Exclusive lepton pair production at JLab Hall B with CLAS12

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Towards improved hadron femtography with hard exclusive reactions: July 18-22, 2022
Virginia Tech, Blacksburg, VA

The outline

- Timelike Compton Scattering
  - Partially completed experiments
- J/psi photoproduction near threshold
  - Partially completed experiments

E12-12-001
E12-12-001A
E12-11-003B

- Luminosity upgrade: Double Deeply Virtual Compton Scattering
  - LOI12-16-004
  - Go with full proposal next PAC

- New opportunities, if there will be an energy upgrade of the CEBAF machine

Timelike Compton Scattering

Experimentally and theoretically the most studied reaction to access GPDs is DVCS.

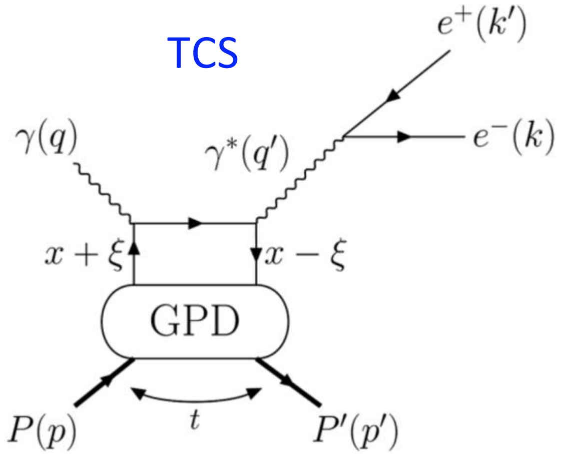
Since early of 2000s, experimental observables are reported: X-sec, Beam and Target spin asymmetries...

However only DVCS is not enough for understanding GPDs. Different reaction(s) are needed in order to assess universalities of GPDs,

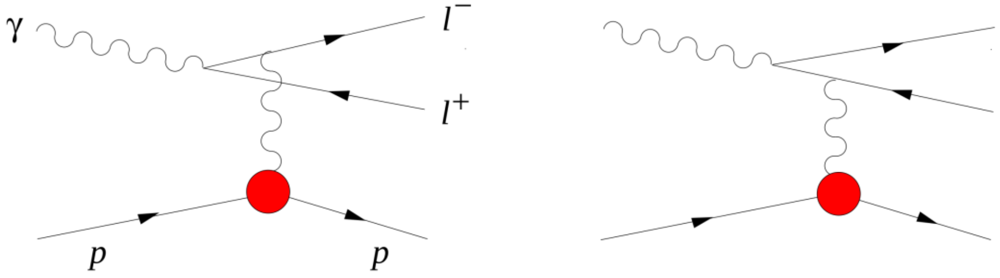
Some CFFs not so easily accessible in DVCS, are easier to access in TCS, e.g. Re part of CFF (H).

Timelike Compton Scattering is an inverse to DVCS process and allows to access GPDs as well.

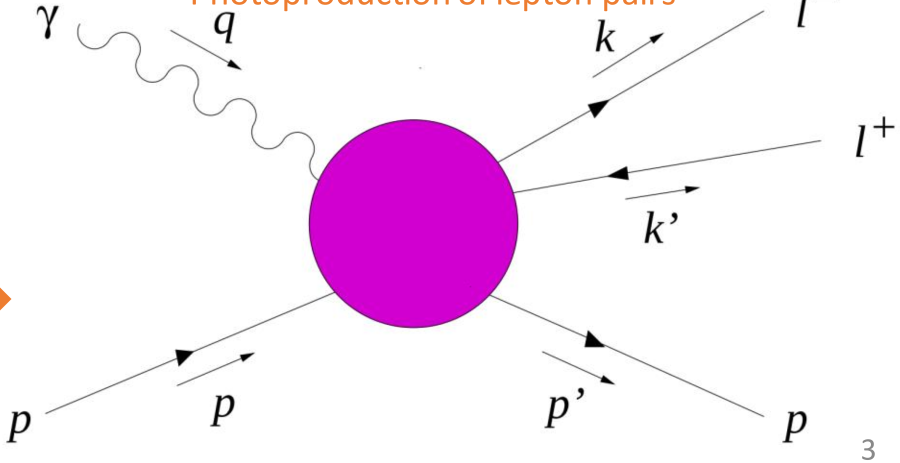
TCS



BH



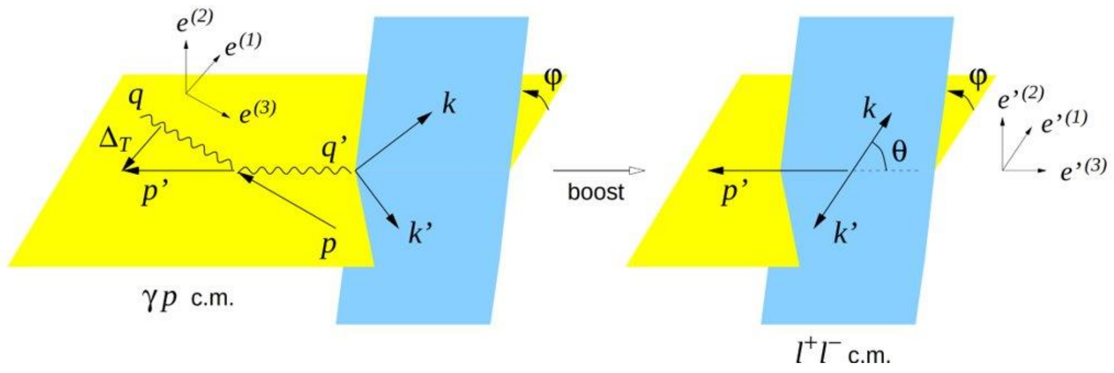
Photoproduction of lepton pairs



TCS scattering amplitude

$$\sigma(\gamma p \to p' e^+ e^-) = \sigma_{\mathrm{BH}} + \sigma_{\mathrm{TCS}} + \sigma_{\mathrm{INT}}$$

At JLab kinematics TCS cross-section is about 2 orders smaller than the BH, but instead the interference term is comparable.



$$\frac{d^4\sigma_{\mathrm{INT}}}{dQ'^2\,dt\,d\Omega} = A\,\frac{1+\cos^2\theta}{\sin\theta} \times \left[\cos\phi\,\mathrm{Re}\tilde{M}^{--} - \nu\sin\phi\,\mathrm{Im}\,\tilde{M}^{--}\right]$$

$$\tilde{M}^{--} = \left[F_1\mathcal{H} - \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4m_p^2}F_2\mathcal{E}\right]$$

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

Projects out the cosine moment of the Interference x-sec, and hence access the Real part of the scattering amplitude.

Polarization asymmetry $$\mathrm{A}_{\odot\mathrm{U}} = \frac{\sigma_{\mathrm{LH}} - \sigma_{\mathrm{RH}}}{\sigma_{\mathrm{LH}} + \sigma_{\mathrm{RH}}}$$

Proportional to the sine moment of the polarized Interference x-sec, and hence access the imaginary part of the scattering amplitude.

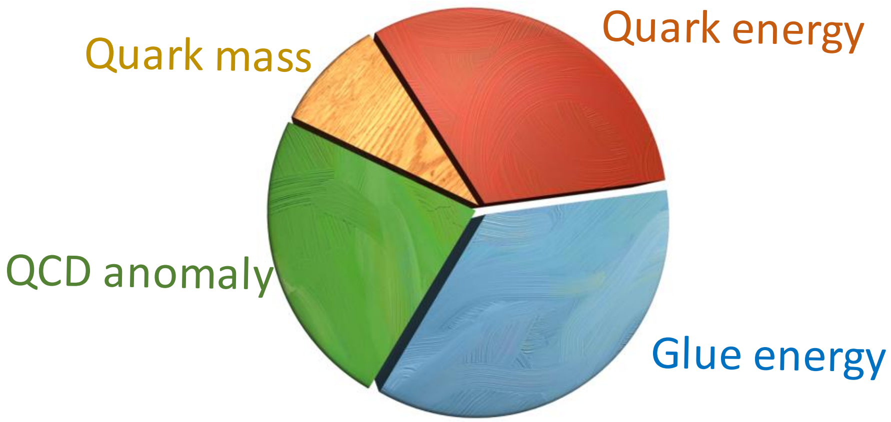
J/ψ production near the threshold

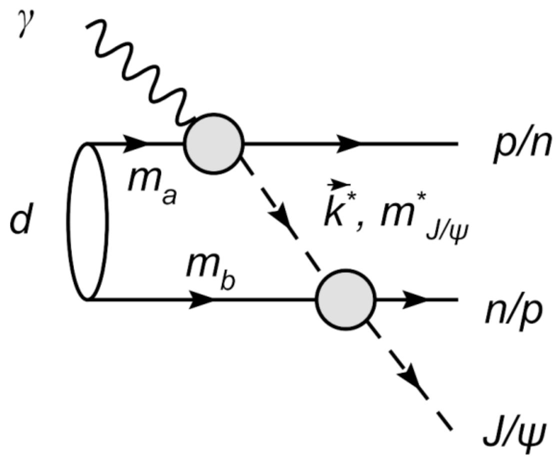
- Cross-section measurement near the threshold gives important insight of the production mechanism

- Access to the gluonic form factor of the nucleon

- Trace anomaly. Decomposition of the proton mass

- Production on Deuterium target
  - Access gluonic structure of the deuterium by measuring coherent J/ψ production at high –t
  - Allows direct access to the J/ψN by final state interactions.



