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Photo-nuclear collisions in Pythia 8

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We present the recent developments in simulations of ultra-peripheral collisions with the Pythia 8 Monte Carlo event generator. We first introducte the simulation framework and the discuss about available photon fluxes. Then we review the status of recent comparisons and tuning efforts to HERA photoproduction data which provide the baseline of photon-nucleon interactions. Then we present the vector-meson-dominance (VMD) based approach to model interactions between a real photon and a nucleus target applying the Angantyr model which provides a framework for simulate heavy-ion collisions in Pythia. We present predictions for inclusive UPC obserables, including charged-particle production and heavy-flavour mesons in kinematics similar to the preliminary measurements.

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1 Introduction

General-purpose Monte Carlo event generators provide complete simulations of high-energy collision events. The event generation typically starts by sampling the type and kinematics of the underlying hard scattering process, or by considering a minimum-bias like event without a hard trigger process. The event generation then proceeds by dressing up the highly virtual partons created in the partonic scattering process with parton showers (PS) that model the subsequent QCD and QED emissions according to DGLAP evolution equations. At the final step, the complete partonic final state is converted into a colour-neutral hadronic state using phenomenological hadronization models. In collision of two composite particles, one needs also to account for multiparton interactions (MPIs) and, in case of heavy ions, also for interactions between all nucleons inside the nucleus. In order to provide a complete picture of hadronic collisions, also diffractive and elastic processes are typically accounted for.

By definition, the UPC events contain one or two photons of low virtuality emitted by the charged beam particle(s). This enables to study either photon-photon ($\gamma\gamma$) or photon-hadron (γh) collisions. For the latter case there have been significant experimental efforts at the LHC and RHIC to study exclusive production of vector mesons already with proton and nuclear targets. In the more recent years there have been an increasing interest also towards inclusive scattering processes where the target hadron (or nucleus) break apart. While the event generators can be applied to $\gamma\gamma$ collisions and exclusive γh events, the inclusive processes are the ones where the whole event-generation chain has to be applied. As the photons emitted from charged hadrons with a condition of keeping the emitting particle intact are of low-virtuality, there are several components in the photon wave function that needs to be accounted for. In addition to acting as a point-like particle (direct), these may fluctuate into a hadronic state perturbatively (anomalous) or non-perturbatively (hadron-like). The latter two form the resolved-photon contribution which can be described with PDFs derived in a global analysis using experimental data. The different components are shown in figure 1.

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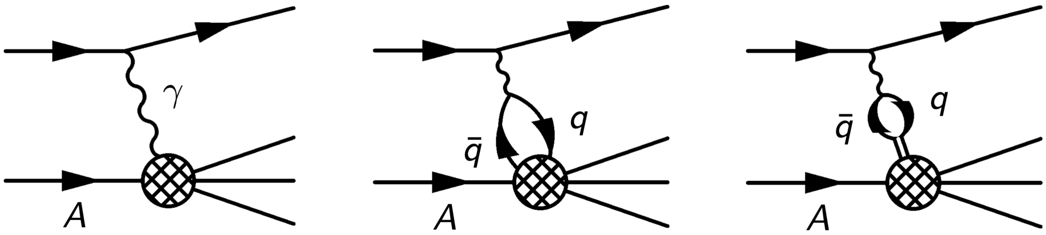

Figure 1 – Different contributions of real-photon wave function, direct, anomalous and hadron-like.

2 Pythia 8 for UPCs

Pythia 8 [1] was the first general-purpose event generator which provided capabilities to simulate UPCs. The basis is the framework orginally introduced to study photoproduction in electron-proton collisions where there are plenty of data available from the HERA collider for large variety of observables. The framework include possibility to generate MPIs in case of resolved-photon component and possibility to collapse back to an unresolved state in the parton shower to account for the anomalous component corresponding to perturbative $\gamma \to q\bar{q}$ splitting. In order to generate MPIs one need to have the QCD cross sections for $2 \to 2$ scatterings valid also at the $p_{\mathrm{T}} \to 0$ limit. In Pythia 8 the massless cross sections are regulated with the so-called screening parameter $p_{\mathrm{T},0}$ which is taken to depend on the collision energy. The value and the energy dependence is tuned to experimental data and, due to different geometric size, is expected to be different in γh compared to proton-proton case for which well constrained tunes exists.

