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# Using Deeply Virtual Compton Scattering to characterise the ePIC detector

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WORLD CHANGING GLASGOW

CELEBRATING 200 YEARS 1824 2024 WILLIAM THOMSON, LORD KELVIN INNOVATION INVENTION INSPIRATION

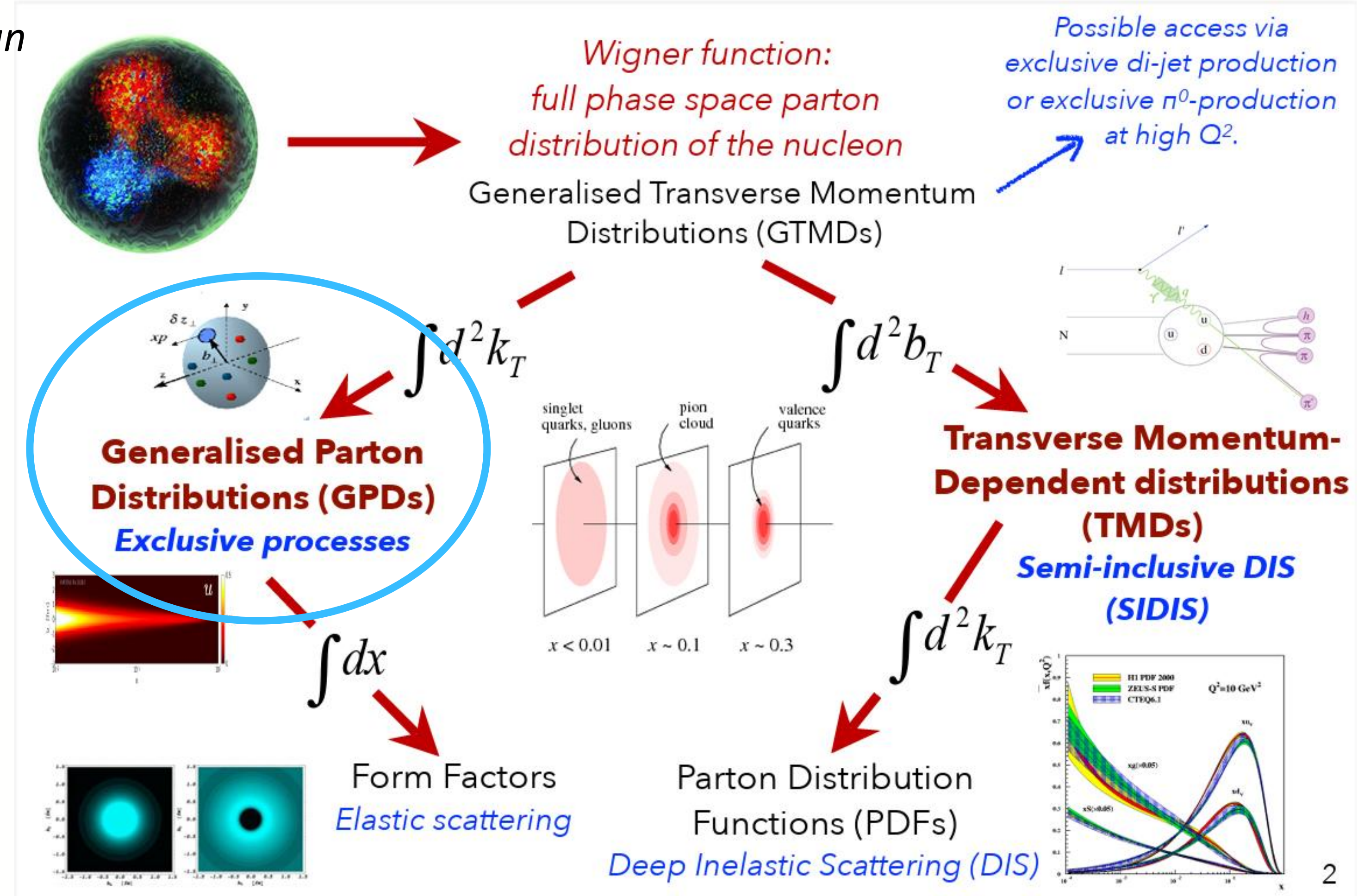
# This presentation

- Context: DVCS and its place in the EIC physics programme.
- DVCS simulations to test ePIC performance.
  - Electrons and photons in the barrel/endcaps.
  - Far forward protons.
  - Fully exclusive DVCS events.
- Where we go from here…

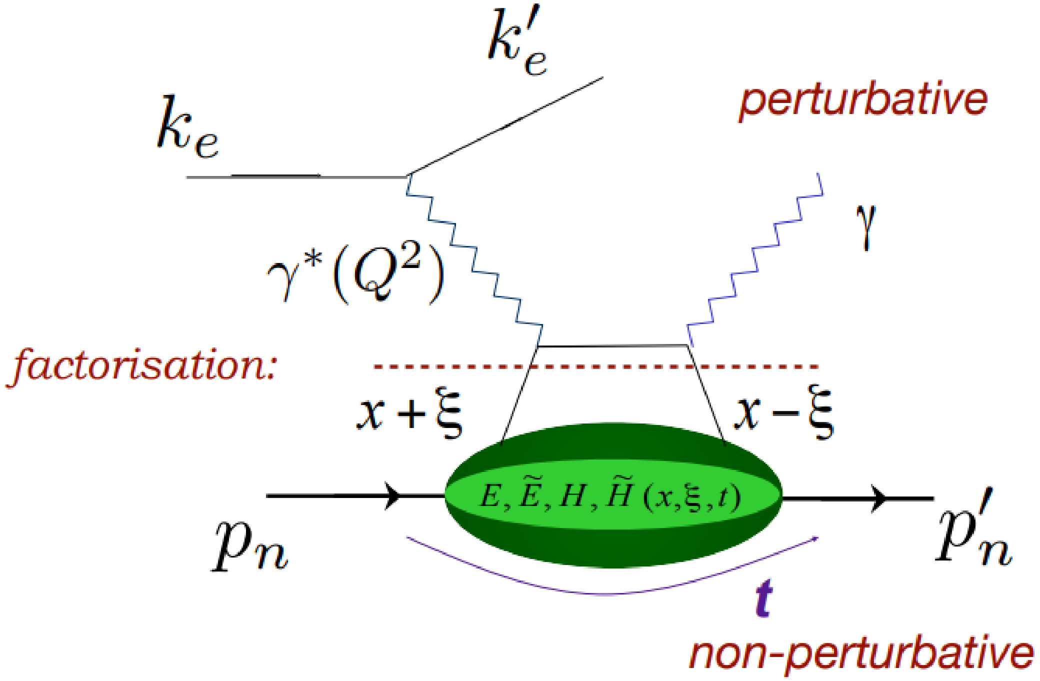
# Deeply Virtual Compton Scattering

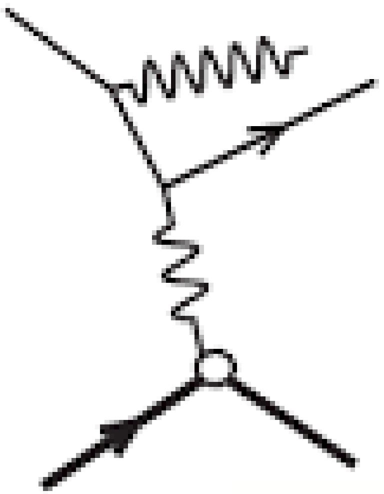
# Nucleon structure – multi-dimensional pictures

D. Sokhan



# Deeply Virtual Compton Scattering



- DVCS: electroproduction of a photon off a hadron target

- QM interference: Bethe-Heitler ($e^-$ radiates final state photon.

# Deeply Virtual Compton Scattering: kinematics

- Default kinematics:
  - $e(k) + p(p) \rightarrow e'(k') + p'(p') + \gamma$

- Inclusive kinematics: scattered electron only ("Electron method" in EICrecon)

$$Q^2 = -q^2 = -(k - k')^2 \qquad y = \frac{q.p}{k.p} \qquad x = \frac{Q^2}{2q.p} \qquad \xi = \frac{x}{2 - x} \approx \frac{x}{2}$$

