Multi freeze-out scenarios and exotica

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University of Wrocław, Wrocław, Poland

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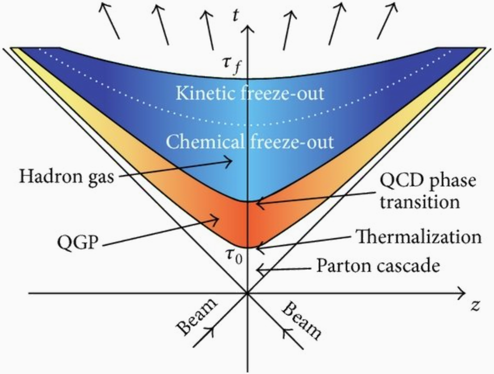
Introduction - Freeze-out

The stages of a heavy-ion collision

- **Thermalization**: after a short time τ_0 the system thermalizes to a QGP (if the energy density is sufficient)
- **Hadronization**: when the system reaches T_C, hadrons are formed
- **Chemical freeze-out**: all inelastic collision cease and chemical composition is fixed (**yields, fluctuations**)
- **Kinetic freeze-out**: elastic collisions cease and spectra are fixed → free streaming to the detectors

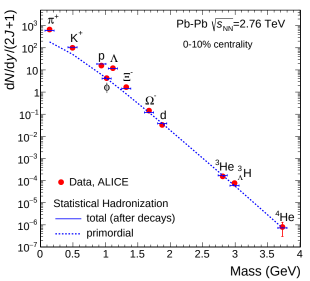


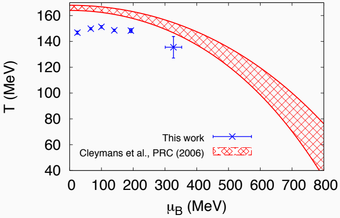
Hui Wang's PhD thesis [Wang:2012jua]

Introduction - Freeze-out parameters

Extract freeze-out parameters $(T_{\rm FO}, \mu_{B,\rm FO}, V_{FO})$:

- Compare theoretical predictions and experimental measurements
  - Thermal models have had great success at reproducing particle yields
  - Also, thermal models have great successs in reproducing thermodynamics from lattice QCD
- Comparison is carried out for **particle yields** and **net-particle fluctuations**
  - Volume dependence can be canceled to first approximation with ratios of yields or fluctuations
- Measurements available in different systems, at different energies, for different observables





Alba *et al.* Phys.Lett. B738 (2014), Andronic *et al.* Nature 561 (2018) no.7723

Thermal models: yields and fluctuations

Thermal yields in the Hadron Resonance Gas (HRG) model can be easily calculated:

$$N_i = -T\frac{\partial \ln \mathcal{Z}_i}{\partial \mu_i} = \frac{d_i V}{2\pi^2}\int_0^\infty dp \frac{p^2}{\exp[(\epsilon_i - \mu_i)/T] \pm 1}$$

Similarly, **fluctuations** are defined as:

$$\chi_{ijk}^{BQS}(T, \mu_B, \mu_Q, \mu_S) = \frac{\partial^{i+j+k} P\left(T, \mu_B, \mu_Q, \mu_S\right)/T^4}{\partial\left(\mu_B/T\right)^i \partial\left(\mu_Q/T\right)^j \partial\left(\mu_S/T\right)^k}$$

and can be related to the moments of net-particle distributions:

mean:	$M = \chi_1$	variance:	$\sigma^2 = \chi_2$
skewness:	$S = \chi_3/\left(\chi_2\right)^{3/2}$	kurtosis:	$\kappa = \chi_4/\left(\chi_2\right)^2$

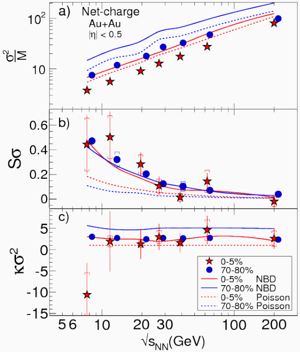
Volume-independent ratios are often used:

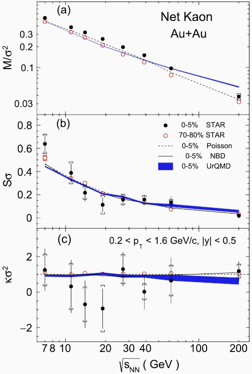
$$M/\sigma^2 = \chi_1/\chi_2 \qquad S\sigma = \chi_3/\chi_2$$

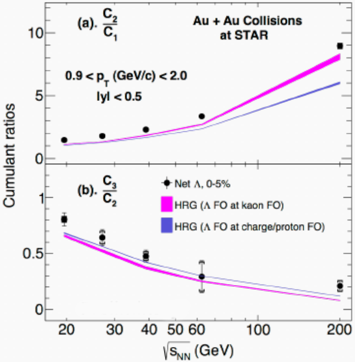
$$S\sigma^3/M = \chi_3/\chi_1 \qquad \kappa\sigma^2 = \chi_4/\chi_2$$

Fluctuations of conserved charges - Experiment

Event-by-event net-particle distributions allow to measure different cumulants (and ratios thereof):