First relevant extension was introduction of photon flux from protons and heavy nuclei. In the former case the default option is to use the virtuality (Q^2) dependent approximation derived by Drees and Zeppenfeld:

$$x f_{\gamma/\mathrm{p}}(x, Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{1 + (1-x)^2}{Q^2} \frac{1}{(1 + Q^2/Q_0^2)^4}, \quad (1)$$

where the last term correspond to the dipole form factor, where $Q_0^2 = 0.71$ GeV for protons, suppressing large-Q^2 part significantly compared to flux from point-like leptons with only $1/Q^2$ behaviour. As the kinematically allowed region in energy fraction x and Q^2 depend on the mass of the emitting particle, the Q^2-integrated photon energy-spectra is somewhat softer in case of hadrons as shown in figure 2. In case of heavy ions, it is more convenient to calculate the photon flux in impact-parameter space which is conjugate to the momentum space. In this case one can use point-like approximation for the flux and set a minimum allowed impact parameter, b_{min}, to cut out events where the nuclei would interact hadronically, see figure 2. The impact-parameter integrated flux then becomes

$$x f_{\gamma/A}(x) = \frac{\alpha_{\mathrm{em}} Z^2}{\pi} \left[2\xi K_1(\xi) K_0(\xi) - \xi^2 (K_1^2(\xi) - K_0^2(\xi)) \right] , \quad (2)$$

where Z is the charge of the nuclei, K_i the modified Bessel functions of the second kind and $\xi = b_{\mathrm{min}} x m_N$ with m_N being the per-nucleon mass. As shown in figure 2, the flux is now amplified with the factor Z^2 but due to requirement of keeping the nuclear intact, a lot softer than in case of charged leptons or protons. To make the framework flexible, Pythia 8 implementation allow user to supply their own flux e.g. to study effects from electromagnetic (EM) dissociation following from further EM-interactions between the two nuclei. Since the shape of the flux may vary significantly, there are a couple of overestimates implemented so that intermediate photon kinematics for each considered case can be efficiently sampled.

When the studied observable is rare enough one may approximate the photon-nucleus collisions simply by photon scattering of from a single nucleon. This would be the case for high-p_{T} jets or heavy-flavour hadrons. However, if one is interested in bulk observables, such as multiplicity distributions, one should account also for the additional interactions between the resolved photons and the other nucleons in the nucleus. As a first step to complete modelling of photon-nucleus (γA) collisions we have implemented the hadron-like part with an explicit vector-meson dominance (VMD) model [2]. In this implementation the hadron-like photon explicity fluctuate into a vector meson which then collides with the target nucleus, an interaction we can model with the Angantyr model [3], the heavy-ion module within Pythia 8.

