

Chemical freeze-out parameters of net-kaons in heavy-ion collisions

Jamie M. Stafford — University of Houston, USA

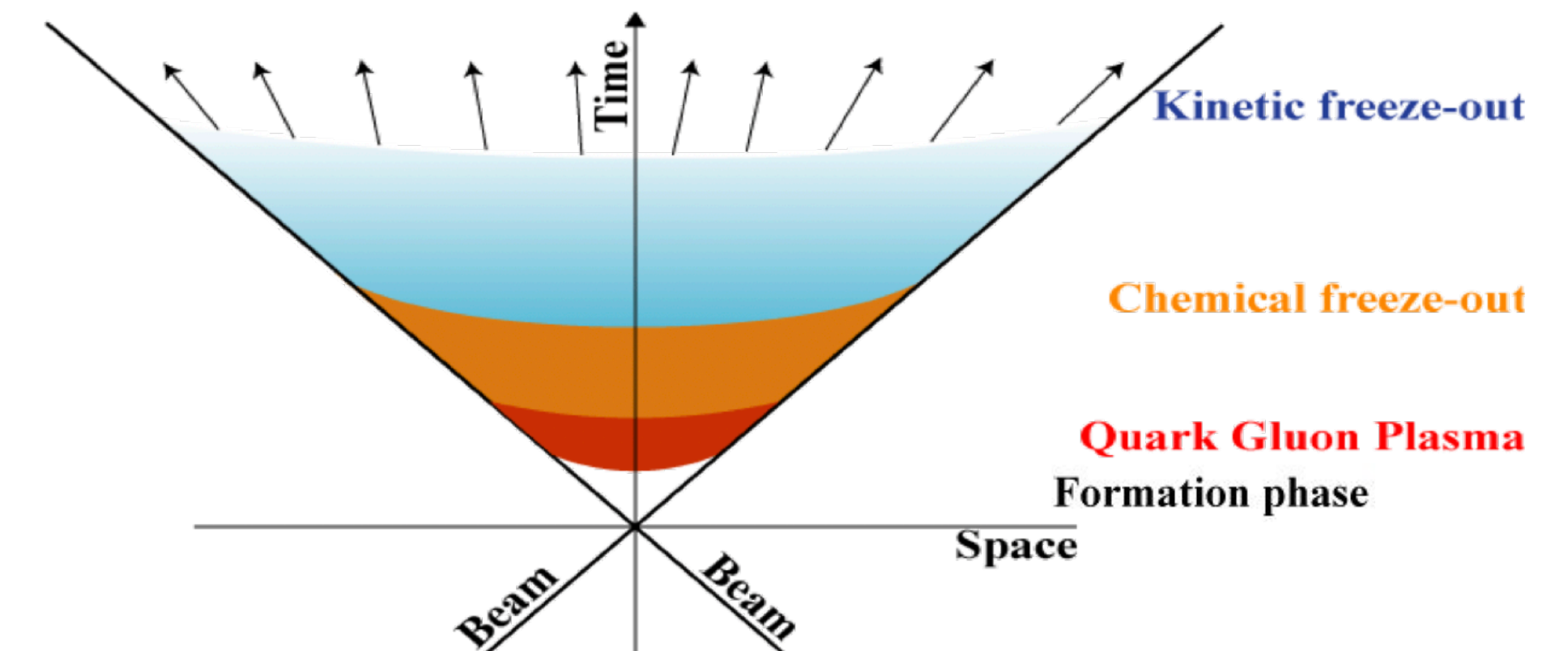
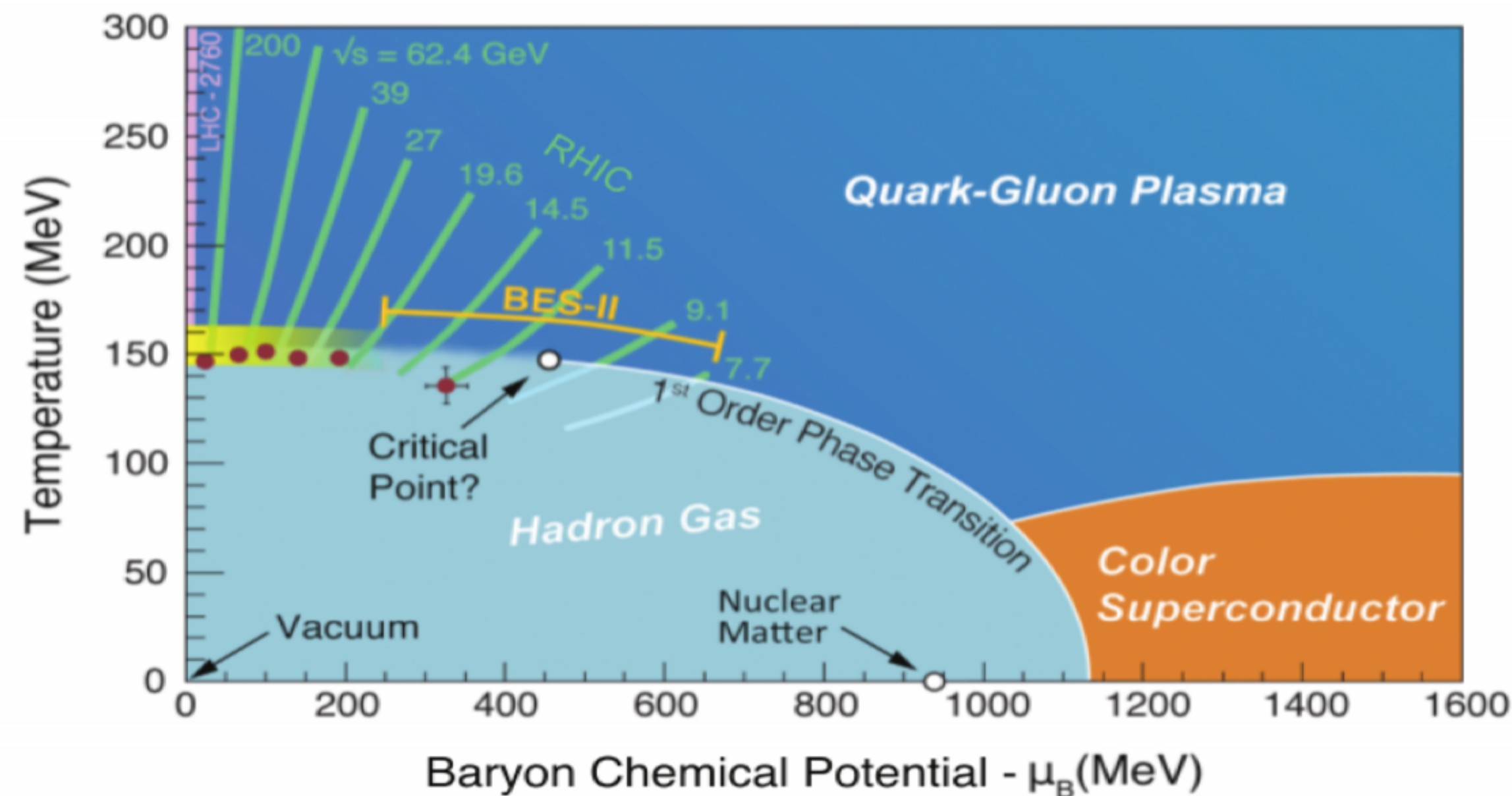
Collaborators: Claudia Ratti, Paolo Alba, Rene Bellwied,
Valentina Mantovani-Sarti, Jaki Noronha-Hostler, Paolo Parotto, Israel Portillo-Vazquez



QCD Phase Diagram and Chemical Freeze-out

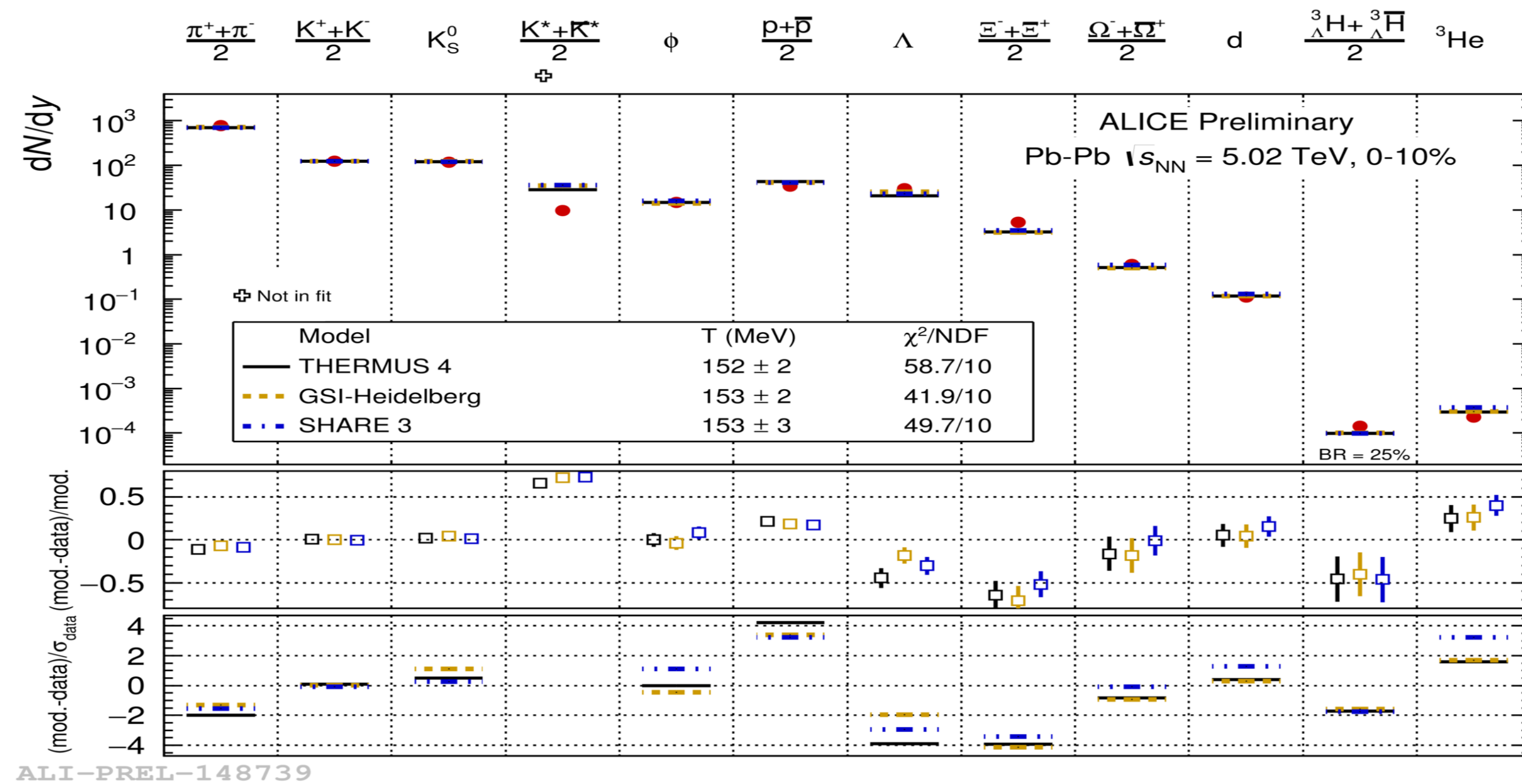
The different phases of strongly-interacting matter can be understood by studying the characteristics of the QCD phase diagram

