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

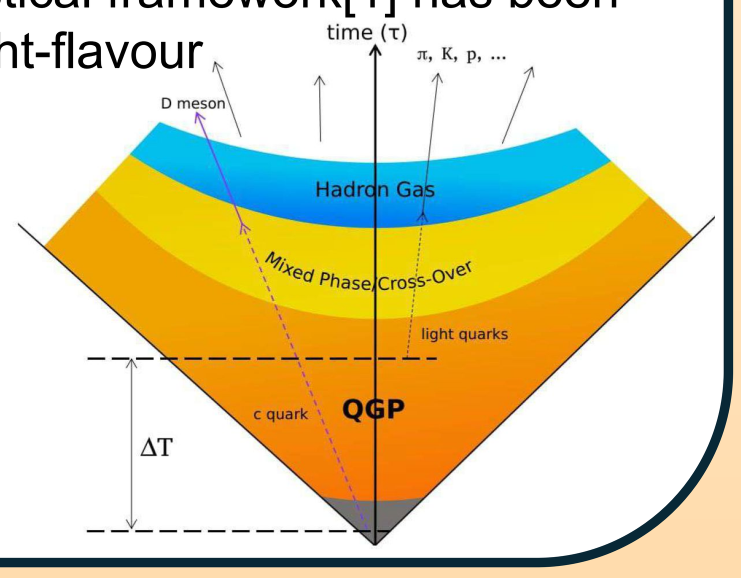
László Gyulai[1,2], Gábor Bíró[2,3], Róbert Vértesi[2], and Gergely Gábor Barnaföldi[2]

[1]Budapest University of Technology and Economics [2]HUN-REN Wigner Research Centre for Physics [3]ELTE Eötvös Loránd University

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 thermodynamical properties of earlier stages of the system



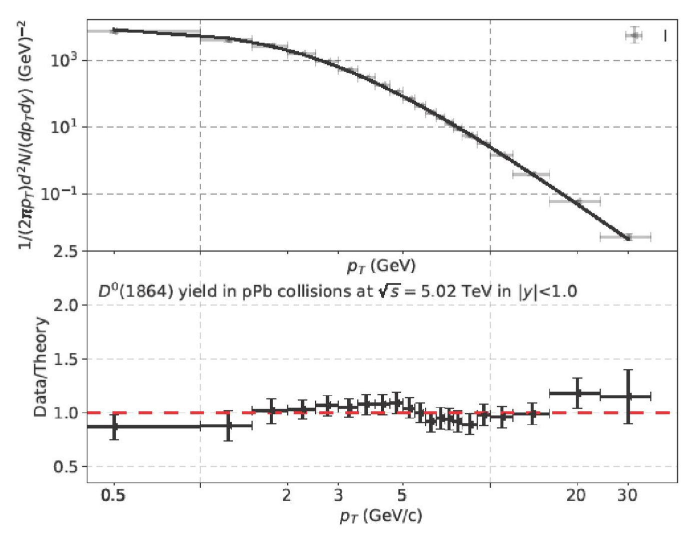
Method

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:

$$\left.\frac{\mathrm{d}^2N}{2\pi p_{\mathrm{T}}\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right|_{y\approx0} \equiv Am_T f^q = Am_{\mathrm{T}}\left[1+\frac{q-1}{T}(m_{\mathrm{T}}-\mu)\right]^{-\frac{q}{q-1}}$$

Spectra used in this analysis

STAR experiment:

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

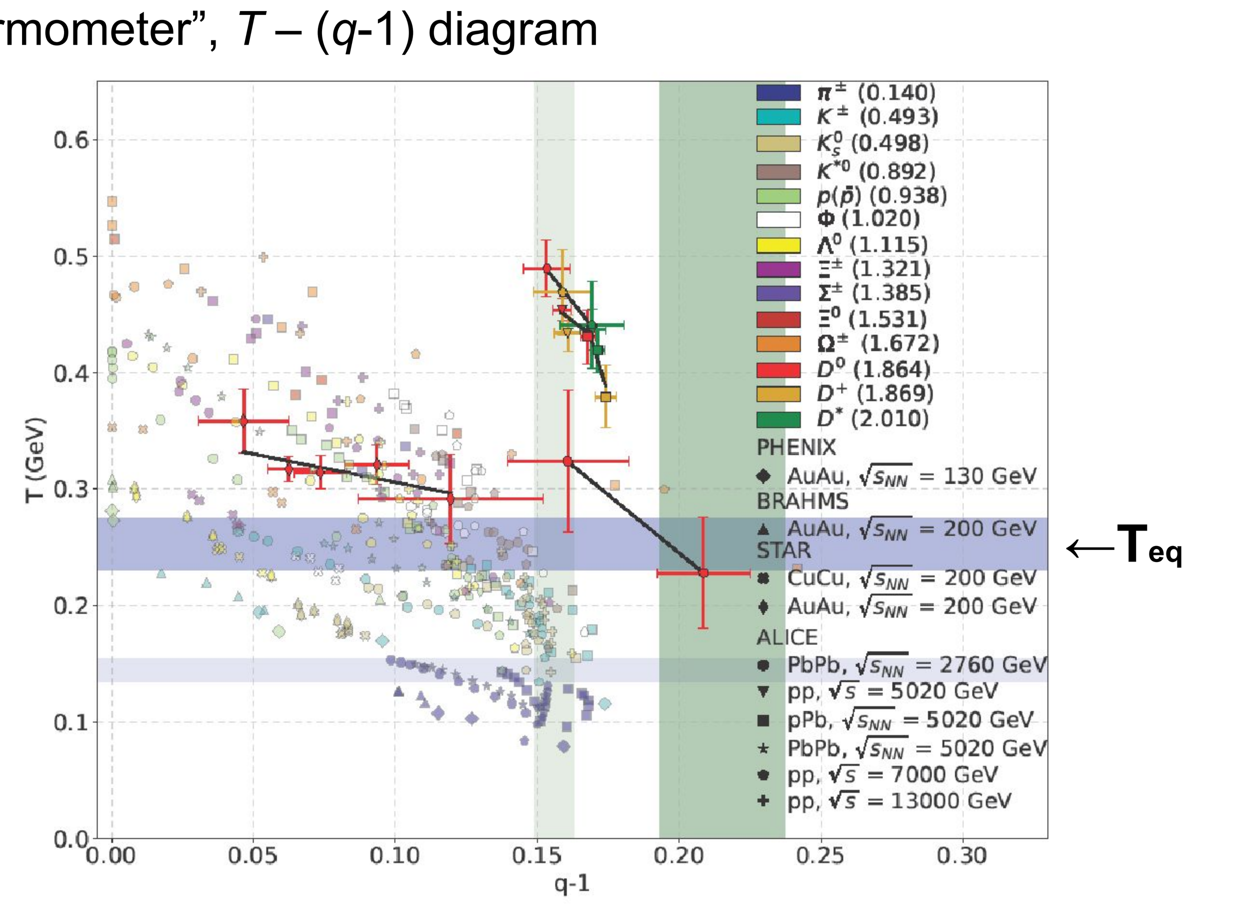
ALICE experiment:

- 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 [2]

Tsallis-thermometer

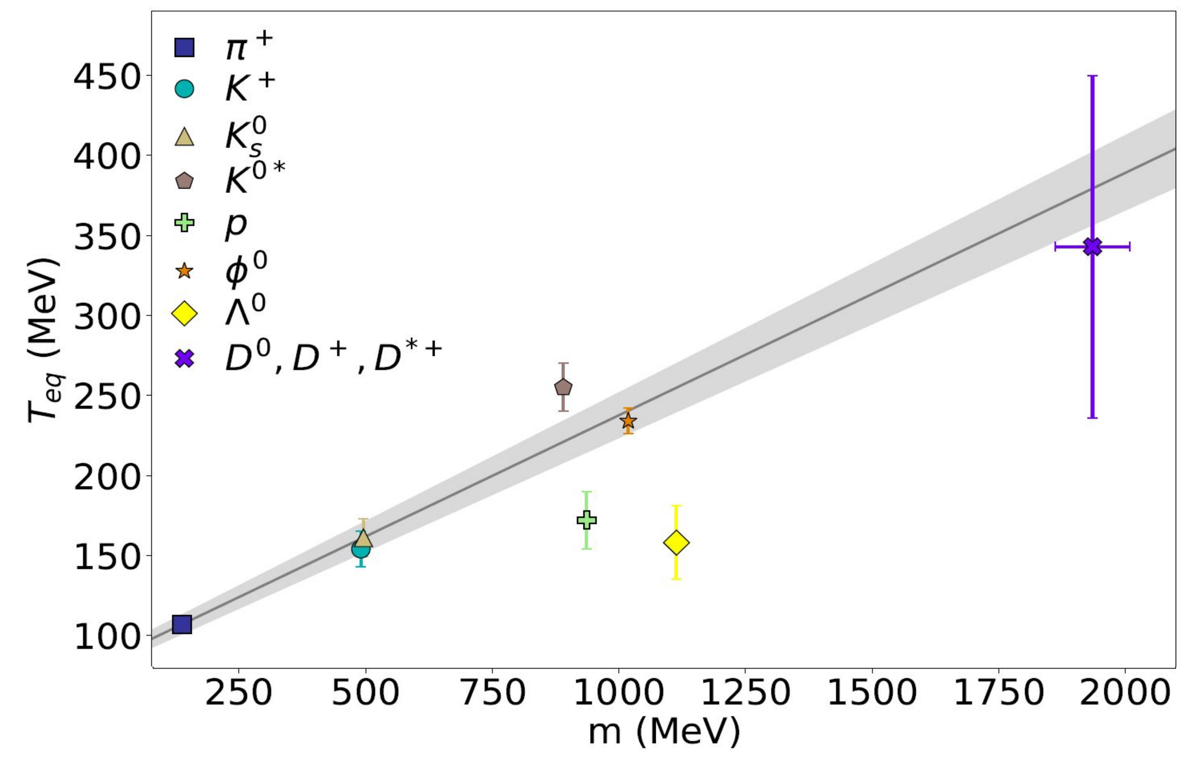
The *T* and *q* parameters, extracted from the D-meson fits, are presented in the „Tsallis-thermometer", *T* – (*q*-1) diagram



