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

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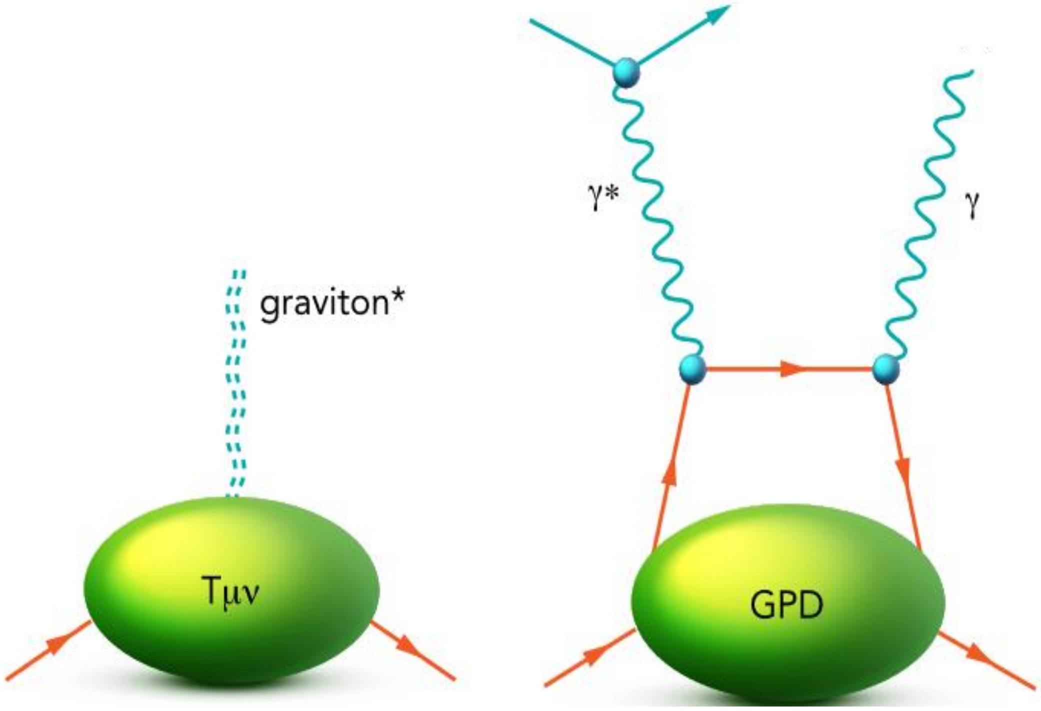
CEBAF Large Acceptance Spectrometer

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.

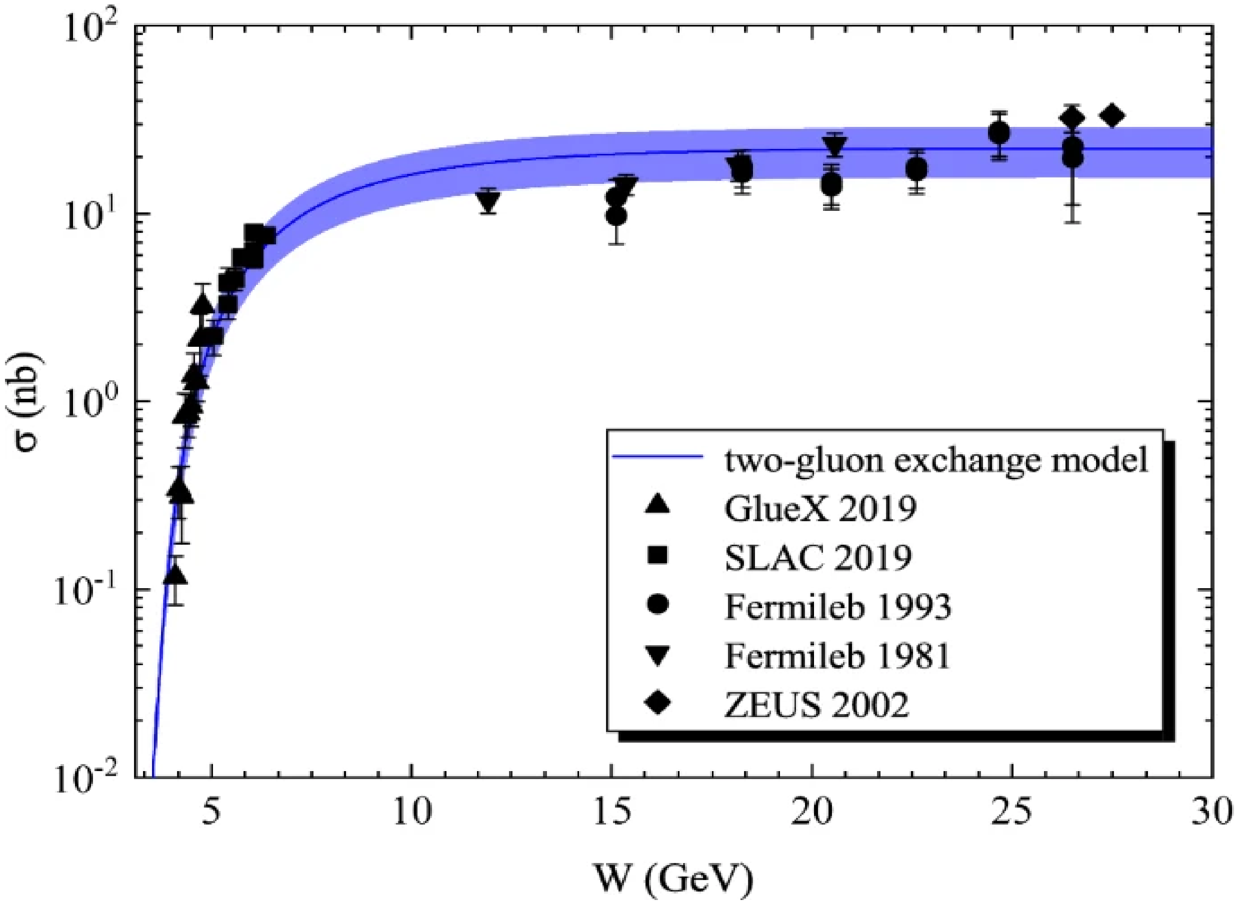


Spin-2 fields in graviton-proton scattering and DVCS [12].

[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 the J/ψ photoproduction total and differential cross section as a function of t [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 (2022).

Trace Anomaly Contribution to the Nucleon Mass

- 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].

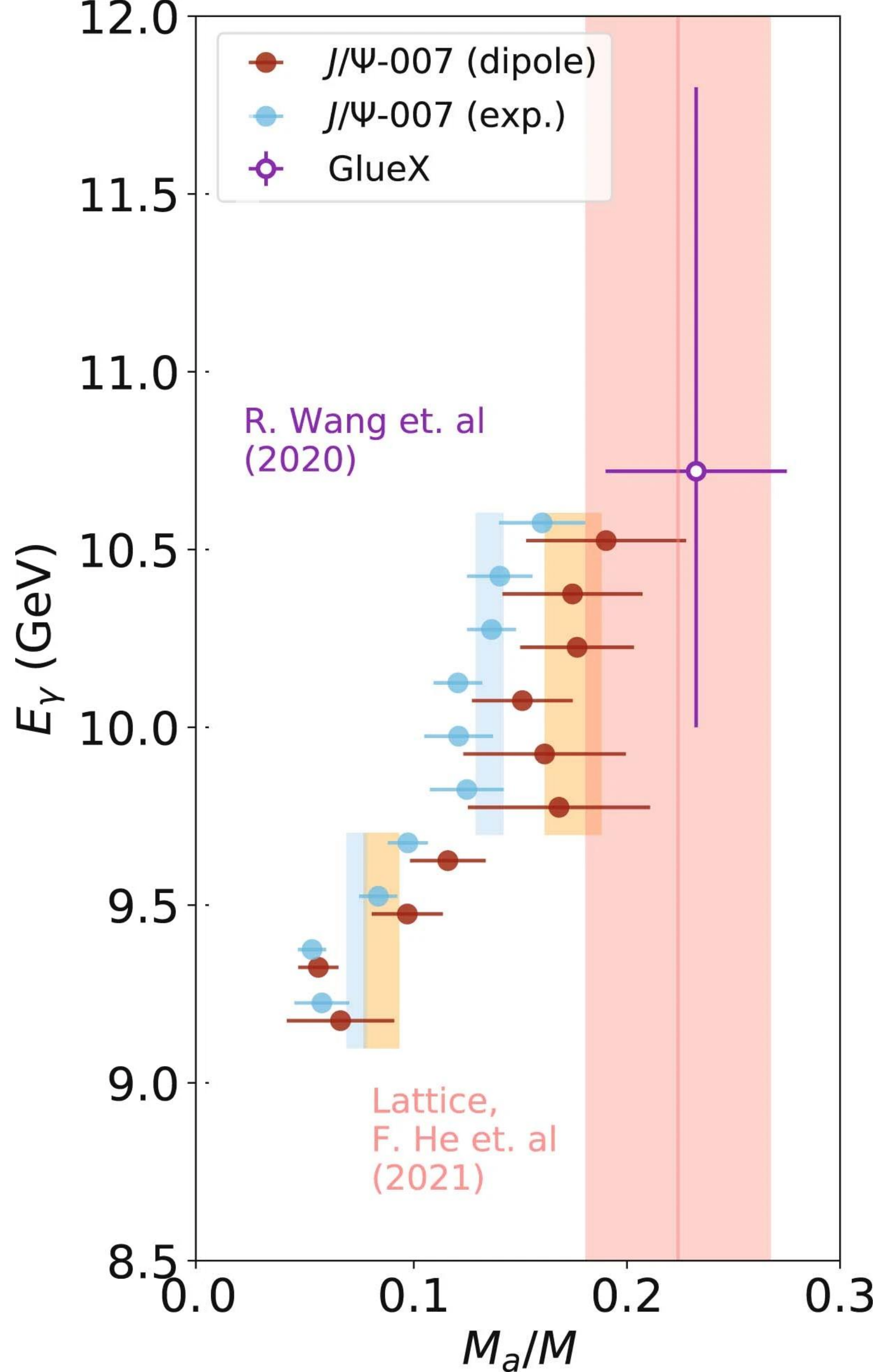
- Estimates of the magnitude of the trace anomaly contribution were obtained at GlueX and Hall-C [11-13].

