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v_2 and R_{AA} of non-photonic single electrons: which restriction do the current measurements pose on the production of charm, beauty?

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Abstract. In relativistic heavy ion collisions, heavy flavor is expected to result predominately from initial hard parton–parton scatterings. Hence, in the absence of later stage effects, the production of heavy flavor in $A+A$ collisions can be viewed as a superposition of $N+N$ collisions. Measurements of v_2 or R_{AA} of heavy flavor (or their decay electrons) in $A+A$ collisions violate the simple superposition picture and therefore present themselves as probes of the medium formed in such collisions. On the basis of the measured v_2 and R_{AA} of non-photonic single electrons in $A+A$ collisions at RHIC, we will investigate the interplay between these observables as well as the restrictions they pose for charm and bottom production.

1 Introduction

In relativistic heavy ion collisions, particle production can be categorized into *soft* and *hard* physics. Here, *soft* stands for processes with relative small momentum transfers which might occur at any stage of collisions. *Hard* – to the contrary – signifies processes with momentum transfers large enough, so that they can be calculated via perturbative quantum chromo dynamics (**pQCD**). These processes can occur only at the initial stage of the collisions via parton–parton scattering. Therefore, at the time of their creation, particles originating from hard processes have no knowledge about the hot and dense medium formed in heavy ion collisions. Hence, in the absence of interactions with the medium, particle distributions from hard processes in heavy ion collisions ($A+A$) should merely present a superposition of individual nucleon-nucleon collisions ($N+N$). Reversing the argument, any deviation from a simple binary collision scaling of particles produced in hard processes must be due to interactions with the medium, hence rendering them as a perfect probe of it.

At RHIC energies, these hard probes manifest themselves in the detector as heavy flavor (charm and beauty) carrying particles, particles of high transverse momentum ($\approx p_{\mathrm{T}} > 5\,\mathrm{GeV/c}$), or particle jets. For all of these probes striking derivations from the naive expectation of binary collision scaling have been found in: (i) the surprisingly strong elliptic flow of non-photonic electrons originating from semi-leptonic heavy flavor decays, (ii) the high p_{T} suppression measured via $R_{AA} \approx 0.2$ for unflavored hadrons and non-photonic electrons, and (iii) the disappearance of the away-side jet in central Au + Au collisions. All these observations can qualitatively be understood in a consistent picture as strong interactions of individual partons with QCD matter and – in fact – (ii) and (iii) have been used to support the case for the creation of a quark gluon plasma (QGP) in RHIC collisions [1].

However, at present date, this qualitative picture lacks a consistent description via pQCD calculations, which are supposed to be applicable for these hard probes. The transverse momentum distributions of non-photonic electrons in $p+p$ collisions as measured by STAR [2] suggests a charm cross-section $\sigma^{c\bar{c}} \approx 1.4\,\mathrm{mb}$, approximately 5.7 times larger than calculated through state of the art pQCD calculations [2, 3] (see Fig. 1). Adding to the inconsistency is the fact that these calculating also suggest a significant contribution of beauty decays to the non-photonic electron spectrum at $p_{\mathrm{T}} > 5\,\mathrm{GeV/c}$, while the energy loss calculations based on high p_{T} non-photonic electron suppression (R_{AA}) leave no room for a significant beauty contribution up to $p_{\mathrm{T}} = 10\,\mathrm{GeV/c}$ as Fig. 2 shows. To reproduce R_{AA} both calculations have to neglect the $b \to e + X$ contribution to the non-photonic electron spectrum. Futhermore, both calculations need to modify crucial parameters by more than a factor of 3 compared to the canonical values of $\mathrm{d}N^g/\mathrm{d}y = 1000$ (gluon density, [8, 9]) and $\hat{q} = 4\,\mathrm{GeV/c^2}$ (transport coefficient, [4, 5]) as evaluated from unflavored hadron measurements. We are aware of recent theoretically developments introducing strong collisional energy loss (previously thought to be negligible)[6–9] which will increase the high p_{T} suppression (smaller R_{AA} values), however it is not yet clear whether a consistent set of parameters for the light and heavy quark sector can be found.

