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ABSTRACT

Recent measurements of particle correlations and the spectra of hadrons at both RHIC and the LHC are suggestive of hydrodynamic behavior in very small collision systems ($p + Pb$, $d + Au$ and possibly high multiplicity $p + p$ collisions at the LHC). The measurements in $p + Pb$ and $d + Au$ collisions are both qualitatively and quantitatively similar to what is seen in heavy ion collisions where low viscosity hot nuclear matter is formed. While light quarks and gluons are thought to make up the bulk matter, one of the most surprising results in heavy ion collisions is that charm quarks also have a large v_2 . Measurements of the transverse momentum spectra of electrons from the decay of D and B mesons in $d + Au$ collisions show an enhancement in central collisions relative to $p + p$ collisions. We employ the blast-wave model to determine if the flow of heavy quarks in $d + Au$ and $p + Pb$ collisions is able to explain the enhancement observed in the data. We find a reasonable description of the data with blast-wave parameters extracted from fits to the light hadron spectra, suggesting hydrodynamics as a possible explanation.

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1. Introduction

The aim of the heavy ion physics programs at RHIC and the LHC is to produce and study the very hot dense strongly interacting matter produced in these collisions, the Quark Gluon Plasma (QGP). There has been enormous success in describing the bulk properties of this matter with hydrodynamics (for a recent review see Ref. [1]). Even more interesting, the ratio of shear viscosity to entropy density, η/s used in the hydrodynamic calculations is constrained by the data [2–4] to be very small and within a few times $1/4\pi$, the conjectured quantum lower bound [5].

One of the most interesting recent developments in heavy ion physics is the possibility of collective behavior in very small systems. This was first explored with the elliptic flow, v_2 , of charged hadrons as measured by the ALICE and ATLAS Collaborations [6,7]. Similar, but slightly larger v_2 was found by the PHENIX Collaboration in $d + Au$ collisions at RHIC [8]. This is in agreement with hydrodynamic calculations which predicted a larger v_2 in $d + Au$ collisions than in $p + Pb$ collisions due to the larger initial state eccentricity driven by the shape of the deuteron [9–11]. While the hydrodynamic descriptions of the data are intriguing, other models such as the Color Glass Condensate [12] have also been invoked to explain the observed correlations.

Hydrodynamic behavior can also be inferred through the shape of the identified particle transverse momentum (p_T) spectra [13].

The ALICE and CMS Collaborations have recently published analyses of the spectra in $p + Pb$ collisions [14,15] that show an increase in the $\langle p_T \rangle$ as a function of the charged particle multiplicity in the event, behavior consistent with increasing radial flow with increasing event multiplicity [16,17].

Another method to extract possible radial flow information from identified particle spectra is with the blast-wave model [18,19]. This model assumes thermalization and expansion with a common velocity field. Extractions of the parameters in $p + Pb$ collisions show increasing flow velocity, β , with increasing charged particle multiplicity [15]. Interestingly, similar behavior has been observed by the STAR Collaboration in $d + Au$ collisions [20]. The $\langle \beta \rangle$ observed in the most central 20% of $d + Au$ collisions is consistent with the $\langle \beta \rangle$ observed in 50–60% central $Au + Au$ collisions [20]. At that centrality the charged particle v_2 is large [21,22] which is taken to be evidence of hydrodynamic behavior. Blast-wave fits have also been performed in $p + p$ collisions. In $\sqrt{s} = 200$ GeV $p + p$ collisions the extracted $\langle \beta \rangle$ values are much smaller: 0.244 ± 0.081 [20] and 0.28 ± 0.02 [23]. A calculation using a modified version of the blast-wave model [24] finds $\langle \beta \rangle = 0.000 + 0.124$ [25]. At higher collision energies, above 900 GeV, $\langle \beta \rangle$ is found to increase within this model. Blast-wave parameters have been studied in multiplicity selected $p + p$ collisions at $\sqrt{s} = 7$ TeV and similar $\langle \beta \rangle$ values are observed in the highest multiplicity $p + p$ and $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV [26]. A quantitative explanation of this similarity has not been put forward. Unfortunately, multiplicity selected $p + p$ collisions have not

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been studied at $\sqrt{s} = 200$ GeV, so a similar comparison at RHIC is not yet possible, but would be extremely informative.