- 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)

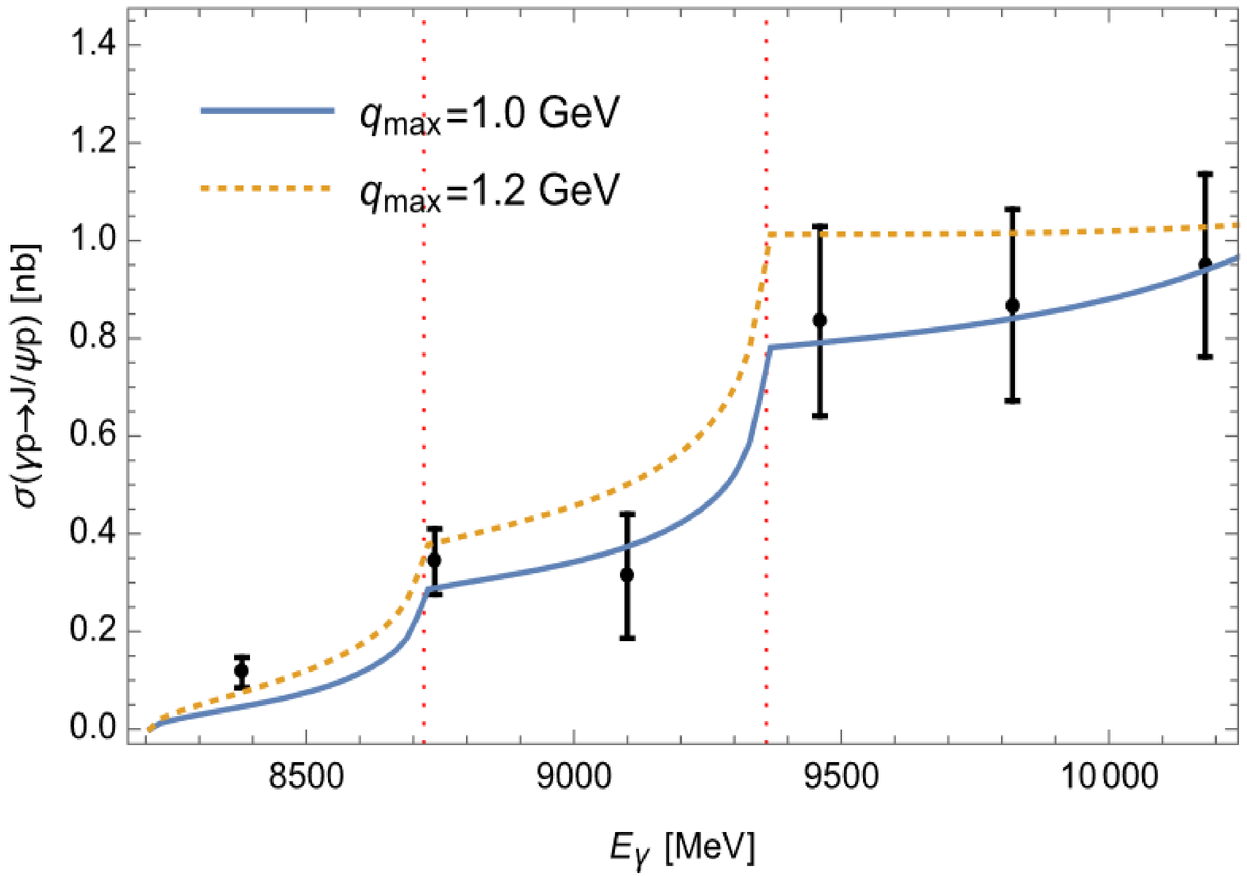


Model Depedence

- There are suggestions that J/ψ near-threshold photoproduction could be dominated by open charm production of $\Lambda^c \overline{D}^{(*)}$ [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.

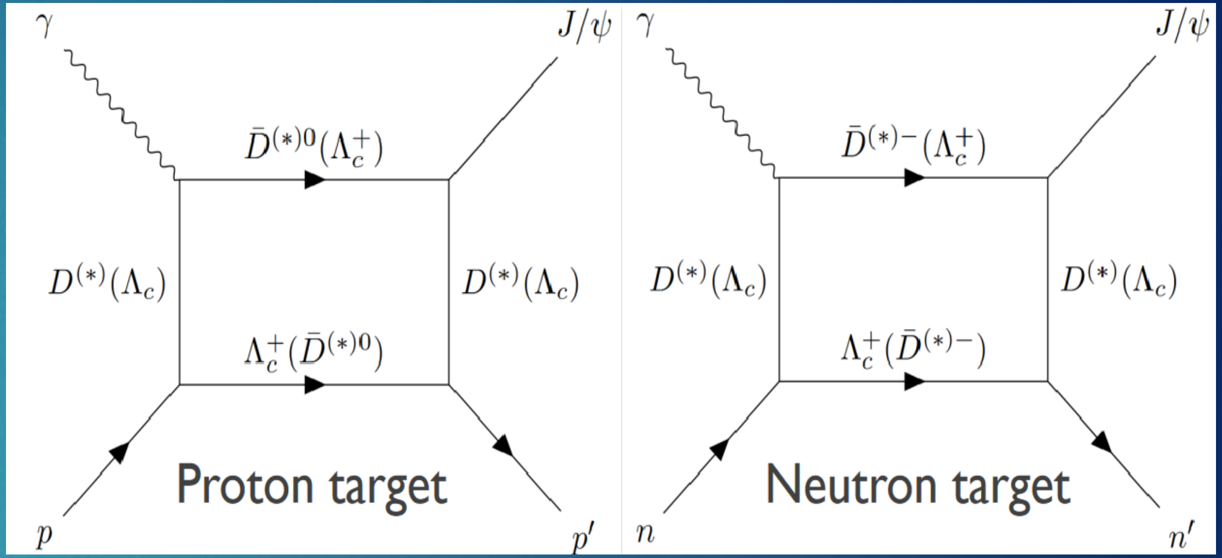


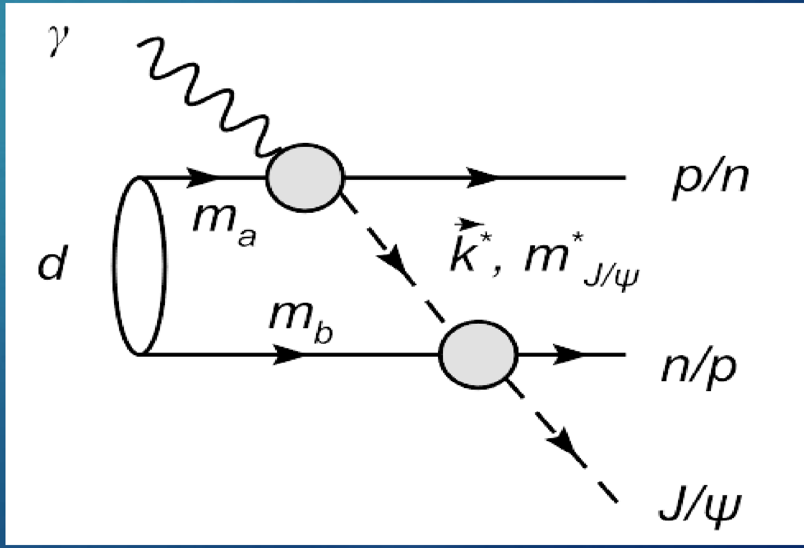
Predictions for the total cross section due to the open charm production of J/ψ p [12], which is consistent with the GlueX measurements [13] in black. Here q_{max} refers to a threshold on Q2.

[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/ψN final state interactions allow to measure the J/ψN cross section which can be related to studies of quark-gluon plasma. The J/ψN cross section at low energies is largely unknown.



