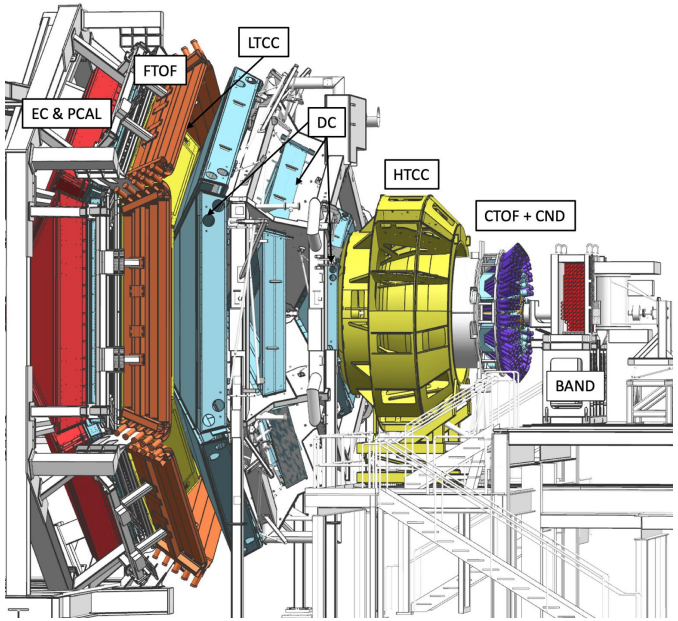
Dilepton production with CLAS12 and μCLAS12

Rafayel Paremuzyan

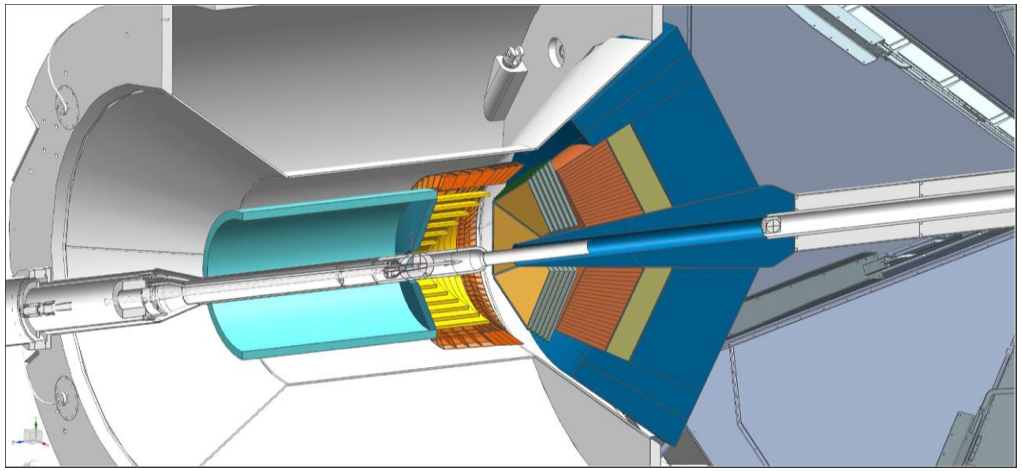
Vector Quarkonia as Pressure Gauges, **Jefferson Lab** from **March 26-27, 2026**.

Outline

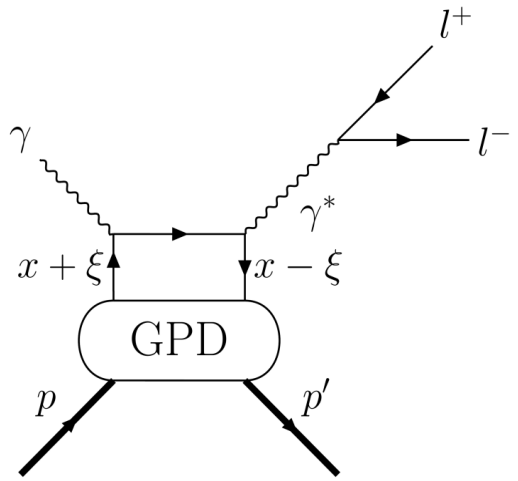
- Recent CLAS12 measurements:
  - TCS and J/ψ photoproduction
    - Focusing on Hydrogen target
  - Tagged J/ψ production will be covered by **M. Tenorio Pita**
  - J/ψ on deuterium and further plans with nuclear targets will be covered by **R. Tyson** (Friday first talk)

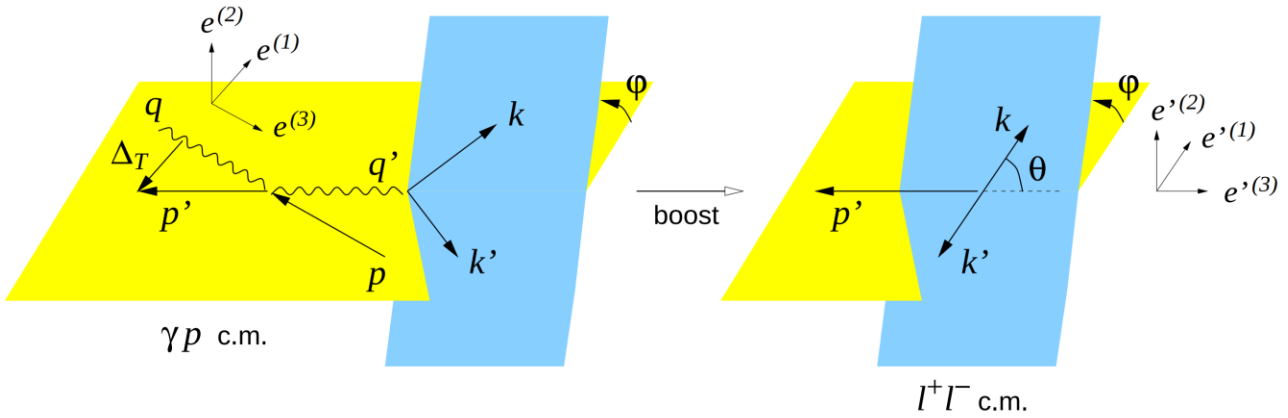


- Recently approved proposal to sutdy ep→ep$\mu^-\mu^+$ with μCLAS12
- DDVCS, J/$\psi$and TCS
- Detector overview
- Observables and estimated uncertainties.



Introduction: Timelike Compton Scattering





- TCS – symmetric to DVCS process
- Probes similar CFFs as tge 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

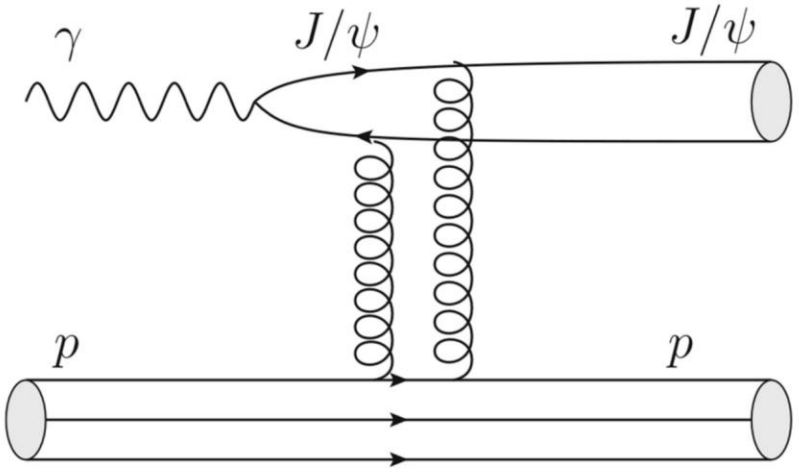
$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta,\,180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta,\,180^\circ+\phi)}$$

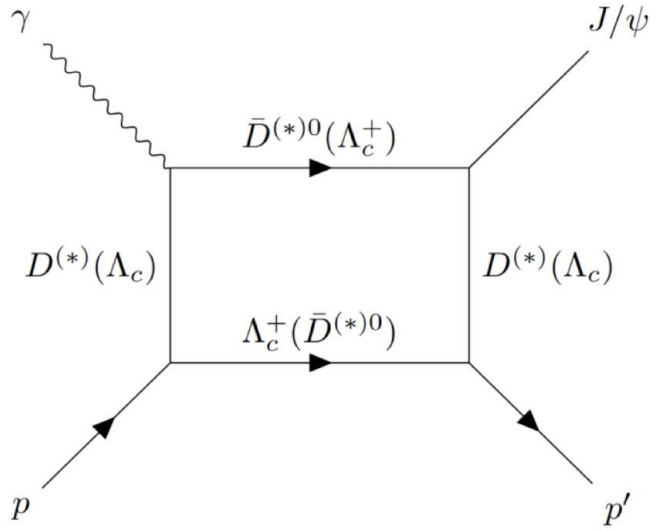
$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = A\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\,\mathcal{H}+\ldots$$

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

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

Introduction: J/ψ photoproduction near the threshold





Hot topic: various theoretical approaches

Holographic QCD and GPD based models allow acess to Gravitational Gorm Factors of the nucleaon.

Holographic QCD $\frac{d\sigma}{dt} = \mathcal{N}^2 \times \frac{e^2}{64\pi(s-M^2)^2} \times \frac{[A_g(t)+\eta^2 D_g(t)]^2}{A_g^2(0)} \times \tilde{F}(s) \times 8$

$D_g(t) = 4C_g(t)$

Phys. Rev. D 106, 086004

GPD based model: $\frac{d\sigma}{dt} = \frac{\alpha_{EM} e_Q^2}{4(s-M^2)^2} \frac{(16\pi\alpha_s)^2}{3M_{J/\psi}} |\psi_{NR}|^2 |G(t,\xi)|^2$

Pomeron exchange: unrelated to the dynamics arXiv:2510.08845

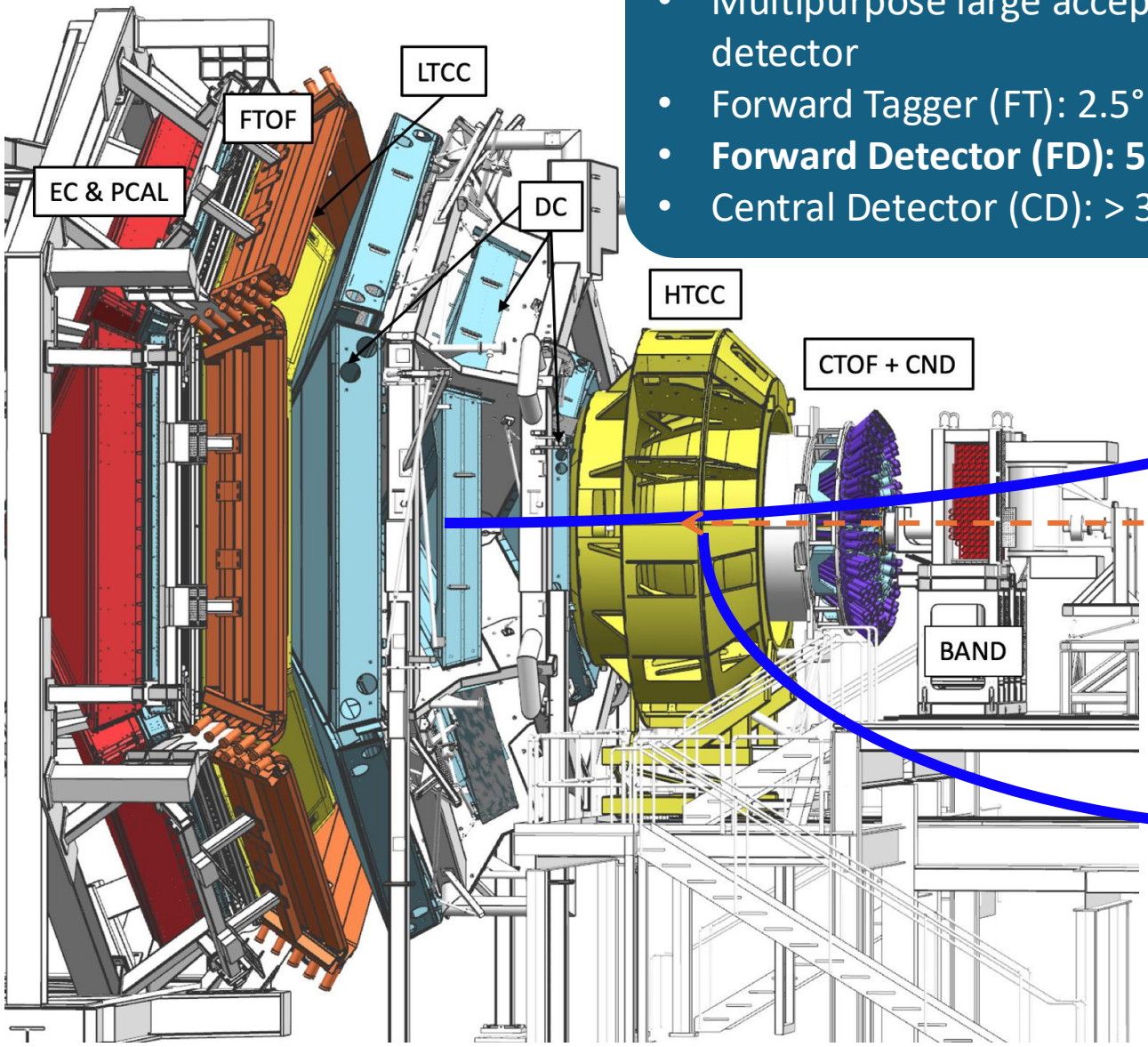
First results from GlueX and Hall-C already out:

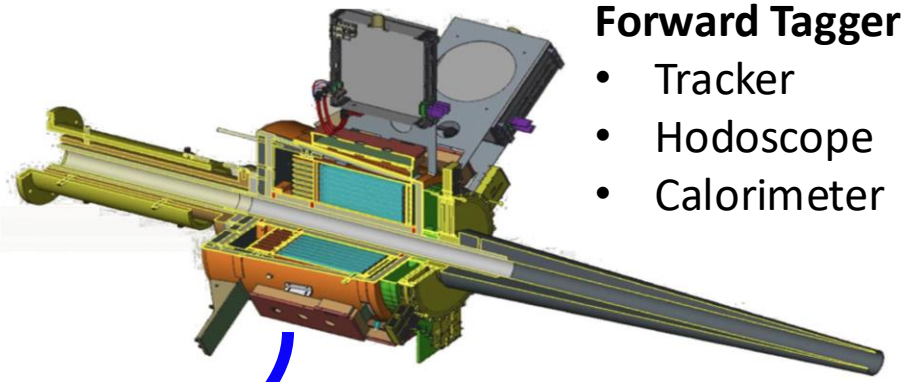
The cusp like behaviour GlueX data suggest open charm contribution in the production mechanism.

