J/ψ Photo-production and Pc

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Workshop on Near-Threshold Production of Heavy Quarkonium
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Outline

- Motivation
- $\gamma\, p \rightarrow J/\psi\, p$ background mechanism
- $\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$
- How to extract information of P_c ?
- Summary

Motivation

- In 2010， from this paper， it was the first propose N*， Λ* with hidden-charm exist around 4 GeV in theory.

PRL **105**, 232001 (2010) PHYSICAL REVIEW LETTERS week ending 3 DECEMBER 2010

Prediction of Narrow N^* and Λ^* Resonances with Hidden Charm above 4 GeV

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[2]*Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Apartado 22085, 46071 Valencia, Spain*
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(Received 5 July 2010; published 29 November 2010)

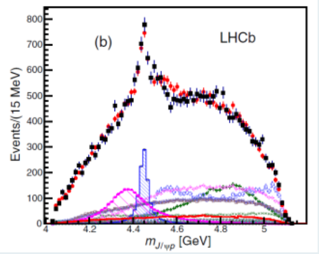
From 2015-Now, there are more than 1000 citations for LHCb experimental paper.

- In 2015, LHCb group first found two peaks of J/ψp invariant mass spectrum from Λ_b → J/ψKp reaction.

Selected for a Viewpoint in *Physics*
PRL **115**, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

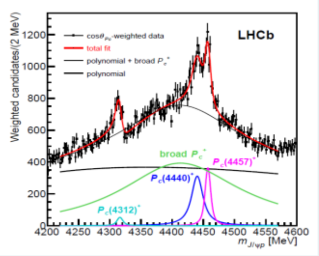
R. Aaij *et al.**
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)



- In 2019, LHCb group updated the new results.

Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$

arXiv:1904.03947v1 [hep-ex] 8 Apr 2019



Motivation

- Why is it important to confirm P_c in photo-production reaction ?

- Three peaks of $J/\psi p$ invariant mass spectrum

1. Resonances? or Kinematics effects (Threshold & TS)?

2. If Resonances confirmed, what is the internal structure ?
Meson-Baryon molecule or 5 quark configuration state ?

3. What the spin and parity (J^p) ?

=> We need more experimental input !

Motivation

- Why is it important to confirm P_c in photo-production reaction ?

- γ p → P_c → J/ψ p VS Λ_b → J/ψK p

1. Resonances? or Kinematics effects (Threshold & TS)?

   No Threshold & TS effect because two bodies final state.

2. If Resonances confirmed, what is the internal structure ?
Meson-Baryon molecule or 5 quark configuration state ?

   Decay width of channels

3. What the spin and parity (J^p) ?

   Angular differential cross section, Two body vs Three body

=> We need more experimental input !

Definitely, it will provide fruitful information of P_c from γ p reaction.

Motivation

- In our 2010 paper, we have mentioned to search Pc in e p → e J/ψ p after update 12 GeV in Jlab experiment, but we did not calculate it in detail at that time. I just give the results in my doctor thesis.
- In 2019, Prof. Harry Lee was suggested by the experimentalist in Argonne National Lab who also collaborates with Jlab. We re-start to research this reaction, and provide estimations of production.

[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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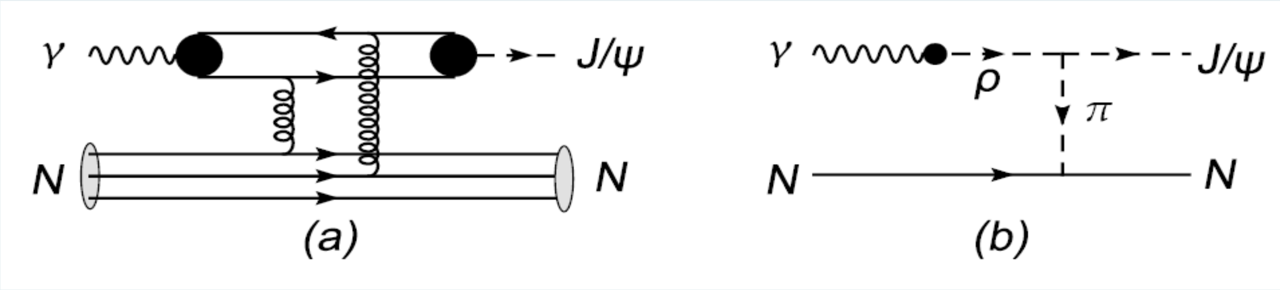
γ p → J/ψ p background mechanism

- **Feynman Diagram**



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

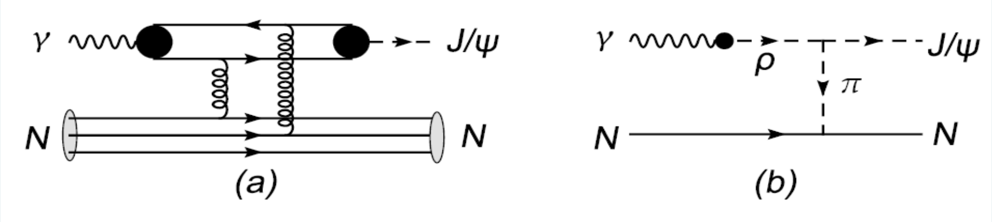
$$\frac{d\sigma}{d\Omega} = \frac{1}{(2\pi)^2}\frac{m_N m_B}{4W^2}\frac{1}{4}\sum_{\lambda_\gamma,\lambda_M}\sum_{m_s,m_s'}\left|\bar{u}_p(p',m_s')\epsilon^*_\mu(q',\lambda'_{J/\Psi})\mathcal{M}^{\mu\nu}(q,p,q',p')u_p(p,m_s)\epsilon_\nu(q,\lambda_\gamma)\right|^2$$

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

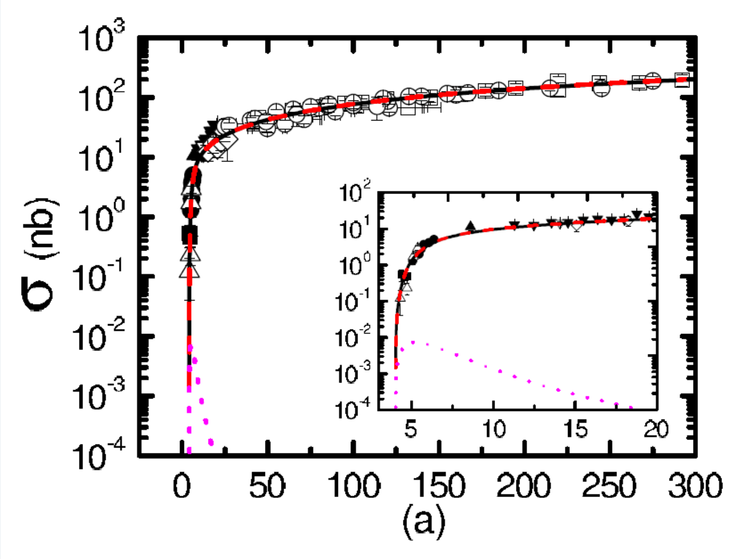
$$\mathcal{M}_\pi^{\mu\nu}(q,q',p,p') = \frac{e}{f_\rho}\frac{g_{J/\Psi,\rho^0\pi^0}}{m_{J/\Psi}}\frac{f_\pi}{m_\pi}\frac{-m_\rho^2}{q^2-m_\rho^2+i\Gamma_\rho m_\rho}\frac{\Lambda_\rho^4}{\Lambda_\rho^4+(q^2-m_\rho^2)^2}\frac{1}{t-m_\pi^2}\left(\frac{\Lambda_\pi^2-m_\pi^2}{\Lambda_\pi^2-t}\right)^4\epsilon^{\mu\nu\alpha\beta}q'_\alpha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