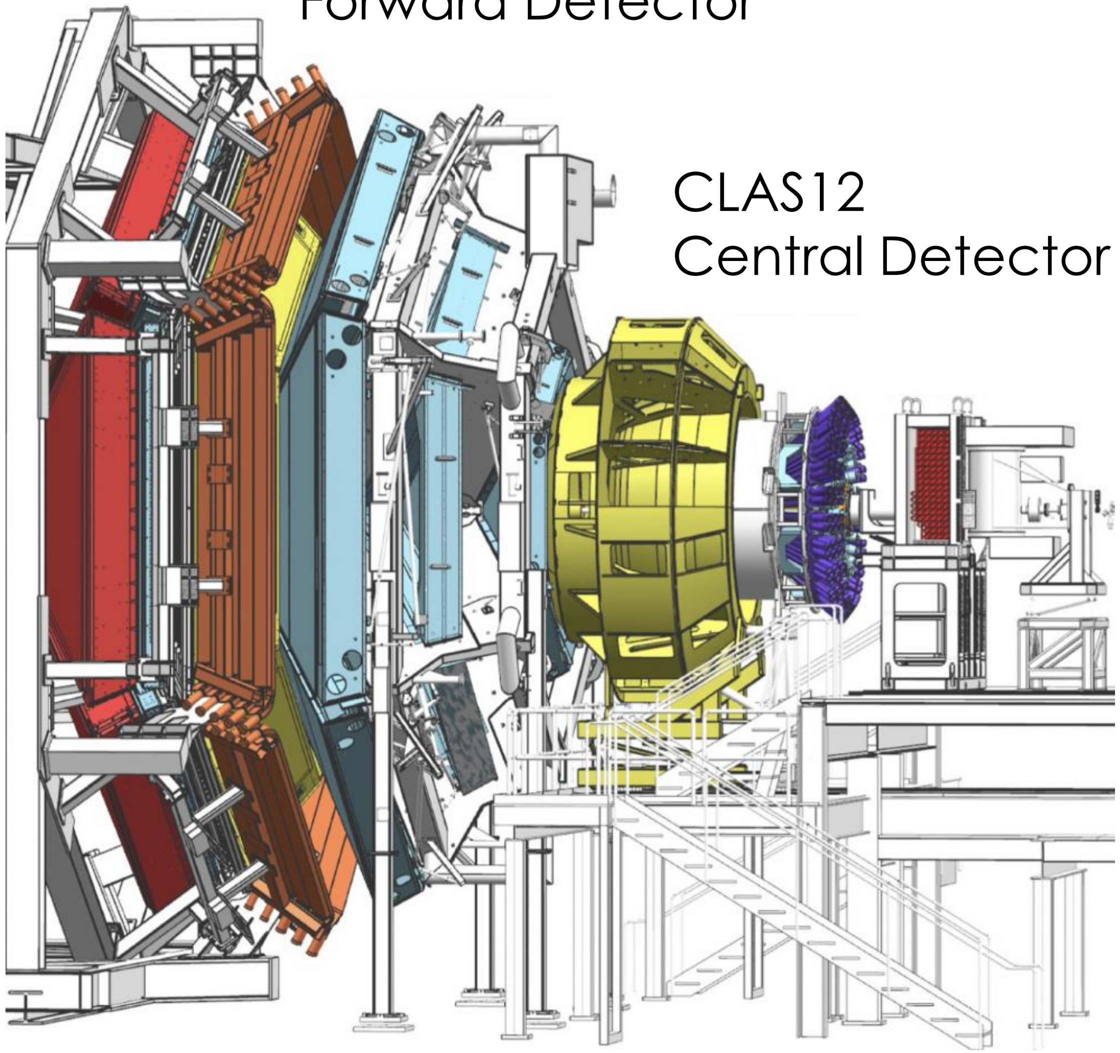


JLab

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

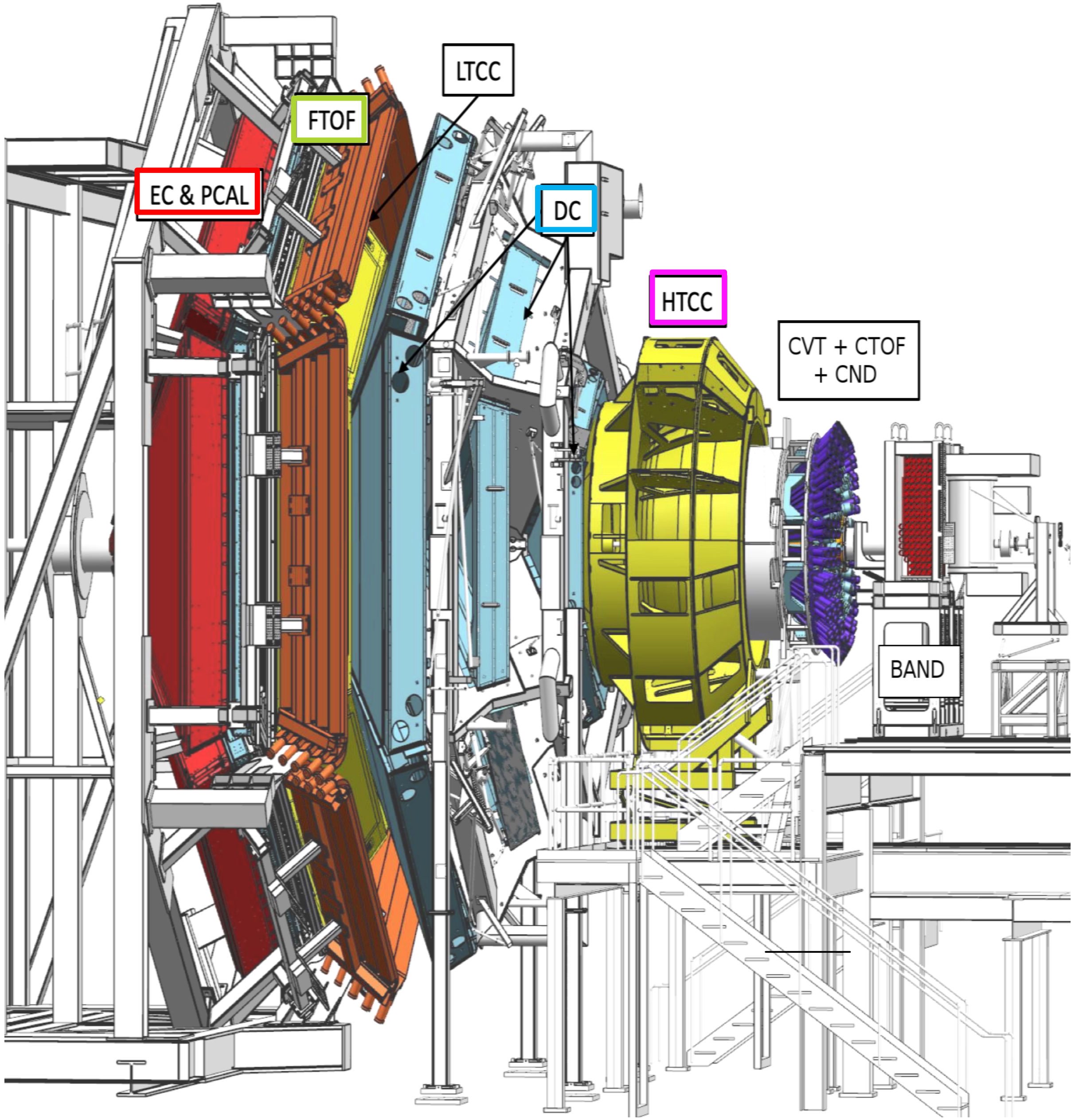
The CLAS12 Detector

- 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

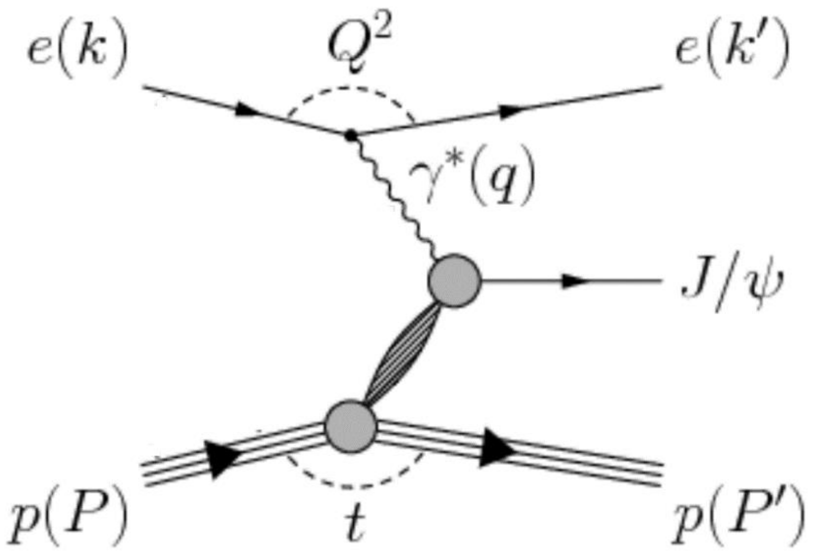
- J/ψ decays to a lepton pair, with l^+l^- denoting either e^+e^- or $\mu^+\mu^-$.

- CLAS12 took data with both a proton and a deuterium target offering several potential final states:

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

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

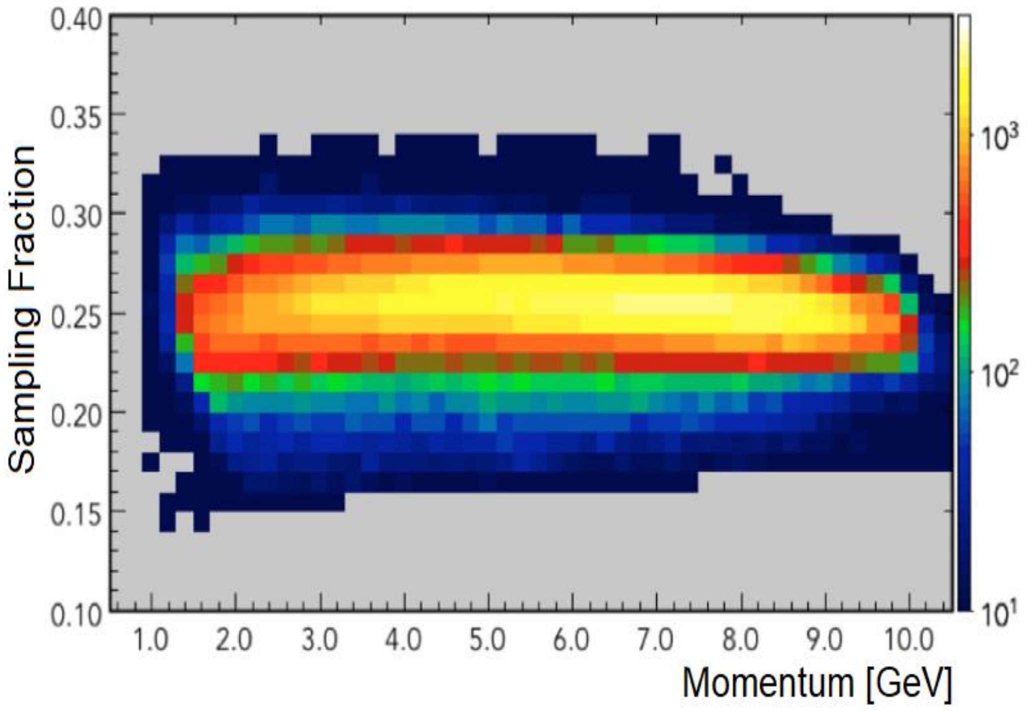
$$e\ n_{bound} \to e' J/\psi\ n \to (e') l^+ l^- n$$

