The Electron-Ion Collider as A Prospective Facility for Pentaquark Measurements

BARYONS 2025

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Pentaquark production in EIC

1. Pentaquark state $P_c(4312)$ observed in 2019 LHCb, 7.3σ (PhysRevLett.122.222001)

2. Branching ratio and J^P unknown

3. EIC: $e^- + p^+$ collision of high luminosity and polarizability

4. Investigation of $d\sigma/d\eta_{P_c}$ for initially unpolarized and polarized state, double spin asymmetry, J/ψ θ_{P_c} distribution

1. GlueX J/ψ photoproduction ($\gamma + p \to J/\psi + p$)

- $\Gamma_{P_c(4312)} = 9.8$ MeV but $\mathcal{B}(P_c(4312) \to J/\psi + p)$ is still unknown
- $\mathcal{B}(P_c(4312)(J^P = (3/2)^-) \to J/\psi + p) = 2.9\%$ (JPAC model)

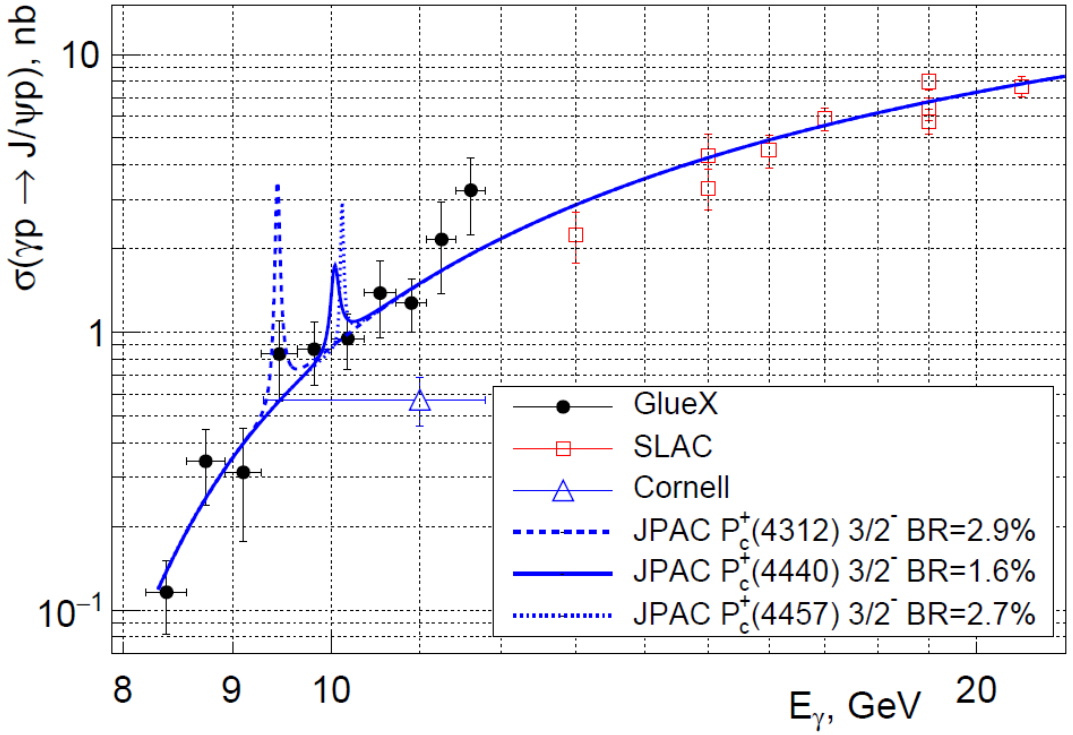
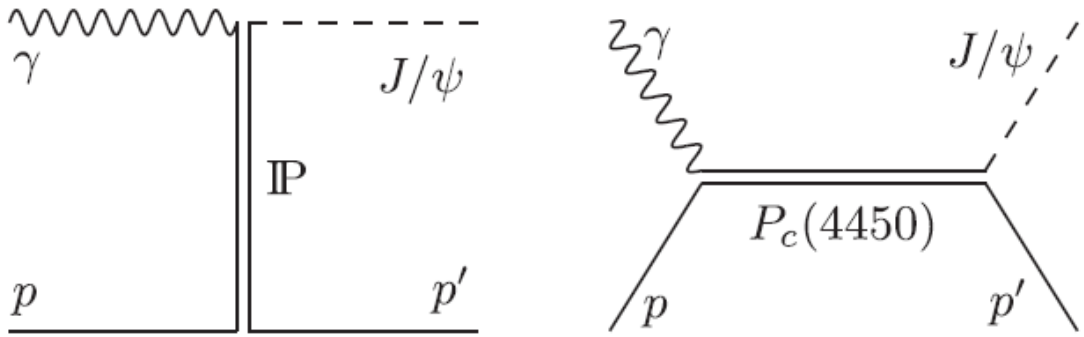


FIG. 2: GlueX results for the J/ψ total cross-section vs beam energy, Cornell [2], and SLAC [1] data compared to the JPAC model [3] corresponding to $\mathcal{B}(P_c^+(4312) \to J/\psi p) = 2.9\%$, $\mathcal{B}(P_c^+(4440) \to J/\psi p) = 1.6\%$, and $\mathcal{B}(P_c^+(4457) \to J/\psi p) = 2.7\%$, for the $J^P = 3/2^-$ case as discussed in the paper.

