Exclusive lepton pair production at JLab Hall B with CLAS12

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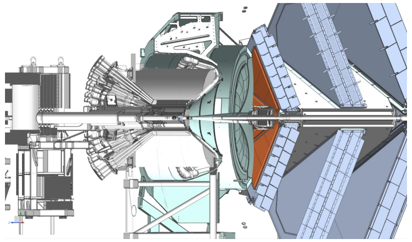
Opportunities with JLab Energy and Luminosity Upgrade
September 26-30, 2022,   Trento, Italy

Outline

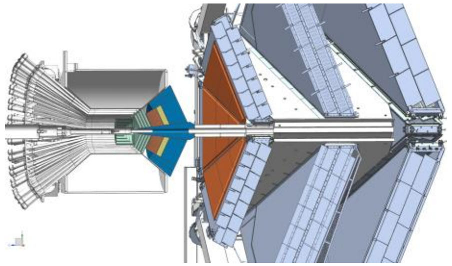
- Current projects with lepton pair production on CLAS12
  - TCS and J/ψ

[E12-12-001](#)
[E12-12-001A](#)
[E12-11-003B](#)

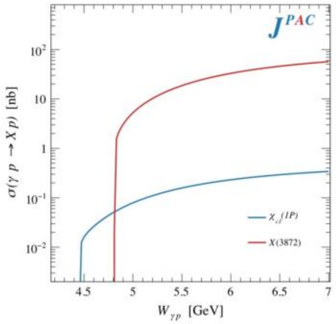
- Luminosity upgrade
  - Phase-I Luminosity upgrade
    - Assist not-fully completed experiments with statistics

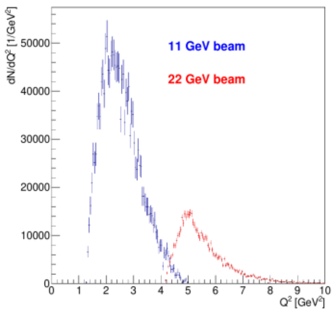


  - Phase-II Luminosity upgrade
    - Access to reactions with very low x-sec: Double DVCS
    - High stat J/ψ and TCS measurements



- Energy upgrade
  - Allows to reach higher Q^2
  - Opens opportunity to measure new states





Timelike Compton Scattering

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

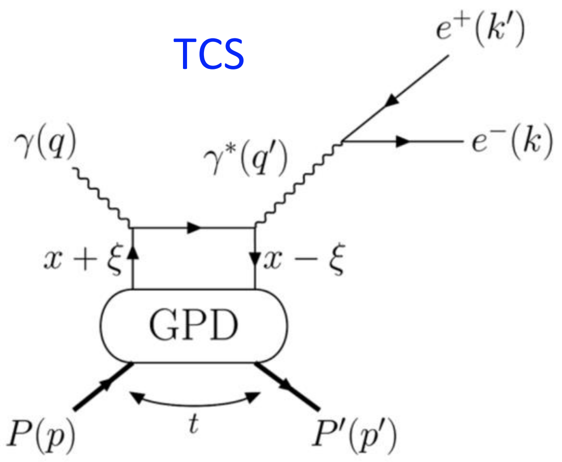
Since early of 2000s, experimental observables are reported: X-sec, Beam and Target spin asymmetries...

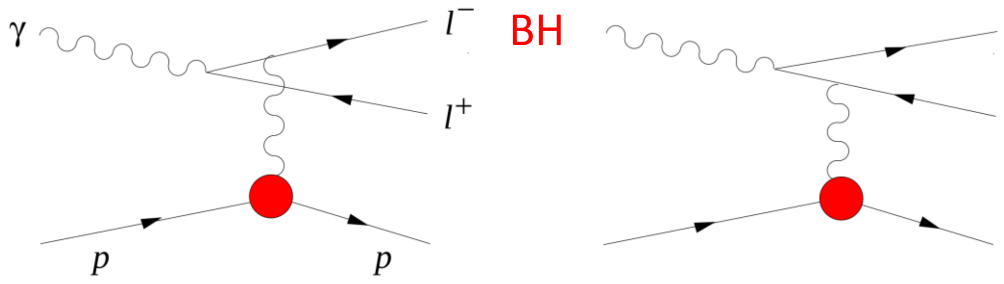
Proper understanding of GPDs requires measurement of different exclusive processes. *Only DVCS is not enough!*.
Universality of GPDs should be demonstrated.

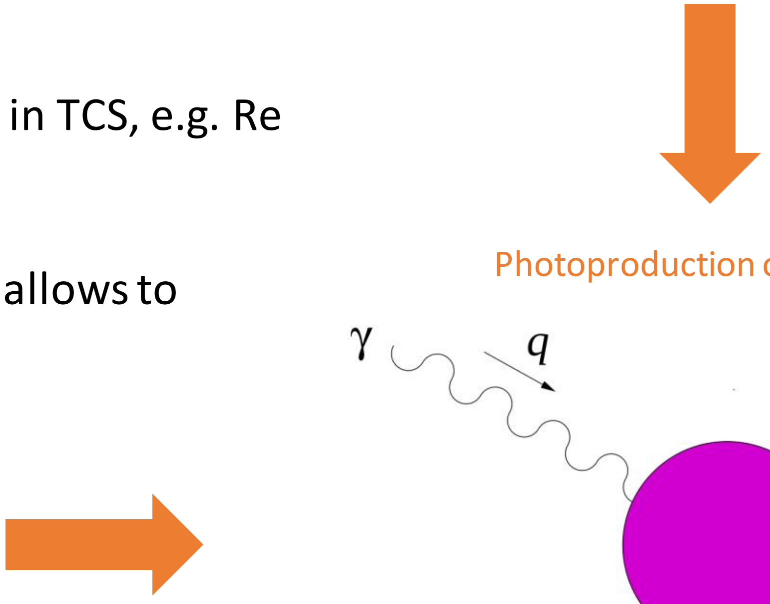
Some CFFs not so easily accessible in DVCS, are easier to access in TCS, e.g. Re part of CFF (H).

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

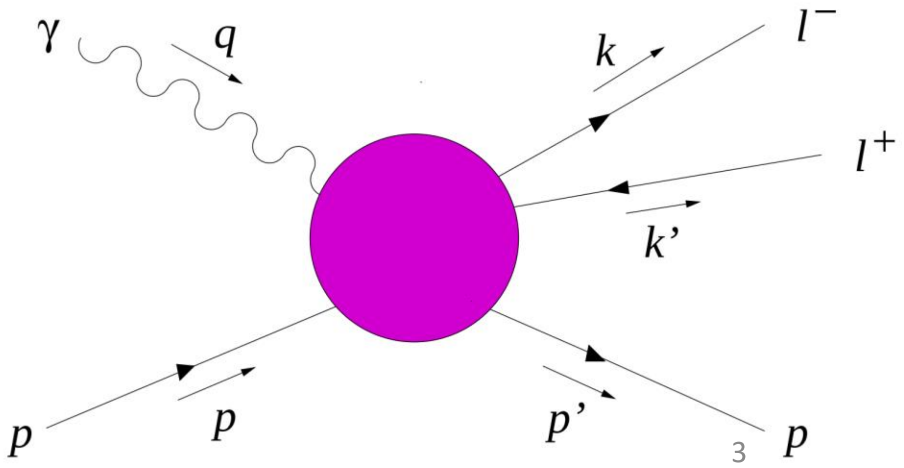
TCS







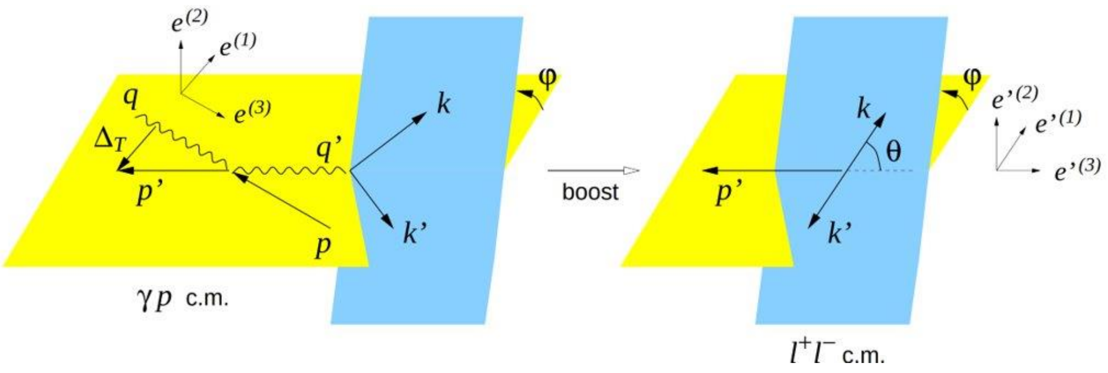
Photoproduction of lepton pairs



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

$$A_{\odot U} = \frac{\sigma_{\mathrm{LH}} - \sigma_{\mathrm{RH}}}{\sigma_{\mathrm{LH}} + \sigma_{\mathrm{RH}}}$$

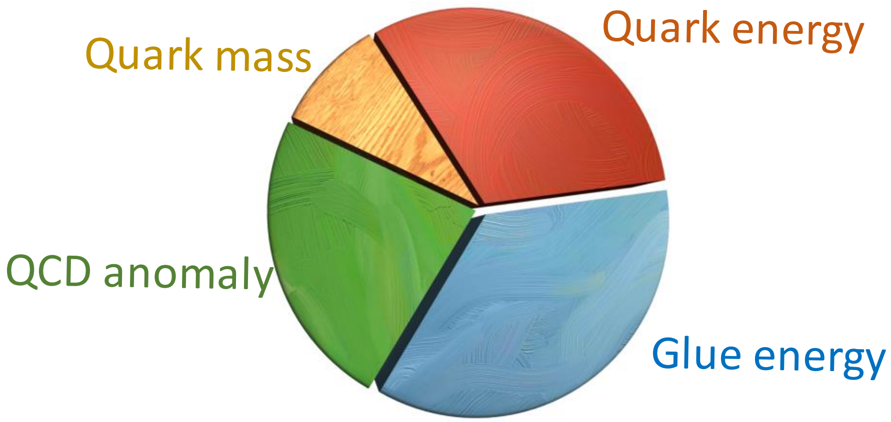
Proportional to the sine moment of the polarized Interference x-sec, and hence access the imaginary part of the scattering amplitude.

J/ψ production near the threshold

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

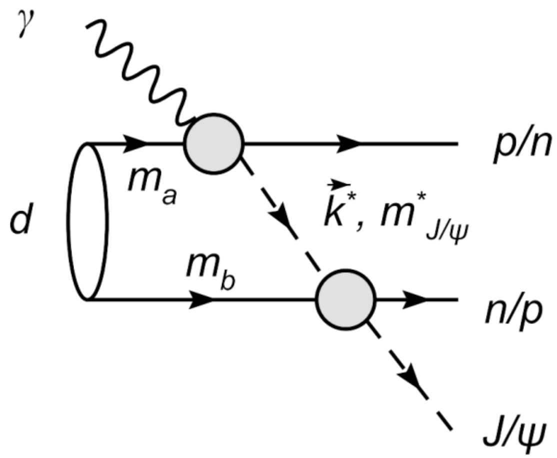
- Access to the gluonic form factor of the nucleon

- Trace anomaly. Decomposition of the proton mass



- Access to the mass radius of the proton

- 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.

