EIC, a factory for heavy pentaquarks?

Yongsun Kim (Sejong University)

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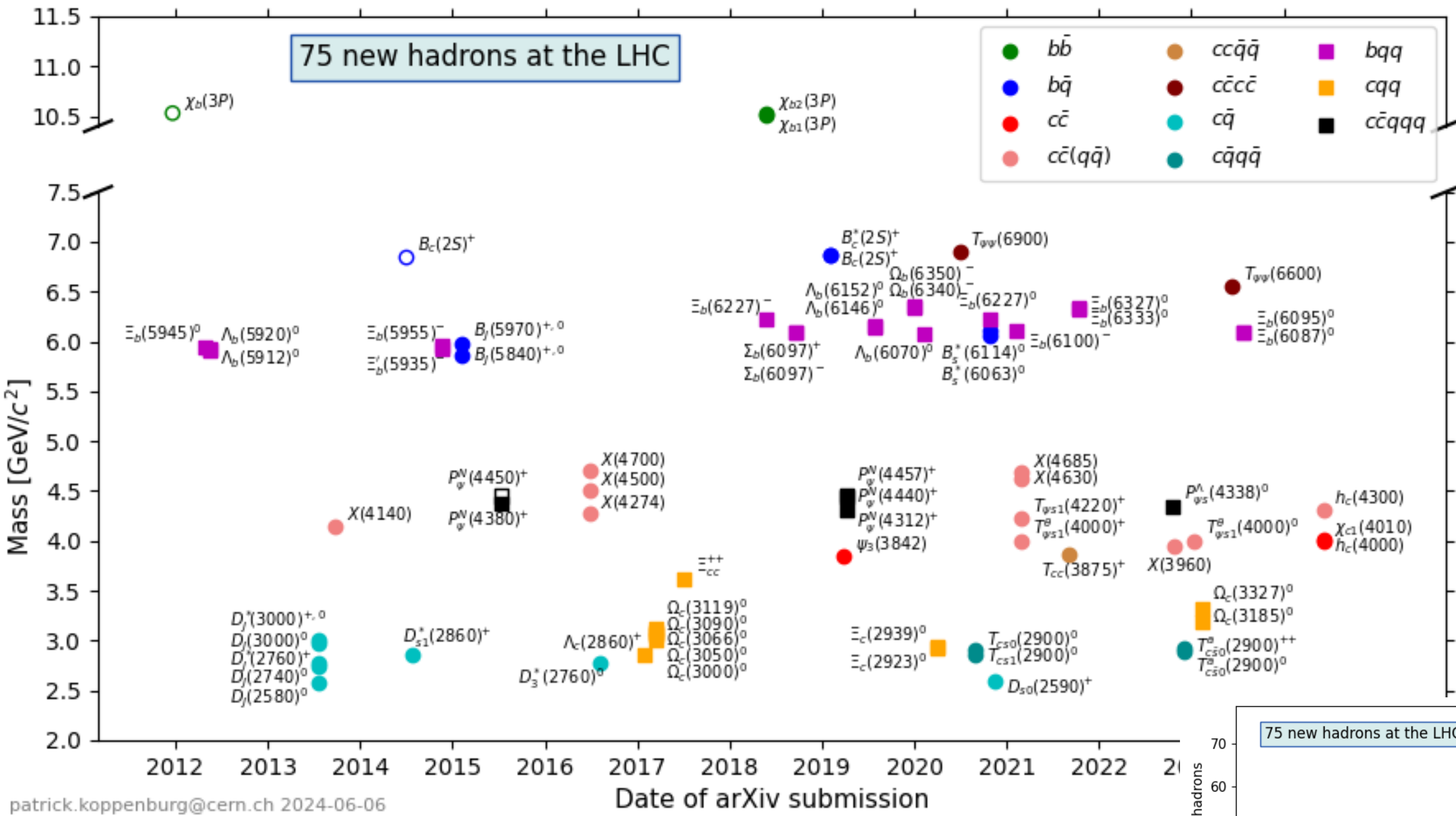
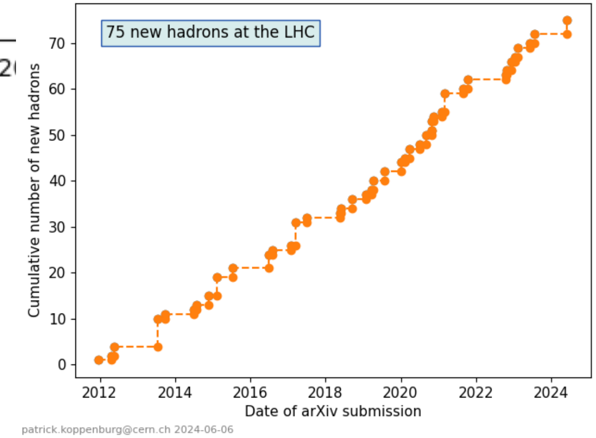
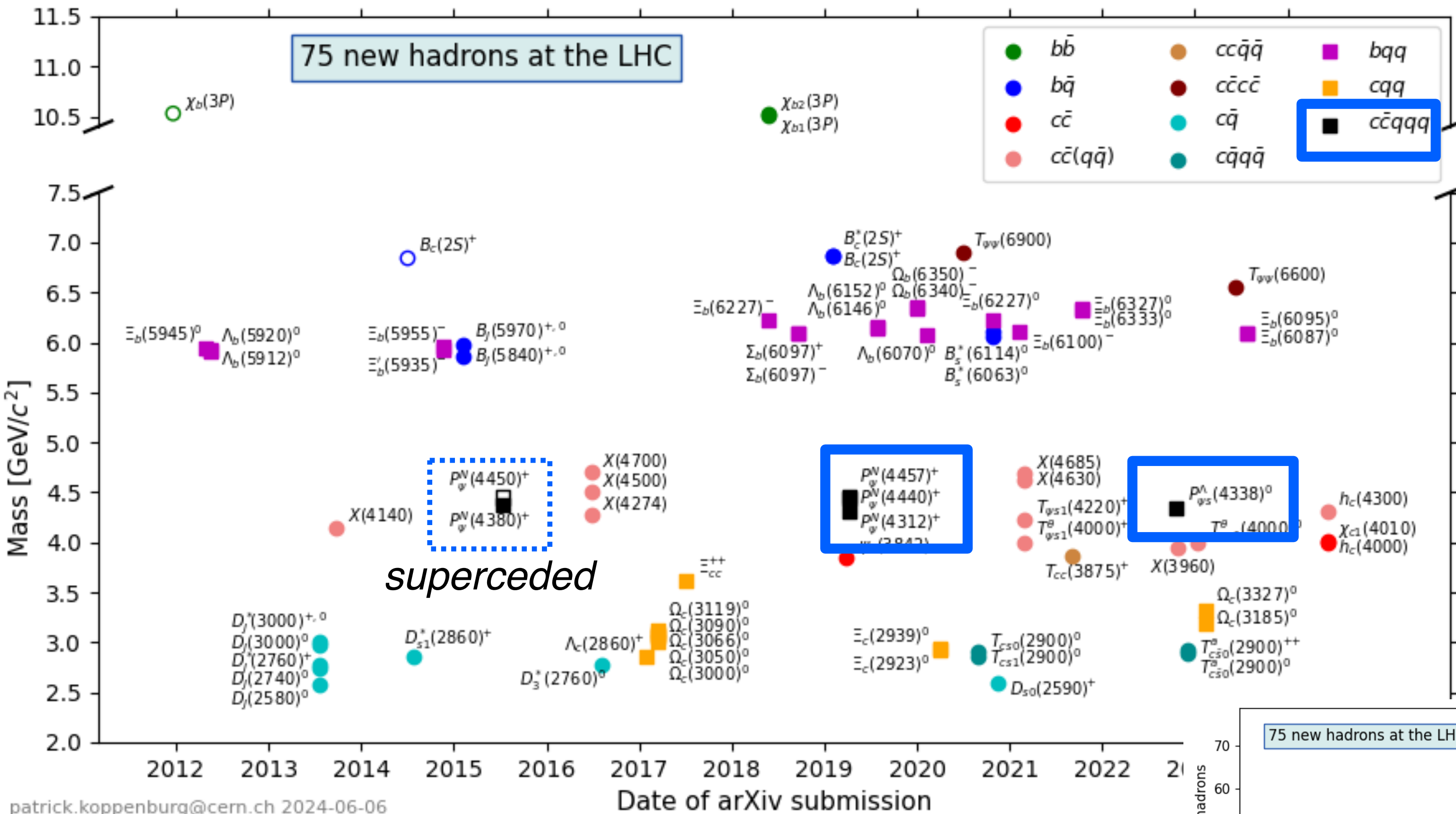
Jul. 09. 2024

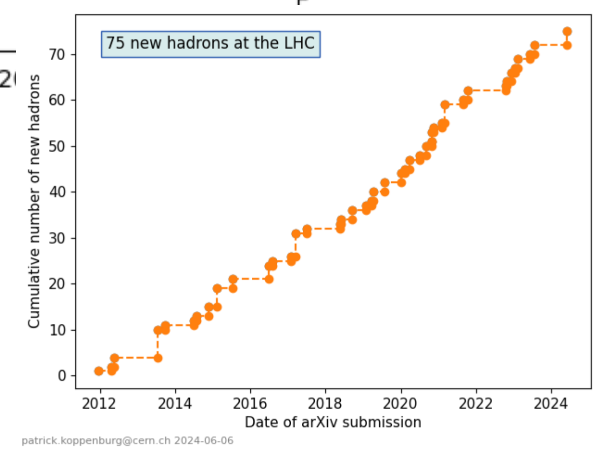
New exotic particles at LHCb





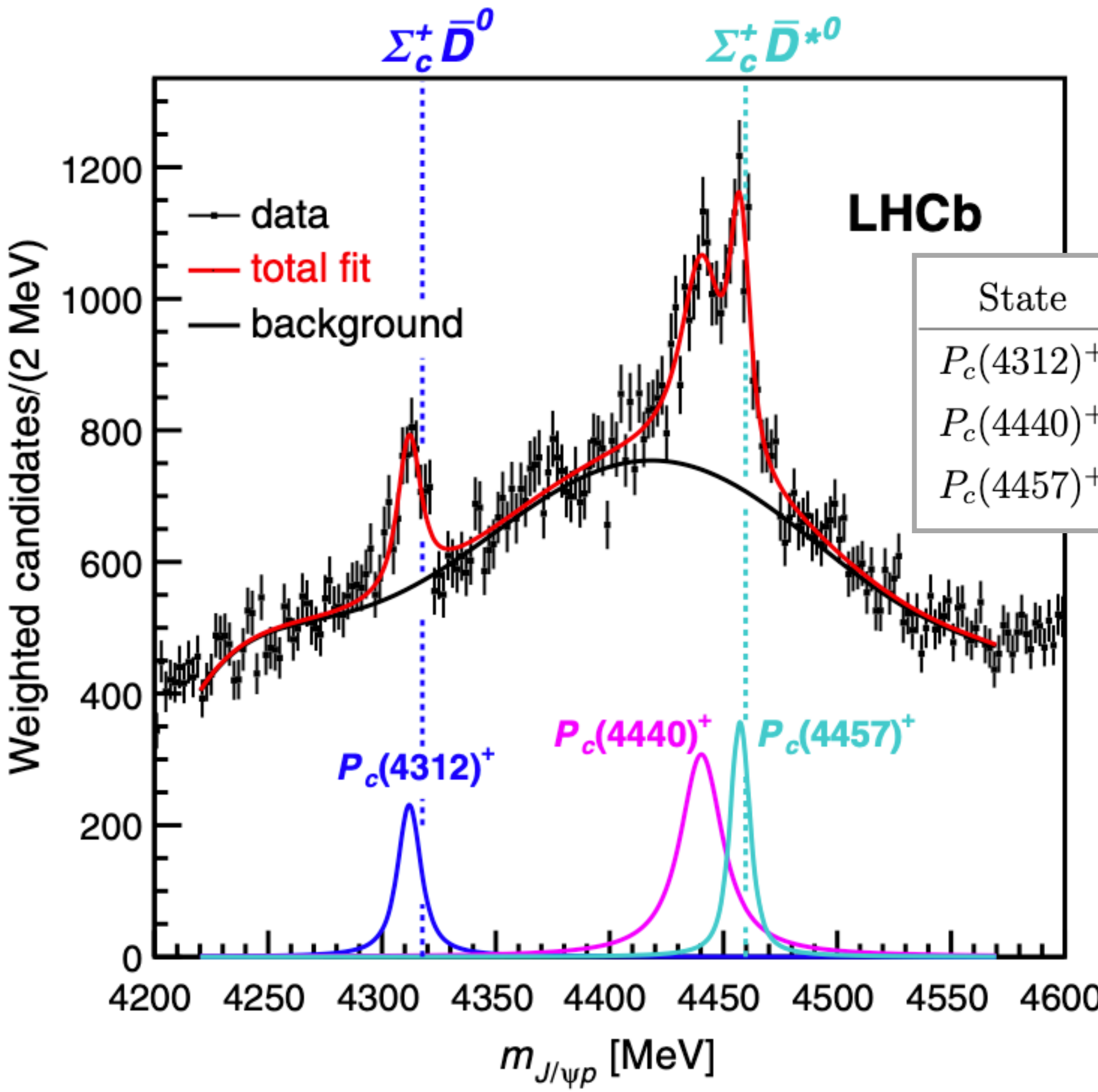
New exotic particles at LHCb





- P_c states decays into $J/\psi + p$
- P_{cs} states decays into $J/\psi + \Lambda$

