

J/ ψ Near-Threshold Photoproduction off the Proton and Neutron with CLAS12

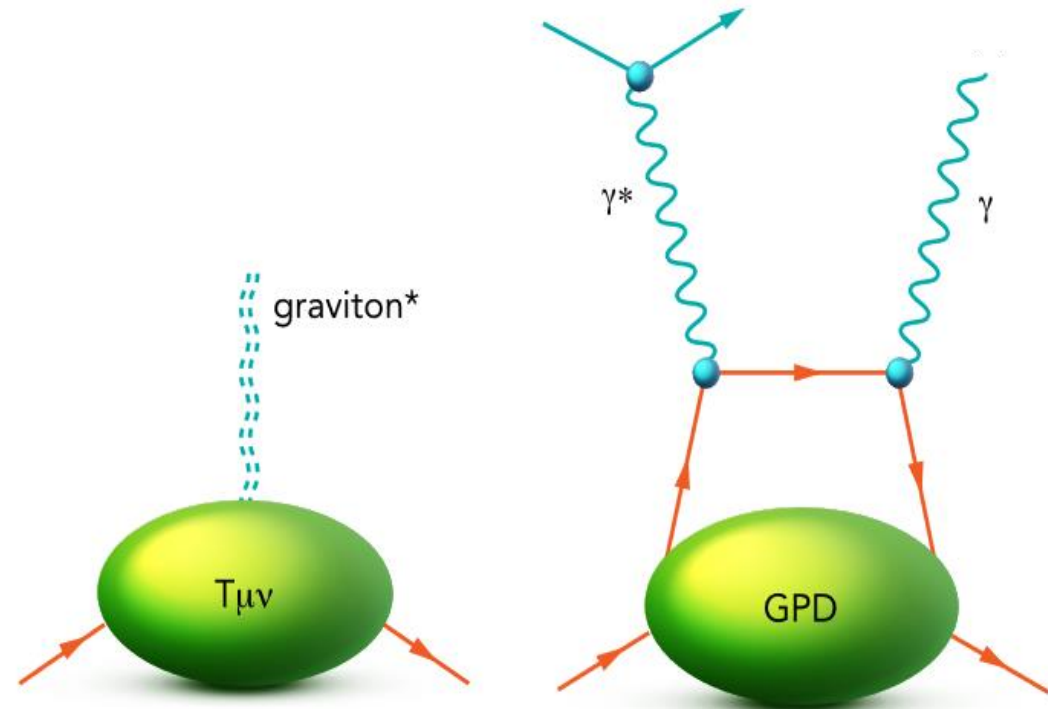
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Probing the Mechanical Properties of the Nucleon

- ▶ The mechanical properties of the nucleon are encoded by Gravitational Form Factors (GFFs) [1].
- ▶ Any spin-2 field gives rise to a force indistinguishable from gravity [2].
- ▶ The quark GFFs have already been estimated in the context of DVCS [3,4].
- ▶ See [Pierre Chatagnon's talk](#) for more details.

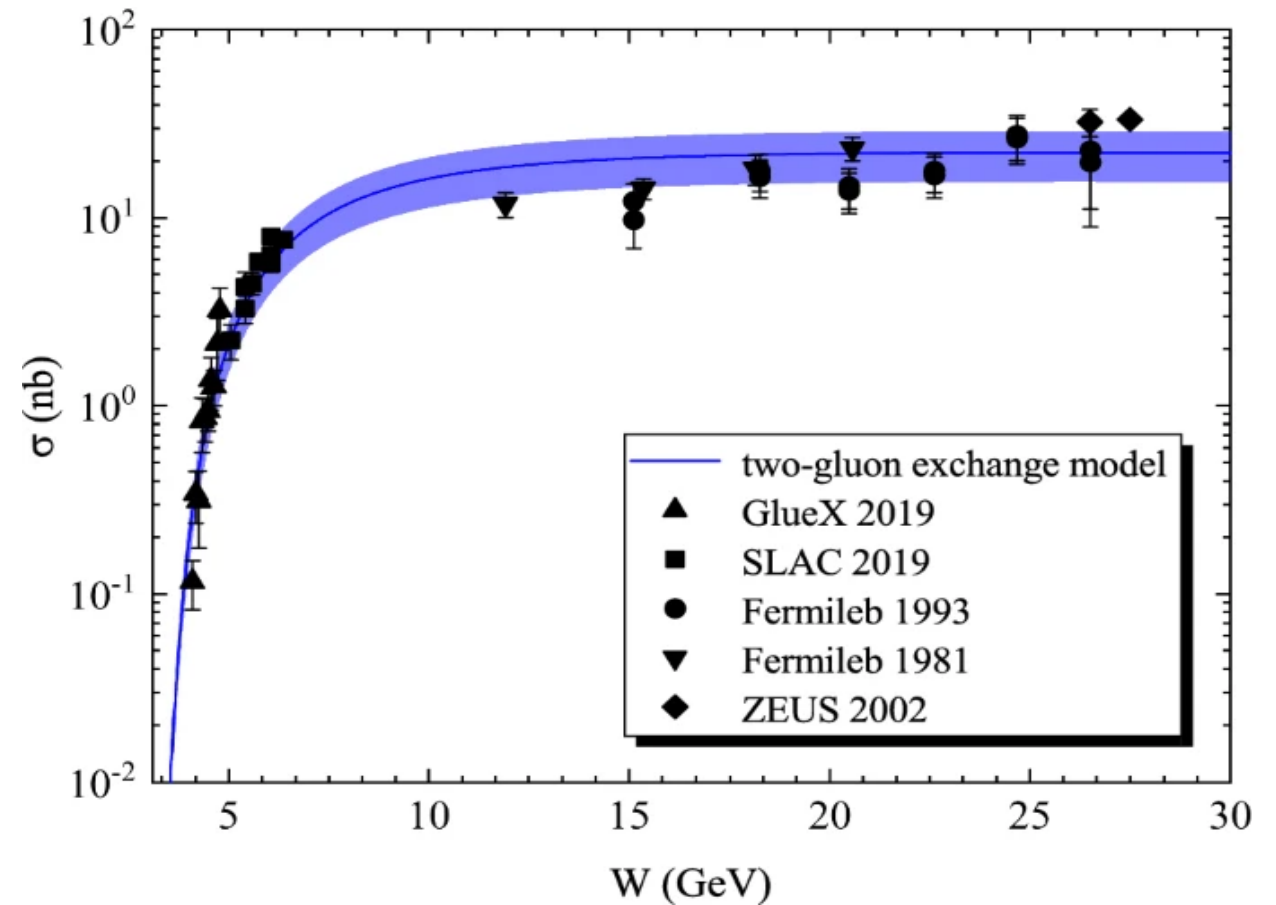


Spin-2 fields in graviton-proton scattering and DVCS [4].

- [1] H. Pagels, *Phys. Rev.* **144** (1966)
- [2] C.W. Misner, K.S. Thorne, J.A Wheeler, *Gravitation*, W.H. Freeman (1973), Box 18.1
- [3] V.D. Burkert, L. Elouadrhiri, F.X. Girod, *Nature* **557** 7705 (2018)
- [4] V.D. Burkert, L. Elouadrhiri, F.Girod, arXiv:2104.02031 (2021)

J/ ψ Near-Threshold Photoproduction

- ▶ A two-gluon exchange forms a spin-2 coupling between J/ ψ and the nucleon.
- ▶ Two-gluon exchange models can adequately describe J/ ψ near-threshold photoproduction [5-7].
- ▶ Holographic QCD [8,9] model J/ ψ photoproduction based on a tensor graviton like exchange (2^{++}).



Prediction for the J/ ψ total cross section based on a two-gluon exchange model and compared to world data.

[5] L. Frankfurt, M. Strikman, *Phys. Rev. D* **66**, 031502 (2002).

[6] D. Kharzeev, H. Satz, A. Syamtomov, G. Zinovev, *Nucl.Phys. A* **661** 568 (1999).

[7] F. Zeng, et. al., *Eur. Phys. J. C* **80** 1027 (2020)

[8] Y. Hatta and D.-L. Yang, *Phys. Rev. D* **98** 074003 (2018).

[9] K.A. Mamo, I. Zahed, *Phys. Rev. D* **106** 086004 (2022).

[10] T.-S. H. Lee, S. Sakinah, Y. Oh [arXiv:2210.02154](https://arxiv.org/abs/2210.02154) (2022).

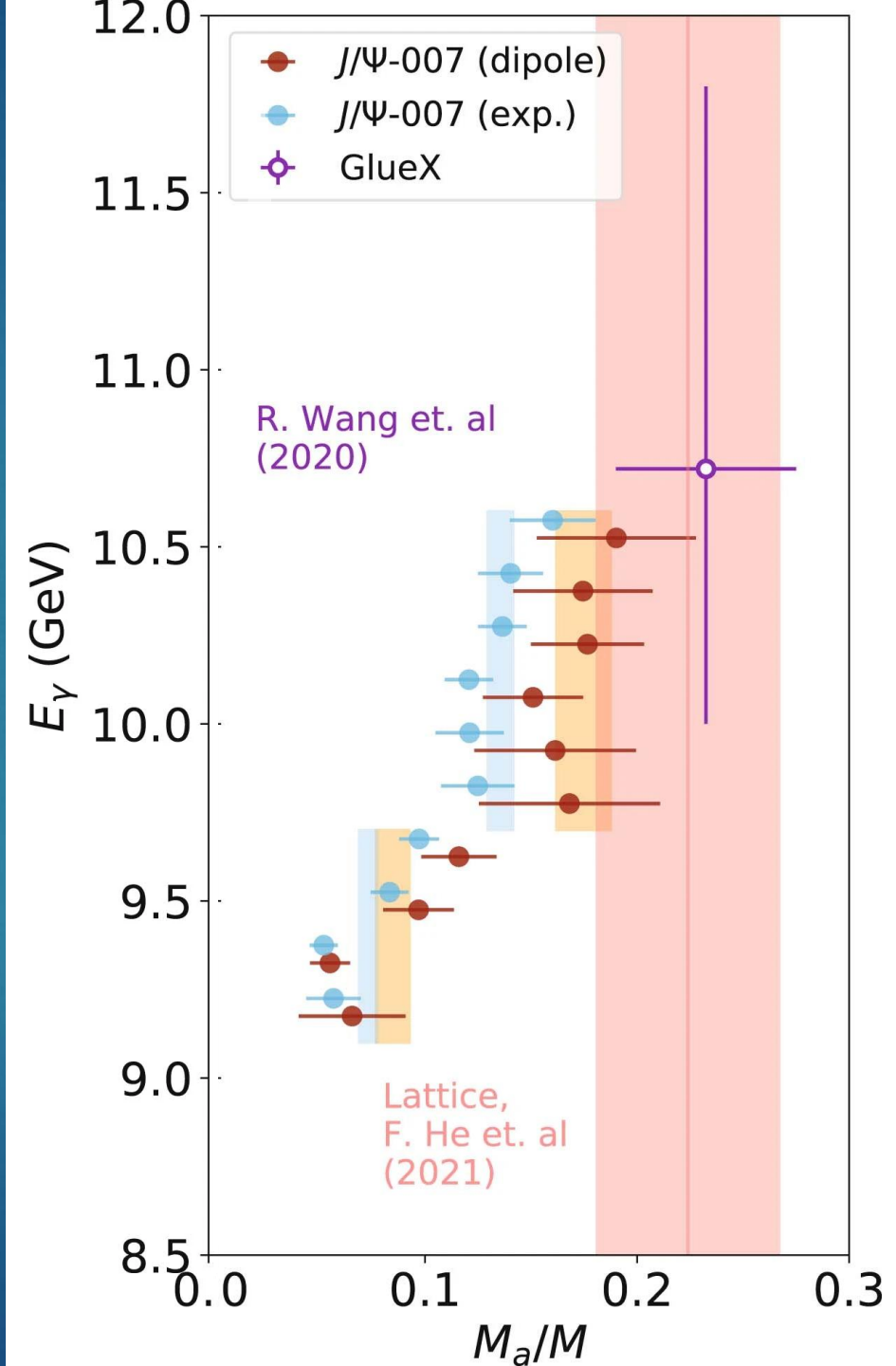
Nucleon Mass Puzzle

- ▶ The nucleon mass can be decomposed into the contributions from the quark masses, the energy of quark and gluons and the trace anomaly contribution [11].
- ▶ Estimates of the magnitude of the trace anomaly contribution were obtained at GlueX and Hall-C ($J/\psi - 007$) [11-13].
- ▶ Deviations at lower photon energies might be indicative of a region where the assumption of two-gluon exchange dominance is invalid.

