

# Measurement of event background fluctuations for charged particle jet reconstruction in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

**ALICE****The ALICE collaboration**

**ABSTRACT:** The effect of event background fluctuations on charged particle jet reconstruction in Pb-Pb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV has been measured with the ALICE experiment. The main sources of non-statistical fluctuations are characterized based purely on experimental data with an unbiased method, as well as by using single high  $p_t$  particles and simulated jets embedded into real Pb-Pb events and reconstructed with the anti- $k_t$  jet finder. The influence of a low transverse momentum cut-off on particles used in the jet reconstruction is quantified by varying the minimum track  $p_t$  between 0.15 GeV/ $c$  and 2 GeV/ $c$ . For embedded jets reconstructed from charged particles with  $p_t > 0.15$  GeV/ $c$ , the uncertainty in the reconstructed jet transverse momentum due to the heavy-ion background is measured to be 11.3 GeV/ $c$  (standard deviation) for the 10% most central Pb-Pb collisions, slightly larger than the value of 11.0 GeV/ $c$  measured using the unbiased method. For a higher particle transverse momentum threshold of 2 GeV/ $c$ , which will generate a stronger bias towards hard fragmentation in the jet finding process, the standard deviation of the fluctuations in the reconstructed jet transverse momentum is reduced to 4.8-5.0 GeV/ $c$  for the 10% most central events. A non-Gaussian tail of the momentum uncertainty is observed and its impact on the reconstructed jet spectrum is evaluated for varying particle momentum thresholds, by folding the measured fluctuations with steeply falling spectra.

**KEYWORDS:** Heavy IonsARXIV EPRINT: [1201.2423](https://arxiv.org/abs/1201.2423)

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**1 Introduction**

High energy heavy-ion collisions explore strongly interacting matter under extreme conditions of energy density, where lattice QCD predicts a phase transition to a new state of matter above a critical value of about  $1 \text{ GeV}/\text{fm}^3$  [1]. In this new state, called the Quark-Gluon Plasma (QGP), quarks and gluons rather than hadrons are expected to be the dominant degrees of freedom over length scales larger than that of a nucleon. Experiments studying the collision of heavy nuclei at high energy at both the Relativistic Heavy Ion Collider (RHIC) [2–5], and recently at the Large Hadron Collider (LHC) [6–9], have made several key observations that point to the formation of a hot, dense and strongly coupled system, possibly the QGP.

Hard (large momentum transfer  $Q^2$ ) probes are well calibrated tools to study the properties of the matter created in such collisions. The scattered partons generated in a hard momentum exchange are created in the initial stages of the heavy-ion collision, with production rates that are calculable using perturbative QCD, which can be compared to the same measurements in proton-proton collisions. The scattered partons then propagate through the medium, where their fragmentation into observed jets of hadrons is expected to be modified relative to the vacuum case by interactions with the medium (*jet quenching*) [10, 11]. This modification of parton fragmentation provides sensitive observables to study properties of the created matter.

Jet quenching has been observed at RHIC [12–15] and at the LHC [16] via the measurement of high  $p_t$  hadron inclusive production and correlations, which are observed to be strongly suppressed in central A–A collisions compared to a scaled pp reference. These high

$p_t$  hadron observables have been the major tool for measuring the energy loss of hard scattered partons and thereby the properties of the medium, but they provide only indirect and biased information on the parton evolution in the medium. The aim of full jet reconstruction is to measure jet modifications due to energy loss in an unbiased way [17, 18]. Already first measurements of reconstructed jets in heavy-ion collisions at the LHC showed an energy imbalance between back-to-back dijets, which is attributed to jet quenching [9, 19].

Jet reconstruction in the complex environment of a heavy-ion collision requires a quantitative understanding of background-induced fluctuations of the measured jet signal and the effects of the underlying heavy-ion event on the jet finding process itself. Here, region-to-region background fluctuations are the main source of jet energy or momentum uncertainty and can have a large impact on jet structure observables, such as the fraction of energy inside the jet core or the shape of the jet, and will distort the measured jet energy balance even in the absence of medium effects [20].

In this paper the measurement of jet transverse momentum fluctuations due to the background in heavy-ion collisions is reported and its sources are identified, based on jet reconstruction using charged particles with varying minimum track  $p_t$ . For this purpose three methods are employed to probe the measured Pb-Pb events: fixed area (*rigid*) cones placed randomly in the acceptance, the simulation of high- $p_t$  single tracks or full jets from pp collisions. Rigid cones enable the identification of contributions to the fluctuations in an unbiased fashion, while single tracks and embedded jets explore the interplay between the jet finding process, the underlying event, and the jet fragmentation pattern.

## 2 Detector Description and Track Selection

The data presented here were collected by the ALICE experiment [21] in the first Pb-Pb run of the LHC in November 2010, at a collision energy of  $\sqrt{s_{NN}} = 2.76$  TeV. This analysis is based on minimum-bias events, triggered by two forward VZERO counters and the Silicon Pixel Detector (SPD) [22]. A description of the minimum-bias trigger can be found in [6]. The VZERO trigger counters are forward scintillator detectors covering a pseudo-rapidity range of  $2.8 < \eta < 5.1$  (V0A) and  $-3.7 < \eta < -1.7$  (V0C). The sum of VZERO amplitudes is also used as a measure of event centrality [23]. The SPD consists of two silicon pixel layers at a radial distance to the beam line of  $r = 3.9$  cm and  $r = 7.6$  cm.

