Determination of chemical freeze-out parameters from net-kaon fluctuations at RHIC

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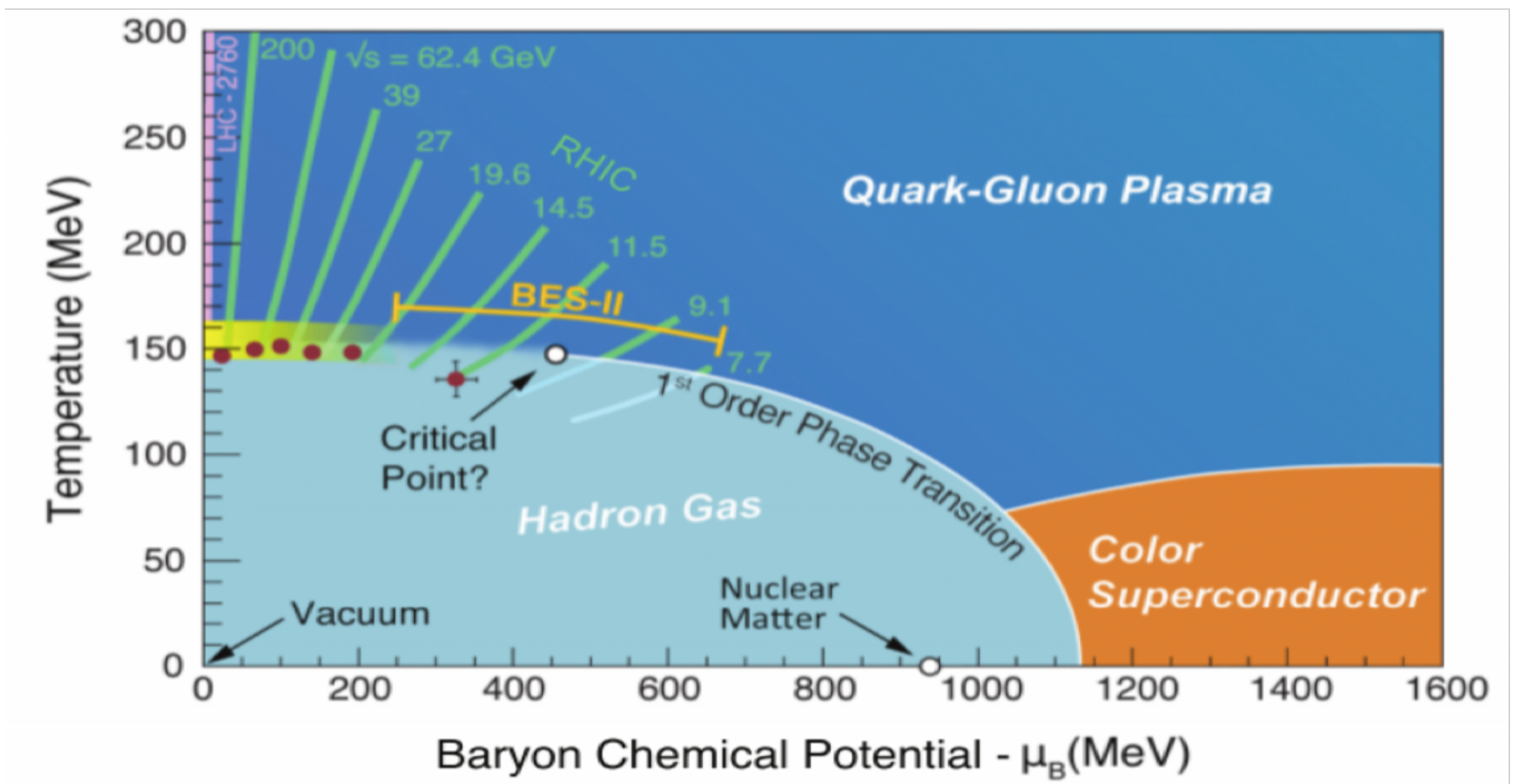
QCD Phase Diagram

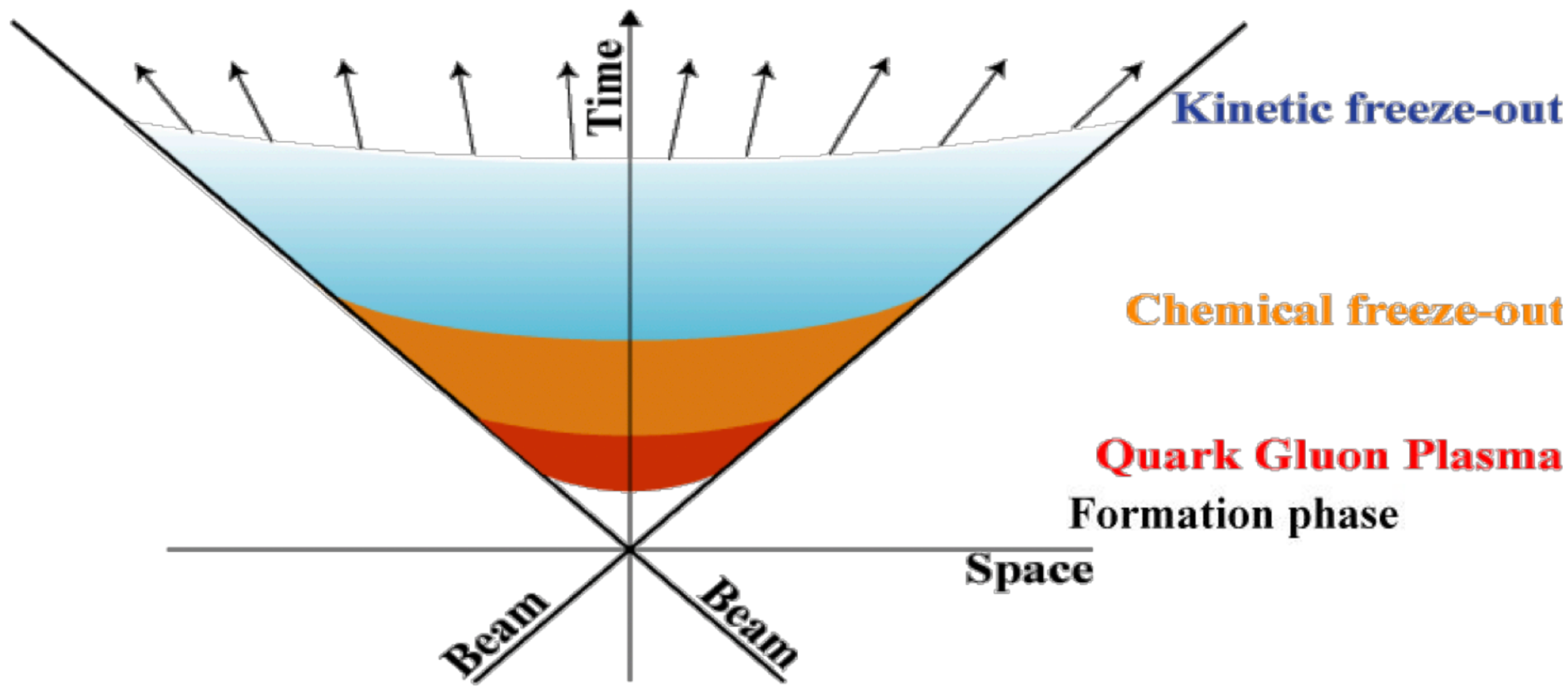
The different phases of QCD matter can be understood by studying the characteristics of the phase diagram

- 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 at high μ_B
    - ❖ Search for the critical point with the RHIC 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 (particle yields and fluctuations)

