J/psi光生和电生过程研究

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轻强子谱国际协同研究研讨会　2021年7月9日　高能所

目录

$\gamma p \to J/\psi\ p$ 和 $e p \to e J/\psi\ p$ 的物理意义

- 研究胶子场如何传递核子和夸克对之间的相互作用是理解QCD理论的一个重要方向。
- 那么一个重要的过程就是研究J/ψ N的相互作用，因为该相互作用领头阶的贡献是J/ψ中的正反粲夸克对湮灭以后变成胶子然后和核子N相互作用。显然J/ψ的光生和电生过程提供了非常好的研究J/ψ N相互作用的场所。

- 2015年Pc态第一次在LHCb中的，而后在2019年更多的实验数据中确实了Pc态的峰结构，并且得到了更加细节的信号。
- 但是至今只有在这个实验中观测到峰结构，这是远远不够的。我们至今不能知道$P_c \to J/\psi\ p$ 的分宽度是多少。所以我们需要更多的实验信息。后面可以看到在J/ψ的光生和电生过程中的$J/\psi\ p$不变质量谱上找到Pc信号对理解Pc态是非常重要的。

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

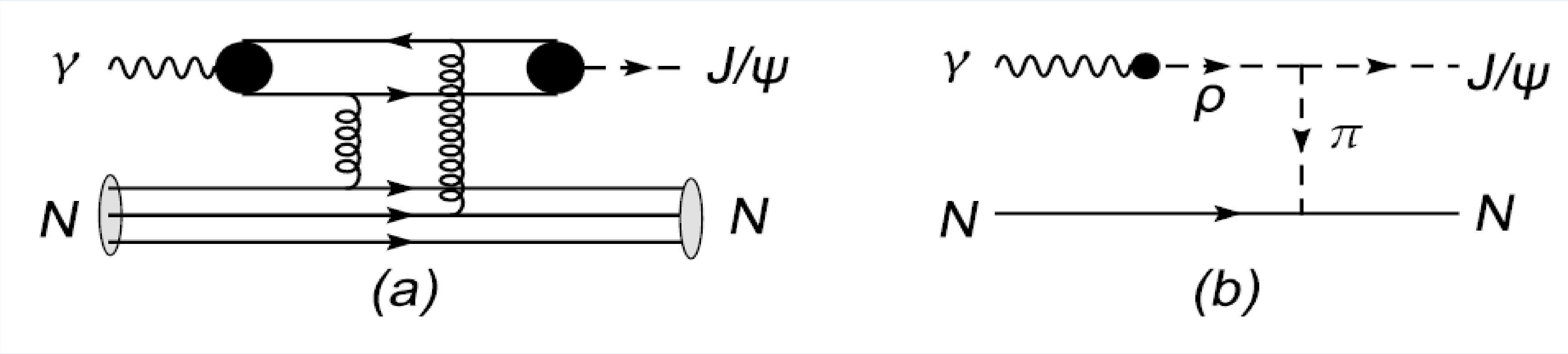
- 我们在2010年的文章中也提到了$e\, p \to e\, J/\psi\, p$ 实验是寻找研究Pc态非常好的地方。随后我在毕业论文里也做了相关计算，但是没有正式发表。

- 去年李老师受到Argonne在Jlab实验组人员委托，希望给他们提供该反应道的建议，所以我们开始从理论估算这个反应道。

[1] Y. Huang, J. He, H.-F. Zhang, and X.-R. Chen, JPG **41**, 115004 (2014), 1305.4434.
[2] Q. Wang, X.-H. Liu, and Q. Zhao, PRD**92**, 034022 (2015), 1508.00339.
[3] V. Kubarovsky and M. B. Voloshin, PRD**92**, 031502 (2015), 1508.00888.
[4] M. Karliner and J. L. Rosner, PLB**752**, 329 (2016), 1508.01496.
[5] A. N. Hiller Blin, C. Fernandez-Ramirez, A. Jackura, V. Mathieu, etc, PRD**94**, 034002 (2016), 1606.08912.
[6] E. Ya. Paryev and Yu. T. Kiselev, NPA**978**, 201 (2018), 1810.01715.
[7] Xu Cao Eur.Phys.J.C 81 (2021) 2, 184
[8] Xu Cao,Jian-ping Dai *Phys.Rev.D* 100 (2019) 5, 054033

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

- 费曼图



- 公式

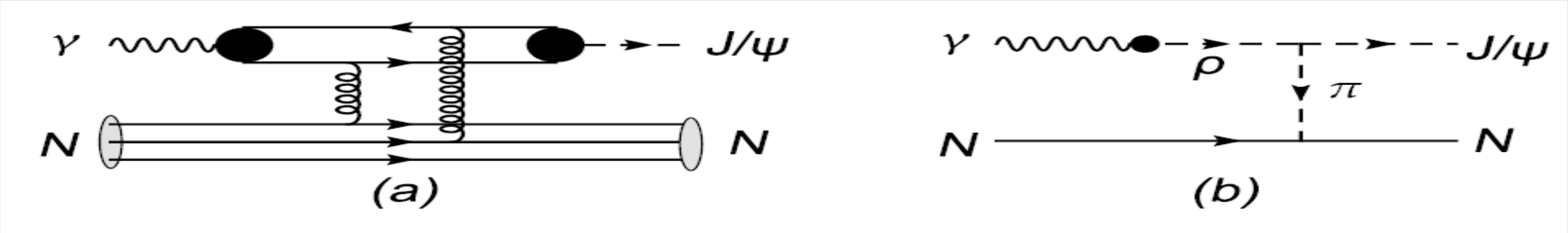
$$\frac{d\sigma}{d\Omega} = \frac{1}{(2\pi)^2}\frac{m_N m_B}{4W^2}\frac{1}{4}\sum_{\lambda_\gamma,\lambda_M}\sum_{m_s,m_s'}\left|\bar{u}_p(p',m_s')\epsilon^*_\mu(q',\lambda'_{J/\Psi})\mathcal{M}^{\mu\nu}(q,p,q',p')u_p(p,m_s)\epsilon_\nu(q,\lambda_\gamma)\right|^2$$

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

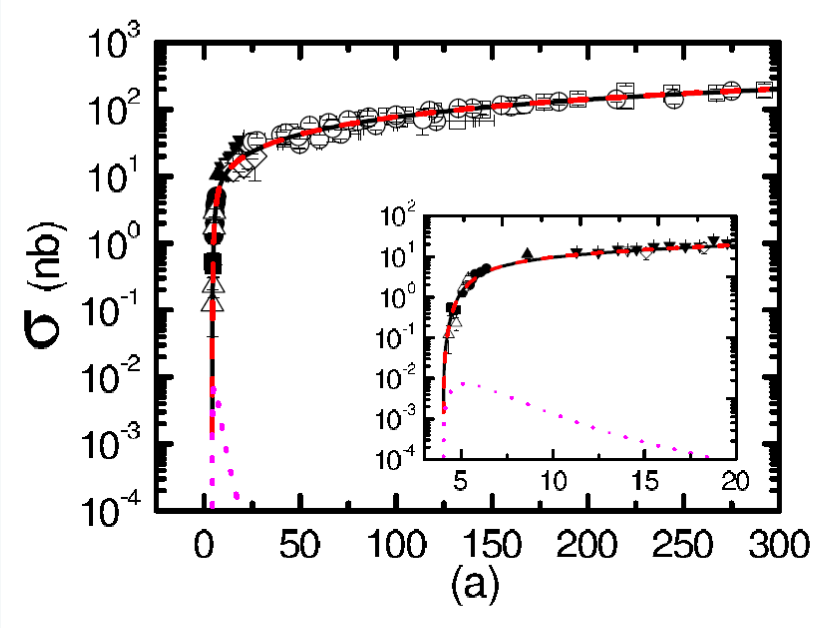
$$\mathcal{M}_\pi^{\mu\nu}(q,q',p,p') = \frac{e}{f_\rho}\frac{g_{J/\Psi,\rho^0\pi^0}}{m_{J/\Psi}}\frac{f_\pi}{m_\pi}\frac{-m_\rho^2}{q^2-m_\rho^2+i\Gamma_\rho m_\rho}\frac{\Lambda_\rho^4}{\Lambda_\rho^4+(q^2-m_\rho^2)^2}\frac{1}{t-m_\pi^2}\left(\frac{\Lambda_\pi^2-m_\pi^2}{\Lambda_\pi^2-t}\right)^4\epsilon^{\mu\nu\alpha\beta}q'_\alpha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

