Jefferson Lab
Exploring the Nature of Matter

J/ψ Near-Threshold Photoproduction at JLab

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clas
CEBAF Large Acceptance Spectrometer

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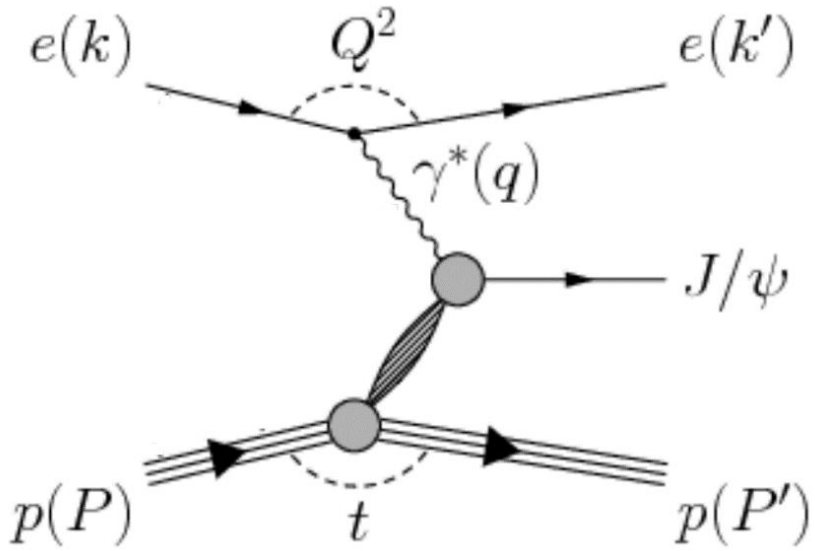
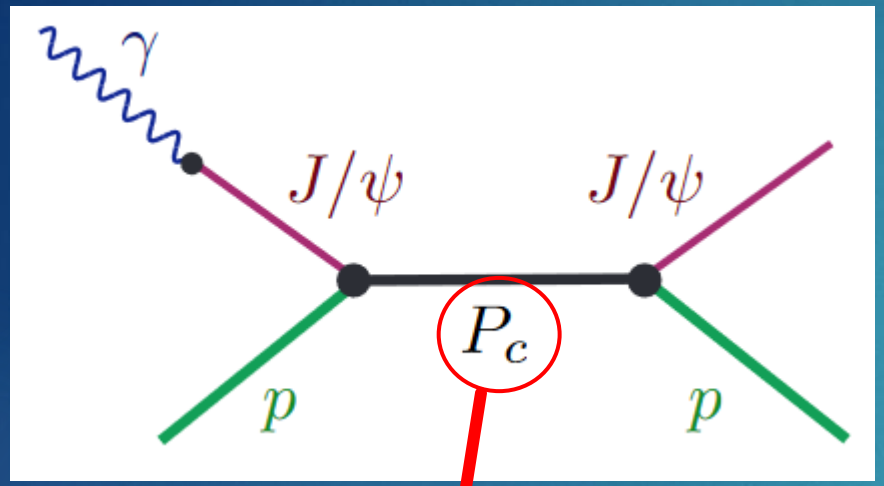
J/ψ Near-Threshold Photoproduction

- The experiments at JLab proceed either through quasi-real or real J/ψ photoproduction.
- J/ψ is produced on a fixed target, simplified to a single nucleon.
- J/ψ then decays to a di-lepton pair, either e^-e^+ or $\mu^-\mu^+$.
- JLab at 12 GeV operates close to the 8.2 GeV J/ψ production threshold.

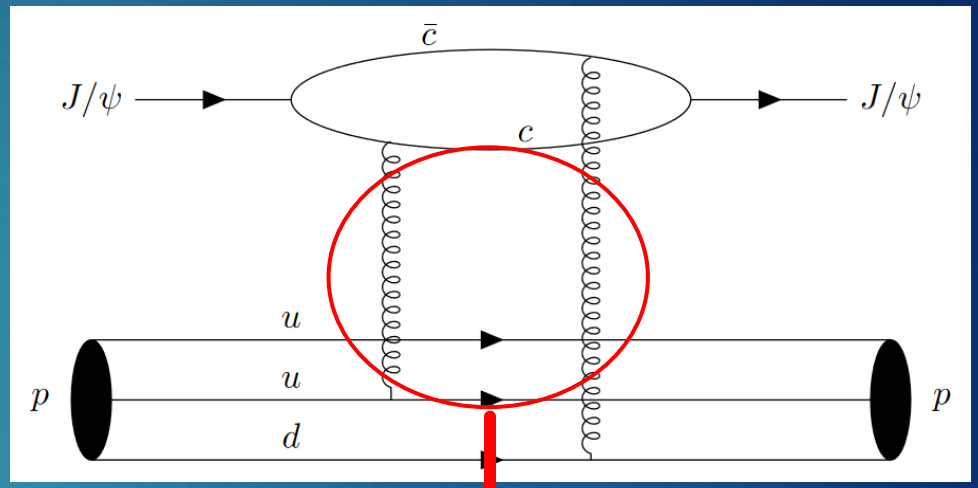


J/ψ quasi-real photoproduction on a proton target

J/ψ Near-Threshold Photoproduction



The P_c^+ pentaquark candidates identified at the LHCb can be studied at JLab.



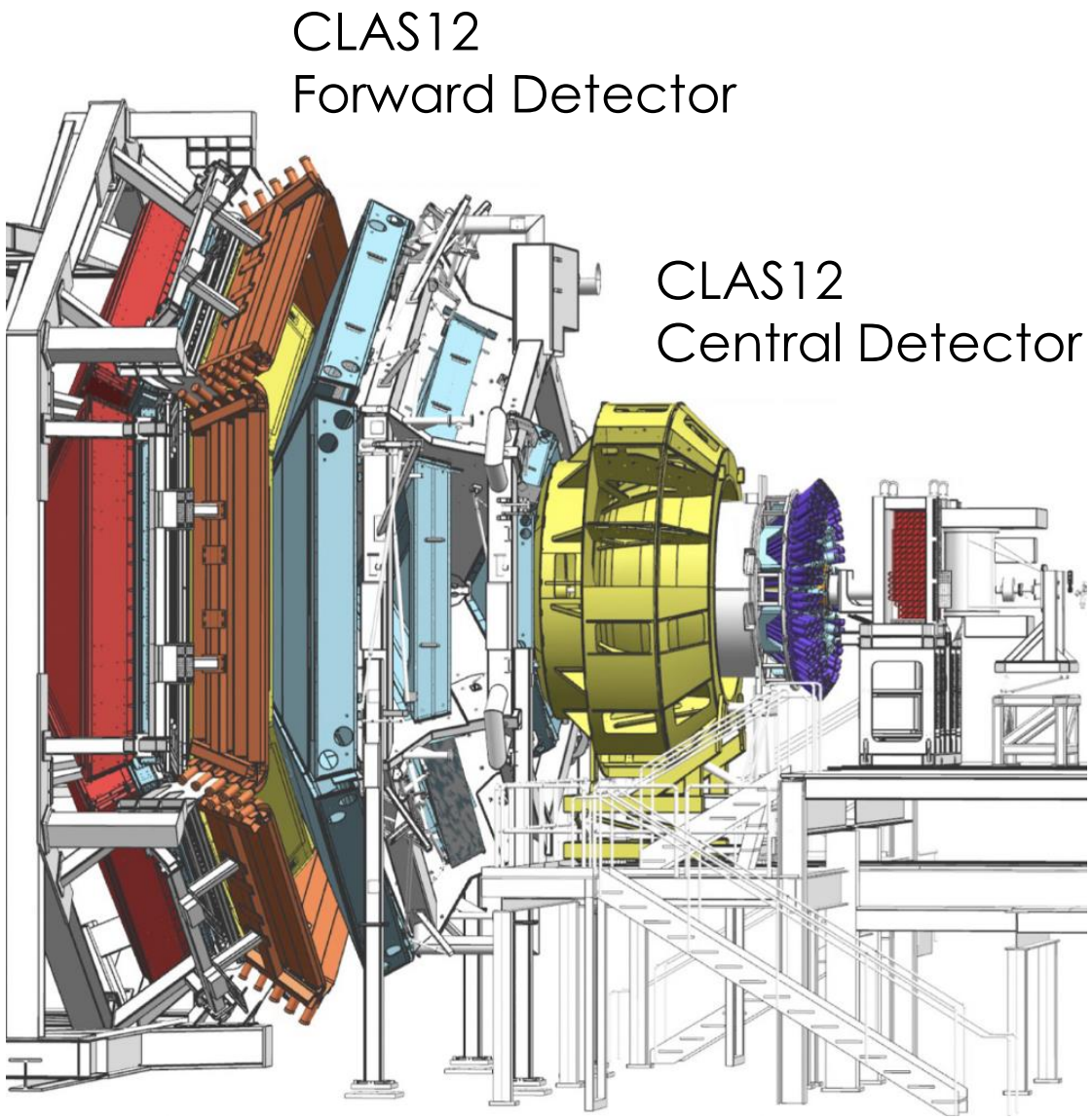
Two-gluon exchange production mechanisms allow to probe the mechanical properties of the nucleon.

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.



J/ψ at CLAS12

- CLAS12 took data with a liquid hydrogen target and a liquid deuteron target.
- Looked at several different channels:

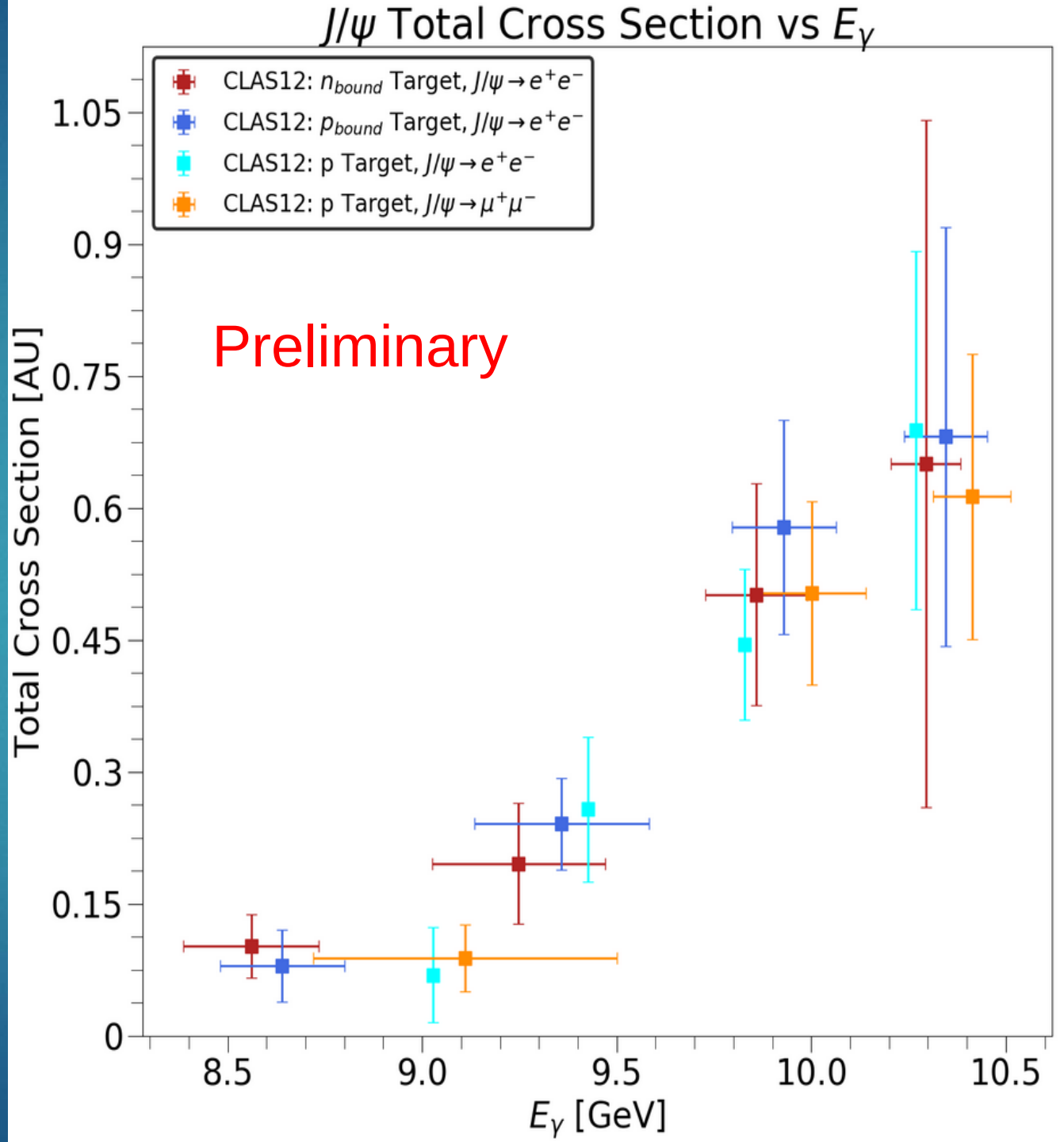
$$ep \rightarrow (e')e^+e^-p$$

$$ep \rightarrow (e')\mu^+\mu^-p$$

$$e\,p_{bound} \rightarrow (e')e^+e^-p$$

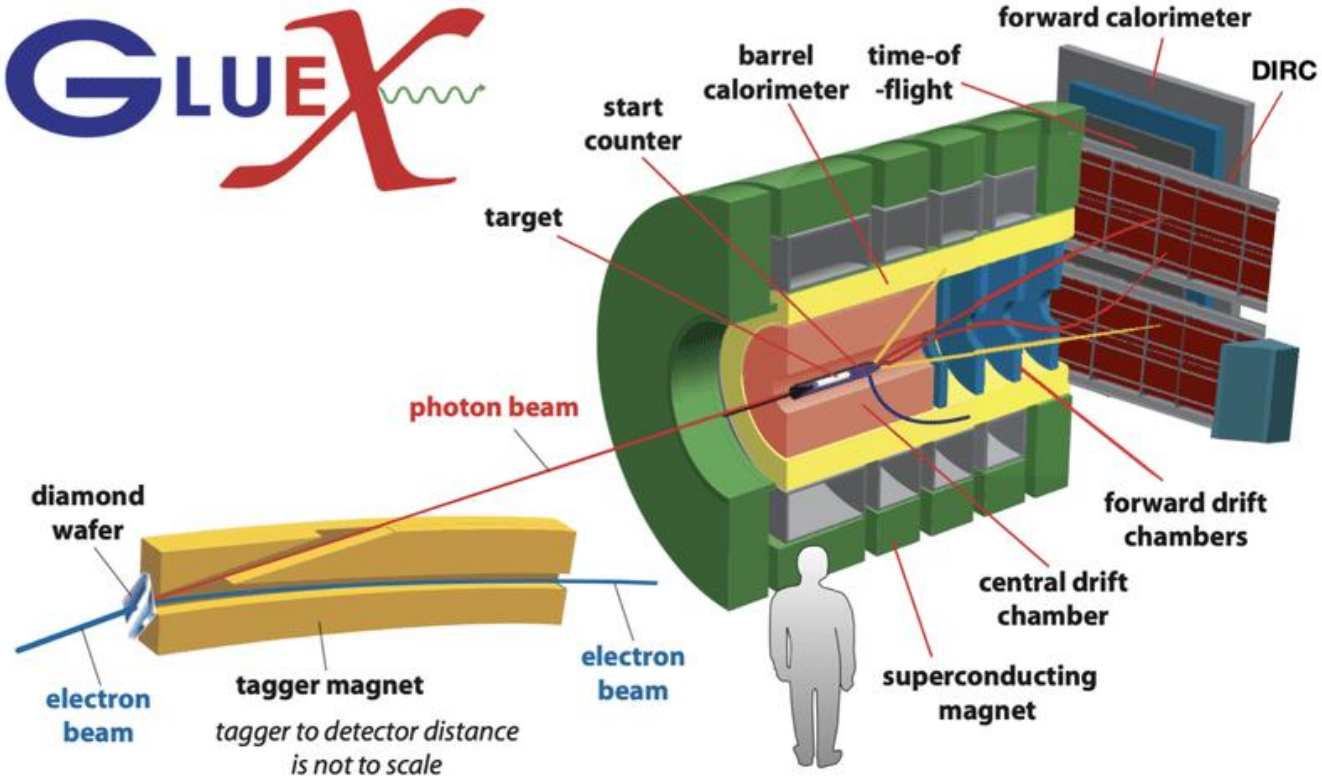
$$e\,n_{bound} \rightarrow (e')e^+e^-n$$

- CLAS12 will make the first measurements of the J/ψ photoproduction cross sections on the bound proton and bound neutron.



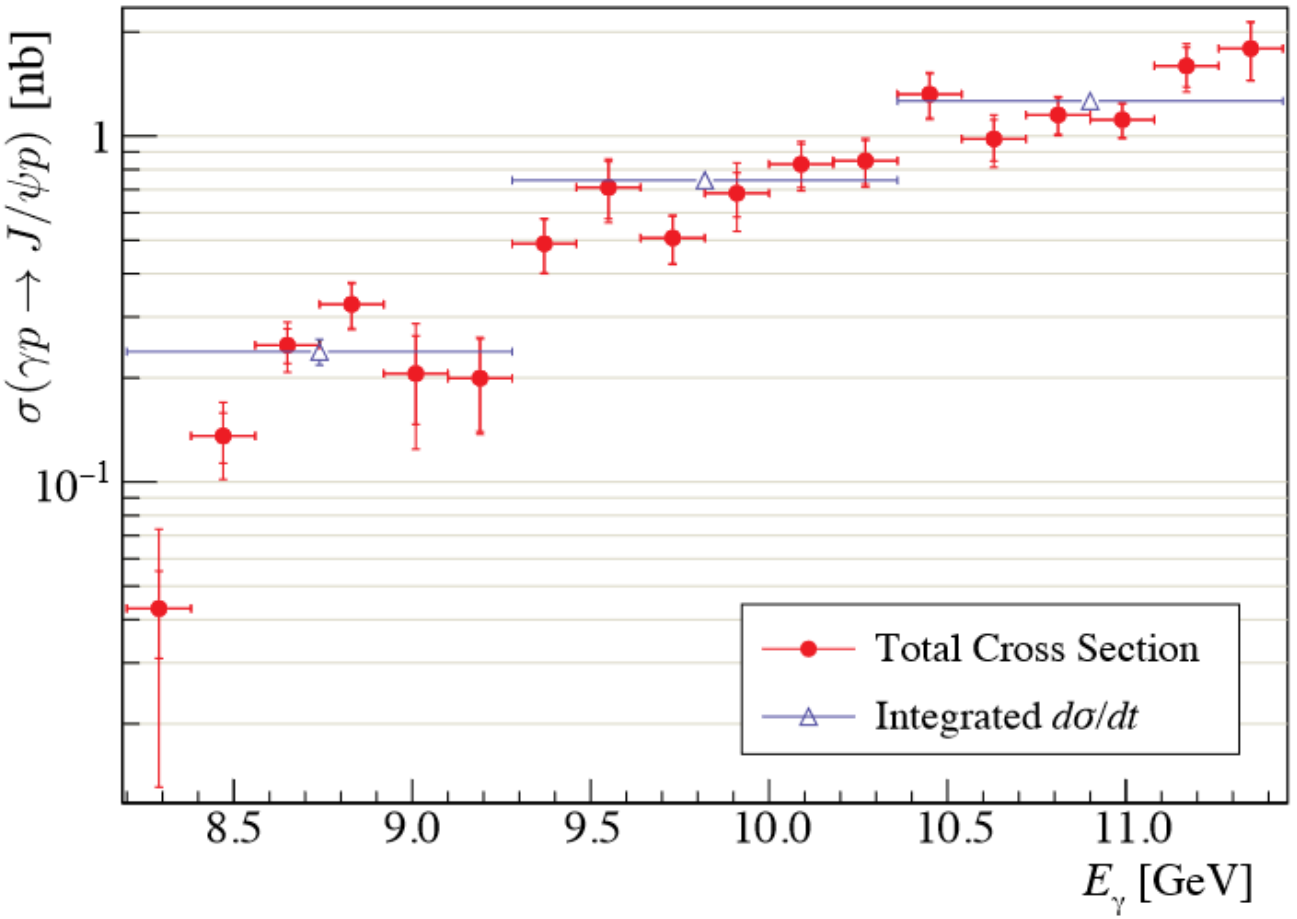
GlueX

- Beam energies up to 12 GeV are delivered to Hall D.
- GlueX produces a bremsstrahlung photon beam using the diamond wafer.
- See Peter Hurck's talk for more details on GlueX!



J/ψ at GlueX

- GlueX has made the highest precision measurement of the J/ψ total cross section [1,1b].
- The differential cross section as a function of t was also measured [1,1b].