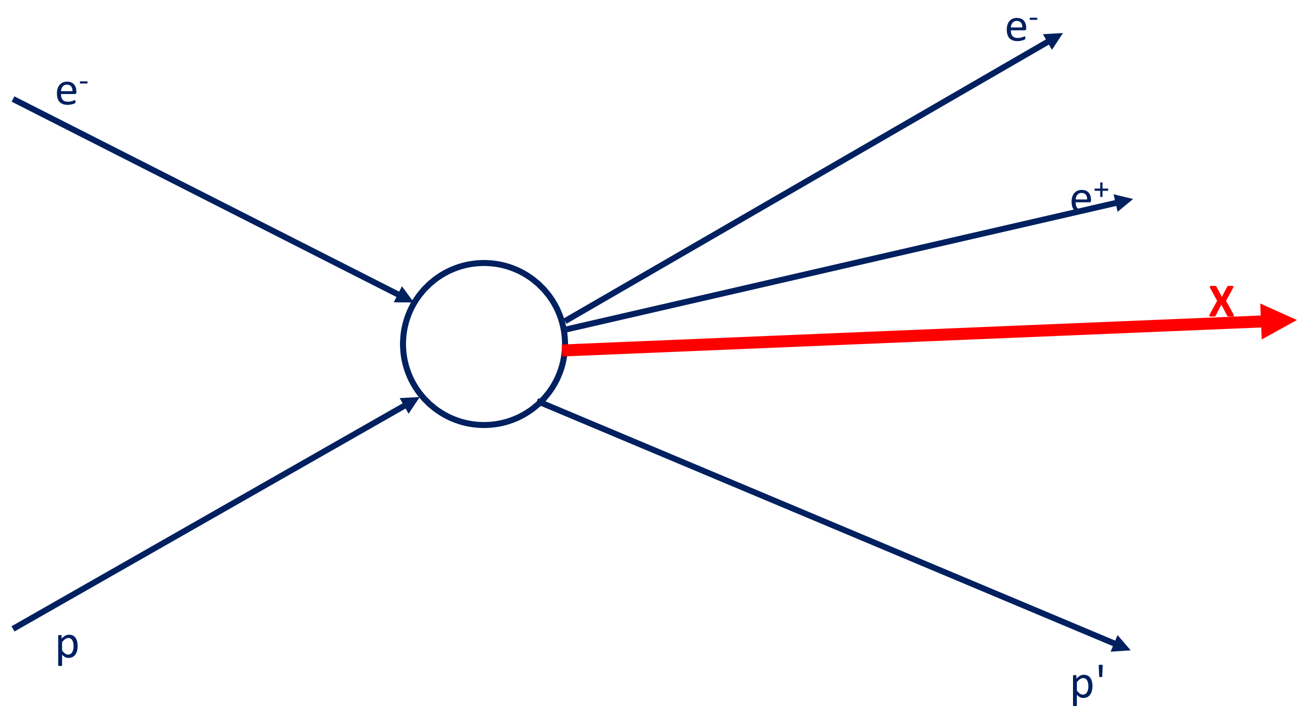


The reaction of interest

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

- The beam electron scatters at ~0 angle.
  - Two photon sources:
    - Quasi-real photons: Q^2~0
    - Real photons, when the Bremsstrahlung photon scatters inside the target

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

TCS analysis

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

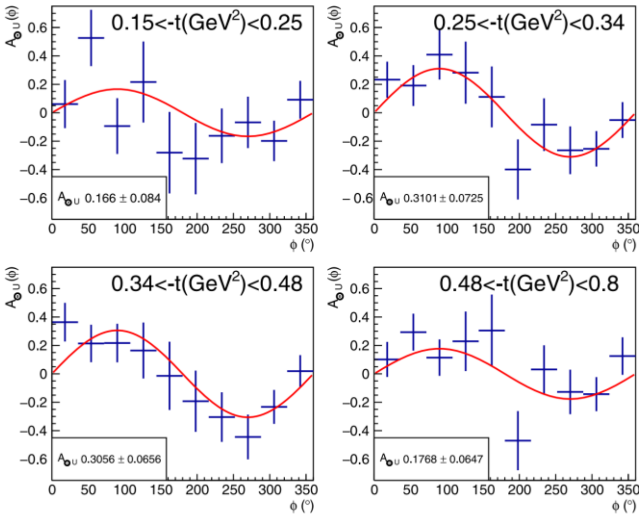
Polarization asymmetry

[Phys. Rev. Lett. 127, 262501](#)

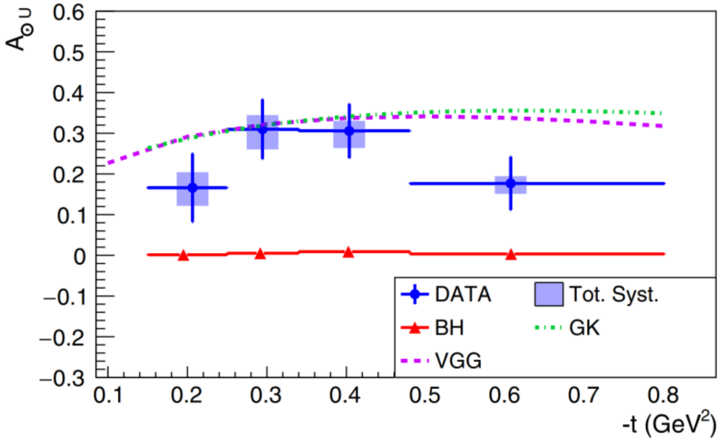
Chatagnon et all

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

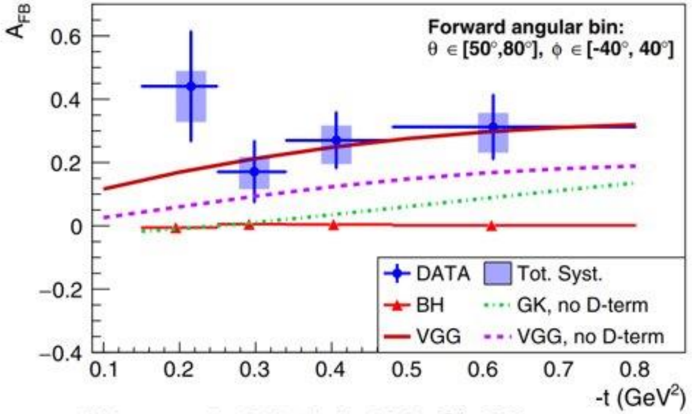
Fwd Bkwd asymmetry



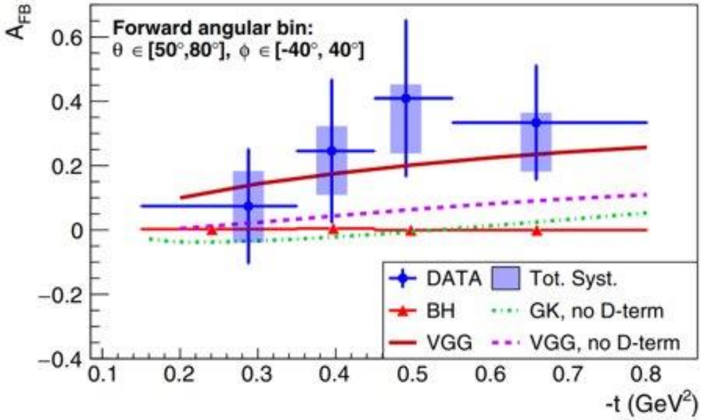
$$E_\gamma = 7.29 \pm 1.55 \text{ GeV}$$
$$M = 1.80 \pm 0.26 \text{ GeV}$$



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



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



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

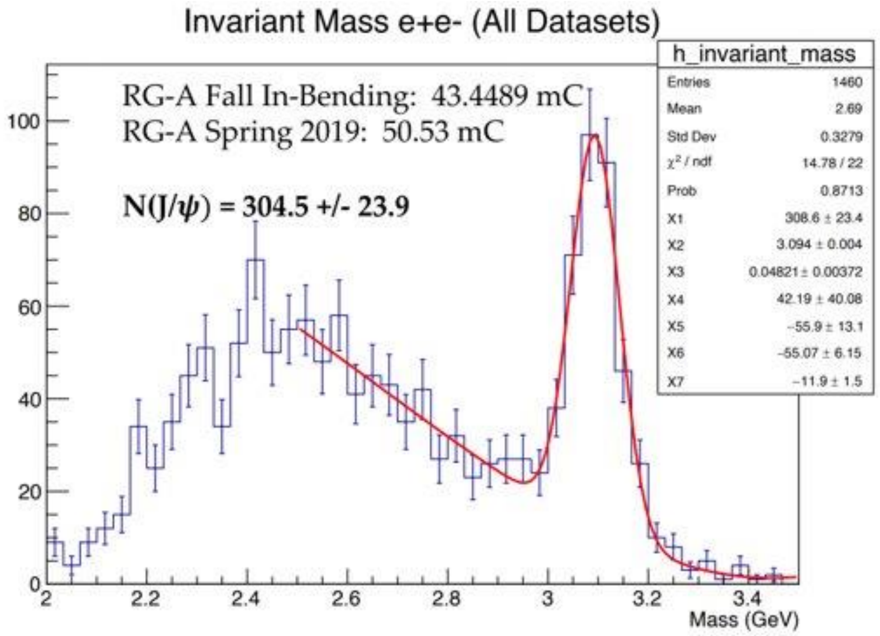
Polarization transfer L is calculated as:

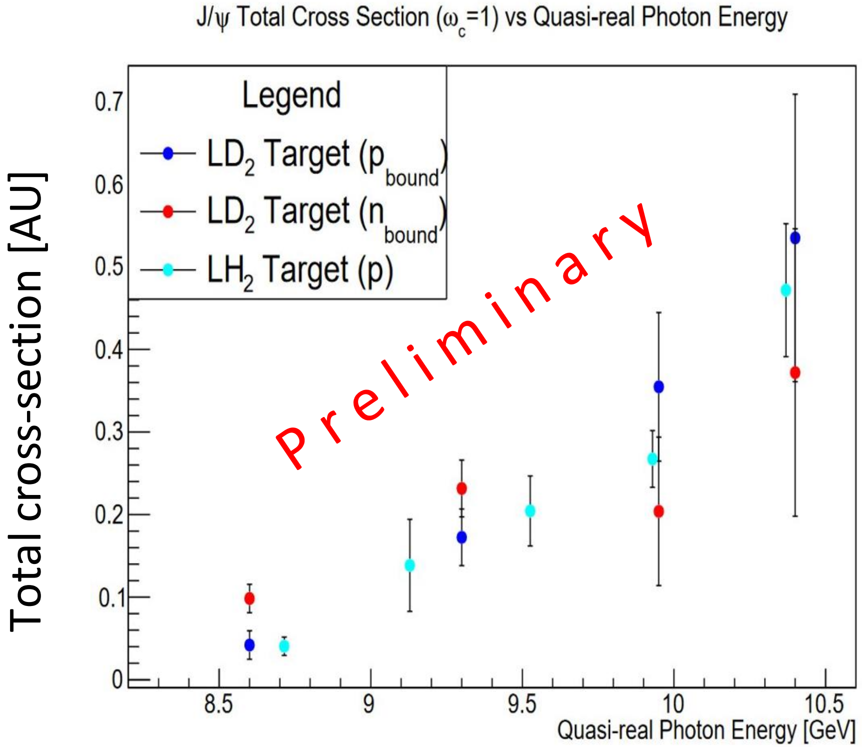
$$L = k\left[(E_1+E_2)(3+2\Gamma) - 2E_2(1+4u^2\xi^2\Gamma)\right]/I_0$$
$$I_0 = (E_1^2+E_2^2)(3+2\Gamma) - 2E_1E_2(1+4u^2\xi^2\Gamma)$$

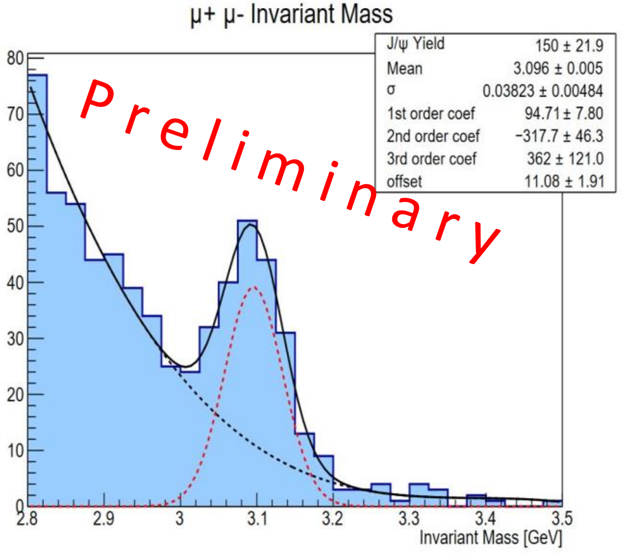
J/J/ψ analysis

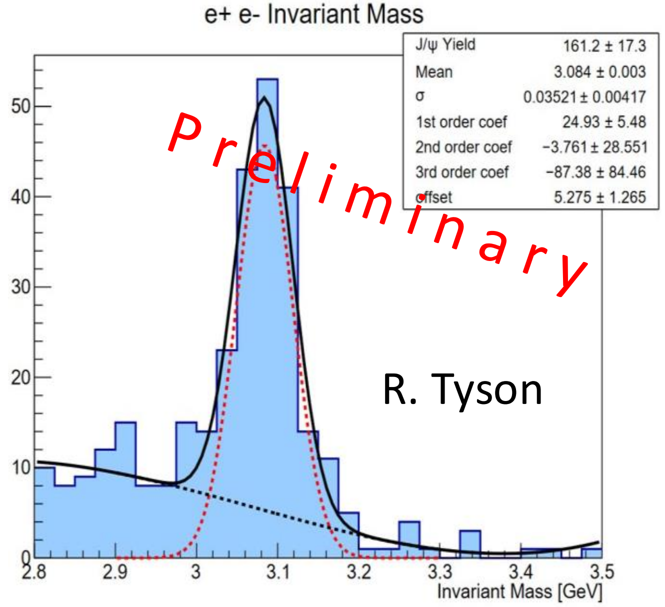
J/psi analysis is being finalized

J. Newton









R. Tyson

Currently J/ψ cross-section results are being cross-checked before releasing.

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
- RG-B
  - Production on Proton
  - Production on Neutron
- RG-C (Ongoing run, till March 2023)
  - Double spin asymmetries in TCS

Analysis is being finalized by Joseph Newton (JLab)

Mariana Tenorio Pita (ODU)

analysis is quite advanced, Richard Tyson (Glasgow)

Kayleigh Gates (Glasgow): Just starting

The RG-A (LH2 target) and RG-B (LD2 target) have more than half of the data yet to be taken.
Analysis (TCS, J/ψ and other exclusive reaction) of already taken data showed that increase of statistics would be very beneficial.

A special task force lead by S. Stepanyan developed a plan for a two stage Luminosity upgrade.