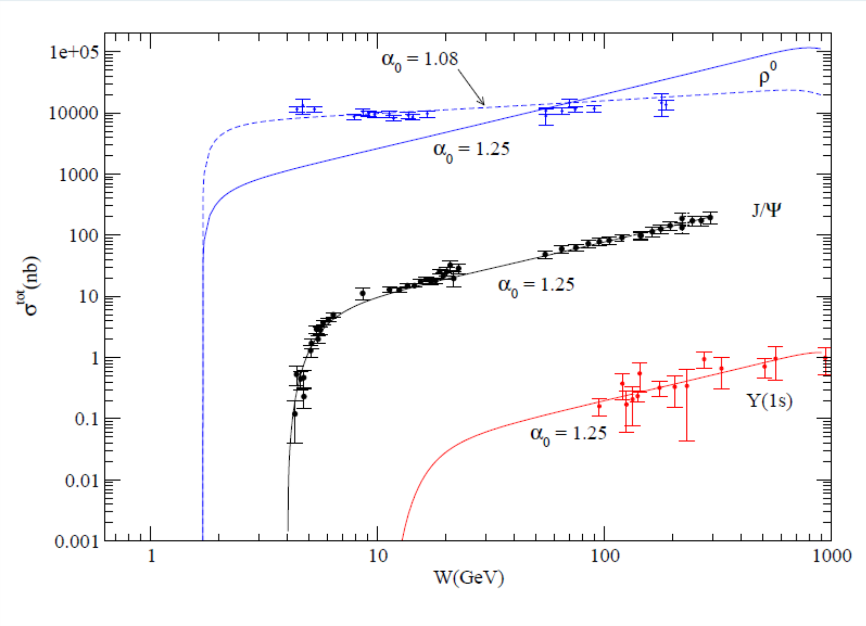
$\gamma\, p \to J/\psi\, p$ 背景项

- 费曼图



- 公式





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

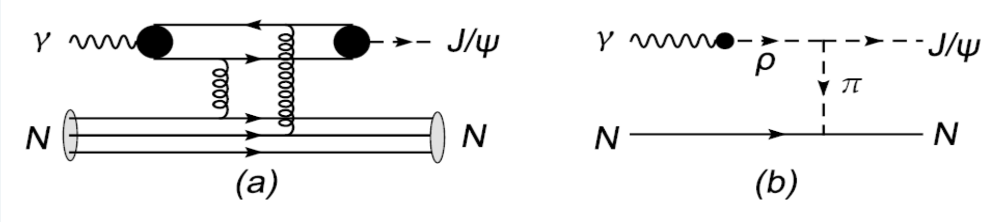
$$\alpha_0 = 1.08$$

$$\alpha_0 = 1.25$$

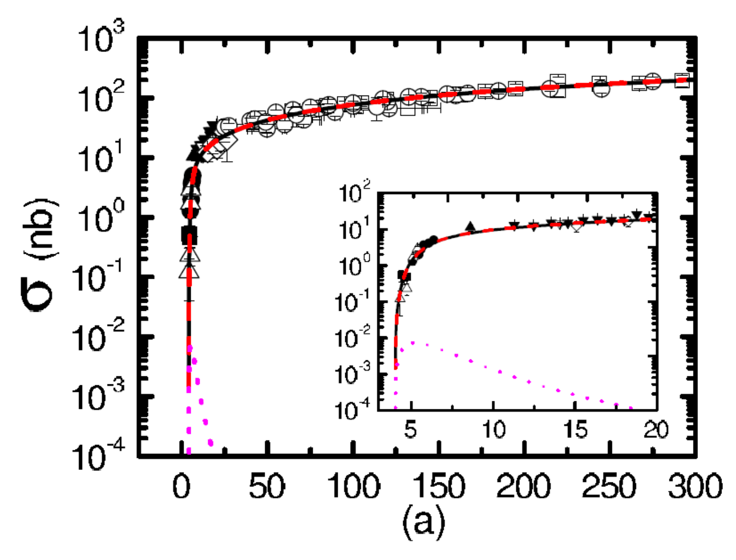
$$\mathcal{M}_P^{\mu\nu}(q,p,q',p') = \left(\frac{s}{s_0}\right)^{\alpha_P(t)-1} \exp\left\{-\frac{i\pi}{2}\left[\alpha_P(t)-1\right]\right\} i12e\frac{M_V^2\beta_q\beta_{q'}}{f_V}\frac{1}{M_V^2-t}\left(\frac{2\mu_0^2}{2\mu_0^2+M_V^2-t}\right)\frac{4M_N^2-2.8t}{(4M_N^2-t)(1-t/0.71)^2}\{\gamma.qg^{\mu\nu}-q^\mu\gamma^\nu\}$$

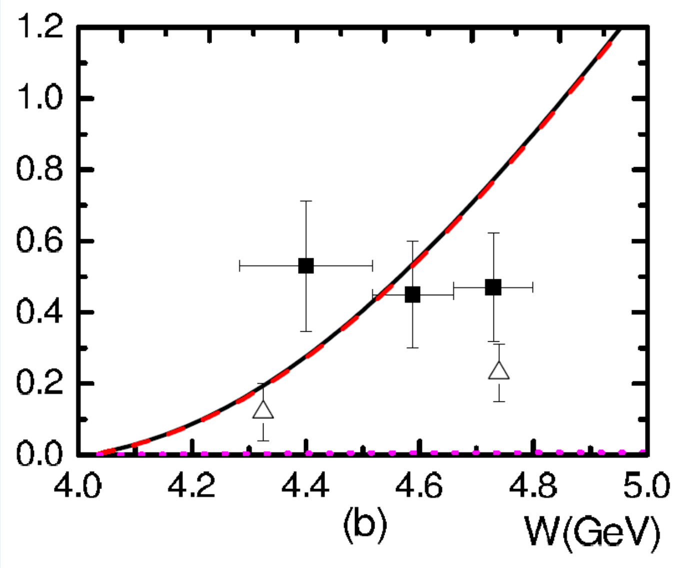
γ p → J/ψ p 背景项

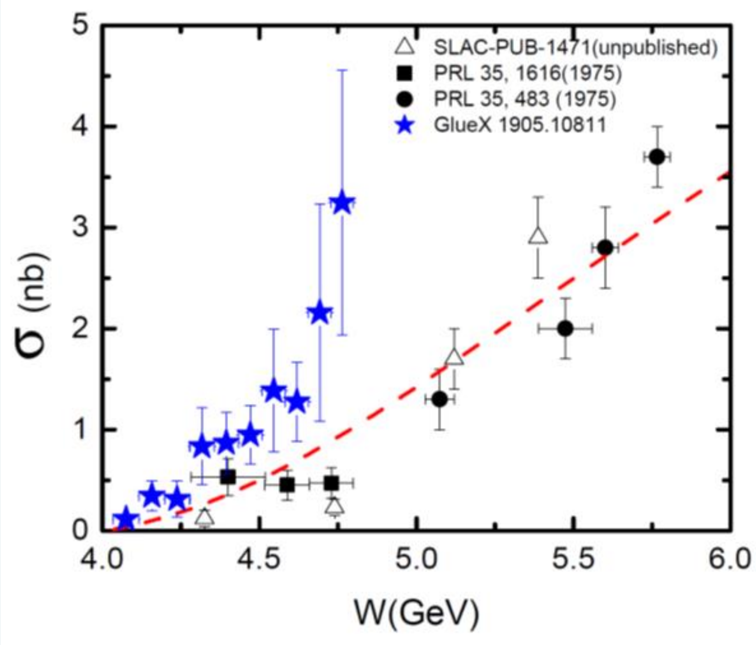
- 费曼图



- 公式



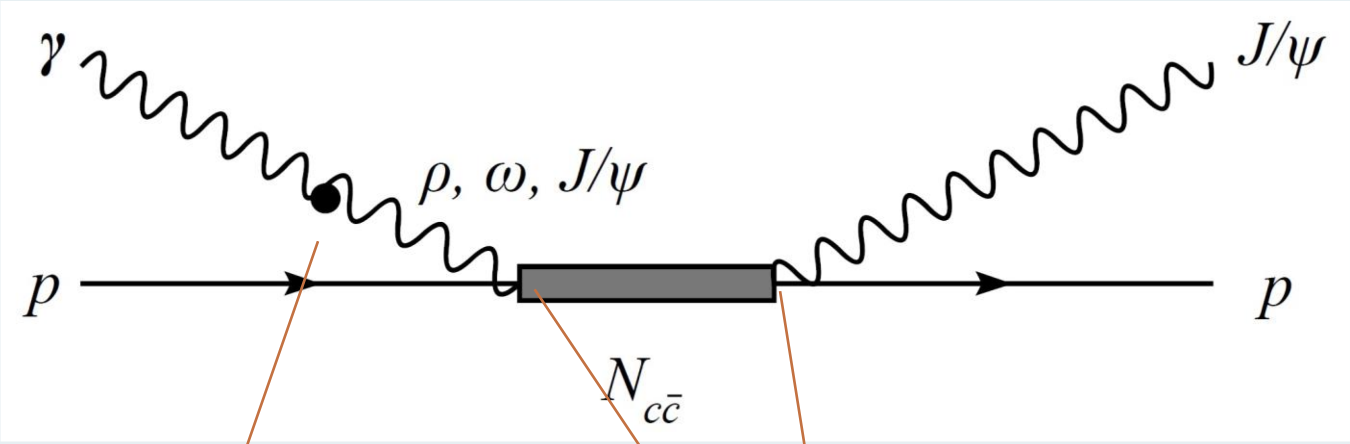




$$\mathcal{M}_P^{\mu\nu}(q,p,q',p') = \left(\frac{s}{s_0}\right)^{\alpha_P(t)-1} \exp\left\{-\frac{i\pi}{2}\left[\alpha_P(t)-1\right]\right\} i12e\frac{M_V^2\beta_q\beta_{q'}}{f_V}\frac{1}{M_V^2-t}\left(\frac{2\mu_0^2}{2\mu_0^2+M_V^2-t}\right)\frac{4M_N^2-2.8t}{(4M_N^2-t)(1-t/0.71)^2}\{\gamma.qg^{\mu\nu}-q^\mu\gamma^\nu\}$$

