EpIC: A Monte Carlo event generator for exclusive processes

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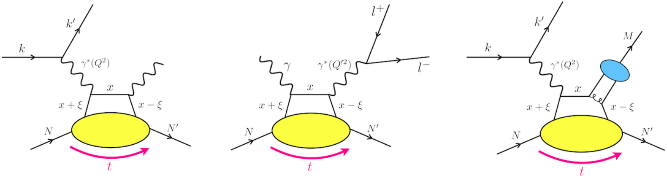
26 October 2022

Brookhaven National Laboratory

EpIC

- EpIC: an event generator for exclusive reactions
- EpIC uses the PARTONS framework [B. Berthou et al., Eur.Phys.J. C78 (2018)]: takes advantage of
  - multiple GPD models that already exist
  - flexibility for adding new models [see H. Moutarde's talk]
- Multiple channels: DVCS, TCS, DVMP (pseudoscalar mesons)



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

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

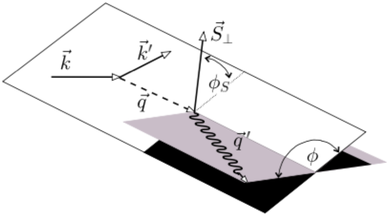
Leptoproduction of a real photon

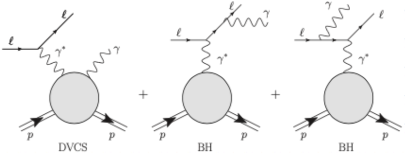
- Differential cross section for the leptoproduction of a real photon

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

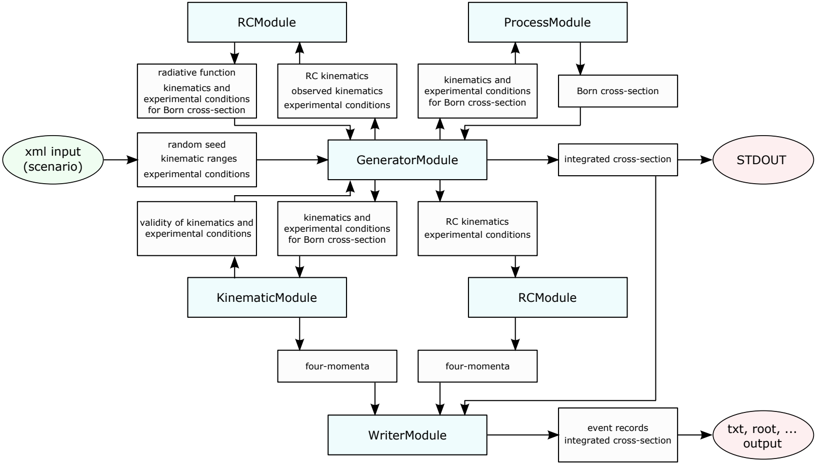
$$\frac{d^5\sigma}{dx_B dQ^2 d|t| d\phi d\phi_S} = \frac{\alpha^3 x_B y}{16\pi^2 Q^2 \sqrt{1+\epsilon^2}} |\mathcal{T}|^2$$

