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

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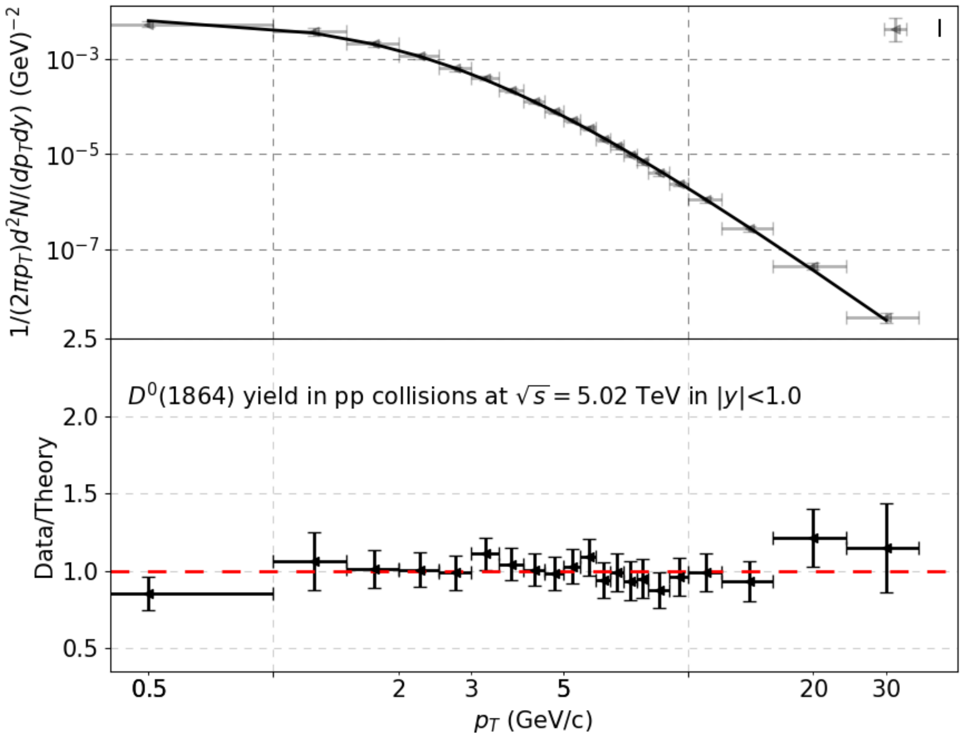
A non-extensive statistical framework

Identified particle spectrum:

- Low-p_T part:
  - soft particle production
  - exponential-like (Boltzmann-Gibbs) distribution
  - stemming from a thermal equilibrium

- High-p_T part:
  - jet-like origin
  - power-law tail distribution
  - described by the perturbative QCD



Tsallis-Pareto distribution smoothly connects the two parts:

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

Motivation for the study

Light-flavoured hadrons (K, π, p, Λ, Φ, Σ, Ξ, Ω) have already been studied in the non-extensive statistical framework in the broad range of collision systems and multiplicities [1]

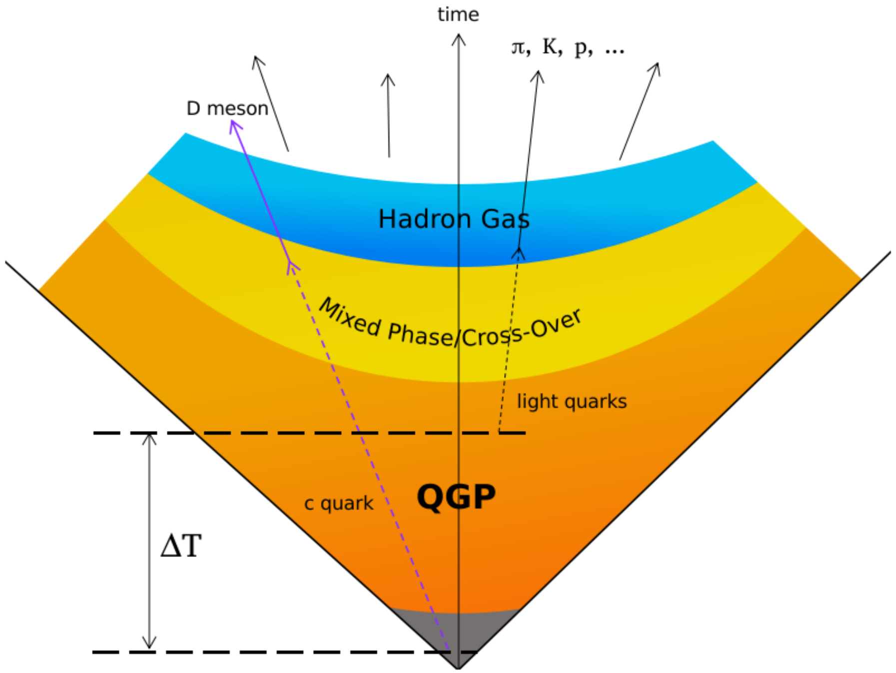
[1] J.Phys.G **47** (2020) 10, 105002

In our latest research [2], we expand the list of studied particles with D mesons (containing *c* quarks), which are produced in the early stages of a collision