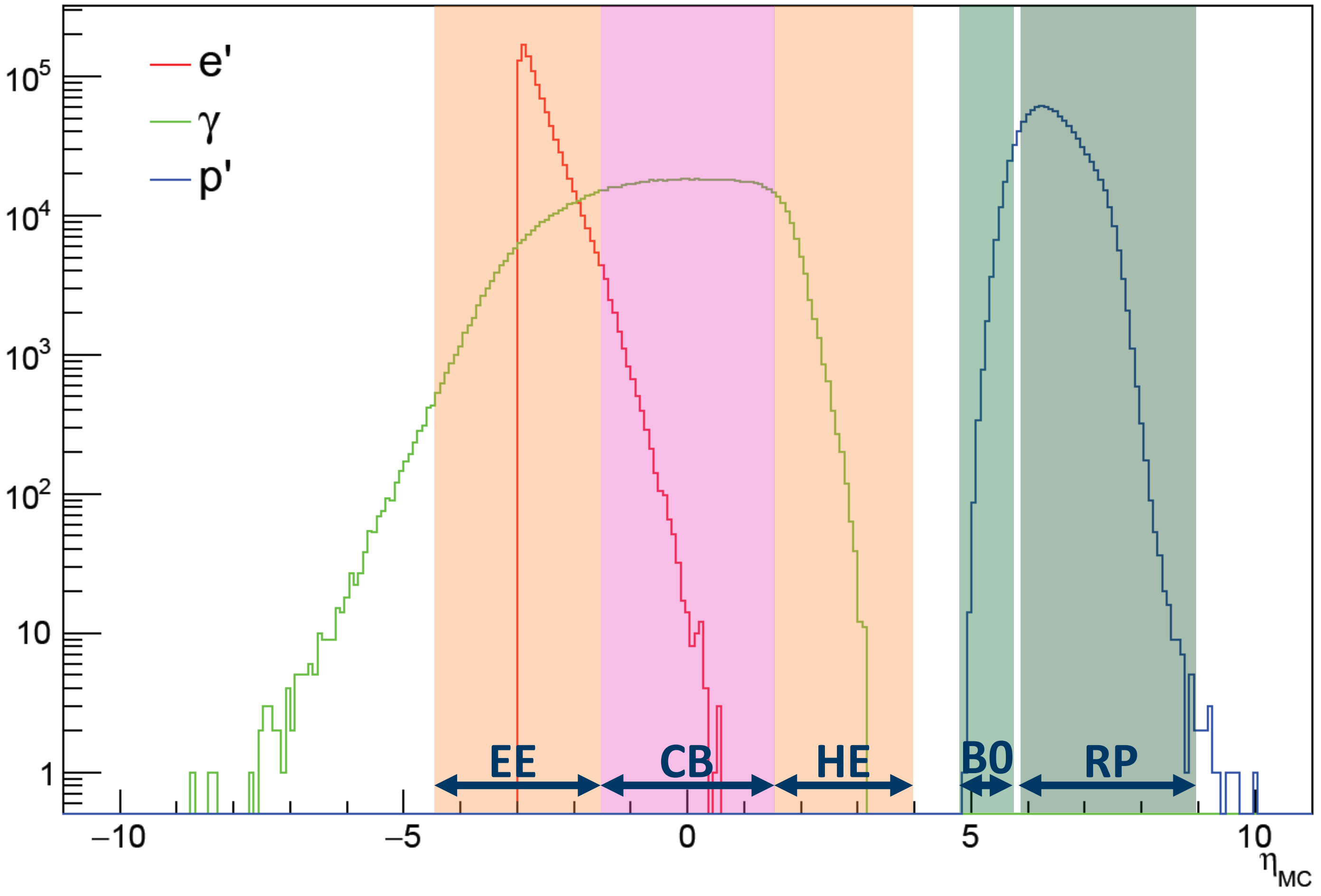
- Mandelstam *t*: beam and scattered proton (BABE method in *tRECO* convention)

$$t = (p - p')^2$$

# Why DVCS @ ePIC?

- Amongst the EIC's physics goals are:
  - Probing the 3D structure of nucleons.
    - Fourier transform of GPDs.
  - Solving the mystery of proton spin.
    - Ji's Sum Rule (combination of GPDs)
- DVCS covers 2 of the stated physics goals in 1 channel!

# Why DVCS @ ePIC?




EpIC MC generator, 1M events (ep 10x100)

- Much of the ePIC detector used for reconstruction.
  - Electrons: **central barrel** and **backward endcap**.
  - Photons: across **central barrel** and **both endcaps**.
  - Protons: **B0** and **Roman Pots** (energy-dependent).
    - 5x41 – 94% B0, 6% RP
    - 10x100 – 3% B0, 97% RP
    - 10x130 – same as 10x100
    - 18x275 – 100% RP

# DVCS simulations for ePIC

Showing output from 25.10.2 simulation campaign

# Simulation details

- Using EpIC generator (GitHub link here).
  - Purpose built generator for such GPD-sensitive processes (DVCS, TCS, DDVCS, etc.).
- Can run in fixed target or colliding beams mode.
  - Useful for JLab and EIC kinematics!
- Cross-sections and CFFs evaluated from models (Guichon and Vanderhaegen / Goloskokov-Kroll respectively).

# Simulation details

- Event samples used:
  - 1M events; DVCS only (5x41, 10x100, 18x275) / DVCS+BH+int. (10x130)
  - $1 < Q^2 < 100$ GeV$^2$ $0.01 < y < 0.9$ $10^{-5} < x_B < 0.7$

- Generated events represent $\mathcal{L}_{int} \sim 2 fb^{-1}$ for the "standard" EIC energy settings, $\mathcal{L}_{int} \sim 0.5 fb^{-1}$ for 10x130 GeV.
- Events are passed through the full EIC simulation pipeline.
  - Afterburner (to add beam smearing and crossing angle).
  - npsim
  - EICrecon

# Cuts applied

- Single species cuts:
  - Electron: only 1 reconstructed and $Q^2 \geq 1$ GeV$^2$
  - Photon: only 1 reconstructed
  - Proton: only 1 reconstructed and track theta appropriate for detector used.
    - $5.5 < \theta_{p'} < 20$ mrad for B0 tracks
    - $0 < \theta_{p'} < 5$ mrad for RP tracks
- DVCS event cuts:
  - Full exclusivity (e’p’γ reconstructed)
    - All single species cuts simultaneously.
  - ${M_{miss}}^2 \leq 1$ GeV$^2$

# Central barrel and backward endcap

Electrons and photons

(Mostly using 10x100 GeV setting for plots)

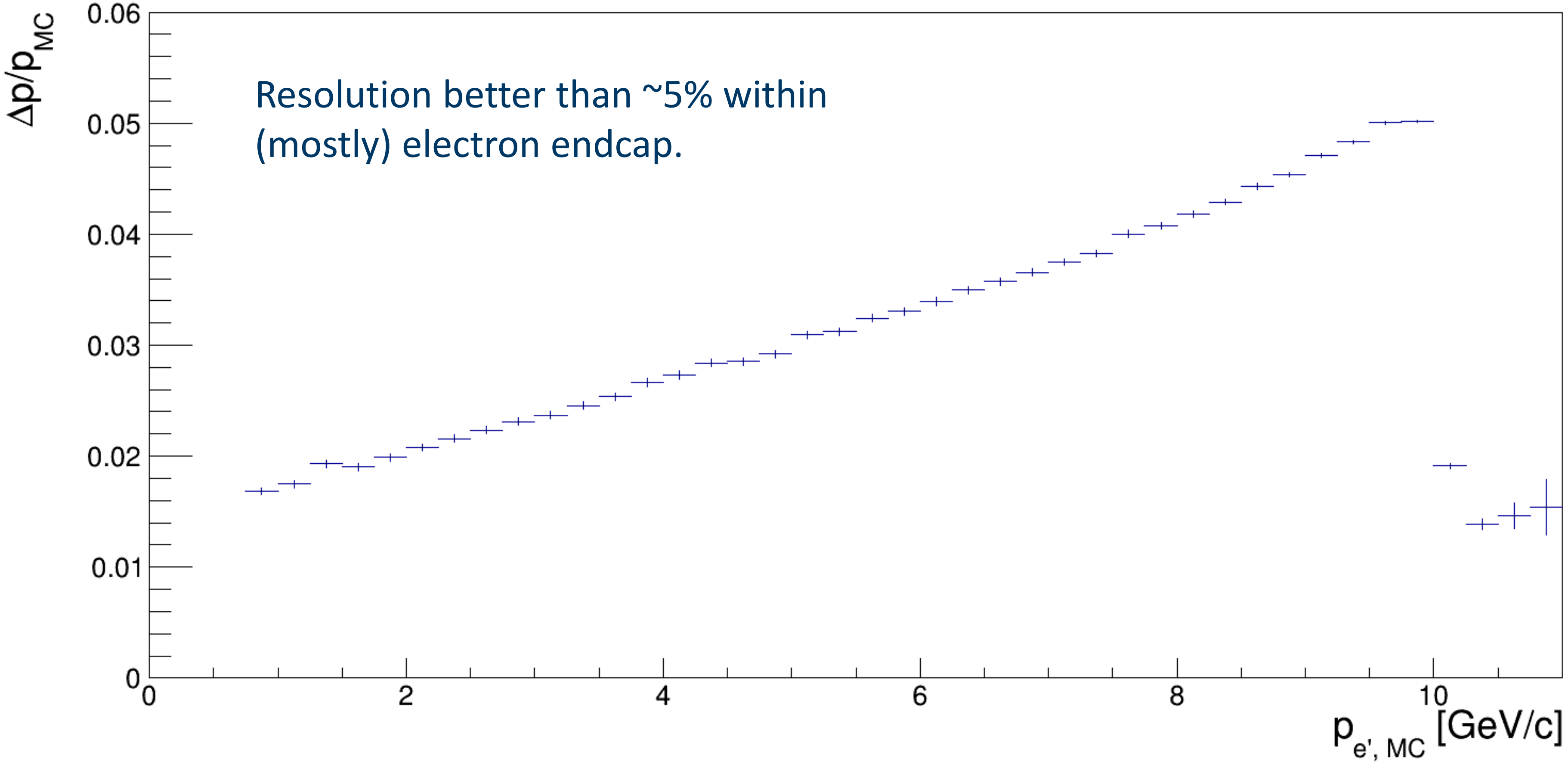
# ePIC PID performance

- Electrons in the barrel/endcaps get passed through ePIC PID simulation.
  - Provides test of PID performance in live physics channel.

