Flavour and Energy Dependence of Chemical Freeze-out in Relativistic Heavy Ion Collisions from RHIC-BES to LHC Energies

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Overview

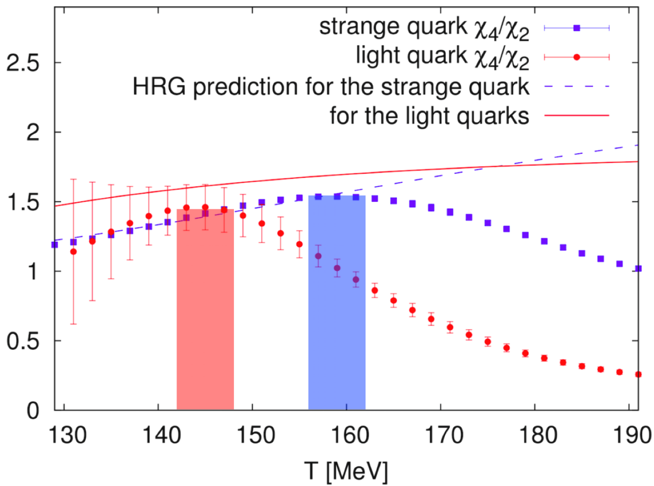
- PART I
  - Sequential Hadronization Evidence
  - Collision Energy Dependence of Chemical Freeze-out Parameters in A-A collisions via The FIST
    - Single Freeze-out Temperature (1CFO)
    - Multiple Freeze-out Temperatures (2CFO)
- PART II
  - Ad Hoc Modifications to Hadronic Spectrum
    - Inclusion of Deuteron
    - Expansion to Charm

Excerpt from King Thrór's Map

Figure: Tolkien, J.R.R., *The Hobbit*. George Allen and Unwin. (1937).

PART I: ENERGY DEPENDENCE

Sequential Hadronization Evidence: Susceptibilities

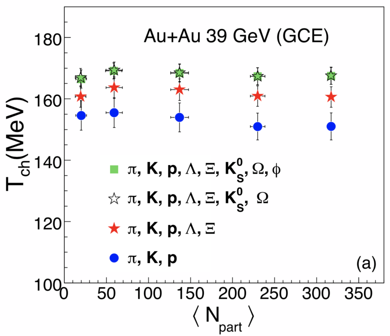


- Continuum extrapolated Lattice QCD χ_4/χ_2 results for light and strange quarks:
  - Depict different behaviors between light and strange quarks
    - flavour-specific "kinks" at particular temperatures
    - Deviations of lattice curves coinciding with said kinks
  - Support flavour separation of characteristic temperatures
    - ~15 MeV higher for strange quarks
- Similar findings exist from Hadron Resonance Gas (HRG) Model Calculations
  - Event-by-event net particle multiplicity fluctuations via flavour specific χ_1/χ_2 ratios
  - Thermal Fits based on Experimental Yields

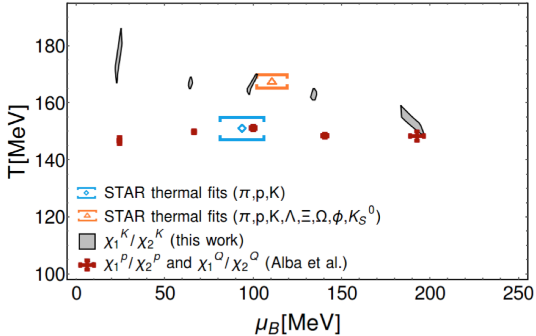
Figure: R. Bellwied and WB Collab. Phys. Rev. Lett. **111** (2013)

Sequential Hadronization Evidence: STAR

Based on Yields



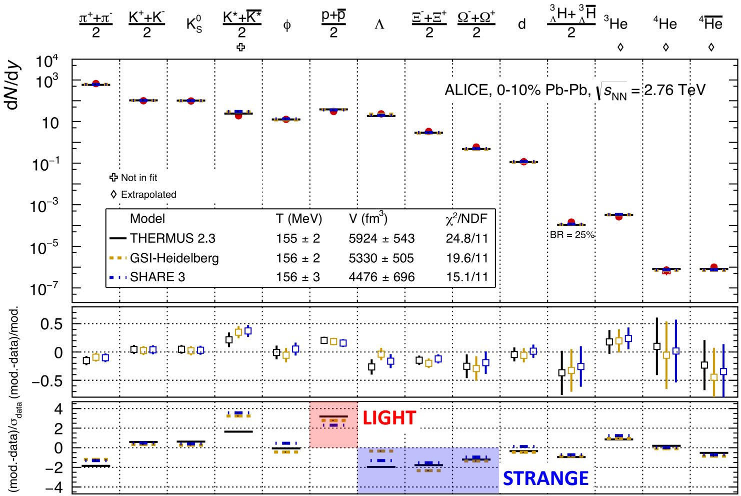
Based on Fluctuations



- Phenomenological Evidence at STAR (AuAu 39 GeV):
  - Common T_{ch} when all particle species are fit
  - T_{ch} "drops" by 15 - 20 MeV if only light-flavor particles are fit (π K p)
- Hadron Resonance Gas (HRG) Model Calculations via flavor specific χ_1/χ_2 ratios
  - Support energy dependent separation of freeze-out temperatures

