PROCEEDINGS OF SCIENCE

Threshold charmonium photoproduction with GlueX

Lubomir Pentchev[a,*] **for the GlueX collaboration**

[a] *Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*

E-mail: pentchev@jlab.org

We report the total and differential cross sections for J/ψ photoproduction obtained using the large acceptance GlueX spectrometer at the 12 GeV JLab accelerator over the full near-threshold kinematic region. The GlueX experiment uses tagged linearly-polarized photon beam from coherent Bremsstrahlung off a thin diamond. Charmonium photoproduction near threshold, under certain assumptions including gluon exchange and factorization, can be used to study important aspects of the gluon structure of the proton, such as the gluon GPD, the gravitational form factors, the mass radius of the proton, and the anomalous contribution to the proton mass. In the measured cross sections we find evidence for possible contributions beyond gluon exchange. The results are compared to a wide range of theoretical predictions including GPD calculations and models with open-charm intermediate states. Photoproduction near threshold of charmonium states with opposite-to-photon parity offer another opportunity, complementary to the J/ψ, to understand the reaction mechanism of the charmonium photoproduction. While we see some evidence for such states, comprehensive studies of such higher-mass charmonia can be done only with the proposed JLab energy upgrade. An electron beam energy of up to 22 GeV significantly increases the photon flux and polarization in the corresponding threshold regions allowing for precise cross section and polarization measurements there.

*25th International Spin Physics Symposium (SPIN 2023),
24-29 September 2023
Durham, NC, USA*

*Speaker

PoS(SPIN2023)152

1. Introduction

The photoproduction of charmonium states near threshold gives a unique opportunity to reveal the gluon structure of the nucleon target. It is argued that the process is dominated by two-gluon exchange [1, 2]. If factorization is assumed, the gluon-proton interaction is described by the gluonic GPD of the proton [3, 4]. For high values of the skewness parameter ξ, the two gluons can mimic a graviton, which allows to study the mass properties of the proton, like the gluonic Gravitational Form Factors (gGFFs), the mass radius of proton, and the anomalous contribution to the proton mass [3–7]. Certainly, such an ambitious program requires detailed studies, both experimental and theoretical, to make sure that the above assumptions about the reaction mechanism are justified.

The 12 GeV upgrade of the Jefferson Lab electron accelerator allowed measurements of the J/ψ photoproduction near the threshold of 8.2 GeV with much higher precision than the old experiments. The GlueX experiment in Hall D performed measurements in the full near-threshold kinematic region, collecting about 2k J/ψ events [8, 9]. The J/ψ-007 experiment in Hall C collected a similar number of events in a narrower kinematic region [10].

Studies of charmonium states with higher masses, also with different J^{PC} numbers, are very important in understanding the reaction mechanism. Such studies are however limited by the maximum energy of the electron accelerator. The χ_{c1} and $\psi(2S)$ states, which have decay modes feasible for detection, have thresholds of 10.1 and 10.9 GeV respectively, very close the maximum achievable photon energy at Jefferson Lab of 11.8 GeV in Hall D. The χ_{c1} state is interesting as it has opposite-to-photon parities, $J^{PC} = 1^{++}$, requiring an odd-parity exchange. It has never been observed in photoproduction. The $\psi(2S)$ state is important to be compared to J/ψ to study the mass dependence of the photoproduction mechanism. The prospects of such studies of higher-mass charmonium states with the proposed Jefferson Lab energy upgrade [11] will be discussed.

2. J/ψ near-threshold photoproduction

The GlueX experiment uses tagged linearly-polarized photon beam from coherent Bremsstrahlung off a thin diamond. The detector is based on a $2T$-solenoid with tracking and calorimetry in the central and forward directions, providing full acceptance for J/ψ photoproduction: $\gamma p \to J/\psi p \to e^+e^-p$. The experiment measured the total cross section from the threshold of $E_\gamma =$ 8.2 GeV up to 11.8 GeV photon energy; see Fig. 1 left panel. The differential cross sections was extracted in three energy slices, covering the full kinematic range in transferred momentum squared, t; see Fig. 1 right panel. The total cross section largely follows the phase space. We see a dip at 9.1 GeV that however is not statistically significant. We also observe an enhancement at high $|t|$ in the lowest energy slice of the differential cross section, which may indicate contributions beyond the t-channel exchange. The measured total cross sections, also including the results from 1970s SLAC [12] and Cornell [13] experiments, are compared to two GPD calculations in Fig. 2 left panel. The factorization for heavy meson photoproduction at high energies has been demonstrated in Ref. [14] in leading and next-to-leading order (LO and NLO). The same calculations in LO, extended down to the threshold [15], are shown with one-sigma error band. There is a very good agreement with both, GlueX data and higher-energy SLAC results. Including NLO results in significant uncertainties, which, at the same time, means that the J/ψ photoproduction data can help in constraining the gluon

