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

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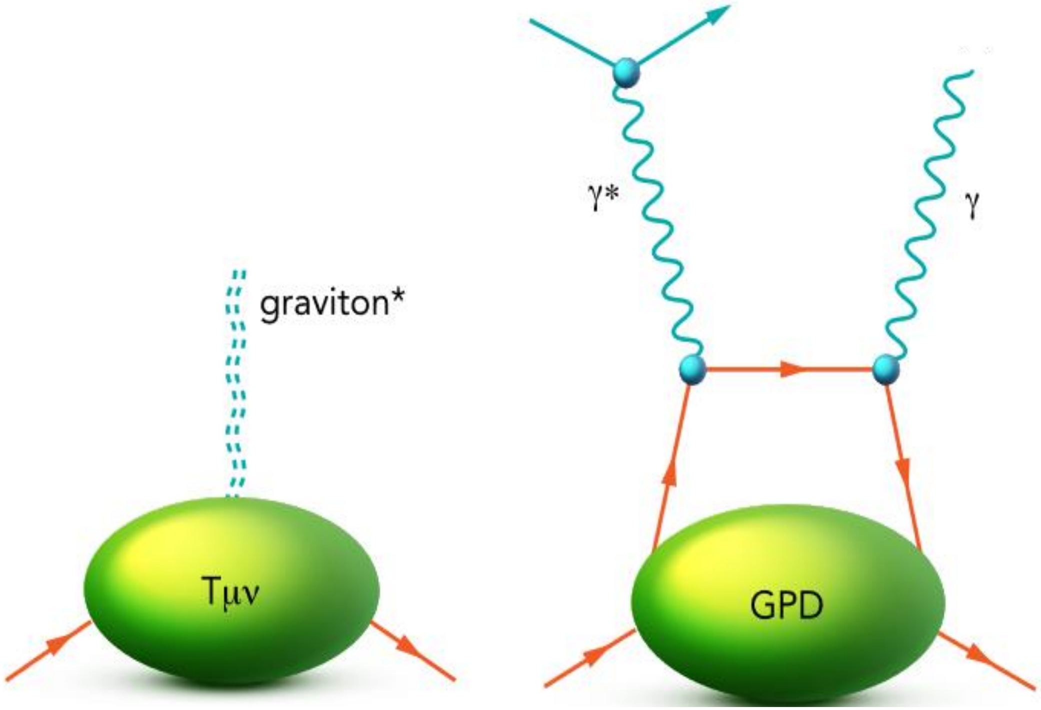
CEBAF Large Acceptance Spectrometer

Probing the Mechanical Properties of the Nucleon

- The mechanical properties of the nucleon are encoded by Gravitational Form Factors (GFFs) which are the elements of the anomalous trace of the energy momentum tensor (EMT) [1].
- The gravitational field of a single nucleon is too weak for direct measurements [1] and graviton-proton scattering is currently inaccessible...
- However, any spin-2 field gives rise to a force indistinguishable from gravity [2], allowing to probe the mechanical structure of the nucleon.
- The quark GFFs have already been estimated in the context of DVCS where the two photon vertices in the handbag diagram of DVCS form a spin-2 system [3,4].



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)

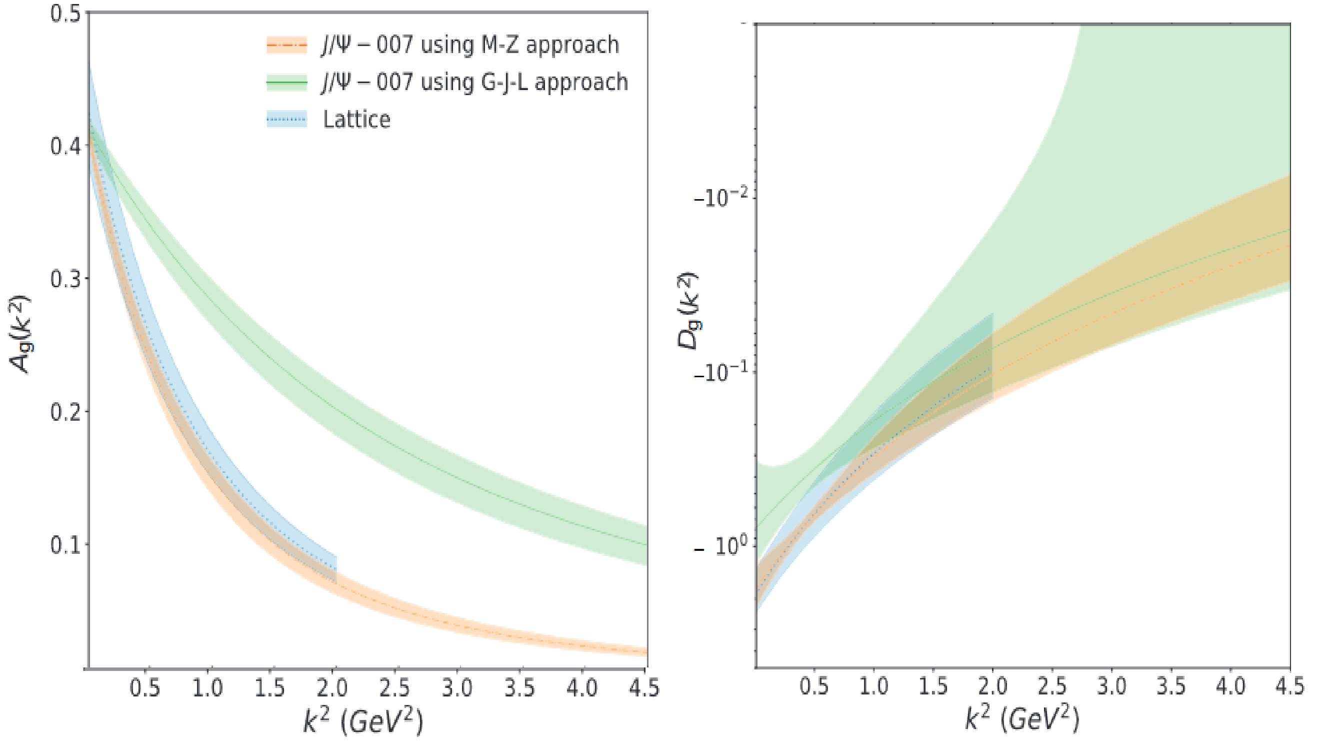
J/ψ Near-Threshold Photoproduction

- A two-gluon exchange as the dominant J/ψ production mechanism forms a spin-2 coupling between J/ψ and the nucleon. This allows to probe the gluonic GFFs.

- Two-gluon exchange models can adequately describe the J/ψ photoproduction total and differential cross section as a function of t [5,6].

- Holographic QCD [7] models also relate the trace anomaly of the EMT to J/ψ photoproduction based on a graviton like exchange [7]. Estimates of the magnitude of the trace anomaly contribution to the nucleon mass were obtained from GlueX data [8,9].

- The $A_g(t)$ and $D_g(t)$ GFFs were estimated at Hall-C for J/ψ photoproduction using holographic QCD, GPD models and compared to lattice QCD predictions [10].



The $A_g(t)$ and $D_g(t)$ GFFs estimated using holographic QCD (orange) and GPD (green) models compared to lattice QCD predictions (blue) [10]. $k^2 \equiv |t|$

[5] L. Frankfurt, M. Strikman, *Phys. Rev. D.* **66**, 031502 (2002).
[6] D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovev, *Nucl.Phys. A* **661** 568 (1999)
[7]Y. Hatta and D.-L. Yang, *Phys. Rev. D* **98** 074003 (2018)
[8] R. Wang, X. Chen, J. Evslin, *Eur. Phys. J. C* **80** 507 (2020)
[9] A. Ali, et. al. (GlueX), Phys. Rev. Lett. 123, 072001 (2019).
[10] B. Duran, et. al. (J/ψ – 007), arXiv:2207.05212 (2022).

Mass Radius of the Nucleon

- A scalar gravitational form factor $G(t)$ gives access to the mass radius of the nucleon [8].

- $G(t)$ can be estimated from the J/ψ differential cross section as a function of t [8]:

$$\frac{d\sigma}{dt} = G(t)^2$$

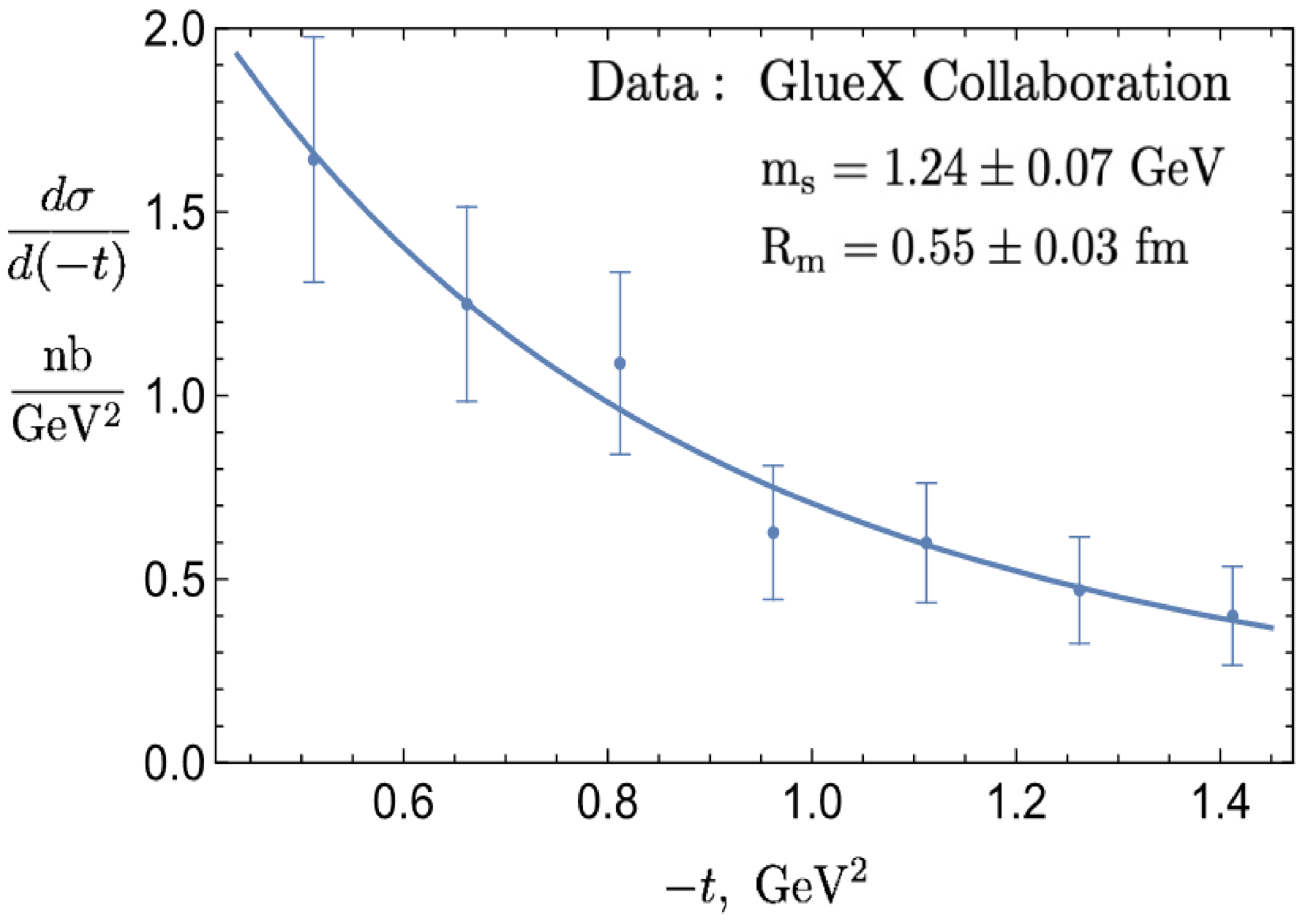
- Assuming a dipole form for $G(t)$:

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

The mass radius r_m is calculated from the free parameter m_s [8]:

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

- Measurements on the proton at Jlab's Hall-C [9] are in good agreement with those from GlueX [8,10] and lattice QCD [12].

