Measurement of four-jet production in proton-proton collisions at $\sqrt{s}$ = 7 TeV, UE tunes and double parton scattering

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Using the "Rivet" and "Professor" framework, we construct a new PYTHIA 6 tune using the CTEQ6L1 PDF and two new PYTHIA 8 UE tunes (one using CTEQ6L1 and one using the HER-APDF1.5LO). By simultaneously fitting CDF data from collisions at 300 GeV, 900 GeV, and 1.96 TeV together with CMS data for pp collisions at 7 TeV, we test the Underlying Event (UE) models and constrain their parameters, allowing for more precise predictions at 13 TeV and 14 TeV. The consistency of these new tunes with measurements of double-parton scattering (DPS) is also investigated. DPS-based tunes are also extracted, relying on differential cross sections as a function of correlation observables, for the production of exactly four jets in proton-proton collisions. From this measurement it is found that the addition of parton showers to fixed-order matrix element calculations describe the measured differential cross sections in only some regions of phase space and that including a contribution from double parton scattering in the models brings the predictions closer to the data.

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1. Introduction

A wide collection of data is currently available for studies of the Underlying Event (UE) in hadronic collisions. These are related to measurements performed at the CDF and the CMS experiment at different collision energies related to the hadronic activity as a function of the scale of the hard scattering. The peculiarity of these data lies on the fact, that they extend the usual UE analysis strategy, as described in [1], in order to disentangle the different contributions coming from parton shower, multiparton interactions (MPI) and beam remnants. This is performed by dividing the transverse region in two parts, according to their charged particle content: the one with larger activity is labelled as "Trans MAX", while the one with less activity is called "Trans MIN". New tunes, obtained with such detailed data, can properly describe the energy dependence of the UE and improve the prediction power at higher collision energies, e.g. 13 TeV as in the coming LHC phase.

In addition, recent data from CMS [2, 3] allow a study of the hardest part of the MPI, namely events with two hard scatterings inside the same collision: this occurrence is generally called Double Parton Scattering (DPS). By tuning event generators to these data, it is possible to estimate the contribution of DPS to be included in the available models, in order to best describe the measurements. The DPS contribution is generally quantified in the current models by σ_{eff} [4] value. The lower σ_{eff} is, the higher is the absolute cross section of a DPS event.

In Section 2, results are shown for the UE-based tunes while in Section 3, the DPS-based tunes are described. Finally, the compatibility between UE and DPS tunes is also checked and studied. Section 4 is dedicated to the conclusions.

2. UE tunes

By using CDF data [5] measured in p$\bar{\text{p}}$ collisions at different energies, 300, 900 and 1960 GeV, and CMS data [6] in pp collisions at 7000 Gev, new tunes have been extracted by the CMS Collaboration, with the machinery provided by the RIVET [7] and the PROFESSOR [8] software. They have used measurements of multiplicity and p_T sum of charged particles with $p_T > 0.4$ GeV in $|\eta| < 0.8$, in the Trans MIN and Trans MAX regions. A new tune has been extracted with the PYTHIA 6 [9] event generator, with the use of the CTEQ6L1 PDF set [10], and two new tunes have been measured with PYTHIA 8, with two different PDF sets, CTEQ6L1 and HERAPDF1.5LO [11]. The parameters, which have been varied in the tuning procedure, are related to the MPI contribution, the matter overlap distribution and the quantity of colour reconnection. The new tunes are able to better describe UE data at all energies and they are considered more reliable for extraction of predictions at higher energy, i.e. 13 TeV, for the coming data taking at LHC. Figure 1 and 2 show comparisons of charged particle multiplicities at 900 and 7000 GeV in the Trans MIN region with predictions obtained with old and new tunes of, respectively, PYTHIA 6 and PYTHIA 8. The plots clearly show that the description of data obtained with the new tunes is much better than the one provided by the old tunes, especially when going at low energy collisions. The whole collection of results and comparisons is widely documented in [12]. The new tunes also offer a very satisfying description of other observables measured in the central region, like energy

