Recent results form Pb+Pb collisions at LHC

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The Pb+Pb collisions at per nucleon center of mass energy of 2.76 TeV are performed to study the properties of strongly interacting matter at high temperatures. At very high temperatures and/or density there exists a phase of matter known as quark gluon plasma (QGP), where the quarks and gluons can move far beyond the size of a nucleon making color degrees of freedom dominant in the medium. Experiments at Relativistic Heavy Ion Collider indicate that such matter is strongly coupled and can consists bound states which carry net color. Most signals from heavy ion collisions are analyzed in terms of nuclear modification factor, which is the ratio of signal measured in heavy ion collisions over that in pp collisions. With the recent Pb+Pb collisions experiments at LHC, a new era has began in this field. LHC with its advanced detectors can probe the matter in many ways. The hard probes such as jets and quarkonia which can be tackled in perturbative QCD and can be very well reconstructed with advanced detector technologies. These hard probes are produced in plenty in LHC and are used to study the detailed tomography of the matter which would not have been possible at lower energies. In addition to the hot matter effects one also has to address the questions such as modification of parton distributions of protons when placed inside a nucleus. This is known as initial state effects and can be well addressed at LHC by measuring the Z boson. In addition, there are (cold) nuclear matter effects which can modify the probes and are planned to be studied in future p+Pb collisions. There are many signals characterizing the features of collisions events such as multiplicity and particle spectra. The flow and particle correlations categorized as soft probes help quantify the collectivity of the matter. In this talk, the current and future plans of LHC along with some of its detectors will be described. How the hard as well as soft probes characterize the system produced in Pb+Pb collision will be explained. Also theoretical interpretations of the results from some of the publications will be touched upon.

1. Introduction

The heavy ion collisions are performed to study the interaction of matter at extreme temperatures and densities where it is expected to be in the form of Quark Gluon Plasma (QGP), a state where color degrees of freedom are dominant. The experimental effort in this direction started with low energy CERN accelerator SPS and evolved through voluminous results [1] from heavy ion collision at Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Lab in recent years. The RHIC experiments have produced the evidence that at the energy $\sqrt{s_{NN}} = 200$ GeV a strongly interacting quark gluon liquid is produced. The scaling of elliptic flow with quark number, and the suppression of the fast quarks in the medium are clear signals of this. At both SPS and RHIC energies the suppression of the J/ψ resonance suggests that a very high temperature system was created [2, 3]. With the start of Pb+Pb collisions at per nucleon center of mass energy $\sqrt{s_{NN}} = 2.76$ TeV at LHC, there is renewed excitement in this field.

The proton-proton physics run at the LHC started in November 2009 at center of mass energies $\sqrt{s} = 0.9$, 2.36 and 7 TeV. The PbPb run started in November 2010 at $\sqrt{s}_{NN} = 2.76$ TeV. The run finished with an integrated luminosity 8.6 μb^{-1} delivered. The results presented in this manuscript are mostly from this run. While the ALICE detector is well suited for soft probes, the CMS detector is well suited for hard probes such as jets, high-p$_T$ hadrons, heavy-quarks, quarkonia and large yields of the non interacting perturbative probes (di-

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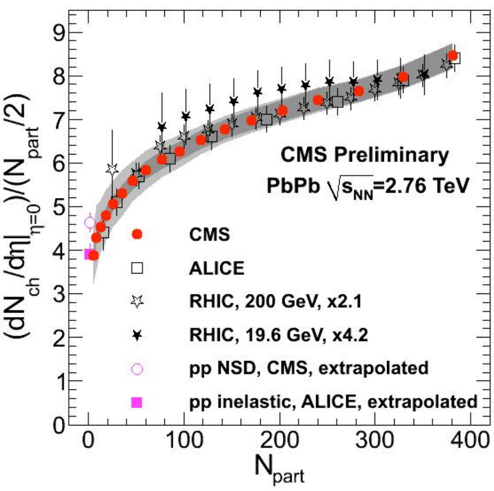

FIG. 1: Charged particle pseudorapidity distribution measured by LHC detectors along with the RHIC measurements and pp extrapolated results.

rect photons, dileptons, Z and $W^{\pm}$ bosons). The second heavy-ion run done in November-December 2011 at the same energy but with a 15-20 times increase in luminosity. In 2012 the plan is to have p-Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV.

