Transverse Momentum Distributions of Charm Meson in Relativistic Heavy-Ions Collisions Studied through Non-Extensive Statistics

Guilherme Felipe Budiski, Pedro Mariano Marques Mendes and Marcelo G. Munhoz, Universidade de São Paulo, Brazil

Introduction

This project aims the application of non-extensive statistics, more specifically that proposed by C. Tsallis [1], in the study of the transverse momentum distribution of hadrons composed of charm quarks produced in collisions between heavy ions at relativistic energies. Non-extensive statistics has been very successful in the description of transverse momentum (p_T) spectra of particles produced in hadronic collisions at high energies and the interpretation of the non-extensive parameter q has been widely discussed. The success of this description might be connected to the degree of equilibrium reached in these collisions, an important condition for a broad understanding of its dynamics. This question is particularly important for heavy quarks in collisions between heavy ions, given its unique role in the investigation of the medium formed in these collisions. In this work, we have used the TBW expression given by [2]:

$$\frac{d^2N}{2\pi p_T dp_T dy} \propto m_T \int_{-y_b}^{y_b} \cosh(y_s) dy_s \int_{-\pi}^{\pi} d\phi \int_0^R r\,dr \left(1 + \frac{q-1}{T}\left(m_T \cosh(y_s)\cosh(\rho) - p_T \sinh(\rho)\cos(\phi)\right)\right)^{-1/(q-1)}$$

where y and y_b are the rapidity of the produced particle and the colliding beam, respectively; m_N is the mass of the colliding nucleon and m_T is the transverse mass. The integration variables are y_s, the rapidity of the particle's emitting source, ϕ, the azimuthal angle perpendicular to the beam direction, and r, the distance to the center of the fireball. The variable $\rho = arctan(\beta_s (r/R)^n)$ is the expansion rapidity of the fireball, β_s being the expansion velocity at its surface. We have studied both constant ($n = 0$) and linear ($n = 1$) velocity profiles.

Transverse Momentum Spectra Fit

The table below shows the data that was used to perform the fits using the equation above, extracted from references from [3] to [7]. Three centrality classes of PbPb collisions at 5.02 TeV were used and three different multiplicity classes of pp collisions at 13 TeV were also included for comparison purposes. Figure 1 shows the results of the fit for the D mesons and Λ_c baryon (when applicable).

Colliding System	Spectra	Cent./Mult. Class	Reference
Pb-Pb 5.02 TeV	D^0, D^+, D^{*+}	0-10%, 30-50%	[3]
Pb-Pb 5.02 TeV	D_s^+	0-10%, 30-50%	[4]
Pb-Pb 5.02 TeV	Λ_c	0-10%, 30-50%	[5]
Pb-Pb 5.02 TeV	D^0, D^+, D^{*+}, D_s^+	60-80%	[6]
pp 13 TeV	D^0, D_s^+	V0M I, II, III	[7]