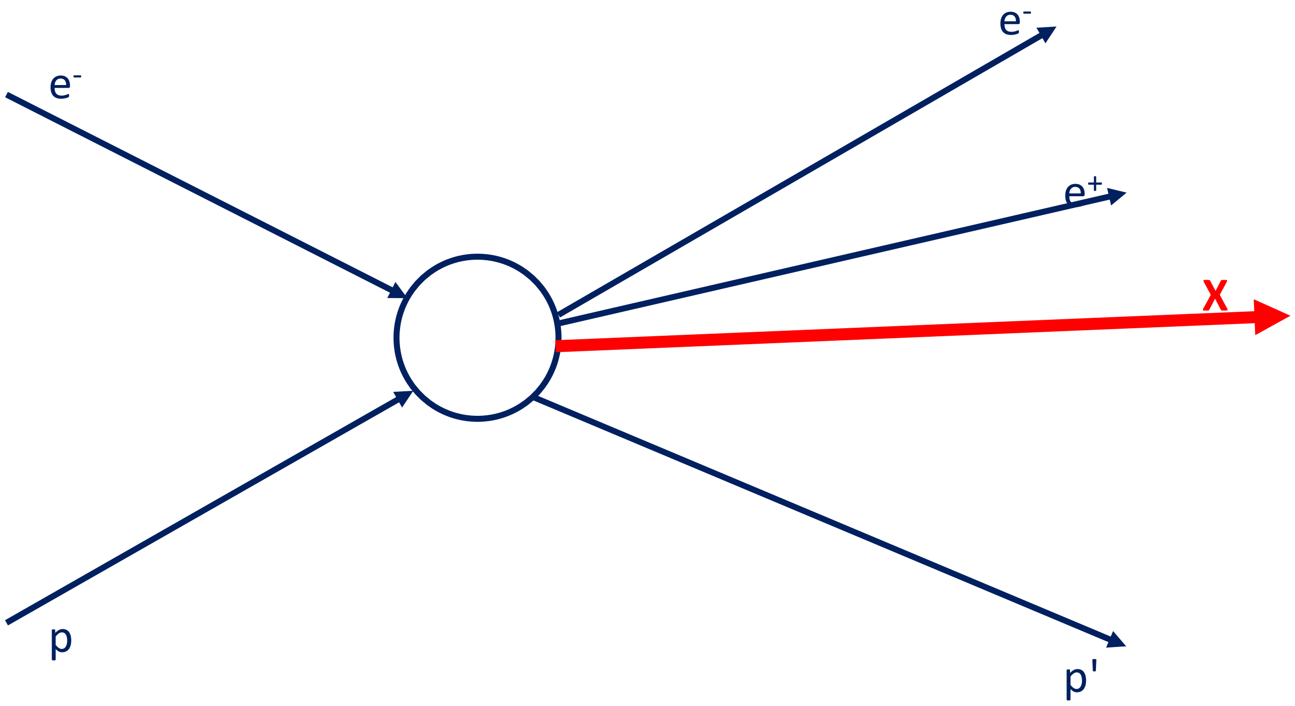


The reaction of interest

Both TCS and J/ψ have the same final state: e^-e^+p

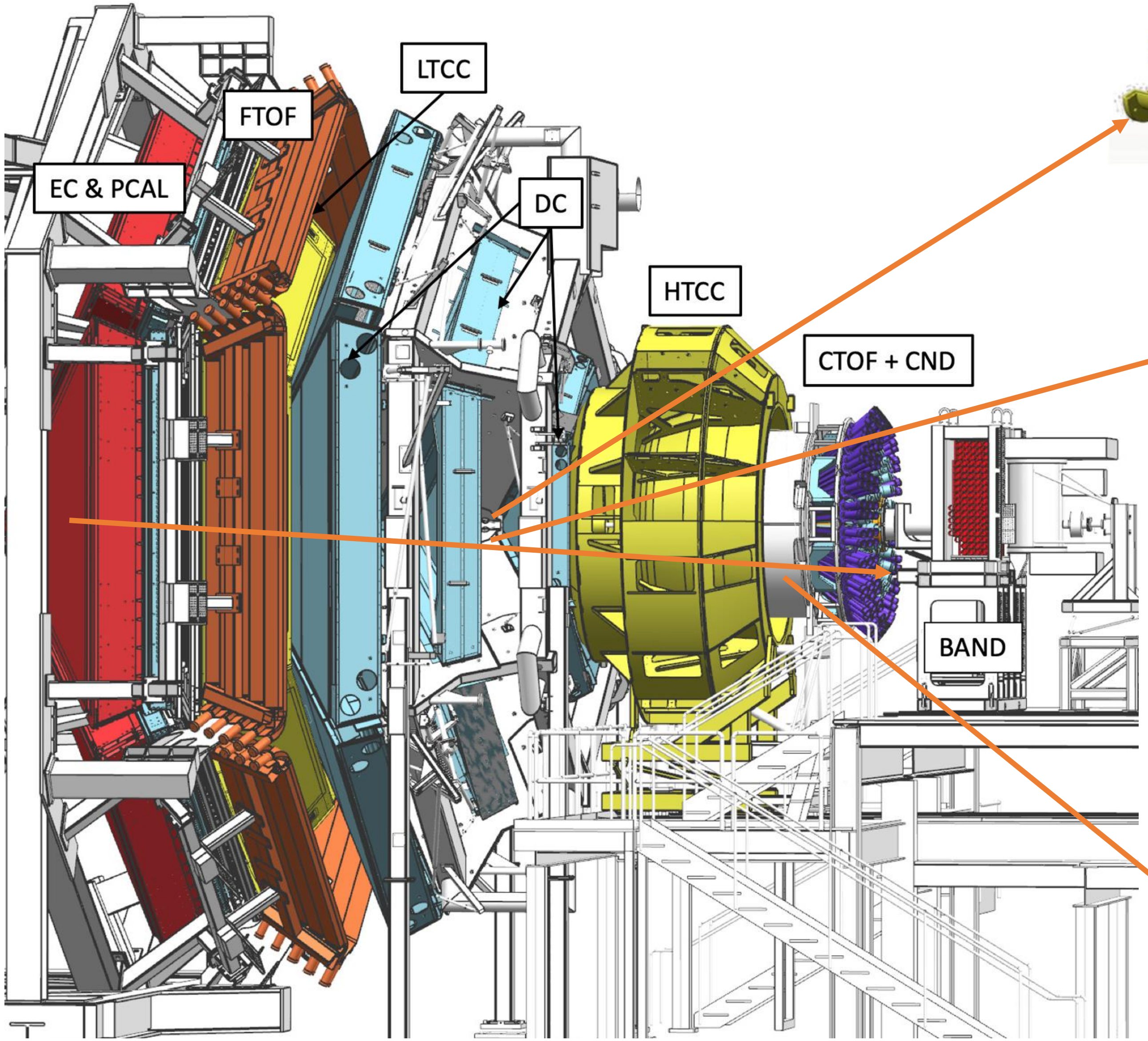
When the beam electron scatters ~0 angle, the exchanged photon is very soft Q^2~0. The production is also known as quasi-real photoproduction.

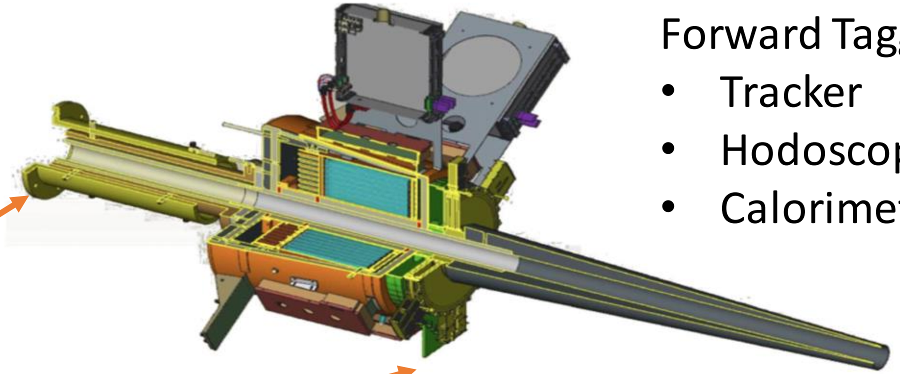
The scattered electron (and consequently the photon energy) is deduced from the missing 4 momentum analysis.



Events with $1e^-$ $1e^+$ and 1 proton are selected for the analysis

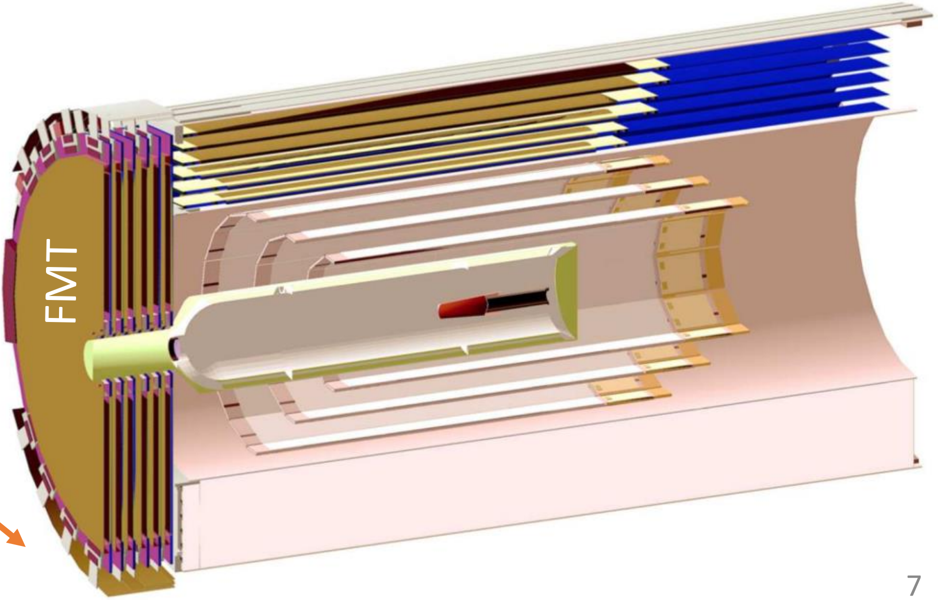
The CLAS12 Detector



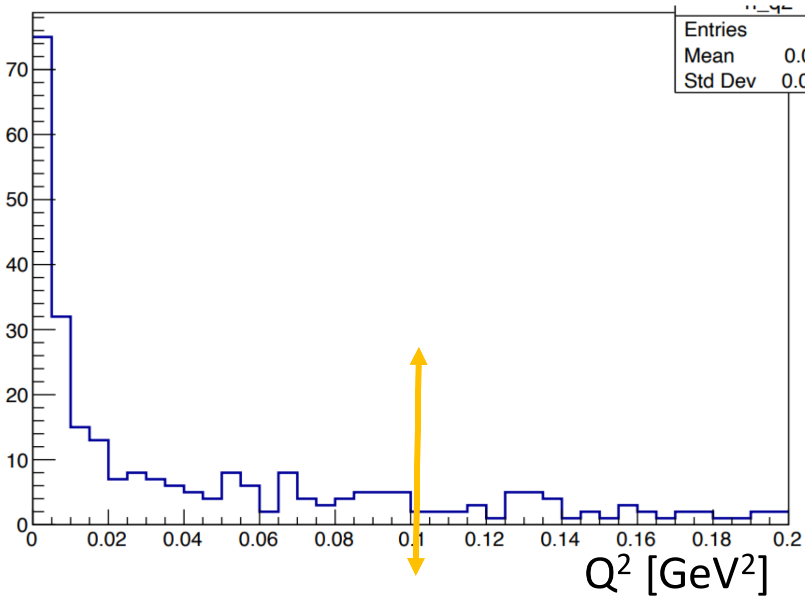


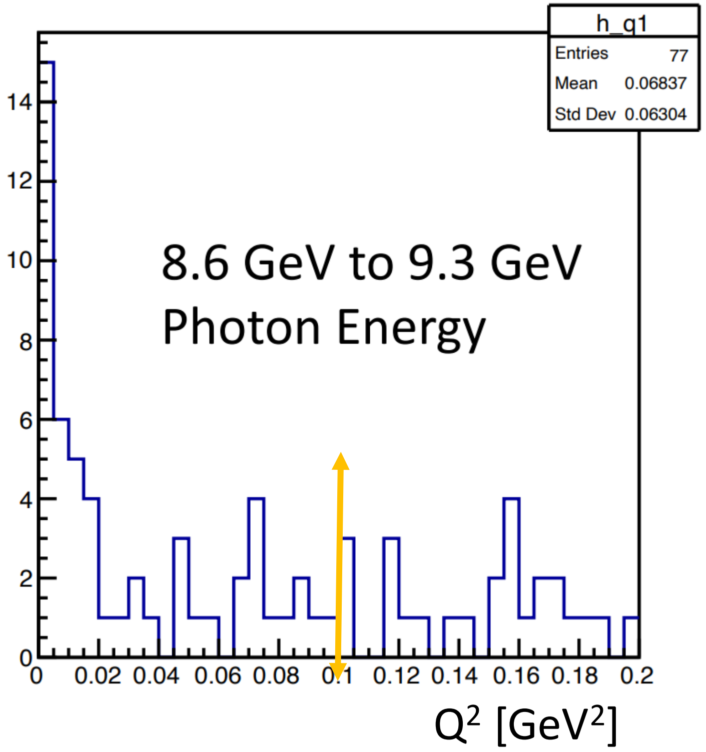
Forward Tagger
- Tracker
- Hodoscope
- Calorimeter

Central Vertex Tracker

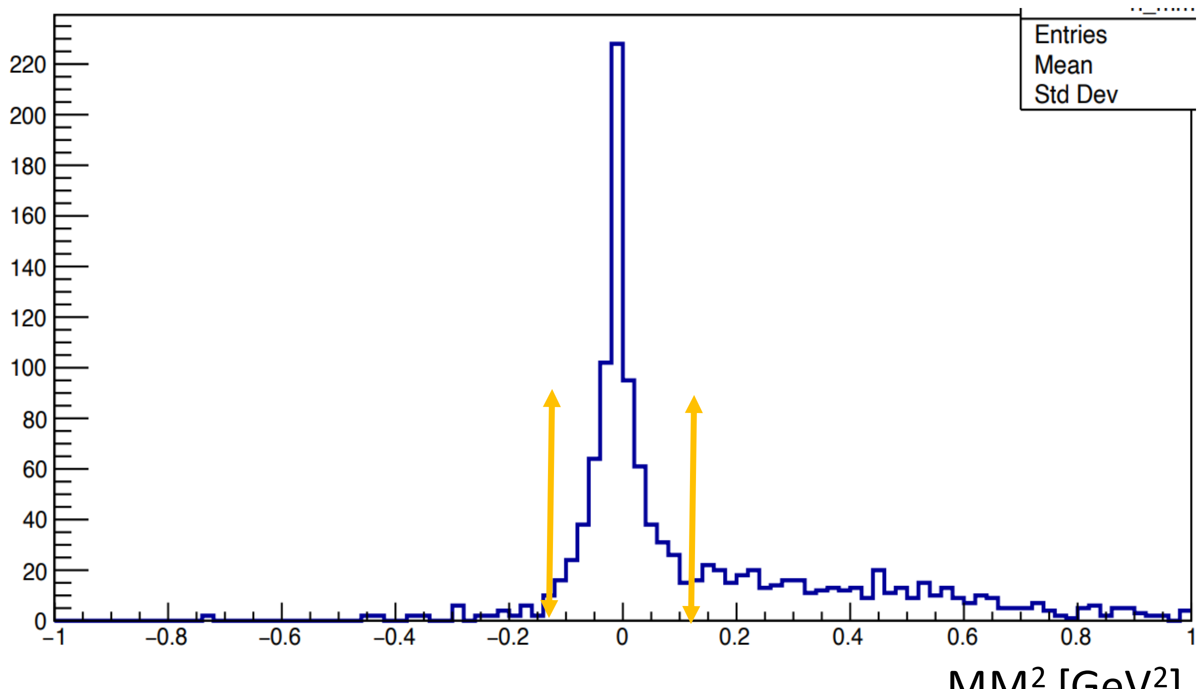


Exclusivity cuts





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



Quasi-real photoproduction events are identified as events with $Q^2 \sim 0$ AND $MM^2 \sim 0$