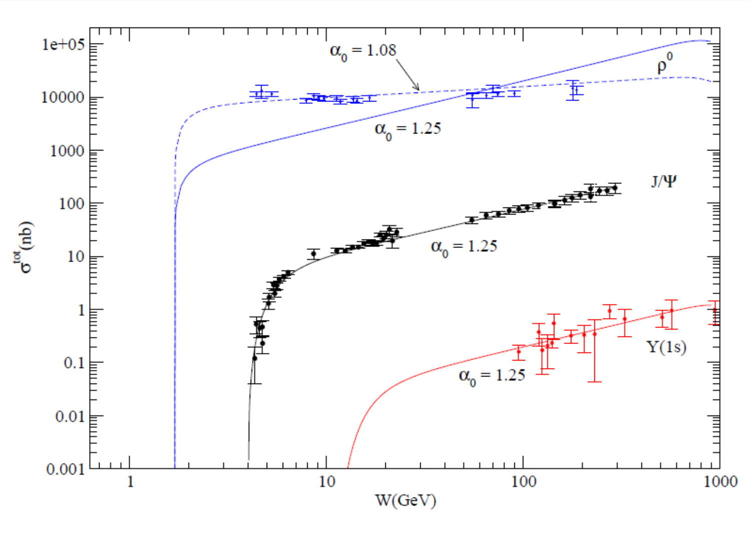
γ p → J/ψ p background mechanism

- **Feynman Diagram**



- **Result**





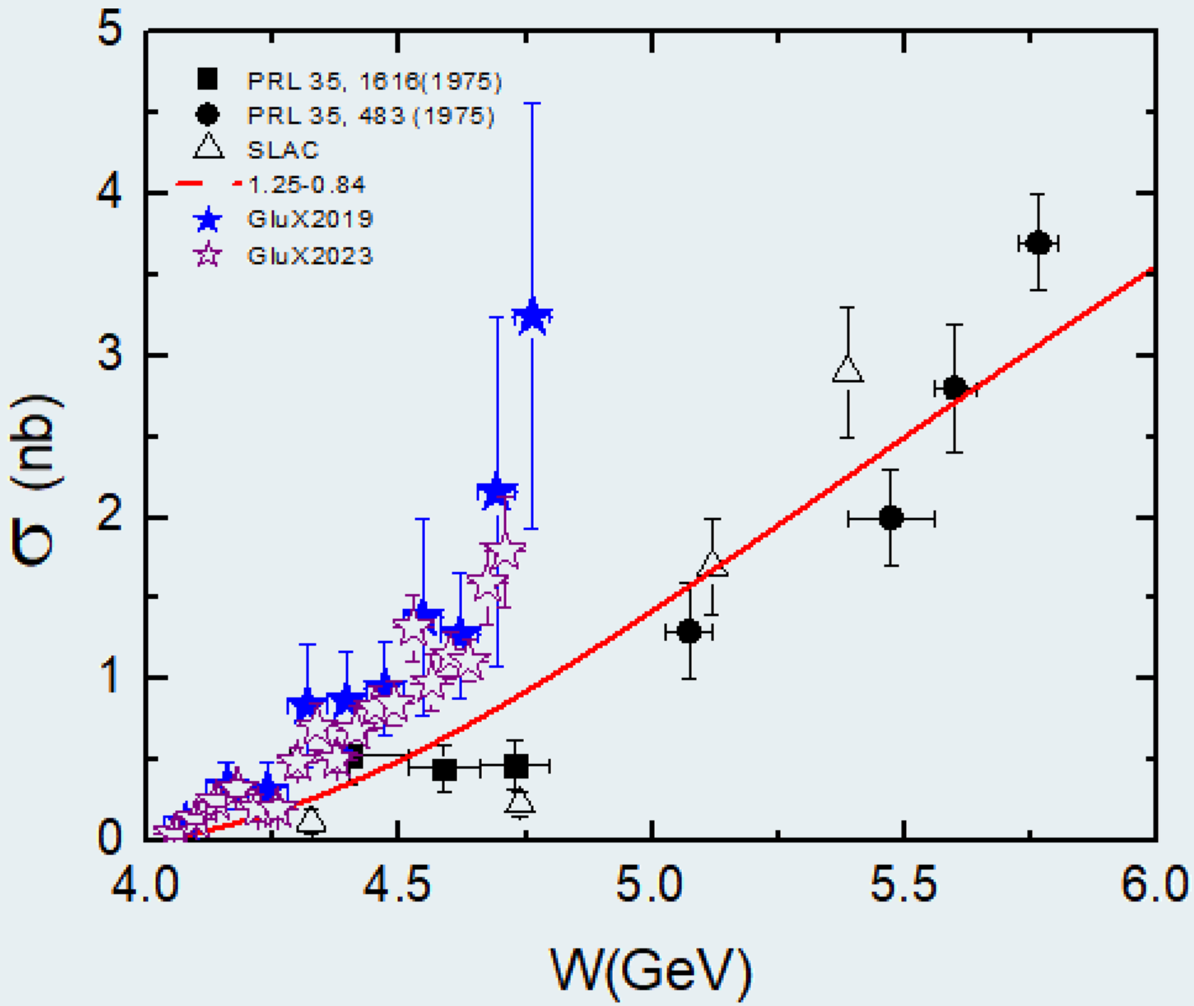
$$\mathcal{M}_P^{\mu\nu}(q,p,q',p') = \left(\frac{s}{s_0}\right)^{\alpha_P(t)-1} \exp\left\{-\frac{i\pi}{2}\left[\alpha_P(t)-1\right]\right\} i12e\frac{M_V^2\beta_q\beta_{q'}}{f_V}\frac{1}{M_V^2-t}\left(\frac{2\mu_0^2}{2\mu_0^2+M_V^2-t}\right)\frac{4M_N^2-2.8t}{(4M_N^2-t)(1-t/0.71)^2}\{\gamma.qg^{\mu\nu}-q^\mu\gamma^\nu\}$$

$\alpha_P(t) = \alpha_0 + \alpha_p' t$ $\alpha_0 = 1.08$ $\alpha_0 = 1.25$

$\gamma\, p \to J/\psi\, p$ background mechanism

- **Result**

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



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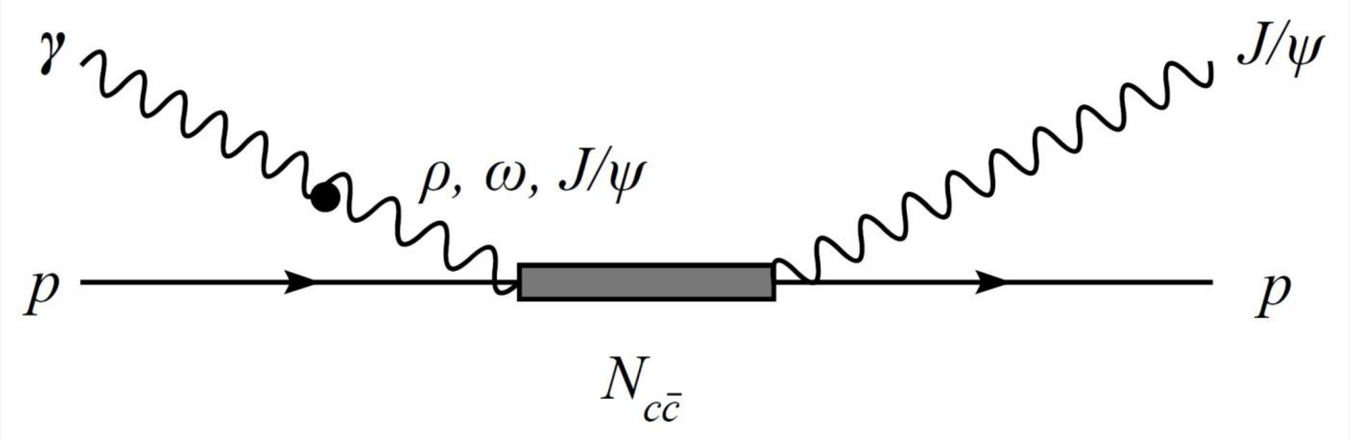
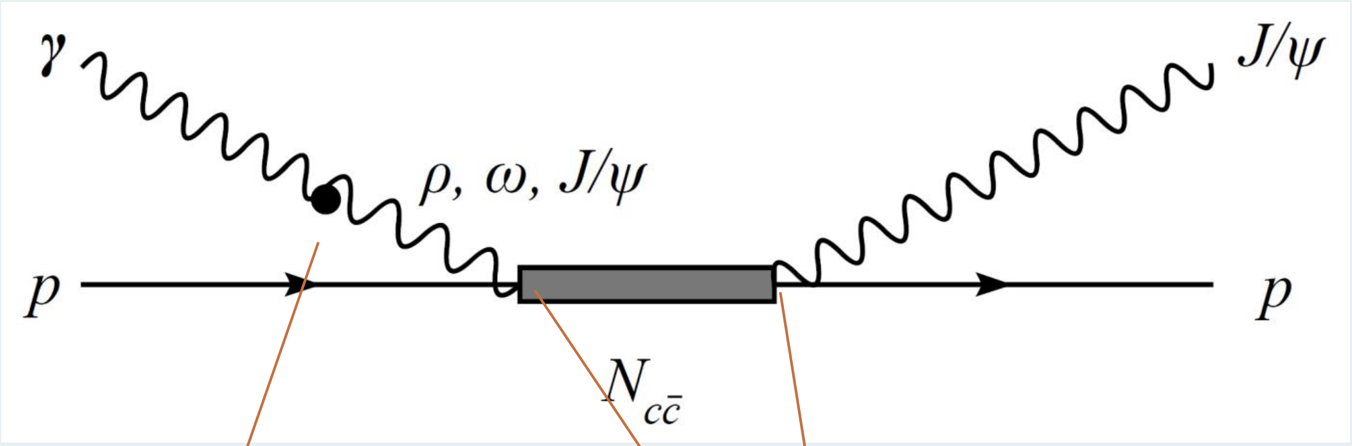
$\gamma\, p \to P_c \to J/\psi\, p$



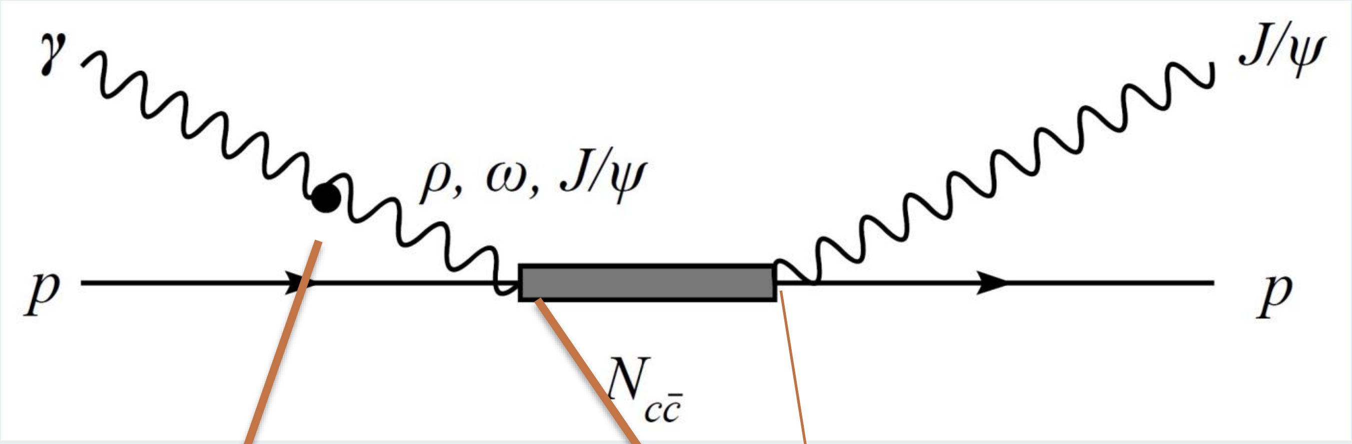
$\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$



