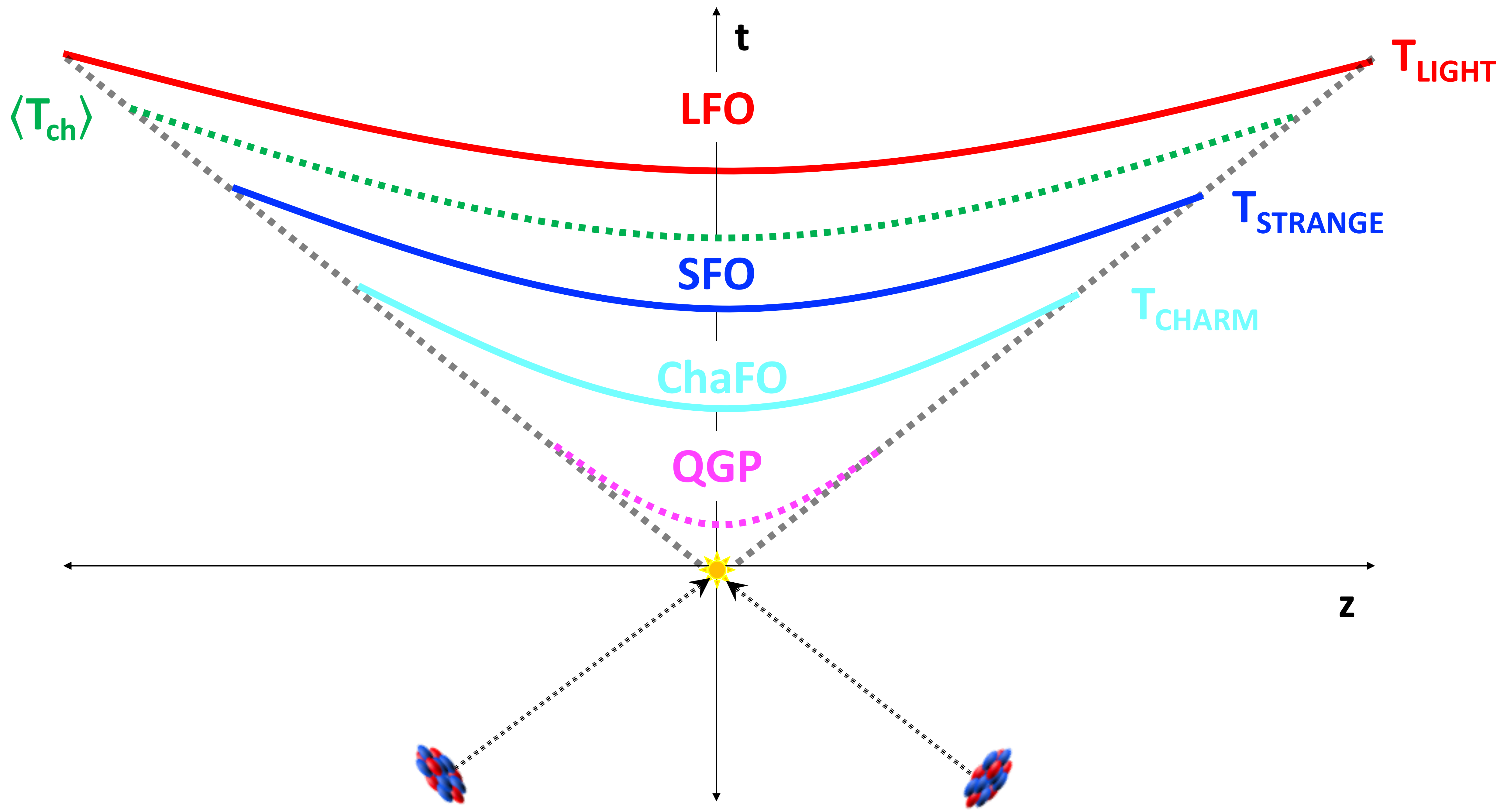
Sequentially Charming Chemical Freeze-out in Heavy Ion Collisions at Top LHC Energies

39th Winter Workshop on Nuclear Dynamics — Jackson Hole, Wyoming



Fernando Antonio Flor
Yale University

February 13th, 2024

with

Selma Mazioud, Iris Ponce Pinto,
Helen Caines, and René Bellwied

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Wright Laboratory

Outlook

- Motivation
  - ☐ Chemical Freeze-out at ALICE
  - ☐ Sequential Flavor Freeze-out
    - Two Temperature Freeze-out (2CFO)
    - Three Temperature Freeze-out (3CFO)
- Methodology
  - ☐ Statistical Hadronization Models
  - ☐ Input Parameters
    - Hadronic Spectrum
    - Experimental Yields
- Results
- Conclusion and Outlook

A. De Saint-Exupéry. *Le Petit Prince* **(1943)**

MOTIVATION

Fernando A. Flor (fernando.flor@yale.edu)

Chemical Freeze-out at ALICE

Statistical Hadronization Models (SHMs) can describe final state particle yields to over nine orders of magnitude via a single Chemical Freeze-out Temperature (T_{ch})

In ALICE Pb+Pb Collisions:

$T_{ch} = 156 \pm 2$ MeV

- Recall: Chemical Freeze-out
  - Inelastic interactions cease
  - Particle Yields are fixed

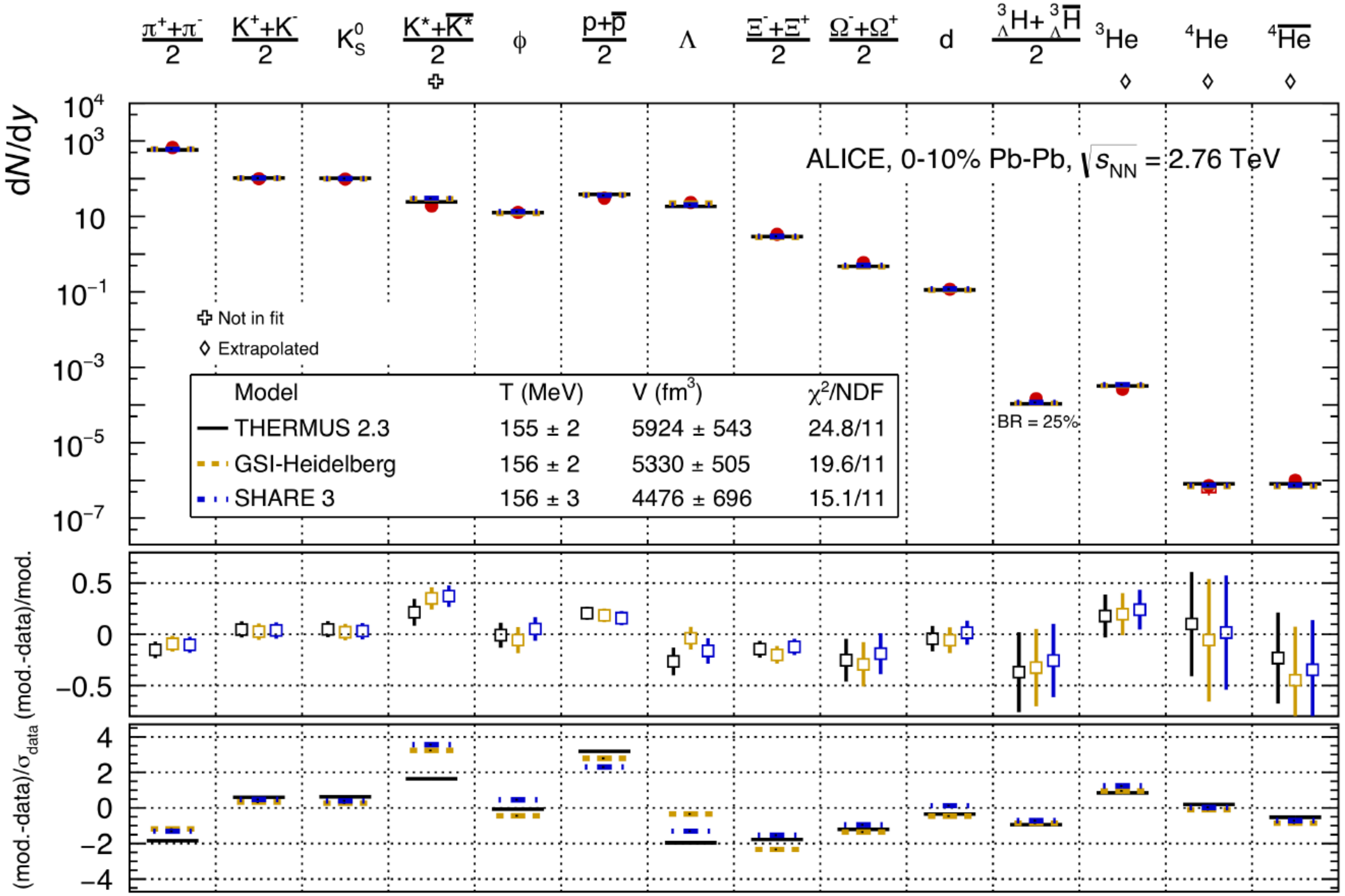

Figure: ALICE Collaboration. Nucl. Phys. A. **971** (2018)

