Particle multiplicity in proton–proton collisions with ALICE

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Abstract. Proton–proton collisions at the LHC will be studied with the ALICE detector, not only as a benchmark for the comparison with heavy-ion reactions, but also as a mean to study important aspects of pp physics in the new energy domain probed by the LHC. A report will be given here on the potentialities of ALICE in the study of the global properties of pp events, and especially of their multiplicity. This will be one of the main issues in pp physics where, because of the special features of its design, ALICE will be competitive with the other LHC experiments.

1. Introduction

ALICE [1, 2, 3] has several features that make it an important contributor to proton–proton physics at the LHC [4]. Its low magnetic field (B<0.5 T) and the low material thickness in the tracker ($\simeq$10% of a radiation length) determine a rather low p_t cut-off (0.1–0.25 GeV/c). Moreover, its design allows particle identification over a broad momentum range, powerful tracking with good resolution from 100 MeV/c to 100 GeV/c, and excellent determination of secondary vertices.

With such features ALICE will be able to explore very effectively the properties of minimum-bias events at $\sqrt{s}$ =14 TeV, such as the distributions of charged tracks in multiplicity, pseudorapidity and transverse momentum, in the total sample of events and in any eventual subclasses.

The knowledge of these properties in a new energy domain is interesting in itself, for a detailed understanding of Pomeron-exchange mechanism and for clarifying problems connected with the discrepancies observed at lower energies in the multiplicity distributions [5, 6, 7]. However, it is also an important input to estimate the background for the experiments searching for rare signals (as the Higgs or SUSY particles), and will provide reference data for comparison with heavy-ion reactions [8]. For these reasons a proton–proton program is considered an integral part of the ALICE experiment, initially designed as a dedicated heavy-ion experiment at the LHC.

In this paper we will present some predictions for minimum-bias event properties as they will be measured with the Inner Tracking System (ITS) and the TPC detector of ALICE. Special attention will be given to the measurement of the charged-hadron multiplicity. Various estimators of the multiplicity, involving the Silicon Pixel Detector (SPD) of the ITS will be

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compared, and the effect of the resolution in the reconstruction of the vertex position will be discussed.

Finally we will discuss the correlation of $\langle p_t \rangle$ with multiplicity in minimum-bias data. Results from other experiments at colliders, especially CDF and E735 at Tevatron, will be taken as a reference.

2. Multiplicity and $dN/d\eta$ reconstruction

In ALICE the measure of the charged-particle multiplicity and the reconstruction of the pseudorapidity will be performed with the Silicon Pixel Detector (SPD) (the two innermost layers of the Inner Tracking System [9]) in the central region, and with the Forward Multiplicity Detector (FMD), a set of five rings of silicon strips (see section 3.13 of ref. [10]), at forward rapidities.

Thanks to the total η-coverage of SPD ($|\eta|$ <2 with the first layer; $|\eta|$ <1.4 with the second one) and FMD (-3.4< η <-1.7 and 1.7< η < 5.1), in ALICE one can measure the charged-particle multiplicity over 8.5 η-units.

Here we report on the measurement of the charged-particle multiplicity and the reconstruction of the $dN/d\eta$ distribution in pp interactions as can be performed by using the Silicon Pixel Detector only (for a discussion on the potentialities of the multiplicity and $dN/d\eta$ reconstruction with the FMD see ref. [11]).

The two pixel layers of the SPD have a cylindrical symmetry around the beam axis and are located at a radial distance from the nominal beam position of r_1 $\simeq$4 cm and r_2 $\simeq$7 cm, respectively.

The position of the interaction vertex along the beam direction (z), which has a r.m.s. of $\simeq$ 5.3 cm, can be reconstructed using an algorithm that exploits the correlation between the reconstructed points in these two layers [12]. The efficiency of this algorithm increases with multiplicity and saturates at 100% already for multiplicity $\simeq$ 6. The resolution on z_{vertex} improves as the multiplicity increases, its average value being around $\simeq$160 μm.

