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Production of leading charged particles and leading charged-particle jets at small transverse momenta in pp collisions at $\sqrt{s} = 8\,\text{TeV}$

The CMS Collaboration*

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Abstract

The per-event yield of the highest transverse momentum charged particle and charged-particle jet, integrated above a given $p_{\mathrm{T}}^{\mathrm{min}}$ threshold starting at $p_{\mathrm{T}}^{\mathrm{min}} = 0.8$ and 1 GeV, respectively, is studied in pp collisions at $\sqrt{s} = 8\,\text{TeV}$. The particles and the jets are measured in the pseudorapidity ranges $|\eta| < 2.4$ and 1.9, respectively. The data are sensitive to the momentum scale at which parton densities saturate in the proton, to multiple partonic interactions, and other key aspects of the transition between the soft and hard QCD regimes in hadronic collisions.

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1 Introduction

The production of jets with large transverse momenta $p_{\mathrm{T}} \gg \Lambda_{\mathrm{QCD}} \approx 0.2\,\mathrm{GeV}$ in high-energy proton-proton (pp) collisions originates from the scattering of partons, a process described by perturbative quantum chromodynamics (pQCD), through the convolution of the parton-parton cross section with the density of partons inside the protons. Jet production in pp collisions at the LHC, at transverse momenta $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and in the pseudorapidity range $|\eta| < 3$, is well described by next-to-leading-order pQCD calculations [1–3]. However, most of the final-state hadrons produced in pp collisions arise from the hadronisation of quarks and gluons scattered through "semi-hard" interactions with exchanged momenta of $\mathcal{O}(1\text{–}3\,\mathrm{GeV})$. At such low values of p_{T}, the theoretical partonic cross section, $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^2 \propto \alpha_S^2(p_{\mathrm{T}})/p_{\mathrm{T}}^4$, where α_S is the strong coupling, becomes very large, and the integrated cross section $\sigma(p_{\mathrm{T}}^{\mathrm{min}}) = \int_{p_{\mathrm{T}}^{\mathrm{min}}} \mathrm{d}p_{\mathrm{T}}^2 d\sigma/\mathrm{d}p_{\mathrm{T}}^2$ exceeds the total inelastic pp cross section, σ_{inel}. At $\sqrt{s} = 8\,\mathrm{TeV}$, where $\sigma_{\mathrm{inel}} \approx 70\,\mathrm{mb}$ [4], this occurs at $p_{\mathrm{T}}^{\mathrm{min}}$ values of $\mathcal{O}(3\,\mathrm{GeV})$, much larger than the QCD scale, Λ_{QCD}, at which the strong coupling diverges [5, 6].

Model calculations of hadronic collisions often regulate such an infrared divergence through an effective parameter connected to the confinement scale of hadrons [7], such that the leading particle or leading jet production cross sections do not exceed the value of σ_{inel}. Contrary to the inclusive particle or jet production cross sections, the *leading* particle or *leading* jet production cross sections must indeed approach the total inelastic cross section because only one particle or one jet, the one with highest p_{T} in this case, is considered per event. In addition, at small p_{T}, the parton densities are probed in a region where parton recombination, i.e. saturation (see e.g. Ref. [8]), may occur.

Reference [9] proposes that the jet cross section integrated over $p_{\mathrm{T}} > p_{\mathrm{T}}^{\mathrm{min}}$ can be used as a probe of the transition from the perturbative ($p_{\mathrm{T}}^{\mathrm{min}} \gg \Lambda_{\mathrm{QCD}}$) to the non-perturbative region ($p_{\mathrm{T}}^{\mathrm{min}} \to \Lambda_{\mathrm{QCD}}$). According to Ref. [9], this transition should also be visible for cross sections defined in restricted ranges of pseudorapidity.

The results presented in this paper are based on measurements of single charged particles and jets reconstructed from charged particles alone. The advantage of jets is that they include more particles originating from the outgoing partons, while single charged hadrons carry only a fraction of the parent parton momentum. On the other hand, jets are sensitive to the underlying event (UE) activity, consisting of particles originating from multiple partonic interactions (MPI) and initial and final state radiation, while single leading tracks are not. The measurements based on leading particles and leading jets are therefore complementary. Throughout the text, the term "track-jets" refers to detector-level jets, reconstructed from charged-particle tracks observed in the detector, while "charged-particle jets" or just "jets" denote corrected, stable-particle level jets, consisting of stable charged particles from the final state.

