Studying the Gluonic GFFs at JLab

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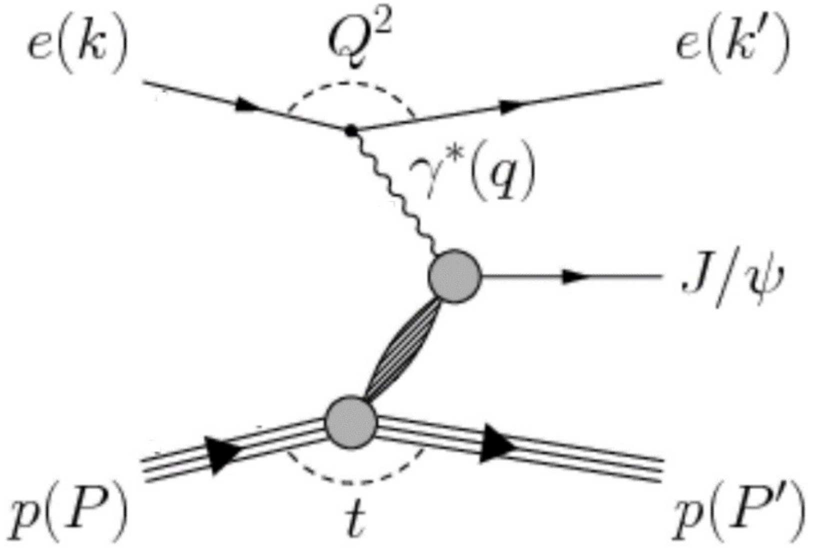
J/ψ Near-Threshold Photoproduction

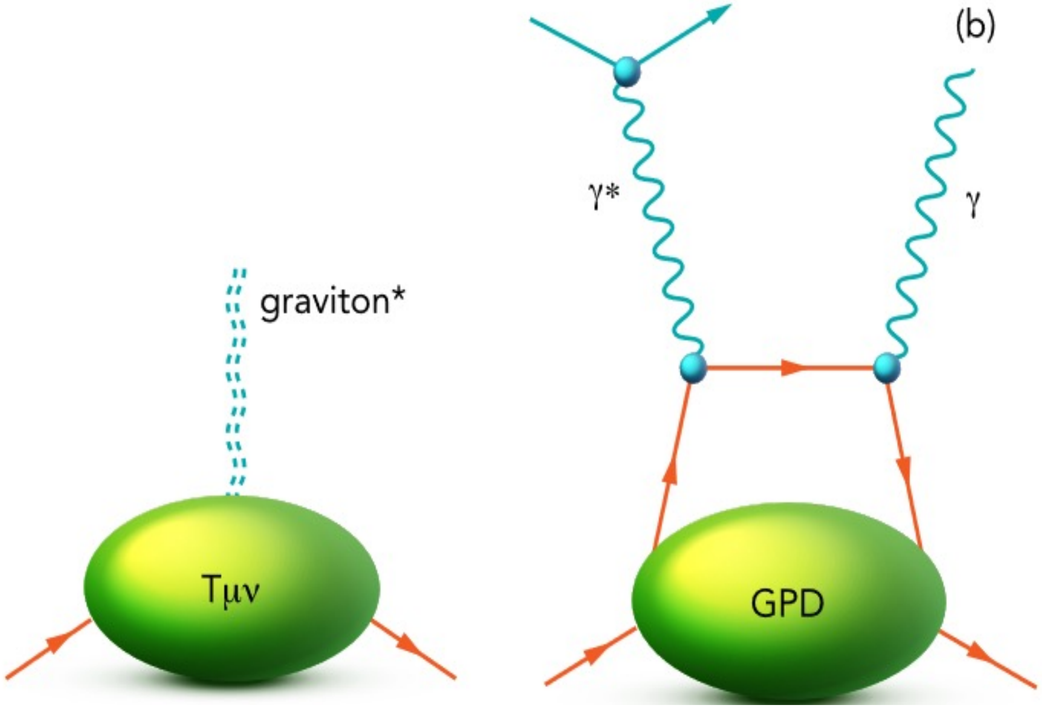
- Employ an electron beam for either:
  - Quasi-real photoproduction where a virtual photon mediates the interaction at Q^2 close to 0.
  - Real photoproduction where a real photon produced via bremsstrahlung interacts with the target
- J/ψ decays to a lepton pair, either e^+e^- or $\mu^+\mu^-$. Other decay channels are OZI suppressed.
- Produce J/ψ close to its 8.2 GeV photoproduction threshold.
- Aim to measure:
  - Total cross section as a function of E_γ.
  - Differential cross section as a function of t.



J/ψ quasi-real photoproduction on a proton target

Probing the Mechanical Properties of the Nucleon

- The mechanical properties of the nucleon are encoded by Gravitational Form Factors (GFFs) [1] defined from the matrix elements of the energy-momentum tensor (EMT).
- Any spin-2 field couples to the EMT and gives rise to a force indistinguishable from gravity [2].
- The quark GFFs have already been investigated in the context of DVCS. This led to estimates of sheer and pressure distributions of quarks inside the proton [3,4].
- A two-gluon exchange forms a spin-2 coupling between J/ψ and the nucleon. This allows to estimate the gluonic GFFs [5-7].



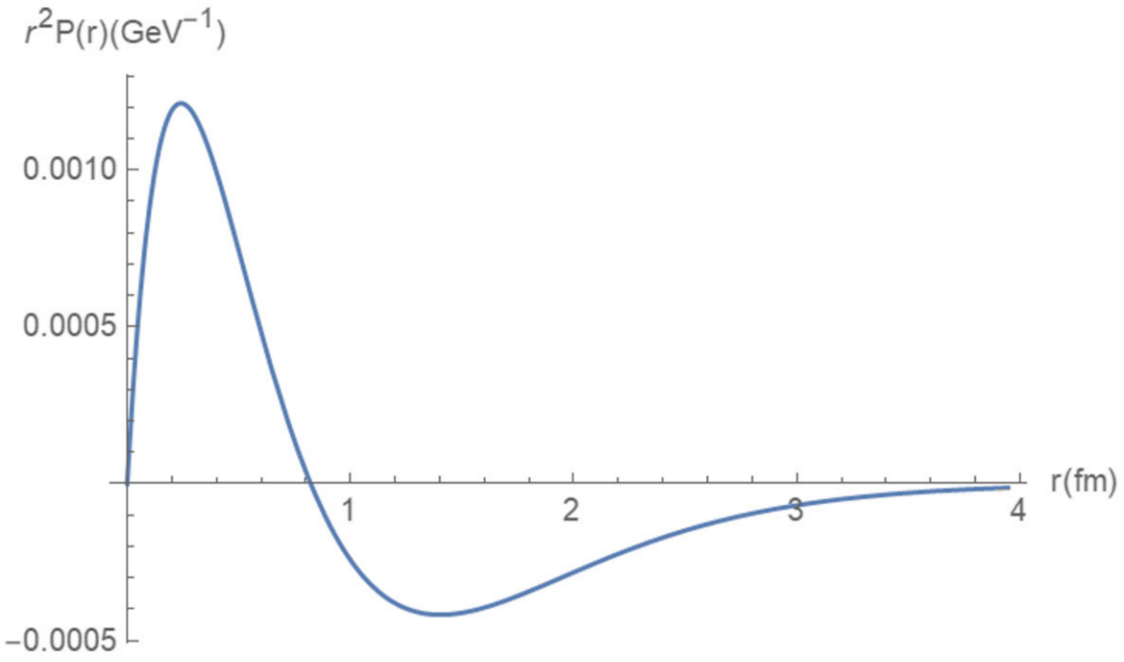
Spin-2 fields in graviton-proton scattering and DVCS.

J/ψ and the GFFs

- VMD based models relate J/ψ photoproduction to the J/ψ-nucleon scattering. The J/ψ-nucleon scattering amplitude gives access to the EMT [5,9].

- 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 [6,10].

- In the GPD framework, large skewness at threshold allows to relate the scattering amplitude to gluon GPDs. The GFFs are extracted from the first moments of the GPDs [7,11,12].



