Exploring the gravitational structure of the proton with the dilepton final state using the CLAS12 detector at Jefferson Lab:
from Timelike Compton Scattering to near-threshold J/ψ photoproduction

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for the CLAS collaboration

Spin2023, 25th to 29th of September 2023, Durham, NC, USA

Outline of the talk

I	Gravitational Form Factors and their link to Generalized Parton Distributions
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 cross-section measurement

Gravitational Form Factors, Generalized Parton Distributions…

The Gravitational Form Factors, …

Talk by C. Lorcé on Monday

- Concept introduced in the 1960s

Y. Kobzarev and L. B. Okun, Gravitational Interaction Of Fermions, Zh. Eksp. Teor. Fiz. 43, 1904 (1962)
Heinz Pagels, Energy-Momentum Structure Form Factors of Particles, Phys. Rev. 144, 1250 (1966)

- Parametrization of the matrix elements of the QCD Energy-Momentum Tensor

$$\langle p'|T^a_{\mu\nu}(0)|p\rangle = \bar{u}'\left[A^a(t)\frac{\gamma_{\{\mu}P_{\nu\}}}{2} + B^a(t)\frac{iP_{\{\mu}\sigma_{\nu\}\rho}\Delta^\rho}{4m} + D^a(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4m} + m\bar{c}^a(t)g_{\mu\nu}\right]u$$

- Related to the spin, the mass and the force distribution in the nucleons

…the Generalized Partons Distributions, …

Talks by S. Bhattacharya, S. Niccolai on Friday

- Concept introduced in the 1990s

Non forward parton distributions A. V. Radyushkin, Phys. Rev. D 56, 5524 (1997)
Deeply virtual Compton scattering Xiangdong Ji, Phys. Rev. D 55, 7114 (1997)

- Encoding both transverse position and longitudinal momentum of the partons in the nucleons.

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

- Closely related to electro-magnetic FFs and PDFs

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t) \qquad \int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t) \qquad H^q(x,0,0) = \begin{cases} q(x), & x>0 \\ -\bar{q}(-x), & x<0 \end{cases}$$

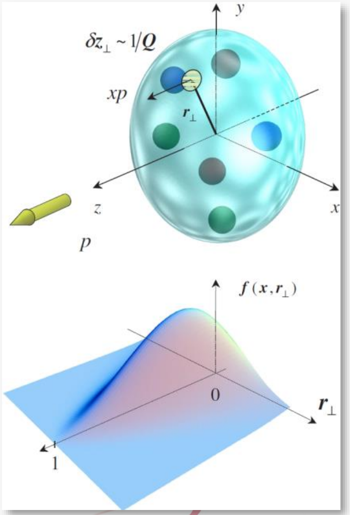


Figure in A.V. Belitsky, A.V. Radyushkin, Unraveling hadron structure with generalized parton distributions, Physics Reports, Volume 418, Issues 1–6 2005

… and their link

- First x-moment of the GPDs

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

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

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

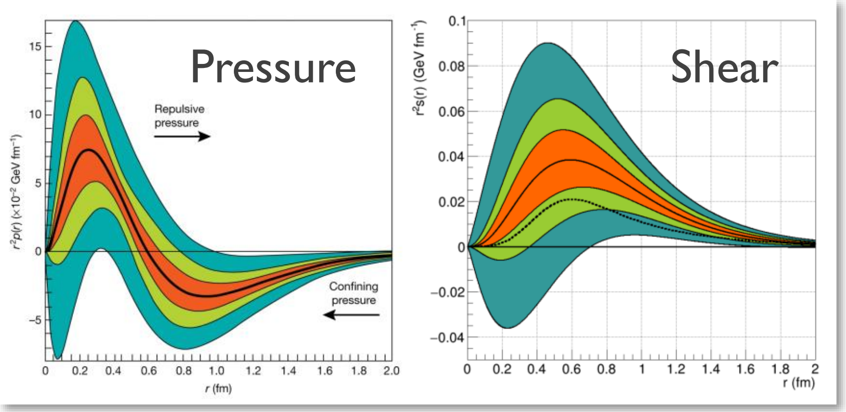
A path toward the experimental extraction of GFFs

- Relations between GPDs and GFFs established in the 2000s

Ji, Xiang-Dong , Gauge-Invariant Decomposition of Nucleon Spin, Phys. Rev. Lett. 78, 610–613 (1997)
Polyakov, M. V. Generalized parton distributions and strong forces inside nucleons and nuclei. Phys. Lett. B 555, 57–62 (2003)

- Since then, the fields has been growing rapidly both theoretically and experimentally

Burkert, V.D. Burkert, L. Elouadrhiri, F.Girod, The pressure distribution inside the proton. Nature 557, 396–399 (2018)
K. A. Mamo and I. Zahed, J/ψ near threshold in holographic QCD: A and D gravitational form factors, Phys. Rev. D 106, 086004 (2022)
Duran, B., Meziani, ZE., Joosten, S. et al. Determining the gluonic gravitational form factors of the proton. Nature 615, 813–816 (2023)

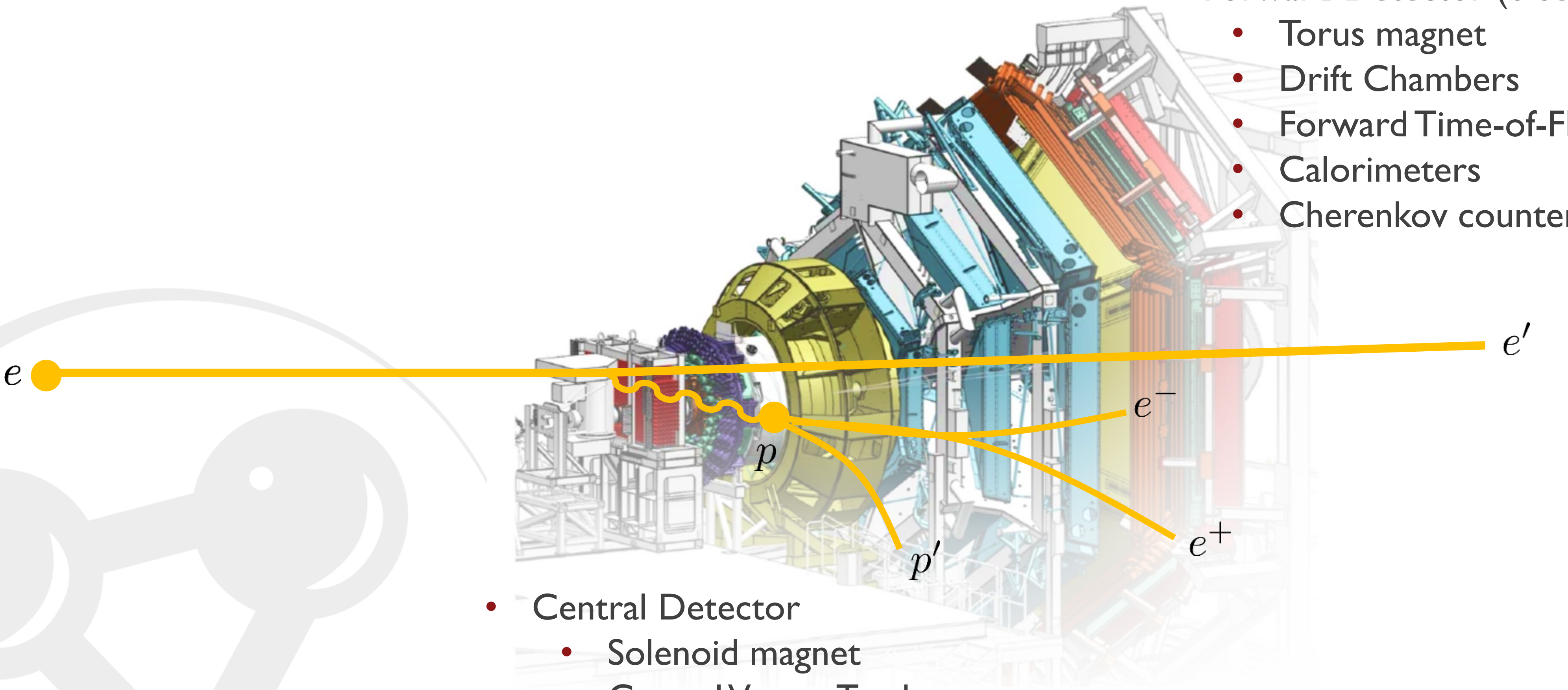


Figures in Burkert et al., The pressure distribution inside the proton. Nature 557, 396–399 (2018) and Burkert et al. arXiv:2104.02031 (2021)

How does this relate to the dilepton final state and what role can the CLAS12 experiment play ?

Measuring the dilepton final state with the CLAS12 experiment at Jefferson Lab

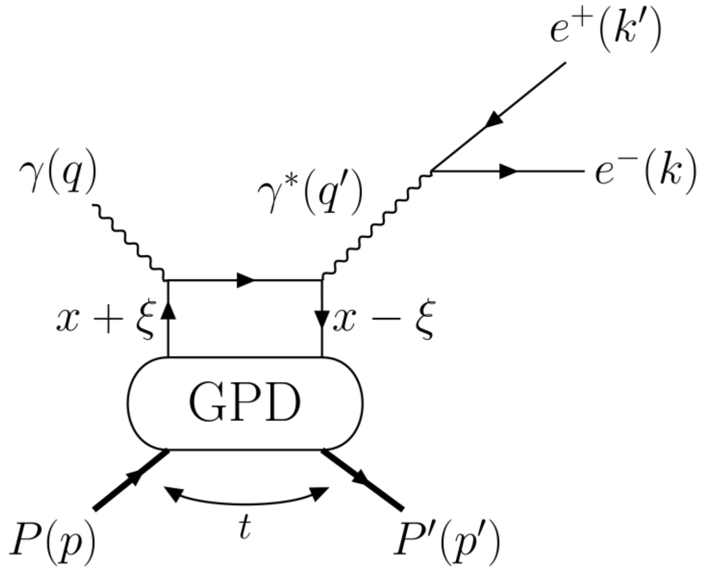
- Forward Detector (6 sectors)
  - Torus magnet
  - Drift Chambers
  - Forward Time-of-Flight
  - Calorimeters
  - Cherenkov counters



