Chemical freeze-out conditions from net-kaon fluctuations at RHIC

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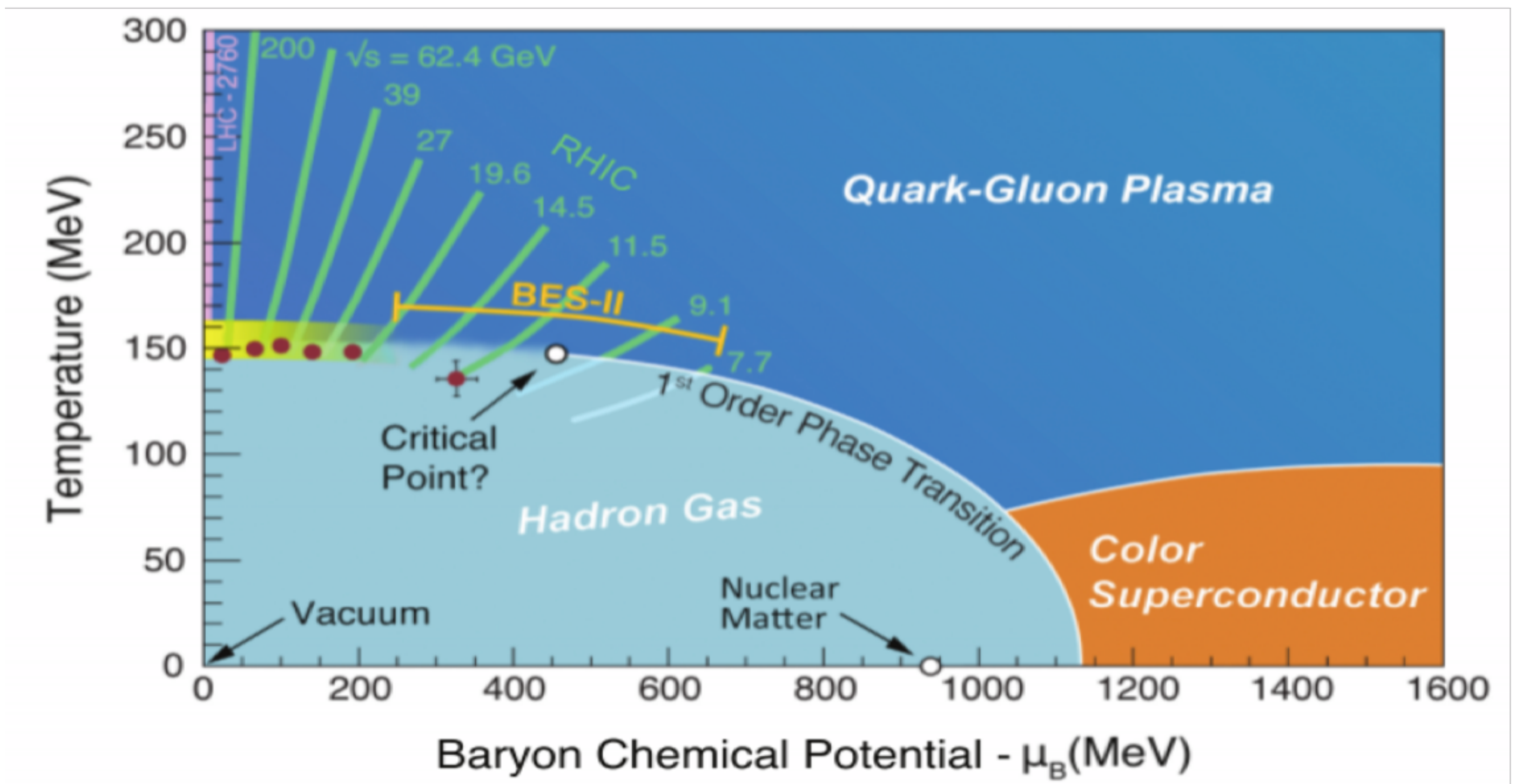
QCD Phase Diagram

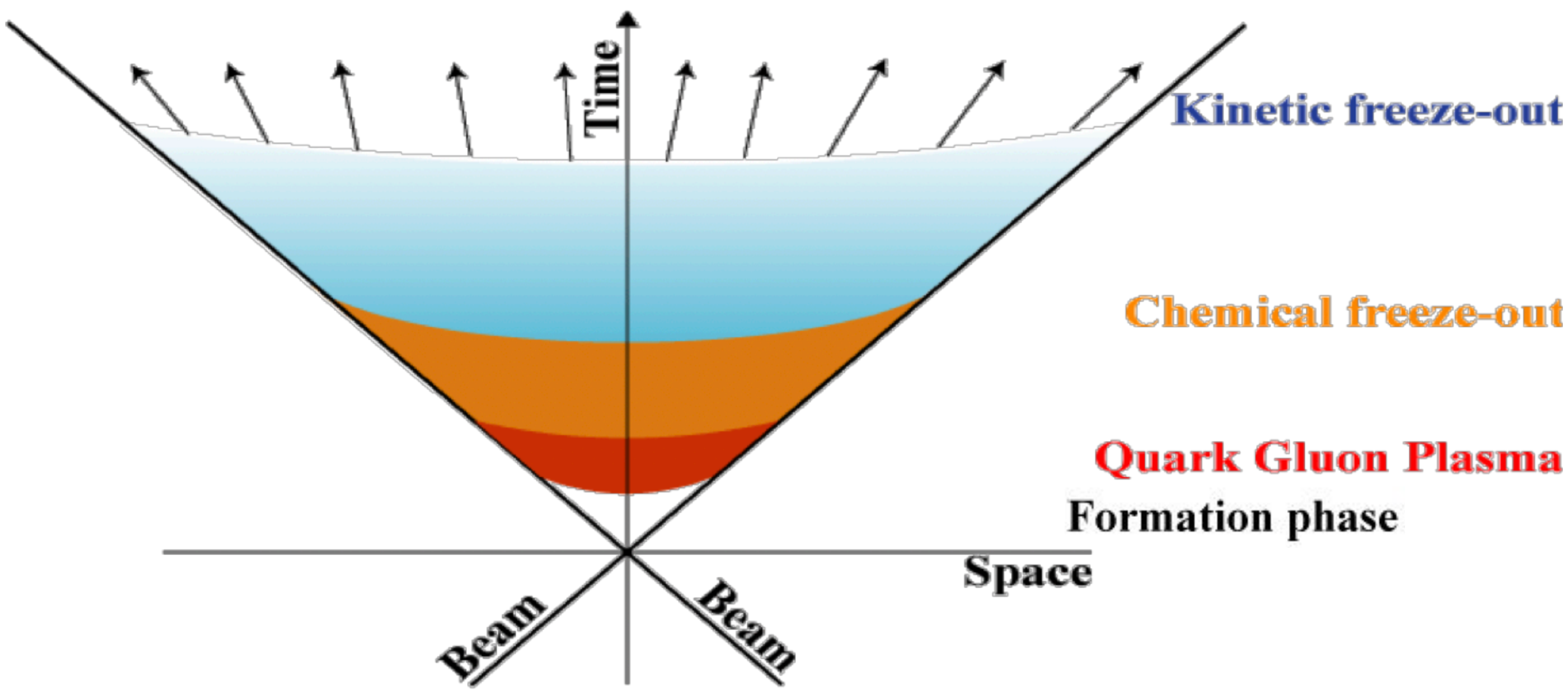
The different phases of QCD matter can be understood by studying the characteristics of the phase diagram

- QGP is formed at large T, μ_B ; ordinary hadronic matter at small T, μ_B
- Crossover transition at T ~ 155MeV; possible first order phase transition
  - Search for the critical point with the Beam Energy Scan (BES)