Clearly more/complementary experimental data is needed near the threshold

The CEBAF Large Acceptance Spectrometer 12

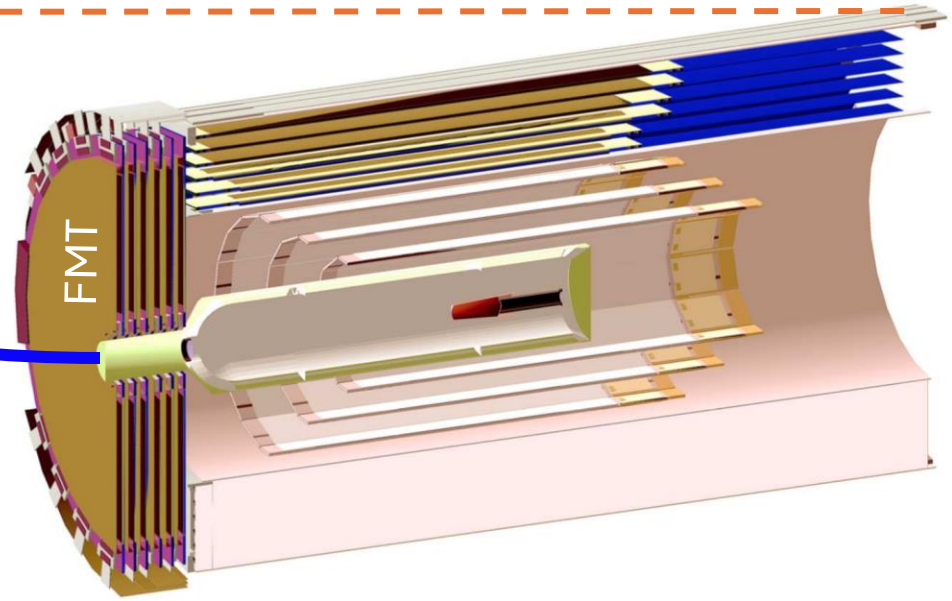
- Multipurpose large acceptance detector
- Forward Tagger (FT): 2.5° - 4.5°
- **Forward Detector (FD): 5°-35°**
- Central Detector (CD): > 35°





Forward Tagger
- Tracker
- Hodoscope
- Calorimeter

Electron beam



Data sets

Run group A:

Electron beam on 5 cm long LH2 target

Data set name	Run period	Bem energy [GeV]	Torus polarity	Accumulated charge [mC]
S18_In	Spring 2018	10.6	-1	67.3152
S18_Out	Spring 2018	10.6	+1	16.9145
F18_In	Fall 2018	10.6	-1	35.667
F18_Out	Fall 2018	10.6	+1	32.451
S19	Spring 2019	10.2	-1	45.994

Calibration for different run periods was completed at different times (some required additional effort); therefore, not all run periods were included in the initial analyses.

- TCS by P. Chatagnon - F18_In
- J/psi photoproduction by P. Chatagnon – F18_In, F18_Out and S19
- Tagged J/ψ prodution by M. Tenorio pita --- F18_In, F18_Out, S19 and S18_In --- Soon to be finished
- TCS by K. Gopal --- F18_In, F18_Out, S19 and S18_In --- Recently started

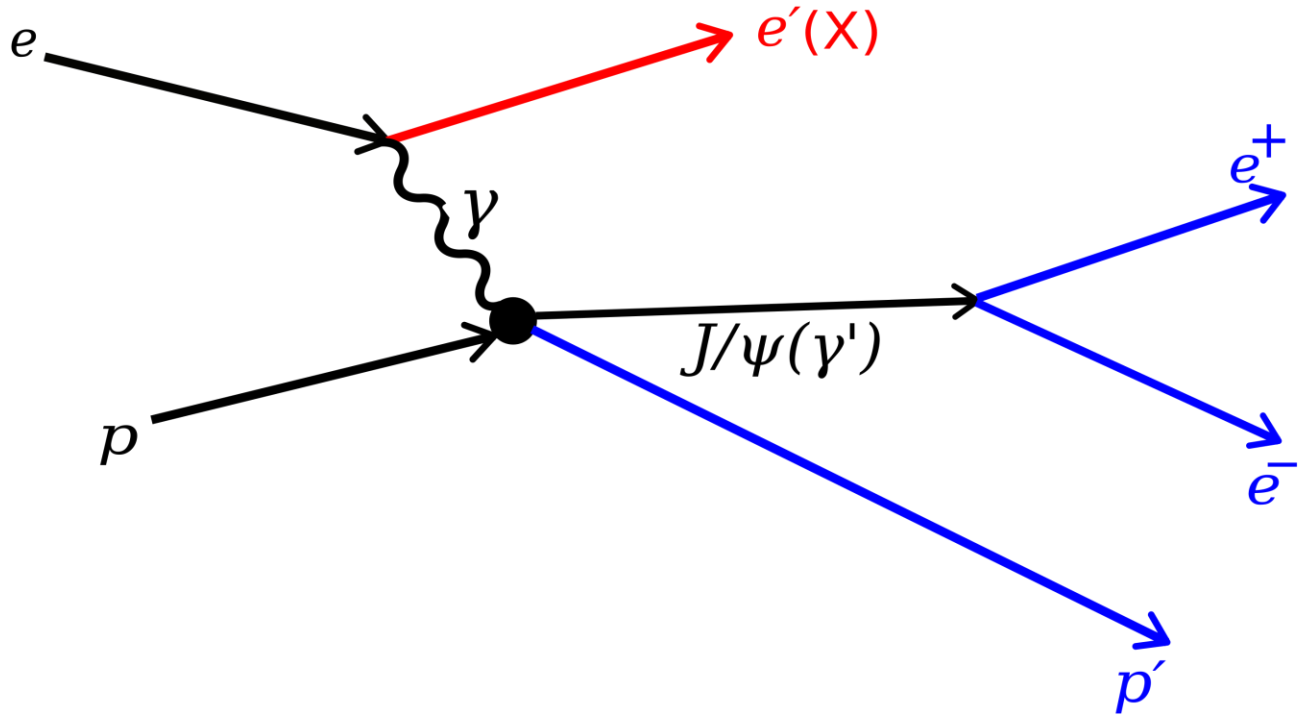
The analysis

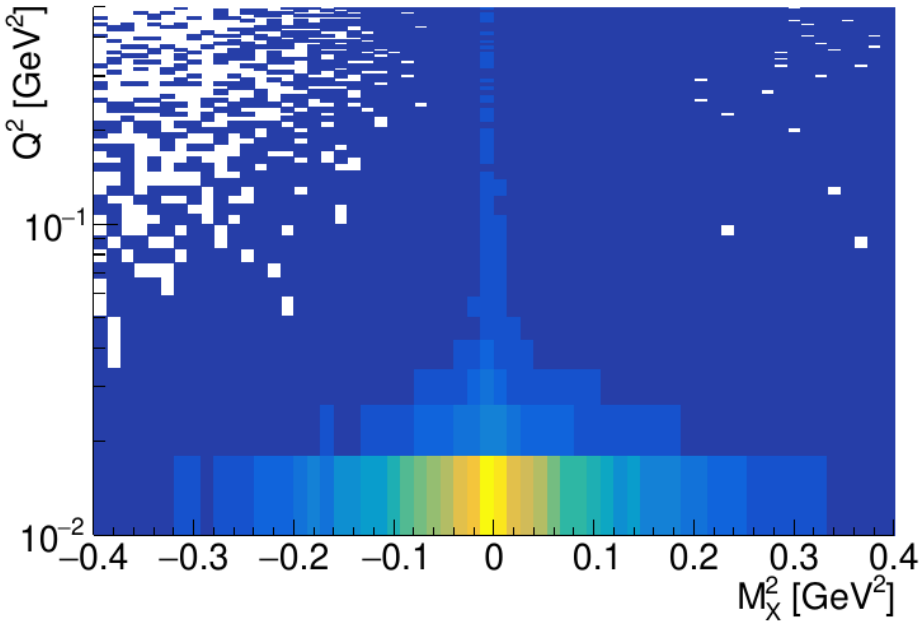
- e^-, e^+ and p' are detected in the Forward detector
- Beam scattered electron is not detected but can be identified requiring missing mass to be ≈0.
  - e'(X) = e + p – e^- - e^+ - p'
- Timelike photon or J/ψ identified through the sum of e^- and e^+ four vectors
- Photon is identified as e^- + e^+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

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

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

$$Q^2 < 0.5\ \mathrm{GeV}^2$$

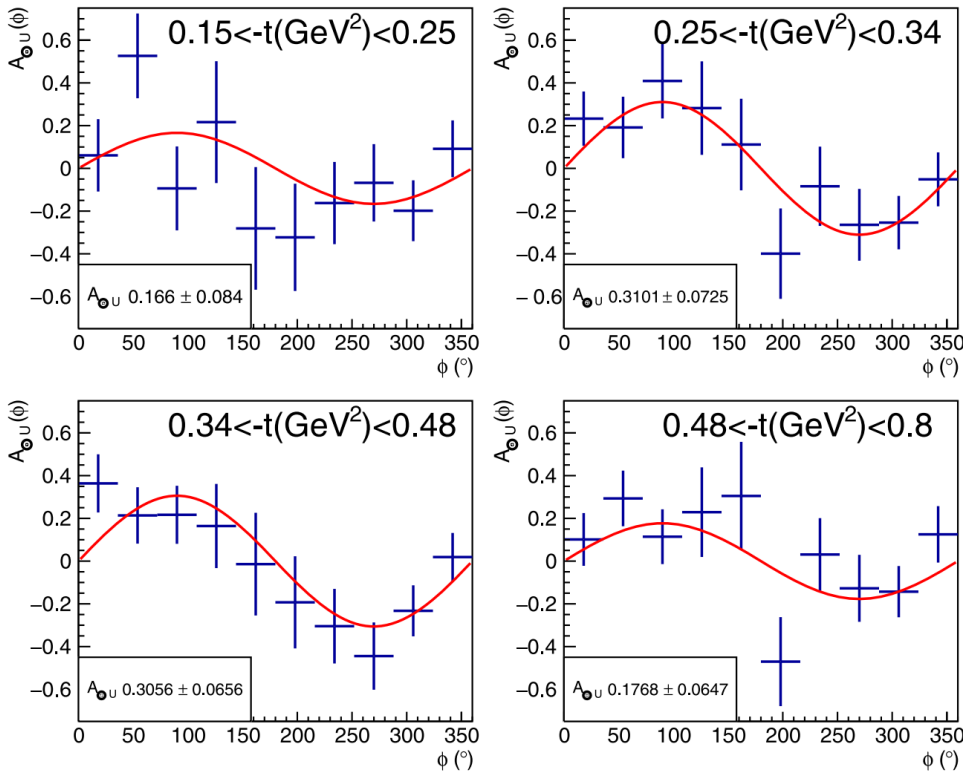




The 1st TCS measurement

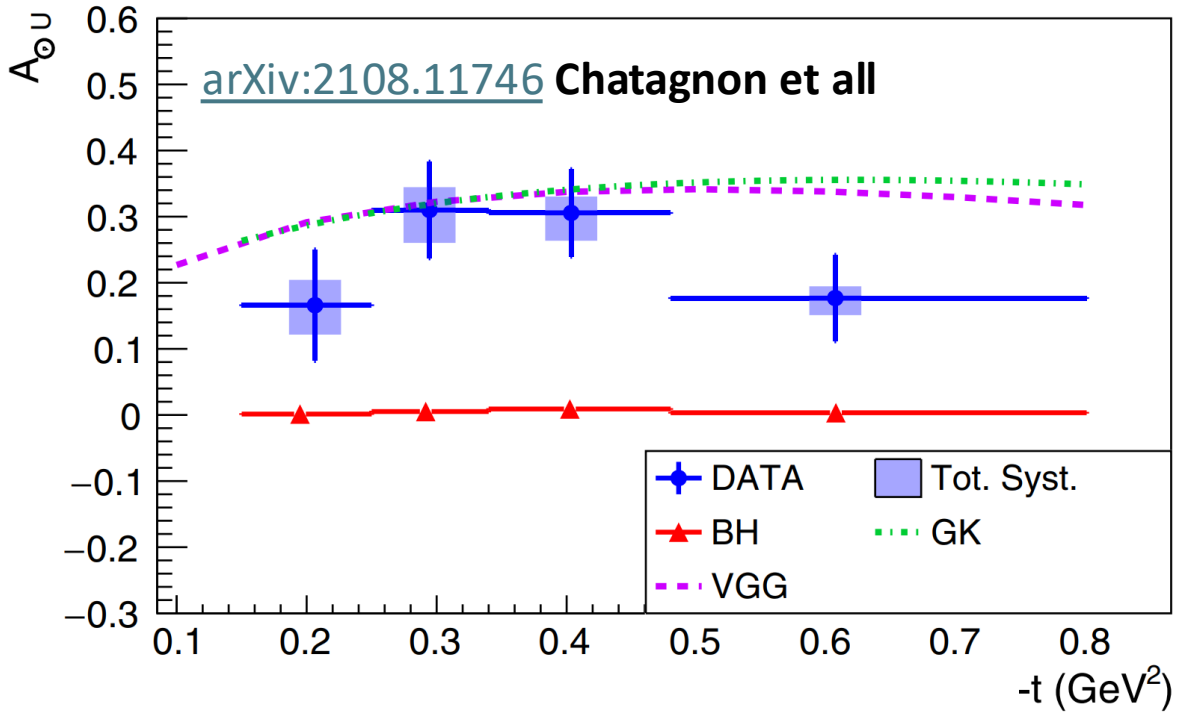
$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

Polarization asymmetry



The polarization asymmetry is measured in 4 –t bins.

