IOP Conf. Series: Journal of Physics: Conf. Series **1271** (2019) 012007 doi:10.1088/1742-6596/1271/1/012007

Heavy Ion Results from ATLAS and CMS

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Abstract. The heavy-ion programmes in the ATLAS and CMS experiments at the Large Hadron Collider aim to probe and characterise properties of the quark-gluon plasma created in relativistic nuclear collisions. This work presents selected results of collective effects, system size effects, and quarkonia production in p-p, p-Pb, Pb-Pb, and Xe-Xe collisions.

1. Introduction

The ATLAS[1] and CMS Collaborations[1] perform measurements in heavy ion (HI) collision programmes, in addition to proton-proton (p-p) discovery physics. The goal of the HI programmes is to discover and explain the properties of Quark-Gluon Plasma (QGP) created in these collisions. Smaller system sizes are also studied as cases in which QGP creation is not favoured. Recent results from Pb-Pb at centre-of-mass energies of 2.76 TeV and 5.02 Tev, Xe-Xe at 5.44 TeV, and p-Pb at 8.16 TeV are presented. Both HI programmes use p-p reactions as reference collisions to explore initial-state and final-state collision effects.

2. Collision System Size Effects

Most of the current HI programme uses the Pb-Pb system to probe hot and dense matter nuclear. More recent measurements are used to explore the Xe-Xe reaction, which provides a tool for exploring system size dependence on the production of hadrons.

2.1 Pb-Pb and Xe-Xe

Figure 1 shows the pseudorapidity density ($dN_{ch} / d\eta$) of charged hadrons produced in nuclear collisions as a function of rapidity (y) at different energies-per-nucleon [2]. The plot shows the expected growth in charged hadron production as both the LHC centre-of-mass energy increases, and the size of the collision region increases when going from Xe-Xe- to Pb-Pb reactions.

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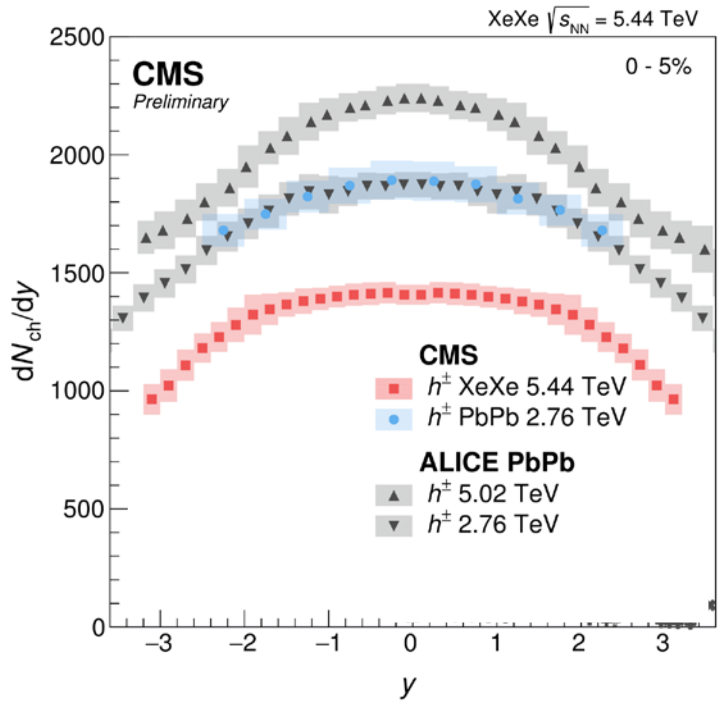

Figure 1. Average and symmetrised dNch/dy as a function of rapidity [2].

2.2 System size scaling

A study of the number of hadronic particles produced as a function of the average number of participants (<Npart>) is shown on the left side of Figure 2, for both Pb-Pb and Xe-Xe collisions. For fixed and large <Npart> no system size scaling is observed.