10.1103/PhysRevD.94.034002



Phys. Rev. Lett. 123, no.7, 072001 (2019)

Estimating branching ratio $\mathcal{B}$ for different J^P

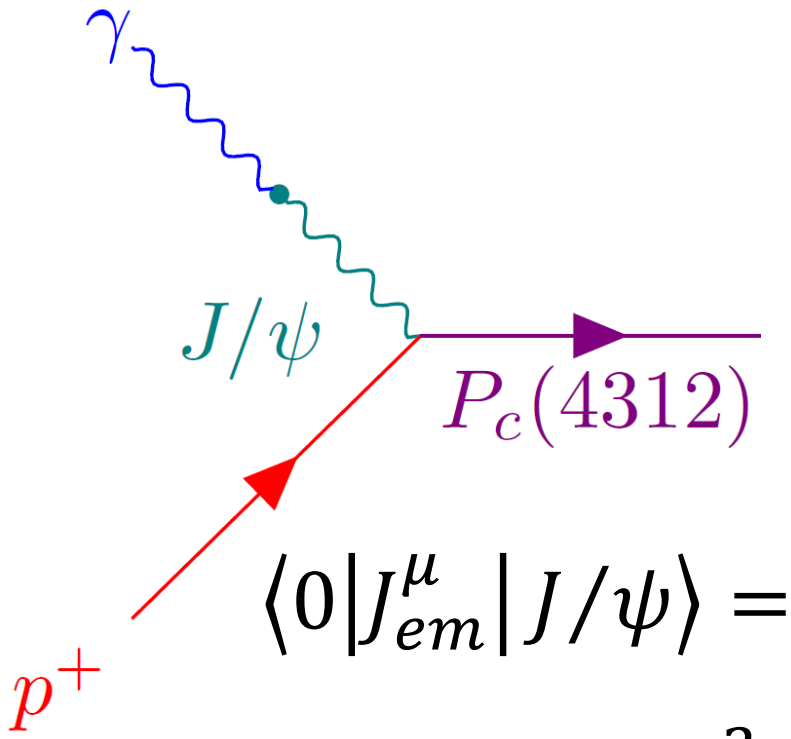
- We use Breit-Wigner resonant cross section

$$\sigma_{\gamma p\to P_c\to J/\psi p}(s)=\frac{4\pi}{p_i^2}\frac{2J+1}{4}\frac{s}{\left(s-m_{P_c}^2\right)^2+s\Gamma_{P_c}^2}\Gamma_{P_c\to\gamma p}(s)\Gamma_{P_c\to J/\psi p}(s)$$

- $\mathcal{B}$ for other J^P, same cross section with $(3/2)^-$ at resonance peak energy
- $\sigma_{\gamma p\to P_c^{(3/2)^-}\to J/\psi p}\left(m_{P_c}^2\right)=\sigma_{\gamma p\to P_c^J\to J/\psi p}\left(m_{P_c}^2\right)$

$$\mathscr{L}_{\text{int}}=\begin{cases}\frac{g_{JpP_c}}{m_{J/\psi}}\bar{\psi}_p\begin{pmatrix}\sigma^{\mu\nu}\\ \gamma_5\sigma^{\mu\nu}\end{pmatrix}F^J_{\mu\nu}\psi_{P_c} & J^P=\left(\frac{1}{2}\right)^{\pm},\\ \frac{g_{JpP_c}}{m_{J/\psi}}\bar{\psi}_p\begin{pmatrix}\gamma_5\gamma^{\nu}\\ \gamma^{\nu}\end{pmatrix}F^J_{\mu\nu}\psi^{\mu}_{P_c} & J^P=\left(\frac{3}{2}\right)^{\pm},\\ \frac{g_{JpP_c}}{m^2_{J/\psi}}\bar{\psi}_p\begin{pmatrix}\gamma^{\nu}\\ \gamma_5\gamma^{\nu}\end{pmatrix}\partial_{\alpha}F^J_{\mu\nu}\psi^{\mu\alpha}_{P_c} & J^P=\left(\frac{5}{2}\right)^{\pm}.\end{cases}$$

VMD connecting $\Gamma_{P_c\to\gamma p}$ & $\Gamma_{P_c\to J/\psi p}$



J^P	$(1/2)^+$	$(1/2)^-$	$(3/2)^+$	$(3/2)^-$	$(5/2)^+$	$(5/2)^-$
g_{JpP_c}	0.048	0.032	0.16	0.10	0.45	0.72
BR[%]	1.6	3.7	1.2	2.9	0.84	0.32