Phase-I Luminosity upgrade

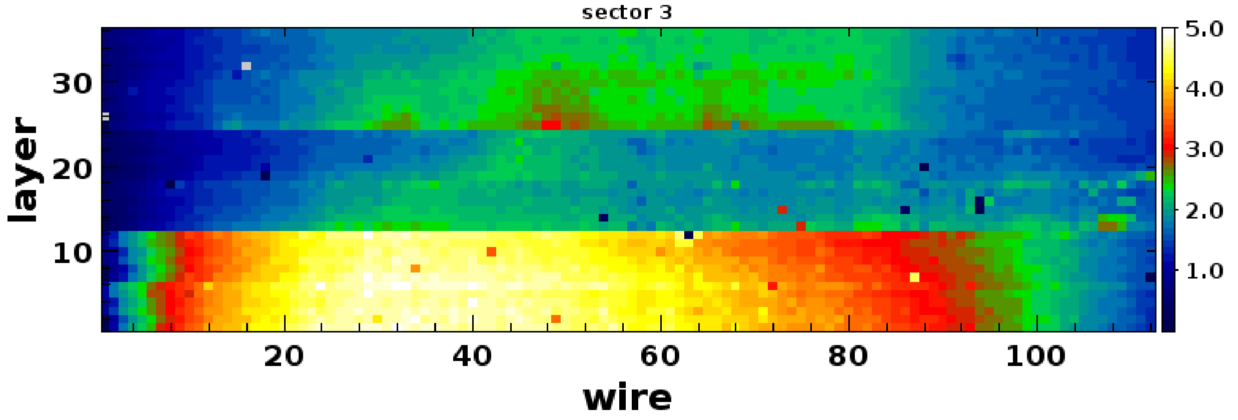
Achieve luminosity of $2x10^{35}cm^{-2}s^{-1}$ for standard CLAS12 operations with reconstruction efficiency of 85% per charged particle.

The main factor in CLAS12 that sets the Limit for standard luminosity is occupancies in Drift Chambers (DC). Occupancies should be below 5%.

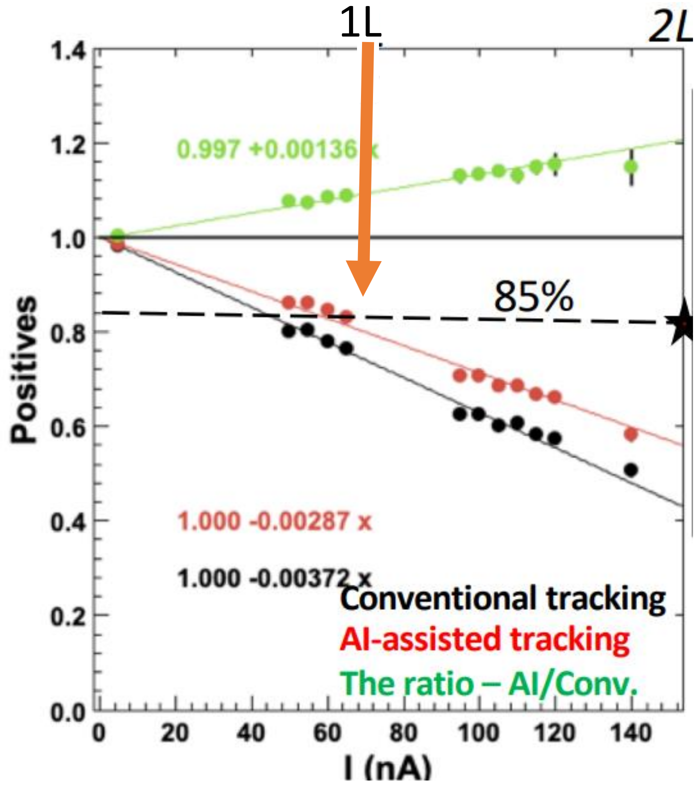
Highest occupancy is in Region 1

Applying AI techniques improves the tracking efficiency, however at 2L new solutions are needed.

R1 cell size 1.5 cm, time window: 250 ns

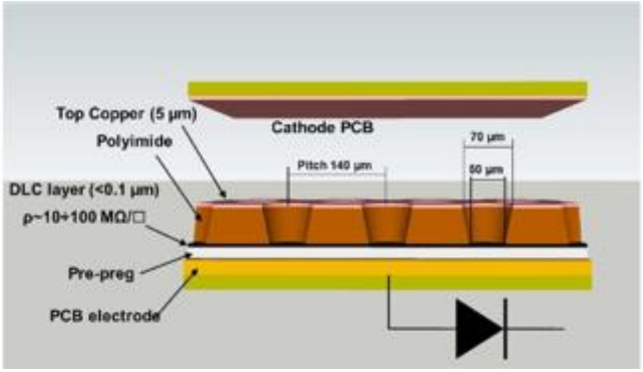


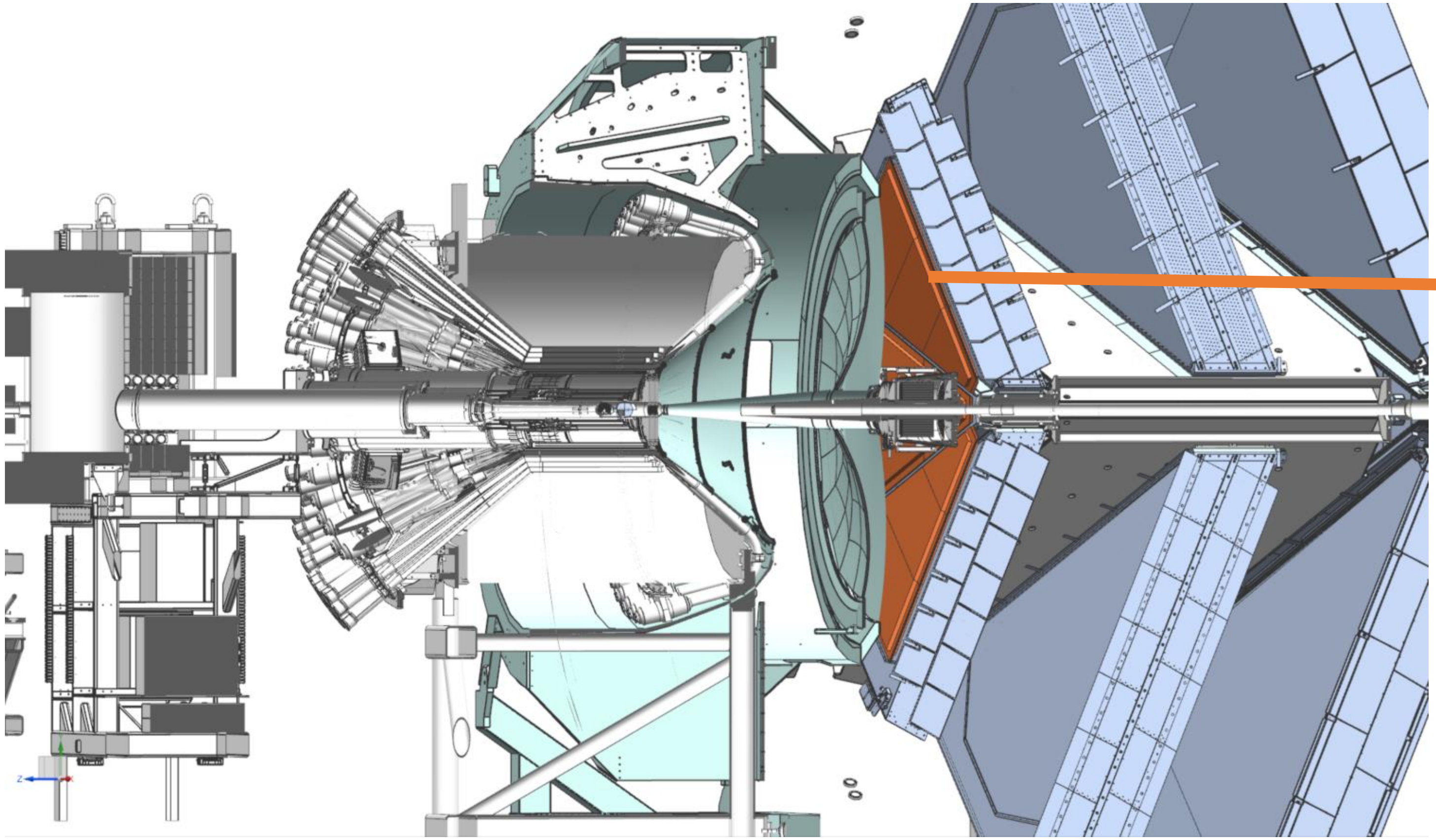
Nominal: $10^{35}cm^{-2}s^{-1}$.

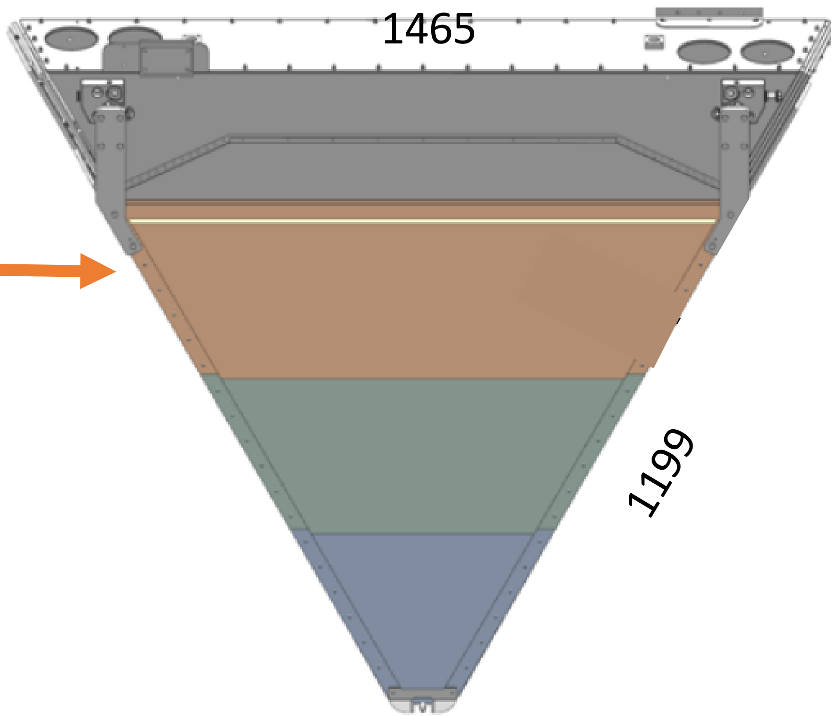


Phase-I Luminosity upgrade

- Add a new fast-tracking detector in between HTCC and DC region 1
- 6 sectors: each sector consists of three sections
- μRWell detector with 2D capacitive sharing readout





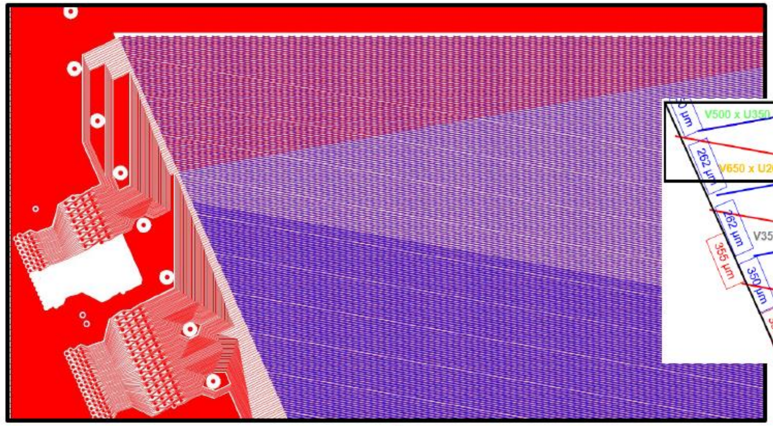
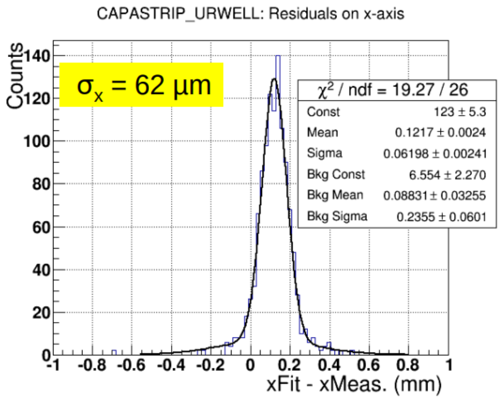


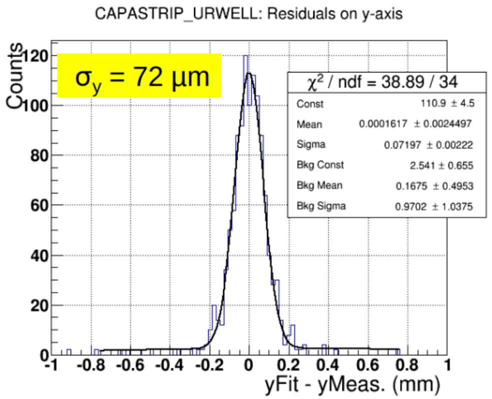
Prototype testing

The test prototype detector will be ready for the test with the beam in Hall-B around January of 2023

A detector with this size was never tested before
Variable pitch size was chosen, in order to find out the optimum pitch size.

