Pc(4312) in ePIC framework

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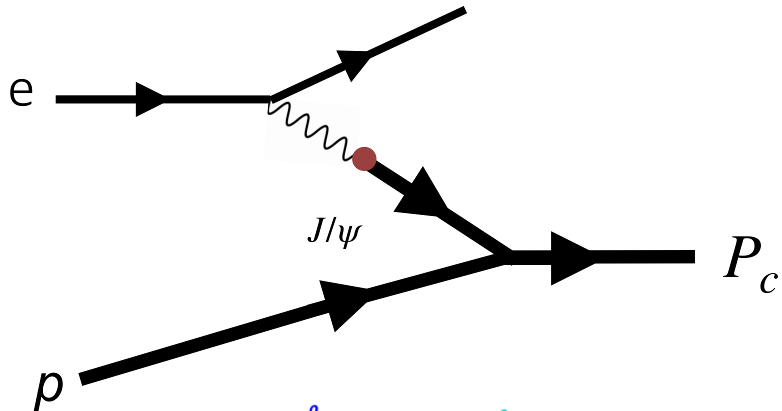
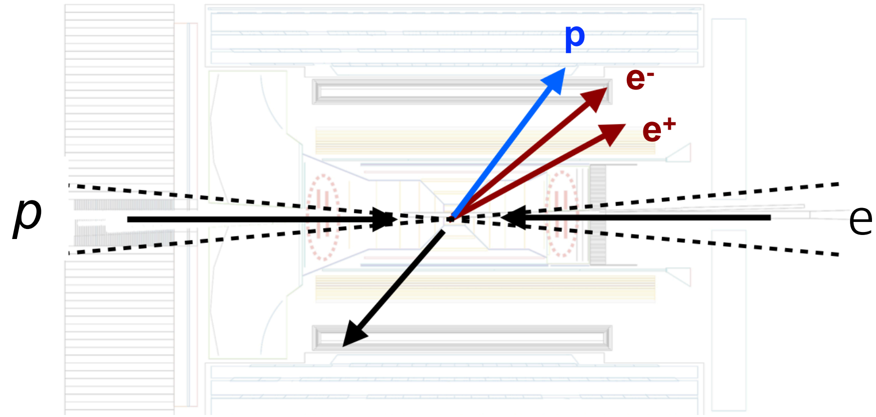
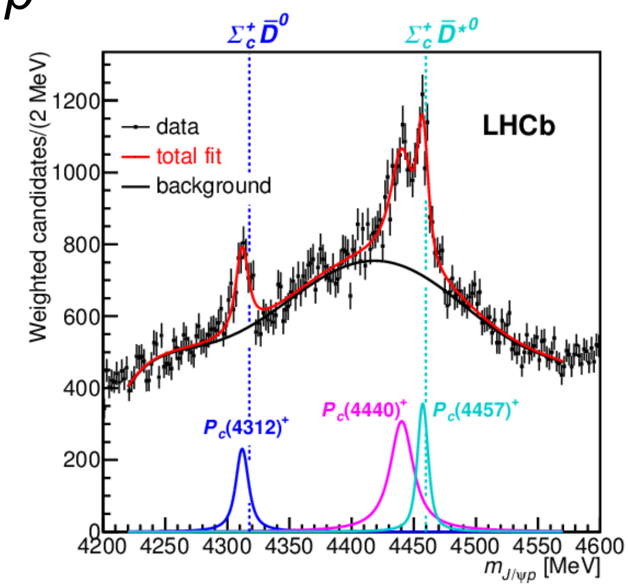
Dec. 12. 2024

Electro-production of P_c







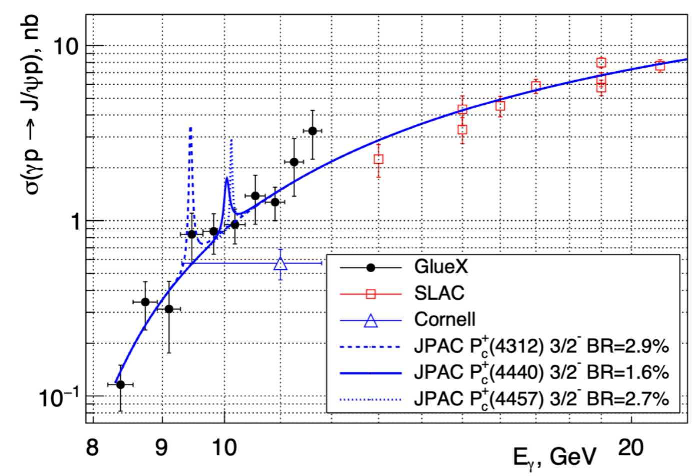


FIG. 4: GlueX results for the J/ψ total cross-section vs beam energy, Cornell [15], and SLAC [16] data compared to the JPAC model [6] corresponding to $\mathcal{B}(P_c^+(4312) \to J/\psi p) = 2.9\%$, $\mathcal{B}(P_c^+(4440) \to J/\psi p) = 1.6\%$, and $\mathcal{B}(P_c^+(4457) \to J/\psi p) = 2.7\%$,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

- LHCb discovered 3 states of P_c through the J/ψ + *p* channel

- GlueX measured inclusive spectra of J/ψ
- Can EIC and ePIC do better that that?

Simulation in ePIC framework

[arxiv2202.11631]

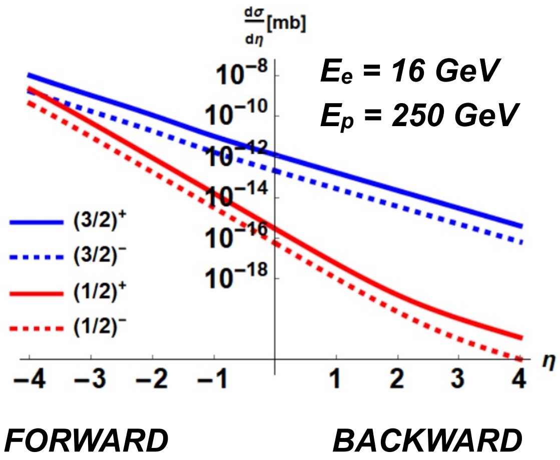
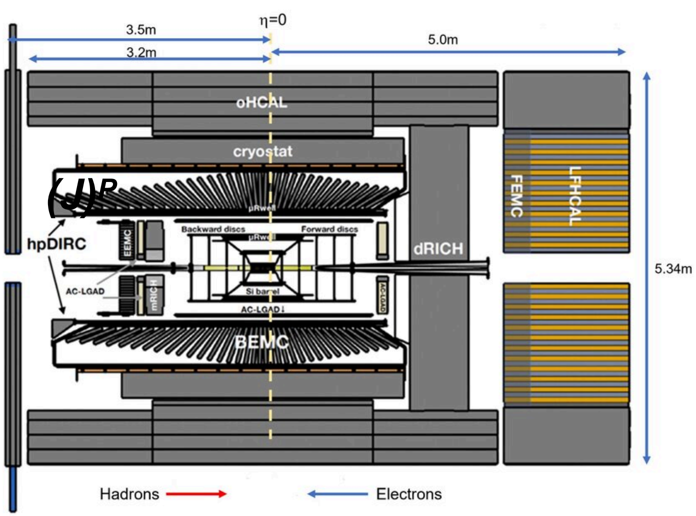
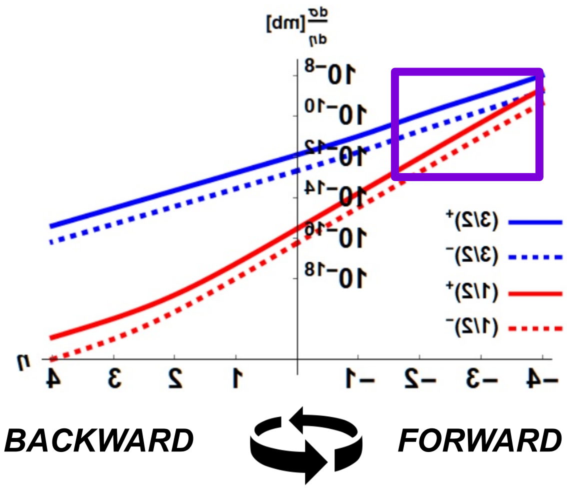


TABLE II. Expected number of $P_c(4312)$ produced at the EIC with 10 fb^{-1} in $|\eta| < 4$

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



Simulation in ePIC framework



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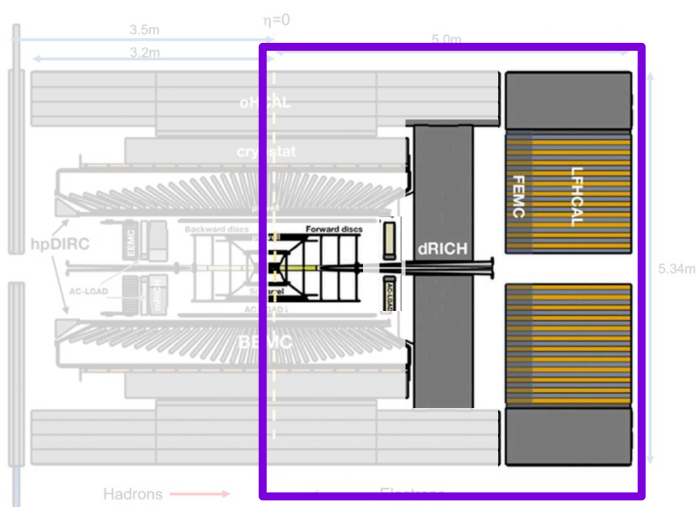
- Cross section is higher for forward region
  - Trackers, dRICH, endcap calorimeters



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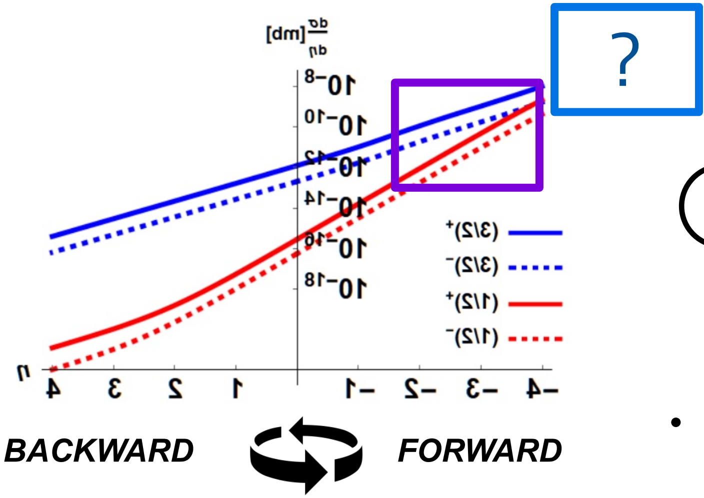
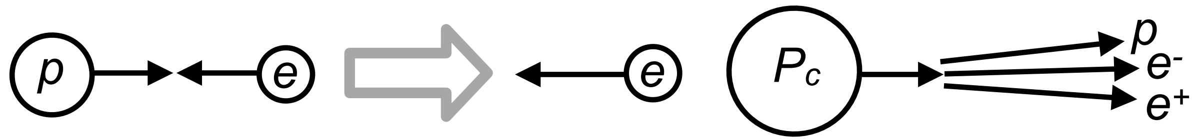
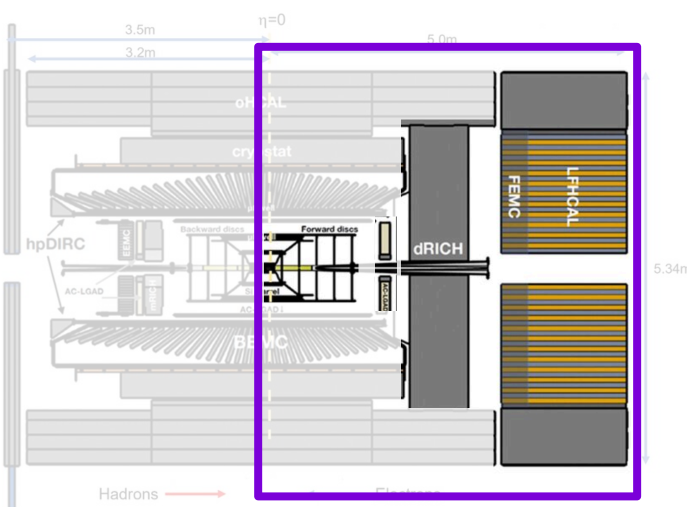
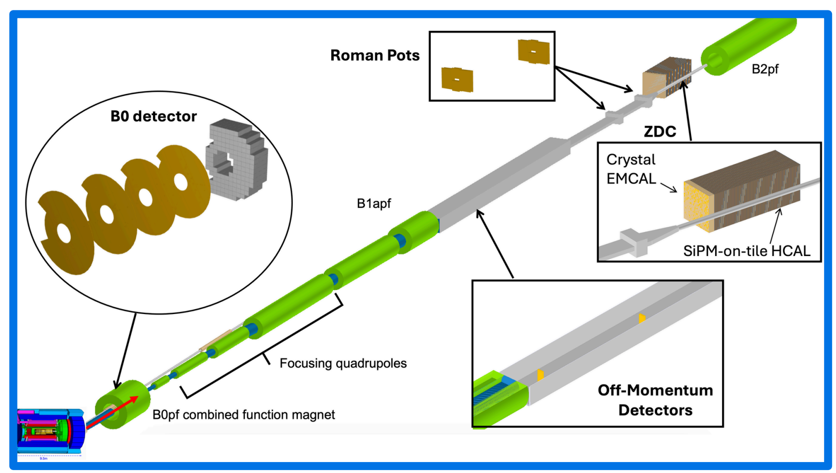




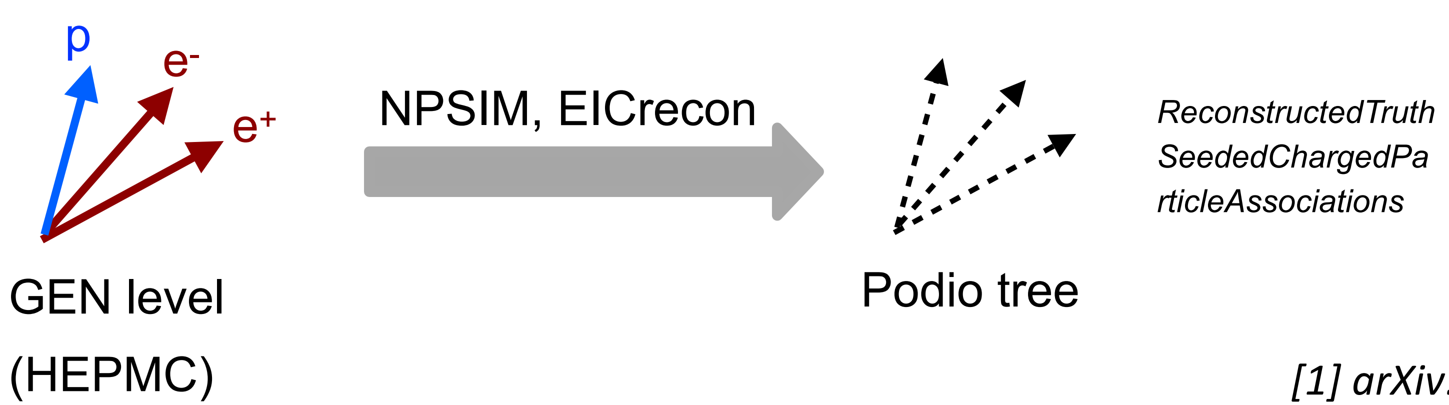
- Cross section is higher for forward region
  - Trackers, dRICH, endcap calorimeters
- Even higher for diffraction-like events
  - Utility of far-forward system in ePIC?





Simulation in ePIC framework

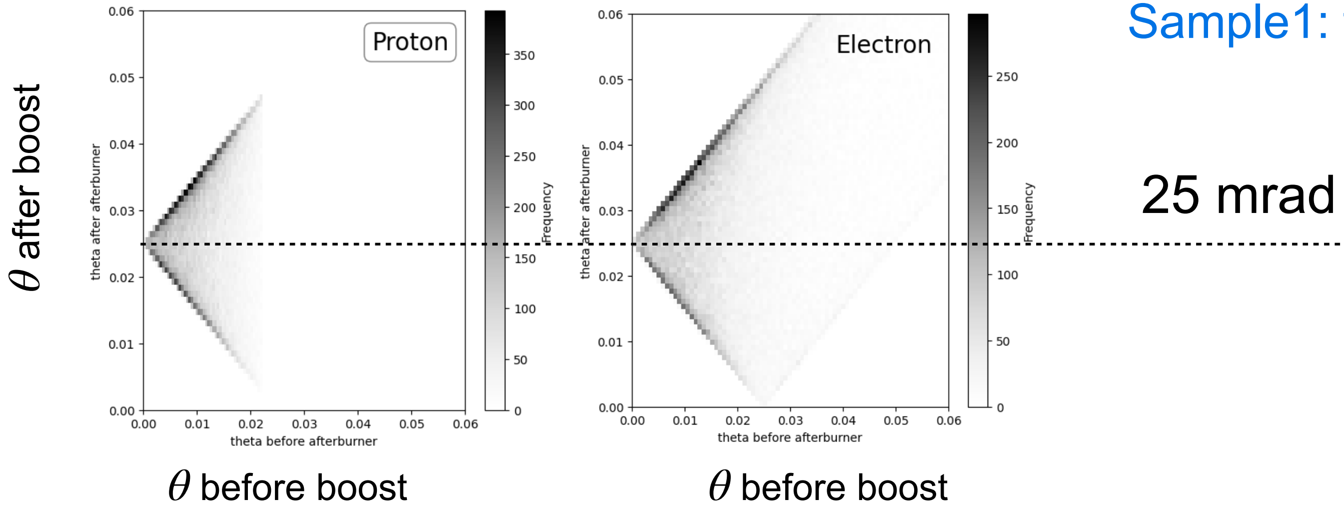
- Analysis procedure and caveats
  - I went through GEN → NPSIM → EICrecon → tree analysis following the ePIC tutorial, which worked almost out-of-box
  - I made $P_c \rightarrow p + J/\psi \rightarrow p + e^{+} + e^{-}$ generator according to the VMD model[1]
    - Polarization for P_c and J/ψ is not addressed
    - 275 GeV ⊗ 18 GeV energy
    - decay width (9.8 MeV) is negligible in typical ePIC tracking resolution
  - Used *ReconstructedTruthSeededChargedParticleAssociations* collection for RECO
    - MC matching and PID algorithm inherent in the package is not used
    - MC matching is done by the closest distance
  - Signal-only study is done



[1] arXiv:2202.11631

Boost by beam crossing angle

- Afterburner (ip6_hidiv_275x18)
- Kinematic distribution of protons and electrons decayed from *Pc*



