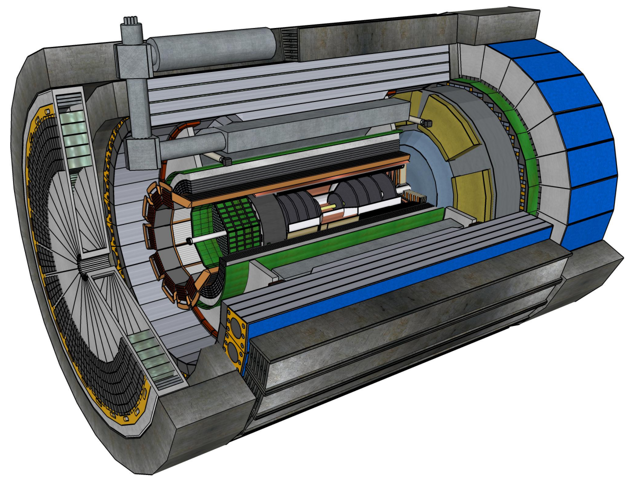
ePIC/EIC resolutions and systematics

Tyler Kutz (MIT)

INT-24-87W: Electroweak and
Beyond the Standard Model Physics at the EIC

February 12, 2024

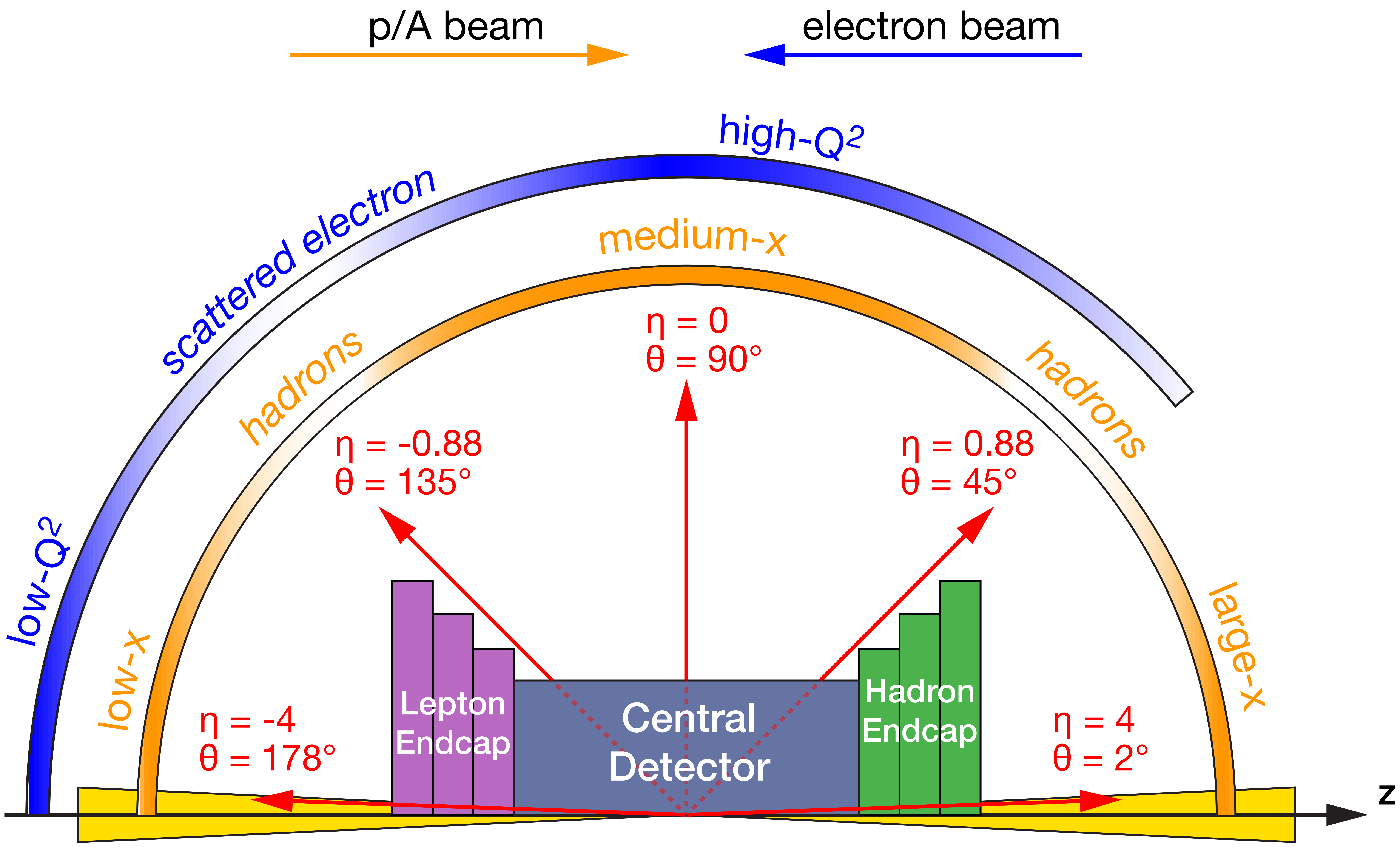


Two caveats

It's difficult to evaluate systematics for an experiment 10 years in the future.

Current simulations/reconstruction results subject to improvement!

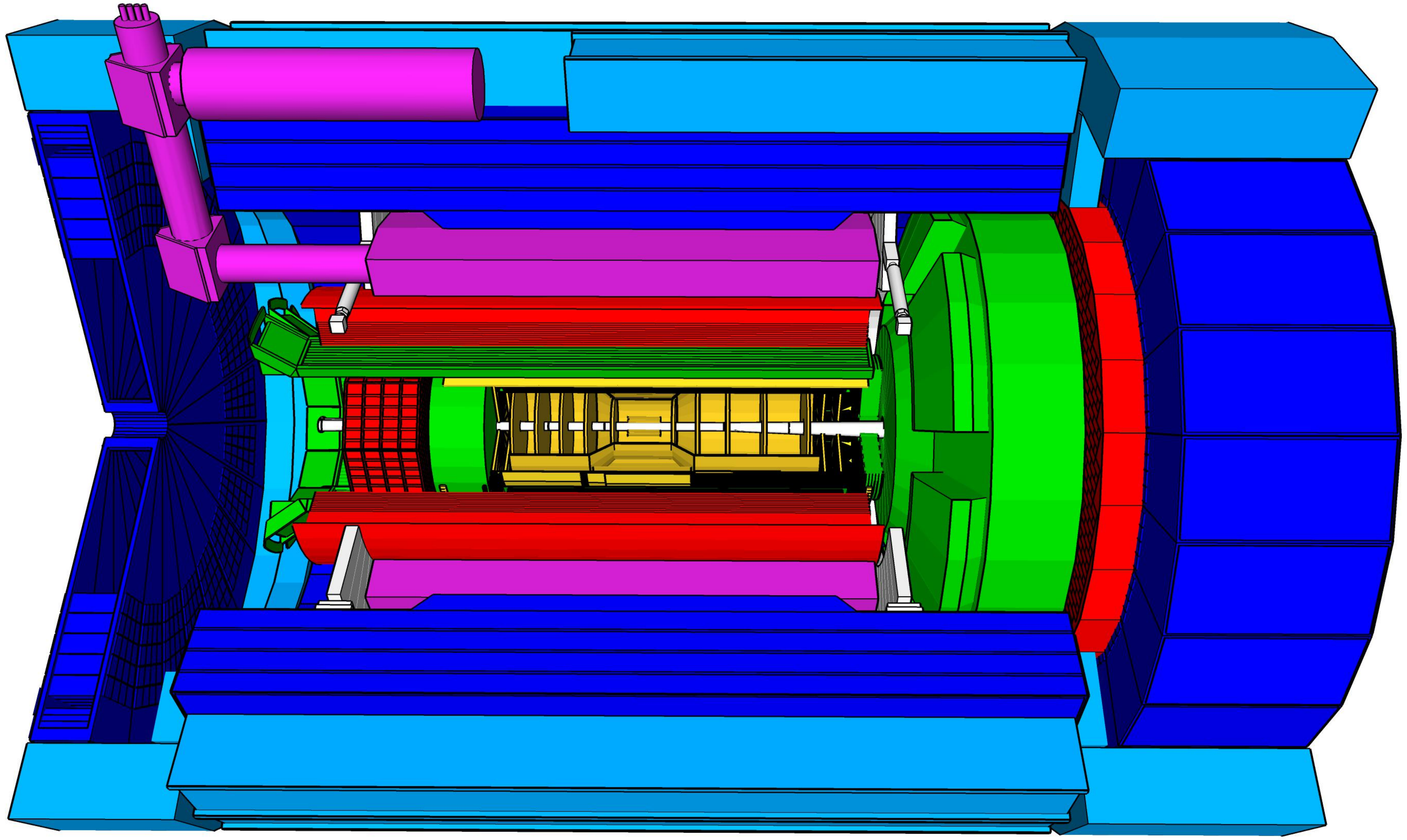
ePIC designed to be hermetic, multi-purpose detector



Reconstruction of *both* scattered electron *and* hadronic final state critical to EIC physics program

ePIC designed to be hermetic, multi-purpose detector

p/A beam →



← e^- beam

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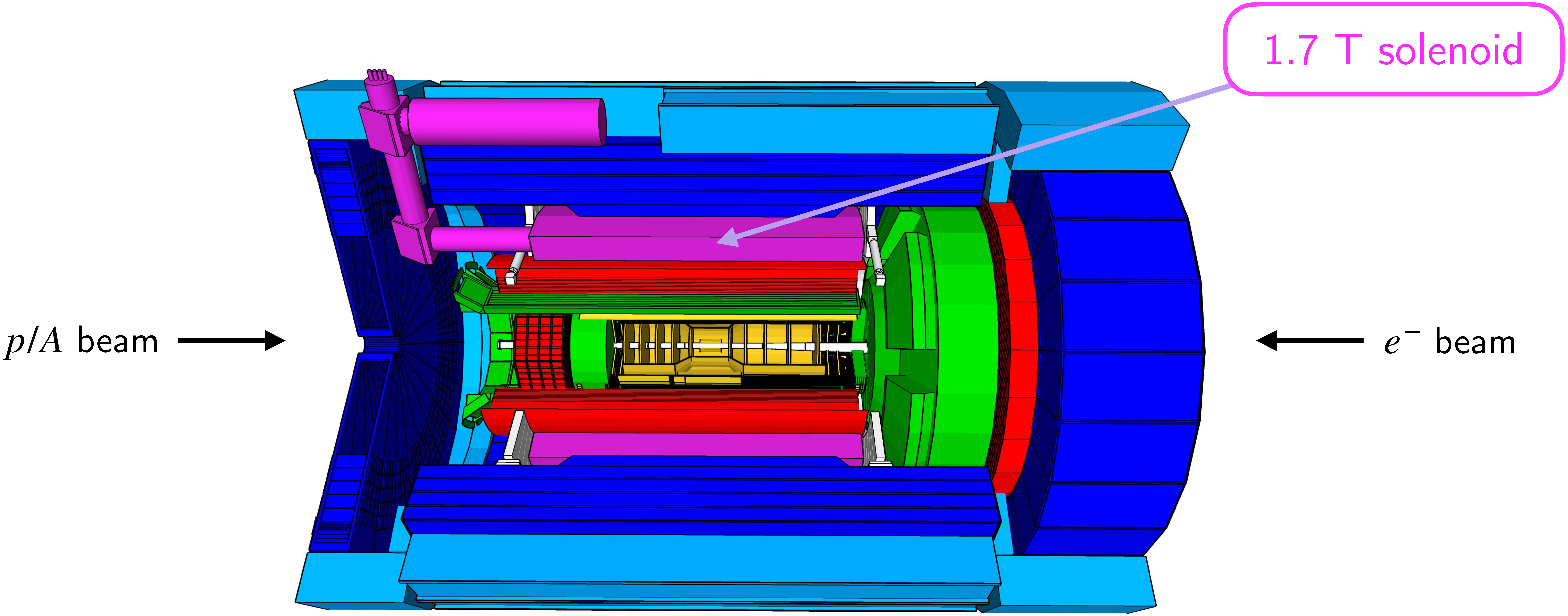

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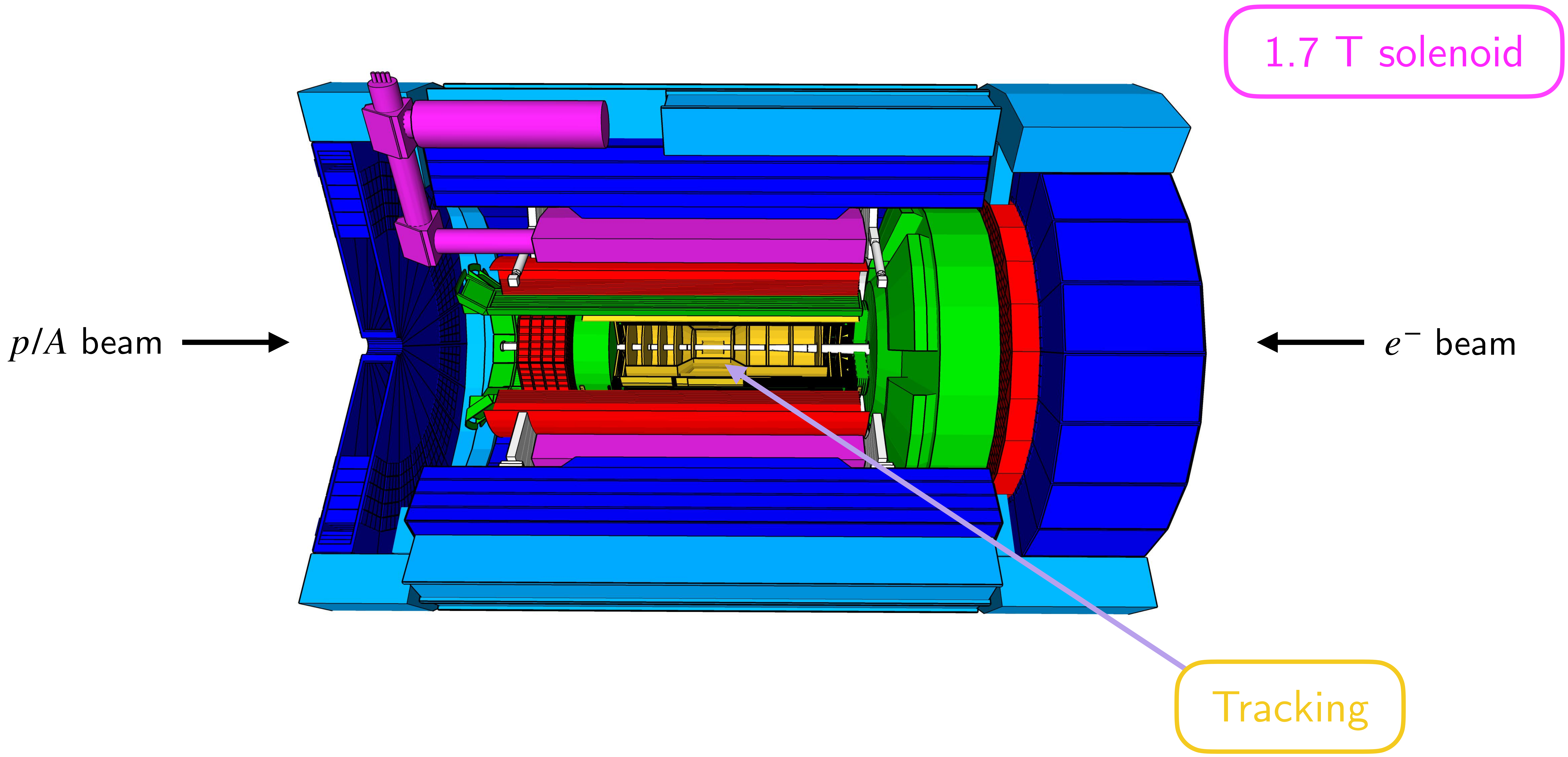

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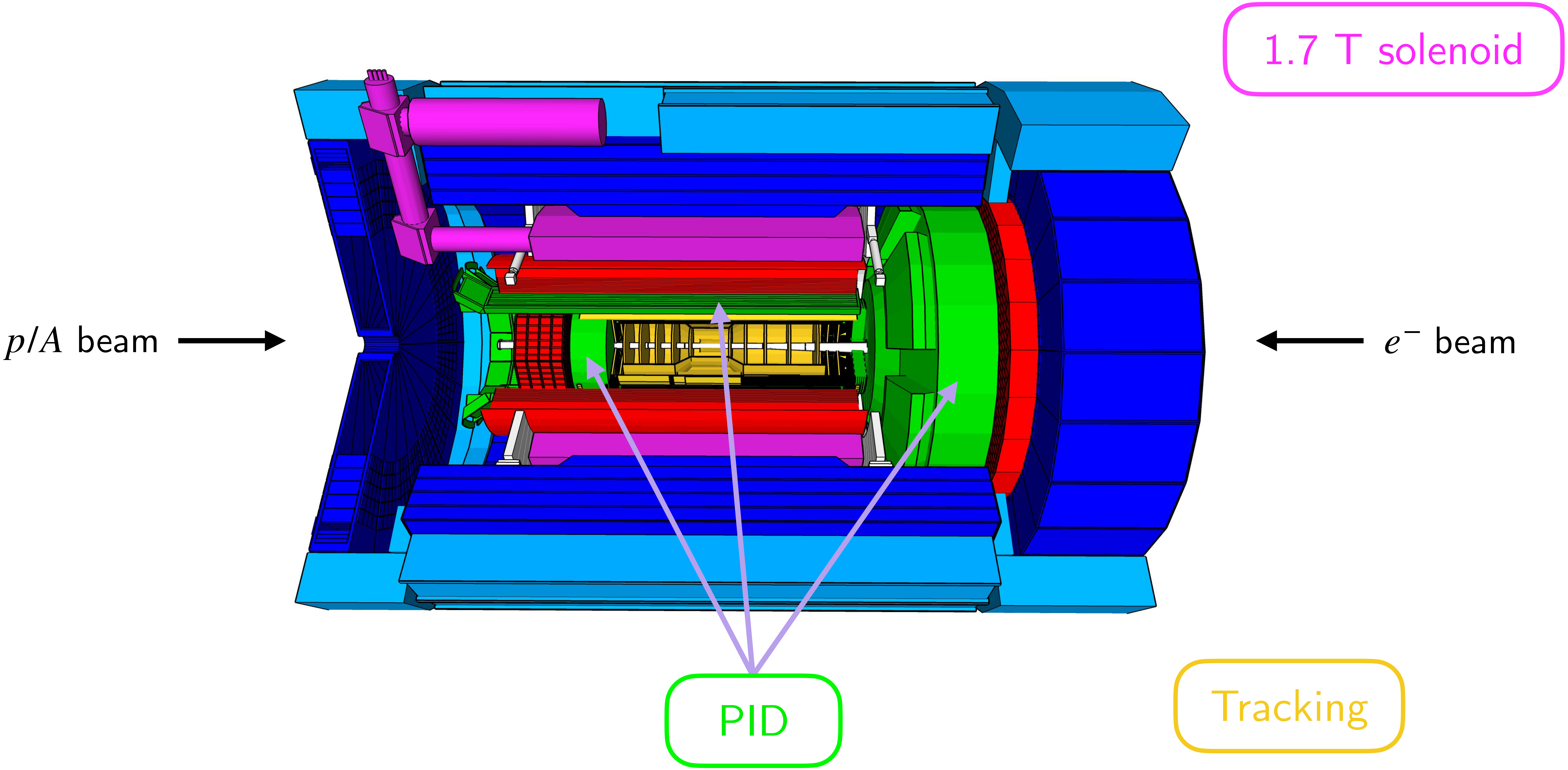