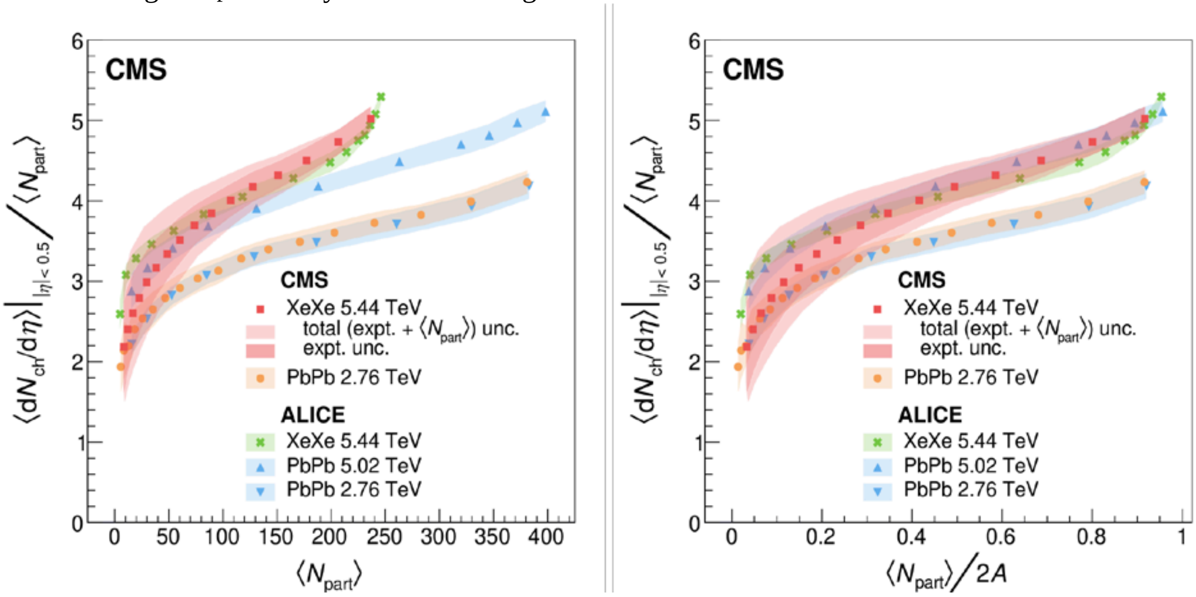

Figure 2. Average dN$_{ch}$/dη at mid-pseudorapidity (η) normalised by <Npart>, shown as a function of <Npart> (left), and <Npart>/2*A* (right), where *A* is the atomic number of the nuclei [2].

The per-participant multiplicity for Xe-Xe and Pb-Pb collisions for the same <Npart> and similar energies but different geometry or centrality are different. This is particularly evident for the most central (largest <Npart>) collisions. However, as in Figure 2 (right), where <Npart>/2A is used as a substitute for centrality, the per-participant charged-hadron multiplicity for different colliding nuclei are equal within uncertainties when the geometry (centrality) and the energy of the compared systems are the same [2].

2.3 Charged particle suppression
Measurement of the nuclear suppression factor R_{AA} indicates how the QGP suppresses the observed charged hadron particle production. The data in Figure 3 show similar numbers of <Npart> but for different centralities in the Xe-Xe and Pb-Pb systems. The Xe-Xe system exhibits slightly stronger suppression in the most central collisions.

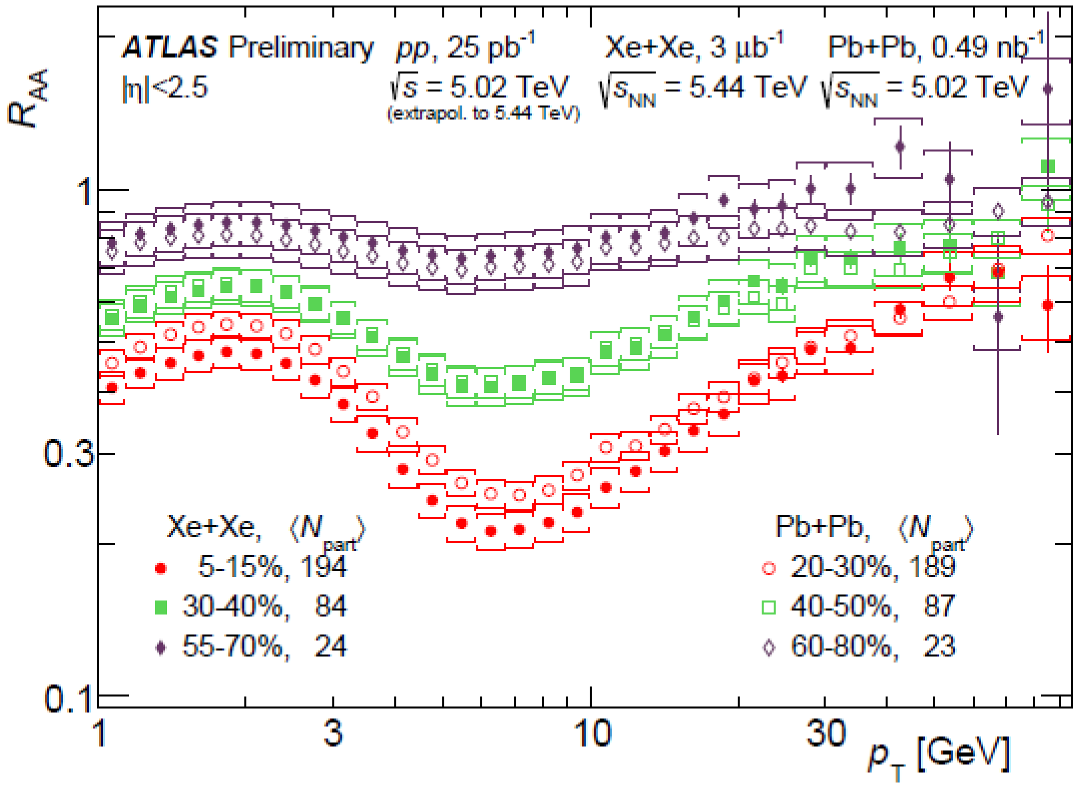

Figure 3. The nuclear modification factor R_{AA} for Xe-Xe and Pb-Pb systems [3].