[11] R. Wang, X. Chen, J. Evslin, *Eur. Phys. J. C* **80** 507 (2020)

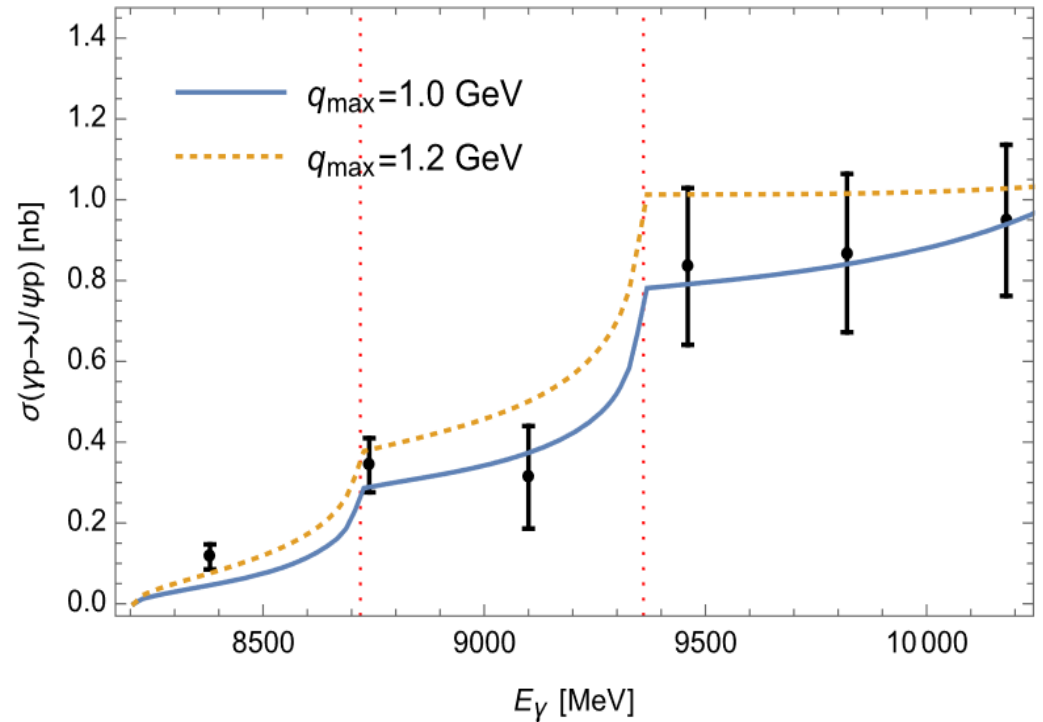
[12] D. Duran, et al. (J/ψ -007 Collaboration), *Nature* **615** (2023)

[13] A. Ali, et. al. (GlueX Collaboration), *Phys. Rev. Lett.* **123**, 072001 (2019)



Model Dependence

- ▶ There are suggestions that J/ψ near-threshold photoproduction could be dominated by open charm production of $\Lambda^c \bar{D}^{(*)}$ [14,15].
- ▶ At lower photon energies the 3-gluon exchange's contribution to the cross section is expected to dominate that of the 2-gluon exchange [16].
- ▶ An increase in luminosity and/or an energy upgrade at JLab would allow to measure the J/ψ SDMEs and calculate the charge naturality with enough precision to distinguish between two or three-gluon exchange.



Predictions for the total cross section due to the open charm production of J/ψ p [14], which is consistent with the GlueX measurements [13] in black. Here q_{max} refers to a threshold on Q^2 .

[14] M.-L. Du, V. Baru, F.-K. Guo, C. Hanhart, U.-G. Meißner, A. Nefediev, I. Strakovsky, *Eur. Phys. J. C* **80** 1053 (2020)

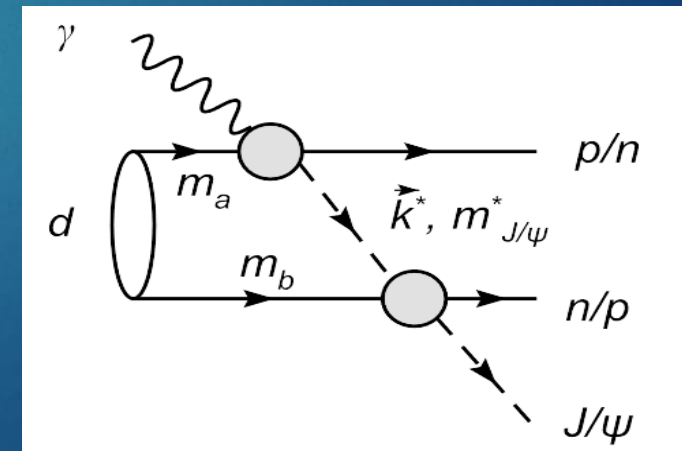
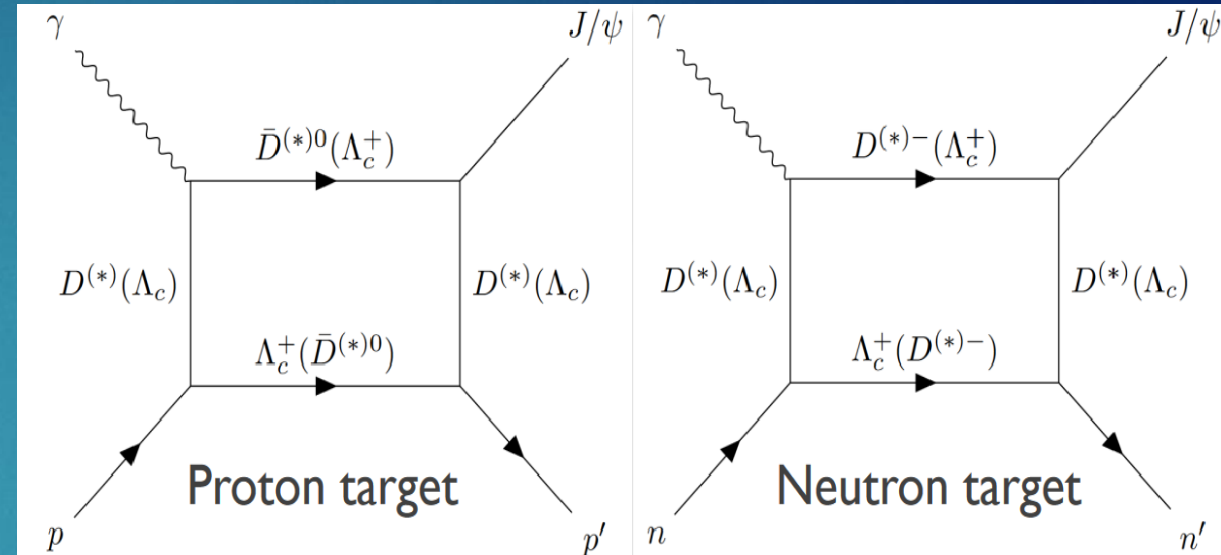
[15] D. Winney *et al* (JPAC) arXiv:2305.01449v1 (2023)

Dynamics in near-threshold J/ψ photoproduction

[16] S. Brodsky, E. Chudakov, P. Hoyer, J. Laget, *Phys. Lett. B.* **498**, 23 (2001).

Why study 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.
- ▶ Measuring photoproduction on both proton and neutron will bring new constraints on open-charm contributions to the cross section
- ▶ Comparing the cross section on proton and neutron also allows to test the isospin invariance of the production mechanism.
- ▶ $J/\psi N$ final state interactions allow to measure the $J/\psi N$ cross section which can be related to studies of quark-gluon plasma. The $J/\psi N$ cross section at low energies is largely unknown.



