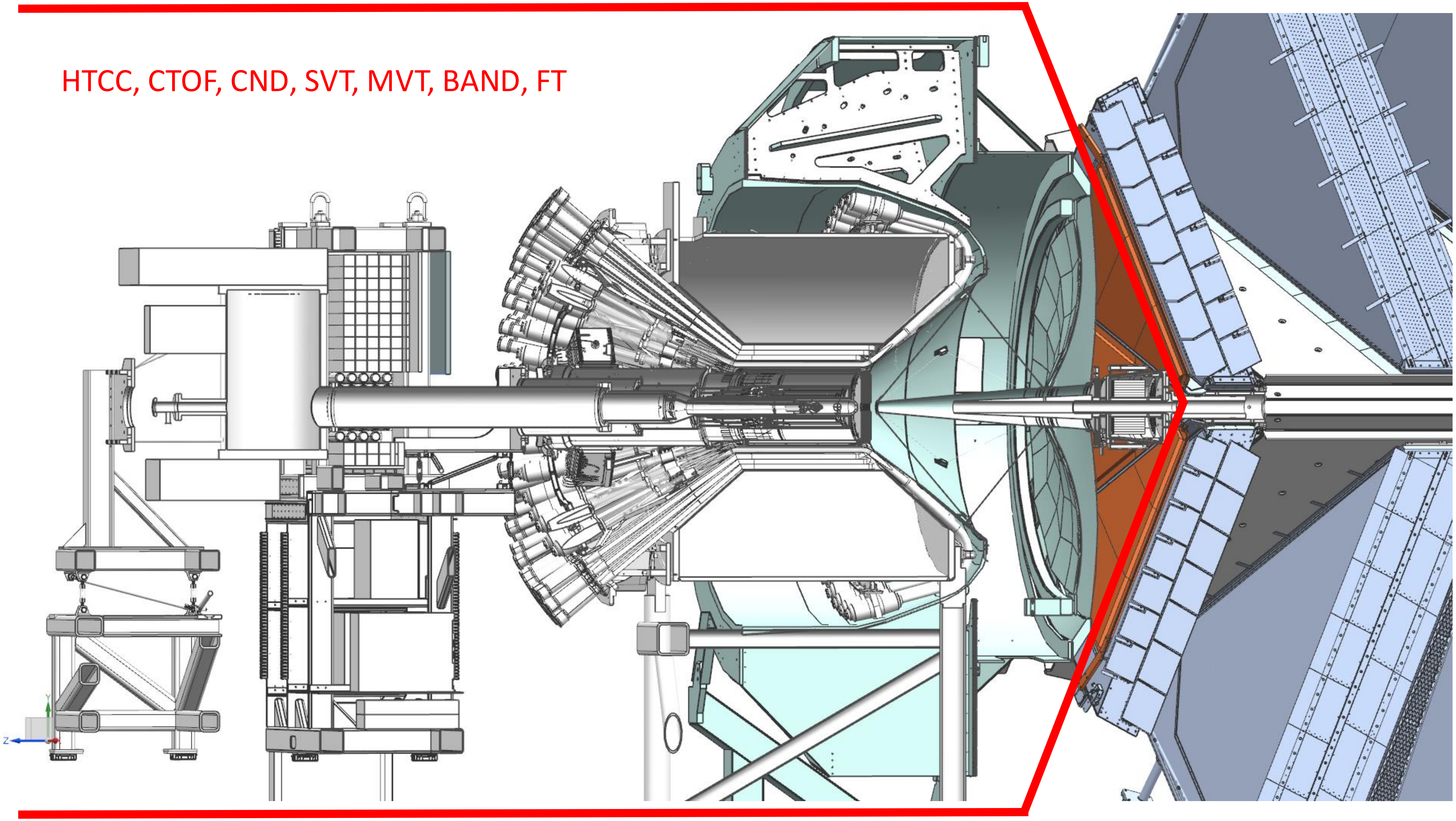
**The reaction of interest is ep → e′$\mu^-\mu^+$p**



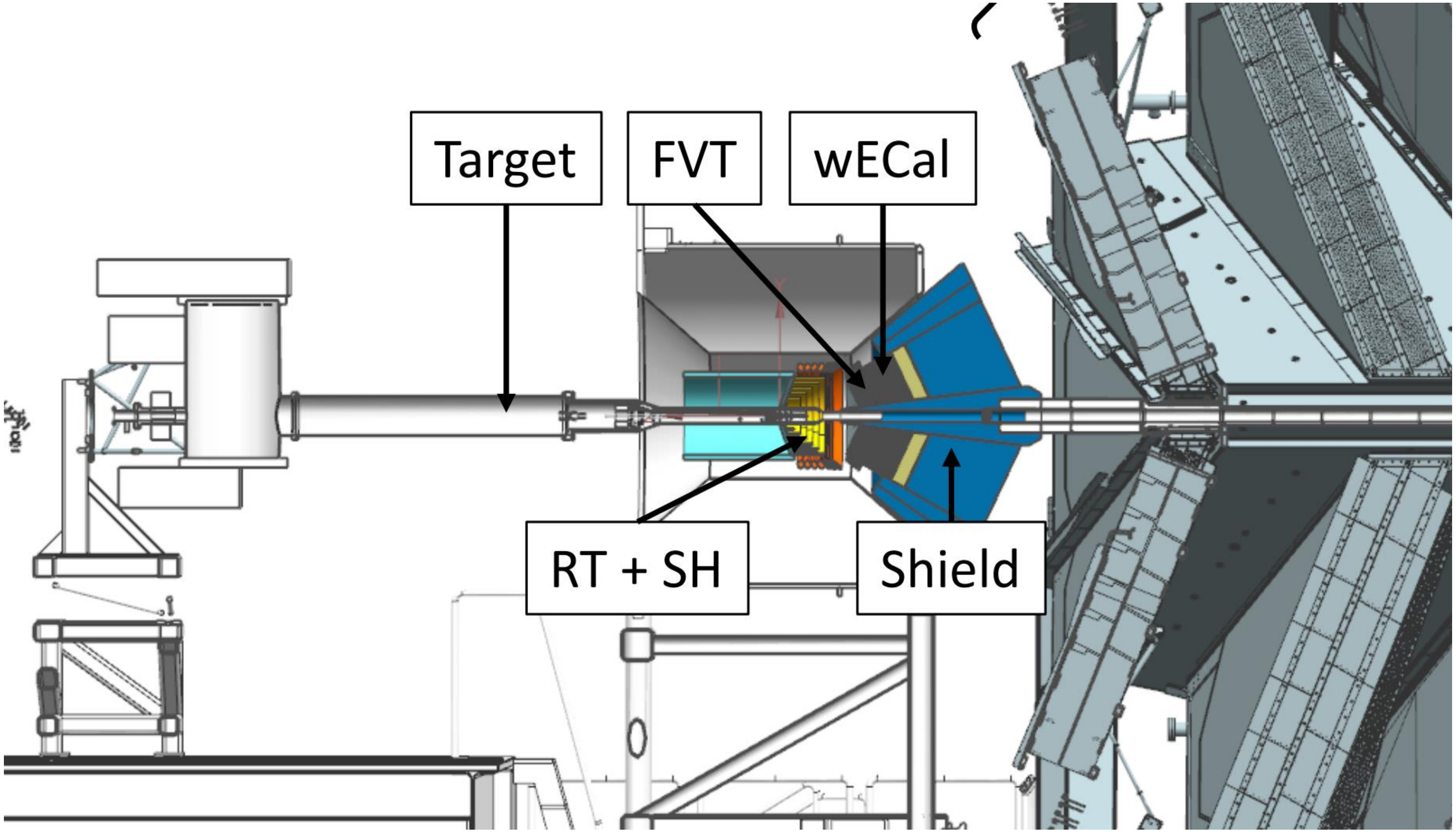

- The timelike photon is identified through the detection of $\mu^-\mu^+$ pair
- We plan to detect at least e′$\mu^-\mu^+$, and the proton kinematics will be deduced from the missing momentum analysis.
- At larger angles (40°-70°) proton will be detected too.

# Remove detectors upstream of R1 Drift chambers

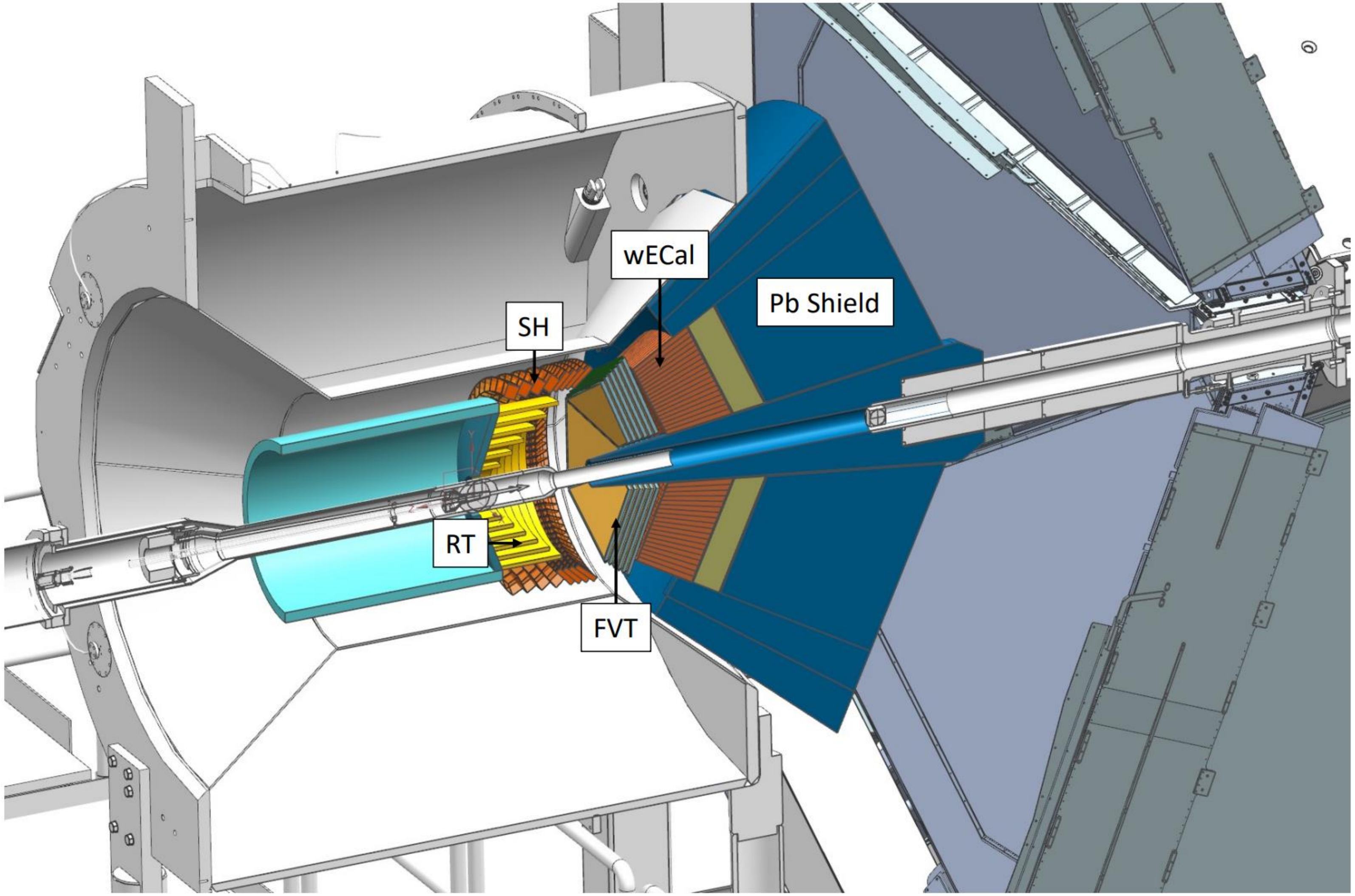
HTCC, CTOF, CND, SVT, MVT, BAND, FT



# Install new detectors and a Lead shielding



# 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 preciese vertext 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 recoild proton.

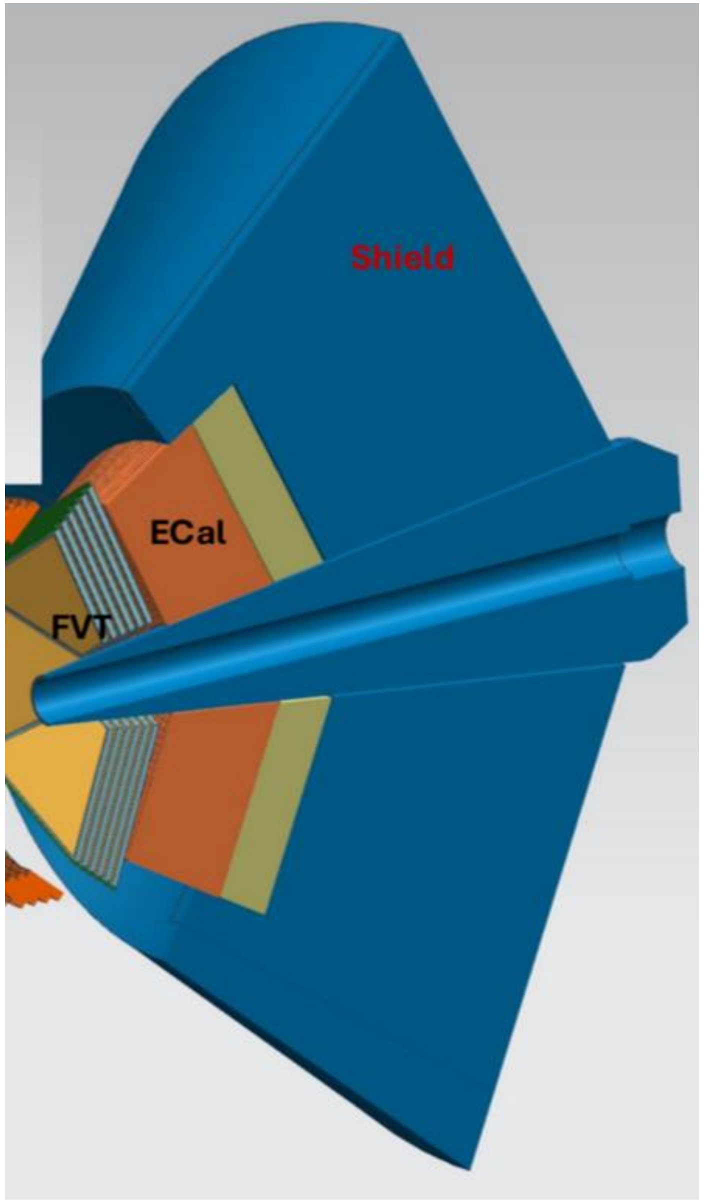
# Critical components

- Occupancies/rates on detectors
  - Drift Chambers DC
  - Forward Vertex Tracker FVT
  - wECal
  - Recoil Tracker (RT)
  - Scintillation Hodoscope (SH)

- Trigger

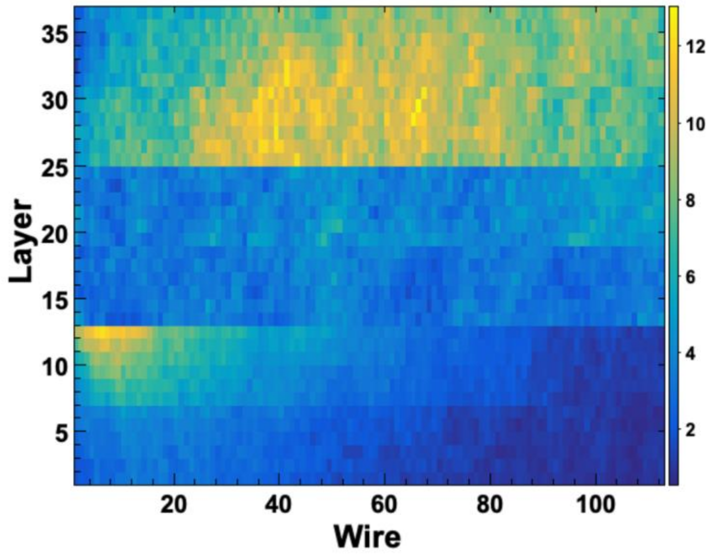
- Ensuring the exclusivity
  - Resolution of critical components.

