Studying proton structure with Deeply Virtual Compton Scattering

Oliver Jevons
University of Glasgow, UK

Exclusive, Diffractive and Tagging PWG meeting
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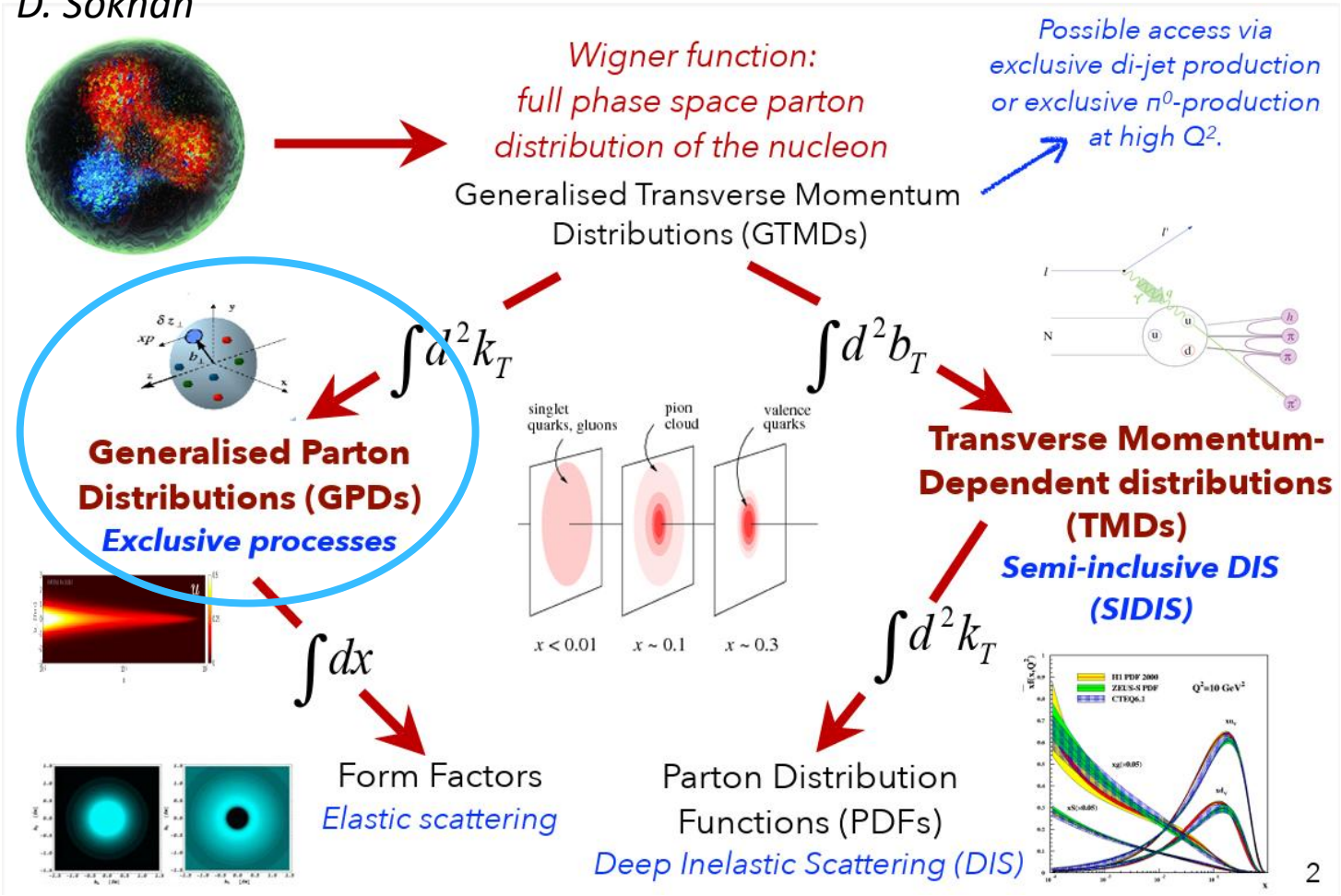
This presentation

- Overview of DVCS and its place in the EIC physics programme.
- Summary of simulation and analysis efforts.
- Current status of analysis.

Deeply Virtual Compton Scattering

Nucleon structure

D. Sokhan

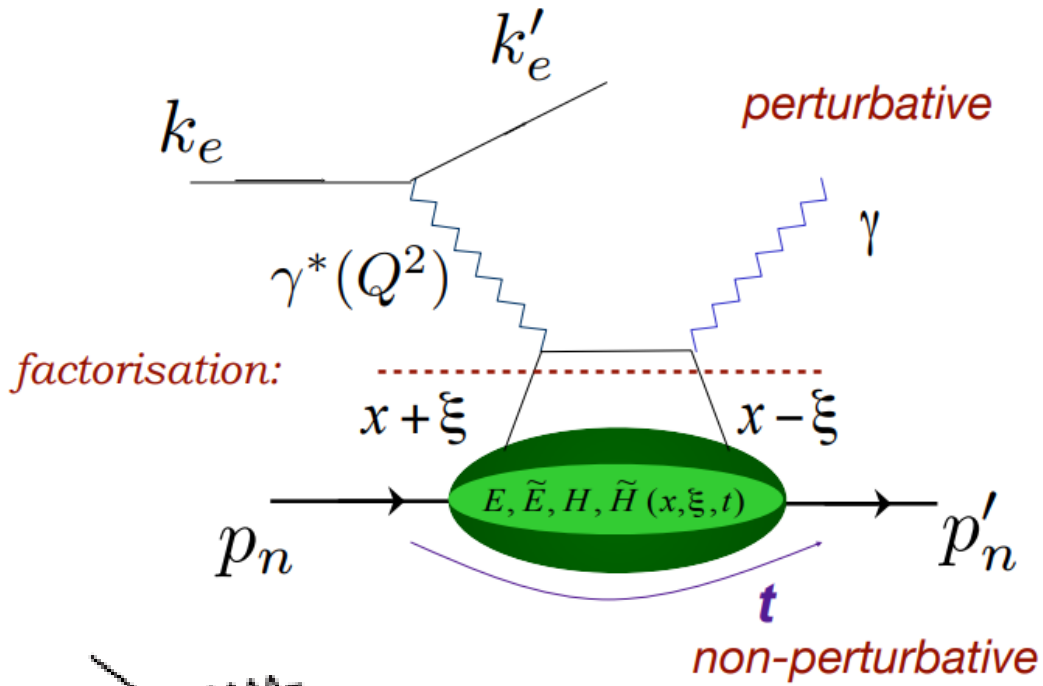


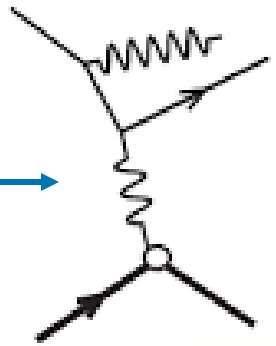
- Nucleon structure can be described within multiple dimensions by a large number of different functions.
  - GTMDs – full 5D phase space distributions.
  - PDFs – 1D as function of parton momentum.
  - Form factors – 1D as function of transverse distance from centre.
- GPDs relate the transverse position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

Deeply Virtual Compton Scattering

- Electroproduction of a single photon off a hadron target.
  - $ep \to e'p'\gamma$
  - 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.





