Deeply Virtual Compton Scattering – 3D binning and asymmetries

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Exclusive, Diffractive and Tagging PWG meeting
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CELEBRATING 200 YEARS 1824 2024 WILLIAM THOMSON, LORD KELVIN INNOVATION INVENTION INSPIRATION

This presentation

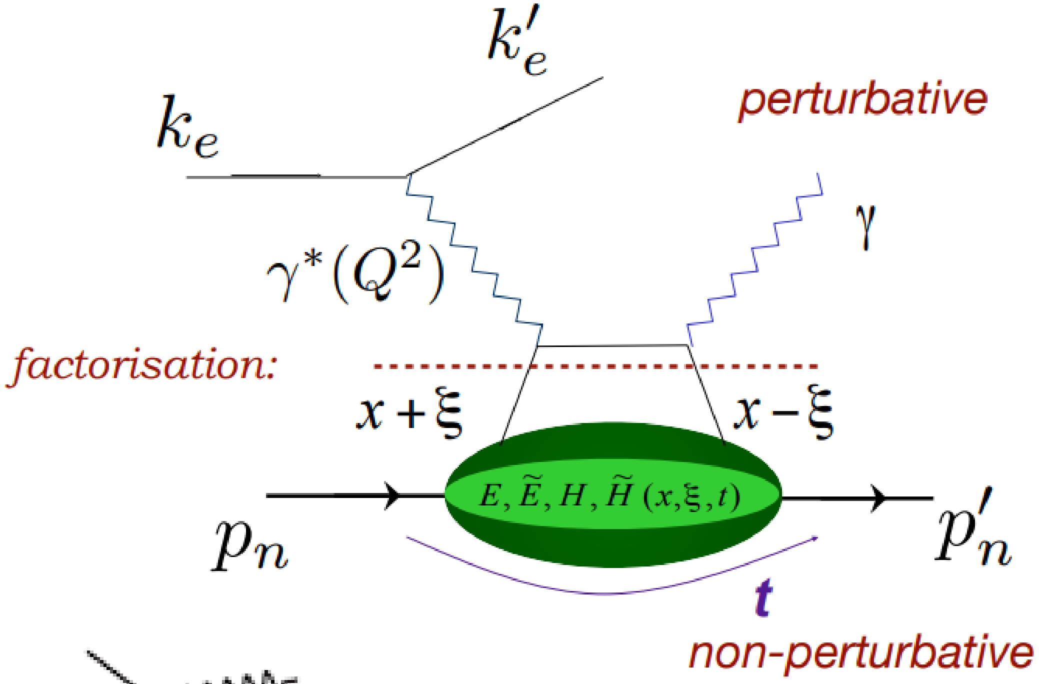
- Overview of DVCS simulation studies
- Asymmetries in exclusive analyses.

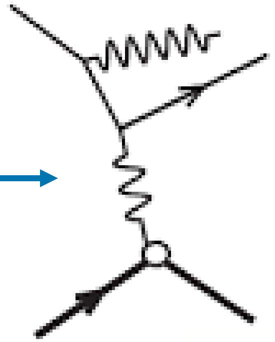
Deeply Virtual Compton Scattering

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.