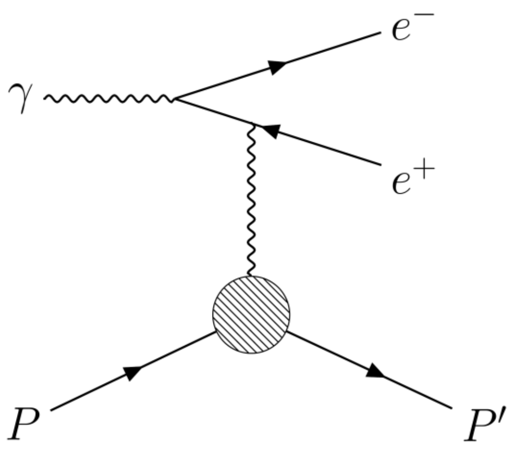
- Central Detector
  - Solenoid magnet
  - Central Vertex Tracker
  - Central Time-of-Flight
  - Central Neutron detector

Timelike Compton Scattering reaction and kinematics

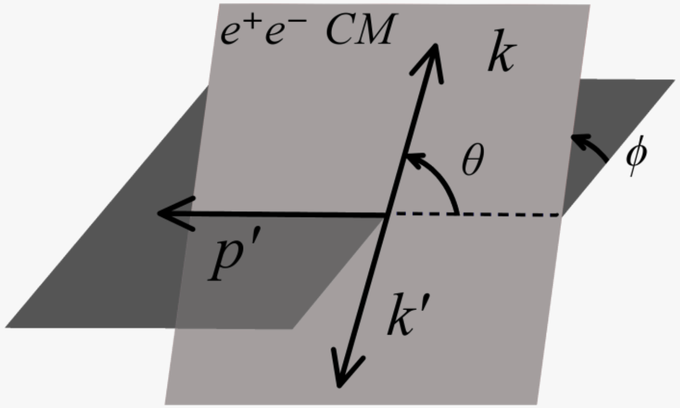
TCS: $\gamma p \to e^+ e^- p'$ DVCS: $ep \to e' p' \gamma$



TCS
(factorization regime, $-t/Q'^2 \ll 1$)



Bethe-Heitler



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

TCS interference cross-section formulae, CFFs and GFFs

TCS unpolarized cross-section

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

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

Compton Form Factors (CFFs)

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

Dispersion relation and link to GFFs

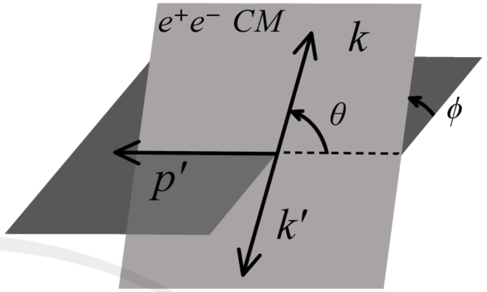
- Angular dependence of the TCS cross-section gives access to the real part of $\mathcal{H}$.
- This quantity is not well constrained by existing DVCS data (accessed in cross-section mostly).
- $\mathrm{Re}(\mathcal{H})$ is related to the GFFs D, itself related to the mechanical properties of the nucleon:

$$\mathrm{Re}\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi + x}\right)\mathrm{Im}\mathcal{H}(\xi,t) + \Delta(t) \longrightarrow \Delta(t) \propto D^Q(t) \propto \int d^3\mathbf{r}\; p(r)\frac{j_0(r\sqrt{-t})}{t}$$

The TCS Forward/Backward asymmetry

Forward/Backward correspondence:

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



Effect on cross-sections

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

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

Observable definition

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

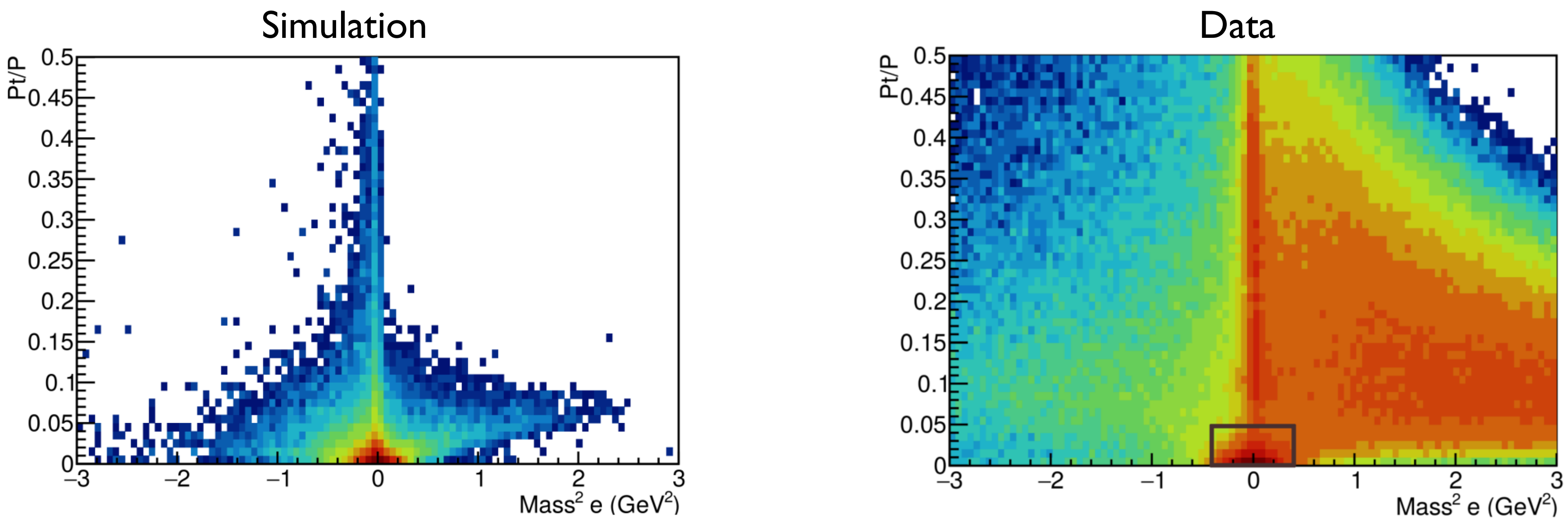
- Concept initially explored for J/ψ production (Gryniuk, Vanderhaeghen, *Phys. Rev. D*, 2016)
- Exploratory studies for TCS performed alongside this work
- Predictions for TCS have been published very recently + **LO radiative correction negligible**
  (Heller, Keil, Vanderhaeghen, *Phys. Rev. D*, 2021)

(Quasi-)Photoproduction events selection

1) CLAS12 PID + Positron NN PID

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

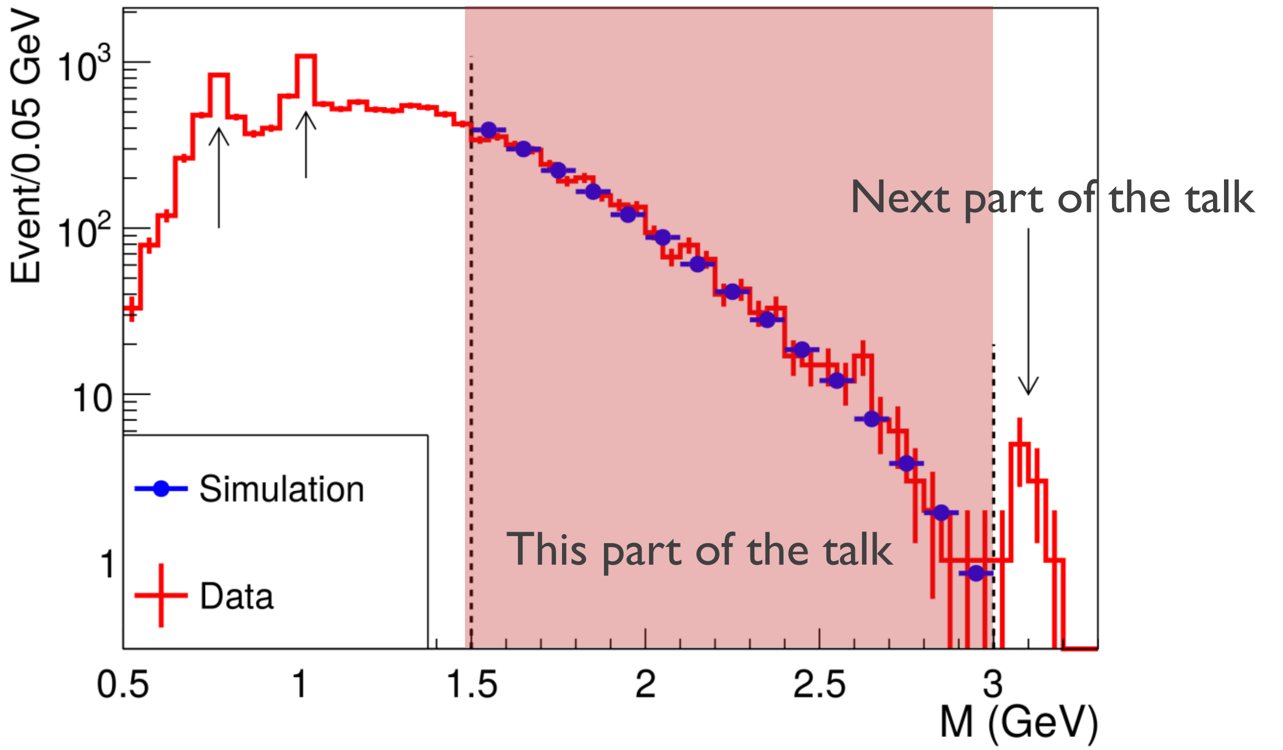
$p_X = p_{beam} + p_p - p_{e^+} - p_{e^+} - p_{p'}$ → 2) $|M_X^2| < 0.4 GeV^2$ → 3) $\frac{Pt_X}{P_X} < 0.05$ $\rightarrow Q^2 < 0.1$ GeV^2



CLAS12 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

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

Forward/Backward asymmetry results

- Integration over the forward angular bin :