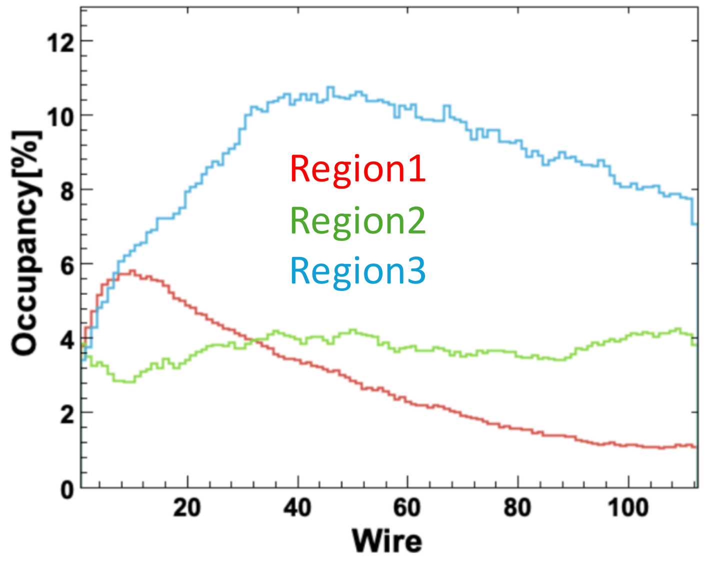
- Control of backgrounds, accidentals



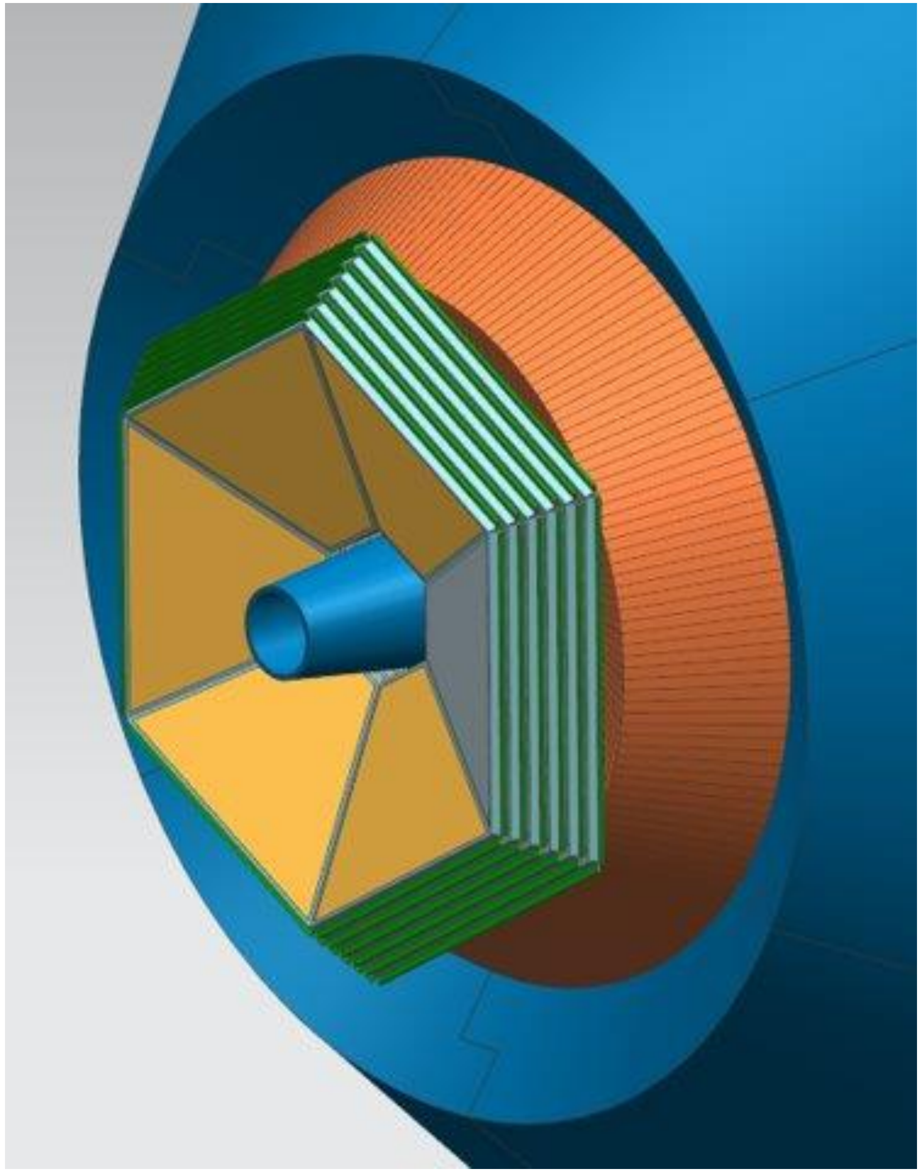

# Occupancies in Drift Chambers

- 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.

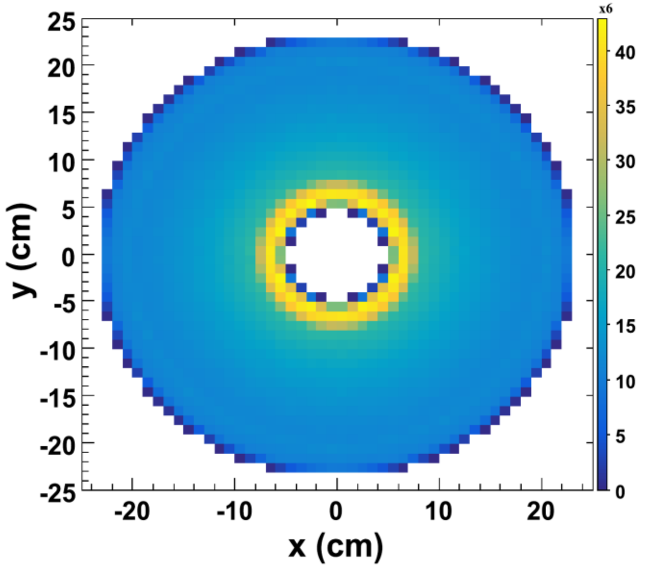


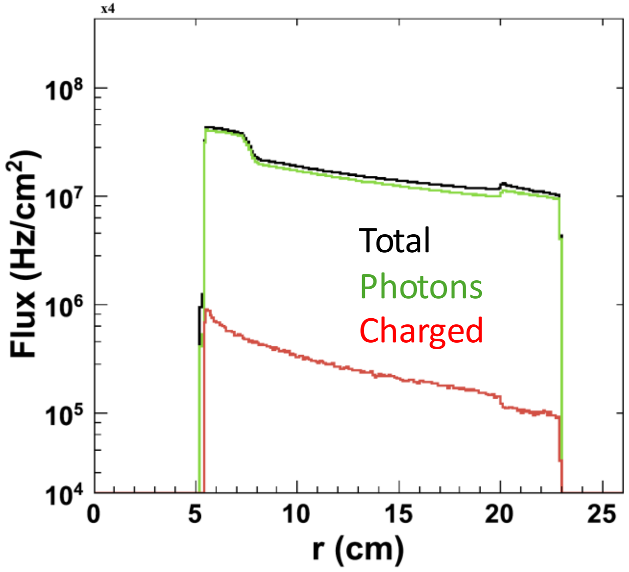



# Forward Vertex Tracker



- 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



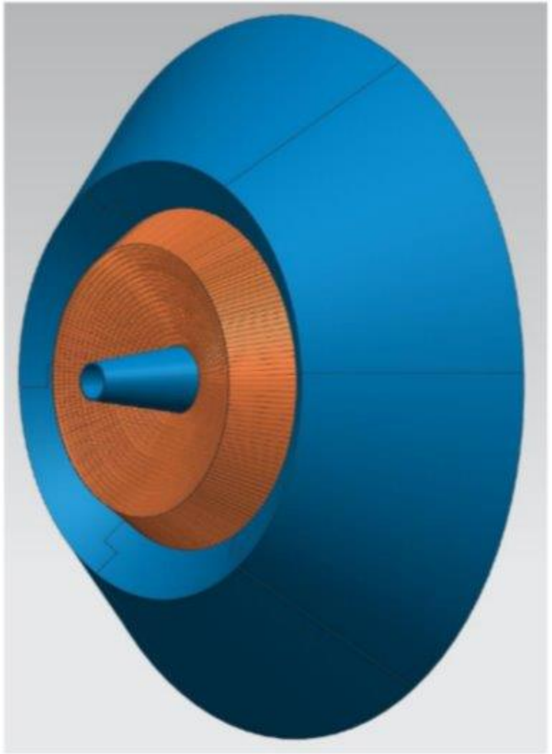
# wECal

- 1320 $PbW0_4$ 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

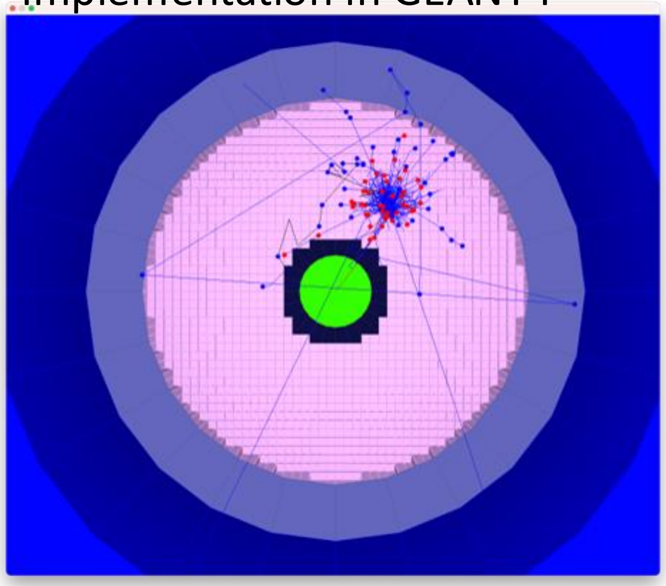
At the 1st ring, rate is less than 2 MHz (per crystal).

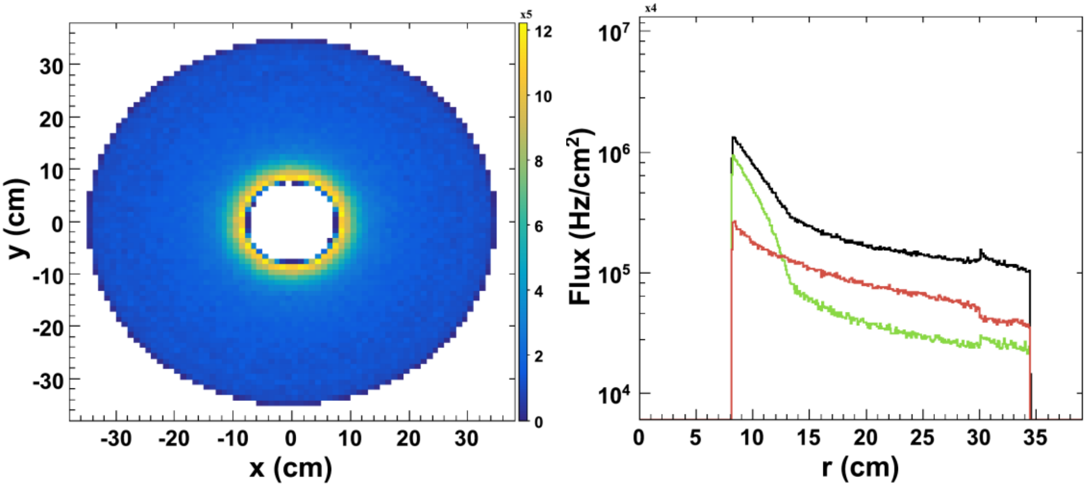
HPS used APD readout and observed comparable rates in hotest crystals.

Manageable rate with pulse fitting.