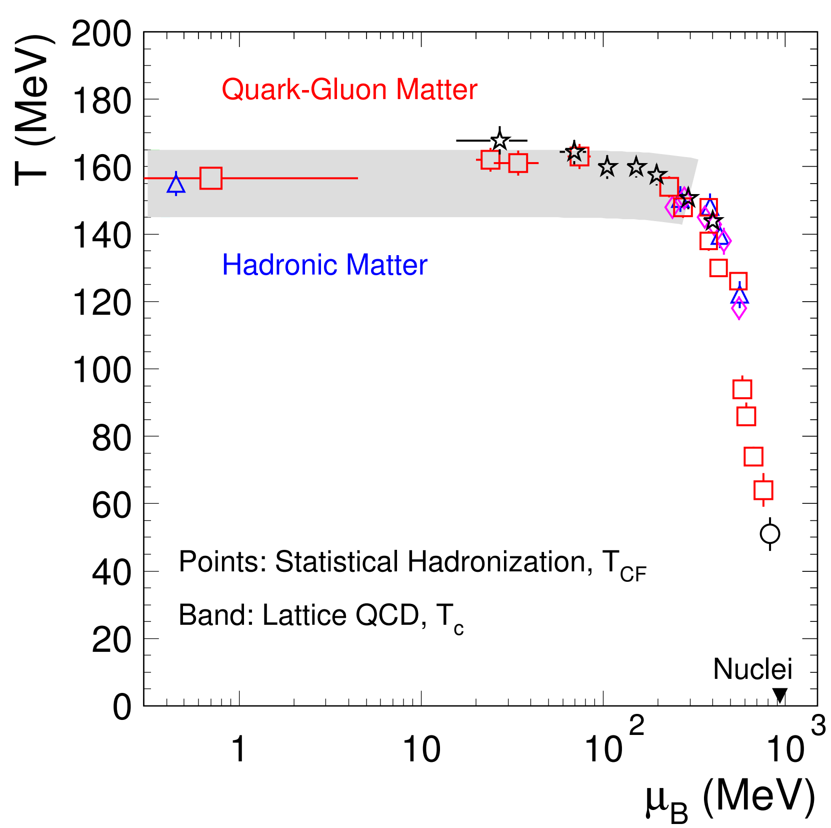
- Kinetic freeze-out: elastic collisions cease; spectra and correlations are fixed

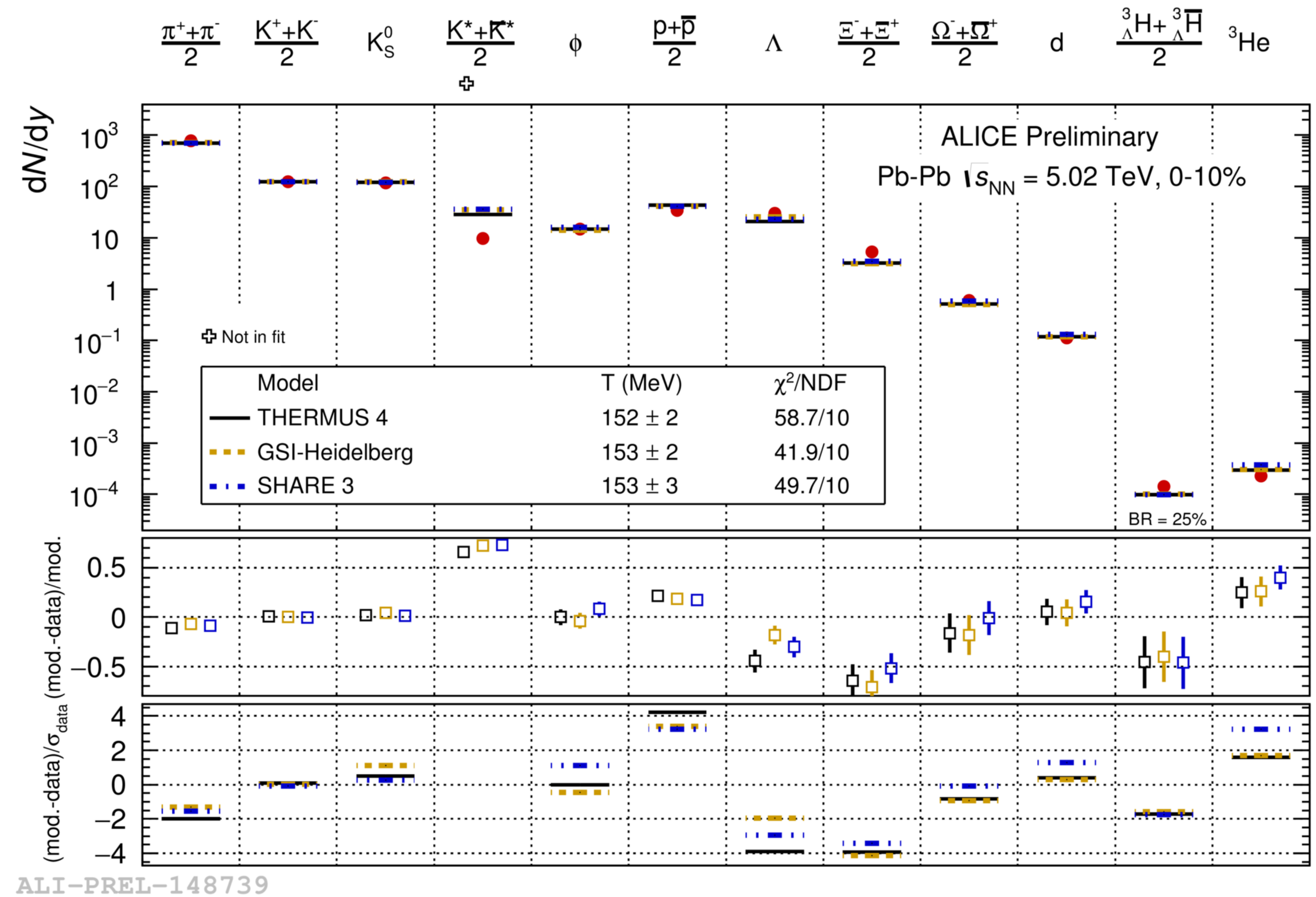
Chemical freeze-out in HICs

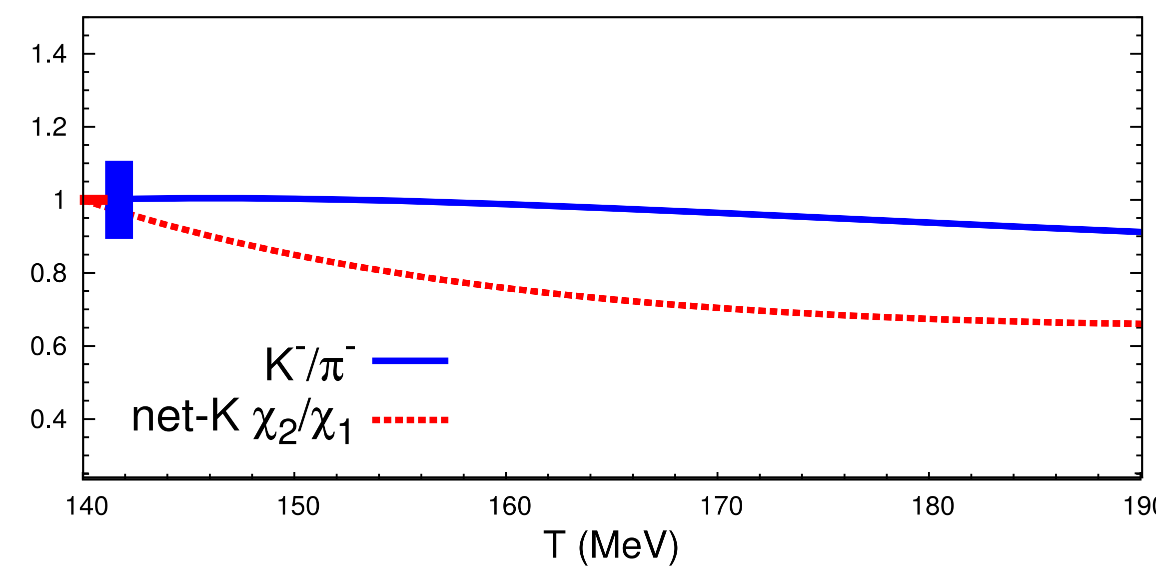
The freeze-out parameters are determined by:

- Thermal fits of particle yields $\{T_f, \mu_{B,f}, V_f\}$ or ratios $\{T_f, \mu_{B,f}\}$
- Fits of the net-charge fluctuations

The hadron freeze-out curve can be drawn by scanning a range of collision energies







