An Impact Study of the 3D Structure of the Nucleon through DVCS and EIC Simulations

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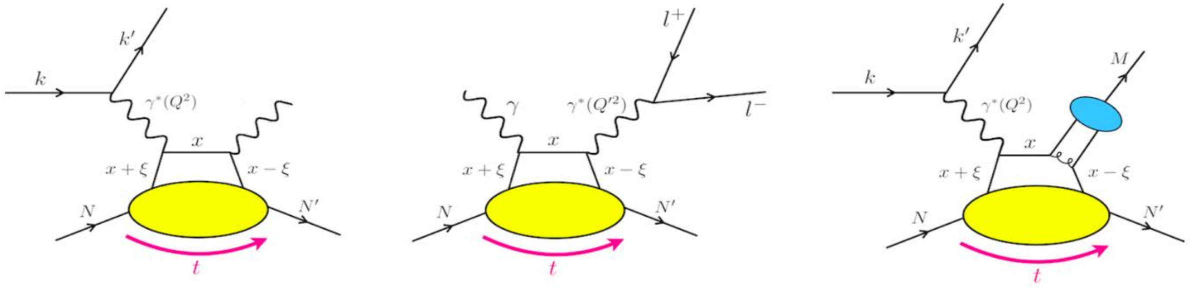
VIRGINIA TECH

Outline

- **EpIC Monte-Carlo Event Generator**
  - Modular structure, automated tasks
  - QED radiative corrections
- **EIC Impact Study**
  - Event generation with EpIC
  - Detector simulations
  - Nucleon tomography
  - CFFs
- **Summary**

EpIC

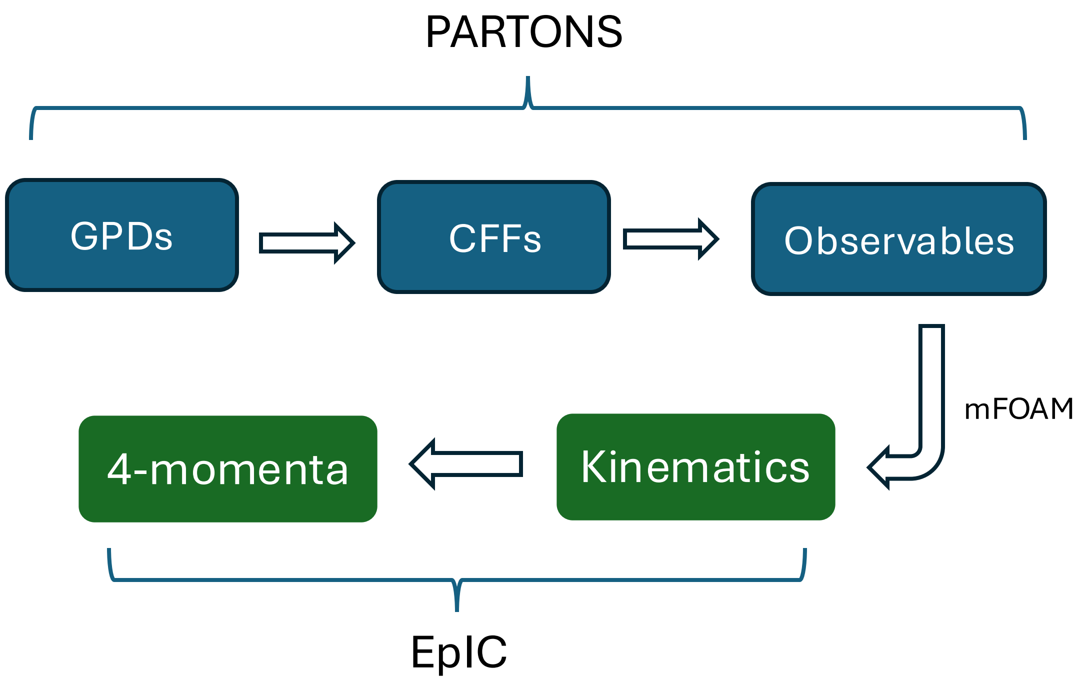
- EpIC: an event generator for exclusive processes
- Built on the PARTONS framework B. Berthou et al., Eur. Phys. J. C78 (2018)
  - Multiple GPD models
  - Flexible architecture
- Multiple channels: DVCS, TCS, DVMP (π^0), DDVCS, ...



- Written in C++, open source https://pawelsznajder.github.io/epic
- XML interface

Aschenauer et al., Eur. Phys. J. C 82 (2022)

mFOAM



- EpIC uses the mini FOAM to generate kinematics randomly Jadach and Sawicki, Comput. Phys. Commun. 177 (2007)
- Fully integrated with ROOT
- Works for dimensions less than 20

GPDs

Chiral-even GPDs parametrize the off-forward nucleon bilinear matrix elements at a light-like separation:

$$P^+ \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p', \lambda'| \bar{\psi}_q(-\frac{z}{2}) \mathcal{W}(-\frac{z}{2}, \frac{z}{2})\, \gamma^+ \psi_q(\frac{z}{2})\, |p, \lambda\rangle \Big|_{z^+=0, \vec{z}_T=0}$$

$$= \bar{u}(p', \lambda') \left[H^q \gamma^+ + E^q \frac{i\sigma^{+\alpha}\Delta_\alpha}{2m} \right] u(p, \lambda)\,,$$

$$P^+ \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p', \lambda'| \bar{\psi}_q(-\frac{z}{2}) \mathcal{W}(-\frac{z}{2}, \frac{z}{2})\, \gamma^+ \gamma_5 \psi_q(\frac{z}{2})\, |p, \lambda\rangle \Big|_{z^+=0, \vec{z}_T=0}$$

$$= \bar{u}(p', \lambda') \left[\tilde{H}^q \gamma^+ \gamma_5 + \tilde{E}^q \frac{\gamma_5 \Delta^+}{2m} \right] u(p, \lambda)\,,$$

parameters: $x, \quad \xi = \frac{p^+ - p'^+}{p^+ + p'^+}, \quad t = \Delta^2, \quad \mu^2 \qquad \text{with} \qquad \Delta^\alpha = p'^\alpha - p^\alpha$

CFFs at LO

CFFs at LO can be computed as follows:

$$
\begin{aligned}
\mathcal{H}^q(\xi, t) &= \int_{-1}^{1} dx \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right] H^q(x, \xi, t) \\
&= \left[-\text{P.V.} \int_{-1}^{1} dx \left(\frac{1}{x+\xi} + \frac{1}{x-\xi}\right) H^q(x, \xi, t)\right] + i\pi \left(H^q(\xi, \xi, t) - H^q(-\xi, \xi, t)\right)
\end{aligned}
$$

Therefore:

$$
\begin{aligned}
\text{Re}\mathcal{H}^q(\xi, t) &= -\text{P.V.} \int_{-1}^{1} dx \left(\frac{1}{x+\xi} + \frac{1}{x-\xi}\right) H^q(x, \xi, t) \\
\text{Im}\mathcal{H}^q(\xi, t) &= \pi \left(H^q(\xi, \xi, t) - H^q(-\xi, \xi, t)\right)
\end{aligned}
$$

