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Deeply Virtual Compton Scattering in ep - Status and Plans

Oliver Jevons

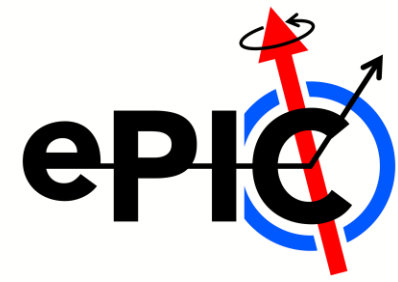
University of Glasgow, UK

ePIC and EIC Physics Readiness Workshop

19/03/26

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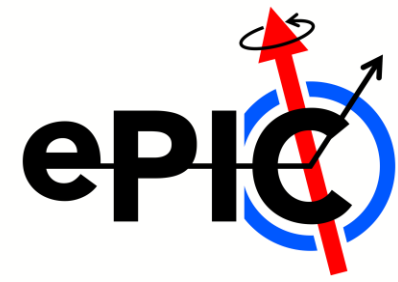
This presentation



- Context: DVCS and its place in the EIC physics programme.
- Summary of simulation and analysis efforts.
 - Focus on early science settings
 - Analysis plots
 - DIS physics background
- Future plans for analysis

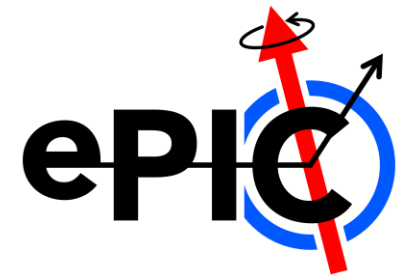


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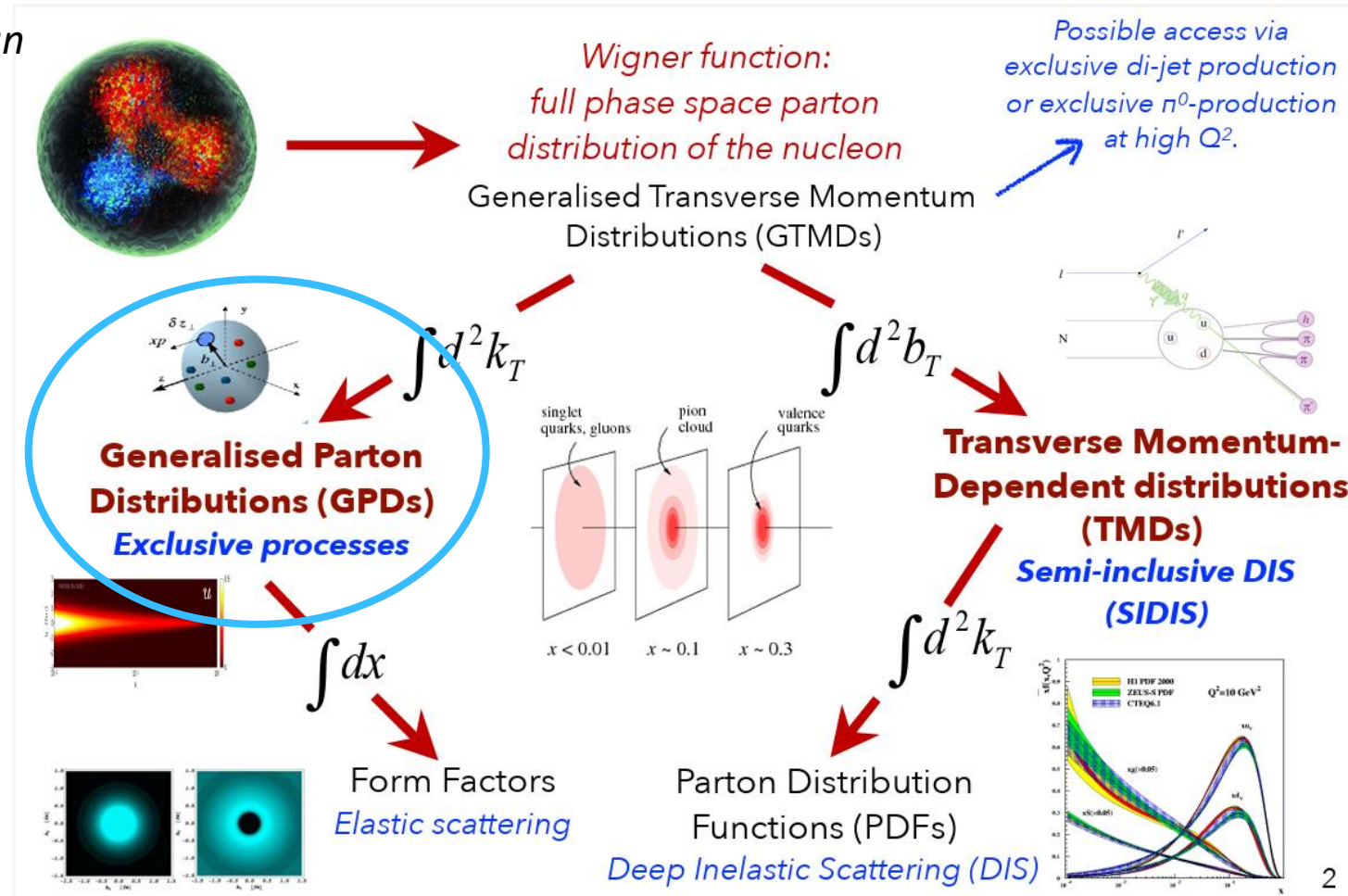


Deeply Virtual Compton Scattering

Nucleon structure – multi-dimensional pictures

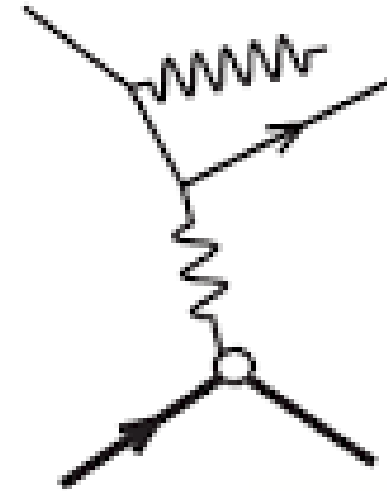
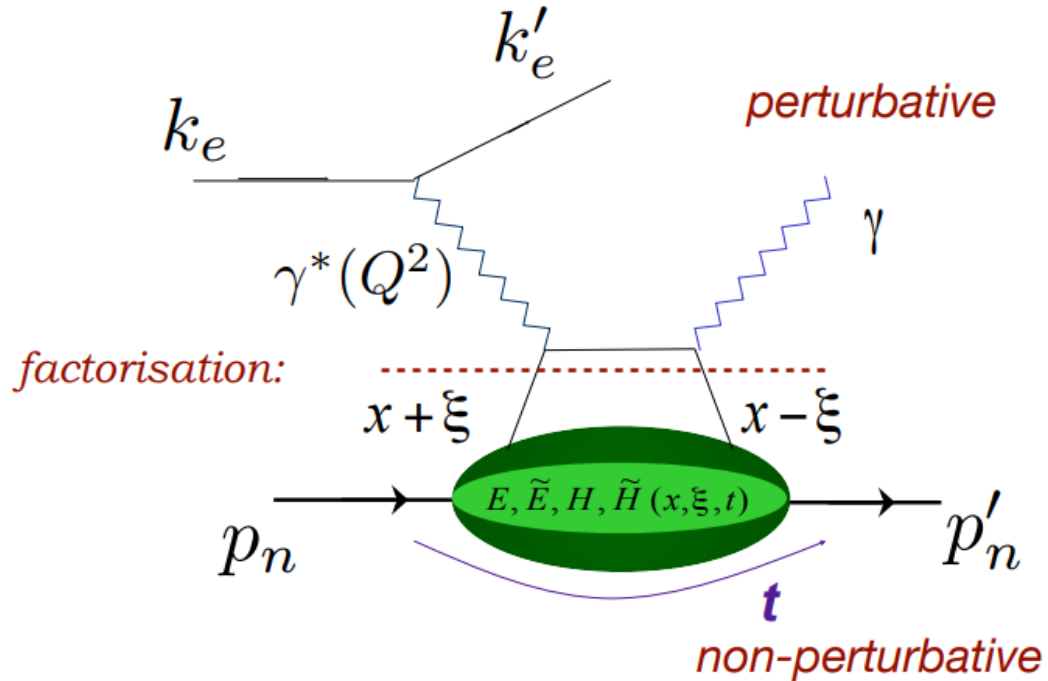
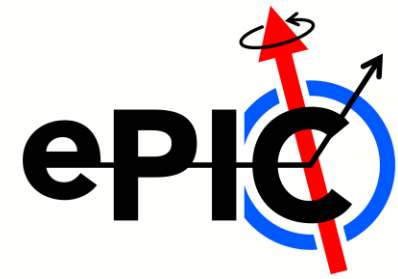


D. Sokhan





Deeply Virtual Compton Scattering

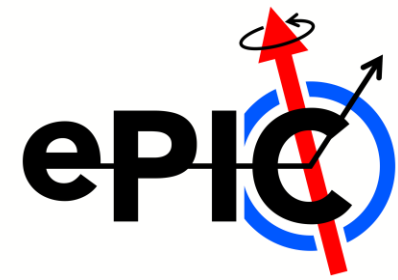


- DVCS: electroproduction of a photon off a hadron target

- 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)

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

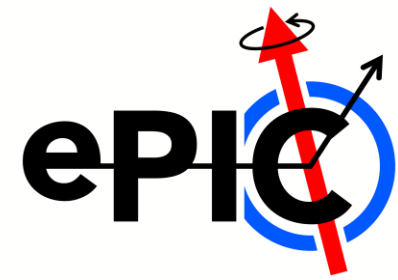
- Mandelstam t : 2 methods

$$\text{BABE: } t = (p - p')^2$$

$$\text{eXBE/Method L: } t = (p - p_{\text{corr}})^2$$

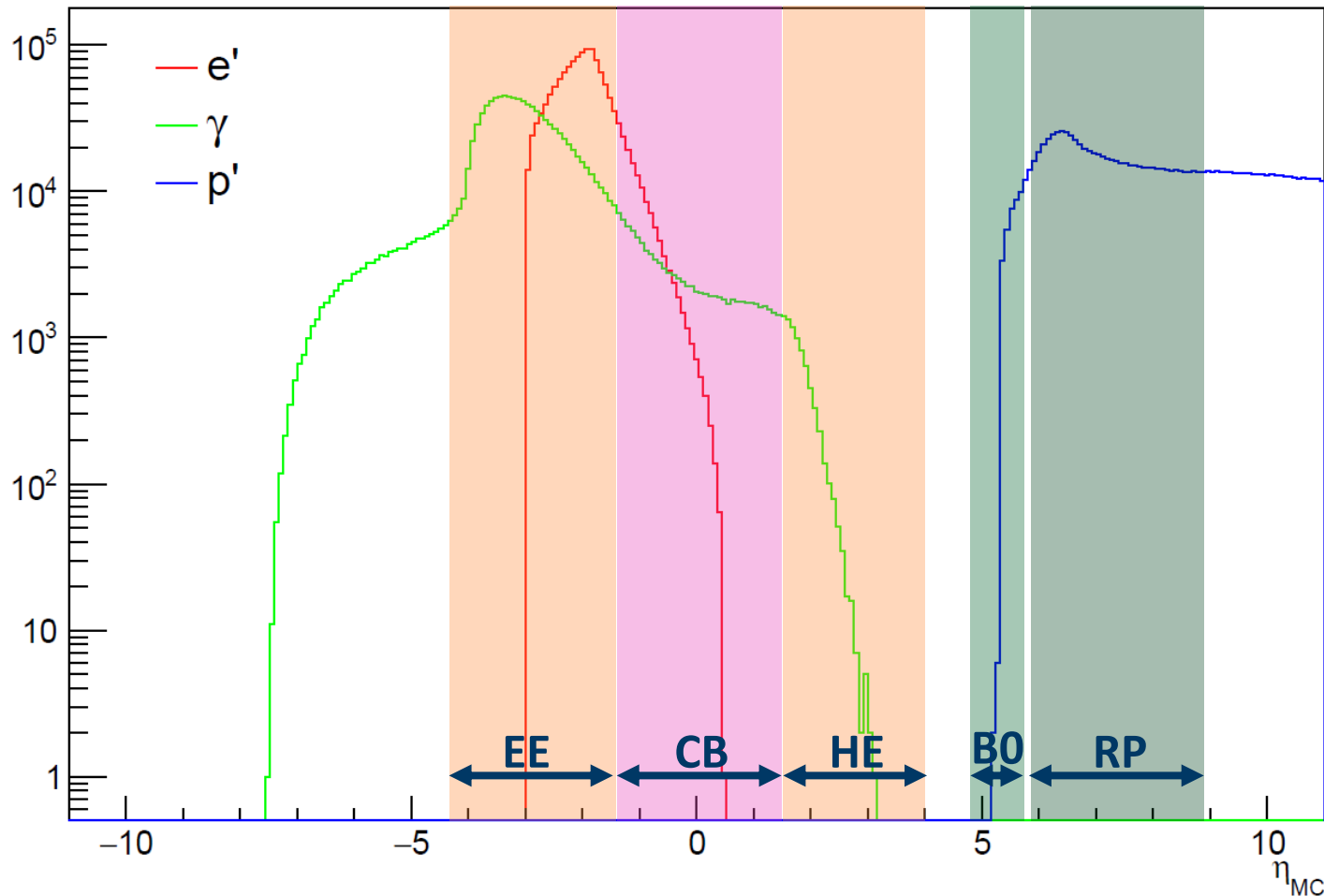
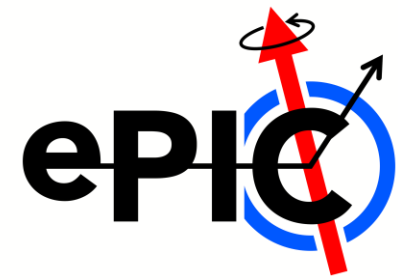


Why DVCS @ ePIC?