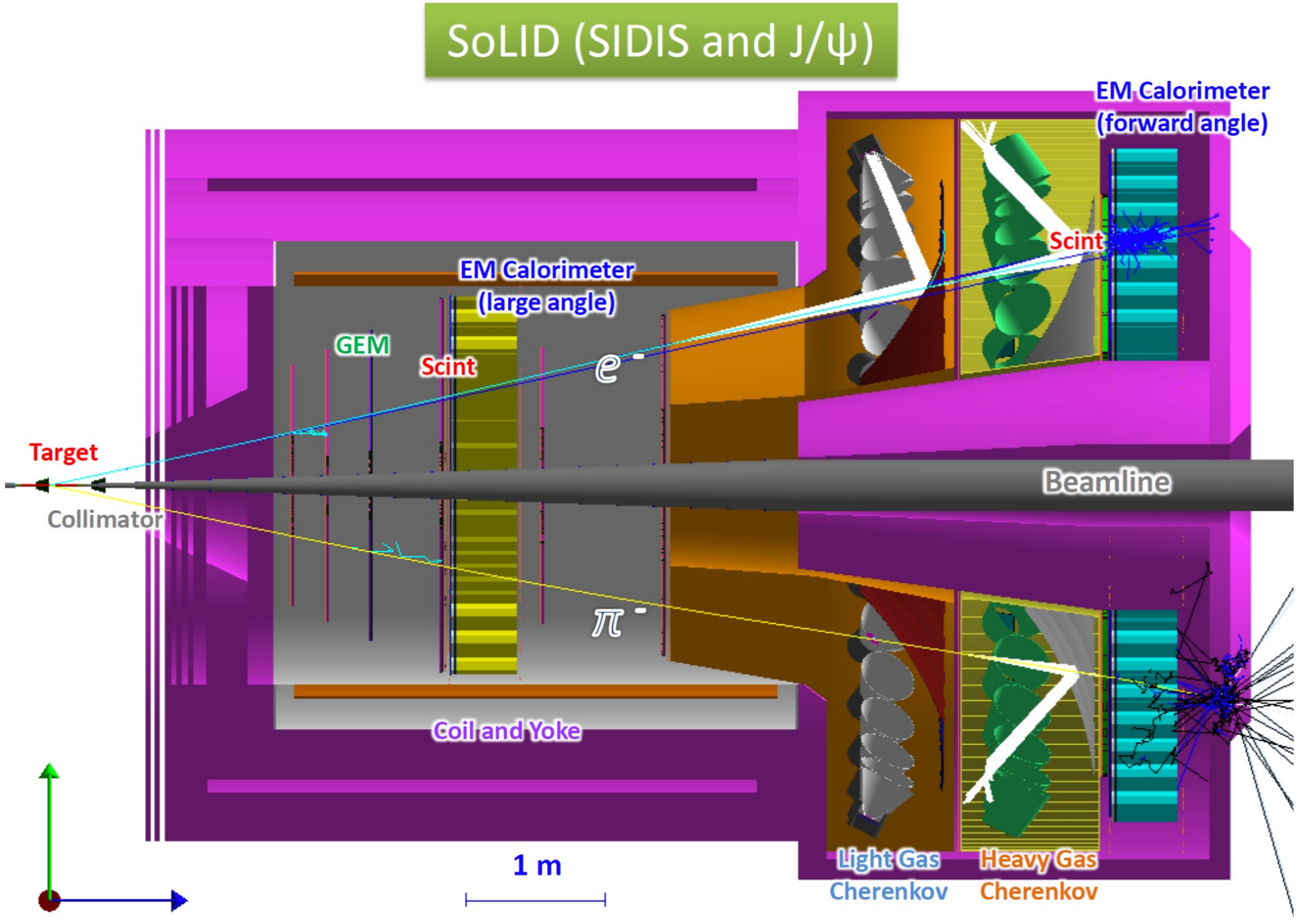
The gluon contribution to the pressure distribution inside the proton from a GPD based model fit to lattice and J/ψ photoproduction data [7].

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.
- Upcoming Solenoidal Large Intensity Device (SoLID) will be located in Hall A.
- 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.

SoLID in Hall A

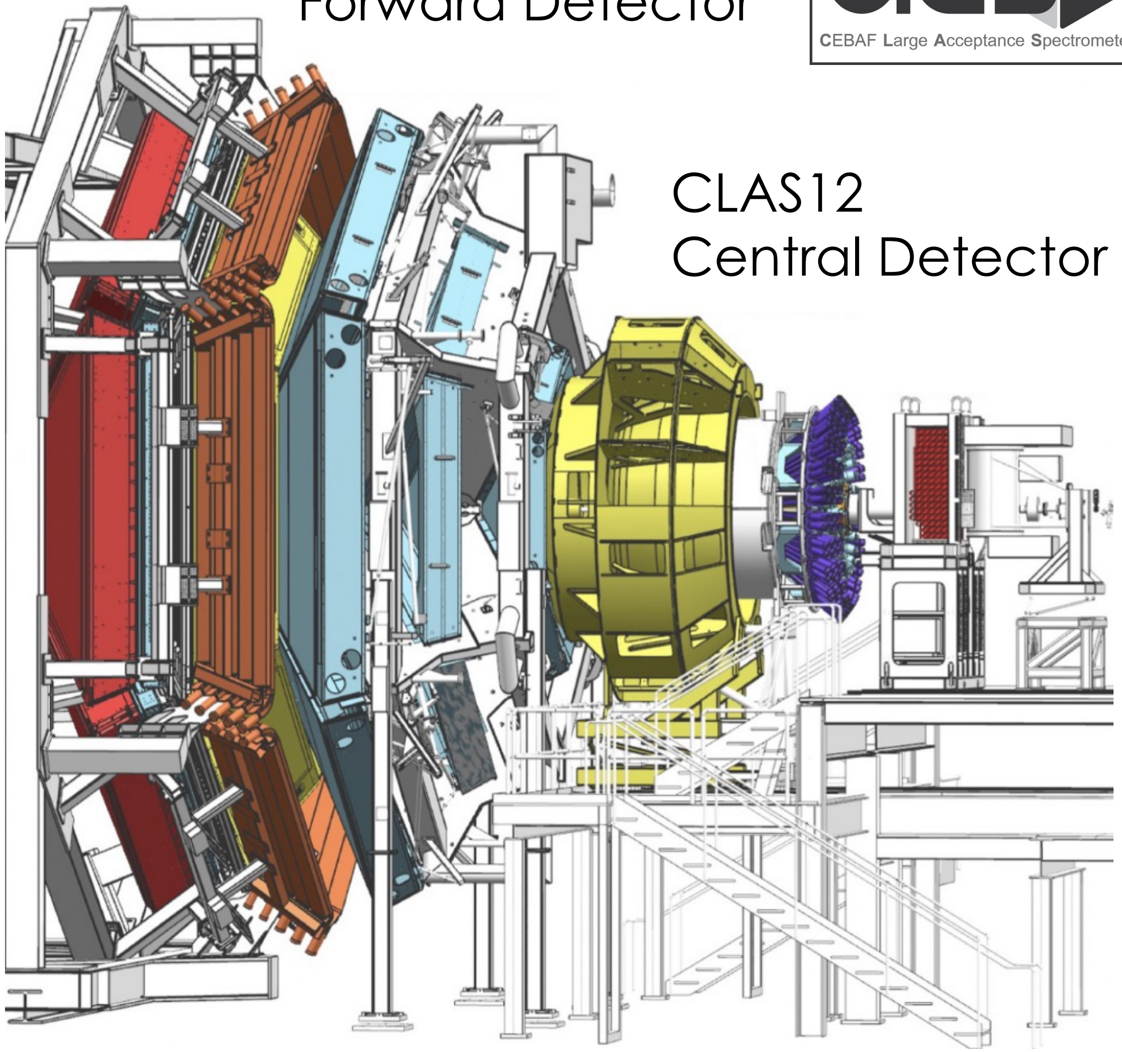
- SoLID is a future facility planned for the 2030s.
- High luminosity ~ 10^{37} cm^{-2}s^{-1}.
- Large acceptance with full azimuthal coverage and polar angles from ~7 to ~24 degrees.
- Good momentum resolution ~2% from 0.8 to 7 GeV (for electrons).
- Planned J/ψ experiment will utilize a 30μA beam on 15 cm LH2 target to reach counts of ~800k J/ψ (in photoproduction).
- Increased statistics at large t will be crucial for the extraction of the gluonic GFFs [11,12].



