TCS and J/ψ at JLab Hall B

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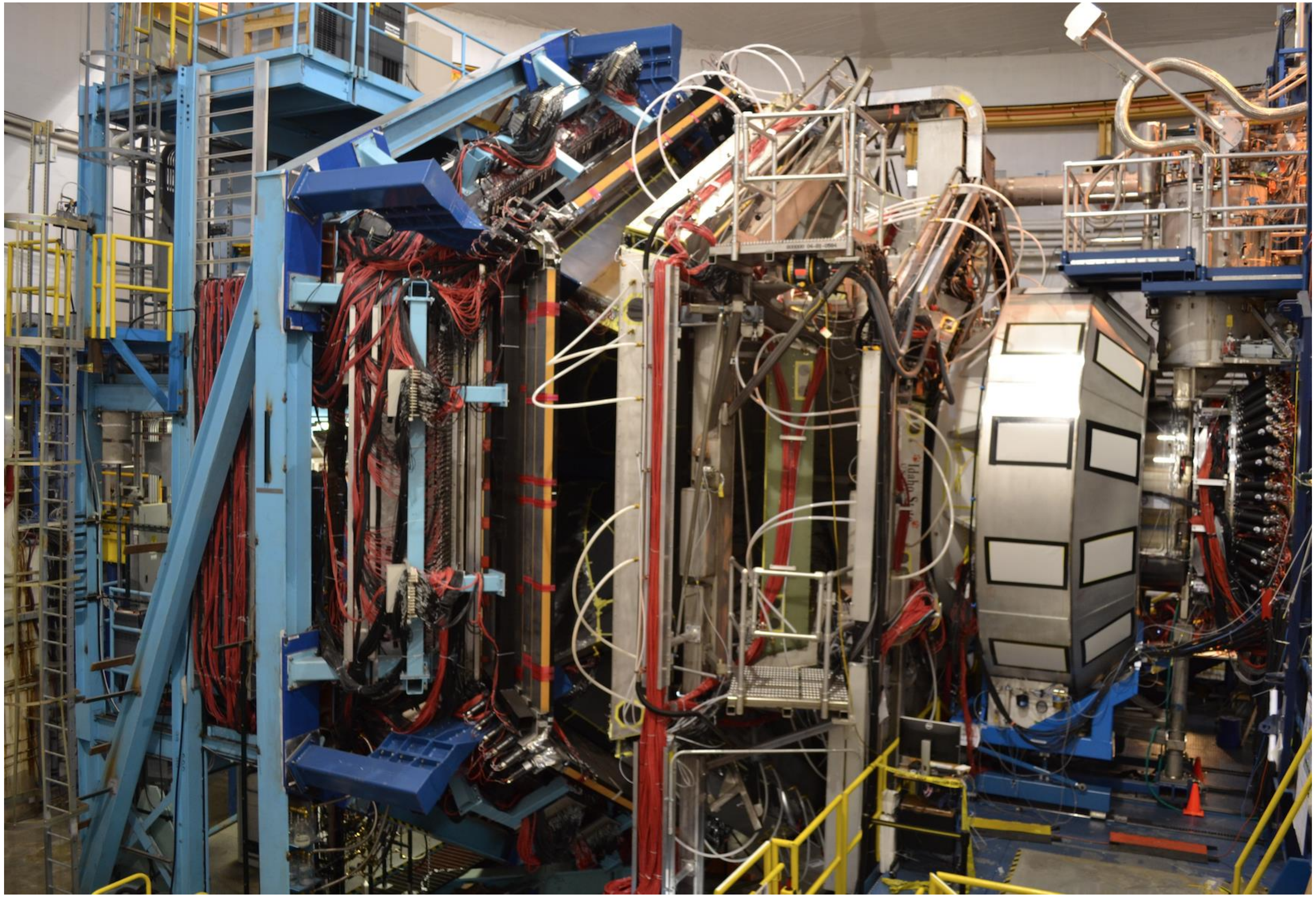
Towards improved hadron femtography with hard exclusive reactions 2023

Aug 7 – 11, 2023 Jefferson Lab



The outline

- Physics motivations
  - What will we learn measuring TCS and J/ψ

- Timelike Compton Scattering
  - Partially completed experiments
    - RG-A : Unpolarized target
    - RG-C : Longitudinally polarized target

- J/ψ photoproduction near threshold
  - Partially completed experiments
    - RG-A : Unpolarized target
    - RG-B : Unpolarized Deuterium target

- Summary

Relevant experiments

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

Timelike Compton Scattering

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

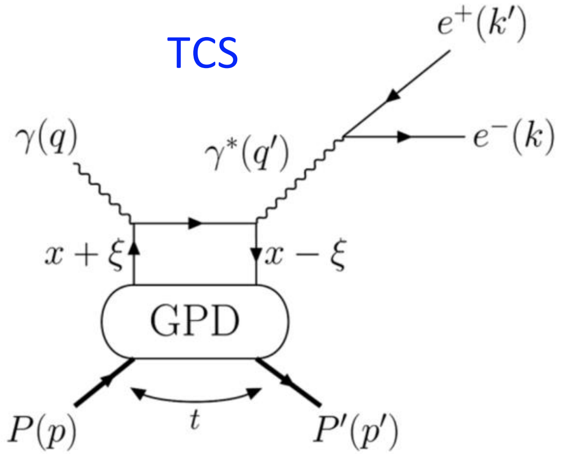
Since early of 2000s, experimental observables are reported: X-sec, Beam and Target spin asymmetries...

However only DVCS is not enough for understanding GPDs. Different reaction(s) are needed in order to constrain GPDs experimentally.

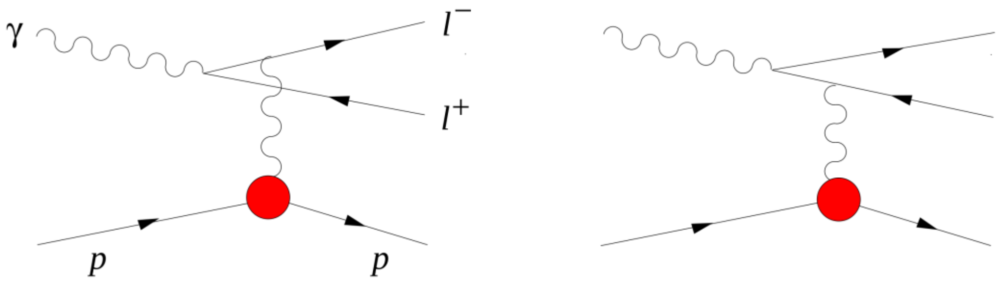
Some information is not easily accessible in DVCS, but are easier to access in TCS, e.g. Re part of CFF (H).