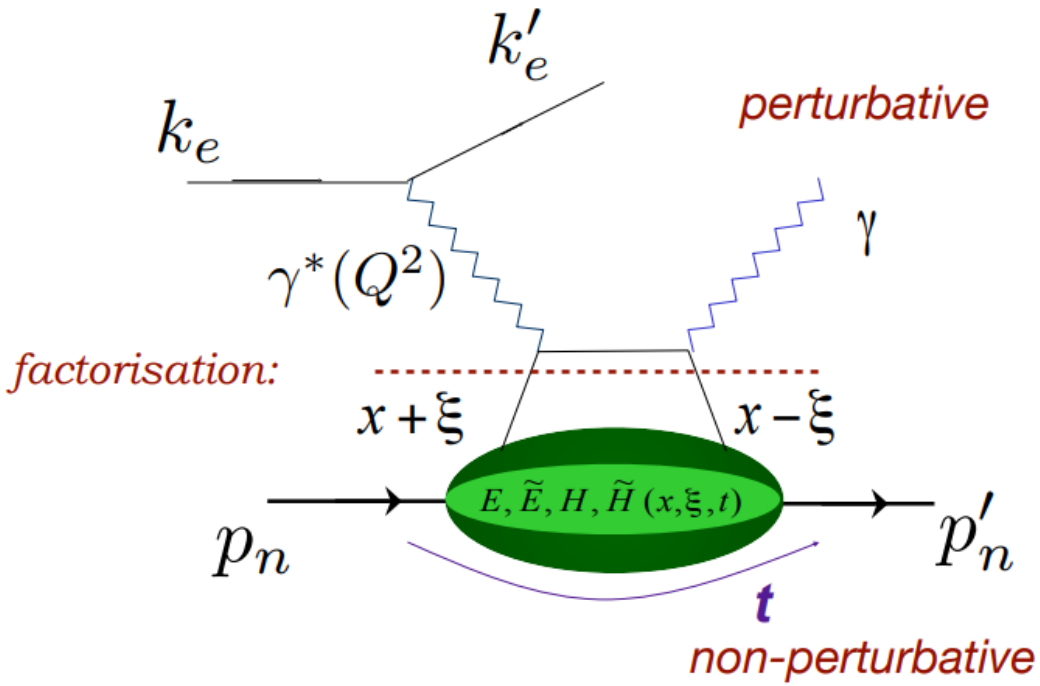
Deeply Virtual Compton Scattering

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

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

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

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

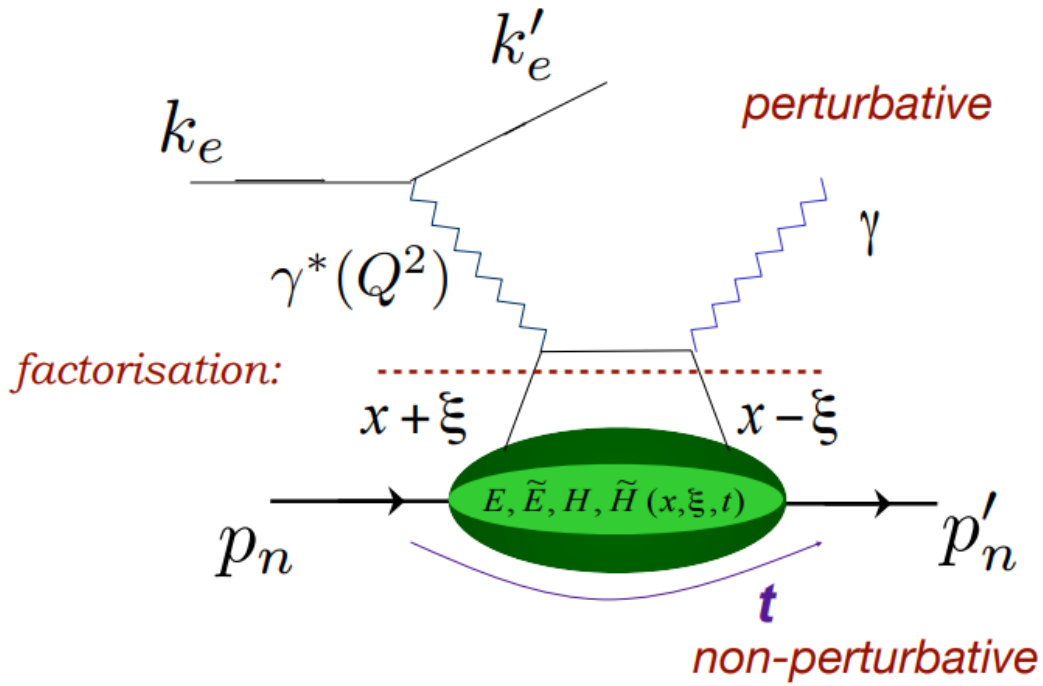


- Other formulae exist, using other combinations of reconstructed quantities, if needed (e.g. see InclusiveKinematics branches in EICrecon trees).

Deeply Virtual Compton Scattering

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

- 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.
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- 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.

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!
- 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)
  - $1 < Q^2 < 100\ GeV^2$
  - $0.01 < y < 0.9$
  - $10^{-5} < x_B < 0.7$
  - (These kinematic ranges are correct for 10x130 – unknown for other energy settings. Have asked Sal, but no response yet).

Simulation details

- 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
- DVCS has been in the monthly simulation campaigns since the start.
  - Early science setting (10x130) since 25.05.0 campaign.
  - Issues present in that first run; **for 10x130** use campaign **25.06.1 and later**!

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.

Cuts applied

- Single species cuts:
  - Electron: only 1 reconstructed and $Q^2 > 1$ 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)
  - $M_{miss}{}^2 < 1$ GeV^2

