Phenomenological Implications of the p_T Spectra of ϕ and Ω produced at LHC and RHIC

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Abstract. The data on the p_T spectra of ϕ and Ω at LHC can be presented in a format that shows exponential behavior up to $p_T \approx 6$ GeV/c with the same slope for both particles and for nearly all centralities. Those empirical properties are found at lower energies also with the inverse slope showing a power-law dependence on $\sqrt{s_{NN}}$. The shared properties of the spectra are shown to emerge naturally from the recombination model. No radial flow is needed. We find experimental hints for the possibility that ϕ and Ω are mostly produced in the ridge region, generated by minijets. Appropriate experimental test is suggested.

The production of ϕ and Ω at LHC with p_T reaching as high as 5 GeV/c (for ϕ) [1] and 7 GeV/c (for Ω) [2] has not been discussed in any theoretical framework ranging from hydrodynamics to QCD. Both the extent of the p_T range and the constituents being only s quarks present challenges to the usual theories. Those difficulties provide a good opportunity for us to investigate the subject in a novel phenomenological way with the hope of discovering clues to what may be flaws in the conventional interpretation of what happens in heavy-ion collisions at very high energies.

The p_T spectra of ϕ have been fitted in [1] by blast wave in the hydro model [3] using 3 free parameters for each centrality bin. Undoubtedly, the same can be done for the Ω spectra. So what does one learn from the 6 parameters for each centrality? We propose a different way to examine the p_T spectra. The usual presentation of data is in terms of $dN_h/p_T dp_T$. Let us define for meson and baryon data, respectively, the two functions

$$M_h(p_T) = \frac{dN_h}{p_T dp_T} \cdot \frac{m_T^h}{p_T}, \tag{1}$$

$$B_h(p_T) = \frac{dN_h}{p_T dp_T} \cdot \frac{m_T^h}{p_T^2}, \tag{2}$$

which are just different ways of presenting of the same data without theoretical adjustments. Note that they have different dimensions. In Figs. 1 and 2 we show the distributions $M_\phi(p_T)$ and $B_\Omega(p_T)$ using only the data points in [1, 2]. They show the strikingly simple exponential behaviors in p_T for nearly all centralities. The straight-line fits of both distributions amazingly have the same inverse slope

$$T_\phi = T_\Omega = 0.51 \text{ GeV/c}, \quad \text{for } \sqrt{s_{NN}} = 2.76 \text{ TeV} \tag{3}$$

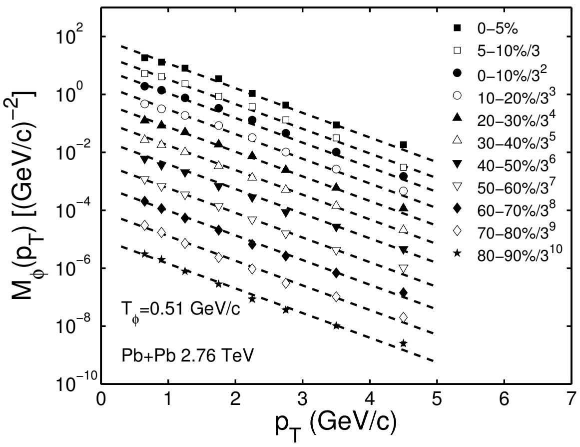

Figure 1. Plot of $M_\phi(p_T)$ from data in [1].

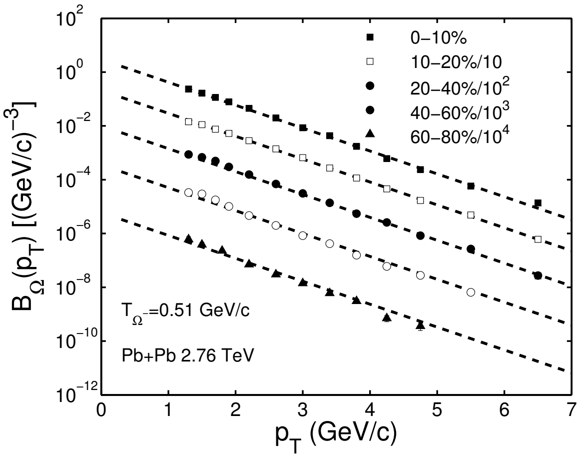

Figure 2. Plot of $B_\Omega(p_T)$ from data in [2].

a property that is totally hidden in the original data.