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.

clas
CEBAF Large Acceptance Spectrometer

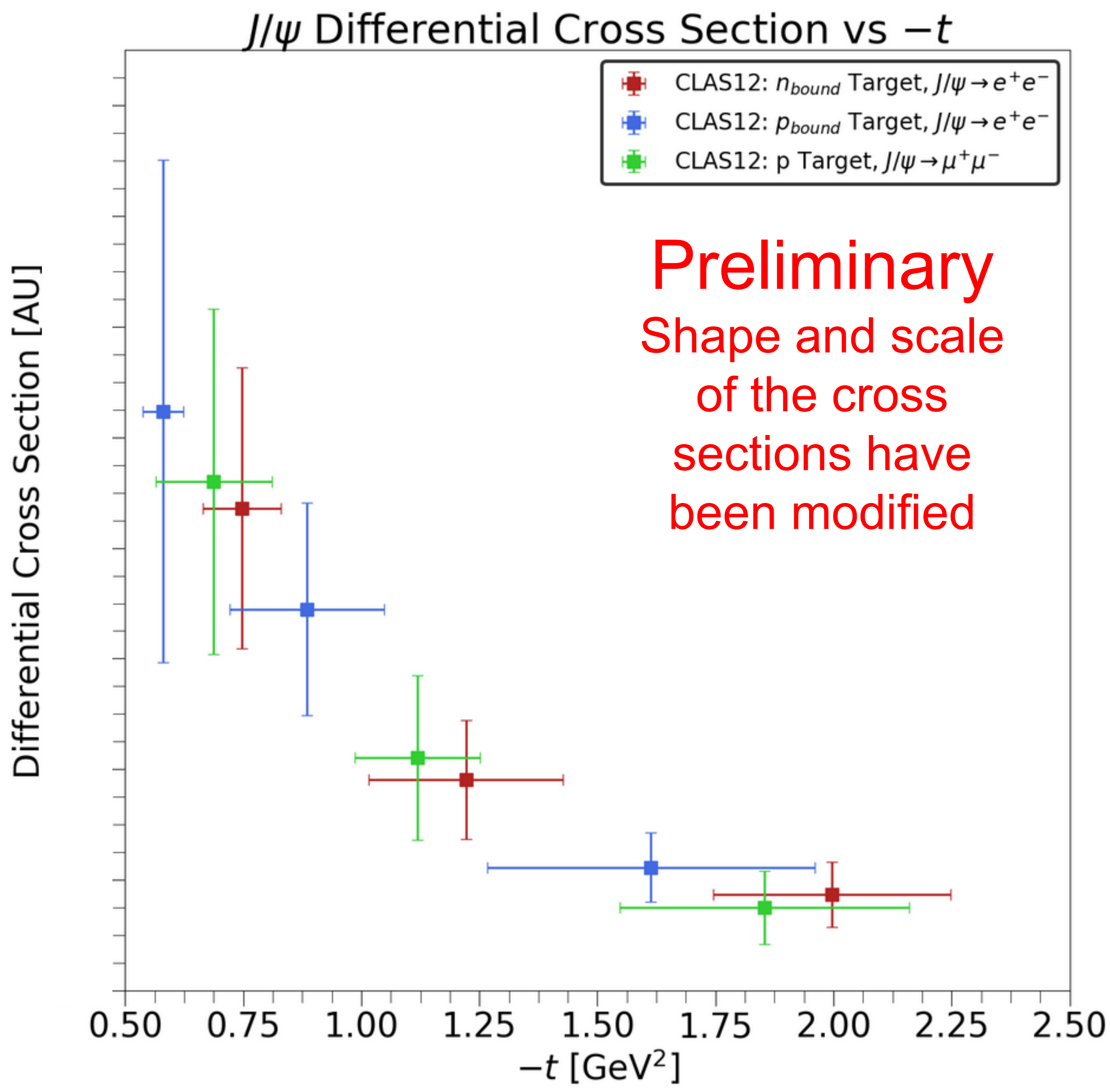


J/ψ at CLAS12

- CLAS12 took data with a liquid hydrogen target and a liquid deuteron target.

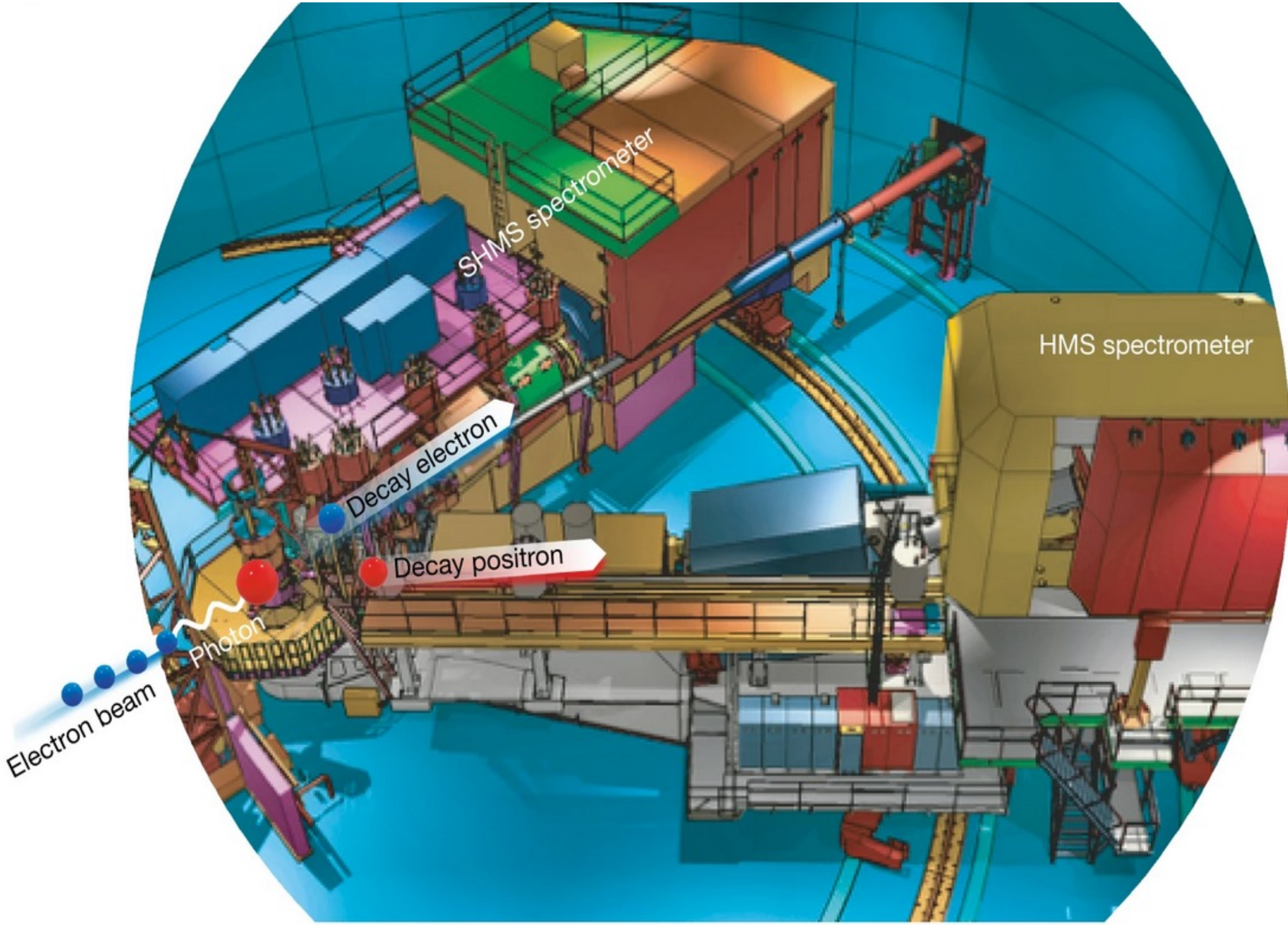
- Shown here is the differential cross section measured in:
  - $en_{bound} \rightarrow (e')e^+e^-n$
  - $ep_{bound} \rightarrow (e')e^+e^-p$
  - $ep \rightarrow (e')\mu^+\mu^-p$

- These measurements will soon be updated with an improvement in efficiency of ~25% per charged particles.