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

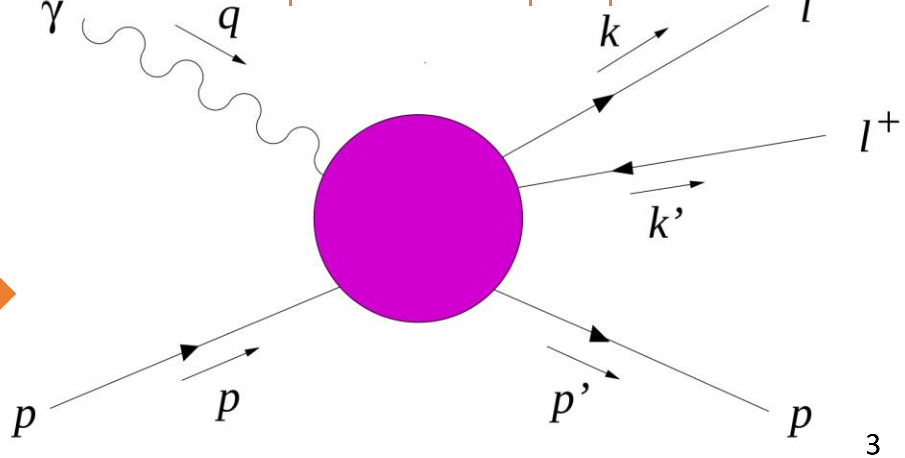
TCS



BH



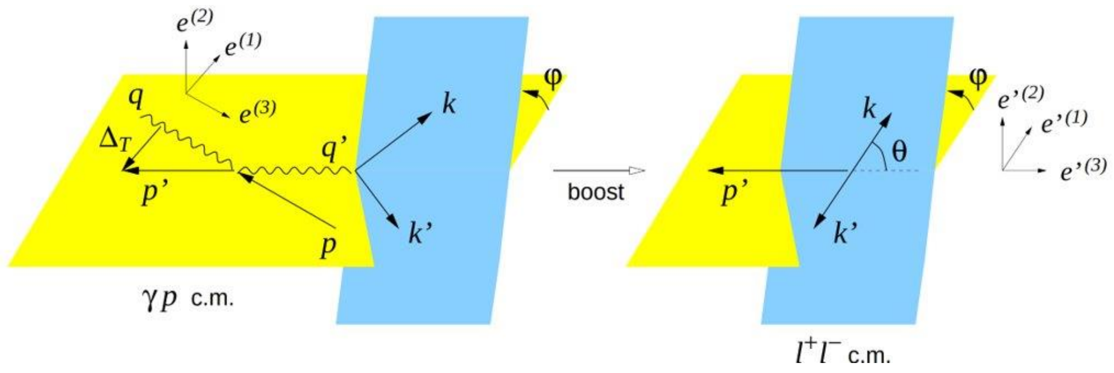
Photoproduction of lepton pairs



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 information on GPDs can be extracted from the interference of BH and TCS amplitudes.



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

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

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

Projects out the cosine moment of the interference part of the cross section, and hence access the Real part of the scattering amplitude.

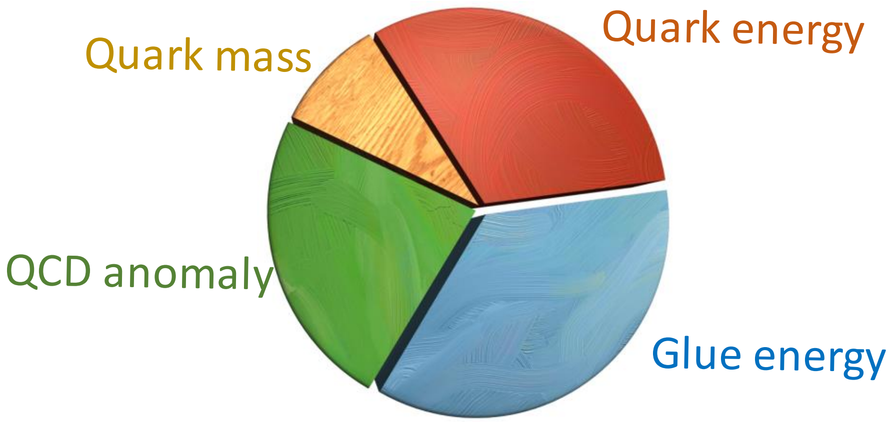
Polarization asymmetry $\mathrm{A}_{\odot\mathrm{U}} = \dfrac{\sigma_{\mathrm{LH}} - \sigma_{\mathrm{RH}}}{\sigma_{\mathrm{LH}} + \sigma_{\mathrm{RH}}}$

Proportional to the sine moment of the polarized interference part of the cross section, and hence access the imaginary part of the scattering amplitude.

J/ψ production near the threshold

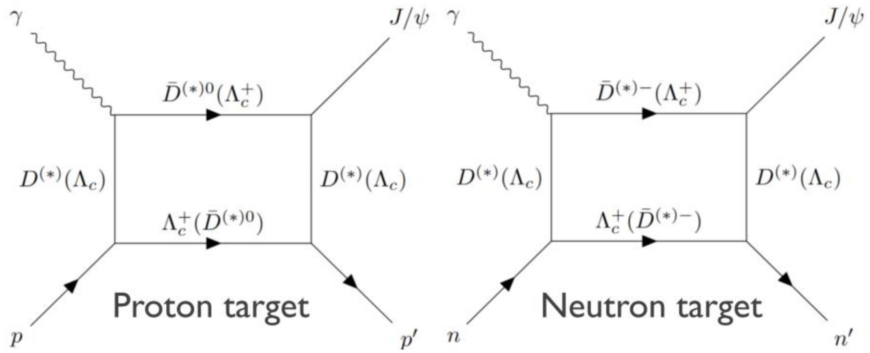
- Cross-section measurement near the threshold gives important insight of the production mechanism