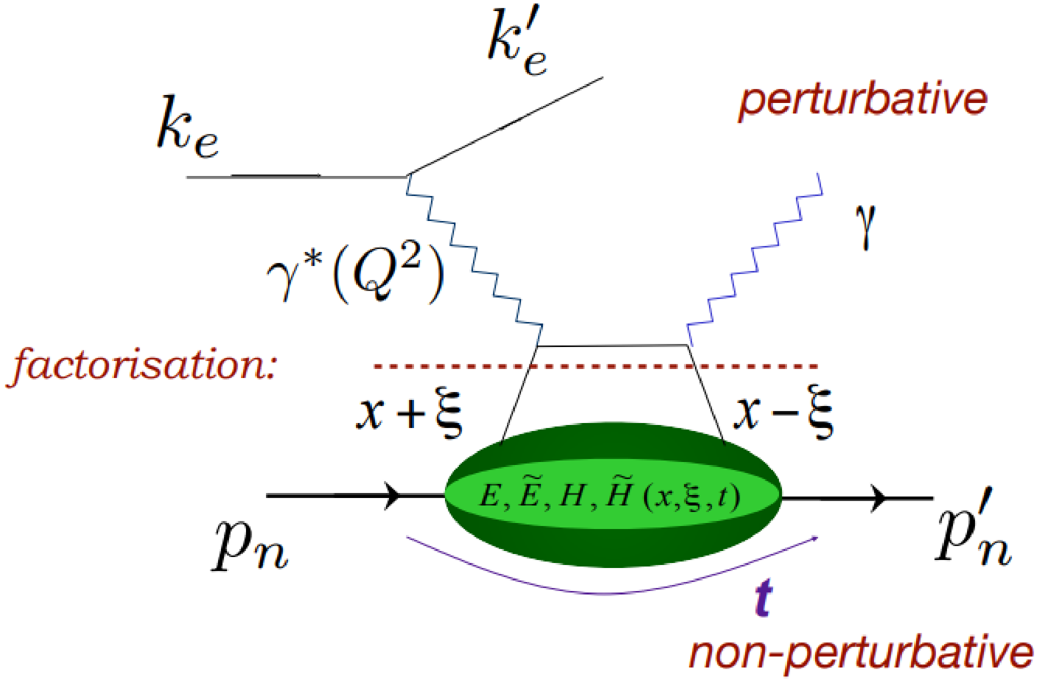
Deeply Virtual Compton Scattering

- 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).

DVCS simulations

Simulation details

- Using EpIC generator (web link here – most recent version 1.1.8).
  - 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).
- Can simulate polarised initial state particles.
  - NB: **does not consider partial polarisation** (±1 or 0 only).

Simulation details

- Event samples used (current sim. campaign datasets – GitHub):
  - 1M (5x41, 10x250, 18x275)/1.3M (10x100, 10x130) events
  - Full DVCS+BH+int.
  - $1 < Q^2 < 100$ GeV^2
  - $0.01 < y < 0.9$
  - $10^{-5} < x_B < 0.7$
  - Unpolarised proton beam, fully polarised electron beam (hel.+ and hel. - files generated)

Simulation details

- Generated events represent $\mathcal{L}_{int} \sim 0.1 - 0.2 fb^{-1}$ ep collisions (dependent on beam energy).

- Events are passed through the full EIC simulation pipeline.
  - Afterburner (to add beam smearing and crossing angle).
  - npsim
  - EICrecon

Analysis details

Analysis code on GitHub.

Analysis details

- Truth level particles in `MCParticlesHeadOnFrameNoBeamFX` branch.
  - Truth level with PID – afterburner removed in `EICrecon`.

- Reconstructed electrons and photons in `ReconstructedParticles` branch.
  - ePIC PID not accurate – using track charge and E/p cut (calo. E/track p cut) instead.

Analysis details

- Reconstructed protons in the B0 detector taken from `ReconstructedTruthSeededChargedParticles` branch.
  - PID based on track charge.
  - Corresponding `Associatons` branch used for 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

See DVCS presentation from Physics Readiness Workshop in Calabria for more details.

Asymmetries

Using 10x130 for plots

Asymmetries

- Final cross-sections are combinations of all processes measured (DVCS, Bethe-Heitler and interference).
- So how do we extract GPDs?
  - DVCS and interference processes depend on GPDs, but BH is a function of form factors.

- Asymmetries!

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Asymmetries

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- Asymmetries!
  - Based on different polarisation states.
  - Available polarisations dictate available asymmetries → different GPDs to extract.

