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Supplemental materials: Measurement of the angle between jet axes in Pb–Pb collisions at $\sqrt{s_{\mathbf{NN}}} = 5.02$ TeV

ALICE Collaboration*

Abstract

This note presents supplemental information for the paper "Measurement of the angle between jet axes in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV" [1]. The first measurement of the angle between different jet axes, denoted as $\Delta R_{\rm axis}$, is presented in Pb–Pb collisions. The measurement is carried out in the 0–10% most-central events at $\sqrt{s_{\rm NN}} = 5.02$ TeV. Jets are assembled by clustering charged particles at midrapidity using the anti-$k_{\rm T}$ algorithm with resolution parameters $R = 0.2$ and 0.4, for jet transverse momenta $40 < p_{\rm T}^{\rm ch\,jet} < 140$ GeV$/c$ and $80 < p_{\rm T}^{\rm ch\,jet} < 140$ GeV$/c$, respectively.

*See Appendix A for the list of collaboration members

1 Track selection

The tracks used in the measurement fall under two categories: 1) tracks that are required to include ≥ 1 hit in the silicon pixel detector (SPD) of the ITS, ≥ 70 (out of 159) TPC space points, and $\geq 80\%$ of the geometrically findable space points in the TPC [2], and 2) tracks that do not contain SPD hits but otherwise satisfy the track-selection criteria and are refitted with a constraint to the primary vertex. The combined sample is approximately uniform in azimuth, and preserves similar p_{T} resolution to tracks with SPD hits. Additional track selection criteria can be found in Refs. 3–5.

2 Soft Drop grooming

The first step to groom a jet of resolution parameter R with Soft Drop [6] is to recluster it with the Cambridge–Aachen (C/A) algorithm [7, 8]. This algorithm clusters particles based on their spatial separation (in the y–φ plane) without taking into account their energies/momenta. Particles closest in distance are clustered first, which results in an angular-ordered clustering sequence. In this analysis, a reclustering resolution parameter R is used. Then, the resulting tree is recursively declustered starting from the widest splitting, checking at each splitting the Soft Drop condition:

$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{1,2}}{R} \right)^{\beta} . \tag{1}$$

Here, z_{cut} and β are user-set parameters, $p_{\mathrm{T},1}$ and $p_{\mathrm{T},2}$ are the transverse momenta of the two prongs in the splitting, and $\Delta R_{1,2}$ is the angular distance between them. If the condition is not satisfied at a given splitting, the softer branch is dropped (removed from the jet), and the procedure continues in the next splitting. When the condition is met, the Soft Drop grooming procedure is concluded, and the remaining tree defines the groomed jet. This procedure is illustrated in Fig. 1. In this analysis, the grooming parameters $(z_{\mathrm{cut}}, \beta)$ used are $(0.1, 0)$ and $(0.2, 0)$.