Figures: STAR Collaboration. Phys. Rev. C. **96** (2017) and R. Bellwied et al. Phys. Rev. C **99**. (2019)

Sequential Hadronization Evidence: ALICE



Preliminary data for PbPb @ 5.02 TeV shows even greater tension.

Pseudo-critical temperature from Lattice QCD: 158±14 MeV †

Seems to coincide with single chemical freeze-out temperature at ALICE, $T_{ch} = 156 \pm 2$ MeV

- Apparent tension between strange and light baryons
  - 3σ effect in protons
  - -2σ effect in Ξ

Question at hand: Does hadronization occur at the same temperature for all quark flavours?

Figure: F. Bellini (ALICE Collaboration). Nucl. Phys. A. **971** (2018)., † Borsanyi, et al. (2020). Phys. Rev. Lett. **125** (2020).

Thermal FIST (The FIST)

- User-friendly package within the family of HRG models
  (Hadron Resonance Gas Model ~ Statistical Hadronization Model)
  - V. Vovchenko, H. Stoecker. (Comput. Phys. Commun. **244** (2019))
  - HRG Model Options
    - Ideal, Diagonal Excluded Volume, van der Waals
    - Parameterization of S-matrix approach
    - Finite resonance widths
  - Statistical Ensemble Options
    - Grand Canonical, Canonical, Strangeness Canonical
- Primary Modes
  - Thermal Fit Mode — Extracting Freeze-out Parameters from Experimental Yields
  - Thermal Model Mode — Calculating Yields from fixed Freeze-out Parameters
  - Event Generator Mode
- User Input
  - Hadronic Spectrum
  - Experimental Yields

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Hadronic Spectrum (Particle Data Group Lists)

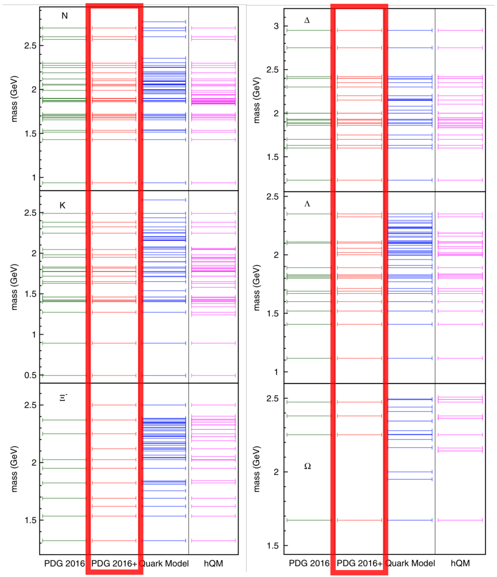


Figure: P. Alba et al. Phys . Rev. D. **96** (2017)

- Ideal HRG Model assumes a noninteracting gas of hadrons and resonances
  - The more complete the hadronic spectrum, the closer the model is to reality
- There exists different levels of confidence on the existence of individual resonances
  - From Particle Data Group (PDG)
  - **** Denotes **Well-Established States**
  - * Denotes States with least experimental confirmation
    - Incomplete decay channel information/branching ratios

From Houston Theory Group:

- **PDG2016+: 738 States (*, **, *** and ****)**
  - Provides best compromise between number of states
  - **Used for entirety of this work**
  - See Alba et al. (Phys. Rev. C. **101** (2020)) for a detailed description of the effect of additional resonances on freeze-out parameters.