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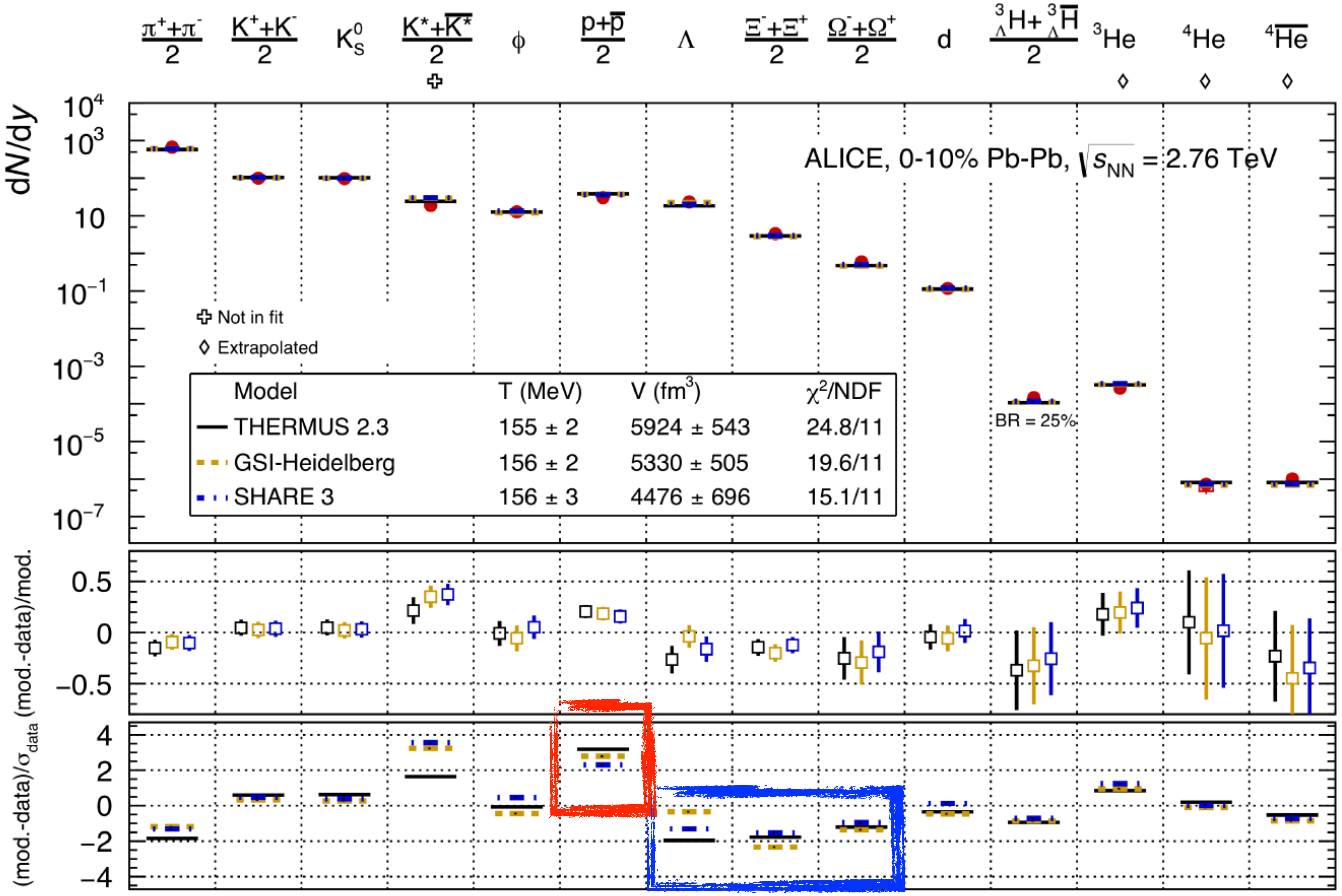
Overall fit quality is quite good, however, it has been shown that the tension from the fit between light and strange hadrons can be ameliorated via flavor-dependent fits

Flor, et al. *Phys. Lett B.* **814** (2021)



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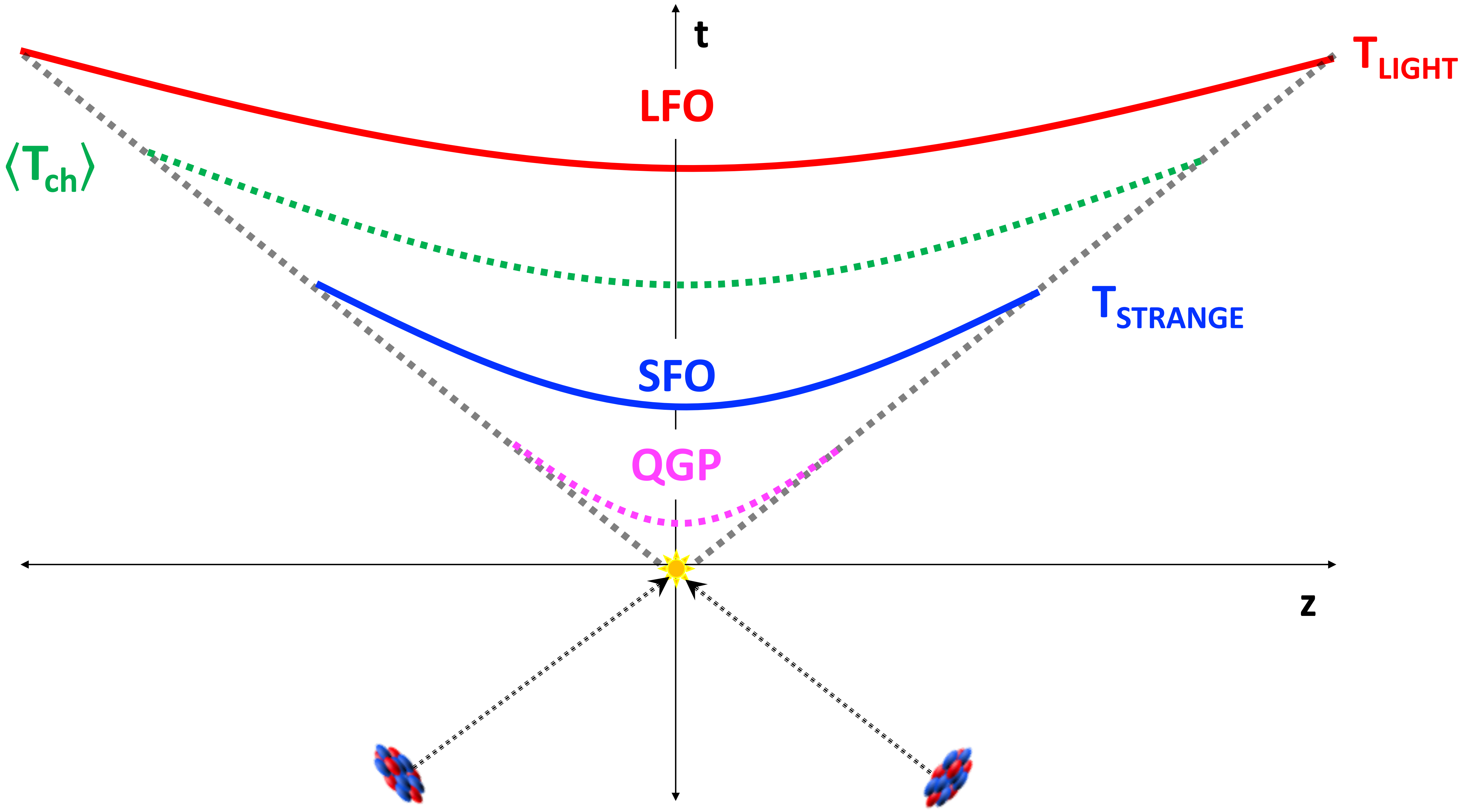