To ensure a uniform track acceptance in pseudo-rapidity  $\eta$ , only events whose primary vertex lies within  $\pm 8$  cm from the center of the detector along the beam line are used, resulting in 13.3 M minimum-bias Pb-Pb events for this analysis.

Charged particle tracking is carried out using the Time Projection Chamber (TPC) [24] and the Inner Tracking System (ITS) [22], located in the central barrel of the ALICE experiment within a 0.5 T solenoidal magnetic field and covering the full azimuth within pseudo-rapidity  $|\eta| < 0.9$ . The ITS consists of six cylindrical layers of silicon detectors, with distances from the beam-axis between  $r = 3.9$  cm and  $r = 43$  cm. The ITS layers measure track points close to the primary vertex, with the two innermost layers (SPD) providing a precise measurement of the primary vertex position. The TPC, a cylindrical drift detector

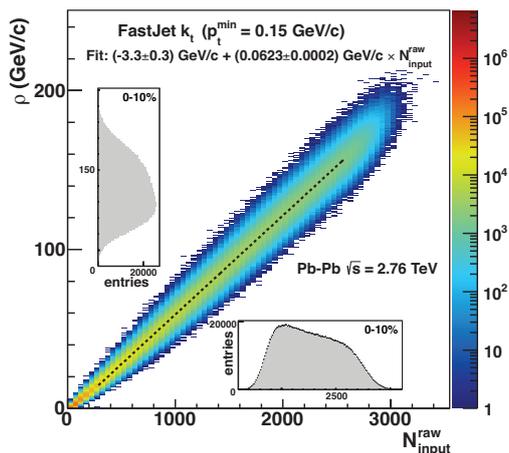
surrounding the ITS, is the main tracking detector in ALICE. The TPC inner radius is 85 cm and the outer radius is 247 cm, with longitudinal coverage  $-250 < z < 250$  cm. It provides a uniformly high tracking efficiency for charged particles. The high precision of the ITS and the large radial lever arm of the TPC provide a good momentum resolution for combined (*global*) tracks.

For this dataset the ITS has significantly non-uniform efficiency as a function of azimuthal angle  $\phi$  and pseudo-rapidity  $\eta$ . In order to obtain high and uniform tracking efficiency together with good momentum resolution, two different track populations are utilized: (i) tracks containing at least one space-point reconstructed in one of the two innermost layers of the ITS (78% of all accepted tracks), and (ii) accepted tracks that lack the position information close to the beam-line. Here, the primary vertex is added to the fit of the track which modifies the reconstructed curvature of the charged track in the magnetic field. Since the majority of the tracks originates from the primary vertex this constraint improves the momentum resolution. Both track types have transverse momentum resolution of  $\sigma(p_t)/p_t \approx 1\%$  at 1 GeV/ $c$ . For the majority of tracks the resolution at  $p_t = 50$  GeV/ $c$  is  $\sigma(p_t)/p_t \approx 10\%$ , only tracks having fewer than three reconstructed space points in the ITS (about 6% of the total population) have a resolution at 50 GeV/ $c$  of  $\sigma(p_t)/p_t \approx 20\%$ .

Tracks are accepted for  $p_t > 0.15$  GeV/ $c$  and  $|\eta| < 0.9$ . The tracking efficiency at  $p_t = 0.15$  GeV/ $c$  is 50%, increasing to 90% at 1 GeV/ $c$  and above. Tracks with measured  $p_t > 100$  GeV/ $c$  are accepted at the tracking stage, but jets containing them are rejected from the analysis to reduce the influence of fake tracks and limited tracking resolution at very high  $p_t$ .

### 3 Jet Reconstruction and Background Subtraction

Charged particle jet reconstruction and estimation of the background employ the sequential recombination algorithms anti- $k_t$  and  $k_t$  from the FastJet package [25]. The clustering starts with the list of tracks that satisfy the quality, acceptance, and  $p_t$ -cuts, with no pre-clustering or grouping of tracks. A list of jet candidates (anti- $k_t$ ) or clusters ( $k_t$ ) is generated, with direction and transverse momentum given by the  $p_t$ -weighted average of  $(\eta, \phi)$  of the individual constituents and the scalar sum of their  $p_t$ , respectively. The distance parameter that determines the terminating condition for the clustering is chosen as  $R = 0.4$ , which is a common value for reconstruction of jets in heavy-ion collisions [9, 18, 26]. As proposed in [27], the clusters found by the  $k_t$  algorithm are used to estimate the event-wise background  $p_t$ -density per unit area,  $\rho$ , defined as the median value of the ratio  $p_t^{\text{rec}}/A^{\text{rec}}$  for all considered  $k_t$ -clusters.  $A^{\text{rec}}$  is the area of the reconstructed cluster in the  $(\eta, \phi)$ -plane calculated by the active ghost area method of FastJet [28], with a ghost area of 0.005. To minimize the influence of the track acceptance interval on  $\rho$ , only reconstructed clusters with  $|\eta| < 0.5$  have been used. In addition, the two clusters with the largest  $p_t^{\text{rec}}$  (leading) in the full acceptance of  $|\eta| < 0.9$  are excluded from the calculation of the median to further reduce the influence of true jets on the background estimate [29]. The jet population reconstructed by the anti- $k_t$  algorithm is used as signal jets. Their  $p_t$



**Figure 1.** Dependence of charged particle background  $p_t$  density  $\rho$  on uncorrected multiplicity of tracks used for jet finding ( $|\eta| < 0.9$ ). The dotted line is a linear fit to the centroids in each multiplicity bin. The insets show the projected distributions of  $\rho$  and raw multiplicity for the 10% most central events.

is corrected for the background  $p_t$ -density in each event using the jet area  $A^{\text{jet,rec}}$  with  $p_t^{\text{jet}} = p_t^{\text{jet,rec}} - \rho \cdot A^{\text{jet,rec}}$ . Signal jets are only considered for  $|\eta| < 0.5$ .