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

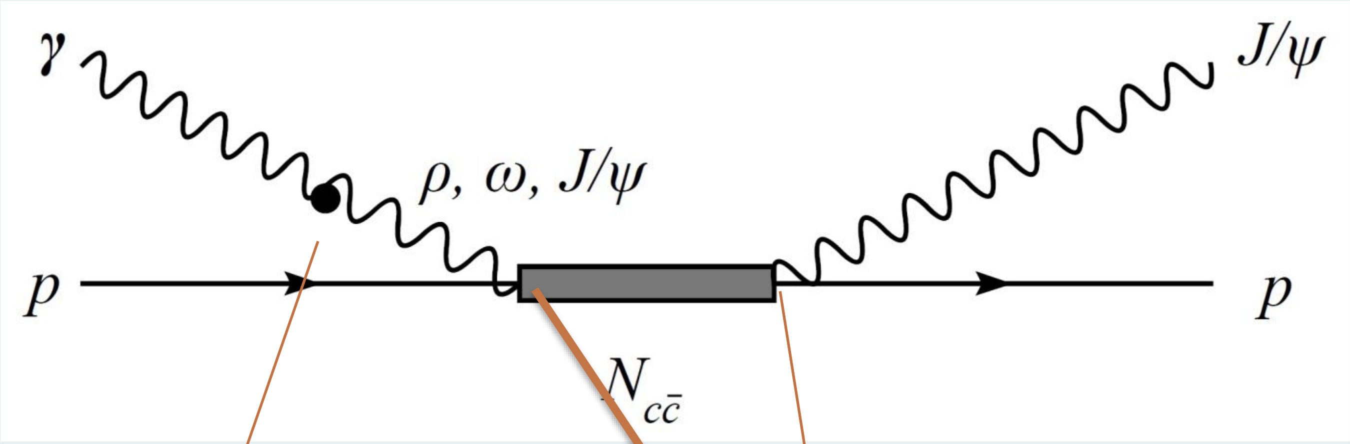
$\gamma\, p \to P_c \to J/\psi\, p$ 的贡献



VMD 模型顶点

PcVN 顶点

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



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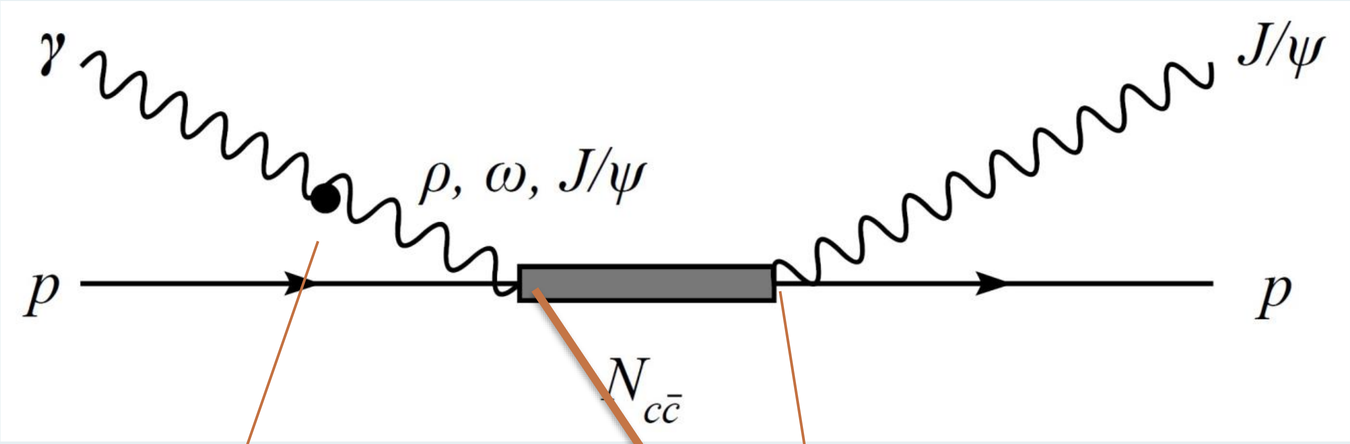
VMD 模型顶点

PcVN 顶点

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



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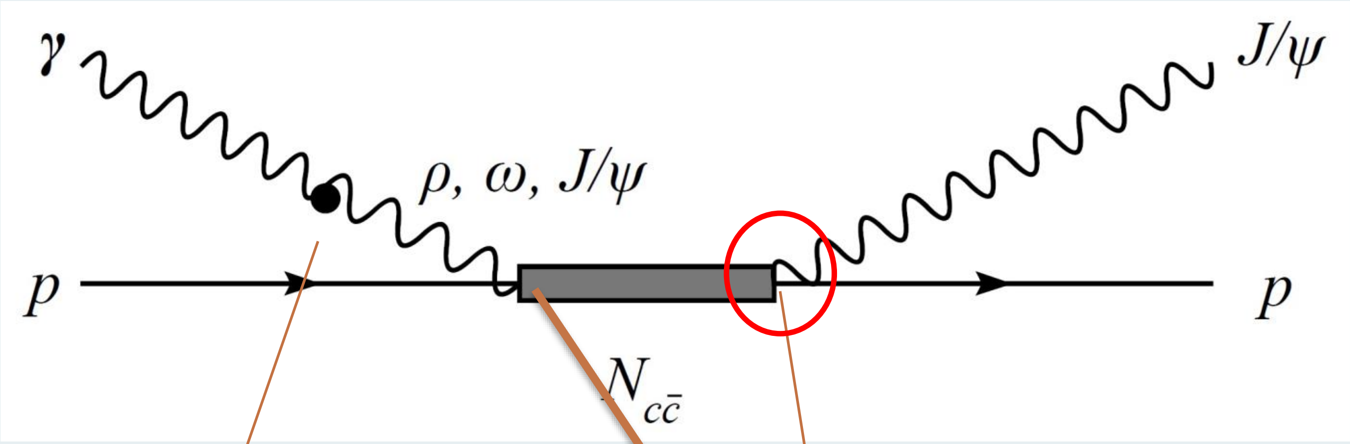
VMD 模型顶点

PcVP 顶点

PcγP 顶点

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



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VMD 模型顶点

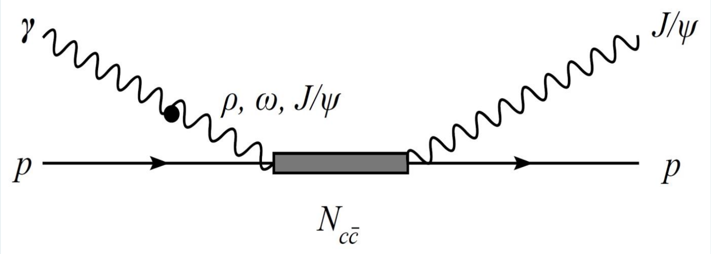
PcVP 顶点

PcγP 顶点

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

- $P_c \rightarrow VB$ 不同的理论模型

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

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

- $P_c \rightarrow VB$ 相互作用的LS耦合的洛伦兹结构

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

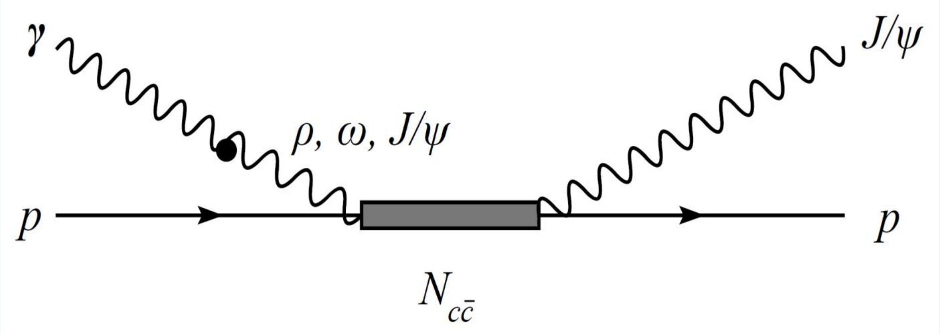
$$\mathcal{M}_{N^*(\frac{3}{2}^-)NV} = \bar{u}_N u_{N^*\ \mu} \epsilon^*_{V\ \nu} \left(g_{3V} g^{\mu\nu} + f_{3V} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}^{\mu\nu}_{N^*} \right) \right)$$

