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

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Fernando Antonio Flor

Gabrielle Olinger

René Bellwied

University of Houston

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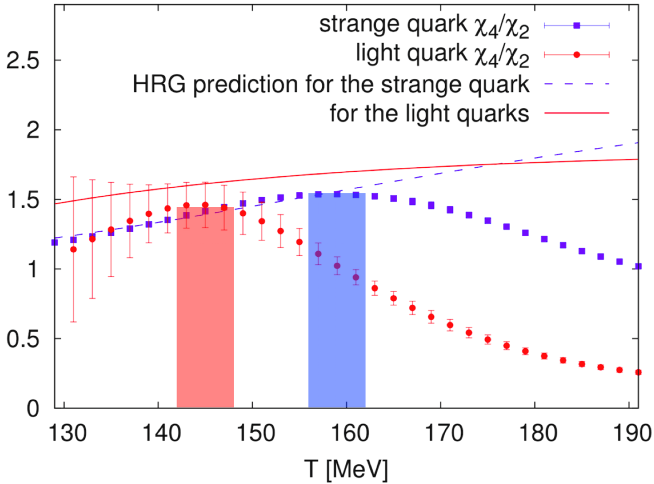
Overview

- Motivation
  - Sequential Hadronization Evidence
- The FIST
- Collision Energy Dependence of Chemical Freeze-out Parameters in A-A collisions
- System Size dependence of Chemical Freeze-out Parameters at ALICE
  - Single Freeze-out Temperature (1CFO)
  - Multiple Freeze-out Temperatures (2CFO)
- Summary
- Cavalry

Alice Meets the Cheshire Cat

Figure: Carroll, Lewis (illustrated by John Tenniel), *Alice's Adventures in Wonderland*. McMillan LTD. 1865.

Sequential Hadronization Evidence: Susceptibilities

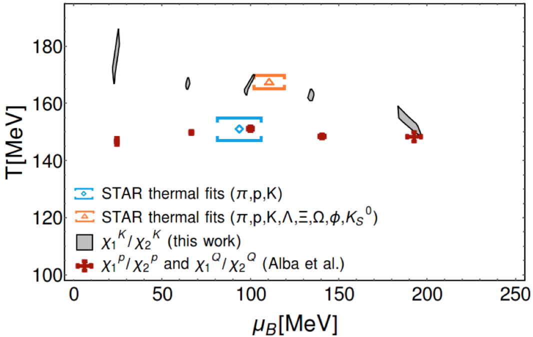


- Continuum extrapolated Lattice QCD χ_4/χ_2 results for light and strange quarks:
  - Depict different behaviors between light and strange quarks
    - Flavour-specific "kinks" at particular temperatures
    - Deviations of lattice curves coinciding with said kinks
  - Support flavour separation of 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

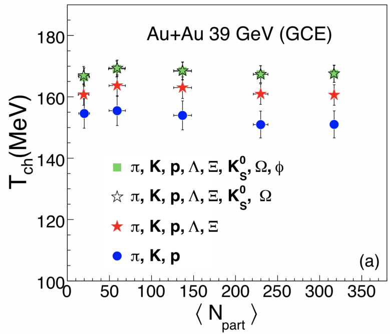
Figure: R. Bellwied and WB Collab. 10.1103/PhysRevLett.111.202302

Sequential Hadronization Evidence: STAR

Based on Fluctuations



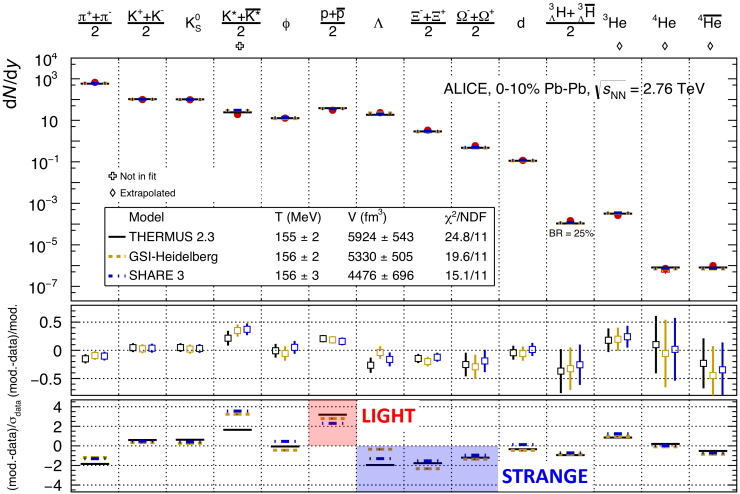
Based on Yields



- HRG Model Calculations via flavour specific χ_1/χ_2 ratios
  - Support energy dependent separation of freeze-out temperatures
- 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-flavour particles are fit (π K p)

