Photoproduction and ultra-peripheral collisions with Pythia 8

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In collaboration with
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Why study photoproduction?

• Monte-Carlo event generators essential to study the potential of future experiments
• Photo-nuclear processes can be used to probe the structure of nucleons (nuclear PDFs)
  ⇒ Connection between EIC and ultra-peripheral heavy ion collisions at the LHC

Outline

1. Photoproduction in PYTHIA 8
2. Comparisons to HERA data
3. Ultraperipheral heavy-ion collisions
4. Summary & Outlook
Photoproduction in PYTHIA 8
Pythia 8

• A general-purpose Monte-Carlo event generator
• Current version 8.230, next release within a few weeks
• Main focus has been in pp, now extensions to ee, ep, pA, AA

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1. Hard process generation
   • Generate according to LO partonic cross section and PDFs
     (or feed in processes from external matrix element generator)

2. Parton showers
   • Generate Initial and Final State Radiation (ISR & FSR)
     according to DGLAP evolution equations

3. Multiparton interactions (MPIs)
   • Use regularized QCD 2 → 2 cross sections finite also at \( p_T \to 0 \)

4. Add beam remnants
   • Minimal number of partons to conserve colour and flavour
   • Fix momenta so that total momentum is conserved

5. Hadronization
   • Using Lund string model with color reconnection
   • Decays into stable hadrons
Photoproduction in ep

Photoproduction: Small photon virtuality $Q_{\gamma}^2 \lesssim 1 \text{ GeV}^2$ (cf. DIS)

- Factorize the flux of photons from the hard scattering (Weizsäcker-Williams)

\[ f_{\gamma}^l(x_{\gamma}) = \frac{\alpha_{\text{em}}}{2\pi} \left( 1 + \frac{1 - x_{\gamma}^2}{x_{\gamma}} \right) \log \left[ \frac{Q_{\text{max}}^2}{Q_{\text{min}}^2(x_{\gamma})} \right] \]

- Direct processes
  - Photon initiator of the hard process
  - No MPIs but FSR and ISR for hadron

- Resolved processes
  - Photon fluctuates into a hadronic state
  - Partonic structure described with PDFs
  - FSR and ISR for both sides, also MPIs
PDFs for resolved photons

Obtained through global DGLAP analysis (LEP data mainly)

\[
xf(x, Q^2)/\alpha_{\text{EM}} 
\]

- Some differences between analyses, especially for gluon
  ⇒ Theoretical uncertainty for resolved processes
- CJKL used as a default in PYTHIA 8, others via LHAPDF5 but only for hard-process generation
MPIs in PYTHIA 8

- Probability for MPIs from $2 \rightarrow 2$ QCD processes
- Partonic cross section diverges at $p_T \rightarrow 0$
  \[ \Rightarrow \text{Regulate the divergence with screening parameter } p_{T0} \]
  \[ \frac{d\sigma^{2\rightarrow2}}{dp_T^2} \propto \frac{\alpha_s(p_T^2)}{p_T^4} \rightarrow \frac{\alpha_s(p_{T0}^2 + p_T^2)}{(p_{T0}^2 + p_T^2)^2} \]

- $pp$: Power-law in $\sqrt{s}$
  \[ p_{T0}(\sqrt{s}) = p_{T0}^{\text{ref}}(\sqrt{s}/7 \text{ TeV})^\alpha \]
  \[ p_{T0}^{\text{ref}} = 2.28 \text{ GeV/c, } \alpha = 0.215 \]
  (Monash tune)

- $\gamma\gamma$: Logarithmic in $\sqrt{s}$
  \[ p_{T0}(\sqrt{s}) = p_{T0}^{\text{ref}} + \alpha \log (\sqrt{s}/100 \text{ GeV}) \]
  \[ p_{T0}^{\text{ref}} = 1.52 \text{ GeV/c, } \alpha = 0.413 \]
  (I.H., T. Sjöstrand, in prep.)

- Parametrization for $\gamma p$?
Comparisons to HERA data
Charged particle $p_T$ spectra in $ep$ collisions at HERA

H1 measurement

- $E_p = 820$ GeV, $E_e = 27.5$ GeV
- $< W_{\gamma p} > \approx 200$ GeV
- $Q_{\gamma}^2 < 0.01$ GeV$^2$

Comparison to PYTHIA 8

- Resolved contribution dominates
- Good agreement with the data using $p_{T0}^{\text{ref}} = 3.00$ GeV/c

$\Rightarrow$ MPI probability between $pp$ and $\gamma\gamma$

Charged particle $p_T$ spectra in $ep$ collisions at HERA

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Dijet photoproduction in $ep$ collisions at HERA