Heavy quarks, charm and bottom, also appear to be affected by the presence of the matter in heavy ion collisions. At high p_T in Au + Au collisions there is observed to be substantial energy loss of heavy quark jets [27] and suppression of heavy mesons [28,29] and electrons from the decay of heavy hadrons [30–32]. In p + p collisions most of these electrons are from heavy meson decay. Here, we neglect the small contributions to the electron yield from the decays of c and b baryons. At lower p_T significant v_2 of the electrons from heavy meson decay is observed in Au + Au collisions [30,31]. The STAR Collaboration has observed a low p_T enhancement of D mesons [29] which has been described by calculations incorporating hydrodynamic behavior [33,34] and the data are well described by a blast-wave calculation [35,36].

In d + Au collisions, the PHENIX Collaboration has measured the yield of electrons from the decays of heavy hadrons in d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Relative to expectations from binary scaled p + p collisions the yield of these electrons is enhanced by approximately 40% in the 20% most central d + Au collisions [37]. The origin of this effect is not understood, though it is consistent with a Cronin enhancement [38,39] which increases with the particle mass. Inspired by the success of a hydrodynamic description of p + Pb and d + Au collisions, in this work we investigate whether a blast-wave calculation constrained to the π , K , p , \bar{p} spectra in d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV can explain the observed enhancement of heavy flavor decay electrons. We also provide calculations for central p + Pb collisions at 5.02 TeV.

2. Method

The blast-wave model [18,19] describes p_T spectra with the following functional form:

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r dr m_T I_0 \left(\frac{p_T \sinh \rho}{T_{fo}} \right) K_1 \left(\frac{m_T \cosh \rho}{T_{fo}} \right) \quad (1)$$

where

$$\rho = \tanh^{-1}(\beta_{max}(r/R)^n) \quad (2)$$

and $m_T = \sqrt{p_T^2 + m^2}$ where m is the particle mass. The model parameters are β_{max} , the maximum velocity at the surface, and T_{fo} , the temperature at which the freeze out occurs. We extract blast-wave parameters from π^\pm , K^\pm , p , \bar{p} p_T spectra in d + Au collisions as published in Ref. [40] for the 20% most central collisions via a simultaneous fit to all particle species. We fit the spectra for $m_T - m < 1$ GeV/c and exclude π^\pm below 0.5 GeV/c because of possible larger contributions from resonance decays. We fix $n = 1$, corresponding to a linear boost profile. The spectra overlaid with the best fit are shown in Fig. 1. The β_{max} value is 0.70 and $T_{fo} = 139$ MeV. These fits describe the data over the appropriate p_T range to better than 10%. The statistical uncertainties on the points in the region of interest are small in comparison to the systematic uncertainties. To provide some estimate of the effect of these uncertainties on the extracted parameters we take the values of the uncertainties which can change the shape of the particle spectra from Table IV in Ref. [40]. Since the correlation of the uncertainties as a function of p_T is unknown we take them to be maximally changing the slopes of the spectra in the range 0.5–3.0 GeV/c by pivoting the spectra around a point such that it is increased by the full systematic uncertainty at the low (high) p_T point and decreased by the full systematic uncertainty at the high (low) p_T point. This procedure provides the maximal

variation in the blast-wave parameters within the measurement uncertainties and is thus likely to be an overestimate of the actual uncertainty. Under this procedure we get $T_{fo} = 145$ MeV and $\beta_{max} = 0.66$ for the scenario where the spectra are made steeper and $T_{fo} = 127$ MeV and $\beta_{max} = 0.74$ for the scenario where the spectra are made flatter. Blast-wave parameters for d + Au collisions with n not fixed to 1 are also reported in Ref. [20].