$$A \propto \mathcal{Im}(DVCS.BH)$$

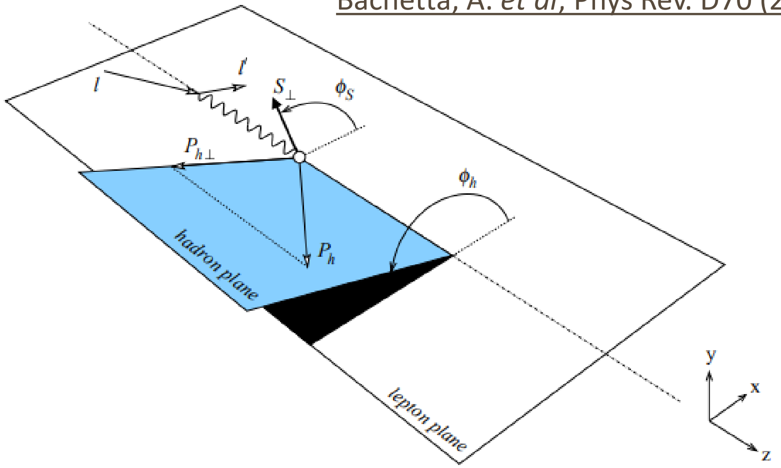
Trento phi - ϕ/ϕ_h

- Asymmetries are plotted as a function of ϕ (sometimes called "Trento phi").
  - This is **not** the azimuthal angle of a track!
  - The angle between the leptonic and hadronic planes in a decay.

- Leptonic plane – defined by beam electron and virtual photon.
- Hadronic plane – defined by virtual photon and produced final state particle (DVCS – γ, DVMP – π^0, etc.)

- BE CAREFUL OF FRAME.

Bachetta, A. *et al*; Phys Rev. D70 (2004)



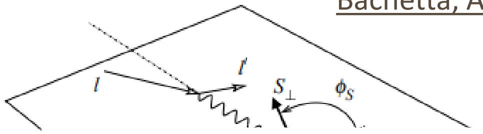
Trento phi - ϕ/ϕ_h

- For DVCS $(e(k) + p(p) \rightarrow e'(k') + p'(p') + \gamma(g))$

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

- <u>Defined in the $(\gamma^* p)$ rest frame</u>
  - Paper claims "target rest frame (or any frame reached…by a boost along $\hat{\boldsymbol{q}}$)"
  - **This is misleading.**

Bachetta, A. *et al*; Phys Rev. D70 (2004)



Convention on range for ϕ will depend on experiment.
Jlab – [0, 2π] (**used here**)
COMPASS – [-π, π]

Back to asymmetries

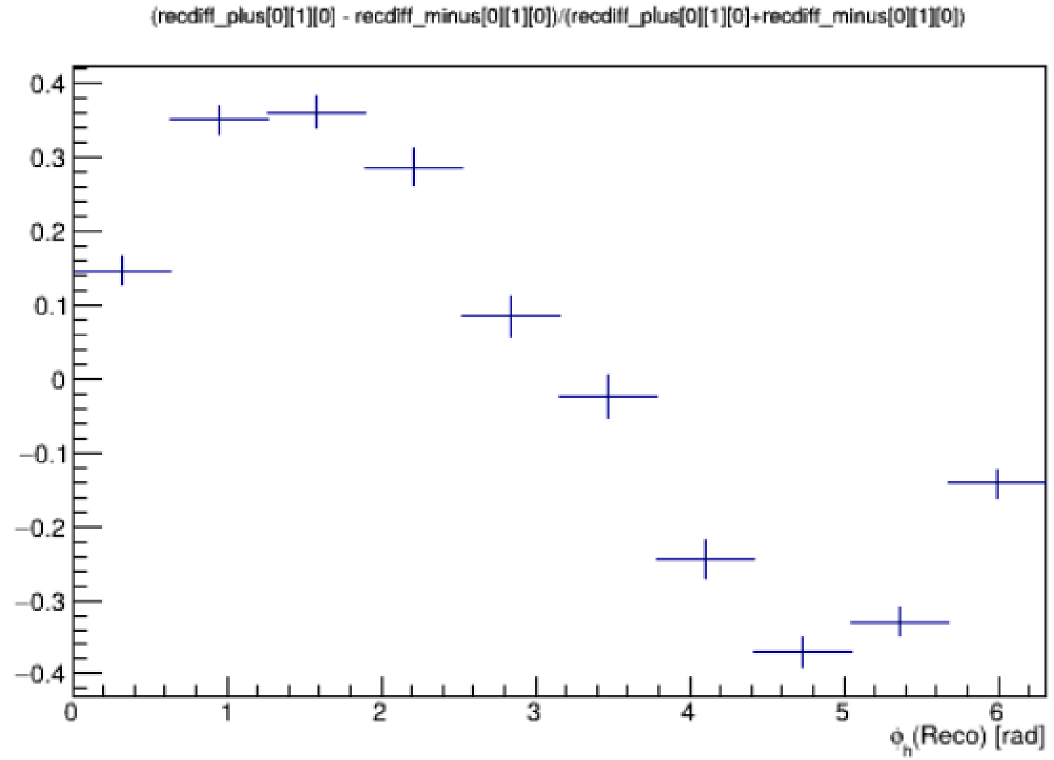
- Most common: Beam Spin Asymmetry (A_{LU})
  - Normally stated with unpolarised target and polarised electron beam