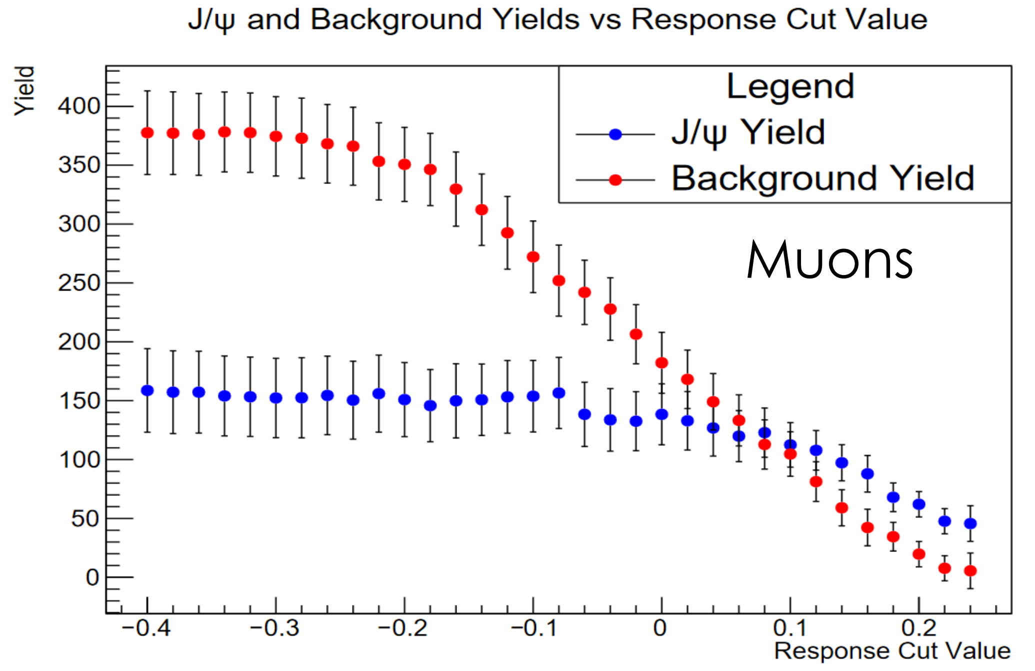


J/ψ quasi-real photoproduction on a proton target

Lepton Identification

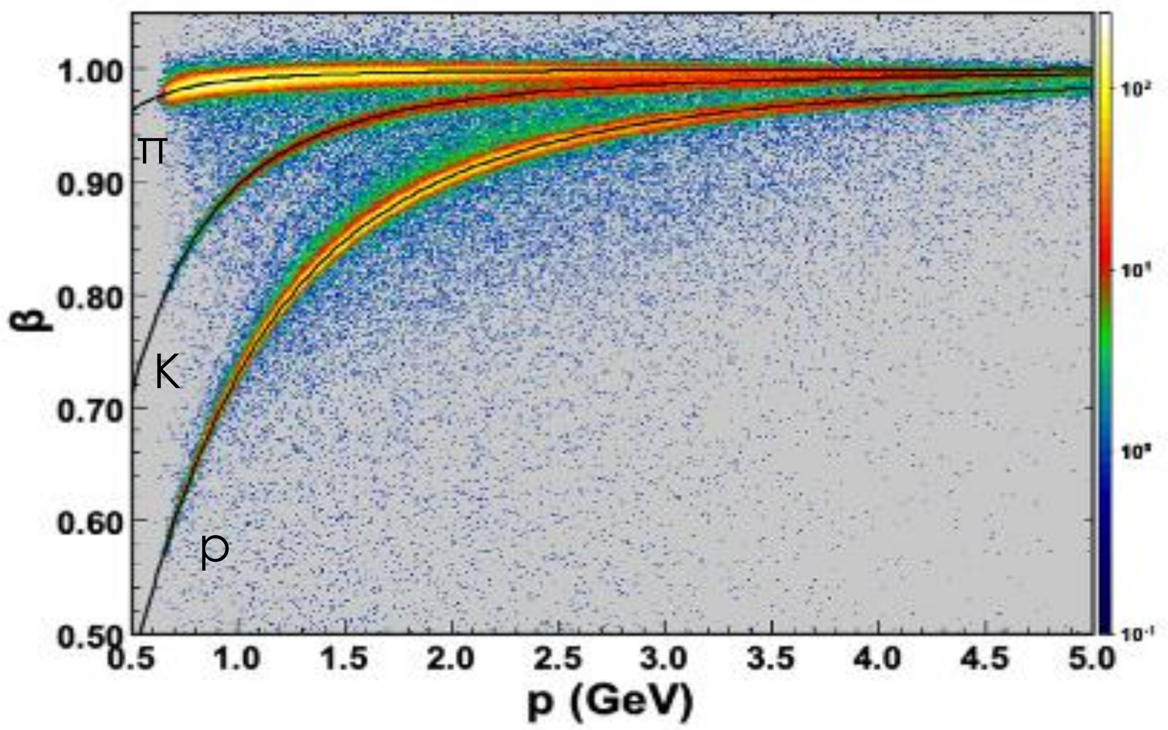
- Electrons and positrons are required to produce a signal in the HTCC and have a ratio of the energy deposition to momentum around 0.25.
- Muons are minimum ionising particles which we select with cuts on their energy deposition in the calorimeters.
- We refine the lepton PID by training a machine learning 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.





