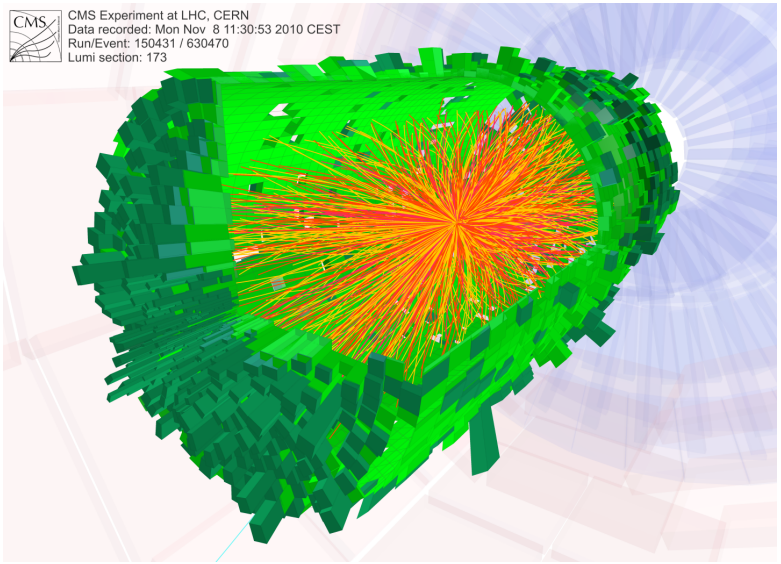
Opportunity of pentaquark measurement at EIC

Yongsun Kim (SJU, BNL)

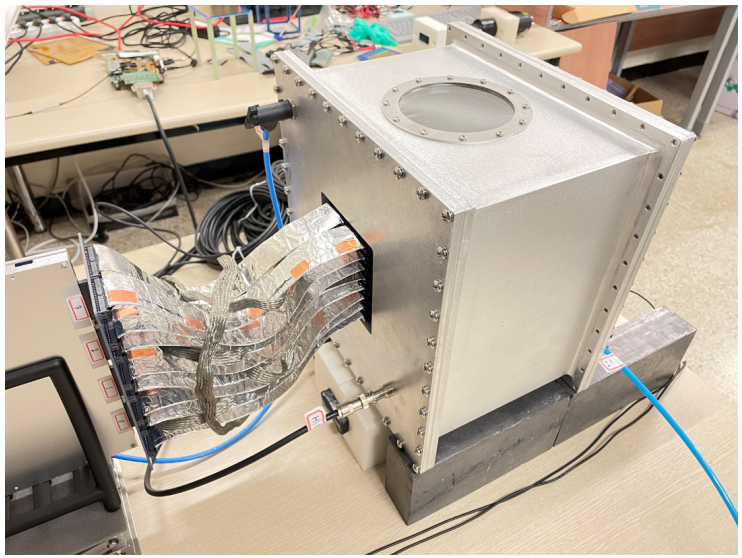
Sept. 25. 2024

About me

- A faculty at Sejong University in Seoul, Korea from 2018
- Working for nuclear collision experiments across wide energy scale
  - CMS : ~1 TeV
  - RHIC experiments : ~100 GeV
  - LAMPS @ RAON : ~0.01 GeV



CMS experiment



TPC made for alpha-cluster search in RIB experiments

SJU (Sejong University)

SJU campus in Seoul

Children's grand park (130 acres)

SJU (Sejong University)

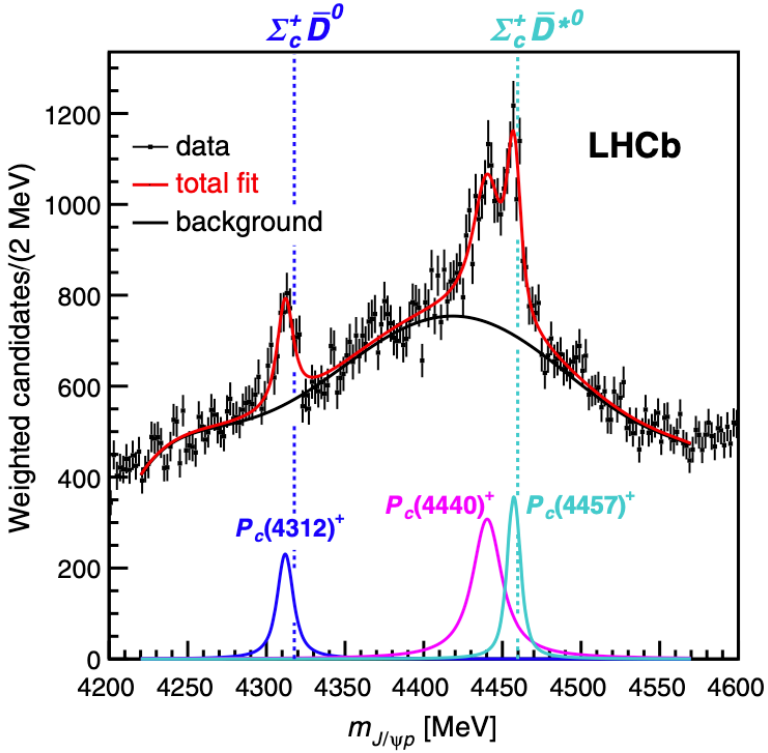
SJU (Sejong University)

SJU (Sejong University)

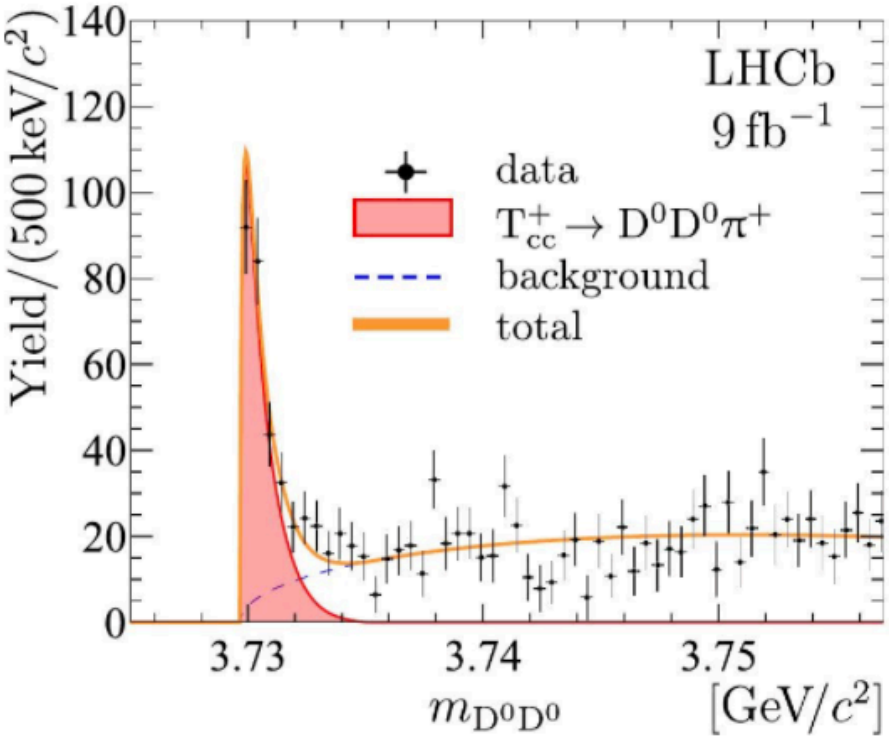
- Four faculties in HEP and NP
  - Me (nucl-ex), Saehanseul Oh (nucl-ex), Seyong Kim (hep-th), Hyunsoo Kim (hep-ex)

- Research invloed
  - CMS (quarkonia, jet, top)
  - ALICE (hard probes, ITS3)
  - STAR (jet)
  - ePIC (ZDC)
  - sPHENIX
  - Lattice gauge theory
  - Rare Isotope accelerator physics
  - Active target TPC

Exotic hadrons



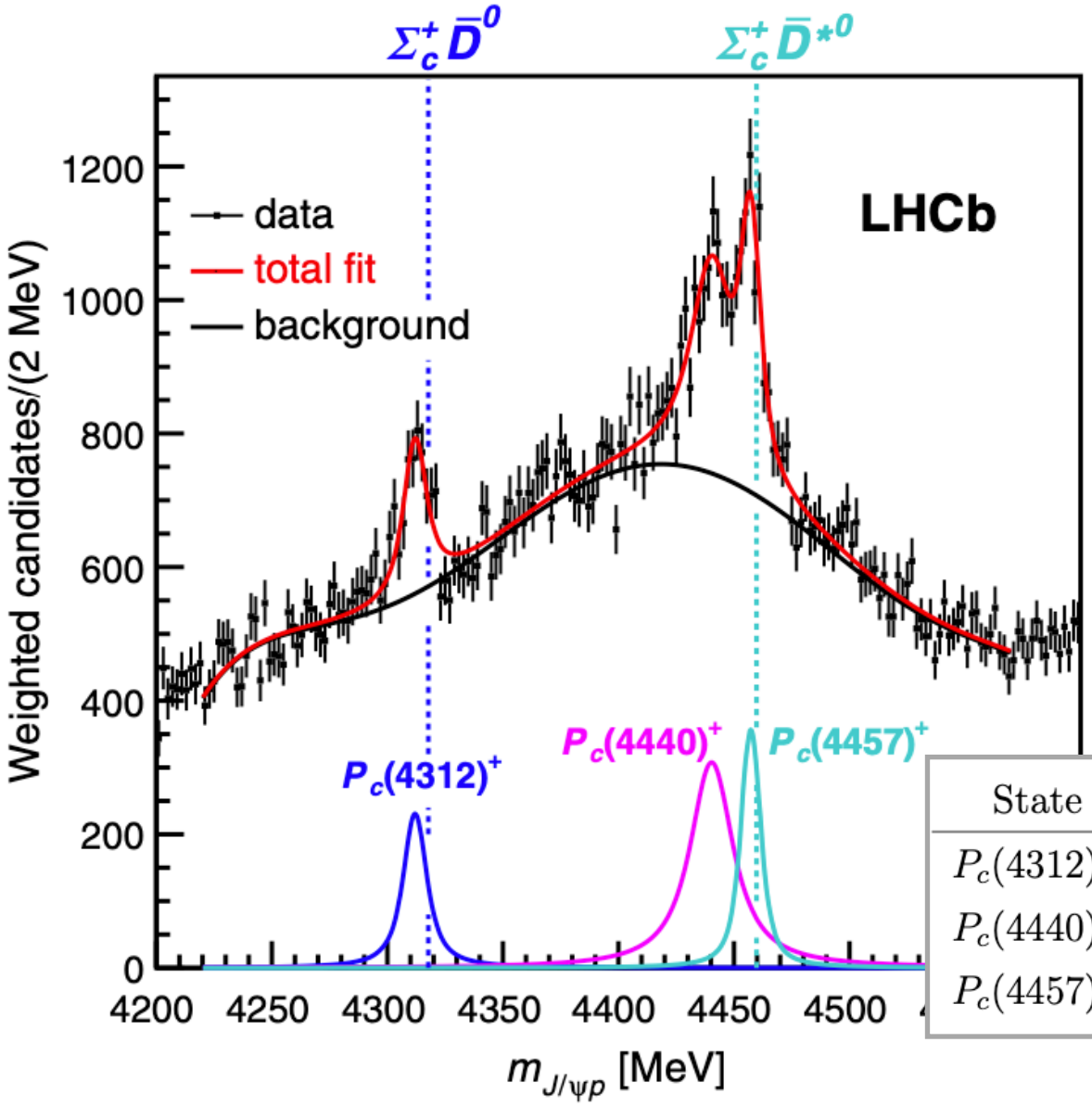
5-quark states, (c=0)



4-quark states, (c = 2)

- Around 2019, a series of very interesting results were released from LHC
  - X(3872) in PbPb at 5 TeV (CMS)
  - Discovery of penta-quark P_c and tetra-quark T_{cc} (LHCb)