Two different estimators of the multiplicity at midrapidity have been developed for the SPD: 1) the number of clusters N_c on each pixel layer; 2) the number of "tracklets" N_t, where each tracklet is defined starting from a cluster on layer 1 and looking for a companion cluster on layer 2 in alignment with the reconstructed primary vertex, within a fiducial window.

In order to study the efficiencies and accuracies of the two methods, a Monte Carlo sample of pp events has been generated with PYTHIA 6.150 [13, 14], where the parameters of the multiple-parton-collision scenario have been tuned according to ref. [15]. A full tracking and event reconstruction has been carried out using the ALICE offline framework, AliRoot (see chapter 4 of ref. [10]), in order to properly take into account the smearing due to experimental acceptance and detector effects.

Results of similar studies performed with PbPb events are thoroughly discussed in [11, 16]. The main differences in the pp case come from the following points:

- In a low multiplicity environment the statistical fluctuations produced by the background are no longer negligible compared to the signal.
- The low number of tracks introduces inefficiency in the vertex determination [12]. Therefore the reconstructed primary vertex position is not always available for the tracklet method, and it must be replaced with its nominal position. In such cases, and also when the vertex is reconstructed with rather large error, a bias affects the multiplicity estimated with the tracklet algorithm, that may also not converge. On the other hand, these problems related to the vertex determination do not affect the cluster method.

The correlation between the generated and reconstructed multiplicity in our Monte Carlo sample is shown in figure 1. The multiplicity is evaluated in the central unit of η ($|\eta| < 0.5$).
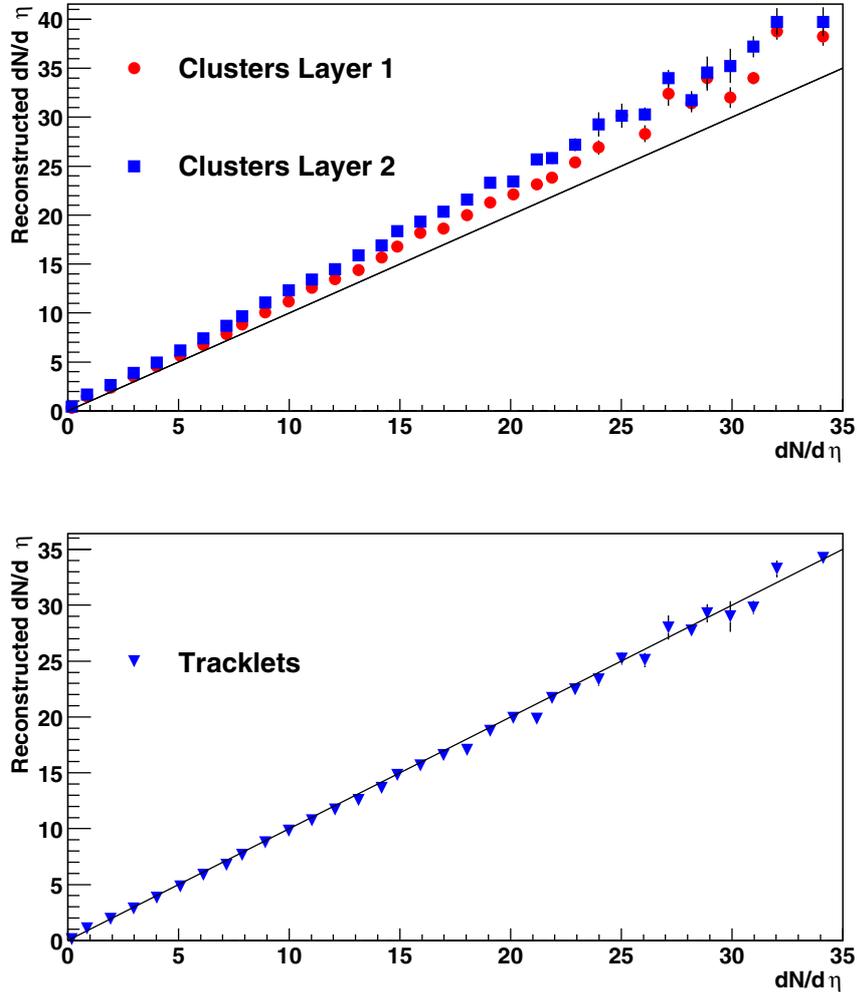
Figure 1. Number of clusters in layers 1 and 2 of SPD (top) and number of tracklets (bottom) in the central unit of η as a function of the generated $dN/d\eta$. The straight line corresponds to the ideal case of a perfect reconstruction.