Figures: R. Bellwied et al. 10.1103/PhysRevC.99.034912 and STAR Collab. 10.1103/PhysRevC.96.044904

Sequential Hadronization Evidence: ALICE



Model	T (MeV)	V (fm³)	χ²/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	24.8/11
GSI-Heidelberg	156 ± 2	5330 ± 505	19.6/11
SHARE 3	156 ± 3	4476 ± 696	15.1/11

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

Pseudo-critical temperature from Lattice QCD: 157±9 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

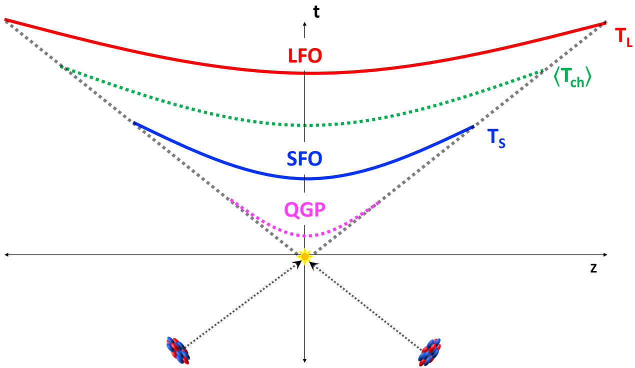
Question at hand:

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

Figure: ALICE Collab. 10.1016/j.nuclphysa.2017.12.004, † WB Collab. PLB (2015). 10.1016/j.physletb.2015.11.011

Sequential Strangeness Freeze-out: 2CFO Approach

- We model the idea of two chemical freeze-out (2CFO) temperatures
  - Strangeness Freeze-Out (SFO) occurs before Light Freeze-Out (LFO) ∋ $T_S > T_L$



Using a state-of-the-art thermal model package, we will show the 2CFO approach produces a more natural explanation of Strangeness Enhancement across various system energies and system sizes.

Thermal FIST (The FIST)

- User-friendly package within the family of HRG models

  (Hadron Resonance Gas Model ~ Statistical Hadronization Model)
  - V. Vovchenko, H. Stoecker. 10.1016/j.cpc.2019.06.024
  - 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)

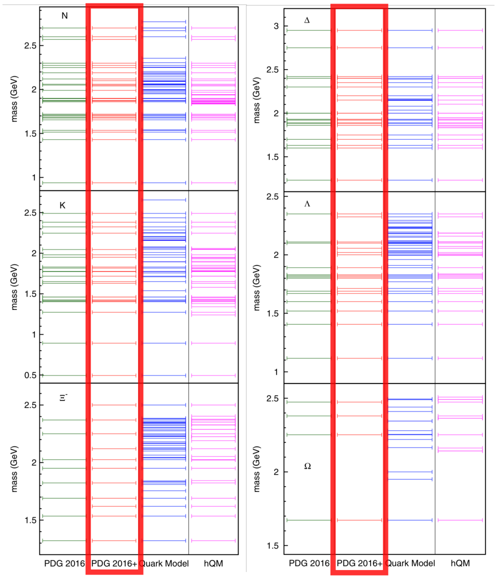


Figure: P. Alba et al. 10.1103/PhysRevD.96.034517

- 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 arXiv:2002.12395 (P. Alba et al.) for a detailed description of the effect of additional resonances on freeze-out parameters.