The average transverse momentum of tracks  $\langle p_t \rangle$  and the total charged multiplicity are global observables that are closely related to the value of  $\rho$ , though the determination of  $\rho$  uses varying phase-space intervals (with typical areas in the  $(\eta, \phi)$ -plane of  $\pi R^2$ ) and suppresses hard jet contributions by using the median of the distribution. Figure 1 shows the correlation between  $\rho$  and the uncorrected multiplicity of tracks with  $|\eta| < 0.9$ . The linear increase corresponds to an uncorrected  $\langle p_t \rangle$  of about 0.7 GeV/c per accepted charged track. Both  $\langle p_t \rangle$  and multiplicity, and thus also the background  $p_t$  density, strongly depend on the minimum  $p_t$  threshold ( $p_t^{\text{min}}$ ) applied for tracks used as input to the jet finding. To minimize the bias on jet fragmentation, a value of  $p_t^{\text{min}} = 0.15$  GeV/c is preferred. In addition,  $p_t^{\text{min}} = 1$  and 2 GeV/c are investigated to facilitate comparisons to other experiments and to Monte-Carlo generators in a region of constant and high tracking efficiency. The mean  $\rho$  over all events and its standard deviation is given for different  $p_t^{\text{min}}$  and two centralities in table 1. As expected, the mean background  $p_t$  density decreases for larger  $p_t^{\text{min}}$ , for central collisions and  $p_t^{\text{min}} = 2$  GeV/c it is reduced by an order of magnitude. As one can see in the insets of figure 1 and the standard deviation in table 1, the spread of  $\rho$  for the 10% most central events is considerable, underlining the importance of the event-by-event background subtraction.

#### 4 Sources of Background Fluctuations

To study the sources of background fluctuations in an unbiased way that is not influenced by a particular choice of jet finder, a single rigid cone with radius  $R = 0.4$  is placed in each reconstructed event at random  $\phi$  and  $\eta$ , with centroid lying within  $|\eta| < 0.5$ . The

$p_t^{\min}$ (GeV/c)	$\langle \rho \rangle$ (GeV/c)	$\sigma(\rho)$ (GeV/c)
0-10%		
0.15	$138.32 \pm 0.02$	$18.51 \pm 0.01$
1.00	$59.30 \pm 0.01$	$9.27 \pm 0.01$
2.00	$12.28 \pm 0.01$	$3.29 \pm 0.01$
50-60%		
0.15	$12.05 \pm 0.01$	$3.41 \pm 0.01$
1.00	$4.82 \pm 0.01$	$1.77 \pm 0.01$
2.00	$4.41 \pm 0.05$	$0.92 \pm 0.04$

**Table 1.** Average and standard deviation of the event-wise charged particle  $p_t$  density  $\rho$  for three choices of minimum particle  $p_t$  and two centrality bins. The quoted uncertainties are purely statistical.

background fluctuations are characterized by calculating the difference of the scalar sum of all track  $p_t$  in the cone and the expected background:

$$\delta p_t = \sum_i p_{t,i} - A \cdot \rho, \tag{4.1}$$

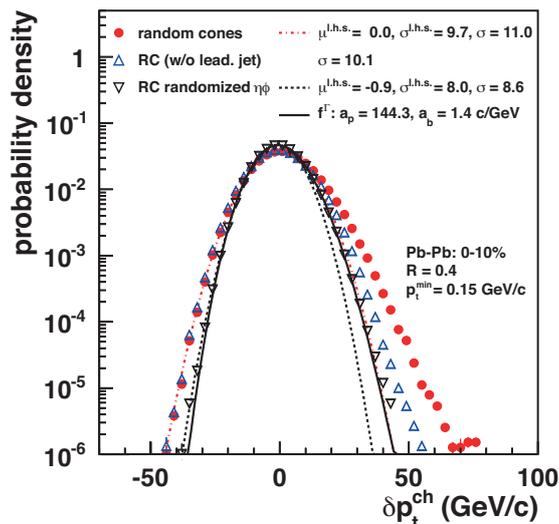
where  $A = \pi R^2$ .

The rigid random cone (RC) area and position are not influenced by the event, so that it provides a sampling of the event structure at the typical scale of a jet, but independent of biases induced by the choice of a particular jet finding algorithm. The RC measurements will be compared to the embedding of jet-like objects, that is directly relevant to the measurement of the inclusive jet spectrum with a specific choice of jet finder.

To characterize the  $\delta p_t$  distribution the standard deviation,  $\sigma(\delta p_t)$ , is utilized. In addition, a Gaussian distribution with mean  $\mu^{\text{l.h.s.}}$  and standard deviation  $\sigma^{\text{l.h.s.}}$  is iteratively fit to the distribution within  $[\mu^{\text{l.h.s.}} - 3\sigma^{\text{l.h.s.}}, \mu^{\text{l.h.s.}} + 0.5\sigma^{\text{l.h.s.}}]$ , i.e. to the left-hand-side. The  $\sigma^{\text{l.h.s.}}$  of the fit provides the lower limit on the magnitude of the fluctuations and is used to characterize shape differences between the positive and negative tails of the distribution, by extrapolating the Gaussian distribution to positive  $\delta p_t$ .