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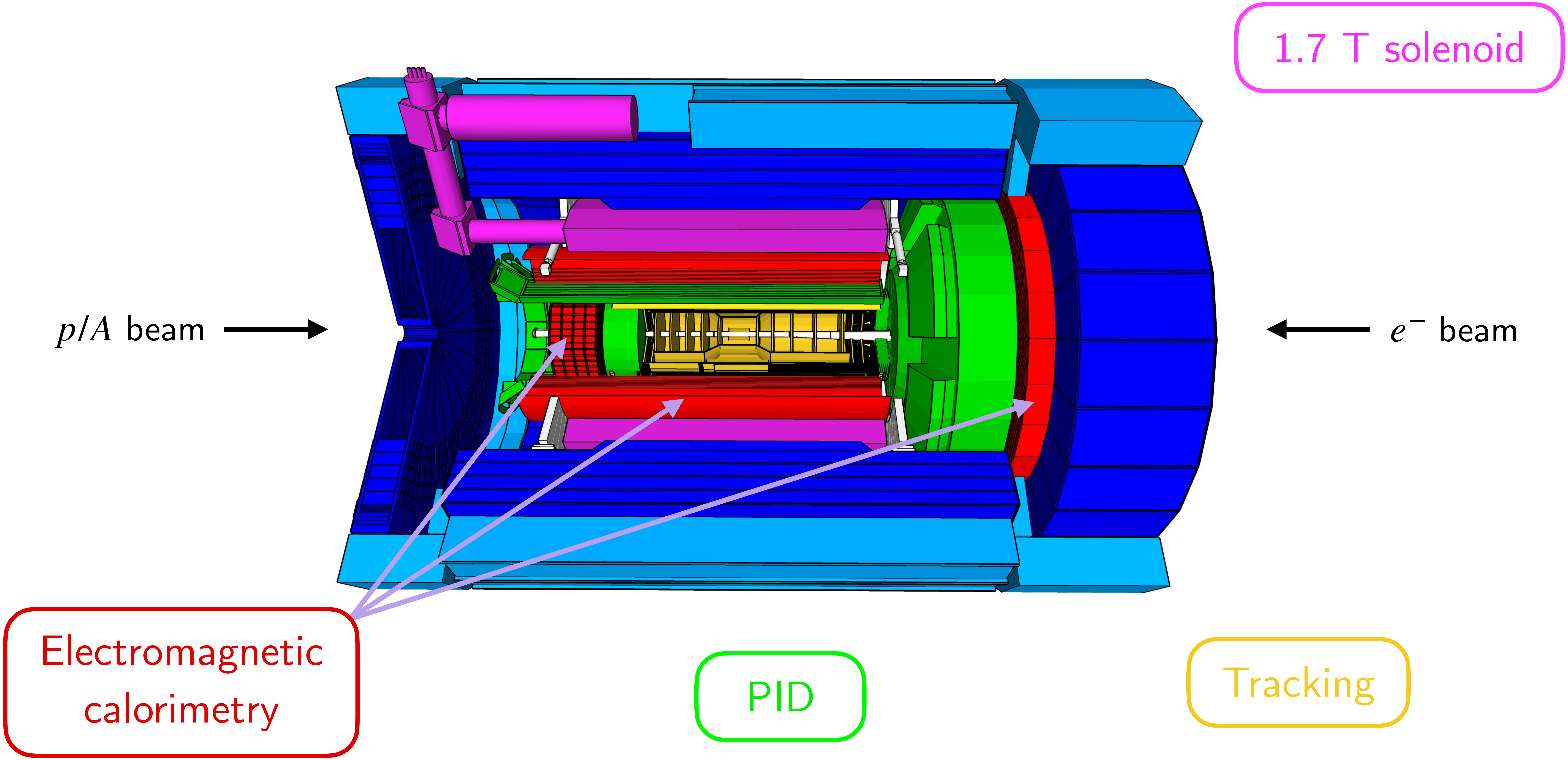

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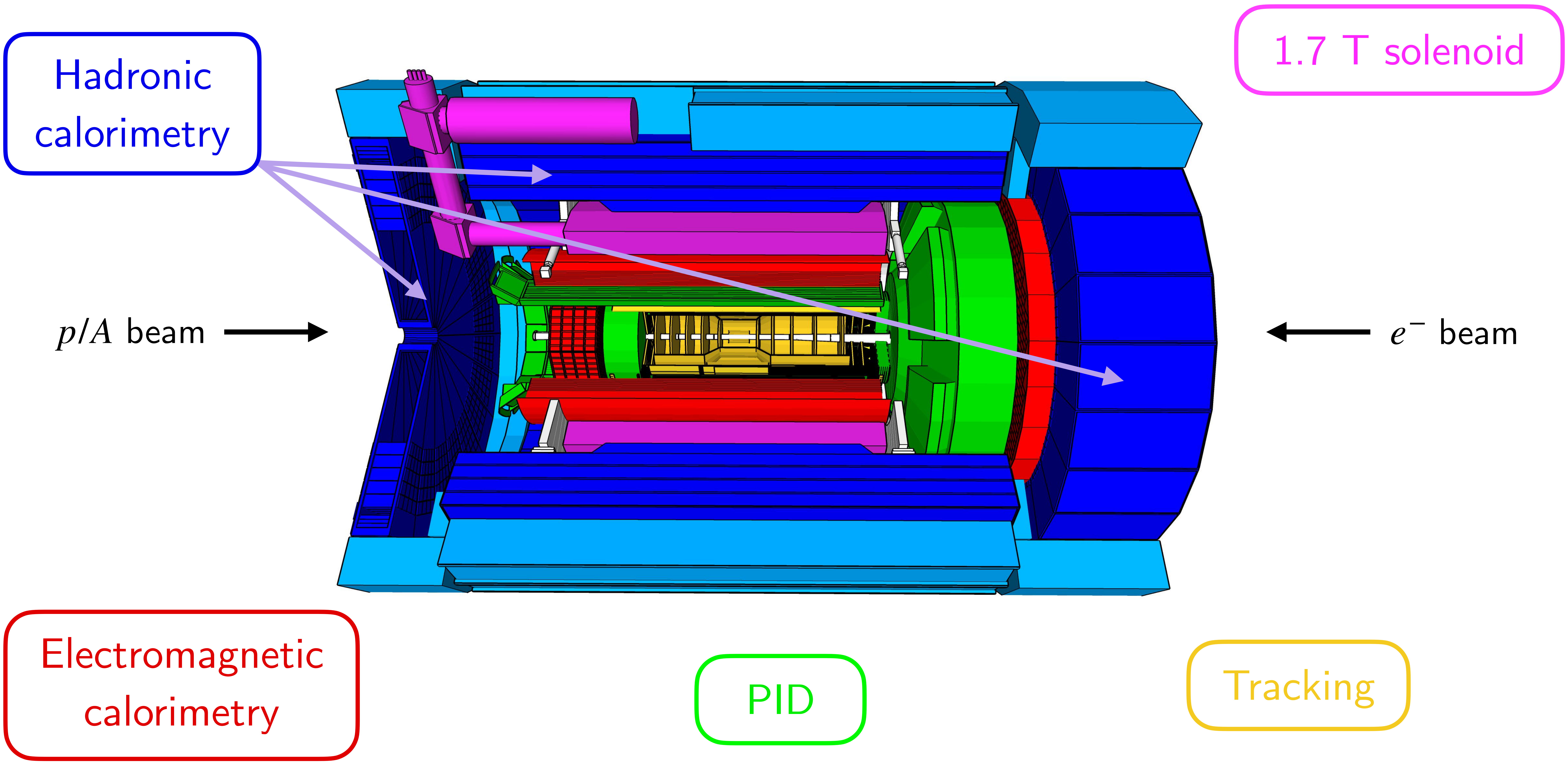
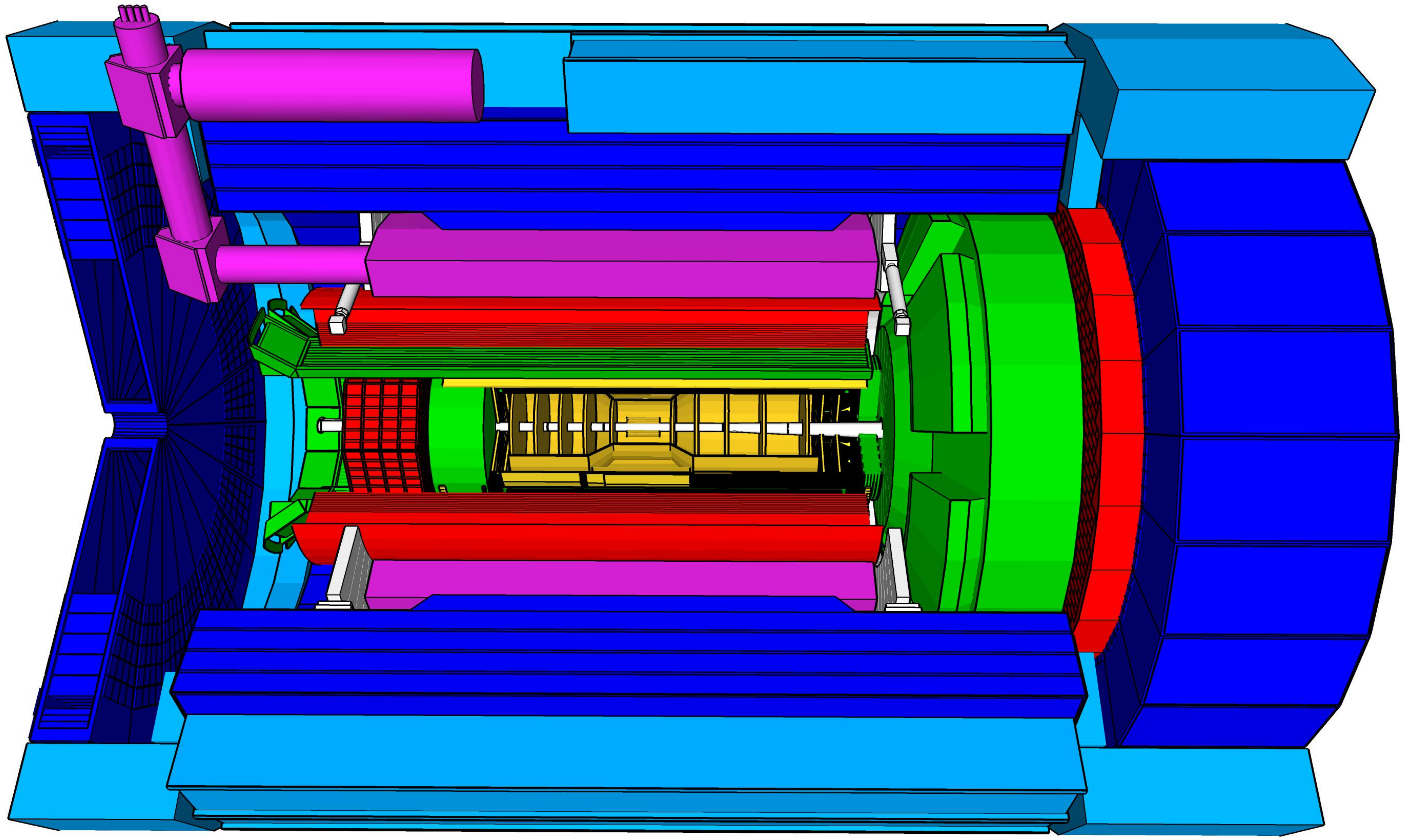


ePIC designed to be hermetic, multi-purpose detector

Hadronic calorimetry

1.7 T solenoid



p/A beam →

← e^- beam

Electromagnetic calorimetry

PID

Tracking

Motivation:
some EIC observables and related systematics

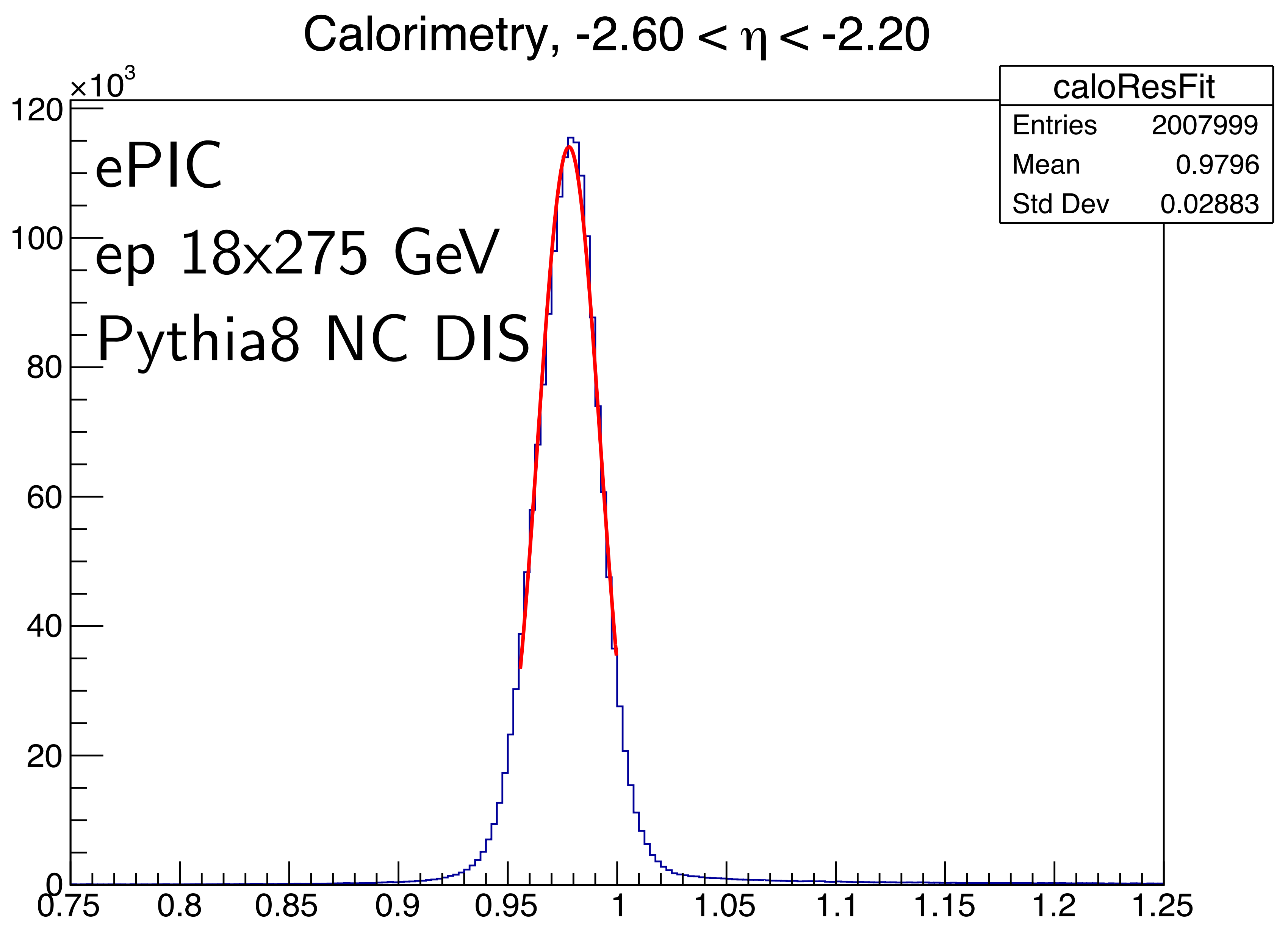
- Parity-violating asymmetries A_{PV}
- A_1^p from double-spin asymmetries
  - Limited by electron purity
  - Q^2 dependence critical!

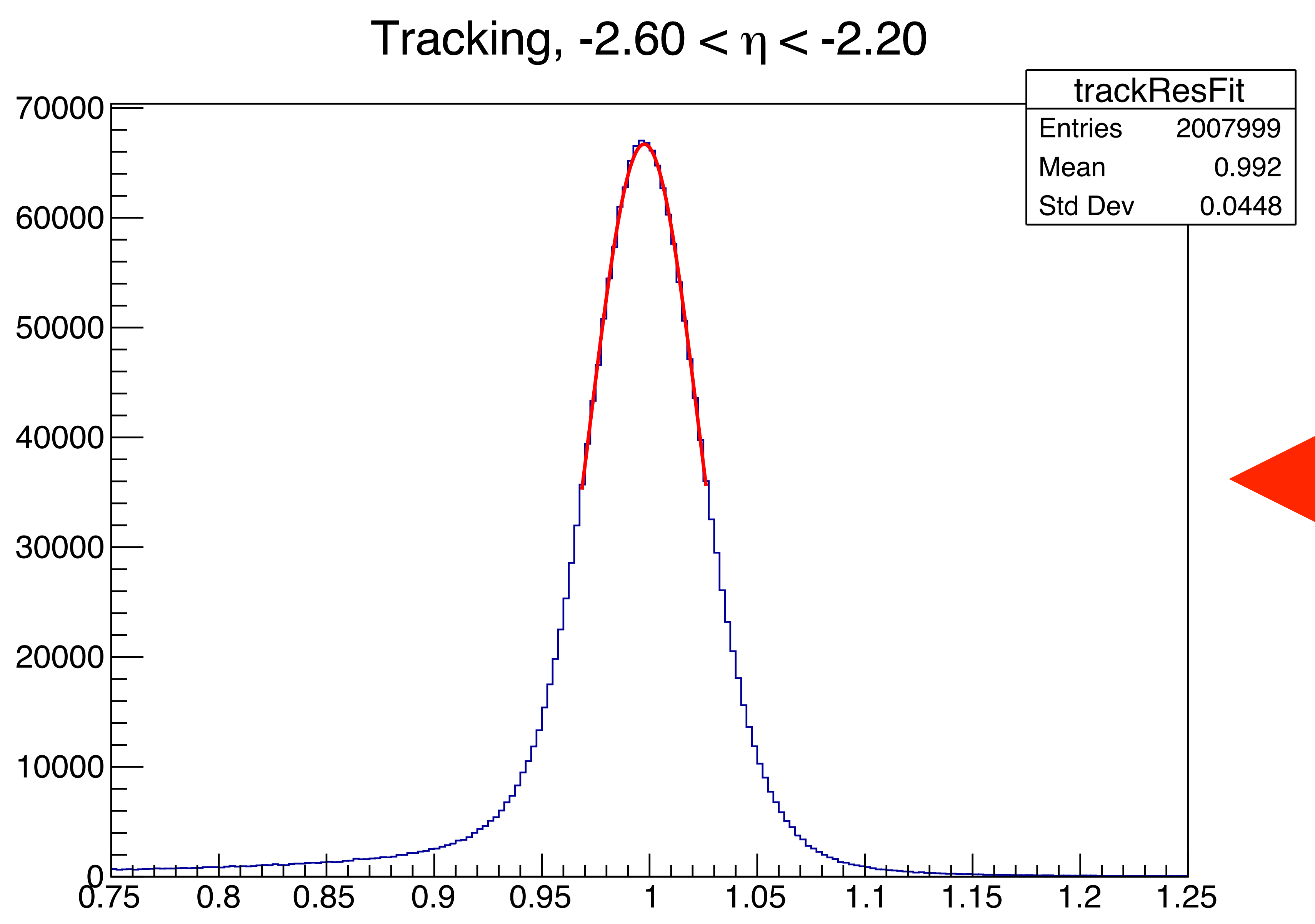
- F_L from reduced cross sections
- Fit y dependence for fixed $\left(x_B, Q^2\right)$
  - Must combine multiple beam energies
  - π contamination depends strongly on y

Overview

- Electron energy resolutions
- Calibration of electromagnetic calorimeters
- Kinematic reconstruction
- Electron identification and purity
- Luminosity & polarization