Experimental Yields Used in this Study

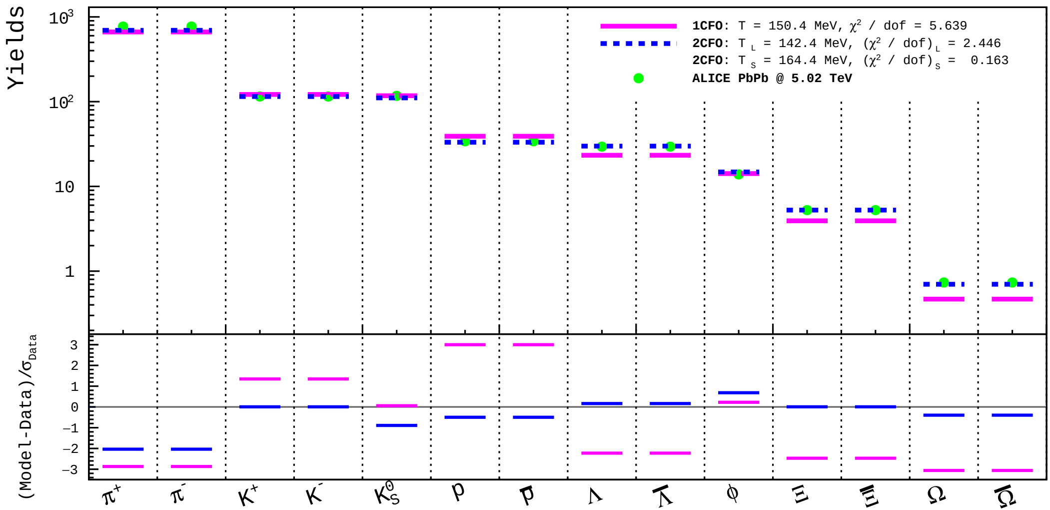
- ALICE
  - PbPb @ 5.02 TeV (10.1016/j.nuclphysa.2018.10.015)
  - PbPb @ 2.76 TeV (10.1103/PhysRevC.88.044910)
  - pPb @ 5.02 TeV (10.1016/j.physletb.2013.11.020)
  - pp @ 7.00 TeV (10.1038/nphys4111)
- STAR
  - AuAu @ 200 GeV (10.1103/PhysRevC.79.034909)
  - AuAu @ 64.2 GeV (10.1103/PhysRevC.83.024901)
  - AuAu @ 39.0 GeV (arXiv:1906.03732v1)
  - AuAu @ 27.0 GeV (arXiv:1906.03732v1)
  - AuAu @ 19.6 GeV (arXiv:1906.03732v1)
  - AuAu @ 11.5 GeV (arXiv:1906.03732v1)

- 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 10.1016/j.nuclphysa.2006.03.012 (Andronic et al. 2006)

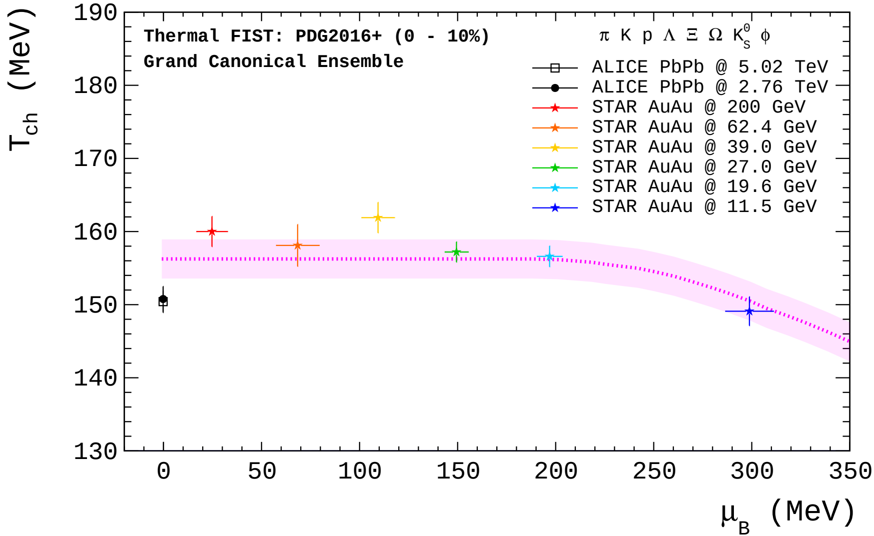
Collision Energy Dependence of Chemical Freeze-out Parameters in A-A collisions

- 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
    - Ensemble: Grand-Canonical
    - 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+

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



Energy Dependence: “Full” Fit

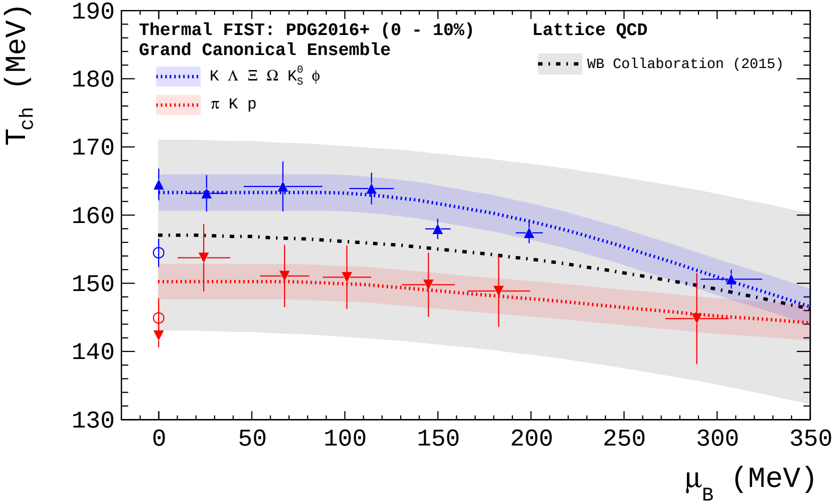


$T|_{\mu_B=0} = 157 \pm 3.8$ MeV

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

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 = 163.1 $\pm$ 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.