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



Polarization transfer L is calculated as:

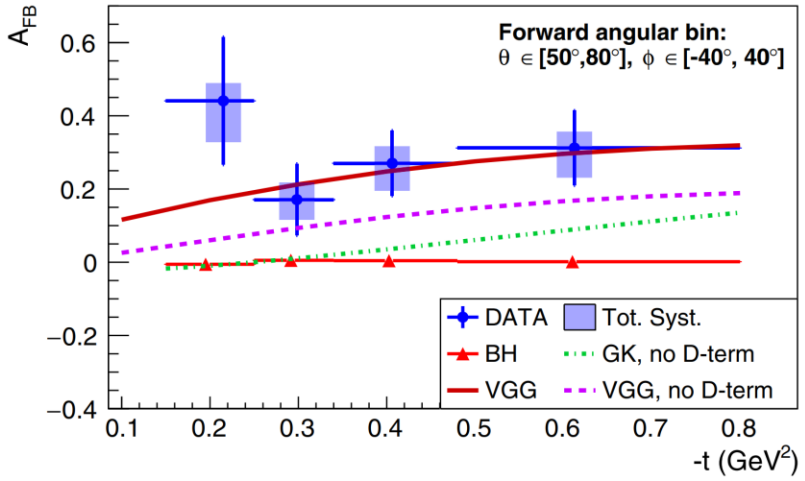
$$L = k\left[(E_1 + E_2)(3 + 2\Gamma) - 2E_2(1 + 4u^2\xi^2\Gamma)\right]/I_0$$
$$I_0 = (E_1^2 + E_2^2)(3 + 2\Gamma) - 2E_1E_2(1 + 4u^2\xi^2\Gamma)$$

The 1st TCS measurement

Forward Backward asymmetry

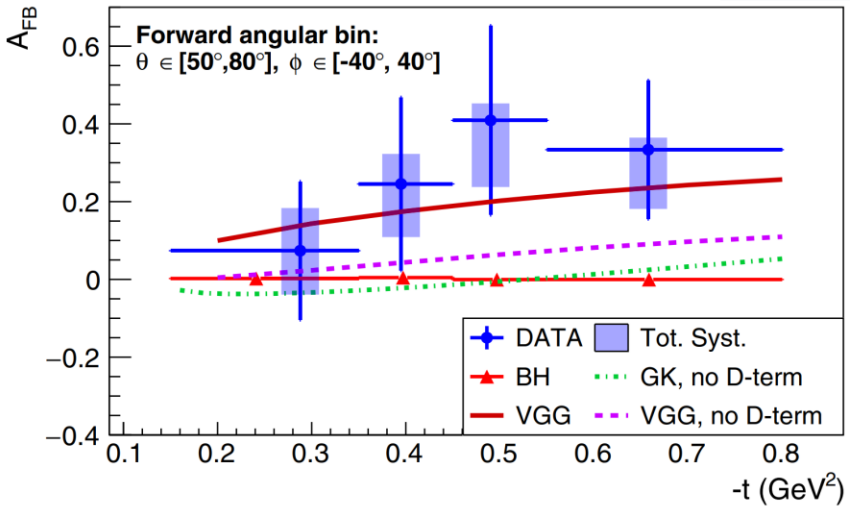
$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta, 180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta, 180^\circ+\phi)}$$

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



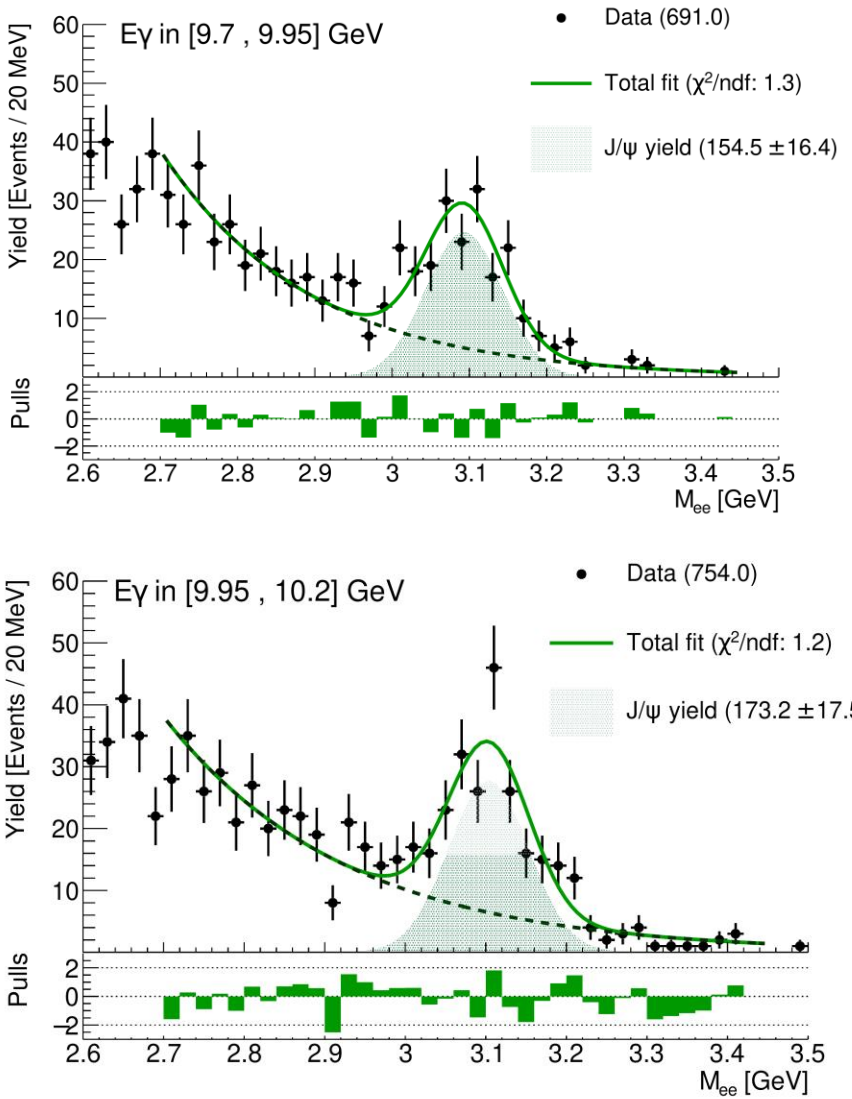
$E_\gamma = 8.13 \pm 1.23$ GeV
$M = 2.25 \pm 0.20$ GeV

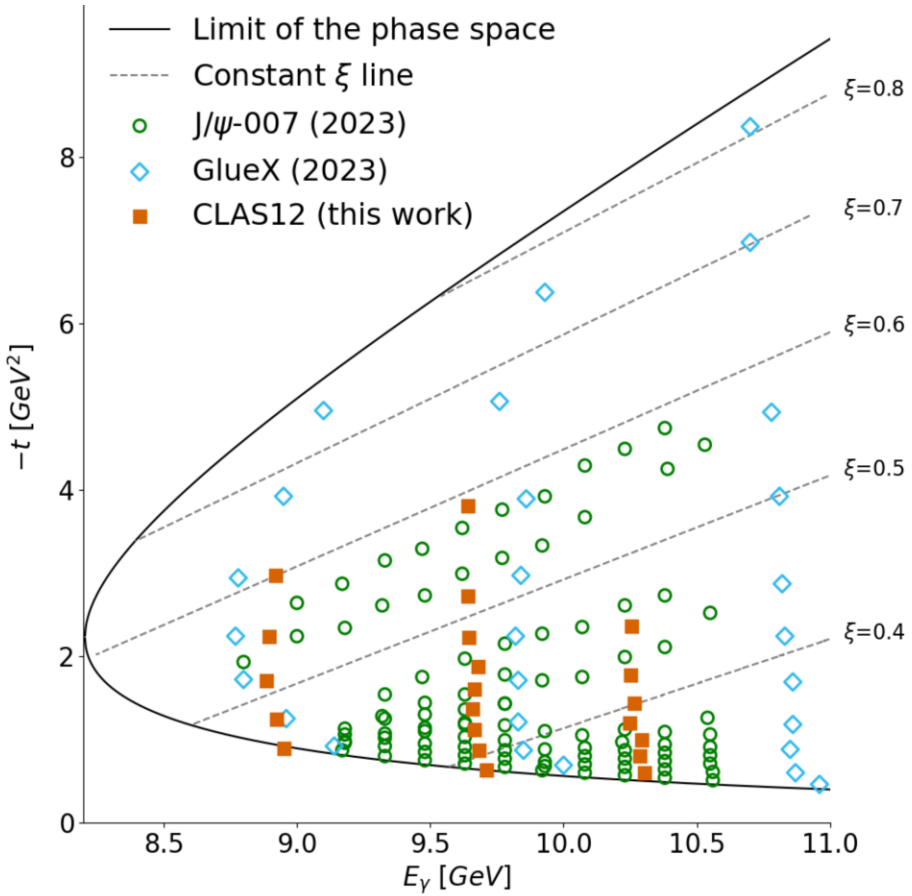
arXiv:2108.11746 **Chatagnon et all**



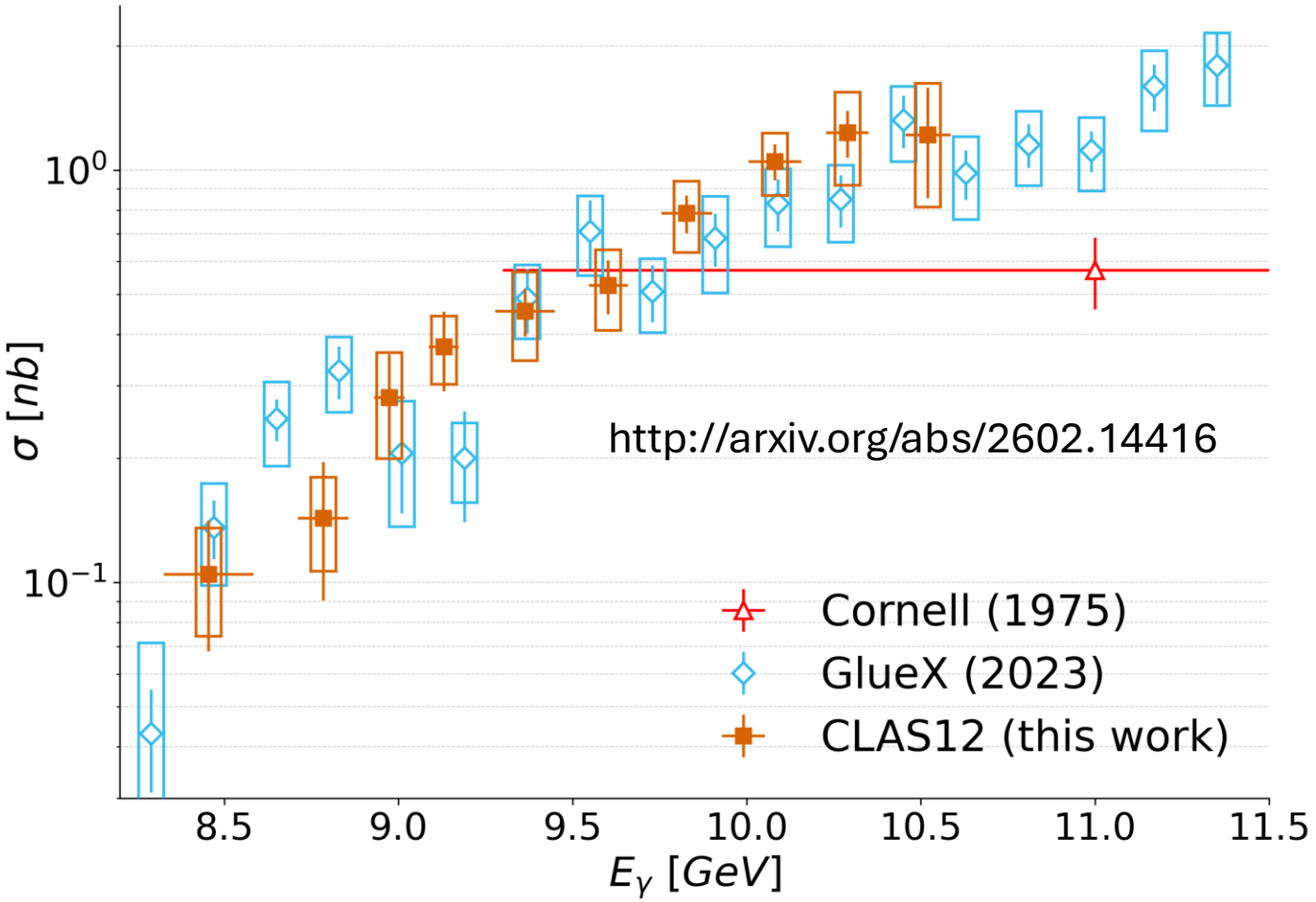
- Since the first TCS publications, track reconstruction efficiency and quality have significantly improved (largely due to AI tools).
- More than twice as much data has already been calibrated and is being analyzed.
- About half of the approved RG-A beam time has yet to be taken.
- CLAS12 plans to increase 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.