F. Bellini, Nucl.Phys. A (2019); A. Andronic, et al, Nature (2018); P. Alba, et al, PRC (2015)

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 : $\sigma^2 = \chi_2$

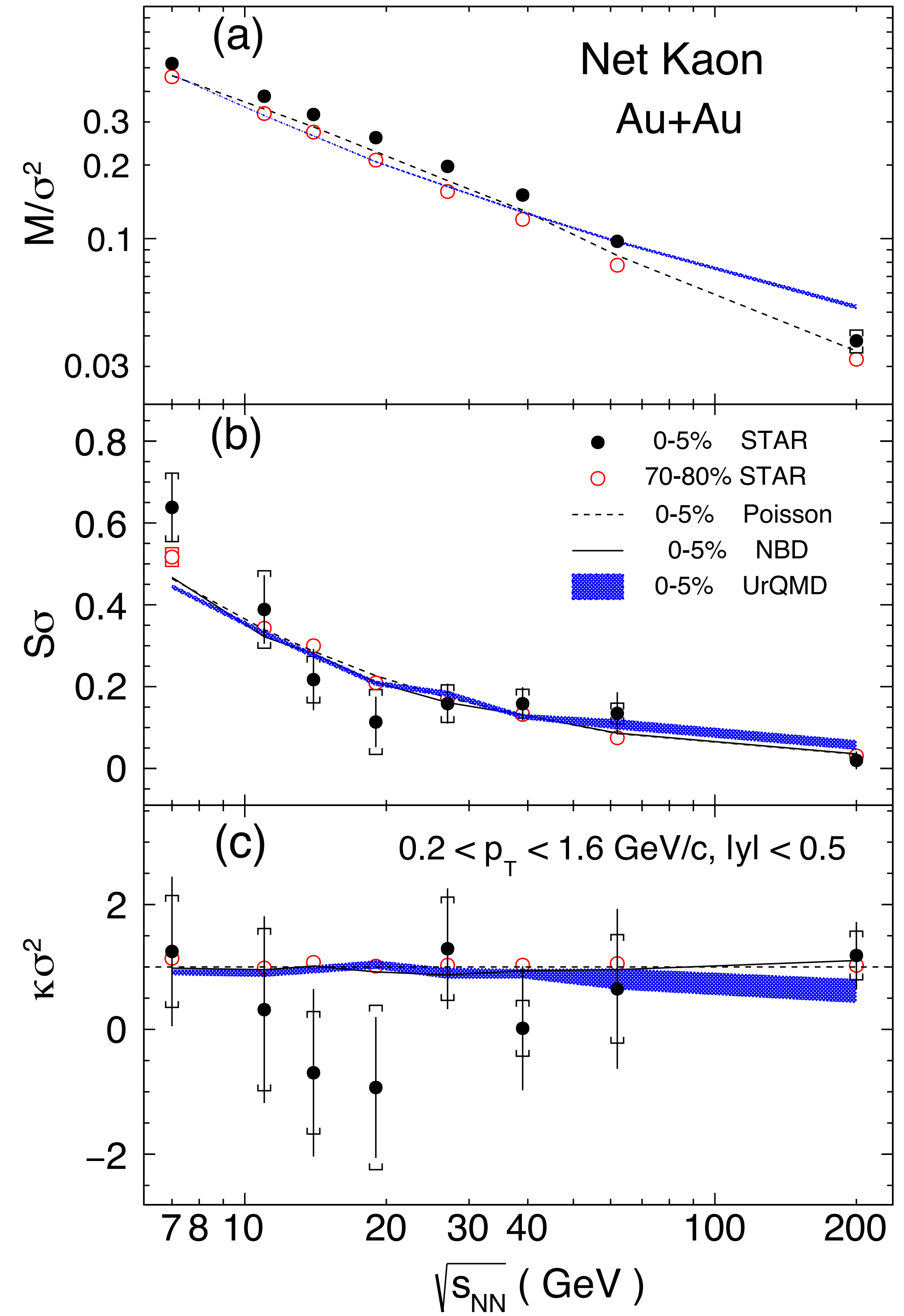
skewness : $S = \chi_3/\chi_2^{3/2}$ kurtosis : $\kappa = \chi_4/\chi_2^2$

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 (2018)

Net-kaon fluctuations

Kaon susceptibilities in the HRG Model are defined as:

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

- ☑ 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., PRC (2019)

Freeze-out parameters from net-kaon fluctuations

Is there a quark flavor hierarchy in chemical freeze-out?

What is the effect of additional states in the HRG model?

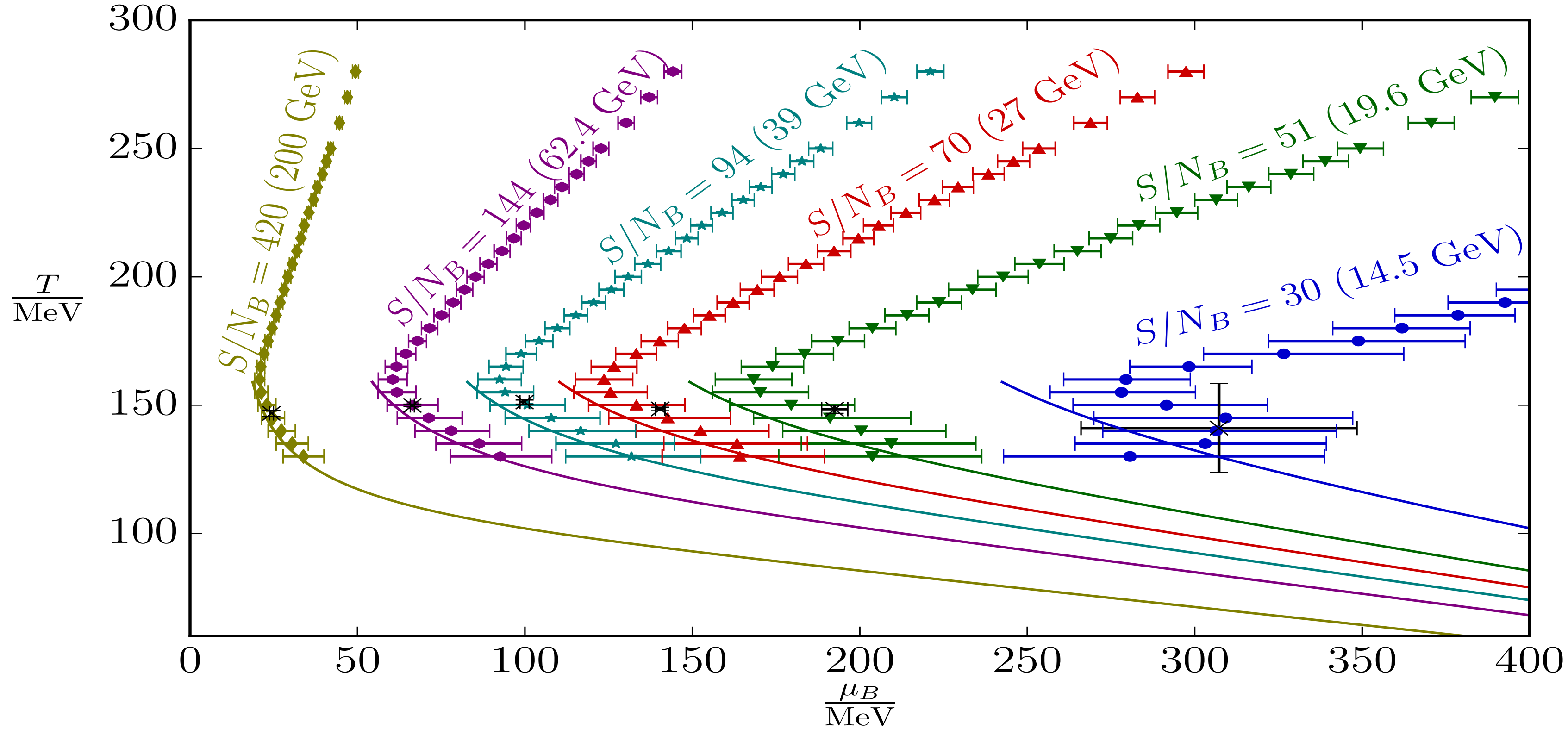
➡ Compare the HRG Model with experimental data from RHIC

- Calculate χ_1/χ_2 for net-kaons in the HRG model, including acceptance cuts and resonance decays
- Find χ_1/χ_2 along the lattice QCD isentropes
- Fit HRG results with experiment to extract freeze-out temperature, T_f
- Obtain $\mu_{B,f}$ from the isentropes

Lattice QCD Isentropes

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

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



Guenther, J. et al. Nucl.Phys. A (2017)