- ▶ QGP is formed at large T, μ_B ; ordinary hadronic matter at small T, μ_B
- ▶ Crossover transition at $T \sim 155\text{MeV}$; possible first order phase transition at high μ_B
 - ❖ Search for the critical point with the RHIC Beam Energy Scan II (BES-II)



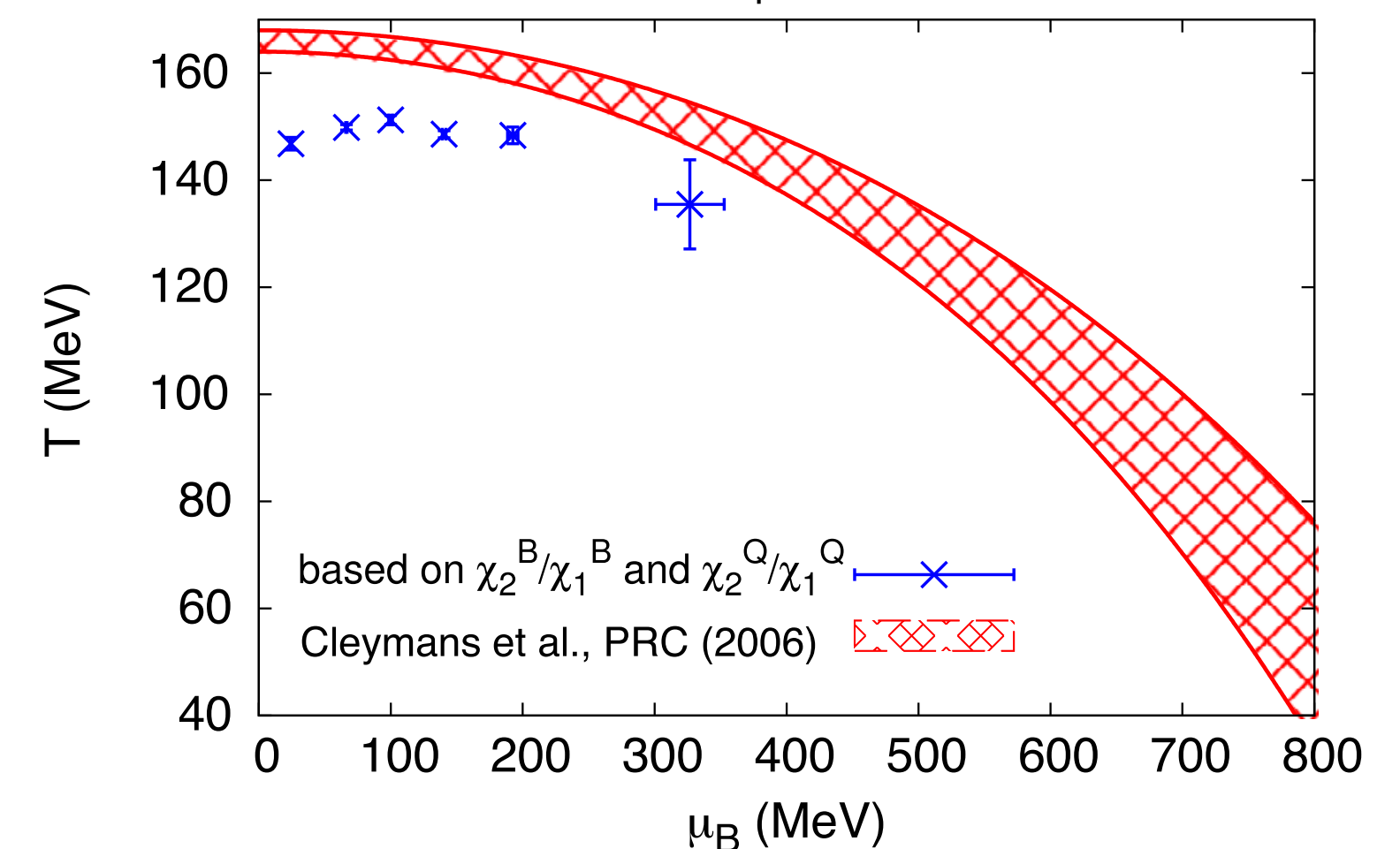
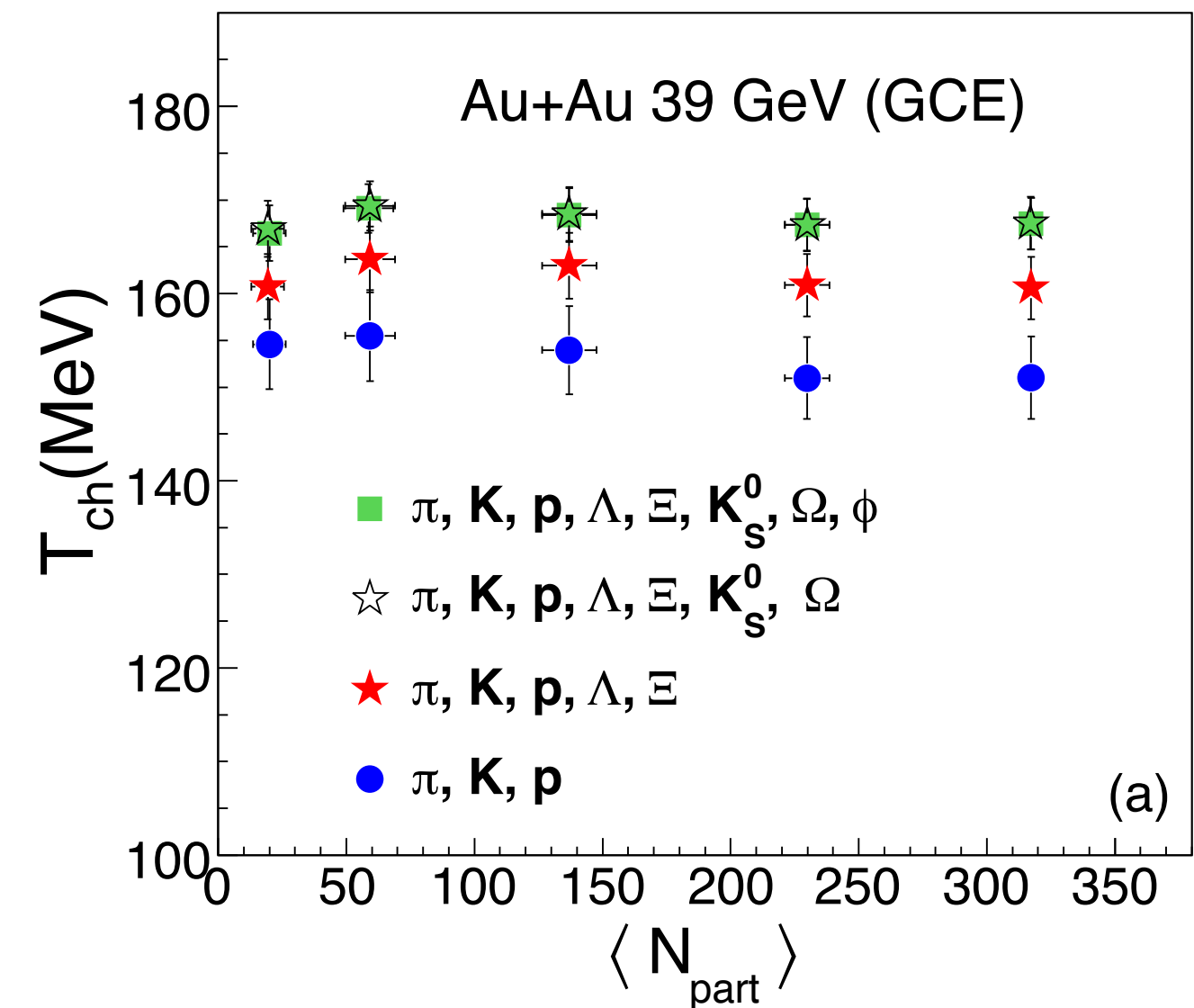
- **Chemical freeze-out:** inelastic collisions cease; the chemical composition is fixed (particle yields and fluctuations)
- **Kinetic freeze-out:** elastic collisions cease; spectra and correlations are fixed

Freeze-out parameters from heavy-ion collisions



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



ALICE (F. Bellini), Nucl. Phys. A (2019); STAR (L. Adamczyk et al.) PRC (2017); P. Alba, et al, PLB (2014)

Freeze-out parameters from fits and 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 STAR by calculating particle multiplicities and fluctuations
 - ▶ Thermal fits
 - ❖ Utilize the Thermal-FIST software to fit particle yields
 - ▶ Fluctuations
 - ❖ Ratio of lowest-order moments of net-kaon distribution
 - ❖ Lattice QCD isentropes

Hadron Resonance Gas Model

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

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

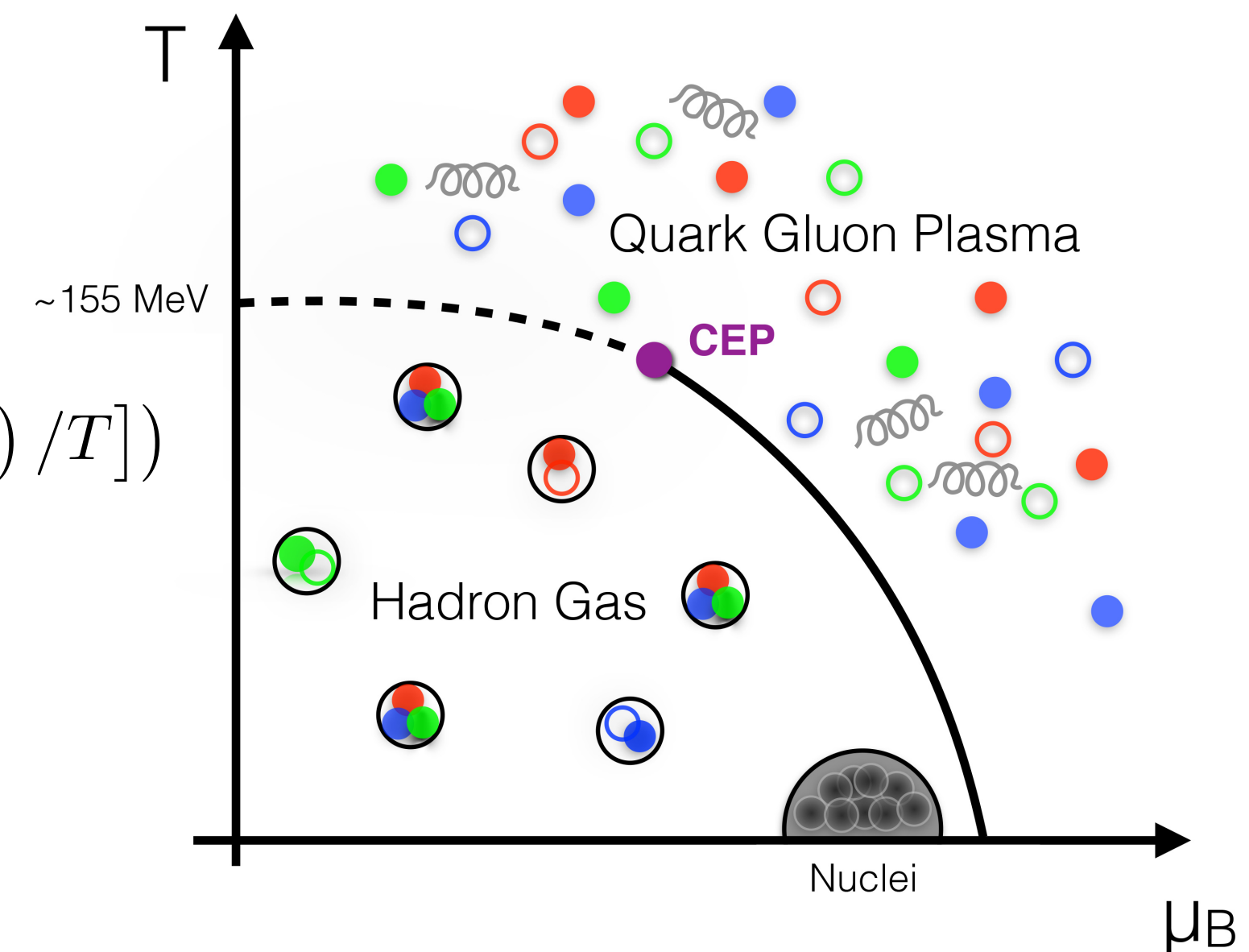
$$\frac{P}{T^4} = \frac{1}{VT^3} \sum_i \ln Z_i(T, V, \vec{\mu})$$