$T_{strange}$ > T_{light}

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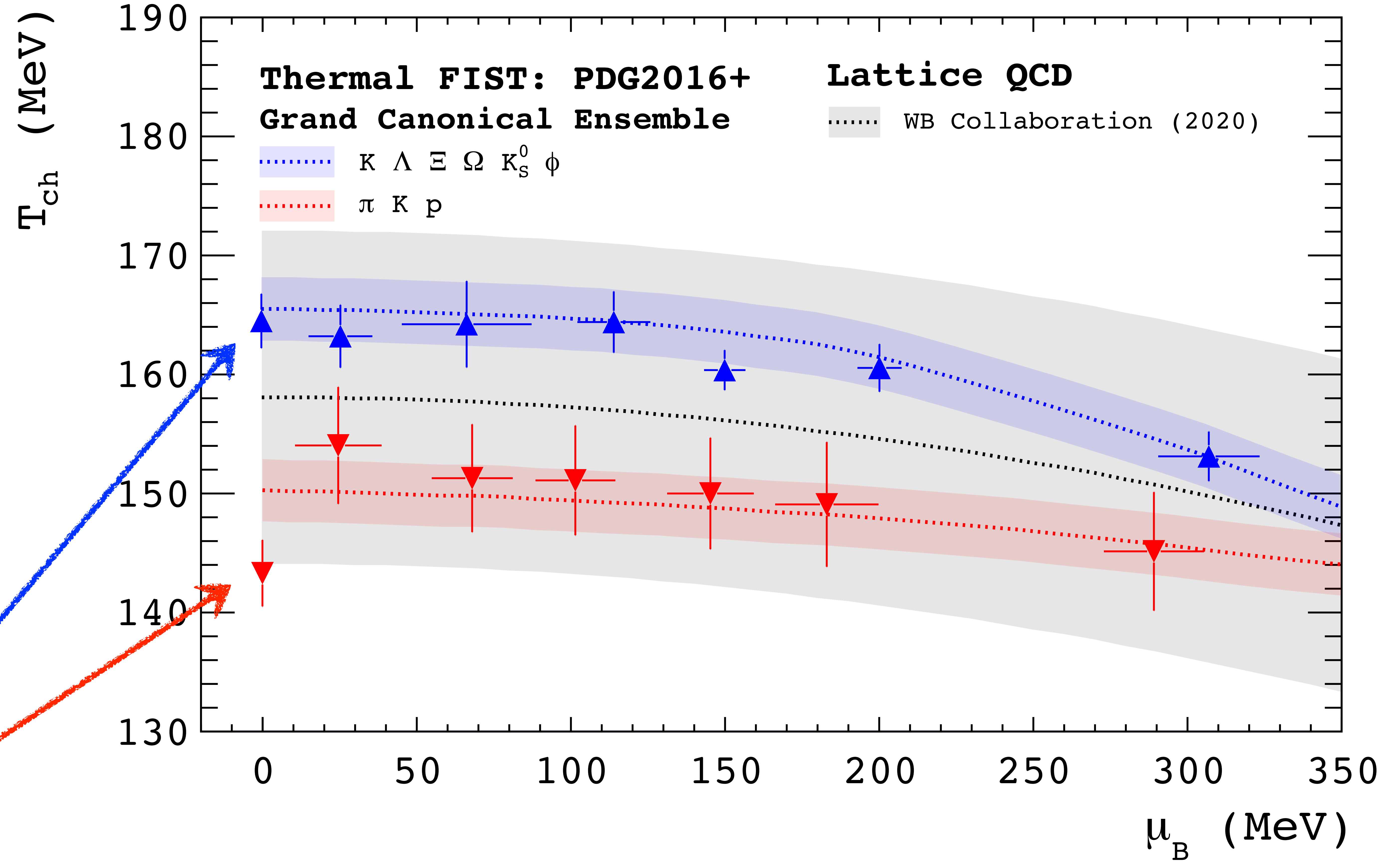

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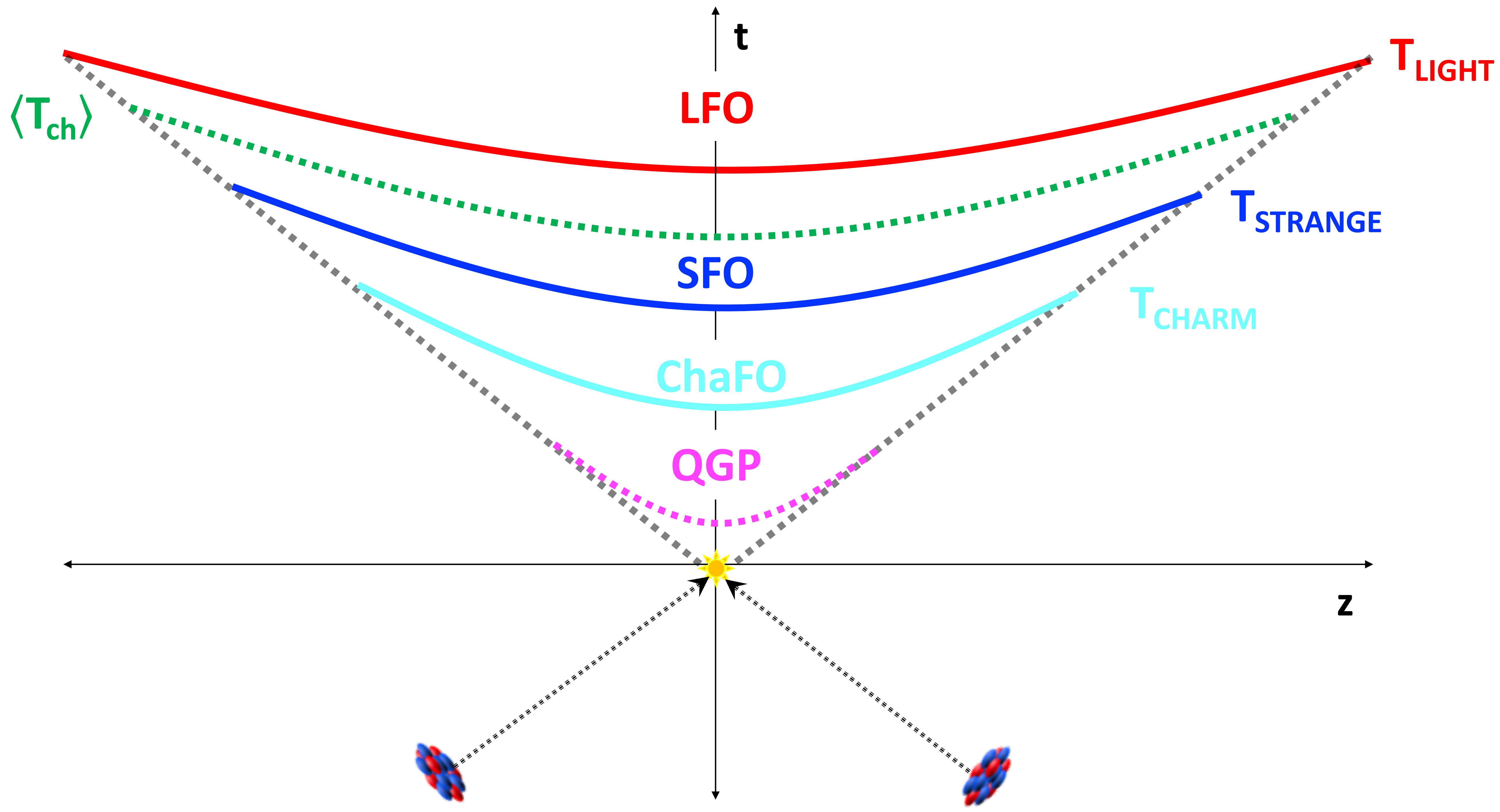
<u>This talk</u>: Can the SHM framework be used to describe hadron production in heavy ion collisions via a sequential flavor-dependent chemical freeze-out including charm?

