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**CMS CR -2012/179**

**The Compact Muon Solenoid Experiment**

# Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

**31 July 2012 (v2, 03 September 2012)**

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Charles Felix Maguire for the CMS Collaboration

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The measurements of the anisotropic flow of single particles and particle pairs have provided some of the most compelling evidence for the creation of a strongly interacting quark-gluon plasma (sQGP) in relativistic heavy ion collisions, first at RHIC, and more recently at the LHC. Using PbPb collision data taken in the 2010 and 2011 heavy ion runs at the LHC, the CMS experiment has investigated a broad scope of these flow phenomena. The $v_2$ elliptic flow coefficient has been extracted with four different methods to cross-check contributions from initial state fluctuations and non-flow correlations. The measurements of the $v_2$ elliptic anisotropy have been extended to a transverse momentum of 60 GeV/c, which will enable the placement of new quantitative constraints on parton energy loss models as a function of path length in the sQGP medium. Additionally, for the first time at the LHC, the CMS experiment has extracted precise elliptic anisotropy coefficients for the neutral $\pi$ meson ($\pi^0$) in the centrality range 20-80% and over a transverse momentum range 1.6 to 8 GeV/c. These results are compared with both the $\pi^0$ results reported by the PHENIX detector at RHIC and with the inclusive charged particle anisotropy results reported from the LHC. Finally, the CMS experiment has mounted an extensive study of charged hadron pair azimuthal correlations using a Fourier harmonic decomposition to fit the data. The relationship between these pair coefficients and the single particle harmonic flow coefficients can be explored for its insight into the early dynamics of this viscous medium.

Presented at *HardProbes2012: The 5th International Conference on Hard and Electromagnetic Probes of High Energy Nuclear Collisions*

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Nuclear Physics A 00 (2012) 1–8

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# Hadron Correlations in CMS

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**Abstract**

The measurements of the anisotropic flow of single particles and particle pairs have provided some of the most compelling evidence for the creation of a strongly interacting quark-gluon plasma (sQGP) in relativistic heavy ion collisions, first at RHIC, and more recently at the LHC. Using PbPb collision data taken in the 2010 and 2011 heavy ion runs at the LHC, the CMS experiment has investigated a broad scope of these flow phenomena. The $v_2$ elliptic flow coefficient has been extracted with four different methods to cross-check contributions from initial state fluctuations and non-flow correlations. The measurements of the $v_2$ elliptic anisotropy have been extended to a transverse momentum of 60 GeV/c, which will enable the placement of new quantitative constraints on parton energy loss models as a function of path length in the sQGP medium. Additionally, for the first time at the LHC, the CMS experiment has extracted precise elliptic anisotropy coefficients for the $\pi^0$ meson in the centrality range 20-80% and over a transverse momentum range 1.6 to 8 GeV/c. These results are compared with both the $\pi^0$ results reported by the PHENIX detector at RHIC, and with the inclusive charged particle anisotropy results reported from the LHC. Finally, the CMS experiment has mounted an extensive study of charged hadron pair azimuthal correlations using a Fourier harmonic decomposition to fit the data. The relationship between these pair coefficients and the single particle harmonic flow coefficients can be explored for its insight into the early dynamics of this viscous medium.

*Keywords:* sQGP, LHC, CMS

## 1. Introduction

We present results from the CMS experiment on the azimuthal anisotropy of charged and neutral particles emitted in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV generated by the LHC. The primary goal of such relativistic heavy ion experiments is the study of the deconfined state of matter predicted to be formed at the extreme temperatures and energy densities produced in these collisions. The original discovery of this novel state of matter occurred at the Relativistic Heavy Ion Collider (RHIC) for which the data analyses revealed unexpectedly the presence of a strongly interacting Quark Gluon Plasma (sQGP) having the proprieties of a near-perfect quantum liquid [1, 2, 3, 4]. Measurements of the azimuthal correlations of the particles produced in these collisions at low (< 3 GeV/c) and intermediate (∼3–6 GeV/c) values of transverse momentum $p_T$ have played a key role in unraveling the dynamics of plasma's expansion. Additionally, at higher transverse momentum a "jet quenching" phenomenon is apparent indicating a substantial loss of energy as the produced partons traverse the sQGP medium. The yields of high $p_T$ particles in central heavy ion collisions are measured to be much less than would be predicted by simple binary scaling from the pp collision yields.