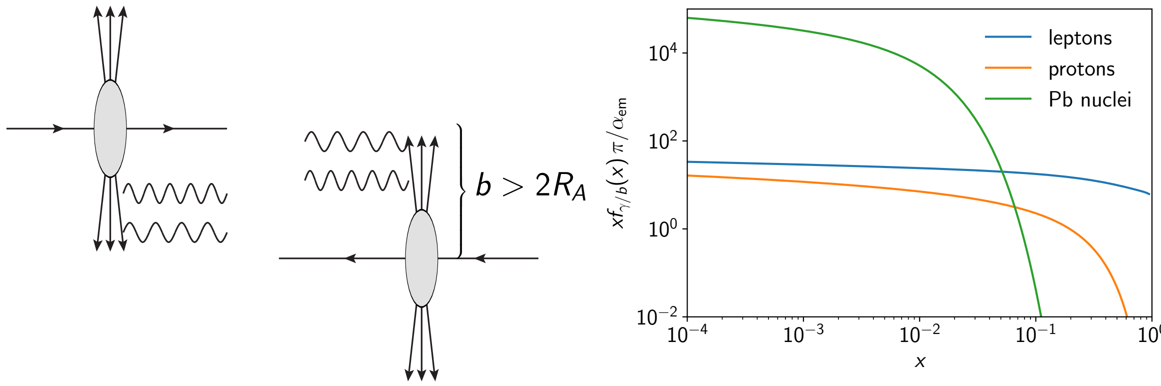

Figure 2 – Schematic picture of an ultraperipheral collision (left) and photon fluxes from leptons (blue), protons (orange) and lead nucleus (green).

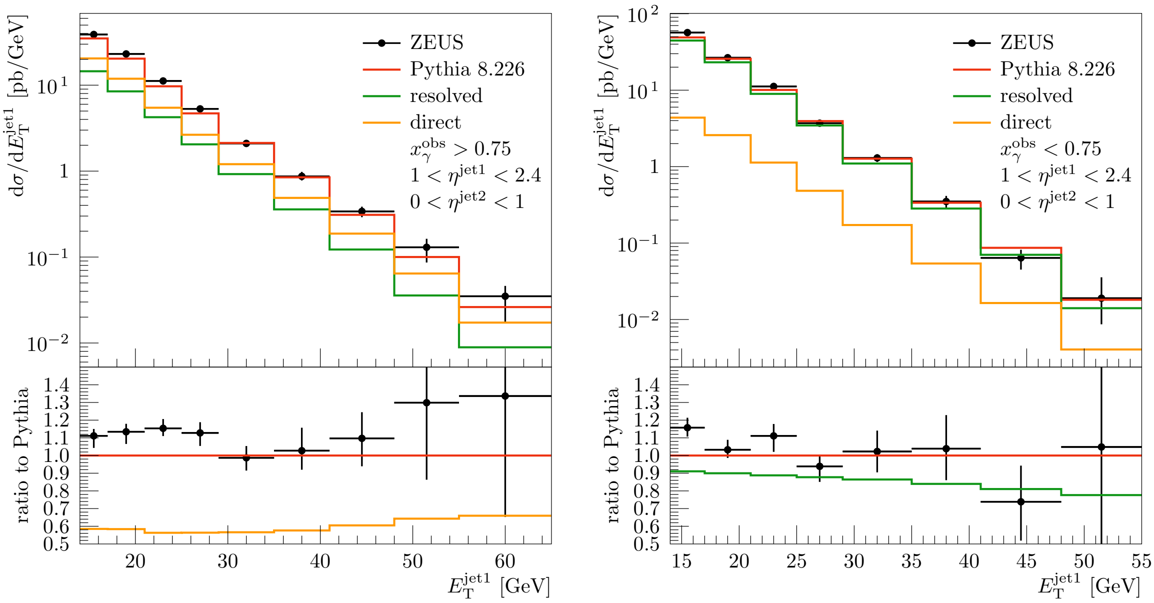

Figure 3 – The dijet photoproduction cross section for $x_\gamma^{obs} > 0.75$ (left) $x_\gamma^{obs} < 0.75$ (right) from ZEUS [4] and Pythia 8 (red). The resolved (green) and direct (yellow) contributions to the simulated cross sectiona are shown separately.

3 Results

3.1 HERA data validation and tuning

The first step in validating the photoproduction setup was to compare to jet photoproduction in electron-proton collisions. The di-jet production cross section is compared to an analysis by the ZEUS experiment [4] in figure 3 for two different kinematic regions, $x_\gamma^{obs} > 0.75$ and $x_\gamma^{obs} < 0.75$. The variable x_γ^{obs} can be calculated from the final-state jet kinematics and in the leading-order parton-level calculation would match the energy fraction of the initiating parton taken from the photon. In case of direct component this would always be 1 whereas the resolved photons covers region $x_\gamma^{obs} < 1$. Due to further PS emissions and hadronization effects, the relation is somewhat smeared but the distinction still have sensitivity to the process type as seen in figure 3 – the direct contribution dominates $x_\gamma^{obs} > 0.75$ selection and the resolved the $x_\gamma^{obs} < 0.75$ case. In total, the simulated cross section provide a good description of the data in both cases.

