Searching hidden-charm baryon in γp reaction

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The spectroscopy program at EIC and future accelerators
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Outline

- Motivation
- γ p → J/ψ p background mechanism
- γ p → P_c → J/ψ p
- How to extract information of P_c ?
- Summary

Motivation

- In 2010, from this paper, 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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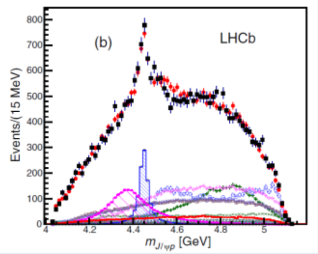
(Received 5 July 2010; published 29 November 2010)

- In 2015, LHCb group first find two peaks of J/ψp invariant mass spectrum from $\Lambda_b \rightarrow$ 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)



- From 2015-Now, there are more than 500 citations for LHCb experimental paper.

Motivation

- How understand two peaks of $J/\psi p$ invariant mass spectrum of LHCb group?

1. Are these two peaks are from two resonances or kinematics effects (Threshold & TS)?
2. If they are really resonances, what is the internal structure ? Meson-Baryon molecule or 5 quark configuration state ?
3. Now the spin and parity (J^p) is not confirmed, $3/2^-$ or $5/2^+$, which one is correct one ? Furthermore, why we do not find $1/2^-$ state ?

=> To answer these questions, we need more reactions to observe these hidden-charm states.

Motivation

- $\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$ VS $\Lambda_b \rightarrow J/\psi K\, p$

1. No Threshold & TS effect because two bodies final state.
2. To distinguish Meson-Baryon molecule and 5 quark configuration state, it needs more decay width of channels.
3. To confirm J^p of state, we need information of angular differential cross section, but in $J/\psi Kp$ system, the interaction of $J/\psi K$ and Kp will infect the angular differential cross section of $J/\psi p$. But two bodies final state will avoid this problem.

=> Definitely, it will provide fruitful information of P_c from $\gamma\, p$ reaction.

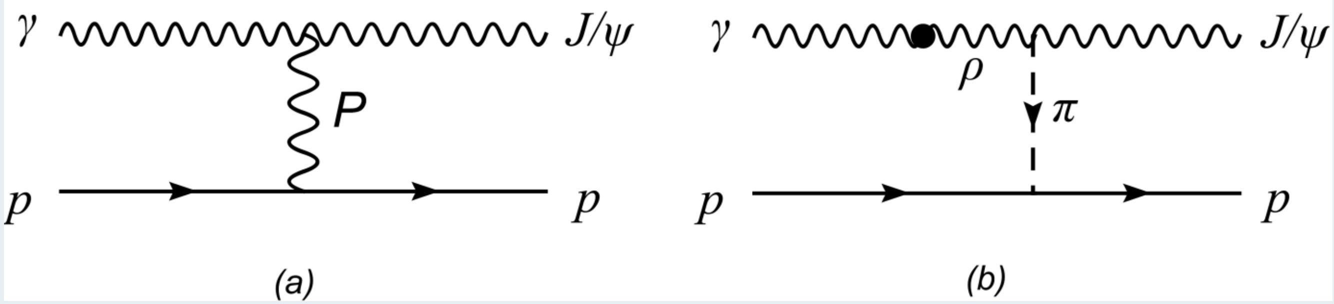
Motivation

- γ p → P_c → J/ψ p is important for understanding P_c .
- Jlab 12 GeV ep reaction can provide enough energy to generate P_c state.

=> In this work, we will use very limited parameters based on theory model to estimate the differential cross section of γ p → J/ψ p for helping search hidden-charm baryon state around the Jlab experimental energy region.

γ p → J/ψ p background mechanism

- **Feynman Diagram**



- **Formulas**

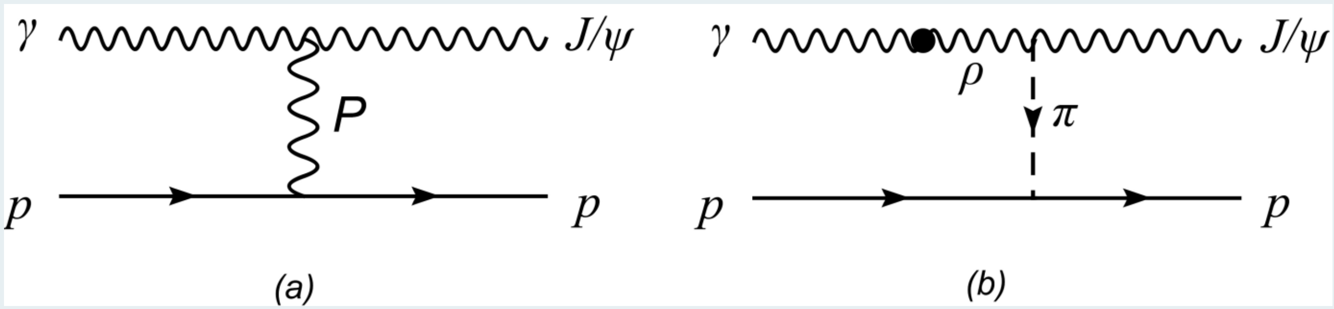
$$\frac{d\sigma}{d\Omega} = \frac{1}{(2\pi)^2}\frac{m_N m_B}{4W^2}\frac{1}{4}\sum_{\lambda_\gamma,\lambda_M}\sum_{m_s,m'_s}\left|\bar{u}_p(p',m'_s)\epsilon^*_\mu(q',\lambda'_{J/\Psi})\mathcal{M}^{\mu\nu}(q,p,q',p')u_p(p,m_s)\epsilon_\nu(q,\lambda_\gamma)\right|^2$$

