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Overview of recent CMS results

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Abstract. Recent results from the CMS Collaboration are presented. These measurements include a full physics program using ultraperipheral collisions such as photon-photon and photon-ion interactions, small collision systems including proton-proton and proton-lead collisions, and many measurements of hadronic ion-ion collisions. The properties of the quark-gluon plasma produced in ion-ion collisions are studied in detail. The measurements examine the number of degrees of freedom of the medium, the strength of jet quenching effects in the medium, the role of heavy flavor in hadronization processes, and more.

The CMS detector [1] is a general purpose experiment that is capable collecting a diverse number of data sets and types, and performing many different physics analyses. The investigations showcased here illustrate the extensive physics program of CMS, encompassing a wide range of collision types, including ultraperipheral collisions (UPCs), small collision systems, and hadronic ion-ion collisions. Most of these measurements focus on the study of the strong force and its unique properties, although some also exploit the strong electric fields surrounding heavy ions to study other interesting physics when accelerated at high energies.

An example of one of these measurements is CMS's recent observation of the $\gamma\gamma \rightarrow \tau^+\tau^-$ process in ultraperipheral PbPb collisions [2], where the production cross section using the decay channel where one τ decays to a muon and the other decays to three pions is measured. The τ anomalous magnetic moment a_τ, which is predicted to be potentially sensitive to the

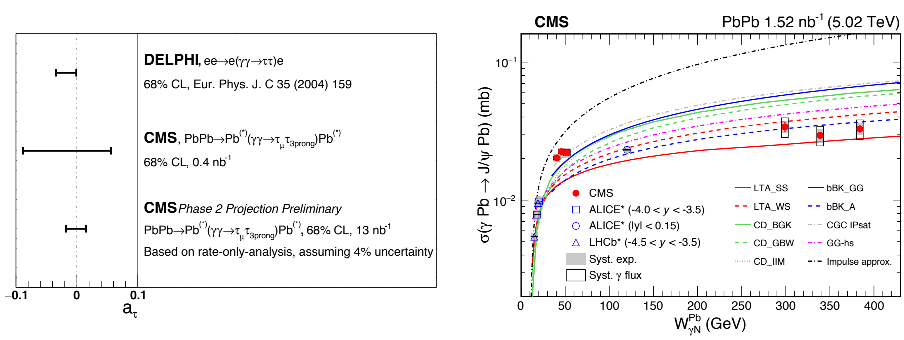

Figure 1. (Left) A measurement of the τ lepton anomalous magnetic moment by CMS compared to previous measurements by DELPHI and a prediction for the LHC Run 4 era [2]. (Right) The cross section of coherent J/ψ production in PbPb UPCs versus the photon-nucleon center of mass energy [3].

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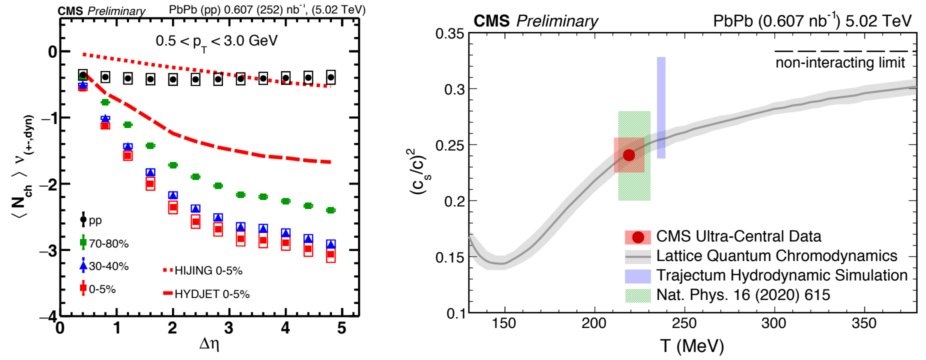

Figure 2. (Left) The net charge fluctuations measured in 5.02 TeV PbPb collisions as a function of the separation between particle pairs, $\Delta\eta$ [5]. (Right) A measurement of the speed of sound in the QGP, plotted as a function of the effective temperature of the system [6]. The measurement agrees with lattice QCD calculations [7].