Detector acceptance correction

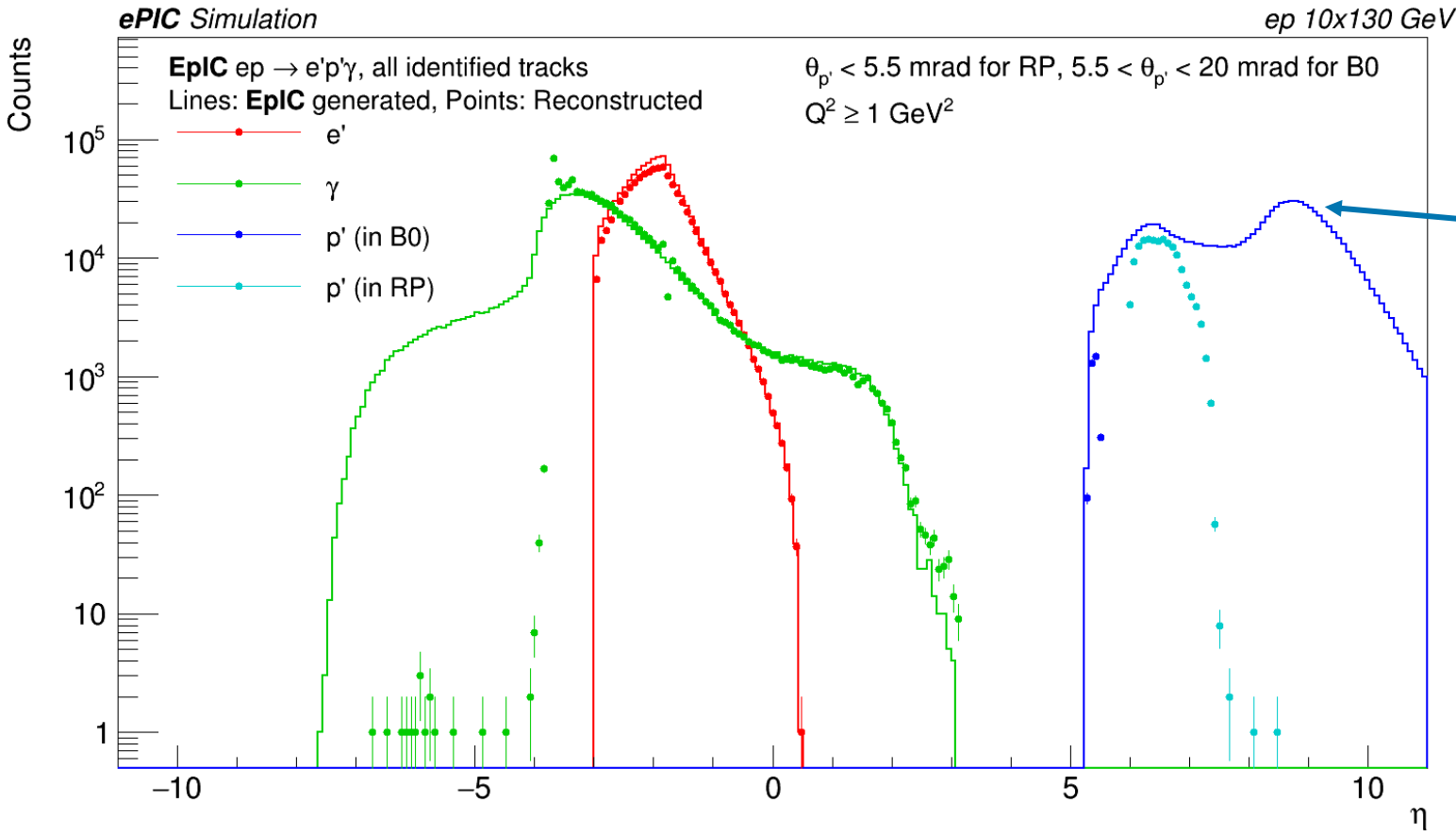
- Calculate acceptance from MC information if a reconstructed particle/event passes cuts.
  - Efficiency, $\varepsilon = \frac{N(MC\ accepted)}{N(MC\ truth)}$

- Correct reconstructed distributions by efficiency.
  - $N(corrected\ reco.) = \frac{N(raw\ reco.)}{\varepsilon}$

