Production of $P_c(4312)$ state in electron-proton collisions

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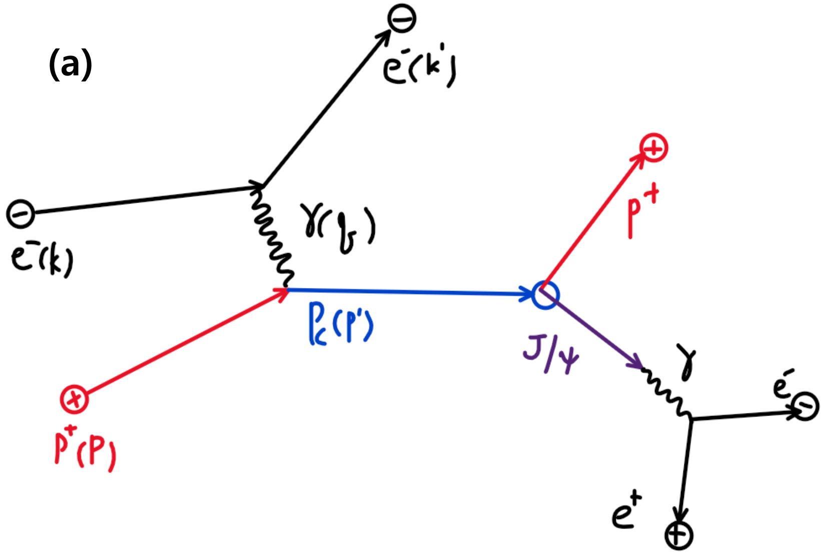
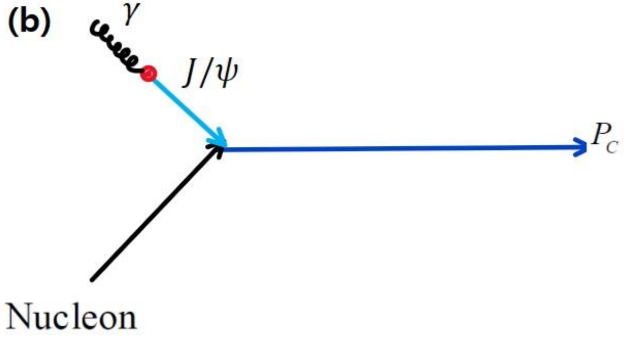
Vector Meson Dominance, Lagrangian, Coupling strength(g_J, g_{JpP_c})

(a)



(b)



$E_{\text{electron}} = 16\text{GeV}, E_{\text{proton}} = 250\text{GeV}$
$\sqrt{s} = 126\text{GeV}$
$J/\psi\ (c\bar{c})$ mediates interaction between photon and proton

$$\mathcal{L}_{J/\psi\to\gamma} = -\frac{e}{2g_J} F^{\mu\nu} F^J_{\mu\nu},\ \mathcal{L}_{\gamma\to e^- e^+} = -e\bar{\psi}\gamma^\mu A_\mu \psi$$

$$\Gamma_{J/\psi\to e^- e^+} = \frac{1}{8\pi}\frac{|\vec{p}_f|}{m^2_{J/\psi}} |\mathcal{M}|^2{}_{J/\psi\to e^- e^+} = 92.9\ \text{keV} \times 0.05971$$

$$g_J = 11.2$$

$$\mathcal{L} = \begin{cases} \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \sigma^{\mu\nu} F^J_{\mu\nu} \psi_{P_c} & (J^P = \frac{1}{2}^+) \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \gamma_5 \sigma^{\mu\nu} F^J_{\mu\nu} \psi_{P_c} & (J^P = \frac{1}{2}^-) \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \gamma_5 \gamma^\mu F^J_{\mu\nu} \psi^\nu_{P_c} & (J^P = \frac{3}{2}^+) \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \gamma^\mu F^J_{\mu\nu} \psi^\nu_{P_c} & (J^P = \frac{3}{2}^-) \end{cases}$$

[F. Klingl, N. Kaiser and W. Weise, Z. Phys. A 356,193−206 (1996)]

$$\Gamma_{P_c\to p+J/\psi} = \frac{1}{8\pi}\frac{|\vec{p}_f|}{m^2_{P_c}} |\mathcal{M}|^2{}_{P_c\to p+J/\psi} = 9.8\ \text{MeV}$$