Leptoproduction of a real photon

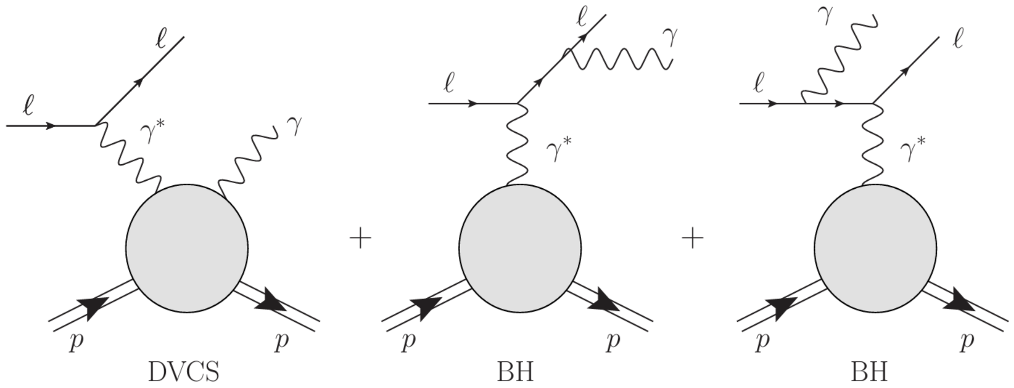
$$\frac{d\sigma}{dx_{\mathrm{B}}dyd|\Delta^2|d\phi d\varphi} = \frac{\alpha^3 x_{\mathrm{B}} y}{16\,\pi^2\,\mathcal{Q}^2\sqrt{1+\epsilon^2}}\left|\frac{\mathcal{T}}{e^3}\right|^2 .$$

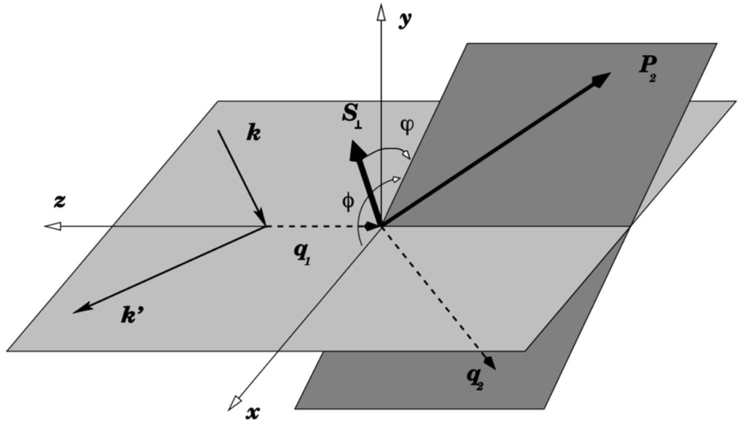
Belitsky, Müller, Kirchner, Nucl. Phys. B 629 (2002)
Kriesten et al., Phys. Rev. D 101 (2020)

$$|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{e^6}{x_{\mathrm{B}}^2 y^2 (1+\epsilon^2)^2 \Delta^2\,\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{c_0^{\mathrm{BH}} + \sum_{n=1}^{2} c_n^{\mathrm{BH}}\,\cos\left(n\phi\right) + s_1^{\mathrm{BH}}\,\sin\left(\phi\right)\right\},$$

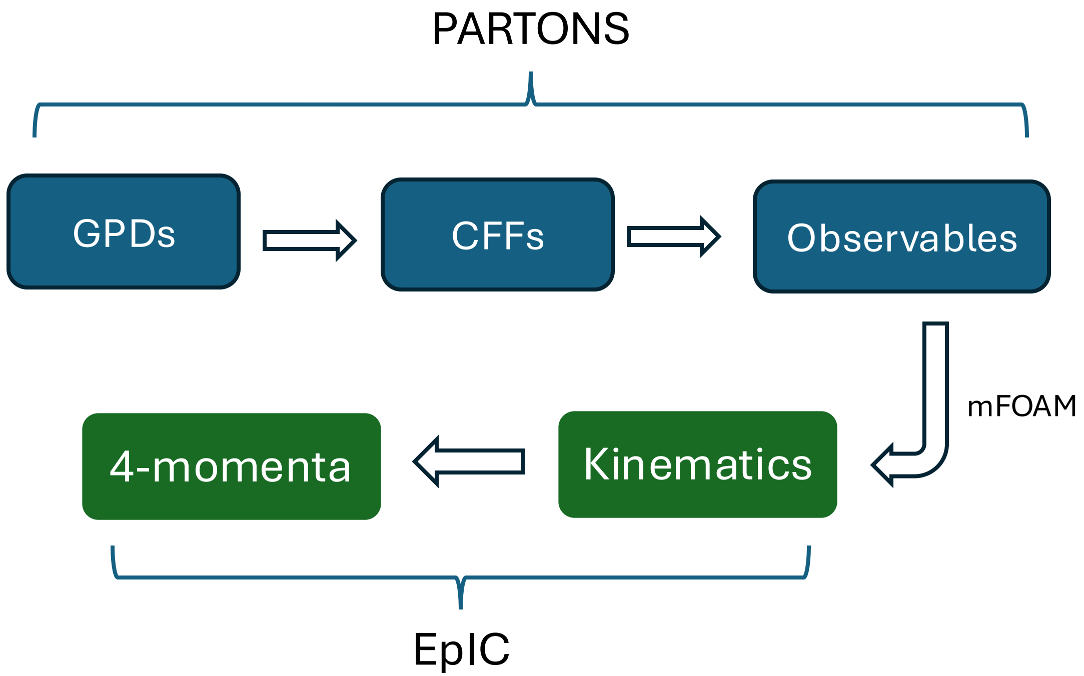
$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = \frac{e^6}{y^2\mathcal{Q}^2}\left\{c_0^{\mathrm{DVCS}} + \sum_{n=1}^{2}\left[c_n^{\mathrm{DVCS}}\cos(n\phi) + s_n^{\mathrm{DVCS}}\sin(n\phi)\right]\right\},$$

$$\mathcal{I} = \frac{\pm e^6}{x_{\mathrm{B}} y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + s_n^{\mathcal{I}}\sin(n\phi)\right]\right\},$$





EpIC



- Input file:
  - GPD (or CFF) model
  - Number of events, kinematic limits
  - Beam – target type, beam helicity
  - mFOAM parameters
  - Radiative corrections
- Output file:

  4 – vectors of all particles

EpIC – output

p_x p_y p_z E m

e
e'
$\gamma *$
p
γ
p'

```
P 1 0 11 0.0000000000000000e+00 0.0000000000000000e+00 -1.7999999992746670e+01 1.8000000000000000e+01 5.1099893142581812e-04 4
P 2 1 11 5.8191009048184650e-01 -8.4131057417372590e-01 -1.7193348506931216e+01 1.7223752667958578e+01 5.0059493812146217e-04 1
P 3 1 22 -5.8191009048184650e-01 8.4131057417372590e-01 -8.0665148567641154e-01 7.7624733203983765e-01 -1.0462072139237577e+00 13
P 4 0 2212 0.0000000000000000e+00 0.0000000000000000e+00 2.7499839935103188e+02 2.7500000000000000e+02 9.3827201300232188e-01 4
V -2 0 [3,4]
P 5 -2 22 -9.1414724095646427e-01 6.7884397811071806e-01 -3.8172689542989247e-01 1.2009203751220301e+00 -8.7639985927784413e-06 1
P 6 -2 2212 3.3223715047460062e-01 1.6246659606303288e-01 2.7457347475966503e+02 2.7457532695580238e+02 9.3827201299456731e-01 1
```