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Given the asymmetric geometry of the participant zone created in heavy ion collisions, a different amount of suppression is expected for partons traveling along the short axis of the participant zone relative to those traveling the long axis [5]. Taken together this ensemble of azimuthal correlation data as a function of $p_T$ should serve to constrain theoretical models of the sQGP insofar as these models depend upon a precise knowledge of the initial state conditions and the partonic energy loss parametrization.

## 2. Charged Single Particle Azimuthal Correlations at Low $p_T$

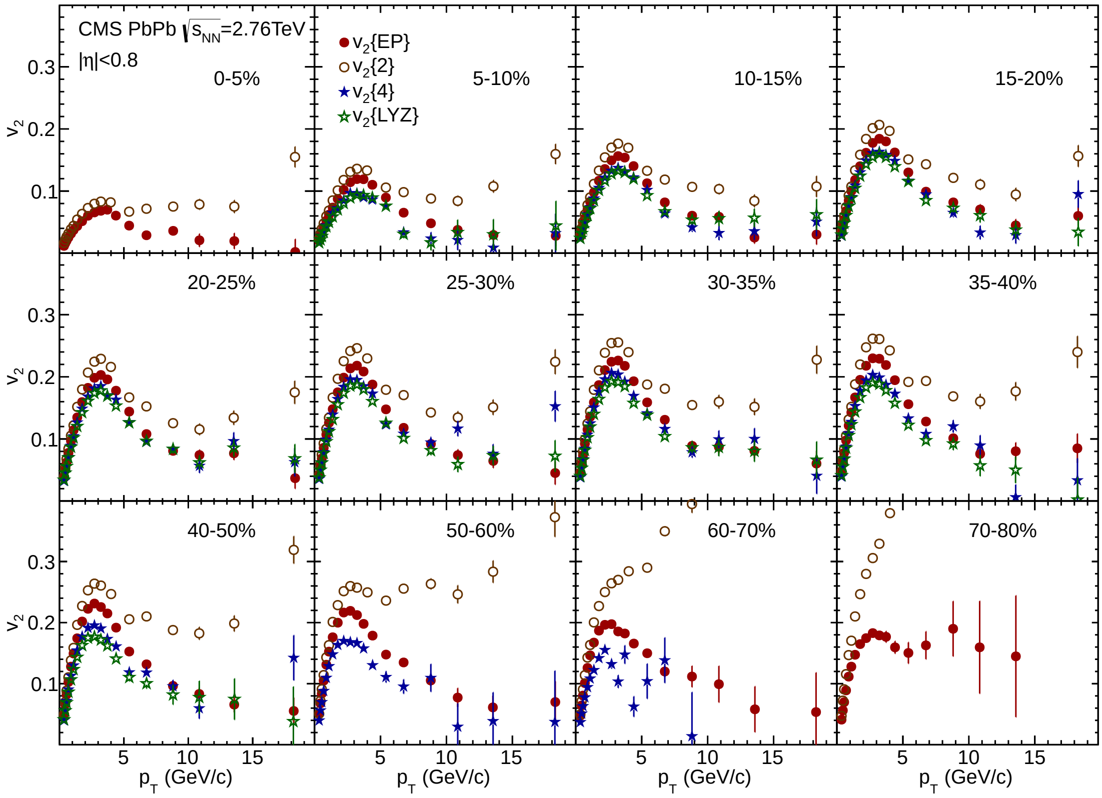


Figure 1: $v_2(p_T)$ distributions for four analysis methods in twelve centrality classes. The analysis methods are described in the text.

In heavy ion collisions at non-zero impact parameter there is an almond-shaped overlap region of participant nucleons. This asymmetric region gives rise to asymmetric pressure gradients which induce anisotropic azimuthal distributions of the emitted particles with respect to the participant plane. The azimuthal anisotropies are given the name "flow" reflecting their hydrodynamic origins. The participant plane is defined as containing the longitudinal direction of the colliding ions and the perpendicular impact parameter direction. Since the impact parameter is not directly measurable then neither is the participant plane. Instead, an empirical approximation of the participant plane called the event plane (EP) [6] is obtained by measuring the anisotropic distribution of a physical quantity such as the energy of the event. This EP determination is made in a region of pseudorapidity sufficiently separated from the pseudorapidity region where the emitted particle flow is being measured so that autocorrelation effects can be minimized.