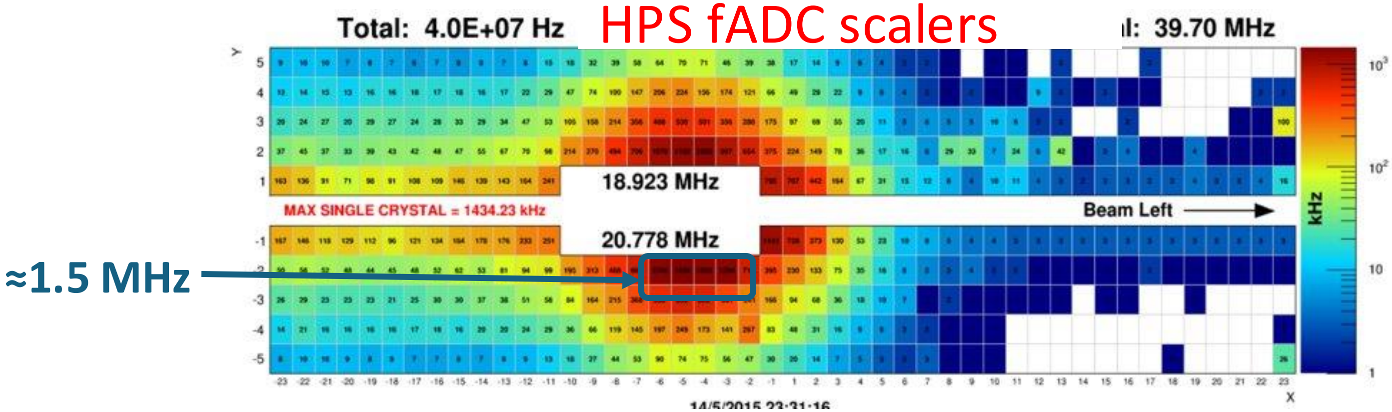


Implementation in GEANT4

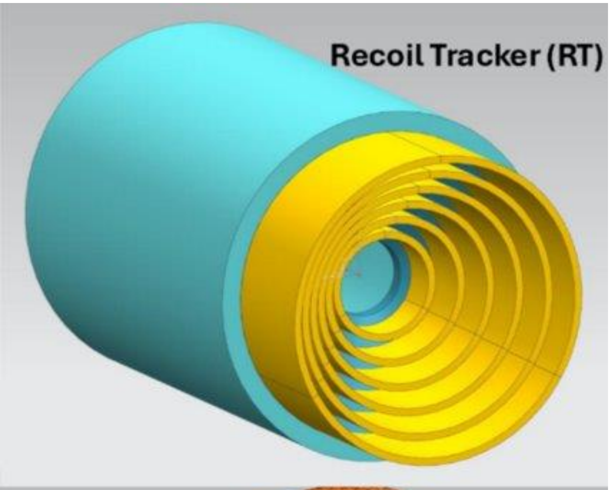




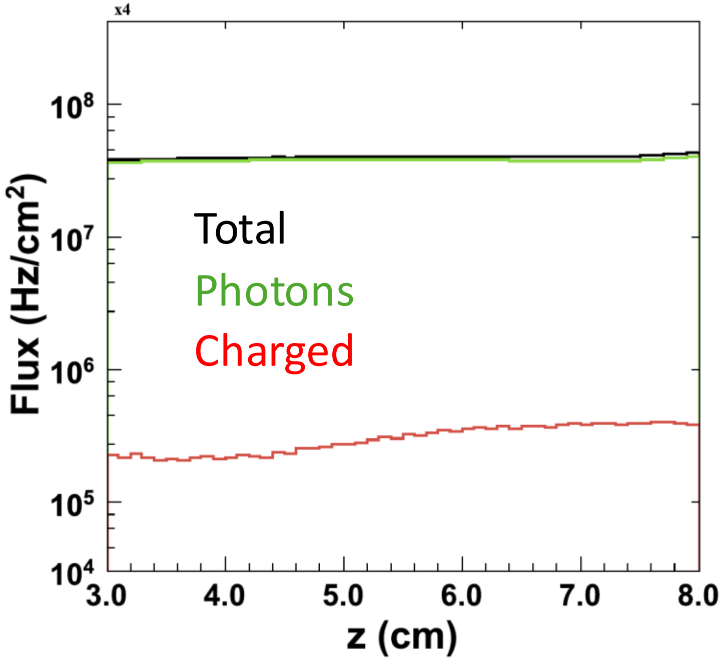

HPS fADC scalers



# RD : Recoil Trackger + Scintillation Hodoscope



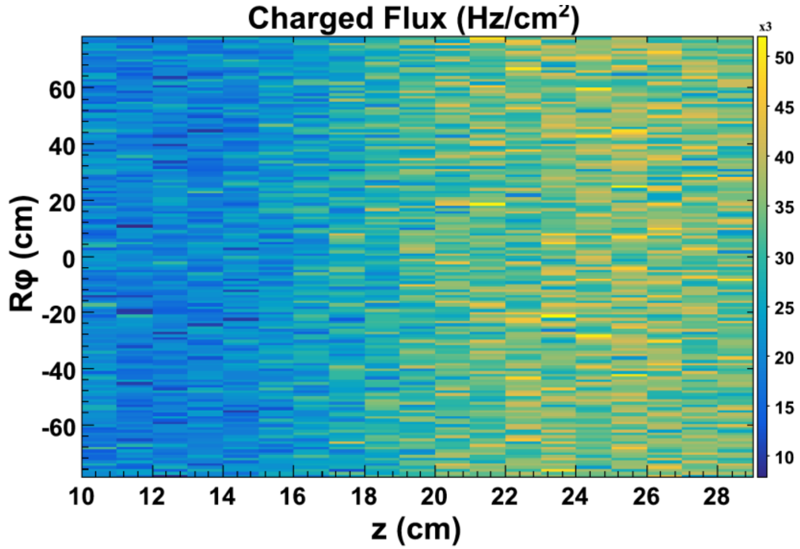

- 6 concentric cylindrical μRWELL layers
  - R = 8 cm (1st layer) and 23.5 (6th layer)
- Each layer is devided into three identical sectors
- Coverage : 40° to 70°
- Total rate < 250 KHz/cm$^2$.





## 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**.



# Trigger

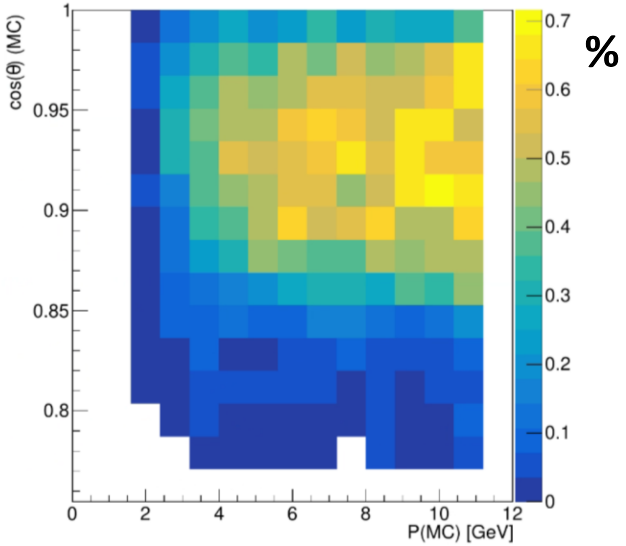
- The trigger "**Single MIP trigger**".
  - MIP energy deposition in Forward Calorimeters (PCal x ECal)
- Allows **simultaneous measurement of DDVCS, TCS and J/$\psi$**.

- 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 **$\mu$CLAS12 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)

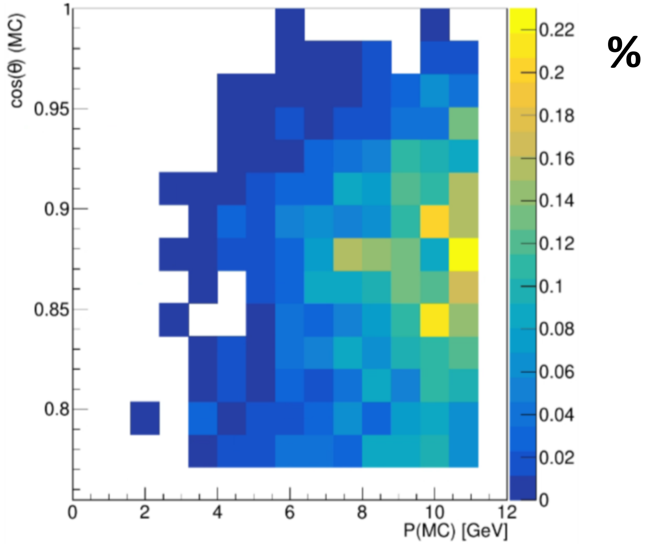
- No increase in data rate is expected, as the number of channels in CLAS12 doesn't increase.
  - New detector channels are compensated with the channels from removed detectors.

# Pion suppression

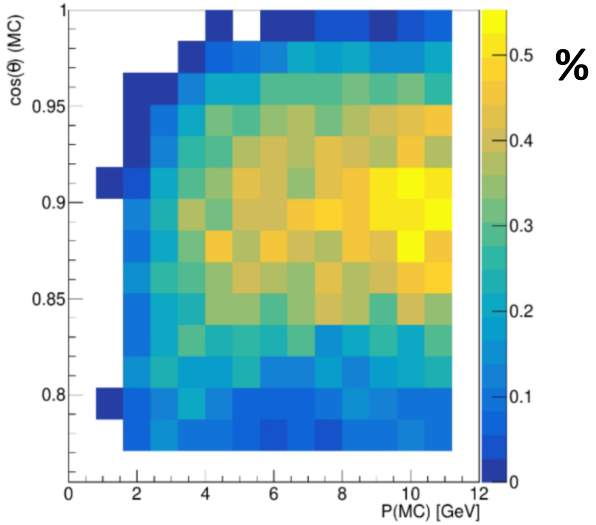
$\pi^+$ survives as $MIP^+$



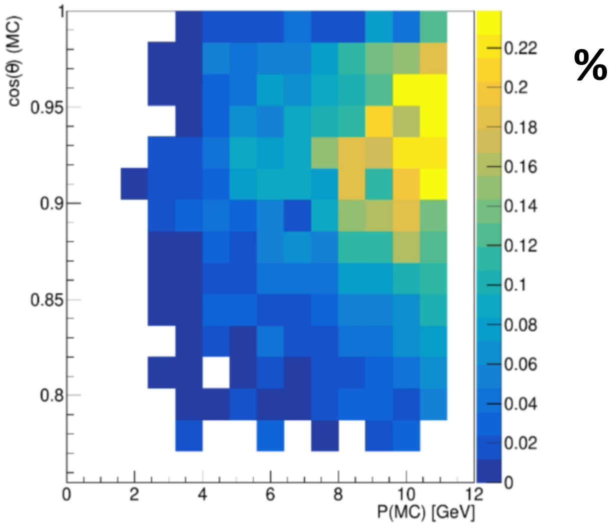

$\pi^+$ survives as $MIP^-$




$\pi^-$ survives as $MIP^-$




$\pi^-$ survives as $MIP^+$

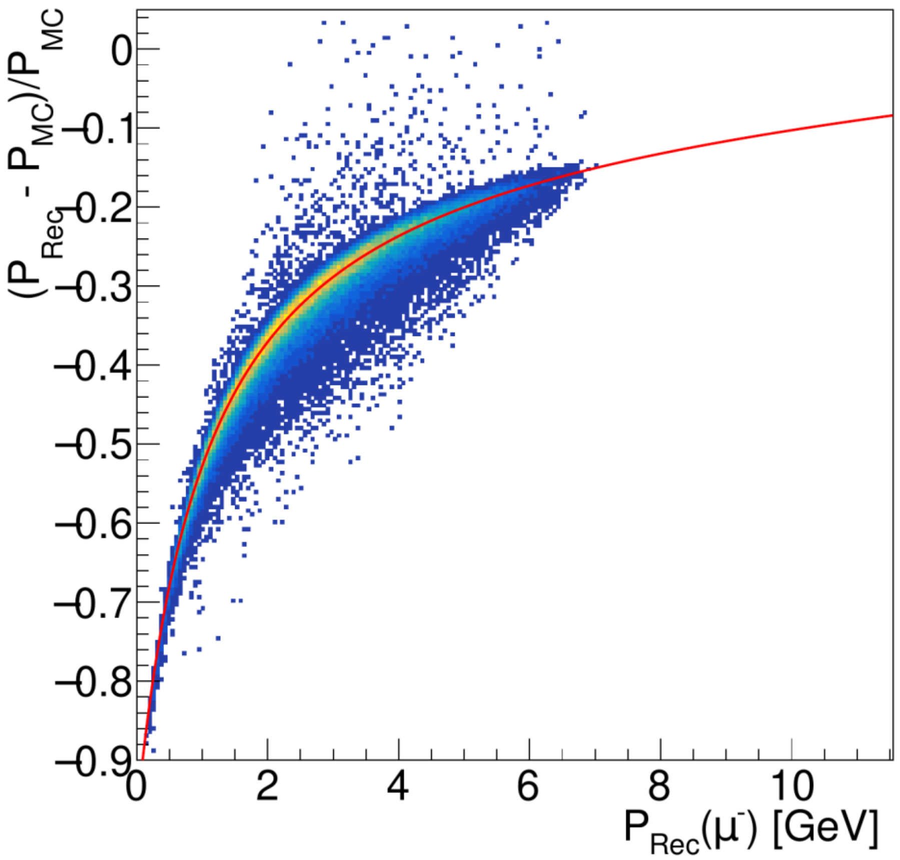



- One of driving factors for choosing the shielding thickness/material was the pion suppression level.
- Multiple shielding thicknesses were studies.
- With 60 cm Lead, the average pion suppression is **over 99%**.

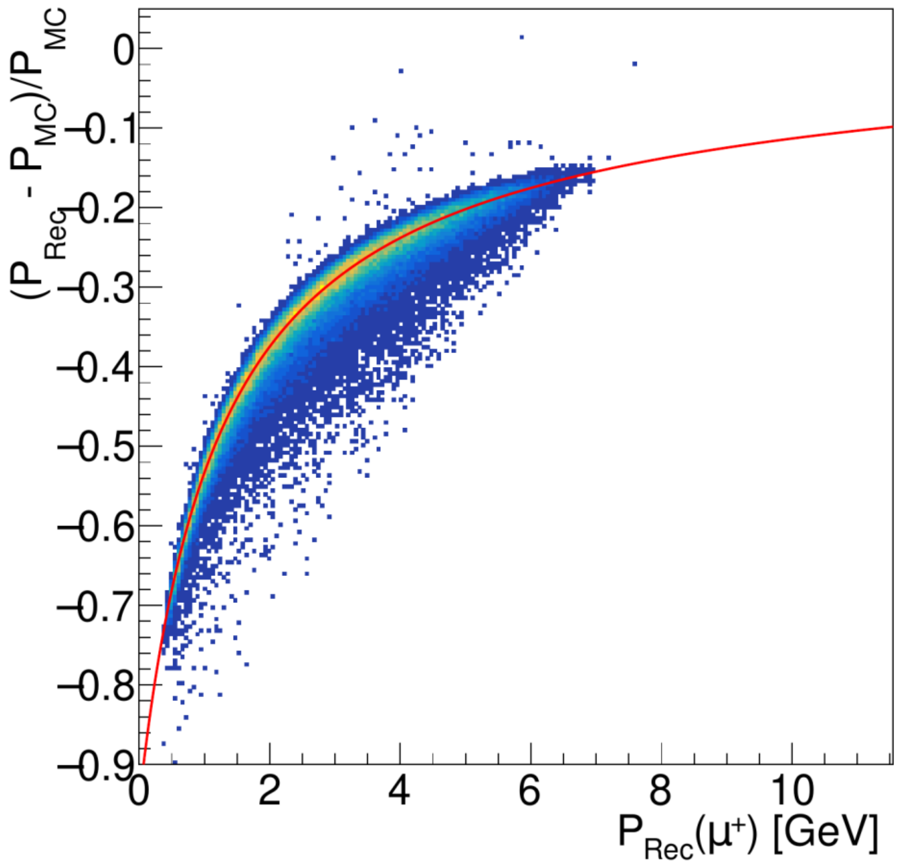
# Energy loss

- 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 corrrection functions
  - Currently an AI model is being developed to predic reconstructed momentum.