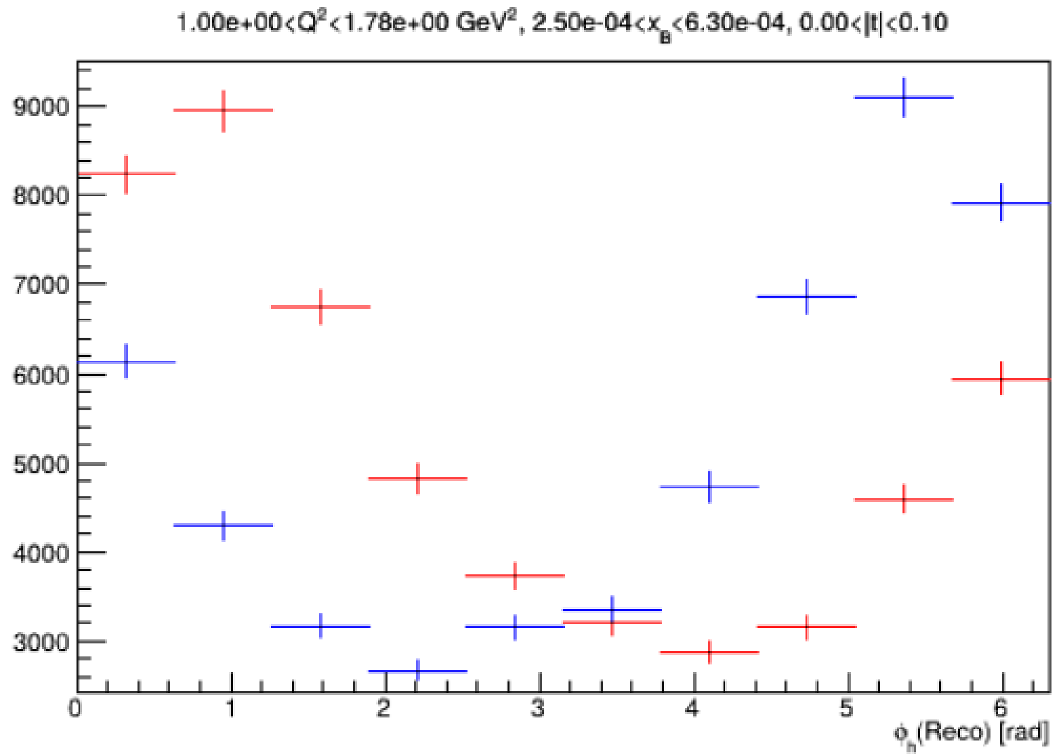
$$A_{LU}(\phi) = \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}$$

- For simulations without polarised hadron beams, this is okay.
  - It will not hold for actual EIC running – need to sum over polarisation states of the beam being ignored.

$$\boldsymbol{A_{LU}(\phi) = \frac{\left(N^{\uparrow+} + N^{\uparrow-}\right) - \left(N^{\downarrow+} + N^{\downarrow-}\right)}{\left(N^{\uparrow+} + N^{\uparrow-}\right) + \left(N^{\downarrow+} + N^{\downarrow-}\right)}}$$

A_{LU} example





Uses RAW reconstructed distributions – detector corrections introduce errors.