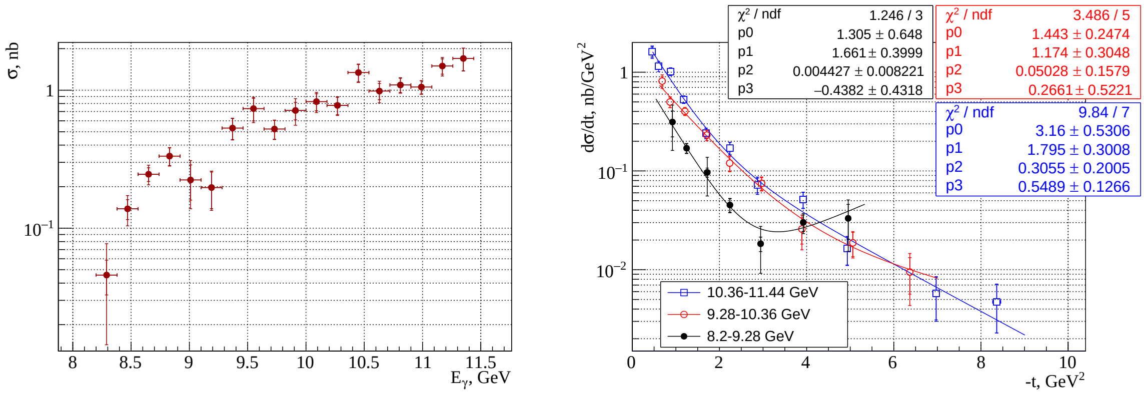

Figure 1: Total (left) and differential (right) cross sections measured by GlueX [9]. Shown are statistical and total (statistical and systematic summed in quadrature) errors. The differential cross sections are parametrized with a sum of two exponential functions: $p_0 e^{tp_1} + p_2 e^{tp_3}$.

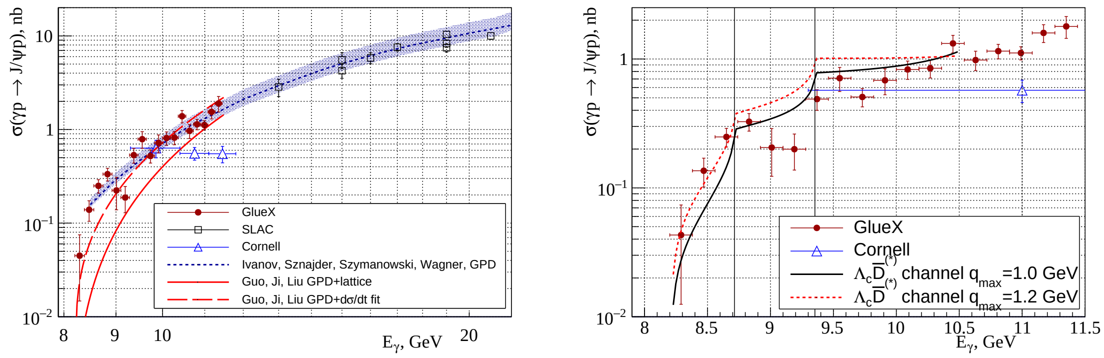

Figure 2: Comparison of the total cross section from GlueX [9], SLAC [12], and Cornell [13] with different theoretical models. Left: GPD calculations of Ref.[15] in LO (shown as one-sigma error band), and Ref. [4] (the two curves). The latter calculations use lattice results for the gGFFs [17] (solid curve), also with some parameters fitted to the GlueX differential cross sections (dashed curve). Right: Open-charm exchange of Ref. [18] - shown are the theoretical curves for two values of a model parameter. The $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ thresholds are indicated with vertical lines.