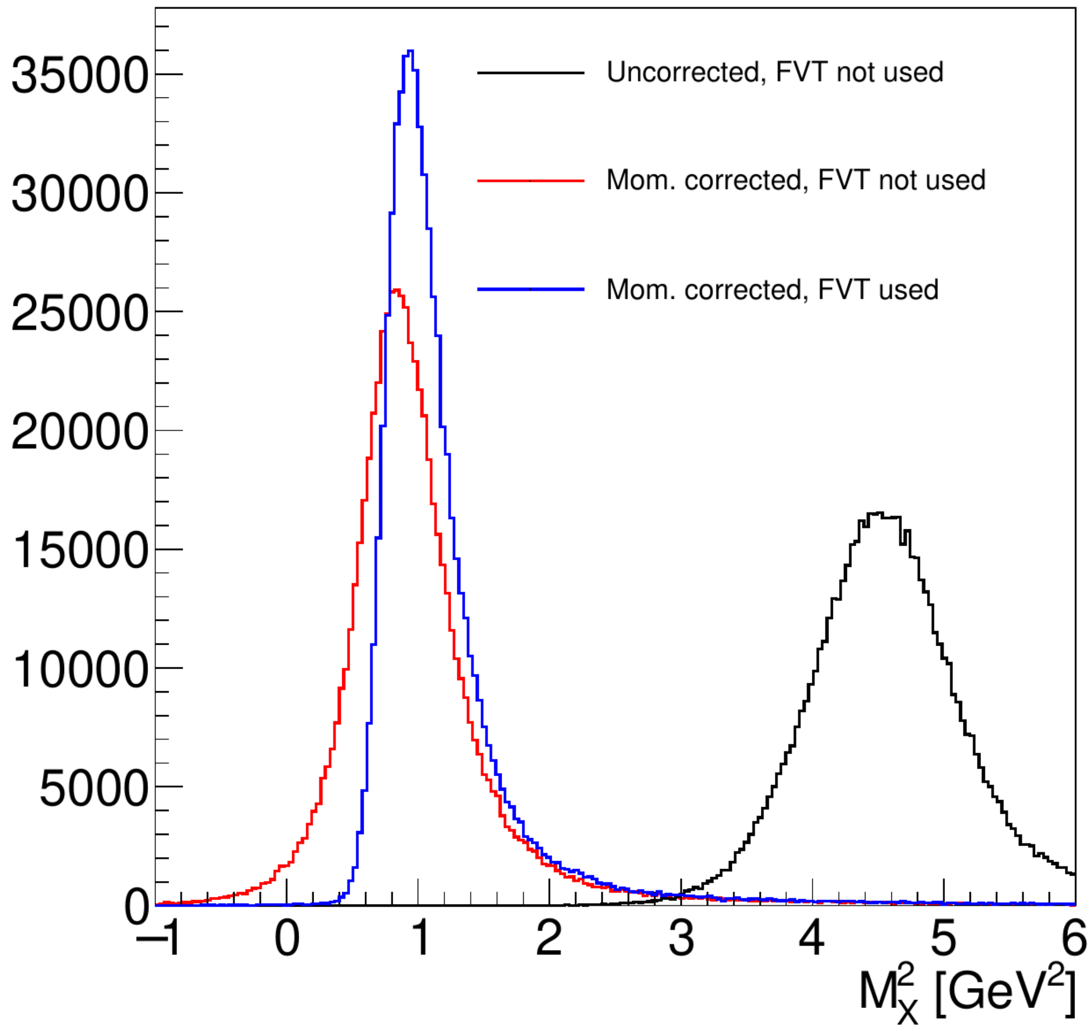
**Negative muon**




**Positive muon**



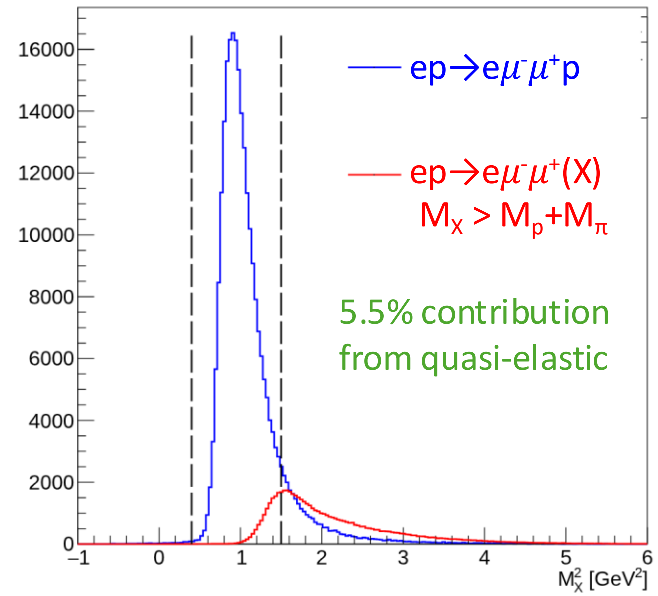
# Missing mass reconstruction




- 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.

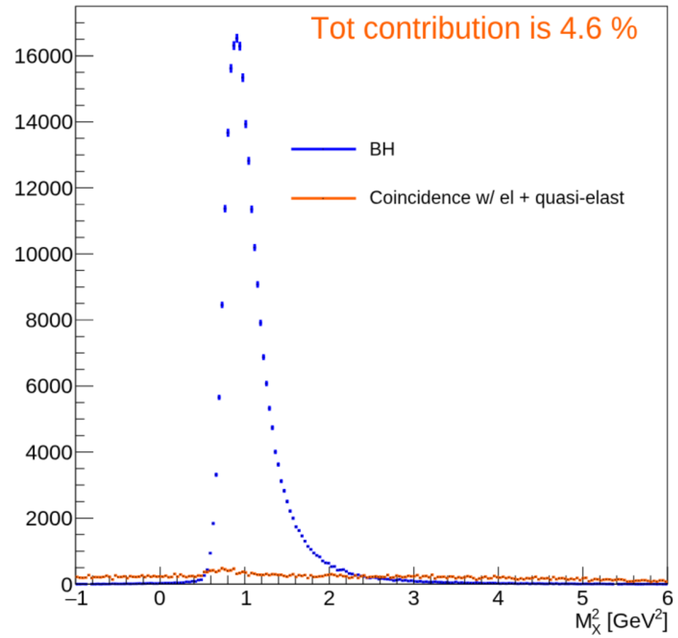
# Backgrounds

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




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

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

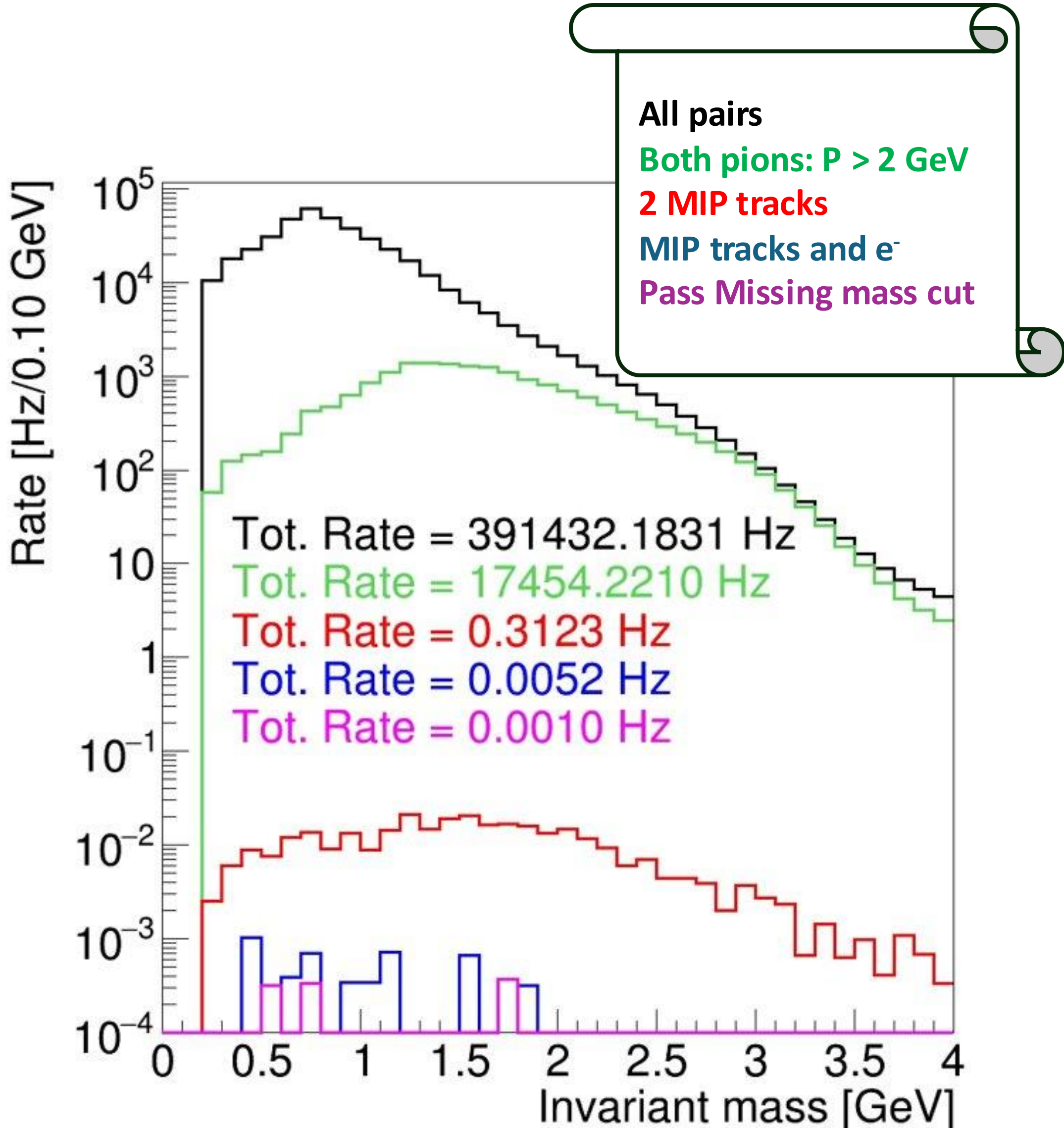
Pion pair production is another source of background too, if both pions survive, they can mimic the ep→e$\mu^-\mu^+$p reaction.

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 ***$\mu$*CLAS12 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:

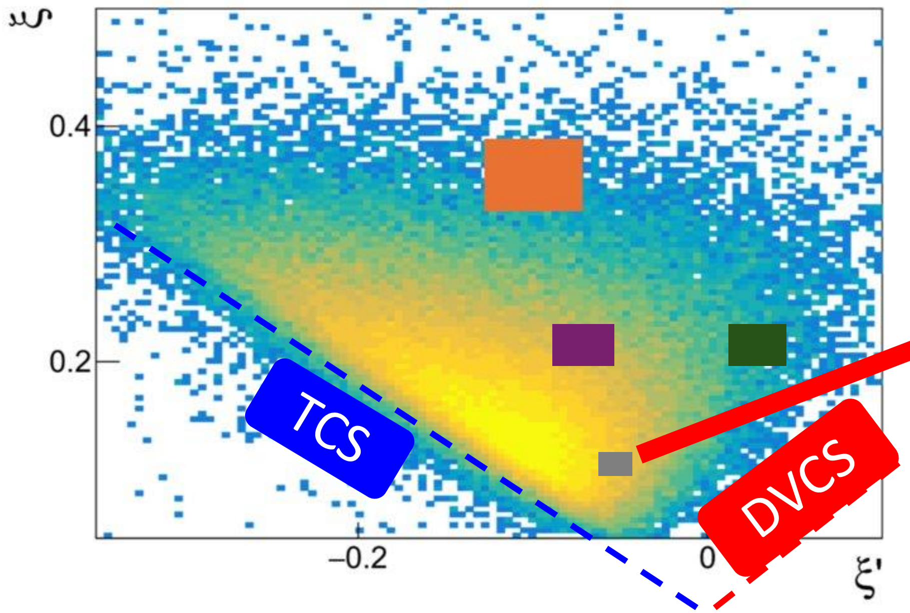
- **200 days** of running at luminosity $\mathbf{10^{37} cm^{-2} s^{-1}}$.
- Beam energy: **11 GeV**.

This corresponds to:

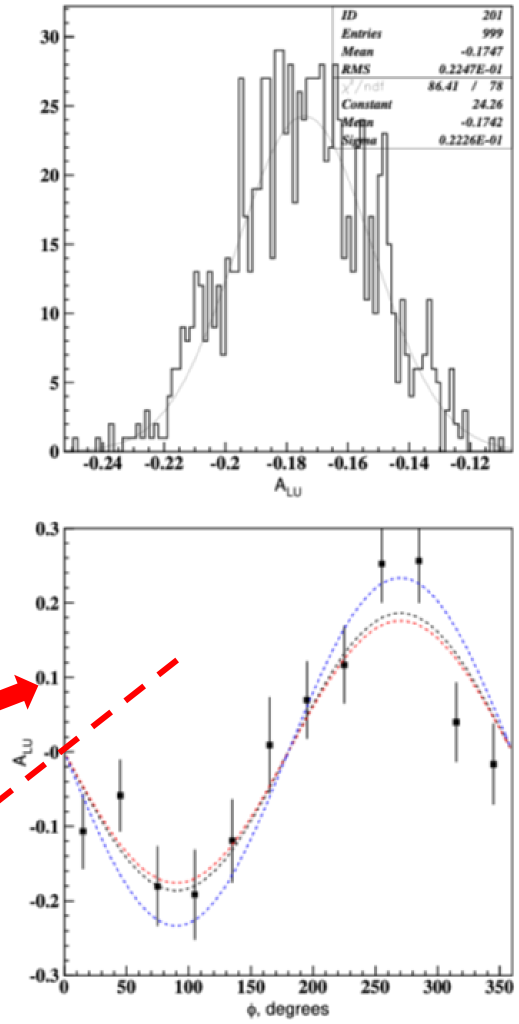
- **7.5 $\mu$A** electron beam on **5 cm LH2** target.