While the dijet cross section considered above is not very sensitive to the MPI parameters, these can have a big impact in multiplicity distribution and to 3- and 4-jet production [5]. Motivated by these findings we have started an effort to re-tune the MPI parameters specifically for γp system. In the first preliminary efforts we applied the ZEUS data for multi-jet production [6] to constrain $p_{T,0}$ parametrization.

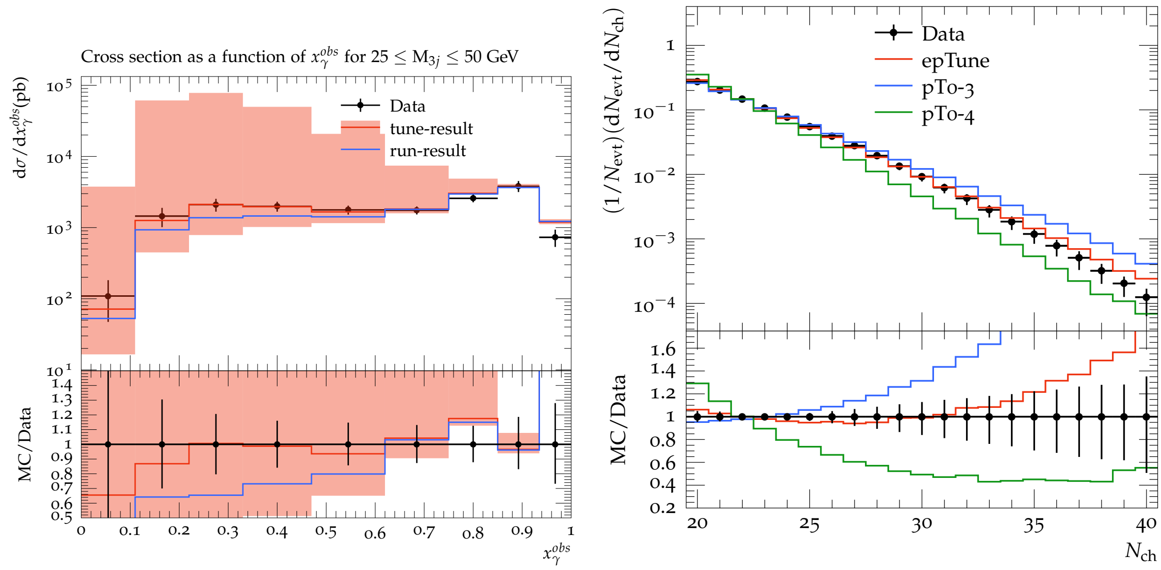

Figure 4 – Left panel: Cross section for 3-jet photoproduction from ZEUS [6], colored band quantify the parameter variations in the tune and lines the result of minimized interpolation (red) and a run with the resulting parameters (blue). Right panel: Multiplicity distribution in photoproduction compared to ZEUS data with two different $p_{\mathrm{T},0}$ values (blue: 3 GeV, red: 4 GeV) and with the tuned parameters using multijet data (red).

The tuning where done with the PROFESSOR 2 tool which constructs and interpolation grid within the defined parameter space for each observable and applies a minimization algortihm to find optimal values for the varied parameters. The width of the initial parameter variations and the resulting tune are shown in figure 4 for a sample of the applied ZEUS data. Encourangingly applying the parameters tuned to multi-jet production data improved also the description of a recent ZEUS analysis for multiplicity distribution compared to some first tuning attemps with H1 charge-particle p_{T} spectra [7] as shown in figure 4. In the ongoing tuning effort we plan to apply all of these data to find a new MPI tune for photoproduction which will also serve as a baseline for γA studies.