GPD of the proton. The GPD calculations in Ref. [4] are based on an expansion in the skewness parameter for $\xi \to 1$ [16], allowing to access the gGFFs. The calculations use a parametrization of the gGFFs from the lattice results in Ref. [17] as input. The results for the total cross section, when fitting some of the lattice parameters to the measured differential cross sections, are shown in Fig. 2, as well.

In Ref. [18] a reaction mechanism different from gluon exchange is proposed to describe the near-threshold J/ψ photoproduction. It is argued that the reaction may proceed through the open-charm channels, $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$, leading to cusps at the corresponding thresholds, see Fig 2 right panel. Indeed, the structure in the measured total cross section can be interpreted as evidence for such cusps, though not statistically significant. Possible interpretation of the structure as a

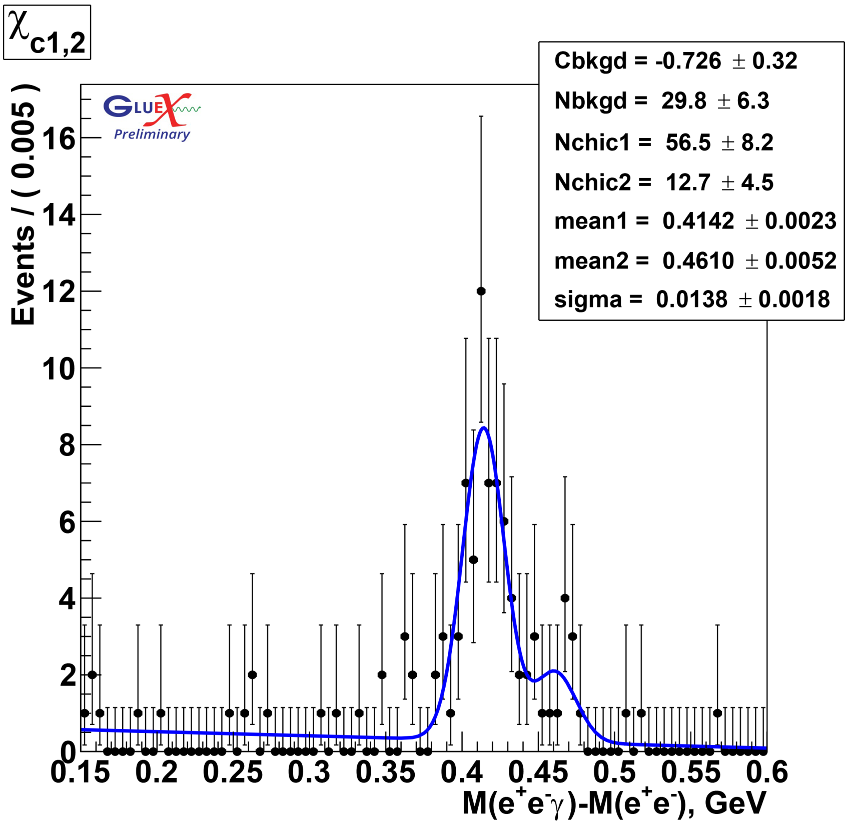

Figure 3: Preliminary GlueX results: invariant mass difference $M(e^+e^-\gamma) - M(e^+e^-)$ from the exclusive reaction $\gamma p \to e^+e^-\gamma p$. The distribution is fitted with sum of two Gaussians with integrals $Nchic1$ and $Nchic2$, mean values $mean1$ and $mean2$, and a common $sigma$, plus a linear background. The mean values, corresponding to the mass difference of χ_{c1} and χ_{c2} w.r.t. J/ψ, are very close to the PDG values [21].

resonance is also discussed [19]. In Ref. [20] the JPAC group performs phenomenological studies of all the data from Jefferson Lab. They use several models starting with gluon exchange only, and including open charm exchanges. They conclude that the present data set cannot discriminate between the different models. If the structure at 9.1 GeV is confirmed with higher statistics, this would require sizable contribution from open-charm exchange, which would obscure the studies of the mass properties of the proton.