A quantitative characterization of the azimuthal anisotropy as a function particle transverse momentum $p_T$ can be obtained in terms of a Fourier decomposition of the invariant yields with respect to the particles's azimuthal coordinate in the participant plane reference frame

$$\frac{d^3N}{p_T\,dp_T\,dy\,d\phi} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1 + \sum_{n=1}^{\infty} 2v_n(p_T, y)\cos\left[n(\phi - \Psi_n^{\rm PP})\right]\right) \qquad 1$$

In the above equation $\phi$ is the particle azimuthal angle in the lab frame, and $\Psi_n^{\mathrm{PP}}$ is the azimuthal orientation of the participant plane as approximated by the event plane orientation angle. The flow coefficients $v_n$ serve to quantify the degree of the given component's anisotropy, and $v_2$ is commonly referred to as "elliptic flow".

In addition to the EP method, there are three other ways of extracting the single particle elliptic flow coefficients. These are the two-particle ($v_2\{2\}$) and the four-particle ($v_4\{2\}$) cumulant methods [7], and the Lee-Yang zeros method ($v_2\{\mathrm{LYZ}\}$) [9]. The four methods have differing sensitivities to statistical fluctuations and non-flow correlations among the particles, such as resonance decays and jet-induced correlations. Hence a comparison of the elliptic flow results from the four different methods should be fruitful in assessing the importance of these non-flow behaviors.

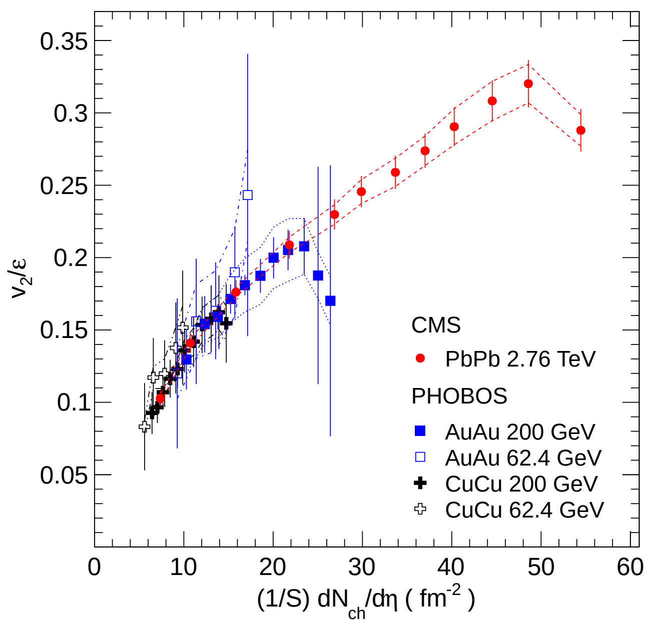


Figure 2: The ratio $v_2/\epsilon_{\mathrm{part}}$ as a function of transverse charged particle density for data from CMS and from PHOBOS.

The data presented here were obtained during the 2010 and 2011 PbPb runs at the LHC using the CMS detector. Specific experimental and analysis details have been published elsewhere [10, 11, 12]. In particular the study of the azimuthal elliptic flow behavior of lower momentum ($0.3 < p_{\mathrm{T}} < 20$ GeV/c) charged particles from the 2010 data set [10] was based on the four methods just mentioned. Figure 1 shows the various $v_2$ results obtained from these methods in twelve centrality classes ranging from the most central 0–5% to the very peripheral 70–80% events. At $p_{\mathrm{T}}$ values below 3 GeV/c the values follow the increasing trend expected from hydrodynamic behavior. Thereafter the elliptic flow values decrease with increasing $p_{\mathrm{T}}$ except for the second-order cumulant results in the most peripheral centrality.

The results from the four methods are manifesting the differences which can be expected from non-flow contributions. Specifically, the two-particle cumulant method, which did not have a pseudorapidity gap between the particle pairs, will have an influence from short-range correlations coming via resonance decays or particles in jet-cones. On the other hand, the EP method has a significant pseudorapidity gap between the particles used to define the event plane and those whose flow is being measured; thus the EP method will be more immune to the short-range correlations. Similarly, the four-particle cumulant and the LYZ methods are intrinsically less sensitive to the pairwise correlations.

These unidentified charged particle elliptic flow EP results from CMS at mid-rapidity in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV can also be compared to the EP results obtained by the PHENIX collaboration for AuAu collisions at $\sqrt{s_{NN}}$ = 200 GeV [13]. This comparison [10] shows that only a small increase in the flow coefficients is found despite a factor of 14 increase in collision energy at the LHC compared to RHIC. The increase in $v_2$ is typically around 10% in most bins rising to 15% in the most peripheral bins.