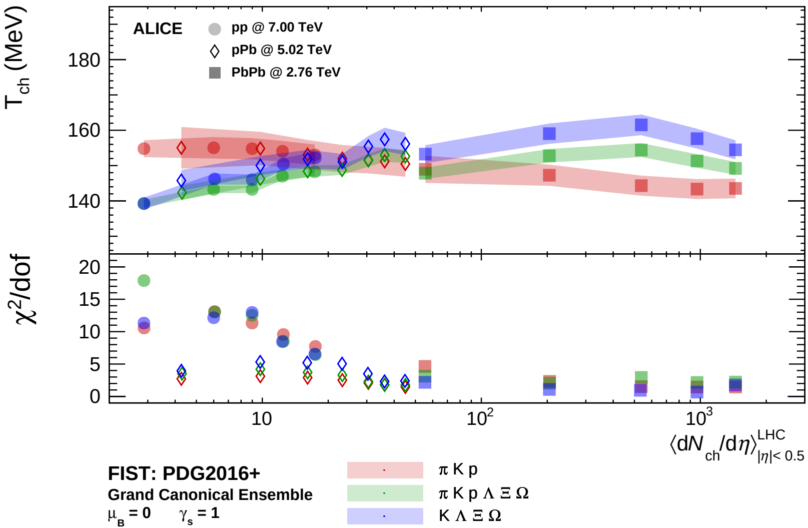
WB Collab. 10.1016/j.physletb.2015.11.011

System Size dependence of Chemical Freeze-out Parameters @ ALICE (1CFO)

- Run The FIST in Thermal Model Mode; extract yields ∀ ALICE Systems †
- All Centralities (Multiplicity classes)
- Fit Parameters:
    - Ensemble: Strangeness Canonical (Ideal Model)†
    - Fixing:
        - $\mu_B = 0$ MeV
        - $V = V_c$
        - $\gamma_S = 1$
    - Fixing freeze-out temperature to values extracted from Energy Dependence Procedure:
        - $T_L = 150$ MeV
        - $T_{ch} = 158$ MeV
        - $T_S = 163$ MeV
    - Particle/Decay List
        - PDG2016+
    - Compare anti-hadron to π^+ Calculated Yield Ratios
        - Normalizing WRT High-Multiplicity pp Limit

† Due to deterioration of GCE fit qualities in small systems (see next slide).

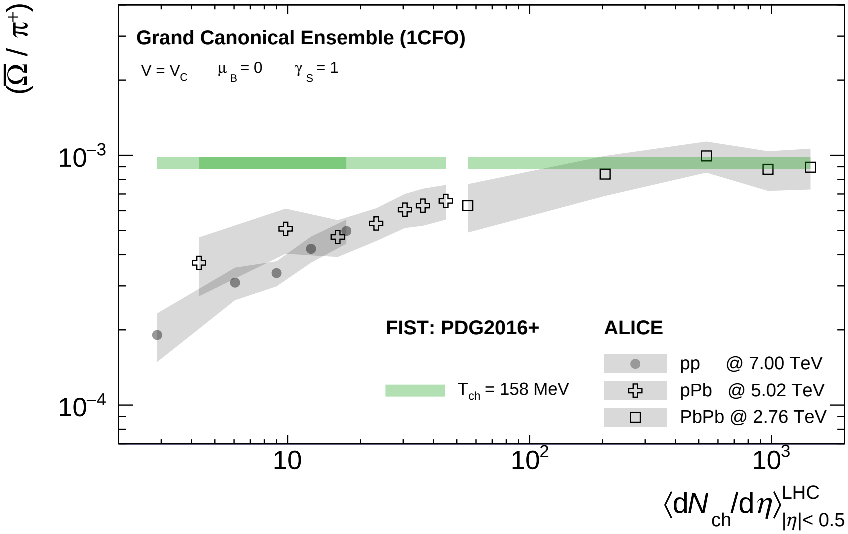
ALICE FIST Fits (GCE Trials)



GCE approach fails to adequately describe all three systems consistently

- Large systems:
  - Favor temperature splitting
  - Quality of fit is consistent ∀ multiplicities
  - Quality of fit slightly improves for flavour specific fits
- Smaller systems:
  - Not described well by SHM
  - Quality of fit worsens at low multiplicities
  - Full equilibration of systems is not likely

ALICE FIST Fits (GCE Trials)

