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A Unified Framework Across Multi-Experiment Vector Meson Physics Programs: JLab and J-PARC

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A Unified Framework Across Multi-Experiment Vector Meson Physics Programs: JLab and J-PARC

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High-statistics total cross sections for vector mesons, V, photoproduction at the threshold: $\gamma p \to \omega p$ (from A2 at MAMI, ELPH, and CBELSA/TAPS), $\gamma p \to \phi p$ (from CLAS6 and LEPS), and $\gamma p \to J/\psi p$ (from GlueX, 007, and CLAS12) allow one to extract the absolute value of the VN scattering lengths using the VMD model, $|\alpha_{Vp}|$. The extended analysis of Υ-meson photoproduction using quasi-data from the QCD approach agrees perfectly with the light V findings from experimental data. The "young" vector meson hypothesis may explain why the obtained scattering length for the $N\phi$ meson, compared to the typical hadron size of approximately 1 fm, indicates that the proton is more transparent to the ϕ meson than to the ω meson and is much less transparent to the J/ψ and Υ mesons, $|\alpha_{Vp}| \propto \exp(1/m_V)$. Perturbative QCD predictions support the phenomenological determination of heavy vector meson-nucleon scattering lengths. We discuss the role of the nucleon form factor F_N and calculate a possible correction to the phenomenological scattering length for heavy vector meson photoproduction using the pole form of F_N. Upcoming J-PARC threshold measurements using the π20 and K10 beamlines of the J-PARC Hadron Experimental Facility for the reactions $\pi^- p \to n\phi$ and $\pi^- p \to nJ/\psi$ will help evaluate VN scattering lengths. The phenomenological scaling $|\alpha_{VP}| \propto \exp(1/m_V)$ allows us to predict the scattering length for the open charm nucleon interaction. The possible role of heavy LHCb pentaquark $P_{c\bar{c}}$ states in low-energy J/ψ production and the effects of nucleon form factors will also be considered using J-PARC measurements.

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Keywords: vector meson-nucleon scattering length, VMD model, "young" vector meson hypothesis, open charm nucleon scattering length, heavy LHCb pentaquark states

I. INTRODUCTION

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Some vector mesons can be measured with very high precision compared to other mesons. This stems from the fact that vector mesons (Vs) have the same quantum numbers as photons: $J^{PC} = 1^{-}{}^{-}$, where J is spin, P is parity, and C is charge conjugation. Let us focus on four narrow vector mesons (ω, ϕ, J/ψ, and Υ) from the SU(4) 15-plet plus singlet structure [1] to study the dynamics of the VN interaction via vector meson photoproduction and vector meson-induced reactions at threshold to determine the VN scattering lengths (SLs).

There are no vector meson beams, so modern experiments using electromagnetic (EM) and hadronic facilities attempt to access VN interactions via EM processes:

$$e + p \to e' + V + p \tag{1}$$

and hadronic reactions:

$$\pi^- + p \to V + n\,. \tag{2}$$

Let us consider what is known from vector meson photoproduction at the threshold and what one can learn from pion-induced measurements at the threshold.

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II. PHOTOPRODUCTION RESULTS

In photoproduction, one applies Sakurai's vector meson dominance (VMD) model [5], assuming a real photon can fluctuate into a virtual one that subsequently scatters off a target nucleon. A $Q\bar{Q}$ pair is produced locally, point by point, by point-like photons, and heavy quarks do not have sufficient time to fly away to distances corresponding to the normal size of the V wave function. That is, we actually deal with a small-sized $Q\bar{Q}$ pair-proton interaction, not with normal elastic scattering:

$$V\,p \to V\,p\,. \tag{3}$$

In perturbative Quantum Chromodynamics (pQCD), the corresponding cross section is $\sigma(Q\bar{Q} + p) \propto r^2$, where r is the $Q\bar{Q}$ separation. Indeed, a small-sized ("young" [6]) colorless object is almost sterile with respect to QCD interactions. Therefore, the SL, *i.e.*, the cross section measured in photo(electro) production, is smaller than that for the (3) interaction. This is an interesting effect that we can observe in photoproduction experiments [7].