In this presentation, the High Energy Heavy Ion Collisions are divided into the following regions: global observables, flow, quarkonia, heavy flavour charged particles, photons and jets.

2. Global observables

The multiplicity of produced particles is probably the most basic of observables. It provides information on the energy density achieved in the collisions and constitutes a primary input for most model calculations. Figure 1 shows the charged particle pseudorapidity distribution measured by LHC detectors [4] along with the RHIC measurements and pp extrapolated results. For central Pb-Pb collisions at the LHC (at $\sqrt{s_{NN}} = 2.76$ TeV), about 8 charged particles per unit of pseudorapidity η are produced about twice as many as at RHIC [4–6]. The centrality dependence of the charged particle multiplicity

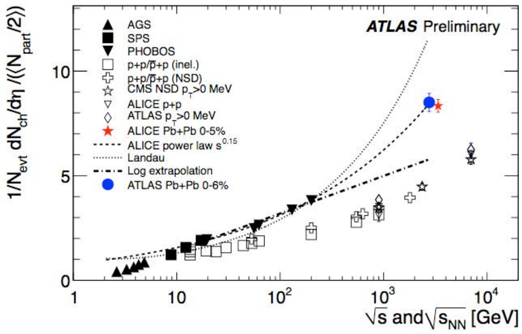

FIG. 2: Charged particle multiplicity in central collisions as function of collision energy.

is rather mild, favouring models incorporating some mechanism (such as parton saturation) moderating the increase with centrality of the average multiplicity per participant pair[7, 8]. Once the multiplicities are rescaled to account for the difference in the central values, the centrality dependences at the LHC and at RHIC are remarkably similar.

Figure 2 shows charged particle multiplicity in central collisions as function of collision energy [9]. The multiplicity measured at LHC is larger than most of the predictions and about 50 % more than expected from simple phenomenological extrapolations from RHIC energy: the logarithmic law that described the energy dependence of multiplicities up to RHIC has finally broken down.

The average amount of transverse energy produced per unit of pseudorapidity per participant pair in central collisions is about 9 GeV, or about a factor 2.7 larger than at RHIC (the larger multiplicity at LHC being accompanied by an increase in the average transverse momentum of the produced particles), corresponding to an energy density of about 16 GeV/fm^3 (taking the conventional value of 1 fm/c for the plasma formation time).

Hanbury Brown – Twiss (HBT) interferometry [10, 11] exploits the quantum interference between identical bosons (e.g. charged pions) to evaluate the size of the system at the time of decoupling. Compared to RHIC, the ALICE experiment finds an increase in the dimensions of the system in all three components [12, 13] (including, finally, also the sidewards component R_{side}). The system expands significantly more than at RHIC, with an estimated increase by about a factor 2 of the homogeneity volume for central collisions.

3. Flow

Most of the lead nuclei do not collide head on, the overlap region will have an elliptical shape. For a liquid, this initial space anisotropy is translated into a final elliptical asymmetry in momentum space. However for a gas, any anisotropy should be much weaker. The elliptic flow parameter, v_2 is the second harmonic of the azimuthal distribution of hadrons with respect to the reaction plane. Comparing the experimental v_2 with hydrodynamical calculations will show us how close the matter is to a fully thermalized perfect fluid.

Detailed measurements of the v_2 parameter and the higher harmonics (up to 6th order) as a function of centrality, p_T and pseudorapidity using charged tracks was done by CMS [14]. The integrated v_2 extrapolated to $p_T = 0$ as measured by CMS for events in a centrality bin of $20 - 30\%$ is compared to the measurements at lower energies in Fig. 3. The average value of the *elliptic flow* coefficient v_2 continues to be large at the LHC (roughly 20% larger than at RHIC for semi-central events) [15–18]: the behaviour of the system is still very close to that of an ideal liquid. When measured as a function of transverse momentum, the values of v_2 at the two colliders are close: although the events at the LHC are on average harder than those at RHIC, the hydrodynamical properties of the system at the two energies seem to be rather similar.