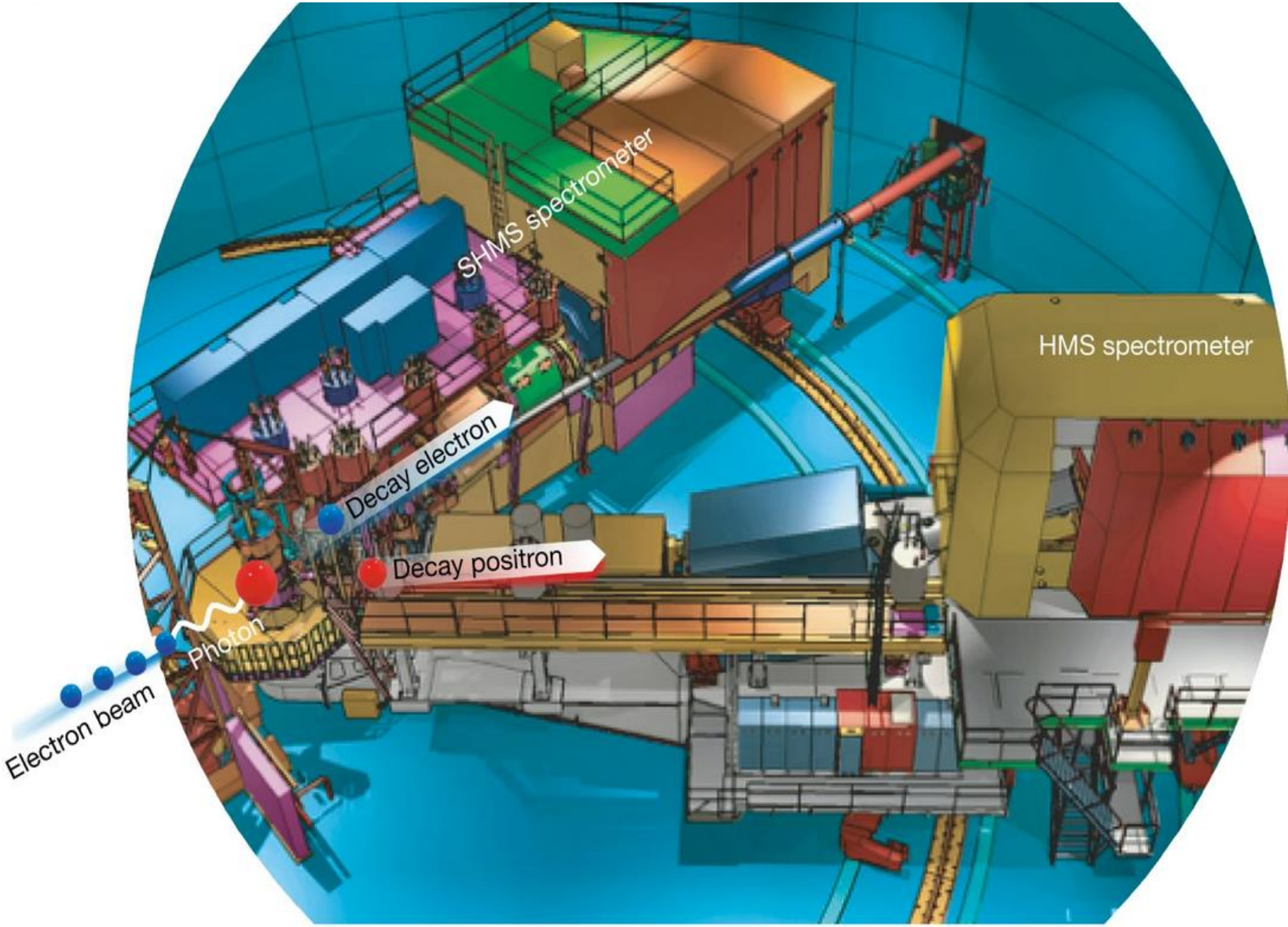


Measurements of the J/ψ total cross section as a function of the photon beam energy [1b].

[1] A. Ali, *et. al.* (GlueX Collaboration), *Phys. Rev. Lett.* **123**, 072001 (2019)
[1b] S. Adhikari, *et. al.* (GlueX Collaboration), arXiv:2304.03845v1 (2023)

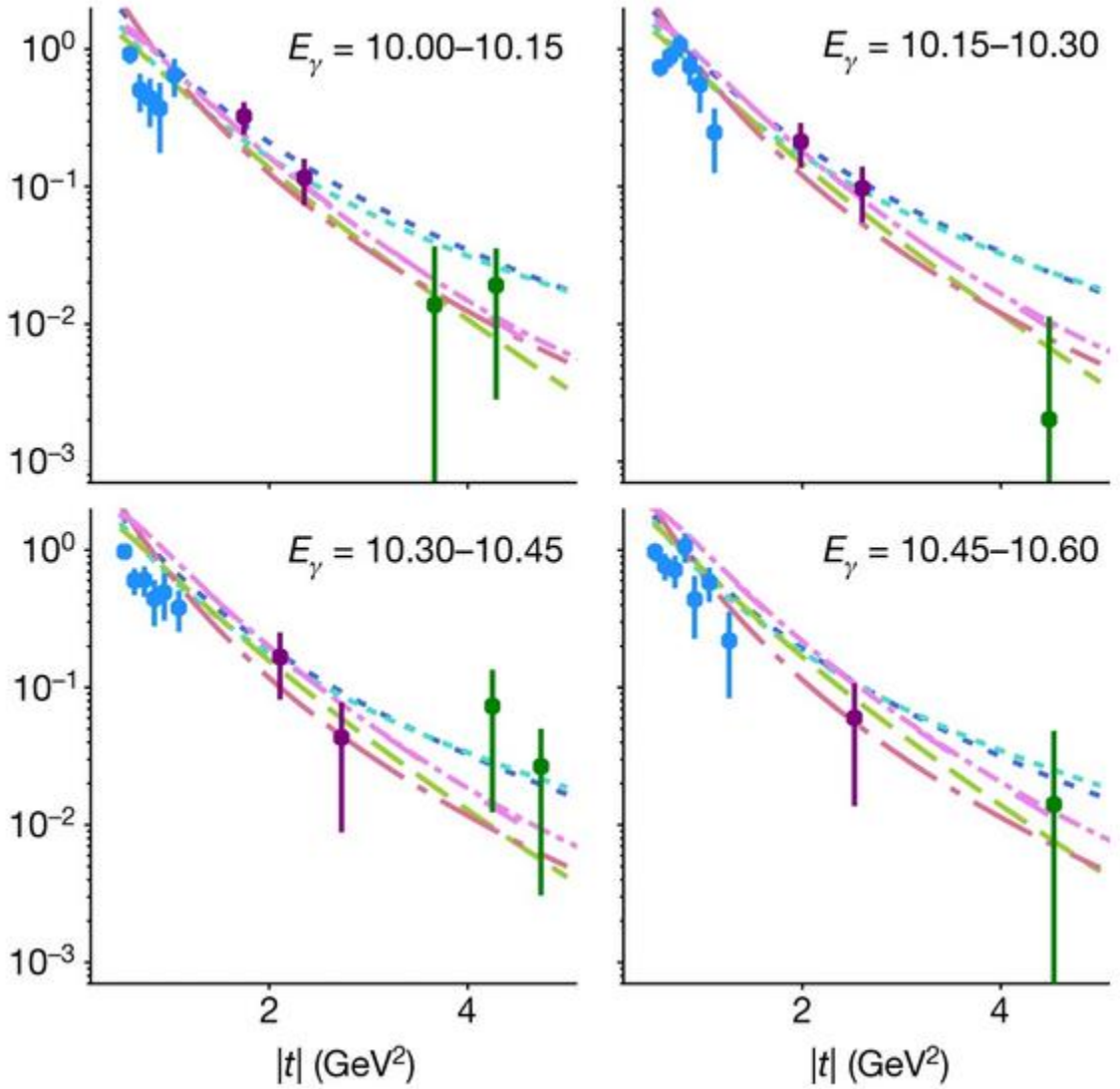
Hall C

- Beam energies up to 11 GeV are delivered to Hall C.
- Hall C employs a high precision spectrometer.
- This allows for precise measurements at specific kinematic points.



J/ψ at Hall C

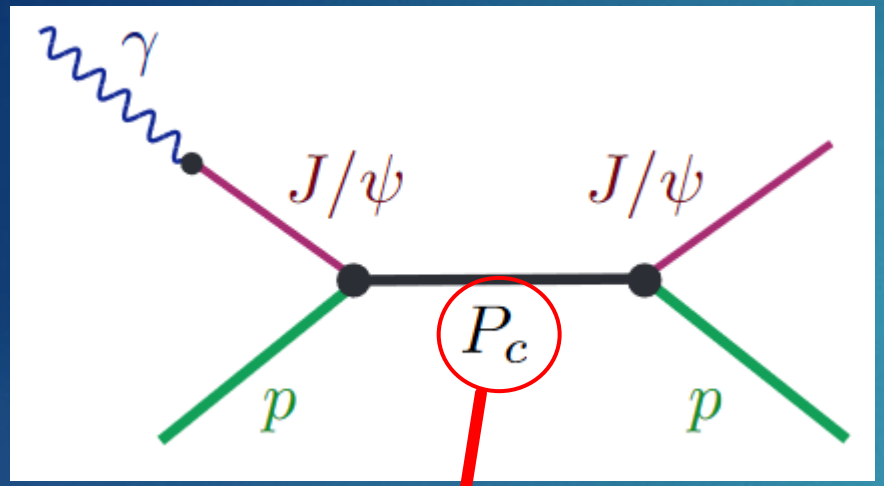
- The J/ψ − 007 Collaboration has made high precision measurements of the differential cross section as a function of t at 10 different photon energies.
- The total cross section was not released.
- The main objective was to probe the mechanical properties of the nucleon.



Measurements of the J/ψ differential cross section as a function of t energy and theoretical predictions [2].

