Reaction Models for Heavy Meson Production
J/ψ / ϒ Photo-production

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Phys.Rev.C 86 (2012) 065203
Phys.Rev.C 100 (2019) 035206
Phys.Rev.D 101 (2020) 074010
Chin.Phys.C 44 (2020) 084102

Strong QCD from Hadron Structure Experiments - VI
2024. 05. 17 Nanjing University

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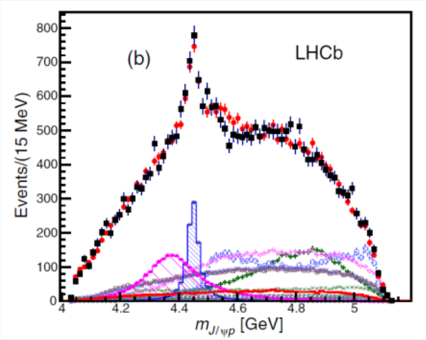
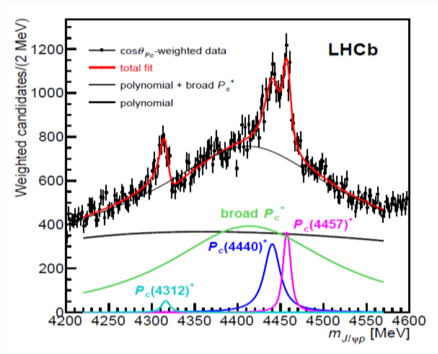
Outline

- Motivation
- γ p → J/ψ p
- γ p → Υ p
- Summary

Motivation

- In 2015, LHCb group first found two peaks of J/ψp invariant mass spectrum from $\Lambda_b \rightarrow J/\psi K p$ reaction. In 2019, LHCb group updated the new results.





Phys.Rev.Lett. 115 (2015) 072001
Phys.Rev.Lett. 122 (2019) 222001

There are 1744 citations and 792 citations.

- In 2010, baryon states with hidden charm has been predicted as the molecule states of $\bar{D}^{(*)}\Sigma_c$. Phys. Rev. Lett. 105, 232001 (2010)
- But the spin and parity (J^p) are not determined.
- We hope to find P_c in $\gamma\, p \rightarrow J/\psi\, p$.

Motivation

- There are so many paper to study γ p → J/ψ p related to P_c

[1] Y. Huang, J. He, H.-F. Zhang, and X.-R. Chen, JPG 41, 115004 (2014).
[2] Q. Wang, X.-H. Liu, and Q. Zhao, PRD92, 034022 (2015).
[3] V. Kubarovsky and M. B. Voloshin, PRD92, 031502 (2015).
[4] M. Karliner and J. L. Rosner, PLB752, 329 (2016).
[5] A. N. Hiller Blin, C. Fernandez-Ramirez, A. Jackura, V. Mathieu, V. I. Mokeev, A. Pilloni, and A. P. Szczepaniak, PRD 94, 034002 (2016).
[6] E. Ya. Paryev and Yu. T. Kiselev, NPA978, 201 (2018).
[7] X.-Y. Wang, X.-R. Chen, J. He, PRD 99, 114007 (2019)
[8] Xu Cao and Jian-ping Dai, PRD 100, 054033 (2019)
[9] J.-J. Wu, T.-S.H. Lee, B.-S. Zou PRC 100, 035206 (2019)
[10] Zhi Yang, Xu Cao, Yu-Tie Liang, Jia-Jun Wu CPC 44, No. 8 (2020) 084102
[11] X. Wang, X. Cao, A.-q. Guo, L. Gong, X.-S. Kang, Y.-T. Liang, J.-J. Wu, and Y.-P. Xie arXiv:2311.07008
[12] T. S. H. Lee, S. Sakinah, and Y. Oh, Eur. Phys. J. A 58, 252 (2022).
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- The roles of gluons (g) in determining the structure of hadrons and hadron-hadron interactions. The progress in this direction can be made by investigating the interactions between the nucleon and the quark-antiquark ($\bar{q}q$) systems which do not share the same up (u) and down (d) quarks with the nucleon. γ p → J/ψ p / Υ p

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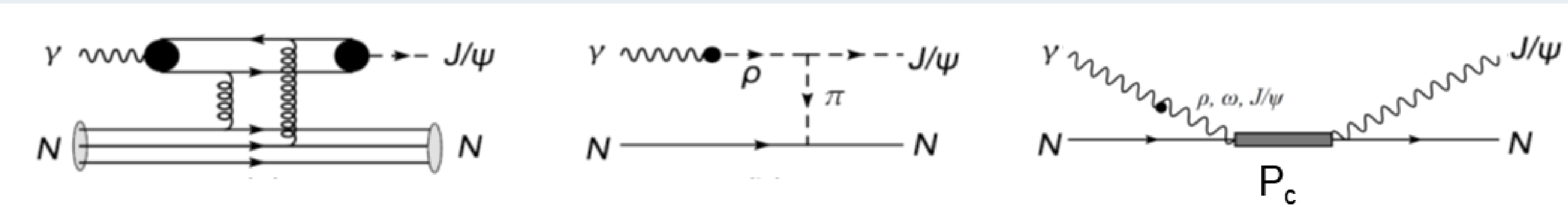
γ p → J/ψ p

J.-J. Wu, T.-S.H. Lee, B.-S. Zou PRC 100, 035206 (2019)

- **Feynman Diagram**



- **Formulas** A. Donnachie and P. V. Landshoff, Nucl. Phys. B244, 322 (1984), [813(1984)].

$$\frac{d\sigma}{d\Omega} = \frac{1}{(2\pi)^2}\frac{m_N m_B}{4W^2}\frac{1}{4}\sum_{\lambda_\gamma,\lambda_M}\sum_{m_s,m_s'}\left|\bar{u}_p(p',m_s')\epsilon^*_\mu(q',\lambda'_{J/\Psi})\mathcal{M}^{\mu\nu}(q,p,q',p')u_p(p,m_s)\epsilon_\nu(q,\lambda_\gamma)\right|^2$$