existence of new heavy particles, has been extracted using these data. This quantity can be see in the left panel of Fig. 1. It is predicted that the UPC measurement may be competitive with existing measurements from LEP in the LHC Run 4 era. The right panel of Fig. 1 shows a measurement of the coherent J/ψ cross section in UPC PbPb collisions as a function of the center of mass energy W of the photon-nucleon system [3]. For the first time, CMS has separated the contributions of low- and high-energy photons to the cross section in a given rapidity range, which allows probing of the high-W, which corresponds to very low Bjorken x of $\approx 10^{-5}$. The fact that the models shown cannot predict the full W-dependence of the data could be an early indication of gluon saturation in the nucleus, or alternatively of the cross section approaching the black disk limit [4].

Figure 2 shows a new measurement of the net charge fluctuations of PbPb collisions using the $\nu_{(+,-,dyn)}$ variable [5]. When scaled by the average charged event multiplicity $\langle N_{ch} \rangle$, this observable is expected to have a value of -3 if the hot medium produced in heavy ion collisions has Quark Gluon Plasma (QGP) degrees of freedom. The value is expected to be -1 if the medium is a hadron gas. The quantity is plotted as a function of the pseudorapidity separation of the pair of particles $\Delta\eta$, which is expected to be larger for particles that result from processes earlier in the evolution of the system. For large values of $\Delta\eta$, the data are close to -3 and for small values, the data are close to -1, indicating the system evolves from an initial QGP to a hadron gas. The right panel of Fig. 2 shows a new extraction of the speed of sound squared $(c_s/c)^2$ performed by examining charged particle spectra in head-on (or ultra-central) PbPb collisions [6]. The speed of sound is plotted as a function of the system's effective temperature T, which is extracted from the average p_T of the produced particles. The value extracted, shown in red, is consistent with predictions from lattice quantum chromodynamics (QCD) calculations [7] of a QGP. This measurement is perhaps the most direct proof to date that the hot medium produced in these collisions has QGP-like degrees of freedom.

The $f_0(980)$ particle has been hypothesized to be either a diquark $s\bar{s}$ state, or a tetraquark state that is a $s\bar{s}u\bar{u}$ state or $K\bar{K}$ molecule [8]. In pPb collisions, strange hadrons have been observed to exhibit a phenomenon known as constituent quark scaling, where the v_2 divided by the number of constituent quarks n_q, plotted against p_T/n_q follows a roughly universal function. Fig. 3 shows a measurement of these quantities for the $f_0(980)$, where it has been hypothesized that either $n_q = 2$ or $n_q = 4$ [9]. A similar quantity has been plotted for other

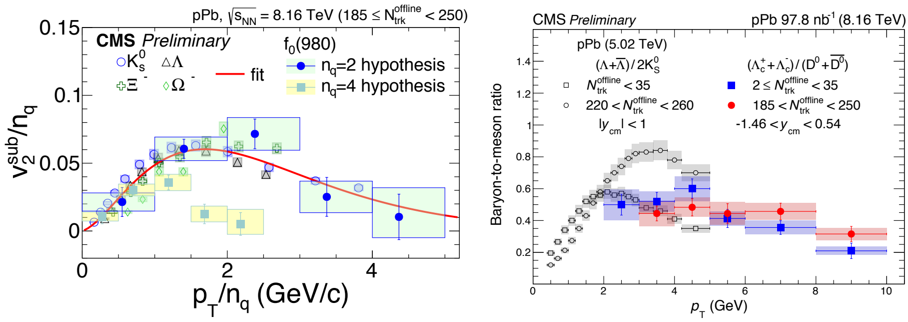

Figure 3. (Left) The v_2 versus p_T of the $f_0(980)$ particle, when both quantities are scaled by different hypotheses for the number of constituent quarks, n_q, in pPb collisions. The results are compared to similar measurements for other strange hadrons [9]. (Right) A measurement of the Λ_c^+ to D^0 ratio as a function of p_T for high-multiplicity pPb collisions, compared to similar results for strange hadrons [10].