Experimental Yields Used in this Study

- ALICE
  - PbPb @ 5.02 TeV (Nuclear Physics A. **982** (2019))
  - PbPb @ 2.76 TeV (Phys. Rev. C. **88** (2013))
- STAR
  - AuAu @ 200 GeV (Phys. Rev. C. **79** (2009))
  - AuAu @ 64.2 GeV (Phys. Rev. C. **83** (2011))
  - AuAu @ 39.0 GeV (Phys. Rev. C. **96** (2017) and Phys. Rev. C. **102** (2020))
  - AuAu @ 27.0 GeV (Phys. Rev. C. **96** (2017) and Phys. Rev. C. **102** (2020))
  - AuAu @ 19.6 GeV (Phys. Rev. C. **96** (2017) and Phys. Rev. C. **102** (2020))
  - AuAu @ 11.5 GeV (Phys. Rev. C. **96** (2017) and Phys. Rev. C. **102** (2020))

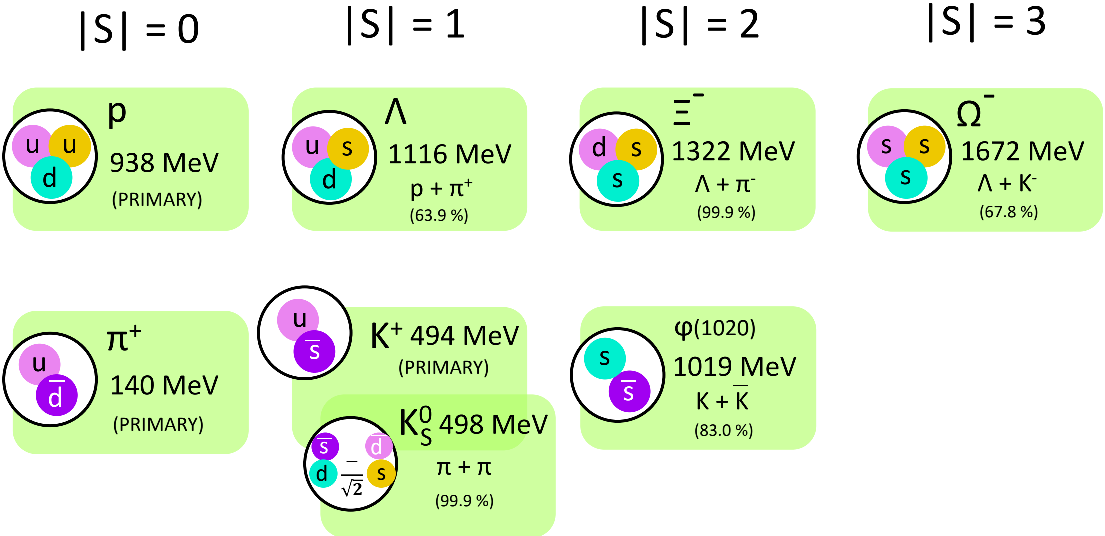
- For all STAR Energies, (anti)proton yields are "all inclusive"
  - Not corrected for weak-decay feed-down contributions from Λs
    - For this work, (anti)proton yields corrected via Andronic et al. (Nucl. Phys. A. **772** (2006))

Collision Energy Dependence of Chemical Freeze-out Parameters in A-A collisions

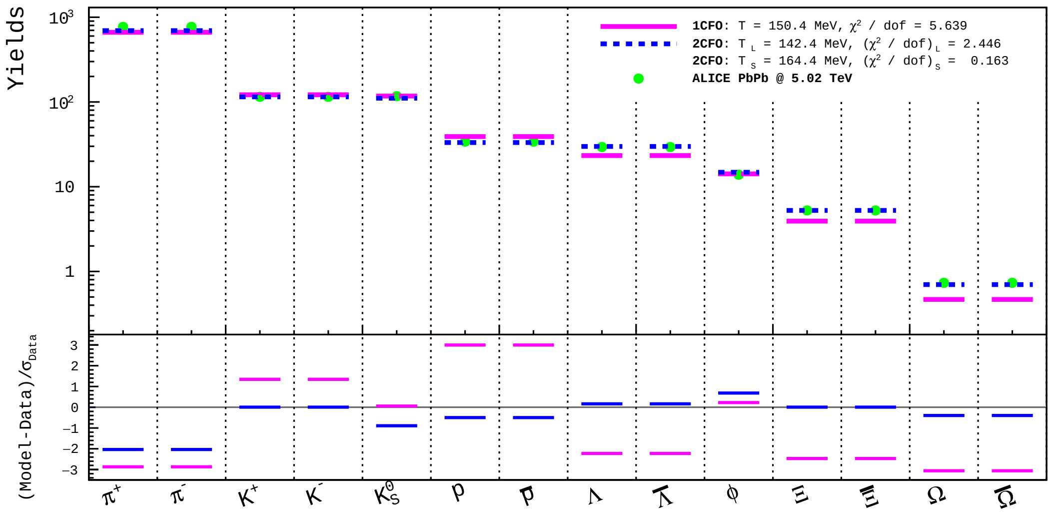
- Input available ALICE and STAR data into The FIST; extract freeze-out parameters
  - **Grand Canonical Ensemble**
  - Most Central Bin (0 - 10 %)
  - Fit Parameters:
    - Model: Ideal
    - **Fitting T, V and μ_B**
  - Particles in Fit:
    - π^+, π^-, K^+, K^-, p, $\bar{p}$, Λ, $\bar{\Lambda}$, Ξ^-, $\bar{\Xi}^+$, Ω^- and $\bar{\Omega}^+$ (K^0_S and ϕ where available)†
    - **Perform multiple fits w/ different combinations of the above**
    - Examine sensitivity of fit parameters when fitting different particle species
    - Compare with HRG Model Susceptibility Calculations
    - Compare with Lattice Calculations
  - Particle/Decay List
    - **PDG2016+**