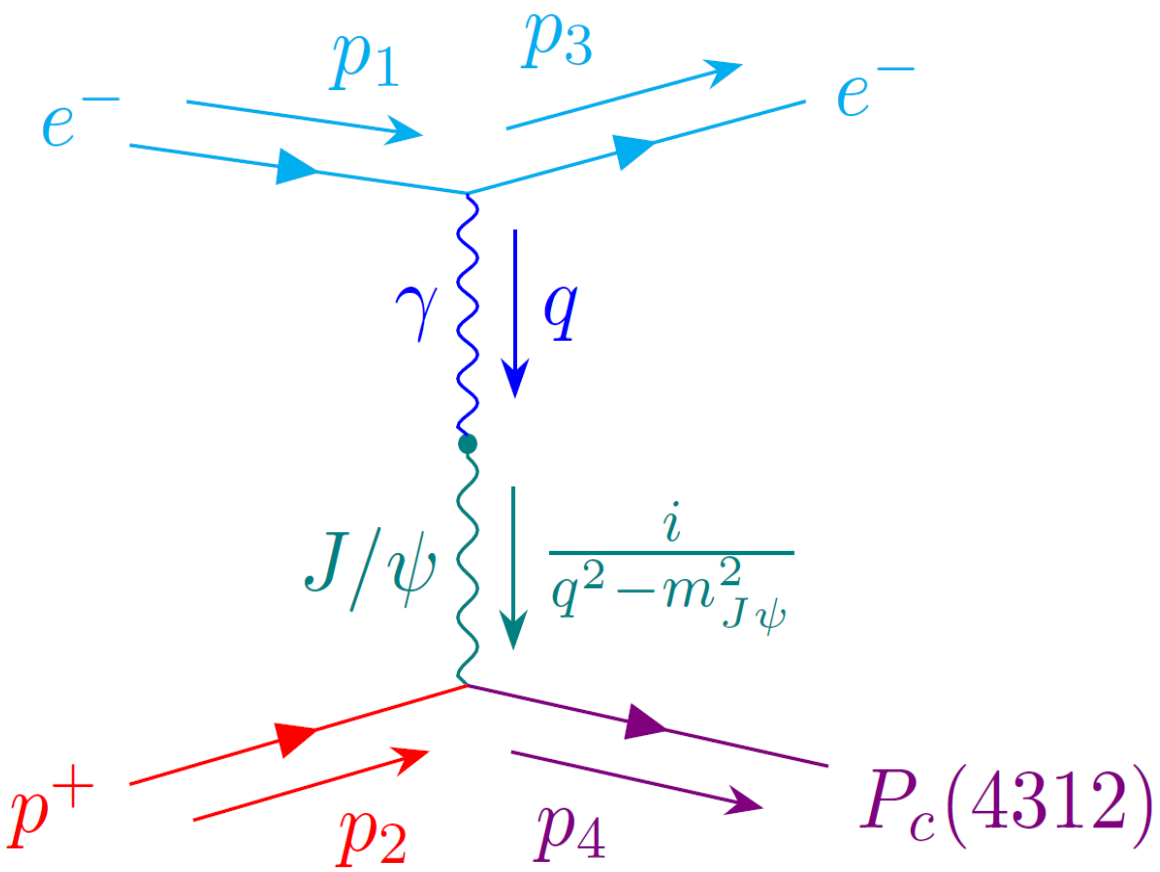
$$\langle 0|J^{\mu}_{em}|J/\psi\rangle = -\frac{m^2_{J/\psi}}{g_J}\varepsilon^{\mu}_{J/\psi}$$

Klingl, F., Kaiser, N. & Weise, W, *Zeitschrift für Physik A* **356**, 193–206 (1996).

$$\Gamma_{J/\psi\to e^+e^-} = \frac{4\pi\alpha^2 m_{J/\psi}}{3g_J^2} \to g_J = 11.2$$