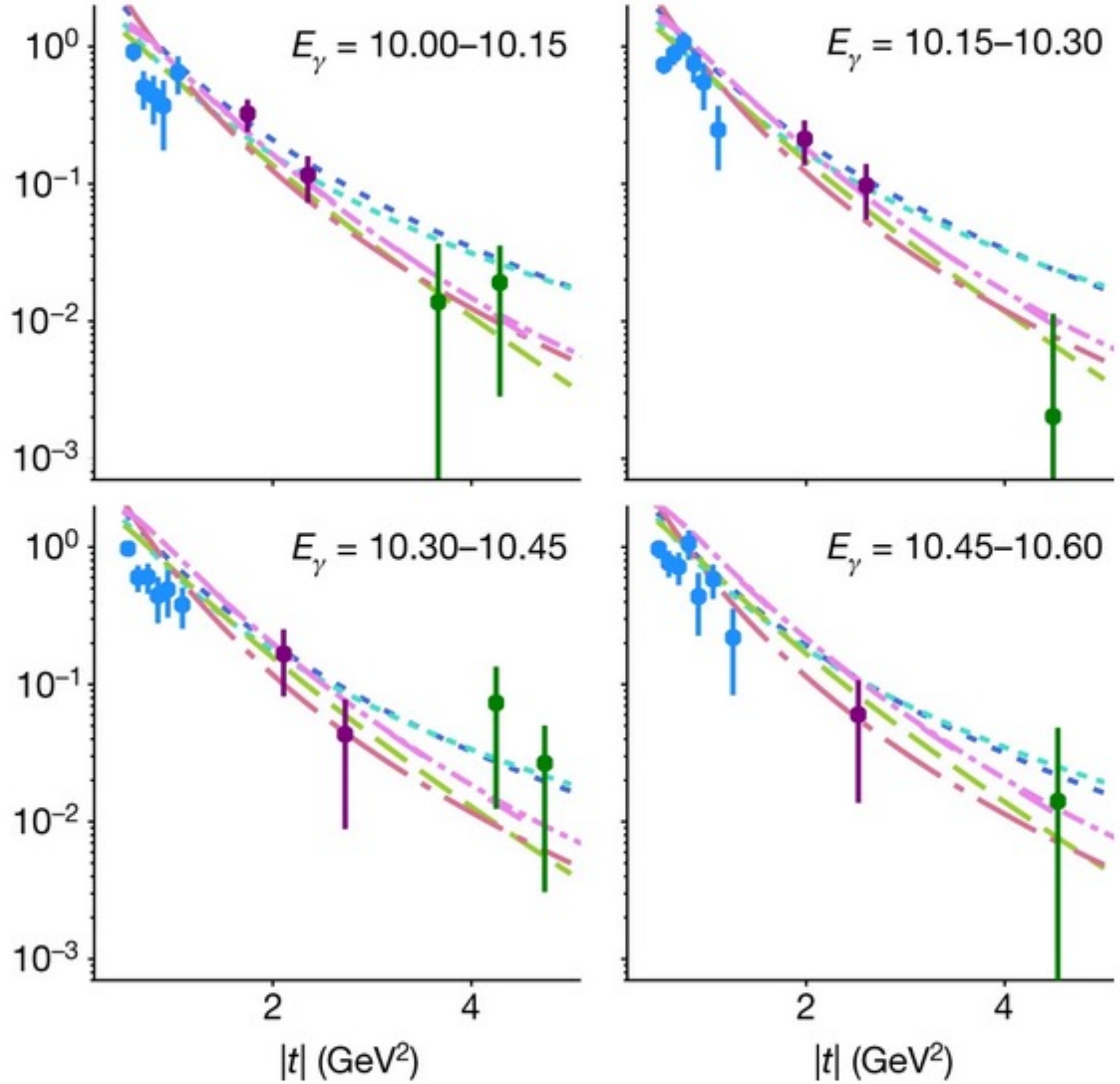
Hall C

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



J/ψ at Hall C

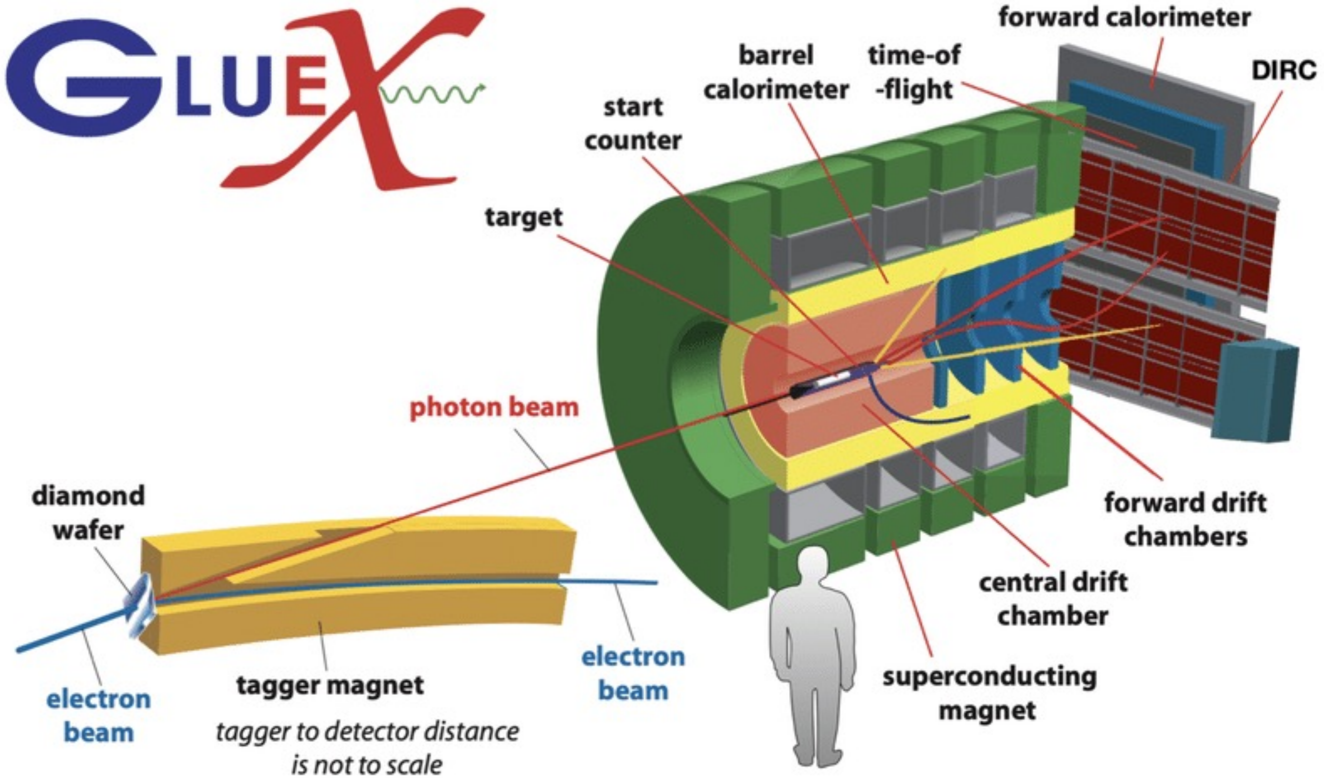
- The J/ψ – 007 Collaboration has made high precision measurements of the differential cross section as a function of t [13].
- The main objective was to probe the mechanical properties of the nucleon.
- Measurements in the decay channel of J/ψ to two muons are underway.



Measurements of the J/ψ differential cross section as a function of t energy and theoretical predictions [13].

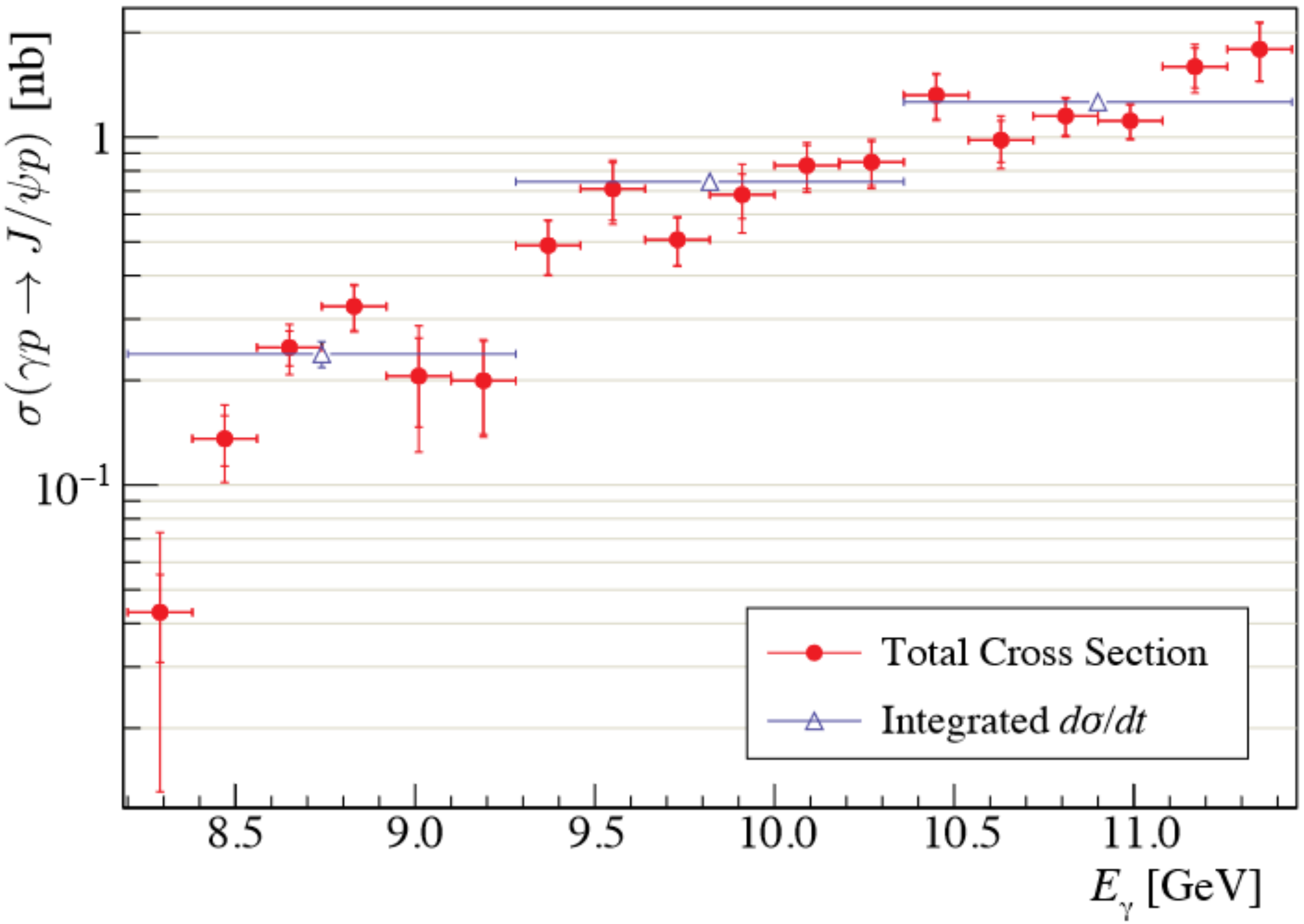
GlueX

- Beam energies up to 12 GeV are delivered to Hall D.
- GlueX produces a bremsstrahlung photon beam using the diamond wafer.
- Electrons are tagged to determine the photon energy.
- Full azimuthal coverage with polar angular coverage from ~1 to 120 degrees.