†Shorthand notation is henceforth used (e.g. Ω refers to both Ω^- and $\bar{\Omega}^+$, etc.)

The Culprits

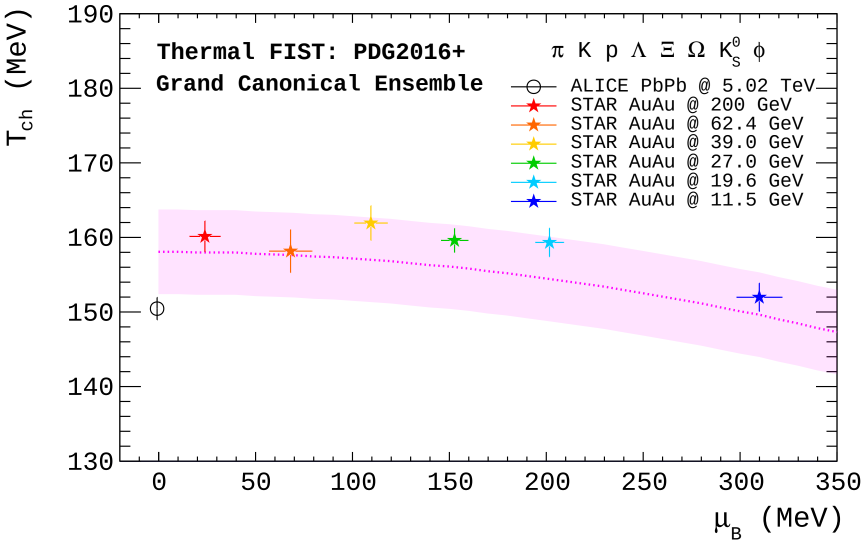


The FIST: PDG2016+ Fits PbPb @ 5.02 TeV (0 - 10%)



FAF et al. Phys. Lett. B. **814** (2021)

Energy Dependence: “Full” Fit



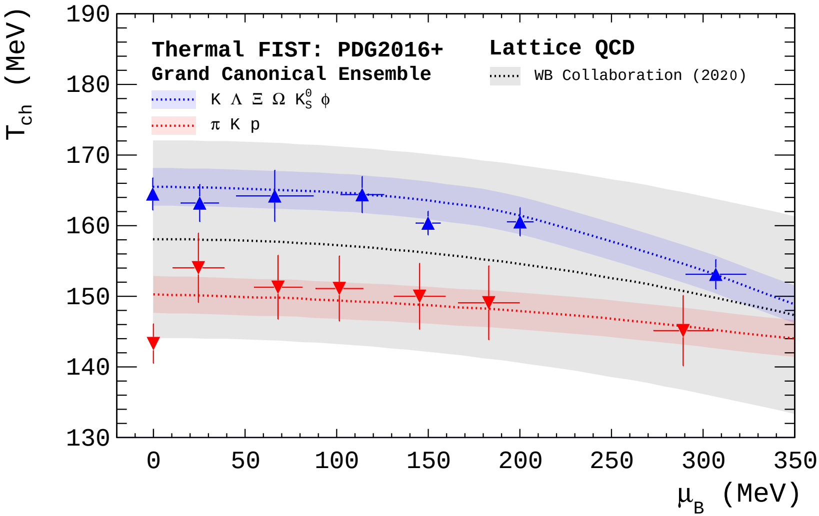
$T|_{\mu_B=0} = 157 \pm 3.8$ MeV

Next, we parameterize $T|_{\mu_B=0}$ value for flavour specific fits and check for energy dependent temperature splitting

FAF et al. Phys. Lett. B. **814** (2021)

Energy Dependence (0 - 10%): Flavour Specific Fits

- Supports a flavour-dependent freeze-out temperature



$T|_{\mu_B=0}$ values:

$T_L = 150.2 \pm 2.6$ MeV

$T_S = 165.1 \pm 2.7$ MeV

$T_{LQCD} = 157 \pm 14$ MeV

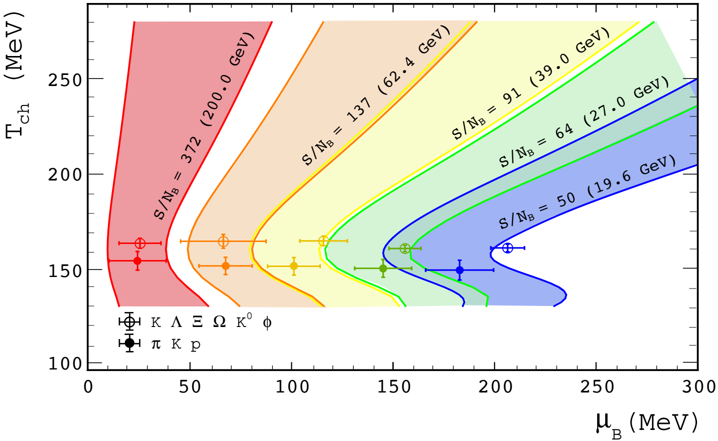
By eye, T_L and T_S lines converge at high μ_B

If we use temperatures extracted from yields that serve as susceptibility (i.e. order parameter) proxies, then our measurements may signal a critical point at high μ_B.

FAF et al. Phys. Lett. B. **814** (2021) and WB Collaboration Phys. Rev. Lett. **125** (2020)

Isentropic Trajectories Cross-Check

- Check if 2CFO parameters lie on isentropes in T-$\mu_{\rm B}$ plane



- Calculated via a Lattice QCD EoS †
- Validity to finite densities has been shown up to $\mu_{\rm B}/{\rm T}=2$
  - Exclusions:
    - STAR AuAu @ 11.5 GeV
    - ALICE PbPb (S/$N_{\rm B}$ diverges)
- ∀ Energies, our light and strange freeze-out parameters lie well within the projected trajectories
  - Uncertainties based on folding errors of the light hadron freeze-out parameters.

Special Thanks to **J.M. Stafford** for these calculations

FAF et al. Phys. Lett. B. **814** (2021) and † Guenther, J.N. et al. Nucl. Phys. A. **967** (2017)

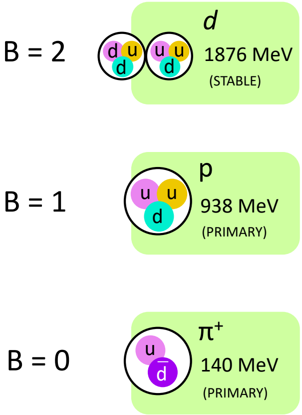
PART II: THERMAL MODEL EXPANSION

Experimental Yields Used in this Study

- ALICE
  - PbPb @ 5.02 TeV (Nuclear Physics A. **982** (2019))
  - PbPb @ 2.76 TeV (Phys. Rev. C. **88** (2013))
    - (anti-)Deuteron Yields: Phys. Rev. C. **93** (2016))
  - pPb @ 5.02 TeV (Phys. Lett. B. **728** (2014))
  - pp @ 7.00 TeV (Nature Phys. **13** (2017))

We begin with an ad hoc cross-check to prove to ourselves the inclusion of K in the *light* fit is OK within some reasonable bound

Addition of Deuteron to Hadronic Spectrum



|S| = 0

Inclusion of (anti-)deuteron to particle list provides extra degree of freedom fo thermal fits

- Allows for a "true" light particle fit to yields
- Removes need for K presence in all fits
  - K Yields have been shown to be insensitive to FO Temperature (D. Magestro Phys. G. **28** (2002).)

Other considerations:

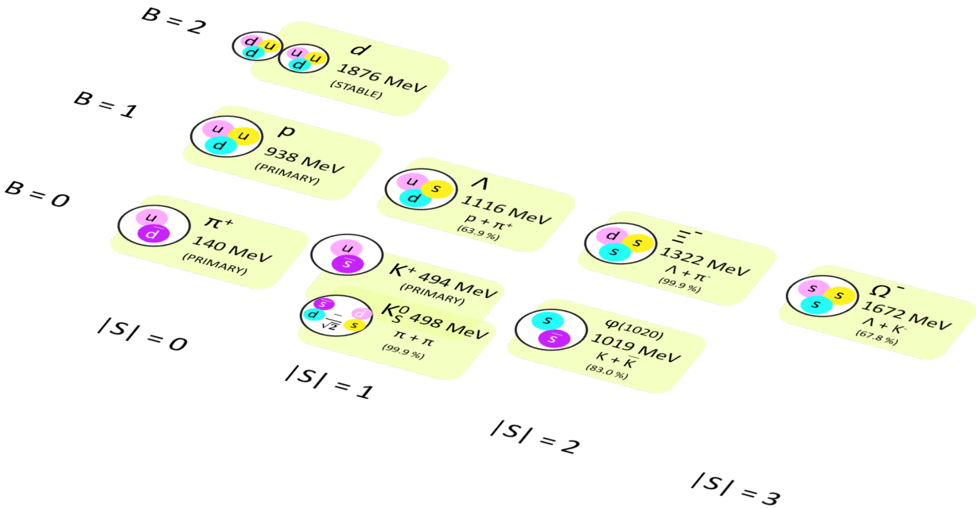
- Increasing Baryon Number
- Mass similar to charmed mesons
  - $m_{D^0} = 1865$ MeV
  - $m_{D^\pm} = 1870$ MeV