P_c brothers discovered by LHCb

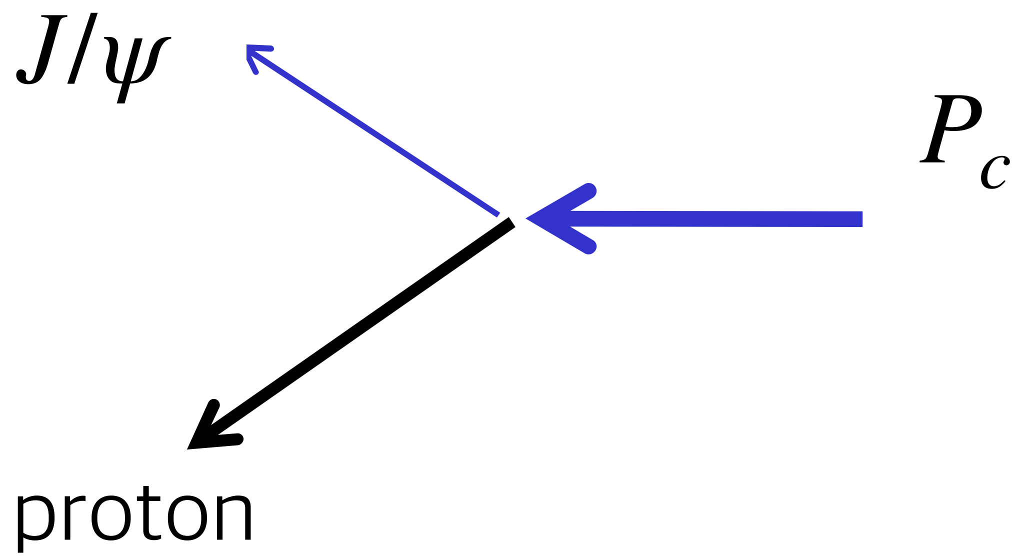


State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$

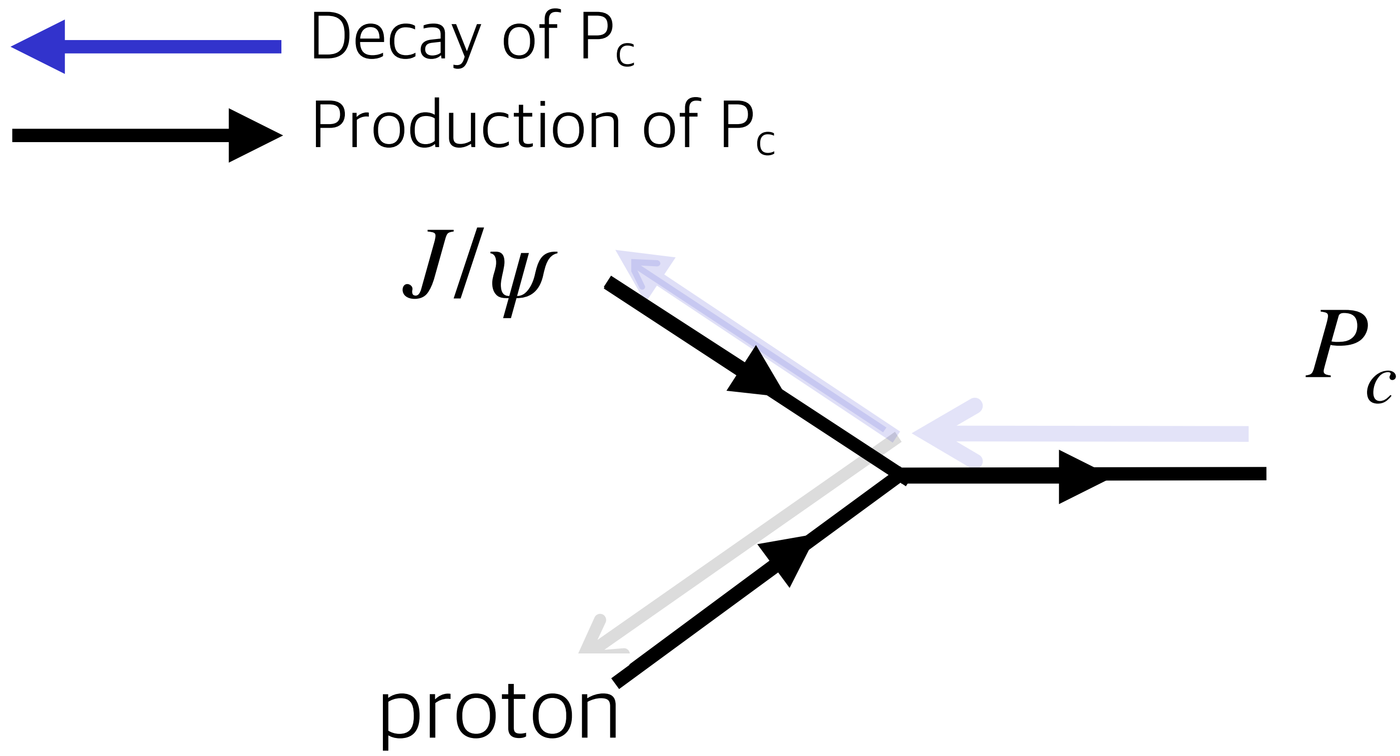
- Decay width of P_c's are measured within ~50%

Decay of P_c

Decay of P_c

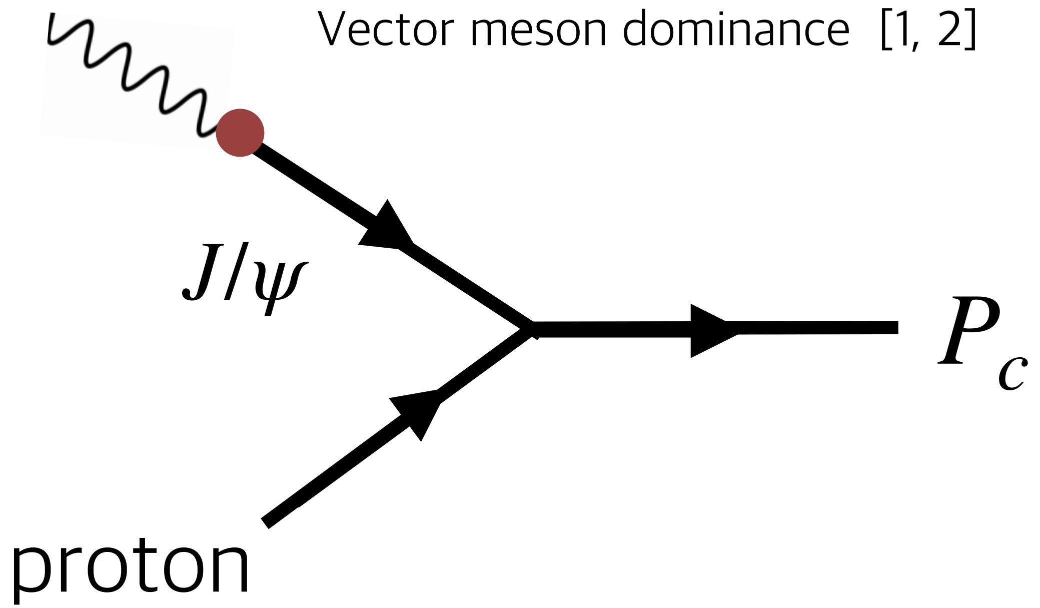


Production of P_c



Perhaps we can create P_c by $J/\gamma + p \to p_c$

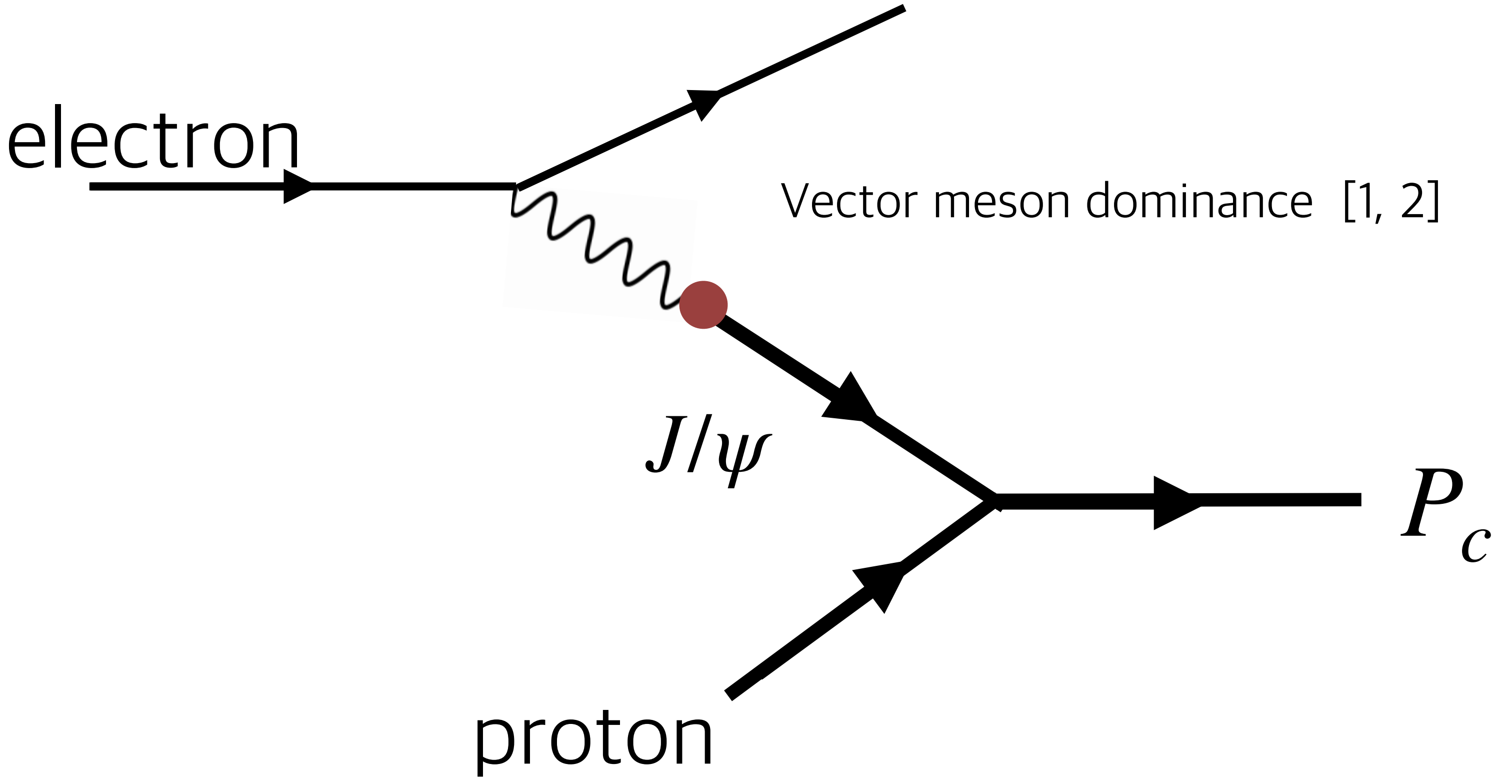
Photo-production of P_c



Perhaps we can create P_c by $\gamma + p \rightarrow p_c$

〔1〕Z.Phys. A356 (1996) 193-206, Klingl et al.
〔2〕Currents and Mesons (1969), Sakurai