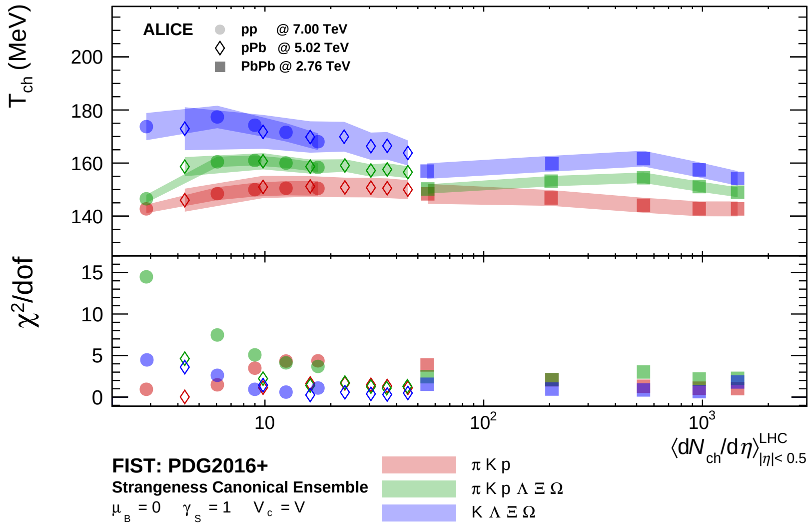


GCE approach fails to adequately describe all three systems consistently

- Particularly in Smaller systems:
  - Not described well by SHM
  - Quality of fit worsens at low multiplicities
  - Full equilibration of systems is not likely

Best bet is the Strangeness Canonical Ensemble

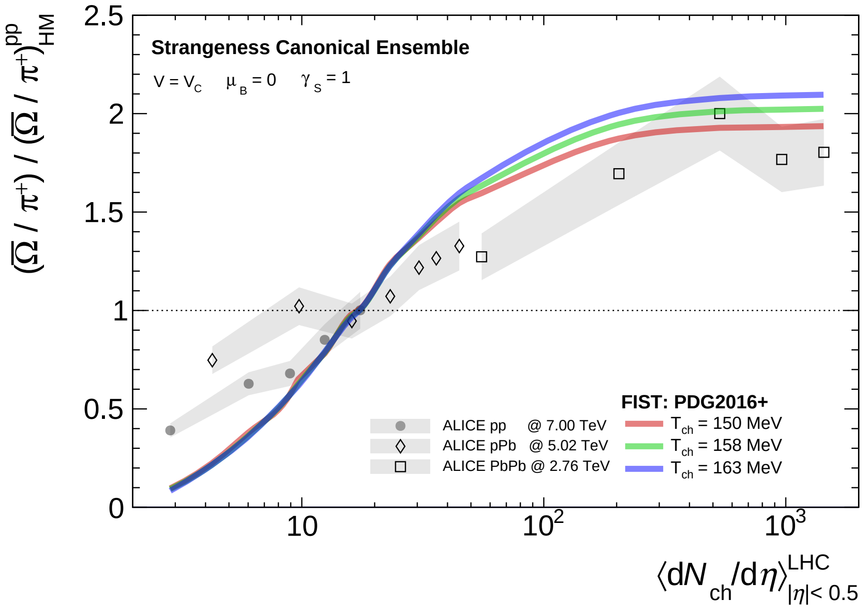
ALICE FIST Fits (SCE)



SCE approach adequately describes all three systems consistently

- Large systems:
  - Favor temperature splitting
  - Quality of fit is consistent ∀ multiplicities
  - Quality of fit slightly improves for flavour specific fits
- Smaller systems:
  - Favor temperature splitting
  - Quality is worst at lowest multiplicity class
  - For $dN_{ch}/d\eta > 10$, quality of fits are consistent with those from large systems
  - Quality of fit improves for flavour specific fits

FIST Thermal Model Mode (Ω) – Single Freeze-out Picture



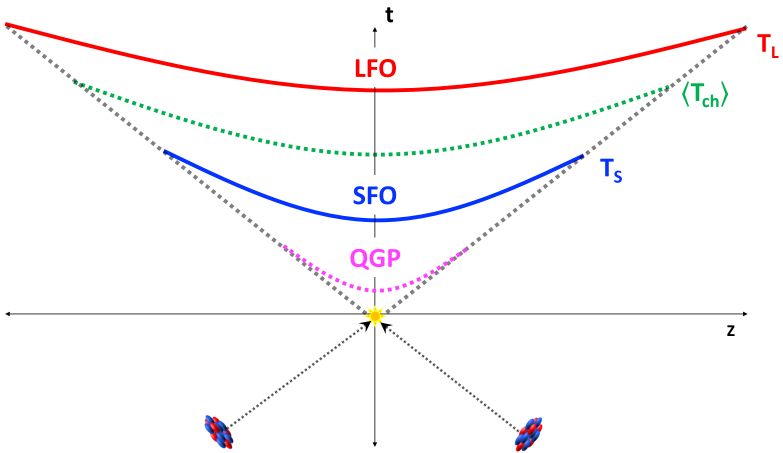
Single Freeze-out Picture (1CFO):

- Calculated Yields for $\bar{\Omega}$ and π^+
  - T_L = 150 MeV
  - T_C = 158 MeV
  - T_S = 163 MeV
- Inadequate description of Small Systems
  - Particularly in low-multiplicity classes
  - Is system really canonically suppressed?

