J/ψ Near-Threshold Photoproduction on the Proton and Neutron at CLAS12

Richard Tyson

J/ψ Near-Threshold Photoproduction

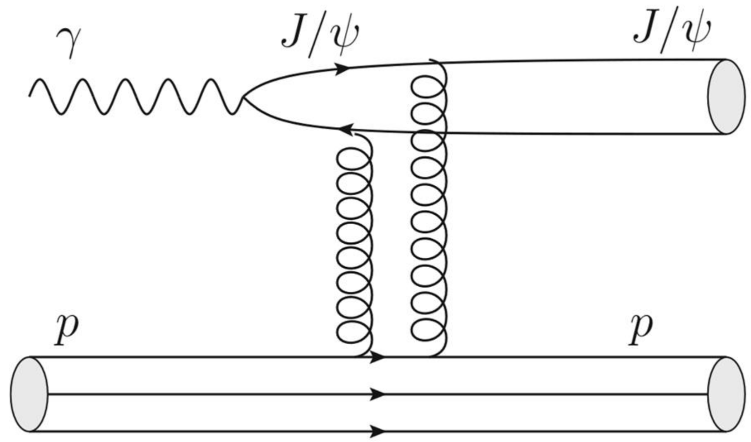
We are interested in measuring the process:

$$eN \rightarrow e'J/\psi N \rightarrow e'l^+l^-N$$

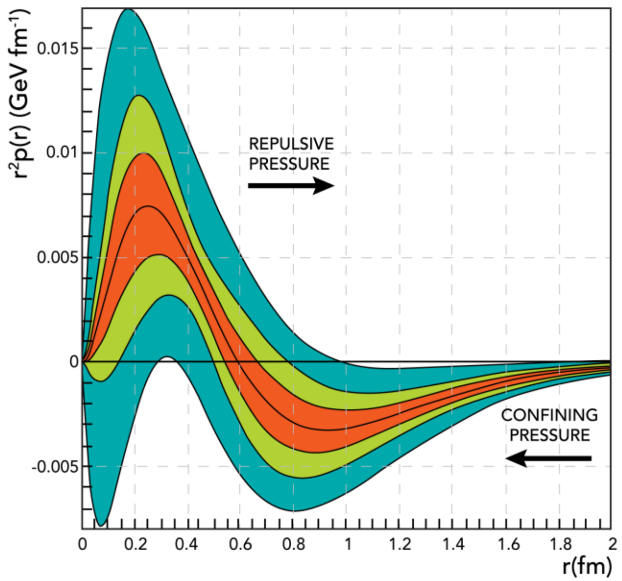
Close to the 8.2 GeV threshold, J/ψ photoproduction is predicted to be mediated by the exchange of two gluons.

Allows to probe the nucleon mechanical form factors via GPD or holographic QCD models.

The quark mechanical form factors have already been investigated in the context of DVCS. J/ψ allows to probe the gluonic mechanical form factors.



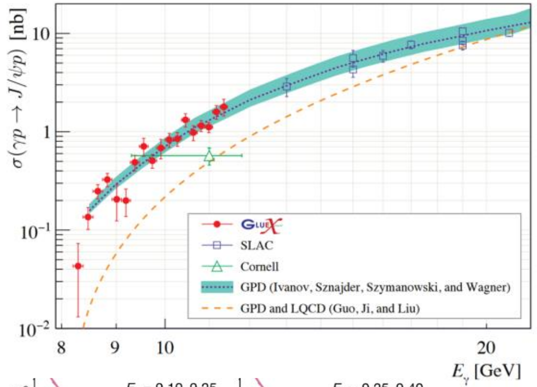
Pressure distributions of quarks inside the proton.

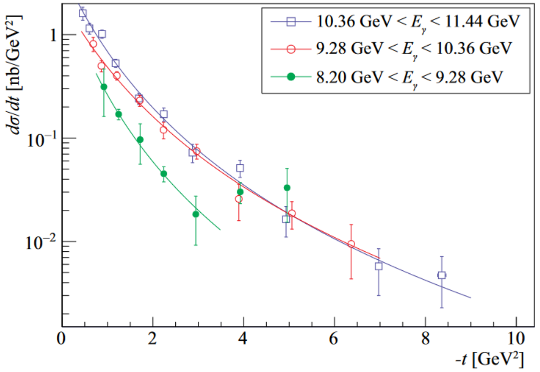


J/ψ Photoproduction on the Free Proton

GlueX – Hall D

The GlueX Collaboration has made measurements of the total and differential cross section over the full near-threshold range.

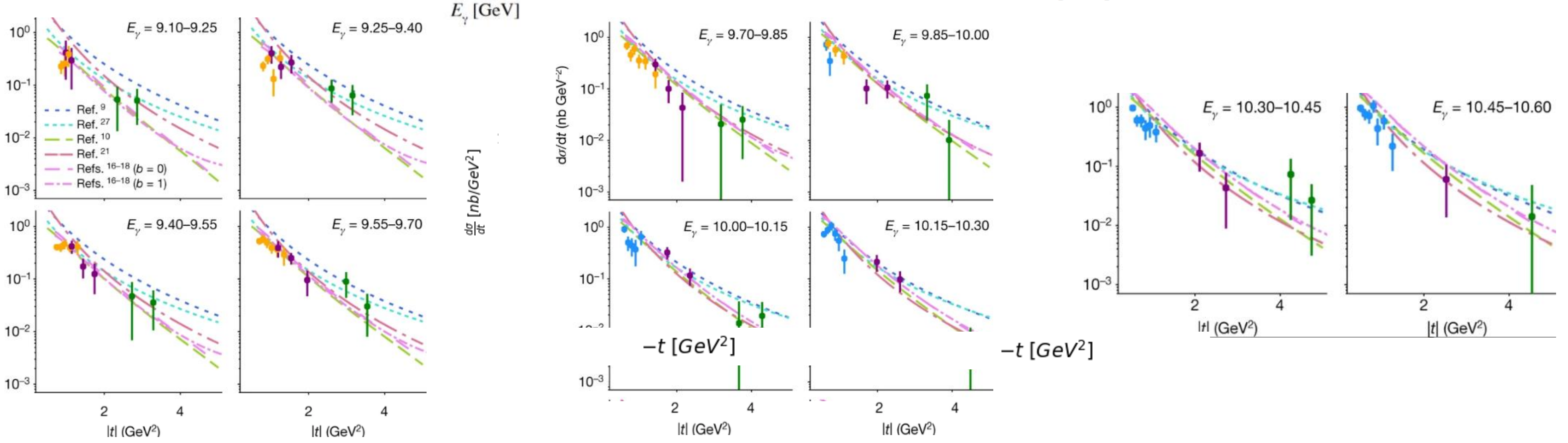




A. Ali, *et. al.* (GlueX Collaboration), *Phys. Rev. Lett.* **123**, 072001 (2019).
S. Adhikari *et al.* (GlueX Collaboration) *Phys. Rev. C* **108**, 025201 (2023).
D. Duran, et al. (J/ψ-007 Collaboration), *Nature* **615** (2023).

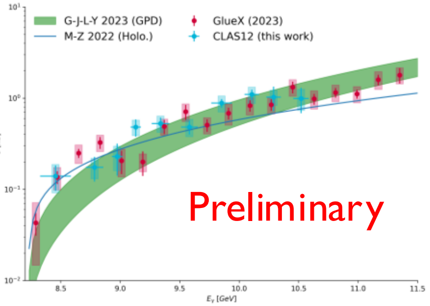
J/ψ 007 – Hall C

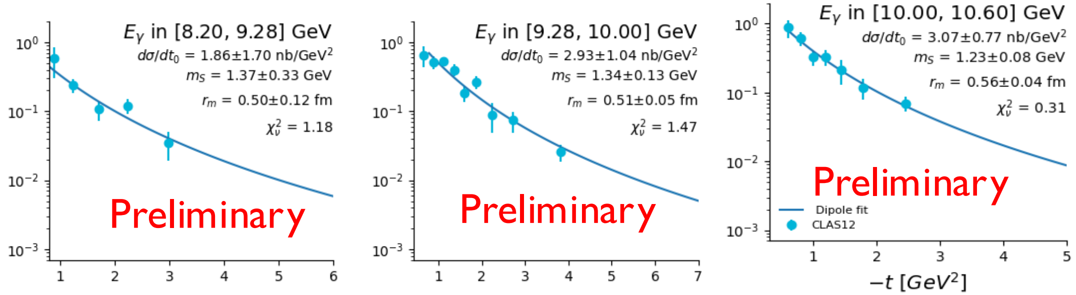
The J/ψ – 007 Collaboration has made precision measurements of the differential cross section as a function of t in 10 bins of E_γ.



CLAS 12 – Hall B (*P. Chatagnon*)

Measurements of the total and differential cross section produced on the free proton are currently undergoing internal CLAS collaboration review.



