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Validation of the PB Framework in PYTHIA via Drell–Yan Production at NLO

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In this paper, we validate a novel method called PDF2ISR, which implements the initial-state shower approach of the Parton Branching framework within PYTHIA. The validation is performed by comparing Drell–Yan lepton-pair transverse-momentum distributions obtained with the standard Parton Branching initial-state shower approach and those generated using the PDF2ISR implementation in PYTHIA. The Drell–Yan p_{T} spectrum, particularly at low p_{T}, is highly sensitive to initial-state radiation, making it an ideal observable for this study. We find excellent agreement between the two approaches, confirming the successful implementation of the Parton Branching initial-state radiation method in PYTHIA.

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1. Introduction

To produce parton showers consistent with parton densities, a new approach for describing QCD initial-state radiation (ISR) in PYTHIA [1] has been developed. This approach implements the methodology of the Parton Branching (PB) framework [2, 3], which is based on transverse-momentum-dependent (TMD) parton distribution functions. The new method, referred to as PDF2ISR, is described in detail in [4]. In that reference, the validation of the new ISR shower implementation was performed using a dedicated toy model. In the present work, we extend this validation by applying the approach to simulations of real Drell–Yan pairs across a wide range of hadron collision energies and invariant masses.

2. The ISR shower modification in PYTHIA

Recent measurements and studies related primarily to the intrinsic motion of partons inside colliding hadrons have revealed trends that cannot be fully explained or described on a firm physical basis. These studies indicate that, in shower-based Monte Carlo event generators, the transverse momentum of partons, arising from their intrinsic motion within hadrons, tends to increase with the center-of-mass collision energy [5]. This behavior has been understood as a consequence of the exclusion of very soft gluon emissions in the MC event generators, implemented to avoid potential divergences [6–8].

Due to the interplay between intrinsic parton motion and multiple soft gluon emissions, the effective internal transverse momentum required to describe the data increases with collision energy. In contrast, using the PB method, no such dependence is observed [9]. This is because the cut limiting the lower value of parton transverse momentum is set below 0.01 GeV, ensuring that the softest gluon emissions are fully taken into account.

The PB method, using angular ordering, ensures full consistency of parton showers with parton densities. To achieve this consistency in the PYTHIA event generator, the same conditions—angular ordering, kinematic limits, and the scale choice in the strong coupling, α_s—were applied, resulting in a novel approach, PDF2ISR. To validate the method, this paper uses the PB PDF set at NLO, termed PB-NLO-2018 Set2 [10], which employs the transverse momentum of partons, q_{T}, from the angular ordering prescription as the argument for α_s. The consistency and validity of the method are tested with real events through Drell–Yan production in hadron–hadron collisions.

The Drell–Yan process, which produces a lepton pair via a virtual photon or Z boson, is particularly well suited for studying ISR effects. The final state consists of a colorless lepton pair, with no final state QCD radiation, unlike processes involving jets or heavy quarks. Consequently, any transverse momentum of the lepton pair (DY–p_{T}) originates primarily from initial-state QCD radiation or intrinsic parton k_T. Studying DY–p_{T} therefore allows ISR contributions to be isolated with minimal contamination.