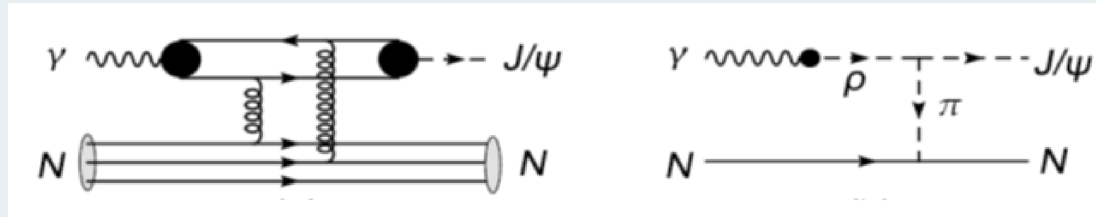
$$\mathcal{M}^{\mu\nu}_P(q,p,q',p') = \left(\frac{s}{s_0}\right)^{\alpha_P(t)-1}\exp\left\{-\frac{i\pi}{2}\left[\alpha_P(t)-1\right]\right\} i12e\frac{M_V^2\beta_q\beta_{q'}}{f_V}\frac{1}{M_V^2-t}\left(\frac{2\mu_0^2}{2\mu_0^2+M_V^2-t}\right)\frac{4M_N^2-2.8t}{(4M_N^2-t)(1-t/0.71)^2}\{\gamma.q g^{\mu\nu}-q^\mu\gamma^\nu\}$$

$$\mathcal{M}^{\mu\nu}_\pi(q,q',p,p') = \frac{e}{f_\rho}\frac{g_{J/\Psi,\rho^0\pi^0}}{m_{J/\Psi}}\frac{f_\pi}{m_\pi}\frac{-m_\rho^2}{q^2-m_\rho^2+i\Gamma_\rho m_\rho}\frac{\Lambda_\rho^4}{\Lambda_\rho^4+(q^2-m_\rho^2)^2}\frac{1}{t-m_\pi^2}\left(\frac{\Lambda_\pi^2-m_\pi^2}{\Lambda_\pi^2-t}\right)^4\epsilon^{\mu\nu\alpha\beta}q'_\alpha q_\beta\left(\gamma.(p'-p)\right)\gamma^5$$

$$\mathcal{M}^{\mu\nu}_{N^*(\frac{1}{2}^-)}(q,p,q',p') = \sum_{V=J/\Psi,\rho,\omega} g_{1J/\Psi}\gamma_5\tilde{\gamma}_\alpha\tilde{g}^{\alpha\mu}(q)\frac{\gamma.(q+p)+m_{N^*_{c\bar{c}}}}{W^2-m^2_{N^*_{c\bar{c}}}+i\Gamma_{N^*_{c\bar{c}}}m_{N^*_{c\bar{c}}}}F_V(0)\times\frac{ie}{f_V}\frac{-m_V^2\tilde{g}_{1V}}{-m_V^2+i\Gamma_V m_V}\gamma_5\tilde{\gamma}_\beta\left(g^{\beta\nu}-\frac{3}{2}\frac{\tilde{r}^\beta\tilde{r}^\nu}{\tilde{r}^2}+\frac{1}{2}\tilde{g}^{\beta\nu}_{N^*}\right)$$