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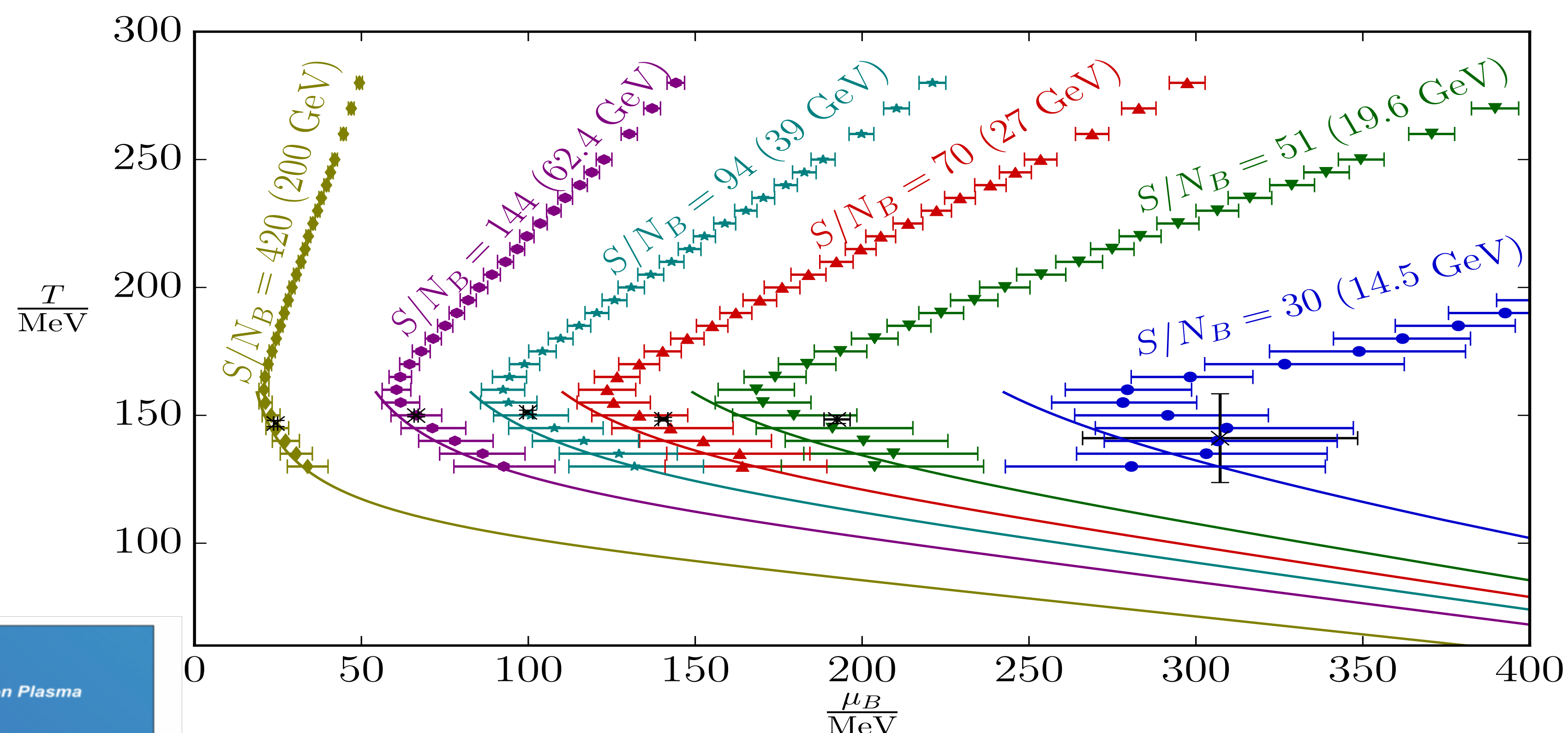
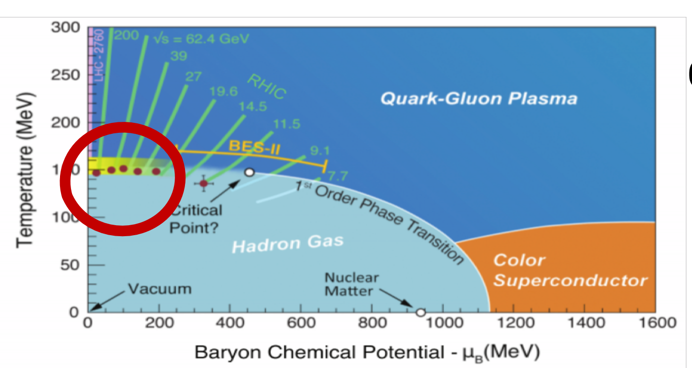


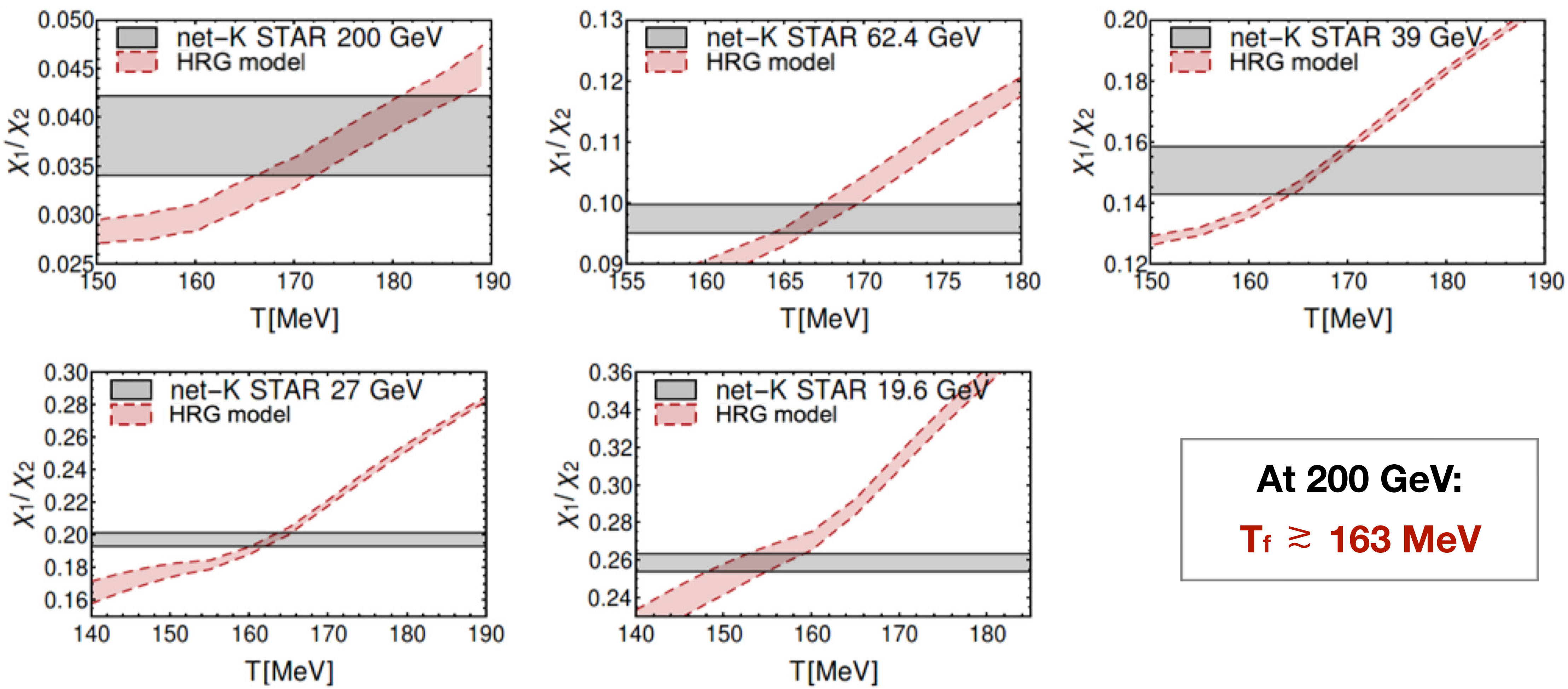


Guenther, J. et al. Nucl.Phys. A (2017)

Results: Net-kaon fluctuations

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:

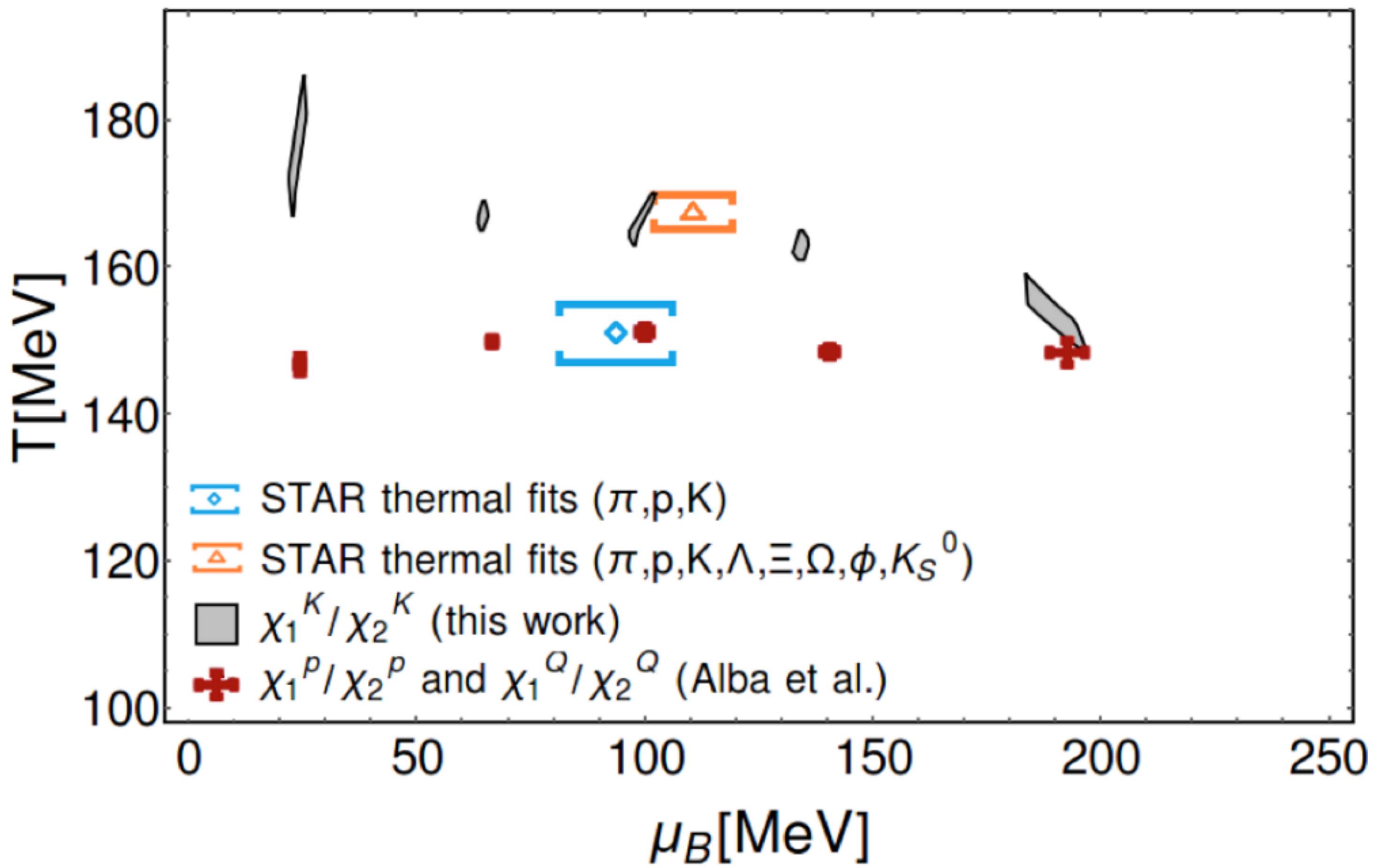
$T_f \gtrsim$ 163 MeV

R. Bellwied, JS, et al., PRC (2019)

Results: Phase diagram

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

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



R. Bellwied, JS, et al., PRC (2019)

PDG2012 v. PDG2016+

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 PDG lists will yield different results for the freeze-out parameters

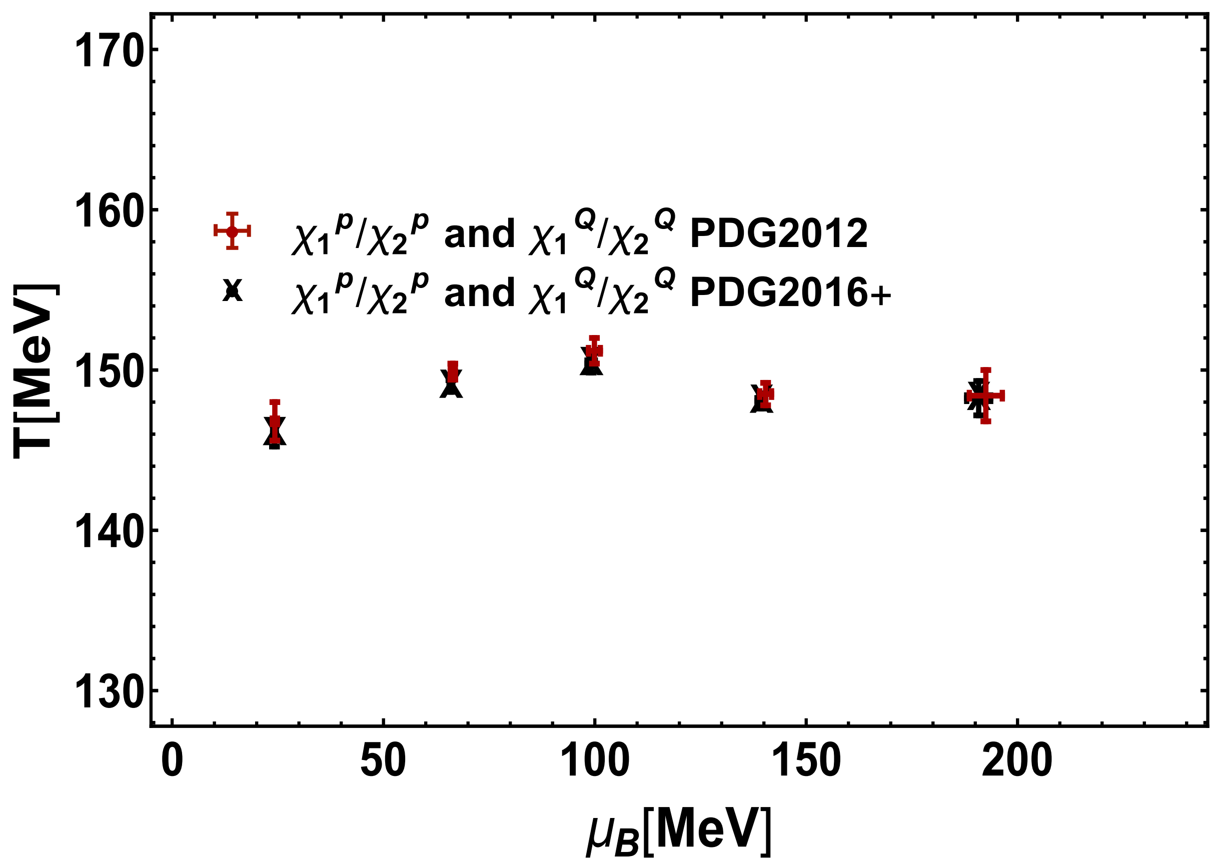
- **PDG2012: 319 species**
- **PDG2016: 608 species** (includes many more particles in the strange sector)
- **PDG2016+: 738 species** (includes all experimentally observed particles, i.e. *,**,***,****)