No RC

```
P 1 7 11 0.0000000000000000e+00 0.0000000000000000e+00 -1.7555047182186104e+01 1.7555047189623277e+01 5.1099887580591512e-04 3
P 2 1 11 2.1263741117230497e+00 -8.5750147900824070e-01 -1.5525145116727799e+01 1.5693530730992936e+01 5.0956386962909691e-04 3
P 3 1 22 -2.1263741117230497e+00 8.5750147900824070e-01 -2.0299020655220374e+00 1.8615164583648587e+00 -2.4314675651455229e+00 13
P 4 0 2212 0.0000000000000000e+00 0.0000000000000000e+00 2.7499839935103188e+02 2.7500000000000000e+02 9.3827201300232188e-01 4
V -2 0 [3,4]
P 5 -2 22 -2.0880347593235600e+00 4.8103807012754679e-01 -1.3556120653520338e+00 2.5355415305049656e+00 1.1490215731358769e-05 1
P 6 -2 2212 -3.8339352399347798e-02 3.7646340888063706e-01 2.7432410934974462e+02 2.7432597492673779e+02 9.3827201298681262e-01 1
P 7 0 11 0.0000000000000000e+00 0.0000000000000000e+00 -1.7999999992746666e+01 1.7999999999999996e+01 5.1099893142581812e-04 4
P 8 7 22 0.0000000000000000e+00 0.0000000000000000e+00 -4.4495281037672052e-01 4.4495281037672052e-01 0.0000000000000000e+00 1
P 9 2 11 2.0972637873230631e+00 -8.4576217777720253e-01 -1.5312603961240068e+01 1.5478684355909582e+01 5.1099890361586738e-04 1
P 10 2 22 2.9110324378018946e-02 -1.1739301222179333e-02 -2.1254115532733986e-01 2.1484637508335802e-01 2.6341780319308772e-09 1
```

Born level

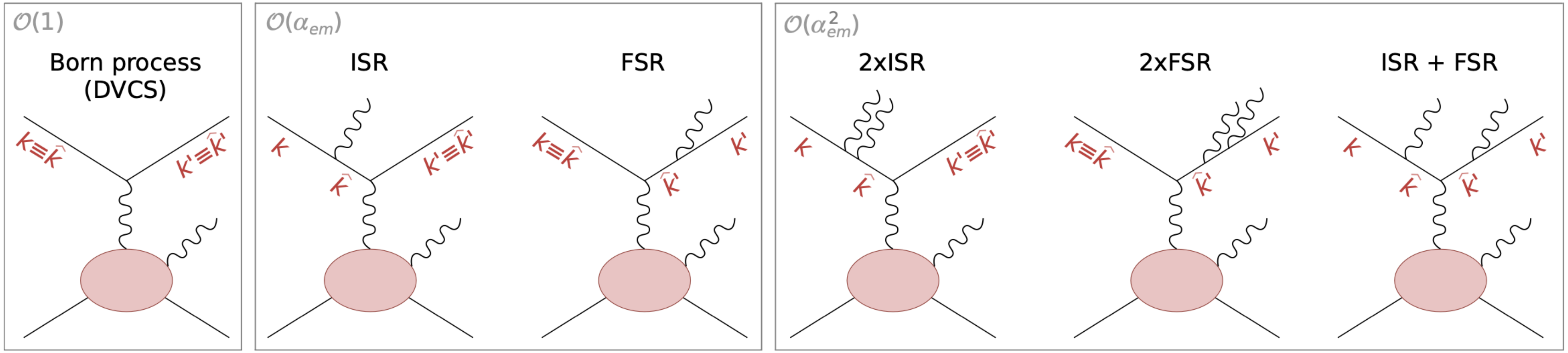
ISR

FSR

```
A generated_events_number 200000
A generation_date Sun May 21 10:39:51 2024\|
A hadron_polarisation 0|0|0
A integrated_cross_section_uncertainty 7.90629280603228e-05
A integrated_cross_section_value 0.114101152889887
A lepton_polarisation 1
A service_name DVCSGeneratorService
A suprocesses_type DVCS
HepMC::Asciiv3-END_EVENT_LISTING
```

Radiative corrections

- QED radiative corrections can have a significant impact on the interpretation of experimental data
- Collinear approximation: Negligible transverse component of the four-momenta of the emitted photon



Radiative corrections

- DIS cross-section in collinear approximation

$$\frac{d^2\sigma}{dxdy} = \int_0^1 \frac{dz_1}{z_1} D_{e/e}(z_1) \int_0^1 \frac{dz_3}{z_3^2} \bar{D}_{e/e}(z_3) \frac{y}{\hat{y}} \frac{d\hat{\sigma}_{\mathrm{Born}}}{d\hat{x}d\hat{y}}$$

$$\frac{d^2\sigma}{dxdQ^2} = \int_0^1 dz_1 z_1 D_{e/e}(z_1) \int_0^1 \frac{dz_3}{z_3^2} \bar{D}_{e/e}(z_3) \frac{y}{\hat{y}} \frac{d\hat{\sigma}_{\mathrm{Born}}}{d\hat{x}d\hat{Q}^2}$$

Kripfganz, Möhring, Spiesberger, Z. Phys. C 49 (1991)

- DVCS cross-section:

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}t\,\mathrm{d}\phi\,\mathrm{d}\phi_S} = \int_{z_1^{\mathrm{min}}}^1 \mathrm{d}z_1 z_1 D(z_1) \int_{z_3^{\mathrm{min}}}^1 \frac{\mathrm{d}z_3}{z_3^2} \overline{D}(z_3) \times \frac{y}{\hat{y}} \frac{\mathrm{d}^5\hat{\sigma}_{\mathrm{Born}}}{\mathrm{d}\hat{x}\,\mathrm{d}\hat{Q}^2\,\mathrm{d}t\,\mathrm{d}\,\phi\,\mathrm{d}\phi_S}$$

$$z_1 = \frac{E_e - E_\gamma}{E_e}\,, \qquad z_3 = \frac{E_{e'}}{E_{e'} + E_{\gamma'}} \qquad E_\gamma \geq \epsilon\, E_e,\ E_{\gamma'} \geq \epsilon\, E_{e'}$$

$$\hat{x} = \frac{z_1 x y}{z_1 z_3 + y - 1}, \qquad \hat{y} = \frac{z_1 z_3 + y - 1}{z_1 z_3}, \qquad \hat{Q}^2 = \frac{z_1}{z_3} Q^2$$

$$z_1^{\mathrm{min}} = \frac{1-y}{1-xy}, \qquad z_3^{\mathrm{min}} = 1 - y(1-x)$$