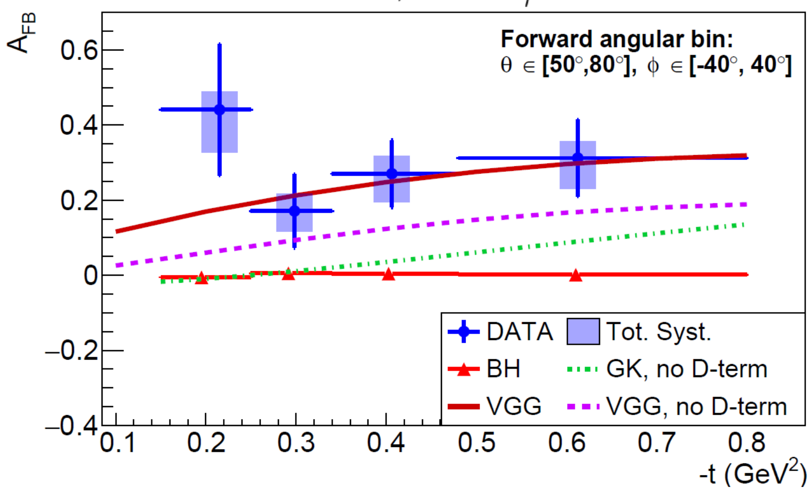
$$\theta \in [50°, 80°] \text{ and } \phi \in [-40°, 40°]$$

- Asymmetry measured in two mass bins:

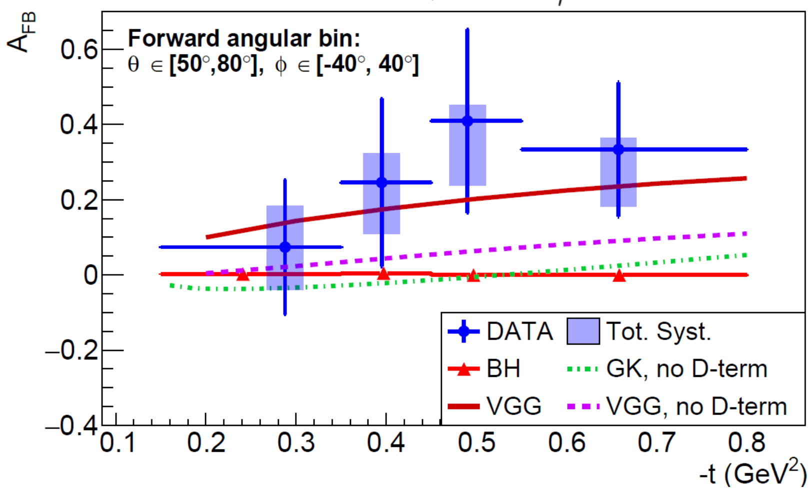
$$M \in [1.5 \text{ GeV}, 3.0 \text{ GeV}] \text{ and } M \in [2.0 \text{ GeV}, 3.0 \text{ GeV}]$$

- 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

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



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

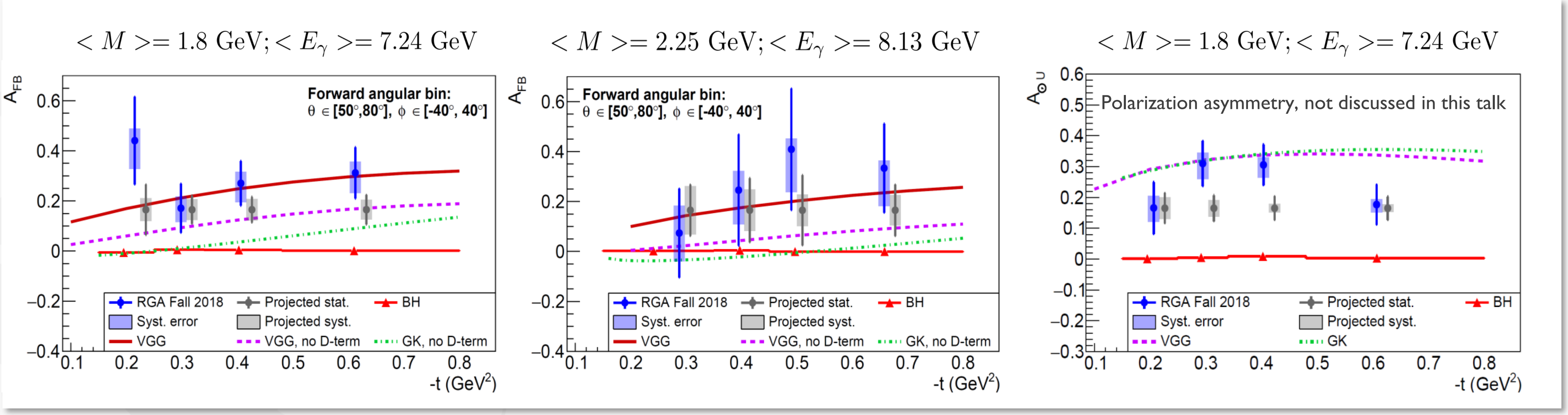


Figures in First Measurement of Timelike Compton Scattering, P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)

Perspective for TCS measurements with CLAS12

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

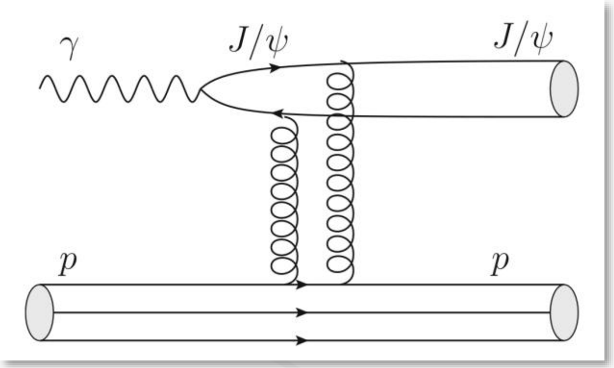
- Only a fraction of CLAS12 proton target dataset was used for in the PRL article (1/3).
- New significant improvement on the tracking software have been done since 2020 → 50% more efficiency for 3-particles final state



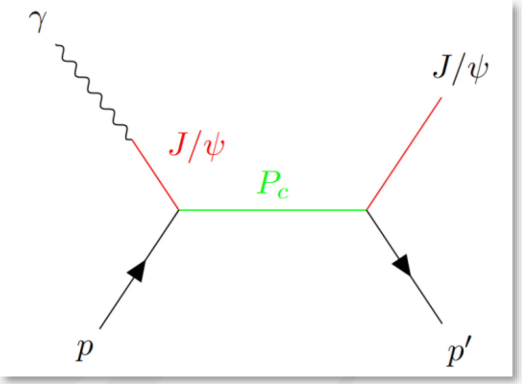
+ TCS on longitudinally polarized target (by K.Gates, U. of Glasgow) + Deuterium target dataset available
+ TCS measurement in JLab Hall C (See D. Biswas on Tuesday)

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

- Probe the gluon content of the proton



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



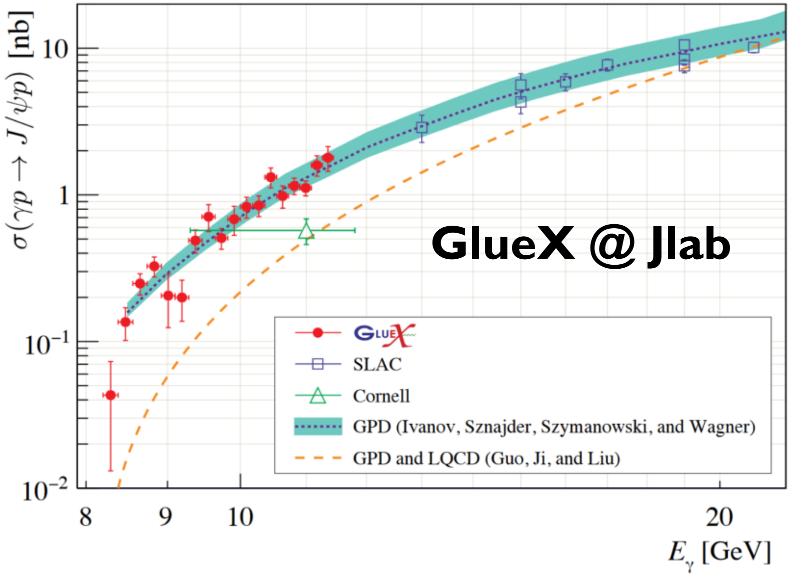


Figure in, Measurement of the J/ψ photoproduction cross section over the full near-threshold kinematic region, S. Adhikari *et al.* (GlueX Collaboration) arXiv:2304.03845

Talk by L. Pentchev on Tuesday

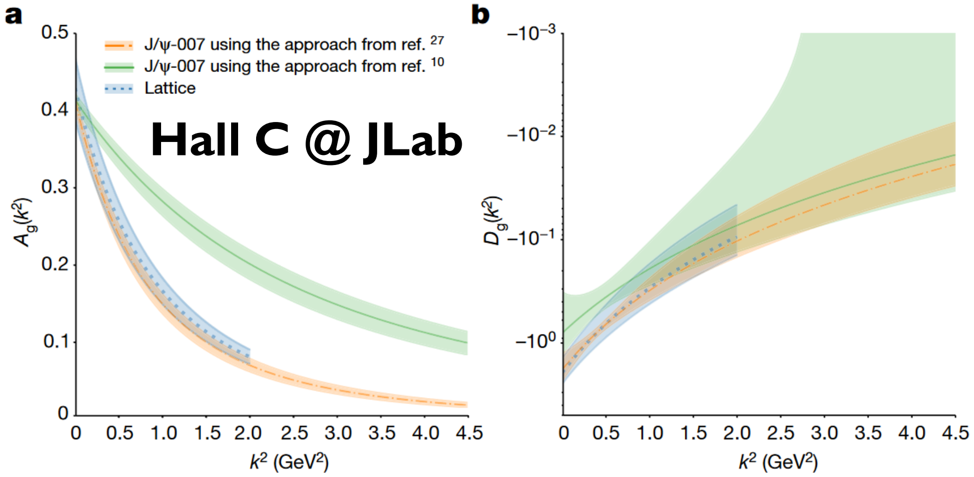


Figure in Duran, B., Meziani, ZE., Joosten, S. *et al.* Determining the gluonic gravitational form factors of the proton. *Nature* 615, 813–816 (2023)