It can be seen that the tracklet multiplicity is very close to the real one, whereas the clusters production is affected by the background (noise, secondary interactions), especially in the second layer. This can be seen also in figure 2, where the ratio between reconstructed and generated multiplicity is shown for both methods. All the generated events have been considered in this figure, where a clear inefficiency of the tracklet method is shown at very low multiplicity, as a consequence of the unavailability of the primary vertex position. On the other hand, the ratio is almost constant and greater than one in the case of clusters for both layers.

In figure 3 the same ratio is shown again, only for the tracklets, but only events with reconstructed primary vertex position are considered. In this case the ratio is close to 100% up to very low multiplicity, whereas the cluster efficiency (not shown) is not changed. The value of the ratio is higher than in the PbPb case [16], because in the case of pp collisions the lower average multiplicity allows to enlarge the size of the fiducial window where clusters are associated to form a tracklet.

The multiplicity distribution reconstructed with tracklets in the range $|\eta| < 1.4$ (the full
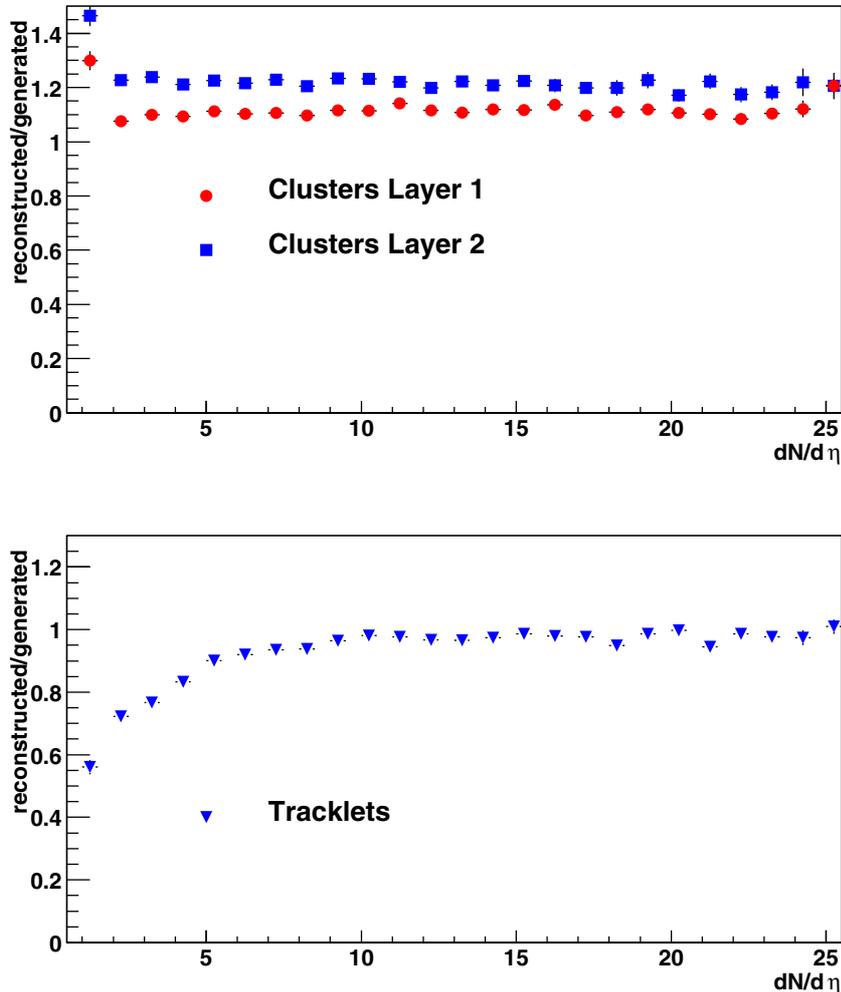
Figure 2. Ratio of reconstructed and generated multiplicity as a function of the generated $\mathrm{d}N/\mathrm{d}\eta$ for clusters (top) and tracklets (bottom). All events have been considered, including those with no determination of the primary vertex position.

