System size scan of D meson $R_{AA}$ and $v_2$ using PbPb, XeXe, ArAr, and OO collisions at LHC

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Experimental measurements indicate no suppression (e.g. $R_{pPb} \sim 1$) but a surprisingly large D meson $v_2$ was measured in pPb collisions. In order to understand these results we use Trento+ν-USPhydro+DAB-MOD to make predictions and propose a system size scan at the LHC involving $^{208}$PbPb, $^{129}$XeXe, $^{40}$ArAr, and $^{16}$OO collisions. We find that the nuclear modification factor approaches unity as the system size is decreased, but nonetheless, in the 0–10% most central collisions $v_2\{2\}$ is roughly equivalent regardless of system size. These results arise from a rather non-trivial interplay between the shrinking path length and the enhancement of eccentricities in small systems at high multiplicity. Finally, we also find a surprising sensitivity of D mesons $v_2\{2\}$ in 0–10% at $p_T = 2–5$ GeV to the slight deformation of $^{129}$Xe recently found at LHC.
1. Introduction. The nature and properties of the smallest fluid known to humanity — the Quark-Gluon Plasma — has pushed the boundaries of our understanding of fluid dynamics. Three significant signatures of the Quark-Gluon Plasma are collective flow, strangeness enhancement, and suppression of hard probes. The first two signatures, collective flow and strangeness enhancement, have been measured in small asymmetric collisions such as pPb, dAu, and $^3$HeAu [1–22]. Relativistic hydrodynamics manages to reproduce most flow observables in small systems well [23–31], although other scenarios that do not rely on relativistic hydrodynamics have been considered [32–35]. New experiments and measurements have been proposed in order to either confirm (or disprove) that relativistic hydrodynamics is the correct dynamical description in these tiny systems. For instance, polarized beams [36] and ultracentral deformed ion-ion collisions [37] both may distinguish between different scenarios in these light nuclei collisions.

The validity of event-by-event relativistic hydrodynamics remains to be studied in intermediate AA collisions across multiple types of ions. It was recently proposed for LHC energies to run a system size scan including ArAr and OO collisions [38] where a variety of hydrodynamic predictions have been made [39–41]. More recently a system size scan has also been proposed for RHIC energies as well [42].

While collective flow experiment/theory comparisons are quite intriguing in small systems, we still lack a fundamental understanding of why jet and heavy flavor suppression is not measured in small systems (e.g. $R_{\text{pPb}} \sim 1$). Predictions of XeXe $R_{\text{AA}}$ have been done in [43, 44] (although only with the assumption of spherical $^{129}$Xe), quarkonium predictions for pA in [45] from the Color Glass Condensate (CGC), preliminary results for photons in pPb, pAu, dAu, and $^3$HeAu collisions were shown in [46], and previous pPb calculations in a variety of scenarios can be found in [47–49]. However, we are not aware of any predictions available for intermediate systems such as ArAr/OO nor any current azimuthal anisotropy predictions assuming event-by-event relativistic hydrodynamics as the medium that hard probes pass through. Meanwhile, the CMS collaboration has measured a significant D meson flow in pPb collisions [50], which is large but also somewhat suppressed compared to other identified particles. Additionally, the ATLAS collaboration has measured a significant $v_2$ from heavy flavor $\mu$'s in pPb collisions [51]. It has also been suggested that the $R_{\text{AA}}$ to $v_2$ puzzle may be a good testing bed for initial conditions [52]. Because D mesons are sensitive to equilibrium vs. out-of-equilibrium dynamics (as shown in Fig. 10 from [53]) combined with the significant $v_2$ in small systems, they appear to be ideal candidates for understanding system size effects.