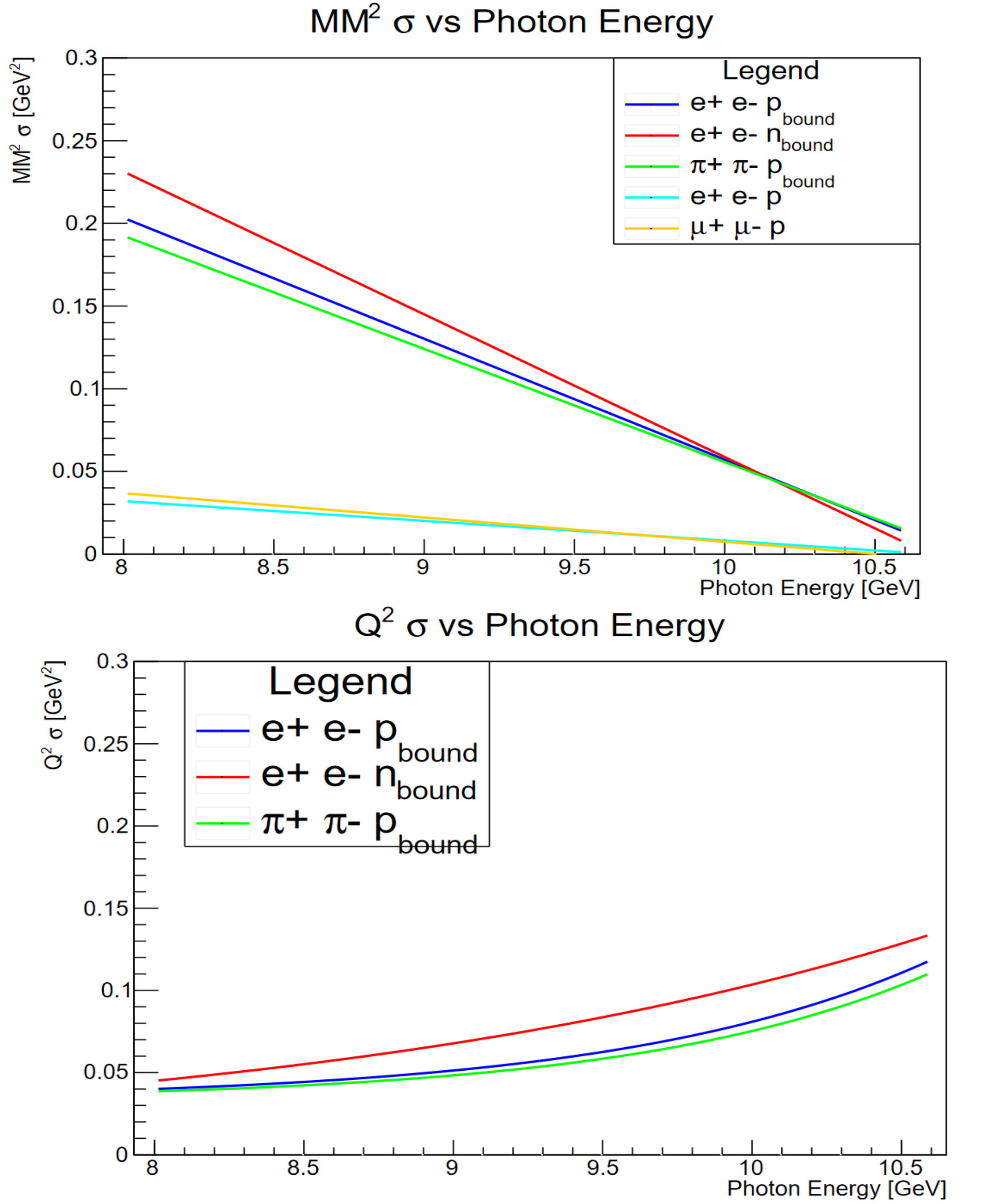
Hadron Identification

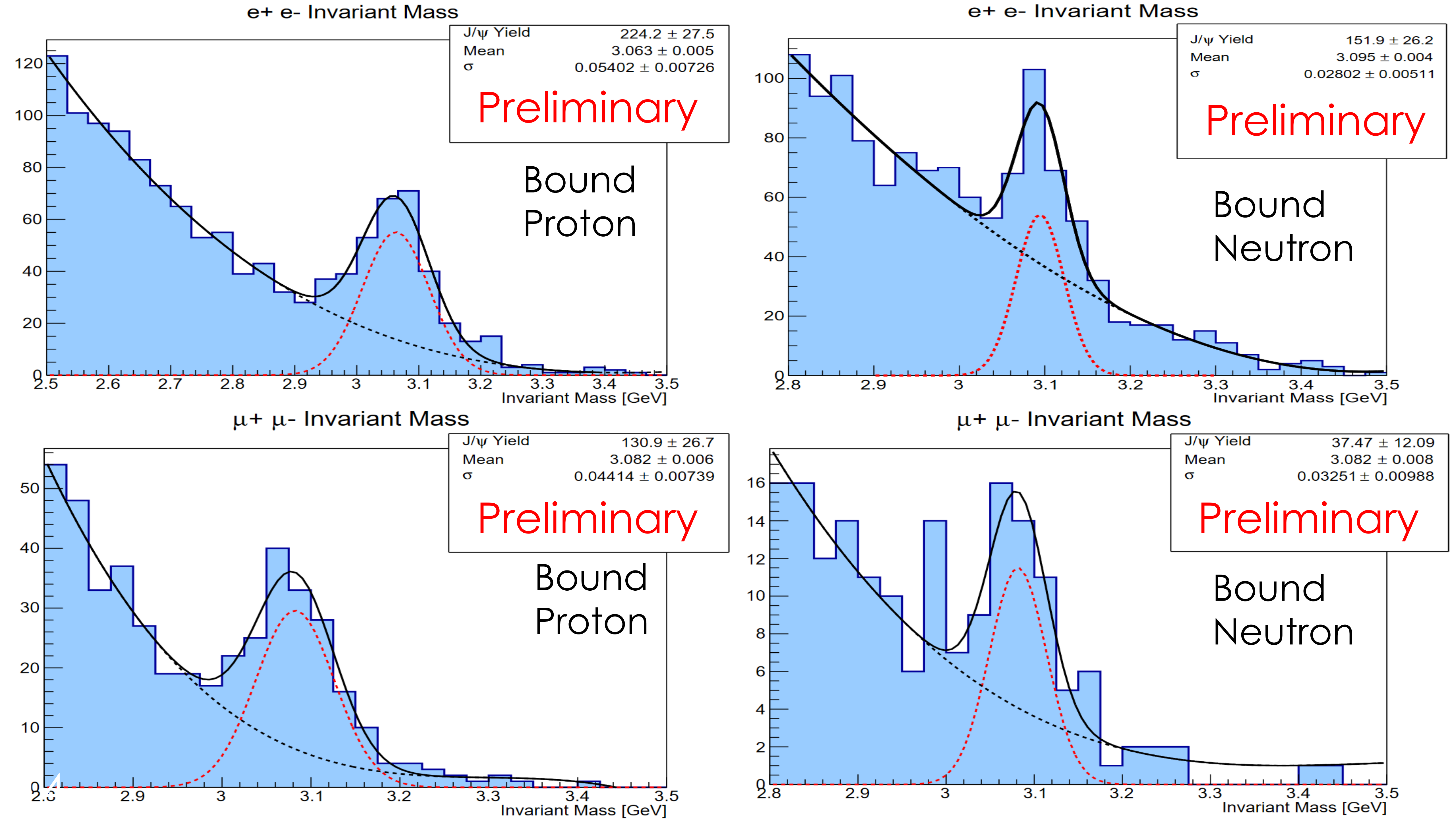
- For protons (and charged hadrons in general) a cut is made on the Beta versus Momentum parametrization.
- For neutrons we require a neutral charge. No further cuts were applied as there isn't any strong evidence of photon contamination.



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.

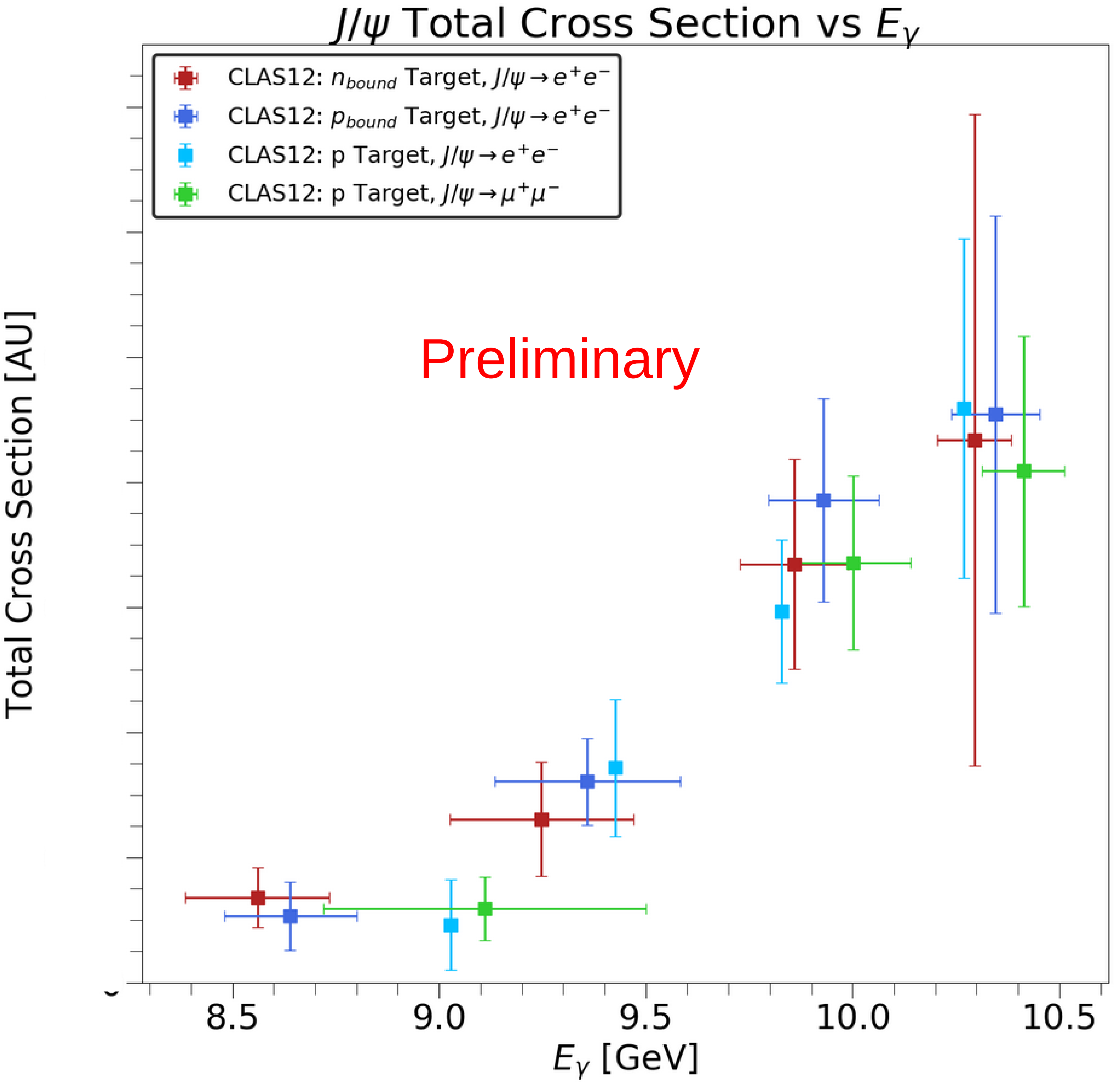



e+ e- Invariant Mass
J/ψ Yield 224.2 ± 27.5
Mean 3.063 ± 0.005
σ 0.05402 ± 0.00726
Preliminary
Bound Proton
Invariant Mass [GeV]
e+ e- Invariant Mass
J/ψ Yield 151.9 ± 26.2
Mean 3.095 ± 0.004
σ 0.02802 ± 0.00511
Preliminary
Bound Neutron
Invariant Mass [GeV]
μ+ μ- Invariant Mass
J/ψ Yield 130.9 ± 26.7
Mean 3.082 ± 0.006
σ 0.04414 ± 0.00739
Preliminary
Bound Proton
Invariant Mass [GeV]
μ+ μ- Invariant Mass
J/ψ Yield 37.47 ± 12.09
Mean 3.082 ± 0.008
σ 0.03251 ± 0.00988
Preliminary
Bound Neutron
Invariant Mass [GeV]

J/ψ Total Cross Section

- Shown here is the total cross section measured in:
  - $en_{bound} \rightarrow (e')e^{+}e^{-}n$
  - $ep_{bound} \rightarrow (e')e^{+}e^{-}p$
  - $ep \rightarrow (e')\mu^{+}\mu^{-}p$
  - $ep \rightarrow (e')\mu^{+}\mu^{-}p$

