Using Deeply Virtual Compton Scattering to characterise the ePIC detector

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ePIC Collaboration Meeting
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This presentation

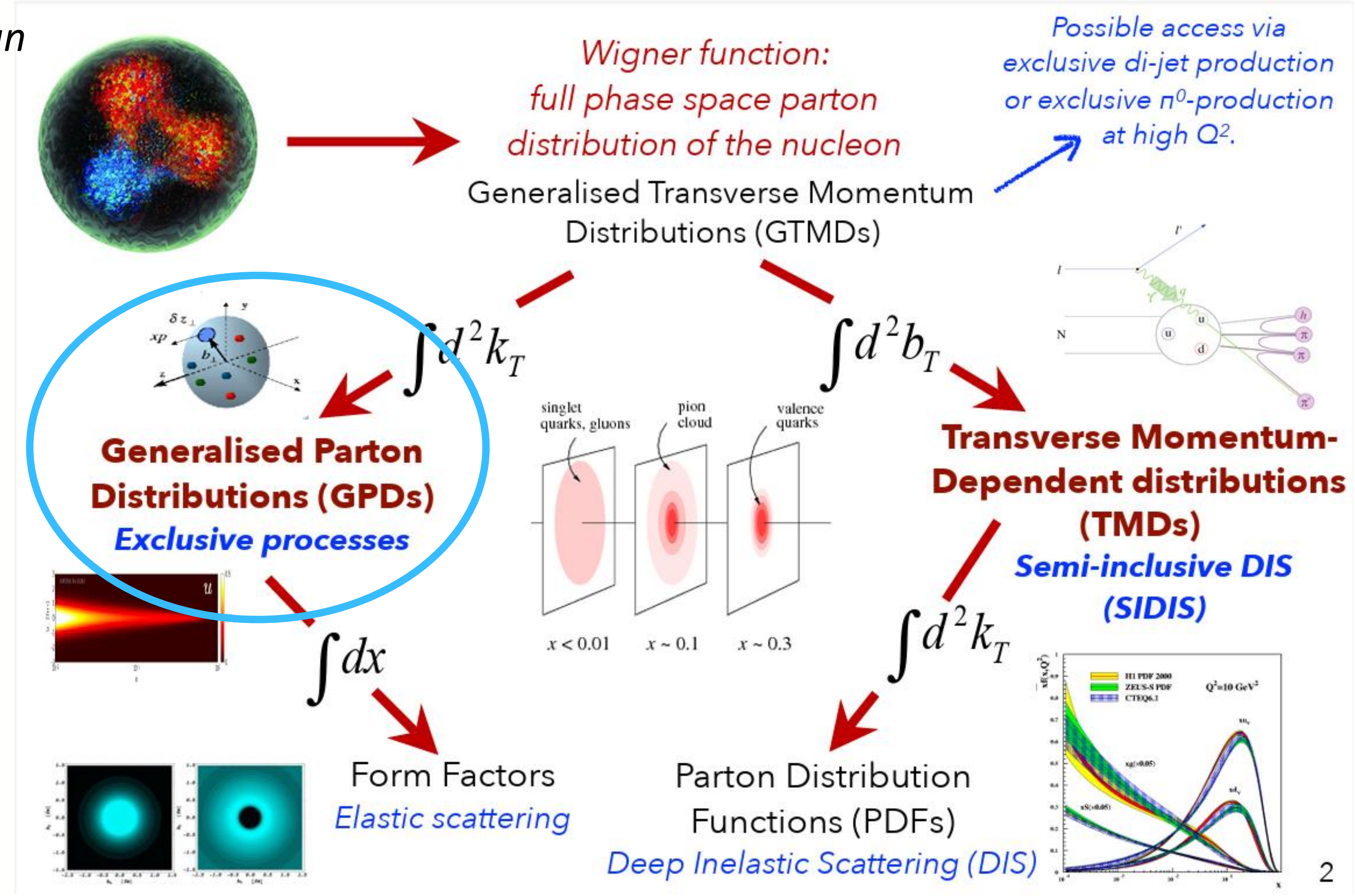
- Context: DVCS and its place in the EIC physics programme.

- Summary of simulation and analysis efforts.
  - Focus on 25.10.2 campaign output

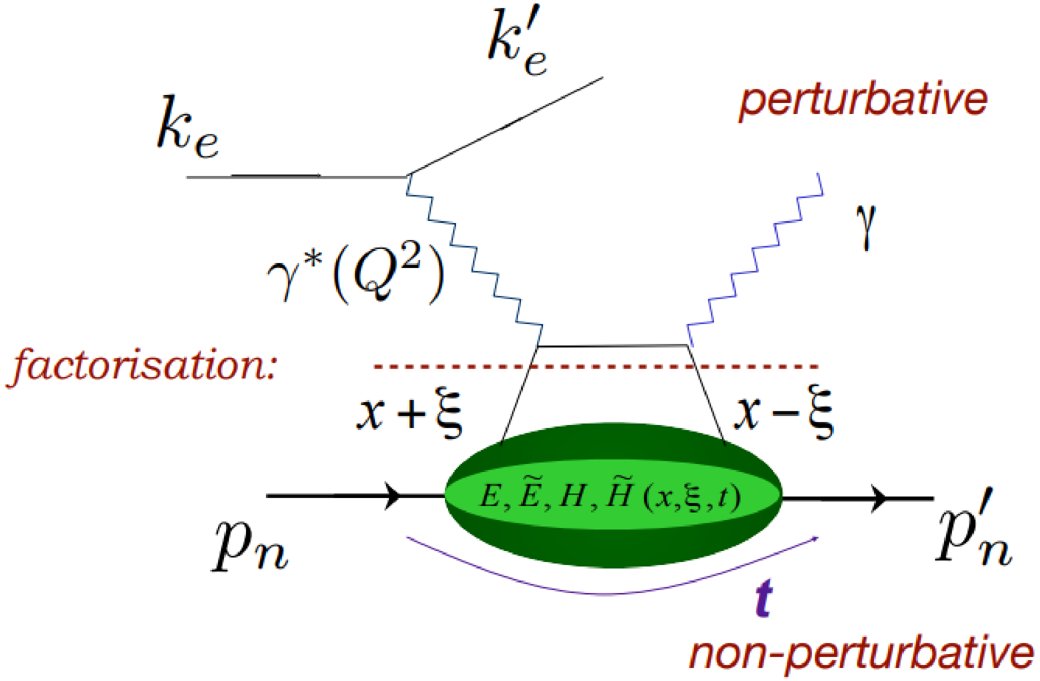
Deeply Virtual Compton Scattering

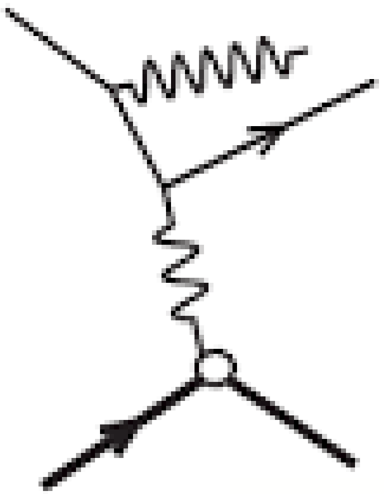
Nucleon structure – multi-dimensional pictures

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* (default): beam and scattered proton (BABE method in *tRECO convention*)