Various sources contribute to background fluctuations in a heavy-ion event, including: (i) random, uncorrelated (Poissonian) fluctuations of particle number and momentum; (ii) region-to-region correlated variations of the momentum density, induced by detector effects, e.g. a non-uniform efficiency, and by the heavy-ion collision itself, e.g. by variation of the eccentricity of the nuclear overlap for collisions with finite impact parameter.

The measured  $\delta p_t$  distribution for random cones in the 10% most central Pb-Pb events is shown in figure 2. The distribution is peaked near zero, illustrating the agreement of the background estimate via  $k_t$ -clusters and that due to random sampling of the event. The distribution exhibits an asymmetric shape with a tail to the right-hand-side of the distribution, which is also reflected in the difference between the standard deviation of



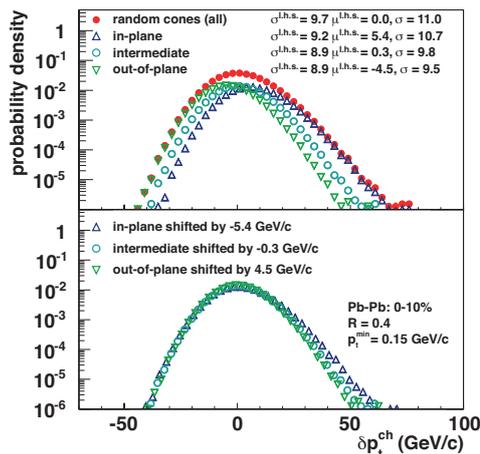
**Figure 2.**  $\delta p_t$  of random cones in the 10% most central Pb-Pb events for the three types of random cone probes with  $p_t^{\min} = 0.15$  GeV/c. A Gaussian fit to the left-hand-side and its extrapolation to positive  $\delta p_t$  are shown for measured Pb-Pb events and for randomized Pb-Pb events ( $\mu^{\text{l.h.s.}}$  and  $\sigma^{\text{l.h.s.}}$  in GeV/c). The solid line is a fit to the  $\delta p_t$  distribution for the randomized events with a  $\Gamma$  distribution shifted to zero (equation (4.2)) as approximation for the shape in case of independent particle emission.

the full distribution of  $\sigma(\delta p_t) = 11.0$  GeV/c and the Gaussian width of the left-hand-side  $\sigma^{\text{l.h.s.}}(\delta p_t) = 9.6$  GeV/c.

To further differentiate random and correlated sources of fluctuations, three variations of the random cone method are employed: (i) sampling of measured Pb-Pb events, (ii) sampling of measured Pb-Pb events, but avoiding overlap with the leading jet candidate in the event after background subtraction by requiring a distance  $D = 1.0$  in  $(\eta, \phi)$  between the random cone direction and the jet axis, and (iii) sampling of Pb-Pb events in which the  $(\eta, \phi)$  direction of the tracks has been randomized within the acceptance, which destroys all correlations in the event. Figure 2 shows that when avoiding the leading jet candidate to suppress upward fluctuations, e.g. due to a hard process, the tail to the right-hand-side is already significantly reduced.

Note that, even for the case of purely statistical fluctuations, the distribution is not expected to be symmetric or to follow a Gaussian shape on the right-hand-side, since the shapes of the underlying single particle  $p_t$  and multiplicity distributions are not Gaussian. In the case of uncorrelated particle emission a  $\Gamma$ -distribution provides a more accurate description of the event-wise  $\langle p_t \rangle$  fluctuations [30]. This also holds for  $\delta p_t$  distributions, which are similar to a measurement of  $\langle p_t \rangle$  fluctuations in a limited interval of phase space. Taking into account the subtraction of the average background the functional form of the probability distribution of  $\delta p_t$  for independent particle emission can be written:

$$f^\Gamma(\delta p_t) = A \cdot a_b / \Gamma(a_p) \cdot (a_b \delta p_t + a_p)^{a_p - 1} \cdot e^{-(a_b \delta p_t + a_p)}. \quad (4.2)$$

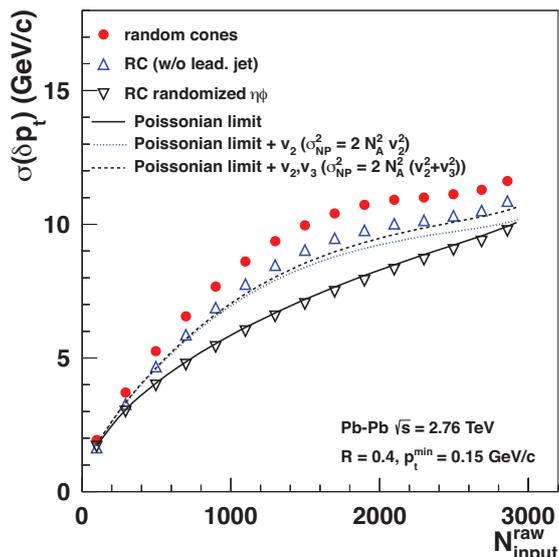


**Figure 3.**  $\delta p_t$  distribution for random cones, averaged over the full azimuth and separated for three bins of random cone azimuthal orientations with respect to the measured event plane. In the bottom panel the distributions have been shifted to zero using the mean of the left-hand-side Gaussian fit ( $\mu^{\text{l.h.s.}}$ ).

This corresponds to a  $\Gamma$ -distribution with mean shifted from  $a_p/a_b$  to zero and standard deviation  $\sigma = \sqrt{a_p/a_b}$ . As seen in figure 2 this functional form provides a good approximation of the  $\delta p_t$  distribution for randomized events, corresponding to uncorrelated emission. In this case the distribution is also narrower on the left-hand-side. This points to the presence of correlated region-to-region fluctuations in addition to purely statistical fluctuations and those expected from hard processes.