NSAC 2015 Long Range Plan for Nuclear Physics

Evolution of a heavy-ion collision



- Chemical freeze-out: inelastic collisions cease; the chemical composition is fixed (yields and fluctuations)
- Kinetic freeze-out: elastic collisions cease; spectra and correlations are fixed

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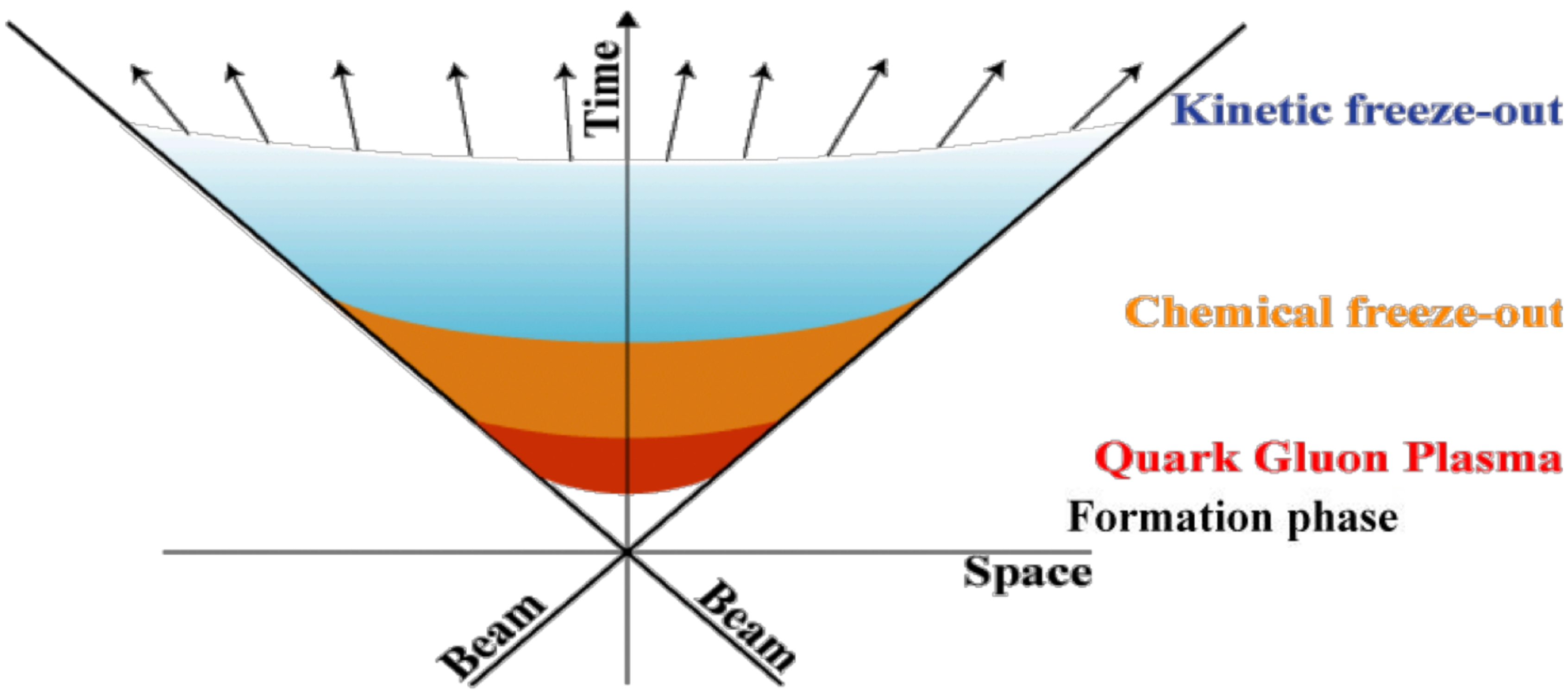

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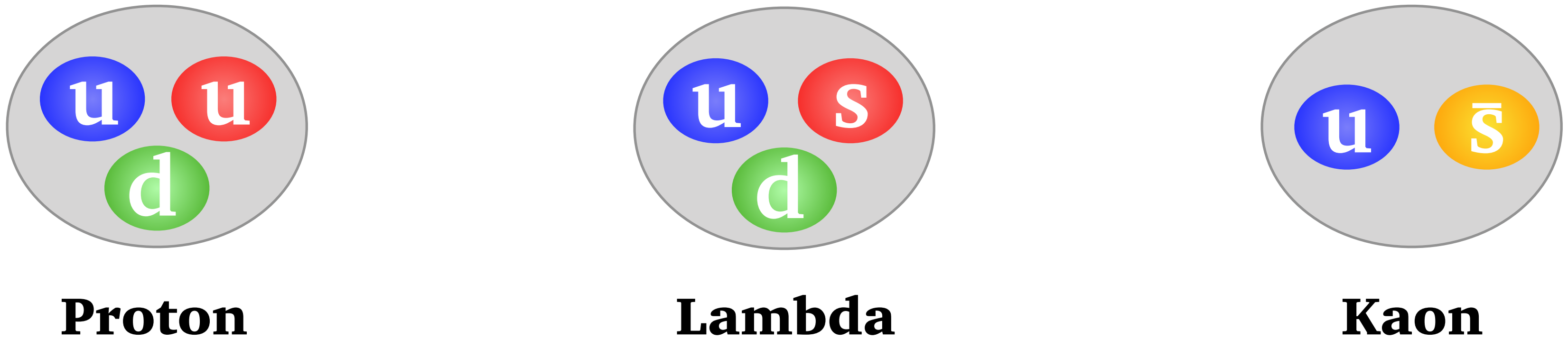
Chemical freeze-out in heavy-ion collisions

Is there a **flavor hierarchy** in the chemical freeze-out temperature?



Utilize Hadron Resonance Gas (HRG) model to directly compare with experiment and extract chemical freeze-out parameters

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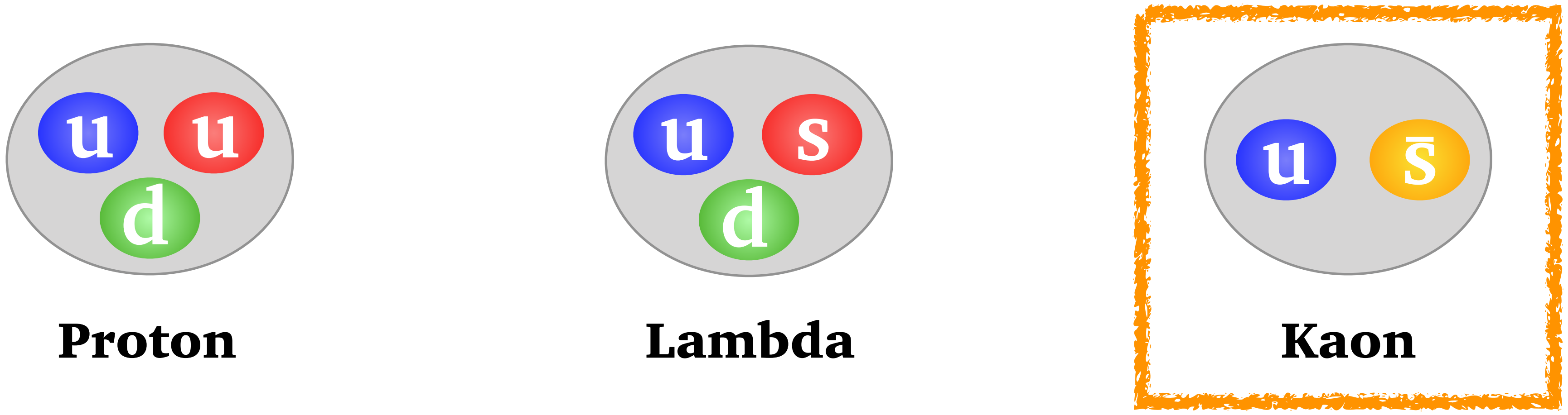