flow or particle multiplicity as a function of η, while some tension with the data is still present for the same quantities, measured in the forward region.
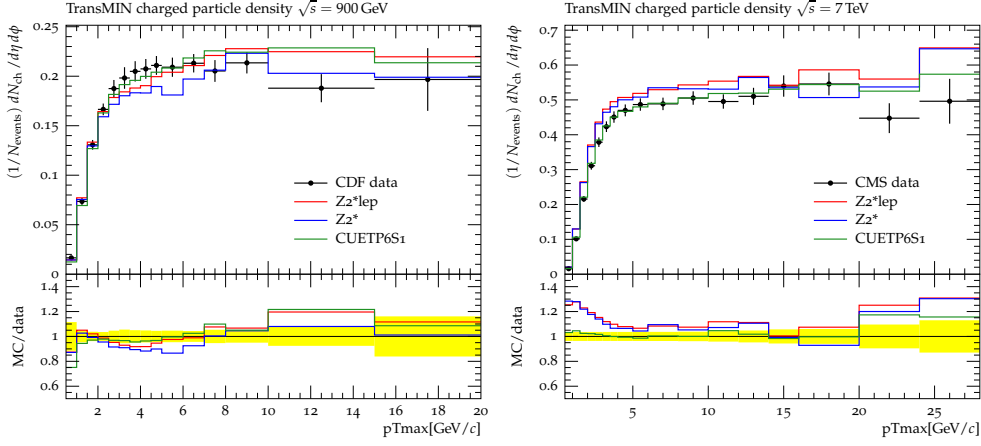
Figure 1: CDF data for p$\bar{\text{p}}$ at 900 GeV and CMS data for pp collisions at 7 TeV: density of charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ in the "transMIN" region as defined by the leading charged particle, as a function of p_T^{max}. The data are compared with PYTHIA 6 tune Z2*, Tune Z2*lep and the new CMS PYTHIA 6 tune.
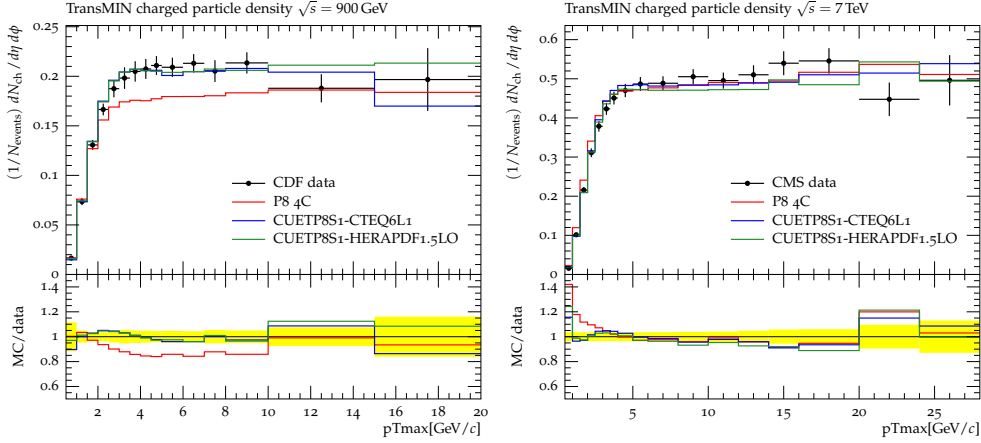
Figure 2: CDF data for p$\bar{\text{p}}$ at 900 GeV and CMS data for pp collisions at 7 TeV: density of charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 0.8$ in the "transMIN" region as defined by the leading charged particle, as a function of p_T^{max}. The data are compared with PYTHIA 8 Tune 4C and the two new CMS PYTHIA 8 tunes using CTEQ6L1 and the HERAPDF1.5LO.

3. DPS tunes

DPS observables are used for tuning as measured at the CMS experiment, in the W+dijet [2] and in the four-jet channels [3]. In particular, the four-jet channel selects an exclusive scenario with exactly four jets in the region $|\eta| < 4.7$, associated in pairs, as follows:

- Hard jet pair: 2 jets with $p_T > 50$ GeV

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- Soft jet pair: 2 jets with $p_T > 20$ GeV

This scenario has been measured in low pile-up data recorded in 2010 by the CMS experiment. Absolute differential cross sections have been measured as a function of p_T and η of the single jets; they show that only a proper admixture of ME and UE contributions can describe well the measurements [3]. Normalized differential cross sections have been also measured as a function of correlation observables between the jets in the final state. The correlation observables are defined as follows:

- the azimuthal angular differences between the jets belonging to the soft pair

$$\Delta\phi_{\text{soft}} = |\phi(\text{jet}^{\text{soft}_1}) - \phi(\text{jet}^{\text{soft}_2})|; \tag{3.1}$$

- the balance in transverse momentum of the two soft jets

$$\Delta^{\text{rel}}_{\text{soft}} p_T = \frac{|\vec{p_T}(\text{jet}^{\text{soft}_1}) + \vec{p_T}(\text{jet}^{\text{soft}_2})|}{|\vec{p_T}(\text{jet}^{\text{soft}_1})| + |\vec{p_T}(\text{jet}^{\text{soft}_2})|}; \tag{3.2}$$