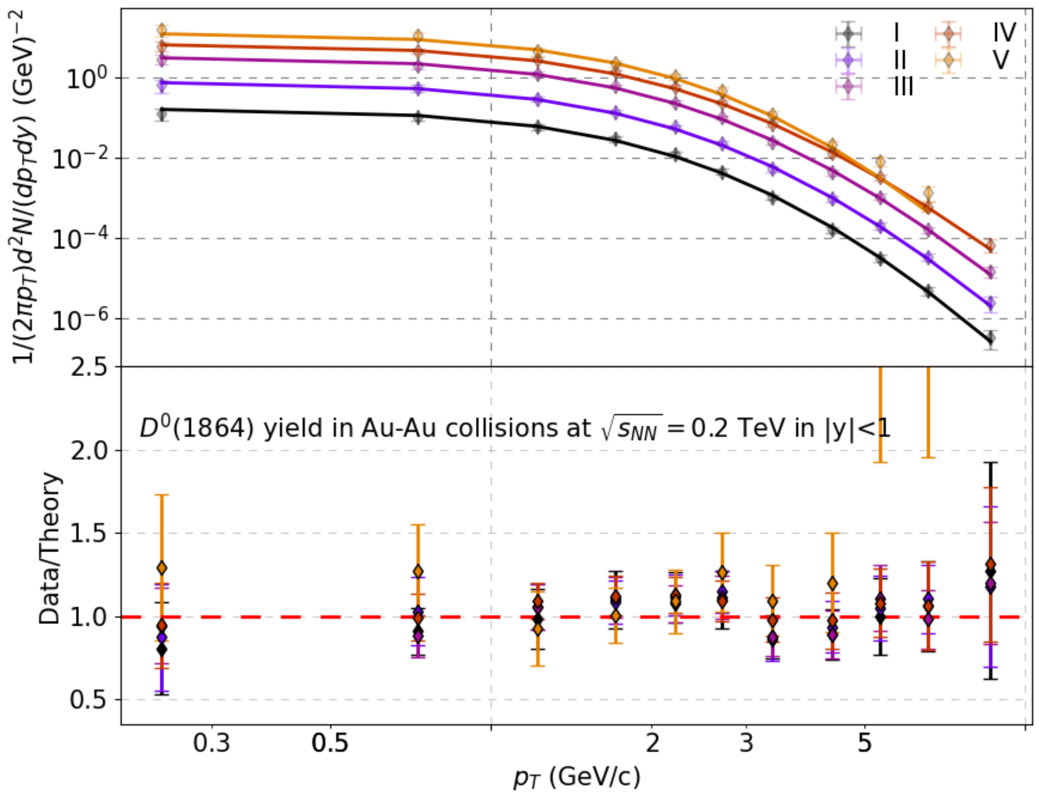
[2] J.Phys.G **51** (2024) 8, 085103

Our aims are:

- check whether D mesons follow the Tsallis-statistics
- find similarities between light and heavy flavours
- find traces of different production timescales



Investigated datasets



Multiplicity-inclusive (minimum bias) spectra:

- ALICE, pp, 5.02 TeV - D^0, D^+, D^{*+}
- ALICE, pp, 7 TeV - D^0, D^+, D^{*+}
- ALICE, pPb, 5.02 TeV - D^0, D^+, D^{*+}

Centrality (multiplicity) dependent:

- ALICE, PbPb, 2.76 TeV - D^0

centralities: 0-20%, 40-80%

- STAR, AuAu, 200 GeV - D^0

centralities: 0-10%, 10-20%, 20-40%, 40-60%, 60%-80%

We compare to the light-flavour hadron spectra from [J.Phys.G **47** (2020) 10, 105002]

Thermodynamical consistency

The investigated Tsallis-statistics satisfies the first law of thermodynamics:

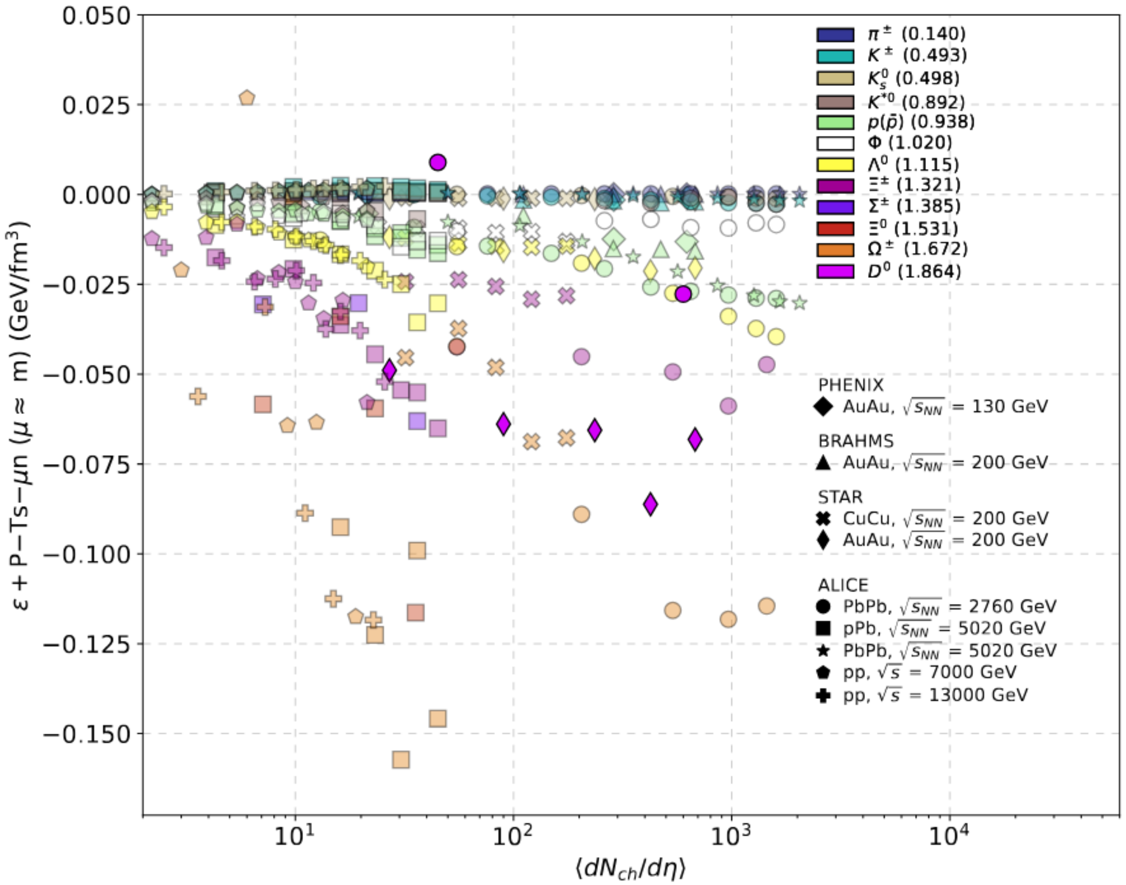
$$\epsilon + P - Ts - \mu n = 0$$

The thermodynamical variables can be expressed with the help of Tsallis-Pareto distribution

The fulfilment of the first law of thermodynamics can be investigated for each of the spectra

In the case of D mesons deviation is below 8%

The Tsallis-Pareto framework shows a significant improvement in description of spectra of all hadron species compared to the Boltzmann-Gibbs statistics



Tsallis-thermometer

Observation: total charged hadron multiplicity in Tsallis theory follows negative binomial distribution

This is also supported by experimental data

Taking fluctuations of the produced particles *n*:

$$T = \frac{E}{\langle n \rangle},$$
$$q = 1 - \frac{1}{\langle n \rangle} + \frac{\Delta n^2}{\langle n \rangle^2}$$

