How far can we see back in time in high-energy collisions using charm quarks?

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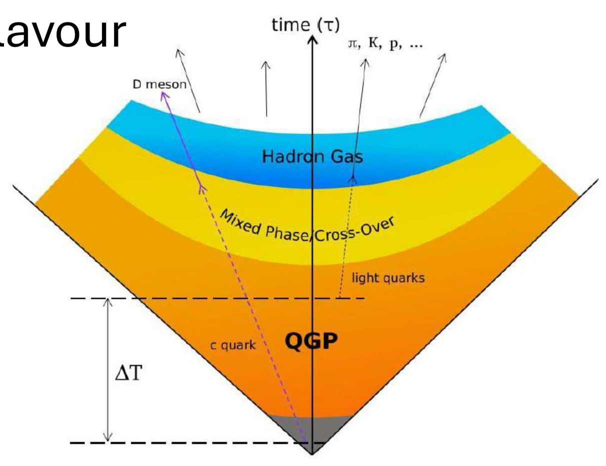
Motivation

- In high-energy collisions light-flavour and strange hadrons mostly carry information about the final state
- Heavy-flavour *c* and *b* quarks are produced in the initial stages of a collision and experience the whole evolution of the system
- Measurement of heavy-flavour hadron production allows for studying the earlier stages of a collision

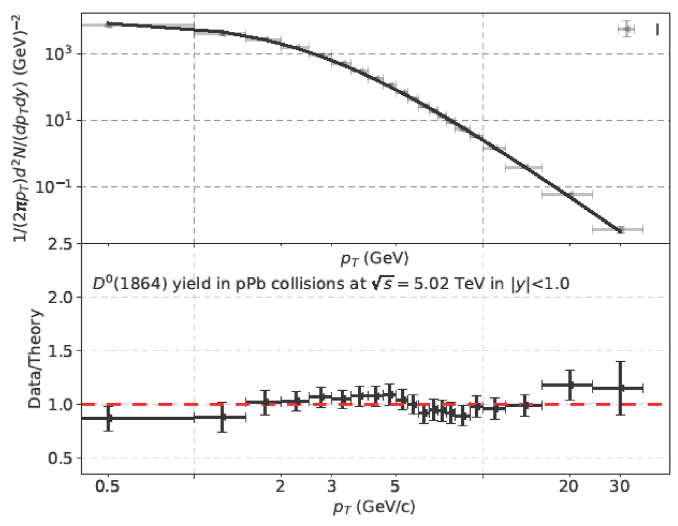
- The non-extensive Tsallis – Pareto statistical framework[1] has been shown to describe well the spectra of light-flavour hadrons[2]
- In this work we evaluate applicability of non-extensive thermodynamical principles on heavy-flavour production
- We use D mesons to investigate the thermo-dynamical properties of earlier stages of the system



Method

Low-p_T part of spectrum:
- Boltzmann – Gibbs distribution
- characterized by the kinetic freeze-out temperature

High-p_T part of spectrum:
- power-law distribution
- perturbative QCD hadron production



The Tsallis – Pareto distribution, motivated by non-extensive thermodynamics, provides a unified description of the full spectrum:

$$\left.\frac{\mathrm{d}^2N}{2\pi p_T \mathrm{d}p_T \mathrm{d}y}\right|_{y\approx 0} \equiv A m_T f^q = A m_T \left[1+\frac{q-1}{T}(m_T-\mu)\right]^{-\frac{q}{q-1}}$$