The large charged particle acceptance capability of the CMS detector has afforded the statistically precise elliptic flow measurements over almost the entire collision centrality domain, as has been shown in Figure 1. This enables these results to be effectively mapped onto the lower energy RHIC results to confirm a universal scaling behavior among many collision systems. The mapping is done in terms of the dependence of the ratio of the $v_2$ value to participant eccentricity value $\epsilon_{\rm part}$ [14] as a function of the transverse charged particle density defined by $(dN_{\rm ch}/d\eta)\,/S$. The dependence of these two ratio quantities is shown in Figure 2. The parameter $S$ is the transverse area of the participant overlap region as computed through Glauber model calculations [15]. There is seen to be a remarkable scaling agreement covering a variety of collision systems at three different $\sqrt{s_{NN}}$ values.

## 3. Azimuthal Correlations of the $\pi^0$ Meson at Low and Intermediate $p_T$

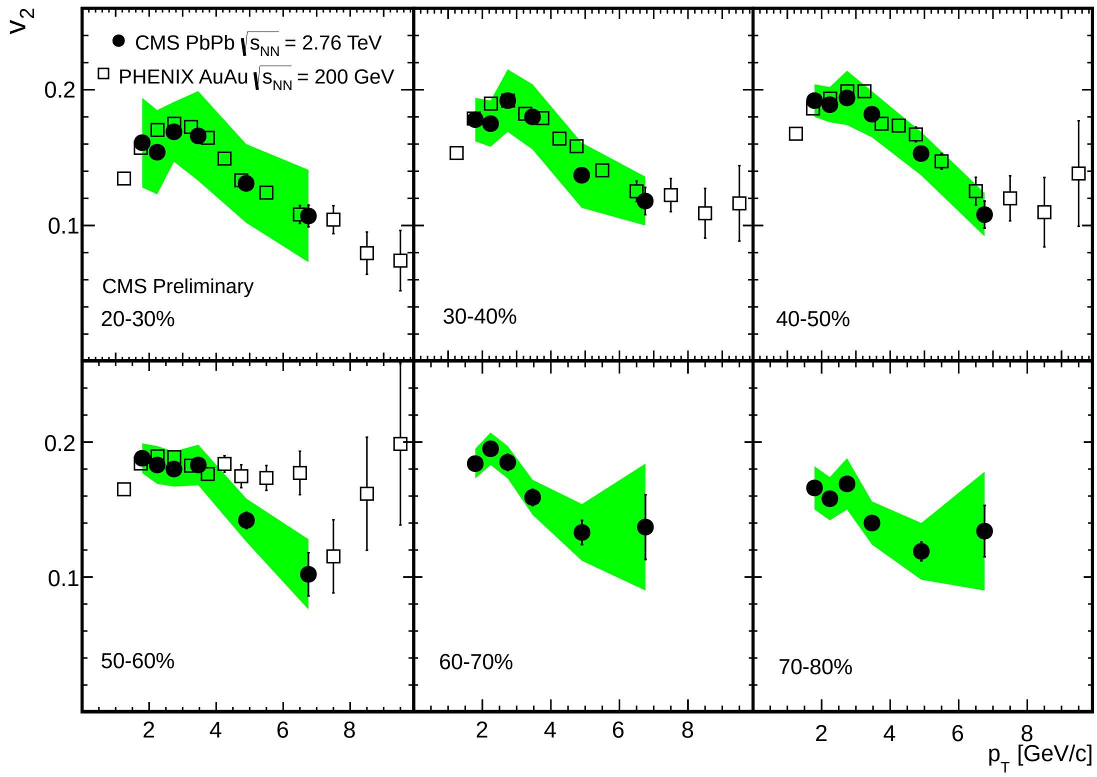


Figure 3: The $v_2(p_T)$ distributions for the $\pi^0$ meson obtained by CMS at the LHC compared to the $v_2(p_T)$ obtained by PHENIX at RHIC . The shaded bands correspond to the systematic uncertainties in the CMS data.

For an insight into the properties of the sQGP one of the most important findings [16, 17, 18, 19] of the RHIC program was the discovery of the "baryon-meson" anomaly. This anomaly refers to the sizes of the jet suppression and elliptic flow values for the produced baryon particles which were determined to be significantly different as a function of transverse momentum than those values for the meson particles. In turn, these difference become a testing ground for models of quark recombination and coalescence as the plasma expands [20].