Sample1: far forward

25 mrad

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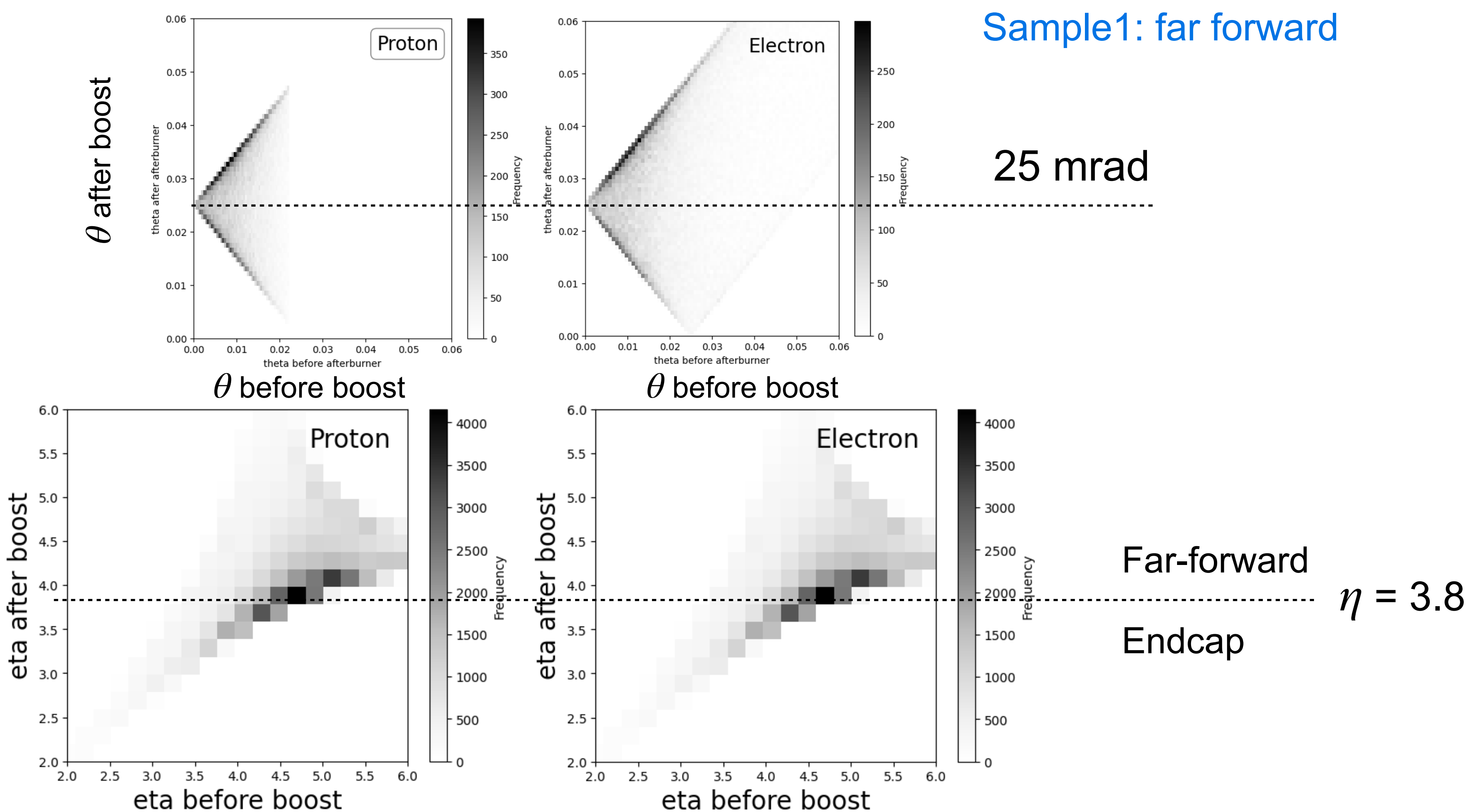

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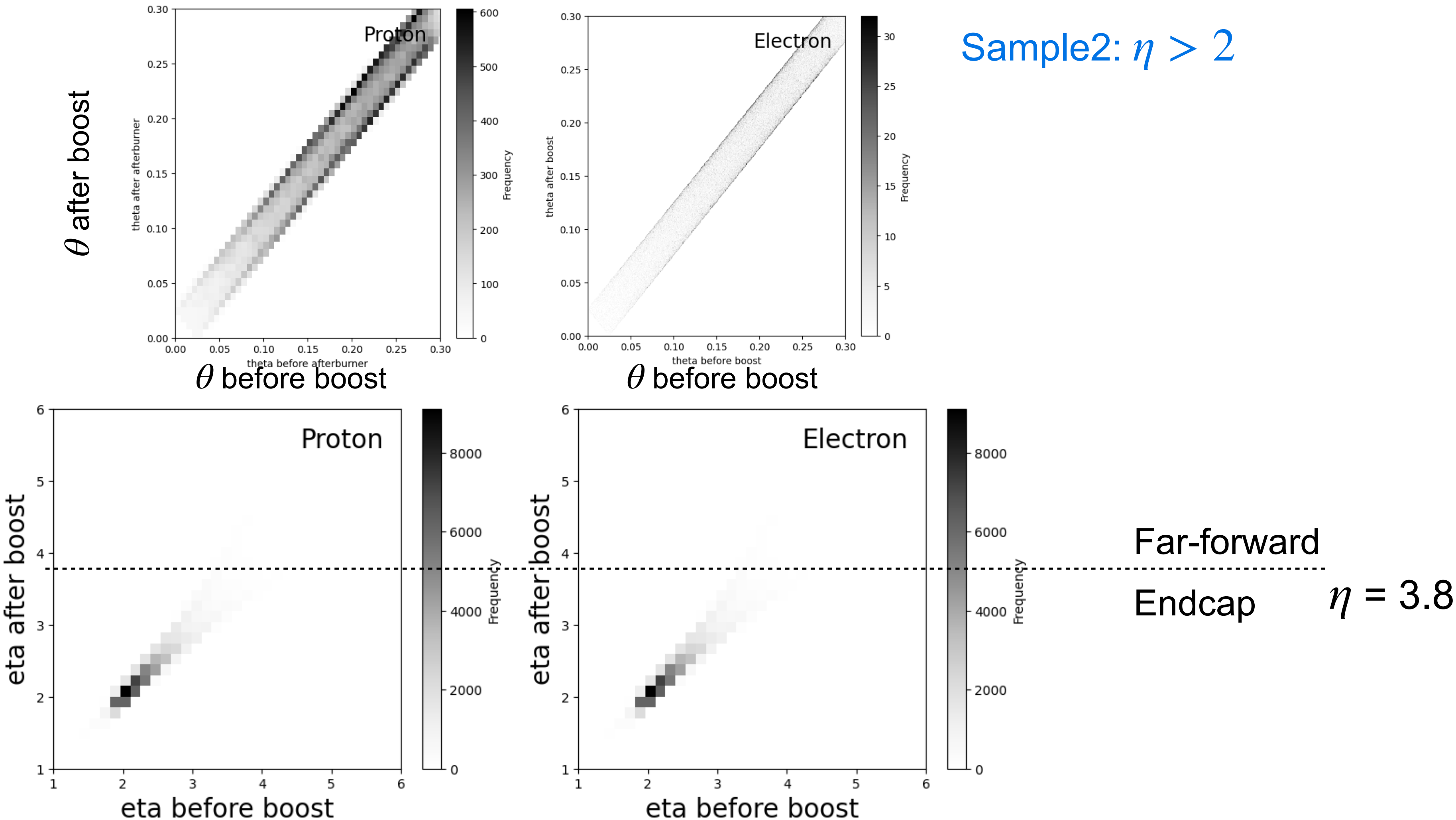
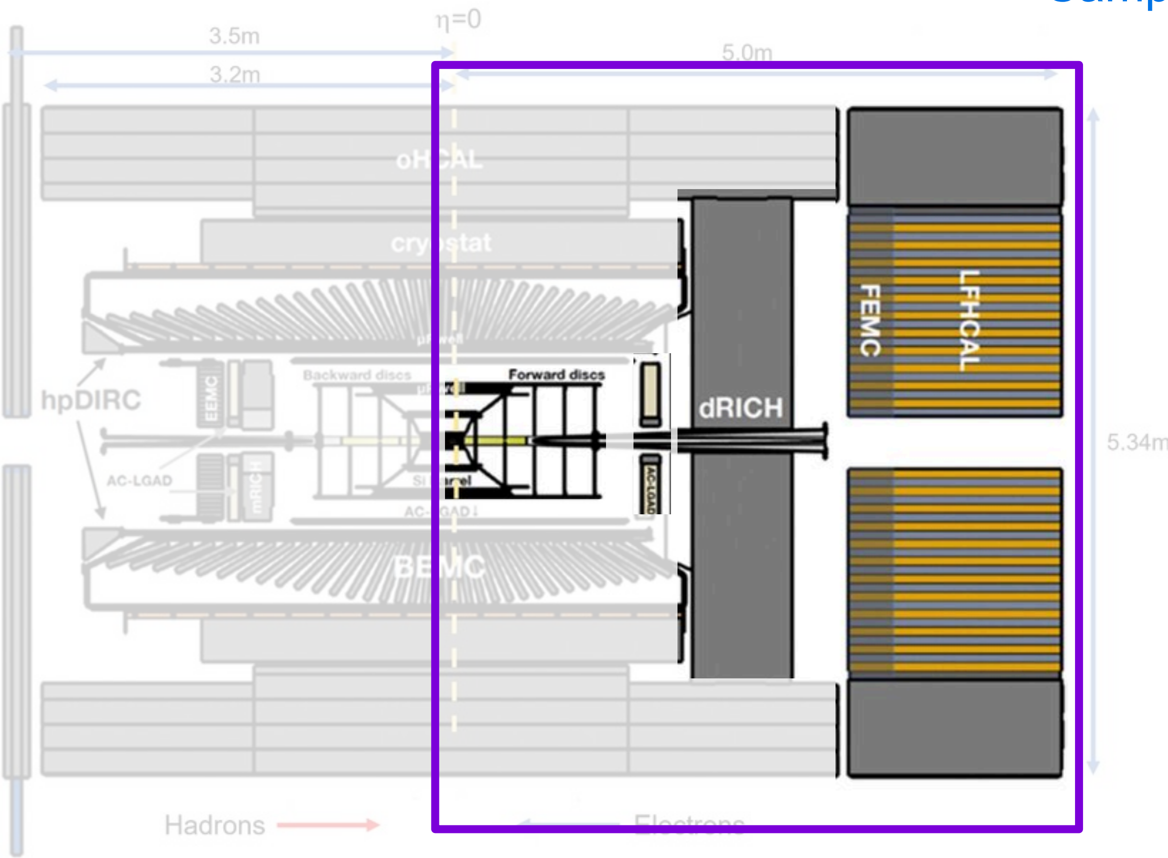


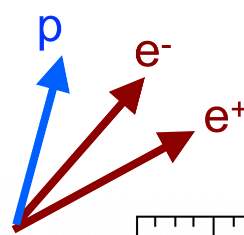
Results in the endcap

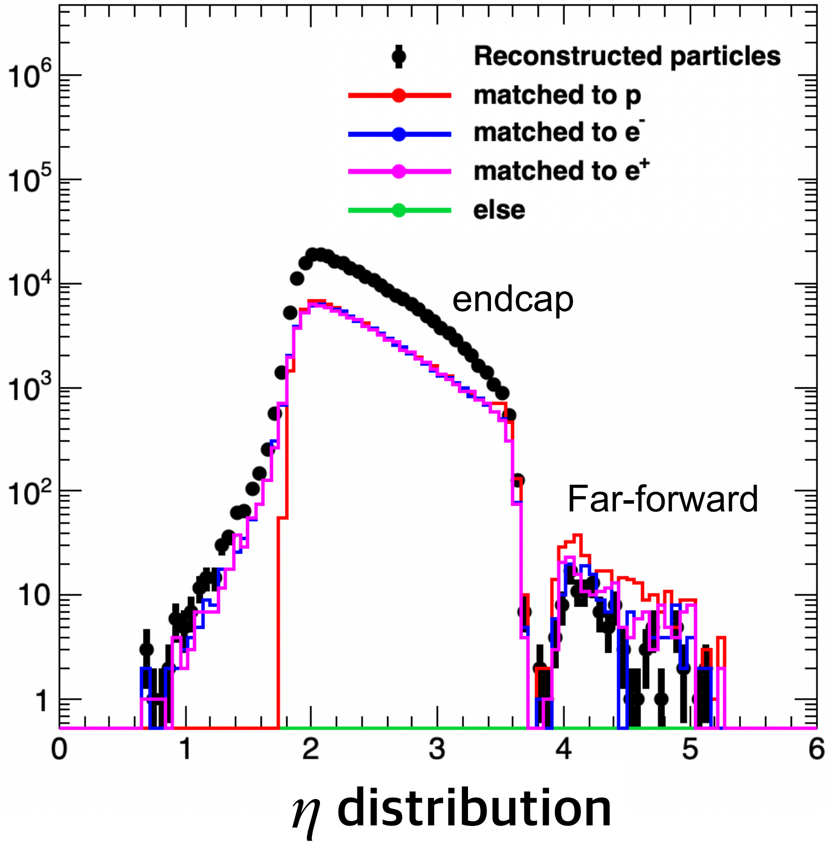
Sample2: $\eta > 2$

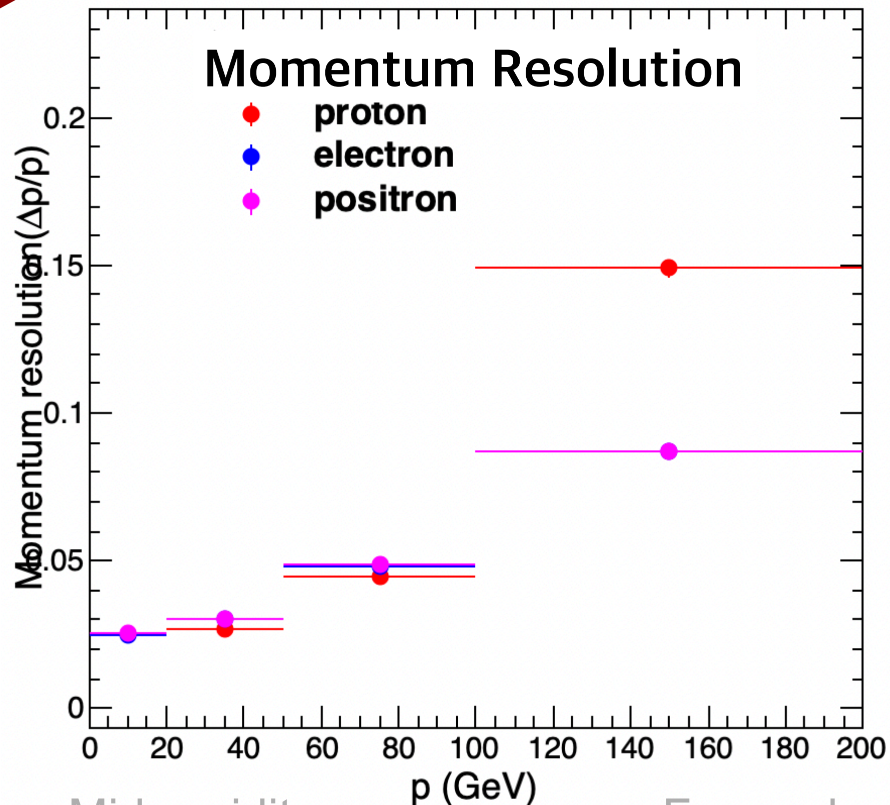


Particle reconstruction performance

$\eta(P_c) > 2$







Mid-rapidity → Forward

(η is one-to-one function of p due to 2-body process)

Particle reconstruction performance

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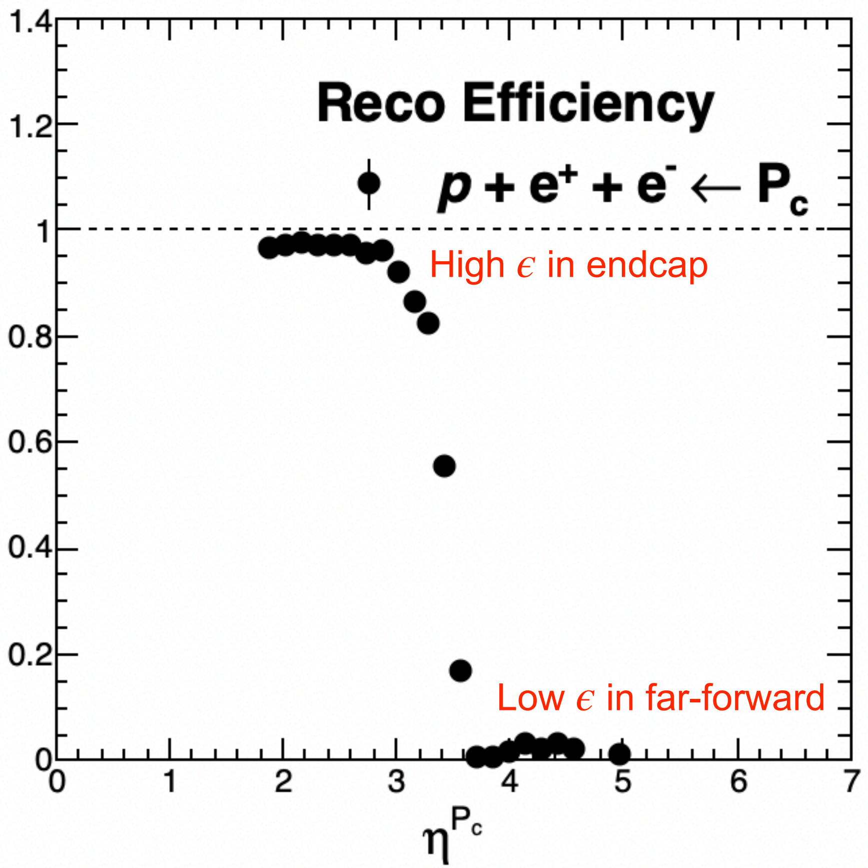