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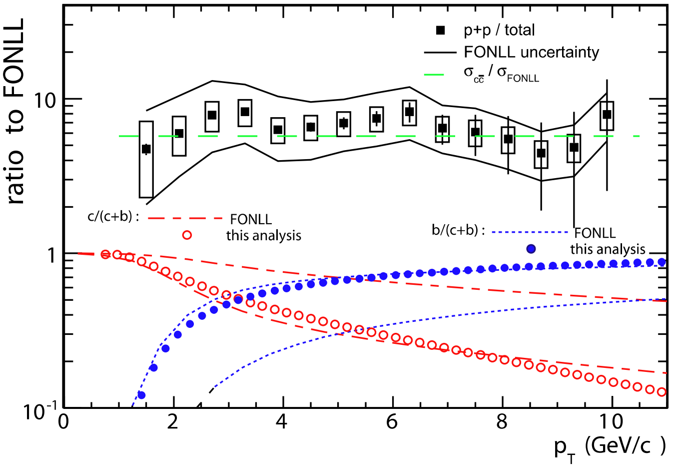

Fig. 1. Taken from [2]. *Data points*: Ratio between measured non-photonic electron yields and FONLL calculations. *Dashed line*: Same ratio averaged over the whole p_T range. *Dash-dotted lines*: Uncertainty band reflecting the semi-leptonic charm decay contribution to the non-photonic electron yields according to FONLL calculations. *Dotted lines*: Same for the semi-leptonic beauty decay contribution. *Open buttels*: Prediction for the semi-leptonic charm decay contribution to the non-photonic electron for this analysis. *Closed buttels*: Same for the semi-leptonic beauty decay contribution

To experimentally resolve the theoretically discrepancy regarding the charm and beauty yields, direct measurements of charm and beauty carrying hadrons would obviously be preferable. However, no such measurements of sufficient quality and p_T-reach are currently available. We therefore propose to use measurements of non-photonic electron elliptic flow (v_2) to determine the relative contributions of charm and beauty to the non-photonic electron transverse momentum spectrum.

2 Calculating relative charm and beauty contributions via non-photonic electron elliptic flow

In heavy ion collisions with finite impact parameter ($b \neq 0$), the overlap zone of the two nuclei has an initial almond-like shape. For particles interacting with the produced medium, this spacial anisotropy will lead a momentum anisotropy in azimuth due to hydro-dynamic pressure, surface radiation, or partial suppression of particles passing through varying integrated densities of the medium. This anisotropy is generally modeled by a Fourrier decompositions as

$$\frac{\mathrm{d}N}{\mathrm{d}\phi}(p_\mathrm{T}) \propto 1 + \Sigma_n 2 v_n(p_\mathrm{T}) \cos(n(\phi-\psi))\,, \tag{1}$$

where $\psi = \mathrm{atan2}\,(p_y, p_x)$ is the azimuth angle for a given particle and the ψ angle gives the orientation of the reaction plane. The second Fourrier component v_2 is called elliptic flow.