3. Photoproduction of higher-mass charmonium states

In the GlueX data we have the first ever evidence for photoproduction of C-even charmonium states, χ_c. They are detected by their radiative decay to J/ψ: $\chi_c \to J/\psi\gamma \to e^+e^-\gamma$. In Fig. 3 we show the difference of the invariant masses of the final state particles corresponding to χ_c and J/ψ: $M(e^+e^-\gamma) - M(e^+e^-)$. The distribution is fitted with two Gaussians with a common σ. The mean values are very close to the PDG values [21] of the masses of χ_{c1} and χ_{c2} with respect to the J/ψ mass, though the fit result for the χ_{c2} state is not statistically significant.

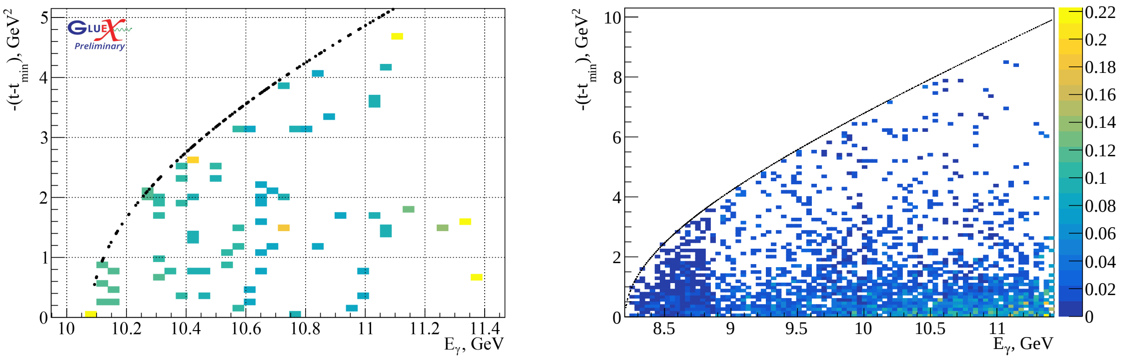

Figure 4: Preliminary GlueX results: comparison of the χ_c (left) and J/ψ (right) distributions on the $|t - t_{min}|$ vs E_γ plot. Both distributions are weighted event-by-event by the photon flux.

The photoproduction of C-even charmonium states at high energies would require exchange of a gluon state with C-odd parity, which is called odderon [22]. In the near threshold region, however, different reaction mechanisms are possible, like vector meson exchange [23], or s-channel mechanism. The threshold photoproduction of another C-even charmonium, η_c, is studied in a recent paper using holographic approach [24]. In Fig.4 we compare the 2D-distribution of the χ_c events from Fig. 3 to the J/ψ distribution, as function of $|t - t_{min}|$ and E_γ. Even though the statistics for χ_c is very low, there is a striking difference between the distributions of charmonia with different parities. The J/ψ events are concentrated close to the $|t|_{min}$ line, which is typical for t-channel exchange. For the χ_c states that have opposite-to-photon parities, the events are distributed more uniformly, a signature for a very different photoproduction mechanism.

In the GlueX data we see also a very small number of $\psi(2S)$ particles in their di-electron decay mode. The photoproduction threshold is 10.9 GeV, very close to the end point of the photon spectrum of 11.4 GeV during the production running. Certainly, comprehensive studies of such higher-mass charmonia can be done only with the proposed JLab energy upgrade.

4. Prospects with Jefferson Lab energy upgrade

A white paper has been recently published about the intent to increase the energy reach of the Jefferson Lab electron accelerator to 22 GeV [11]. This would give unique opportunities to study charmonium photoproduction near threshold.

In Fig.5 left, we demonstrate how GlueX would benefit from the energy upgrade. It shows the photon spectrum from coherent Bremsstrahlung with the current 12 GeV accelerator. By increasing the end point to 17 GeV in this example, we not only extend the energy reach above 12 GeV, but the coherent peak becomes wider covering the most important region near the J/ψ threshold. There is also increase of the intensity in the high energy region, while at low energy the change is not significant, thus keeping the same load on the detectors. To study the higher-mass charmonium states near threshold, it would be optimal to use the maximum 22 GeV electron energy.