- 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!

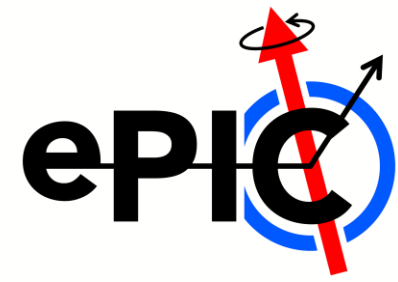
Why DVCS @ ePIC?



- 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

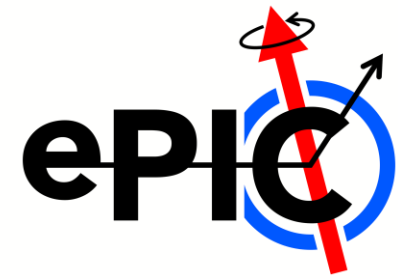


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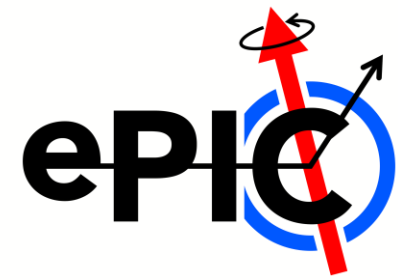
DVCS simulations for ePIC

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.

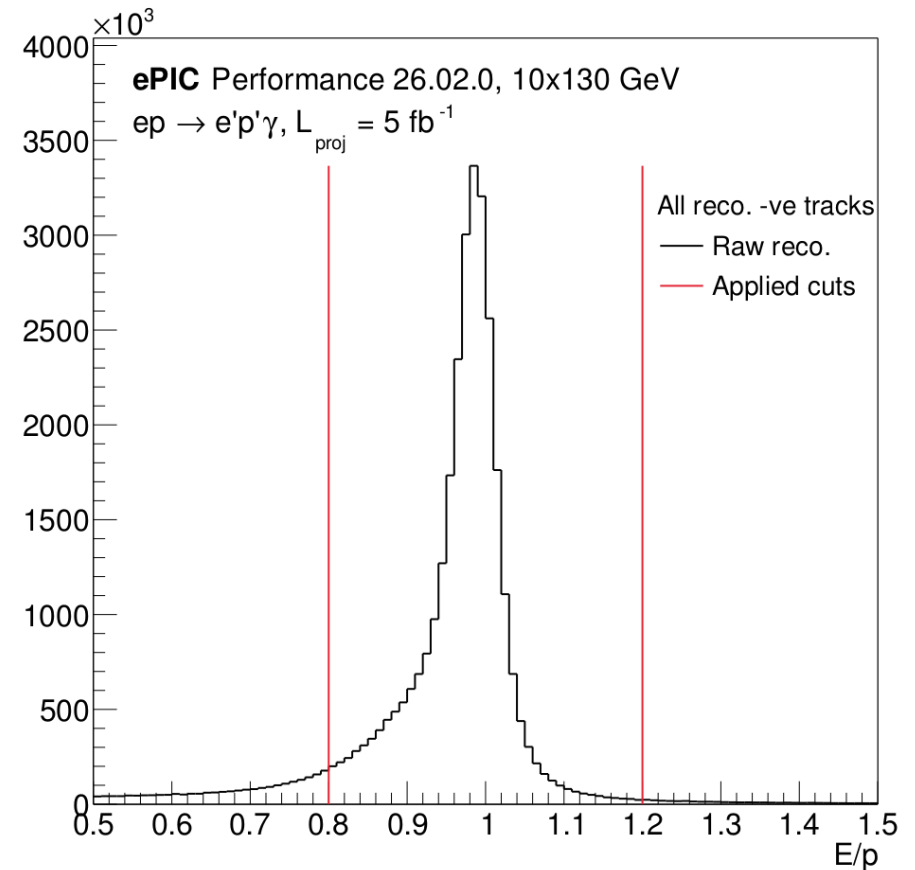
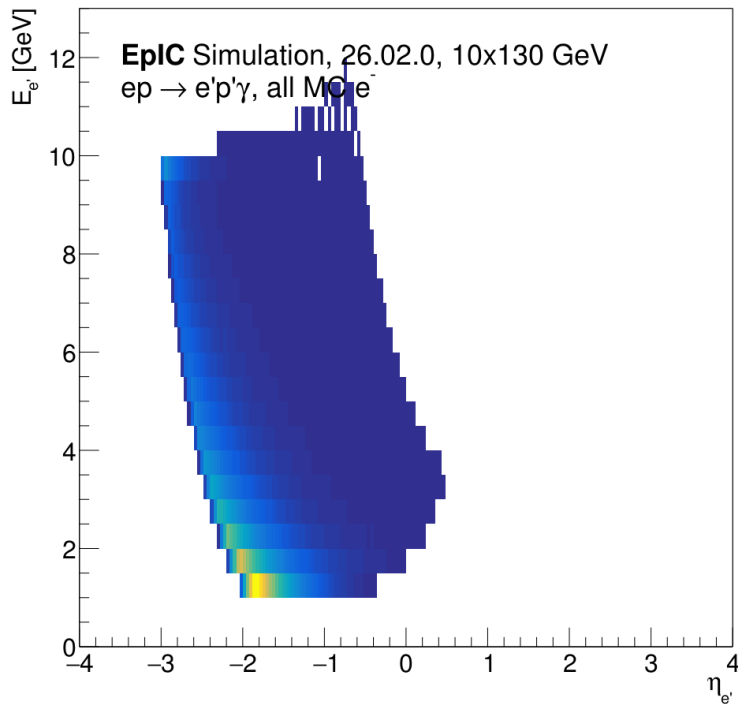
Simulation details



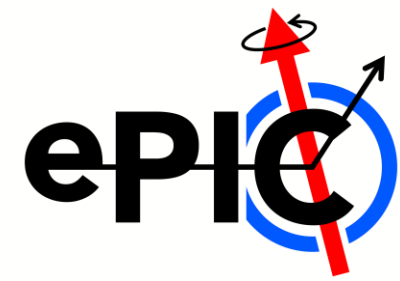
- Event samples used:
 - DVCS+BH+int.
 - 1M events (5x41, 10x250, 18x275); 1.3M events (10x100, 10x130)
 - $1 < Q^2 < 100 \text{ GeV}^2$ $0.01 < y < 0.9$ $10^{-5} < x_B < 0.7$
- Generated events represent $\mathcal{L}_{int} \sim 0.2 \text{ fb}^{-1}$ for most energies (0.1 fb^{-1} for 5x41).
- Events are passed through the full EIC simulation pipeline.
 - Plots shown are from **26.02.0** campaign
 - Beam setting: **10x130, high acceptance**

/volatile/eic/EPIC/RECO/26.02.0/RECO/epic_craterlake/EXCLUSIVE/DVCS_ABCONV/EpIC_v1.1.6-1.2/10x130/q2_1_100

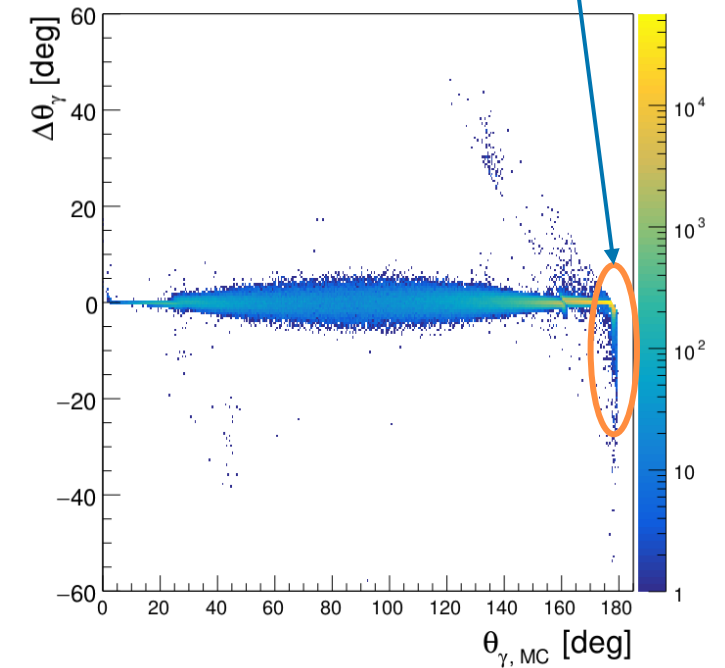
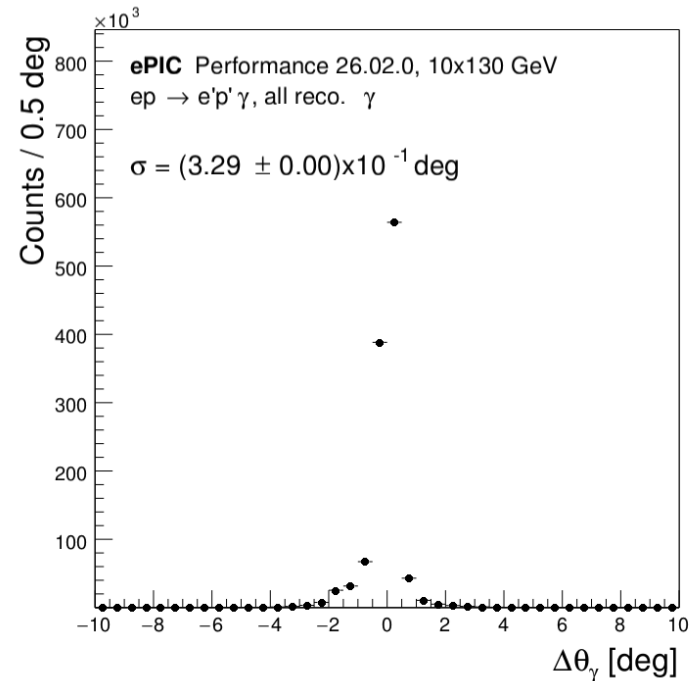
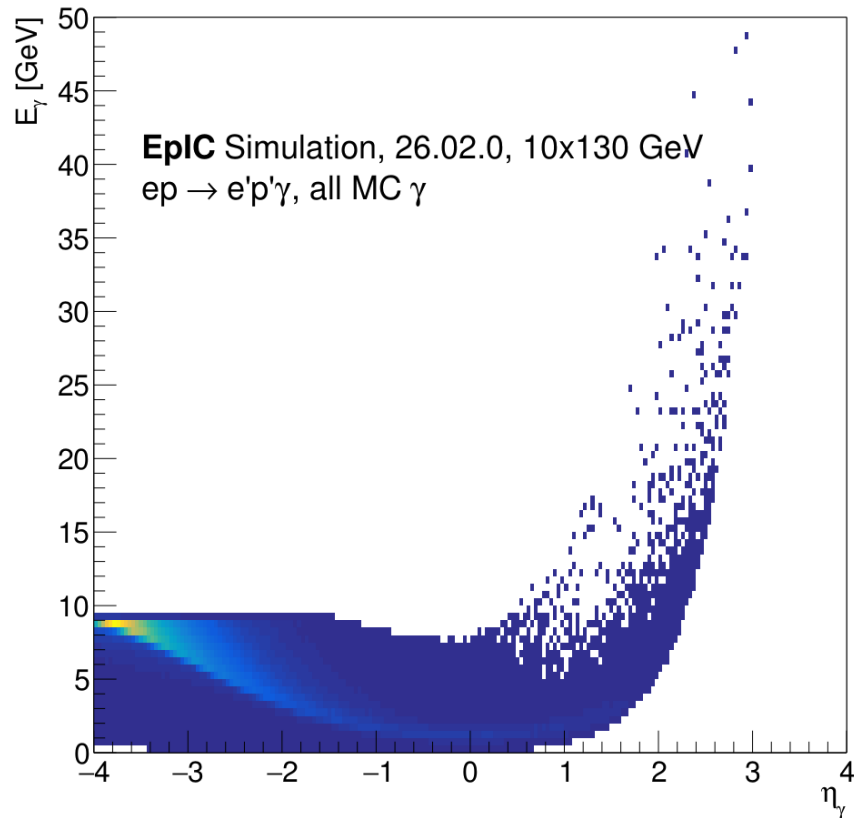
- Taken from ReconstructedParticles (pseudo-Electron Finder)
 - $Q = -1$
 - $0.8 < E/p < 1.2$