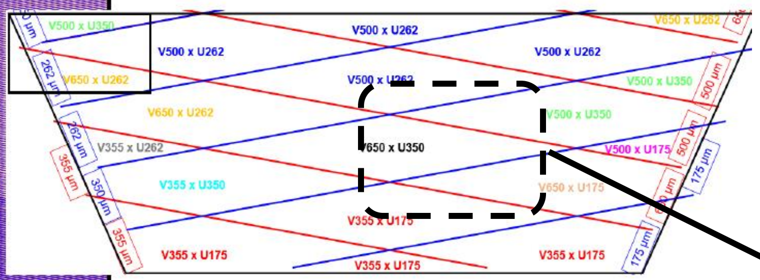
10 cm × 10 cm µRWELL with capacitive-sharing 2D strip readout was tested in Hall-D a year ago.

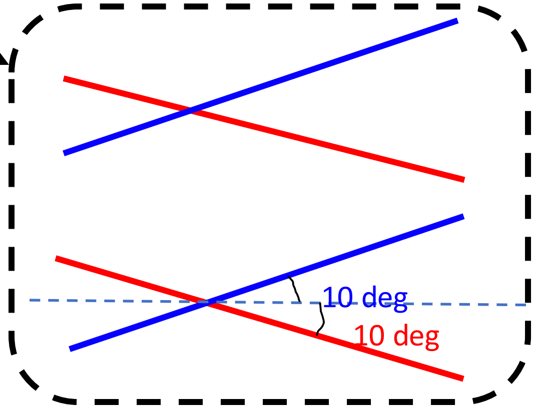





K. Gnanvo

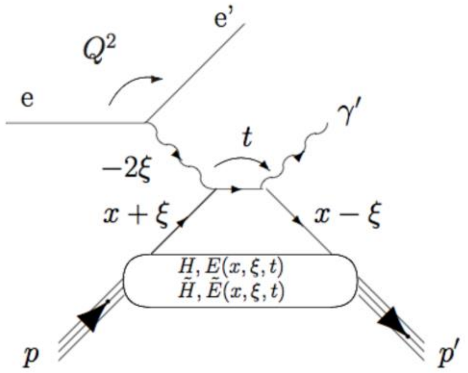
3 regions with different U and V width combinations





Accessing GPDs experimentally

DVCS



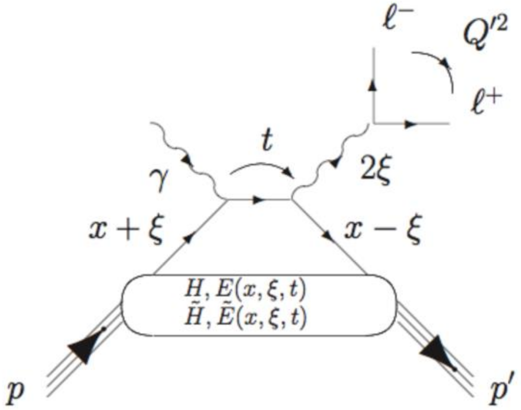
Experimentally and theoretically most studied
Many CLAS papers on x-sec, asymmetries on p,n,Nuclei
New BSA on p and n are undergoing collaboration wide review, and x-sec is in advanced state.

DVCS/TCS amplitudes are proportional to

$$\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} + \cdots \text{ Same for } (\tilde{H}, E, \tilde{E})$$

$$PV\left(\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}\right) - i\pi H(\xi,\xi,t)$$

TCS

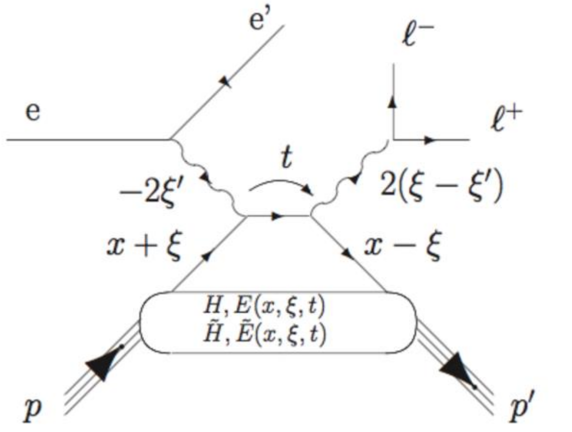


1st measured with CLAS12
Phys. Rev. Lett. **127**, 262501, arXiv:2108.11746 P. Chatagnon/CLAS colab

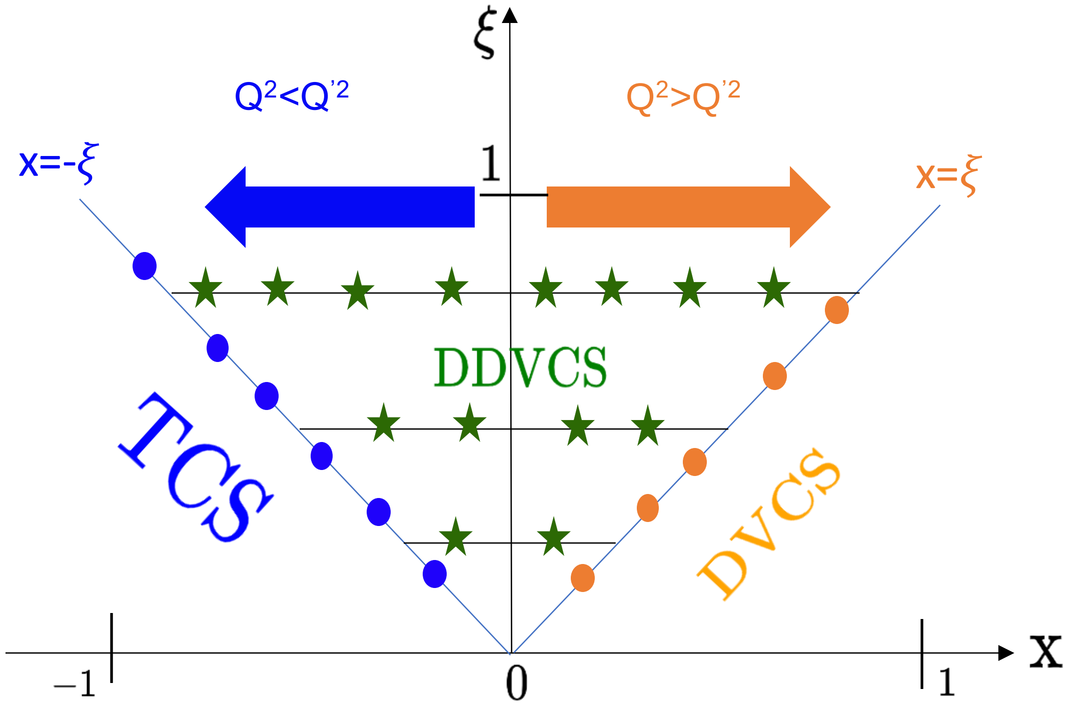
- A significant challenge in the extraction of GPDs is, that observables depend only on two of them ξ and t.
- The variable x is however is integrated over in both the DVCS and TCS amplitudes
- Or, one can access GPDs directly at limited phase space ((x=ξ, ξ, t) points) with DVCS and TCS, by measuring observables proportional to the Im part of the amplitude, e.g. BSA
    - A big part of phase space remains unreachable through direct measurements.

The way to avoid integration over x, is DDVCS

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:

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

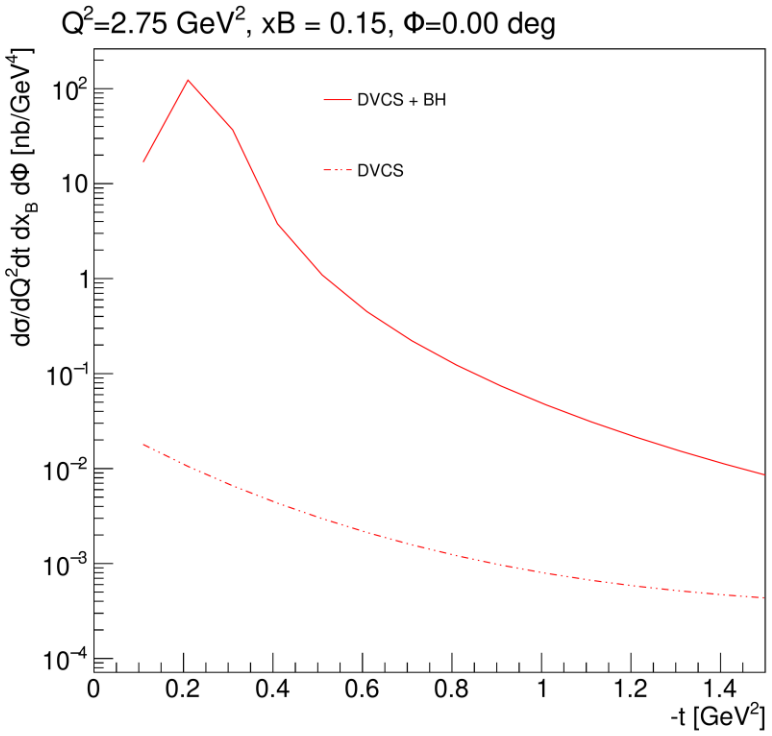
Observables (e.g. BSA) proportional to the Im part of the amplitude, allow direct measurement of GPDs at ($x=2\xi' - \xi$, ξ, t) points.

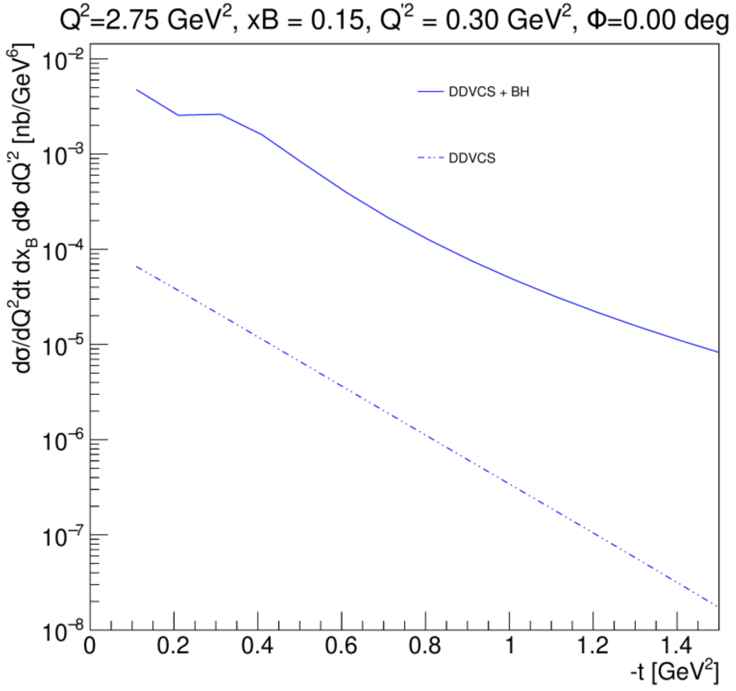
Here one can get away from the $x=\xi$ line by varying virtualities of incoming and outgoing photons

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

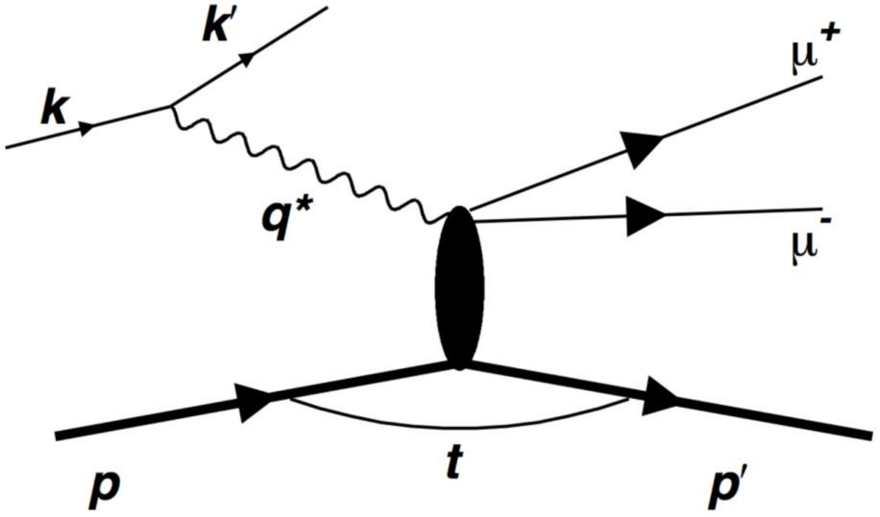




Based on these arguments, on 2016 we have submitted a LOI "LOI-12-16-004" to upgrade the CLAS12 detector which will allow to take luminosities of the of the order of 10^{37} $cm^{-2}s^{-1}$.