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

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



H.T. Ding, et al, Int. J. Mod. Phys. (2015)

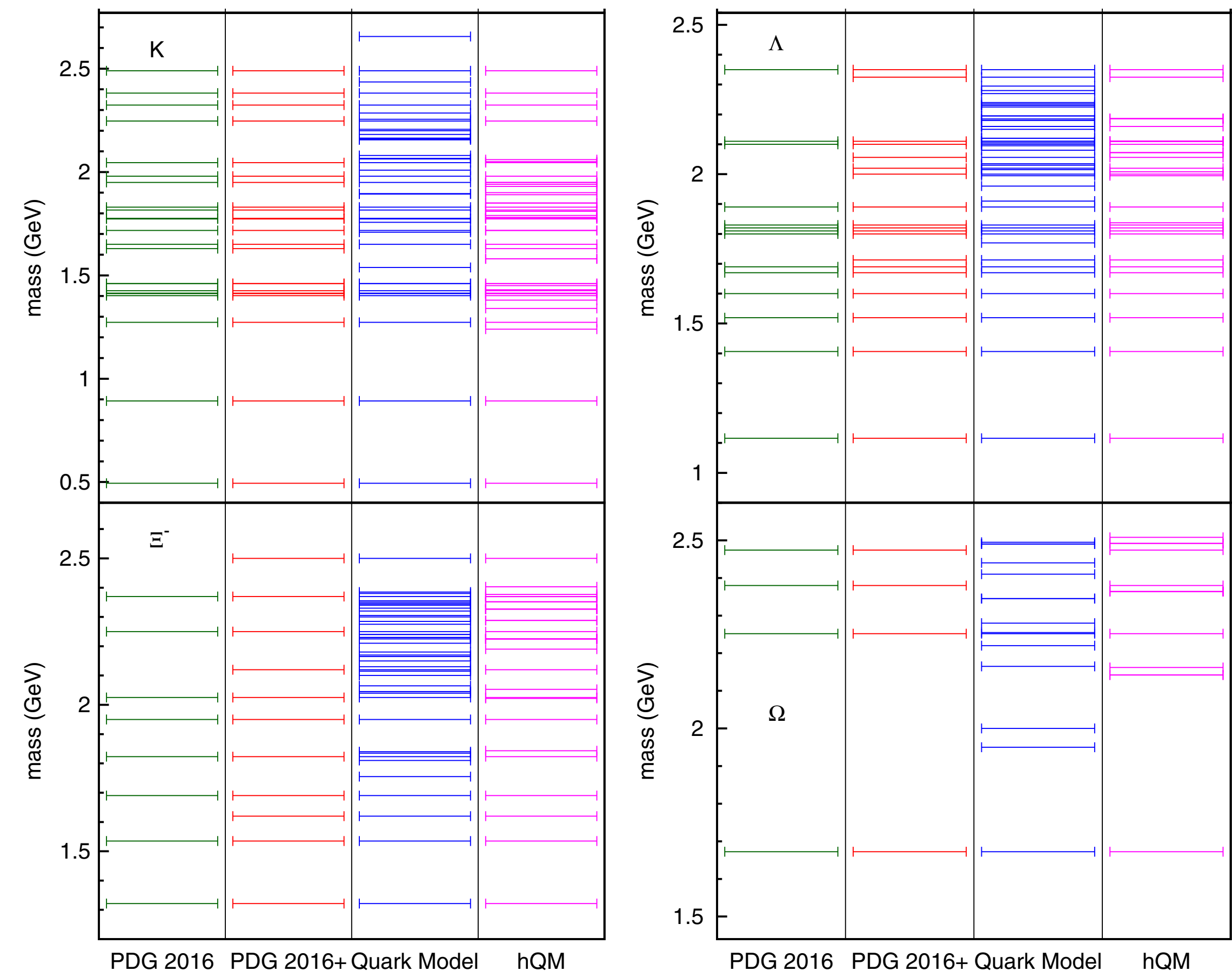
PDG-based particle lists in HRG model

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

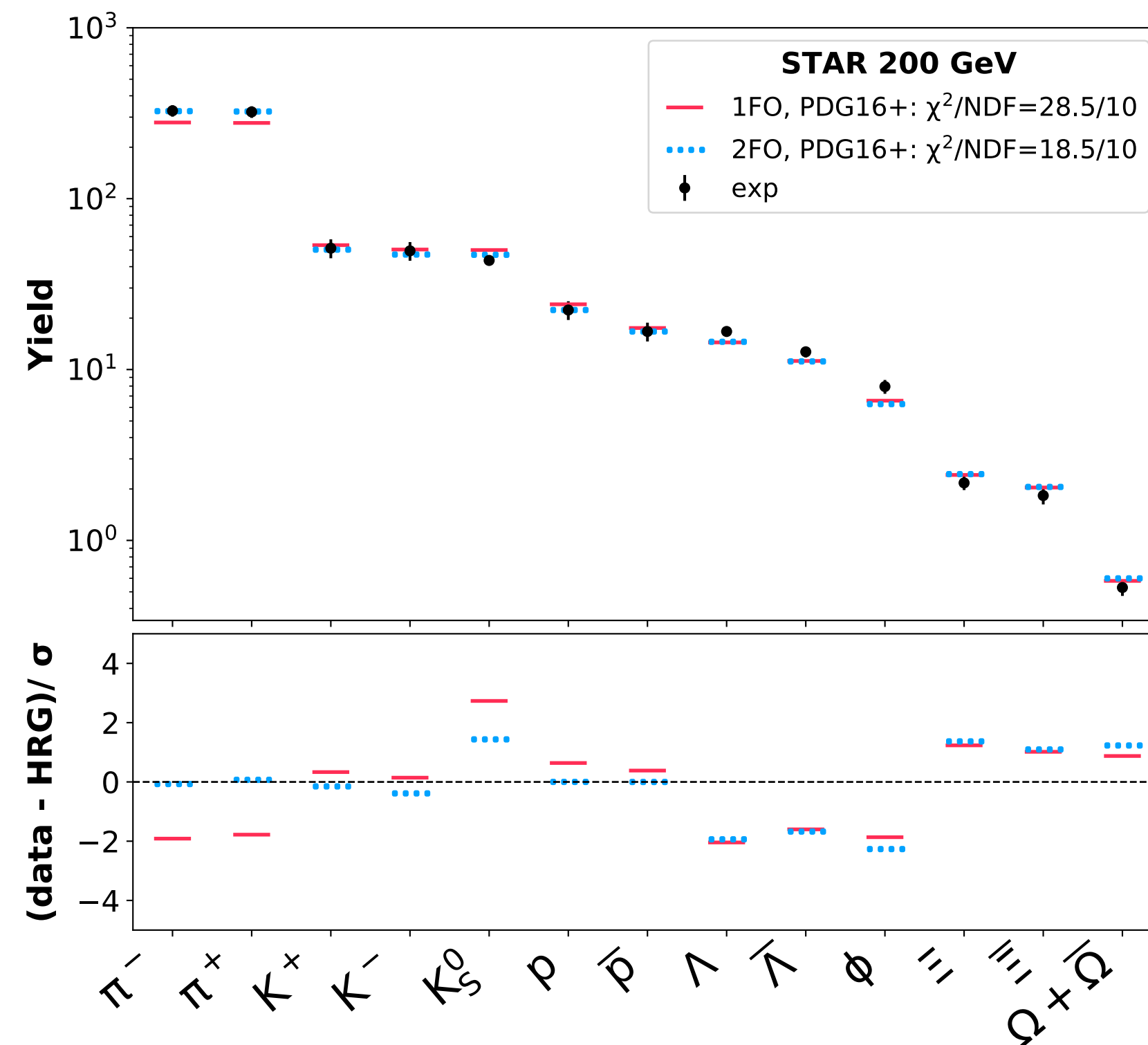


P. Alba et al, PRD (2017); C. Patrignani et al. (Particle Data Group), Chin. Phys. C (2016)

Thermal Fits

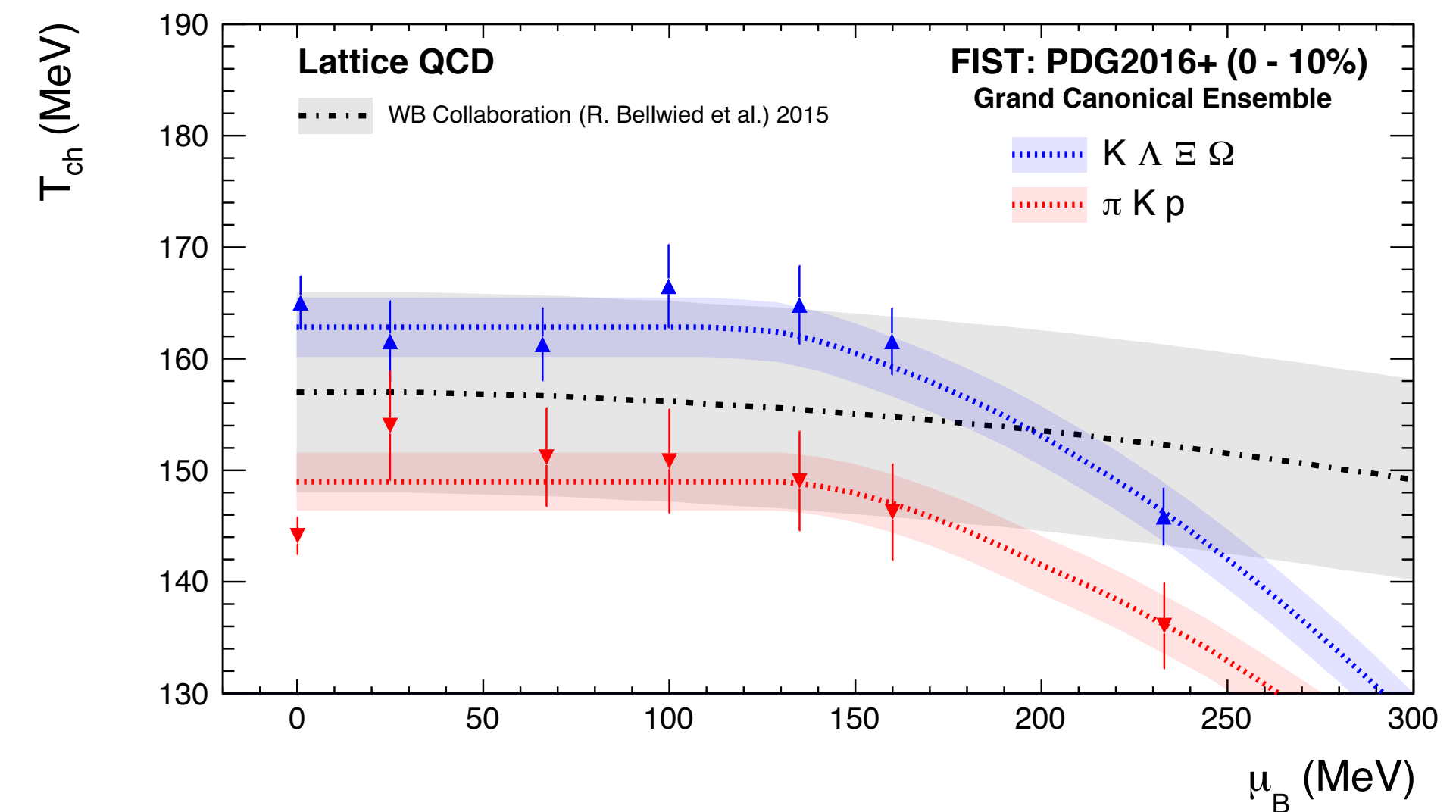


Calculate particle yields by minimizing χ^2 in the ideal HRG model with the Grand Canonical formalism



