Deeply Virtual Compton Scattering in ep - Status and Plans

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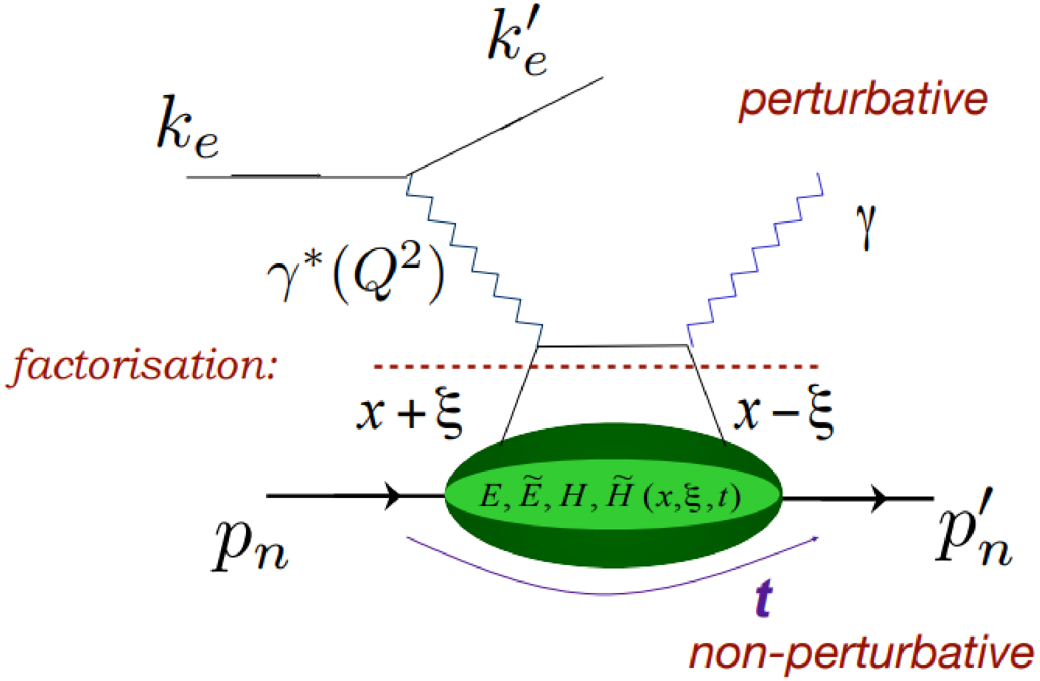
This presentation

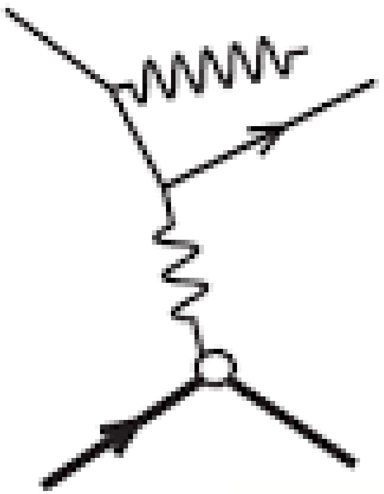
- Context: DVCS and its place in the EIC physics programme.

- Analysis updates:
  - Beam-gas backgrounds
  - Asymmetries
    - Prep. for upcoming simulation campaign
    - Focus – early science (both beam energies)

Deeply Virtual Compton Scattering

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:
  - $e(k) + p(p) \to e'(k') + p'(p') + \gamma$

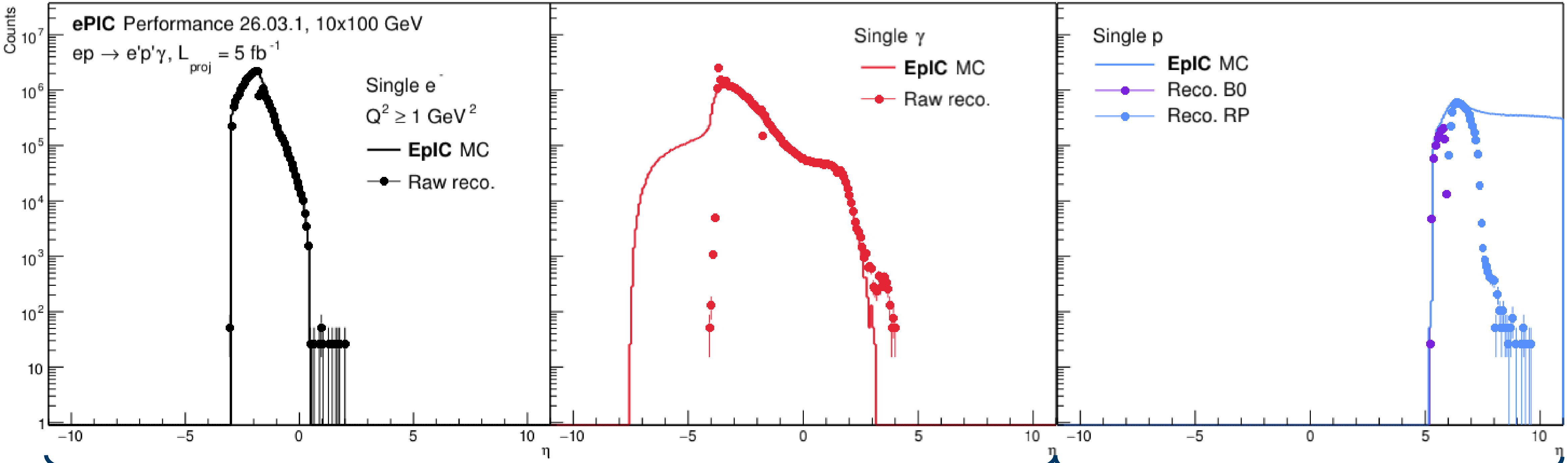
- Inclusive kinematics: scattered electron only ("Electron method" in EICrecon)

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

- Mandelstam *t*: 2 methods

BABE: $t = (p - p')^2$ eXBE/Method L: $t = (p - p_{corr})^2$

Why DVCS @ ePIC?



Electron, photon – **central barrel** and (mostly) **backwards endcap**

Proton – **B0/RP** (beam-dependent)
→ 5x41 – 94% B0, 6% RP
→ 10x100 – 3% B0, 97% RP
→ 10x130 – same as 10x100
→ 18x275 – 100% RP

DVCS simulations for ePIC

Simulation details – currently running

- Using EpIC generator v1.1.2 (GitHub link to latest build).
  - 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.

Simulation details

- Event samples used:
  - DVCS+BH+int.
  - 1M events (5x41, 10x250, 18x275); 1.3M events (10x100, 10x130)
  - $1 < Q^2 < 100$ GeV^2 $0.01 < y < 0.9$ $10^{-5} < x_B < 0.7$
- Generated events represent $\mathcal{L}_{int} \sim 0.2 fb^{-1}$ for most energies ($0.1\ fb^{-1}$ for 5x41).
- Events are passed through the full EIC simulation pipeline.
  - Plots shown are from **26.03.1/26.04.1** campaign
  - Beam setting: **10x130, high acceptance**

/volatile/eic/EPIC/RECO/26.XX.X/RECO/epic_craterlake/EXCLUSIVE/DVCS_ABCONV/EpIC_v1.1.6-1.2/10x130/q2_1_100

Reconstruction details

- Electron –
  - `ReconstructedParticles`
  - charge -1 (needs track)
  - $0.8 < E/p < 1.2$ (calo/tracker)
- Photon –
  - `ReconstructedParticles`
  - charge 0 (needs ECAL cluster *without track*)
- Proton – depends on detector
  - B0: `ReconstructedTruthSeededChargedParticles`, charge +1, $5.5 < \theta < 20$ mrad.
  - RP: `FarForwardRomanPotRecParticles`, all tracks assumed to be protons, $\theta < 5$ mrad

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.

- DVCS event cuts:
  - Full exclusivity (e'p'γ reconstructed)
    - All single species cuts simultaneously.
  - 2 types: kinematic exclusivity and detector vetoes

Cuts applied (event cuts)

- Detector vetoes
  - No +ve tracks in the central barrel (expect proton in the FF region)
  - No –ve tracks that aren't e^- (only expect single –ve track from e')
  - OMD/ZDC track veto (only expect proton to hit B0/RP)
- Kinematic cuts
  - $15 < (E\text{-}p_z) < 25$ GeV (reduces radiative effects)
  - $|M_{miss}^2| < 1$ GeV^2 (*)

(*) - Missing mass cut from legacy analysis, now looking to move to other exclusivity variables.

Effect of cuts (N_{MC} ~ 1.3M)

Cut	No. of events remaining	% of total	Cut	No. of events remaining	% of total
Single e' reco.	1.11×10^6	85.4	Semi-inclusive (e' γ)…	1.00×10^6	77.2
Single γ reco.	1.14×10^6	87.7	…and barrel +ve veto..	9.77×10^5	75.3
Single p' reco.	2.89×10^5	22.3	…and –ve track veto…	9.77×10^5	75.3
Final state (e'p'γ)…	1.89×10^5	14.6	…and other FF veto…	9.41×10^5	72.5
…and $Q^2 > 1$ GeV^2…	1.81×10^5	14.0	…and (E-p_z) cut	8.08×10^5	62.3
…and θ_p cuts…	1.76×10^5	13.6			
…and –ve track veto…	1.76×10^5	13.6			
…and other FF veto…	1.52×10^5	11.8			
…and (E-p_z) cut…	1.18×10^5	9.1			
…and MM^2 cut	8.00×10^4	6.2			

Raw generated file had 1.3M events, some job failures in the campaign loses 200 events

Validity? (w.r.t DIS @ 10x100)

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Cut	No. of events remaining	% of total	Cut	No. of events remaining	% of total
Single e' reco.	8.55×10^5	85.9	Semi-inclusive (e' γ)…	1.07×10^5	10.7
Single γ reco.	1.18×10^5	11.9	…and barrel +ve veto..	5.36×10^4	5.4
Single p' reco.	2.44×10^5	24.5	…and –ve track veto…	4.68×10^4	4.7
Final state (e'p'γ)…	4.08×10^4	4.1	…and other FF veto…	4.26×10^4	4.3
…and $Q^2 > 1$ GeV^2…	3.92×10^4	3.9	…and (E-p_z) cut	4.26×10^4	4.3
…and θ_p cuts…	1.82×10^4	1.8			
…and –ve track veto…	1.55×10^4	1.6			
…and other FF veto…	1.48×10^4	1.5			
…and (E-p_z) cut…	1.48×10^4	1.5			
…and MM^2 cut	514	0.05			

Current DVCS event cuts effectively reduce physics-induced background.