3. Collective effects
Strong collective flow behaviour is exhibited in high energy nucleus-nucleus collisions. Studies of smaller systems such as p-Pb collisions and high multiplicity p-p collisions also reveal collective flow. Current research is aimed at measuring the flow of heavy quarks in small systems.

3.1 Charm and strange quark elliptic flow
In Figure 4 the background corrected V_2, called V_2^{sub}, per constituent quark for mesons and baryons is presented. For particle transverse kinetic energy per constituent quark values less than 1GeV, the V_2^{sub} of prompt J/ ψ mesons is consistent with prompt D^0, K_S^0 and Λ scaling along with the D^0meson. There is a suggestion of prompt J/Ψ mesons, which consist of two charm quarks, breaking the scaling at higher

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transverse kinetic energies. This is a hint that heavy quarks show weaker collective behavior in compressed nuclear matter.

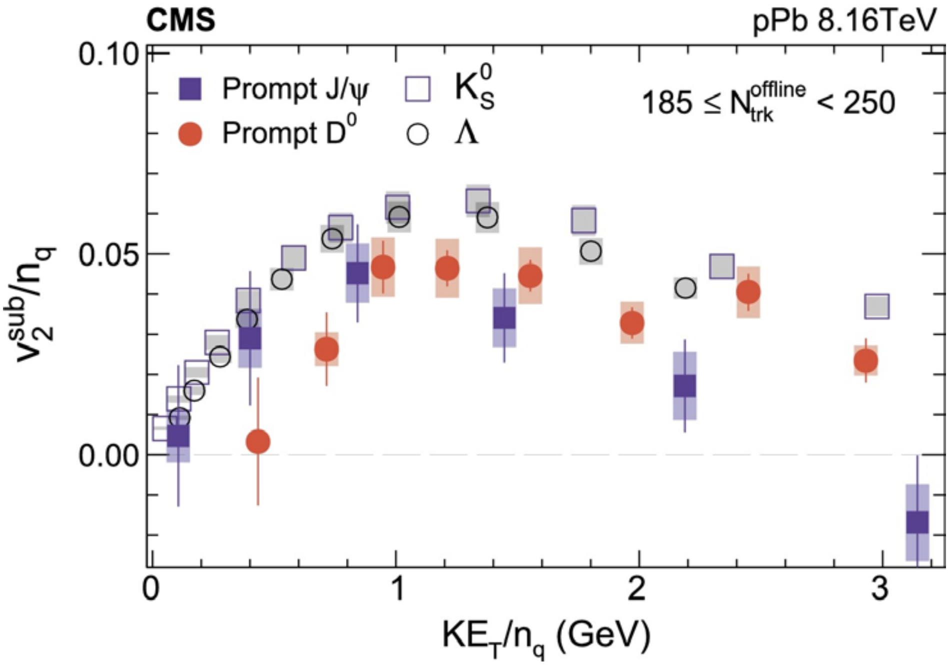

Figure 4. Background subtracted constituent quark normalized elliptic flow (V_2^{sub} / nq) as a function of normalized traverse kinetic energy [4].

3.2 Multiparticle correlations in azimuthal distributions

Multiparticle azimuthal correlations produced in heavy ion collisions extend over a considerable range in pseudorapidity. The observed azimuthal correlations are characterized by Fourier harmonics, with V_2 and V_3 referred to as elliptic and triangular flow, respectively [5]. The ratio between the four-particle and two-particle harmonics provides information on the relative importance of the global geometry and the fluctuation-driven asymmetries.

The first ever small system four-particle measurements of V_3 are shown in Figure 5. For the small system formed in p-Pb (left side of Figure 5) the four-particle and two-particle harmonics are very similar. This is consistent with the origin of these harmonics coming from the same initial state fluctuation. For the larger system Pb-Pb (right side of Figure 5) the elliptic flow harmonic ratio is larger than the triangular flow harmonic. This result if expected if the global collision geometry dominates the Pb-Pb results [5].