J^P	$(1/2)^+$	$(1/2)^-$	$(3/2)^+$	$(3/2)^-$
g_{JpP_c}	0.379	0.169	1.47	0.599

Coupling strength ($g_{\gamma p P_c}$), Form factor and P_c distribution

$$g_{\gamma p P_c} = -g_{JpP_c}\frac{e}{g_J}\frac{q^2}{q^2-m_{J/\psi}^2}$$

$$\left(\frac{d\sigma}{d\theta}\right)_{CM} = \frac{2\pi\sin\theta}{64\pi^2E_{CM}^2}\frac{|\vec{p}_f|}{|\vec{p}_i|}\left(\frac{m_{J/\psi}^2-\Lambda^2}{q^2-\Lambda^2}\right)^2|\mathcal{M}|^2 \rightarrow \left(\frac{d\sigma}{d\eta_{P_c}}\right)_{LAB} \;\&\; \left(\frac{d\sigma}{dp_T}\right)$$

θ: Scattering angle of electron in the CM frame

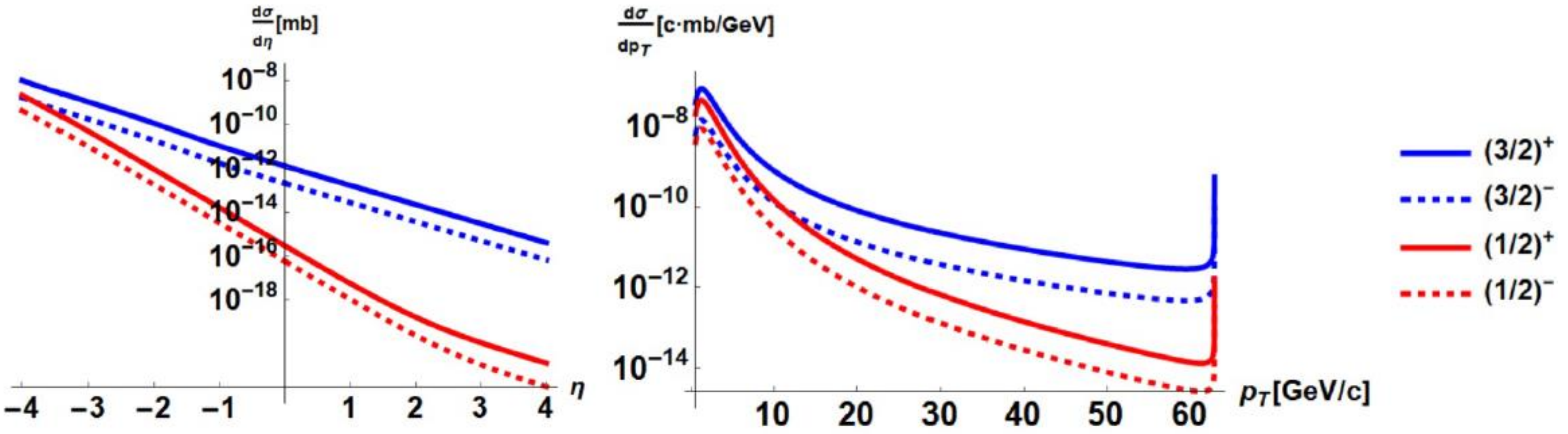
η_{P_c}: Pseudorapidity of P_c in the Lab frame

p_T: Transverse momentum of P_c

Coupling(g_J) is obtained at the on-shell point of J/ψ
But photon momentum transfer is spacelike so we consider form factor to explain the off-shell effect.

$$F(q^2) = \frac{m_{J/\psi}^2-\Lambda^2}{q^2-\Lambda^2} \quad (\Lambda = 1\text{GeV: cutoff parameter})$$

J/ψ Propagator's off-shell effect(Spacelike momentum) decreases the cross section→ Y. Oh, C. M. Ko and K. Nakayama, Phys. Rev.C 77, 045204 (2008)



Expected number of $\mathbf{P_c(4312)}$ produced at the Electron Ion Collider(EIC) with integrated luminosity of $\mathbf{10fb^{-1} = 10^{40}cm^{-2}}$

J^P of $\mathrm{P_c(4312)}$	$(1/2)^+$	$(1/2)^-$	$(3/2)^+$	$(3/2)^-$
Yield	5.67×10^3	1.13×10^3	4.32×10^4	7.15×10^3