Still need to quantify effects of other exclusive kinematic cuts, but will likely be able to reduce DIS background to ~percent level.

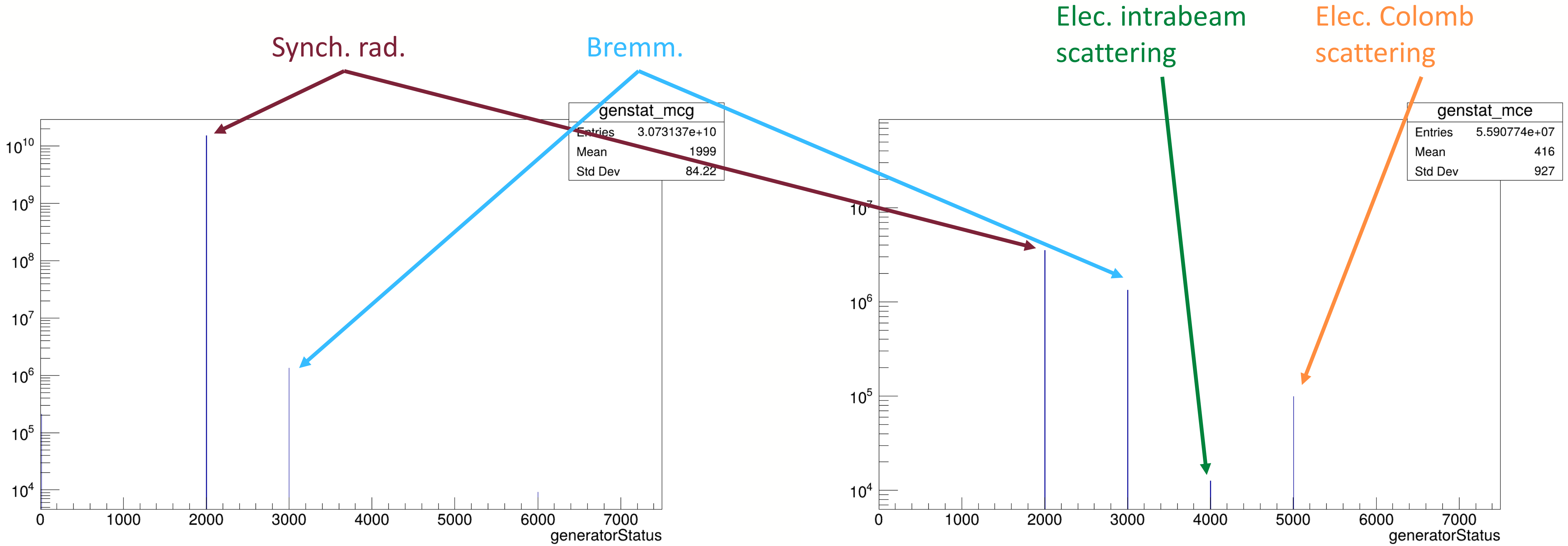
@ short notice – only had 26.02.0 files to had to test this. Assuming application to latest 9/10x130

Beam gas background

Using files from 26.02.0 campaign

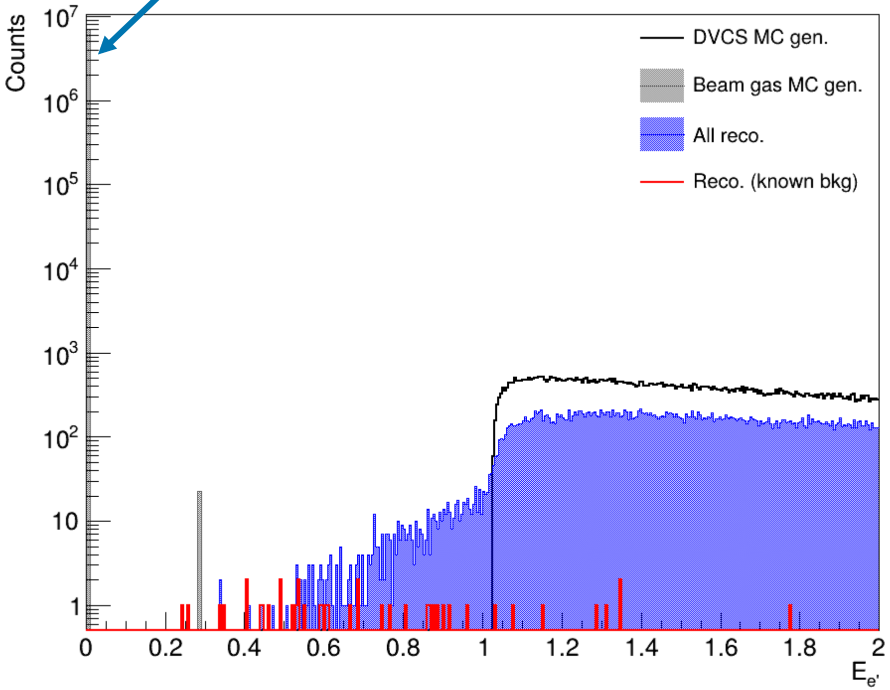
Sample details

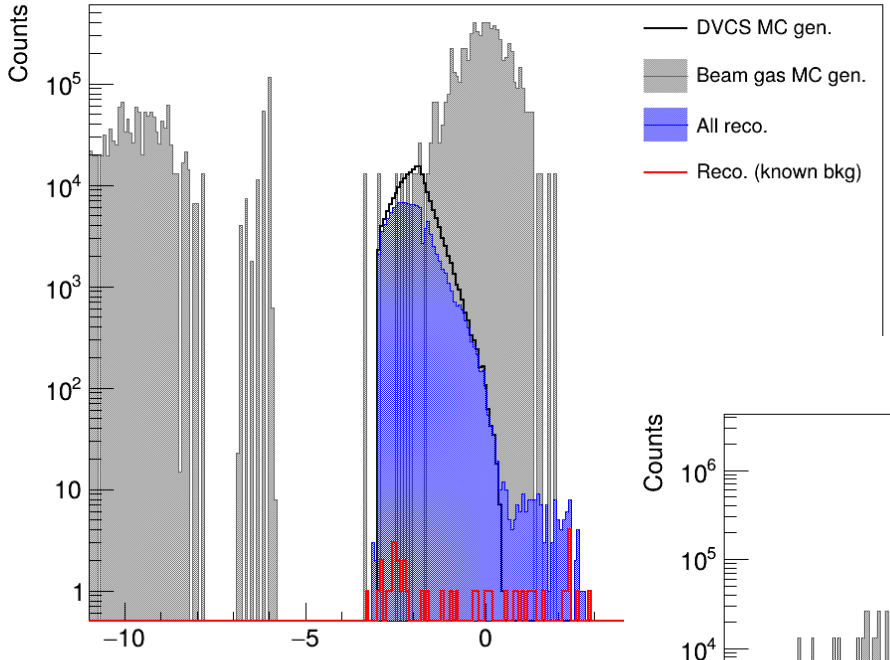
- 10x100 GeV files
- 1 DVCS event per 2μs frame