While in the CGC scenario one can reproduce the experimentally measured heavy flavor $v_2$ [45], no one has demonstrated in a initial condition+hydrodynamic+energy loss/Langevin scenario how such a large $v_2$ in small systems is compatible with $R_{\text{AA}} \rightarrow 1$. Here we systematically study the effect of system size (by varying the colliding nuclei) on the nuclear modification factor, $R_{\text{AA}}$, azimuthal anisotropies $v_n\{2\}$, and multiparticle cumulants $v_2\{4\}/v_2\{2\}$. To conduct this study we use Trento [54]+v-USPhydro [55, 56]+DAB-MOD [57] using the exact same soft sector backgrounds as in [39, 58, 59] and the Langevin set up that works well compared to PbPb data from [60]. We find that as the system size is shrunk $R_{\text{AA}} \rightarrow 1$, however, the $v_n\{2\}$'s have a rather non-trivial relationship with the system size that can only be understood with direct comparisons with the soft sector from [39]. Finally, we also find a non-trivial sensitivity to a deformed nucleus in intermediate $p_T = 2–5$ GeV D meson $v_2$ calculations, which is consistent with soft sector calculations [59].

2. Model Description. In this paper we couple 2D+1 event-by-event hydrodynamical backgrounds that fit the soft sector well to the heavy flavor code DAB-MOD [57, 60] — a modular Monte Carlo simulation package developed to study D and B mesons — that samples heavy quarks using distributions from pQCD FONLL calculations [61, 62]. Then, either a parametrized energy loss model that includes energy loss fluctuations (sampled from an underlying distribution) is
used for the heavy quarks evolution or a relativistic Langevin model based on an input drag or diffusion coefficient. Once the decoupling temperature $T_d$ is reached, hadronization follows via a hybrid fragmentation/coalescence model from which the final nuclear modification factor can be reconstructed. In [60] it was shown that with the Langevin description using the spatial diffusion coefficient from [63] one obtains a reasonable description of experimental data at low $p_T$, while for the high $p_T$ sector it was found that an energy loss model works best [64]. Because our main focus in this paper is the low $p_T$ sector, we hereby only consider the Langevin scenario and leave the energy loss setup for a future work. The initial conditions + hydrodynamical backgrounds are identical to those used in [39, 58, 59] where the Trento initial conditions used the parameters $p = 0$, $k = 1.6$, and $\sigma = 0.51$ fm, as established by a Bayesian analysis [65]. The parameters of the viscous hydrodynamic code v-USPhydro are $\tau_0 = 0.6$ fm, $\eta/s = 0.047$, $T_{FO} = 150$ MeV, which have been shown to fit well compared to experimental data. We test both a spherical $^{129}$Xe nucleus and a prolate one (per the parameterization of the deformed Wood-Saxon in [59, 66]).

One should note that in our model there is some ambiguity on the overall magnitude of $R_{AA}$ in the absence of experimental data since we generally fix the scaling constant of the transport model using high $p_T$ $R_{AA}$ in most central collisions. Thus, it is possible that there may be a system size dependence to this constant, whereas we use here for all systems the value obtained in PbPb collisions. Furthermore, while we write $v_n(2)$ to indicate that this is a two particle correlation — obtained via the scalar product method for cumulants — we also point out that one of these particles is a soft particle while the other is a heavy flavor hadron, as has been discussed extensively in [57, 67–70].

3. Results. In small systems it was found that the nuclear modification factor is consistent with unity within error bars [71–78]. However, it is not clear how $R_{AA}$ changes with system size as one moves towards small systems: does it smoothly increase as the size shrinks or does it suddenly jump to 1 at a certain critical size? Additionally, is the lack of light flavor jet suppression unique to asymmetric systems? These questions are precisely investigated in Fig. 1 where we show the $R_{AA}$ of D mesons in 0–10% and 30–50% centrality classes. There are a number of conclusions that can be drawn from these results. First, 0–10% centralities are more sensitive to system size effects whereas for 30–50% centralities one cannot see a distinguishable difference between ArAr and Oo even though there is a clear difference in system size [39]. We note that $R_{AA}$ is insensitive to any effects of a deformed nucleus regardless of the centrality class. Finally, it is clear that $R_{AA} \to 1$ as the system size decreases, $(1 - R_{AA})$ being roughly proportional to the system initial radius $\sim A^{1/3}$, which implies that we expect a smooth decrease in the suppression of hard probes as one decreases the system size, eliminating the idea of a sharp critical system size.