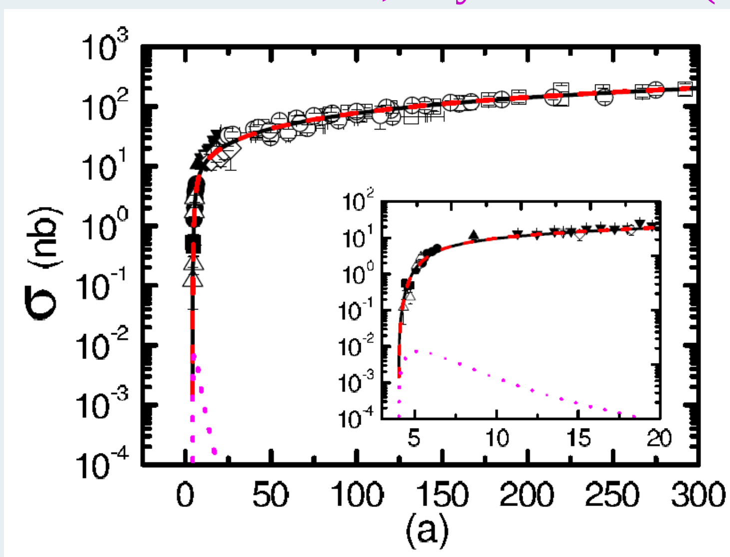
$\gamma\, p \rightarrow J/\psi\, p$

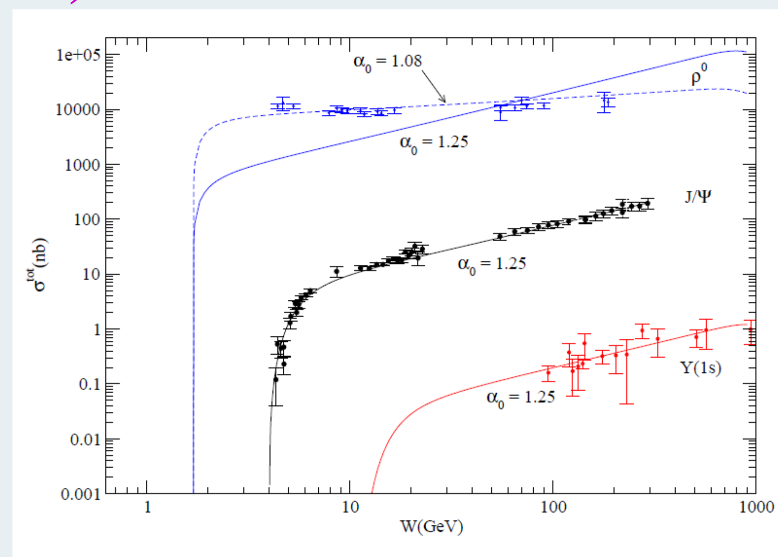
- **Feynman Diagram**



Jia-jun Wu and T.-S. H. Lee, Phys.Rev.C 86 (2012) 065203

- **Result**





$$\mathcal{M}_P^{\mu\nu}(q,p,q',p') = \left(\frac{s}{s_0}\right)^{\alpha_P(t)-1} \exp\left\{-\frac{i\pi}{2}\left[\alpha_P(t)-1\right]\right\} i12e\frac{M_V^2\beta_q\beta_{q'}}{f_V}\frac{1}{M_V^2-t}\left(\frac{2\mu_0^2}{2\mu_0^2+M_V^2-t}\right)\frac{4M_N^2-2.8t}{(4M_N^2-t)(1-t/0.71)^2}\{\gamma.qg^{\mu\nu}-q^\mu\gamma^\nu\}$$

$\alpha_P(t) = \alpha_0 + \alpha'_p t$ $\qquad \alpha_0 = 1.08 \qquad \alpha_0 = 1.25$

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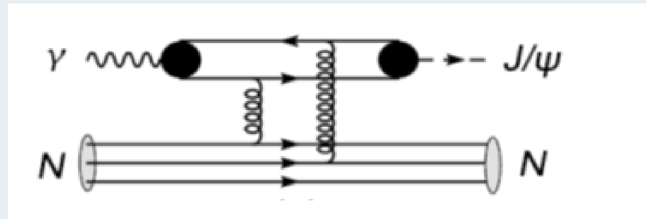
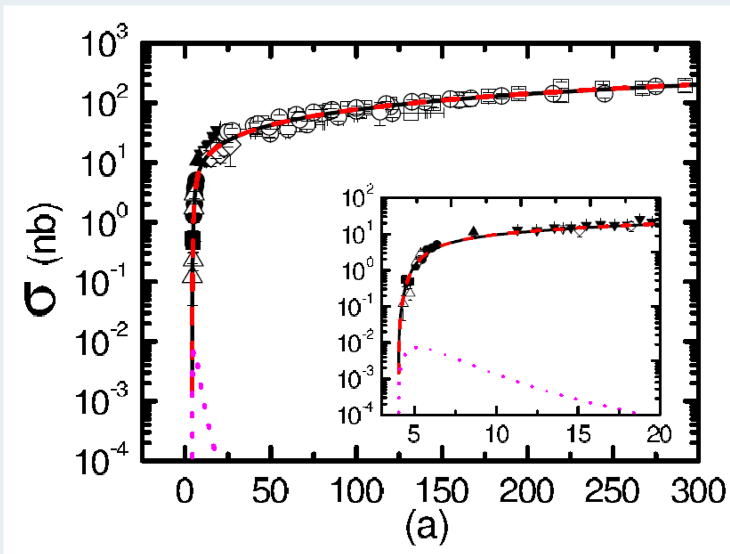
$\gamma\, p \rightarrow J/\psi\, p$

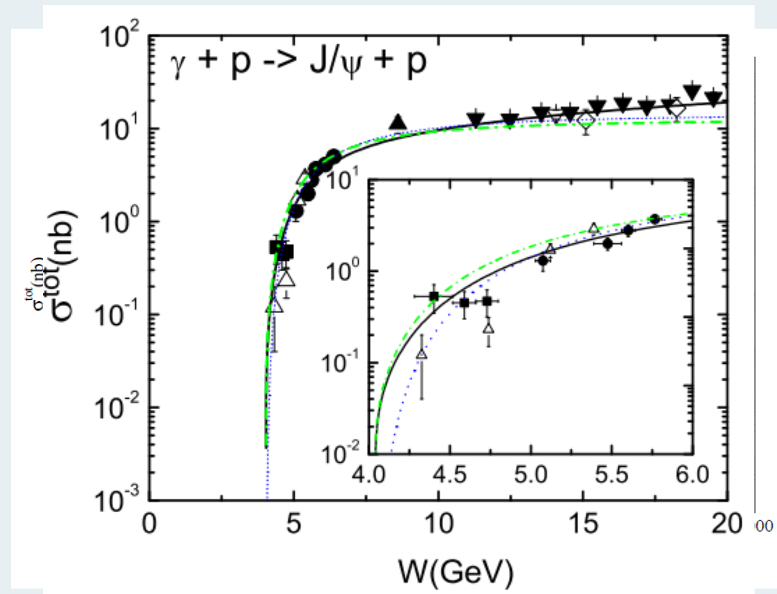
- **Feynman Diagram**



$$M_{2g} = \frac{A_{2g}}{4\sqrt{\pi}} \frac{1-x}{R m_{J/\psi}} e^{bt/2},$$
$$M_{3g} = \frac{A_{3g}}{4\sqrt{\pi}} \frac{1}{R^2 m_{J/\psi}^2} e^{bt/2},$$
$$x = \frac{2 m_N m_{J/\psi} + m_{J/\psi}^2}{W^2 - m_p^2}.$$