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

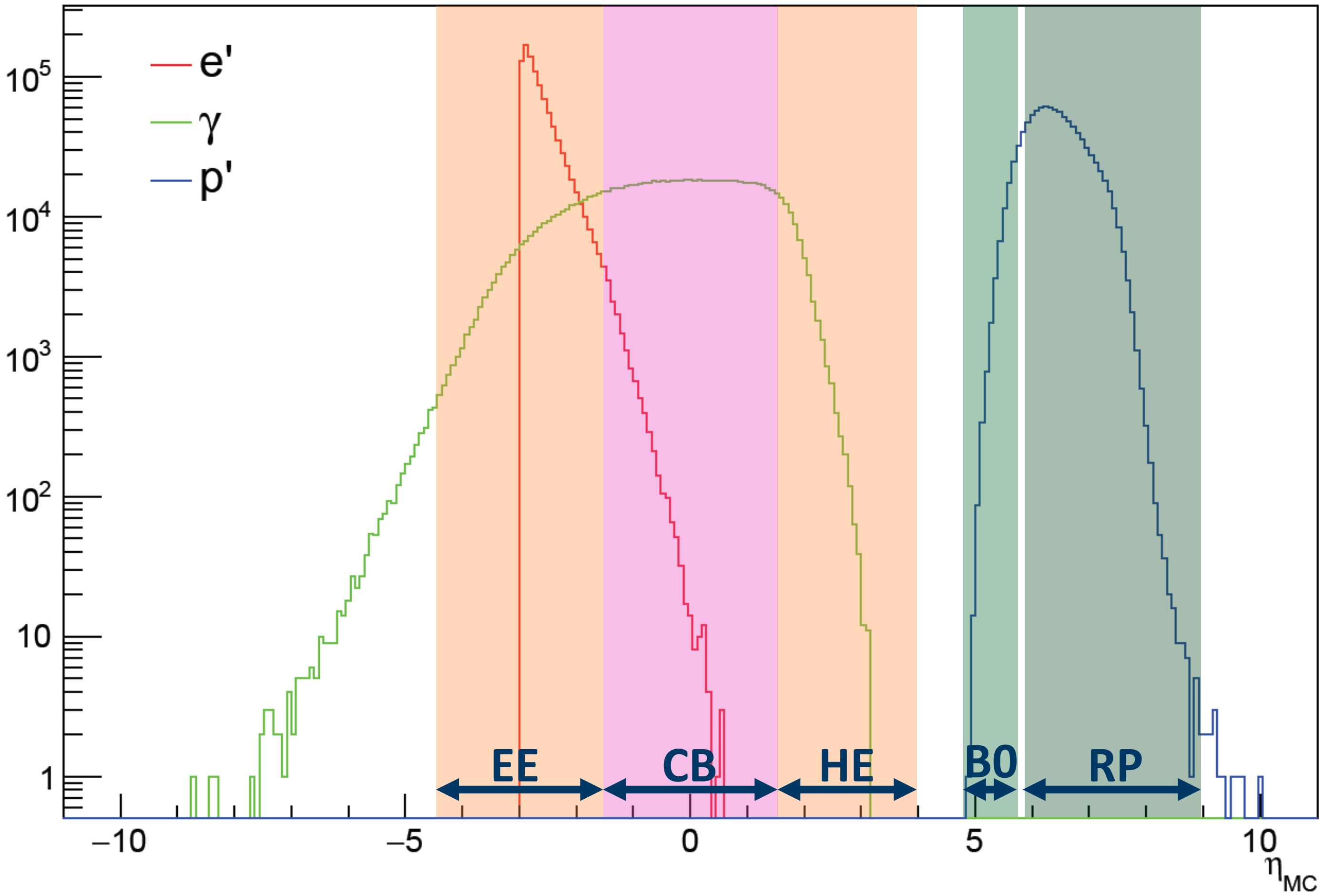
Why DVCS @ ePIC?

- 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

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!
- DVCS[1]/BH[2] amplitudes (for samples used) from Belitsky and Mueller

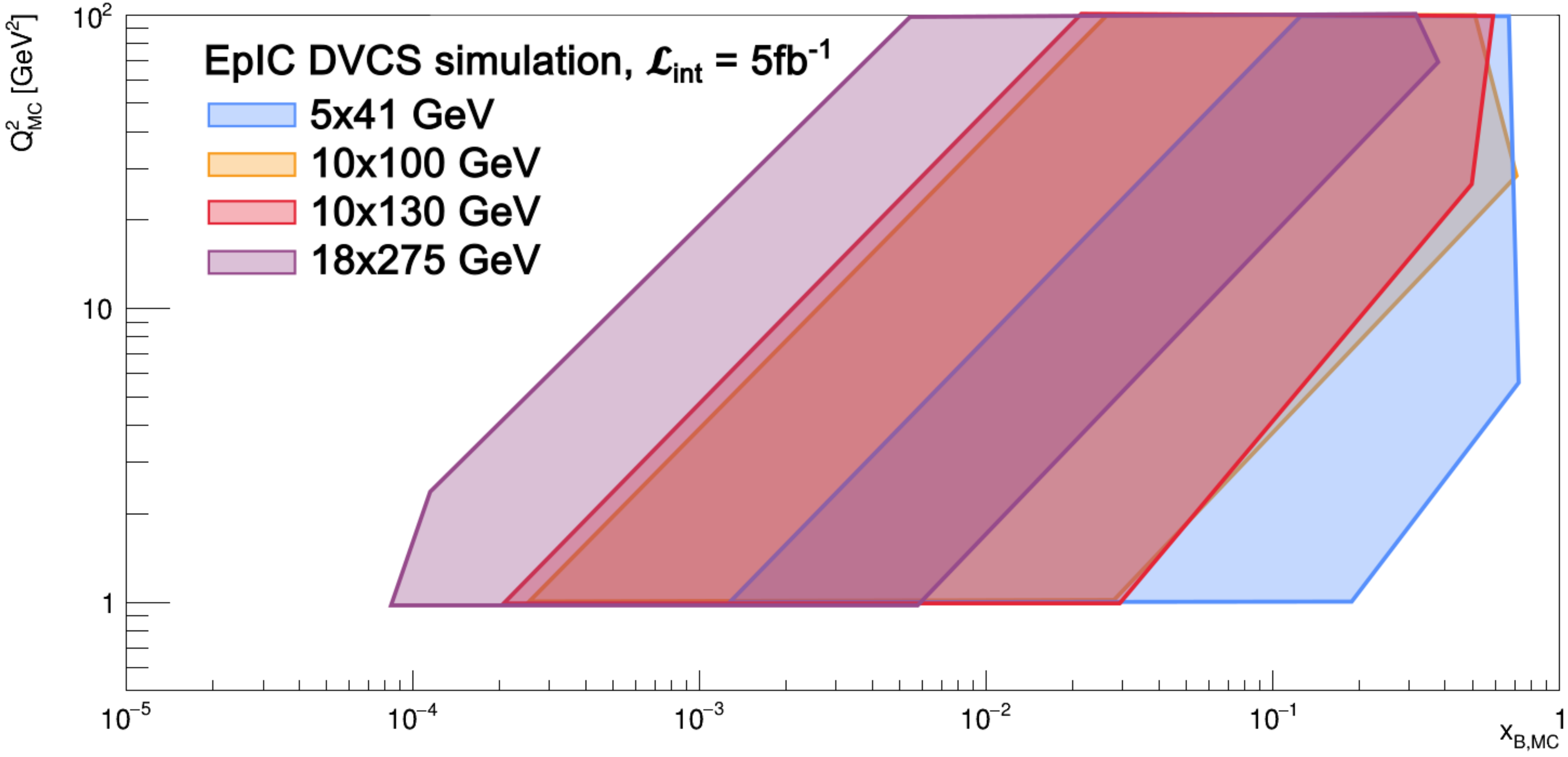
[1] Belitsky, Mueller and Kirchner; Nucl. Phys. B **629** (2002); pp 323-392
[2] Belitsky, Mueller and Ji; Nucl. Phys. B **878** (2014); pp 214-268

Simulation details

- Current 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

Coverage of generated data



Analysis details

- MC information from MCParticlesHeadOnFrameNoBeamFX.

- 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.

- Full afterburner removal based on procedure detailed by A. Jentsch in PWG meeting on 20th May 2024.

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

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.
  - $N(corrected\ reco.) = \frac{N(raw\ reco.)}{\varepsilon}$