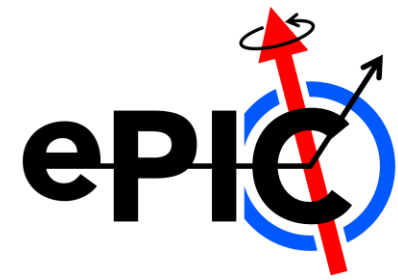
Analysis details – photons



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

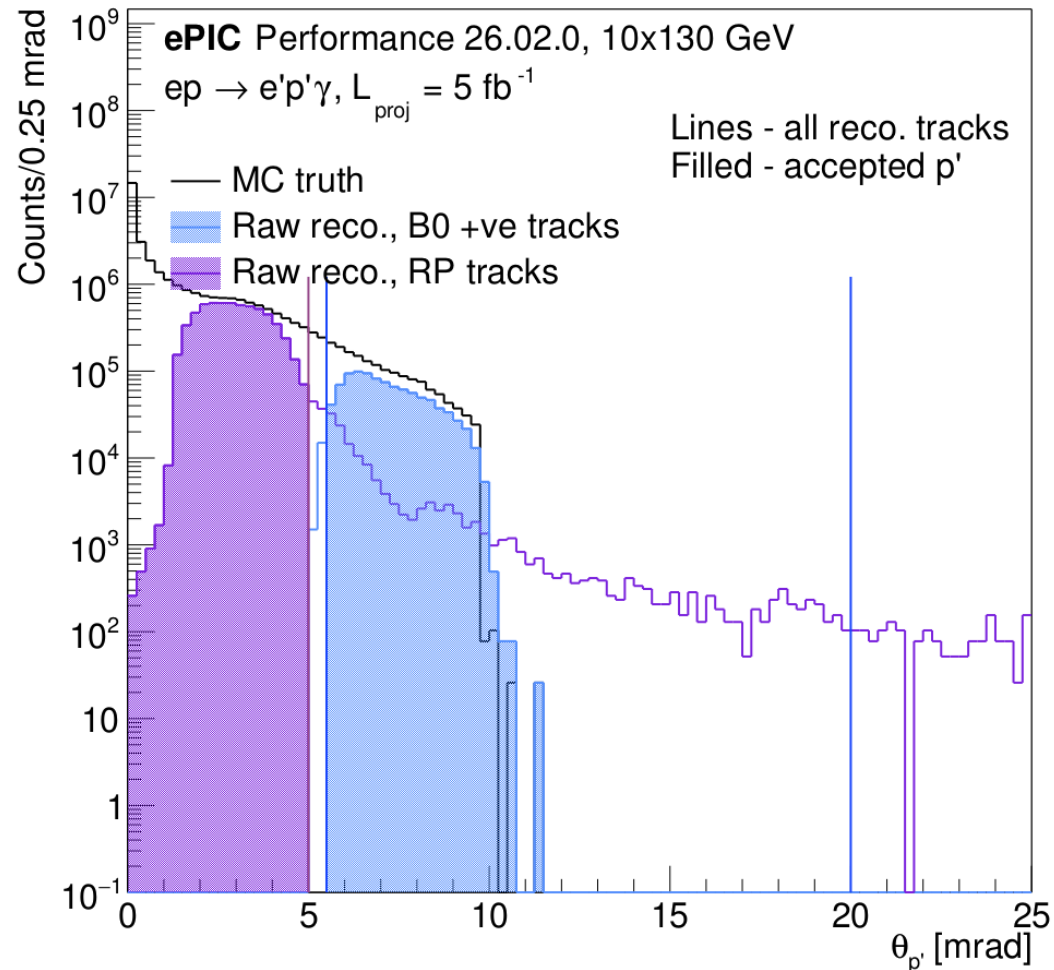
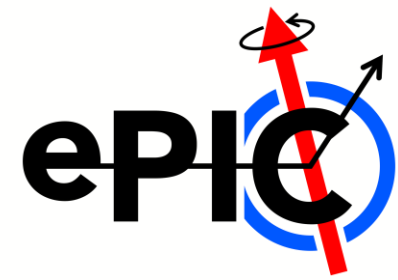


Analysis details – protons



- 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

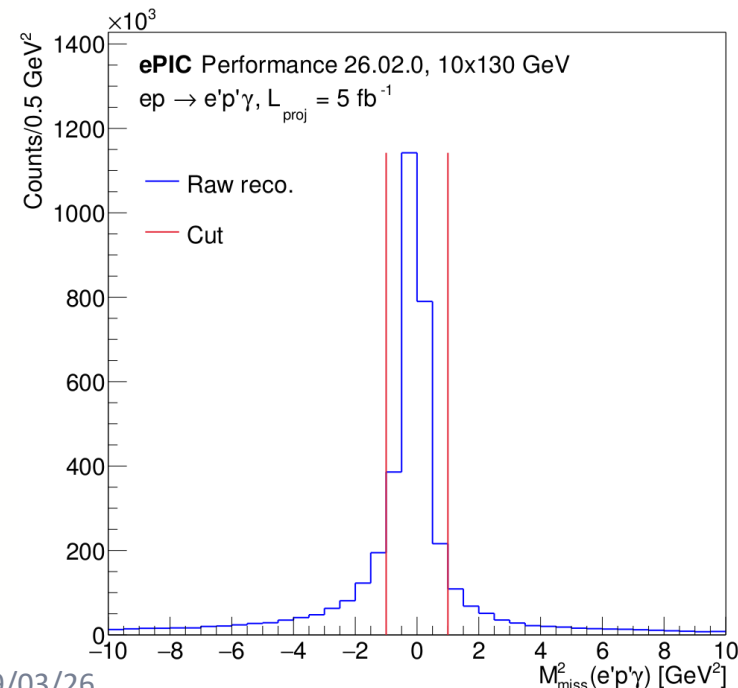
$$5.5 < \theta_{p'} < 20 \text{ mrad}$$

- For RP protons

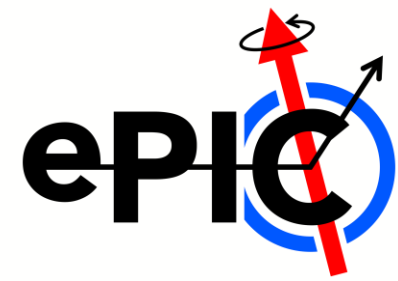
$$\theta_{p'} < 5 \text{ mrad}$$

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

- Single species cuts:
 - Electron: only 1 reconstructed and $Q^2 \geq 1 \text{ GeV}^2$
 - Photon: only 1 reconstructed
 - Proton: only 1 reconstructed and track theta appropriate for detector used.
- DVCS event cuts:
 - Full exclusivity ($e'p'\gamma$ reconstructed)
 - All single species cuts simultaneously.
 - $M_{miss}^2 \leq 1 \text{ GeV}^2$



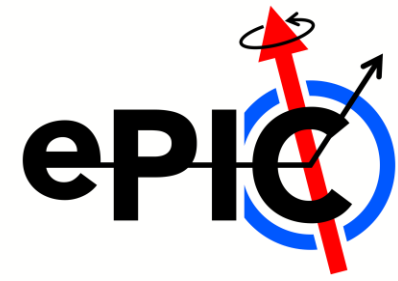
Effect of cuts ($N_{MC} \sim 1.3M$)



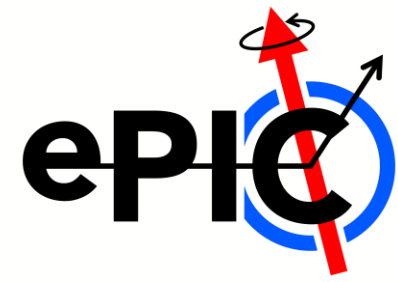
Cut	No. of events remaining	% of total	Cut	No. of events remaining	% of total
Single e' reco.	1.11×10^6	85.4%	All single species cuts	1.79×10^5	13.8%
...and $Q^2 > 1 \text{ GeV}^2$	1.10×10^6	84.3%	...and $M_{\text{miss}}^2 < 1 \text{ GeV}^2$	9.77×10^4	7.52%
Single γ reco.	1.16×10^6	89.1%			
Single p' reco.	2.90×10^5	22.3%	Only $e'\gamma$ reco.	9.91×10^5	77.2%
...and θ_p cuts	2.82×10^5	21.7%			