- Access to the gluonic GPDs of the nucleon



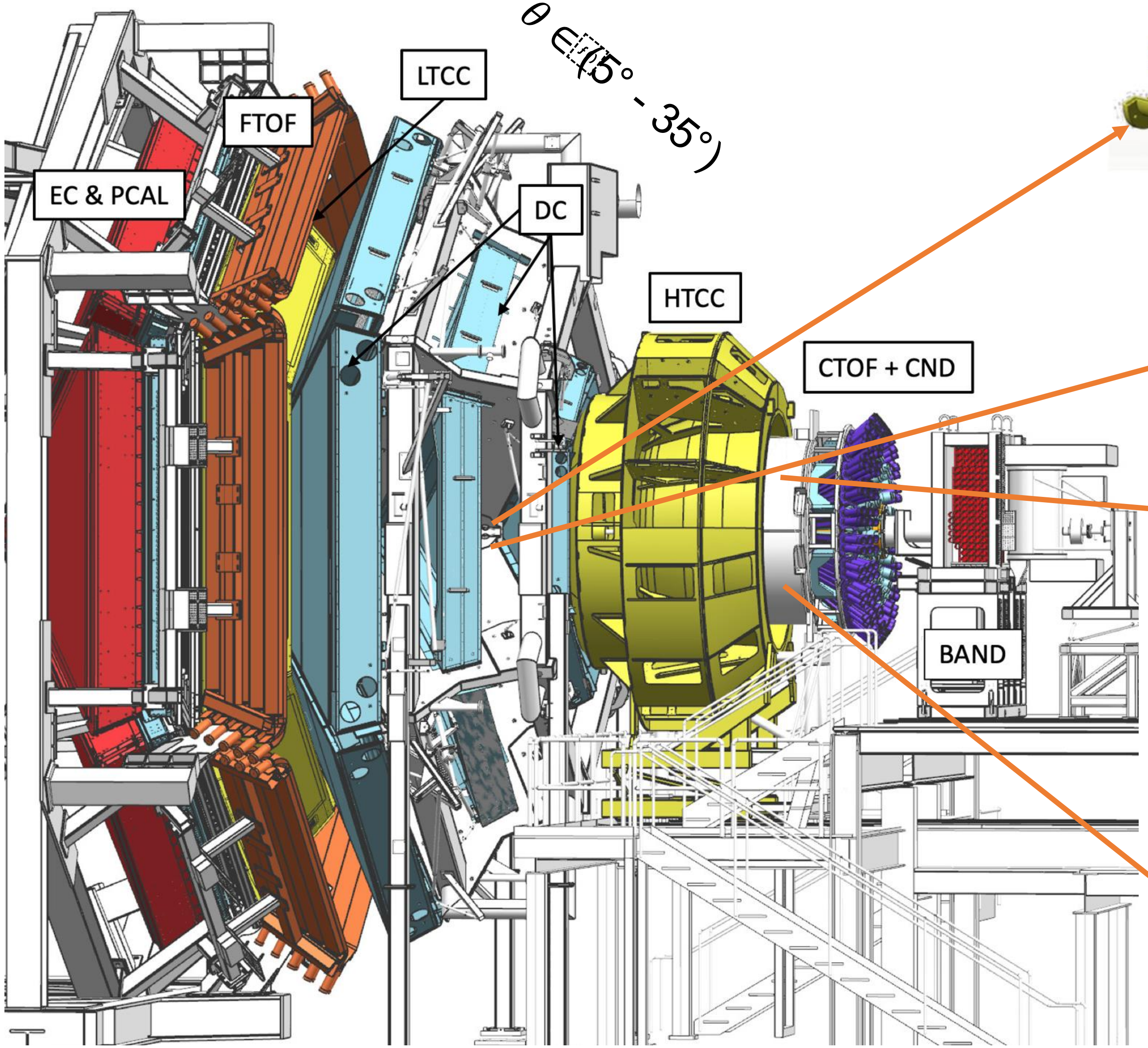
- Trace anomaly. Decomposition of the proton mass
- Mass radius of the proton
- Access Gravitational Form factors (or EMT form factors)

- Production on Deuterium target
  - Comparing J/ψ cross-sections on the proton and neutron can shed more light on the production mechanism, if only gluon exchange, cross sections should be identical.
  - Allows direct access to the J/ψN by final state interactions.



The CLAS12 Detector

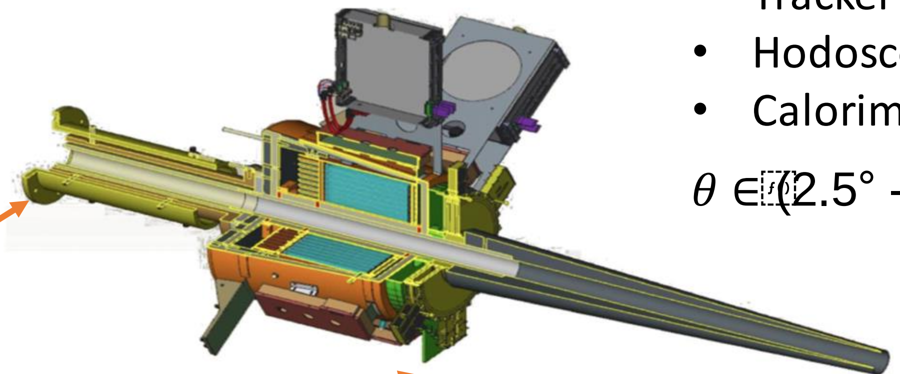
$\theta \in (5° - 35°)$



Forward Tagger

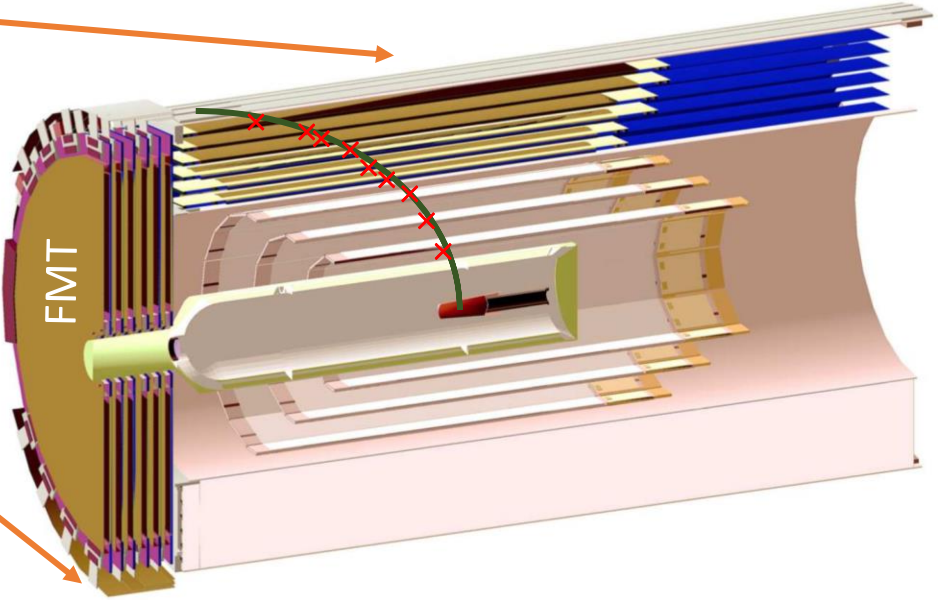
- Tracker
- Hodoscope
- Calorimeter

$\theta \in (2.5° - 4.5°)$



Central Vertex Tracker

$\theta > 35°$



Photoproduction with electron beam

Two photon sources:

Real photons + Virtual photons

Electroproduction cross-section can be expressed as:

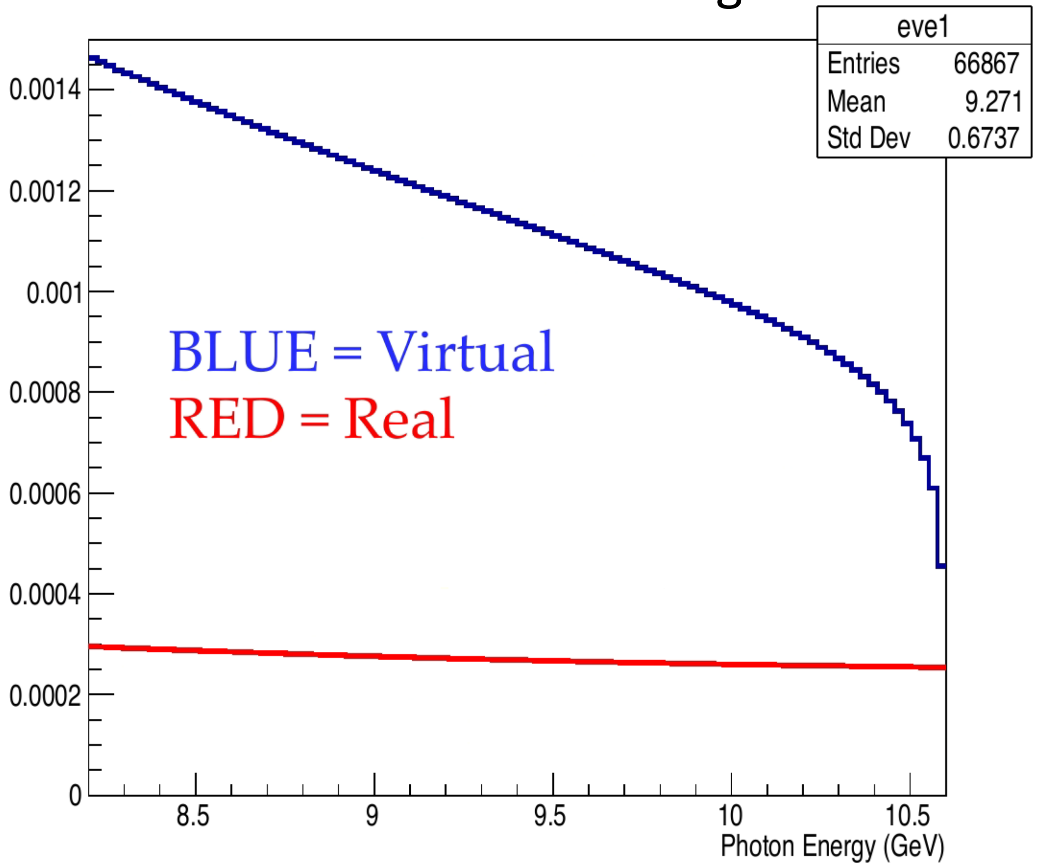
$$\frac{d\sigma}{dt} = \Gamma_\gamma \cdot \frac{d\sigma_\gamma}{dt} + \Gamma_{\gamma *} \cdot (\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt})$$

Real photon flux Virtual photon flux

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

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

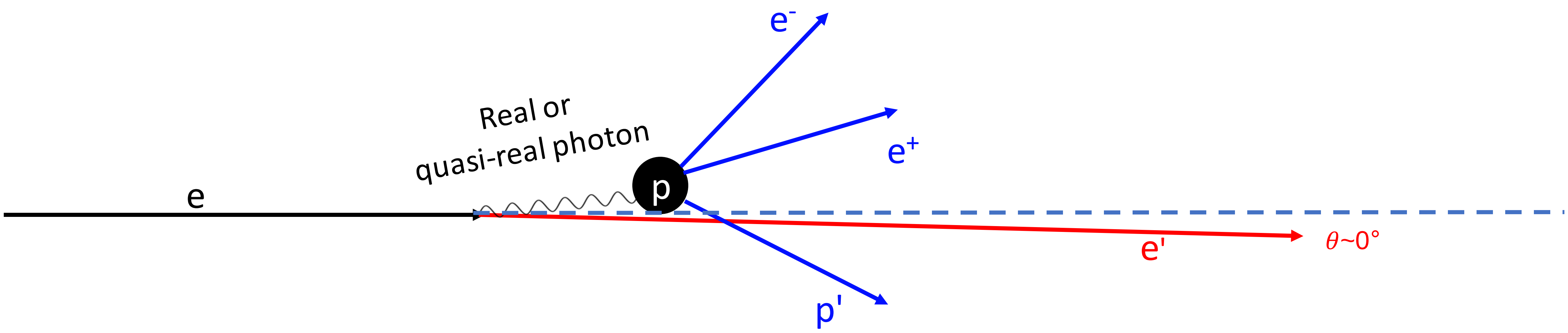
Flux for 5cm LH2 target



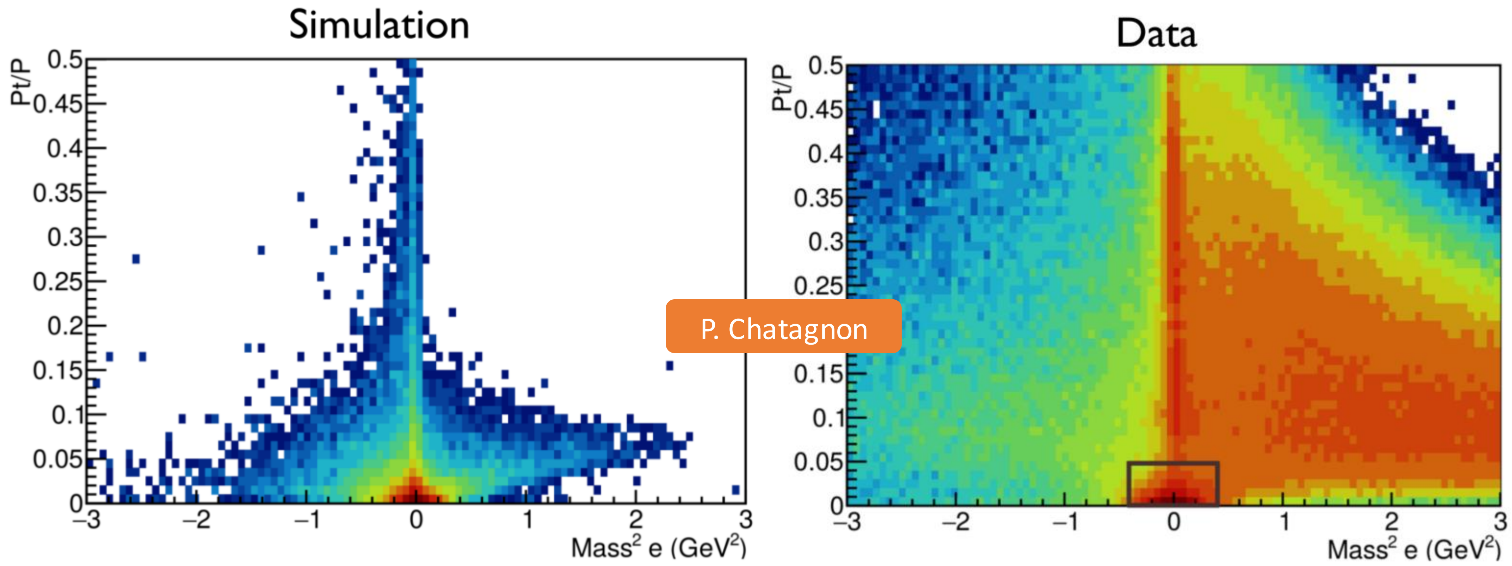
$$n(E_\gamma) = \frac{l}{2 \cdot X_0} \frac{1}{E_\gamma} \cdot \left(\frac{4}{3} - \frac{4}{3} \frac{E_\gamma}{E_b} + \frac{E_\gamma^2}{E_b^2} \right) dE$$ Real photon flux