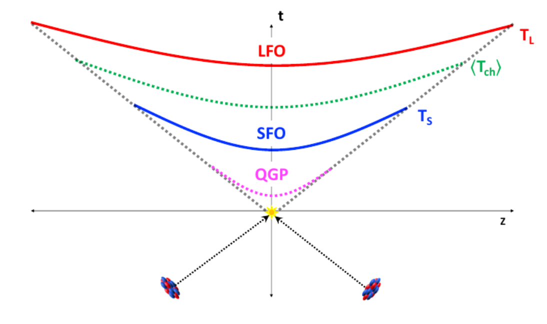
STAR: Phys. Rev. Lett. 113 (2014) 92301; Phys. Lett. B 785 (2018) 551; (Preliminary) Nucl.Phys.A 982 (2019) 863-866

Multi-freeze-out scenarios

The idea:

- Light and strange particles might freeze-out on different hypersurfaces, i.e. **at different temperatures**

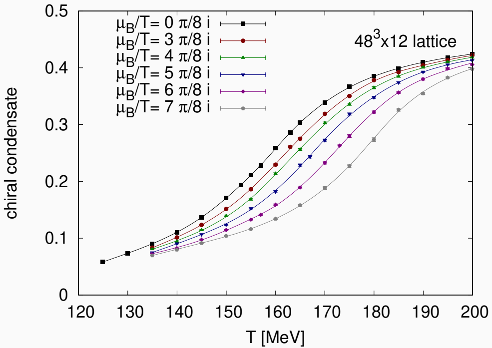
- **Flavour hierarchy**: flavour (i.e. quark mass) drives the decoupling from the medium
- **Different hadronization temperatures** for strange and light hadrons $T_{H,S} > T_{H,L}$
- **Different chemical freeze-out temperatures** for strange and light hadrons $T_{FO,S} > T_{FO,L}$

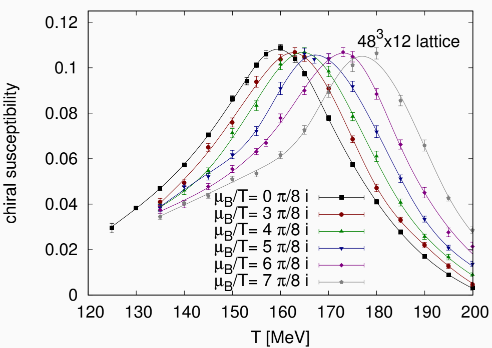


QM 2019: Poster by F. A. Flor

The QCD transition: a smooth, broad crossover

- We well know from lattice QCD that the transition at $\mu_B = 0$ is **a smooth crossover**
- Also, it is **a very broad crossover**

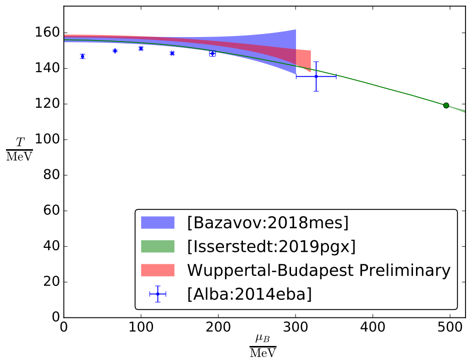


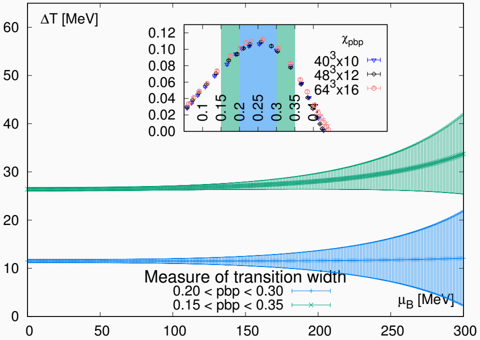


WB Collaboration: in preparation

The QCD transition: a smooth, broad crossover

- We now know with high precision the QCD transition temperature, and the (extrapolated) transition line for small μ_B
- We can study the width of the transition from $\langle\bar{\psi}\psi\rangle(T)$





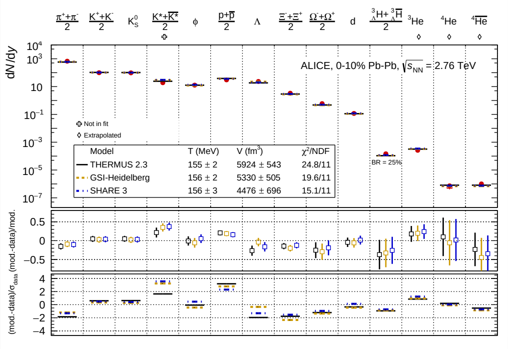
The width of the transition seems not to change also for small (real) chemical potential

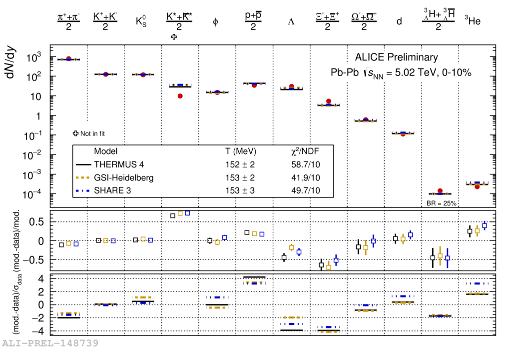
WB Collaboration: in preparation

A multi-freeze-out scenario: why?