For the azimuthal anisotropies, it is important to understand that not only does the system size shrink but also the geometrical shape of the initial conditions change as well [39]. In Fig. 2 we plot the radius of the initial conditions $R$ versus the eccentricities $\varepsilon_n$ in the two centrality classes considered here: 0–10% and 30–50%. The systems coming from PbPb, XeXe, ArAr, and Oo central collisions have both significantly different sizes and significantly different eccentricities: as one decreases the radius, the eccentricities increase. In contrast, mid-central collisions have roughly equivalent eccentricities and only vary in system size. Thus, the mid-central collisions give us a better insight into pure system size effects. However, one should caution that the D meson results from [5] are measured in central pPb collisions so, to some extent, they may experience both varying system size and eccentricities compared to large AA collisions.

The azimuthal anisotropies of hard probes can be useful too to study energy loss [44, 53, 57, 67, 68, 79, 88]. In Fig. 3 the elliptical azimuthal anisotropies are shown for D mesons at 0–10%
and 30–50% centralities. As discussed above, we find that when we hold $\varepsilon_2 \sim \text{const.}$ in the 30–50% centrality class the influence of the smaller system size plays a dramatic role in Fig. 3. It is quite clear that in small systems D mesons $v_2$ is significantly suppressed across all $p_T$. Nevertheless, what is somewhat surprising is that $v_2\{2\}(p_T)$ of OO collisions is roughly equivalent to $v_2\{2\}(p_T)$ of ArAr collisions.

Now that we have shown that the system size suppresses D meson $v_2$ when the eccentricities are held fixed, we can understand the results in the 0–10% centrality class in Fig. 3 where the $v_2$ is roughly equivalent regardless of system size. Additionally, the $v_2$ in ArAr and OO collisions is larger in central collisions than in mid-central collisions. Returning to Fig. 2 we know that for central collisions as the system size decreases the eccentricities increase. Thus, there are now two competing factors that can contribute to the final $v_2$: a suppression effect from decreasing the system size and an enhancement effect from increasing eccentricities. In Fig. 3 when we see that all curves are very similar in 0–10% centrality it simply is because these two competing effects roughly cancel each other out. This implies that in the CMS pPb D mesons data likely there is a large enough eccentricity such that $v_2$ does not vanish completely due to shrinking system size (although it may be that some initial flow could also influence D meson $v_2$, we have not yet explored this possibility).

Another interesting consequence from Fig. 3 is that $v_2$ between $p_T = 2–5$ GeV shows some sensitivity to the deformation present in the $^{129}$Xe nucleus. Using a prolate nucleus we find that there is an enhancement in this regime compared to a spherical nucleus. This is a surprising result since 0–10% is quite a wide centrality bin whereas in the soft sector the large deformation effects

![D^0 meson, Trento, Langevin, frag. & coal., $T_d = 160$ MeV](image1)

![D^0 meson, Trento, Langevin, frag. & coal., $T_d = 160$ MeV](image2)

FIG. 1. $D^0$ meson $R_{AA}$ for PbPb, XeXe with spherical and prolate initial nuclei, ArAr, and OO collisions at the LHC top energies in 0–10% (top) and 30–50% (bottom) centrality classes.
FIG. 2. $\varepsilon_2\{2\}$ (left) and $\varepsilon_3\{2\}$ (right) versus radius for PbPb, XeXe, ArAr, and OO collisions at the LHC top energies in 0–10% and 30–50% centrality classes.

FIG. 3. $D^0$ meson $v_2\{2\}$ for PbPb, XeXe with spherical and prolate initial nuclei, ArAr, and OO collisions at the LHC top energies in 0–10% (top) and 30–50% (bottom) centrality classes.

come from primarily ultracentral collisions [51, 53, 90–98].

We also explore these effects on $v_3\{2\}(p_T)$ in Fig. 4 and find that $v_3$ is more sensitive to system size effects i.e. $v_3$ is more consistently suppressed in small systems in both centrality classes, even when there is a significant increase in $\varepsilon_3$. Additionally, we find that the approximate universality of $v_3\{2\}(p_T)$ across centralities in PbPb collisions (see also [50, 85]) is not observed in smaller systems. This approximate universality can then be explained by a balance between the variations in path length and eccentricity with centrality. The different response of $v_2$ and $v_3$ to system size
dependence is quite interesting and may be helpful to constrain certain model parameters that could be considered in future studies.