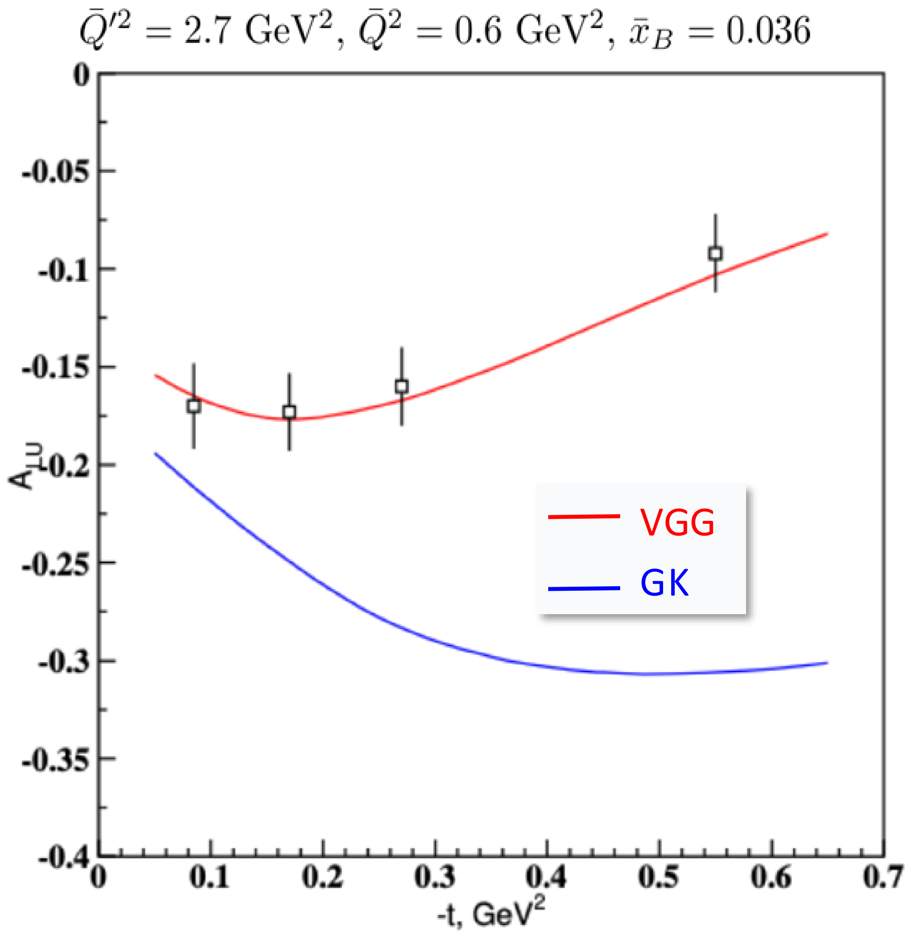
# Expected results: t dependence

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




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



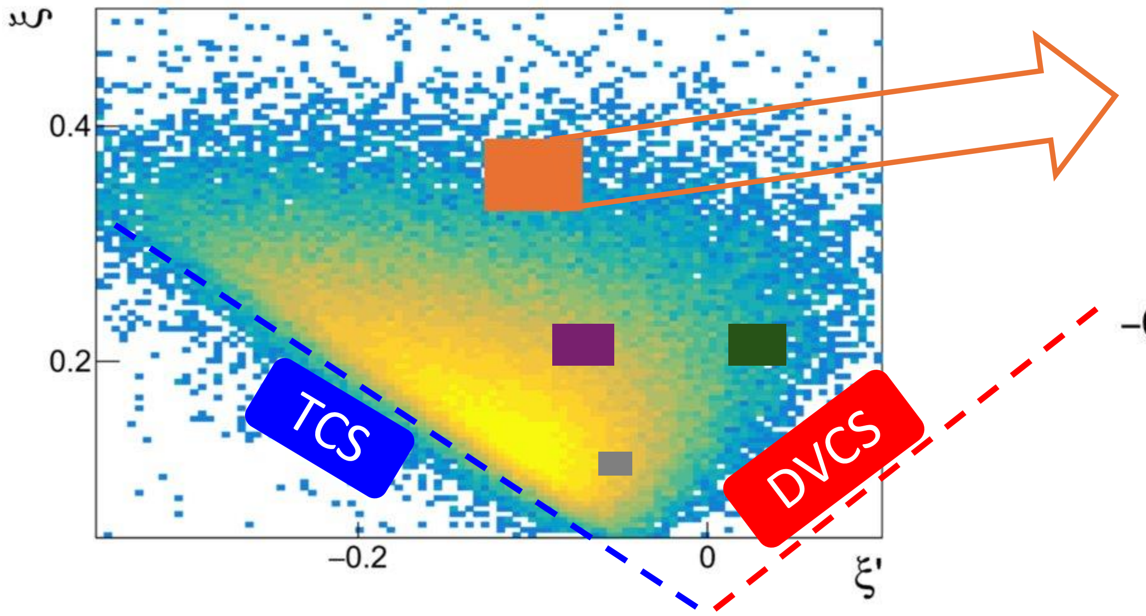



# Expected results: Constraining shadow GPDs

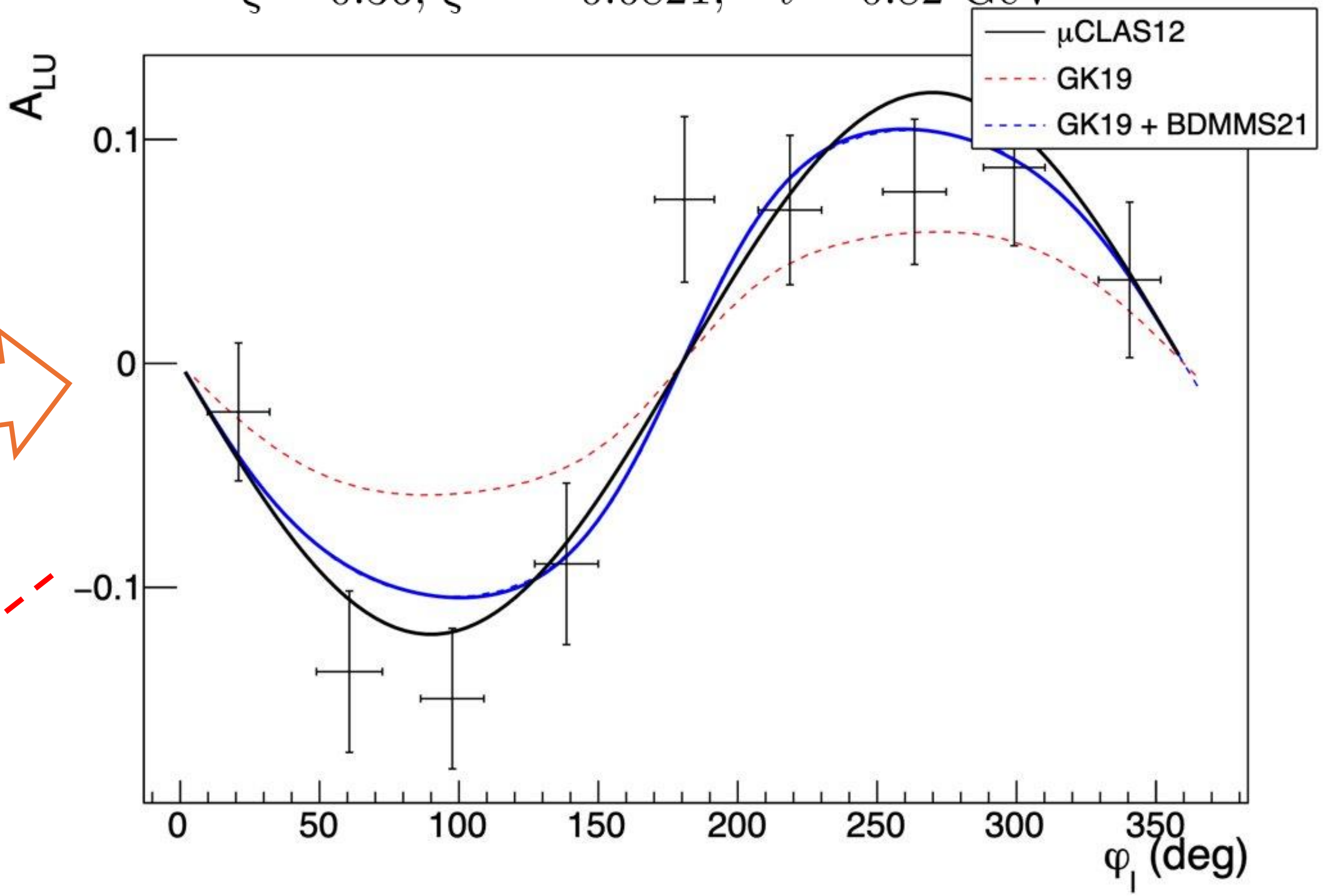
$$A_{LU} = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$

Asymmetries from PARTONS

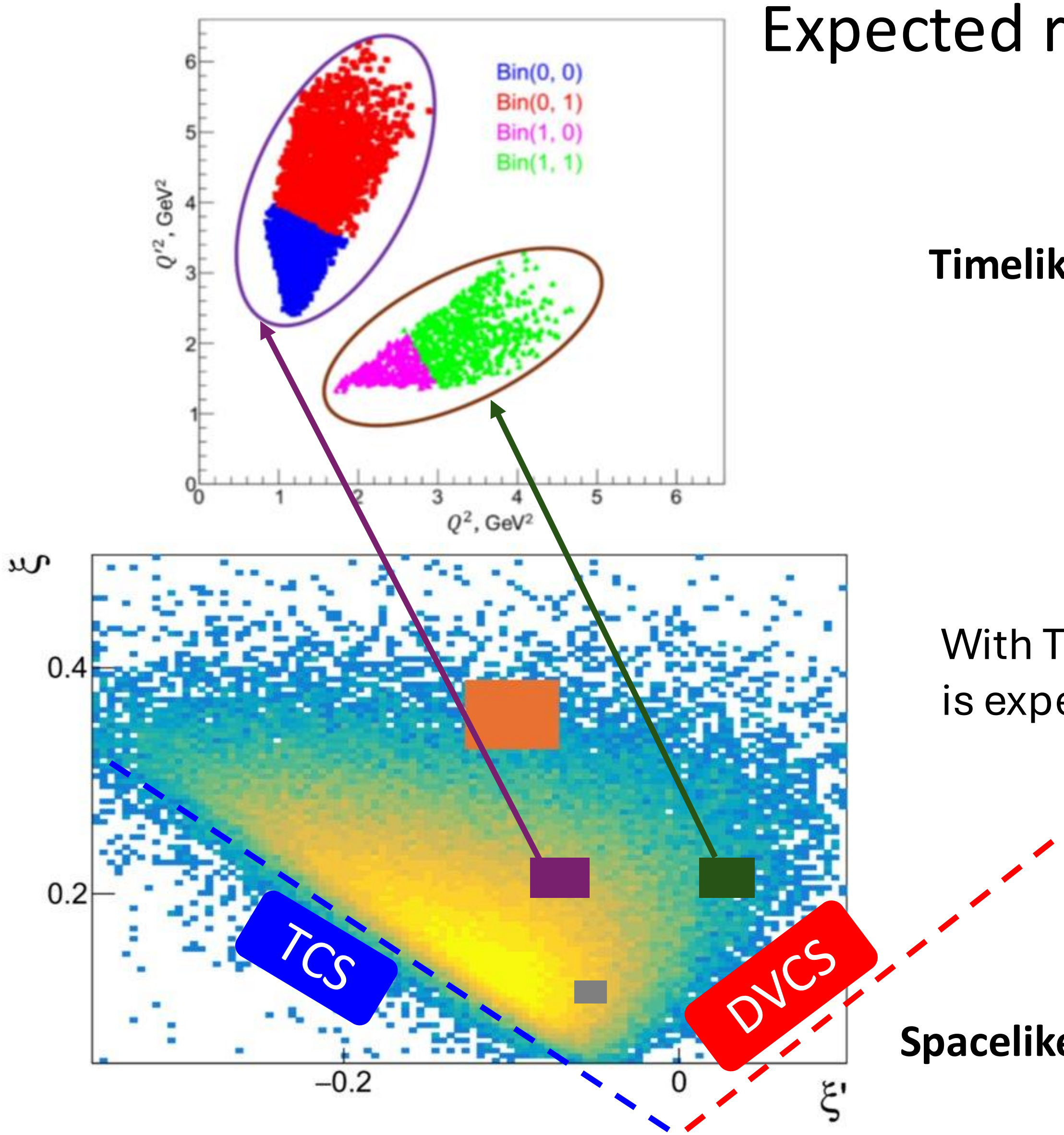
- As DDVCS allows to access GPDs at x≠∓ξ, This measurement will allow to reduce uncertainties coming from shadow GPDs.




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

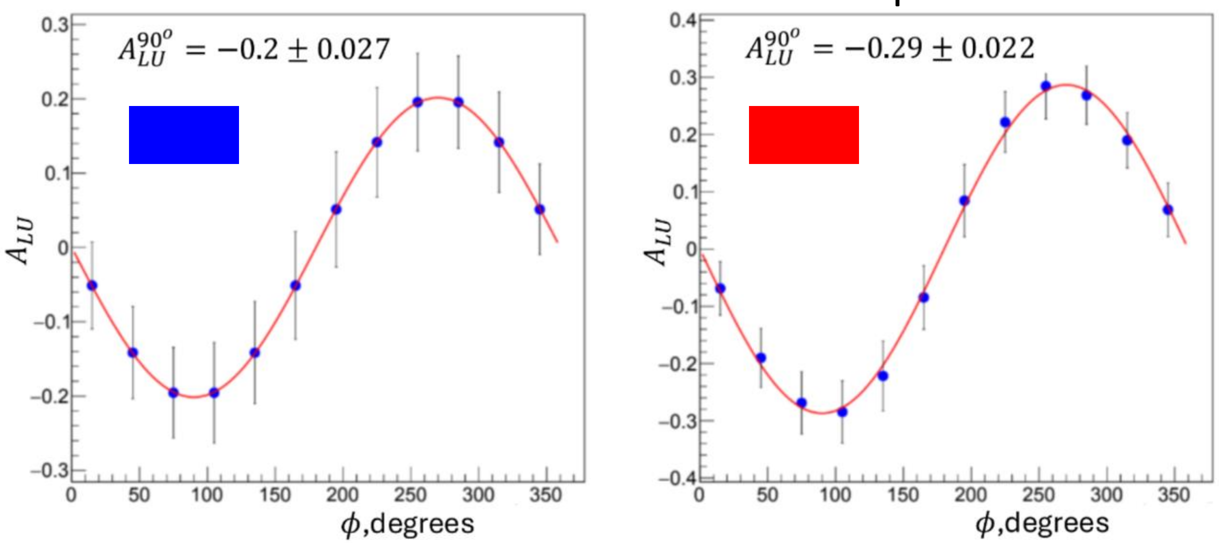


# Expected results: timelike vs spacelike regions



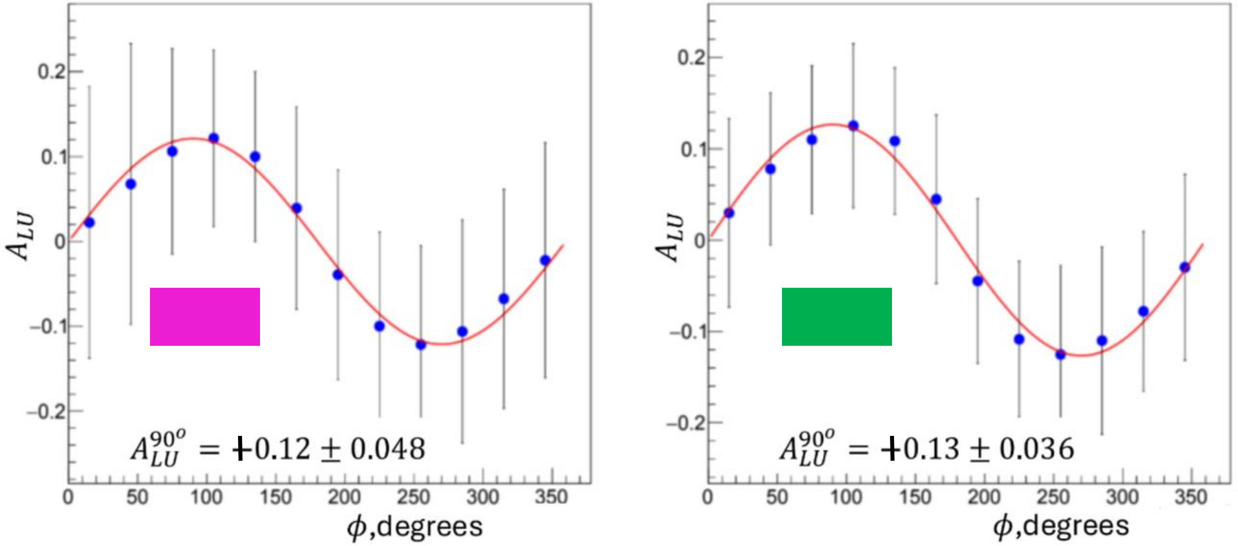

VGG predictions

**Timelike**

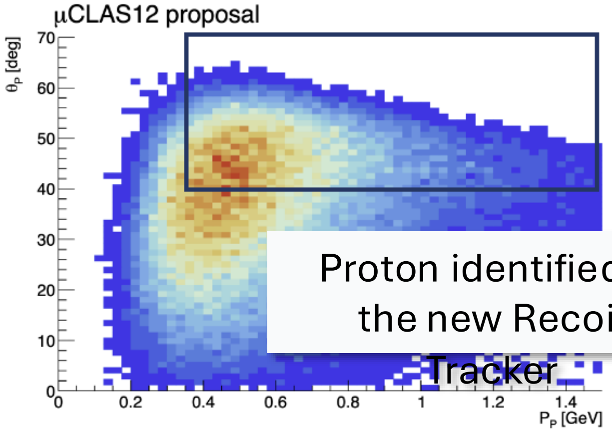



With Timelike → Spacelike transition a change of the sign of the asymmetry is expected.