Utilize Hadron Resonance Gas (HRG) model to directly compare with experiment and extract chemical freeze-out parameters

Hadron Resonance Gas Model

In the low temperature regime, the system is well-described by a gas of hadrons:

- Grand Canonical Ensemble
- Interacting gas of ground-state hadrons
  - Treat as non-interacting system of resonant states
- Adaptable to match experimental conditions
- List of particles from the Particle Data Group (PDG)

$$\frac{P}{T^4} = \frac{1}{VT^3} \sum_i \ln Z_i(T, V, \vec{\mu})$$

where: $$\ln Z_i^{M/B} = \mp \frac{V d_i}{(2\pi)^3} \int d^3p \, \ln\left(1 \mp \exp\left[-\left(\epsilon_i - \mu_a X_a^i\right)/T\right]\right)$$

energy $\epsilon_i = \sqrt{p^2 + m_i^2}$

conserved charges $\vec{X}_i = (B_i, S_i, Q_i)$

degeneracy d_i, mass m_i, volume V

Hadron Resonance Gas Model

hadron	m_i (GeV)	d_i	B_i	S_i	I_i	hadron	m_i (GeV)	d_i	B_i	S_i	I_i
π	0.140	3	0	0	1	N (1535)	1.530	4	1	0	1/2
K	0.496	2	0	1	1/2	π_1 (1600)	1.596	9	0	0	1
$\overline{K}$	0.496	2	0	-1	1/2	Δ (1600)	1.600	16	1	0	3/2
η	0.543	1	0	0	0	Λ (1600)	1.600	2	1	-1	0
ρ	0.776	9	0	0	1	Δ (1620)	1.630	8	1	0	3/2
ω	0.782	3	0	0	0	η_2 (1645)	1.617	5	0	0	0
K^*	0.892	6	0	1	1/2	N (1650)	1.655	4	1	0	1/2
$\overline{K}^*$	0.892	6	0	-1	1/2	ω (1650)	1.670	3	0	0	0
N	0.939	4	1	0	1/2	Σ (1660)	1.660	6	1	-1	1
η'	0.958	1	0	0	0	Λ (1670)	1.670	2	1	-1	0
f_0	0.980	1	0	0	0	Σ (1670)	1.670	2	1	-1	1
a_0	0.980	3	0	0	1	ω_3 (1670)	1.667	7	0	0	0
ϕ	1.020	3	0	0	0	π_2 (1670)	1.672	15	0	0	1
Λ	1.116	2	1	-1	0	Ω^-	1.672	4	1	-3	0
h_1	1.170	3	0	0	1	N (1675)	1.675	12	1	0	1/2
Σ	1.189	6	1	-1	1	ϕ (1680)	1.680	3	0	0	0
a_1	1.230	9	0	0	1	K^* (1680)	1.717	6	0	1	1/2
b_1	1.230	9	0	0	1	$\overline{K}^*$ (1680)	1.717	6	0	-1	1/2
Δ	1.232	16	1	0	3/2	N (1680)	1.685	12	1	0	1/2
f_2	1.270	5	0	0	0	ρ_3 (1690)	1.688	21	0	0	1
K_1	1.273	6	0	1	1/2	Λ (1690)	1.690	4	1	-1	0
$\overline{K}_1$	1.273	6	0	-1	1/2	Ξ (1690)	1.690	8	1	-2	1/2
f_1	1.285	3	0	0	1	ρ (1700)	1.720	9	0	0	1
η (1295)	1.295	1	0	0	0	N (1700)	1.700	8	1	0	1/2
π (1300)	1.300	3	0	0	1	Δ(1700)	1.700	16	1	0	3/2

List made by C. Ratti

Fluctuations of Conserved Charges

$$\chi^{BSQ}_{lmn} = \frac{\partial^{l+m+n} p/T^4}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}.$$

mean : $M = \chi_1$ variance : $\sigma^2 = \chi_2$

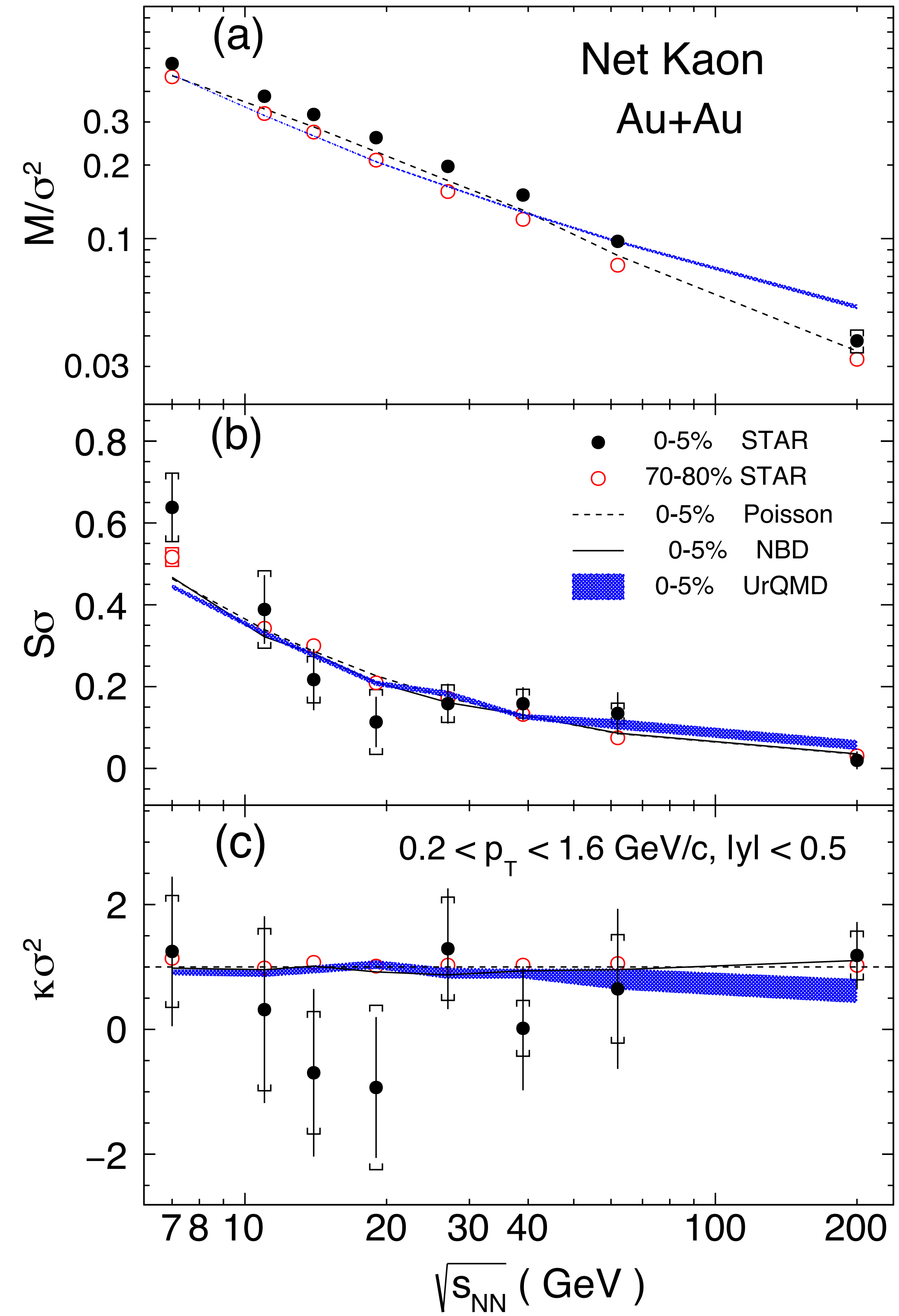
skewness : $S = \chi_3/\chi_2^{3/2}$ kurtosis : $\kappa = \chi_4/\chi_2^2$

The volume-independent ratios are:

$S\sigma = \chi_3/\chi_2$ $\kappa\sigma^2 = \chi_4/\chi_2$

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

Directly compare HRG Model to experiment to identify chemical freeze-out conditions!