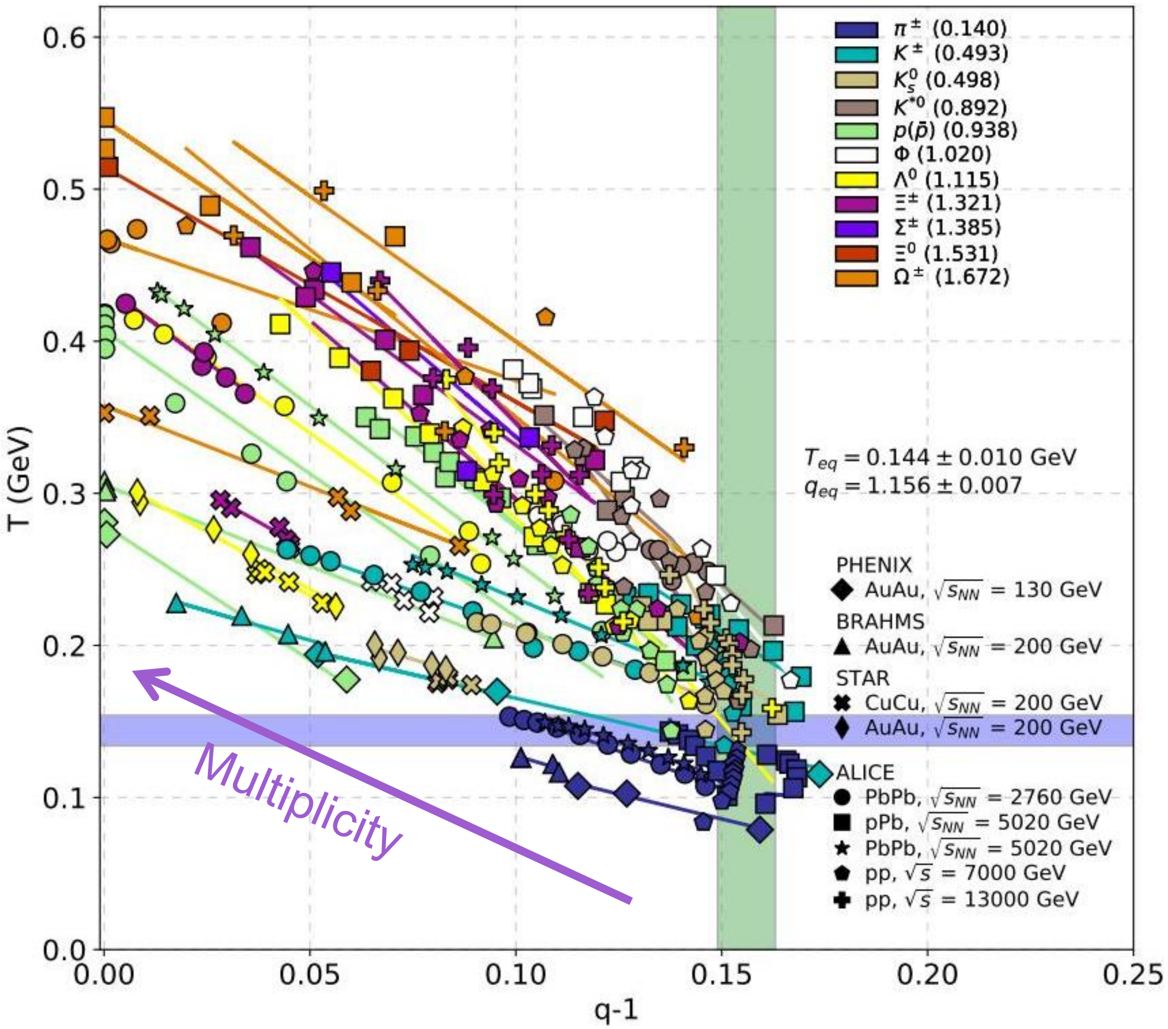
T and *q* are correlated:

$$T = E\left(\delta^2 - (q-1)\right) \qquad \frac{\Delta n^2}{\langle n \rangle^2} := \delta^2$$