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

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

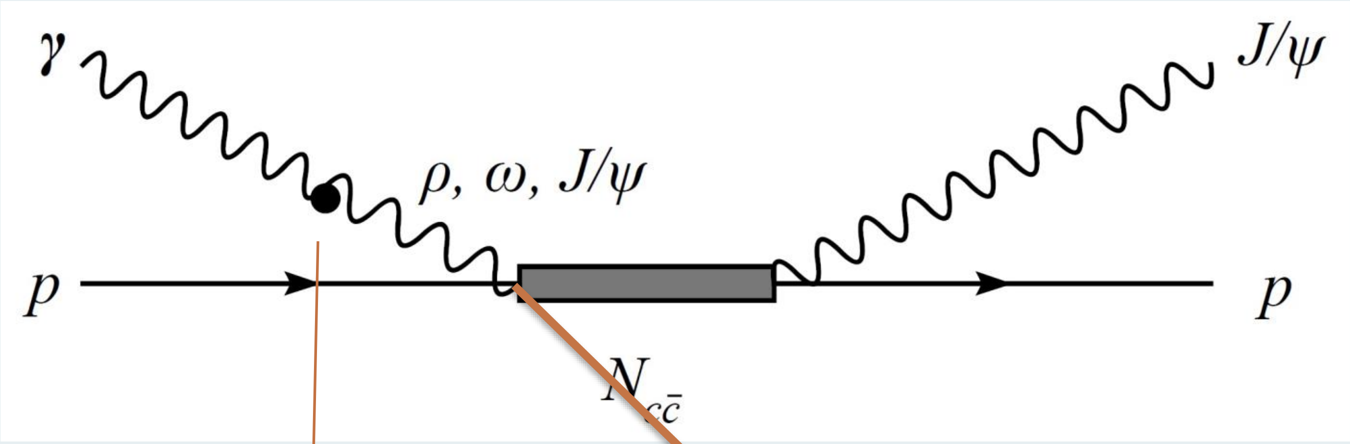
$$+ \frac{h_{5V}}{m_N} \epsilon_{\mu\nu\lambda\delta} \bar{u}_N \gamma_5 \left(\tilde{\gamma}^\mu g_{\xi\alpha} g_{\sigma\beta} + \tilde{\gamma}_\xi g_{\sigma\beta} g_{\mu\beta} + \tilde{\gamma}_\sigma g_{\mu\beta} g_{\xi\beta} \right) u^{\alpha\beta}_{N^*} \epsilon^{*\ \mu}_{V}$$

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



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

$\gamma\, p \to P_c \to J/\psi\, p$ 的贡献中$\gamma\, p \to P_c$ 顶点



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

问题2. off-shell的影响

VMD 模型顶点

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

PcVP 顶点

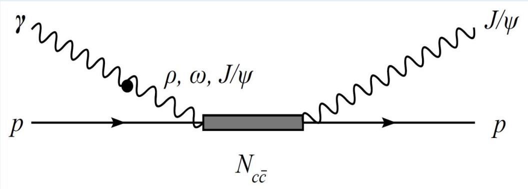
$$\mathcal{L}_{N^*(\frac{1}{2}^-)NV} = \overline{N}^* \gamma_5 \tilde{\gamma}_\mu N V_\nu \left(g_{1V} g^{\mu\nu} + f_{1V} \left(\frac{3}{2} \frac{\tilde{r}^\mu \tilde{r}^\nu}{\tilde{r}^2} - \frac{1}{2} \tilde{g}^{\mu\nu}_{N^*} \right) \right) + h.c.$$

问题1. 光子的规范不变性

PcγP 顶点

$\gamma\, p \to P_c \to J/\psi\, p$ 的贡献中$\gamma\, p \to P_c$ 顶点

- $\gamma\, p \to P_c$ 顶点的光子的规范不变性



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

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

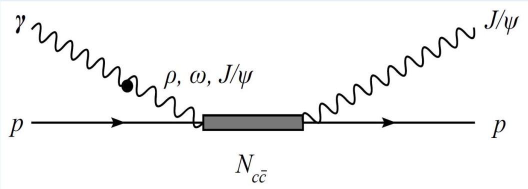
$$\mathcal{T}_{N*(\frac{1}{2}^-)\to NV \to N\gamma} = \overline{u}_N \mathcal{M}^\nu u_{N^*} \epsilon^*_\nu,$$

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

$\mathcal{M}^\nu q_\nu \sim (g_{1V} - f_{1V}) \neq 0$ 破坏了光子的规范不变性

$\gamma\, p \to P_c \to J/\psi\, p$ 的贡献中$\gamma\, p \to P_c$ 顶点

- $\gamma\, p \to P_c$ 顶点的光子的规范不变性



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

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

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

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

$\mathcal{M}^\nu q_\nu \sim (g_{1V} - f_{1V}) \neq 0$ 破坏了光子的规范不变性

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

Dulat, Wu, Zou, PRD83, 094032　J/ψ -> $\overline{B}$B γ

一个简单粗暴的方案是：(不是说我们解决了这个问题)

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

γ p → P_c → J/ψ p 的贡献中γ p → P_c 顶点

- γ p → P_c 顶点的光子的规范不变性

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

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

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

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

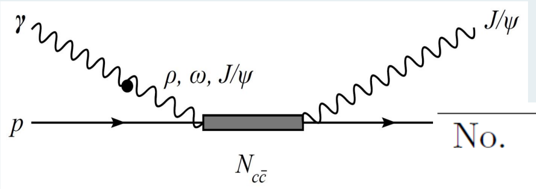
$\mathcal{M}^\nu q_\nu \sim (g_{1V} - f_{1V}) \neq 0$ 破坏了光子的规范不变性

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

Dulat, Wu, Zou, PRD83, 094032 J/ψ -> $\overline{B}$B γ

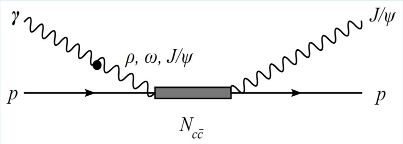
一个简单粗暴的方案是：(不是说我们解决了这个问题)

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



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

$\gamma\, p \to P_c \to J/\psi\, p$ 的贡献中$\gamma\, p \to P_c$ 顶点



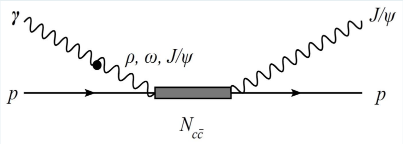
- $\gamma\, p \to P_c$ 顶点的矢量介子off-shell的影响

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

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

γ p → P_c → J/ψ p 的贡献中γ p → P_c 顶点

- γ p → P_c 顶点的**矢量介子off-shell的影响**



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

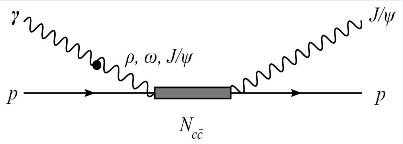
$$\mathcal{M}^\nu = \frac{ie}{f_V}\frac{-m_V^2\tilde{g}_{1V}}{q^2-m_V^2+i\Gamma_V m_V}\gamma_5\tilde{\gamma}_\mu\left(g_{\mu\nu'}-\left(\frac{3}{2}\frac{\tilde{r}_\mu\tilde{r}_\nu}{\tilde{r}^2}-\frac{1}{2}\tilde{g}_{N^*\ \mu\nu'}\right)\right)\tilde{g}_V^{\nu'\nu}(q)\times F_V(q^2)$$

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

D* -> Dγ 用VMD 模型来处理， D* -> D(ρ & ω & J/ψ) -> Dγ 来估算 Λ的大小，这个值其实挺小的，650 MeV左右。这个结果给我们一个非常强烈的暗示，N*Nγ的强度可能被这个矢量介子的off-shell极大的压低了，所以我们在随后的计算中，尽量选取符合现有实验数据的结果，避免出现预言非常大的共振态贡献。最后我们取 $\Lambda = 550$ MeV 。

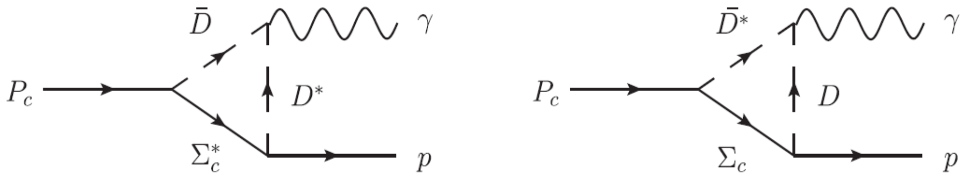
$\gamma\, p \to P_c \to J/\psi\, p$ 的贡献中$\gamma\, p \to P_c$ 顶点

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}



• γ … 响

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]

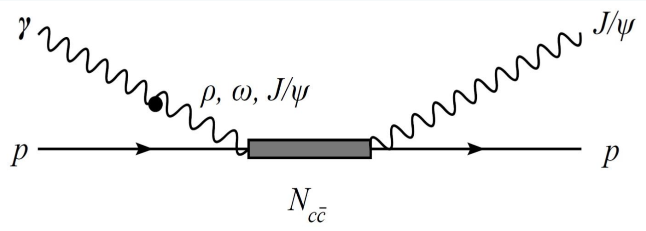


$\mathcal{M}^\nu$ … $\Lambda^4 + m_V^4$

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

D* -> Dγ … Dγ来估算Λ的大小，这个值其实挺小的，650 MeV左右。
这个结果 … 个矢量介子的off-shell极大的压低了，所以我们在随
后的计算 … 预言非常大的共振态贡献。最后我们取 $\Lambda = 550$ MeV 。