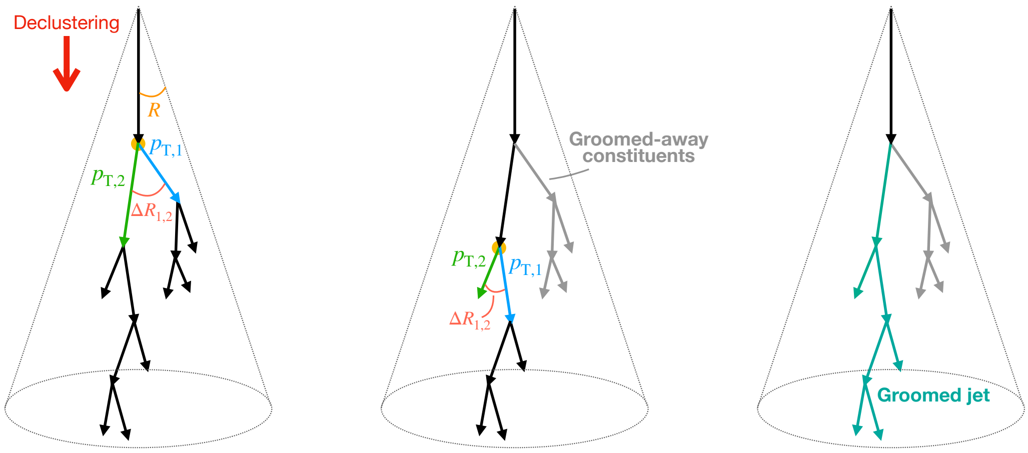

Fig. 1: Illustration of the Soft Drop grooming procedure [6]. Left: a jet of resolution parameter R has been reclustered with the C/A algorithm, thus resulting in an angular-ordered tree. The jet is declustered and, in the first splitting, the Soft Drop condition (see equation 1) is checked. Center: in this case, the splitting from the left panel does not satisfy the condition and the softer (lower-p_{T}) branch is dropped (gray color). Then, the next splitting following the harder branch is checked, and in this case the Soft Drop condition is satisfied. Right: the remaining tree (turquoise color) defines the groomed jet.

3 Systematic uncertainties

The systematic uncertainties considered are: from uncertainty on the tracking efficiency, from generator model dependence, from the unfolding procedure, from background-subtraction bias, and from residual effects of combinatorial jets. Tables 1 and 2 summarize the ranges of the different uncertainties for jets of $R = 0.2$ and 0.4, respectively. In the $40 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 60$ GeV/c interval, the subtraction systematic is dominant. Elsewhere, different sources dominate in different regions. The procedure followed to quantify these uncertainties is described below. All uncertainties are symmetrized. The total uncertainty is determined by adding the uncertainties from the different sources in quadrature.

Table 1: Range of the estimated value of relative systematic uncertainties in % for jets of $R = 0.2$. The unfolding, tracking efficiency, generator, combinatorial-jet, and subtraction-bias systematic uncertainties can be found in the columns labeled Unf., Trk. Eff., Gen., Comb. Jets, and Sub., respectively. In the case of the groomed observables, the grooming parameters are specified as (z_{cut}, β). The displayed uncertainties correspond to the lowest and highest values for a given setting.

$p_{\mathrm{T}}^{\mathrm{ch\,jet}}$ (GeV/c)	observable	Unf.	Trk. Eff.	Gen.	Comb. Jets	Sub.	total
40, 60	WTA–Standard	1–8	0–8	1–9	1–16	3–49	4–53
	WTA–SD (0.1, 0)	1–8	0–8	1–7	1–15	3–49	4–52
	WTA–SD (0.2, 0)	1–8	0–8	2–8	0–13	1–54	6–56
60, 80	WTA–Standard	0–4	0–6	1–6	1–14	1–13	3–20
	WTA–SD (0.1, 0)	1–5	0–4	1–4	0–15	1–15	3–21
	WTA–SD (0.2, 0)	1–8	0–5	1–9	1–13	1–15	4–21
80, 100	WTA–Standard	1–5	1–6	1–3	0–4	1–4	2–9
	WTA–SD (0.1, 0)	1–5	0–7	1–6	1–4	0–10	2–15
	WTA–SD (0.2, 0)	2–9	1–4	1–14	0–5	2–11	3–20
100, 140	WTA–Standard	1–3	0–7	1–9	0–5	0–8	4–14
	WTA–SD (0.1, 0)	1–5	1–6	1–12	0–12	2–10	4–18
	WTA–SD (0.2, 0)	1–10	1–9	2–12	0–3	1–9	6–20

Table 2: Same as Table 1 for jets of $R = 0.4$

$p_{\mathrm{T}}^{\mathrm{ch\,jet}}$ (GeV/c)	observable	Unf.	Trk. Eff.	Gen.	Comb. Jet	Sub.	total
80, 100	WTA–Standard	2–8	1–2	2–17	1–20	1–5	11–25
	WTA–SD (0.1, 0)	3–9	1–7	8–13	5–25	3–13	11–32
	WTA–SD (0.2, 0)	2–13	5–8	5–23	9–41	2–16	16–50
100, 140	WTA–Standard	1–9	0–24	2–28	1–43	1–31	4–61
	WTA–SD (0.1, 0)	2–10	1–19	2–26	1–44	3–29	8–59
	WTA–SD (0.2, 0)	2–11	1–19	2–41	3–34	1–24	19–49

The tracking-efficiency uncertainty for hybrid tracks in ALICE is determined to be in the range of 3–4% from track-selection variations and potential imperfections in the ITS–TPC matching efficiency description in simulations. To estimate the uncertainty related to this effect, the analysis is repeated by unfolding the measured results with a response matrix constructed after randomly rejecting an additional 4% of tracks before jet finding. The bin-by-bin differences between the main result and the result obtained with this response matrix are assigned as an uncertainty.