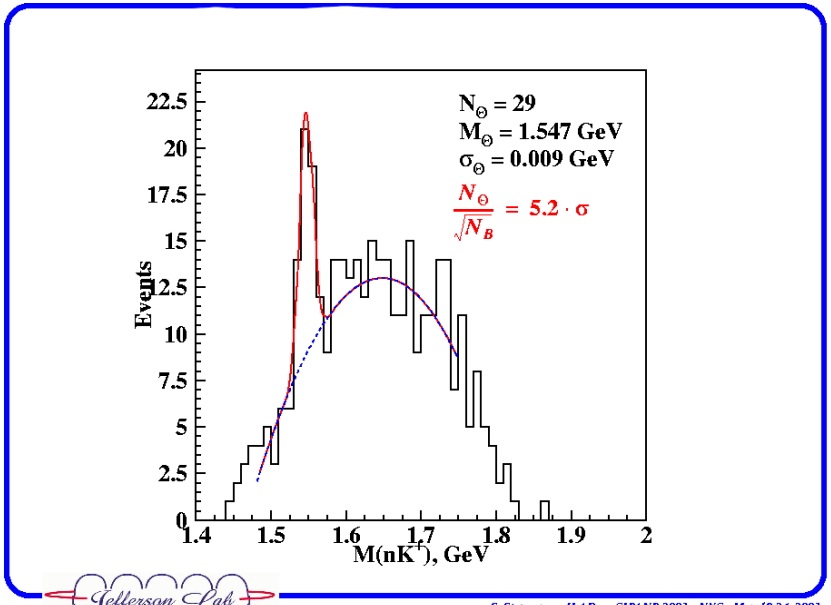
P_c brothers discovered by LHCb



- Decay width of P_c's

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

Bizzare history of pentaquark hunting



Nuclear Theory

arXiv:1012.3781 (nucl-th)

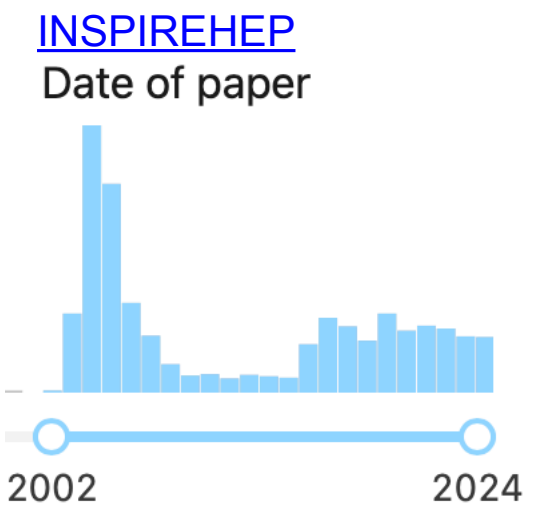
[Submitted on 16 Dec 2010]

Critical view of the claimed Θ^+ pentaquark

E. Oset, A. Martinez Torres

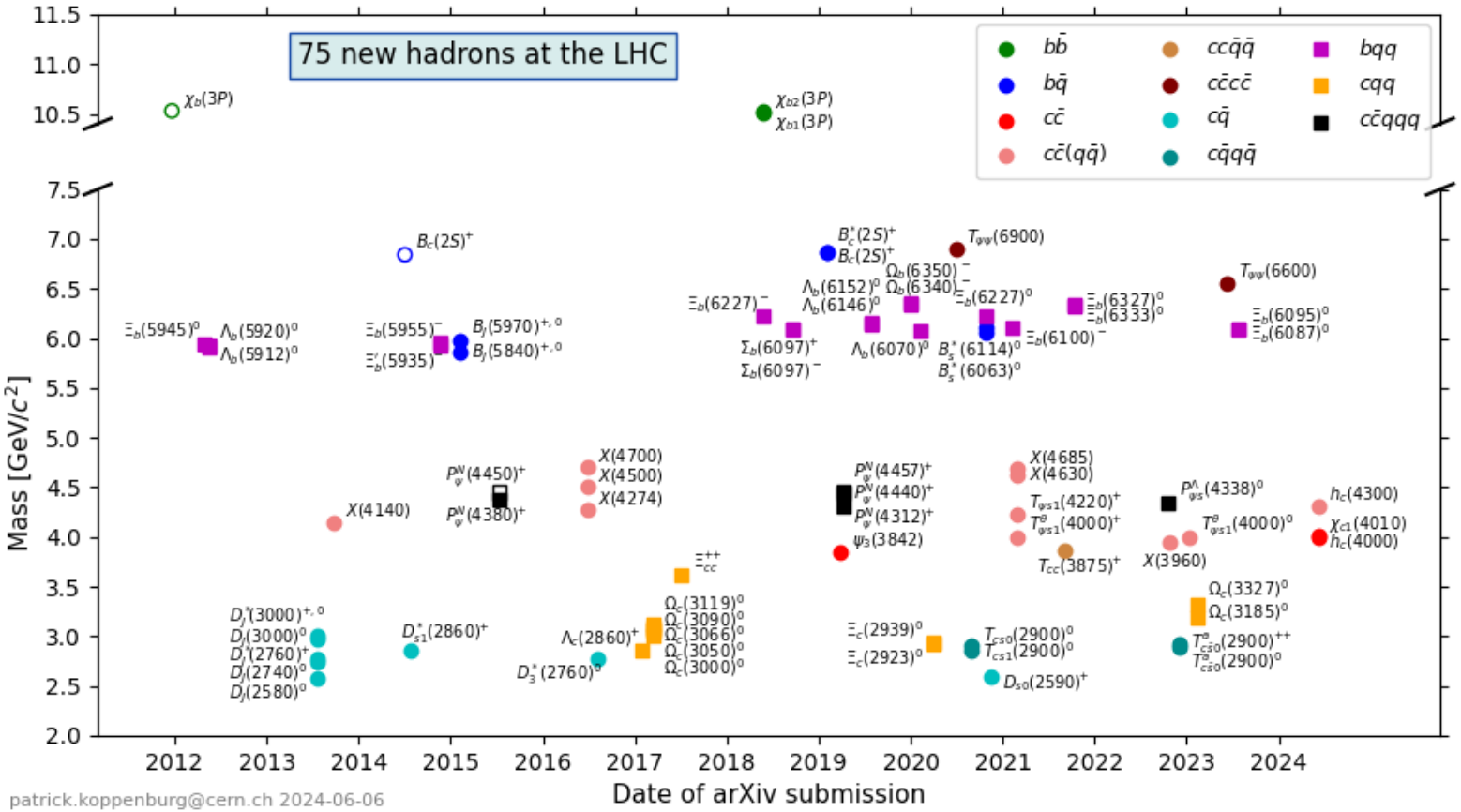
Download PDF

We use a theoretical model of the $\gamma d \to K^+K^- n p$ reaction adapted to the experiment done at LEPS where a peak was observed and associated to the $\Theta^+(1540)$ pentaquark. The study shows that the method used in the experiment to associate momenta to the undetected proton and neutron, together with the chosen cuts, necessarily creates an artificial broad peak in the assumed K^+n invariant mass in the region of the claimed $\Theta^+(1540)$. It is shown that the LEPS fit to the data, used to make the claim of the $\Theta^+(1540)$, grossly distorts the background. An alternative fit, assuming a background plus a fluctuation, returns a background practically equal to the theoretical one and a fluctuation identical to the one seen in the experimental K^-p spectrum of 2σ significance.

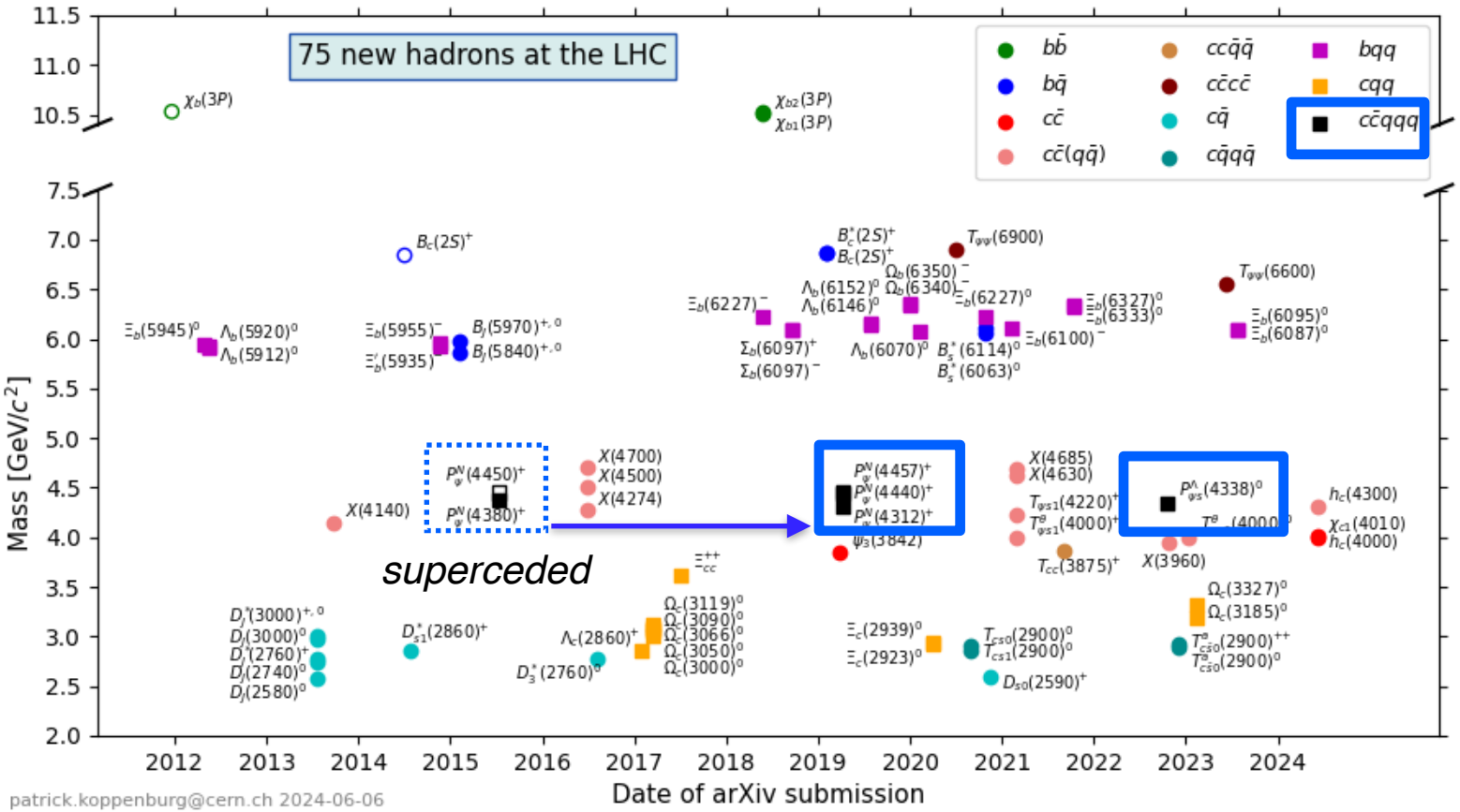


- 2003: A new state, aka Θ^+, is claimed to be a pentaquark ($uudd\bar{s}$) by LEPS
- Later ten experiments attempted cross-check without success
- The result in 2003 turned out to be flaw by wrong methodology
- No clear evidence of the existence of penta-quark state until LHCb's discovery in 2015

New exotic particles at LHCb

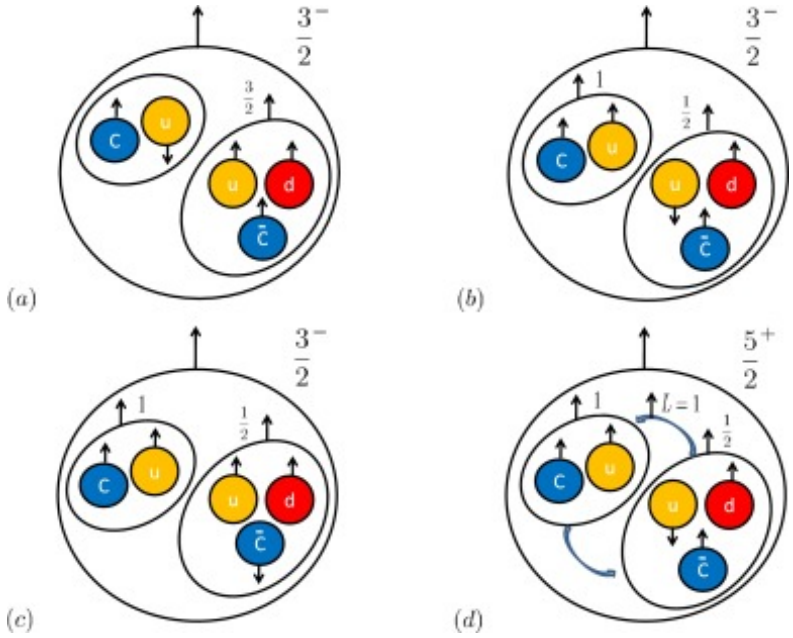


New exotic particles at LHCb



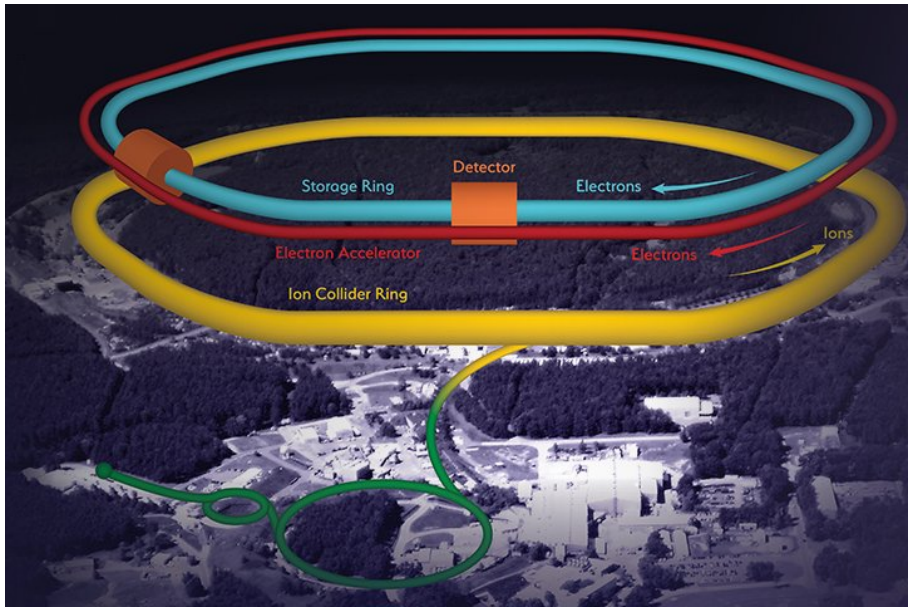
- $P_c\ (uudc\bar{c}) \rightarrow J/\psi + p$
- $P_{cs}\ (uusc\bar{c}) \rightarrow J/\psi + \Lambda$