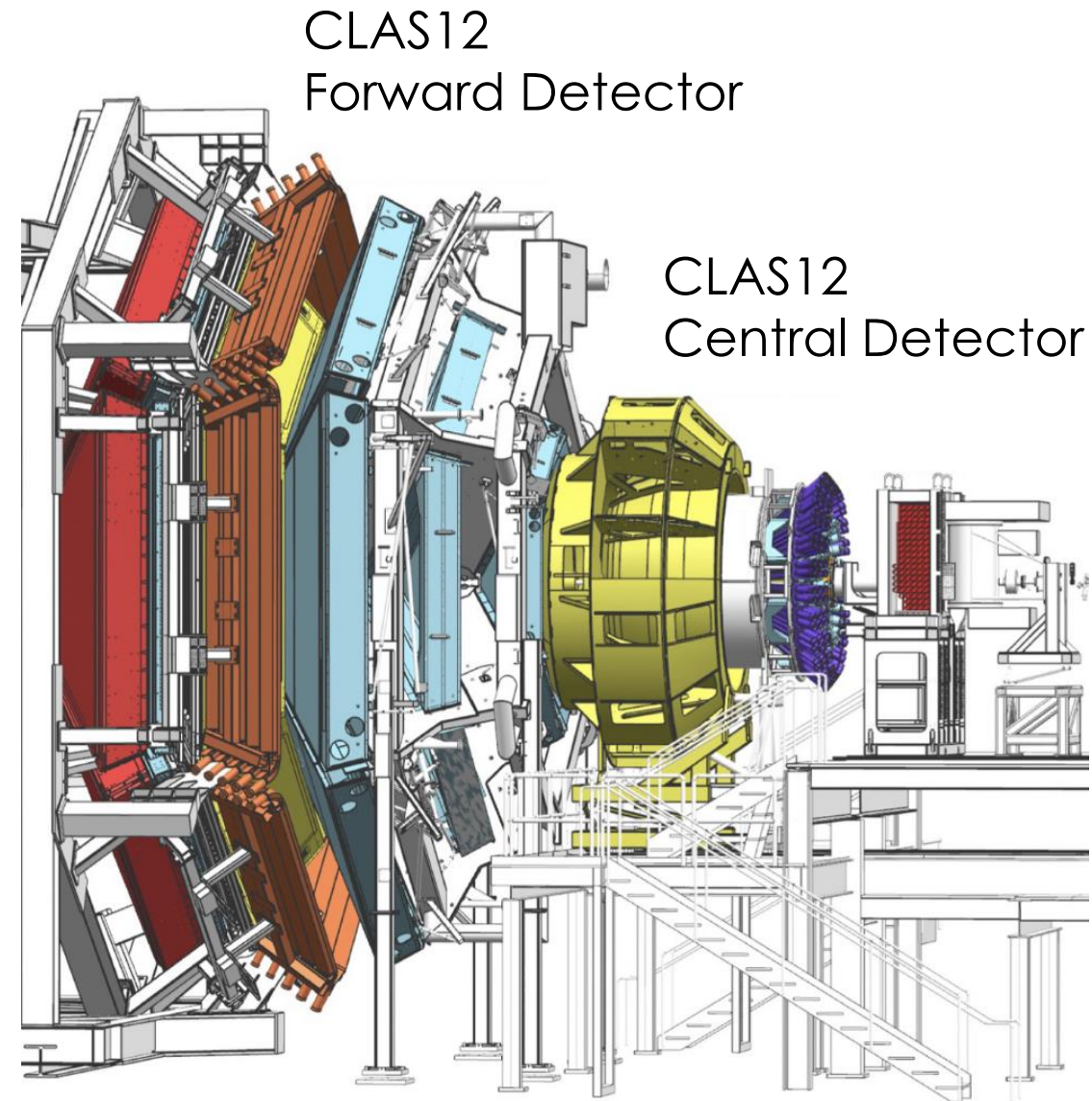
JLab

- ▶ The Thomas Jefferson National Accelerator Facility (JLab) is located in Newport News, Virginia.
- ▶ The Continuous Electron Beam Accelerator Facility (CEBAF) produces a 12 GeV electron beam.
- ▶ The CEBAF Large Acceptance Spectrometer (CLAS12) is located in Hall B.
- ▶ The J/ψ – 007 Collaboration located in Hall C.
- ▶ The GLUonic Excitation Experiment (GlueX) is located in Hall D.



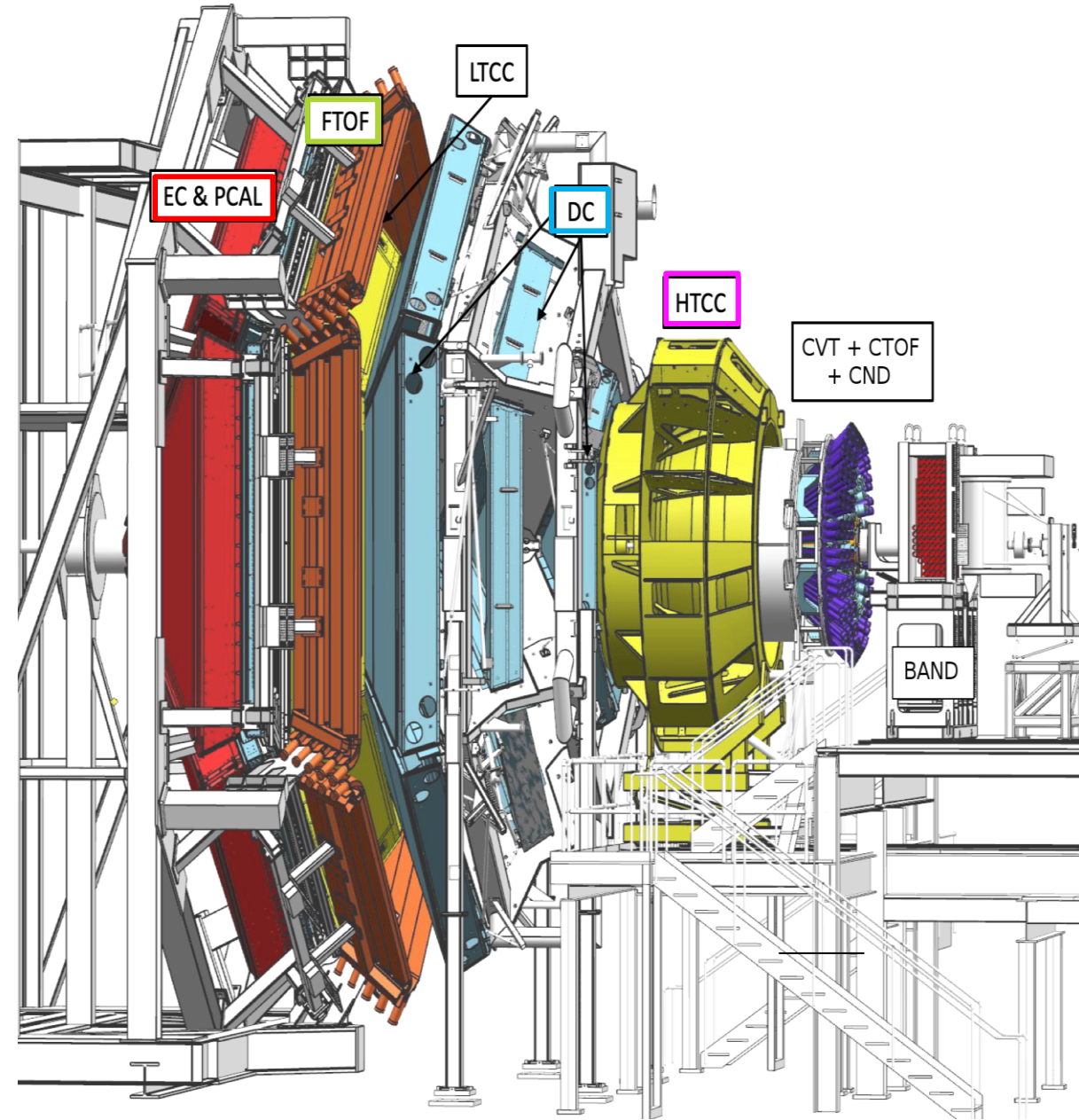
The CLAS12 Detector

- ▶ Beam energies up to 11 GeV are delivered to Hall B.
- ▶ The Forward Detector has polar angle coverage of 5 to 35 degrees.
- ▶ The Central Detector has polar angle coverage of 35 to 125 degrees.
- ▶ Both have full azimuthal coverage.



CLAS12 Forward Detector

- ▶ The High Threshold Cherenkov Counter (HTCC) was built to identify electrons.
- ▶ The Drift Chambers (DC) measure the charge and momentum of particles.
- ▶ The Forward Time Of Flight (FTOF) counters were designed to identify charged hadrons.
- ▶ The Electromagnetic Calorimeters (PCAL and EC) are used to detect neutrals and identify electrons and muons.



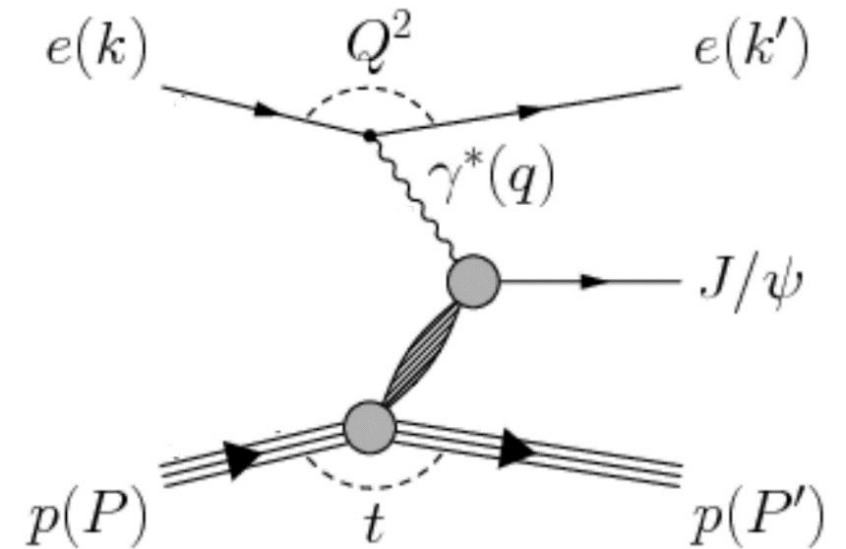
Experiment Overview

- ▶ J/ψ decays to a lepton pair, with l^+l^- denoting either e^+e^- or $\mu^+\mu^-$.
- ▶ CLAS12 took data with both a proton and a deuterium target offering several potential final states:

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

$$e p_{\text{bound}} \rightarrow e' J/\psi p \rightarrow (e') l^+ l^- p$$

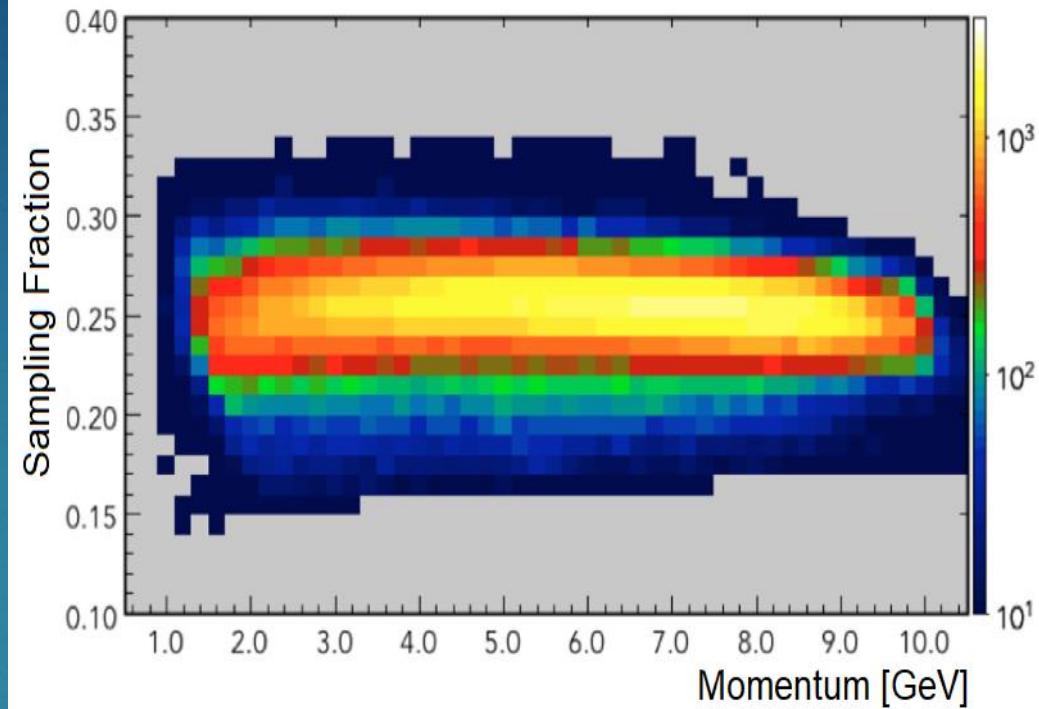
$$e n_{\text{bound}} \rightarrow e' J/\psi n \rightarrow (e') l^+ l^- n$$