Other possibilities

- Target Spin Asymmetry (TSA) – A_{UL}
  - Unpolarised electrons on longitudinally-polarised target.

$$A_{LU}(\phi) = \frac{(N^{\uparrow +} + N^{\downarrow +}) - (N^{\uparrow -} + N^{\downarrow -})}{N^{\uparrow +} + N^{\uparrow -} + N^{\downarrow +} + N^{\downarrow -}}$$

- Double asymmetries – A_{LL}
  - Both beams have polarised states.

$$A_{LL}(\phi) = \frac{(N^{\uparrow +} + N^{\downarrow -}) - (N^{\uparrow -} + N^{\downarrow +})}{N^{\uparrow +} + N^{\uparrow -} + N^{\downarrow +} + N^{\downarrow -}}$$

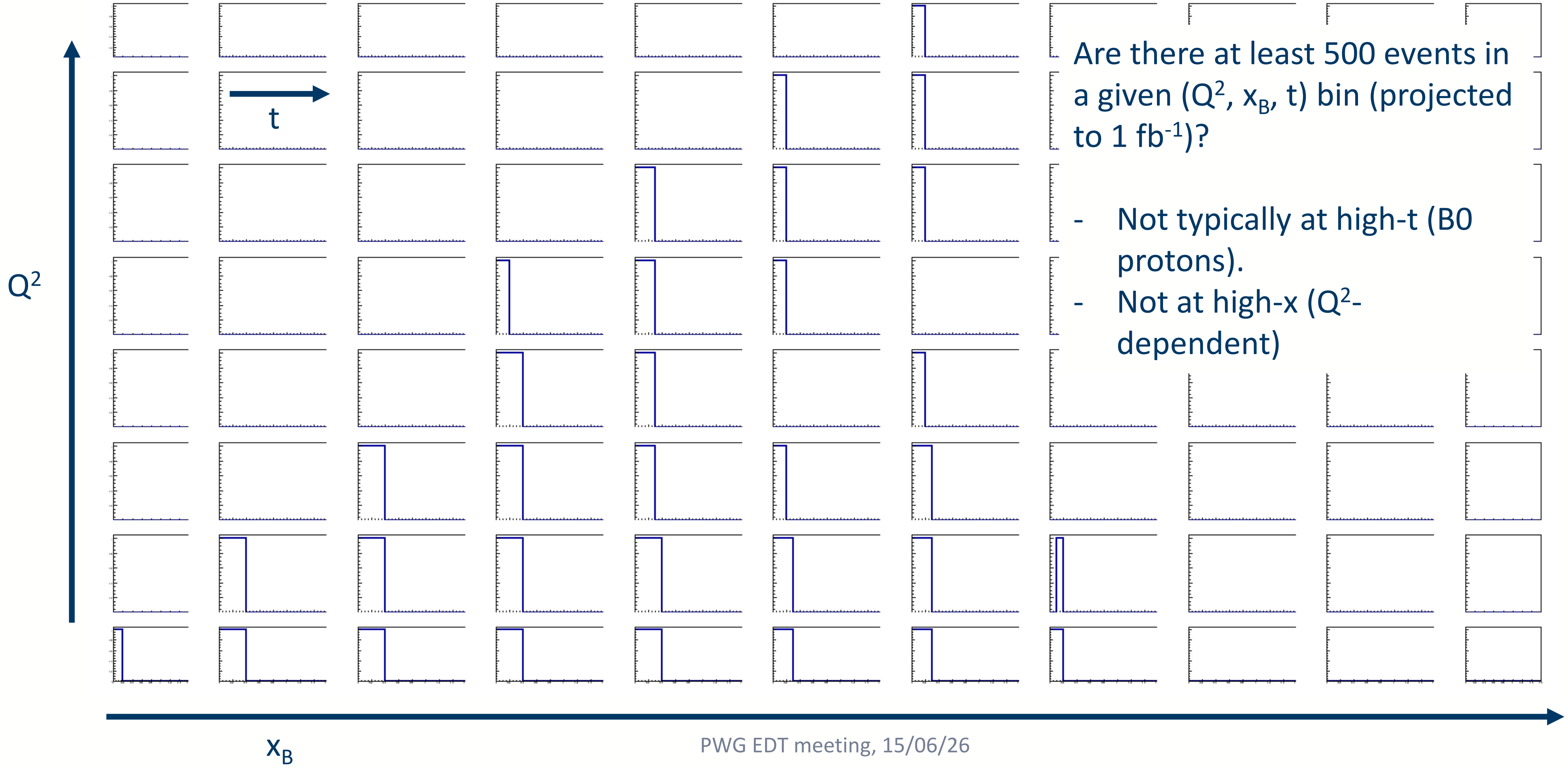
- Same for transversely polarised hadrons (A_{UT}, A_{LT}).