The corrections applied in the analysis are based on PYTHIA 8 simulations embedded in Pb–Pb measured events. To assess the dependence of the results on the choice of this event generator, the analysis is repeated using response matrices (RM) constructed from two other event generators: JEWEL [9] with parameters from Ref. 10 and Herwig 7 [11] (default tune). The RMs for these generators are constructed from a fast simulation that applies three operations on the generated particles: an acceptance selection ($|\eta| < 0.9$), an efficiency selection, and a Gaussian smearing of the transverse momentum. The efficiency selection and transverse-momentum smearing are implemented by interpolating the single-track efficiency and track p_{T} resolution from the ALICE GEANT 3 simulation [4]. The bin-by-bin differences between the final distributions unfolded with these alternative RMs to the PYTHIA 8 case are assigned as uncertainties. The individual uncertainties are combined into a 'generator' uncertainty by calculating their standard deviation, σ:

$$\sigma \equiv \sqrt{\frac{1}{N}\sum_{i=1}^{N}\sigma_i^2}, \quad (2)$$

where σ_i corresponds to the sizes of individual uncertainties.

The uncertainty from the unfolding procedure is estimated by carrying out several variations, which were chosen following the analysis in pp collisions [12]. Differences between each of these variations and the nominal result are taken as uncertainties. The individual uncertainties are combined into a total 'unfolding' uncertainty by calculating their standard deviation (see Eq. 2).

An uncertainty for the systematic bias introduced by the choice of parameters used for the event-wide constituent subtraction is estimated by repeating the analysis two times, with different parameter choices: an undersubtraction ($\Delta R^{\max} = 0.05$ (0.1) for $R = 0.2$ (0.4)) and an oversubtraction ($\Delta R^{\max} = 0.5$ (0.7) for $R = 0.2$ (0.4)) around the nominal case ($\Delta R^{\max} = 0.1$ (0.25) for $R = 0.2$ (0.4)). The maximum deviation between these variations is assigned as an uncertainty.

An uncertainty to assess residual combinatorial jet effects is determined by embedding PYTHIA 8 events into background events which model the uncorrelated thermal-like particle distribution typical for heavy-ion collisions. The resulting sample is analyzed identically to the measured data. Deviations between the unfolded and PYTHIA 8 truth spectra are assigned as an uncertainty.

4 Additional results

Figures 2 and 3 show ΔR_{axis} distributions for WTA–SD with ($z_{\mathrm{cut}} = 0.1, \beta = 0$) and ($z_{\mathrm{cut}} = 0.2, \beta = 0$), respectively, for jets of $R = 0.2$ in the $40 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 60$ GeV$/c$ and $60 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 80$ GeV$/c$ intervals. Figures 4, 5, and 6 show the WTA–Standard, WTA–SD ($z_{\mathrm{cut}} = 0.1, \beta = 0$), and WTA–SD ($z_{\mathrm{cut}} = 0.2, \beta = 0$) ΔR_{axis} distributions, respectively, for jets of $R = 0.2$ and 0.4 in the $80 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 100$ GeV$/c$ interval. In all these figures, the top panels show the spectra from Pb–Pb and pp collisions. The vertical error bars (rectangles) represent the statistical (total systematic) uncertainties. The central and bottom panels show the measured Pb–Pb/pp ratio, as well as predictions from a selection of jet quenching models. As described in Ref. 1, the inclusion of grooming doesn't change the measured distributions within uncertainties, and the results are consistent with narrowing of the angular substructure in Pb–Pb relative to pp collisions.

Figure 7 shows the WTA–SD ($z_{\mathrm{cut}} = 0.1, \beta = 0$) distributions in the $100 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 140$ GeV$/c$ interval for jets of $R = 0.2$ and 0.4, which is the intermediate case between the two panels of Fig. 3 in Ref. [1]. The top panel shows the spectra from $R = 0.2$ and 0.4 jets. The vertical error bars (rectangles) represent the statistical (total systematic) uncertainties. The central and bottom panels show the measured Pb–Pb($R = 0.4$)/Pb–Pb($R = 0.2$) ratio, as well as predictions from a selection of jet quenching models.

