EpIC: an event generator for exclusive processes

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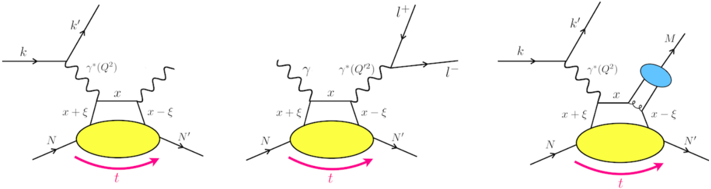
30 June 2023

EpIC

- EpIC: an event generator for exclusive reactions
- PARTONS provides the cross-section for EpIC [B. Berthou et al., Eur.Phys.J. C78 (2018)]
  - multiple GPD models that already exist
  - flexibility for adding new models
- Multiple channels: DVCS, TCS, DVMP (pseudoscalar mesons)



- Written in C++
- XML interface for automated tasks
- Open-source [https://pawelsznajder.github.io/epic]

GPDs

- GPDs parametrize the off-forward matrix elements of quark operators at a light-like separation
  D.Müller, D.Robaschik, B.Geyer, F.-M.Dittes, J.Hořejši, Fortsch. Phys. **42**, 101 (1994)
  X.D.Ji, PRL **78**, 610 (1997); PRD **55**, 7114 (1997). A.V.Radyushkin, PLB **380**, 417 & **385**, 333 (1996).

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

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

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

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

  where $\Delta = p' - p$, $P^+ = (p'^+ + p^+)/2$ and $z^\pm = (z^0 \pm z^3)/\sqrt{2}$.
- Depend on three parameters

$$x, \qquad \xi = \frac{p^+ - p'^+}{p^+ + p'^+}, \qquad t = \Delta^2$$

mFOAM

- EpIC uses mini FOAM (mFOAM, a compact version of FOAM) to generate events randomly
- mini FOAM is a general-purpose Monte Carlo event simulator

[Jadach and Sawicki, Comput.Phys.Commun. 177 (2007)]

- fully integrated with ROOT
- works for dimensions ≤ 20

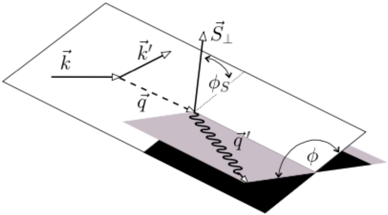
Leptoproduction of a real photon

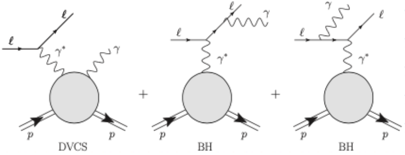
- Differential cross section for the leptoproduction of a real photon

[Belitsky, Mueller, and Kirchner Nucl.Phys.B 629 (2002)]

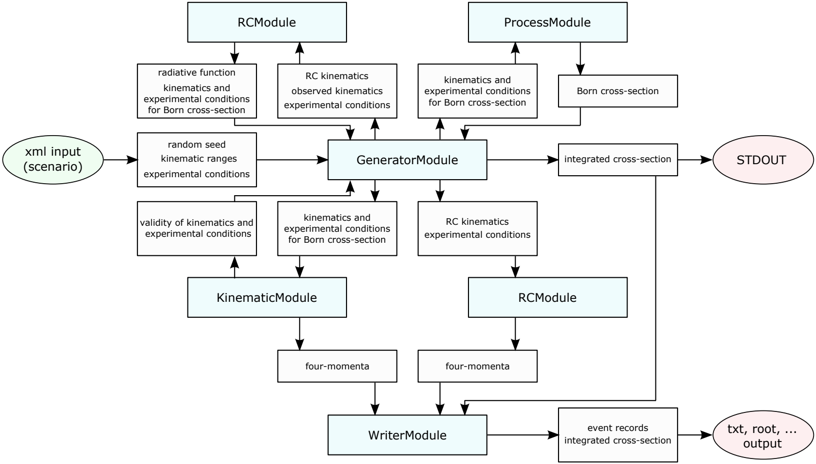
$$\frac{d^5\sigma}{dx_B dQ^2 d|t| d\phi d\phi_S} = \frac{\alpha^3 x_B y}{16\pi^2 Q^2 \sqrt{1+\epsilon^2}} |\mathcal{T}|^2$$

where $|\mathcal{T}|^2 = |\mathcal{T}_{\text{DVCS}}|^2 + |\mathcal{T}_{\text{BH}}|^2 + \mathcal{I}$