SPD acceptance) is superimposed in figure 4 to the multiplicity distribution af all generated events. There is a good agreement between the two distributions, apart from the region at very low multiplicity, where the algorithm for the primary vertex reconstruction and the tracklet algorithm are both inefficient.

The relative errors on the reconstructed multiplicity are shown in figure 5 as a function of the generated multiplicity, for all the considered methods, based on cluster and tracklet counting. The multiplicity is evaluated in the full SPD acceptance ($|\eta| < 1.4$). As expected, the relative error is worse for the clusters in the second layer (central plot), and is better for tracklets (lowest plot). The relative errors decrease as multiplicity increase, and become $\simeq 5$–6% at large multiplicity.

Finally, the reconstructed $\mathrm{d}N/\mathrm{d}\eta$ is shown in figure 6. Only events with multiplicity larger than a defined cut are selected for the analysis, in order to exclude events without reconstructed vertex position. It can be seen that the tracklet reconstruction is very good in the range $|\eta| < 1$, whereas outside this range its efficiency is smoothly decreasing. Also, the inefficiencies
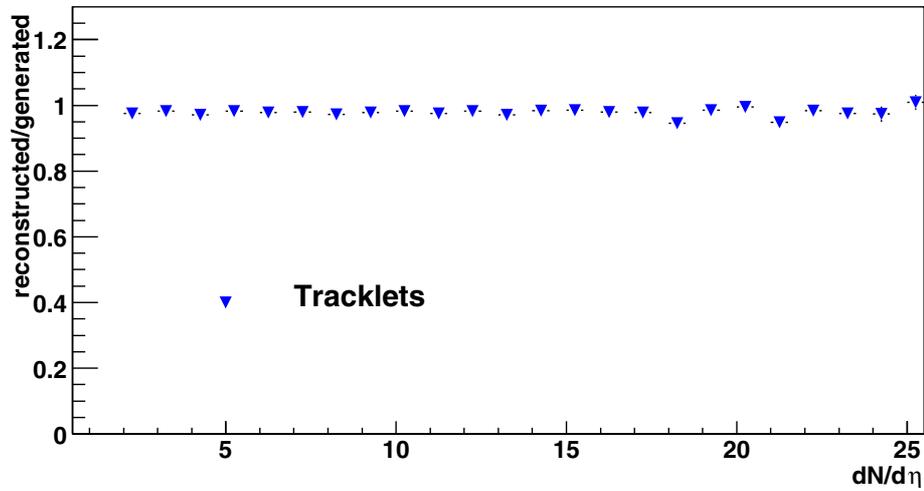
Figure 3. Ratio of reconstructed and generated multiplicity as a function of the generated $dN/d\eta$ just for tracklets, and considering only the events where the primary vertex position has been reconstructed.
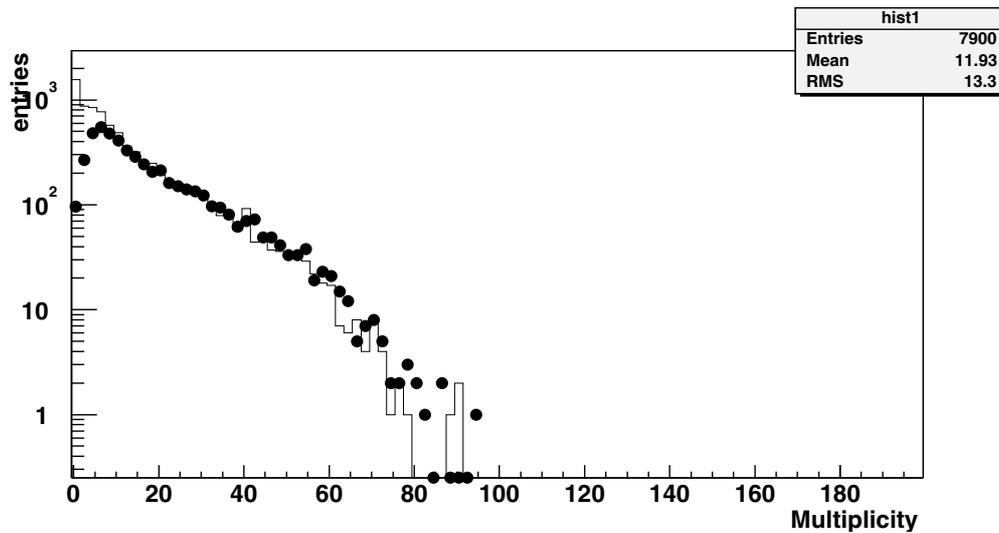