The blast-wave heavy meson spectra are determined from Eq. (1) using the parameters extracted above and the D and B meson masses (separately). In order to quantify the enhancement for heavy mesons expected from the blast-wave, we determine the R_{dAu} . Here R_{dAu} is the ratio of the blast-wave heavy meson spectra divided by the expected heavy meson spectra from the Fixed-Order-Next-to-Leading-Log (FONLL) calculation of the heavy meson spectra in p + p collisions [41–43]. FONLL calculations compare well with a wide variety of heavy flavor data in p + p collisions at $\sqrt{s} = 200$ GeV [31,32,44,45]. We use the default values from Ref. [43] of $m_c = 1.5$ GeV/c², $m_b = 4.75$ GeV/c² and $\mu_R = \mu_F = \sqrt{m^2 + p_T^2}$ where μ_R and μ_F are the renormalization and factorization scales, respectively. We normalize the blast-wave spectra to have the same number of D and B mesons as the FONLL calculation. The p_T spectra for D and B mesons from FONLL and the blast-wave calculation are shown in the left panel of Fig. 2.

We observed the blast-wave spectra to be below the FONLL spectra at both low and high p_T . They are greater than the FONLL spectra from approximately 1–4 GeV/c for D mesons and 2.5–7 GeV/c for B mesons. Regardless of the low p_T physics, at high p_T we expect binary scaling of heavy mesons in d + Au collisions due to the dominance of hard physics (unless other effects such as shadowing play a role). Mesons from a range of momenta contribute to the electron spectrum at a given p_T . Therefore, in order to have a sensible expectation for the electron p_T spectra, we must include mesons from a wide range of p_T in the construction of the electron R_{dAu} [46]. At high p_T , in the calculations shown here when the blast-wave expectation decreases below the FONLL calculation, we artificially enforce binary scaling of the mesons (this is a 1% change in the normalization for D s and a 5% change for B s). The meson R_{dAu} is shown for D and B mesons in the right panel of Fig. 2. We observe a large enhancement of D mesons, approximately a factor of two increase over FONLL at $p_T \approx 2$ GeV/c. We observe a smaller enhancement of B mesons, approximately a factor of 1.8 at around 5 GeV/c. The dashed lines in the figure show the variation of the expected meson R_{dAu} from the uncertainties on the blast-wave parameters extracted from the light hadron data. In all cases a large enhancement ($R_{dAu} > 1.5$) is expected for both D and B mesons. When the blast-wave values from Ref. [20] are used, the D and B meson R_{dA} values have peaks at approximately the level of the lower value of the uncertainties shown in Fig. 2 and the peak positions are shifted to slightly higher p_T . Since the blast-wave spectra are normalized to the integral of D and B mesons from FONLL, the uncertainties on the FONLL calculation are relevant only to the extent that shape of the spectra is changed. The uncertainties on the FONLL calculation are also available from Ref. [43]. Comparisons with the data [31,45] show that the data favors the higher crosses sections within the FONLL uncertainty band. On the high end of the systematic uncertainty band the FONLL calculation has an excess of low p_T particles compared to the central value. This shape change increases the R_{dA} of the mesons compared to the central values.