Thermal fits to ALICE Pb-Pb 2.76 TeV and 5.02 TeV (preliminary) yields:

- Apparent tension between proton and strange baryons:
  - At $\sqrt{s} = 2.76\,\text{TeV}$: $\sim 3\sigma$ effect in protons, $\sim -2\sigma$ effect in Ξ, Λ
  - At $\sqrt{s} = 5.02\,\text{TeV}$ **it's worse**: $\sim 4\sigma$ effect in protons, $\sim -4\sigma$ effect in Ξ, Λ

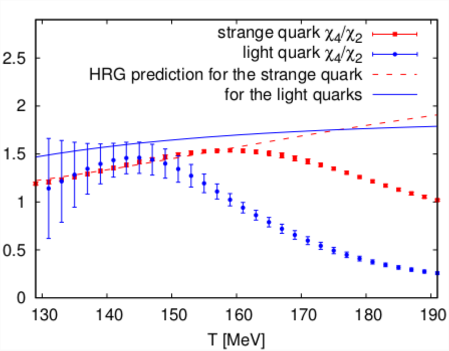


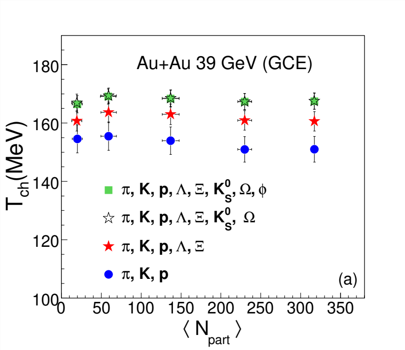


ALICE Collaboration: Nucl.Phys. A971 (2018); Nucl.Phys. A982 (2019)

A multi-freeze-out scenario: why?

- Lattice QCD study of light- and strange-quark susceptibilities **hints at different hadronization temperatures** for light and strange
- Thermal fits to yields tend to higher FO temperatures when more and more (strange) species are included



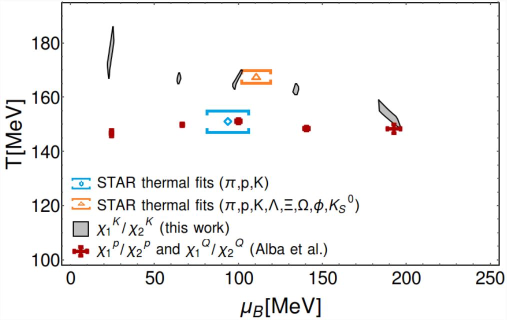


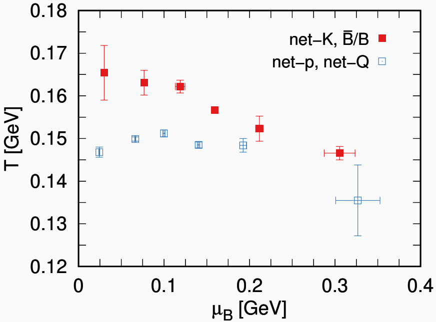
WB Collaboration: PRL 111 (2013) 202302; STAR: PRC 96 (2017) no.4, 044904

Strange v light freeze-out from fluctuations

With new STAR results on net-kaon fluctuations, new analyses:

- Freeze-out temperature from net-kaon fluctuations is **systematically higher** than for net-p and net-Q





- NOTE: analysis in left plot carried out with same hadron list as Alba *et al.* (2014)

Bellwied, PP *et al.* PRC 99 (2019) no.3, 034912; Bluhm, Nahrgang EPJ C79 (2019) no.2, 155

Disclaimer

- **S-matrix approach:** including $\pi - p$ interactions, the "proton anomaly" is reduced **Lo *et al.* Phys.Lett. B778 (2018), Andronic *et al.* Phys.Lett. B792 (2019)**
- **Additional hadronic states:** the inclusion of additional states in the hadron spectrum (e.g. from Quark Model predictions) would reduce the discrepancy in T_{FO} of strange v light. **Bazavov *et al.* PRL 113 (2014) no.7, 072001**
    - Important! In HRG model calculations the hadronic spectrum becomes a "variable"
    - Analysis of different hadron spectra in **Alba, PP *et al.* Phys.Rev. D96 (2017) no.3, 034517** led to **PDG2016+ list** we now use ($\sim$ 700 states)
    - We also check the list with QM states ($\sim$ 1400 states)

New results in this talk

I. New analysis of net-p-net-Q and net-K at STAR BES with state-of-the-art hadron list PDG2016+ (**PP *et al.* forthcoming**)

II. Analysis of χ_{11}^{BS} correlator and hadronic proxy (**Bellwied, PP *et al.* arXiv: 1910.14592**)

III. Fits to ALICE Pb-Pb 5.02 TeV yields (and ratios) in single and double freeze-out scenarios (**PP *et al.* forthcoming**)

IV. Systematic analysis of thermal fits to yields across different energies and systems (**Bellwied *et al.* forthcoming; QM 2019 Poster by F. A. Flor**)

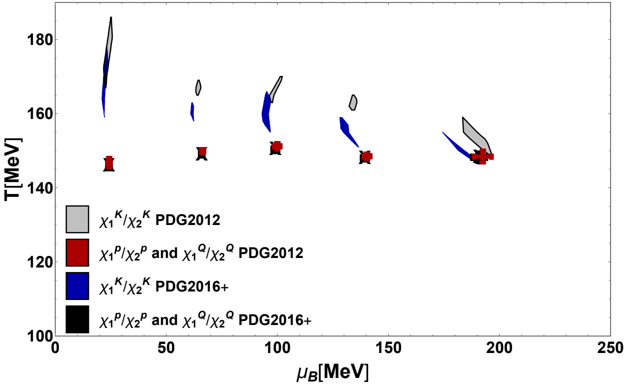
V. Work in progress: exotica at ALICE from Bellwied's group (U. of Houston)