J/ψ Photoproduction near the threshold





Total cross section

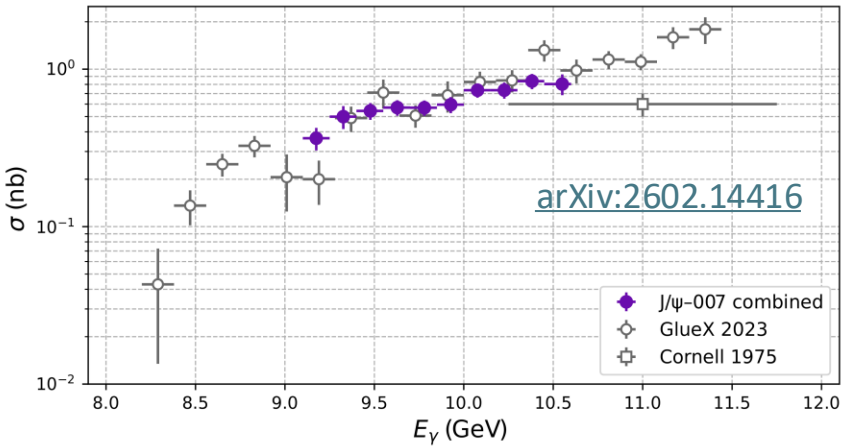


Boxes – Systematic uncertainties

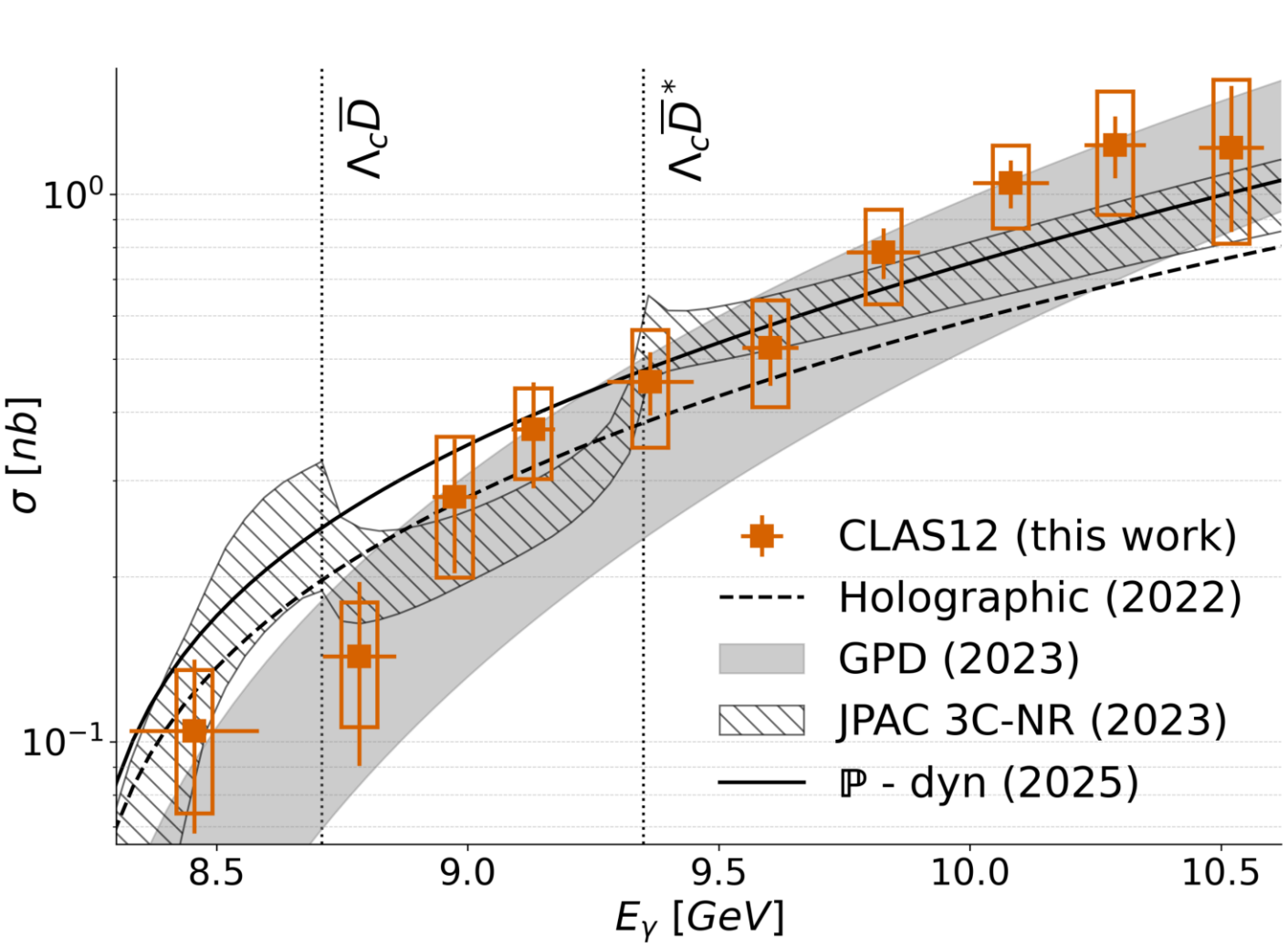
Vertical bars – Stat. uncertainties

- 10 Energy bins from 8.5 GeV to 10.5 GeV
- Reasonably good agreement with GlueX
- Monotonic behaviour around 9 GeV:
  - No dip around $\Lambda_c \bar{D}$ and $\Lambda C \bar{D}^*$

Newly released J/ψ-007 also doesn't seem to support cusp like structure.



Total cross section



Boxes – Systematic uncertainties

Vertical bars – Stat. uncertainties

All predictions are consistent with the data within 2 standard deviations.

Phys. Rev. D 106, 086004

Phys. Rev. D 108, 034003

Phys. Rev. D 108, 054018

arXiv:2510.08845 (Pomeron exchange)

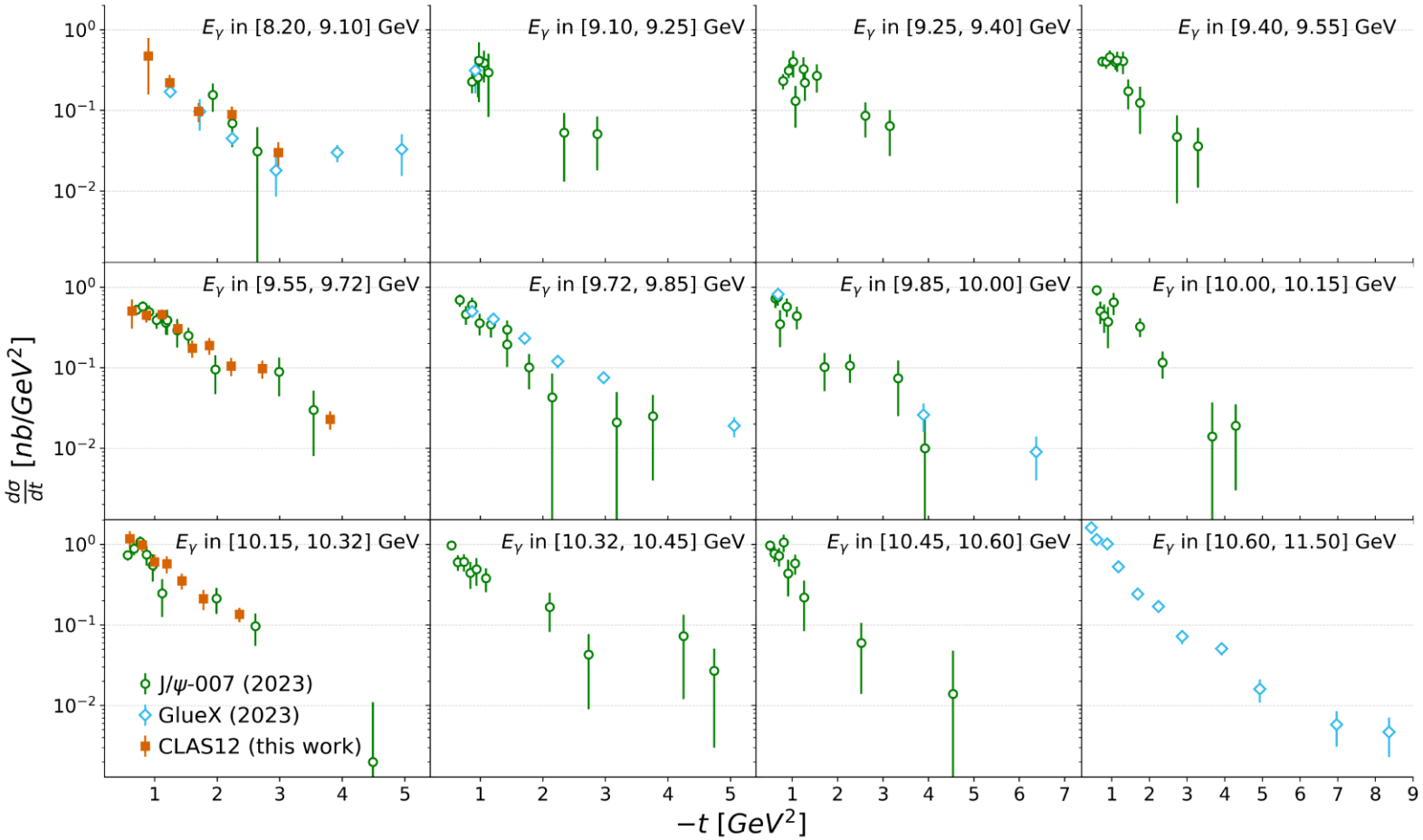
Differential cross section

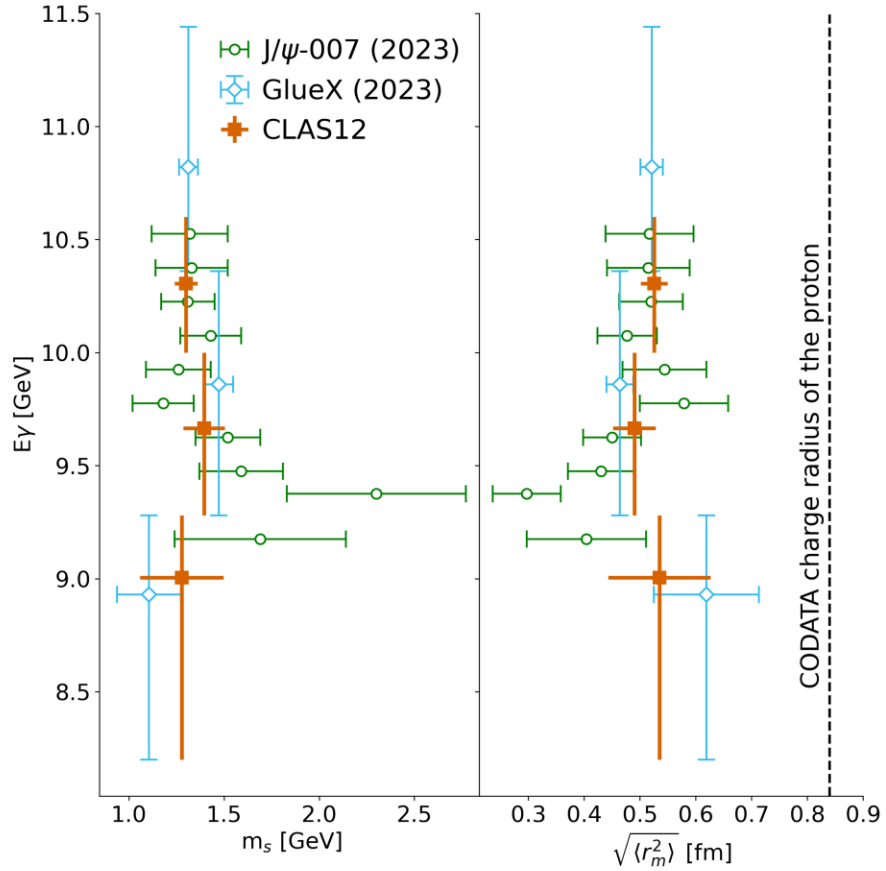
In the overlap regions CLAS12 data agrees with GlueX and J/ψ-007