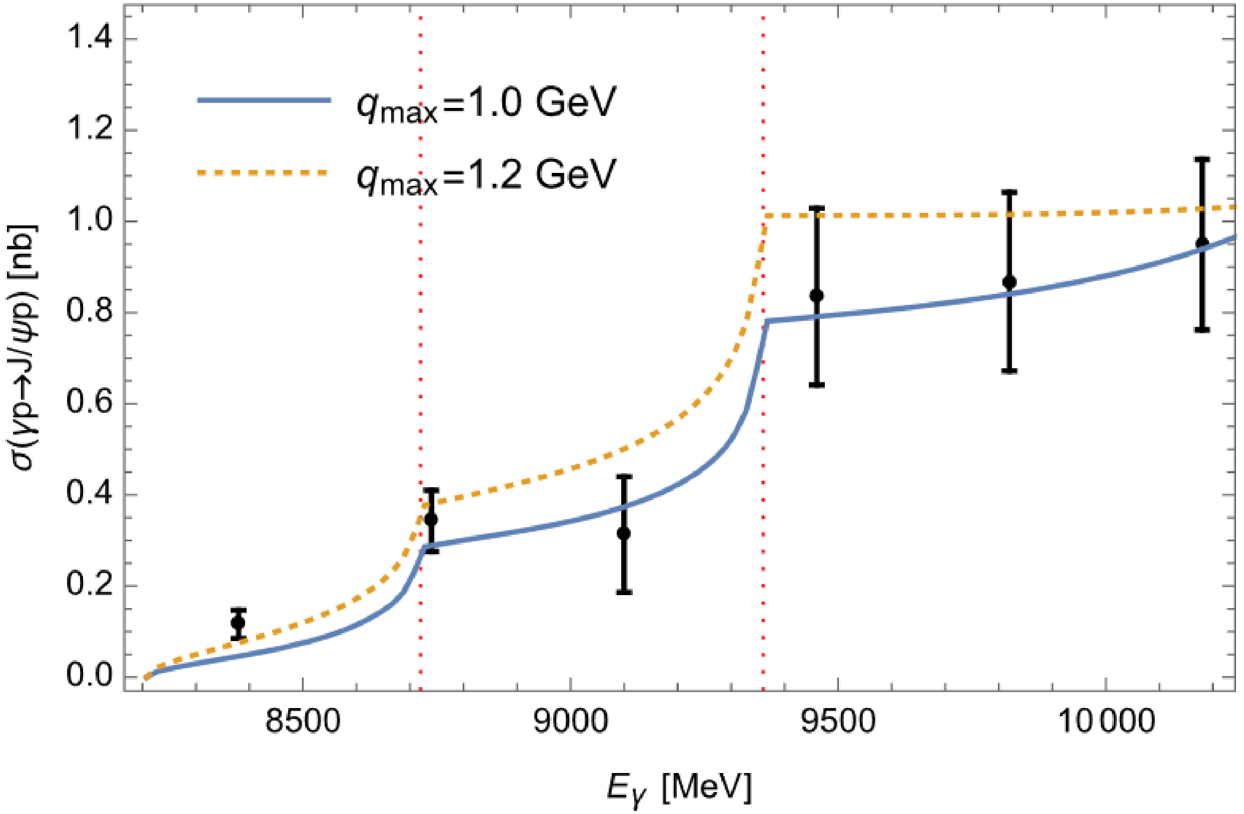


J/ψ differential cross section as a function of –t. Data from the GlueX Collaboration [10], plot taken from [8].

[9] A. Ali, et. al. (GlueX), Phys. Rev. Lett. 123, 072001 (2019).
[10] B. Duran, et. al. (J/ψ – 007), arXiv:2207.05212 (2022).
[11] D.E. Kharzeev, *Phys. Rev. D* **104**, 054015 (2021).
[12] D.A Pefkou, D.C Hackett, P.E Shanahan, *Phys. Rev. D* **105**, 054509 (2022).

Model Dependence

- There are suggestions that J/ψ near-threshold photoproduction could be dominated by open charm production of $\Lambda^c \overline{D}^{(*)}$ [12].
- Estimates of the J/ψ p scattering length favor the open charm models [12].
- Near threshold, the 3-gluon exchange's contribution to the cross section is expected to dominate that of the 2-gluon exchange [13].
- A luminosity upgrade at Jlab would allow to measure the J/ψ SDMEs with enough precision to measure the charge naturality which would allow to distinguish between two or three-gluon exchange and possibly open charm models.



Predictions for the total cross section due to the open charm production of J/ψ p [12], which is consistent with the GlueX measurements [9] in black. Here q_{max} refers to a threshold on Q2.

[9] A. Ali, *et. al.* (GlueX Collaboration), *Phys. Rev. Lett.* **123,** 072001 (2019)
[12] M.-L. Du, V. Baru, F.-K. Guo, C. Hanhart, U.-G. Meißner, A. Nefediev, I.Strakovsky, *Eur. Phys. J. C* **80** 1053 (2020)
[13] S. Brodsky, E. Chudakov, P. Hoyer, J. Laget, Phys. Lett. B. 498, 23 (2001).

J/ψ at CLAS12

- Analysis on Golden Runs of RG-A fall2018 inbending (liquid hydrogen target) and RG-B spring2019 inbending (liquid deuteron target).

- Looked at several different channels:

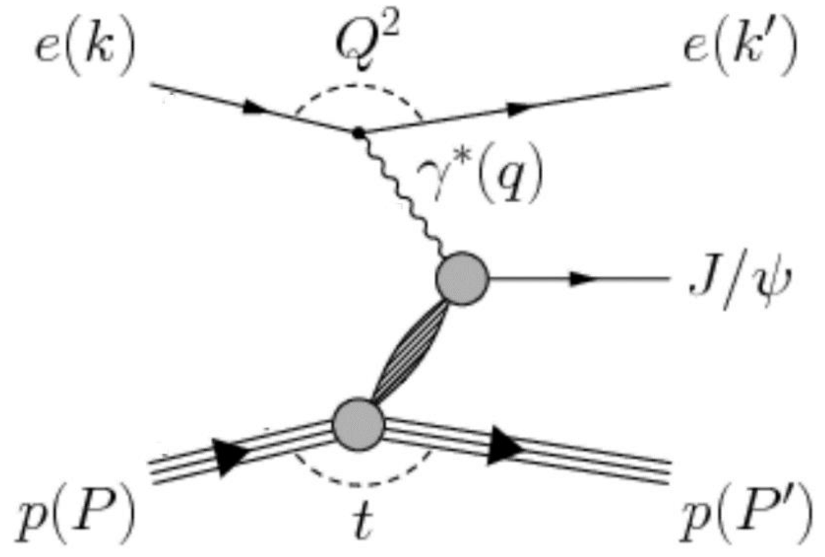
$$ep \to (e')e^+e^-p \text{ (see Pierre's talk)}$$

$$ep \to (e')\mu^+\mu^-p \text{ (RG-A)}$$

$$e\, p_{bound} \to (e')e^+e^-p \text{ (RG-B)}$$

$$e\, n_{bound} \to (e')e^+e^-n \text{ (RG-B)}$$

- CLAS12 will make the first measurement of the mass radius of the bound proton and bound neutron!



J/ψ quasi-real photoproduction on a proton target

Dataset	Accumulated Charge
RG-A fall2018	36.7 mC
RG-B spring2019 (10.6 GeV Beam)	27.0 mC
RG-B spring2019 (10.2 GeV Beam)	39.4 mC

Analysis Procedures

Particle	Detector	PID	Refined PID	Corrections	Other
$e^{\pm}$	FD	Event Builder	ML Based PID	Radiated Photons	N/A
$\mu^{\pm}$	FD	Energy in ECAL	ML Based PID	N/A	N/A
p	FD	Event Builder	N/A	N/A	N/A
n	FD	Charge Only	N/A	Path Length Corrections	Remove Secondary Neutrals

- Cut on missing mass squared and Q^2 to ensure exclusivity and select quasi-real photoproduction events.
- Data analysis based on clas12root and chanser.
- Simulations with clas12-elSpectro and GEMC.

J/ψ Total Cross Section Calculation

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

- $N_{J/\psi}$ is the number of J/ψ in each E_γ bin.
- N_γ is the number of photons.
- ρ_T the target density (ie the number of protons or neutrons per cm^3)
- l_T the target length (5 cm for both LH2, LD2)
- Br is the branching ratio (~6%)
- $\epsilon(E_\gamma)$ is the acceptance in each E_γ bin
- ω_c is an overall normalisation factor