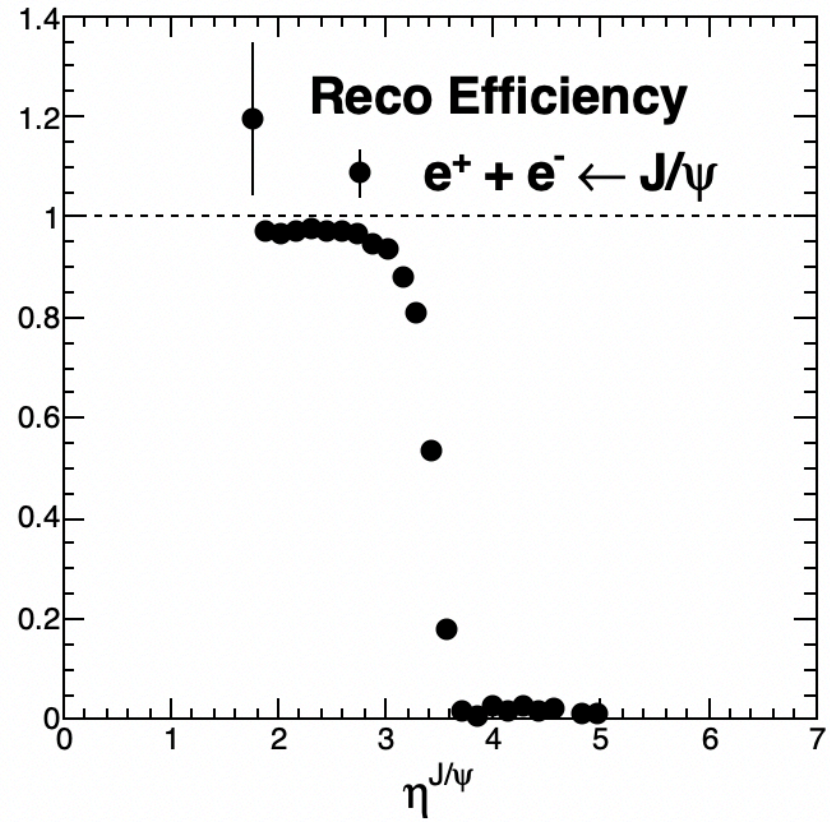

Particle reconstruction performance

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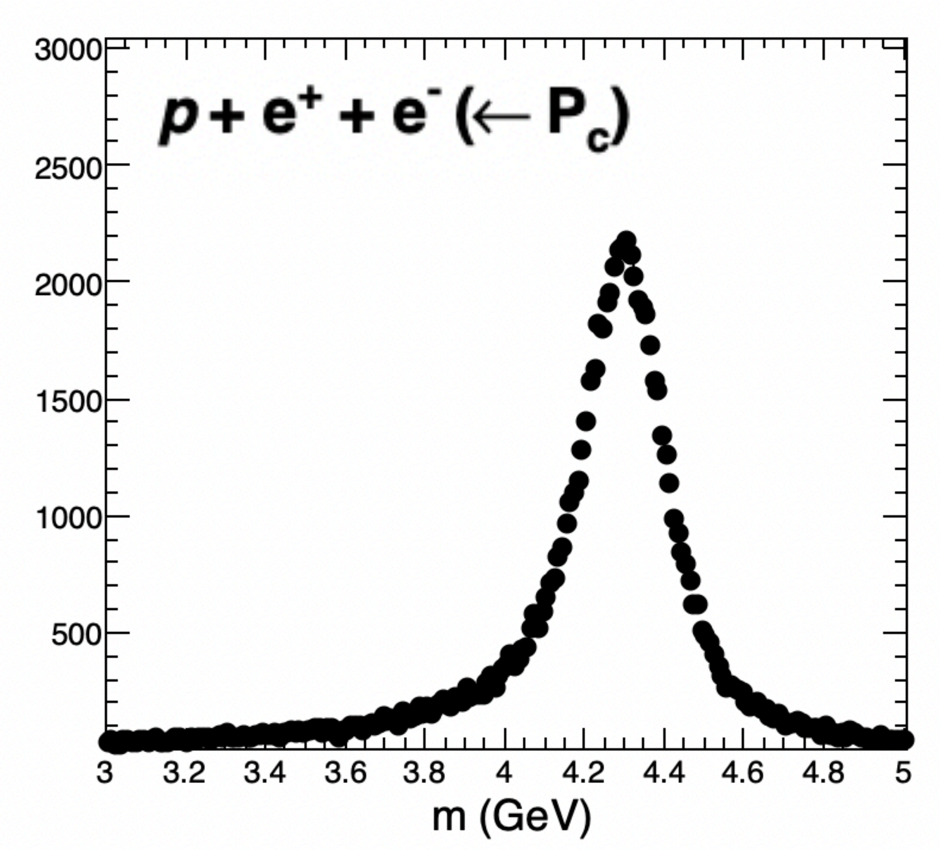
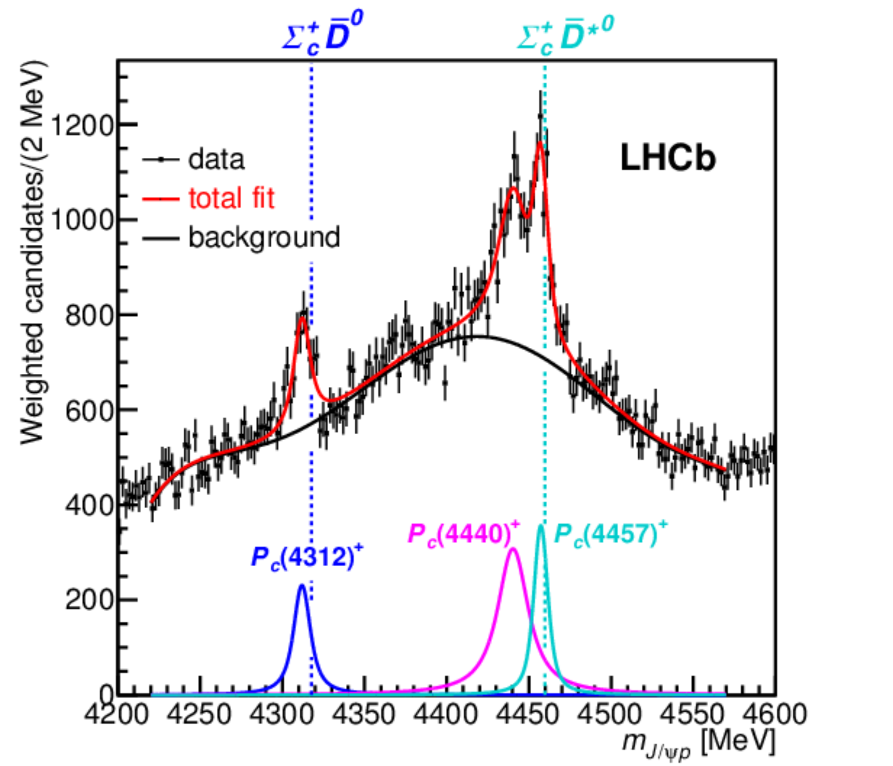


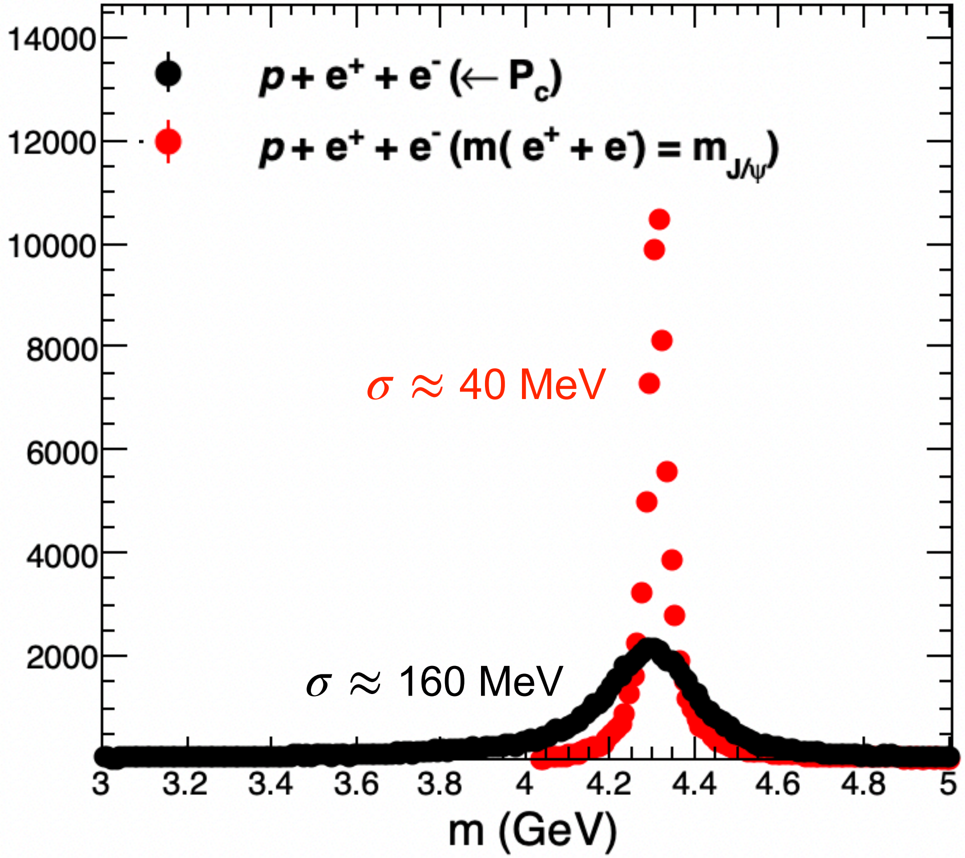


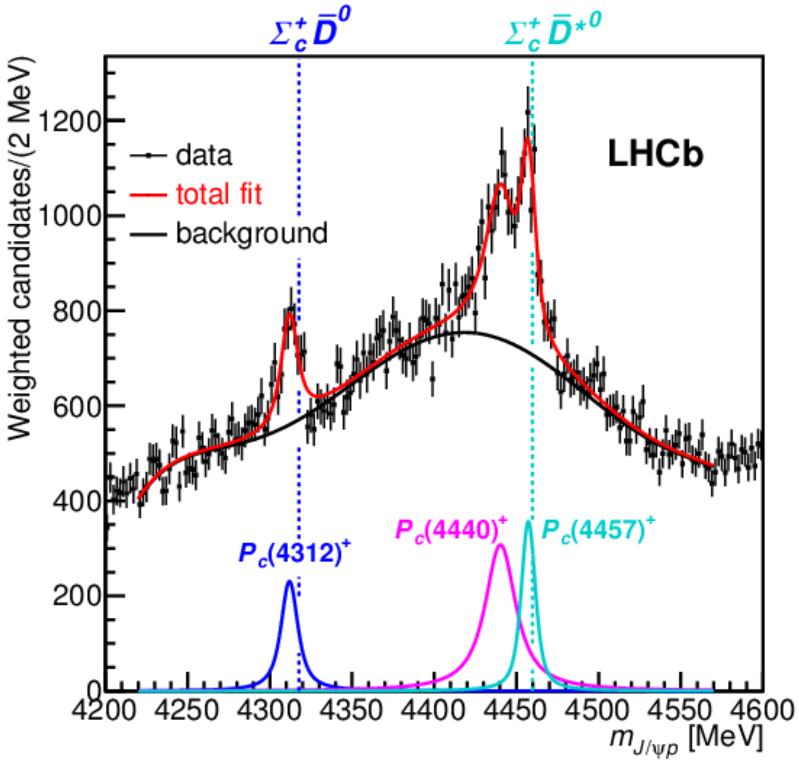
$\sigma \approx 160$ MeV

σ measured in LHCb: 9.8 (±2.7 +3.7/-4.5) MeV

Particle reconstruction performance

$\eta(P_c) > 2$





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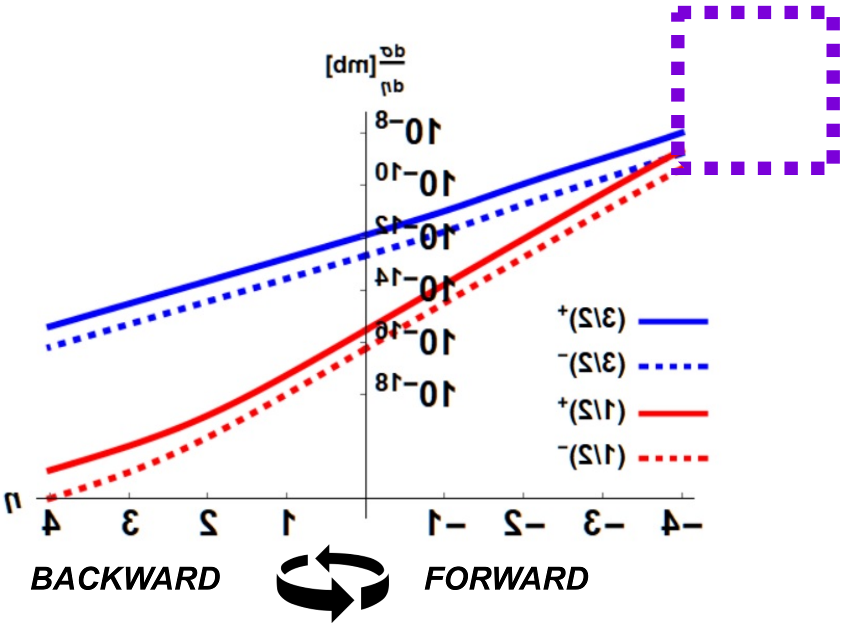
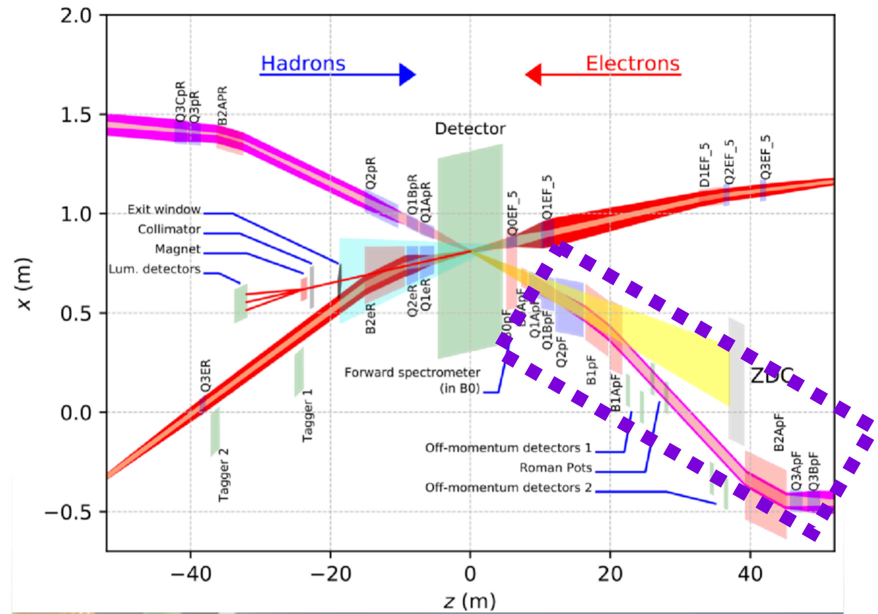
Fixing $m_{e^+e^-} = m_{J/\psi}$, we can resolve *P_c(4312)* and *P_c(4440)* with ePIC

Results in far-forward



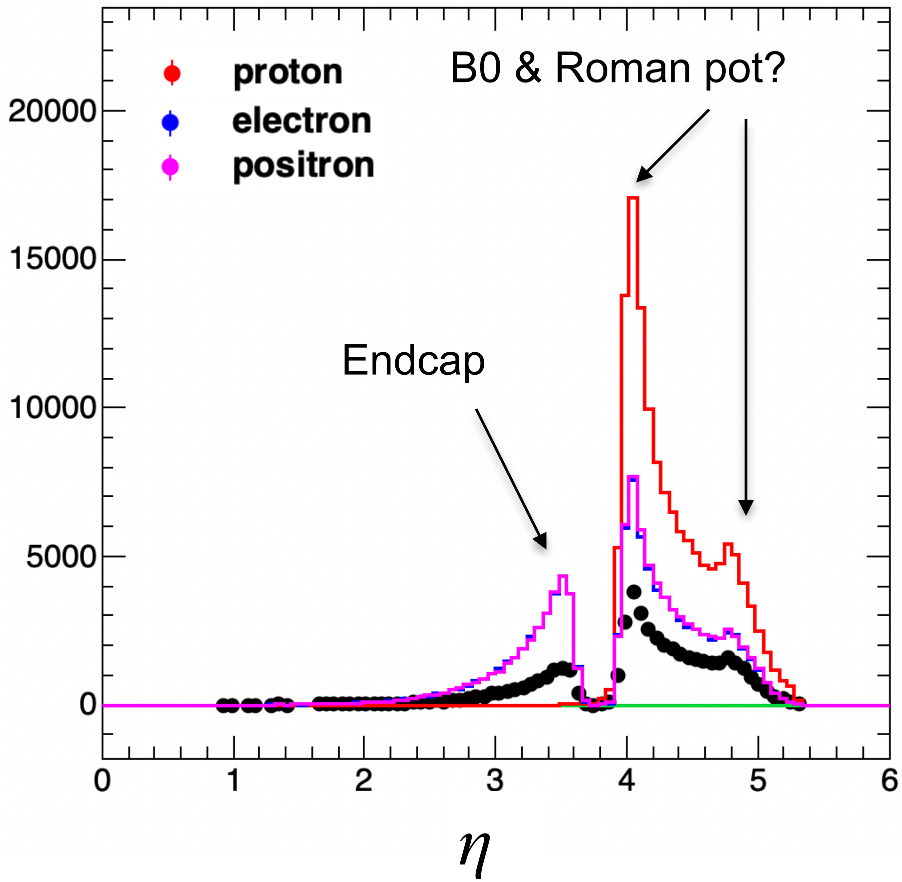


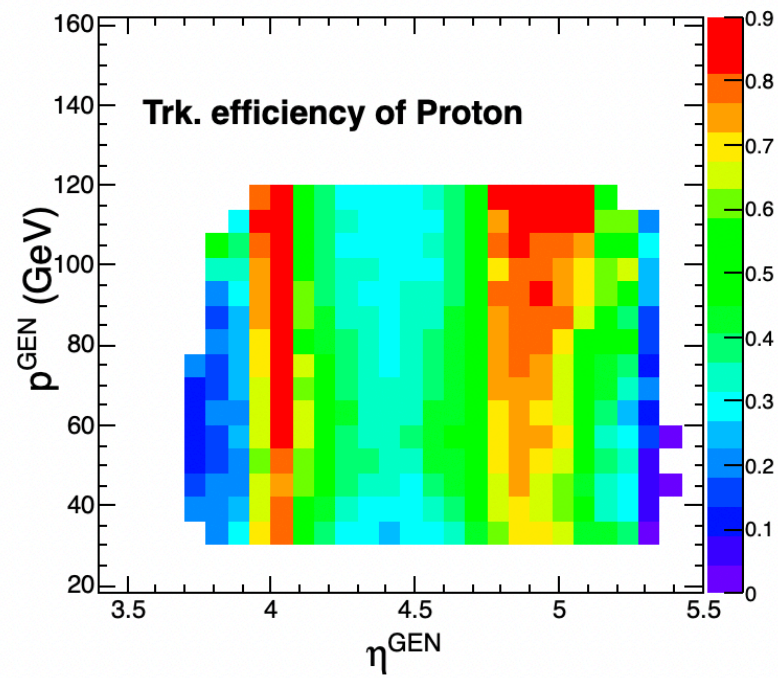
[$\eta(P_c) \gtrsim 4.5$ in physics frame] = [$\eta(P_c) > 3.8$ in ePIC frame]

Pro: High cross-section

Con: low geometrical acceptance

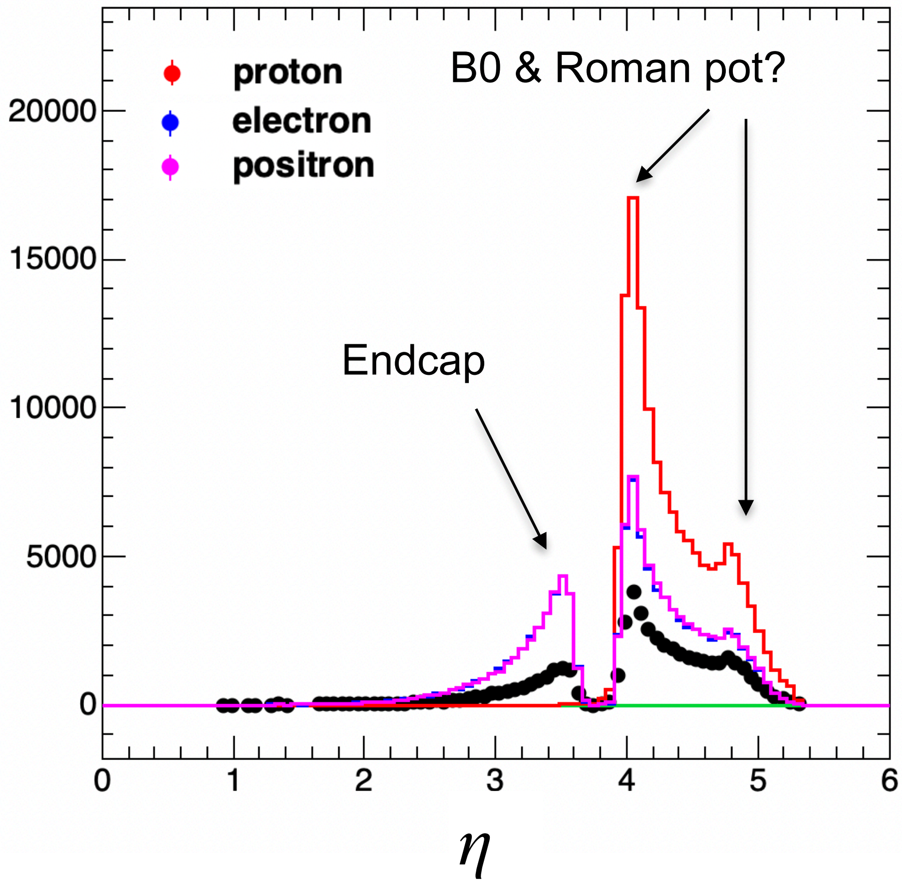
Particle reconstruction performance

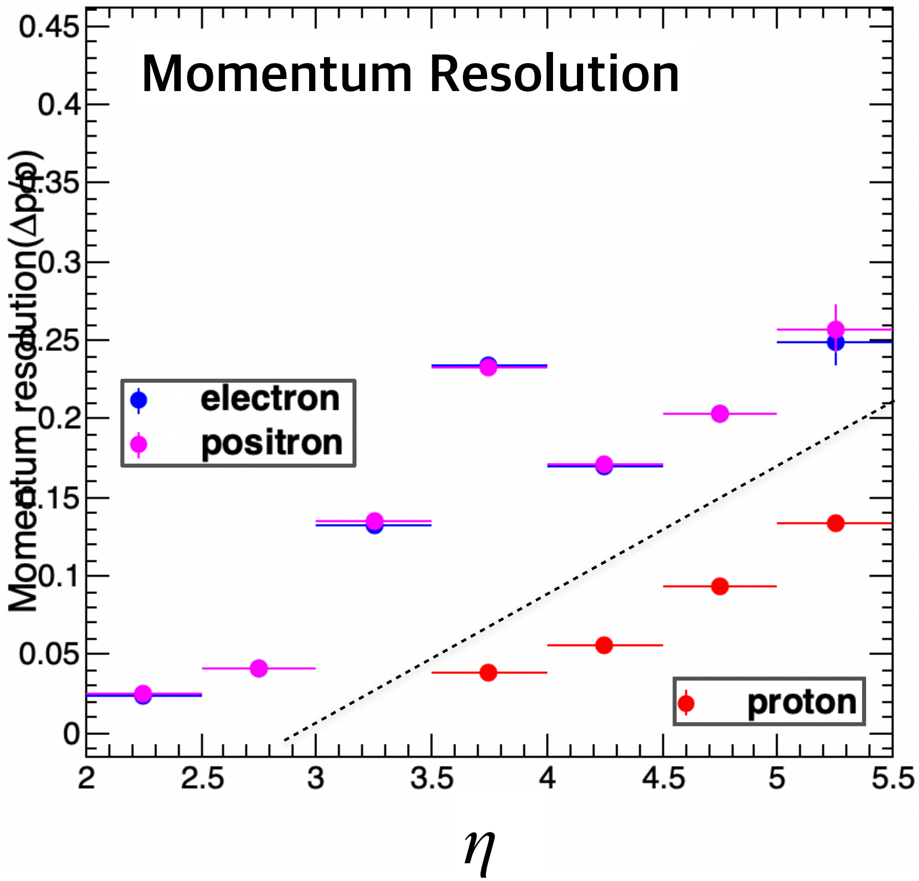




- Most protons arrive in far forward
- Some e^+, e^- in forward and some in the endcap

