# The Interplay of Baryon and Strangeness at the Beam Energy Scan

*Jamie M. Stafford, University of Houston/LBNL*

# Outline

I. Motivation for QCD modeling with all conserved charges

II. Investigation of quark flavor hierarchy at chemical freeze-out

III. Development of measurable cross-correlators of conserved charges

IV. Recent model and theoretical approaches incorporating all conserved charges

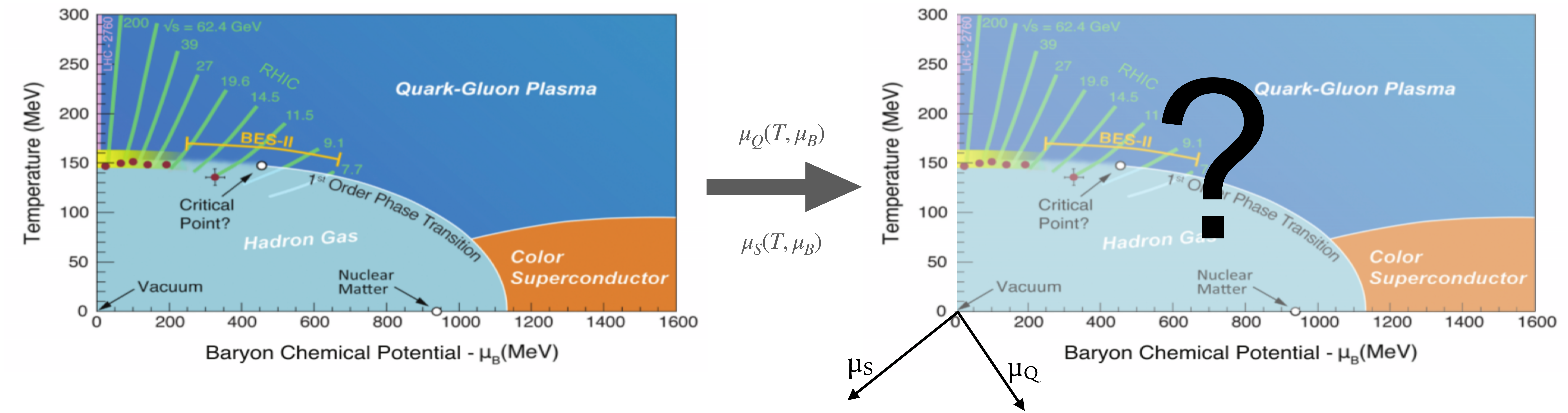
V. Conclusions

# I. Motivation

# QCD Phase Diagram

- The strongly interacting matter present in heavy-ion collisions carries a multitude of conserved quantum numbers: baryon number, strangeness and electric charge
  - This effects thermodynamics since each charge has an associated chemical potential

