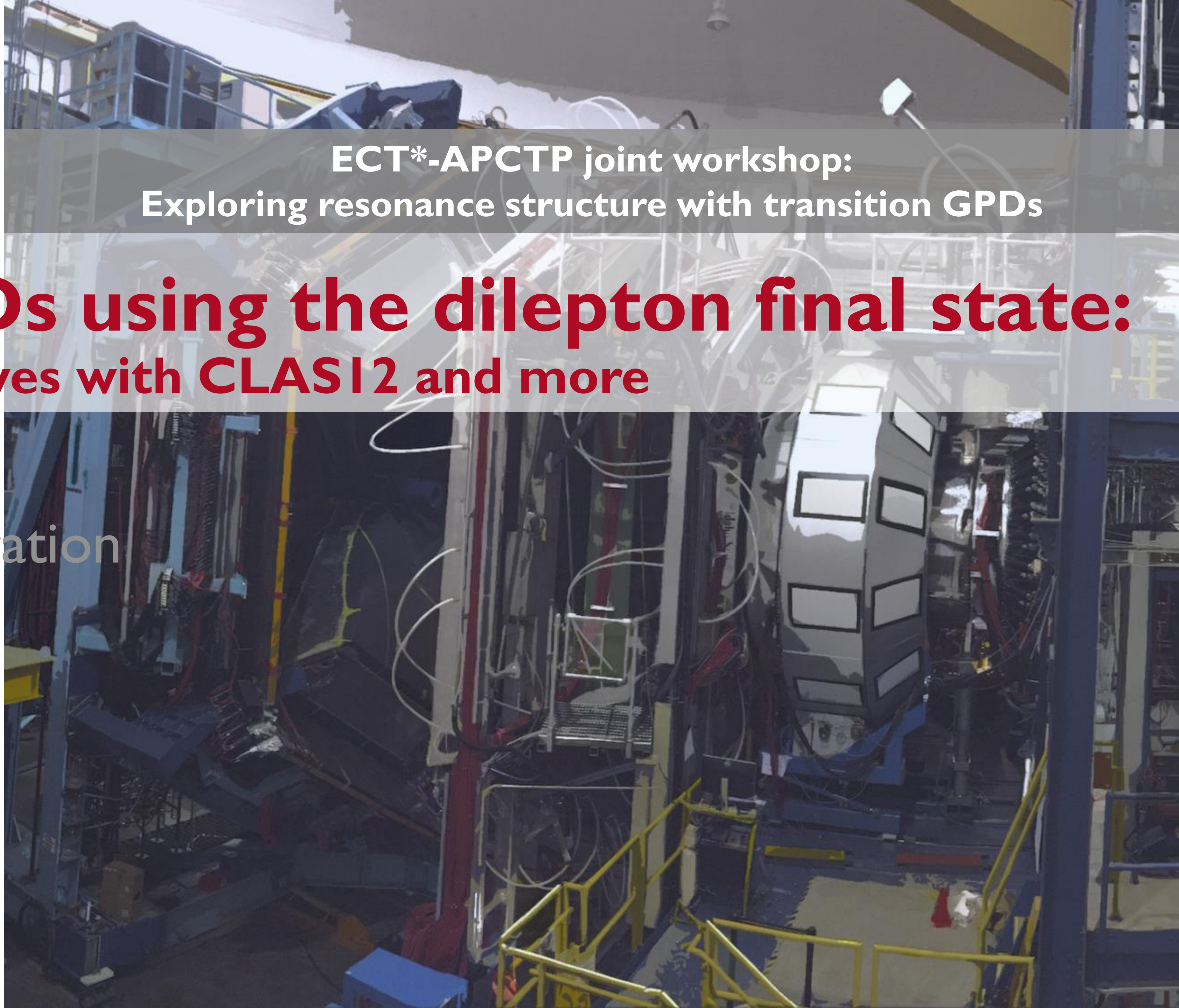

ECT*-APCTP joint workshop:
Exploring resonance structure with transition GPDs

Accessing GPDs using the dilepton final state:

Results and perspectives with CLAS12 and more

Pierre Chatagnon,

for the CLAS collaboration

August 21st to 25th 2023

Trento, Italy

Jefferson Lab clas

Outline of the talk

I	Introduction to GPDs and motivations for their measurements
II	The CLAS12 experiment at Jefferson Lab
III	Early results: First Timelike Compton Scattering measurement with CLAS12
IV	Ongoing effort : near threshold J/ψ photoproduction measurement on protons and neutrons
V	Long term perspectives with CLAS12: Luminosity upgrade and muon detection

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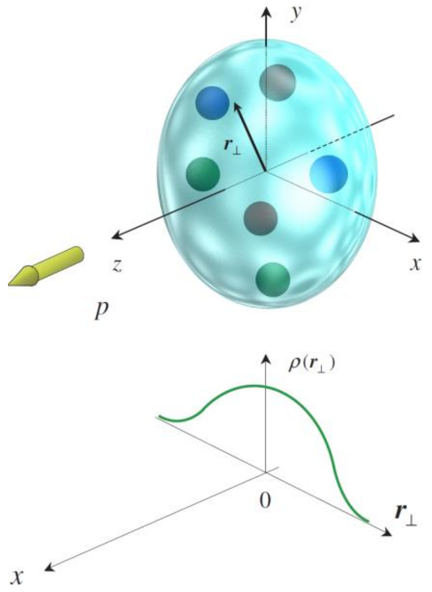
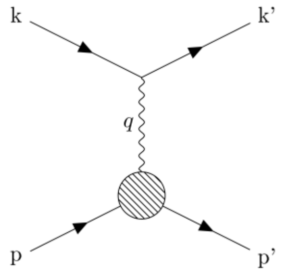
Part I: The Generalized Parton Distributions

Form Factors



Accessed via elastic scattering

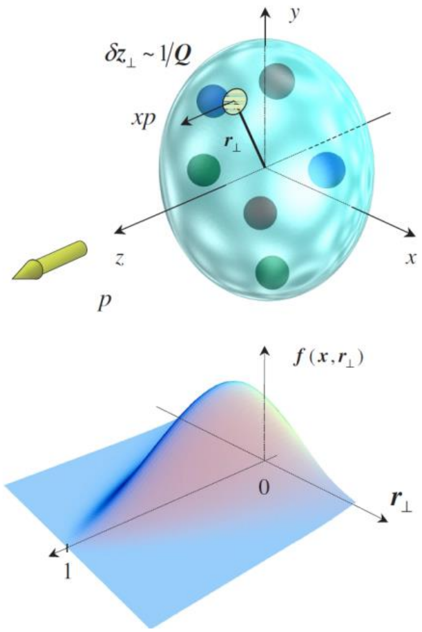


Position in the transverse plane

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$

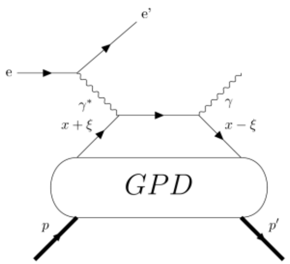
$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

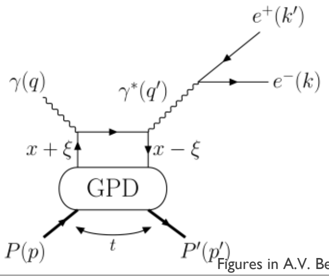
GPDs



… and their correlations

Accessed via exclusive reactions

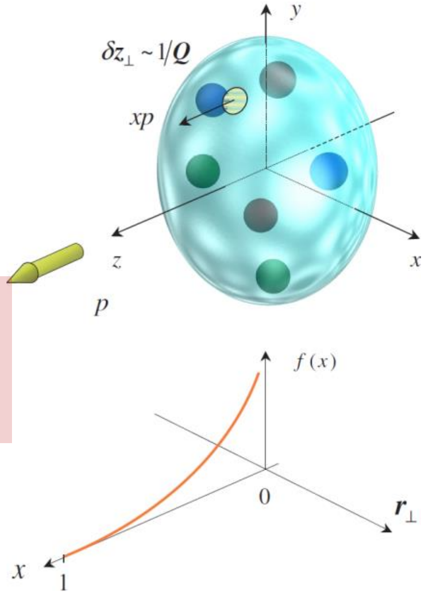




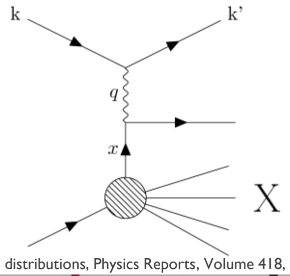
Momentum in the longitudinal direction

$$H^q(x,0,0) = \begin{cases} q(x), & x > 0 \\ -\bar{q}(-x), & x < 0 \end{cases}$$

PDFs



Accessed via Deep Inelastic Scattering



Figures in A.V. Belitsky, A.V. Radyushkin, Unraveling hadron structure with generalized parton distributions, Physics Reports, Volume 418, Issues 1–6 2005

What can we learn from GPDs ?

- Tomography of the nucleon: the Fourier transform of the GPDs can be interpreted as a probability density:

$$H^q(x, b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-ib_\perp \Delta_\perp} H^q(x, 0, -\Delta_\perp^2)$$

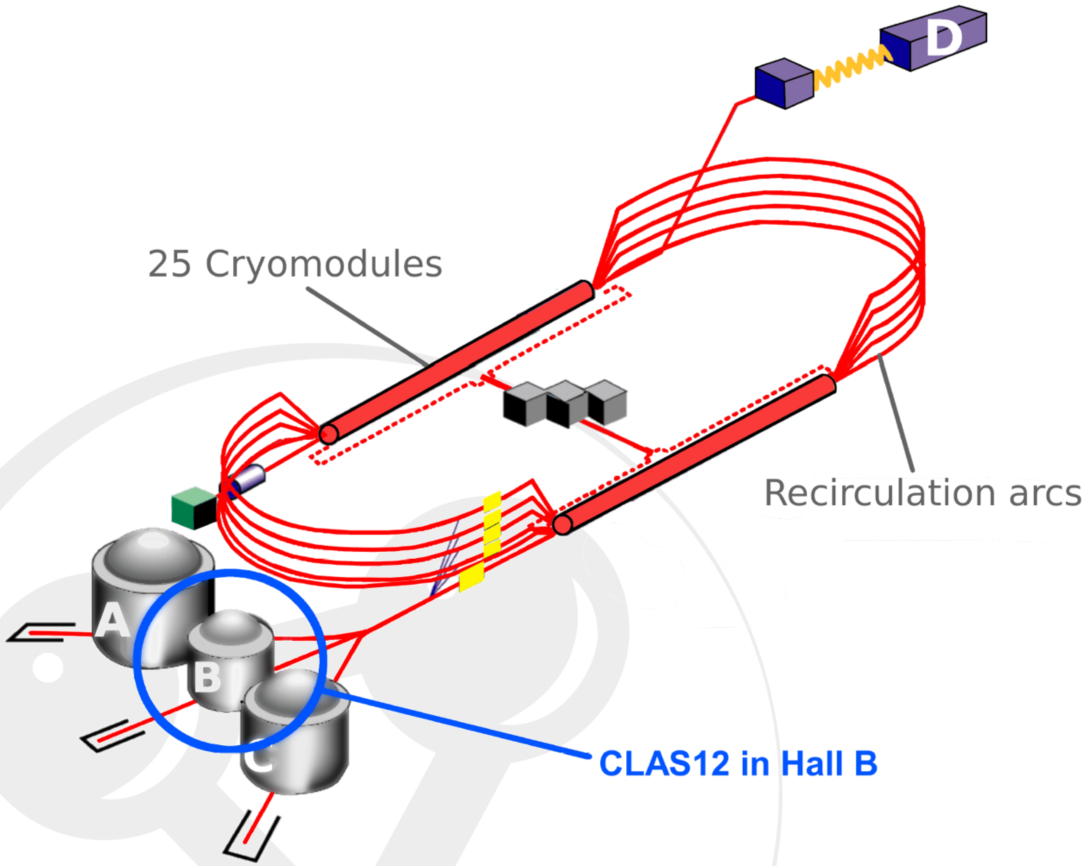
- Understanding the spin composition of the nucleon (aka the "spin puzzle") using the Ji's sum rule:

$$\frac{1}{2} = J_Q + J_G \longrightarrow J_Q = \sum_q \frac{1}{2} \int_{-1}^{1} dx\ x(H^q(x, \xi, 0) + E^q(x, \xi, 0)) = \sum_q \frac{1}{2}(A^q(t) + B^q(t))$$

- Accessing Gravitational Form Factors by mimicking a spin-2 interaction:

$$\int_{-1}^{1} dx\ xH^q(x, \xi, t) = A^q(t) + \xi^2 D^q(t) \qquad \int_{-1}^{1} dx\ xE^q(x, \xi, t) = B^q(t) - \xi^2 D^q(t)$$

Part II: The CLAS12 experiment at Jefferson Lab



- The Continuous Electron Beam Accelerator Facility provides a quasi-continuous beam of polarized electron, up to 12 GeV.
- Build around two anti-parallel linacs, with recirculation arcs on both ends. The maximum energy is reached after 6 pass through the linacs.
- 4 experimental halls: A,B,C and D
  - A. C. Small acceptance but large luminosity
  - B. Housing CLAS12, a large acceptance detector
  - D. Tagged photon beam, dedicated to spectroscopy

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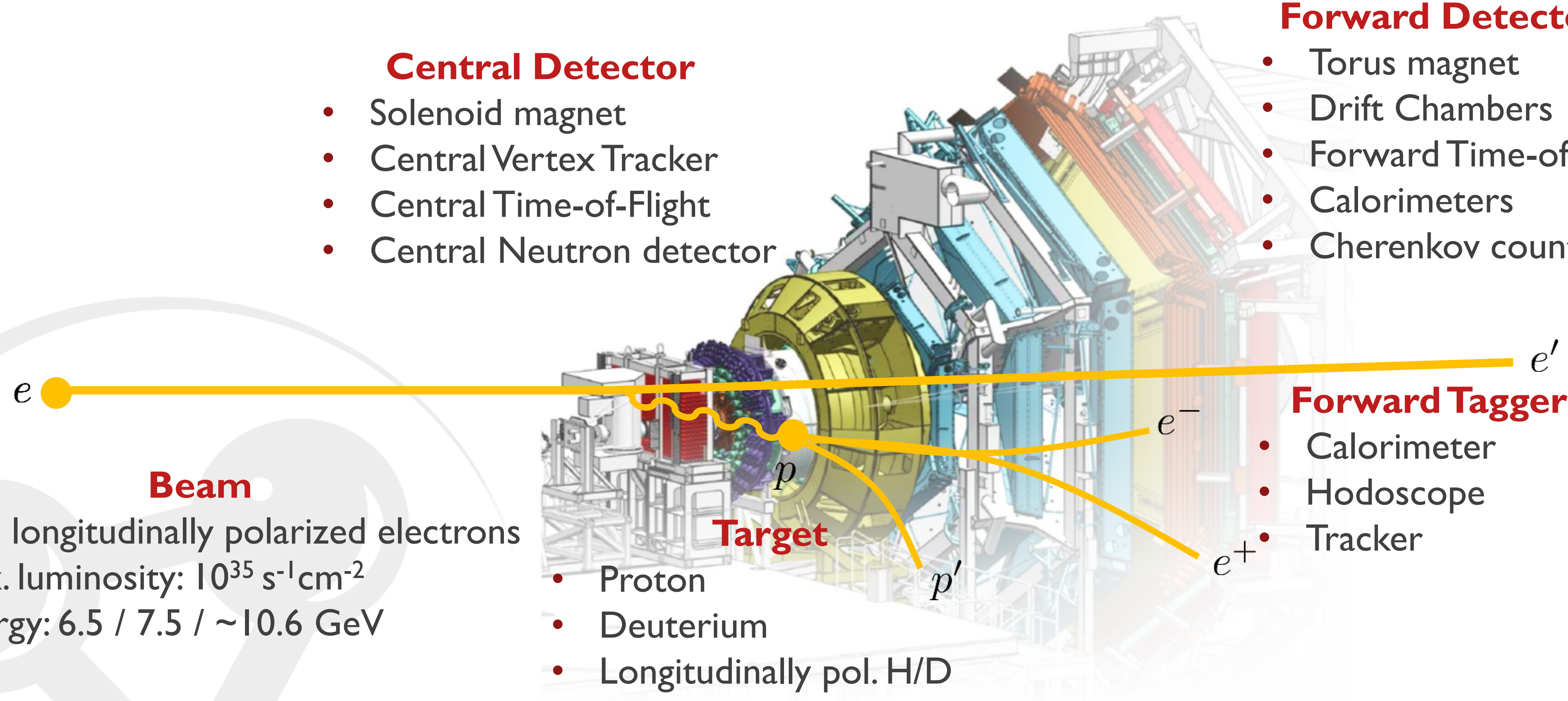
The CLAS12 detector