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

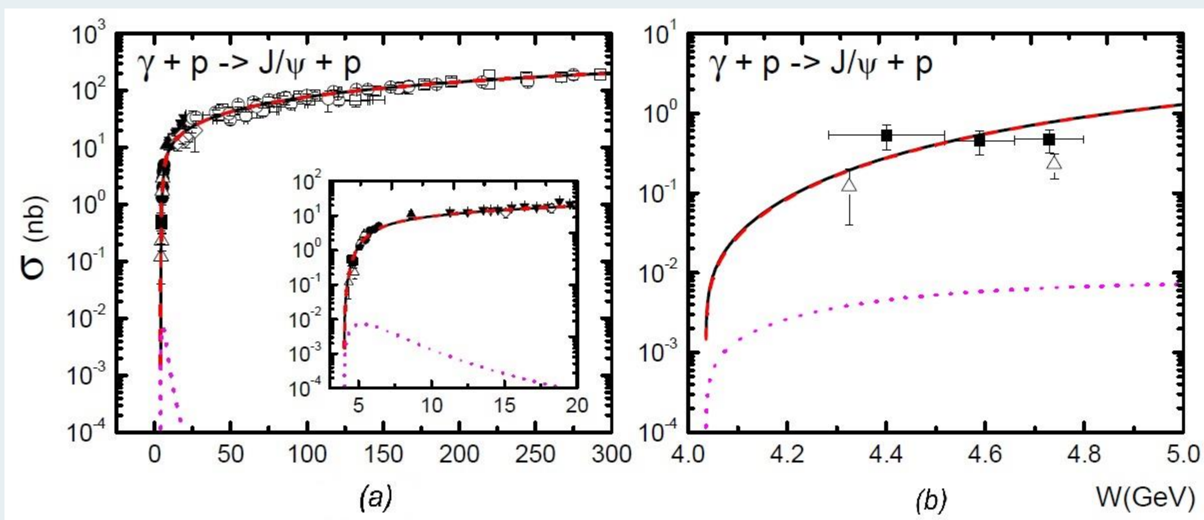
$$\mathcal{M}^{\mu\nu}_\pi(q,q',p,p') = \frac{e}{f_\rho}\frac{g_{J/\Psi,\rho^0\pi^0}}{m_{J/\Psi}}\frac{f_\pi}{m_\pi}\frac{-m_\rho^2}{q^2-m_\rho^2+i\Gamma_\rho m_\rho}\frac{\Lambda_\rho^4}{\Lambda_\rho^4+(q^2-m_\rho^2)^2}\frac{1}{t-m_\pi^2}\left(\frac{\Lambda_\pi^2-m_\pi^2}{\Lambda_\pi^2-t}\right)^4\epsilon^{\mu\nu\alpha\beta}q'_\alpha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

γ p → J/ψ p background mechanism

- **Feynman Diagram**



- **Result**



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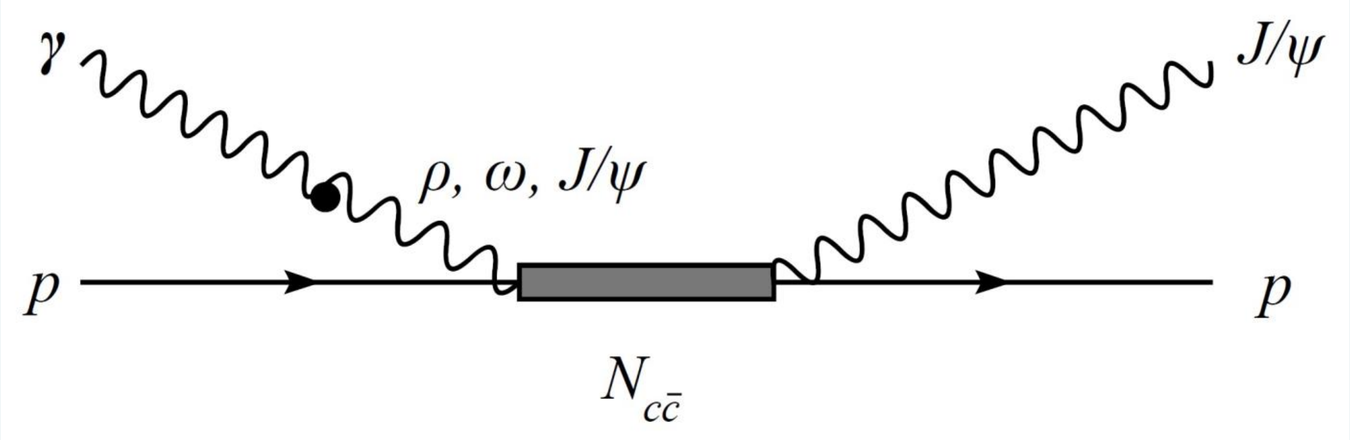
$\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$