$$\frac{p}{T^4} = \frac{1}{VT^3} \ln Z(V, T, \mu_B, \mu_S, \mu_Q)$$



# Lattice QCD Predictions

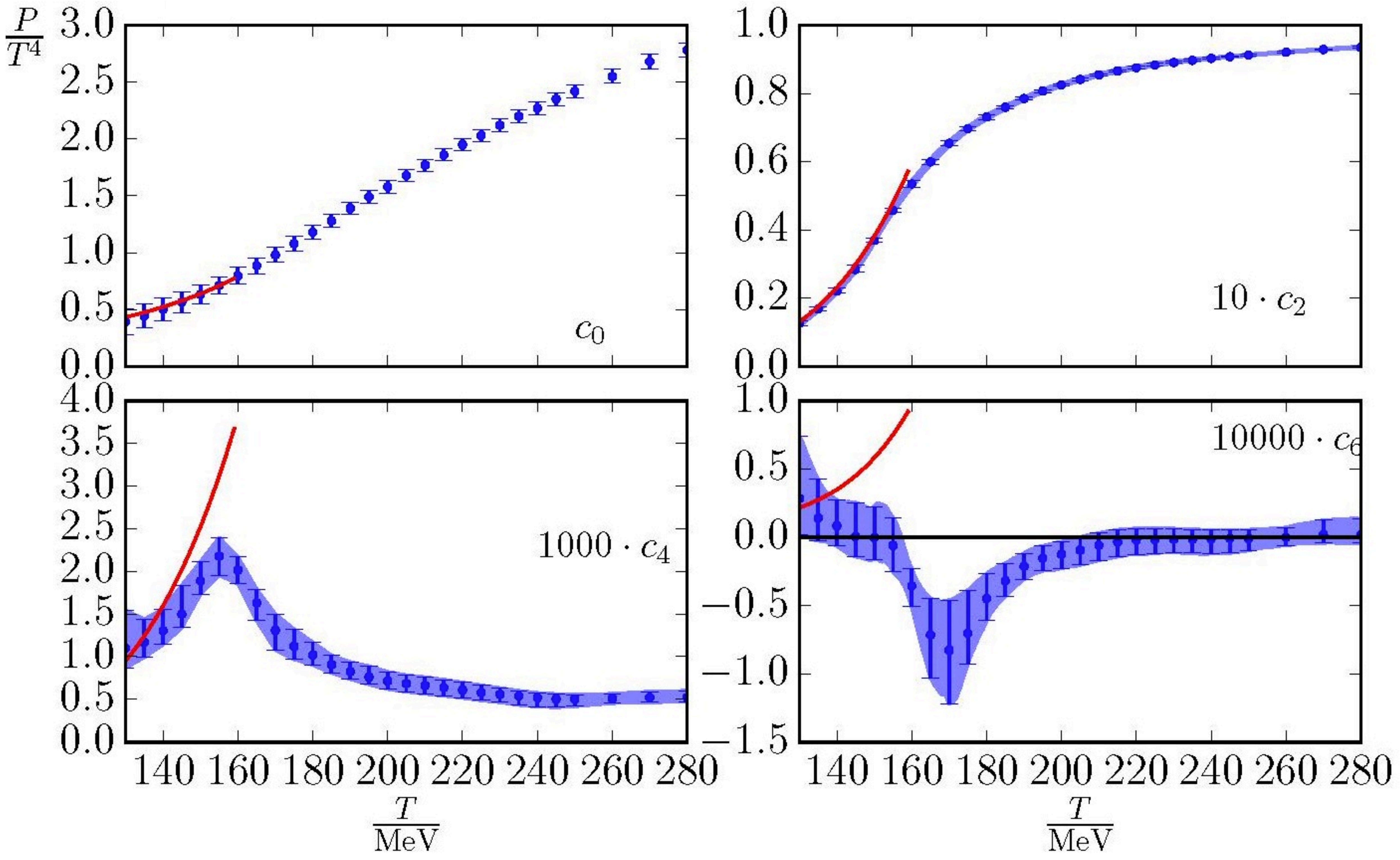
- The equation of state (EoS) for QCD has been calculated on the lattice under strangeness neutrality and fixed ratio of baryon number to electric charge, matching the heavy-ion situation

$$\frac{p(T,\mu_B)}{T^4} = \frac{p(T,0)}{T^4} + \sum_{n=1}^{\infty} \frac{1}{(2n)!} \frac{\mathrm{d}^{2n}(p/T^4)}{d(\frac{\mu_B}{T})^{2n}}\bigg|_{\mu_B=0} \left(\frac{\mu_B}{T}\right)^{2n}$$