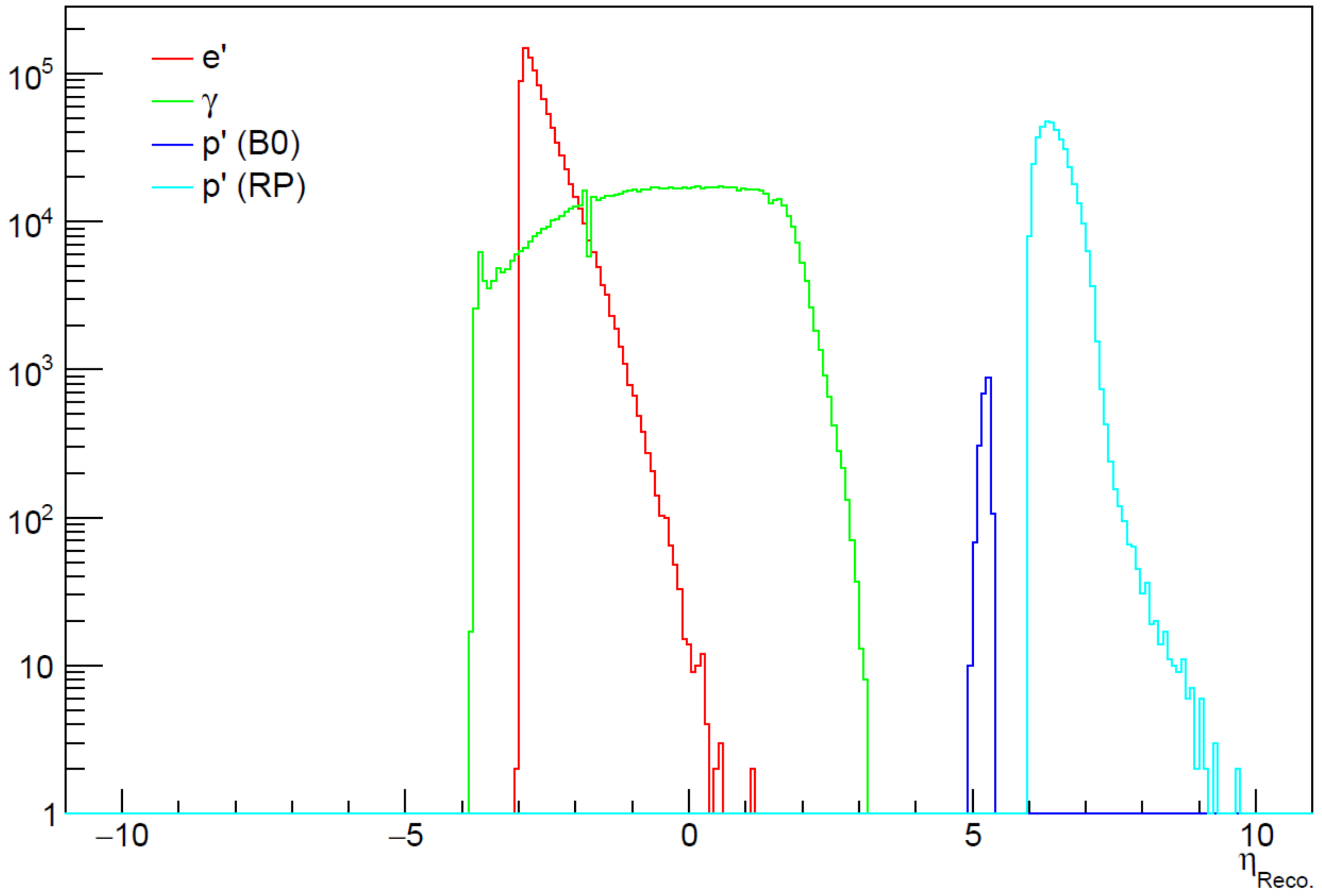
- Only correcting for detector acceptances for now.

Analysis output

Results shown are based on 25.10.2 campaign

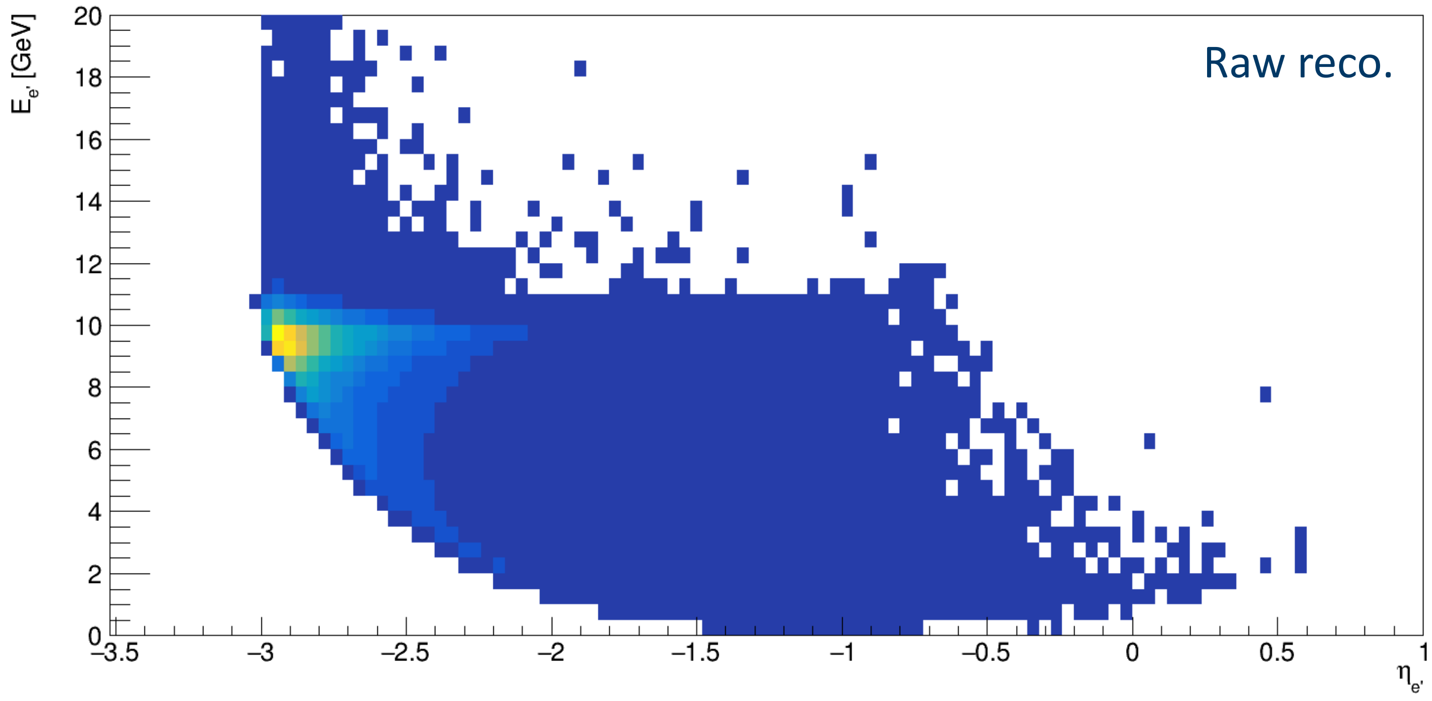
Using 10x100 GeV as example, scaled to 5 fb^{-1}

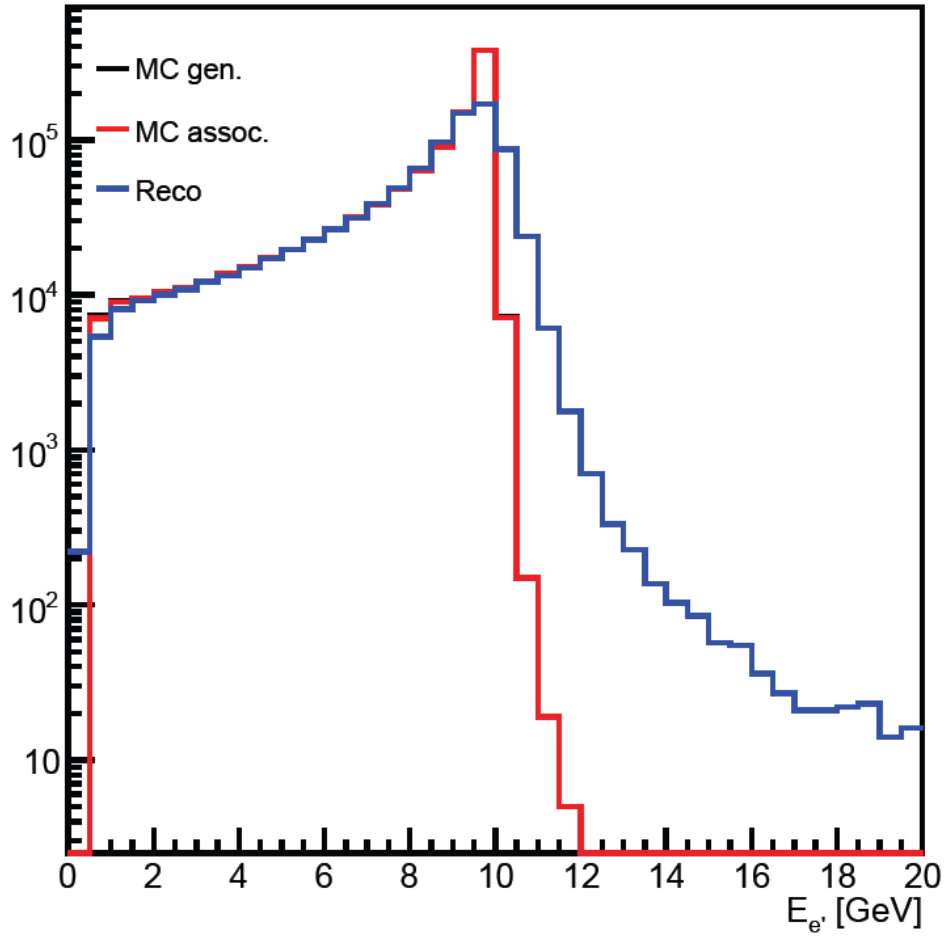
All final state particles (10x100)



- Some overlap between final state species (e'/γ), but easily separated by charge.
- Clean detector signatures.