3D binning

- Asymmetries need to be plotted in 3D binning scheme: Q^2, x_B and $|t|$.
  - Currently use slightly modified version of bins from last year's paper.

- Bin edges:
  - Q^2: {1., 1.78, 3.16, 5.62, 10., 18., 32., 56., 100} GeV^2
  - x_B: {1×10^{-4}, 2.5×10^{-4}, 6.3×10^{-4}, 1×10^{-3}, 2.5×10^{-3}, 6.3×10^{-3}, 1×10^{-2}, 2.5×10^{-2}, 6.3×10^{-2}, 0.1, 0.25, 0.7}
  - $|t|$: {0., 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1., 1.1, 1.2, 1.4, 1.6} GeV^2

Filling events

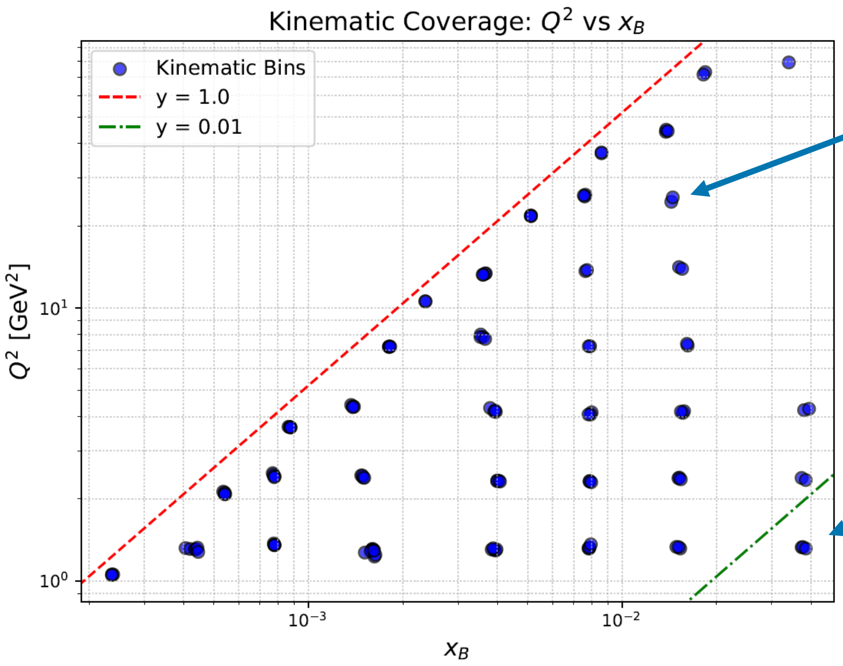


Are there at least 500 events in a given (Q^2, x_B, t) bin (projected to 1 fb^{-1})?

- Not typically at high-t (B0 protons).
- Not at high-x (Q^2-dependent)

Asymmetry data

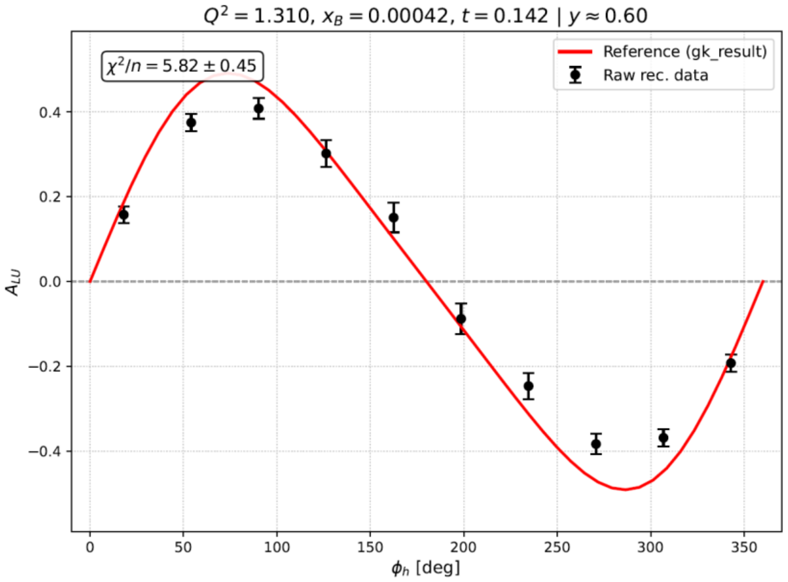
- Currently only for A_{LU} (proof of workflow).
- Results (from 26.03.1 campaign) plotted and sent (with statistical uncertainties) sent to theory colleagues to extract impact plots.