Photoproduction with electron beam

Electroproduction cross-section can be expressed as:

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

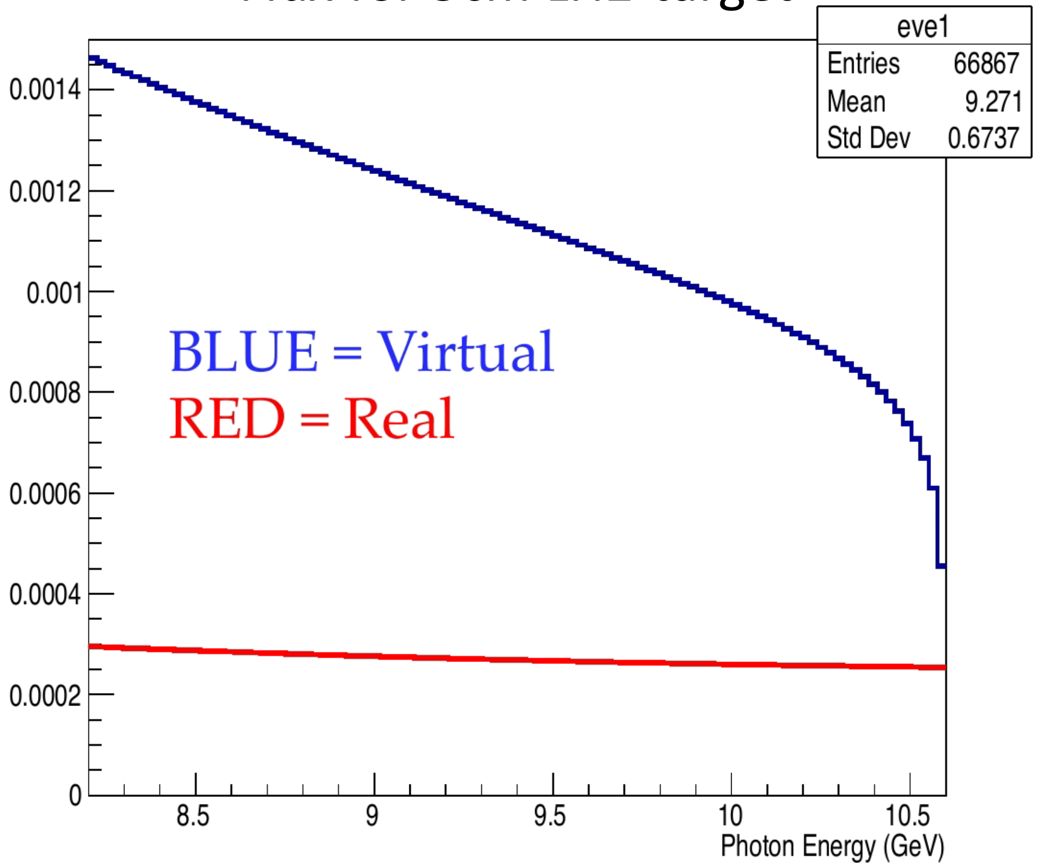
Real photon flux

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



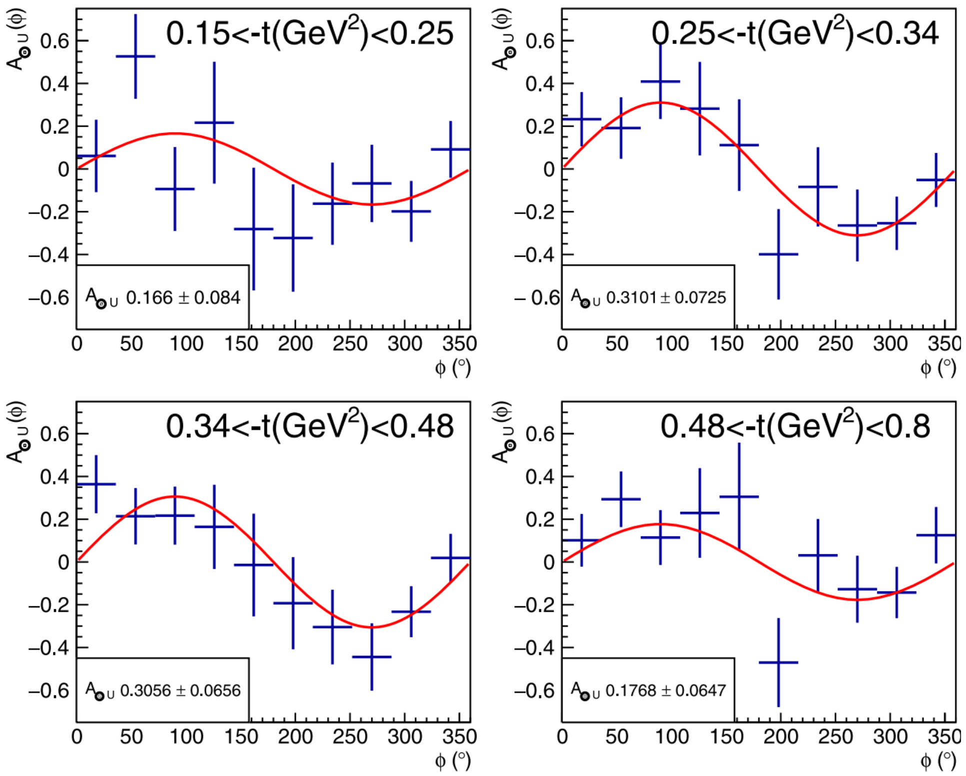
$$n(E_\gamma) = \frac{l}{2 \cdot X_0} \frac{1}{E_\gamma} \cdot \left(\frac{4}{3} - \frac{4}{3}\frac{E_\gamma}{E_b} + \frac{E_\gamma^2}{E_b^2}\right) dE$$

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

The 1st TCS measurement

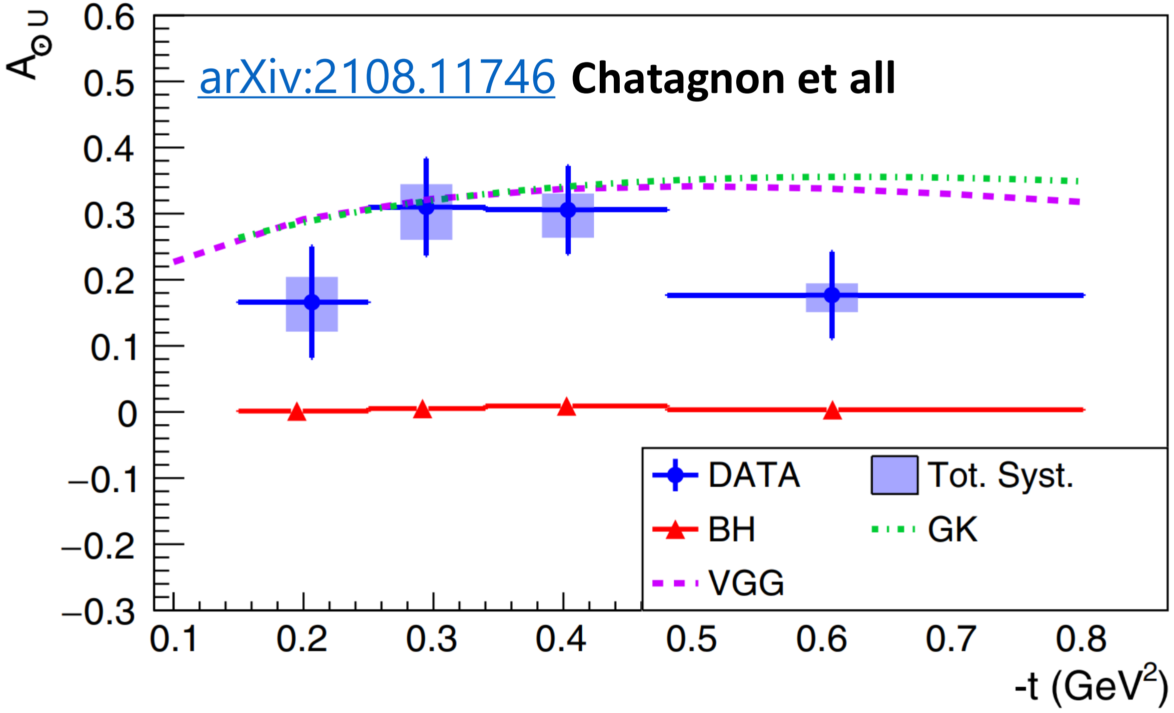
$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

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:

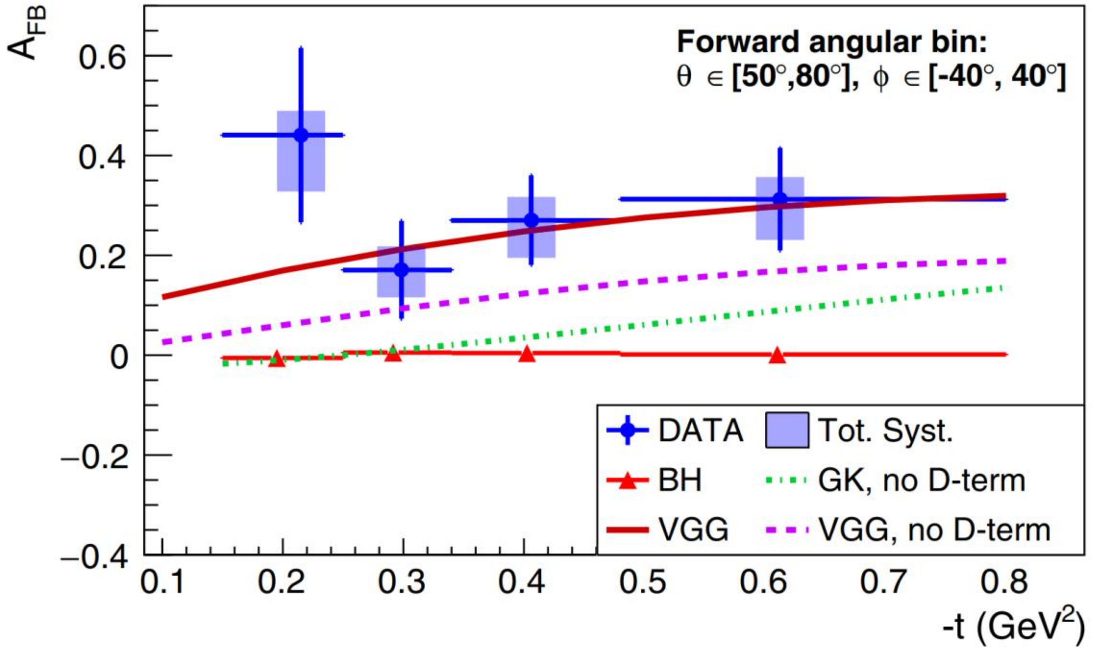
$$L = k\left[(E_1+E_2)(3+2\Gamma) - 2E_2(1+4u^2\xi^2\Gamma)\right]/I_0$$
$$I_0 = (E_1^2+E_2^2)(3+2\Gamma) - 2E_1E_2(1+4u^2\xi^2\Gamma)$$

The BH contribution is consistent with 0, as it is expected to be.