	Single Freeze-out	Two-flavor Freeze-out	
		Light	Strange
T [MeV]	161.4 ± 2.2	150.9 ± 4.5	164.8 ± 2.6
μ_B [MeV]	27.2 ± 8.6	22.7 ± 14.0	29.9 ± 11.4

See poster by F. A. Flor



JS, et al in preparation; V. Vovchenko and H. Stöcker, Thermal-FIST, Comp. Phys. Comm. (2019)

Fluctuations of Conserved Charges

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

$$\text{mean : } M = \chi_1$$

$$\text{variance : } \sigma^2 = \chi_2$$

$$\text{skewness : } S = \chi_3 / \chi_2^{3/2}$$

$$\text{kurtosis : } \kappa = \chi_4 / \chi_2^2$$

Volume-independent ratios:

$$S\sigma = \chi_3 / \chi_2$$

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

$$\sigma^2 / M = \chi_2 / \chi_1$$

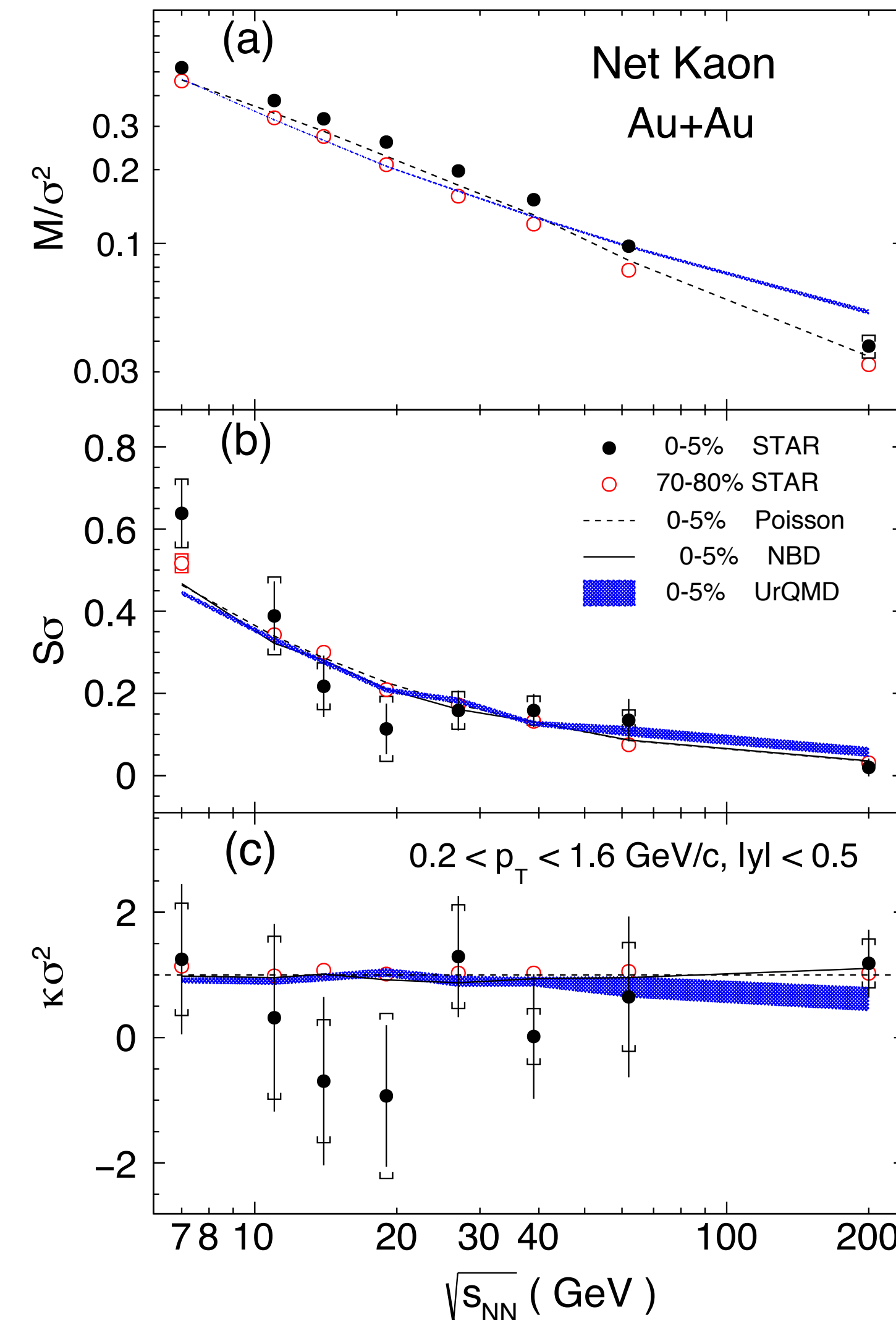
$$S\sigma^3 / M = \chi_3 / \chi_1$$

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

Freeze-out conditions from net-kaon fluctuations

Determination of freeze-out parameters given only one experimental quantity:

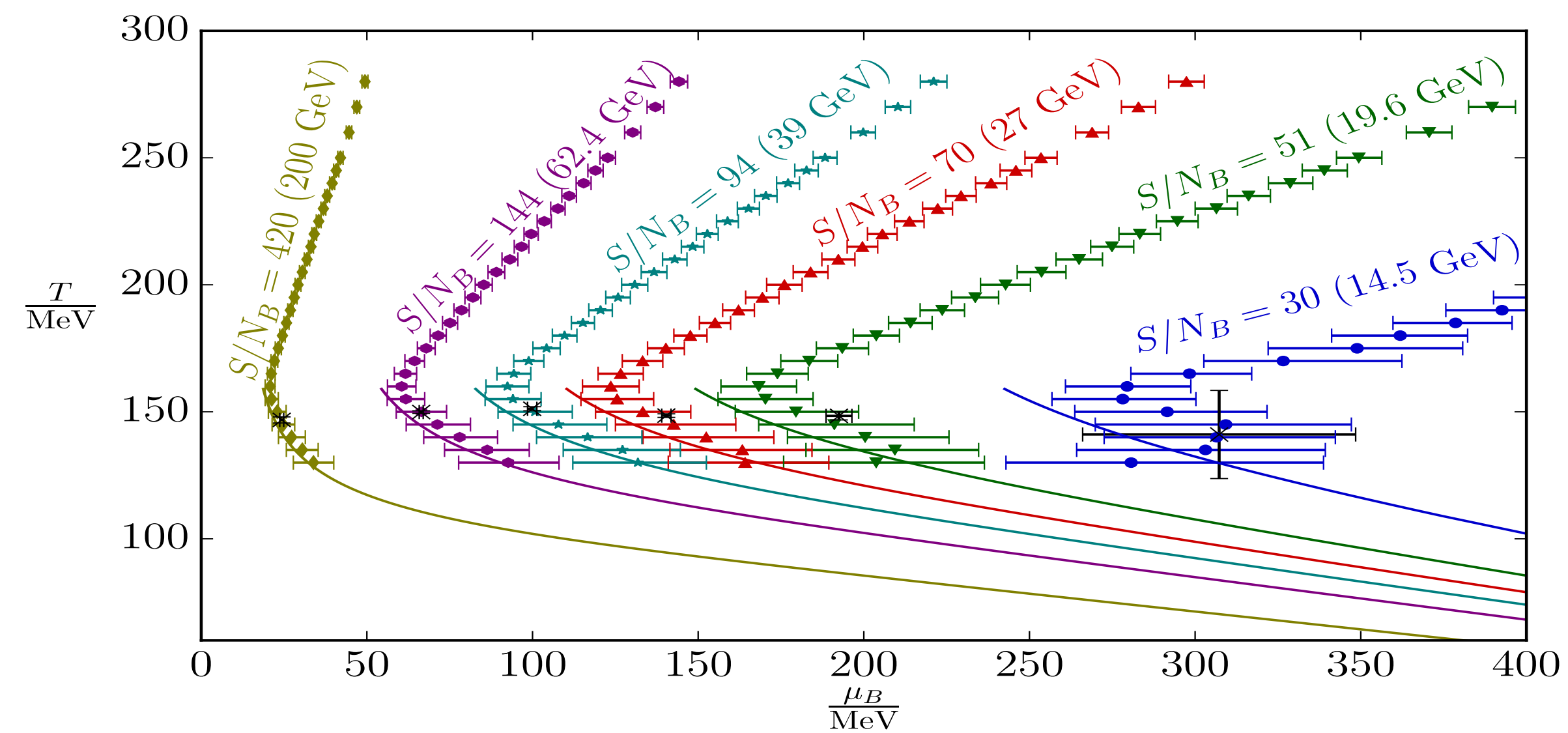
- ▶ Calculate χ_1/χ_2 for net-kaons in the HRG model, including acceptance cuts and resonance decays
- ▶ Find χ_1/χ_2 along the lattice QCD isentropes
- ▶ Fit HRG results with experiment to extract freeze-out temperature, T_f
- ▶ Obtain $\mu_{B,f}$ from the isentropes



STAR Collaboration (Adamczyk, L. et al.) PLB (2018)