Observations for the light flavours

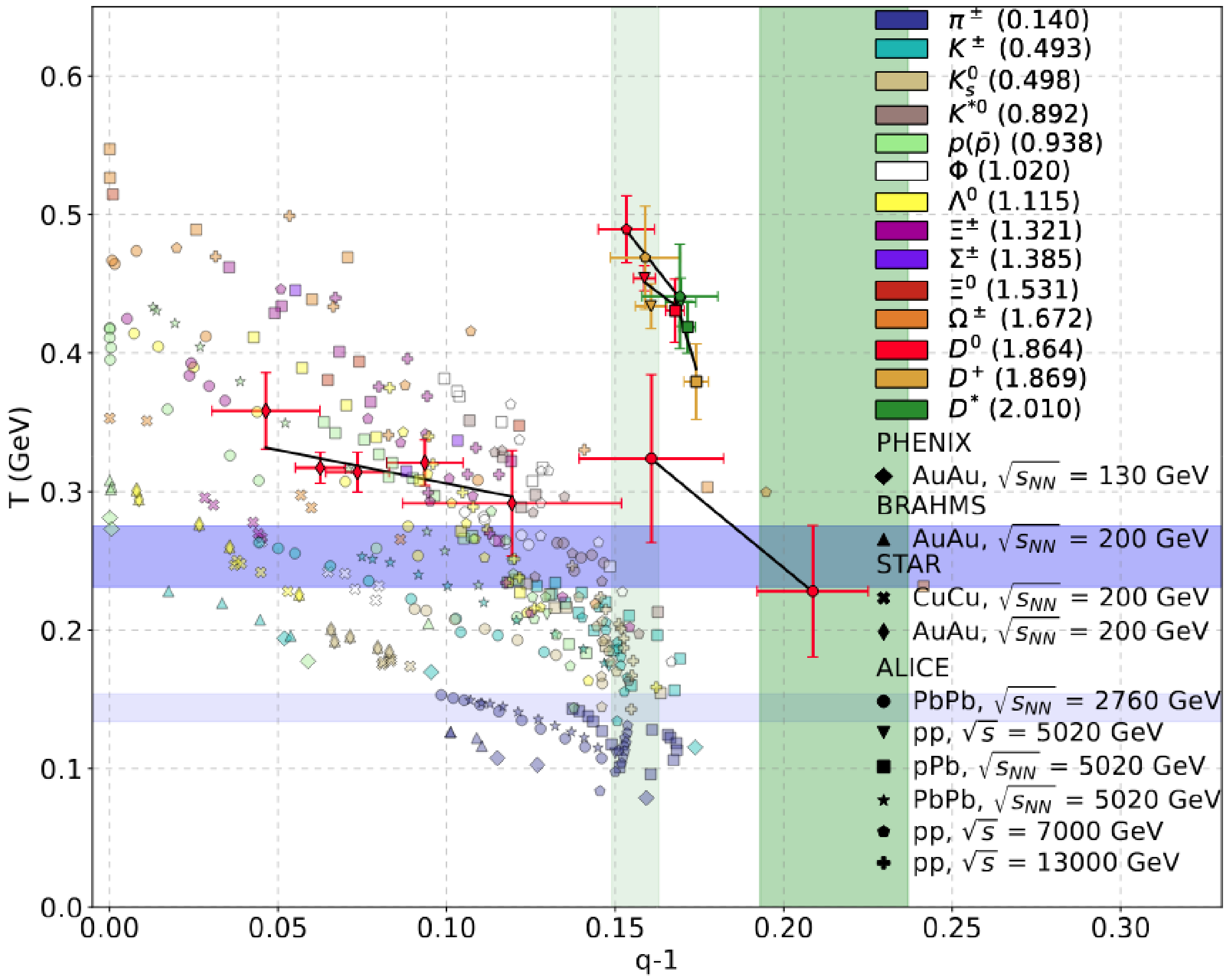
- Strong dependence on event multiplicity
- Mass hierarchy, stronger towards heavier particles
- All points aiming towards $T_{eq} \approx 0.14$ GeV and $q_{eq} \approx 1.15$

$$T = E\left(\delta^2 - (q-1)\right)$$



D mesons in the Tsallis theory

- Strong dependence on event multiplicity
- Mass hierarchy is even stronger, than for light flavours
- Dependence on the collision energy is more prominent, than for the light hadrons
- A grouping is also present, however, the “common point” is shifted compared to the light flavours



$$T = E\left(\delta^2 - (q-1)\right)$$

Tsallis-thermometer

- Th energy (E) of a D-meson system is larger
- Fluctuations (δ^2) are also stronger

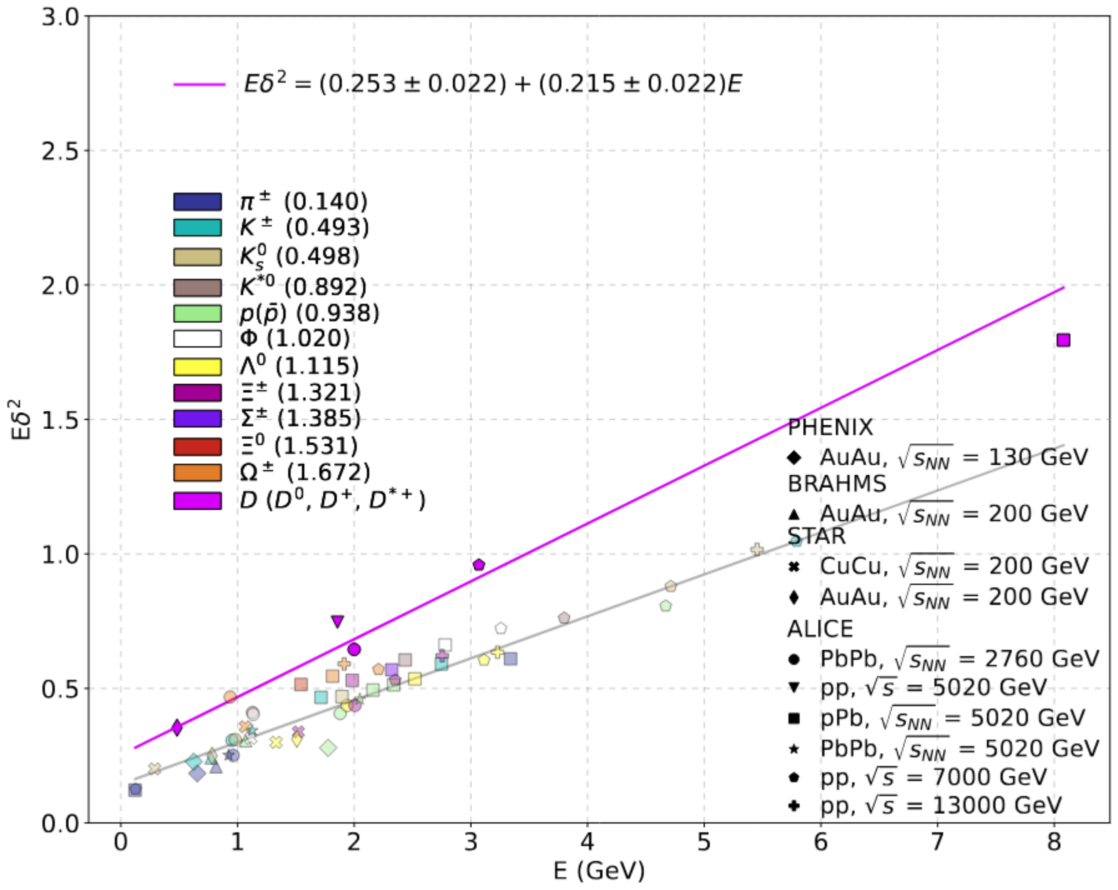
Fitting the E-Eδ^2 points, one can define the “common grouping point” values for the T (offset) and q (slope) parameters.