Analysis plots
10x130 GeV

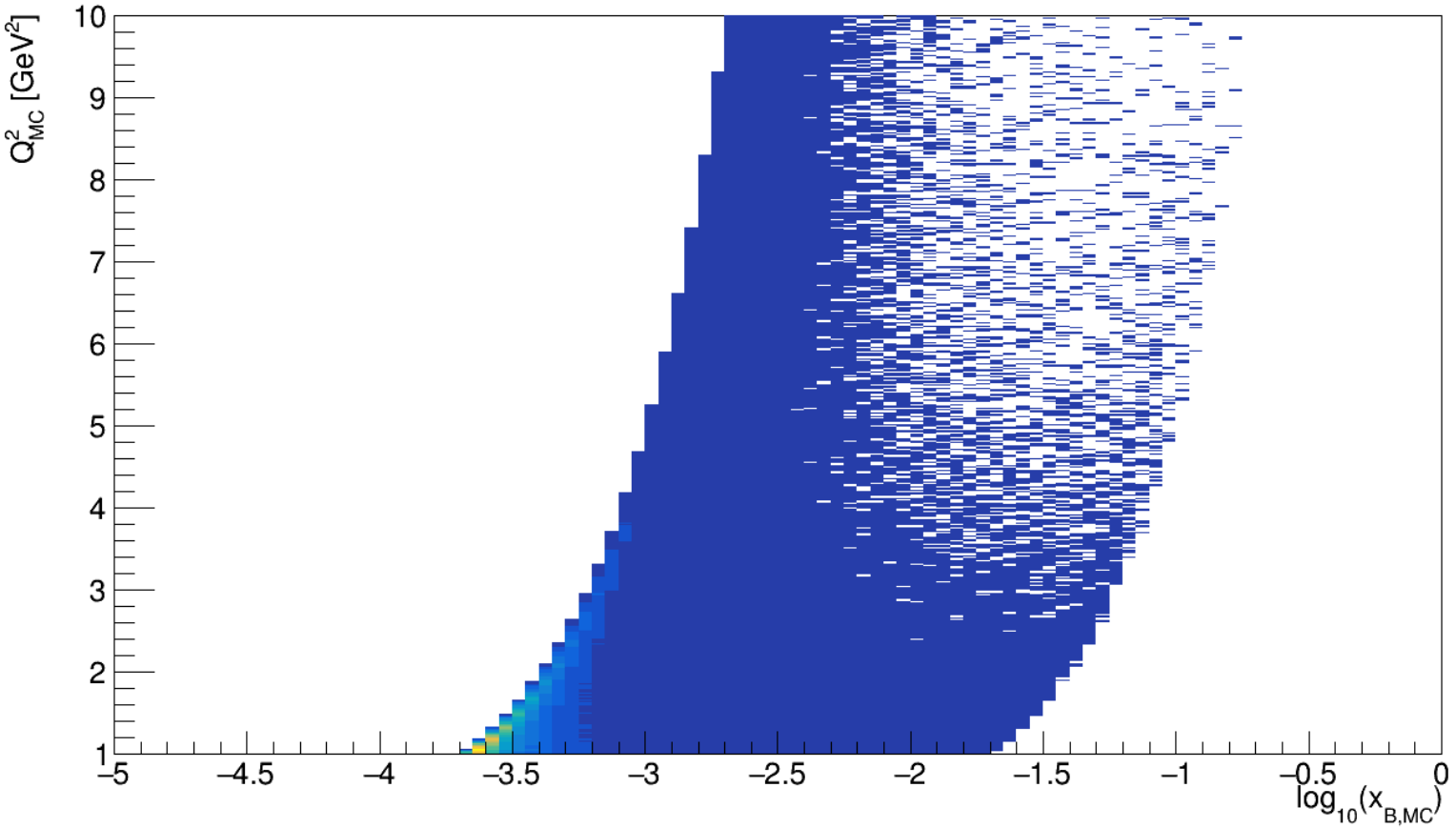
Early Science energy setting

Detector occupancy

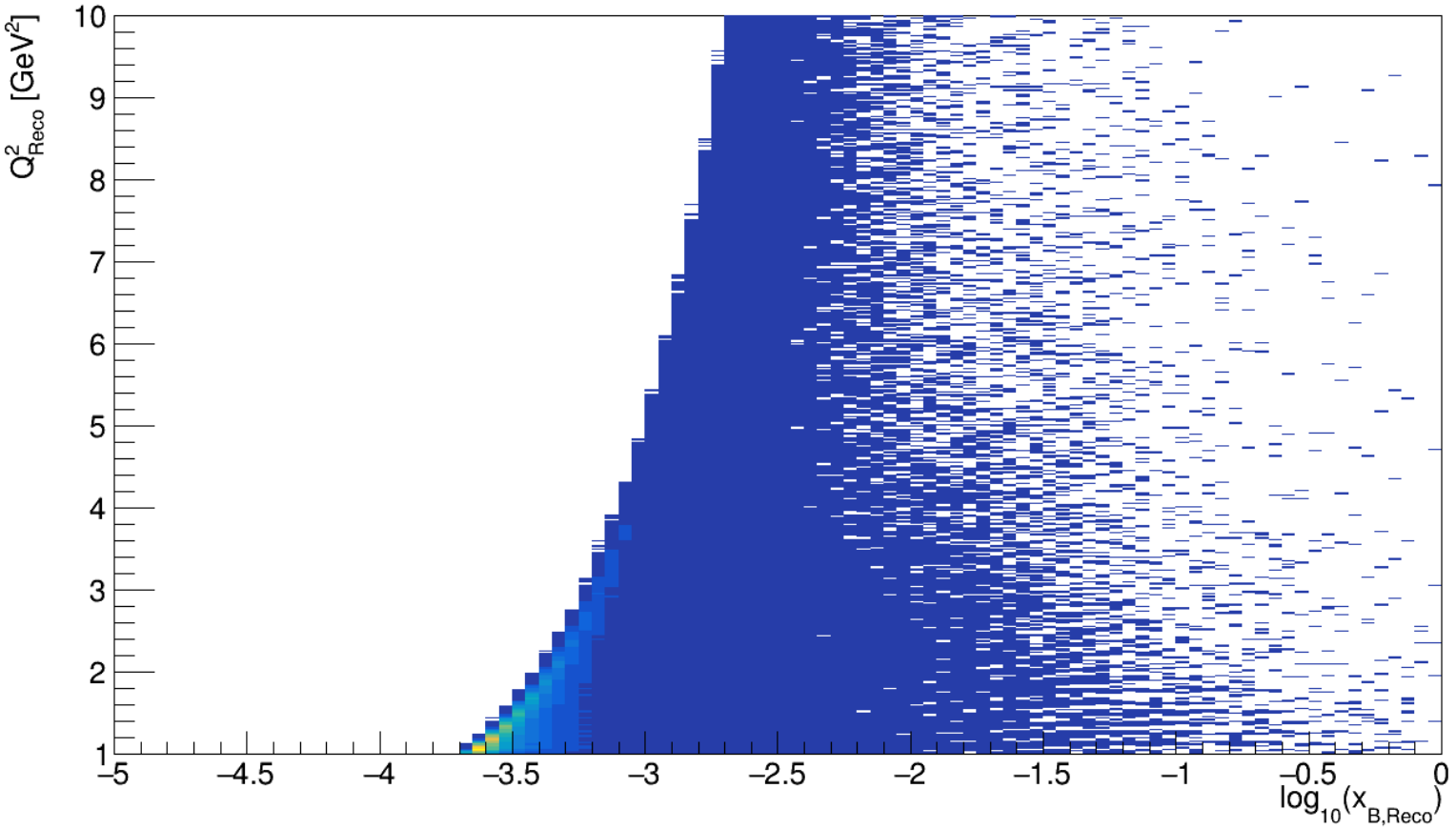


Lot of BH background is removed by RP acceptance!

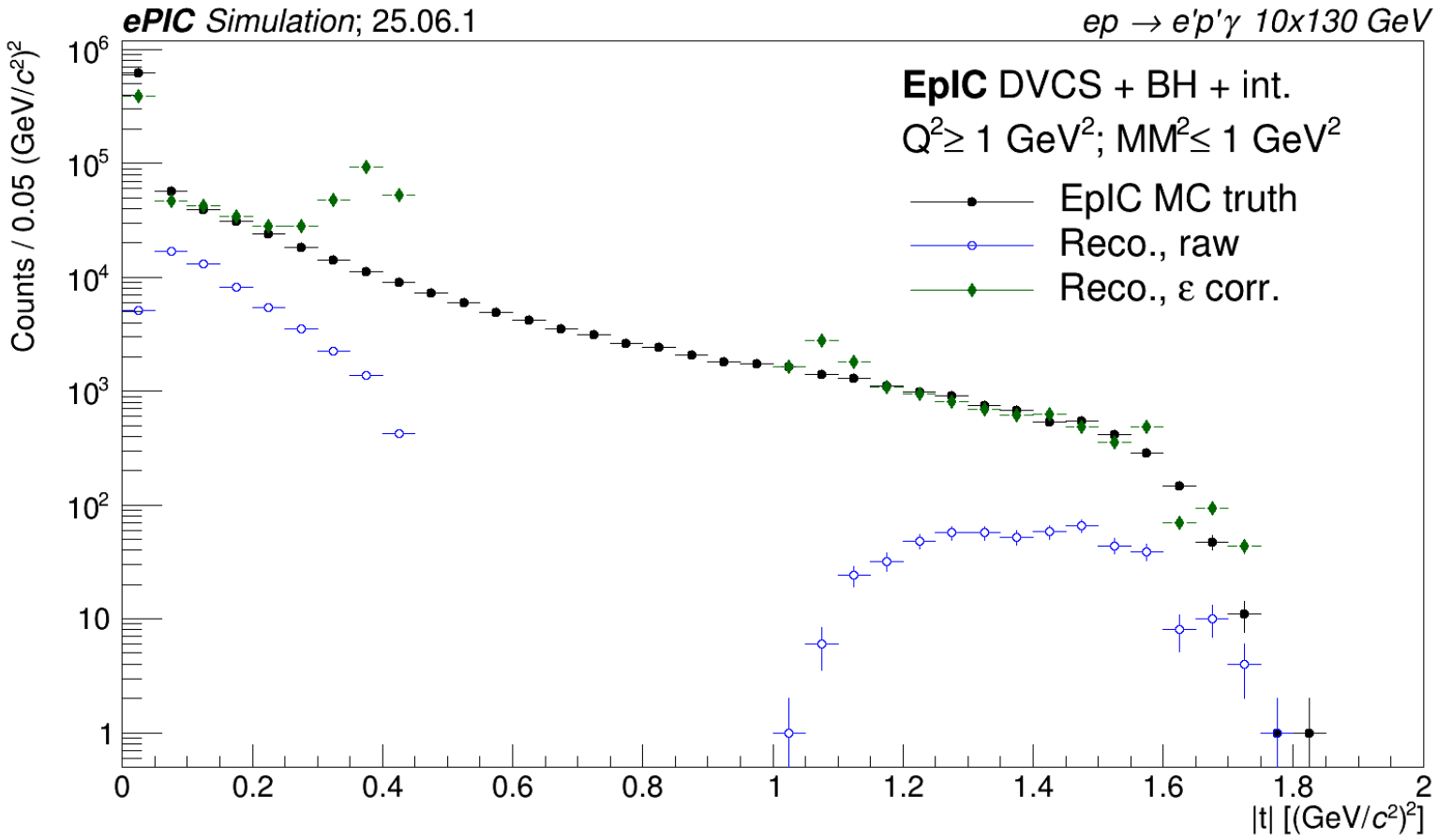
Q^2 vs x_B coverage (inclusive electrons)