The FIST: PDG2016+ Fits PbPb @ 2.76 TeV (0 - 10%)

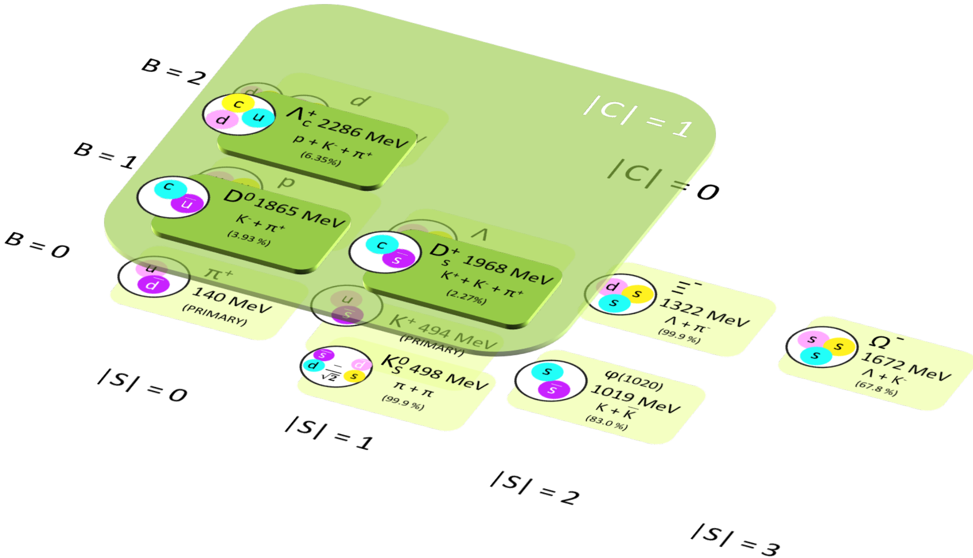
Fit	μ_{B} (MeV)	T_{ch} (MeV)	$V(fm^3)$	χ^2/dof
πpd	0.0	144.6 ± 2.39	7911.6 ± 1177	1.36
$\pi Kp\Lambda\Xi\Omega K^0_S\phi d$	0.0	150.1 ± 1.65	5613.6 ± 588.5	1.71
$K\Lambda\Xi\Omega K^0_S\phi$	0.0	153.9 ± 2.30	4389.7 ± 640.8	1.31
πKp	0.0	143.2 ± 2.79	8031.7 ± 1263	1.41
$\pi Kp\Lambda\Xi\Omega K^0_S\phi$	0.0	149.6 ± 1.76	5764.4 ± 635.8	1.95
$K\Lambda\Xi\Omega K^0_S\phi$	0.0	153.9 ± 2.30	4389.7 ± 640.8	1.31

- Inclusion of πpd fit instead of πKp improves quality of light fit
  - Good compromise between fit quality and flavour content
  - Ad Hoc Cross-check: Success

Addition of Charmed Hadrons to Hadronic Spectrum



Addition of Charmed Hadrons to Hadronic Spectrum



Addition of Charmed Hadrons to Hadronic Spectrum

- Inclusion of 80 additional states to the PDG2016+ List from PDG2020
  - Including (Hyper) Nuclei
  - Mass Cut-off: 5.62 GeV (Λ_{b}^{0})
  - Specifically with feed-down contributions to
    - D^0, $D^{\pm}$, $D_{\mathrm{s}}^{\pm}$,D^{0*}, $D^{\pm *}$, and J/ψ (incomplete)