5 JEWEL recoil subtraction

Medium-response effects can be included (excluded) in events generated with JEWEL [9] by turning on (off) recoiling partons or recoils. When recoils are included, the event contains an excess energy from the thermal background activity of the recoils, which has to be subtracted [10]. In this analysis, this subtraction is carried out using the "negative-energy recombiner" method [13]. Besides the "event particles"

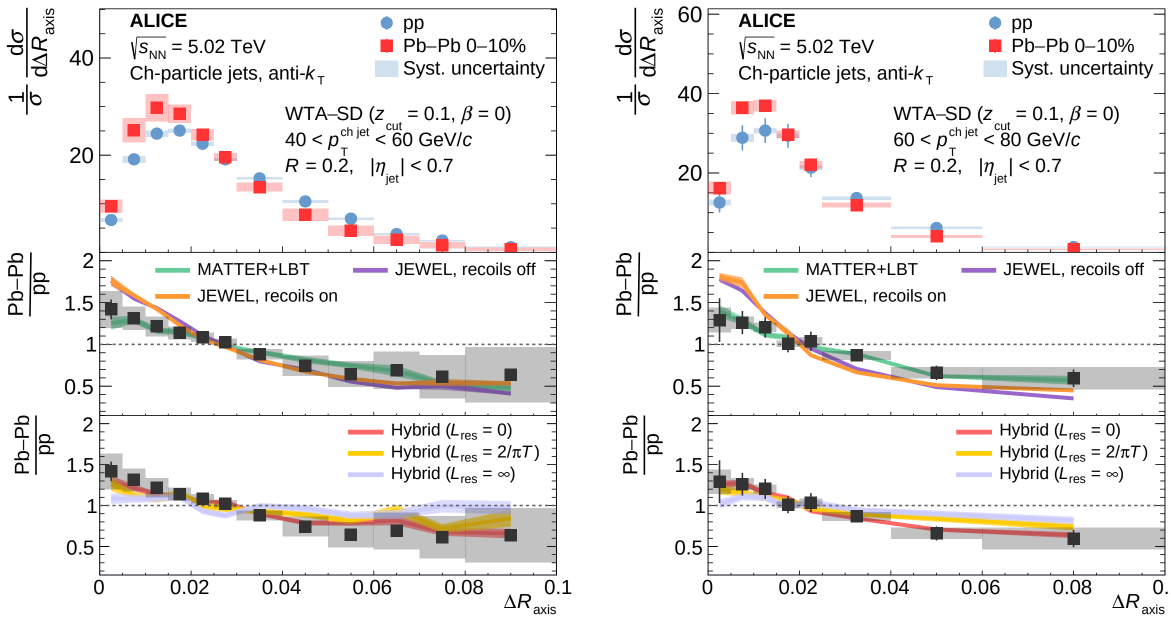

Fig. 2: Fully corrected ΔR_{axis} distributions for jets of $R = 0.2$ for WTA–SD with $z_{\text{cut}} = 0.1, \beta = 0$. Left: $40 < p_{\text{T}}^{\text{ch jet}} < 60$ GeV/c interval. Right: $60 < p_{\text{T}}^{\text{ch jet}} < 80$ GeV/c interval.