In order to determine the expected heavy flavor decay electron R_{dAu} we use PYTHIA (v 8.176) [47] to get the correlation between the D or B p_T and the p_T of the decay electron. The correlations are shown in Fig. 3. The x -axis shows the p_T of the

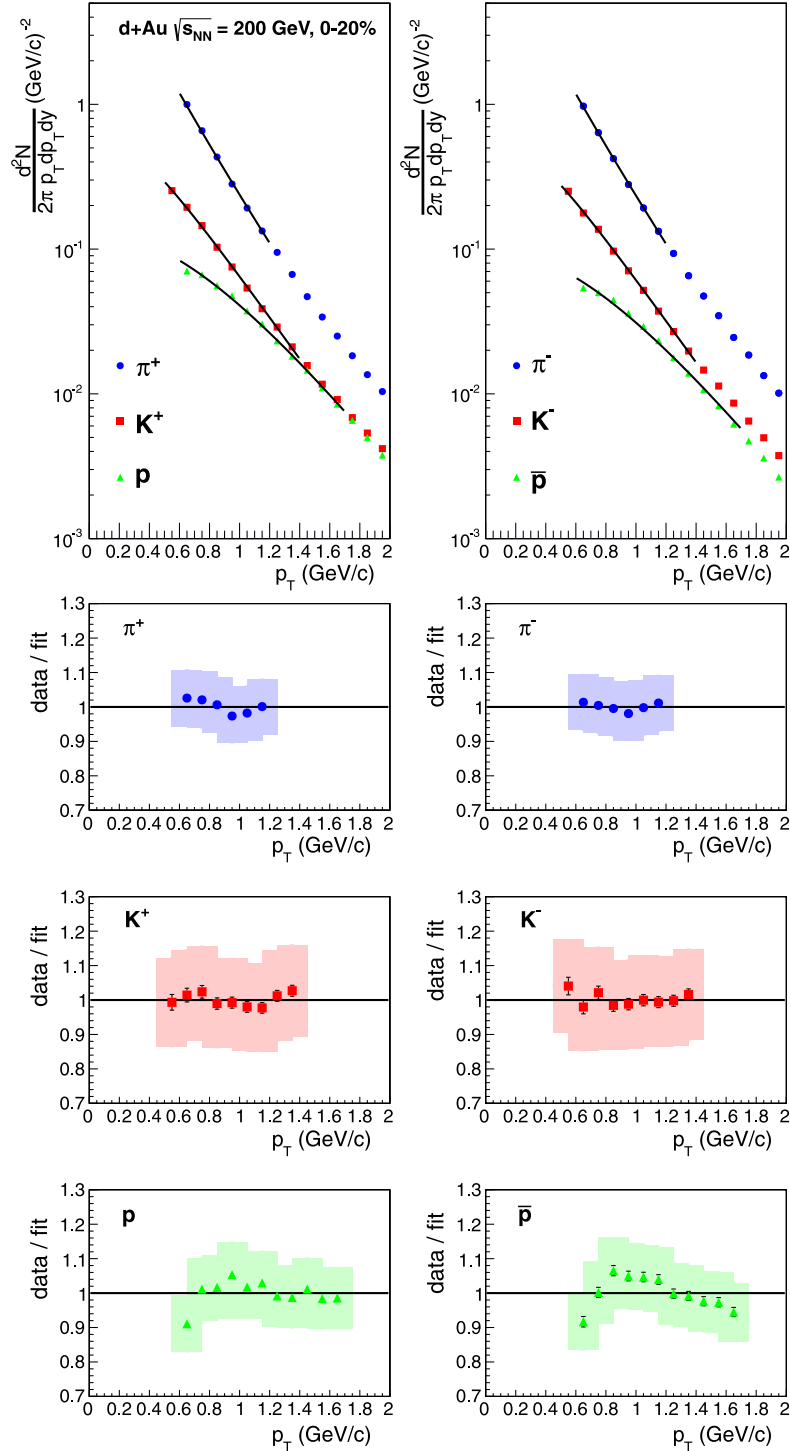


Fig. 1. (Top panels) Charged hadron spectra for the 0–20% most central d + Au collisions [40]. Overlaid with the data are the results of a simultaneous blast-wave fit to the data. (Bottom panels) Ratios of the experimental data to the blast-wave fits. Statistical uncertainties on the points are shown as error bars and systematic uncertainties are shown as boxes.

electrons and positrons (which are required to have $|\eta| < 0.35$ as in the experimental measurements) and the y -axes have the p_T of the parent D and B meson (decays in which a B decays to a D which subsequently decays to an electron are included in the B meson plot). We use the same procedure to extract the electron p_T spectra for both the FONLL and blast-wave meson p_T spectra. We take the branching ratios to be: $BR(B \rightarrow e) = 10.86\%$, $BR(B \rightarrow D \rightarrow e) = 9.6\%$ and $BR(D \rightarrow e) = 10.3\%$ [48].