The behavior of the photoproduction cross section at threshold is sensitive to the Vp SL, $|\alpha_{Vp}|$, of the Vp systems. The Thomas Jefferson National Accelerator Facility (JLab), which currently operates with a 12 GeV beam of electrons, has the capacity to measure J/ψ photoproduction cross sections at threshold with high statistics. The threshold energy for the J/ψ photoproduction for a fixed proton target is $E = 8.2$ GeV. Fig. 1(left) shows several recent JLab measurements reported by GlueX [2], 007 [3] (data extracted from

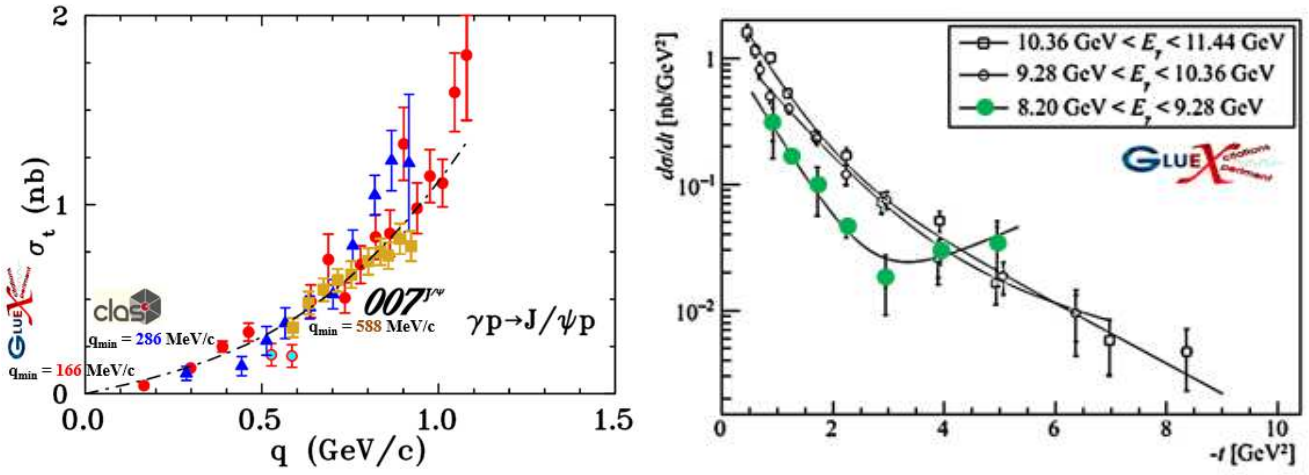


FIG. 1: Left: The total $\gamma\ p \to J/\psi\ p$ cross sections, σ_t, as a function of the J/ψ CM momentum, q, reported by the GlueX Collaboration (red filled circles) [2] (two points are filled in cyan at the dip around $q = 0.5 - 0.6$ GeV/c are discussed in the main text, Sec. VII), the 007 Collaboration (shown in yellow-filled squares [3]), and the CLAS12 Collaboration (shown in blue-filled triangles) [4]. The black dash-dotted curve represents a polynomial fit to σ_t using Eq. (4). Right: The GlueX-measured differential cross sections for the reaction $\gamma p \to J/\psi p$ with total (statistical and systematic in quadrature) uncertainties shown for the three energy regions [2]. The points are fitted with a sum of two exponential functions. The second exponential contribution is most significant in the lowest-energy bin (shown by green-filled circles and associated with the dip around $q = 0.5 - 0.6$ GeV/c in the left plot), where the slope changes sign.

Fig. 3 of Ref. [3] using ChatGPT), and CLAS12 [4]. The analysis of new threshold data by 007 and CLAS12, along with previous GlueX measurements, is given in Ref. [7].

The absolute value of SL is determined by the interplay of strong (hadronic) and EM dynamics, where the hadronic component is the linear term that comes from the best fit of $\sigma_t(q)$ for the reaction $\gamma\ p \to V\ p$:

$$\sigma_t = a_1\ q + a_3\ q^3 + a_5\ q^5\ , \tag{4}$$

the pure EM VMD-motivated kinematic factor depends on $\Gamma(V \to l^+l^-)$ [8].

The advantage of the GlueX data is that this experiment measured σ_t directly, while 007 and CLAS12 require the determination of σ_t using differential cross sections measured only at small momentum transfer t. The low statistics and energy limitations of the 007 and CLAS12 for σ_t do not allow one to "kill" a dip (2.6 standard deviations) in the GlueX data at $q = 0.5 - 0.6$ GeV/c (Fig. 1(left)), specifically, that the differential cross section in this case demonstrates different behavior compared to two "high-energy" pieces (Fig. 1(right)).