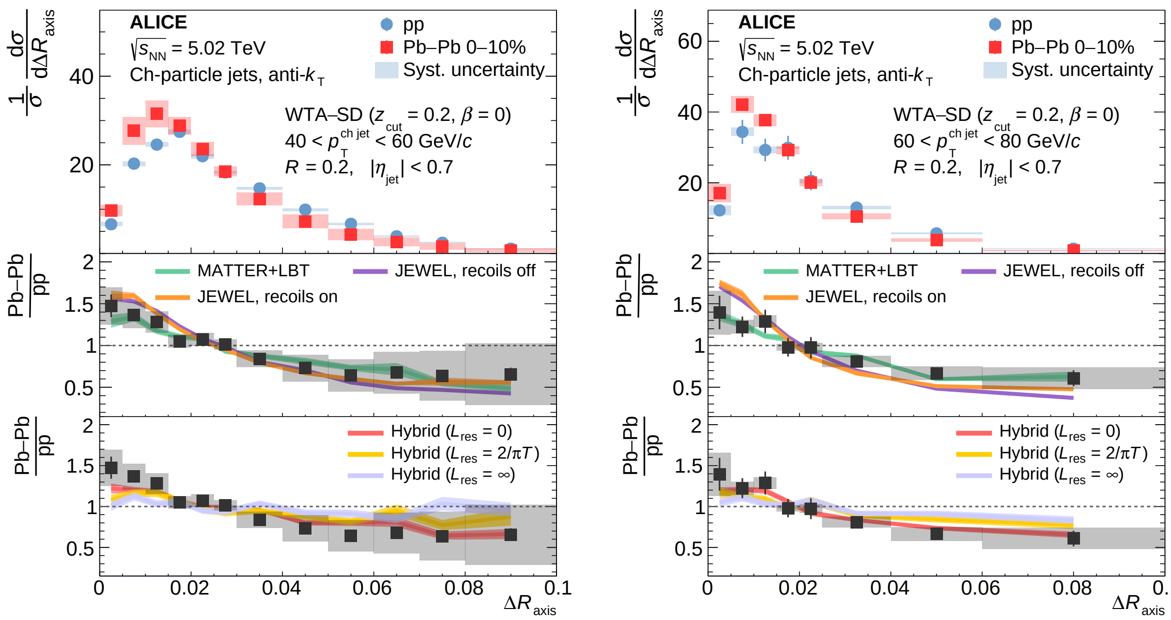

Fig. 3: Fully corrected ΔR_{axis} distributions for jets of $R = 0.2$ for WTA–SD with $z_{\text{cut}} = 0.2, \beta = 0$. Left: $40 < p_{\text{T}}^{\text{ch jet}} < 60$ GeV/c interval. Right: $60 < p_{\text{T}}^{\text{ch jet}} < 80$ GeV/c interval.

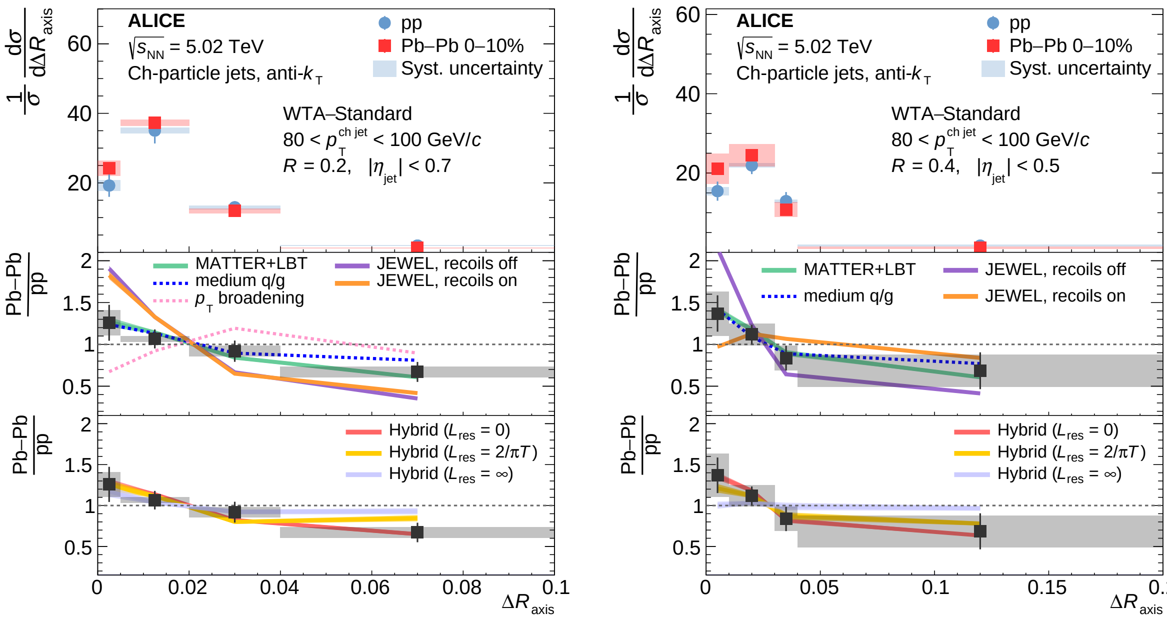

Fig. 4: Fully corrected WTA–Standard ΔR_{axis} distributions for jets of $R = 0.2$ (left) and 0.4 (right) in the $80 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 100$ GeV/c interval.