Central Detector
- Solenoid magnet
- Central Vertex Tracker
- Central Time-of-Flight
- Central Neutron detector

Forward Detector
- Torus magnet
- Drift Chambers
- Forward Time-of-Flight
- Calorimeters
- Cherenkov counters



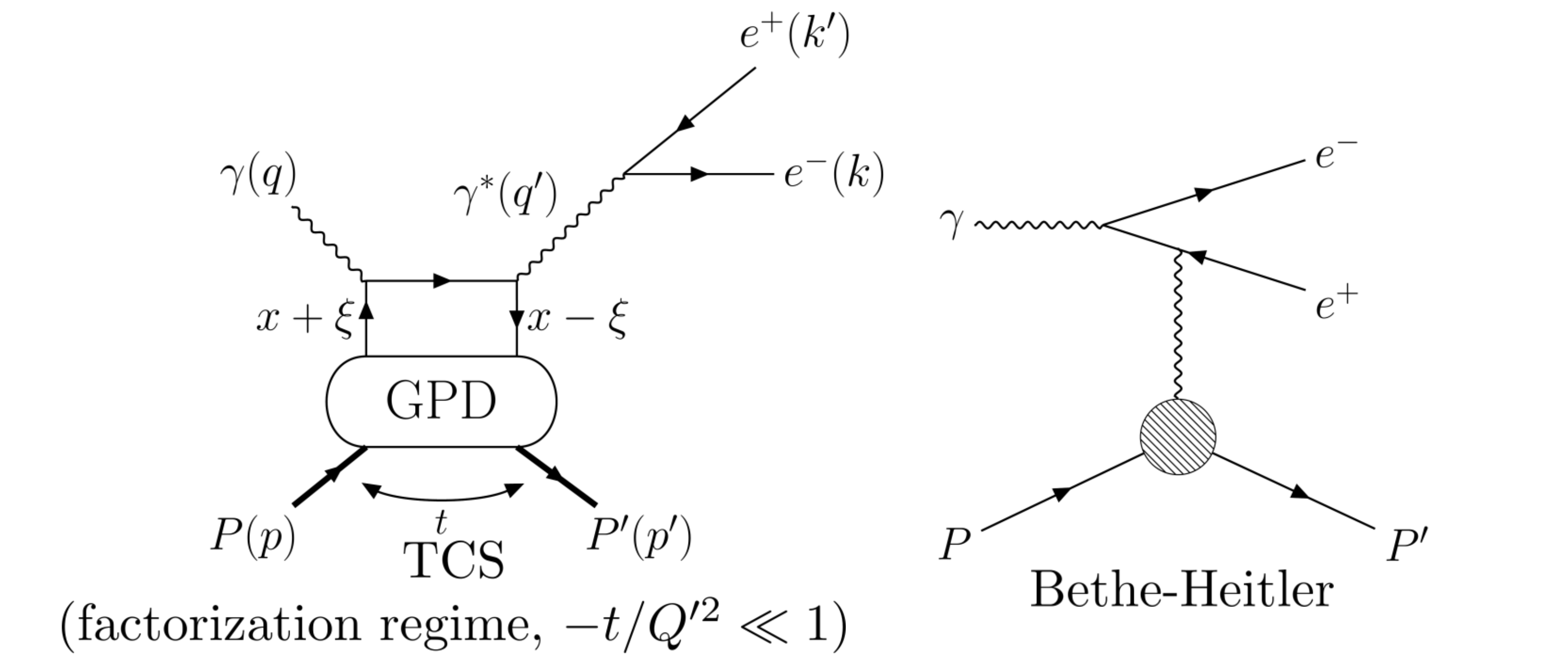
Forward Tagger
- Calorimeter
- Hodoscope
- Tracker

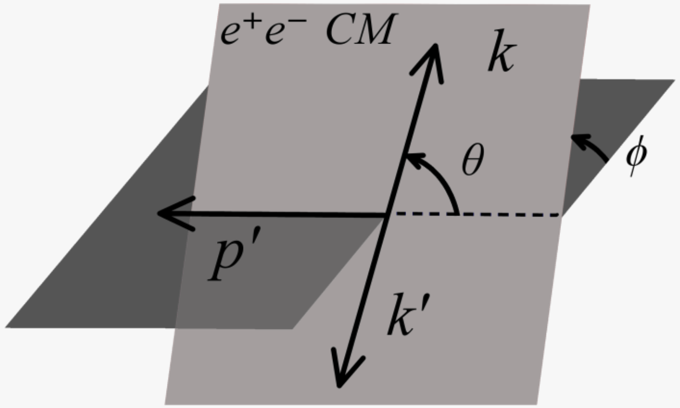
Beam
- 85% longitudinally polarized electrons
- Max. luminosity: 10^{35} $s^{-1}cm^{-2}$
- Energy: 6.5 / 7.5 / ~10.6 GeV

Target
- Proton
- Deuterium
- Longitudinally pol. H/D

Part III: First Timelike Compton Scattering measurement with CLAS12

$$\text{DVCS: } ep \to e'p'\gamma \qquad \text{TCS: } \gamma p \to e^+e^-p'$$





$$-t = (p - p')^2$$
$$Q'^2 = (k + k')^2$$
$$L = [(q-k)^2 - m_l^2][(q-k')^2 - m_l^2]$$
$$L_0 = (Q'^2 \sin^2\theta)/4$$

- BH cross section only depends on electromagnetic FFs.
- At JLab, energies the BH cross section is expected to be larger than the TCS one.
  We aimed at measuring the interference cross section between BH and TCS.

Motivations to measure TCS

Test of the universality of the GPDs

- Both DVCS and TCS amplitudes are parametrized by GPDs.
- The imaginary part of the CFF $\mathcal{H}$ is well known from DVCS results…
  …and also accessible from TCS polarization asymmetry.
- TCS does not involve Distribution Amplitudes unlike Deeply Virtual Meson Production (DVMP)
  $\rightarrow$ Direct comparison between TCS and DVCS (at leading twist).

Unique access to the real part of the CFF $\mathcal{H}$

- Angular dependence of the unpolarized interference cross-section gives access to the real part of $\mathcal{H}$
- This quantity is not well constrained by existing data.
- However it is of great interest as related to the GFFs D, itself related to the mechanical properties of the nucleon:

$$\mathrm{Re}\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right) \mathrm{Im}\mathcal{H}(\xi,t) + \Delta(t)$$

$$\Delta(t) \propto D^Q(t) \propto \int d^3\mathbf{r}\; p(r) \frac{j_0(r\sqrt{-t})}{t}$$

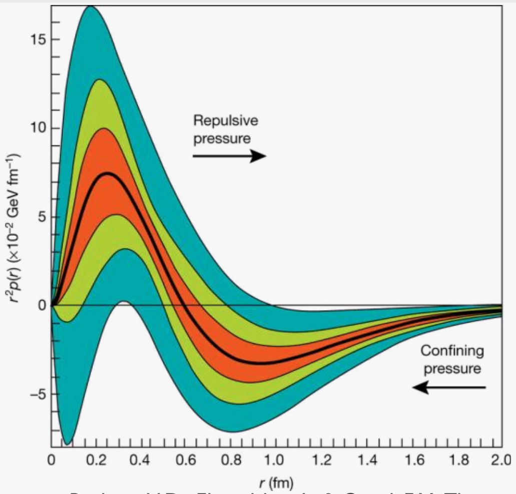


Figure in Burkert, V.D., Elouadrhiri, L. & Girod, F.X. The pressure distribution inside the proton. Nature 557, 396–399 (2018)

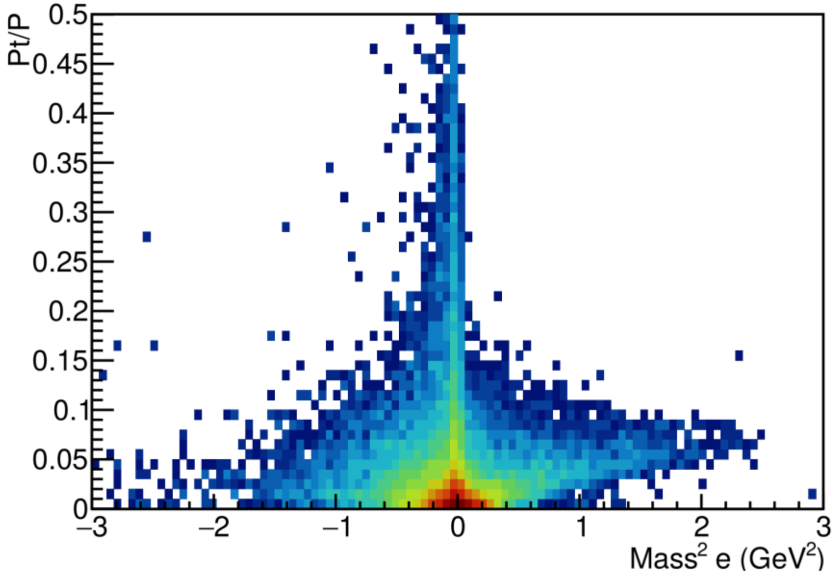
(Quasi-)Photoproduction events selection

1) CLAS12 PID + Positron NN PID

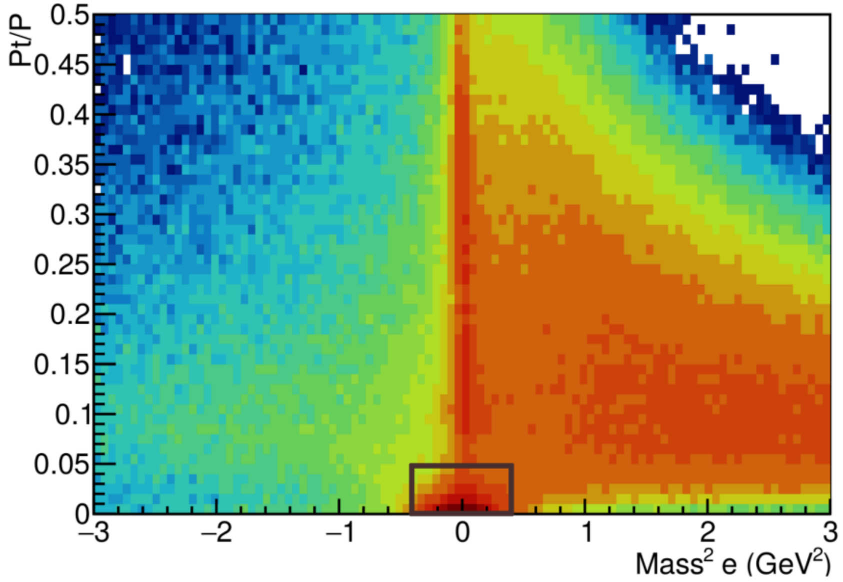
$$ep \rightarrow (e')\gamma p \rightarrow (X)e^+e^-p'$$

$p_X = p_{beam} + p_p - p_{e^+} - p_{e^+} - p_{p'}$ → 2) $|M_X^2| < 0.4 GeV^2$ → 3) $\frac{Pt_X}{P_X} < 0.05$ $\rightarrow Q^2 < 0.1$ GeV^2

Simulation



Data



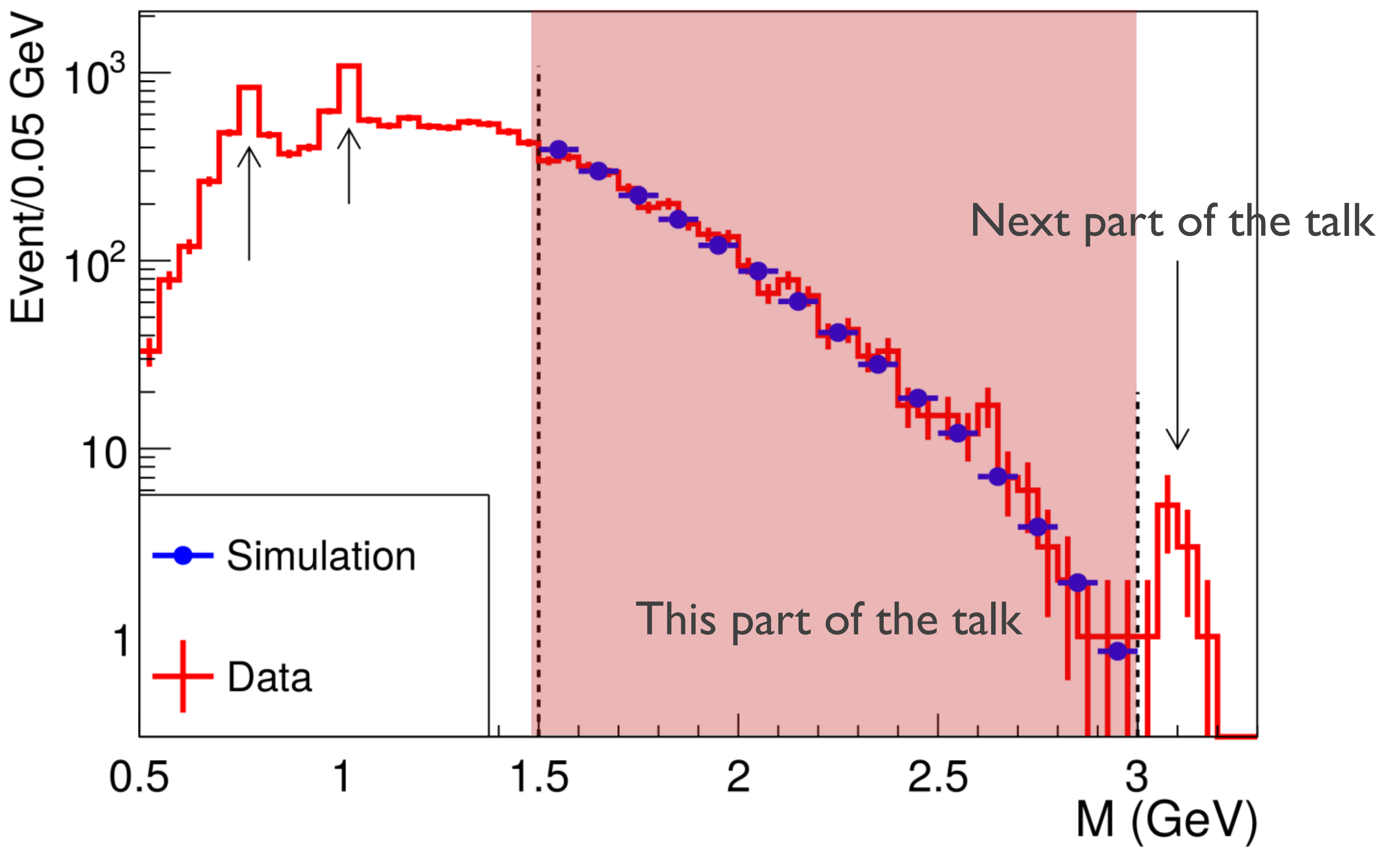
The dilepton invariant mass spectrum

- Data taken in Fall 2018
- 10.6 GeV beam on Liquid H_2 target
- Accumulated charge: 37mC or 48 fb^{-1}

- Vector mesons peaks are visible in data: ω (770), ρ (782), ϕ (1020) and J/ψ (3096).
- Data/simulation are matching at the 15% level, up to an overall normalization factor.
- No clear contribution of higher mass vector meson production (ρ (1450), ρ (1700)).