Seeing two different functions of different dimensions having the same inverse slope in semi-log plots stimulates curiosity. Exponential behavior in p_T usually means thermal distribution, but being valid out to $p_T \approx 6$ GeV/c is not what QCD thermodynamics can offer to explain. The fits in Figs. 1 and 2 can be expressed in the factorizable form

$$M_\phi(p_T, N_{\rm part}) = A_\phi(N_{\rm part}) \exp(-p_T/T_\phi), \tag{4}$$

$$B_\Omega(p_T, N_{\rm part}) = A_\Omega(N_{\rm part}) \exp(-p_T/T_\Omega), \tag{5}$$

where the centrality dependences for $N_{\rm part} > 70$ can be shown to satisfy

$$A_{\phi,\Omega}(N_{\rm part}) = A^0_{\phi,\Omega} N_{\rm part}^{a_{\phi,\Omega}}, \quad a_\phi = 0.9, \quad a_\Omega = 1.35. \tag{6}$$

What is found above for $\sqrt{s_{NN}} = 2.76$ TeV at LHC turns out to be also true at lower energies with different inverse slopes down to 7.7 GeV at RHIC [4, 5, 6, 7]. In Fig. 3 we show how $T_{\phi,\Omega}$ depends on $\sqrt{s_{NN}}$ empirically. The extension of the power-law behavior to 5.02 TeV yields $T_{\phi,\Omega} = 0.54$ GeV/c, which is a prediction without deeper theoretical explanation. We note that the values of $T_{\phi,\Omega}$ shown in Fig. 3 are not the temperatures discussed in hydro models.

Now, we summarize briefly how the observed behaviors of M_ϕ and B_Ω can be understood in the recombination model, a review of which can be found in the first few sections of [9]. The invariant distribution of ϕ at mid-rapidity is

$$E\frac{dN_\phi}{dp_T} = \int \frac{dp_1}{p_1}\frac{dp_2}{p_2} \mathcal{T}_s(p_1)\mathcal{T}_{\bar{s}}(p_2) R_\phi(p_1, p_2, p_T), \tag{7}$$

where only the thermal-parton distributions, $\mathcal{T}(p_i)$, are retained, since the production of strange shower partons is suppressed. The recombination function $R_\phi(p_1, p_2, p_T)$ contains a momentum-conservation factor $\delta((p_1 + p_2)/p_T - 1)$. Inserting into (7) $\mathcal{T}_s(p_1) = p_1^0 dN_s/dp_1 = C_s p_1 e^{-p_1/T_s}$ where T_s is the inverse slope for s quark distribution, and a similar form for $\mathcal{T}_{\bar{s}}(p_2)$, yields (with the assumption $T_s = T_{\bar{s}}$)

$$E\frac{dN_\phi}{dp_T} = C_s C_{\bar{s}} Z_\phi p_T^2 e^{-p_T/T_s}, \tag{8}$$

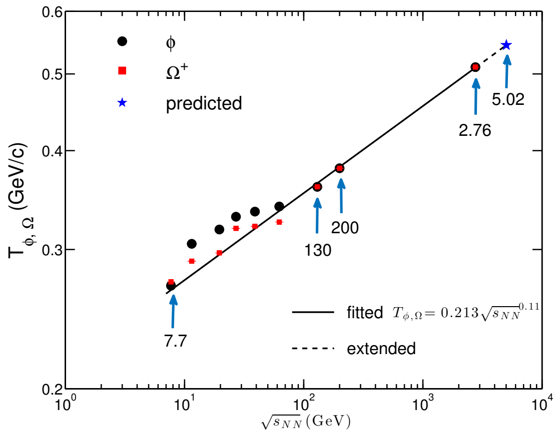

Figure 3. $T_{\phi,\Omega}$ derived from [1, 2, 4, 5, 6, 7].