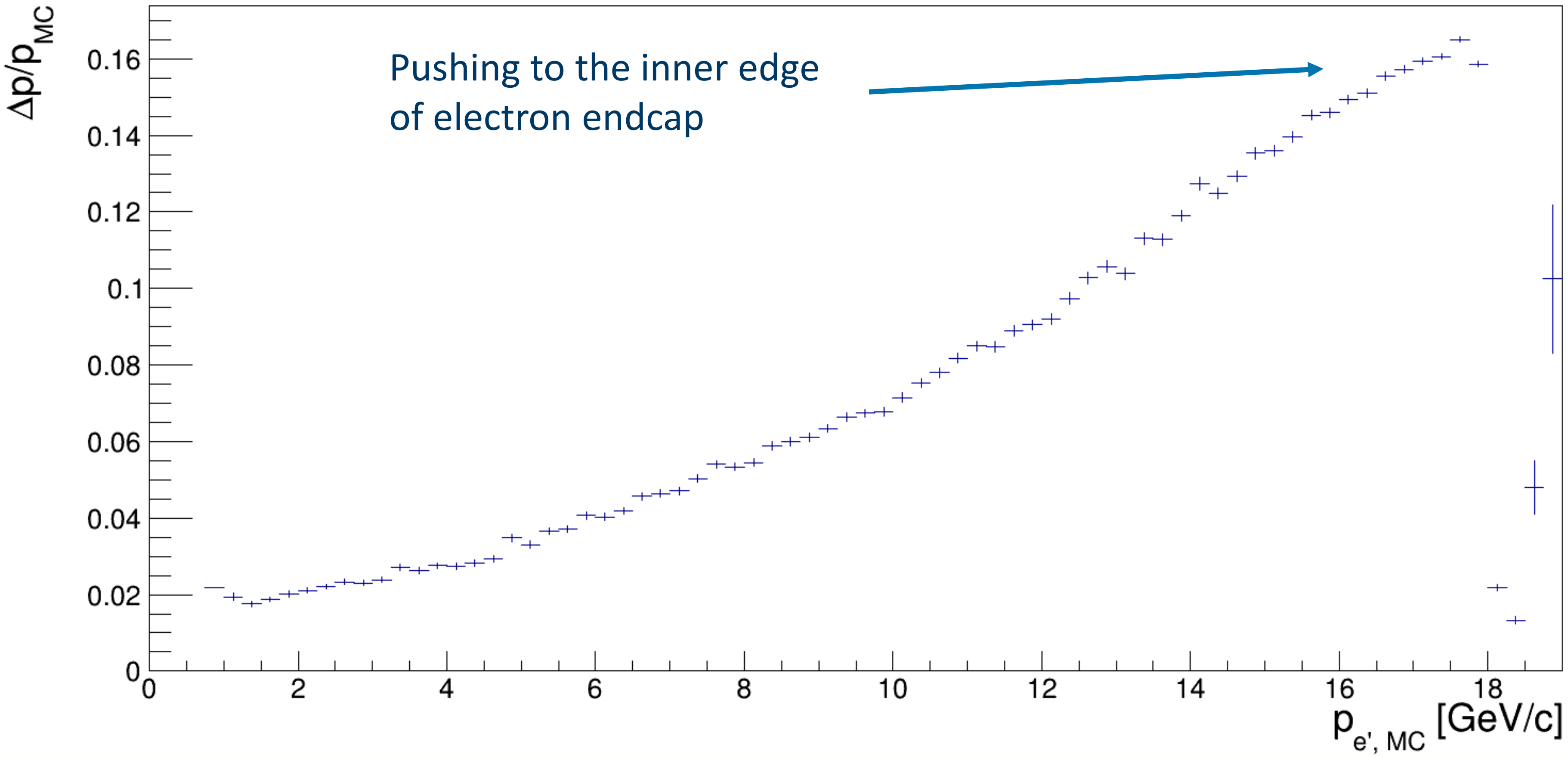
- Current PID performance (using small sample, ~10k DVCS events):
  - 5x41, 10x100 – ~60% PID efficiency.
    - ~25-30% mis-ID'ed as $\pi^-$ (small proportion as $K^-$).
  - 18x275 – ~20% efficiency.
    - ~10% as $\pi^-$, ~5% as $K^-$.
    - ~60% without valid PID flag.

- Needs work; DVCS can help monitor this as the algorithm changes.

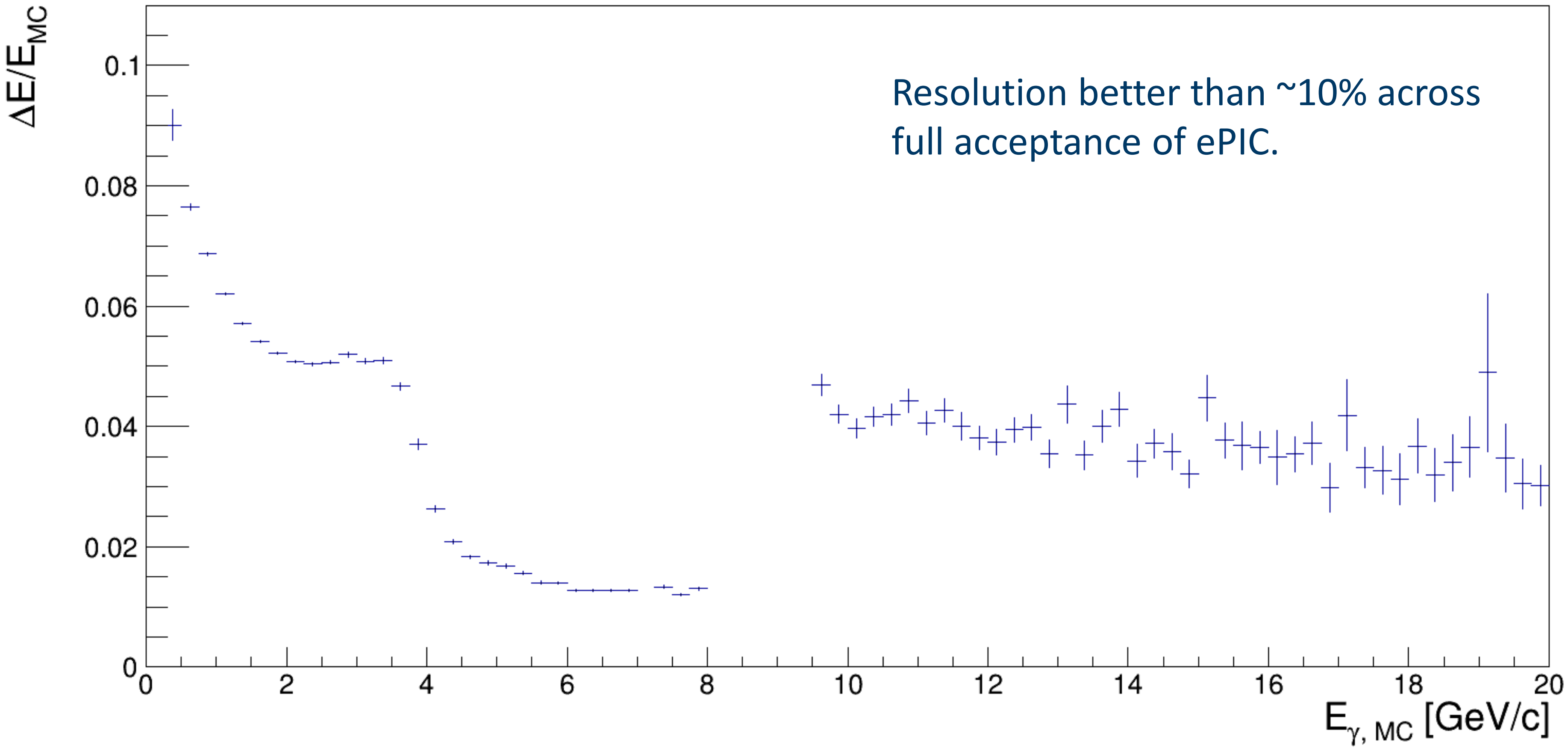
# Momentum resolution – e'



