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Recent results from CMS

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Abstract. Recent results from the CMS Collaboration are reported, covering the wide variety of probes accessible to the experiment.

The strongly interacting matter created in nuclear collisions at the LHC, in pPb and PbPb collisions but also high multiplicity pp collisions, can be studied with the means of a large variety of probes, from identified hadrons to jets, from light flavours and strangeness to heavy flavours, charm and beauty. The CMS collaboration [1] uses many different observables in these studies, starting with the production cross section. Nuclear modification factors (R_{AA}) can also be built, from the ratio of the cross section in heavy ions collisions (HIC), pPb or PbPb, to that in pp collisions. In this way, one can clearly see if the production of a given probe is suppressed or enhanced in HIC: for instance, in the case of charmonia, colour charge Debye screening in the quark-gluon plasma (QGP) induces a suppression in the production in PbPb collisions, while recombination can also play a role and enhance the yields at low transverse momentum (p_{T}). Much information can also be gained by focusing on collective properties of each event, such as N-particle correlations, or event-by-event fluctuations of such quantities. In particular, the Fourier coefficients of the azimuthal correlations (v_2, v_3, etc.) provide information on the anisotropic flow in the event (resp. elliptic, triangular, etc). A collective behaviour is observed not only in PbPb collisions, but also in small systems: pPb and even pp collisions. In dijet production, the imbalance of the two jets can be measured and compared between different systems, pp and PbPb. Heavy flavour jets, such as b jets, then allow to probe the flavour dependence of parton energy loss.

1 Charmonia

The different charmonium states (J/ψ, $\psi(2S)$) can be reconstructed through their decay to a pair of oppositely charged muons. The invariant mass distribution $m_{\mu\mu}$ of these pairs is then fitted to extract the observed yields. However, further work is needed to disentangle the different sources of charmonium production. Some fraction of it, called nonprompt, originates from the decay of B mesons, which can be resolved using the pseudo-proper decay length $\ell_{\mathrm{J}/\psi}$, reconstructed using the distance between the primary and dimuon vertices. In the case of the J/ψ meson, a two-dimensional fit allows to simultaneously extract the prompt and nonprompt production, while in the case of the $\psi(2S)$ meson, a cut-based method was used to remove the nonprompt contribution. The prompt component of J/ψ meson production receives also a contribution from the feed-down from excited charmonium states, χ_c and $\psi(2S)$ mesons. This cannot be separated from direct J/ψ meson production in the results reported here.

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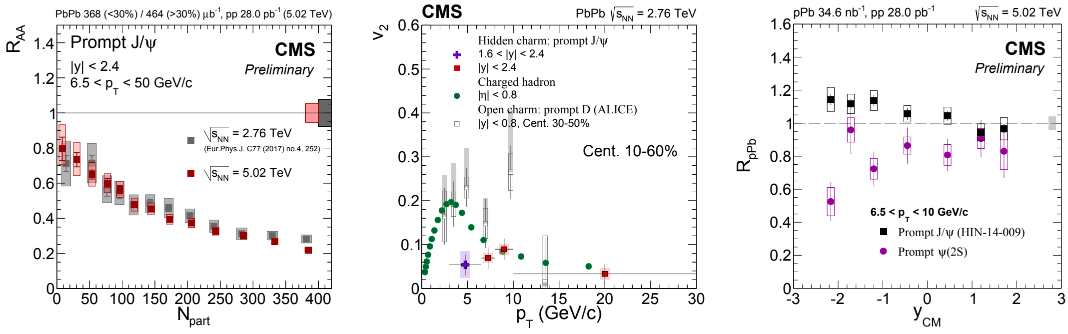

Figure 1. Left: R_{AA} of prompt J/ψ mesons as a function of the number of participants to the collision, at $\sqrt{s_{NN}}$ = 2.76 [2] and 5.02 TeV [3]. Center: v_2 of prompt J/ψ mesons as a function of p_T, at $\sqrt{s_{NN}}$ = 2.76 TeV, compared to that of other hadrons. Right: R_{pPb} of prompt $\psi(2S)$ [4] and prompt J/ψ [5] mesons at $\sqrt{s_{NN}}$ = 5.02 TeV, as a function of rapidity in the centre-of-mass frame.