Characterization of P_c



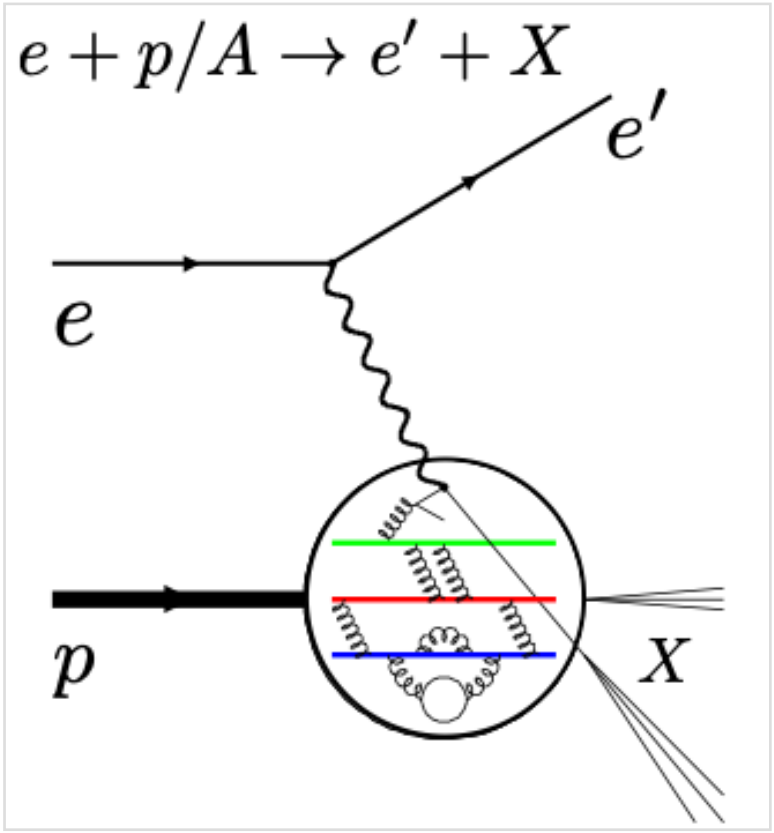
- Discovered, yet the internal structure and quantum numbers remains in question
- In particular, the spin and parity can be determined using spin-polarized collisions
- What **the best machine** to shed light on it? We all know the answer!

Electron Ion Collider



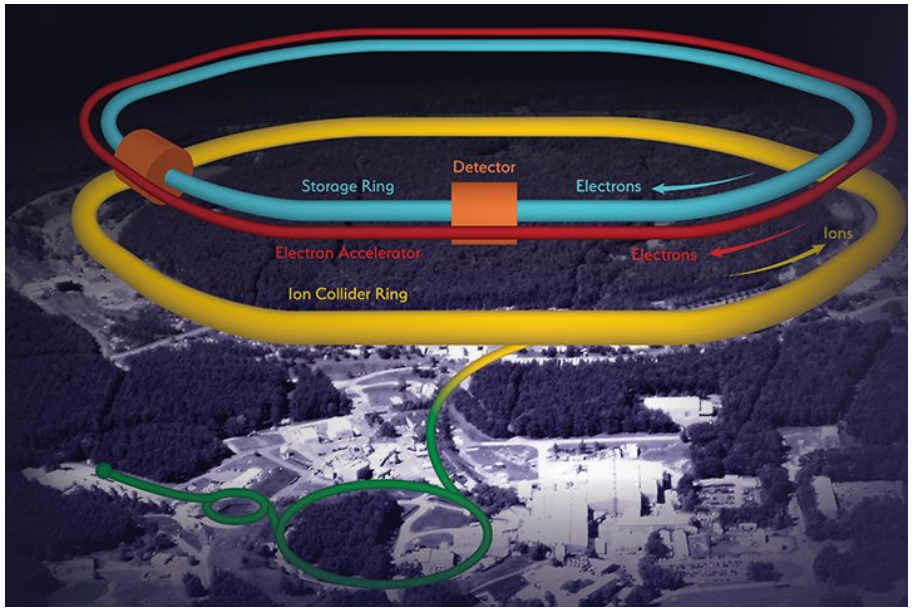
Science mission of EIC[1]

- Precision 3D imaging of protons and nuclei
- Solving the proton spin puzzle
- Quark and gluon confinement
- PDF modification in nuclei



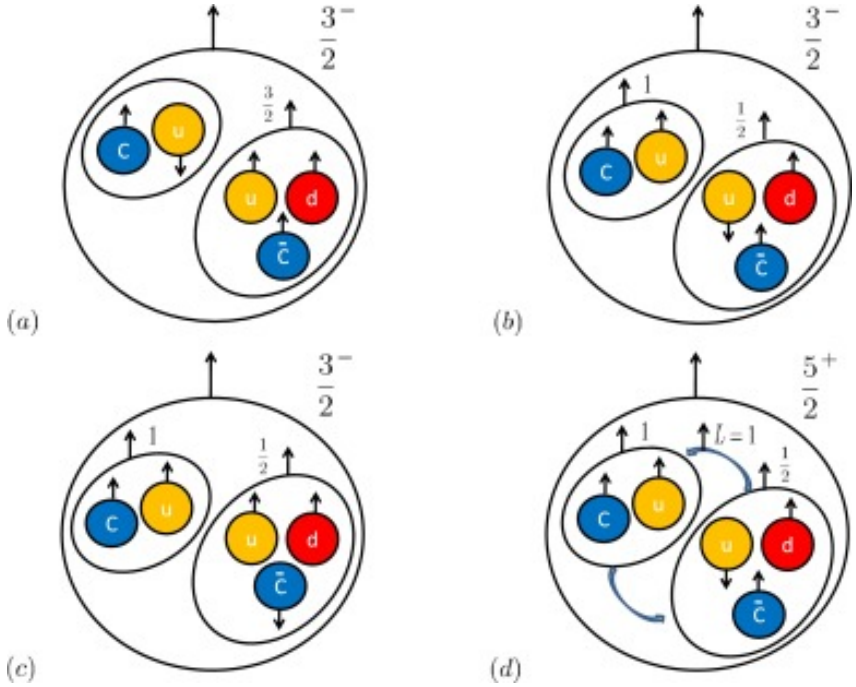
[1] *https://www.bnl.gov/eic/science.php*

Electron Ion Collider



Science mission of EIC[1]

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



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

Papers on P_c and P_s

High Energy Physics - Phenomenology

[Submitted on 23 Feb 2022]

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

In Woo Park, Su Houng Lee, Sungtae Cho, Yongsun Kim

We study the cross sections for the electro-production of $P_c(4312)$ particle, a recently discovered pentaquark state, in electron-proton collisions assuming possible quantum numbers to be $J^P = \frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}$. $\sqrt{s}$ is set to the energy of the future Electron Ion Collider at Brookhaven National Laboratory, in order to asses the possibility of the measurement in this facility. One can discriminate the spin of $P_c(4312)$ by comparing the pseudorapidity distribution in two different polarization configurations for proton and electron beams. Furthermore, the parity of $P_c(4312)$ can be discerned by analyzing the decay angle in the $P_c \to p + J/\psi$ channel. As the multiplicity of P_c production in our calculation is large, the EIC can be considered as a future facility for precision measurement of heavy pentaquarks.

High Energy Physics - Phenomenology

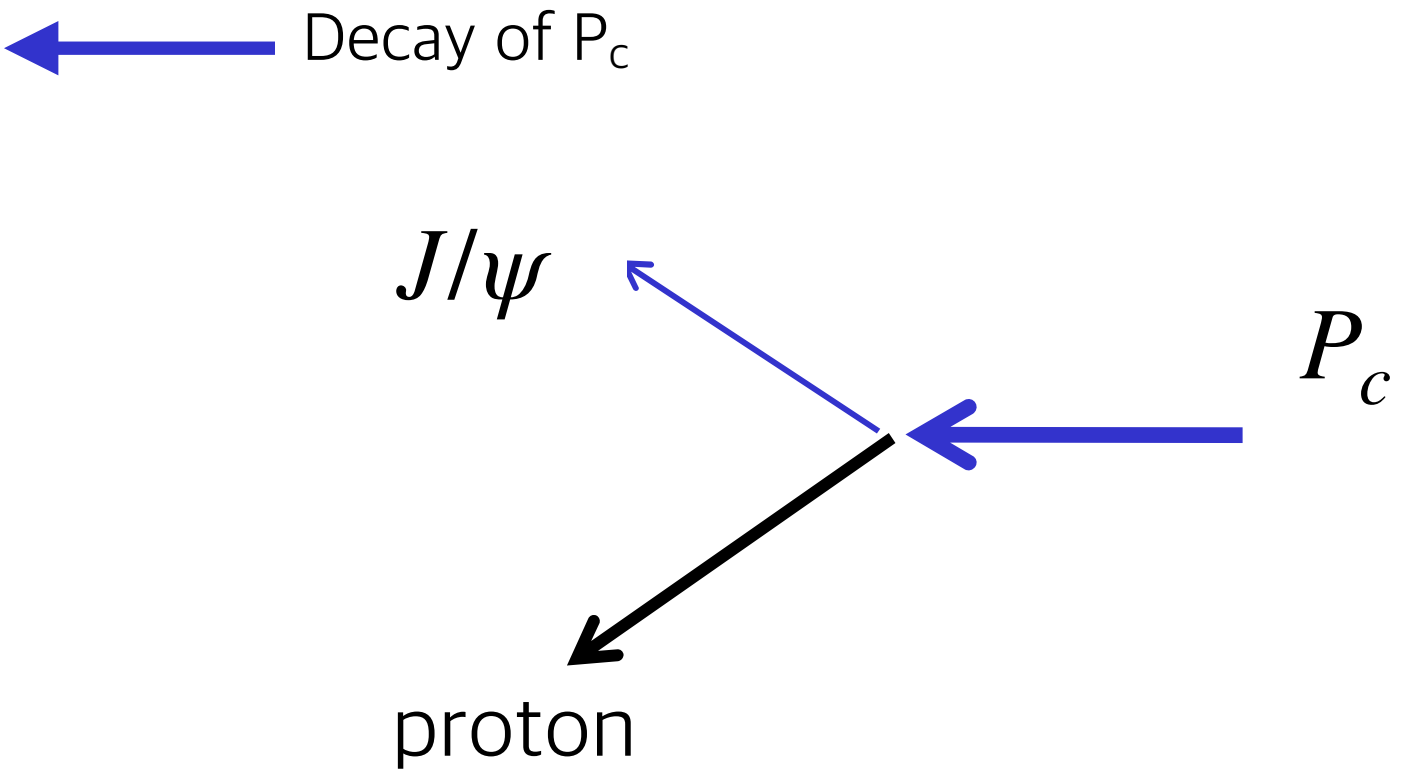
[Submitted on 12 Feb 2024]

Study on the ϕ-meson photoproduction off the proton target with the pentaquark-like $K^*\Sigma$ bound state P_s