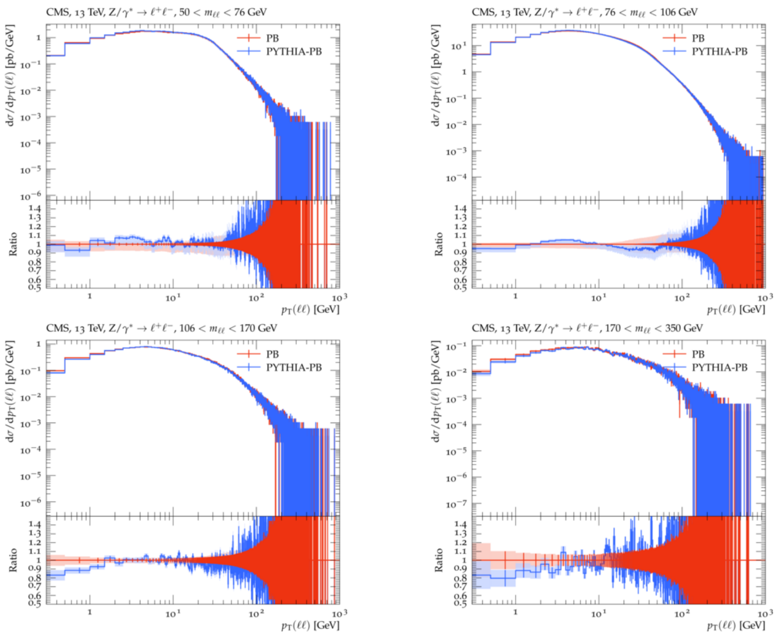

Figure 1: Cross section as a function of DY–p_{T} at $\sqrt{s}$ = 13 TeV obtained using PB method (red histogram) and the PDF2ISR method (blue histogram), shown for four invariant mass bins as measured in [15]. The binning in DY–p_{T} in the figure is smaller than that used in the measurements. The invariant mass ranges are shown in the histograms. The bands indicate the corresponding scale uncertainties.

3. PB-TMD vs PDF2ISR in the production of real DY pairs

Next-to-leading order (NLO) calculations of inclusive Drell–Yan production in hadron–hadron collisions are performed using MadGraph5_aMC@NLO [11]. The PB-NLO-2018 Set2 collinear parton densities are employed for the hard-process calculation within the PDF2ISR approach implemented in PYTHIA8. The resulting distributions from the PDF2ISR approach are then compared with those obtained from NLO hard scattering matrix elements matched with TMD parton distributions derived from PB-NLO-2018 Set2, combined with parton showers generated through PB evolution and included via the CASCADE3 event generator [12].

Using the Rivet tool [13], we study the DY lepton-pair p_{T} distributions obtained at LHC energies as well as at lower energies down to a few GeV. The results from CASCADE3 (labelled PB) are compared with those from the new PDF2ISR approach implemented in PYTHIA (labelled PYTHIA-PB). It has already been demonstrated that the PB method based on PB-NLO-2018 Set2 provides an excellent description of the data across a wide range of energies and invariant masses [9, 14].

Figure 1 shows a comparison of the PB and PYTHIA-PB predictions across four invariant mass bins measured by the CMS experiment at $\sqrt{s}$ = 13 TeV [15], using a finer binning in transverse momentum than the one used in the measurement. A very good agreement is observed between the two approaches in each mass bin over a wide range of lepton-pair transverse momenta.

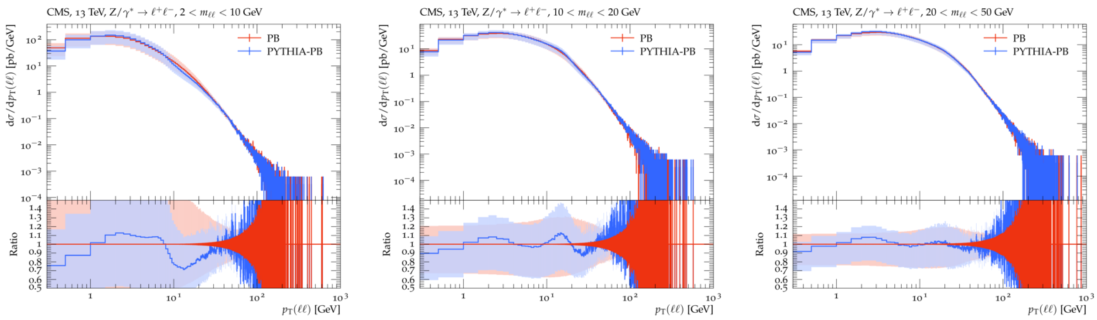

Figure 2: Cross section as a function of DY–p_T at $\sqrt{s}$ = 13 TeV obtained using PB method (red histogram) and the PDF2ISR method (blue histogram), shown for three low invariant mass ranges that have not been measured experimentally. The invariant mass ranges are shown in the histograms. The bands indicate the corresponding scale uncertainties.