- **Result**





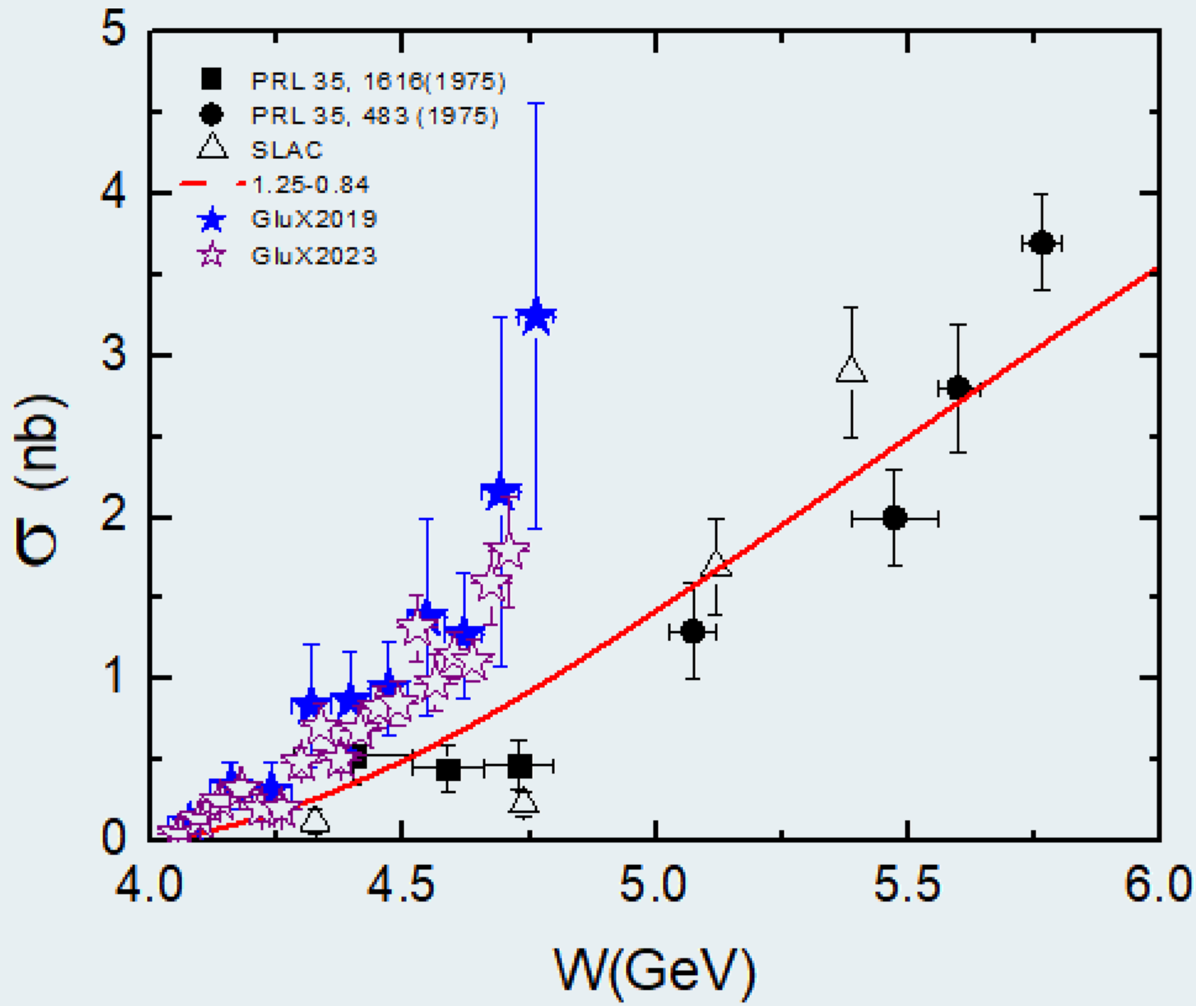
Jia-jun Wu and T.-S. H. Lee, Phys.Rev.C 86 (2012) 065203

S. J. Brodsky, E. Chudakov, P. Hoyer, and J.M. Laget, Phys. Lett B498, 23 (2001)

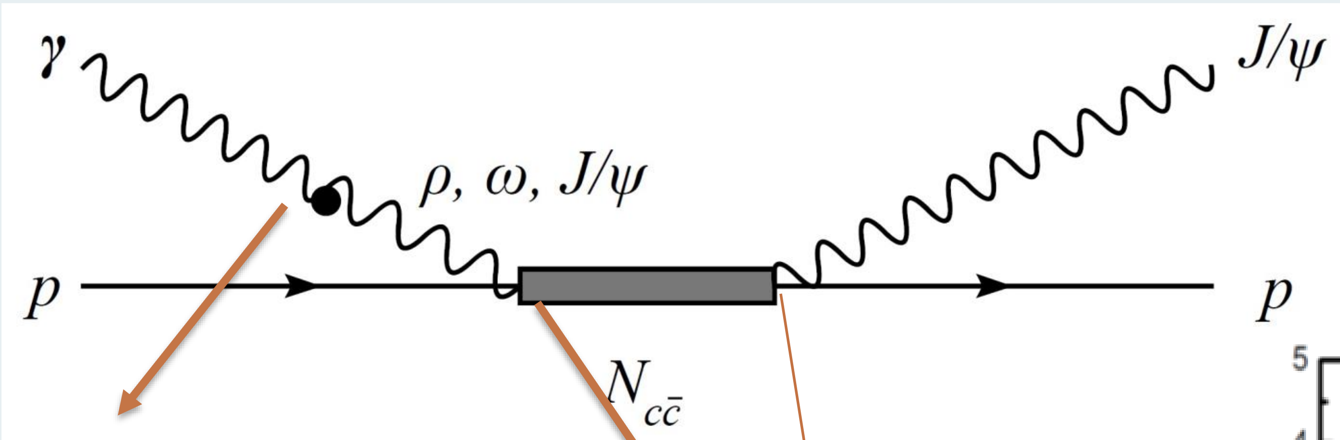
γ p → J/ψ p background mechanism

- **Result**

The Pomeron exchange still take very important role even at the threshold of J/ψ production.



