Statistical Hadronization Model Calculations of Heavy Flavor Hadron Production in Relativistic Heavy-Ion Collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV

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Statistical Hadronization Models (SHMs) can adequately reproduce final state hadronic particle yields over nine order of magnitude in high energy collisions of heavy ions. Assuming thermal equilibrium, experimental particle yields from heavy ion collisions can readily be used to determine the baryon chemical potential ($\mu_{\rm B}$) and the chemical freeze-out temperature ($T_{\rm ch}$) via SHM thermal fits. Heavy flavor particle production in A+A collisions is of particular interest by virtue of the large difference between the mass of the bare heavy quarks and the calculated pseudo critical hadronization temperature. Heavy quarks are produced in the initial hard scattering of each collision and later combine with the deconfined lighter quarks generated thermally in the fireball. Assuming the total number of heavy quarks is constant until the point of hadronization, final state heavy hadron yields can be modeled by the SHM by introducing an additional out-of-equilibrium parameter. In this contribution, we show thermal fits to single charmed hadrons in A+A collisions at ALICE with an updated version of the 2023 hadronic spectrum. We additionally show thermal model predictions of heavy quarkonia, and beauty and multi-charm hadron yields and gauge their sensitivity to different $T_{\rm ch}$ values.

I. Motivation

Experimental yields of light, strange and charmed final state hadrons measured by the ALICE detector can be excellently described by the use of a *charmed* version of the traditional SHM [1].

- Performed using a **simultaneous chemical freeze-out** of all hadrons
- Charm hadron production modified by charm balance function
  - Requires a priori knowledge of charm cross section(s)
  - Individual particle yields calculated by the model usually possess relatively high deviation when compared to data

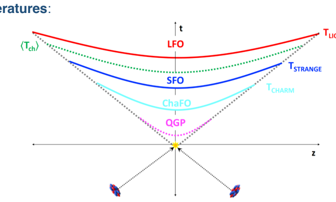
We test:

1.) If sensible results can achieved via a simple modification to the traditional Grand Canonical partition function instead.

2.) If tension between the deviations of individual particle yields are alleviated when employing flavor-dependent chemical freeze-outs when compared to the traditional simultaneous chemical freeze-out.

II. Methodology

Expanding on [2], we entertain the idea of **three chemical freeze-out (3CFO) temperatures**:



Charm Freeze-out (ChaFO) occurs prior to Strangeness Freeze-out (SFO), which occurs prior to Light Freeze-out (LFO) ∋

$$T_{\rm charm} > T_{\rm strange} > T_{\rm light}$$

III. Model Configuration

We performed all calculations using the **Thermal FIST** Hadron Resonance Model Package [3]:

Configuration: Ideal Hadron Resonance Gas Model
Ensemble: Grand Canonical Ensemble
- Quantum numbers are globally conserved

Yield Data: ALICE Pb+Pb at 5.02 TeV (0 - 10%) [4]
Hadronic Spectrum: PDG 2023 Live [5]
- Procedurally automated on-the-fly
- 622 state carry-over from PDG2020
- 60 additional charmed states

Assuming thermal equilibrium, the chemical freeze-out parameters $T_{\rm ch}$, $\mu_{\rm B}$, and the fireball volume (V) — as well as all final state particle yields $(N_{\rm i})$ — are constant at chemical freeze-out

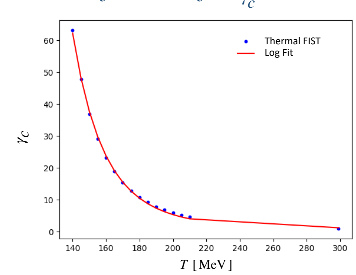
Hence, by virtue of the statistical bootstrap

Knowing $N_{\rm i}$ $\longrightarrow$ $T_{\rm ch}$, $\mu_{\rm B}$, and V are determined
Conversely,
Knowing $T_{\rm ch}$, $\mu_{\rm B}$, and V $\longrightarrow$ $N_{\rm i}$ are calculated

Charm Fugacity (γ_C)