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

Detector acceptance correction



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

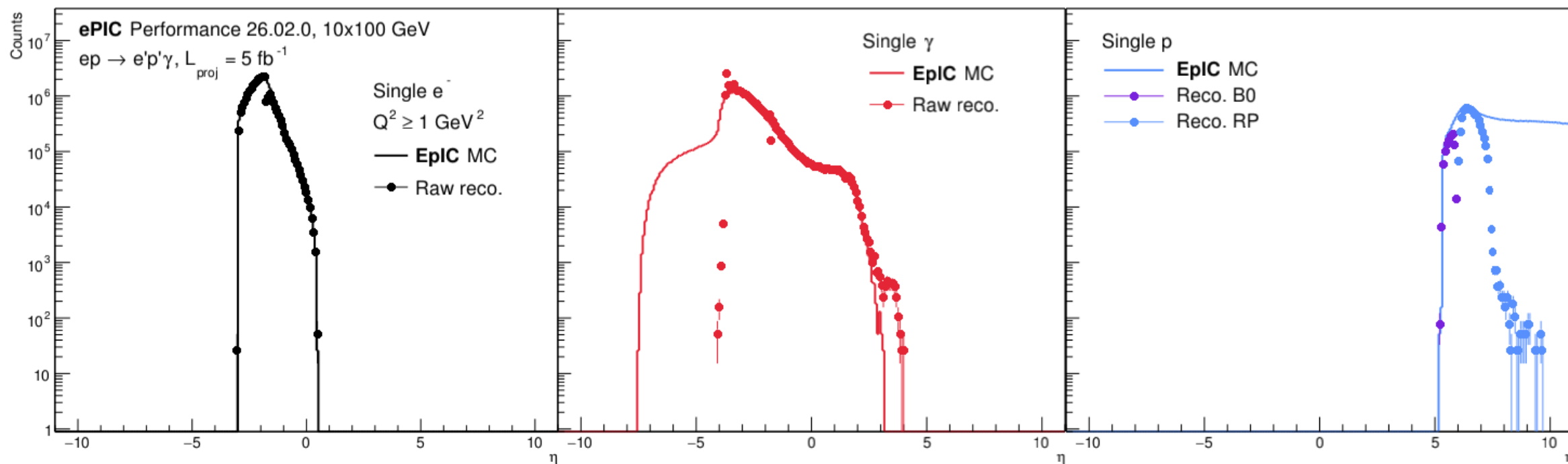


Plots

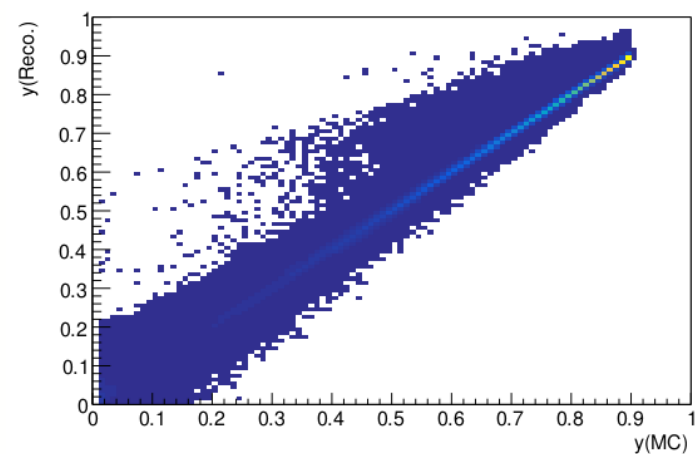
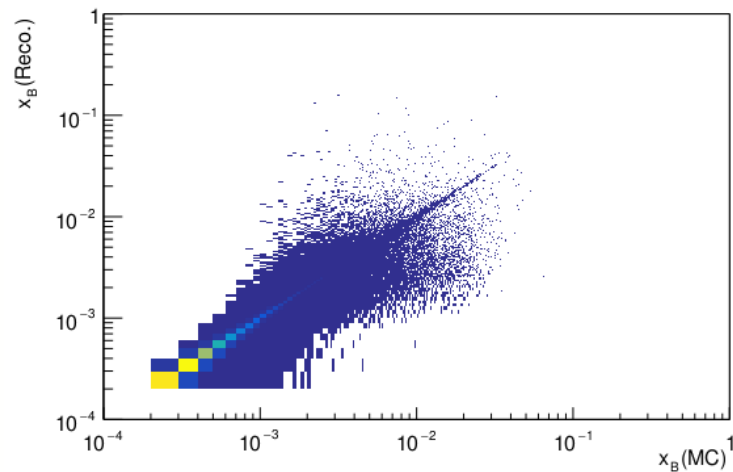
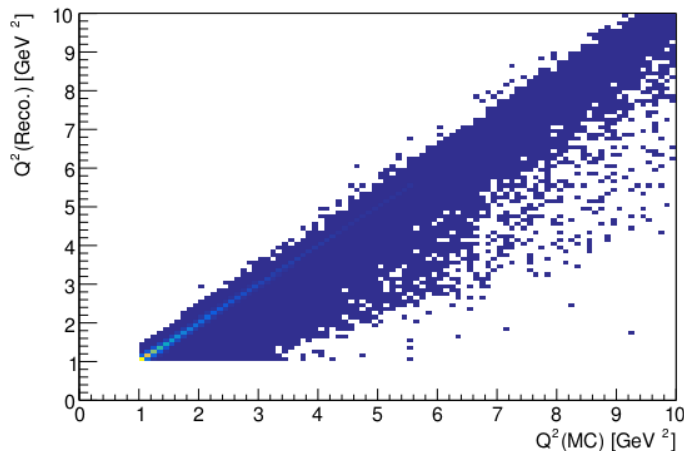
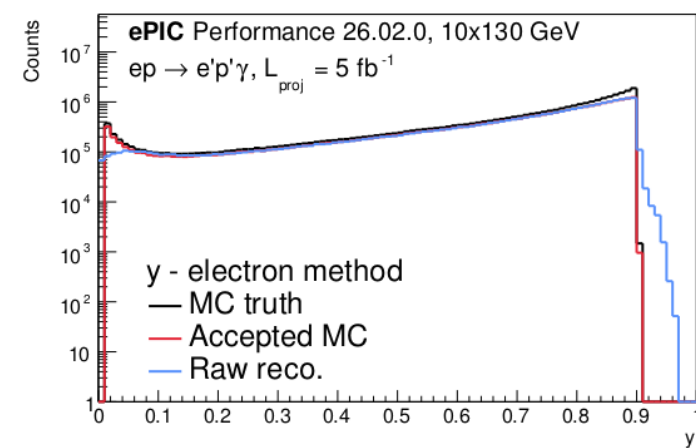
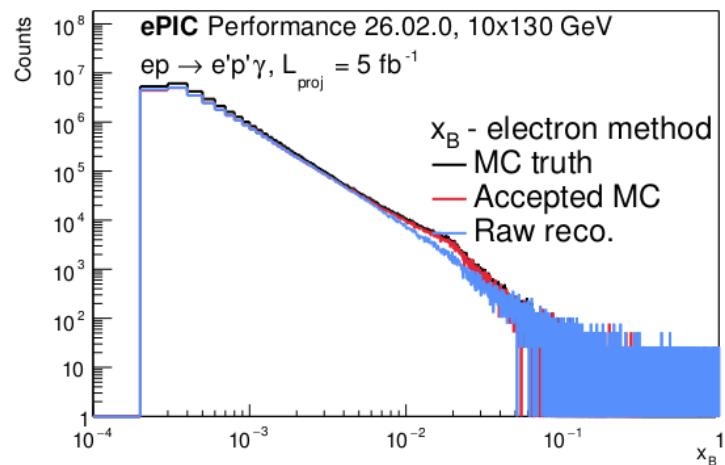
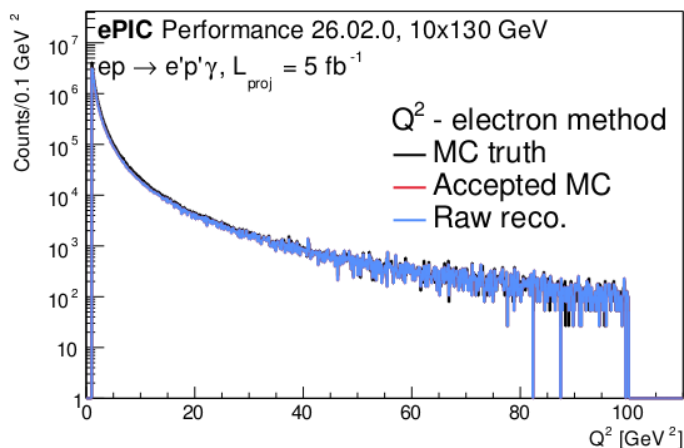
Plots are scaled to 5 fb^{-1}

Showing (Reco. – MC) for resolutions

Detector occupancy

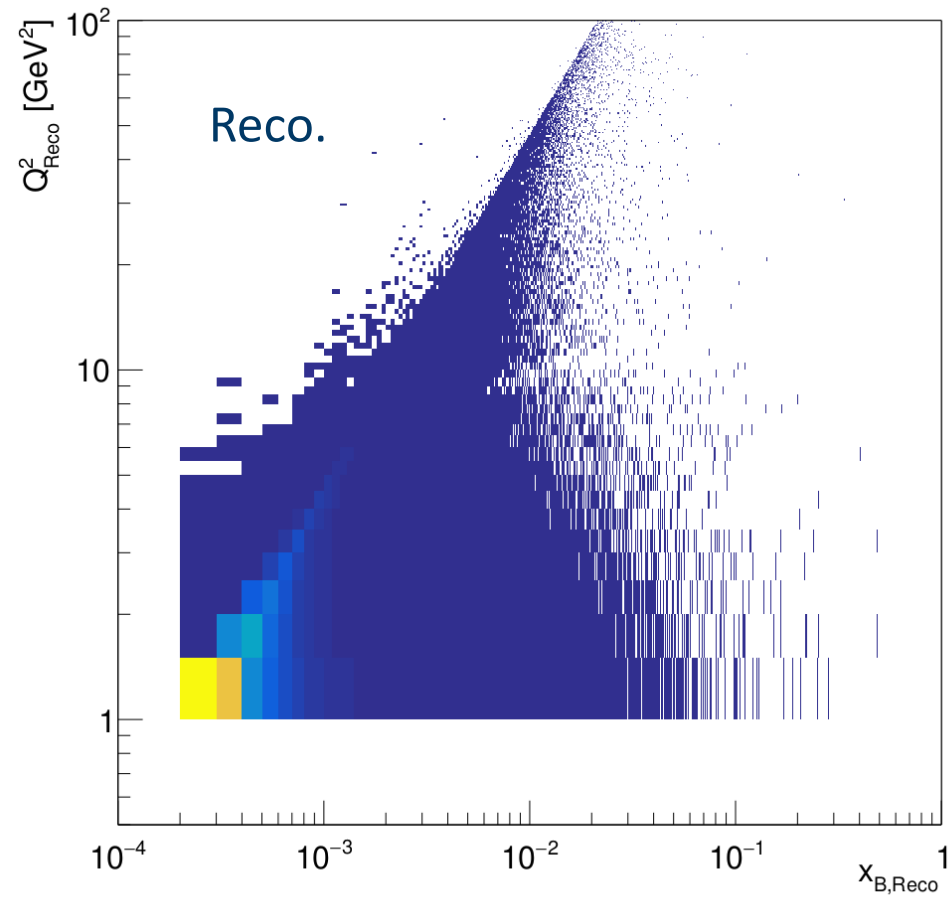
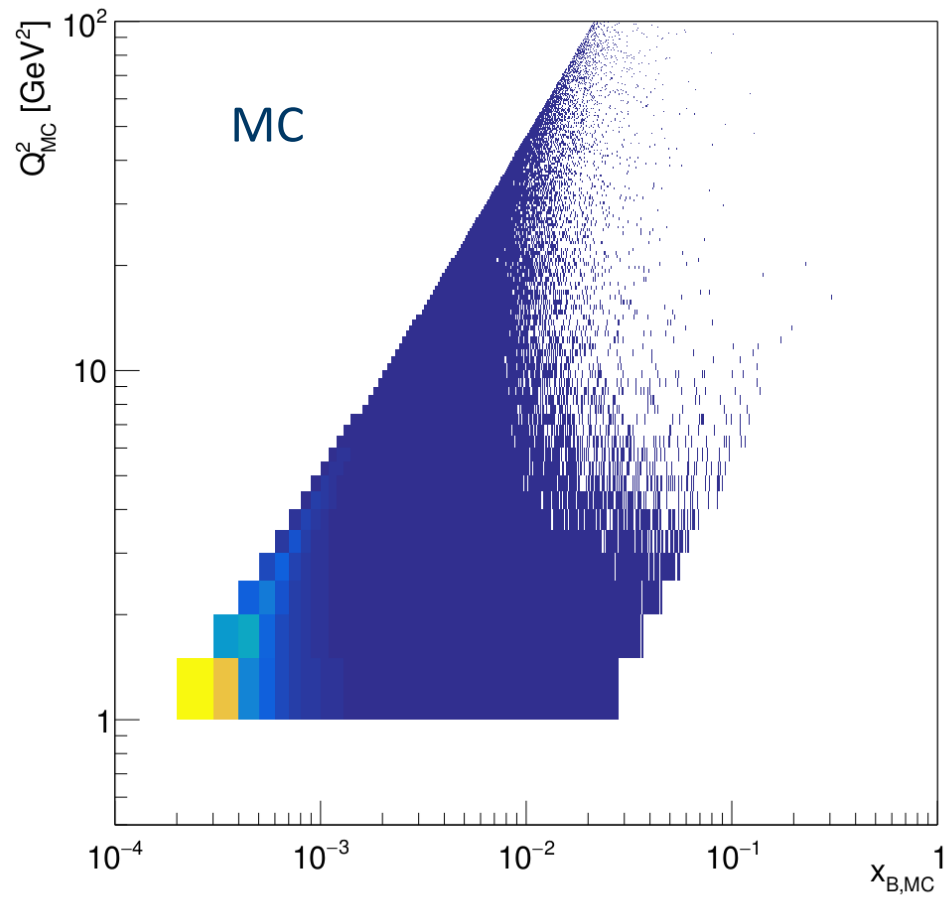


Inclusive kinematics

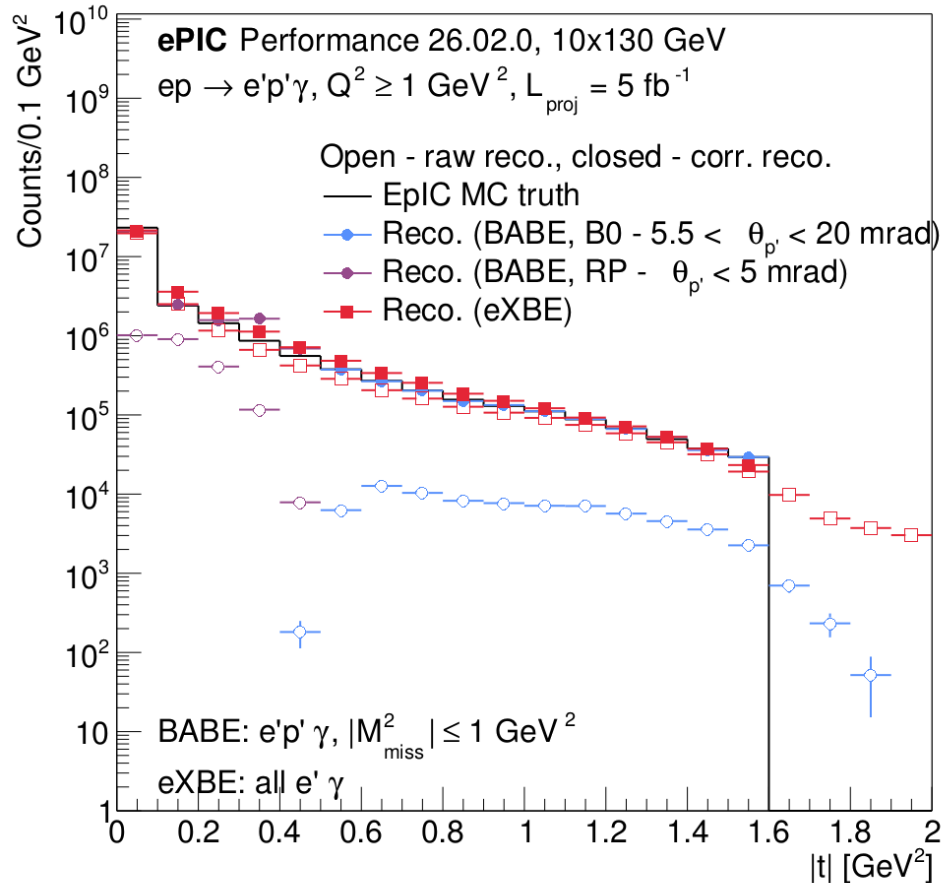
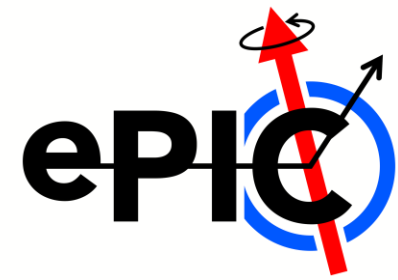




Inclusive kinematics



Mandelstam t distribution



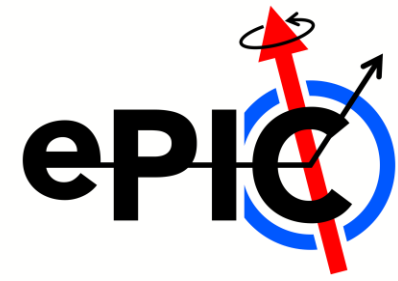
- Showing t -reconstruction from 3 sources:

- BABE from B0 protons
- BABE from RP protons
- eXBE from all $e'\gamma$ events

- Bin-by-bin choose t reconstruction method.