Figure 4. Comparison of the generated multiplicity distribution (solid line) in the SPD acceptance $|\eta| < 1.4$ with the multiplicity distribution reconstructed with tracklets (full circles).

corresponding to the geometrical holes of the SPD are not visible. Both these effects are due to the broad dispersion of the longitudinal position of the primary vertex.

On the other hand, the $dN/d\eta$ reconstructed with clusters show in both layers a large background which is not flat as a function of the pseudorapidity, showing a clear increase with $|\eta|$. This result is consistent with naïve expectation.
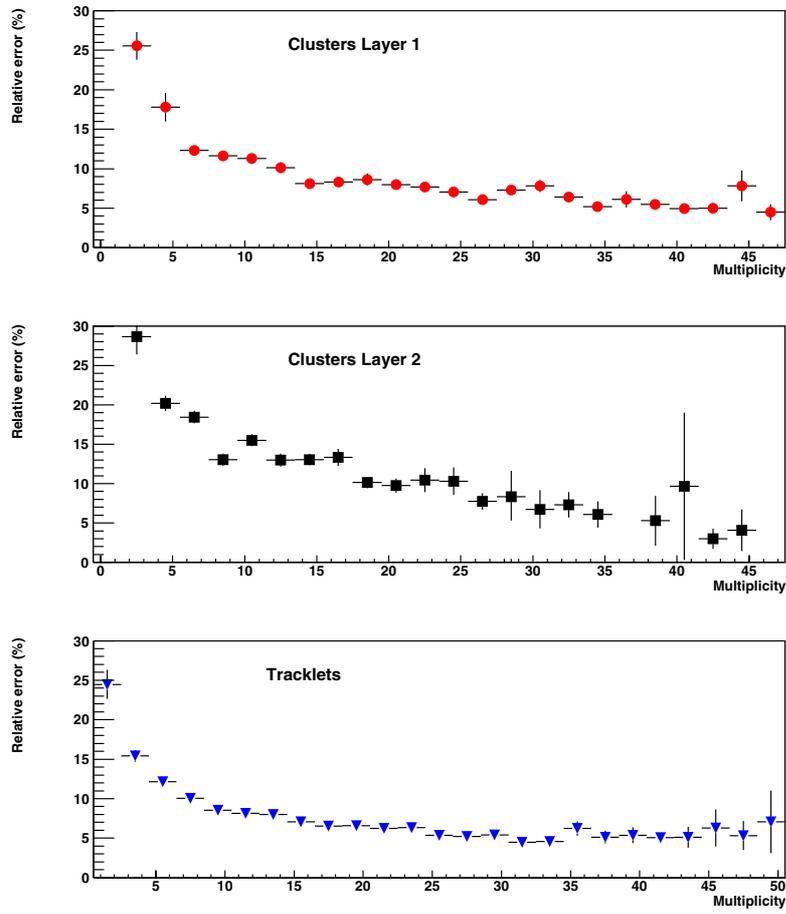
Figure 5. Relative error on the multiplicity (in the SPD acceptance) as a function of the generated one, when using clusters or tracklets as multiplicity estimators.
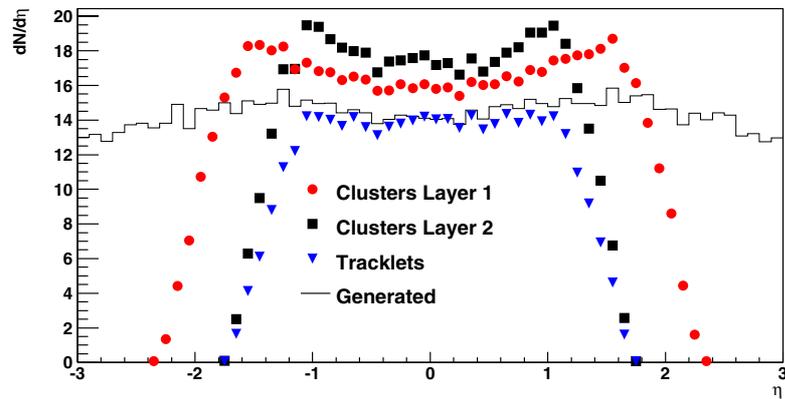