The nuclear modification factor of prompt J/ψ mesons has been measured in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV [5], as well as in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [2] and 5.02 TeV [3], always compared to pp measurements at the same collision energy. In pPb collisions, nuclear modifications of the parton distribution functions are expected to impact the prompt J/ψ meson production. The CMS measurement of the R_{pPb} as a function of the rapidity of the J/ψ meson is consistent with this expectation, but other effects could also contribute, such as energy loss in cold nuclear matter. In PbPb collisions and at high p_T ($p_T > 6.5$ GeV), the creation of a QGP further suppresses J/ψ meson production, because of parton energy loss, especially at very high p_T, and melting induced by Debye colour charge screening in the deconfined medium. This suppression is even more pronounced in central collisions, where the QGP is hotter and longer lived, as can be seen in Fig. 1. The elliptic flow v_2 of prompt J/ψ mesons has also been measured and is found to be non-zero, even at relatively high p_T (up to 10 GeV, see Fig. 1)), possibly pointing to a path length dependence of parton energy loss. On the other hand, the v_2 measurement is found to be compatible at high p_T with that of charged hadrons, dominated by light hadrons, which could be pointing to a flavour independence of this path length dependence.

Additional information can be gained by comparing the behaviour of the ground and excited charmonium states, the J/ψ and $\psi(2S)$ mesons. A higher suppression of the $\psi(2S)$ meson, compared to the J/ψ meson, is observed both in pPb [4] and PbPb [6] collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. This difference seems to be more pronounced at backward rapidity in pPb collisions, as shown in Fig. 1, and it is observed at all p_T between 3 and 30 GeV in PbPb collisions. This points to the importance of final state effects, which have a different impact on the ground and excited states. Understanding such different behaviours of the J/ψ and $\psi(2S)$ mesons is challenging to understand theoretically, especially in pPb where final state effects should be of lesser importance.

Bottomonia are measured in the CMS experiment, inclusively from p_T = 0 GeV. In addition, as opposed to J/ψ and $\psi(2S)$ meson production, $\Upsilon(nS)$ meson production is free from any nonprompt contribution, because they are heavier than B mesons. Feed-down from P-wave and heavier S-wave states is however also present in the $\Upsilon(1S)$ and $\Upsilon(2S)$ meson measurements. The comparison of the R_{AA} of the different $\Upsilon(nS)$ states [7] shows a clear ordering, with the heavier, weaker bound excited states being more suppressed, as expected from sequential suppression because of the lower

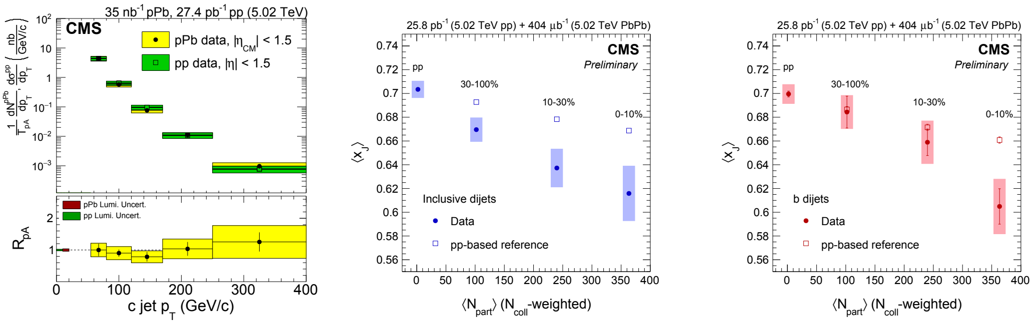

Figure 2. Left: differential cross section for c-jet production in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as a function of p_T [9]. The R_{pPb} is also shown in the bottom panel. Center: dijet momentum imbalance of inclusive dijets in pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as a function of the number of participants weighted by the number of binary collisions [10]. Right: same as center, for b dijets.

dissociation temperature of the $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons with respect to the $\Upsilon(1S)$ meson. This suppression is also higher in central than in peripheral events. The $\Upsilon(3S)$ meson is not observed in the PbPb dataset at $\sqrt{s_{NN}} = 5.02$ TeV, even in the most peripheral events [8].