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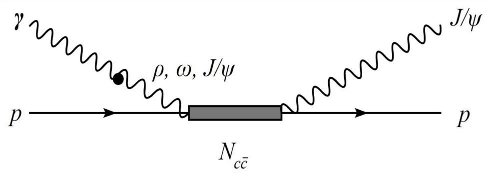
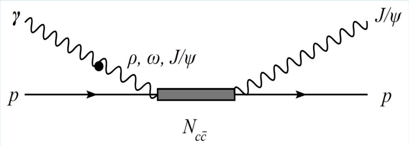


- $P_c \rightarrow$ VB with various Model

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 [10] Eides, Petrov, 1811.01691
[7] Huang, Ping, 1811.04260 [8, 9] Wu, Molina, Oset, Zou, PRL 105 232001, PRC 84 015202

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



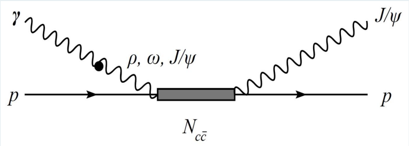
- $P_c \rightarrow$ VB with various Model

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

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

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

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



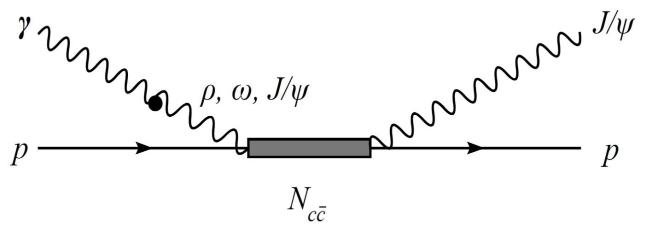
- $P_c \rightarrow VB$ with various Model

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.
$\frac{3}{2}^-$	4380	144.3	3.8	1.4	5.3	1.2	131.3	$\bar{D}\Sigma_c^*$	[5]
	4450	39.5	0.03	—	—	1.4	6.8	$\bar{D}^*\Sigma_c$	[10]

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

No.	J^P for N^*	N^*BV	$g_v(f_v = h_v = 0)$	$f_v(g_v = h_v = 0)$
1	$\frac{3}{2}^-$	$N^*(4380)J/\psi N$	0.36	0.50
2		$N^*(4380)\rho N$	0.061	0.066
3		$N^*(4380)\omega N$	0.12	0.13
4		$N^*(4450)J/\psi N$	0.030	0.042

γ p → P_c → J/ψ p



- γ p → P_c with VDM

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

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

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

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

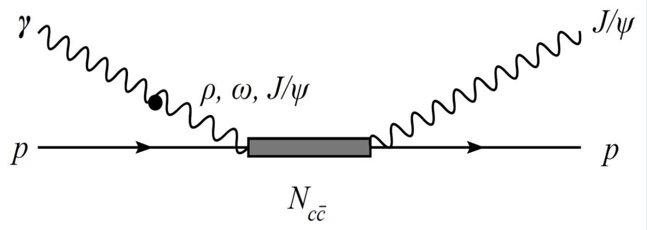
$$\mathcal{M}^\nu = \frac{ie}{f_V} \frac{-m_V^2 (g_{1\rho}(1-\alpha) + f_{1\rho}\alpha)}{q^2 - m_V^2 + i\Gamma_V m_V} \gamma_5 \tilde{\gamma}_\mu \left(g_{\mu\nu'} + \left(\frac{3}{2} \frac{\tilde{r}_\mu \tilde{r}_\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}_{N^*\ \mu\nu'} \right) \right) \tilde{g}_V^{\nu'\nu}(q)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

$$g_{1\rho}(1-\alpha) + f_{1\rho}\alpha \in (g_{1\rho}, f_{1\rho})$$

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

With Λ = 1 - 2 GeV

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



- $\gamma\, p \to P_c$ with VDM

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

No.	J^P for N^*	N^*BV	$g_v(f_v = h_v = 0)$	$f_v(g_v = h_v = 0)$
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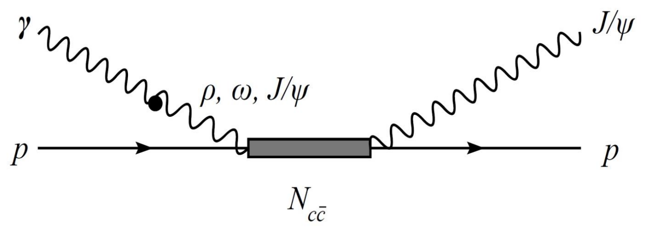
With $\Lambda = 1 - 2$ GeV