III. VECTOR MESON DOMINANCE MODEL

To estimate the theoretical uncertainty in VN SL related to the VMD model, one refers to the estimation of the cross section of J/ψ photoproduction in the peripheral model and finds a strong energy dependence close to the threshold because non-diagonal $\gamma p \to Vp$ and elastic (3) processes must have larger transfer momenta compared to elastic scattering. This results in a violation of VMD by a factor of 5 [9]. The color factor for hidden charm is $1/9$, while for open charm, it is $8/9$ [10].

Strong suppression in VN interaction close to the threshold is observed because the $Q\bar{Q}$ pair in a point-like configuration lacks sufficient time to form the complete wave function of the vector meson; that is, the proton interacts with the "young" (undressed quarks) V, whose size is smaller than that of the "old" one participating in elastic (3) scattering [6].

In a recent study, the effect of the VMD assumption was studied in the formalism of Dyson-Schwinger equations, which one can consider an alternative interpretation of "young age" in connection with QCD [11].

IV. NUCLEON FORMFACTOR

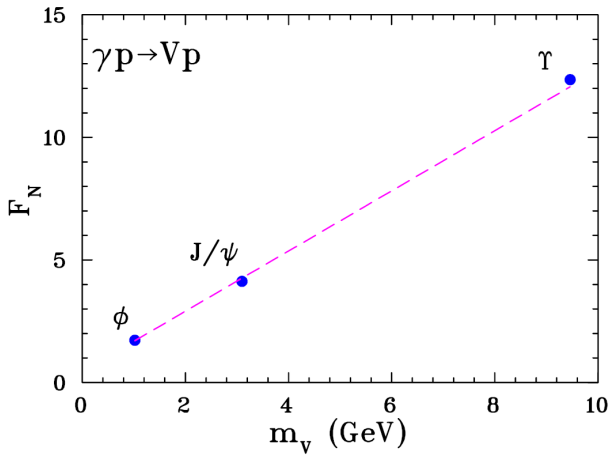


FIG. 2: Nucleon FF $F_N(t)$ vs mass of V m_V [7]. The linear dependence (magenta dashed line) of FF arose unexpectedly.

To measure the SL of heavy Vp interaction, we have to consider not ϕ, J/ψ, and Υ photoproduction, but ϕ, J/ψ, and Υ elastic scattering on a proton (3). In comparison with the elastic processes in the case of photoproduction, we have three additional factors that may depend on the mass of the V, m_V. The zero mass of the incoming photon is much smaller than the V mass. In terms of VMD, the resulting amplitude is proportional to the $\gamma \to V$ transition coupling $f_V(m_V^2)$, the probability amplitude not to destroy the target proton $F_N(t)$, and the $s\bar{s} \to \phi$, $c\bar{c} \to J/\psi$, and $b\bar{b} \to \Upsilon$ transition formfactors (FFs)$F_\phi(t)$, $F_\psi(t)$, and F_Υ, respectively. We have to emphasize that to produce a heavy V at the threshold, we need to have a rather large momentum transfer t. Thus, SL extracted via VMD from the photoproduction of heavy V will be smaller than that in elastic meson-proton scattering by a factor of $[F_N(t)\ F_V(t)\ f_V(m_V^2)]$. Keeping in mind the large uncertainty in F_N, we take $(F_V\ f_V) = 1$ [7].

We do not know the formfactor $F_N(t)$ experimentally, and for our numerical estimate, we will take the pole form: $F_N(t) = \frac{1}{1-t/\Lambda^2}$, where $\Lambda^2 = 0.71$ GeV^2 and $-t = 0.50, 2.22, \text{and } 8.07$ GeV^2 are for $\phi, J/\psi, \text{and } \Upsilon$, respectively. The linear dependence of $F_N(t)$ vs m_V in Fig. 2 has arisen unexpectedly.

Besides the formfactor suppression, we expect a smaller SL due to the "young effect" [6, 7], where the reaction, rather than proceeding through the Vp interaction, proceeds through the interaction of the recently produced $Q\bar{Q}$ pair, which is smaller than that of the fully formed vector meson.

To study both the "formfactor" and the "young effect" in more detail, it would be interesting to measure the electroproduction at Q^2 values comparable to m_ϕ^2 and $m_{J/\psi}^2$, and JLab is capable of doing that.

Recall that the aim of this project is not to build a model that describes data but to perform phenomenological analysis. Models and corresponding theoretical uncertainties can be found, *e.g.*, in Refs. [12, 13].

V. VECTOR MESON NUCLEON SCATTERING LENGTH PUZZLE

Due to the small size of "young" V vs "old" V, the measured and predicted SL is very small (Fig. 3 and Table I). V is created by a photon at threshold, so it is most probable that V is not completely formed, and its radius is smaller than that of a normal ("old") V. Therefore, one observes stronger suppression for the Vp interaction.