# Momentum resolution – e' (18x275)



# Energy resolution – γ

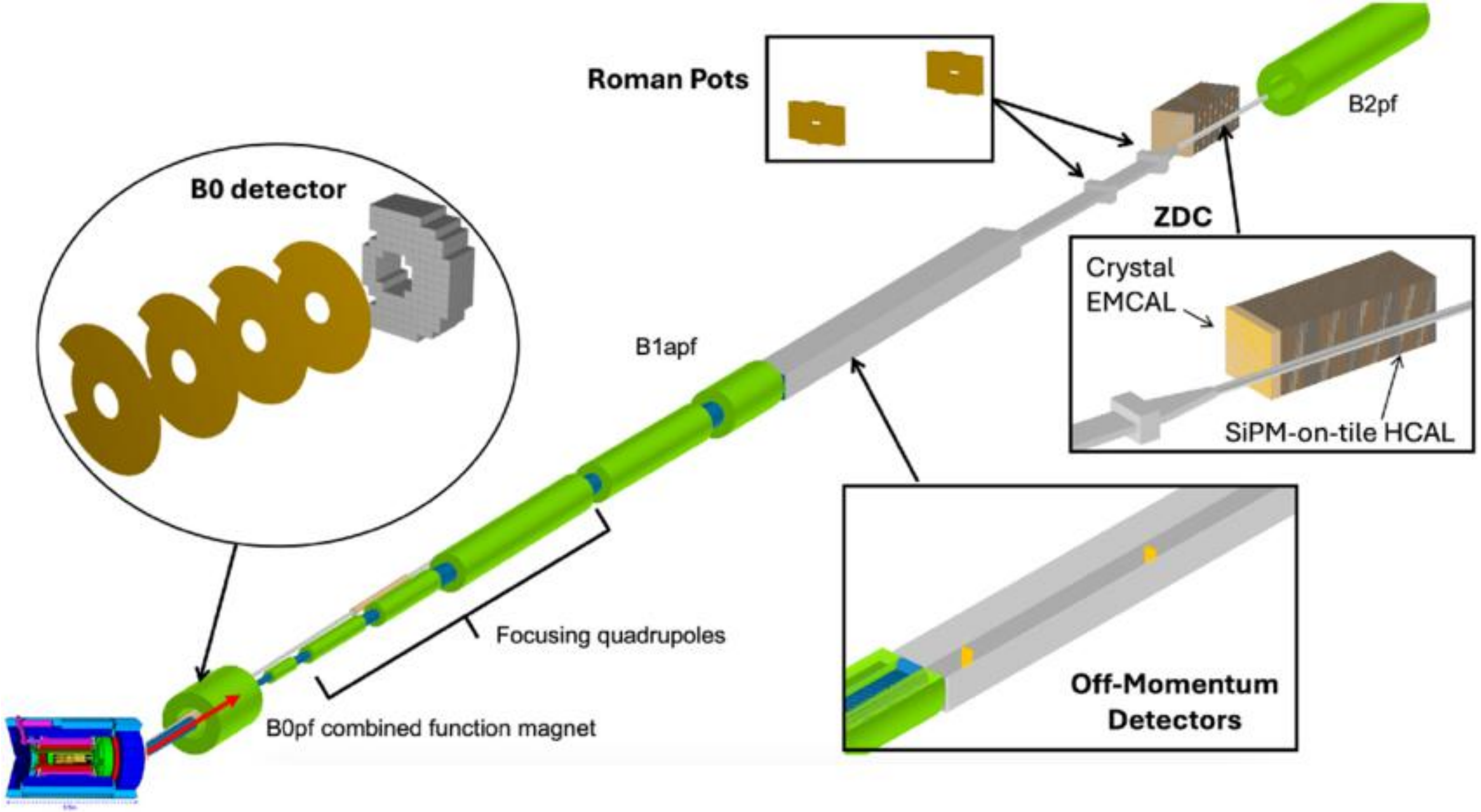



Resolution better than ~10% across full acceptance of ePIC.

# Far forward detectors – B0 and Roman Pots

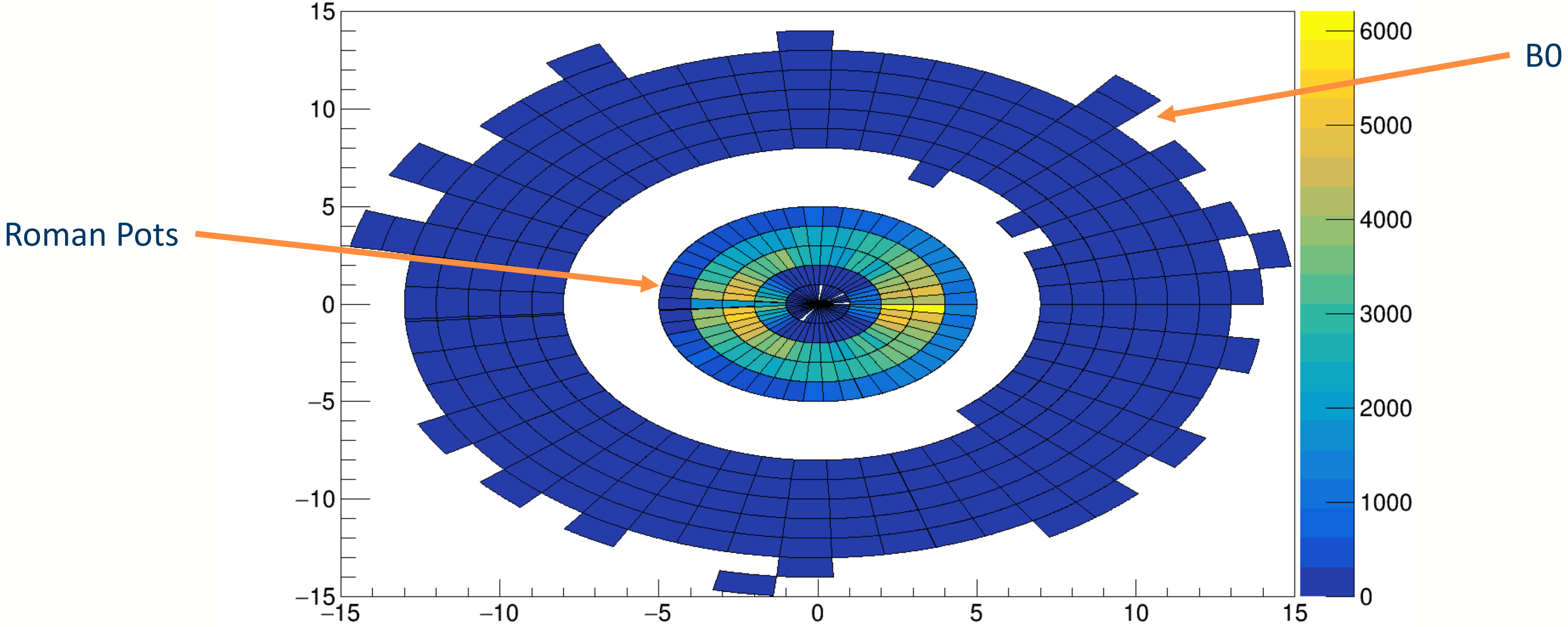
Scattered protons

# The far forward region

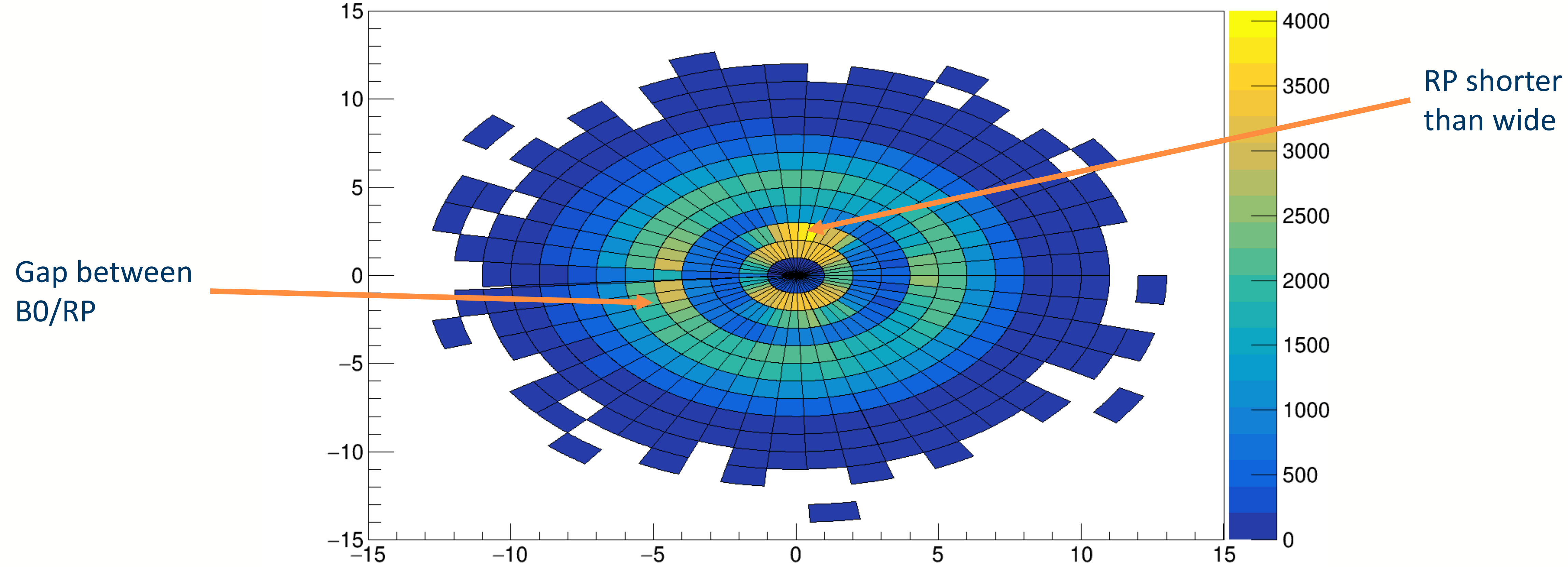



- B0 spectrometer – charged particles at higher angles (5.5 – 20 mrad).
- Zero Degree Calorimeter – far forward neutral reconstruction.
- Roman Pots – protons scattered at v. small angles.
- Off Momentum Detectors – detection of protons from nuclear breakup.