In Fig.5 right, we plot the anticipated results for the total cross sections of charmonium photoproduction. These estimates are based on the current GlueX statistics, scaled by the photon

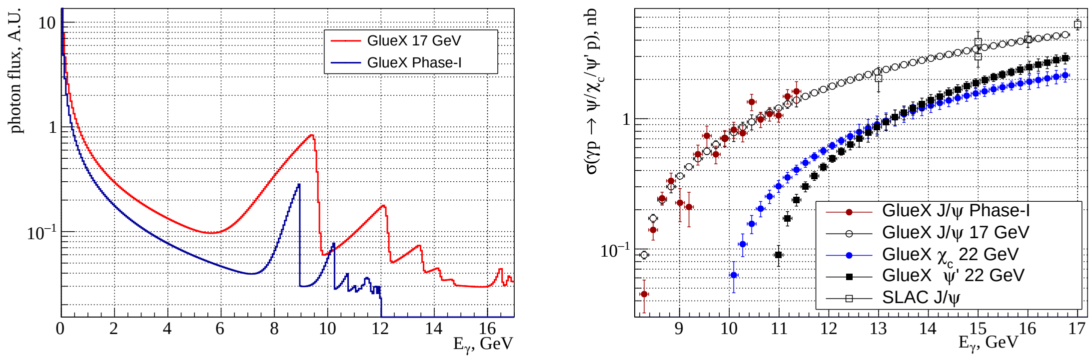

Figure 5: Left: Comparison of the photon fluxes in GlueX with 12 GeV (current accelerator energy) and 17 GeV electron beam, assuming the same running time. Right: anticipated total cross sections of charmonium photoproduction with 17 GeV (for J/ψ) and 22 GeV (for χ_{c1} and $\psi(2S)$) accelerator, compared to the existing J/ψ data.

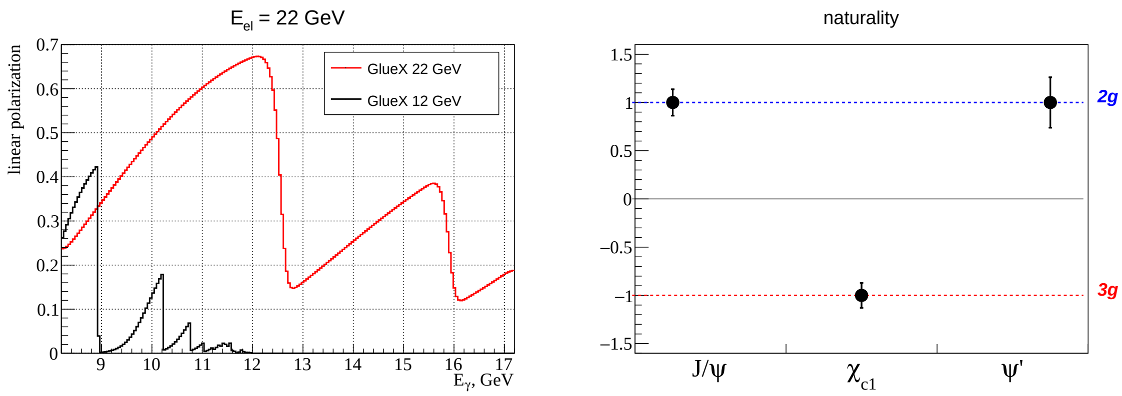

Figure 6: Left: comparison of the linear polarization of the beam photons in GlueX with 12 GeV (current accelerator energy) and 22 GeV electron beam. Right: anticipated results for $naturality \times (-1)^J$ assuming two-gluon exchange for J/ψ and $\psi(2S)$ and three-gluon exchange for χ_{c1}.

flux increase, assuming the same running time. For J/ψ the data points are sitting on a smooth fit of the available data. In case of χ_{c1} we have used the energy dependence as given in Ref. [23] normalized by the number of events detected by GlueX in the current energy region. For the $\psi(2S)$ cross section we have assumed the same energy dependence as for J/ψ also normalized by the number of detected events.

The most important benefit from the energy upgrade for the GlueX experiment would be the significant increase of the linear polarization of the photon beam, see Fig. 6 left. Thus, the 22 GeV energy upgrade would allow polarization measurements in the near-threshold region of the charmonium photoproduction. Such measurements would significantly improve our understanding of the reaction mechanism. To demonstrate this we study the naturality, defined as $P(-1)^J$, where P is the parity and J is the spin of the exchange particle. In Fig. 6 right we show the anticipated errors of such polarization measurements for the three charmonium states.

