Study the particle transverse-momentum spectra at LHC with nonextensive statistics

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Abstract

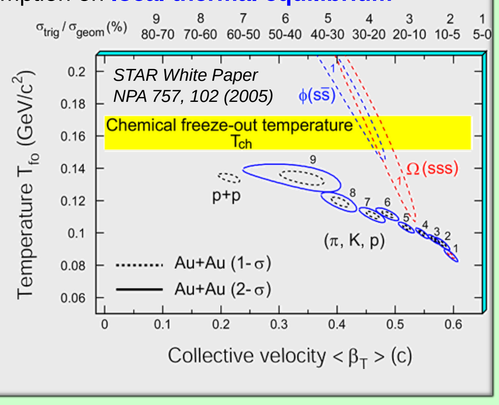
The hydrodynamics-inspired thermal approach - Blast-Wave (BW) model - implemented with non-equilibrium Tsallis statistics has gained increasing interest (and application) in high-energy heavy-ion physics. The transverse-momentum spectra at LHC, from both p+p and Pb+Pb collisions, are systematically studied within the Tsallis Blast-Wave model. Good agreement between the data and the fit is achieved over a broad kinetic range, upto 10 GeV/c for $p+p$ collisions from 200 to 7000 GeV, and upto 5 GeV/c for Pb+Pb collisions at 2.76 TeV. The kinetic freeze-out temperature T, the average radial flow velocity $\langle\beta\rangle$ and the parameter q, which is a measure of the degree of non-equilibrium of the system, are extracted from the fit. The evolution of these parameters with collision energy and centrality will be presented. A detailed fit to non-strange, single-strange and multi-strange particle species separately will be also given. Together with the observations at lower energy, the physics implication of the particle production during the fireball evolution in heavy-ion collisions will be discussed.

Blast-Wave Model

- A Hydrodynamics-inspired model based on Boltzmann-Gibbs statistics
- Describes the p_T spectra of various particle species in heavy-ion collisions with a compact set of parameters $(T, \langle\beta\rangle)$

$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right), \quad \rho = \tanh^{-1}\beta(r)$$

- **Limitations**: strong assumption on **local thermal equilibrium**
  - Limited p_T range
  - Arbitrary choice of the fit range
  - Flow velocity on 0.2c in $p+p$ collisions at 200 GeV
  - Unable to describe the evolution from p+p to peripheral and central heavy-ion collisions



Tsallis Statistics

Tsallis Entropy: Generalization of the standard Boltzmann-Gibbs entropy introduced by Constantino Tsallis in 1988.

$$S_q = \frac{1-\sum_i p_i^q}{q-1} \xrightarrow{q\to 1} S_{BG} = -\sum_i p_i \ln p_i$$

C. Tsallis, J. Stat. Phys. 52, 479 (1988)

Non--additive: Nonextensive

$$S_q(A+B) = S_q(A) + S_q(B) + (1-q)S_q(A)S_q(B)$$

Parameter q is a measure of the nonextensivity in the system

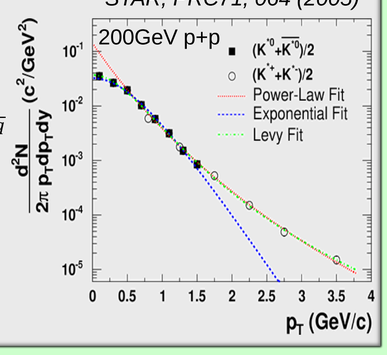
Tsallis distribution:

$$exp_q\left(-\frac{m_T}{T}\right) = \left[1+(1-q)\left(-\frac{m_T}{T}\right)\right]^{\frac{1}{1-q}}$$

$$exp_q\left(-\frac{m_T}{T}\right) \xrightarrow{q\to 1} exp\left(-\frac{m_T}{T}\right)$$

Levy function: $\left(1+\frac{m_T}{nT}\right)^{-n}$

STAR, PRC71, 064 (2005)



Tsallis Blast-Wave Model

Implement the Tsallis statistics, generalization of the Boltzmann-Gibbs statistics, in the Blast-Wave model.