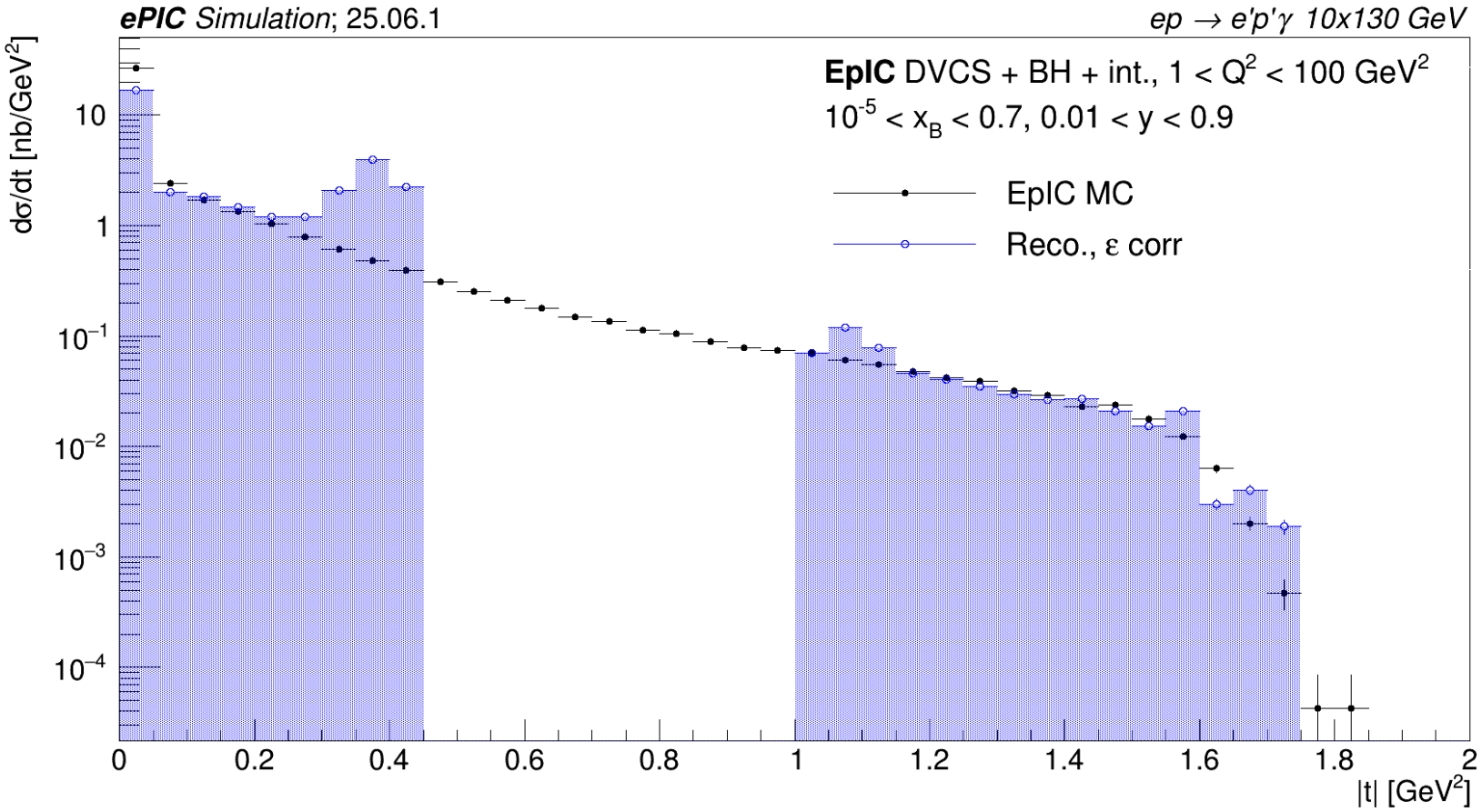
Q^2 vs x_B coverage (inclusive electrons)



t-distribution (with corrected)



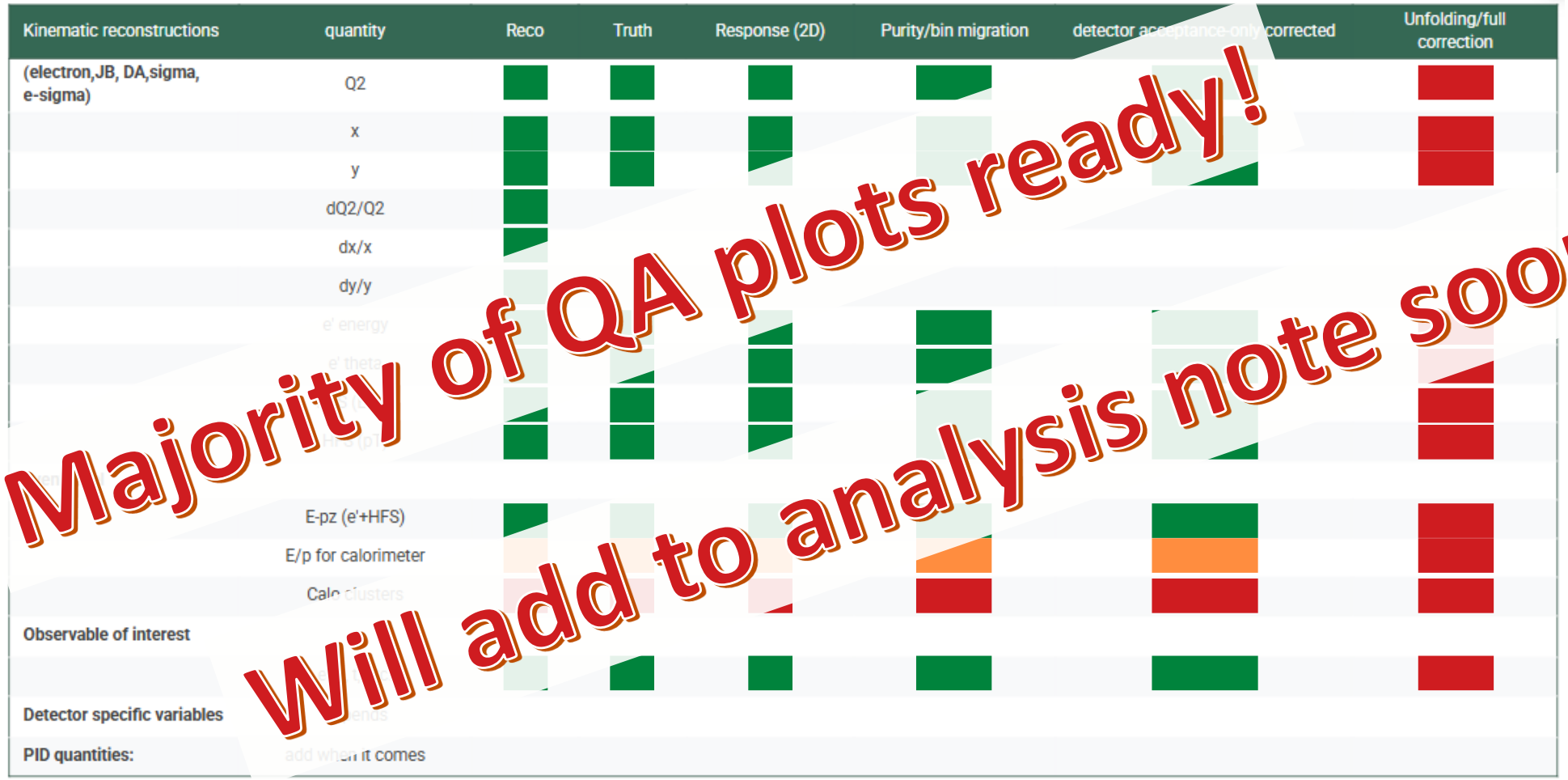
Cross-section ($\mathcal{L}_{int} \sim 0.5 fb^{-1}$)