$\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$



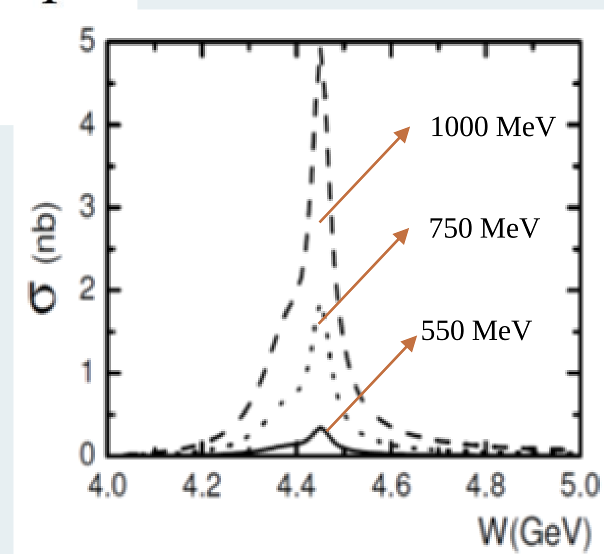
VMD vertex

Off shell

On shell

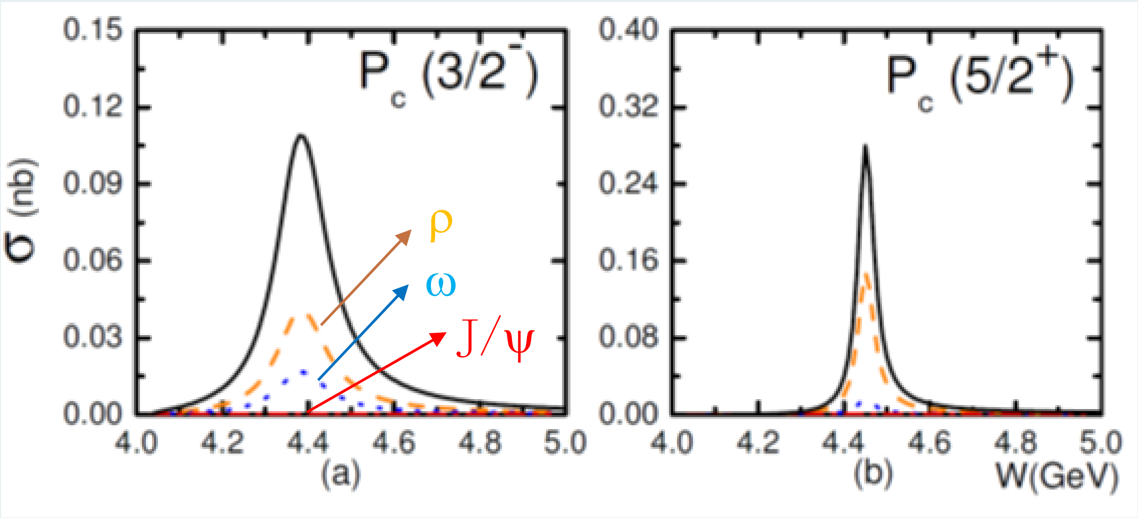
PcγP vertex

PcVP vertex

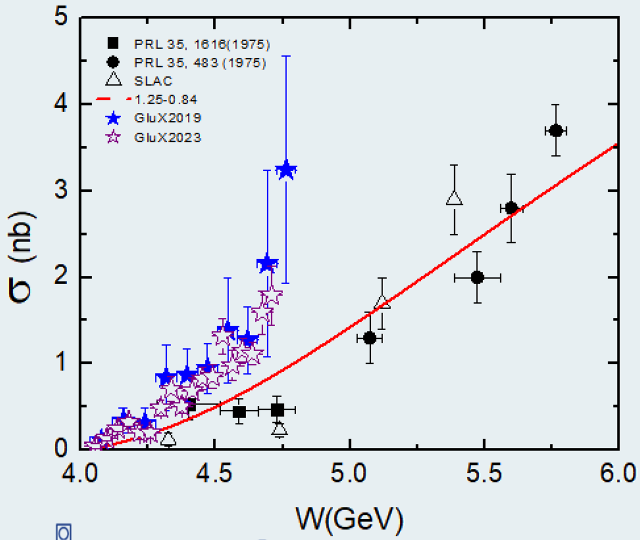


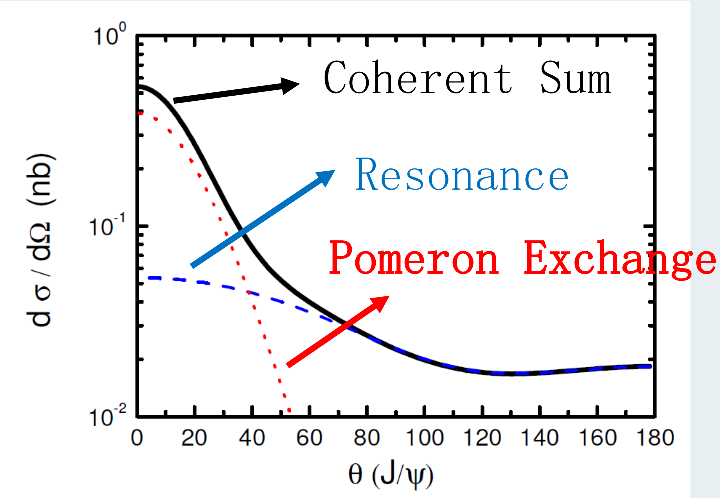
$$\mathcal{M}^{\mu\nu}_{N^*(\frac{1}{2}^-)}(q,p,q',p') = \sum_{V=J/\Psi,\rho,\omega} g_{1J/\Psi}\gamma_5\tilde{\gamma}_\alpha \tilde{g}^{\alpha\mu}(q)\frac{\gamma.(q+p)+m_{N^*_{c\bar{c}}}}{W^2-m^2_{N^*_{c\bar{c}}}+i\Gamma_{N^*_{c\bar{c}}}m_{N^*_{c\bar{c}}}} F_V(0)\times\frac{ie}{f_V}\frac{-m_V^2\tilde{g}_{1V}}{-m_V^2+i\Gamma_V m_V}\gamma_5\tilde{\gamma}_\beta\left(g^{\beta\nu}-\frac{3}{2}\frac{\tilde{r}^\beta\tilde{r}^\nu}{\tilde{r}^2}+\frac{1}{2}\tilde{g}^{\beta\nu}_{N^*}\right)$$