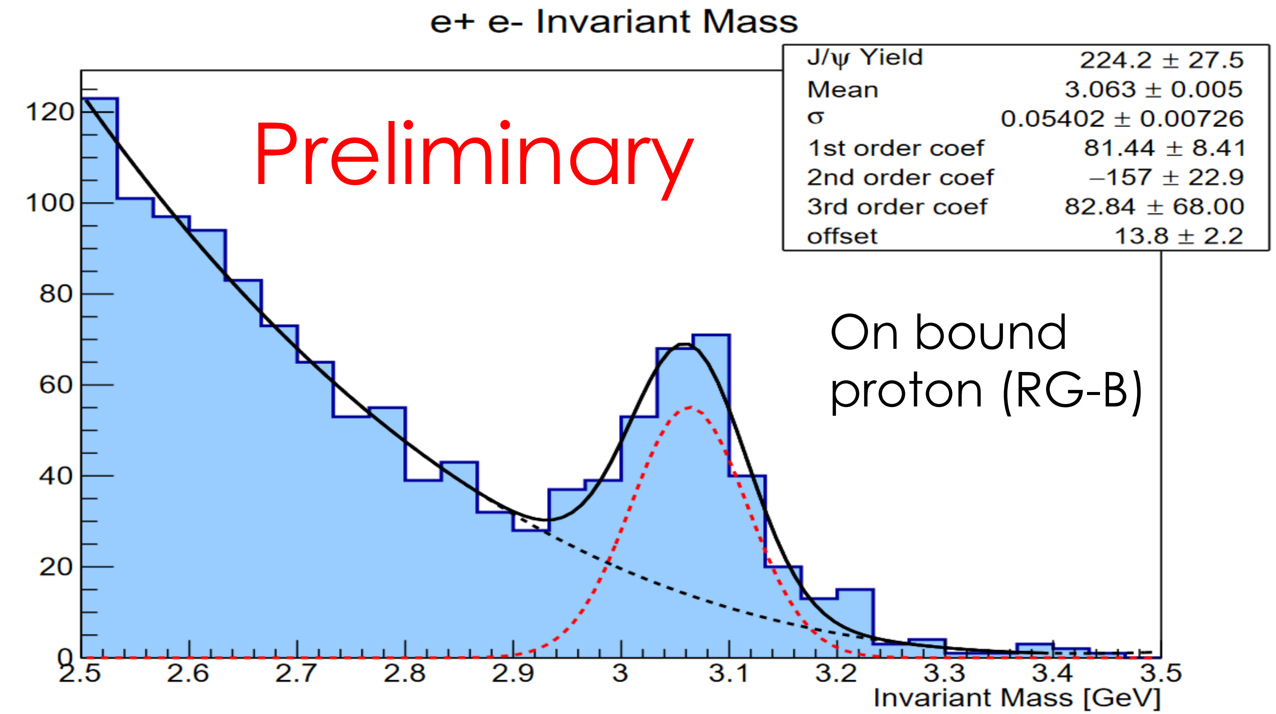
$$N_\gamma = \frac{Q*(F_V+F_R)}{e}$$

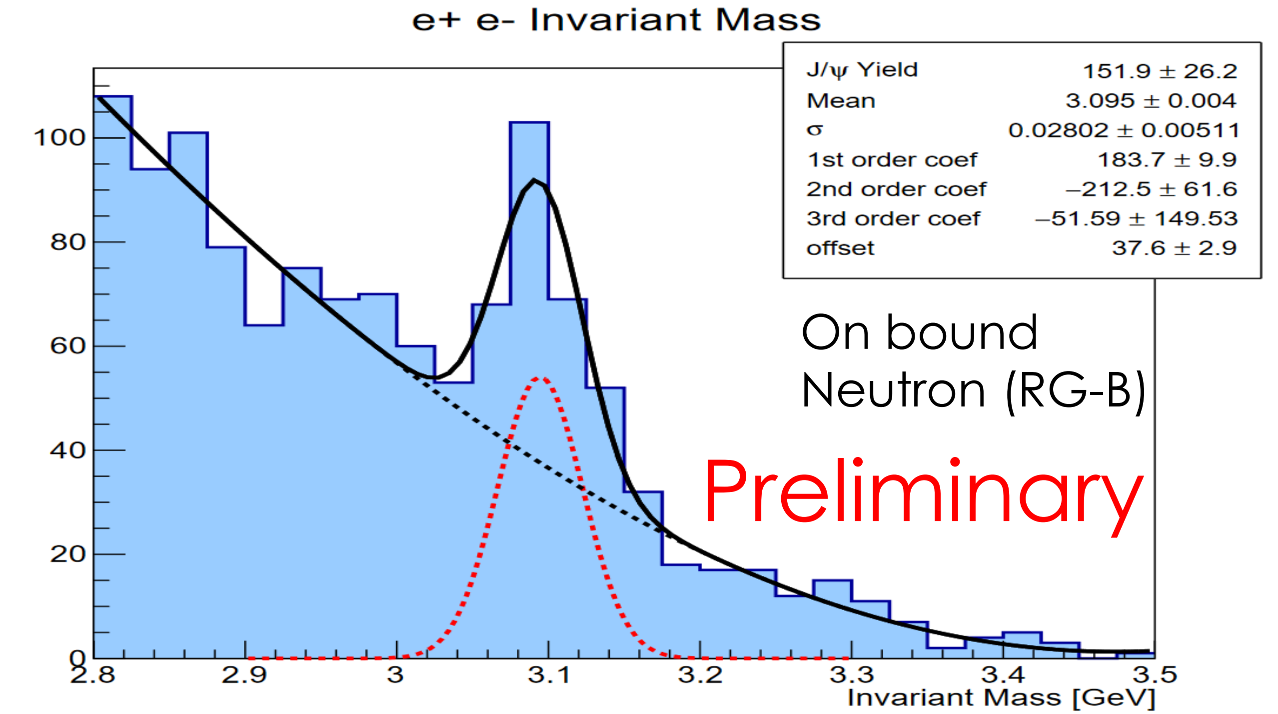
Q the accumulated charge
F_V, F_R the real and virtual photon flux
e the electron charge

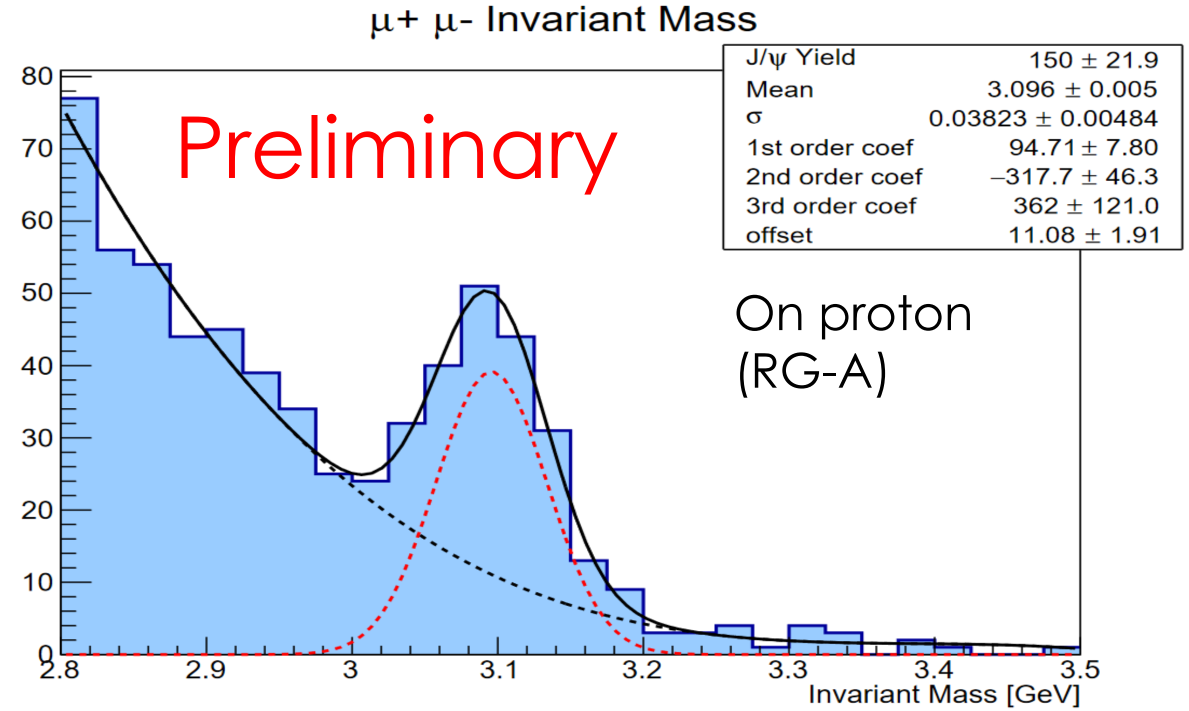
$$\rho_N = N_{neutron}$$

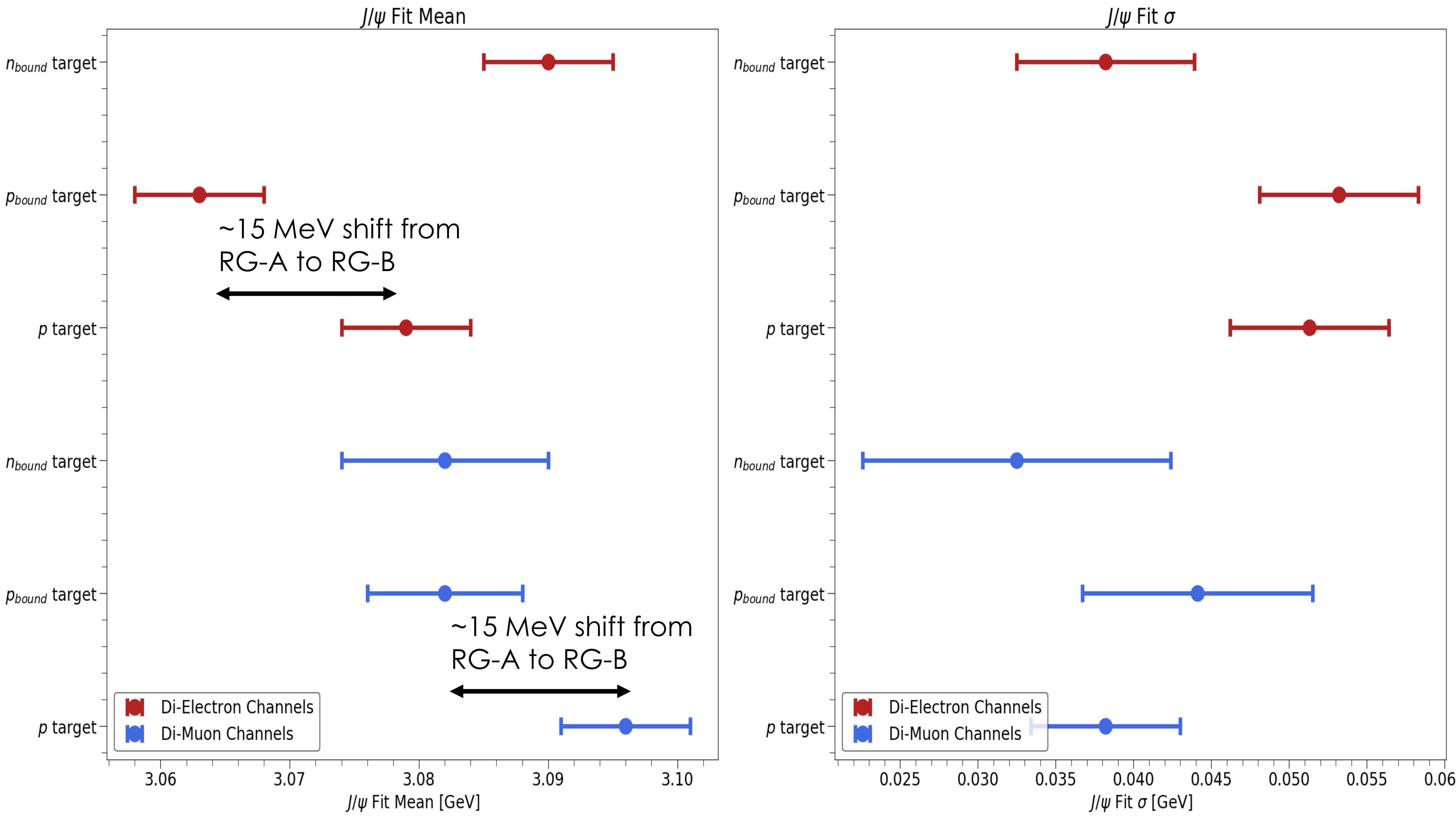
$$\rho_N = \frac{0.163g}{cm^3}\frac{1\,mol}{4.028}\frac{N_A\,D_2}{1\,mol}\frac{2\,neutrons}{1D_2}$$

ρ_N = 4.87e22 per cm^3


e+ e- Invariant Mass
J/ψ Yield 224.2 ± 27.5
Mean 3.063 ± 0.005
σ 0.05402 ± 0.00726
1st order coef 81.44 ± 8.41
2nd order coef −157 ± 22.9
3rd order coef 82.84 ± 68.00
offset 13.8 ± 2.2
Preliminary
On bound proton (RG-B)
Invariant Mass [GeV]


e+ e- Invariant Mass
J/ψ Yield 151.9 ± 26.2
Mean 3.095 ± 0.004
σ 0.02802 ± 0.00511
1st order coef 183.7 ± 9.9
2nd order coef −212.5 ± 61.6
3rd order coef −51.59 ± 149.53
offset 37.6 ± 2.9
On bound Neutron (RG-B)
Preliminary
Invariant Mass [GeV]