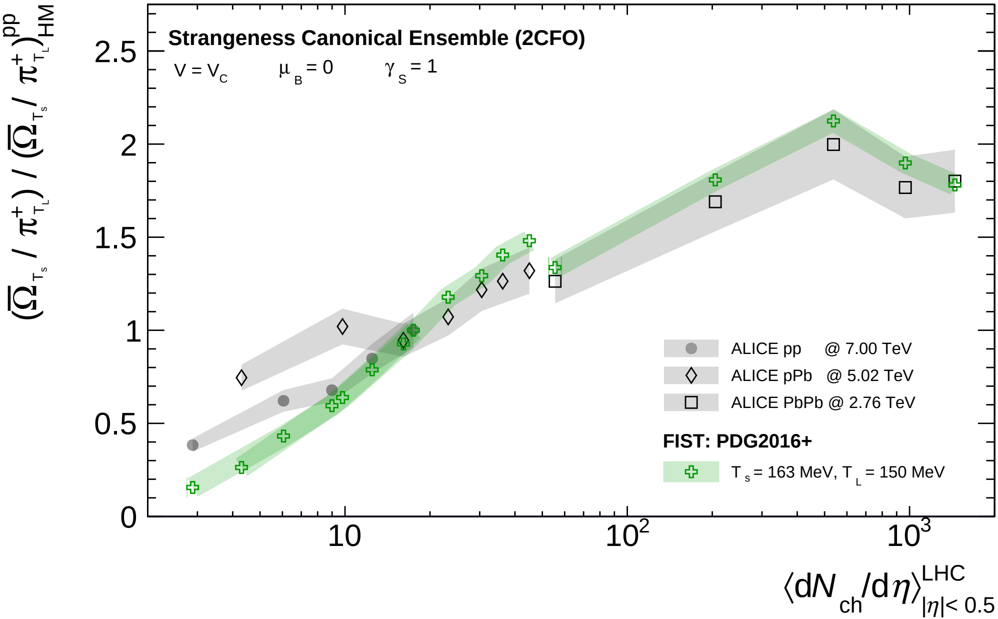
Is this effect different outside 1CFO picture?

System Size dependence of Chemical Freeze-out Parameters @ ALICE (2CFO)

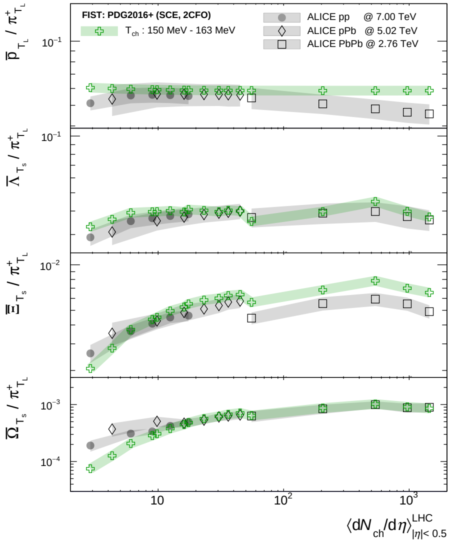
- Repeat previous procedure, now assuming **two** freeze-out temperatures (2CFO)
  - π^+ Yields Extracted from T_L = 150 MeV – Light Freeze-out (LFO)
  - $\bar{h}$ Yields Extracted from T_S = 163 MeV – Strange Freeze-out (SFO)
  - Ratios calculated and normalized accordingly
    - WRT High-Multiplicity pp Limit



FIST Thermal Model Mode (Ω) – 2CFO Picture



Summary – FIST Thermal Model Mode 1CFO v. 2CFO



- 2CFO Picture describes all systems more adequately than the 1CFO picture
  - Strangeness Equilibration in small systems seems inaccurate
    - γ_S and V_c to be considered
- Questions at hand:
  - Does the 2CFO Picture more adequately describe Strange Baryon Production across all LHC Systems?
  - Can the 2CFO treatment be applied across all BES Energies
    - Namely for $\mu_B \neq 0$
  - Is Strangeness fully saturated at top LHC Energies?

See Cavalry for Deviation plots.