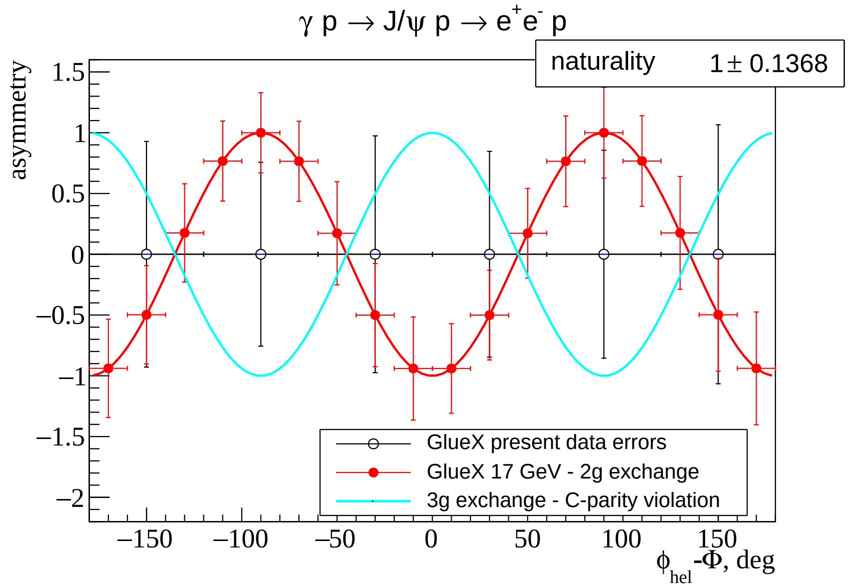

Figure 7: Measurements of the asymmetry from Eq.(1) as function of the angle difference, $\phi_{hel} - \Phi$, ϕ_h is the azimuthal angle of e^+ and e^- in the helicity frame, Φ is the angle of the polarization plane. Shown are errors only of the present measurements and anticipated results with the energy upgrade, assuming two-gluon exchange, compared to the three-gluon exchange curve.

In the experiment we measure the asymmetry defined as

$$A = \frac{2}{P_\gamma} \frac{Y_{J/\psi}(0^\circ) - Y_{J/\psi}(90^\circ)}{Y_{J/\psi}(0^\circ) + Y_{J/\psi}(90^\circ)} \tag{1}$$

where P_γ is the linear polarization of the photon beam and $Y_{J/\psi}$ are the yields depeding on the angle of the polarization plane. The asymmetry is proportional to $cos[2(\phi_{hel} - \Phi)]$ function, where ϕ_{hel} is the azimuthal angle of the decay particles, e^+ and e^-, in the helicity frame and Φ is the angle of the polarization plane. The amplitude of the asymmetry gives the naturality. In Fig. 7 we show the errors of the current measurements. They are scaled by the expected increase of the Figure Of Merit (FOM) and set on a curve assuming two-gluon exchange. The anticipated results for χ_{c1} and $\psi(2S)$ in Fig. 6 are estimated also with respect to the current J/ψ measurements. As χ_{c1} decays to two spin-1 particles, additional assumptions are made about the corresponding photocouplings. Note that the procedure in this paragraph was given to demonstrate the feasibility of polarization measurements with the energy upgrade. The actual extraction of the Spin Density Matrix Elements (SDMEs), including the naturality, uses event-by-event minimization.

In case of gluon exchange the parity of the gluons is defined by the parity of the charmonium. The photoproduction of J/ψ and $\psi(2S)$ requires two-gluon exchange that has C-even parity [2]. As χ_{c1} has opposite-to-photon parities, its production requires tree-gluon exchange with C-odd parity. As demonstrated in Fig. 6, with the 22 GeV upgrade, GlueX can perform polarization measurements with a precision that would discriminate between the gluon exchange, that is needed to study the mass properties of the proton, and the other possible reaction mechanisms.

Notice: Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irre- vocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

References

[1] S.J. Brodsky and G.A. Miller, *Is scattering dominated by the gluonic van der waals interaction?*, *Physics Letters B* **412** (1997) 125?130.

[2] P. Sun, X.-B. Tong and F. Yuan, *Perturbative QCD Analysis of Near Threshold Heavy Quarkonium Photoproduction at Large Momentum Transfer*, 2103.12047.