Charmed Statistical Hadronization Model

- Charmonia are "implanted" into QGP (Matsui and Satz ca. 1986)
  - Modification is observed in terms of sequential melting
- Charmonia are screened by QGP (Stachel and PBM ca. 2000)
  - Production occurs at phase boundary
  - Signal for deconfined charm quarks
  - Production scales as a function of collision energy
  - Thermalized charm quark production probability scales with $N_{c\bar{c}}^2$ with fugacity g_c

Preliminary D^0 Yield Calculation

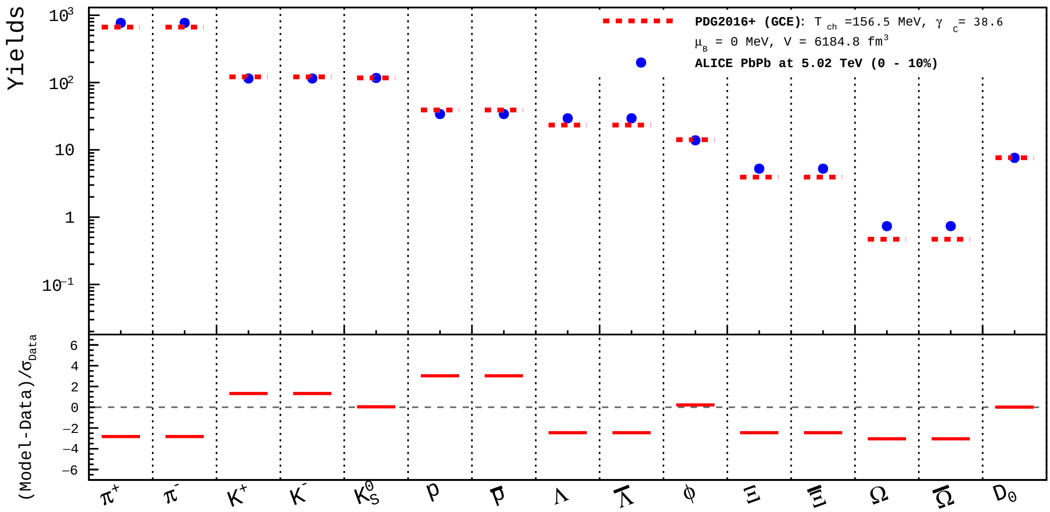
- Grand Canonical Ensemble
  - $T_{\mathrm{ch}} = 156.5$ MeV
  - $\mu_{\mathrm{B}} = 0$ MeV
- Experimental D^0 Yield is used in fit
  - Charmed hadrons are calculated by Model

Fugacity g_c determined by charm balance function:

$$N_{c\bar{c}} = \frac{1}{2} g_c V \Big(\textstyle\sum_i n^{th}_{D_i} + n^{th}_{\Lambda_i} + \ldots \Big) + g_c^2 V \Big(\textstyle\sum_i n^{th}_{\psi_i} + n^{th}_{\chi_i} + \ldots \Big) + \ldots$$

Where $N_{c\bar{c}}$ obtained from measured charm cross-section from pp @ 7 TeV, shown to be 0.954 ± 0.69 mb (Eur. Phys. J. C77 (2017) 550)

The FIST: PDG2016+C Fits PbPb @ 5.02 TeV (0 - 10%)



Based off BGBW Fit to D^0 p_T Spectrum: ALICE Collaboration. JHEP. 174 (2018)

Summary/Discussion

PART I:

At a vanishing baryochemical potential, we calculate light and strange flavour freeze-out temperatures, respectively:

- $T_{\mathrm{L}} = 150.2 \pm 2.6$ MeV
- $T_{\mathrm{S}} = 165.1 \pm 2.7$ MeV

- Flavour separation confirmed from LHC down to lower RHIC energies
  - Confirms flavor hierarchy extends into BES
  - Flavour dependent fits consistently depict an overall better quality of fit
  - Potential convergence of T_L and T_S lines at high μ_B might signal interesting physics

SCAN ME

Summary/Discussion (cont.)