STAR Collaboration (Adamczyk, L. et al.) Phys.Lett. B 785 (2018) 551-560 arXiv:1709.00773 [nucl-ex]

Fluctuations of Conserved Charges

Kaon susceptibilities in the HRG Model:

$$\chi_n^{\text{net-}K} = \sum_{i \in \text{HRG}} \frac{(Pr_{i\to\text{net-K}})^n}{T^{3-(n-1)}} \frac{S_i^{1-n} d_i}{4\pi^2} \frac{\partial^{n-1}}{\partial \mu_S^{n-1}} \times \left\{ \int_{-0.5}^{0.5} dy \int_{0.2}^{1.6} dp_T \frac{p_T \sqrt{p_T^2 + m_i^2}\,\text{Cosh}[y]}{(-1)^{B_i+1} + \exp\left((\text{Cosh}[y]\sqrt{p_T^2 + m_i^2} - (B_i\mu_B + S_i\mu_S + Q_i\mu_Q))/T\right)} \right\}$$

- ☑ Limits of integration correspond to the acceptance cuts from the experiment
- ☑ Strangeness neutrality imposed on μ_B, μ_Q, μ_S matches the experimental conditions:

$$\langle n_s \rangle = 0 \qquad \langle n_Q \rangle = 0.4 \langle n_B \rangle$$

- ☑ Include feed-down from resonances by utilizing the branching ratios:

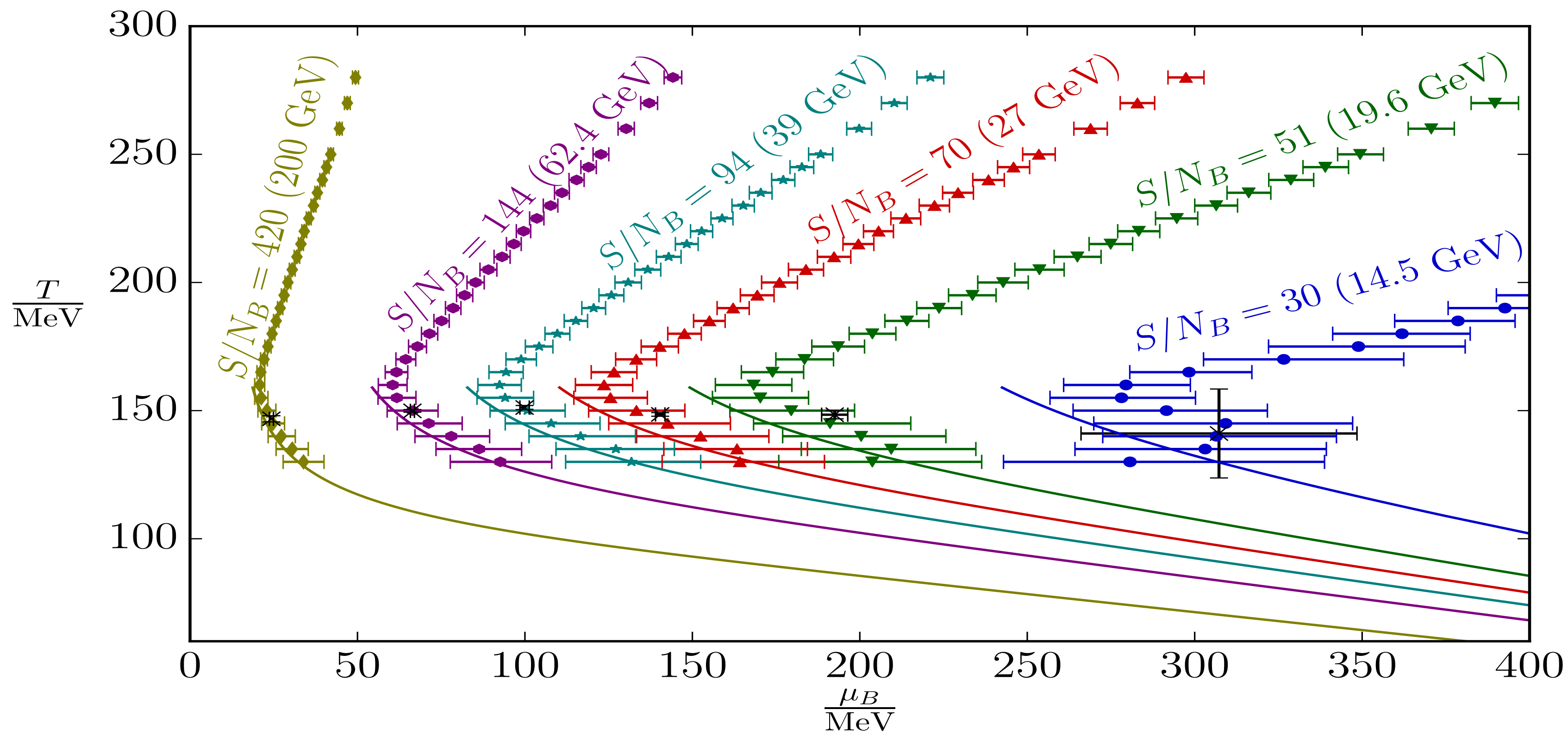
$$Pr_{i\to K_{net}} = Br_{i\to K_{net}} n_i(K_{net})$$

R. Bellwied, JS, et al., Phys. Rev. C99 (2019) 034912

Lattice QCD Isentropes

In order to extract the { $T_f, \mu_{B,f}$ }, we utilize the isentropic trajectories from Lattice QCD