$p \to V$ coupling $Q\bar{Q}$ is proportional to the strong coupling α_s and the separation of the corresponding quarks. This separation (in the zero-approximation) is proportional to $1/m_V$:

$$|\alpha_{Vp}| \propto \exp(1/m_V)\,. \tag{5}$$

The problem is the "young effect." SL depends on $Q\bar{Q}$ separation. In the case of open charm, this separation is driven solely by m_Q, while in V photoproduction, it is somewhere between Vs size (which is larger than $1/m_Q$) and $1/m_Q$. That is, we expect open charm SL to be smaller than the prediction coming from this curve (one can consider this prediction as an upper limit).

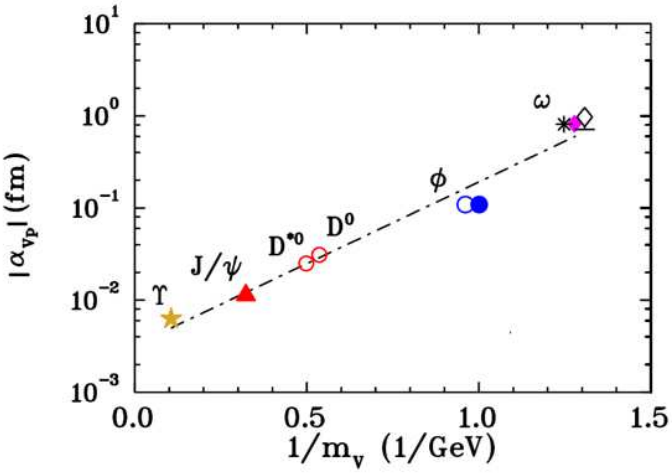


FIG. 3: Comparison of $|\alpha_{Vp}|$ estimated from threshold V photoproduction on the proton target assuming VMD versus the inverse mass of the Vs, *i.e.*, $1/M_V$. Input data for phenomenological analyses came from A2 at MAMI (magenta filled diamond) [14], ELPH (black open diamond) [15], and CBELSA/TAPS (black asterisk) [16] Collaborations for the ω-meson case; CLAS6 (blue filled circle) [17] and LEPS (black open circle) [16] Collaborations for the ϕ-meson case; GlueX, 007, and CLAS12 (red filled triangle) Collaborations for the J/ψ-meson case; and theoretical predictions from the Center for Nuclear Femtography (yellow filled star) [18, 19] for the Υ-meson case. The black dash-dotted line is a hypothetical fit to the SL data from Refs. [14, 17, 18] with high-luminosity GlueX, 007, and CLAS12 for J/ψp results using Eq. (5) and corrected by the nucleon pole form factor. Using this phenomenological scaling curve, one can predict SLs for open-charm cases, D^0N and $D^{*0}N$, shown by open red circles (see text for details).

Theory is "blind" at the threshold; most couplings for theory to understand the dynamics of V photoproduction at the threshold are unknown. Only experimental data will allow one to understand $c\bar{u}$ and qqq interaction dynamics.

A. pQCD for Vector Meson Nucleon Scattering Length

Our analysis shows an almost linear (on an exponential scale) increase in (5) with increasing $1/m_V$. This is an interesting observation; however, the behavior does not satisfy the expected asymptotic $|\alpha_{Vp}| \to 0$ as $m_V \to \infty$.

Taking current quark masses [8] with a one-loop diagram for α_s, one can obtain SL for ϕ, J/ψ, and Υ (Table I).

Of course, that is not a real perturbative QCD calculation; this is just a naive estimate. However, it demonstrates that the observed SLs are consistent with perturbative QCD and accounts for suppression due to the young effect.

TABLE I: The values of the obtained SL for vector meson photoproduction, neglecting, accounting for SL, and accounting for SL/$F_N(t)$, for the nucleon form factor effects. 1st column is the name of V. 2nd column is the phenomenological SL using the conventional VMD. Uncertainties come from our phenomenological fits of total threshold cross sections of heavy vector meson photoproduction. 3rd column is the corrected SL using the nucleon pole formfactor, $F_N(t)$. No theoretical uncertainties are added. 4th column is the prediction using naive pQCD [7]. No theoretical uncertainties are added. 5th column is the prediction using the QCD model (dynSL) from Ref. [12]. 6th column is the prediction for the coupled-channel mechanism with VMD (CC) from Ref. [13].