2 Heavy flavour jets

Tagged jets provide another probe in the study of heavy flavour production in HIC. Tagging relies on several properties of the jet, such as the secondary vertex mass, which allow to discriminate jets originating from a charm or bottom quark from those initiated by a light parton. The contribution from these different categories of jets is then extracted thanks to templates of this discriminating variable. Heavy flavour jets allow to probe charm and bottom production at high p_T, above 55 GeV, and include contributions from all hadron species. The comparison with light jets can provide information on the importance of the quark mass in energy loss mechanisms and other phenomena.

The production of both charm [9] and bottom [11] jets has been measured in both pp and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. In the case of c jets, the first measurement of this kind in pp and pPb collisions, the spectra have been found to be compatible between the two systems (see Fig. 2). The b jet measurement is also the first in pPb collisions, and is compared to expectations from PYTHIA: again no significant differences are found between the data and the pp model.

The measurement of jet pair production, and of the momentum imbalance between the two jets, $\langle x_J \rangle = \langle p_{T,1}/p_{T,2} \rangle$, is another tool in the understanding of heavy quark energy loss in HIC. In the case of light jets, a smaller $\langle x_J \rangle$ is found in PbPb than in pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV [10], possibly more pronounced in the most central collisions. A similar behaviour is observed when comparing the $\langle x_J \rangle$ of b jets in PbPb and pp collisions (see Fig. 2). Several processes give a significant contribution to b jet production, from gluon splitting to flavour creation, but the former is suppressed by selecting back-to-back b dijets.

3 Open heavy flavour

Numerous measurements of open heavy flavour production have been performed by the CMS Collaboration, from pp to pPb and PbPb collisions, using D mesons (down to a p_T of 2 GeV) and B mesons.

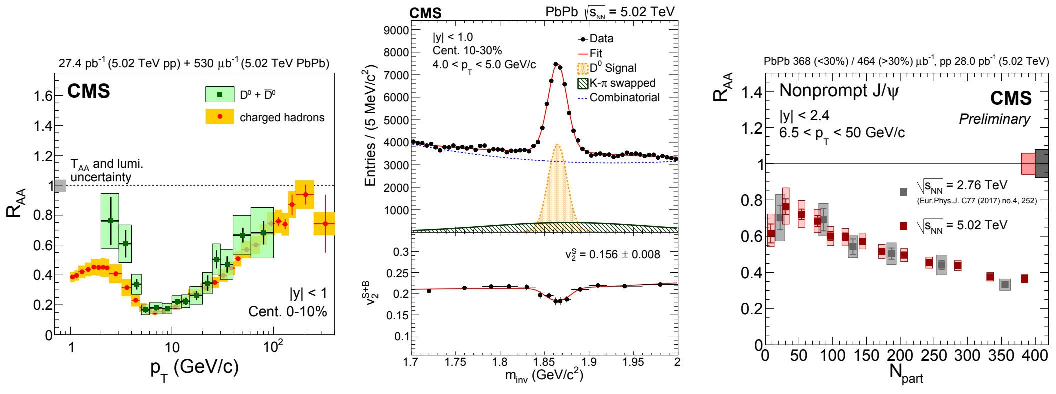

Figure 3. Left: R_{AA} of prompt D^0 mesons and charged hadrons in pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as a function of p_T [12]. Center: example of simultaneous fit of the invariant mass spectrum and the v_2, for the extraction of the v_2 of prompt D^0 mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [13]. Right: R_{AA} of nonprompt J/ψ mesons as a function of the number of participants to the collision, at $\sqrt{s_{NN}} = 2.76$ [2] and 5.02 TeV [3].

The decay channels used are $D^0 \to K\pi$ and $B^\pm \to J/\psi K$. Similarly to J/ψ, they also include a nonprompt component from the decay of B mesons, which can be separated from the prompt component using the impact parameter of the D^0 meson decay vertex with respect to the primary vertex.