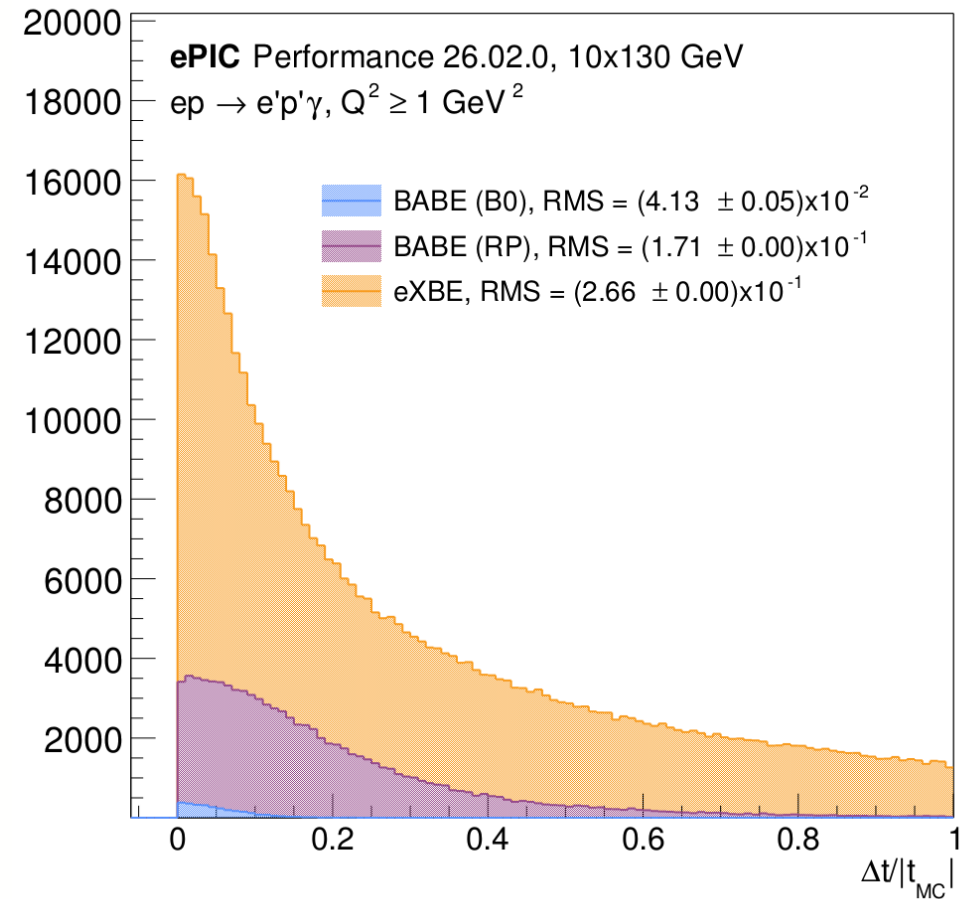
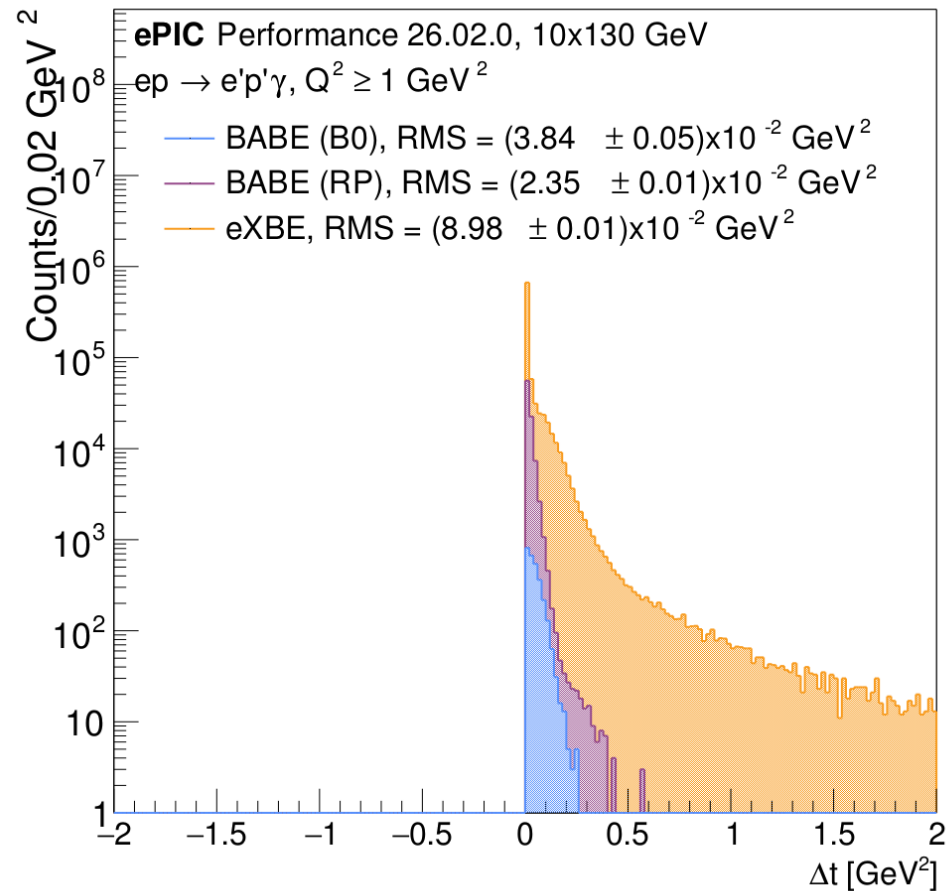
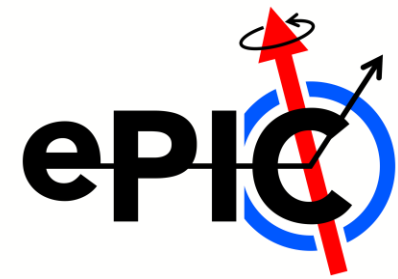
- Prioritises reconstruction using the scattered proton.
- Uses eXBE only if efficiency for BABE reco. is $< 5\%$.

Aside: why use scattered proton at all?

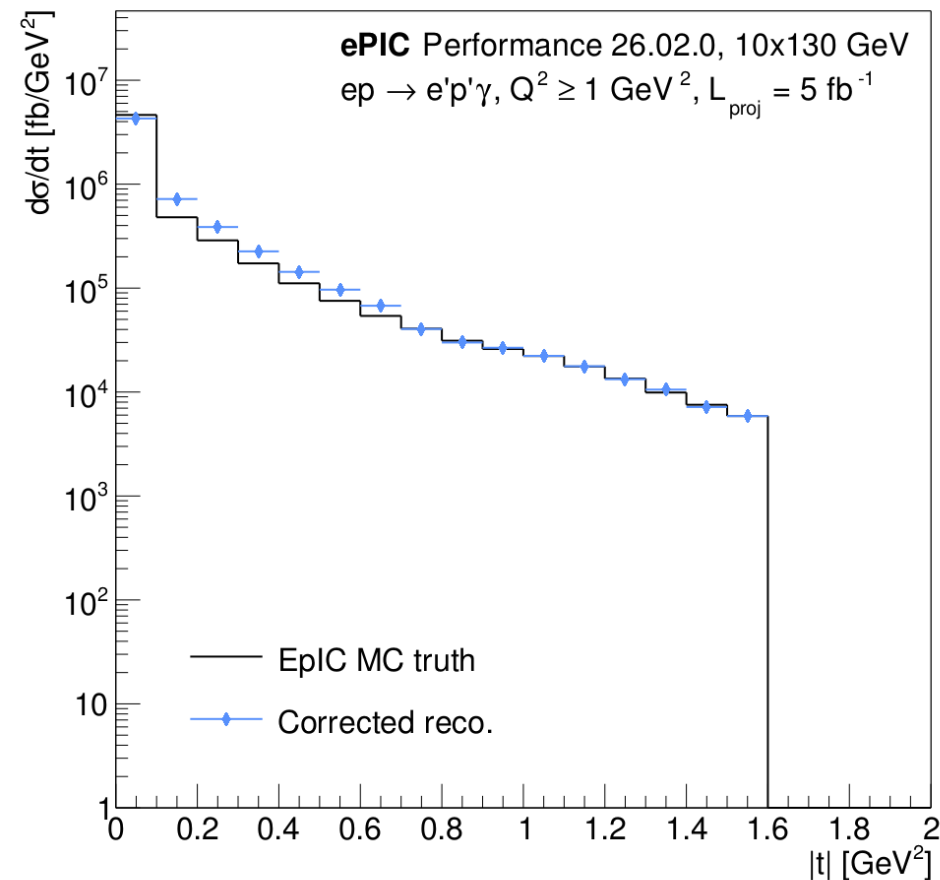
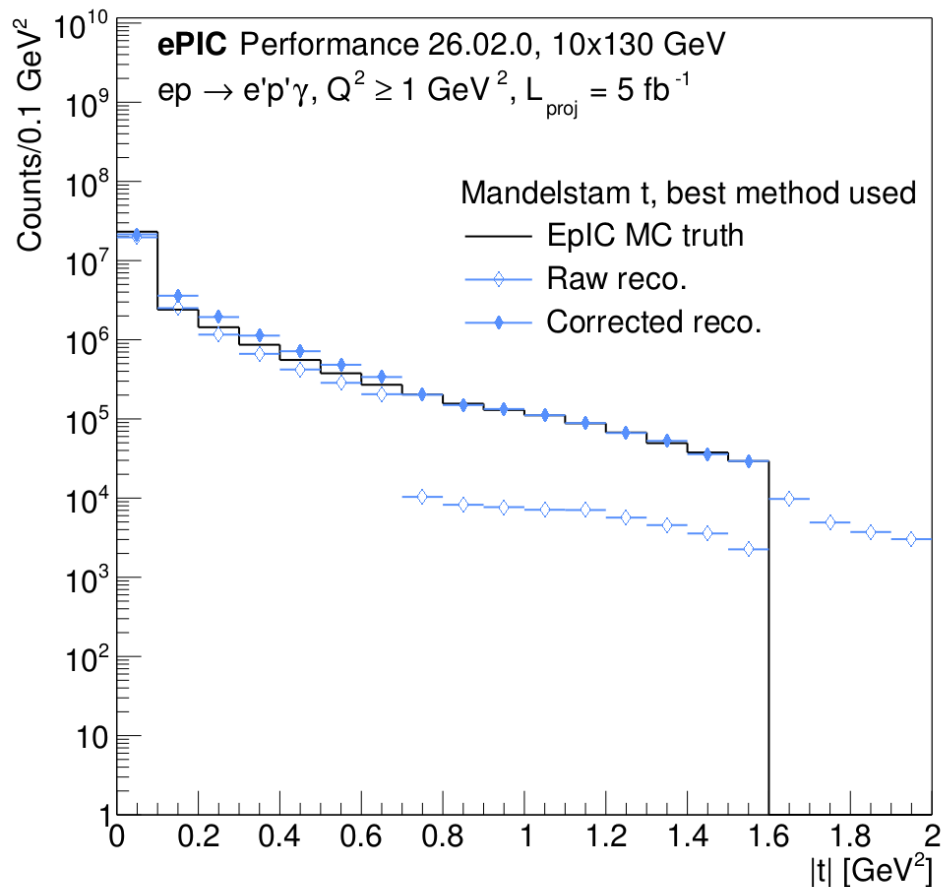


- Less than 10% of events pass all DVCS event cuts – so why bother caring?
 - Why not just use eXBE method? Looks like it agrees pretty well with the MC, right?
- Resolutions!
- The methods of t-reconstruction which involve the scattered proton have much better resolution than the eXBE method.