EpIC – architecture



EpIC

- Input file: model, model parameters, number of events, kinematic limits, beam and target type, beam helicity, target polarization, beam and target energy, mFOAM parameters
- Output file: 4-vectors of all particles

EpIC – input

```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>

<!-- Scenario starts here -->
<!-- For your convenience and for bookkeeping provide creation date and unique description -->
<scenario date="2017-07-18" description="Select specific GPD types">

   <!-- Indicate service and its methods to be used -->
   <task service="DVCSGeneratorService" method="generate">

      <!-- General configuration -->
      <!-- Subprocess can be "ALL", "BH" or "DVCS" -->
      <general_configuration>
         <param name="number_of_events" value="1000000" />
         <param name="subprocess_type" value="DVCS" />
      </general_configuration>

      <!-- Kinematic limits -->
      <!-- Limit on 'y' is optional, if not set 0 < y < 1 is assumed -->
      <kinematic_range>
         <param name="range_xB" value="0.0001|0.6" />
         <param name="range_t" value="-1.0|-0.0" />
         <param name="range_Q2" value="1.0|100.0" />
         <param name="range_phi" value="0.0|2*pi" />
         <param name="range_phiS" value="0.0|2*pi" />
         <param name="range_y" value="0.01|0.95" />
      </kinematic_range>

      <!-- Experimental conditions -->
      <experimental_conditions>
         <param name="lepton_energy" value="10.0" />
         <param name="lepton_type" value="e-" />
         <param name="lepton_helicity" value="1" />
         <param name="hadron_energy" value="100.0" />
         <param name="hadron_type" value="p" />
         <param name="hadron_polarisation" value="0.|0.|0." />
      </experimental_conditions>
```

EpIC – input

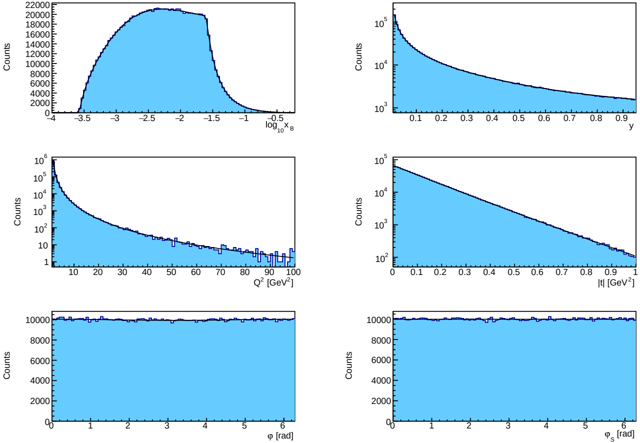
```xml
<!-- Computation scenario -->

<computation_configuration>

   <module type="DVCSProcessModule" name="DVCSProcessBMJ12">

          <module type="DVCSScalesModule" name="DVCSScalesQ2Multiplier">
                  <param name="lambda" value="1." />
          </module>

          <module type="DVCSXiConverterModule" name="DVCSXiConverterXBToXi">
          </module>

          <module type="DVCSConvolCoeffFunctionModule" name="DVCSCFFCMILOU3DTables">
                  <param name="qcd_order_type" value="LO" />
                  <param name="cff_set_file" value="/gpfs/mnt/gpfs02/eic/sznajder/software/epic/data/DVCSCFFCMILOU3DTables/tables_GK.root" />
          </module>
   </module>
</computation_configuration>

<!-- Generator module configuration -->
<generator_configuration>
   <module type="EventGeneratorModule" name="EventGeneratorFOAM">
          <param name="nCells" value="8000" />
          <param name="nSamples" value="1600" />
          <param name="nBins" value="1600" />
          <!-- param name="state_file_path" value="/gpfs/mnt/gpfs02/eic/tezgin/initialization.txt" /-->
   </module>
</generator_configuration>

<!-- Kinematic module configuration -->
<kinematic_configuration>
   <module type="DVCSKinematicModule" name="DVCSKinematicDefault">
   </module>
</kinematic_configuration>

<!-- Radiative correction module configuration -->
<rc_configuration>
   <module type="DVCSRCModule" name="DVCSRCNull">
          <!--param name="epsilon" value="1.E-6" /-->
   </module>
</rc_configuration>

<!-- Writer module configuration-->
<writer_configuration>
   <module type="WriterModule" name="WriterHepMC3">
          <param name="output_file_path" value="events.txt" />
          <param name="HepMC3_writer_type" value="ascii" />
   </module>
</writer_configuration>
```