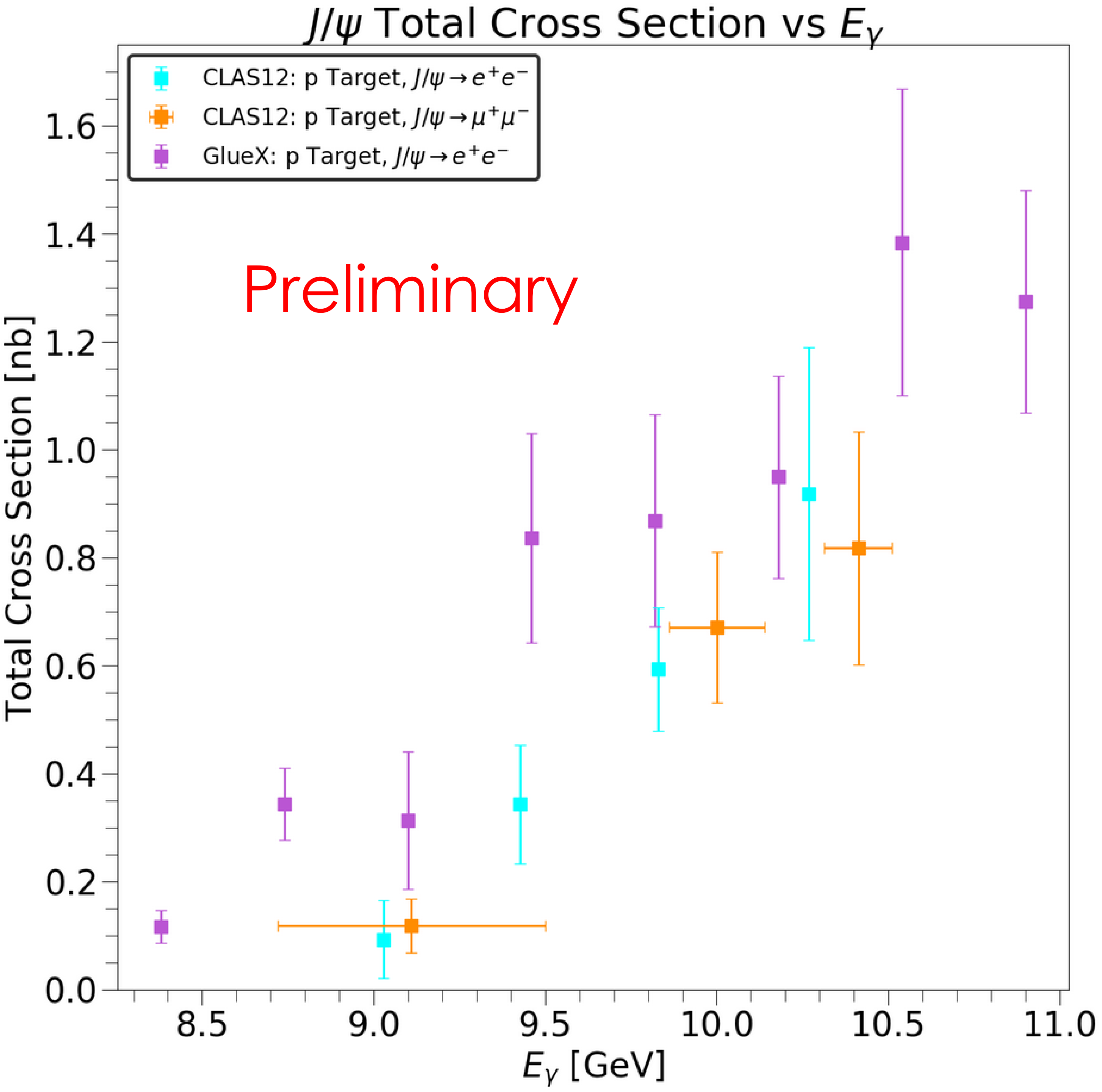

μ+ μ- Invariant Mass
J/ψ Yield 150 ± 21.9
Mean 3.096 ± 0.005
σ 0.03823 ± 0.00484
1st order coef 94.71 ± 7.80
2nd order coef −317.7 ± 46.3
3rd order coef 362 ± 121.0
offset 11.08 ± 1.91
Preliminary
On proton (RG-A)
Invariant Mass [GeV]



J/ψ Fit Mean
J/ψ Fit σ
n_bound target
p_bound target
p target
~15 MeV shift from
RG-A to RG-B
Di-Electron Channels
Di-Muon Channels
3.06
3.07
3.08
3.09
3.10
J/ψ Fit Mean [GeV]
0.025
0.030
0.035
0.040
0.045
0.050
0.055
J/ψ Fit σ [GeV]

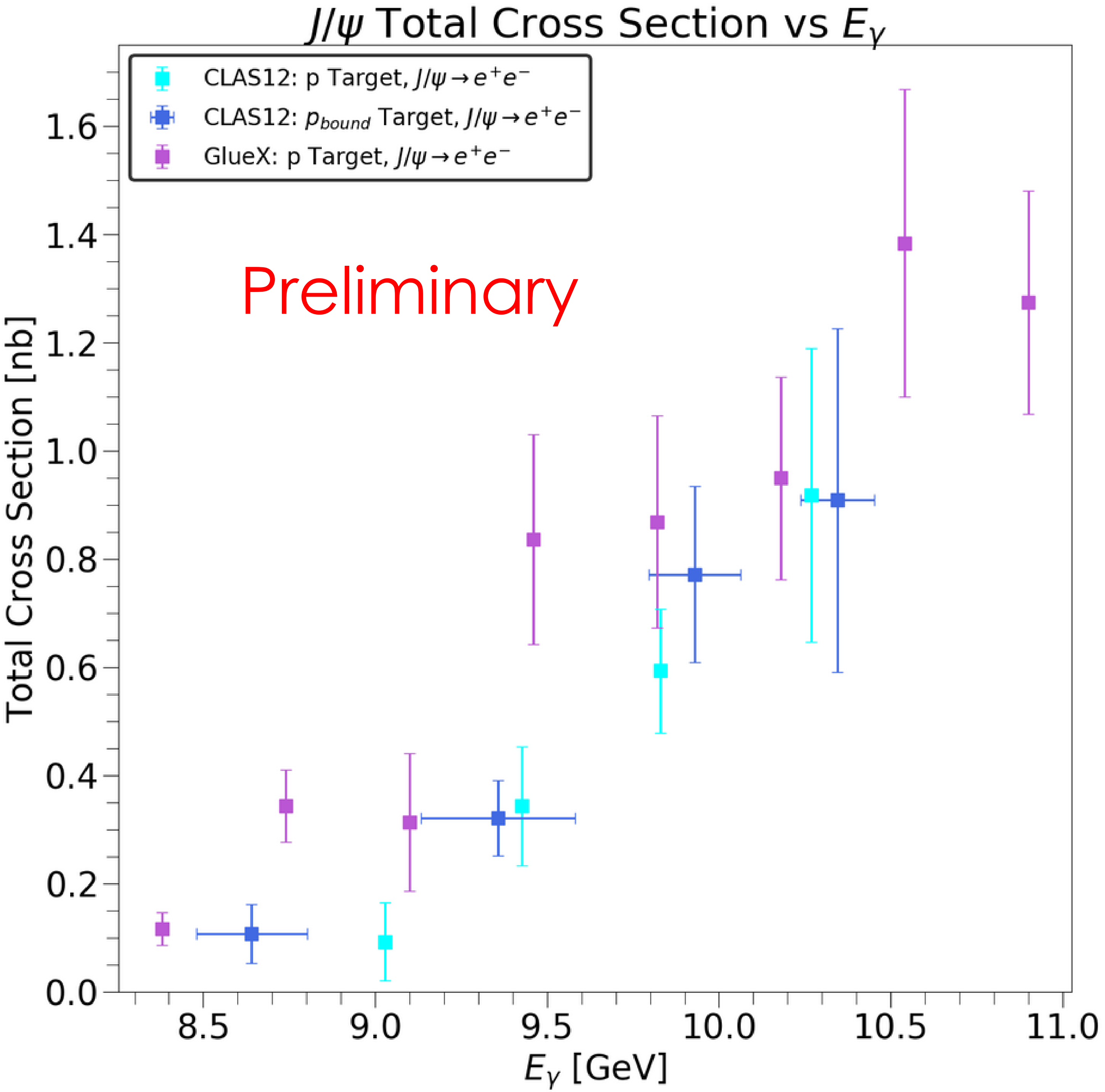
Di-muon cross section

- This is the first analysis which detects muons at CLAS12.
- Demonstrates CLAS12 and ML capabilities for muon physics.
- Good agreement between di-muon and di-electron channels.
- Only show statistical uncertainty here as we haven't seen evidence of systematic effects due to cuts and analysis procedures.



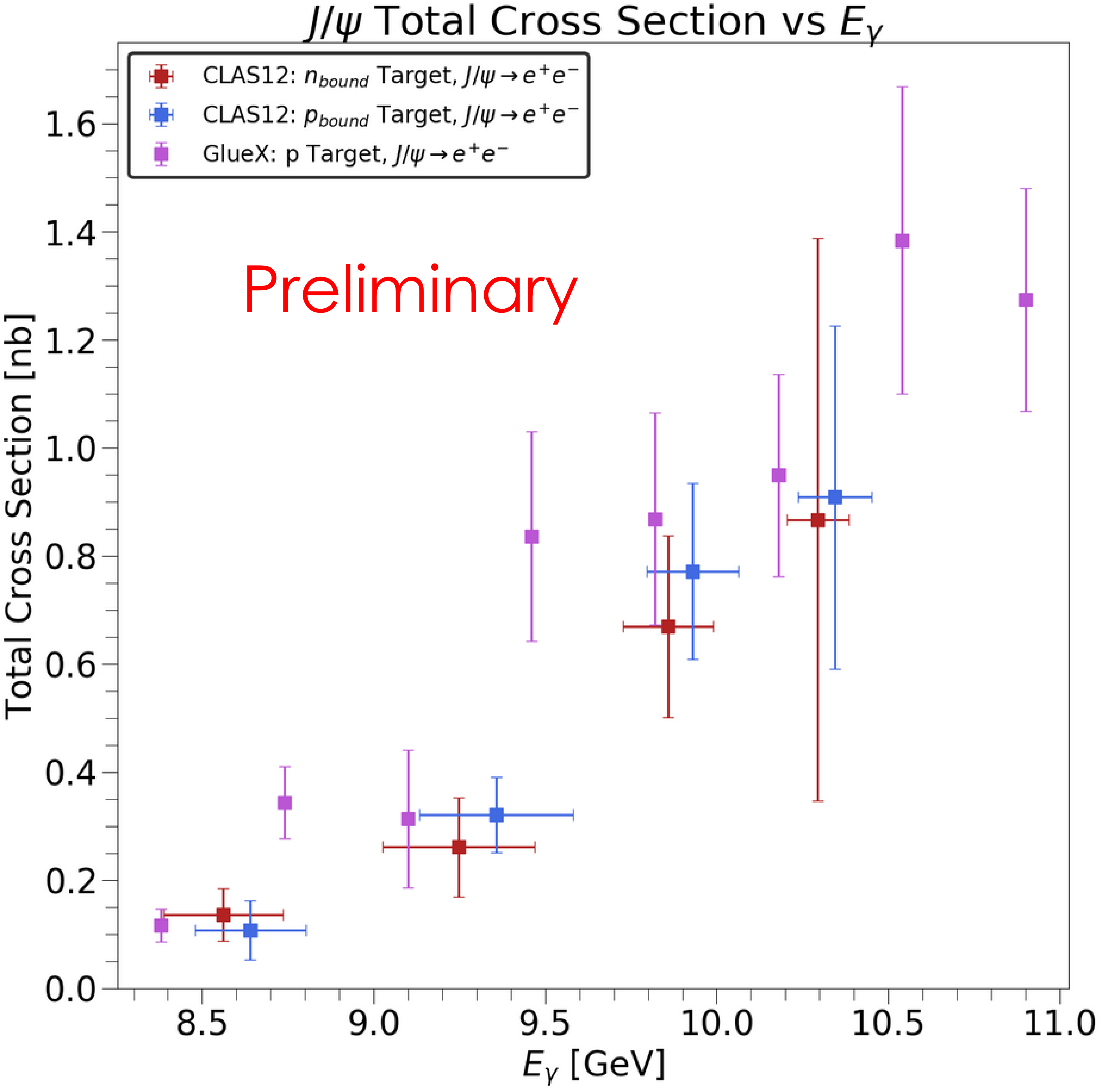
Cross section on bound proton

- First measurement of J/ψ cross section on the bound proton.
- Agreement within the statistical uncertainties of cross section on bound and free proton suggests that we don't have the precision to observe any contributions due to final-state interactions.