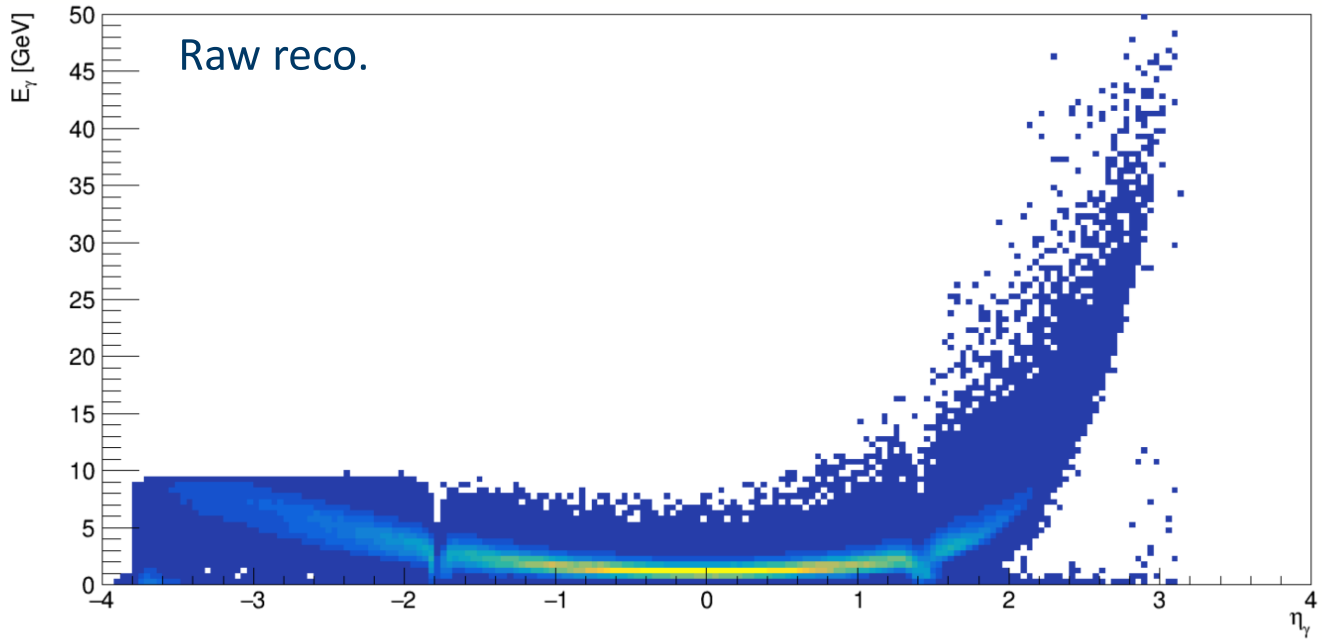
Scattered electrons

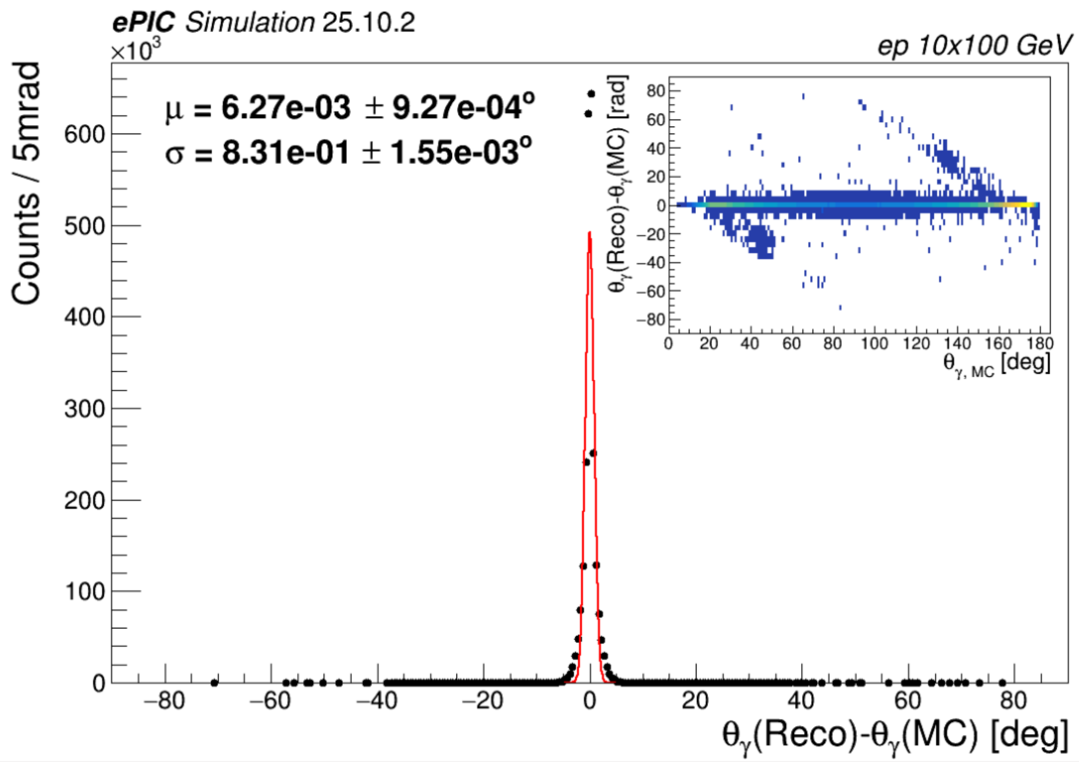




- Most at inner edge of backward ECAL.
- Noticeable smearing, particularly at higher momenta.