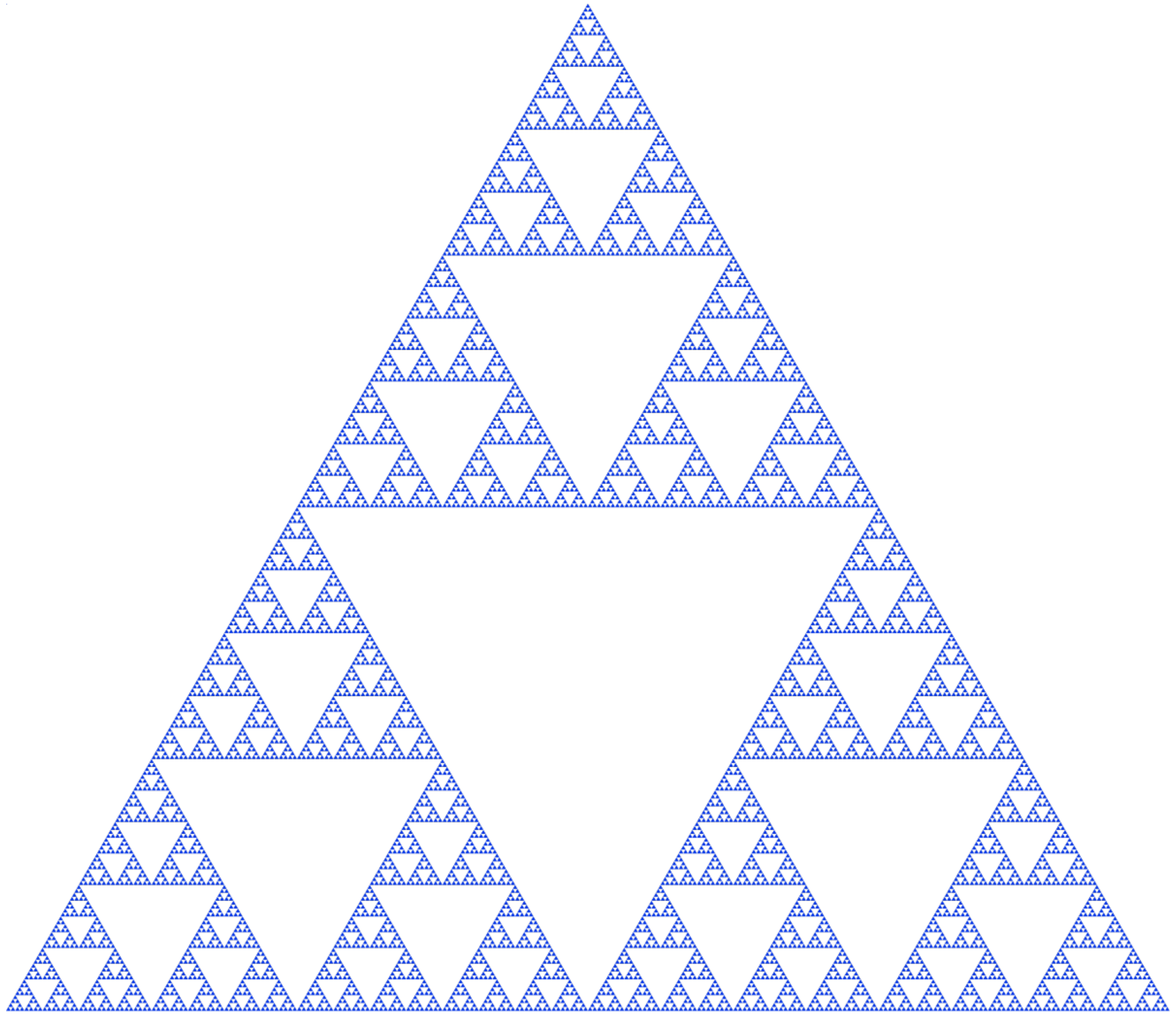


$T_{charm} > T_{strange} > T_{light}$

METHODOLOGY

Statistical Hadronization Models (SHMs)

- Basic Assumptions
  - Thermally Equilibrated System at chemical freeze-out
    - T_{ch}, Volume (V), chemical potential (μ) and particle yields (N_i) are constant
    - Out-of-equilibrium parameter γ_i may also be considered
- By knowing N_i a priori, one can calculate T_{ch}, V and μ
  - In a Grand Canonical Ensemble, B,S, and Q are globally conserved
- Conversely, N_i can be calculated by knowing T_{ch}, V and μ



Due to the self-similarity of the system at every stage of its evolution, **highly interacting ground state hadrons can be well-described via a non-interacting (ideal) gas of hadrons and hadronic resonances**

Ideal Hadron Resonance Gas Model (HRG)

For the Ideal HRG, the pressure is given by:

$$p(T,\mu) = \sum_i p_i^{ideal}(T,\mu_i)$$

Where p_i^{ideal} is the pressure of the ideal Bose or Fermi gas at T and μ:

$$p_i^{ideal}(T,\mu_i) = \frac{d_i}{6\pi^2}\int_0^\infty \frac{k^4 dk}{\sqrt{k^2+m_i^2}}\left[exp\left(\frac{\sqrt{k^2+m_i^2}-\mu_i}{T}+\eta_i\right)\right]^{-1} \ni$$

$d_i =$ Spin Degeneracy Factor

$m_i =$ Hadron Mass of species i

$\eta_i =$ +1 for fermions, -1 for bosons and 0 in the Boltzmann Approximation Spin Degeneracy Factor

$\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$

Yield Calculations in Ideal HRG Model

In the Thermal Model, particle species are determined by:

$$N_i = V \frac{d_i m_i^2 T}{2\pi^2} K_2\left(\frac{m_i}{T}\right) exp\left(\frac{\mu_i}{T}\right)$$

The overall quality of the fit is determined by the parabolic minimization (through a vanishing first derivative of the χ^2 value given by:

$$\chi^2 = \sum_{i,j} \left(\frac{(x_i - y_i(\mathbf{a}))}{e_i^2}\right) \ni$$

x_i are the calculated values

$\mathbf{y}(\mathbf{a})$ is the vector of yield values used in fit

e_i^2 is the square of the error for each x_i determined by the least-squares method in the fit

Model Configuration

We performed all calculations using the Thermal FIST

- Configuration: Ideal Hadron Resonance Gas Model
- Ensemble: Grand Canonical Ensemble
  - Relevant quantum numbers are globally conserved
- Yield Data: ALICE Pb+Pb at 5.02 TeV (0 - 10%)
- Hadronic Spectrum: PDG 2023 Live
  - 622 state carry-over from PDG 2020
  - 60 charmed states in total

V. Vochenko et al. *Comput. Phys. Commun.* **244** (2019)

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Given that charm (anti-)quarks are produced in the initial had scattering of incoming partons — due to their large masses — it is necessary to modify the Boltzmann factors associated with each individual charmed particle densities

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

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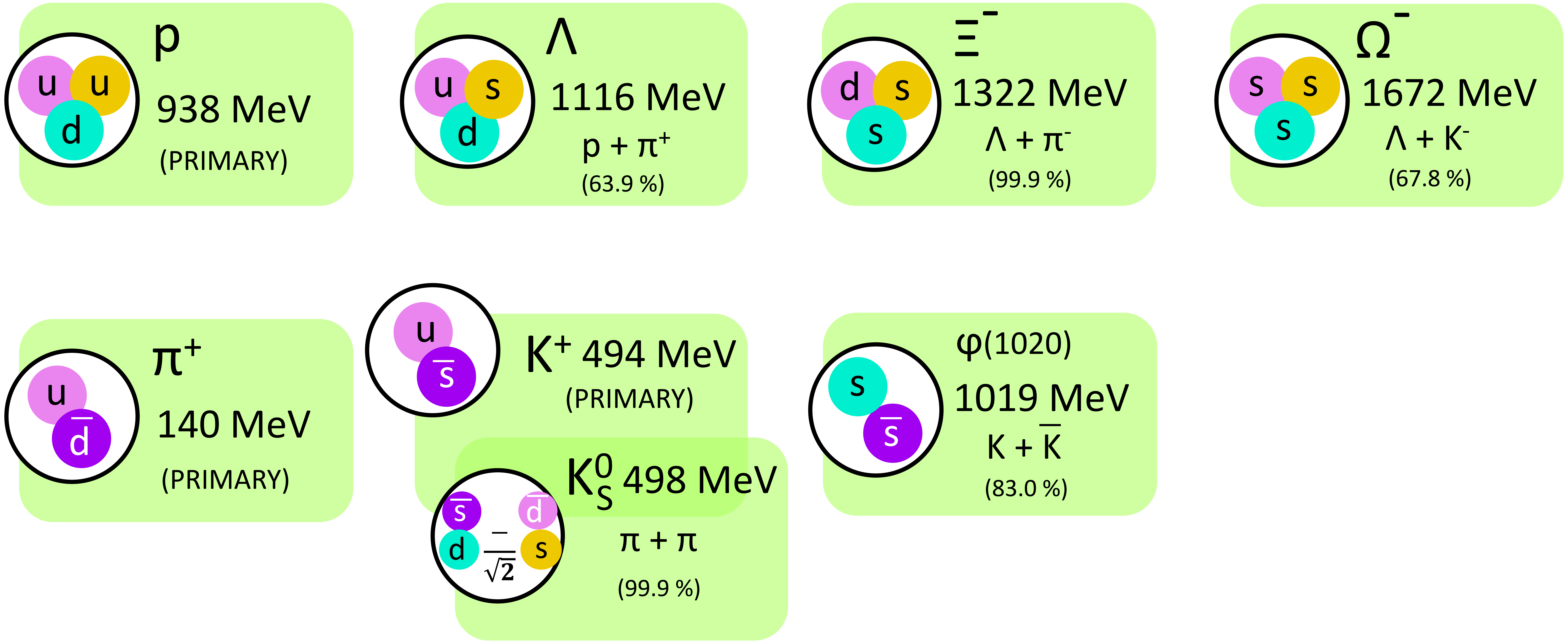
In this manner, the charm fugacity (γ_c) is treated as an out of equilibrium pseudo impurity which remains constant throughout the lifetime of the collision fireball.