Hence it is important to obtain elliptic flow values for identified particles such that the existence of the "baryon-meson" anomaly can be confirmed and explored in the new heavy ion collision energy regime of the LHC. First measurements of the elliptic azimuthal anisotropy of neutral pions $\pi^0$ produced in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been obtained by the CMS detector from the 2010 data set taken at the LHC [21]. The $v_2$ values were extracted using the event plane method in a manner identical to the EP analysis for the unidentified charged particles shown here in Figure 1. The $\pi^0$ yields were identified statistically using reconstructed electromagnetic shower clusters from the CMS ECAL barrel system [22]. Candidate $\pi^0$ particles were formed by taking pairs of clusters and forming their invariant mass, with the clusters selected according to shower-shape and other analysis cuts. These candidate pairs were seen to produce a distinct $\pi^0$ mass peak superimposed upon a random combinatoric background which is rapidly rising as a function of pair mass. The combinatoric background shape was determined by a standard mixed-event prescription accepting clusters according to identical analysis cut conditions as in the foreground event. The $\pi^0$ yields were sorted into event six azimuthal bins in the event plane, according to six transverse momentum bins and six centrality classes. The decomposed yields were fitted with the usual $(1 + 2v_2 2\cos\phi)$ shape in order to extract the $v_2$ values for each transverse momentum and centrality bin. These CMS results are shown first in Figure 3 where a comparison is made with the $\pi^0$ $v_2$ results obtained by the PHENIX experiment at RHIC. There is seen to be a notable agreement between the two sets of elliptic flow values despite the factor of 14 increase in collision energy at the LHC. This agreement speaks to the persistence of the near-perfect liquid character of the sQGP at the LHC, as has been inferred already by the similarity of the unidentified charged particle elliptic flow values.

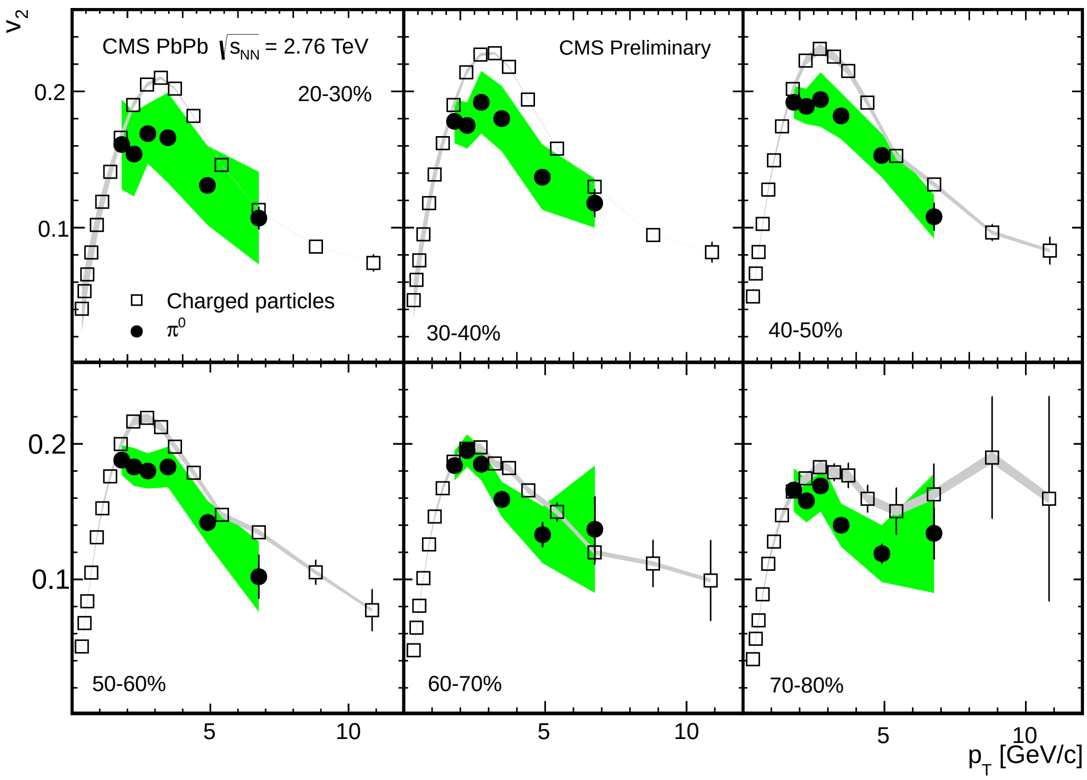


Figure 4: The $v_2(p_T)$ distributions for the $\pi^0$ meson obtained by CMS at the LHC compared to the $v_2(p_T)$ for unidentified charged particles obtained by CMS in the same dataset.