ZEUS dijet measurement

- $Q^2 < 1.0$ GeV$^2$
- $134 < W_{\gamma p} < 277$ GeV
- $E_{T}^{\text{jet1}} > 14$ GeV, $E_{T}^{\text{jet2}} > 11$ GeV
- $-1 < \eta^{\text{jet1,2}} < 2.4$

Different contributions

- Define
  $$x_{\gamma}^{\text{obs}} = \frac{E_{T}^{\text{jet1}} e^{\eta^{\text{jet1}}} + E_{T}^{\text{jet2}} e^{\eta^{\text{jet2}}}}{2yE_e}$$
  to discriminate direct and resolved processes
  (=x in $\gamma$ at LO parton level)

- At high-$x_{\gamma}^{\text{obs}}$ direct processes dominate

Dijet in $ep$ collisions at HERA

Pseudorapidity dependence of dijets

• Simulations tend to overshoot the dijet data by $\sim 10\%$
• $\sim 10\%$ uncertainty from photon PDFs for $x_{\gamma}^{\text{obs}} < 0.75$
Ultraperipheral heavy-ion collisions
Motivation: Nuclear parton distribution functions (nPDFs)

Data available for nPDF fits
- Fixed-target ($\nu$)DIS and DY
- Pions in dAu at RHIC
- Dijets in pPb at the LHC
- EW bosons at the LHC

⇒ Limited kinematic reach

⇒ Large uncertainties especially for gluon nPDFs
⇒ Uncertainty in the pQCD baseline for heavy-ion physics at the LHC

Ultra-peripheral heavy-ion collisions

- Large impact parameter $b \Rightarrow$ No strong interaction
- EM-field of nuclei described with quasi-real photons (EPA)
  - Flux of photons with low virtuality ($\Rightarrow$ Photoproduction)
    - Photon-photon (dileptons, light-by-light)
      $\Rightarrow$ Useful to calibrate the photon flux
    - Photon-nucleus (dijets, incl. hadrons, heavy flavours, ...)
      $\Rightarrow$ Can be used to probe nuclear PDFs

Photon flux from nuclei in impact-parameter $b$ space

- Obtained by a Fourier transformation of the time-dependent EM-field

$$x_\gamma f^A_\gamma(x_\gamma, b) = \frac{\alpha_{\text{EM}} Z^2}{\pi^2} \left[ \frac{x_\gamma m}{\hbar c} K_1 \left( \frac{x_\gamma b m}{\hbar c} \right) \right]^2$$

where $Z$ is nuclear charge, $m$ (per-nucleon) mass and $K_1$ modified Bessel function [Jackson, Classical Electrodyn., 2nd ed.]

Effective photon-photon luminosity

- Need to reject events with hadronic interactions
  - Reject events based on hard-sphere approximation
    ⇒ Possible to set up in PYTHIA 8
  - Use hadronic interaction probabilities based on nuclear overlap, e.g. STARLIGHT [Comput.Phys.Commun. 212 (2017) 258-268]
High-mass dimuons in ultraperipheral Pb+Pb at the LHC

\[
Pb+Pb \rightarrow \mu^+ + \mu^- + Pb^* + Pb^*
\]

- Data well described by STARlight MC
- Confirms EPA for Pb+Pb at the LHC

PYTHIA hard-sphere flux agrees with STARlight
- Small difference at high-\(W\) from nuclear density (\(\sim\) high-\(x_\gamma\))
Flux for photon-nucleus interactions

- Integrate over $b > 2R_A$ to reject hadronic interactions

$$x_\gamma f^A_\gamma(x_\gamma) = \frac{2\alpha_{EM} Z^2}{\pi} \left[ \xi K_1(\xi)K_0(\xi) - \frac{\xi^2}{2} (K_1^2(\xi) - K_0^2(\xi)) \right],$$

where $\xi = 2R_A x_\gamma m/\hbar c$

- Maximum $W_{\gamma Pb} \approx 2\sqrt{s}$ in HERA

Photo-nuclear dijet production

- ATLAS analysis [ATLAS-CONF-2017-011]
  - anti-$k_T$, $R = 0.4$, $p_T^{\text{lead}} > 20$ GeV, $p_T^{\text{jets}} > 15$ GeV, $|\eta| < 4.4$

- Event-level variables:

  $$m_{\text{jets}} = \sqrt{(\Sigma_i E_i)^2 - \left| \Sigma_i \vec{p}_i \right|^2},$$

  $$H_T = \Sigma_i p_{Ti},$$

  $$y_{\text{jets}} = \frac{1}{2} \log \left( \frac{\Sigma_i E_i + \Sigma_i p_{zi}}{\Sigma_i E_i - \Sigma_i p_{zi}} \right),$$

  $$x_A = \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}}$$
EPPS16 will be implemented to the next PYTHIA release

- The expected nPDF features visible in $x_A$: shadowing, etc...
- Nuclear modifications only in hard-process cross sections
Expected potential of the dijet data