Meson	Photoproduction SL (fm)	SL/F$_N(t)$ [7] (fm)	pQCD [7] (fm)	dynSL [12] (fm)	CC [13] (fm)
ϕ	0.063±0.010 [17]	0.109±0.017	0.065	0.123	
J/ψ	0.00274±0.00027 [7]	0.0113±0.0011	0.0029	0.00634	0.0002-0.0030
Υ	0.00051±0.00003 [18]	0.0063±0.0004	0.00047	0.00196	

B. SU(3)$_F$ for Light Vector Meson Nucleon Scattering Length

The paper by Titov *et al.* [20] gives the relationship between SLs of ϕN and ωN using $SU(3)_F$ symmetry:

$$|\alpha_{\phi N}| = \epsilon |\alpha_{\omega N}| \,, \tag{6}$$

where $\epsilon = -\mathrm{tg}(\Delta\theta_V)$ and $\Delta\theta_V = 3.7^\circ$ represents the deviation of the $\phi-\omega$ mixing angle from the ideal mixing angle (the vector mixing angle $\theta_V = 36.5^\circ$ is very close to the ideal mixing angle [8]). This relation assumes that SL originates from light (u, d) quarks only, most likely from nucleon resonances.

The ratio of our phenomenological SL determinations $|\alpha_{\omega N}| = 0.82$ fm [14] and $|\alpha_{\phi N}| = 0.063$ fm [20] corresponds to $\Delta\theta_v = 4.4^\circ$. This result demonstrates that the determined SLs are consistent with $SU(3)_F$ predictions.

VI. J-PARC FUTURE MEASUREMENTS

The Hadron Experimental Facility (HEF) at the Japan Proton Accelerator Research Complex (J-PARC) has played a central role in addressing these questions through high-intensity hadron beam experiments (in particular, using K10 (separated and up to 10 GeV/c) and π20 (unseparated and up to 20 GeV/c) beamlines). The HEF provides intense secondary beams of pions, kaons, and antiprotons, enabling precision studies of hadron spectroscopy, hadron interactions, hypernuclear systems, and rare strangeness-related processes [21].

Additionally, hidden and open charm hadronic-induced measurements with photoproduction allow us to understand the dynamics of charm-light quark interactions and to search for the heavy LHCb pentaquarks. No open-charm and hidden-charm threshold data are available for the $\pi^- p$ initial case, and theory is "blind" because most of the couplings are unknown. All predictions for open and hidden charm production at the threshold are arbitrary. At the threshold, the proton form factor should reveal itself. However, if the process goes via some resonance/pentaquark, there may be a slightly different form factor.

A. $\pi^- p \to \phi\, n$

There are no threshold measurements for $\pi^- p \to \phi\, n$, and the J-PARC E95 experiment is capable of performing them [22]. Theoretical predictions for ϕ production cross section span a wide range, from 1 μb to 60 μb at $W = 2$ GeV, depending on the interpretations of these limits [23–28].

The sharp rise in the total cross section near the threshold is due to sub-threshold N^* contributions. To explain the discrepancy between theory and experiment around $W \approx 2.15$ GeV, one can introduce a new $N^*(2150)$ decaying into $N\phi$ [26]. As an alternative, Ref. [24] proposes $N^*(2080)$, decaying into $N\phi$ as well.

New $\pi^- p \to \phi\, n$ E95 measurements allow us to understand the dynamics of $s\bar{s}$ production at the threshold. It is free from VMD and allows for determining ϕp SL independently of JLab photoproduction [17].

B. $\pi^- p \to J/\psi\, n$

To understand the dynamics of $c\bar{c}$ production at the threshold, the J-PARC P111 proposal is being developed [29]. The spectrometer MARQ is equipped with Dilepton Detectors. They are core equipment for this experiment.

Still no threshold measurements for the reaction $\pi^- p \to J/\psi\, n$. Theoretical predictions for J/ψ production cross section span a huge range, from 1 pb to 50 nb at $W = 4.4$ GeV, depending on interpretations of these limits [23, 30–33]. If the cross section reaches approximately 4 nb at $p = 9.5$ GeV/c, the anticipated J/ψ yield in the momentum range of $p = 8.2 - 11.0$ GeV/c is estimated to be 10^4 events. Let us note that the hybridized Regge model, for instance, predicts a huge difference between the thresholds for ϕ and J/ψ production, by a factor of 10^6 [23].