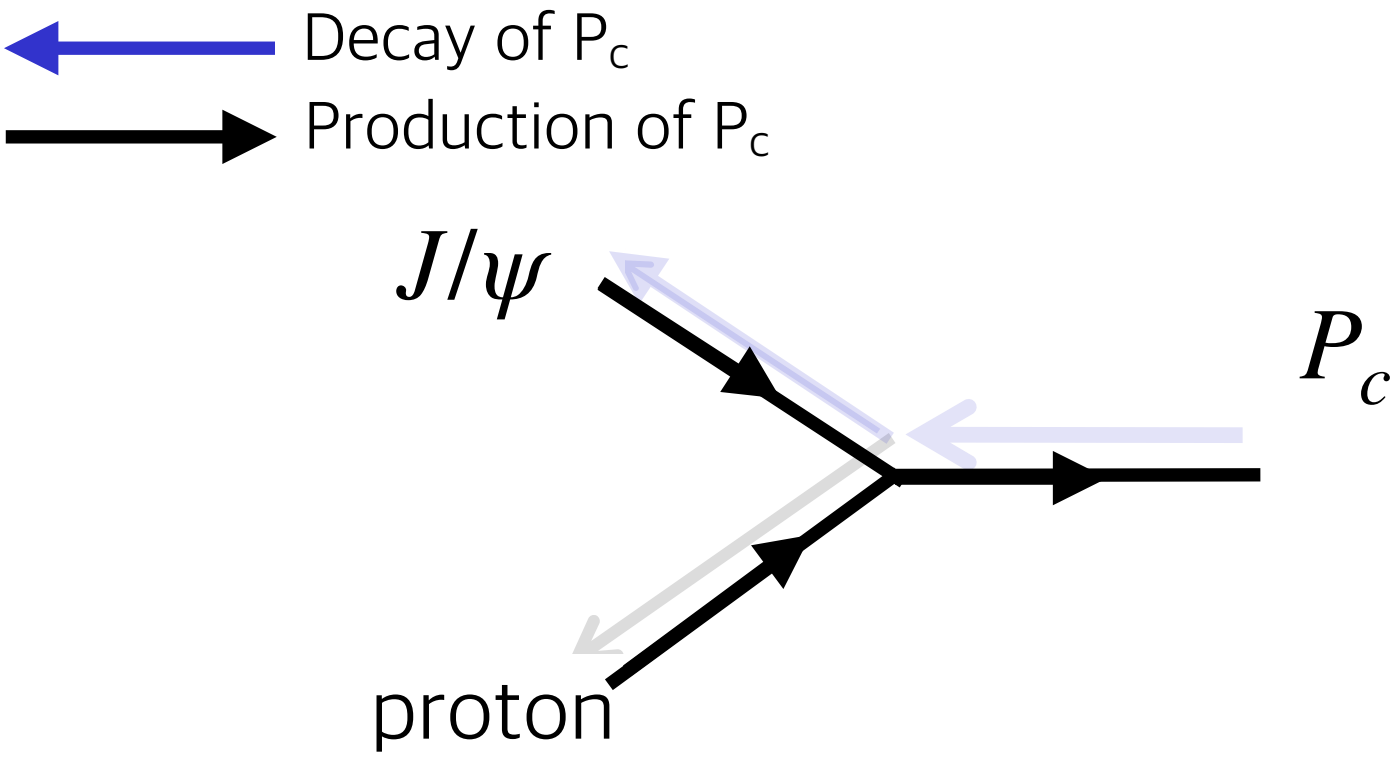
Sang in Shim, Yongsun Kim, Seung-il Nam

We utilize the effective Lagrangian method within the tree-level Born approximation to explore ϕ-meson photoproduction, i.e., $\gamma p \to \phi p$. Our analysis encompasses contributions from various sources, including the Pomeron, f_1-Regge, pseudoscalar particles (π, η), scalar particles (a_0, f_0), protons, and three-nucleon resonance states. In addition, we consider a possible pentaquark-like $K^*\Sigma$-bound state P_s. The findings indicate that, apart from the region near the threshold, contributions other than the Pomeron generally have a limited impact on the total cross section. However, at specific angles, alternative contributions become crucial, particularly at smaller values of $\cos\theta$. The incorporation of P_s and other nucleon resonances proves