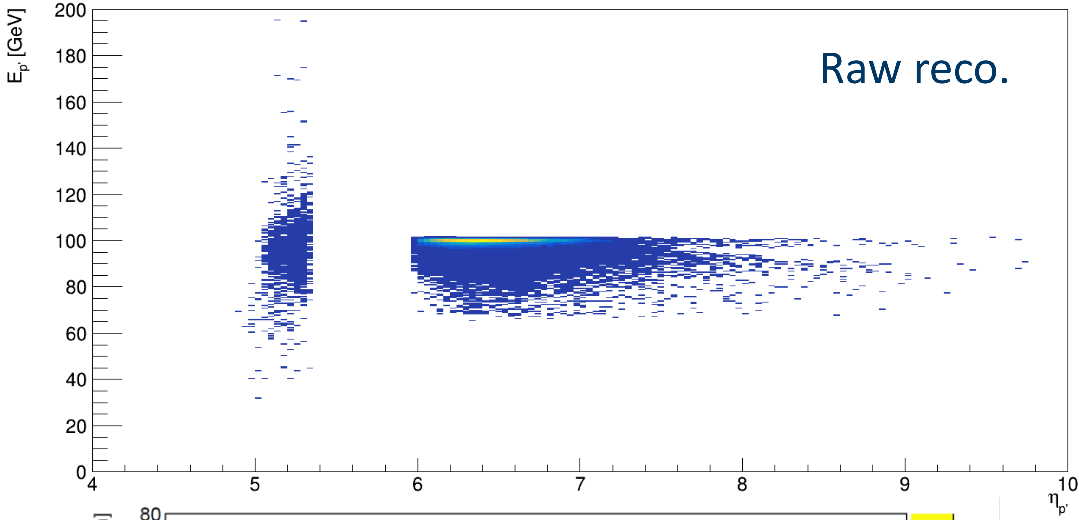
Real photons

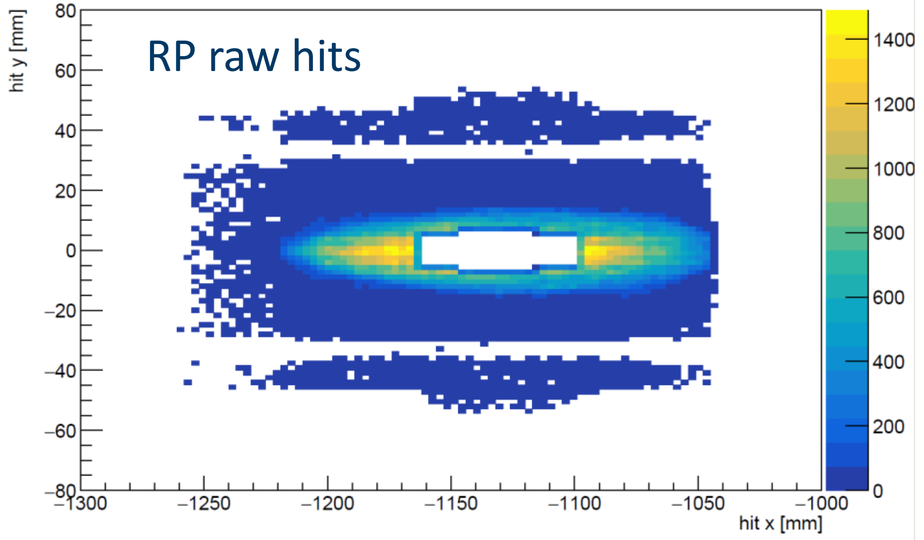




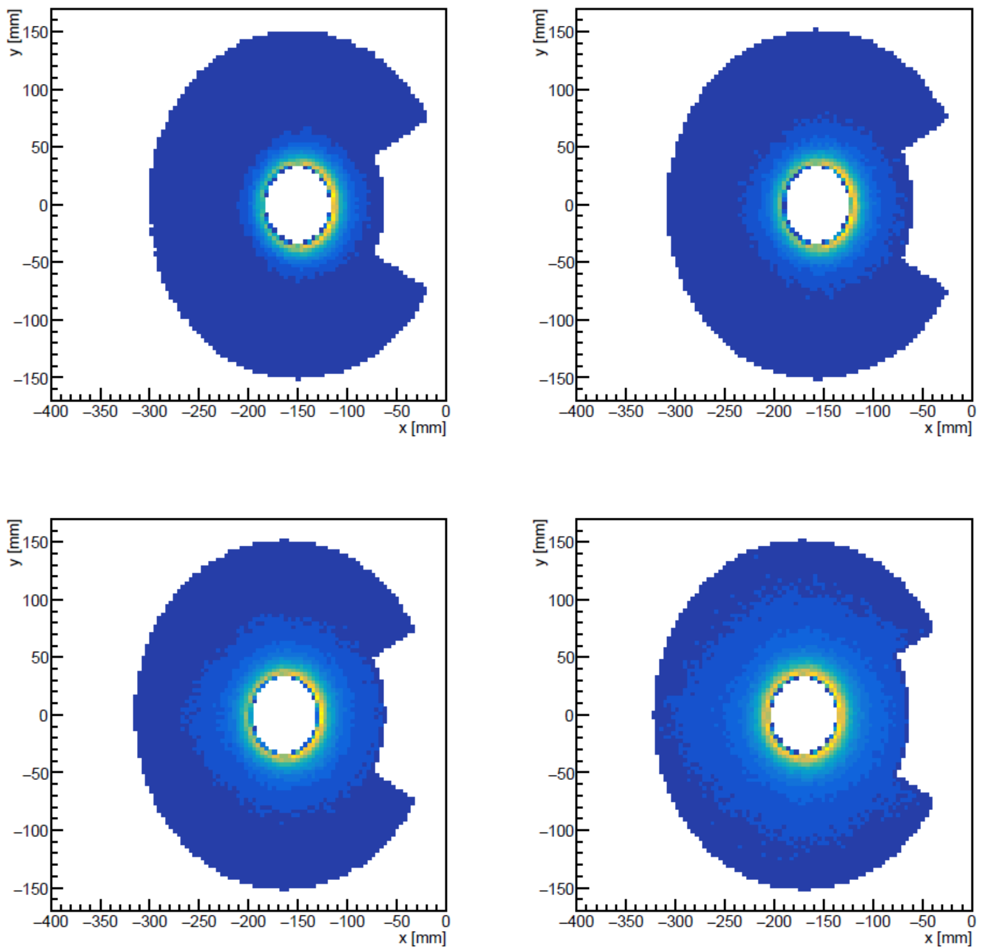
- ~20% in backwards endcap (η < -1.7), ~70% in central barrel (-1.7 ≤ η ≤ 1.4), ~10% in forward endcap (η > 1).