Particle reconstruction performance

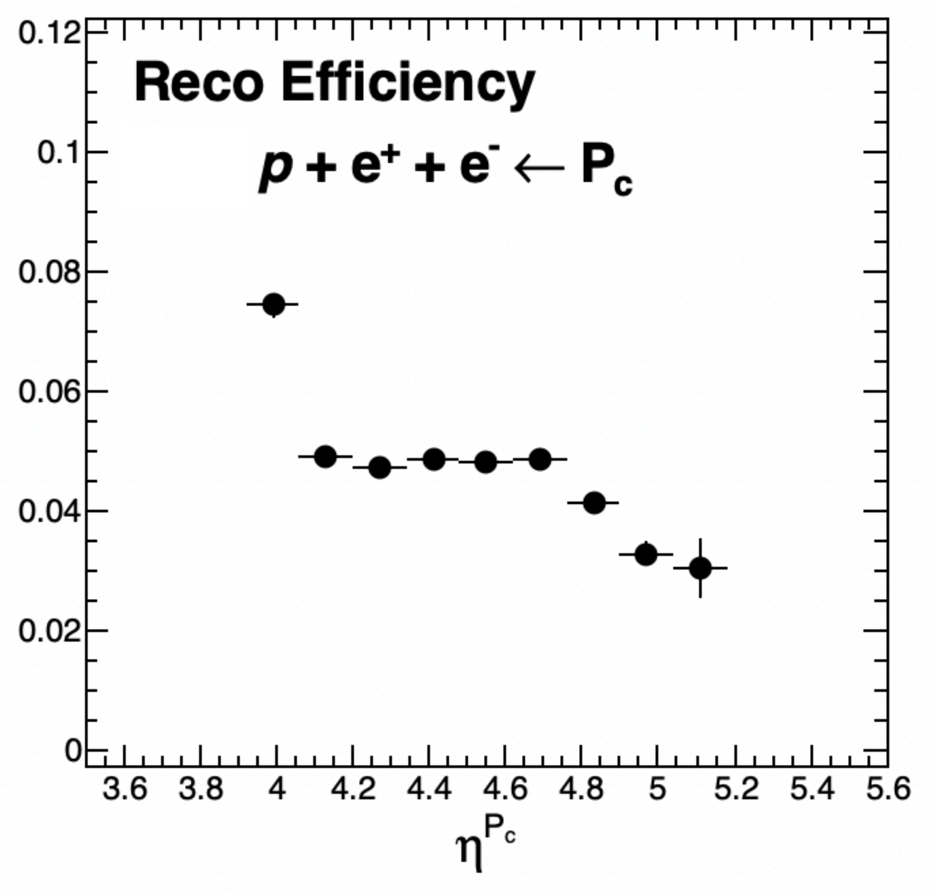


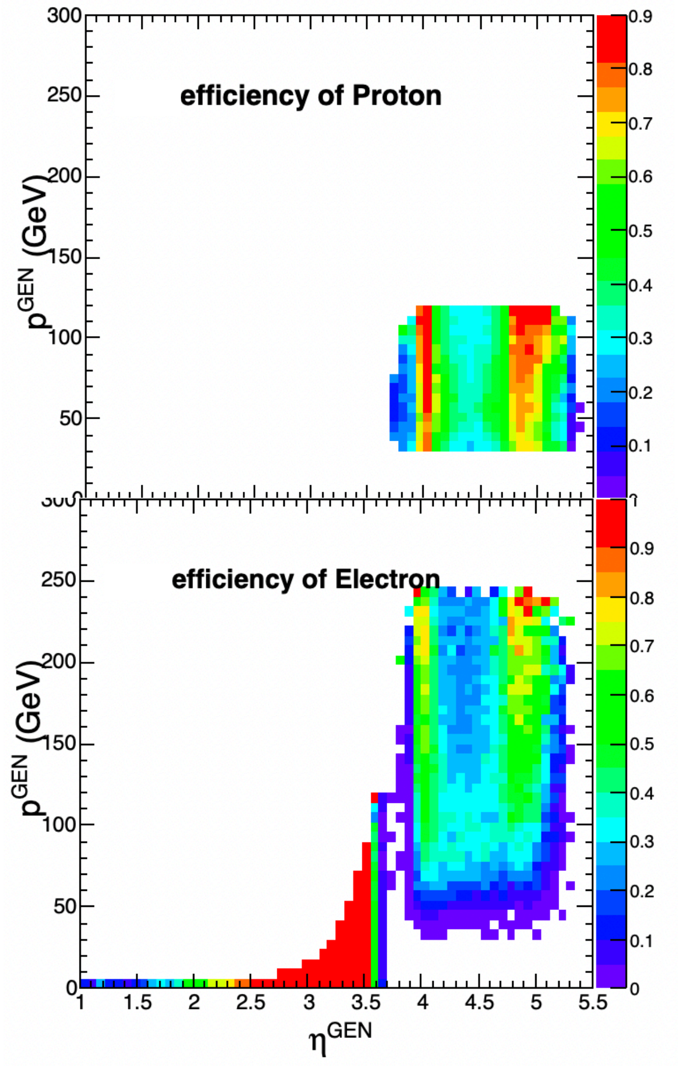


- Most protons arrive in far forward
- Some e^+, e^- in forward and some in the endcap

- Degradation of electron momentum resolution in far forward

Particle reconstruction performance





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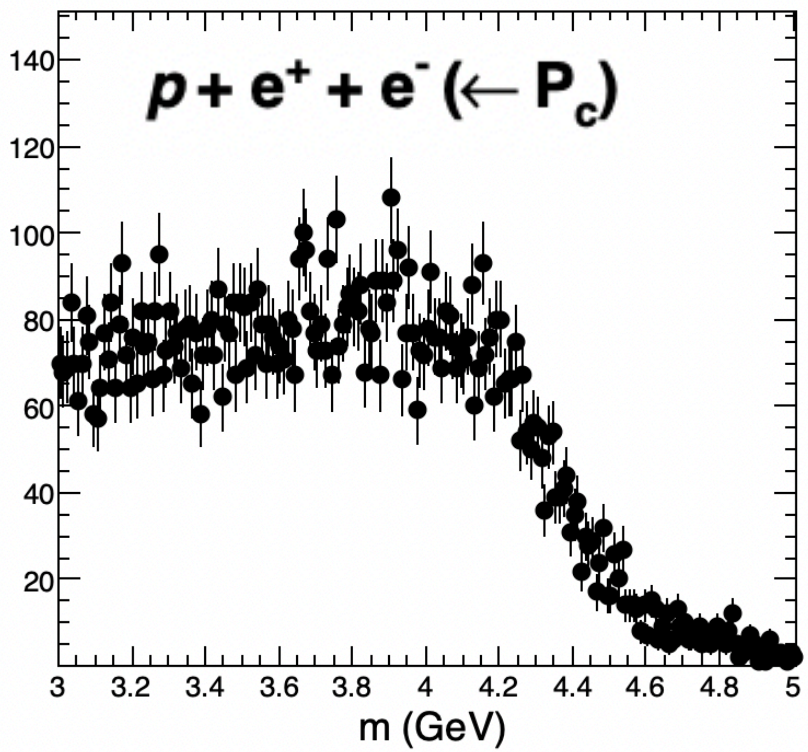
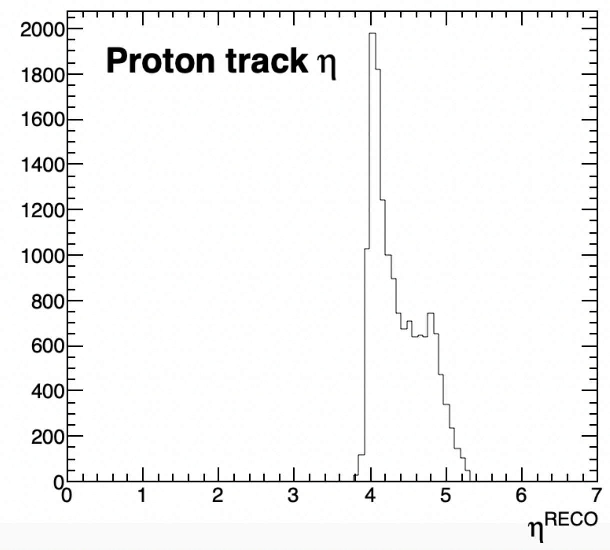
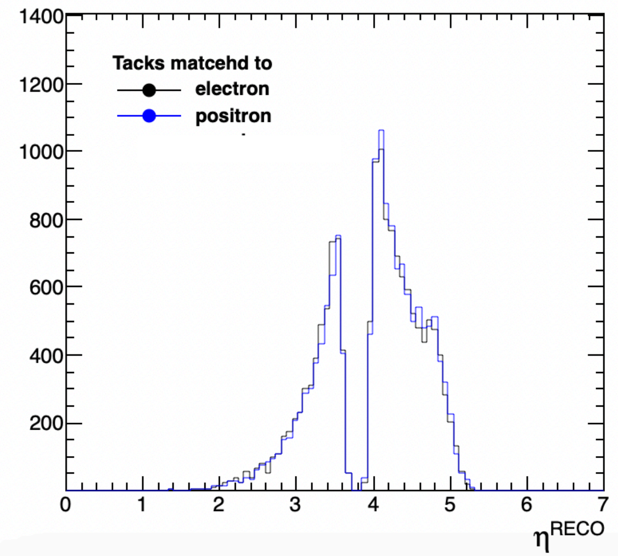
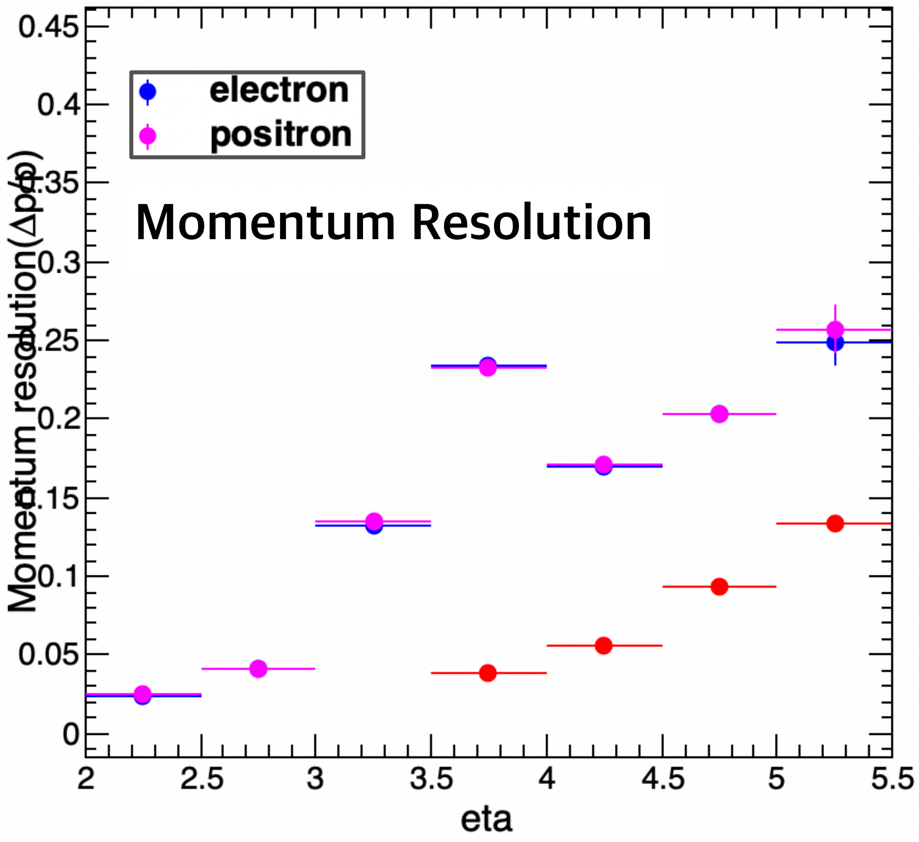


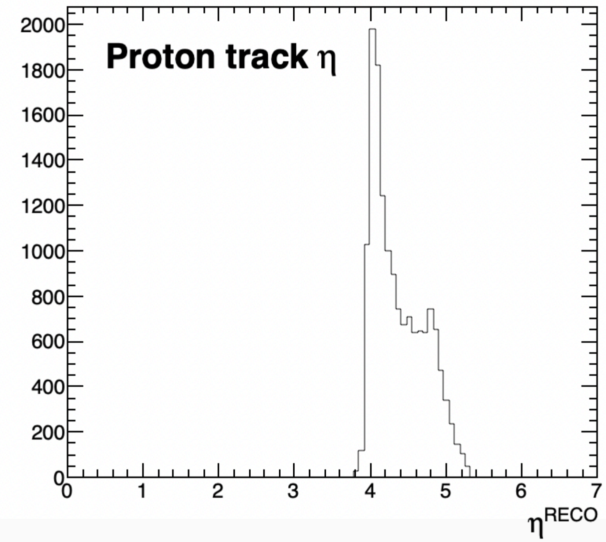


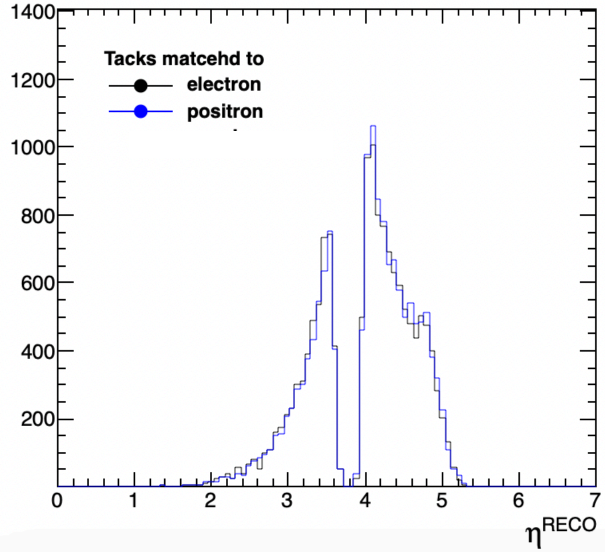


- Invariant mass has bad resolution

Particle reconstruction performance







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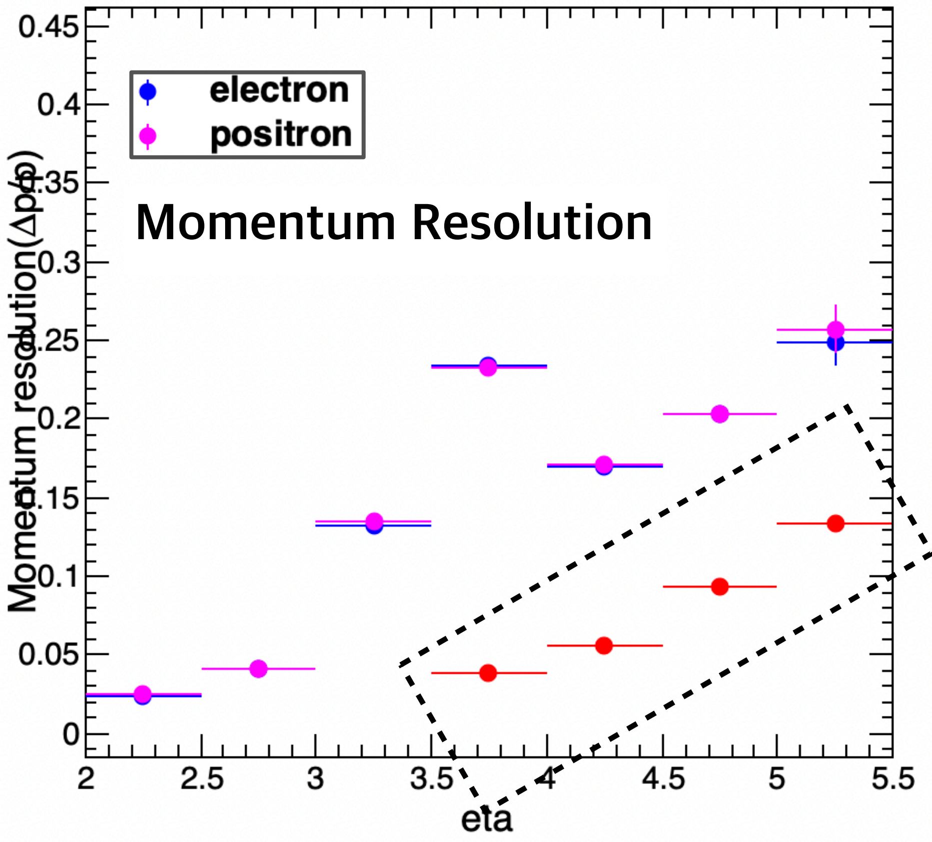
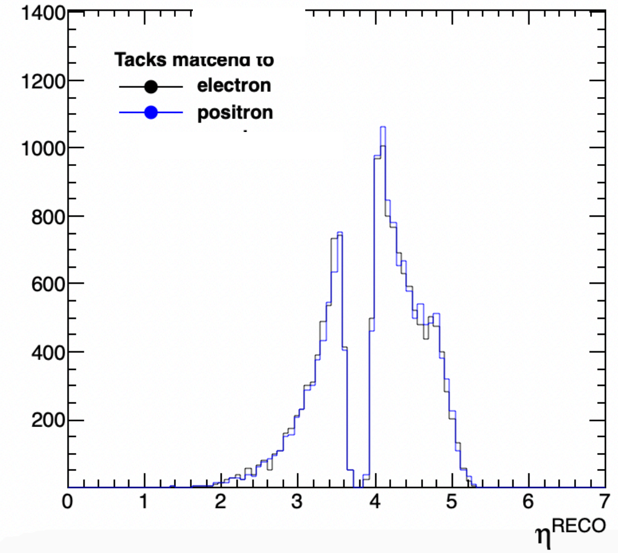
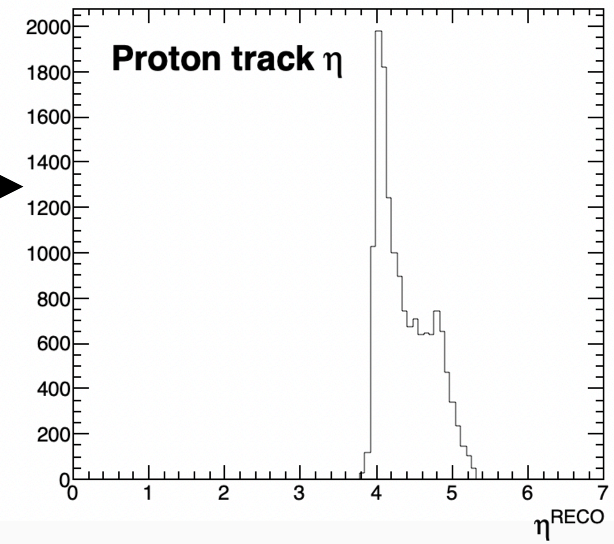
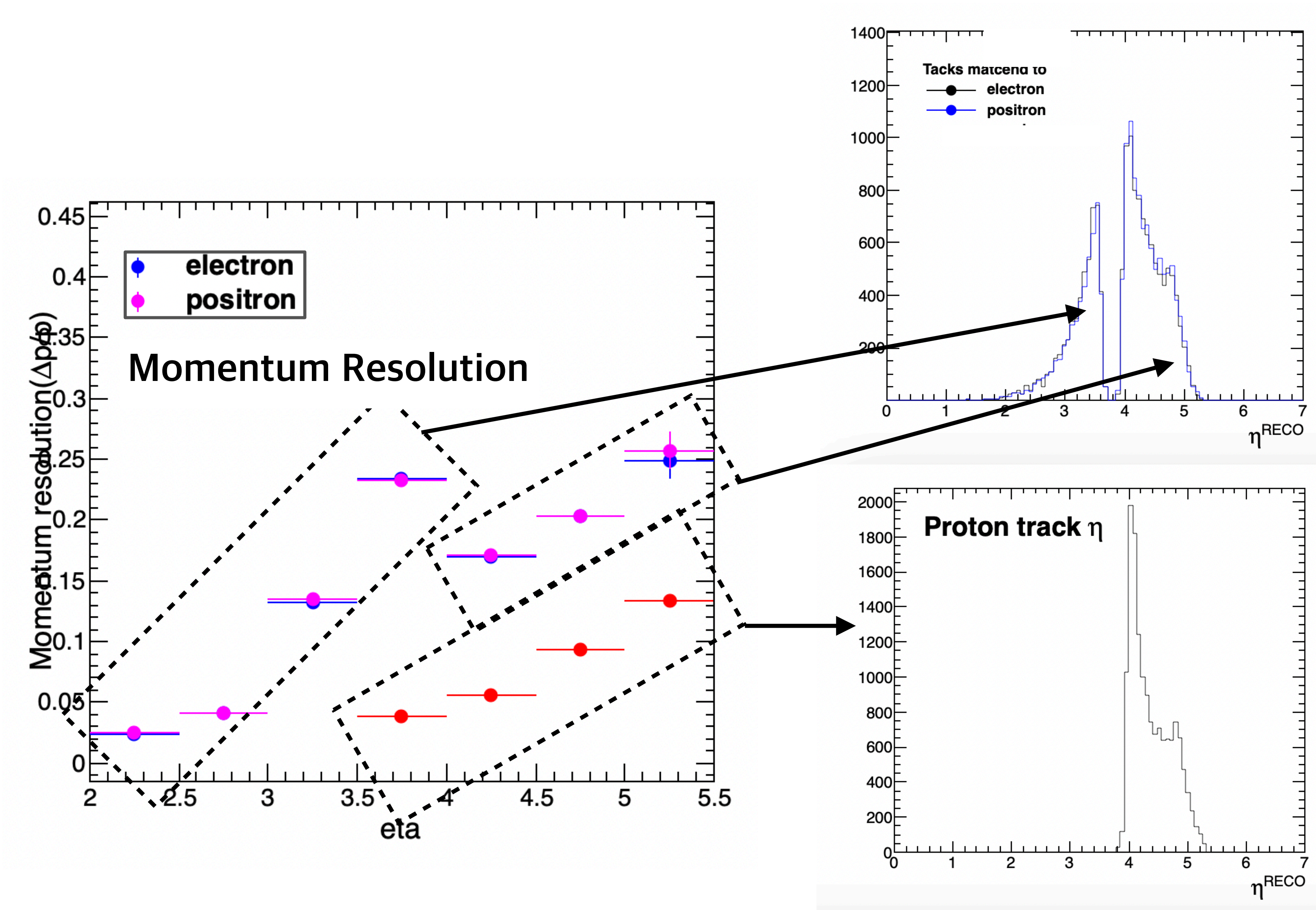