Decay channel of P_c in LHCb

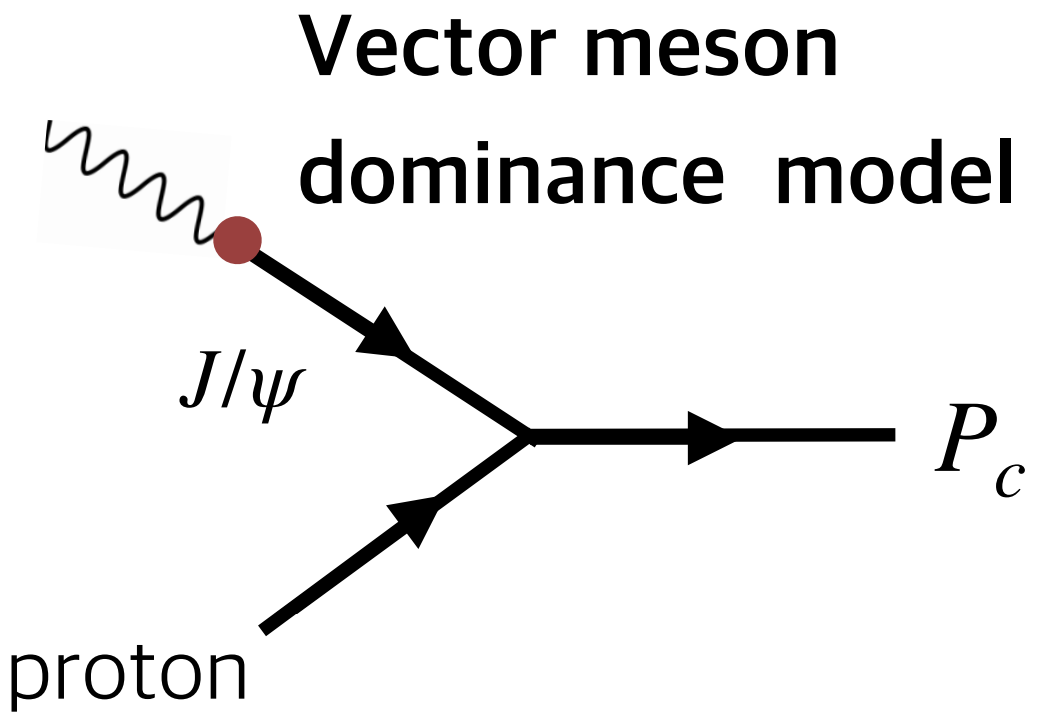


Production of P_c



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

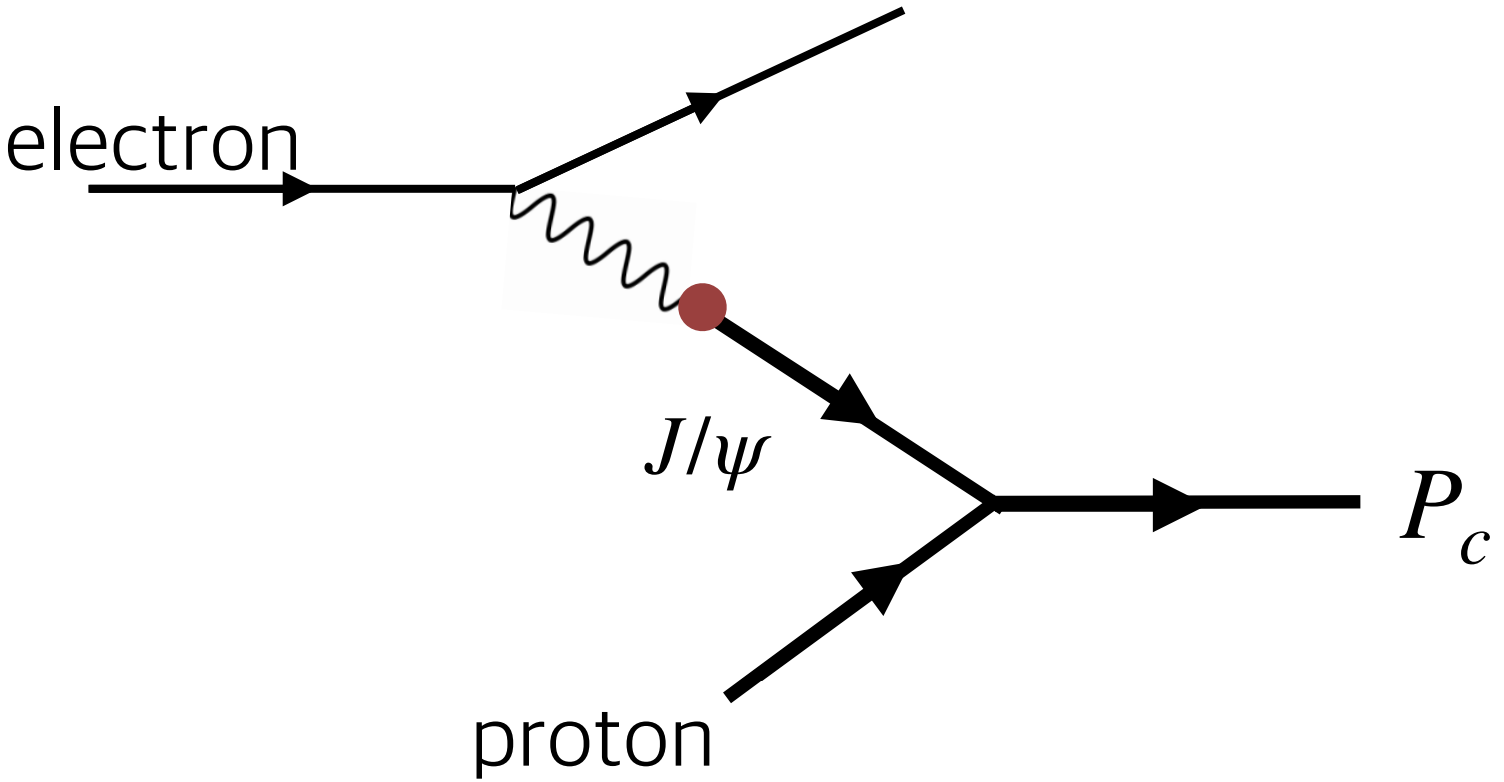
Photo-production of P_c



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

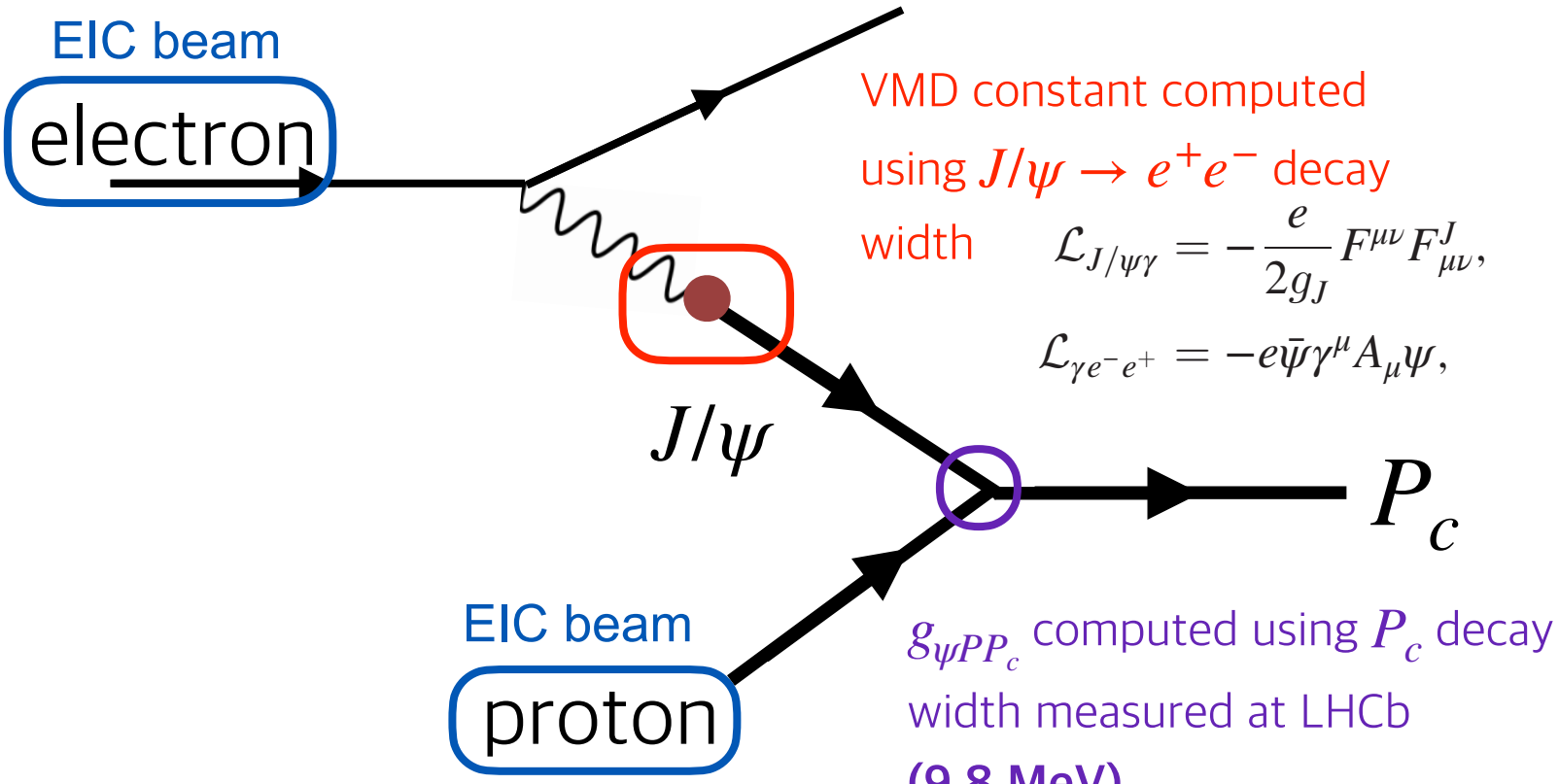
Electro-production of P_c



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

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

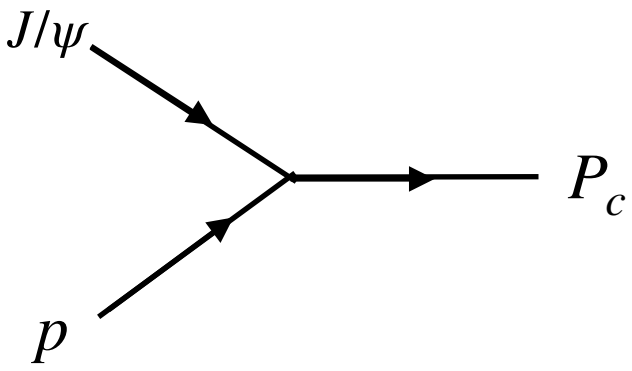
Computation of P_c cross section at EIC



[1] *Klingl et al, Z.Phys. A356 (1996) 193-206*

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

Formalism



Interaction strength J/ψ, proton and P_c is computed from the decay width measured by LHCb

- Lagrangian (tensor potential & R-S eq.)

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

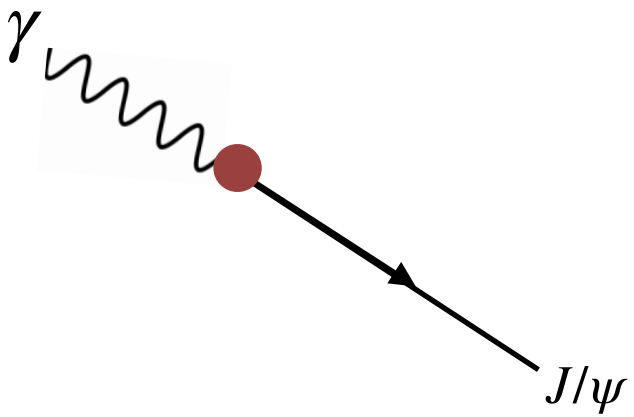
- Fixing interaction strength from Γ

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

- 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

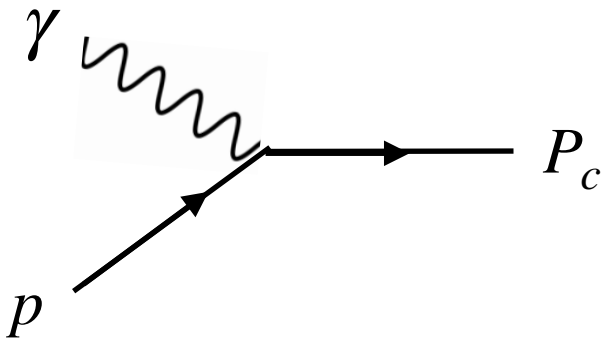


- Vector meson dominance model

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

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

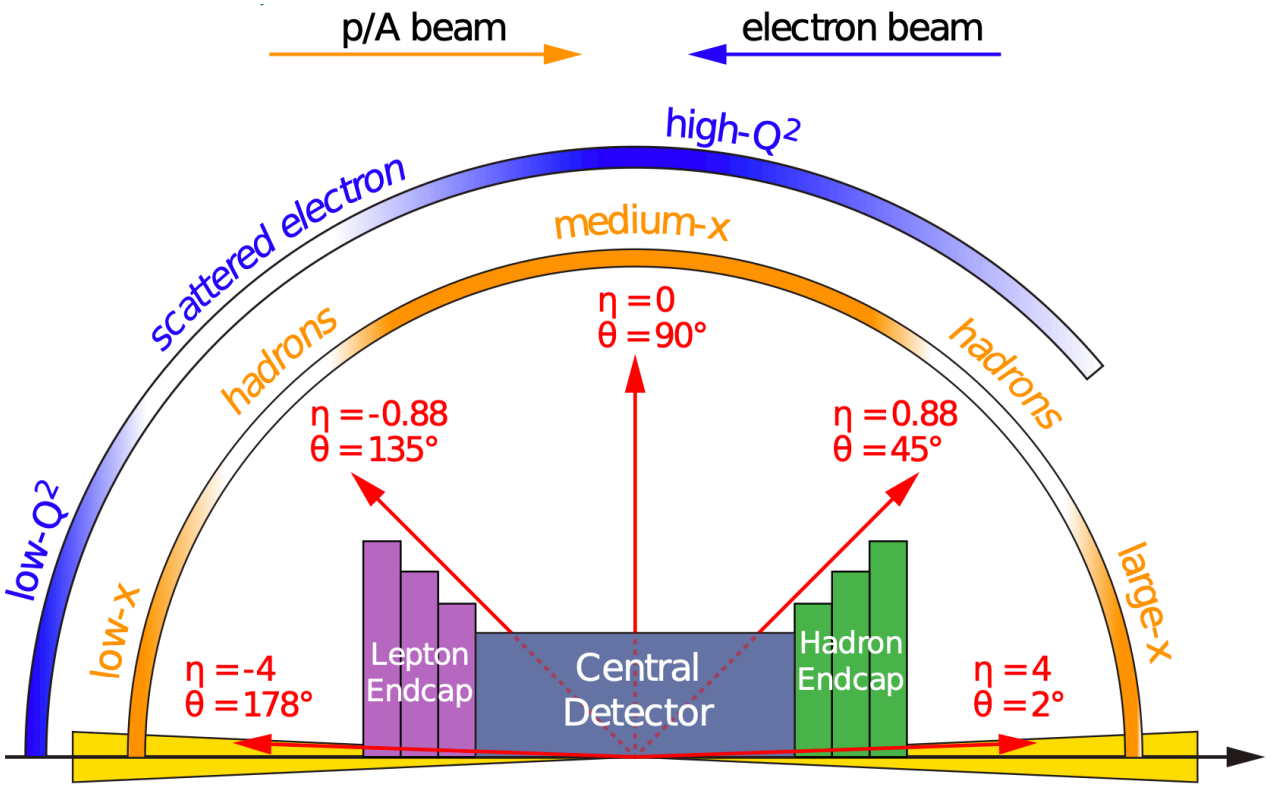
- Coupling constant g_J is computed from $J/\psi \rightarrow e^+e^-$ decay width
  - Γ = 95.9 keV x 5.97%



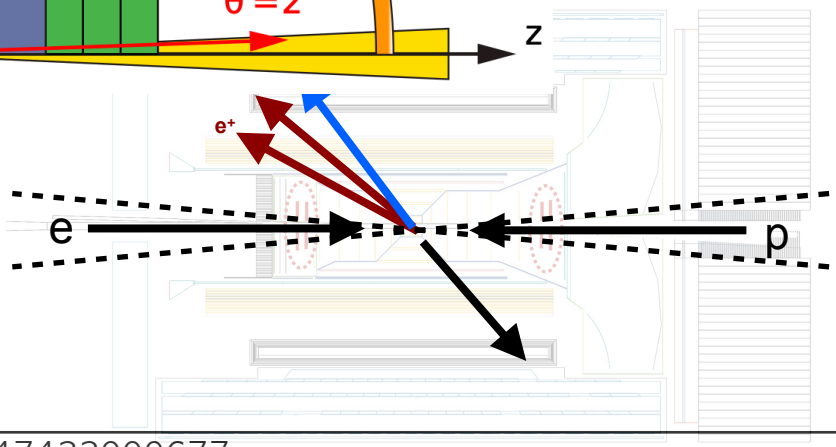
- Photo-production strength

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

ePIC detector

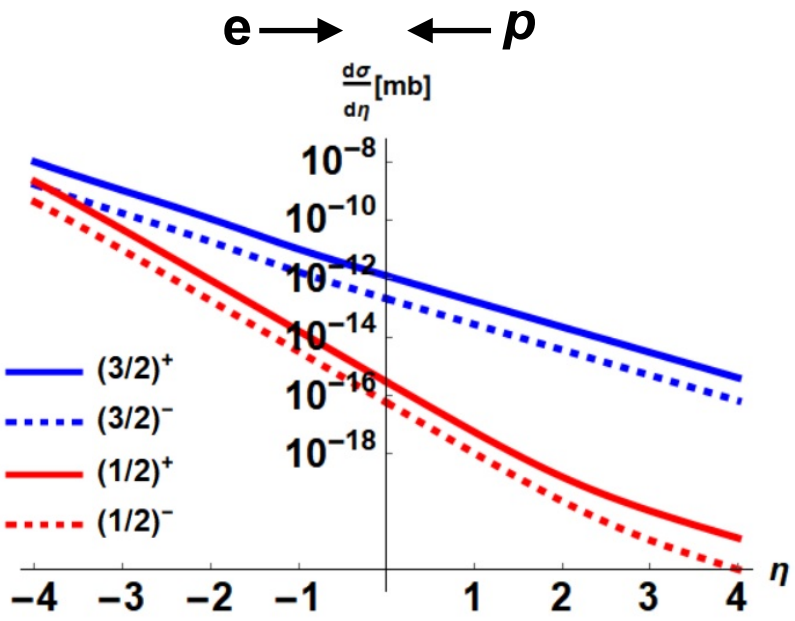


Typical coverage for tracks: $|\eta| < 4$



〔1〕https://www.sciencedirect.com/science/article/pii/S0375947422000677

$P_c(4312)$ yields at EIC



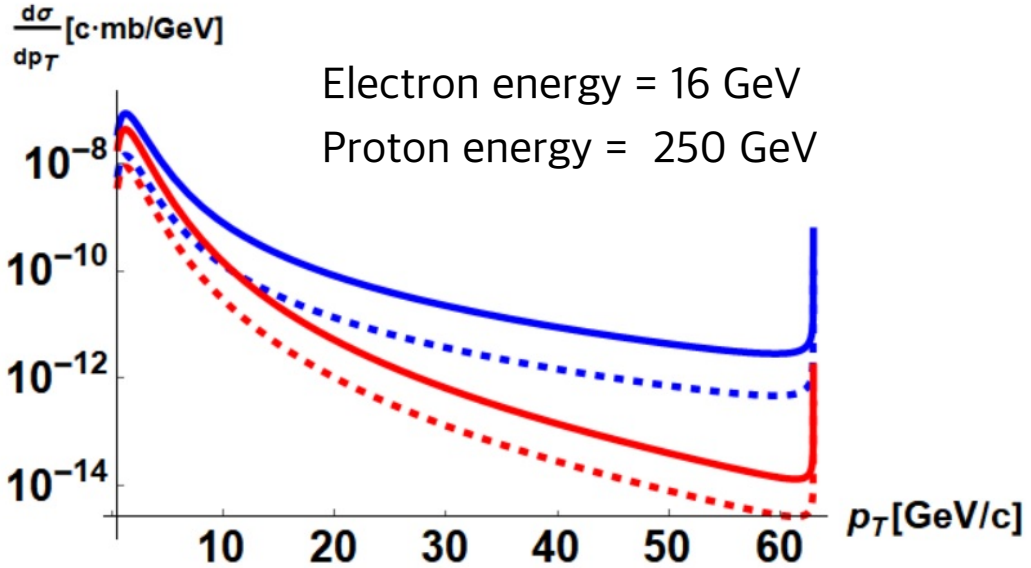


TABLE II. Expected number of $P_c(4312)$ produced at the EIC with 10 fb^{-1}.