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



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

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

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

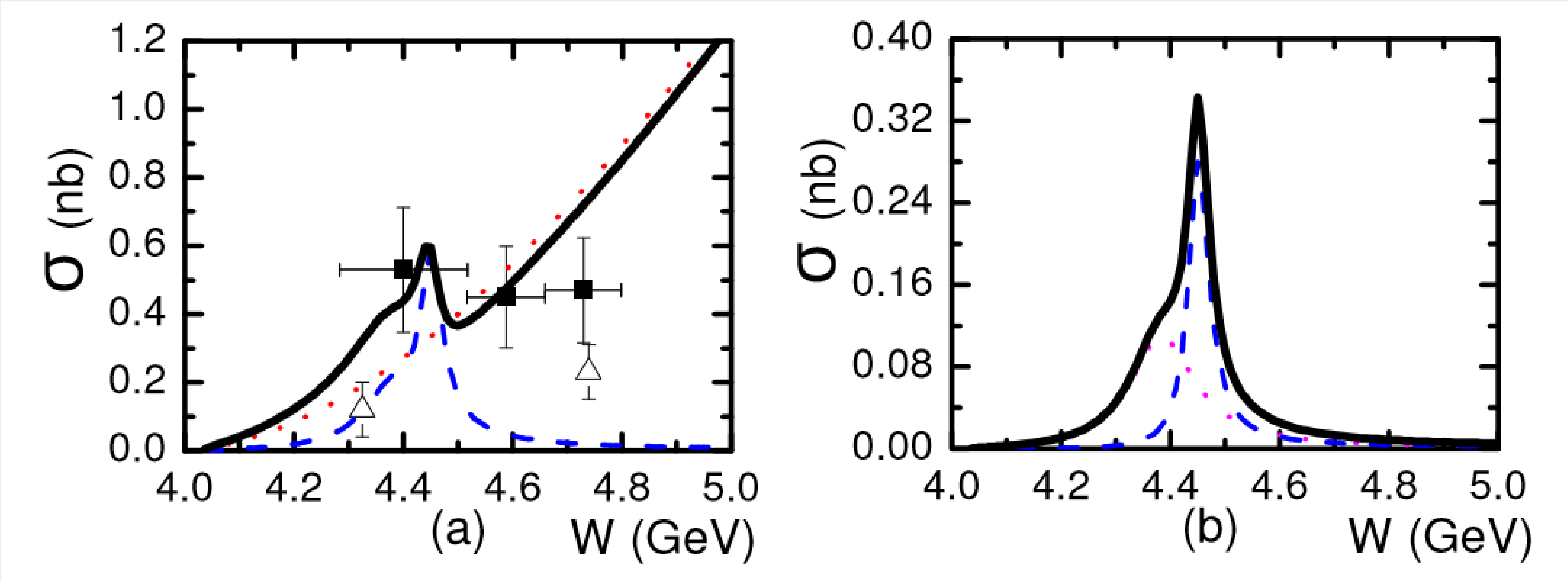
$$\mathcal{M}^{\mu\nu}_{N^*(\frac{3}{2}^-)}(q,p,q',p') = \sum_{V=J/\Psi,\rho,\omega} g_{3J/\Psi}g^{\mu\alpha}\frac{(\gamma.(q+p)+m_{N^*_{c\bar{c}}})P^{\frac{3}{2}}_{\alpha\beta}(p+q)}{W^2-m^2_{N^*_{c\bar{c}}}+i\Gamma_{N^*_{c\bar{c}}}m_{N^*_{c\bar{c}}}}F_V(0)\frac{ie}{f_V}\frac{-m_V^2\tilde{g}_{3V}}{-m_V^2+i\Gamma_V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

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

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

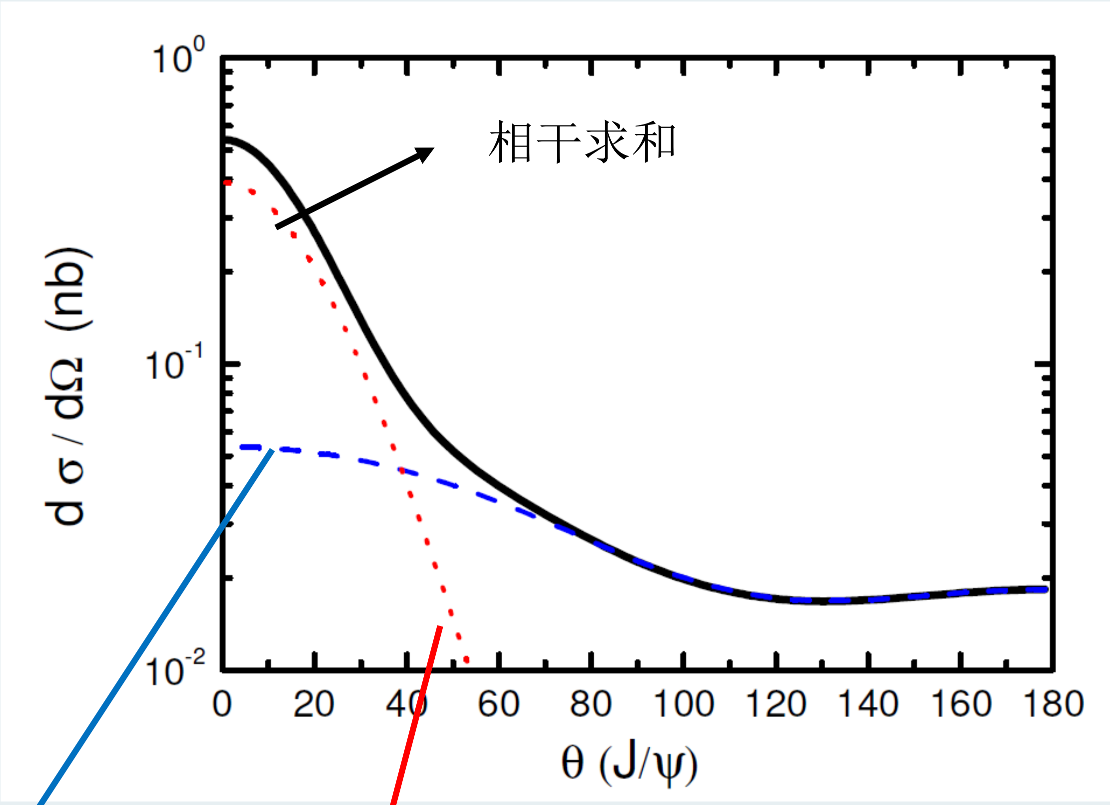
$$P^{\frac{5}{2}\ \alpha\alpha'\beta\beta'}(p) = \frac{1}{2}(\tilde{g}^{\alpha\alpha'}_{N^*}\tilde{g}^{\beta\beta'}_{N^*}+\tilde{g}^{\alpha\beta'}_{N^*}\tilde{g}^{\beta\alpha'}_{N^*})-\frac{1}{5}\tilde{g}^{\alpha\beta}_{N^*}\tilde{g}^{\alpha'\beta'}_{N^*}-\frac{1}{10}\left(\tilde{\gamma}^\alpha\tilde{\gamma}^{\alpha'}\tilde{g}^{\beta\beta'}_{N^*}+\tilde{\gamma}^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