In this paper, the yields, $r(p_{\mathrm{T}}^{\mathrm{min}})$, for pp collisions with a leading charged particle or a leading jet are measured as a function of a minimum transverse momentum, $p_{\mathrm{T}}^{\mathrm{min}}$:

$$r(p_{\mathrm{T}}^{\mathrm{min}}) = \frac{1}{N_{\mathrm{evt}}} \int_{p_{\mathrm{T}}^{\mathrm{min}}} \mathrm{d}p_{\mathrm{T}}^{\mathrm{lead}} \left(\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{lead}}} \right), \tag{1}$$

where N_{evt} is the number of selected events with a leading charged particle with $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$ and $|\eta| < 2.4$, and N is the number of events with a leading charged particle or a leading jet with transverse momentum $p_{\mathrm{T}}^{\mathrm{lead}}$ within $|\eta| < 2.4$ or 1.9, respectively.

2 Phenomenological models

The measured distributions are compared to the predictions of different hadronic interaction models whose tunable parameters (mostly connected to non-perturbative and semi-hard QCD phenomena) are obtained from comparisons to LHC data such as those on UE activity, inclusive multiparticle production and diffraction.

The PYTHIA 6 [10] and 8 [11] event generators tame the low-p_{T} behaviour of the leading-order pQCD 2→2 cross sections with a phenomenological factor [5, 6] $[\alpha_s^2(p_{\mathrm{T},0}^2 + p_{\mathrm{T}}^2)/\alpha_s^2(p_{\mathrm{T}}^2)]$ $[p_{\mathrm{T}}^4/(p_{\mathrm{T},0}^2 + p_{\mathrm{T}}^2)^2]$, where $p_{\mathrm{T},0}$ is a (tunable) infrared regulator that runs with centre-of-mass energy. The tunes 4C [12], CUET [13], and MONASH [14] are used, featuring different choices of the $p_{\mathrm{T},0}$ cutoff, proton transverse profile, and/or parton distribution functions.

The HERWIG++ [15] Monte Carlo (MC) includes a hard (pQCD 2→2 interactions) [16] and a soft (non-perturbative) component for multiple interactions [17]. The soft part is parametrised phenomenologically as $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^2 = A\mathrm{e}^{-\beta p_{\mathrm{T}}^2}$. The transition scale between the hard and the soft regions is set by the parameter $p_{\mathrm{T},0}$, obtained from fits to MPI and UE data, as well as to the effective cross section for double-parton scatterings. The parameters A and β are fixed by the requirements that the transverse momentum distribution be continuous at the matching scale $p_{\mathrm{T},0}$, and that the model reproduces the measured total cross section. Tune UE-EE-5C [18] is used.

The other two models, QGSJET-II [19] and EPOS [20, 21], are based on Regge-Gribov effective field theory [22], which allows for a consistent treatment of soft and hard scattering processes in terms of the same degrees of freedom (reggeons and pomerons), based on unitarity cuts of the corresponding elastic scattering diagrams. Perturbative parton-parton processes are obtained via "cut (hard) pomeron" diagrams, and multi-scattering phenomena (saturation, MPI) are implemented through various procedures [23]. The two models differ in their approximations for the collision configurations (with exact energy sharing imposed in the case of EPOS), and the treatment of diffractive and perturbative contributions (the effective soft-hard transition occurs at $p_{\mathrm{T},0} \sim 1.6\,\mathrm{GeV}$ for QGSJET-II and at $p_{\mathrm{T},0} \sim 2\,\mathrm{GeV}$ for EPOS). Finally, in contrast to other MCs, EPOS includes also collective expansion effects in the final state that boost the final p_{T} distribution of the produced hadrons. It is worth to highlight that, for all MC models, the (centre-of-mass energy dependent) $p_{\mathrm{T},0}$ cutoff plays a very similar role to the "saturation scale" (Q_{sat}), which controls the onset of gluon fusion effects in the parton densities [24].

3 Experimental analysis

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator sampling hadron calorimeter are located within the volume of the solenoid.