Scattered protons





B0 raw hits

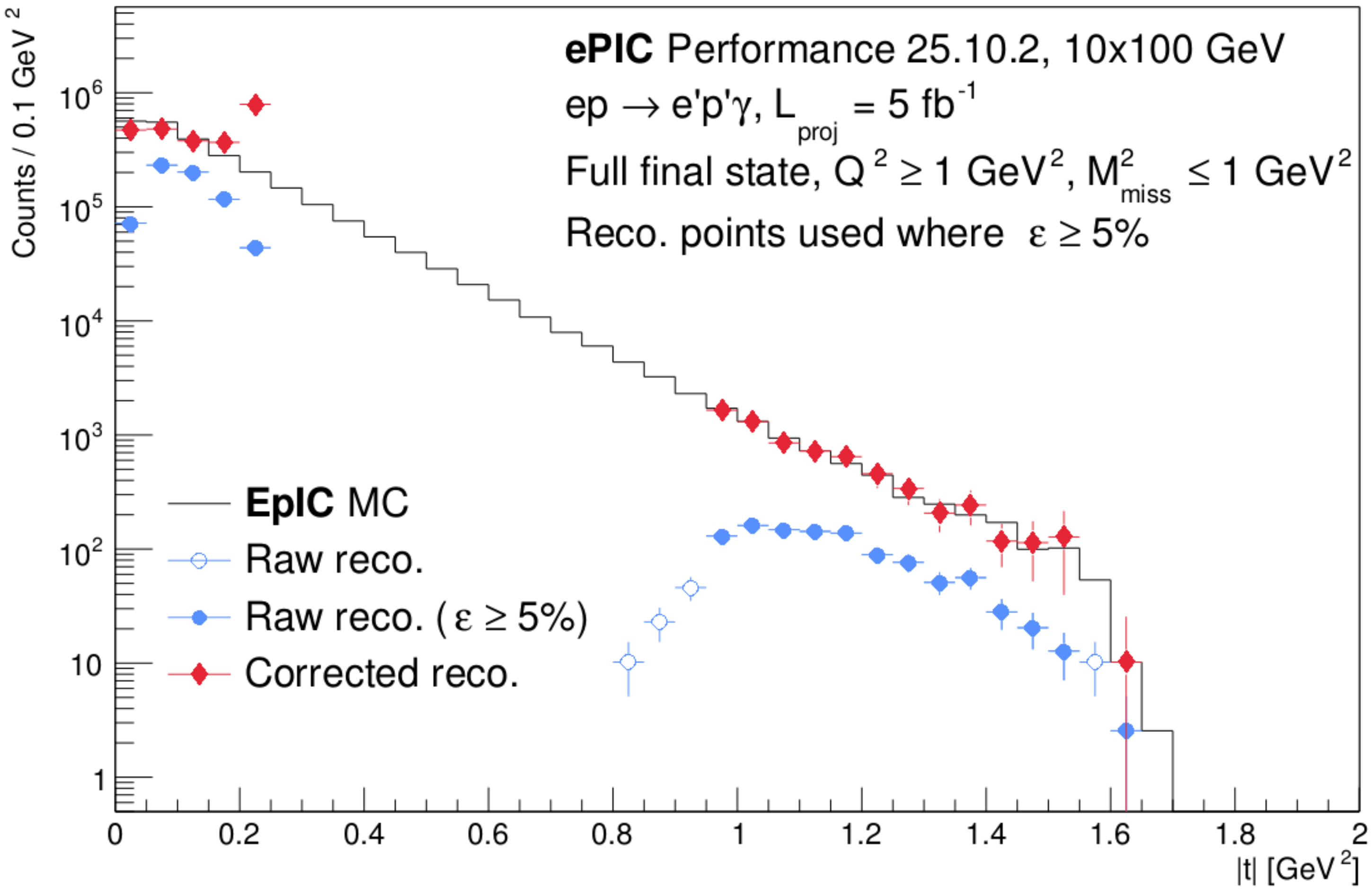


Full DVCS events

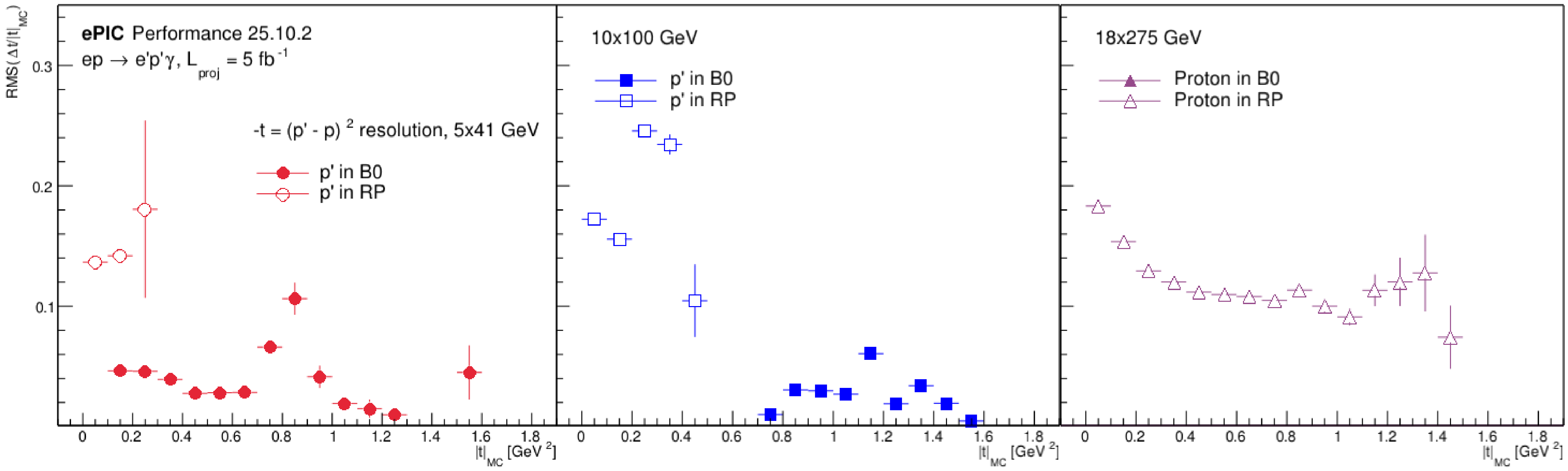
- All cuts applied:
  - Full exclusivity (1x electron, 1x photon, 1x proton)
  - Full final state missing mass, ${M_{miss}}^2 \leq 1$ GeV^2
- Effect of cuts (sample of ~10k generated events):
  - All events: 10439
  - Full exclusivity: 4182 (~40%)
    - 1x e': 10237 (~98%)
    - 1x γ: 9820 (~94%)
    - 1x p': 4486 (~43%)
  - …with $\theta_{p'}$ cut: 3882 (~37%)
  - …with Q^2 cut: 3522 (~33%)
  - …with MM^2 cut: 3165 (~30%)

Still limited by proton acceptance, but far less than before.

Calculation of Mandelstam t – full DVCS events

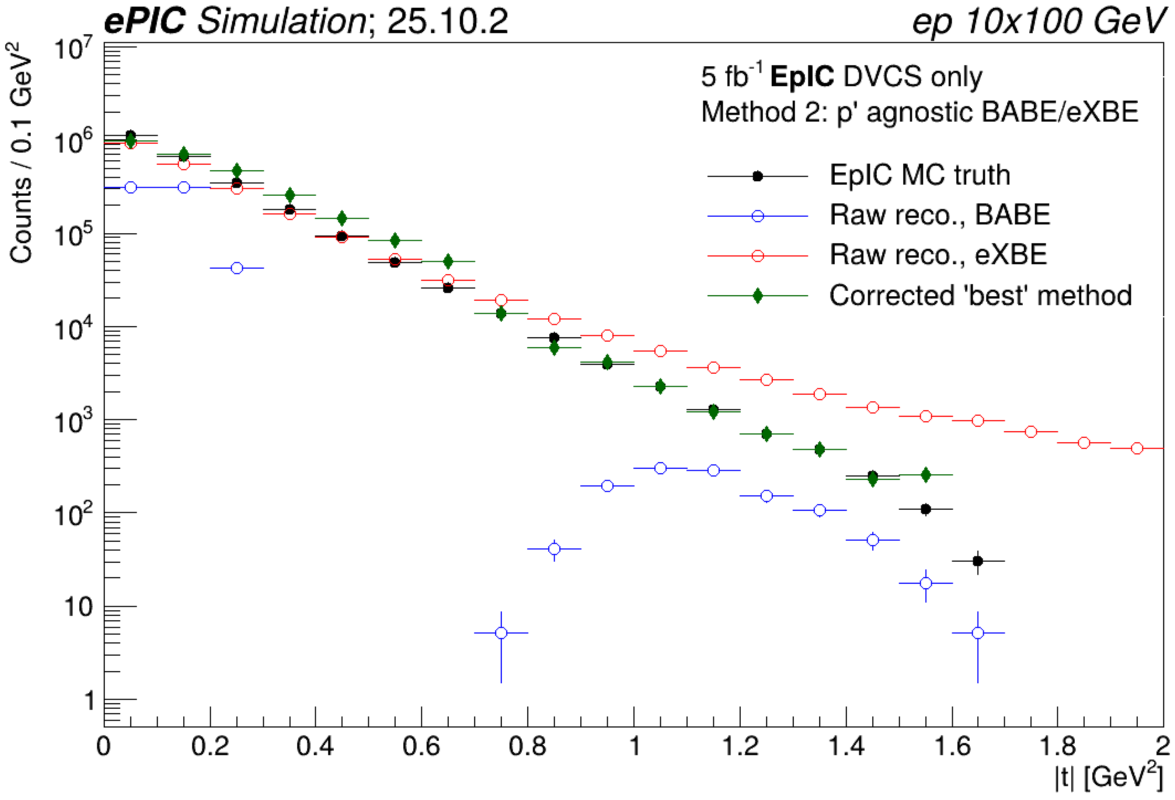


Mandelstam t resolution



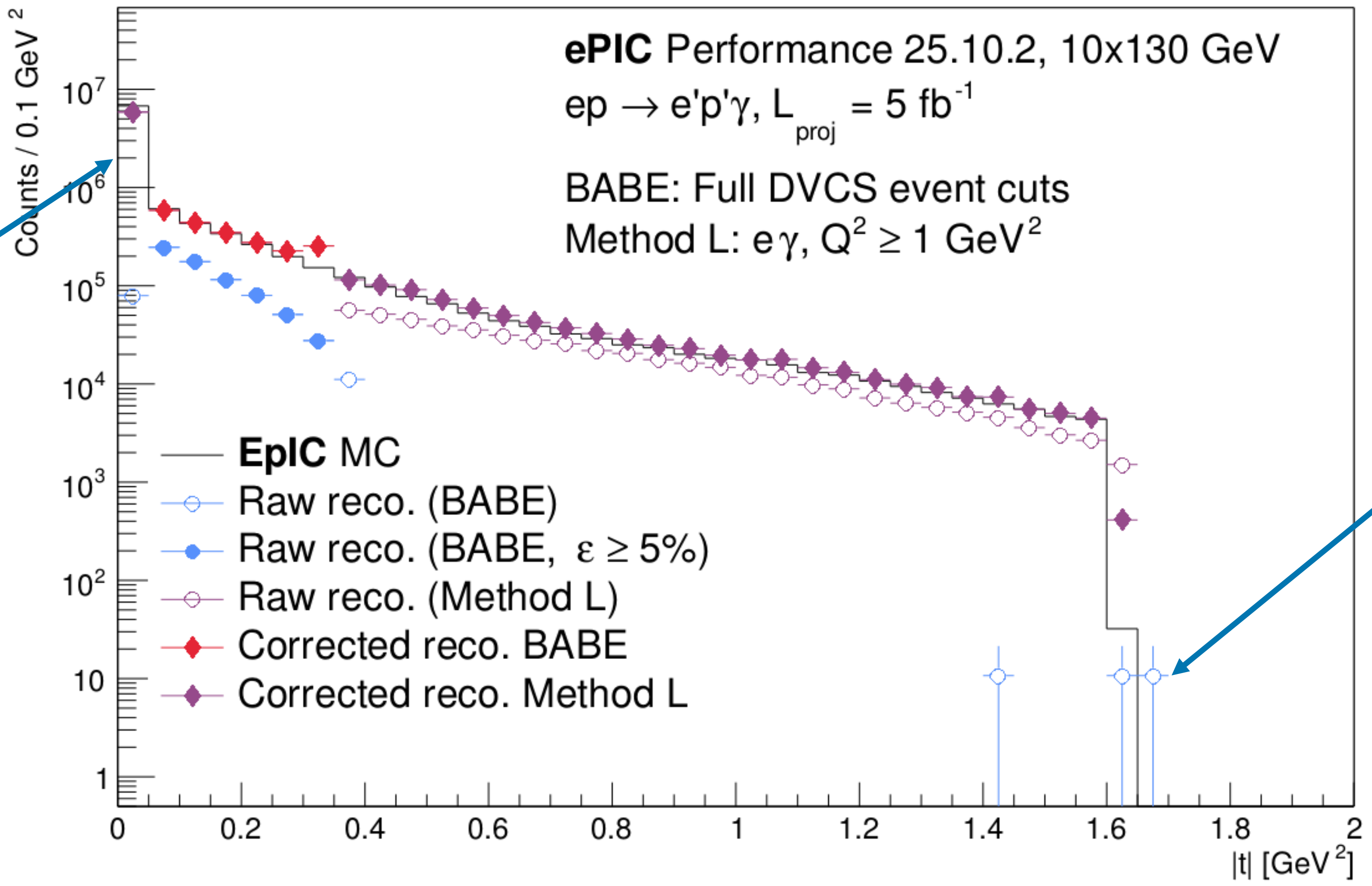
Alternative calculations for t

- Alternative methods for calculating Mandelstam t have been proposed but never seem to have worked for the DVCS simulation data.
- Had decided on using 'eXBE' method (tRECO) from looking at behaviour of MC.
  - This method overshoots the MC distribution at higher t.
- Need to make new choice: use 'Method L' (as for DVπ^0P).
  - Still **only works for 10x130 data**.
  - Issue in older data makes semi-inclusive calculations fail.