Polarized set of electron and proton collision

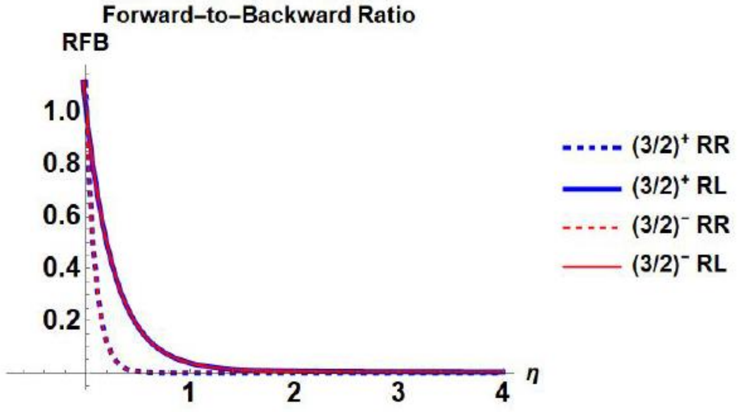
Massive spin ½ spin projection operator

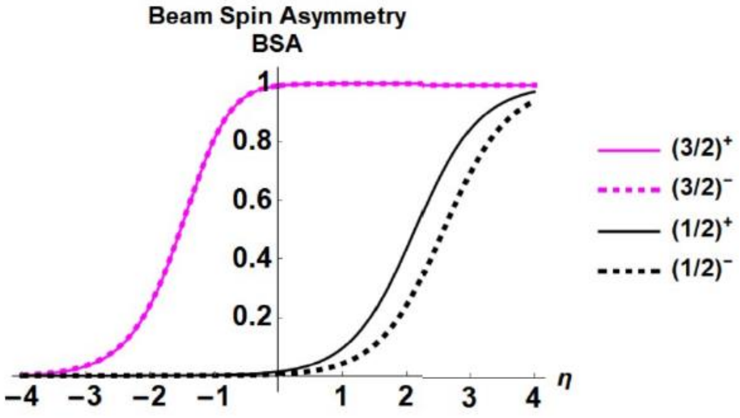
$\frac{1\pm\gamma_5 s\cdot\gamma}{2}u^p(p,\pm1) = u^p(p,\pm1)$

s^μ: Spin four-vector of spin ½ particle

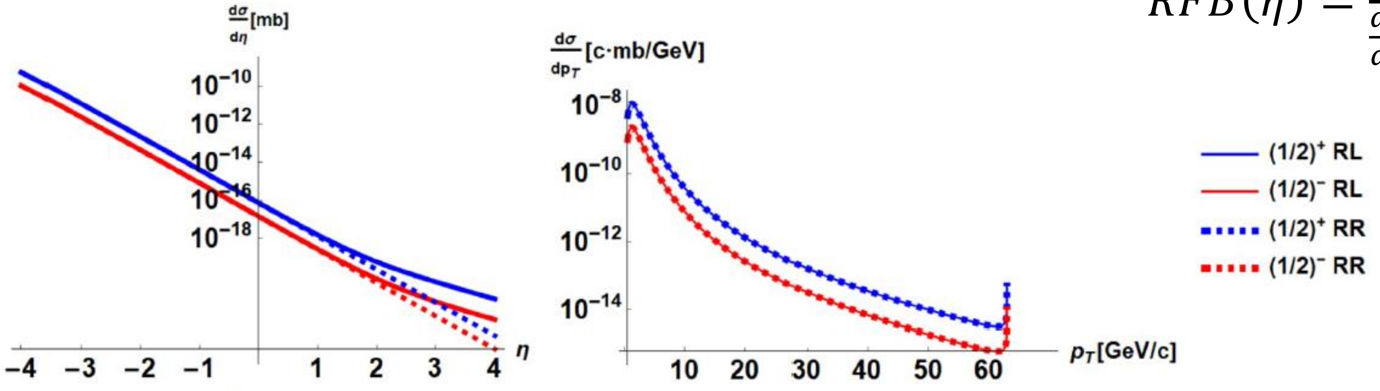
Massless spin ½ spin projection operator