The inner silicon tracker measures charged-particle trajectories ("tracks" in the following) within the pseudorapidity range $|\eta| < 2.5$. It provides an impact parameter resolution of about 100 μm and a p_{T} resolution of about 0.7% for 1 GeV tracks at $\eta = 0$ [25]. A more detailed description of the CMS detector, together with definitions of the coordinate system and kinematic variables can be found in Ref. [26].

The data analysed in this study were collected during a dedicated proton-proton run with an integrated luminosity of 45 $\mu\mathrm{b}^{-1}$ at a centre-of-mass energy of $\sqrt{s} = 8\,\mathrm{TeV}$. This run has a low instantaneous luminosity and a low probability (∼2%) of multiple pp interactions occurring in

the same bunch crossing (pileup). Pileup events are rejected by requiring exactly one vertex, following the method described in Ref. [27].

Minimum bias events were selected online with the TOTEM T2 telescopes that are placed symmetrically at about 14 m on both sides from the interaction point. These telescopes detect charged particles with $p_T > 40$ MeV produced in the angular range of $5.3 < |\eta| < 6.5$ [28]. The minimum bias trigger, defined by the requirement of the presence of at least one track candidate in either of the T2 detectors [29], has an efficiency close to 100% [27] for events where a charged particle is produced within the T2 acceptance. According to the PYTHIA 8 and QGSJETII-04 [19] generators, about 91–96% of the total inelastic cross section at $\sqrt{s} = 8$ TeV is seen by T2 [4]. The present analysis follows the procedure described in Ref. [27], where more details are given on the trigger, data selection, and correction procedures.

Corrections for the contribution of background events triggered by T2 but without a charged primary particle in the T2 acceptance are estimated with simulated events from PYTHIA 8 and EPOS. These models were found to enclose the measured pseudorapidity distributions of charged particles in the forward region [27]. The average corrections for the two models vary from 4% and 1% at $p_T^{min} \approx 1$ GeV to 7% and 5% at $p_T^{min} \approx 45$ GeV, for the track and track-jet analysis, respectively. The deviation of PYTHIA 8 and EPOS from the average correction is taken as an estimate of the systematic uncertainty related to the T2 trigger efficiency; it is less than 0.7% for the leading track measurement and varies between 0.1 and 1.0% for the leading track-jet measurement [27].

Events are selected offline by requiring the presence of a leading track in the region $|\eta| < 2.4$ with $p_T > 0.4$ GeV. These events are used to normalise the integrated distributions in both the leading track and the track-jet measurements. Track-jets are reconstructed offline from tracks with $p_T > 0.1$ GeV and $|\eta| < 2.4$, clustered by using the anti-k_T algorithm [30–32] with a distance parameter of 0.5. The track-jet momentum is determined from the sum of all track momenta in the track-jet. The pseudorapidity restriction $|\eta^{jet}| < 1.9$ assures that the track-jet is contained within the tracker acceptance.

Detailed MC simulations of the CMS and T2 detectors are based on GEANT4 [33]. Simulated events are processed and reconstructed in the same manner as collision data. For the correction of detector effects, as well as for comparison with models, we use both the PYTHIA 6 [10] (version 6.426) event generator with tune Z2* [34] and the PYTHIA 8 (version 8.153) generator with tune 4C. The final correction is obtained by averaging those from the two generators.

The data are corrected to the stable-particle level, which is defined to include primary charged particles with lifetimes of $c\tau > 1$ cm, either directly produced in the pp collisions or from decays of particles with shorter lifetimes. According to this definition, K_S^0 and Λ hadrons are considered stable. Generated events are selected at the stable-particle level if at least one charged particle with $p_T > 40$ MeV is present within the range $5.3 < |\eta| < 6.5$, and at least one charged particle with $p_T > 0.4$ GeV is found within $|\eta| < 2.4$. In each event, the highest-p_T charged particle within $|\eta| < 2.4$ and $p_T > 0.8$ GeV is selected as the leading particle. Charged particles are clustered into jets by using the anti-k_T algorithm with a distance parameter of 0.5 with no restriction on p_T or η. The leading charged-particle jet is then defined as the charged-particle jet with the highest p_T above 1 GeV and $|\eta^{jet}| < 1.9$.