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

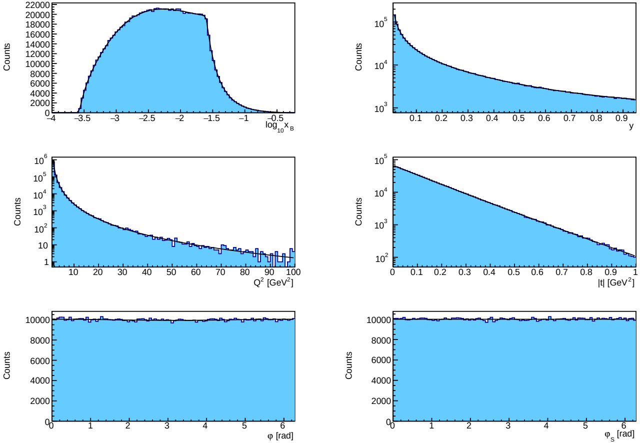
```xml
<!-- Computation scenario -->

<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, $E_e = 10\,\mathrm{GeV}$, $E_p = 100\,\mathrm{GeV}$ (DVCSProcessBMJ12 & GK GPDs)



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

Consistency check

Compare generated events with the theory values

$$\text{Events}\Big|_{\text{bin}} = \text{Total number of events} \times \frac{\int_{\text{bin}} \frac{d\sigma}{dx_B}\, dx_B}{\sigma_{\text{total}}}$$

$$\int_{\text{bin}} \frac{d\sigma}{dx_B}\, dx_B = \int_{\text{bin}} dx_B \int dQ^2 \int d|t| \int d\phi \int d\phi_S \frac{d^5\sigma}{dx_B dQ^2 d|t| d\phi d\phi_S}$$

EpIC – performance

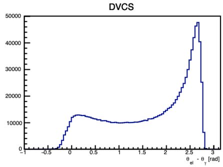
- Generation of 1M events
- `DVCSCFFCMILOU3DTables` for the parameterisation of CFFs obtained from the GK GPD model and LO coefficients functions
- `DVCSProcessBMJ12` for the evaluation of DVCS cross-section
- FOAM parameters: `nCells` $= 3000$, `nSamples` $= 600$, `nBins` $= 600$
- Initialisation time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

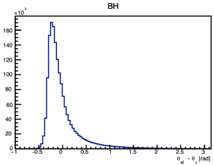
EIC impact

- 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)]
- For instance, t-slope extraction: the dominance of the BH at large-y [see S. Fazio's talk]

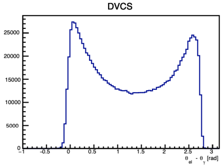
EIC impact

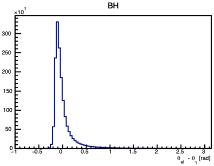
- 5×41 GeV



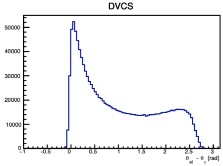


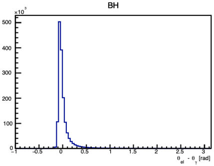
- 10×100 GeV





- 18×275 GeV

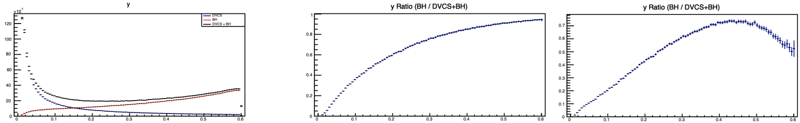




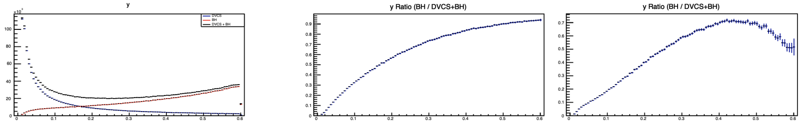
EIC impact

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

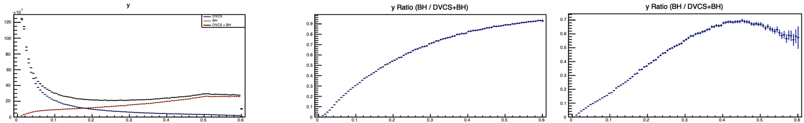
- 5×41 GeV



- 10×100 GeV

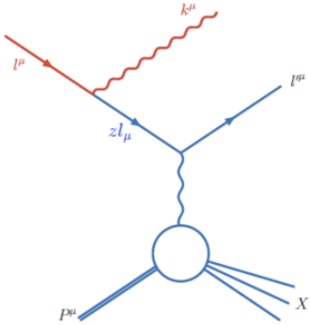


- 18×275 GeV



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)]