The proposed measurement

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



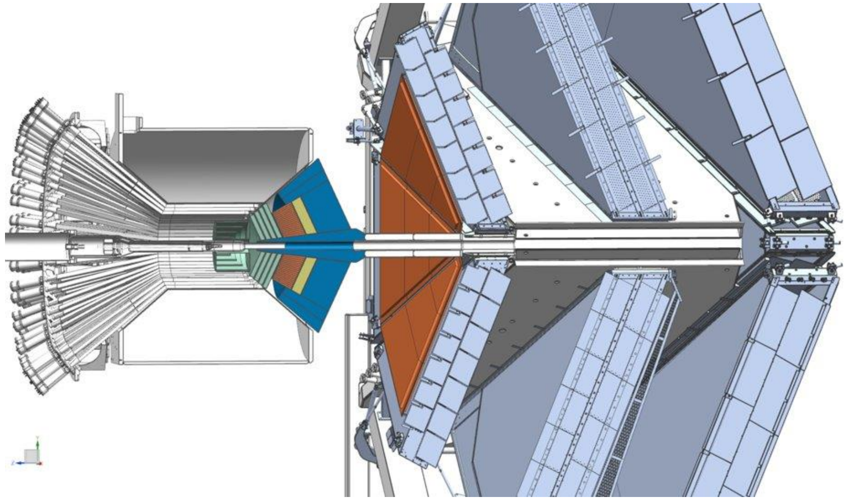
- In order to avoid ambiguity arising from the detection of two electrons in the final state, the timelike photon is identified through the detection of $\boldsymbol{\mu}$-$\boldsymbol{\mu}$+ pair.
  - **<u>Requires a muon detection</u>**
- Proposed Luminosity: 10^{37} $cm^{-2}s^{-1}$.
- We plan to detect at least e′$\boldsymbol{\mu}^{-}\boldsymbol{\mu}^{+}$, and the proton kinematic will be deduced from the missing momentum analysis, if proton is outside of the acceptance.

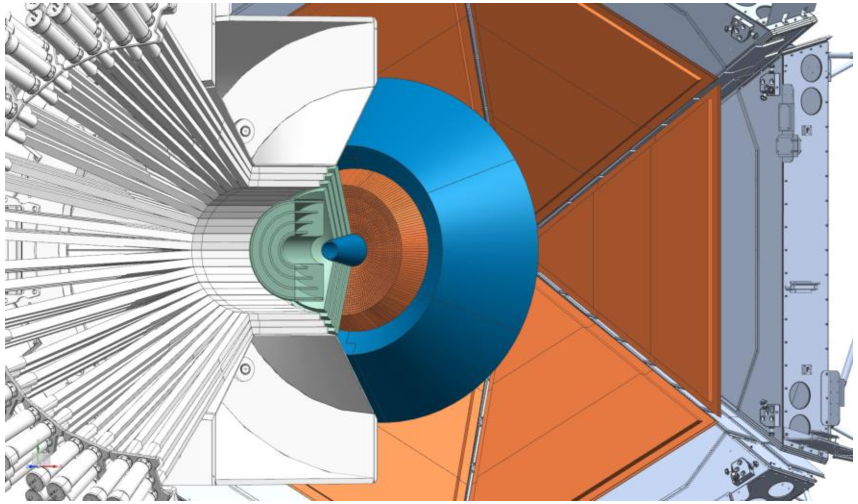
Proposal for μCLAS12

- 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

- 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 MPGD detectors in front of the calorimeter
    - In order to be able to reconstruct vertex parameters (angles and positions)

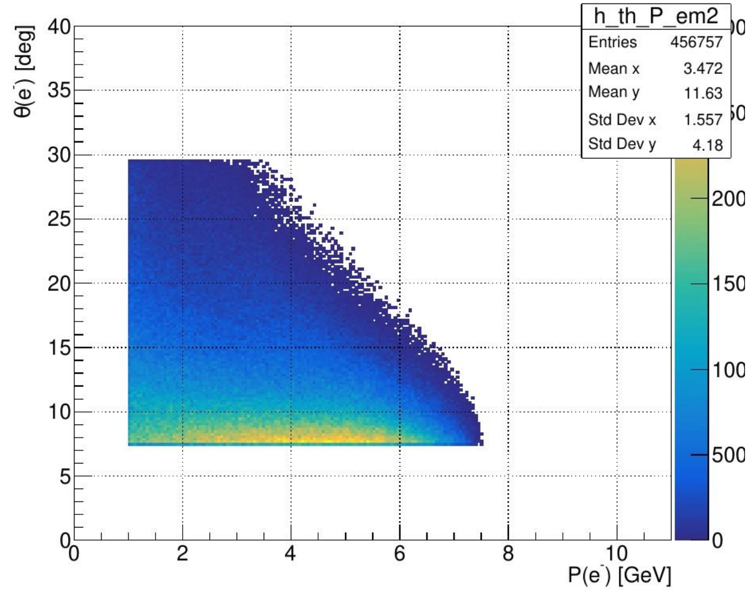
- $7^\circ - 12^\circ$, crystals are 13 mm x 13 mm to keep rates per crystal at an acceptable level
- Above 12°, crystals 20mm x 20 mm will be used
- Readout: APD from the downstream face of crystals
- Similar crystals and readout were used during the DVCS calorimeter, and HPS electromagnetic calorimeter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



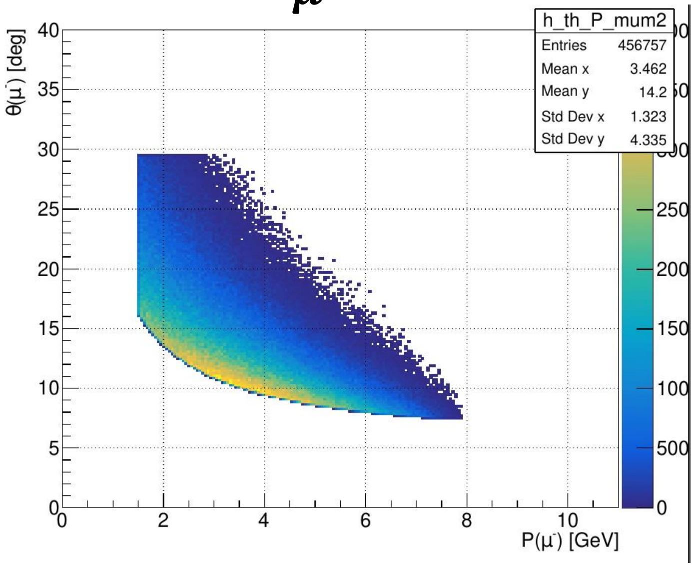


Expected kinematic coverage

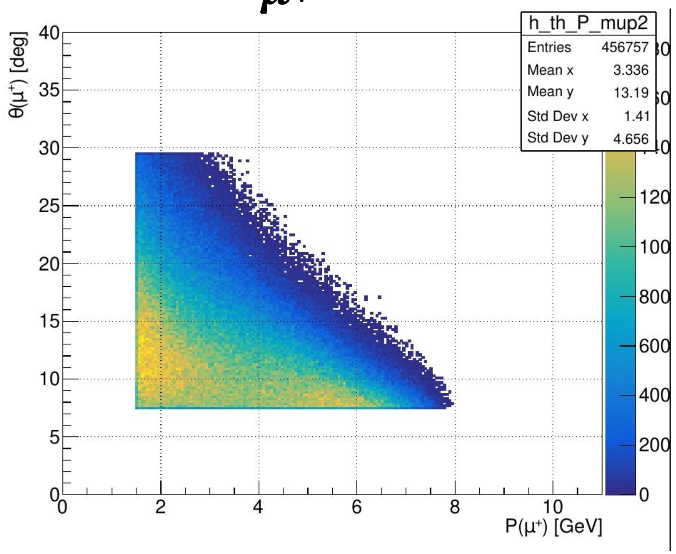
Electrons



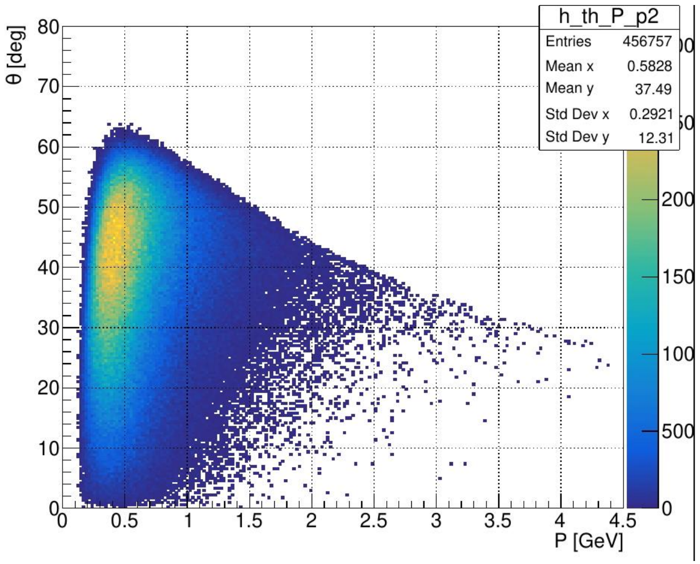
$\boldsymbol{\mu^-}$



$\boldsymbol{\mu}$+



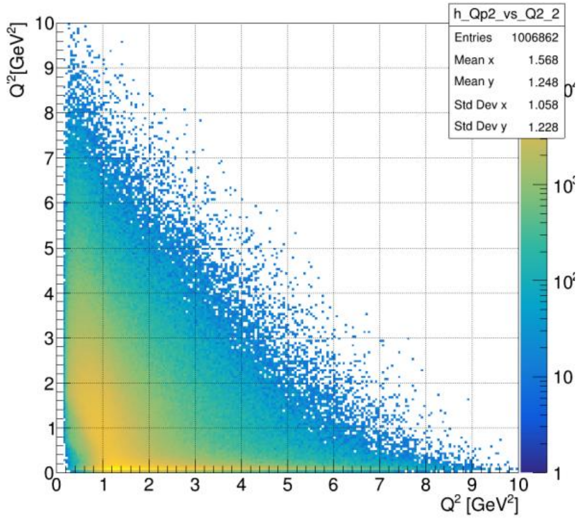
Protons

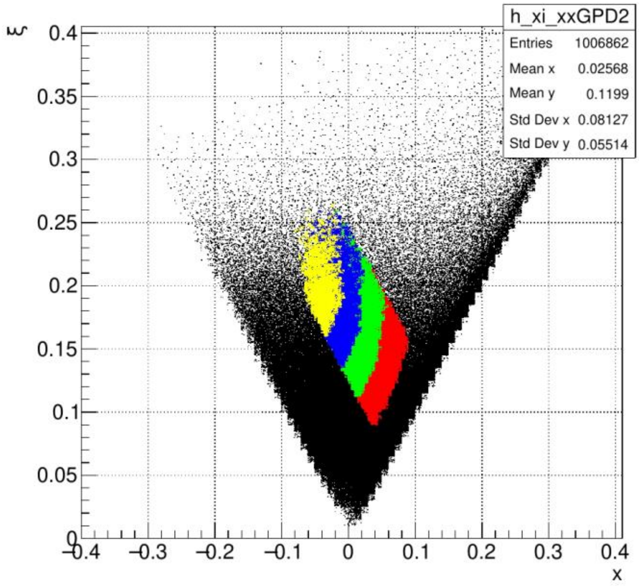


We should start more realistic simulations for the proposal, but for understanding the kinematics and expected rates this geometric acceptances should be good enough.

- Events were generated with GRAPE which has BH component only
- Electron: P > 1 GeV, 8 < theta [deg] < 29.5
- $\boldsymbol{\mu}^-$: 8 < theta [deg] < 29.5, Parametrized using CLAS12 Acceptance.
- $\boldsymbol{\mu}^+$: P > 1.5 GeV, 8 < theta [deg] < 29.5

Expected kinematic coverage





Scan over Q'^2

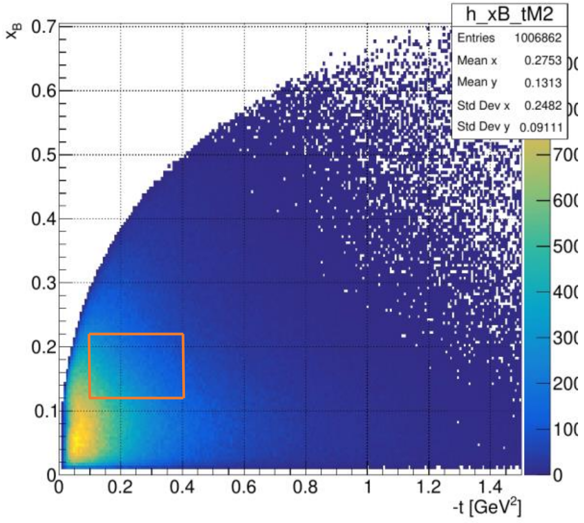
$2\ \mathrm{GeV}^2 < Q^2 < 3\ \mathrm{GeV}^2$