$$D(z) = \sum_{n=0} D^{(n)}(z) \qquad L = \ln(Q^2/m_l^2)$$

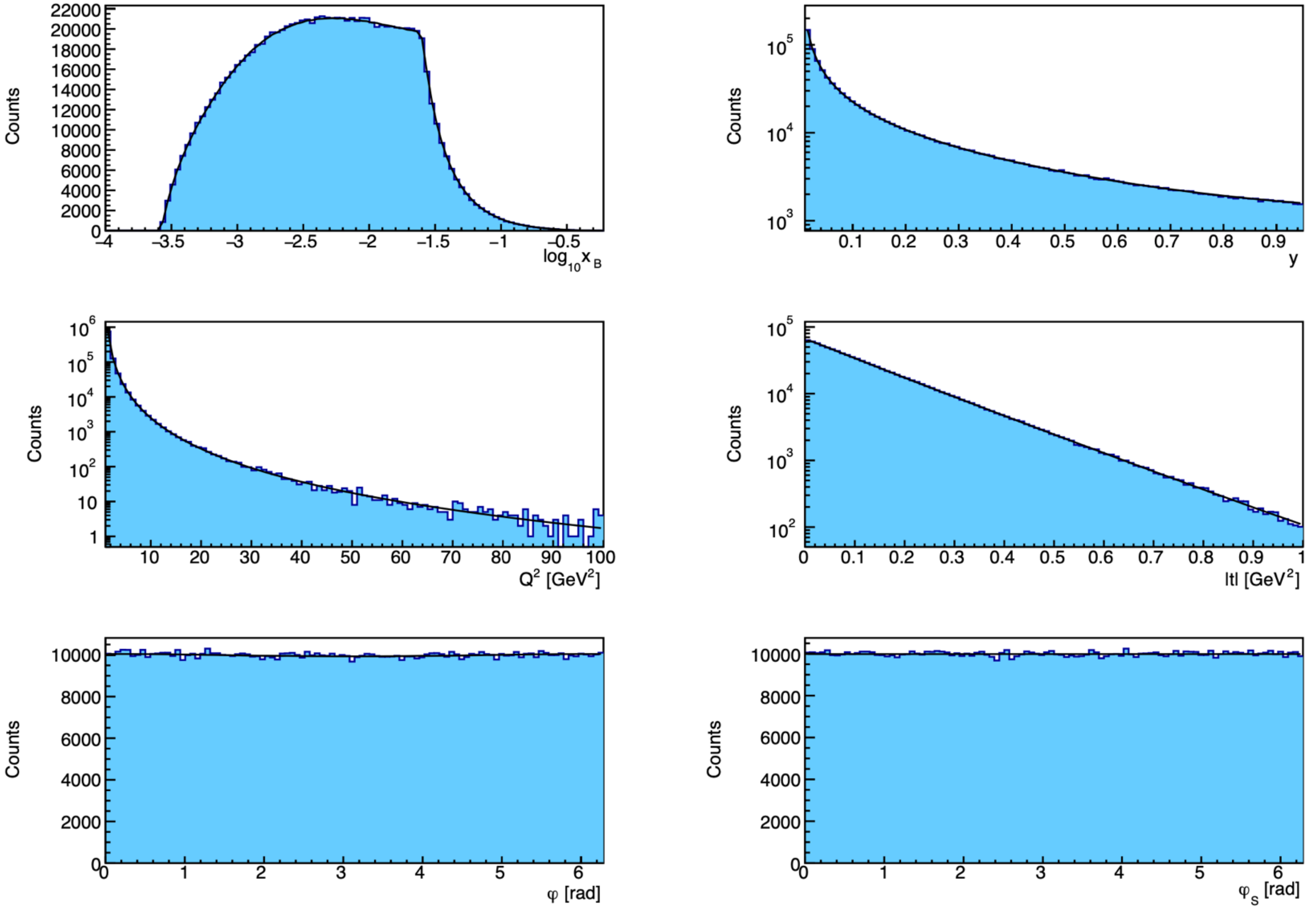
$$D^{(0)}(z) = \delta(1-z)\,,$$

$$D^{(1)}(z) = \delta(1-z)\left[\frac{\alpha}{2\pi} L \left(2\ln\epsilon + \frac{3}{2}\right)\right] + \Theta(1-\epsilon-z)\frac{\alpha}{2\pi} L \frac{1+z^2}{1-z}\,,$$

$$D^{(2)}(z) = \delta(1-z)\left(\frac{\alpha}{2\pi}\right)^2 \frac{L^2}{2}\left[\frac{13}{4} + 6\ln\epsilon + 4\ln^2\epsilon + 2\,z_{\mathrm{min}}^2 \ln(z_{\mathrm{min}}) - z_{\mathrm{min}}^2\right]$$

$$+\,\Theta(1-\epsilon-z)\left(\frac{\alpha}{2\pi}\right)^2 \frac{L^2}{2}\left[2\frac{1+z^2}{1-z}\left(2\ln(1-z) - \ln(z) + \frac{3}{2}\right) + (1+z)\ln(z) - 2(1-z)\right]$$

EpIC – DVCS



- 1M generated events
- Pre-calculated tables for the CFFs obtained from the convolution of GK GPDs and LO coefficients functions
- DVCSProcessBMJ12 for the evaluation of DVCS cross-section
- No radiative corrections

Unpolarized target, E_e = 10 GeV, E_p = 100 GeV

EIC Impact Study

- Simulate events using EpIC MC at EIC kinematics
  - Produce pure DVCS, BH and DVCS+BH+INT events within the expected EIC kinematics
  - Include 2nd order radiative corrections

- Apply detector effects and reconstruct events
  - Process simulated events through EICROOT framework to model detector response
  - Use reconstruction algorithms to extract kinematics

- Evaluate the impact of EIC data on nucleon tomography Aschenauer, Fazio, Kumerički, Müller JHEP 09 (2013)
  - Assess how detector-corrected data improve the spatial imaging
  - Quantify the precision of extracted CFFs

Event Generation Conditions

- MC Events generated in kinematics:

$$10^{-5} < x_{Bj} < 0.95$$
$$0.0001 < y < 0.95$$
$$0.7\, GeV^2 < Q^2 < 1000\, GeV^2$$
$$0.01\, GeV^2 < |t| < 1.6\, GeV^2$$
$$0.03\, rad < \phi < 2\pi - 0.03\, rad \qquad \epsilon = 10^{-4}$$