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 temperature

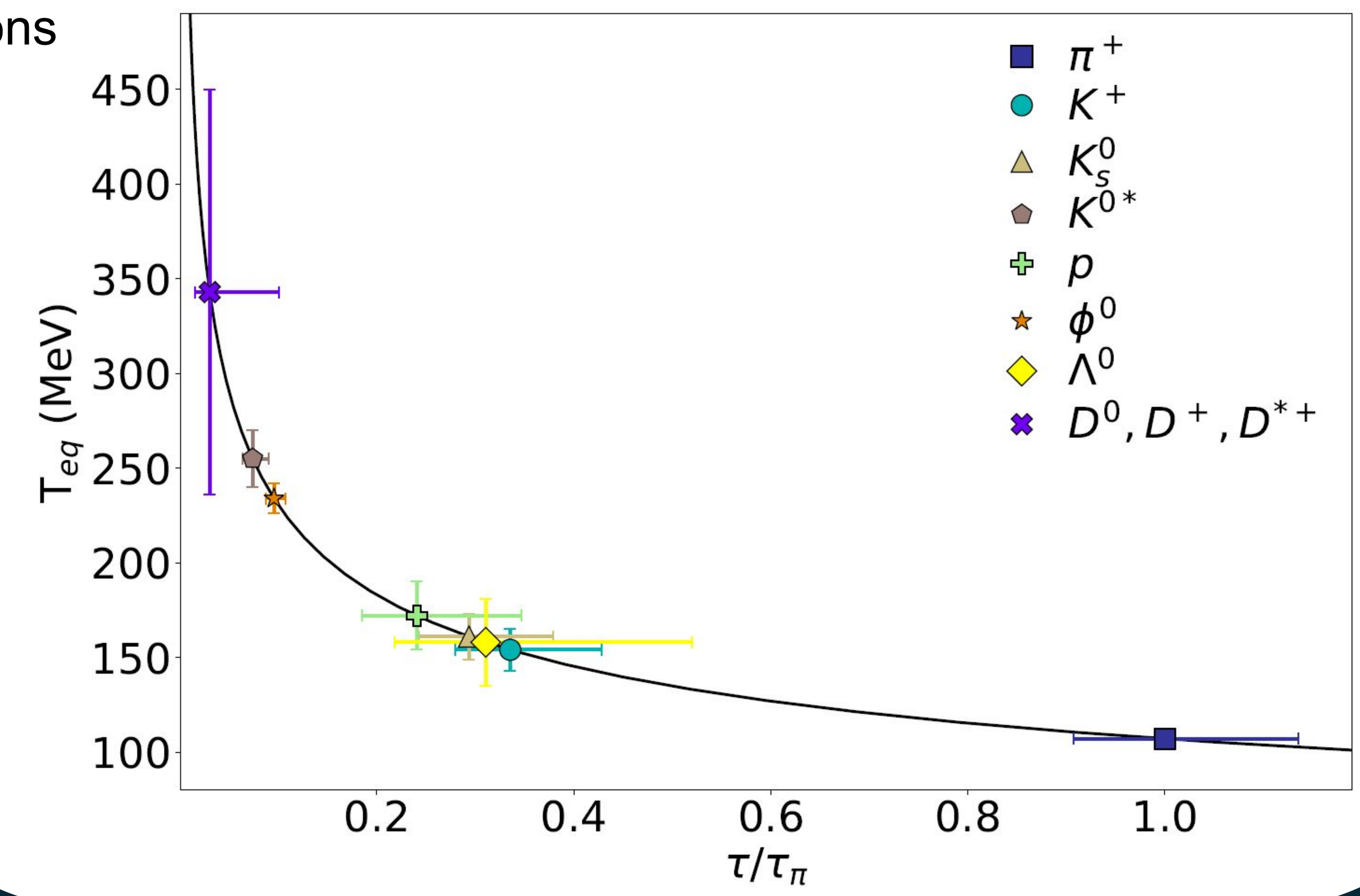


- The common Tsallis temperature increases with the mass of **mesons**
- The common Tsallis temperature of **baryons** is lower compared to the mesons with similar masses

How far can we see back in time?

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

- The spectrum of pions forms much later compared to other hadrons
- Baryons are formed later compared to mesons with similar masses
- The formation time of D-meson spectra is ~30 times shorter than for pions



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. The formation time of meson spectra is also mass-dependent

References

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

Acknowledgements

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Full papers

arXiv:2401.14282 arXiv:2409.01085