QA plot status

Kinematic reconstructions	quantity	Reco	Truth	Response (2D)	Purity/bin migration	detector acceptance-only corrected	Unfolding/full correction
(electron,JB, DA,sigma, e-sigma)	Q2						
	x						
	y						
	dQ2/Q2						
	dx/x						
	dy/y						
	e' energy						
	e' theta						
	HFS (E-pz)						
	HFS (pT)						
Event level							
	E-pz (e'+HFS)						
	E/p for calorimeter						
	Calo clusters						
Observable of interest							
	e.g., t, etc.						
Detector specific variables	Depends						
PID quantities:	add when it comes						

QA plot status



Analysis note

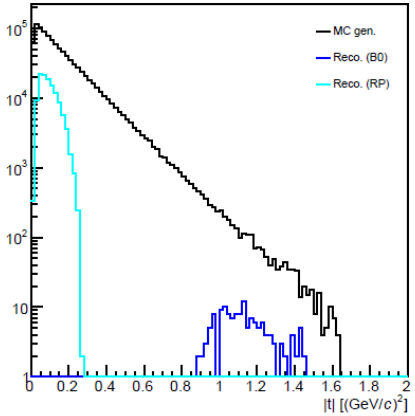
- Template of analysis note made and few preliminary plots added.
- Sections to clean up/improve:
  - Introduction
  - Event generator
- Sections to properly write:
  - Analysis procedure
  - Results

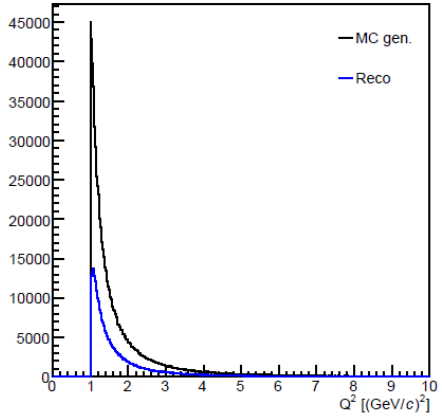
Comment on 25.07.0 campaign

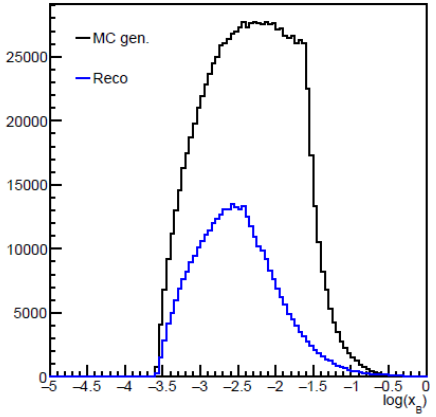
DVCS files run over the weekend.

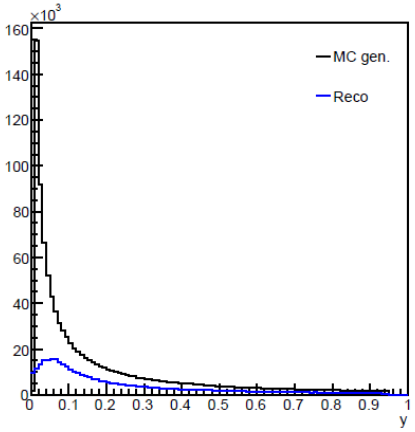
Only cursory glance at plots so far.

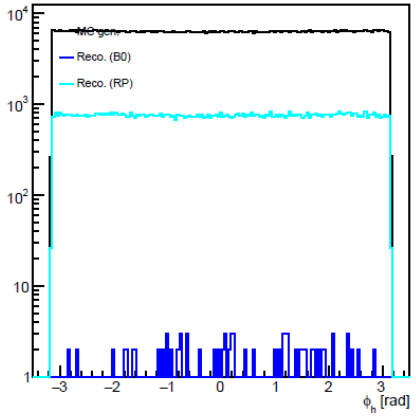
Event kinematics (10x100, 25.07.0)