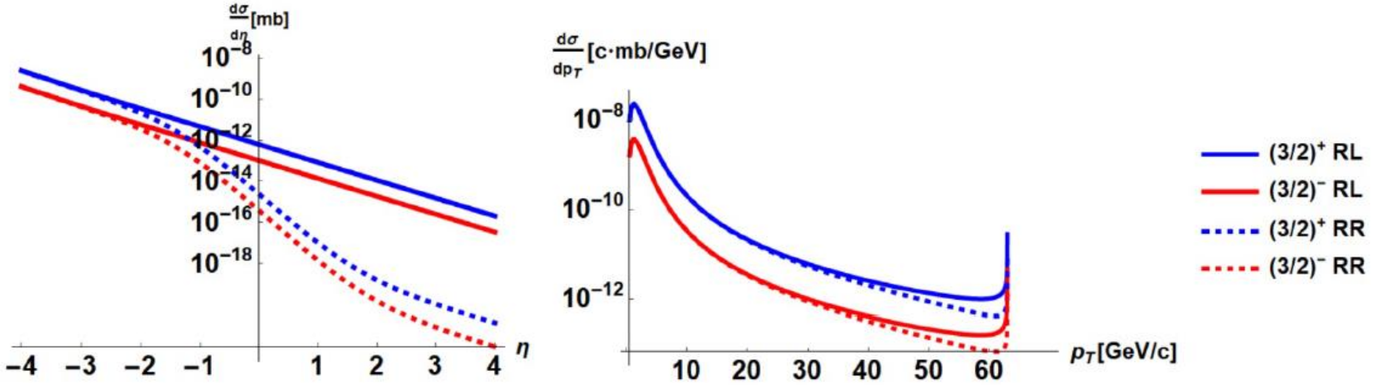
$\frac{1\pm\gamma_5}{2}u(k,\pm1) = u(k,\pm1)$





$$RFB(\eta) = \frac{\frac{d\sigma}{d\eta}(+\eta)}{\frac{d\sigma}{d\eta}(-\eta)}(\eta > 0) \qquad BSA(\eta) = \frac{\frac{d\sigma}{d\eta}[RL]-\frac{d\sigma}{d\eta}[RR]}{\frac{d\sigma}{d\eta}[RL]+\frac{d\sigma}{d\eta}[RR]}$$

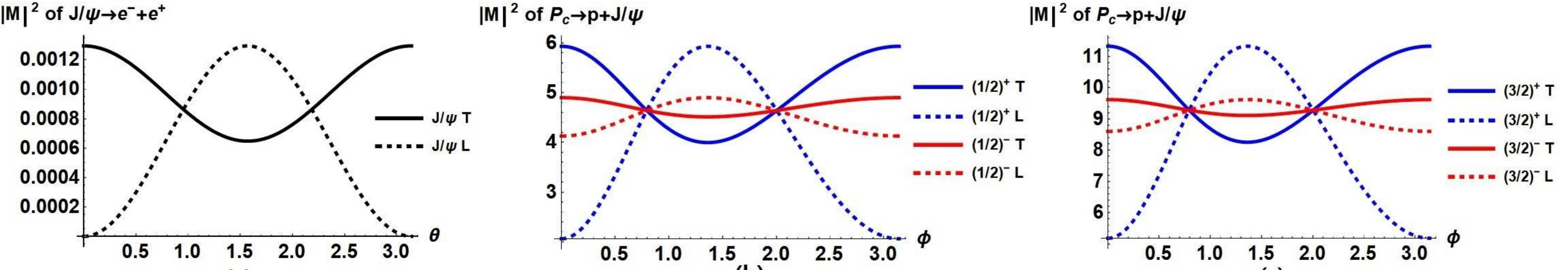




For spin $1/2$ case, pseudorapidity distribution separates at $\eta = 2$ and they are almost identical in the backward region. While for $3/2$ case, separation begins at $\eta = -2$.

Spin can be determined by measuring Beam Spin Asymmetry in the midrapidity region.

Determination of $P_c(4312)$'s parity using polarization of J/ψ



(a) (b) (c)

θ: angle between electron and boost axis of J/ψ in the J/ψ rest frame

ϕ: angle between proton and boost axis of P_c in the P_c rest frame

In $P_c \to p + J/\psi$ decay, difference between transverse and longitudinal contribution is more dramatic in the positive parity then the negative parity.

Parity can be determined by measuring angular distribution

$$P_{\mu\nu} = \sum_{i=1}^{3} \varepsilon_\mu^{(i)} \varepsilon_\nu^{(i)} = P_{\mu\nu}^T + P_{\mu\nu}^L = -g_{\mu\nu} + \frac{q_\mu q_\nu}{{m_{J/\psi}}^2}$$

$$P_{\mu\nu}^T = \begin{pmatrix} 0 & 0 \\ 0 & \delta_{ij} - \frac{q_i q_j}{\vec{q}^2} \end{pmatrix}, P_{\mu\nu}^L = \begin{pmatrix} \frac{\vec{q}^2}{{m_{J/\psi}}^2} & -\frac{q_0 q_i}{{m_{J/\psi}}^2} \\ -\frac{q_0 q_i}{{m_{J/\psi}}^2} & \frac{q_0^2 q_i q_j}{{m_{J/\psi}}^2 \vec{q}^2} \end{pmatrix}$$