Particle reconstruction performance



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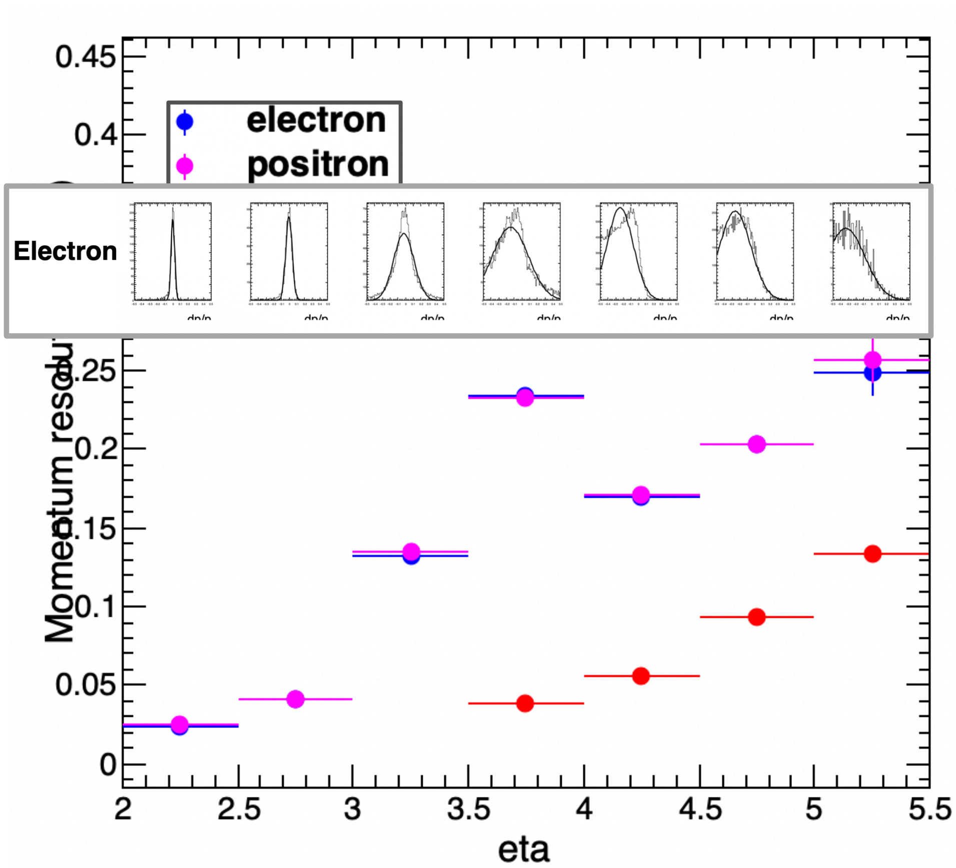
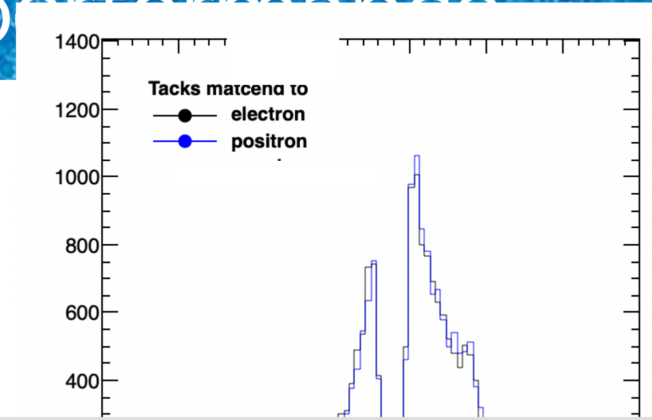
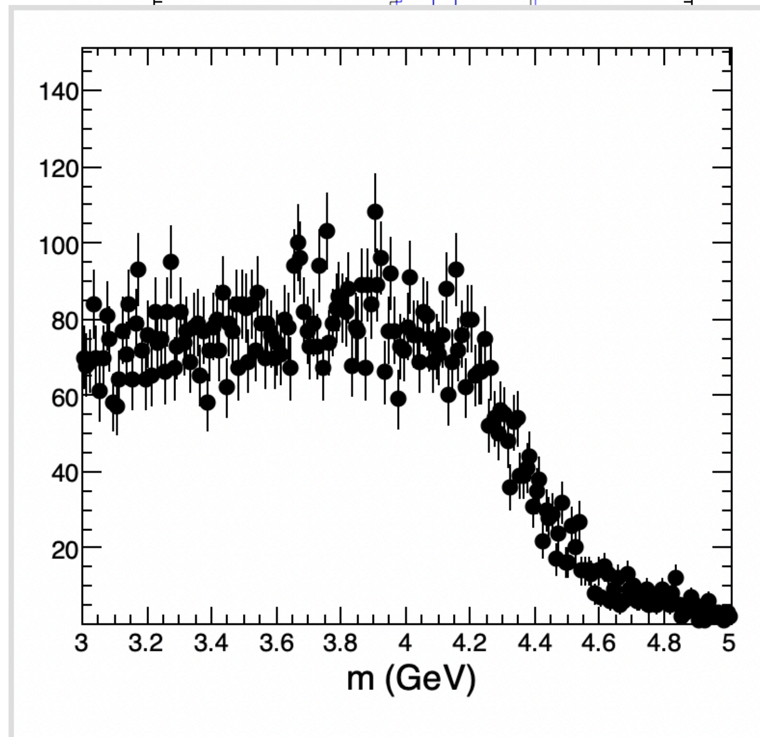


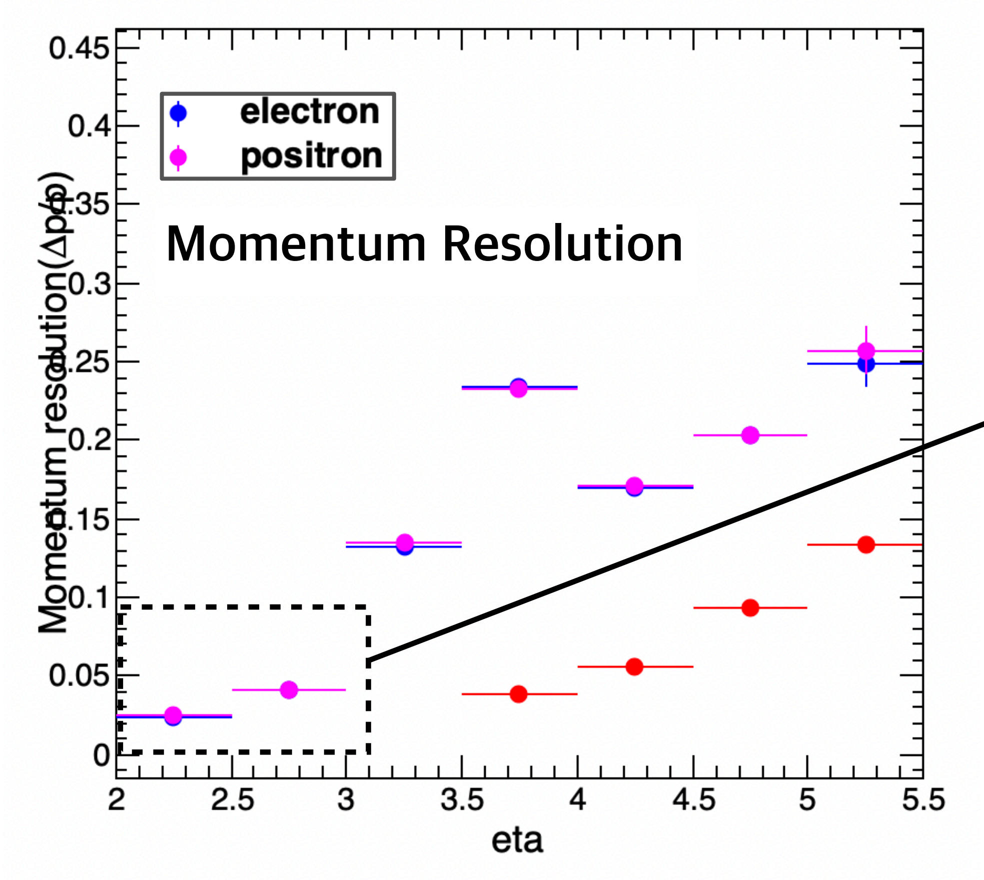


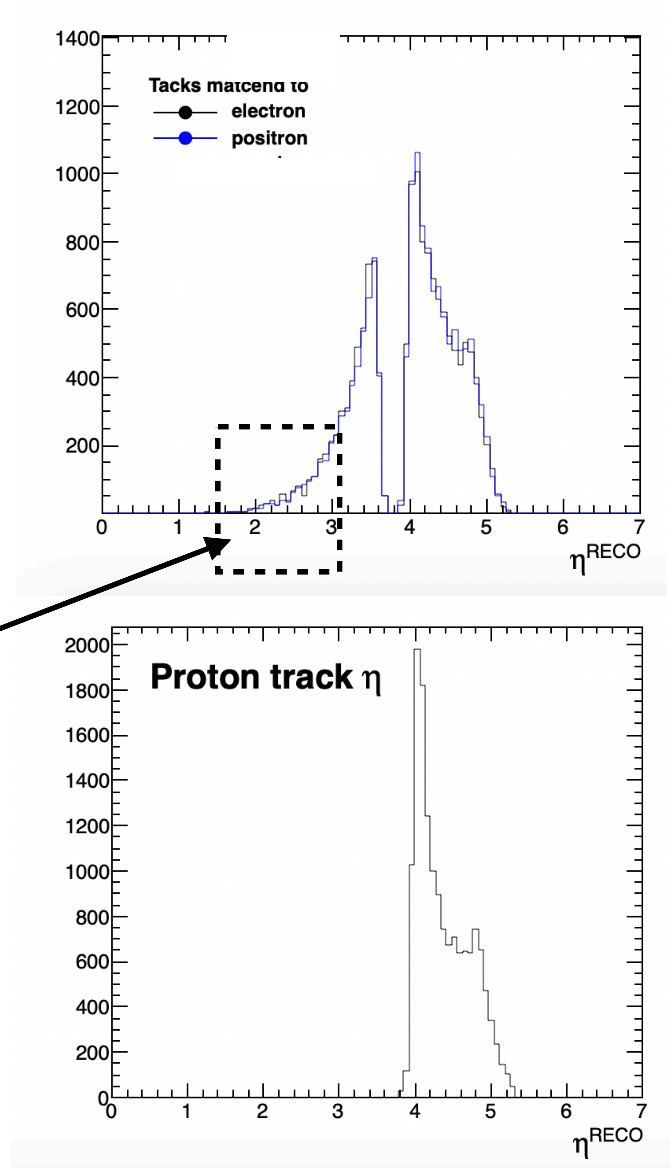


- Explains why the mass is shifted to the left and smeared

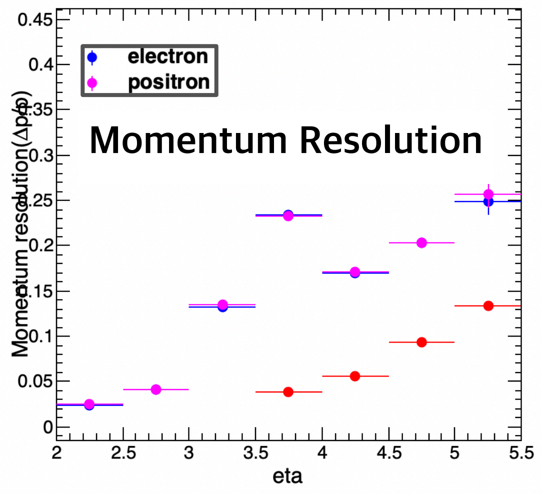
Particle reconstruction performance

- Electrons with η < 3 have decent resolution

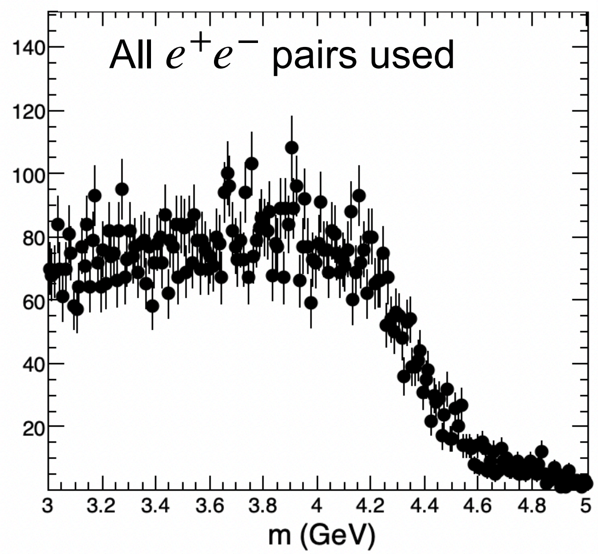




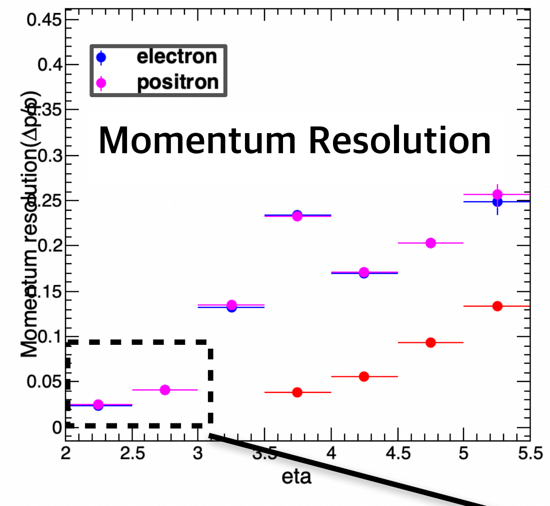
Particle reconstruction performance



Invariant mass of pe^+e^-



Particle reconstruction performance



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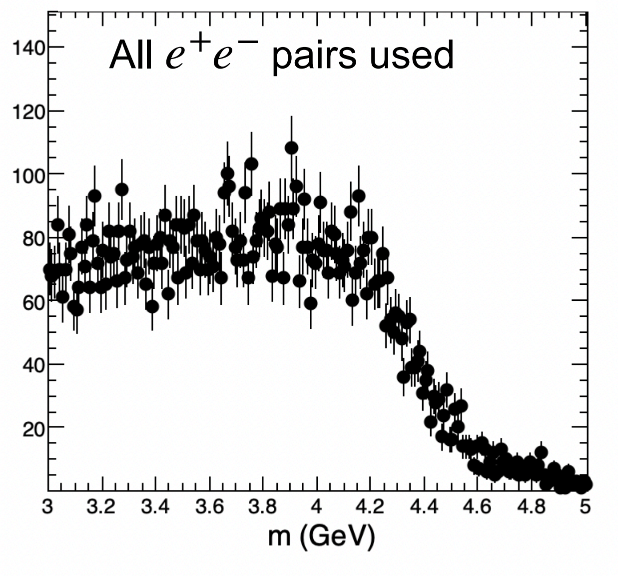

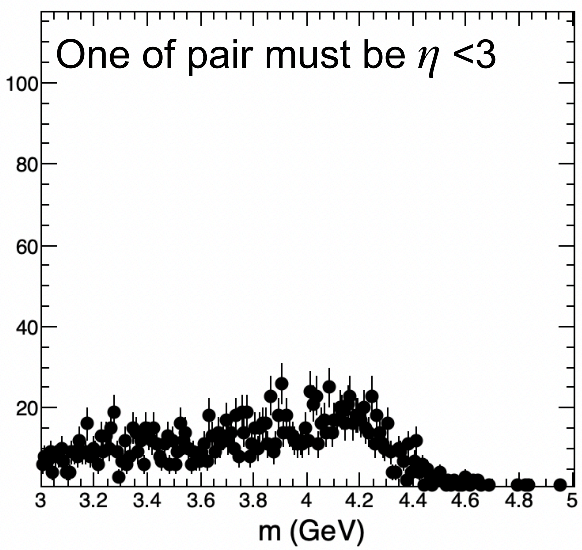

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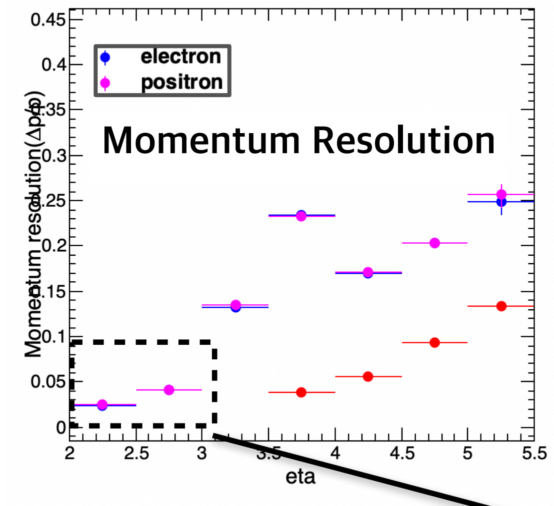