Higher order flow coefficients were also measured [14] as a function of centrality using dihadron correlations and are shown in Fig. 4. Note that the higher order coefficients change little with centrality and remain important even for the most central collisions

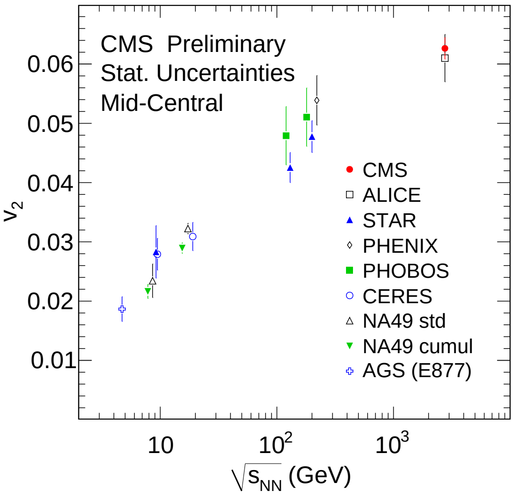

FIG. 3: Integrated flow coefficient $v_2\{LYZ\}$ compared to measurements by LHC detectors from low energy experiments for mid-central collisions (20-30%).

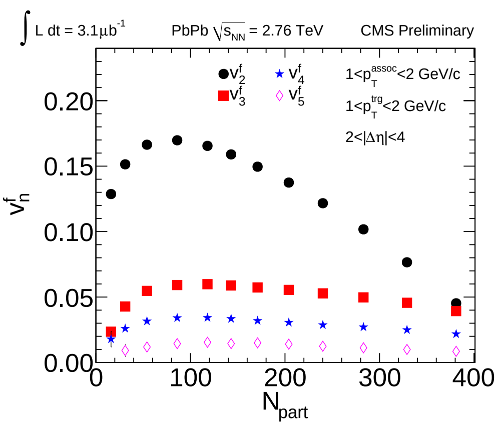

FIG. 4: Higher order Fourier coefficients as a function of centrality extracted using dihadron correlations.

4. Quarkonia

Quarkonia are important for studying the quark gluon plasma (QGP) since they are produced early in the collision and their survival is affected by the surrounding medium. The bound states of charm and bottom quarks are expected to be suppressed in heavy-ions, as

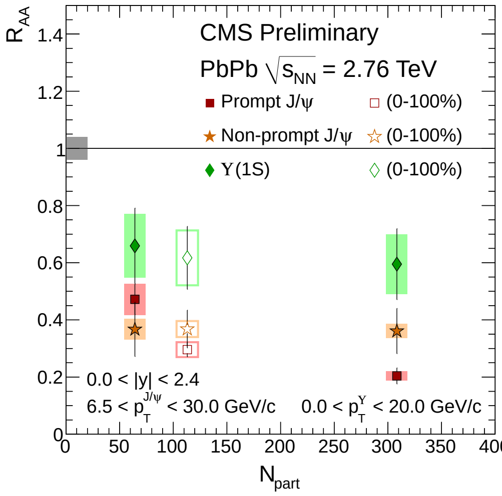

FIG. 5: Suppression of quarkonia states, R_{AA} as a function of centrality, for prompt J/ψ, non-prompt J/ψ and $\Upsilon(1S)$.

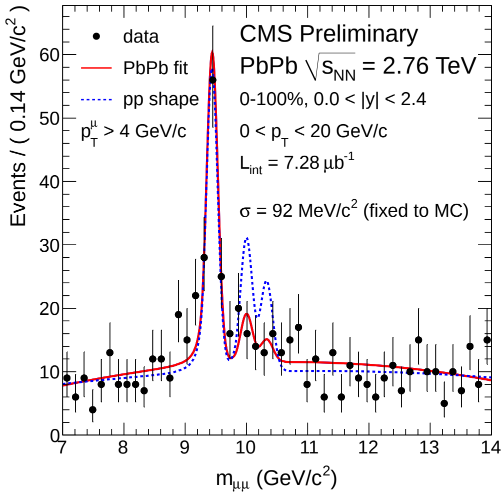

FIG. 7: Mass spectrum of Υ family in PbPb collisions compared to the fit obtained in pp events at the same energy.