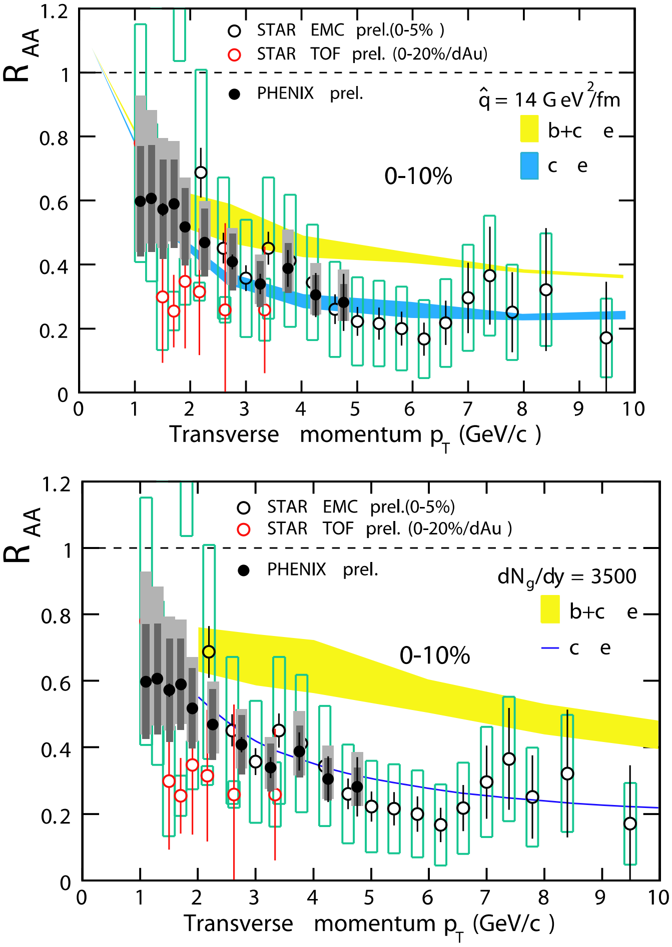

Fig. 2. R_{AA} for non-photonic electrons. *Both pannels*: *Circles*: STAR preliminary (QM2005). *Squares*: PHENIX preliminary (QM2005) *Upper panel*: *Lower band*: pQCD prediction for R_{AA} from charm decays only [4, 5] *Upper band*: pQCD prediction R_{AA} from charm and beauty decays [4, 5] *Lower panel: Lower band*: pQCD prediction for R_{AA} from charm decays only [8, 9] *Upper band*: pQCD prediction for R_{AA} from charm and beauty decays [8, 9]

At RHIC energies, a surprising finding has been made above the hydro-dynamically dominated soft physics region ($p_\mathrm{T} < 2\,\mathrm{GeV/c}$): Elliptic flow for mesons (v_2^m) and baryons (v_2^b) scales independent of particle mass with the number of constituents quarks

$$\left.\frac{v_2^m(p_\mathrm{T}/n_c)}{n_c}\right|_{n_c=2} = \left.\frac{v_2^b(p_\mathrm{T}/n_c)}{n_c}\right|_{n_c=3}\,. \tag{2}$$

This observation has theoretically been interpreted as quark coalescence [10–17] which models the hadron v_2 as

$$v_2^h = \sum_{i=1}^{n} v_2^{q_i}\left(\frac{1}{n}p_\mathrm{T}\right) \quad [12, 15]\,. \tag{3}$$

Here, $v_2^{q_i}$ is the v_2 of an individual quark. No significant dependence on the specific flavor content (i.e. π, K, and p, Λ, Ξ, Ω) has been found, suggesting the v_2

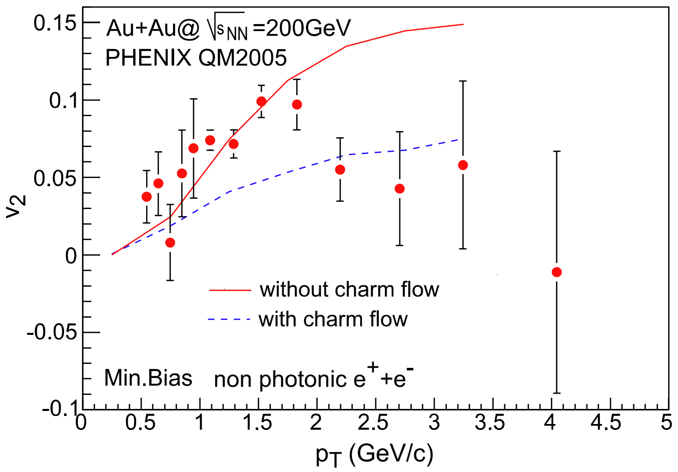

Fig. 3. Non-photonic single electrons elliptic flow [18]

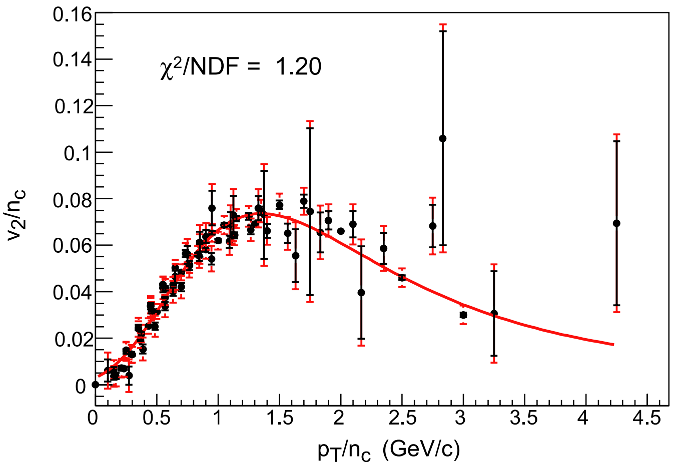

Fig. 4. World data set of elliptic flow of light quark carrying hadrons at Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV as $v_2/n_c(p_\mathrm{T}/n_c)$

of u, d, and s quarks to be of similar strength. Assuming the general validity of this quark coalescence scaling and having the light quark v_2 therefore determined, limits for the elliptic flow of open charm carrying hadrons can be calculated. The upper limit is given by the assumption that the charm quark flows just like the light quarks $v_2^c = v_2^{u,d,s}$, while the lower limit is given by the opposite extreme, $v_2^c = 0$.