These $\pi^0$ $v_2$ flow values obtained by CMS can also be compared with the $v_2$(EP) values of the unidentified charge particles previously shown in Figure 1, and this comparison is illustrated in Figure 4. The $\pi^0$ $v_2$ flow values are clearly smaller than the unidentified charge particles $v_2$ flow values . This disparity in $v_2$ flow values is just what is to be expected if the baryon-meson anomaly persists for the sQGP at the LHC. The magnitude of the disparity may well be different at the LHC, but qualitatively the effect is certainly present.

## 4. Charged Particle Pair Azimuthal Correlations at Intermediate $p_T$

A global azimuthal correlation with respect to the participant plane in the single particle yields inevitably will produce an azimuthal anisotropy in the particle pair yields. All orders of the single particle anisotropy components will contribute to the particle pair anisotropy distribution. The particle pair correlations have the advantage of not depending on the empirical measurement of the event plane since the orientation angle of the event plane cancels out in the particle pair azimuthal angle difference, $\Delta\phi$. In the particle pair correlation studies it is necessary to introduce a pseudorapidity gap in the accepted particle pairs to avoid the short-range correlations coming from resonance decays and from jet fragmentation. The large acceptance of the CMS detector allows an acceptance gap of 2 units in pseudorapidity without a seriously affecting the statistical precision of the data.

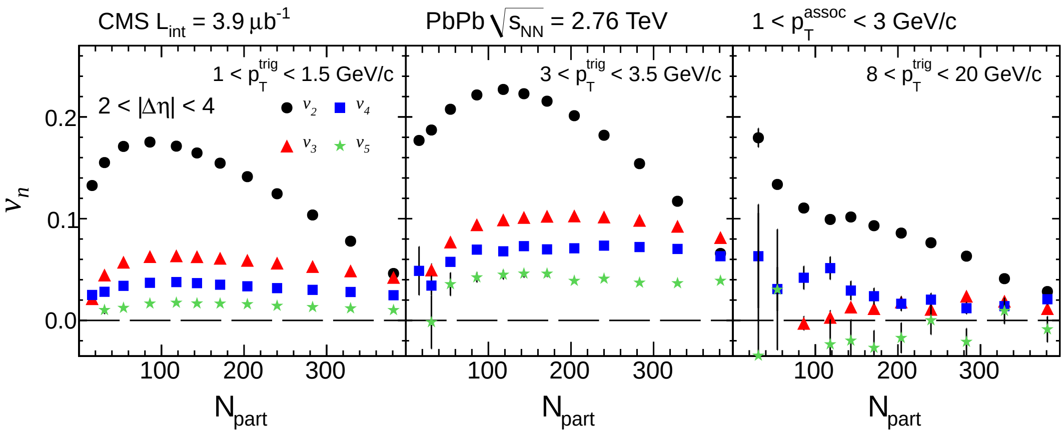


Figure 5: The single-particle azimuthal anisotropy harmonics $v_2$–$v_5$ extracted from the long–range ($2 < \Delta\eta < 4$) azimuthal dihadron correlations as a function the participant number $N_{part}$ in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV.

The 1D $\Delta\phi$-projected distribution for a given $\Delta\eta$ gap can be quantified with a Fourier decomposition for a given choice of $p_T$ binning of the first pair member (called the "trigger" particle) and another choice of $p_T$ binning of the second member (termed the "associated" particle)

$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi}\left[1 + \sum_{n=1}^{N_{max}} 2V_{n\Delta}cos(n\Delta\phi)\right] \qquad 2$$

The strengths of the different Fourier components are set by the pair amplitude $V_{n\Delta}$ which are analogous to the single particle flow coefficients $v_n$. Moreover, to the extent that the pair correlations are strictly produced by convolving the single particle correlations, then the pair amplitudes $V_{n\Delta}$ can be factorized in terms of the $v_n$, specifically

$$V_{n\Delta}(p_T^{trig}, p_T^{assoc}) = v_n(p_T^{trig}) \times v_n(p_T^{assoc}) \qquad 3$$