The results for the electron R_{dAu} are shown in Fig. 4 overlaid with the measured electron R_{dAu} [37]. The uncertainties on the data are large and the uncertainties on the blast-wave calculation are shown as the dashed lines. The magnitude of the enhancement expected from the blast-wave calculation is in good agreement with the data. At $p_T \approx 1\text{--}2.5$ GeV/c there is a peak in the calculation that is not seen in the data. At high p_T , both the data and the calculation, by construction, approach unity at high p_T in

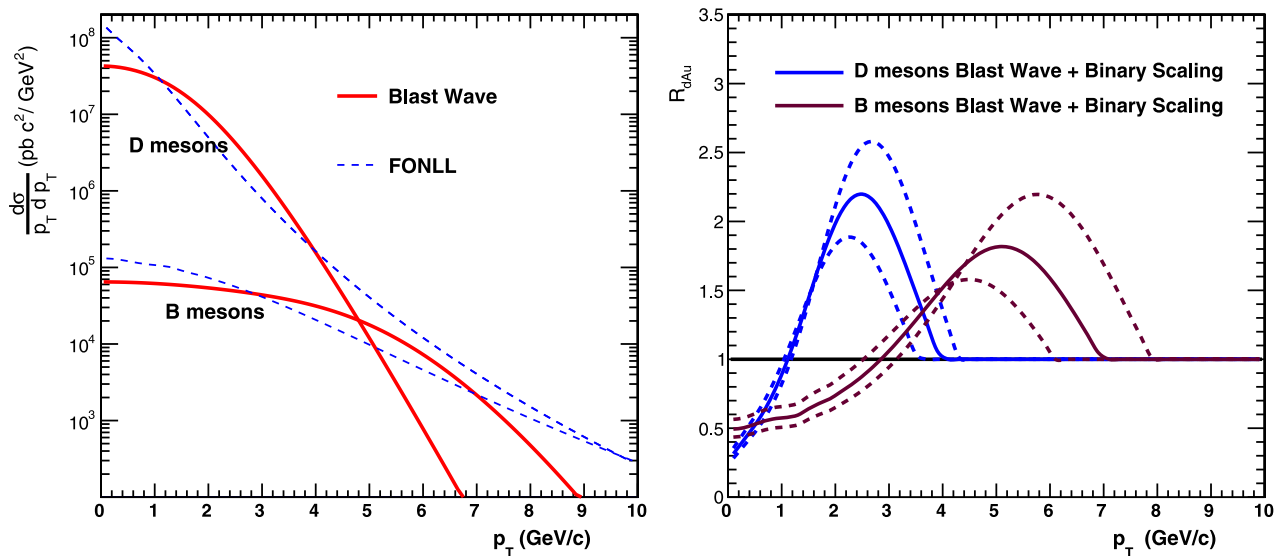


Fig. 2. (Left) D and B meson p_T spectra from FONLL [41–43] (dashed lines) and from the blast-wave calculation presented here (solid lines). (Right) The R_{dA} from the comparison of the blast-wave and FONLL curves in the left panel with binary scaling added at high p_T . The dashed lines show the changes in the blast-wave expectations from the uncertainties on the blast-wave parameters discussed above.