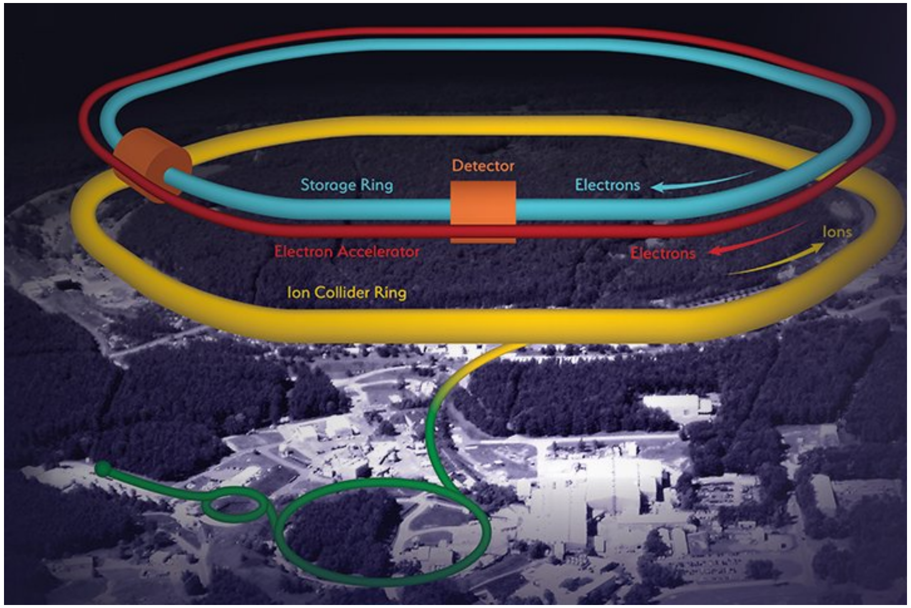
Electro-production of P_c

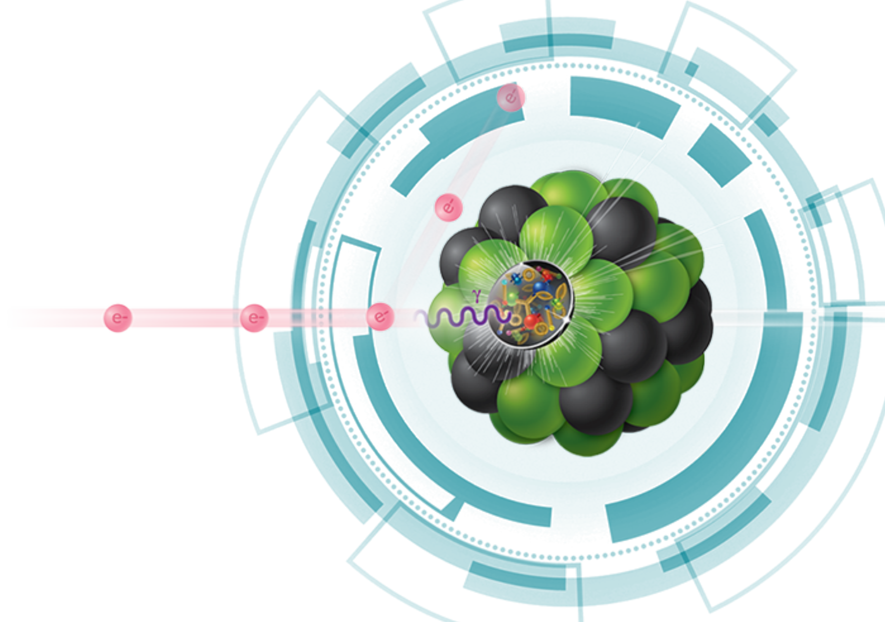


Perhaps we can create P_c by $e + p \to e + p_c$
in the e+p collision

〔1〕Z.Phys. A356 (1996) 193-206, Klingl et al.
〔2〕Currents and Mesons (1969), Sakurai

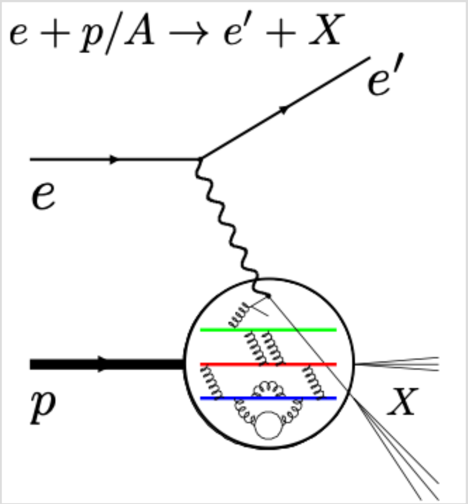
Electron Ion Collider





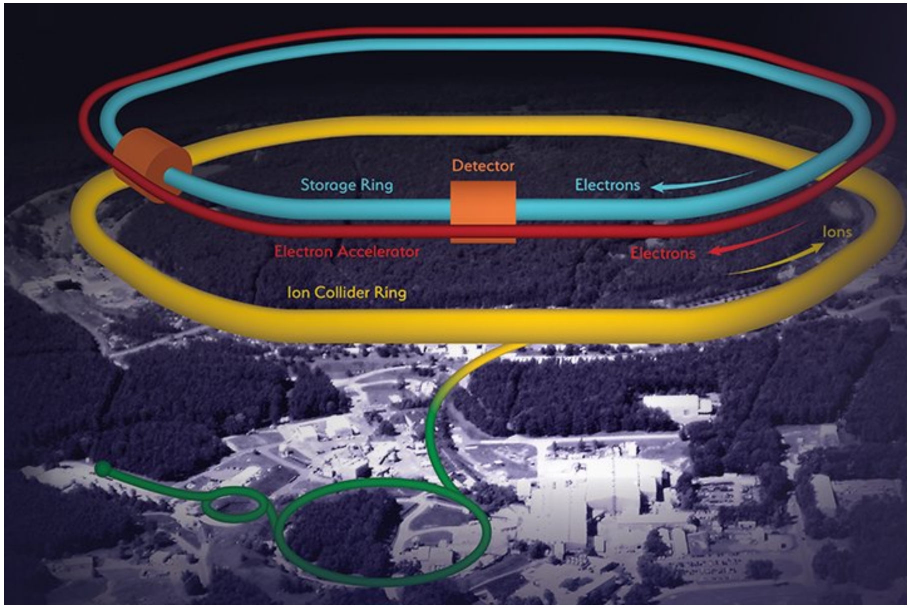
Science mission of EIC[1]

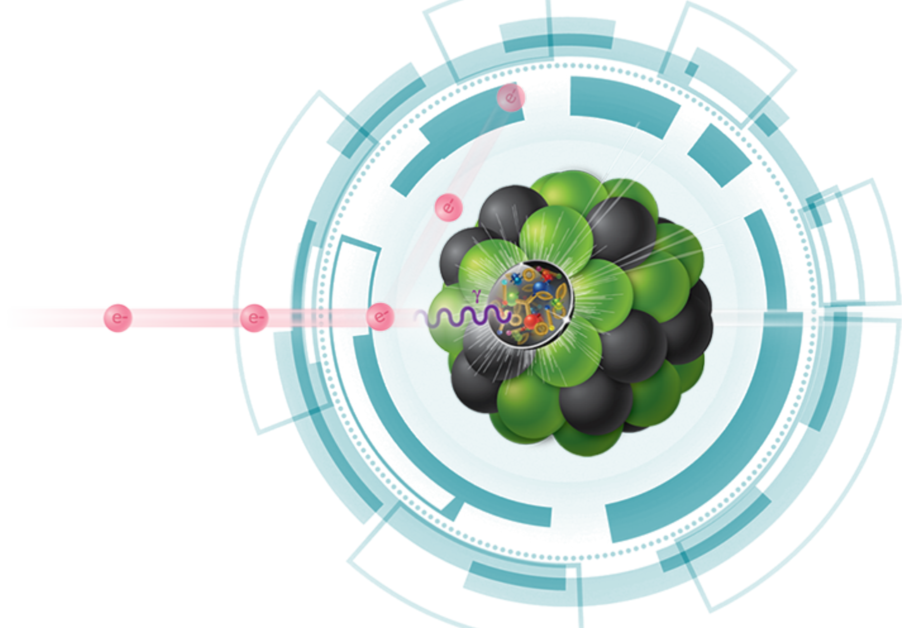
- Precision 3D imaging of protons and nuclei
- Solving the proton spin puzzle
- Search for saturation
- Quark and gluon confinement
- Quarks and gluons in nuclei



[1] *https://www.bnl.gov/eic/science.php*

Electron Ion Collider





Science mission of EIC[1]

- Precision 3D imaging of protons and nuclei
- Solving the proton spin puzzle
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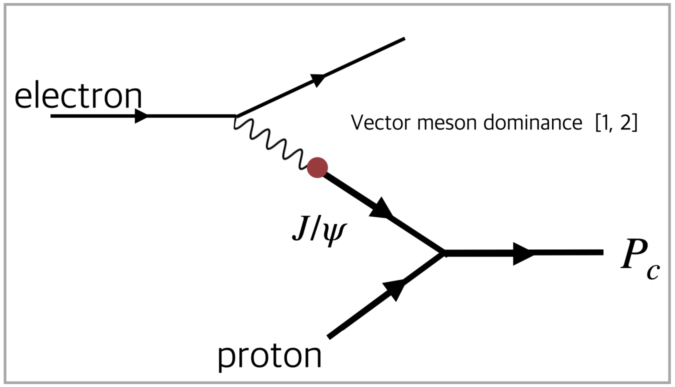
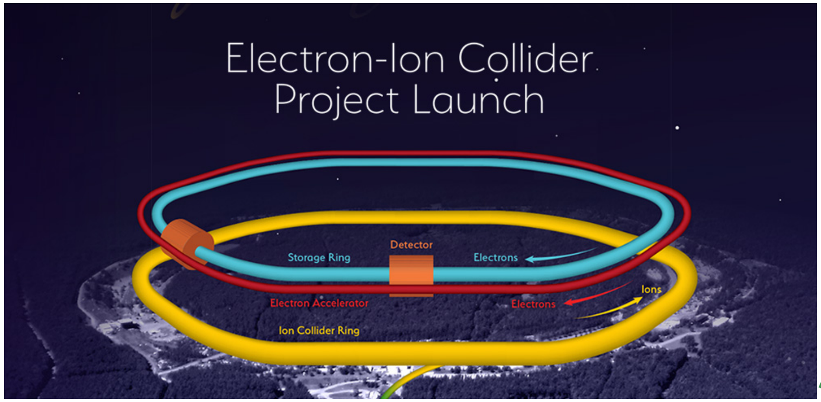
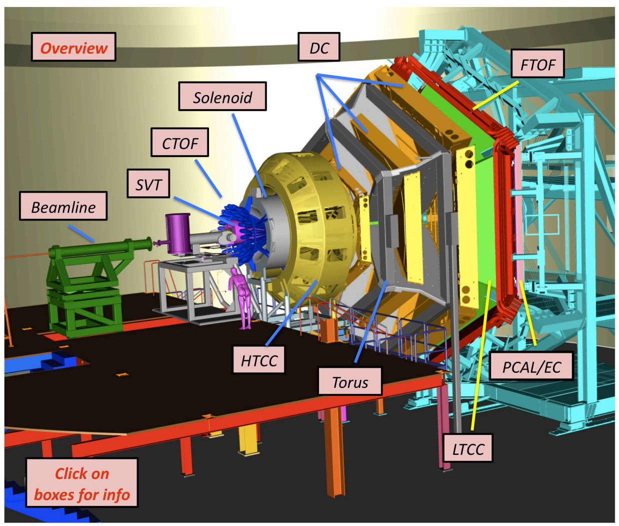
- Quark and gluon confinement
- Quarks and gluons in nuclei
- **Discovery and characterization of exotic hadrons?**