Spectra used in this analysis

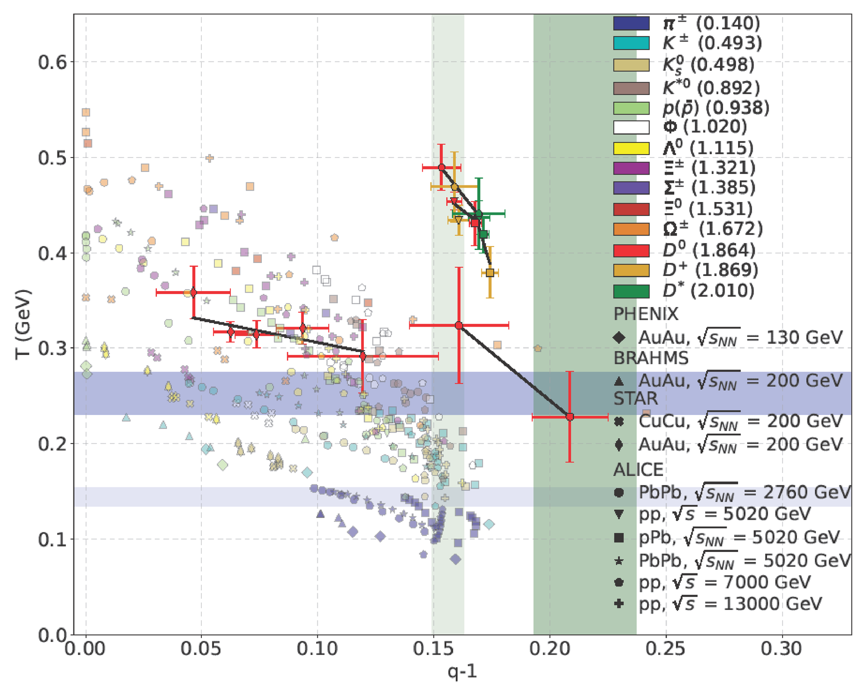
STAR experiment:
- D^0 in Au–Au collisions at $\sqrt{s_{NN}}$ =200 GeV

ALICE experiment:
- D^0 in Pb–Pb collisions at $\sqrt{s_{NN}}$ =2.76 TeV
- D^0, D^+ and D^{*+} in p–Pb collisions at $\sqrt{s_{NN}}$ =5.02 TeV
- D^0, D^+ and D^{*+} in pp collisions at $\sqrt{s}$ =5.02 TeV
- D^0, D^+ and D^{*+} in pp collisions at $\sqrt{s}$ =7 TeV

Light-flavour and strange hadron spectra are from references in [1]

Tsallis-thermometer

The *T* and *q* parameters, extracted from the D-meson fits, are presented in the „Tsallis-thermometer", *T* – (*q*-1) diagram



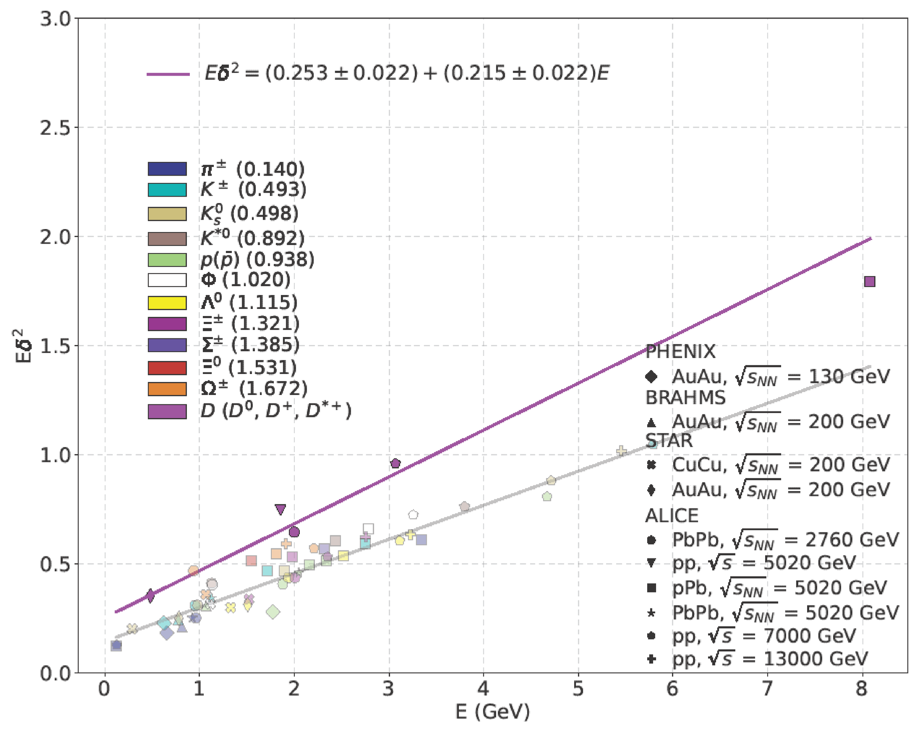
Observations:
- mass hierarchy (*T* increases with particle mass and multiplicity)
- grouping based on the center-of-mass energy and collision system
- in small systems *c* quarks come directly from the early stages of the collisions, corresponding to high *T* values
- grouping of all the hadrons at small multiplicities around specific common T_{eq} and q_{eq} values