Extracted mass radius ≈0.5 fm also is in agreement with GlueX and J/ψ-007

Dipole parametrization Phys. Rev. D 104, 054015

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





Extraction of GFFs

Using tripole ansatz for $A_g(t)$ and $C_g(t)$

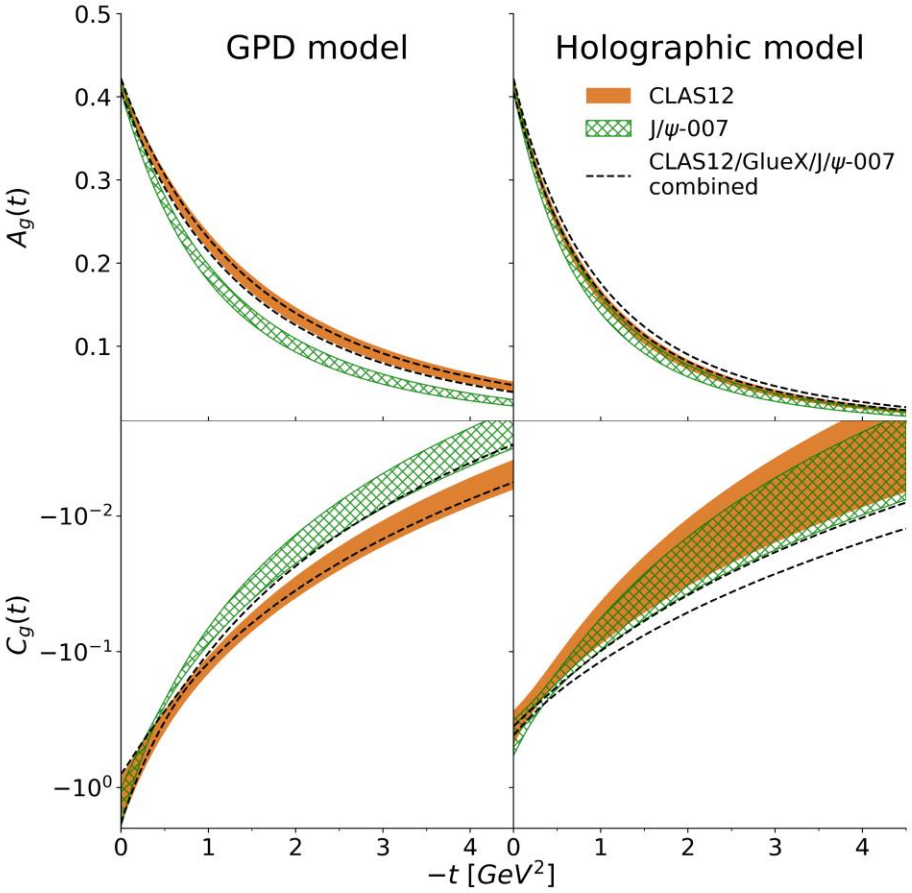
$$A_g(t) = \frac{A_g(0)}{\left(1 - \frac{t}{m_A^2}\right)^3}, \; C_g(t) = \frac{C_g(0)}{\left(1 - \frac{t}{m_C^2}\right)^3}$$

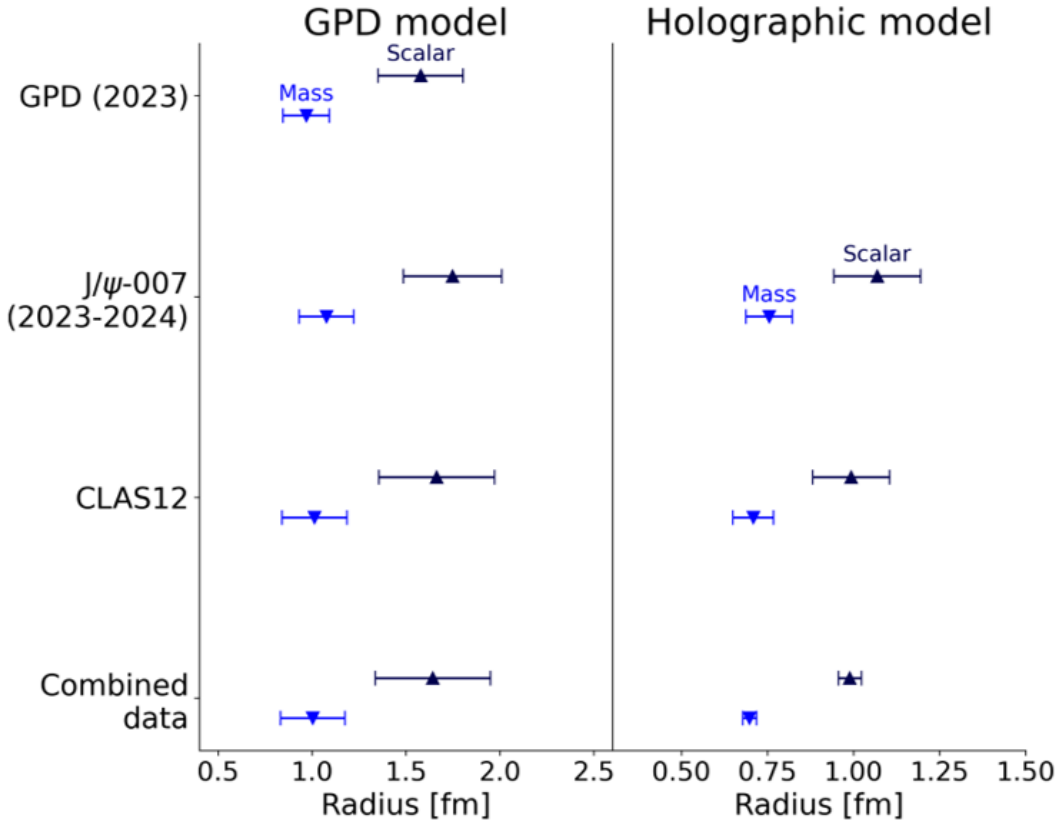
$B_g(t)$ and $\bar{C}_g(t)$ are ignored

For the GPD model only data with ξ>0.4 were used

$A_g(0)$ is fixed to 0.414

Two fits for each model: Using only CLAS12 data and all data combined.



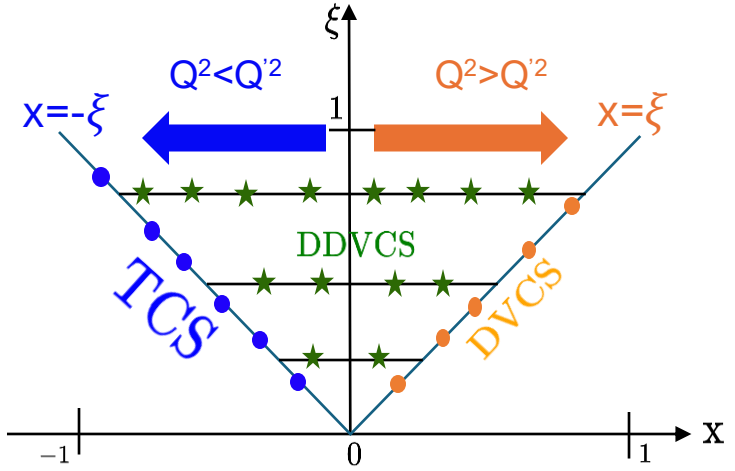


J/ψ Conclusions and outlook

- Total cross-section is overall in a good aagreement with previously published GlueX data, however around the open charm thresholds CLAS12 points are monotonic .
- Differential cross sections are in a good agreement with existing GlueX and Hall-C J/ψ-007 experiment.
- $A_g(t)$ and $C_g(t)$ gravitational form factors of the proton have been extracted using GPD and Holographic QCD approaches.
- Statistical precision and coverage in t is comparable to those from previous measurements.
- Recently approved experiment proposal with μCLAS12 will provide significantly larger number of J/ψ

Factor of 100 Luminosity upgrade and the μCLAS12

One of challenges in the extraction of GPDs is that the variable "x" is integrated over, excpt x=$\mp\xi$ line when an observable is proportional to the Im part of the scattering amplitude, e.g. BSA in DVCS.



Changing virtualities in Double DVCS one can access GPDs at the -ξ< x < ξ

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

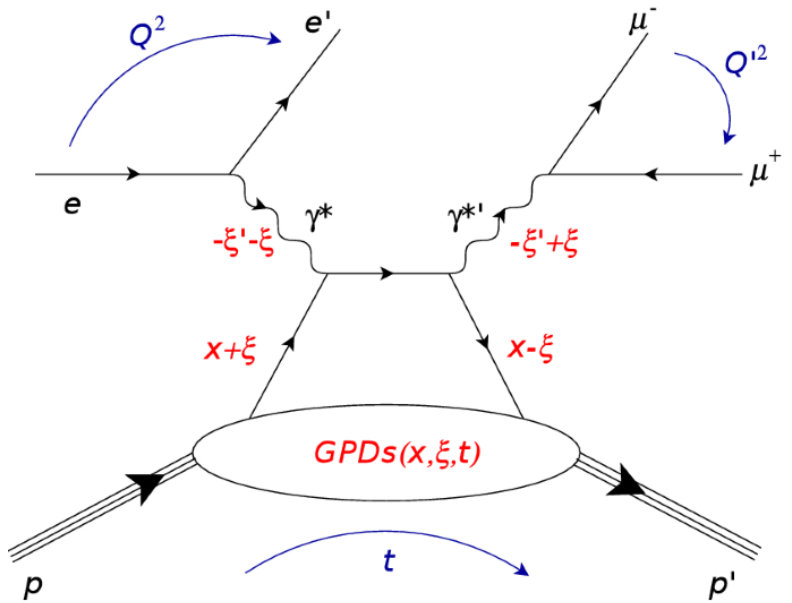
Main Challenge is more than ×**100 smallesr x-sec wrt DVCS**.

- **Need at least ×100 higher luminosity** in order to measure it in a reasonable time frame.
- **Need Muon detection**: to avoid interference between the beam and decay electrons.

- Has the same final state as the **J/ψ electroproduction**, and when beam electron scatters ≈0 degree, even **TCS can be measured**.

We have proposed an experiment at PAC52 to perform these measrueements in a single experimental configuration. Approved with A rating (C1)

Double DVCS



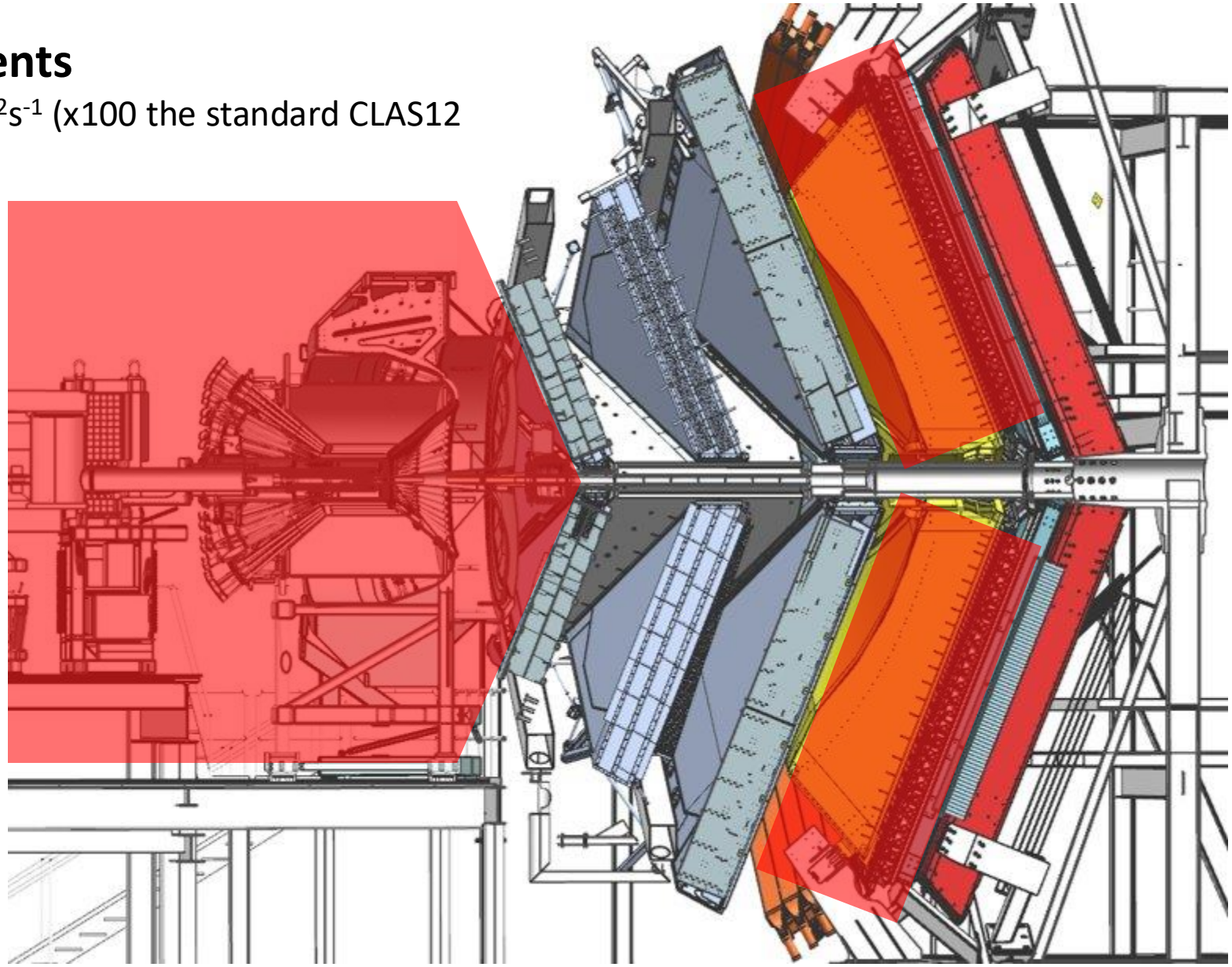
Proposed changes to CLAS12

Requirements

- Increase the CLAS12 luminosity to $10^{37}cm^{-2}s^{-1}$ (x100 the standard CLAS12 luminosity.
- Ability to identify muons.