Assuming the total number of charm (anti-)quarks is constant until hadronization, we can model final state heavy flavor yields within the SHM framework

The 1CFO Culprits: Global Fit



$|S| = 0$

p
938 MeV
(PRIMARY)

π^+
140 MeV
(PRIMARY)

$|S| = 1$

Λ
1116 MeV
$p + \pi^+$
(63.9 %)

K^+ 494 MeV
(PRIMARY)

K^0_S 498 MeV
$\pi + \pi$
(99.9 %)

$|S| = 2$

Ξ^-
1322 MeV
$\Lambda + \pi^-$
(99.9 %)

φ(1020)
1019 MeV
$K + \bar{K}$
(83.0 %)

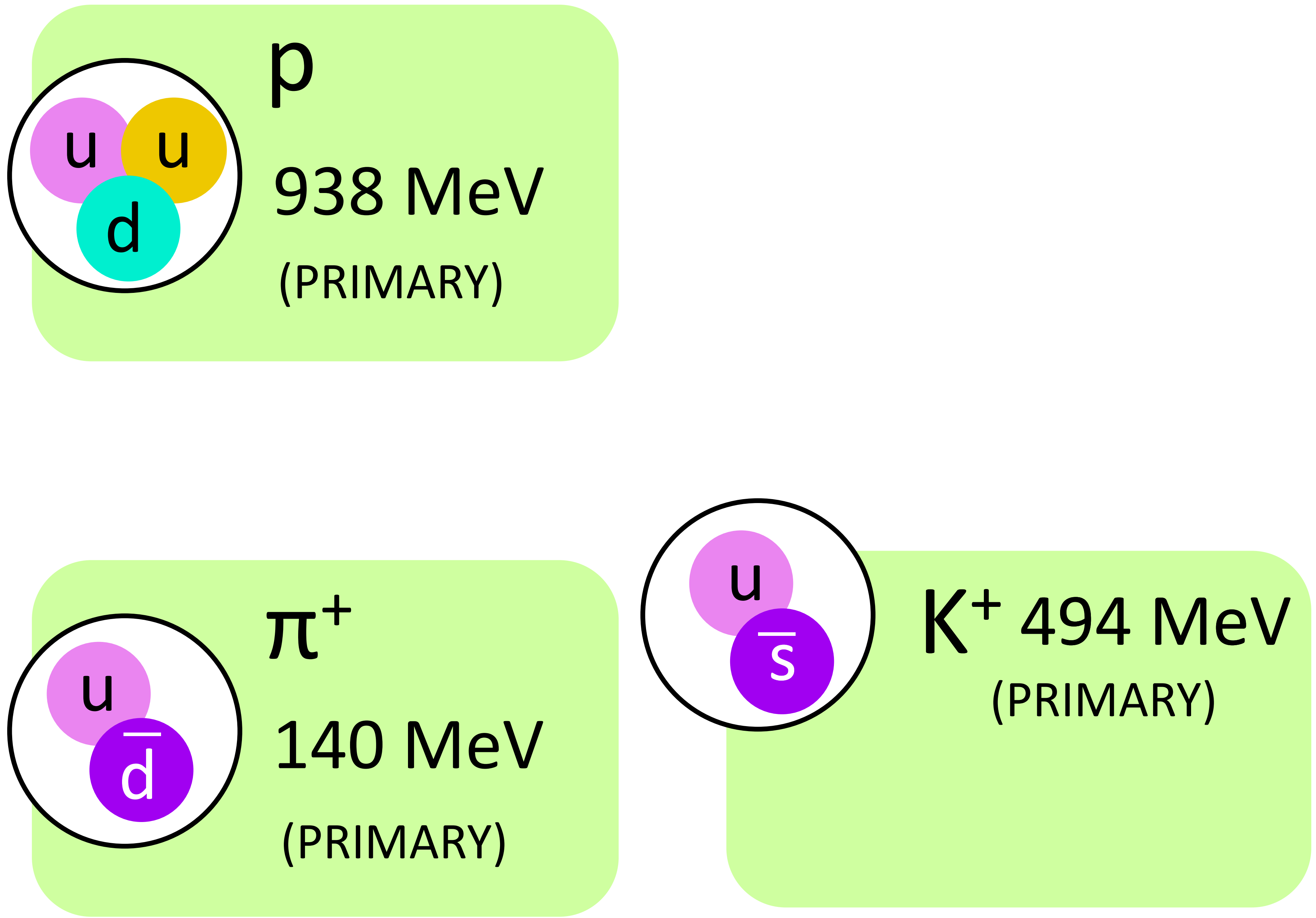
$|S| = 3$

Ω^-
1672 MeV
$\Lambda + K^-$
(67.8 %)

Note: Anti-hadrons not shown

The 3CFO Culprits: Light Fit

|S| = 0 |S| = 1 |S| = 2 |S| = 3

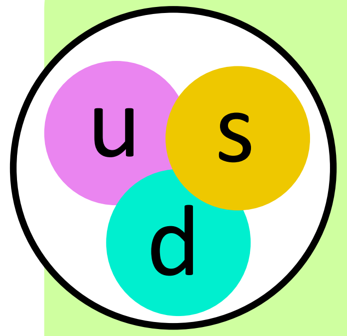


Note: Anti-hadrons not shown

The 3CFO Culprits: Strange Fit

|S| = 0

|S| = 1

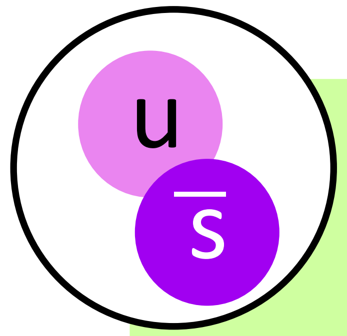


Λ

1116 MeV

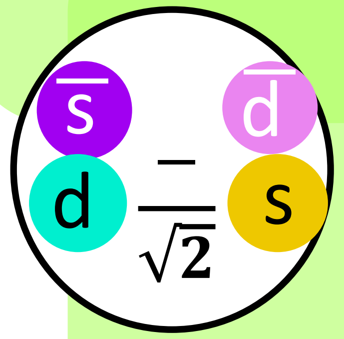
$p + \pi^+$

(63.9 %)



K^+ 494 MeV

(PRIMARY)

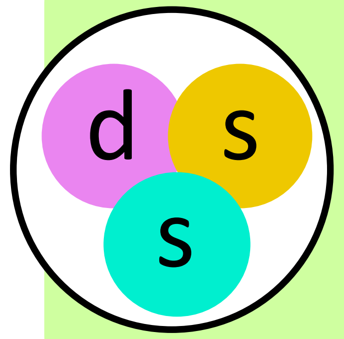


K^0_S 498 MeV

$\pi + \pi$

(99.9 %)

|S| = 2

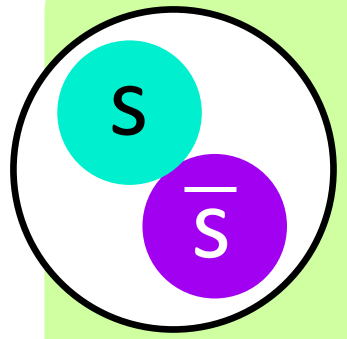


Ξ^-

1322 MeV

$\Lambda + \pi^-$

(99.9 %)



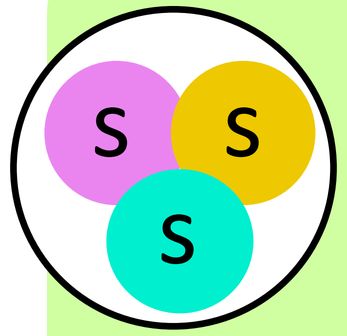
φ(1020)

1019 MeV

$K + \overline{K}$

(83.0 %)