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



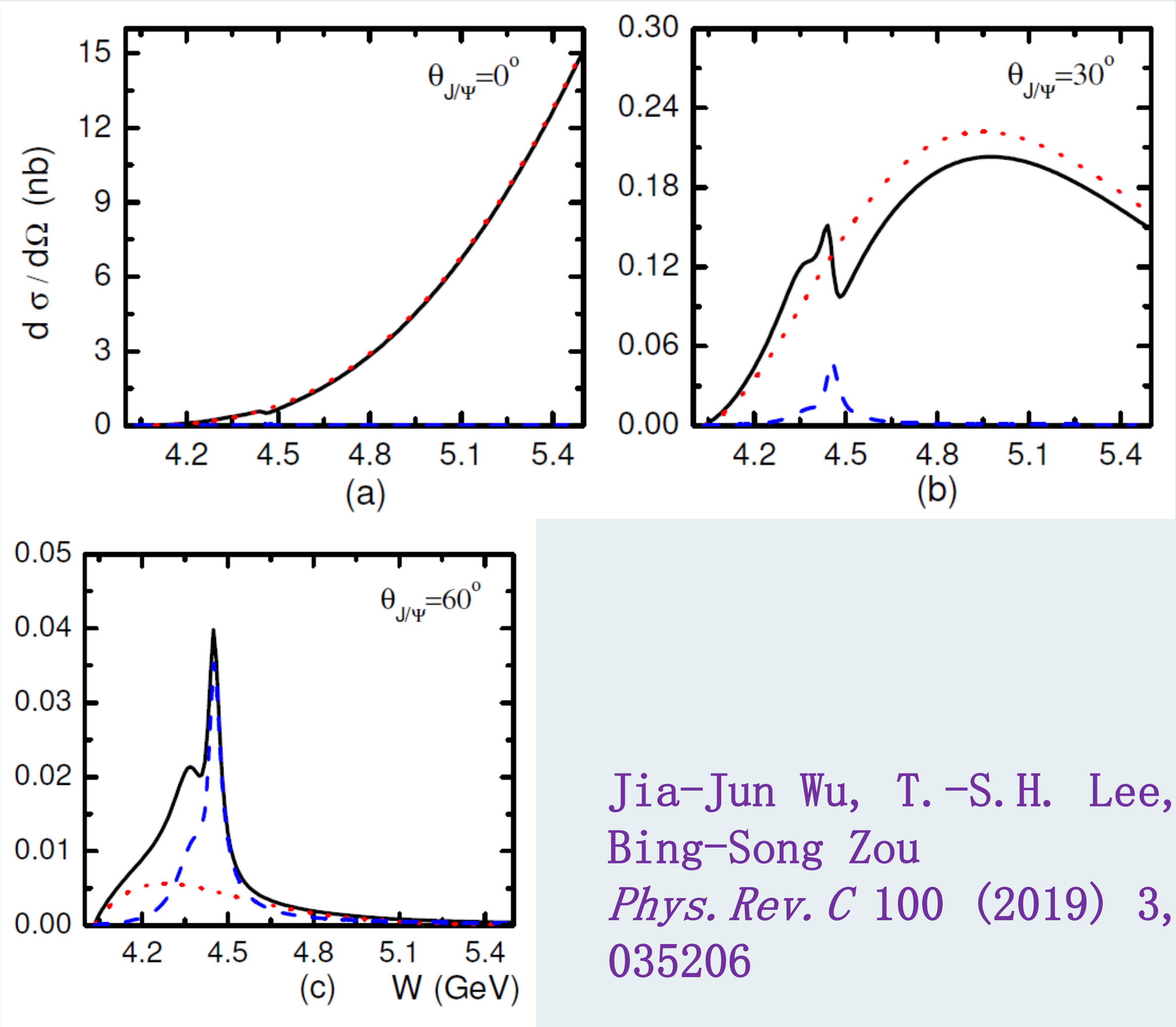
Black: total
Red: Pomeron-exchange
Blue: Pc

如何从J/ψ p末态中尽可能抽取 P_c 的峰结构?



共振态

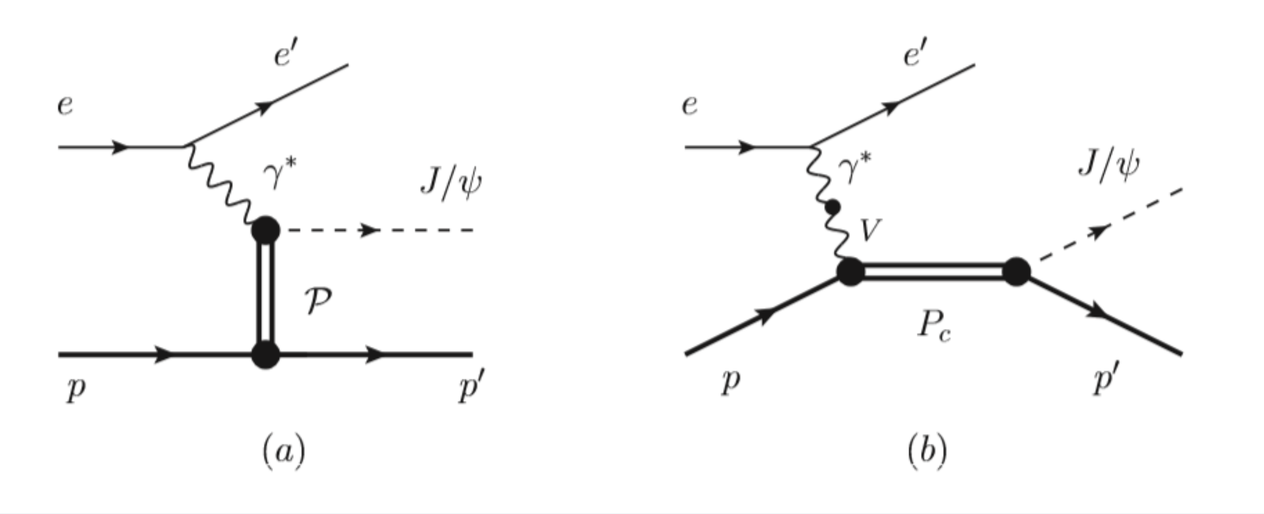
Pomeron Exchange



Jia-Jun Wu, T.-S.H. Lee, Bing-Song Zou
Phys. Rev. C 100 (2019) 3, 035206

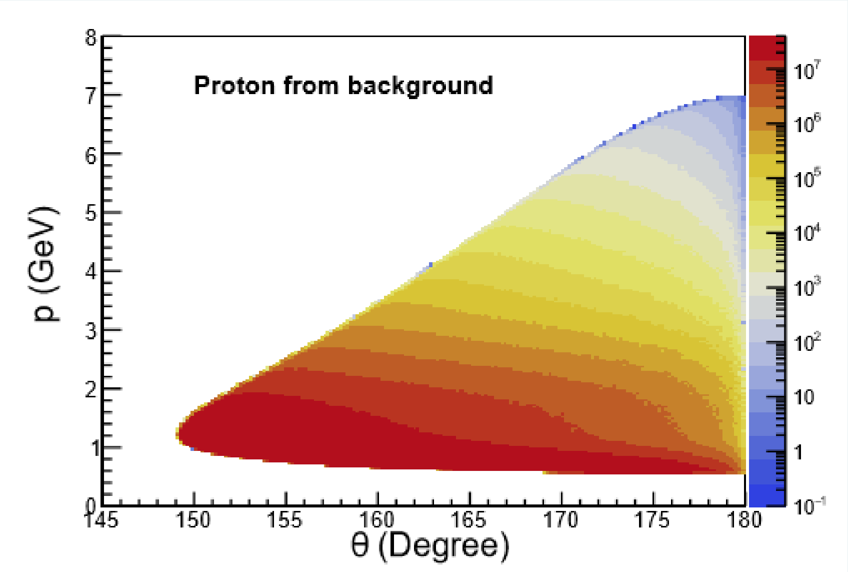
如何从J/ψ p末态中尽可能抽取 P_c 的峰结构?

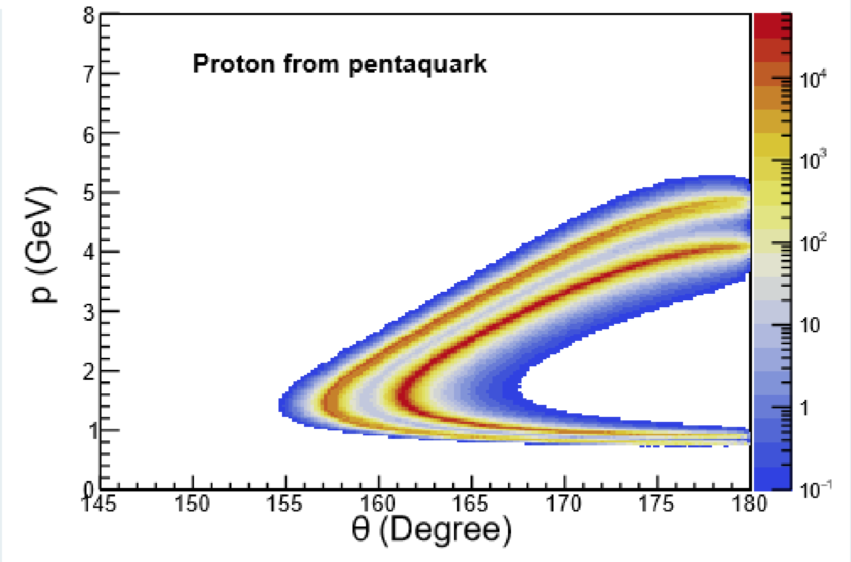
$e\,p \rightarrow e\,J/\psi\,p$



The distribution of momentum versus scattering angles of final proton in the laboratory frame at the JLab energy configuration, with 12 GeV electron beam projectile on rest proton.