Phase-space for the TCS analysis

$$0.15\ \mathrm{GeV}^2 < -t < 0.8\ \mathrm{GeV}^2$$
$$1.5\ \mathrm{GeV} < M_{e^+e^-} < 3\ \mathrm{GeV}$$
$$4\ \mathrm{GeV} < E_\gamma < 10.6\ \mathrm{GeV}$$



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Photon polarization asymmetry results

Definition

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto \frac{\frac{L_0}{L}\sin\phi \frac{(1+\cos^2\theta)}{\sin(\theta)}\mathrm{Im}\mathcal{H}}{d\sigma_{BH}}$$

Experimentally:

$$A_{\odot U}(-t, E\gamma, M; \phi) = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$

- A sizeable asymmetry is measured, above the expected vanishing asymmetry predicted for BH.
- Results have been compared to 2 model predictions:
  1. VGG model
  2. GK model
- The size of the asymmetry is well reproduced by both models, giving a hint for the universality of GPDs.

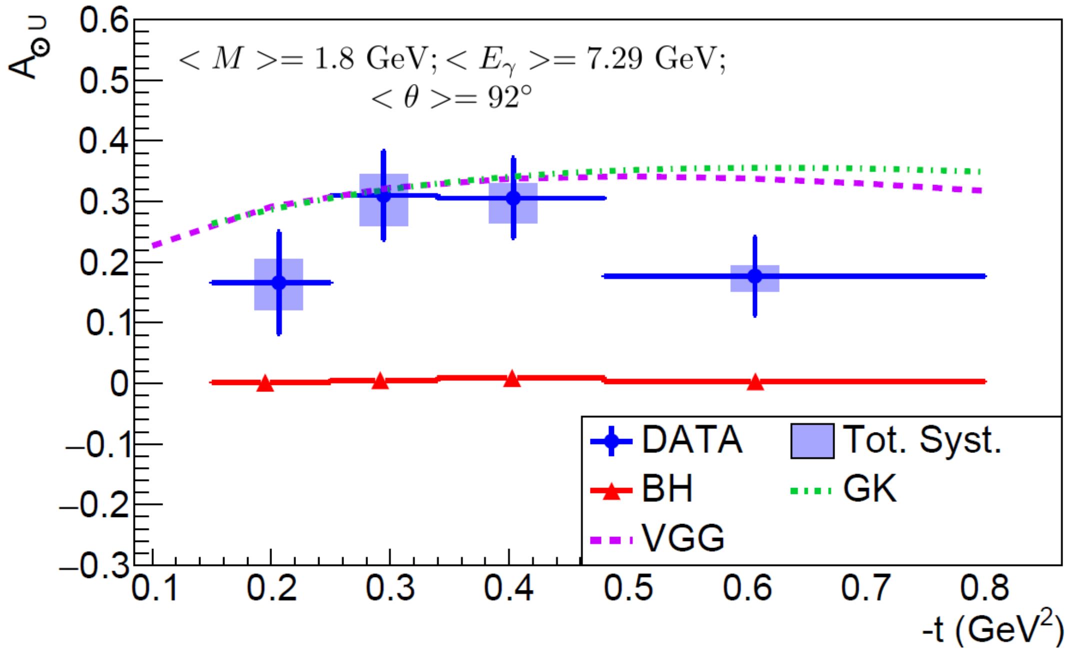

Figure in First Measurement of Timelike Compton Scattering, P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)

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Forward/Backward asymmetry results

Observable definition

$$A_{FB}(\theta_0,\phi_0) = \frac{d\sigma(\theta_0,\phi_0) - d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}{d\sigma(\theta_0,\phi_0) + d\sigma(180^\circ-\theta_0, 180^\circ+\phi_0)}$$

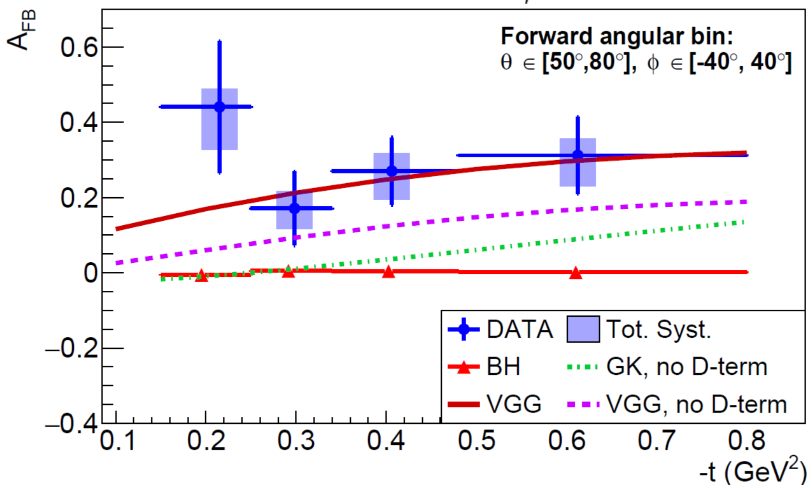
$$\propto \frac{\frac{L_0}{L}\cos\phi_0 \frac{(1+\cos^2\theta_0)}{\sin(\theta_0)} \mathrm{Re}\tilde{M}^{--}}{d\sigma_{BH}(\theta_0,\phi_0) + d\sigma_{BH}(180^\circ-\theta_0, 180^\circ+\phi_0)}$$

- Integration over the forward angular bin :

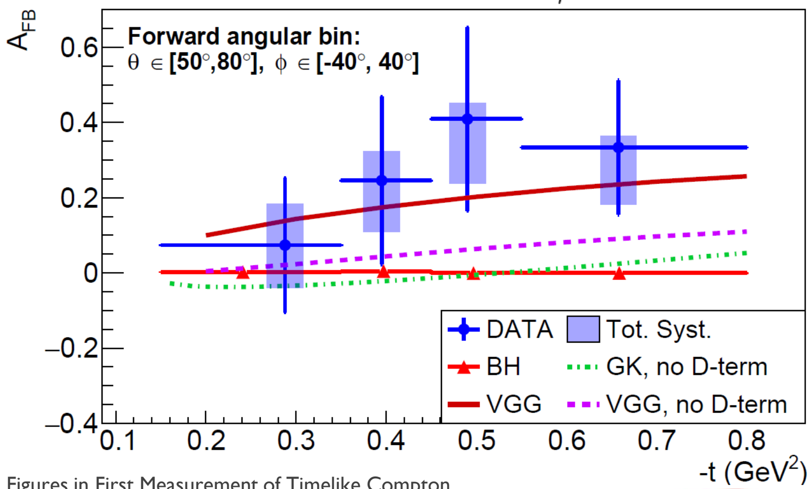
$$\theta \in [50^\circ, 80^\circ] \text{ and } \phi \in [-40^\circ, 40^\circ]$$

- The measured asymmetry is non-zero: **evidence of signal** beyond pure BH contribution
- Measured asymmetry is better reproduced by the VGG model including the D-term
    1. Confirmation of the importance of the D-term in the parametrization of the GPD
    2. One can use TCS data to constrain it

$< M >= 1.8$ GeV; $< E_\gamma >= 7.24$ GeV



$< M >= 2.25$ GeV; $< E_\gamma >= 8.13$ GeV



Figures in First Measurement of Timelike Compton Scattering, P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)

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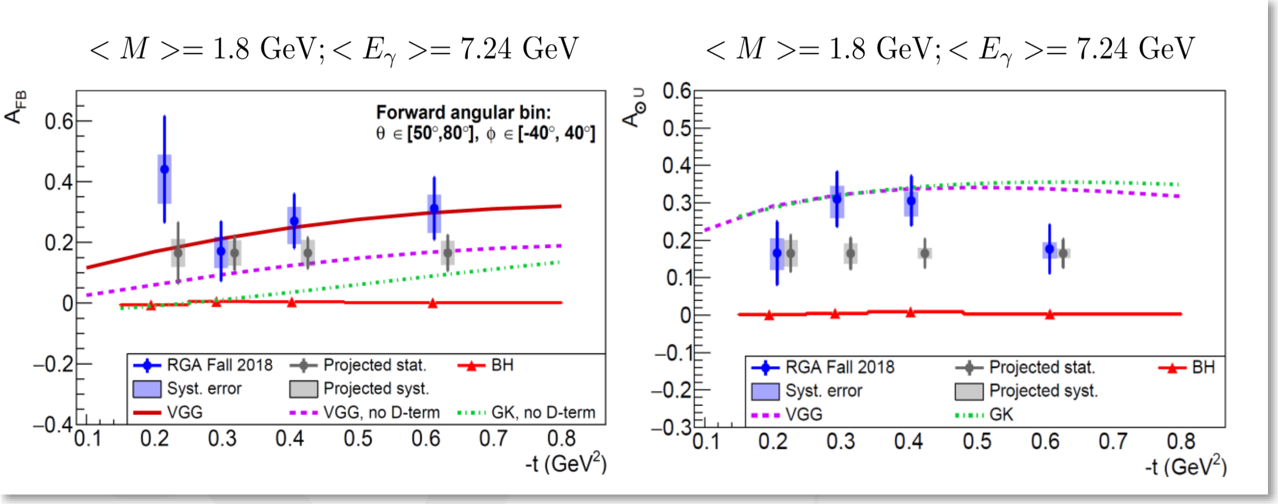
Short-term perspectives for TCS measurements with CLAS12

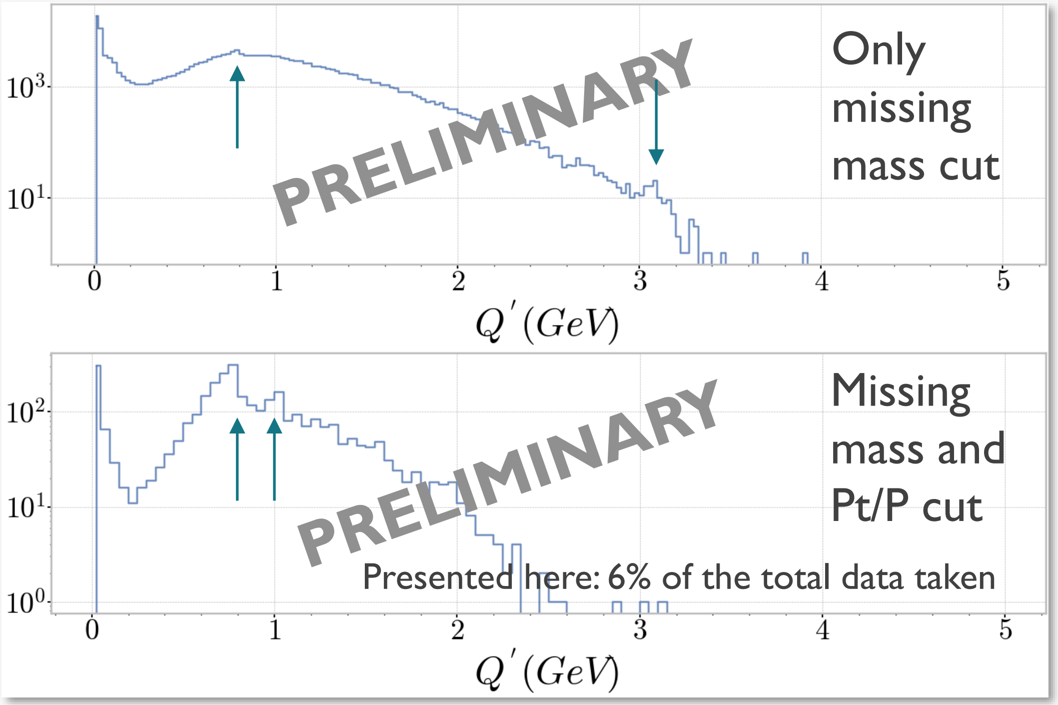
Projections for the full proton target dataset (RG-A)

- Only a fraction of RGA was used for in the PRL article (1/3)
- New significant improvement on the tracking software have been done since 2020 → 50% more efficiency for the 3-particle final state



Analysis on longitudinally polarized proton target dataset (RG-C)

Analysis by K. Gates, Univ. of Glasgow



+ Deuterium dataset available for nTCS and bound proton TCS

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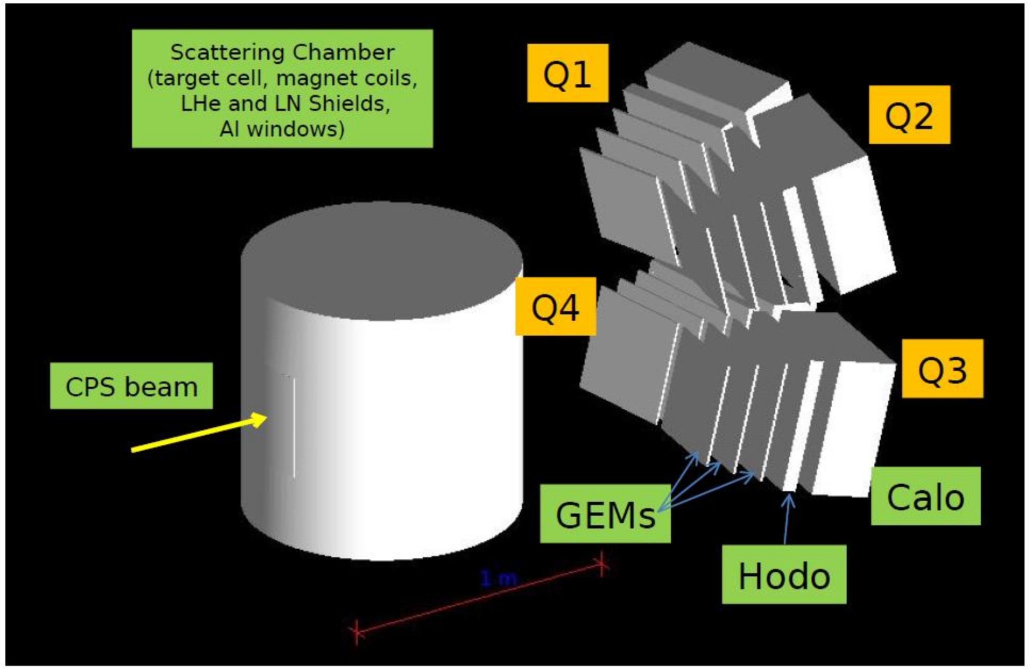
Oher TCS measurements at Jefferson Lab