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

Selection of events with quasi-real photoproduction



The kinematics of the scattered beam electron is identified as the missing 4 momentum of the e^-e^+p' system with Q^2~0 and M_{mis}~0



Experiments/data sets

Run Group A (RG-A)

Target:
5cm Unpolarized LH2

Run periods
- Spring 2018
  - Beam energy 10.6 GeV
  - DC HVs were not optimized: poor mom. resol.
  - Data was not used in the analysis
- Fall 2018
  - Beam energy 10.6 GeV
  - Run with inbending and *outbending* torus polarities
- Spring 2019
  - Beam energy 10.2 GeV.
  - Inbending only

Run Group B (RG-B)

Target:
5cm Unpolarized LD2

Run periods
- Spring2019
  - Beam energy 10.6 GeV and 10.2 GeV
  - Torus polarity inbendng
- Fall 2019
  - Beam energy 10.4 GeV
  - Torus polarity *outbending*
- Winter 2020
  - Beam energy 10.4 GeV
  - Torus polarity inbending

Run Group C (RG-C)

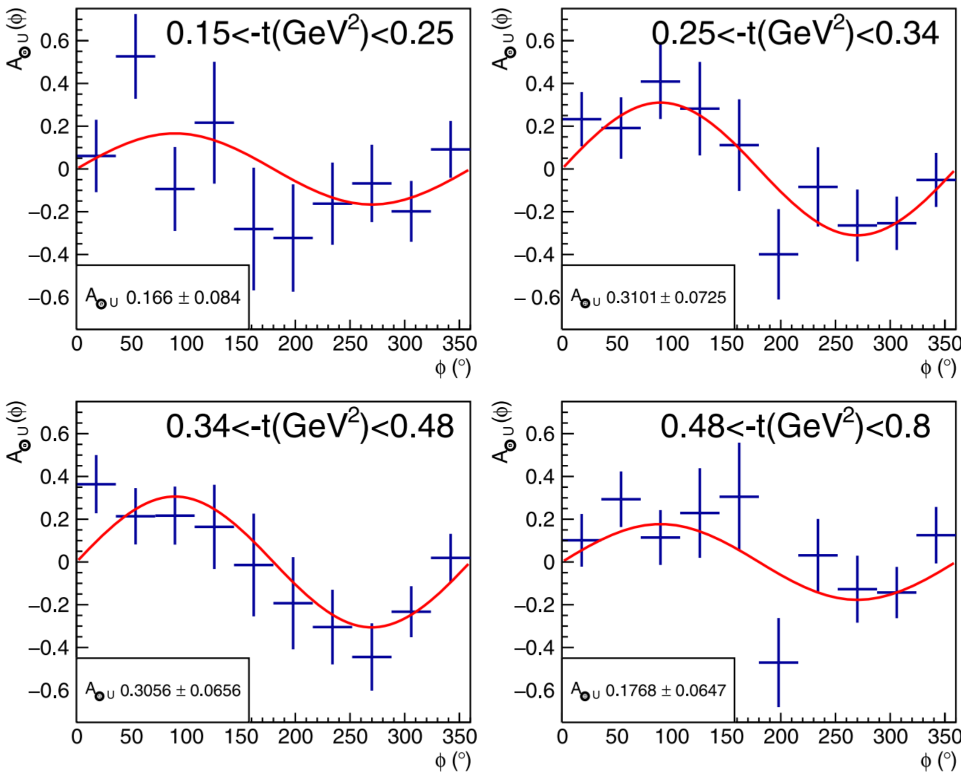
- June 2022 to March 2023
- Longitudinally polarized NH2 and ND2 targets
- Beam energy 10.56 GeV
- Inbending/Outbending

Note: Inbending (Outbendng) means that the torus magnetic field bends negative tracks in the forward detector towards (away) from the beamline.

The 1st TCS measurement

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

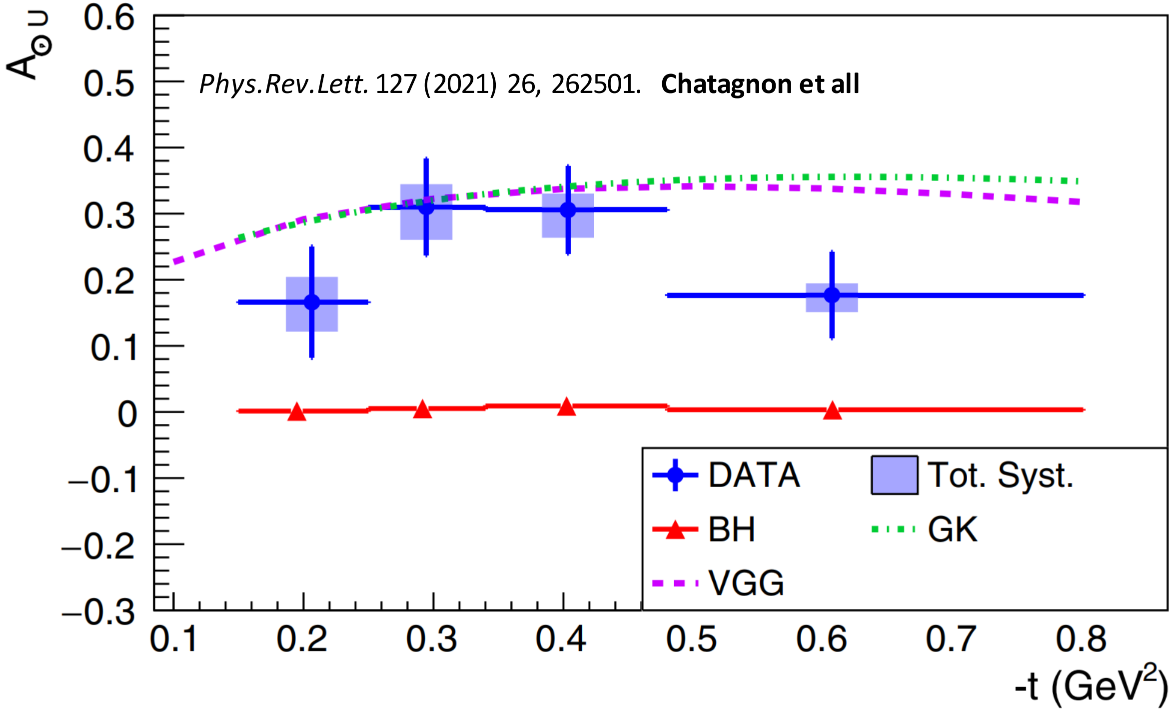
Polarization asymmetry



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

The polarization asymmetry is measured in 4 –t bins.