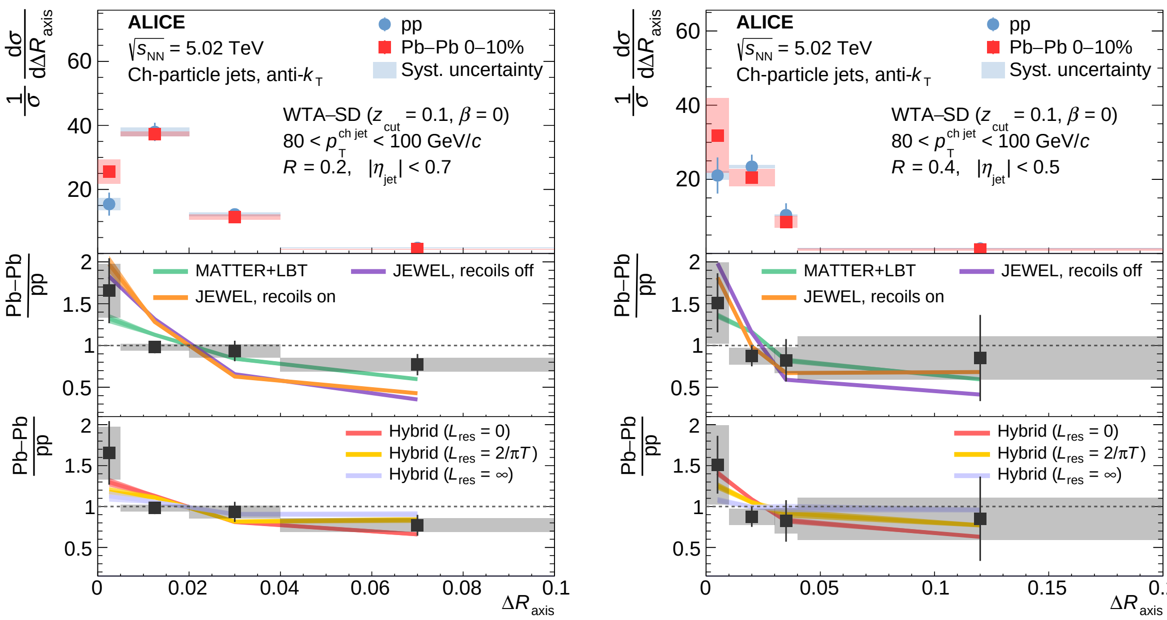

Fig. 5: Fully corrected WTA–SD ($z_{\mathrm{cut}} = 0.1, \beta = 0$) ΔR_{axis} distributions for jets of $R = 0.2$ (left) and 0.4 (right) in the $80 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 100$ GeV/c interval.