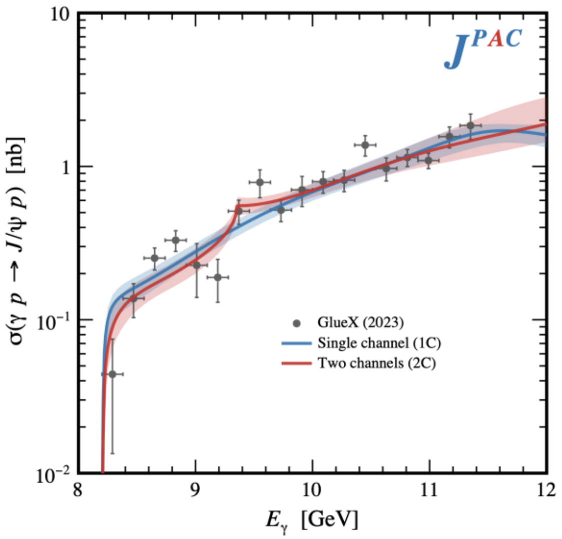


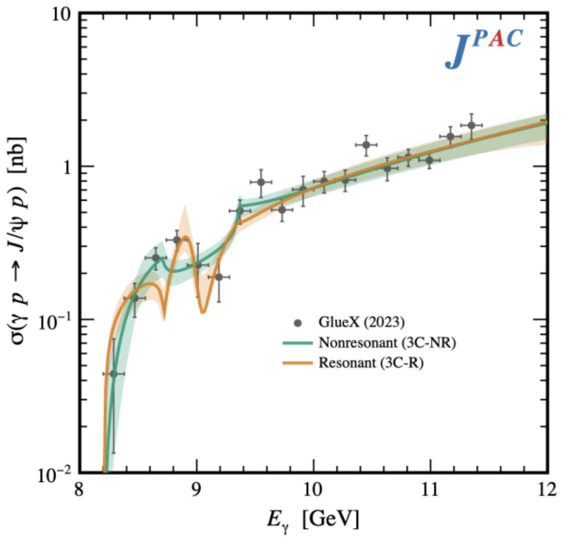
J/ψ Photoproduction On the Neutron

CLAS12 can make a first measurement of the near-threshold cross section on the bound neutron (and proton) in deuteron.

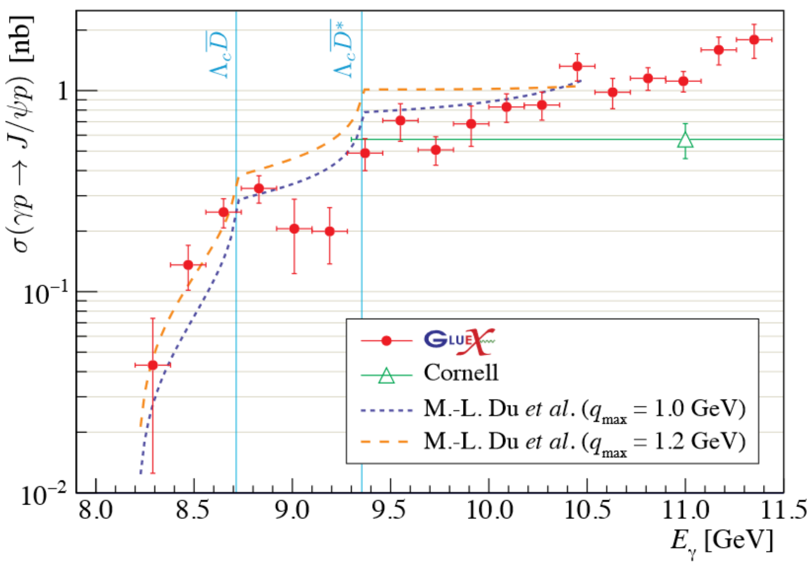
The cross section can be used to compare the proton and neutron gluonic properties.

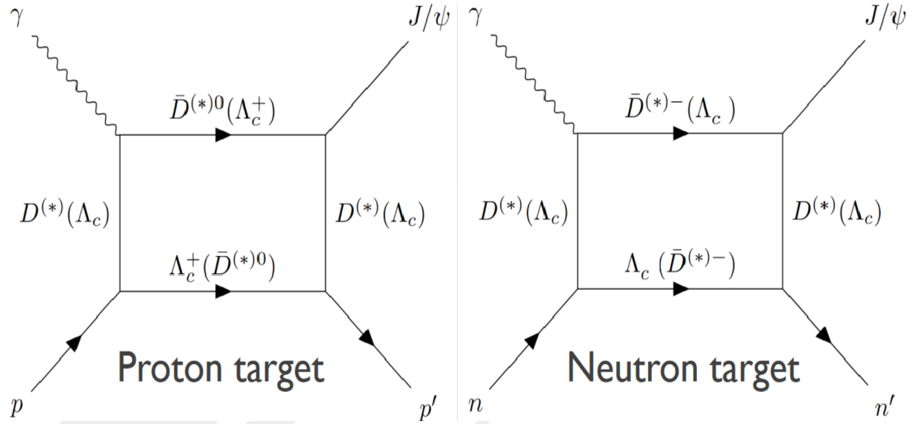
Comparing the cross section on proton and neutron allows to test the isospin invariance of the production mechanism.





Estimating the contribution to the J/ψ cross section from intermediate open charm production.





J/ψ Photoproduction in RG-B

We are interested in measuring incoherent J/ψ (quasi-real) photoproduction on the proton and neutron in the RG-B deuterium target.

Look at the channels:

$$e\ p_{bound} \rightarrow \mathrm{e}'\mathrm{J}/\psi\ \mathrm{p} \rightarrow (\mathrm{e}')e^{+}e^{-}\mathrm{p} \quad (LD_2 \text{ target})$$
$$e\ n_{bound} \rightarrow \mathrm{e}'\mathrm{J}/\psi\ \mathrm{n} \rightarrow (\mathrm{e}')e^{+}e^{-}\mathrm{n} \quad (LD_2 \text{ target})$$

Can compare with RG-A measurements:

$$ep \rightarrow \mathrm{e}'\mathrm{J}/\psi\ \mathrm{p} \rightarrow (\mathrm{e}')e^{+}e^{-}\mathrm{p} \quad (LH_2 \text{ target})$$

Use all available RG-B data.

Run Period	Beam Energy (GeV)	Beam Current (nA)	Accumulated Charge (mC)	Fraction of Total (%)
spring2019	10.60	35	7.1	6.63
spring2019	10.60	50	19.91	18.59
spring2019	10.20	50	39.39	36.78
fall2019	10.41	40	12.29	11.48
spring2020	10.39	50	28.40	26.52
Total			107.09 mC	

Cross Section Calculation

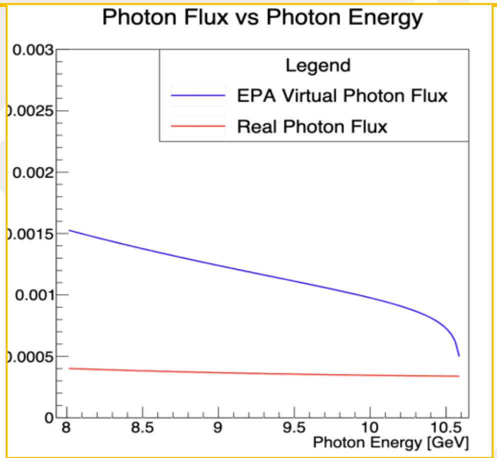
Total cross section as a function of quasi-real virtual photon energy

Number of J/ψ from fit in E_γ bins

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

Normalisation to Bethe Heitler process

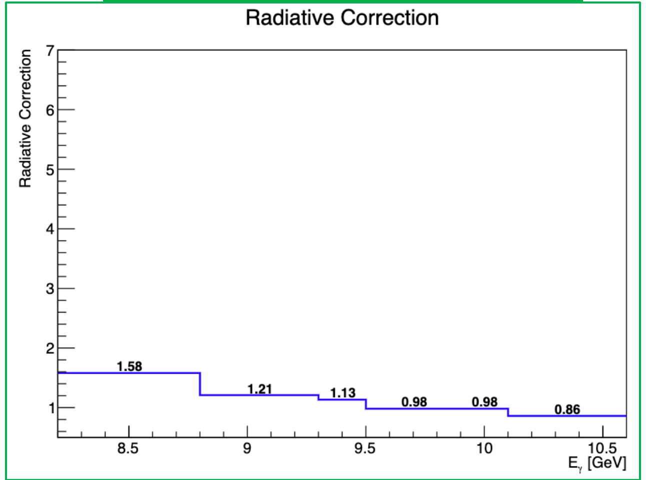
Luminosity:
N_γ is calculated from the photon flux
l_T and ρ_T are the target length and density



6 % Branching Ratio ($J/\psi \to e^+e^-$)

Efficiency in E_γ bins from MC

Radiative Corrections



Could also call this a correction to the efficiency and flux calculations.

Final State Particles

$$eN \to (e')e^{+}e^{-}N$$

Identification

e^{+}/e^{-} ID starts with event builder PID & fiducial cuts.

Refine the lepton identification with ML.

Event Builder PID for protons.

No ID for neutrons, only use charge.

Select earliest neutrals to remove secondary neutrons.

Systematic uncertainty around 5-15 % for ID procedures.

Corrections

Apply some corrections to reconstructed momentum.

Correct for $e^{-} \to e^{-}\gamma$ by adding momentum of nearby photons.

Variation <10% for momentum correction

Obtain ratio of neutron detection efficiency in data to simulation to correct simulation.

Systematic uncertainty ~10 % for efficiency correction.

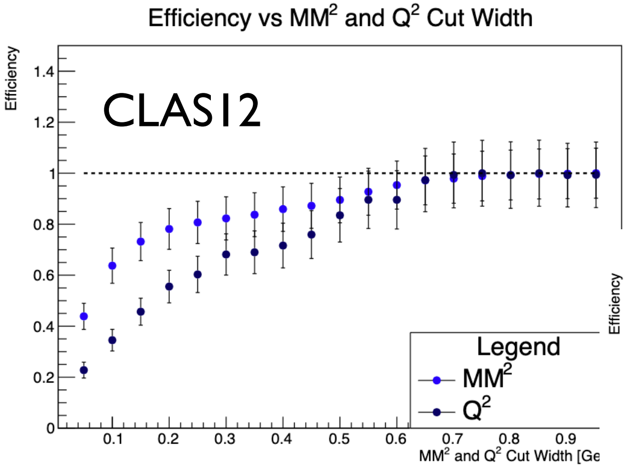
Event Selection

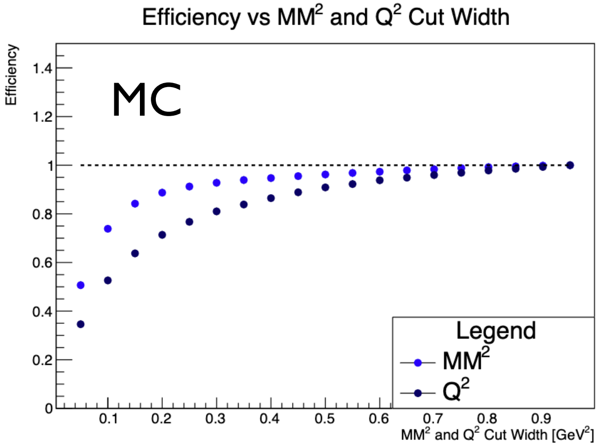
Exclusivity

Cut on the missing mass of $eN \rightarrow e^+e^-\mathrm{N(X)}$

Work in the quasi-real photoproduction regime ie Q^2 should be close to zero.