Modifications

- All detectors upstream of Drift Chambers (DC) will be taken out.
- BAND, CTOF, CND, CVT, FT
- RICH and LTCC also will be taken out
- Solenoid will stay
- Install thick shielding upstream of DC to suppress all EM background but muons.
- Install new Calorimeter to detect electrons
- Install Vertex tracker for vertex (position and angle) reconstruction
- Install recoil tracker and hodoscope for proton detection



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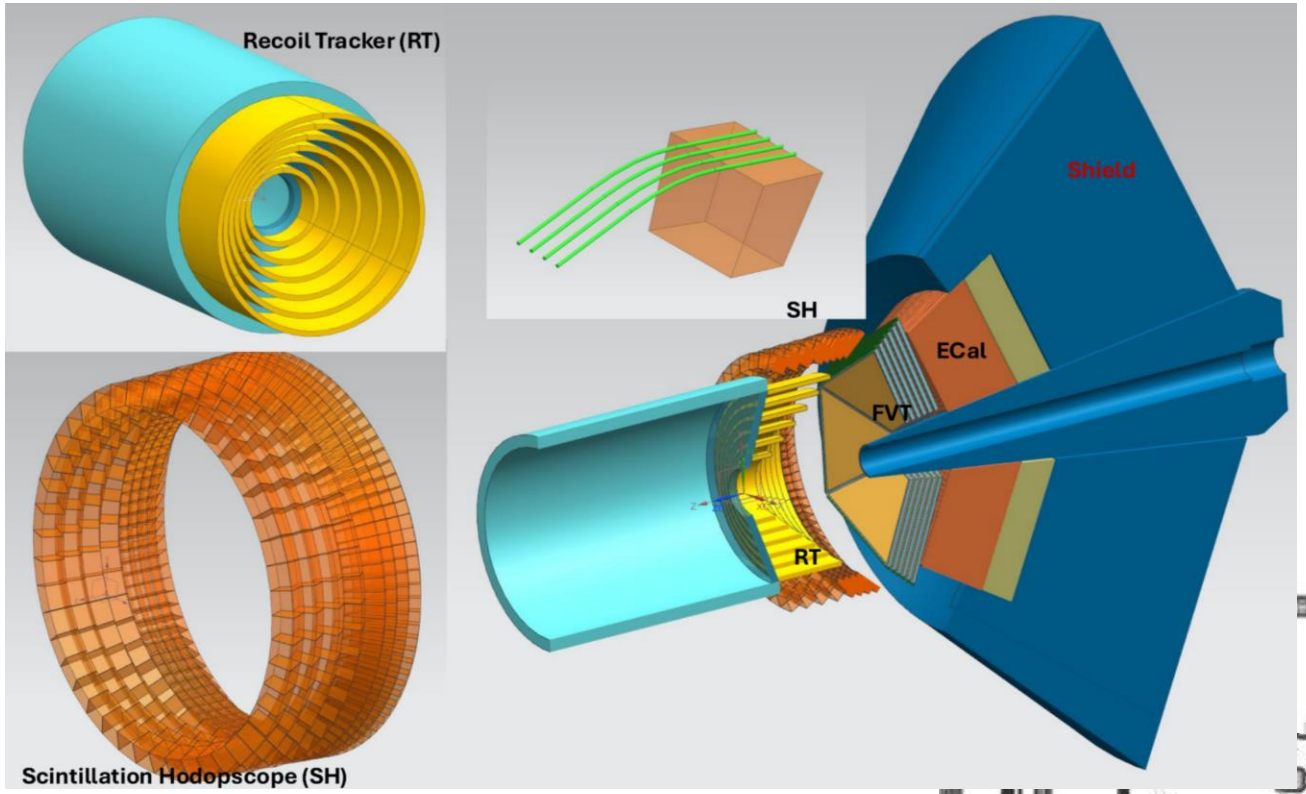
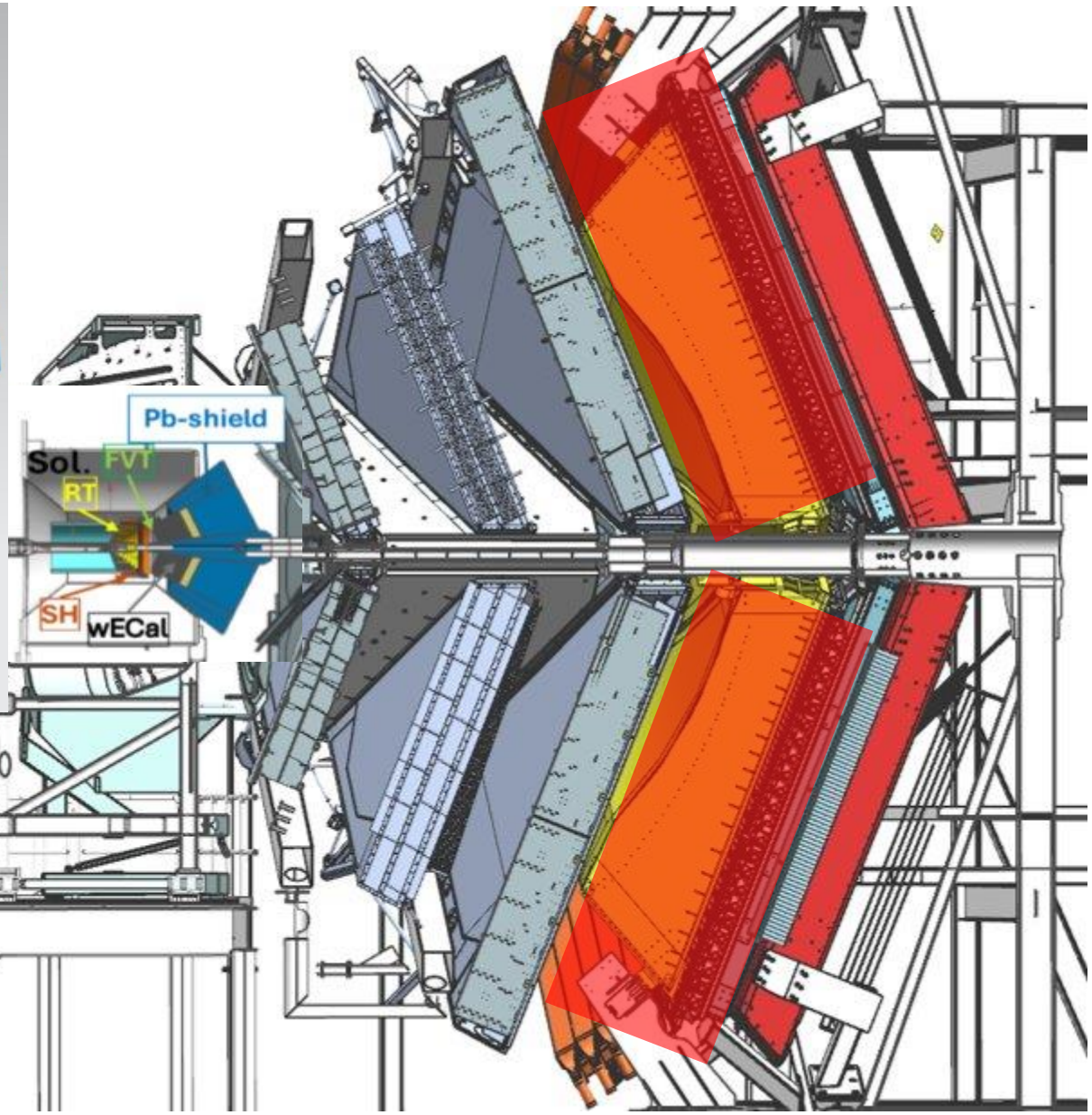




- 60 cm Lead
- Thicker Moeller cone up to 7°.
- wECal to detect electrons (7°-30°)
- 6 layers of FVT to reconstruct vertex (7°-35°)
- 6 layers of barrel tracker (40°-70°)
- Scintillation Hodoscope (40°-70°)

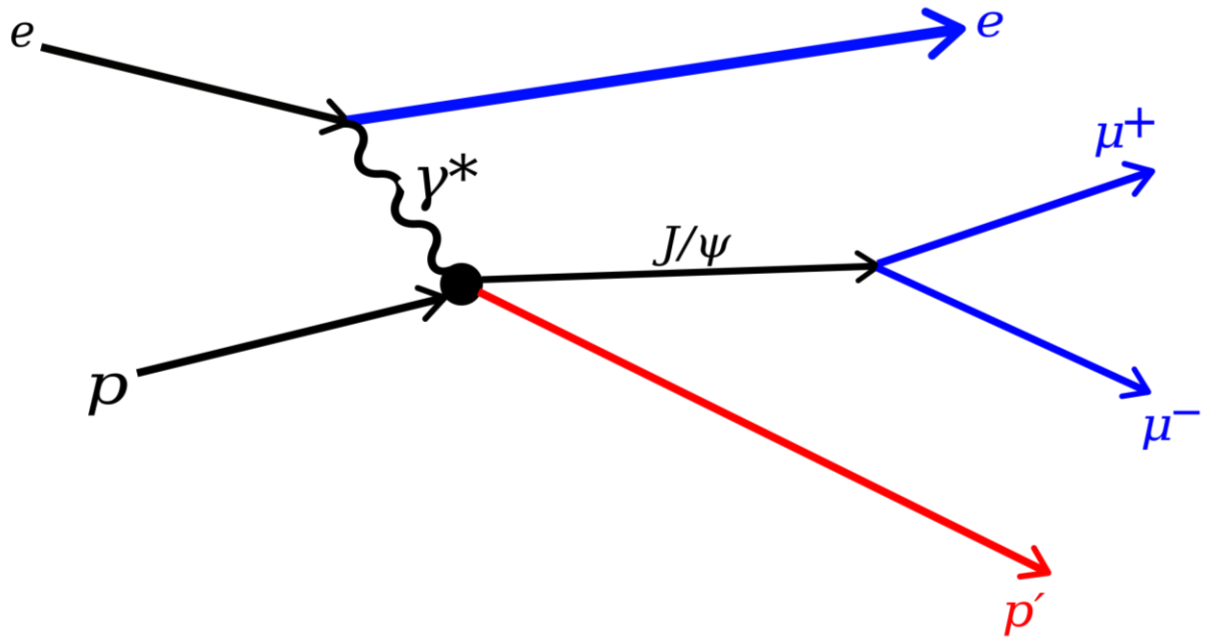
Event selection

DDVCS and J/ψ analysis

- Electron is detectred in the wECal
- $\mu^-\mu^+$ are detected in CLAS12
- Proton detection is optional

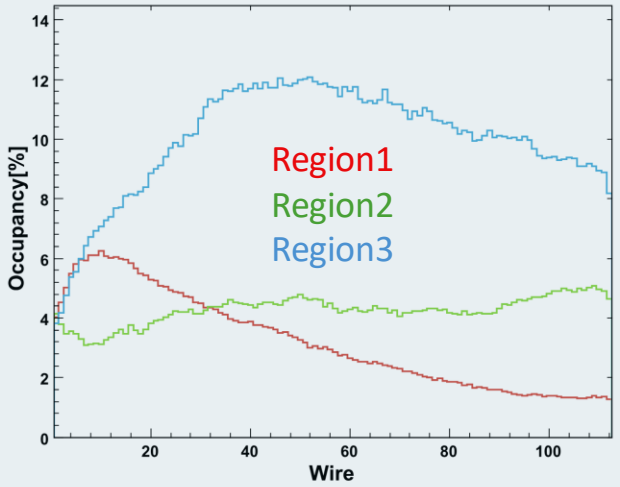
TCS analysis

- Electron scatters ≈0 degree // not detected
- $\mu^-\mu^+$ are detected in CLAS12
- Proton detected in the recoil detector



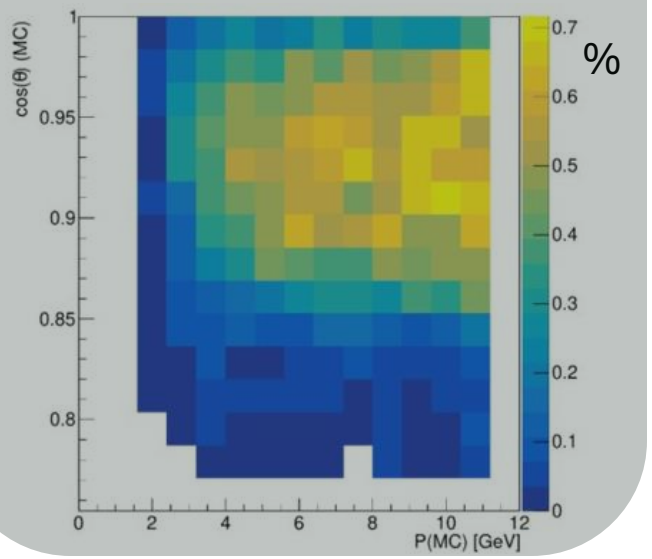
Expected Performance

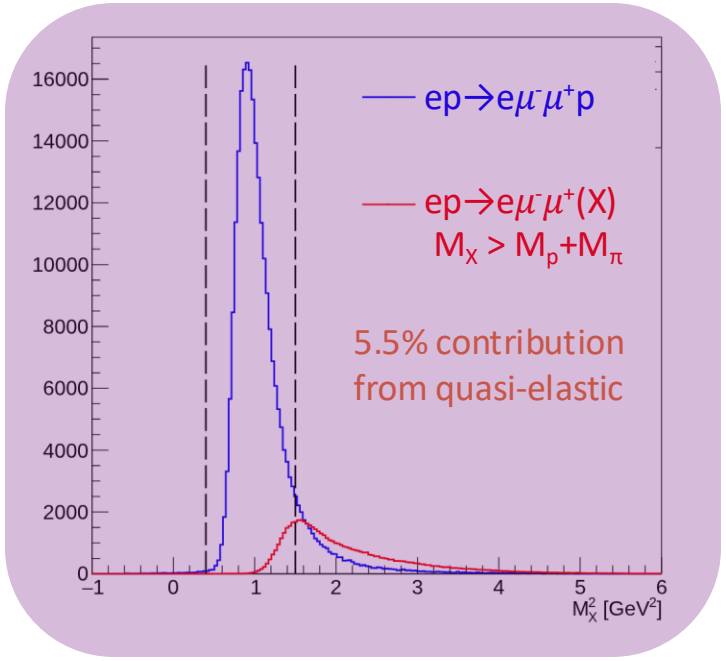
Occupancies in DC

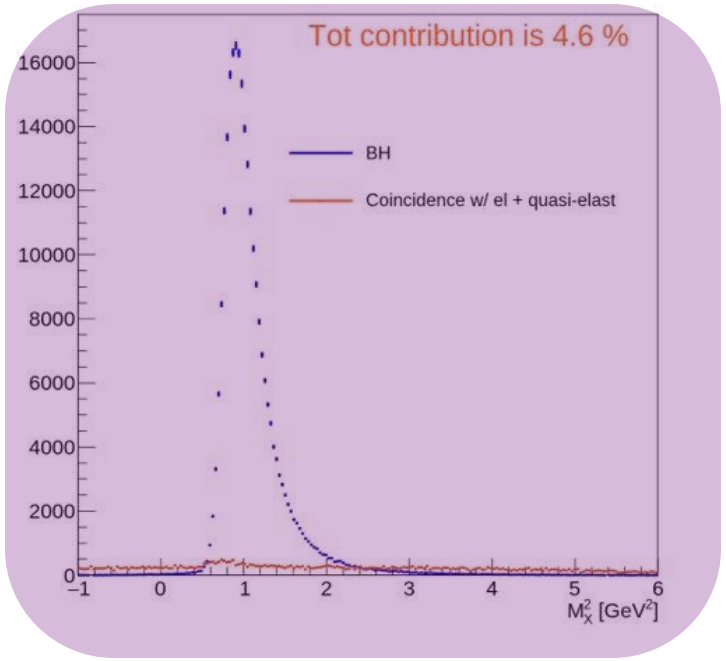


Maximum occupancy will be under 12 %
With Nuclear targets CLAS12 DC occupany reached 10%