Talk by Z.E. Meziani on Monday

Jefferson Lab

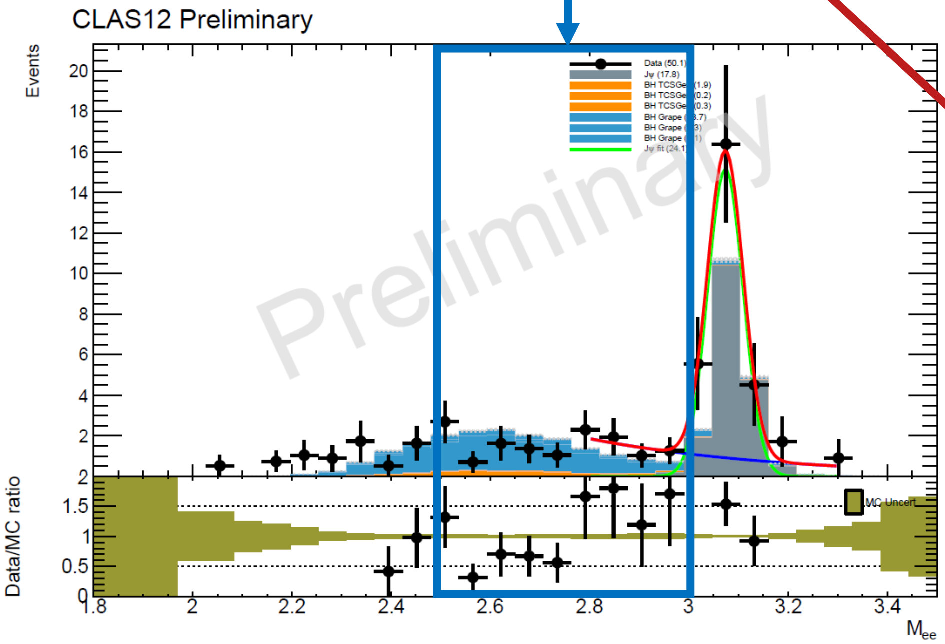
J/ψ (quasi-)photoproduction events selection & cross-section extraction

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

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

Number of J/ψ

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

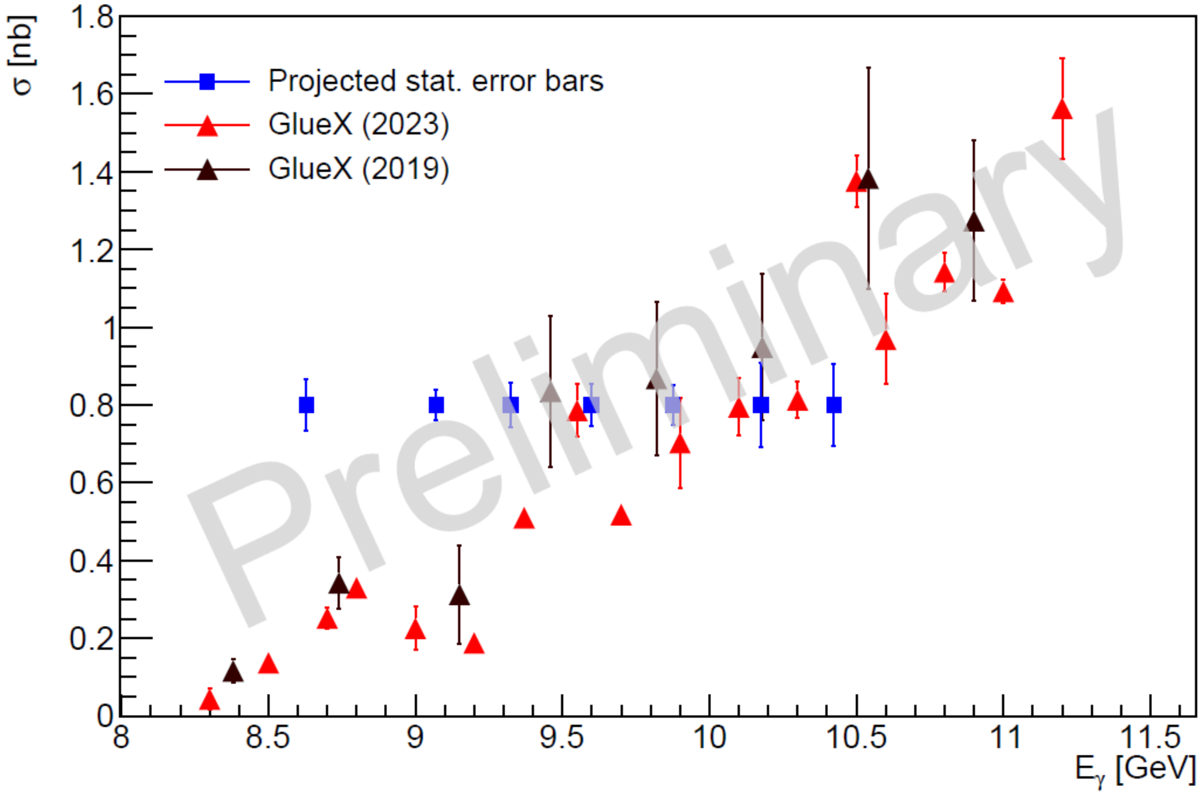


Reconstruction efficiency of the J/ψ → from MC

Branching ratio of J/ψ → e^+e^- → 6%

Projections for the full CLAS12 proton target dataset

- Projected statistics error bars based on full dataset available on proton target and expected 50% improvement for tracking.
- Maximum photon energy slightly smaller than GlueX.
- Projected error bars are competitive with GlueX.
- t-dependence will also be extracted.
- J/ψ photoproduction on neutron is also measured (Analysis by R. Tyson, U. of Glasgow).



Including all data taken on unpolarized proton and improved tracking efficiency

Summary and take-aways

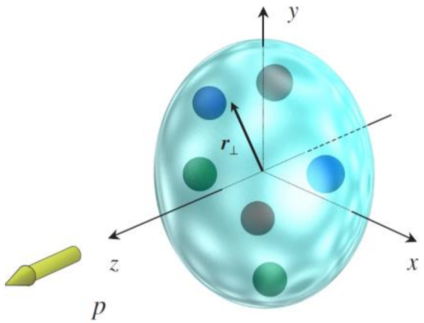
- The dilepton final state reactions (TCS and J/ψ) play a crucial role in experimentally extracting GFFs (and GPDs).
- The CLAS12 detector is the ideal place to perform such measurement, with large angular coverage and great particle identification.
- First TCS measurement have been published in 2021, and the Forward/Backward asymmetry shows promising results. Full re-processing of the proton dataset is ongoing.
- J/ψ photoproduction cross-section on proton target will soon be available. Stay tuned !

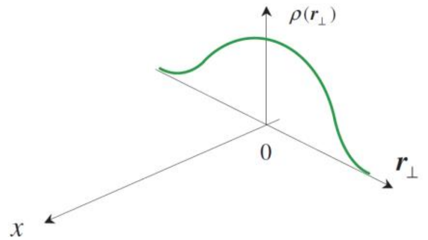
BACK-UP

GPDs and other theoretical considerations

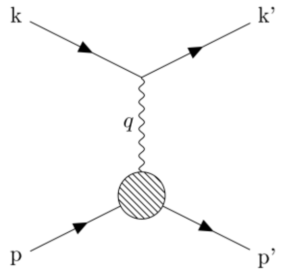
The Generalized Parton Distributions

Form Factors





Accessed via elastic scattering

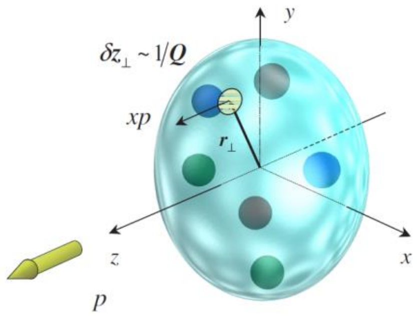


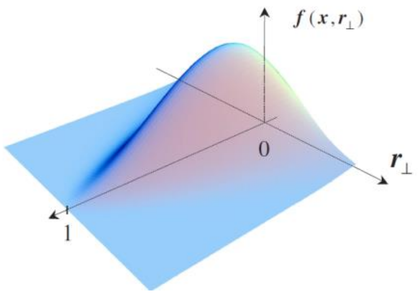
Position in the transverse plane

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

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

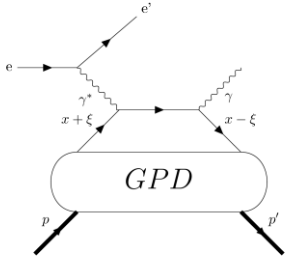
GPDs

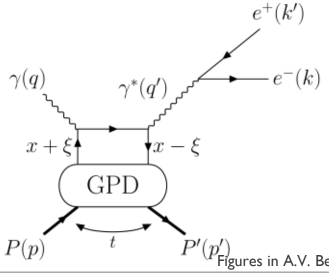




… and their correlations

Accessed via exclusive reactions

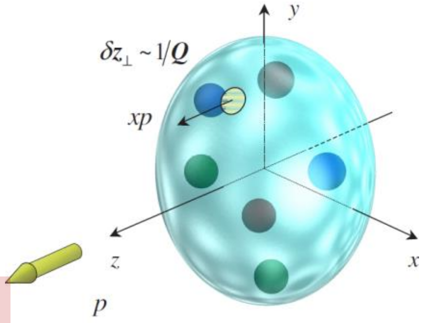


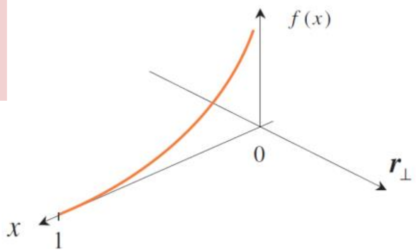


Momentum in the longitudinal direction

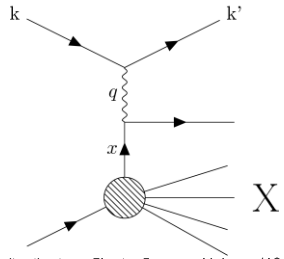
$$H^q(x,0,0) = \begin{cases} q(x), & x > 0 \\ -\bar{q}(-x), & x < 0 \end{cases}$$