- S/N_B is conserved
- Shows the path of the system across the phase diagram



Guenther, J. et al. Nucl.Phys. A967 (2017) 720-723

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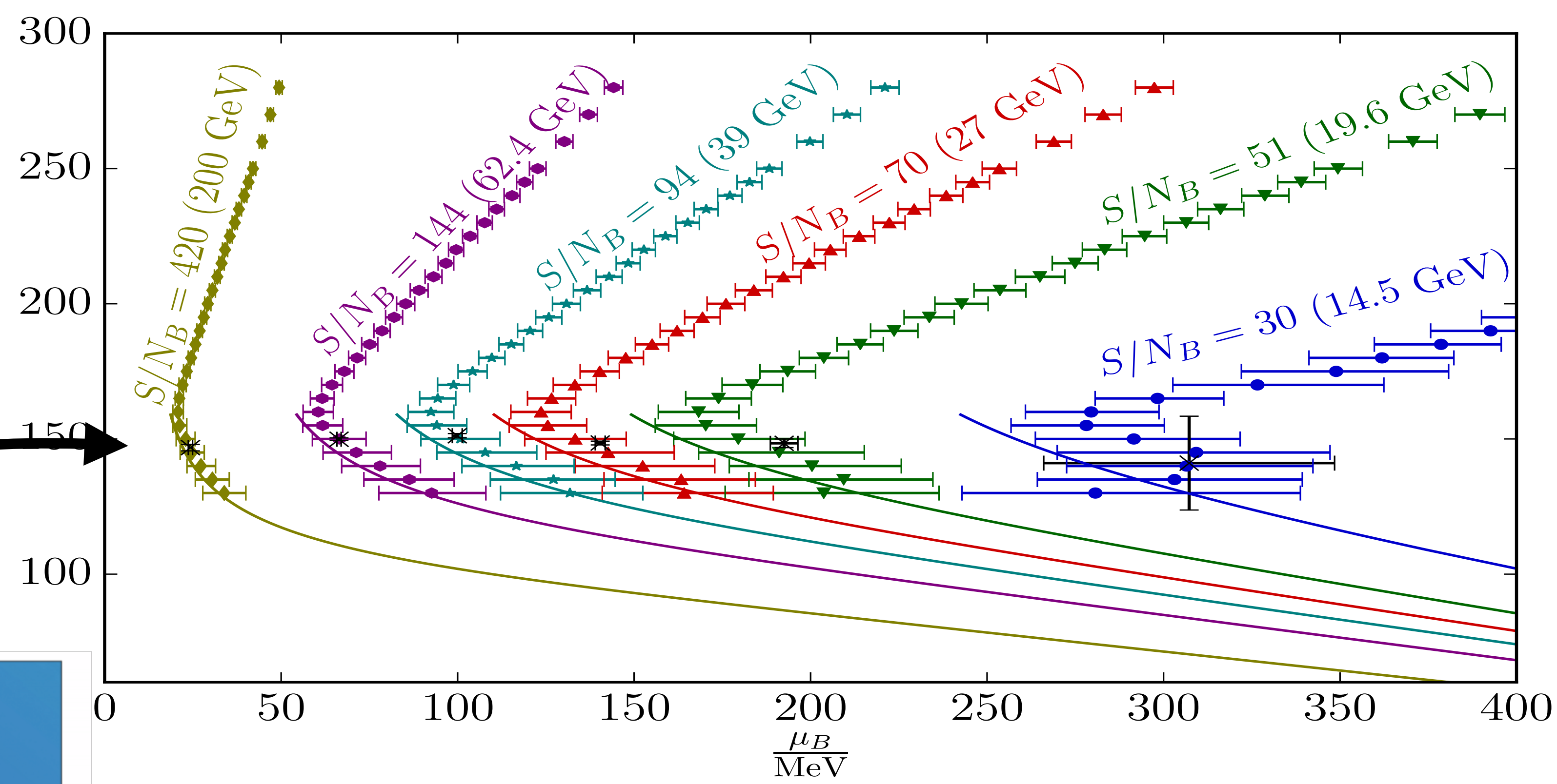
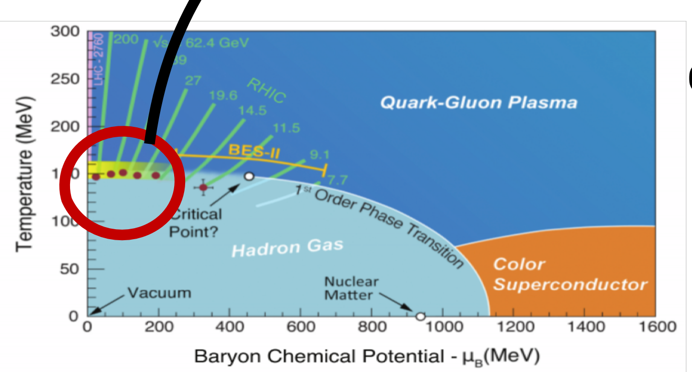
Combined fit of net-p & net-Q





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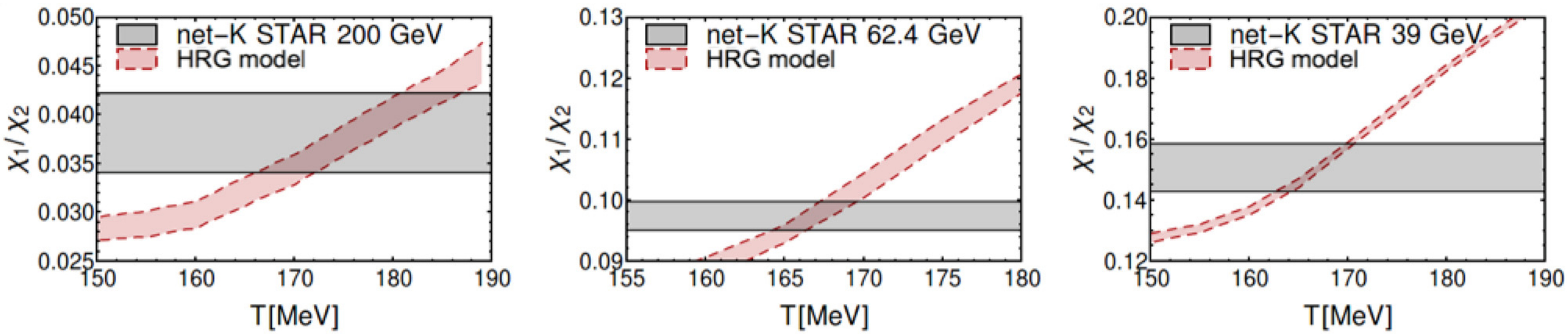
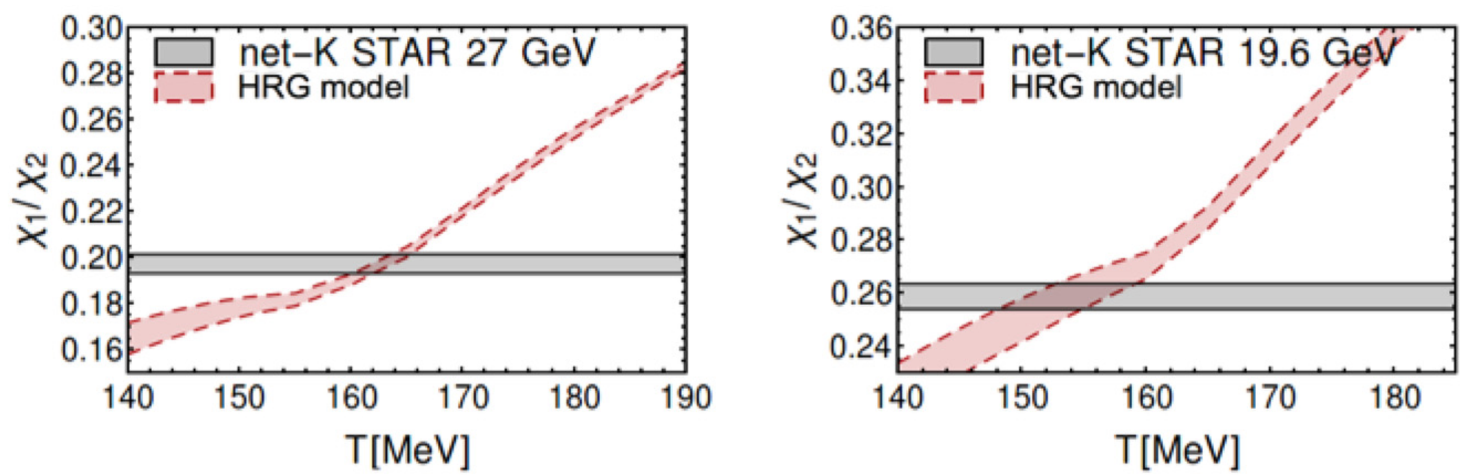
Calculate χ_1/χ_2 along the isentropes corresponding to the five highest energies of the Beam Energy Scan at RHIC