Calculation of Mandelstam t – 10x130

Low-t peak from inclusion of Bethe-Heitler events in 10x130 sample.



Loss of reconstruction for B0 protons since 25.07.0 campaign.

Due to change in ACTS behaviour.

Fix expected in most recent campaign – have not yet had a chance to test this.

New EpIC MC samples

- New DVCS event samples have been generated and are now being tested locally on the Glasgow systems.
  - 1M events (5x41, 10x250, 18x275) / 1.3M events (10x100, 10x130)
  - 2 helicity settings for each energy (2/2.6M events total per energy)
  - Using EpIC v1.1.6

- When these have been verified, they will be used for future simulation campaigns.
  - Can now start looking at asymmetries.
  - Fixed t calculations without the proton.

Concluding remarks

Summary

i. Efforts ongoing with looking at DVCS simulations with ePIC.
   - Extraction of $d\sigma/dt$ possible.

ii. Newer MC samples are available and will replace the current simulation campaigns.
   - 2x e-beam helicity settings to study asymmetries.
   - Fixed calculation of Mandelstam t when ignoring the proton.
   - Now including 10x250 ep energy setting for early science studies.

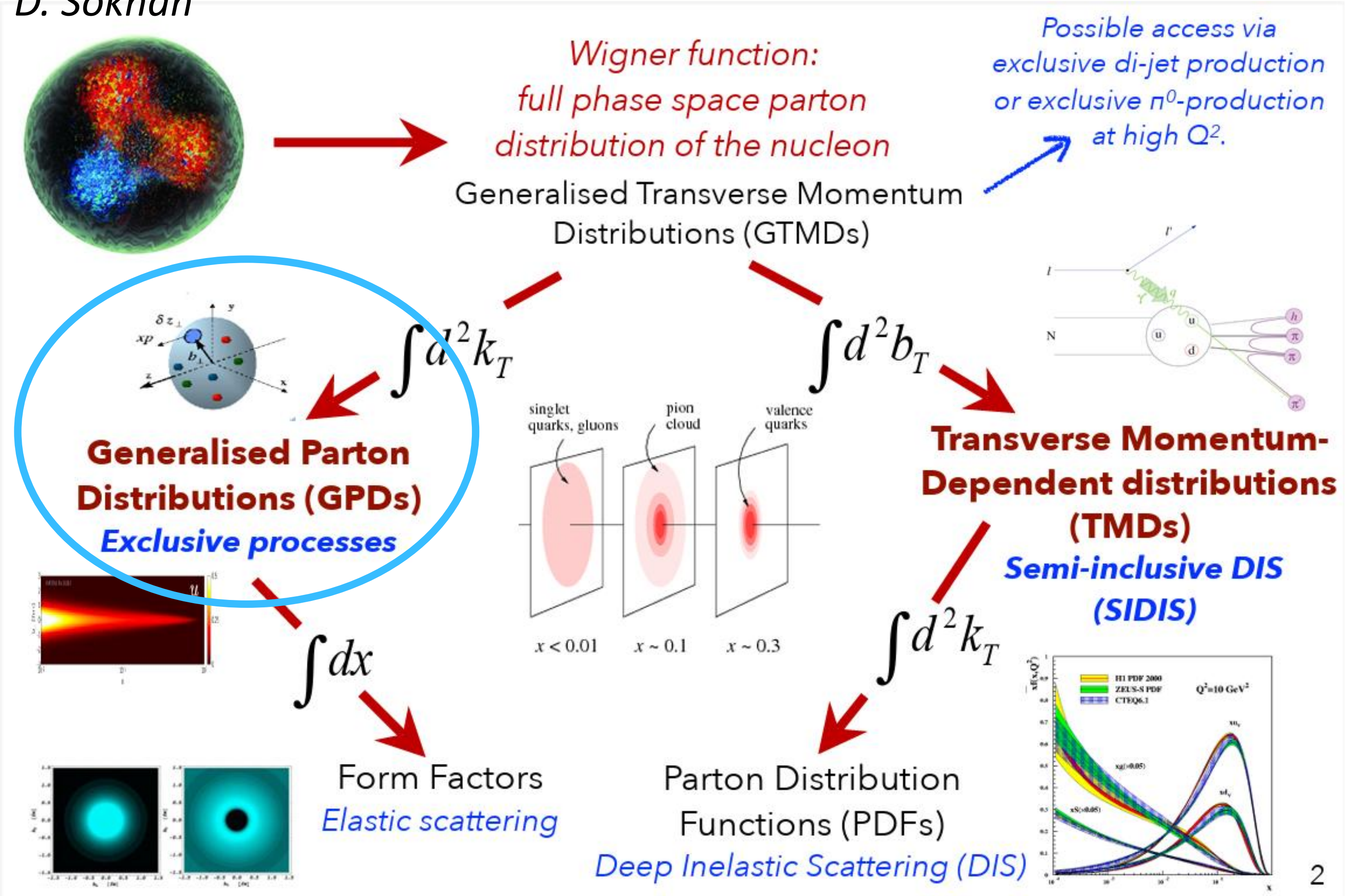
Thank you for listening!

Any questions?

Backup

Nucleon structure

D. Sokhan

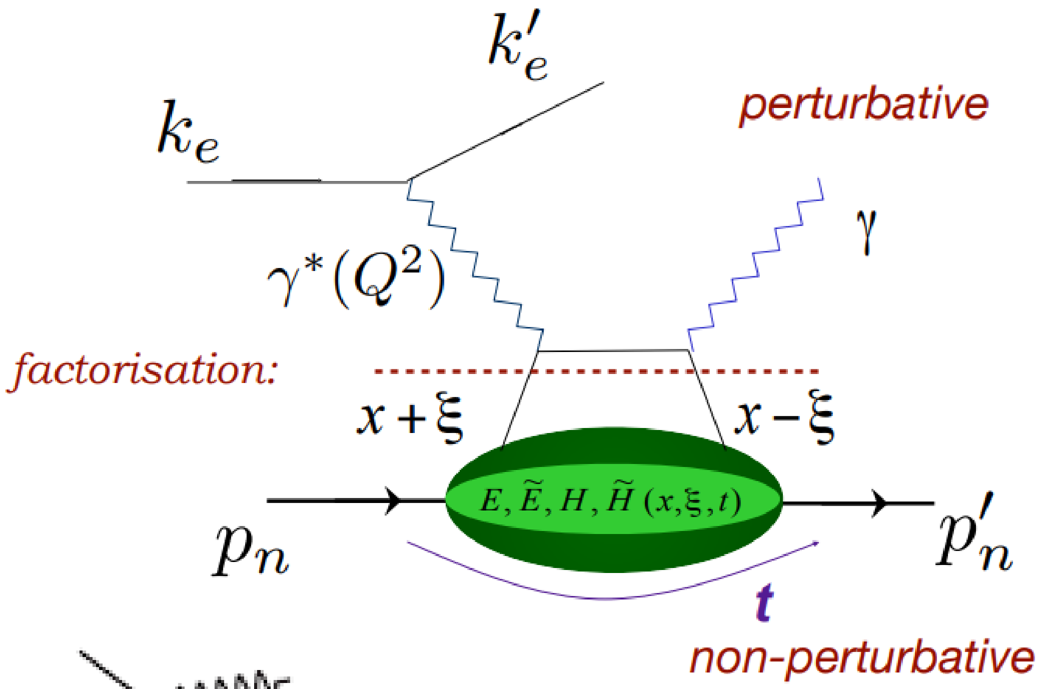


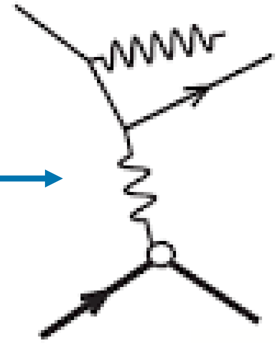
- Nucleon structure can be described within multiple dimensions by a large number of different functions.
  - GTMDs – full 5D phase space distributions.
  - PDFs – 1D as function of parton momentum.
  - Form factors – 1D as function of transverse distance from centre.
- GPDs relate the transverse position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