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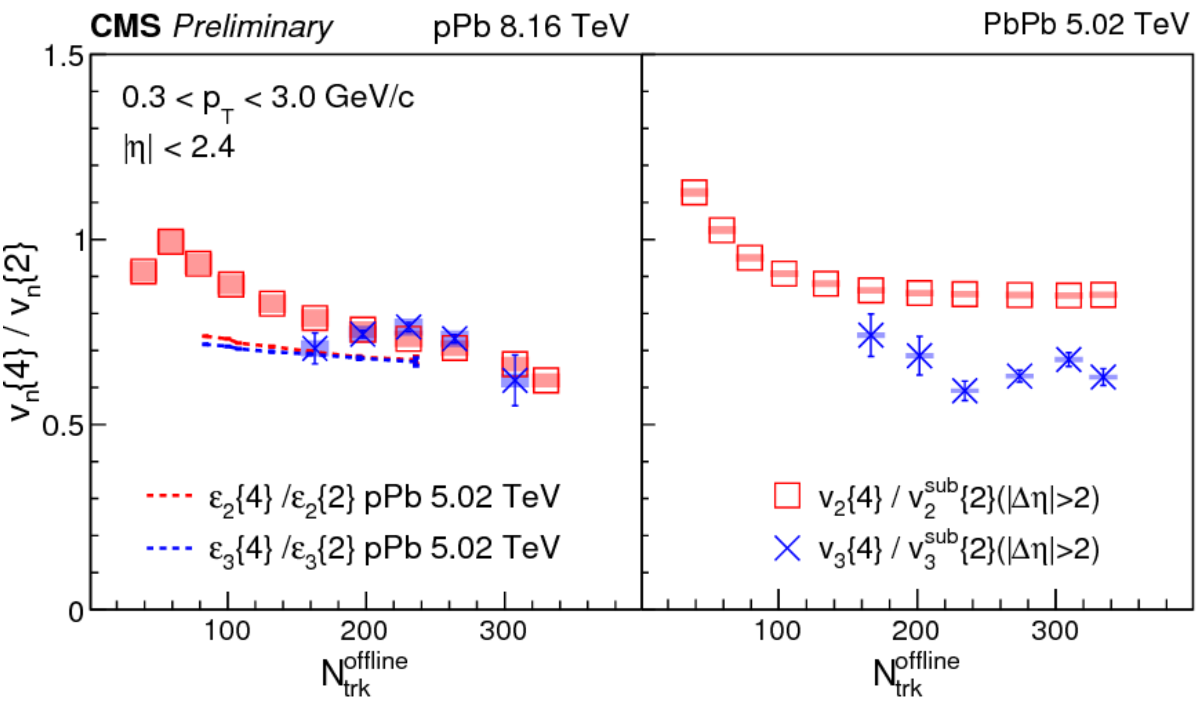

Figure 5. The ratios of four- and two-particle harmonics for pPb at 8.16 TeV (left), and for PbPb at 5.02 TeV (right) [5].

3.3 Dijet asymmetry

Dijets are sprays of particles produced in nucleus-nucleus collisions. If the dijets are approximately back-to-back then the phenomenon of jet quenching, the difference between thetransverse energies of the two jets, can be observed.

New results on the dijet asymmetry (defined as $X_J = P_T^2/P_T^1$, in which P_T^1 is the leading jet transverse momentum, and P_T^2 is the sub-leading jet transverse momentum) for Xe-Xe and Pb-Pb collisions are presented across four centrality bins in Figure 6 [3]. There appears to be very little difference in the behaviour of X_J as the size of the nuclear overlap changes. The jet quenching is uniform for central (0-10%) collisions and potentially evolves smoothly towards a non-uniform shape in the most peripheral (60-80%) collisions.