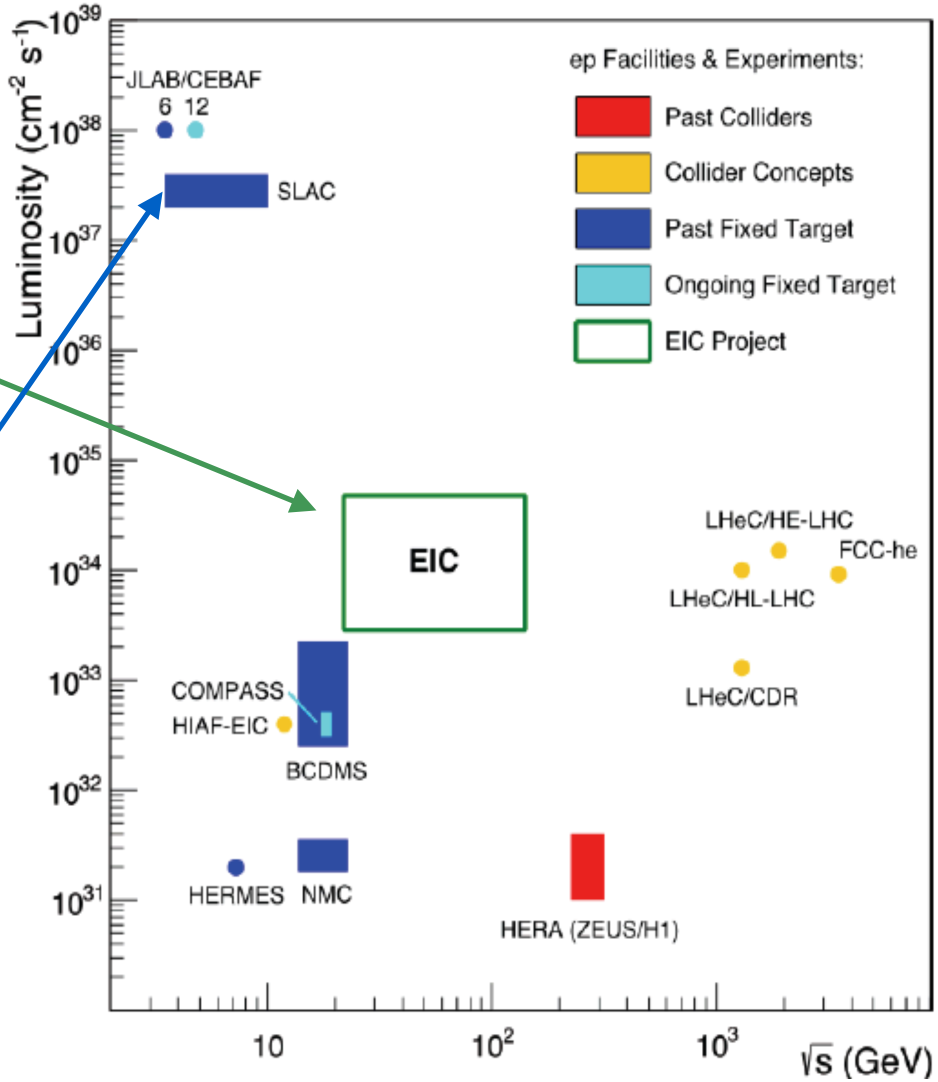


[1] *https://www.bnl.gov/eic/science.php*

Electron Ion Collider

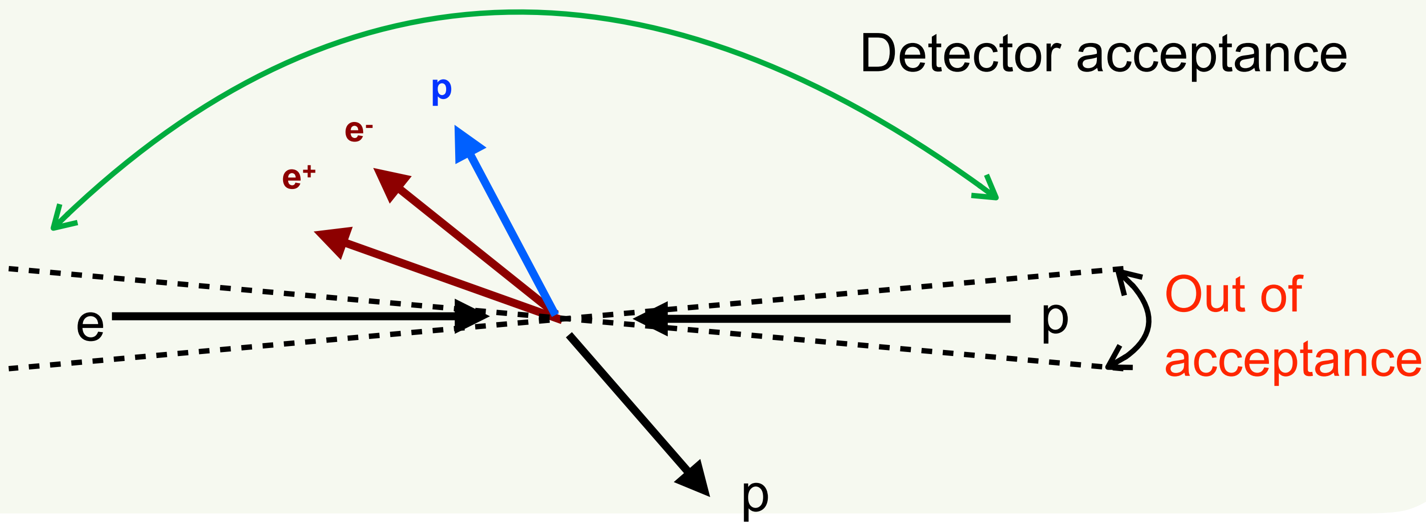




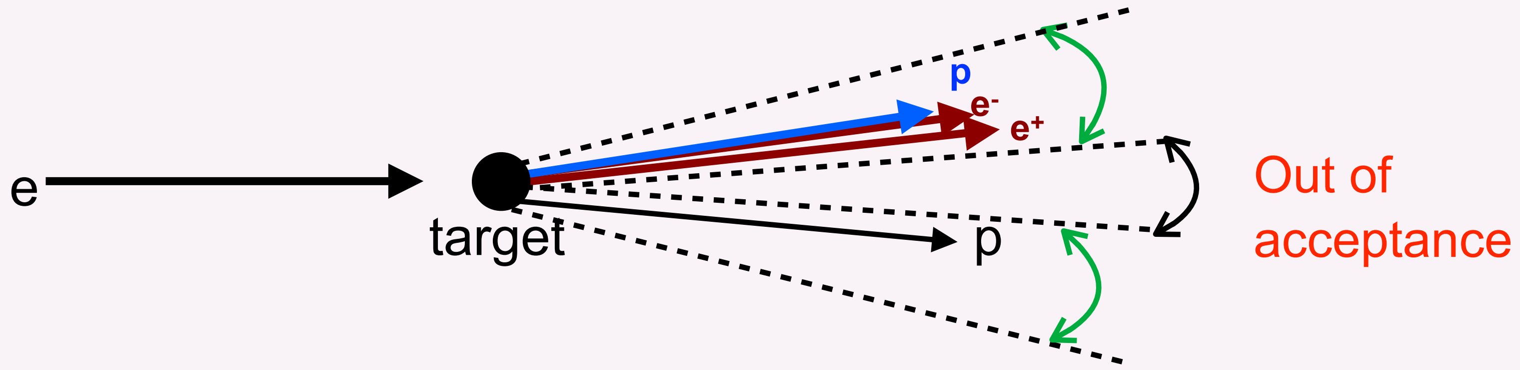


Collider experiment v.s target experiment

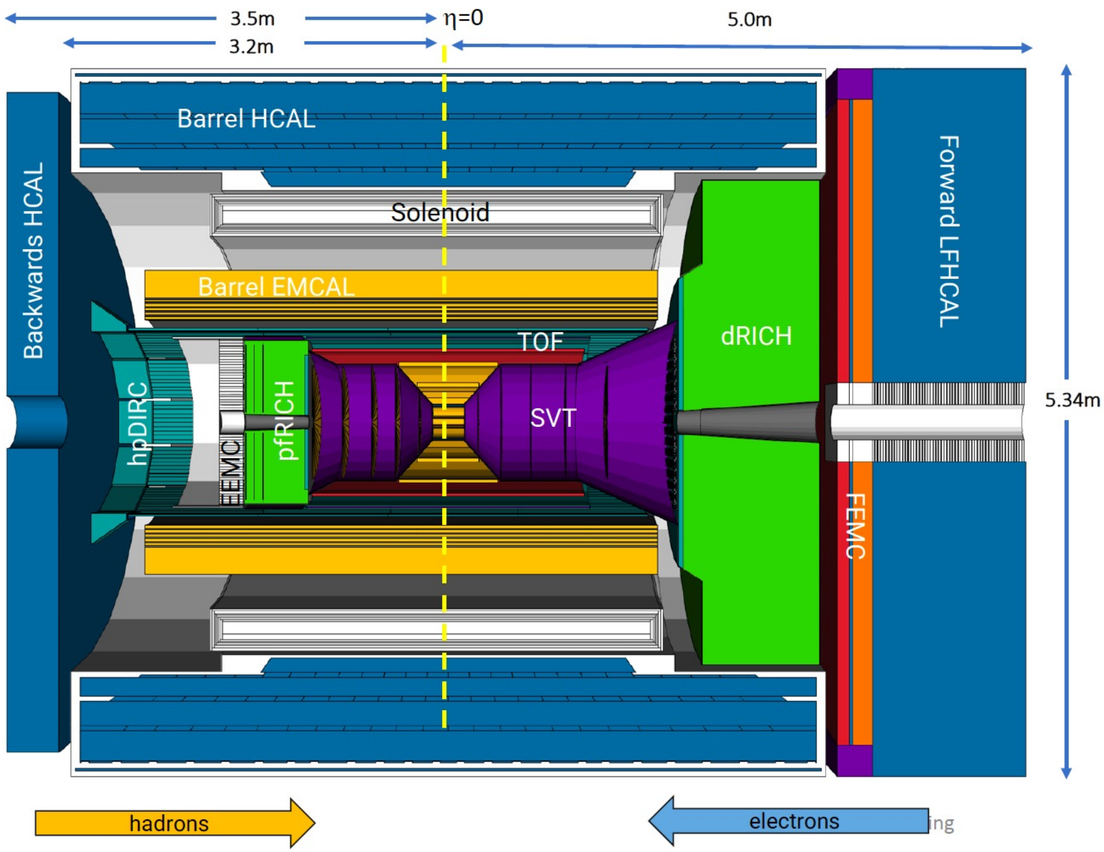
Collider experiment



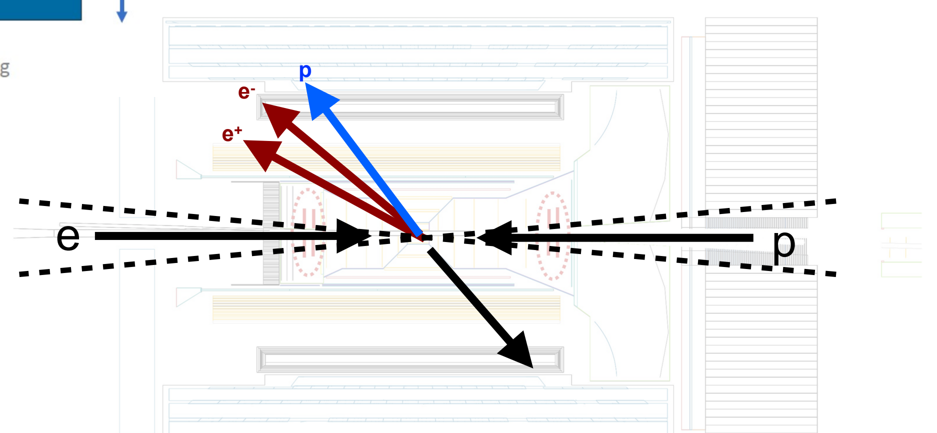
Target experiment



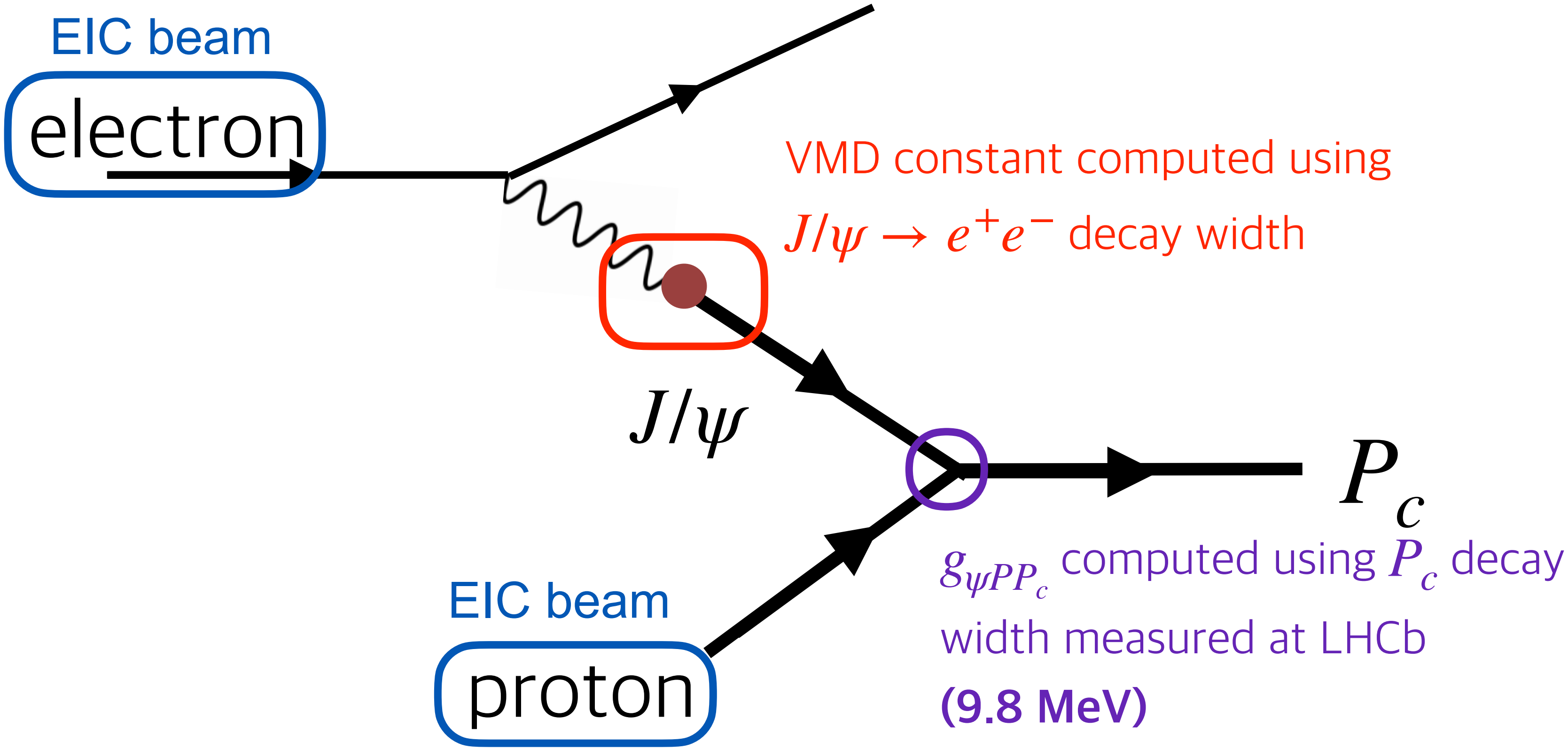
ePIC detector



Charged particles can be measured for $|\eta| < 4$



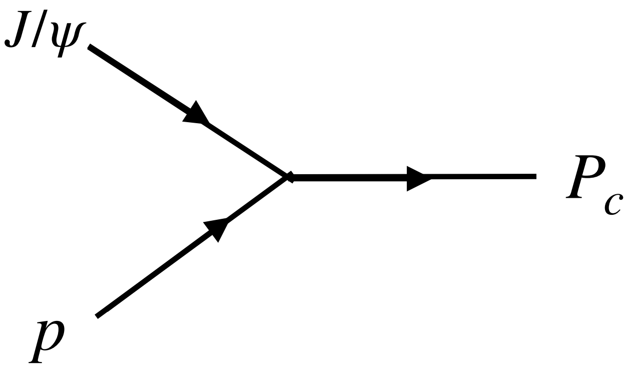
Computation of P_c cross section at EIC



[1] *Z.Phys. A356 (1996) 193-206*

[2] *PRL 21, 244-247 (1968)*

Formalism



- Lagrangian

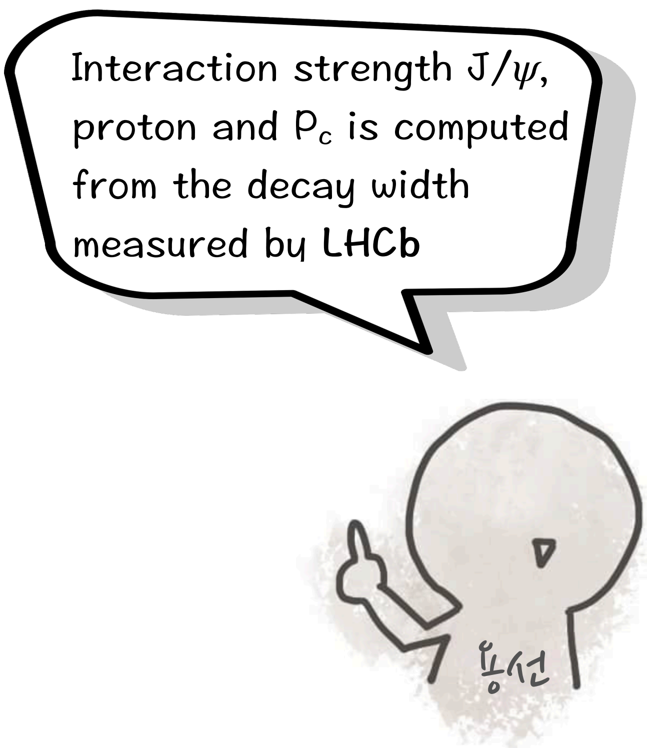
$$\mathcal{L}_{\rm int} = \begin{cases} \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \sigma^{\mu\nu} F^J_{\mu\nu} \psi_{P_c} & J^P = \frac{1}{2}^+, \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p \gamma_5 \sigma^{\mu\nu} F^J_{\mu\nu} \psi_{P_c} & J^P = \frac{1}{2}^-, \\ \frac{g_{JpP_c}}{m_{J/\psi}} \bar{\psi}_p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