Zhi Yang, Xu Cao, Yu-Tie Liang, Jia-Jun Wu
Chin. Phys. C 44 (2020) 8, 084102

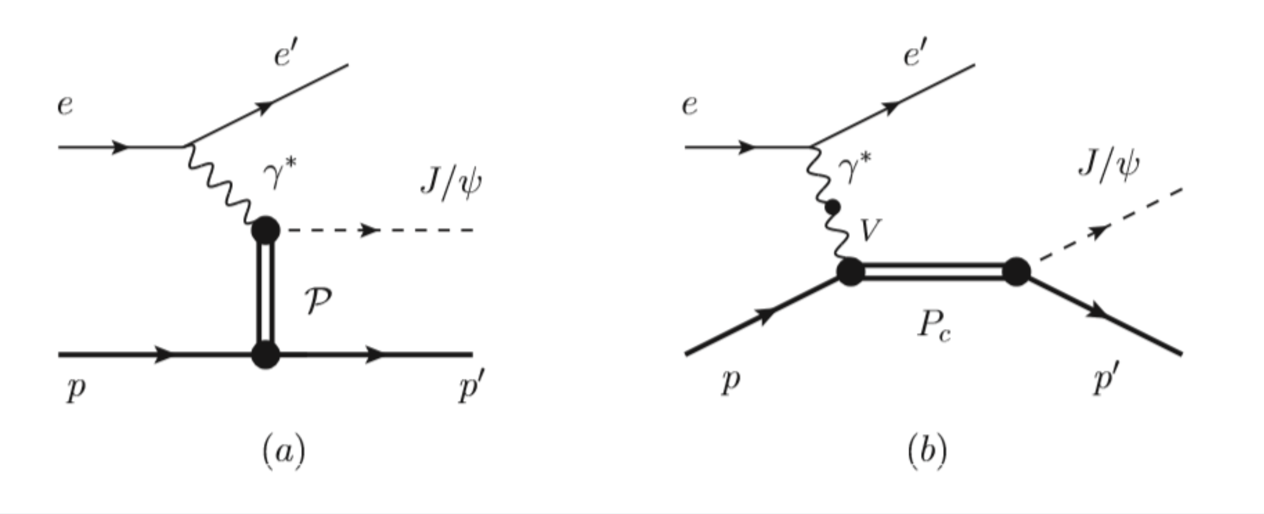


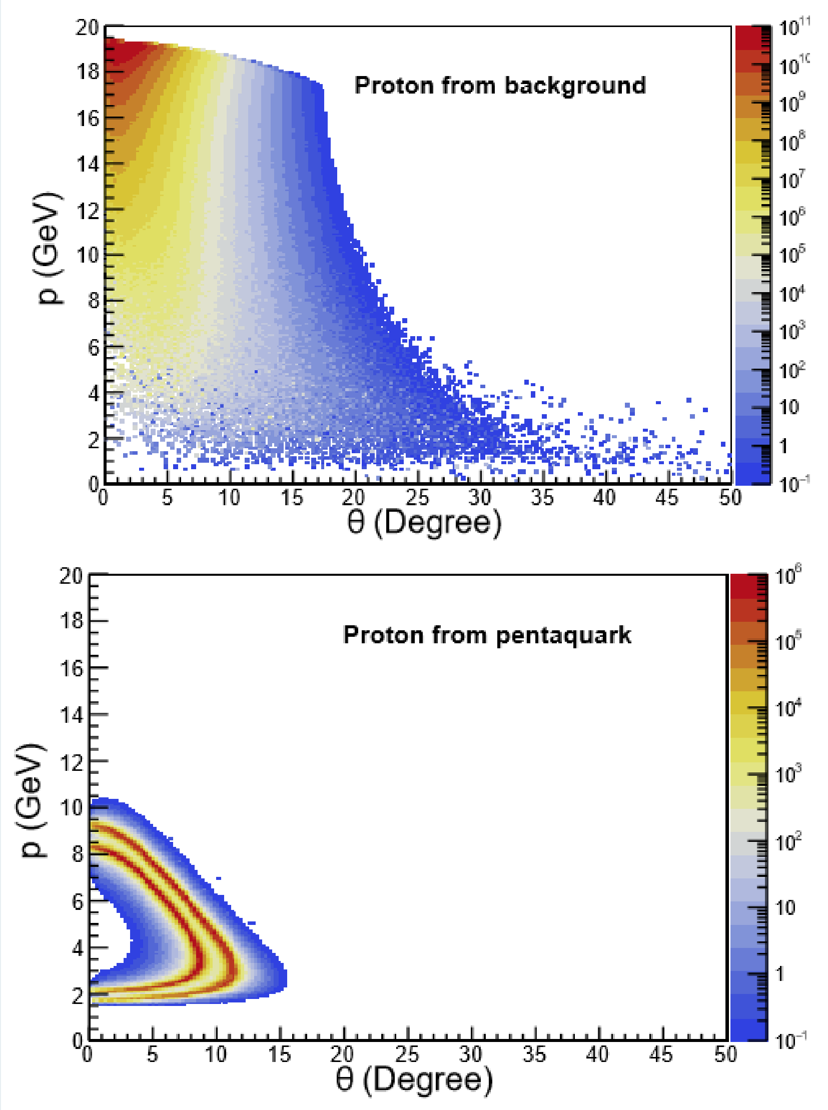


中国科学院大学
University of Chinese Academy of Sciences

如何从J/ψ p末态中尽可能抽取 P_c 的峰结构?

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





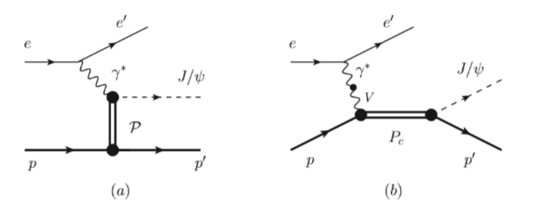
The distribution of momentum versus scattering angles of final proton in the laboratory frame at the but at the EicC energy configuration, which is 20 GeV proton colliding with 3.5 GeV electron.

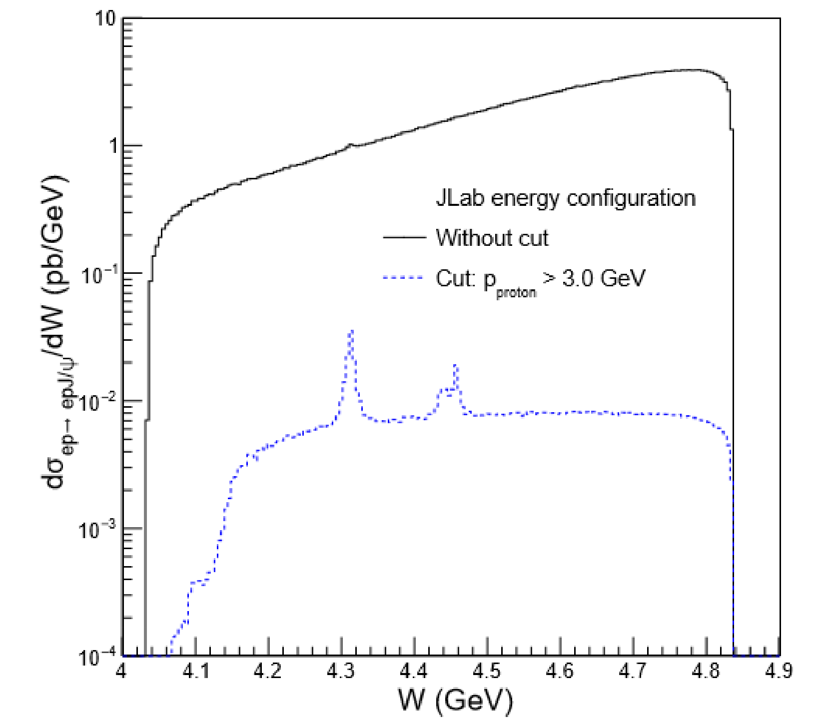
Zhi Yang, Xu Cao, Yu-Tie Liang, Jia-Jun Wu
Chin. Phys. C 44 (2020) 8, 084102

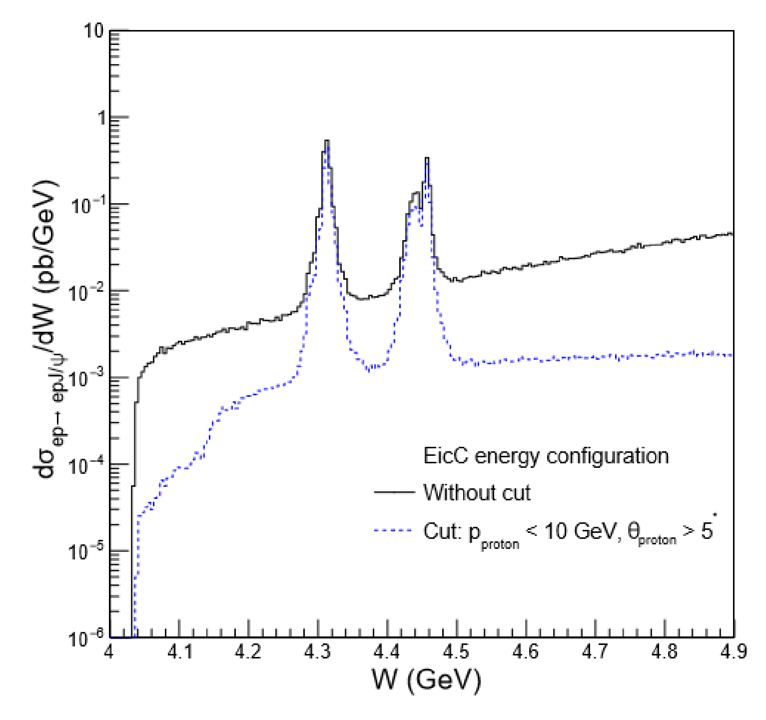
University of Chinese Academy of Sciences

如何从J/ψ p末态中尽可能抽取 P_c 的峰结构?