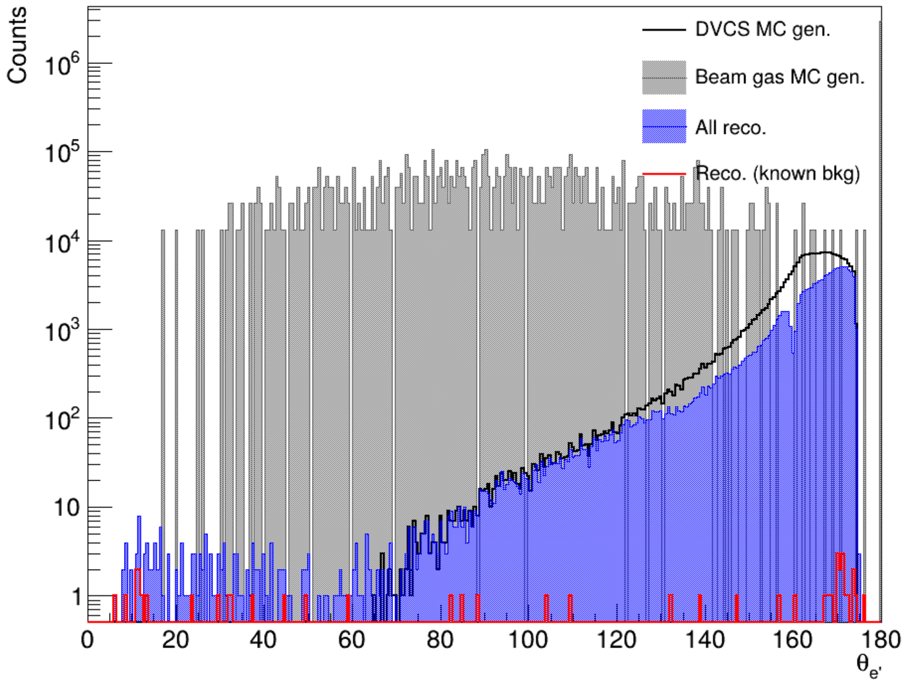


Kinematics - electrons

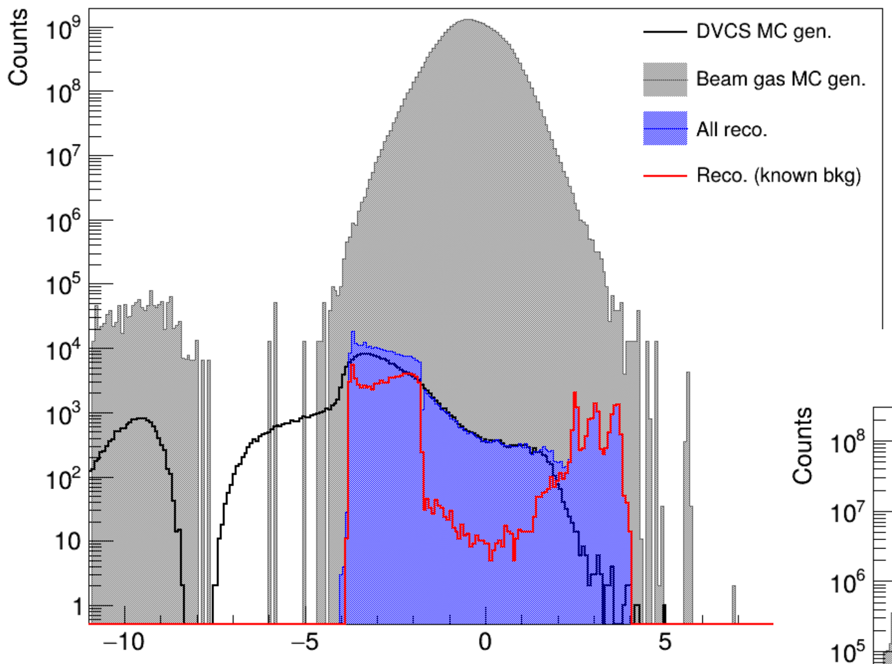
Almost all generated bkg electrons have very low energy

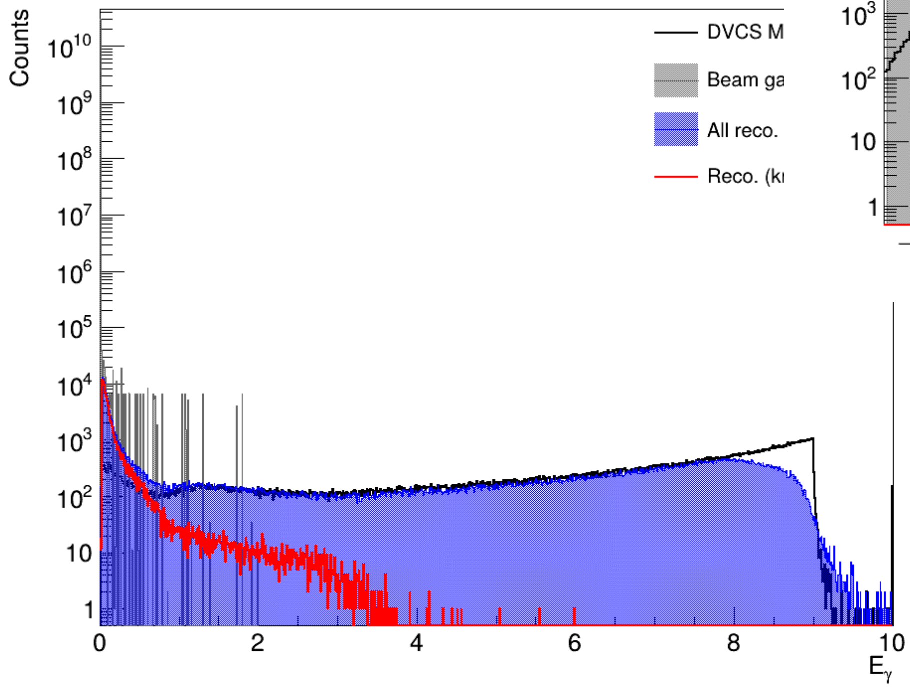


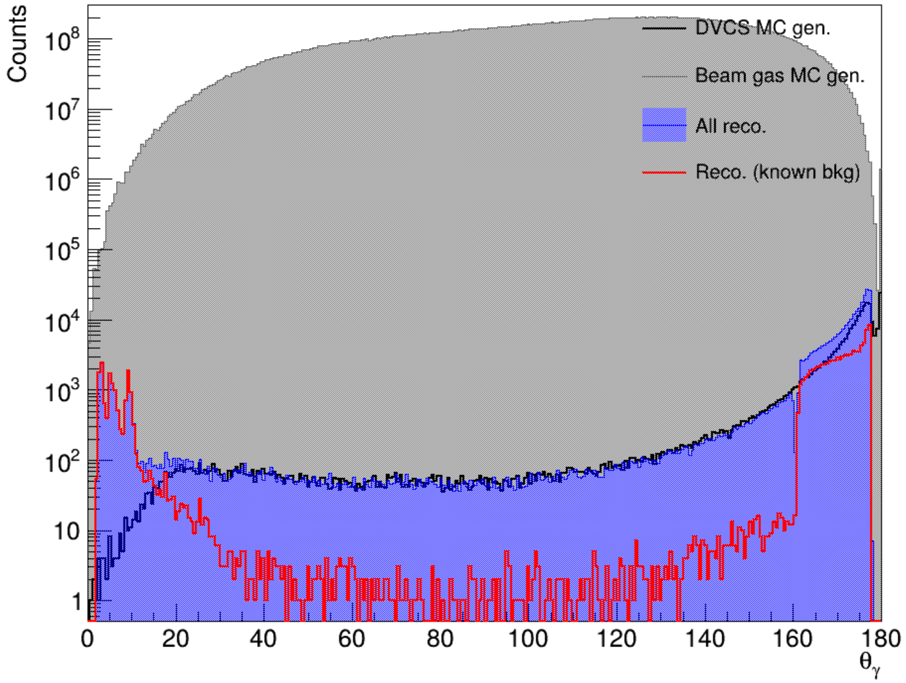




Kinematics - photons

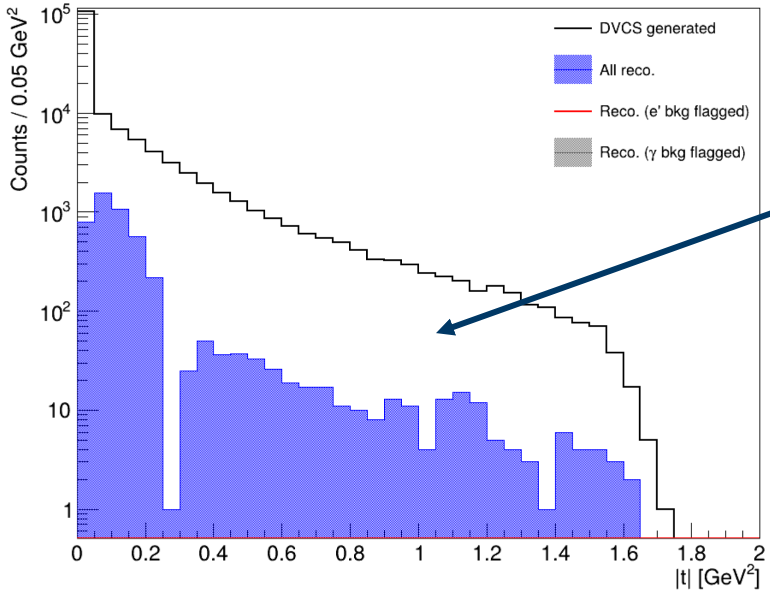






Observations

- Beam background electrons provide negligible direct contribution.
- Beam background photons can be reduced with other cuts.
  - $E_\gamma < 1$ GeV
  - Removes 99% of bkg photons
  - Removes 3% of DVCS photons



Fully exclusive DVCS: 0 events passing cuts where electron or photon is from background!

Asymmetries

Asymmetries

- Mentioned this in detail on 15th June.

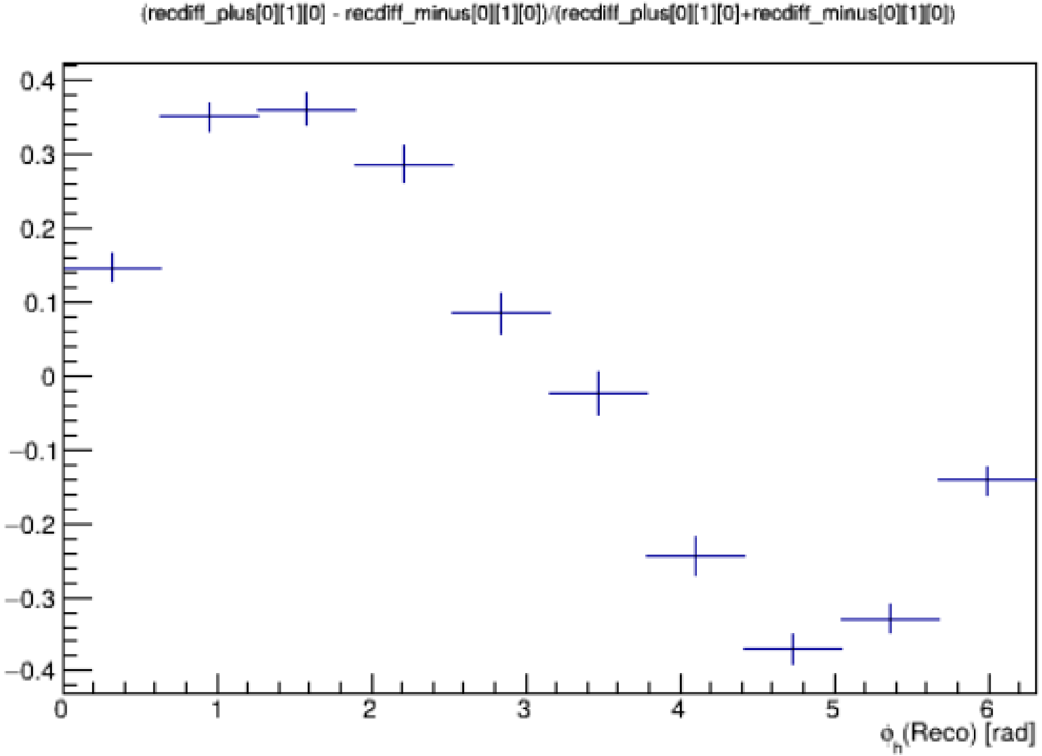
- Calculate "Trento phi" in rest-frame of virtual photon-beam proton system.

