Investigation of the heavy-flavour hadronization time-scale using the Tsallis-thermometer

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OTKA numbers?
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:

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

Light-flavoured hadrons \((K, \pi, p, \Lambda, \Phi, \Sigma, \Xi, \Omega)\) have already been studied in the non-extensive statistical framework in the broad range of collision systems and multiplicities [1] 


In our study we expand the list of investigated particles with D mesons (containing c quark), which are mostly produced in hard interactions early in the collisions.

Our aims are:
- check the feasibility of such a study
- find similarities between light and heavy flavours
- find traces of different production mechanisms and timelines
Investigated datasets

Minimum bias spectra:
• ALICE, pp, 5.02 TeV - D⁰, D⁺, D*⁺
• ALICE, pp, 7 TeV - D⁰, D⁺, D*⁺
• ALICE, pPb, 5.02 TeV - D⁰, D⁺, D*⁺

Centrality (multiplicity) dependent:
• ALICE, PbPb, 2.76 TeV - D⁰
centralities: 0-20%, 40-80%
• STAR, AuAu, 200 GeV - D⁰
centralities: 0-10%, 10-20%, 20-40%, 40-60%, 60%-80%
**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:

$$T = E \left( \delta^2 - (q - 1) \right), \quad \frac{\Delta n^2}{\langle n \rangle^2} = \delta^2$$
Observations for the light flavours

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

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

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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 “center” is shifted compared to the light flavours

\[ T = E \left( \delta^2 - (q - 1) \right) \]
Tsallis-thermometer

• D mesons reach higher E values
• Fluctuations are stronger on the average

Fitting the $E - E\delta^2$ points with a line defines the equilibrium values for the $T$ (offset) and $q$ (slope) parameters.

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

$$\frac{\Delta n^2}{\langle n \rangle^2} := \delta^2$$

Light flavours: $T_{eq} \approx 0.14$ GeV and $q_{eq} \approx 1.15$

Heavy flavours: $T_{eq} \approx 0.25$ GeV and $q_{eq} \approx 1.21$
Production time-scale differences between light and heavy flavours

Light flavours: $T_{eq} \approx 0.14$ GeV and $q_{eq} \approx 1.15$

Heavy flavours: $T_{eq} \approx 0.25$ GeV and $q_{eq} \approx 1.21$

$\Delta T_{eq} \approx 0.11$ GeV

pPb 5.02 TeV:
- $\Delta T(D\text{ meson-pion}) > 0.3$ GeV
- $\Delta T(D\text{ meson-proton}) > 0.2$ GeV
- $\Delta T(D\text{ meson-Omega}) < 0.1$ GeV

AuAu 200 GeV:
- $\Delta T(D\text{ meson-light flavour}) \approx 0.10 - 0.15$ GeV
Conclusion

- We extended the non-extensive statistical framework beyond the light flavours.
- Broad range of D meson data from ALICE and STAR experiments was used, consisting of 5 different collision systems: from pp to AA, from 200 GeV to 7 TeV, from minimum bias to low and high centralities.
- The Tsallis-Pareto fits of the D meson spectra describe precisely both the low-$p_T$ and the high-$p_T$ regions.
- Lot of similar trends to the light-flavour hadrons, however having different scale:
  - dependence on multiplicity and collision systems
  - mass hierarchy
  - overall grouping
- The results show that D mesons indeed interact with a hot medium after being produced in the initial stages of a collision.
Thank you for your attention!
Back-up
$D^0(1864)$ yield in Au-Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV in $|y|<1$

$D^0(1864)$ yield in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in $|y|<1$
$D^0(1864)$ yield in pp collisions at $\sqrt{s} = 7$ TeV in $|y|<1.0$

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Thermodynamical consistency