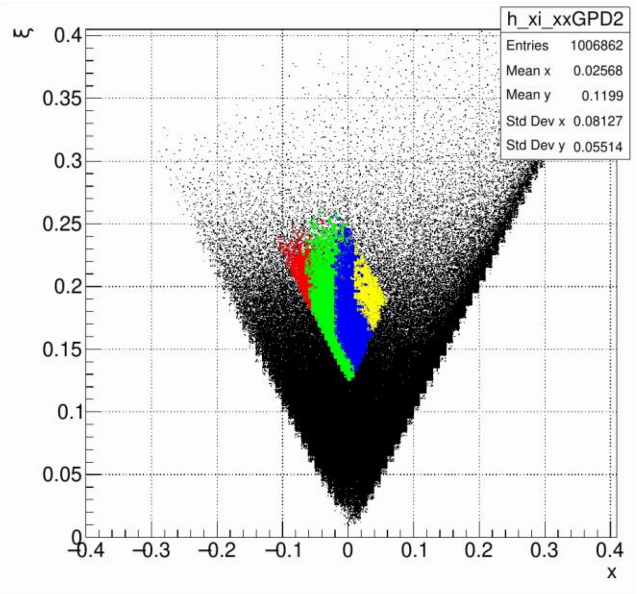
$0.8\ \mathrm{GeV}^2 < Q'^2 < 1.6\ \mathrm{GeV}^2$

$1.6\ \mathrm{GeV}^2 < Q'^2 < 2.4\ \mathrm{GeV}^2$

$2.4\ \mathrm{GeV}^2 < Q'^2 < 3.2\ \mathrm{GeV}^2$

$3.2\ \mathrm{GeV}^2 < Q'^2 < 4.\ \mathrm{GeV}^2$





Scan over Q^2

$2\ \mathrm{GeV}^2 < Q'^2 < 3\ \mathrm{GeV}^2$

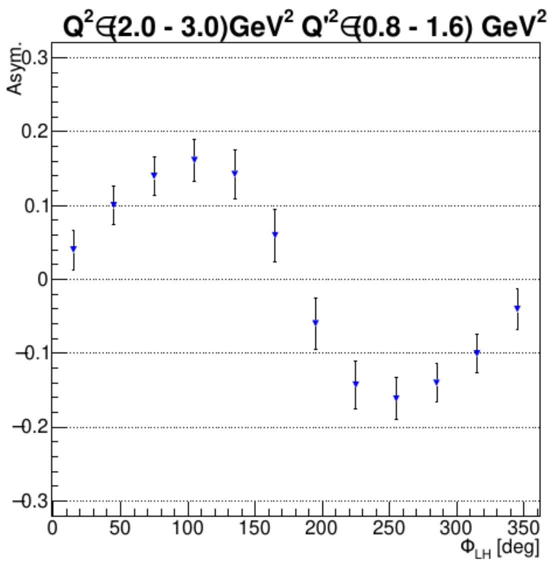
$1\ \mathrm{GeV}^2 < Q'^2 < 1.6\ \mathrm{GeV}^2$

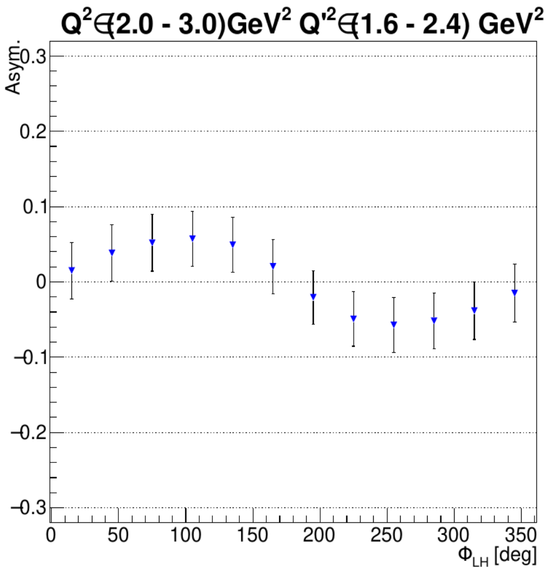
$1.6\ \mathrm{GeV}^2 < Q'^2 < 2.4\ \mathrm{GeV}^2$

$2.4\ \mathrm{GeV}^2 < Q'^2 < 3.2\ \mathrm{GeV}^2$

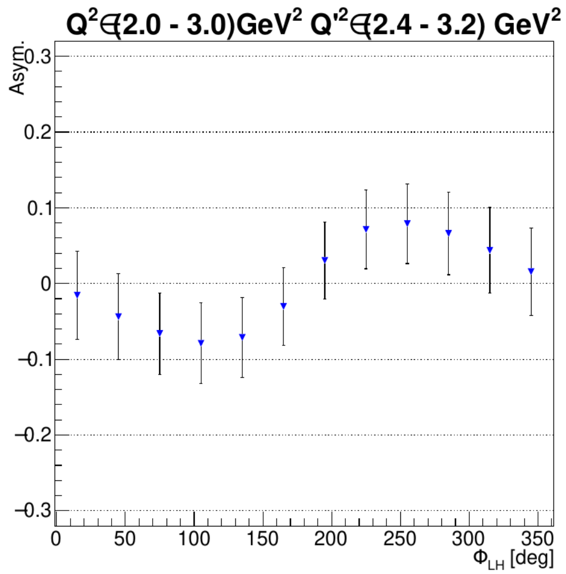
$3.2\ \mathrm{GeV}^2 < Q'^2 < 4.\ \mathrm{GeV}^2$

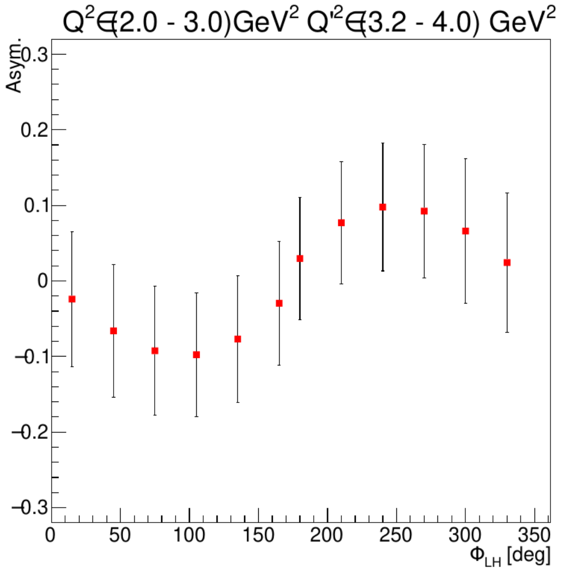
Estimated uncertainties





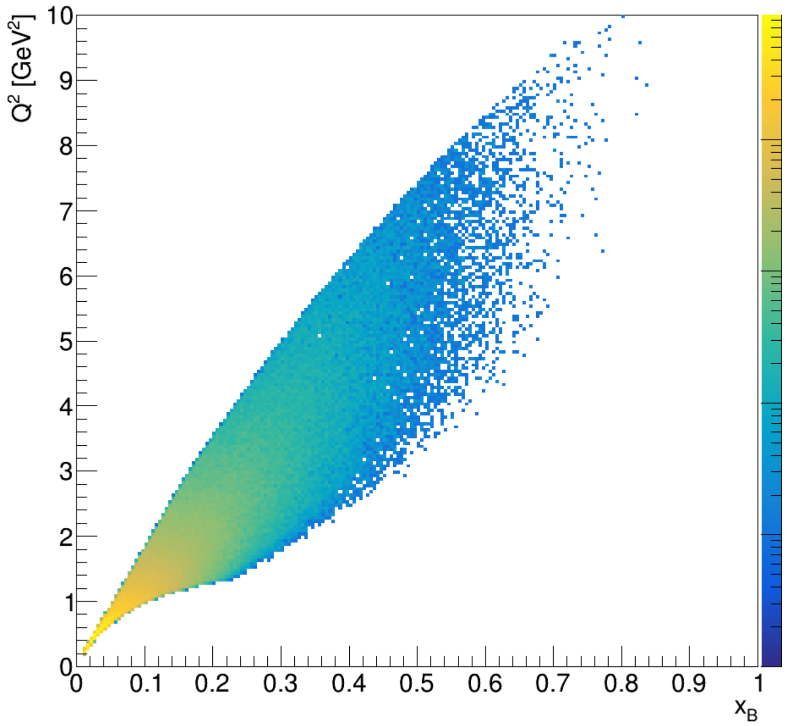
In addition to accessing GPDs on $x \neq \xi$ line, we should also be able to demonstrate the BSA sign change when we go $Q'^2 < Q$ regime to $Q'^2 > Q2$ regime: a signature of the handbag mechanism.



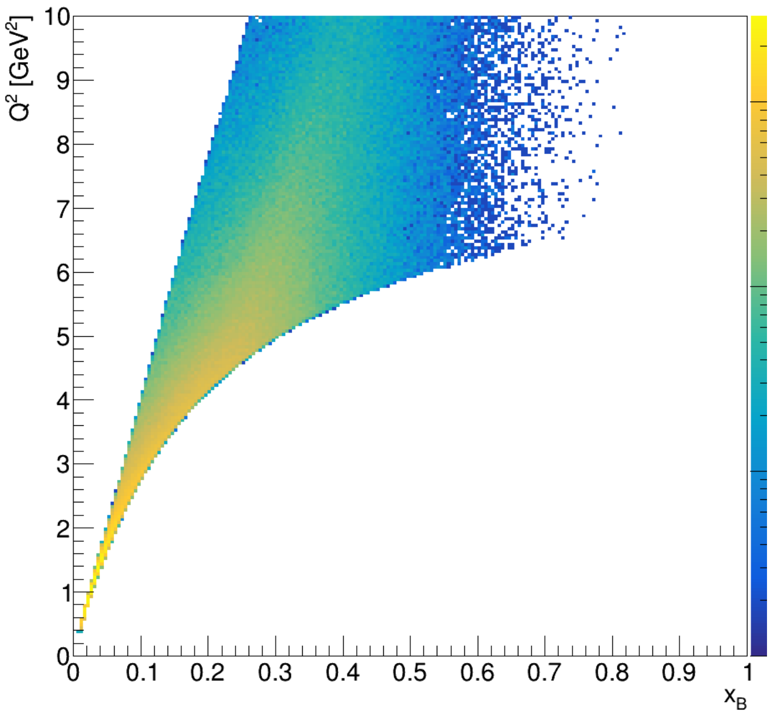


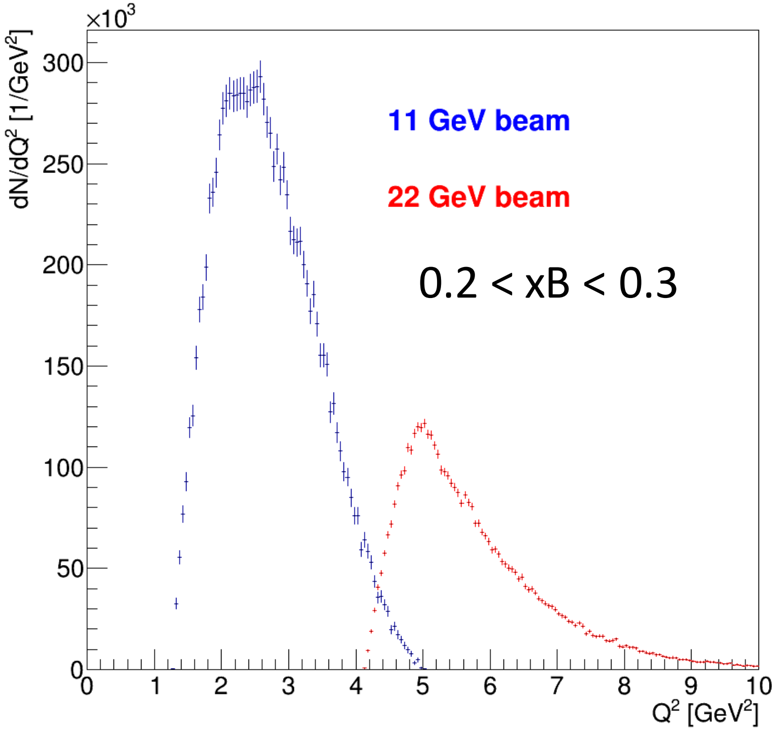
DDVCS at 22 GeV

11 GeV beam



22 GeV beam

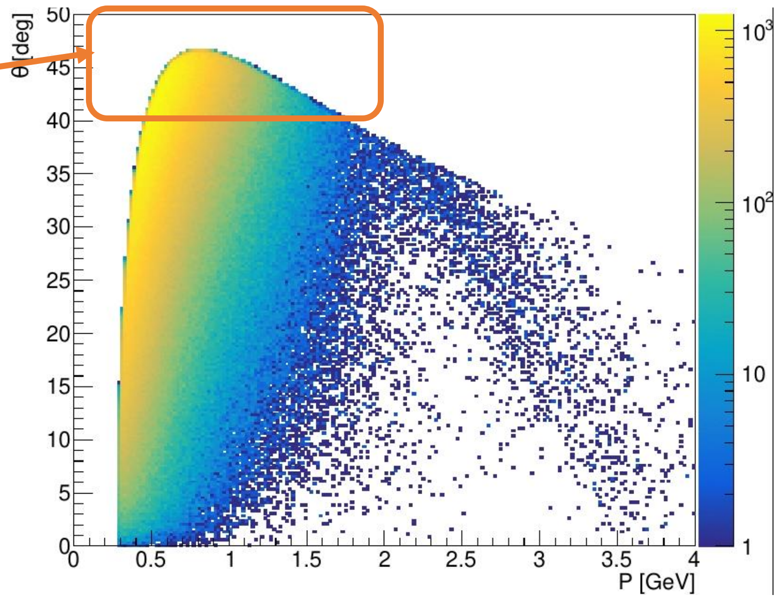




At 20+ one can access higher Q^2. Will allow to study evolutions of GPDs

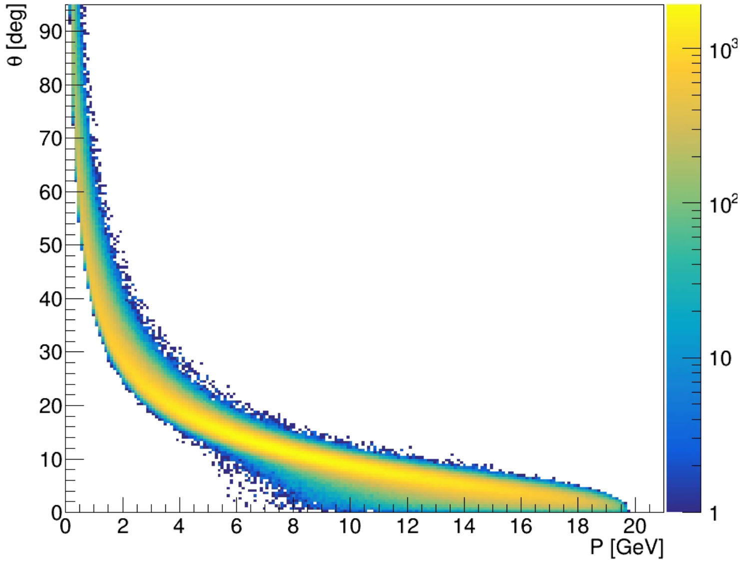
J/ψ production: particle kinematics and acceptance

J/ψ was generated by ElSpectro (developed by D. Glazier).