$\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$



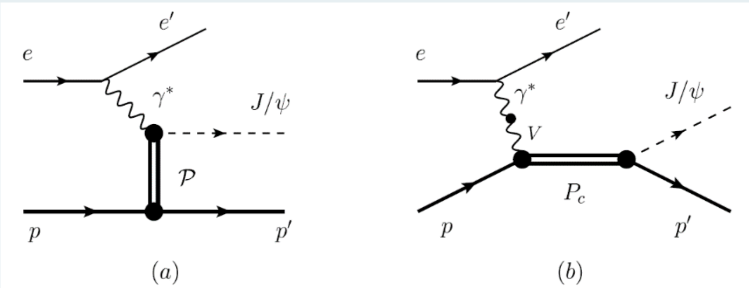
After using a form factor for off shell vector with 550 MeV, we will find the main contribution of VMD is just from ρ/ω meson, and J/ψ contribution is negligible.





$e\,p \to e\,J/\psi\,p$

Zhi Yang, Xu Cao, Yu-Tie Liang, Jia-Jun Wu CPC 44, No. 8 (2020) 084102



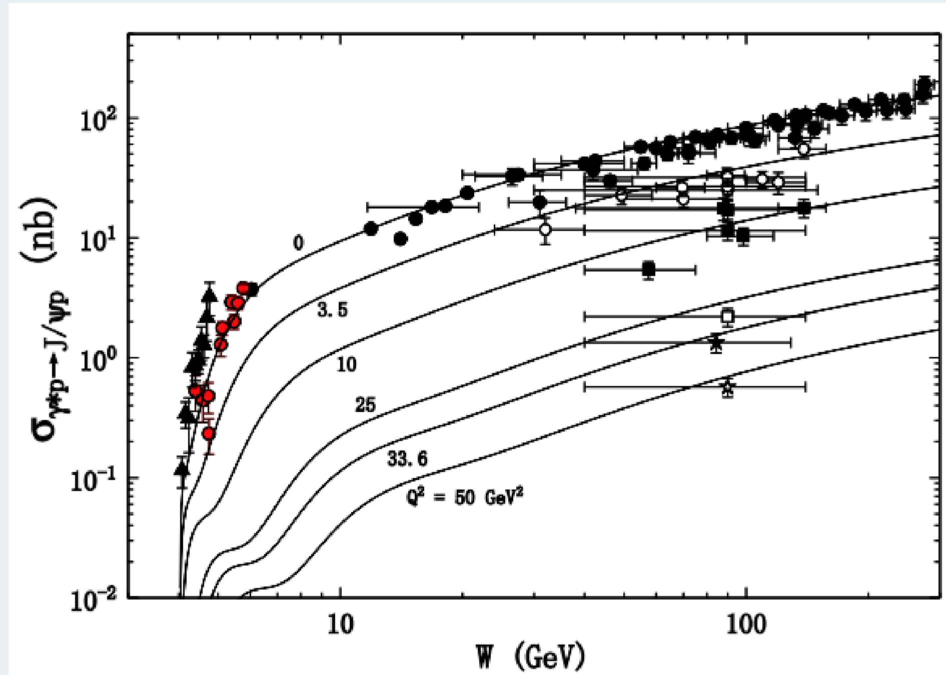
$$\mathcal{M}^{\mathcal{P}}_{\gamma p\to Vp} = \mathcal{P}(z,t,M_V^2,Q^2) + \mathcal{F}(z,t,M_V^2,Q^2),$$

$$\mathcal{P}(z,t,M_V^2,Q^2) = \mathrm{i}g_0(-\mathrm{i}z)^{\alpha_P(t)-1} + \mathrm{i}g_1\ln(-\mathrm{i}z)(-\mathrm{i}z)^{\alpha_P(t)-1},$$

$$\mathcal{F}(z,t,M_V^2,Q^2) = \mathrm{i}g_f(-\mathrm{i}z)^{\alpha_f(t)-1}.$$

P: dipole Pomeron & F: Reggeon

E. Martynov, E. Predazzi, and A. Prokudin, PRD, 67: 074023 (2003)



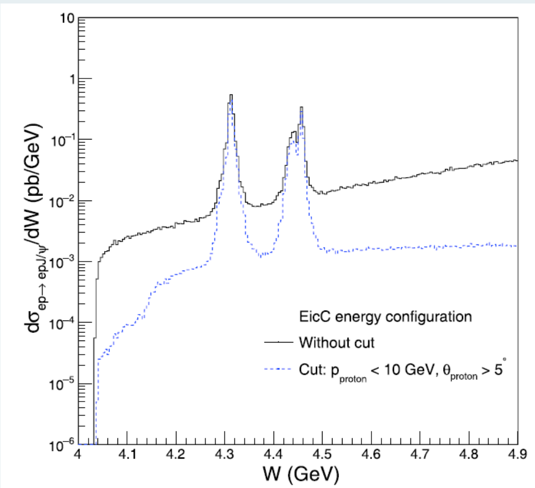
$$\alpha_{\mathbb{P}}(t) = 1 + \gamma\left(\sqrt{4m_\pi^2} - \sqrt{4m_\pi^2 - t}\right) \quad \gamma = 0.05\ \mathrm{GeV}^{-1} \quad g_0 = -0.03 \quad g_1 = 0.01$$