Outlook

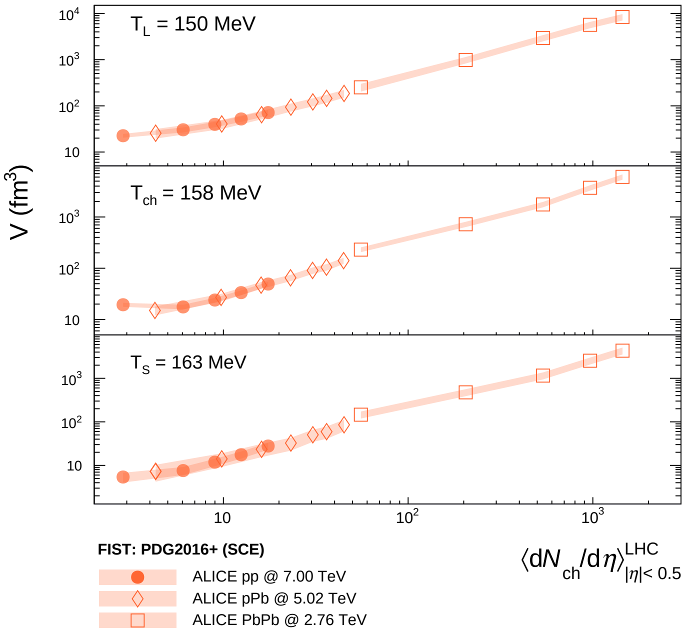
- Flavour separation confirmed from LHC down to lower RHIC energies
  - Flavor dependent fits consistently depict an overall better quality of fit
  - Confirms flavour hierarchy extends into BES
  - Potential convergence of T_L and T_S lines at high μ_B might signal interesting physics

- We show evidence for a flavour-dependent chemical freeze-out temperatures in the cross-over region of the QCD phase diagram
  - Converge above $\mu_B = 300$ MeV

- Ongoing analyses:
  - Centrality Dependent 2CFO Scheme for BES Energies
  - SCE with Strangeness Saturation Factor γ_S and Correlation Volume V_C
  - Charm Canonical Ensemble (CCE); including charmed hadrons in thermal fit
  - Upper-bound thermal model calculations for exotica yields

CAVALRY

System Size Volume Dependence (ALICE)



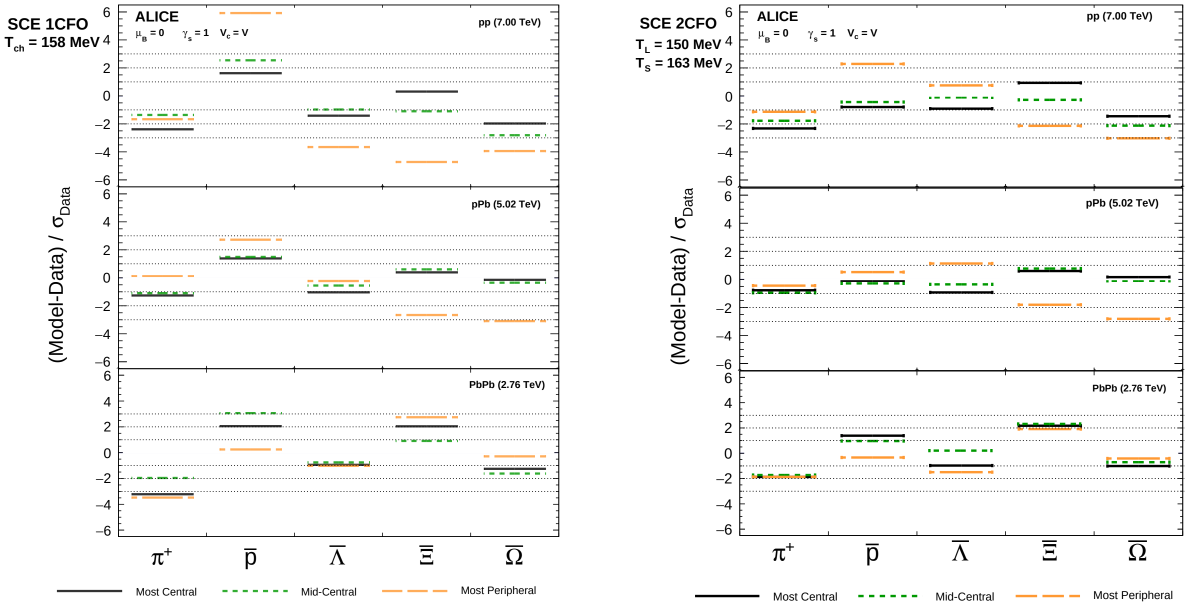
Extrapolated STAR (Anti)Proton Feed-down Contributions