3.2 Multiplicities in UPCs at the LHC

While the photoproduction framework with proton target provide a good description of multiplicity distribution measured by CMS in UPCs with a proton target, it significantly underestimated the rate of high multiplicity events in the ATLAS analysis for UPCs with Pb-target [8]. Similar observation holds also for the normalized multiplicity as a function of rapidity – the multiplicity in lead-going direction was underestimated with the simulation accounting only a single nucleon target. Applying the VMD implementation we can account also the subsequent interactions between the resolved photon and the target nucleons in PYTHIA 8. While there are some modelling uncertainties present in the current implementation [2], the VMD model does seem to describe well the relative increase of high multiplicity events and the change in the rapidity distribution shown in figure 5.

3.3 Inclusive heavy-meson production

Another novel UPC observable with recent experimental interest is the inclusive production of heavy-flavor mesons. In particular CMS collaboration has produced two new analyses on inclusive D^0 production [9,10]. Similarly as with dijets, there are several processes producing charmed-hadron in the final state. The dominant channel is the photon-gluon fusion process where the heavy-quark pair is produced in the hard scattering of a direct photon and a gluon from the hadron target. Resolved photons have a significant charm content due to the anomalous component where the rate of $q\bar{q}$ pair production is proportional to the EM charge of the quark flavor. Thus a significant fraction of the final-state D mesons originate from resolved process with a (anti-)charm in the initial state. Charm-quark pairs can also be produced in the gluon splittings and flavor creation processes in the parton shower. As accounting for the accurate photon PDFs including the anomalous component is important for this observable, the setup with just

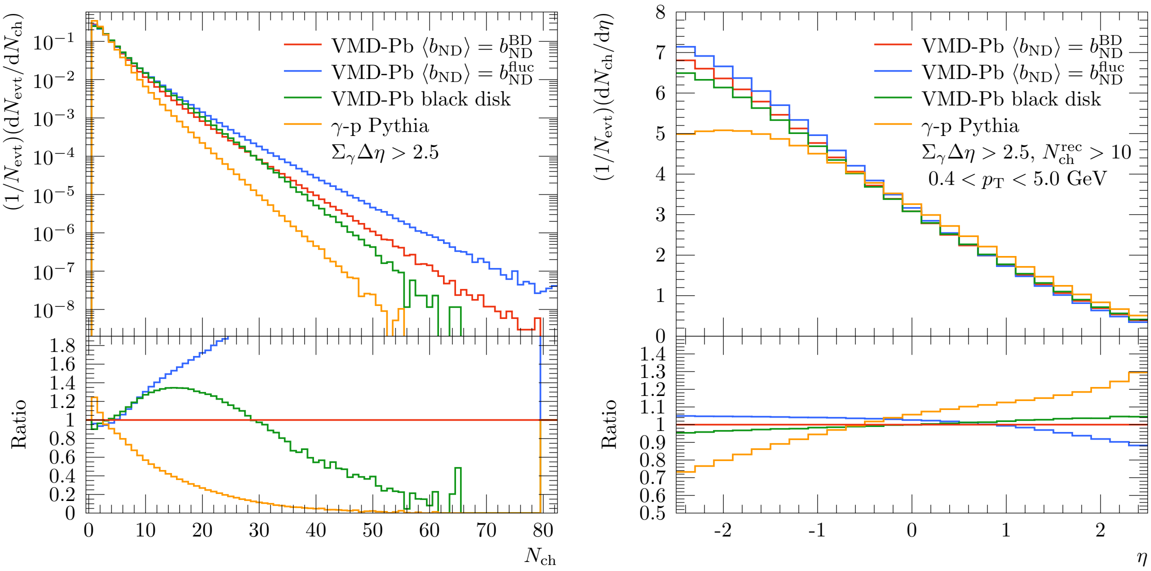

Figure 5 – The multiplicity (left) and rapidity (right) distributions in UPCs with cuts matching the ATLAS analysis [8]. The simulation with proton target (yellow) is compared to simulation with varying modeling assumptions detailed in Ref. [2] .

a single-nucleon target with all possible production channels is more realistic one than the VMD-model for the hadron-like contribution only.