- Extract Tf by identifying the overlap regions





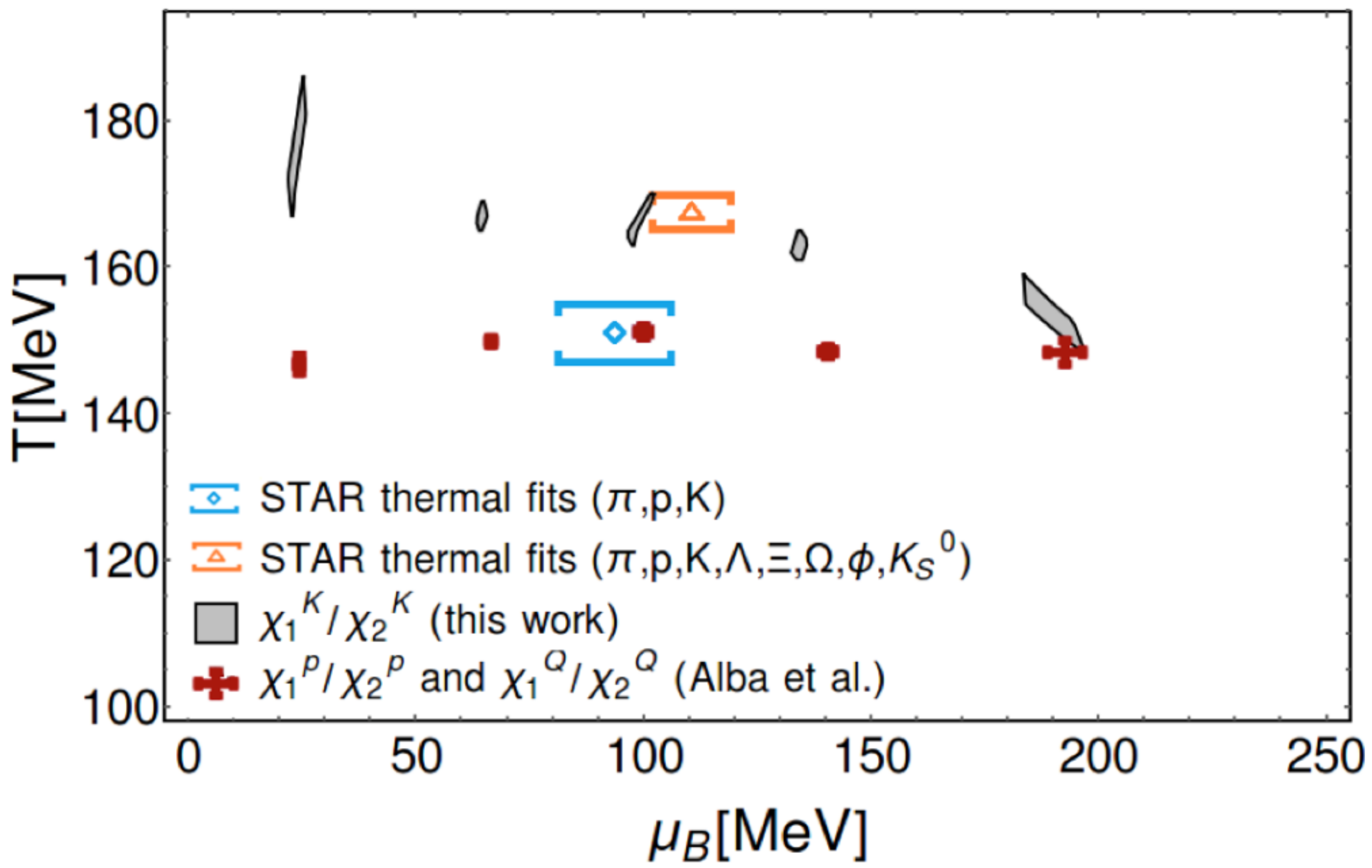
At 200 GeV:
T_f ~ 163 - 190 MeV

R. Bellwied, JS, et al., Phys. Rev. C99 (2019) 034912

Freeze-out parameters for net-kaons

Compare the freeze-out parameters for net-K to:

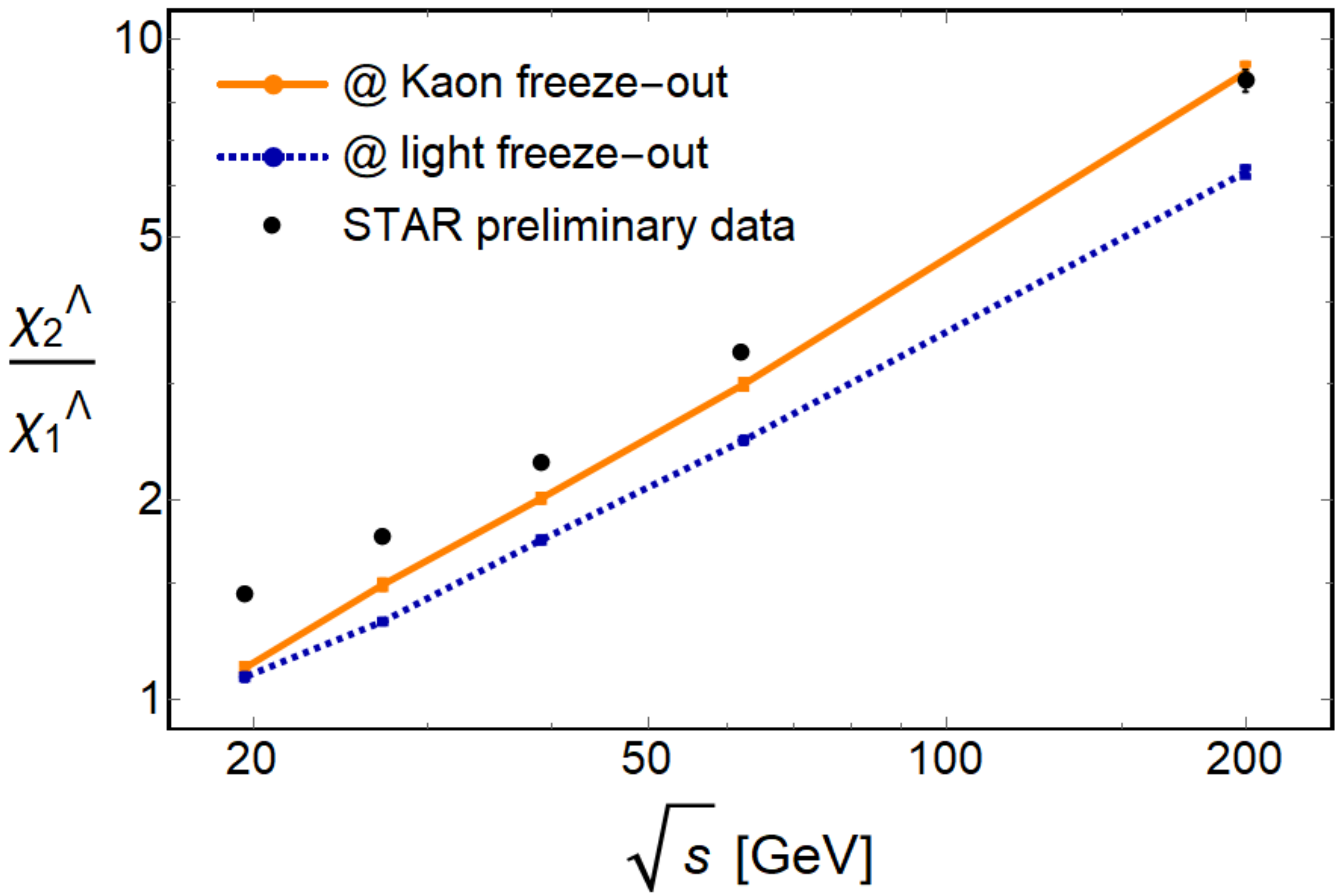
- light freeze-out (combined fit of net-proton and net-electric charge)
- thermal fits from the experiment



R. Bellwied, JS, et al., Phys. Rev. C99 (2019) 034912

Lambda predictions

Calculate fluctuations for net-Λ using the kaon and light hadron freeze-out parameters and compare with preliminary experimental data