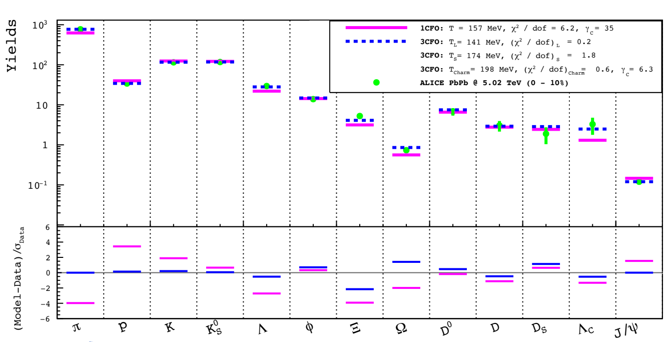
Since charm (anti-)quarks are produced in the initial hard scattering of partons — due to their large mass — it becomes necessary to modify the Boltzmann factors used to calculate individual charmed particle densities:

$$e^{\mu_i/T} \longrightarrow e^{\mu_i/T}\gamma_c^{|c_i|}$$



IV. Results

Thermal Fits to final state light, strange and charmed hadrons at top LHC Energies



Shorthand used to represent arithmetic mean of hadrons and their respective anti-hadrons

Thermal Fit Comparisons

1CFO

All particles chemically freeze-out simultaneously (e.g. at one temperature) — γ_c determined by $T_{\rm ch}$ of combined fit, $\mu_{\rm B}$ fixed to 1 MeV:

$$T_{\rm ch} = 157 \text{ MeV and } \gamma_c = 35$$

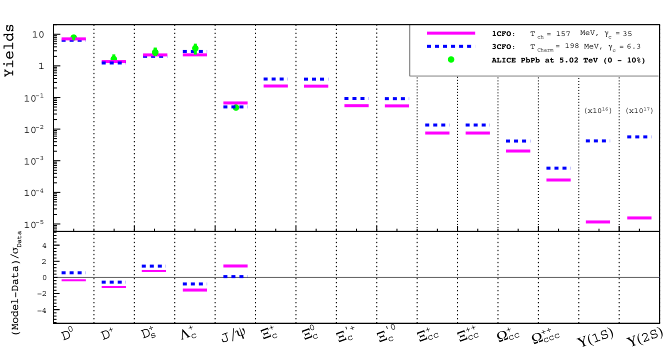
3CFO

Light, strange and charm particles chemically freeze-out separately (e.g. not at one temperature) — γ_c determined by $T_{\rm charm}$:

$$T_{\rm charm} = 198 \text{ MeV and } \gamma_c = 6.3$$
$$T_{\rm strange} = 174 \text{ MeV}$$
$$T_{\rm light} = 141 \text{ MeV}$$

- With a **considerable improvement** in the combined reduced goodness-of-fit value of all three fits when compared to the 1CFO result

Thermal Model Predictions of heavy flavor hadrons at top ALICE Energies



Thermal Model Predictions

We then use the fit parameters to predict yields of additional (multi-)charmed baryons and beauty quarkonia (assuming γ_b = 1) not yet reported by ALICE:

- We observe a drastic increase in the predicted value of yields when using the 3CFO fit parameters
- The largest differences occurring in the multi-charmed baryons as well as beauty charmonia

V. Conclusion and Outlook

Confirmed final state charmed hadron particle yields from Pb+Pb collisions at 5.02 TeV in the (0 - 10%) class are well described within the SHM framework through the use of a charm fugacity
- Tested the sensitivity of said yield calculations both in terms of $T_{\rm ch}$ and γ_c
- Successfully employed a 3CFO formalism to improve fit quality
- Predicted heavy flavor hadron yields, including various multi-charmed hadrons

Exploited versatility of the updated *PDG Live* structure
- **Planning on procedurally updating the hadronic spectrum**
  - Comparing newly found states to the PDG2016+ list [6] and its successors

We aim to contrast to a similar analysis to charmed hadron yield data in RHIC Au+Au collisions at 200 GeV, where a non-trivial $\mu_{\rm B}$ dependence is present.

References & Acknowledgements

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