NOTE: all thermal fits shown in this talk are obtained via the Thermal FIST package **Vovchenko, Stöcker, Comput.Phys.Commun. 244 (2019)**

I. Analysis of p,Q,K fluctuations with updated hadron list

We repeated the complete analysis of net-p, net-Q (Alba *et al.*) as well as net-Kaon fluctuations (Belwied, PP *et al.*) with a state-of-the-art hadron list PDG2016+:

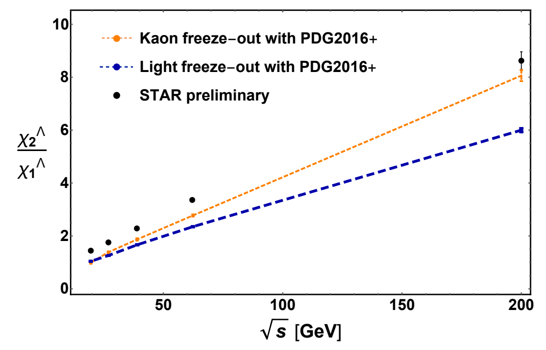
- The light freeze-out temperatures is slightly reduced
- The kaon freeze-out temperature is also reduced, **but the difference remains**



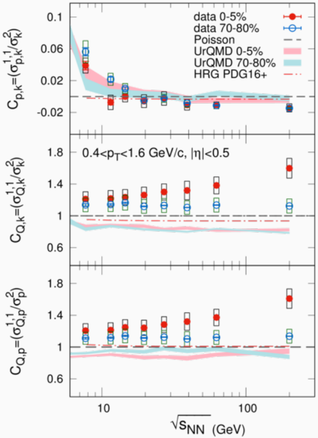
Prediction for net-Lambda fluctuations

Using the same setup, we predicted the net-Λ fluctuations at STAR in the case:

- The Λ freeze-out together with the light particles (net-p, net-Q)
- The Λ freeze-out together with the kaons



II. Opportunities from cross-correlators: χ_{11}^{BS}/χ_2^S



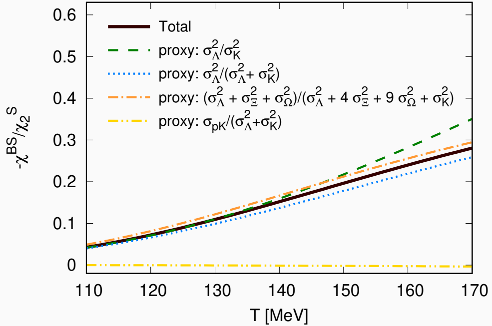
STAR: Phys.Rev. C100 (2019)

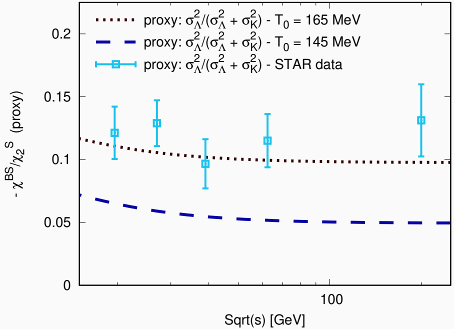
- New measurements of correlators between different species are becoming available
- How much do they tell us about the **correlation between conserved charges**?
- We can look at proxies constructed with observed particle-particle correlators
- We focus on the ratio χ_{11}^{BS}/χ_2^S and determine the leading contributions from particle-particle correlations

II. Opportunities from cross-correlators: χ_{11}^{BS}/χ_2^S

- We find that different-species correlators like $p - K$ are negligible!
- **We construct a hadronic proxy** for $\chi_{11}^{BS}\chi_2^S$, and compare to STAR preliminary results:

$$\widetilde{C}_{BS,SS}^{\Lambda,\Lambda K} = \sigma_\Lambda^2 / \left(\sigma_\Lambda^2 + \sigma_K^2\right)$$





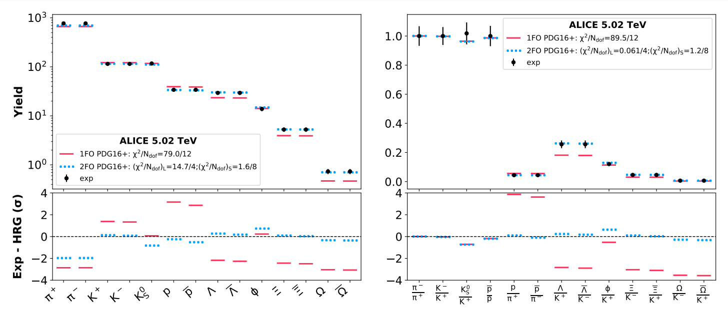
- The proxy we constructed **also favors a higher freeze-out temperature**

WB Collaboration: Bellwied, PP *et al.* arXiv: 1910.14592

III. Thermal fits with different hadron lists

Thermal fits to ALICE 5.02 TeV yields and ratios **with the PDG2016+ list** ($\sim$ 700 states)