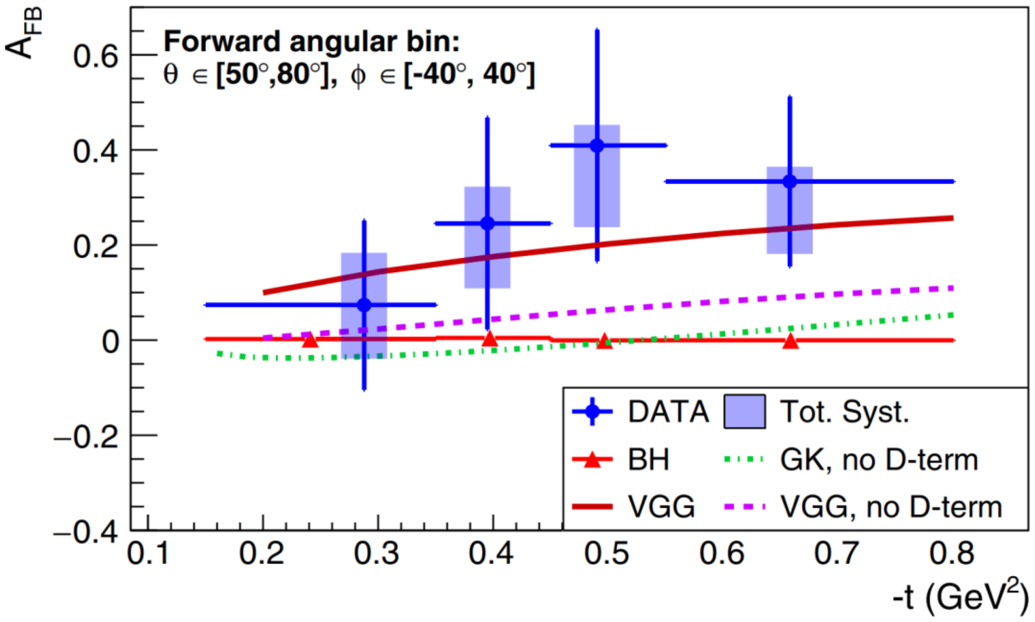
The 1st TCS measurement

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

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

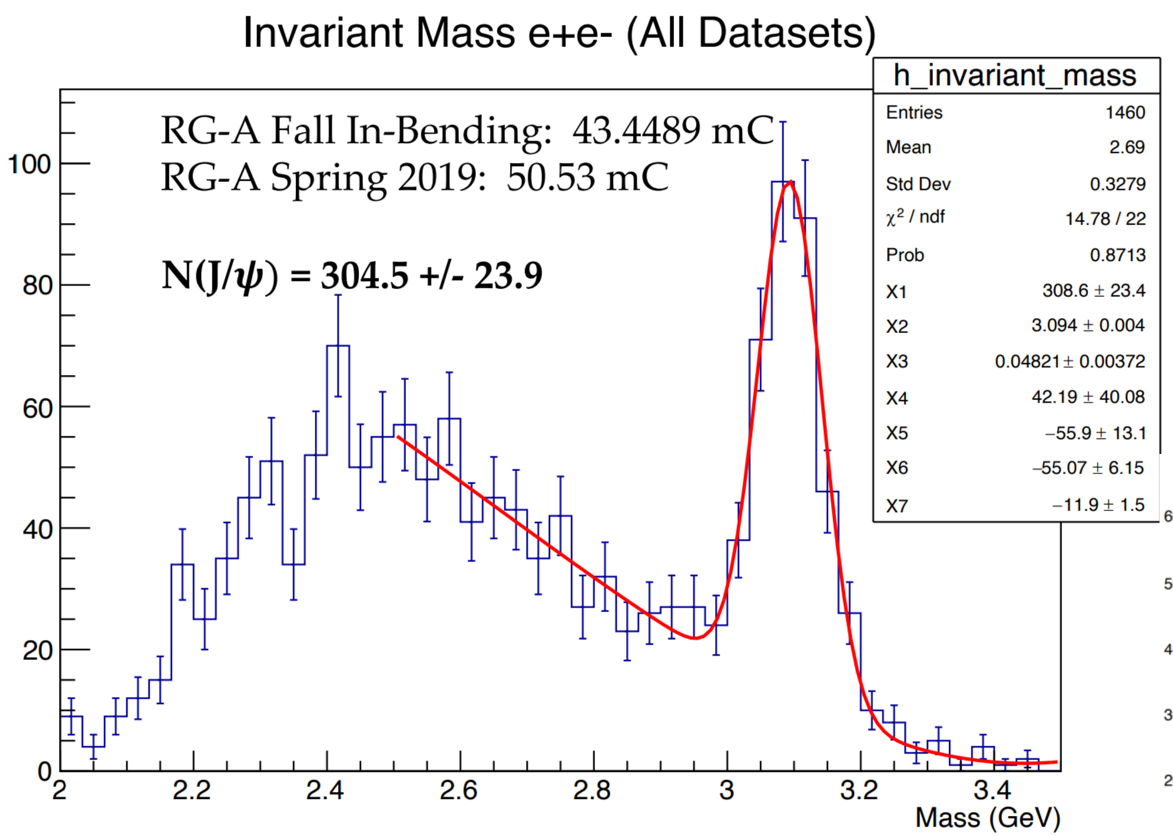


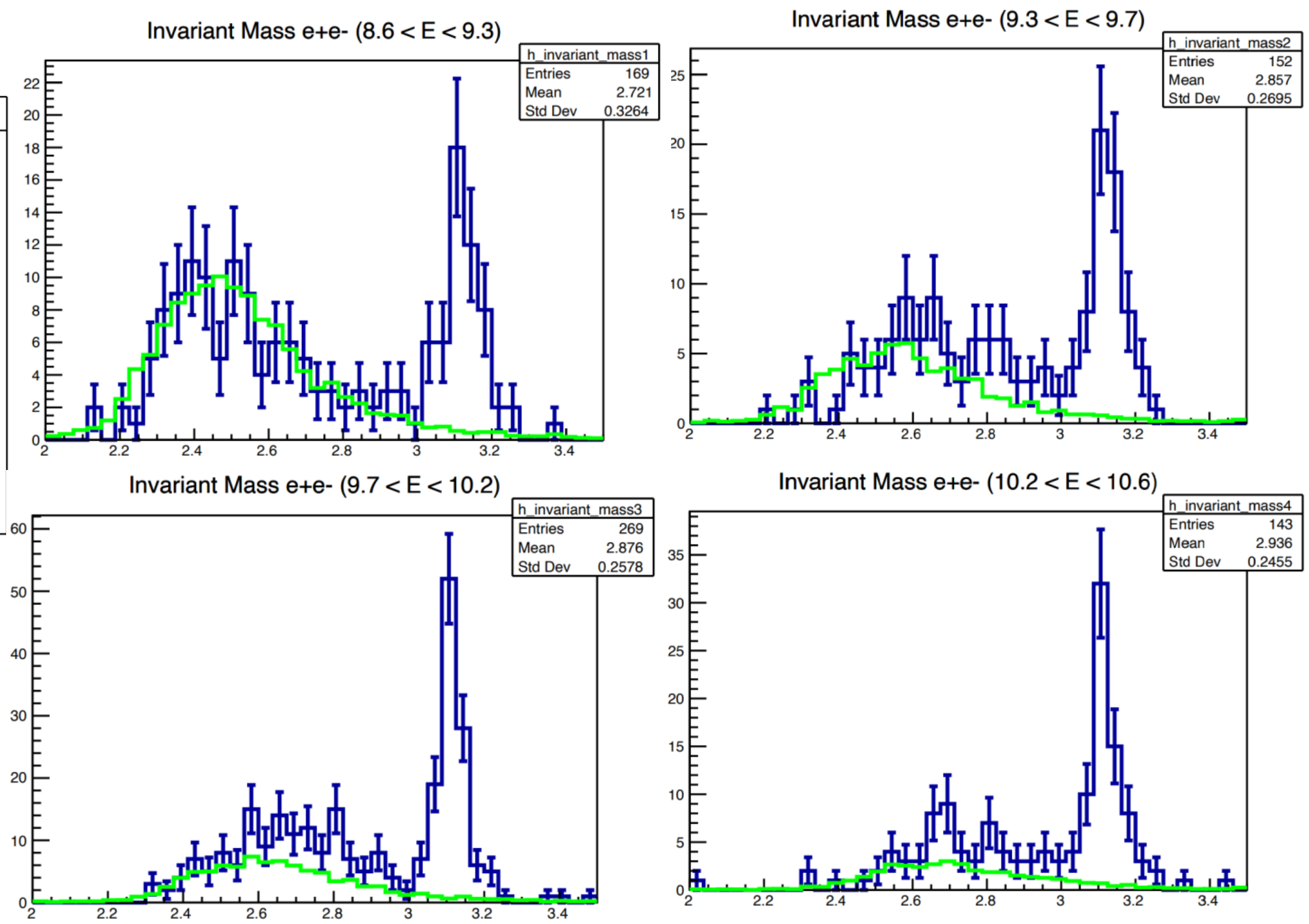
$$E_\gamma = 8.13 \pm 1.23 \text{ GeV}$$
$$M = 2.25 \pm 0.20 \text{ GeV}$$