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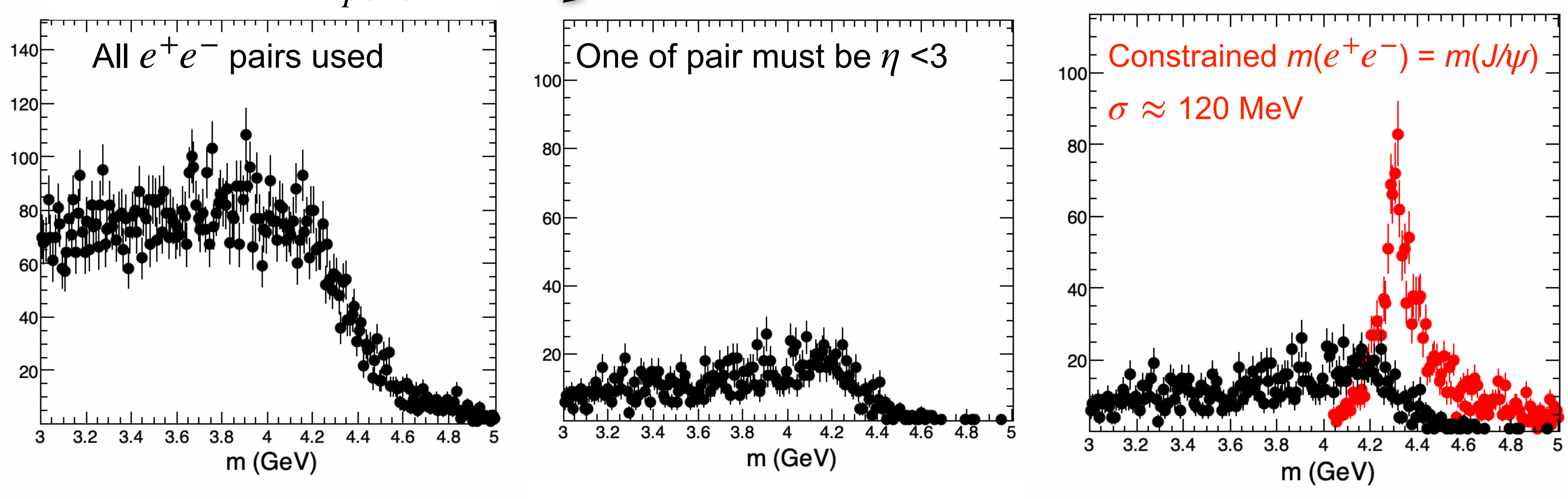

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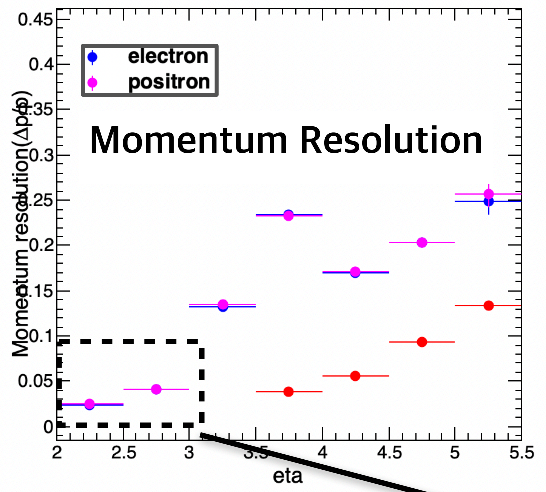
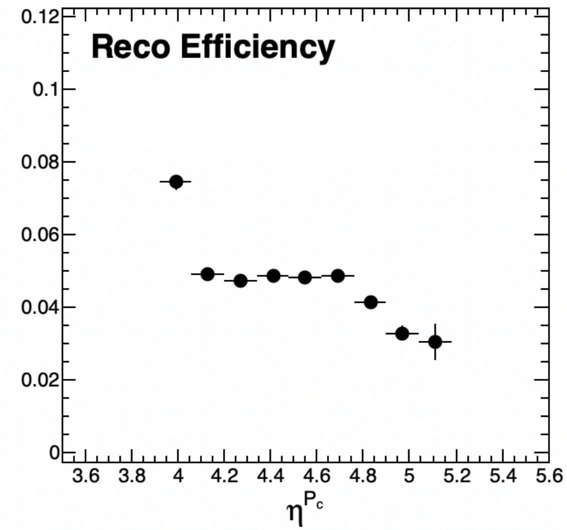


- Low efficiency
- Can be complemented by higher cross section



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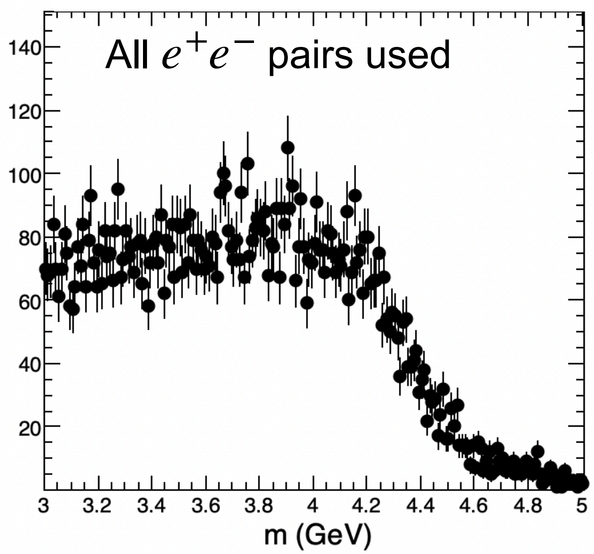
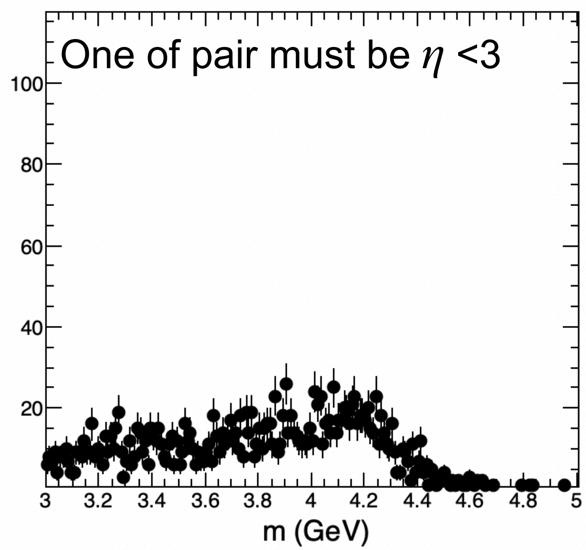
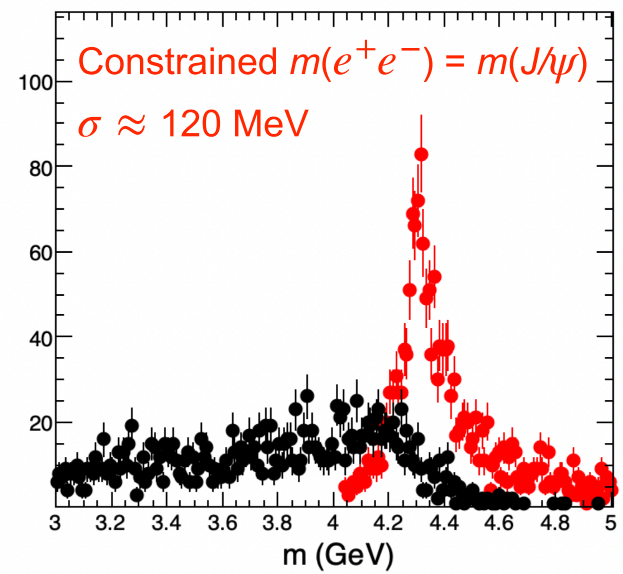
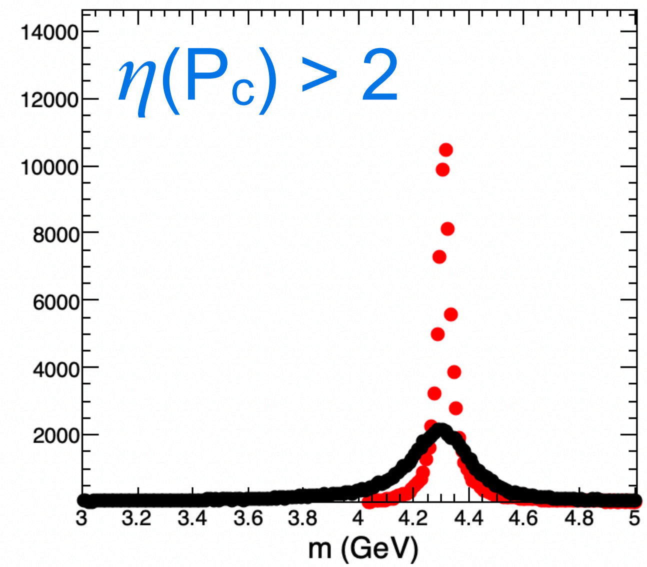


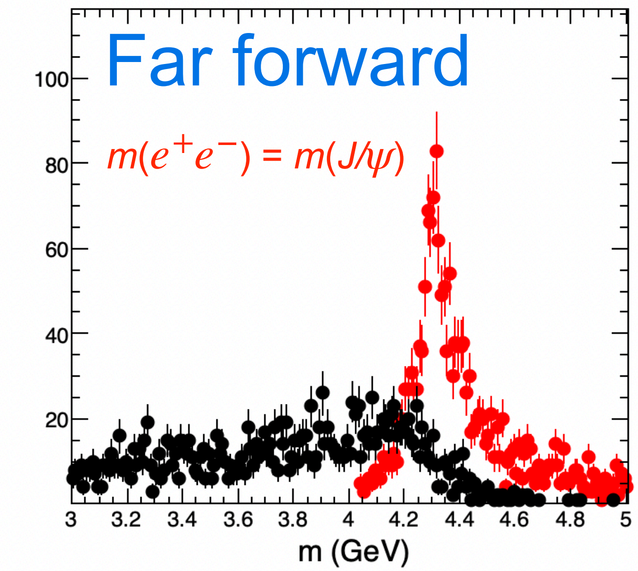




Summary

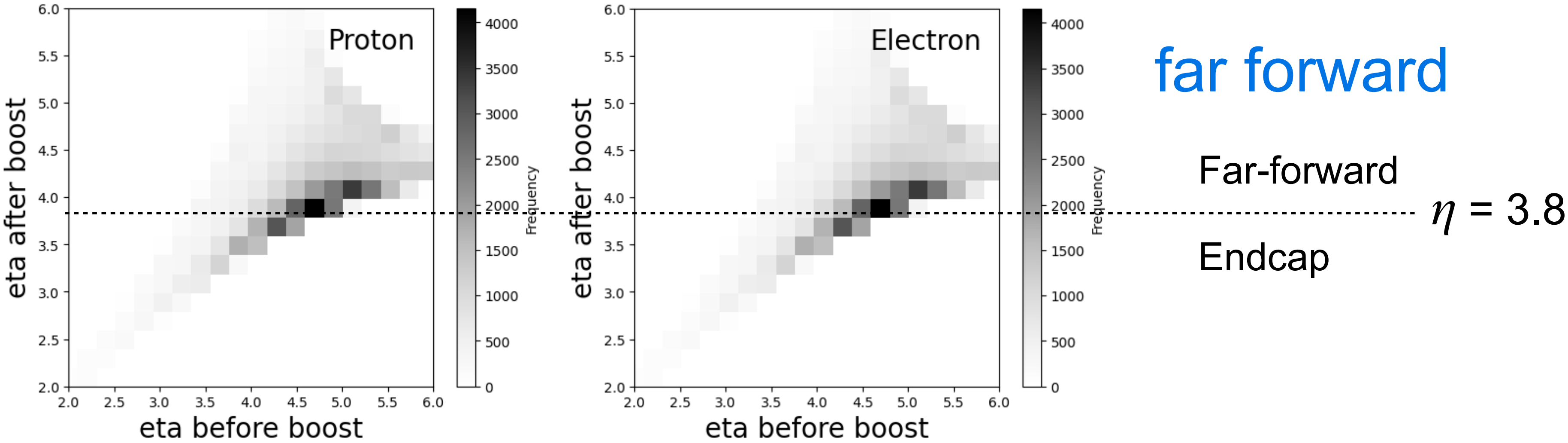
- $\mathrm{P_c}$(4312), pentaquark of $uudc\bar{c}$, can be well observed by ePIC through $p + J/\psi \;\rightarrow\; p + e^+ + e^-$ channel
- Endcap $(\eta \gtrsim 2)$
  - Good mass resolution, enough to separate $\mathrm{P_c}$(4440)
- Far-forward $(\eta \gtrsim 3.8)$
  - Far-forward system useful for proton reconstruction
  - Worse resolution and efficiency (acceptance)
  - High cross-section is predicted from VMD model
- Caveat (= rooms for improvement)
  - Assumed PID works perfectly
  - No backgrounds from other *pe⁺e⁻ channels*
  - Study for other beam energies