R. Bellwied, JS, et al., Phys. Rev. C99 (2019) 034912

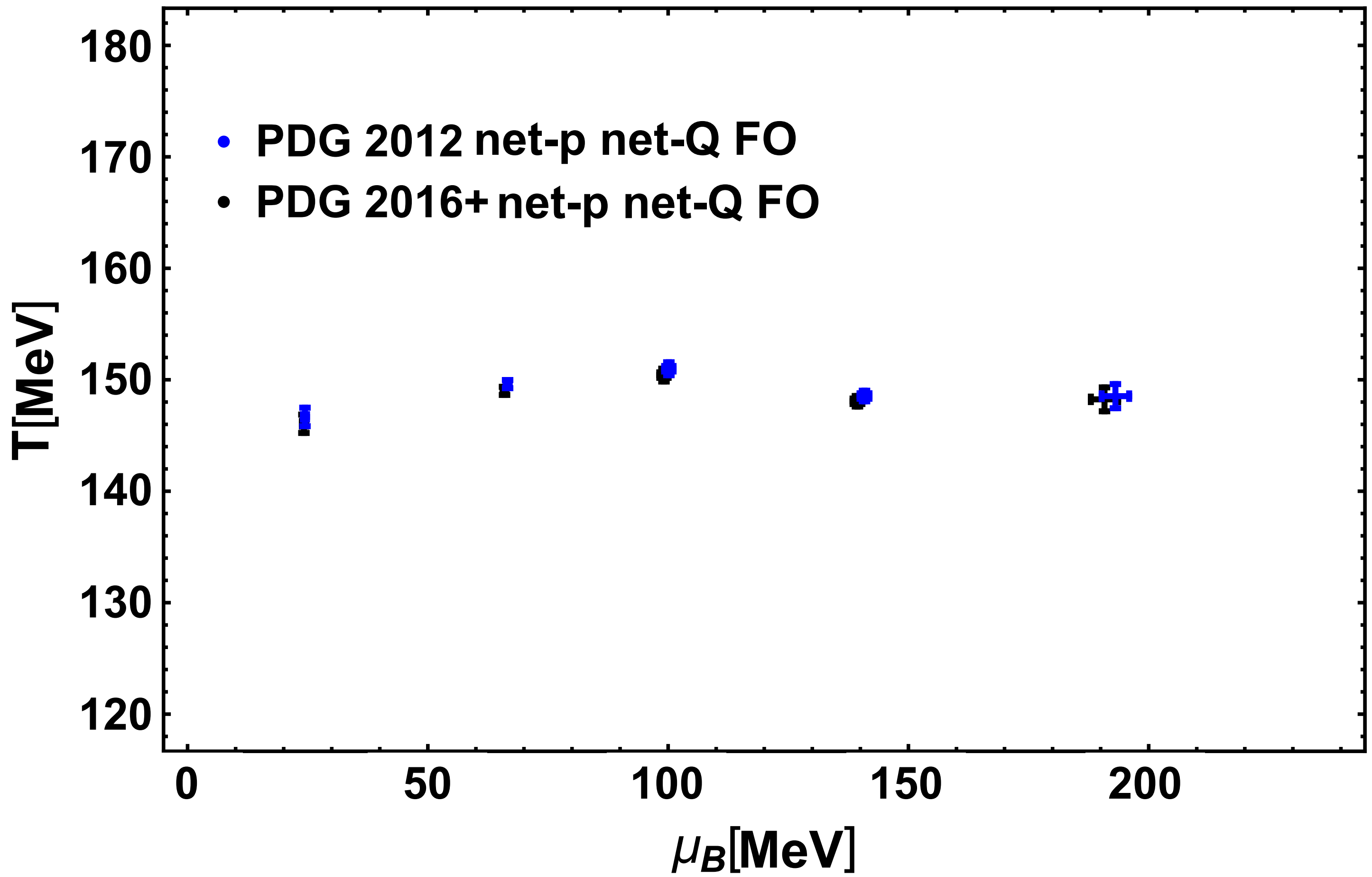
Freeze-out with different PDG lists

Recall the pressure in the HRG Model: $$\frac{P}{T^4} = \frac{1}{VT^3}\sum_i \ln Z_i(T, V, \vec{\mu})$$

Different particle lists will yield different results for the freeze-out parameters