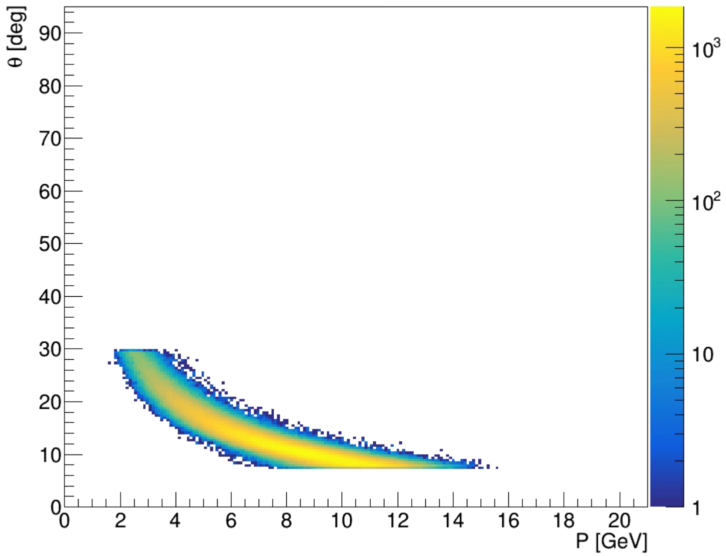


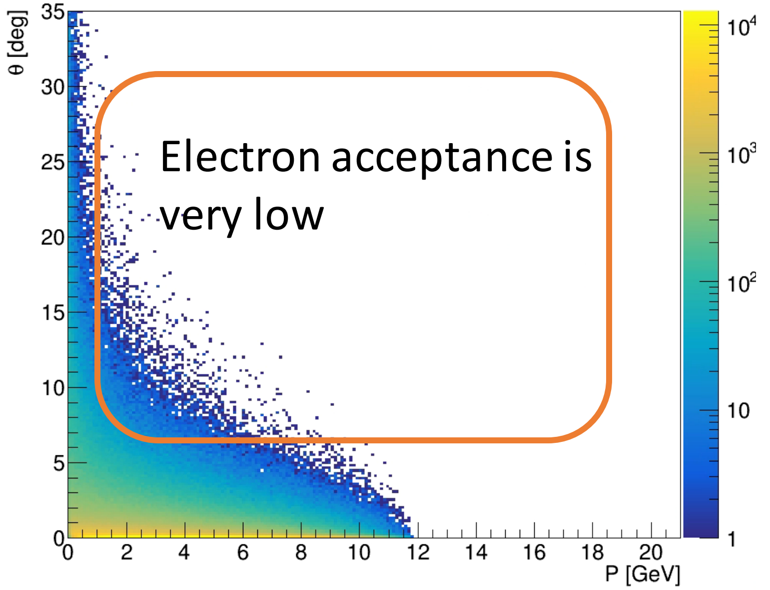
- About 20% of protons can be detected by the recoil detector
- Exclusiviry can be ensured by detecting $\boldsymbol{\mu}^-$, $\boldsymbol{\mu}^+$ and proton.

All $\boldsymbol{\mu}$-.



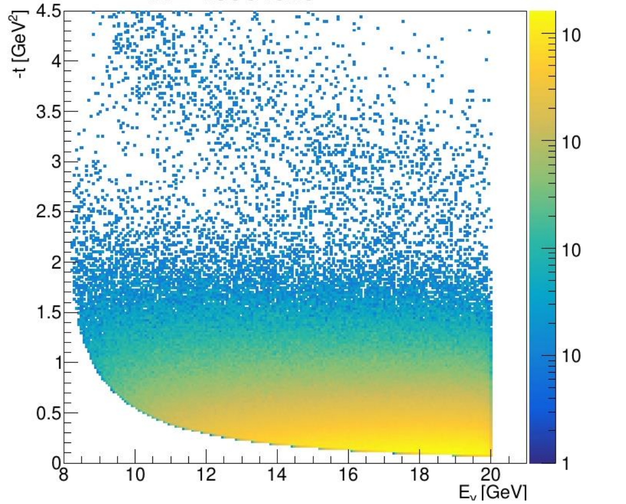
Detected $\boldsymbol{\mu}$-



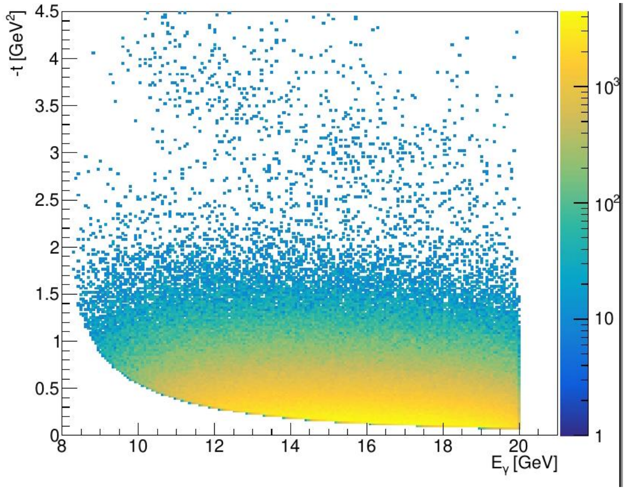


J/ψ production

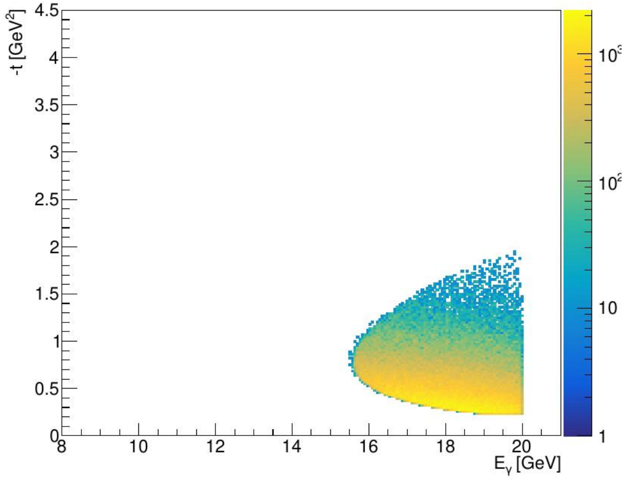
15.9 M J/ψ decaying into $\boldsymbol{\mu}$-$\boldsymbol{\mu}$+



5.8 M J/ψ detected, no requirement on p or e$^-$.



1.25 M J/ψ and p detected, no requirement on e$^-$.



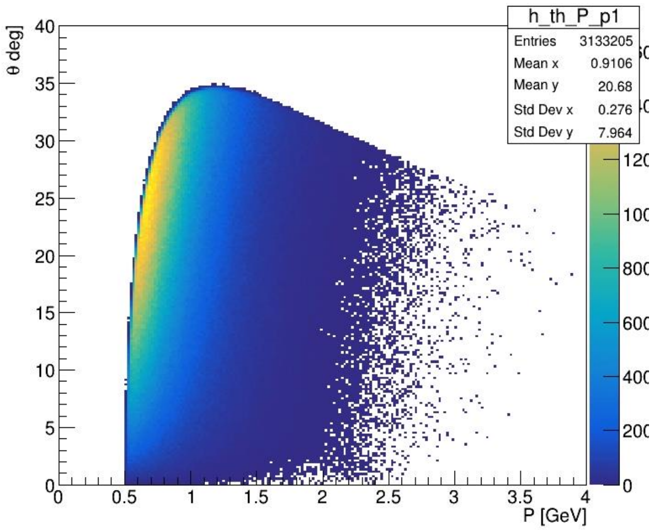
- Unfortunately, with only J/ψ detection, we cannot ensure exclusivity: Cannot uniquely determine E_{γ}.
- Currently studying possibility if, only polar angle detection of the proton can help.
- Though with proton detection, we should be able to do high stat measurement of J/ψ x-sec as a function of E_{γ} in the E_{γ} > 16 GeV.
- We should be able to extract high stat differential x-sec on t in more than 10 E_{γ} bins above 16 GeV.

X(3872) production

Possible decays that can be detected with $\boldsymbol{\mu}$CLAS12

- $\boldsymbol{\chi}\rightarrow\boldsymbol{\gamma}$J/$\boldsymbol{\psi}$ // 8*10^{-3} x 0.059 = 4.7*10^{-4}.
  - J/$\boldsymbol{\psi}\rightarrow\mu$-$\mu$+ // 0.059
- $\boldsymbol{\chi}\rightarrow\boldsymbol{\gamma}\boldsymbol{\psi}$' // 0.045 x 8*10^{-3} = 4.7*10-4..
  - $\boldsymbol{\psi}$' $\rightarrow\mu$-μ+ //8*10-3
- $\chi\rightarrow\omega\, J/\psi$ // 2*10-4
  - $\omega\rightarrow\gamma\pi^0$ // 0.0828
  - J/$\boldsymbol{\psi}\rightarrow\mu$-$\mu$+ // 0.059

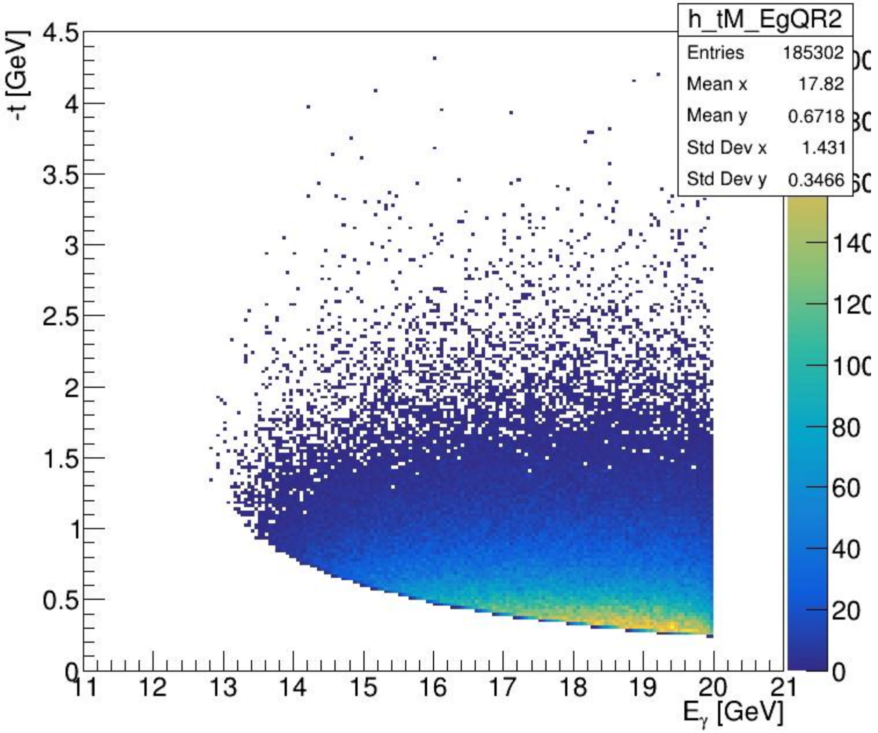
Protons



No acceptance for protons in the recoil detector!

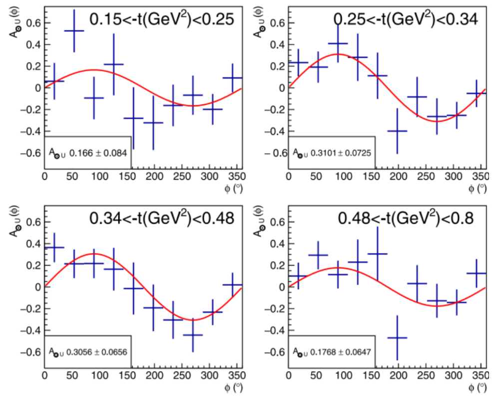
Studying possibilities to recover photon energy...