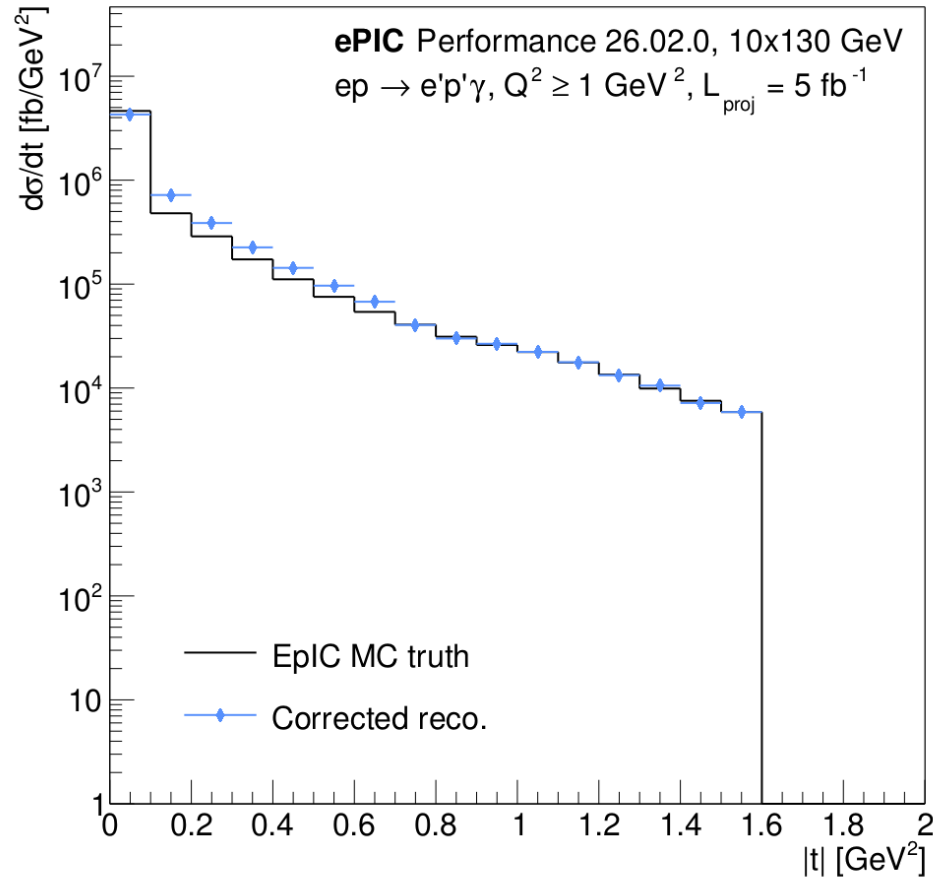
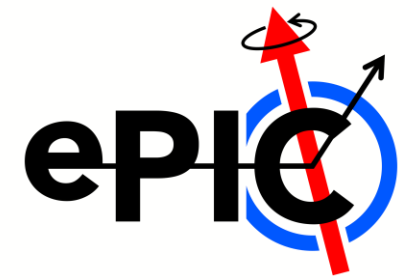
Aside: why use scattered proton at all?



Mandelstam t distribution



From σ to distributions

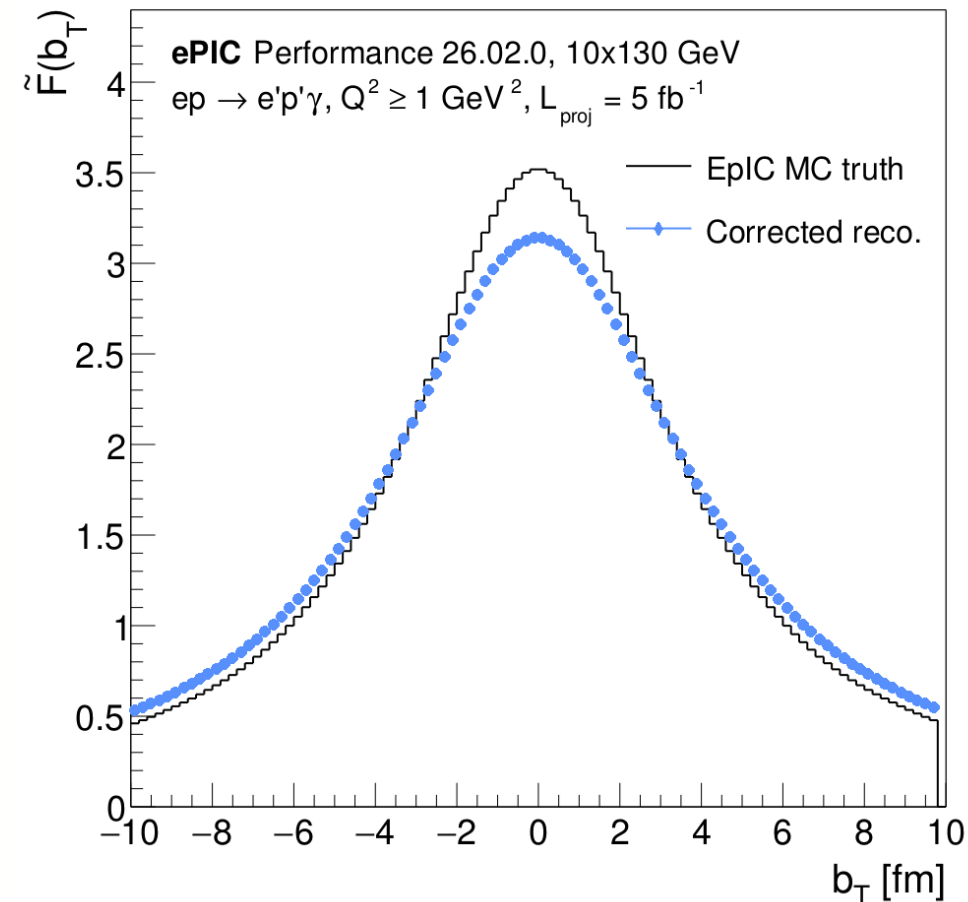
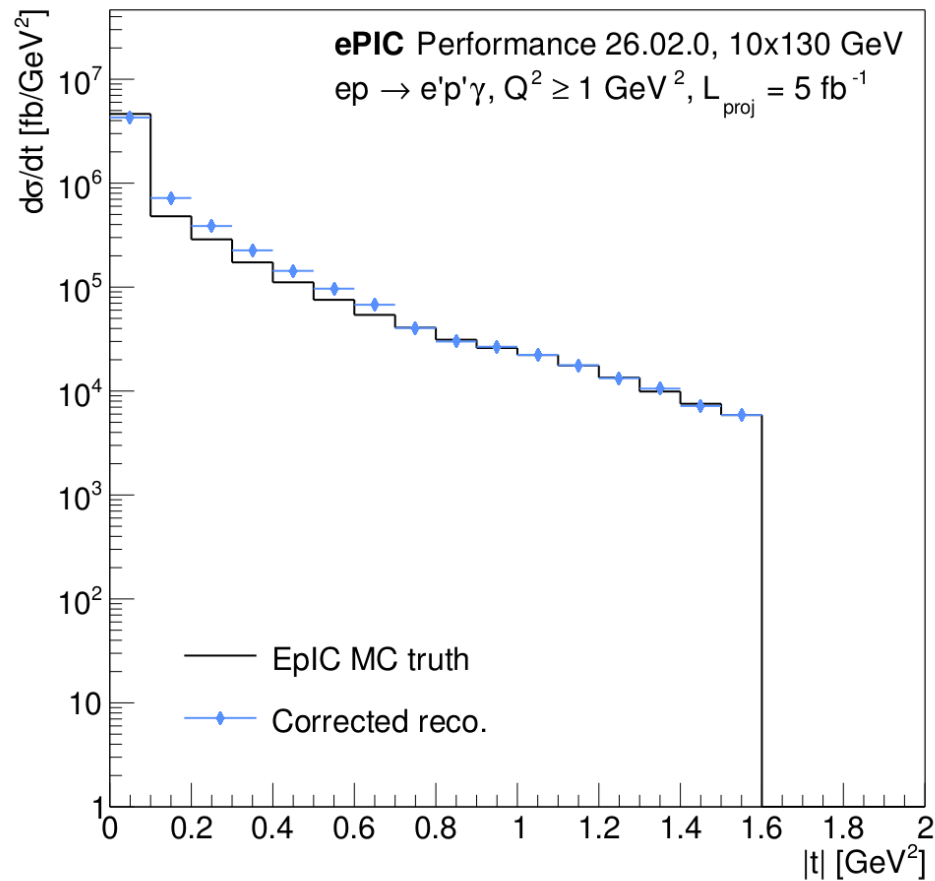


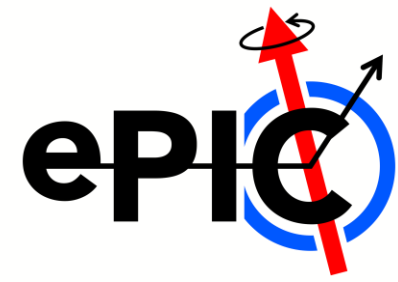
- Fit $d\sigma/dt$ with exponential(*)
 - Fit range: 0.1 – 1.6 GeV^2

- Calculate Fourier Transform of the fitted function
 - Functional form of FT and errors implemented by hand.

(*) Direct exponential decay does not best describe shape of t-distribution; was chosen for expediency.

From σ to distributions





DIS physics background

Very fresh plots.

Take with a pinch of salt...

DIS sample details



- For February simulation campaign, early science NC DIS samples have not been run.
- Using 26.02.0 Pythia8 10x100 sample for this study.
 - DVCS events have Q^2 range 1-100 GeV^2
 - Use 2 DIS files to cover this: $Q^2 > 1$ and $Q^2 > 10$
 - 1M events generated per setting
- Apply same cuts as for DVCS analysis

```
/volatile/eic/EPIC/RECO/26.02.0/RECO/epic_craterlake/DIS/NC/10x100/minQ2=[1,10]/...
```

Reduction from cuts



Min. $Q^2 = 1 \text{ GeV}^2$

Cut applied	No. of remaining events	% of total (w.r.t MC non-e'p'γ)
Single e'	959500	96.46%
Single γ	7999	0.80%
Single p'	577654	58.07%
Final state mult.	3510	0.35%
...and $Q^2 < 1$...	3503	0.35%
...and θ_p cut...	2105	0.21%
...and $MM^2 < 1$	592	0.06%

Min. $Q^2 = 10 \text{ GeV}^2$

Cut applied	No. of remaining events	% of total (w.r.t MC non-e'p'γ)
Single e'	944118	94.54%
Single γ	4084	0.41%
Single p'	555349	55.61%
Final state mult.	1632	0.16%
...and $Q^2 < 1$...	1632	0.16%
...and θ_p cut...	691	0.07%
...and $MM^2 < 1$	8	0.0008%