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

- $\gamma\, p \to P_c \to J/\psi\, p$ total cross section



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

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

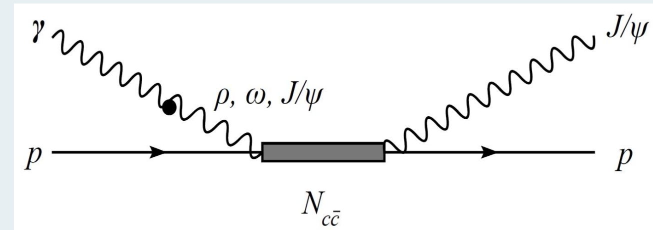
$$\mathcal{M}^{\mu\nu}_{N^*(\frac{3}{2}^-)}(q,p,q',p') = g_{3V}g^{\mu\alpha}\frac{(\gamma.(q+p)+m_{N^*_{c\bar{c}}})P^{\frac{3}{2}}_{\alpha\beta}(p+q)}{W^2-m^2_{N^*_{c\bar{c}}}+i\Gamma_{N^*_{c\bar{c}}}m_{N^*_{c\bar{c}}}}F_V(0)\times\frac{ie}{f_V}\frac{-m_V^2 g_{3V\gamma}}{-m_V^2+i\Gamma_V m_V}\left(g^{\beta\nu}+\frac{3}{2}\frac{\tilde{r}^\beta\tilde{r}^\nu}{\tild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

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

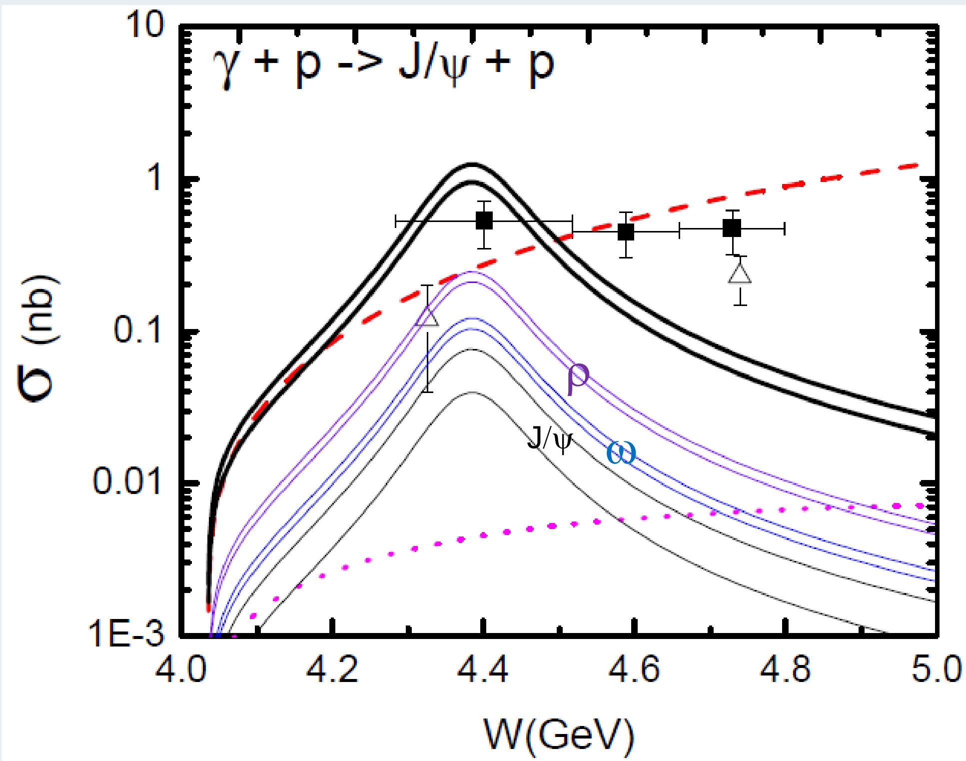
$$P^{\frac{3}{2}}_{\alpha\beta}(p) = -g_{\alpha\beta}+\frac{1}{3}\gamma_\mu\gamma_\nu+\frac{2}{3}\frac{p_\mu p_\nu}{m^2_{N^*}}+\frac{1}{3m_{N^*}}(\gamma_\mu p_\nu-\gamma_\nu p_\mu)$$

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

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



- $\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$ total cross section



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Lin, Shen, Guo, Zou, PRD95 114017