**Spacelike**



# Expected results: TCS

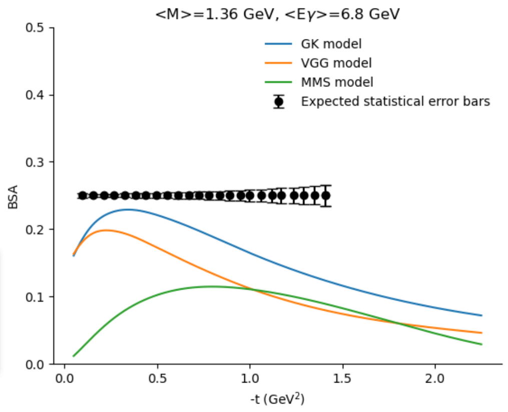


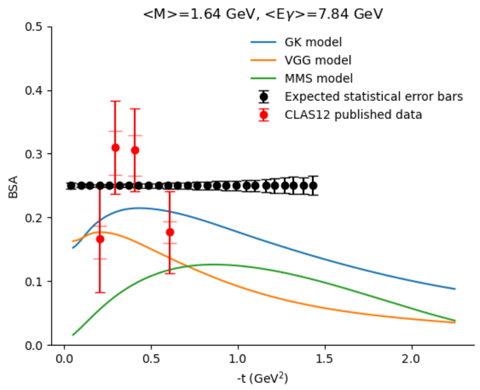

Proton identified in the new Recoil Tracker

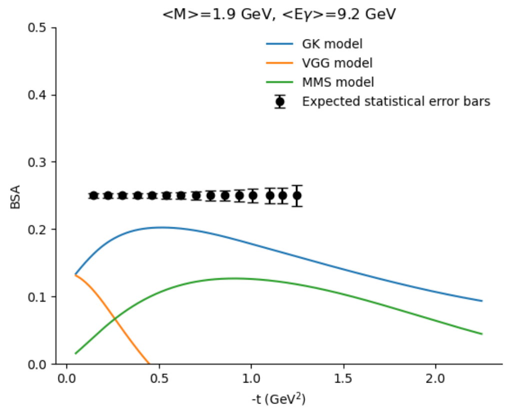
**7.7M expected with events M(µµ) >1.2 GeV)**

**precision** measurement of TCS

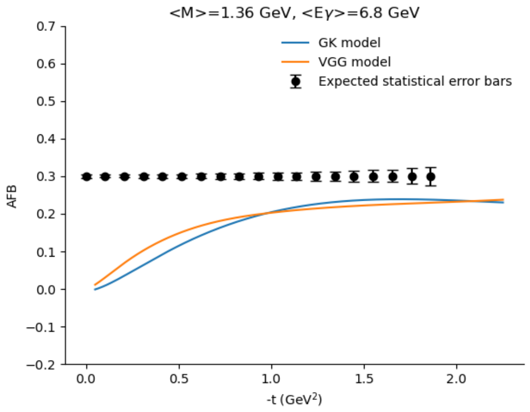
**Photon polarization asymmetry** $A_{\odot U} = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$

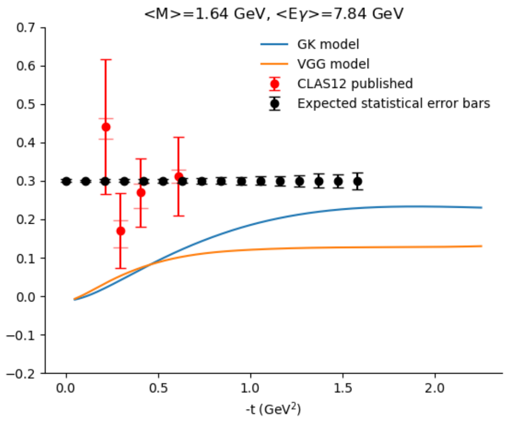


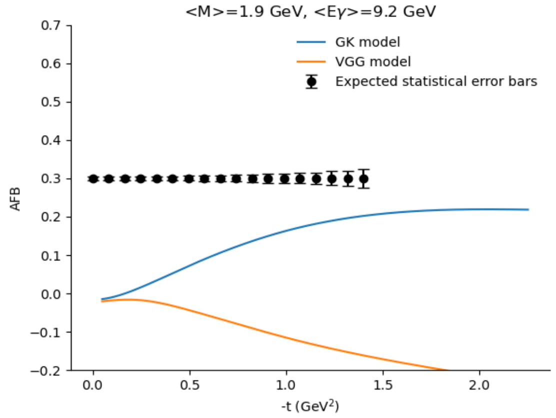




**Forward-Backward asymmetry** $A_{FB} = \frac{N_F - N_B}{N_F + N_B}$



[Slide from P. Chatagnon's talk]

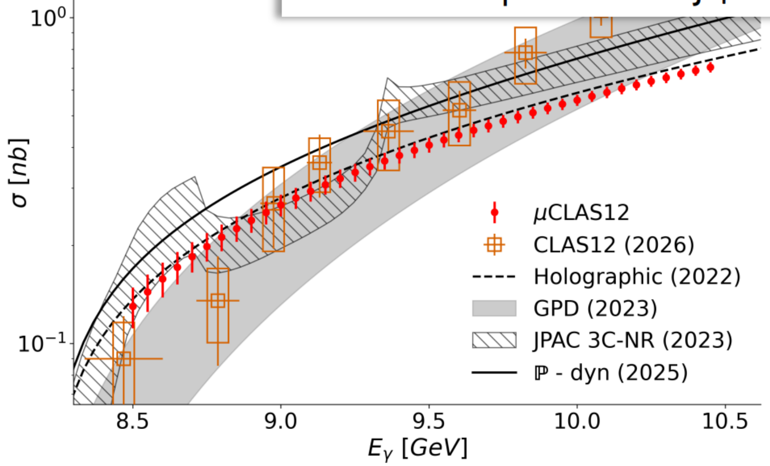


# An ideal setup for dilepton final state measurements

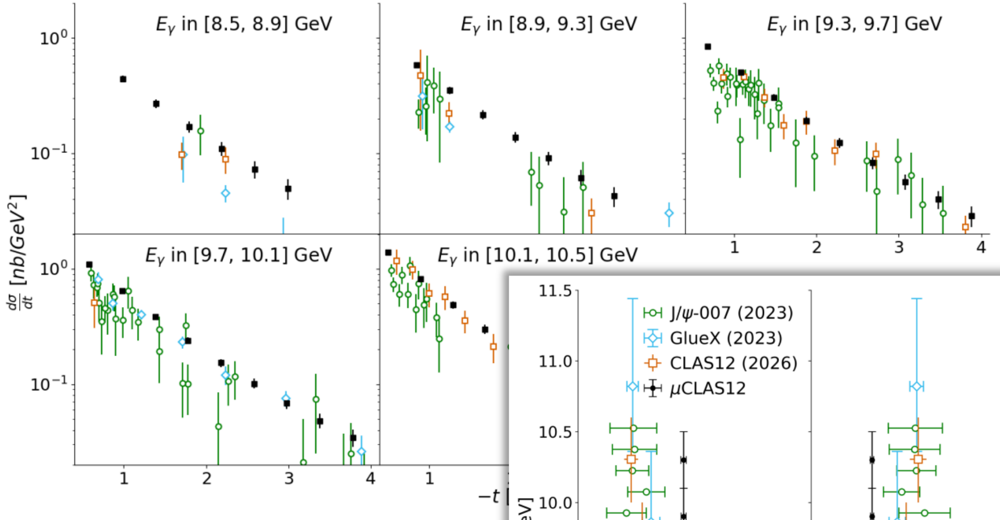
- Double Deeply Virtual Compton Scattering
  $ep \to e'\gamma^* p \to e'p'\gamma^* \to e'\mu^+\mu^- p'$
- Timelike Compton Scattering
  $\gamma p \to \gamma^* p' \to \mu^+\mu^- p'$
- **Exclusive J/ψ production**

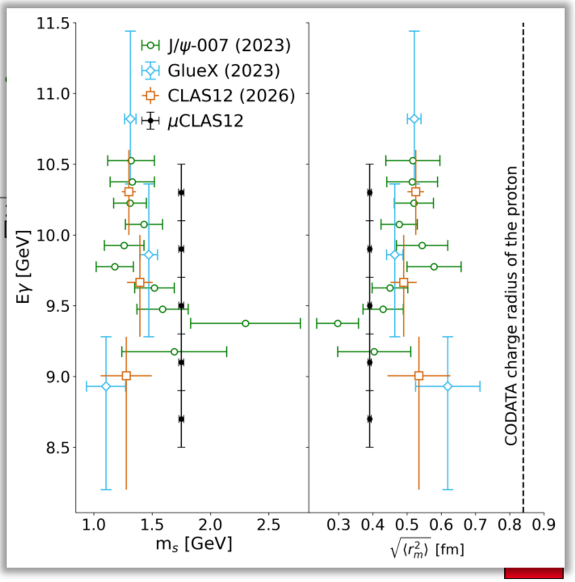
$$e'\gamma^* p \to e' J/\psi\ (p') \to e'\mu^+\mu^-(p')$$

- ~30k J/ψ are expected !
- ~3 times more than GlueX-III
- ¾ of the expected SoLID J/ψ rate.




## Projection for the differential cross section




**μCLAS12 article**
**2605.11690**
**accepted in EPJA**

*Near threshold J/ψ production with CLAS12– Pierre Chatagnon – 23rd of June 2026*

# Current status of the project

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

- Concise version of the proposal with minor modifications has been submitted to EPJ-A.
  - Got accepted last week!  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/

# Other opportunities with $\mu$CLAS12

R. Tyson is exploring possibilities to run on Deuteron target

## A Deuterium Target at $\mu$CLAS12

Slide curtesy of Richard Tyson

### J/ψ Near-Threshold Production

CLAS12 has taken data with a deuterium target, however the statistics are limited.

Incoherent production probes:
- Gluon structure of the neutron
- Comparisons of bound vs free nucleon gluon structure & via subthreshold production
- Potential isospin partner to the LHCb pentaquarks by studying polarization observables (SDMEs)

Coherent production probes the gluon content of the deuteron, first glimpse at nuclear gluon structure.

### TCS & DDVCS

Measurements on the neutron and bound nucleon are important to constrain nucleon GPDs.

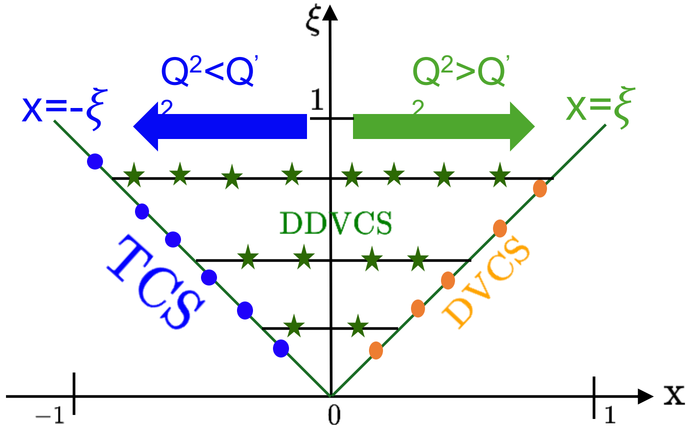
There is also a growing body of work on deuteron GPDs suggesting that coherent production data could be used to probe the deuteron mechanical form factors.

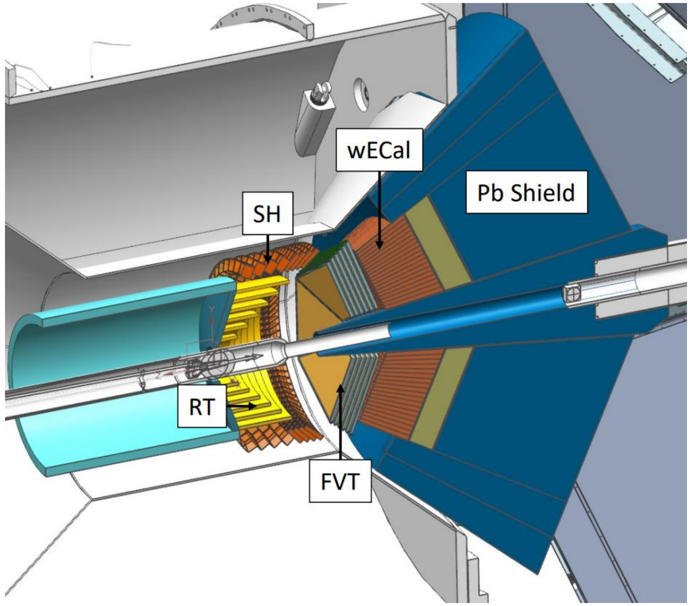
CLAS12 may provide initial TCS on neutron results, but $\mu$CLAS12 would be necessary for DDVCS on neutron and coherent TCS/DDVCS on the deuteron.

Currently investigating measurement strategies via detailed simulation studies to understand active vs indirect neutron/deuteron detection capabilities.