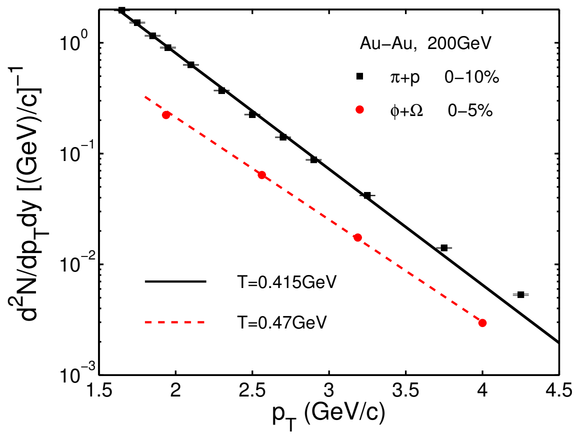

Figure 4. RHIC data on $\pi + p$ and $\phi + \Omega$ [4, 6, 8].

where Z_ϕ is a numerical factor arising from the integration. At $y \approx 0$ where $E \approx m_T$, Eq. (8) can be put into the form for M_ϕ given in (4) with $A_\phi(N_{\rm part}) = C_s C_{\bar{s}} Z_\phi$ and $T_\phi = T_s$.

For Ω production three $\mathcal{T}_{\bar{s}}(p_i)$ are involved in EdN_Ω/dp_T, so one obtains (5) with $A_\Omega(N_{\rm part}) = C_s^3 Z_\Omega$ and $T_\Omega = T_s$. Comparing M_ϕ with B_Ω, one gets $T_\phi = T_\Omega = T_s$ and that the ratio $A_\phi(N_{\rm part})/A_\Omega(N_{\rm part})$ is proportional to $C_s C_{\bar{s}}/C_s^3$, which agrees with the empirical $N_{\rm part}$ dependence in (6) at LHC, i.e., 2:3 in the exponents, in the reasonable assumption that $C_{\bar{s}}$ depends on $N_{\rm part}$ as C_s does.

What is important in our description above is that we have made no mention of radial flow. There is no need for radial velocity, $T_{\rm kin}$ or blast wave. The system must expand in some way, but it need not be prescribed by hydrodynamics without jets. We have for nearly all centralities used only one parameter T_s, which we have referred to as inverse slope, not temperature, although $\mathcal{T}_s(p_i)$ is regarded as thermal distribution. Since hadronization by recombination occurs at the end of the evolutionary process, we have not made use of any specific expansion dynamics. $\mathcal{T}_s(p_i)$ is the invariant s quark distribution at the time of hadronization without any contribution from the shower partons that arise from fragmentation of high-p_T jets. But at LHC minijets are copiously produced and must influence the bulk of the medium that hydro ignores. In our view $\mathcal{T}_s(p_i)$ must contain the effects of minijets.