The single-particle spectrum can be written as:

$$\frac{d^2N}{2\pi m_T dm_T dy}|_{y=0} = A\int_{-y_b}^{+y_b} e^{\sqrt{y_b^2-y_s^2}} m_T \cosh(y_s)\, dy_s \int_0^R r dr \int_{-\pi}^{\pi}\left[1+\frac{q-1}{T}E_T\right]^{-1/(q-1)} d\phi.$$

$$E_T = m_T\cosh(y_s)\cosh(\rho) - p_T\sinh(\rho)\cos(\phi)$$

$$m_T = \sqrt{p_T^2+m^2}$$

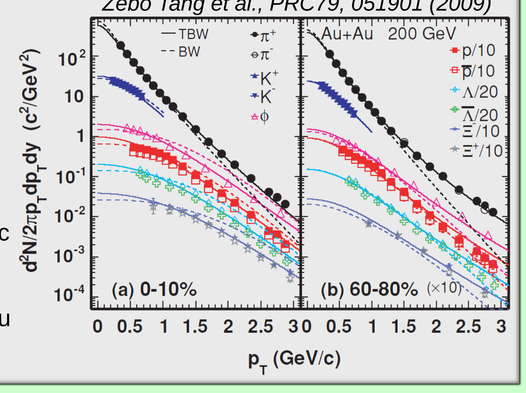
$$y_b = \ln\left(\sqrt{s_{NN}}/m_N\right)$$