- the azimuthal angle ΔS between the two dijet pairs, defined as:

$$\Delta S = \arccos\left(\frac{\vec{p_T}(\text{jet}^{\text{hard}_1}, \text{jet}^{\text{hard}_2}) \cdot \vec{p_T}(\text{jet}^{\text{soft}_1}, \text{jet}^{\text{soft}_2})}{|\vec{p_T}(\text{jet}^{\text{hard}_1}, \text{jet}^{\text{hard}_2})| \cdot |\vec{p_T}(\text{jet}^{\text{soft}_1}, \text{jet}^{\text{soft}_2})|}\right), \tag{3.3}$$

where $\text{jet}^{\text{soft}_1}, (\text{jet}^{\text{soft}_2})$ and $\text{jet}^{\text{hard}_1}, (\text{jet}^{\text{hard}_2})$ stand for the leading (subleading) soft and hard jet pairs, respectively. Figure 3 shows the measurements of the normalized cross section as a function of the correlation observables, compared to predictions obtained with different event generators, implementing different ME interfaced with PS and UE simulation. The PYTHIA 8 [13] and HERWIG ++ [14] event generators simulate Leading Order (LO) 2→2 processes, SHERPA [15] and MADGRAPH [16] generate LO 2→3 and 2→4 diagrams, respectively, while POWHEG [17] produces Next-to-Leading-Order (NLO) 2→2 processes, with an additional parton included at LO in the ME. The PS and UE contributions are simulated with the most updated tunes. Predictions from POWHEG are shown with and without the contribution of MPI. The measurements of the correlation observables show that, while $\Delta\phi$ and $\Delta^{\text{rel}}_{\text{soft}} p_T$ are well described by all predictions which include MPI, the shape of ΔS is more problematic to describe: none of the predictions is able to properly reproduce the data. In particular, the predictions from POWHEG without the simulation of MPI are far below the data at low values, where a DPS contribution is expected.

This is the motivation for tuning these observables in order to get the best description of DPS-sensitive measurements. The shape of $\Delta^{\text{rel}}_{\text{soft}} p_T$ and ΔS have been considered in the tune, with the same choice of parameters, as done for the UE. New tunes have been obtained with the PYTHIA 8 generator: one, CDPSP8S1-4j, which has varied only the overlap matter distribution function, leaving the other parameters equal to the Tune 4C, and one, CDPSP8S2-4j, which has considered all four UE parameters. Figure 4 shows the measurements, compared to the predictions obtained with PYTHIA 8 Tune 4C, with PYTHIA 8 Tune 4C with no MPI simulated and with PYTHIA 8 CDPSP8S1-4j. It can be seen that the agreement progressively improves when going from predictions without MPI until the new tune which simulates the MPI contribution that fits the data best.
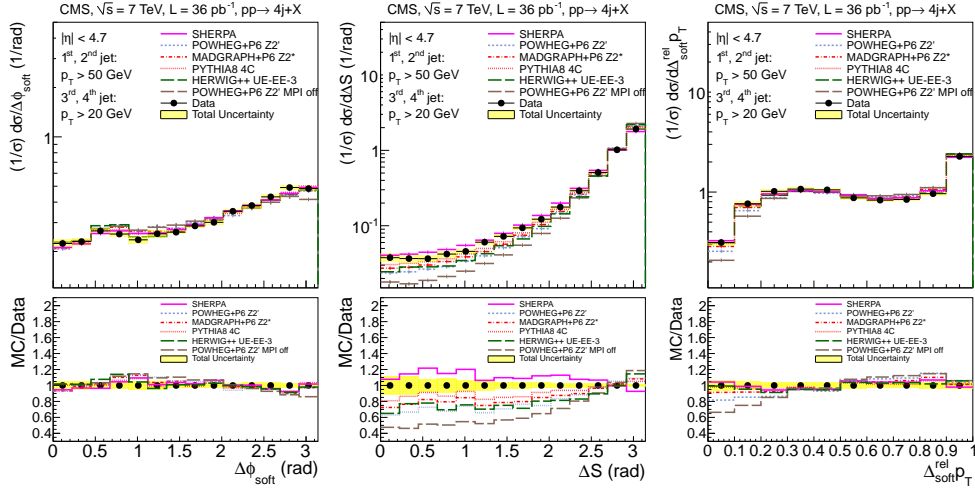
Figure 3: Normalized differential cross sections as a function of $\Delta\phi_{soft}$ (left), ΔS (middle), $\Delta_{soft}^{rel}p_T$ (right), compared to the predictions of POWHEG, MADGRAPH, SHERPA, PYTHIA 8 and HERWIG ++. A comparison with the POWHEG predictions interfaced with the parton shower PYTHIA 6 tune Z2' without MPI is also shown.
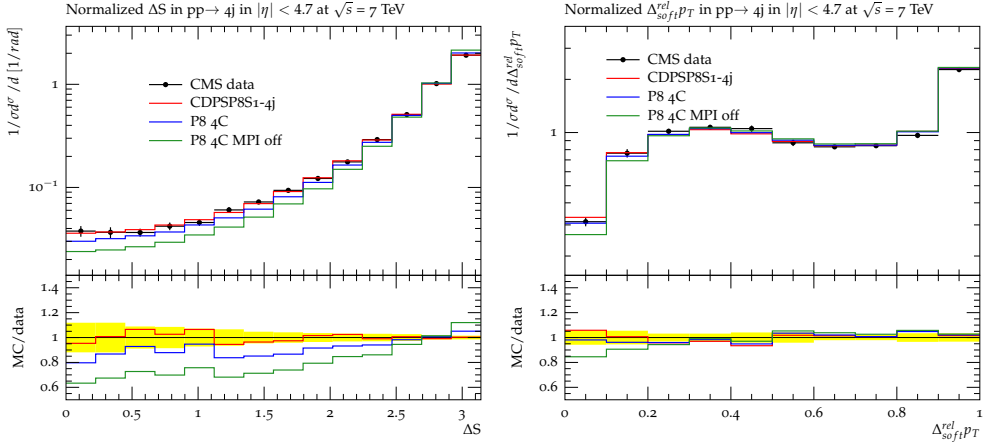
Figure 4: CMS data on the normalized distributions of the correlation observables ΔS (left) and $\Delta^{rel}p_T$ (right) measured in 4-jet production compared with PYTHIA 8 Tune 4C, Tune 4C with no MPI, and the new PYTHIA 8 tune.