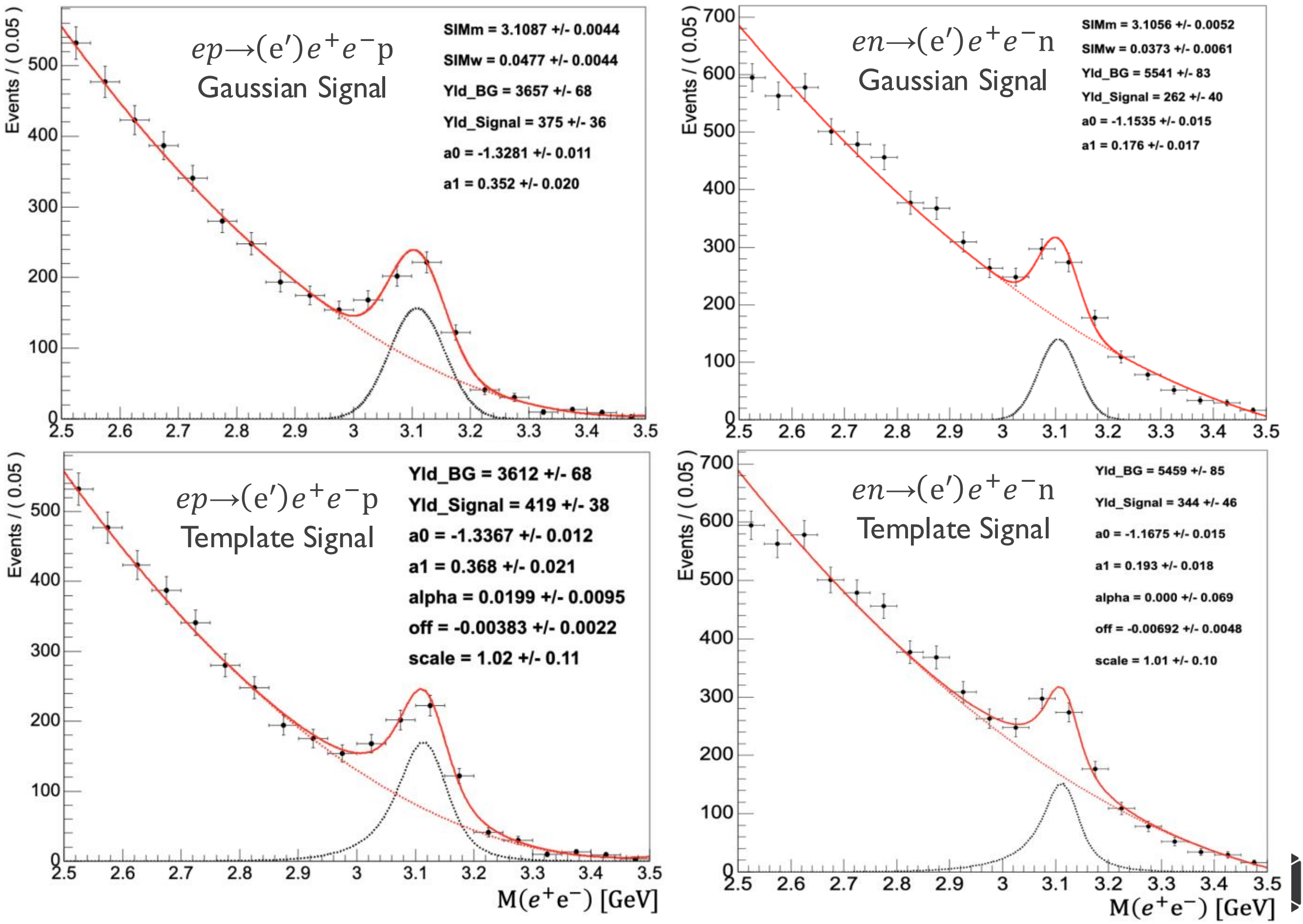
Systematic uncertainty due to cuts ~20% .





Counting J/ψs

Use gaussian or template fit, vary background between 2nd order and exponential.



Efficiency Calculation

The efficiency calculation takes into account geometrical acceptance and detection efficiency effects on the measured J/ψ rate.

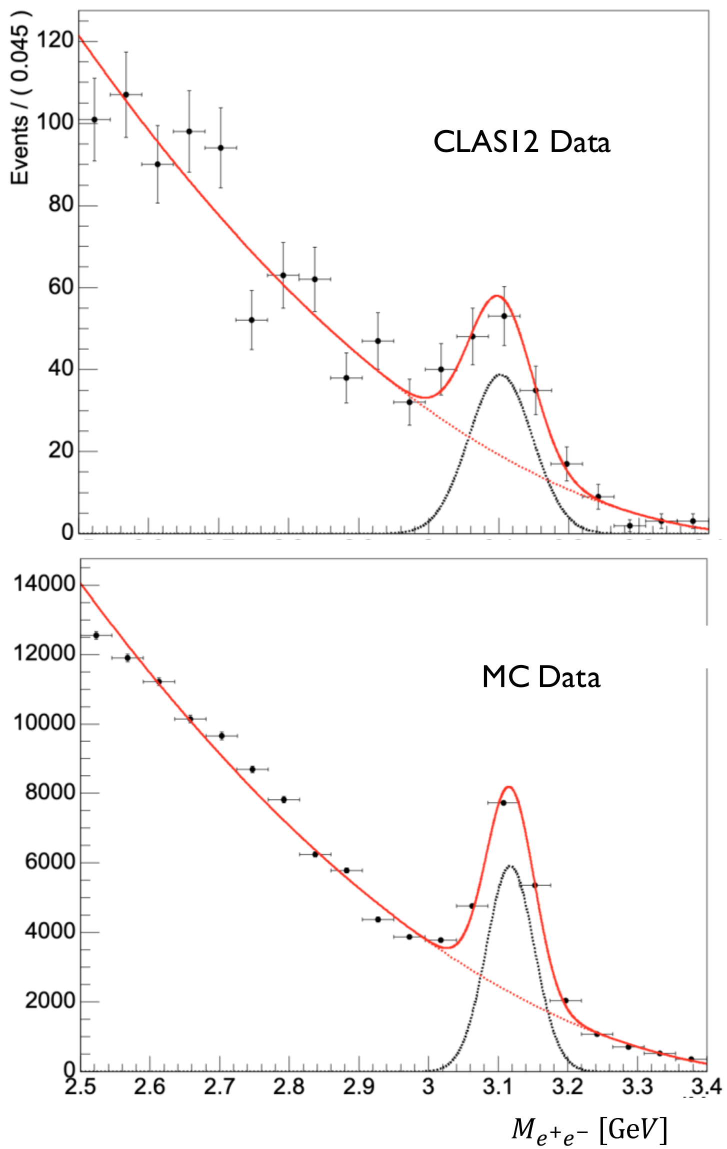
This is obtained by looking at the ratio of generated to reconstructed events.

Several corrections are applied to the MC:

- Smearing to reconstructed momentum and angles.
- Neutron detection efficiency.
- Reconstruction efficiency as a function of beam current.
- Fiducial cuts.
- Efficiency ratios for e+/e- PID and exclusivity cuts.

Mixed event background is added to the MC and the e^+e^- is fitted as the data to account for fit systematics in obtaining the number of J/ψ in E_γ, t bins.

Systematic uncertainty due to fit functions ~10-15 %.



Bethe Heitler Normalisation

Compare the expected number of Bethe Heitler events in MC to that in CLAS12 data, the ratio of the two gives us our normalization.

This accounts for errors in the efficiency and flux calculations.

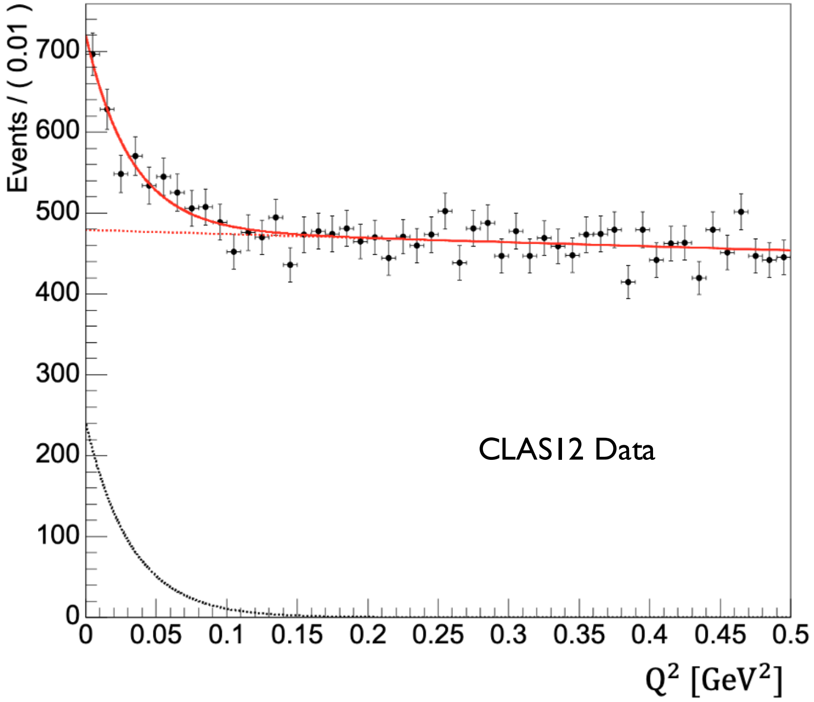
Fit Q^2 in e^+e^- invariant mass region of 2.0 - 2.9 GeV. Only photoproduction events in this region are from Bethe Heitler. Add background to MC.