Direct open charm elliptic flow has not been measured so far at RHIC, however elliptic flow results from non-photonic electrons, which serve as a proxy for D-mesons – the most abundant open charm carrier – are already available. Such results from the PHENIX collaboration are shown in Fig. 3 [18]. Indeed, at $p_\mathrm{T} < 2$ GeV/c, the electrons seem to follow the maximum charm flow assumption: $v_2^c = v_2^{u,d,s}$. However, above 2 GeV/c, the electron v_2 distribution deviates strongly from this assumption. In the quark coalescence model, this could be interpreted as a break down of charm quark v_2, since the light quark v_2 seems to remain strong out to even larger p_T.

An alternative explanation might be an increasing contribution of semi-leptonic beauty decays to the non-photonic electron yield, which are not expected to show significant elliptic flow [17]. Following this explanation, we make the anstatz

$$v_2 = \frac{v_2^{c\to e} * n_c + v_2^{b\to e} * n_b}{n_c + n_b}\,, \qquad (4)$$

for the measured elliptic flow v_2. Here, $v_2^{c\to e}$ and $v_2^{b\to e}$ are the elliptic flow values for electrons from charm and beauty; n_c and n_b are their respective contributions to the non-photonic electron yield. With $v_2^{b\to e} = 0$, their fractions calculate as :

$$r_{c\to e} = \frac{n_c}{n_c + n_b} = \frac{v_2}{v_2^{c\to e}} \quad \text{and} \qquad (5)$$

$$r_{b\to e} = 1 - r_{c\to e}\,. \qquad (6)$$

To construct the elliptic flow for electrons from charm decays ($v_2^{c\to e}$), we use the worlds data set on elliptic flow for light quark carrying hadrons [24] and evaluate $v_2/n_c(p_\mathrm{T})$ according to (3), which we parametrize with a Landau distribution[1] (see Fig. 4). We then simulate a D^0 meson distribution according to the STAR p_T spectrum[19] and the coalescence prediction for $v_2^c = v_2^{u,d,s}$ (see Fig. 5). Calculating the elliptic flow of the D^0 distribution's decay electrons gives $v_2^{c\to e}$.

Our prediction for the contribution for electrons from semi-leptonic charm (beauty) decays are shown in Fig. 1 as the open (closed) bullets. They indicate a beauty contribution close to the upper limit of the FONLL uncertainty band, hence a charm contribution close to the lower limit is favored. For both, the charm and beauty contribution we estimate an uncertainty form fitting and extrapolating the $v_2^{u,d,s}(p_\mathrm{T})$ parameterisation of $\Delta n_{c,b} \pm 0.1$ (absolute). However, the main uncertainties originate from the validity of the key assumptions $v_2^c = v_2^{u,d,s}$ and $v_2^b = v_2^{b\to e} = 0$. Only more precise measurements will confirm to which degree they are applicable.

3 Summary

At the present date, pQCD calculations for top RHIC energies are not able to consistently describe the transverse momentum distributions and high-p_T suppression of non-photonic single electrons, which serve as a proxy for heavy flavor production. To disentangle whether the problem lies in the calculation of cross-sections or in the understanding of heavy quark energy loss, it is important determine the relative contributions of charm and beauty

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[1] There is now physics motivation why $v_2(p_\mathrm{T})$ should be Landau distributed. We merely use it because it satisfies two fundamental requirements of elliptic flow: $v_2(0) = 0$ and $v_2(\mathrm{inf}) = 0$. It also happens to describe the data quite well.