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







Jlab 能量下可能就是信号道非常小。

而在EicC可能会大一些。

希望将来实验能够进一步研究。

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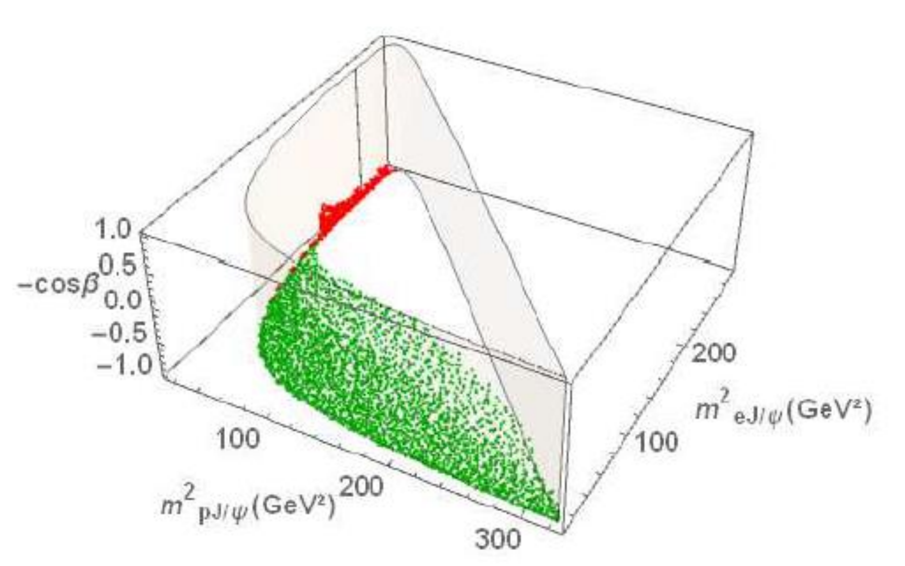
如何从J/ψ p末态中尽可能抽取 P_c 的峰结构?



e p → e J/ψ p

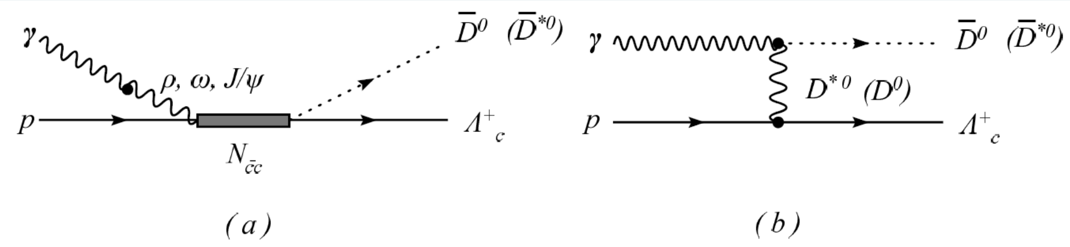
三体，四体相空间的解析表达

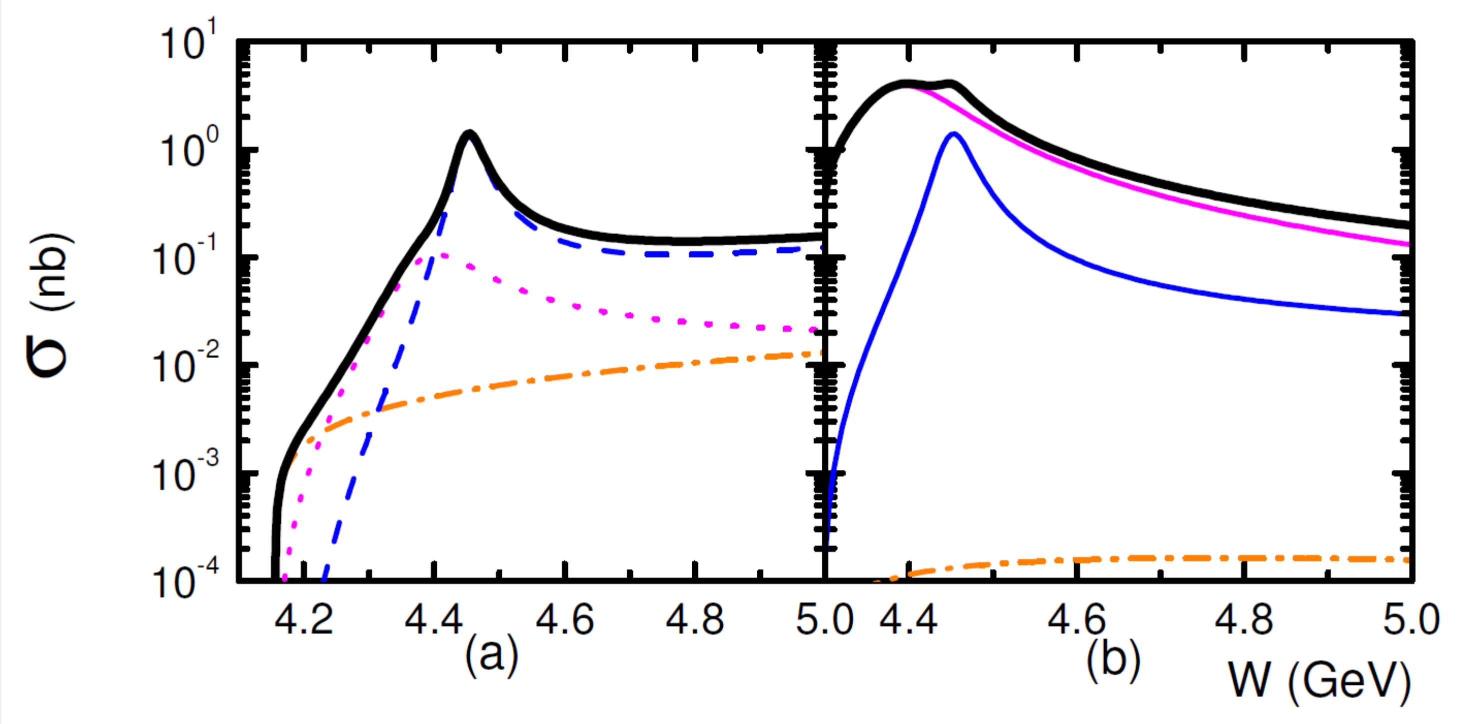
contribution number	$(3;7;3220)$
kinematic variables chosen	$m_{12}^2, m_{13}^2, m_{123}^2, \cos\theta_2^\star, \cos\theta_3^\star$
phase space factor	$\frac{A_g \lvert\boldsymbol{p}_2^\star\rvert\lvert\boldsymbol{p}_3^\star\rvert\lambda(m,m_{123},m_4)}{(2\pi)^{12}2^9 m^3 m_{123}^2 \lvert\boldsymbol{p}_1\rvert\lvert\boldsymbol{p}_2\rvert\lvert\boldsymbol{p}_3\rvert}$
intrisinc quantities	$p_1^0 = \frac{1}{2m}\left(m^2+m_{123}^2-m_4^2\right) - 2mp_2^0 - 2mp_3^0$ $p_2^0 = \gamma_L\sqrt{\lvert\boldsymbol{p}_2^\star\rvert^2 + m_2^2} - \gamma_L\beta_L \lvert\boldsymbol{p}_2^\star\rvert\cos\theta_2^\star$ $p_3^0 = \gamma_L\sqrt{\lvert\boldsymbol{p}_3^\star\rvert^2 + m_3^2} - \gamma_L\beta_L \lvert\boldsymbol{p}_3^\star\rvert\cos\theta_3^\star$ $m_{23}^2 = m_{123}^2 + m_1^2 + m_2^2 + m_3^2 - m_{12}^2 - m_{13}^2$
parameters	$\lvert\boldsymbol{p}_2^\star\rvert = \frac{1}{2m_{123}}\lambda^{\frac{1}{2}}(m_{123}, m_{13}, m_2)$ $\quad\lvert\boldsymbol{p}_3^\star\rvert = \frac{1}{2m_{123}}\lambda^{\frac{1}{2}}(m_{123}, m_{12}, m_3)$ $\gamma_L = \frac{1}{2mm_{123}}\left(m^2+m_{123}^2-m_4^2\right)$ $\quad\gamma_L\beta_L = \frac{1}{2mm_{123}}\lambda^{\frac{1}{2}}(m, m_{123}, m_4)$

$$d\phi_4 = \delta\left(\sqrt{S} - \sum_{i=1}^{4} p_i^0\right)\delta\left(\sum_{i=1}^{4}\vec{p}_i\right)\frac{d^3\vec{p}_1}{(2\pi)^3 2E_1}\frac{d^3\vec{p}_2}{(2\pi)^3 2E_2}\frac{d^3\vec{p}_3}{(2\pi)^3 2E_3}\frac{d^3\vec{p}_4}{(2\pi)^3 2E_4}$$

$\gamma\, p \rightarrow$ other final states

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





Jia-Jun Wu, T.-S.H. Lee, Bing-Song Zou
Phys. Rev. C 100 (2019) 3, 035206

小结

- 详细讨论了 $\gamma p \to P_c \to J/\psi\, p$ 的信号以及背景贡献。
- 讨论了如何从 $J/\psi\, p$ 末态中尽可能抽取 P_c 的峰结构。

谢谢!

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