Simulations of photo-nuclear dijets with Pythia 8 and their sensitivity to nuclear PDFs

DIS 2018

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April 17th, 2018

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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 (EIC)
  ⇒ Photoproduction implemented into PYTHIA 8
- Photo-nuclear processes in ultra-peripheral collisions can be used to probe the structure of nucleons (nuclear PDFs)

Outline

1. Photoproduction in PYTHIA 8
2. Comparisons to HERA photoproduction data
3. Ultra-peripheral heavy-ion collisions
4. Summary & Outlook
Photoproduction in PYTHIA 8
· A general-purpose Monte-Carlo event generator
· Current version 8.235, released a couple of weeks ago
· Main focus has been in pp, now extensions to ee, ep, pA, AA

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Event generation in PYTHIA 8

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

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

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

- 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)

- 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 $p_T \rightarrow 0$
  \[ \Rightarrow \text{Regulate the divergence with parameter } p_{T0} \]
  \[
  \frac{d\sigma^{2\rightarrow 2}}{dp_T^2} \propto \frac{\alpha_s(p_T^2)}{p_T^4} \rightarrow \frac{\alpha_s(p_{T0}^2 + p_T^2)}{(p_{T0}^2 + p_T^2)^2}
  \]

- **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 $e\text{p}$ 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**

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

**Different contributions**

- Define
  
  $$x_{\gamma}^{\text{obs}} = \frac{E_{T}^{\text{jet}1} e^{\eta^{\text{jet}1}} + E_{T}^{\text{jet}2} e^{\eta^{\text{jet}2}}}{2yE_e}$$

  to discriminate direct and resolved processes
  
  (= $x$ in $\gamma$ at LO parton level)
- At high-$x_{\gamma}^{\text{obs}}$ direct processes dominate

---

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)

The kinematic reach of the experimental input
The data in global fits in a \((x, Q^2)\) plane.
The LHC data opens a previously unexplored kinematic region.

\[
\begin{array}{c}
\times 10^{-1} \\
\times 10^{-2} \\
\times 10^{-3} \\
\times 10^{-4} \\
10^{-5}
\end{array}
\]

\[
\begin{array}{c}
10^0 \\
10^1 \\
10^2 \\
10^3 \\
10^4 \\
10^5
\end{array}
\]

- 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

Data available for nPDF fits

Ultra-peripheral heavy-ion collisions

- Large impact parameter $b \Rightarrow$ No strong interaction
- EM-field of nuclei described with quasi-real photons (EPA)
  $\Rightarrow$ Flux of photons with low virtuality (\(=\) 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

Ultra-peripheral heavy-ion collisions

[J. Nystrand’s talk on Monday]

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Photon-photon interactions

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

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

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

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
    \[ \Rightarrow \text{Possible to set up in PYTHIA 8} \]
  - 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

\[ \text{Pb+Pb} \rightarrow \mu^+ + \mu^- + \text{Pb}^* + \text{Pb}^* \]

- **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-\( x_\gamma \) )

[ATLAS-CONF-2016-025]
Photon-nucleus interactions

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

• Preliminary 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:

  $$m_{\text{jets}} = \sqrt{(\Sigma_i E_i)^2 - (\Sigma_i \vec{p}_i)^2}, \quad H_T = \Sigma_i p_{Ti}$$

  $$y_{\text{jets}} = \frac{1}{2} \log \left( \frac{\Sigma_i E_i + \Sigma_i p_{zi}}{\Sigma_i E_i - \Sigma_i p_{zi}} \right), \quad x_A = \frac{m_{\text{jets}}}{\sqrt{s}} e^{-y_{\text{jets}}$$
Differential photo-nuclear dijet distributions (Preliminary)

Preliminary data well described with γp from PYTHIA 6 and photon flux from STARLight

Nuclear PDFs and photon flux now included in PYTHIA 8

Direct processes dominate at $x_A \lesssim 10^{-2}$
Expected potential of the dijet data with ATLAS cuts

Photon PDF dependence

- Largest sensitivity ($\sim 10\%$) at $x_A > 0.1$
- Negligible effect at $x_A < 0.02$

Expected statistical error

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

$\Rightarrow$ Potential to provide constraints for nPDFs down to $x \approx 10^{-3}$ with the ATLAS cuts on jet kinematics
Dijets at lower $p_T$

Lower the jet $p_T$

- $p_{T_{\text{jet1}}} > 8$ GeV
- $p_{T_{\text{jet2}}} > 6$ GeV
- Similar cuts as in HERA
- Increase cross section and $x_A$ reach

Expected statistical error

- Sufficient statistics at $x_A > 2 \cdot 10^{-4}$ ($L = 1 \text{ nb}^{-1}$)
- Larger nPDF uncertainties due to smaller $Q^2$ and $x_A$
  ⇒ Enhanced potential to constrain nPDFs
- Possible to use other observables at lower $p_T$ (e.g. $\gamma$+jet)
Summary & Outlook
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
- ATLAS dijets can provide nPDF constraints down to $x \sim 10^{-3}$
- Number of potential observables, increased low-$x_A$ reach with lower $p_T$
Outlook

Ongoing work for UPCs and eA simulations in PYTHIA 8

- Improve UPC sampling efficiency (optimized for ep)
- Merge with new heavy-ion machinery (Angantyr) recently introduced to PYTHIA 8 [by L. Lönnblad and C. Bierlich]
- Study hard diffraction in $\gamma A$ using new implementation for photoproduction in ep [I.H., C. O. Rasmussen, T. Sjöstrand]
  - Based on diffractive PDFs and dynamical rapidity gap survival from MPIs
    [originally implemented for pp by C. O. Rasmussen, T. Sjöstrand]
- Smooth merging of photoproduction and DIS events
Backup slides
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 $\gamma \to q\bar{q}$ splittings

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

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

- Solution has two components:

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

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

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

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

$\frac{d\sigma}{d\eta}[\text{nb}]$

$p_T > 2.0 \text{ GeV/c}$

$p_T > 3.0 \text{ GeV/c}$

Dijet in $ep$ collisions at HERA


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