The most notable feature about the above description is that the common value of the inverse slopes in Figs. 1 and 2 is $T_{\phi,\Omega} = 0.51$ GeV/c, as given in (3) for $\sqrt{s_{NN}} = 2.76$ TeV. Even at 7.7 GeV in the BES program the value is $T_{\phi,\Omega} = 0.27$ GeV/c, still much larger than the chemical freeze-out temperature of $T_{\rm ch} < 0.165$ GeV and kinetic freeze-out temperature of $T_{\rm kin} < 0.14$ GeV [10]. The fact that the exponential fits of $M_\phi(p_T)$ and $B_\Omega(p_T)$ are so good for such a wide range of p_T demands an explanation. An equation such as (8) relates T_s to the observed value of $T_{\phi,\Omega}$ but does not explain why T_s is so high. Our first step is to ask how high T_s is relative to the inverse slope for light quarks. It turns out that, when (1) is applied to pions, $M_\pi(p_T)$ cannot be fitted by a simple exponential because the fragmentation products and resonance decay contributions bend the distribution above a straight line at both high and low p_T regions. The situation is better for $B_p(p_T)$ for proton, but still not as good as in Fig. 2. Nevertheless, the common straight-line fits of $M_\pi(p_T)$ and $B_p(p_T)$ yields $T_{\pi,p} = 0.41$ GeV/c. That gives us an estimate of the difference between T_Ω and T_p: $\Delta T = T_\Omega - T_p = 0.1$ GeV/c at LHC. A similar comparison at RHIC-200 yields $\Delta T = 0.065$ GeV/c.

That leads us to recall the difference in inverse slopes when ridge was first discovered by STAR

[11]: $T_{\rm ridge} - T_{\rm incl}$=40-50 MeV. We use the STAR data for Au-Au collisions at 200 GeV and compare d^2N/dp_Tdy at mid-rapidity between $\pi + p$ (0-10%) and $\phi + \Omega$ (0-5%) as shown in Fig. 4. In the range between $p_T = 1.5$ and 4 GeV/c, which is the range on ridge in [11], the data can be well fitted by straight lines, showing the difference in inverse slopes to be $T_{\phi+\Omega} - T_{\pi+p} = 55$ MeV. That gives us a strong hint that ϕ and Ω may be a component in the ridge, but instead of being in the triggered events, they are identified.

So far there are no data from LHC on the $p_T^{\rm assoc}$ dependence of the particles in the ridge. However, CMS does have evidence that the ridge yield increases with decreasing $p_T^{\rm trig}$ [12]. Since a trigger particle comes from the fragmentation of a hard parton that emerges from the expanding medium, lower $p_T^{\rm trig}$ is more likely to be associated with a hard parton originated from the interior of the medium, thus losing a larger portion its energy traversing that medium. The energy lost enhances the thermal partons, so the ridge that comes from the enhanced thermal partons [9, 13] gets higher inverse slope and thus more yield. To confirm our interpretation that ϕ and Ω are in the ridge with higher $T_{\phi,\Omega}$ than $T_{\pi,p}$, we need data from LHC to identify ϕ and Ω in the triggered events and to compare the inverse slopes of their $p_T^{\rm assoc}$ distributions with (3).

In the usual QCD thermodynamics the chemical and kinetic freeze-out temperatures are less than 160 MeV. The larger $\langle p_T \rangle$, corresponding to our much larger value of inverse slope $T_{\phi,\Omega}$, is then achieved in hydro models by transverse flow, which is a description predicated on the assumption that the system evolves smoothly from early times. But we know from the parton distribution functions $F(x)$ that they increase steeply with decreasing momentum fraction x, so in an AA collision the probability is high for scattering among low-x partons resulting in a preponderance of minijets which can propagate inside the expanding medium and lose energy in ways that invalidate the rapid thermalization hypothesis. Minijets with $p_T \sim$ 2-3 GeV/c cannot be calculated reliably in pQCD, but their effects cannot be ignored. They are almost all absorbed by the environment, resulting in enhancement of the thermal partons that creates the ridge phenomenon [13, 14]. The minijets can produce more $s\bar{s}$ pairs than in equilibrium QCD thermodynamics. It is therefore natural for us to interpret the large value of $T_{\phi,\Omega}$ in (3) as a manifestation of s quarks in the ridge. If future LHC data can verify the correlation between (ϕ, Ω) and the ridge, then they not only give support to our view that is outside hydro flow, but also pose a strong challenge to any other approach for a satisfactory explanation.

Acknowledgments

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