VMD vertex

PcVP vertex

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



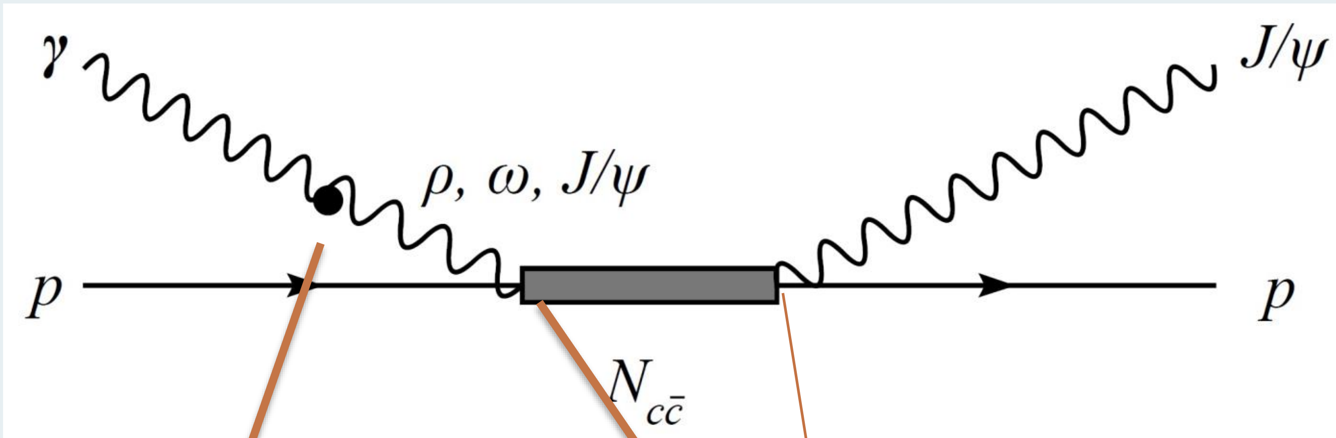
Off shell

On shell

VMD vertex

PcVP vertex

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



Off shell

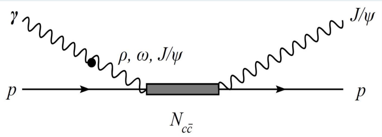
On shell

VMD vertex

PcVP vertex

PcγP vertex

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



- **Various Models for** $P_c \to VB$

No.	J^P	m	Γ	$\Gamma_{J/\psi N}$	$\Gamma_{\rho N}$	$\Gamma_{\omega N}$	$\Gamma_{\bar{D}\Lambda_c}$	$\Gamma_{\bar{D}^*\Lambda_c}$	Main Channel	Ref.
1	$\frac{1}{2}^-$	4262	35.6	10.3	–	–	0.01	–	$\bar{D}\Sigma_c$	[6]
2		4308	–	1.2	–	–	0.02	1.4	$\bar{D}\Sigma_c$	[7]
3		4412	47.3	19.2	3.2	10.4	–	–	$\bar{D}^*\Sigma_c$	[8, 9]
4		4410	58.9	52.5	–	–	0.8	0.7	$\bar{D}^*\Sigma_c$	[6]
5		4460	–	3.9	–	–	1.0	0.3	$\bar{D}^*\Sigma_c$	[7]
6		4481	57.8	14.3	–	–	1.02	0.3	$\bar{D}^*\Sigma_c^*$	[6]
7	$\frac{3}{2}^-$	4334	38.8	38.0	–	–	–	0.8	$\bar{D}\Sigma_c^*$	[6]
8		4375	–	1.5	–	–	–	0.9	$\bar{D}\Sigma_c^*$	[7]
9		4380	144.3	3.8	1.4	5.3	1.2	131.3	$\bar{D}\Sigma_c^*$	[5]
10		4380	69.9	16.6	0.15	0.6	17.0	35.3	$\bar{D}^*\Sigma_c$	[5]
11		4412	47.3	19.2	3.2	10.4	–	–	$\bar{D}^*\Sigma_c$	[8, 9]
12		4417	8.2	4.6	–	–	–	3.1	$\bar{D}^*\Sigma_c$	[6]
13		4450	139.8	16.3	0.14	0.5	41.4	72.3	$\bar{D}^*\Sigma_c$	[5]
14		4450	21.7	0.03	–	–	1.4	6.8	$\bar{D}^*\Sigma_c$	[10]
15		4450	16.2	11	–	–	0.6	4.2	$\Psi' N$	[10]
16		4453	–	1.5	–	–	–	0.3	$\bar{D}\Sigma_c^*$	[7]
17		4481	34.7	32.8	–	–	–	1.2	$\bar{D}^*\Sigma_c^*$	[6]
18	$\frac{5}{2}^+$	4450	46.4	4.0	0.3	0.3	18.8	20.5	$\bar{D}^*\Sigma_c$	[5]
19	$\frac{3}{2}^-$ / $\frac{5}{2}^+$	$4380^{\pm 8}_{\pm 29}$	$205^{\pm 18}_{\pm 86}$	–	–	–	–	–	Exp	[1, 2]
20		$4450^{\pm 2}_{\pm 3}$	$39^{\pm 5}_{\pm 19}$	–	–	–	–	–	Exp	[1, 2]

[5] Lin, Shen, Guo, Zou, PRD95 114017

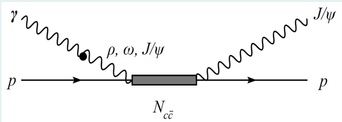
[6] Xiao, Nieves, Oset, PRD88 056012

[7] Huang, Ping, 1811.04260

[8, 9] Wu, Molina, Oset, Zou, PRL 105 232001, PRC 84 015202

[10] Eides, Petrov, 1811.01691

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



- $P_c \rightarrow VB$ interaction: Lorentz structure

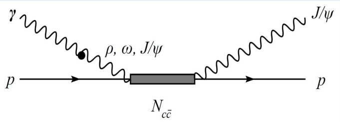
$$\mathcal{M}_{N^*(\frac{1}{2}^-)NV} = \bar{u}_N \gamma_5 \tilde{\gamma}_\mu u_{N^*} \epsilon^*_{V\ \nu} \left(g_{1V} g^{\mu\nu} + f_{1V} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}^{\mu\nu}_{N^*} \right) \right)$$

$$\mathcal{M}_{N^*(\frac{3}{2}^-)NV} = \bar{u}_N u_{N^*\ \mu} \epsilon^*_{V\ \nu} \left(g_{3V} g^{\mu\nu} + f_{3V} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}^{\mu\nu}_{N^*} \right) \right)$$
$$+ h_{3V} \epsilon_{\mu\nu\lambda\delta} \bar{u}_N \gamma_5 (\tilde{\gamma}^\mu g^\beta_\alpha + \tilde{\gamma}_\alpha g^{\mu\beta}) u_{N^*\ \beta} \epsilon^*_{V\ \nu} \left(\frac{\tilde{r}^\alpha \tilde{r}^\lambda}{\tilde{r}^2} - \frac{1}{3} \tilde{g}^{\alpha\lambda}_{N^*} \right) \hat{P}^\delta$$

$$\mathcal{M}_{N^*(\frac{5}{2}^+)NV} = \bar{u}_N u_{N^*\ \mu\nu} \epsilon^*_{V\ \alpha} \left(\frac{g_{5V}}{m_N} g^{\alpha\mu} \tilde{r}^\nu + \frac{f_{5V}}{m_N} \left(\frac{3}{5} \frac{\tilde{r}^\mu \tilde{r}^\nu \tilde{r}^\alpha}{\tilde{r}^2} - \frac{1}{5} (\tilde{g}^{\mu\nu}_{N^*} \tilde{r}^\alpha + \tilde{g}^{\nu\alpha}_{N^*} \tilde{r}^\mu + \tilde{g}^{\alpha\mu}_{N^*} \tilde{r}^\nu) \right) \right)$$

$$+ \frac{h_{5V}}{m_N} \epsilon_{\mu\nu\lambda\delta} \bar{u}_N \gamma_5 \left(\tilde{\gamma}^\mu g_{\xi\alpha} g_{\sigma\beta} + \tilde{\gamma}_\xi g_{\sigma\beta} g_{\mu\beta} + \tilde{\gamma}_\sigma g_{\mu\beta} g_{\xi\beta} \right) u^{\alpha\beta}_{N^*} \epsilon^{*\ \mu}_V$$
$$\times \left(\frac{\tilde{r}^\xi \tilde{r}^\lambda \tilde{r}^\sigma}{\tilde{r}^2} - \frac{1}{3} \left(\tilde{g}^{\xi\sigma}_{N^*} \tilde{r}^\lambda + \tilde{g}^{\sigma\lambda}_{N^*} \tilde{r}^\xi + \tilde{g}^{\lambda\xi}_{N^*} \tilde{r}^\sigma \right) \right) \hat{P}^\delta$$

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



- $P_c \rightarrow$ VB interaction: Lorentz structure

$$\mathcal{M}_{N^*(\frac{1}{2}^-)NV} = \bar{u}_N \gamma_5 \tilde{\gamma}_\mu u_{N^*} \epsilon^*_{V\ \nu} \Big(g_{1V} g^{\mu\nu} + \ldots$$

$$\mathcal{M}_{N^*(\frac{3}{2}^-)NV} = \bar{u}_N u_{N^*\ \mu} \epsilon^*_{V\ \nu} \Big(g_{3V} g^{\mu\nu} + f_3 \ldots$$

$$+ h_{3V} \epsilon_{\mu\nu\lambda\delta} \bar{u}_N \gamma_5 (\tilde{\gamma}^\mu g \ldots \frac{1}{3} \tilde{g}^{\alpha\lambda}_{N^*} \Big) \hat{P}^\delta$$

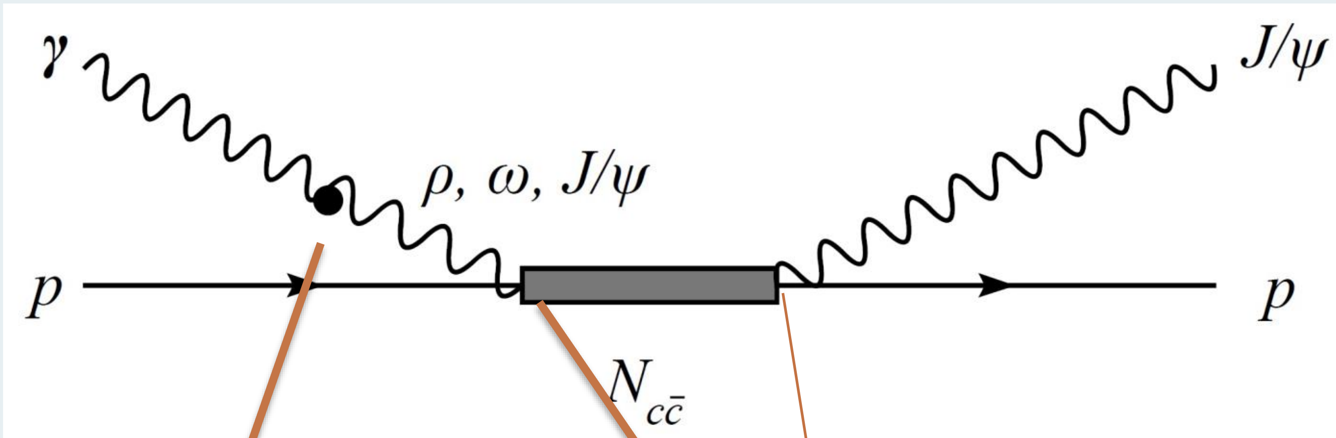
$$\mathcal{M}_{N^*(\frac{5}{2}^+)NV} = \bar{u}_N u_{N^*\ \mu\nu} \epsilon^*_{V\ \alpha} \Big(\frac{g_{5V}}{m_N} g^{\alpha\mu} \tilde{r}^\nu + \ldots \tilde{r}^\mu + \tilde{g}^{\alpha\mu}_{N^*} \tilde{r}^\nu) \Big) \Big)$$

$$+ \frac{h_{5V}}{m_N} \epsilon_{\mu\nu\lambda\delta} \bar{u}_N \gamma_5 \left(\tilde{\gamma}^\mu g_{\xi\alpha} g_\sigma \ldots \epsilon^{*\ \mu}_V \right.$$

$$\times \left(\frac{\tilde{r}^\xi \tilde{r}^\lambda \tilde{r}^\sigma}{\tilde{r}^2} - \frac{1}{3} \left(\tilde{g}^{\xi\sigma}_{N^*} \tilde{r}^\lambda + \ldots \right.\right.$$

No.	J^P	m	Γ_{tot}	g_V $J/\Psi p$
1	$\frac{1}{2}^-$	4262	35.6	0.39
2		4308	—	0.13
3		4412	47.3	0.46
4		4410	58.9	0.75
5		4460	—	0.20
6		4481	57.8	0.37
7	$\frac{3}{2}^-$	4334	38.8	1.19
8		4375	—	0.23
9		4380	144.3	0.36
10		4380	69.9	0.75
11		4412	47.3	0.79
12		4417	8.2	0.39
13		4450	139.8	0.71
14		4450	21.7	0.030
15		4450	16.2	0.58
16		4453	—	0.21
17		4481	34.7	0.98
18	$\frac{5}{2}^+$	4450	46.4	0.35