$$= \sum_{n=0}^{\infty} c_{2n}(T) \left(\frac{\mu_B}{T}\right)^{2n}$$

$$\langle n_s \rangle = 0$$

$$\langle n_Q \rangle = 0.4 \langle n_B \rangle$$

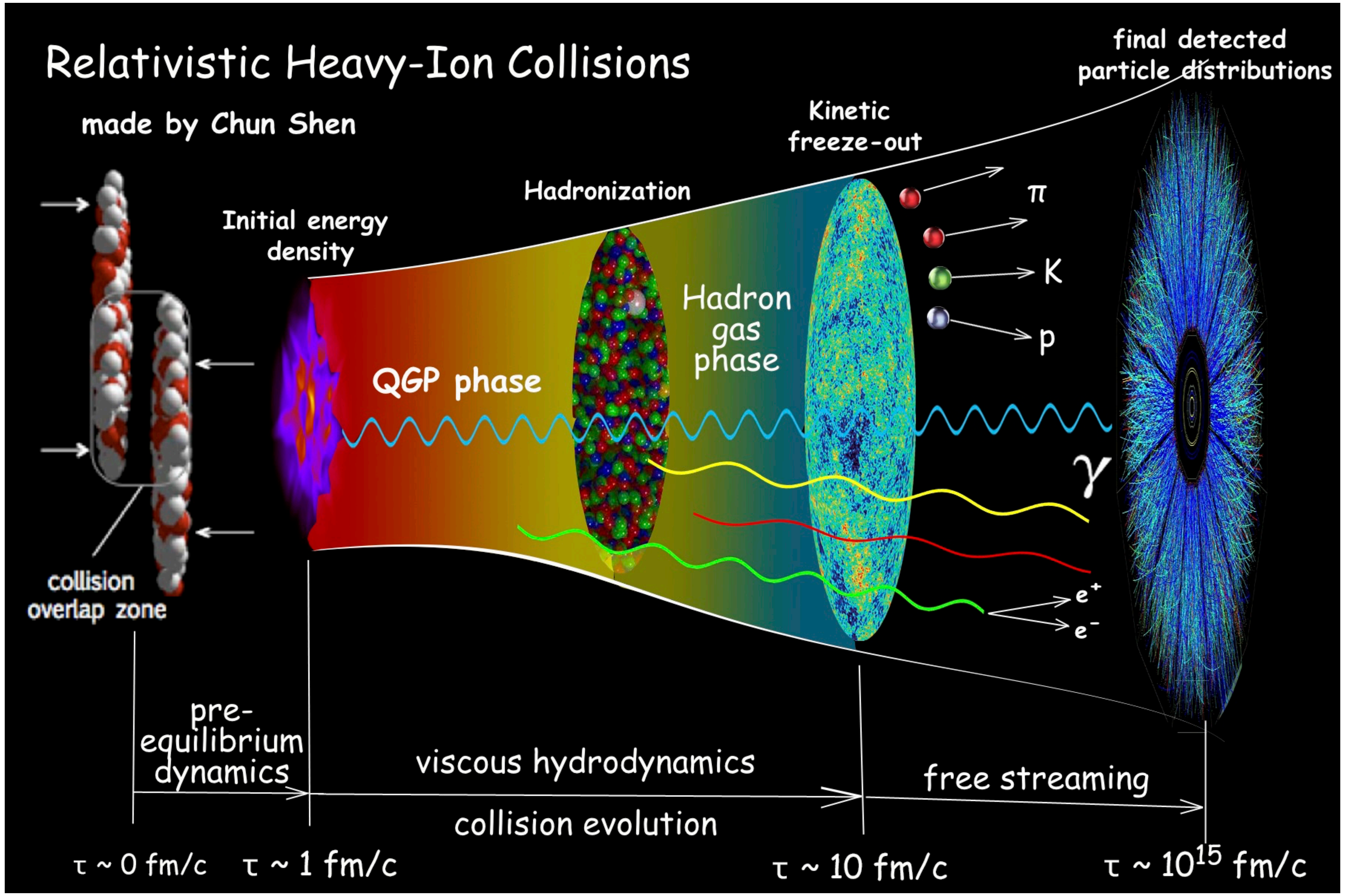



*For $\mu_S = \mu_Q = 0$ see: S. Borsanyi et al, JHEP (2018)*

*WB: J. Guenther et al, NPA (2017)*
*HotQCD: A. Bazavov et al, PRD (2017)*

# QCD Phenomenology

- All stages of heavy-ion collision modeling should seek to investigate the same slice of the phase diagram as the experiments