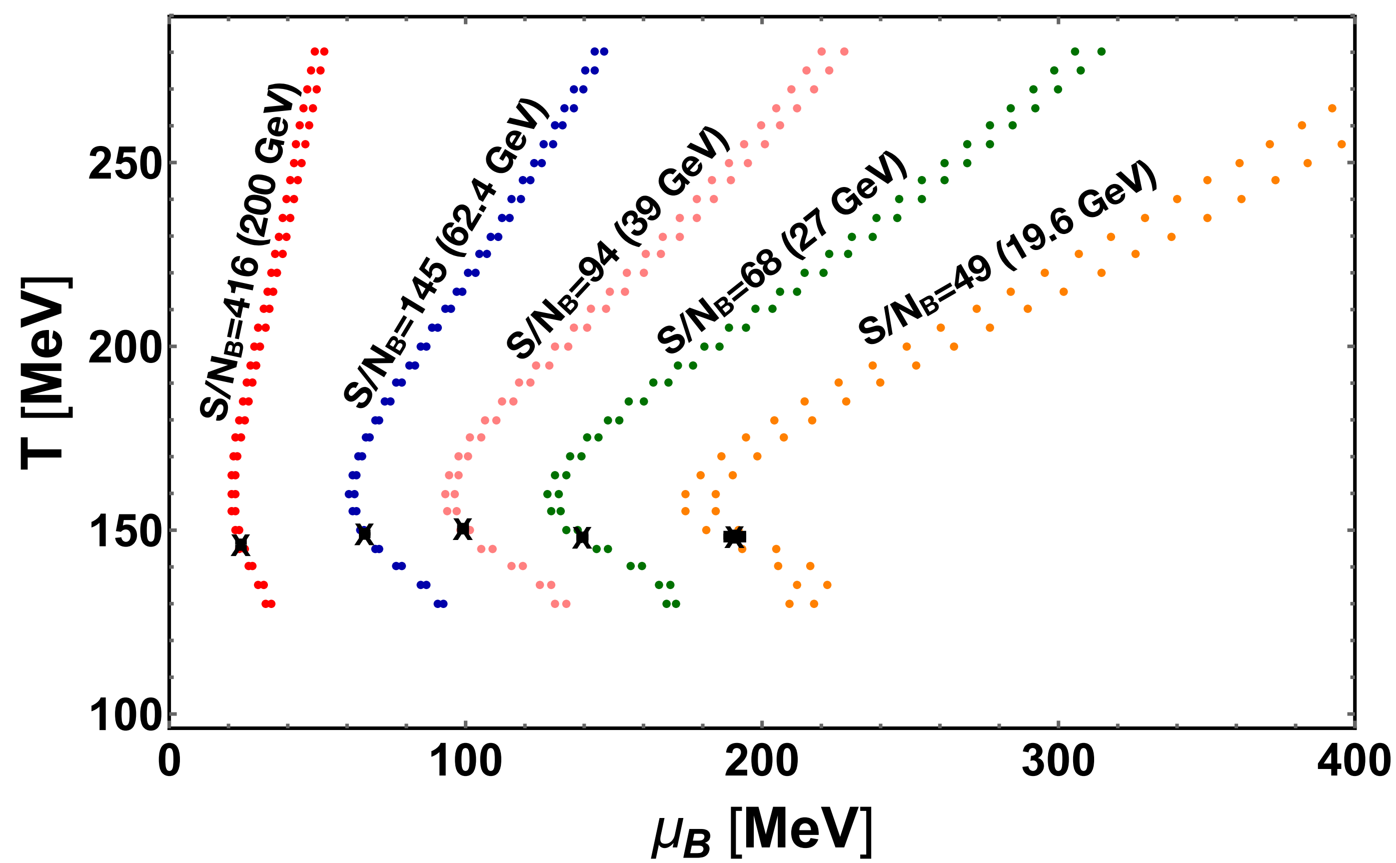
p	$1/2^+$	****
n	$1/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$\Delta(1232)$	$3/2^+$	****
$\Delta(1750)$	$1/2^+$	*

P. Alba et al, PRD (2017); C. Patrignani et al. (Particle Data Group), Chin. Phys. C (2016)

Lattice QCD Isentropes with 2016+

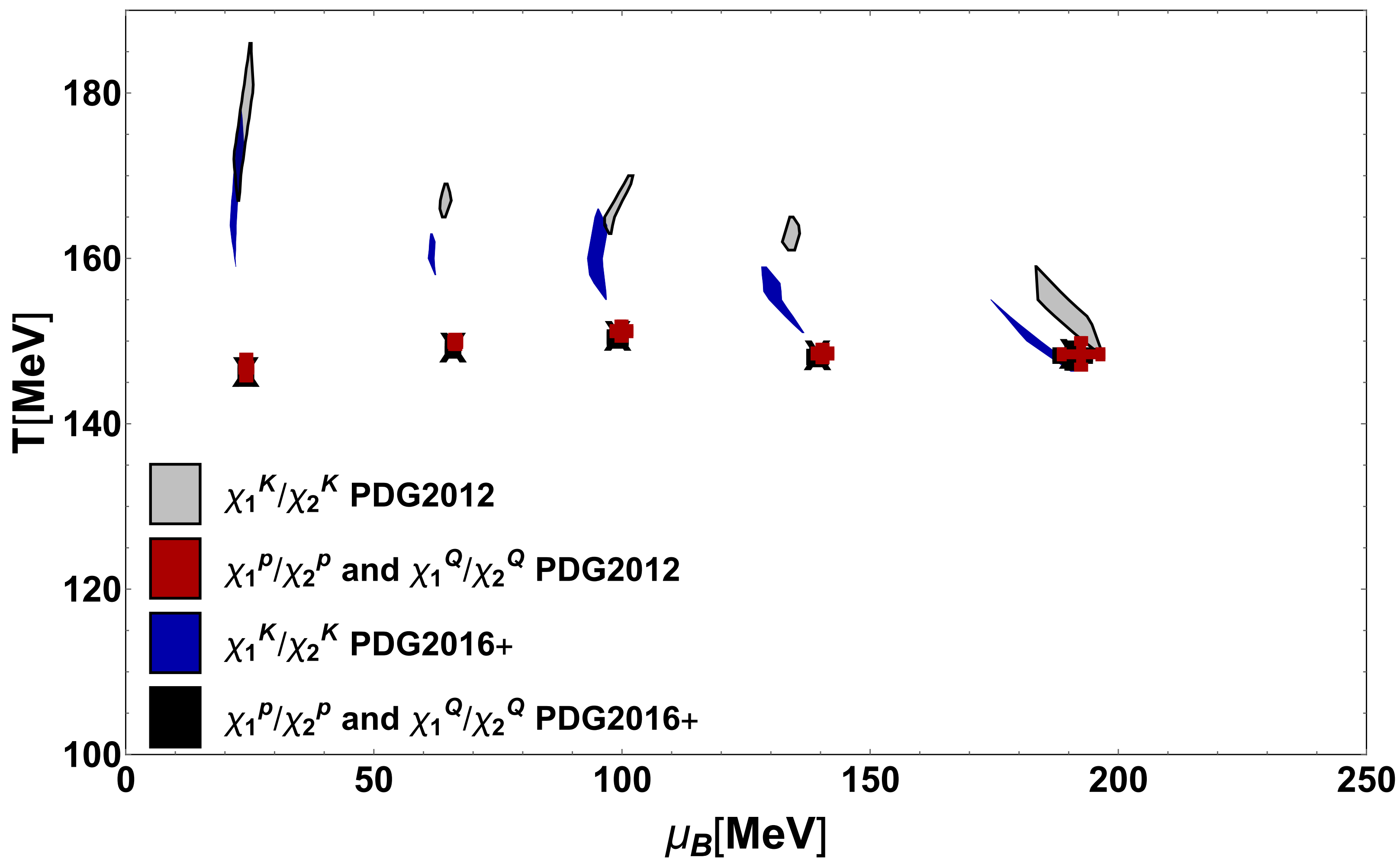
Calculate new isentropes from light particle freeze-out parameters determined by combined fit of net-p and net-Q with PDG2016+





Results: PDG2012 and PDG2016+

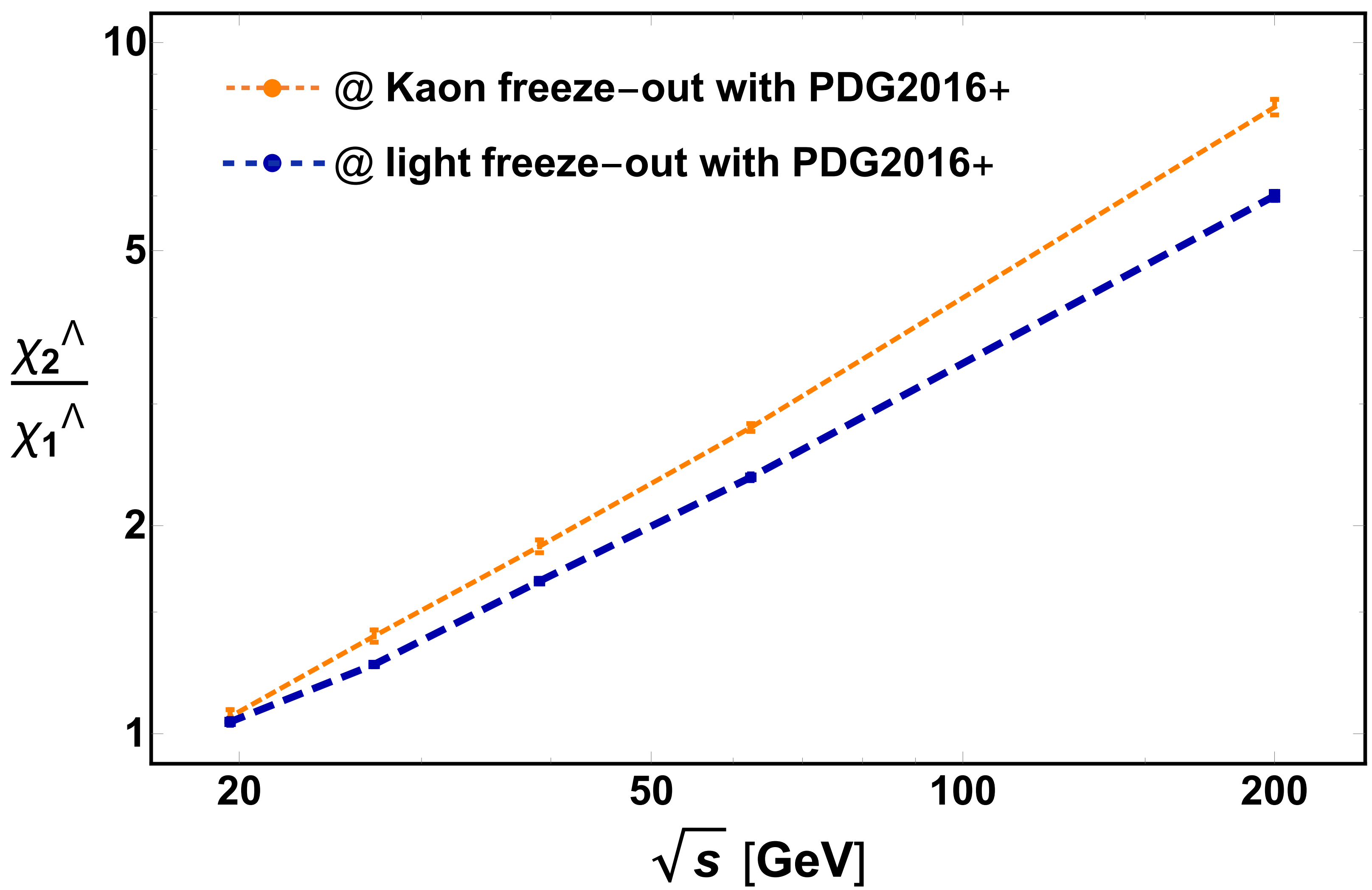
Compare the freeze-out parameters for the kaons and light particles for the different lists in order to determine the effect of the number of resonant states:



With the inclusion of more states in the HRG Model the kaon freeze-out temperature is decreased, but the separation remains

Results: Net-lambda predictions with 2016+

Calculate fluctuations for net-Λ using the kaon and light hadron freeze-out parameters.



Conclusions

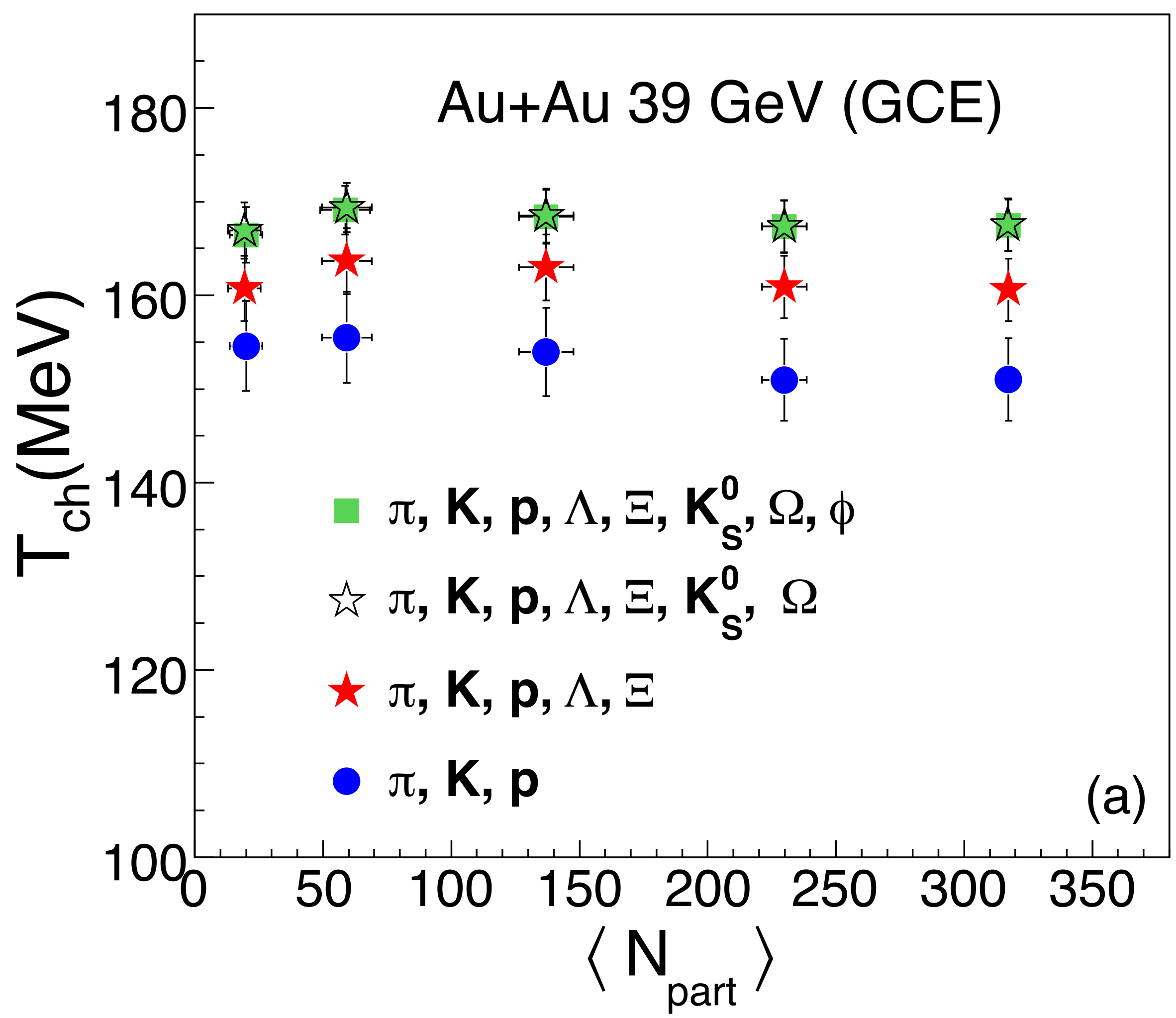
- The net-kaon fluctuation data from the STAR collaboration cannot be reproduced in the HRG model by using the freeze-out parameters obtained from the combined fit of χ^p_1/χ^p_2 and χ^Q_1/χ^Q_2.

- At the highest collision energy, the kaon freeze-out with PDG2012 is above T=163 MeV, about 10-15 MeV higher than the light hadrons.

- With the inclusion of more strange resonances in the HRG Model, the kaon freeze-out temperature becomes T $\gtrsim$ 160 MeV at $\sqrt{s_{NN}}$ = 200 GeV.