In order to test the compatibility among UE- and DPS-based tunes, σ_{eff} values measured in all tunes have been compared: results are shown in Table 1. While UE-based tunes, 4C, CUETP8S1-CTEQ6L1 and CUETP8S1-HERAPDF1.5LO, predict a relatively high value of σ_{eff}, around 28-30 mb, translating into a low DPS contribution, in DPS-based tunes, CDPSTP8S1-4j and CDPSTP8S2-4j, σ_{eff} is lower with values around 19-22 mb. The DPS component, which describes the four-jet measurements best, turns out to be higher than the one predicted by the UE tunes.

In addition, UE data [18] have been compared to predictions obtained with the DPS-based tunes: they have shown an agreement only in some regions of the phase space, with an underestimation of the lower part of the spectrum [12]. Results indicate that the description of softer and harder parts

of the MPI within the same framework still shows some tension and might need some additional refinement.

Table 1: Values of σ_{eff} obtained for each PYTHIA 8 tune. The values of the old Tune 4C, the new UE tunes, CUETP8S1-CTEQ6L1 and CUETP8S1-HERAPDF1.5LO, and the new DPS tunes, CUETP8S1-4j and CDPSTP8S2-4j, are compared. The uncertainties are obtained from the Professor eigentunes and express the value of σ_{eff} to a variation of the χ^2 of the fit by one unit, with respect to the best tune.

PYTHIA 8 Tune	PYTHIA 8 σ_{eff} value (mb)
4C	30.3
CUETP8S1-CTEQ6L1	$27.8^{+1.2}_{-1.3}$
CUETP8S1-HERAPDF1.5LO	$29.1^{+2.3}_{-2.0}$
CDPSTP8S1-4j	$21.3^{+1.2}_{-1.6}$
CDPSTP8S2-4j	$19.0^{+4.7}_{-3.0}$

4. Conclusions

New tunes have been measured by the CMS Collaboration in order to best describe the energy dependence of UE data: measurements of charged particle multiplicity and p_T sum have been used as measured at the CDF experiment at 300, 900 and 1960 GeV and at the CMS experiment at 7000 GeV. A new set of UE parameters is available for PYTHIA 6, when the CTEQ6L1 PDF set is used, and two new sets have been released for PYTHIA 8, when respectively the CTEQ6L1 PDF set and the HERAPDF1.5LO are used. They offer a very good description of observables in the central region, like energy flow and particle multiplicity as a function of pseudorapidity, but some discrepancies are still present for measurements in the forward region.

Cross sections of jet spectra and correlation observables have been measured at the CMS experiment in a four-jet scenario: they have shown that a proper admixture of ME and UE contribution is crucial for a good description of the data. For the description of the correlation observables, the MPI contribution is strictly necessary in the simulation. New tunes have been constructed based on the four-jet correlation observables, bringing to values of σ_{eff} around 19-22 mb. These are lower with respect to new UE-based tunes which are around 28-30 mb. This indicates a slight tension in the description of softer and harder MPI within the same framework.

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