# Scattered proton acceptance



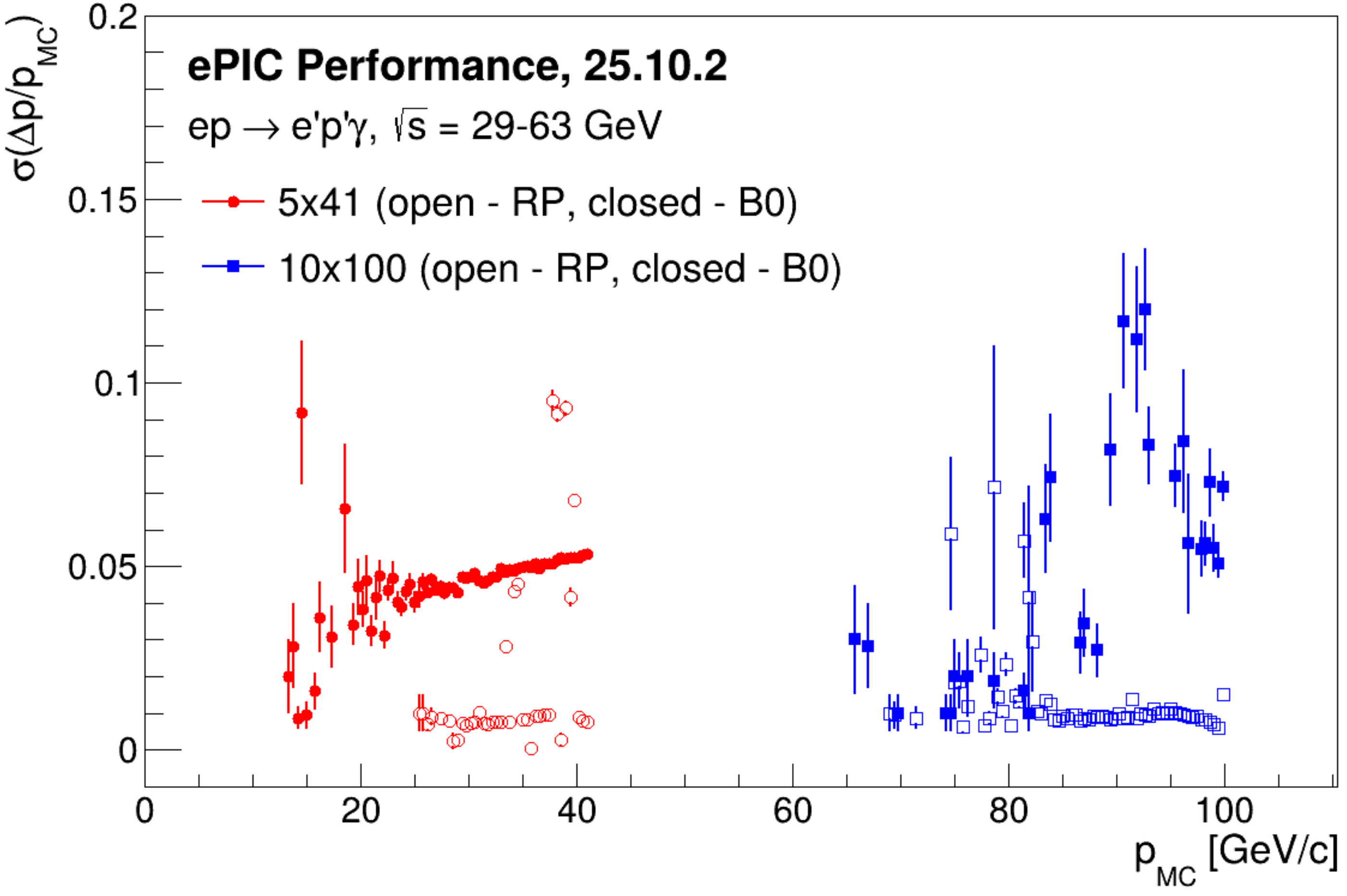
# Missing protons



# FF momentum resolution

Statistical fluctuations aside, B0 p resolution around ~few percent.

Roman Pot resolution significantly improved by move away from static matrix reconstruction.

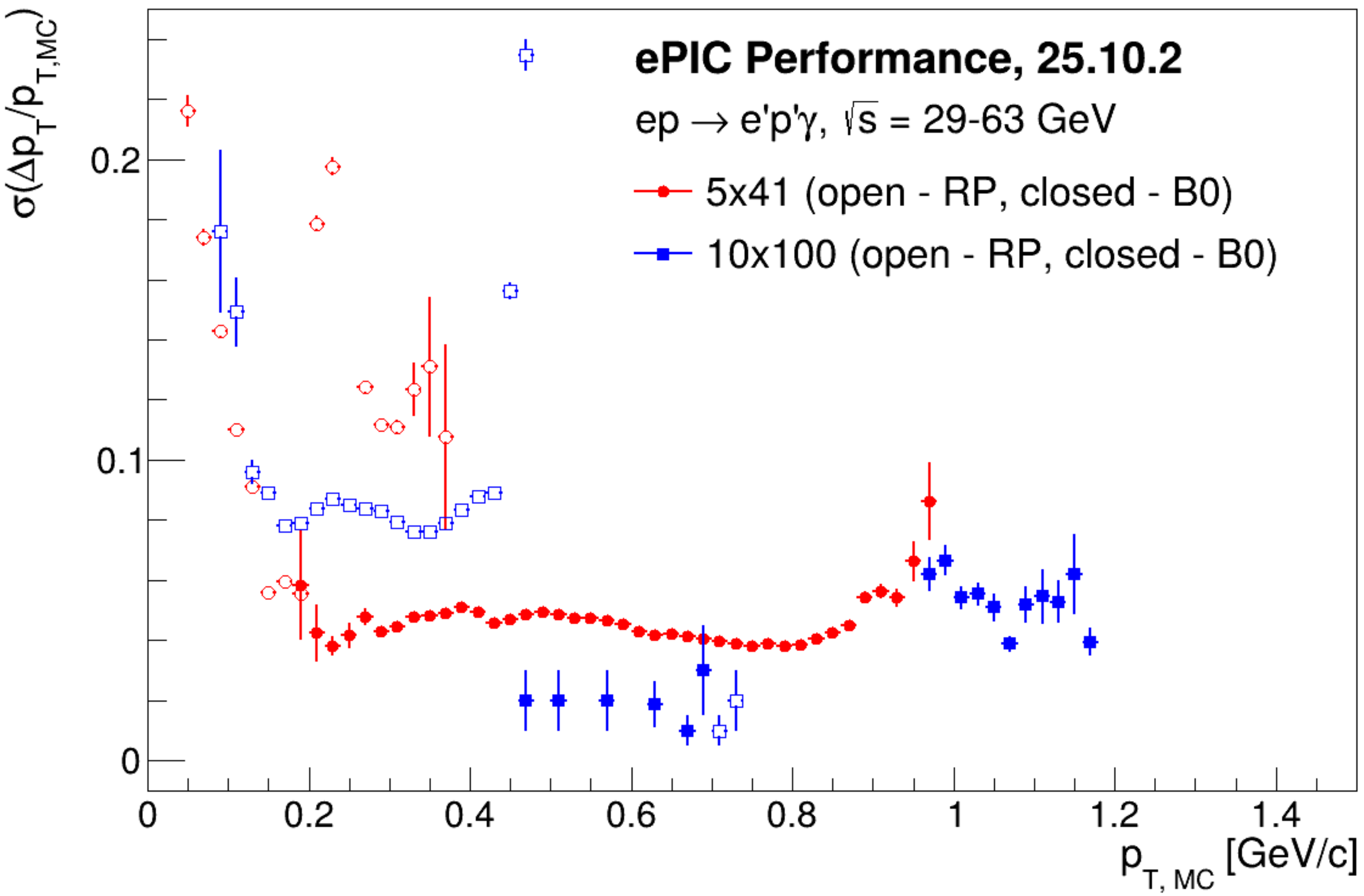



NB: B0 performance unintentionally worsened in recent campaigns.

More noticeable in higher energy settings, where fewer protons hit the B0.

Issue is known about, and fix being developed.