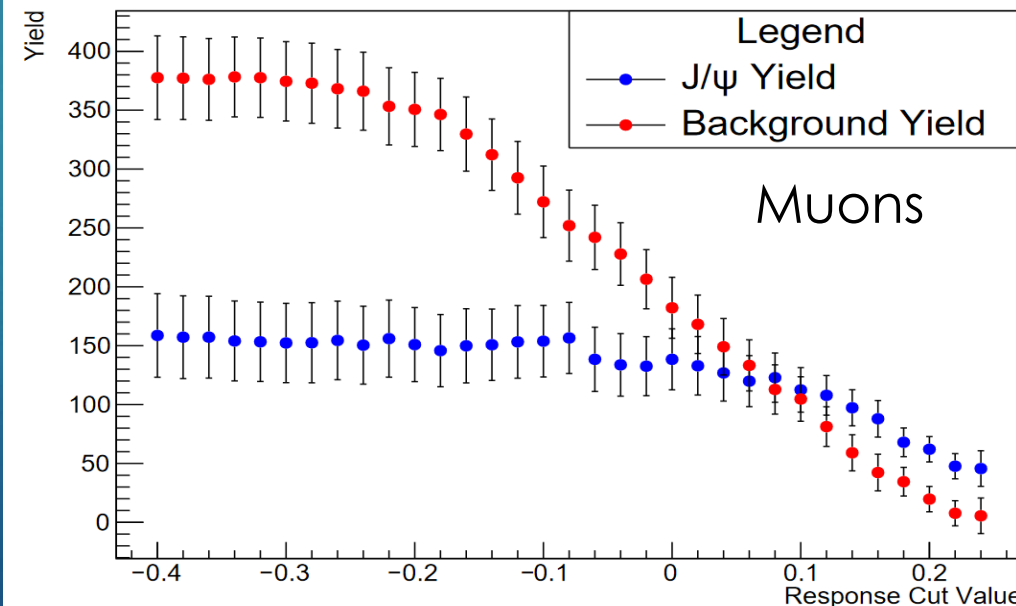
J/ψ quasi-real photoproduction
on a proton target

Lepton Identification

- ▶ Electrons and positrons are required to produce a signal in the HTCC and have a ratio of the energy deposition to momentum around 0.25.
- ▶ Muons are minimum ionising particles which we select with cuts on their energy deposition in the calorimeters.
- ▶ We refine the lepton PID by training a machine learning classifier on variables from several CLAS12 detector subsystems such as:
 - ▶ Energy deposition and cluster information in the calorimeters.
 - ▶ Number of photoelectrons produced in the HTCC.
- ▶ The PID process is then reduced to a cut on the response of the classifier.

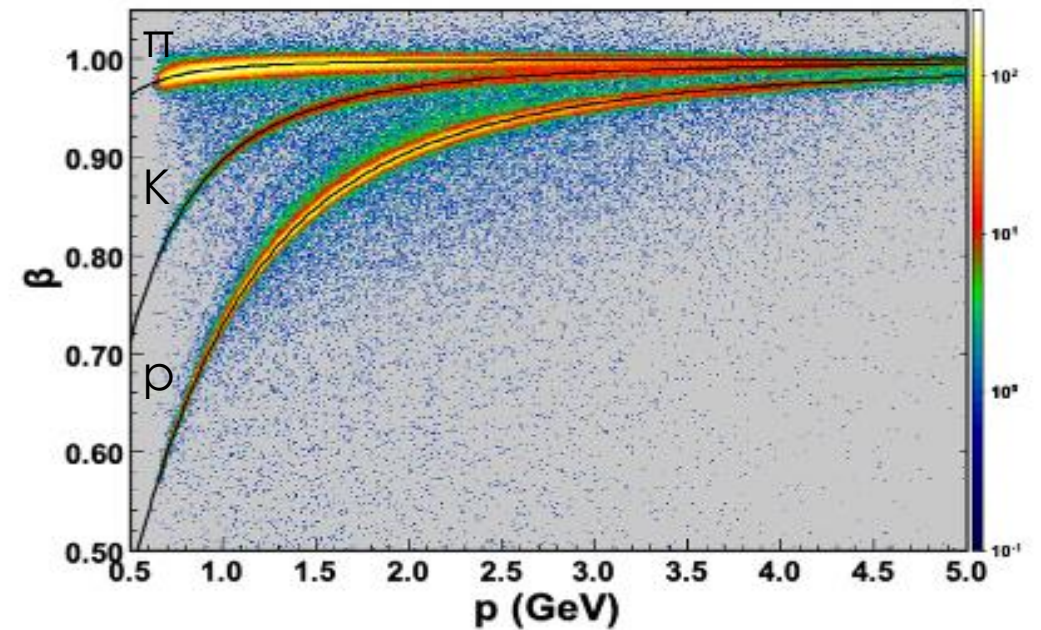


J/ ψ and Background Yields vs Response Cut Value

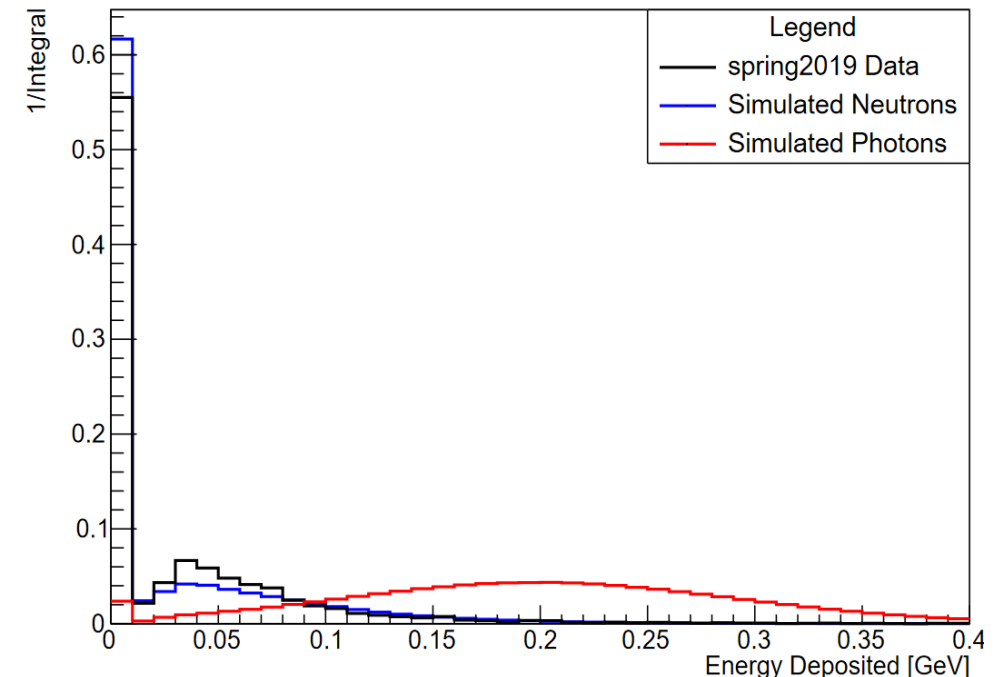


Hadron Identification

- ▶ For protons (and charged hadrons in general) a cut is made on the Beta versus Momentum parametrization.
- ▶ For neutrons we require a neutral charge. No further cuts were applied as there isn't any strong evidence of photon contamination.



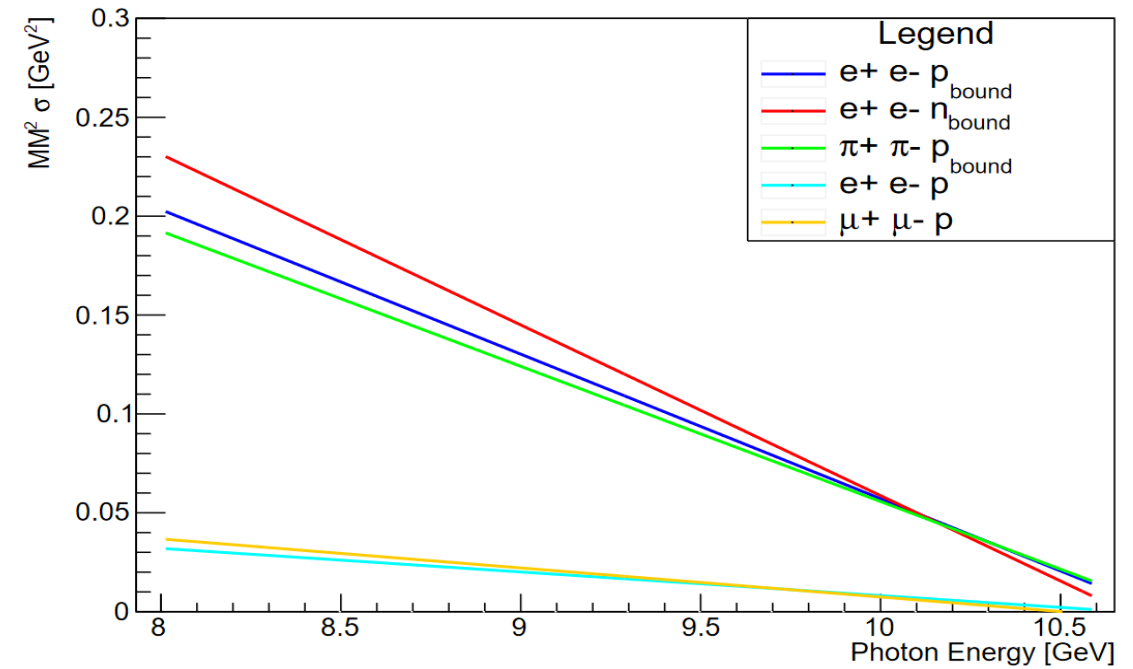
Energy Deposited in PCal



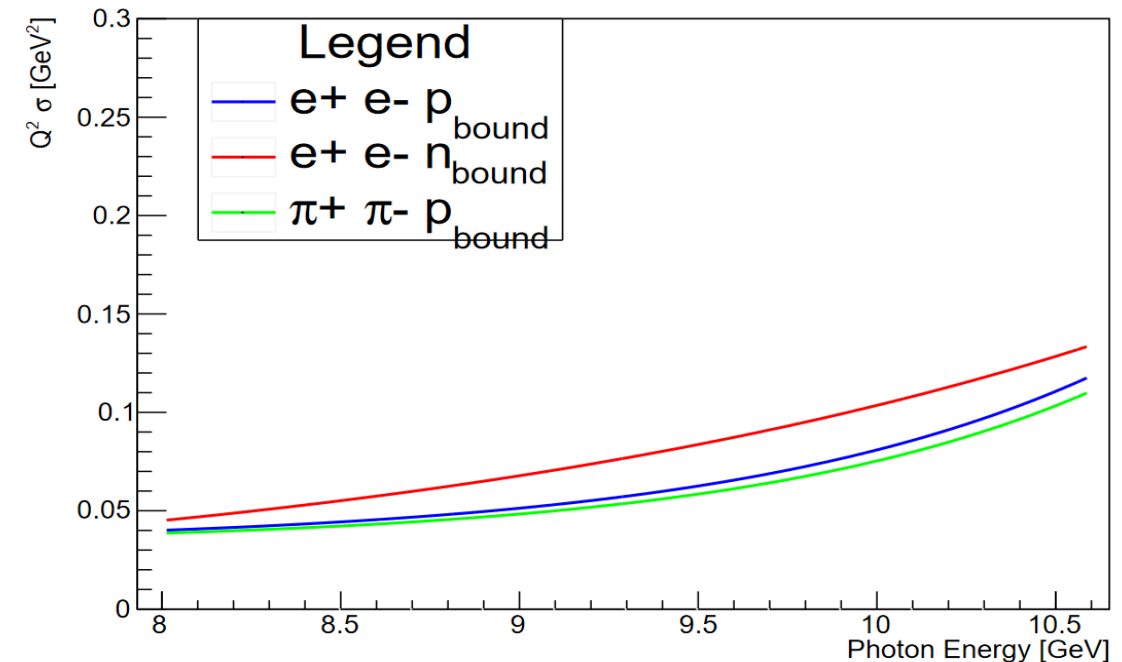
Event Selection

- ▶ We remove high Q^2 events to select only quasi-real photoproduction events.
- ▶ We also want the missing mass close to the mass of the scattered electron.
- ▶ We can parametrise the width of these distributions as a function of the quasi-real photon energy.