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

- Thousands of P_c can be produced depending on its quantum numbers per 10 fb^{-1} (~1 month at designed lumi.)

Search in GlueX

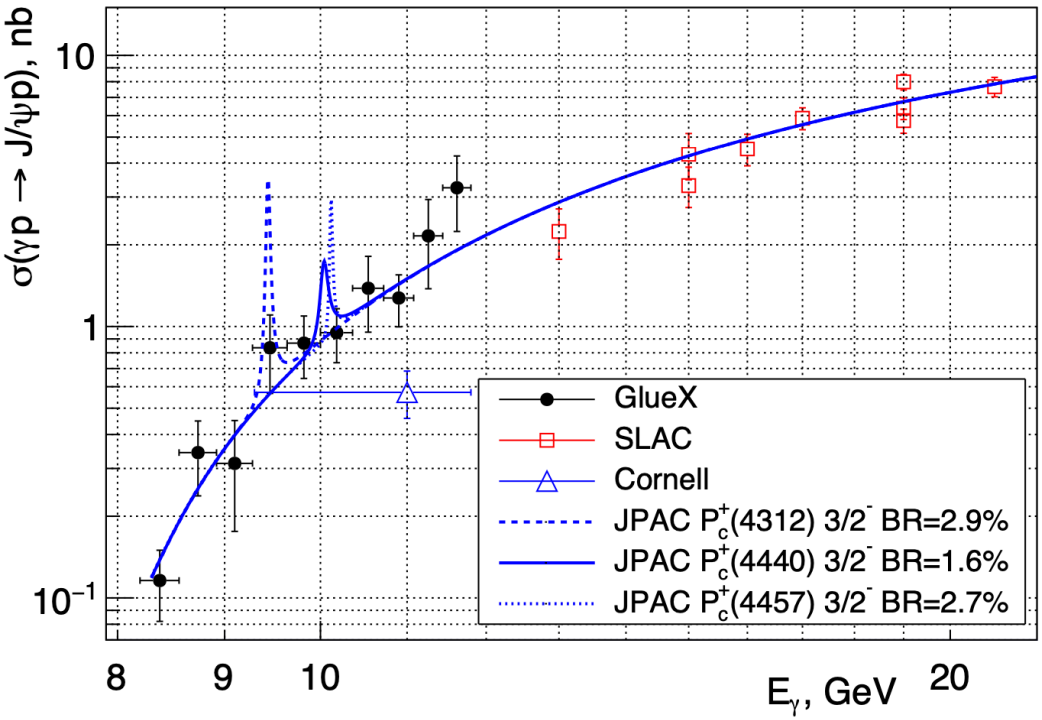
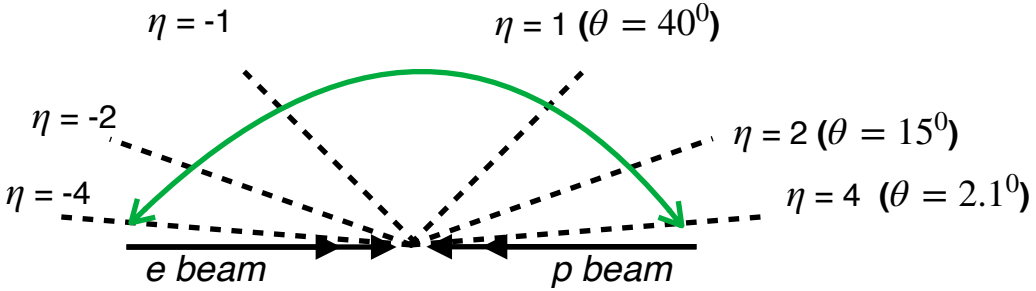


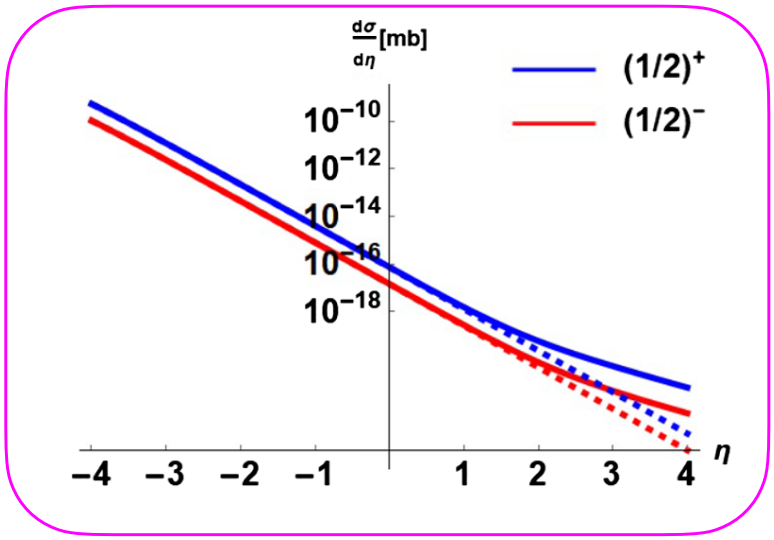
FIG. 4: GlueX results for the J/ψ total cross-section vs beam energy, Cornell [15], and SLAC [16] data compared to the JPAC model [6] corresponding to $\mathcal{B}(P_c^+(4312) \to J/\psi p) = 2.9\%$, $\mathcal{B}(P_c^+(4440) \to J/\psi p) = 1.6\%$, and $\mathcal{B}(P_c^+(4457) \to J/\psi p) = 2.7\%$, for the $J^P = 3/2^-$ case as discussed in the paper.

- EIC is better for its higher luminosity
- ePIC is capable of full reconstruction of $M_{inv}(e^- + e^+ + p)$