$$g^{\text{GlueX}}_{\gamma pP_c} = -\frac{e}{g_J}\frac{m^2_{J/\psi}}{q^2 - m^2_{J/\psi}} g_{JpP_c} = \frac{e}{g_J} g_{JpP_C}$$

2. EIC $P_c(4312)$ electroproduction ($e + p \to e + P_c(4312)$)



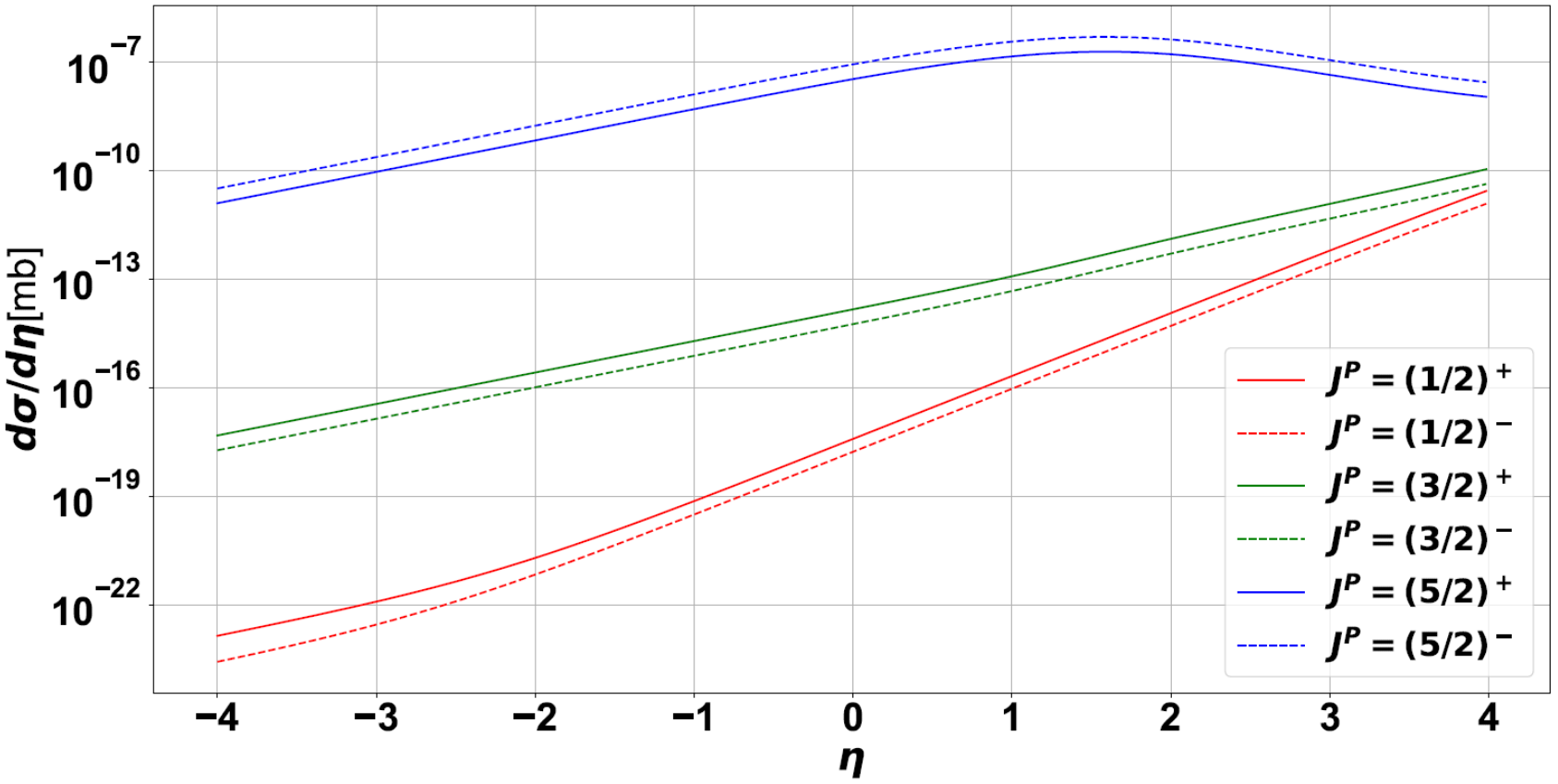
$$g^{\text{EIC}}_{\gamma p P_c} = -\frac{e}{g_J}\frac{m^2_{J/\psi}}{q^2 - m^2_{J/\psi}} g_{J p P_c}$$