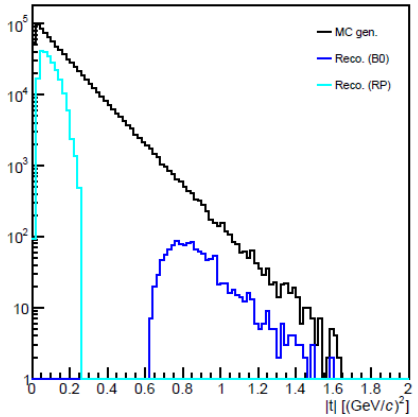


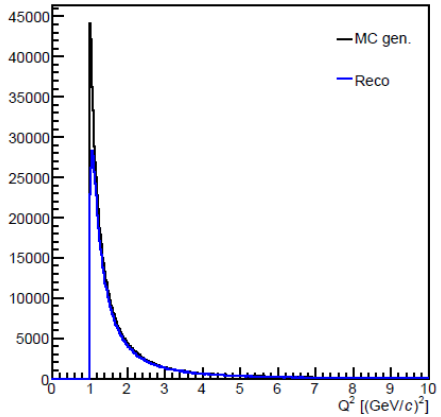


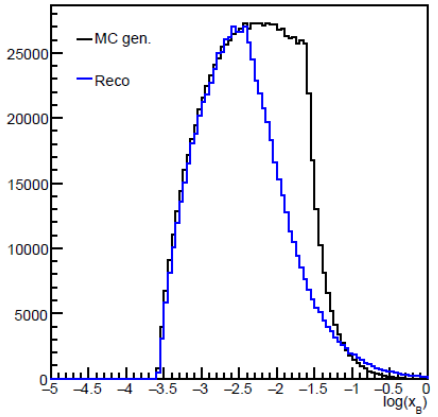


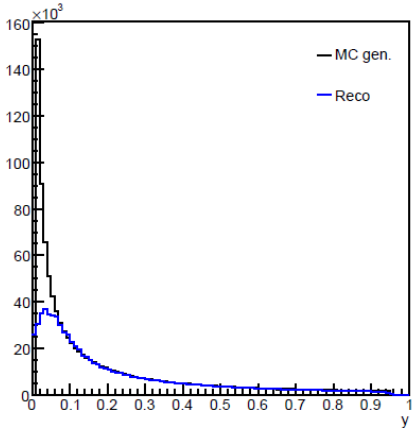


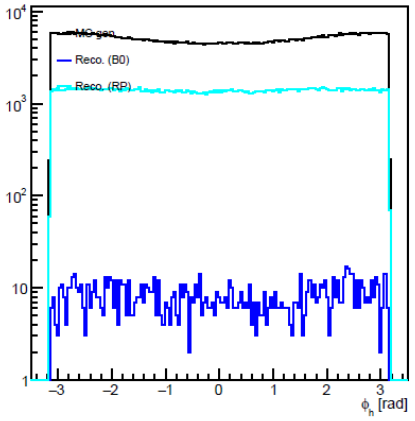
Event kinematics (10x100, 25.06.1)











Comments

- Significant drop in accepted events.
- Seems to be tied to drop in accepted electron candidates.

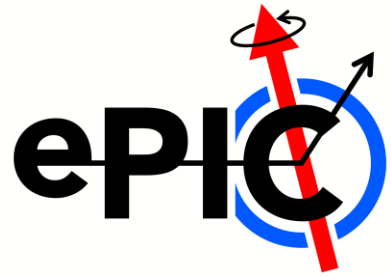
- Need to investigate further.

Concluding remarks

Next steps

- Look into applying ElectronFinder algorithm for reconstructed e^-.
- Apply calorimeter cluster energies to particle 4-vectors.
- More appropriate event cuts.
- Finer x_B/Q^2 binning – what to use?

- More generator files are being prepared.
  - Only 10x130 for now.
  - 2 different beam helicities – project asymmetries.
- Continue with analysis note.

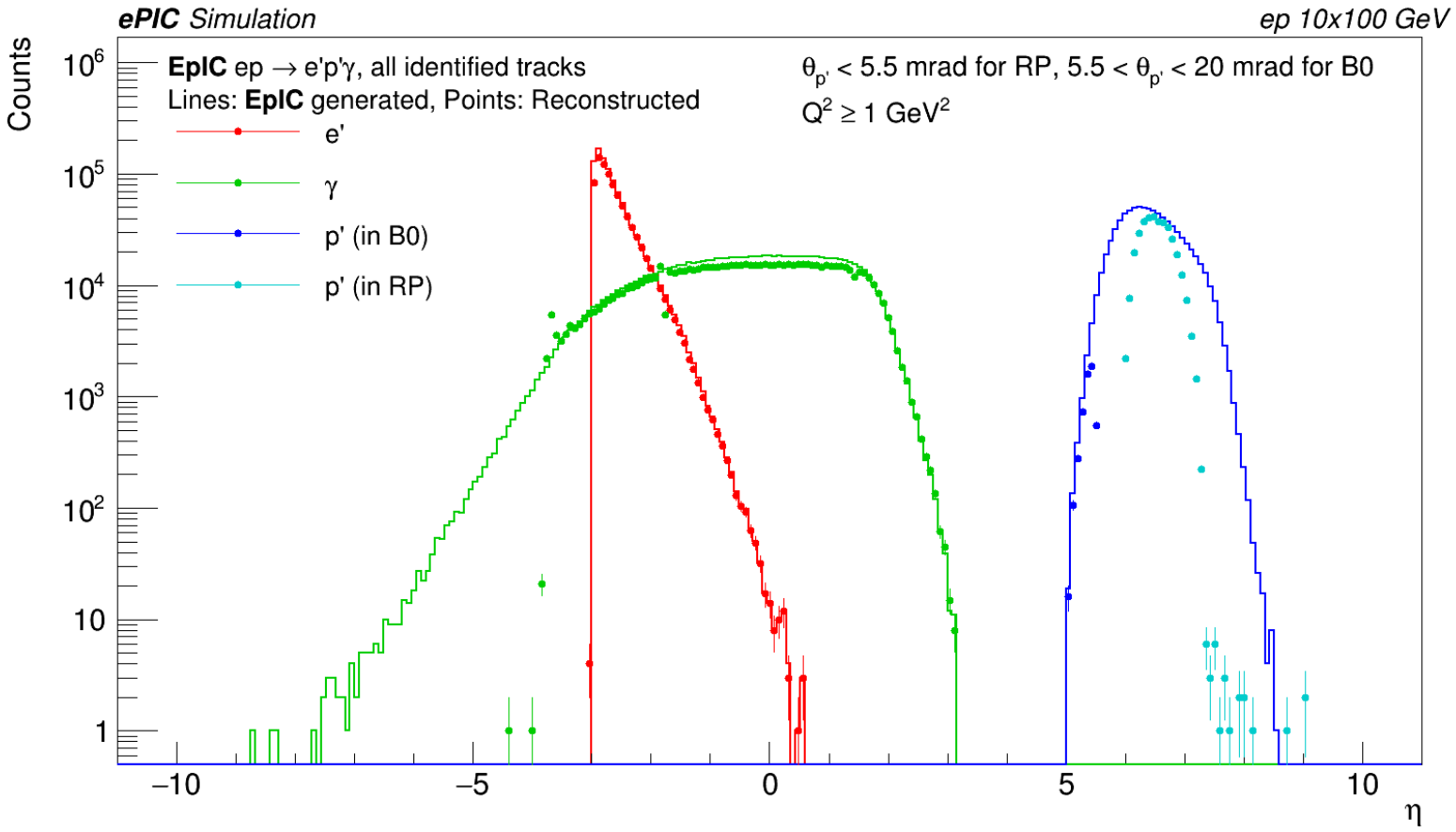


Thank you for listening!