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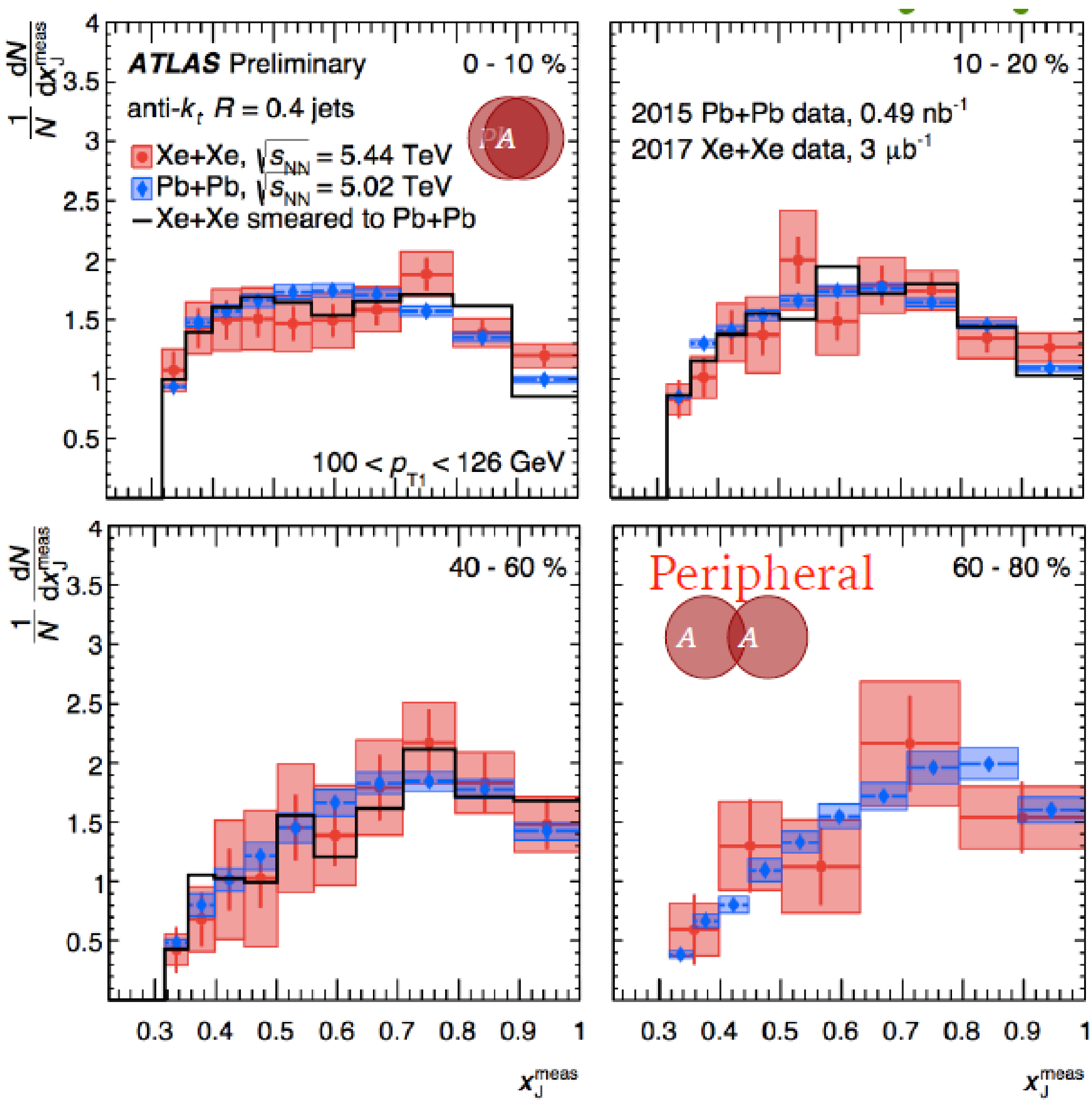

Figure 6. The normalised dijet asymmetry X_J in Xe-Xe and Pb-Pb collisions for four centrality bins [3].

Photons act as calibration probes in HI collisions as they essentially lose no energy as they traverse the QGP. One of the jets can be replaced by a high energy gamma ray. When comparing p-p collisions to Pb-Pb collisions the jet-gamma asymmetry parameter (defined as $X_{J\gamma} = P_T^{jet}/P_T^{\gamma}$) behaves in a substantially different way than X_J defined for Figure 6. The $X_{J\gamma}$ parameter for p-p reactions is compared to two centrality choices in Pb-Pb collisions at 5.02 TeV in Figure 7. Since the gamma-ray balances the jet momentum in p-p reactions we see a prominent peak at $X_{J\gamma} = 1$. In the Pb-Pb collisions we see a similar peak in peripheral collisions, but this peak smoothly evolves with increasing centrality. It nearly disappears for the most central (0-10%) Pb-Pb collisions. The jet momentum is quenched by the QGP in the central Pb-Pb collisions.