|S| = 3



Ω^-

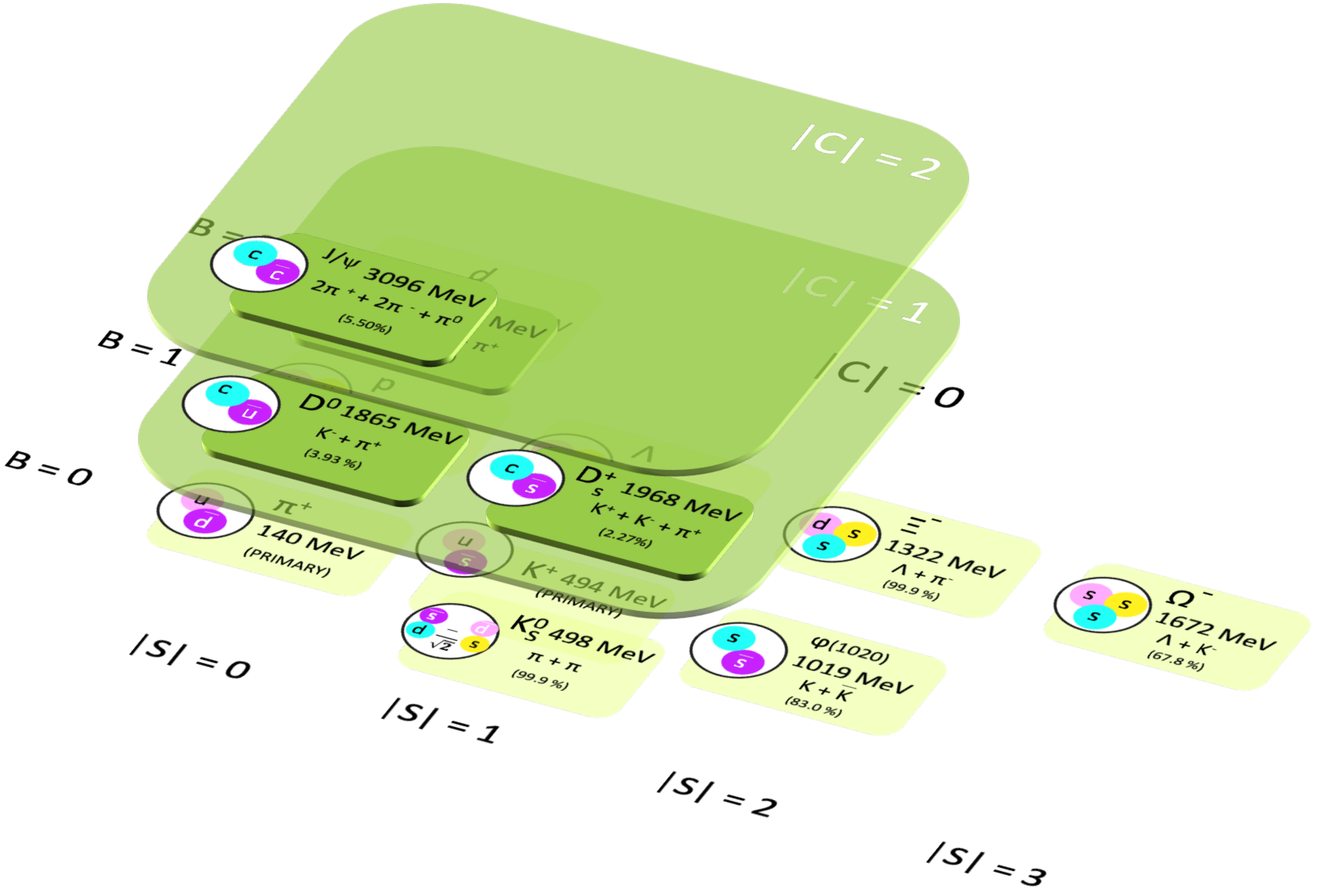
1672 MeV

$\Lambda + K^-$

(67.8 %)

Note: Anti-hadrons not shown

The 3CFO Culprits: Charm Fit

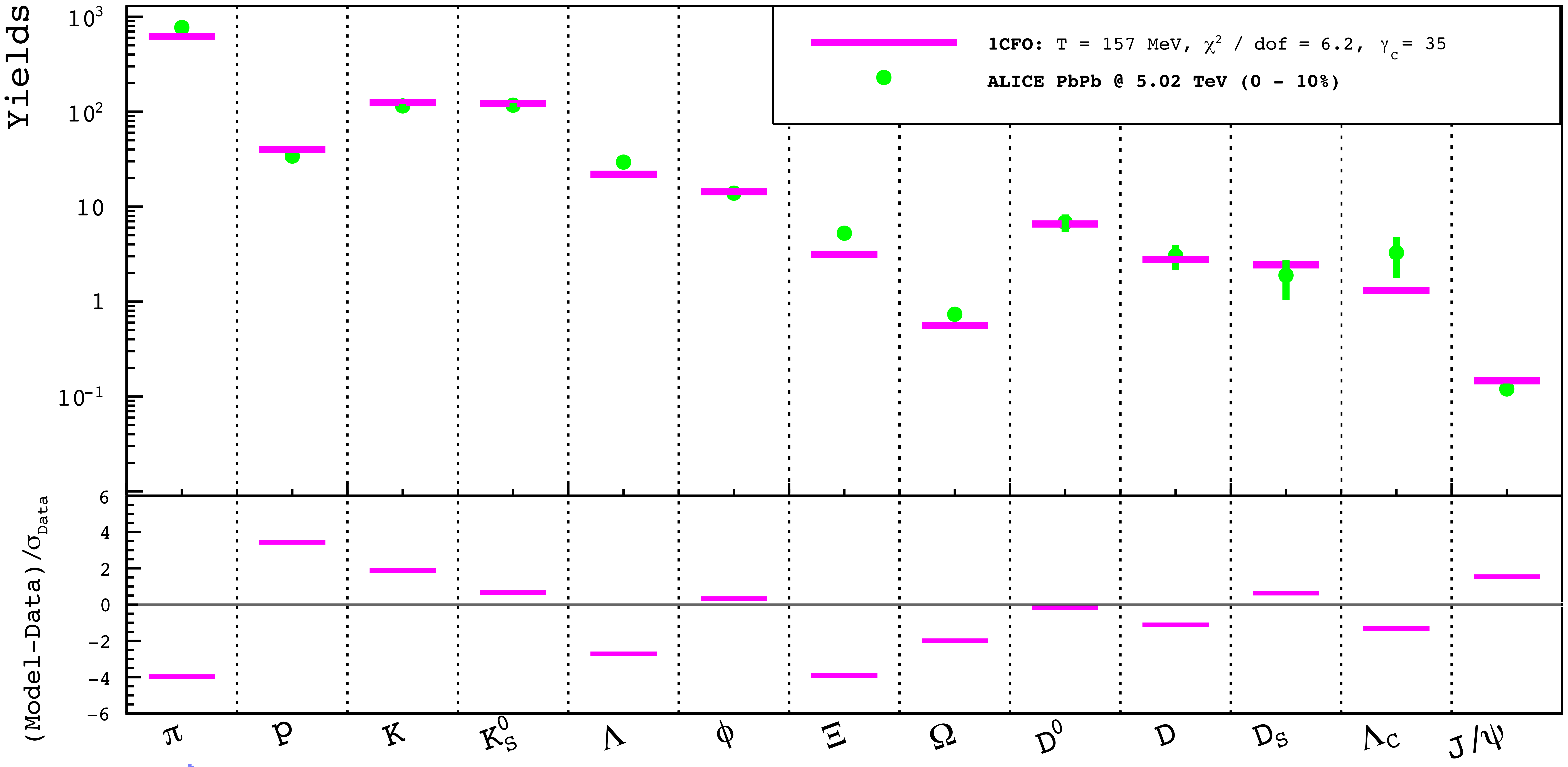


Note: Anti-hadrons not shown

RESULTS

Fernando A. Flor (fernando.flor@yale.edu)

1CFO Thermal Fits: ALICE Pb+Pb @ 5.02 TeV (0 - 10%)



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

To first order, all particles were fit simultaneously (1CFO) while fixing $\mu_B = 1$ MeV

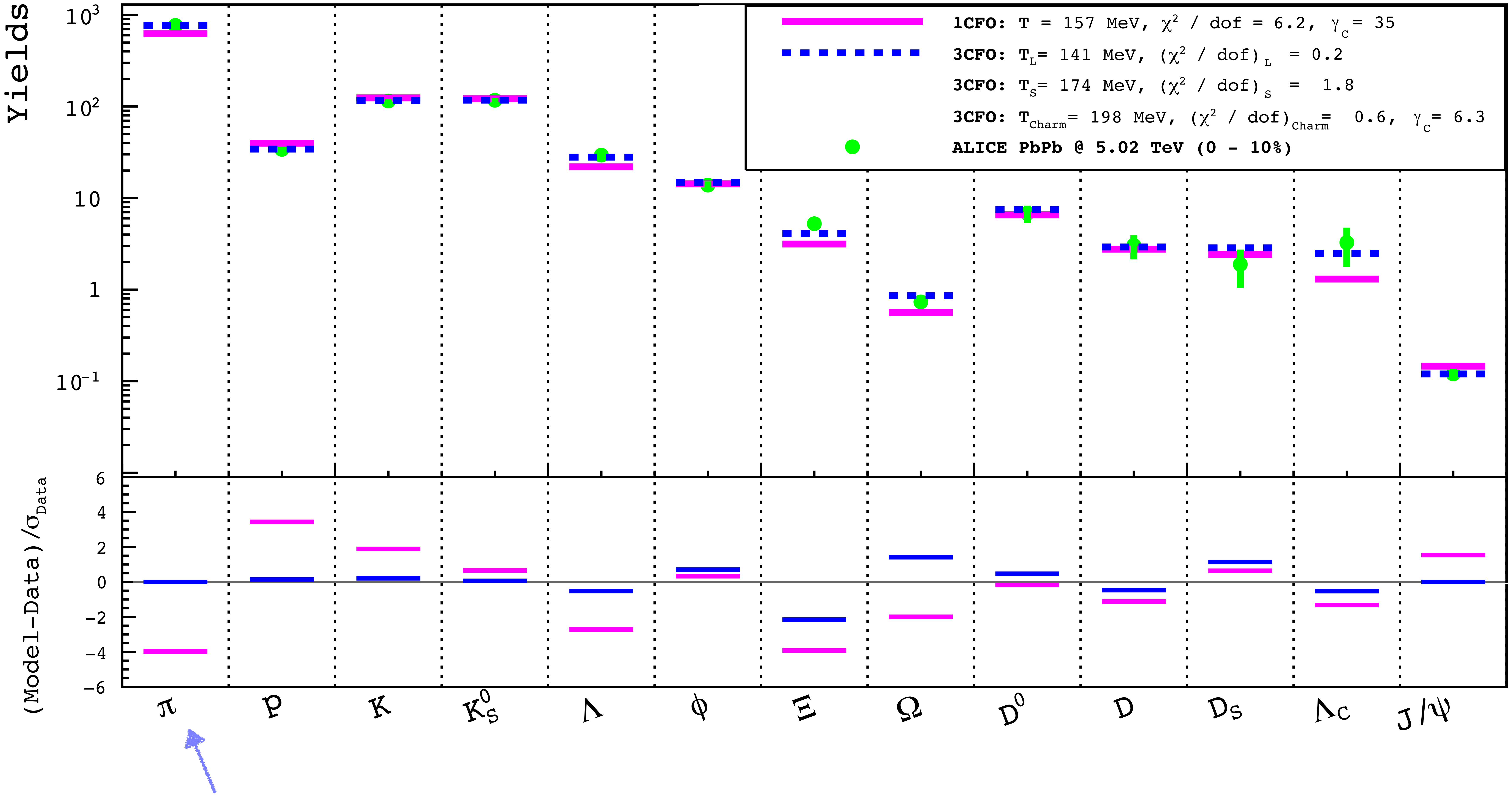
Charm fugacity was determined based on the fit at a global freeze-out temperature