Polarized measurements are essential for model-independent PWA. J/ψ is somewhat polarized. Still, it is much less polarized than Drell-Yan dilepton production, as Fermilab measurements of the polarization of J/ψ in pA inclusive production at 800 GeV have shown by the NuSea Collaboration [34, 35]. The J/ψ polarization matrix is measured via the angular distribution of electrons in $J/\psi \to e^+e^-$ decay. The J-PARC experiment P111,

JLab GlueX, 007, and CLAS12 may also help resolve the polarization effects in quarkonium production.

A key distinction of the $\pi^- p \to J/\psi\, n$ reaction at J-PARC is that, unlike photon-induced reactions — where a photon creates a quark pair $Q\bar{Q}$ at the interaction point, as seen in JLab at GlueX, 007, and CLAS12 — the pion-induced process involves two quarks that are already separated from the beginning. We would add, however, that in the s-channel resonance, $c\bar{c}$ separation may be different from that in J/ψ photoproduction.

VII. PLAUSIBILITY OF HEAVY PENTAQUARK IN GLUEX AND J-PARC DATA

The search for exotics (tetraquarks, pentaquarks, *etc.*) has a long history, spanning more than 50 years. There is a renaissance now, which Fig. 4 illustrates. If we have no chance to find exotics, then we will face a fundamental question: WHY are there no exotics?

A. GlueX Results

Most analyzes of the GlueX J/ψ photoproduction looked for the LHCb heavy pentaquarks [36] as bumps in the total cross sections and reported only upper limits (see, for instance, [38]). One concern regarding the apparent dip (2.6σ [2]) in the GlueX data at $q = 0.5\tilde{}0.6$ GeV/c ($W = 4.2\tilde{}4.3$ GeV)[1] (Fig. 1(left)). This could hypothetically be caused by destructive interference between the s-channel pentaquark state, plausibly the $P_c(4312)^+$) observed at LHCb (Fig. 5(left) [36], and nonresonant J/ψ production (Fig. 5(right) [37].

Phenomenologically, the total cross section of the inelastic reaction (J/ψ photoproduction) using Landau-Lifshitz normalization is

$$\sigma_t = \frac{\pi}{4k^2} \sum_{J=0}^{\infty} (2J+1)|f|^2 \,, \tag{7}$$

where k is the photon CM momentum, J is the total angular momentum, and the amplitude is

$$f = b + R\exp(2i\alpha) \,, \tag{8}$$

where b is the non-resonant background, R is the resonance contribution (presumably a relativistic Breit-Wigner function), and α is the relative (interference) phase shift that comes from the data fitting. The relative phase leads to constructive (bump) or destructive (dip) interference for a particular partial wave.

[1] While the 007 data [3] lacks coverage in q to make a firm statement about the existence of the dip, more recent CLAS12 electroproduction at small Q^2 [4] does not show evidence of the dip. Still, the data uncertainties are very large (low statistics), making it difficult to resolve this puzzle.

Let us note that the effect of charm exchange in the J/ψ photoproduction is smaller than that of gluon exchange [13]. The gluon contribution can be strongly suppressed due to the "young" effect [37]. Furthermore, the interference between open charm and gluon exchange may produce a dip, but there is room for a resonance (Fig. 5(right)) [37].

B. J-PARC in Future

Furthermore, the J-PARC P111 experiment is suitable for searching for isospin partners of the $P_{c\bar{c}}$ states [36] via the $\pi^- p \to J/\psi\, n$ reaction near the threshold.

We therefore consider whether simple background or resonance interference is capable of reproducing the low-energy behavior visible in the cross-section data. Through interference, the cross section can develop either a peak or a dip (through constructive or destructive interference). We suggested applying the rearrangement interference to reveal faint resonance signals (amplification by interference with a strong background signal). Relative phase leads to constructive (bump) or destructive (dip) interference for a particular partial wave [37].

A pedagogical review of quantum interference is given in Ref. [39].

Fig. 6 shows samples of the cross sections for the $\pi^- p \to J/\psi n$ process with significant interference vs. interference phase of $\alpha = 0°$, $90°$, $180°$, and $270°$ in Eq. (8) [40]. We look forward to seeing the P111 data and its ability to observe heavy pentaquark(s).

VIII. SUMMARY

- "Young" vector meson hypothesis may explain the fact that the obtained scattering length value for ϕp, compared to the typical hadron size of 1 fm, indicates that the proton is more transparent for the ϕ-meson compared to the ω-meson and is much more transparent for the J/ψ-meson:

$$|\alpha_{\Upsilon N}| \ll |\alpha_{J/\psi N}| \ll |\alpha_{\phi N}| \ll |\alpha_{\omega N}| \,. \tag{9}$$

- Furthermore, pQCD predictions support the phenomenological determination of heavy vector meson-nucleon scattering lengths.