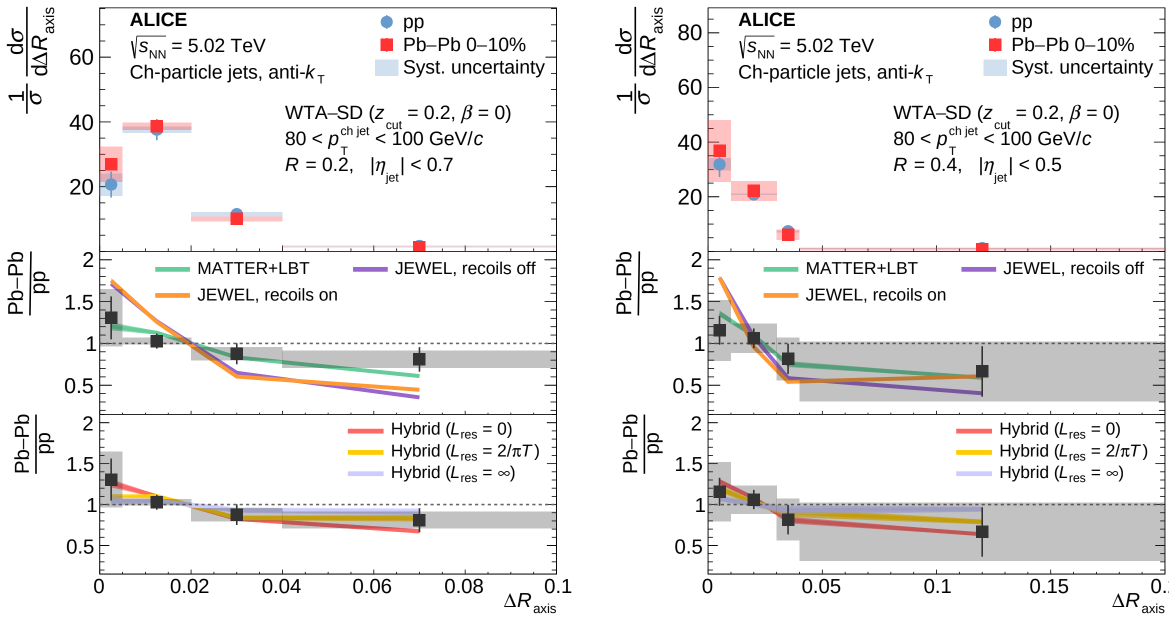

Fig. 6: Fully corrected WTA–SD ($z_{\text{cut}} = 0.2, \beta = 0$) ΔR_{axis} distributions for jets of $R = 0.2$ (left) and 0.4 (right) in the $80 < p_{\text{T}}^{\text{ch jet}} < 100$ GeV/c interval.

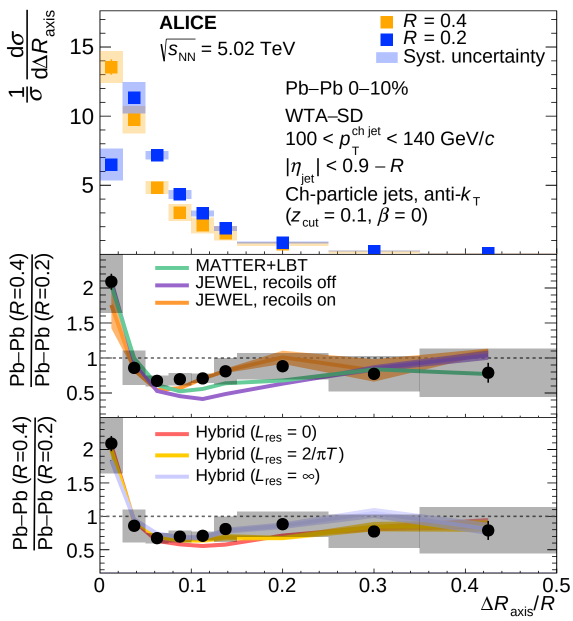

Fig. 7: Fully corrected WTA–SD ($z_{\text{cut}} = 0.1, \beta = 0$) distributions in the $100 < p_{\text{T}}^{\text{ch jet}} < 140$ GeV/c interval.

(all hadrons in the event; it is impossible to know whether partons composing a specific hadron came from a hard scattering or are recoils), JEWEL includes thermal particles, which quantify the thermal recoil activity in the event. In the subtraction procedure, jets are clustered with the anti-$k_{\rm T}$ algorithm and with the negative-energy recombination scheme. This recombination scheme is identical to the E scheme when combining two event particles (i.e. their four-momenta are added together). On the other hand, when an event particle and a thermal particle are to be combined, the thermal four-momentum is subtracted from the event particle, effectively removing the excess energy.

6 Medium response (*wake effect*) in the Hybrid model

Figures 8 and 9 show standalone predictions from the Hybrid model [14] for the Pb–Pb/pp ratios for $R = 0.2$ and 0.4, respectively. The different colors represent different medium-resolution length values [15] ranging from fully incoherent ($L_{\rm res} = 0$) to fully coherent ($L_{\rm res} = \infty$) energy loss. The bands correspond to the predictions in which the medium-response (wake) effect [16] is included (same Hybrid-model predictions that were shown in Ref. 1), and the circular markers connected by dashed lines correspond to the same calculations, but excluding the medium response. As seen in the JEWEL case, for $R = 0.2$ the wake has a negligible effect. On the other hand, as expected, for $R = 0.4$ the wake has a larger impact, but the measured data has lower precision in this case. The effect is larger at low $\Delta R_{\rm axis}$ values, and is qualitatively consistent with JEWEL. However, JEWEL predicts larger medium-response effects.