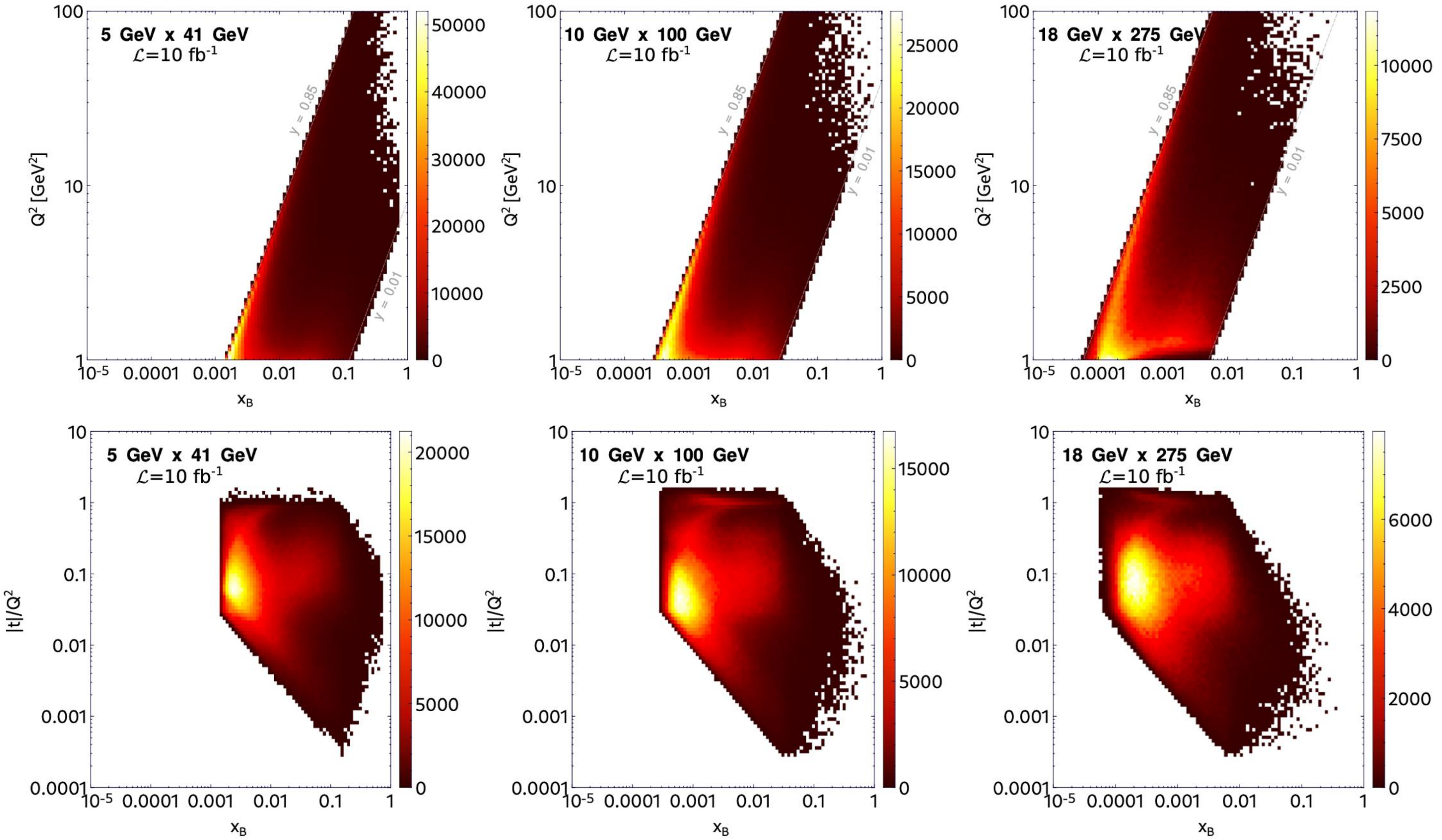
- Cuts at the analysis level:

$$1\, GeV^2 < Q^2 < 100\, GeV^2$$
$$0.01 < y < 0.6 \; (in\ nucleon\ tomography\ analysis)$$
$$0.01 < y < 0.85 \; (in\ the\ extraction\ of\ CFFs)$$
$$0.00001 < x_{Bj} < 0.7$$
$$0.03\, GeV^2 < |t| < 1.5\, GeV^2$$

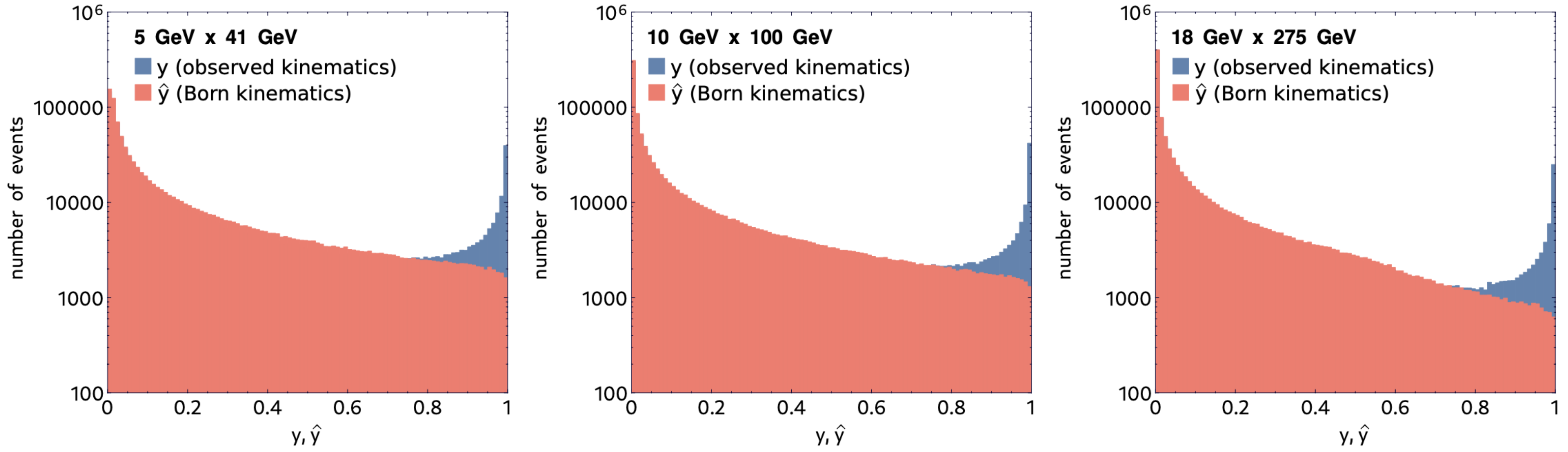
DVCS CFFs obtained from convoluting the GK model GPDs with LO coefficient functions

E_e [GeV]	E_p [GeV]	$0.01 < y < 0.6$		$0.01 < y < 0.85$	
		σ / σ_{DVCS} [nb]	N / N_{DVCS} (in M)	σ / σ_{DVCS} [nb]	N / N_{DVCS} (in M)
5	41	0.83 / 0.36	8.3 / 3.6	1.72 / 0.39	17.2 / 3.9
10	100	0.85 / 0.38	8.5 / 3.8	1.76 / 0.41	17.6 / 4.1
18	275	0.90 / 0.43	9.0 / 4.3	1.79 / 0.45	17.9 / 4.5

Reconstructed events



Radiative corrections



- DVCS subprocess only – no detector effects
- RCs affect the edges of the y-spectra
- Negligible shift of the mean kinematic variables $\langle x_{Bj} \rangle$ and $\langle Q^2 \rangle$ obtained in bins used in the extractions
- The relative magnitude of this shift is at the order of 1%

Nucleon tomography at EIC

- Nucleon tomography based on GPDs:

$$q(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp\cdot\vec{\Delta}_\perp} H^q\left(x,0,t=-\vec{\Delta}_\perp^2\right)$$

Burkardt, Int. J. Mod. Phys. A 18 (2003)

- The “direct” extraction of nucleon tomography is based on two assumption:
  i. The dominance of the imaginary part of the CFF $\mathcal{H}$
  ii. Constant skewness, i.e., $H^q(\xi,\xi,t)\ /\ H^q(\xi,0,t) = const$ (valid only at small ξ)

Akhunzyanov et al. (COMPASS), Phys. Lett. B 793 (2019)

$$\frac{d\sigma^{\gamma^* p\to\gamma p}}{dt} \propto (\mathrm{Im}\mathcal{H}(\xi,t))^2 \propto \left(\sum_q e_q^2 H^{q(+)}(\xi,\xi,t)\right)^2 \propto \left(\sum_q e_q^2 H^{q(+)}(\xi,0,t)\right)^2 \quad \text{(LO/LT)}$$

$$\sum_q \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp\cdot\vec{\Delta}_\perp} e_q^2 H^{q(+)}(\xi,0,t=-\vec{\Delta}_\perp^2) = q^{\mathrm{DVCS}}(\xi,\vec{b}_\perp) = \sum_q e_q^2 q^{(+)}(\xi,\vec{b}_\perp)$$