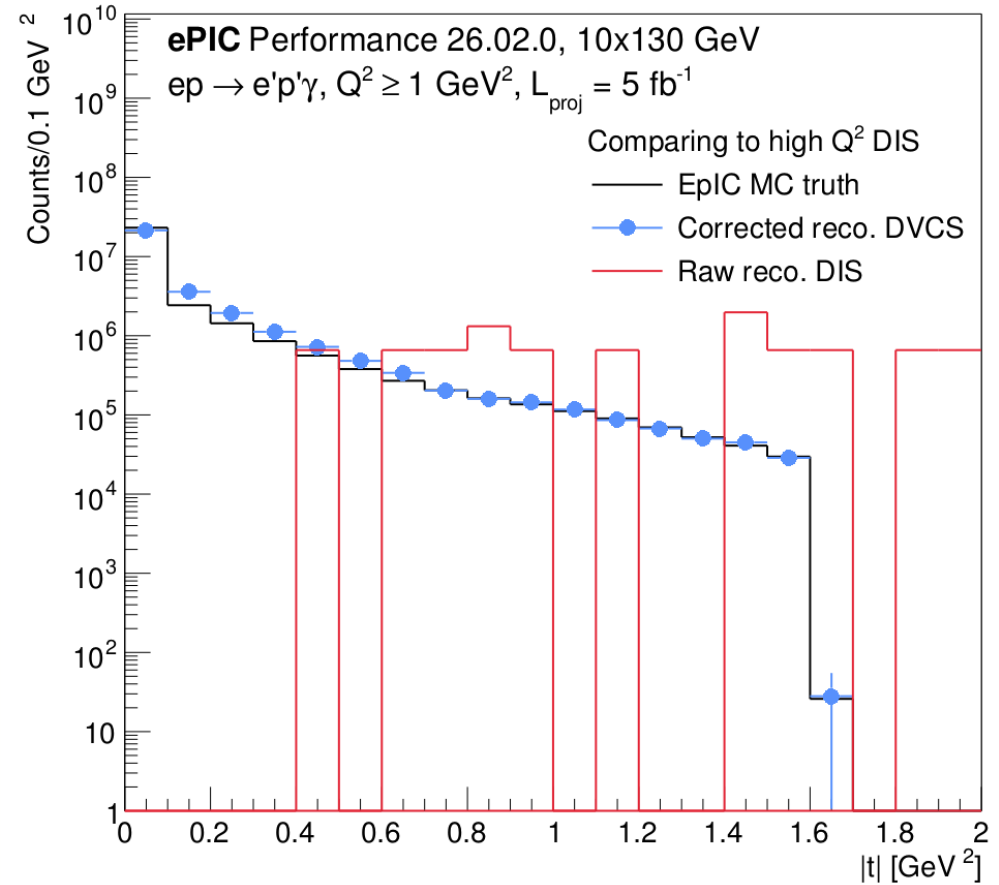
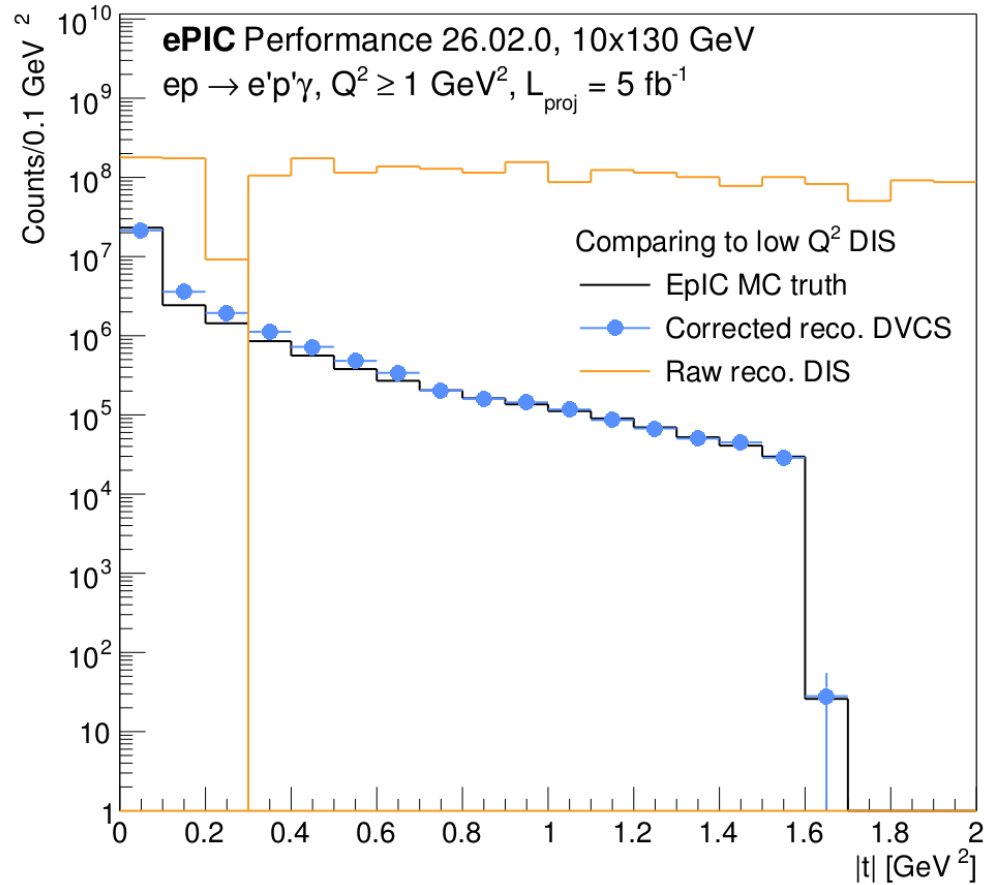


Counts/0.1 GeV²
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10
1



Counts/CS
[GeV²]

DIS backgrounds - t



DIS sample details

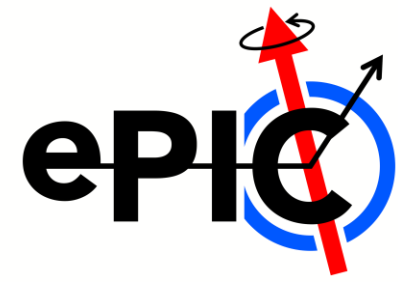


- Clearly some sort of issue shows up.
- DIS data represents much lower lower luminosity than DVCS sample.
 - Factor $\sim 200k$ for low- Q^2 data, $\sim 25k$ for high- Q^2 data
- Scaling to 5 fb^{-1} swamps DVCS!

- Need to look more into this.
 - Something in the analysis code?
 - Something in the generated events?
 - Due to use of non-matching energies?
 - High divergence/high acceptance?

Observation \rightarrow DVCS:DIS factors as shown in London were 600/30 for different DIS samples.

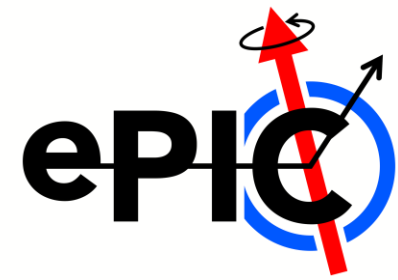
Why so much higher now?



Concluding remarks

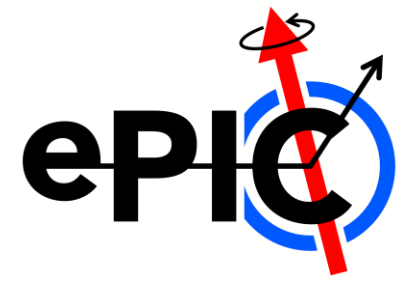


Future plans



- i. Simulated events have 2 helicity settings – can start to look at asymmetries.
 - Only available since Feb. campaign, so this hasn't been looked at much yet.
 - Prior focus has been on finalising plots from TDR/ESR.
- ii. Extracting physical quantities.
 - More accurate way of extracting gluon distributions.
 - CFF / GPD extraction.
- iii. Beam gas backgrounds
 - Have already started to look into these; use of extended timeframes causes issues with current DVCS identification algorithm.

Summary

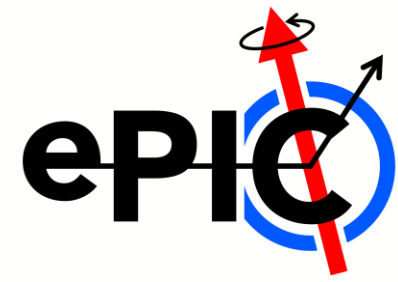


- i. DVCS is a very useful channel for ePIC to study.
 - Provides a good probe of detector resolutions and reconstruction efficiencies.
 - Have ended up acting as the ‘canary in the coal mine’ for a lot of issues with EICrecon.
- ii. Relatively mature analysis.
 - Pretty much ready for TDR/ESR plots as decided pre-Christmas.
 - Clearly more work to be done depending on decisions made following this meeting.





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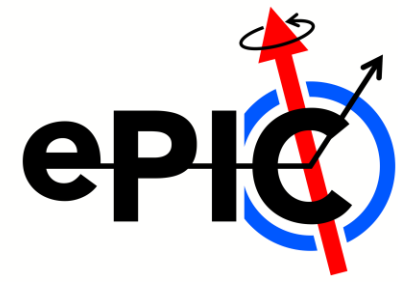


Thank you for listening!

Any questions?

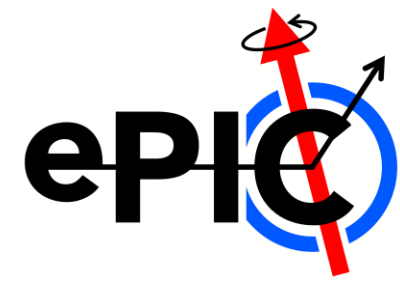


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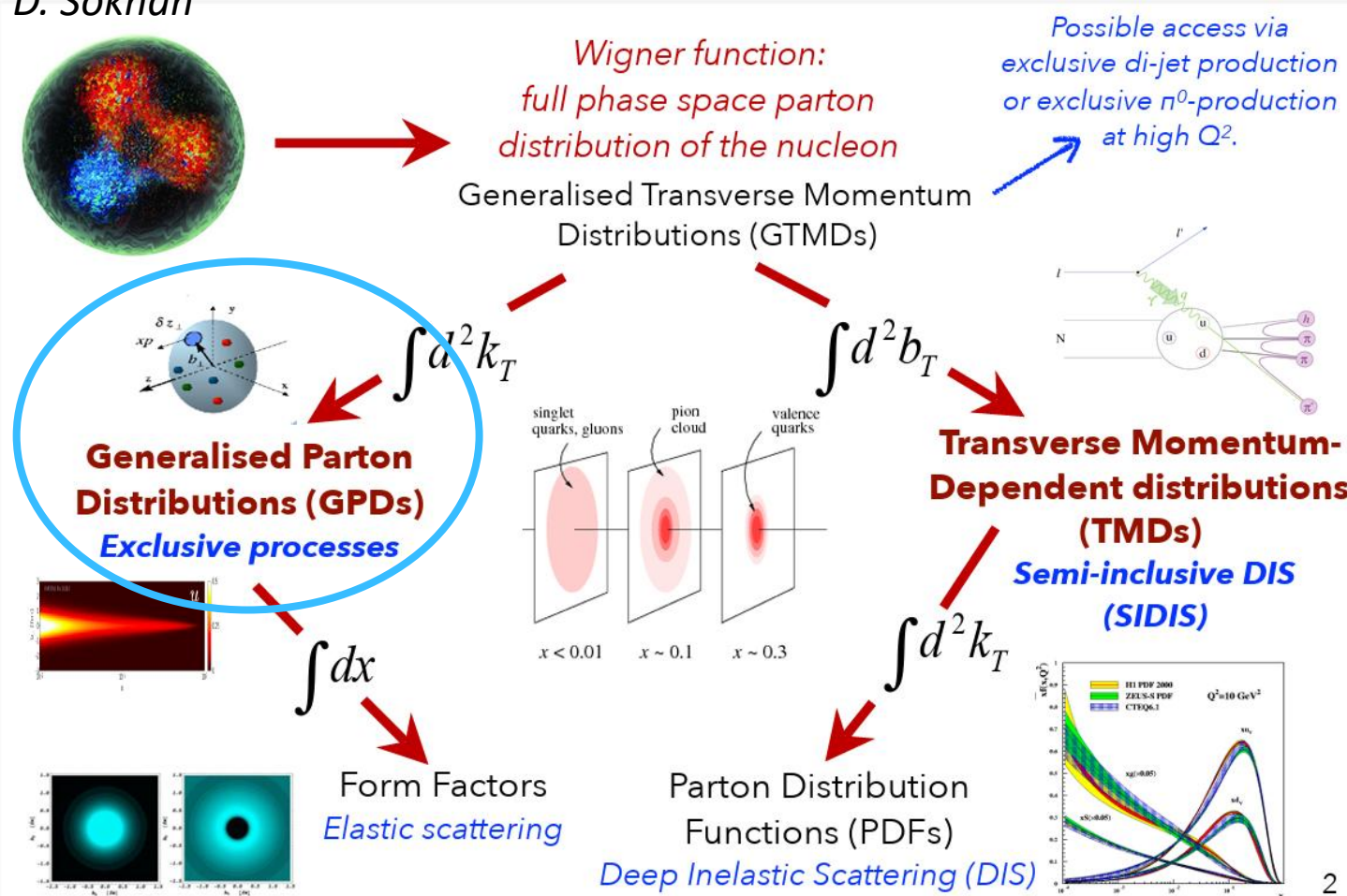