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

ePIC coverage

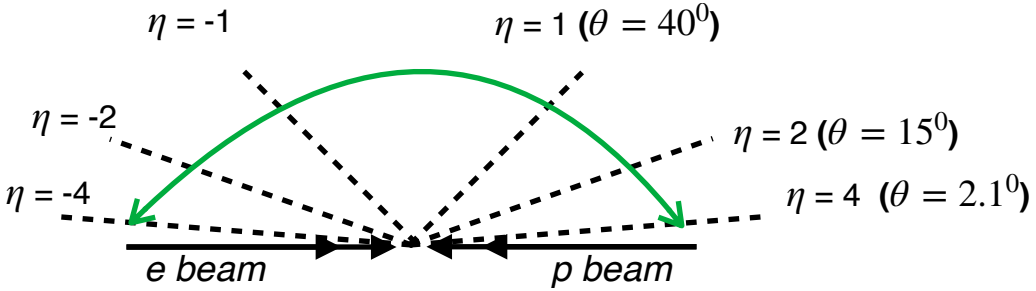


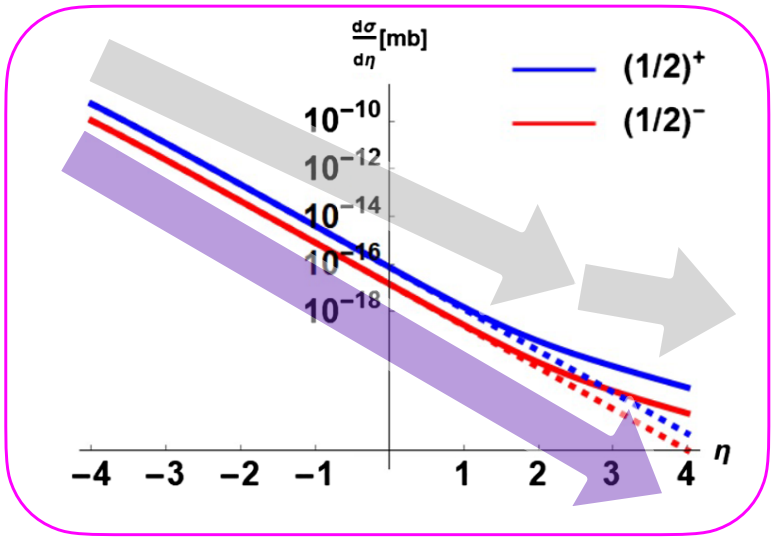


Spin 1/2 scenario

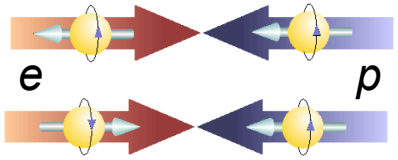
$P_c(4312)$ yields in polarized e+p

ePIC coverage





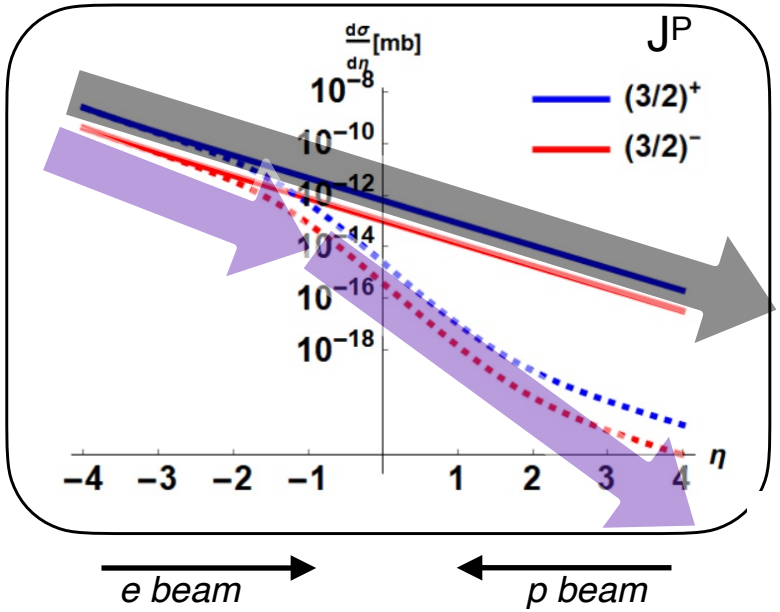
Spin 1/2 scenario



Parallel polarization

Anti-parallel

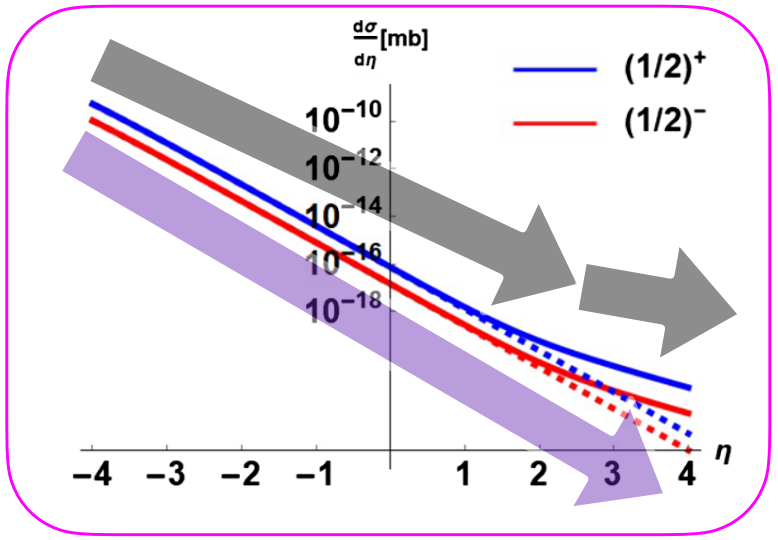
$P_c(4312)$ yields in polarized e+p



Spin 3/2 case

Parallel polarization

Anti-parallel polarization



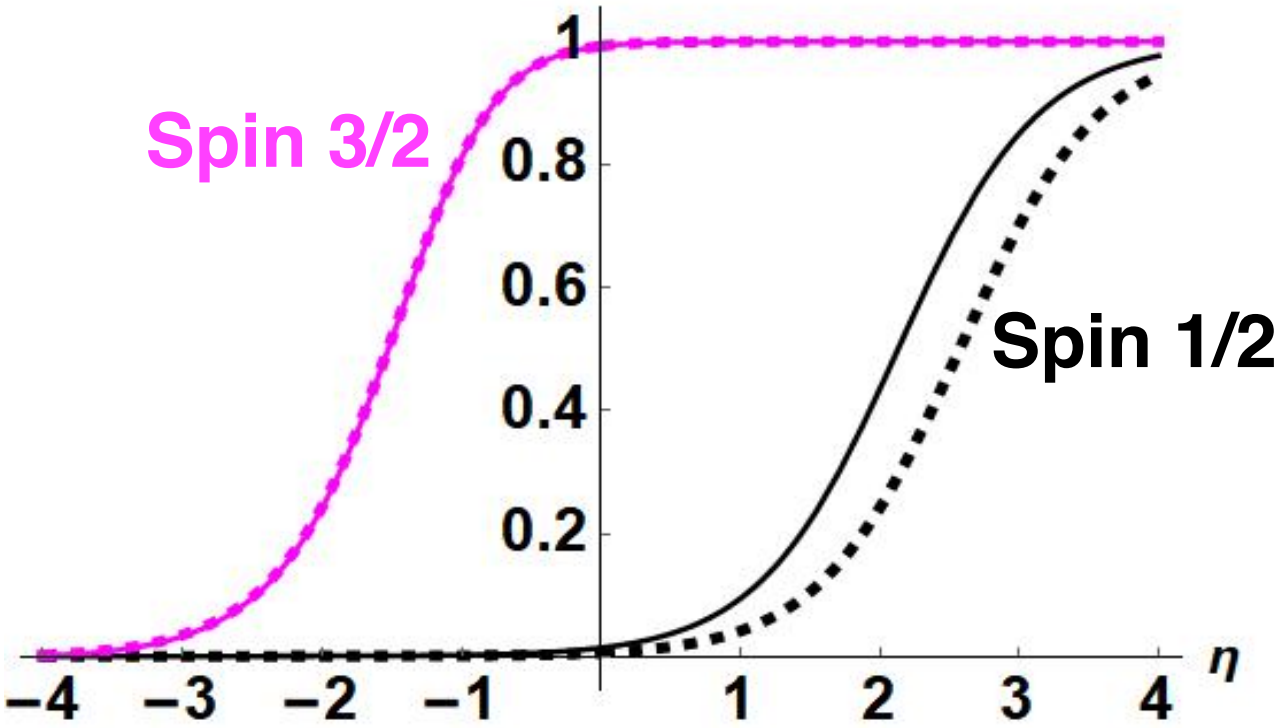
Spin 1/2 case

Parallel polarization

Anti-parallel polarization

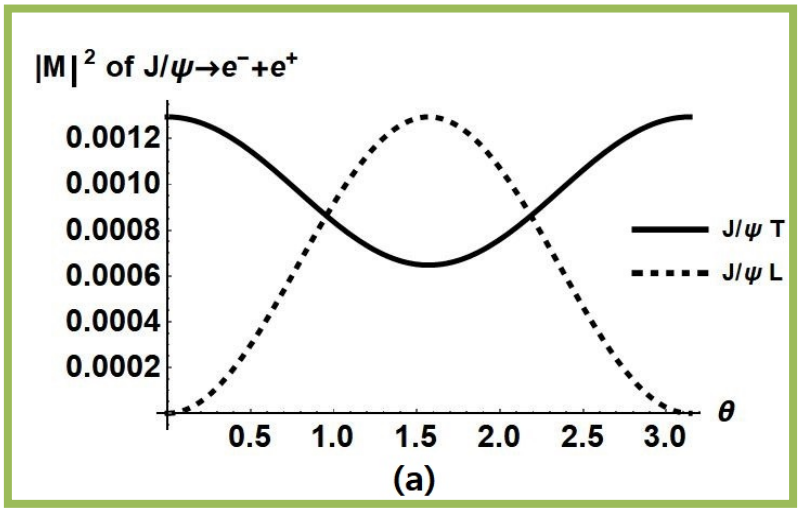
$P_c(4312)$ yields in polarized e+p

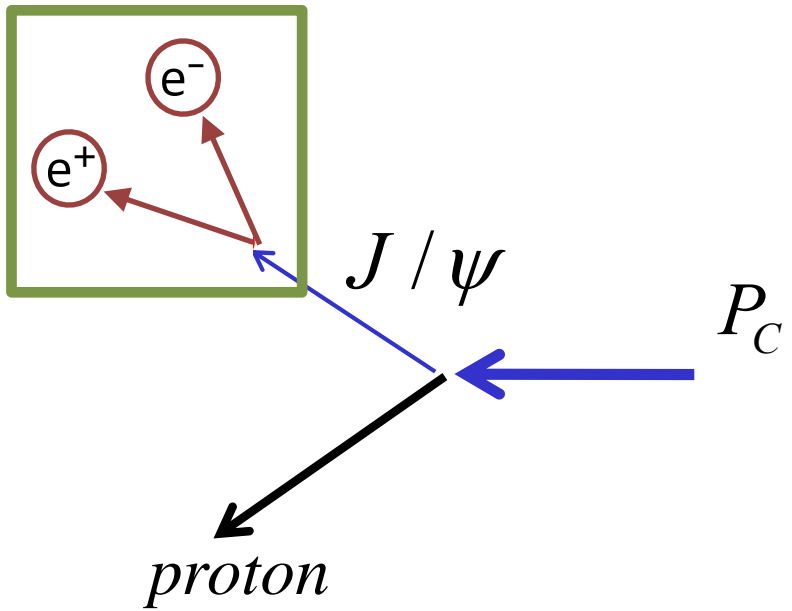
$$BSA\ (\eta) = \frac{d\sigma/d\eta\ [RL] - d\sigma/d\eta\ (RR)}{d\sigma/d\eta\ [RL] + d\sigma/d\eta\ [RR]}$$



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

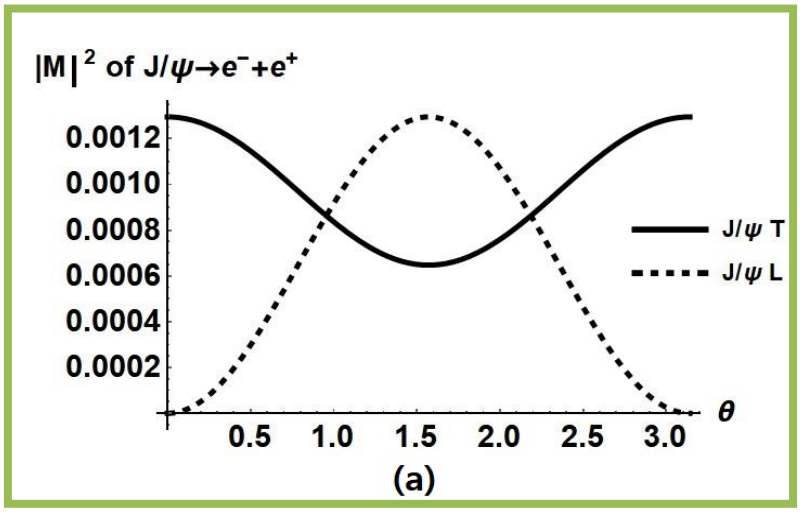
Determination of parity at EIC

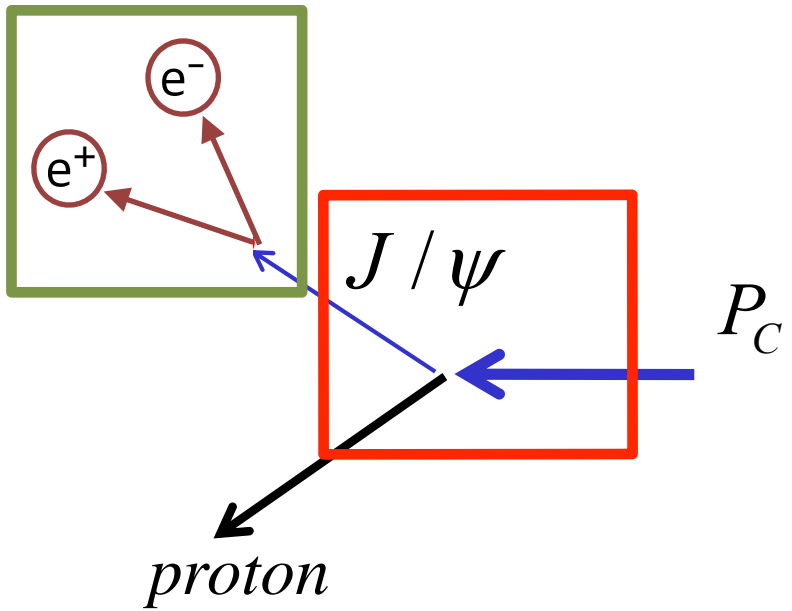




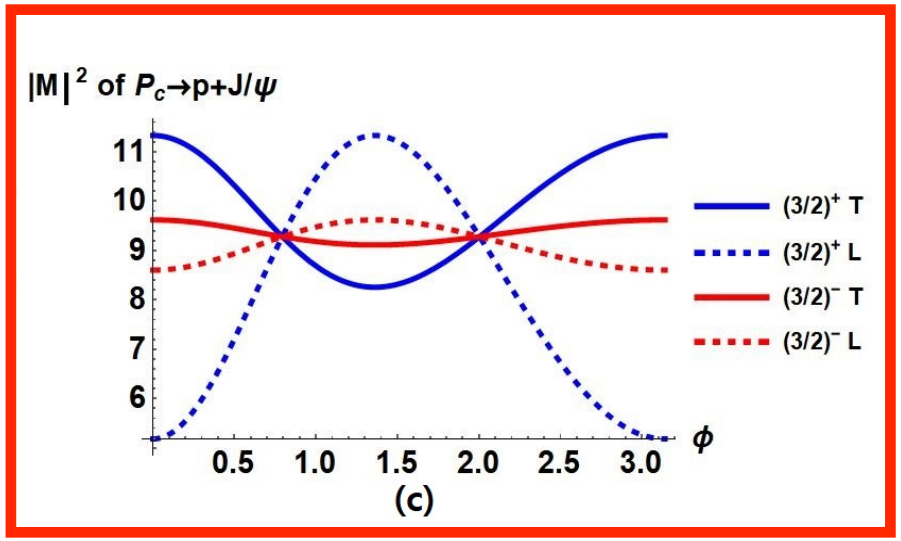
- J/ψ has spin-1 and its polarity can be measured from the decay kinematics

Determination of parity at EIC

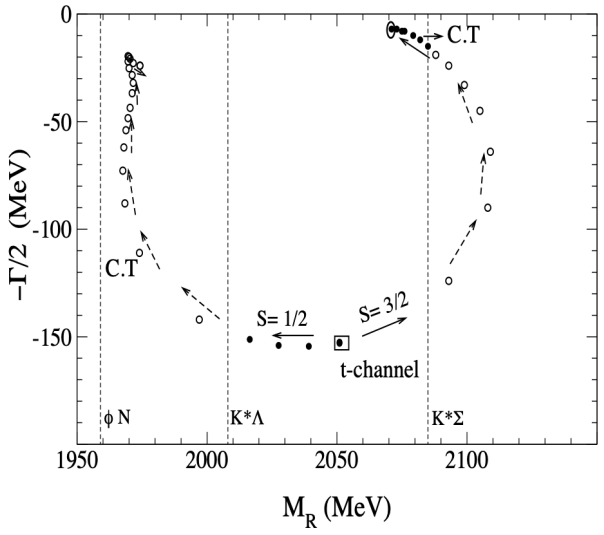


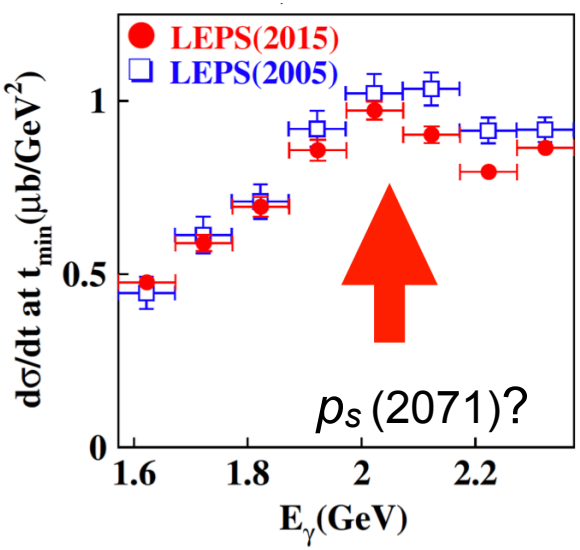


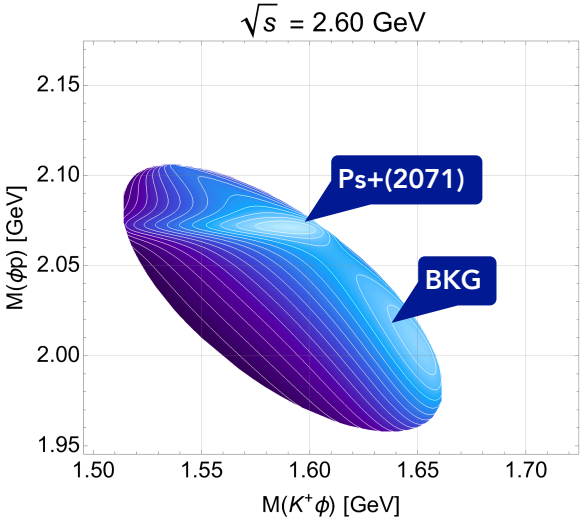
- J/ψ has spin-1 and its polarity can be measured from the decay kinematics
- Parity can be experimentally determined by polarized e+p collision at EIC