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

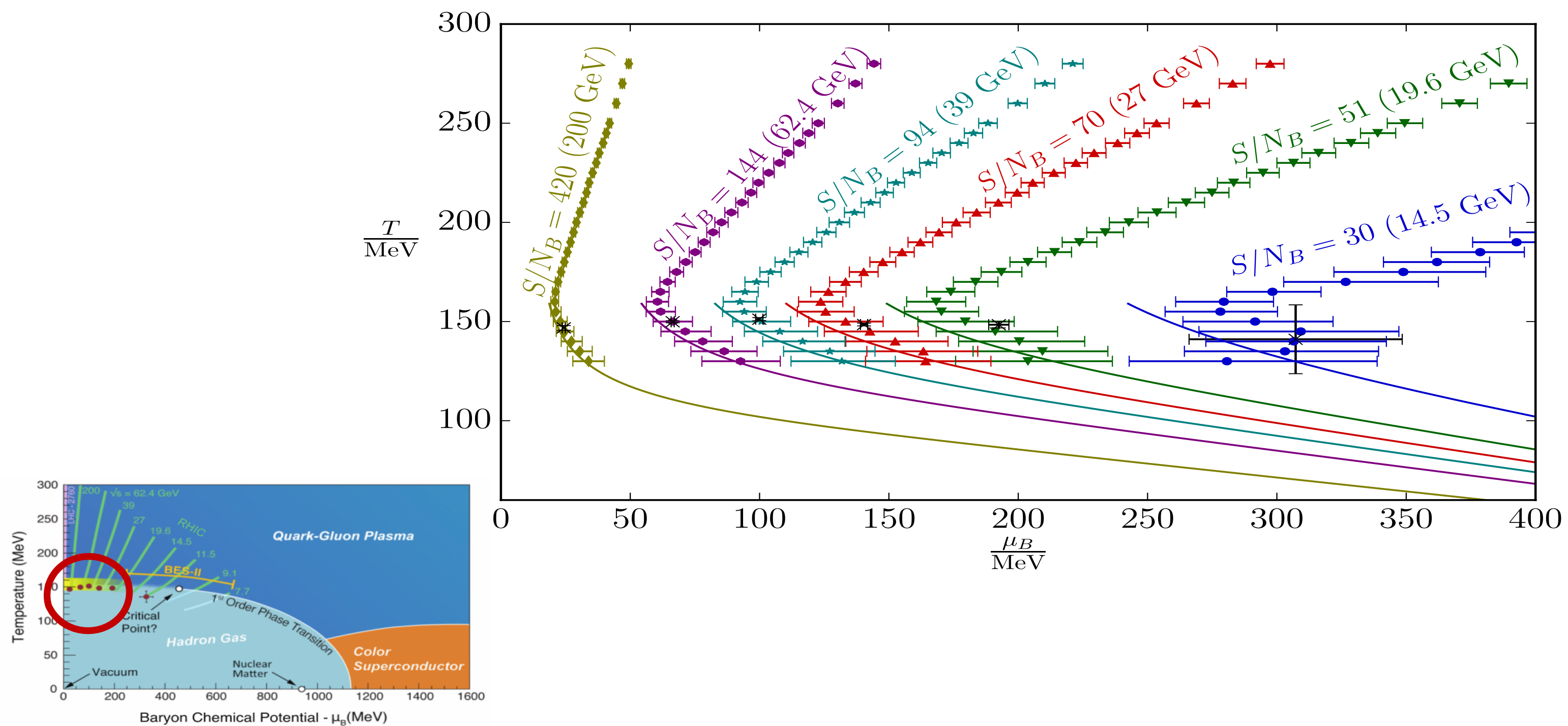
- ▶ Shows the path of the system across the phase diagram
- ▶ S/N_B is conserved



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

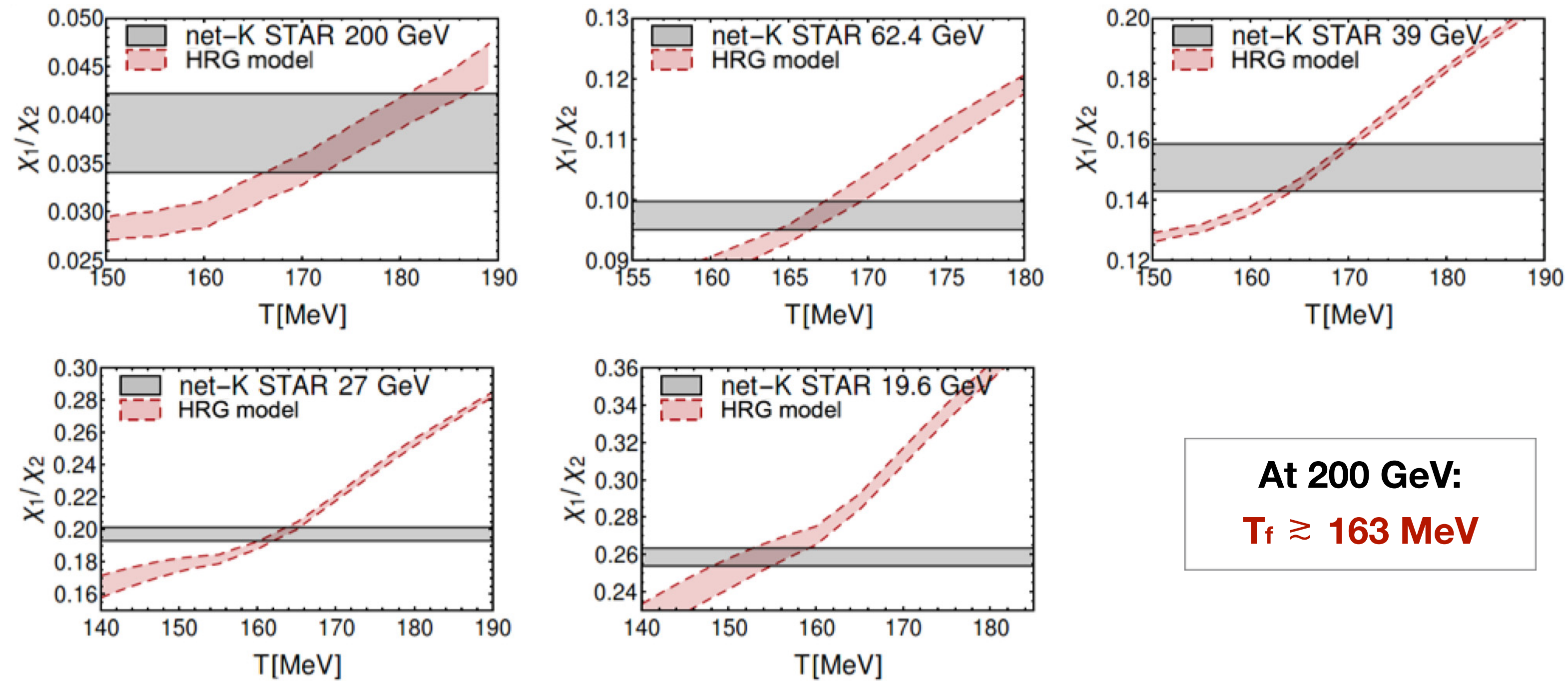


Guenther, J. et al. Nucl.Phys. A (2017)

Net-kaon fluctuations along Lattice QCD Isentropes

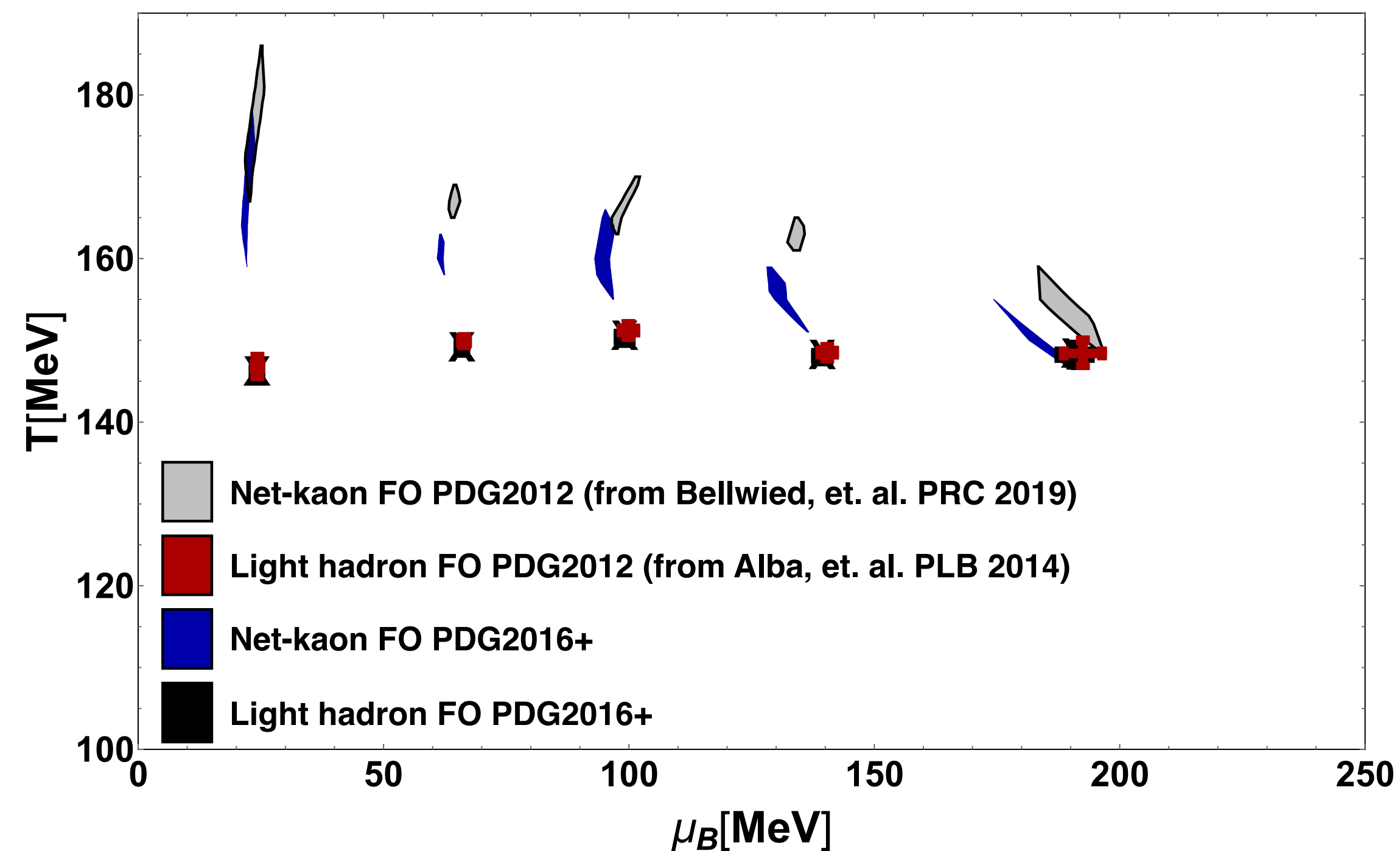
Calculate χ_1/χ_2 along the isentropes corresponding to the five highest energies of the Beam Energy Scan at RHIC