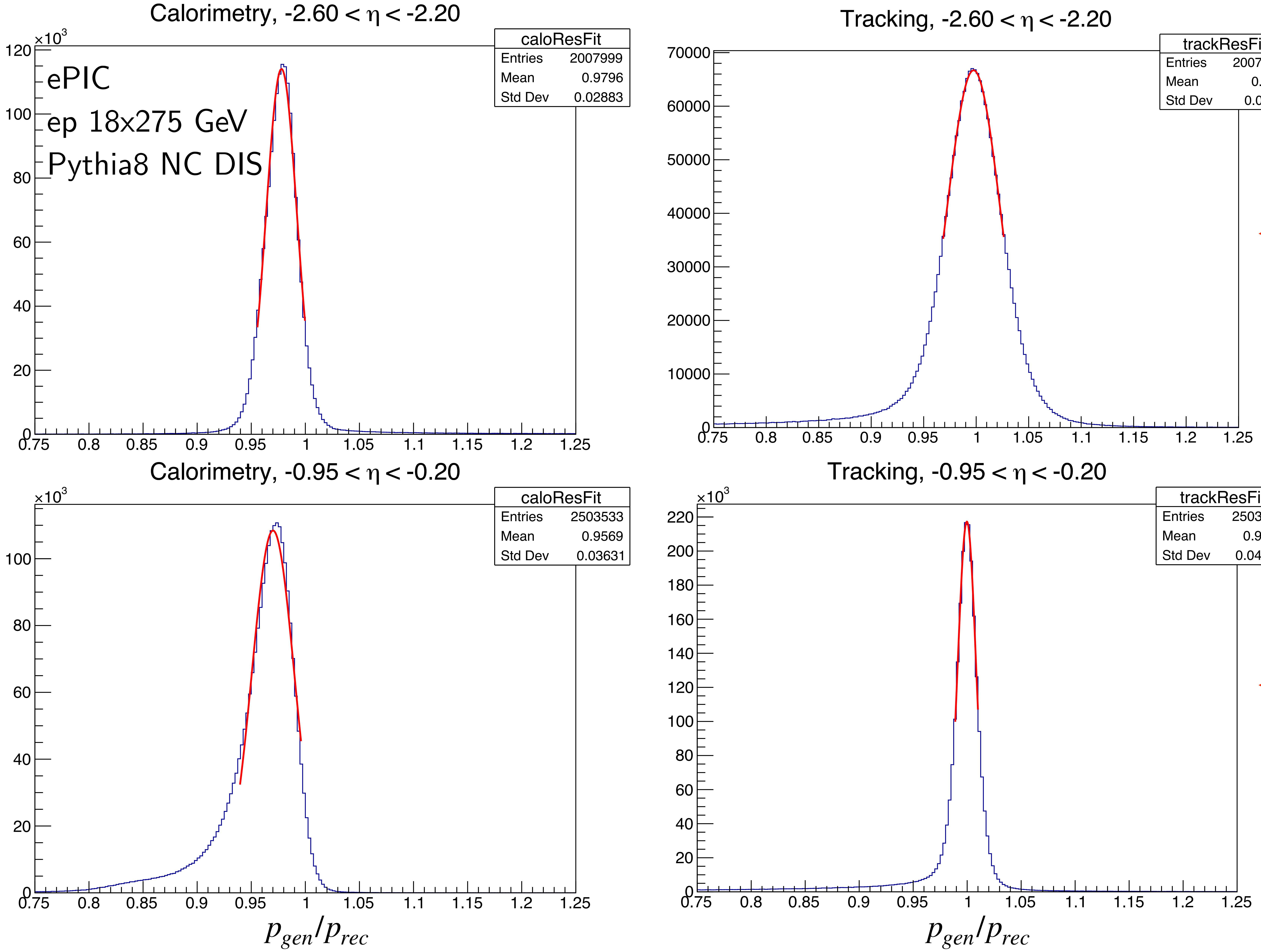
Electron momentum resolutions





Calorimeter resolution better in endcap

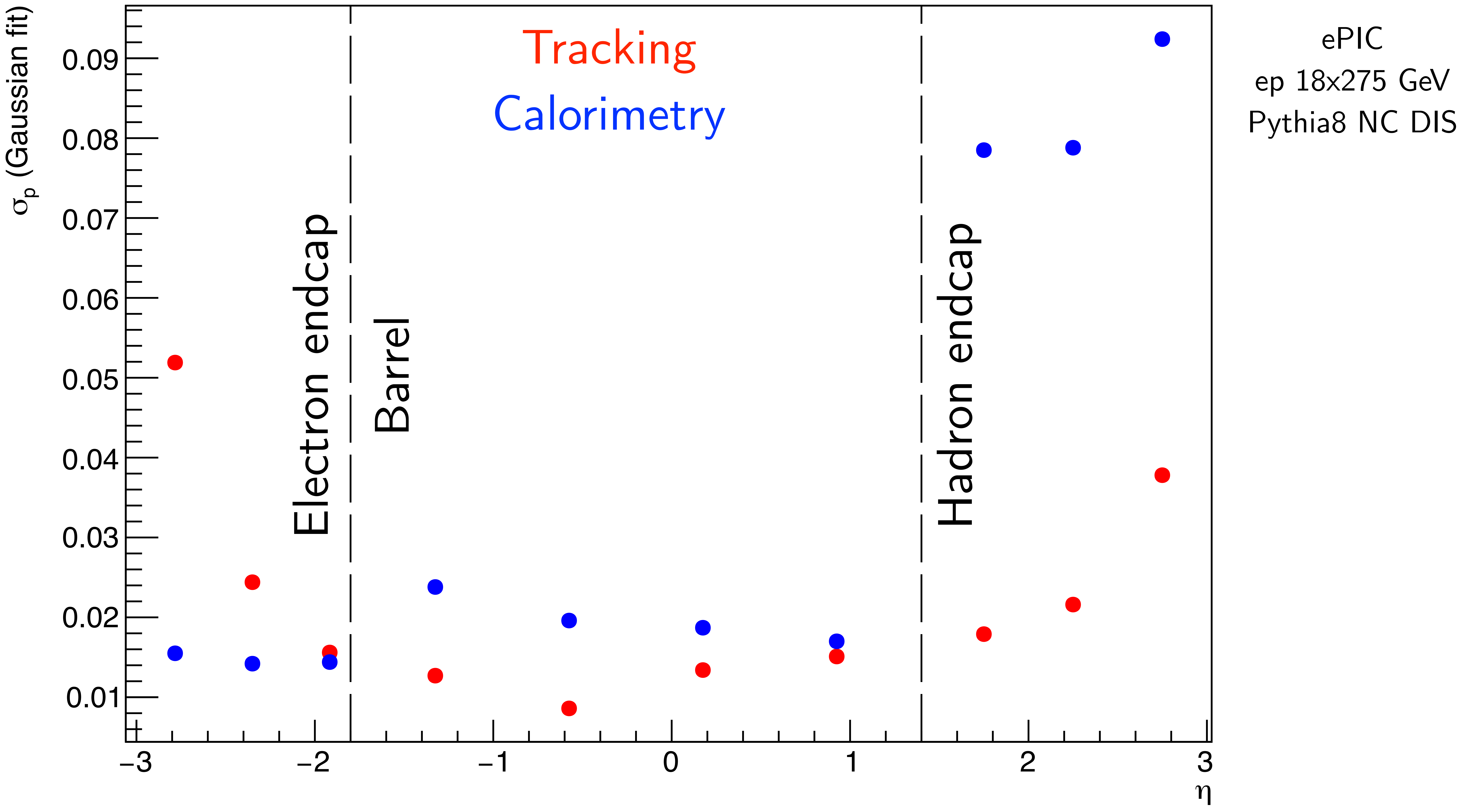
Electron momentum resolutions



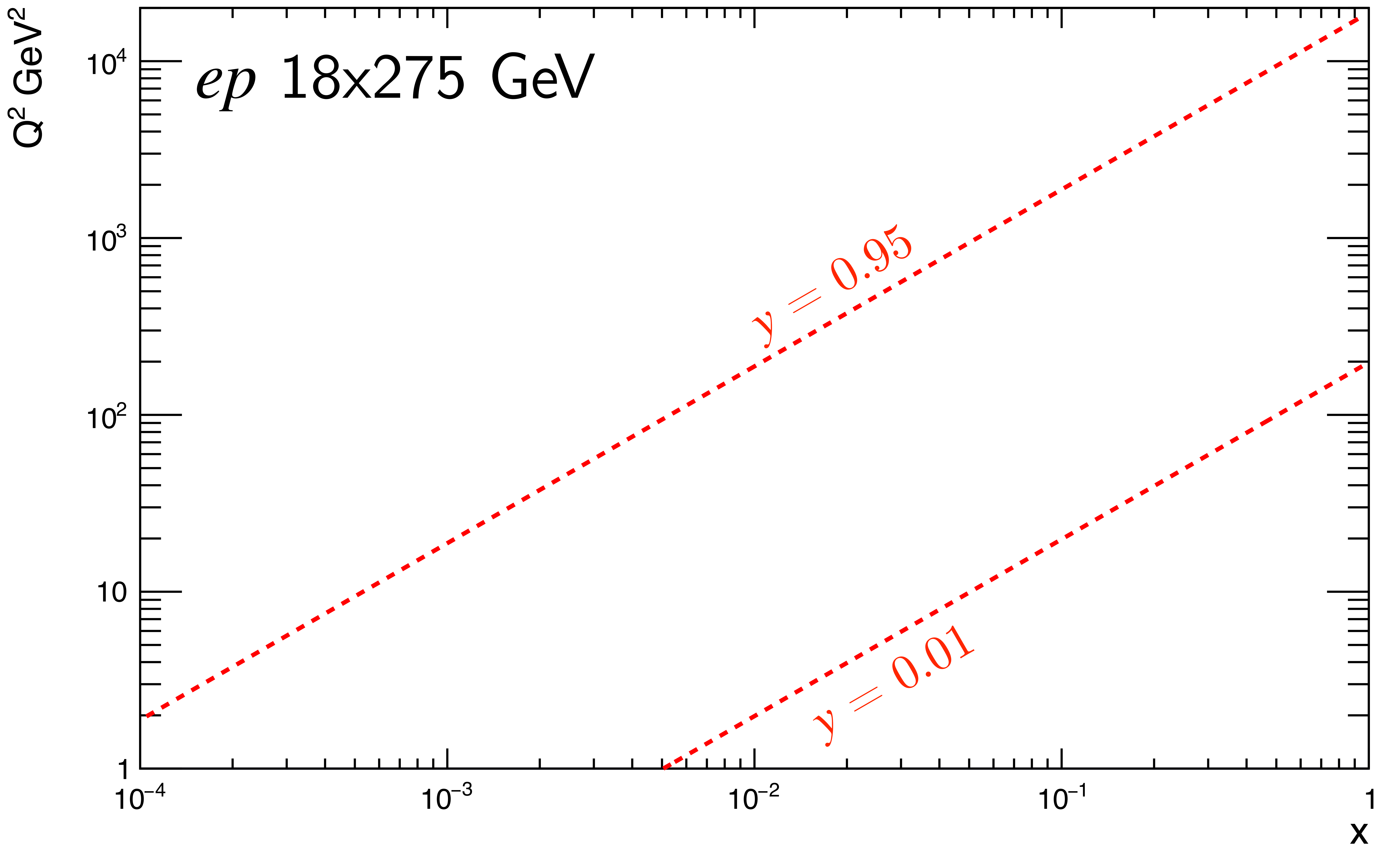
Calorimeter resolution better in endcap

Tracking resolution better in barrel

Electron momentum resolutions across η



Kinematic peak method for ECAL calibration



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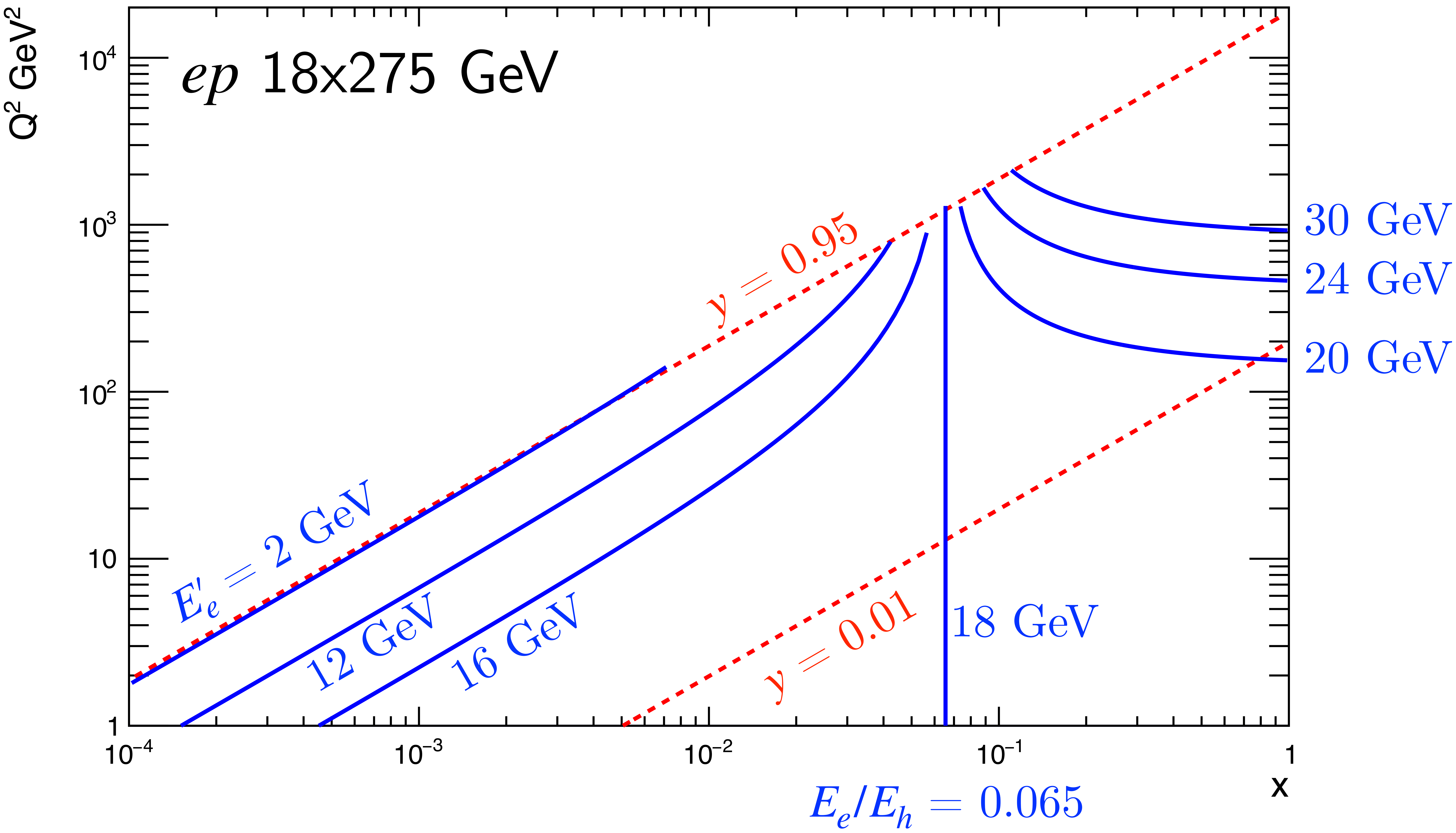

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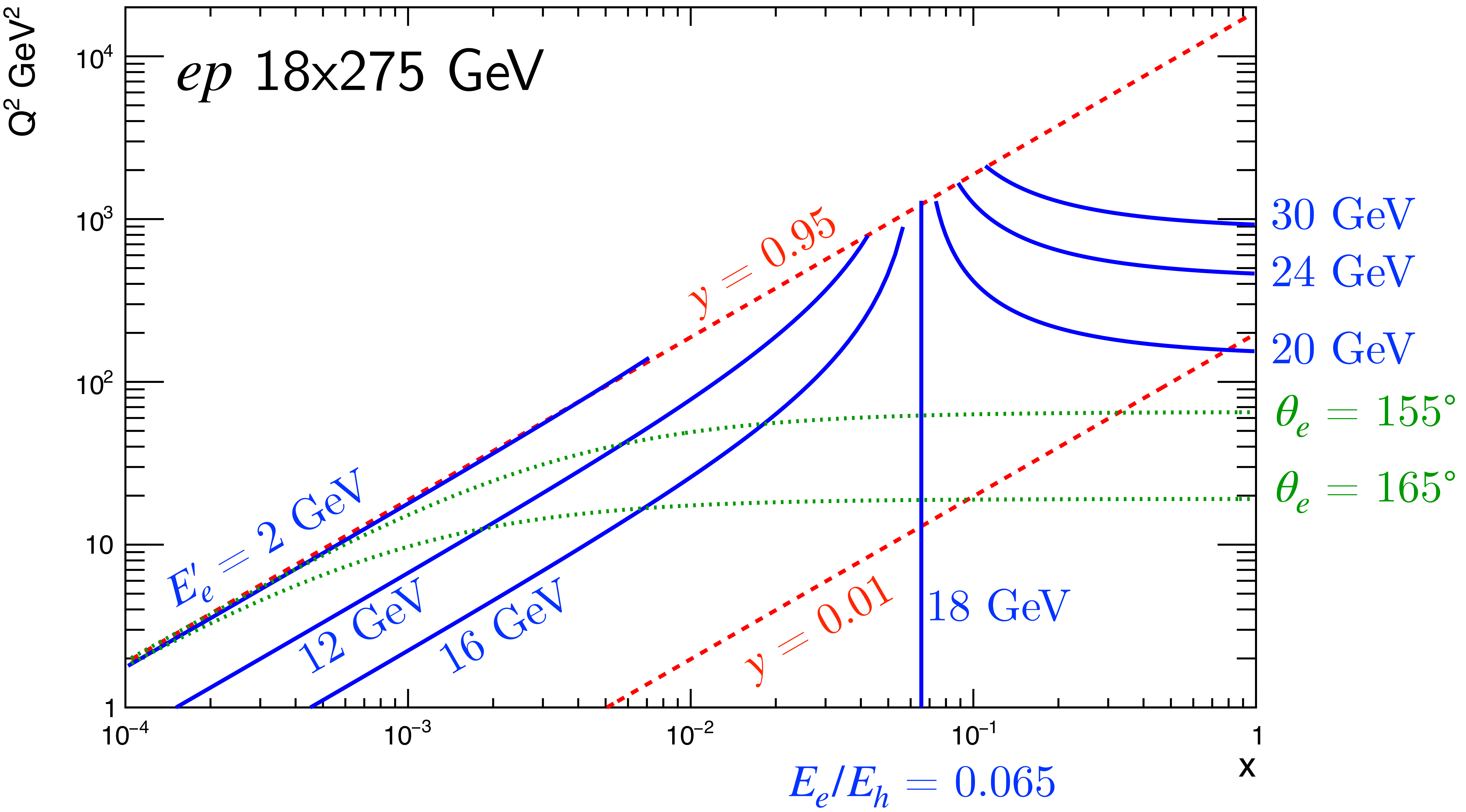

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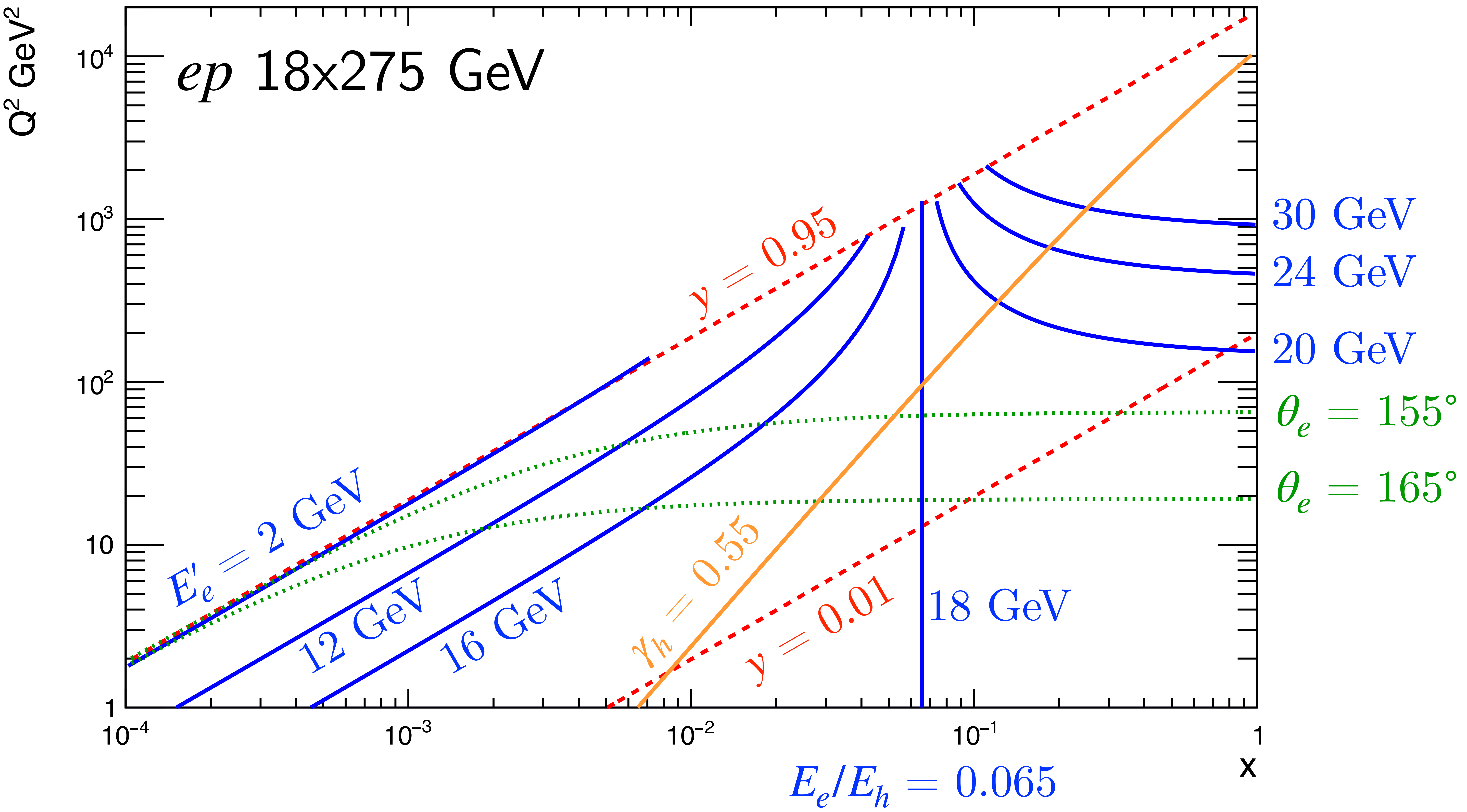

Traditional reconstruction methods use subset of lepton, hadron quantities

Lepton

E'_e, θ_e

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E'_e, θ_e

- Electron

  $Q^2\left(E'_e, \theta_e\right),\ y\left(E'_e, \theta_e\right)$

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$$E'_e,\ \theta_e$$

Hadron

$$\delta_h = \sum_i \left(E_i - p_{z,i}\right)$$

$$p_{T,h} = \sqrt{\left(\sum_i p_{x,i}\right)^2 + \left(\sum_i p_{y,i}\right)^2}$$

$$\cos\gamma_h = \frac{p_{T,h}^2 - \delta_h^2}{p_{T,h}^2 + \delta_h^2}$$

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  $Q^2\left(\delta_h,\ p_{T,h}\right),\ y\left(\delta_h,\ p_{T,h}\right)$

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- Double-angle
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- $e\Sigma$
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- Neutral-current analyses can leverage over-constrained kinematics to optimize resolution