Finally, in Fig. 5 we compare the multiparticle cumulants ratio $v_2\{4\}/v_2\{2\}$ where for the 4-particle cumulant one correlates one heavy particle and three soft ones. These were first proposed in [57, 67] and have yet to be measured in the heavy flavor sector. In [60] it was shown this ratio was mostly dependent on the type of soft initial fluctuations used. In Fig. 5 we find that generally $v_2\{4\}/v_2\{2\}$ is suppressed with decreasing system size, which is in line with eccentricity calculations from [39]. Though the lower $p_T$ cut is generally less sensitivity to system size, high $p_T$ $v_2$ fluctuations appear to be significantly more affected by system size.

There has been a proposal for an intermediate system size scan at RHIC [42] (sPHENIX would also have these capabilities) and we anticipate a similar effect at these lower energies as well, as shown in Fig. 6. To see this directly we also calculate the $\varepsilon_2\{2\}$ vs. radius relationship at RHIC using ions that have been previously ran ($^{238}$U and $^{197}$Au), the isobar run ($^{96}$Ru and $^{96}$Zr), and the proposed intermediate system size scan ($^{40}$Ar and $^{16}$O). Generally, we find the same inverse relationship between $\varepsilon_2\{2\}$ and radius in 0–10% centralities (with the exception of Uranium due to its deformed structure) and the same constant eccentricities at 30–50% centralities. Thus, the proposal for a system size scan at RHIC should see a similar effect on the D mesons as we have shown here but with the added consideration of a lower beam energy.

4. Conclusions. In this letter we make the first predictions for the D meson observables for the proposed intermediate system size scan at the LHC. We predict that $R_{AA} \to 1$ gradually as the
FIG. 5. $D^0$ meson low $p_T$ (top) and high $p_T$ (bottom) integrated $v_2/\langle v_2 \rangle$ for PbPb, XeXe with spherical and prolate initial nuclei, ArAr, and OO collisions at the LHC top energies.

FIG. 6. $\varepsilon_2\{2\}$ versus radius for the proposed system size scan at RHIC in 0–10% and 30–50% centrality classes.

system size is decreased with mid-central collisions reaching unity before central collisions (as expected due to their smaller system size). In mid-central collisions we find a clear suppression of $v_n\{2\}$ in small systems, which shows the significant role played by the system size itself as the geometry of the initial conditions is nearly identical over different systems. However, in central collisions the eccentricities become larger with a shrinking system size, which cancels out or overcomes the usual suppression effects on $v_2$. Thus, we predict that in central collisions $v_2\{2\}(p_T)$
will be roughly constant across the system size scan. While the triangular eccentricities in central collisions increase with decreasing system size, triangular azimuthal anisotropy is more sensitive to the system size itself and, thus, one should observe a system size hierarchy. Additionally, we find that $v_3$ in small systems decreases with increasing centrality, whereas it is known to be roughly constant in PbPb collisions, which can now be explained by a balance between path length and eccentricity variations with centrality.

If confirmed, these results can help to elucidate the nature of hard probes in small systems. Heavy quarks still lose energy in the system but as the system size path length is decreased they loose significantly less energy. However, this does not appear to affect $v_2$ in central collisions because of a significant enhancement of the ellipticity of the initial state. In future work, we hope to explore further soft-heavy correlations system size dependence such as \cite{99}. As was previously shown in \cite{57, 60, 70, 85} both the initial time and decoupling temperature play a significantly role in the $v_n$'s in the hard sector, thus, indicating that the lifetime of the system matters (especially for $v_3$). We point out that these results fall out naturally with an initial conditions+hydrodynamics+heavy flavor Langevin scenario and appear to be consistent with pPb results as well, which provides further evidence that a Quark-Gluon Plasma is also formed in small systems.

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