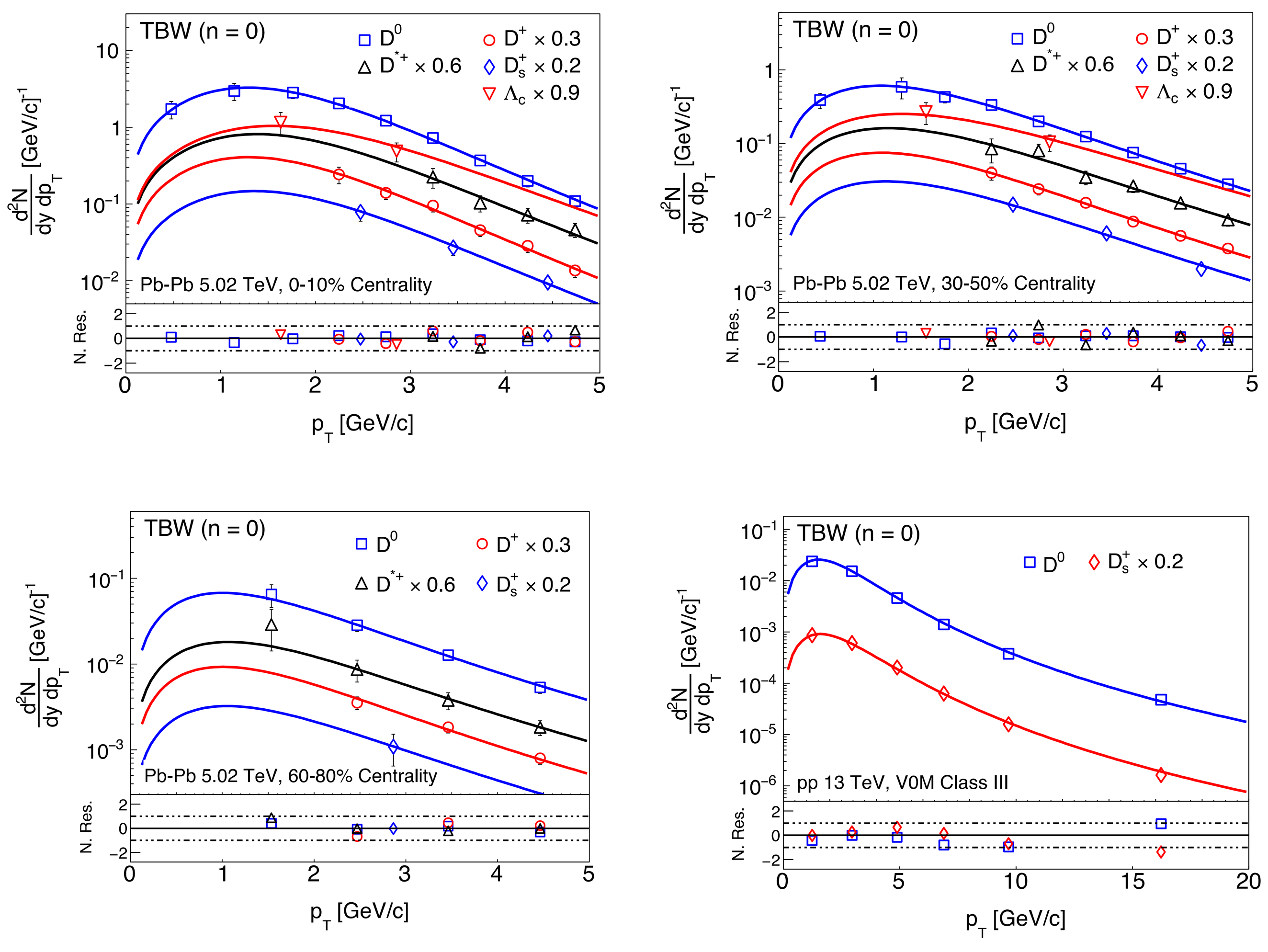

Fig.1 – TBW fits to D mesons and Λ_c baryon spectra from three different centralities of PbPb collisions at 5.02 TeV and one multiplicity bin of pp collisions at 13 TeV, all fits using n=0. The panels below show the normalized residuals, with the dashed lines indicating a 1σ deviation from the model.

Since the data represent the average number of particles on each bin of transverse momentum, we have fitted averages of the TBW function over the measured bins of p_T to the data, using a least-χ^2 method. The parameters q, T and $\langle\beta\rangle$ are common for all particles, and each spectrum had a separate normalization constant. The minimizations were performed using the TMinuit class in ROOT. In the fits, we have used as uncertainty the square-root of the sum of the squares of the statistical and systematic uncertainties of the data.

Final Considerations

We presented some results of a systematic study of charmed hadrons transverse momentum distributions fits, mainly the relative behavior of the non-extensive q parameter for different particles and collision centralities. The purpose of this study is to investigate whether this approach can give hints regarding the dynamics of charm quarks in these collisions. The next step of this work is precisely to seek for an understanding of the behavior of these parameters that seems to be sensitive to the different dynamics of heavy quarks (charm, in this case) in the medium formed in collisions between heavy ions when compared to other particles.

Fit Results – q Parameter Behavior

Figure 2 shows the values of parameters obtained from the fits when compared to each other. In these figures, besides the fits to heavy hadrons performed in this work, we have also included the results of fits to lighter particles spectra (π, K, p, K^{*0} and ϕ) performed in [8] and [9]. Our main focus is the behavior of the q parameter. In pp collisions, for both light and charmed hadrons, this parameter has an almost constant value above unity. In PbPb collisions, q seems to decrease as $\langle\beta\rangle$ (and centrality) increases towards unity, with similar behavior for light and charmed hadrons. The relation between q and T is not so clear, as the temperature does not varies considerably for different centralities in PbPb collisions.