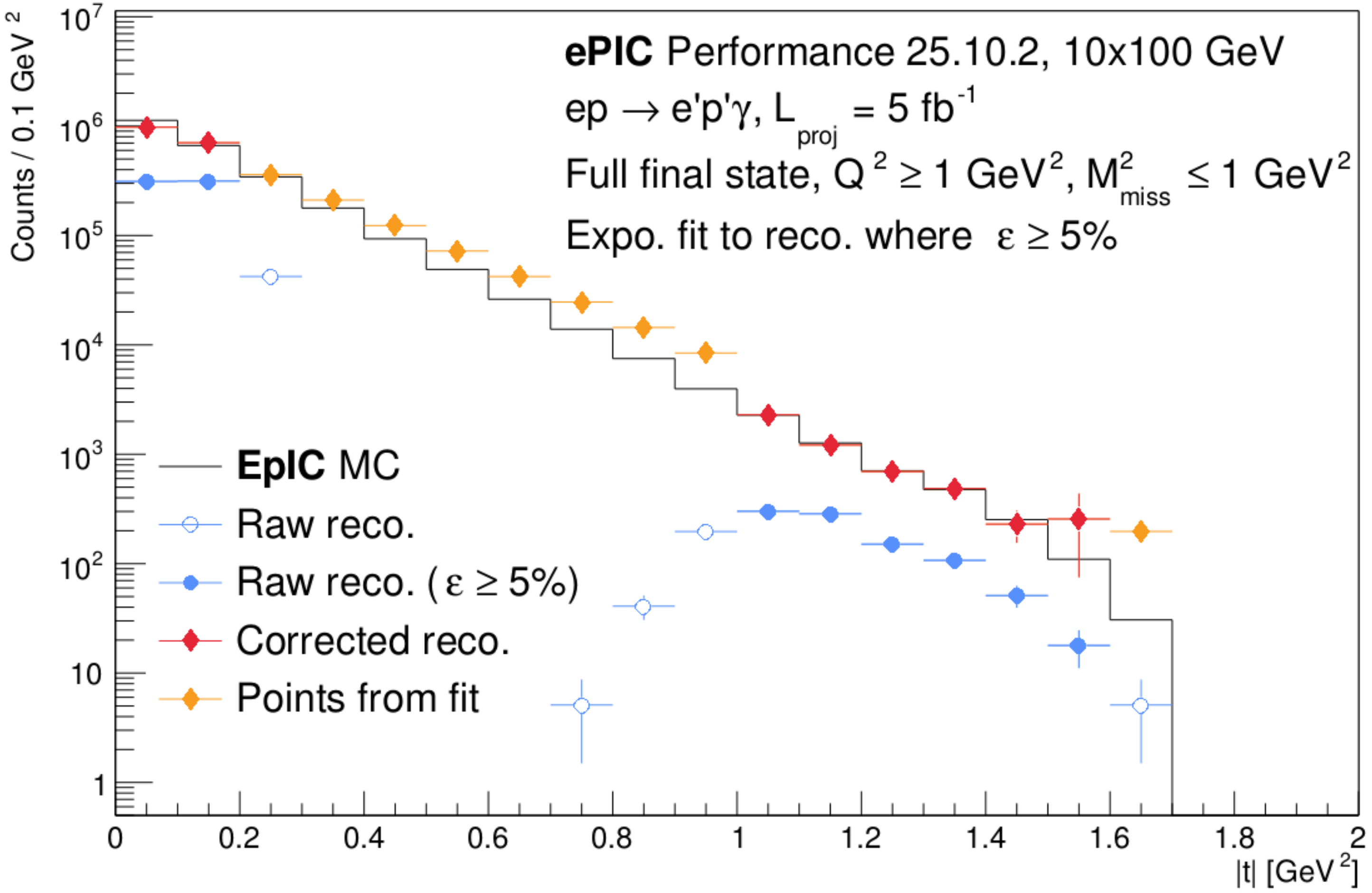
# FF $p_T$ resolution



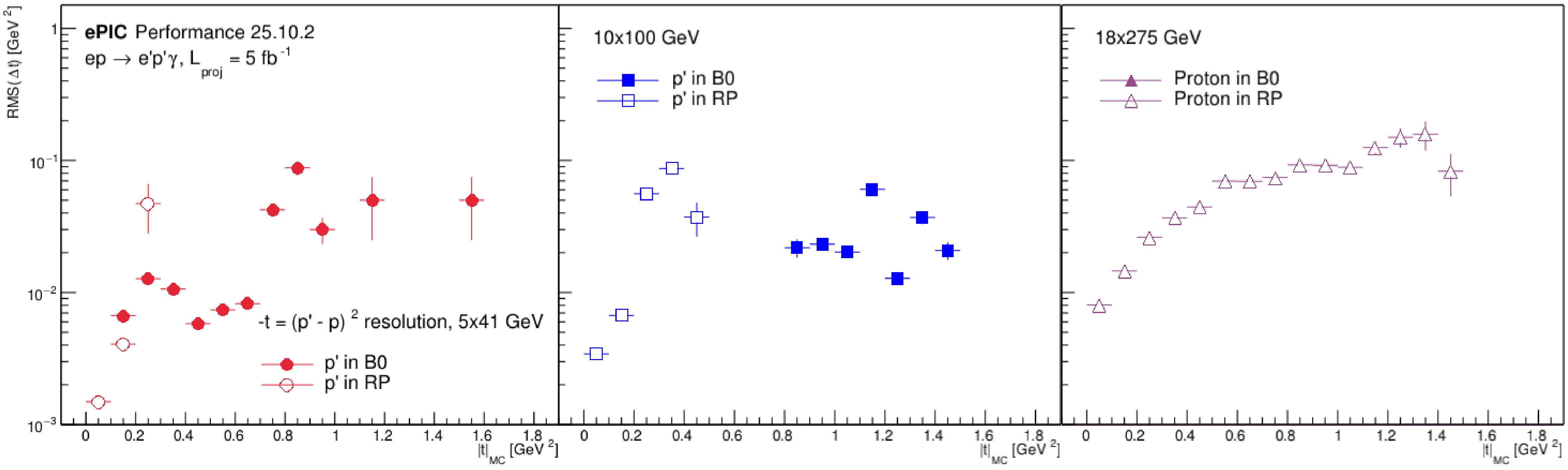
# Full DVCS events

Only fully exclusive events (for now…)

# Mandelstam t distribution



# Mandelstam t resolution



# Work ongoing…

# Mandelstam t reconstruction

- Looking into trying to reconstruct t via other methods.
  - If scattered proton is missed/poorly reconstructed.

- Constrained semi-inclusive reconstruction (tRECO “eXBE”/Yellow Report “method L”) look promising in other channels.
  - DVCS shows large smearing towards high-t.
  - Another method needed?

# More simulations

- Integrated beam background simulations now available.
  - Single DVCS event per 1μs event frame…
  - …plus synchrotron radiation, bremsstrahlung, beam-gas events…
  - Only made available as of yesterday (Monday 8$^{th}$), so events not yet analysed.

- New DVCS event samples prepared (but not yet added to analysis chain).
  - Using different beam helicities (unpolarized target), to give estimate on asymmetry uncertainties.

# Concluding remarks

# Summary

i. DVCS is a very useful channel for ePIC to study.
   - Covers key EIC physics goals.
   - Provides a good probe of detector resolutions and reconstruction efficiencies.
   - Effective test bed for much of ePIC coverage.

ii. Significant efforts currently going into analysis of regular simulation campaigns.
   - DVCS provides input to both pre-TDR and Early Science paper.

iii. Soon to also test effects of beam-related backgrounds.

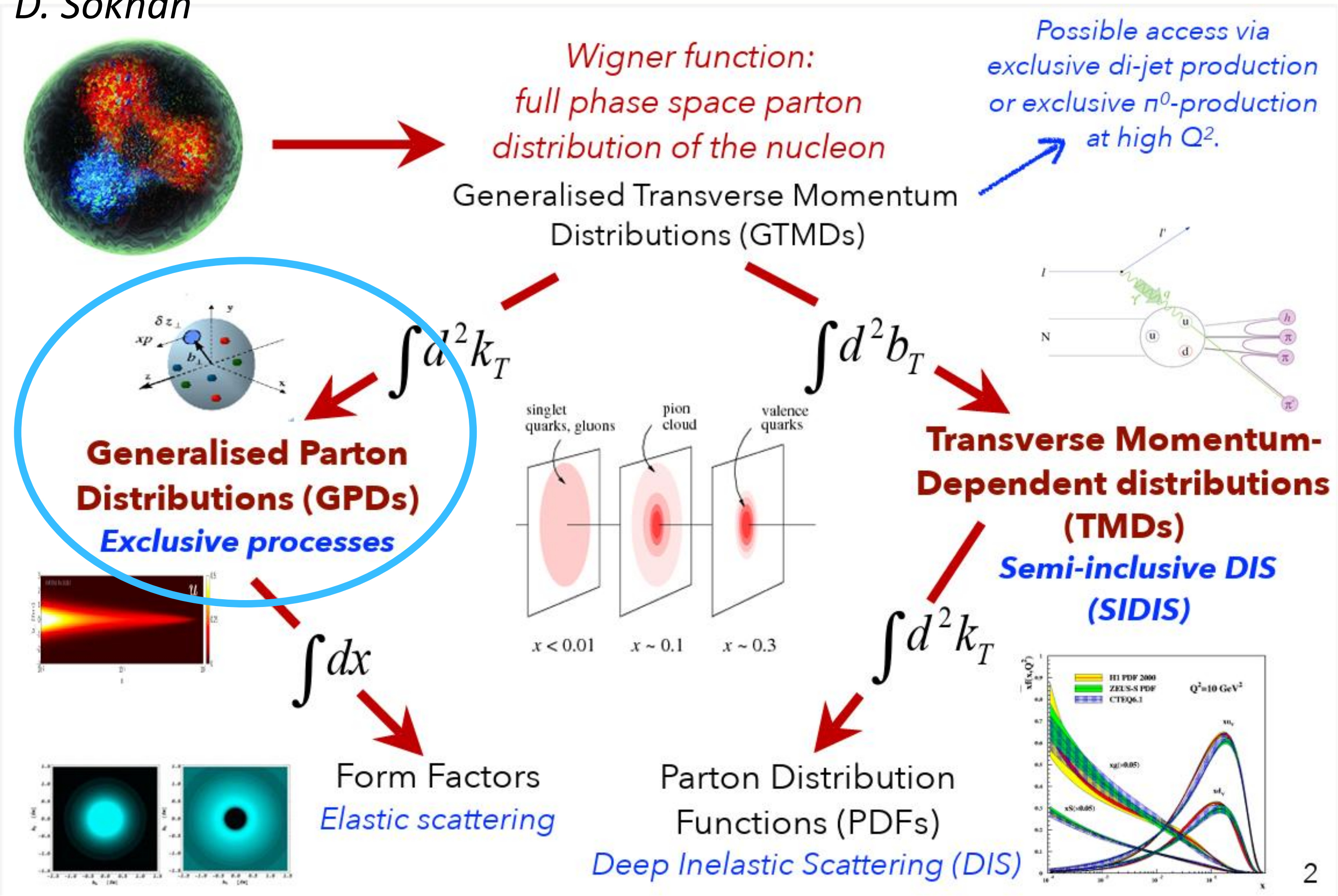
# Thank you for listening!

Any questions?