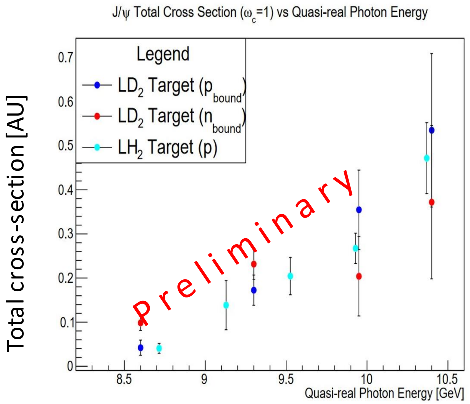
185 K $\boldsymbol{\chi}$ (will be detected) just in single decay mode: $\boldsymbol{\chi}\rightarrow\boldsymbol{\gamma}$J/$\boldsymbol{\psi}$



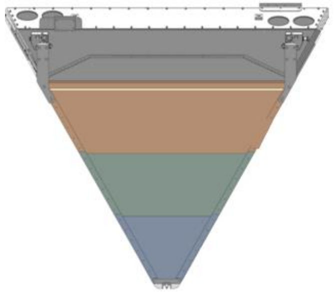
Summary

- There are multiple ongoing analysis on J/$\boldsymbol{\psi}$ and TCS with CLAS12 data.
    - One publication and another close to be publication

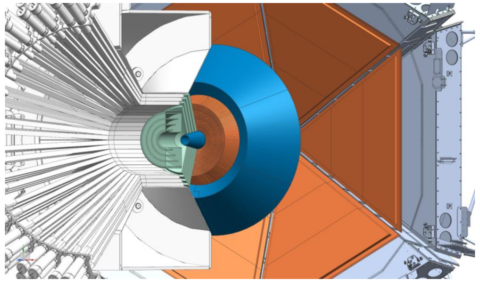




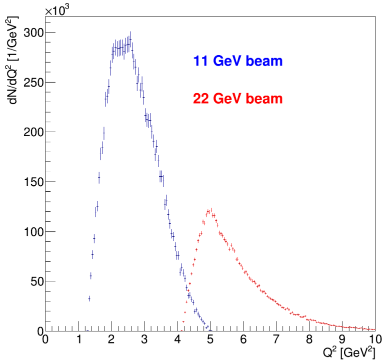
- CLAS12 tracking will be upgraded, that will allow the remaining of the data to be taken at x2 Luminosity.

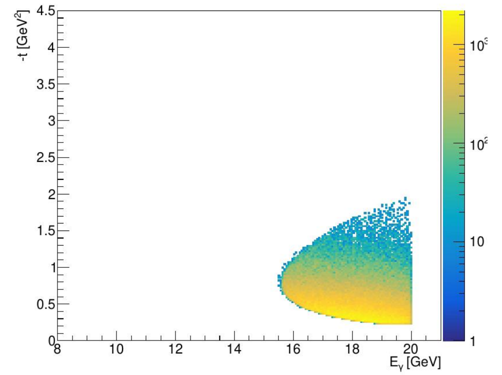


- Planning to submit a proposal to upgrade the CLAS12 detector which can take x 100 of standard Luminosity

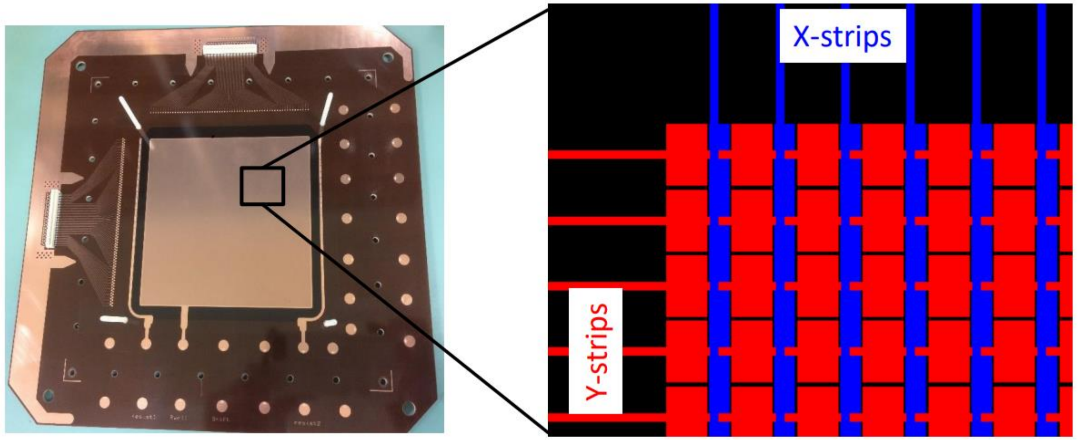


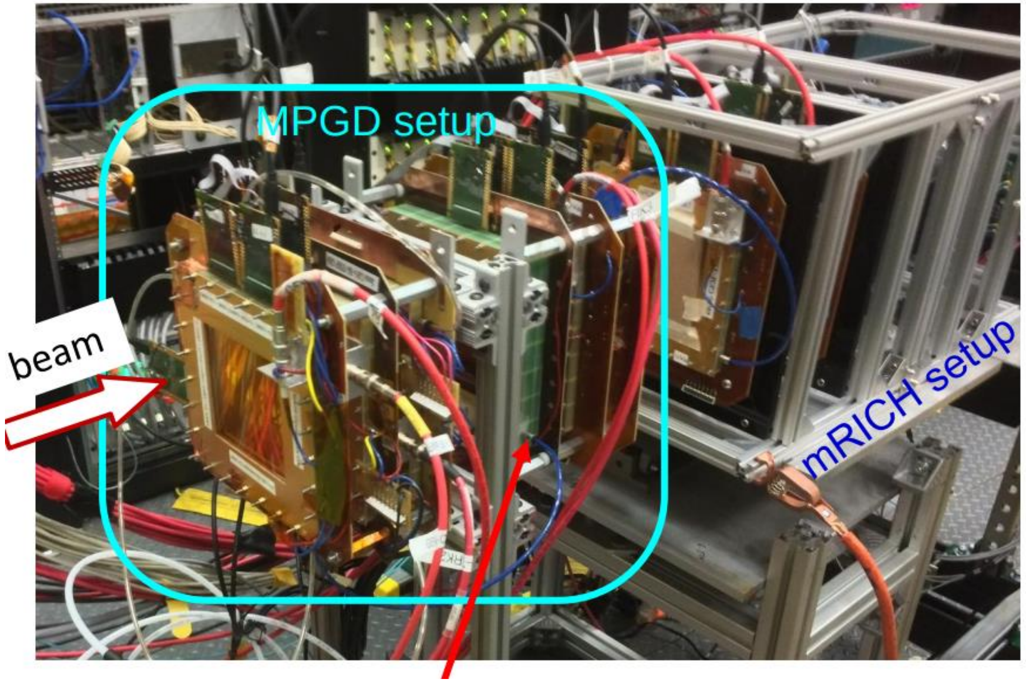
- The same detector will work for 20+ GeV upgrade:
    - Will allow to access GPDs through higher Q^2 regime
    - High stat J/$\boldsymbol{\psi}$ measurements at E$\boldsymbol{\gamma}$ > 16 GeV
    - New Stats will be available too, currently studying possibilities to ensure exclusivity of reactions.





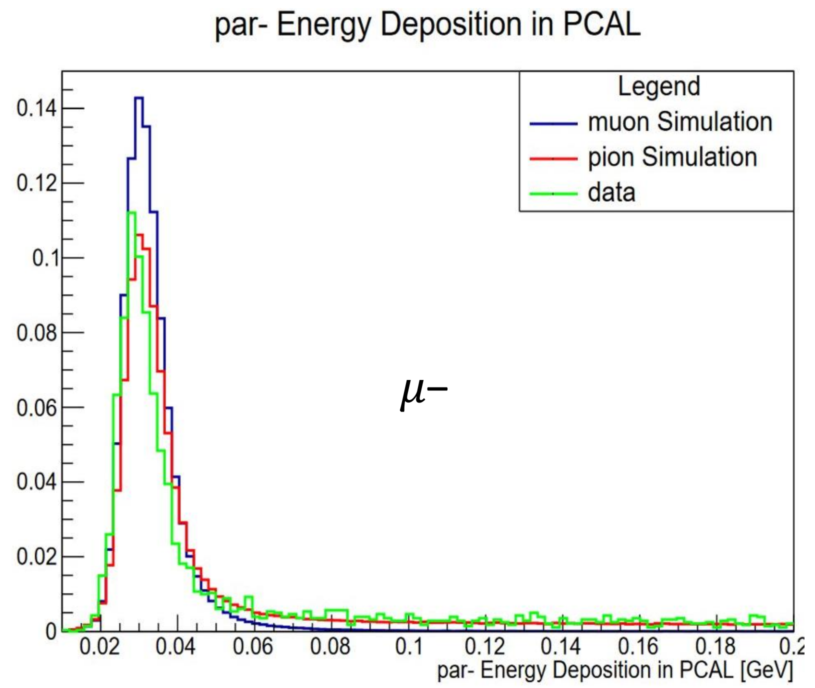
Backup


X-strips
Y-strips


MPGD setup
beam
mRICH setup

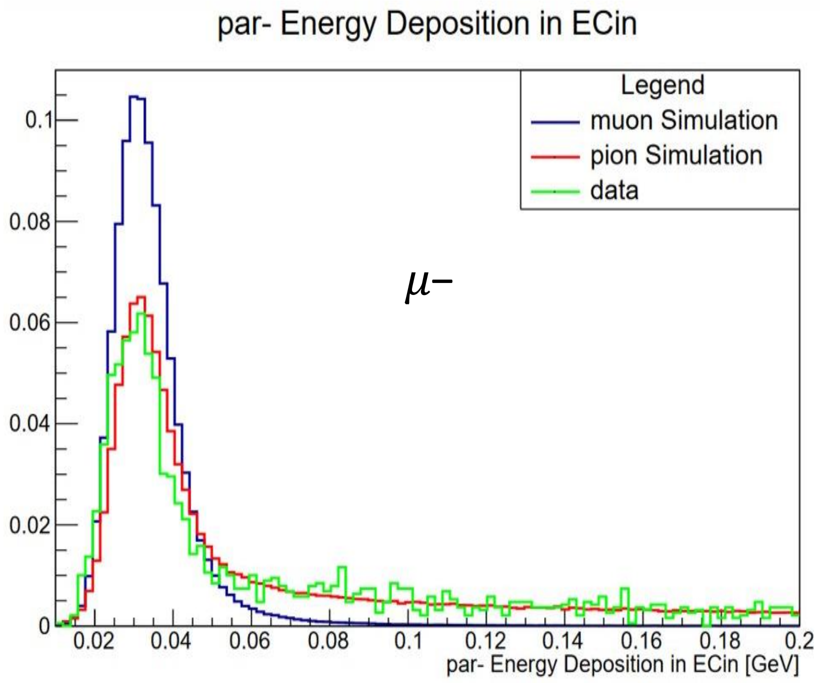
Muon selection

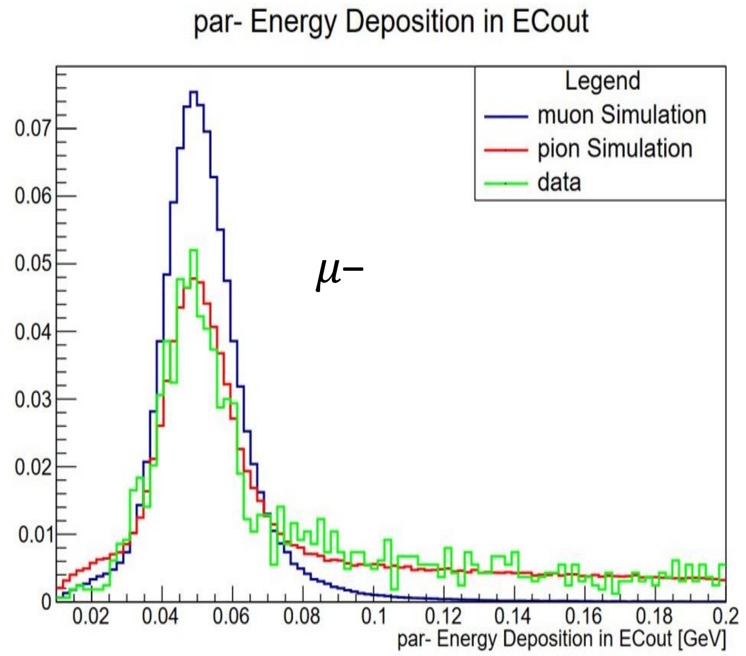
Analysis of R. Tyson



While in the PCal most of pions show MIP signature, at the ECOuter, already a significant number of pions will not pass the MIP selection cuts.

Similar distribution for positive muons





Muon energy deposition cuts

$$E_{\mathrm{PCal}} < 60\ \mathrm{MeV}$$

$$E_{\mathrm{EC_{in}}} < 80\ \mathrm{MeV}$$

$$E_{\mathrm{EC_{out}}} < 110\ \mathrm{MeV}$$