- A multi-freeze-out scenario **improves the quality of the fit**
- **In 2FO scenario:** light fit to π, p, K, strange fit to $K, \phi, \Lambda, \Xi, \Omega$



$$\textbf{1FO: } T_{\mathrm{FO}} = 150.4 \pm 1.5\,\mathrm{MeV}$$

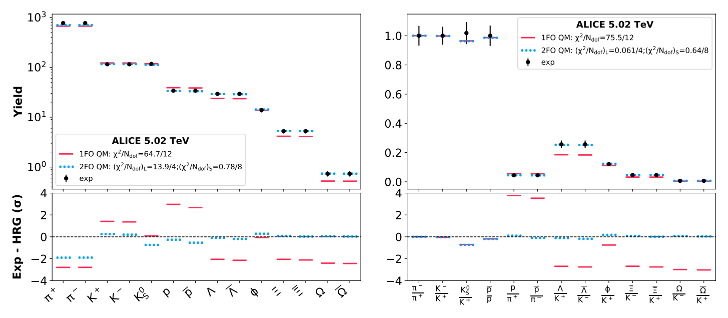
$$\textbf{2 FO: } T_{\mathrm{FO}}^{\mathrm{light}} = 142.5 \pm 1.7\,\mathrm{MeV},\ T_{\mathrm{FO}}^{\mathrm{strange}} = 164.5 \pm 2.3\,\mathrm{MeV}$$

PP *et al.* forthcoming

III. Thermal fits with different hadron lists

Thermal fits to ALICE 5.02 TeV yields and ratios **with the QM2016+ list** (~ 1400 states)

- A multi-freeze-out scenario **improves the quality of the fit**
- **In 2FO scenario:** light fit to π, p, K, strange fit to $K, \phi, \Lambda, \Xi, \Omega$



1FO: $T_{\mathrm{FO}} = 147.9 \pm 1.3\,\mathrm{MeV}$

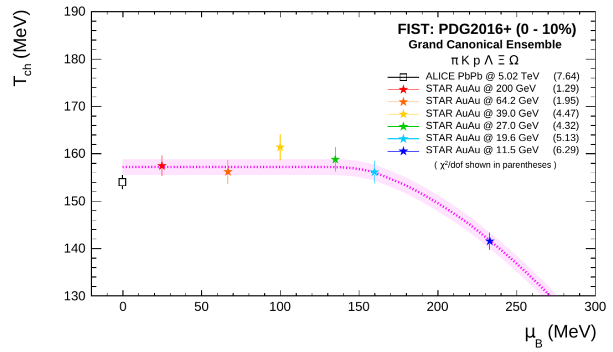
2 FO: $T_{\mathrm{FO}}^{\mathrm{light}} = 140.9 \pm 1.6\,\mathrm{MeV}$, $T_{\mathrm{FO}}^{\mathrm{strange}} = 158.2 \pm 1.9\,\mathrm{MeV}$

PP *et al.* forthcoming

IV. Thermal fits to yields across energies

Systematic analysis of yields:

- ALICE, Pb-Pb at $\sqrt{s} = 5.02\,\mathrm{TeV}$ (**Nucl.Phys. A982 (2019)**)
- STAR, Au-Au at $\sqrt{s} = 200 - 11.5\,\mathrm{GeV}$ (**PRC. 96 (2017) 044904; arXiv: 1906.03732**)



In 1FO scenario: $T_{\mathrm{FO}} = 158.0 \pm 3.8\,\mathrm{MeV}$

Bellwied *et al.* forthcoming; QM 2019 Poster by F. A. Flor

IV. Thermal fits to yields across energies

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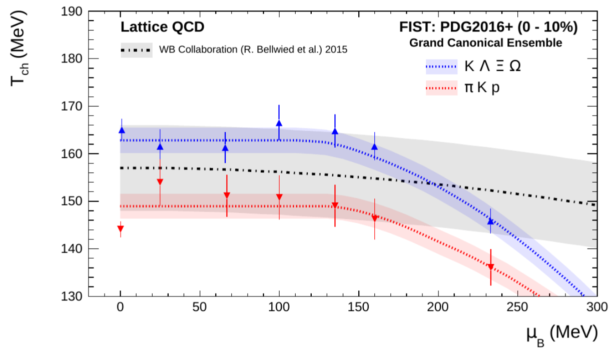
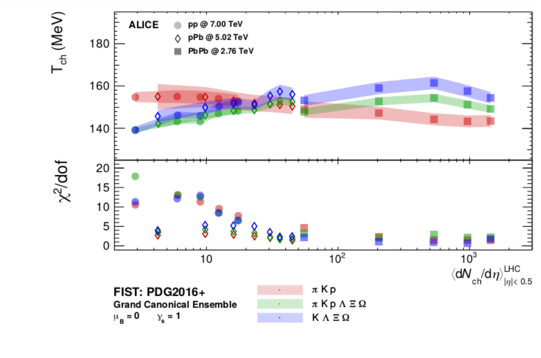


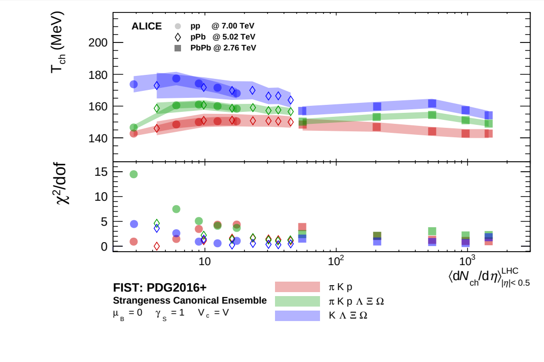
In 2FO scenario: $T_{\mathrm{FO}}^{\mathrm{light}} = 150.0 \pm 2.5\,\mathrm{MeV}$, $T_{\mathrm{FO}}^{\mathrm{strange}} = 163.0 \pm 4.0\,\mathrm{MeV}$

Bellwied *et al.* forthcoming; QM 2019 Poster by F. A. Flor

IV. Thermal fits to yields across systems

- Also in small systems, 2FO scenario improves on 1FO
- In SCE (right) fit χ^2 is "good"-ish even in small systems
- Strangeness suppression factor is not needed ($\gamma_S = 1$)