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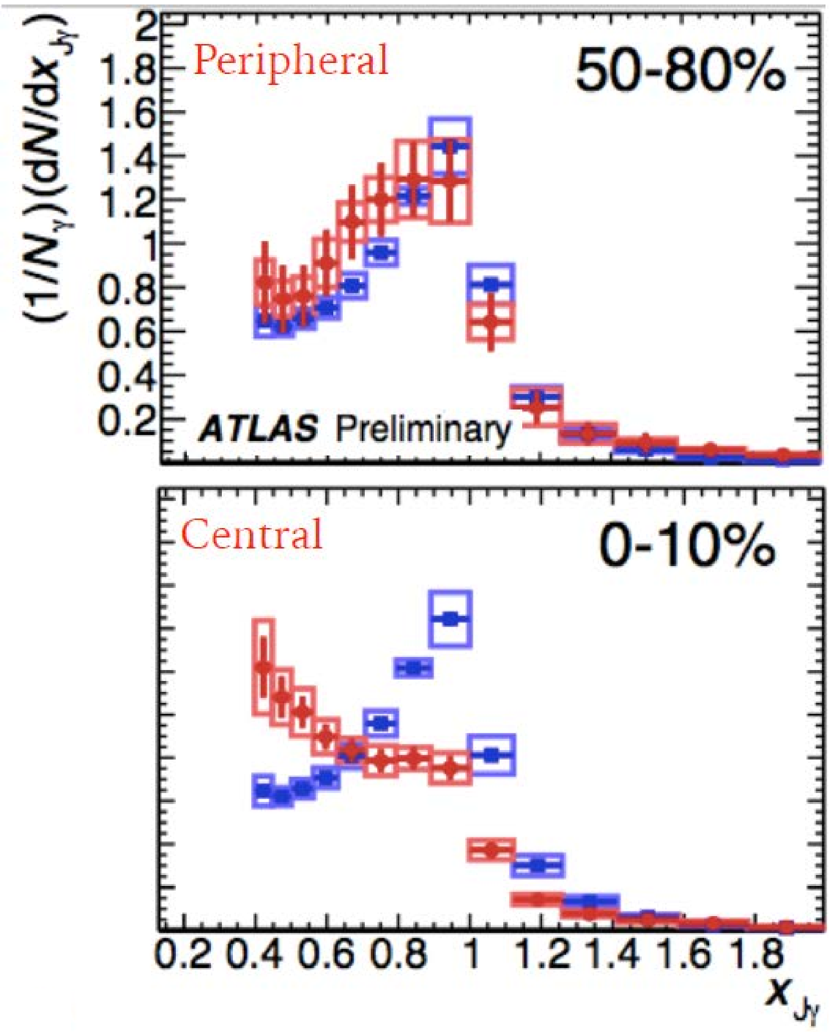

Figure 7. The jet-gamma asymmetry $X_{J\gamma}$ in p-p and Pb-Pb collisions at 5.02 TeV for two centrality bins [6].

4. Quarkonia and heavy quarks

Quarkonia and heavy quarks are also useful probes of QGP produced in HI collisions. The relevant observable quantity is the nuclear suppression factor (R_{AA}). The J/ψ meson is composed of charm and anti-charm quarks. As shown in Figure 8, suppression of J/ψ production in Pb-Pb collisions gets larger as the collision centrality increases, e.g., more QGP is produced in the most central collisions (0-10%).

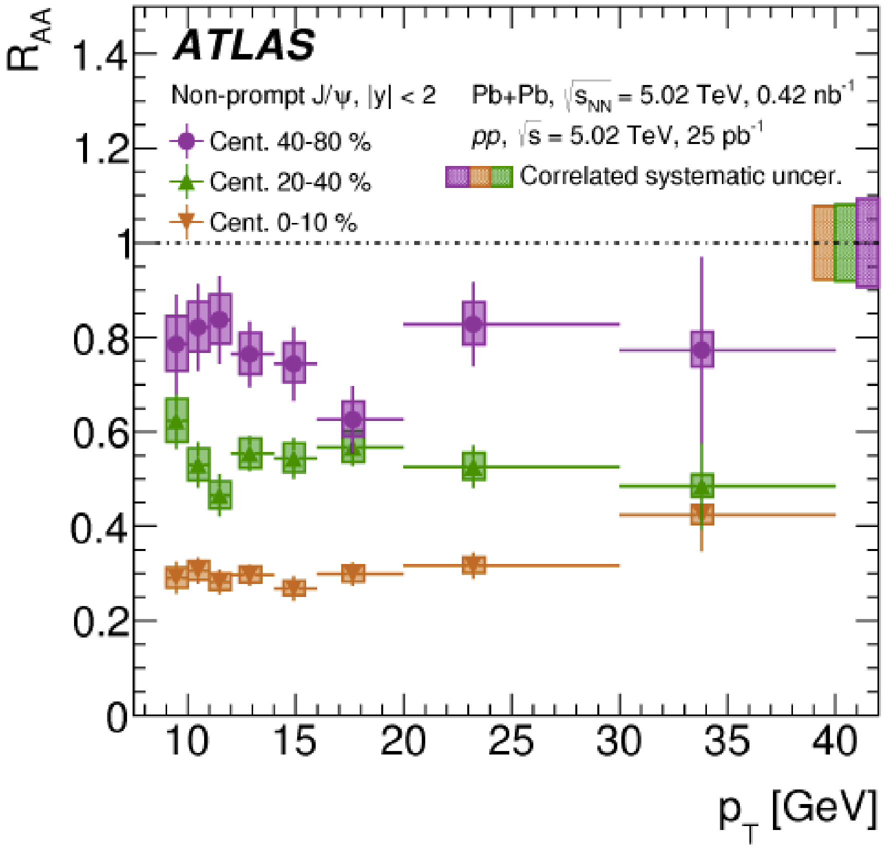

Figure 8. The nuclear modification factor R_{AA} as a function of p_T for prompt J/ψ production in Pb-Pb collisions at 5.02 TeV, shown for three centrality bins [7].