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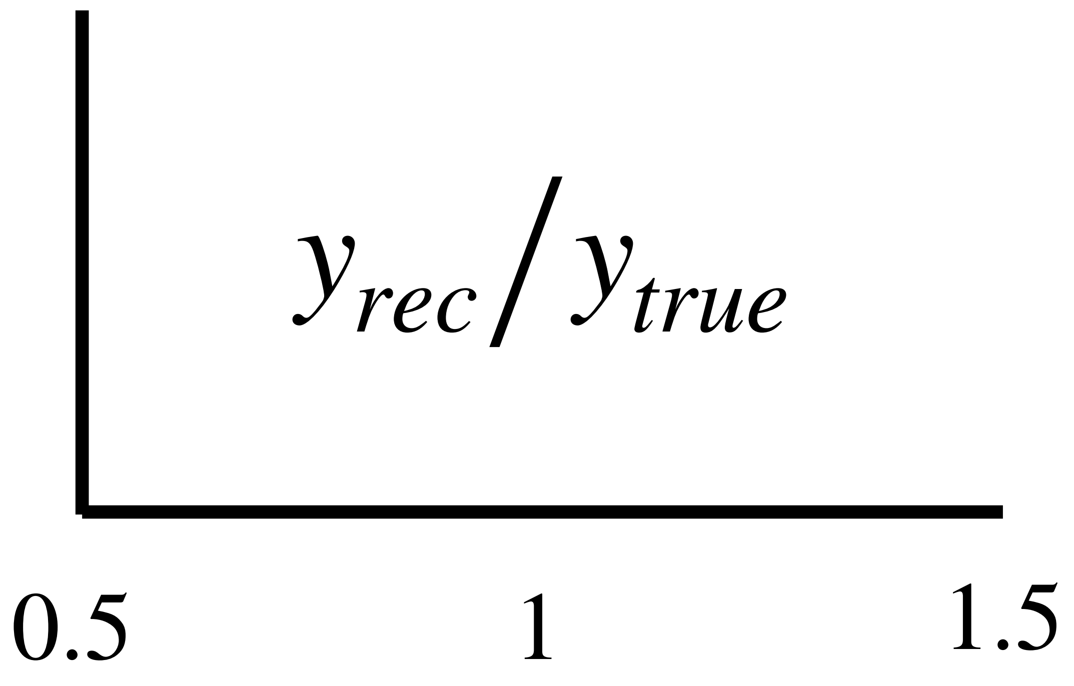
- Neutral-current analyses can leverage over-constrained kinematics to optimize resolution
- Hadronic final state:
  - *Only* option for charged-current analyses
  - PID needed to determine mass
  - Electron ID needed to eliminate scattered electron (and veto NC)

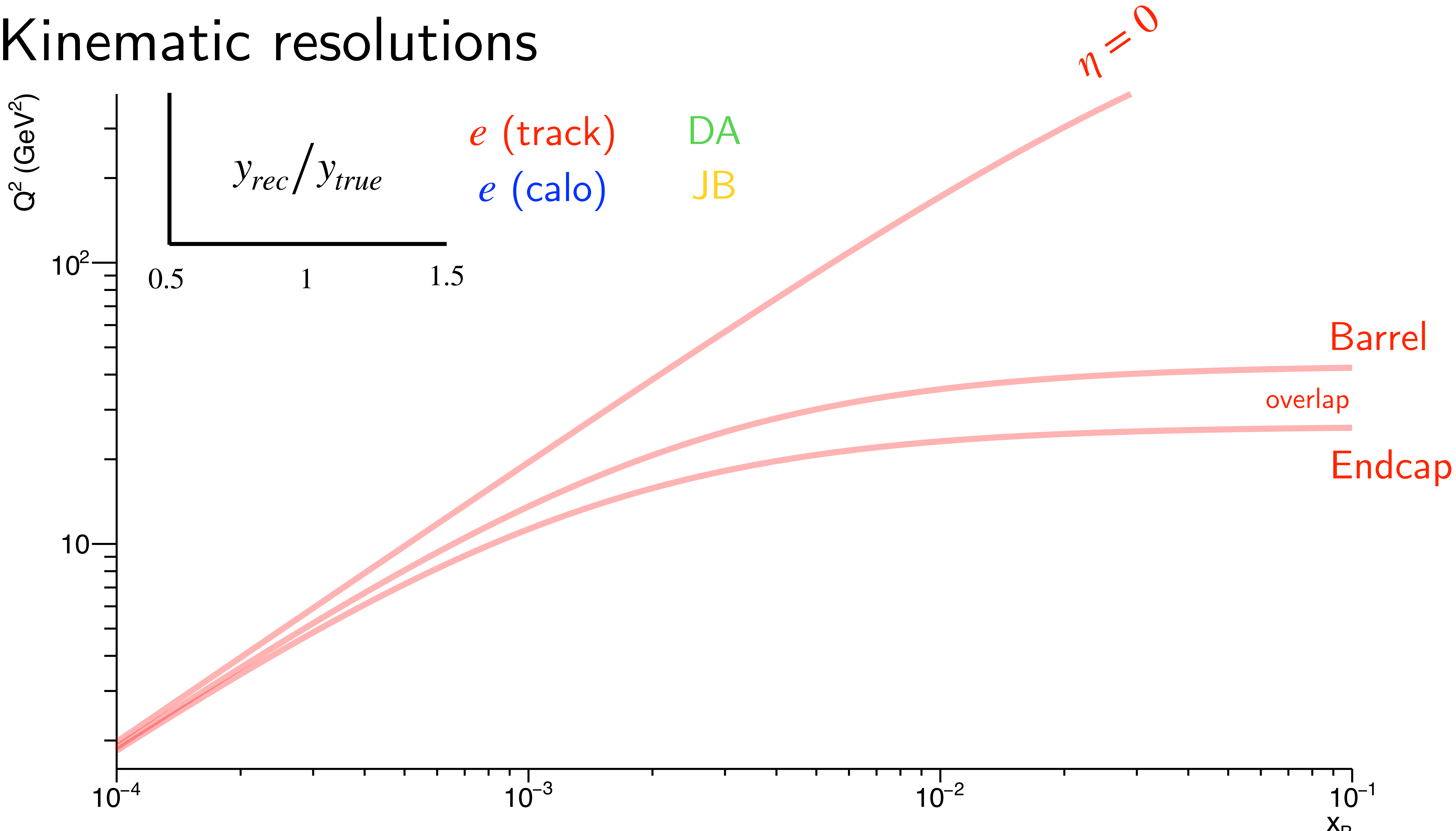
Kinematic resolutions



e (track) DA

e (calo) JB

Kinematic resolutions



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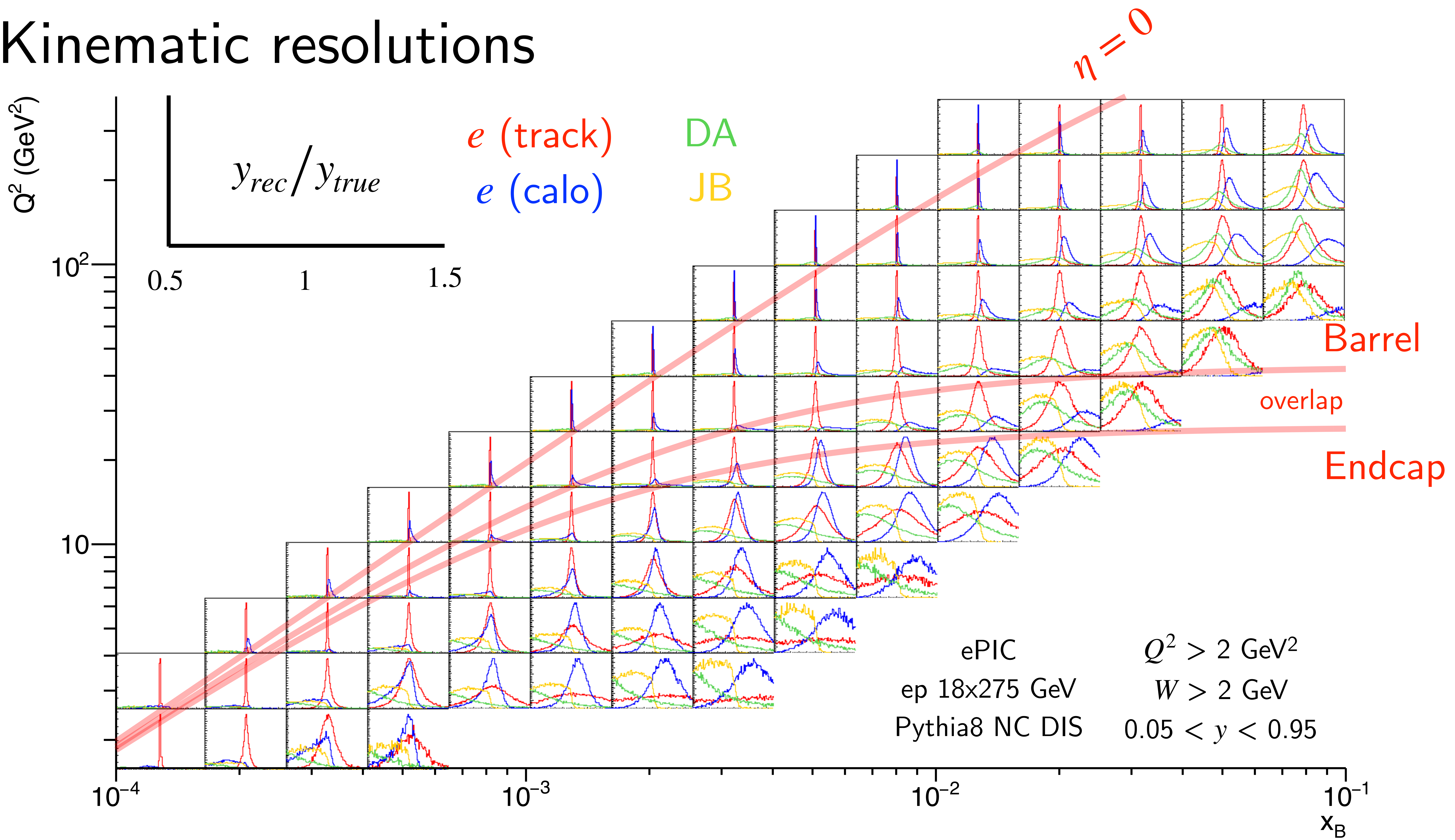

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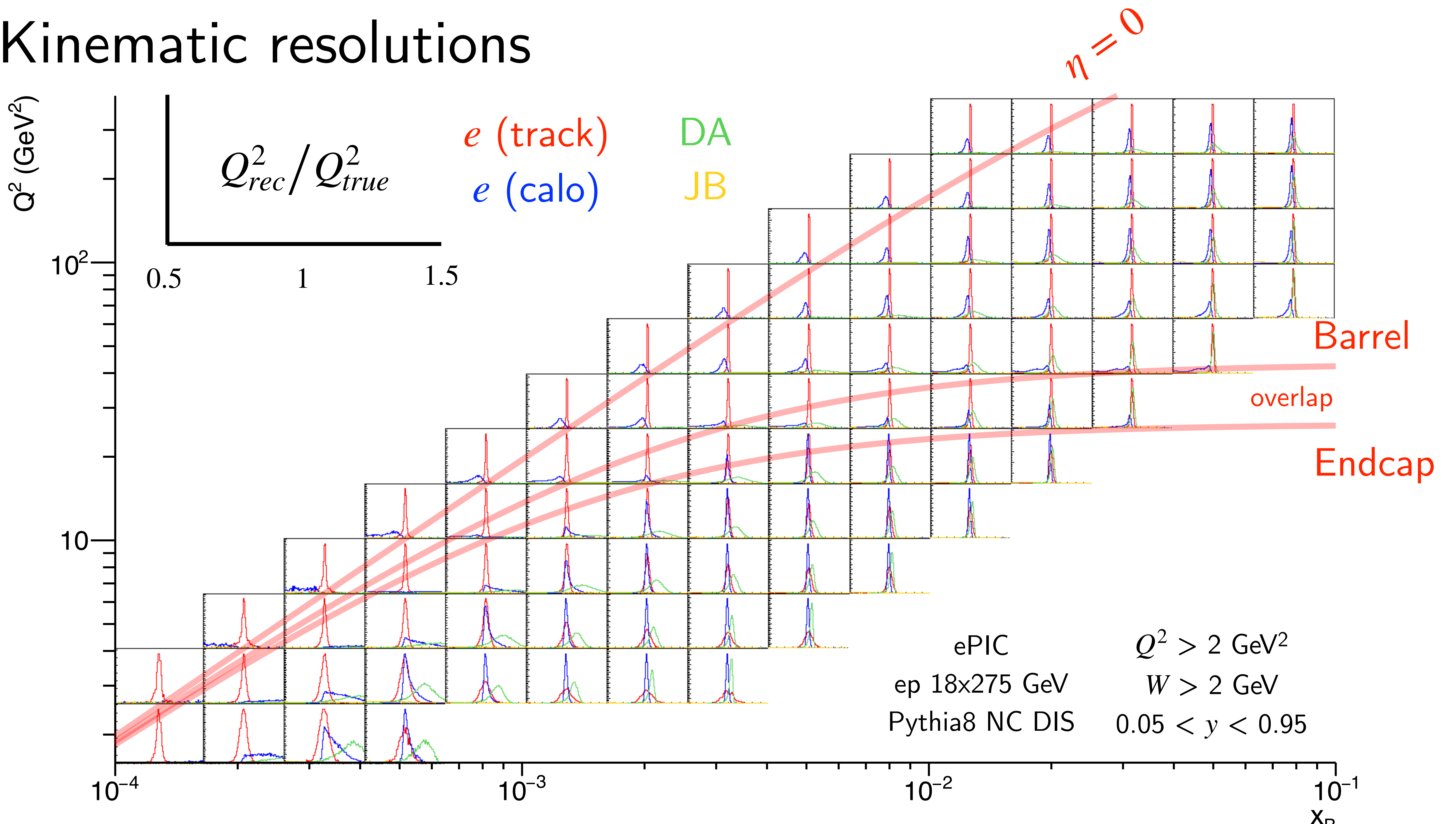
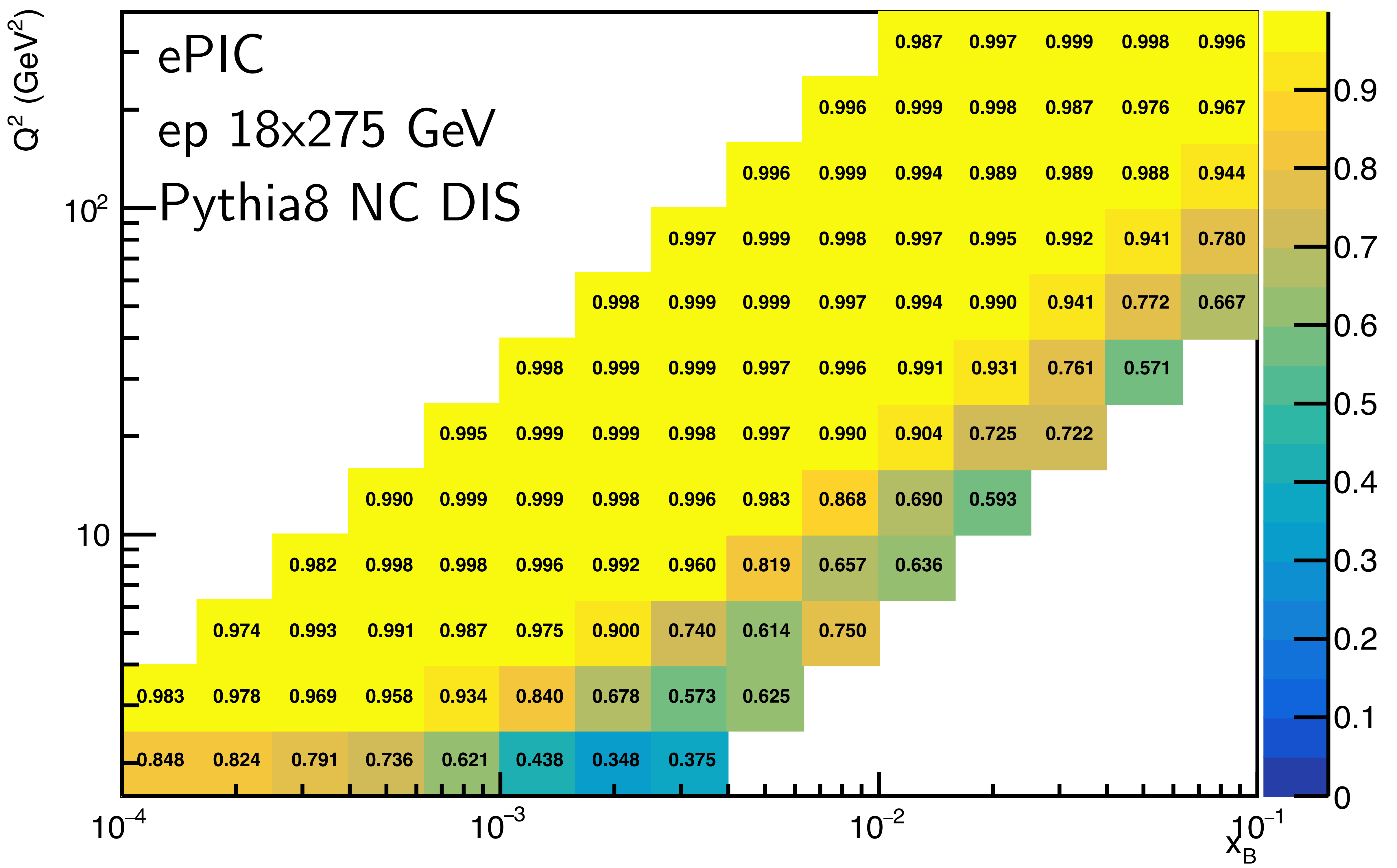
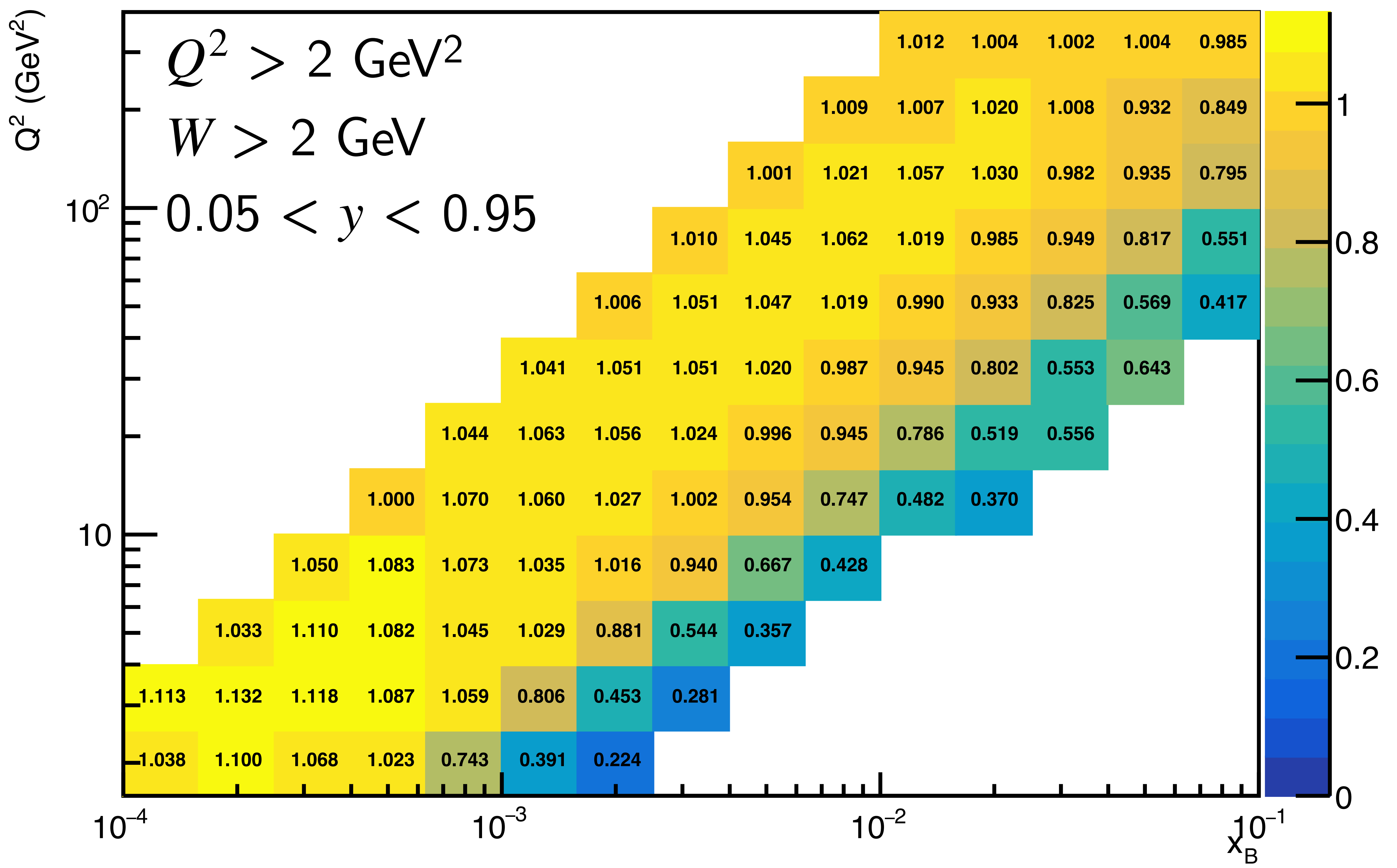


Acceptance and bin migration (electron track)