- Fixing interaction strength from Γ

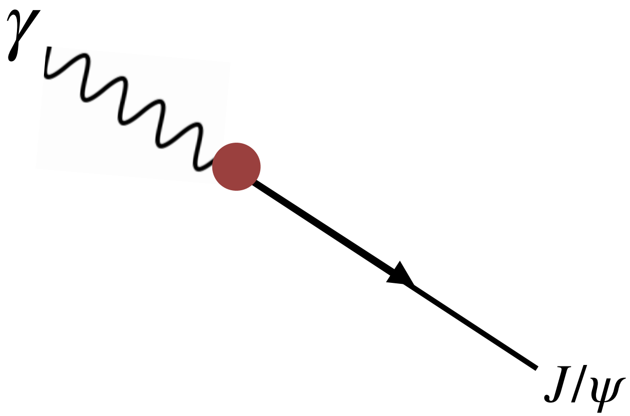
$$\Gamma_{P_c \to p + J/\psi} = \frac{1}{8\pi} \frac{|\vec{p}_f|}{m^2_{P_c}} |\mathcal{M}|^2$$

- Results in 2 spin x 2 parity cases

J^P	$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$
g_{JpP_c}	0.379	0.169	1.47	0.599



Formalism



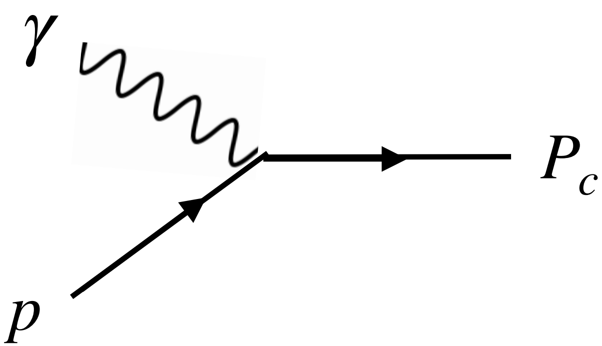
- Vector meson dominance model

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

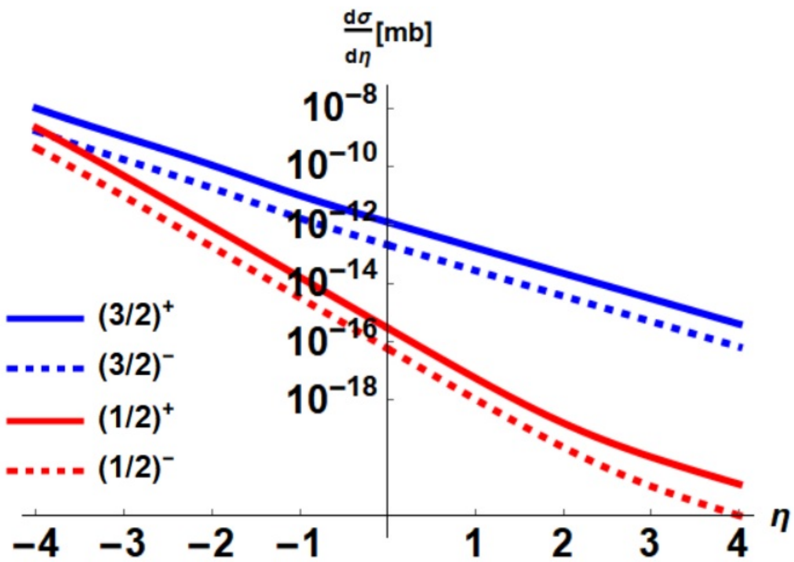
$$\mathcal{L}_{\gamma e^- e^+} = -e\bar{\psi}\gamma^\mu A_\mu \psi,$$

- Coupling constant g_J is computed from $J/\psi \to e^+e^-$ decay width
  - Γ = 95.9 keV x 5.97%
- Photo-production strength

$$g_{\gamma p P_c} = -\frac{e g_{J p P_c} q^2}{g_J} \frac{1}{q^2 - m^2_{J/\psi}}$$



$P_c(4312)$ yields at EIC



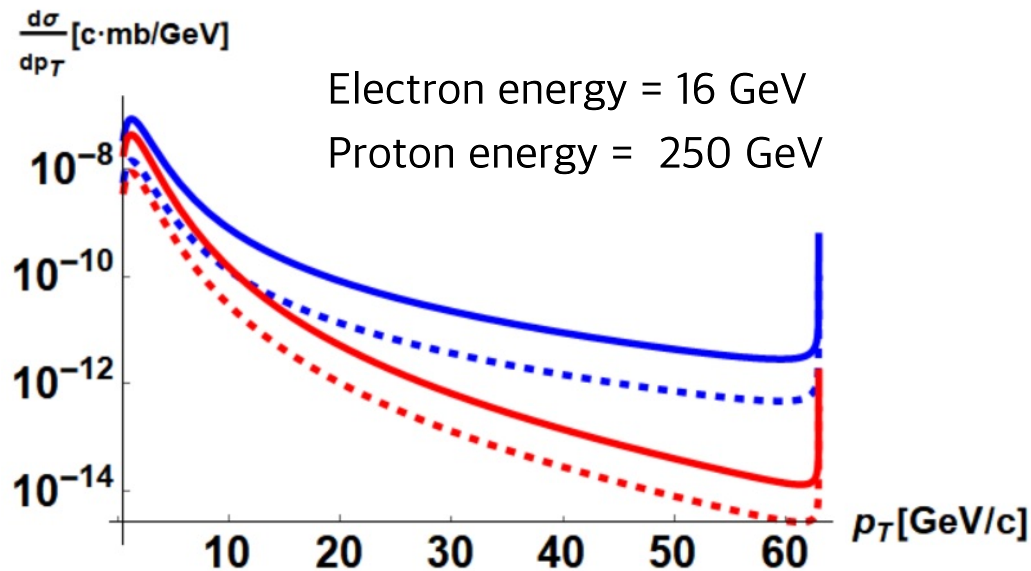


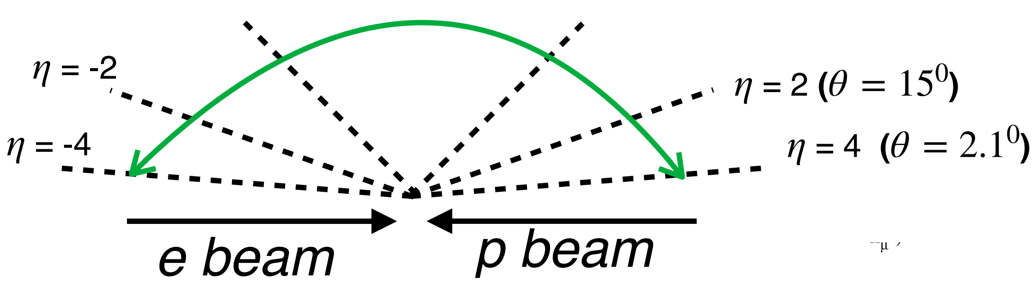
TABLE II. Expected number of $P_c(4312)$ produced at the EIC with 10 fb^{-1}.