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



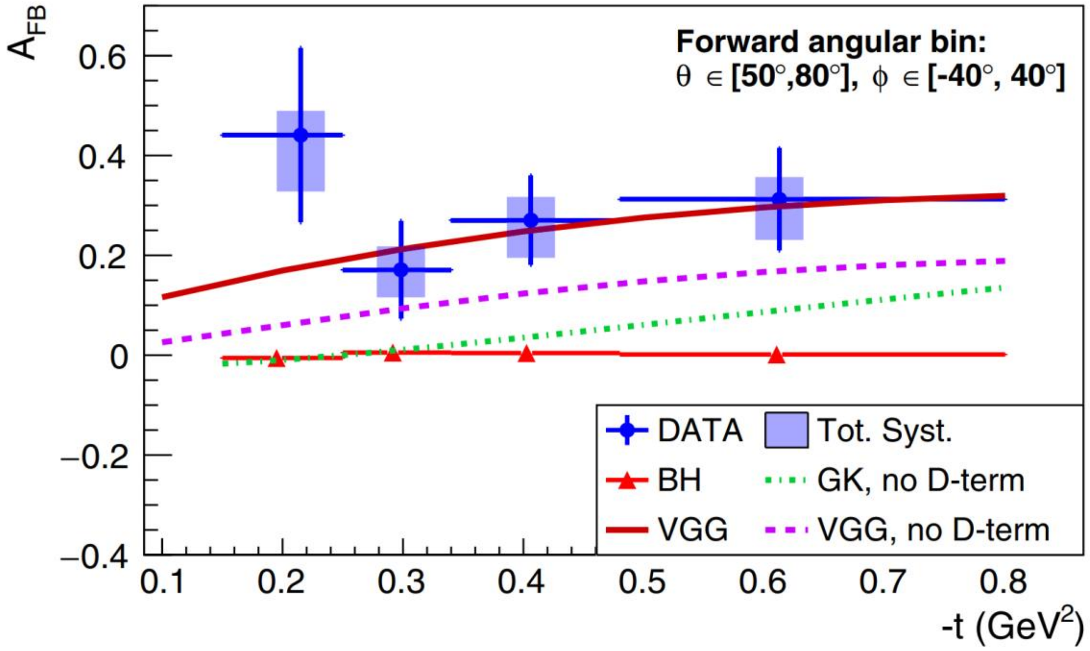
Polarization transfer L is calculated as:

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

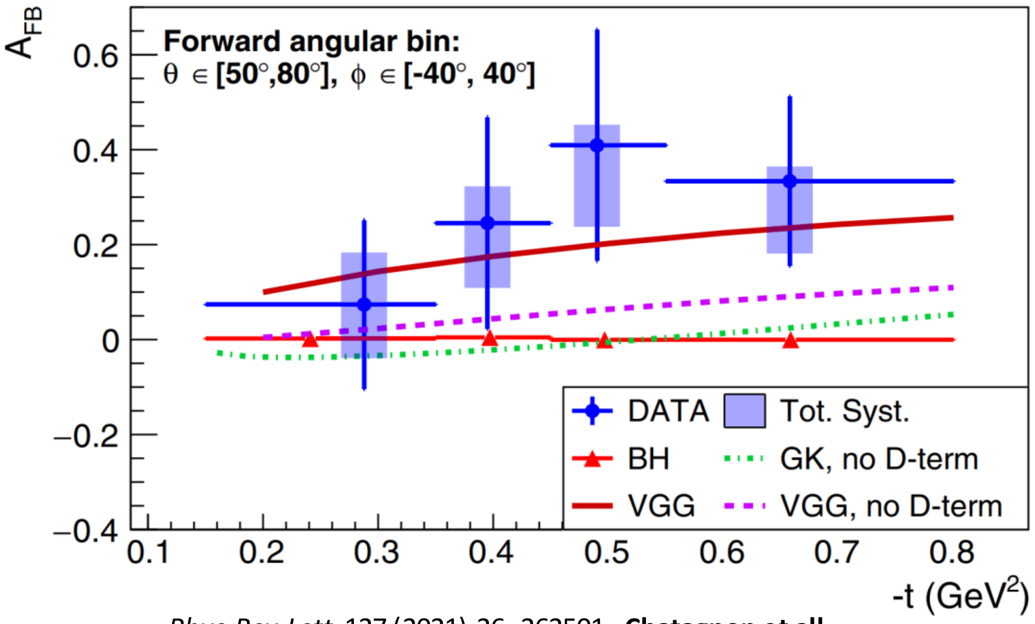
The 1st TCS measurement

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

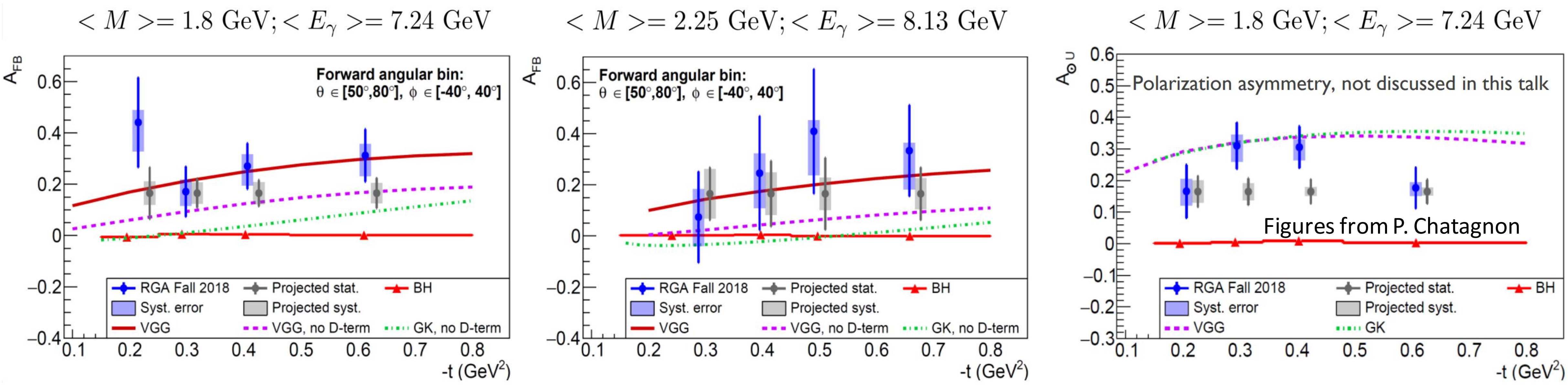


Phys.Rev.Lett. 127 (2021) 26, 262501. **Chatagnon et all**

- Clear contribution from the TCS diagram
- Hints at the universality of GPDs

Expected improvements on TCS measurements

- The TCS paper used only about 1./3 of the so far collected data on the proton target
- Since that, significant improvements in the offline reconstruction
    - Better detector calibrations
    - Using AI based techniques, charged track reconstruction in the Forward detector is significantly improved
        - Close to x2 for TCS/JPsi final state
- The Spring 2019 part of the proton target data is already re-processed, and the rest of Fall 2018 (inbending and outbending) is expected to be completed within couple of months.
- This is expected to significantly improve uncertainties on TCS asymmetries.