Cross section on proton/neutron

- First measurement of J/ψ total cross section on the bound neutron.
- Direct comparison between the bound proton and bound neutron channels.
- Agreement within uncertainty is expected for two- or three-gluon exchange which are isospin invariant.



Differential Cross Section

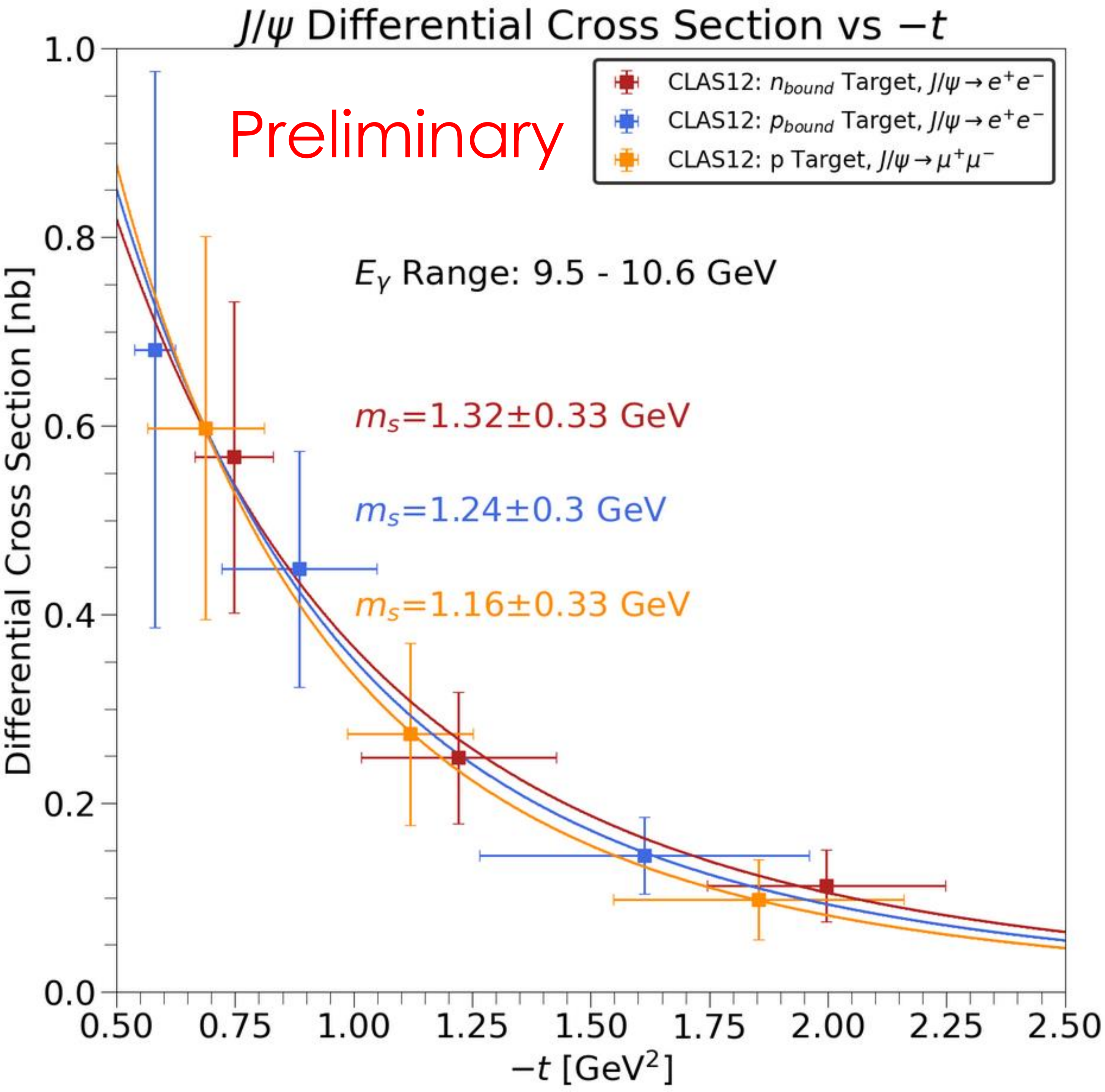
- Fit the differential cross section with:

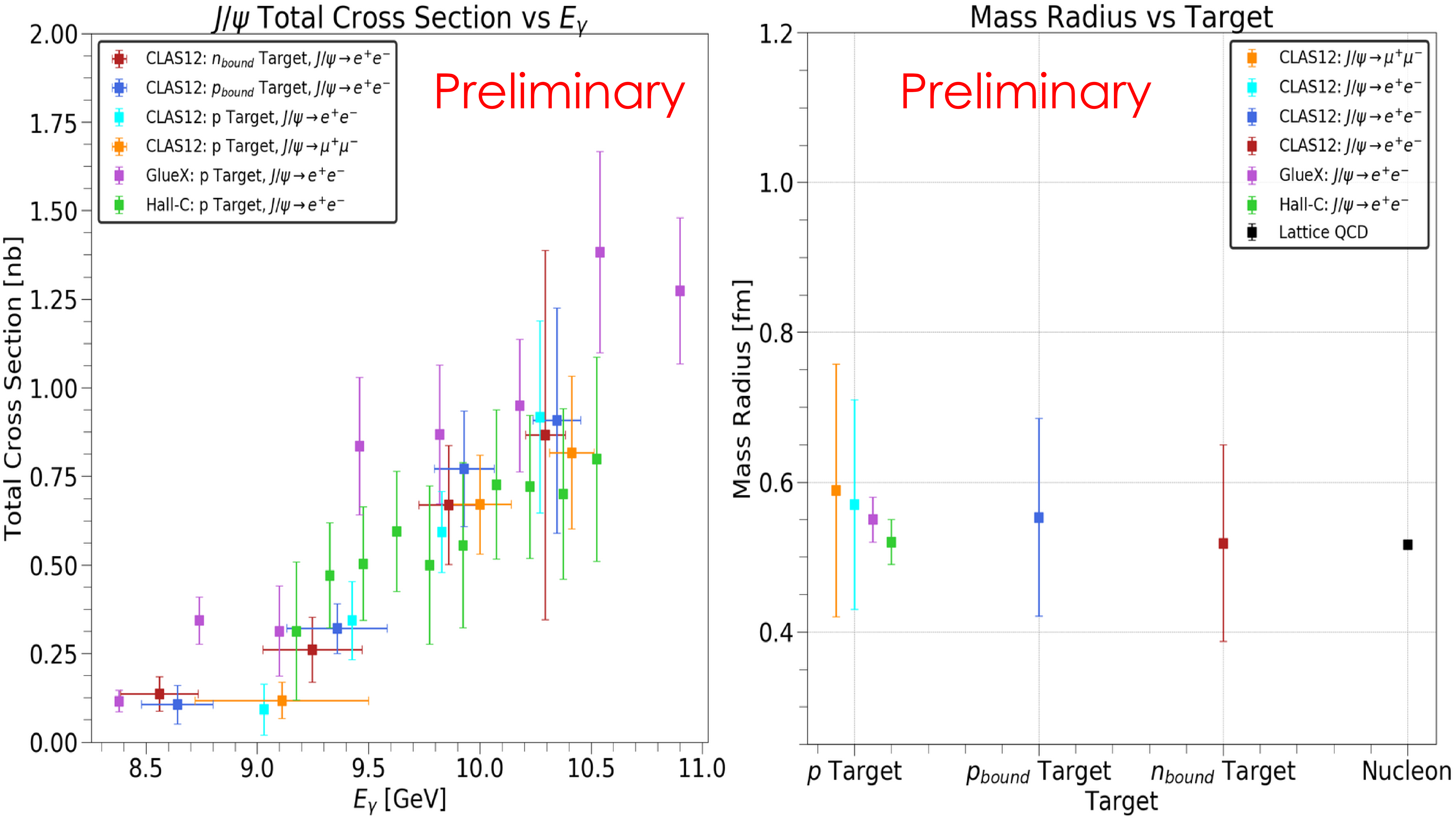
$$f(t) = p_s * \left(\frac{M_p}{(1-\frac{t}{m_s^2})^2}\right)^2$$

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

$$\sigma_{rm} = \sqrt{12}\hbar c \frac{\sigma_{ms}}{m_s^2}$$

Channel	r_m
$ep_{bound} \to (e')e^+e^-p$	0.55± 0.13 fm
$en_{bound} \to (e')e^+e^-n$	0.52± 0.13 fm
$ep \to (e')\mu^+\mu^-p$	0.58 ± 0.17 fm
$ep \to (e')e^+e^-p$ (GlueX)	0.55 ± 0.03 fm