Transversely polarized TCS in Hall C

$\gamma P \rightarrow e^+ e^- P'$



1. High intensity photon source 1.5×10^{12} γ/sec (CPS)

2. Target chamber: NH3, 3cm Polarized via DNP

3. Tracking: GEM+hodoscopes, 4 symmetric quadrants

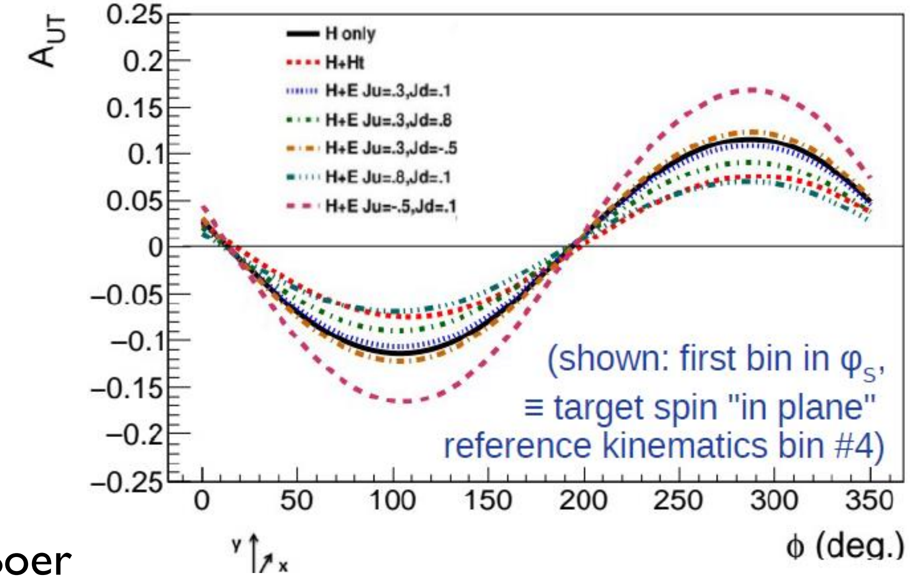
4. Calorimeters: 4 symmetric quadrants, equivalent of 2 NPS

~ 6° to 27° aperture
Lumi request: 5.85×10^5 pb^{-1}

Material provided by M.Boer

GPD E in a complementary way to neutron and transversely polarized DVCS

Dependence in GPD parametrization and J_u, J_d (VGG model) vs φ and φ_S

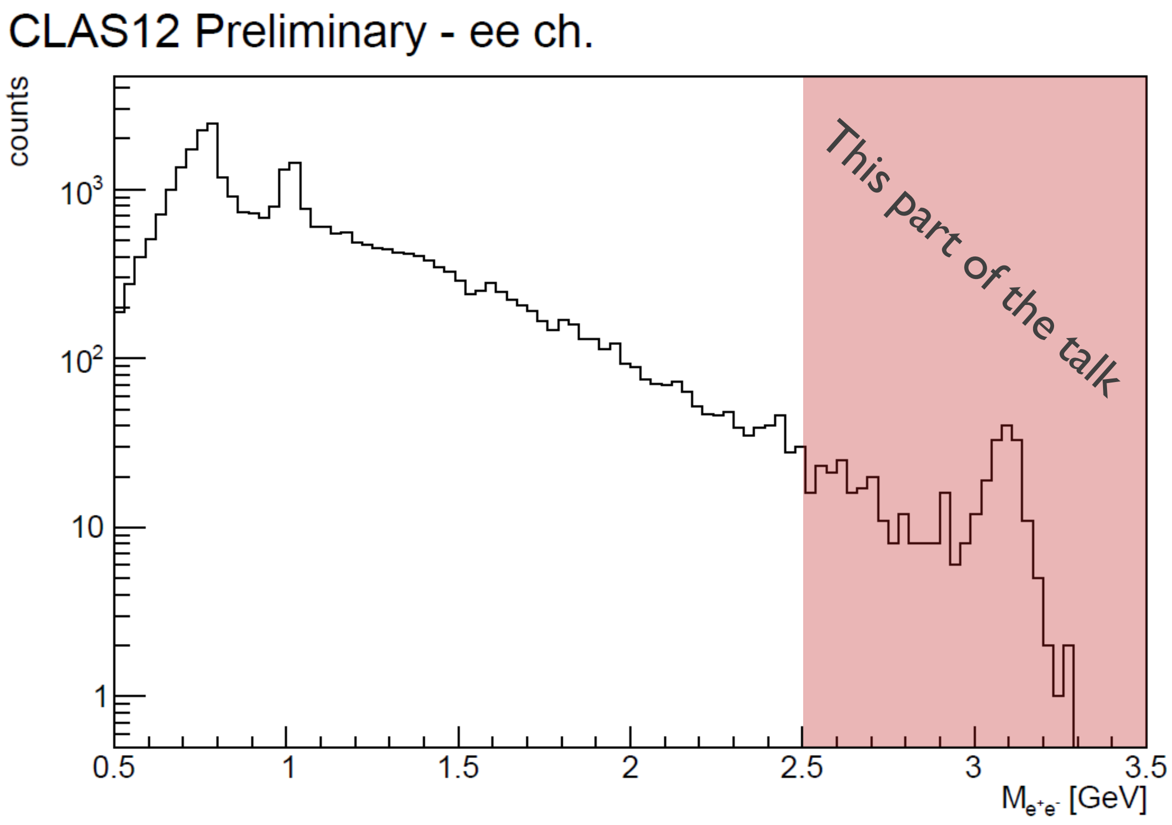


+ Ongoing measurement by GlueX on unpolarized proton

Part IV: Toward the measurement of the near threshold photo-production of J/ψ using CLAS12

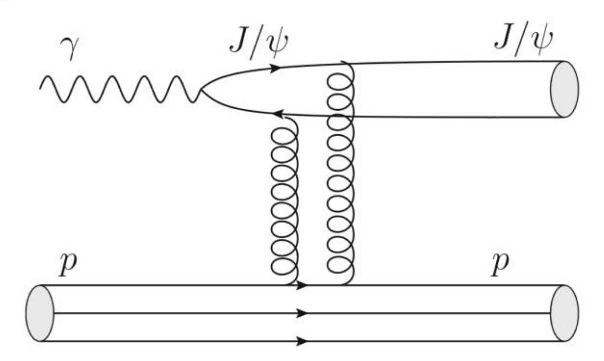
- Analysis initiated by J. Newton for his PhD thesis and postdoc.
- Joseph left in December and I took over the analysis since then.

- In the following I will show only the same dataset as for the TCS analysis.
- 10.6 GeV beam on Liquid H_2 target
- Accumulated charge: 37mC or 48 fb^{-1}

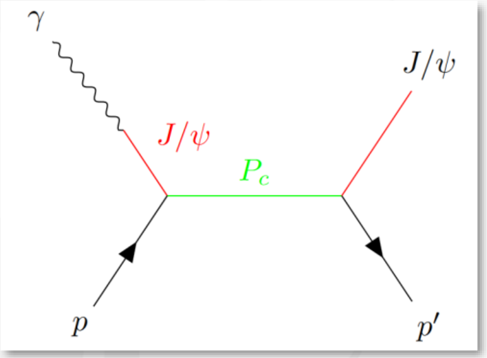


J/ψ photoproduction near threshold: motivations and results

- Probe the gluon content of the proton (under 2-gluon exchange assumption and no open-charm contributions discussed in the next slide)



- The t-dependence of the cross-section allow to access gluon Gravitational Form Factors (GFFs), mass radius of the nucleon (under 2-gluon exchange assumption and no open-charm contributions, see back-up).
- Model-dependent limit on the branching ratio of the Pc pentaquark.



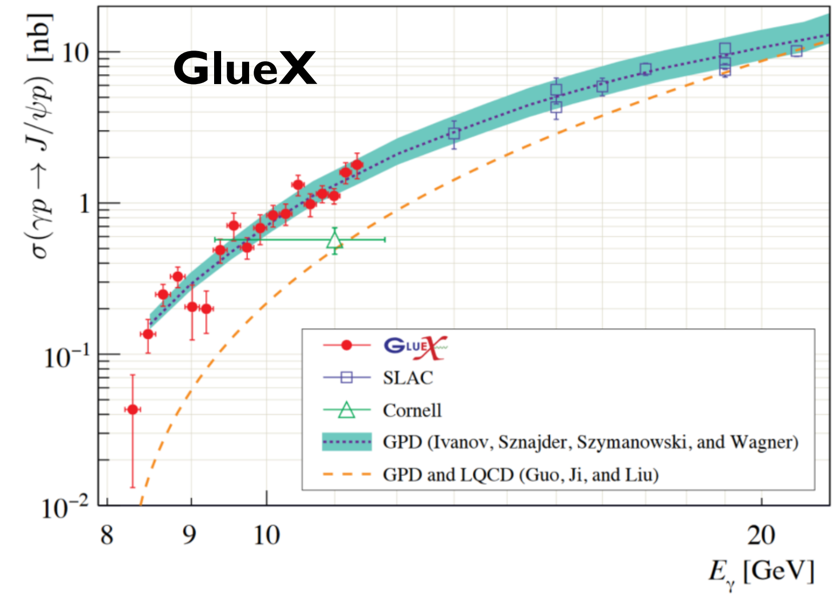


Figure in, Measurement of the J/ψ photoproduction cross section over the full near-threshold kinematic region, S. Adhikari *et al.* (GlueX Collaboration) arXiv:2304.03845

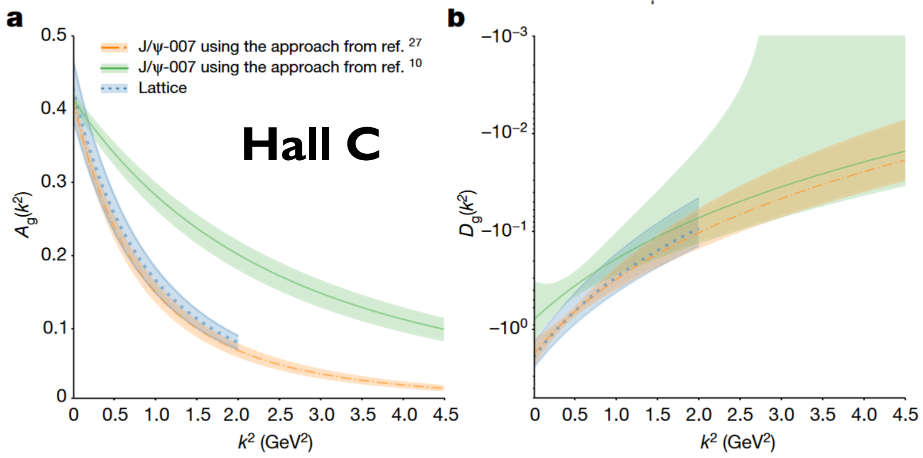
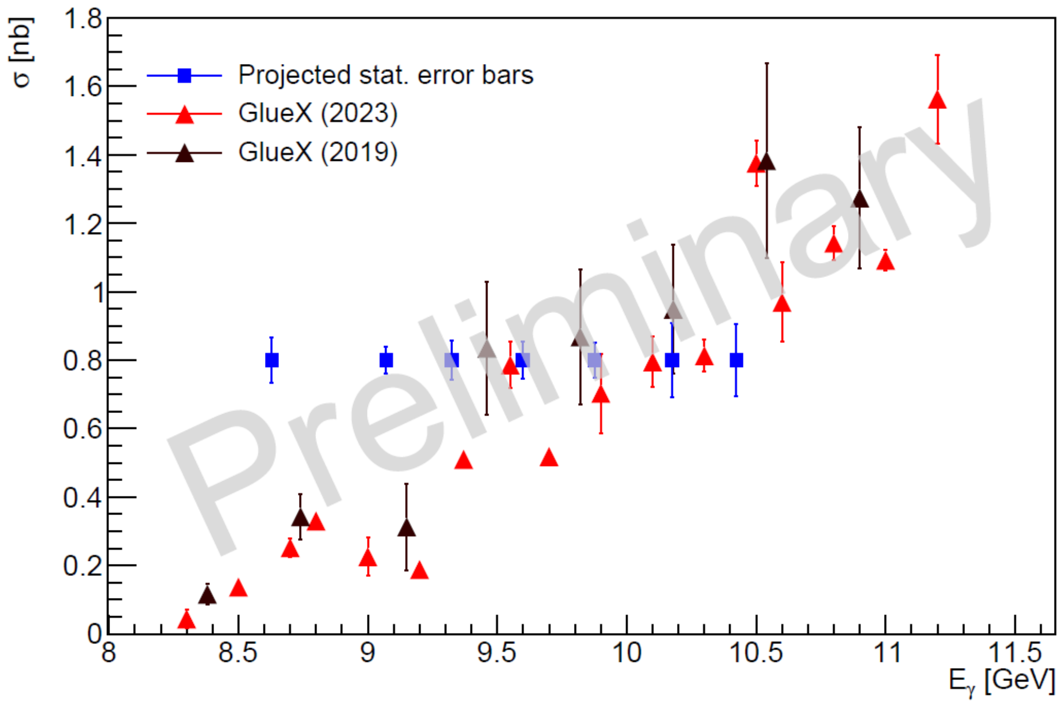


Figure in Duran, B., Meziani, ZE., Joosten, S. *et al.* Determining the gluonic gravitational form factors of the proton. *Nature* 615, 813–816 (2023)

Projections for CLAS12 proton data

$$ep \to (e')\gamma p \to (e')J/\psi\ p' \to (X)e^+e^-p'$$

- Projected statistics error bars based on full dataset available on proton target and expected improvement for tracking.
- Smaller range of photon energy than GlueX.
- Error bars are slightly less competitive than GlueX.
- Very different systematics.
- t-dependence will also be extracted.