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



Off shell

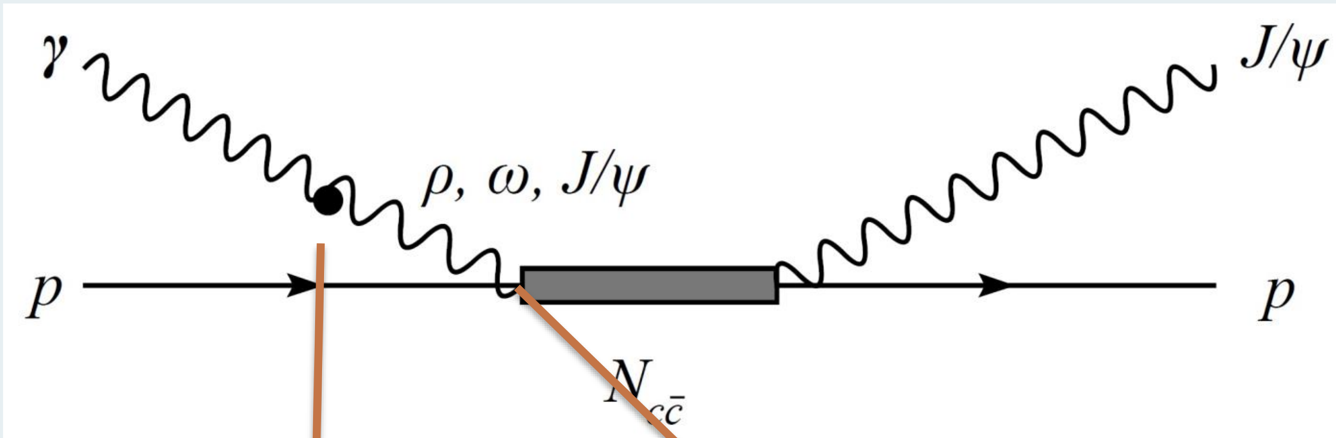
On shell

VMD vertex

PcVP vertex

PcγP vertex

$\gamma p \rightarrow P_c \rightarrow J/\psi p$: $\gamma p \rightarrow P_c$ vertex



Off shell

VMD vertex

$$\mathcal{L}_{VMD} = \frac{iem_V^2}{f_V} A_\mu V^\mu$$

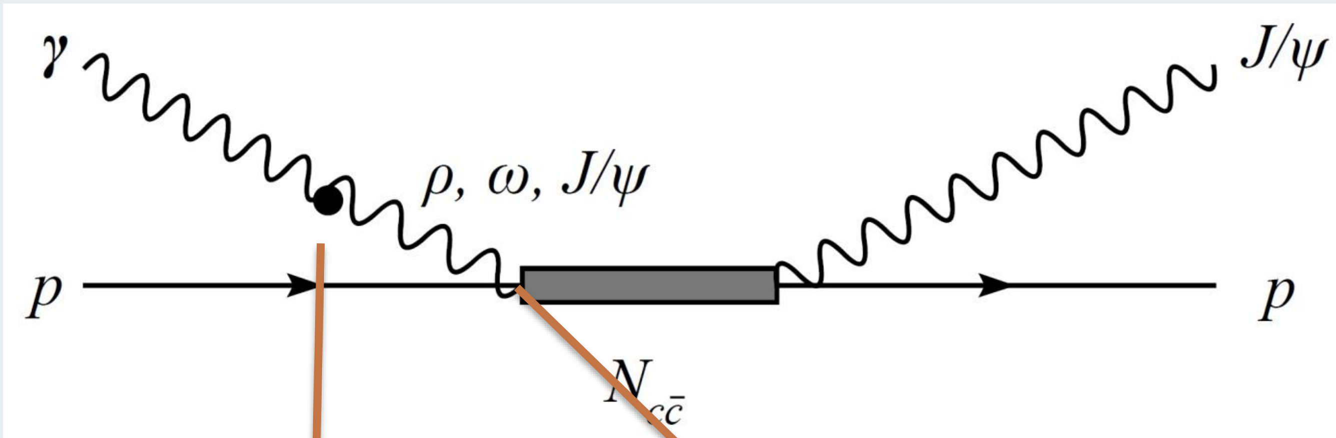
PcVP vertex

$$\mathcal{L}_{N^*(\frac{1}{2}^-)NV} = \overline{N}^* \gamma_5 \tilde{\gamma}_\mu N V_\nu \left(g_{1V} g^{\mu\nu} + f_{1V} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}^{\mu\nu}_{N^*} \right) \right) + h.c.$$

1. Gauge invariance

PcγP vertex

$\gamma\, p \to P_c \to J/\psi\, p$: $\gamma\, p \to P_c$ vertex



Off shell

2. The effect of off-shell

$$F_V(q^2) = \frac{\Lambda^4}{\Lambda^4 + (q^2 - m_V^2)^2}$$

VMD vertex

$$\mathcal{L}_{VMD} = \frac{iem_V^2}{f_V} A_\mu V^\mu$$

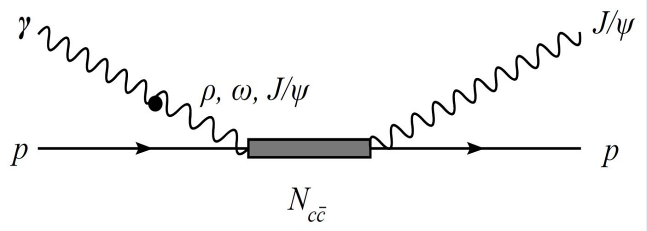
PcVP vertex

$$\mathcal{L}_{N^*(\frac{1}{2}^-)NV} = \overline{N}^* \gamma_5 \tilde{\gamma}_\mu N V_\nu \left(g_{1V} g^{\mu\nu} + f_{1V} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}^{\mu\nu}_{N^*} \right) \right) + h.c.$$

1. Gauge invariance

PcγP vertex

$\gamma p \to P_c \to J/\psi\, p$: $\gamma p \to P_c$ vertex



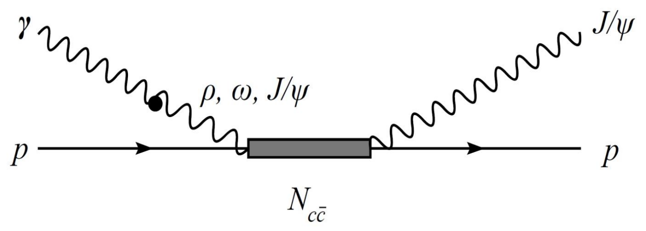
- $\gamma p \to P_c$: **Gauge invariance**

$$\mathcal{L}_{VMD} = \frac{iem_V^2}{f_V} A_\mu V^\mu$$

$$\mathcal{L}_{N^*(\frac{1}{2}^-)NV} = \overline{N}^* \gamma_5 \tilde{\gamma}_\mu N V_\nu \left(g_{1V} g^{\mu\nu} - f_{1V} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}^{\mu\nu}_{N^*} \right) \right) + h.c.$$

$$\mathcal{T}_{N*(\frac{1}{2}^-)\to NV \to N\gamma} = \overline{u}_N \mathcal{M}^\nu u_{N^*} \epsilon^*_\nu,$$

$\gamma p \to P_c \to J/\psi p$ ： $\gamma p \to P_c$ vertex



- $\gamma p \to P_c$: **Gauge invariance**

$$\mathcal{L}_{VMD} = \frac{iem_V^2}{f_V} A_\mu V^\mu$$

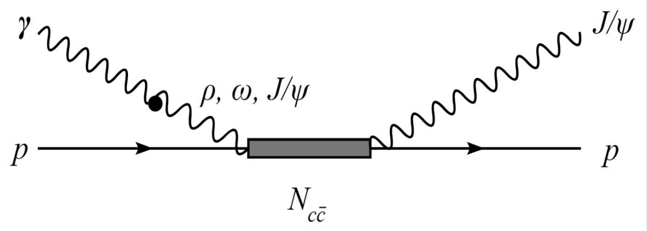
$$\mathcal{L}_{N^*(\frac{1}{2}^-)NV} = \overline{N}^* \gamma_5 \tilde{\gamma}_\mu N V_\nu \left(g_{1V} g^{\mu\nu} - f_{1V} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}^{\mu\nu}_{N^*} \right) \right) + h.c.$$

$$\mathcal{T}_{N*(\frac{1}{2}^-) \to NV \to N\gamma} = \overline{u}_N \mathcal{M}^\nu u_{N^*} \epsilon^*_\nu,$$

$$\mathcal{M}^\nu = \frac{ie}{f_V} \frac{-m_V^2}{q^2 - m_V^2 + i\Gamma_V m_V} \gamma_5 \tilde{\gamma}_\mu \left(g_{1V} g_{\mu\nu'} - f_{1V} \left(\frac{3}{2} \frac{\tilde{r}_\mu \tilde{r}_\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}_{N^*\ \mu\nu'} \right) \right) \tilde{g}_V^{\nu'\nu}(q) \times F_V(q^2)$$

$\mathcal{M}^\nu q_\nu \sim (g_{1V} - f_{1V}) \neq 0$ Destroy **Gauge invariance**

$\gamma\, p \to P_c \to J/\psi\, p$: $\gamma\, p \to P_c$ vertex



- $\gamma\, p \to P_c$: **Gauge invariance**

$$\mathcal{L}_{VMD} = \frac{iem_V^2}{f_V} A_\mu V^\mu$$

$$\mathcal{L}_{N^*(\frac{1}{2}^-)NV} = \overline{N}^* \gamma_5 \tilde{\gamma}_\mu N V_\nu \left(g_{1V} g^{\mu\nu} - f_{1V} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}_{N^*}^{\mu\nu} \right) \right) + h.c.$$

$$\mathcal{T}_{N*(\frac{1}{2}^-)\to NV \to N\gamma} = \overline{u}_N \mathcal{M}^\nu u_{N^*} \epsilon_\nu^*,$$

$$\mathcal{M}^\nu = \frac{ie}{f_V} \frac{-m_V^2}{q^2 - m_V^2 + i\Gamma_V m_V} \gamma_5 \tilde{\gamma}_\mu \left(g_{1V} g_{\mu\nu'} - f_{1V} \left(\frac{3}{2} \frac{\tilde{r}_\mu \tilde{r}_\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}_{N^*\ \mu\nu'} \right) \right) \tilde{g}_V^{\nu'\nu}(q) \times F_V(q^2)$$

$\mathcal{M}^\nu q_\nu \sim (g_{1V} - f_{1V}) \neq 0$ Destroy **Gauge invariance**