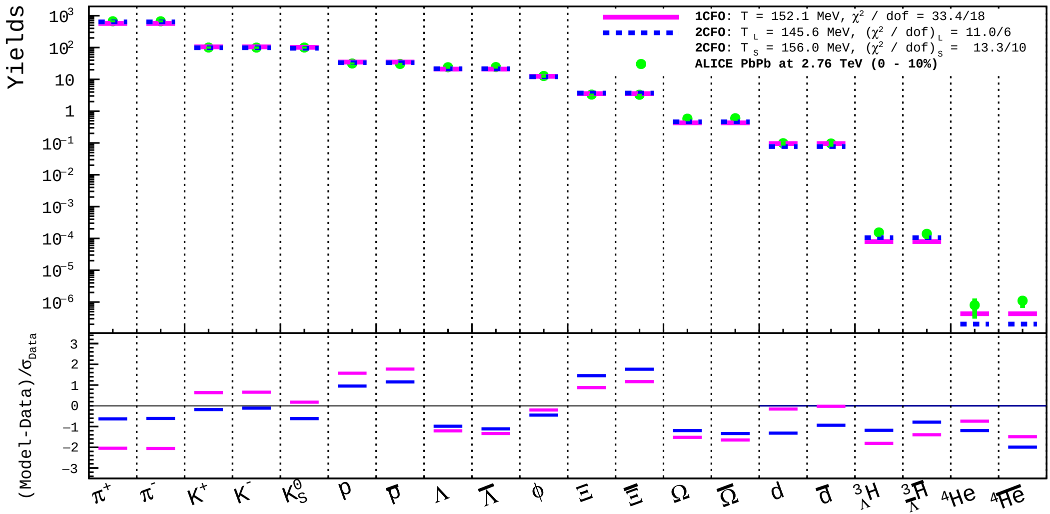
PART II: (IN PROGRESS)

- Mass similarity between (anti-)deuteron to charmed meson to be exploited
  - $m_d = 1876$ MeV
  - $m_{D^0} = 1865$ MeV
  - $m_{D^\pm} = 1870$ MeV
    - Vast differences in particle production of charmed vs non-charmed hadrons
- Charm extension to SHM underway †
  - Considering scaling factor γ_C to take initial charm production into account
  - D^0 Yield seems to be properly replicated by preliminary Thermal Model calculations
- Inclusion of H^3_Λ into strange fit
- Expansion of 2CFO Campaign
  - System Size Multiplicity Dependence at ALICE

† In Collaboration with B. Hippolyte and O. Poncet (U. Strasbourg)

CAVALRY

The FIST: PDG2016+ Fits PbPb @ 2.76 TeV (0 - 10%)



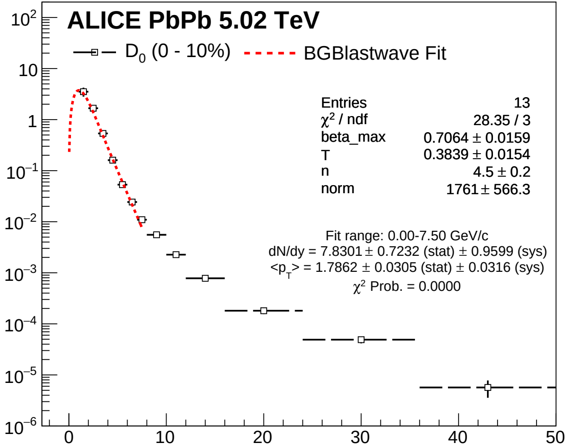
(anti-)H^3_Λ and (anti-)He^4 Yields: ALICE Collaboration. Phys. Lett. B. 754 (2016) and Nucl. Phys. A. 93 (2018)

The FIST: PDG2016+ Fits PbPb @ 2.76 TeV (0 - 10%)

Fit	μ_B (MeV)	T_{ch} (MeV)	$V(fm^3)$	χ^2/dof
$\pi p d \mathrm{He}^4$	0.0	145.6 ± 2.55	7450.4 ± 1179.3	11.0/6
$\pi K p \Lambda \Xi \Omega K^0_S \phi d \mathrm{H}^3_\Lambda \mathrm{He}^4$	0.0	152.1 ± 1.71	4973.0 ± 542.0	33.4/18
$K \Lambda \Xi \Omega K^0_S \phi \mathrm{H}^3_\Lambda$	0.0	156.0 ± 2.19	3887.5 ± 543.5	13.3/10
$\pi p d$	0.0	144.6 ± 2.39	7911.6 ± 1177	5.45/4
$\pi K p \Lambda \Xi \Omega K^0_S \phi d$	0.0	150.1 ± 1.65	5613.6 ± 588.5	23.9/14
$K \Lambda \Xi \Omega K^0_S \phi$	0.0	153.9 ± 2.30	4389.7 ± 640.8	10.5/8
$\pi K p$	0.0	143.2 ± 2.79	8031.7 ± 1263	5.65/4
$\pi K p \Lambda \Xi \Omega K^0_S \phi$	0.0	149.6 ± 1.76	5764.4 ± 635.8	23.4/12

- Inclusion of $\pi p d \mathrm{He}^4$ fit instead of $\pi p d$ does not seem improve quality of any fit

ALICE PbPb @ 5.02 TeV (0 - 10%) D^0 BGBW Fit



D^0 p_T Spectrum: ALICE Collaboration. JHEP. 174 (2018)