EpIC – output

```
P 1 0 11 0.0000000000000000e+00 0.0000000000000000e+00 -9.9999999869440064e+00 1.0000000000000000e+01 5.1099888971089147e-04 4
P 2 1 11 -1.6312711640584632e+00 -1.0719364504885067e+00 -8.3614755990274716e+00 8.5862895256760741e+00 5.1090927818740880e-04 1
P 3 1 22 1.6312711640584632e+00 1.0719364504885067e+00 -1.6385243878612528e+00 1.4137104743909799e+00 -2.1204429322167280e+00 13
P 4 0 2212 0.0000000000000000e+00 0.0000000000000000e+00 9.9995598131265865e+01 1.0000000000000001e+02 9.3827201300135255e-01 4
V -2 0 [3,4]
P 5 -2 22 1.1283554718872257e+00 7.8035908453753633e-01 -1.2167636309168302e+00 1.8337557376446791e+00 8.0478135311501022e-06 1
P 6 -2 2212 5.0291569217122734e-01 2.9157736595096451e-01 9.9573837374175241e+01 9.9579954736597685e+01 9.3827201299941387e-01 1
```

EpIC – DVCS

Unpolarized target, $E_e = 10\,\text{GeV}$, $E_p = 100\,\text{GeV}$ (DVCSProcessBMJ12 & GK GPDs)



$$0.0001 \le x_B \le 0.6,\ 0.01 \le y \le 0.95,\ 1 \le Q^2 \le 100\ \text{GeV}^2,\ 0 \le |t| \le 1\ \text{GeV}^2$$

EpIC – performance

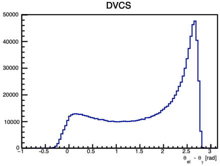
- Generation of 1M events
- `DVCSCFFCMILOU3DTables` for the parameterisation of CFFs obtained from the GK GPD model and LO coefficients functions
- `DVCSProcessBMJ12` for the evaluation of DVCS cross-section
- FOAM parameters: $\texttt{nCells} = 3000$, $\texttt{nSamples} = 600$, $\texttt{nBins} = 600$
- Initialisation time $\approx$ 40 min
- Generation time per event $\approx$ 0.0052 sec at BNL farms

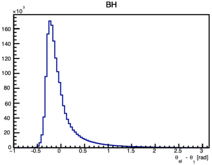
EIC impact

- Use EpIC to generate events at EIC kinematics
- Add detector effects
- Assess how EIC data will impact the extraction of certain observables [see, E.C. Aschenauer, S. Fazio, K. Kumericki, and D. Mueller JHEP 09 (2013)]

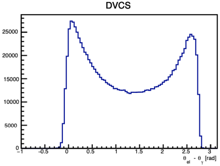
EIC impact

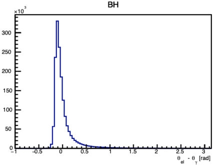
- 5×41 GeV



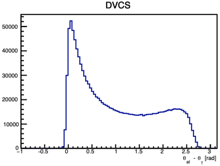


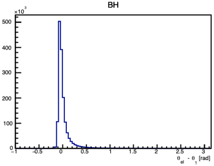
- 10×100 GeV





- 18×275 GeV

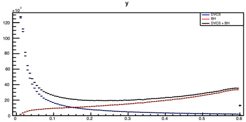


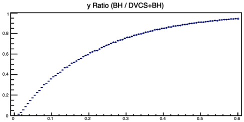


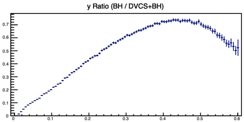
EIC impact

Effect of the θ-cut ($\theta_{el} - \theta_{\gamma} > 0$) on the y ratios:

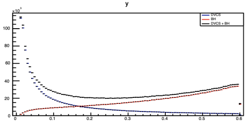
- 5×41 GeV

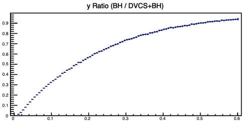


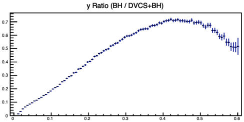




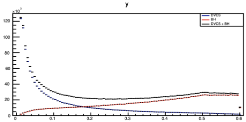
- 10×100 GeV

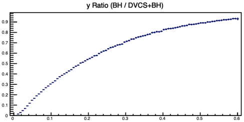


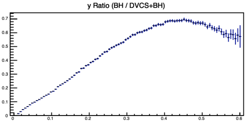




- 18×275 GeV

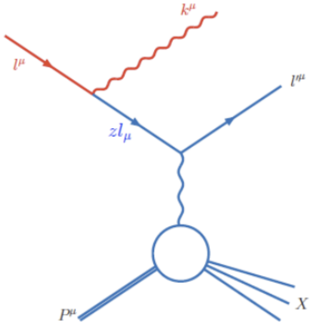






Radiative corrections – collinear approximation

- Radiative corrections can have a significant impact on the interpretation of experimental data
- Collinear approximation: Neglect the transverse component of the 4-momenta of the emitted photon



Radiative Corrections in DIS

Initial and final state radiative corrections [Kripfganz, Möhring, Spiesberger, Z.Phys.C 49 (1991)]

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

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

$$D_{e/e}(z) = \bar{D}_{e/e}(z) = \left[\delta(1-z)\left[1+\frac{\alpha}{2\pi}L\left(2ln\,\epsilon+\frac{3}{2}\right)\right] + \theta(1-\epsilon-z)\frac{\alpha}{2\pi}L\frac{1+z^2}{1-z}\right]$$

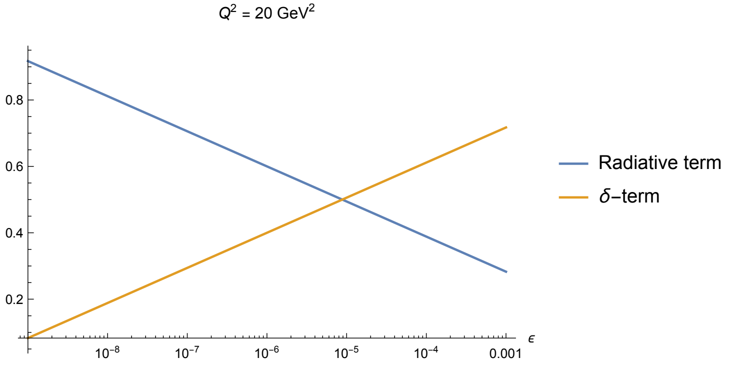
where $L = ln\frac{Q^2}{m_e^2}$

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

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

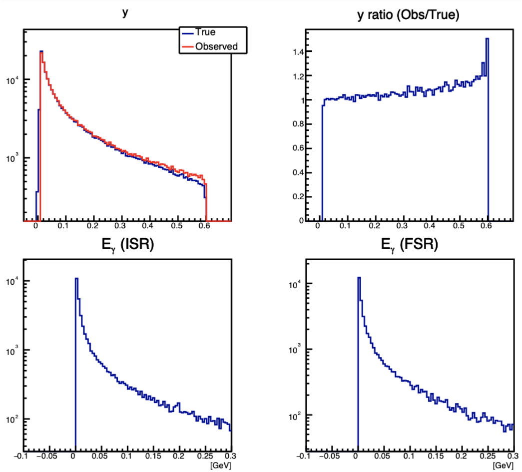
Radiative Corrections in DIS

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



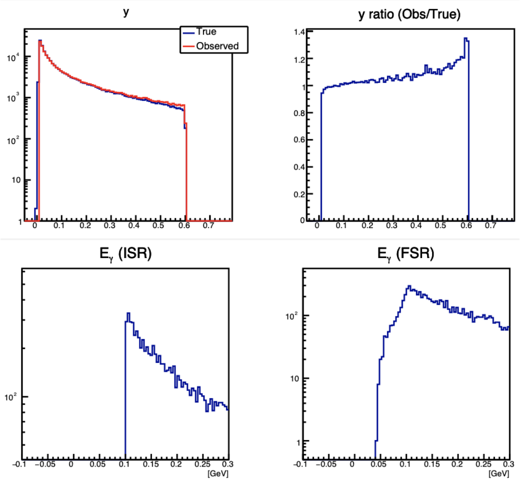
Radiative corrections – collinear approximation