$$T = E\left(\delta^2 - (q-1)\right) \qquad \frac{\Delta n^2}{\langle n \rangle^2} := \delta^2$$

Light flavours: T_{eq}≈0.14 GeV and q_{eq}≈1.15

Heavy flavours: T_{eq}≈0.25 GeV and q_{eq}≈1.21

The spectra of heavy flavours exhibit higher temperature and stronger non-extensivity
ΔT_{eq}≈0.11 GeV
Δq_{eq}≈0.06



The timescale of light-flavour and heavy-flavour hadron production

The Bjorken-model gives an opportunity to connect temperatures and timescales:

$$\tau = \tau_0 \left(\frac{T_0}{T}\right)^3$$

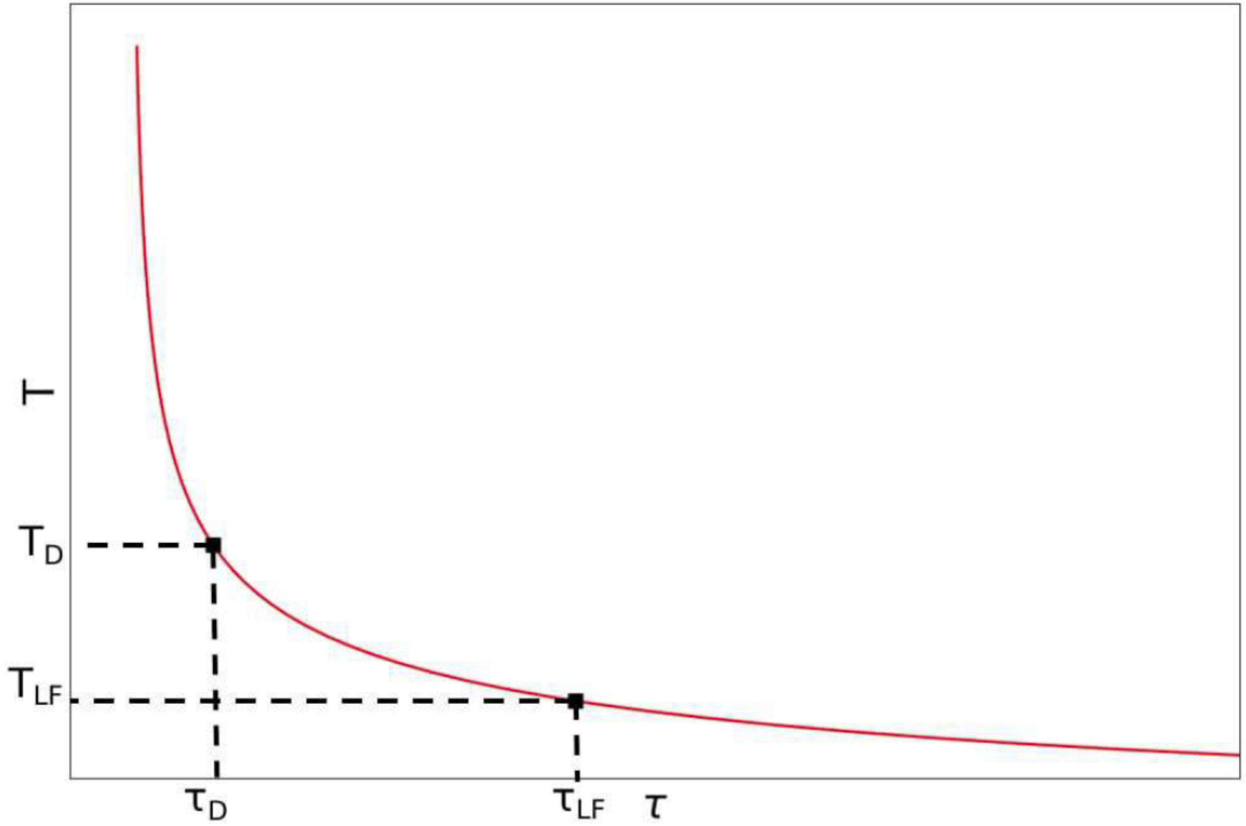
This model is independent of thermodinamical description