Photoproduction of P_s





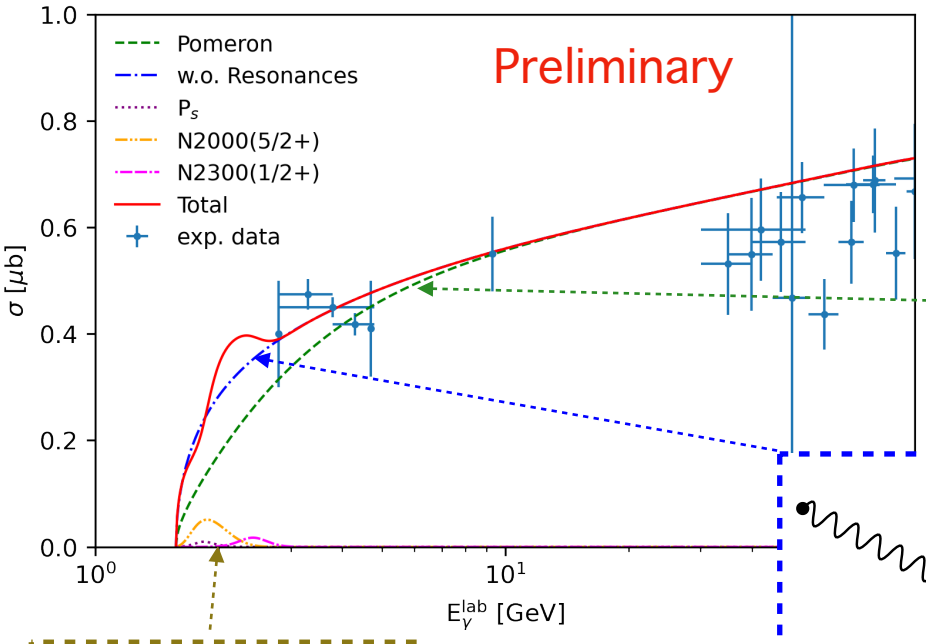


- Calculation predicted a resonance of P_s ($uuds\bar{s}$) near $\Sigma + K^*$ [1]
- SI Nam showed that if $p_s(2071)$ ever exists, the resonance would appear in the $K^+p \to K^+\phi p$ Dalitz plot [1]
- Considering VMD model, the same phenomenon can happen in the $\gamma + p \to (p_s \to)\,\phi + p$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

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

Cross section of ϕ photo-production

Total cross cross section



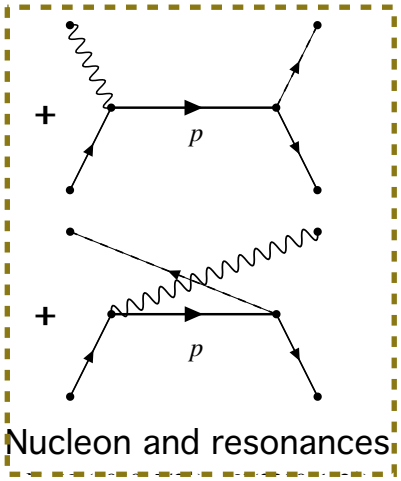
Experimental data points

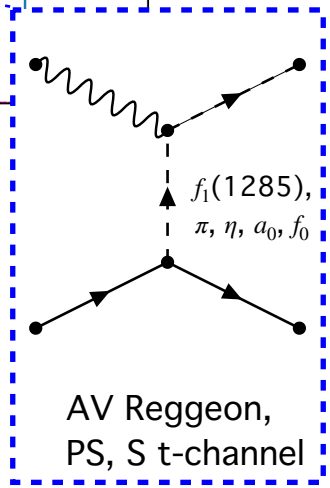
J. Ballam et al. PRD 7, 3150 (1973)

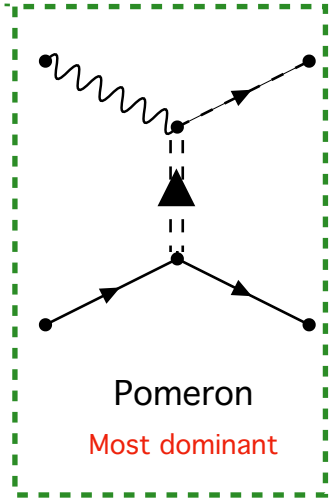
D. P. Barber et al., Z. Phys. C 12, 1 (1982)

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

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





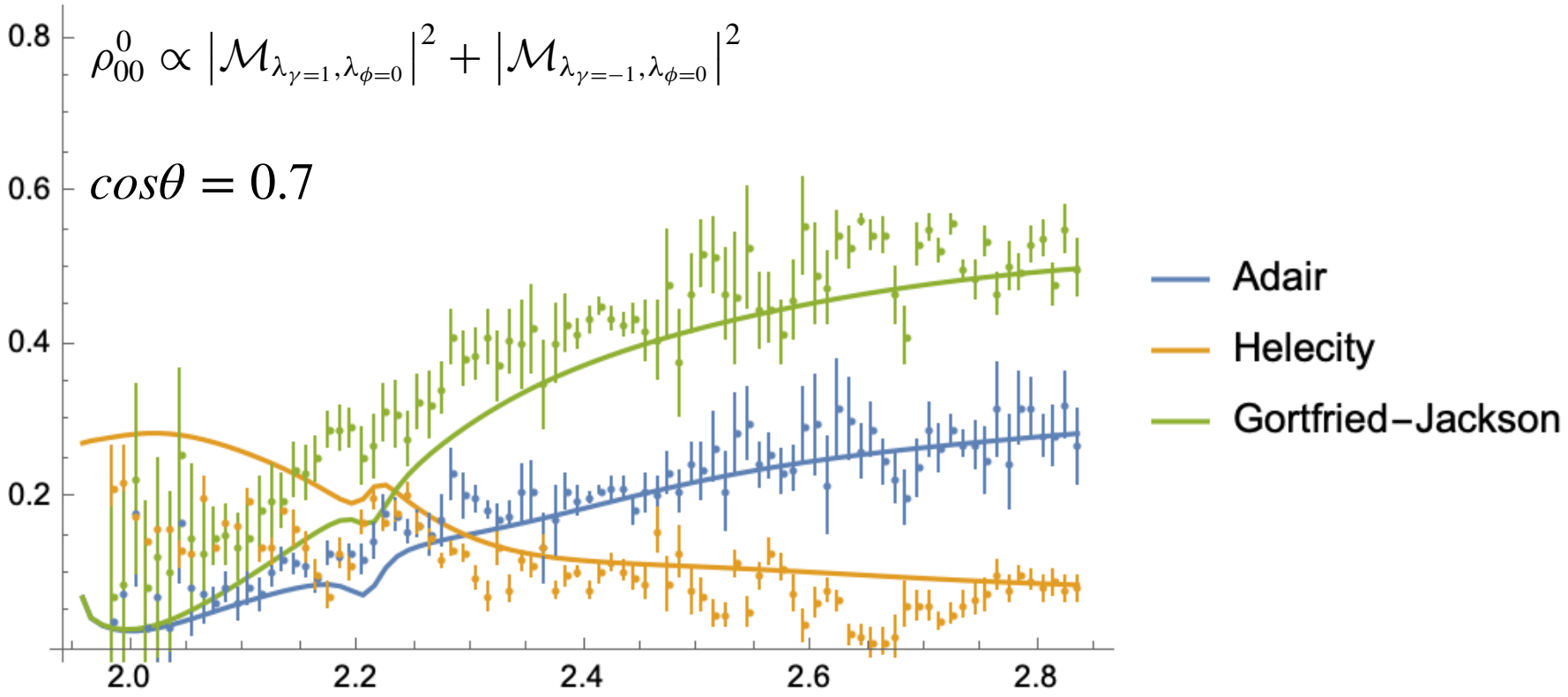


[1] *A. I. Titov et al. PRC58, 2429(1998); 67, 065205(2003)*

[2] *S. Kim, SiNam PRC100.065208(2019); 101.065201(2020)*

〔1〕arxiv:2402.07392

Spin density matrix component



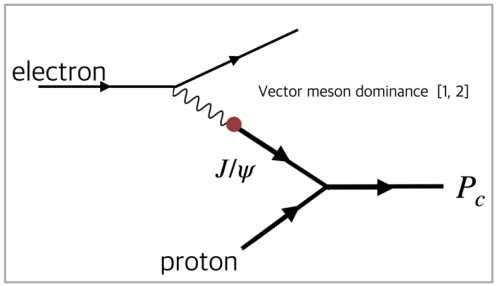
- ρ^0_{00} reflects the single helicity-flip transition between the incoming photon and the outgoing ϕ meson [1]
- WIP to find visible signals expected using polarized *ep* at EIC

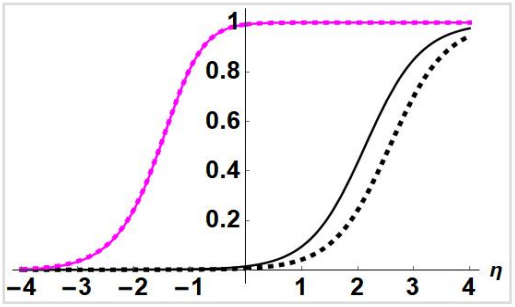
〔1〕 arxiv:2402.07392

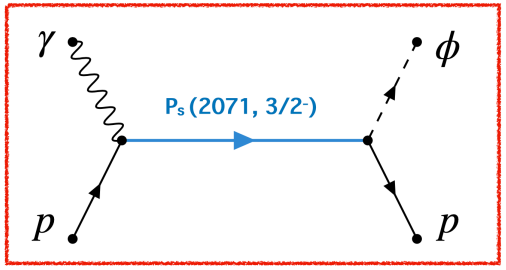
Summary

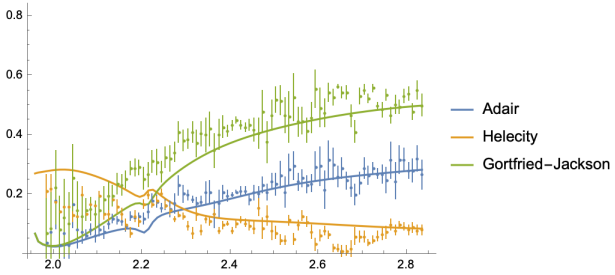
Science mission of EIC[1]

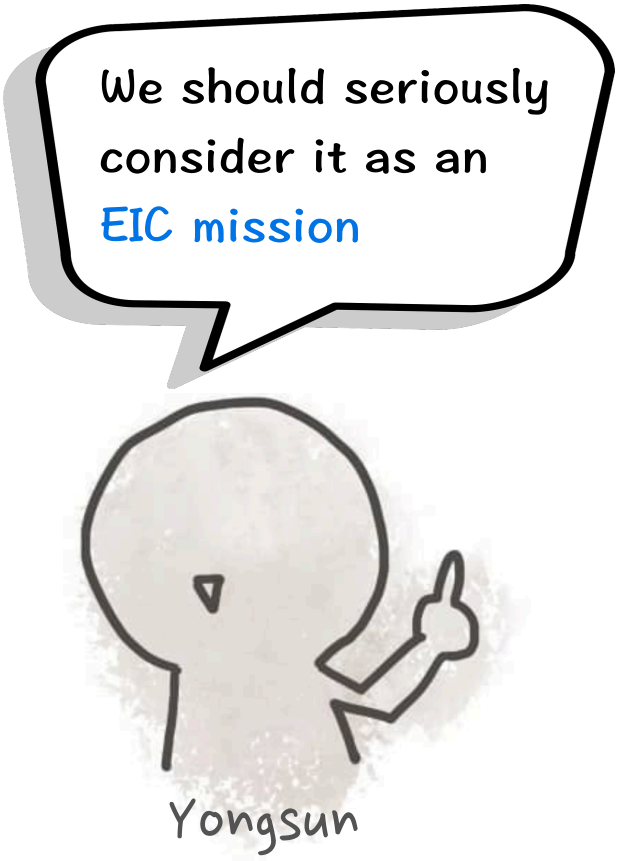
- Precision 3D imaging of protons and nuclei
- Solving the proton spin puzzle
- Search for saturation
- Quark and gluon confinement
- Quarks and gluons in nuclei
- **Discovery and characterization of exotic hadrons?**











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