J/ψ at GlueX

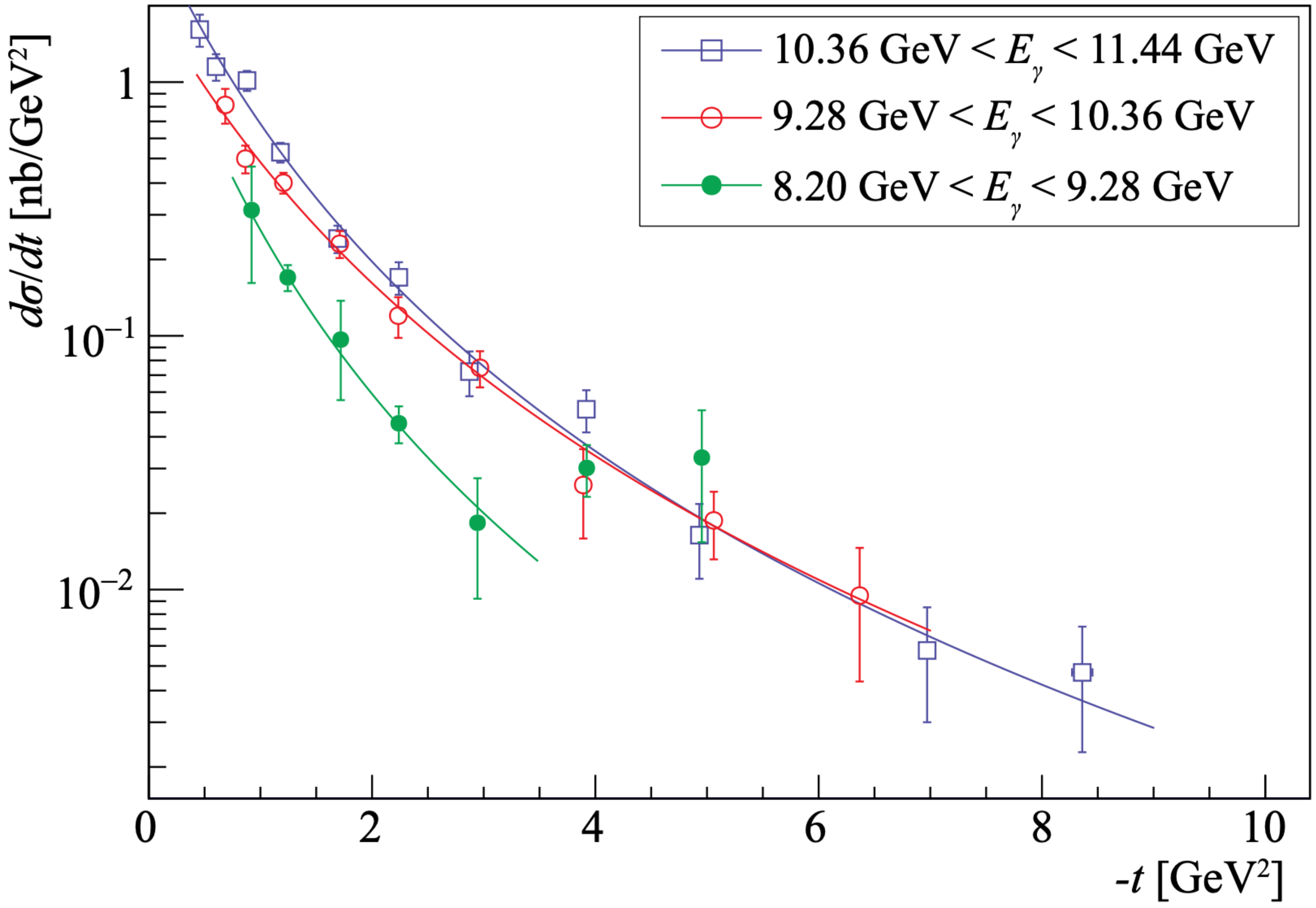
- GlueX has made high precision measurements of the J/ψ total cross section [14,15].
- The differential cross section as a function of t was also measured [14,15].



Measurements of the J/ψ total cross section as a function of the photon beam energy [15].

J/ψ at GlueX

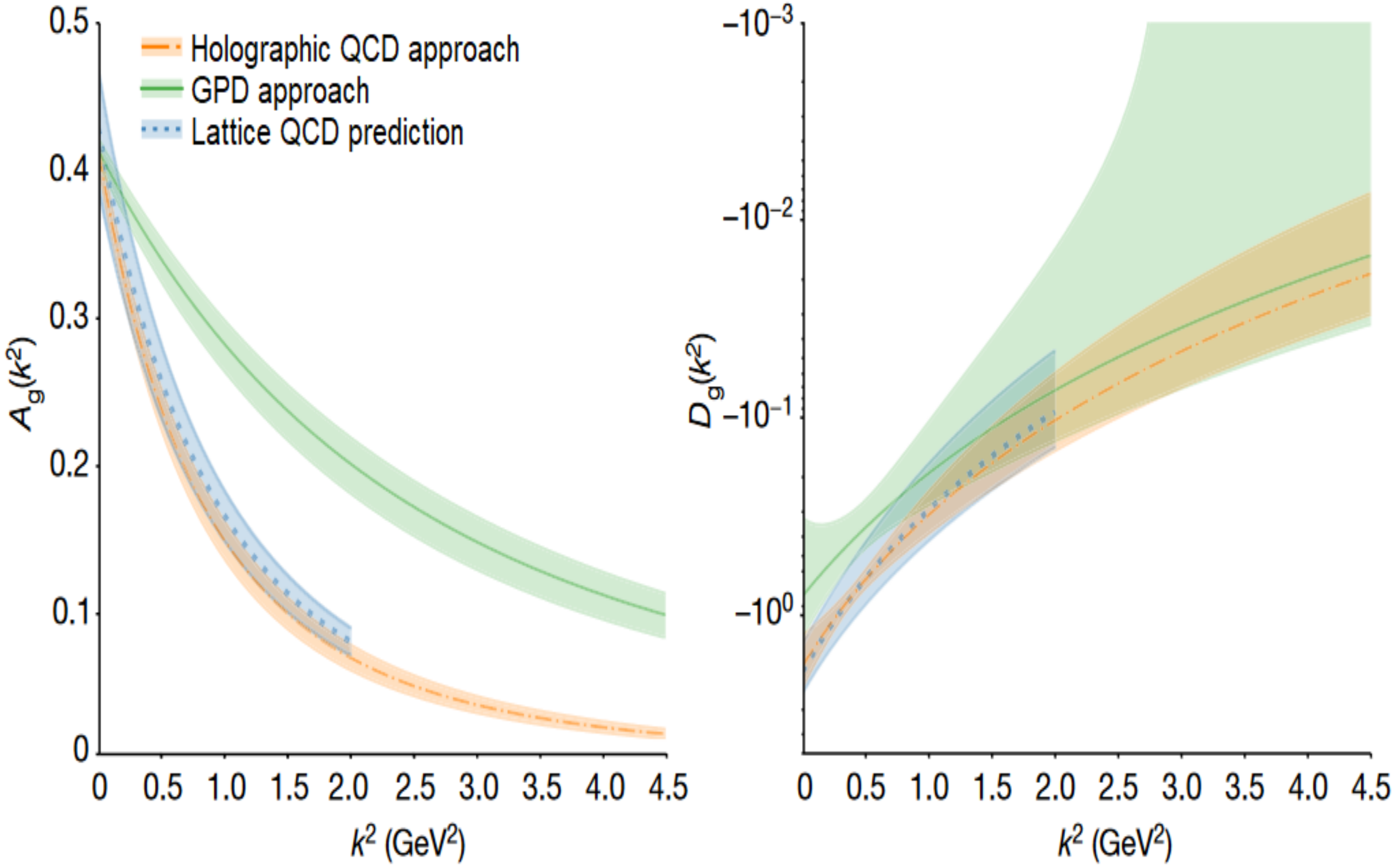
- The low t differential cross section is consistent with a dominant gluon exchange production mechanism.
- Structure in the total and differential cross sections are consistent with contributions from other production mechanisms.