The J/ψ meson has an excited state called the ψ(2S). The less tightly bound ψ(2S) is more sensitive to the high temperature QGP. This is illustrated in Figure 9 (left) where the R_{AA} is plotted for both the J/ψ and ψ(2S) mesons, as a function of participant particles in the Pb-Pb collision [8]. Prompt ψ(2S) are suppressed uniformly across the number of participants when compared to prompt J/ψ in Pb-Pb collisions at 5.02 TeV.

On the right side of Figure 9 is presented the nuclear suppression factor R_{pPb} for the p-Pb collisions at 5.02 TeV. p-Pb collisions are used to observe final state interactions. The ψ(2S) is expected to be suppressed by the same amount as the J/ψ meson, but the data in the negative rapidity region suggests that the ψ(2S) is more suppressed [8]. This may be due to the larger size of the ψ(2S) meson.

The ϒ meson also has a third excited state accessible in HI collisions. These mesons are labelled ϒ(1S), ϒ(2S), and ϒ(3S) in Figure 10 [9]. Similar to the J/ψ meson and the ψ(2S) the three upsilon mesons, consisting of bottom and anti-bottom quarks, show a sequential suppression that increases as the collision centrality increases. The ϒ(3S) has the smallest R_{AA} observed for any hadron. Superimposed upon the data are ideal fluid hydrodynamics calculations [9].
Strangeness enhancement in HI collisions is accompanied by heavy quark creation. This motivates the search for strange neutral B mesons; e.g., $B_S^0 \rightarrow J/\Psi\ \varphi \rightarrow \mu^+\mu^- K^+ K^-$ in A-A collisions. In Figure 11 (left) is an invariant mass yield plot of B_S^0 mesons[10]. In Figure 11 (right) is the nuclear suppression R_{AA} for B mesons, with and without a strange quark, moving through QGP. Within current uncertainties, the results are consistent with models of strangeness enhancement and a suppression as observed for the B+ mesons.

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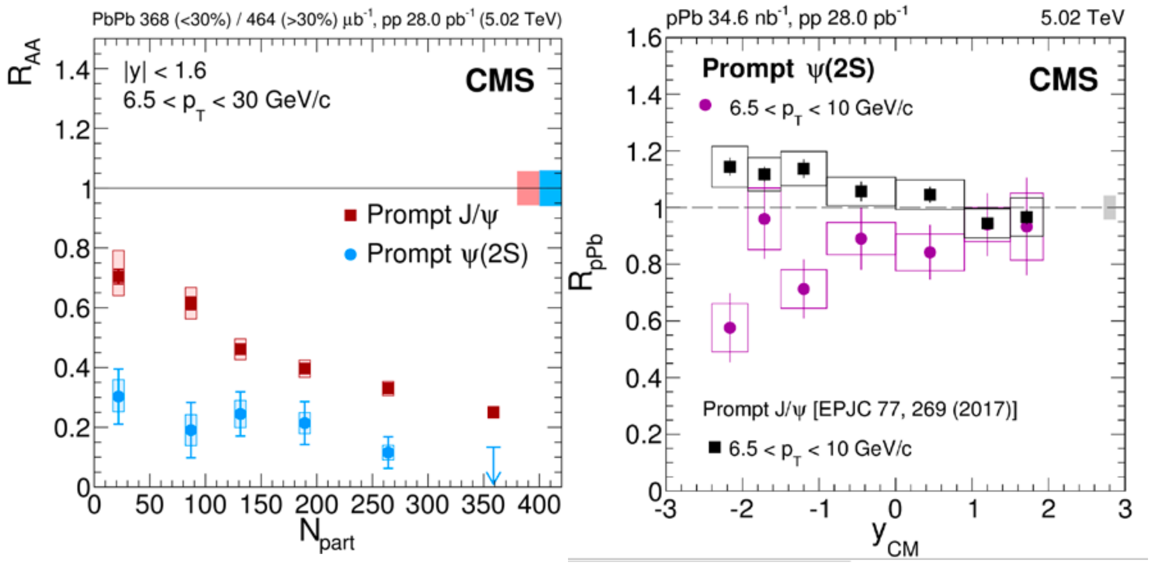

Figure 9. Nuclear suppression factors R_{AA} for J/ψ and ψ(2S) mesons in Pb-Pb(left) and in p-Pb (right) collisions plotted versus the number of participating particles (N_{part}), and the rapidity (y_{CM}), respectively [8].