Nucleon tomography at EIC

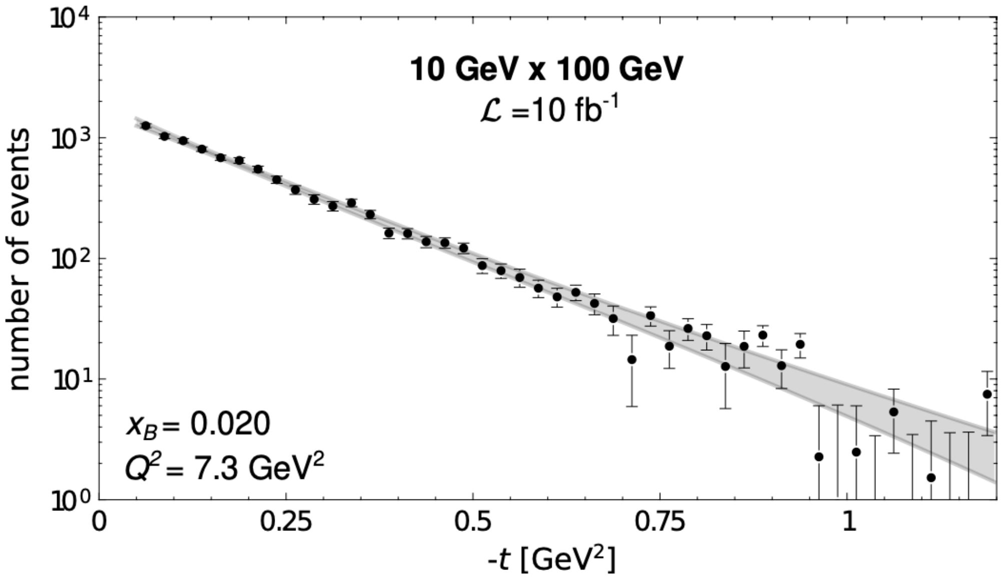
- Measure event distribution

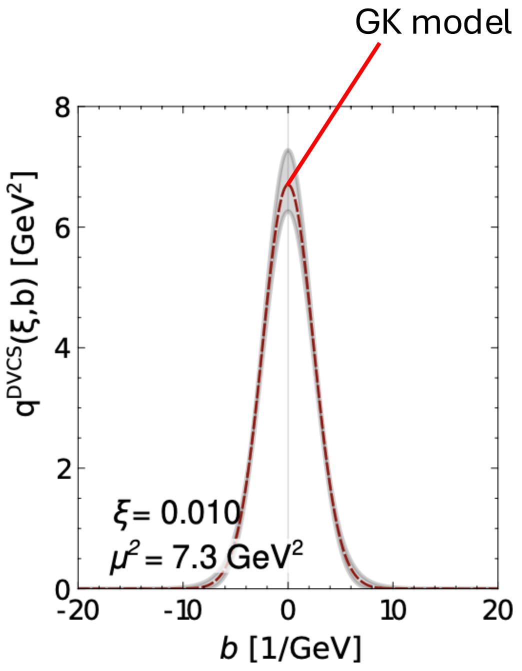
$$N(t_i) = N^{\exp}(t_i)/a(t_i) - N^{\text{gen,BH}}(t_i)$$

- Correct for detector acceptance

$$a(t_i) = \frac{N^{\text{rec,ALL}}(t_i)}{N^{\text{gen,ALL}}(t_i)}$$

- Subtract the BH contribution to isolate the DVCS part





Distribution of events corrected for acceptance and after subtraction of the BH contribution as a function of t (left)
Resulting tomographic picture (right)

E. Aschenauer, V. Batozskaya, S. Fazio, A. Jentsch, J. Kim, K. Kumerički, H. Moutarde, K. Passek-K., D. Sokhan, H. Spiesberger, P. Sznajder, KT, arXiv:2503.05908

EIC impact on CFFs

CFFs extracted from the Beam Spin Asymmetry:

$$A_{\mathrm{LU}}(\phi) = \frac{\mathrm{d}^4\sigma^+(\phi) - \mathrm{d}^4\sigma^-(\phi)}{\mathrm{d}^4\sigma^+(\phi) + \mathrm{d}^4\sigma^-(\phi)}$$

$$\mathrm{d}^4\sigma^+(\phi) - \mathrm{d}^4\sigma^-(\phi) \propto \sin\phi \times \mathrm{Im}\left(F_1\mathcal{H} + \cancel{\frac{x_{\mathrm{Bj}}}{2-x_{\mathrm{Bj}}}}(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4m^2}F_2\mathcal{E}\right)$$

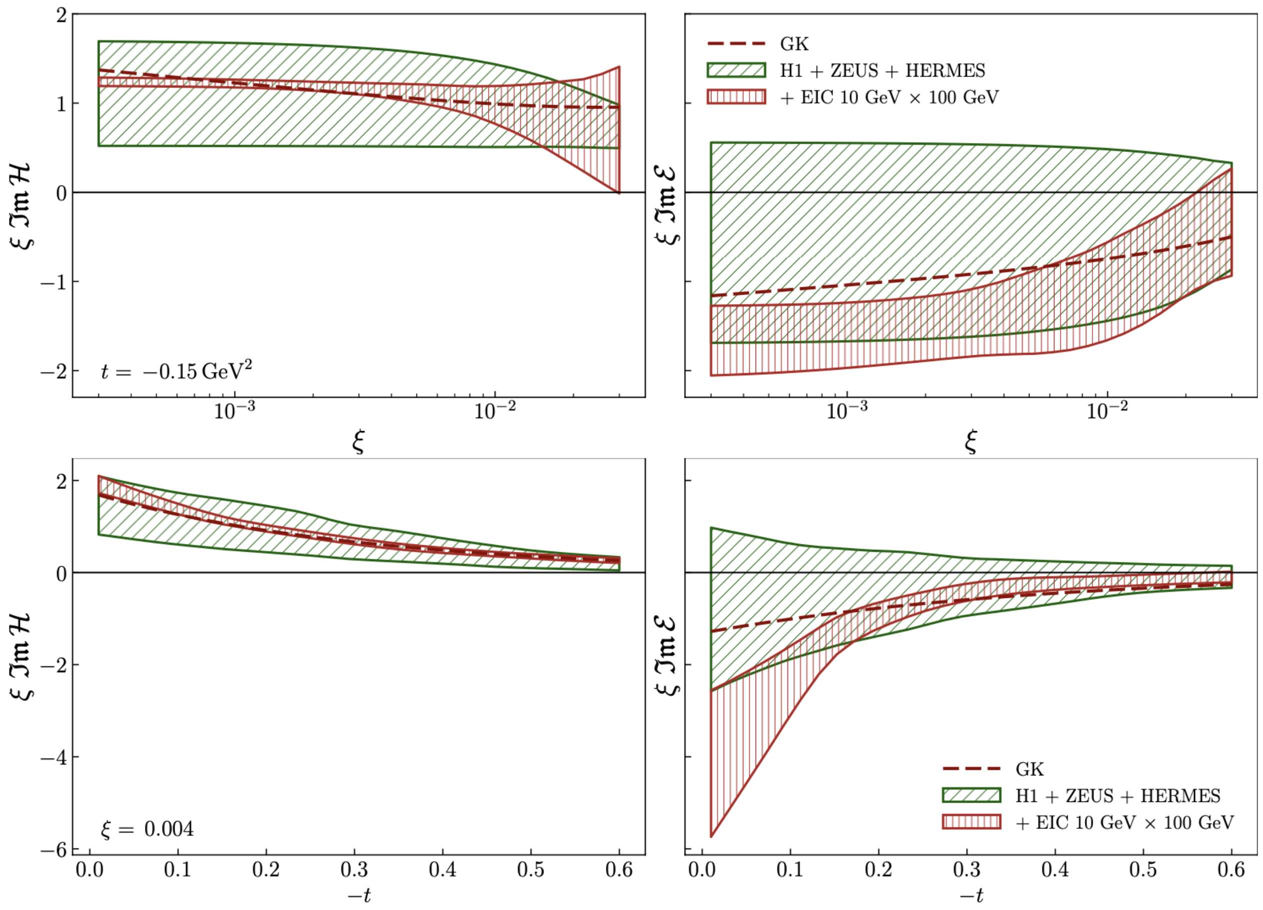
Small at EIC kinematics
No statistically significant effect