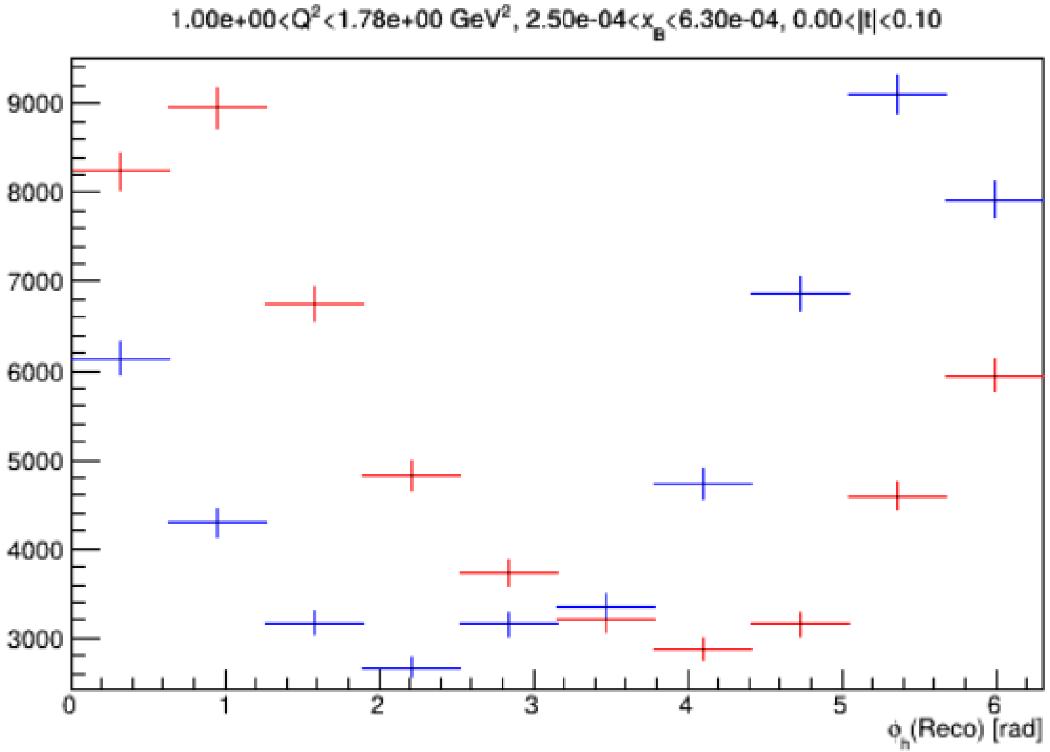
$$\cos\phi_h = \frac{(\hat{q}\times k)}{|\hat{q}\times k|}\cdot\frac{(\hat{q}\times g)}{|\hat{q}\times g|}$$

- Asymmetry = difference/sum for a given set of polarisation states.

A_{LU} example

- A_{LU} / Beam Spin Asymmetry – consider unpolarised protons, diff/sum over electron beam helicity states (+/-).





July simulation campaign

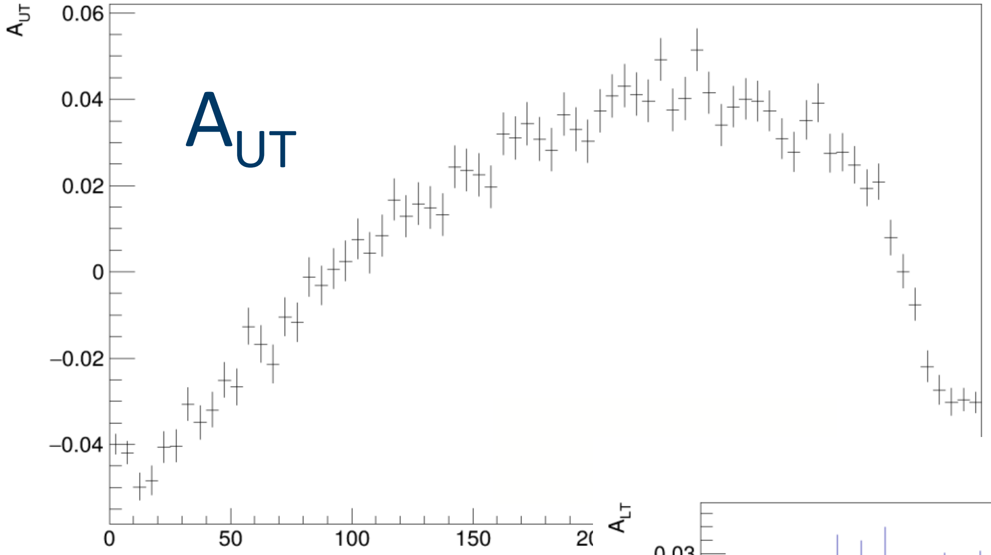
- Have requested large dataset for the July campaign.
  - All possible combinations of electron/proton polarisation (assuming full polarisation, will scale asymmetries post-hoc)
  - Both early science beam energies

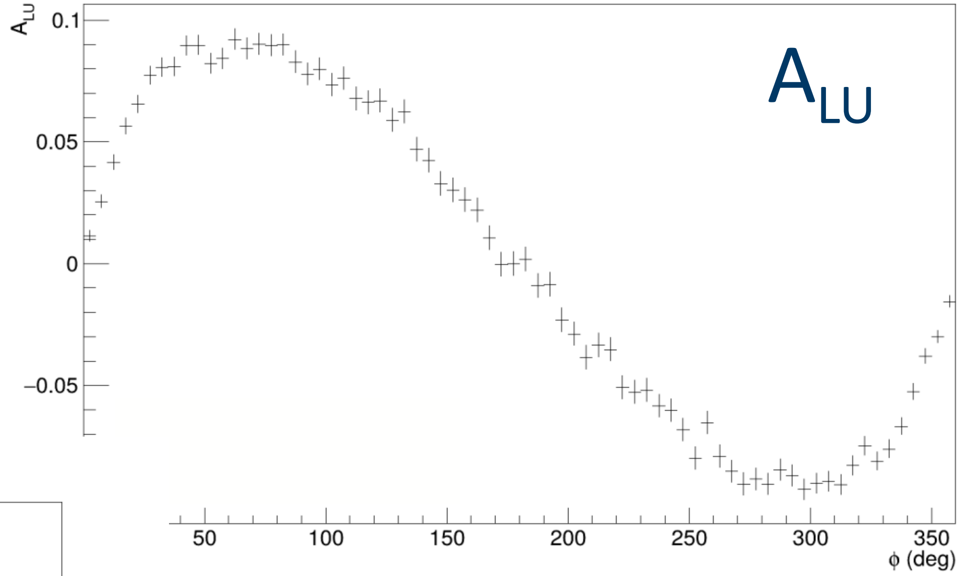
Issue found – EpIC currently has a problem generating longitudinal protons. Will have to wait for generator fix for true

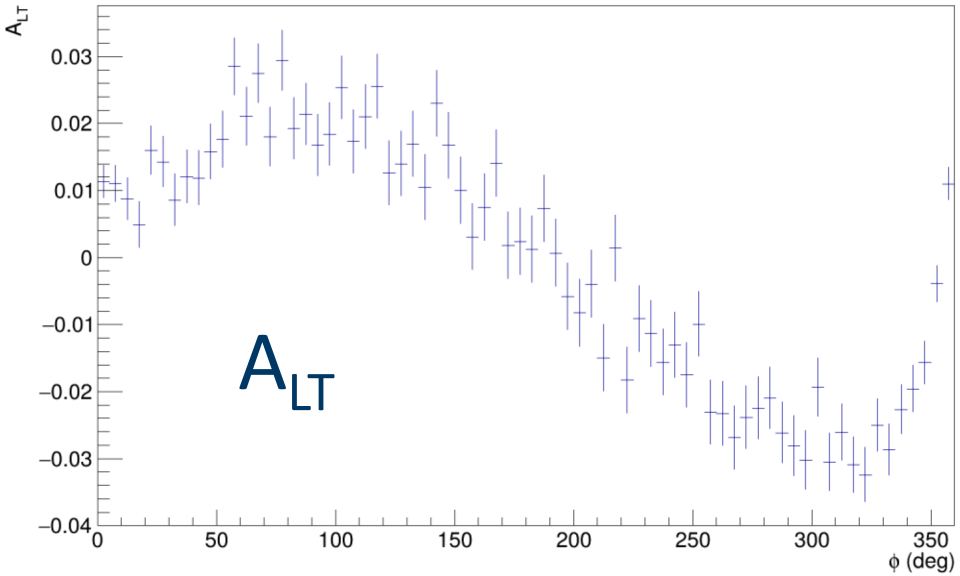
Electron beam helicity	Proton transverse (+ve)	Proton transverse (-ve)	Proton longitudinal (+ve)	Proton longitudinal (-ve)
+ve	✓	✓	✓	✓
-ve	✓	✓ ✓ ✓	✓	✓ ✓ ✓

- 1M events per file 9x130 (1fb^{-1} total DVCS+BH+int), 2.5M per file 9x275 (2.5fb^{-1} total, assuming high-acceptance beams)

Generated asymmetries







(*) – Issues in EpIC w/ longitudinal hadrons. Will need to wait for fix before getting true projected asymmetries.