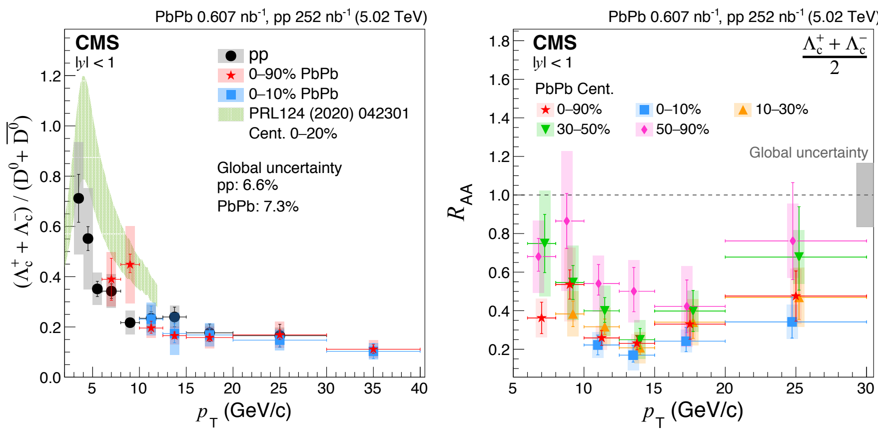

Figure 4. (Left) The Λ_c^+ to D^0 ratio as a function of p_T for PbPb and pp collisions at 5.02 TeV. (Right) The nuclear modification factor for different centrality classes for Λ_c^+ baryons in PbPb collisions [11].

strange hadrons, with a red line fit to these data. The $n_q = 4$ hypothesis for the $f_0(980)$ is not consistent with the trend extracted from other hadrons, while the $n_q = 2$ hypothesis agrees well. This measurement strongly supports the diquark interpretation for the structure of the $f_0(980)$ particle, and shows a novel technique for studying hadron structure. The right panel of Fig. 3 displays a measurement of the Λ_c^+ to D^0 ratio as a function of p_T for high-multiplicity pPb collisions [10]. This quantity has relatively mild p_T dependence, which is in contrast to the same quantity shown in gray for strange hadrons. This could indicate that charm hadronization mechanisms differ from those for strange quarks in high-multiplicity environments.

The role of charm quarks in hadronization has been explored further in the context of PbPb collisions. The left panel in Fig. 4 shows a measurement of the Λ_c^+ to D^0 ratio as a function of p_T for PbPb and pp collisions [11]. The ratio in pp collisions is around 0.7 at about 3 GeV, but quickly falls to values around 0.15 for $p_T > 10$ GeV. This value is consistent with the measurement of the same quantity in PbPb collisions. When comparing

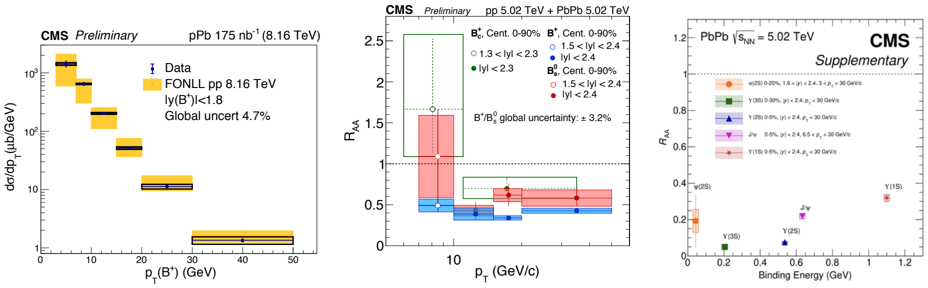

Figure 5. (Left) The p_T differential cross section of B^+ mesons in 8.16 TeV pPb collisions. The results are compared to predictions from FONLL [12]. (Middle) A comparison of the R_{AA} of three different beauty mesons in 5.02 TeV PbPb collisions. Figure compiled from Refs. [13, 14]. (Right) The R_{AA} values for five different quarkonia states, plotted against their binding energy [15].