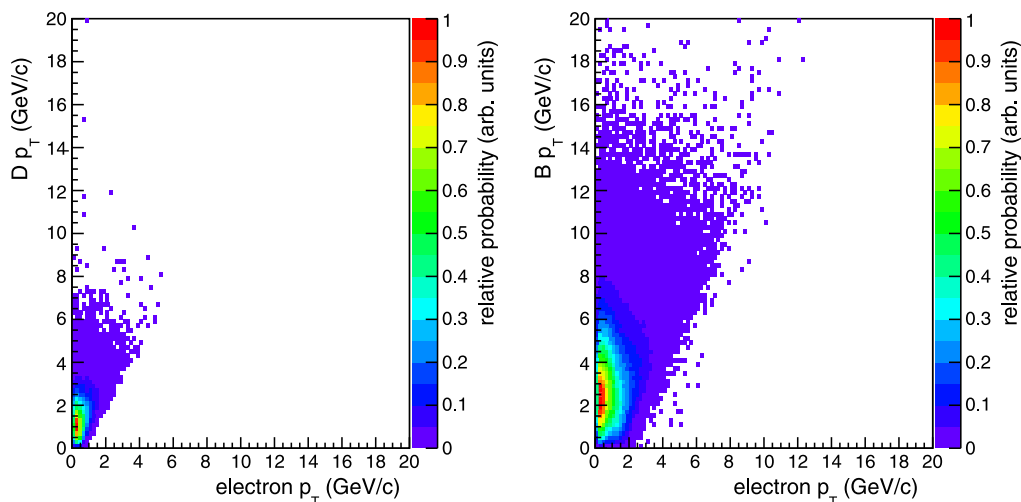


Fig. 3. The relative probability to for a heavy meson to decay into an electron at a given p_T . D mesons are shown in the left panel and B mesons are shown in the right panel. The decay kinematics are from PYTHIA8 [47].

a similar manner. However, since the blast-wave calculation qualitatively reproduces the data, if a hydrodynamic description of the light hadrons is valid in $d + Au$ collisions, then it is possible that the same is also true for heavy flavor.

3. Predictions for $p + Pb$ collisions at 5.02 TeV

It is, of course, natural to ask whether this effect could also play a role in $p + Pb$ collisions at the LHC. The ALICE Collaboration has published the results of blast-wave fits to identified particle spectra in multiplicity classes in Ref. [15]. The blast-wave implementation that they have used is slightly different from the one used above and allows n to be a fit parameter as well. Preliminary results on the R_{pPb} exist from ALICE for both reconstructed D mesons and electrons from the decay of heavy mesons [49, 50]. In both cases the R_{pPb} is consistent with unity; however the uncertainties are large. The D meson measurement is compatible with a 10–20% enhancement. The heavy flavor decay electron mea-

surement has a central value of approximately 30% enhancement for $p_T < 6$ GeV/c with uncertainties of approximately the same size.

Unfortunately, the heavy flavor results currently only are measured for minimum bias data so a direct comparison of the predictions with data is not possible. As an illustration of the possible magnitude of the effect, we have used the blast-wave parameters from the highest multiplicity bin, 0–5%, and FONLL calculations for 5.02 TeV [42,43]. Results for electrons and D mesons are shown in Fig. 5. The D meson enhancement reaches a maximum of approximately 20% at $p_T \approx 3$ GeV/c and the electrons are enhanced by 10–20% nearly independently of p_T over the range of 1–6 GeV/c. The calculations are for the highest multiplicity event class and show larger modifications than what would be expected for minimum bias collisions. Because of the harder D and B meson p_T spectra at the higher collision energy there is a smaller enhancement of heavy flavor mesons than at RHIC, despite the larger maximal velocity extracted from the blast-wave fits.