PDG2012: 524 particles

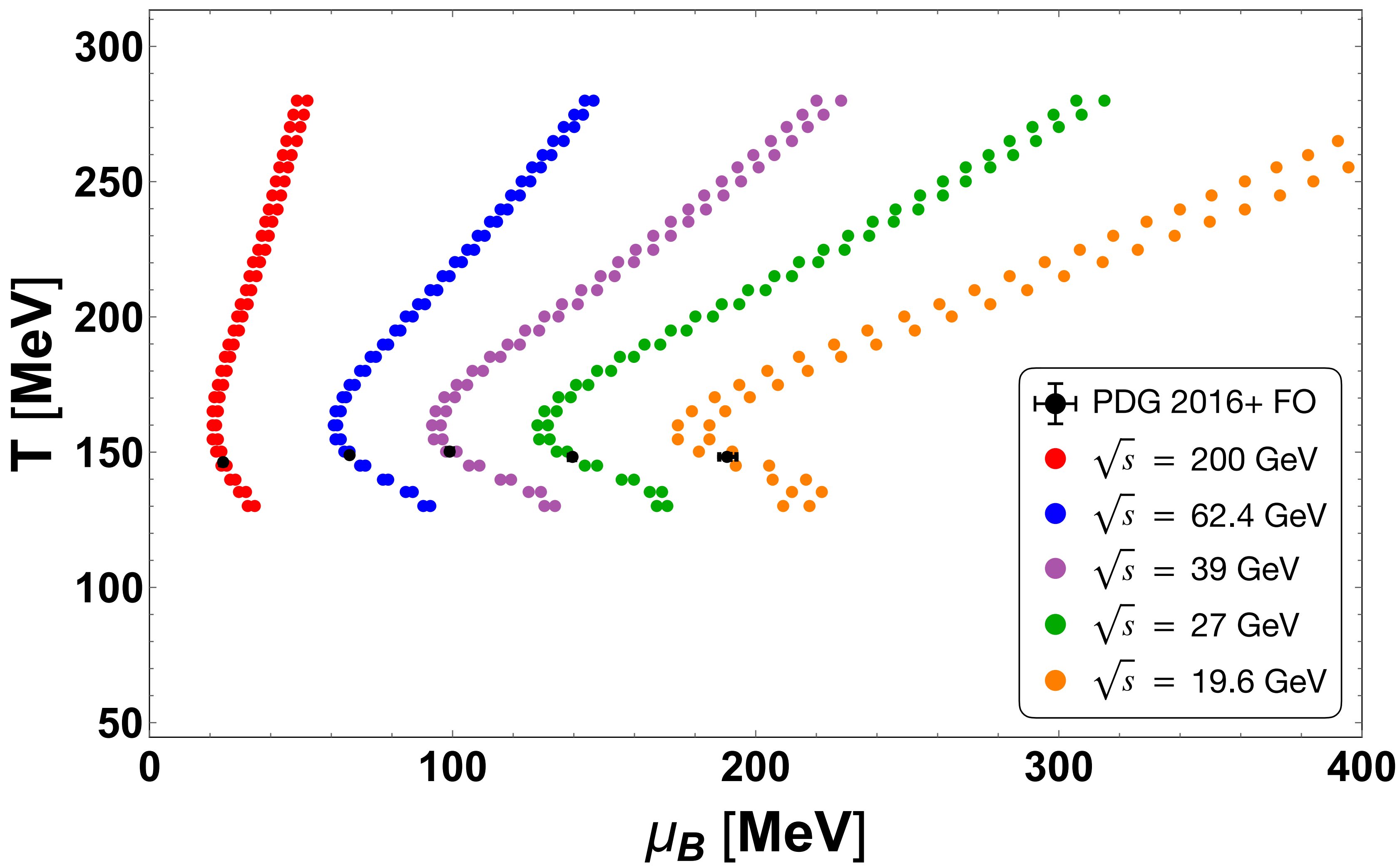
PDG2016+: 739 particles



Lattice QCD Isentropes with 2016+

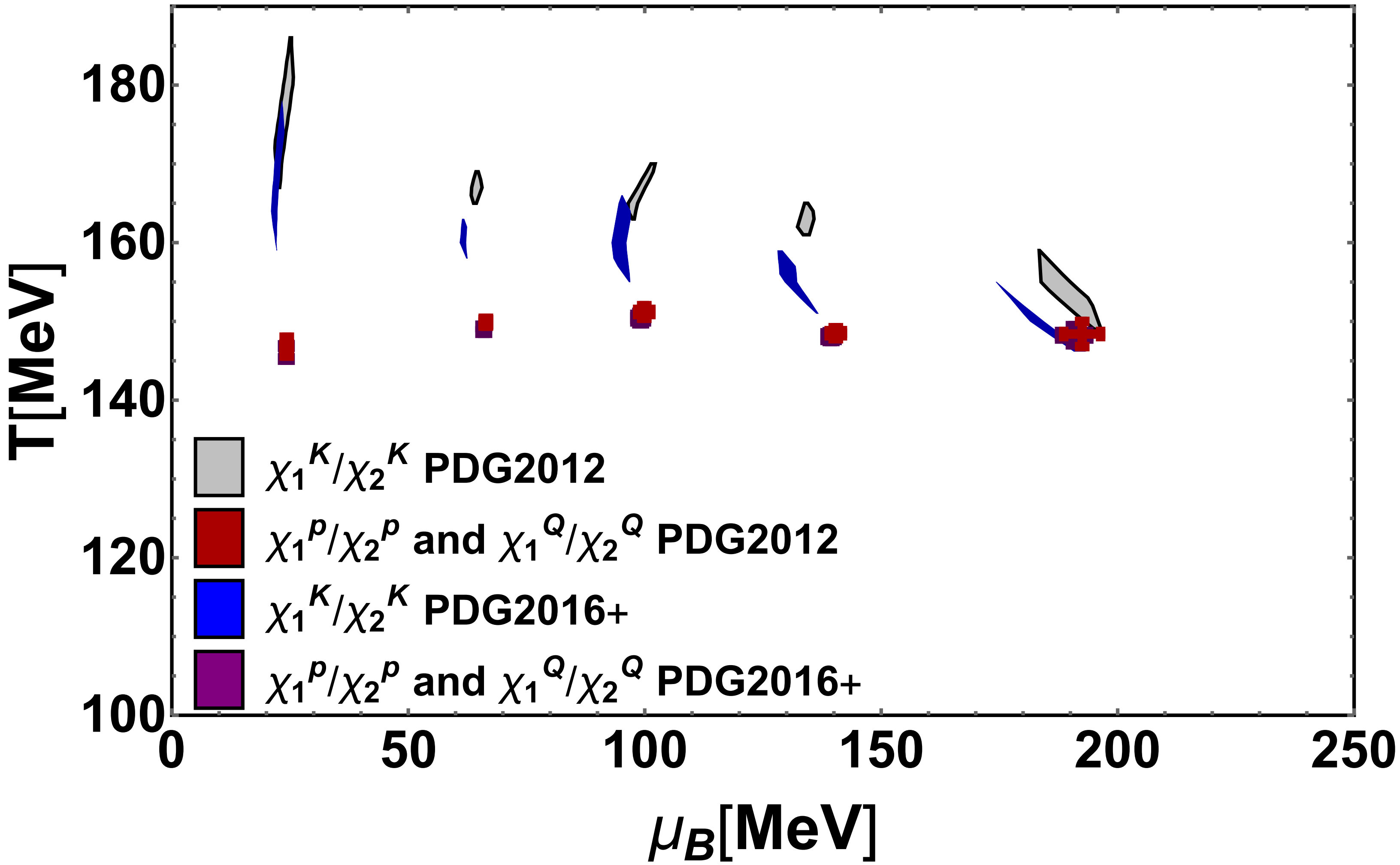
Calculate new isentropes from freeze-out parameters determined with PDG 2016+

$$\frac{s}{T^3} = \frac{1}{T^3}\frac{\partial p}{\partial T}\bigg|_{\mu_i} \qquad \frac{n_i}{T^3} = \frac{1}{T^3}\left(\frac{\partial p}{\partial \mu_i}\right)\bigg|_{T,\mu_j}$$



Kaon freeze-out for PDG2012 and PDG2016+

Compare the freeze-out parameters for the kaons and light particles for the different lists in order to determine the effect of the number of resonant states:



Even with the inclusion of more states in the HRG Model, there is evidence of a flavor hierarchy

Conclusions

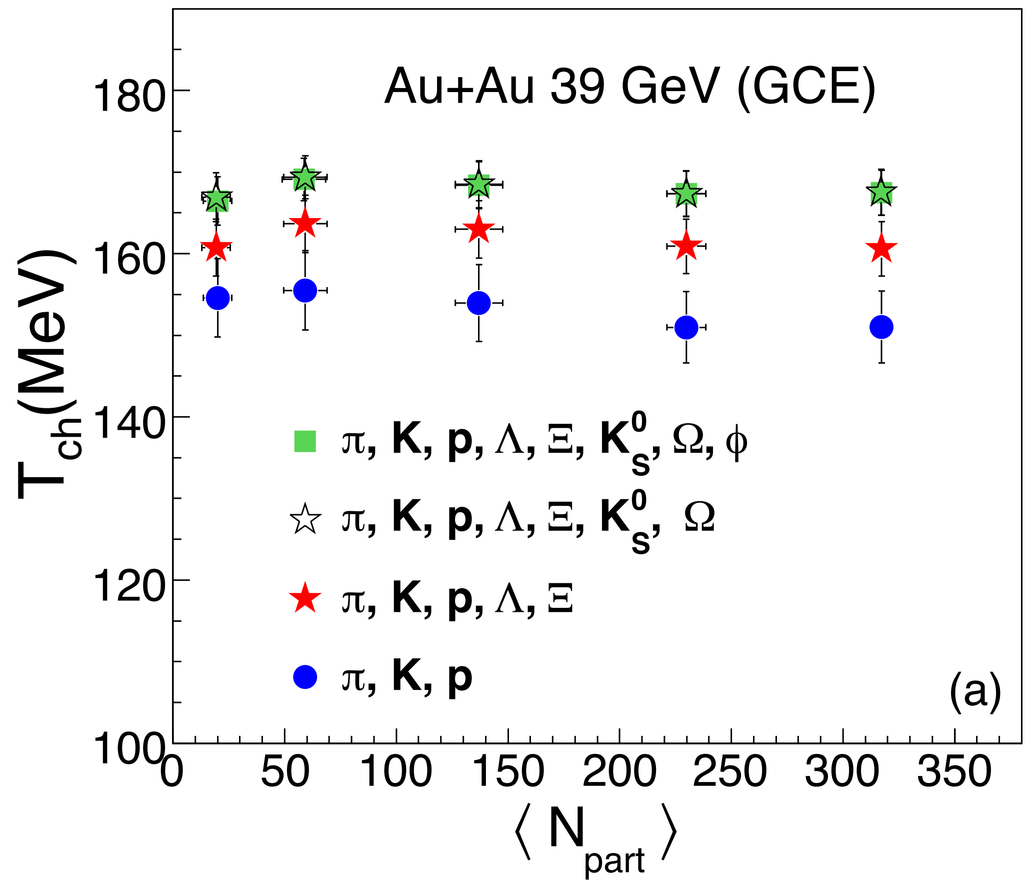
- The net-kaon fluctuation data from the STAR collaboration cannot be reproduced in the HRG model by using the freeze-out parameters obtained from the combined fit of χ^p_1/χ^p_2 and χ^Q_1/χ^Q_2.

- At the highest collision energy, the kaons freeze-out above T=163 MeV, about 10-15 MeV higher than the light hadrons.

- Confirmation of a freeze-out flavor-hierarchy by the inclusion of more resonances in the HRG Model.

Back-up slides

Is there a flavor hierarchy for chemical freeze-out?



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