- **PbPb, $\sqrt{s_{NN}} = 5.02$ GeV**
- **anti-$k_T, R = 0.4**
- $p_T^{\text{lead}} > 20$ GeV/c
- $m_{\text{jets}} > 35$ GeV

**NNPDF2.3 CJKL EPPS16**

**Resolved Direct**

**Ratio to NNPDF2.3**

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<td>1.00</td>
</tr>
</tbody>
</table>

**Dominant contribution**

- Large $x_A$: resolved
- Small $x_A$: direct

**Expected statistical error**

- Assume $L = 1$ nb$^{-1}$ for the measurement
- Clearly smaller than nPDF uncertainty

⇒ Potential to provide further constraints for nPDFs down to $x \approx 10^{-3}$
Dijet $\eta$ distribution

**Dijet kinematics**
- Due to soft $\gamma$ spektrum jets asymmetrically distributed in $\eta$
- No need to push for large $\eta$ to gain sensitivity to small $x$

Quantifying the impact of the data to nPDFs requires
- Finalized data
- NLO calculation for photoproduction of dijets
- Accurate description of photon flux from nuclei
Summary & Outlook
Summary

Photoproduction implemented into PYTHIA 8

- Automatic mixing of direct and resolved processes
- Full parton-level evolution (parton showers, MPIs)
- Agreement with HERA data, support for MPIs
- Can simulate UPCs by using heavy-ion specific photon flux (though not yet with nuclear target but with nPDFs)

Ultra-peripheral heavy-ion collisions

- Use dilepton production to calibrate the photon flux
- Can study photo-nuclear processes with LHC before EIC
- Dijets provide nPDF constraints down to $x \sim 10^{-3}$
- Number of potential observables, increased low-$x$ reach at lower $p_T$
Outlook

Things to do

• Merge UPCs with new heavy-ion machinery (Angantyr) recently introduced to PYTHIA 8
• Improve efficiency (currently optimized for ep)
• Hard diffraction for photoproduction (see I.H. on Friday)
  • Based on diffractive PDFs and dynamical rapidity gap survival from MPIs, extend to nuclear target
• Smooth merging of photoproduction and DIS
Backup slides
MPI and parton shower generation

Common evolution scale ($p_T$) for FSR, ISR and MPIs

- Probability for something to happen at given $p_T$

$$\frac{d\mathcal{P}}{dp_T} = \left( \frac{d\mathcal{P}_{\text{MPI}}}{dp_T} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp_T} + \sum \frac{d\mathcal{P}_{\text{FSR}}}{dp_T} \right)$$

$$\times \exp \left[ - \int_{p_T}^{p_T^\text{max}} dp'_T \left( \frac{d\mathcal{P}_{\text{MPI}}}{dp'_T} + \sum \frac{d\mathcal{P}_{\text{ISR}}}{dp'_T} + \sum \frac{d\mathcal{P}_{\text{FSR}}}{dp'_T} \right) \right]$$

where $\exp[...]$ is a Sudakov factor

(probability that nothing else has happened before $p_T$)

Simultaneous partonic evolution

1. Start the evolution from a scale related to the hard process
2. Sample $p_T$ values for each $\mathcal{P}_i$, pick one with highest $p_T$
3. Continue from the sampled $p_T$ until reach $p_{T\text{min}} \sim \Lambda_{\text{QCD}}$
Partonic evolution for resolved photons

DGLAP equations for photons

- Additional term due to $\gamma \rightarrow q\bar{q}$ splittings

$$\frac{\partial f_i^\gamma(x, Q^2)}{\partial \log(Q^2)} = \frac{\alpha_{\text{em}}}{2\pi} e_i^2 P_{i\gamma}(x) + \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z) f_j(x/z, Q^2)$$

where $P_{i\gamma}(x) = 3(x^2 + (1 - x)^2)$ for quarks, 0 for gluons (LO)

- Solution has two components:

$$f_i^\gamma(x, Q^2) = f_i^{\gamma, \text{pl}}(x, Q^2) + f_i^{\gamma, \text{had}}(x, Q^2)$$

- Point-like part from perturbative QCD
- Non-perturbative input required for the hadron-like part

$$f_i^{\gamma, \text{had}}(x, Q_0^2) = N_i x^{a_i} (1 - x)^{b_i}$$

Parameter fixed in a global analysis
Charged particle $\eta$ dependence in $ep$ collisions at HERA

\[ \text{H1} \]
\[ \text{Pythia 8.226} \]
\[ \text{resolved} \]
\[ \text{direct} \]
\[ p_T > 2.0 \text{ GeV/c} \]

\[ p_T > 3.0 \text{ GeV/c} \]

\[ \text{ratio to Pythia} \]

Dijet in $ep$ collisions at HERA


- Good agreement with the data
- Some sensitivity to MPIs with $x^\text{obs}_\gamma < 0.75$