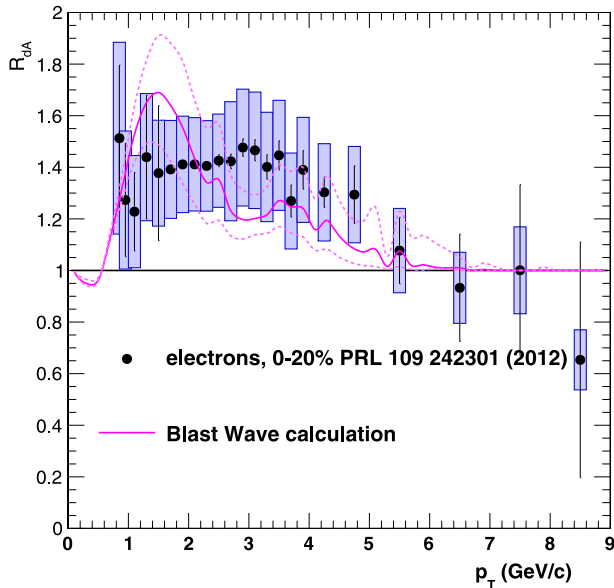


Fig. 4. The heavy flavor decay electron R_{dA} for 0–20% central d + Au collisions from Ref. [37] (solid points) and from the blast-wave calculations presented in this work (curve). The dashed lines show the changes in the blast-wave expectations from the uncertainties on the blast-wave parameters discussed above.

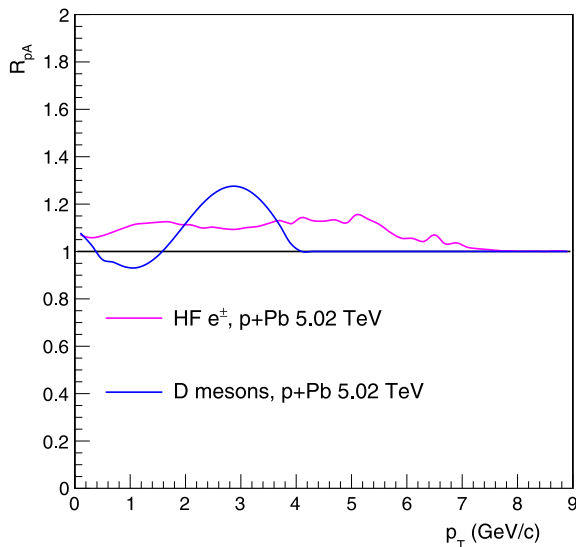


Fig. 5. Predictions for p + Pb collisions at 5.02 TeV. Blast-wave fit results from the 5% highest multiplicity p + Pb collisions [15] and FONLL [42,43] heavy meson spectra have been used to generate these results.

4. Conclusions

Given the large uncertainties on the available heavy flavor data in d + Au collisions at RHIC and the large uncertainties on the blast-wave calculation here, it is important to consider how a radial flow interpretation of heavy flavor data in very small collision systems would be verified or ruled out. The clearest evidence will come from charm and bottom separated results being made possible by recently installed vertex detectors at both STAR and PHENIX. Reconstructed D mesons from STAR and charm and bottom separated electron measurements from PHENIX will show the meson mass dependence of the heavy flavor enhancement seen by PHENIX [37]. Additionally, it is of interest to study multiplicity selected p + p collisions at $\sqrt{s} = 200$ GeV in order to investigate how the blast-wave parameters evolve with both collision system

and event activity and how that informs the interpretation of the d + Au data discussed here in terms of radial flow.

Recently, there has been much interest in the possibility of hydrodynamic flow in very small collision systems. Here we have raised the possibility that the enhancement of heavy flavor decay electrons previously observed [37] could be caused by radial flow using a blast-wave parameterization constrained by the light hadron data. We find qualitative agreement between the data and the prediction of this model, suggesting hydrodynamics as one possible explanation of the enhancement of electrons from heavy flavor decay observed in d + Au collisions. Further measurements have the potential to constrain any possible role of hydrodynamics in very small collision systems. D meson spectra at RHIC are especially interesting as the modifications should be significantly larger than is seen at the LHC.

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