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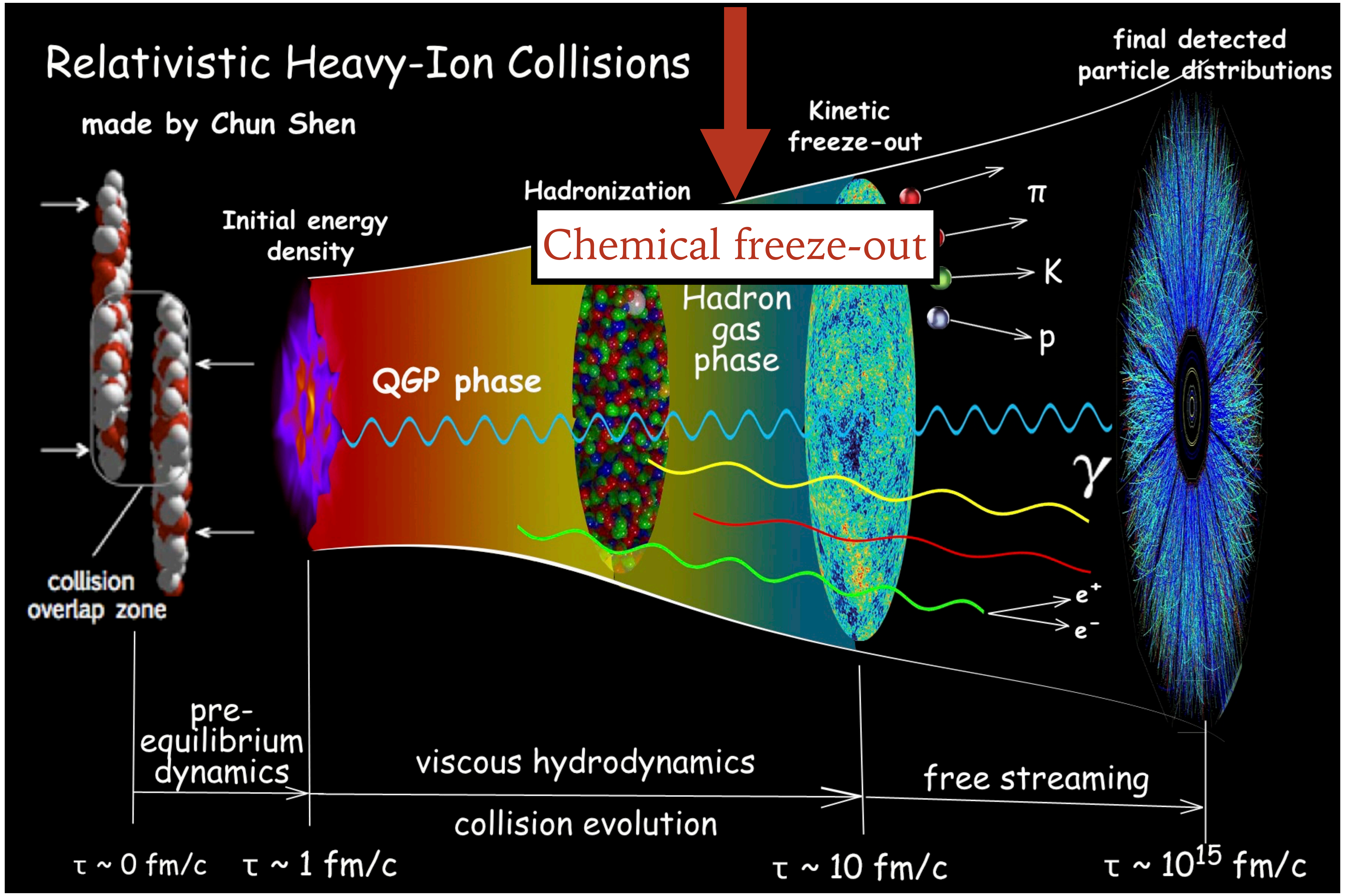
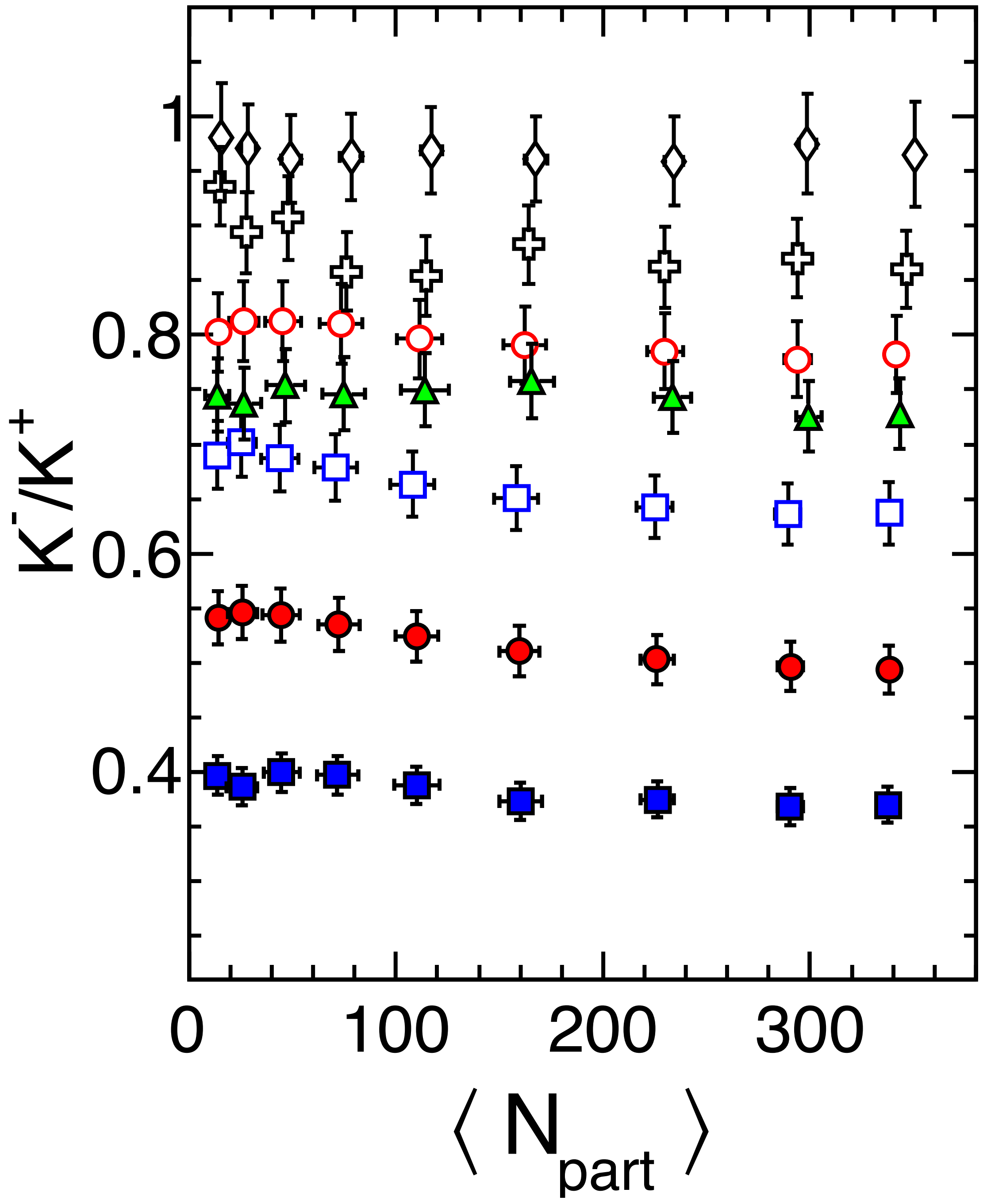