The average systematic uncertainty in the track reconstruction efficiency is taken to be 3.9% [35]. Its effect is studied by randomly rejecting 3.9% of the tracks and then repeating the analysis. In the jet analysis, for tracks with low p_T, the rejection probability is taken as 15% for $p_T < 1$ GeV. However, since the measurement is integrated over p_T, it is nearly insensitive to even such large

values of the rejection probability. The resulting uncertainty varies between 0.4% and 3.7% for the leading charged particle analysis and between 2% and 12% for the leading jet analysis. The larger uncertainties correspond to higher $p_{\mathrm{T}}^{\mathrm{min}}$.

The p_{T} distribution of leading track-jets is unfolded to the stable-particle level by applying the iterative procedure [36] implemented in ROOUNFOLD [37] in order to correct for the jet reconstruction efficiency and for migrations in jet p_{T}. Thanks to the good p_{T} resolution of the reconstructed tracks a simple correction for the track-finding efficiency is found to be sufficient for obtaining the p_{T} distribution of leading charged particles. The PYTHIA 6 and PYTHIA 8 MC models are used to generate the response matrices and efficiency corrections, and the average correction from the two generators is used to obtain the p_{T} distributions at stable-particle level. The corrections vary between 5% and 10% at $p_{\mathrm{T}} \approx 1\,\mathrm{GeV}$, to 10% and 40% at $p_{\mathrm{T}} \approx 45\,\mathrm{GeV}$, for the charged particle and the jet measurements, respectively. The deviation from the average is taken as an estimate of the systematic uncertainty related to the correction procedure. This uncertainty varies from 0.6 to 3% for the leading charged particle analysis, and from 2 to 10% for the leading jet analysis, depending on $p_{\mathrm{T}}^{\mathrm{min}}$.

The systematic uncertainties are summarised in Table 1.

Table 1: The systematic uncertainties for the leading charged particle ($0.8 < p_{\mathrm{T}}^{\mathrm{min}} < 50\,\mathrm{GeV}$) and leading jet ($1 < p_{\mathrm{T}}^{\mathrm{min}} < 50\,\mathrm{GeV}$) measurements.

Source	Uncertainty (%)	
	Leading charged particle	Leading jet
T2 trigger efficiency	0.7	0.1–1.0
Tracking efficiency	0.4–3.7	2–12
Correction procedure	0.6–3.0	2.0–10
Total	0.7–4.6	2.5–16

The per-event yields, defined in Eq. (1), are obtained experimentally as

$$r(p_{\mathrm{T}}^{\mathrm{min}}) = \frac{1}{N_{\mathrm{evt}}} \sum_{p_{\mathrm{T}}^{\mathrm{lead}} > p_{\mathrm{T}}^{\mathrm{min}}} \Delta p_{\mathrm{T}}^{\mathrm{lead}} \left(\frac{\Delta N}{\Delta p_{\mathrm{T}}^{\mathrm{lead}}} \right), \tag{2}$$

where N_{evt} is the number of events with a leading charged particle within $|\eta| < 2.4$ and with $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$, $\Delta p_{\mathrm{T}}^{\mathrm{lead}}$ is the bin width, and ΔN is the number of events with a leading charged particle or leading jet in the bin.

4 Results

Figure 1 shows the integrated distributions for the leading charged particle and leading jet events for $p_{\mathrm{T}}^{\mathrm{min}} > 0.8$ and $1\,\mathrm{GeV}$, respectively. The distributions fall steeply at large transverse momenta, and by construction approach unity at small $p_{\mathrm{T}}^{\mathrm{min}}$. The turnover from a relatively flat to a steeply-falling distribution takes place between 1 and 10 GeV. However, the turnover point is different for the leading charged particles and the leading jet measurements. This reflects the fact that when particles are clustered into jets, more energy from additional particles is collected within the jet cone. In fact, when the jet cone size is reduced, the leading jet distribution approaches the leading charged particle distribution.