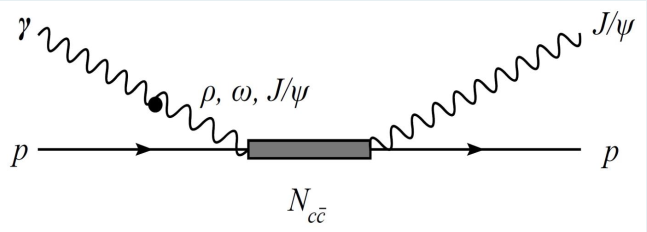
$$\mathcal{L}_{N^*(\frac{1}{2}^-)N\gamma} = \overline{N}^* \gamma_5 \tilde{\gamma}_\mu N A_\nu \left(g_{1\gamma} g^{\mu\nu} - g_{1\gamma} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}_{N^*}^{\mu\nu} \right) \right) + h.c.$$

Dulat, Wu, Zou, PRD83, 094032 $J/\psi \to \bar{B}B\,\gamma$

One possible prescription:

$$\mathcal{L}_{N^*(\frac{1}{2}^-)NV} = \overline{N}^* \gamma_5 \tilde{\gamma}_\mu N V_\nu \left(\tilde{g}_{1V} g^{\mu\nu} - \tilde{g}_{1V} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}_{N^*}^{\mu\nu} \right) \right) + h.c.$$

$\gamma\, p \to P_c \to J/\psi\, p$: $\gamma\, p \to P_c$ vertex



- $\gamma\, p \to P_c$: **Gauge invariance**

$\mathcal{L}_{VMD} =$

No.	J^P	m	Γ_{tot}	g_V $J/\Psi p$	$\tilde{g}_V$ $J/\Psi p$	$\tilde{g}_V$ ρp	$\tilde{g}_V$ ωp
1	$\frac{1}{2}^-$	4262	35.6	0.39	0.32	–	–
2		4308	–	0.13	0.11	–	–
3		4412	47.3	0.46	0.38	0.078	0.14
4		4410	58.9	0.75	0.62	–	–
5		4460	–	0.20	0.16	–	–
6		4481	57.8	0.37	0.31	–	–
7	$\frac{3}{2}^-$	4334	38.8	1.19	0.98	–	–
8		4375	–	0.23	0.19	–	–
9		4380	144.3	0.36	0.30	0.090	0.17
10		4380	69.9	0.75	0.62	0.039	0.059
11		4412	47.3	0.79	0.65	0.14	0.24
12		4417	8.2	0.39	0.32	–	–
13		4450	139.8	0.71	0.58	0.028	0.053
14		4450	21.7	0.030	0.025	–	–
15		4450	16.2	0.58	0.48	–	–
16		4453	–	0.21	0.18	–	–
17		4481	34.7	0.98	0.81	–	–
18	$\frac{5}{2}^+$	4450	46.4	0.35	0.27	0.016	0.016

$\mathcal{L}_{N^*(\frac{1}{2}^-)NV} = \ldots \frac{1}{2}\tilde{g}^{\mu\nu}_{N^*}\Big)\Big) + h.c.$

$\mathcal{T}_{N*(\frac{1}{2}^-)} \ldots$

$\mathcal{M}^\nu = \frac{ie}{f_V}\frac{-m \ldots}{q^2 - m_V^2 \ldots} \ldots - \frac{1}{2}\tilde{g}_{N^*\ \mu\nu'}\Big)\Big)\, \tilde{g}_V^{\nu'\nu}(q) \times F_V(q^2)$

$\mathcal{M}^\nu q_\nu \sim (\ldots$ invariance

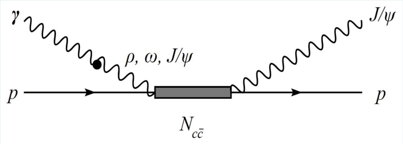
$\mathcal{L}_{N^*(\frac{1}{2}^-)N\gamma} = \bar{N} \ldots \frac{1}{2}\tilde{g}^{\mu\nu}_{N^*}\Big)\Big) + h.c.$

Dulat, W ... -> $\bar{B}B\ \gamma$

One possible pre ...

$\mathcal{L}_{N^*(\frac{1}{2}^-)NV} = \ldots \Big(\frac{\ldots}{2} \ldots \tilde{r}^2 \ldots - \frac{1}{2}\tilde{g}^{\mu\nu}_{N^*}\Big)\Big) + h.c.$

$\gamma\, p \to P_c \to J/\psi\, p$: $\gamma\, p \to P_c$ vertex



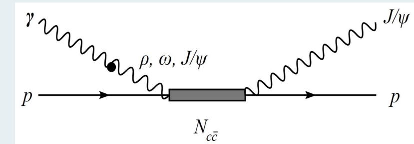
- $\gamma\, p \to P_c$: **The effect of off-shell vector**

$$\mathcal{T}_{N*(\frac{1}{2}^-)\to NV\to N\gamma} = \overline{u}_N \mathcal{M}^\nu u_{N^*} \epsilon^*_\nu,$$

$$\mathcal{M}^\nu = \frac{ie}{f_V} \frac{-m_V^2 \tilde{g}_{1V}}{q^2 - m_V^2 + i\Gamma_V m_V} \gamma_5 \tilde{\gamma}_\mu \left(g_{\mu\nu'} - \left(\frac{3}{2} \frac{\tilde{r}_\mu \tilde{r}_\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}_{N^*\ \mu\nu'} \right) \right) \tilde{g}_V^{\nu'\nu}(q) \times F_V(q^2)$$

$$F_V(q^2) = \frac{\Lambda^4}{\Lambda^4 + (q^2 - m_V^2)^2} = \frac{\Lambda^4}{\Lambda^4 + m_V^4}$$

$\gamma\, p \to P_c \to J/\psi\, p$: $\gamma\, p \to P_c$ vertex



- $\gamma\, p \to P_c$: **The effect of off-shell vector**

$$\mathcal{T}_{N*(\frac{1}{2}^-)\to NV \to N\gamma} = \bar{u}_N \mathcal{M}^\nu u_{N^*} \epsilon^*_\nu,$$

$$\mathcal{M}^\nu = \frac{ie}{f_V} \frac{-m_V^2 \tilde{g}_{1V}}{q^2 - m_V^2 + i\Gamma_V m_V} \gamma_5 \tilde{\gamma}_\mu \left(g_{\mu\nu'} - \left(\frac{3}{2} \frac{\tilde{r}_\mu \tilde{r}_\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}_{N^*\ \mu\nu'} \right) \right) \tilde{g}_V^{\nu'\nu}(q) \times F_V(q^2)$$

$$F_V(q^2) = \frac{\Lambda^4}{\Lambda^4 + (q^2 - m_V^2)^2} = \frac{\Lambda^4}{\Lambda^4 + m_V^4}$$

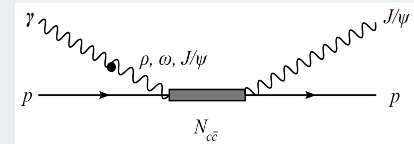
It is just a suppress factor, we have no idea how large it is. In other word, in model, the strength of N*Nγ is not determined. To compare with existed experimental data, we take a small cut: $\Lambda = 550$ MeV 。

The most unsatisfactory aspect of this work is the phenomenological determination of the off-shell form factor $F_V(q^2)$. It is determined by only using the data of total cross sections of $\gamma p \to J/\psi\, p$ near the threshold, shown in Fig. 3. While our predictions could be used as a first step to determine whether the $N^*_{c\bar{c}}$ predicted by the available meson-baryon coupled-channel models can be found in the new data from JLab, it is necessary to develop a more fundamental approach to also predict $F_V(q^2)$ from QCD models. Obviously, such an improvement is necessary for using the q^2 dependence of the J/ψ electroproduction cross section data to investigate nucleon resonances with hidden charm.

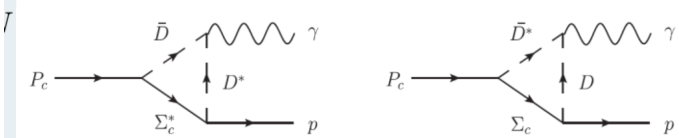
$\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$: $\gamma\, p \rightarrow P_c$ vertex

No.	J^P	m	Γ_{tot}	g_V $J/\Psi p$	$\tilde{g}_V$ $J/\Psi p$	$\tilde{g}_V$ ρp	$\tilde{g}_V$ ωp	$\Gamma_{p\gamma}$ (kev)
1	$\frac{1}{2}^-$	4262	35.6	0.39	0.32	–	–	3.9×10^{-5}
2		4308	–	0.13	0.11	–	–	4.5×10^{-6}
3		4412	47.3	0.46	0.38	0.078	0.14	1.14
4		4410	58.9	0.75	0.62	–	–	1.5×10^{-4}
5		4460	–	0.20	0.16	–	–	1.1×10^{-5}
6		4481	57.8	0.37	0.31	–	–	3.8×10^{-5}
7	$\frac{3}{2}^-$	4334	38.8	1.19	0.98	–	–	1.3×10^{-4}
8		4375	–	0.23	0.19	–	–	4.6×10^{-6}
9		4380	144.3	0.36	0.30	0.090	0.17	0.53
10		4380	69.9	0.75	0.62	0.039	0.059	0.060
11		4412	47.3	0.79	0.65	0.14	0.24	1.1
12		4417	8.2	0.39	0.32	–	–	1.4×10^{-5}
13		4450	139.8	0.71	0.58	0.028	0.053	0.054
14		4450	21.7	0.030	0.025	–	–	8.4×10^{-8}
15		4450	16.2	0.58	0.48	–	–	3.1×10^{-5}
16		4453	–	0.21	0.18	–	–	4.2×10^{-6}
17		4481	34.7	0.98	0.81	–	–	8.8×10^{-5}
18	$\frac{5}{2}^+$	4450	46.4	0.35	0.27	0.016	0.016	8.3×10^{-2}

l vector



No.	J^P	m	Γ_{tot}	$\Gamma_{J/\Psi p}$	$\Gamma_{p\gamma}$ (kev)	$\sigma^{(tot)}$(nb)	Ref.
9	$\frac{3}{2}^-$	4380	144.3	3.8	0.53	0.11	This work
		4380	144, 3	3.8	0.70	0.15	[19]
18	$\frac{5}{2}^+$	4450	46.4	4.0	0.083	0.25	This work
		4450	46.4	4.0	1.13	3.4	[19]



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idea how large it is.
h of N*Nγ is not
imental data, we

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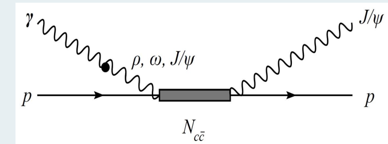
γ p → P_c → J/ψ p

$$\sigma^{(tot)}(W = M_R) = \frac{2J+1}{4}\frac{4\pi}{q_R^2}\frac{\Gamma_{N^*_{c\bar{c}}J/\psi p}\Gamma_{N^*_{c\bar{c}}\gamma p}}{\left[\Gamma^{(tot)}_{N^*_{c\bar{c}}}\right]^2}$$