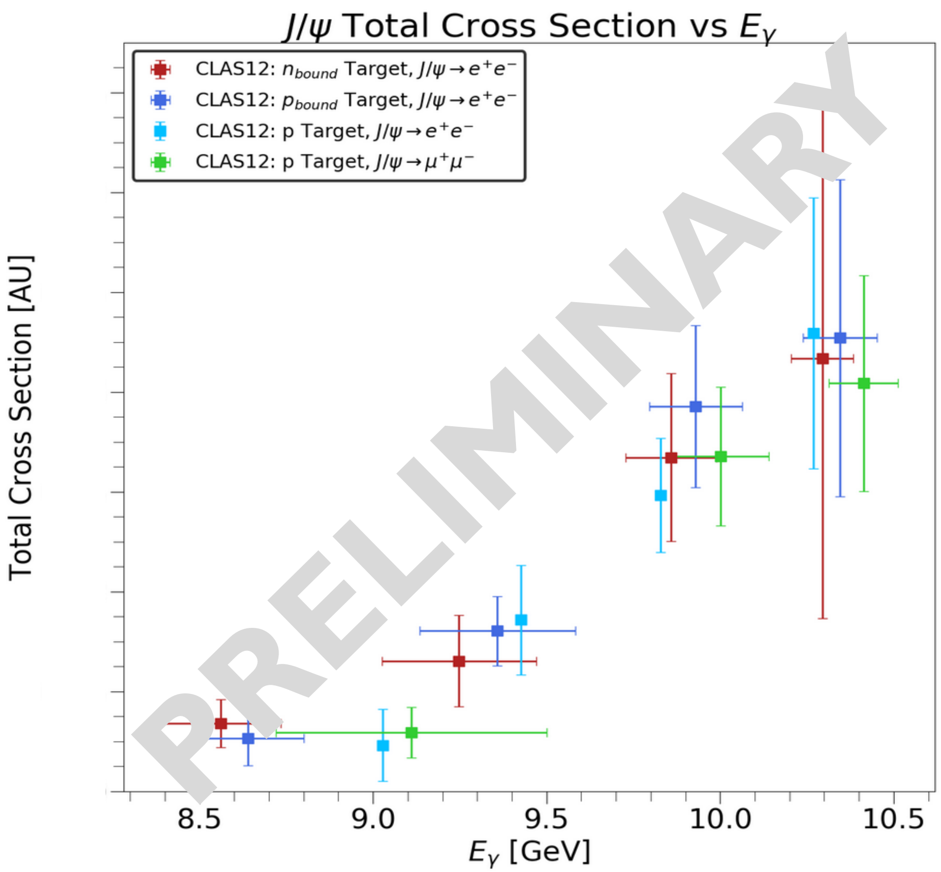


Including all data taken on unpolarized proton (150 fb^{-1}) and improved tracking efficiency (+50%)

Preliminary results for CLAS12 proton/neutron data

- Deuterium data were taken by CLAS12 in 2019/2020.
- Opportunity to measure J/ψ production on (bound) neutron and (bound) proton.
- Alongside this analysis, a framework to explore the muon decay channel was developed.
- This effort is lead by R. Tyson from University of Glasgow.

- Preliminary results for the comparison of decay channels and target nucleon.
- This measurement could have implication on understanding open-charm channels contribution.

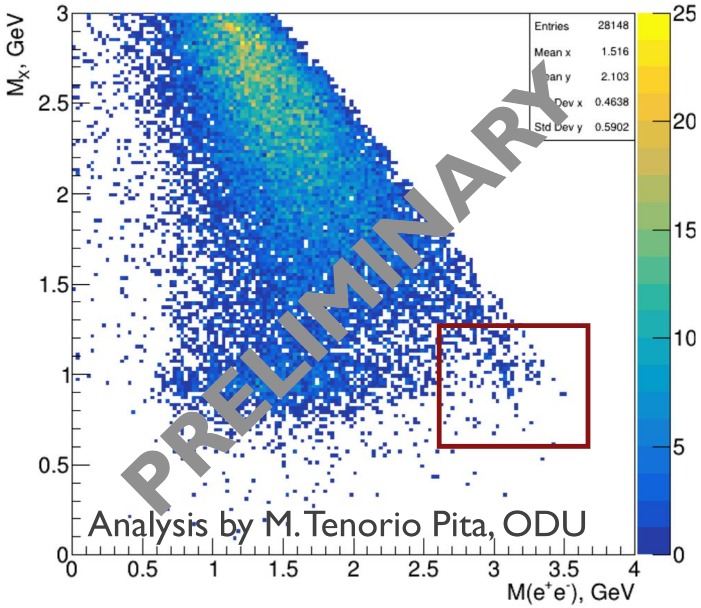


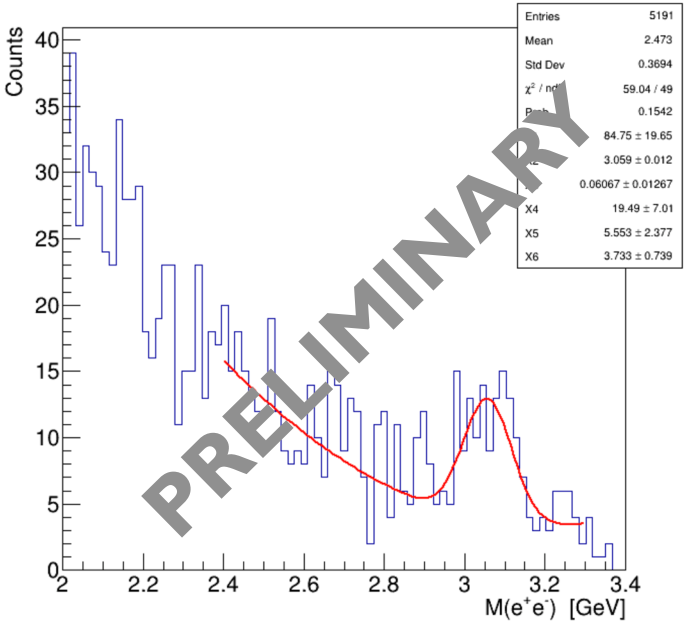
Taken from R. Tyson PhD analysis, Univ. of Glasgow

Tagged J/ψ quasi-photoproduction with CLAS12

$$ep \to e' J/\psi\ p' \to e' l^+ l^- (X)$$

- Analysis conducted by M. Tenorio Pita, ODU.
- In this case, one electron in the Forward Tagger (Low lab angle <5°) and a lepton pair in CLAS12.
- Excellent cross-check of the quasi-photoproduction approach.
- Early results show low statistics, the new data "cooking" including better tracking efficiency will be beneficial for this analysis.
- Other event topologies will be explored.





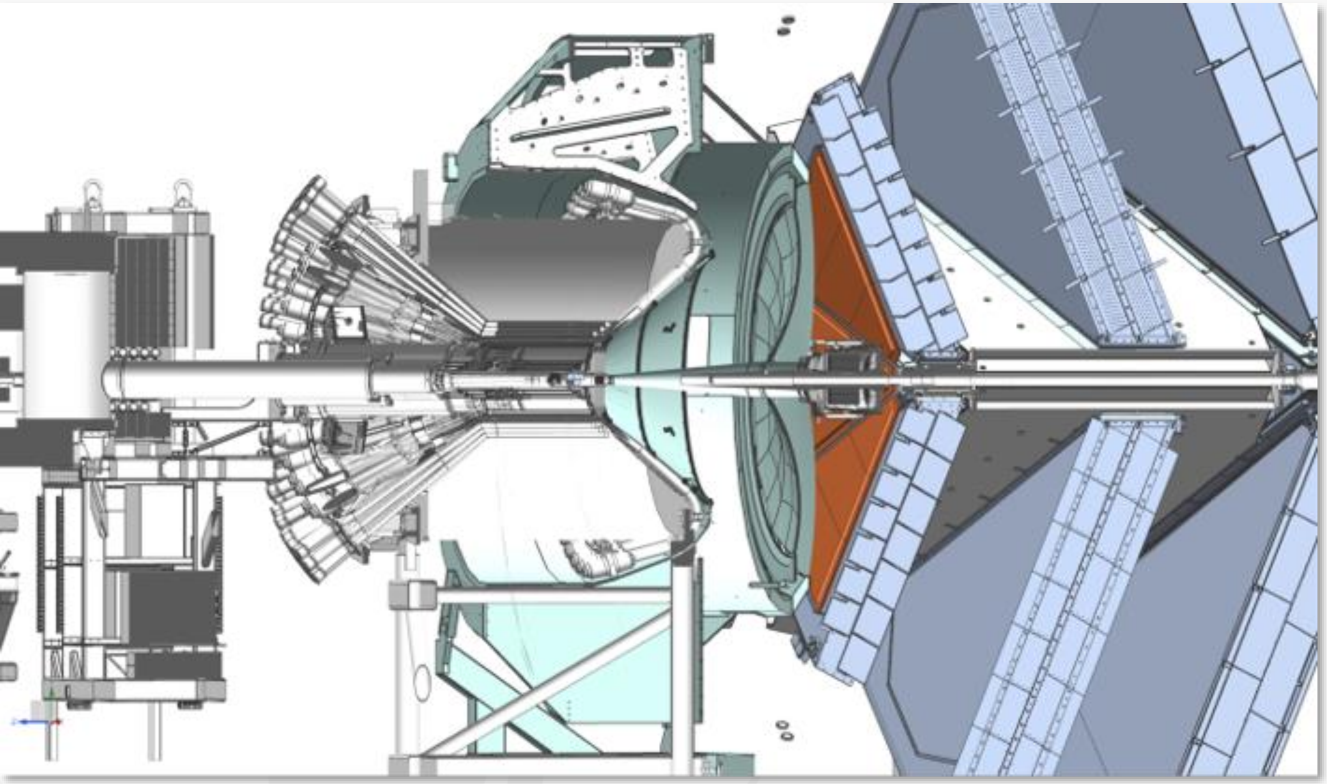
Other potential J/ψ analysis using CLAS12 data

- Available data for longitudinally polarized proton target

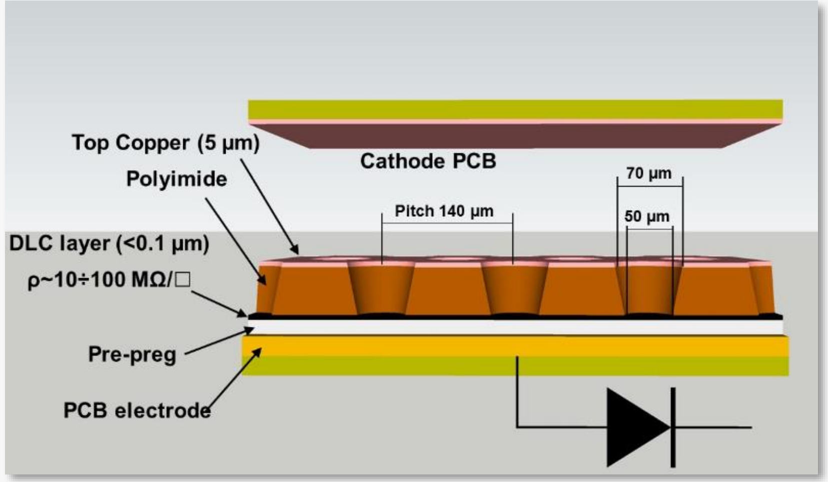
A mid-term perspective with CLAS12: Luminosity upgrade

- Exclusive reaction have typically a low cross-section
- Each additional detected track/particle comes with a detection efficiency "penalty"
- These measurement require large luminosity, which is mostly limited by DC occupancies in CLAS12

A potential solution



- µRwell-based detector in front of DC region 1…



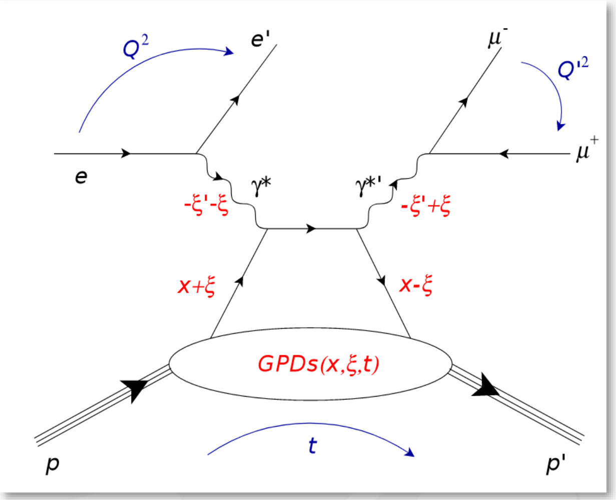
- … combined with increased efficiency of AI tracking, already in place for the current data-processing
- Goal: doubling the luminosity

Figures courtesy of R. Paremuzyan

A long term perspective: Double DVCS measurement

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

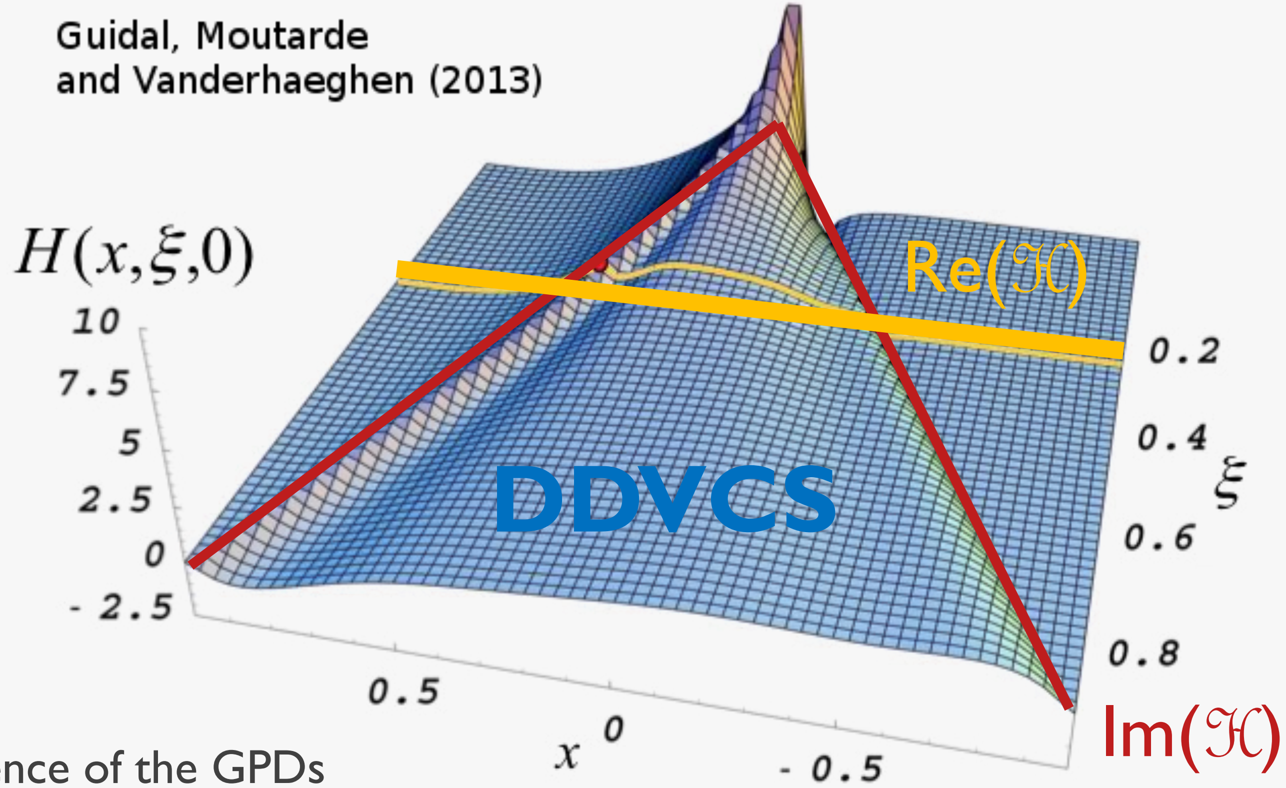
Capturing the complete kinematic dependence of GPDs