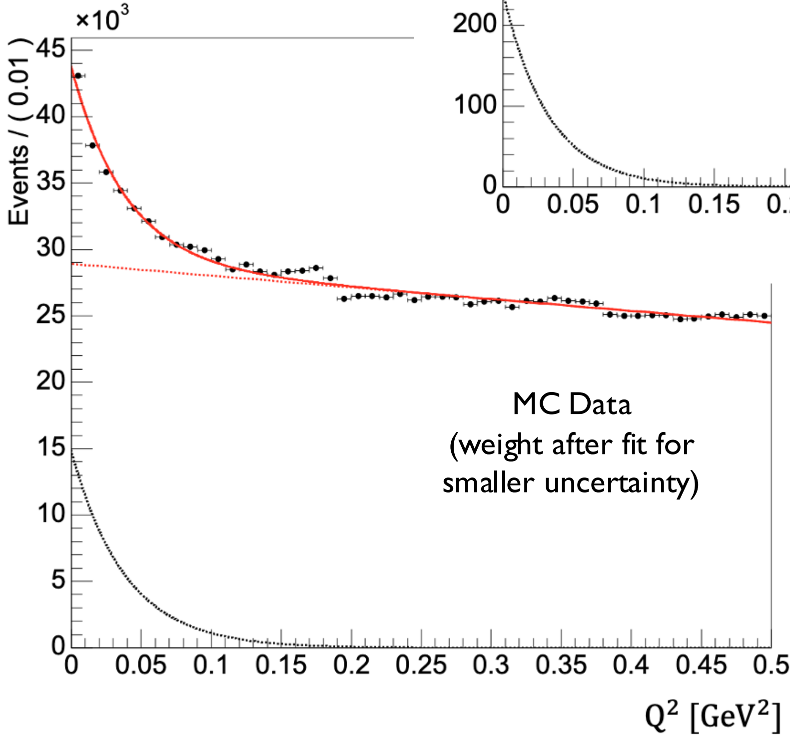
Uncertainty propagated to statistical uncertainty on cross section.

The size of the normalization factor is well understood:

- $\boldsymbol{\omega = 0.954 \pm 0.193} \Rightarrow$ with corrections to MC
- $\boldsymbol{\omega = 0.695 \pm 0.140} \Rightarrow$ without (some) corrections to MC

Variations due to flux or corrections <5%.



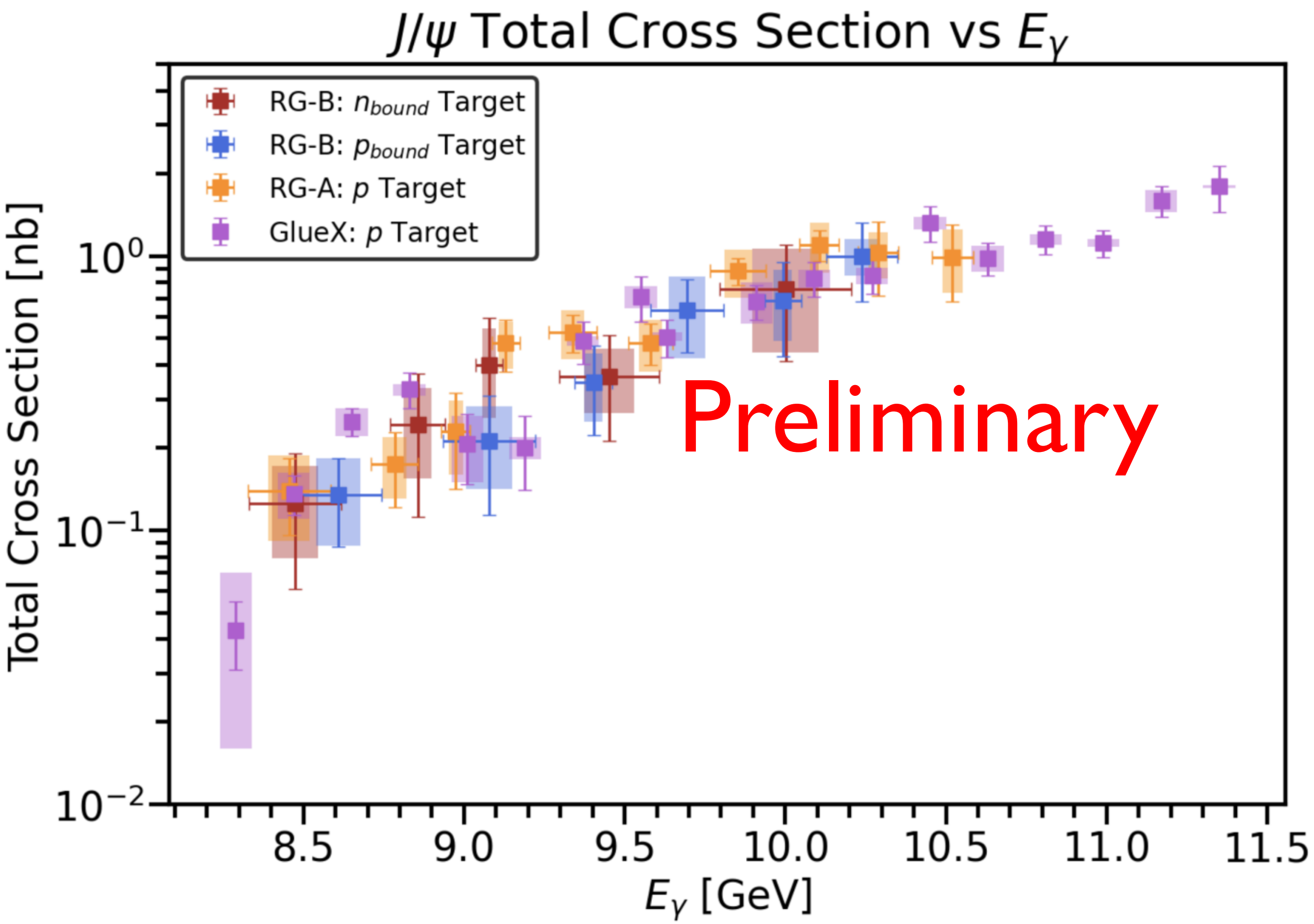


Total Cross Section

Points plotted at mean of E_γ distribution in bin, with error bar given by the uncertainty on the mean.

The comparison between the proton and neutron is informative in that it suggests that the production mechanism of J/ψ near-threshold must be isospin invariant, or that the isospin breaking is smaller than the uncertainty on the cross section.

The comparison between the free and bound proton cross sections demonstrates that the contribution from final state interactions (or EMC type effects) must be smaller than the uncertainty on the cross section.



Differential Cross Section

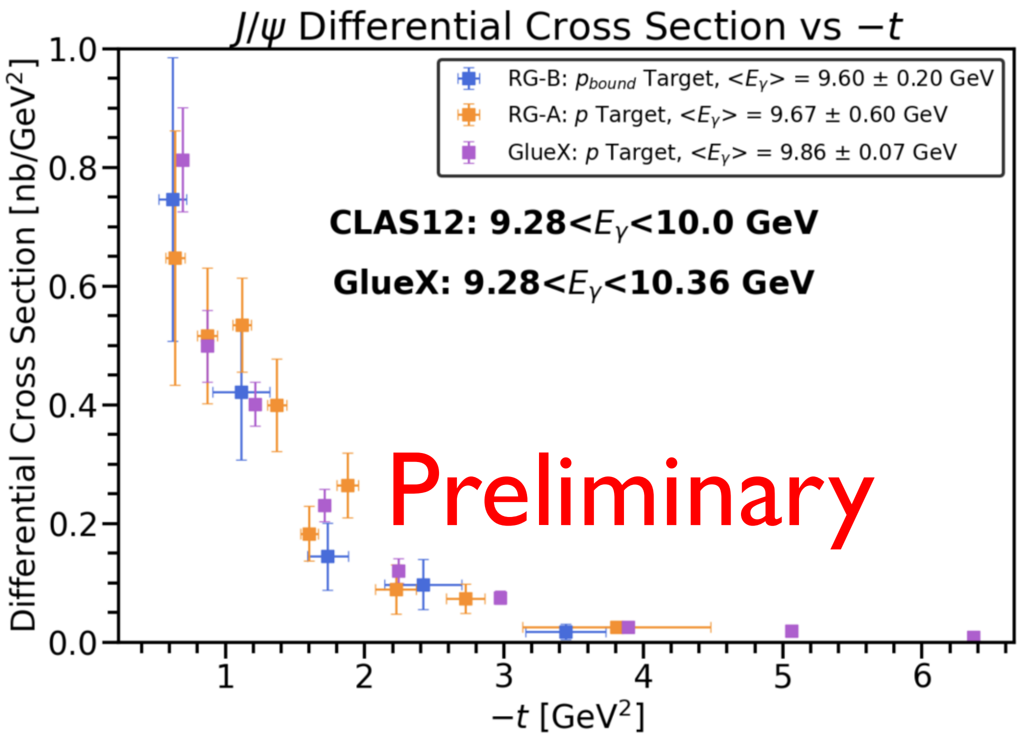
The differential cross section can be related to the gluonic mechanical form factors and the mass radius of the nucleon.