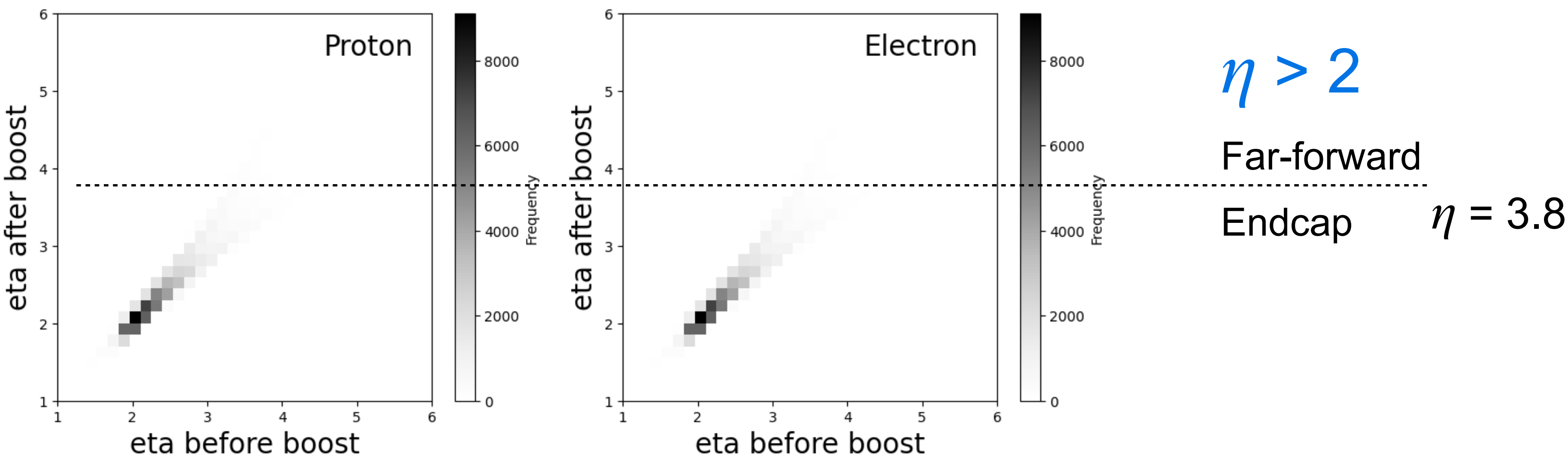


BACKUP

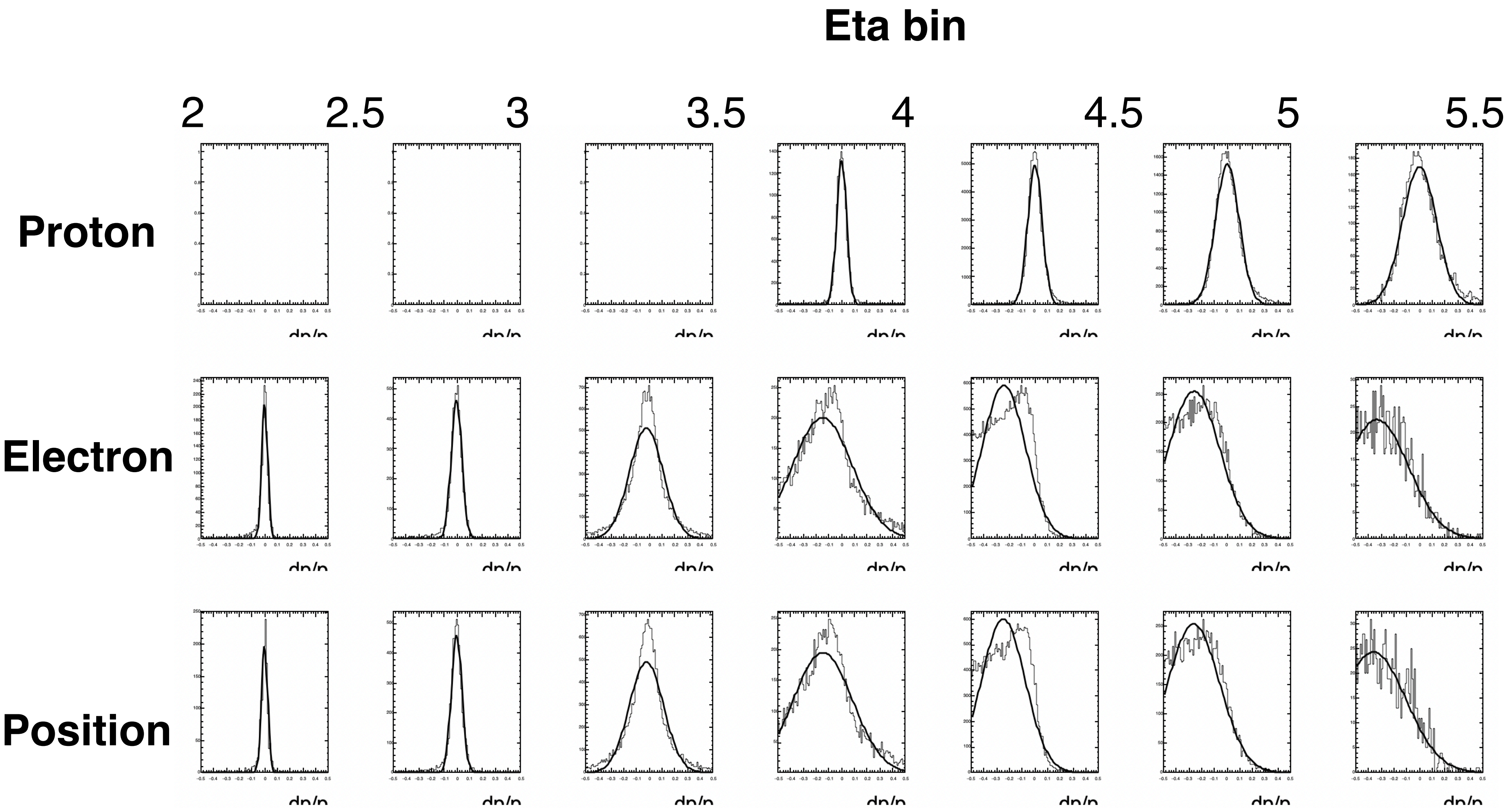
far forward



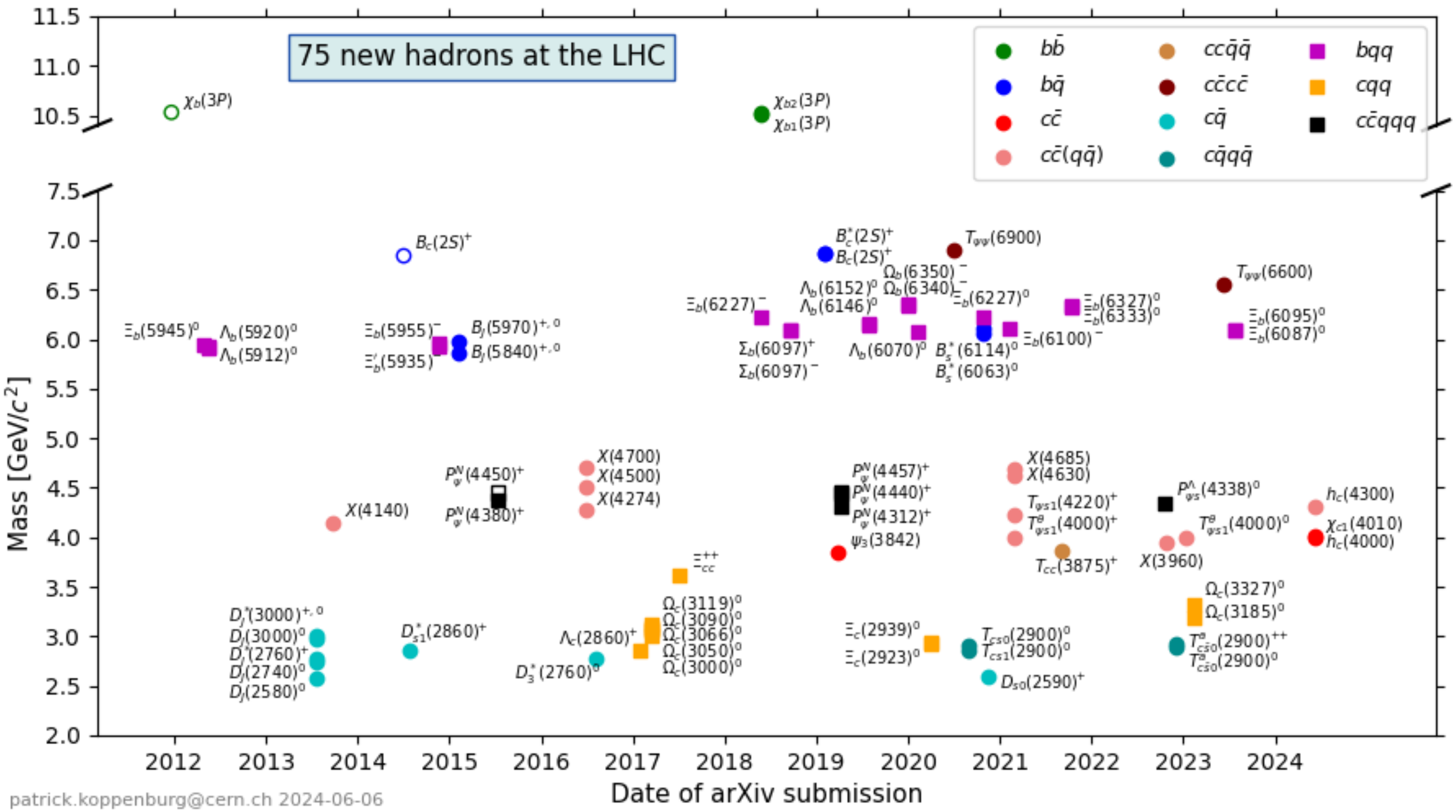
$\eta > 2$



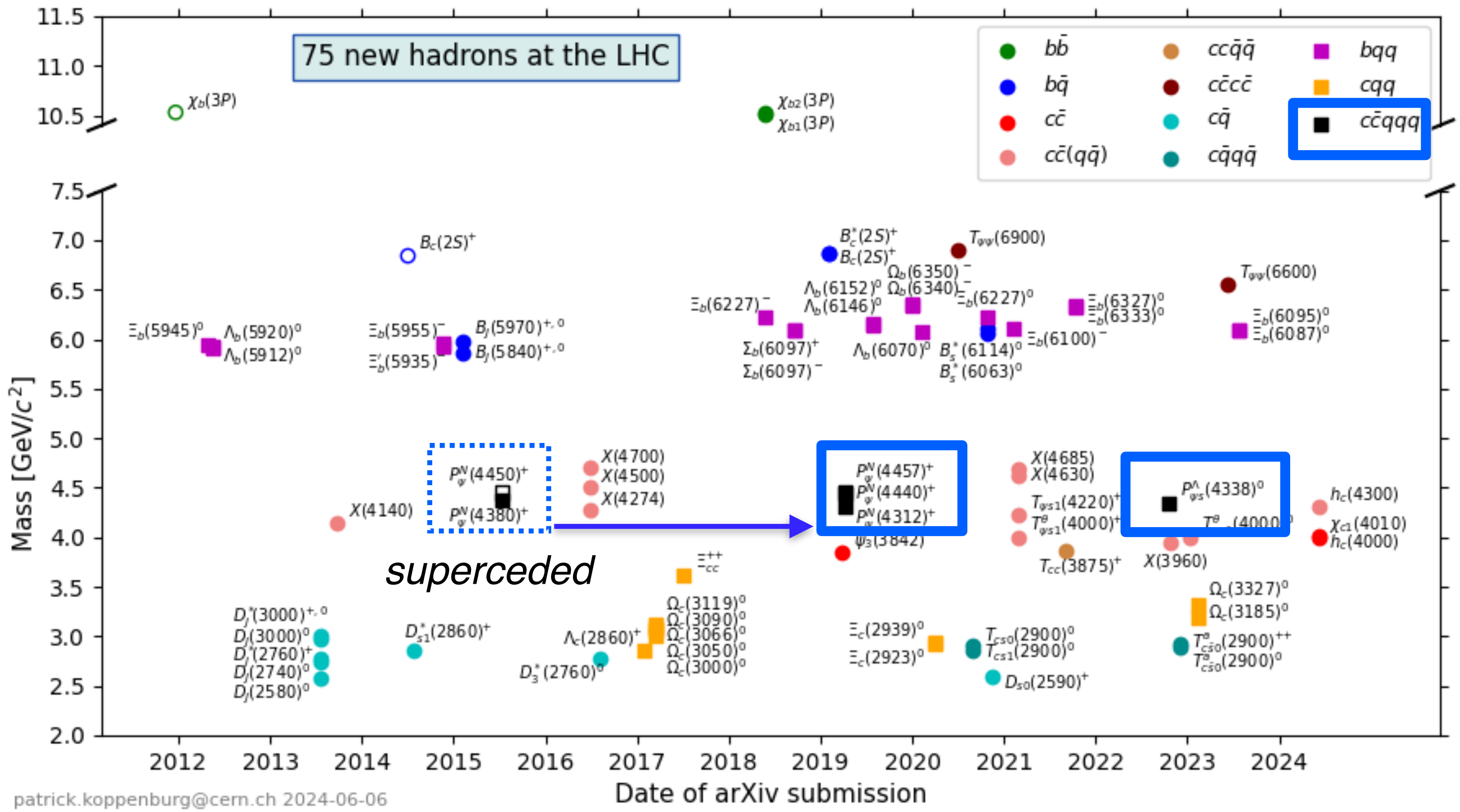
Momentum ($|\vec{p}|$) resolution



New exotic particles at LHCb



New exotic particles at LHCb



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

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

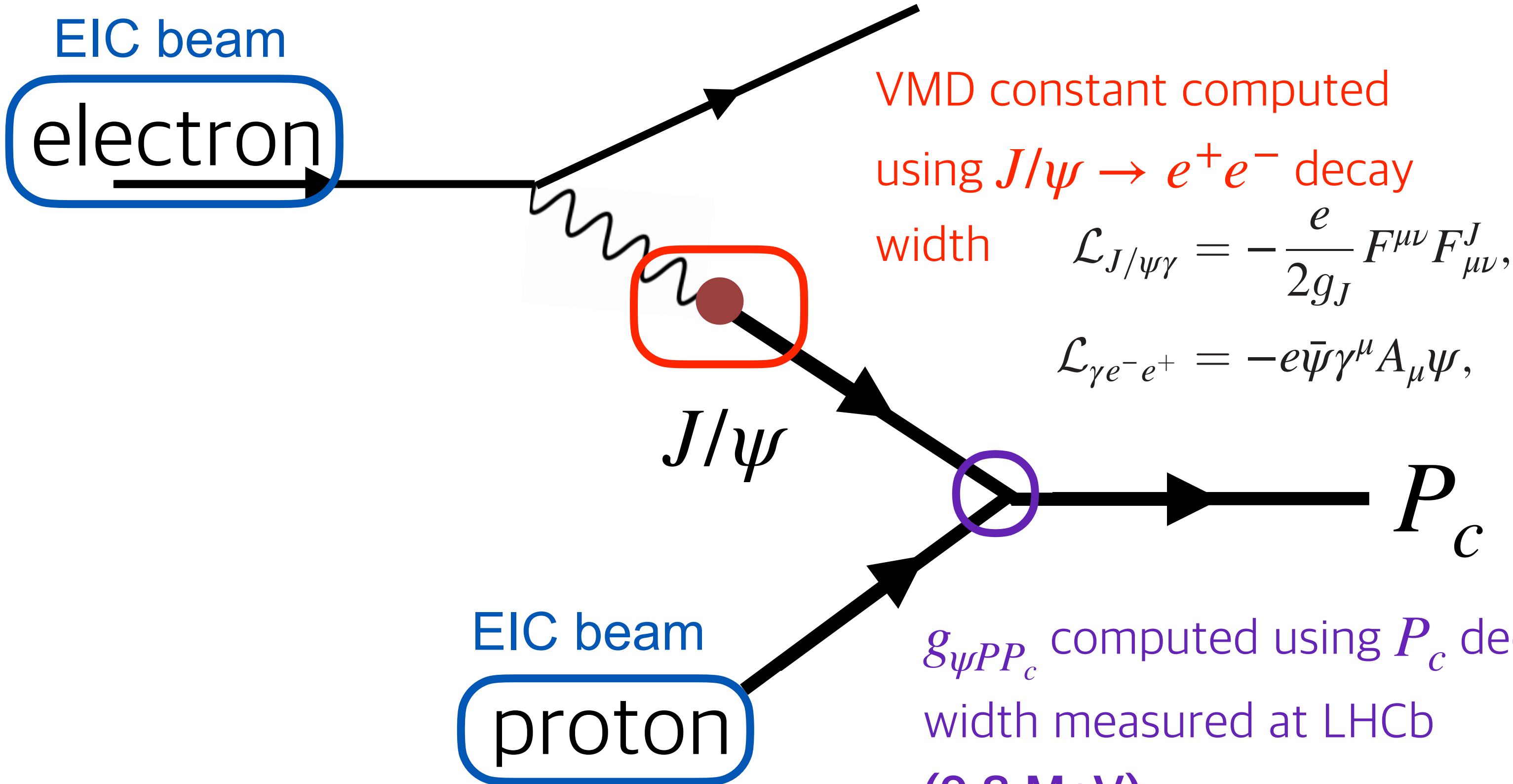
[Submitted on 12 Feb 2024]

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

Computation of P_c cross section at EIC



VMD constant computed using $J/\psi \to e^+e^-$ decay width

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

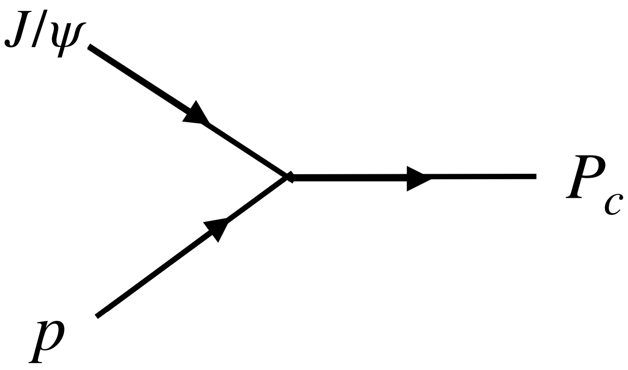
$$\mathcal{L}_{\gamma e^- e^+} = -e\bar{\psi}\gamma^\mu A_\mu \psi,$$

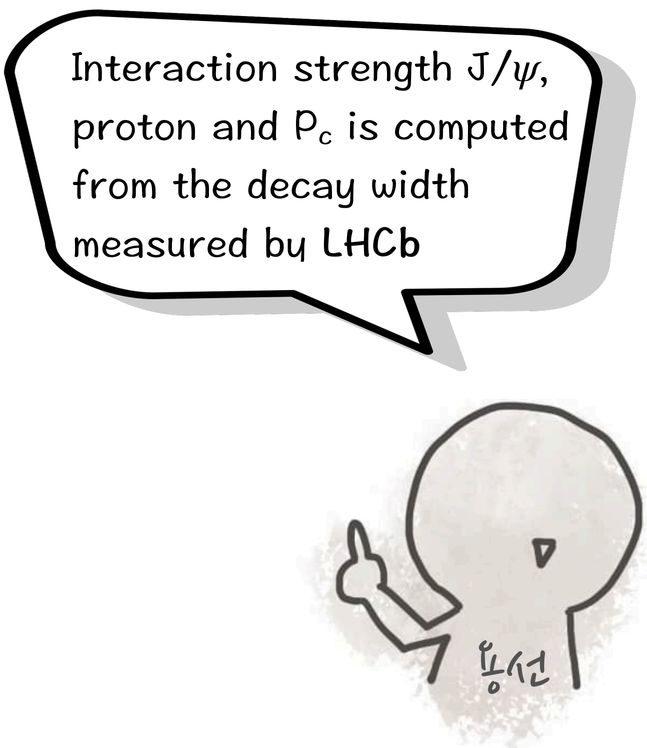
$g_{\psi P P_c}$ computed using P_c decay width measured at LHCb **(9.8 MeV)**

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

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

Formalism





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

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

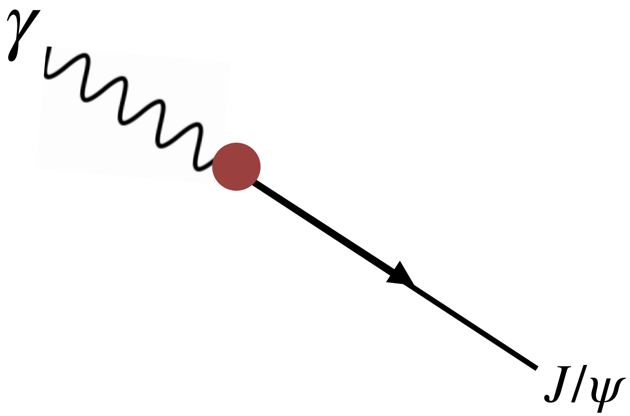
- Fixing interaction strength from Γ

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

- 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

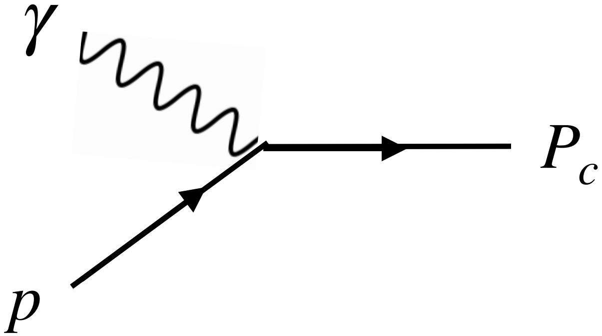


- Vector meson dominance model

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

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

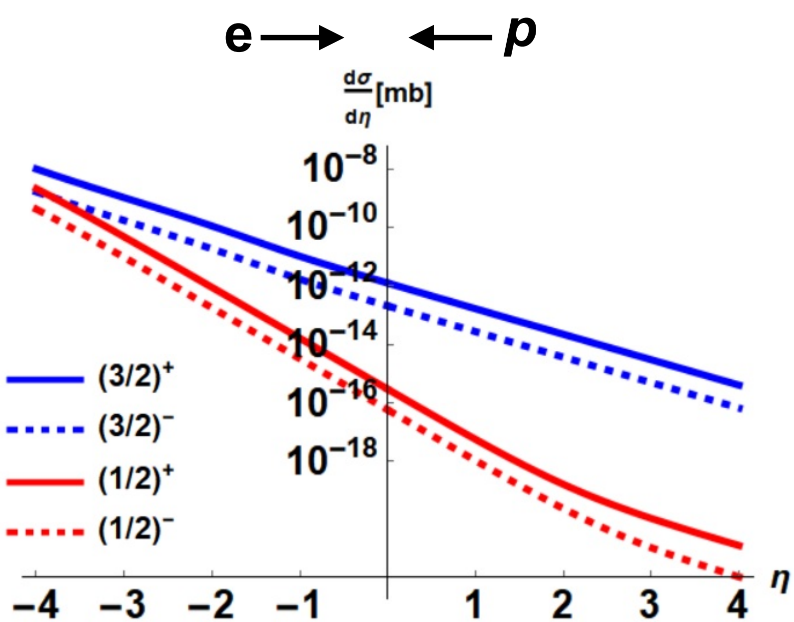
- Coupling constant g_J is computed from $J/\psi \to e^+e^-$ decay width
  - Γ = 95.9 keV x 5.97%



- 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



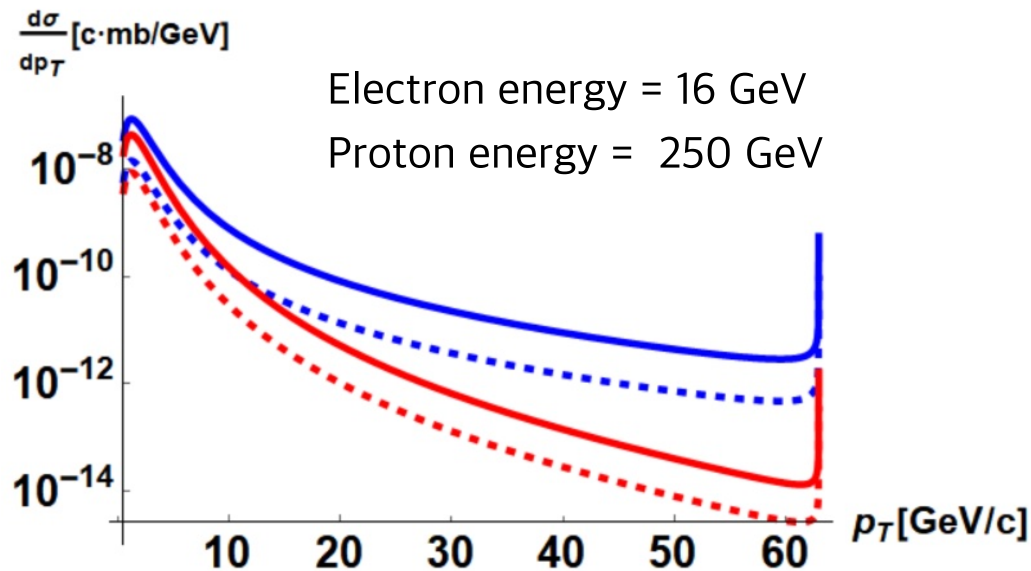
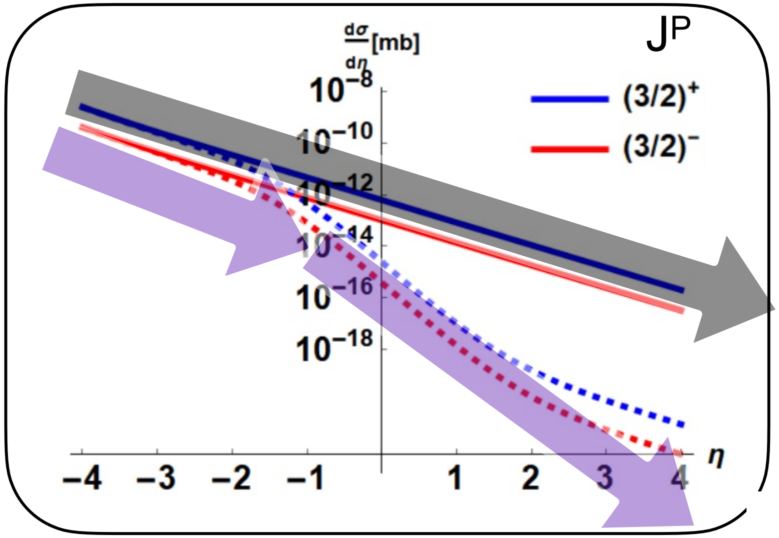


TABLE II. Expected number of $P_c(4312)$ produced at the EIC with 10 fb^{-1}.