Concluding remarks

Future plans

i. Finalise analysis procedure and confirm choices of cuts
   - Mostly in-place but needs to be wrapped up.

ii. Quantify backgrounds and systematics

iii. Finalise $\{Q^2, x_B, -t\}$ binning scheme
   - Currently using slightly modified choices from 2025 paper. Does not consider actual phasespace.

iv. July campaign – extract projections for all possible asymmetries
   - Waiting on news from the simulation team. Currently having to assume that no issues have been raised.

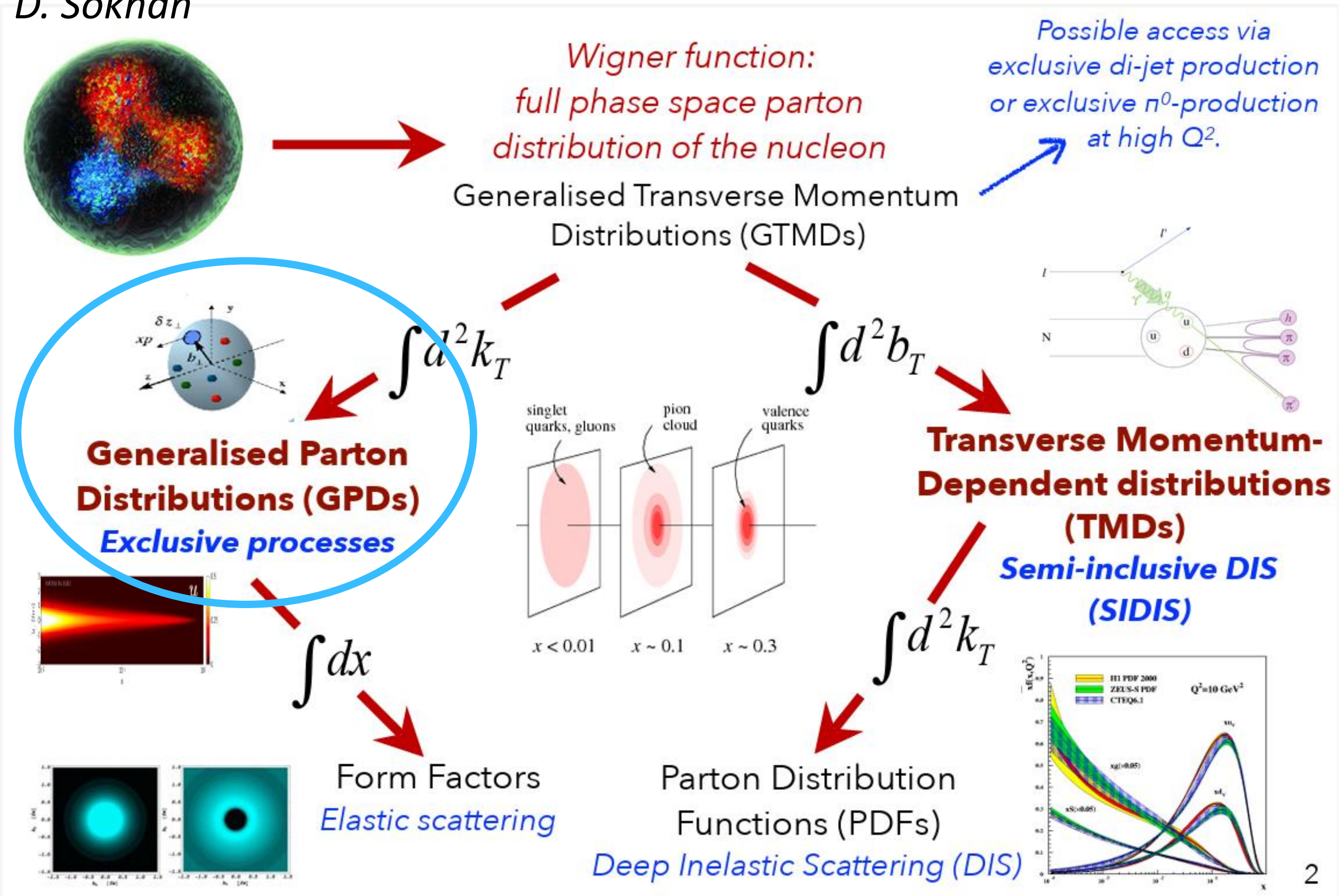
Thank you for listening!

Any questions?

Backup

Nucleon structure

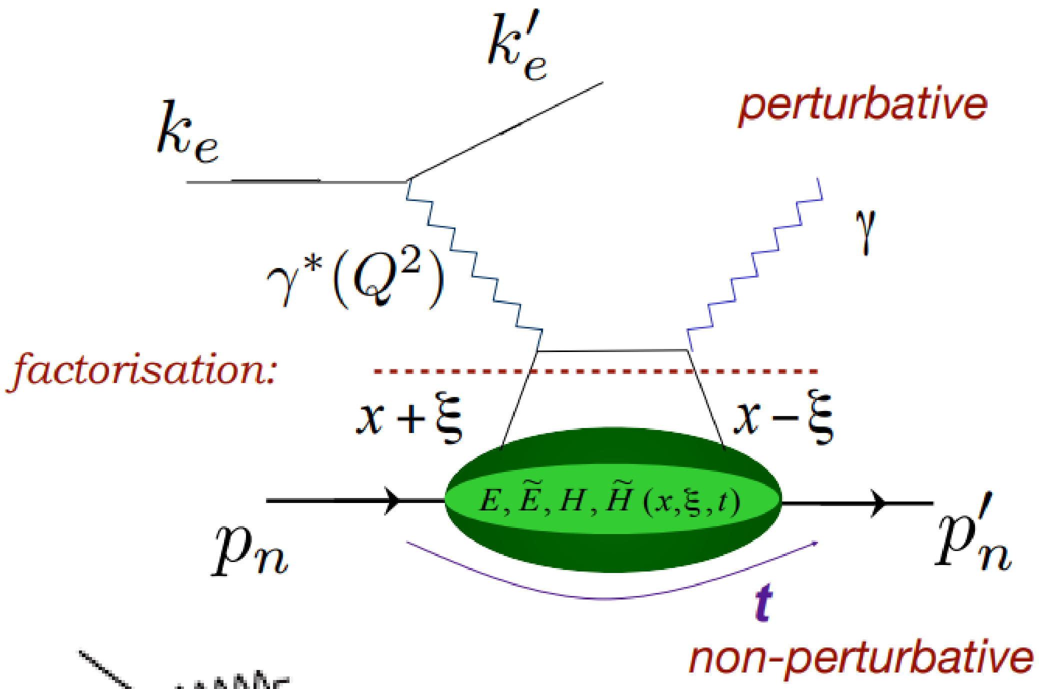
D. Sokhan



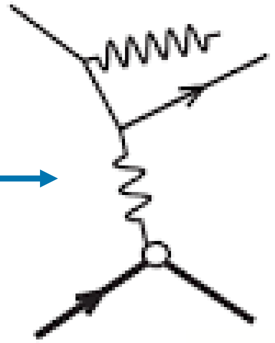
- Nucleon structure can be described within multiple dimensions by a large number of different functions.
  - GTMDs – full 5D phase space distributions.
  - PDFs – 1D as function of parton momentum.
  - Form factors – 1D as function of transverse distance from centre.
- GPDs relate the transverse position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