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

J/ψ Near-Threshold Photoproduction



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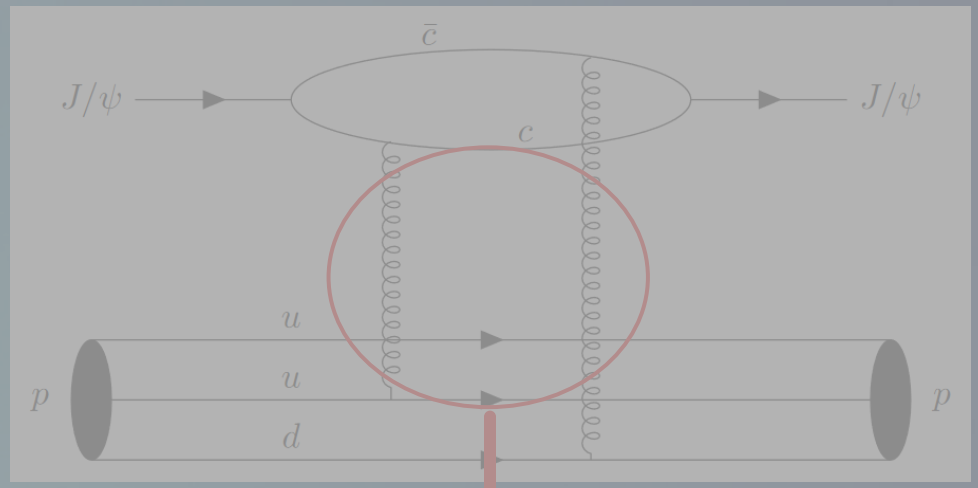
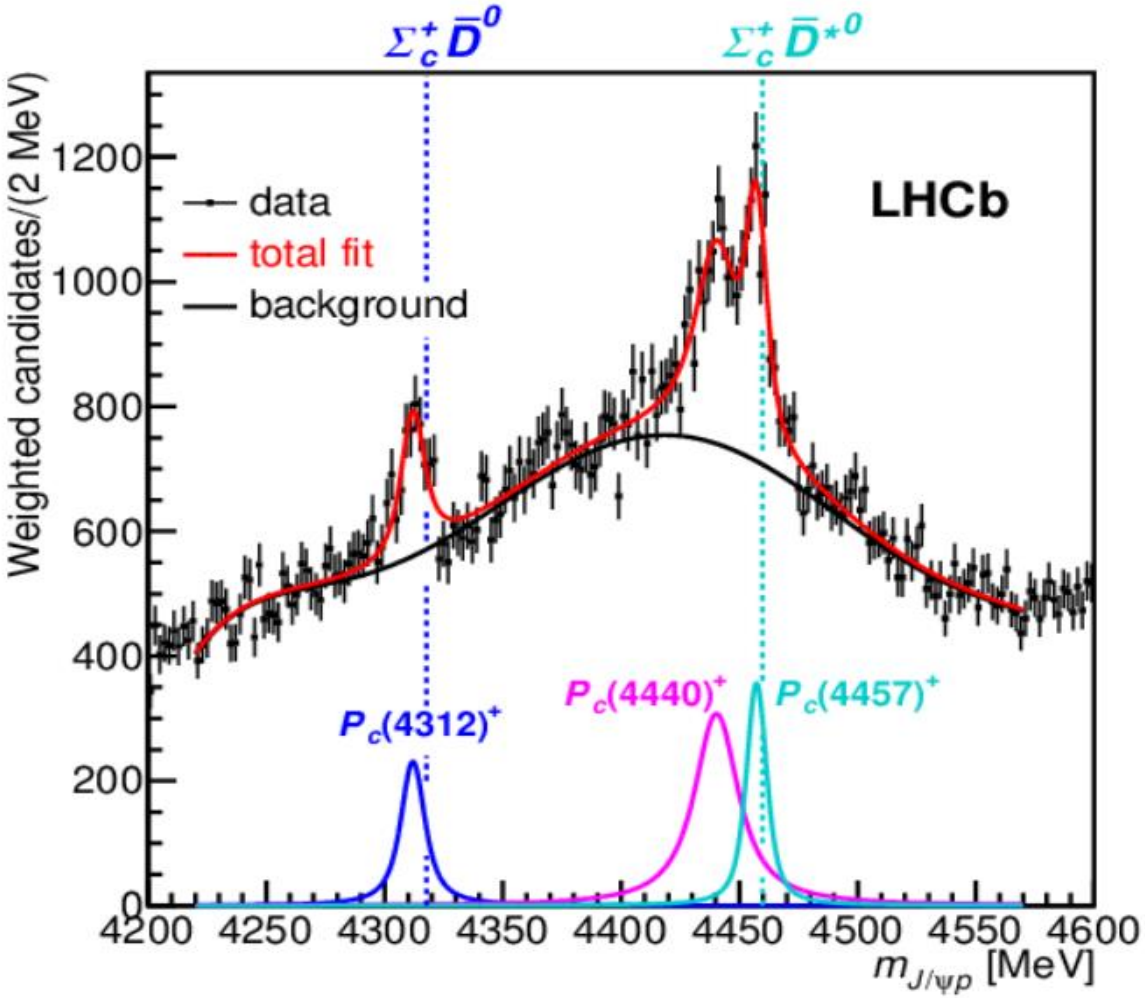


Two-gluon exchange production mechanisms allow to probe the mechanical properties of the nucleon.

P_c^+ Resonances

- P_c^+ photoproduction is not susceptible to non-resonant kinematic effects [4].
- JLab should be able to place upper limits on the branching fraction $\mathrm{B}(P_c^+ \rightarrow \mathrm{J/\psi\ p})$ and $\mathrm{B}(P_c^0 \rightarrow \mathrm{J/\psi\ n})$.



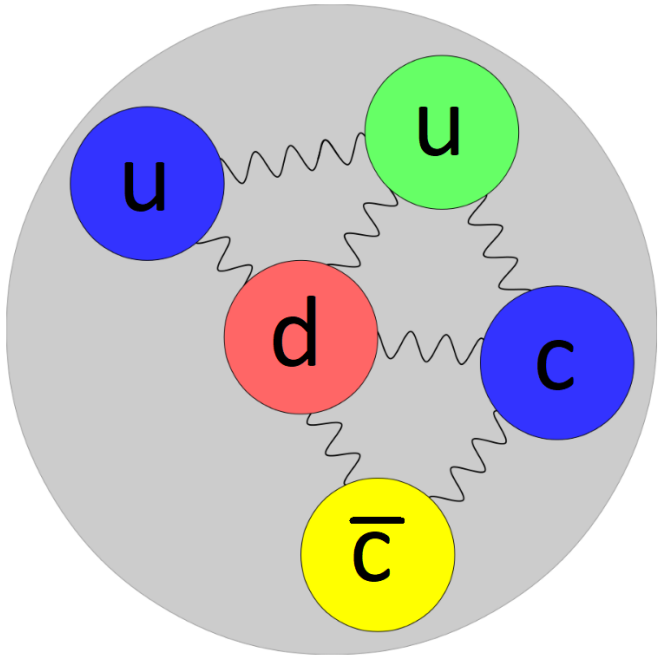
The J/ψ p invariant mass distribution measured at the LHCb [3].

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

[4] A.N. Hiller Blin, C. Fernandez-Ramirez, A. Jackura, V. Mathieu, V.I. Mokeev, A. Pilloni, A. P. Szczepaniak, *Phys. Rev. D* **94** 034002 (2016)

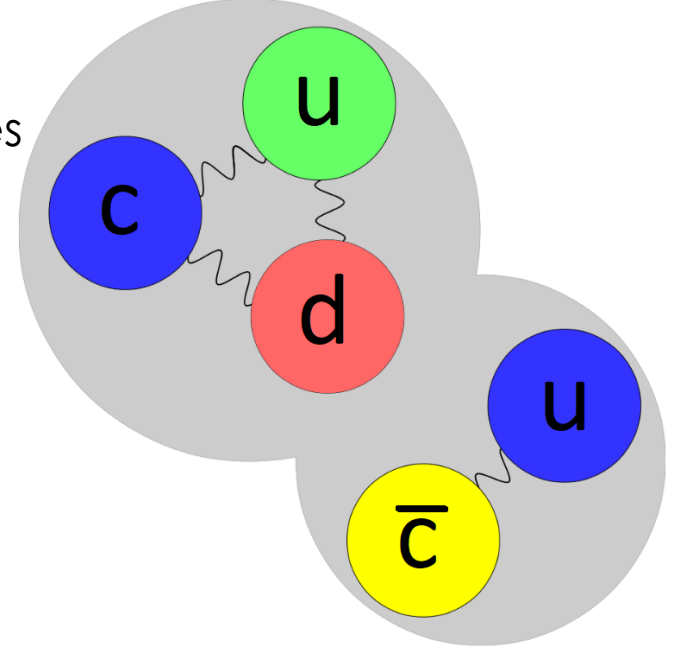
P_c^+ Models

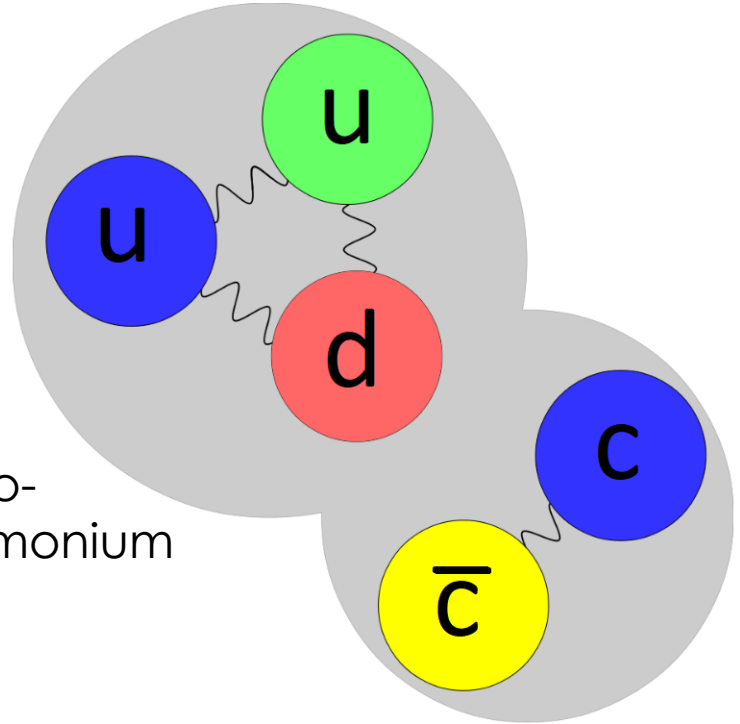
- Hadronic molecules: Weekly coupled charmed baryon and charmed meson.
- Hadro-charmonium states: compact bound $c\bar{c}$ state and light quarks.
- Quarks in a bag: Two tightly correlated di-quarks and an anti-quark.