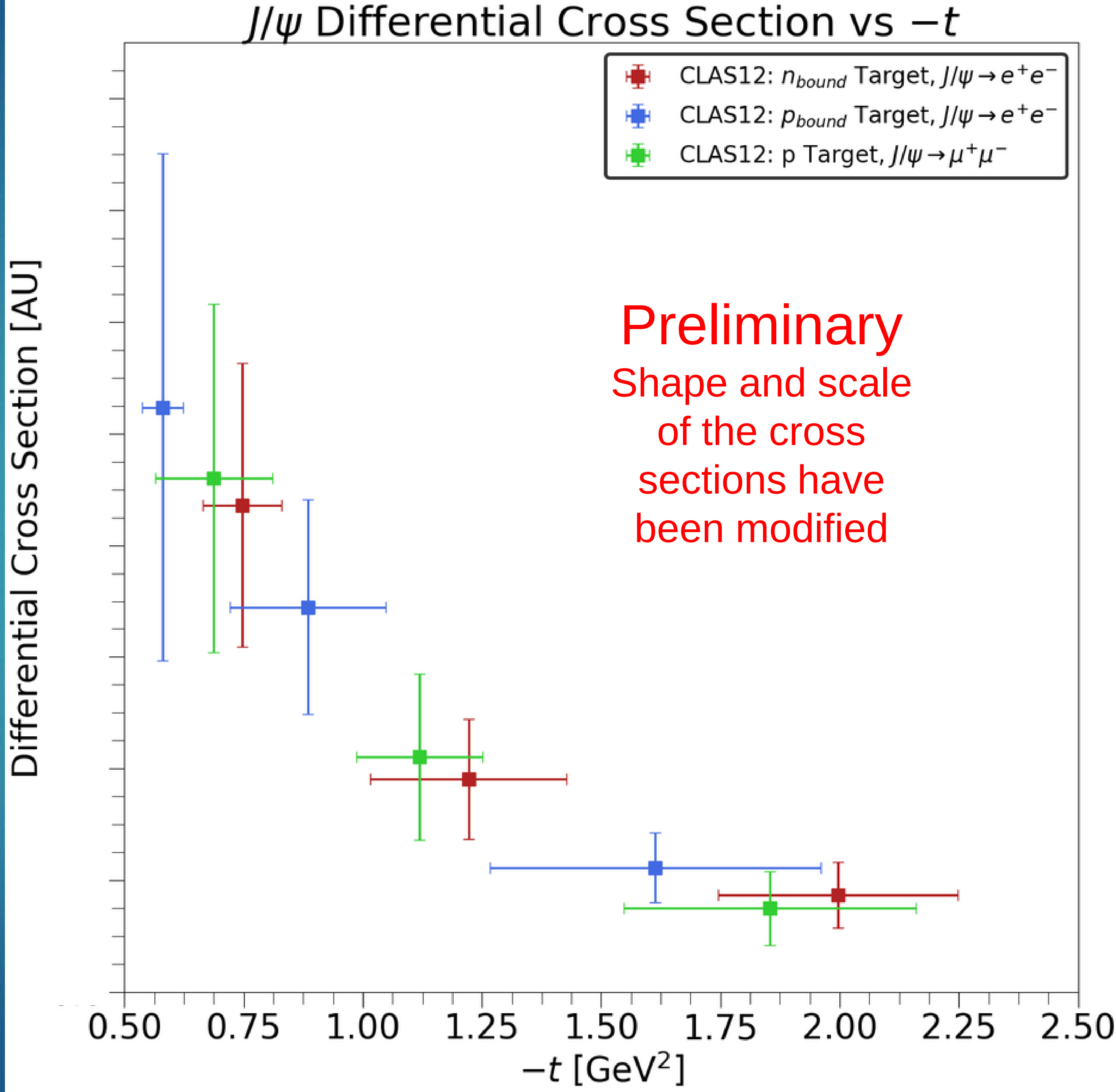
- We are still working on the absolute normalization.



J/ψ Differential Cross Section

- Shown here is the differential cross section measured in:
  - $en_{bound} \to (e')e^{+}e^{-}n$
  - $ep_{bound} \to (e')e^{+}e^{-}p$
  - $ep \to (e')\mu^{+}\mu^{-}p$

- Good agreement between the proton and neutron channels suggest similar gluonic gravitational form factors for the proton and neutron.



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.

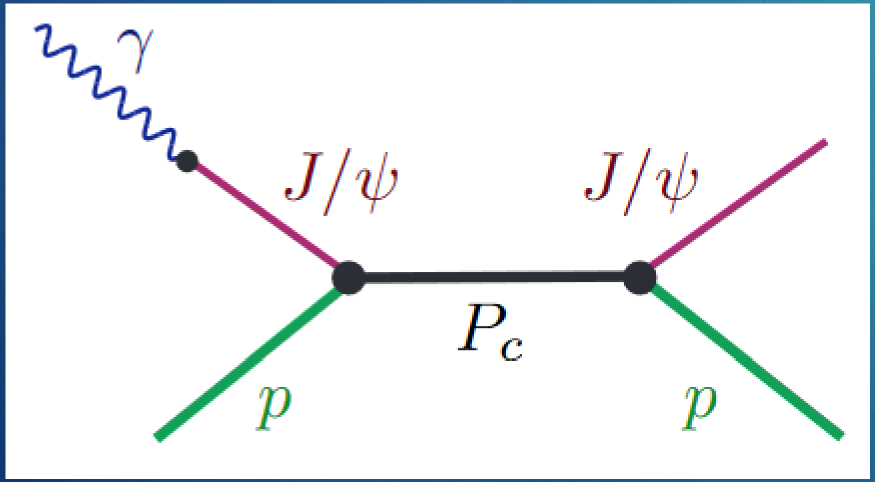
Outlook

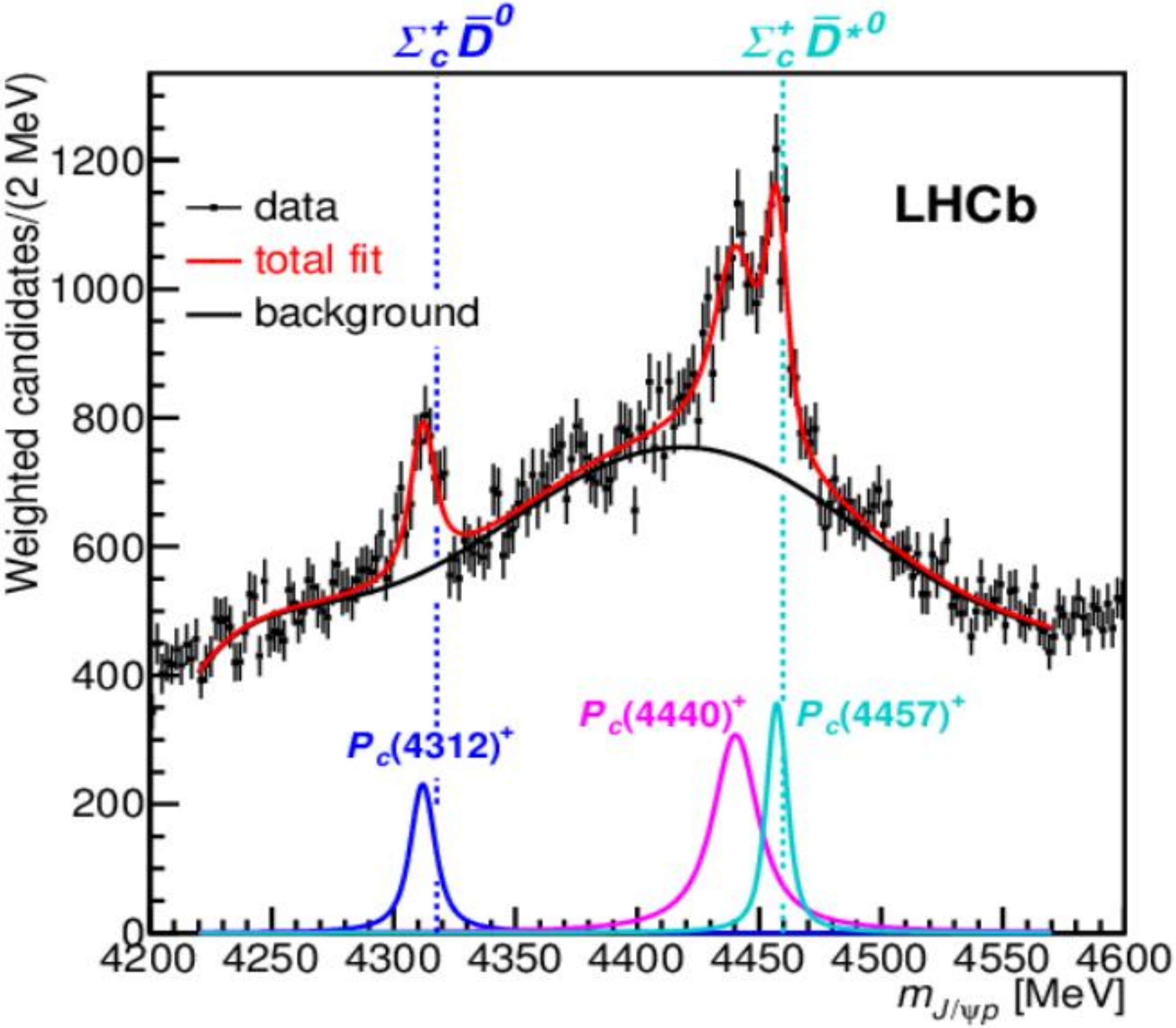
- AI based improvements in the tracking reconstruction at CLAS12 show an average 50% increase in the efficiency for 3 charged particles. The data already taken at CLAS12 is about to be reprocessed with the new tracking improvements.
- The experiment aiming for the measurements of J/ψ photoproduction on deuterium still has roughly ~40% 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 $\mathrm{B}(P_c^+ \rightarrow J/\psi\ p)$ and $\mathrm{B}(P_c^+ \rightarrow J/\psi\ n)$.