Background subtracted data using same-charge lepton events

- Opposite charge leptons

Background final states ($\pi^+ \rightarrow e^+$)

$$e'p'e^+(e^- + X) + e'p'\pi^+(\pi^- + X)$$

Physics final state

$$e^-e^+p'(e')$$

$$N(e^+e^-p') = n_S(e^+e^-) + n_{BG}(e'e^+/\pi^+)$$

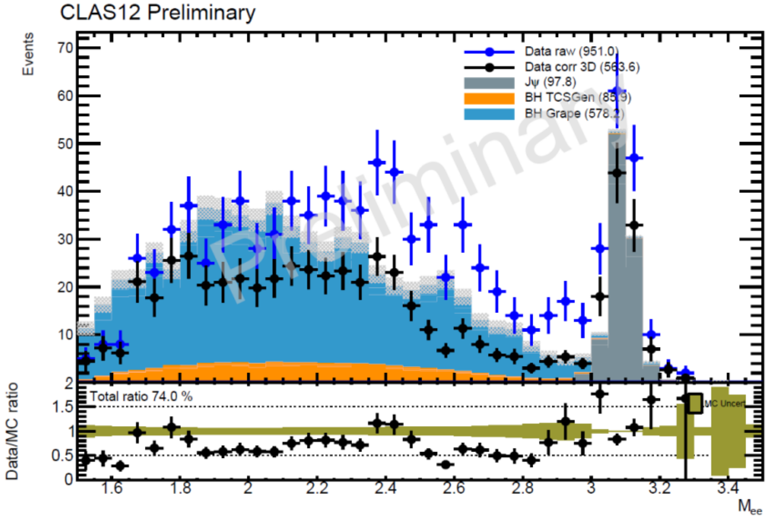
- Same charge leptons

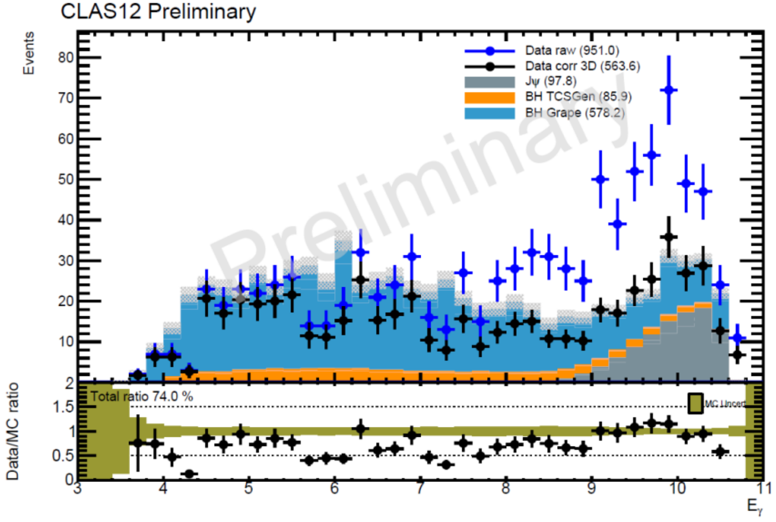
$$ep \rightarrow p'e^-e^-(X \simeq e)$$

$$e'p'\pi^-(\pi^+ + X) + e'p'e^-(e^+ + X)$$

- Background correction weight, combining inbending and outbending data:

$$w = \frac{n_S}{(n_S+n_{BG})} = 1 - \sqrt{\frac{N_{e^-e^-p}}{N_{e^+e^-p}}\bigg|_{In}\frac{N_{e^-e^-p}}{N_{e^+e^-p}}\bigg|_{Out}}$$



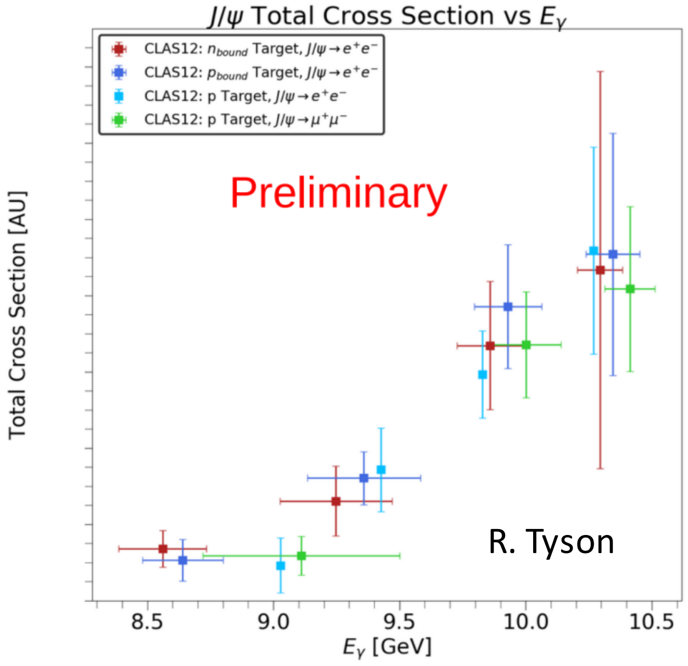


Slide from P. Chatagnon's presentation

Deuteron target and full statistics projections

R. Tyson analysis of RG-B data (LD2 target) is quite advanced.

- This represents about 30% of RG-B data.
- Extending the analysis to the full RG-B data, plus AI-assisted and denoised tracking, will significantly improve uncertainties.