One source of region-to-region variation in the background  $p_t$  density is the initial anisotropy of the nuclear overlap for finite impact parameter collisions, which translates via the collective expansion of the medium into an anisotropy in momentum space [7, 31] with respect to the symmetry plane of the collision. The event plane direction can be calculated using the azimuthal distribution of all accepted tracks within each event, which is dominated by soft particle production. The final state hadron azimuthal distribution with respect to the reaction plane of the event, is characterized by a Fourier expansion where the leading term is the second moment, called elliptic flow  $v_2$ . In addition to the geometry driven even harmonics (mainly  $v_2$ ), odd flow components (e.g.  $v_3$ ) driven by initial state fluctuations can modify the azimuthal distribution within the event [32].

To explore the effect on background fluctuations of azimuthal orientation relative to the reaction plane, the  $\delta p_t$  distribution from random cone sampling is studied as a function of the azimuthal orientation of the cone axis,  $\phi$ , relative to the reconstructed event plane orientation,  $\psi_{\text{RP}}$ . Three bins are chosen; the out-of-plane orientation where the azimuthal angle between the reconstructed event plane and the cone axis is  $> 60^\circ$ , the in-plane orientation where this angle is  $< 30^\circ$ , and the intermediate orientation where the angle is between 30 and  $60^\circ$ . The distributions of  $\delta p_t$  for random cones averaged over the full azimuth and for the three different orientations are shown in figure 3. It can be seen



**Figure 4.** Dependence of the standard deviation of the  $\delta p_t$  distributions on uncorrected charged particle multiplicity, compared to the limit derived from the measured track  $p_t$  spectrum (equation (4.3)) and from additional elliptic and triangular flow contributions (equation (4.4)).  $R = 0.4$ ,  $p_t^{\min} = 0.15$  GeV/c.

that, for out-of-plane cones, the most probable background  $p_t$  density is smaller by almost 5 GeV/c relative to the azimuthally averaged estimate of  $\rho$ , with opposite effect in-plane. This shift scales with the average flow and the background  $p_t$  density for a given centrality ( $\propto v_2 \cdot \rho$ ), and is seen to be sizable in central events, though discrimination of the event plane orientations is limited by finite event-plane resolution [33] and possible biases due to hard jets. The decreasing width of left-hand-side Gaussian is qualitatively consistent with the expectation from reduced particle number fluctuations out-of-plane compared to in-plane. For a visual comparison of their shape, the distributions have been shifted such that the centroid of the left-hand-side Gaussian fit is zero (see figure 3). Notably, the left-hand-side of the distribution appears similar for all orientations of the random cones to the event-plane. The random cones distributed in-plane show a more pronounced tail to the right-hand-side, compared to out-of-plane. This may point to a dependence of the jet spectrum on the orientation relative to the reaction plane, though further systematic studies are needed to assess biases in the event plane determination due to jet production and possible auto-correlations. For the measurement of the inclusive jet spectrum the correction via an event-plane dependent  $\rho$  will reduce the influence of even flow components on the average reconstructed jet momentum, but its systematic precision is limited by the finite event-plane resolution.

The width of the  $\delta p_t$  distribution due to purely random fluctuations can be estimated from the measured single particle  $p_t$  spectrum via [18]:

$$\sigma(\delta p_t) = \sqrt{N_A \cdot \sigma^2(p_t) + N_A \cdot \langle p_t \rangle^2}. \quad (4.3)$$

Here,  $N_A$  is the expected number of tracks in the cone area  $A$  for a given event centrality or multiplicity class,  $\langle p_t \rangle$  the average  $p_t$  and  $\sigma(p_t)$  the standard deviation of the track  $p_t$  spectrum. Local variations of the average multiplicity,  $\langle p_t \rangle$ , or  $\sigma(p_t)$ , lead to additional fluctuations. These region-to-region variations can be induced e.g. by (mini-)jets, where the particle  $p_t$  spectrum is considerably harder than for the global event average, and by collective flow. Uncorrelated non-Poissonian (NP) fluctuations can be added to equation (4.3) knowing their standard deviation, e.g. for additional region-to-region variation of the average multiplicity:

$$\sigma(\delta p_t) = \sqrt{N_A \cdot \sigma^2(p_t) + (N_A + \sigma_{\text{NP}}^2(N_A)) \cdot \langle p_t \rangle^2}. \quad (4.4)$$

Figure 4 shows the comparison of the multiplicity dependence of  $\sigma(\delta p_t)$  for the three different types of random cones. The distribution of purely statistical fluctuations given by equation (4.3) well describes the randomized events. Also shown are two parameterizations following equation (4.4). Additional multiplicity fluctuations due to elliptic flow are approximated from the  $p_t$ -integrated  $v_2$  values measured by ALICE for different centralities [7] as  $\sigma_{\text{NP}}^2(N_A) \approx 2v_2^2 N_A^2$ . This approximate inclusion of  $v_2$ -effects accounts qualitatively for the larger fluctuations in mid central collisions compared to the randomized events and the deviation from a  $\sqrt{N}$ -increase. The random cone sampling with an anti-bias on the leading jet has, by construction, a reduced standard deviation and is close to the parameterization of elliptic flow. Taking into account also region-to-region fluctuations from triangular flow,  $v_3$ , is of particular importance in central events where it reaches a similar magnitude as  $v_2$  [32]. The contribution of  $v_3$  can be added in quadrature ( $\sigma_{\text{NP}}^2(N_A) \approx 2N_A^2(v_2^2 + v_3^2)$ ) since the second and the third harmonic are not correlated via a common plane of symmetry [32], for simplicity  $v_3$  has been approximated by a constant value of  $v_3 = 2.4\%$ . As expected, the inclusion of  $v_3$  can account partially for the difference to the randomized event in the most central events. In the comparison one has to consider that in practice the contribution from hard processes to the right-hand-side tail cannot be cleanly separated from (soft) upward multiplicity fluctuations induced by flow. In addition, the approximate description of flow effects following equation (4.4) does not take into account any flow-correlated changes of  $\langle p_t \rangle$  and  $\sigma(p_t)$ .