No.	J^P	m	Γ_{tot}	g_V $J/\Psi p$	$\tilde{g}_V$ $J/\Psi p$	$\tilde{g}_V$ ρp	$\tilde{g}_V$ ωp	$\Gamma_{p\gamma}$ (kev)	$\sigma^{(tot)}$(nb)
1	$\frac{1}{2}^-$	4262	35.6	0.39	0.32	–	–	3.9×10^{-5}	1.9×10^{-4}
2		4308	–	0.13	0.11	–	–	4.5×10^{-6}	–
3		4412	47.3	0.46	0.38	0.078	0.14	1.14	5.4
4		4410	58.9	0.75	0.62	–	–	1.5×10^{-4}	1.3×10^{-3}
5		4460	–	0.20	0.16	–	–	1.1×10^{-5}	–
6		4481	57.8	0.37	0.31	–	–	3.8×10^{-5}	8.8×10^{-5}
7	$\frac{3}{2}^-$	4334	38.8	1.19	0.98	–	–	1.3×10^{-4}	3.7×10^{-3}
8		4375	–	0.23	0.19	–	–	4.6×10^{-6}	–
9		4380	144.3	0.36	0.30	0.090	0.17	0.53	0.11
10		4380	69.9	0.75	0.62	0.039	0.059	0.060	0.23
11		4412	47.3	0.79	0.65	0.14	0.24	1.1	10.8
12		4417	8.2	0.39	0.32	–	–	1.4×10^{-5}	1.0×10^{-3}
13		4450	139.8	0.71	0.58	0.028	0.053	0.054	0.048
14		4450	21.7	0.030	0.025	–	–	8.4×10^{-8}	5.8×10^{-9}
15		4450	16.2	0.58	0.48	–	–	3.1×10^{-5}	1.4×10^{-3}
16		4453	–	0.21	0.18	–	–	4.2×10^{-6}	–
17		4481	34.7	0.98	0.81	–	–	8.8×10^{-5}	0.0026
18	$\frac{5}{2}^+$	4450	46.4	0.35	0.27	0.016	0.016	8.3×10^{-2}	0.25

No.	J^P	m	Γ_{tot}	$\Gamma_{J/\Psi p}$	$\Gamma_{p\gamma}$ (kev)	$\sigma^{(tot)}$(nb)	Ref.
9	$\frac{3}{2}^-$	4380	144.3	3.8	0.53	0.11	This work
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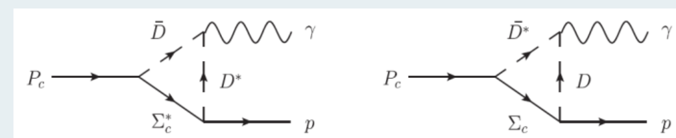
		4450	46.4	4.0	1.13	3.4	[19]



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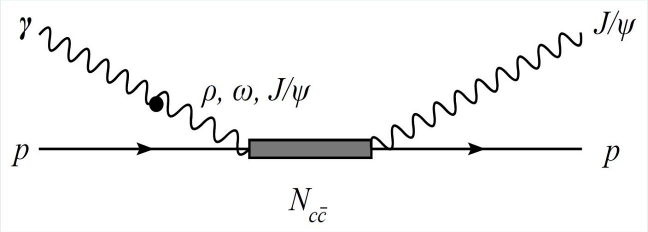
$\gamma\, p \to P_c \to J/\psi\, p$



- $\gamma\, p \to P_c \to J/\psi\, p$ 的振幅

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

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

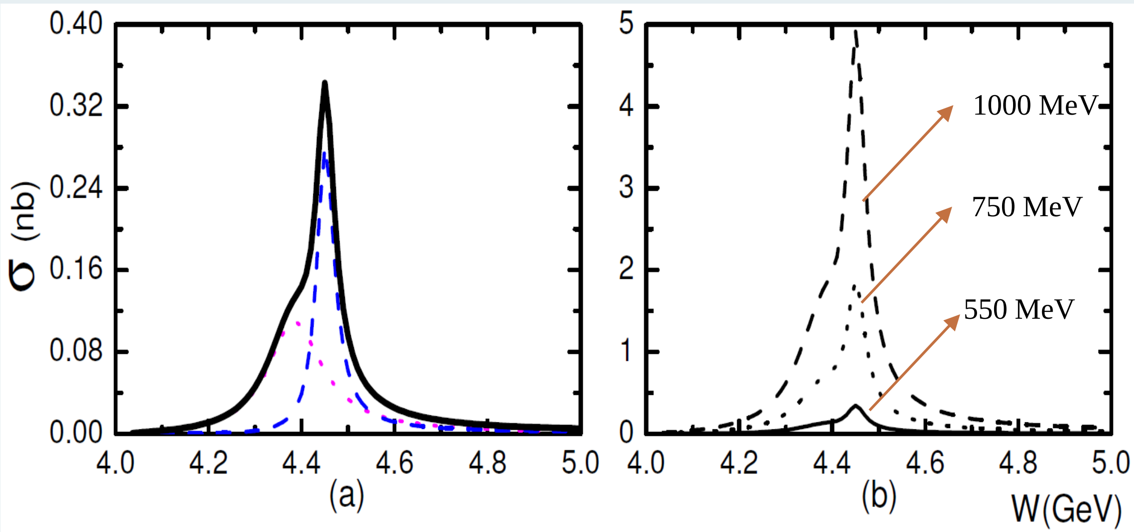
$$\mathcal{M}^{\mu\nu}_{N^*(\frac{3}{2}^-)}(q,p,q',p') = \sum_{V=J/\Psi,\rho,\omega} g_{3J/\Psi}g^{\mu\alpha}\frac{(\gamma.(q+p)+m_{N^*_{c\bar{c}}})P^{\frac{3}{2}}_{\alpha\beta}(p+q)}{W^2-m^2_{N^*_{c\bar{c}}}+i\Gamma_{N^*_{c\bar{c}}}m_{N^*_{c\bar{c}}}}F_V(0)\frac{ie}{f_V}\frac{-m_V^2\tilde{g}_{3V}}{-m_V^2+i\Gamma_V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

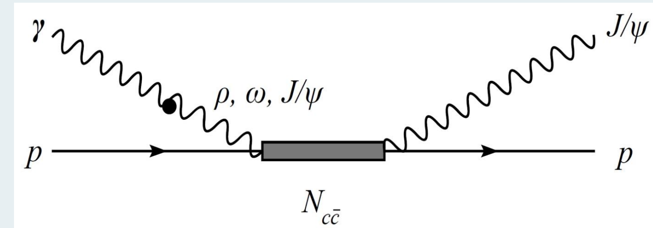
$$\mathcal{M}^{\mu\nu}_{N^*(\frac{5}{2}^+)}(q,p,q',p') = \sum_{V=J/\Psi,\rho,\omega}\frac{g_{5J/\Psi}}{m_N}g^{\mu\alpha}\tilde{r}^\beta\frac{(\gamma.(q+p)+m_{N^*_{c\bar{c}}})P^{\frac{5}{2}}_{\alpha\beta\,\alpha'\beta'}(p+q)}{W^2-m^2_{N^*_{c\bar{c}}}+i\Gamma_{N^*_{c\bar{c}}}m_{N^*_{c\bar{c}}}}F_V(0)$$
$$\times\frac{ie}{f_V}\frac{-m_V^2\tilde{g}_{5V}/m_N}{-m_V^2+i\Gamma_V m_V}\left(g^{\nu\alpha'}\tilde{r}^{\beta'}-\frac{5}{3}\frac{\tilde{r}^\nu\tilde{r}^{\alpha'}\tilde{r}^{\beta'}}{\tilde{r}^2}+\frac{1}{3}\left(\tilde{g}^{\nu\alpha'}_{N^*}\tilde{r}^{\beta'}+\tilde{g}^{\nu\beta'}_{N^*}\tilde{r}^{\alpha'}+\tilde{g}^{\alpha'\beta'}_{N^*}\tilde{r}^\nu\right)\right)$$

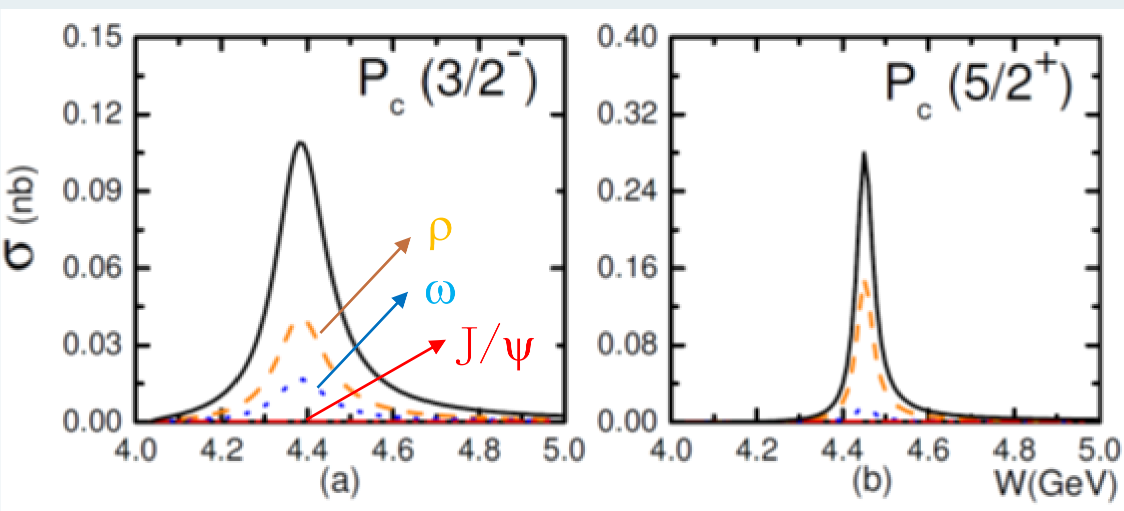
$$P^{\frac{3}{2}}_{\alpha\beta}(p) = -g_{\alpha\beta}+\frac{1}{3}\gamma_\mu\gamma_\nu+\frac{2}{3}\frac{p_\mu p_\nu}{m^2_{N^*}}+\frac{1}{3m_{N^*}}(\gamma_\mu p_\nu-\gamma_\nu p_\mu)$$

$$P^{\frac{5}{2}\ \alpha\alpha'\beta\beta'}(p) = \frac{1}{2}(\tilde{g}^{\alpha\alpha'}_{N^*}\tilde{g}^{\beta\beta'}_{N^*}+\tilde{g}^{\alpha\beta'}_{N^*}\tilde{g}^{\beta\alpha'}_{N^*})-\frac{1}{5}\tilde{g}^{\alpha\beta}_{N^*}\tilde{g}^{\alpha'\beta'}_{N^*}-\frac{1}{10}\left(\tilde{\gamma}^\alpha\tilde{\gamma}^{\alpha'}\tilde{g}^{\beta\beta'}_{N^*}+\tilde{\gamma}^\alpha\tilde{\gamma}^{\beta'}\tilde{g}^{\beta\alpha'}_{N^*}+\tilde{\gamma}^\beta\tilde{\gamma}^{\alpha'}\tilde{g}^{\alpha\beta'}_{N^*}+\tilde{\gamma}^\beta\tilde{\gamma}^{\beta'}\tilde{g}^{\alpha\alpha'}_{N^*}\right)$$