- Applied to STAR Data prior to performing fits via The FIST

	Proton		Anti-Proton	
$\sqrt{s_{NN}}$	δ	$(1-\delta)$	δ	$(1-\delta)$
7.70 GeV	19.00%	81.00%	56.50%	43.50%
11.5 GeV	23.00%	77.00%	48.00%	52.00%
19.6 GeV	27.50%	72.50%	44.00%	56.00%
27.0 GeV	29.50%	70.50%	41.50%	58.50%
39.0 GeV	31.00%	69.00%	40.00%	60.00%
64.2 GeV	32.00%	68.00%	38.50%	61.50%
200 GeV	34.00%	66.00%	36.50%	63.50%

Extrapolation to BES Data from methods in: Andronic et al. (2006). 10.1016/j.nuclphysa.2006.03.012 (Andronic et al. 2006)

FIST 1CFO and 2CFO Deviations



Centrality (Multiplicity) Classifications

- ALICE pp @ 7.00 TeV
  - Most Central: 0 - 4.7%; dubbed as "High-Multiplicity pp Limit" (HMpp)
    - Used ∀ Normalizations
  - Mid-Central: 14 - 28%
  - Most Peripheral: 48 - 100%
- ALICE pPb @ 5.02 TeV
  - Most Central: 0 - 5%
  - Mid-Central: 20 - 40%
  - Most Peripheral: 80 - 100%
- ALICE PbPb @ 2.76 TeV
  - Most Central: 0 - 10%
  - Mid-Central: 20 - 40%
  - Most Peripheral: 60 - 80%

ALICE pp @ $\sqrt{s} = 7$ TeV Reference Multiplicities

Enhanced Production of Multi-Strange Hadrons in High-Multiplicity Proton-Proton Collisions.
ALICE Collaboration. 2017. Nature.Phys.13.2017.535-539.

Class Name	$\sigma/\sigma_{INEL>0}$	$\langle dN_{ch}/d\eta \rangle$
I	0 - 0.95 %	21.3 ± 0.6
II	0.95 - 4.7 %	16.5 ± 0.5
III	4.7 - 9.5 %	13.5 ± 0.4
IV	9.5 - 14 %	11.5 ± 0.3
V	14 - 19 %	10.1 ± 0.3
VI	19 - 28 %	8.45 ± 0.25
VII	28 - 38 %	6.72 ± 0.21
VIII	38 - 48 %	5.40 ± 0.17
IX	48 - 68 %	3.90 ± 0.14
X	68 - 100 %	2.26 ± 0.12

Event multiplicity classes, their corresponding fraction of the INEL>0 cross-section ($\sigma/\sigma_{INEL>0}$) and their corresponding $\langle dN_{ch}/d\eta \rangle$ at midpseudorapidity ($|\eta| < 0.5$).

ALICE pPb @ $\sqrt{s_{NN}} = 5.02$ TeV Reference Multiplicities

Multiplicity Dependence of Pion, Kaon, Proton and Lambda Production in p-Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. ALICE Collaboration. 2014. Phys. Lett. B 728 (2014) 25-38.

Event Class	V0A Range	$\langle dN_{ch}/d\eta \rangle$
0 - 5 %	> 227	45 ± 1
5 - 10 %	187 - 227	36.2 ± 0.8
10 - 20 %	142 - 187	30.5 ± 0.7
20 - 40 %	89 - 142	23.2 ± 0.5
40 - 60 %	52 - 89	16.1 ± 0.4
60 - 80 %	22 - 52	9.8 ± 0.2
80 - 100 %	< 22	4.4 ± 0.1

Definition of the event classes as fractions of the analyzed event sample and their corresponding $\langle dN_{ch}/d\eta \rangle$ within ($|\eta_{lab}| < 0.5$).

ALICE PbPb @ $\sqrt{s_{NN}} = 2.76$ TeV Reference Multiplicities

Centrality Dependence of π, K, and p Production in Pb-Pb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. ALICE Collaboration. 2013. Phys. Lett. C 88, 044019 (2013).

Centrality	$\langle dN_{ch}/d\eta \rangle$	Norm. Uncertainty
0 - 5 %	1601 ± 60	0.5 %
5 - 10 %	1294 ± 49	0.5 %
10 - 20 %	966 ± 37	0.7 %
20 - 30 %	649 ± 23	1 %
30 - 40 %	426 ± 15	2 %
40 - 50 %	261 ± 9	2.4 %
50 - 60 %	149 ± 6	3.5 %
60 - 70 %	76 ± 4	5 %
70 - 80 %	35 ± 2	6.7 %
80 - 90 %	$13.4 + 1.6 - 1.2$	$+12$ % - 8.5%

$\langle dN_{ch}/d\eta \rangle$ within ($|\eta| < 0.5$) with additional uncertainties from centrality definitions.