# Backup

# Nucleon structure

D. Sokhan

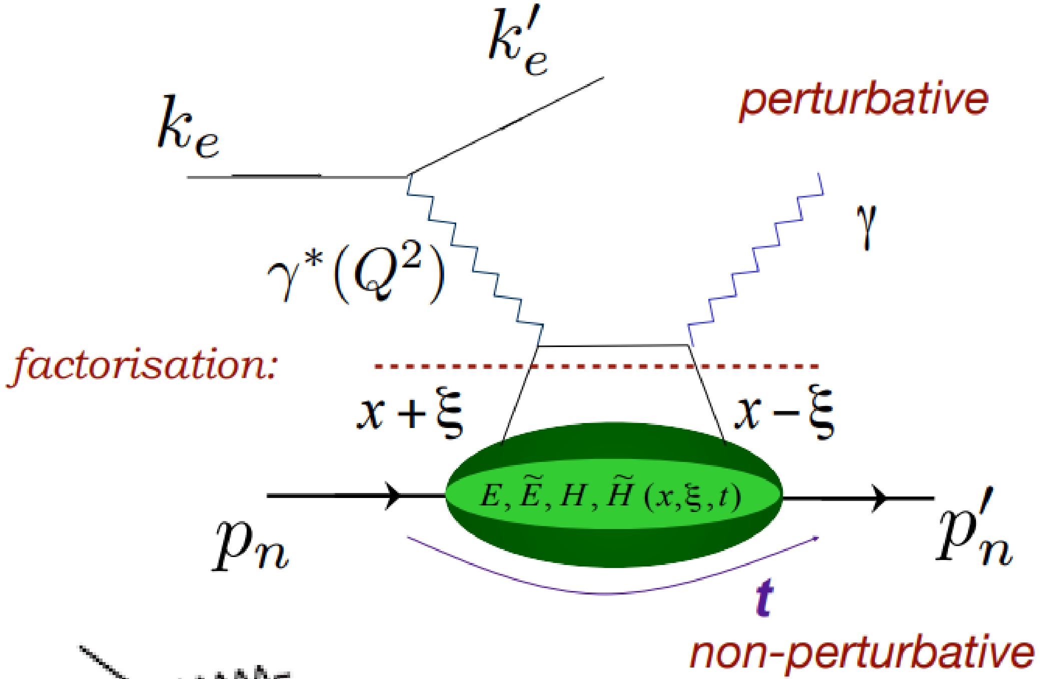


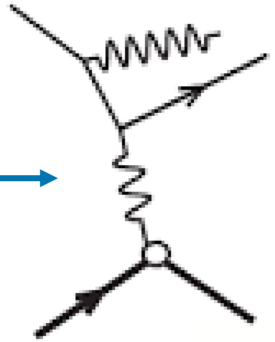

- Nucleon structure can be described within multiple dimensions by a large number of different functions.
  - GTMDs – full 5D phase space distributions.
  - PDFs – 1D as function of parton momentum.
  - Form factors – 1D as function of transverse distance from centre.
- GPDs relate the transverse position of partons to their longitudinal momentum fraction.

# Deeply Virtual Compton Scattering

- Electroproduction of a single photon off a hadron target.
  - $ep \rightarrow e'p'\gamma$
  - Simplest inelastic channel the EIC can study.
  - Easiest channel for probing GPDs.

- The cross-section for this process is related to its matrix element, $|\mathcal{T}|^2$.
  - $|\mathcal{T}|^2 = |\mathcal{T}_{DVCS}|^2 + |\mathcal{T}_{BH}|^2 + \mathcal{I}$
  - $\mathcal{I}$ is an interference term.
  - Bethe-Heitler: purely EM process, which does not probe partonic content.



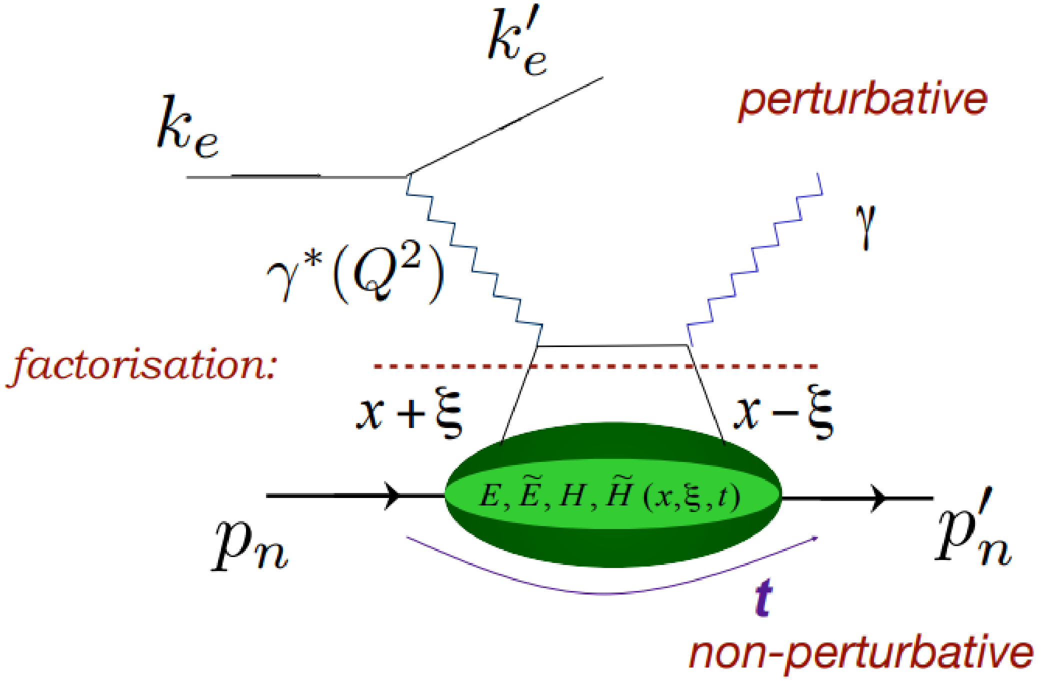
# Deeply Virtual Compton Scattering

- Default kinematics:
  - $e(k) + p(p) \rightarrow e'(k') + p'(p') + \gamma$

$$Q^2 = -q^2 = -(k - k')^2 \qquad x = \frac{Q^2}{2q.p}$$

$$y = \frac{q.p}{k.p} \qquad \xi = \frac{x}{2 - x} \approx \frac{x}{2}$$

$$t = (p - p')^2$$

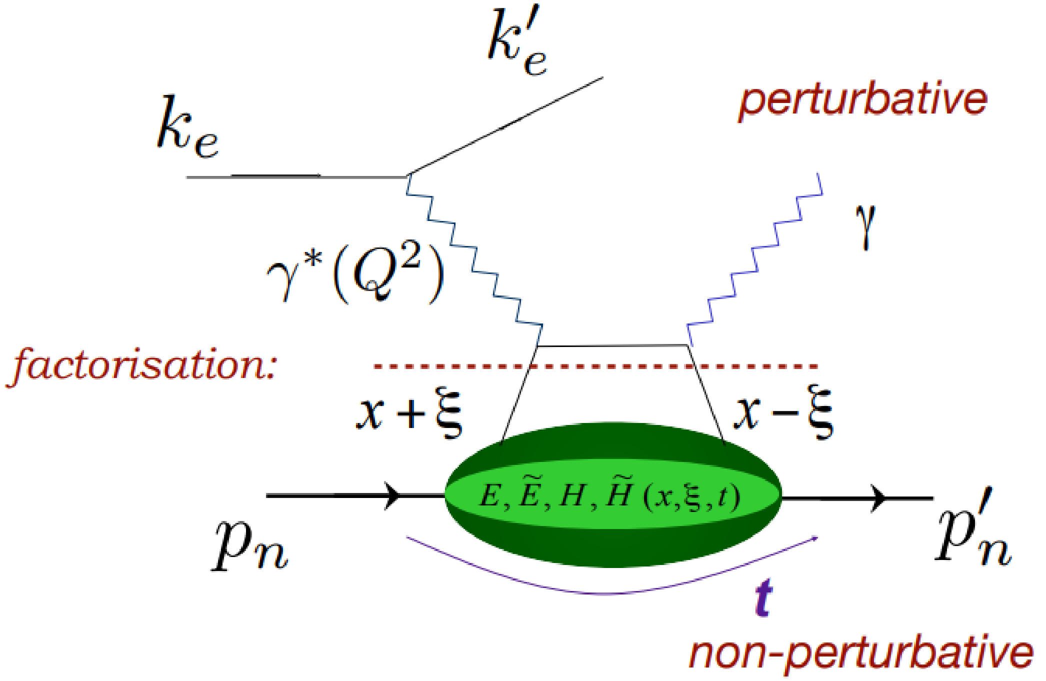



- Other formulae exist, using other combinations of reconstructed quantities, if needed (e.g. see InclusiveKinematics branches in EICrecon trees).

# Deeply Virtual Compton Scattering

- DVCS amplitude can be parameterized in terms of Compton Form Factors (CFFs).
  - Experimentally accessible!
  - Access 4 quark GPDs: $H_q$, $\widetilde{H}_q$, $E_q$, $\widetilde{E}_q$.
  - Note: does not access GPDs directly, but linear combinations of GPDs.
- $Re\,\mathcal{F}_q(\xi,t) \propto \int_0^1 [F_q(x,\xi,t) - F_q(-x,\xi,t)]dx$
- $Im\,\mathcal{F}_q(\xi,t) \propto [F_q(\xi,\xi,t) - F_q(-\xi,\xi,t)]$

- Different combinations of (un)polarised beam and target are sensitive to different combinations of CFFs.




Extract CFFs from asymmetries between different beam polarisation states!

# Why DVCS @ ePIC?

- Amongst the EIC's physics goals are:
  - Probing the 3D structure of nucleons.
  - Solving the mystery of proton spin.

- For an unpolarised target, the distribution of unpolarised quarks is the Fourier transform of the GPD $H_q$.

$$q(x, b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-ib_\perp\Delta_\perp} H_q\left(x, 0, t = -{\Delta_\perp}^2\right)$$

# Why DVCS @ ePIC?

- Amongst the EIC's physics goals are:
  - Probing the 3D structure of nucleons.
  - Solving the mystery of proton spin.