all the CMS measurements of this ratio, it seems to have relatively lower values at higher p_T in pp, pPb, and PbPb collisions. Using the same Λ_c^+ measurement, the nuclear modification factor R_{AA} has also been measured [11], as shown in the right panel of Fig. 4. The production of this hadron is heavily suppressed in PbPb collisions as compared to pp collisions, and the magnitude of this suppression seems to be somewhat similar to previous measurements of other charm hadrons like the D^0. In general, the suppression is larger for lower centrality classes, which is consistent with the behavior observed for many other hadrons.

CMS has also made multiple measurements probing the role of beauty quarks in hadronization processes. A new measurement of the p_T differential cross section of B^+ mesons in pPb collisions is shown in the left panel of Fig. 5 [12]. The measurement is consistent with theoretical predictions from FONLL. The middle panel of Fig. 5 shows measurements of the nuclear modification factors of B_s^0 and B^+ mesons in PbPb collisions that have been updated using the high-luminosity data gathered by CMS in 2018 [13]. The precision of the measurement is significantly better than previous measurements, especially in the highest p_T range probed. The measurements are compared to a recently finalized measurement of the B_c^+ meson [14]. In general, an approximate ordering for the R_{AA} with $B_c^+ > B_s^0 > B^+$ is observed, which could be an indication of coalescence effects in the hadronization process. Finally, studies of quarkonia have also been performed, as shown on the right panel of Fig. 5 [15]. Here, the R_{AA} values of five vector quarkonia states are plotted against their binding energy, including a recently finalized observation of the highly suppressed $\Upsilon(3S)$. In general, the mesons tend to be more highly suppressed for lower binding energies. The R_{AA} for $\psi(2S)$ seems to ignore this trend, but has a large uncertainty. Nonetheless, bottomonia seem more suppressed than charmonia, which is different than the trend observed in the open heavy flavor sector. This highlights the different production dynamics, such as recombination, that are relevant for quarkonia production in heavy ion collisions.

As jets pass through the QGP medium, they suffer energy loss and have their structure modified via interactions with the medium. A useful observable to study this phenomenon is the groomed jet radius, R_g, which is the opening angle between the two subjets left at the end of the SoftDrop grooming algorithm [16]. This quantity is predicted to be sensitive to the presence or absence of color coherence effects in the parton shower of the jet. The ratio of this quantity in PbPb and pp collisions has been measured for an inclusive jet selection and has been found to be strongly modified, with a narrower distribution seen. Although this could be a signature of modified coherence, this could also be the result of a jet selection

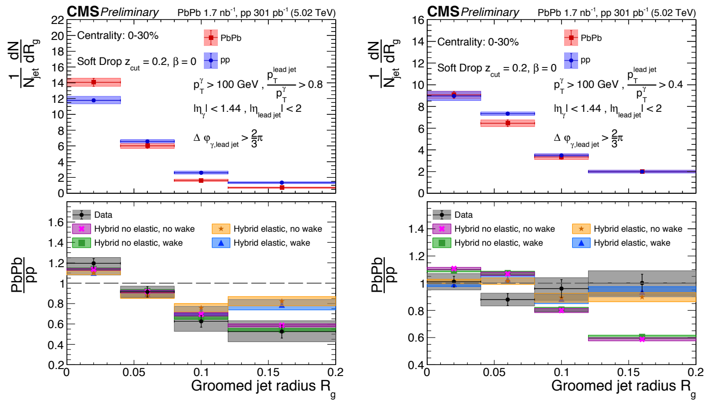

Figure 6. Measurements of the groomed jet radius R_g in photon-jet events for PbPb collisions. The left panel shows events where the photon and jet are required to have a roughly balanced p_T values. The right panel shows the results for an event selection that includes both balanced and unbalanced configurations of the photon and jet p_T [17].