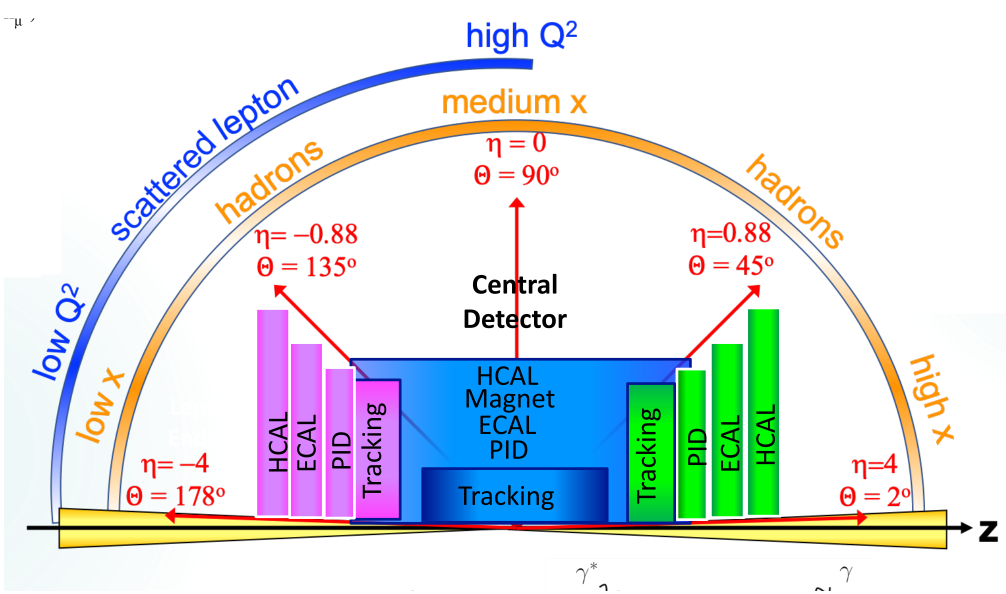
J^P of P_c	$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$
Yield	5.67×10^3	1.13×10^3	4.32×10^4	7.15×10^3

$O(10^3)$ - $O(10^4)$ of P_c produced in a month, EIC being a potential pentaquark factory!