- J/ψ propagator acts as a form factor

$$\frac{d\sigma}{d\theta} = \frac{2\pi \sin\theta}{64\pi^2 s}\frac{p_f}{p_i}|\mathcal{M}|^2$$

3. Results

$\frac{d\sigma}{d\eta_{P_c}}\left(-4 \leq \eta_{P_c} \leq 4\right)$ initially unpolarized $\sqrt{s} = 141\text{GeV}$

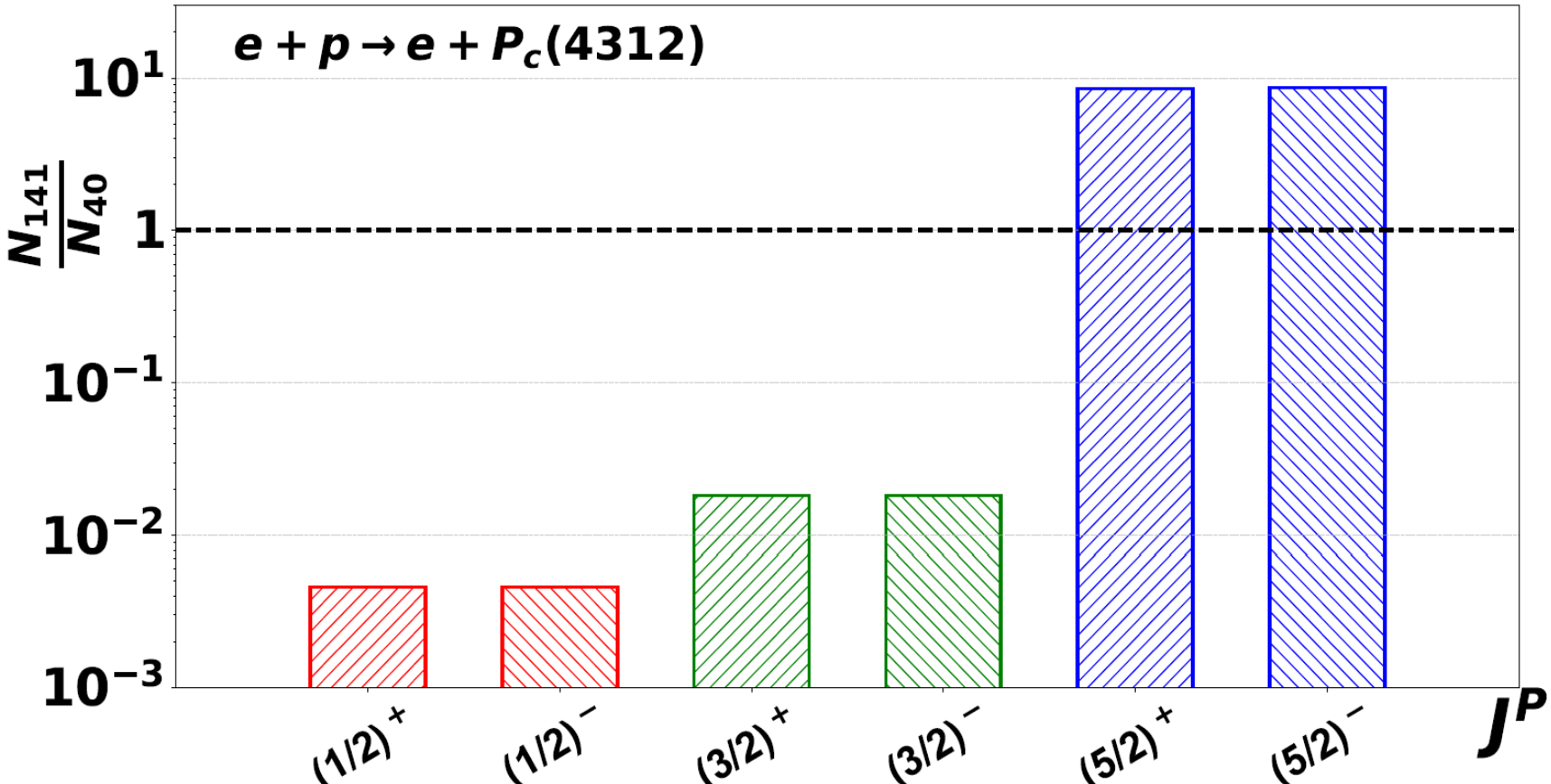


- Proton moving direction($\eta > 0$)
- $(5/2)^{\pm}$ field with higher order derivative.

$$E_e = 18\ \text{GeV}, E_p = 275\ \text{GeV}$$

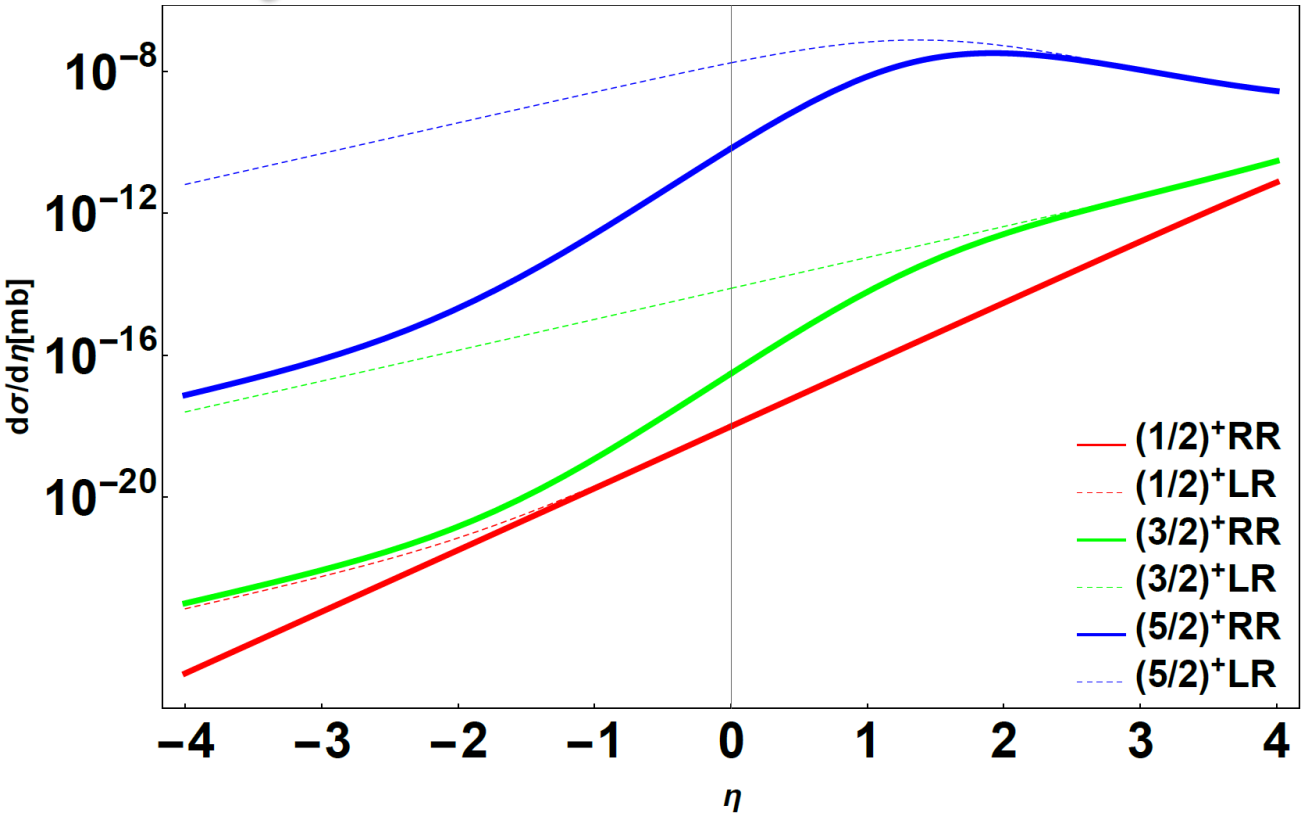
Integrated $P_c(4312)$ yields at $\sqrt{s} = 141$ GeV and $\sqrt{s} = 40$ GeV and their ratio