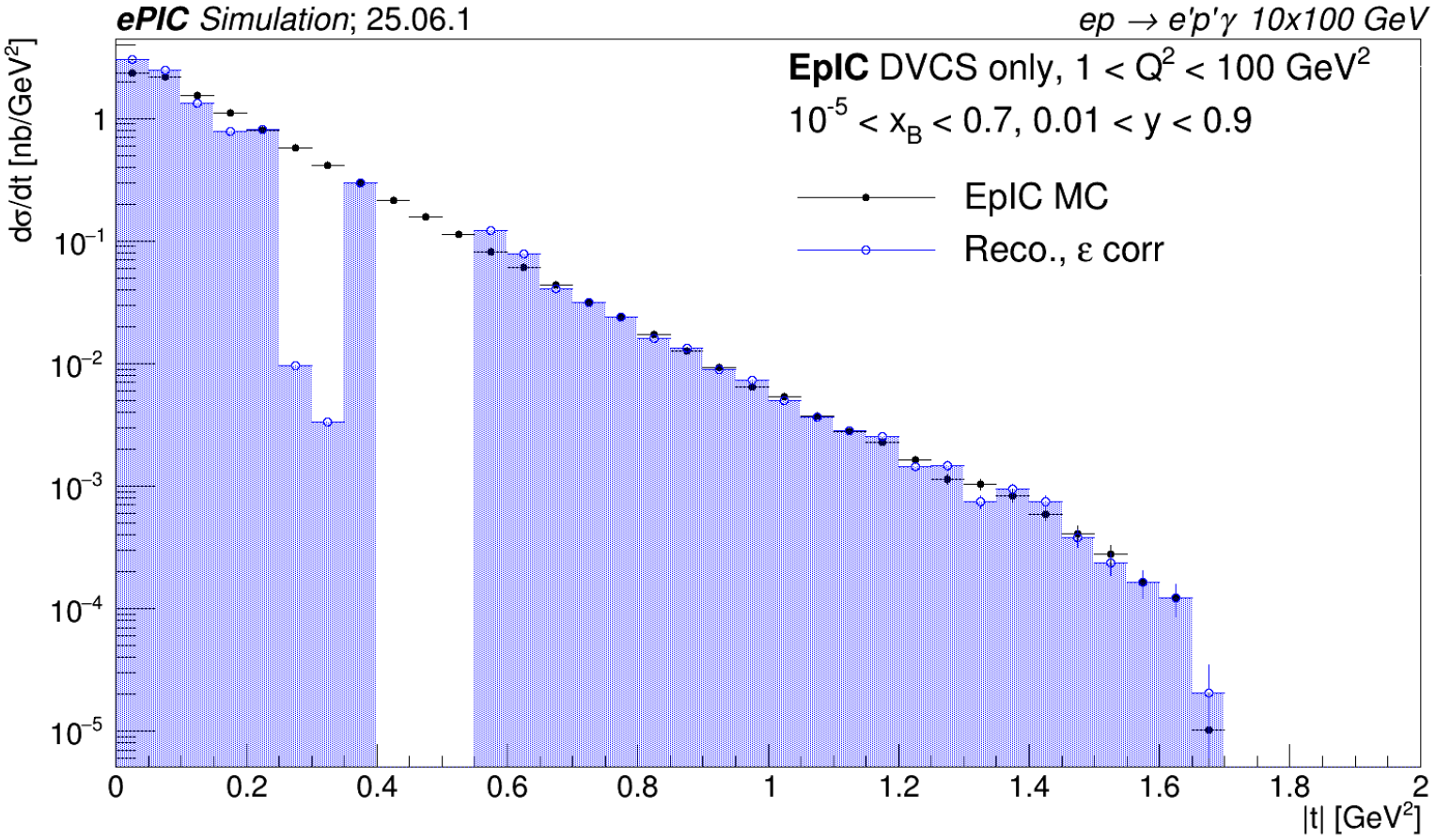
Any questions?

Backup

Eta coverage (10x100)

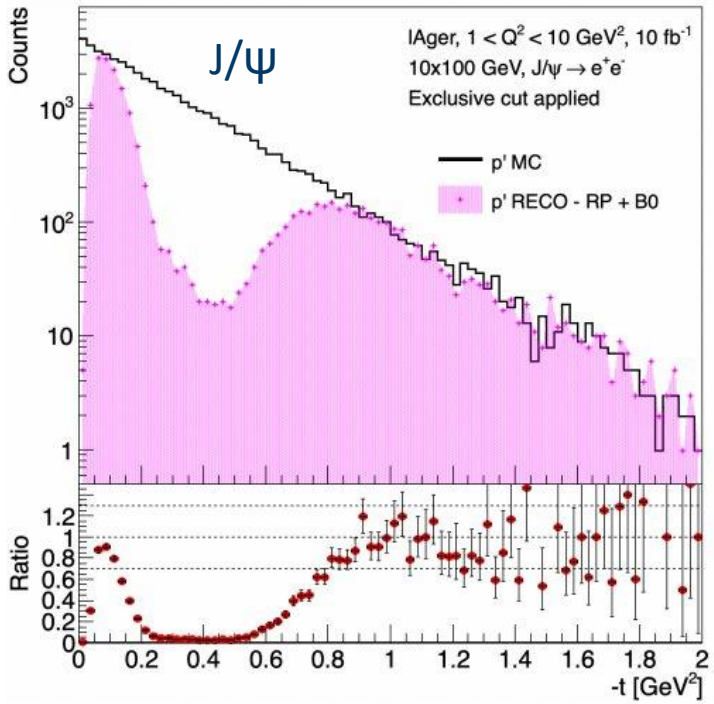


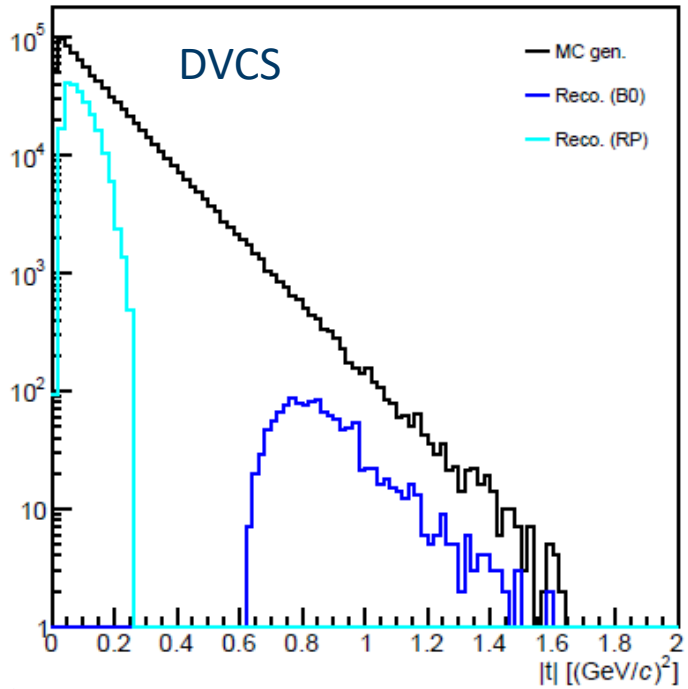
Cross-section ($\mathcal{L}_{int} \sim 2 fb^{-1}$)



Noted differences between DVCS and other analyses

- Observed in the presentations at the EICUG, that Jihee and Olaiya see drops in their acceptance for t, but not a full gap in coverage.
  - Emails sent the day after; have heard back from Jihee.





Noted differences between DVCS and other analyses

- Cause: Jihee's DVπ^0P analysis does not include a cut on proton track angle.
  - Assume that this is true for Olaiya's?
- Pion analysis sees "poorly reconstructed tracks, particularly from the Roman Pot".
  - Not sure how 'poor' these tracks are.
  - Would be nice to see raw eta/theta/t distributions from J/ψ or DVπ^0P files for proton tracks (separating B0 from RP).

Noted differences between DVCS and other analyses

- Another observation: the reconstructed distributions for DVCS do not agree with MC truth as well as for the J/ψ / DVπ^0P plots.
- Cause: there is a MM^2 cut applied for the DVCS analysis, but not for the other 2.
  - This reduces the number of accepted events, roughly uniformly.
  - This is somewhat addressed by the MC correction, but not entirely.
  - Edge effects in RP causing fluctuations in σ plot.