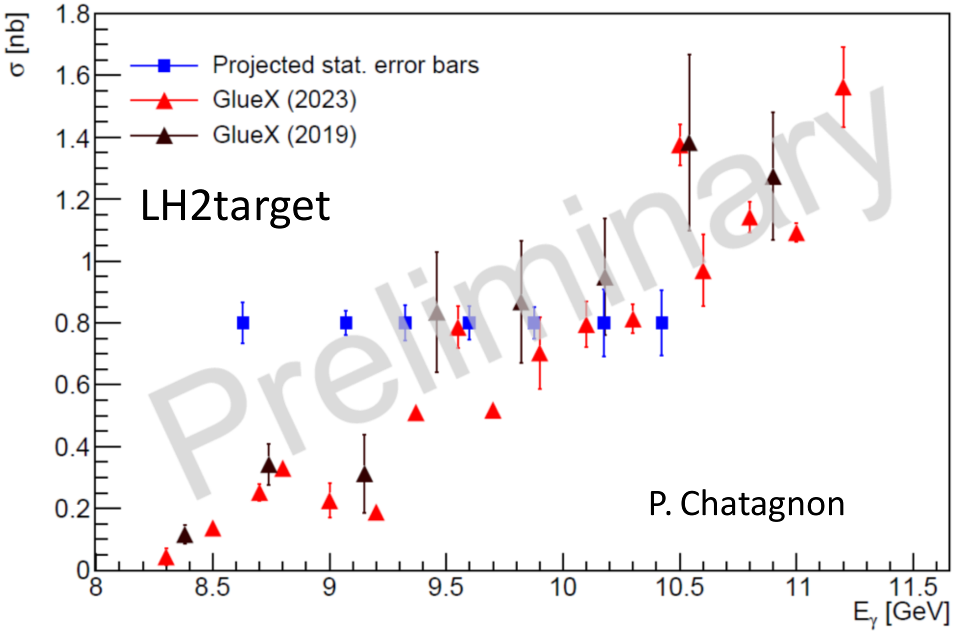


- $en_{bound} \to (e')e^+e^-n$
- $ep_{bound} \to (e')e^+e^-p$
- $ep \to (e')\mu^+\mu^-p$
- $ep \to (e')e^+e^-p$

RG-A data

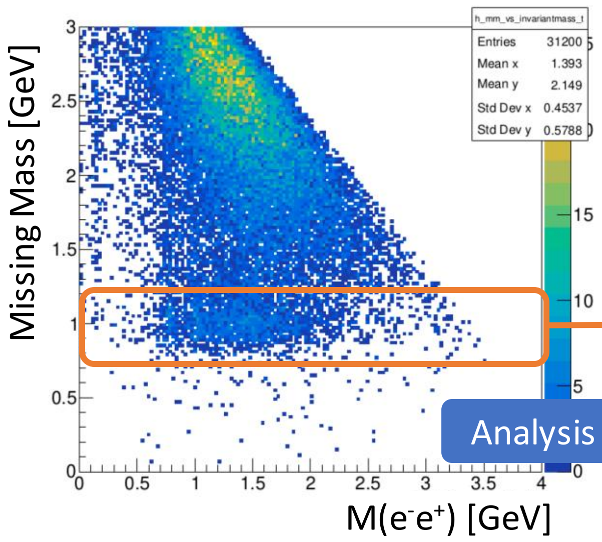
Analysis by P. Chatagnon is quite advanced, waiting the pass-2 data to be fully cooked before finalizing.

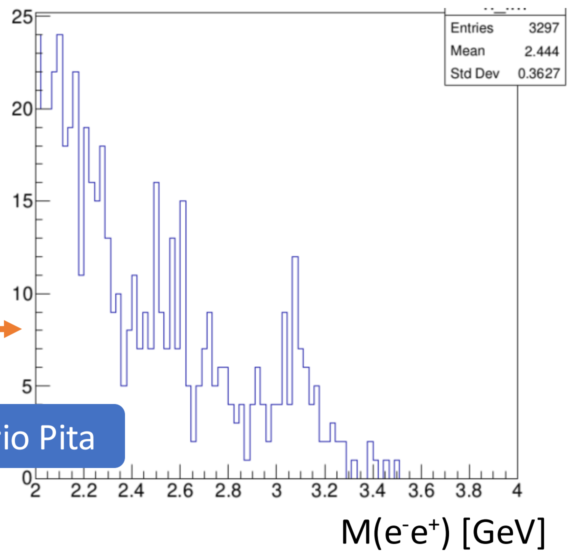
- Uncertainties are estimated for All RG-A data (unpolarized proton target), and 50% boost of the statistics (compared to pass1).
- Comparable to GlueX uncertainties.



Other ongoing analysis

Tagged J/ψ production:



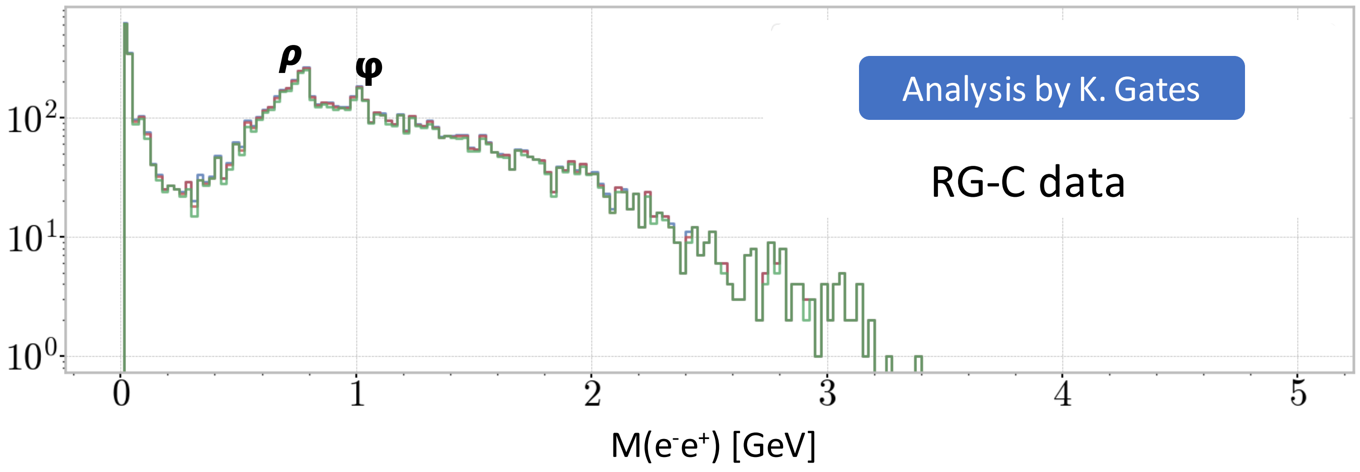


The beam scattered electron is tagged by the forward tagger.

$$ep \rightarrow e'J/\psi\ p' \rightarrow e'e^-e^+(p')$$

Statistics is not great; however, it serves as an important cross-check for the quasi-real photoproduction technique.

Doble spin asymmetries in TCS using RG-C



Small fraction of run numbers on NH3 target

RG-C finished data taking in March of 2023

Summary

- The first TCS asymmetries are measured in Hall-B
  - Direct access to the real part of the CFF $\mathcal{H}$.
  - Observation of universality of GPDs.
  - Combining all the data on proton target, and tracking efficiency improvements will allow to significantly reduce uncertainties on asymmetries.

- J/ψ analyses on both proton and Deuteron targets are in an advanced stage
  - Reprocessing of data with improved reconstruction increased the statistics by almost twice. Analysis of available data set started.

- We have other analysis "tagged J/ψ" and "Double Spin Asymmetries in TCS"