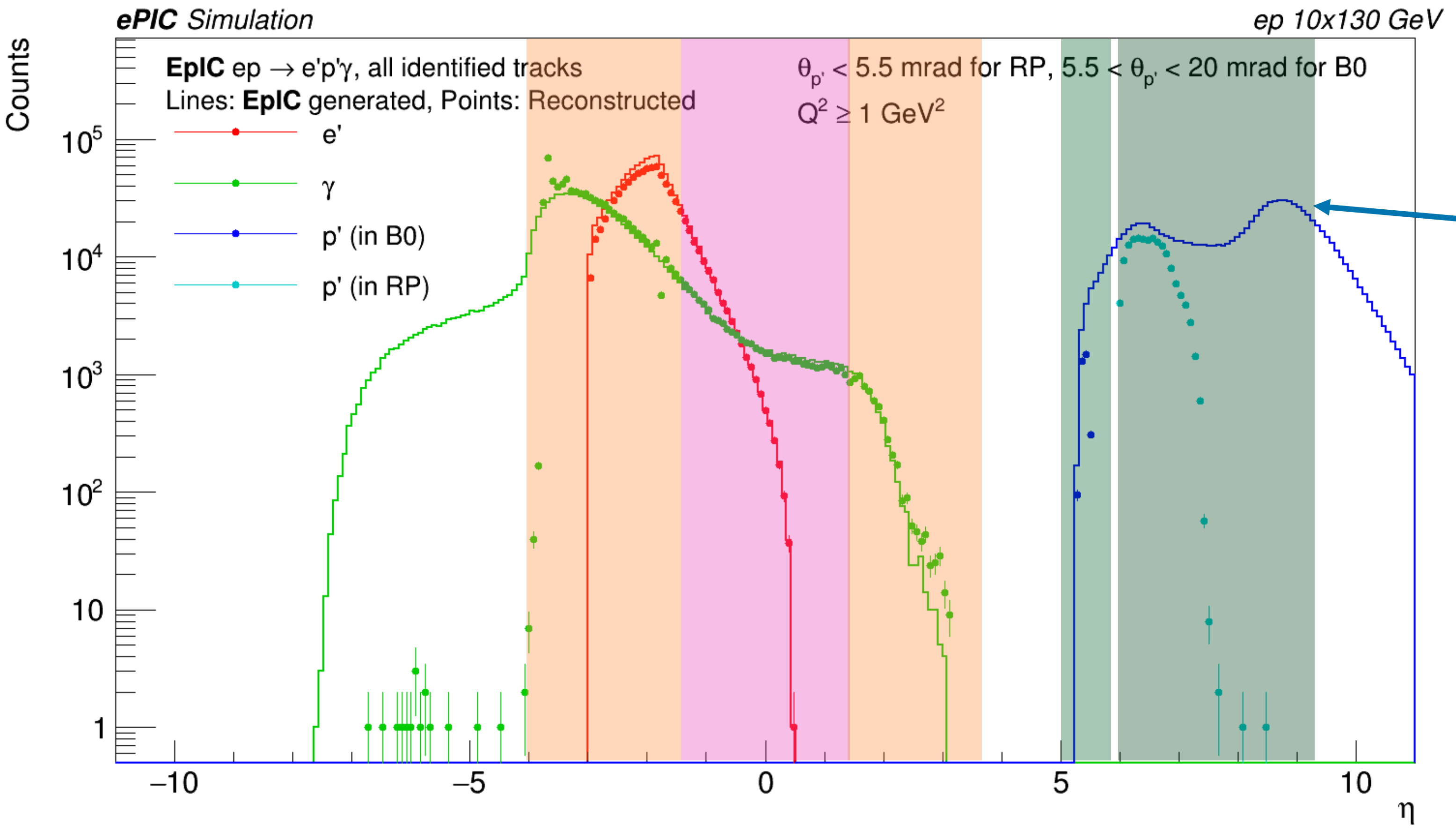
- By Ji's Sum Rule, quark angular momentum can be given by a combination of GPDs.

$$J = \frac{1}{2}\int_{-1}^{1} x dx [H(x, \xi, t = 0) + E(x, \xi, t = 0)]$$

# Why DVCS @ ePIC?

- The final state of the DVCS reaction will utilise many of the subsystems present in ePIC and provide useful probes of their resolutions.
  - The scattered proton will only be deflected by a small angle and will end up in the far forward region.
    - Tests B0 spectrometer and Roman Pots.
  - The scattered electron will be detected in the central barrel or (mostly) the backward endcap.
    - Test of trackers, PID detectors and calorimeters almost everywhere in the barrel (just not hadron endcap/planes).
  - The scattered photon will be detected in the barrel or either endcap.
    - Very clean test of EEEMCAL resolution.

# Detector occupancy (10x130)




Lot of BH background is removed by RP acceptance!

# Analysis details

Analysis code on GitHub.

# Analysis details

- Truth level particles in `MCParticles` branch.
  - Truth level with PID – afterburner applied.

- Reconstructed electrons and photons in `ReconstructedParticles` branch.
  - ePIC PID not accurate – using `ReconstructedParticleAssociations` to select candidates.
  - Electron energy is calculated using given momenta and $e^-$ mass.
  - Associations branch also used for MC acceptance.

# Analysis details

- Reconstructed particle PID using known Associations.
  - Scattered electron and photons reconstructed from tracker and calorimeter information.
  - Scattered protons in the B0 need truth seeding.
  - (For now) Assume all tracks from Roman Pots are real protons.

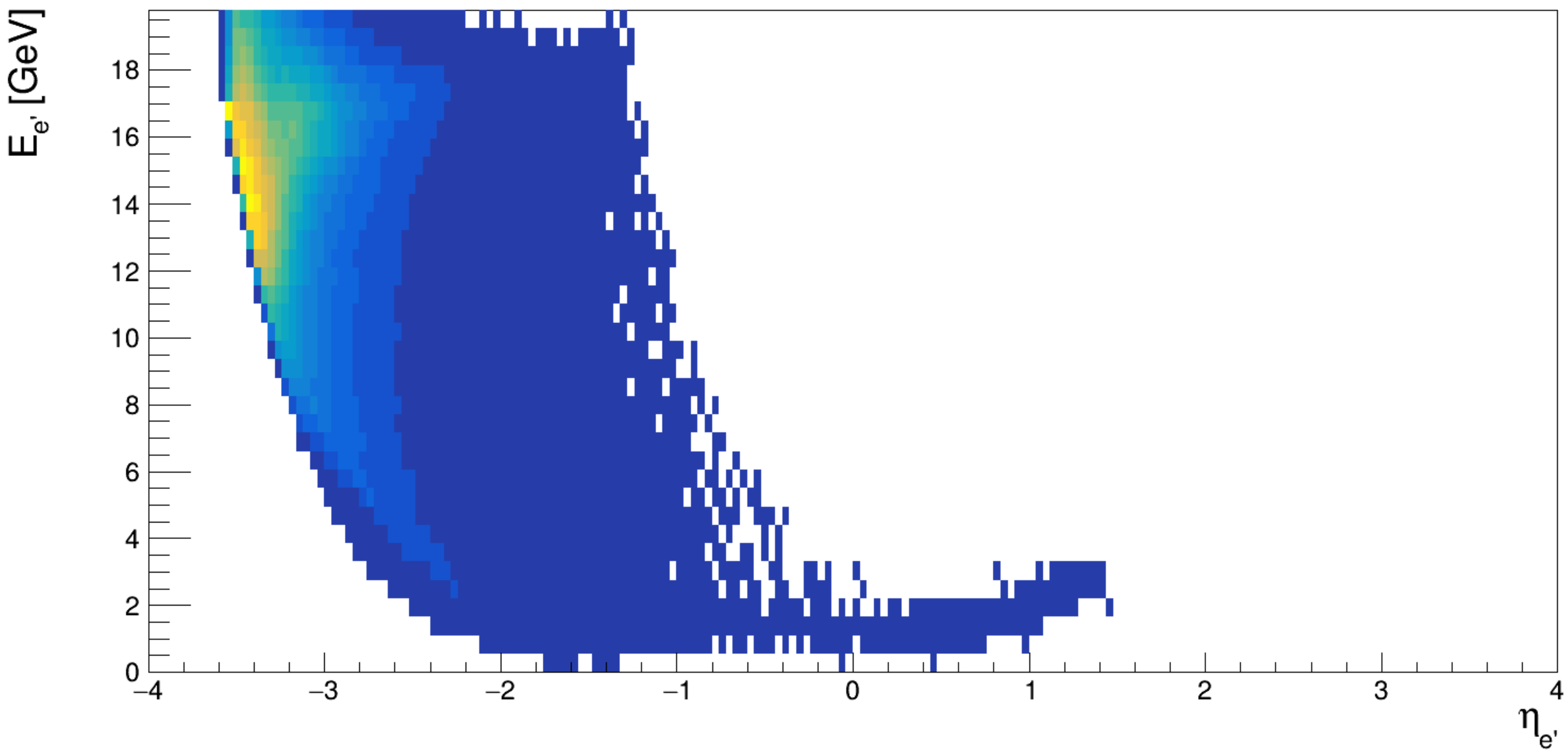
# Detector acceptance correction

- Calculate acceptance from MC information if a reconstructed particle/event passes cuts.
  - Efficiency, $\varepsilon = \frac{N(MC\ accepted)}{N(MC\ truth)}$
- Correct reconstructed distributions by efficiency.
  - $N(corrected\ reco.) = \frac{N(raw\ reco.)}{\varepsilon}$
- Only correcting for detector acceptances for now.

# Analysis details

- Reconstructed protons in the B0 detector taken from `ReconstructedTruthSeededChargedParticles` branch.
  - Corresponding `Associations` branch used for PID.
  - Energy calculated from momentum and proton mass.
  - `Associations` also used for MC acceptance.
- Reconstructed protons in Roman Pots taken from tracks in `ForwardRomanPotRecParticles` branch.
  - All tracks in RP branch assumed to be protons.
  - If RP track is present, assume that MC proton is the correct associated particle.

# E vs η – e’ (18x275)



# E vs η – γ (10x100)