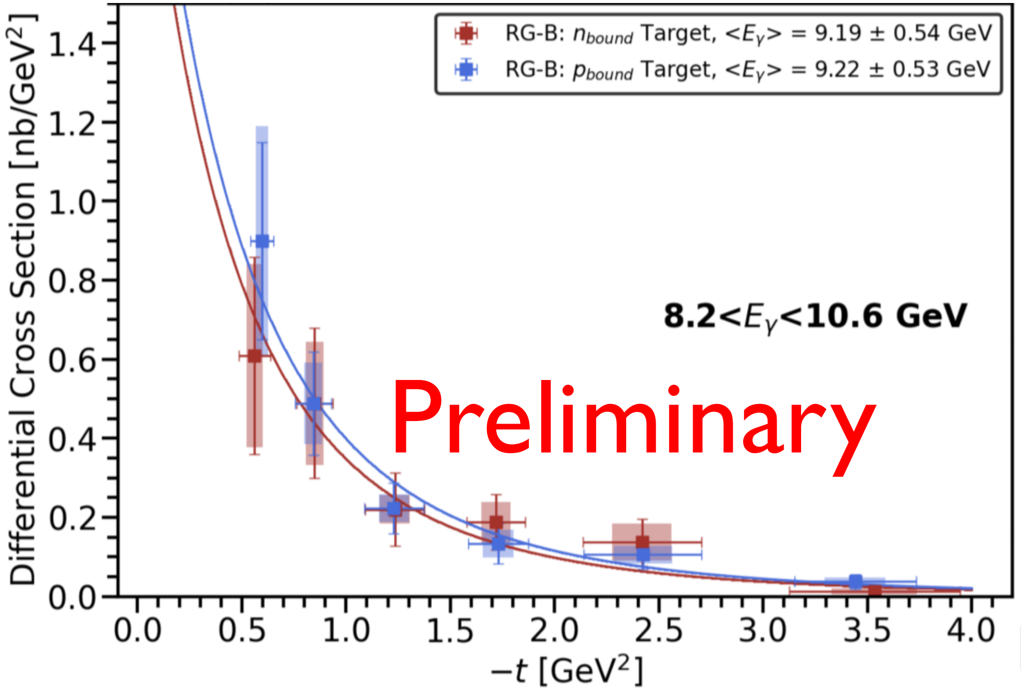
Due to limited statistics in neutron channel, extract cross sections in one large E_γ bin.

Compare bound proton to RG-A & GlueX in smaller E_γ bin as sanity check.

The comparison of the cross sections produced on the proton and neutron suggests a similar distribution of the gluonic content of both nucleons.

The comparison between the free and bound proton suggests that the nuclear in-medium effects for the deuteron are smaller than the uncertainty on the differential cross section.





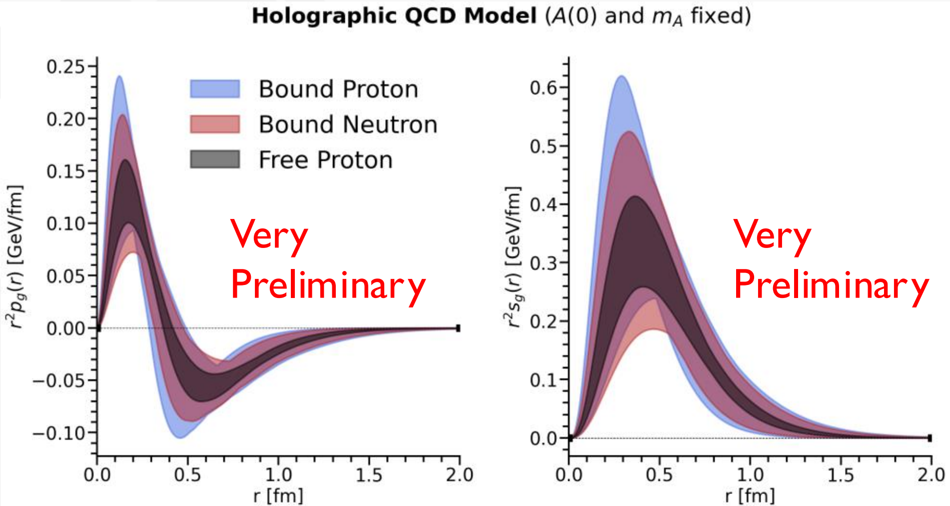
Mechanical Form Factors

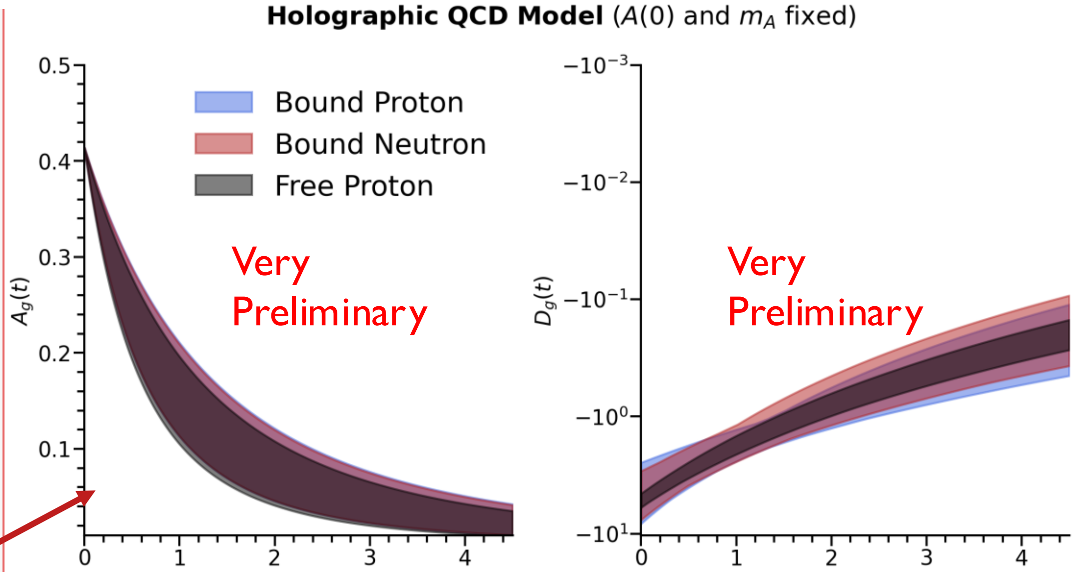
Fit the mechanical form factors shown below to differential cross section:

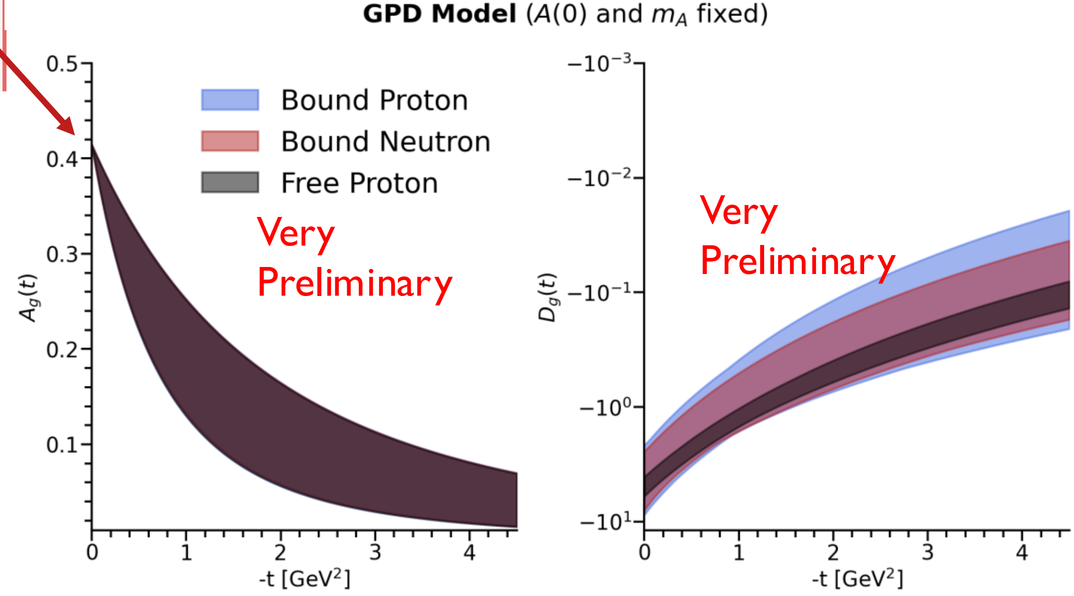
$$< N'|T^{\mu,\nu}_{q,g}|N >= \bar{u}(N')\left(\boldsymbol{A_{q,g}(t)}\gamma^{\mu p \nu} + \boldsymbol{B_{q,g}(t)}\frac{iP^{\mu\sigma\nu}\rho\Delta_\rho}{2M} + \boldsymbol{C_{q,g}(t)}\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \boldsymbol{\bar{C}_{q,g}(t)}Mg^{\mu\nu}\right)u(N)$$

Some assumptions in fit:

- Neglect $B(t)$ and $\bar{C}(t)$.
- Assume tripole shape for mechanical form factors.
- Use bootstrapping to estimate uncertainty.
- Fix $A_{t=0}$ to the average gluon PDF from CT18, do N iterations where vary value of A slope parameter which is fixed during fits.