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:

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

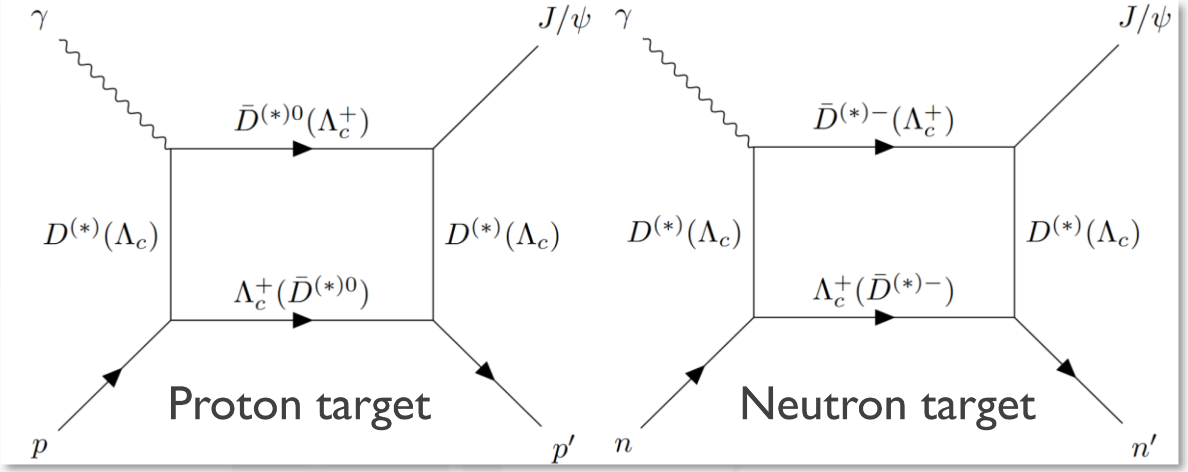
- Accessing Gravitational Form Factors by mimicking a spin-2 interaction:

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

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

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.
- Measuring photoproduction on both proton and neutron probes different channel and will bring new constraints on open-charm contributions.



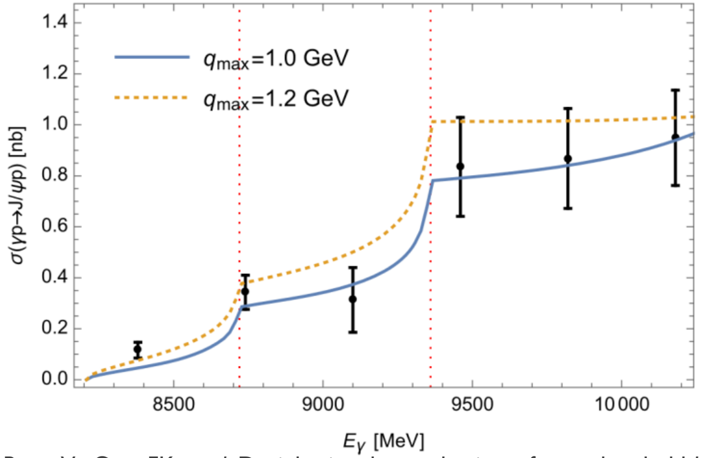


Figure in Du, ML., Baru, V., Guo, FK. *et al.* Deciphering the mechanism of near-threshold J/ψ photoproduction. *Eur. Phys. J. C* 80, 1053 (2020)

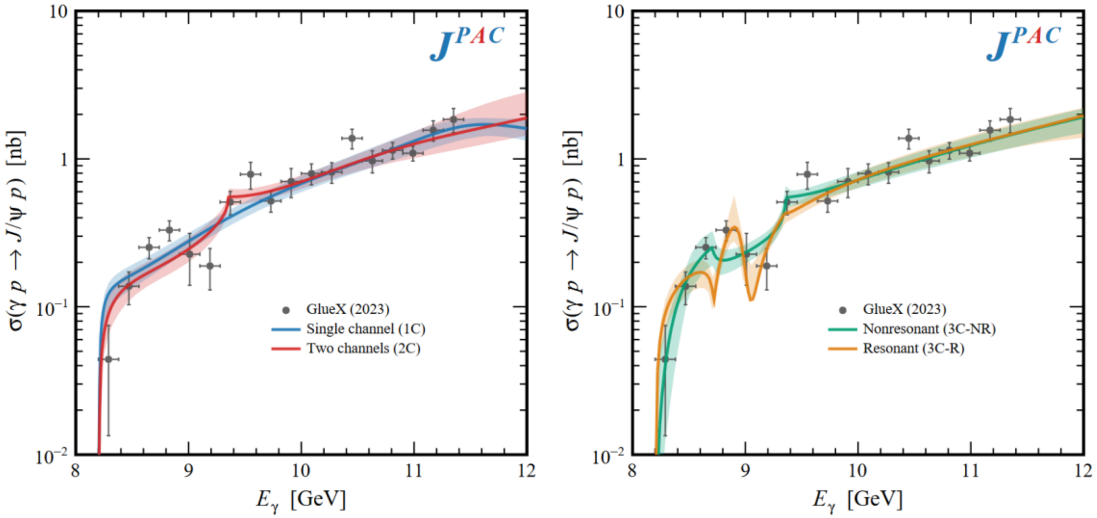


Figure in D. Winney, C. Fernandez-Ramirez, A. Pilloni, A. N. Hiller Blin et al. (JPAC), Dynamics in near-threshold J/ψ photoproduction arXiv:2305.01449

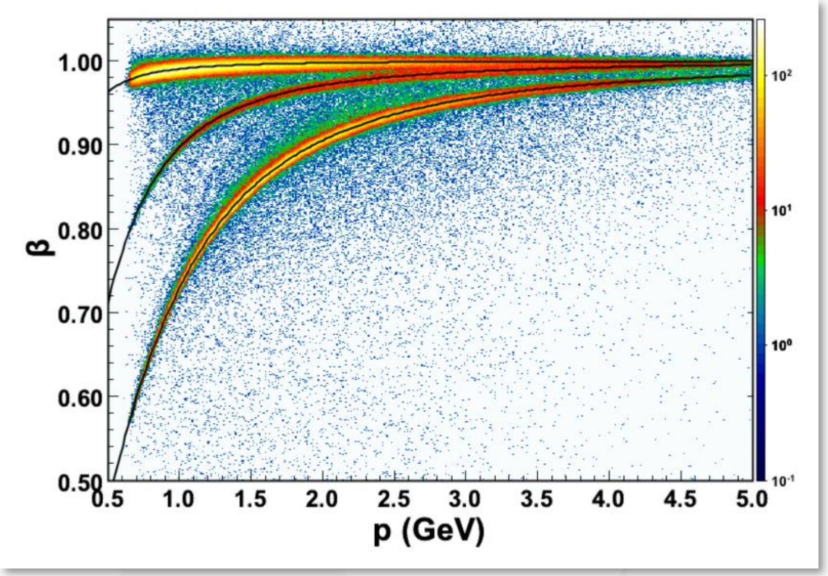
Event selection

Particle identification

1) CLAS12 PID + Positron NN PID

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

Proton identification

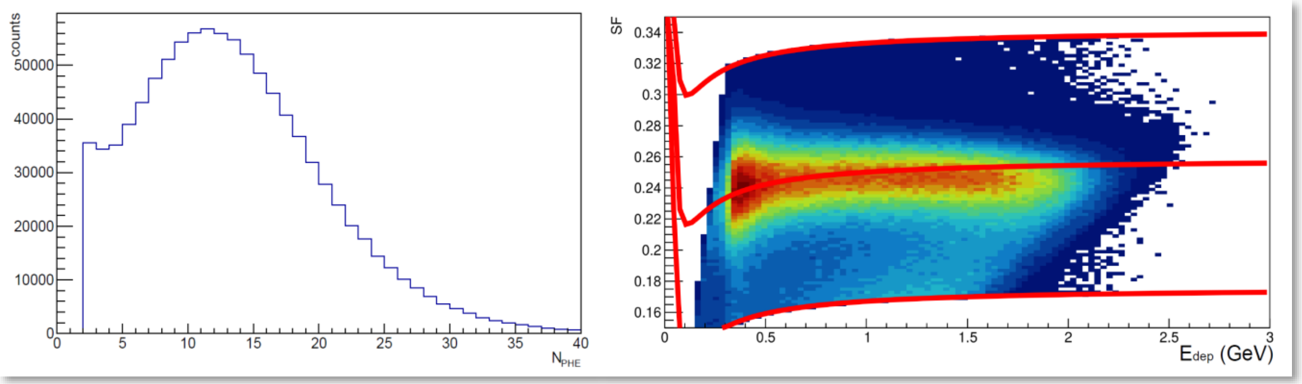


Velocity from the time-of-flight

Momentum from the track curvature

Lepton identification

Cherenkov counters + Calorimeter energy deposition



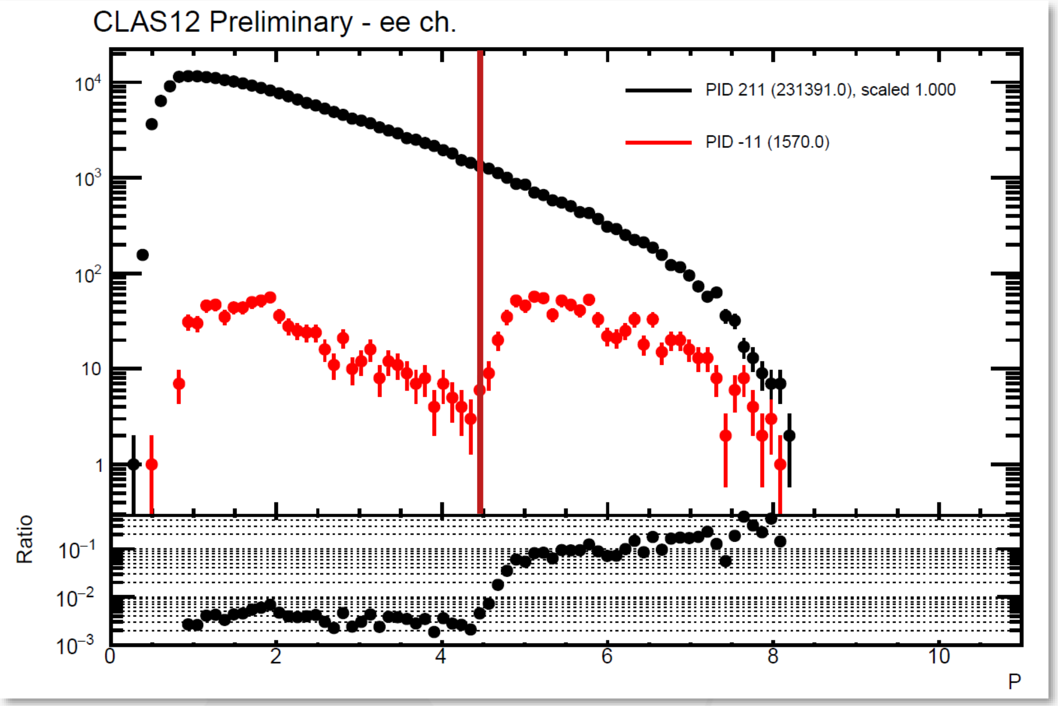
$$Sampling\ Fraction = \frac{E_{dep}}{P}$$