J^P	N^*BV	$g_v(f_v = h_v = 0)$	$f_v(g_v = h_v = 0)$
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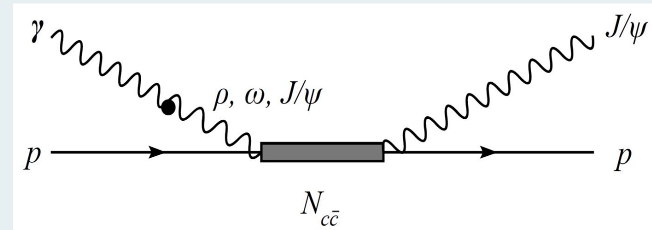
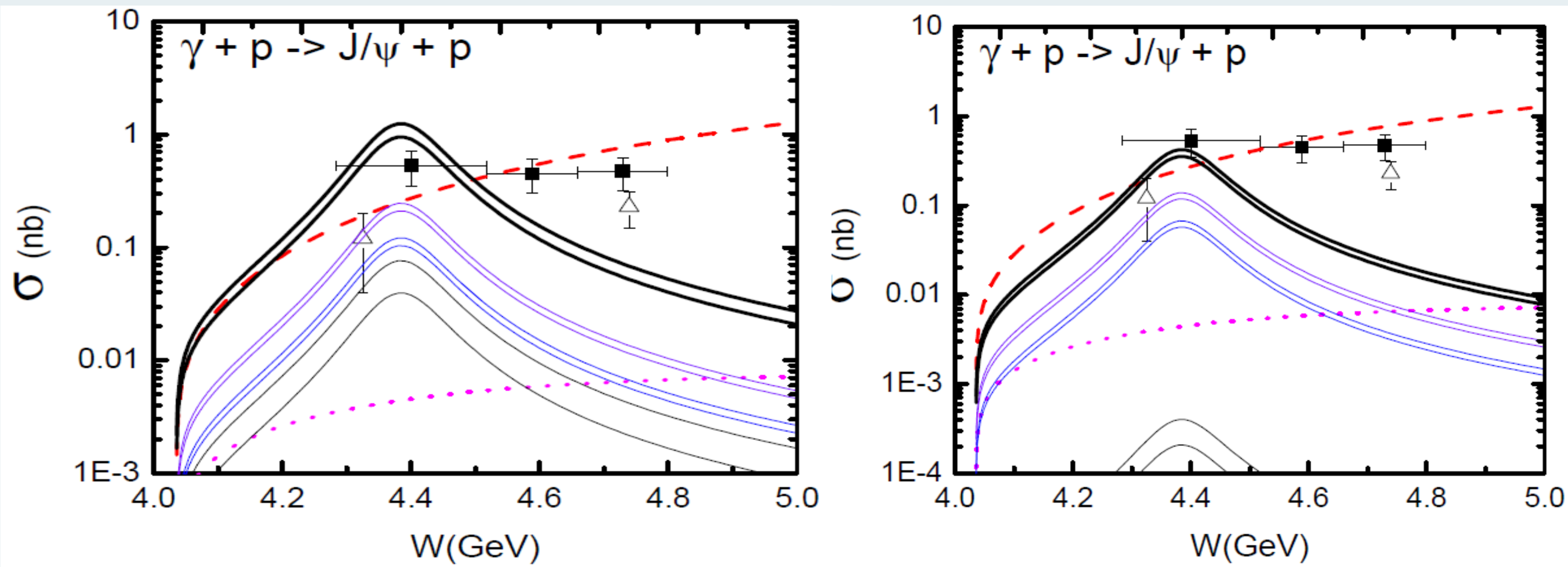
$\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$