The J/ψ p invariant mass distribution measured at the LHCb. Taken from:

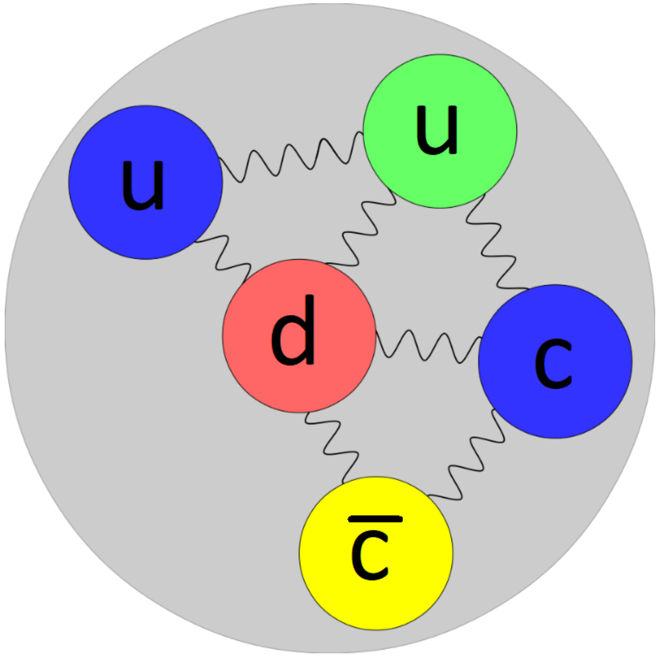
R. Aaij, *et. al.* (LHCb Collaboration), *Phys. Rev. Lett.* **122**, 22 (2019).

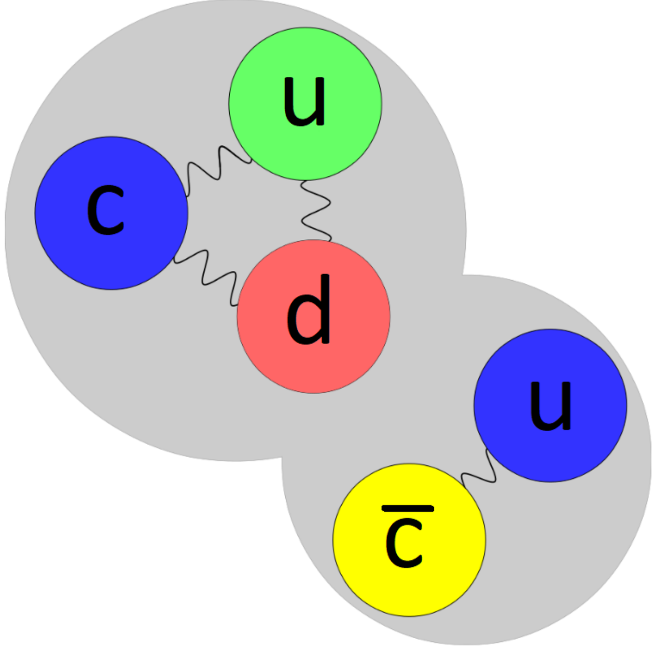
P_c^+ Models

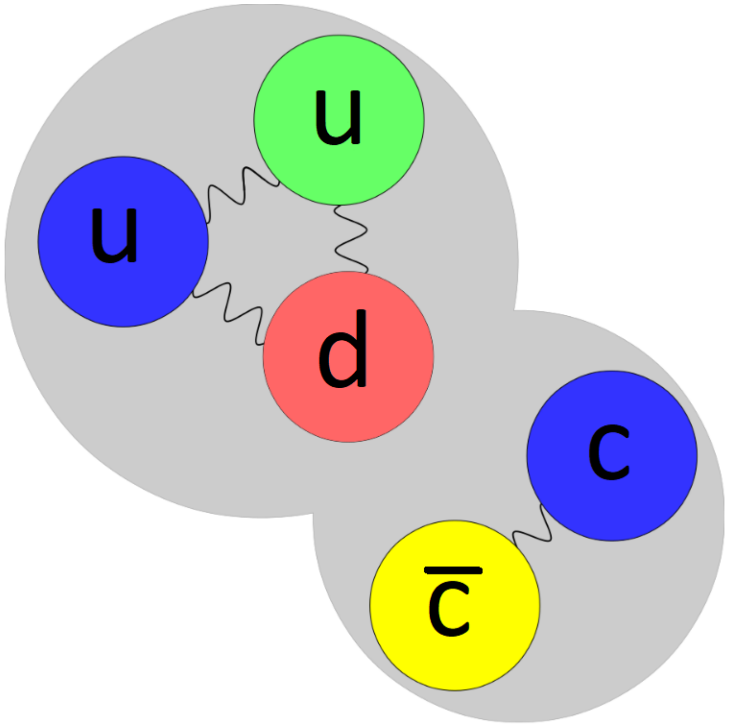
- Hadronic molecules: Weekly coupled charmed baryon and charmed meson.

- Hadro-charmonium states: compact bound $\mathbf{c\bar{c}}$ state and light quarks.

- Quarks in a bag: Two tightly correlated di-quarks and an anti-quark.