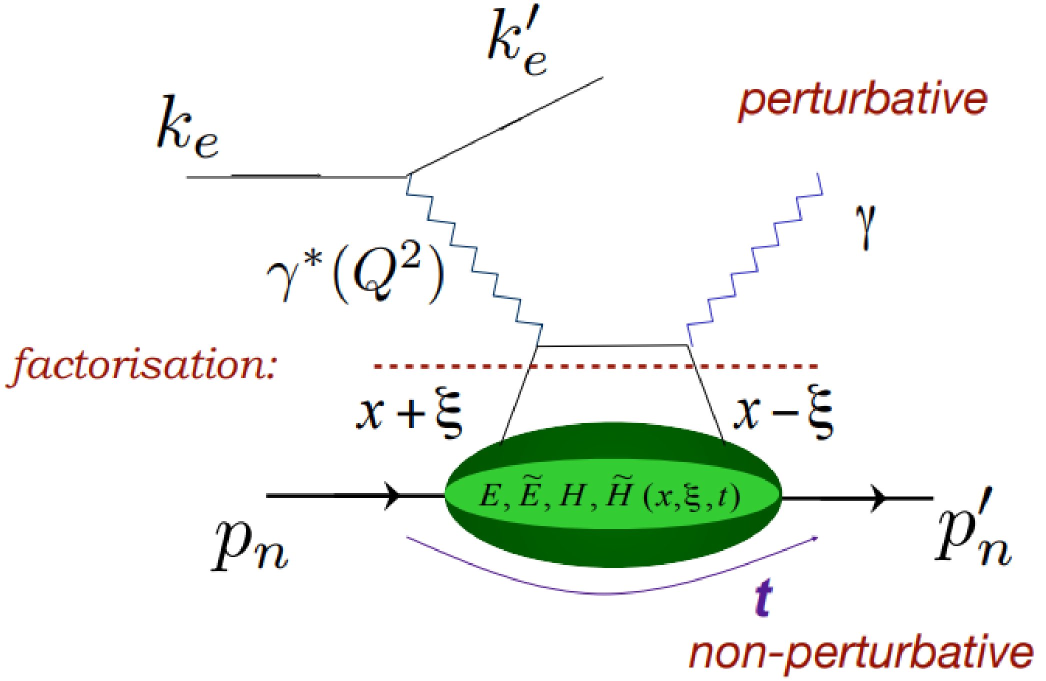
Deeply Virtual Compton Scattering

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

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

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

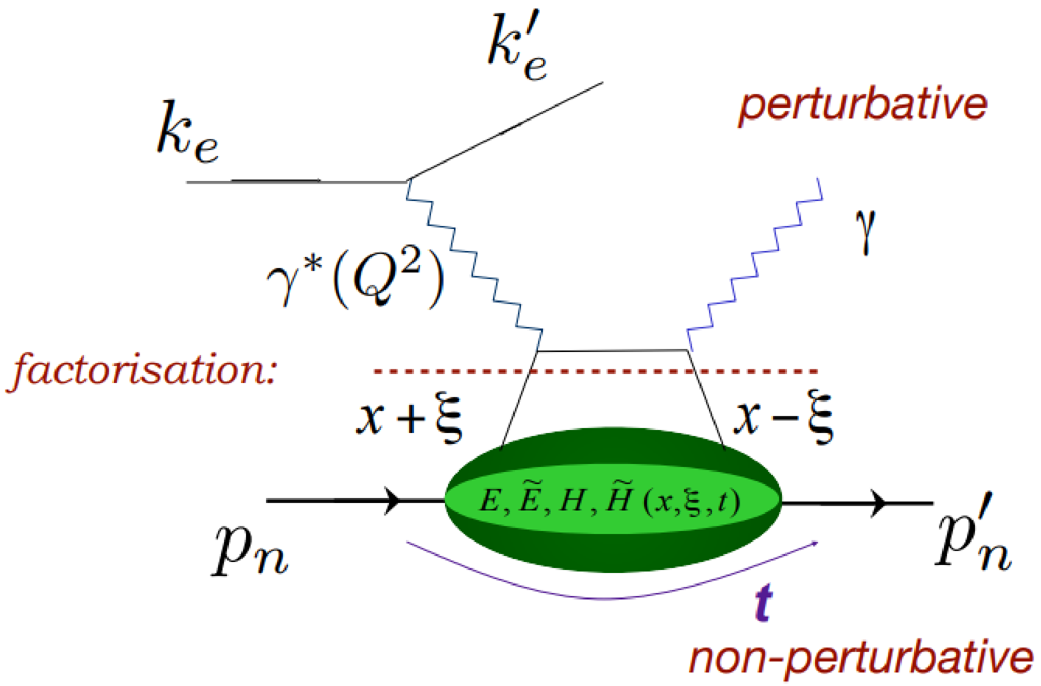
$$t = (p - p')^2$$



- 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, $\tilde{E}_q$.
  - 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!

Mandelstam *t*; "Method L"

- Reconstruction expresses missing proton 4-momentum using light-cone variables.

1. Calculate missing baryon from 4-momentum conservation

$$p_{p'} = (p_p + p_e) - (p_{e'} + p_\gamma)$$

2. Correct final state baryon components
   - $p_{p'}^{+} = E_{p'} + p_{z,p'}$
   - $p_{T,p'}^{2} = p_{x,p'}^{2} + p_{y,p'}^{2}$
   - $p_{p'}^{-} = \left(M_{p'}^{2} + p_{T,p'}^{2}\right)/p_{p'}^{+}$
   - $p_{p'}^{corr} = \left[p_{x,p'}, p_{y,p'}, \frac{\left(p_{p'}^{+} - p_{p'}^{-}\right)}{2}, \frac{\left(p_{p'}^{+} + p_{p'}^{-}\right)}{2}\right]$

$$t = \left(p_p - p_{p'}^{corr}\right)^2$$

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.

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

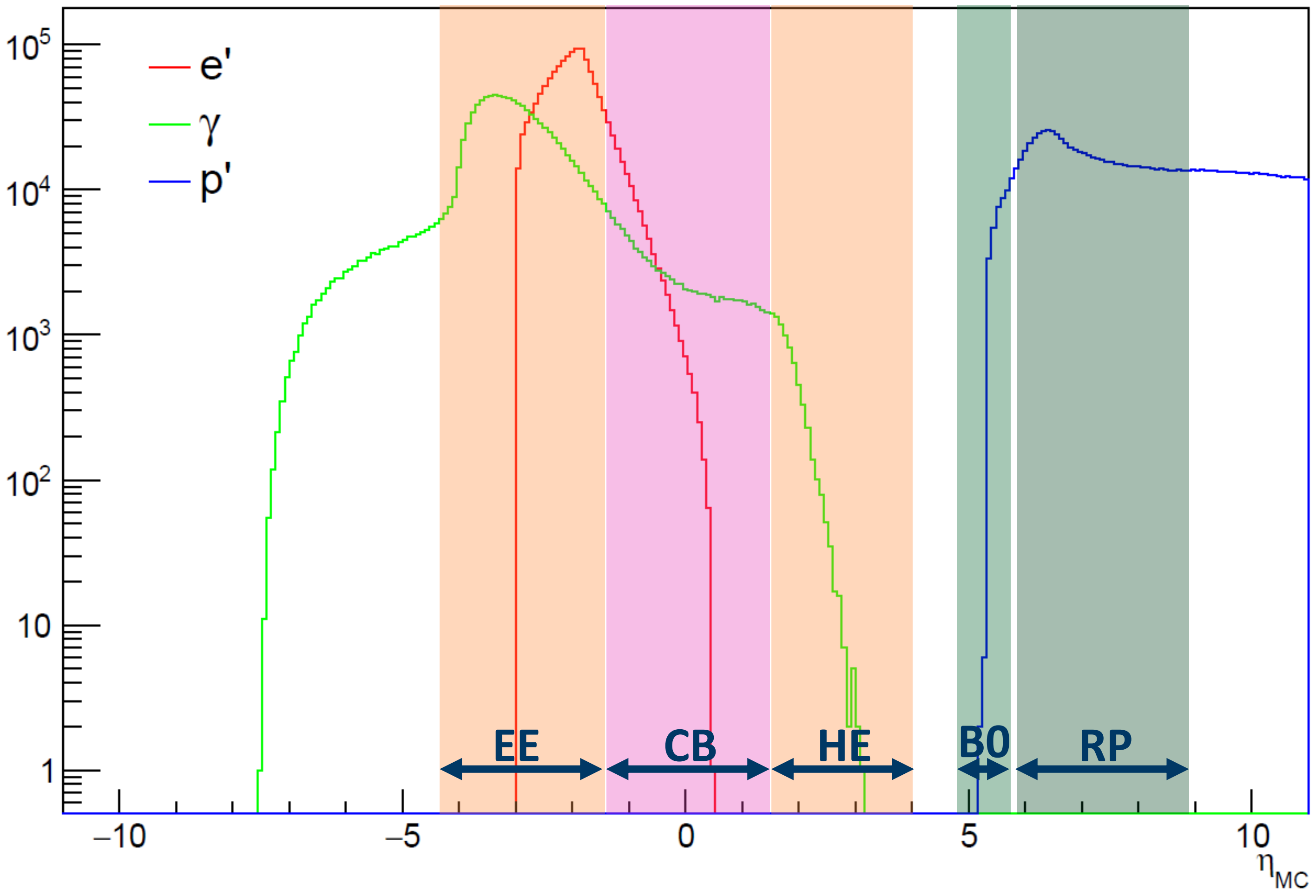
Why DVCS @ ePIC?

- 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?



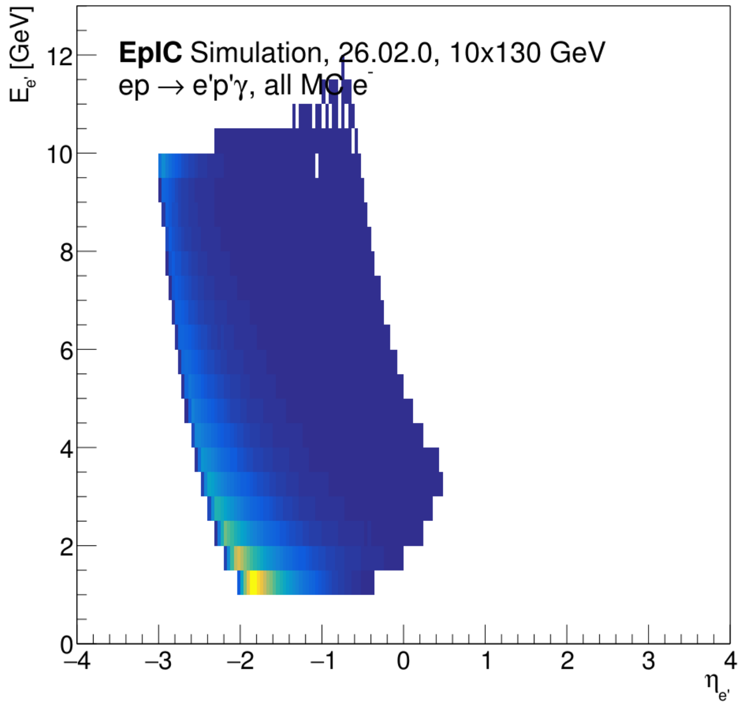
- Much of the ePIC detector used for reconstruction.
  - Electrons: **central barrel** and **backward endcap**.
  - Photons: across **central barrel** and **both endcaps**.
  - Protons: **B0** and **Roman Pots** (energy-dependent).
    - 5x41 – 94% B0, 6% RP
    - 10x100 – 3% B0, 97% RP
    - 10x130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