To further test consistency, we analyzed the DY–p_T distributions at much lower invariant masses by applying only a loose cut on the single-lepton transverse momentum of 1 GeV (compared to 20 GeV in the CMS analysis). The results are shown in Figure 2 for three invariant mass ranges: 2–10 GeV, 10–20 GeV, and 20–50 GeV. Although consistent within the scale uncertainties, the distributions deviate somewhat from each other in the lowest mass bin shown (2–10 GeV). This deviation might be related to the enhanced production of charm and beauty resonances in this mass range and to the different treatments of heavy-quark masses in CASCADE3 and PYTHIA8. From these results, we conclude that the method remains reliable even at low invariant masses, when tested at the highest collision energy of 13 TeV.

Finally, Figure 3 shows the DY–p_T distributions in five very low invariant mass bins, using the transverse momentum binning from the E605 experiment [16]. The two methods exhibit very good agreement at low DY–p_T and in the lowest mass ranges, also at low center-of-mass energy of 38.8 GeV.

4. Conclusion

In this paper, we have extended the validation of the new PDF2ISR approach, implemented in PYTHIA, using real Drell–Yan lepton pairs produced in hadron–hadron collisions at NLO across different center-of-mass energies and invariant masses. Since the PDF2ISR approach is based on incorporating the PB–TMD framework within PYTHIA, the validation has been performed by comparing the DY–p_T distributions obtained with the PB method to those produced using PDF2ISR. An excellent agreement was confirmed across a wide range of center-of-mass energies and invariant masses.

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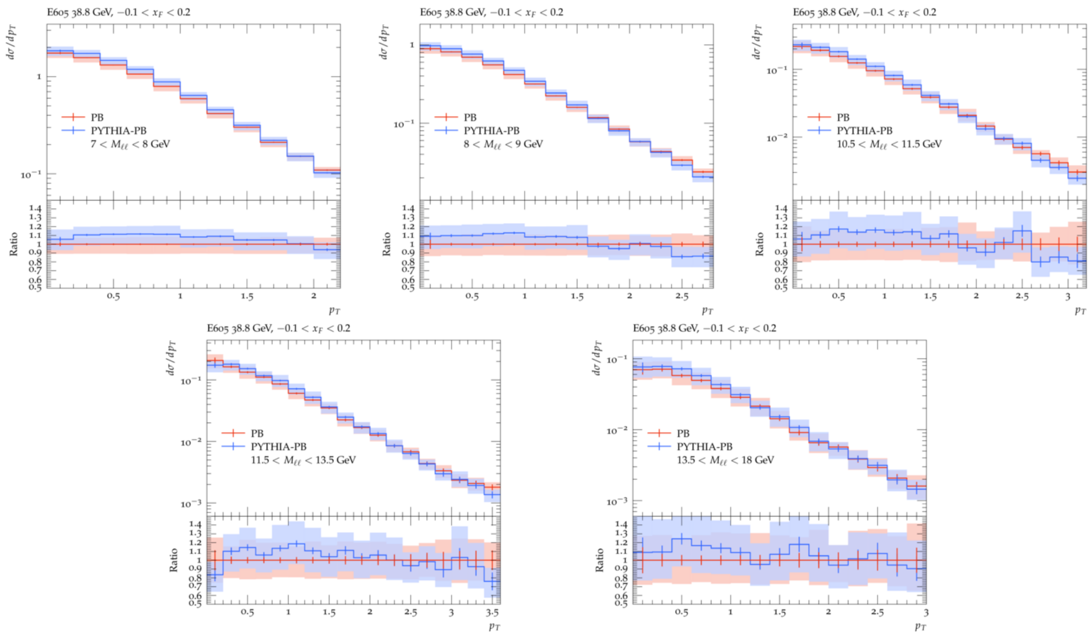

Figure 3: Cross section as a function of DY-$p_T$at $\sqrt{s}$ = 38.8 GeV obtained using PB method (red histogram) and the PDF2ISR method (blue histogram), shown for five invariant mass bins as measured in [16]. The invariant mass ranges are shown in the histograms. The bands indicate the corresponding scale uncertainties.

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