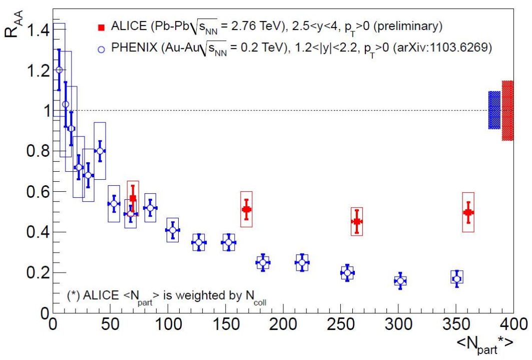

FIG. 6: R_{AA} of J/ψ as a function of centrality measured by ALICE.

compared to pp. The magnitude of the suppression for different quarkonia states is expected to depend on their binding energy. The PHENIX collaboration has updated the results on J/ψ suppression using the 2007 data sample [19, 20]. The previous results, and in particular the stronger suppression at forward than at central rapidity, are confirmed, with reduced statistical and systematic uncertainties.

The CMS collaboration obtained production rates of J/ψ mesons and of the Υ family in dimuom channel [21]. Non-prompt J/ψs (those produced from B-meson decays) could be identified by their displaced decay vertex. The suppressions of prompt and non-prompt J/ψ particles were measured separately. The non-prompt J/ψ suppression is one measure of the quenching of b-quarks. The R_{AA} as function of the number of participants N_{part} indicates that high p_T J/ψs are strongly suppressed as low as 0.2 for central collisions as shown in Fig. 5.

ATLAS also observes strong centrality dependence in the central-to-peripheral nuclear modification factor $R_{cp}^{J/\psi}$ at high p_T [22]. For $p_T > 0$ and $2.5 < y < 4$, ALICE observes a J/ψ nuclear modification factor $R_{AA}^{J/\psi}$ of about 0.5, practically independent of centrality [23] as shown in Fig. 6.

CMS reported suppression for the Υ(1S) (around 0.6, with a weak energy dependence) and further suppression by about a factor 3 relative to the Υ(1S) for the excited states Υ(2S+3S) [21]. Fig. 7 shows that the excited states, $\Upsilon(2S)$ and $\Upsilon(3S)$, are suppressed as compared to the $\Upsilon(1S)$. This is compatible with differential melting of quarkonia states

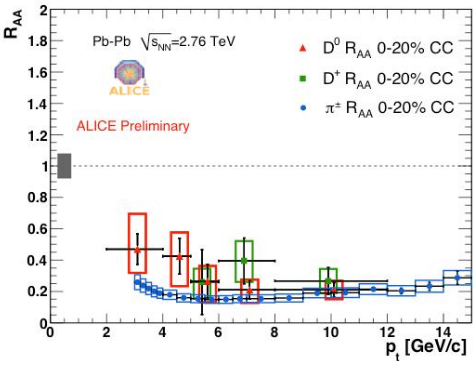

FIG. 8: R_{AA} of D mesons as a function of p_T measured by ALICE experiment.

in the high temperatures produced by PbPb collisions.

The detailed pattern of quarkonia suppression will emerge with high statistics measurements. Establishing a good pA reference will also be essential in order to disentangle the contributions from cold nuclear effects.

5. Heavy flavours

The heavy flavour such as D and B probe the medium properties. At RHIC it has been observed that heavy quarks loose substantial energy in the medium. Both STAR and PHENIX are planning to upgrade the apparatus with the addition of vertex detectors, which should allow them to separate the vertices of the weak decays of heavy flavour particles from the primary vertex. Heavy flavour vertexing is already available in the LHC experiments. Reconstructed D^0 and D^+ signals have been presented by ALICE [24, 25], which shows substantial suppression of the production of D mesons over the currently available transverse momentum range (out to 12 GeV/c) in both central (0-20%) and peripheral (40-80%) Pb–Pb collisions. Figure 8 shows such measurement for central collisions. The values of the nuclear modification factor R_{AA} are found to be compatible with those of the pions, except below 5 GeV/c. In BDMPS energy loss calculations for LHC, D are expected to be suppressed about a factor 2 less than pions for $p_T \sim 8$ GeV/c [26]). Could charm quarks be essentially thermalized in the QGP, and thereby "lose memory" of their energy loss history? CMS have presented results on the nuclear modification factor of J/ψ originating in the decay of B mesons for $p_T^{(J/\psi)} > 6.5$ GeV/c [21]. The suppression is again about a factor 3, with very little – if any – centrality dependence.