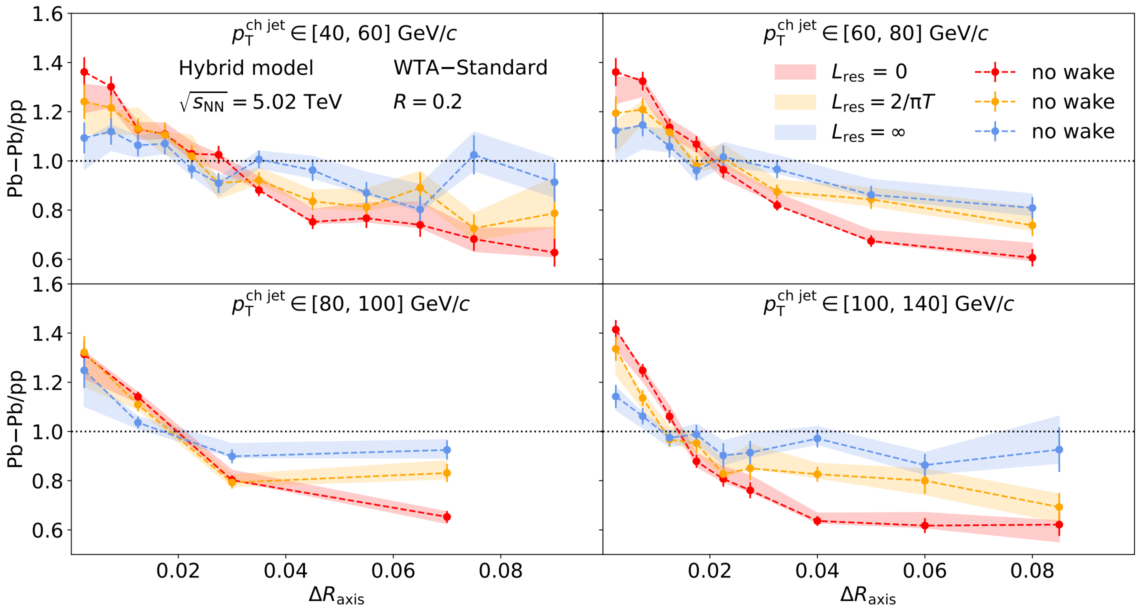

Fig. 8: Hybrid-model prediction for the Pb–Pb/pp ratio as a function of WTA–Standard $\Delta R_{\rm axis}$ for jets of $R = 0.2$. Each panel corresponds to a different $p_{\rm T}^{\rm ch\ jet}$ interval. The bands correspond to the prediction for different values of $L_{\rm res}$ with medium-response effects included. These are the same predictions shown in Ref. 1. The markers connected by dashed lines of the same colors correspond to the equivalent prediction in which the medium-response effects are not included.

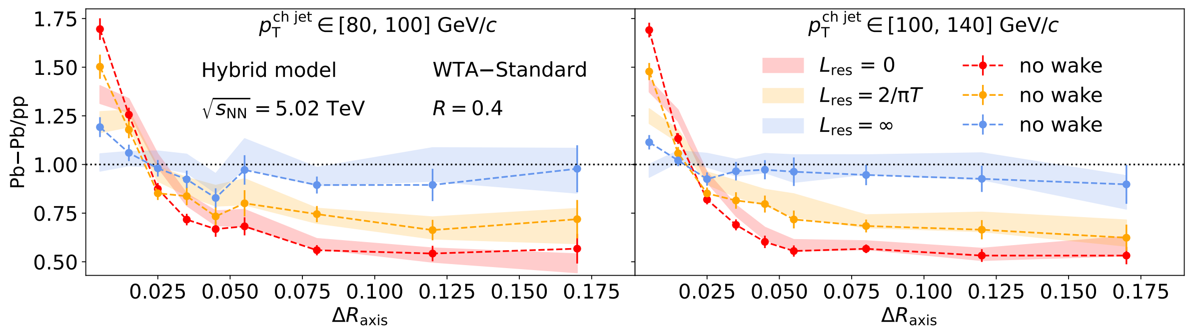

Fig. 9: Same as Fig. 8, in the case of $R = 0.4$.

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