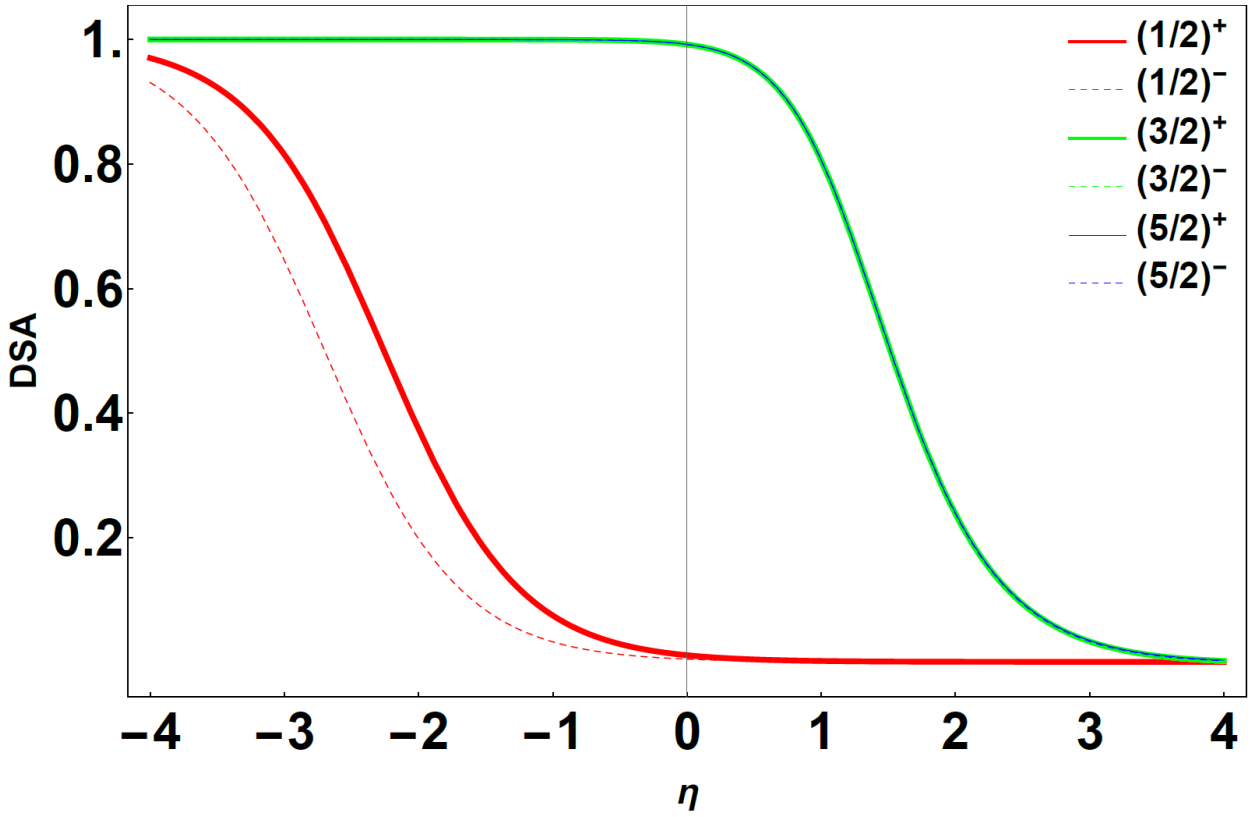
J^P	$(1/2)^+$	$(1/2)^-$	$(3/2)^+$	$(3/2)^-$	$(5/2)^+$	$(5/2)^-$
N_{141}	790	350	5.1×10^3	2.0×10^3	4.1×10^7	1.0×10^8
N_{40}	1.7×10^5	7.7×10^4	2.8×10^5	1.1×10^5	4.8×10^6	1.2×10^7



- $L_{int} = 100 fb^{-1}$
- $J^P = (1/2)^{\pm}$ & $(3/2)^{\pm}$ are preferred in the low energy
- $J^P = (5/2)^{\pm}$ are preferred in the high energy

$\frac{d\sigma}{d\eta_{P_c}}(-4 \leq \eta_{P_c} \leq 4)$ initially polarized $\sqrt{s} = 141$ GeV