In the Eq. 3 $v_n(p_T^{trig})$ and $v_n(p_T^{assoc})$ are the harmonics for the trigger and associated particles averaged over all the events, respectively. It is obvious that different pairs of trigger and associated $p_T$ bins can be used to test the goodness of the factorization assumption. Indeed, it is found that for $p_T^{assoc} < 3$ GeV/c, that factorization does work well for the CMS charged particle pair correlation data obtained from the PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [12]. Factorization being true permits the particle pair correlation studies to become a powerful complement to the single particle correlation studies for precisely determining the amplitude of the flow harmonics. This extended scope is illustrated in Figure 5 which shows the $v_2$–$v_5$ anisotropy harmonics as a function of the number of participants (centrality) for three different sets of $p_T^{trig}$ values. It is seen that while $v_2$ is a strong function of centrality, the higher order harmonics are not. This can be understood as the $v_2$ values being largely driven by the predominant ellipsoidal shape of the overlap zone whose eccentricity increases for the more peripheral collisions. On the other hand, the higher order components are more driven by the fluctuations in the initial geometry, and as such will be less dependent on the centrality of the event. For more information on this study please see the contribution by Rylan Conway elsewhere in these proceedings.

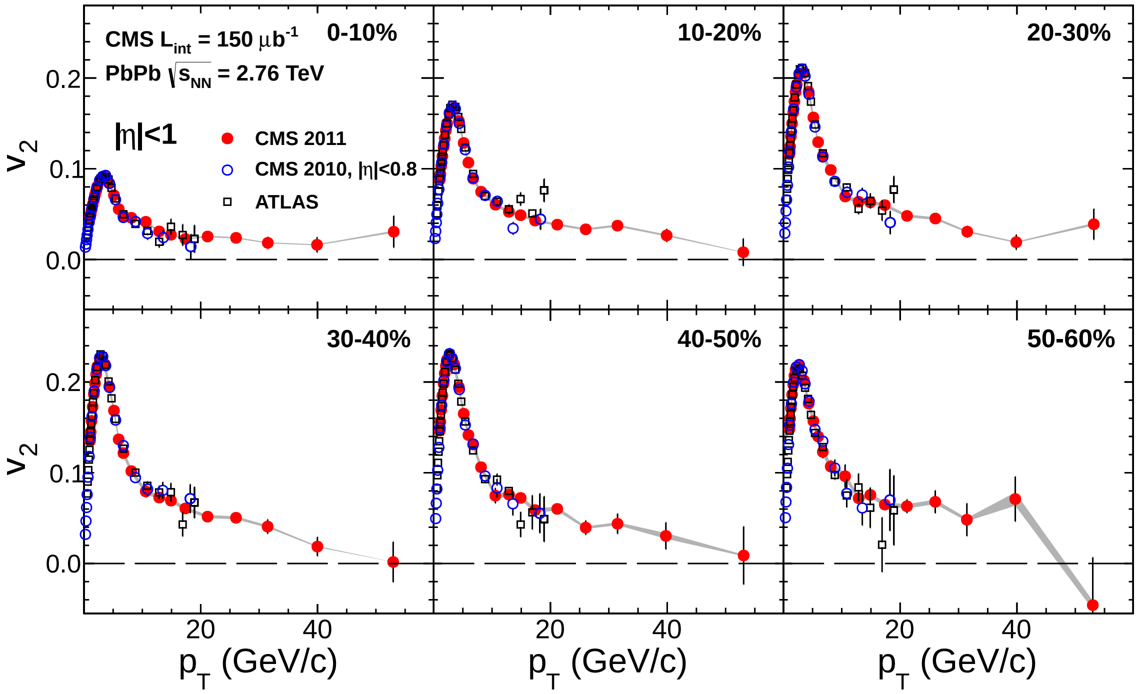


Figure 6: $v_2(p_T)$ distributions for charged particles extending to 60 GeV/c for six centrality classes. Previous results out to 20 GeV/c from CMS and ATLAS are also shown.

## 5. Charged Single Particle Azimuthal Correlations at High $p_T$

Particles having higher values of transverse momentum $p_T$ are known be affected by the jet quenching process, and that process will have different net effects depending on the orientation of the jet in the participant plane due to path length changes. Therefore, one will observe changes in the relative yields of high $p_T$ particles depending on their azimuthal correlation with the event plane. These relative yield changes can be equally well quantified with a $v_2$ coefficient, although now the source of the anisotropy is not hydrodynamic flow but rather differential quenching according to path length in the medium. Figure 6 shows the CMS $v_2$ results extending out to 60 GeV/c, where these were obtained via a special trigger condition during the 2011 data set acquisition. Also shown in this figure are the $v_2$ results at $p_T < 20$ GeV/c obtained in the 2010 data set by CMS and by ATLAS. There is excellent agreement between the 2011 data values and the 2010 analyses in the lower $p_T$ range. For the newer results a measurable $v_2$ coefficient is seen to be present until at least $p_T = 40$ GeV/c. Above 40 GeV/c the $v_2$ values become consistent with zero for events with a centrality 30% or greater.