Common Tsallis parameters

Tsallis parameters can be defined from the fluctuations of the number of the produced particles: $T = \frac{E}{\langle n \rangle}$, $q = 1 - \frac{1}{\langle n \rangle} + \frac{\Delta n^2}{\langle n \rangle^2}$, $\delta^2 := \frac{\Delta n^2}{\langle n \rangle^2}$

This leads to an energy-dependent linear correlation between the Tsallis parameters: $T = E(\delta^2 - (q-1))$

Observations from the $E - E\delta^2$ diagram:
- relative size of multiplicity fluctuations is larger for D mesons compared to the light-flavour hadrons
- fitted *E* values increase with decreasing system size



The common Tsallis parameters were determined by fitting D-meson points with the inverted equation $E\delta^2 = T - (q-1)E$

Obtained values:

T_D=0.253±0.022 GeV T_{LF}=0.144±0.010 GeV
q_D=1.215±0.022 q_{LF}=1.156±0.007

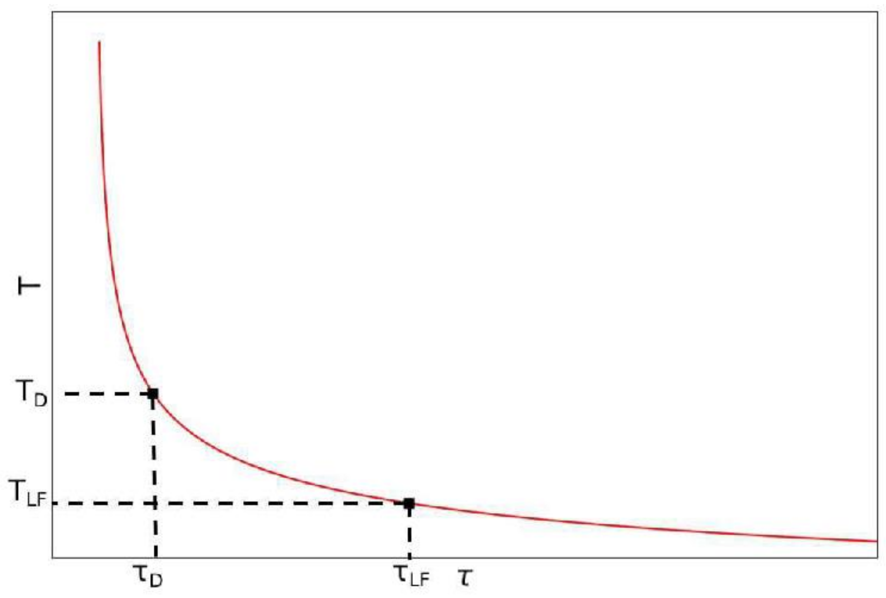
How far can we see back in time?

A simple Bjorken model can be utilized as the expansion mechanism of the ideal, ultra-relativistic matter. It yields the relation between temperature and proper time (cooling curve) [2]: $\tau = \tau_0 \left(\frac{T_0}{T}\right)^3$

Assuming the same initial conditions for light- and heavy-flavour hadrons: $\tau_D = \tau_{LF}\left(\frac{T_{LF}}{T_D}\right)^3$

By substituting the common Tsallis-temperatures we obtain:

$$\tau_D = (0.18 \pm 0.06)\tau_{LF}$$



Summary

- Transverse momentum distributions of heavy-flavour D mesons are well described by the Tsallis – Pareto distribution motivated by non-extensive thermodynamics
- The Tsallis parameters of the fits to D-meson data exhibit a scaling behaviour with charged particle multiplicity and with the collision energy
- The T_{eq} parameter for D mesons is higher compared to the light flavours. Coming from a much hotter state of the system, D mesons preserve this information, unlike the light-flavour hadrons
- Production of D mesons corresponds to a significantly earlier proper time than light-flavour hadrons. Based on the Bjorken expansion, we estimated it as $\tau_D = (0.18 \pm 0.06)\tau_{LF}$

References

[1] Eur.Phys.J.A 40 (2009) 257-266
[2] J. Phys. G, 47(10):105002, 2020
[3] Phys. Rev. C, 97(6):064903, 2018

Acknowledgements

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Full paper