Bellwied *et al.* forthcoming; QM 2019 Poster by F. A. Flor

Multi-freeze-out scenario: consequences

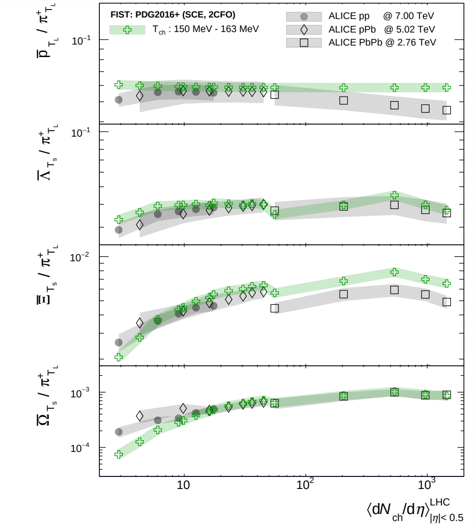
Let us assume a multi-freeze-out scenario: what then?

- **Strangeness enhancement/suppression**
- Chiral symmetry restoration at different T?
  Aarts *et al.* Phys.Rev. D99 (2019) no.7, 074503
- **Exotica production?**

Multi-freeze-out: strangeness enhancement

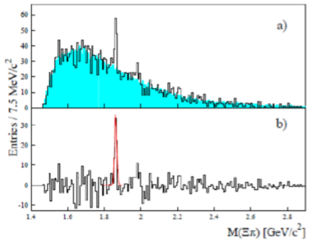
A multi-freeze-out scenario could provide a simple explanation of strangeness enhancement:

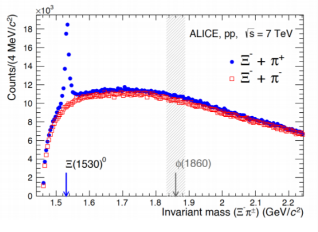
- Calculate yields of π, p at $T_{\mathrm{FO}}^{\mathrm{light}} = 150.0\,\mathrm{MeV}$
- Calculate yields of Λ, Ξ, Ω at $T_{\mathrm{FO}}^{\mathrm{strange}} = 163.0\,\mathrm{MeV}$
- $\Rightarrow$ Even without a strangeness suppression factor data are well reproduced



Bellwied *et al.* forthcoming; QM 2019 Poster by F. A. Flor

V. Multi-freeze-out and exotica





Very speculative at the moment:

- Yields of strange penta- or exa-quarks would go up
- If strangeness FO happens earlier, is there more room for strange clusters formation?

First we need to find strange exotic particles!

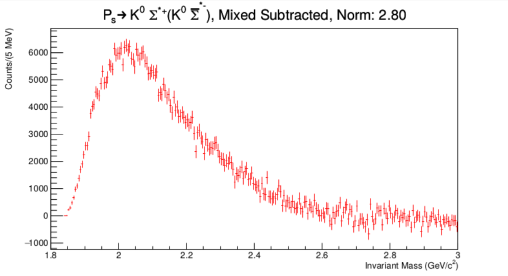
Searches in Houston's group:

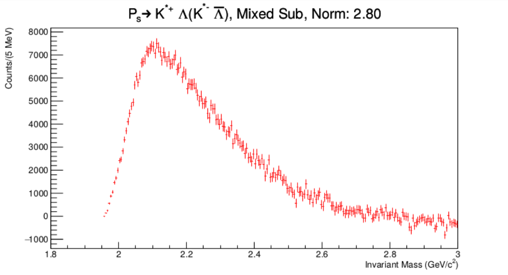
- Strange pentaquark P_S (dsdsū, aka $\Phi(1860)$, old (2004) candidate from NA49) was never confirmed, more recent analysis in $\Sigma\pi$ didn't see anything
  $\rightarrow$ keep looking then!
- $H-$dibaryon, $p\Xi$, $p\Omega$

V. Multi-freeze-out and exotica

Currently being looked at (in pp) are:

- In analogy with LHCb: closed strangeness channels ϕp, $\phi\Lambda$, ϕK, $\phi\pi$ $\rightarrow$ **nothing yet**
- Open strangeness channels too: $K\Sigma^*$, $K^*\Lambda$ $\rightarrow$ **also nothing yet**
- H-dibaryon as well as di-baryon channels with attractive potentials





Why can't we seem to find strange exotica where we could expect it to be?

Summary

We see hints to a **multi-freeze-out scenario** appearing in:

- **Thermal fits** of yields and ratios at new ALICE Pb-Pb 5.02 TeV
- **Analysis of net-kaon v net-p/net-Q** fluctuations (even when considering up-to-date particle lists)
- Analysis related to off-diagonal correlator of conserved charges χ_{11}^{BS}/χ_2^S
- Systematic analysis of yields **with different systems and energies**

Consequences?

- A higher FO temperature for strangeness might explain strangeness enhancement at LHC energies
- If strangeness formation happens earlier in the fireball evolution, strange clusters – hence e.g. strange pentaquarks – formation would be enhanced → **first we need to find them!**

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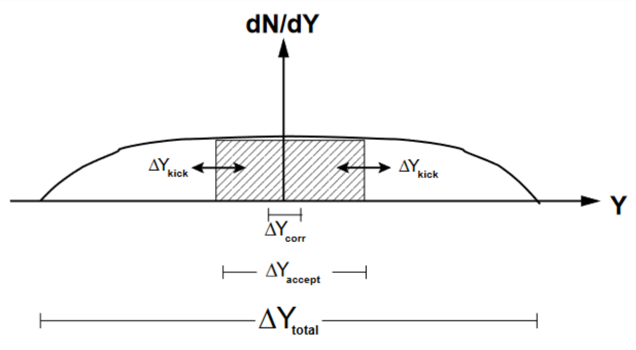
Thank you!