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



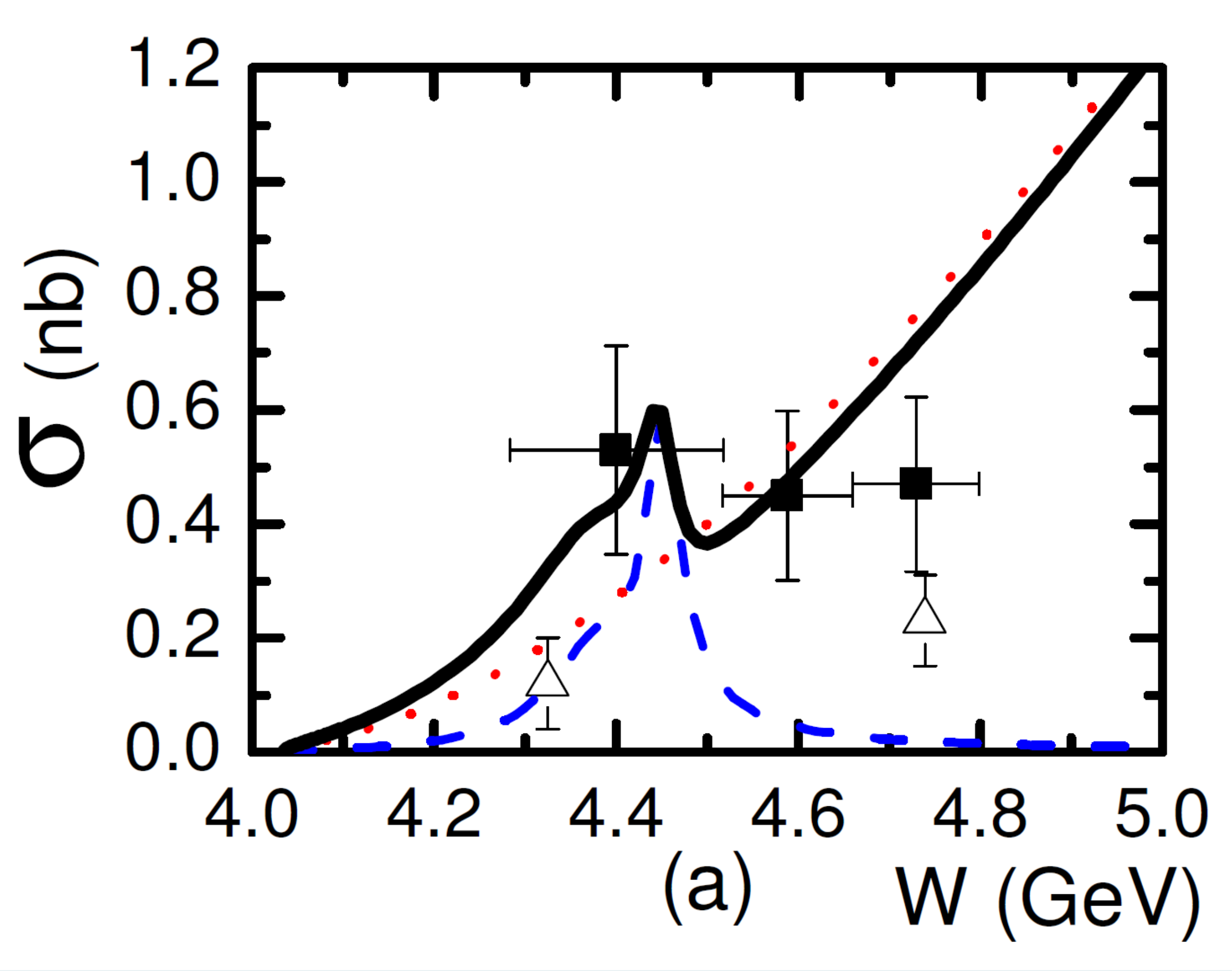




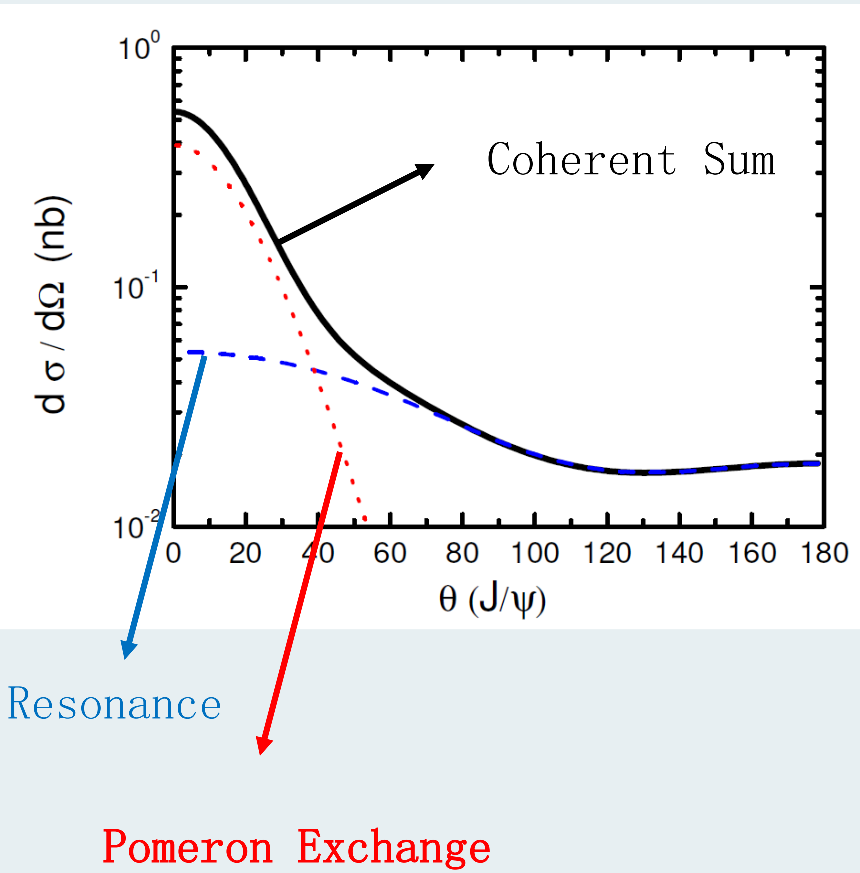
The pure Pc contribution is very dependent on the choice of cut-off.

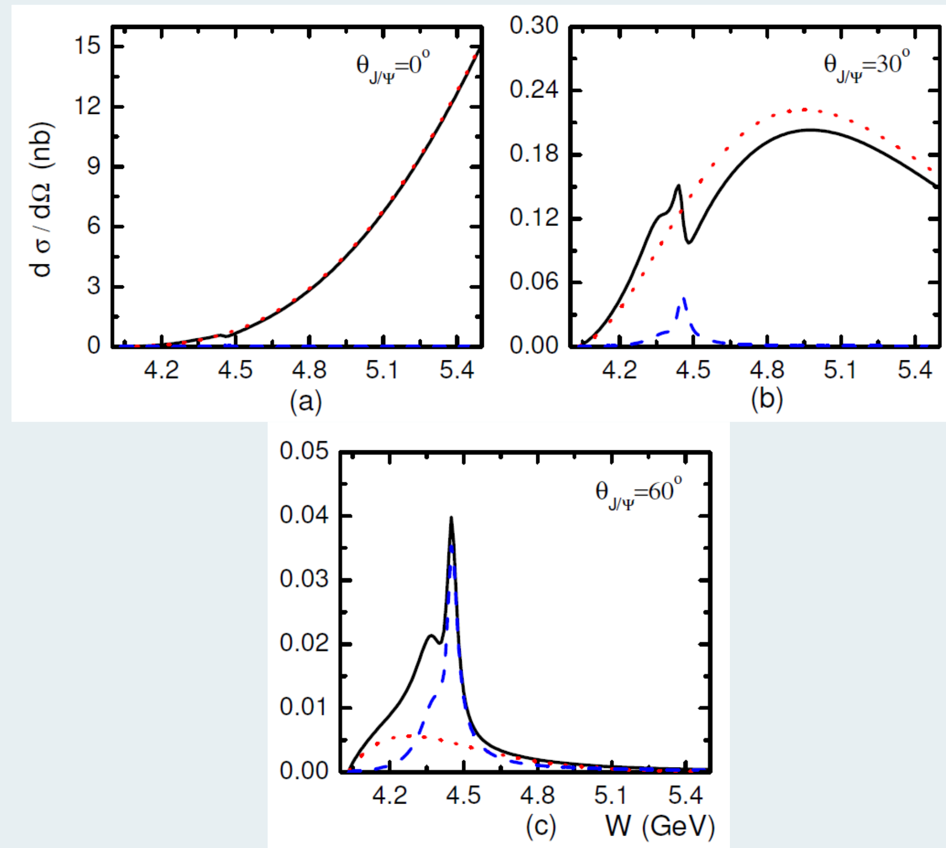
After using a form factor for off shell vector with 550 MeV, we will find the main contribution of VMD is just from ρ/ω meson, and J/ψ contribution is negligible.

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



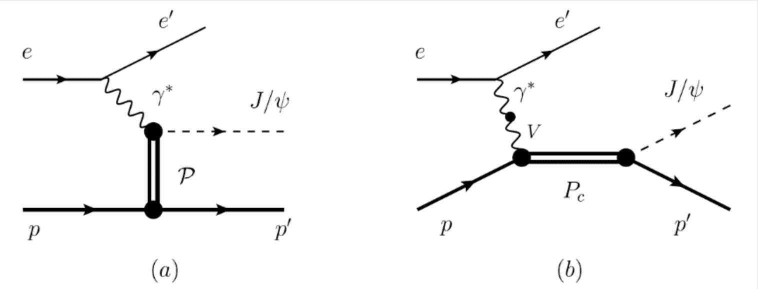
How to extract information of P_c ?





How to extract information of P_c ?