$MM^2 \sigma$ vs Photon Energy



$Q^2 \sigma$ vs Photon Energy



Cross Section Calculation

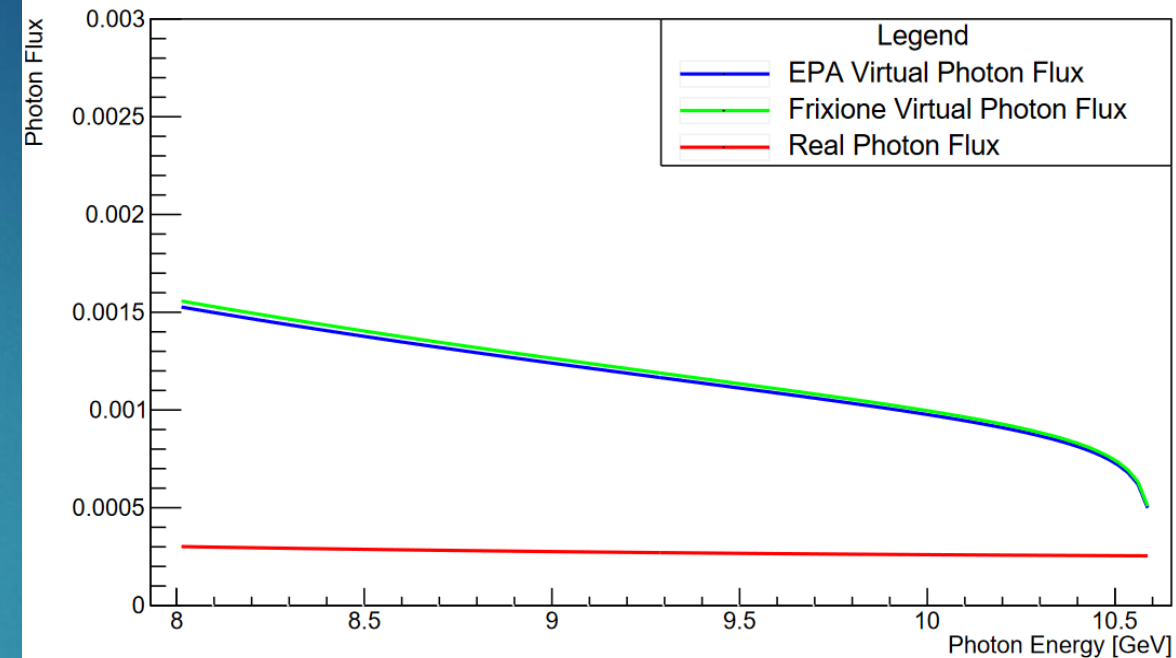
- ▶ We can calculate the total cross section as:

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

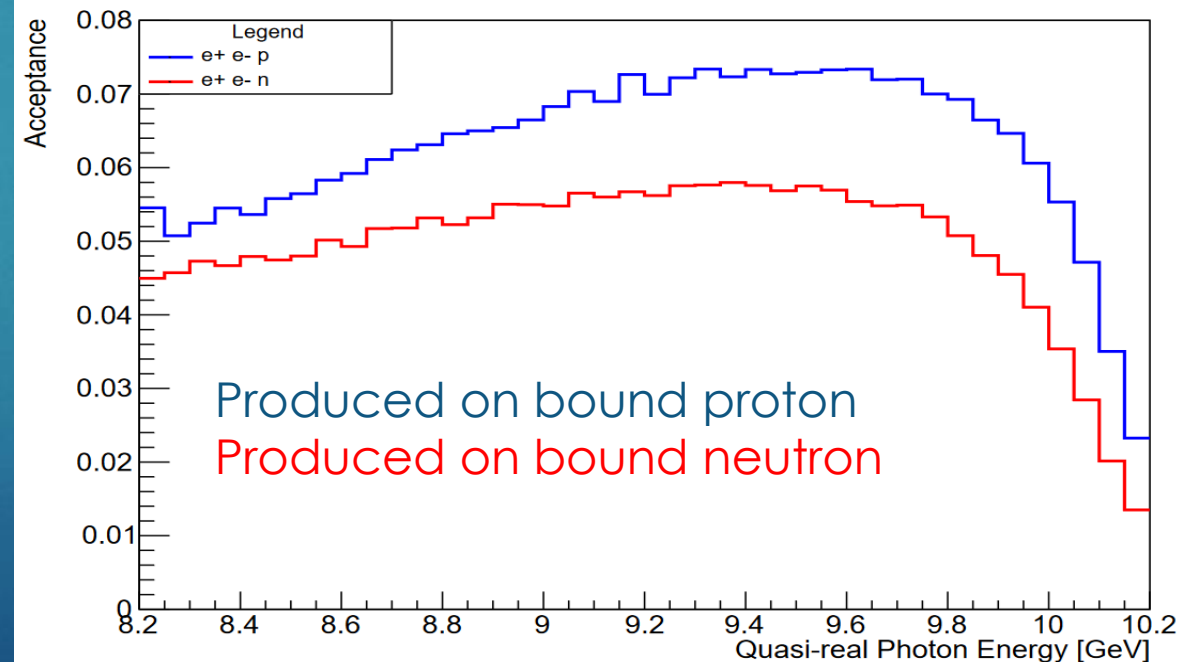
- ▶ Where:

- ▶ $N_{J/\psi}$ is the J/ψ yield in each E_γ bin
- ▶ N_γ is taken from the sum of real and virtual photon flux
- ▶ l_T/ρ_T is the target length and density
- ▶ Br is the branching ratio (~6%)
- ▶ $\epsilon(E_\gamma)$ is the acceptance in each E_γ bin
- ▶ ω_c is a normalisation factor (arbitrary for this talk)