effect where wider, more quenched jets, are preferentially removed from a given jet p_T selection where the analysis is performed. To study this effect further, CMS has measured R_g in the photon-jet system for the first time in both 5.02 TeV PbPb and pp collisions [17]. The presence of a photon allows a selection on the initial unquenched p_T of the jet, which serves as a handle to study the contribution of quenching and selection effects. Fig. 6 shows the results for two different selections. The left panel shows the results for a selection where the jet is required to have at least 80% of the photon p_T, which is a roughly balanced system. This corresponds to less quenched jets. A narrowing is observed when comparing PbPb to pp collisions, which is consistent with previous inclusive jet results. The right panel shows a selection where the jet is only required to have 40% or more of the photon p_T. This includes both balanced and unbalanced configurations, and shows less narrowing. This result is consistent with the narrowing of the jet R_g being significantly affected by selection effects, and indicates this is an important contribution when considering the interpretation of these substructure observables. Interestingly, comparisons to the Hybrid model show that different selections also change which parameters of the model (inclusion of elastic scatterings or wake effects) that are needed to better predice the data.

To probe the possibility of collectivity in systems as small as a jet, CMS has a new result that using 138 fb^{-1} of high-pileup 13 TeV pp collisions [18]. In this measurement, shown in the left panel of Fig. 7, jets are selected on their charged particle multiplicity after the PUPPI pileup subtraction. The v_2 of the jet constituents are then calculated after rotating the coordinate system such that the jet axis lies along the positive z axis. This aligns all the jets along their axis of propagation, and means v_2 then quantifies azimuthal anisotropies with respect to the jet axis. When the v_2 is plotted against the jet multiplicity, which is shown as the abscissa of Fig. 7, a decreasing trend is observed for multiplicities less than 80. However, a distinctive uptick is seen in for multiplicities above 80, which is not reproduced by the Monte Carlo models studied. This could indicate some onset of collective effects at these multiplicities, although there also might be other possible explanations for such behavior.

Finally, CMS has performed a measurement of the charged hadron pseudorapidity density in PbPb collisions at a new energy of 5.36 TeV using the first LHC Run 3 data delivered to the

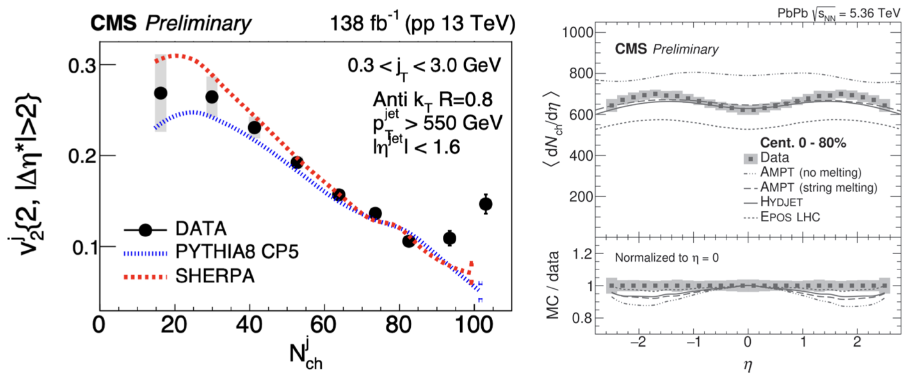

Figure 7. (Left) A measurement of the v_2 of jet constituents in 13 TeV pp collisions as a function of the number of charged constituents in the jet. The coordinate basis used for measuring the particle momenta has been transformed to be parallel and perpendicular to the jet axis [18]. (Right) The charged hadron pseudorapidity density for 5.36 TeV PbPb collisions. The bottom inset shows a ratio of the data with the various simulations shown, where the ratio has been normalized to unity at $\eta = 0$ [19].

experiment at the end of 2022 [19]. As can be seen by the magnitude and shapes of the Monte Carlo models the data are compared to in the right panel of Fig. 7, the data can constrain event generators at this new collision energy. This measurement represents a first entrance into the exciting new Run 3 era which is just beginning. A higher luminosity is expected at the end of 2023, which will allow further exciting studies using heavy ion collisions.

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