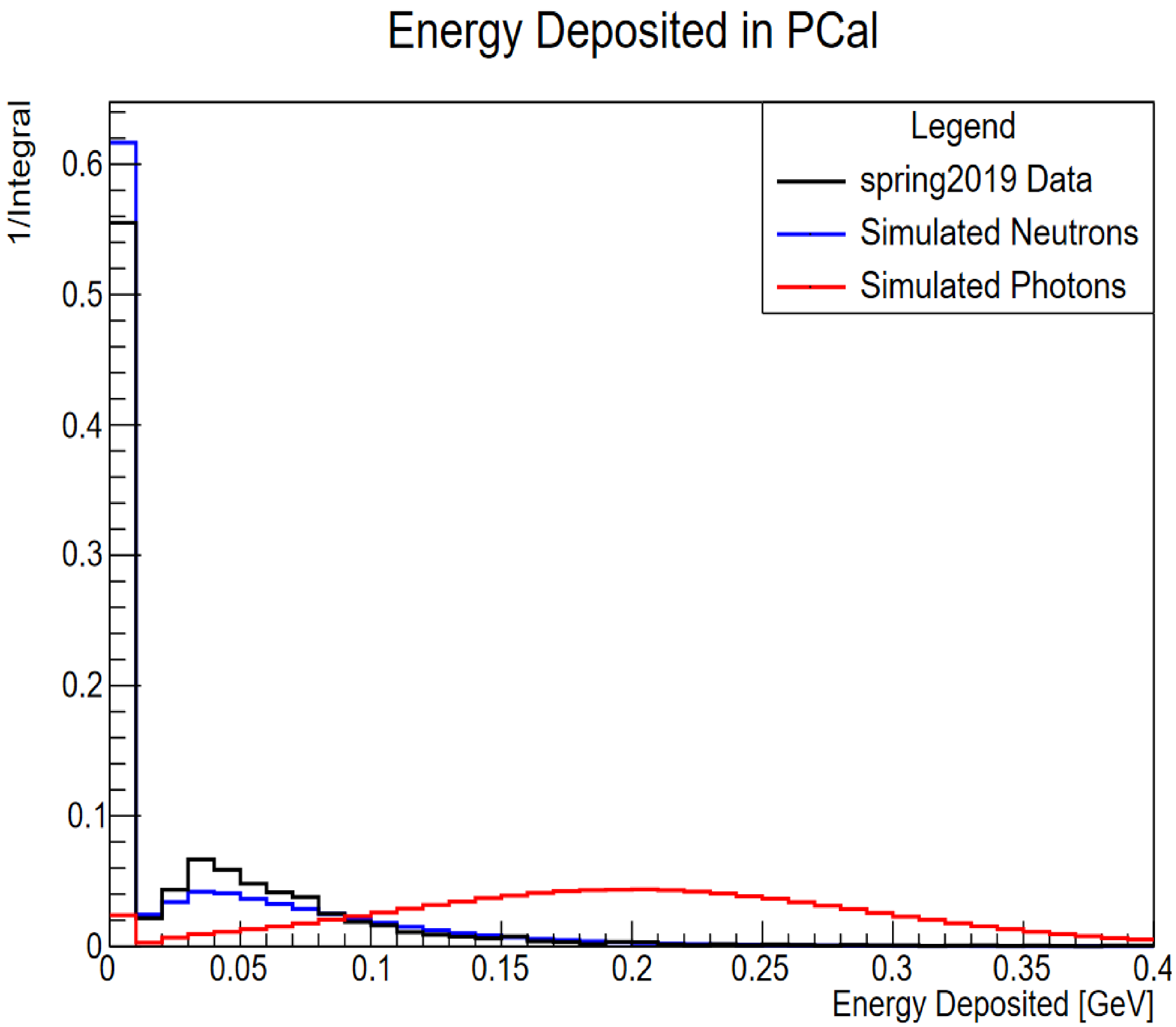






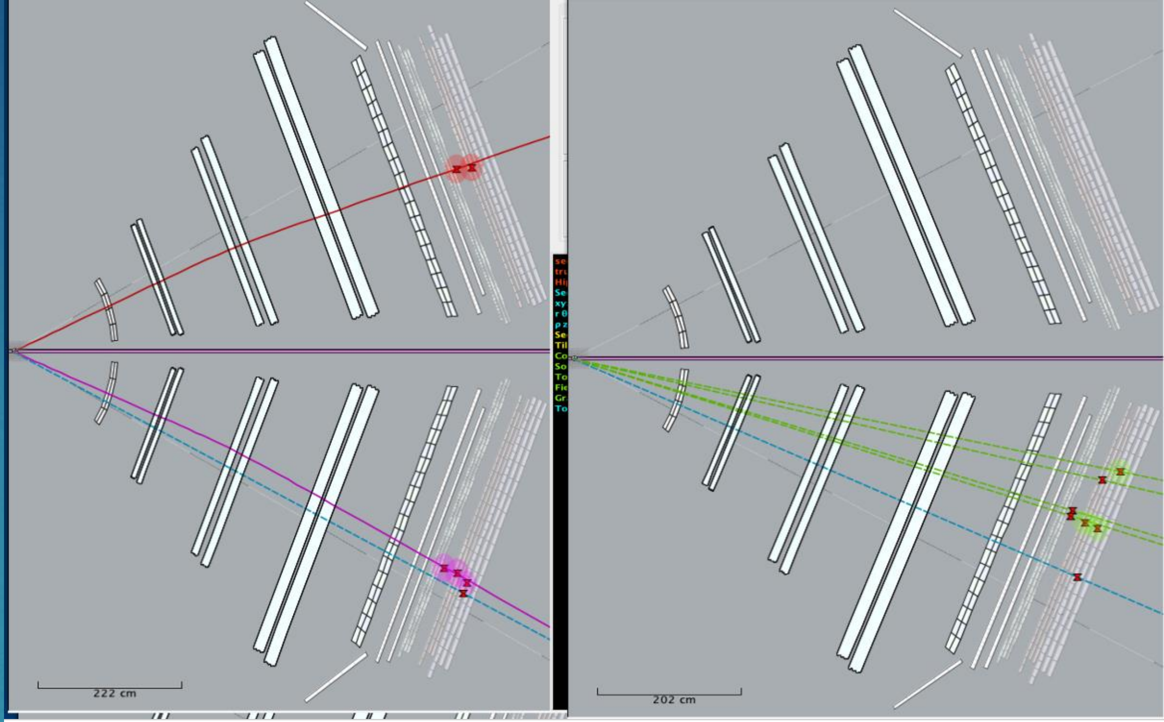
Neutron Identification

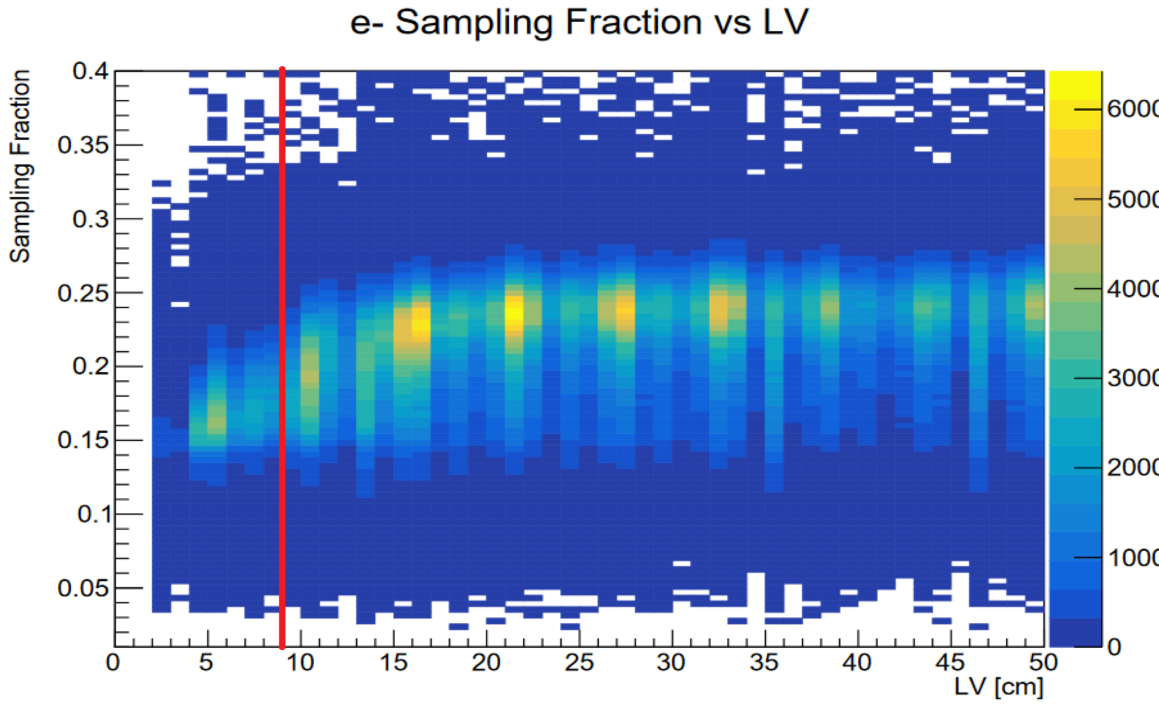
- Qualitative arguments suggest there isn't strong evidence of photon contamination.
- For example, photons will deposit more energy in the pre-shower calorimeter (PCAL) than neutrons.



Particle Corrections

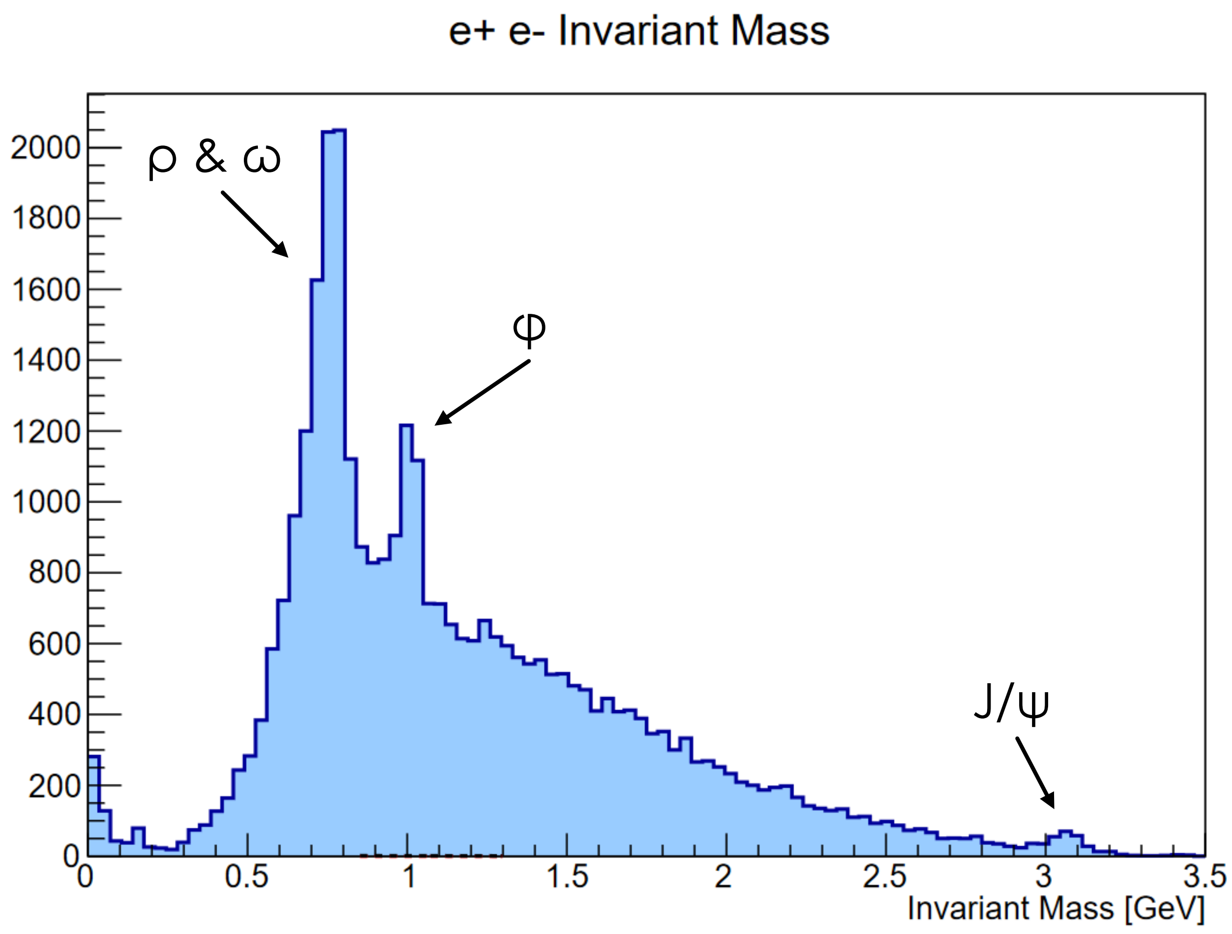
- Radiative corrections for electrons/positrons add the momentum of radiated photons.
- Neutrons also produce secondary clusters. These are removed by taking the earliest neutral in a given sector.
- The reconstructed path length for neutrons is corrected for a more accurate calculation of the momentum.
- 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.





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.



Cross Section Calculation

- We can calculate the total cross section as:

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

- Where:
  - $N_{J/\psi}$ is the J/ψ yield in each E_γ bin
  - N_γ is the sum of real and virtual photon flux
  - η_T is the integrated luminosity
  - ω_c is the Bethe Heitler normalisation factor
  - Br is the branching ratio (~6%)
  - $\epsilon(E_\gamma)$ is the acceptance in each E_γ bin