The future will bring high statistics D and B measurements, allowing us to establish the mass and colour charge dependence of the parton energy loss.

6. Charged particles and photons

The modification of charged particle p_T spectrum, compared to nucleon-nucleon collisions at the same energy can shed light on the detailed mechanism by which hard partons lose energy traversing the medium. Results on high p_T suppression at the LHC have been presented by the three experiments (R_{AA} by CMS [27], by ALICE [28, 29] and R_{cp} by ATLAS [30]). The nuclear modification ratio R_{AA} was measured in CMS for all charged particles with p_T up to 100 GeV/c. The ratio is plotted in Fig. 9 and compared to theoretical predictions. The R_{AA} measured by ALICE is shown in Fig. 10. The production of high p_T particles in Pb–Pb collisions at the LHC is strongly suppressed. R_{AA} reaches a minimum of about 0.14 for transverse momenta around 6-7 GeV/c, and then increases again very slowly, almost levelling off around 0.5 for transverse momenta above 30 GeV/c.

High transverse energy (E_T) prompt photons in nucleus-nucleus collisions are produced directly from the hard scattering of two partons. Once produced, photons traverse the hot and dense medium without any interaction, hence they provide a direct test of perturbative QCD and the nuclear parton densities. A CMS measurement of direct photon production as a function of centrality and p_T is compared to the NLO pQCD predictions [31]. The ratio R_{AA} as a function of photon p_T for the most central events is shown in Fig. 11. Within statistical uncertainties, the direct photons are not suppressed as com-

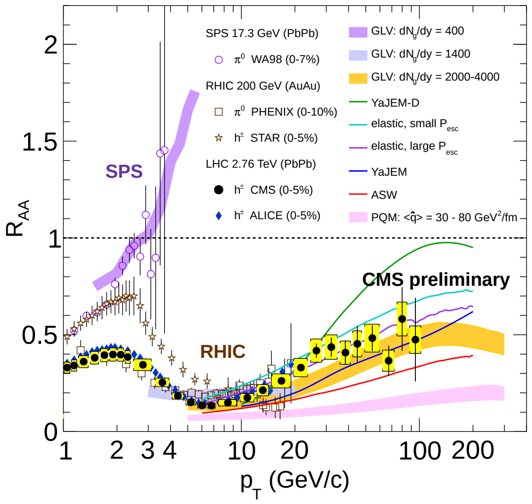

FIG. 9: Comparison of data for R_{AA} as a function of p_T for neutral pions and charged hadrons in central heavy-ion collisions at three different center-of-mass energies and several theoretical predictions

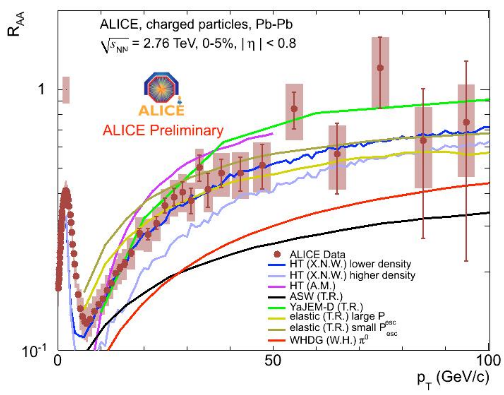

FIG. 10: R_{AA} of charged particles as a function of p_T measured by ALICE.

pared to pp collisions.

7. Jets

Studying the modification of jets as they are formed from high p_T partons propagating thorough the hot and dense QGP has been proposed as a particularly useful tool for probing the produced matter's properties. Intriguing results on jet production at the LHC have been published by ATLAS [32] (using the anti-k_T algorithm [33]) and CMS [34] (based on the use of an iterative cone algorithm [35]). A strong increase in the di-jet unbalance is observed when comparing Pb-Pb to pp collisions [36, 37], when jets are studied with jet radii $R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} \simeq 0.2 - 0.4$.