Acceptance



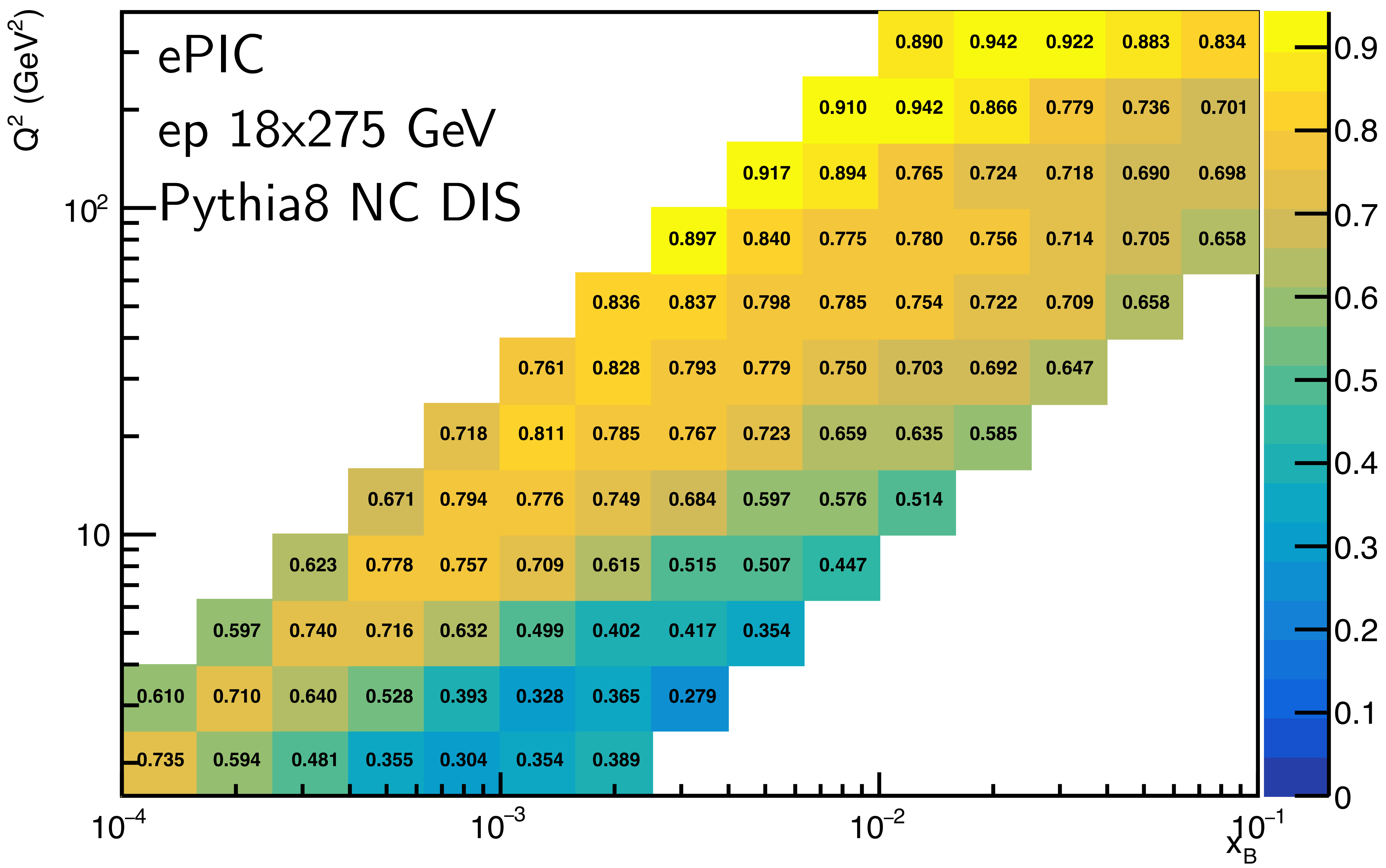
Bin migration

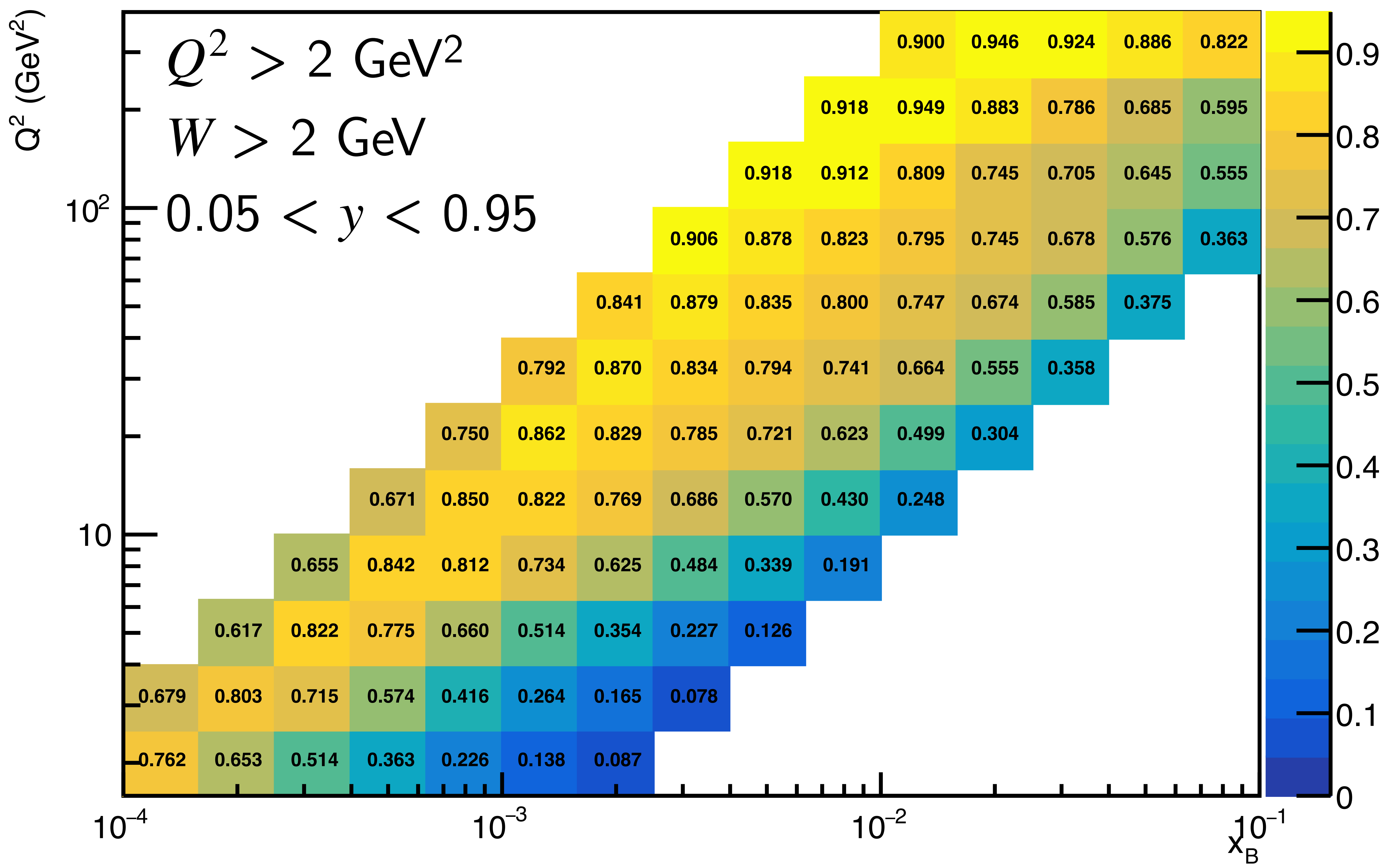


$$C_{acc} = \frac{N_{rec}(x_{gen}, Q^2_{gen})}{N_{gen}(x_{gen}, Q^2_{gen})}$$

$$C_{bin} = \frac{N_{rec}(x_{rec}, Q^2_{rec})}{N_{rec}(x_{gen}, Q^2_{gen})}$$

Bin stability and purity (electron track)

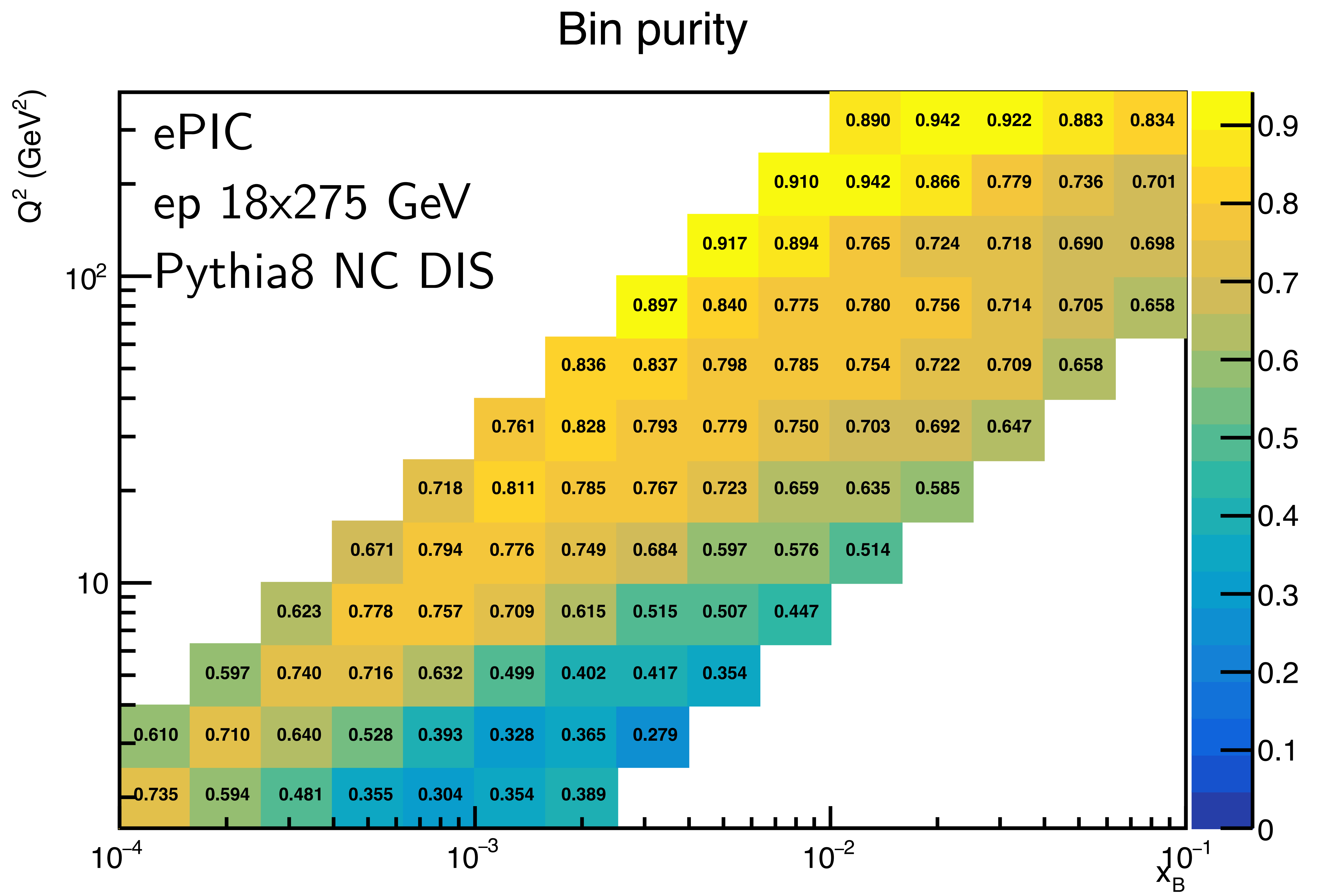


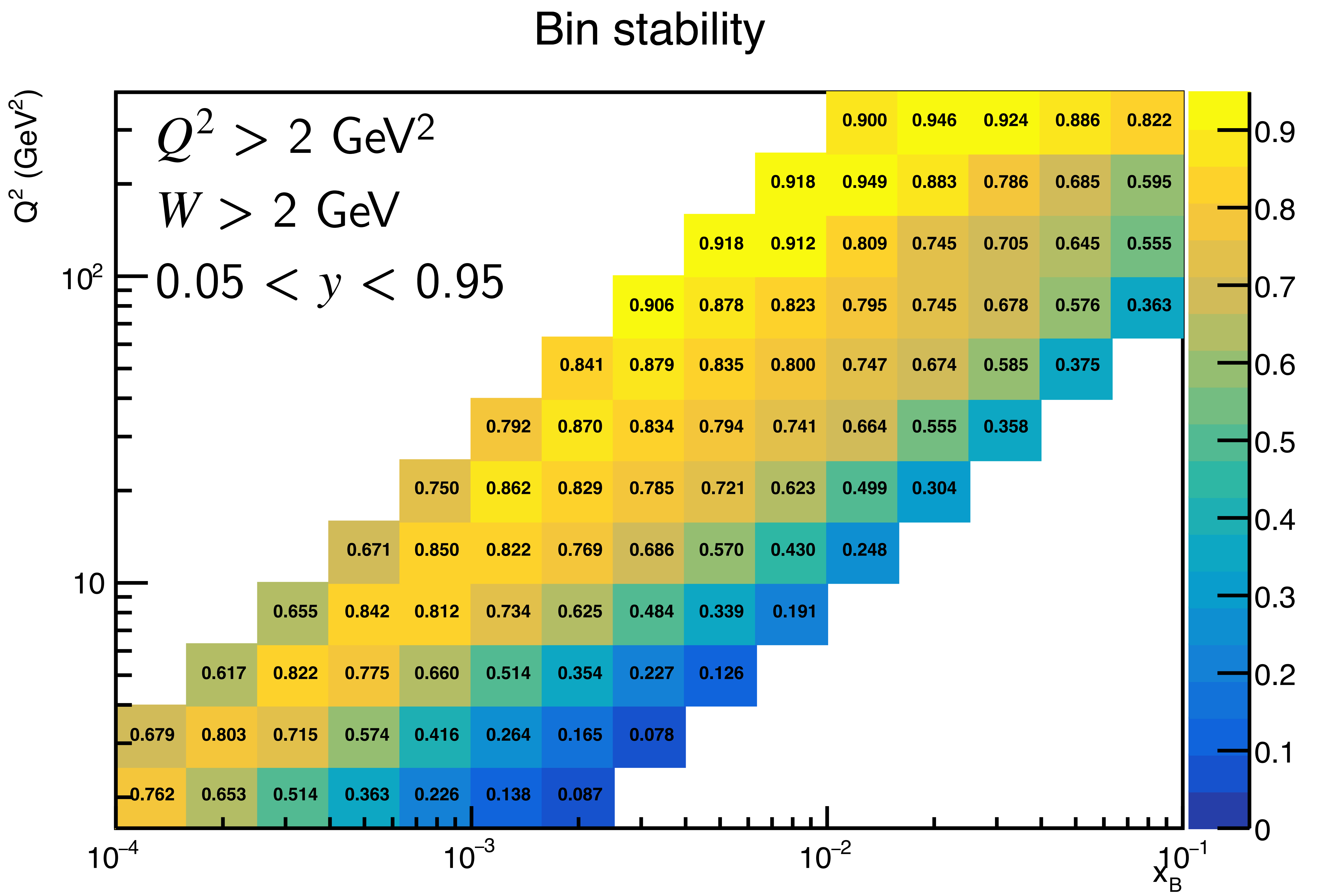


$$P = \frac{N_{gen+rec}}{N_{rec}}$$

$$S = \frac{N_{gen+rec}}{N_{gen}}$$

Bin stability and purity (electron track)



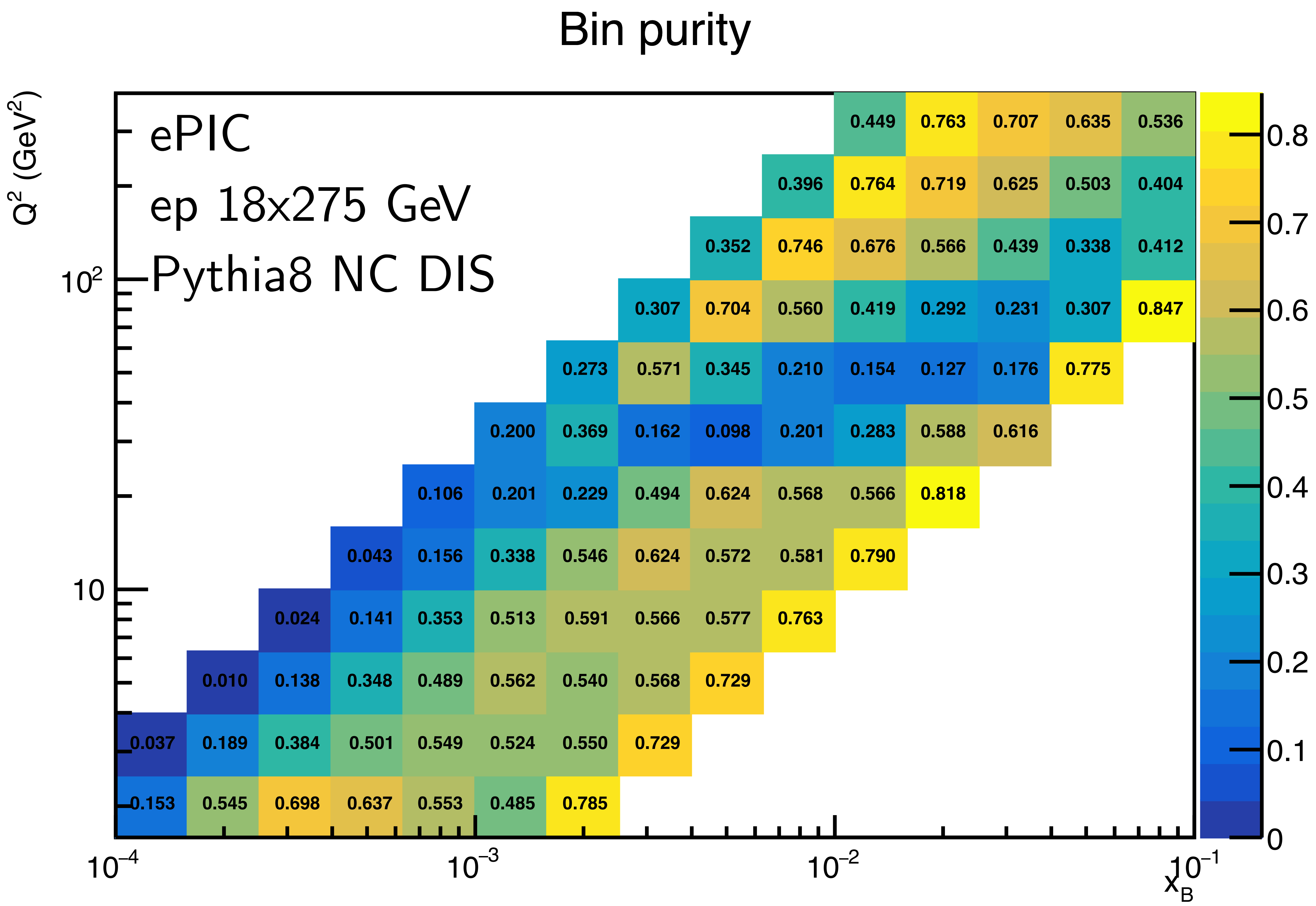


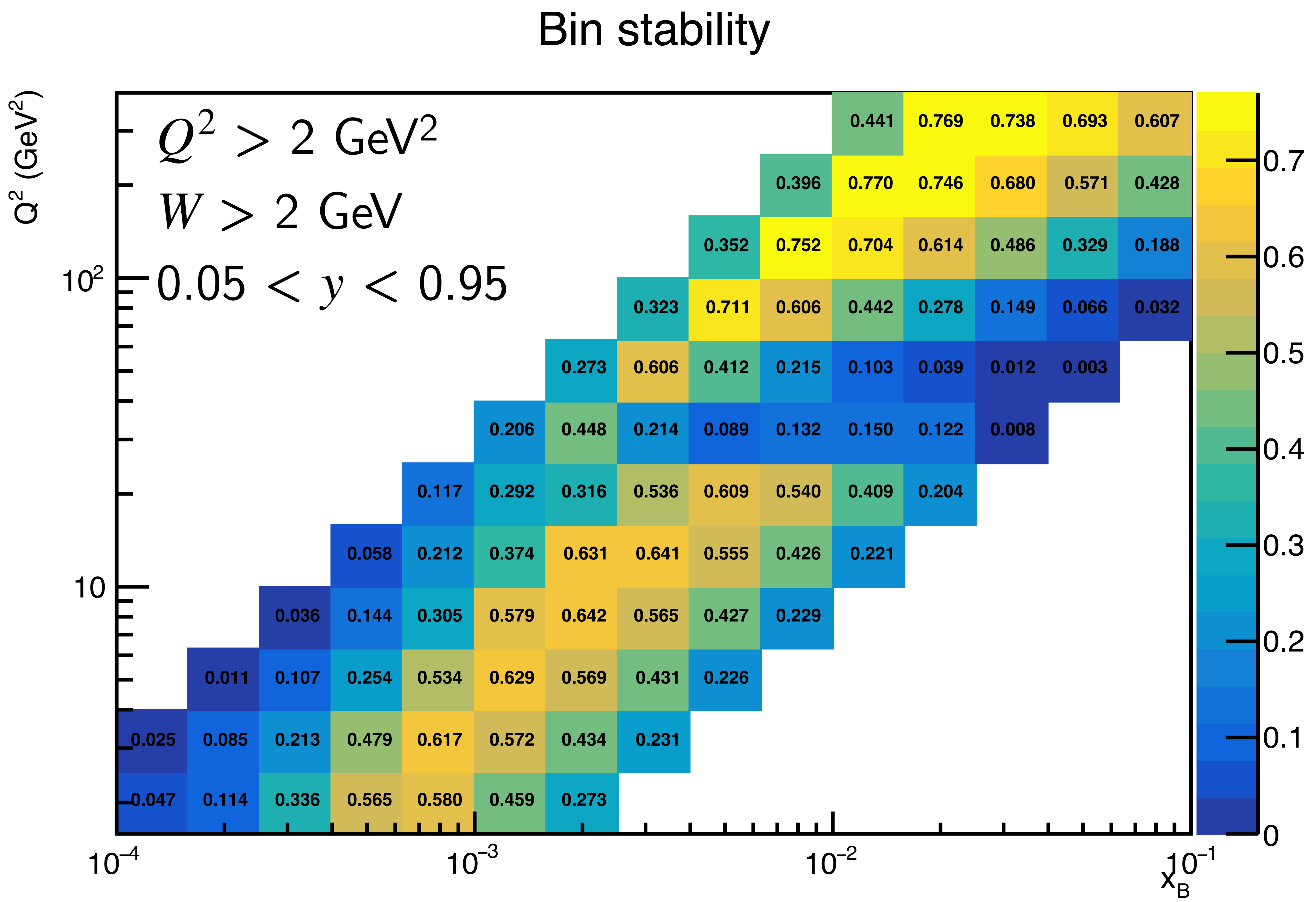
$$P = \frac{N_{gen+rec}}{N_{rec}}$$

HERA F_L analyses:
>30% required,
>70% typical

$$S = \frac{N_{gen+rec}}{N_{gen}}$$

Bin stability and purity (electron cluster)