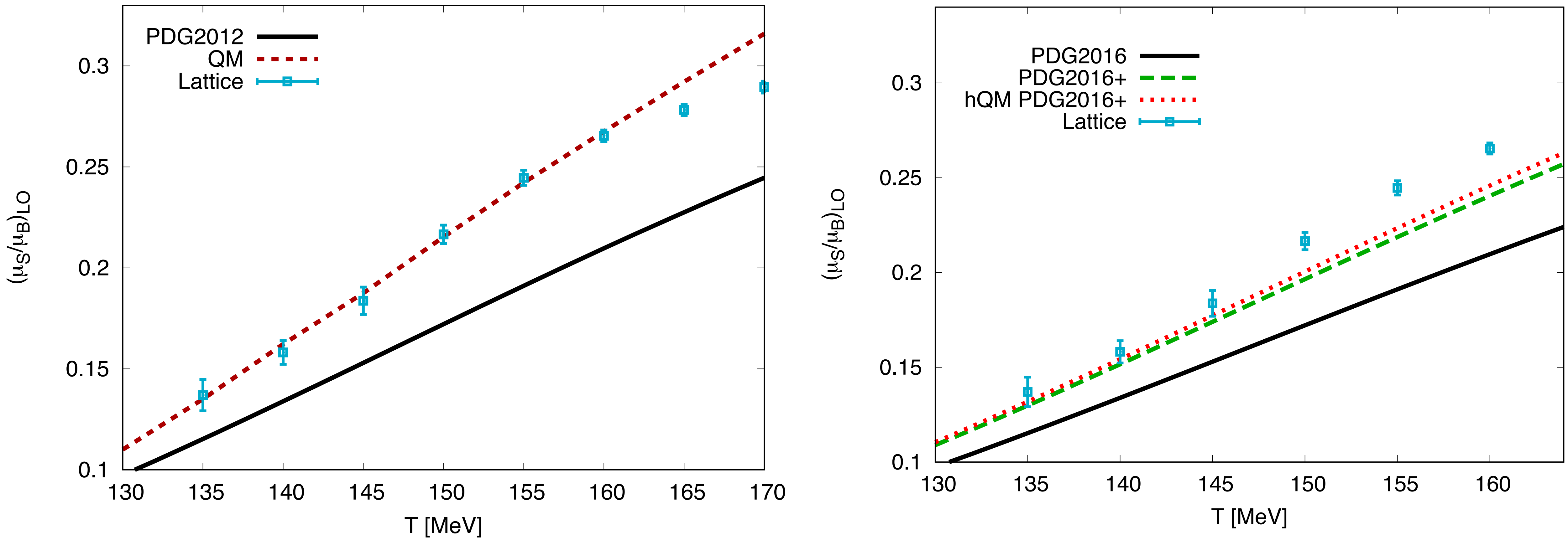
Back-up slides

STAR THERMUS fits of particle yields



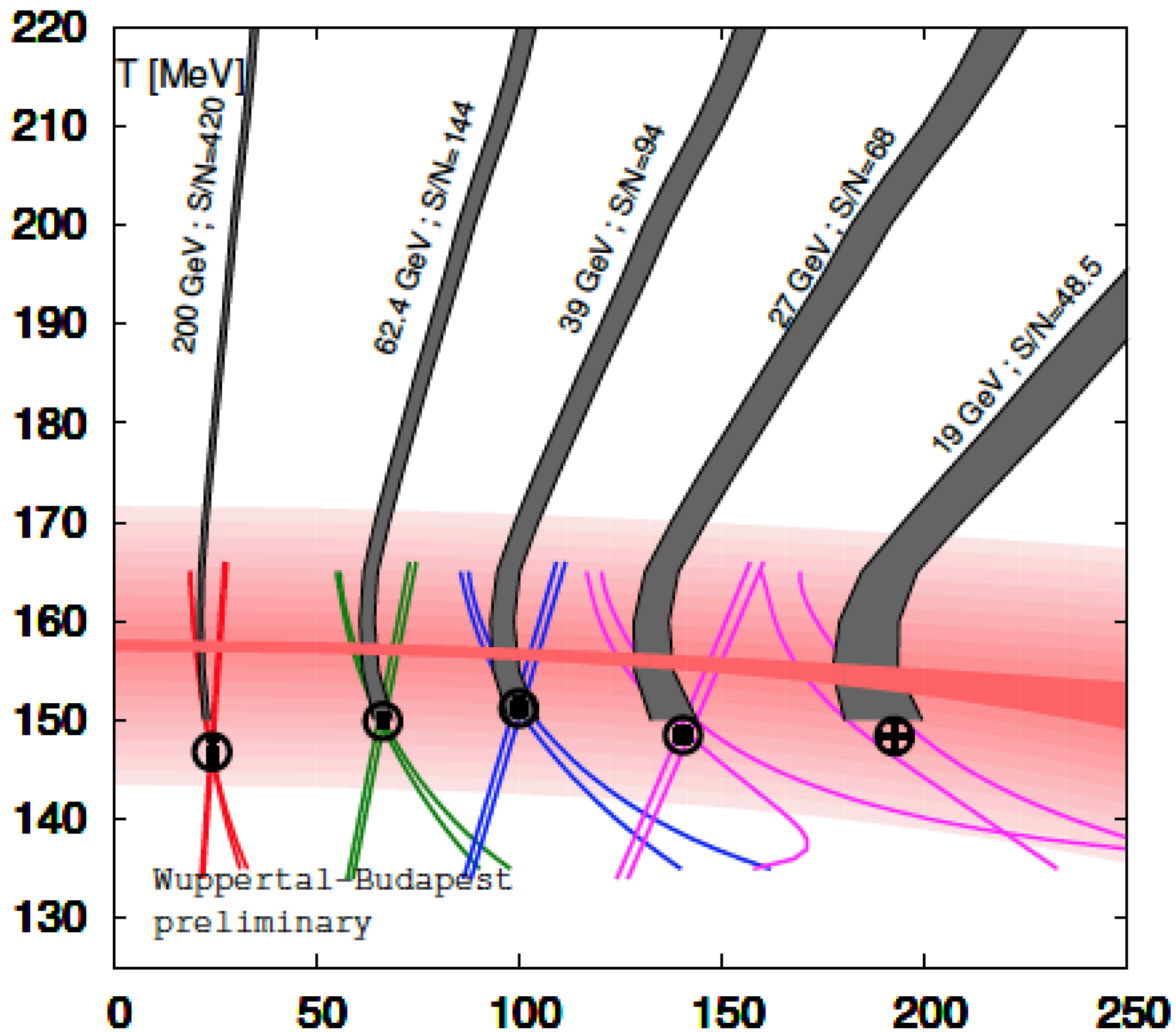
arXiv: 1701.07065

Comparison of HRG & Lattice results



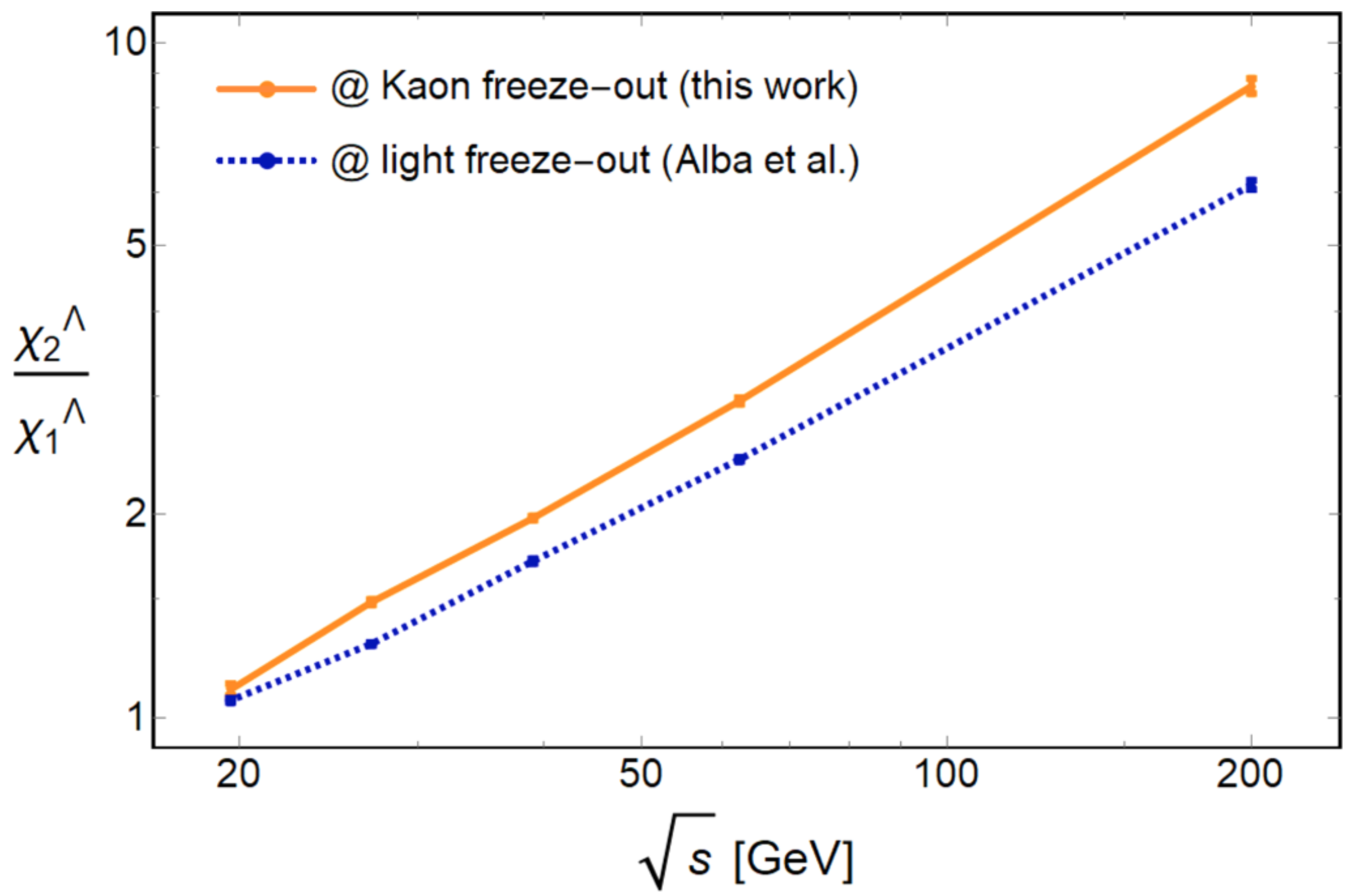
arXiv: 1702.01113

Freeze-out from net-p & net-Q



arXiv: 1601.02367

Net-lambda predictions with PDG2012



arXiv: 1805.00088