arXiv:2108.11746 **Chatagnon et all**

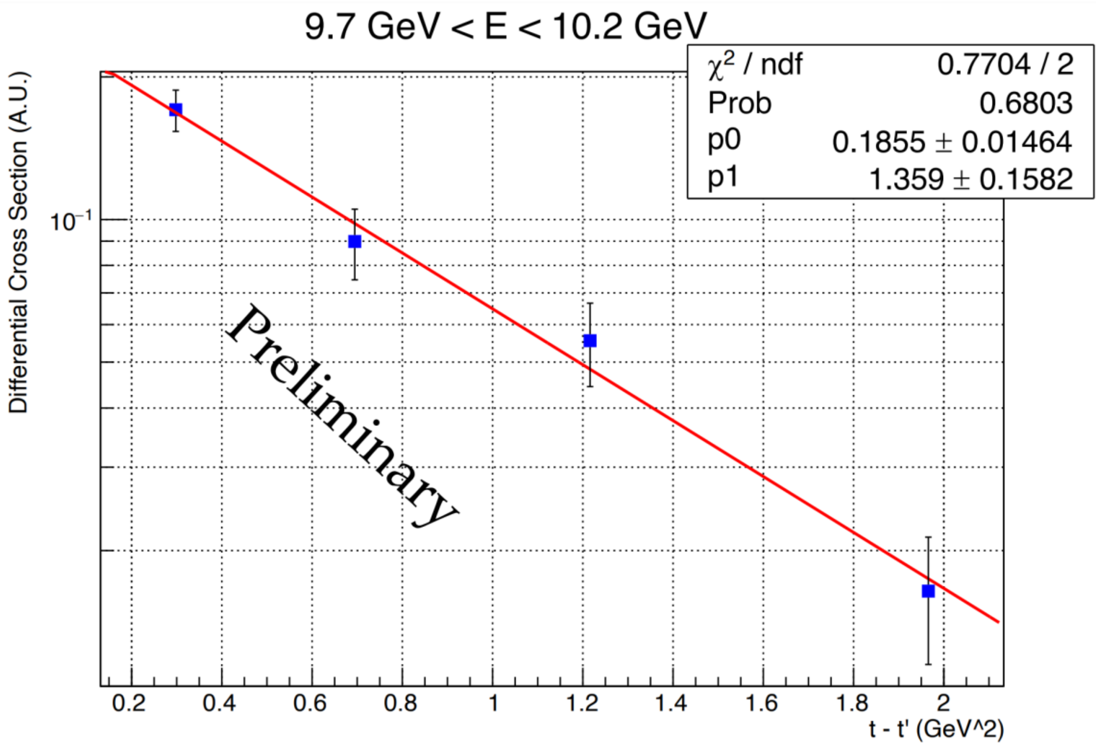
J/ψ photoproduction

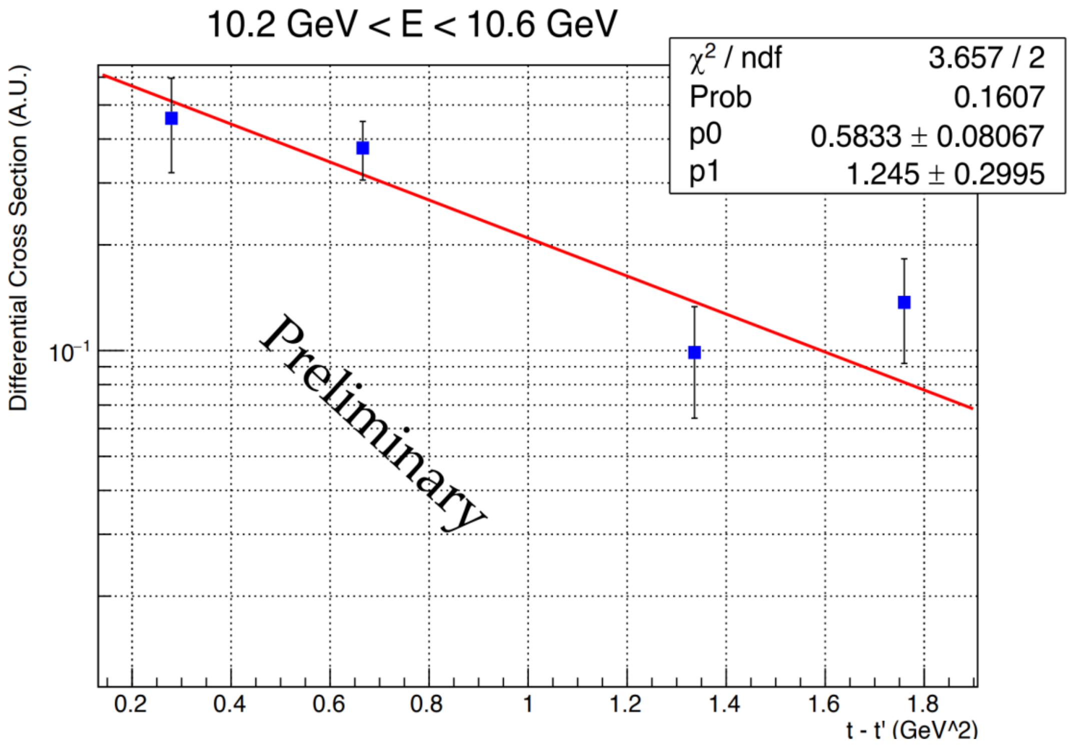




Preliminary differential cross-sections

The –t slope is measured in two energy bins

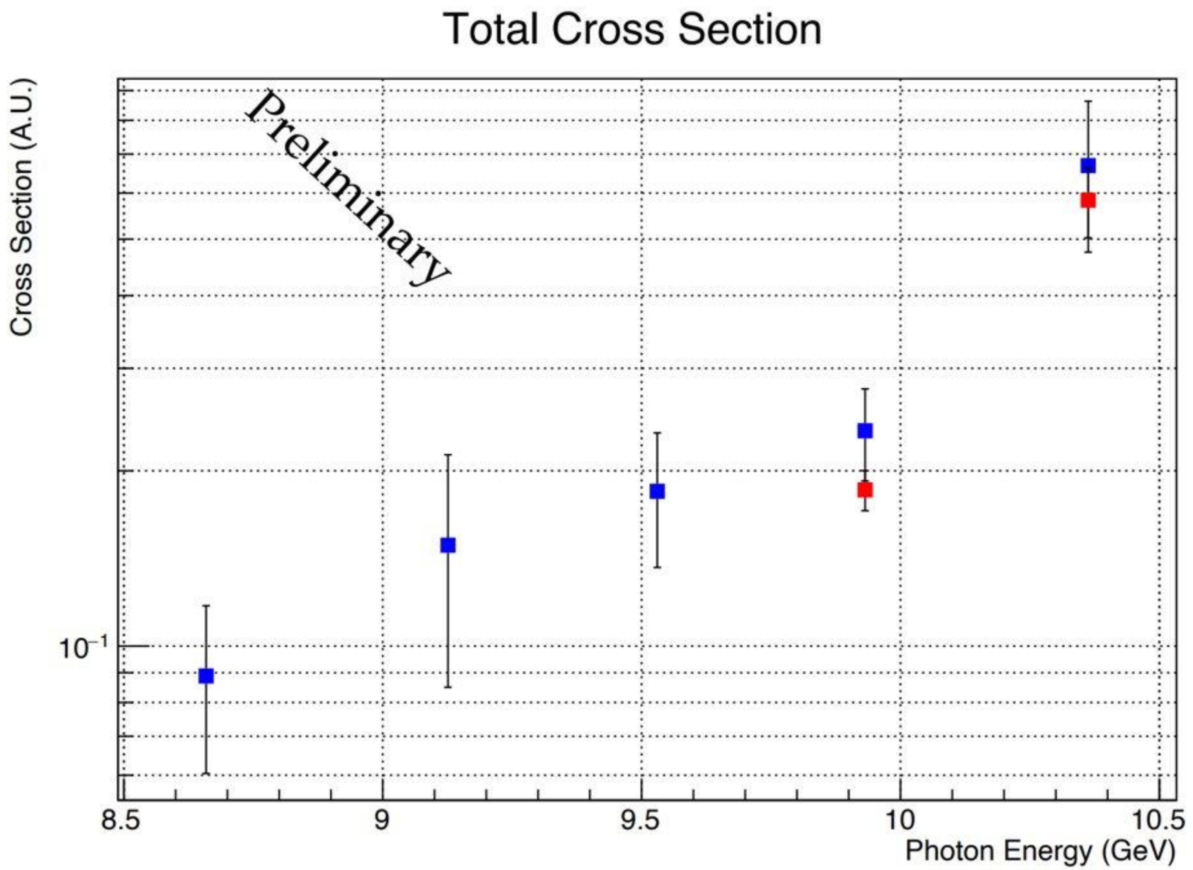




Measuring the –t slope, the total cross-section can be deduced

$$\int_{-\infty}^{0} \frac{d\sigma}{dt'} dt' = \int_{-(t_{min}-t_{max})}^{0} \sigma_0 \cdot b \cdot e^{b \cdot t'} dt \simeq \sigma_0(E_\gamma)$$

Preliminary total cross-sections



$$\sigma_0(E_\gamma) = \frac{N_{J/\psi}}{\mathcal{N}_\gamma \cdot n_T \cdot \omega_c \cdot Br \cdot \epsilon(E_\gamma)}$$

Blue points represent the cross-section measured by counting all J/psi events in the given energy bin.

Red points represent cross-sections deduced from the measurement of the –t slope.

Analysis is very close to be finalized.

Ongoing analyses

TCS is only measured using small fraction of data.
We should extend these measurements with higher statistics.

- RG-A:
  - J/ψ Cross-section as a function of Eγ
  - J/ψ -t slope in two Eg bins
  - Tagged J/ψ

Analysis is being finalized by Joseph Newton (JLab)

Mariana Tenorio Pita (ODU)

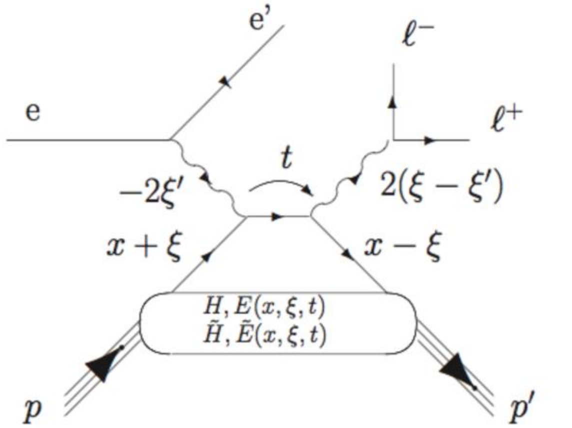
- RG-B
  - Production on Proton
  - Production on Neutron

analysis is quite advanced, Richard Tyson (Glasgow)

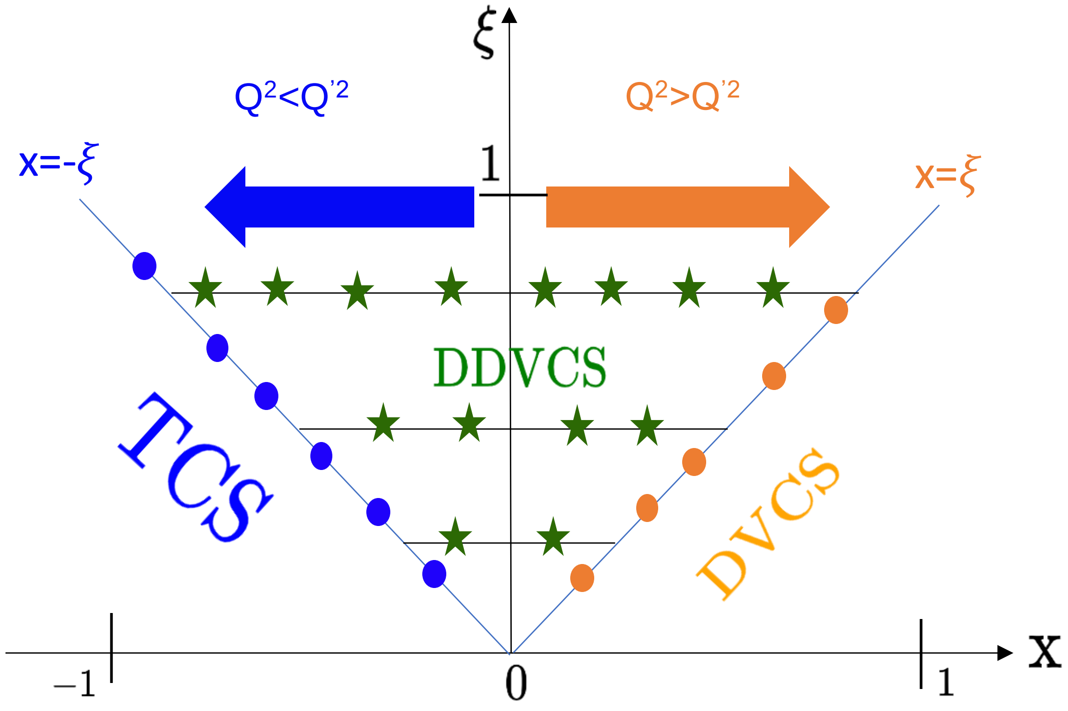
- RG-C (Ongoing run, till March 2023)
  - Double spin asymmetries in TCS

Kayleigh Gates (Glasgow): Just started

Double DVCS



Kinematics of two photons are described by ξ and ξ'.



$$\xi' = \frac{x_B}{2 - x_B}$$

$$\xi = \xi' \frac{Q^2}{Q^2 + Q'^2}$$

Quark propagators between two photons now reads as:

$$\frac{1}{x - (2\xi' - \xi) + i\epsilon} + \frac{1}{x + (2\xi' - \xi) - i\epsilon}$$

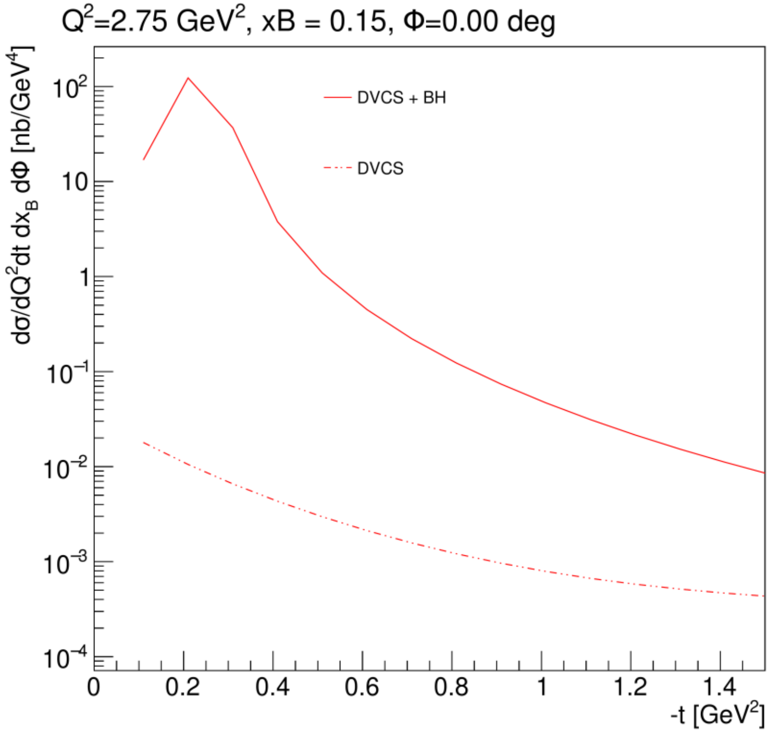
Observables (e.g. BSA) proportional to the Im part of the amplitude, allow direct measurement of GPDs at ($x=2\xi' - \xi$, ξ, t) points.