Plot Q^2, x_B, $|t|$ for events in each bin in 3D space.

<Q^2>, <x_B> and <$|t|$> for each bin calculated from averages of these distributions.

Events with $y < 0.01$ from smearing.



Concluding remarks

Next steps

- Generating full set of files for dedicated DVCS simulation run.
  - 2 electron helicity states.
  - Both longitudinal and transverse pol. for protons.
  - (Assume transverse pol. in y-direction; i.e. vertical w.r.t. ring plane.)
  - BH-only to estimate background removal.
  - DVCS only to check BH-removal procedure.
  - Total number of events for each beam energy = 1fb^{-1} ep collisions (currently assuming 50/50 split for each polarisation possibility).

- Also still looking into effect of beam gas backgrounds (previous tests taking significant amounts of time to process).

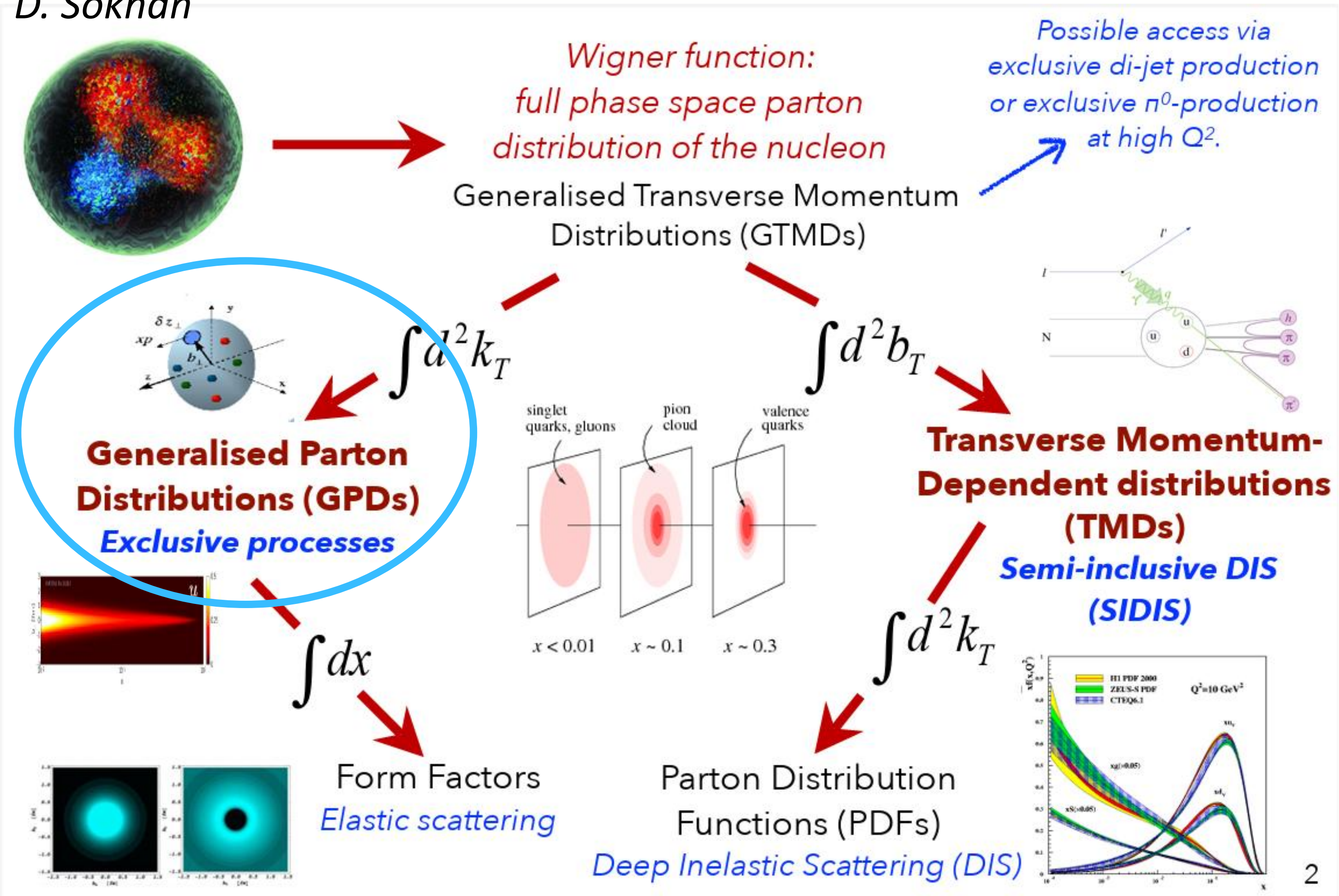
Thank you for listening!