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



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

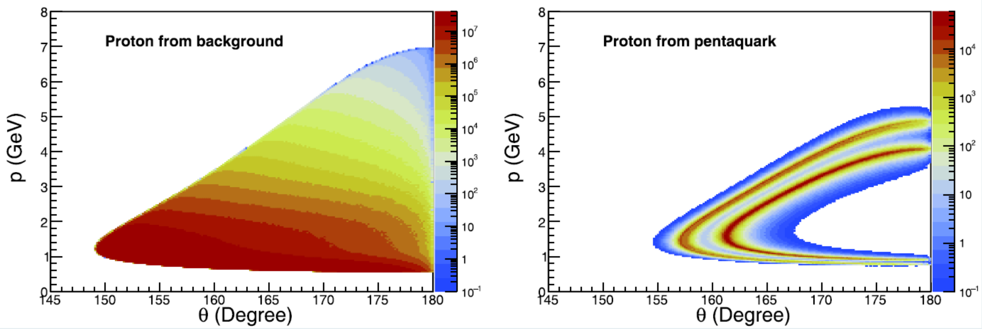
$$\mathcal{P}(z,t,M_V^2,Q^2) = \mathrm{i}g_0(-\mathrm{i}z)^{\alpha_{\mathcal{P}}(t)-1} + \mathrm{i}g_1\ln(-\mathrm{i}z)(-\mathrm{i}z)^{\alpha_{\mathcal{P}}(t)-1},$$

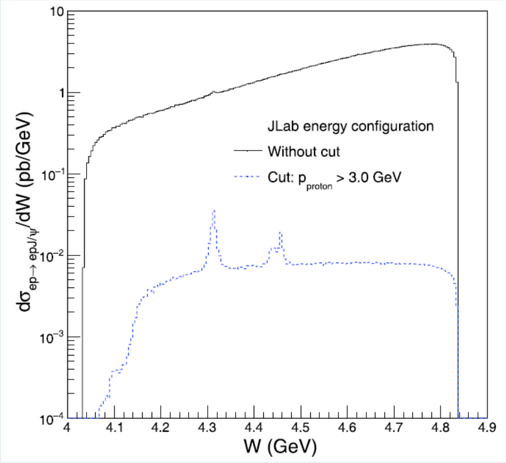
$$\mathcal{F}(z,t,M_V^2,Q^2) = \mathrm{i}g_f(-\mathrm{i}z)^{\alpha_f(t)-1}.$$

	M/MeV	Γ/MeV	J^P
$P_c(4312)$	$4311.9\pm0.7^{+6.8}_{-0.6}$	$9.8\pm2.7^{+3.7}_{-4.5}$	$\frac{3}{2}^-$
$P_c(4440)$	$4440.3\pm1.3^{+4.1}_{-4.7}$	$20.6\pm4.9^{+8.7}_{-10.1}$	$\frac{3}{2}^-$
$P_c(4457)$	$4457.3\pm0.6^{+4.1}_{-1.7}$	$6.4\pm2.0^{+5.7}_{-1.9}$	$\frac{3}{2}^-$

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

Jlab 12 GeV

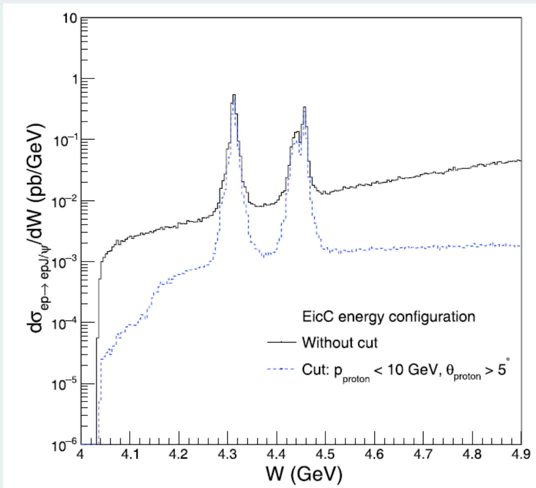




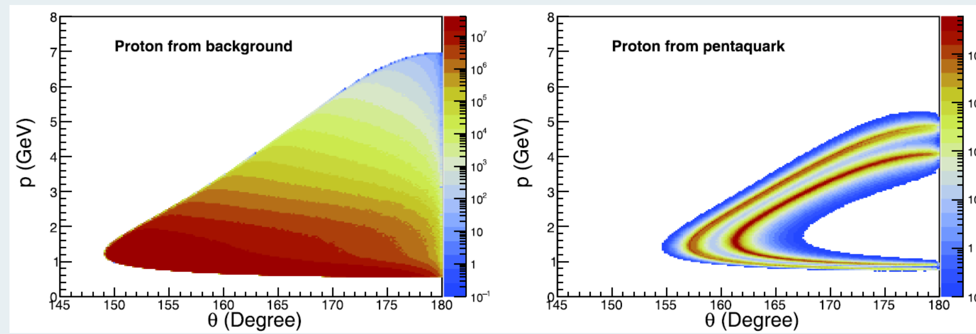
How to extract information of P_c ?

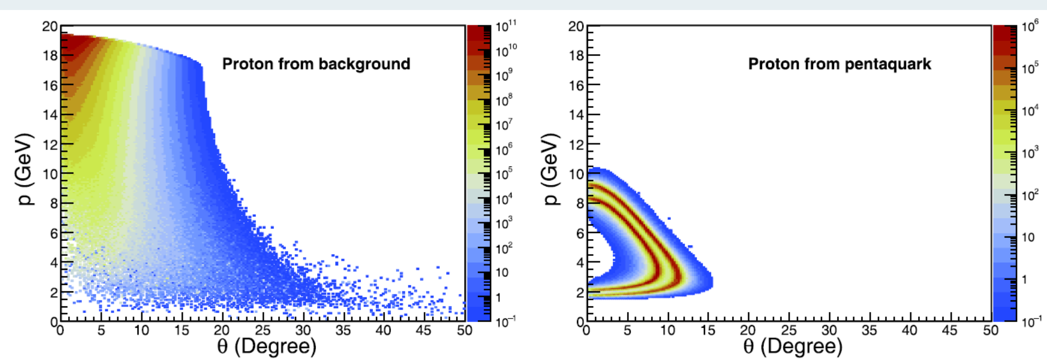
Zhi Yang, Xu Cao, Yu-Tie Liang, Jia-Jun Wu CPC 44, No. 8 (2020) 084102

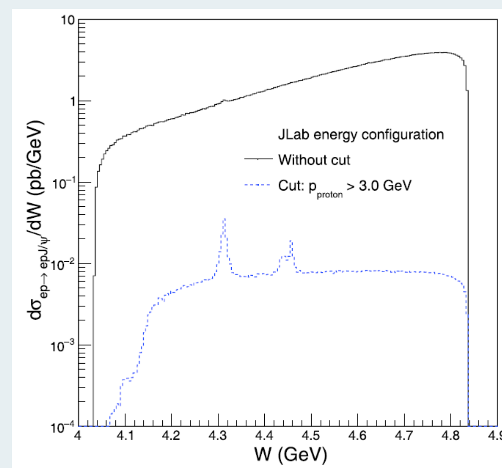
EicC 12 GeV



Jlab 12 GeV

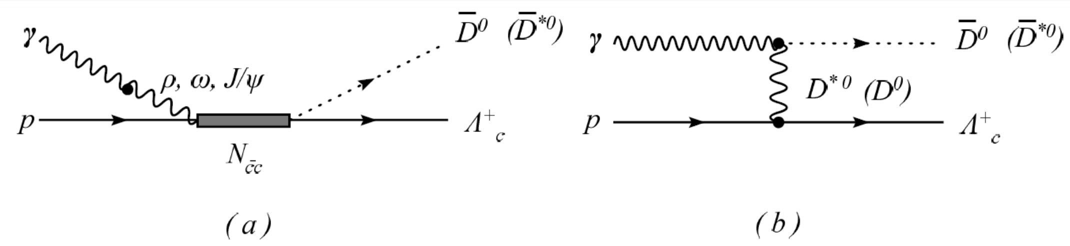


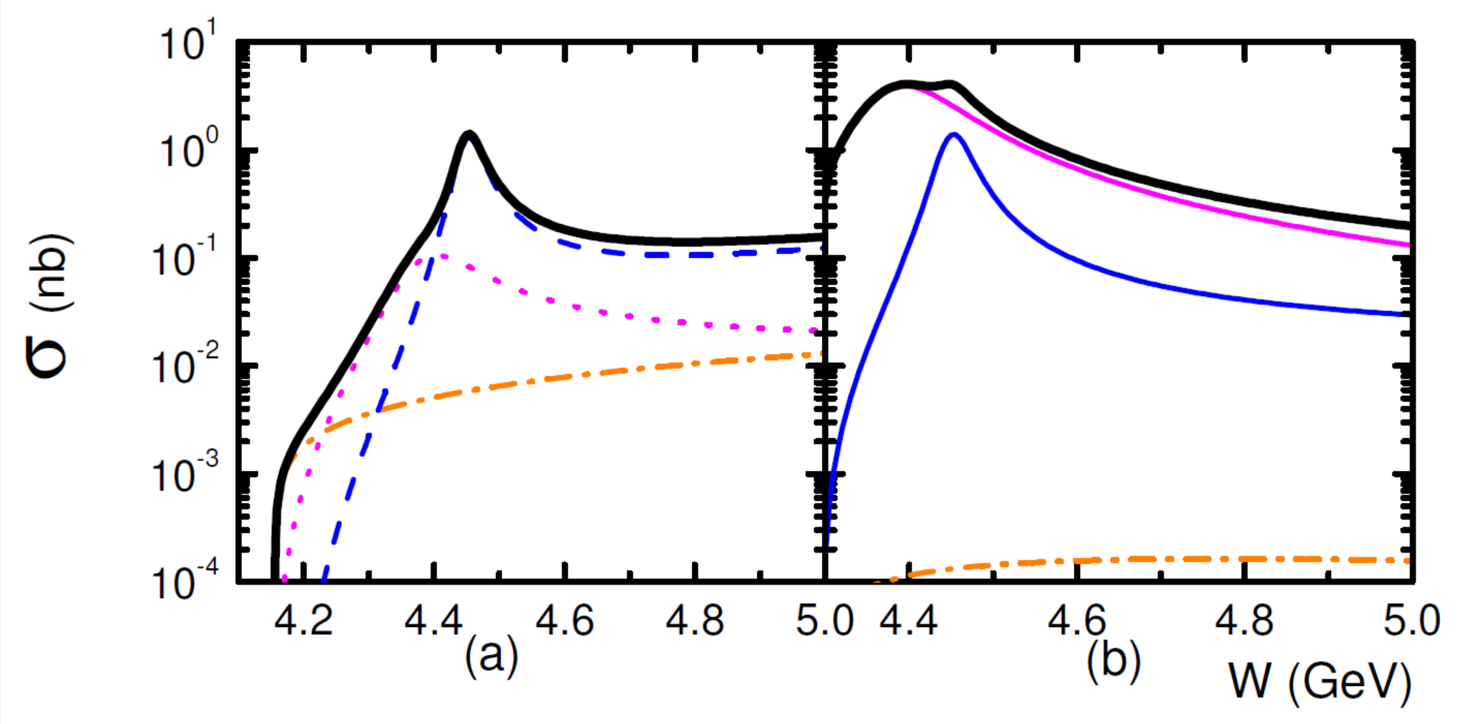




γ p → other final states

- $\gamma\, p \rightarrow \Lambda^{+}_{c}\ \bar{D}^{0}\ (\ \bar{D}^{*0}\ )$





Summary

- We calculated the cross section of $\gamma\, p \to J/\psi\, p$ reaction through background and resonance with hidden-charm.
- How to check pomeron exchange contribution at threshold ?
- How to make amplitude gauge invariance refer to real photon ?
- How to account the off-shell effect in the VMD model ?
- How to find the proper cut to strengthen the signal of P_c ?

Thank very much！

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