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

This result is in good agreement with previously shown in the SHMc framework through the use of a charm balance equation

A. Andronic, et al. JHEP. **2021** (2021)

3CFO Thermal Fits: ALICE Pb+Pb @ 5.02 TeV (0 - 10%)



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We then used a flavor-dependent freeze-out (3CFO) while fixing $\mu_B = 1$ MeV

Charm fugacity was determined based on the temperature when only fitting charmed hadron yields

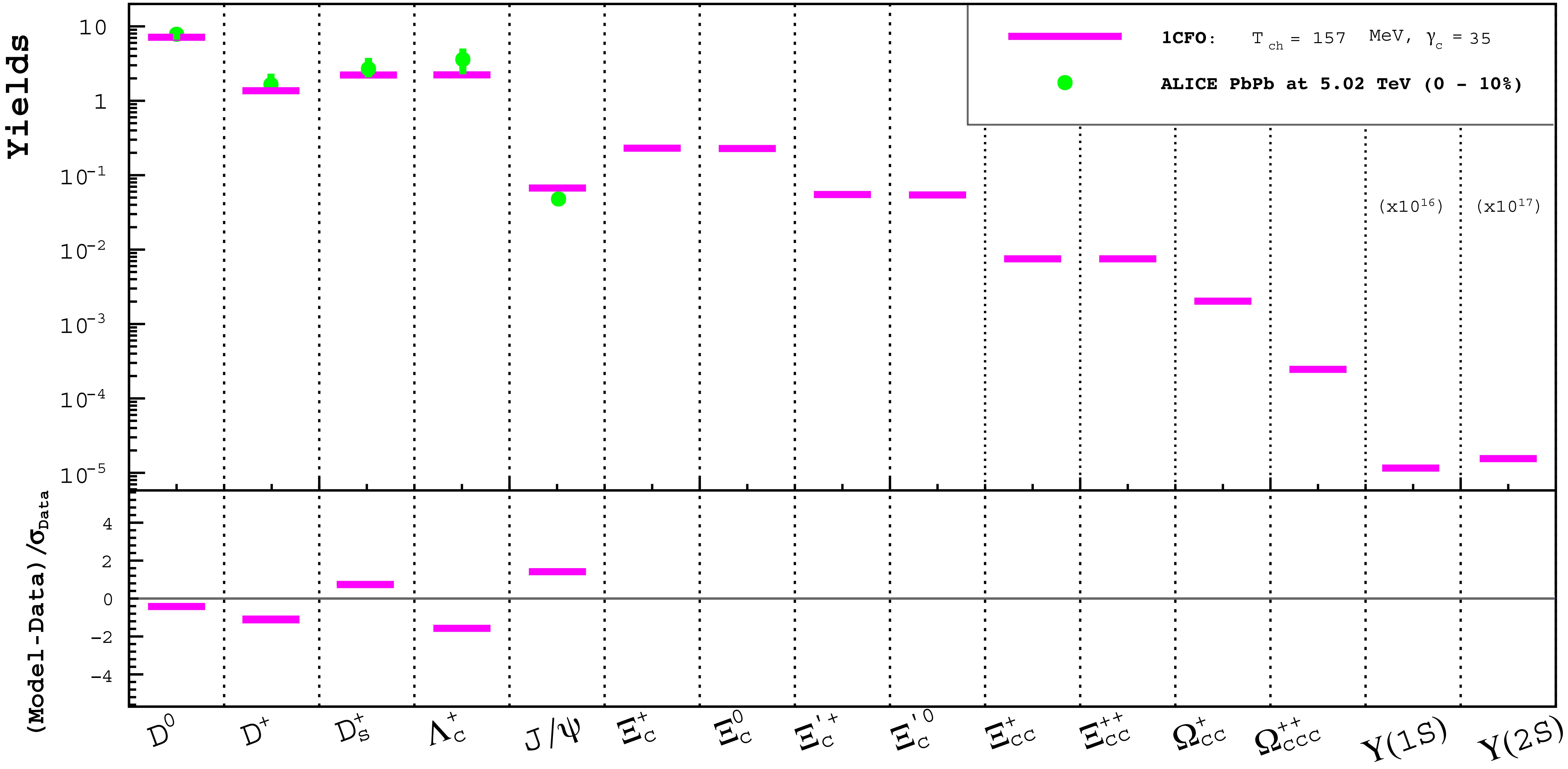
T_{charm} = 198 MeV and $\gamma_C = 6.2$

$T_{strange}$ = 174 MeV

T_{light} = 141 MeV

We observe a considerable improvement in the combined reduced goodness-of-fit values of all thee fits when compared to the 1CFO result

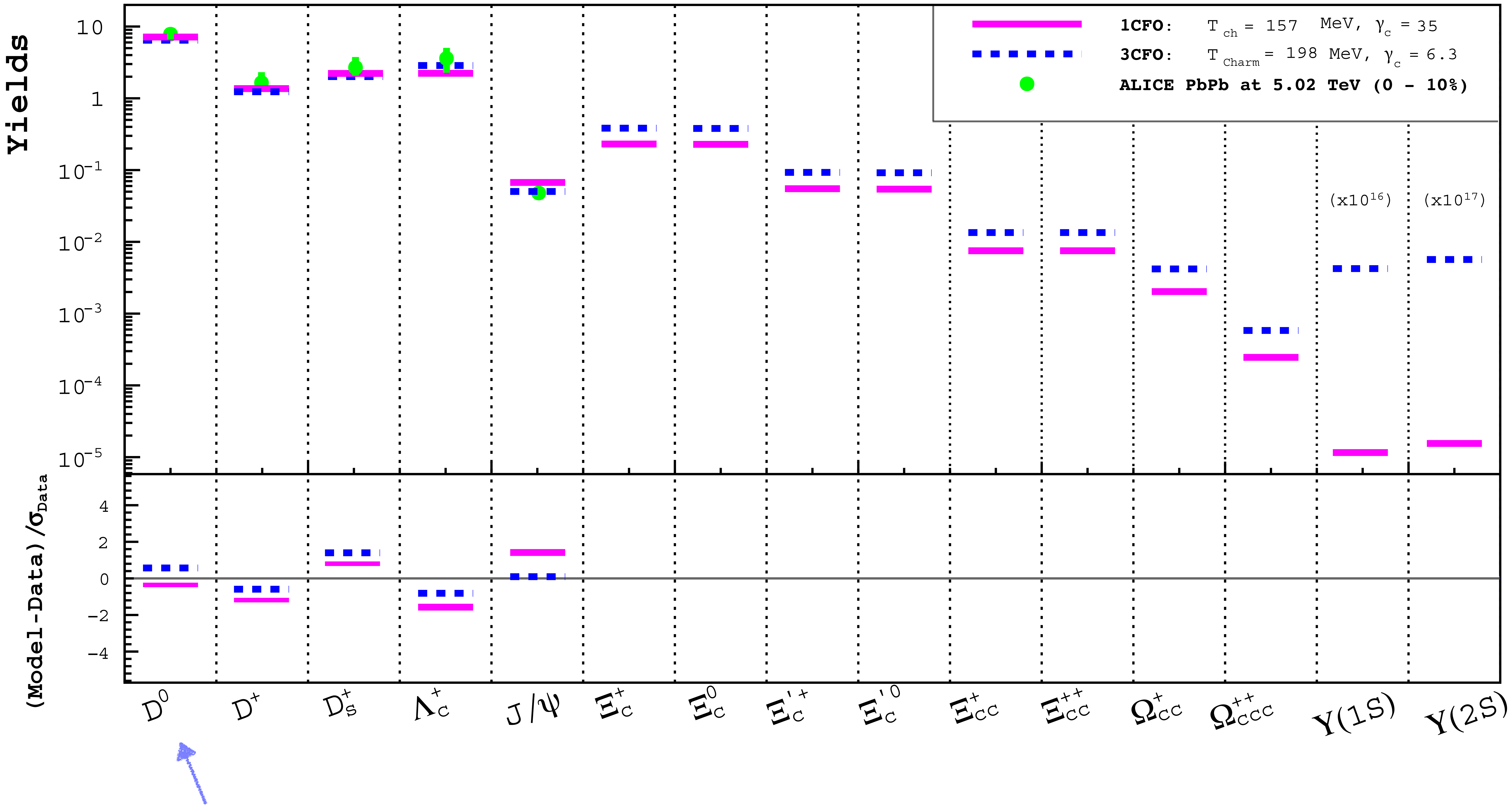
(Multi-)Charmed Hadron Predictions (1CFO)