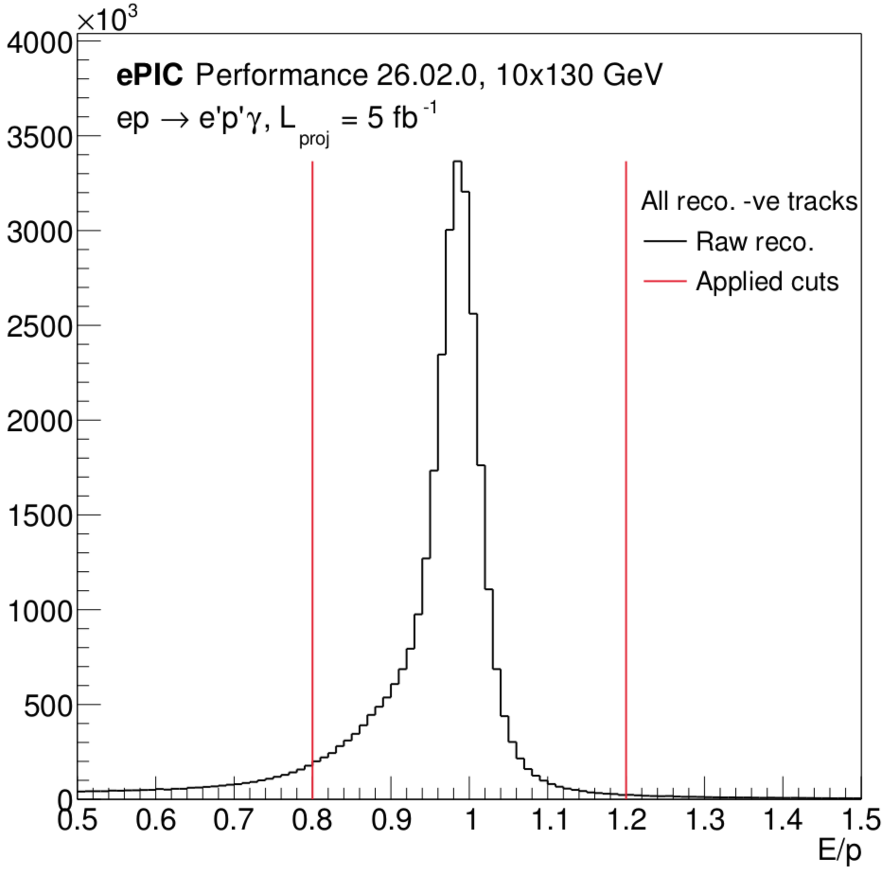
Why DVCS @ ePIC?

- 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.

Analysis details – electrons

- Taken from `ReconstructedParticles` (pseudo-Electron Finder)
  - Q = -1
  - 0.8 < E/p < 1.2