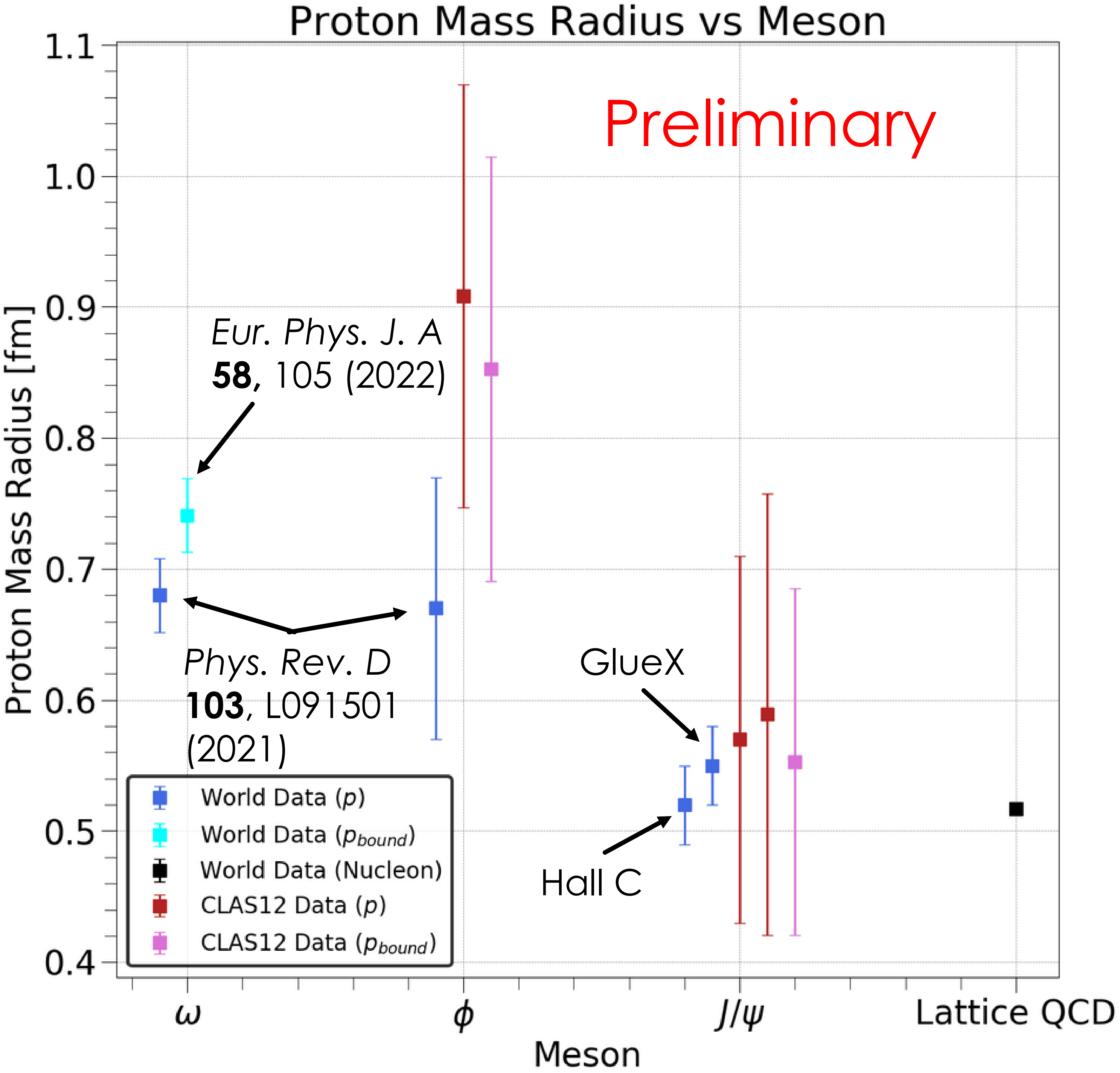




J/ψ Total Cross Section vs Eγ
Total Cross Section [nb]
Eγ [GeV]
CLAS12: n_bound Target, J/ψ → e+e−
CLAS12: p_bound Target, J/ψ → e+e−
CLAS12: p Target, J/ψ → e+e−
CLAS12: p Target, J/ψ → μ+μ−
GlueX: p Target, J/ψ → e+e−
Hall-C: p Target, J/ψ → e+e−
Preliminary
Mass Radius vs Target
Mass Radius [fm]
Target
p Target
p_bound Target
n_bound Target
Nucleon
CLAS12: J/ψ → μ+μ−
CLAS12: J/ψ → e+e−
CLAS12: J/ψ → e+e−
CLAS12: J/ψ → e+e−
GlueX: J/ψ → e+e−
Hall-C: J/ψ → e+e−
Lattice QCD
Preliminary

Mass Radius from ω & φ

- There's some suggestion in literature that the mass radius could be measured from ω & φ photoproduction.
- We made some very preliminary measurements in the φ decay to e^+e^-.
- Differences of the mass radius when measured from J/ψ and lighter vector mesons are attributed to the effect of the larger mass of the color dipole.
- Differences between the radius of the bound/free proton from ω are attributed to the nucleon swelling interpretation of the EMC effect.



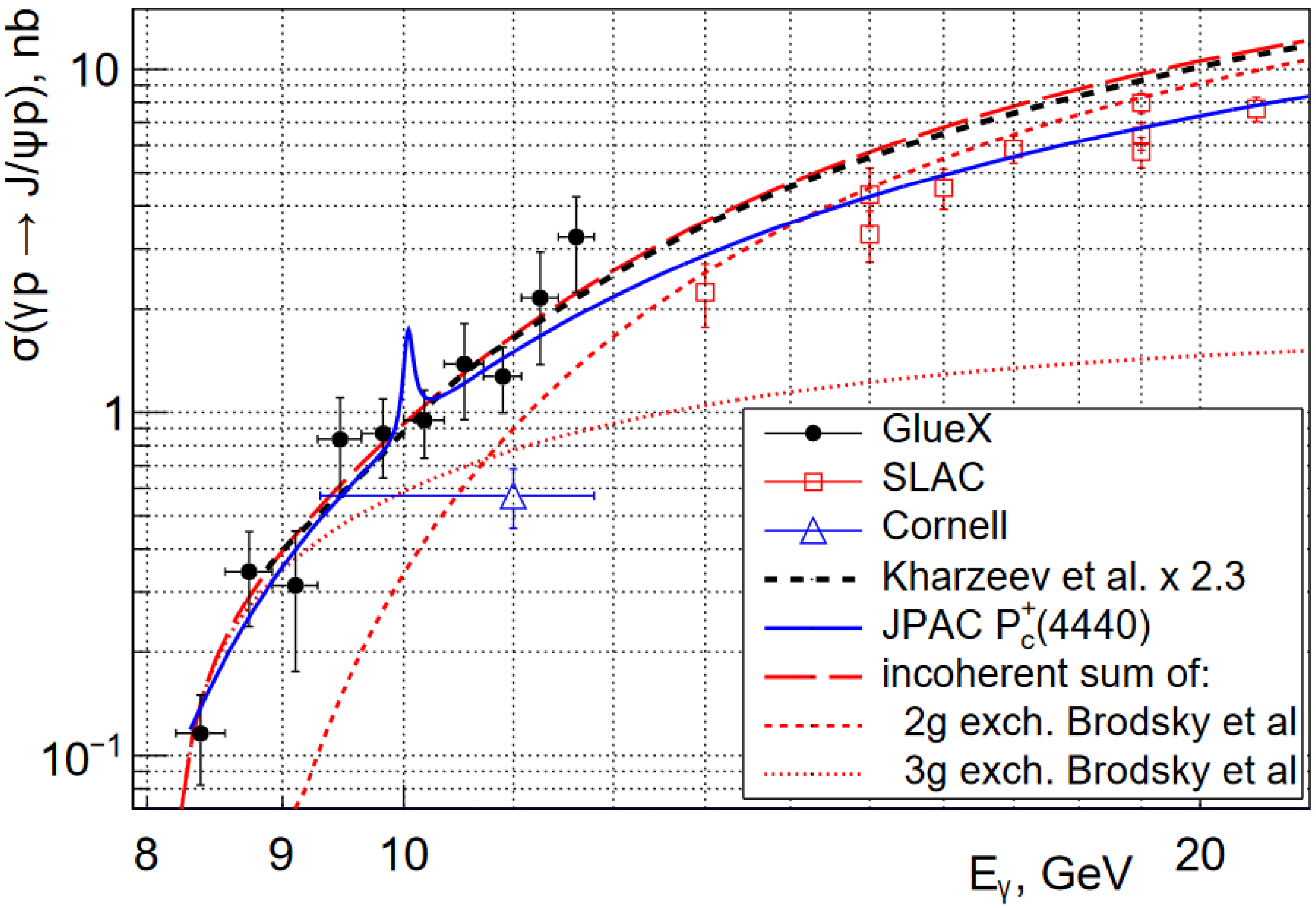
Conclusion

- The mechanical properties of the nucleon can be probed using near-threshold J/ψ photoproduction. Along with DVCS, J/ψ photoproduction offers an exciting new direction for hadronic physics.
- CLAS12 has made a first measurement directly comparing the J/ψ photoproduction cross sections on the bound proton and bound neutron. This constitutes a first measurement of the mass radius of the bound neutron and bound proton.
- At present our results have large statistical uncertainties. AI based improvements in the tracking reconstruction show an average 40% increase in efficiency for 3 charged particles.
- Some work left to understand why the J/ψ fit mean and sigma are different when J/ψ is produced on the bound proton or neutron and decays to an electron/positron pair.
- 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.

Backup Slides

Two or Three-Gluon Exchange?

- Near threshold, the 3-gluon exchange's contribution to the cross section is expected to dominate that of the 2-gluon exchange [13].
- A luminosity upgrade at Jlab would allow to measure the J/ψ SDMEs with enough precision to measure the charge naturality which would allow to distinguish between two or three-gluon exchange.



Measurements of the J/ψ total cross section as a function of the photon beam energy and theoretical predictions scaled to GlueX data [10].

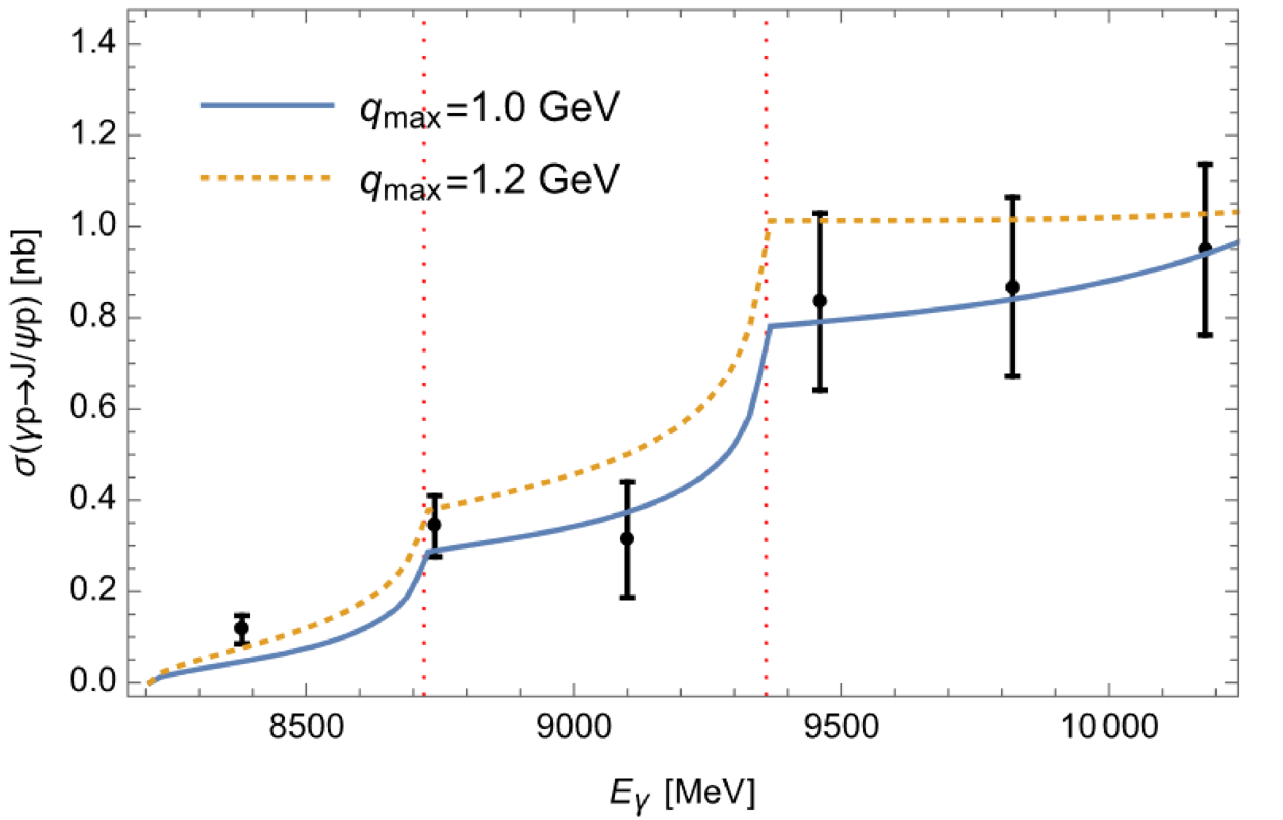
[10] A. Ali, *et. al.* (GlueX Collaboration), *Phys. Rev. Lett.* **123,** 072001 (2019).
[13] S. Brodsky, E. Chudakov, P. Hoyer, J. Laget, *Phys. Lett. B.* **498**, 23 (2001).