Simultaneously fit the spectrum of 11 particle species

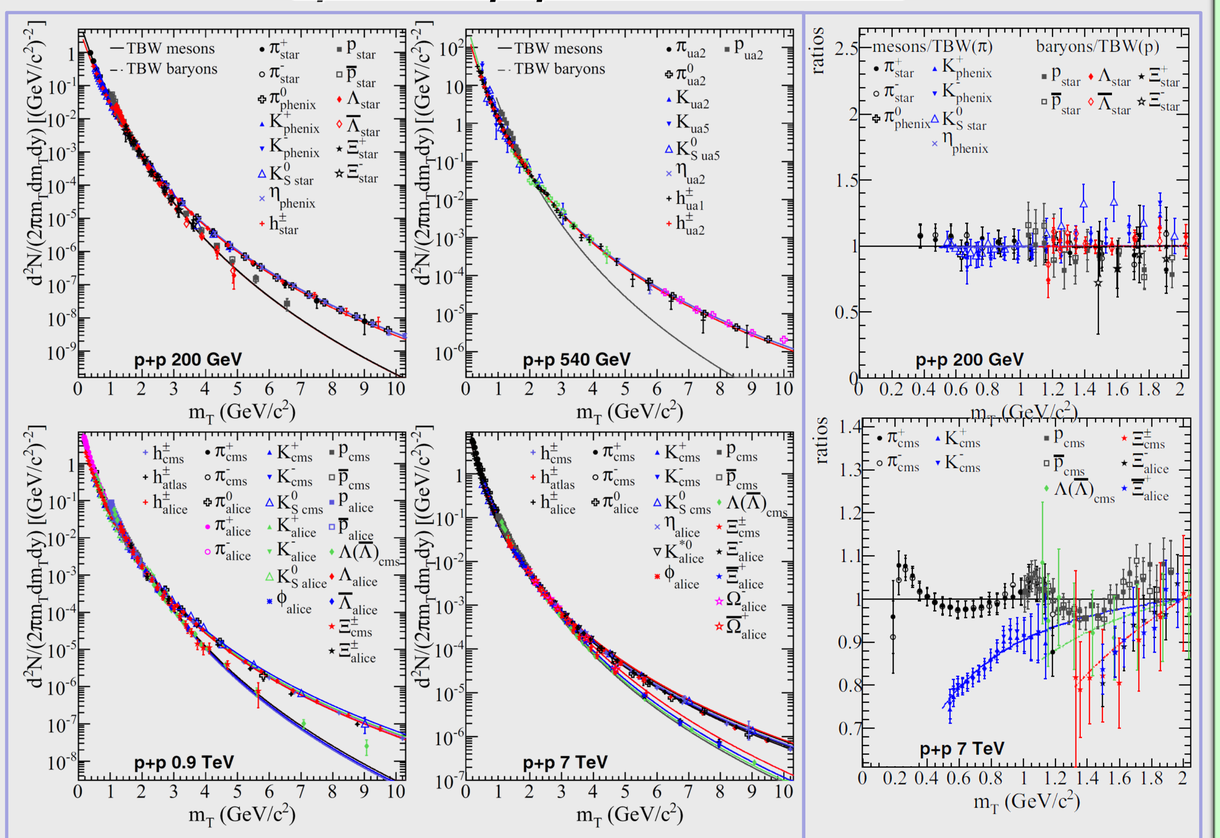
BW: Fails above 1 GeV/c

TBW: Describes upto 3 GeV/c in 200 GeV Au+Au

Zebo Tang et al., PRC79, 051901 (2009)



Spectra in p+p from RHIC to LHC



Identified particle m_T spectra in p+p collisions at 200, 540, 900 and 7000 GeV. The symbols depict experimental measurements from STAR, PHENIX, UA1, UA2, UA5, E735, CMS, ALICE, ATLAS and CMS collaborations. The curves represent the TBW fit results. The data points and curves are rescaled to π^+ at m_T=2 GeV/c².

m_T scaling test of the identified particle spectra in p+p collisions. The reference is π^+ and p for mesons and baryons, respectively.

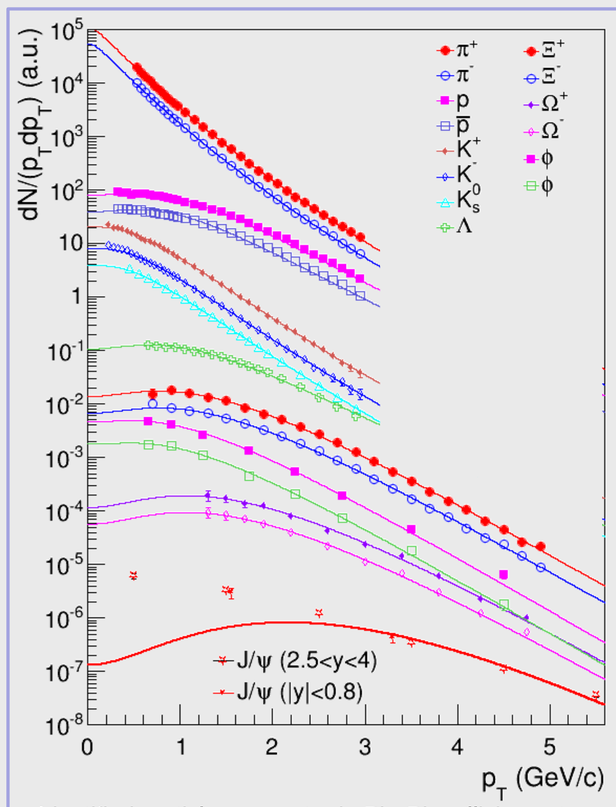
Summary of parameters

$\sqrt{s}$	$\langle\beta\rangle$	T (MeV)	$q_M - 1$	$q_B - 1$	χ^2/ndf
7 TeV	0.320 ± 0.005	70.3 ± 0.8	0.1314 ± 0.0003	0.1035 ± 0.0008	490/431
900 GeV	0.264 ± 0.005	74.6 ± 0.5	0.1127 ± 0.0003	0.0827 ± 0.0008	545/501
540 GeV	$0.000^{+0.105}_{-0.000}$	81.8 ± 0.6	0.1158 ± 0.0007	0.0841 ± 0.0036	205/168
200 GeV	$0.000^{+0.124}_{-0.000}$	92.3 ± 2.7	0.0946 ± 0.0006	0.0743 ± 0.0015	268/268