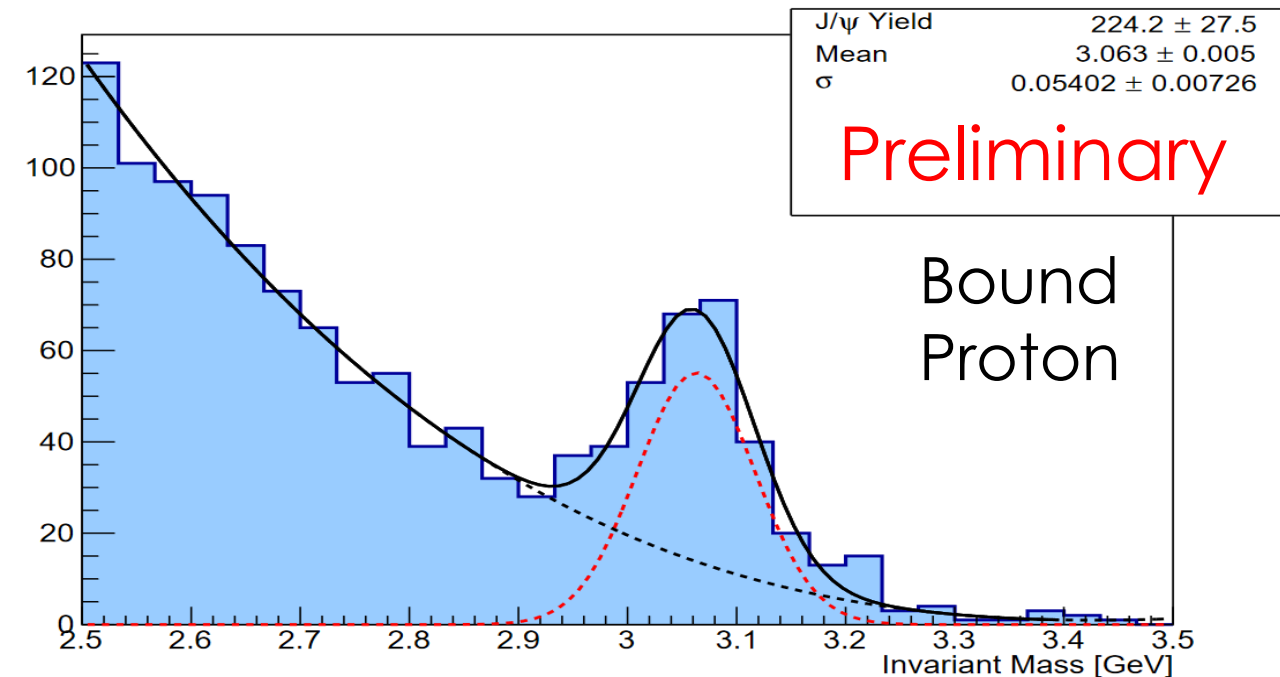
Photon Flux vs Photon Energy



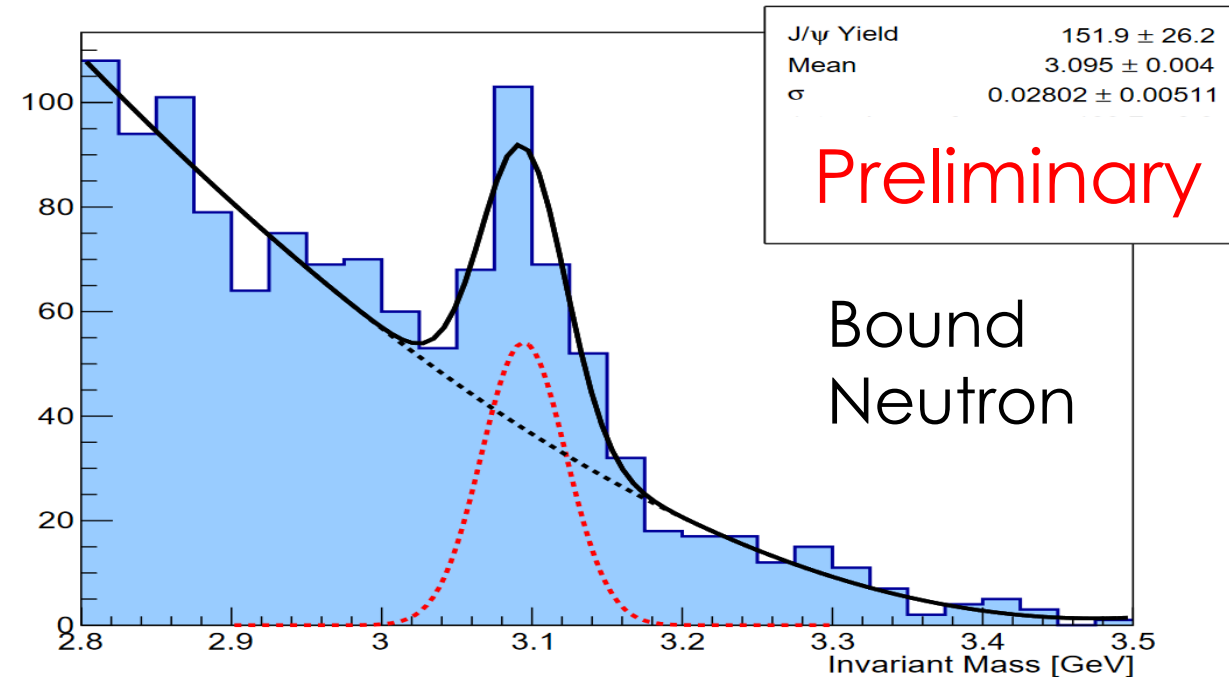
Acceptance vs Quasi-real Photon Energy



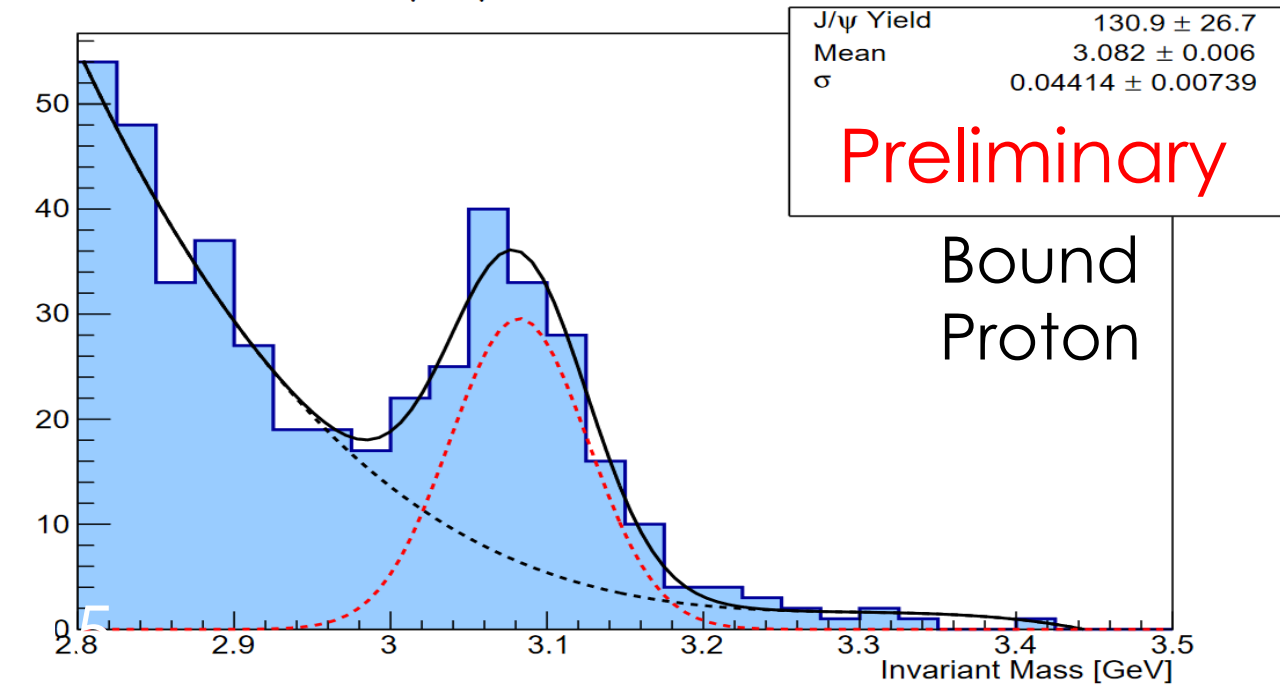
e+ e- Invariant Mass



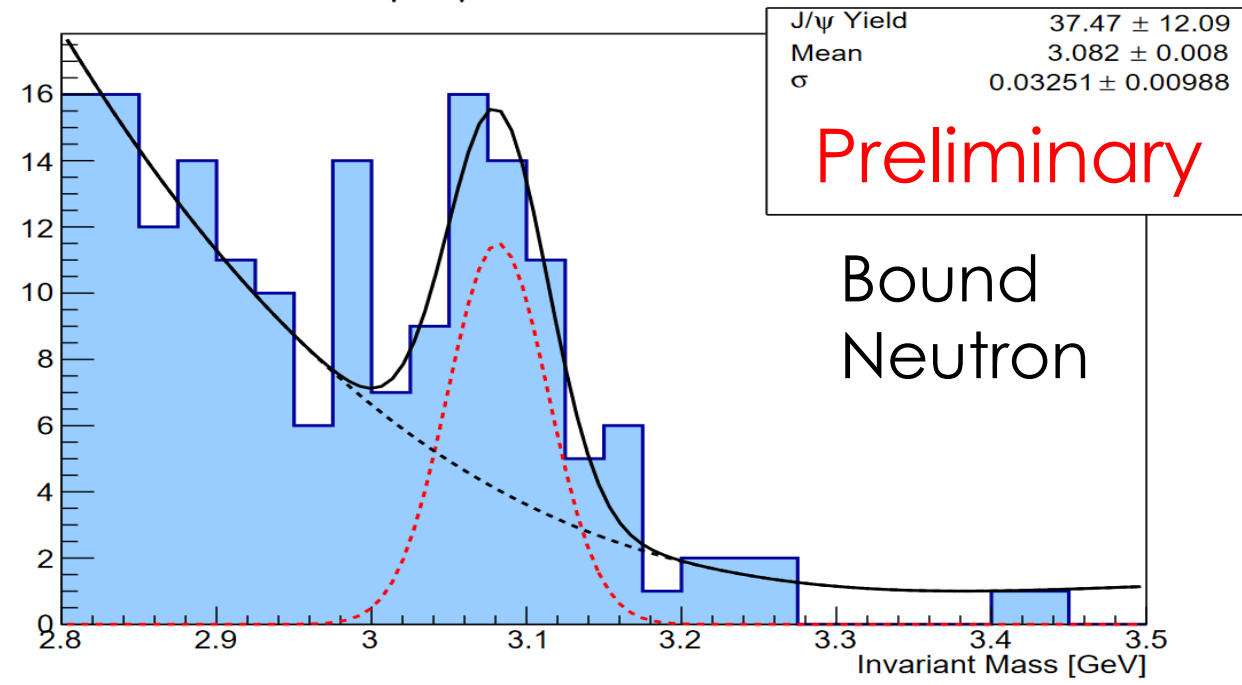
e+ e- Invariant Mass



μ+ μ- Invariant Mass



μ+ μ- Invariant Mass

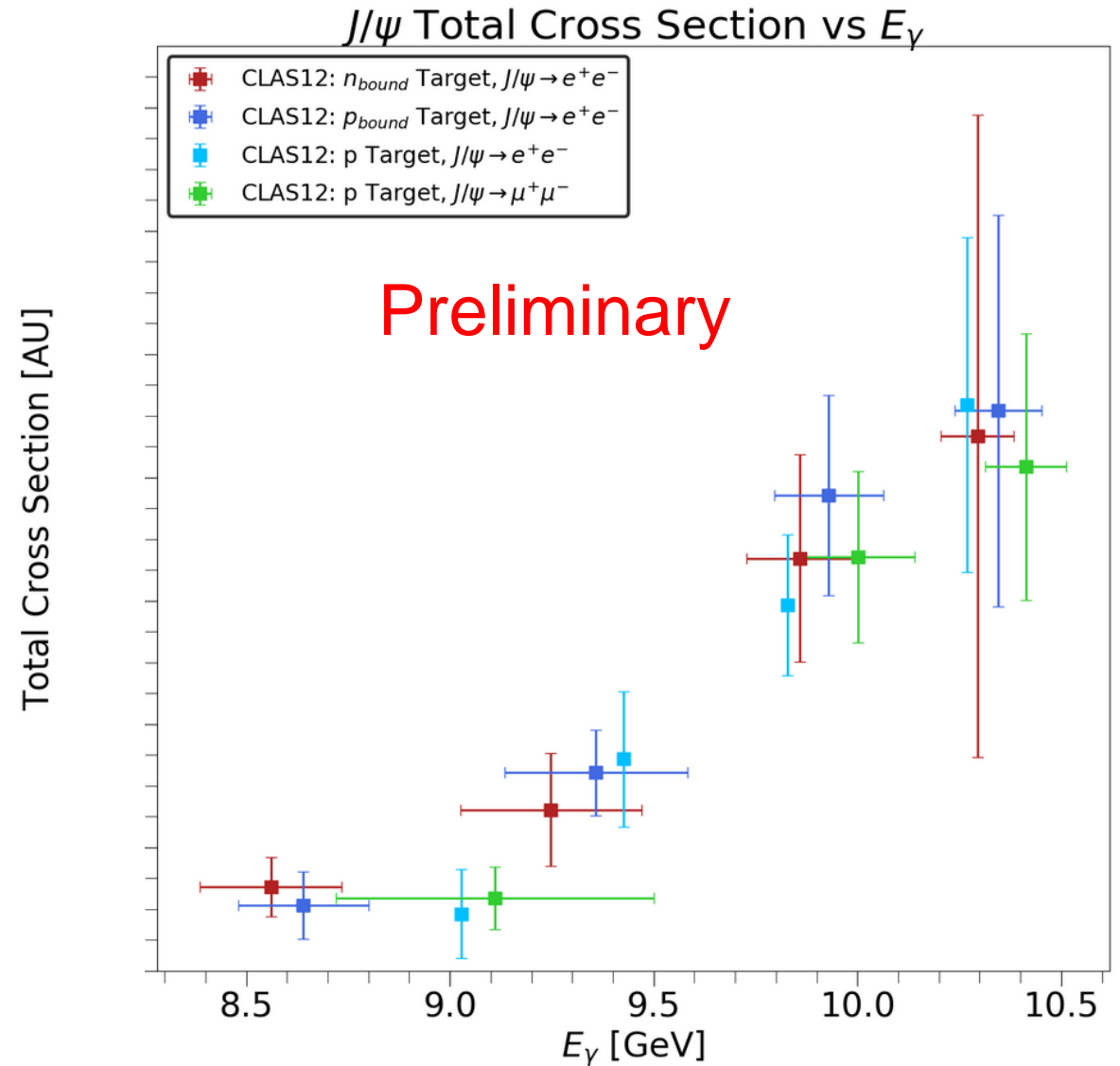


J/ ψ Total Cross Section

- Shown here is the total cross section measured in:

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

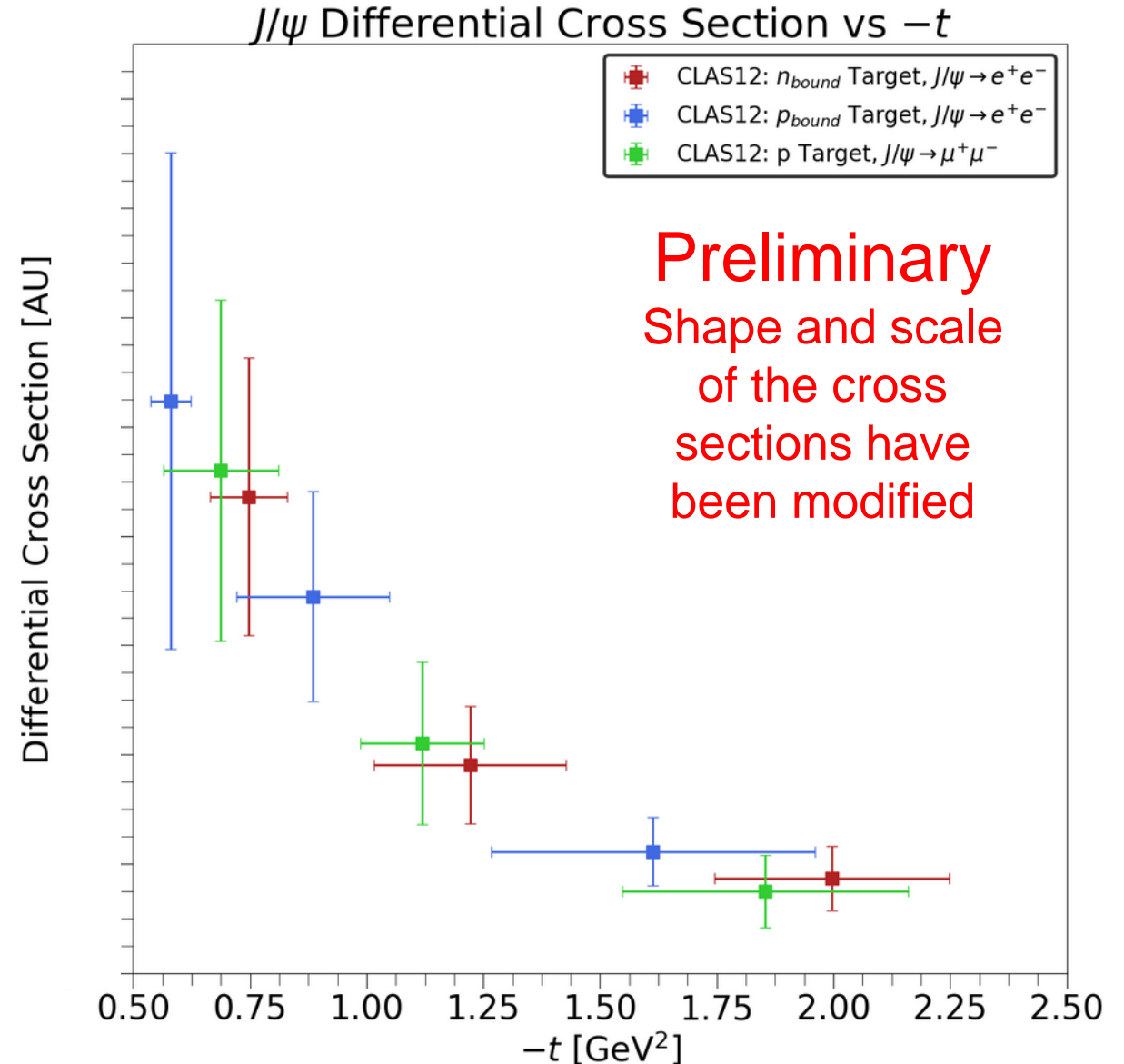
- We are still working on the absolute normalization.



J/ ψ Differential Cross Section

- ▶ The differential cross section is used to study the mechanical properties of the nucleon.
- ▶ Shown here is the differential cross section measured in:

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



Conclusion

- ▶ The mechanical properties of the nucleon can be probed using near-threshold J/ψ photoproduction. Along with DVCS and TCS, J/ψ photoproduction offers an exciting new direction for hadronic physics.
- ▶ CLAS12 is aiming towards a first measurement directly comparing the near-threshold J/ψ photoproduction cross sections on the bound proton and bound neutron.
- ▶ Measuring the cross section on the neutron allows to place further constraints on the near-threshold J/ψ production mechanism.
- ▶ Some work remains on the absolute normalization of the CLAS12 measurements.
- ▶ With some minimal effort we will also be able to measure the J/ψ photoproduction cross sections on the bound proton and bound neutron from the J/ψ decay to a di-muon pair.

Outlook

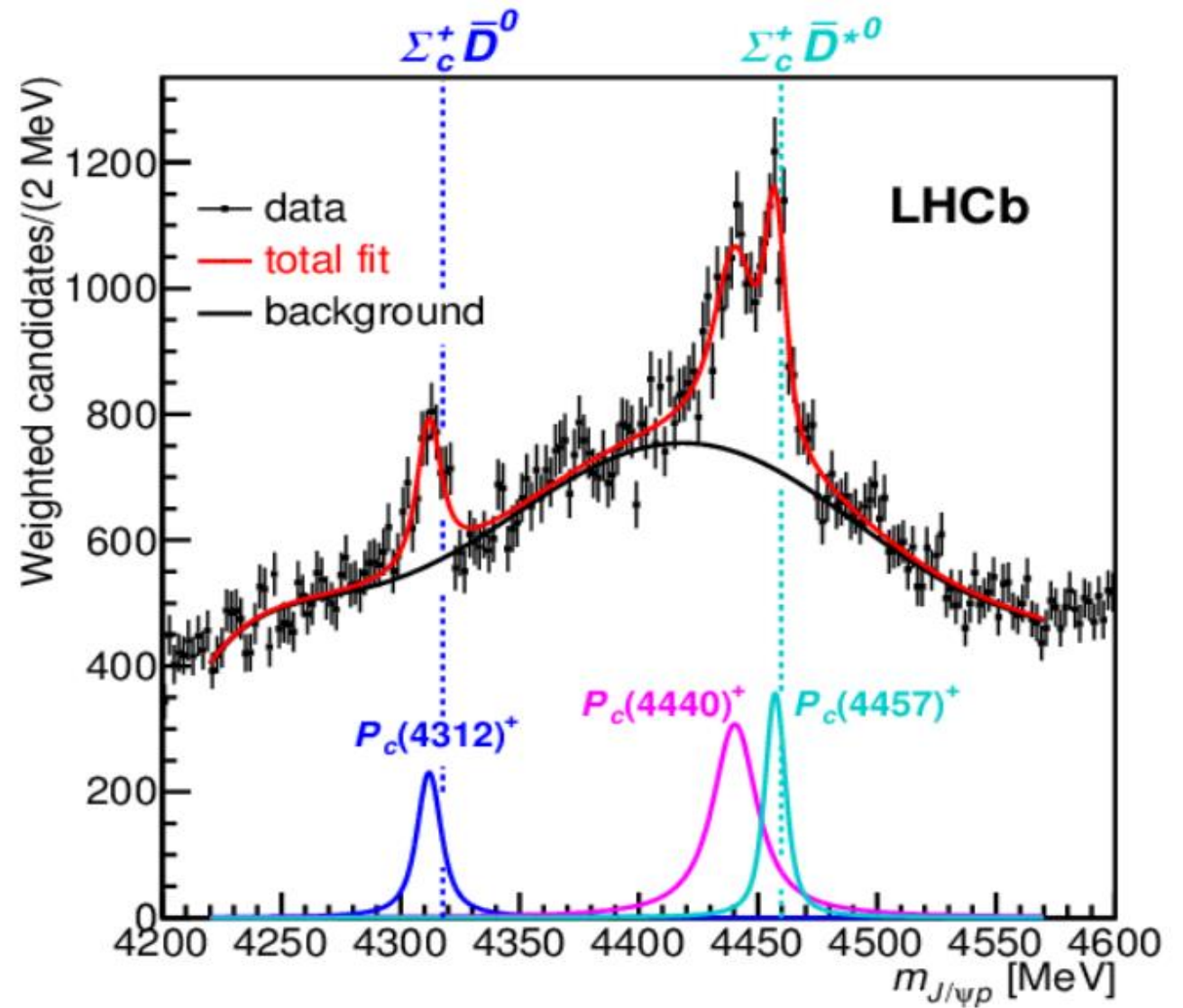
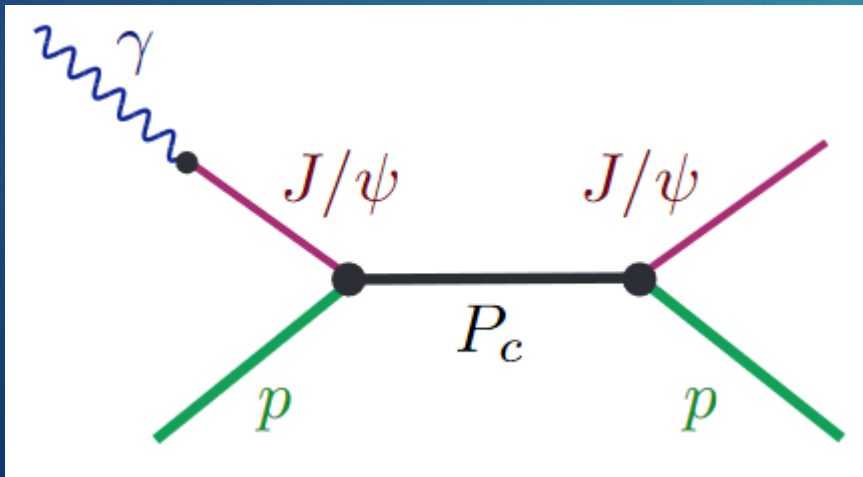
- ▶ AI based improvements in the tracking reconstruction at CLAS12 show an average 50% increase in the efficiency for 3 charged particles. The data already taken at CLAS12 is about to be reprocessed with the new tracking improvements.
- ▶ The experiment aiming for the measurements of J/ψ photoproduction on deuterium still has roughly ~60% left to run.
- ▶ Future luminosity upgrades at JLab and CLAS12 will enable high statistics measurements of J/ψ photoproduction and a better understanding of the production mechanism of J/ψ near-threshold. See [Nathan Baltzell's talk](#) for more information on a luminosity upgrade at CLAS12.



Backup Slides

P_c^+ resonances with CLAS12

- CLAS12 should be able to place upper limits on the branching fraction $B(P_c^+ \rightarrow J/\psi p)$ and $B(P_c^+ \rightarrow J/\psi n)$.