Figure 6. Generated and reconstructed (uncorrected) pseudorapidity distributions. Events are selected with a cut at low multiplicity.

3. Correlation of $\langle p_\text{t} \rangle$ with charged-particle multiplicity

Transverse momentum measurement for charged particles is available from the tracking system of the ALICE central barrel, that is composed by three sub-detectors: the Inner Tracking System (ITS) [9], the Time Projection Chamber (TPC) [17], and the Transition Radiation Detector (TRD) [18], which have an outer radius of $\simeq$45 cm, $\simeq$250 cm and $\simeq$350 cm, respectively. These detectors are embedded in a large solenoidal magnet providing a low magnetic field (B<0.5 T), and they allow track reconstruction in the central pseudorapidity range $|\eta| < 0.9$. However, in the case of pp collisions, the lower particle density allows to increase the TPC acceptance by considering also tracks with only a partial path through the TPC, i.e. ending in the readout chambers; in that case the pseudorapidity coverage can be enlarged up to $|\eta| < 1.5$, with a lower momentum resolution.

In ALICE the event reconstruction is performed in several steps. Firstly, the position of the primary-interaction vertex is estimated using the correlation between the reconstructed points in the two layers of the Silicon Pixel Detector (the two innermost layers of the ITS). Then, track finding and fitting in the TPC are performed from outside inward by means of a Kalman filtering algorithm [19]. In the next step, tracks reconstructed in the TPC are matched to the outermost ITS layer and followed in the ITS down to the innermost pixel layer. As a last step, reconstructed tracks can be back-propagated outward in the ITS and in the TPC up to the TRD innermost layer and then followed in the six TRD layers, in order to improve the momentum resolution.

However, in the following we will presents results obtained from the reconstruction of Monte Carlo events with the ITS and the TPC sub-detectors only, in the pseudorapidity range $|\eta| < 0.9$ where momentum resolution is optimal.

We will present the study of the correlation between charged-track $\langle p_\text{t} \rangle$ and multiplicity, that is known since its first observation by UA1 [20], and it has been successively studied at the ISR [21] and Tevatron [22, 23] energies. The increase of $\langle p_\text{t} \rangle$ as a function of multiplicity has been also suggested by cosmic ray measurements [24]. This correlation between $\langle p_\text{t} \rangle$ and multiplicity is generally attributed to the onset of gluon radiation, and explained in terms of the minijet production increasing with energy [25]. Since this mechanism should become dominating and saturate at large energies, this correlation is expected to disappear.