One important challenge: a clean positron identification

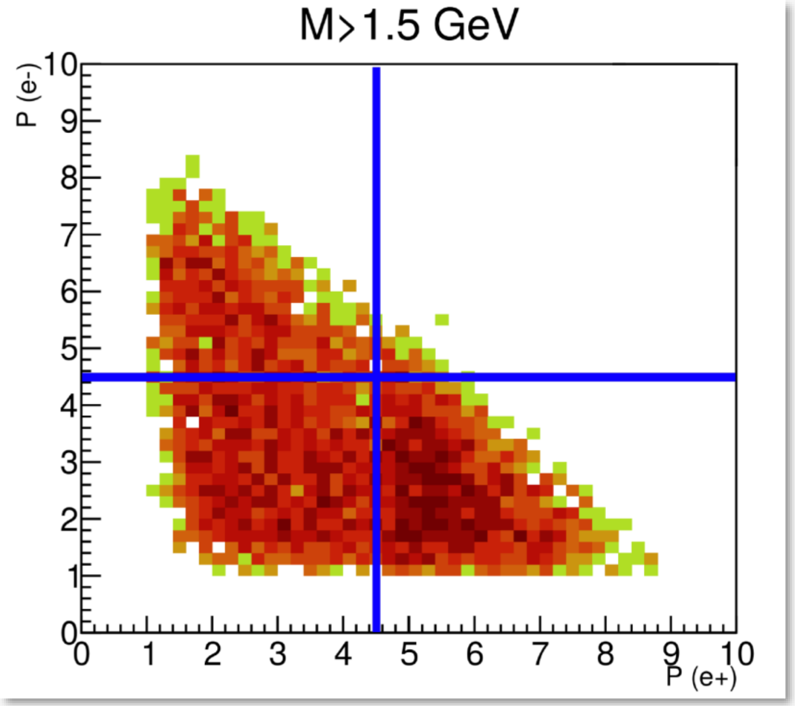
Pion background at large momenta

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

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



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

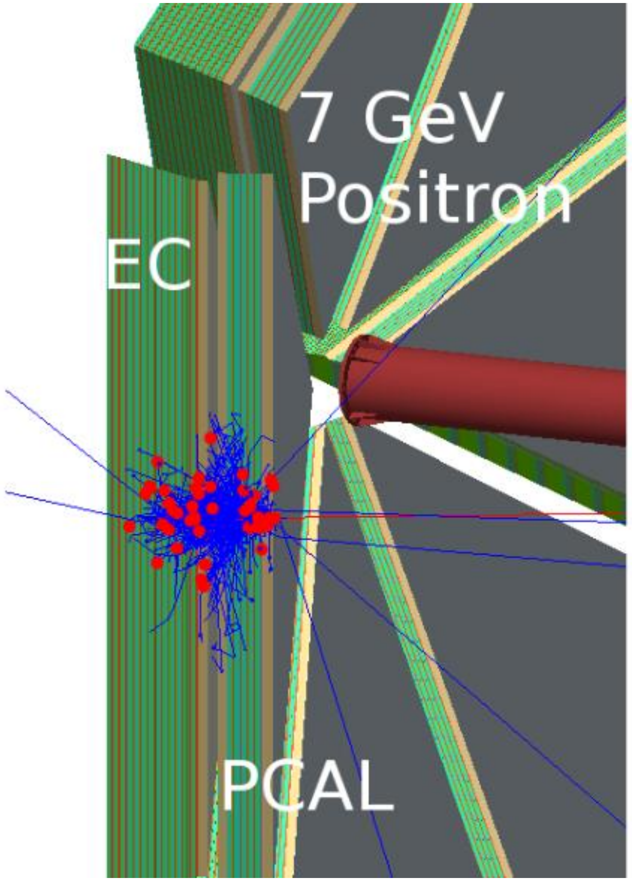


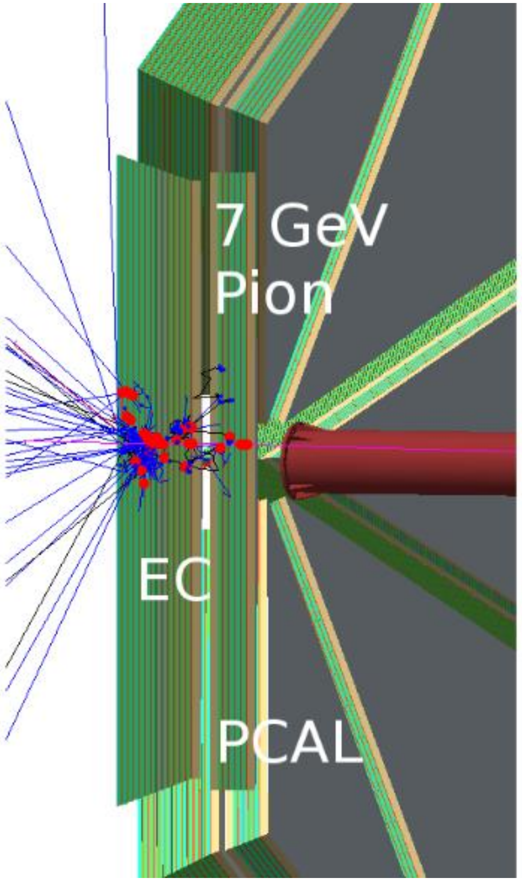
AI identification of the positrons

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. $$SF_{\text{EC Layer}} = \frac{E_{dep}(\text{EC Layer})}{P}$$
  2. $$M_2 = \frac{1}{3}\sum_{U,V,W} \frac{\sum_{\text{strip}}(x-D)^2 \cdot \ln(E)}{\sum_{\text{strip}} \ln(E)}$$





Performances of AI identification of the positrons

Strategy and discriminating variables

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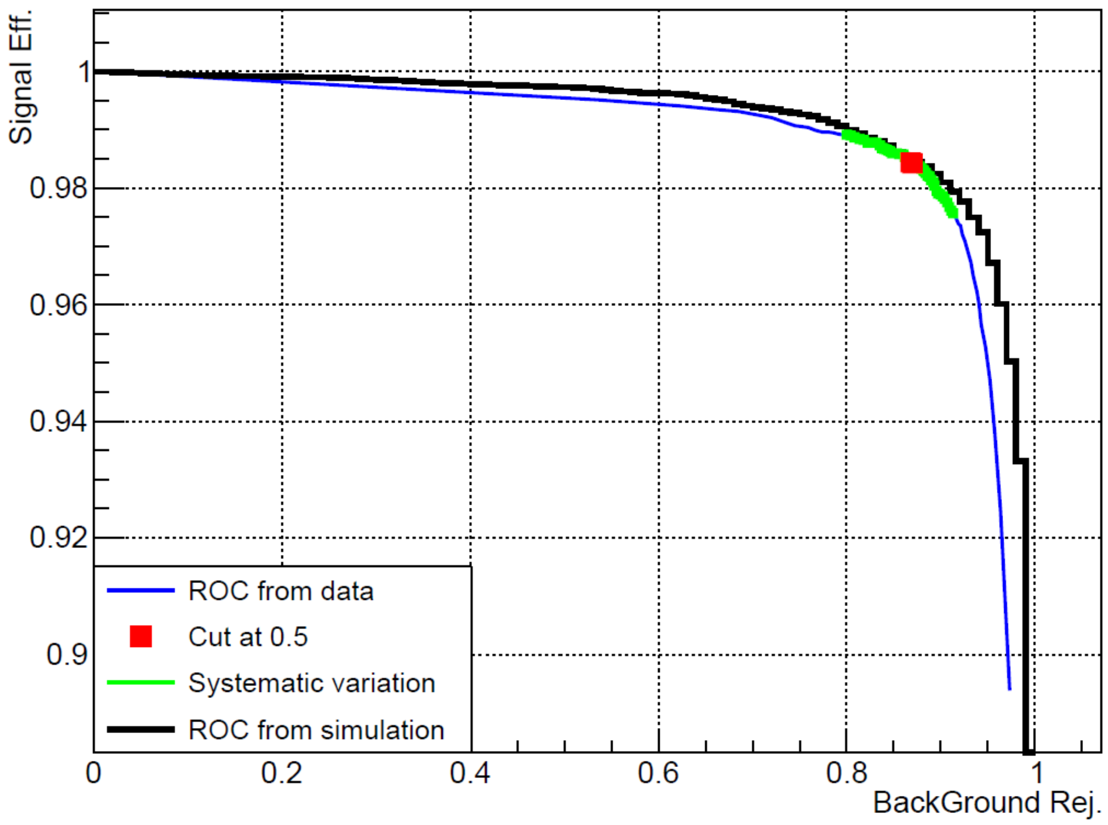


More on TCS

TCS interference cross-section formulae and CFFs

Unpolarized cross-section

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

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

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

Compton Form Factors (CFFs)