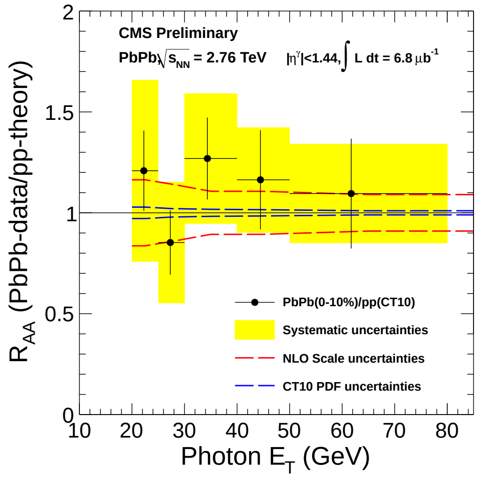

FIG. 11: R_{AA} of isolated photons as a function of p_T for central events (0-10%).

The CMS [37] studied events with at least two jets with the leading (sub-leading) jet with p_T of at least 120 (50) GeV/c and with an opening angle $\Delta\phi_{12} > 2\pi/3$ to study these medium effects. The most striking observation is the large, centrality-dependent, imbalance in the energy of the two jets, as measured in the CMS calorimeters (See Fig. 12). While their energies were very different, the two jets were observed to be very close to back-to-back in the azimuthal plane, implying little or no angular scattering of the partons during their traversal of the medium. To find the 'missing energy', the calorimetric measurement was complemented by a detailed study of low p_T charged particles in the tracker and by using missing p_T techniques. The apparent missing energy was found among the low p_T particles, predominantly with $0.5 < p_T < 2$ GeV/c,

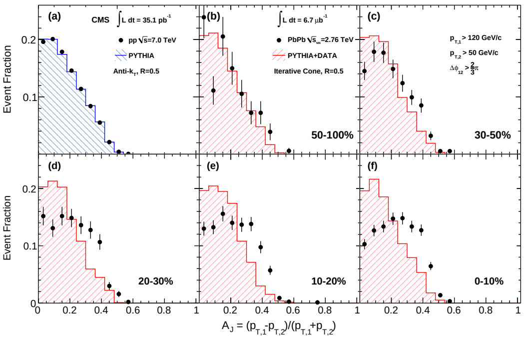

FIG. 12: Calorimetric jet imbalance in dijet events as a function of collision centrality for pp and PbPb events.

emitted outside of the sub-leading jet cone.

The suppression of jets is substantial and apparently rather independent of the jet energy, with a nuclear modification factor (R_{cp}) around 0.5 for central (10%) events.

PHENIX, reconstructing jets using a gaussian filter, report a centrality-dependent suppression of the jet yields (up to about a factor 2 relative to pp for central Au–Au collisions) [38]. Interestingly, they also report non-negligible jet suppression in d–Au collisions (about a 20% effect in central versus peripheral d–Au), underlying once more the importance of measuring the "cold nuclear reference".

This is one of the most interesting areas in this field at the moment. The prospect are enticing with γ-jet and Z^0-jet fragmentation function measurements coming up. It would also be very interesting to single out and study in fine detail the most extreme "mono-jets" events, where one of the jets is almost completely absorbed.

8. Conclusions

With the start of LHC with its high tech detectors high energy nucleus-nucleus collisions are entering an era of precision measurements that should allow us to impose tight constraints on the properties of the medium.

The multiplicity and transverse energy measured at LHC are larger than most of the predictions. The average value of the *elliptic flow* coefficient v_2 continues to be large at the LHC, the behaviour of the system is still very close to that of an ideal liquid. High p_T J/ψs are strongly suppressed as low as 0.2 for central collisions. CMS shows that the excited states, $\Upsilon(2S)$ and $\Upsilon(3S)$, are suppressed as compared to the $\Upsilon(1S)$. This is compatible with differential melting of quarkonia states in the high temperatures produced by PbPb collisions.

The production of high p_T particles in Pb-Pb collisions at the LHC is strongly suppressed. R_{AA} reaches a minimum of about 0.14 for transverse momenta around 6-7 GeV/c, and then increases again very slowly, almost levelling off around 0.5 for transverse momenta above 30 GeV/c. The suppression of jets is substantial and apparently rather independent of the jet energy, with a nuclear modification factor (R_{cp}) around 0.5 for central (10%) events. For heavy flavours, the nuclear modification factor are found to be compatible with those of the pions.

With a high luminosity LHC Pb–Pb run in 2011 (15-20 times the 2010 luminosity) and possibly a p–Pb run as early as next year, we could be in for some paradigm shifting in this field.

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