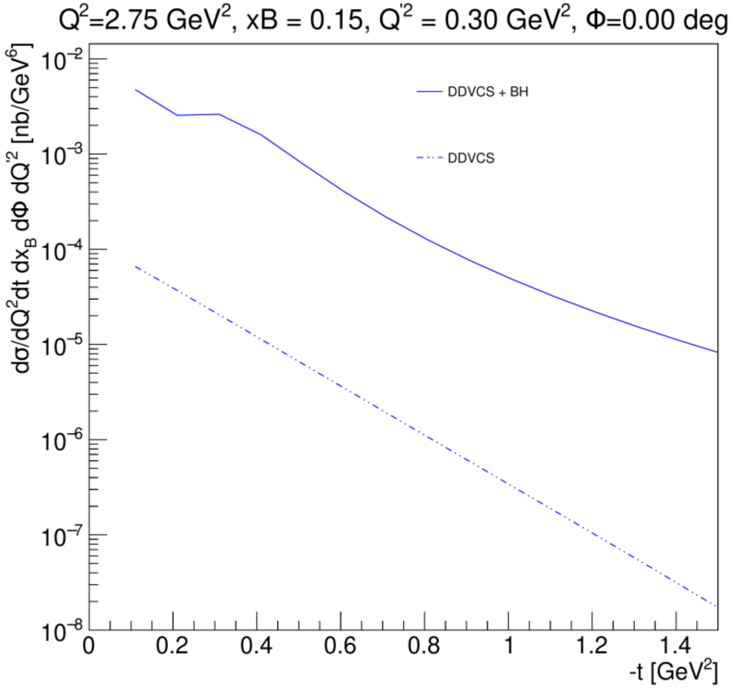
Here one can get away from the $x=\xi$ line by varying virtualities of incoming and outgoing photons

Cross-sections

The downside of the DDVCS is it involves an additional α_e which makes the DDVCS cross-section 2-3 orders of magnitude smaller than the DVCS cross-section.

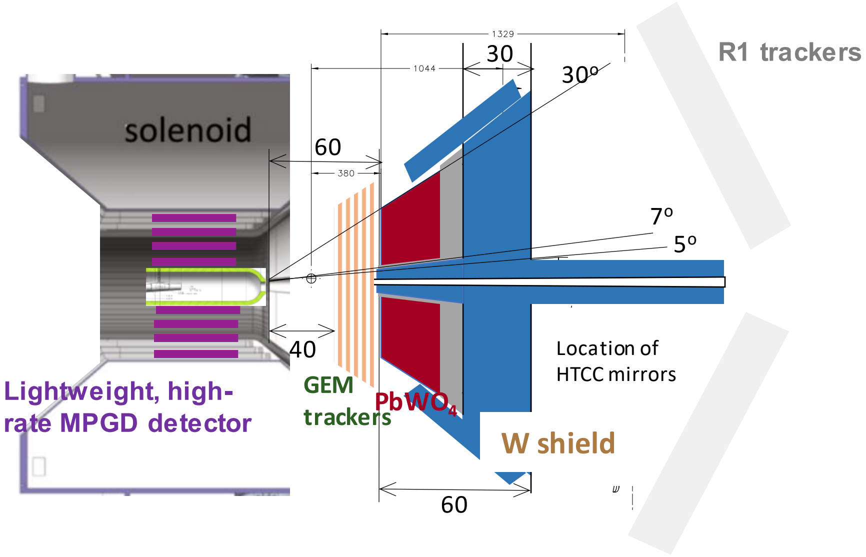
With standard CLAS12 detector package it is unrealistic to get sufficient statistics in a reasonable data taking time



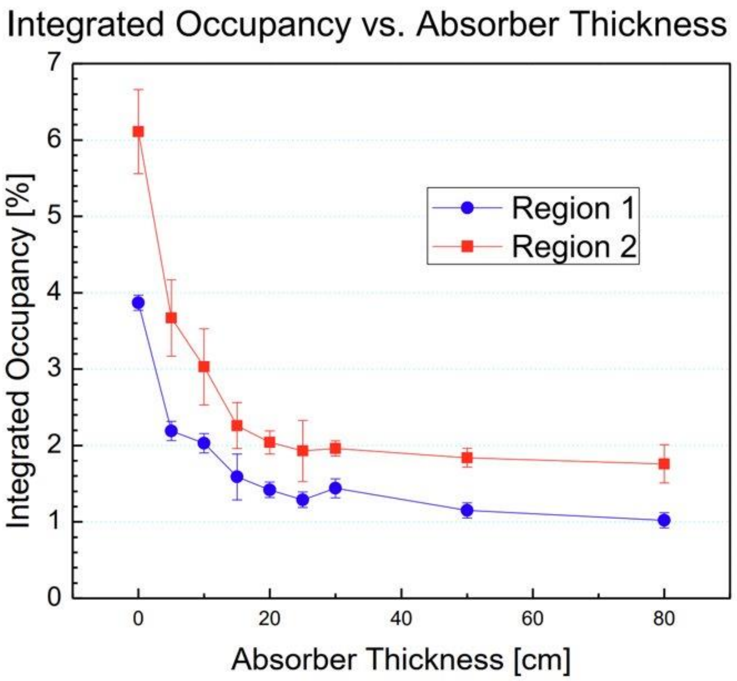


Based on these arguments, on 2016 we have submitted a LOI "LOI-12-16-004" to upgrade the CLAS12 detector which will allow to take luminosities of the of the order of 10^{37} $cm^{-2}s^{-1}$.

Detector configuration for ep->e'$\mu^-\mu^+$



- Detector should handle luminosities **10^{37} $cm^{-2}s^{-1}$.**
  - Main limiting factor is occupancies in the Drift chamber
- Should be able to **detect muons**
  - With muons ambiguity between detection of scattered and decay electrons will be resolved



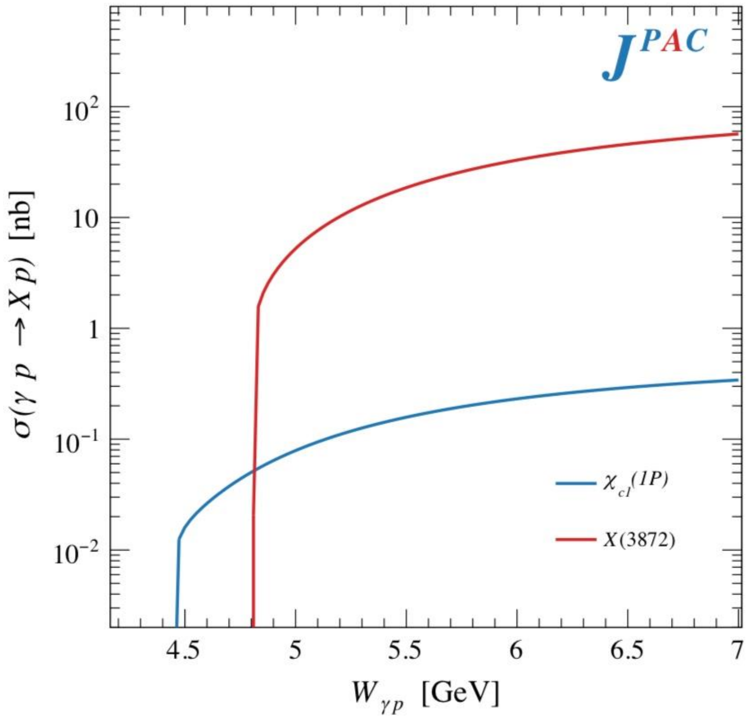
- Remove HTCC
- Install a Moeller cone (tungsten material) extending up to 7.5 deg polar angel
  - In order to reduce huge rate of Moeller electrons
- Add a new $PbWO_4$ calorimeter that covers 7° to 30° polar angular range with 2π azimuthal coverage
  - In order to recover electron detection
- Next to the $PbWO_4$ calorimeter add thick tungsten shield/absorber covering the full FD region
  - In order to absorb all electromagnetic and hadronic background originating from the target.
- Install a new GEM based detector in front of the calorimeter
  - In order to be able to reconstruct vertex parameters (angles and positions)

XYZ spectroscopy: $\chi_{c1}(3872)$

Slide from S. Stepanyan

In case there will be an energy upgrade for CEBAF machine...

- Several states in charmonium region have been discovered that do not fit into a simple $q\bar{q}$ model.
- JLAB energy upgrade (20+ GeV) will open a phase space for photoproduction of some of these states.
- Lowest mass state and the best-known exotic is $\chi_{c1}(3872)$, also known as X(3872), first discovered by Belle in 2003. The quantum numbers have been determined by LHCb, $J^{PC} = 1^{++}$(Phys. Rev. Lett. 110, 222001 (2013), arXiv:1302.6269)
- Photoproduction cross section for $\chi_{c1}(3872)$ has been estimated by [JPAC] M. Albaladejo et al., arXiv:2008.01001, doi:10.1103/PhysRevD.102.114010
- Energy and the t dependence should be studied, which provide important insight to the production mechanism



$\chi_{c1}(3872)$ decay modes:

- $\chi_{c1} \to \omega\, J/\psi$ B.R. ≈ 4.3%
  - $\omega \to \gamma\pi^0$ BR=8.28%
  - $J/\psi \to \mu^+\mu^-$ BR=6%
    - $\chi c1 \to \gamma\gamma\gamma\mu^+\mu^-$ > 2*10^{-4}

- $\chi_{c1} \to \gamma\, \psi(2S)$ > 4%
  - $\psi(2S) \to \mu^+\mu^-$ BR=0.8%
    - $\chi_{c1} \to \gamma\mu + \mu -$ ≥ 2.3*10^{-4}

μCLAS12 at 10^{37} cm^{-2} sec^{-1}

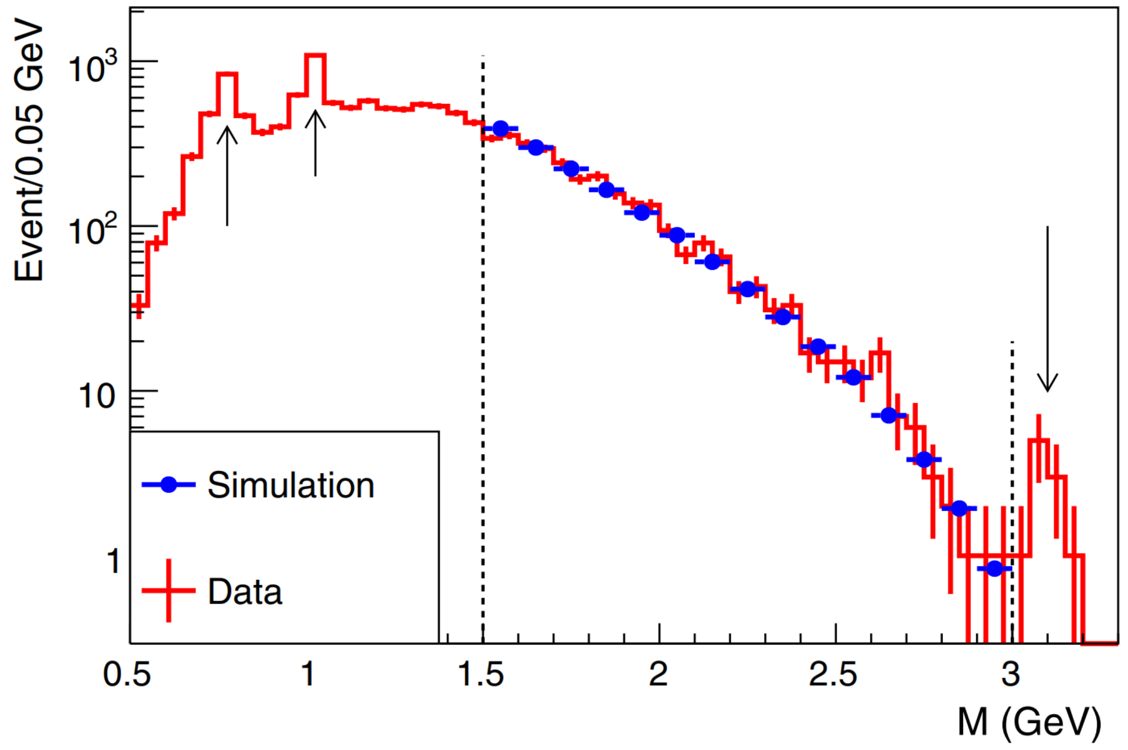
Photon luminosity in the energy range: 13 GeV to 22 GeV is 100 nb^{-1}, even with modest efficiency of 2% one expects about **50 detected χ_{c1}(3872) per hour** in each decay mode