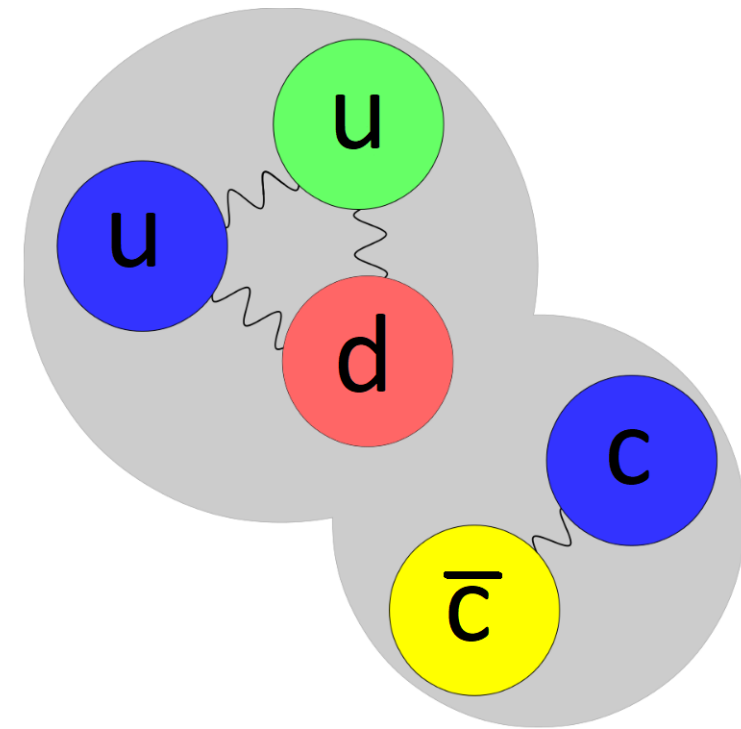
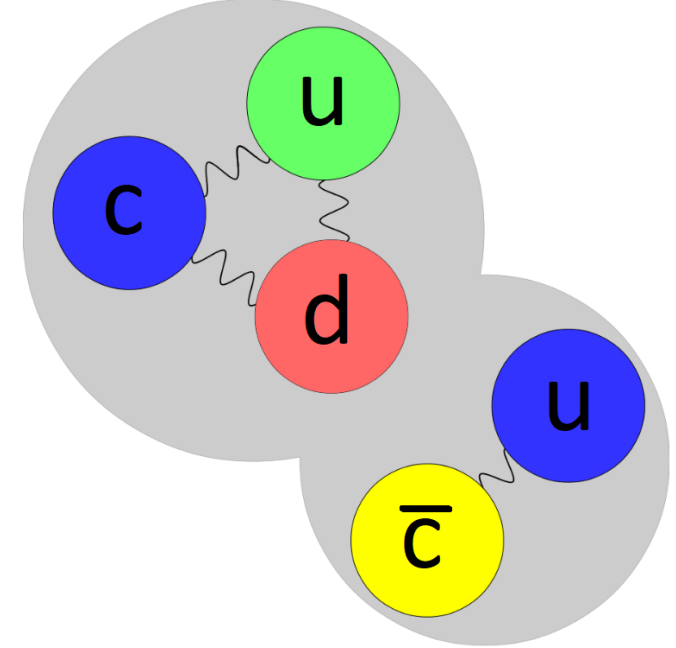
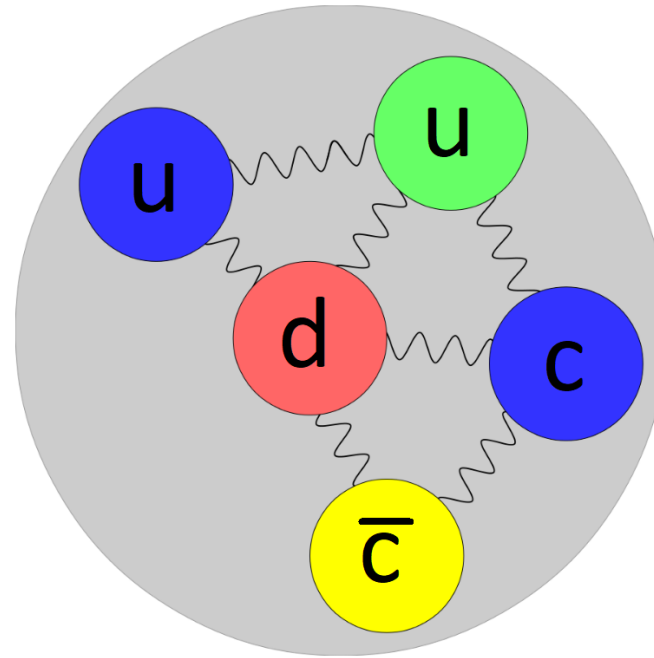


The $J/\psi p$ invariant mass distribution measured at the LHCb. Taken from:

R. Aaij, et. al. (LHCb Collaboration), *Phys. Rev. Lett.* **122**, 22 (2019).

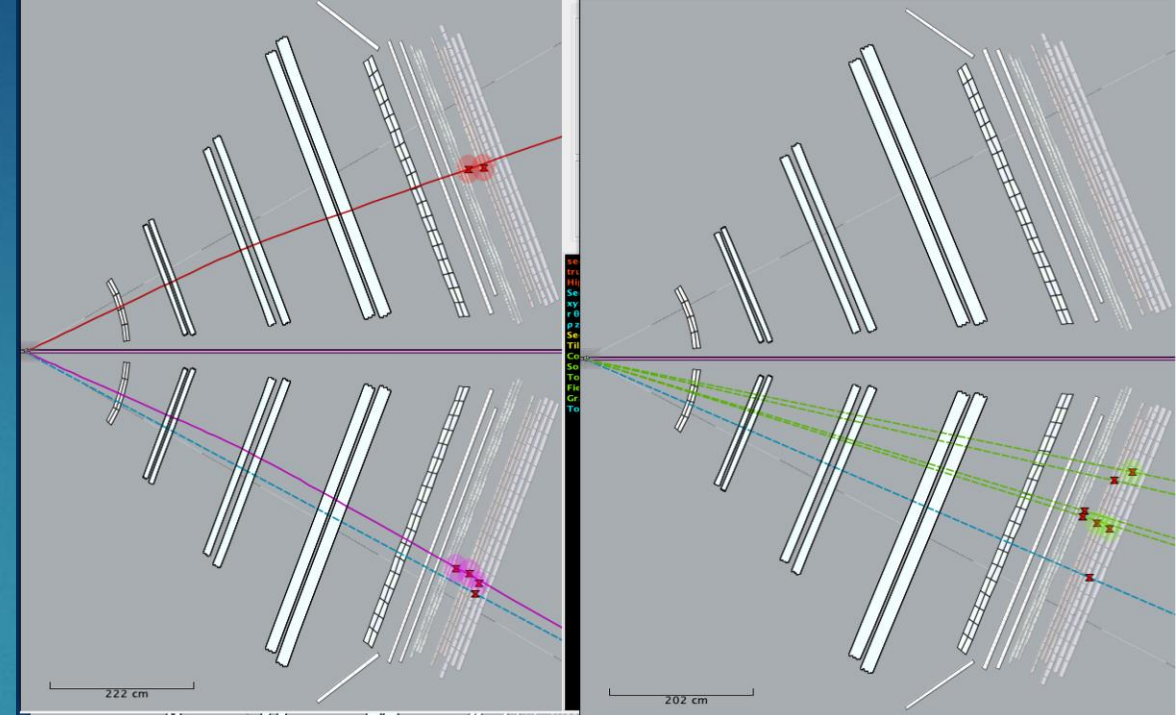
P_c^+ Models

- ▶ Hadronic molecules: Weakly coupled charmed baryon and charmed meson.
- ▶ Hadro-charmonium states: compact bound $c\bar{c}$ state and light quarks.
- ▶ Quarks in a bag: Two tightly correlated di-quarks and an anti-quark.

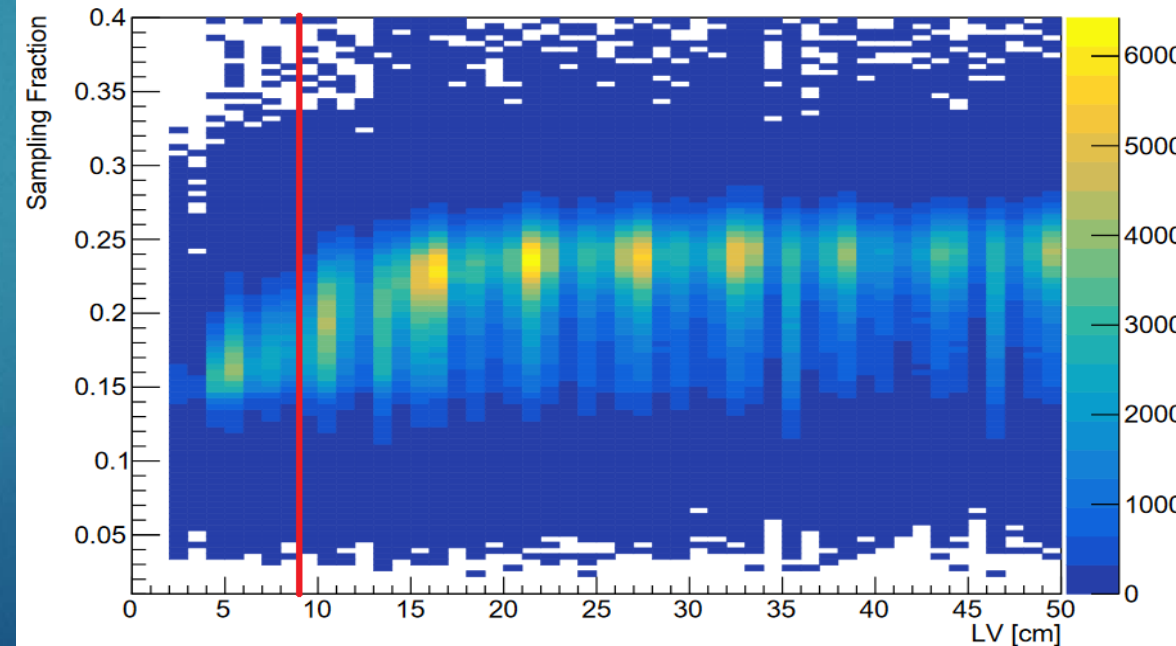


Particle Corrections

- ▶ Radiative corrections for **electrons/positrons** add the momentum of **radiated photons**.
- ▶ **Neutrons** also produce **secondary clusters**. These are removed by taking the earliest neutral in a given sector.
- ▶ The reconstructed path length for neutrons is corrected for a more accurate calculation of the momentum.
- ▶ We apply fiducial cuts to remove e^+/e^- hits close to the edges of the PCAL where the shower is not fully contained within the calorimeter.
- ▶ Fiducial cuts in the drift chambers are applied to electrons, positrons, protons and muons by removing hits at the edge of the layers.



e- Sampling Fraction vs LV



ρ , ω and ϕ mesons

- ▶ Plotted here is the invariant mass of e^+e^- produced on a bound proton in the deuteron target.
- ▶ ϕ mesons are clearly resolved.
- ▶ ρ and ω mesons are unresolvable but clearly present.