$P_c(4312)$ yields in polarized e+p

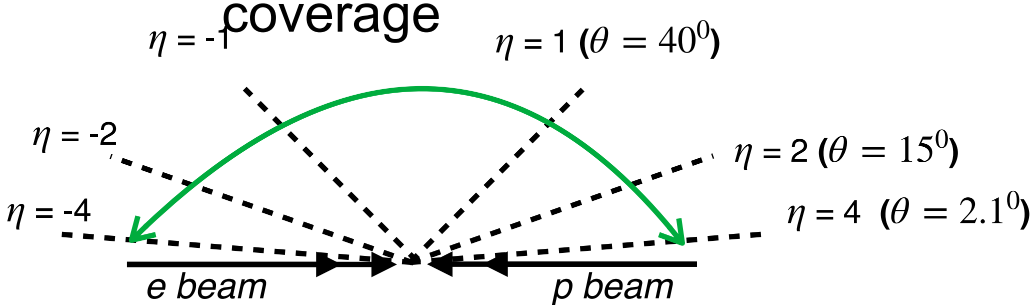
ePIC detector coverage

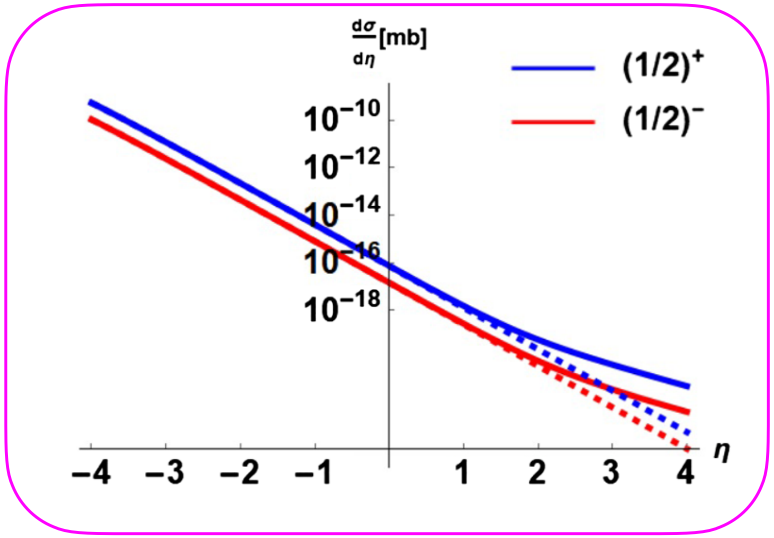




$P_c(4312)$ yields in polarized e+p

ePIC detector coverage

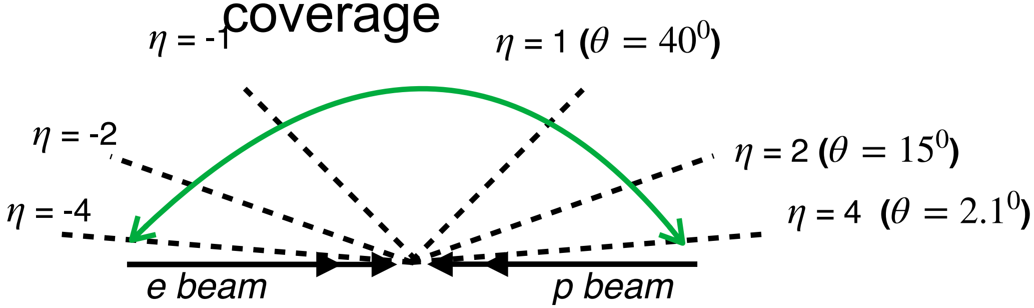


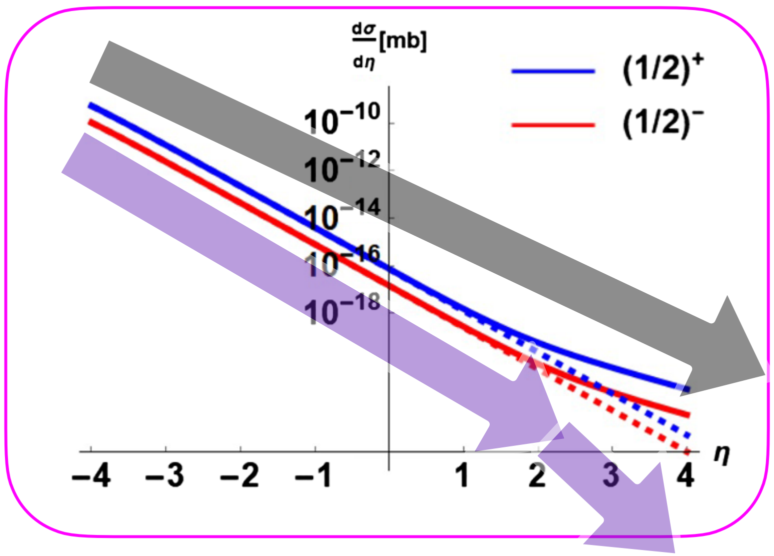


Spin 1/2 scenario

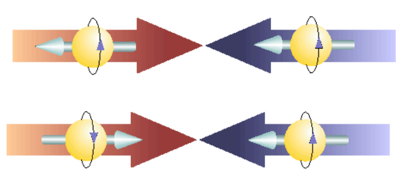
$P_c(4312)$ yields in polarized e+p

ePIC detector coverage





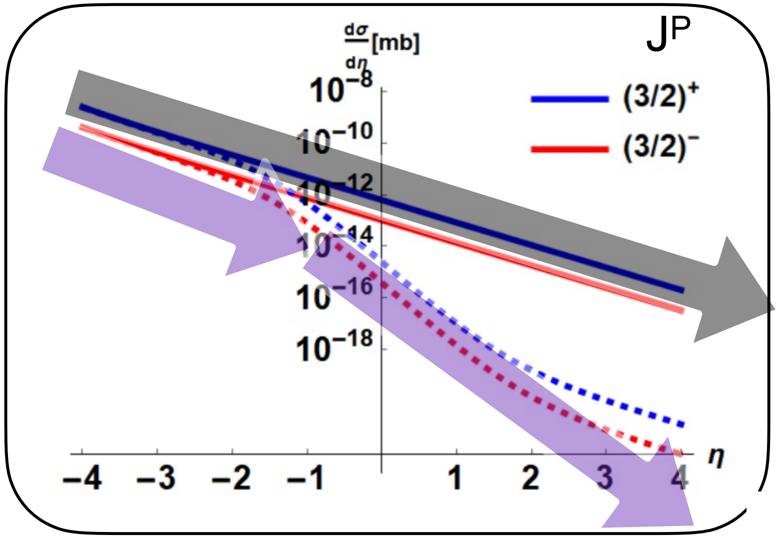
Spin 1/2 scenario



Parallel polarization

Anti-parallel

$P_c(4312)$ yields in polarized e+p

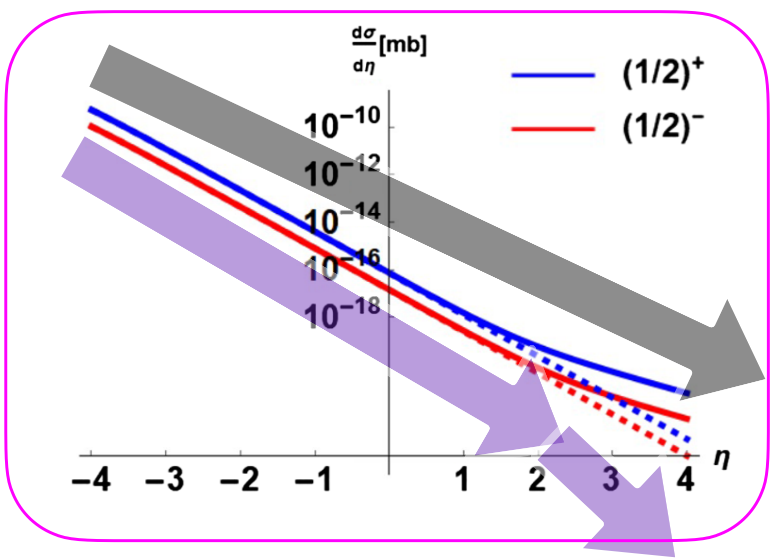


e beam → ← *p beam*

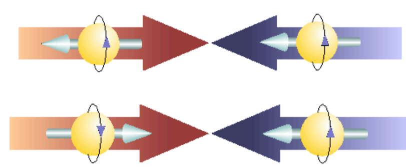
Spin 3/2 case

Parallel polarization

Anti-parallel



Spin 1/2 case



Parallel polarization

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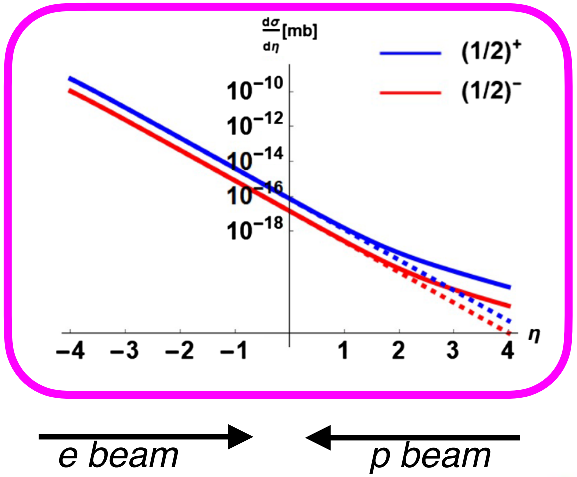
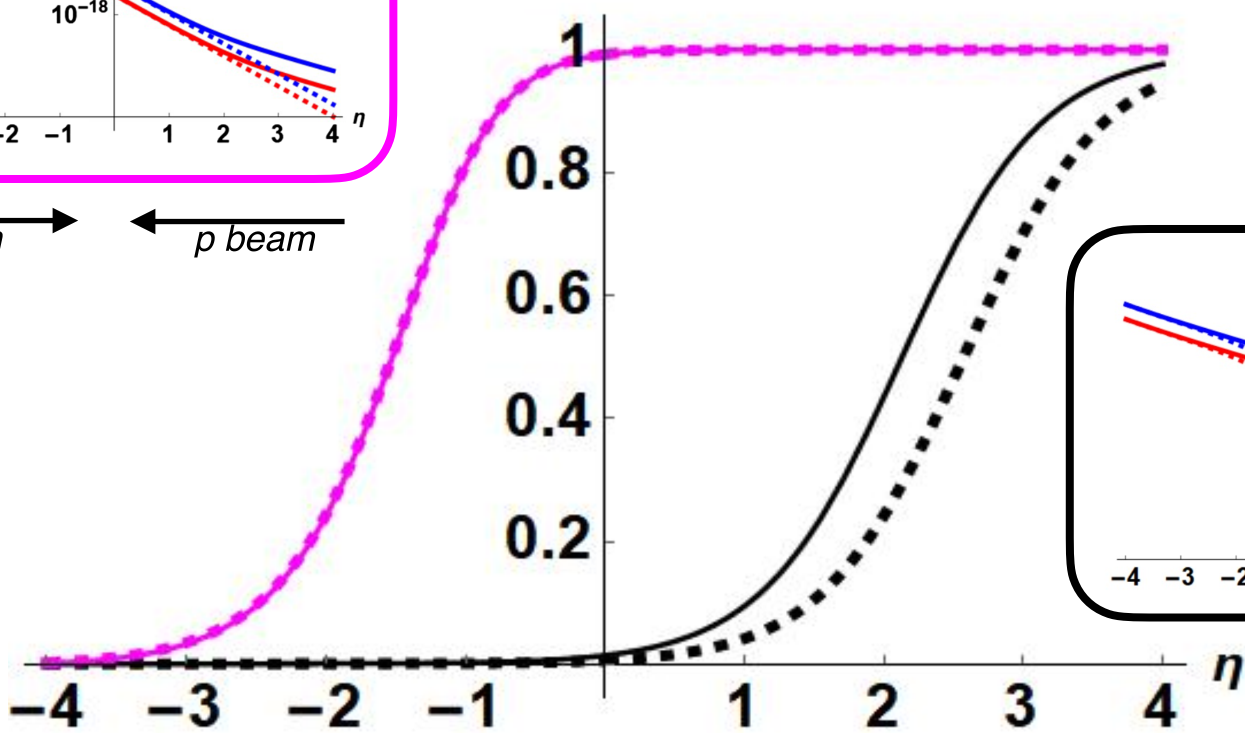
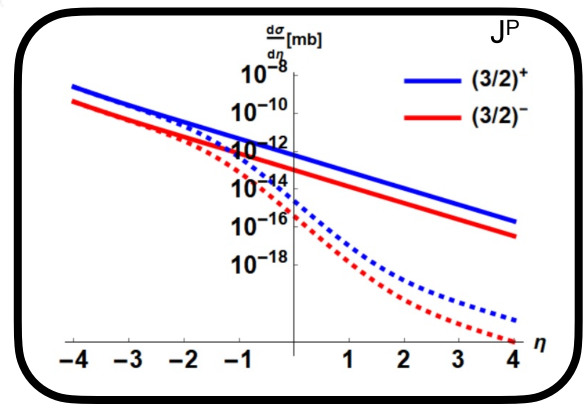
P_c(4312) yields in polarized e+p



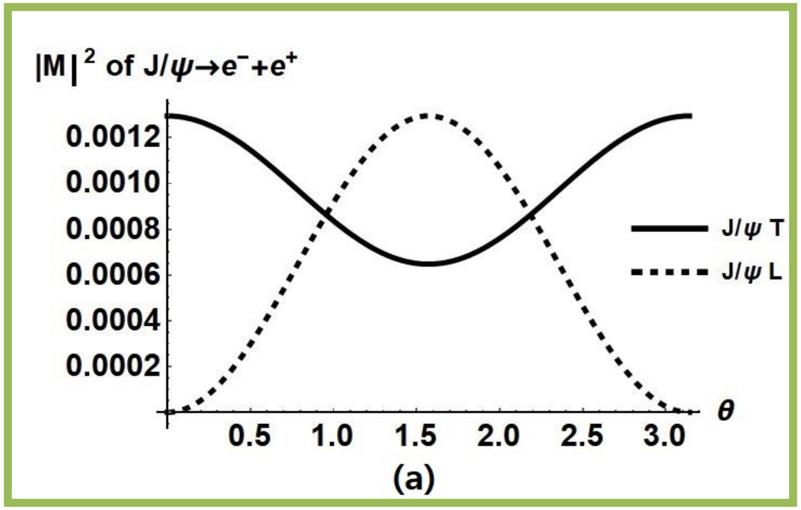
$$BSA\ (\eta) = \frac{d\sigma/d\eta\ [RL] - d\sigma/d\eta\ (RR)}{d\sigma/d\eta\ [RL] + d\sigma/d\eta\ [RR]}$$

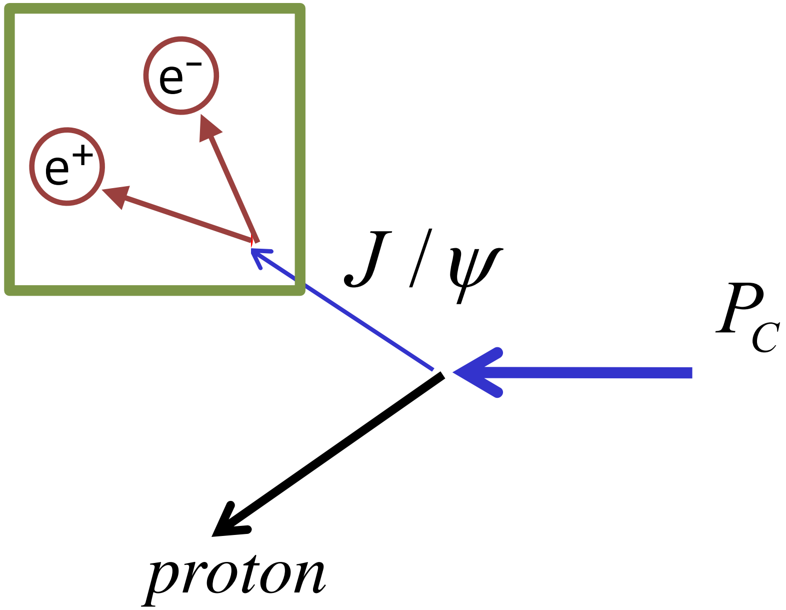




Spin of P_c can be resolved by measuring forward-to-backward ratio!

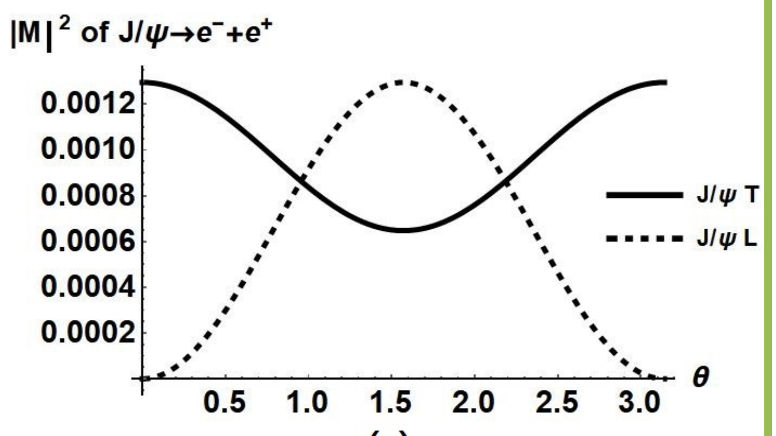
Determination of parity



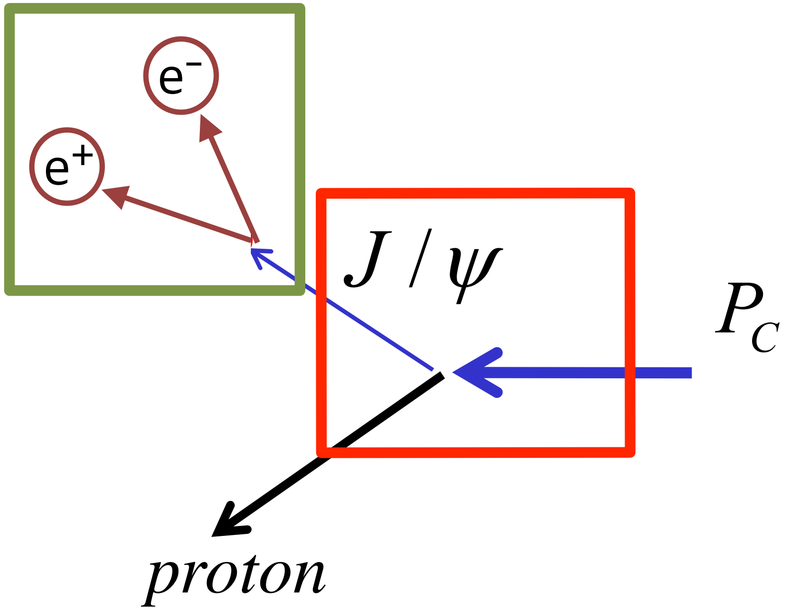


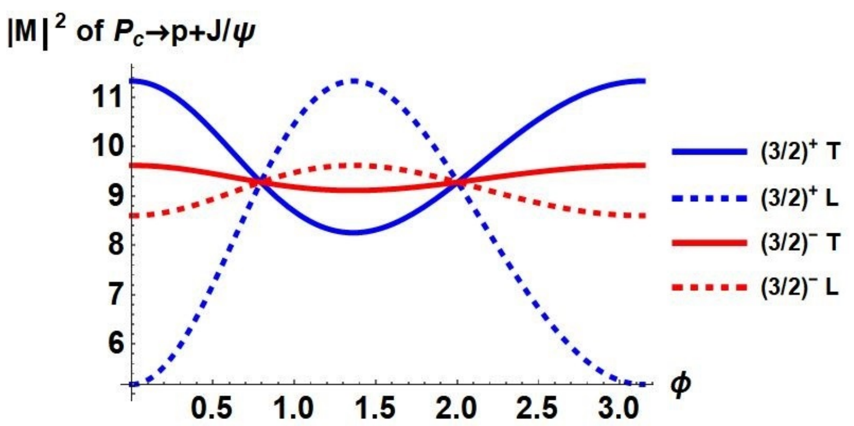
- J/ψ has spin-1 and its polarity can be measured from the decay kinematics

Resolution of parity by polarized ep at EIC



(a)

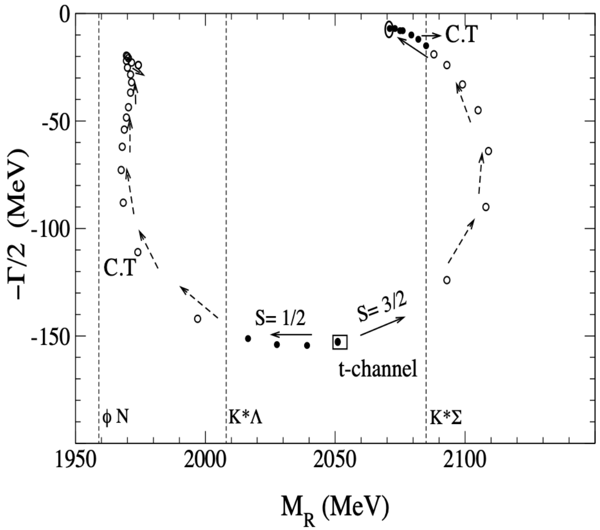


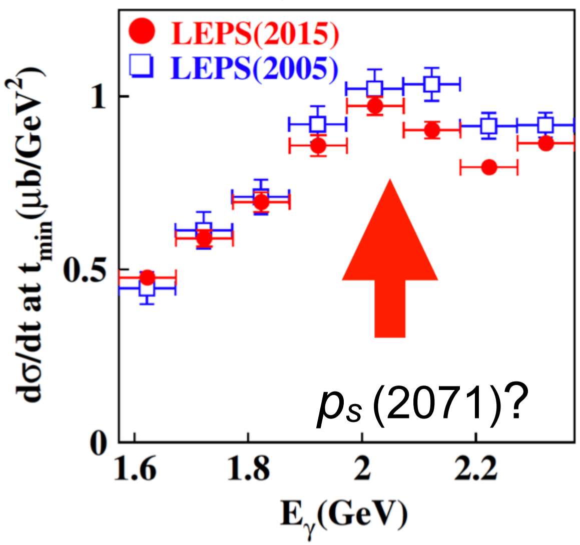


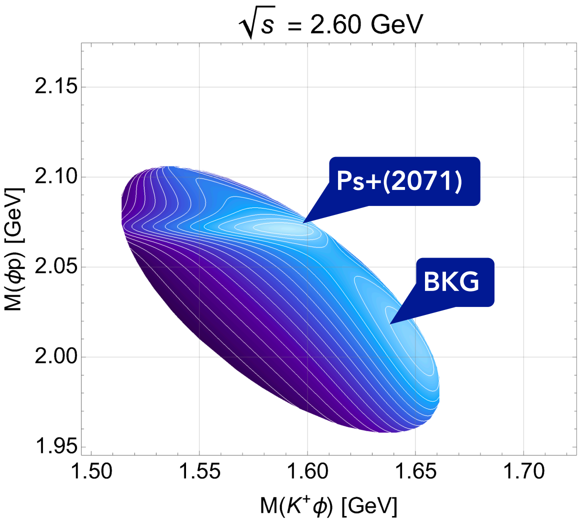
(c)