The track reconstruction efficiency affects the total multiplicity and the shape of the measured  $p_t$ -spectrum at low  $p_t$ . Using equation (4.3), the change of the uncorrelated fluctuations due to finite efficiency can be estimated from the efficiency corrected  $p_t$ -spectrum in each centrality bin. This procedure suggests that, for  $p_t^{\text{min}} = 0.15 \text{ GeV}/c$ , there is an increase of the standard deviation by 5.4-6.0%, depending on centrality. The complete correction requires the knowledge of all correlations within the heavy-ion event and is beyond the scope of the present study.

## 5 Background Fluctuations in Jet Reconstruction

The measured jet spectrum in heavy-ion collisions is affected over the entire  $p_t$  range by background fluctuations, especially due to the large and asymmetric tail towards positive  $\delta p_t$ . For the measurement of the inclusive jet cross section, background fluctuations can

only be corrected on a statistical basis via unfolding. Such background fluctuations are evaluated using embedding and reconstruction of a probe with identical jet algorithm and parameters as those applied to the data analysis, to account for the jet-finder-specific response to the heavy-ion background.

In the present study, two probes are embedded into the Pb-Pb events measured by ALICE: (i) single high- $p_t$  tracks at various  $p_t$ , and (ii) pp jet events generated using PYTHIA [34] followed by a detailed simulation of the full detector response. Jet candidates are reconstructed from the event using the anti- $k_t$  algorithm with  $R = 0.4$  and matched to the embedded probe, by either finding the single track in it, or by requiring that the  $p_t$  of the embedded tracks within the reconstructed jet sum up to at least 50% of the original probe jet transverse momentum ( $p_t^{\text{probe}}$ ). The difference between the reconstructed, background subtracted jet and the embedded probe is then given, similar to equation (4.1), by [29, 35]:

$$\delta p_t = p_t^{\text{jet,rec}} - A^{\text{jet,rec}} \cdot \rho - p_t^{\text{probe}}. \quad (5.1)$$

The response may depend on the jet finder, its settings, and the properties of the embedded probe, such as  $p_t^{\text{probe}}$ , area, and fragmentation pattern. In particular the insensitivity to the latter is essential for a robust and unbiased reconstruction of jets in heavy-ion collisions, where the fragmentation pattern is potentially modified relative to that in pp collisions, and is indeed the observable of interest.

The  $\delta p_t$  distributions measured for each of the methods are shown in figure 5. Here, the focus is on high  $p_t^{\text{probe}}$  ( $> 60 \text{ GeV}/c$ ), where the efficiency of matching the embedded probe to the reconstructed jet approaches unity. The results are very similar to the random cone method, including the presence of an asymmetric tail to the right-hand-side of the distribution. The standard deviations, however, show a small increase compared to the random cone method, which is largest for jet embedding (see table 2). The increase may be due to sensitivity of the jet finder to back-reaction, e.g. the stability of the probe area and jet direction after embedding. The single particle embedding can be considered as extreme fragmentation leading to rather rigid cones with stable area  $\pi R^2$ , while in the case of true pp-jets the probe and reconstructed area may differ, depending on the fragmentation pattern. In addition the finite jet area resolution due to the size of the ghost area has to be taken into account [29]. With a ghost area of 0.005 a compromise between reasonable jet area resolution and computing time and memory consumption was chosen. In the case of track embedding at high  $p_t$ , the jet area resolution fully accounts for the difference of 200 MeV/c observed in the standard deviation.

The broadening of the  $\delta p_t$  distribution for jets with  $p_t^{\text{min}} = 0.15 \text{ GeV}/c$ , as seen in figure 5, has been investigated more closely. The additional left-hand-side structure is caused by probe jets with large area ( $A^{\text{probe}} > 0.6$ ) that are split in the heavy-ion event into two separate objects of smaller size. Jets with a large area ( $A > 0.6$ ) are only formed by the anti- $k_t$  algorithm in exceptional cases, where there are two hard cores at distance close to  $R$  [36]. It is also seen in figure 5 that, with increasing  $p_t^{\text{min}}$ , the deviations on the left-hand-side in the case of jet embedding become more pronounced, suggesting that the jet-splitting is an effect of hard fragmentation.

In the determination of  $\delta p_t$  fluctuations as described above, the probes have been embedded into an event population recorded with a minimum-bias trigger. However, the requirement of a hard process biases the population towards more central (small impact parameter) collisions, due to nuclear geometry. Correction of this effect for centrality bins of 10% width, generates a negligible increase of the fluctuations ( $< 0.1 \text{ GeV}/c$ ).