In Fig. 1 (left plots) the normalised cross sections as a function of $p_{\mathrm{T}}^{\mathrm{min}}$ are compared to the predictions of the event generator PYTHIA 6 with tunes Z2* and CUET, as well as with the default version of PYTHIA 6, both with and without MPI. Also shown is the impact of turning off the

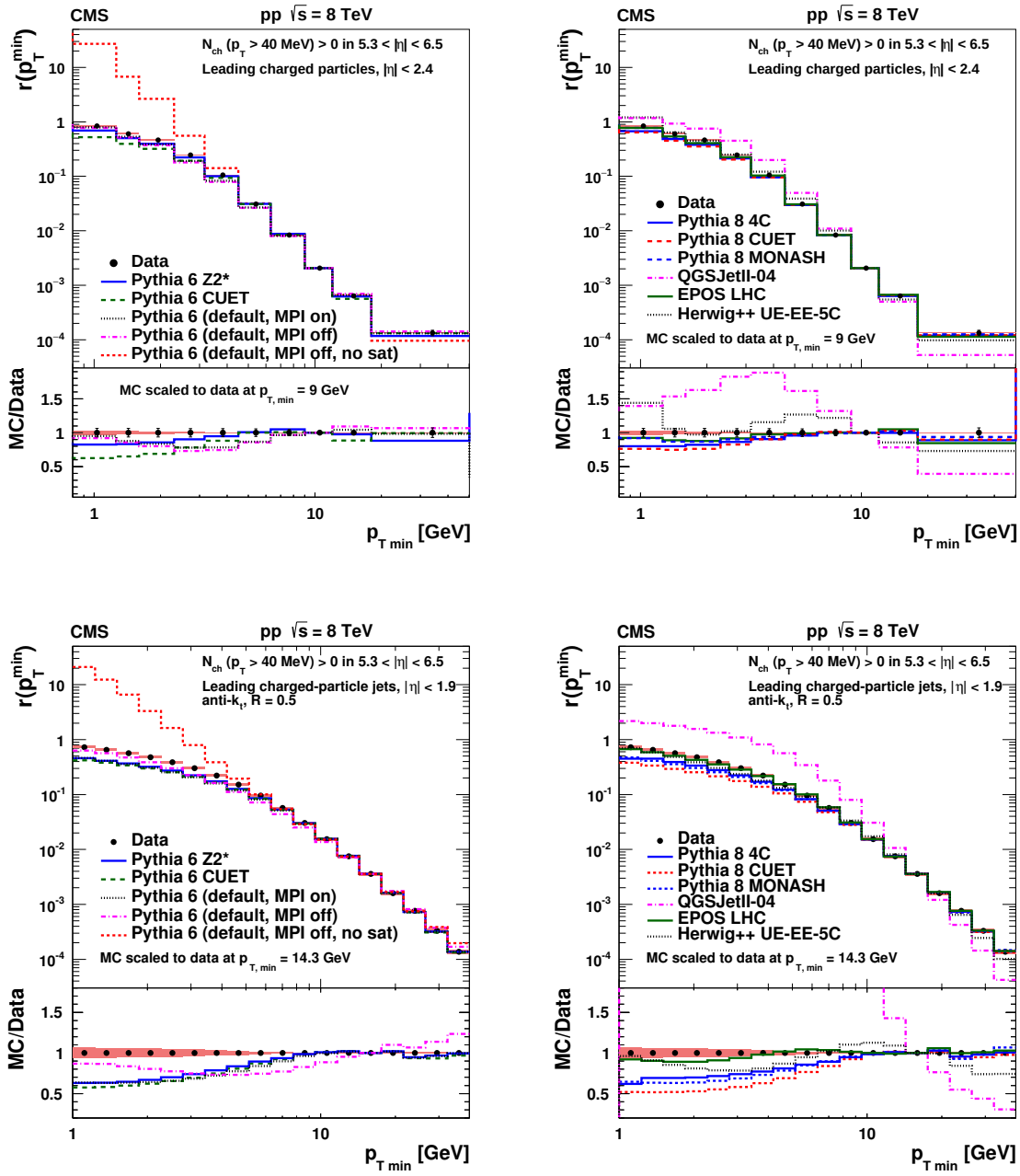

Figure 1: The integrated yield, $r(p_{\mathrm{T}}^{\mathrm{min}})$, of events with a leading charged particle within $|\eta| < 2.4$ (top) and with a leading jet within $|\eta| < 1.9$ (bottom), as a function of $p_{\mathrm{T}}^{\mathrm{min}}$. The data are compared to predictions from several PYTHIA 6 tunes (left) and various other event generators (right). The lower panels show the ratios of the MC and the data yields (MC/Data). The error bars indicate the statistical uncertainty and the red shaded area (only visible in the ratio plots) represents the systematic uncertainty. The predictions are scaled to the measured value of $r(p_{\mathrm{T}}^{\mathrm{lead}} > 9.0\,\mathrm{GeV})$ (top) and 14.3 GeV (bottom). The prediction from PYTHIA 6 with MPI off and no parton saturation is not shown in the MC/data ratio plot (left) because of the large disagreement with the data.