Simulated double-differential cross section for inclusive D^0 production is presented in figure 6 with the same binning in transverse momentum p_T and rapidity y of the observed D^0-meson as in the CMS analyses. The frame is fixed in such a way that the intermediate photon has positive p_z and we notice that the cross section drops towards larger y especially at the highest p_T bin. This can be explained by the steeply falling photon energy spectrum as larger y and p_T require higher energy photon.

Experimentally inclusive UPC events are typically identified with a criteria of $0\mathrm{n}X\mathrm{n}$ which refers to not having any neutrons in the other zero-degree calorimeter (intact nucleus) and to have at least 1 neutron at the other side (resolved nucleus). To match with this criteria we should remove the contribution of the photon flux where the emitting nucleus breaks apart due to EM-dissociation effects. Thanks to the flexible flux-sampling in Pythia 8, we can also study these by supplying a flux calculation accounting for the EM break-up. Here we have used to point-like flux with and without EM dissociation [11] (equation (2)) where the probability for such additional interactions was taken from the STARLight generator [12]. The effect is milder at backward rapidities but increases towards larger rapiditi bins. This can again be explained with the steep photon-energy spectrum – requiring high-energy will bias photons to be closer to the emitting and the target nucleus leading to increased probability for EM interactions. Similarly as in case of dijets, the effect is significant and can be up to 60 % within the considered kinemtics.

4 Conclusions and Outlook

We have presented the current Pythia 8 capabilities to simulate ultra-peripheral heavy ion collisions with a focus in inelastic γh events. We updated on the validation and tuning efforts using HERA data to fix model parameters, discussed the implemented VMD modelling to account for multi-nucleon interactions and presented predictions for inclusive heavy-meson production cross sections. in the last observable we quantified the expected EM-dissociation effects and pointed out it's significance in the new CMS analysis for D^0 production. There are ongoing developments in many fronts, to finalized the tuning effort with wider range of HERA data, implement the full description of real photons in case of nuclear target and to include modelling of single-diffractive processes in UPCs.

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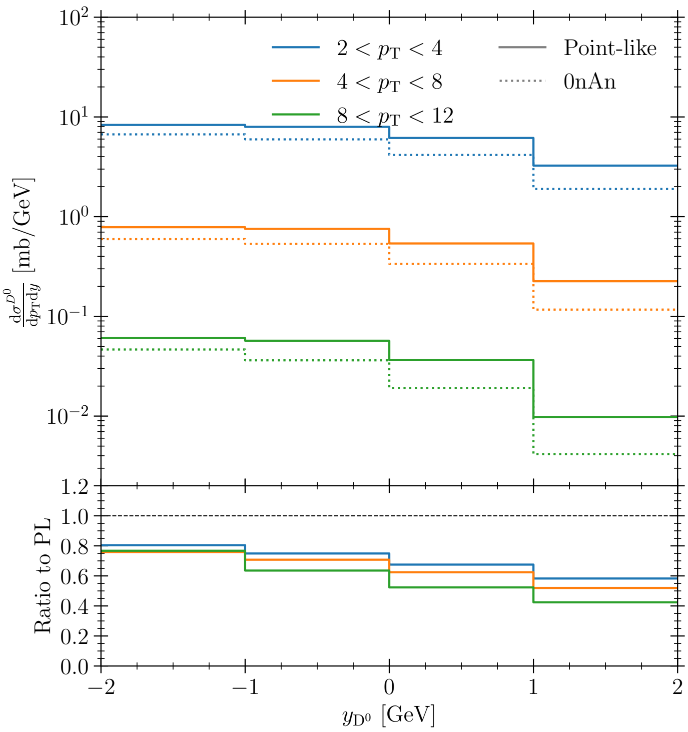

Figure 6 – Double-differential cross section for inclusive D^0 production in Pb+Pb UPCs at the similar kinematics as the preliminary CMS analysis [10]. The solid lines show the cross sections calculated with point-like flux without accounting for EM-dissociation and the dashed lines when these are accounted for. The lower panel shows the ration of these two for each p_T bin.

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