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

$$Im\mathcal{H}(\xi',\xi,t) \propto H(\xi',\xi,t) - H(-\xi',\xi,t)$$

→ Allow to completely map the kinematic dependence of the GPDs



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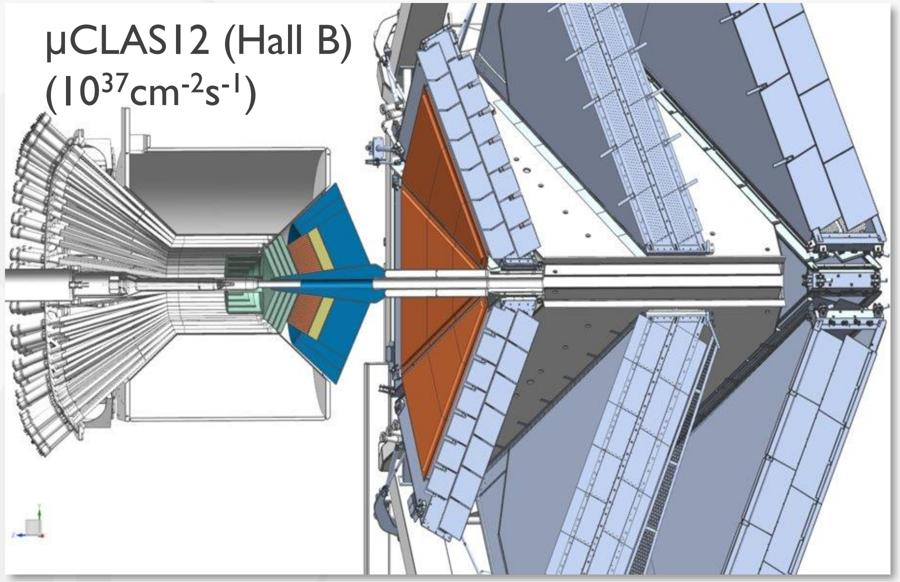
µCLAS12 in Hall B

$$ep \rightarrow e'\mu^+\mu^- p$$

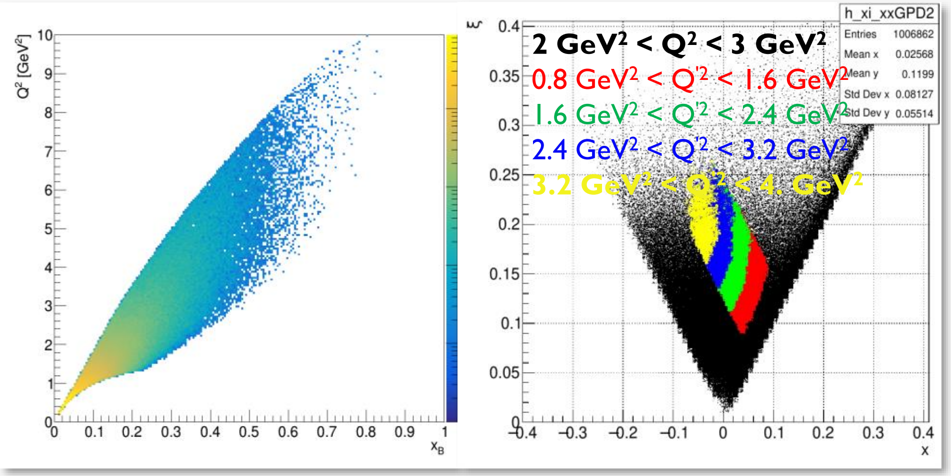
- Two main challenges for DDVCS measurement:
  1. Low x-section: requires high-luminosity
  2. Muon detection needed

A potential solution: µCLAS12

- Luminosity increase by a factor 100
- Shielding to reduce DC occupancy and pion background
- Additional calorimeter for electron ID
- New tracking system around the target



Kinematic reach for DDVCS with µCLAS12



Figures courtesy of Rafayel Paremuzyan

Material from LOI-12-16-004 (Stepanyan, Paremuzyan, Baltzell, De Vita,Ungaro et al.)

+ Potential measurement with the SoLID detector

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Summary and take-aways

- The dilepton final state allows to access fundamental properties of the nucleon (GPDs, GFFs).
- Rich experimental program at Jefferson Lab, already producing some important results
- The first extraction of Timelike Compton Scattering observables on unpolarized proton target was done using the CLAS12 detector. More results from CLAS12, GlueX, Hall A/C to come.
- Large effort to extract J/ψ cross-section on various targets both for electron and muon final state (GlueX, Hall C, and CLAS12).
- New experiments are proposed to extend this program to DDVCS, J/ψ electro-production, μ-TCS

BACK-UP

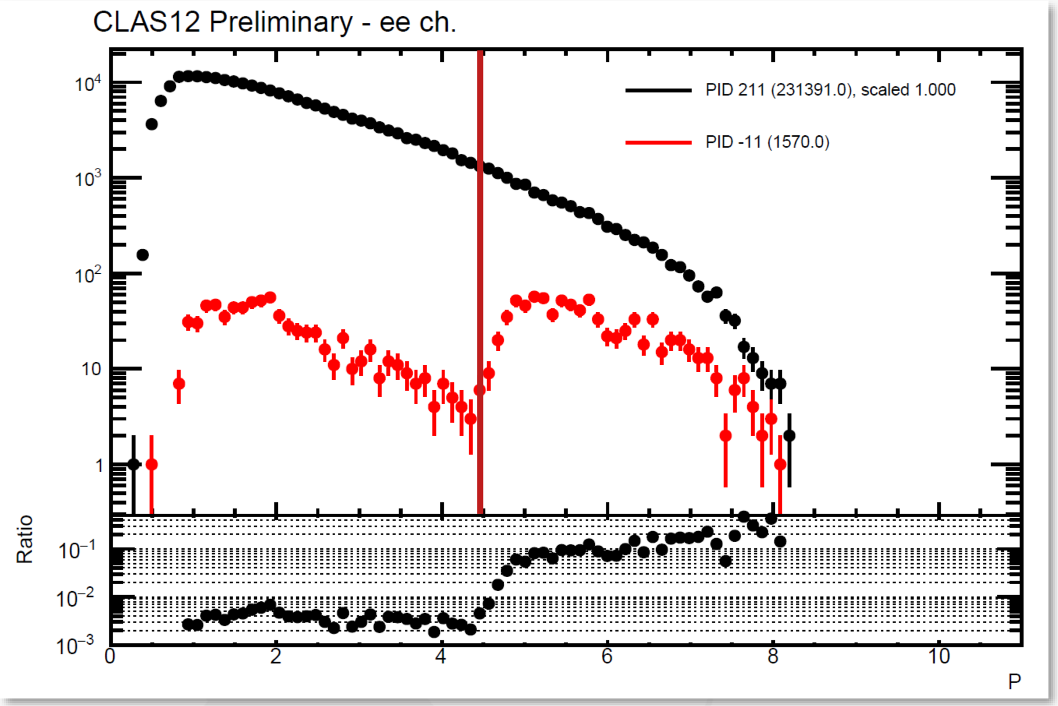
Positron PID

One important challenge: a clean positron identification

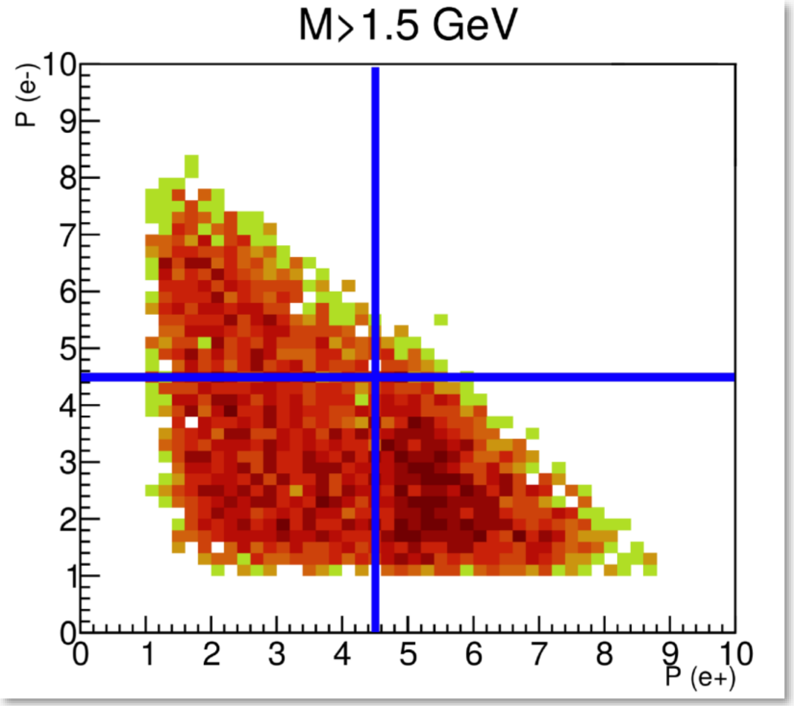
Pion background at large momenta

At high momenta (typically above the HTCC threshold at 4.5 GeV), both pions and leptons will emit Cherenkov light.

$$ep \to ep\pi^+\pi^- \text{ VS } ep \to epe^+\pi^-$$



$$\gamma p \to e^+e^-p$$



AI identification of the positrons

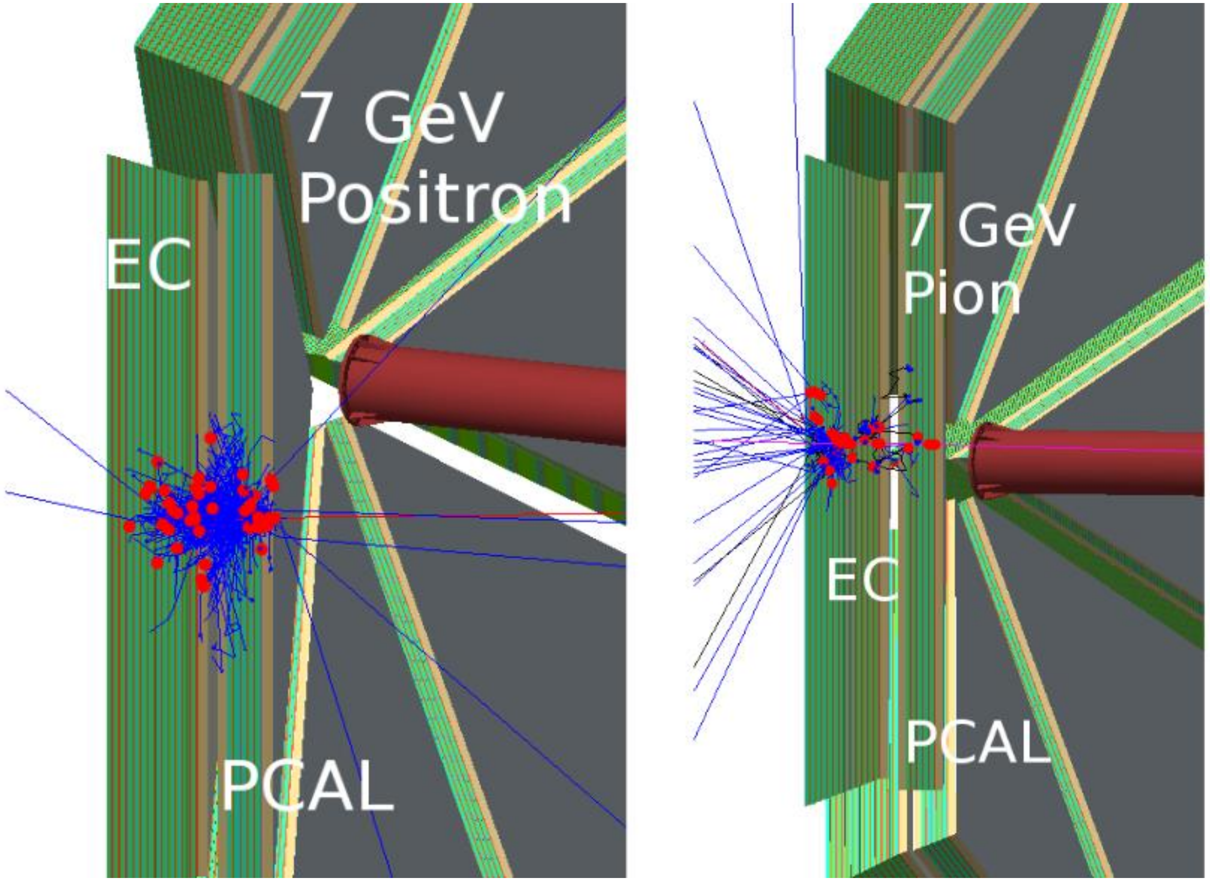
Strategy and discriminating variables

- Leptons produce electromagnetic showers and tend to deposit energy in the first layers of the calorimeters.
- Pions are **M**inimum **I**onizing **P**articles in the GeV region, they deposit small amounts of energy all along their path.

- Two main characteristics to use:

1. $$SF_{\mathrm{EC\ Layer}} = \frac{E_{dep}(\mathrm{EC\ \ Layer})}{P}$$

2. $$M_2 = \frac{1}{3}\sum_{U,V,W}\frac{\sum_{\mathrm{strip}}(x-D)^2\cdot\ln(E)}{\sum_{\mathrm{strip}}\ln(E)}$$



Performances of AI identification of the positrons

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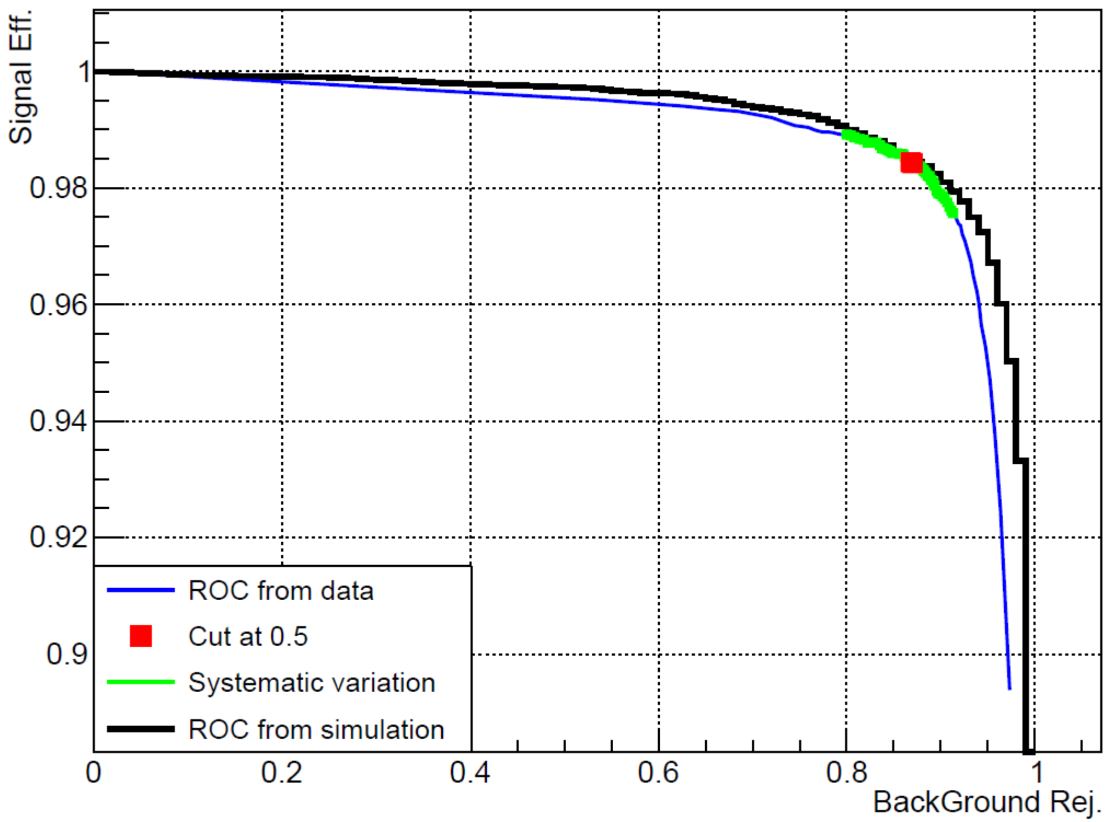