An ensemble of 200 NNs were trained:

$$\mathrm{Im}\mathcal{F}(\xi, t, Q^2) = \xi^\alpha \cdot \mathrm{ANN}(\xi, t, Q^2)\,, \qquad \mathcal{F} = (\mathcal{H}, \mathcal{E}, \ldots)$$

Similar to analyses:

Kumerički, Müller, Schäfer, JHEP 07 (2011)
Moutarde, Sznajder, Wagner, Eur. Phys. J. C 79 (2019)

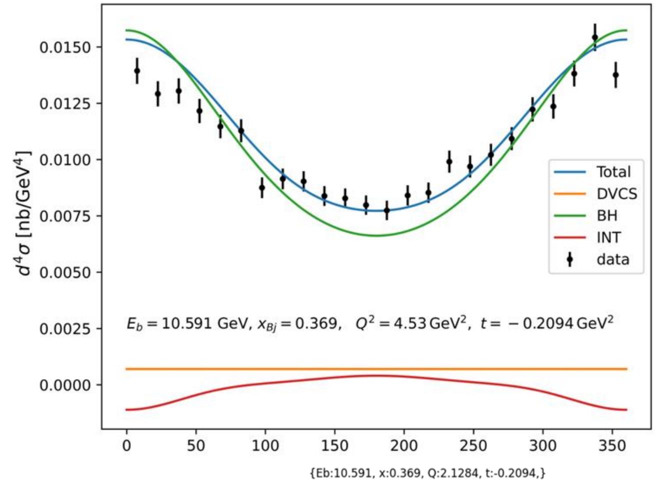


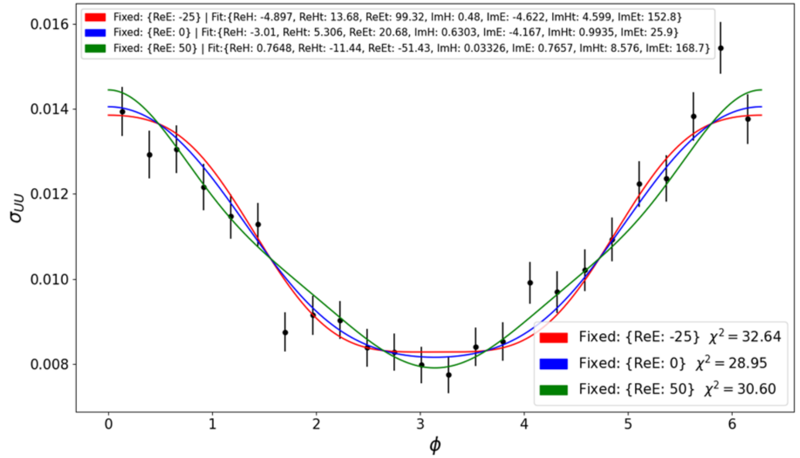
E. Aschenauer, V. Batozskaya, S. Fazio, A. Jentsch, J. Kim, K. Kumerički, H. Moutarde, K. Passek-K., D. Sokhan, H. Spiesberger, P. Sznajder, KT, arXiv:2503.05908

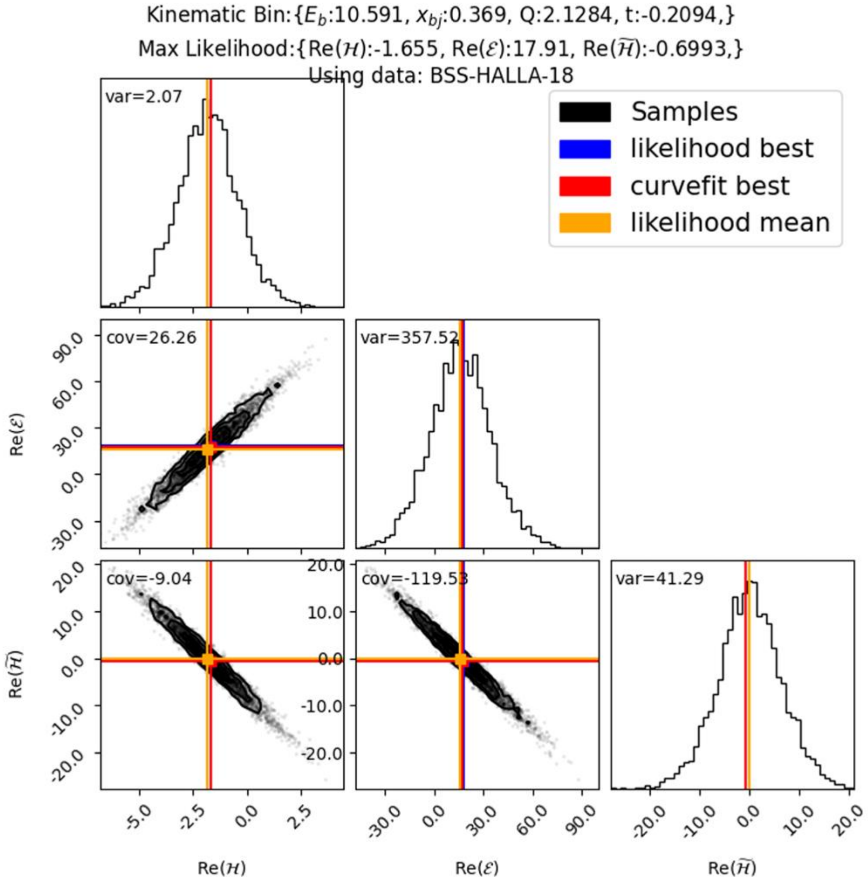
JLAB unpolarized data

Unpolarized JLab DVCS data alone leads to degenerate CFF extractions in MCMC analysis

F. Georges et al. (Jefferson Lab Hall A), PRL 128 (2022)







D. Adams et al., arXiv:2410.23469

Summary

- EpIC: A MC event generator for exclusive processes utilizing a flexible architecture
- Includes initial and final state QED radiative corrections
- Enables precision tests of spatial imaging and CFFs (and GPDs) extraction
- EIC impact studies suggest that the EIC has huge potential for accessing the 3D structure of the nucleon