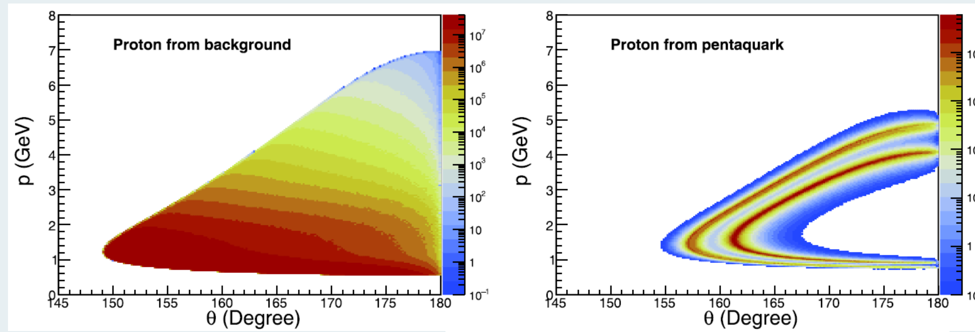
$$\alpha_f(t) = \alpha_f(0) + \alpha_f'(0)t \quad \alpha_f(0) = 0.8 \quad \alpha_f'(0) = 0.85\ \mathrm{GeV}^{-2} \quad g_f = 0.08 \quad z \sim \cos\theta$$