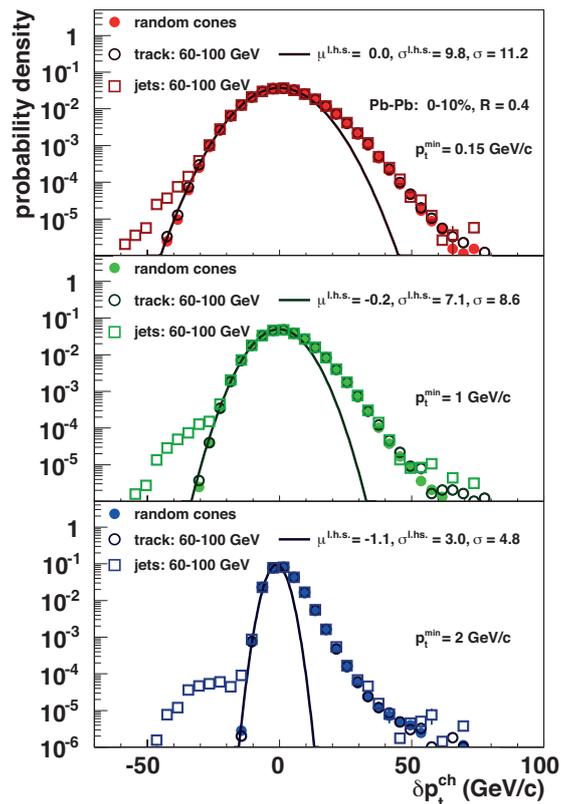
The full centrality dependence of the fluctuations is given via the standard deviation of the distributions and for different  $p_t^{\text{min}}$  cuts in table 3.

The increase of the  $p_t^{\text{min}}$  cut on the input tracks for jet finding reduces the background fluctuations, due to the smaller influence of statistical and soft region-to-region fluctuations. This is observed in figure 5 when the  $p_t^{\text{min}}$  is varied from 0.15 to 2 GeV/c. A  $p_t^{\text{min}}$  of 2 GeV/c reduces the standard deviation by more than a factor of two compared to 0.15 GeV/c. Soft region-to-region fluctuations that dominate the left-hand-side of the distribution are reduced by a factor of three (see table 2). A high  $p_t^{\text{min}}$  significantly reduces the impact of fluctuations in the jet spectrum (see table 4). However, it may also introduce a bias in the jet reconstruction towards hard fragmentation.

To estimate the influence of the observed fluctuations on the jet measurement, a power law spectrum starting at  $p_t = 4 \text{ GeV}/c$  has been folded with a Gaussian of width  $\sigma^{\text{Gauss}} = 11 \text{ GeV}/c$  (5 GeV/c) and with the measured  $\delta p_t$  distributions for  $p_t^{\text{min}} = 0.15 \text{ GeV}/c$  (2 GeV/c). The yield increase relative to the unsmearred spectrum in one high  $p_t$ -bin for the most central collisions is given in table 4. For the different probes, they agree within the uncertainties given by the statistical fluctuations in the tails of the  $\delta p_t$ -distributions; about a factor of ten increase for  $p_t^{\text{min}} = 0.15 \text{ GeV}/c$  and a 30% effect for  $p_t^{\text{min}} = 2 \text{ GeV}/c$ . Minor differences in the standard deviation as well as the left-hand-side differences have no sizable effect on the spectral shape after folding. The difference between smearing with the full  $\delta p_t$  and with a Gaussian distribution illustrates the strong influence of the right-hand-side tail, which must be taken into account in the analysis of background fluctuation effects on jet reconstruction. The extracted values naturally depend on the choice of the input spectrum, so, in addition to the power law, a jet spectrum for pp collisions at  $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$  extracted from PYTHIA simulations has been used. These studies indicate that the increase of yield due to background fluctuations falls below 50% for reconstructed charged jets in the region of  $p_t \approx 100 \pm 15 \text{ GeV}/c$  ( $60 \pm 10 \text{ GeV}/c$ ) for  $p_t^{\text{min}} = 0.15 \text{ GeV}/c$  (2 GeV/c). Repeating the exercise with a Gaussian smearing of a  $\sigma^{\text{Gauss}} = 11 \text{ GeV}/c$  and with the  $\delta p_t$  distribution of random cones avoiding the leading jet for  $p_t^{\text{min}} = 0.15 \text{ GeV}/c$  leads, as expected, to a reduced influence of the tail. Here, the relative yield increase falls below 50% in the range of  $p_t \approx 75 \pm 10 \text{ GeV}/c$ . The employed input spectra do not consider the geometrical limitation on the number of jets that can be reconstructed within the acceptance for a single event [37]. This effect also limits the extraction of jet spectra at lower  $p_t$  via unfolding.

## 6 Summary

The first detailed study of event background fluctuations for jet reconstruction using charged particles in Pb-Pb collisions at the LHC has been presented. The standard devia-



**Figure 5.**  $\delta p_t$  distribution of charged particles for jet reconstruction with the three methods in the 10% most central Pb-Pb events for  $p_t^{\min} = 0.15$  GeV/c, 1 GeV/c, and 2 GeV/c.

tion of the fluctuations in the 10% most central events is  $\sigma = (10.98 \pm 0.01)$  GeV/c within a rigid cone of  $R = 0.4$  and for a low  $p_t$  cut-off of 0.15 GeV/c. It has been shown that the non-statistical sources of fluctuations are driven in part by the anisotropy of the particles emitted from the collision (elliptic and triangular flow). The variation of multiplicity in different orientations with respect to the event plane, induces shifts in the background-subtracted jet  $p_t$  even for central Pb-Pb-collisions.