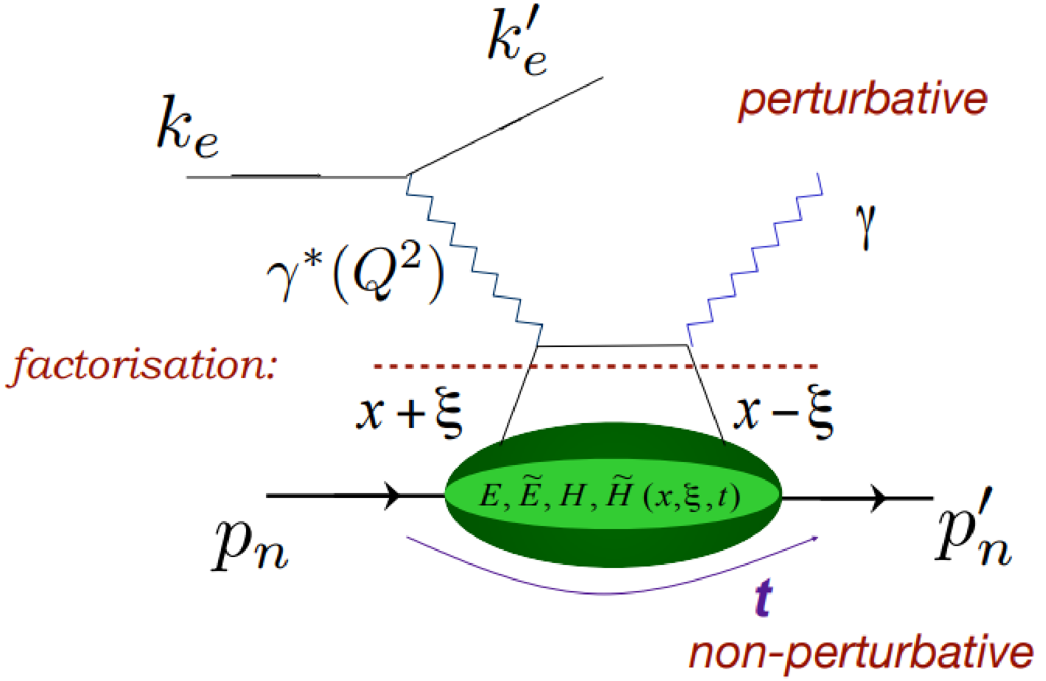
Deeply Virtual Compton Scattering

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

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

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

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



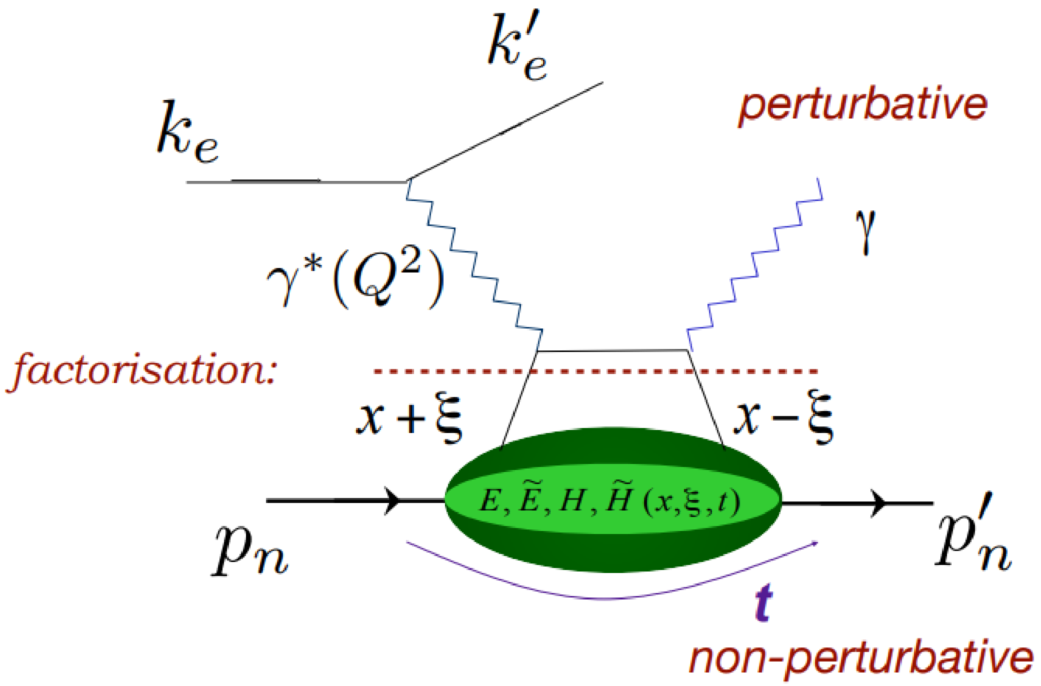
- Other formulae exist, using other combinations of reconstructed quantities, if needed (e.g. see InclusiveKinematics branches in EICrecon trees).

Deeply Virtual Compton Scattering

University of Glasgow

ePIC

- 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.

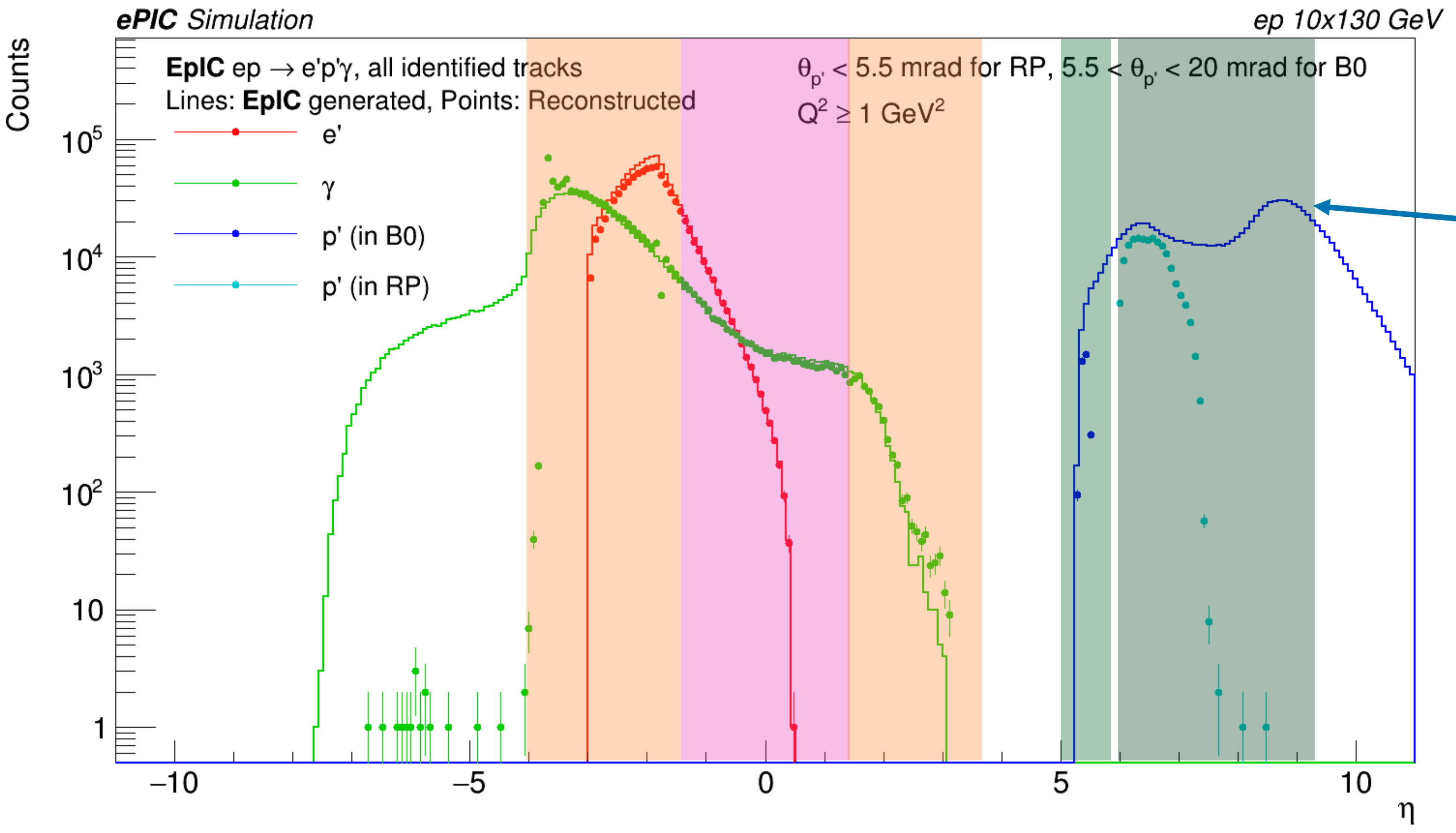
- By Ji's Sum Rule, quark angular momentum can be given by a combination of GPDs.

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

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 backward 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 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.