TCS analysis

TCS interference cross-section formulae and CFFs

Unpolarized cross-section

Formulae and notations of Berger, Diehl, Pire, Eur.Phys.J.C23:675-689,2002

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} \propto \frac{L_0}{L}\left[\cos(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)}\mathrm{Re}\tilde{M}^{--} + \dots\right]$$

$$\rightarrow \tilde{M}^{--} = \frac{2\sqrt{t_0 - t}}{M}\frac{1-\xi}{1+\xi}\left[F_1\mathcal{H} - \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]$$

Compton Form Factors (CFFs)

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

Polarized cross-section

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = \frac{d^4\sigma_{INT}\,|_{\mathrm{unpol.}}}{dQ'^2 dt d\Omega} - \nu \cdot A \frac{L_0}{L}\left[\sin(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)}\mathrm{Im}\tilde{M}^{--} + \dots\right]$$

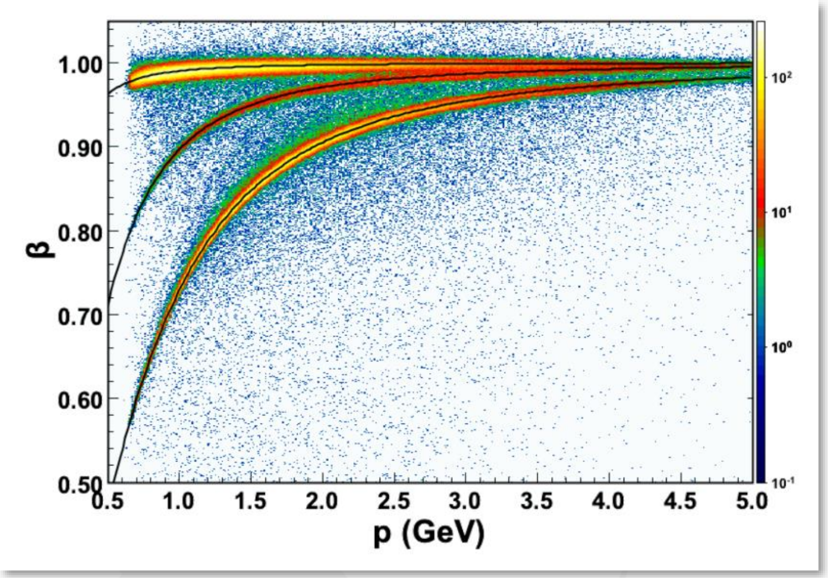
(Quasi-)Photoproduction events selection

1) CLAS12 PID + Positron NN PID

$$ep \to (e')\gamma p \to (X)e^+e^-p'$$

Proton identification

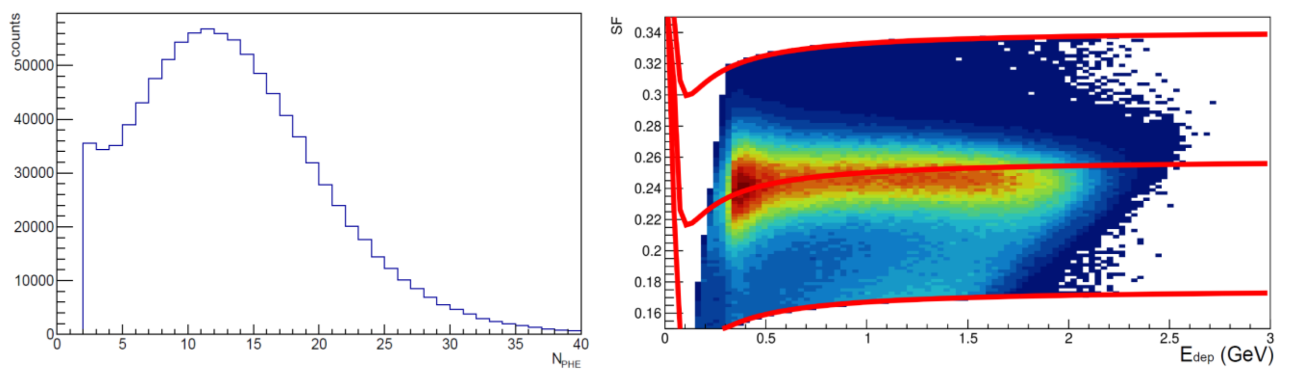
Velocity from the time-of-flight



Momentum from the track curvature

Lepton identification

Cherenkov counters + Calorimeter energy deposition



$$Sampling\ Fraction = \frac{E_{dep}}{P}$$

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First observable: the photon polarization asymmetry

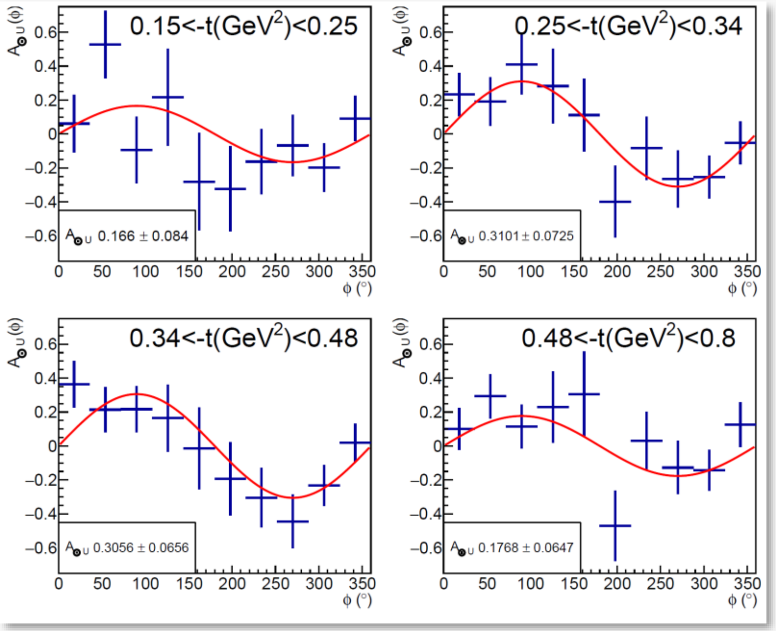
Definition

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\sin\phi\frac{(1+\cos^2\theta)}{\sin(\theta)}\,\mathrm{Im}\tilde{M}^{--}}{d\sigma_{BH}}$$

Measurement

$$A_{\odot U}(-t, E\gamma, M;\phi) = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-} \text{ where } N^\pm = \sum \frac{1}{Acc} P_{trans.}$$

- $P_{trans.}$ is the transferred polarization from the electron to the photon, fully calculable in QED.
  Olsen, Maximon, Phys. Rev.114 (1959)
- P_b is the polarization of the electron beam at 85%.
- The obtained distributions of $A_{\odot U}(-t;\phi)$ are then fitted with a sine function.



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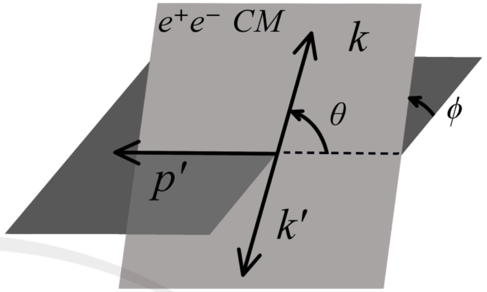
Second observable: the Forward/Backward asymmetry

Forward/Backward correspondence:

$$k \leftrightarrow k' \iff (\theta, \phi) \leftrightarrow (180° - \theta, 180° + \phi)$$



Effect on cross-sections

$$\frac{d\sigma_{BH}}{dQ^2\, dt\, d\Omega} \propto \frac{1 + \cos^2\theta}{\sin^2\theta} \xrightarrow{FB} \frac{d\sigma_{BH}}{dQ^2\, dt\, d\Omega}$$

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} \propto \frac{L_0}{L} cos(\phi) \frac{1 + cos^2(\theta)}{sin(\theta)} \xrightarrow{FB} -\frac{d\sigma_{INT}}{dQ^2\, dt\, d\Omega}$$

Observable definition

$$A_{FB}(\theta_0, \phi_0) = \frac{d\sigma(\theta_0, \phi_0) - d\sigma(180° - \theta_0, 180° + \phi_0)}{d\sigma(\theta_0, \phi_0) + d\sigma(180° - \theta_0, 180° + \phi_0)} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2} \frac{1}{-t} \frac{m_p}{Q'} \frac{1}{\tau\sqrt{1-\tau}} \frac{L_0}{L} \cos\phi_0 \frac{(1+\cos^2\theta_0)}{\sin(\theta_0)} \mathrm{Re}\tilde{M}^{--}}{d\sigma_{BH}(\theta_0, \phi_0) + d\sigma_{BH}(180° - \theta_0, 180° + \phi_0)}$$

- Concept initially explored for J/ψ production
  (Gryniuk, Vanderhaeghen, *Phys. Rev. D*, 2016)
- Exploratory studies for TCS performed alongside this work
- Predictions for TCS have been published very recently + **LO radiative correction negligible**
  (Heller, Keil, Vanderhaeghen, *Phys. Rev. D*, 2021)

J/ψ analysis

J/ψ (quasi-)photoproduction events selection

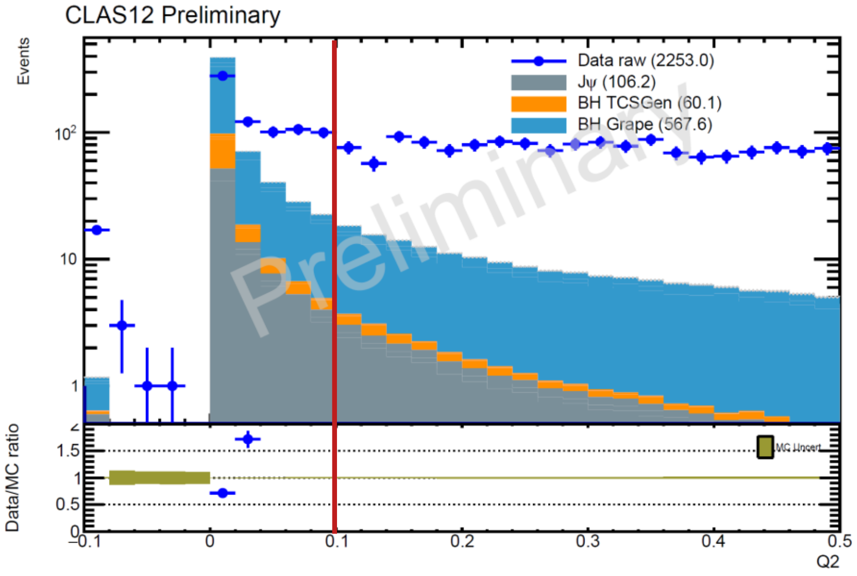
Can we do the same as for TCS ? In principle yes…

1) CLAS12 PID + Positron NN PID

$$ep \to (e')\gamma p \to (e')J/\psi\ p' \to (X)e^+e^-p'$$

$p_X = p_{beam} + p_p - p_{e^+} - p_{e^+} - p_{p'}$ → 2) $|M_X^2| < 0.4 GeV^2$ → 3) $|\frac{Pt_X}{P_X}| < 0.05$

In practice, it is not so simple



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Background removal procedure

Sample contents

Opposite charge leptons

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

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

Physics final state

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

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

Same charge leptons

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

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

$$R^{in} = \frac{N^{in}(e'e^-p')}{N^{in}(e^+e^-p')} = \frac{a^2 \cdot \sigma_{BG}}{a \cdot b \cdot \sigma_{BG+S}} = \frac{a \cdot \sigma_{BG}}{b \cdot \sigma_{BG+S}}$$

$$R^{out} = \frac{N^{out}(e'e^-p')}{N^{out}(e^+e^-p')} = \frac{b^2 \cdot \sigma_{BG}}{a \cdot b \cdot \sigma_{BG+S}} = \frac{b \cdot \sigma_{BG}}{a \cdot \sigma_{BG+S}}$$

$$w = \frac{S}{(S+B)_{In}} = 1 - \frac{N_{e^-e^-p}}{N_{e^-e^+p}}_{In} \frac{b}{a} = 1 - \sqrt{\frac{N_{e^-e^-p}}{N_{e^-e^+p}}_{In} \frac{N_{e^-e^-p}}{N_{e^-e^+p}}_{Out}}$$

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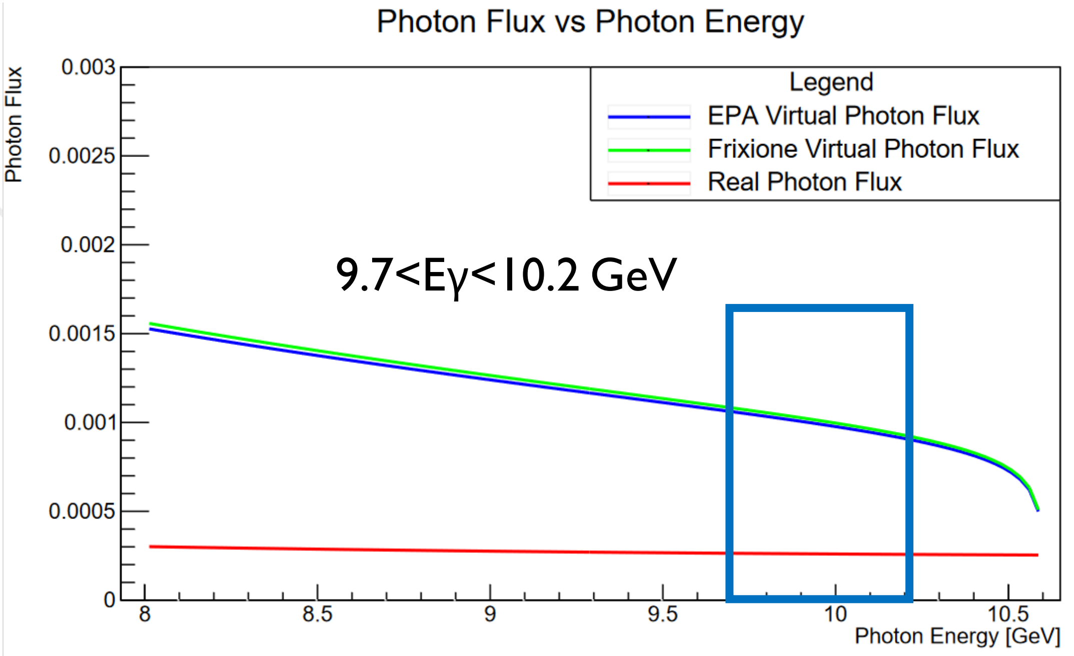
Photon flux and accumulated charge