BACKUP

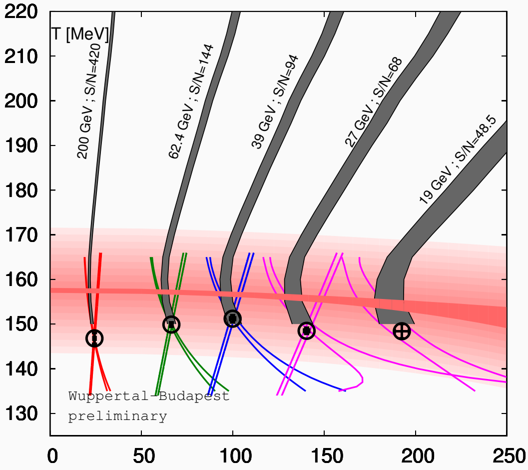
Fluctuations of conserved charges

How can CONSERVED CHARGES fluctuate?

- If we could measure ALL particles in a collision, they would not
- If we look at a small enough subsystem, fluctuations occur and become meaningful



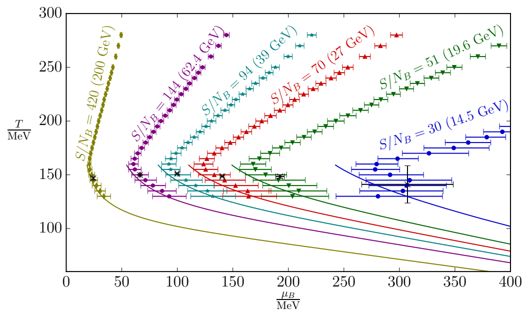
Net-p/net-Q analysis and isentropes



C. Ratti, Nucl.Phys. A956 (2016) 51-58

Freeze-out in HICs: Net-Kaon fluctuations

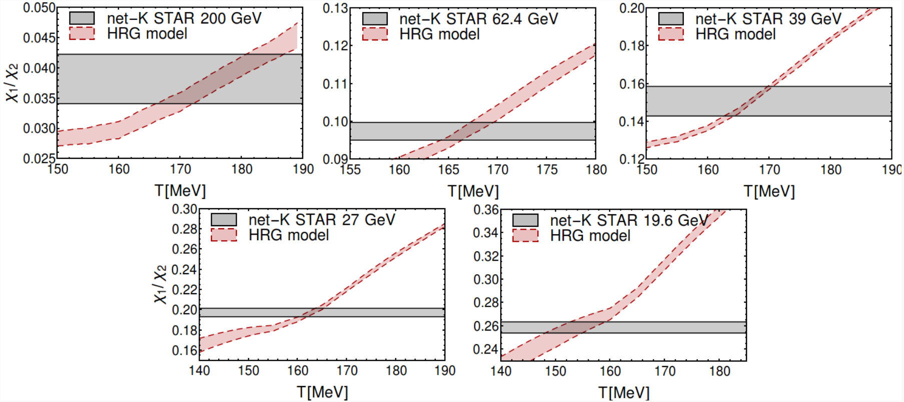
- Only use χ_1^K/χ_2^K, because experimental errors on χ_3^K/χ_2^K are too large
- **Alternative:** follow **"isentropic" curves**: entropy per baryon ratio s/n_B is constant (true in the limit of no dissipative effects)
- **Starting point:** net-proton and net-charge freeze-out points from previous work



J. Guenther *et al.*, **Nucl.Phys. A967 (2017)**

Freeze-out in HICs: Net-Kaon fluctuations

- Calculate χ_2^K/χ_1^K along the isentropes, and compare to experimental data



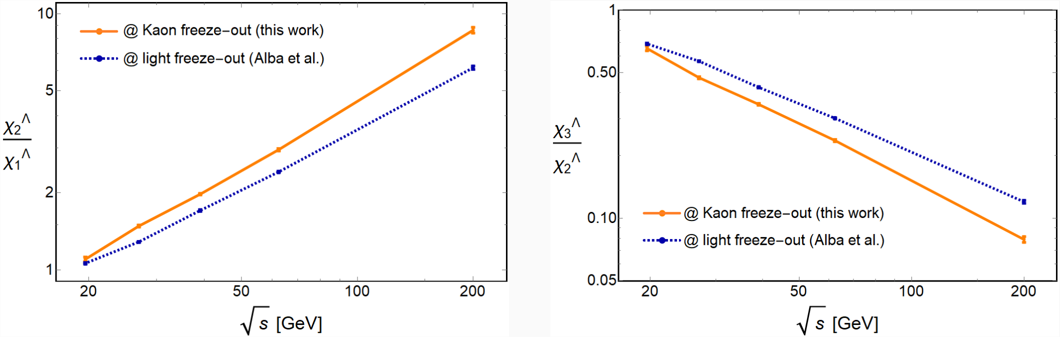
The overlap regions indicate the freeze-out points for net-Kaons