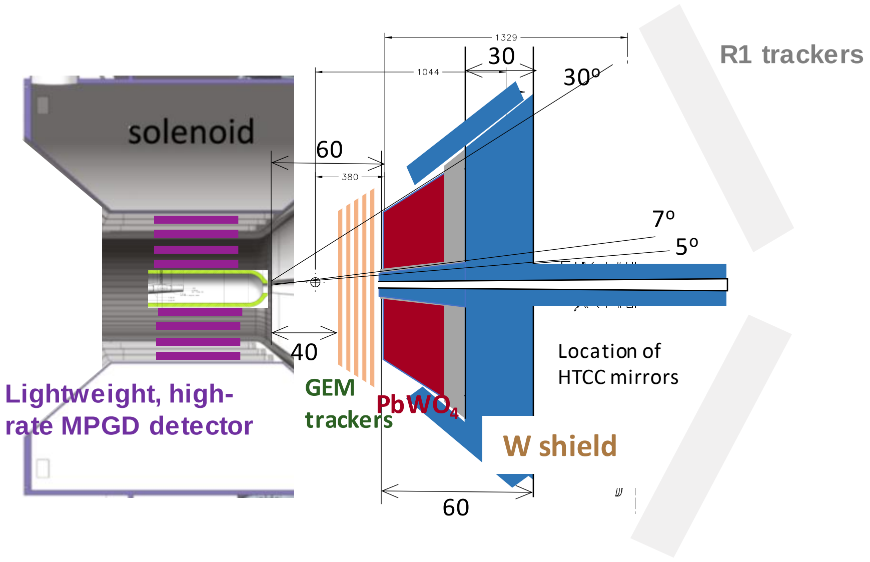
Summary

- Rach physics program with exclusive lepton pair production with CLSA12 in Hall-B
- First asymmetries in TCS are have already published
- J/ψ analysis is quite advanced and very close to be released
- J/ψ analysis on deuterium is progressing well, hopefully we will have first cross-sections soon
- Increasing the luminosity by about 2 orders of magnitude, we will be able to measure DDVCS with CLAS12 in Hall-B
  - If, PAC proposal will be approved.
- In case of an upgrade of JLab energy, lepton pair production can offer very interesting physics at higher energies too

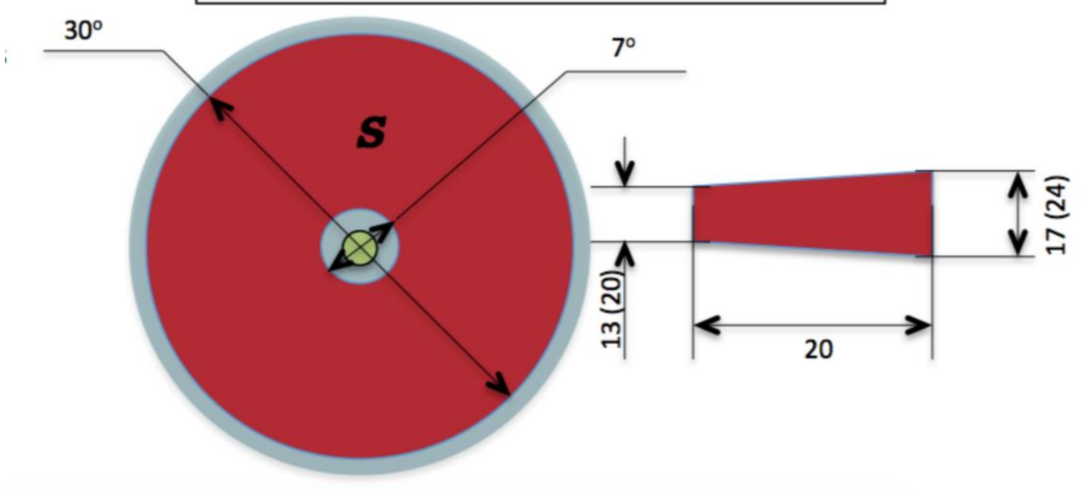
Backup slides

The agreement between MC and Data shows the contribution from $\rho(1450)$ and $\rho(1700)$ is negligibly small

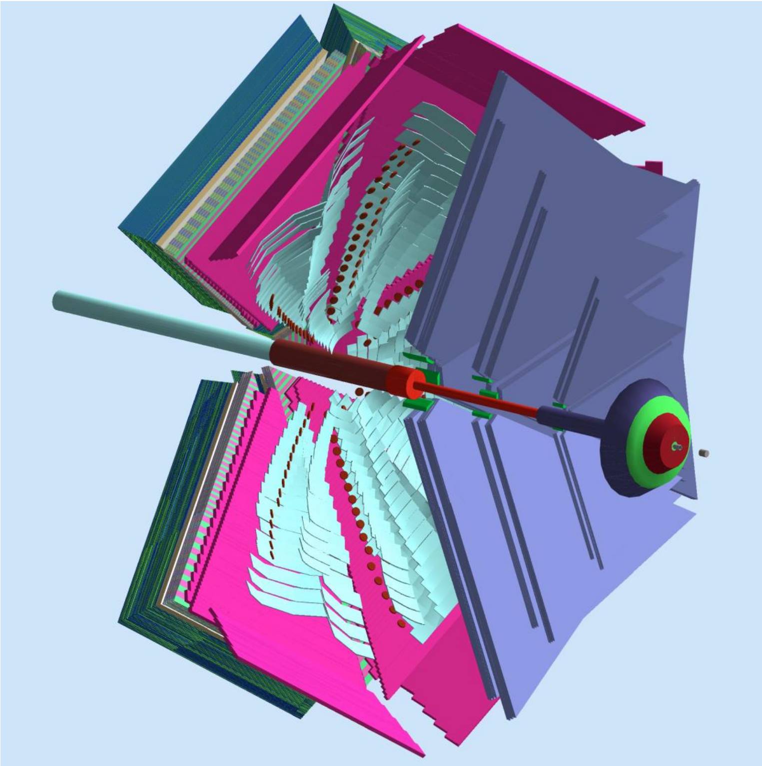




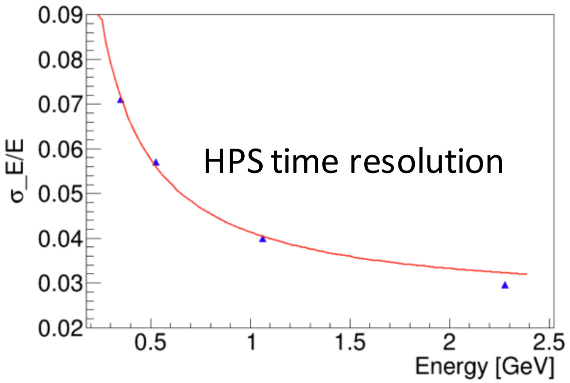
$$S = \pi l^2[(tg^2(30^o) - tg^2(7^o)] = 3600\,cm^2;\ l = 60\,cm$$

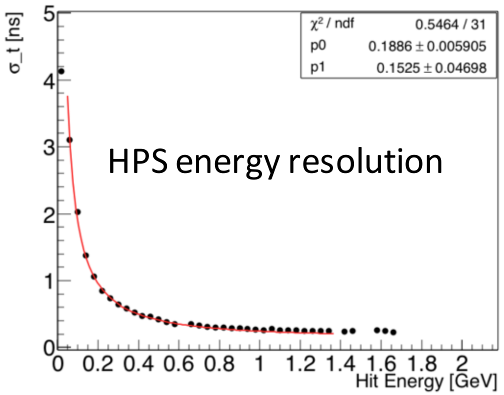


PbWO$_4$ modules with APD readout - ~ 1200 modules



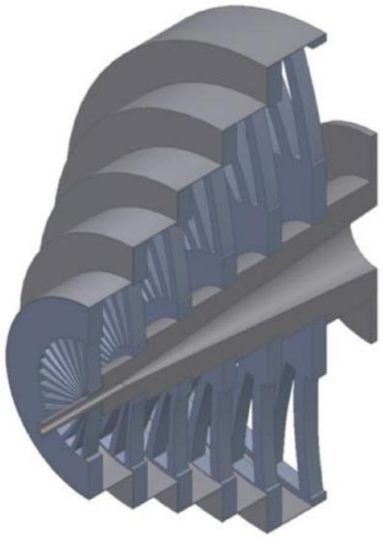
- 7° – 12°, crystals are 13 mm x 13 mm to keep rates per crystal at an acceptable level
- Above 12°, crystals 20mm x 20 mm will be used
- Readout: APD from the downstream face of crystals
- Similar crystals and readout were used during the DVCS calorimeter, and HPS electromagnetic calorimeter
- Expected rates at 7° is around 1.5 MHz
    - Similar rates were observed in HPS experiment on close to the beam crystals.