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

Polarized cross-section

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

First observable: the photon polarization asymmetry

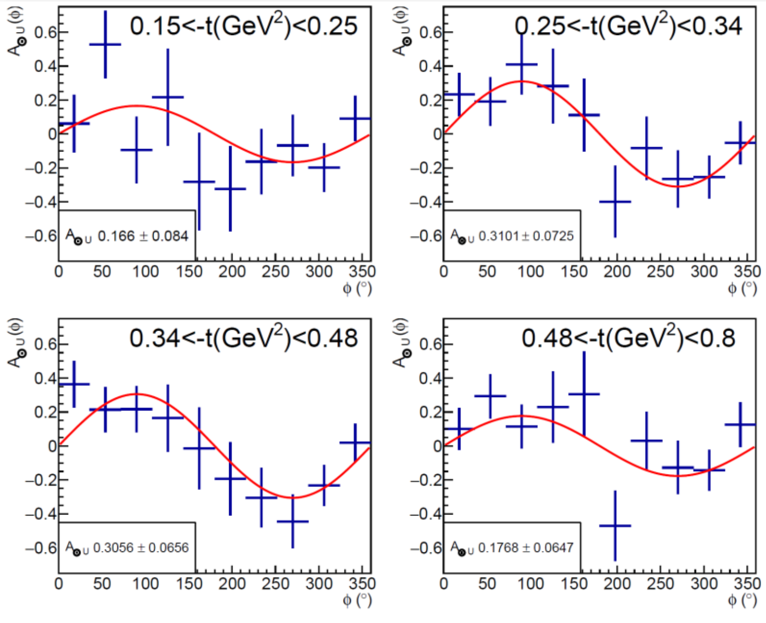
Definition

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

Measurement

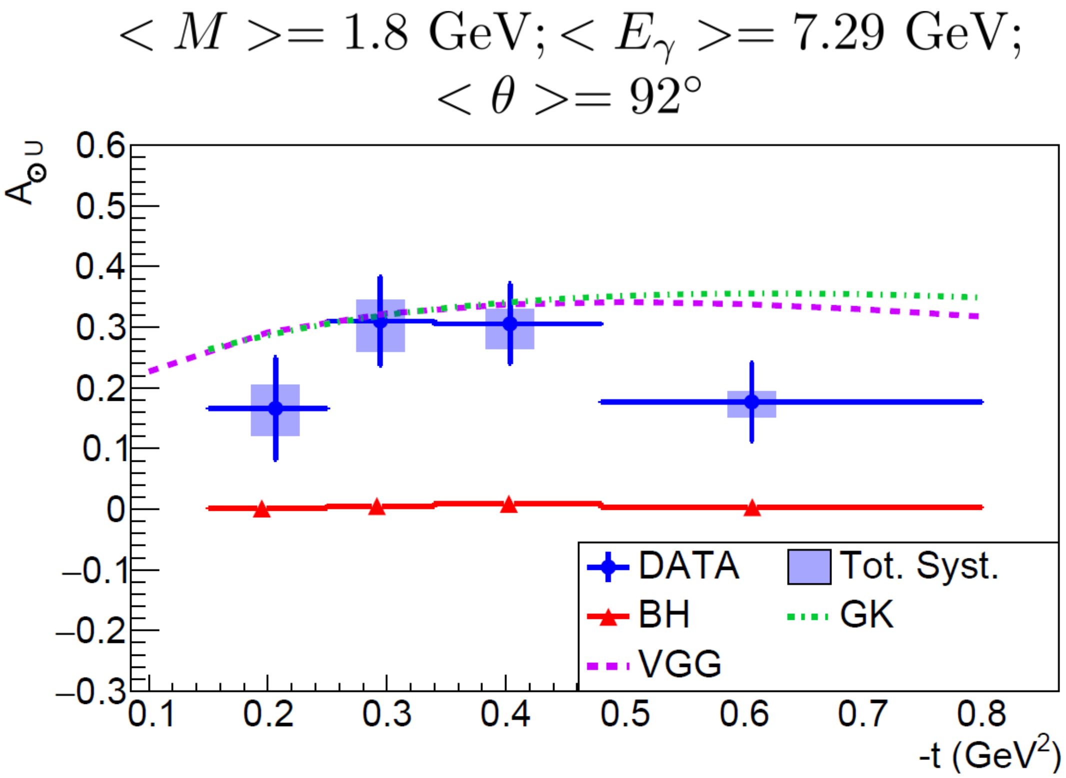
$$A_{\odot U}(-t, E\gamma, M; \phi) = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-} \text{ where } N^{\pm} = \sum \frac{1}{Acc} P_{trans.}$$

- $P_{trans.}$ 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.



Photon polarization asymmetry results

- 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.



J/ψ analysis

Background subtracted data using same-charge lepton events

- Opposite charge leptons

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

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

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

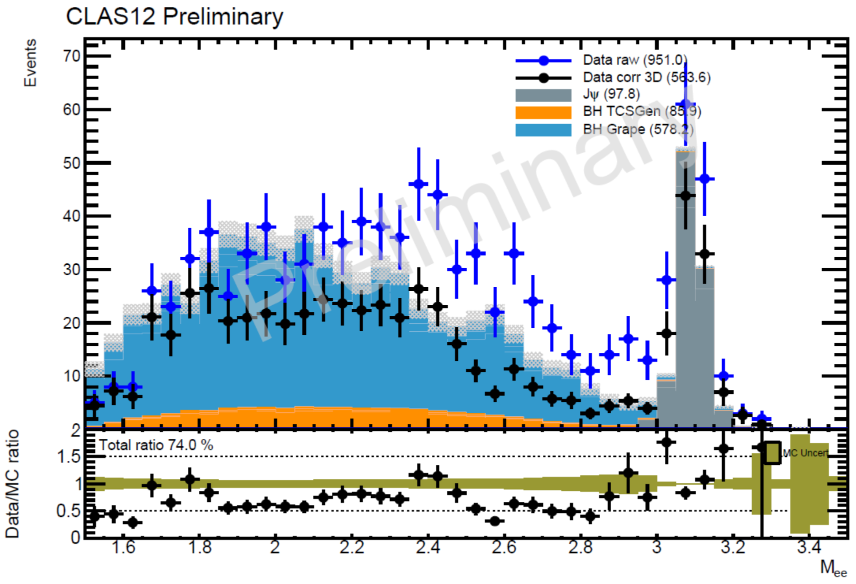
- Same charge leptons

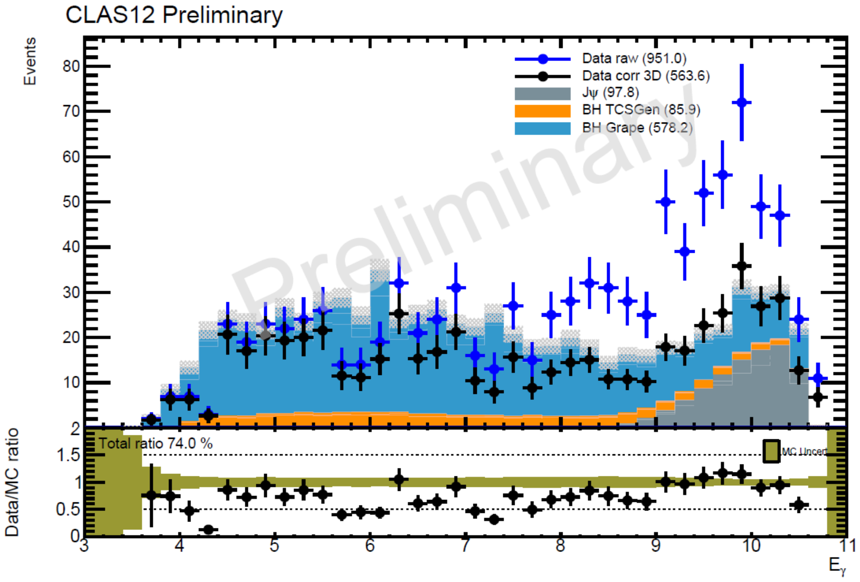
$$ep \to p'e^-e^-(X \simeq e)$$

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

- Background correction weight, combining inbending and outbending data:

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





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

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

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

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

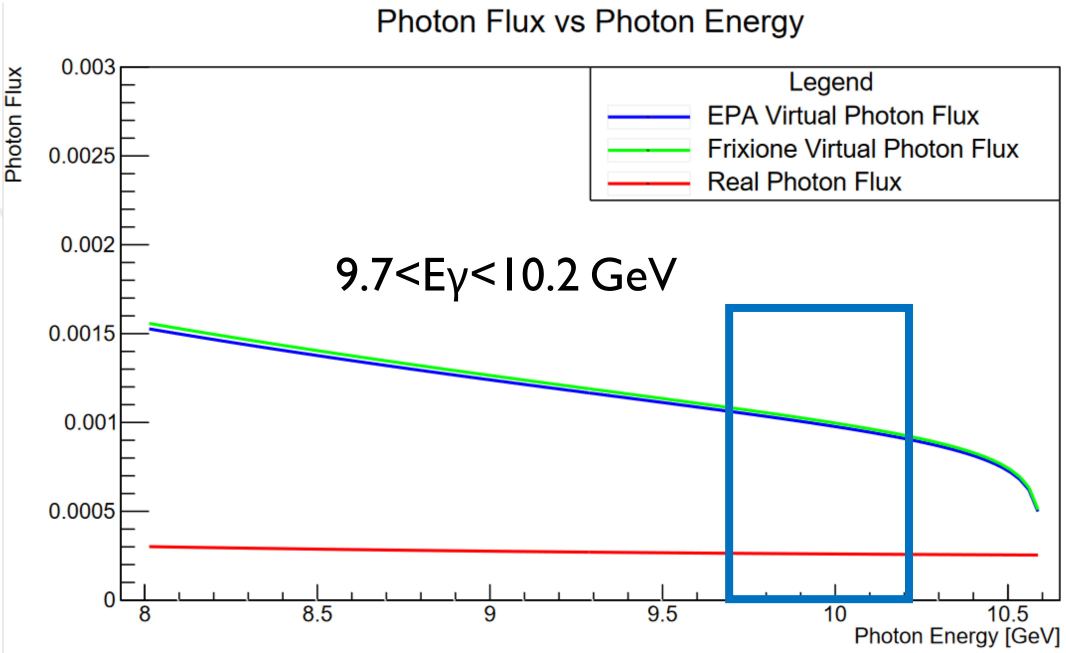
$$R^{out} = \frac{N^{out}(e'e^-p')}{N^{out}(e^+e^-p')} = \frac{b^2 \cdot \sigma_{BG}}{a \cdot b \cdot \sigma_{BG+S}} = \frac{b \cdot \sigma_{BG}}{a \cdot \sigma_{BG+S}}$$