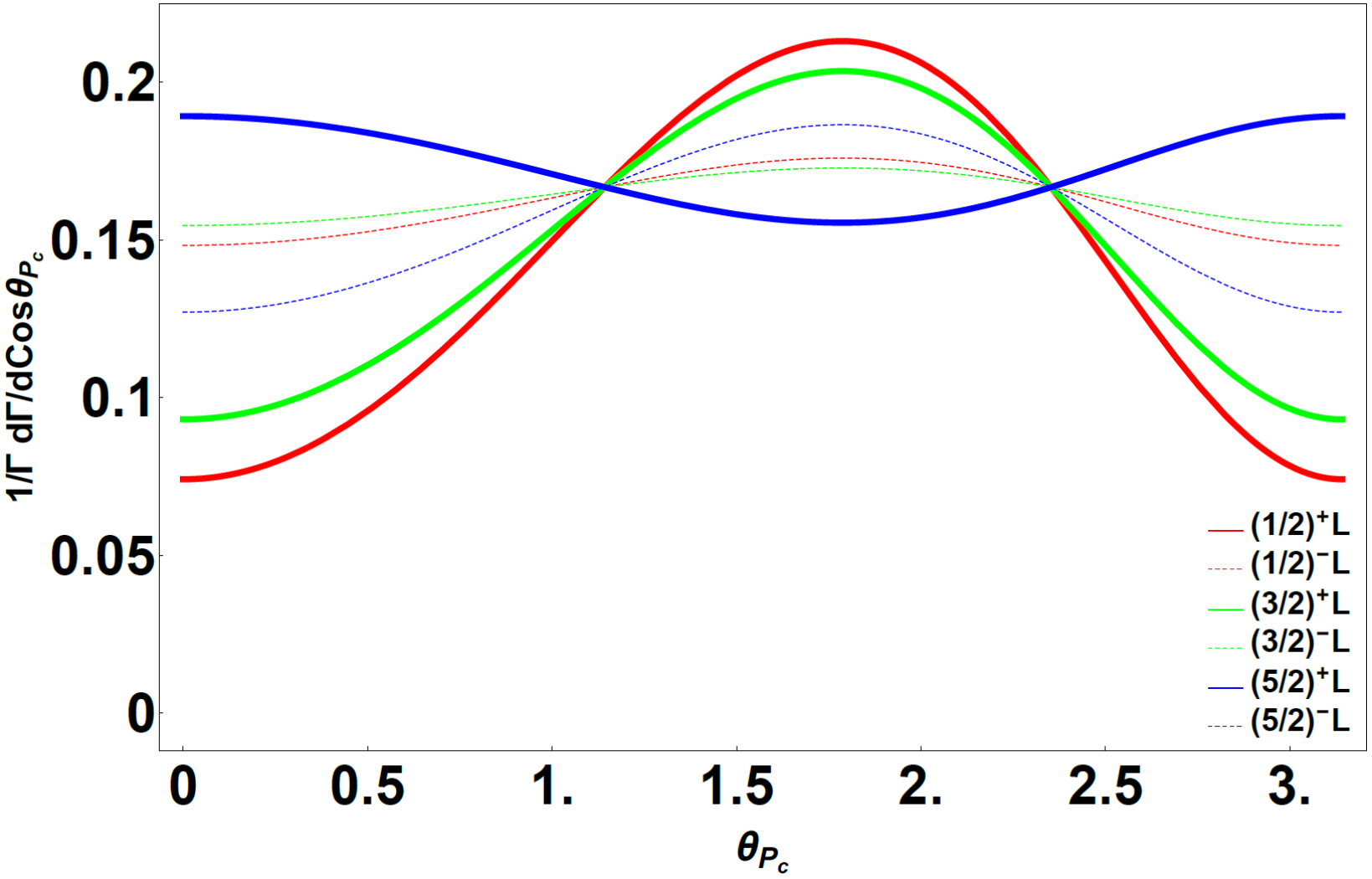


- LR(RL) cross section is bigger than RR(LL)
- Ex) (Left-handed e^- and right-handed p^+)
- Similar pattern for negative parity P_c

$$DSA = \frac{\frac{d\sigma}{d\eta_{P_c}}[LR] - \frac{d\sigma}{d\eta_{P_c}}[RR]}{\frac{d\sigma}{d\eta_{P_c}}[LR] + \frac{d\sigma}{d\eta_{P_c}}[RR]}$$

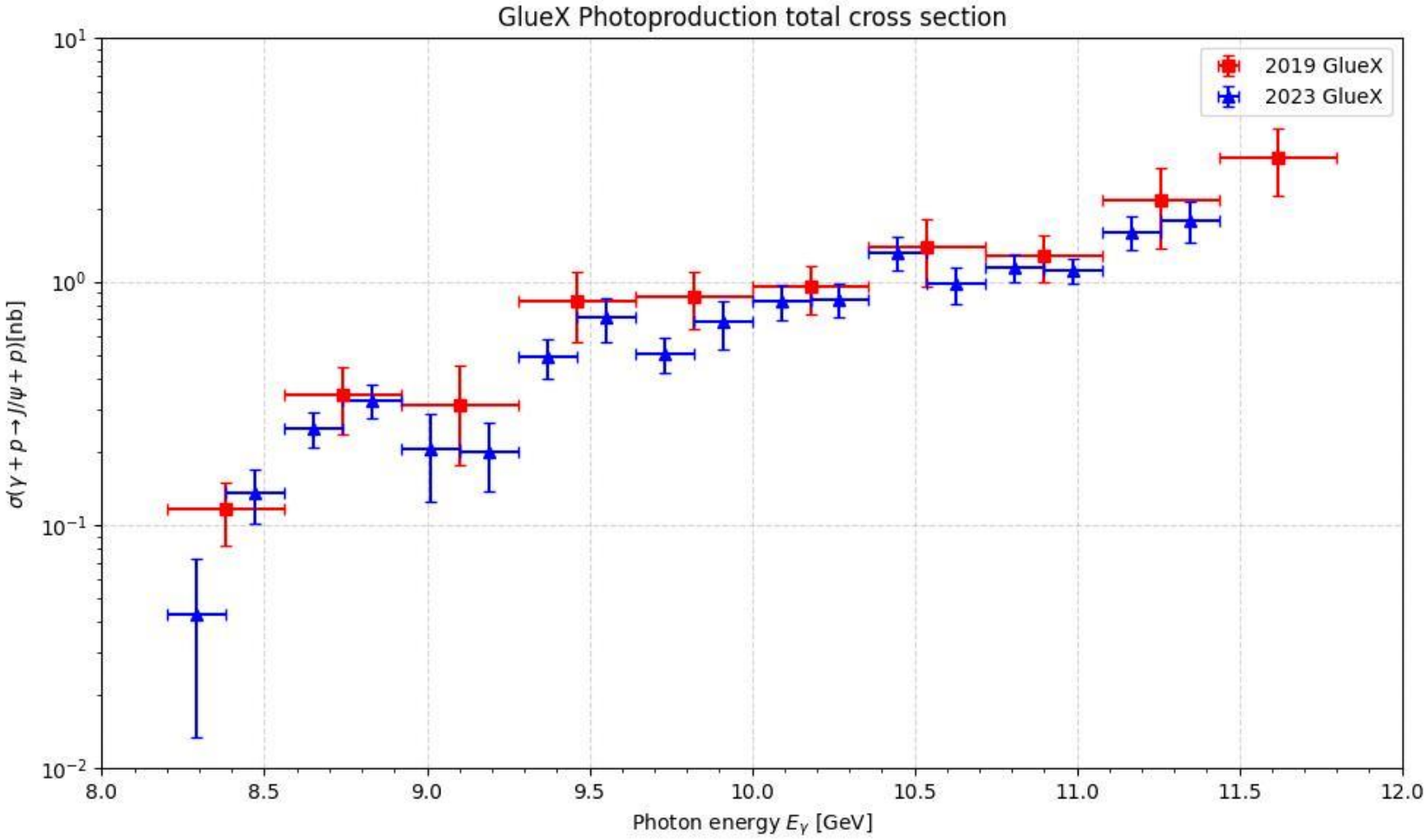
- $(3/2)^{\pm}$ and $(5/2)^{\pm}$ overlap