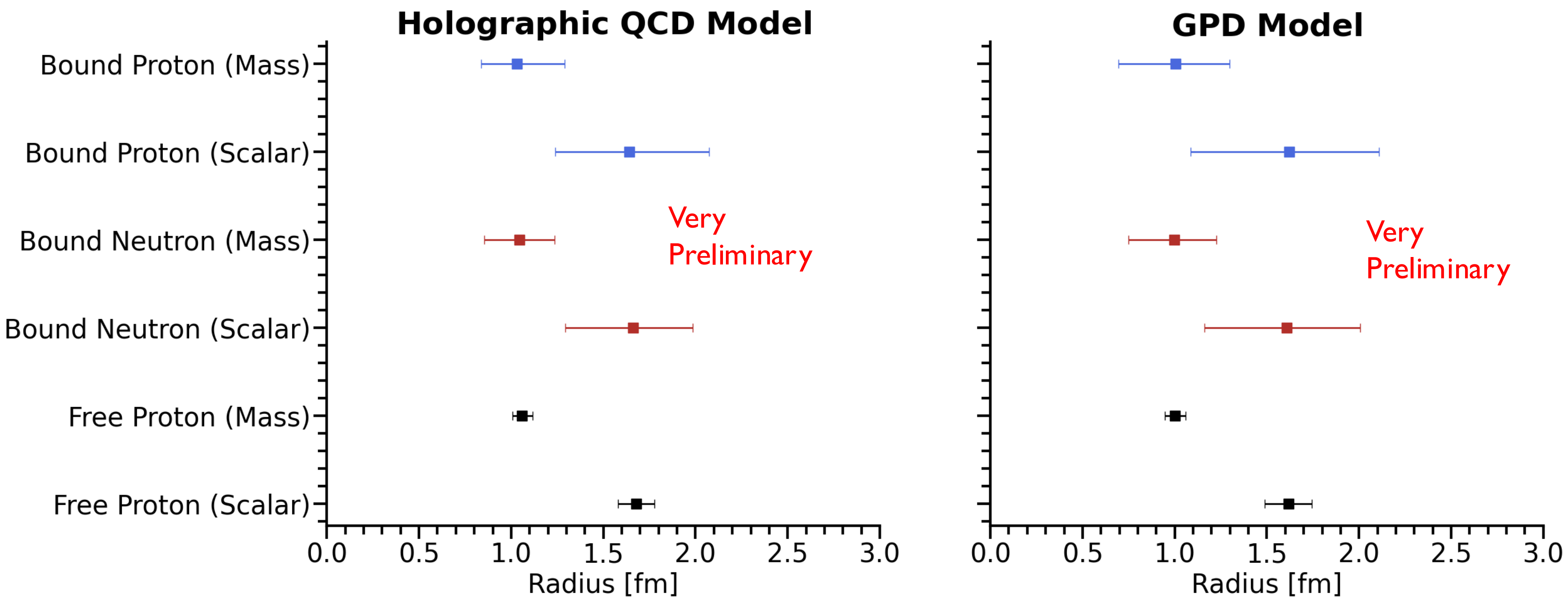




Mass Radii

Scalar Radius: $< r_s^2 >_g = \frac{6}{A_g(0)} \frac{dA_g(t)}{dt}\Big|_{t=0} - \frac{18}{A_g(0)} \frac{C_g(0)}{M_N^2}$

Mass radius: $< r_m^2 >_g = \frac{6}{A_g(0)} \frac{dA_g(t)}{dt}\Big|_{t=0} - \frac{6}{A_g(0)} \frac{C_g(0)}{M_N^2}$



VMD Interpretation

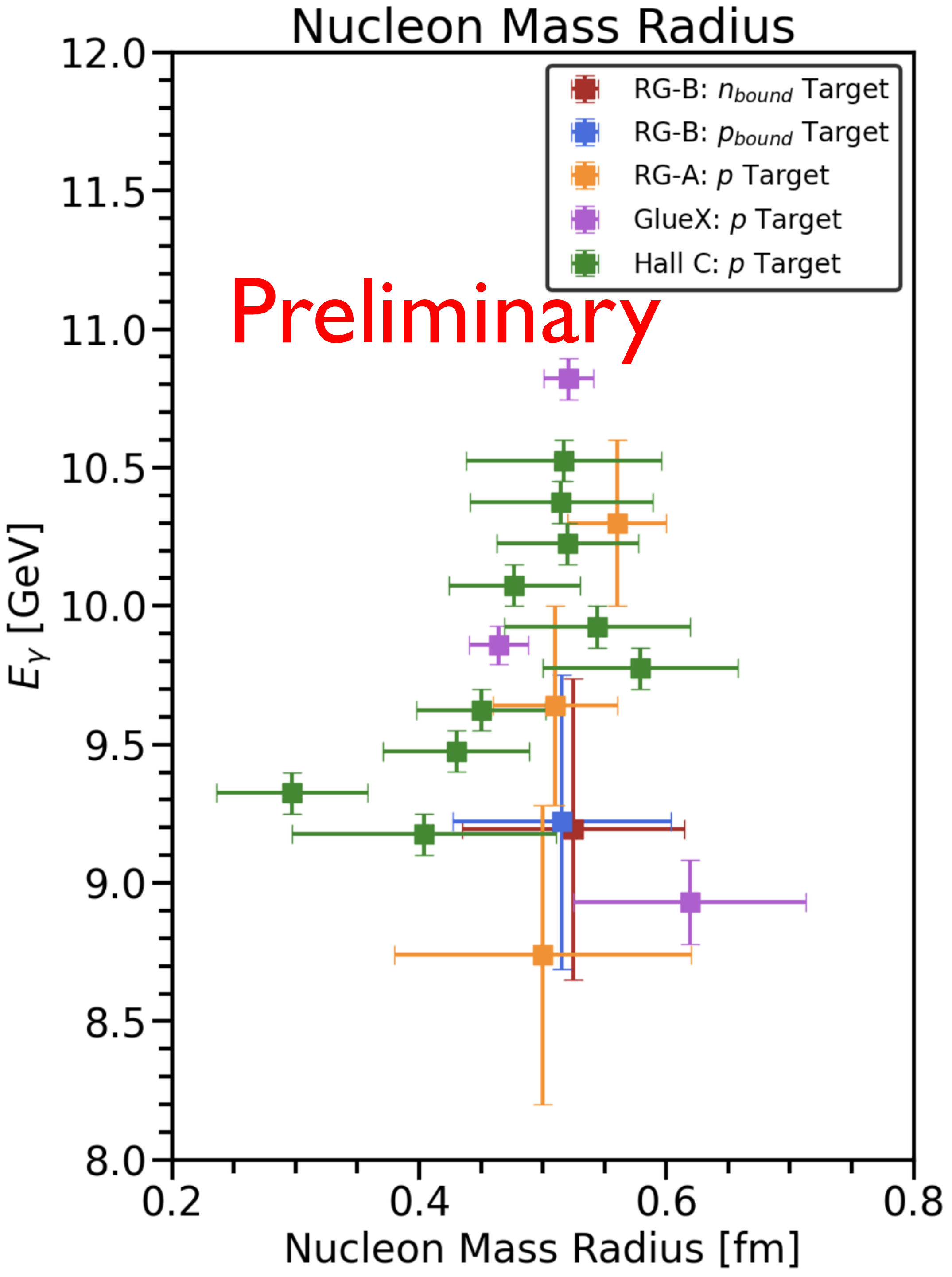
A scalar mechanical form factor $G(t)$ gives access to the mass radius of the nucleon. Assuming a dipole form for $G(t)$:

$$\frac{d\sigma}{dt} = G(t)^2 = \left(\frac{M_p}{(1-\frac{t}{m_s^2})^2}\right)^2$$

The mass radius r_m is calculated from the free parameter m_s :

$$r_m = \frac{\sqrt{12}\hbar c}{m_s}$$

JPAC analysis of Hall C and GlueX data showed that VMD might be unsuited to high mass meson production at JLab energies.



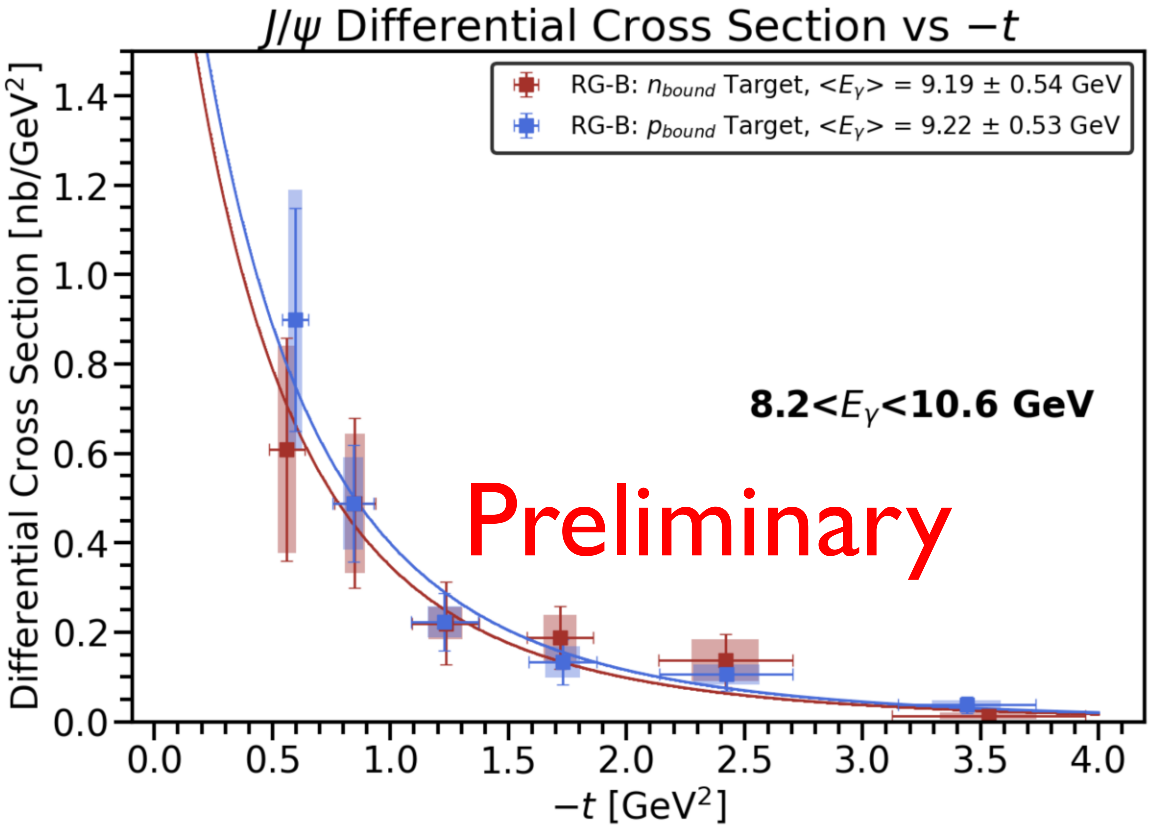
Conclusion

J/ψ near threshold photoproduction has received a lot of interest in recent times due to its predicted ability to probe the nucleon gluonic properties.