Quarks in a bag

Hadronic Molecules

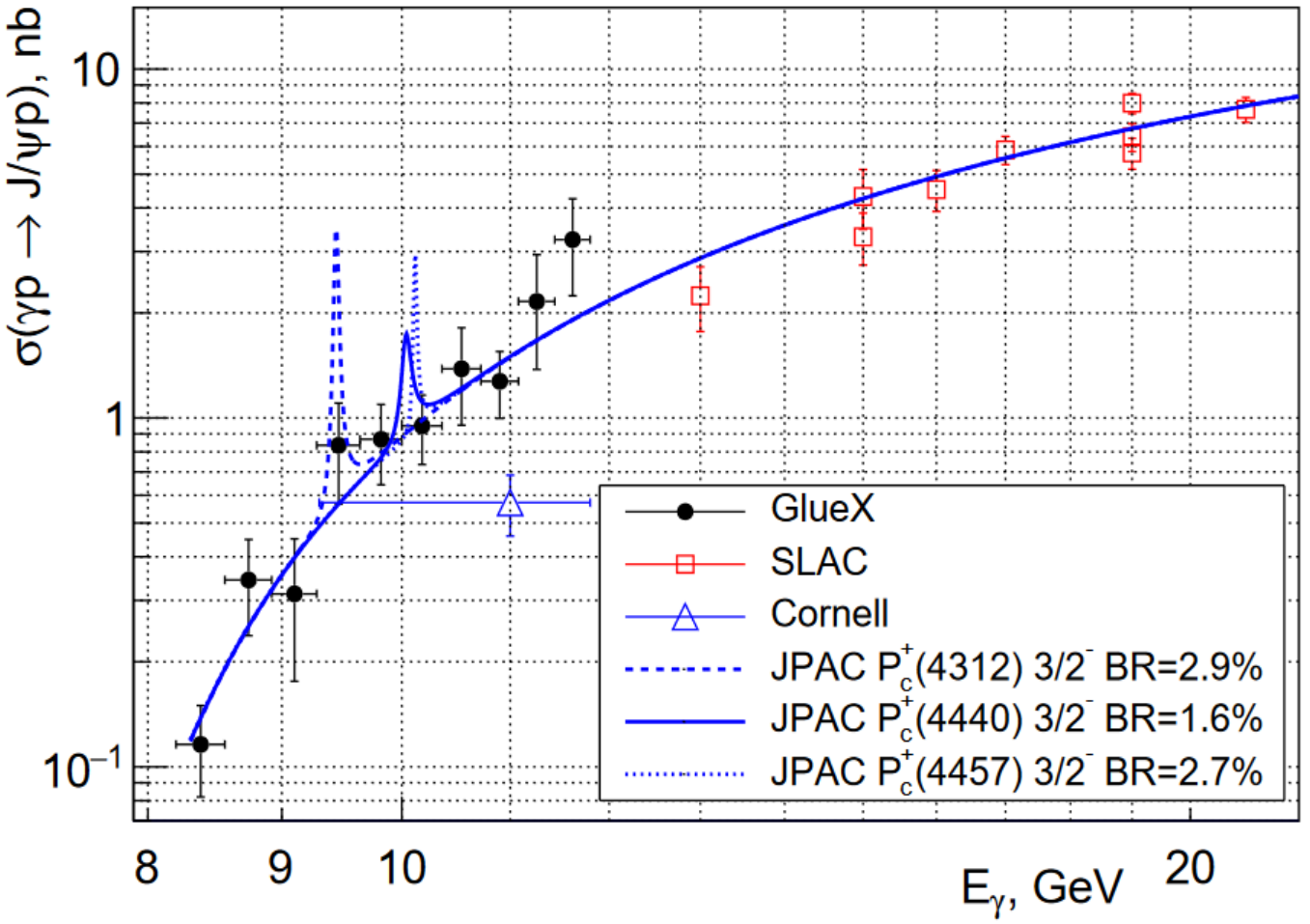




Hadro-charmonium

P_c^+ at GlueX

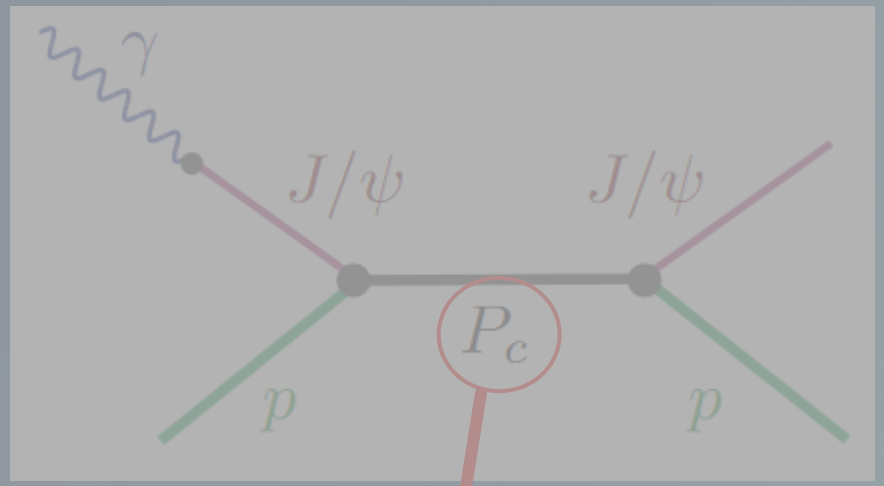
- The upper limits on the branching fractions from GlueX [1] rule out the hadro-charmonium scenario without excluding the molecular scenario [5-7].
- This does not fully rule out the existence of P_c^+ resonances [8].



Measurements of the J/ψ total cross section from GlueX [1] and compared to theoretical predictions including the P_c^+ resonances [3].

[5] M.I. Eides, V.Y. Petrov, M.V. Polyakov, *Mod.Phys.Lett.A* **35** 18 (2020).
[6] M. I. Eides, V. Yu. Petrov, and M. V. Polyakov, *Eur. Phys. J. C* **78** 36 (2018).
[7] M. I. Eides and V. Yu. Petrov, *Phys. Rev. D* **98** 114037 (2018).
[8] I. Strakovsky, W.J. Briscoe, E. Chudakov, I. Larin, L. Pentchev, A.Schmidt, R.L. Workman, arxiv:2304.04924v1 (2023)

J/ψ Near-Threshold Photoproduction



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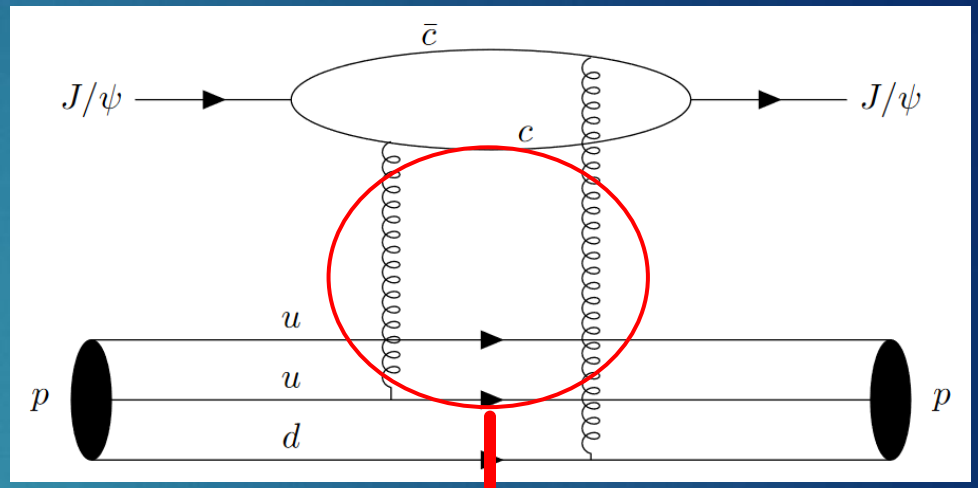
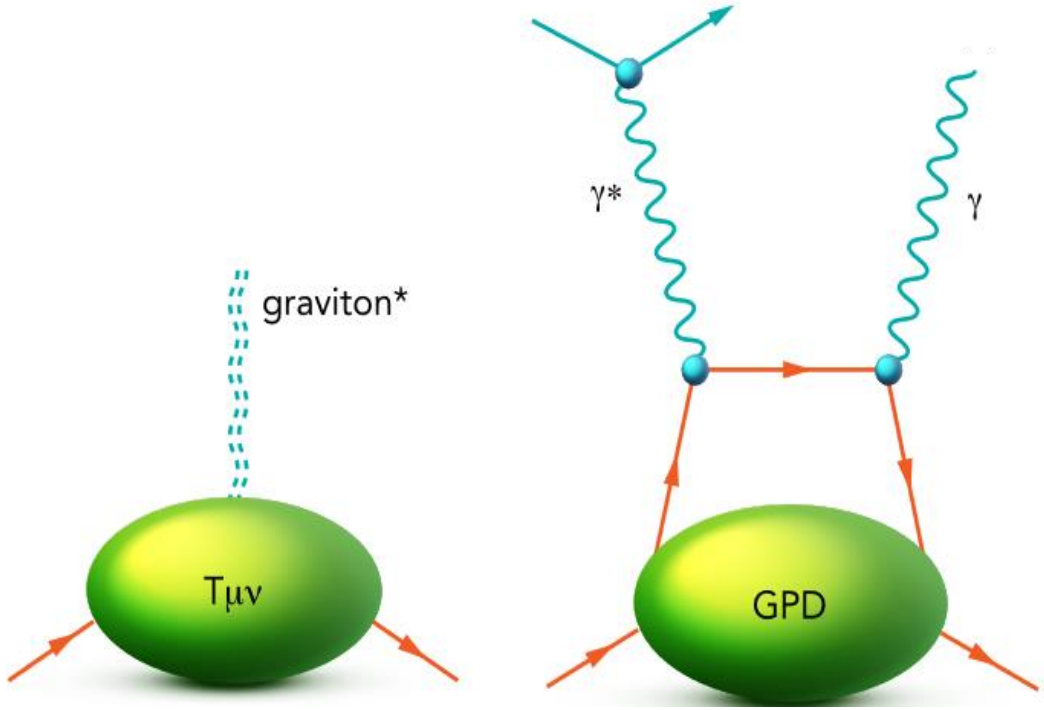


Two-gluon exchange production mechanisms allow to probe the mechanical properties of the nucleon.

Probing the Mechanical Properties of the Nucleon

- The mechanical properties of the nucleon are encoded by Gravitational Form Factors (GFFs) [9].
- Any spin-2 field gives rise to a force indistinguishable from gravity [10].
- The quark GFFs have already been estimated in the context of DVCS [11,12].