- Extract T_f by identifying the overlap regions



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



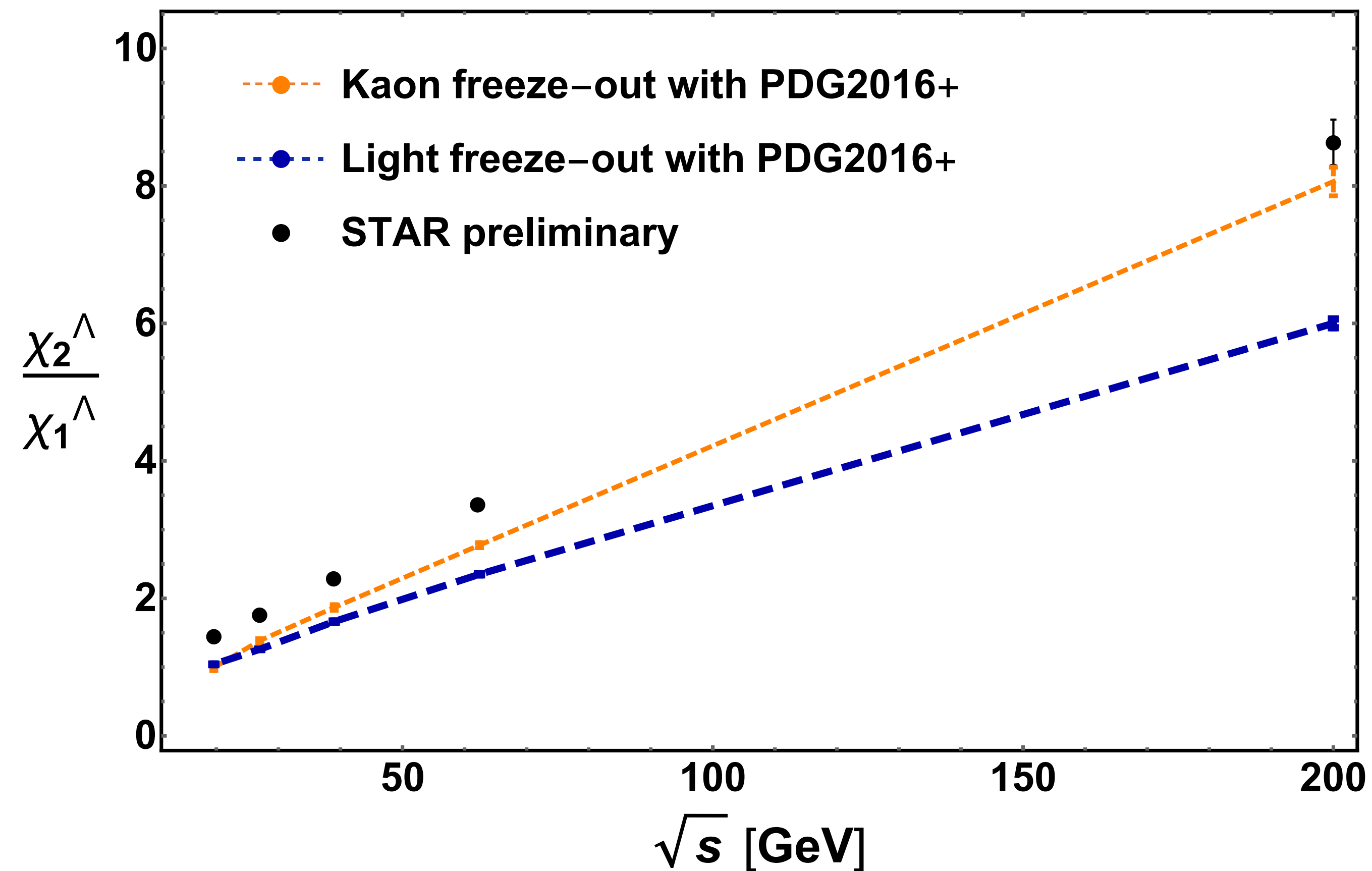
With the inclusion of more states in the HRG Model the kaon freeze-out temperature is decreased, but separation from light hadrons remains

See also:
M. Bluhm and M. Nahrgang
Eur.Phys.J. (2019)

JS, et. al. in preparation

Net-lambda predictions with PDG2016+

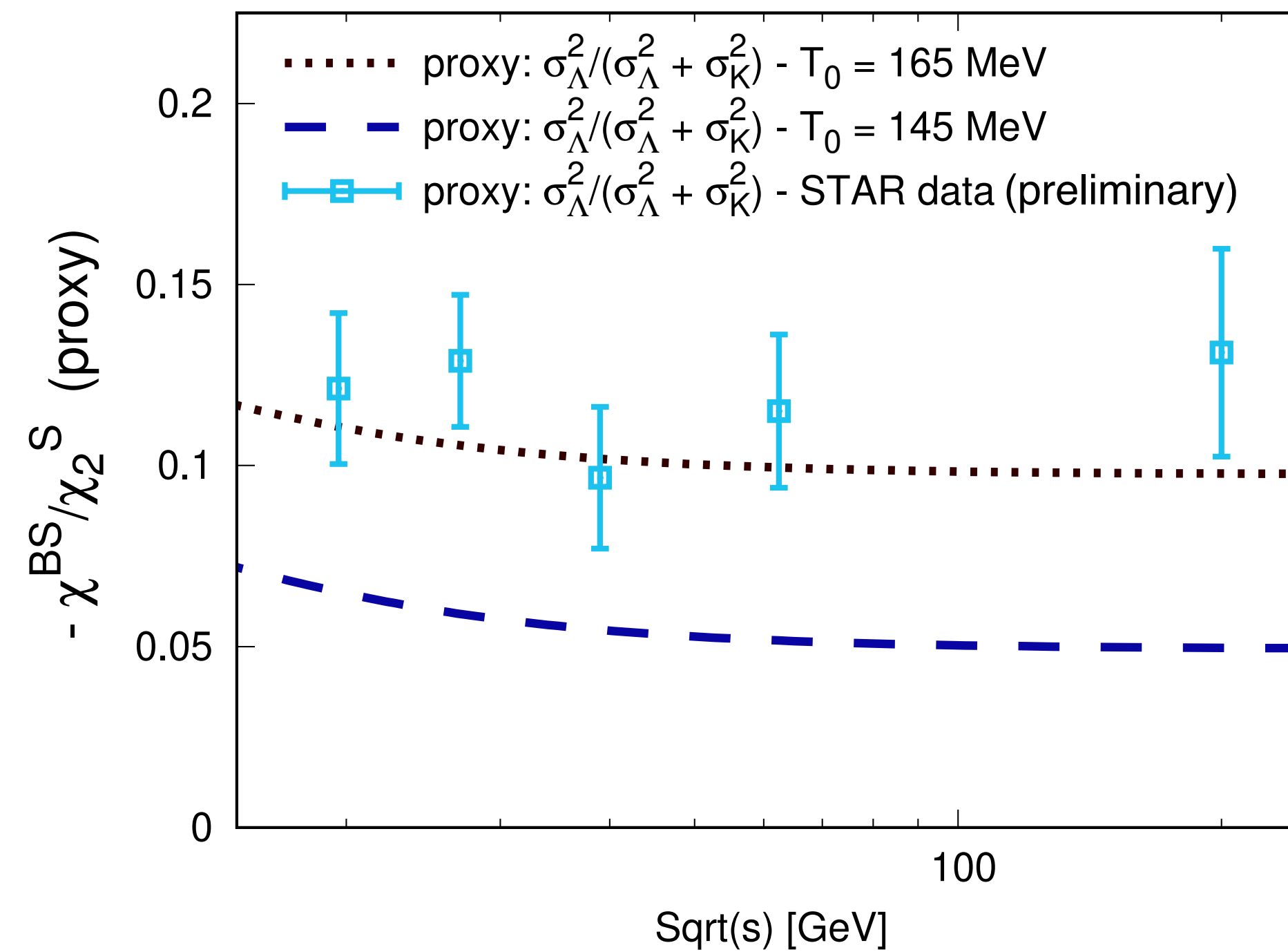
Calculate fluctuations for net- Λ using the kaon and light hadron freeze-out parameters



JS, et. al. in preparation; R. Bellwied SQM 2019

Cross-correlators of Conserved Charges

The two freeze-out scenario is also seen in the determination of the correlations between baryon number and strangeness