J/ψ polarization and P_c parity



- θ_{P_c}: Polar angle of J/ψ in the P_c rest frame
- If we measure the polarization of J/ψ, it may be a clue to the distinguishing parity

4. Discussion



- Larger number of samples

→We can improve the branching ratio estimation.

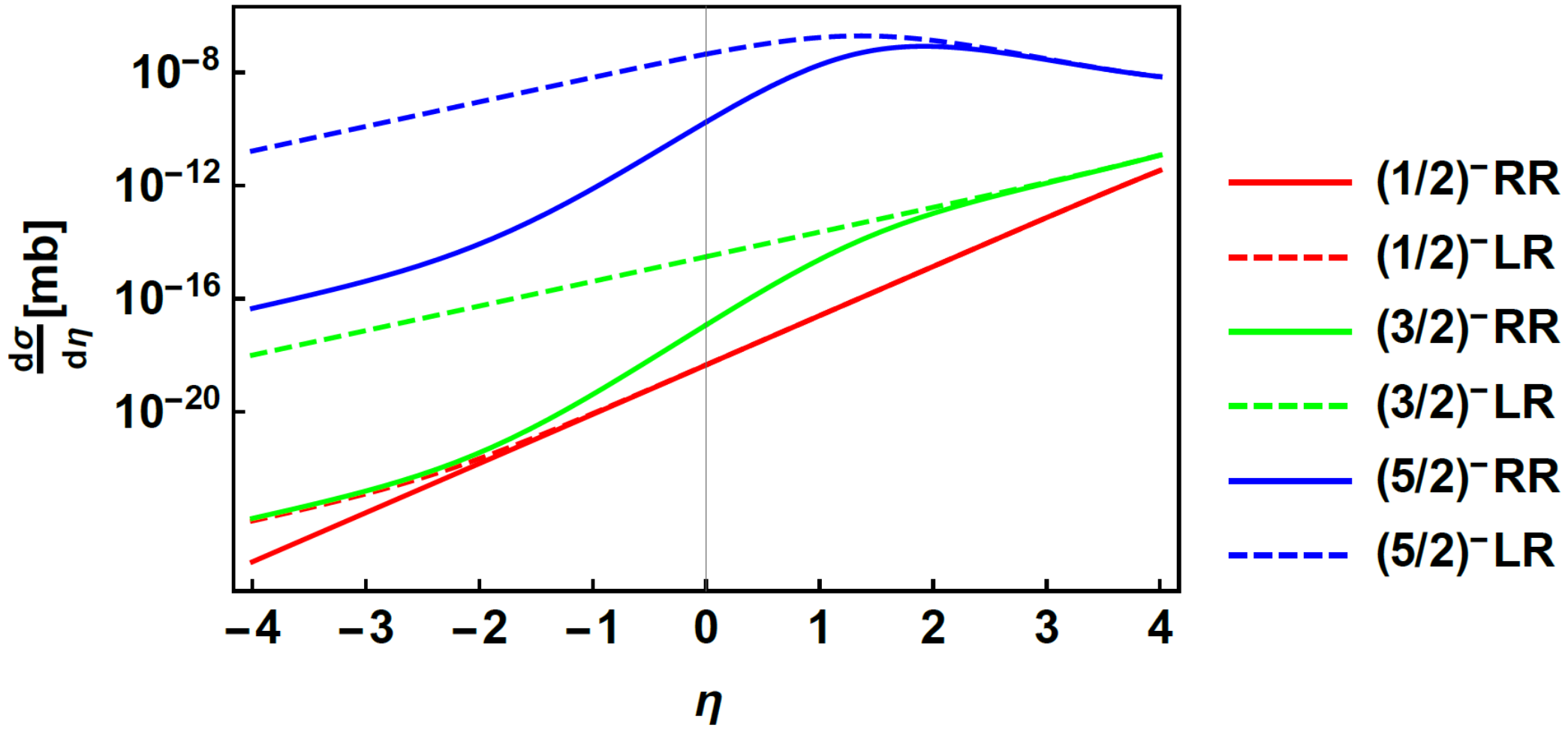
- Extend the calculation to hidden bottom pentaquark states.

Phys. Rev. C 108, no.2, 025201 (2023)

5. Summary

- $(1/2\,,3/2)^{+} > (1/2\,,3/2)^{-}$ while $(5/2)^{+} < (5/2)^{-}$
- $(1/2)^{\pm}$ & $(3/2)^{\pm}$ rich at low energy and $(5/2)^{\pm}$ rich at high energy
- Cross section is larger when electron and proton are oppositely polarized
- J/ψ polarization can be used to differentiate parity of $P_c(4312)$
- Branching ratio estimation using 2023 GlueX data

Backup slides



Backup slides