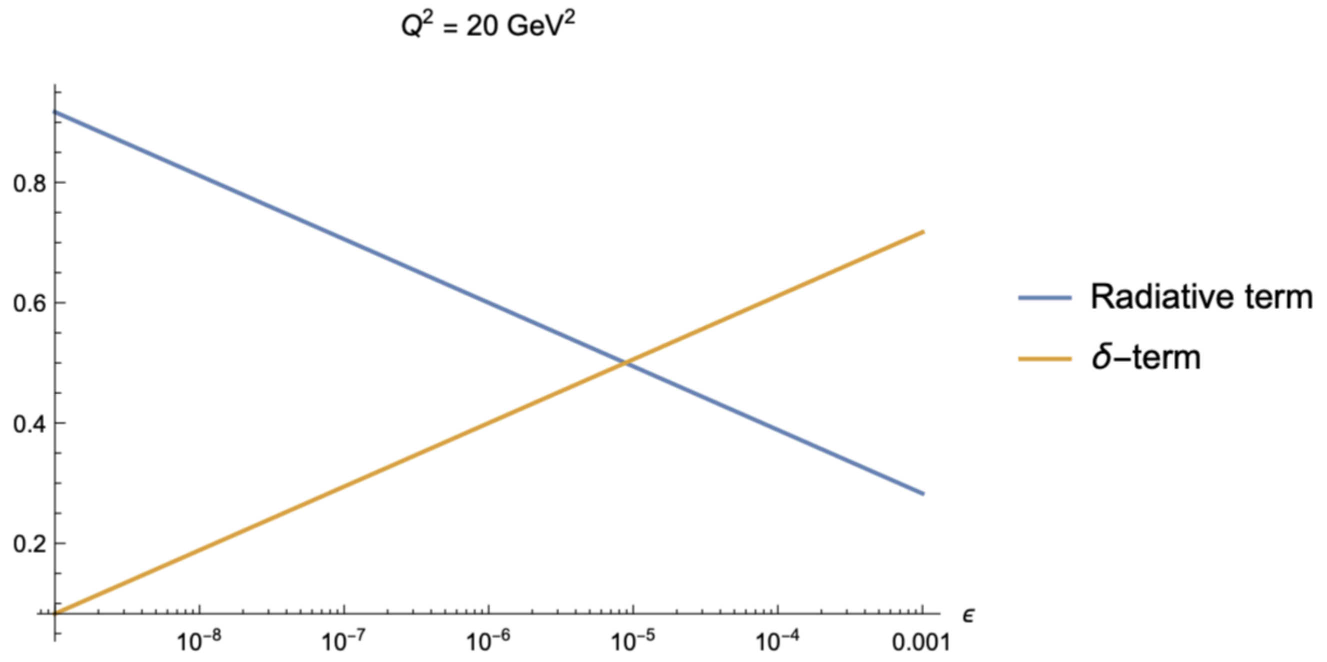
Back up

Probabilities for reconstructing all final states

E_e [GeV]	E_p [GeV]	$p_{e'}$	$p_{p'}$	p_γ	$p_{e'+p'+\gamma}$
5	41	0.90	0.76	0.72	0.49
10	100	0.90	0.90	0.59	0.48
18	275	0.87	0.81	0.46	0.29

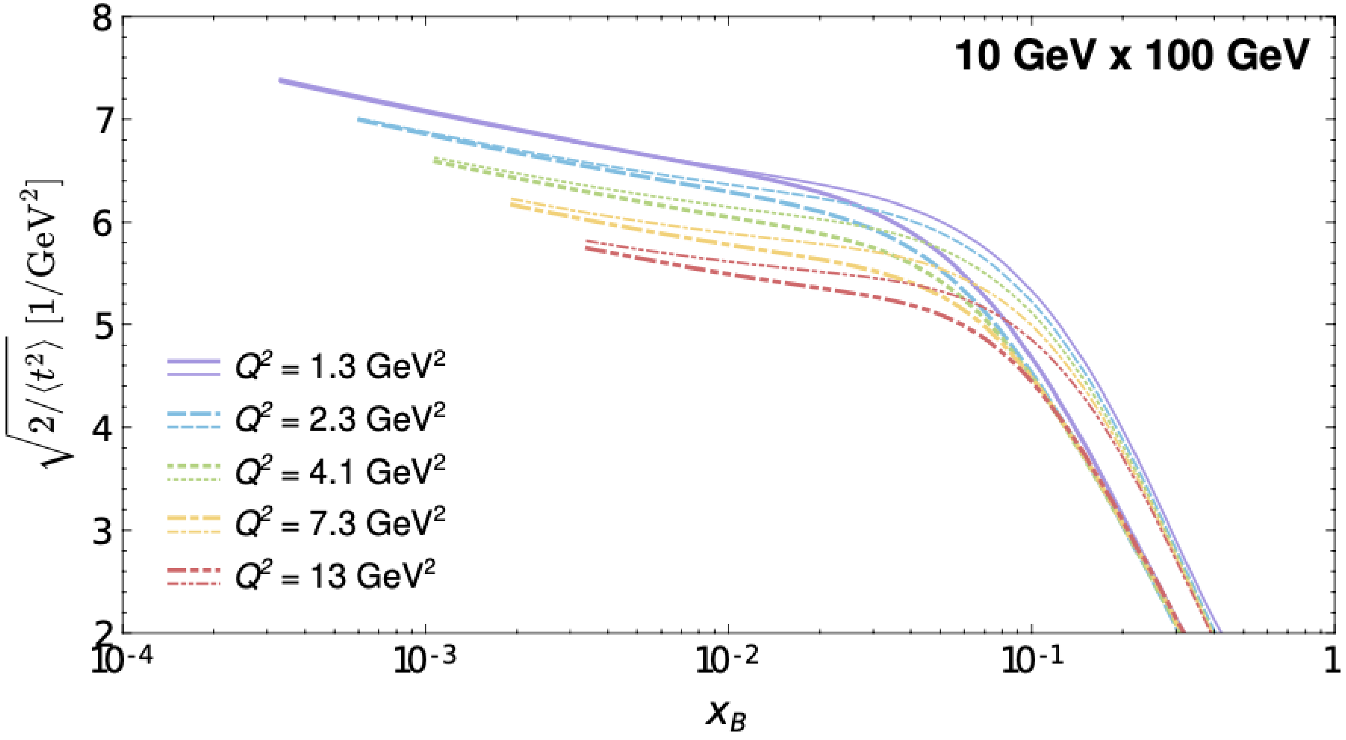
Back up

Probability of emitting a sizable photon as a function of the IR cut-off parameter ϵ



$$\int_0^1 dz \left[\delta(1-z)\left[1+\frac{\alpha}{2\pi}L\left(2\ln\epsilon+\frac{3}{2}\right)\right]+\theta(1-\epsilon-z)\frac{\alpha}{2\pi}L\frac{1+z^2}{1-z}\right] \qquad L=\ln(Q^2/m_l^2)$$

Back up



$$\langle t^2\rangle_{\mathrm{DVCS}} = \frac{\int_{t_0}^{t_1} \mathrm{d}t\, t^2\, \mathrm{d}\sigma^{\gamma^* p\to\gamma p}/\mathrm{d}t}{\int_{t_0}^{t_1} \mathrm{d}t\, \mathrm{d}\sigma^{\gamma^* p\to\gamma p}/\mathrm{d}t}$$

$$\langle t^2\rangle_{\mathrm{GPD}} = \frac{\int_{t_0}^{t_1} \mathrm{d}t\, t^2 \left(\sum_q e_q^2 H^{q(+)}(\xi,0,t)\right)^2}{\int_{t_0}^{t_1} \mathrm{d}t \left(\sum_q e_q^2 H^{q(+)}(\xi,0,t)\right)^2}$$