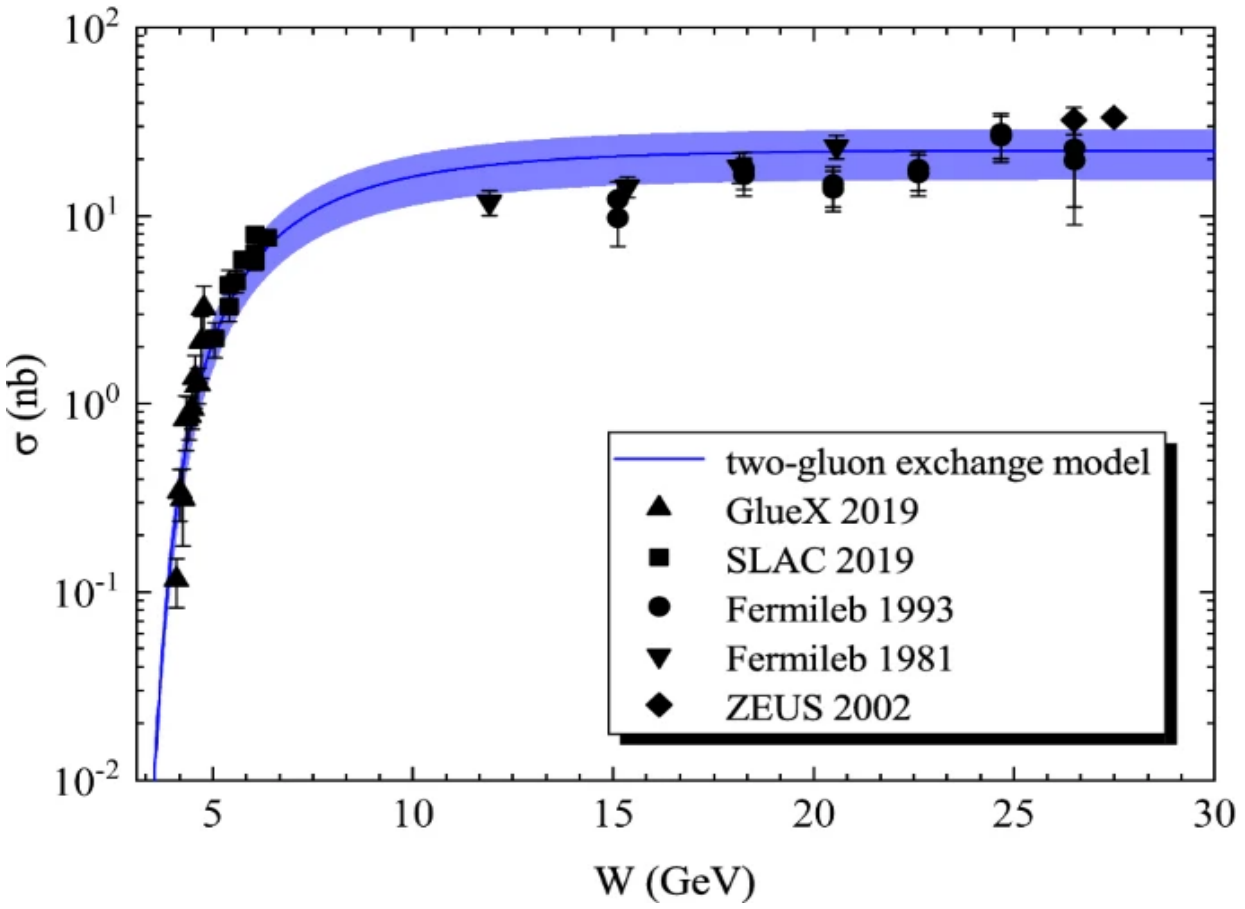


Spin-2 fields in graviton-proton scattering and DVCS [12].

[9] H. Pagels, *Phys. Rev.* **144** (1966)
[10] C.W. Misner, K.S. Thorne, J.A Wheeler, *Gravitation*, W.H. Freeman (1973), Box 18.1
[11] V.D. Burkert, L. Elouadrhiri, F.X. Girod, *Nature* **557** 7705 (2018)
[12] 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 [13-15].
- Holographic QCD [16-17] model J/ψ photoproduction based on a tensor graviton like exchange (2^{++}).

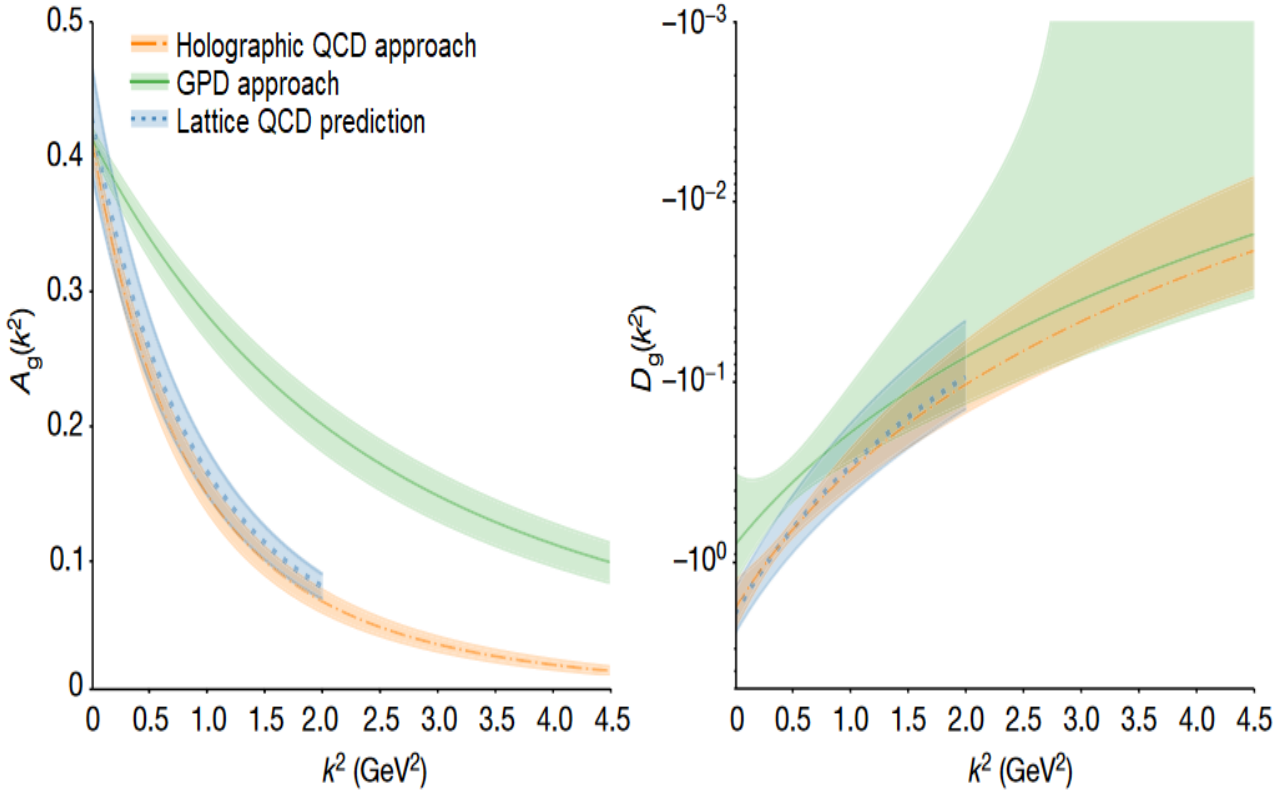


Prediction for the J/ψ total cross section based on a two-gluon exchange model and compared to world data.

[13] L. Frankfurt, M. Strikman, *Phys. Rev. D.* **66**, 031502 (2002).
[14] D. Kharzeev, H. Satz, A. Syamtomov, G. Zinovev, *Nucl.Phys. A* **661** 568 (1999).
[15] F. Zeng, *et. al., Eur. Phys. J. C* **80** 1027 (2020)
[16]Y. Hatta and D.-L. Yang, *Phys. Rev. D* **98** 074003 (2018).
[17] K.A. Mamo, I. Zahed, *Phys. Rev. D* **106** 086004 (2022).
[18] T.-S. H. Lee, S. Sakinah, Y. Oh arXiv:2210.02154 (2022).

Gluonic GFFs

- Both holographic QCD and two-gluon exchange models relate the trace anomaly of the EMT to J/ψ photoproduction and give access to the nucleon gluon GFFs.
- The $A_g(t)$ and $D_g(t)$ GFFs were estimated at Hall-C for J/ψ photoproduction [2].



The $A_g(t)$ and $D_g(t)$ GFFs estimated using holographic QCD (orange) and GPD (green) models [2] compared to lattice QCD predictions (blue) [19].

$$k^2 \equiv |t|$$

[19] D.A Pefkou, D.C Hackett, P.E Shanahan, *Phys. Rev. D* **105**, 054509 (2022).

Mass Radius of the Nucleon

- A scalar gravitational form factor $G(t)$ gives access to the mass radius of the nucleon [20].

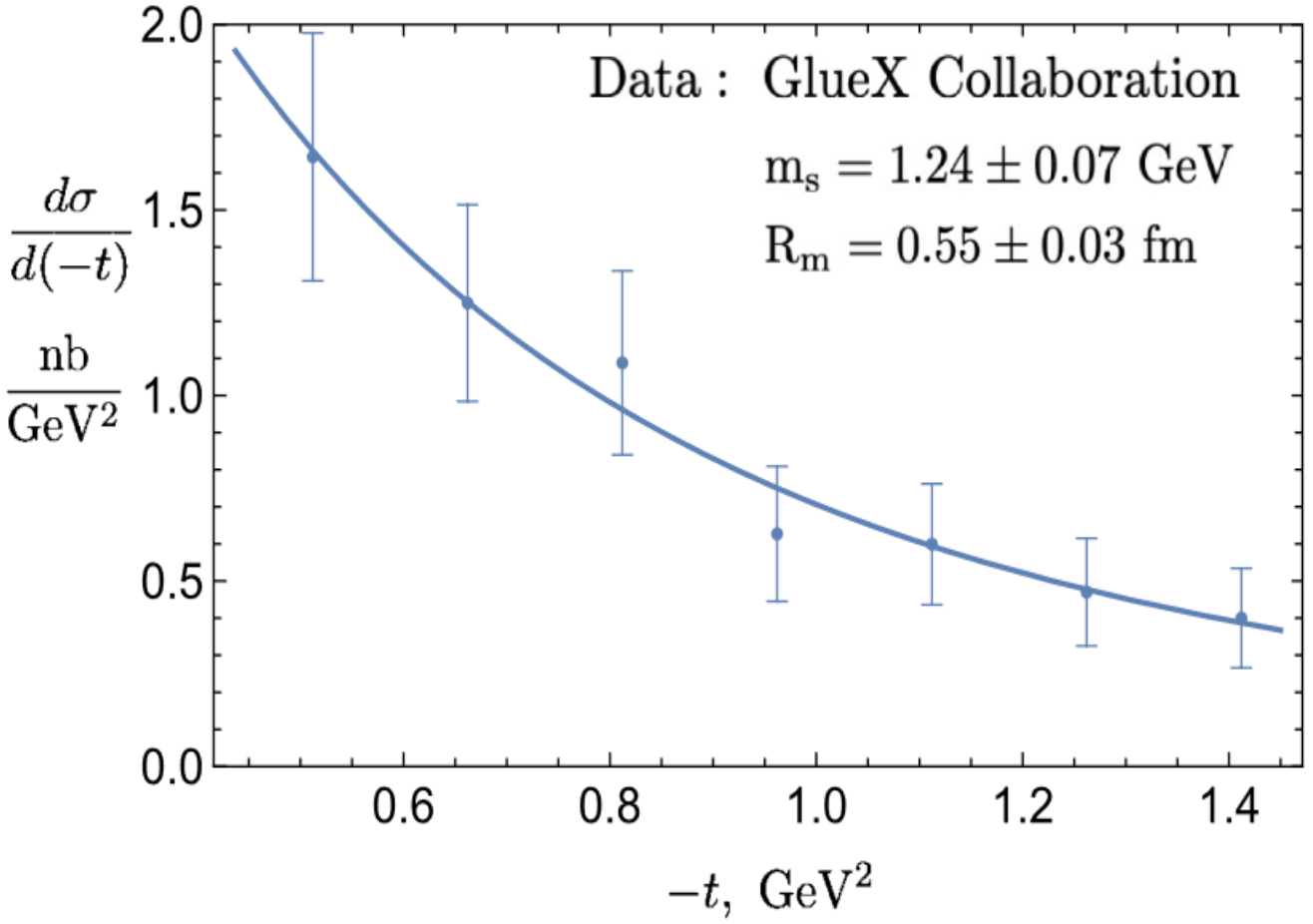
$$\frac{d\sigma}{dt} = G(t)^2$$

- 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 [20]:

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

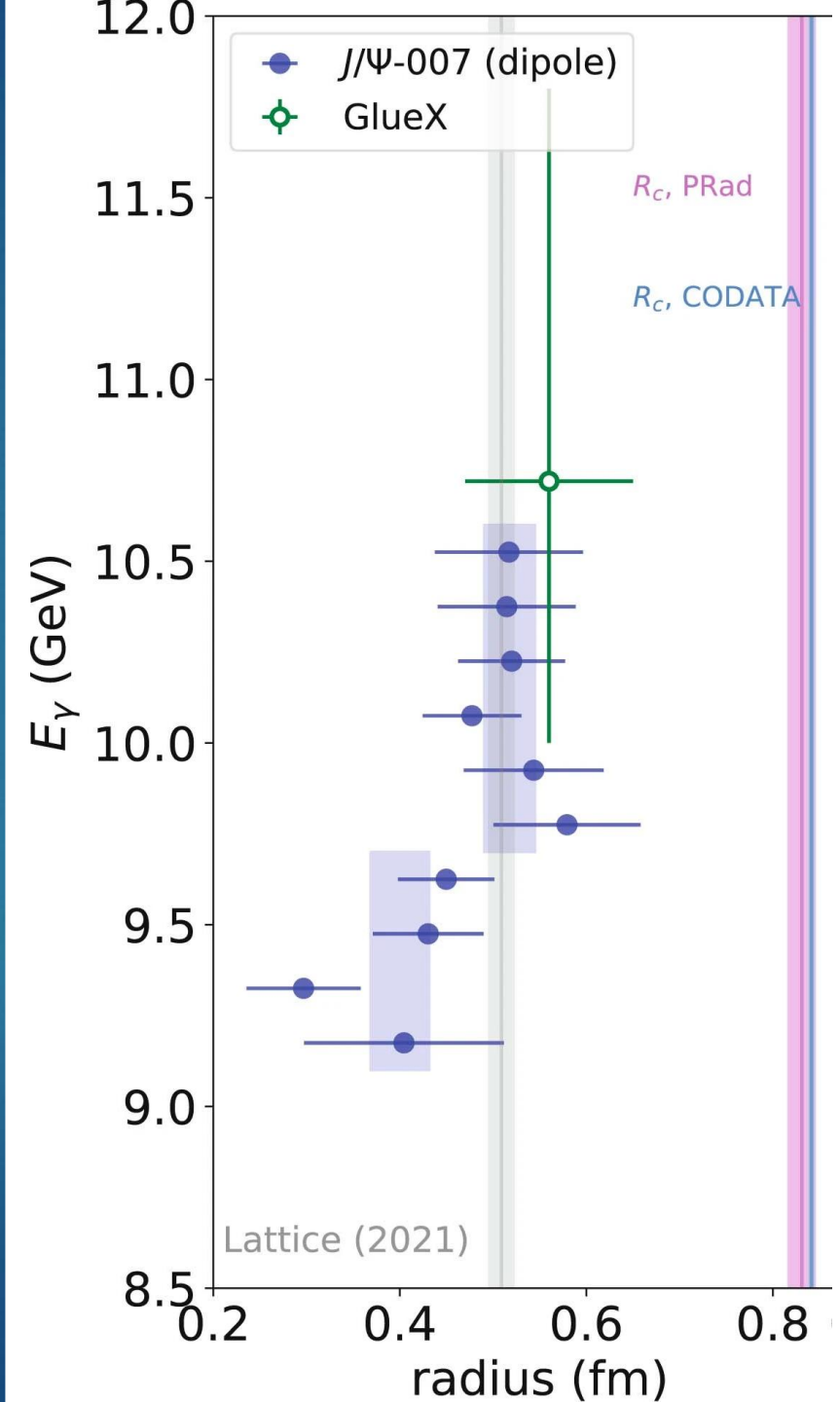


J/ψ differential cross section as a function of –t. Data from the GlueX Collaboration [1], plot taken from [20].

[20] D.E. Kharzeev, *Phys. Rev. D* **104**, 054015 (2021).

Mass Radius of the Nucleon at JLab

- Preliminary measurements from CLAS12 are in good agreement with the GlueX and Hall C estimates and suggest an equal sized mass radius of the neutron.
- A larger charge radius than mass radius suggests than the quark radius within the nucleon is larger than the gluon radius.
- Deviations at lower photon energies might be indicative of a region where the assumption of two-gluon exchange dominance is invalid.

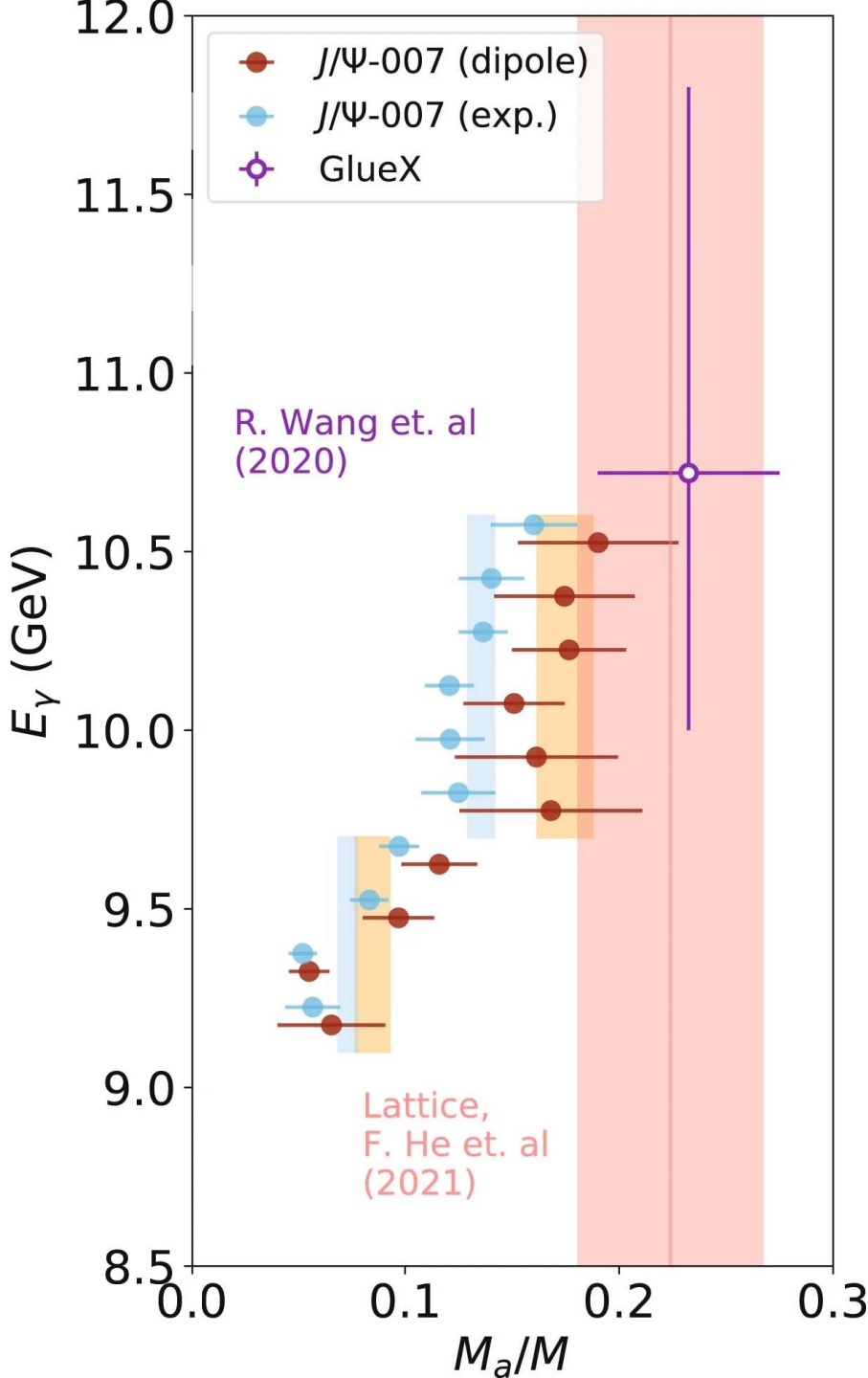


Trace Anomaly Contribution to the Nucleon Mass

- The nucleon mass can be decomposed into the contributions from the quark masses, the energy of quark and gluons and the trace anomaly contribution [21].

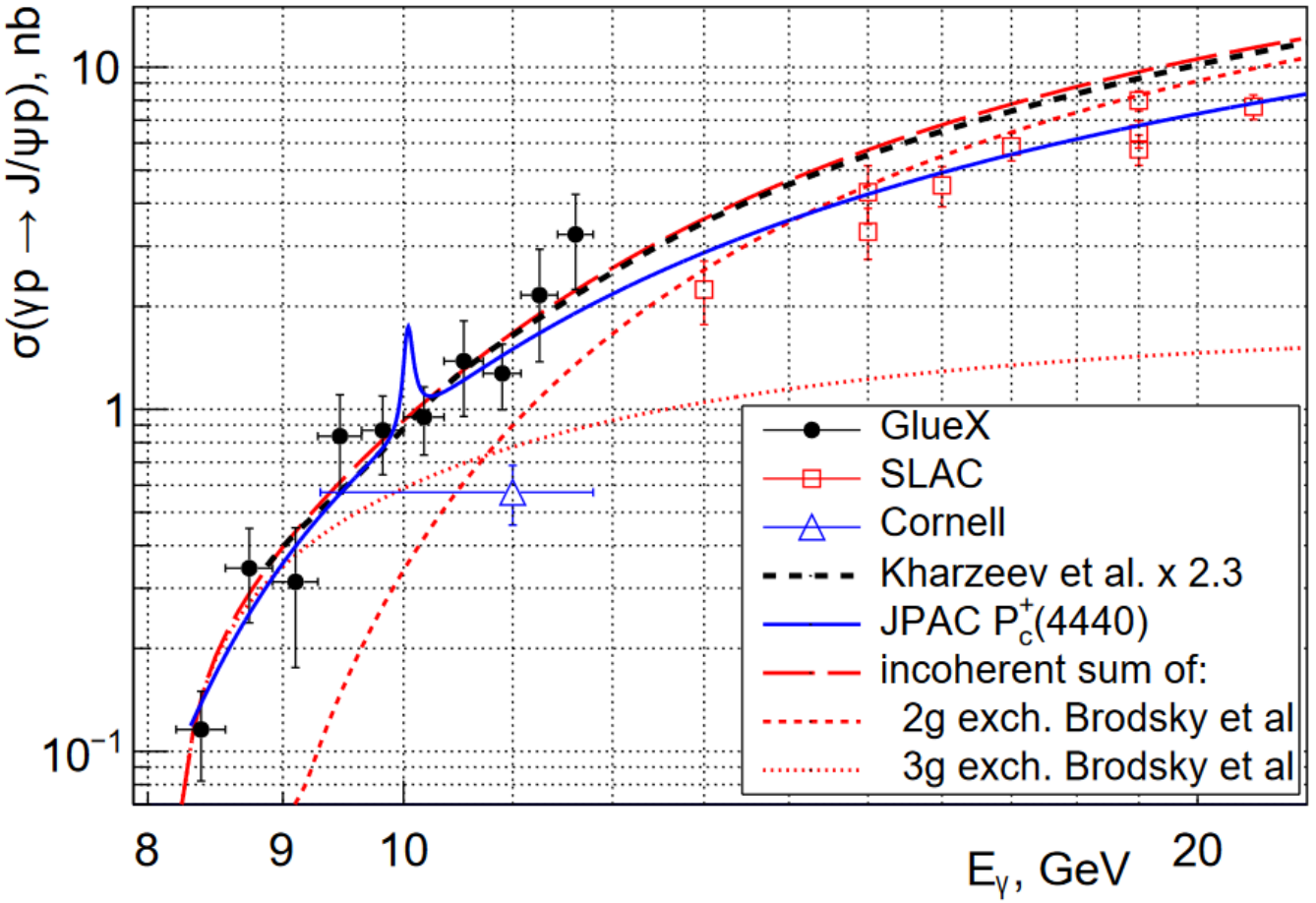
- Estimates of the magnitude of the trace anomaly contribution to the proton mass were obtained from GlueX and Hall C data [21,1,2].