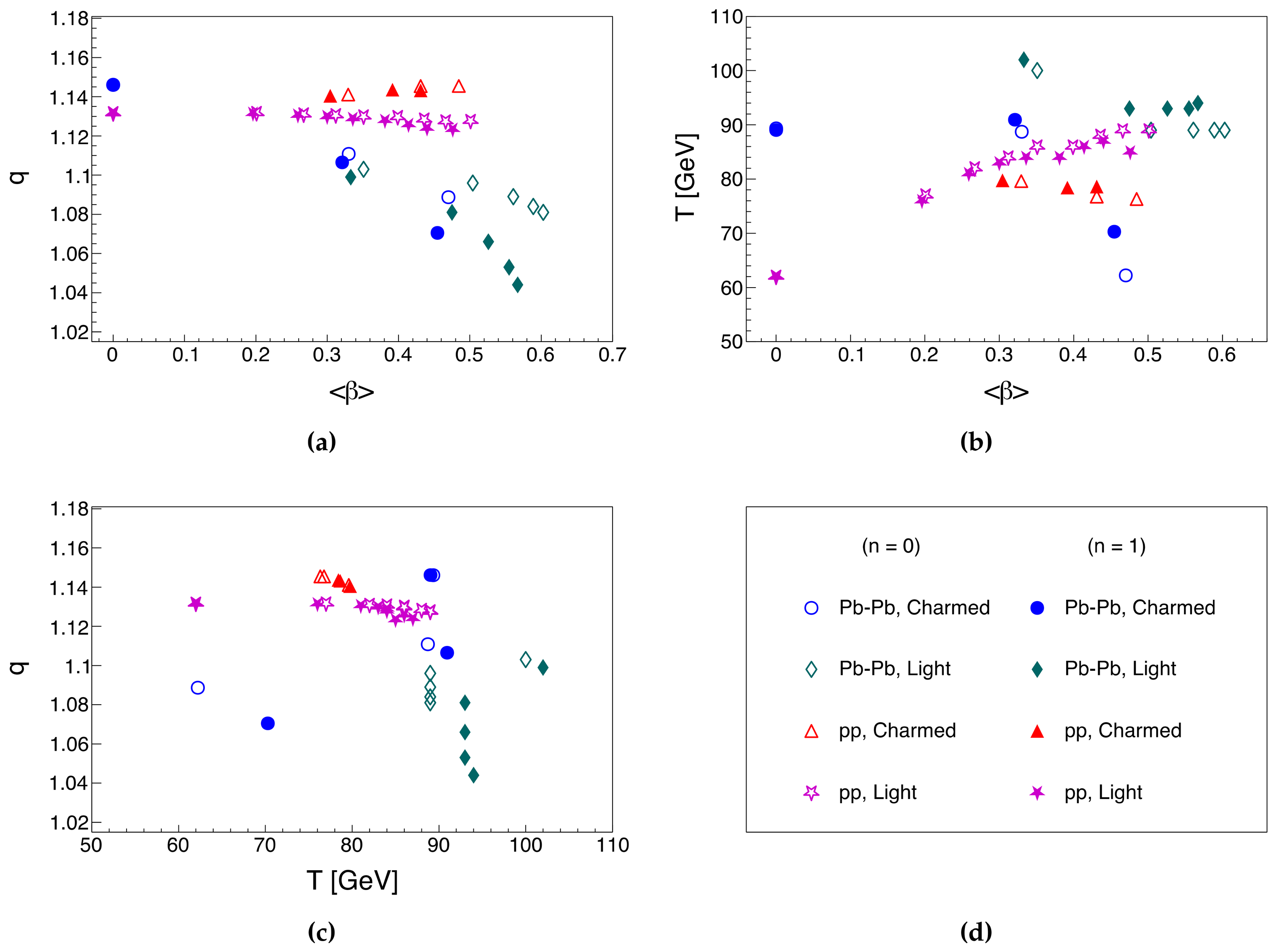

Fig. 2 – Correlation between the TBW parameters for both charmed and light [8, 9] particles in Pb-Pb 5.02 TeV and pp 13 TeV collisions. The error bars have been omitted to improve visualization.

We have also analyzed the behavior of the parameters as a function of $\langle dN_{ch}/d\eta\rangle$, which values were taken from [10] and [11] for each studied centrality or pp collisions multiplicity bin. Figure 3 shows the behavior of the parameters q, T and $\langle\beta\rangle$ as a function of $\langle dN_{ch}/d\eta\rangle$. In this case, the behavior of the parameters are simpler to visualize. The q value tends smoothy to unity as the multiplicity increases matching the behavior of pp and PbPb collisions. An interesting observation from this work is the fact that the heavy hadrons follow the same trend as the light ones, but with q values higher for heavy hadrons. The values for $\langle\beta\rangle$ increase with multiplicity but have smaller values for heavy hadrons. And the temperature decreases suddenly in the highest multiplicity bin for heavy hadrons.