Measurements of the J/ψ differential cross section as a function of –t in bins of photon beam energy [15].

Gluonic GFFs

- The $A_g(t)$ and $D_g(t)$ GFFs were estimated at Hall-C from J/ψ photoproduction [13].
- Relate to:
  - Momentum fraction of gluons in the nucleon.
  - Shear forces and pressure distribution of the gluonic content of the nucleon.
- The discrepancy between GPD and holographic models is now resolved [11].

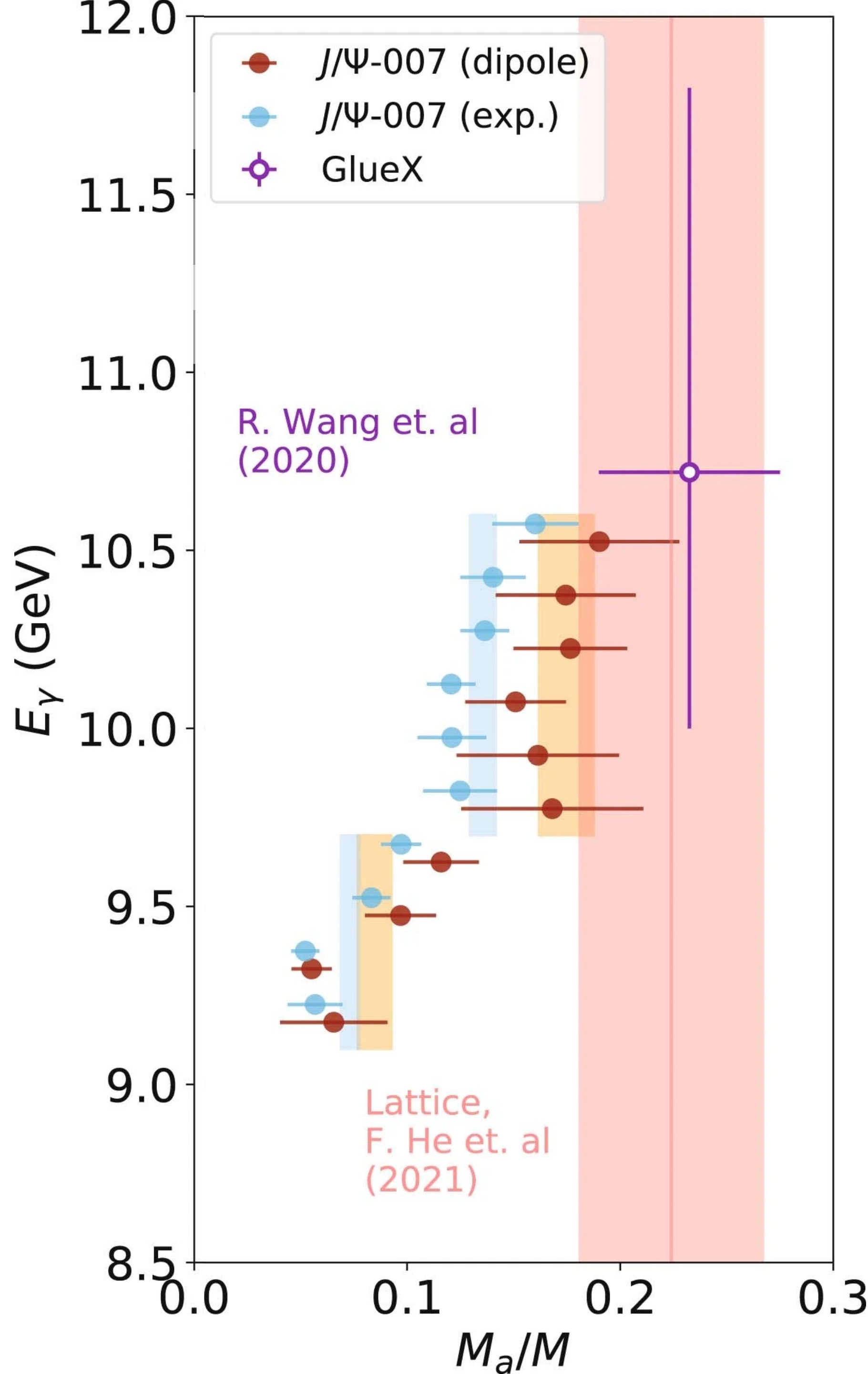


The $A_g(t)$ and $D_g(t)$ GFFs estimated using holographic QCD [10] (orange) and GPD [7] (green) models compared to lattice QCD predictions [16] (blue). ($k^2 \equiv |t|$)

Trace Anomaly Contribution to the Nucleon Mass

- The nucleon mass can be decomposed into the contributions from the quark masses, the energy of quarks and gluons and the trace anomaly contribution [17].

- Estimates of the magnitude of the trace anomaly contribution to the proton mass were obtained from GlueX and Hall C data [13,14,17].



Mass Radius of the Nucleon

- A scalar gravitational form factor $G(t)$ gives access to the mass radius of the nucleon [9].

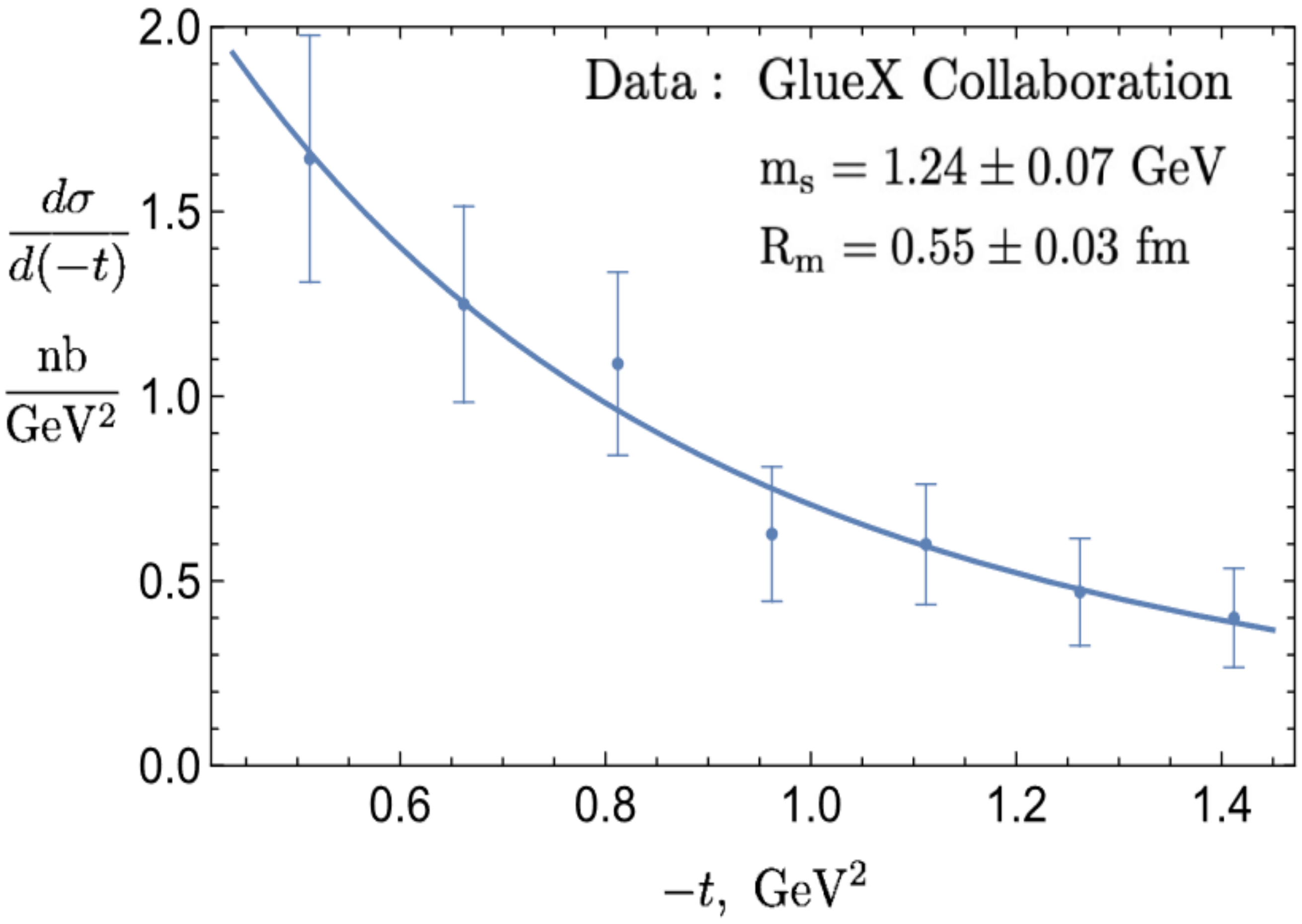
$$\frac{d\sigma}{dt} = G(t)^2$$

- 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:

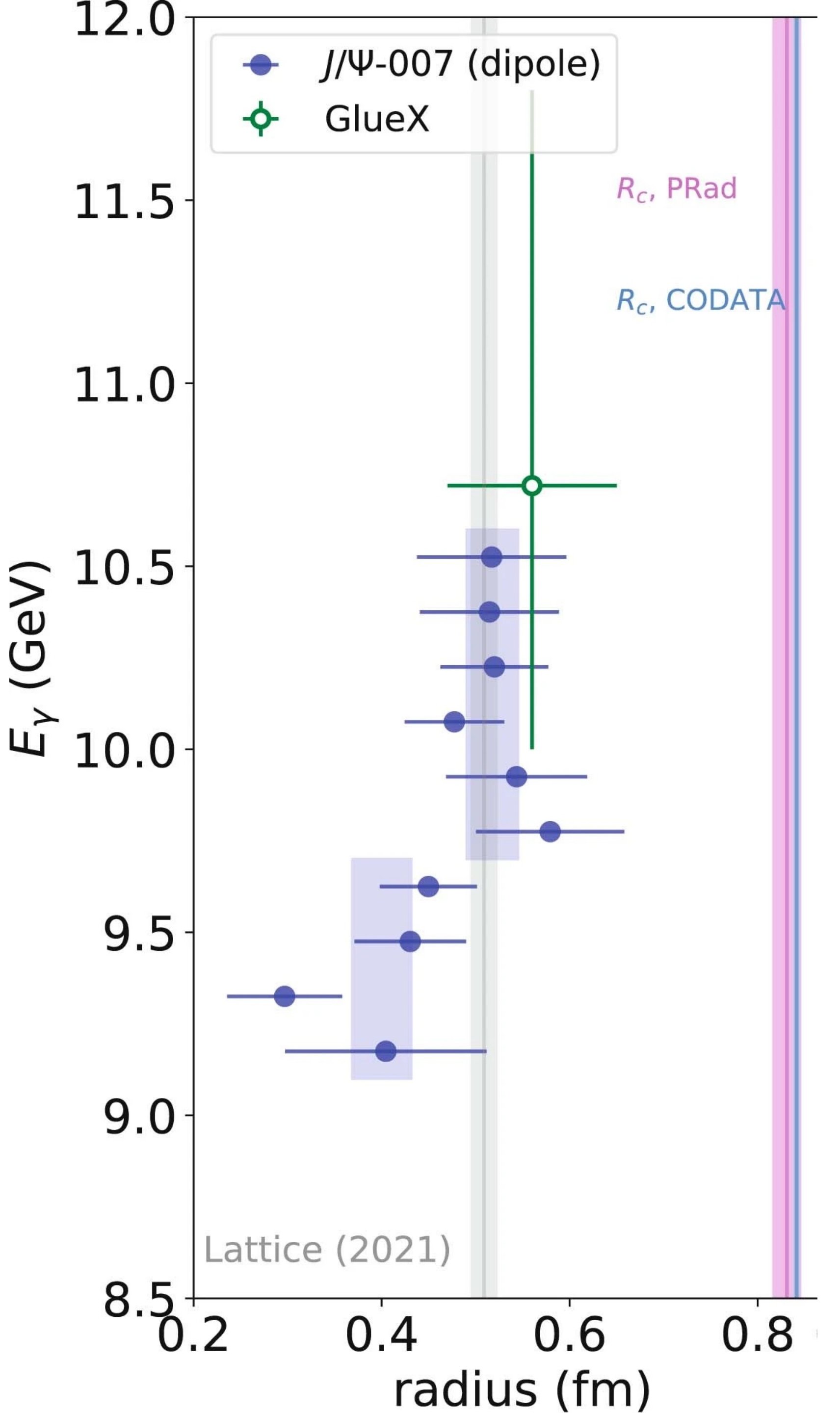
$$r_m = \frac{\sqrt{12}\hbar c}{m_s}$$



J/ψ differential cross section as a function of –t. Data from the GlueX Collaboration [14], plot taken from [9].

Mass Radius of the Nucleon at JLab

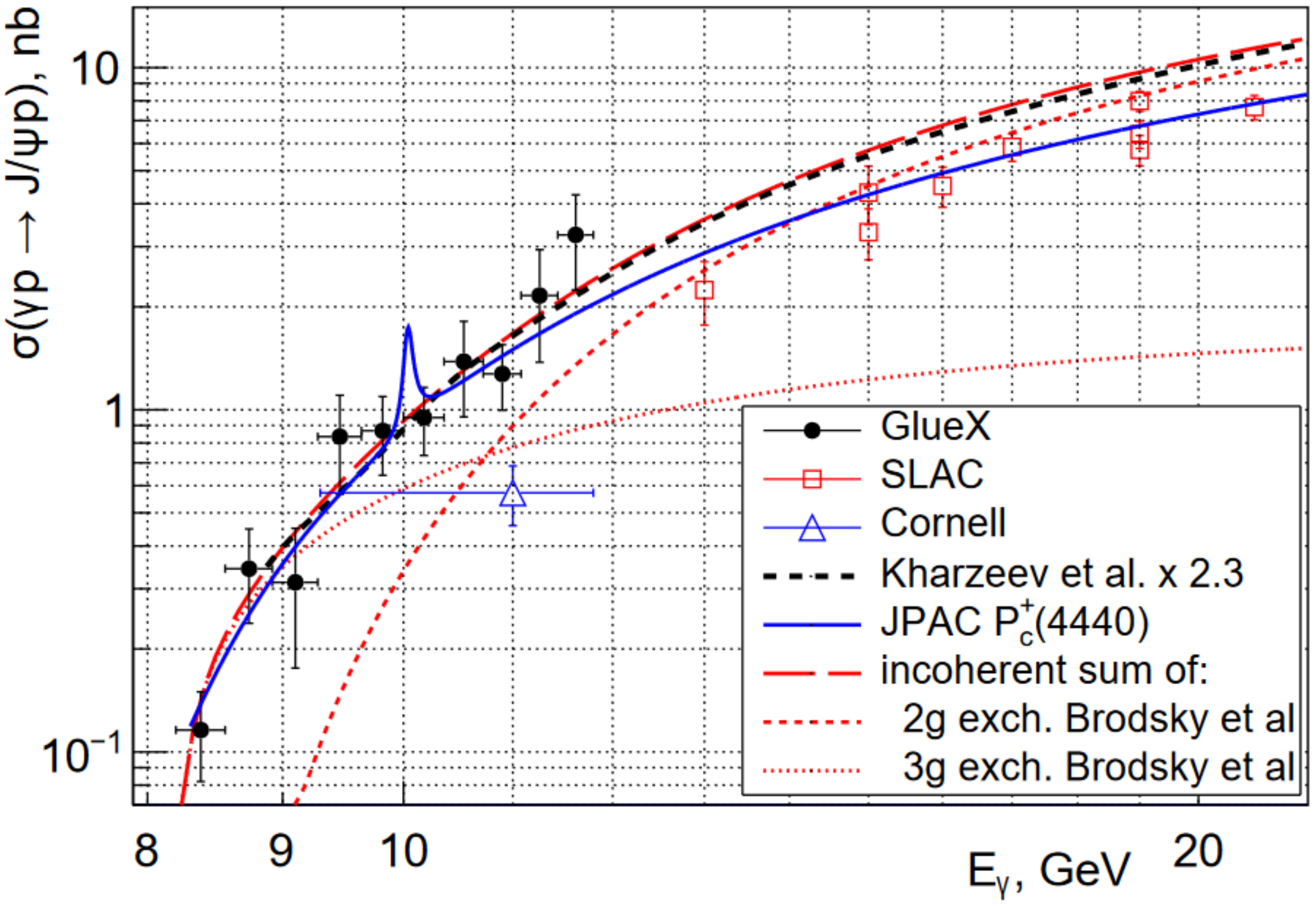
- The mass radius of the proton has been measured from GlueX and Hall C data [13,14].
- A larger charge radius than mass radius suggests than the quark radius within the nucleon is larger than the gluon radius.
- Deviations at lower photon energies might be indicative of a region where the assumption of two-gluon exchange dominance is invalid.