When comparing the nuclear modification factor of D^0 mesons [12] to that of charged hadrons, as shown in Fig. 3, a similar suppression is observed, especially at high p_T. Within the larger uncertainties, the R_{AA} of $B^\pm$ mesons [14] is also comparable. Such a comparison of the behaviour of the suppression of different flavours of hadrons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to pp at the same collision energy, provides information on the flavour dependence of parton energy loss. The v_2 of prompt D^0 mesons [13] has also been measured in PbPb as a function of p_T, in several centrality intervals. At low p_T, up to about 7 GeV, the v_2 of D^0 mesons is smaller than that of charged hadrons, hinting to a mass ordering in the flow of hadrons. At high p_T, on the other hand, the charmed mesons feature a similar v_2 as the light hadrons, consistent with a flavour independence of the path length dependence of energy loss.

Coming back to J/ψ measurements, their nonprompt component provides another way to study B meson (open beauty) production, up to 30 GeV. In pPb collisions [5], no large modification is observed, in any rapidity or p_T bin. On the other hand, a strong suppression is observed in PbPb collisions, both at $\sqrt{s_{NN}} = 2.76$ TeV [2] and 5.02 TeV [3], even stronger in central events, which can be seen in Fig. 3. The elliptic flow of nonprompt J/ψ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [2] has also been measured, but still suffers from large uncertainties at the moment, preventing from drawing firm conclusions about the collective behaviour of the bottom quark.

4 Collectivity

Detailed studies of the collective behaviour of particle production in HIC help better understand the properties of the medium and the fluctuations in the initial state. Thus, the event-by-event fluctuations in the v_2 have been quantified with the measurement of the probability distribution of this quantity [15], in several centrality classes in PbPb data at $\sqrt{s_{NN}} = 5.02$ TeV. These distributions are fitted with two analytic functions, and the data is found to be better described by an elliptic power than

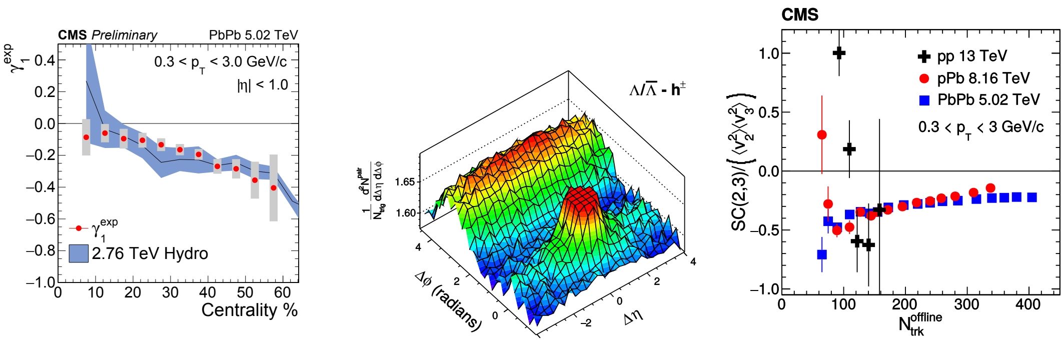

Figure 4. Left: the estimated skewness for the unfolded $p(v_2)$ in PbPb data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, as a function of centrality [15]. Center: correlations between the hyperon and a charged hadron in high multiplicity pp collisions at $\sqrt{s} = 13$ TeV, as a function of $\Delta\eta$ and $\Delta\phi$ [16]. Right: normalised symmetric cumulant between the second and third harmonics, as a function of the number of offline tracks, in pp, pPb and PbPb collisions [17].

by a Bessel-Gaussian function. The skewness of the fluctuations, γ_1^{exp}, is also extracted and found to be in good agreement with predictions from an hydrodynamic model, as can be seen in Fig. 4. Such observations suggest non-Gaussian fluctuations of the eccentricity of the collisions.