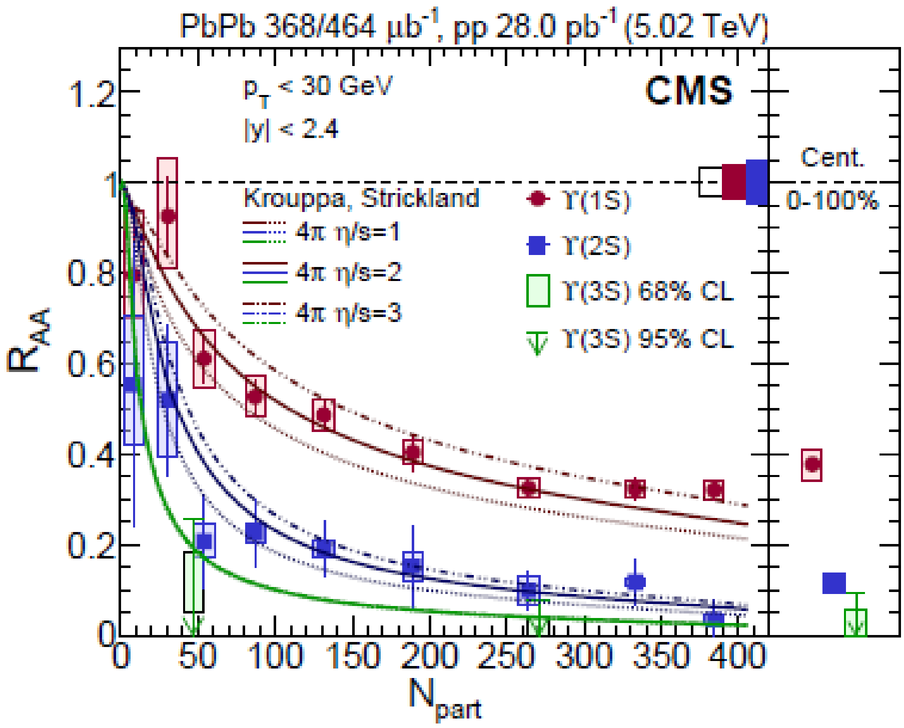

Figure 10. The nuclear modification factor R_{AA} as a function of p_T for ϒ(1S), ϒ(2S), and ϒ(3S) production in Pb-Pb collisions at 5.02 TeV, shown as a function of the number of participating nucleons [9]. Ideal fluid model calculations by Krouppa and Strickland are also presented [9].

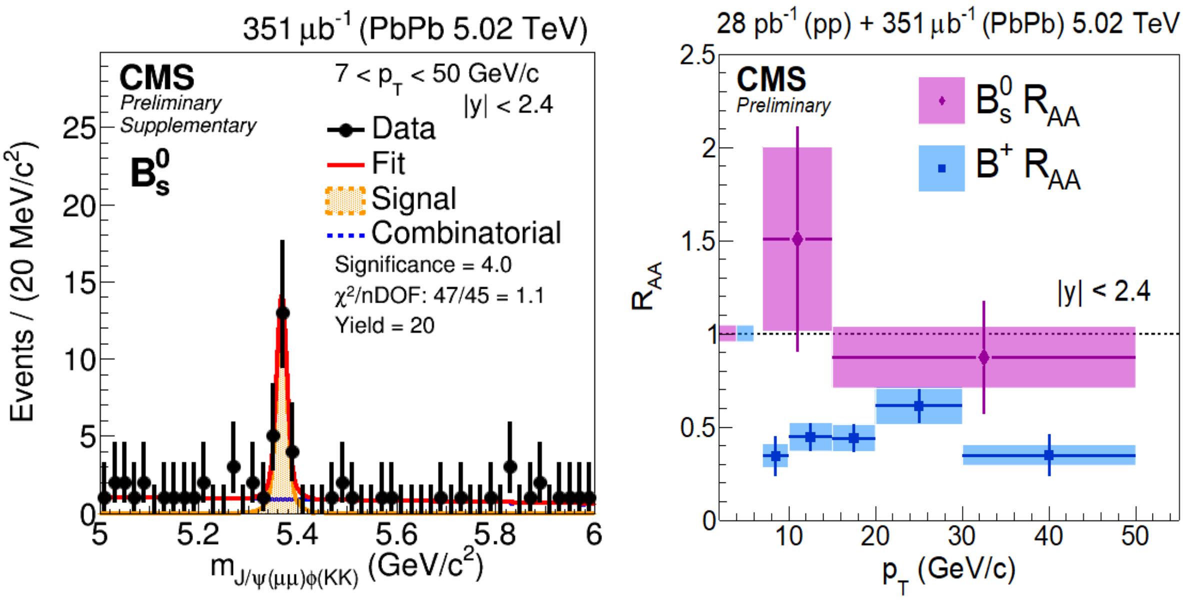

Figure 11. The invariant mass distribution for B_s^0 decay in Pb-Pb collisions (left). Nuclear suppression factor for B measons from Pb-Pb collisions (right) [10].

5. Conclusions

The heavy ion reaction programmes at both ATLAS and CMS are focussed on the study of QGP. A variety of particles and observables are used to investigate the earliest stages of nucleus-nucleus collision. System size effects, particle correlations, jet quenching, quarkonia, and heavy quark nuclear suppression provide insight to the earliest moments in relativistic nucleus-nucleus collisions.

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