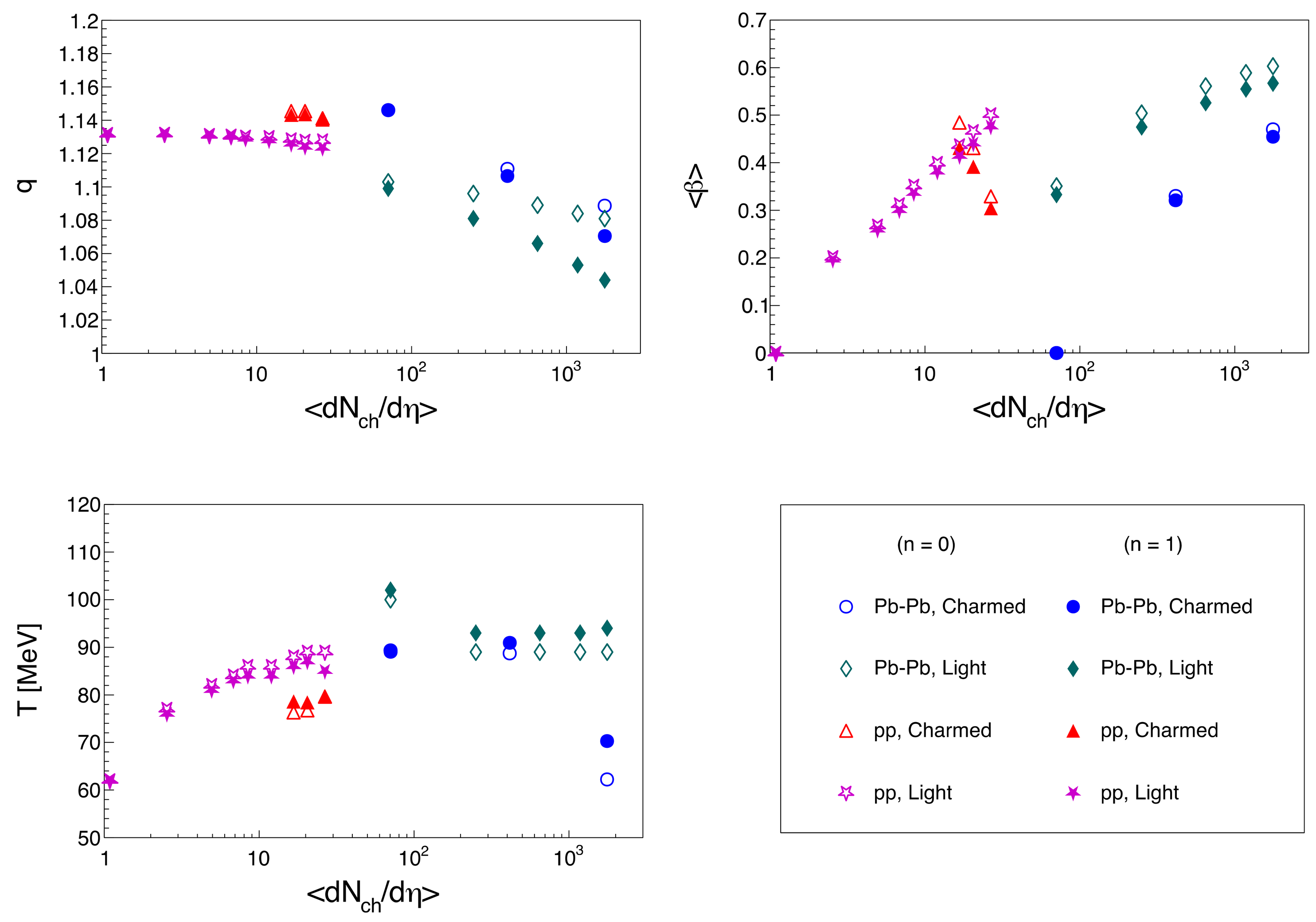

Fig. 3 – TBW parameters as a function of the average multiplicity of charged particles. The colliding systems studied are Pb-Pb 5.02 TeV and pp 13 TeV. Error bars have been omitted to improve visualization.

References

[1] C. Tsallis, J Stat Phys, vol. 52, 1988.
[2] Zebo Tang, Yichun Xu, Lijuan Ruan, Gene van Buren, Fuqiang Wang, and Zhangbu Xu. Physical Review C, 79 (2009) 051901
[3] ALICE Collaboratiion, JHEP 01 (2022) 174
[4] ALICE Collaboratiion, PLB 827 (2022) 136986
[5] ALICE Collaboratiion, PLB 839 (2023) 137796
[6] ALICE Collaboration, JHEP 10 (2018) 174
[7] ALICE Collaboratiion, PLB 829 (2022) 137065
[8] Guorong Che, Jinbiao Gu, Wenchao Zhang, and Hua Zheng. J. Phys. G: Nucl. Part. Phys. 48 (2021) 095103
[9] Jinbiao Gu, Chenyan Li, Qiang Wang, Wenchao Zhang, and Hua Zheng. J. Phys. G: Nucl. Part. Phys. 49 (2022) 115101
[10] ALICE Collaboratiion, Eur.Phys.J. C79 (2019) 857
[11] ALICE Collaboratiion, Physical Review Letters, 116(2016) 222302

Financial Support

FAPESP – São Paulo Research Foundation