Open-Charm Photoproduction?

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

- The most straightforward path to rule out open charm photoproduction would be to rule out the distinct cusp like structure of the cross section.

- At present we don't have the statistical precision to do so.



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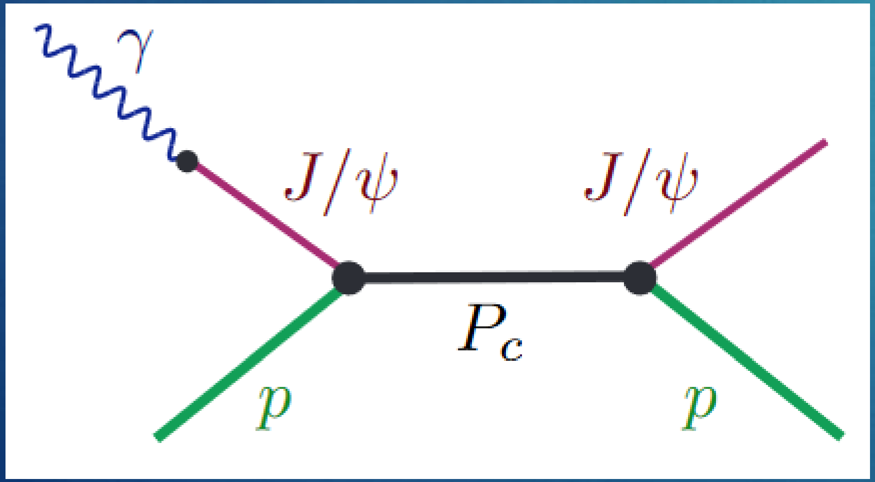
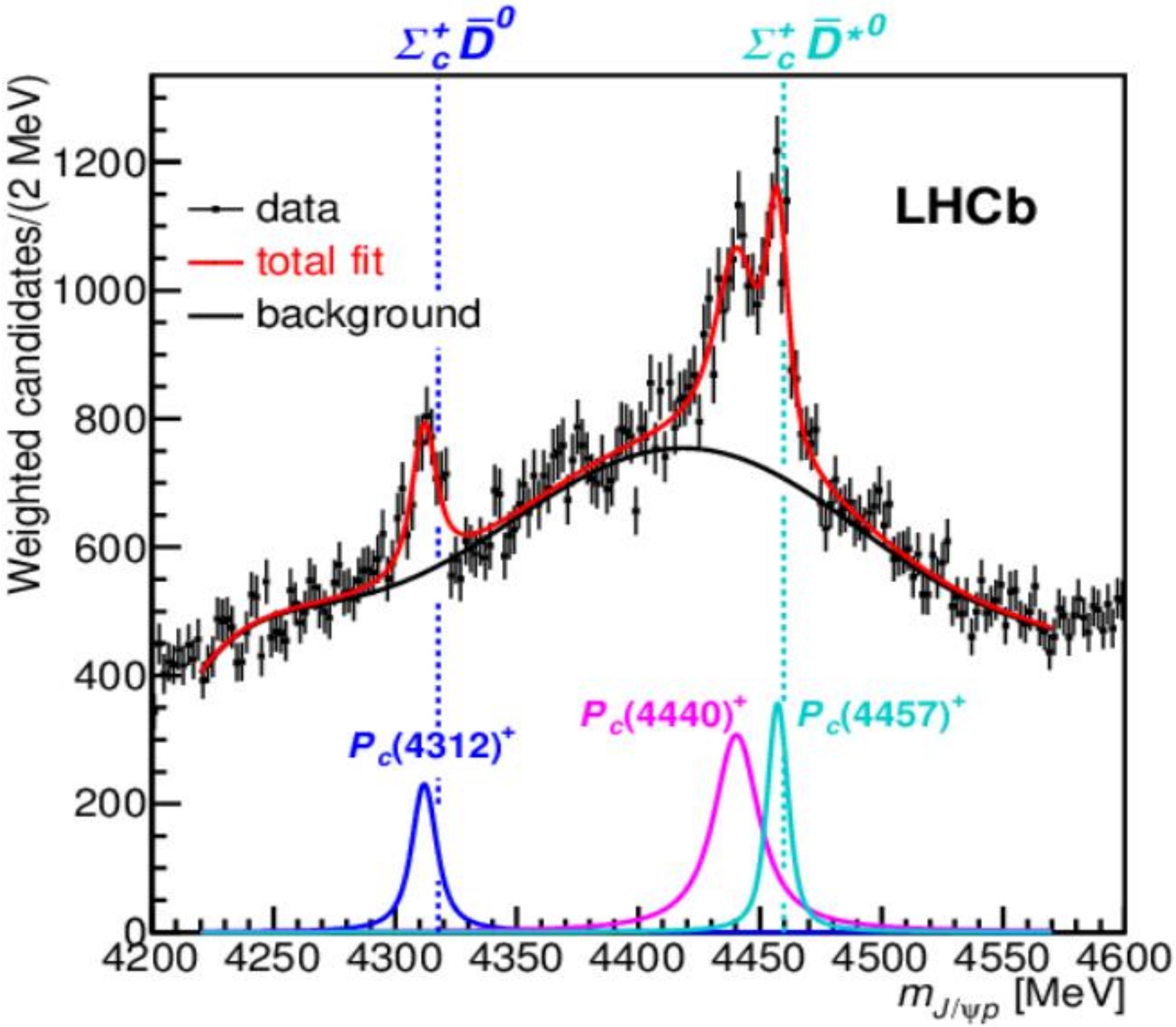
P_c^+ resonances with CLAS12

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



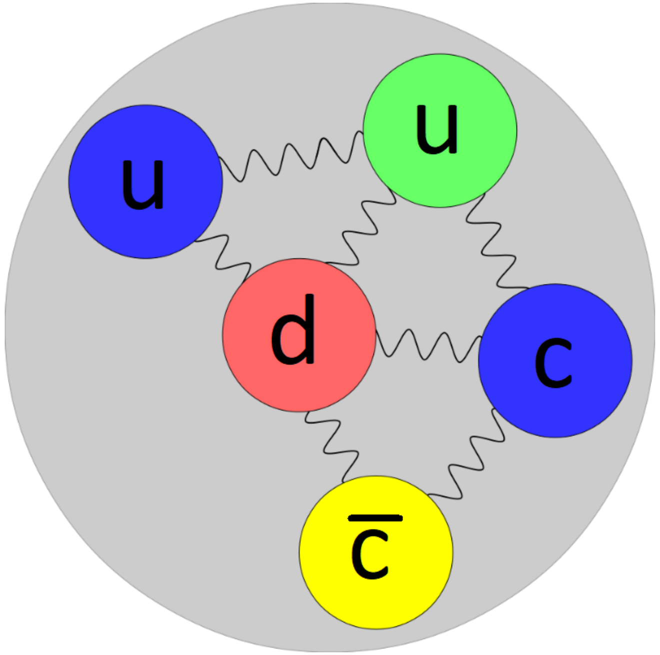


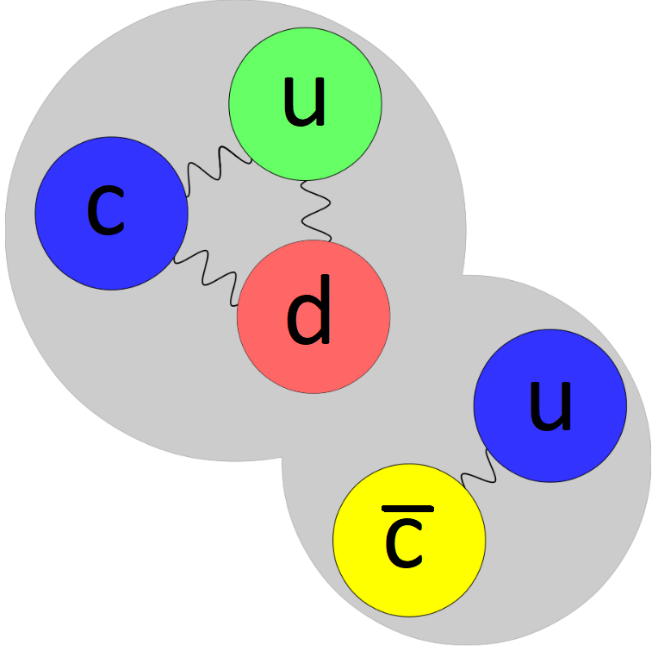
The J/ψ p invariant mass distribution measured at the LHCb. Taken from:

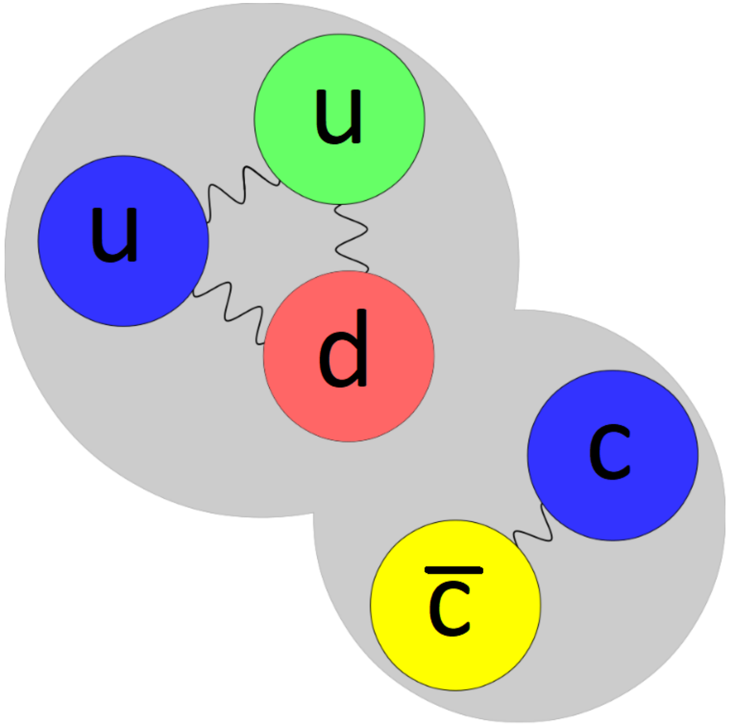
R. Aaij, *et. al.* (LHCb Collaboration), *Phys. Rev. Lett.* **122**, 22 (2019).

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.