In our analysis the $\langle p_\text{t} \rangle$ of each event has been calculated as the arithmetic mean of the p_t of all the reconstructed charged tracks. The distribution of the reconstructed $\langle p_\text{t} \rangle$ for our Monte Carlo sample of about 5000 minimum-bias events is shown in figure 7, superimposed on the original $\langle p_\text{t} \rangle$ distribution of the generated events. From this plot we can conclude that the distribution of $\langle p_\text{t} \rangle$ is well reconstructed. According to the model used for the simulation (PYTHIA 6.150), the expected $\langle p_\text{t} \rangle$ is of the order of 0.6 GeV/c, a momentum where CMS is essentially blind and ATLAS is reaching its lower limit.

Values of average transverse momentum $\langle p_\text{t} \rangle$ are presented in figure 8 as a function of charged multiplicity N_{ch}, evaluated from the number of tracklets within the pseudorapidity range $|\eta| < 0.9$. Also in this case there is a good agreement between the distributions obtained from the reconstructed and generated data.

It should be noticed that at CDF [23] interesting features of the hadronic reaction have been investigated, by subdividing the minimum-bias sample into two classes, characterized respectively by the absence ('soft' events) or the presence ('hard' events) of minijets. The correlation between charged-track $\langle p_\text{t} \rangle$ and multiplicity was observed to some extent for both the soft and the hard subsamples, but the soft subsample was seen to start to saturate, pointing to different particle production mechanisms. This kind of analysis could be repeated also in ALICE, after the development of some tools to select event samples enriched in hard interactions, for example via algorithms of cluster finding (charged tracks in TPC or towers in the e.m. calorimeter).
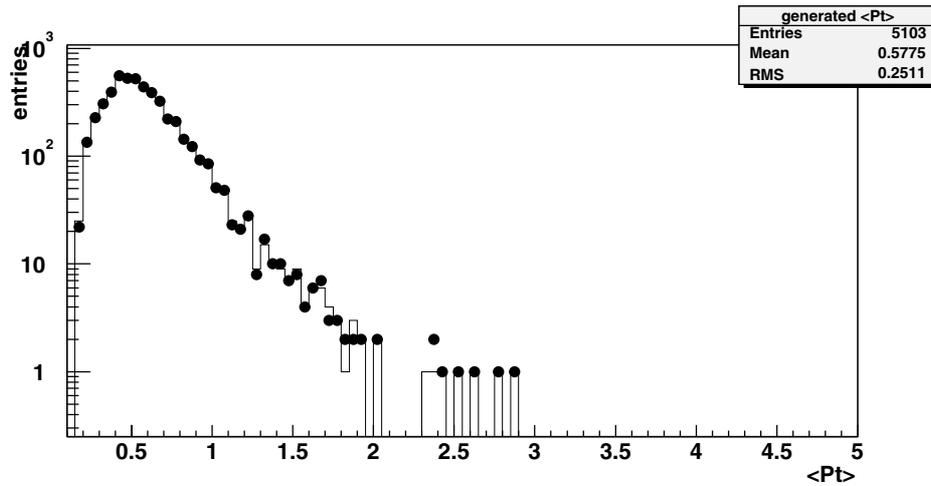
Figure 7. Average transverse momentum of charged tracks per event in minimum-bias proton–proton events in ALICE ($|\eta| < 0.9$). Generated (solid line) and reconstructed (full circles) distributions are superimposed.
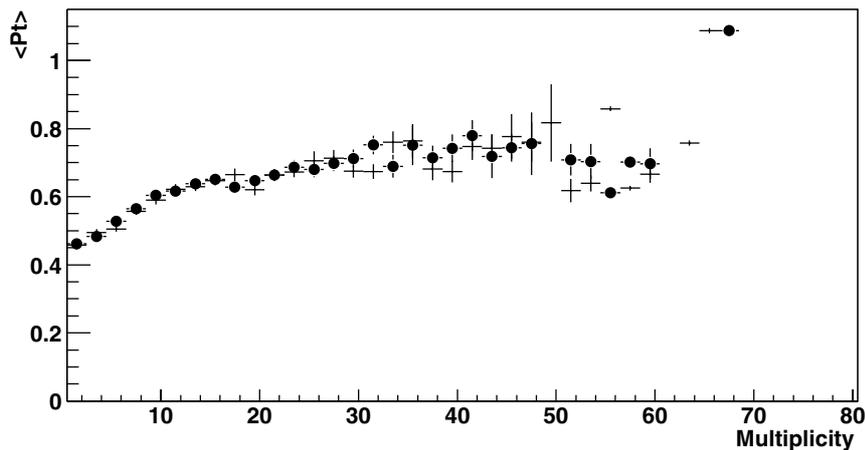