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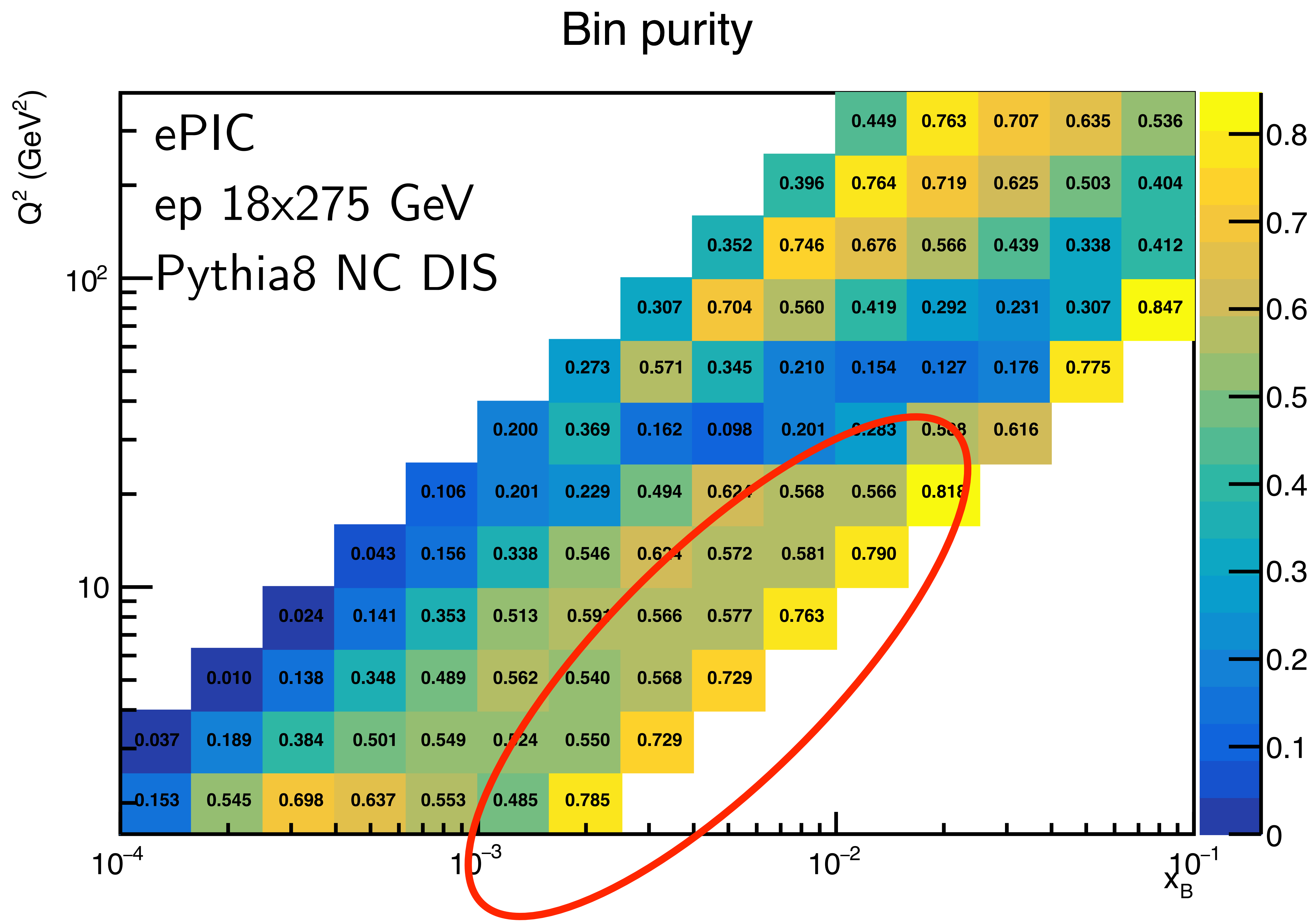
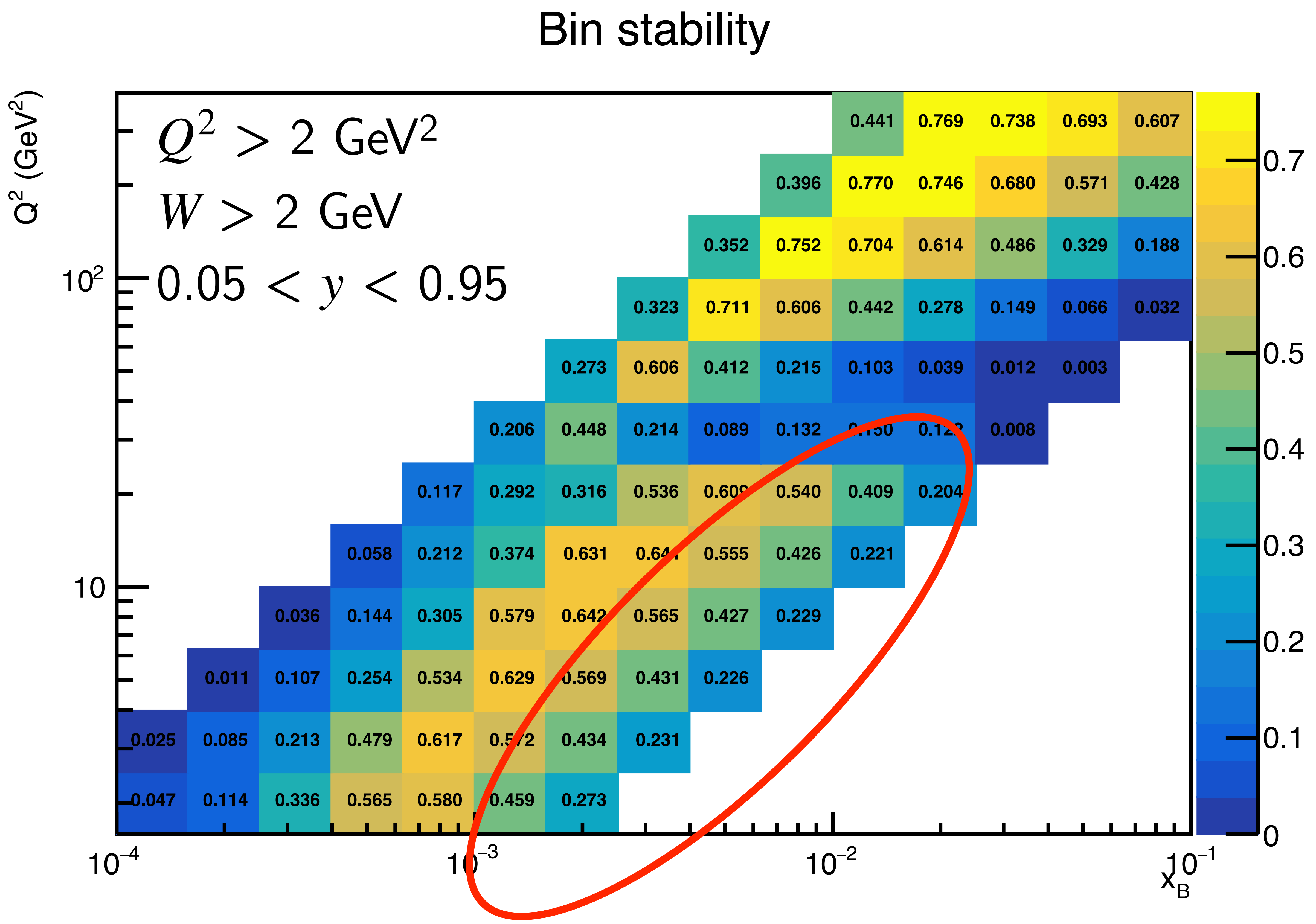




$$P = \frac{N_{gen+rec}}{N_{rec}}$$

Improvement in backward ECAL region

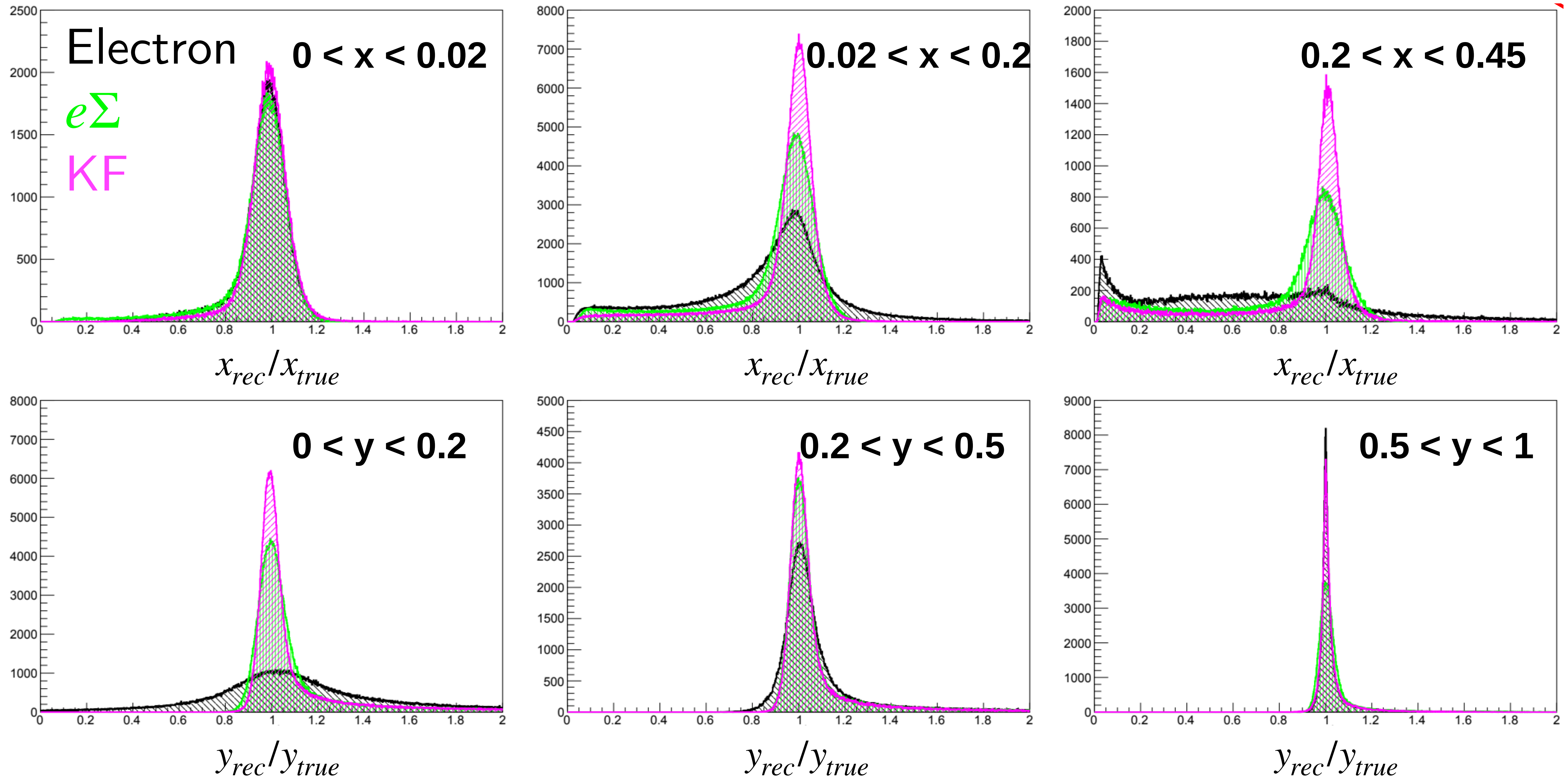
$$S = \frac{N_{gen+rec}}{N_{gen}}$$

More advanced reconstruction methods

More advanced reconstruction methods

- Kinematic fitting: reconstruct $\bar{\lambda} = \{x_B, y, E_\gamma\}$ from $\overline{D} = \{E'_e, \theta'_e, \delta_h, p_{T,h}\}$ using likelihood function (Stephen Maple, et al.)

Proof of concept: Smeared DJANGOH events with ISR



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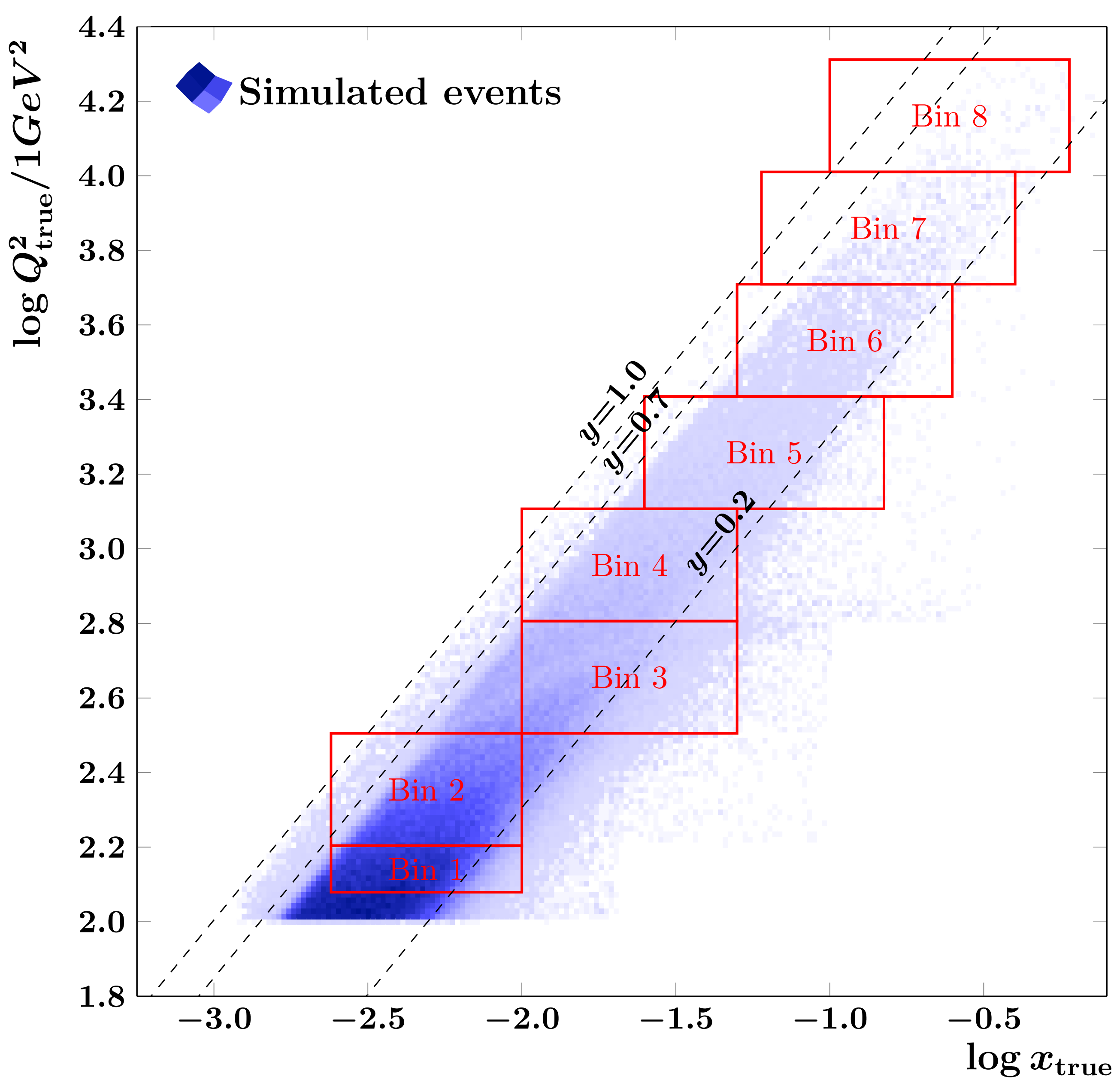
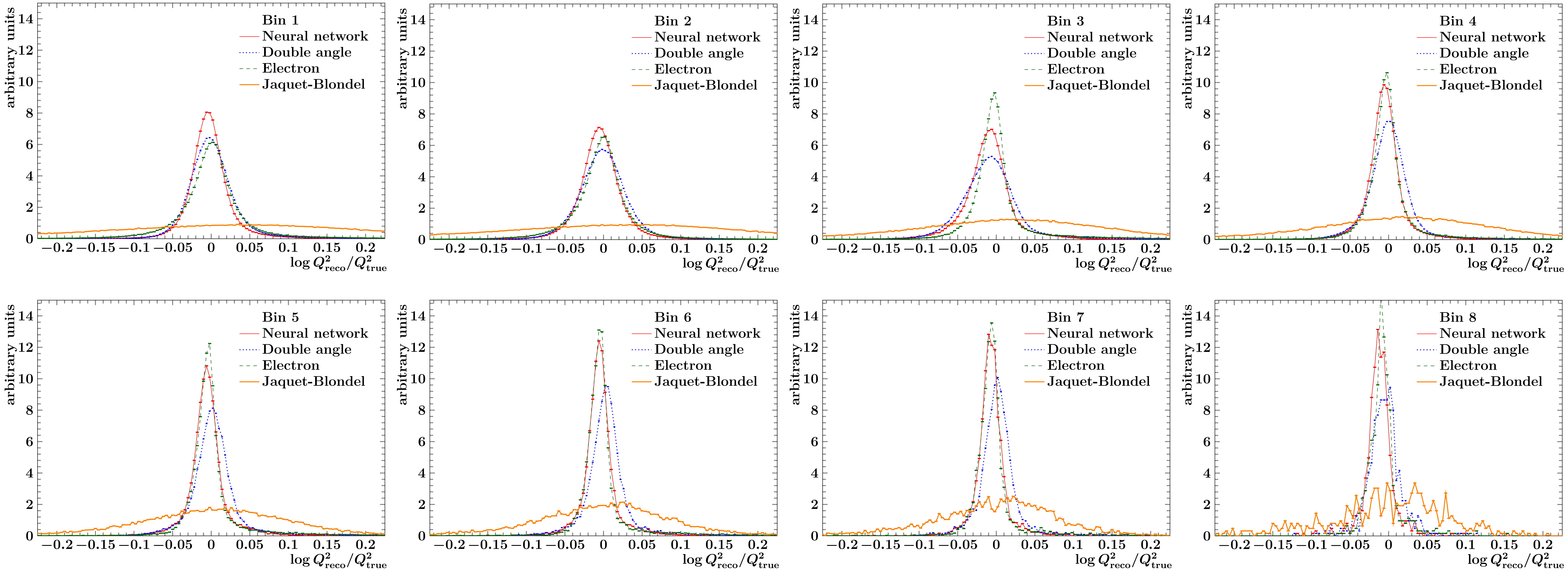
- Machine learning: use simulation to train neural network ([M. Diefenthaler, A. Farhat, A. Verbytskyi and Y. Xu]())