We can also compare predicted yield values by the model of additional charmed and multi-charmed baryons (and beauty quarkonia)

Representative of both hadrons and their respective anti-hadrons

(Multi-)Charmed Hadron Predictions (3CFO)



Representative of both hadrons and their respective anti-hadrons

We can also compare predicted yield values by the model of additional charmed and multi-charmed baryons (and beauty quarkonia)

We observe a drastic increase in the predicted values of the yields when comparing the 1CFO vs. the 3CFO Model Predictions

The largest differences occurring in the multi-charmed baryons as well as in beauty charmonia

Conclusions and Outlook

Final State charmed hadron yields at ALICE Pb+Pb collisions are well described within the SHMc framework

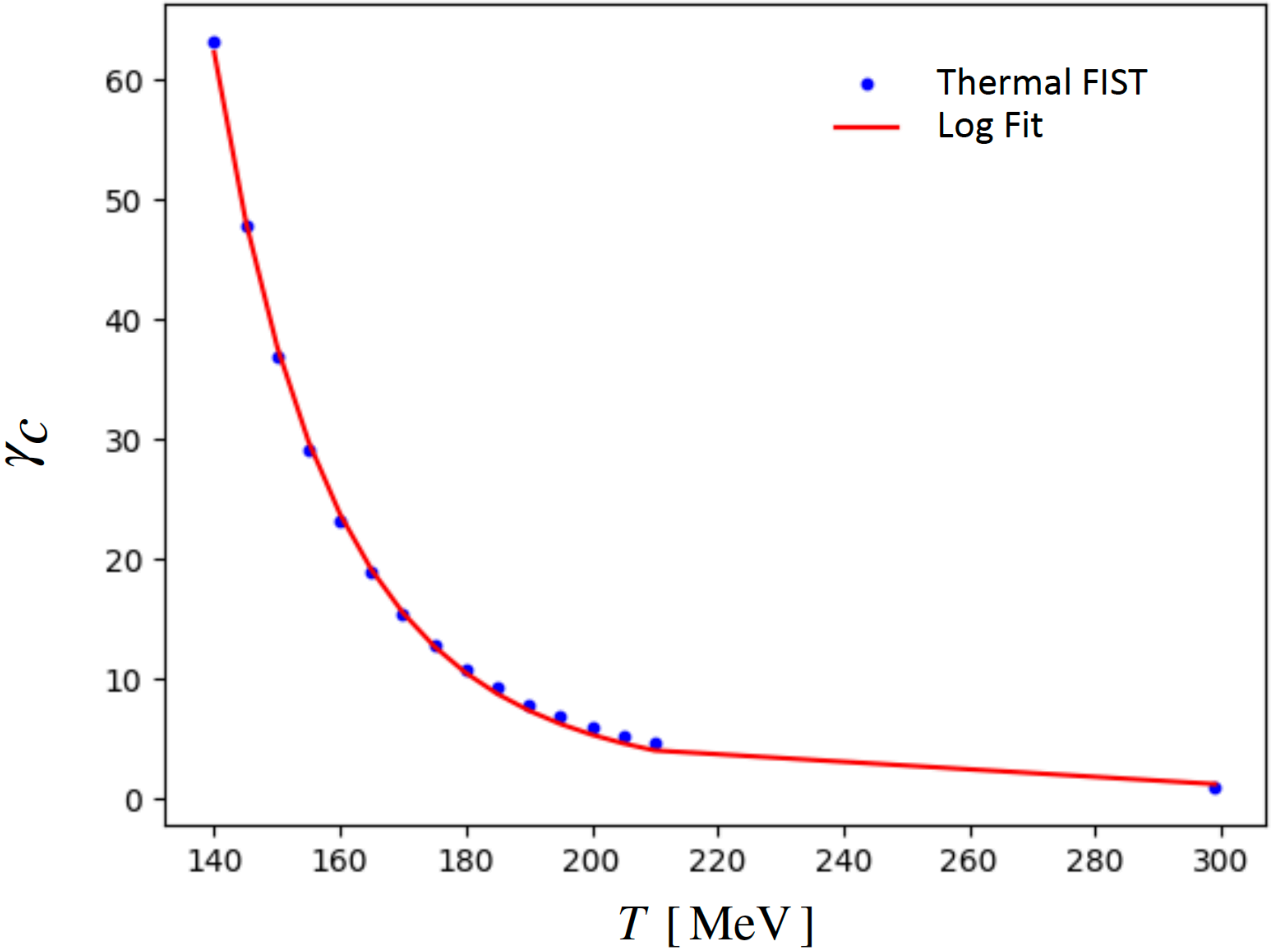
- Tested sensitivity of yield calculations in terms of T_{ch} and γ_c
- Successfully employed 3CFO formalism to improve fit quality
- Produced predictions of heavy flavor yields, including various multi-charmed hadrons
- Exploited versatility of updated *PDG Live* structure
  - ☐ Procedurally generated on the fly

Onslaught of copious charmed hadron yields — both at the LHC and RHIC — to be exploited for more robust and definitive test of the 3CFO paradigm

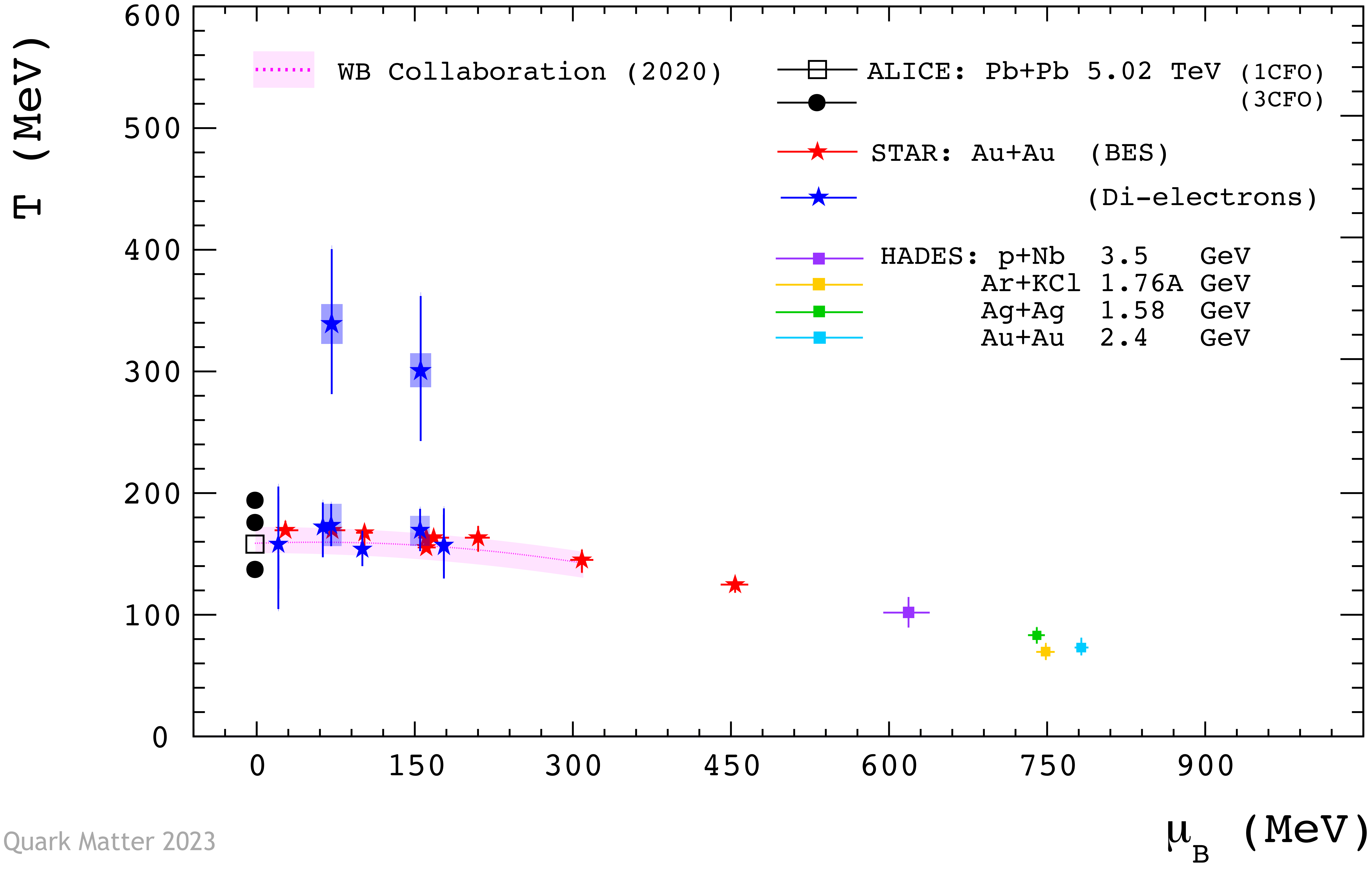
THANK YOU!

CAVALRY

Variation of Charm Fugacity WRT Temperature



QCD Phase Diagram



H. Caines. Quark Matter 2023