# Summary and outlook

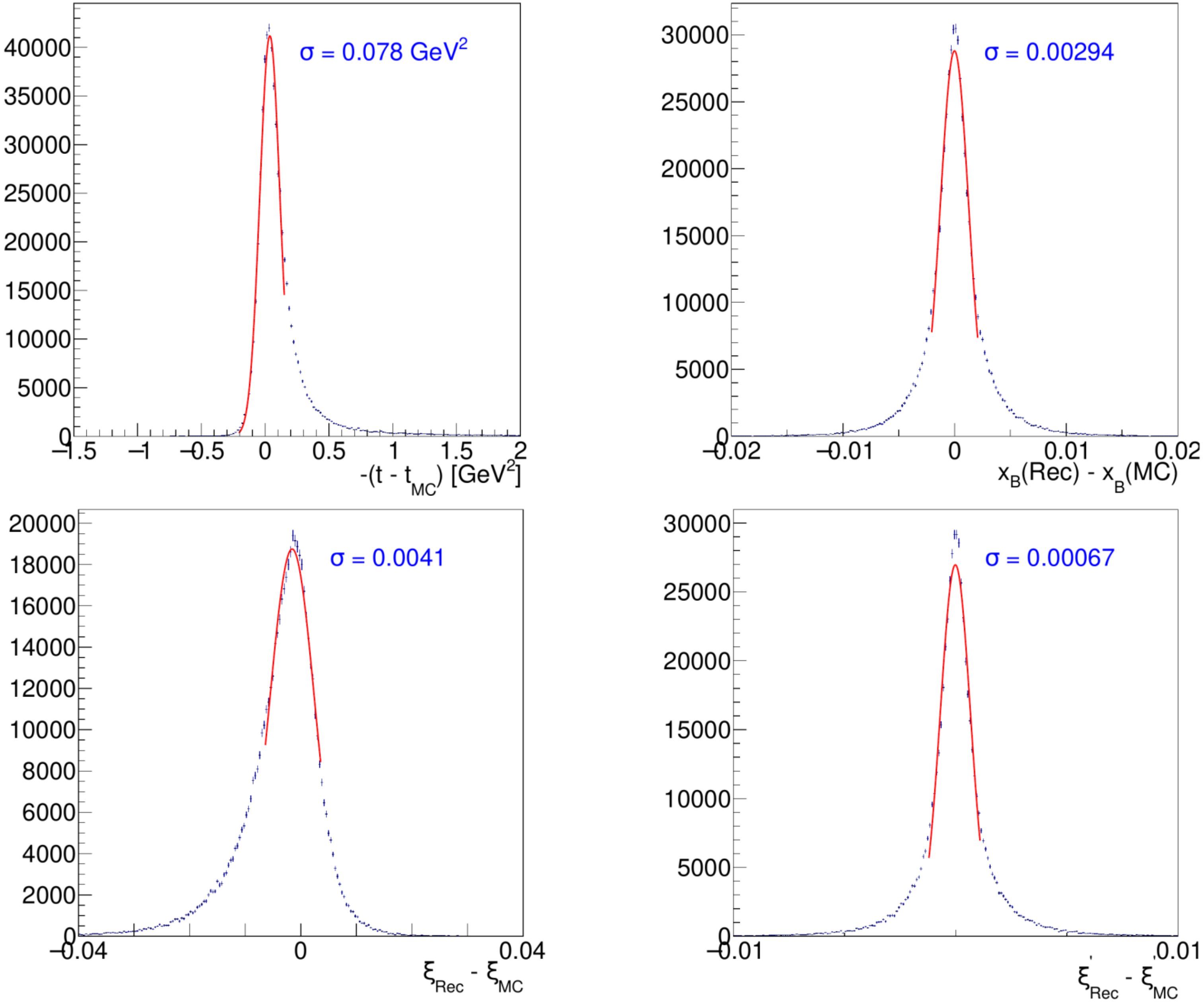
- DDVCS is an important process which allows to access GPDs in a domain inaccessible with DVCS or TCS
- It has not been measured because of the very low cross-section
- $\mu$CLAS12 allows to measure **ep→e$^-\mu^-\mu^+$p** process and will be able to take **x100** the standard CLAS12 Luminosity : **$10^{37}$cm$^{-2}$s$^{-1}$**.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