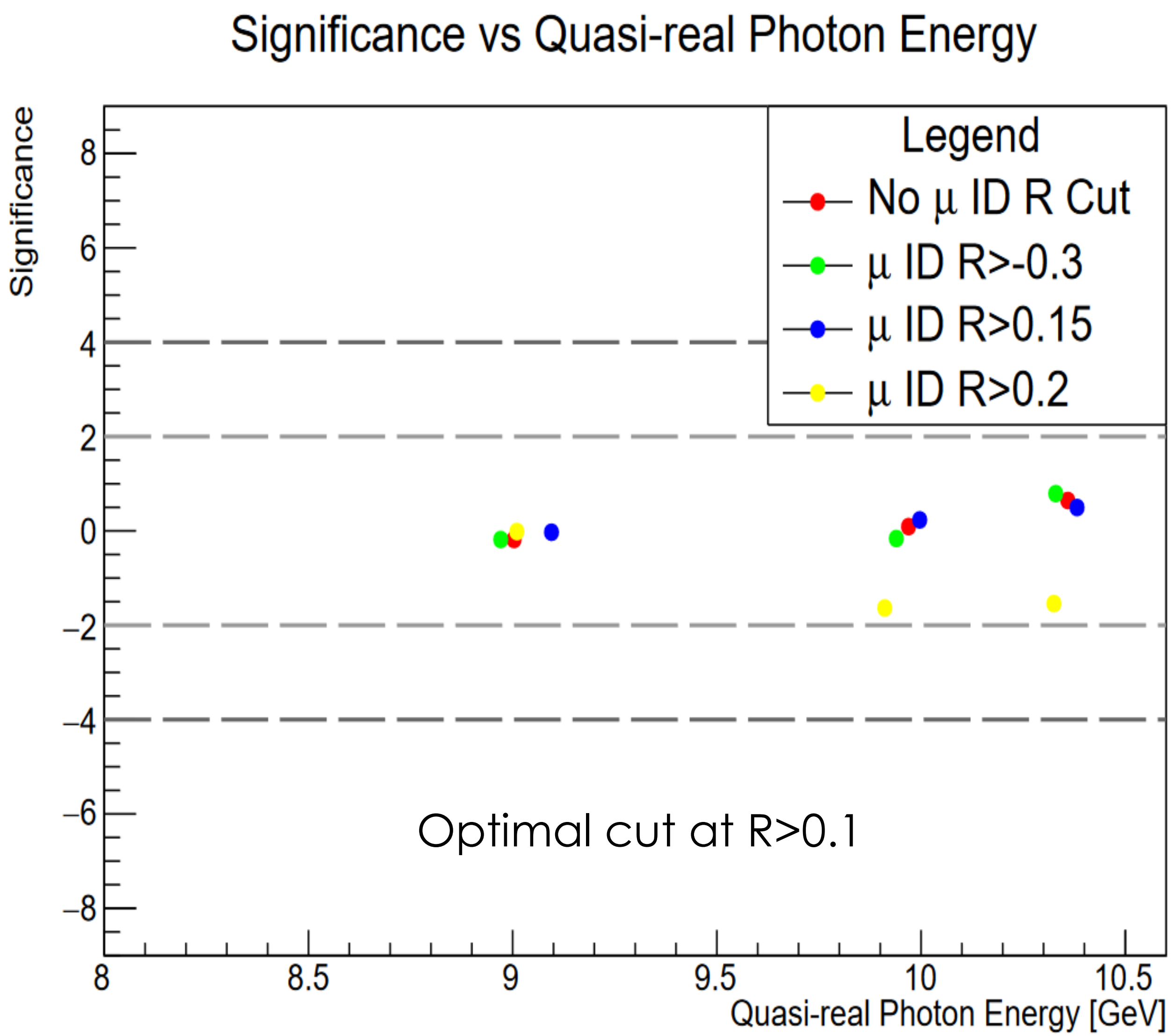
Systematics

- Define a systematic effect as deviations in results outwith statistical or counting effects due to some aspect of the measurement or analysis.

- Barlow Significance:
-
$$S = \frac{\rho_n - \rho_f}{\sqrt{|\sigma_f^2 - \sigma_n^2|}}$$

- If significance is:
  - S<2, no evidence of a systematic effect
  - 2<S<4, no evidence of a systematic effect if this a one off
  - S>4, evidence of systematic effect

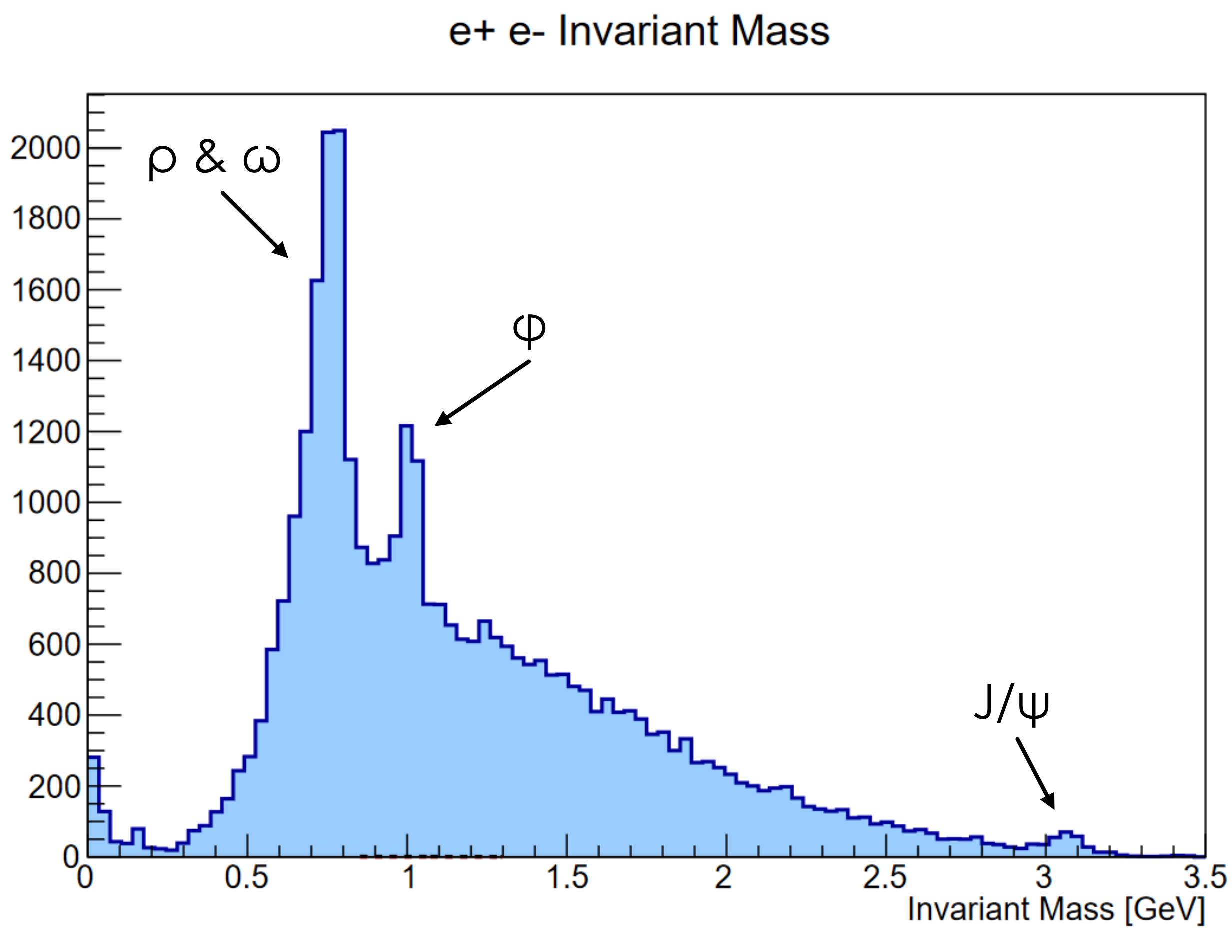
- No systematic effects were identified in the analysis.



Evaluating the significance of the machine learning based muon ID

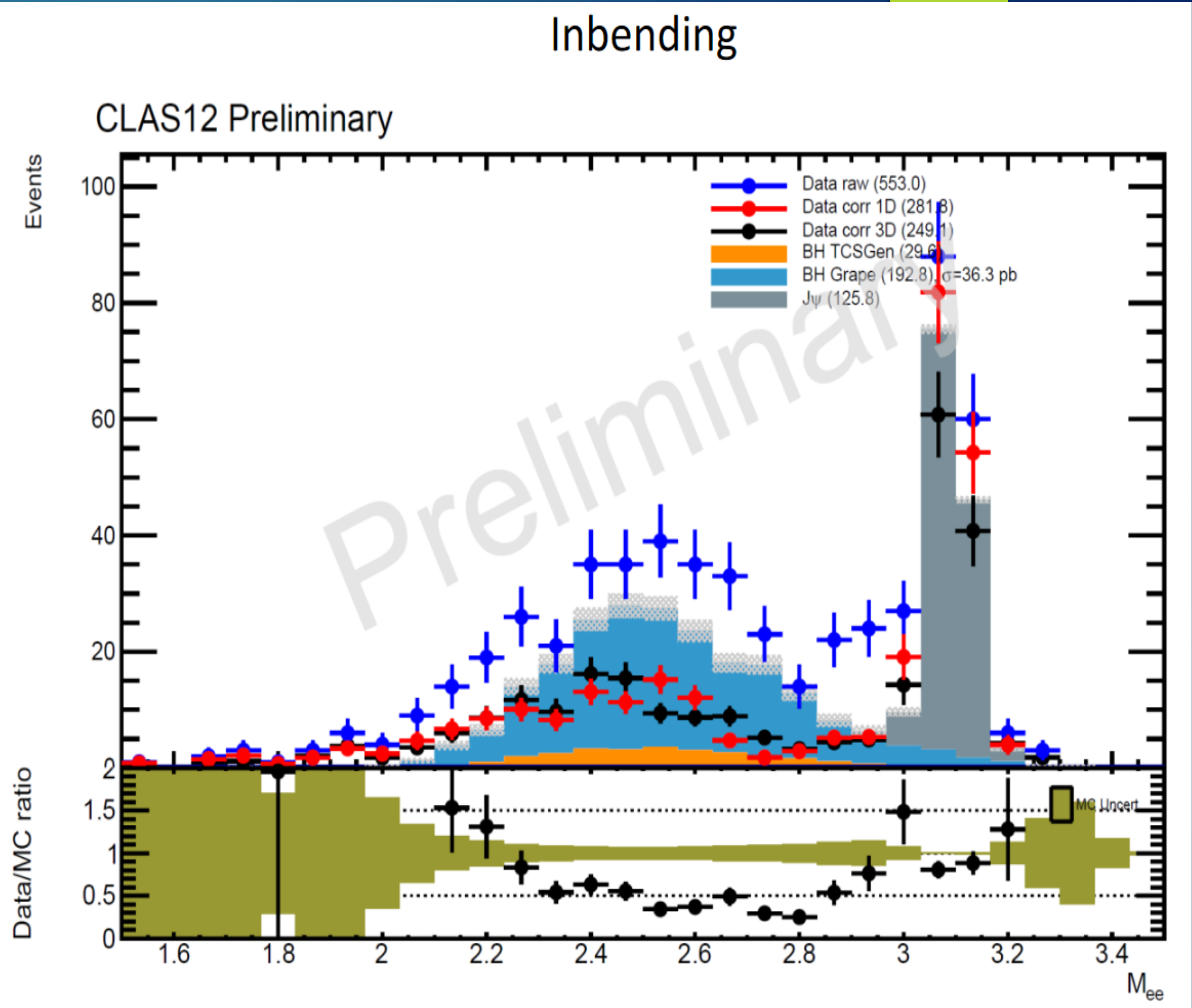
ρ, ω and φ mesons

- 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.



Bethe Heitler Normalisation

- Pierre has extracted a normalization factor based on the known Bethe Heitler cross section.
- This corrects for errors in the acceptance and flux calculations
- Initially background was too high for this. However, we can use channels with two same charge lepton (e+e+ or e-e-) pairs to estimate the background rate and apply a correction.
- This was done for J/ψ produced on a hydrogen target, decaying to an electron/positron pair



Effect of ω_c on J/ψ Total Cross Section

- The CLAS12 results are taken from the RG-B analysis of J/ψ produced on the bound proton, decaying to an electron/positron pair.
- Here we're comparing different normalisations:
  - ω_c=1
  - ω_c=0.388
- Pierre has also calculated a normalization term per E_γ bin.