The anti- $k_t$  jet finder response for charged particle jet reconstruction has a modest dependence on the method used to characterize the fluctuations. For embedded, simulated pp-jets the standard deviation increases to  $(11.34 \pm 0.02)$  GeV/c. In addition, certain rare fragmentation patterns in pp are likely to be split in the heavy-ion environment leading to minor effects in the background response. The observed differences between the two types of embedded probes (namely single tracks and pp jets) do not indicate a strong sensitivity of the reconstructed anti- $k_t$  jet spectrum on fragmentation. The case of a strong broadening of the jet due to medium effects has not been considered here.

The use of reconstructed charged particles down to  $p_t^{\min} = 0.15$  GeV/c allows a comparison of the impact of background fluctuations with a minimal bias on hard fragmentation in jet finding to the case with increased bias ( $p_t^{\min} \geq 1$  GeV/c). The observed reduc-

	$\sigma$ (GeV/c)	$\sigma^{1.h.s.}$ (GeV/c)	$\mu^{1.h.s.}$ (GeV/c)
$p_t^{\min} = 0.15$ GeV/c			
random cones	$10.98 \pm 0.01$	$9.65 \pm 0.02$	$-0.04 \pm 0.03$
track emb.	$11.19 \pm 0.01$	$9.80 \pm 0.02$	$0.00 \pm 0.03$
jet emb.	$11.34 \pm 0.02$	$9.93 \pm 0.06$	$0.06 \pm 0.09$
$p_t^{\min} = 1$ GeV/c			
random cones	$8.50 \pm 0.01$	$7.08 \pm 0.01$	$-0.22 \pm 0.02$
track emb.	$8.61 \pm 0.01$	$7.11 \pm 0.01$	$-0.25 \pm 0.02$
jet emb.	$8.78 \pm 0.02$	$7.25 \pm 0.04$	$-0.08 \pm 0.08$
$p_t^{\min} = 2$ GeV/c			
random cones	$4.82 \pm 0.01$	$3.41 \pm 0.01$	$-0.01 \pm 0.01$
track emb.	$4.88 \pm 0.01$	$3.05 \pm 0.01$	$-0.92 \pm 0.01$
jet emb.	$5.03 \pm 0.01$	$3.52 \pm 0.01$	$0.01 \pm 0.02$

**Table 2.** Background fluctuations in central events. Comparison of the Gaussian fit to the left-hand-side of the  $\delta p_t$ -distributions and the standard deviation in central Pb-Pb collisions for the three different methods and for the three  $p_t^{\min}$ -cuts. The quoted uncertainties are purely statistical.

	$p_t^{\min}$ (GeV/c)		
	0.15	1.0	2.0
Centrality Class	$\sigma(\delta p_t)$ (GeV/c)		
0-10%	$11.19 \pm 0.01$	$8.61 \pm 0.01$	$4.88 \pm 0.01$
10-20%	$10.19 \pm 0.01$	$7.67 \pm 0.01$	$4.29 \pm 0.01$
20-30%	$8.46 \pm 0.01$	$6.35 \pm 0.01$	$3.58 \pm 0.01$
30-40%	$6.51 \pm 0.01$	$4.93 \pm 0.01$	$2.68 \pm 0.01$
40-50%	$4.71 \pm 0.01$	$3.63 \pm 0.01$	$1.95 \pm 0.01$
50-60%	$3.28 \pm 0.01$	$2.61 \pm 0.01$	$1.41 \pm 0.01$
60-70%	$2.22 \pm 0.01$	$1.70 \pm 0.01$	$0.95 \pm 0.01$
70-80%	$1.48 \pm 0.01$	$1.01 \pm 0.01$	$0.62 \pm 0.01$

**Table 3.** Centrality dependence of fluctuations. Standard deviation of  $\delta p_t$  distributions and statistical uncertainty for different centrality bins and  $p_t^{\min}$  cuts using the track embedding probe.

tion of the standard deviation to  $\sigma = (4.82 \pm 0.01)$  GeV/c for the unbiased sampling and  $p_t^{\min} = 2$  GeV/c is driven by the smaller number fluctuations and the reduced influence of soft region-to-region fluctuations.

The asymmetric shape of the  $\delta p_t$  distribution with a tail towards positive fluctuations has a large impact on the jet measurement, compared to purely Gaussian fluctuations, though the role of signal jets contributing to the tail has to be considered. Using different assumptions on the shape of the true jet spectrum it is found that for  $p_t^{\min} = 0.15$  GeV/c fluctuations can have a large influence on the charged jet yield for transverse momenta up to  $100 \pm 15$  GeV/c.

$f(p_t)$ folded with	relative yield for $p_t = 60 - 68 \text{ GeV}/c$		
$\delta p_t$	RC	tracks	jets
$p_t^{\min} = 0.15 \text{ GeV}/c$	$9.8 \pm 1.7$	$11.4 \pm 1.1$	$10.9 \pm 3.4$
$p_t^{\min} = 2 \text{ GeV}/c$	$1.30 \pm 0.02$	$1.31 \pm 0.02$	$1.65 \pm 0.25$
Gauss			
$\sigma = 11 \text{ GeV}/c$	$1.82 \pm 0.04$		
$\sigma = 5 \text{ GeV}/c$	$1.05 \pm 0.01$		

**Table 4.** Yield modification for power law spectrum. Relative yield in the bin  $p_t = 60 - 68 \text{ GeV}/c$  for a power law spectrum ( $f(p_t) = 0.7/(0.7 + p_t^5)$ ) and  $p_t > 4 \text{ GeV}/c$ , folded with the different  $\delta p_t$  distributions for 0-10% centrality and with a Gaussian, where the width is similar to the standard deviation of the  $\delta p_t$  distributions.

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