DVCS, 10×100 GeV, $\epsilon = 10^{-4}$



Radiative corrections – collinear approximation

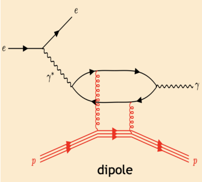
DVCS, 10×100 GeV, $\epsilon = 10^{-2}$



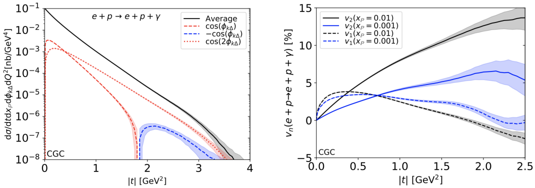
Implementation of DVCS CGC in EpIC

- DVCS cross-section has been computed in the CGC framework

  Hatta, Xiao, Yuan, PRD **95**, no.11, 114026 (2017). Mäntysaari, Roy, Salazar, Schenke PRD **103**, no.9, 094026 (2021).
- Based on the initial color charge configurations in the McLerran-Venugopalan model coupled with JIMWLK evolution
- The azimuthal angle between the electron and photon has a sensitivity to the spatial correlations in the gluon distribution of the target



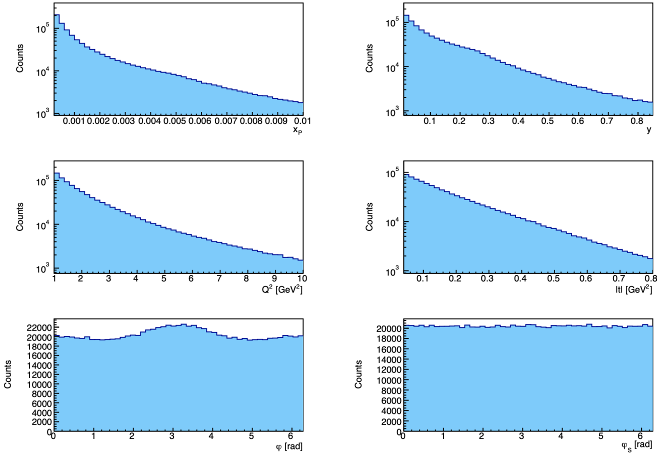
DVCS at small x



Mäntysaari, Roy, Salazar, Schenke PRD **103**, no.9, 094026 (2021).

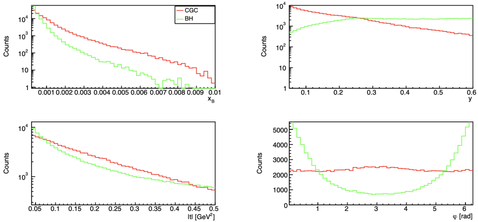
EpIC – DVCS in CGC

Unpolarized target with $\sqrt{s} = 140\,\text{GeV}$

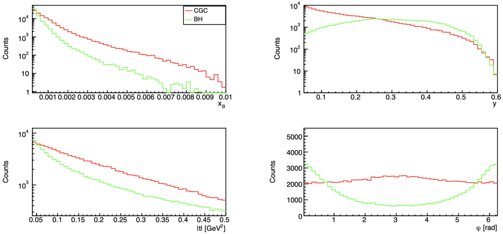


$$0.0002 \leq x_B \leq 0.01,\ 0.01 \leq y \leq 0.85,\ 1 \leq Q^2 \leq 10\ \text{GeV}^2,\ 0.04 \leq |t| \leq 0.8\ \text{GeV}^2$$

EpIC – DVCS in CGC vs. BH



no cut, luminosity 1 fb^{-1}



$$\theta_{el} - \theta_{\gamma} > 0$$

Summary

- EpIC is a Monte Carlo event generator designed for exclusive reactions, featuring a flexible architecture
- Initial and final state of radiative corrections based on the collinear approximation are implemented
- DVCS at small x, based on the CGC framework, has been implemented.
- EpIC is a generic framework that enables easy implementation of existing modules in PARTONS.