- $\gamma\, p \rightarrow P_c \rightarrow J/\psi\, p$ total cross section





With Λ = 2 GeV

With Λ = 1 GeV

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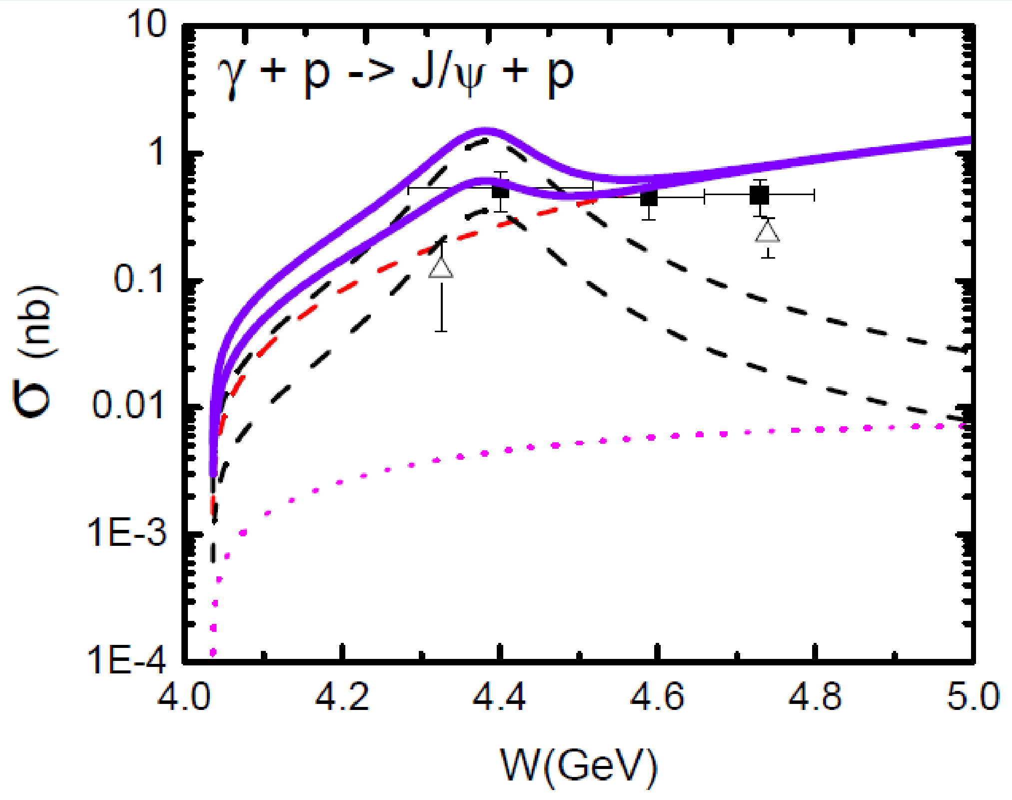
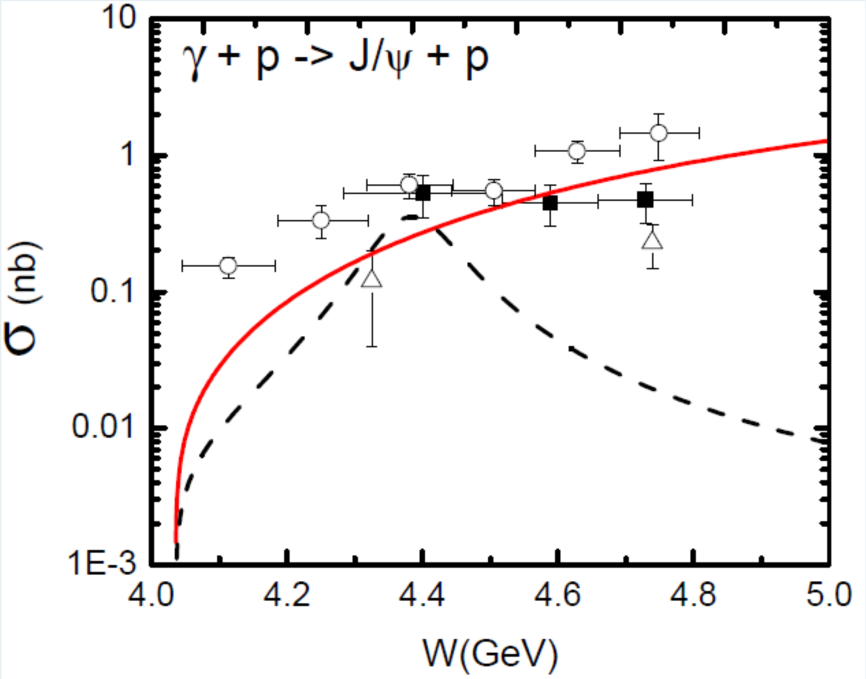
$\gamma p \to J/\psi p$