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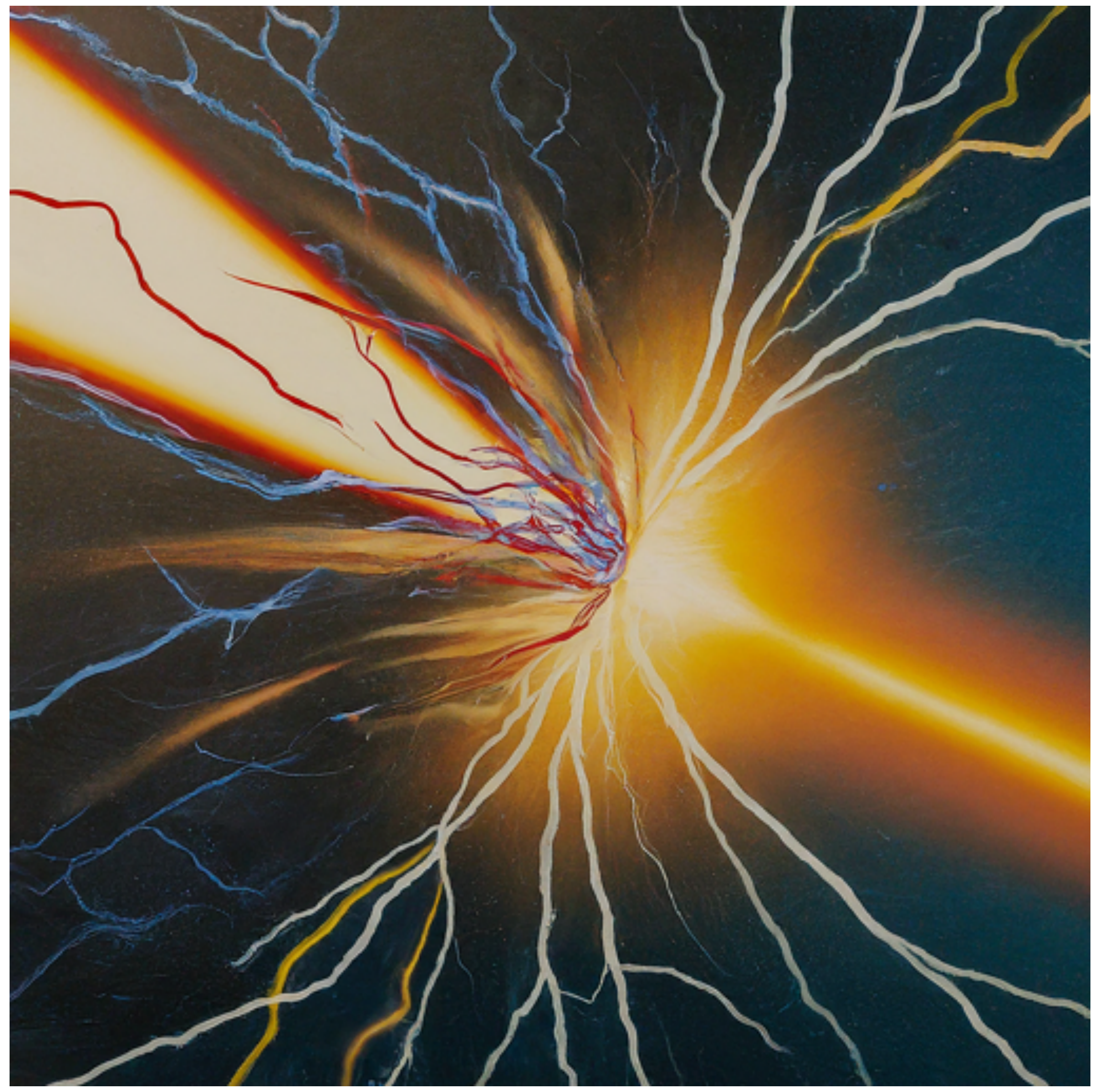
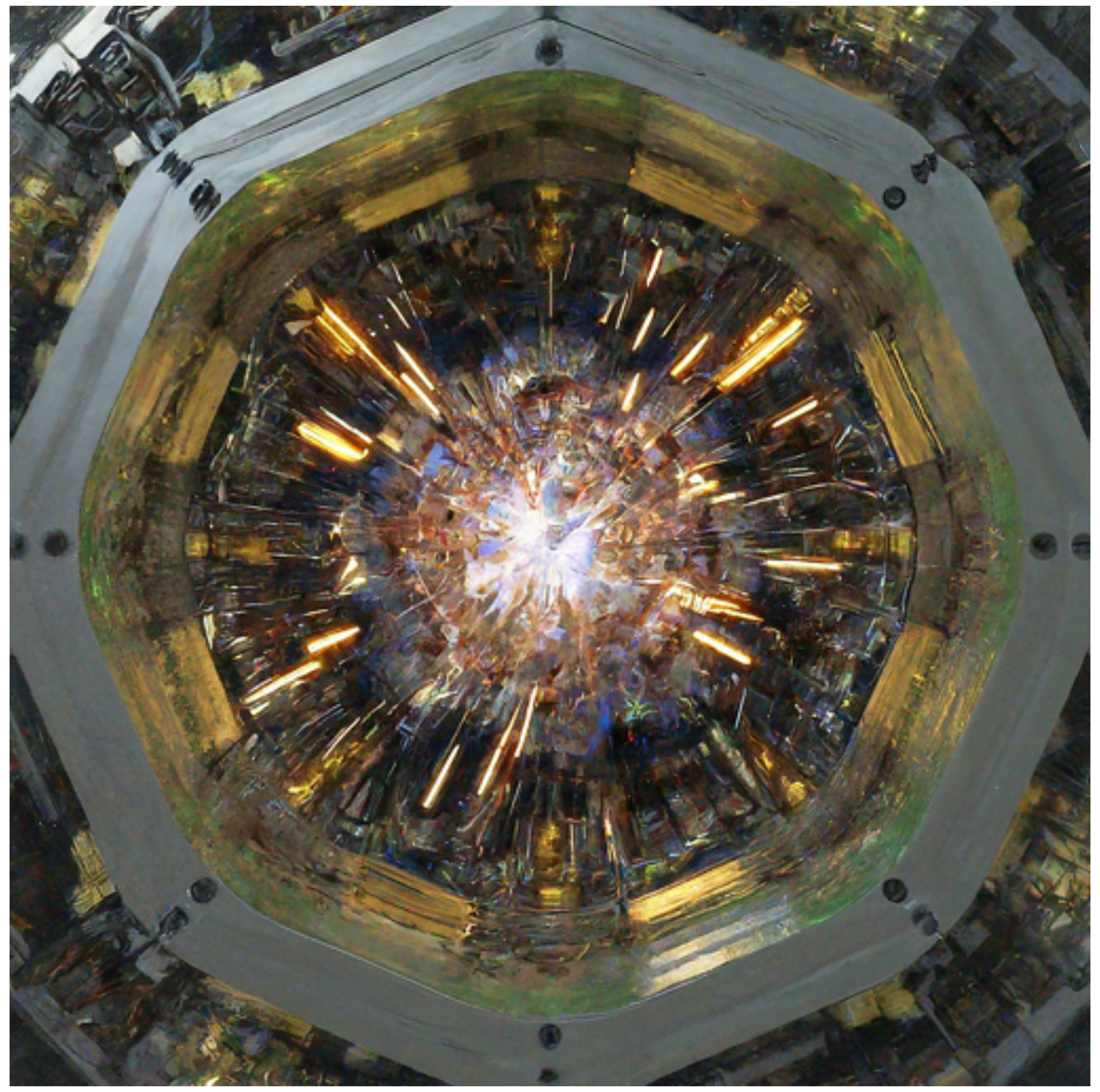
- Machine learning: use simulation to train neural network (M. Diefenthaler, A. Farhat, A. Verbytskyi and Y. Xu)
- Particle-flow: optimize combination of all detector information (Derek Anderson, et al.)





*Images by Gemini (the AI chatbot formerly known as Bard)

Impact of pion contamination on observables

- Pions passing all electron ID cuts give contamination $f_{\pi/e}$
- Contamination can be corrected or treated as dilution

Cross sections
(correct contamination):

$$\left(\frac{\Delta\left(\sigma^{r,NC}\right)}{\sigma^{r,NC}}\right)_{\pi^-} = \Delta f_{\pi/e}$$

$$\approx 0.1 \times f_{\pi/e}$$

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$$\approx 0.1 \times f_{\pi/e} - 1 \times f_{\pi/e}$$

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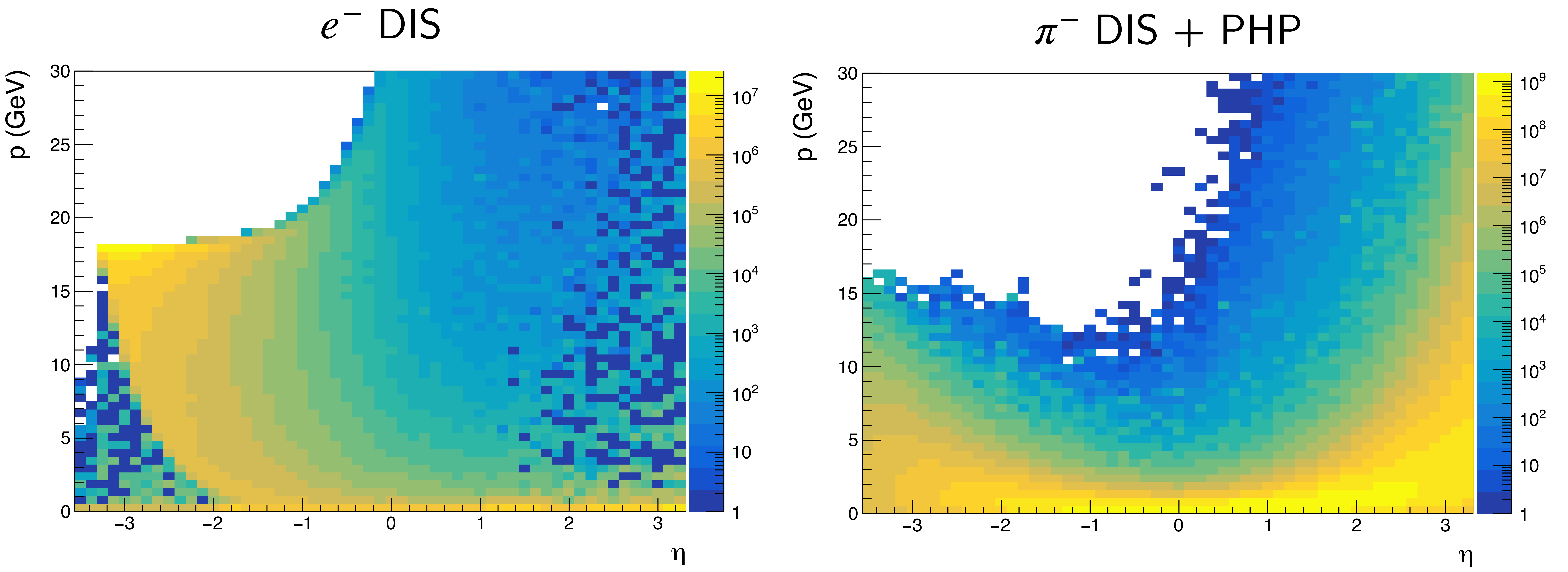
$$\approx 0.1 \times f_{\pi/e} - 1 \times f_{\pi/e}$$

Large A^e, nonzero $|A^\pi| < A^e$ (↑ first term)

Small A^e, $|A^\pi| \approx 0$ (↑ second term)

Electron to pion ratios



- Signal e^- from DJANGOH DIS
- Background π^- from DJANGOH DIS, Pythia6 photoproduction ($Q^2 < 2$ GeV²)

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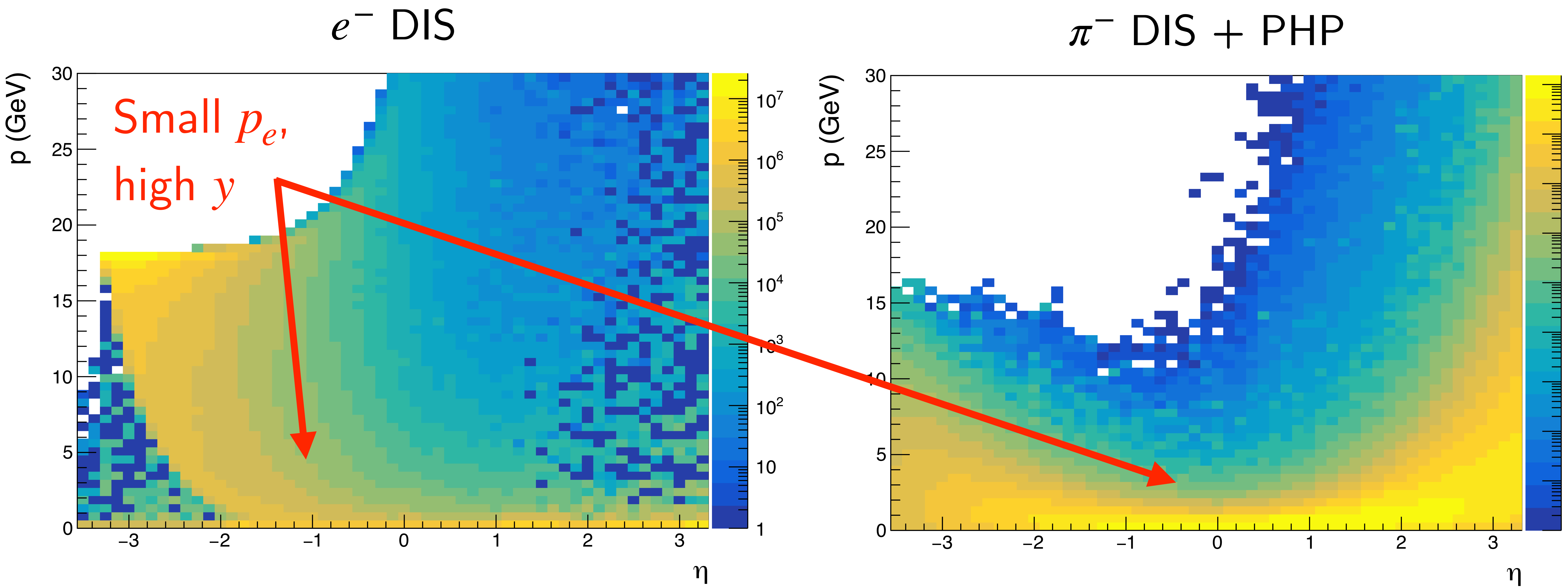

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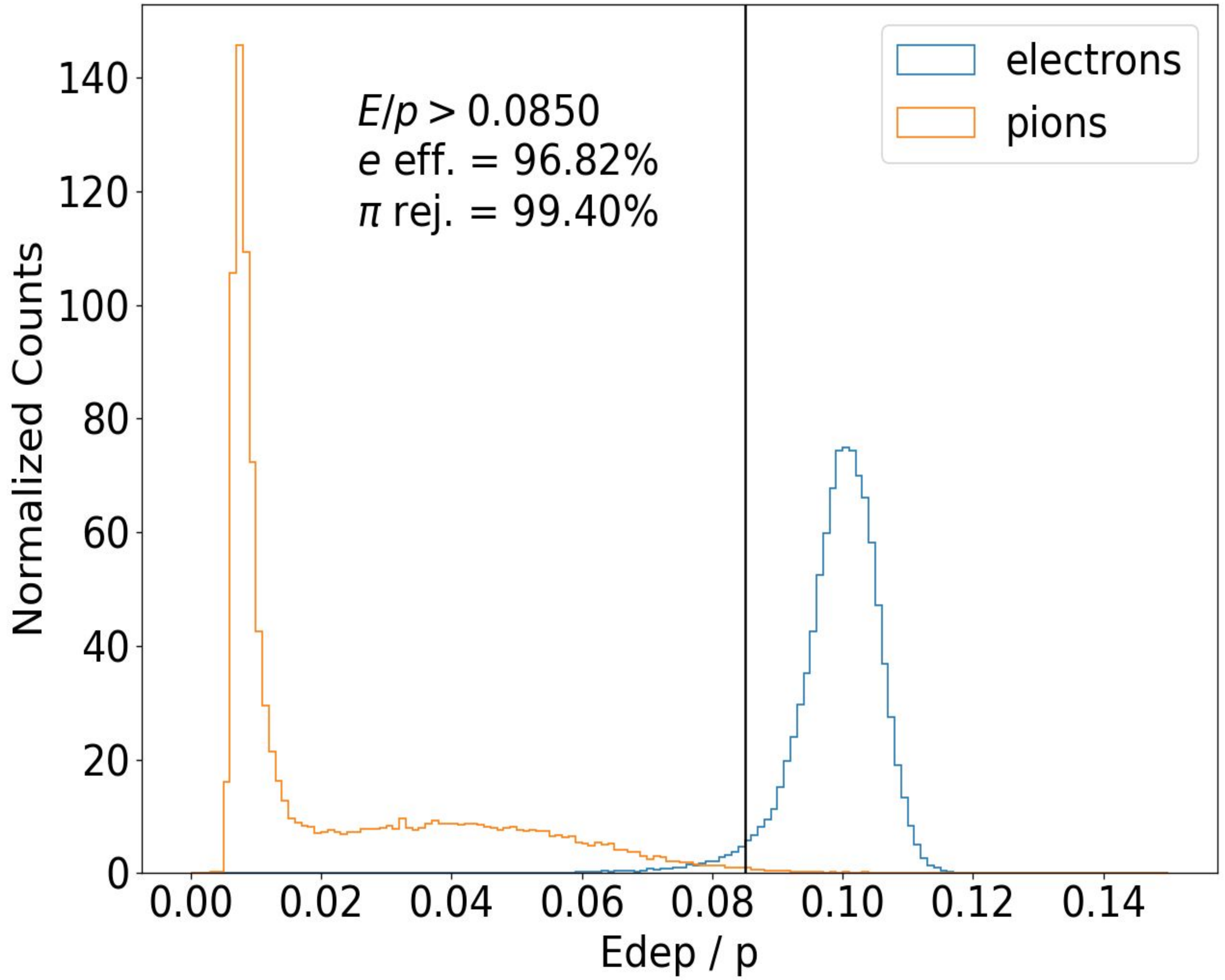
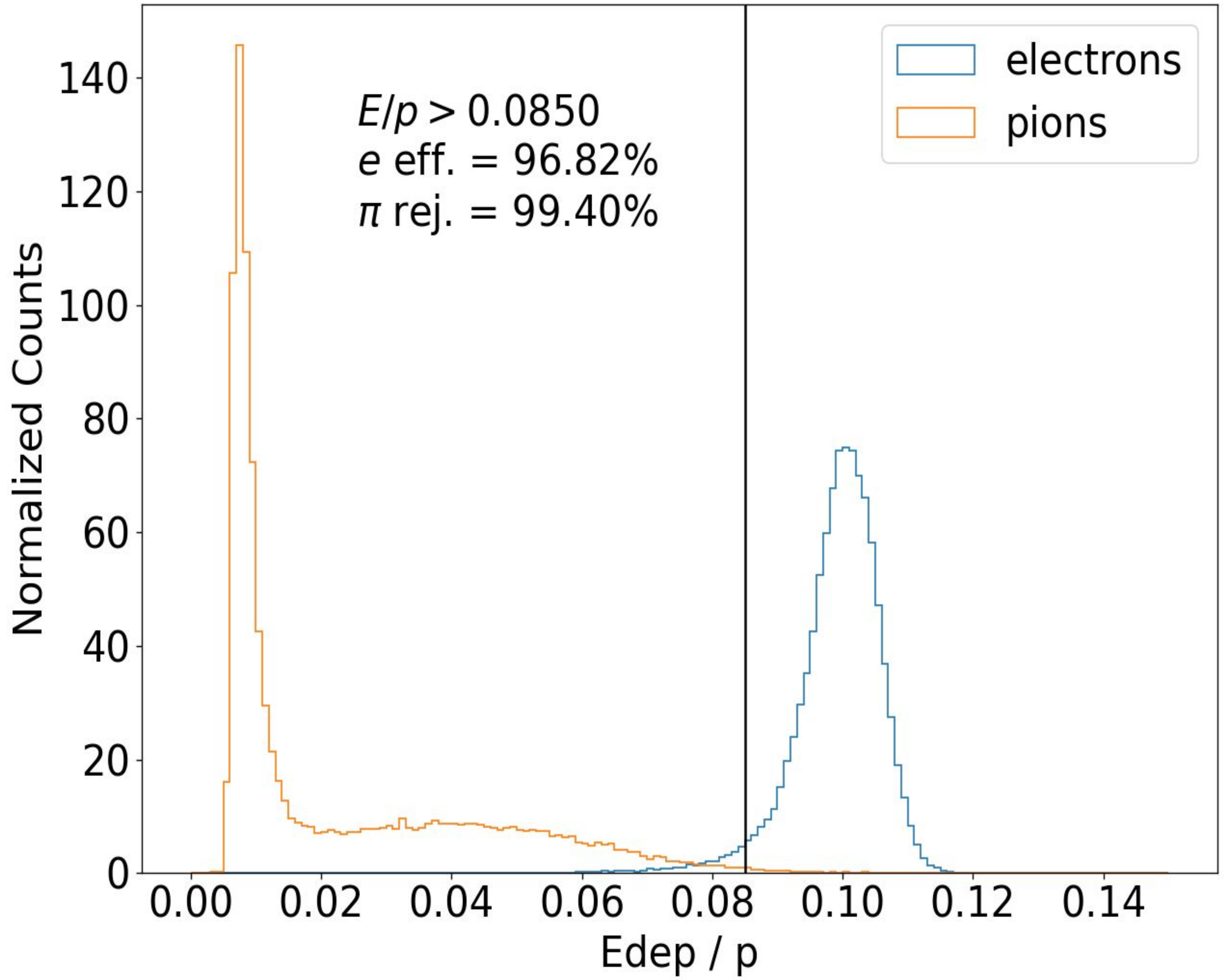
Pion suppression cuts