With this one can express the relation between the D-meson and light-flavour production timescales:

$$\tau_{\mathrm{D}} = \tau_{\mathrm{LF}} \left(\frac{T_{\mathrm{LF}}}{T_{\mathrm{D}}}\right)^3$$

Substituting the T_{eq} values:

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



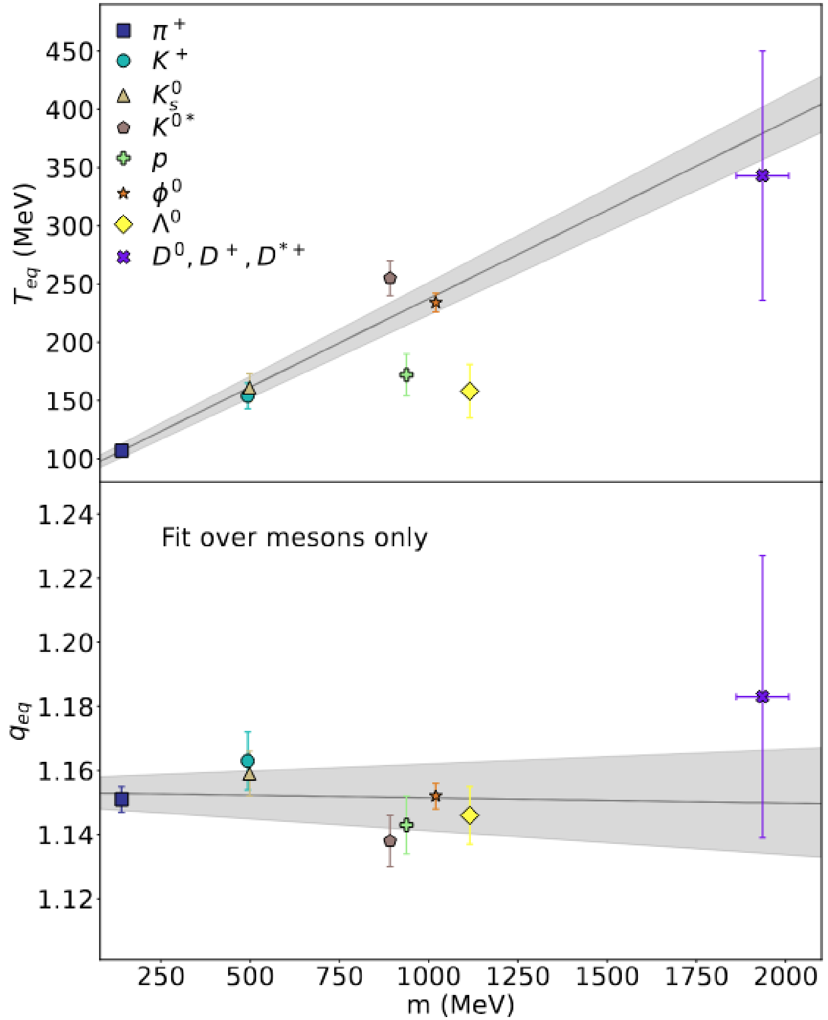
Investigation of hadrons by species (new results, just LHC data)

Submitted to IJMPA, preprint: arXiv:2409.01085

The temperature of the "common grouping point" increases with the mass of mesons

The temperature of the "common grouping point" of baryons is lower compared to the mesons with similar masses

The non-extensivity value of the "common grouping point" does not show any significant mass dependance



Investigation of hadrons by species (new results, just LHC data)