- **Background + Signal**



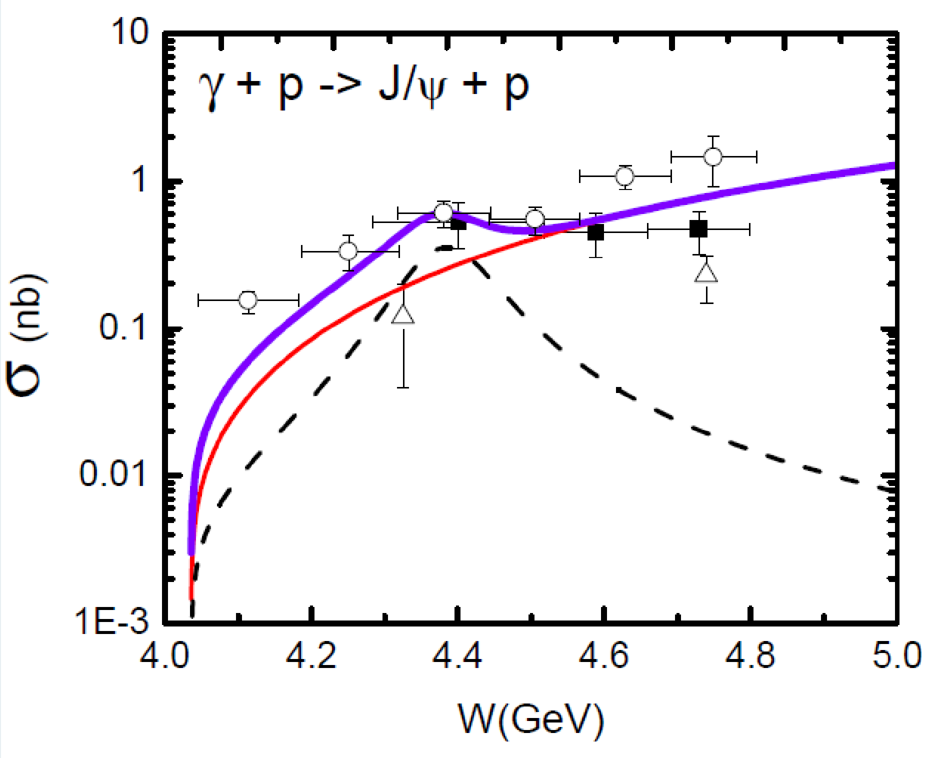
$\gamma\, p \rightarrow J/\psi\, p$

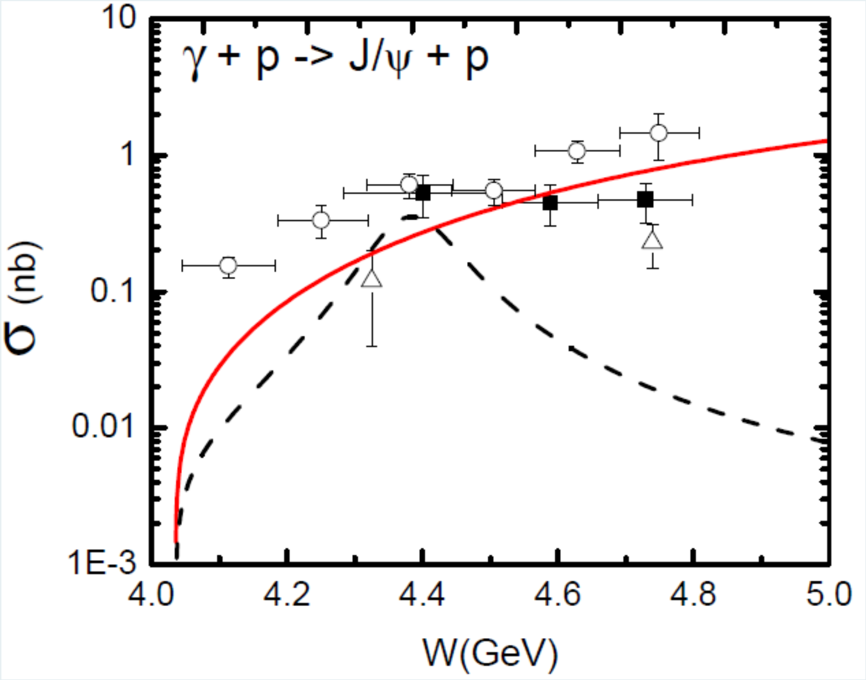
- **Background + Signal**
- **Lowest Signal**



γ p → J/ψ p

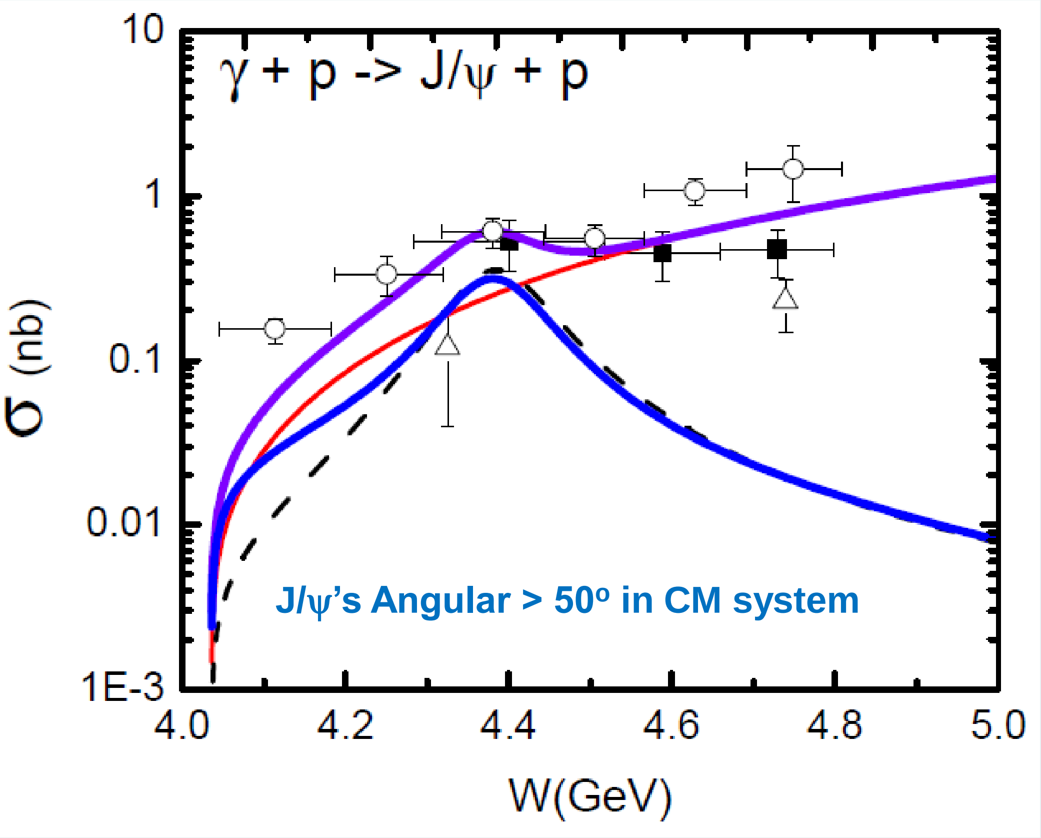
- **Background + Signal**
- **Lowest Signal**