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

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

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

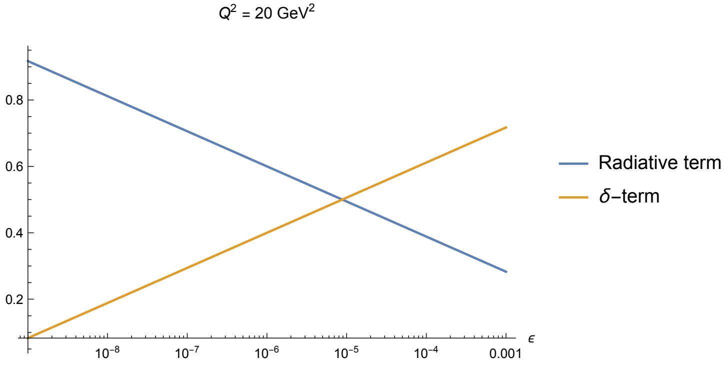
where $L = ln\frac{Q^2}{m_e^2}$

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

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

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 in DVCS

Initial and final state radiative corrections

$$\frac{d^5\sigma}{dxdQ^2dtd\phi d\phi_S} = \int_0^1 dz_1 z_1 D_{e/e}(z_1) \int_0^1 \frac{dz_3}{z_3^2} \bar{D}_{e/e}(z_3) \frac{y}{\hat{y}} \frac{d^5\hat{\sigma}_{\text{Born}}}{d\hat{x}d\hat{Q}^2dtd\phi d\phi_S}$$

Define new variables: $z_1 = 1 - 10^{z_1'}, \quad z_3 = 1 - 10^{z_3'}, \quad z_1', z_3' \in [-8, 0]$

$$\frac{d^5\sigma}{dxdQ^2dtd\phi d\phi_S} = \int_{-8}^0 dz_1' \, (1 - z_1)\, z_1 \, ln(10)\, D_{e/e}(z_1)$$

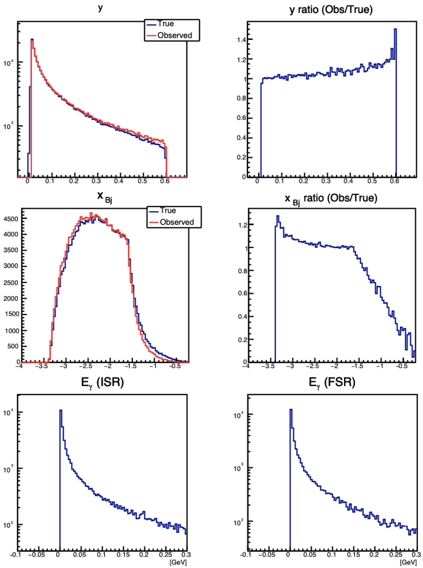
$$\int_{-8}^0 dz_3' \, \frac{1 - z_3}{z_3^2} \, ln(10)\, \bar{D}_{e/e}(z_3) \frac{y}{\hat{y}} \frac{d^5\hat{\sigma}_{\text{Born}}}{d\hat{x}d\hat{Q}^2dtd\phi d\phi_S}$$

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

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

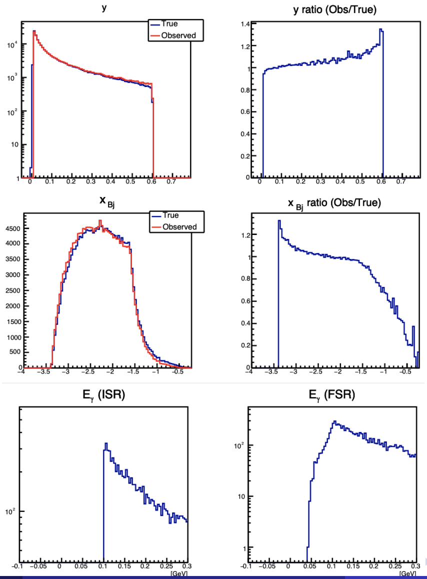
Radiative corrections – collinear approximation

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



Radiative corrections – collinear approximation

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



Summary

- EpIC is a new MC event generator for exclusive reactions
- EpIC has a flexible architecture that utilises a modular programming paradigm
- Generation of events are consistent with the values from the theory side
- Initial and final state of radiative corrections based on the collinear approximation are implemented
- TCS and DVMP (pseudoscalar mesons) are also available
- EpIC is generic: easy to implement the existing modules in PARTONS