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



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 [22].
- GlueX has already identified a path forward based on an increase in luminosity and/or an energy upgrade at JLab.
- This would allow to measure the J/ψ SDMEs and calculate the charge naturality with enough precision to distinguish between two or three-gluon exchange.

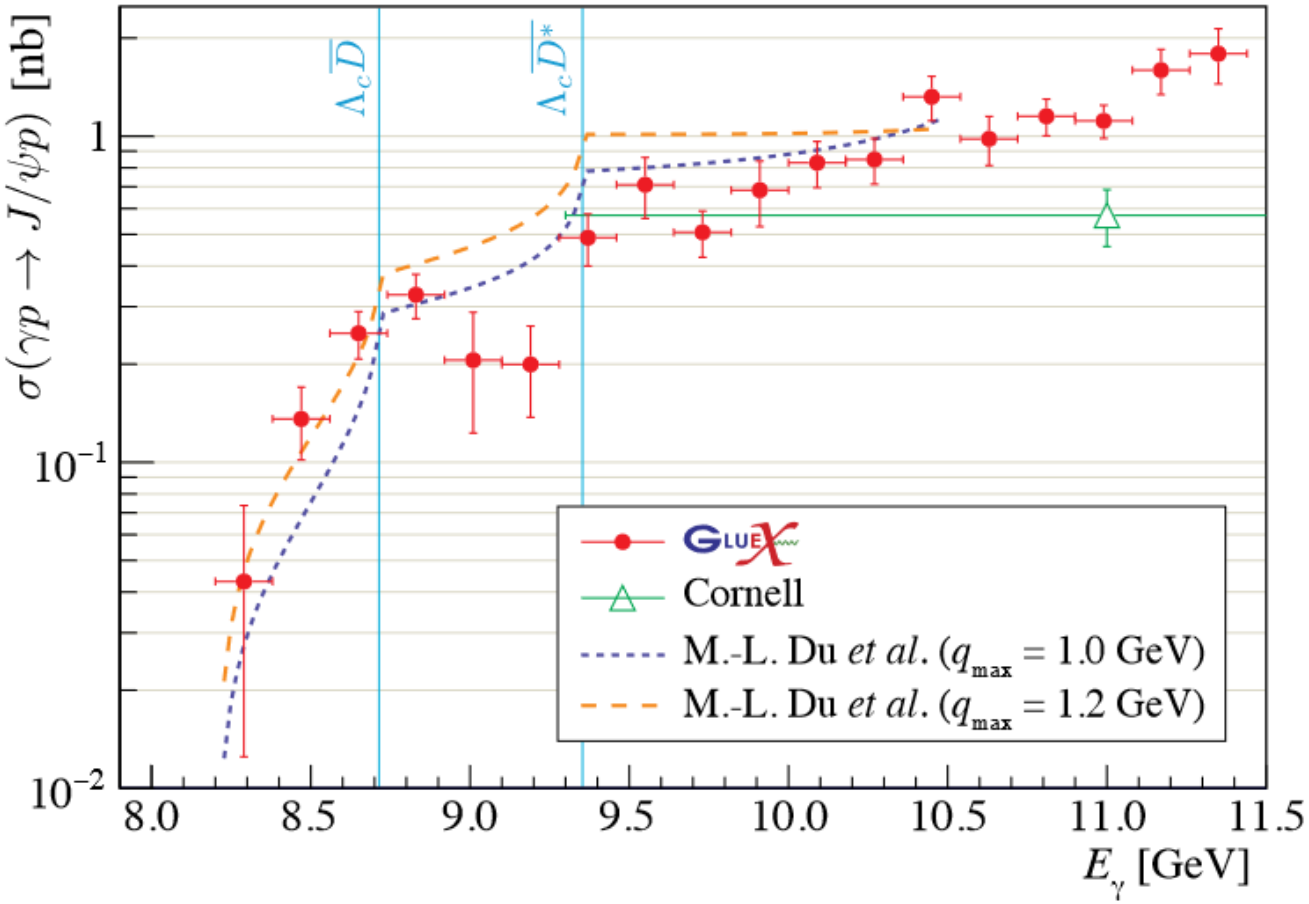


Measurements of the J/ψ total cross section as a function of the photon beam energy and theoretical predictions scaled to GlueX data [1].

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

Open-Charm Photoproduction?

- There are suggestions that J/ψ near-threshold photoproduction could be dominated by open charm production of $\Lambda^c \overline{D}^{(*)}$ [23].
- The most straightforward path to rule out open charm photoproduction would be to rule out the distinct cusp like structure of the cross section.



Predictions for the total cross section due to the open charm production of J/ψ p [23], which is consistent with the GlueX measurements [1b] in red. Here q_{max} refers to a threshold on Q^2.

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

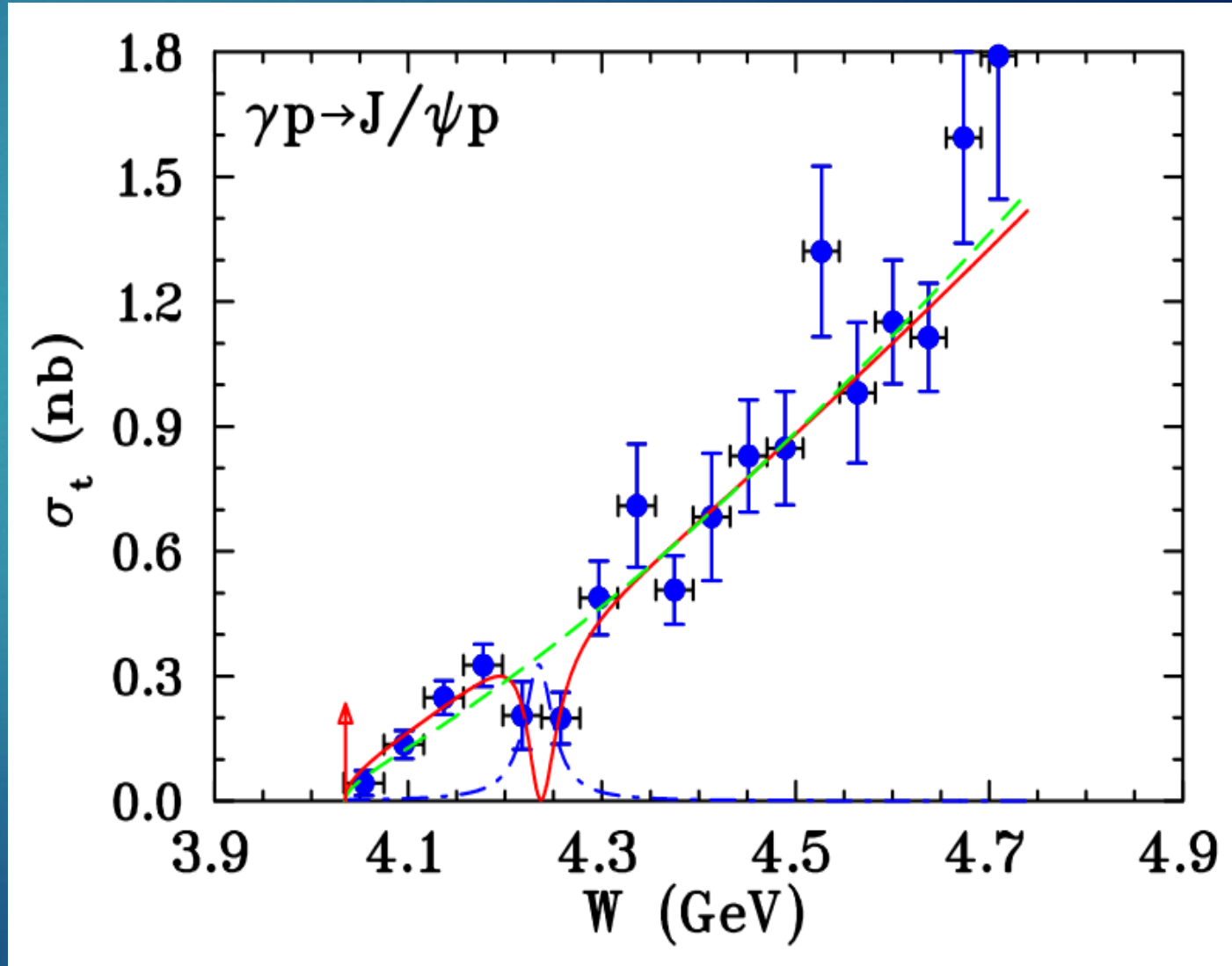
Conclusion

- J/ψ near-threshold photoproduction plays a key role in the physics program of the 12 GeV upgrade at JLab due to the wealth of information it has to offer.
- At present no direct observation of the P_c^+ pentaquarks has been made at JLab. Upper limits on the branching fraction from GlueX support the molecular interpretation of the P_c^+ structure.
- Two-gluon exchange as the dominant J/ψ production mechanism offers an exciting new way of probing the mechanical properties of the nucleon and its gluonic contents.
- Future upgrades at JLab will be key for higher precision measurements of the J/ψ cross section. In particular this will allow to test the assumptions made on the dominant J/ψ production mechanism.

Backup Slides

Is the $P_c^+(4312)$ Compatible with GlueX data?

- In [8] it is shown how a non-resonant background could interfere with a S-channel resonance leading to the dip in the GlueX total cross section measurements.
- At the least this demonstrates that one cannot exclude the presence of all 4 LHCb P_c^+ resonances together with open charm and 2- or 3-gluon exchanges [8].



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