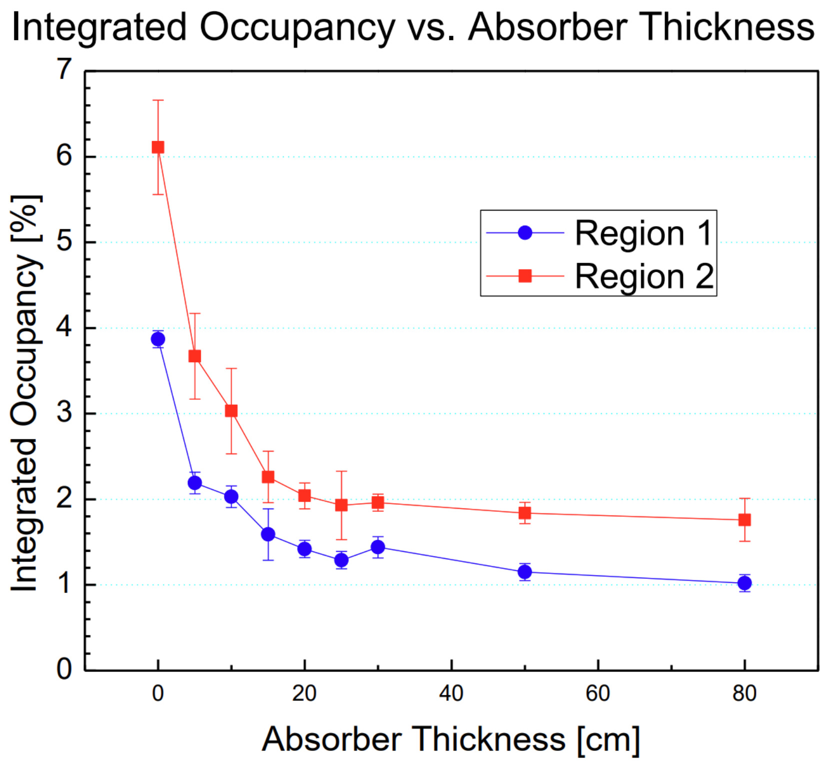


HPS has already demonstrated very good energy and time resolution

GEM trackers, Expected rates and occupancies

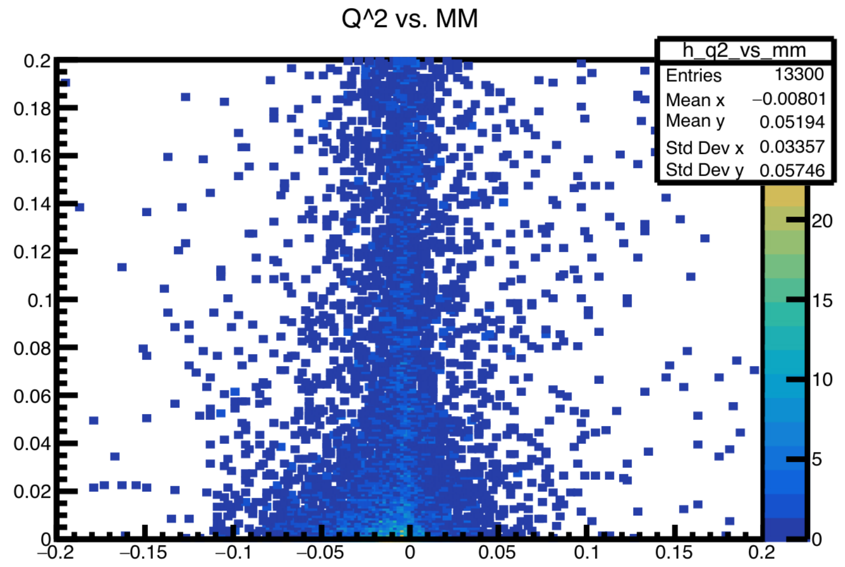


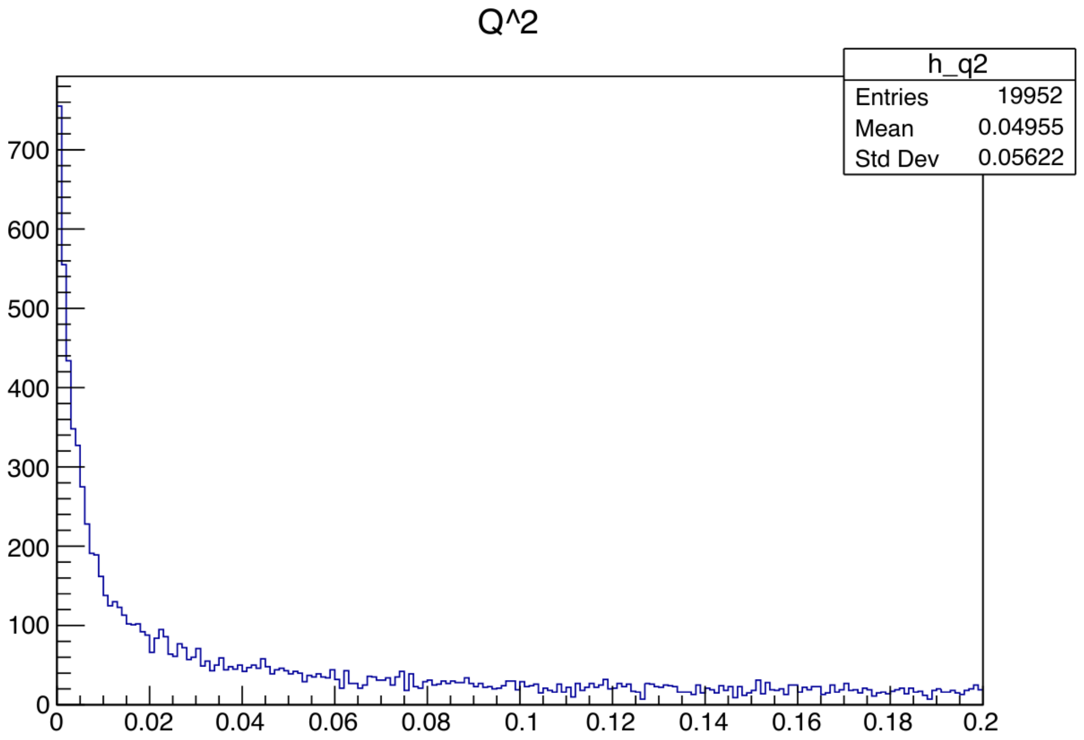
Five layers of GEM trackers (disks) covering angular range from 5° to 35°.
Each disc will be divided azimuthaly into six trapezoidal sections to match six-fold symmetry of CLAS12
Readout: 2D readout with radial and phi strips
Average length of radial strips at 5° is 4.6 cm with pitch size of 400$\boldsymbol{\mu}$.

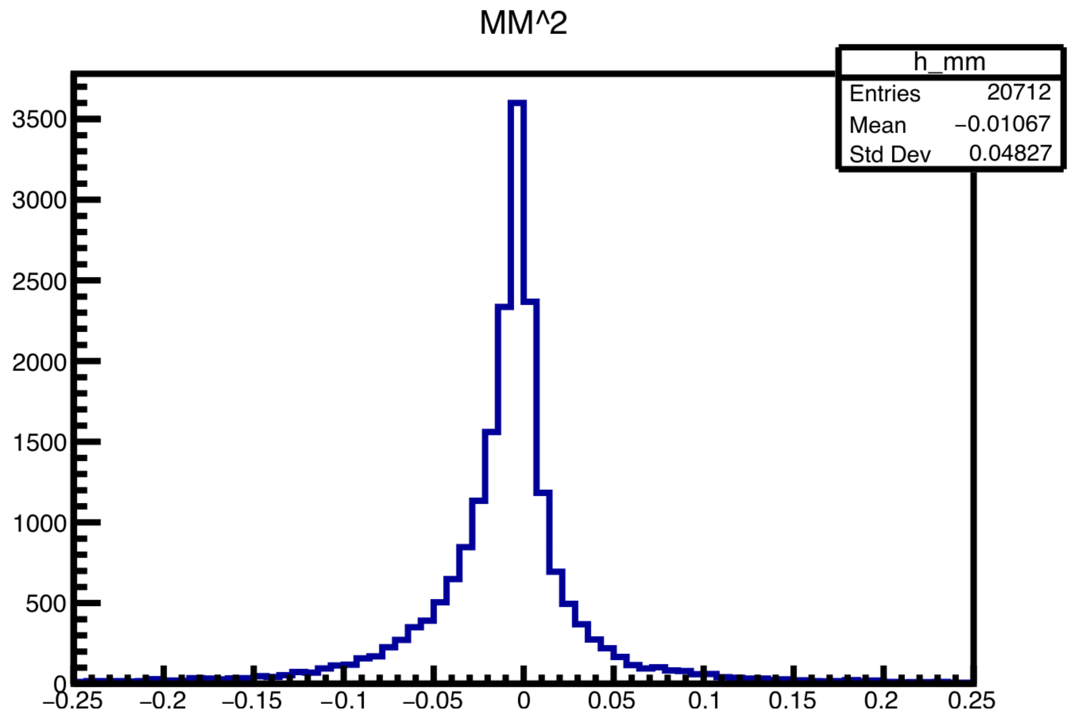


- An absorber with a thickness of 30 cm was used to bring DC occupancies to an acceptable level.
- Rates were studied for protons, pions, electrons and photons by placing a scoring plane between 4.8° and 35° at 40 cm from the target.
  - The tot rate from all particles at 5° is less than 0.5 MHz/cm^2. This translates into about 0.1 MHz for the hottest strip.
- Trigger rate:
  - Requiring 5 hits FDC AND MIP signature in calorimeter have 75/95 KHz for positive/negative single tracks:
  - Using a 50 ns coincidence time this translates into about 360 Hz

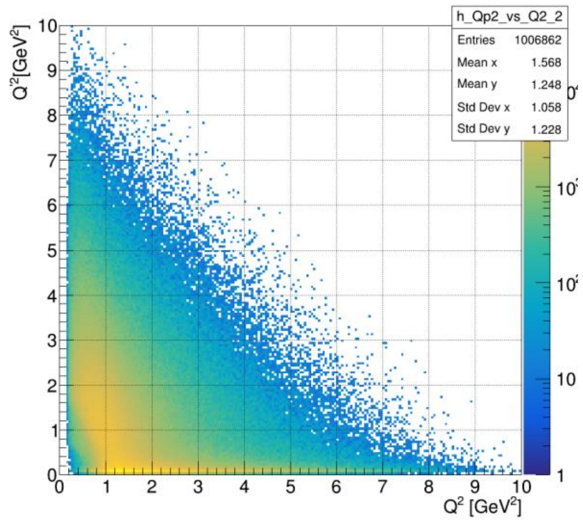
MC exclusivity cuts

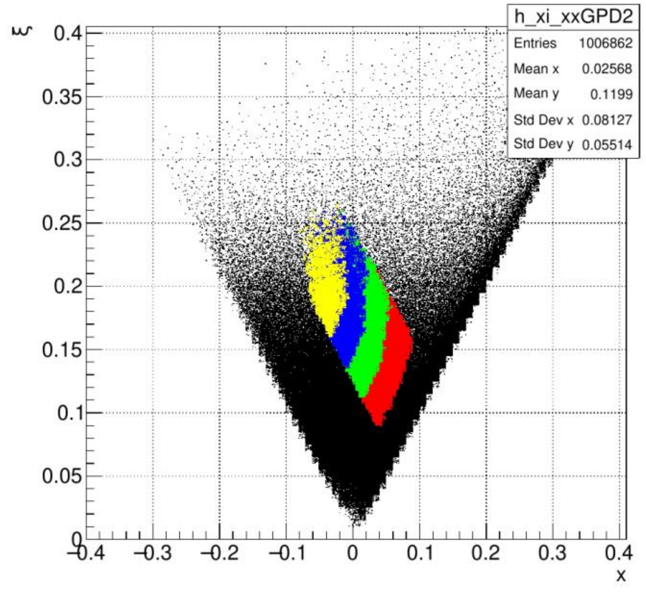






Expected kinematic coverage





Scan over Q'^2

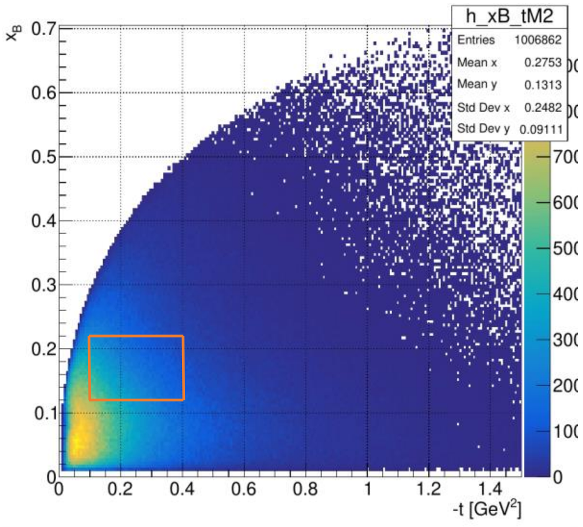
2 GeV^2 < Q^2 < 3 GeV^2

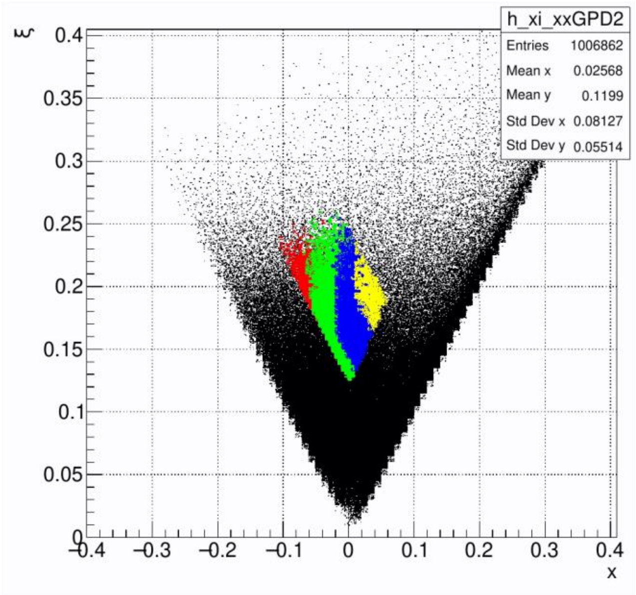
0.8 GeV^2 < Q'^2 < 1.6 GeV^2

1.6 GeV^2 < Q'^2 < 2.4 GeV^2

2.4 GeV^2 < Q'^2 < 3.2 GeV^2

3.2 GeV^2 < Q'^2 < 4. GeV^2





Scan over Q^2

2 GeV^2 < Q'^2 < 3 GeV^2

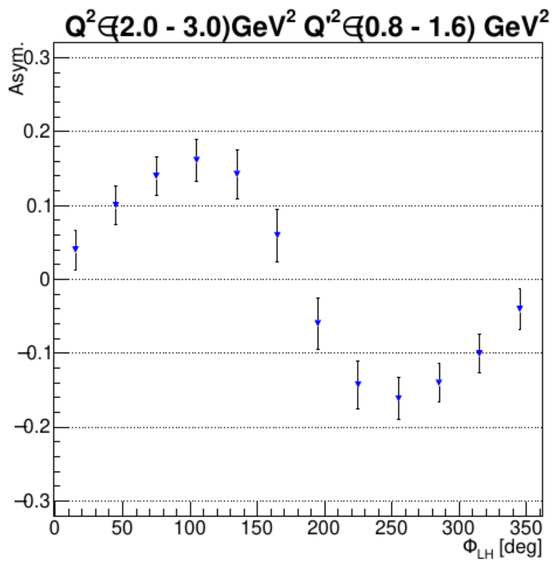
1 GeV^2 < Q'^2 < 1.6 GeV^2

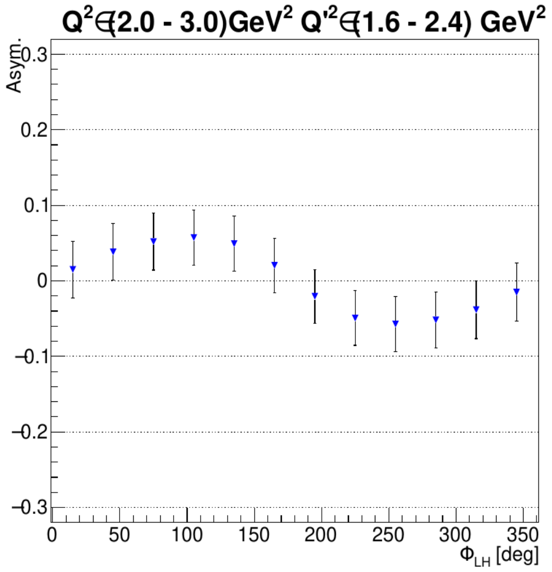
1.6 GeV^2 < Q'^2 < 2.4 GeV^2

2.4 GeV^2 < Q'^2 < 3.2 GeV^2

3.2 GeV^2 < Q'^2 < 4. GeV^2

Estimated uncertainties





Those uncertainties on asymmetries were estimated at the LOI, using CLAS12 FASTMC which is more realistic than geometric cuts.