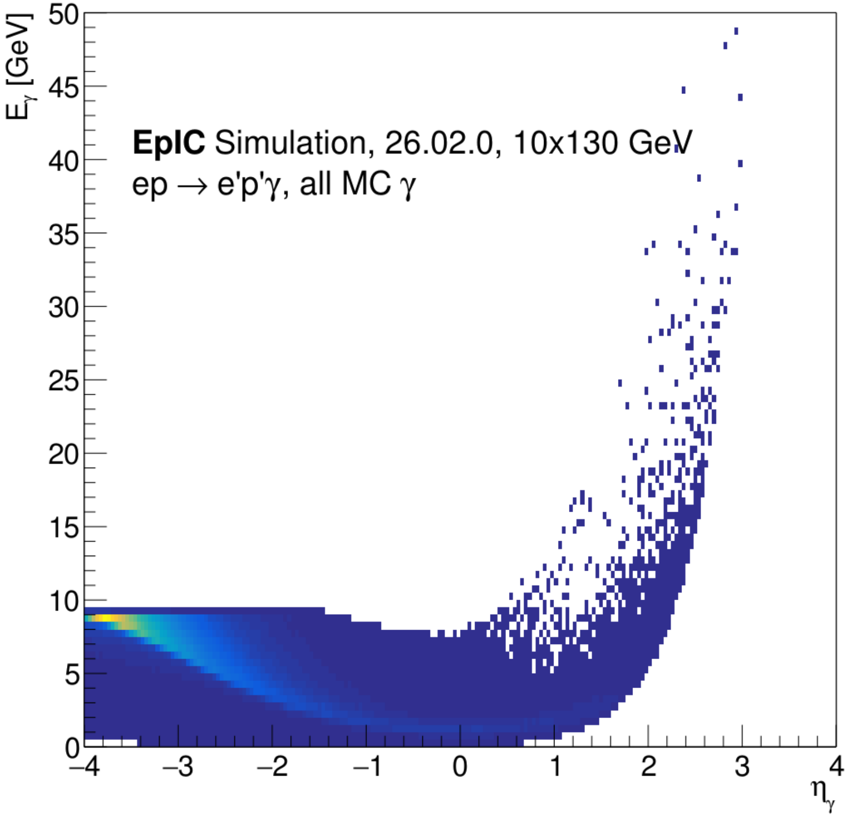


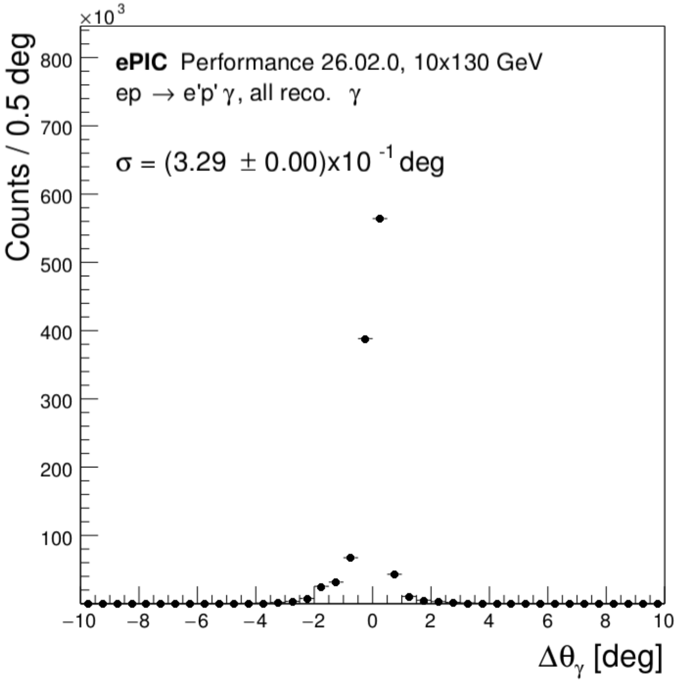


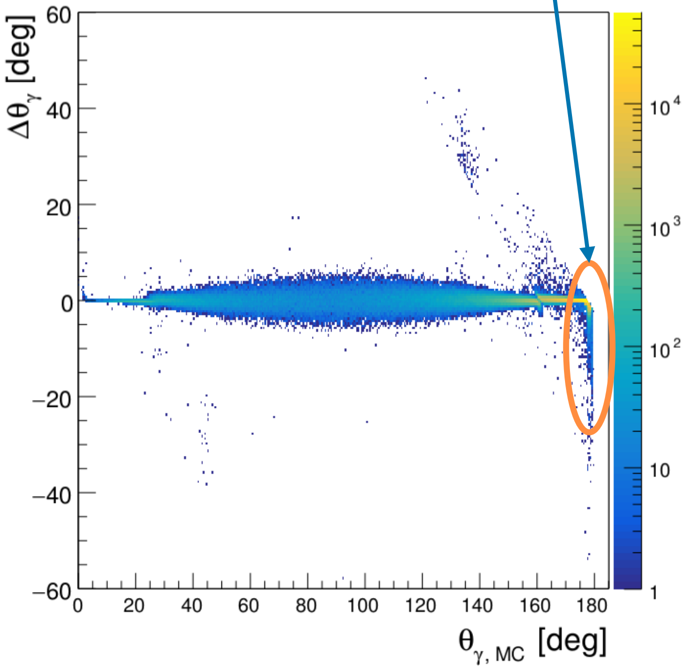
Analysis details – photons

- Taken from `ReconstructedParticles` *(very coarse)*
  - Q = 0

Smearing @ inner edge of EEEMCAL





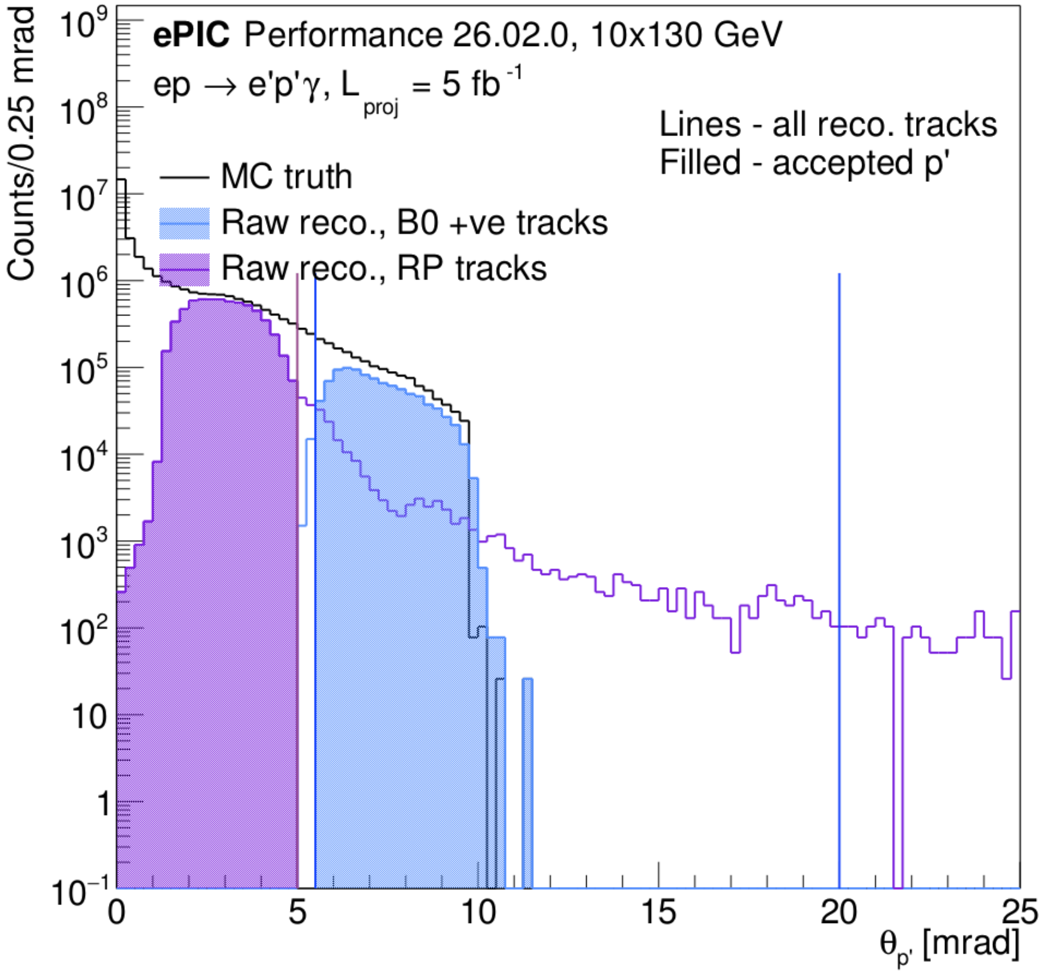


Analysis details – protons

- 2 sources:
  i. `ReconstructedTruthSeededChargedParticles` (for particles in the B0 spectrometer)
  ii. `FarForwardRomanPotRecParticles` (for particles in the Roman Pots)
- PID depends on location of track
  - B0 – using track charge (Q = +1)
  - RP – assuming all tracks are protons

- Track quality cut applied: theta of proton track (ensure is within appropriate detector acceptance)

Analysis details – protons



- For B0 protons

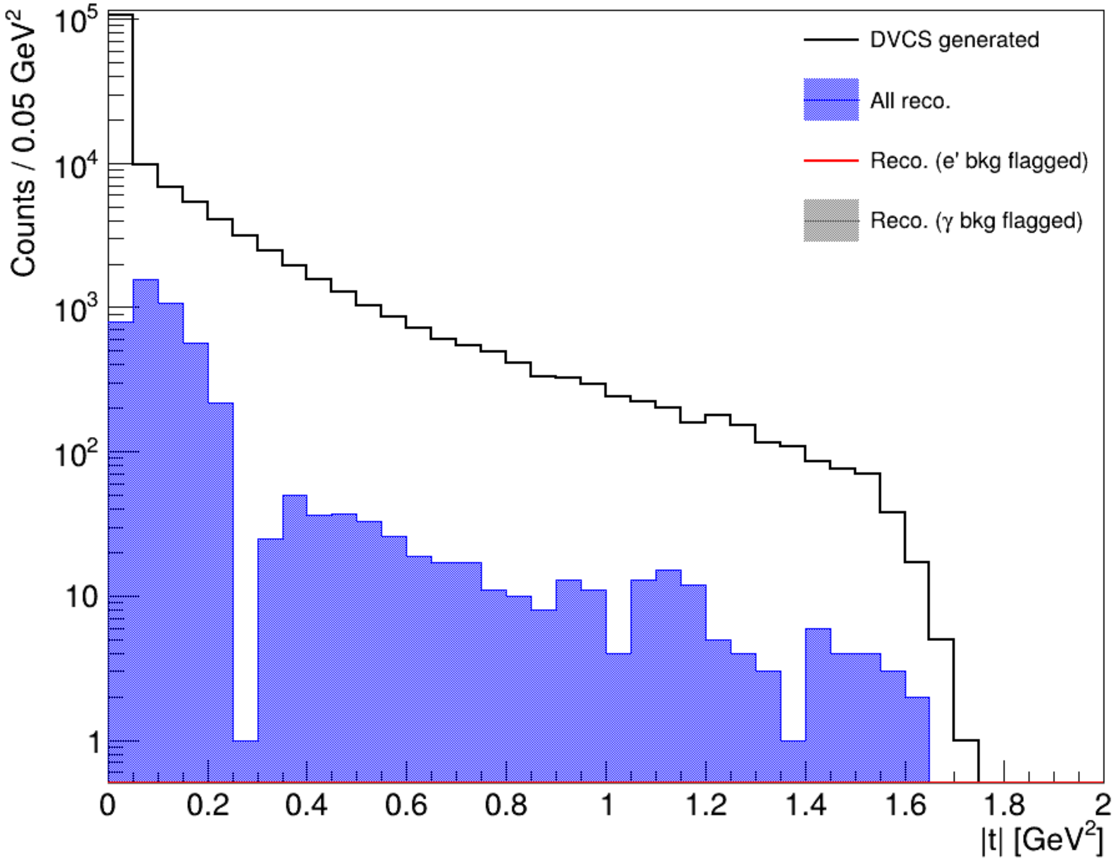
$$5.5 < \theta_{p'} < 20\,\mathrm{mrad}$$

- For RP protons

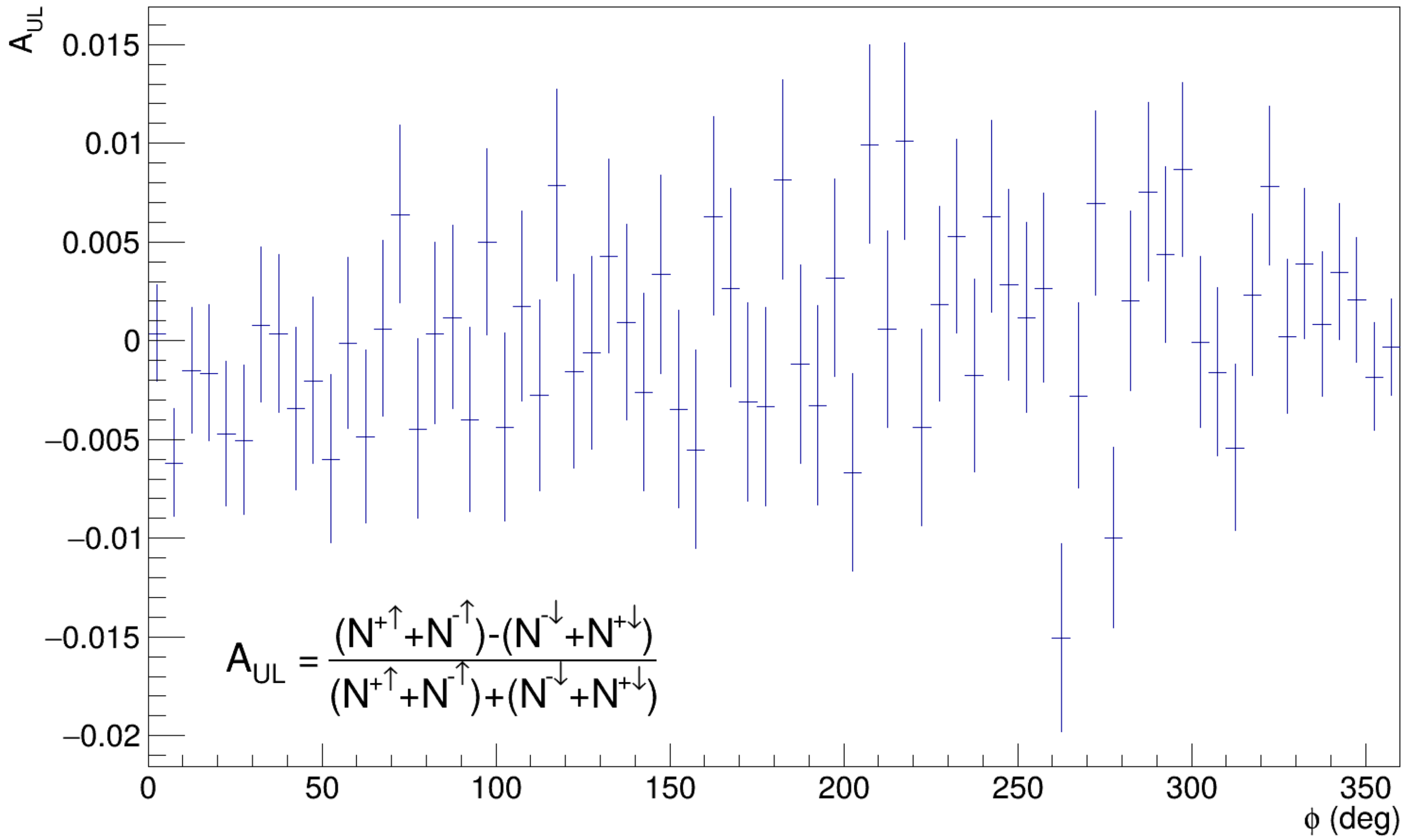
$$\theta_{p'} < 5\,\mathrm{mrad}$$

(Less important for B0 tracks, but applied for completeness)

Beam gas backgrounds - |t|



EpIC – generated A_UL



EpIC – generated A_LL