- J-PARC can measure $\pi^- p \to \phi\, n$ by E95 and $\pi^- p \to J/\psi\, n$ by P111 at thresholds that are free from VMD, which is an important input for phenomenological PWAs.

- Upcoming J-PARC P111 threshold measurements of the inelastic reaction $\pi^- p \to J/\psi\, n \to (l^+ l^-)\, n$ will help evaluate the possible role of the heavy pentaquark $P_{c\bar{c}}$ states in low-energy J/ψ production and the effects caused by the nucleon formfactor.

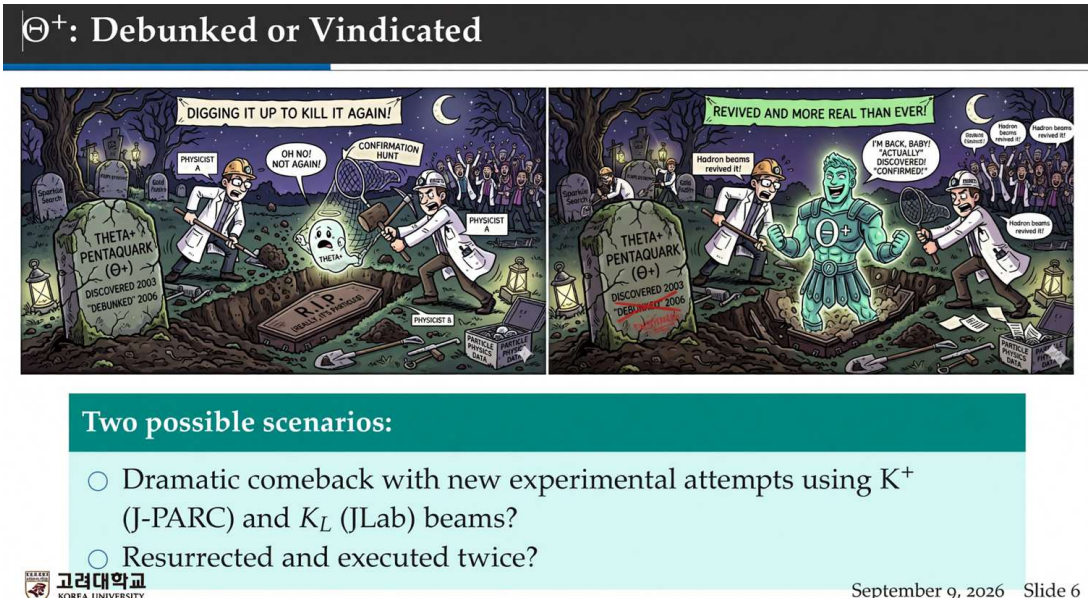


FIG. 4: Slide from Jung Keun Ahn's talk at the *15th International Workshop on the Physics of Excited Nucleons* (NSTAR 2026), Seville, Spain, September 7-11, 2026.