Figure 8. Average transverse momentum $\langle p_t \rangle$ as a function of charged-track multiplicity in ALICE ($|\eta| < 0.9$). Generated (solid line) and reconstructed (full circles) values are superimposed.

Another interesting subject for ALICE (not covered by this paper), due to its powerful PID system at low and high p_t, will be the correlation between $\langle p_t \rangle$ and multiplicity studied separately for pions, kaons and proton/antiprotons. The data collected at Tevatron by the E735 experiment [22] indicate that the correlation has rather different behaviour for the three types of particles, especially as regards the proton/antiproton $\langle p_t \rangle$, that appears to saturate at high multiplicities. This is not yet understood in terms of the available hadronic models.

We conclude by reporting that the ALICE experimental program will also involve specific studies on jet and high-p_t particle production in pp collisions. The standard jet definitions used in pp experiments rely on a calorimetric criterion. The challenge for ALICE, where no extensive hadronic calorimetry is available (at least in the original detector configuration), is to define and construct jets out of tracking measurements.

Recent progress in this respect has been reported by the CDF Collaboration at the Fermilab Tevatron. CDF has extensively studied the properties of jets in p$\overline{\text{p}}$ collisions [26] in $|\eta| < 1$,

measuring only the charged particles in the jets. Charged jets have been defined as clusters of charged particles in circular regions ($R = 0.7$) of η–ϕ space. The scalar sum of the transverse momenta of the charged particles making up a jet has been defined as the jet transverse momentum. Jet observables, such as the multiplicity and momentum distribution of charged particles within the leading charged jet (i.e. the jet with the highest transverse momentum), the size of the leading charged jet (the radius containing 80% of the charged particles in the jet, or 80% of the jet transverse momentum), and the R-distributions of charged-particle multiplicity and transverse momentum around the leading-charged-jet direction, have been compared with the predictions of some QCD Monte Carlo models (PYTHIA [13, 14], HERWIG [27] and ISAJET [28]).

Furthermore the direction of the leading charged jet in each jet event was used to define a region in the η–ϕ space (where ϕ is the azimuthal angle) that is approximately normal to the plane of the hard 2-to-2 parton scattering. The particle production in this transverse region is sensitive to the underlying-event activity that is to the particle production not related to the hard scattering but to spectator-parton fragmentation, initial and final state radiation, and any hadronization leakage from the jet cones. With respect to this, some observables related to the underlying-event properties, like the correlation between the average multiplicity in the transverse region and the $p_{\rm t}$ of the leading charged jet, were thoroughly investigated.

ALICE will reconstruct charged particles with sufficient accuracy to allow similar measurements up to charged-particle momenta of ~ 100 GeV/c. In addition, charged-particle identification up to 5 GeV/c for protons will allow detailed comparisons with the QCD Monte Carlo models, thus providing a benchmark for comparison of the fragmentation function of similar energy jets in heavy-ion collisions where in-medium effects are expected.

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