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

- Number of photons (from accumulated charge and photon flux from QED)
- Number of targets (from the density of dihydrogen and length of the target)



Motivations to measure J/ψ photoproduction near threshold: the open-charm "issue"

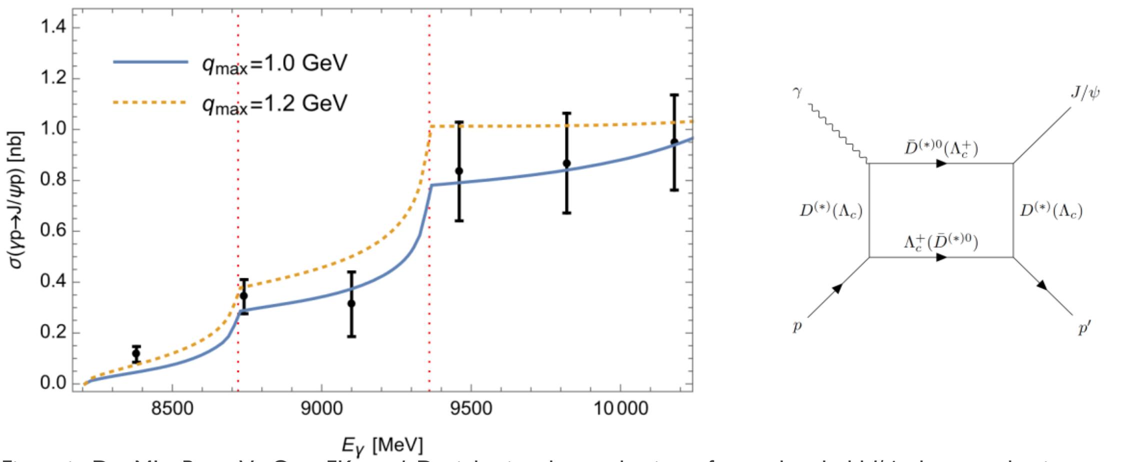


Figure in Du, ML., Baru, V., Guo, FK. *et al.* Deciphering the mechanism of near-threshold *J/ψ* photoproduction. *Eur. Phys. J. C* 80, 1053 (2020)

Open-charm "issue"

- The previous considerations rely on the application of Vector Meson Dominance.
- Thus the contribution from open-charm meson channels must be ruled-out/understood.

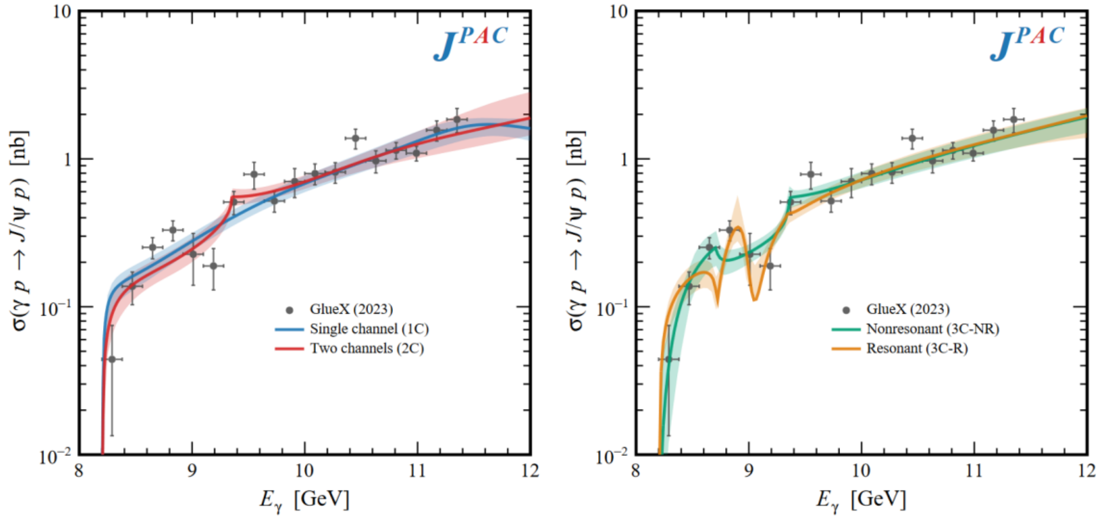


Figure in D. Winney, C. Fernandez-Ramirez, A. Pilloni, A. N. Hiller Blin et al. (JPAC), Dynamics in near-threshold J/ψ photoproduction arXiv:2305.01449

Background subtracted data using same-charge lepton events

- Opposite charge leptons

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

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

Physics final state

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

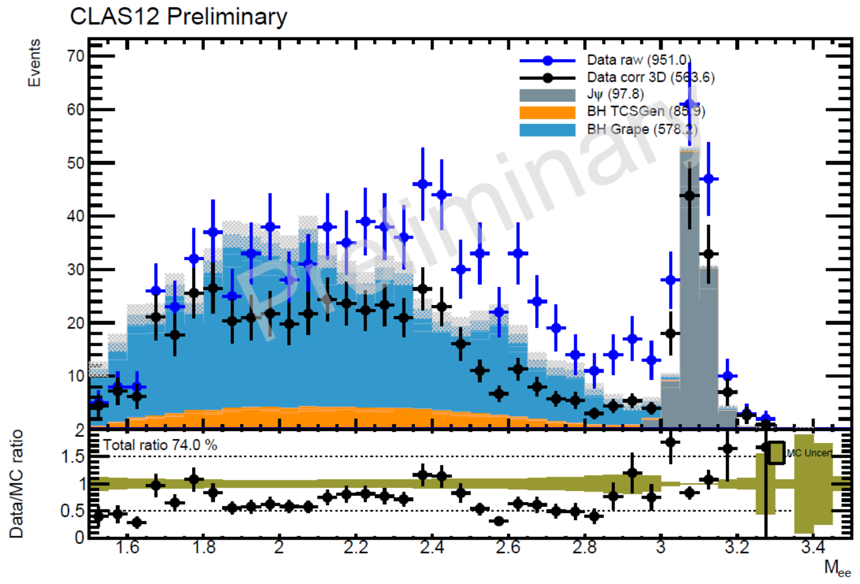
$$N(e^+e^-p') = n_S(e^+e^-) + n_{BG}(e'e^+/\pi^+)$$

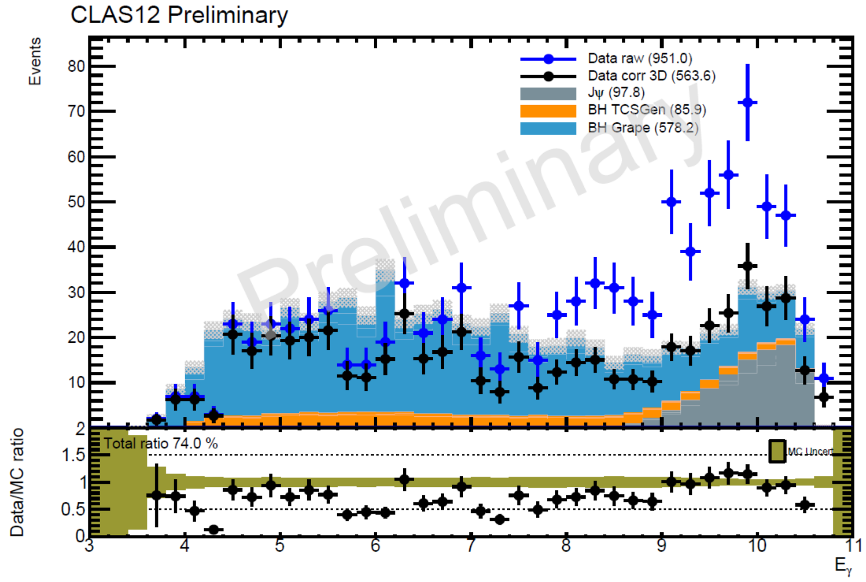
- Same charge leptons

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

- Background correction weight, combining inbending and outbending data:

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





Cross-section extraction

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

Number of J/ψ

- Number of photons (from accumulated charge and photon flux from QED).
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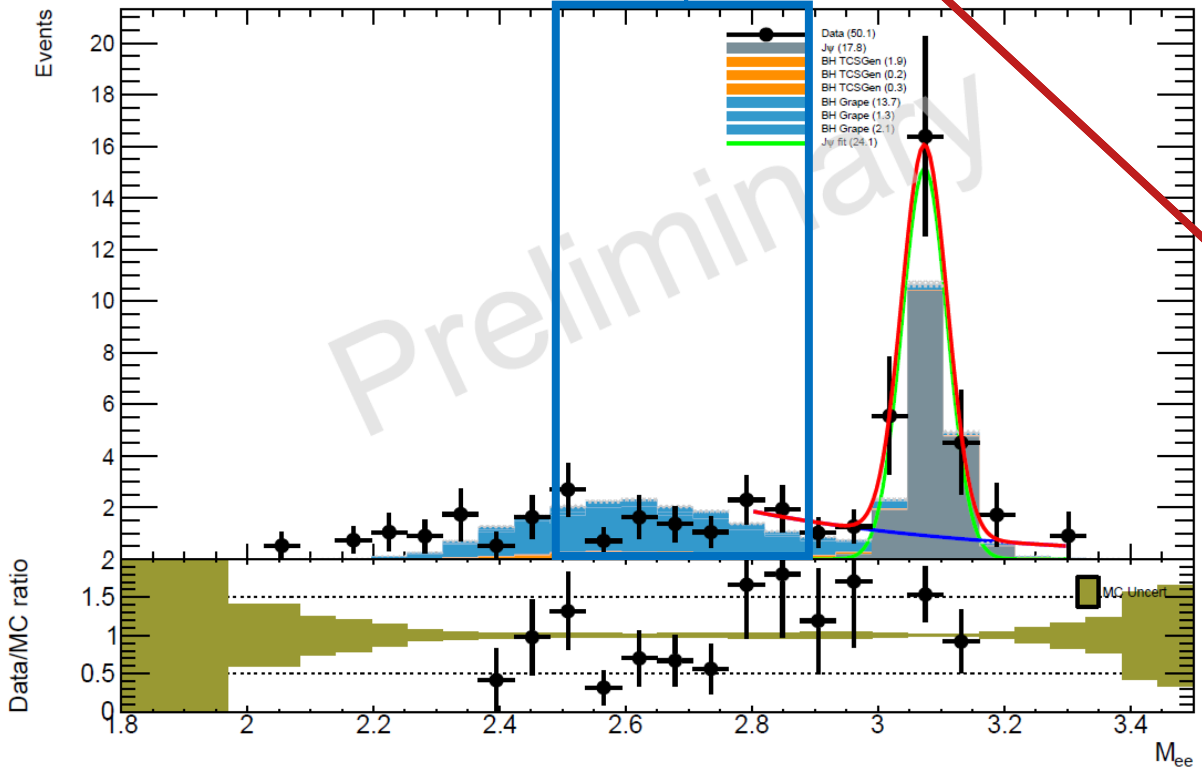


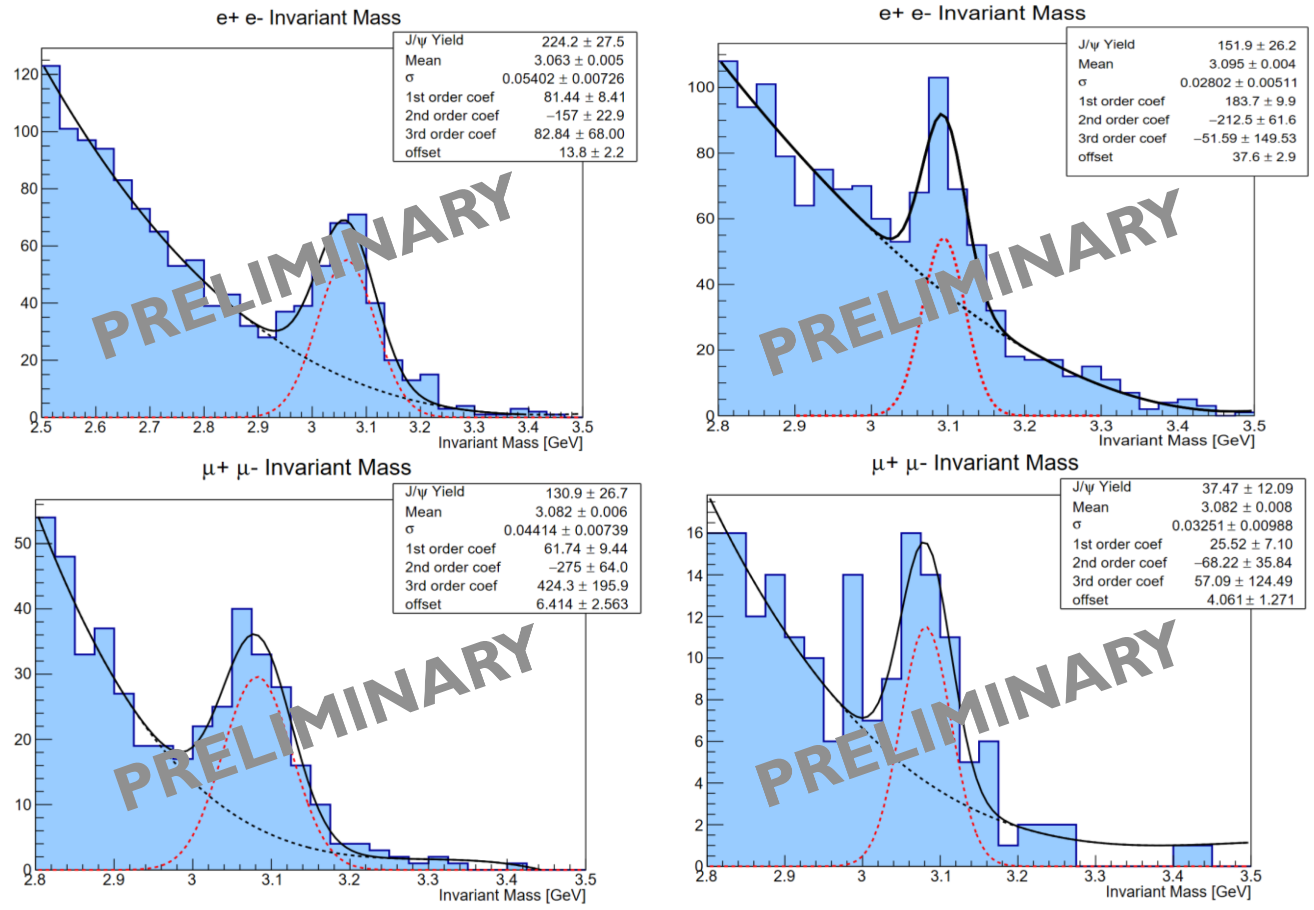
Reconstruction efficiency of the J/ψ → from MC

Branching ratio of J/ψ → e^+e^- → 6%

Deuterium target and muon final state

- Deuterium data were taken by CLAS12 in 2019/2020.
- Opportunity to measure J/ψ production on (bound) neutron and (bound) proton.
- Alongside this analysis, a framework to explore the muon decay channel was developed.
- This effort is lead by R. Tyson from University of Glasgow.

Bound proton | Bound neutron



Taken from R. Tyson PhD analysis, Univ. of Glasgow