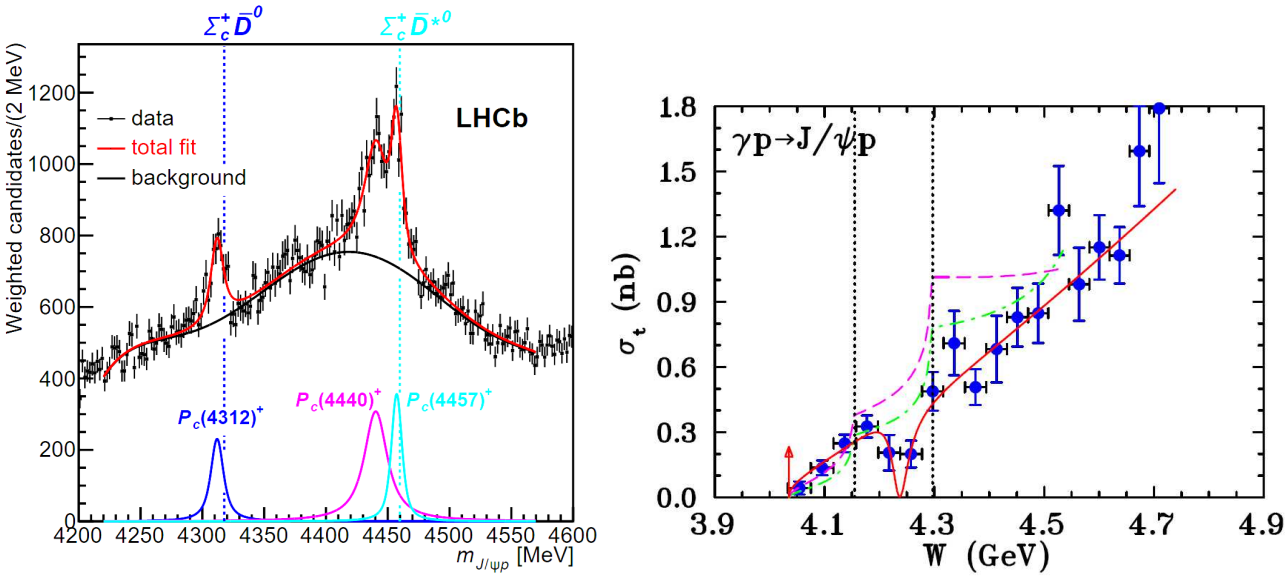


FIG. 5: Left: Fit to the $J/\psi p$ mass distribution, in which events were weighted to suppress $\Lambda^* \to pK^-$ backgrounds, of three Breit-Wigner functions and a sixth-order polynomial background. This fit was used to determine the central values of the masses and widths of the $P_{c\bar{c}}^+$ states reported by LHCb [36]. The mass thresholds for the $\Sigma_c^+\bar{D}^0$ and $\Sigma_c^+\bar{D}^{*0}$ final states are superimposed. Right: The GlueX total cross section for the $\gamma p \to J/\psi\, p$ photoproduction (blue filled circles) [2]. The magenta dashed (green dash-dotted) curve shows the hidden-charm model predictions [13] with $q_{max} = 1$ GeV/c ($q_{max} = 1.2$ GeV/c). This model does not fit the GlueX data and has no normalization factor. The phenomenological best- fit result including the effect of the destructive interference is shown by the red solid curve [37]. Vertical black dotted lines show $\Lambda_c\bar{D}^{(*)}$ thresholds. The red vertical arrow indicates the J/ψ production threshold ($W = 4.035$ GeV).

- JLab further studies on both nucleons and nuclei by SRC and by CLAS12 RGA and RGK in heavy vector meson photo(electro) production will significantly extend our knowledge of the gluonic structure of nuclear matter.

- The EIC at BNL allows us to understand the dynamics of $s\bar{s}$, $c\bar{c}$, and $b\bar{b}$ production at the threshold.

IX. DECLARATION

Ethics approval and consent to participate: Not applicable. This work is theoretical and does not involve human

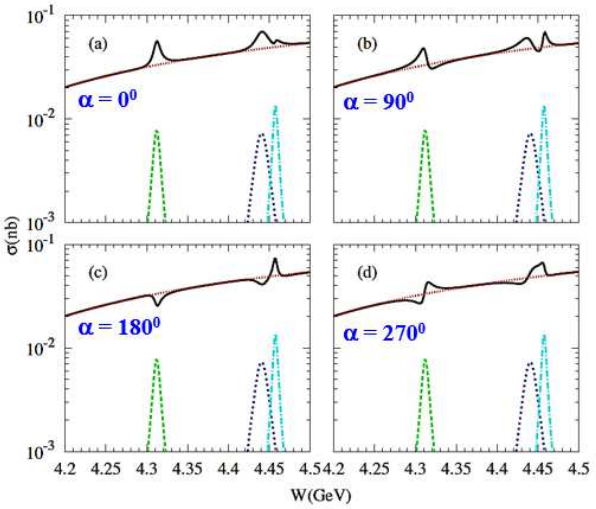


FIG. 6: The cross sections for $\pi^- p \to J/\psi n$ process with significant interference [40]. The black solid, green dashed, blue dotted, cyan dash-dotted, and red fine-dotted lines represent the total cross section, $P_{c\bar{c}}(4312)$, $P_{c\bar{c}}(4440)$, and $P_{c\bar{c}}(4457)$, and background contributions, respectively. The interference phase α in Eq. (8) is shown on each plot in blue.

participants, human tissue, or animal experiments.

Consent for publication: Not applicable.

Availability of data and materials: The data and materials supporting the findings of this study are available from the author upon reasonable request.

Competing interests: The author declares that there are no competing interests.

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Author's contributions: The author conceived the study, carried out the analysis, interpreted the results, and wrote the manuscript.

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