The influence of the initial state geometry on the $v_2$ values can be probed by quantifying the results according to the number of participant nucleons $N_{part}$ [15] in two different pseudorapidity bins. This is depicted in Figure 7. There is no dependence on pseudorapidity observed for any of the $p_T$ bins within the statistical uncertainty limits; the $v_2$ values generally decrease with increasing $N_{part}$ up to $p_T \approx 14$ GeV/c. The lowest region of $p_T$ can be understood in the hydrodynamic framework. Above 14 GeV/c the increase in $v_2$ for the more peripheral collisions (decreasing $N_{part}$) corresponds to the increase in eccentricity of the participant zone, allowing for a greater path difference of the partons traversing the medium depending on their direction in the participant plane. For more information on this study please see the contribution by Victoria Zhukova elsewhere in these proceedings.

## 6. Summary

Summarizing, the CMS experiment has determined the azimuthal asymmetry harmonics of charged and neutral $\pi^0$ particles emitted in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV over wide ranges of pseudorapidity, event centrality, and

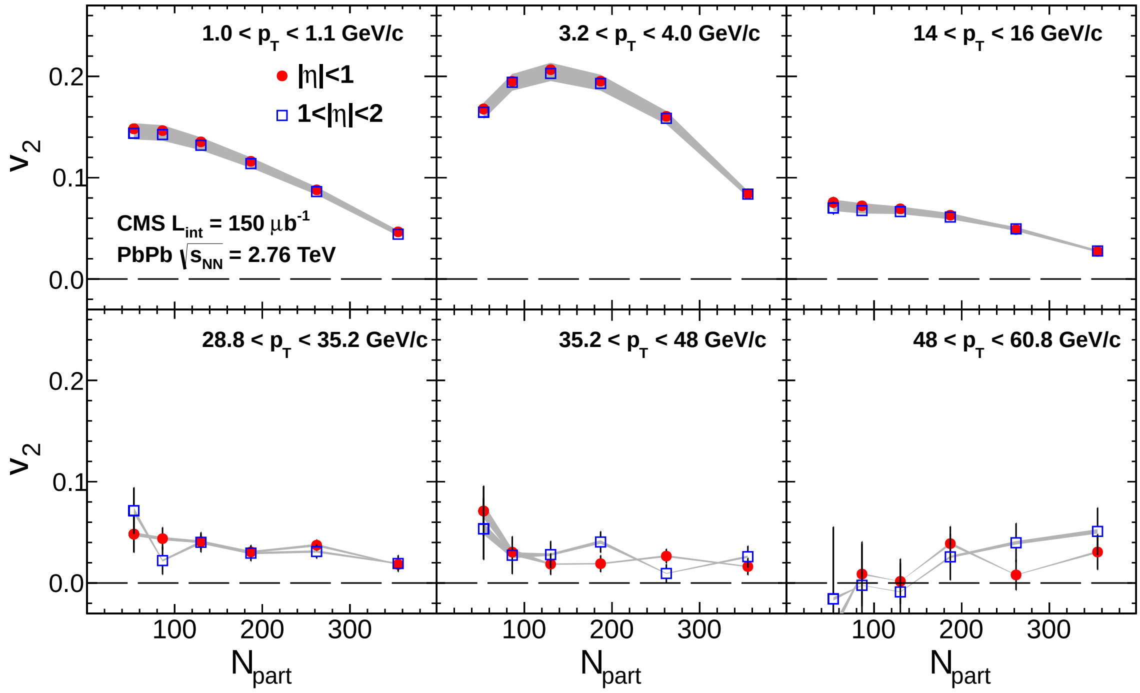


Figure 7: $v_2(p_T)$ distributions for charged particles for selected $p_T$ ranges as a function of the number of participant nucleons.

particle transverse momentum. Complementary methods have been used in the charged single particle studies, and these results are matched to the charged particle pair results. The identified $\pi^0$ $v_2$ results demonstrate that aspects of the baryon-meson anomaly found at RHIC persist at the LHC. The observation of azimuthal asymmetry in the high $p_T$ particles paves the way to analyzing the path-length dependence of parton energy loss in the sQGP medium.

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