Single pion survival rate is less than 1%





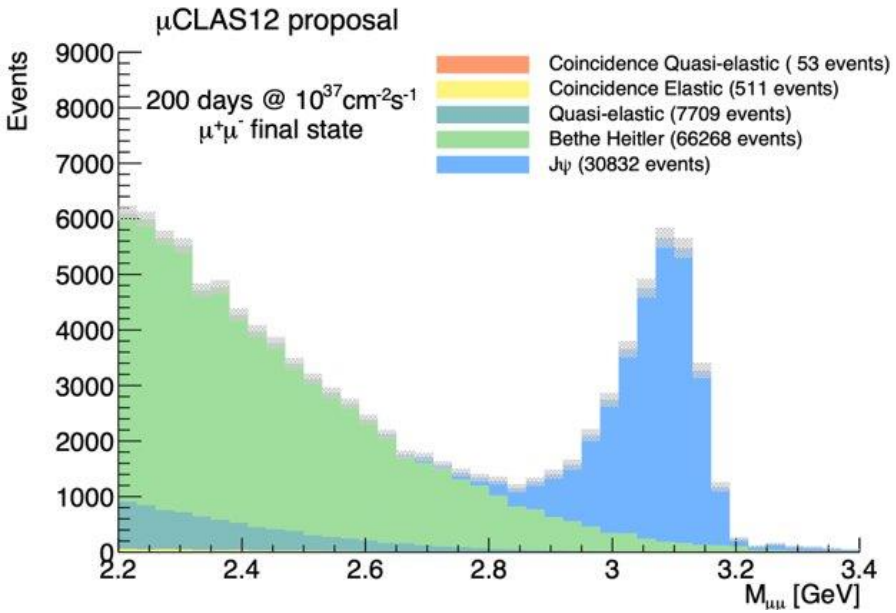


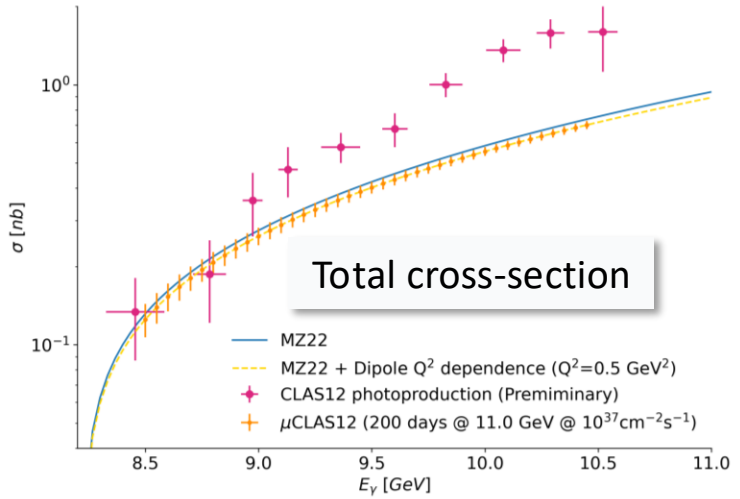
- Beam energy – 11 GeV
- 5 cm LH_2 target
- Beam current – 7.5 μA
- 200 Days of Production running + 45 days of calibration and Comissionning.
- Trigger: Single muon trigger ~ 21 KHz // Well within CLAS12 DAQ capabilities
- Rate of pion pairs passing analysis cuts: ~0.001 Hz. This is about 1% background for DDVCS, and negligible for J/ψ.

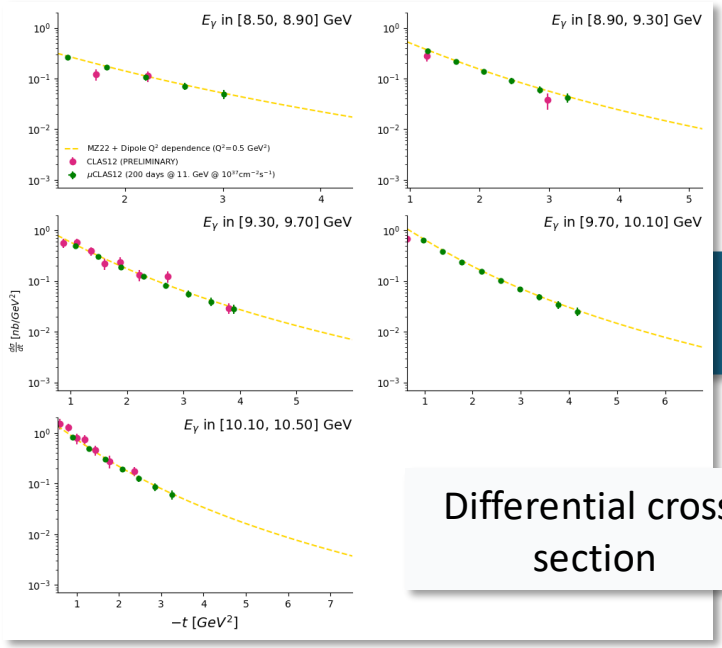
Expected results: J/ψ production

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

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

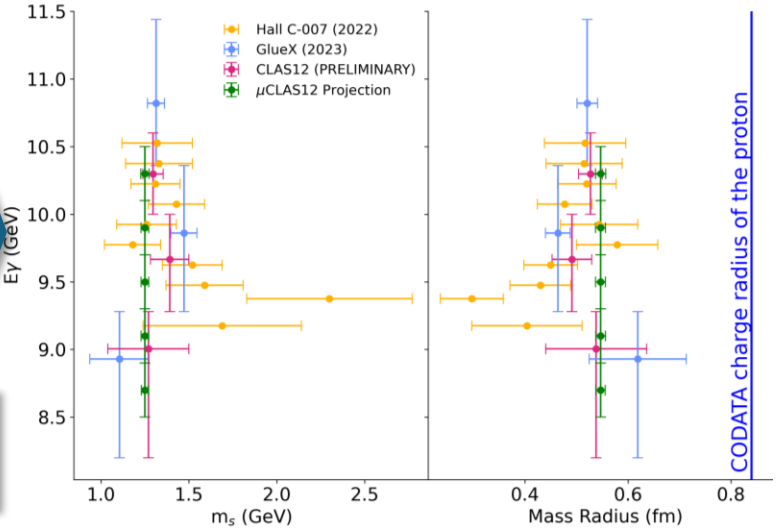






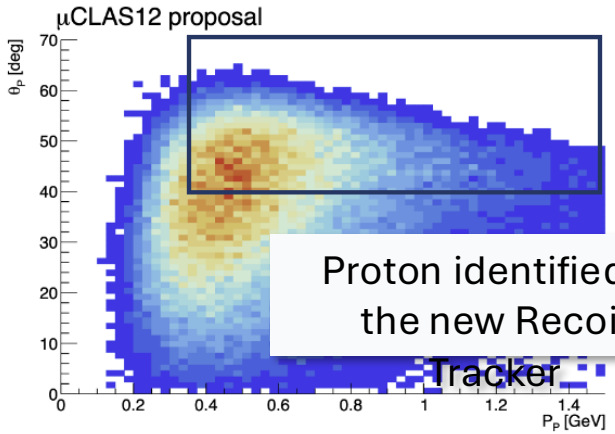
- 10 times more events than the current largest J/ψ sample at JLab.
- ¾ of the expected SoLID J/ψ rate.
- Energy reach limited by the wECAL threshold.

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



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

Expected results: TCS

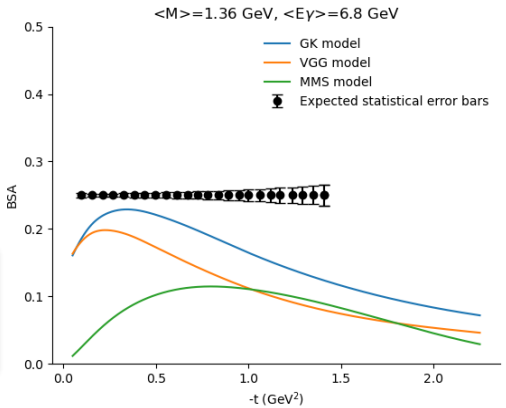


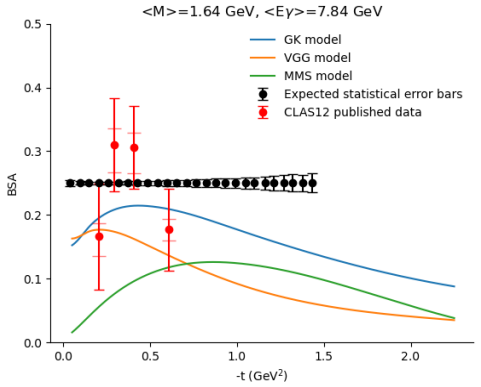
Proton identified in the new Recoil Tracker

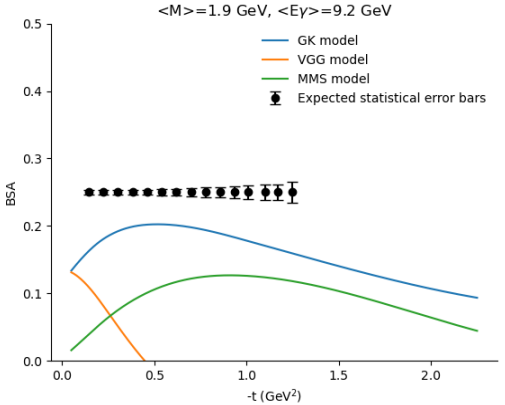
7.7M expected with events M(μμ) >1.2 GeV)

precision measurement of TCS

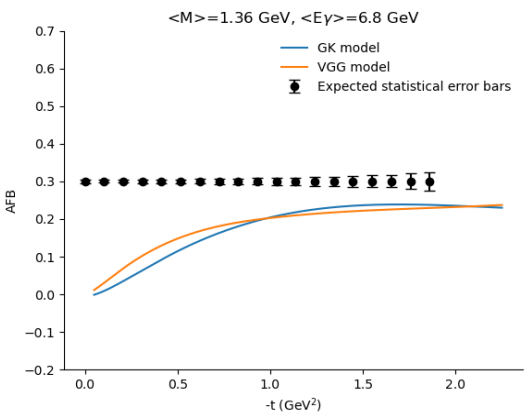
Photon polarization asymmetry $A_{\odot U} = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$

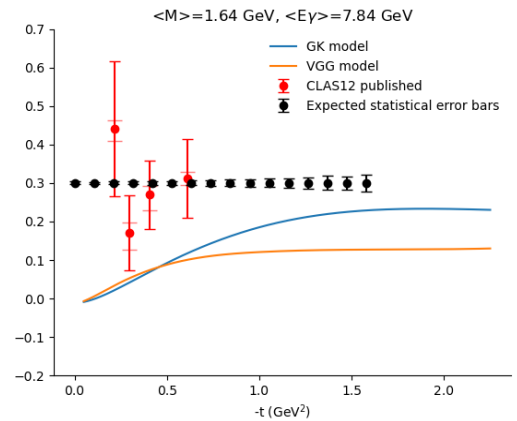


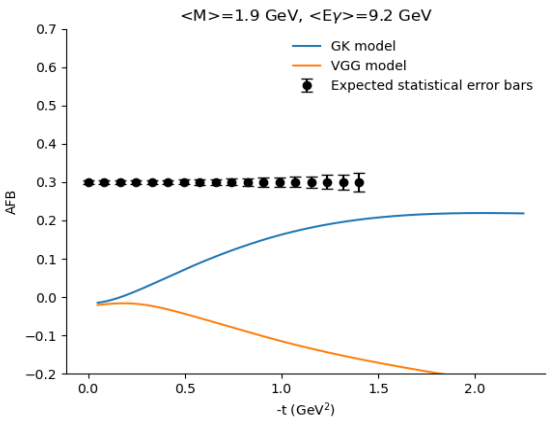




Forward-Backward asymmetry $A_{FB} = \frac{N_F - N_B}{N_F + N_B}$







Summary

- CLAS12 has broad physics program with dilepton final state
  - Two released analsyis (J/ψ and TCS) + J/ψ on LD2 is undergoing analysis review (R. Tyson)
  - More analysis ongoing
  - This talk was focused on Hydrogen target, however R. Tyson will overview nuclear and polarised targets as well. // First talk on Friday