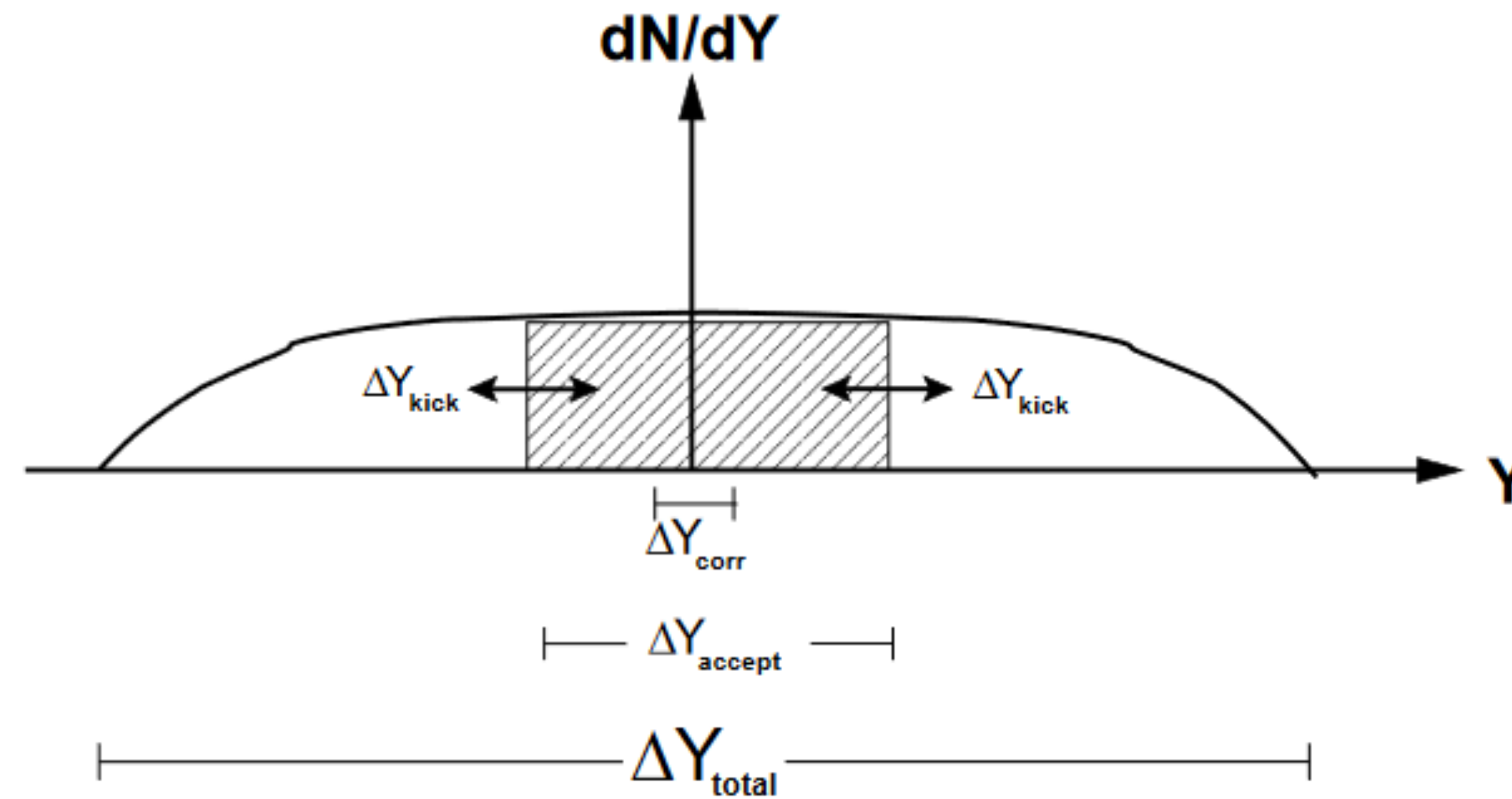


See poster by P. Parotto

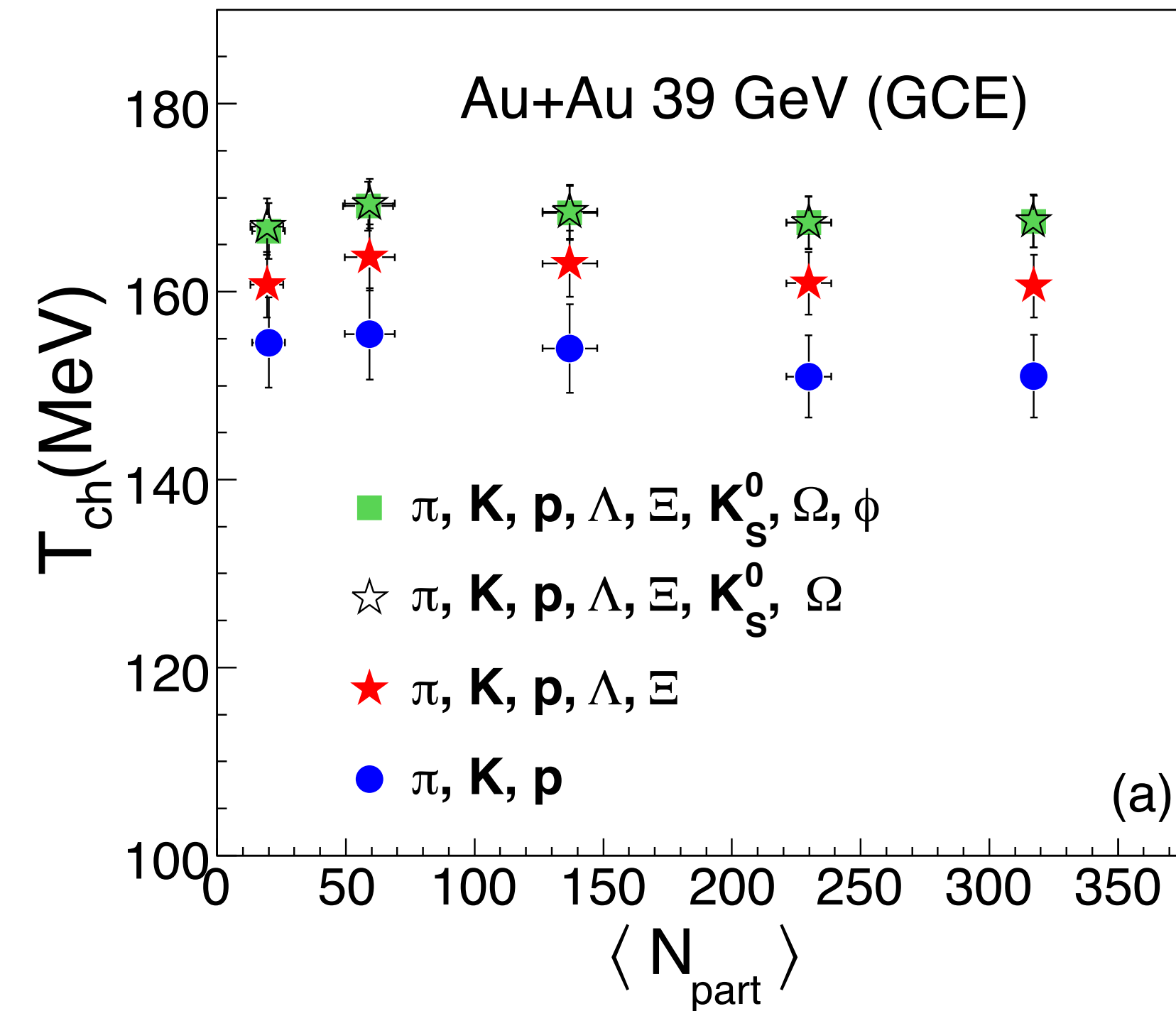
- With the PDG2016+ list, the **two-freeze-out scenario** fits the experimental data for particle yields better.
- The **net-kaon fluctuation** data from the STAR collaboration cannot be reproduced in the HRG model by using the freeze-out parameters obtained from the combined fit of χ^p_1/χ^p_2 and χ^Q_1/χ^Q_2 ($T \gtrsim 150$ MeV).
- With the inclusion of **more strange resonances** in the HRG Model, the kaon freeze-out temperature becomes $T \gtrsim 160$ MeV in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV.

Back-up slides

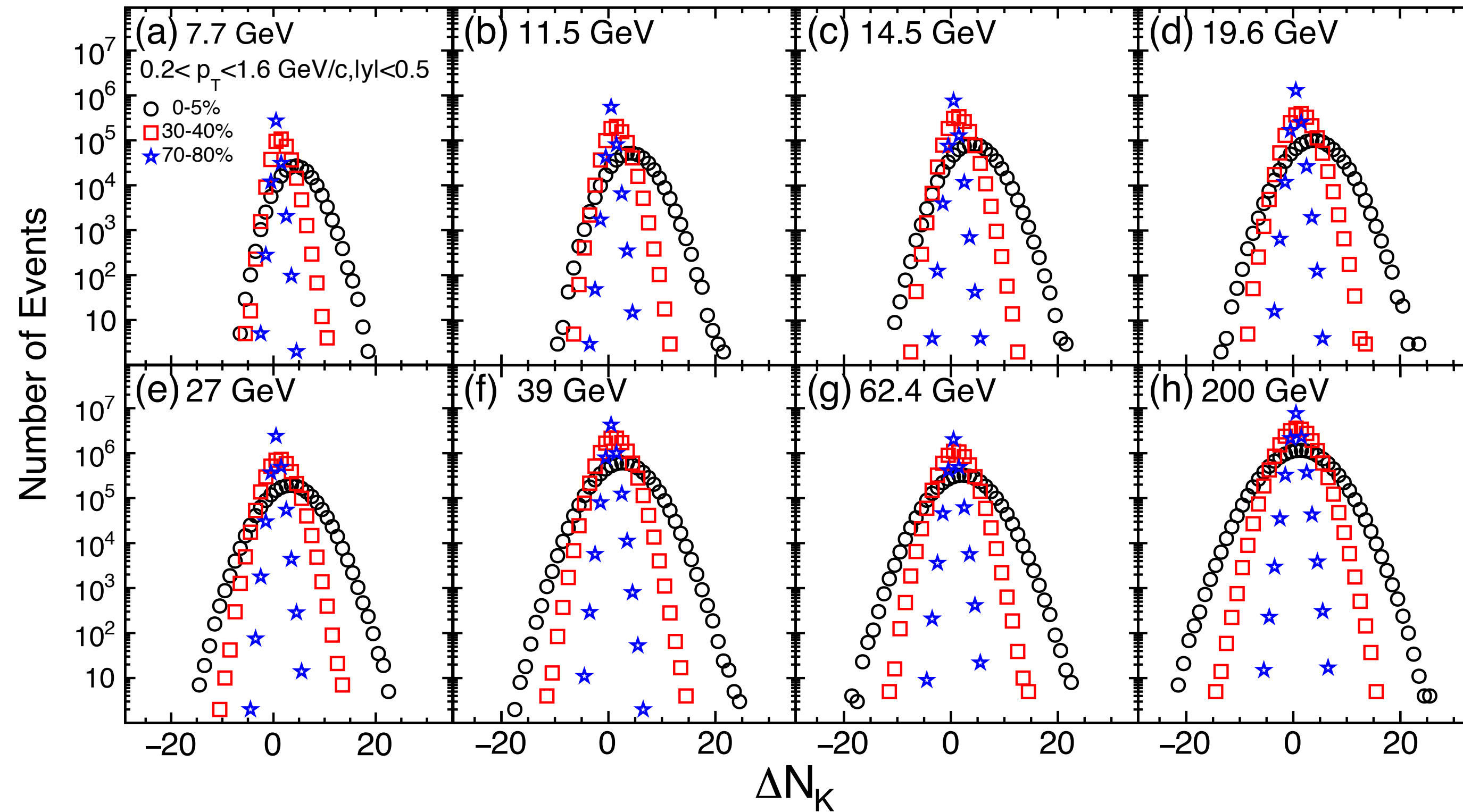
Rapidity cuts and conserved charge fluctuations



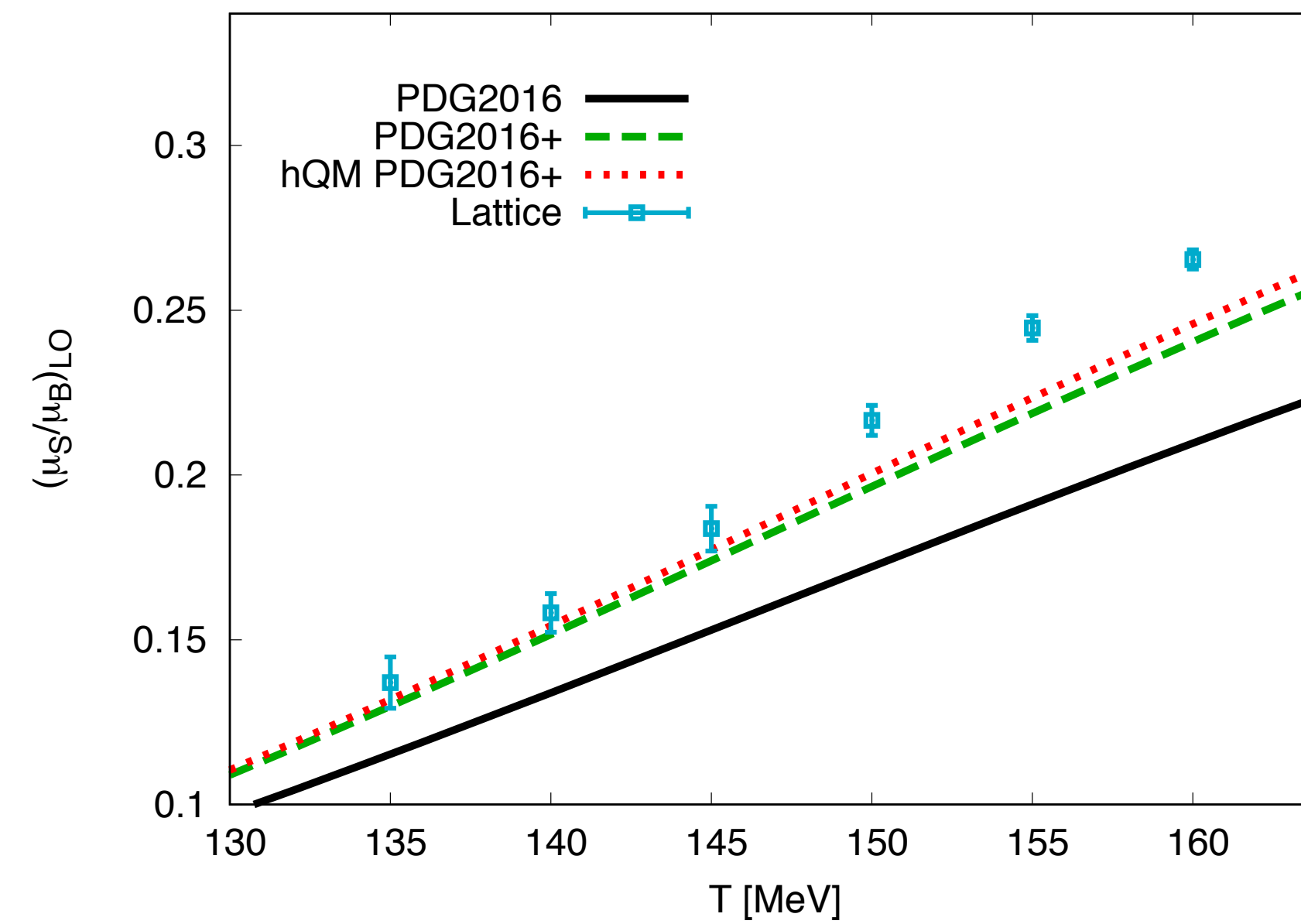
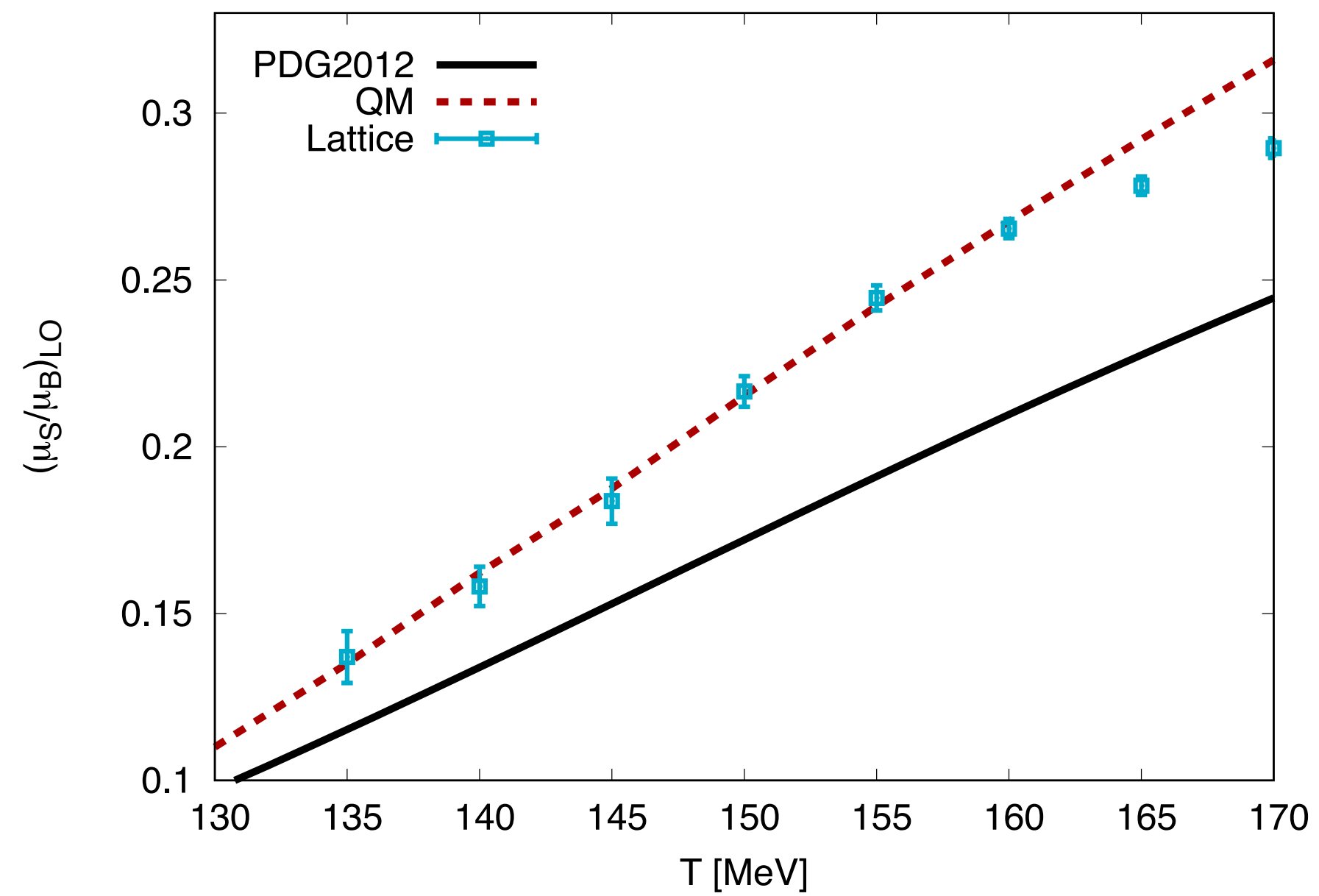
STAR THERMUS fits of particle yields