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 [8].

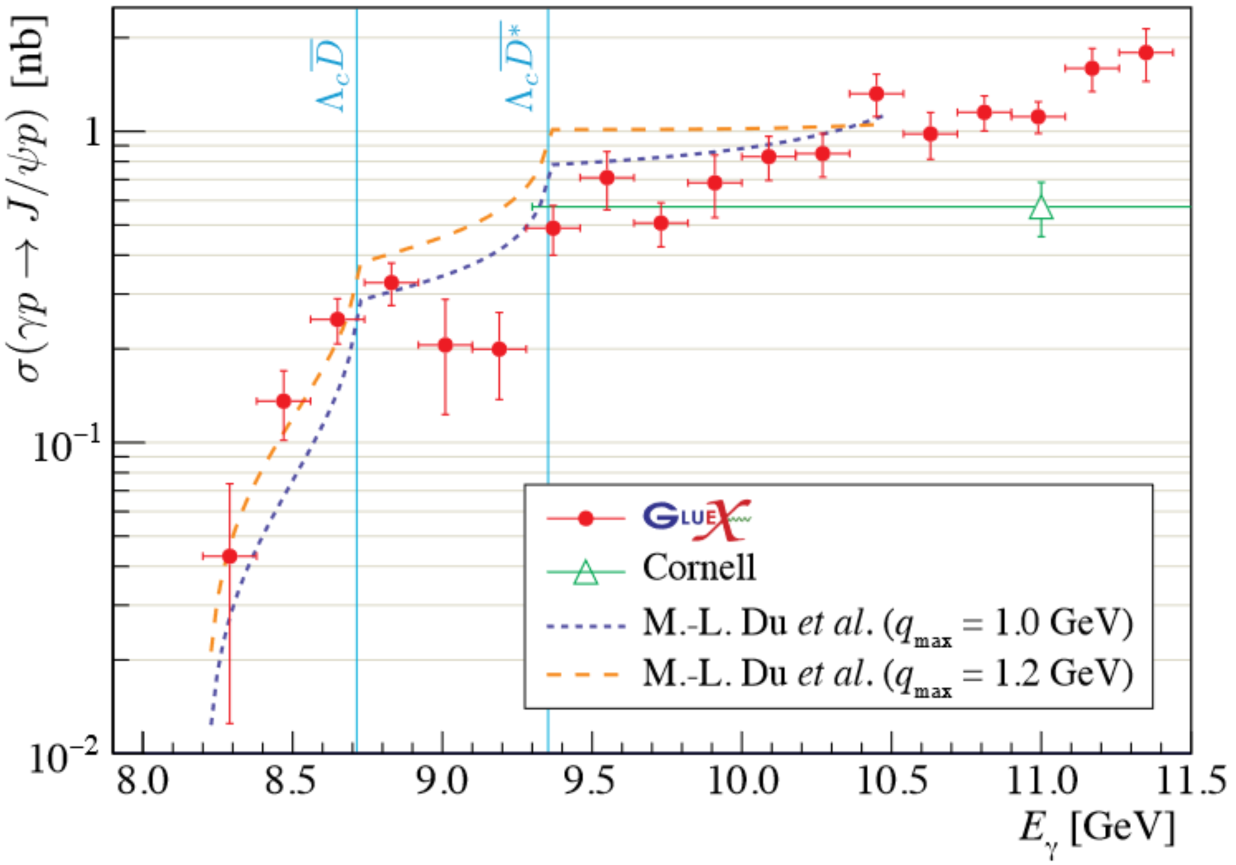
- GlueX has already identified a path forward based on an energy upgrade at JLab [18].



Measurements of the J/ψ total cross section as a function of the photon beam energy [14] compared to predictions of the 2- and 3-gluon exchange contribution [8].

Open-Charm Photoproduction?

- J/ψ near-threshold photoproduction could be dominated by open charm production of $\Lambda^c\overline{D}^{(*)}$ [19].
- JPAC analysis of GlueX and Hall C data suggests a non-negligible contribution from open-charm intermediate states [20].
- Additional data, in particular at high t, would be helpful [19,20]. Measuring $\Lambda^c\overline{D}^{(*)}$ cross sections even more so.
- J/ψ production on the neutron could place further constraint on the open charm production mechanism.



Predictions for the total cross section due to the open charm production of J/ψ p [19], which is consistent with the GlueX measurements [15] in red.

Key Takeaways

- The study of the gluonic GFFs are an active area of research at JLab.
- Understanding the J/ψ near-threshold production mechanism(s) will be key in establishing the validity of the estimates of the gluonic GFFs from J/ψ photoproduction.
- Need additional data and complementary measurements of open charm channels.

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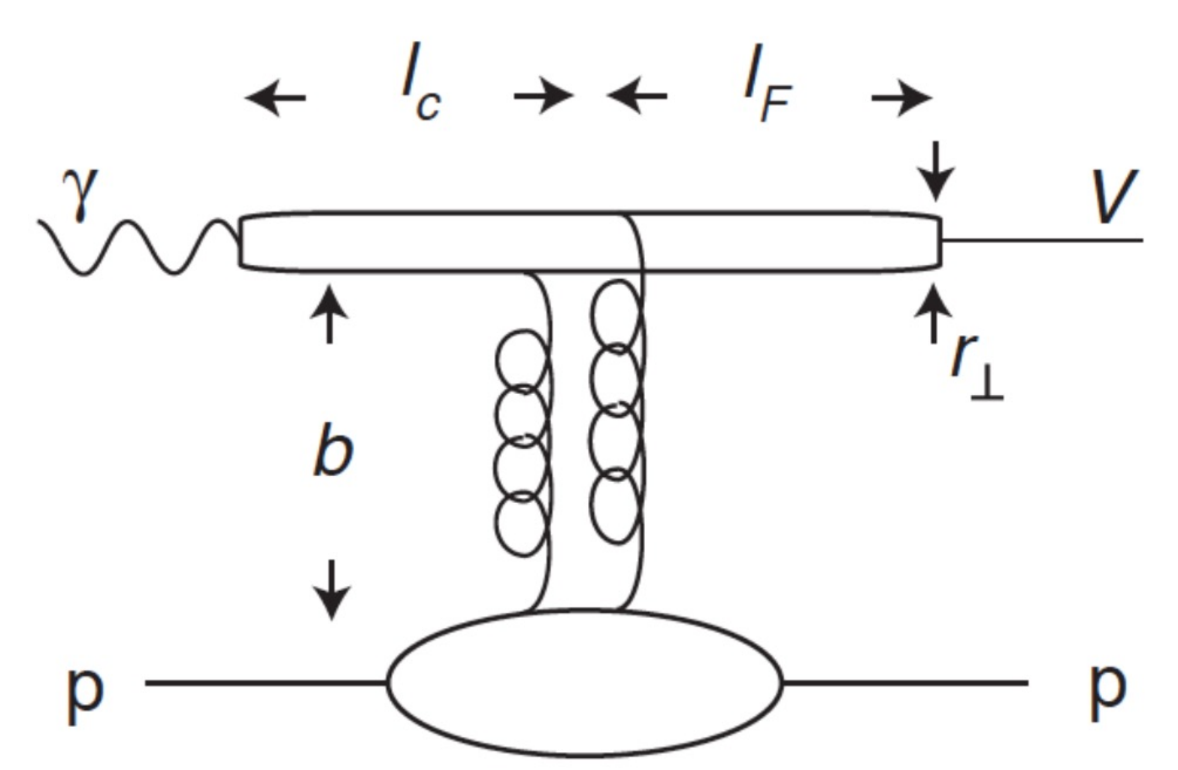
Backup Slides

J/ψ Photoproduction in VMD

- In the VMD picture J/ψ is produced on the proton in the following steps:
  - Photon γ fluctuates into a $c\bar{c}$ pair of size $r_\perp$ at a distance l_c
  - $c\bar{c}$ pair scatters off the proton with impact parameter b
  - $c\bar{c}$ forms J/ψ at some distance l_F after the scattering

$$\frac{d\sigma_{\gamma N \to VN}}{dt} = \kappa \frac{3\Gamma(V \to e^+e^-)}{\alpha_{em} m_V} \frac{d\sigma_{VN \to VN}}{dt}$$

- Near the J/ψ production threshold, the large mass of J/ψ imposes a small transverse size $r_\perp$ and impact parameter b and a large minimum momentum transfer t_{min}.
- In order to have elastic scattering at threshold, quarks in the nucleon must share the large momentum transfer and must therefore be in a compact Fock state.



Gluon Exchange

At high energies, leading twist (single gluon) exchange dominates due to a requirement for all involved quarks to be in area of $\frac{1}{m_c^2}$ [8].

At threshold, higher twist (2,3-gluon) exchange dominates due to the large momentum transfer [8].