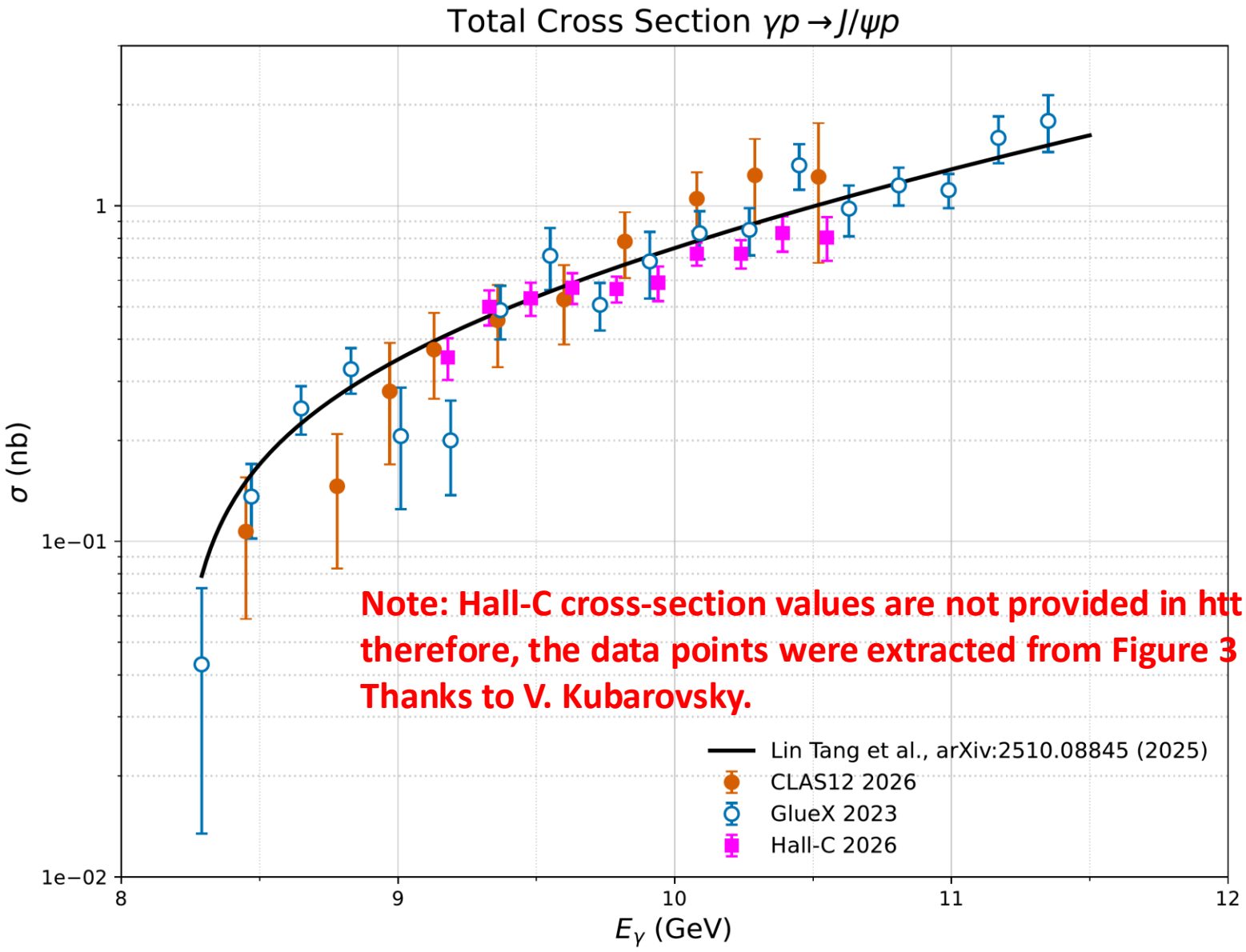
- CLAS12 recently released J/ψ total and differential cross-sections
  - In general good agreement observed with GlueX and J/ψ-007 results
  - CLAS12 don't see the cusp near the open charm thresholds observed by GLueX

- μCLAS12 detector will allow to run at x100 nominal CLAS12 luminosity
  - About x10 of JLab available statistics is expected
    - More clearity in the open charm contribution
    - Better fits in extracting GFFs
  - First time DDVCS measurement
  - High statistics TCS measurement

- New physics ideas with μCLAS12 are welcome!
  - Recent workshop on new physics μCLAS12 with https://indico.jlab.org/event/1018/

Backup

Hall-C, CLAS12 and GlueX



Note: Hall-C cross-section values are not provided in https://arxiv.org/pdf/2602.14416; therefore, the data points were extracted from Figure 3 as accurately as possible from the image. Thanks to V. Kubarovsky.

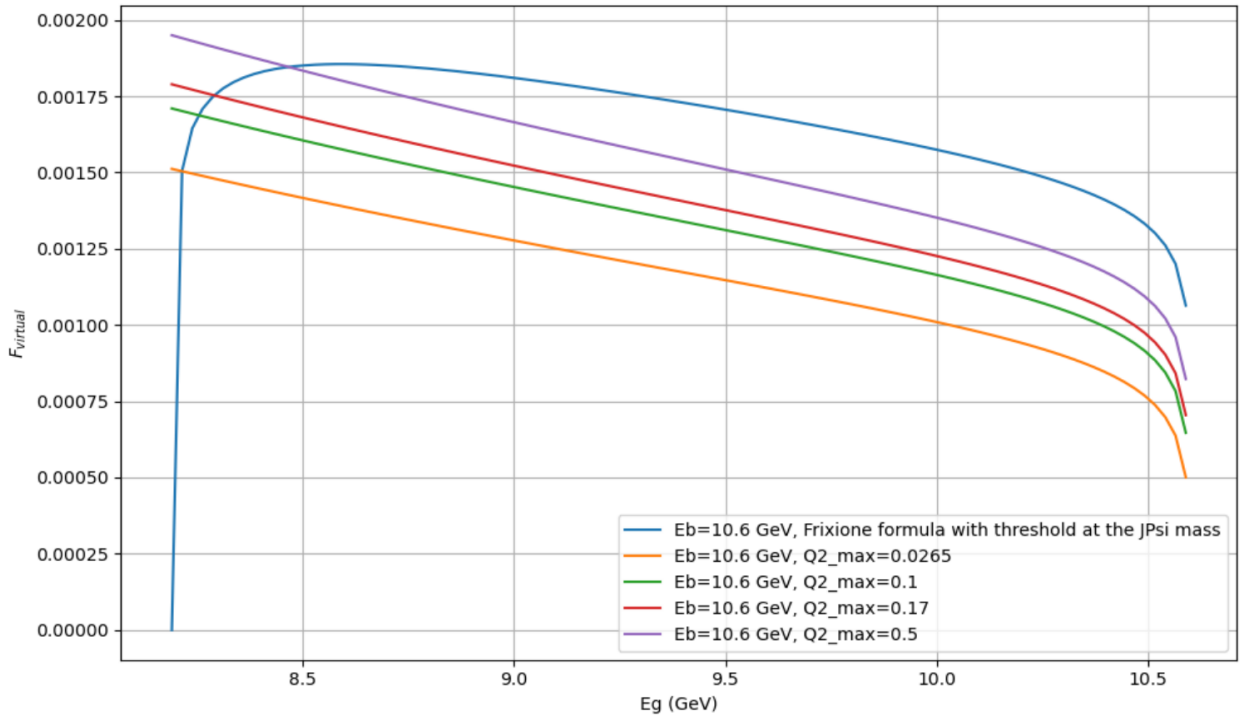
Photon Flux

$$\mathcal{F}(E_\gamma)|_{real} = \frac{1}{2}\frac{L}{X_0}\frac{1}{E_\gamma}\left(\frac{4}{3} - \frac{4}{3}\frac{E_\gamma}{E_{beam}} + \frac{E_\gamma^2}{E_{beam}^2}\right)$$

Real photon flux

$$\mathcal{F}(E_\gamma)|_{virtual} = \frac{1}{E_{beam}}\frac{\alpha}{\pi \cdot x}\left(\left(1 - x + \frac{x^2}{2}\right) \cdot \ln\left(\frac{Q^2_{max}}{Q^2_{min}}\right) - (1 - x)\right)$$

Virtual photon flux



GFF fits

$A_g(0)$ is fixed for all fits

GPD model		
Dataset	CLAS12	Combined
χ^2/ndf	1.29	1.37
$A_g(0)$	$[0.414 \pm 0.008]$	$[0.414 \pm 0.008]$
m_A [GeV]	2.12 ± 0.08	2.08 ± 0.06
$C_g(0)$	-1.36 ± 0.52	-1.32 ± 0.52
m_C [GeV]	(0.91 ± 0.10) 0.89 ± 0.11	0.88 ± 0.12

Holographic model		
Dataset	CLAS12	Combined
χ^2/ndf	0.62	1.05
$A_g(0)$	$[0.414 \pm 0.008]$	$[0.414 \pm 0.008]$
m_A [GeV]	1.64 ± 0.05	1.70 ± 0.032
$C_g(0)$	-0.38 ± 0.11	-0.38 ± 0.03
m_C [GeV]	(1.12 ± 0.21) 1.12 ± 0.15	1.38 ± 0.09

$$\langle r_m^2 \rangle_g = 6 \frac{1}{A_g(0)} \frac{dA_g(t)}{dt}\bigg|_{t=0} - 6 \frac{1}{A_g(0)} \frac{C_g(0)}{m_p^2} = \frac{18}{m_A^2} - 6 \frac{1}{A_g(0)} \frac{C_g(0)}{m_p^2},$$

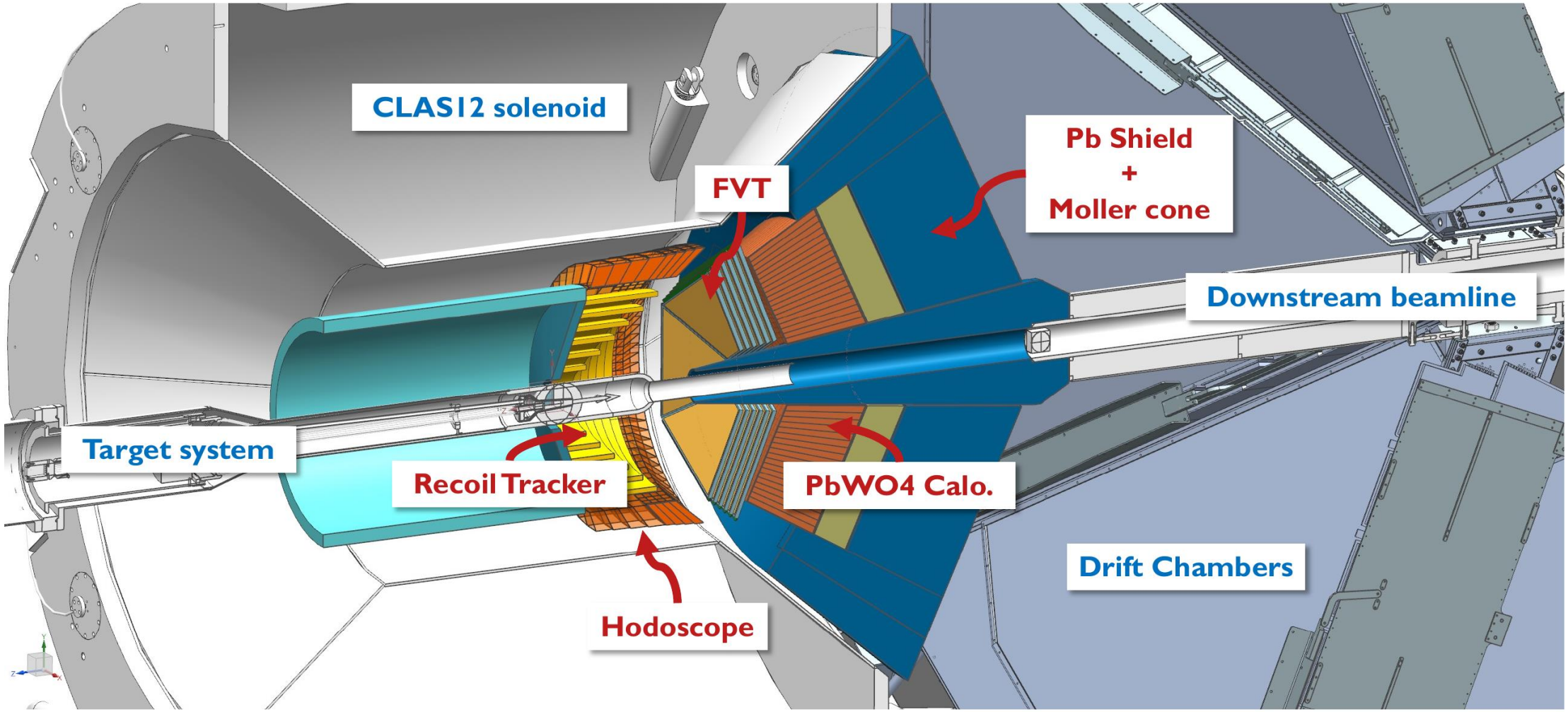
$$\langle r_s^2 \rangle_g = 6 \frac{1}{A_g(0)} \frac{dA_g(t)}{dt}\bigg|_{t=0} - 18 \frac{1}{A_g(0)} \frac{C_g(0)}{m_p^2} = \frac{18}{m_A^2} - 18 \frac{1}{A_g(0)} \frac{C_g(0)}{m_p^2},$$

Systematic uncertainties

Average Bin-by-bin Systematics	[%]
Photon virtuality	6.53
Missing mass squared	2.16
Fit function	13.36
Lepton identification	4.54
Lepton momentum	0.39
Proton identification	4.88
Spin Density Matrix Elements	8.66
Radiative corrections	5.40

Scale Systematics	[%]
Virtual photon flux calculation	4.00
Efficiency-correction factor	10.39
Accumulated charge	1.20

The μCLAS12



Systematic uncertainties for J/ψ with μCLAS12

- FCup charge < 1.5 %
- Rad. Effects < 10%
- Modeling the detector efficiency ~ 10.4%