Evidence for a collective behaviour is also found in particle production in smaller systems, in pp and pPb collisions. One striking feature is the observation of long-range correlations, the so-called ridge effect, even in high multiplicity pp collisions [16]. A correlation (the "ridge") is found at $\Delta\phi = 0$, even at large $\Delta|\eta|$, in pairs of charged hadrons, but also with strange particles, such as short kaons $\mathrm{K^0_S}$ or hyperons Λ (see Fig. 4). The v_2 of charged particles has also been measured as a function of track multiplicity, in pp, pPb and PbPb collisions, using different methods. In all three systems, the v_2 computed from two-particle correlations is found to be larger than that obtained with other correlators, but four-, six- and eight-particle correlations, as well as the Lee-Yang zeroes method, all yield to similar v_2 values, as expected from a collective origin for the correlations.

Another useful observable in the study of collectivity is the event-by-event correlation between Fourier harmonics of different orders, v_n and v_m. The CMS Collaboration has measured these normalised symmetric cumulants in pp, pPb and PbPb collisions, as a function of track multiplicity [17]. Similar observations are made in all three systems. In the case of $\mathrm{SC}(2,3)$, which gauges the correlation between v_2 and v_3, an anti-correlation is found at high track multiplicity, as shown in Fig. 4. On the contrary, $\mathrm{SC}(2,4) > 0$: the v_2 and v_4 values are positively correlated event-by-event. Similar trends are observed in pPb and PbPb collisions, and high multiplicity pp collisions, regarding the trend of these observables as a function of track multiplicity.

Characteristics of strangeness production have been compared between pp, pPb and PbPb collisions. A higher average kinematic energy $\langle KE_{\mathrm{T}} \rangle$ has been found at higher multiplicities, for all three systems, and for $\mathrm{K^0_S}$, Λ and Ξ^- particles alike [18]. In addition, the increase of $\langle KE_{\mathrm{T}} \rangle$ is faster in smaller systems, and for heavier particles. A similar mass ordering is also seen in pp collisions [16], when comparing the v_2 of charged hadrons and of $\mathrm{K^0_S}$ and Λ particles as a function of p_{T} at high multiplicity, after correcting for back-to-back jet correlations estimated from low-multiplicity data, as shown in Fig. 5. Blast-wave fits have also been performed to the p_{T} spectra of strange particles [18], in several multiplicity bins (see Fig. 5). The interpretation of the parameters of these fits, $\mathrm{T_{kin}}$ and β_{T}, is model dependent. However, similar trends are found in all three systems: β_{T} increases with the

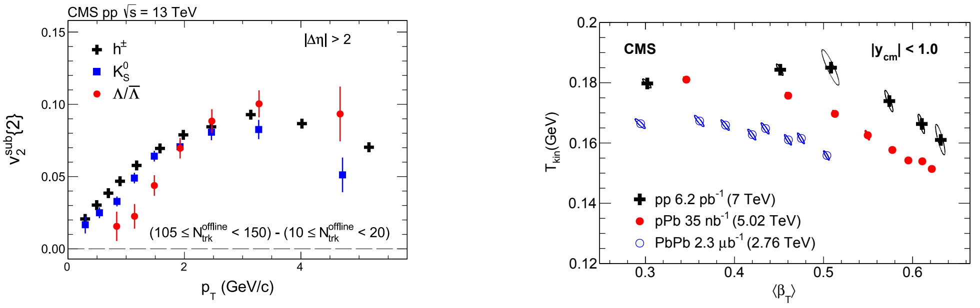

Figure 5. Left: the v_2 results of inclusive charged particles, K^0_S and $\Lambda/\bar{\Lambda}$ particles as a function of p_T for high multiplicity in pp collisions, after correcting for back-to-back jet correlations estimated from low-multiplicity data [16]. Right: the extracted kinetic freeze-out temperature, T_{kin}, versus the average radial-flow velocity, $\langle\beta_T\rangle$, from a simultaneous blast-wave fit to the K^0_S and Λ particles p_T spectra for different multiplicity intervals in pp , pPb , and PbPb collisions [18].

multiplicity in the event, while T_{kin} tends to decrease. In addition, a larger radial flow velocity (large β_T) is found in smaller systems.

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