STAR net-kaon distributions

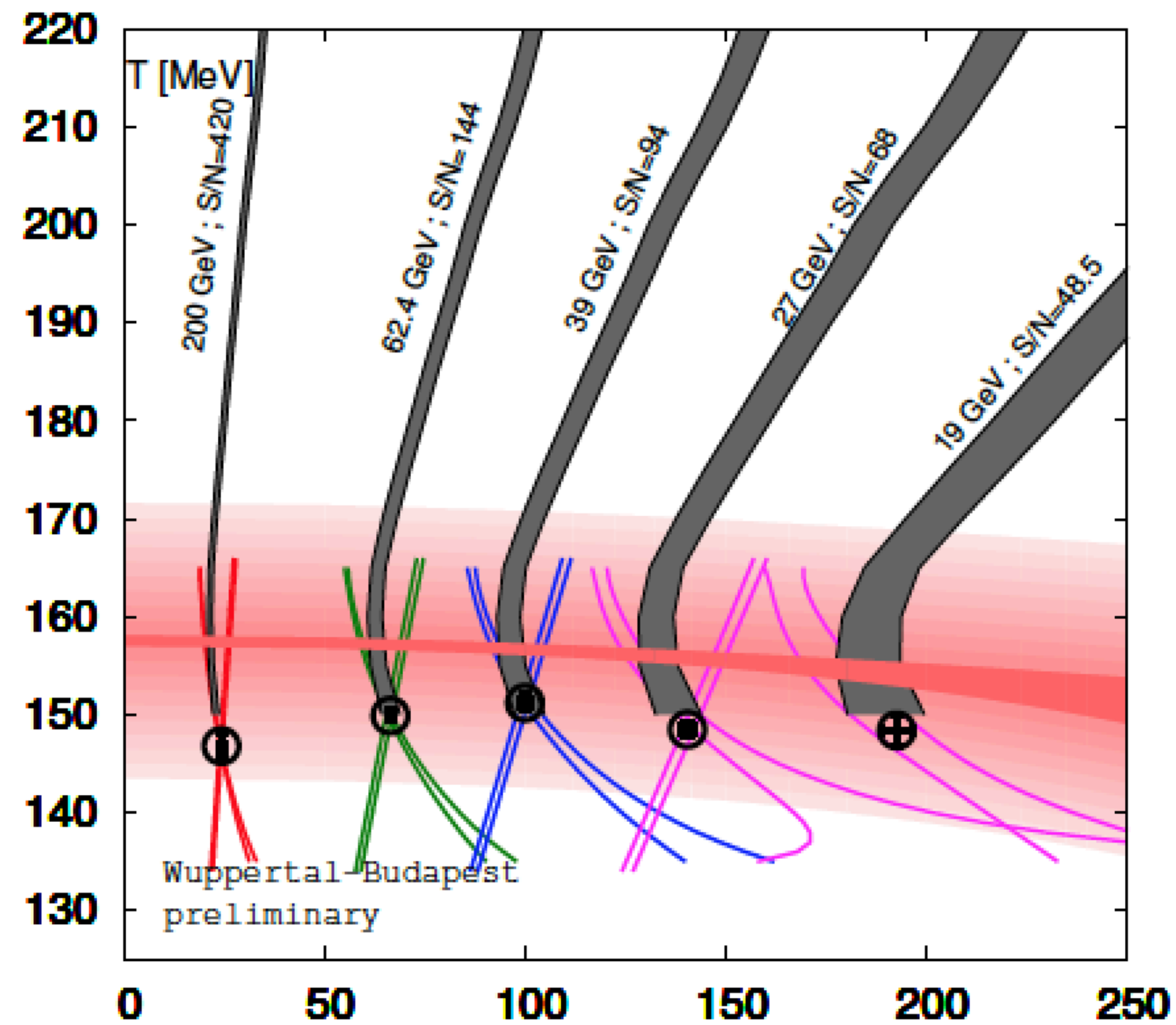


Comparison of HRG & Lattice results

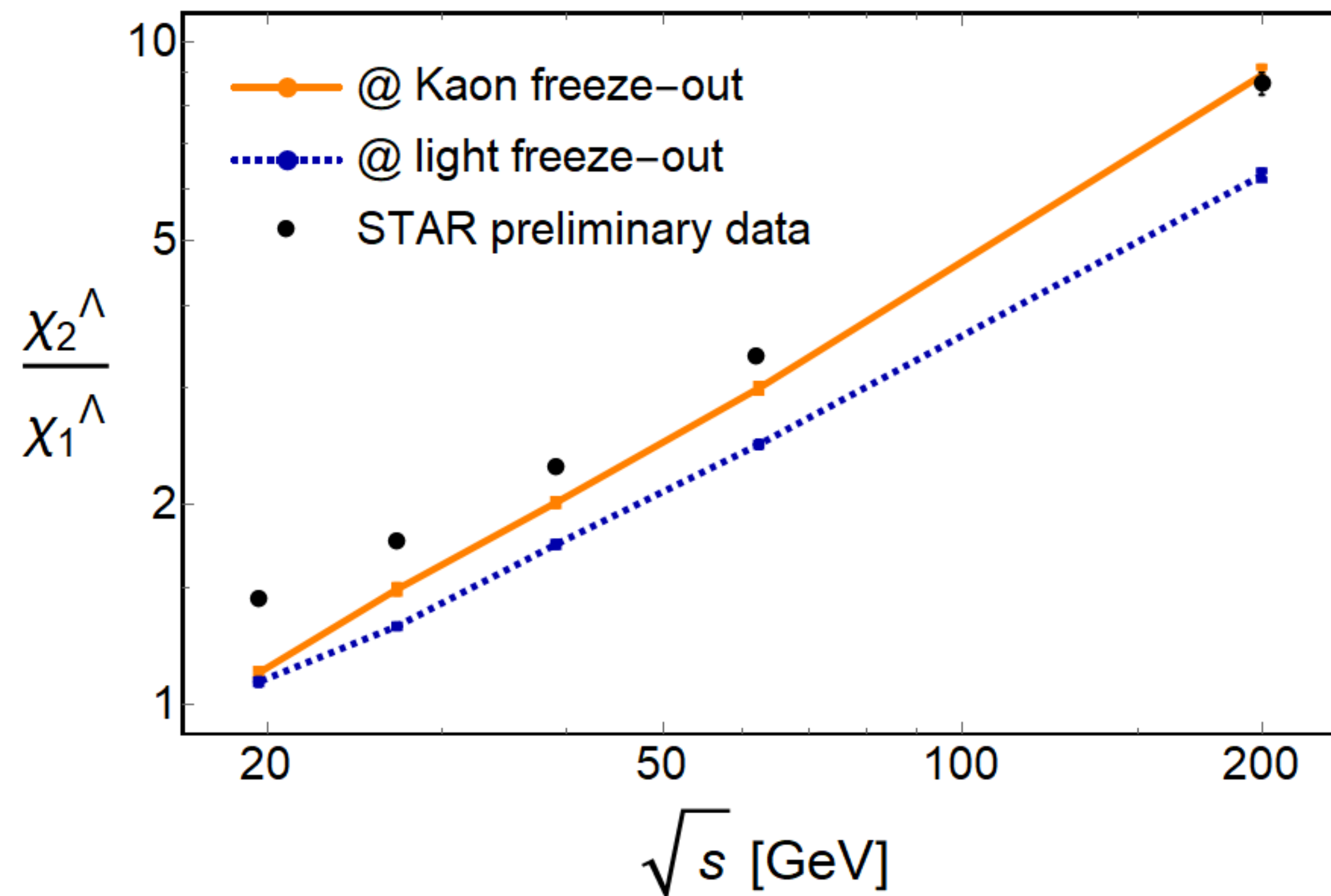


arXiv: 1702.01113

Freeze-out from net-p & net-Q



Net-lambda predictions with PDG2012



arXiv: 1805.00088