[3] Y. Guo, X. Ji and Y. Liu, *QCD analysis of near-threshold photon-proton production of heavy quarkonium*, *Physical Review D* **103** (2021) .

[4] Y. Guo, X. Ji, Y. Liu and J. Yang, *Updated analysis of near-threshold heavy quarkonium production for probe of proton's gluonic gravitational form factors*, *Physical Review D* **108** (2023) .

[5] Y. Hatta and D.-L. Yang, *Holographic j/psi production near threshold and the proton mass problem*, *Phys. Rev. D* **98** (2018) .

[6] K.A. Mamo and I. Zahed, *Diffractive photoproduction of j/psi and upsilon using holographic qcd: Gravitational form factors and gpd of gluons in the proton*, *Phys. Rev. D* **101** (2020) .

[7] D. Kharzeev, *Quarkonium interactions in QCD*, *Proc. Int. Sch. Phys. Fermi* **130** (1996) 105 [nucl-th/9601029].

[8] A. Ali et al. (GlueX collaboration)*Phys. Rev. Lett.* **123** (2019) 072001.

[9] S. Adhikari et al. (GlueX collaboration), *Measurement of the j/ψ photoproduction cross section over the full near-threshold kinematic region*, *Physical Review C* **108** (2023) .

[10] B. Duran, Z.-E. Meziani, S. Joosten, M.K. Jones, S. Prasad, C. Peng et al., *Determining the gluonic gravitational form factors of the proton*, *Nature* **615** (2023) 813.

[11] A. Accardi, P. Achenbach, D. Adhikari, A. Afanasev, C.S. Akondi, N. Akopov et al., *Strong interaction physics at the luminosity frontier with 22 gev electrons at jefferson lab*, 2023.

[12] U. Camerini, J. Learned, R. Prepost, C. Spencer, D. Wiser, W. Ash et al.*Phys. Rev. Lett.* **35** (1975) 483.

[13] B. Gittelman, K.M. Hanson, D. Larson, E. Loh, A. Silverman and G. Theodosiou*Phys. Rev. Lett.* **35** (1975) 1616.

[14] D.Y. Ivanov, A. Schafer, L. Szymanowski and G. Krasnikov, *Exclusive photoproduction of a heavy vector meson in QCD*, *Eur. Phys. J. C* **34** (2004) 297 [hep-ph/0401131].

[15] P. Sznajder and J. Wagner*(private communication)* (2022) .

[16] Y. Hatta and M. Strikman, *ϕ-meson lepto-production near threshold and the strangeness d-term*, Phys. Lett. B **817** (2021) 136295.

[17] D.A. Pefkou, D.C. Hackett and P.E. Shanahan, *Gluon gravitational structure of hadrons of different spin*, Physical Review D **105** (2022) .

[18] M.-L. Du, V. Baru, F.-K. Guo, C. Hanhart, U.-G. MeiÃner, A. Nefediev et al., *Deciphering the mechanism of near-threshold j/ψ photoproduction*, Eur.Phys.J.C **80** (2020) .

[19] I. Strakovsky, W.J. Briscoe, E. Chudakov, I. Larin, L. Pentchev, A. Schmidt et al., *Plausibility of the lhcb $P_c(4312)^+$ in the gluex $\gamma p \to j/\psi p$ total cross sections*, Phys. Rev. C **108** (2023) 015202.

[20] D. Winney, C. Fernandez-Ramirez, A. Pilloni, A.N.H. Blin, M. Albaladejo, L. Bibrzycki et al., *Dynamics in near-threshold j/ψ photoproduction*, 2023.

[21] M. Tanabashi et al. (Particle Data Group)*Phys. Rev. D* **98** (2018) 030001.

[22] A. Dumitru and T. Stebel, *Multiquark matrix elements in the proton and three gluon exchange for exclusive η_c production in photon-proton diffractive scattering*, Phys. Rev. D **99** (2019) 094038.

[23] Joint Physics Analysis Center collaboration, *xyz spectroscopy at electron-hadron facilities: Exclusive processes*, Phys. Rev. D **102** (2020) 114010.

[24] F. Hechenberger, K.A. Mamo and I. Zahed, *Threshold production of $\eta_{c,b}$ using holographic qcd*, 2024.