Backup

Nucleon structure

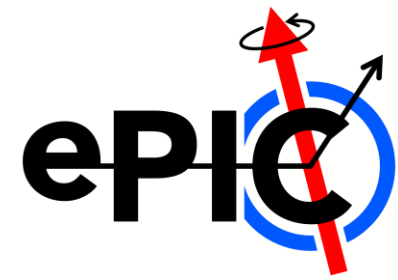


D. Sokhan

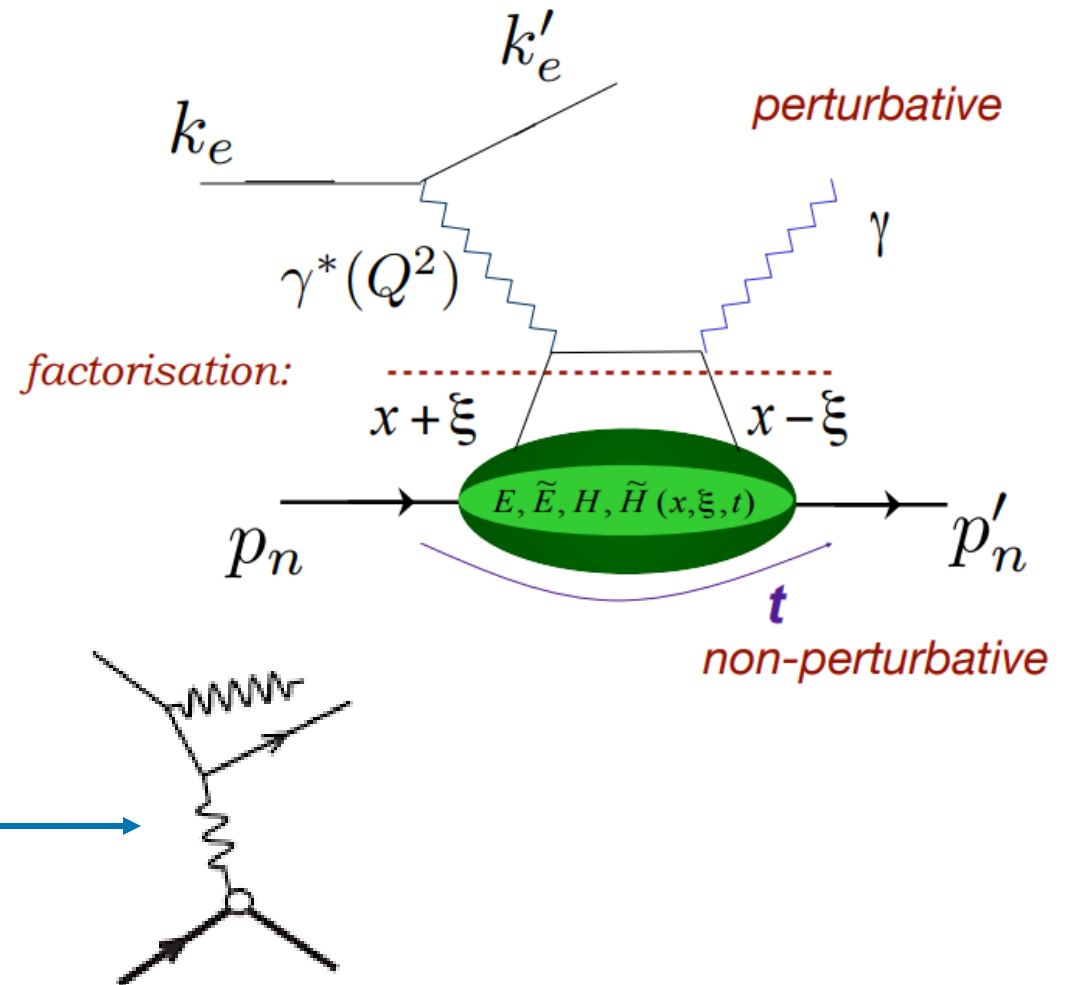


- Nucleon structure can be described within multiple dimensions by a large number of different functions.
 - GTMDs – full 5D phase space distributions.
 - PDFs – 1D as function of parton momentum.
 - Form factors – 1D as function of transverse distance from centre.
- GPDs relate the transverse position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

Deeply Virtual Compton Scattering

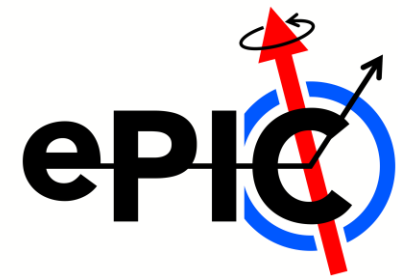


- Electroproduction of a single photon off a hadron target.
 - $ep \rightarrow e'p'\gamma$
 - Simplest inelastic channel the EIC can study.
 - Easiest channel for probing GPDs.
- The cross-section for this process is related to its matrix element, $|\mathcal{J}|^2$.
 - $|\mathcal{J}|^2 = |\mathcal{J}_{DVCS}|^2 + |\mathcal{J}_{BH}|^2 + \mathcal{I}$
 - \mathcal{I} is an interference term.
 - Bethe-Heitler: purely EM process, which does not probe partonic content.





Deeply Virtual Compton Scattering



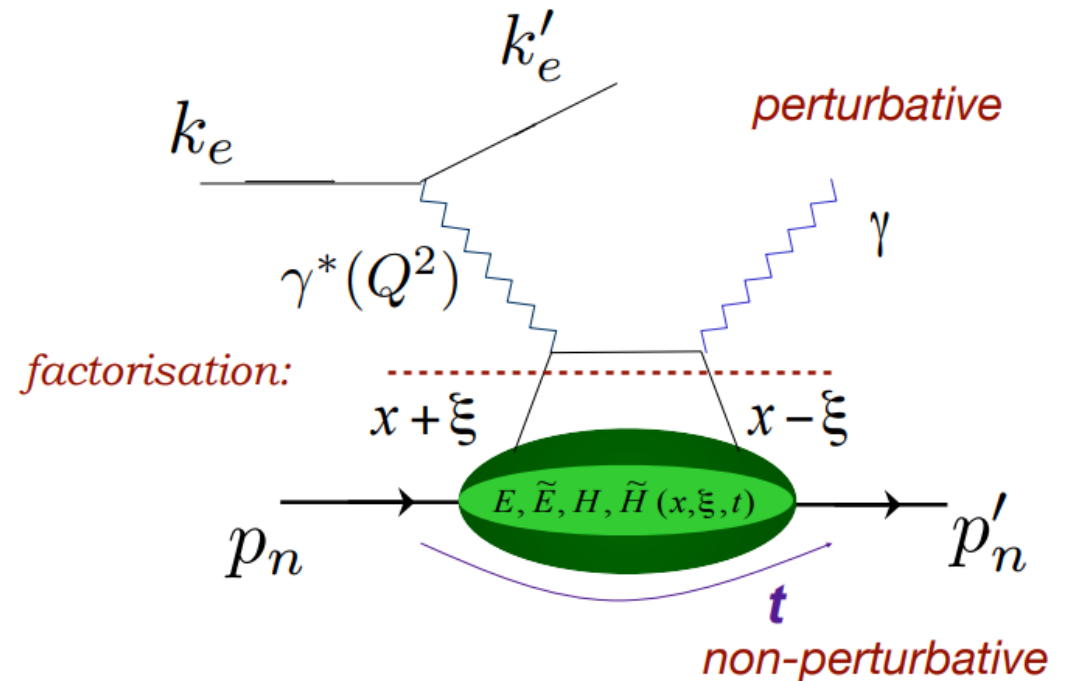
- Default kinematics:
 - $e(k) + p(p) \rightarrow e'(k') + p'(p') + \gamma$

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

$$y = \frac{q \cdot p}{k \cdot p} \quad \xi = \frac{x}{2 - x} \approx \frac{x}{2}$$

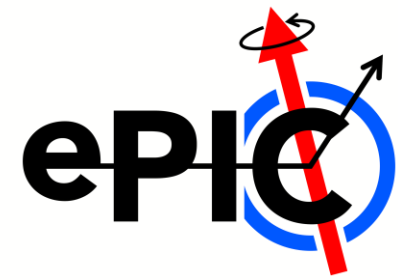
$$t = (p - p')^2$$

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

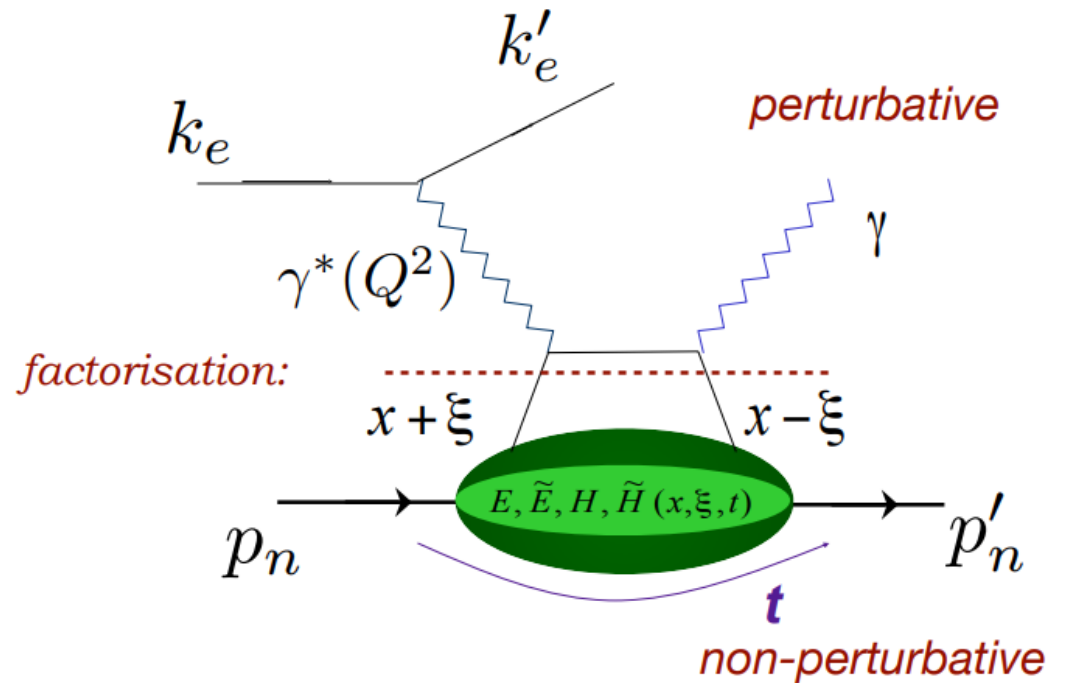




Deeply Virtual Compton Scattering

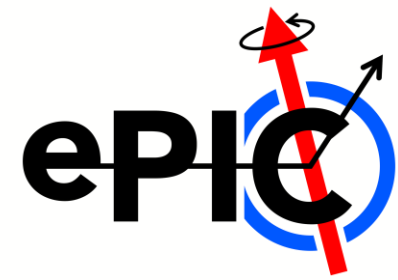


- DVCS amplitude can be parameterized in terms of Compton Form Factors (CFFs).
 - Experimentally accessible!
 - Access 4 quark GPDs: $H_q, \tilde{H}_q, E_q, \tilde{E}_q$.
 - Note: does not access GPDs directly, but linear combinations of GPDs.
- $Re \mathcal{F}_q(\xi, t) \propto \int_0^1 [F_q(x, \xi,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

- $p_{p'}^+ = E_{p'} + p_{z,p'}$

- $p_{T,p'}^2 = p_{x,p'}^2 + p_{y,p'}^2$

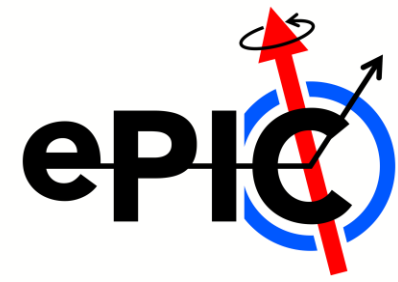
- $p_{p'}^- = (M_{p'}^2 + p_{T,p'}^2) / p_{p'}^+$

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

- $p_{p'}^{corr} = \left[p_{x,p'}, p_{y,p'}, \frac{(p_{p'}^+ - p_{p'}^-)}{2}, \frac{(p_{p'}^+ + p_{p'}^-)}{2} \right]$



Why DVCS @ ePIC?

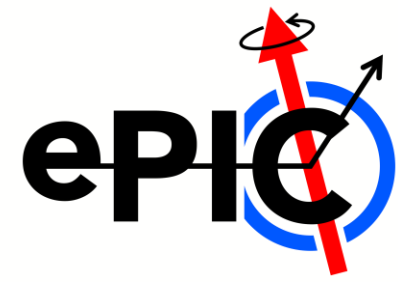


- Amongst the EIC's physics goals are:
 - Probing the 3D structure of nucleons.
 - Solving the mystery of proton spin.
- For an unpolarised target, the distribution of unpolarised quarks is the Fourier transform of the GPD H_q .

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



Why DVCS @ ePIC?

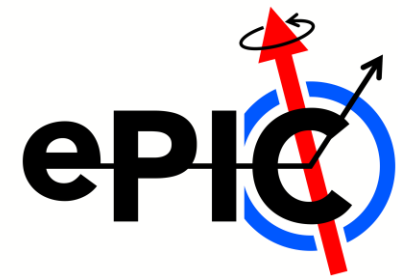


- Amongst the EIC's physics goals are:
 - Probing the 3D structure of nucleons.
 - Solving the mystery of proton spin.

- 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.