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

Photon flux and accumulated charge

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

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

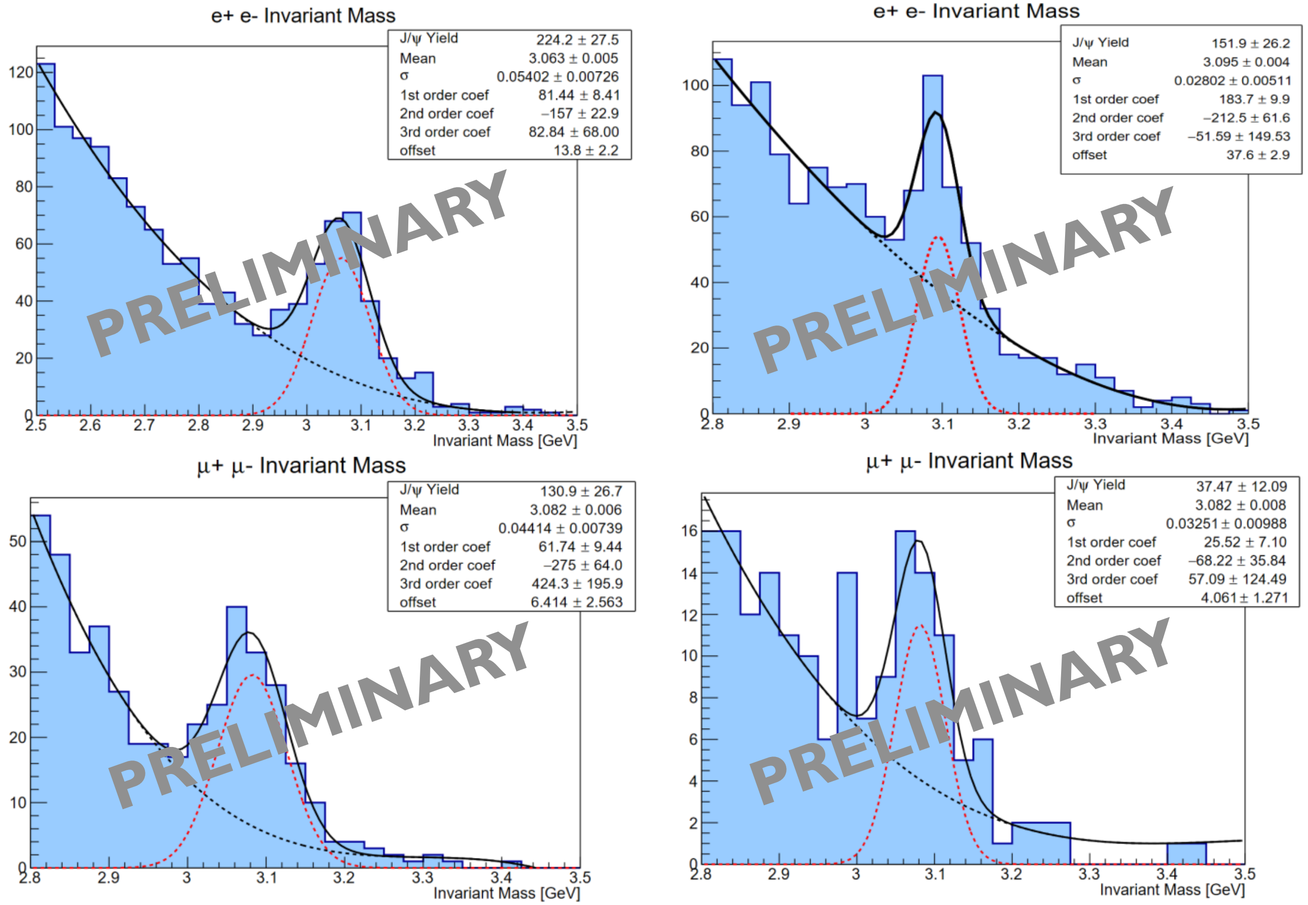


Deuterium target and muon final state

- 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

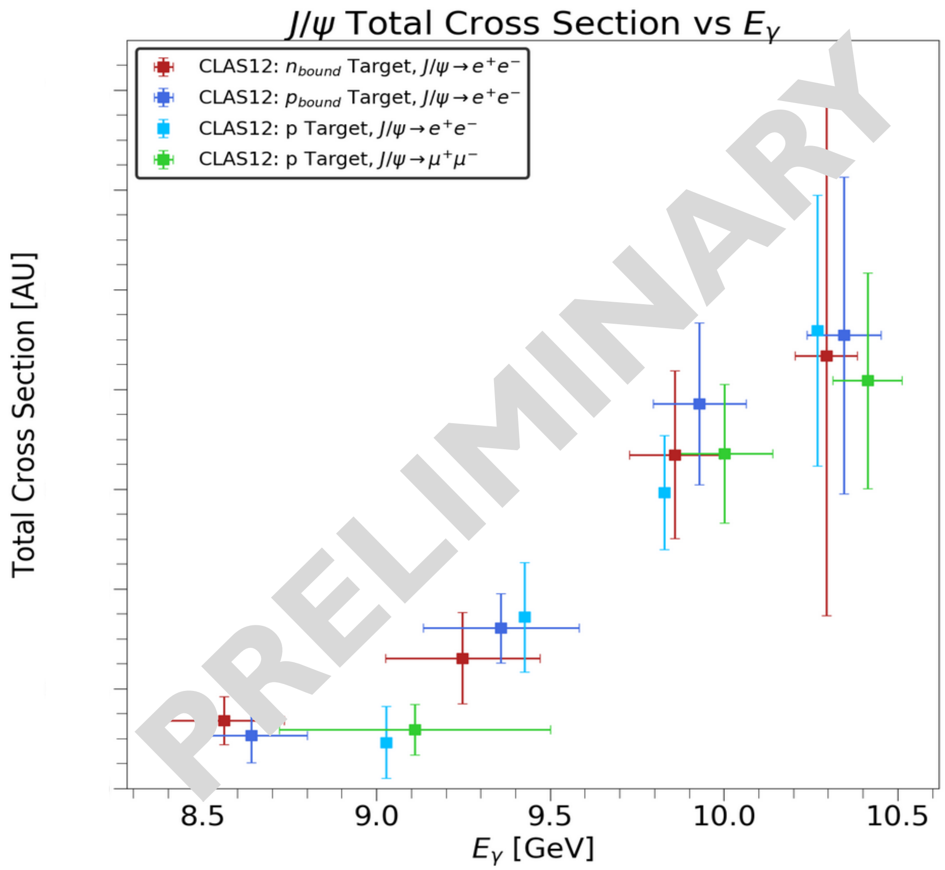
Bound neutron



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

Preliminary results for proton/neutron data

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

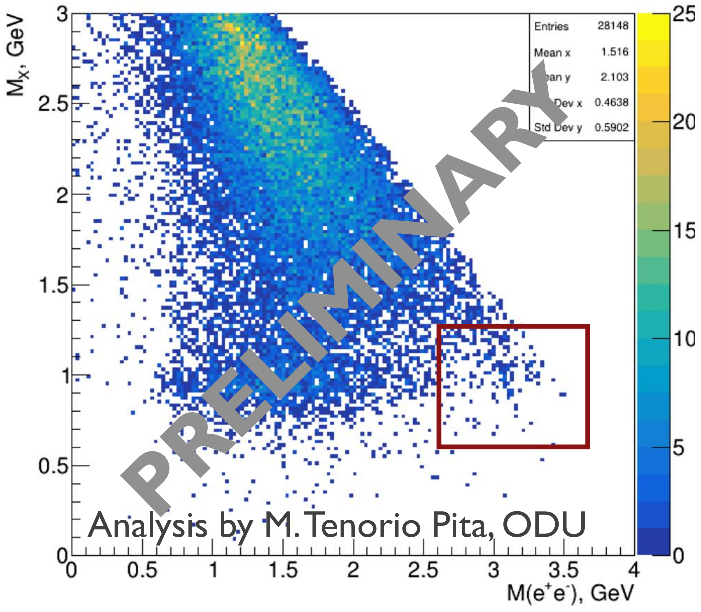


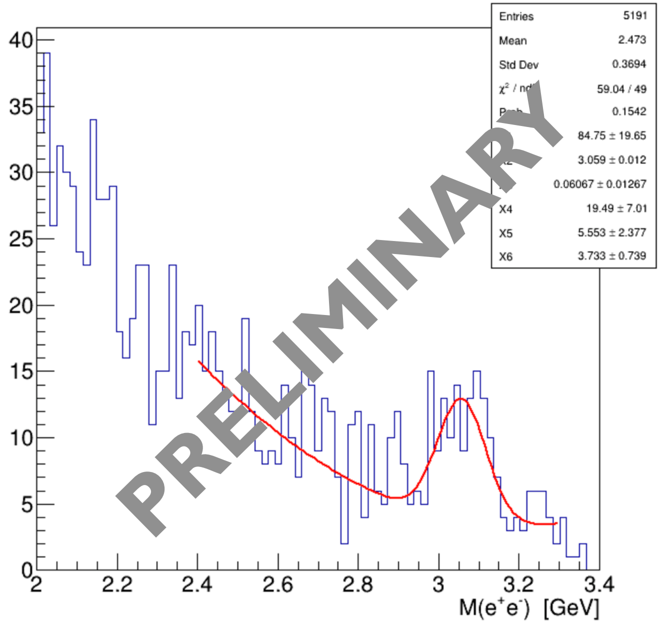
Taken from R. Tyson PhD analysis, Univ. of Glasgow

Tagged J/ψ quasi-photoproduction analysis

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

- 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

Jefferson Lab