Any questions?

Backup

Nucleon structure

D. Sokhan

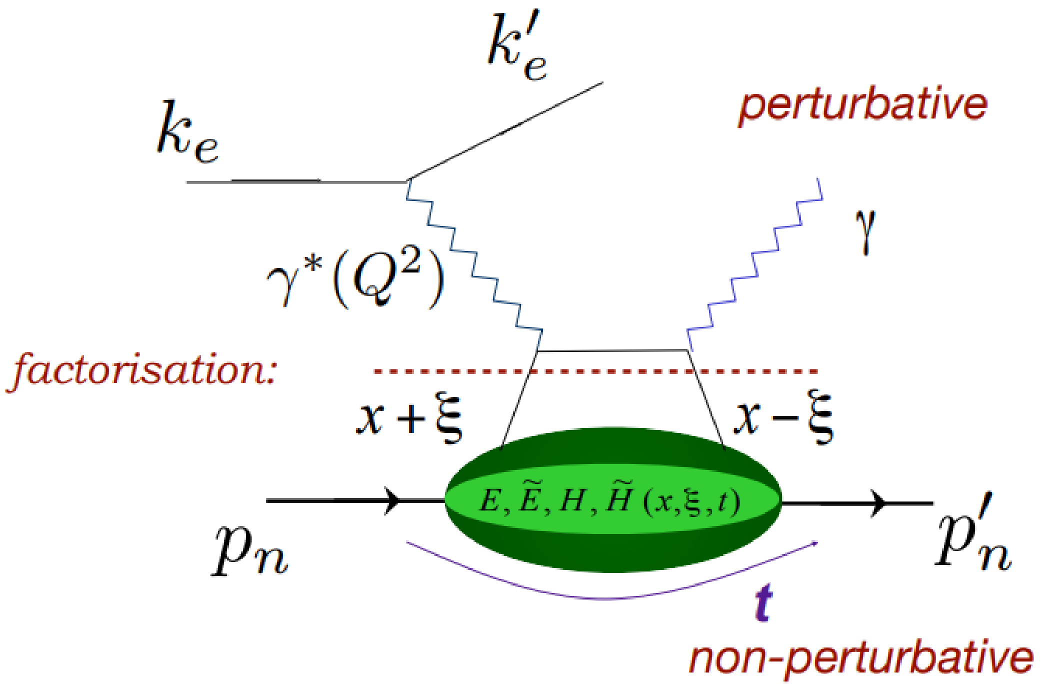


- Nucleon structure can be described within multiple dimensions by a large number of different functions.
  - GTMDs – full 5D phase space distributions.
  - PDFs – 1D as function of parton momentum.
  - Form factors – 1D as function of transverse distance from centre.
- GPDs relate the transverse position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

Deeply Virtual Compton Scattering

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