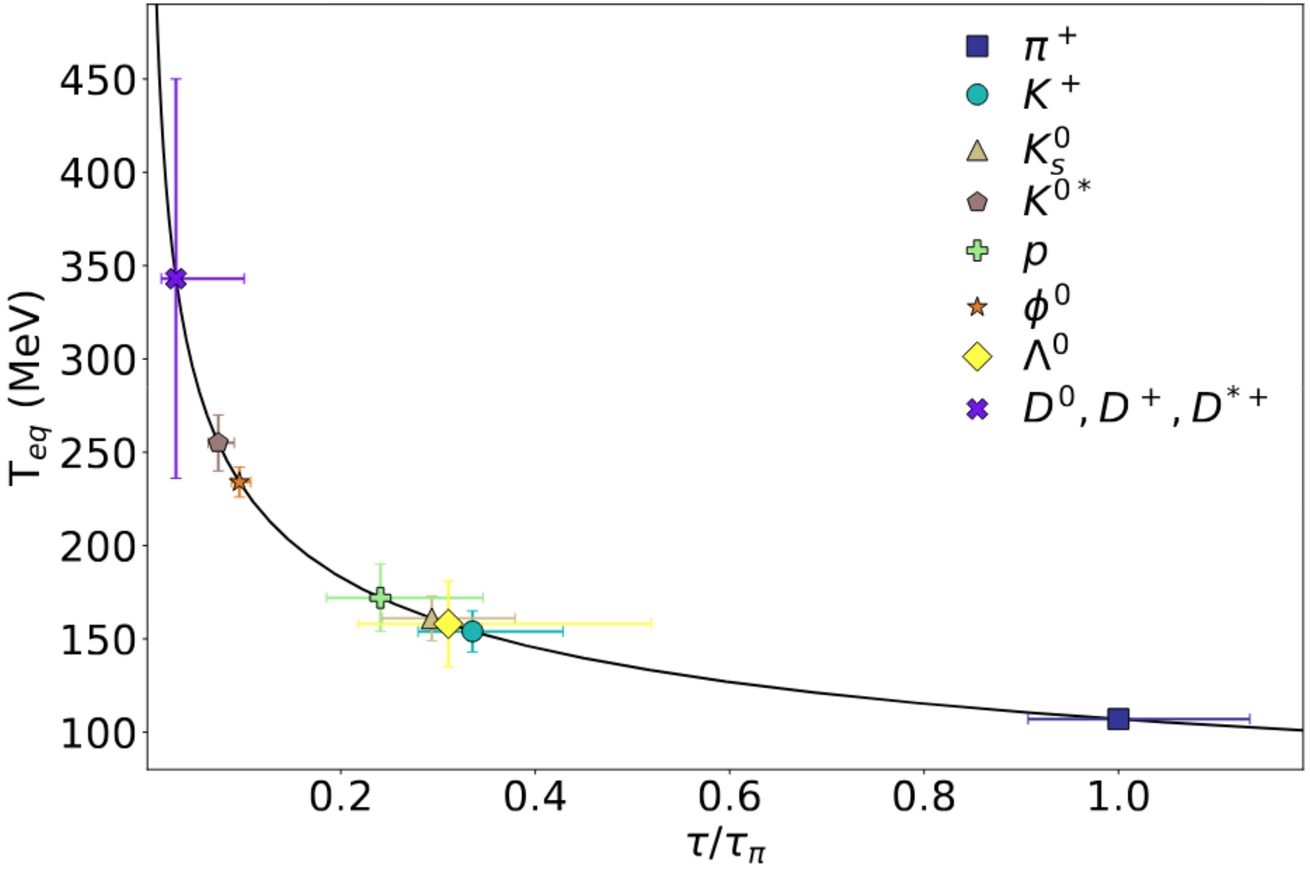
Submitted to IJMPA, preprint: arXiv:2409.01085

The spectrum of pions forms much later compared to other hadrons

Spectra of lighter mesons are formed later than the spectra of heavier mesons

Heavier baryons are formed later compared to the mesons with similar masses

The formation time of D-meson spectra is ~30 times shorter than for pions



Summary

- We expanded the non-extensive statistical model with D mesons
- We investigated the D-meson spectra obtained in the ALICE and the STAR experiments: from pp, p-A, A-A systems, from $\sqrt{s_{NN}}$=200 GeV to 7 TeV, multiplicity-inclusive, as well as multiplicity-dependent data
- The D-meson spectra are well described by the Tsallis-Pareto distribution over the whole p_T-range
- Lot of similarities between the behaviours of light and heavy flavours:
  - dependence on multiplicity and collision energy
  - mass ordering
  - grouping of points at low multiplicity
- The spectra of D mesons are formed later than for the light flavours: $\tau_{\mathrm{D}} = (0.18 \pm 0.06)\tau_{\mathrm{LF}}$
- The formation time of meson spectra is mass-dependent

Thank you for attention!