regularisation of the cross section, labeled "PYTHIA 6 (default, MPI off, no sat)". At low $p_{\mathrm{T}}^{\mathrm{min}}$, the distribution predicted by this latter model differs by more than one order of magnitude from predictions with the regularised cross section. The normalisation of the MC curves is fixed in the perturbative region to the measured values of $r(p_{\mathrm{T}}^{\mathrm{lead}} > 9.0\,\mathrm{GeV})$ and $r(p_{\mathrm{T}}^{\mathrm{lead}} > 14.3\,\mathrm{GeV})$ for the leading charged particle and the leading jet distributions, respectively.

In Fig. 1 (right plots) the leading charged particle and leading jet data are compared with PYTHIA 8 with tunes 4C, CUET, and MONASH, HERWIG++ (version 2.7.0) with tune UE-EE-5C, EPOS (version 1.99) with LHC tune, and QGSJETII-04.

The leading charged particle and leading jet cross sections are best described by EPOS, which deviates only by up to 10% from the data at very low $p_{\mathrm{T}}^{\mathrm{min}}$ and reproduces the data well for $p_{\mathrm{T}}^{\mathrm{min}} > 4\,\mathrm{GeV}$. The event generator HERWIG++ (UE-EE-5C tune) describes the leading jet cross sections fairly well, but does not reproduce the transition from large to small p_{T} in the leading charged particle cross section. The event generators PYTHIA 6 (Z2* and CUET tunes) and PYTHIA 8 (4C, CUET, and MONASH tunes) predict a somewhat different shape for the measured distributions at small p_{T}.

The comparison of the MC predictions for MPI switched on and off indicates that the effect of MPI is small for leading charged particles. However, when clustering particles into jets, the additional particles from MPI play a role, and a large difference is seen when such interactions are switched off in the simulation as in Fig. 1 (bottom left); this brings PYTHIA 6 closer to the data at low $p_{\mathrm{T}}^{\mathrm{min}}$.

The predictions with MPI and saturation turned off (dashed curves in Fig. 1, left plots) exhibit a significant deviation from the data at small p_{T}.

In general, PYTHIA and HERWIG++ describe the trend of the measured distributions but fail to reproduce the details in the $\mathcal{O}$(1–5 GeV) region, which calls for an improvement in their modelling of the transition from the non-perturbative to perturbative regime.

5 Summary

The integrated yields of events with a leading charged particle or a leading charged-particle jet with p_{T} above a given $p_{\mathrm{T}}^{\mathrm{min}}$ threshold, starting at $p_{\mathrm{T}}^{\mathrm{min}} = 0.8$ and 1 GeV, respectively, have been measured in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ in a data sample corresponding to an integrated luminosity of $45\,\mu\mathrm{b}^{-1}$. The particles and jets are measured in the pseudorapidity ranges $|\eta| < 2.4$ and 1.9, respectively.

The yields are found to be relatively flat in the $p_{\mathrm{T}}^{\mathrm{min}}$ region around 1 GeV—where the fixed-order perturbative parton-parton cross section diverges in the absence of any mechanism that saturates or unitarises the pQCD scattering—followed by a steep decrease for $p_{\mathrm{T}}^{\mathrm{min}} > 10\,\mathrm{GeV}$. The flattening behaviour observed at very low $p_{\mathrm{T}}^{\mathrm{min}}$ is best described by EPOS, which deviates by at most 10% from the data. The comparison of the data with different phenomenological predictions of hadronic interaction models may help to improve the description of the transition between the perturbative and non-perturbative QCD regimes, which is dominated by the effects of parton density saturation and multiple partonic interactions.

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