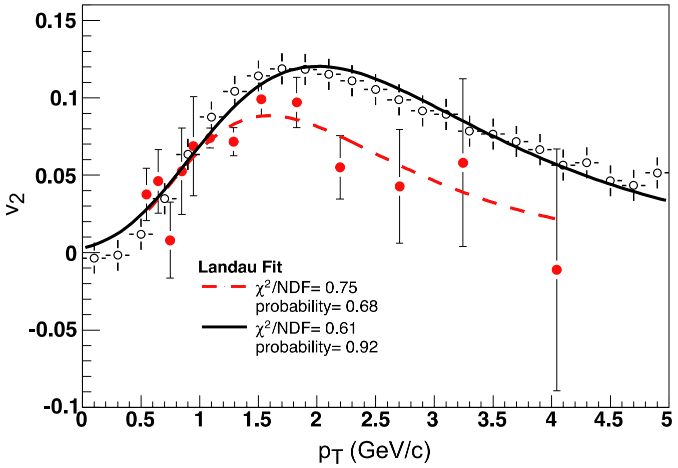

Fig. 5. Elliptic flow of non-photonic single electron as measured by PHENIX (*closed bullets*) and for electrons from semileptonic charm decays (*open bullets*, simulation, see text). The *lines* represent fits to Landau distributions

decays to the non-photonic electron spectrum, thus the relative charm and beauty yields. While no direct measurements of charm and beauty of sufficient quality and p_T reach are expected in the near future (2–3 years), we outlined a way how measurements of non-photonic single electron elliptic flow might help to settle outstanding question about heavy flavor production and suppression at RHIC.

Our preliminary results favor a beauty production near the upper limit of the uncertainty band given by current state of the art pQCD calculation. While this result relies on the key assumptions of $v_2^c = v_2^{u,d,s}$, the applicability of the quark coalescence model, and proper modeling of the charm quark flow for extrapolation to higher p_T, if confirmed, it will constitute a challenge to the descriptions of heavy quark energy loss in the high density medium produced in Au + Au collisions at RHIC.

References

1. M. Gyulassy, L. McLerran, Nucl. Phys. A **750**, 30 (2005)
2. L. Adams, et al., arXiv:nucl-ex/0607012
3. M. Cacciari, P. Nason, R. Vogt, Phys. Rev. Lett. **95**, 122 001 (2005)
4. N. Armesto, M. Cacciari, A. Dainese, C.A. Salgado, U.A. Wiedemann, arXiv:hep-ph/0510284
5. N. Armesto, M. Cacciari, A. Dainese, C.A. Salgado, U.A. Wiedemann, Phys. Lett. B **637**, 362 (2006)
6. Y.L. Dokshitzer, D.E. Kharzeev, Phys. Lett. B **519**, 199 (2001)
7. S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, arXiv: nucl-th/0512076
8. M. Djordjevic, M. Gyulassy, S. Wicks, Eur. Phys. J. C **43**, 135 (2005)
9. M. Djordjevic, M. Gyulassy, R. Vogt, S. Wicks, Phys. Lett. B **632**, 81 (2006) [arXiv:nucl-th/0507019]
10. A. Voloshin, Nucl. Phys. A **715**, 379 (2003)
11. Z. Lin, D. Molnar, Phys. Rev. C **68**, 044 901 (2003)
12. C. Nonaka, B. Muller, S.A. Bass, R.J. Fries, M. Asakawa, J. Phys. G **31**, S429 (2005)
13. V. Greco, C.M. Ko, nucl-th/0405040
14. D. Molnar, J. Phys. G **31**, S421 (2005)
15. D. Molnár, A. Voloshin, Phys. Rev. Lett. **91**, 09 230 (2003)
16. V. Greco, C.M. Ko, R. Rapp, Phys. Lett. B **595**, 202 (2004)
17. H. van Hees, V. Greco, R. Rapp, Phys. Rev. C **73**, 034 913 (2006)
18. S. Sakai, arXiv:nucl-ex/0510027
19. STAR Collaboration, J. Adams et al., Phys. Rev. Lett. **94**, 062 301 (2005)
20. K.H. Ackerman et al., Nucl. Instrum. Methods A **499**, 624 (2003)
21. STAR Collaboration, M. Beddo et al., Nucl. Instrum. Methods A **499**, 725 (2003)
22. K.H. Ackerman et al., Phys. Rev. Lett. **86**, 402 (2001)
23. PHENIX Collaboration, S.S. Adler et al., Phys. Rev. C **72**, 024 901 (2005)
24. P.R. Sorensen, arXiv:nucl-ex/0510052 and references therein