R. Bellwied, PP *et al.*, **PRC 99 (2019) no.3, 034912**

Freeze-out in HICs: Net-Lambda fluctuations

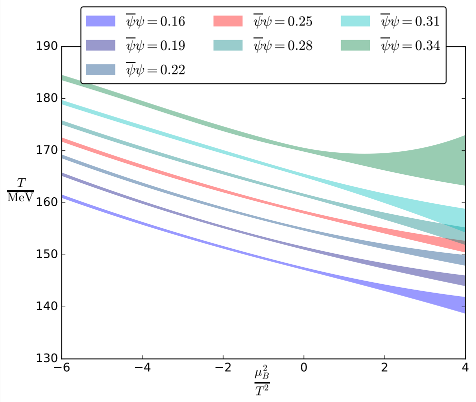
Predict the values of $\chi_2^\Lambda/\chi_1^\Lambda$ and $\chi_3^\Lambda/\chi_2^\Lambda$ **in two scenarios**:

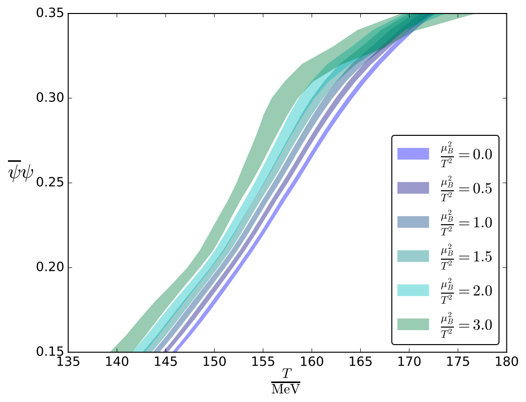
- i. In the case the Λ freeze-out occurs together with the net-proton and net-charge
- ii. In the case it occurs together with the net-Kaons



R. Bellwied, PP *et al.*, **PRC 99 (2019) no.3, 034912**

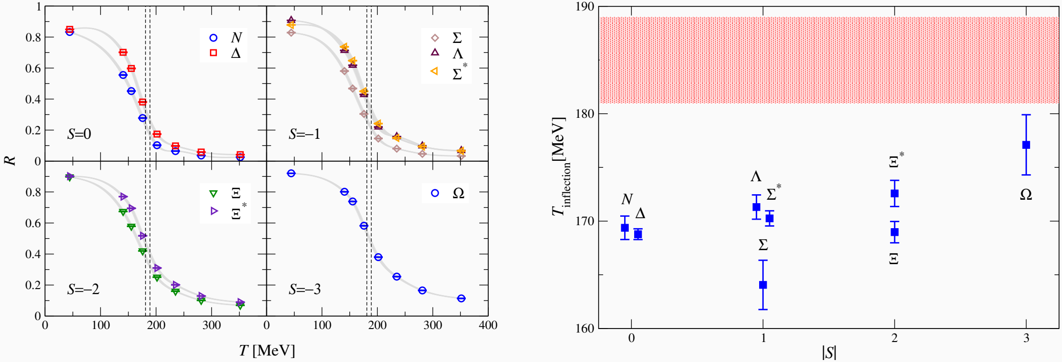
The QCD transition





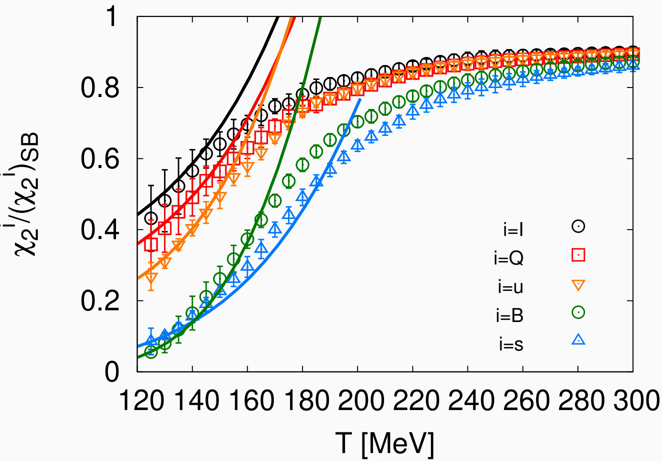
WB Collaboration: in preparation

Chiral restoration from lattice QCD masses



Aarts *et al.* Phys.Rev. D99 (2019) no.7, 074503

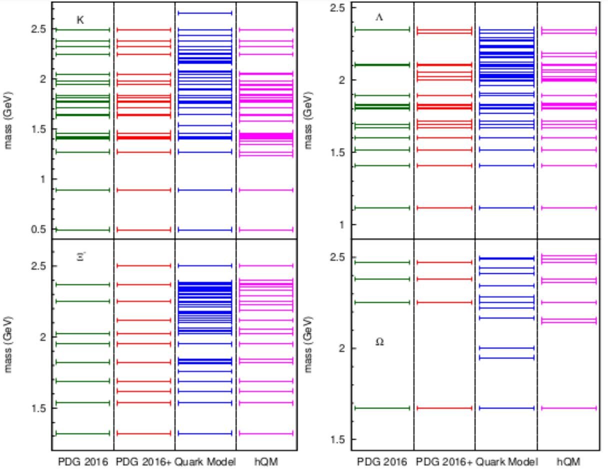
The QCD transition



Borsanyi *et al.* JHEP 1201 (2012) 138

Different hadron lists

- **PDG 2016** (**, *** and **** states):
  608 states
- **PDG 2016+** (*, **, *** and **** states):
  738 states
- **Quark Model**:
  1517 states
- **Hypercentral QM (hQM)**:
  985 states



Alba, PP *et al.* Phys.Rev. D96 (2017) no.3, 034517

Others P_S searches