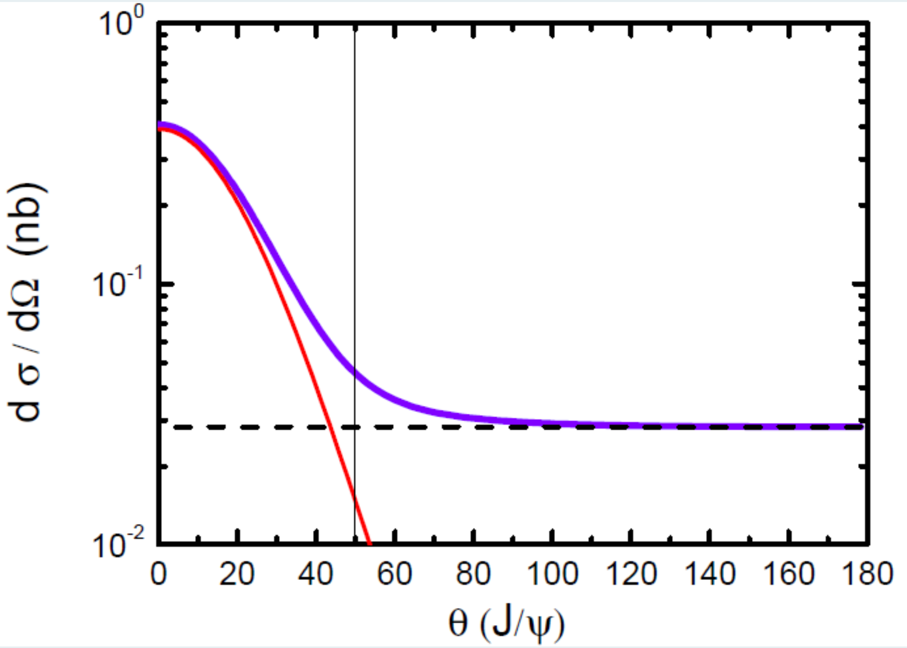
How to extract information of P_c ?

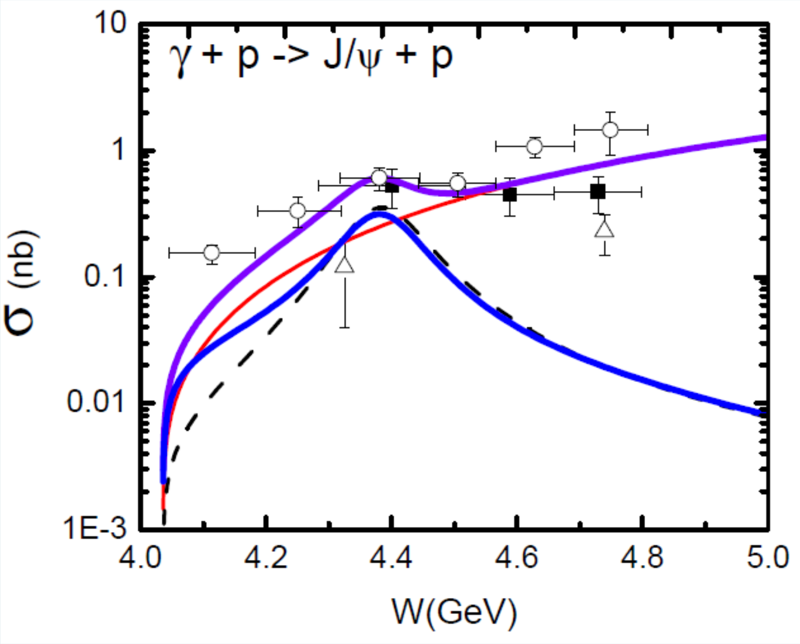
- **Angular cut**



How to distinguish J^p of P_c ?

- **The differential cross section of Pomeron exchange and Pc s-channel contribution**



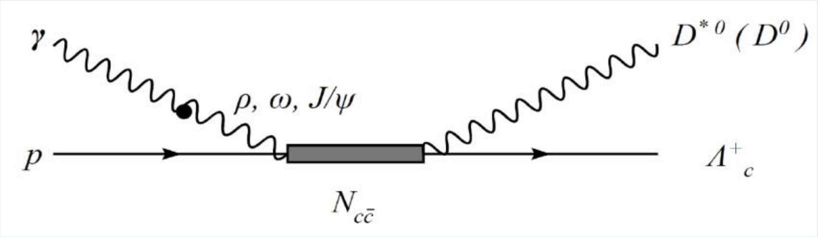


Summary

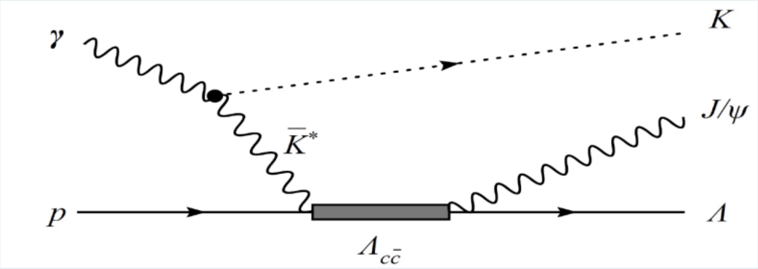
- We calculated the cross section of $\gamma\, p \to J/\psi\, p$ reaction through background and resonance with hidden-charm.
- Discuss how to extract the $\gamma\, p \to P_c \to J/\psi\, p$ signal from the background.
- Outlook, there will be some other diagrams for P_c and Λ^* with hidden-charm.

γ p → other final states

- γ p → P_c → $\bar{D}^0 \Lambda^+_c$ or $\bar{D}^{*0} \Lambda^+_c$
- **Feynman diagram and Total cross section**



- γ p → K $\Lambda^*_{c\bar{c}}$ → K J/$\psi\Lambda$
- **Just on the energy edge of Jlab, around 11.5 GeV**



Thank very much！