- J/ψ has spin-1 and its polarity can be measured from the decay kinematics
- Parity would be experimentally determined by polarized e+p collision at EIC

Photoproduction of P_s





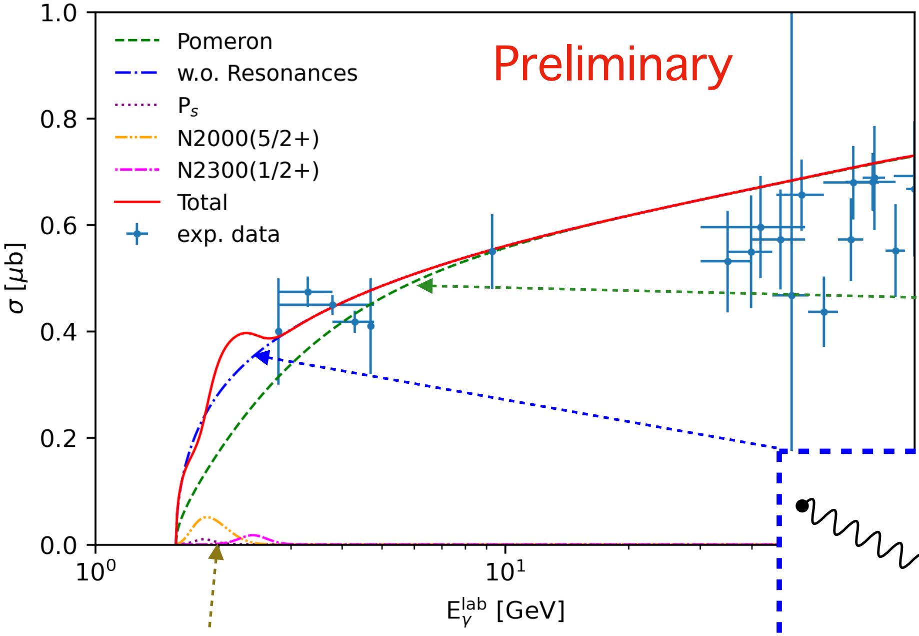


- Calculation predicted a resonance of P_s ($uuds\bar{s}$) near $\Sigma + K^*$ [1]
- SI Nam showed that if $p_s(2071)$ ever exists, the resonance would appear in the $K^+p \to K^+\phi p$ Dalitz plot [1]
- Considering VMD model, the same phenomenon can happen in the $\gamma + p \to (p_s \to\ ) \, \phi + p$ process

〔1〕Khemchandani et al PRD 83, 114041 (2011)

Cross section of ϕ photo-production

Total cross cross section



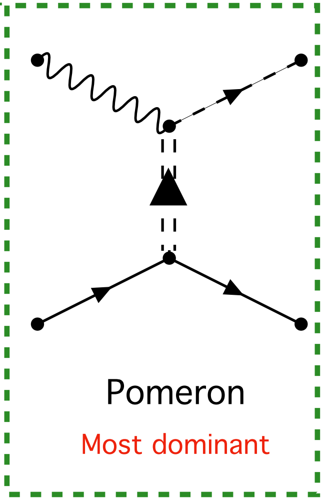
Experimental data points

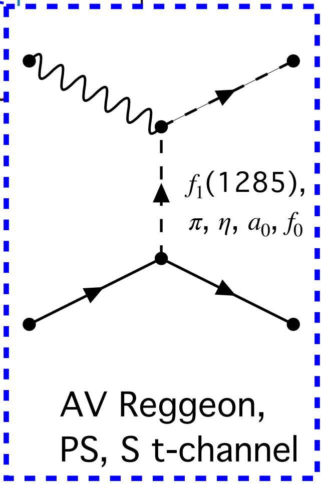
J. Ballam et al. PRD 7, 3150 (1973)

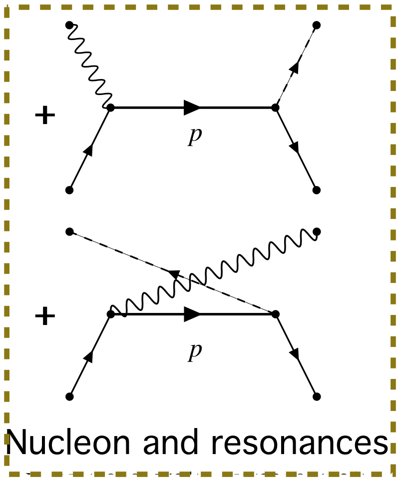
D. P. Barber et al., Z. Phys. C 12, 1 (1982)

R. M. Egloff et al., PRL **43**, 657(1979)

J. Busenitz et al., PRD 40, 1 (1989)



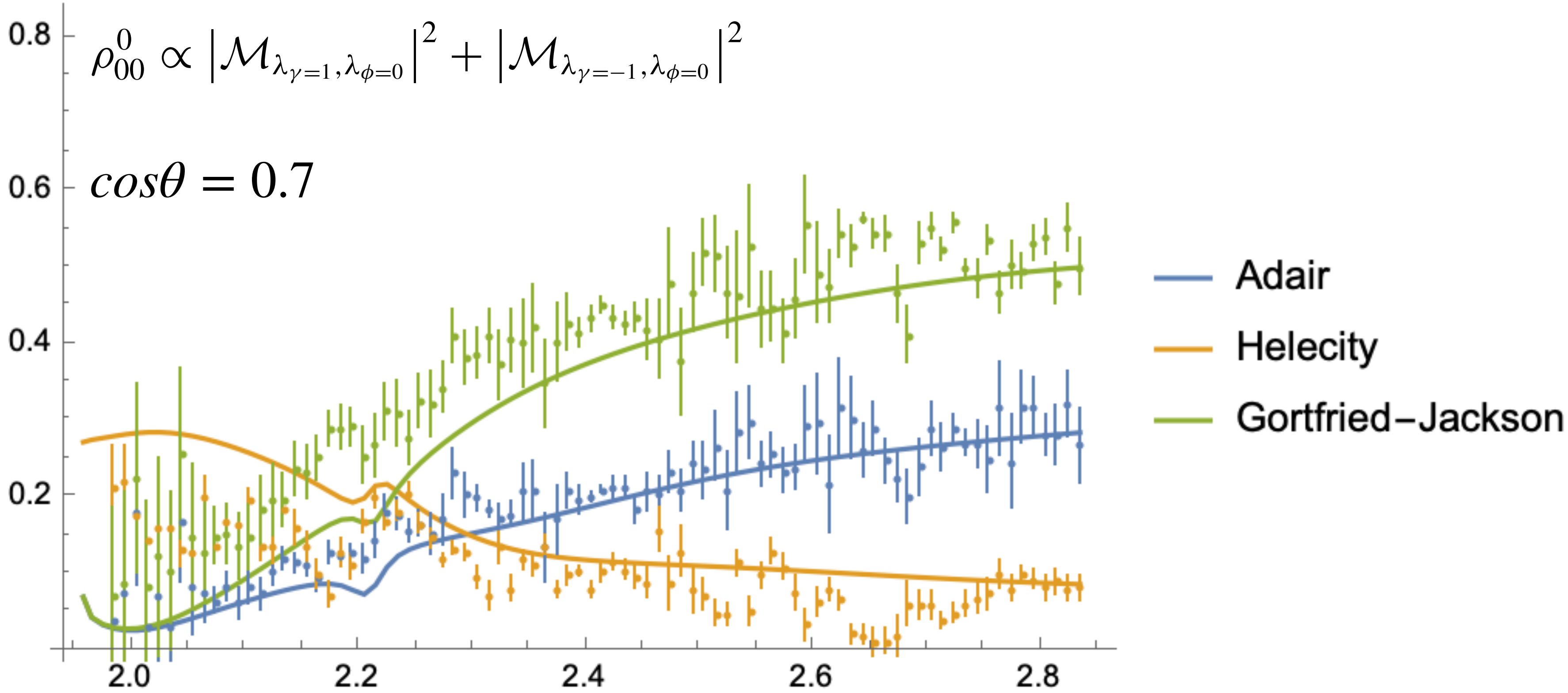




[1] *A. I. Titov et al. PRC58, 2429(1998); 67, 065205(2003)*
[2] *S. Kim, SiNam PRC100.065208(2019); 101.065201(2020)*

〔1〕arxiv:2402.07392

Spin density matrix component



- ρ^0_{00} reflects the single helicity-flip transition between the incoming photon and the outgoing ϕ meson [1]
- WIP to find visible signals expected using polarized *ep* at EIC

〔1〕arxiv:2402.07392

Summary

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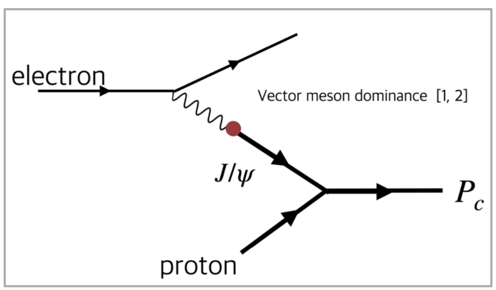
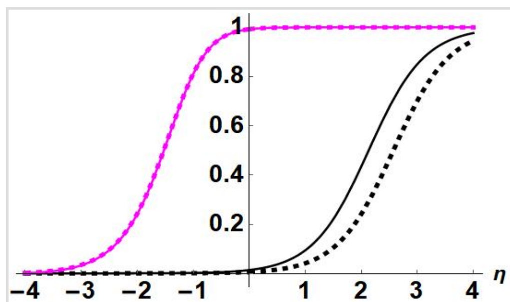
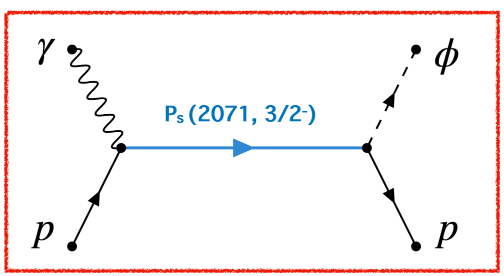
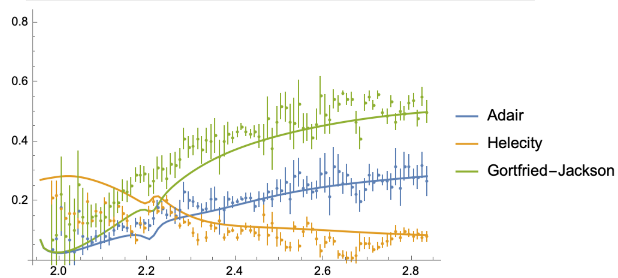
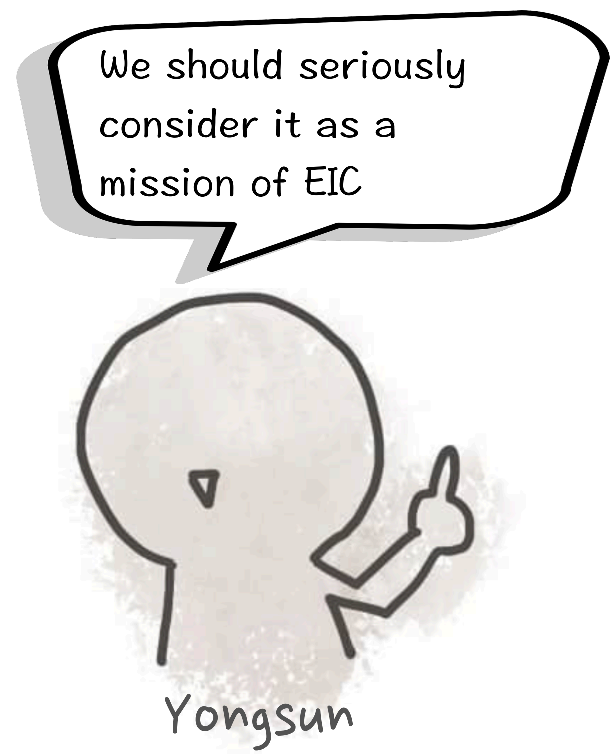
- **Discovery and characterization of exotic hadrons?**











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