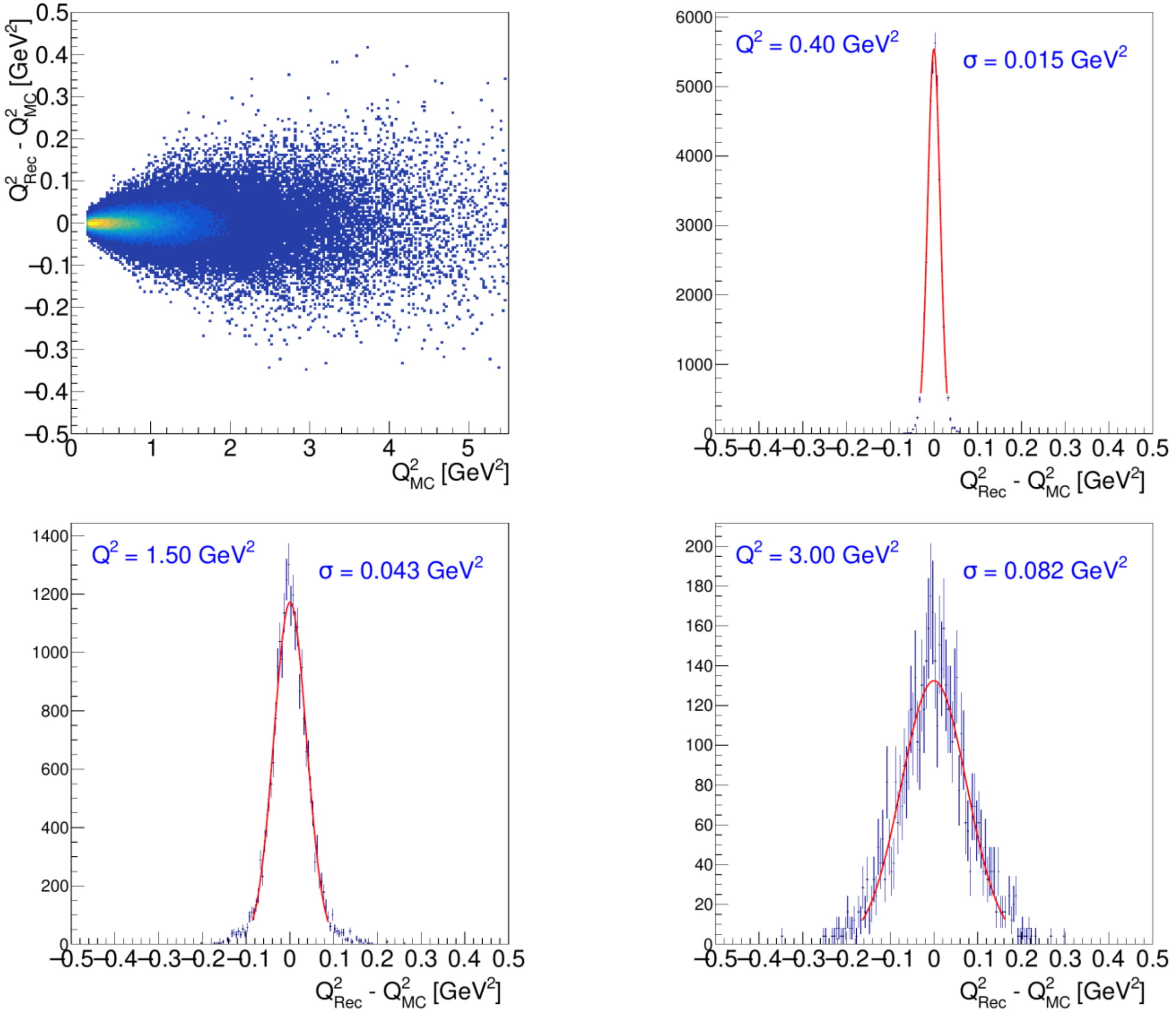
# Backup slides

# Resolutions: Kinematic variables

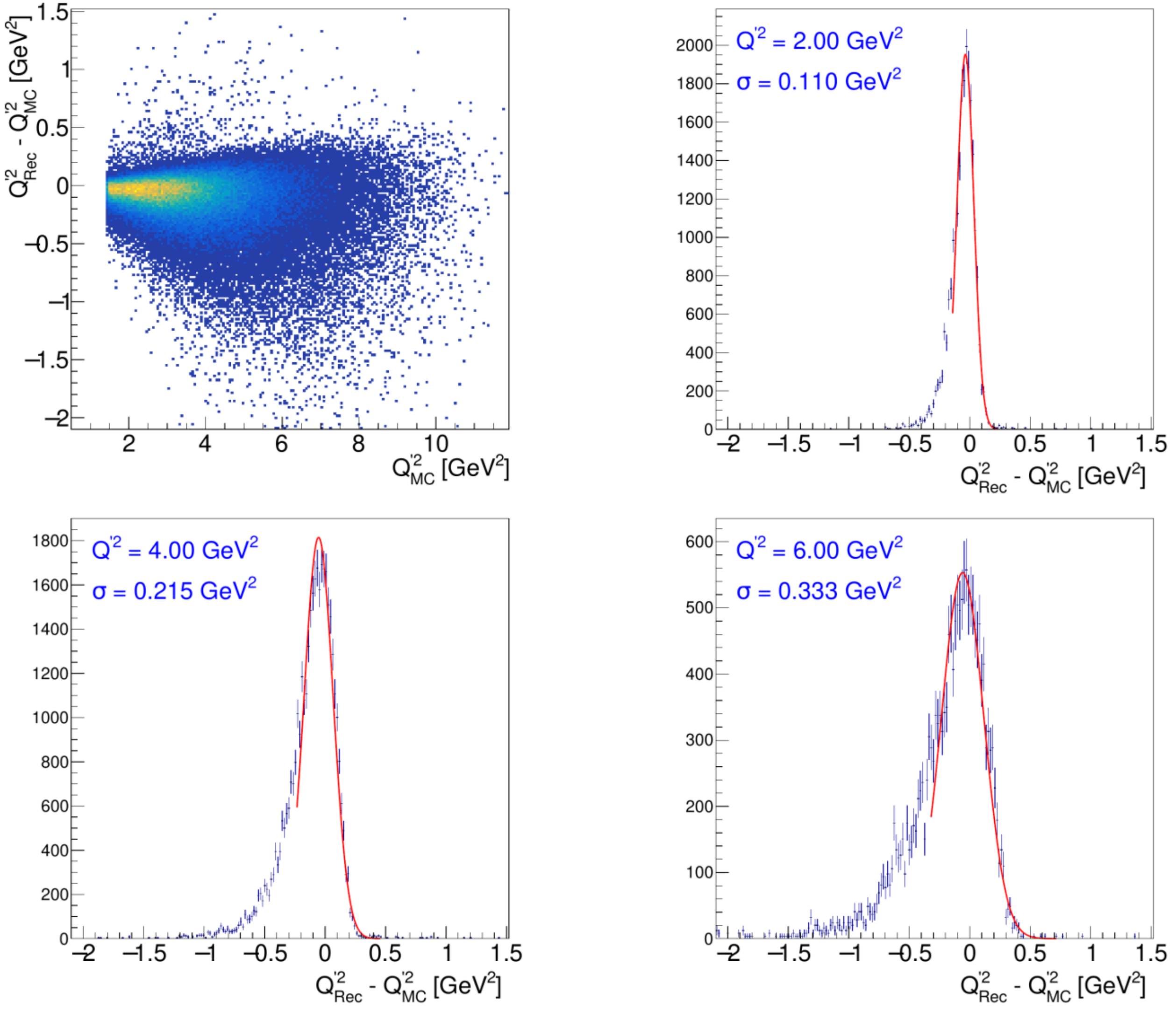


# Resolutions: Virtualities

$Q^2$



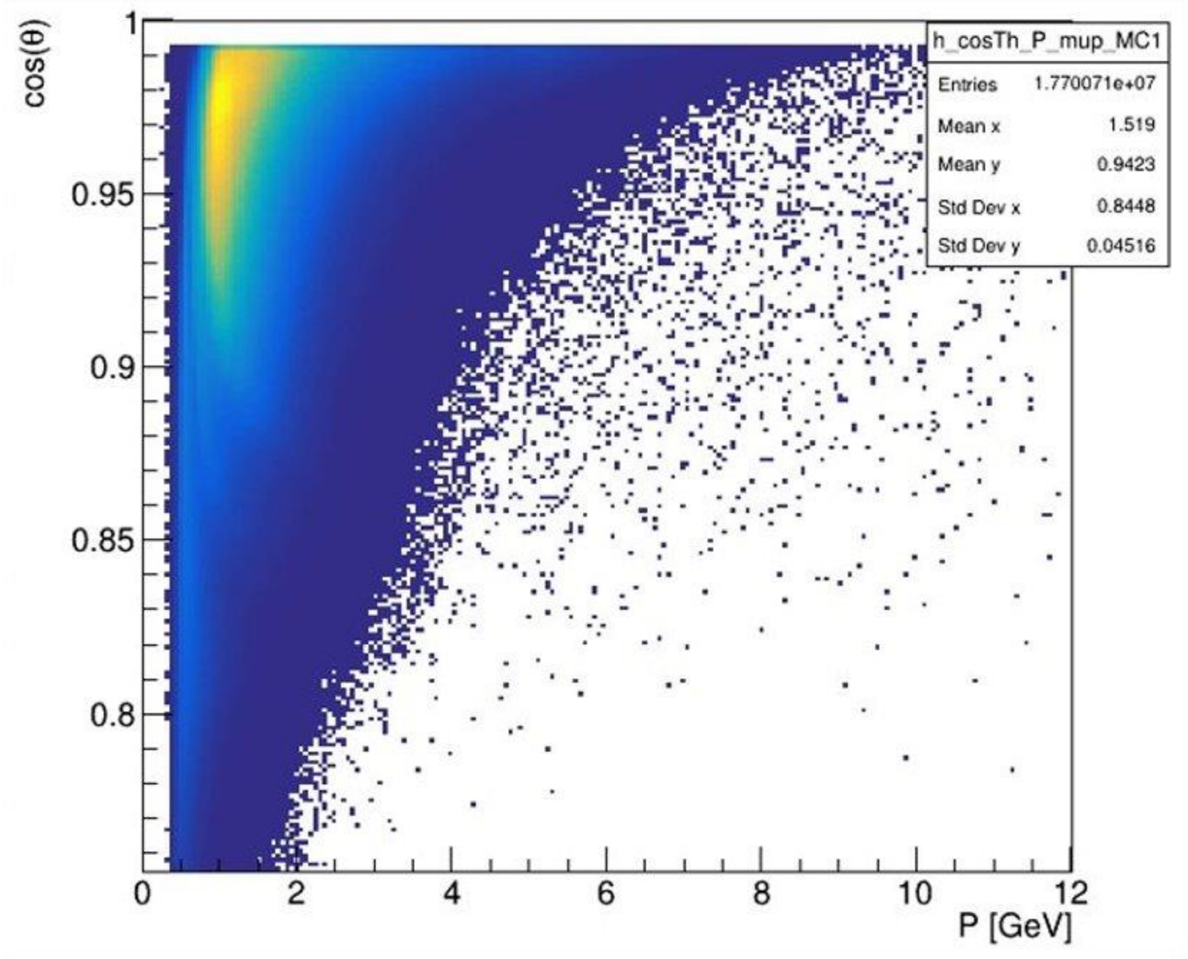

$Q'^2$

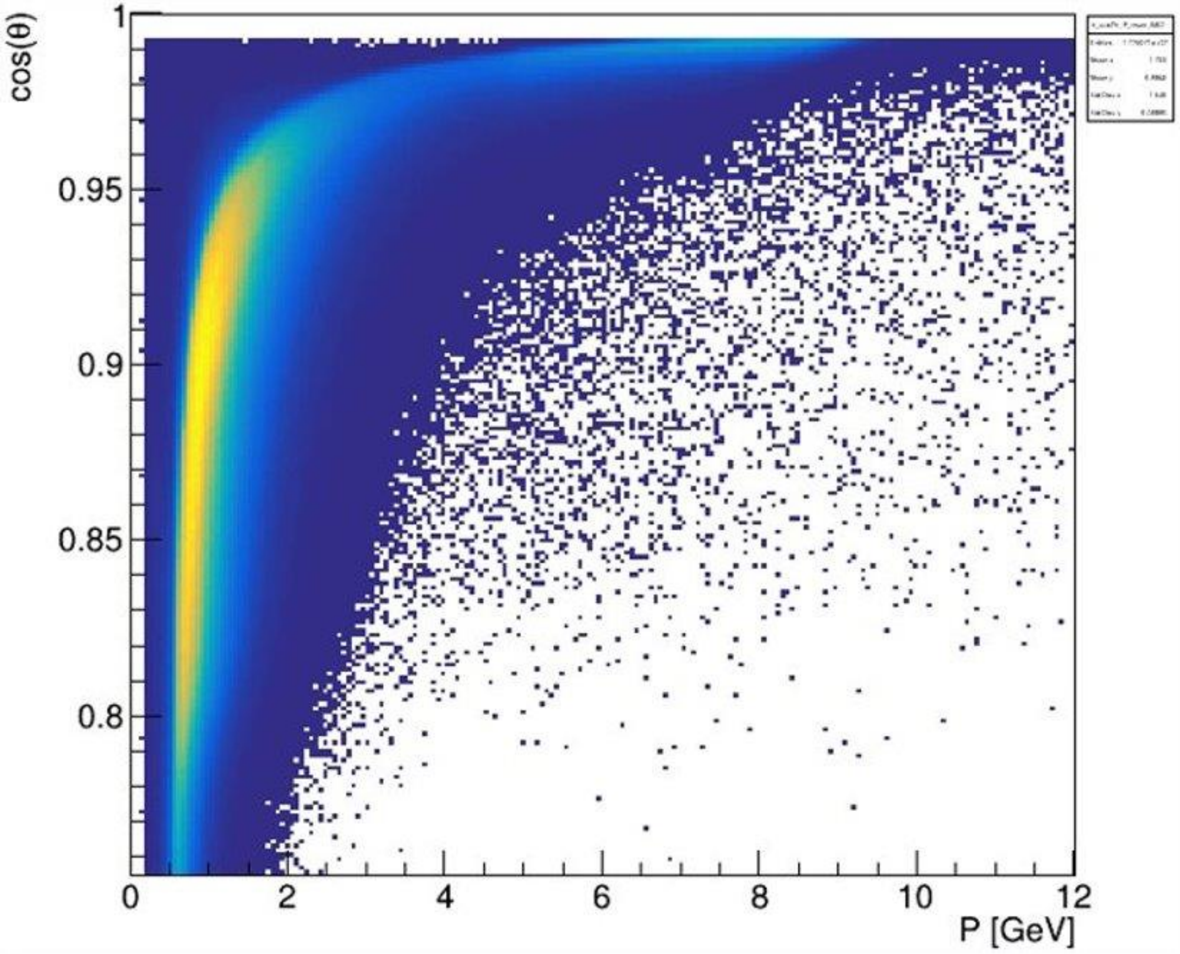


# Pion background

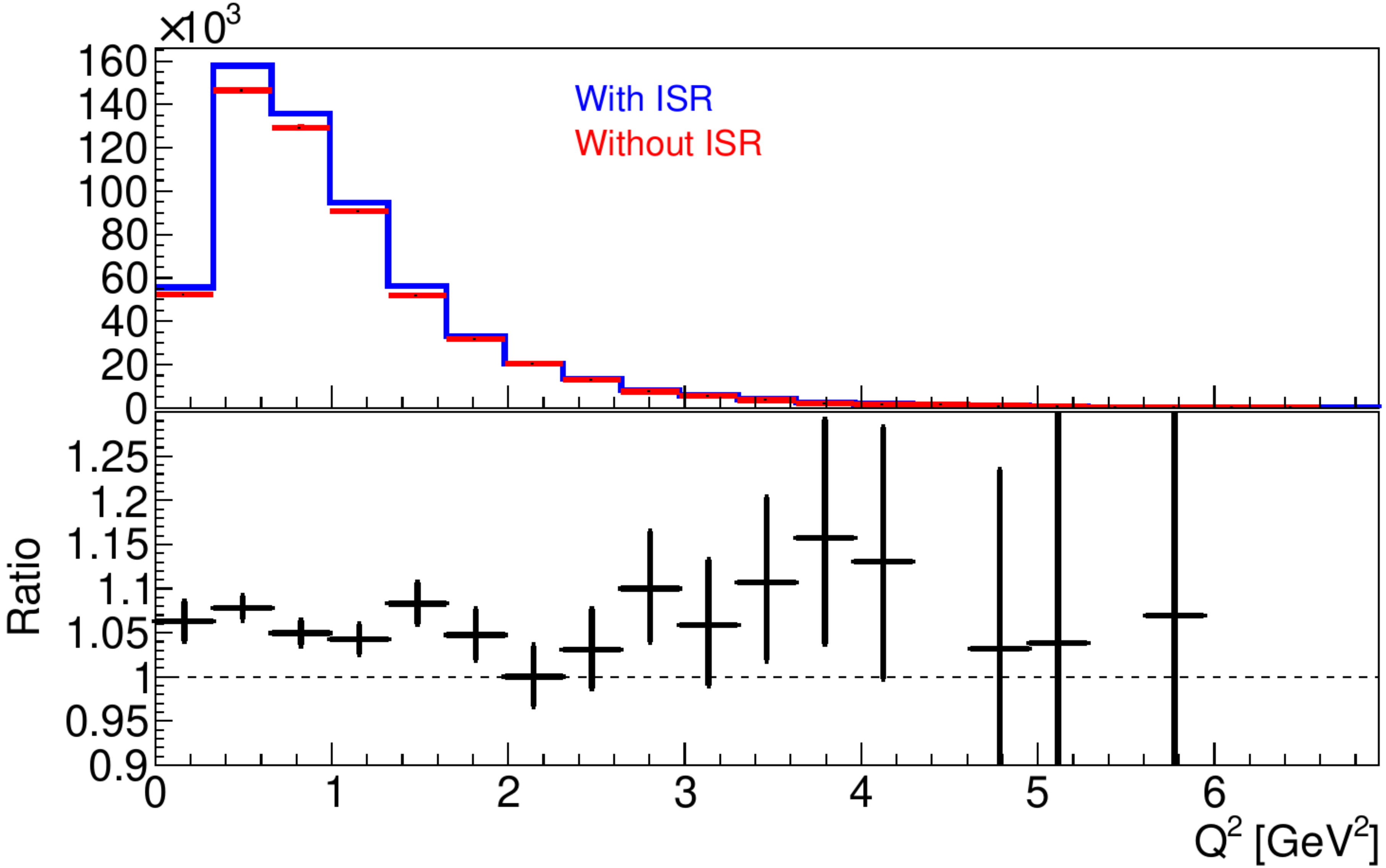
**Kinematic distributions from CLAS12 RG-A**

- 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%



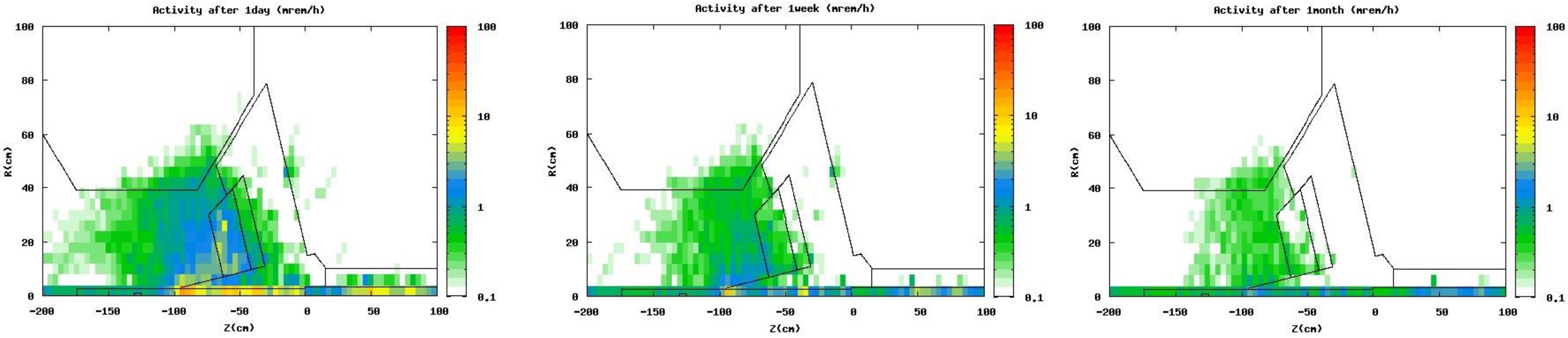



# Initial state radiation



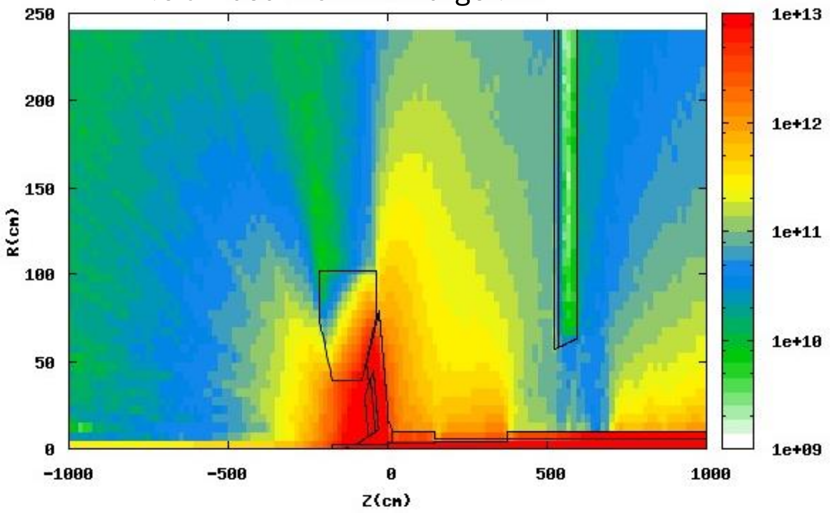
# Activation of the setup and decommissioning

- 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

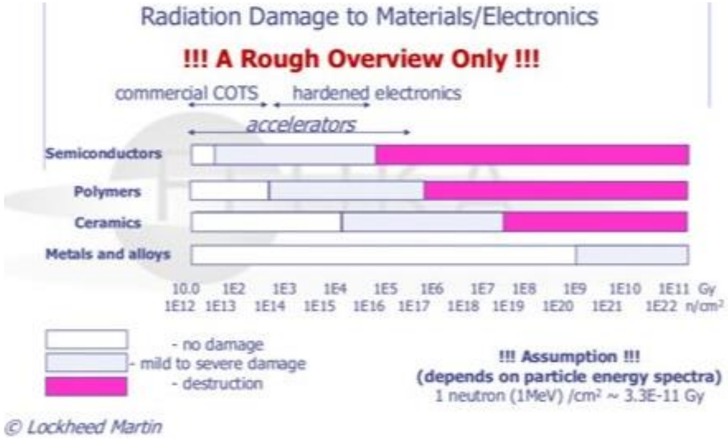


# Neutron Radiation

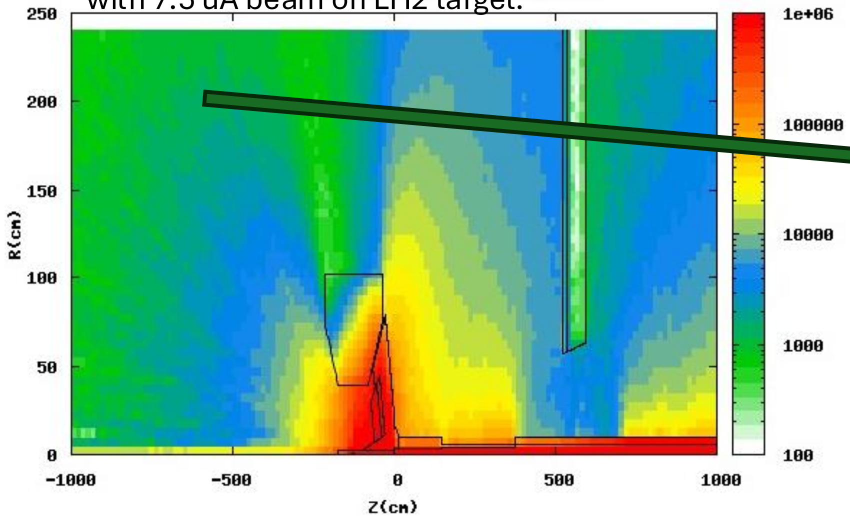
1 MeV equivalent neutron fluence in Si [$sm^{-2}$ 200 days] with 7.5 uA beam on LH2 target.



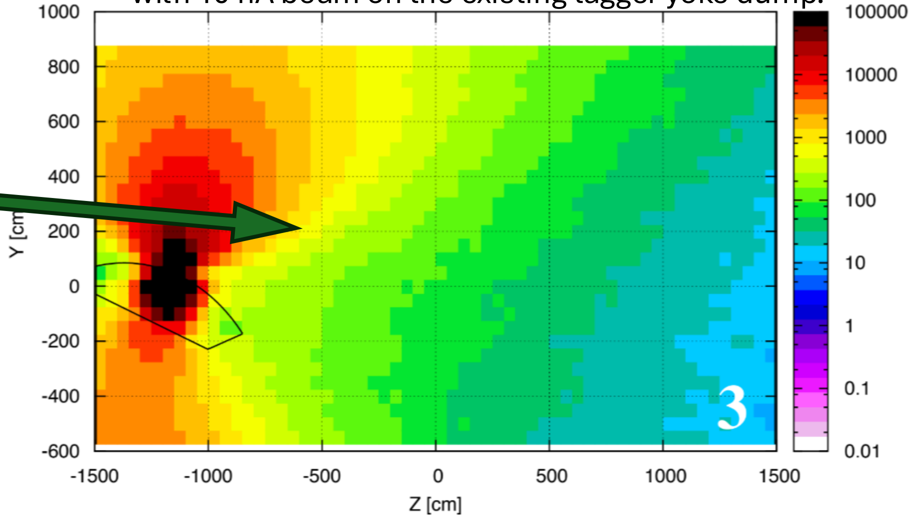

The accumulated dose in the wECal and tracker electronics region is less than $2\times10^{12}$ n/cm$^2$, close to but below the levels that cause damage to the semiconductors.




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 ($\mu$A) | 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 %** |

| $J/\psi$ 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 %** |

# Cost estimate

- PbWO: 1320-channel : $3K/channel (crystal, APD FEB) ≈ **4M**
- FVT: 36 modules (6sector x 6 layers) $20K/module ≈ **720K**
- RT: 6 layer cylindrical tracker: Total **270K**
- Readout: ≈63K channels (including both trackers) ≈ **768 K**
  - If we use CLAS12 CVT HV/LV, the cost will be **$443 K**
- SH **$71 K**

- **Total: 5.5M - 6M**