We can make a first measurement of the cross section of J/ψ near threshold photoproduction on the neutron.

Preliminary results have been obtained demonstrating good agreement between the cross section measurements on the neutron and proton in the deuteron and with the free proton.

The analysis has been submitted for CLAS collaboration review. We aim to submit the article to PRL.



Back-up Slides

Simulated Data

Use JpsiGen and TCSGen event generators.

Add fermi momentum of proton and neutron in deuterium.

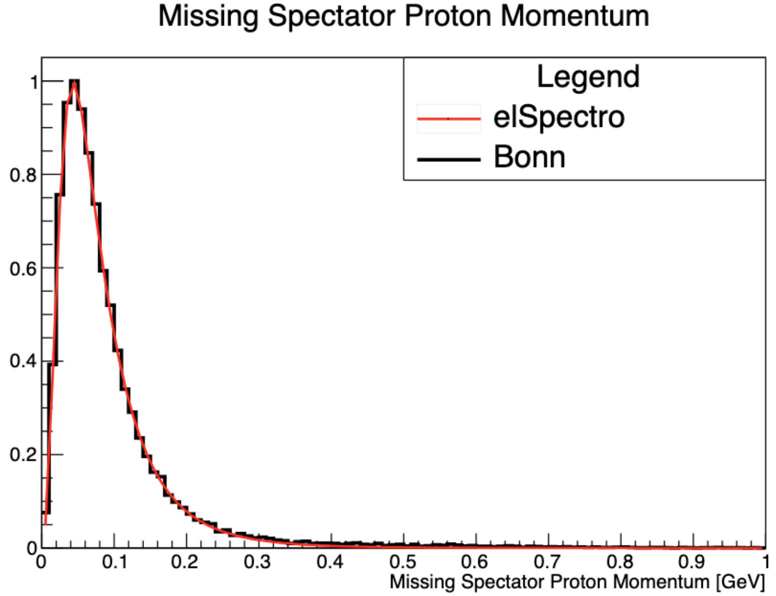
Calculates simple J/ψ and Bethe Heitler (BH) cross sections, weight data using:

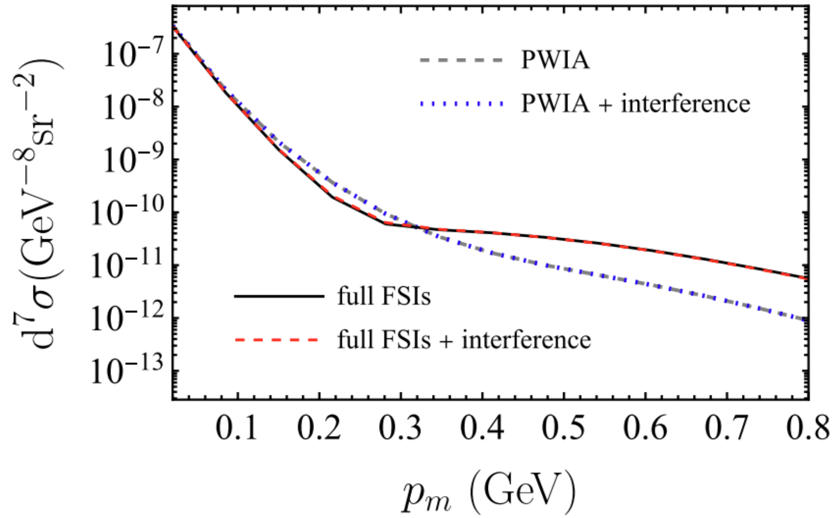
$$w = \frac{psf \cdot L_{int} \cdot \sigma}{N_{gen}}$$

Final state interaction contribution to BH cross section assumed to be negligible (see M. Cai, T. Liu, B.-Q. Ma, *Chinese Phys. C* **48** 014103 (2024)).

Rate of change as a function of beam current is corrected.

Ad-hoc smearing obtained by comparing widths of J/ψ invariant mass peak, missing mass squared peak and Q^2 slope.





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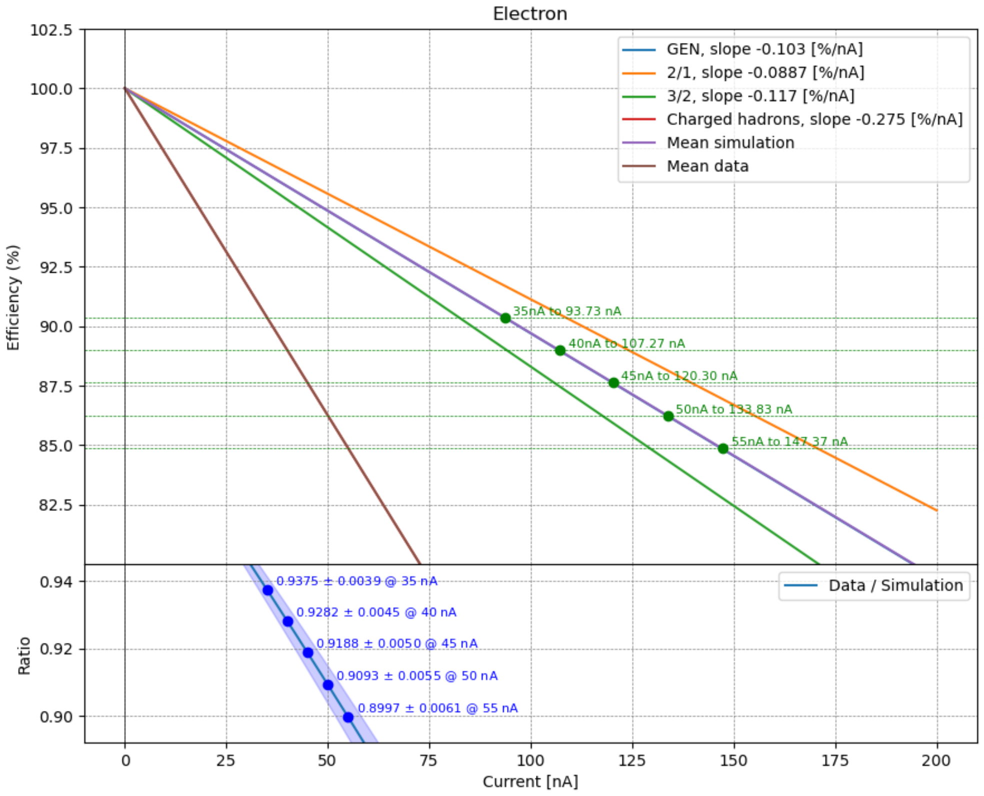

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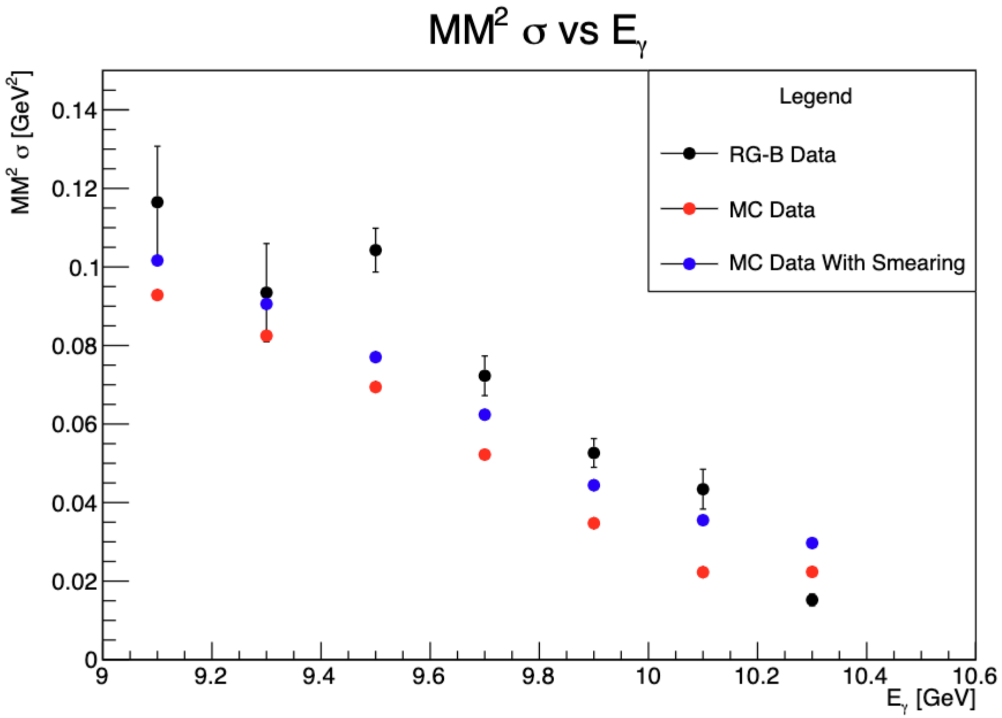