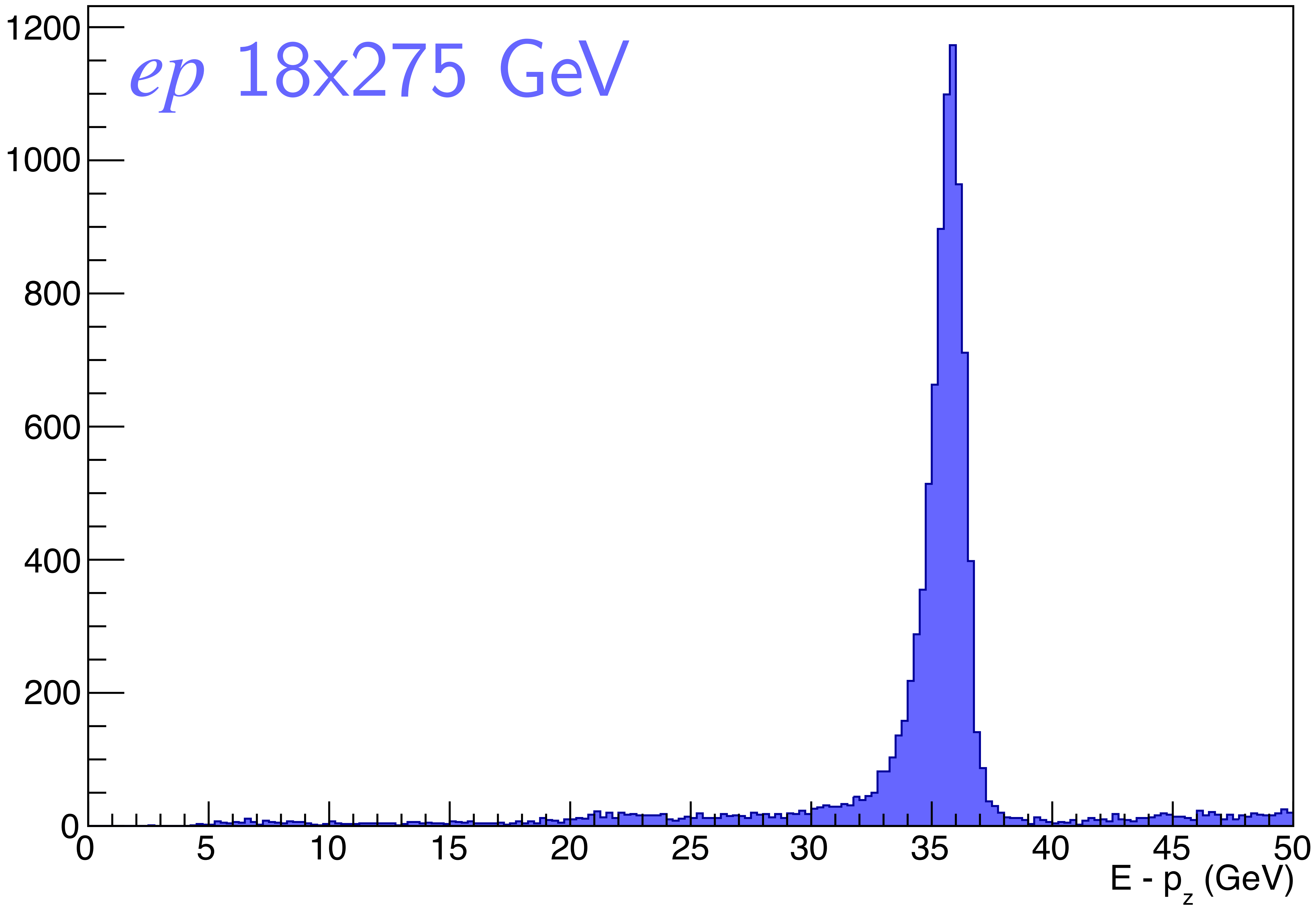


Detector:

- Electrons deposit most/all energy in ECAL

Pion suppression cuts





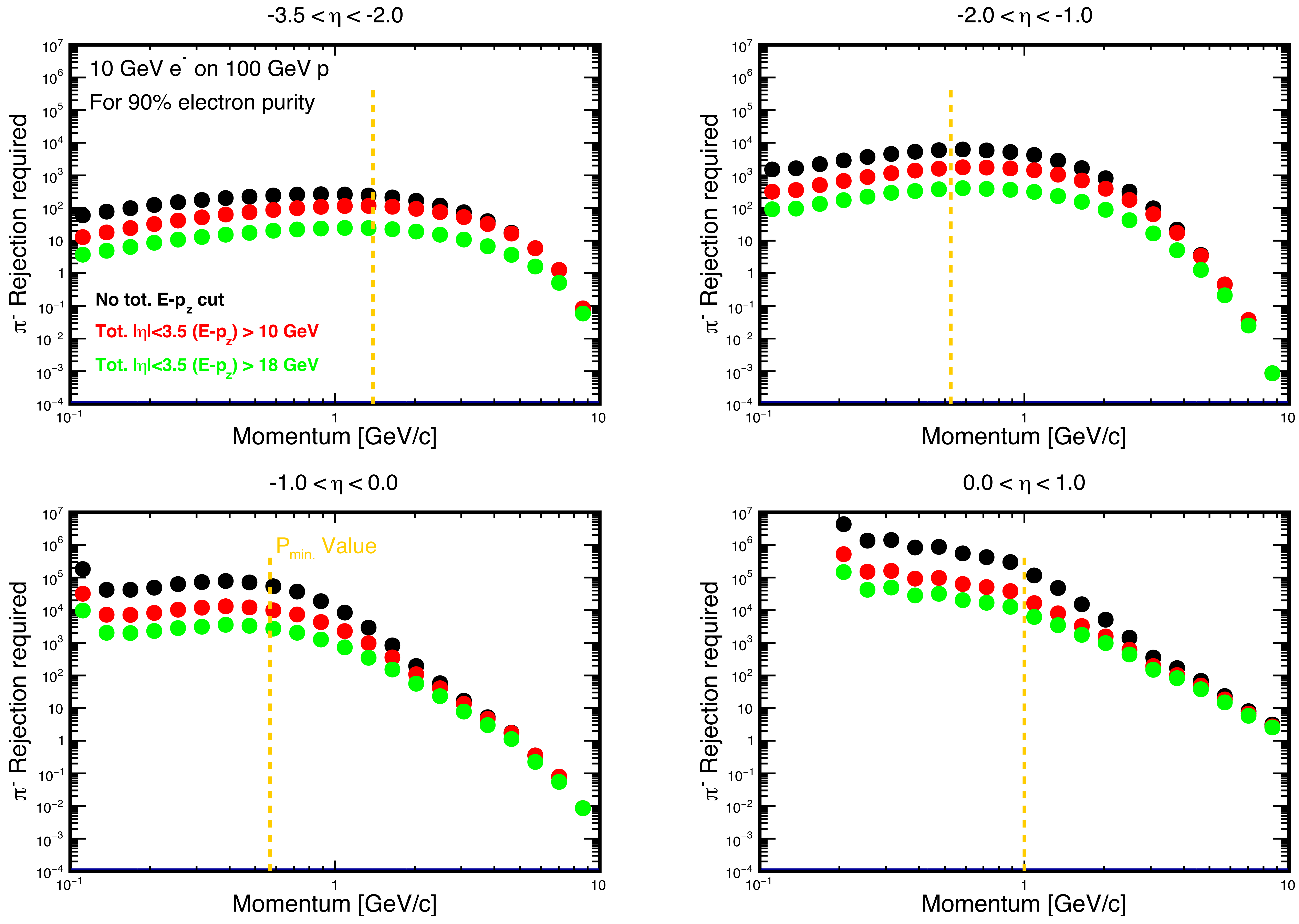
Detector:

- Electrons deposit most/all energy in ECAL

Kinematic:

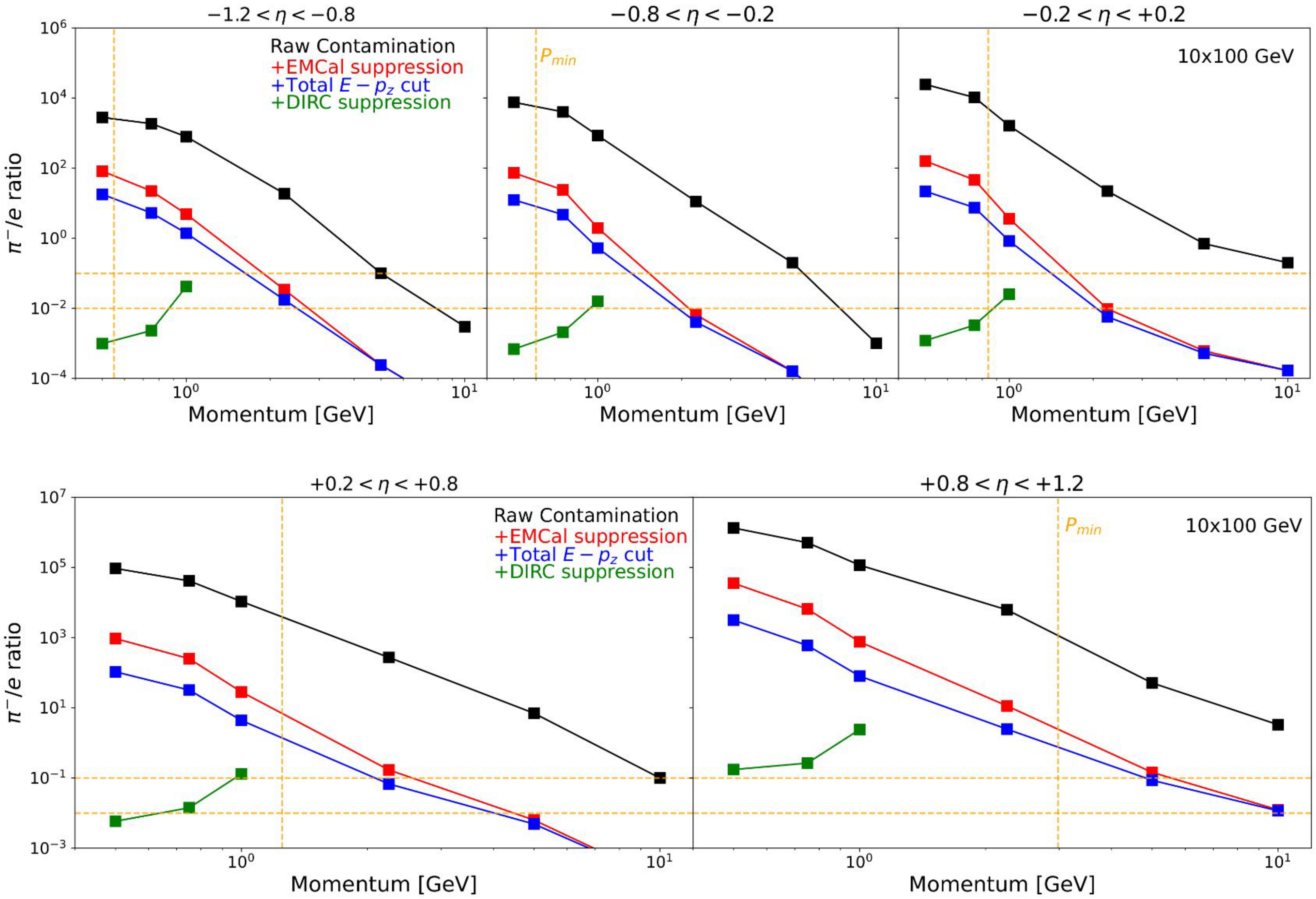
- If electron lost down beampipe, $\Sigma_h(E - p_z) < 2E_e$
- Significant reduction in required E/p suppression

Required suppression for 90% purity



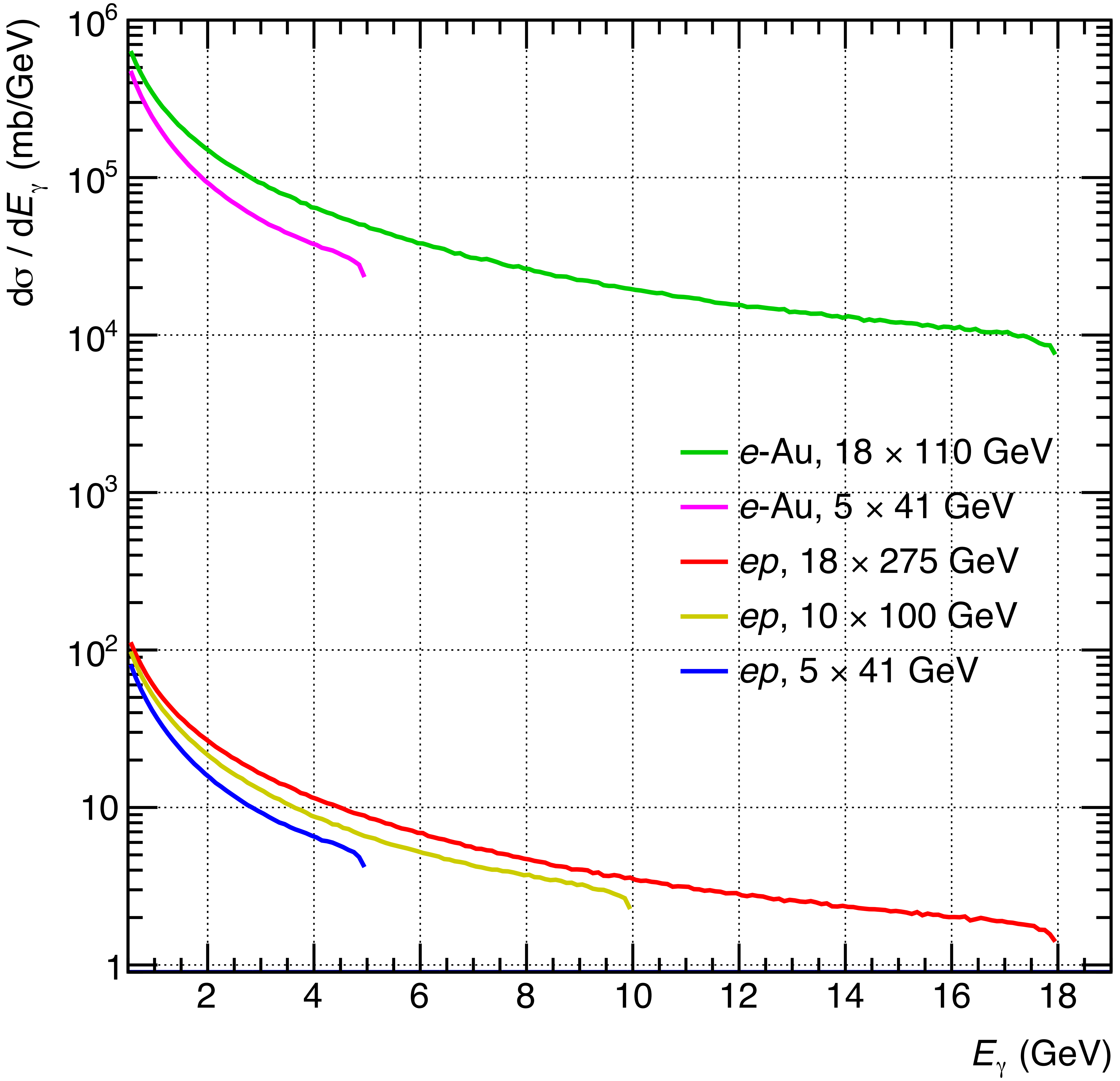
- $E - p_z$ cut reduces required suppression by up to 20x
- Electron ID depends on how well ePIC reconstructs *hadronic* final state
- Barrel critical region due to large raw π^-/e^- ratio

Pion contamination in the barrel



- DIRC assists at low momentum
- Further EMCal suppression possible from shower shape

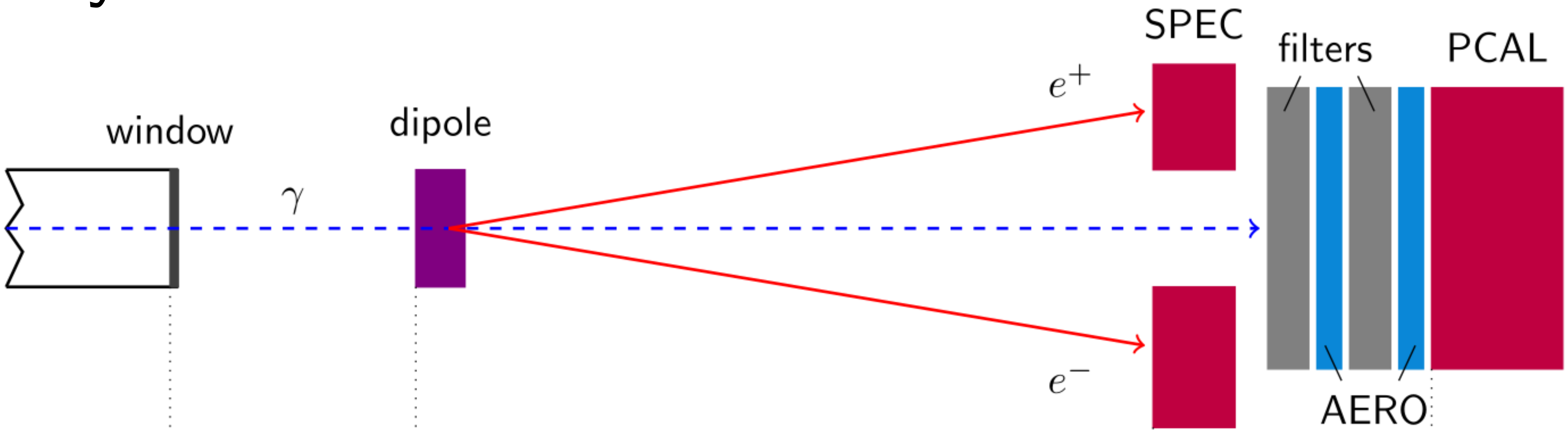
Luminosity determination from bremsstrahlung



$$\frac{d\sigma}{dE_\gamma} = 2\alpha r_e^2 \frac{E_e'}{E_\gamma E_e}\left(\frac{E_e}{E_e'} + \frac{E_e'}{E_e} - \frac{2}{3}\right)\left(\ln\frac{4E_p E_e E_e'}{m_p m_e E_\gamma} - \frac{1}{2}\right)$$

- Large cross section driven by QED
- Significant increase in cross section with Z
- Luminosity determined by photon counting

Luminosity detectors for the EIC



- Two methods to detect bremsstrahlung photons:
  - Unconverted photons detected in preshower calorimeter
  - Converted e^+e^- pairs detected in spectrometer
- EIC goal is 1% precision:
  - Naive assumption is that uncertainty is correlated between beam configurations
  - However, relative performance of each method could depend on hadron type, beam energy

Polarization measurements at the EIC

- Hadron polarimetry:
  - Hydrogen jet
  - p-carbon
  - Low-energy polarimeter
- Electron polarimetry:
  - Møller
  - Compton (transverse and longitudinal)
  - Mott

At RHIC, has achieved high precision $(\delta P/P)_{sys} = 0.6\%$,

but is time consuming $(\delta P/P)_{stat} = 3.6\%$ for 8 hours

Compton polarimetry performance

Polarimeter	Energy	Sys. Uncertainty
CERN LEP*	46 GeV	5%
HERA LPOL	27 GeV	1.6%
HERA TPOL*	27 GeV	1.9-3.5%
SLD at SLAC	45.6 GeV	0.5%
JLAB Hall A	1-6 GeV	1-3%
JLab Hall C	1.1 GeV	0.6%

*transverse

Goal for EIC is $\delta P/P = 1\%$ for both hadron and electron

Theory systematics

experiment

$$\sigma(x_B, Q^2) = \frac{N - B}{\mathcal{L} \cdot \mathcal{A}} \cdot \mathcal{C} \cdot (1 + \Delta)$$

theory

- Bin-centering $\mathcal{C}$
- Radiative corrections Δ
  - Recent efforts to unify QED radiative effects with QCD radiation
    Liu, Melnitchouk, Qiu, Sato PRD 104, 094033 (2021)
  - Electroweak radiation...?
- Traditional approach is binned *unfolding* of experiment,
  but event-by-event *folding* of theory becoming more feasible

Concluding remarks

- Optimum electron, kinematic reconstruction methods differ across detector
  - Comparing kinematic bins will have different systematics
- Electron ID is critical for EIC physics
  - Asymmetry measurements limited by electron purity
  - Especially important in the barrel region, where pion background is largest
- High-precision polarimetry critical to polarized asymmetry measurements
- Absolute measurements require precise luminosity

Backup

Definitions of reconstruction methods

Electron

$$y = 1 - \frac{E'_e}{2E_e}(1 - \cos\theta_e)$$

$$Q^2 = 2E_e E'_e(1 + \cos\theta_e)$$

Jacquet-Blondel

$$y = \frac{\delta_h}{2E_e}$$

$$Q^2 = \frac{p^2_{T,h}}{1 - y}$$

Double-angle

$$y = \frac{\sin\theta_e(1 - \cos\gamma_h)}{\sin\gamma_h + \sin\theta_e - \sin(\gamma_h + \theta_e)}$$

$$Q^2 = 4E_e^2 \frac{\sin\gamma_h(1 + \cos\theta_e)}{\sin\gamma_h + \sin\theta_e - \sin(\gamma_h + \theta_e)}$$