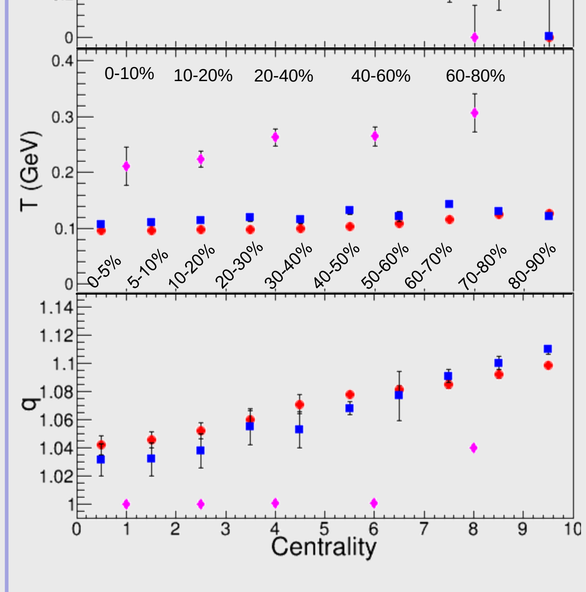
Kun Jiang, Yinying Zhu, Weitao Liu, , Hongfang Chen, Cheng Li, Lijuan Ruan, Zebo Tang and Zhangbu Xu, PRC91, 024901 (2015) arXiv: 1312.4230

- The TBW model describes the shape of the m_T spectra of more than 10 particle species over a broad m_T range of 0-10 GeV/c² with only 4 common parameters!
- Grouping of baryons and mesons at high-m_T. Mesons and Baryons require different parameter q.
- No radial flow in p+p collisions at 200 GeV and 540 GeV. Spectra follow the m_T scaling.
- Significant radial flow velocity in p+p collisions at LHC energies. $\langle\beta\rangle = 0.264 \pm 0.005$ and 0.320 ± 0.005 for 900 GeV and 7000 GeV collisions, respectively.
- Comparable to 0.320 ± 0.005 in 40-60% Au+Au collisions at 200 GeV.
- Supported by the breaking of m_T scaling.

Spectra in Pb+Pb at LHC



Identified particle p_T spectra in Pb+Pb collisions at 2.76 TeV. Pions, Kaons, protons and Λs are fit simultaneously upto 3 GeV/c. Multi-strange mesons and baryons are fit simultaneously upto 5 GeV/c. The curve for J/ψ is a prediction based on the fit to multi-strange particles.



Extracted parameters, mean radial flow velocity, freezeout temperature and q, as a function of centrality in Pb+Pb collisions at 2.76 TeV, for three different groups of particles.

Summary of parameters from the fit to SPS and RHIC data

	Pb+Pb at 158 A GeV			Au+Au at 200 GeV		
	All	Strange	Non-strange	All	Strange	Non-strange
$\langle\beta\rangle$ (c)	0.426±0.004	0.420±0.007	0.442±0.005	0.472±0.009	0.464±0.006	0.463±0.012
T (GeV)	0.113±0.001	0.119±0.004	0.109±0.001	0.122±0.003	0.150±0.005	0.107±0.004
$q-1$	0.015±0.001	0.009±0.004	0.015±0.001	0.017±0.006	0.000±0.002	0.039±0.006
χ^2/nDoF	267/159	137/70	102/86	140/155	51/99	43/53

Ming Shao, Li Yi, Zebo Tang, Hongfang Chen, Cheng Li and Zhangbu Xu, J. Phs. G 37, 085104 (2010)

- The TBW model describes the shape of the p_T spectra of more than 6 particle species over a broad p_T range with only 3 common parameters!
- Non-strange and single-strange particles has similar radial flow velocity, freezeout temperature and parameter q.
  - Radial flow velocity increases with beam energy.
  - Beam energy dependence of T and q-parameter is weak.
- Multi-strange particles:
  - Radial flow velocity: similar as non- and single-strange particles.
  - Freezeout temperature: significantly higher than non- and single-strange particles. significantly higher than at SPS and RHIC.
  - q-parameter: significantly lower than non- and single-strange particles. consistent with Boltzmann distribution in central and semi-central collisions.

Summary:

- TBW describes identified particle spectra in p+p and Pb+Pb at LHC.
- Parameters of radial flow, temperature and q are extracted.
- Significant radial flow found in p+p collisions at LHC energy.
- Results in Pb+Pb at LHC follows the trend from SPS to RHIC.

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