Electron/positrons

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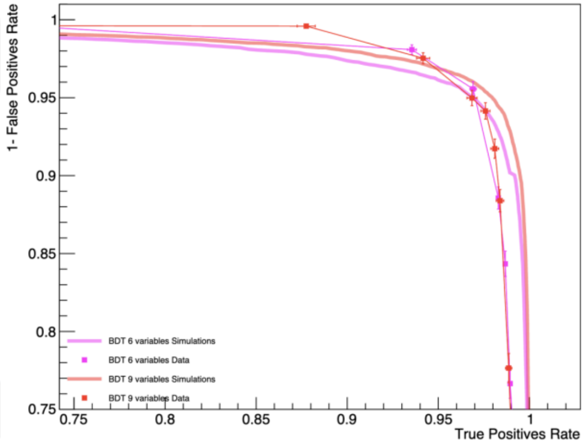
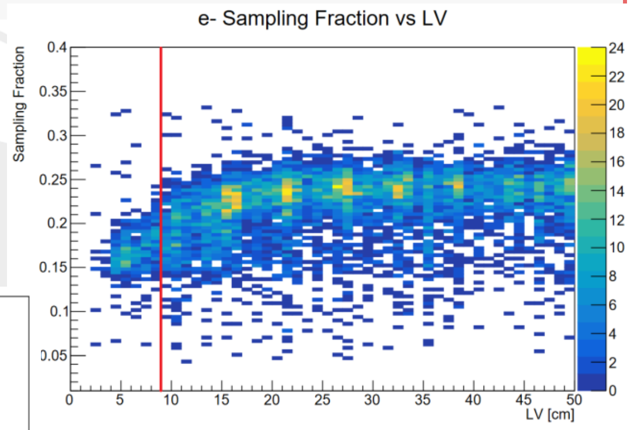
Systematic uncertainty around 5-15 % for ID procedures.



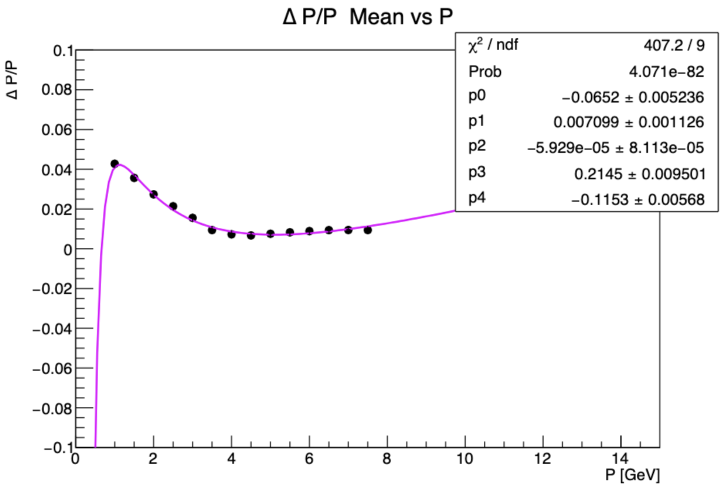


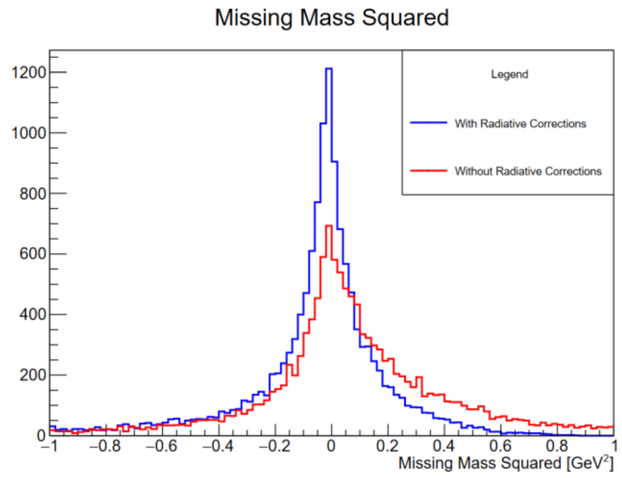
Momentum Corrections

Correct for $e^- \rightarrow e^- \gamma$ by adding momentum of nearby photons.

Add more general momentum corrections.

Variation <10% for momentum correction.





Jefferson Lab

Protons & Neutrons

Identification

Event Builder PID for protons.

No ID for neutrons, only use charge

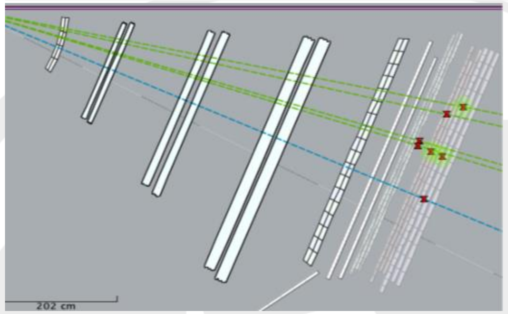
Select earliest neutrals to remove secondary neutrons.

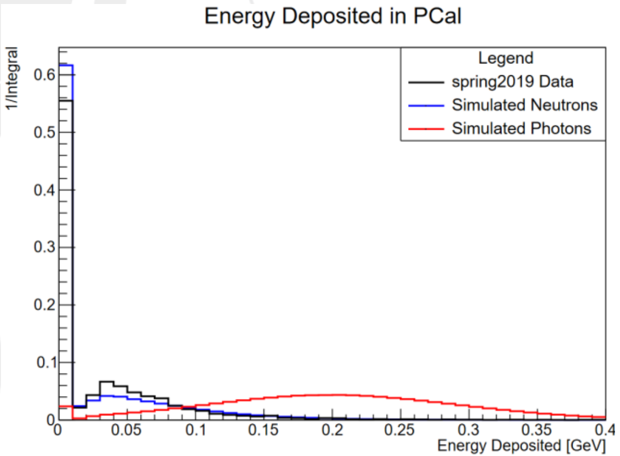
Corrections

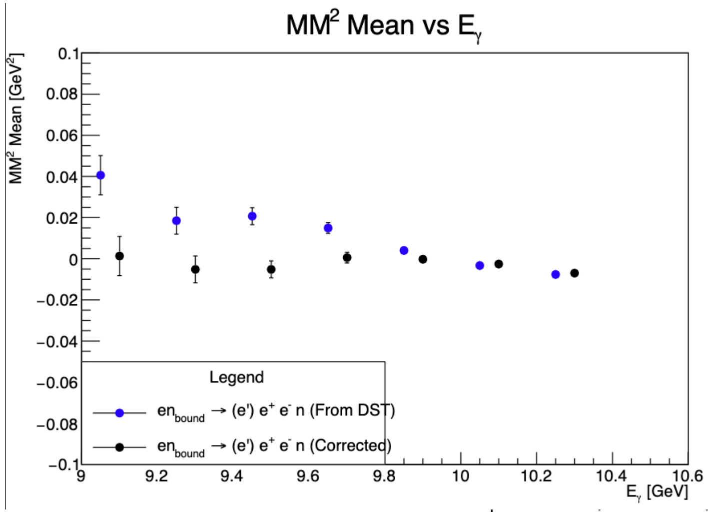
Apply some corrections to momentum.

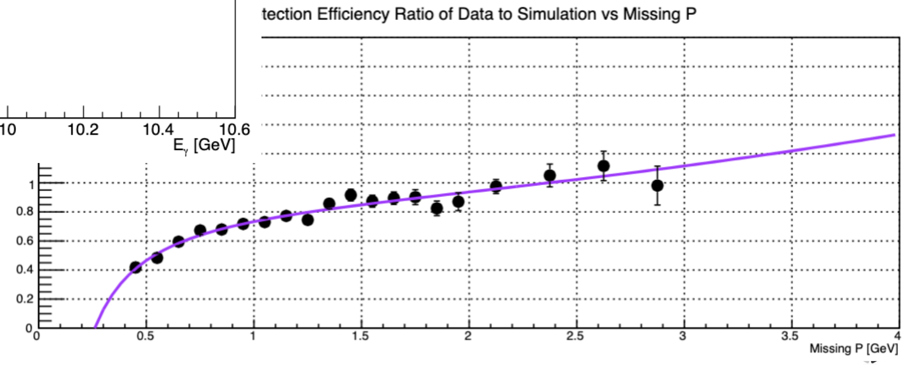
Obtain ratio of neutron detection efficiency in data to simulation to correct simulation.

Systematic uncertainty ~10 % for efficiency correction.









Fitting Details I

Models

In holographic QCD a higher dimensional duality relates spin-2 fields to gravity. J/ψ is produced by the exchange of gravitons (tensor 2++ glueballs) and scalar (0++) glueballs.

In the GPD framework, large skewness at threshold allows to relate the scattering amplitude to gluon GPDs. The mechanical form factors are extracted from the first moments of the GPDs.

Hall C Assumptions

Use same assumptions as Hall C analysis:

- Neglect $B(t)$ - in concordance with both models and lattice QCD.
- Neglect $\bar{C}(t)$ when evaluating the cross section and radii .
- Assume tripole shape for mechanical form factors.
- Fix $A_{t=0}$ to the average gluon PDF from CT18.

Fitting Details II

Use bootstrapping to correctly estimate uncertainties.

Have four parameters:

- m_A, A^0 slope and intercept of A form factor
- m_C, C^0 ~ slope and intercept of D form factor

A^0 was fixed in analyses on free proton, choose to do the same.

When varying parameters within reasonable range, several solutions for m_A parameter are found ⇒ not enough information in data to constrain all parameters.

Fix m_A parameters when fitting, repeat bootstrapping for 50 values m_A sampled from gaussian with mean/σ taken from free proton fit.

Cut on fit reduced χ^2, and parameters less than 3 σ