Heavy Ion Results from ATLAS and CMS

David Krofcheck
The University of Auckland
For the CMS and ATLAS Collaborations
d.krofcheck@auckland.ac.nz

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 (dNch/ dη) 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.
Figure 1. Average and symmetrised $dN_{ch}/dy$ 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 ($<N_{\text{part}}>$) is shown on the left side of Figure 2, for both Pb-Pb and Xe-Xe collisions. For fixed and large $<N_{\text{part}}>$ no system size scaling is observed.

Figure 2. Average $dN_{ch}/d\eta$ at mid-pseudorapidity ($\eta$) normalised by $<N_{\text{part}}>$, shown as a function of $<N_{\text{part}}>$ (left), and $<N_{\text{part}}>/2A$ (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 $<N_{\text{part}}>$ and similar energies but different geometry or centrality are different. This is particularly evident for the most central (largest $<N_{\text{part}}>$) collisions. However, as in Figure 2 (right), where $<N_{\text{part}}>/2A$ 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 $<N_{\text{part}}>$ 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].](image)

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 $V_{2}^{\text{sub}}$, per constituent quark for mesons and baryons is presented. For particle transverse kinetic energy per constituent quark values less than 1GeV, the $V_{2}^{\text{sub}}$ of prompt $J/\psi$ mesons is consistent with prompt $D^0$, $K_S^0$ and $\Lambda$ scaling along with the $D^0$ meson. There is a suggestion of prompt $J/\Psi$ mesons, which consist of two charm quarks, breaking the scaling at higher
transverse kinetic energies. This is a hint that heavy quarks show weaker collective behavior in compressed nuclear matter.

![Graph](image)

**Figure 4.** Background subtracted constituent quark normalized elliptic flow ($V_{2}^{\text{sub}} / n_{q}$) 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 is expected if the global collision geometry dominates the Pb-Pb results [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 the transverse energies of the two jets, can be observed.

New results on the dijet asymmetry (defined as \( X_J = \frac{P_T^2}{P_T^1} \), 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.

**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].
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 $X_{J\gamma} = p_{T}^{\text{jet}} / p_{T}^{\gamma}$) 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.
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 $J/\psi$ meson is composed of charm and anti-charm quarks. As shown in Figure 8, suppression of $J/\psi$ 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 7. The jet-gamma asymmetry $X_{J\gamma}$ in p-p and Pb-Pb collisions at 5.02 TeV for two centrality bins [6].
Figure 8. The nuclear modification factor $R_{AA}$ as a function of $p_T$ for prompt $J/\psi$ production in Pb-Pb collisions at 5.02 TeV, shown for three centrality bins [7].

The $J/\psi$ meson has an excited state called the $\psi(2S)$. The less tightly bound $\psi(2S)$ is more sensitive to the high temperature QGP. This is illustrated in Figure 9 (left) where the $R_{AA}$ is plotted for both the $J/\psi$ and $\psi(2S)$ mesons, as a function of participant particles in the Pb-Pb collision [8]. Prompt $\psi(2S)$ are suppressed uniformly across the number of participants when compared to prompt $J/\psi$ 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 $\psi(2S)$ is expected to be suppressed by the same amount as the $J/\psi$ meson, but the data in the negative rapidity region suggests that the $\psi(2S)$ is more suppressed [8]. This may be due to the larger size of the $\psi(2S)$ meson.

The $\Upsilon$ meson also has a third excited state accessible in HI collisions. These mesons are labelled $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ in Figure 10 [9]. Similar to the $J/\psi$ meson and the $\psi(2S)$ the three upsilon mesons, consisting of bottom and anti-bottom quarks, show a sequential suppression that increases as the collision centrality increases. The $\Upsilon(3S)$ 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., $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ 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.
Figure 9. Nuclear suppression factors $R_{AA}$ for $J/\psi$ and $\psi(2S)$ mesons in Pb-Pb (left) and in p-Pb (right) collisions plotted versus the number of participating particles ($N_{\text{part}}$), and the rapidity ($y_{CM}$), respectively [8].

Figure 10. The nuclear modification factor $R_{AA}$ as a function of $p_T$ for $Y(1S)$, $Y(2S)$, and $Y(3S)$ 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].
5. Conclusions
The heavy ion reaction programmes at both ATLAS and CMS are focused 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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Figure 11. The invariant mass distribution for B_0^0 decay in Pb-Pb collisions (left). Nuclear suppression factor for B mesons from Pb-Pb collisions (right) [10].