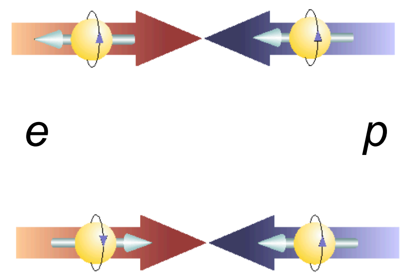
J^P of P_c	$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$
Yield	5.67×10^3	1.13×10^3	4.32×10^4	7.15×10^3

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

P_c(4312) yields in polarized e+p



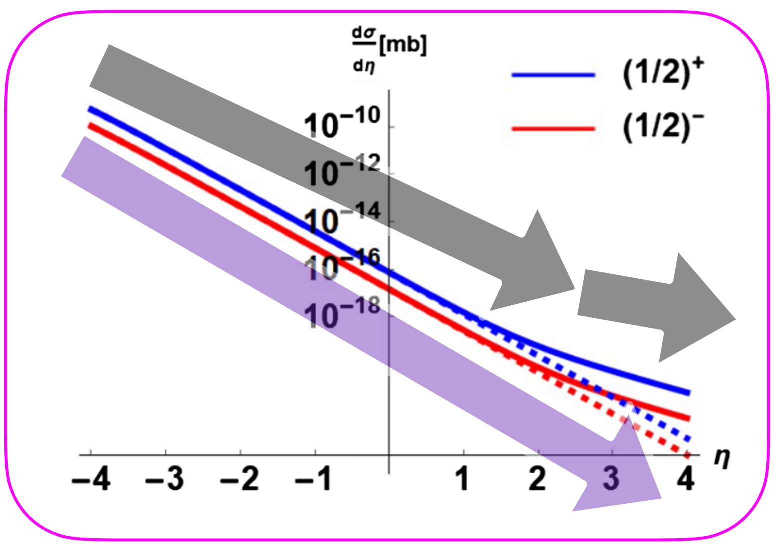
Spin 3/2 case



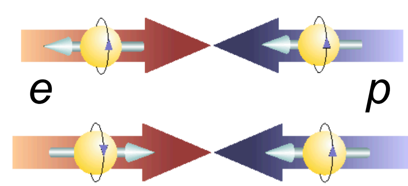
Parallel polarization

Anti-parallel polarization

e beam *p beam*



Spin 1/2 case

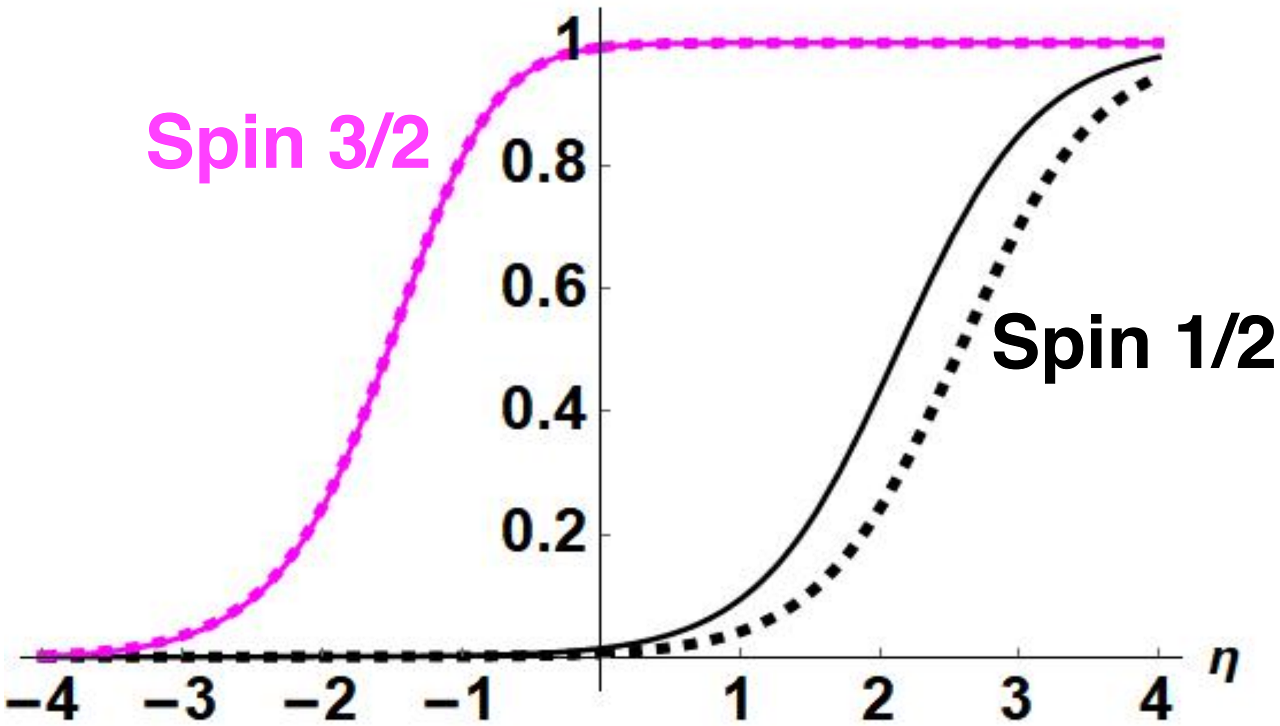


Parallel polarization

Anti-parallel polarization

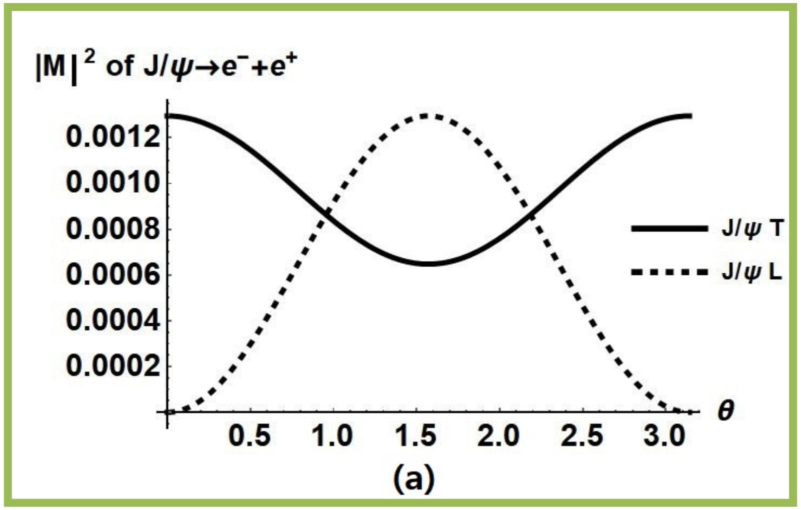
$P_c(4312)$ yields in polarized e+p

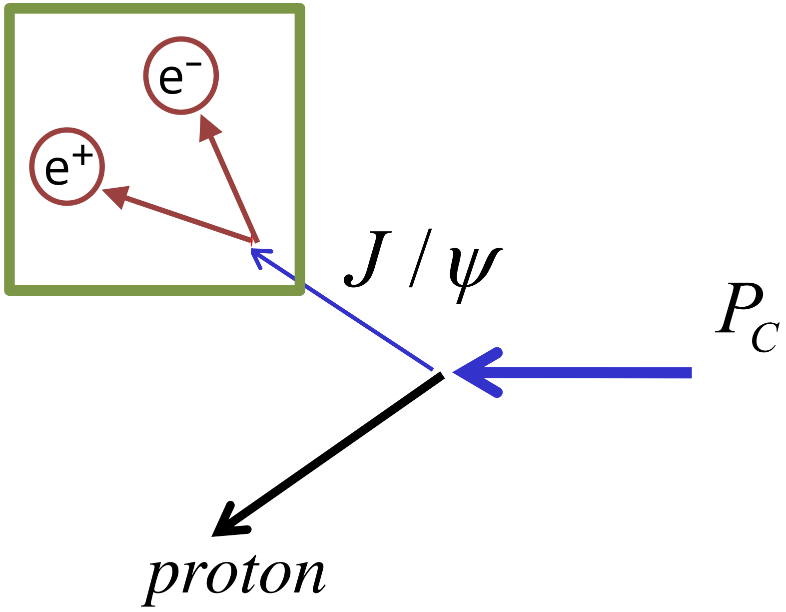
$$BSA\ (\eta) = \frac{d\sigma/d\eta\ [RL] - d\sigma/d\eta\ (RR)}{d\sigma/d\eta\ [RL] + d\sigma/d\eta\ [RR]}$$



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

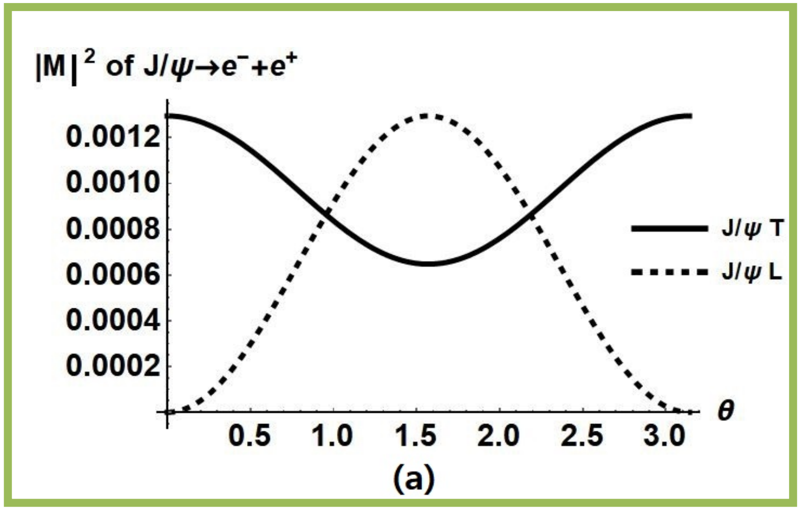
Determination of parity at EIC

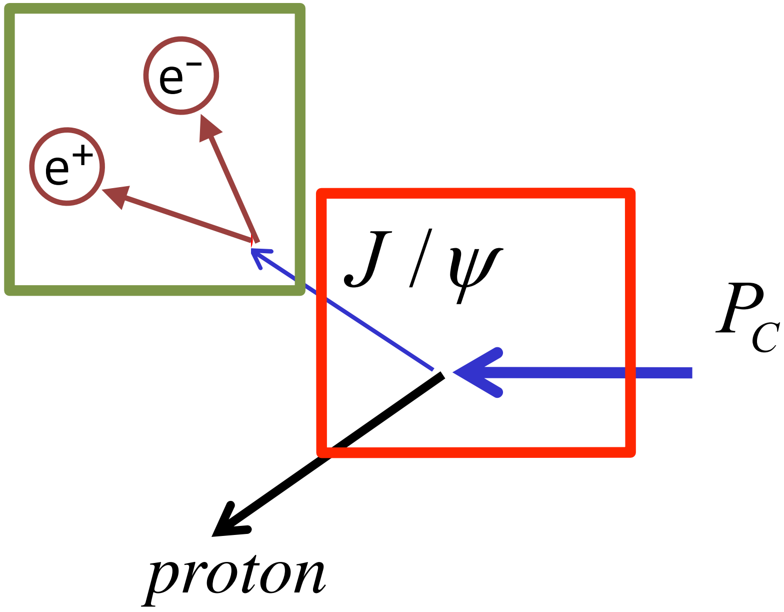




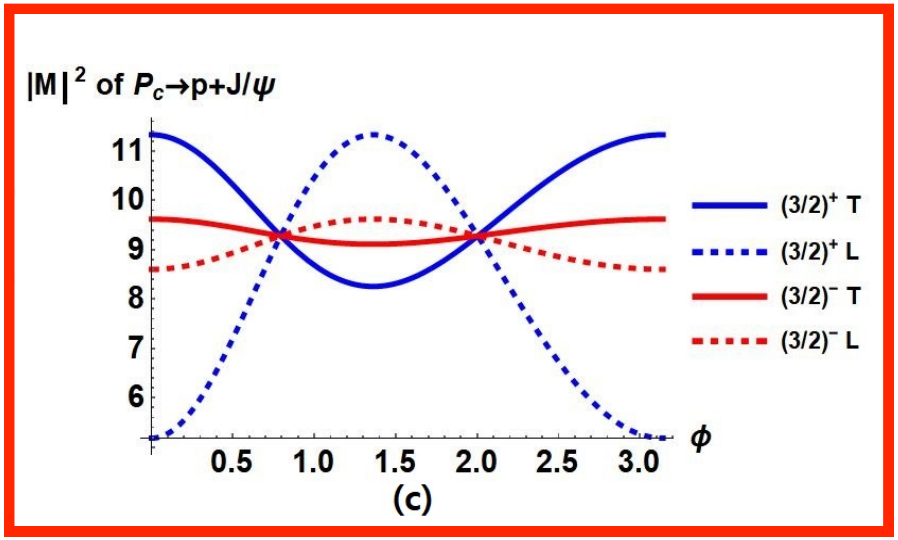
- J/ψ has spin-1 and its polarity can be measured from the decay kinematics

Determination of parity at EIC

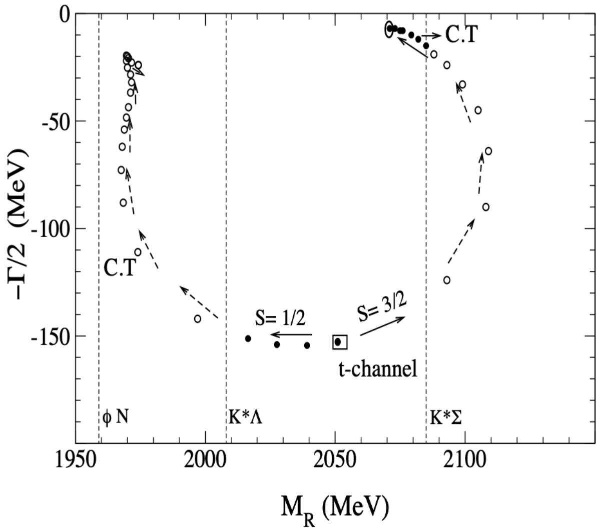


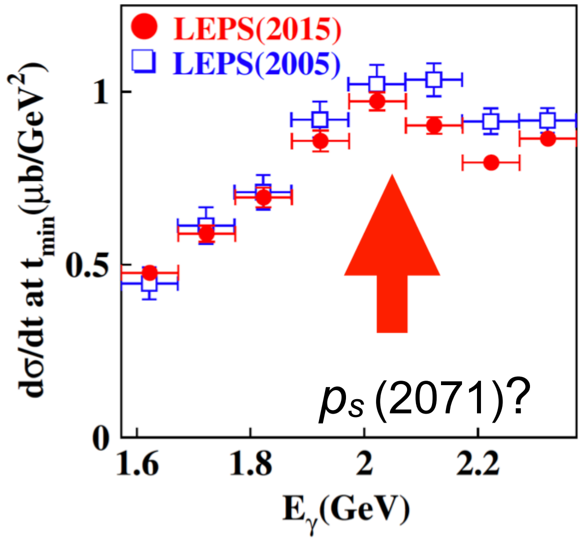


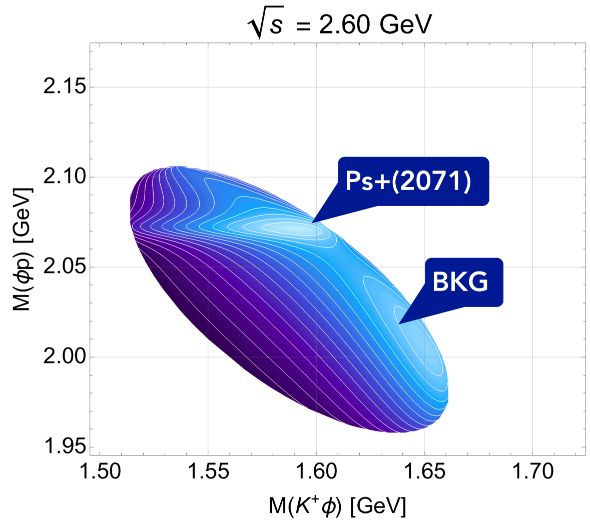
- J/ψ has spin-1 and its polarity can be measured from the decay kinematics
- Parity can be experimentally determined by polarized e+p collision at EIC



Photoproduction of P_s





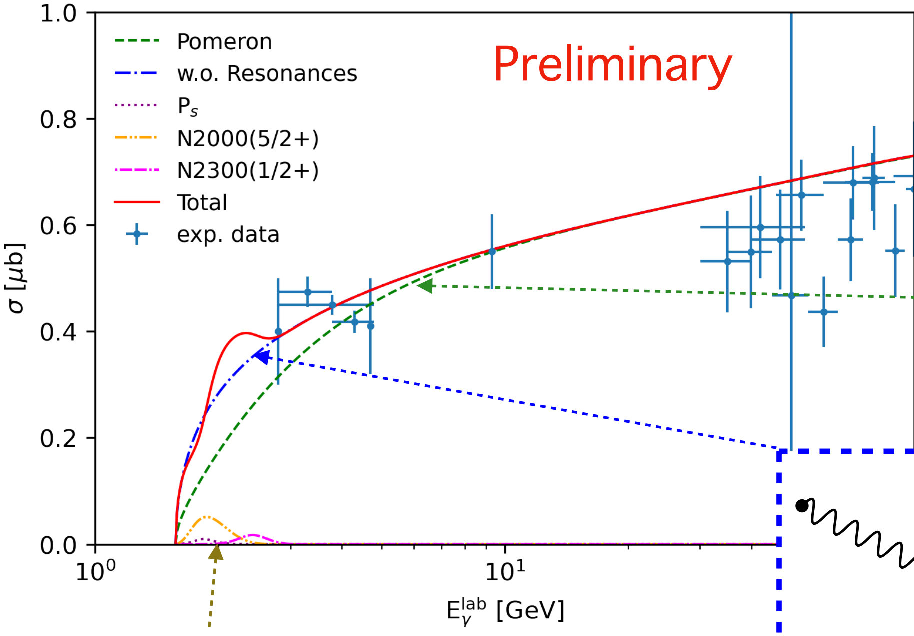


- Calculation predicted a resonance of P_s ($uuds\bar{s}$) near $\Sigma + K^*$ [1]
- SI Nam showed that if $p_s(2071)$ ever exists, the resonance would appear in the $K^+p \rightarrow K^+\phi p$ Dalitz plot [1]
- Considering VMD model, the same phenomenon can happen in the $\gamma + p \rightarrow (p_s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

[1] Khemchandani et al PRD 83, 114041 (2011)

Cross section of ϕ photo-production

Total cross cross section



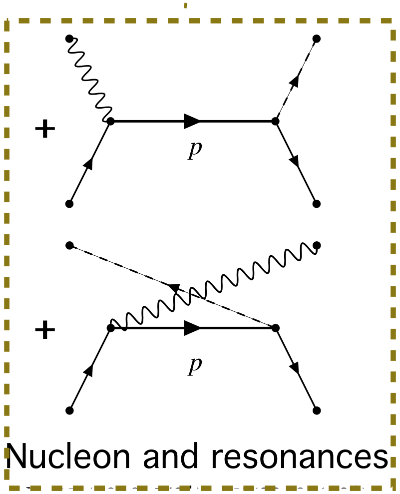
Experimental data points

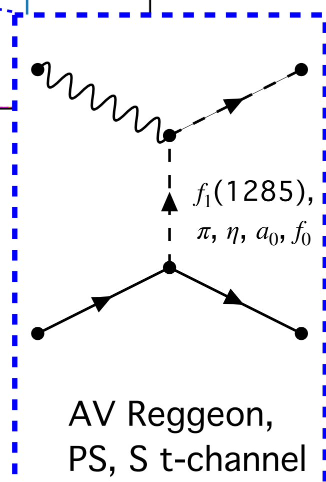
J. Ballam et al. PRD 7, 3150 (1973)

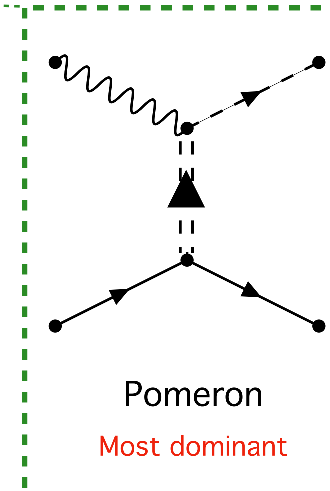
D. P. Barber et al., Z. Phys. C 12, 1 (1982)

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

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?**