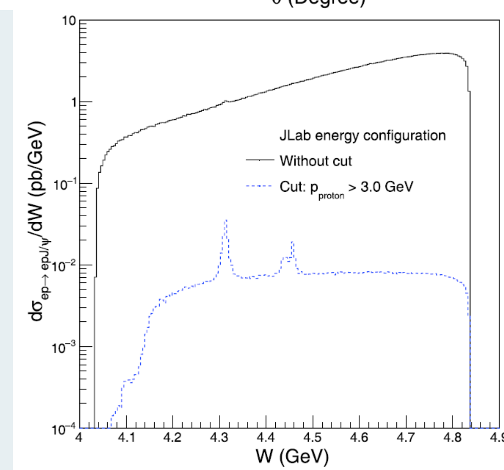
$e\,p \rightarrow e\,J/\psi\,p$

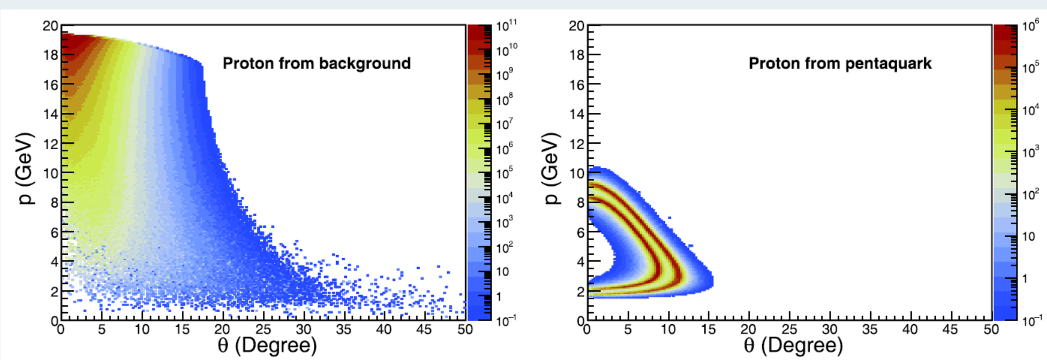
EicC 12 GeV

Jlab 12 GeV





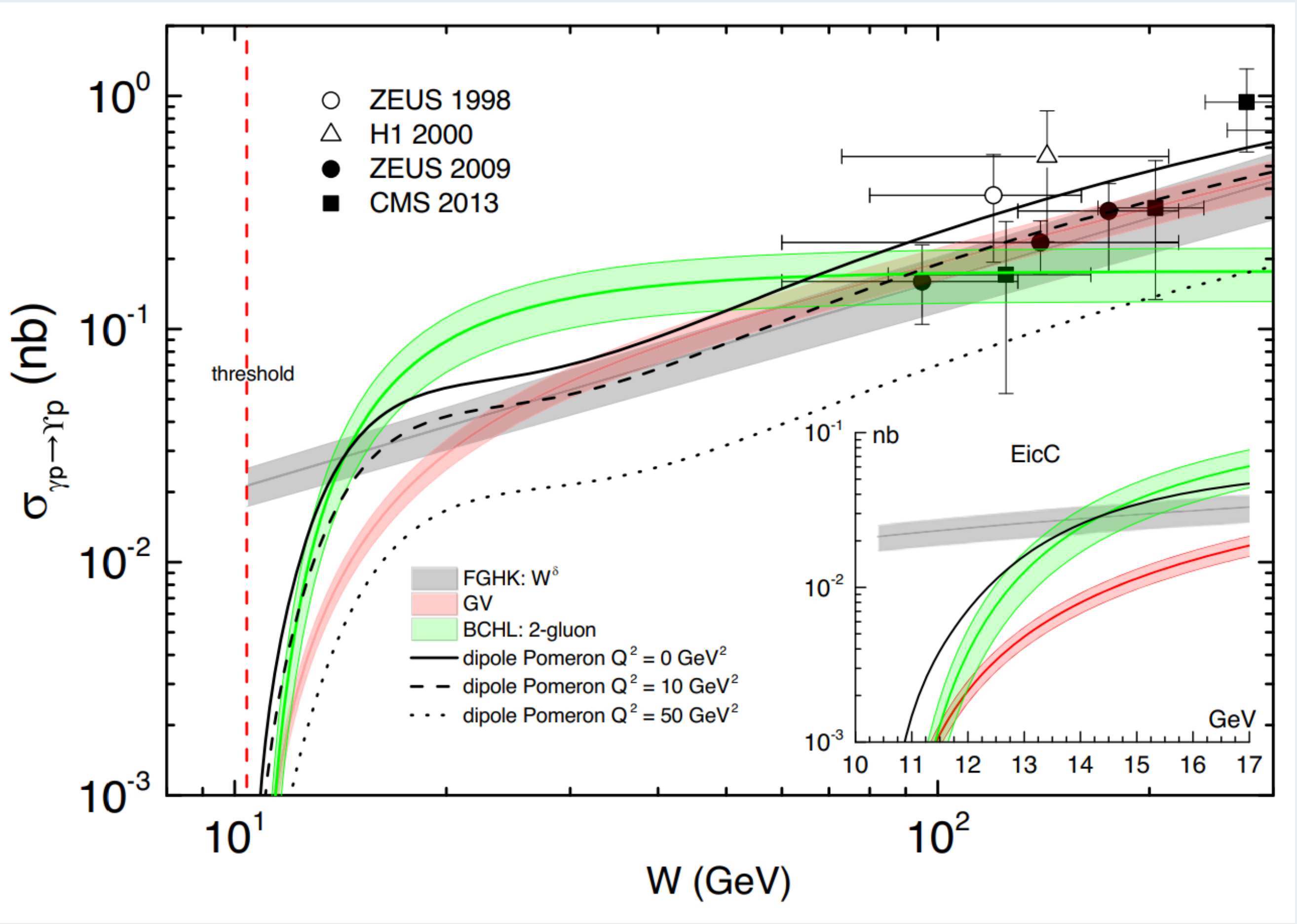




	M/MeV	Γ/MeV	J^P
$P_c(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$\frac{3}{2}^-$
$P_c(4440)$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$\frac{3}{2}^-$
$P_c(4457)$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$\frac{3}{2}^-$

$\gamma\, p \rightarrow \Upsilon\, p$

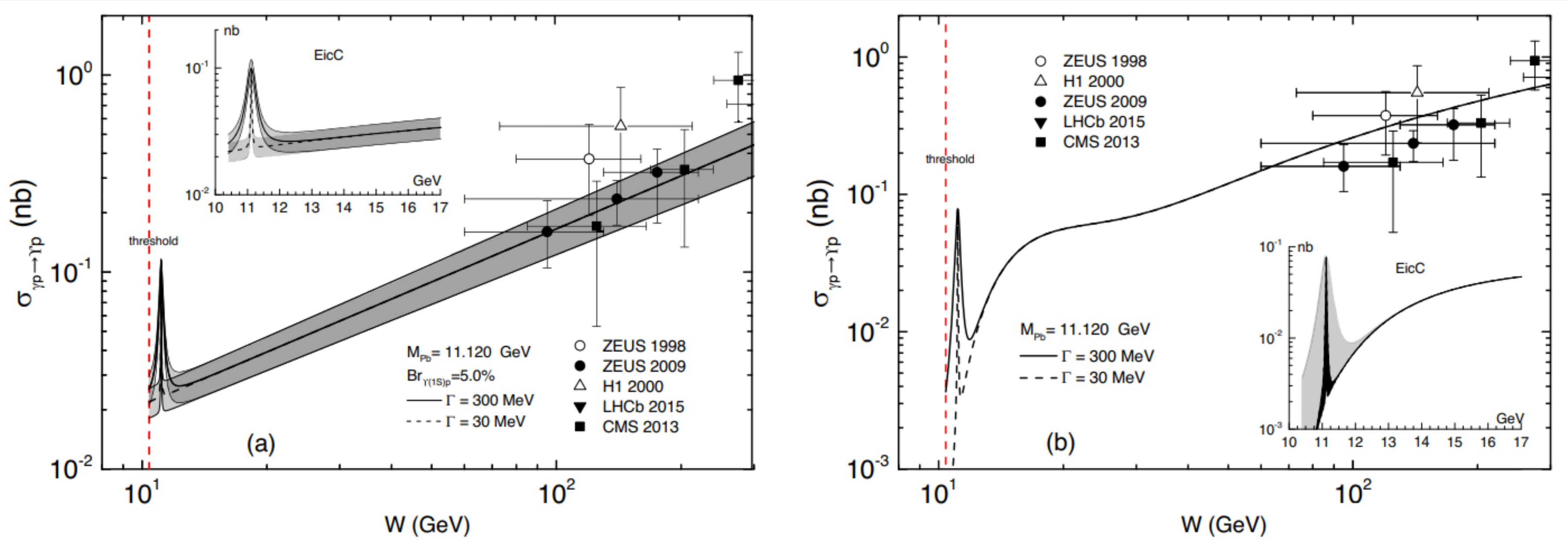
Xu Cao, Feng-Kun Guo, Yu-Tie Liang, Jia-Jun Wu, Ju-Jun Xie, Ya-Ping Xie, Zhi Yang, and Bing-Song Zou Phys.Rev.D 101 (2020) 7, 074010



Various Pomeron and Regge trajectories Models exist and can not rule out based on present data.

$\gamma\, p \rightarrow \Upsilon\, p$

Xu Cao, Feng-Kun Guo, Yu-Tie Liang, Jia-Jun Wu, Ju-Jun Xie, Ya-Ping Xie, Zhi Yang, and Bing-Song Zou Phys.Rev.D 101 (2020) 7, 074010



$$\sigma(\gamma^* p \to Vp) = \mathcal{N} W^{\delta(Q^2)} = \mathcal{N} W^{\alpha+\beta \ln(Q^2+M_V^2)},$$

L. Favart, M. Guidal, T. Horn, and P. Kroll, EPJA 52, 158 (2016)

Soft dipole Pomeron

E. Martynov, E. Predazzi, and A. Prokudin, EPJC 26, 271 (2002)
PRD 67, 074023 (2003).

Summary

- We calculated the cross section of γ p → J/ψ p / Υ p reaction through background and resonance with hidden-charm.
- How to check pomeron exchange contribution at threshold ?
- How to account the off-shell effect in the VMD model ?
- How to find the proper cut to strengthen the signal of P_c ?

- To be honest, I feel a pure theoretical description is so hard ! More data input is very necessary !

Thank very much！

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