# II. Flavor Hierarchy

# Chemical Freeze-out Parameters

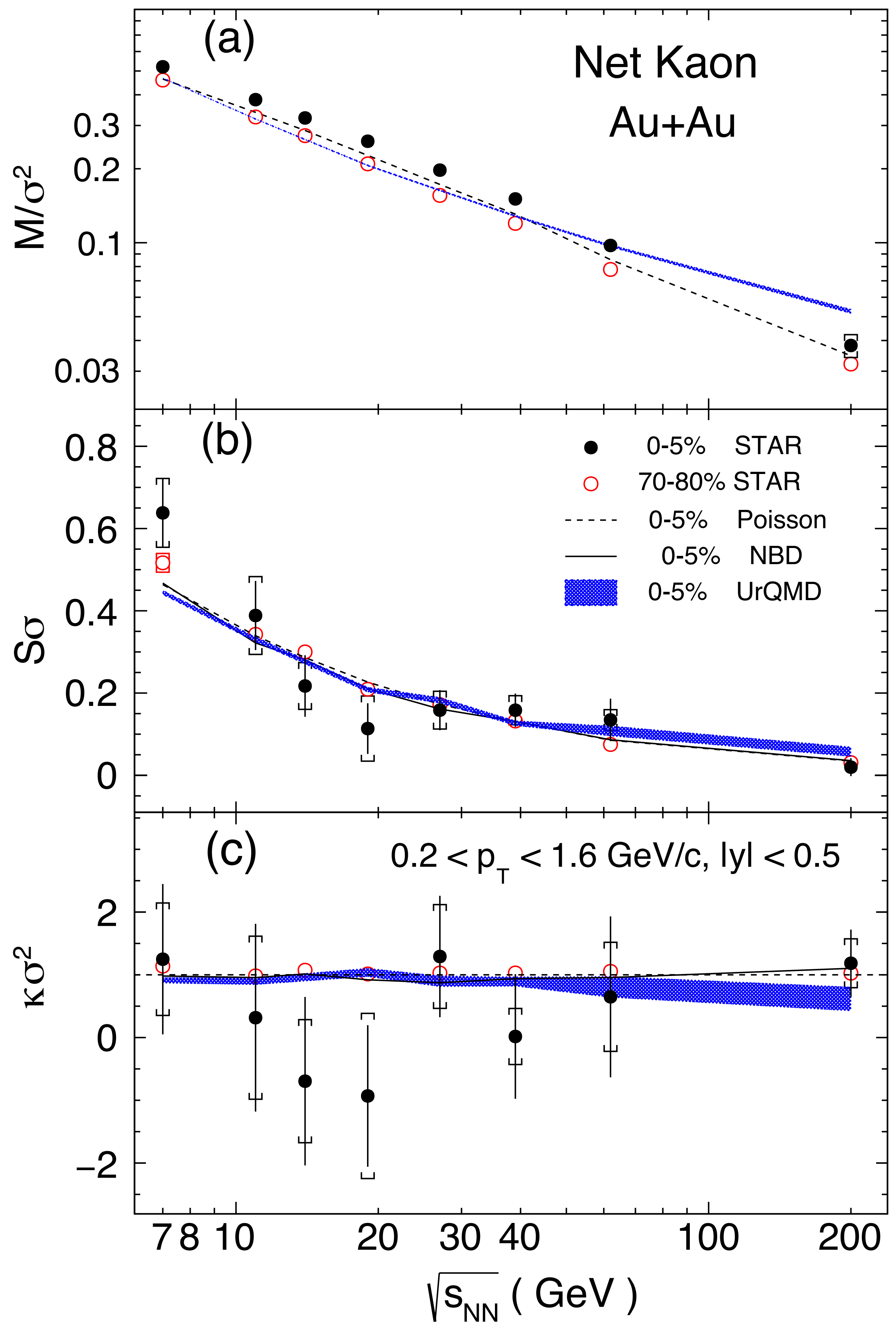
➤ Experimental particle yields and fluctuations tell us about the system at chemical freeze-out

Particle yields




➤ Ratios eliminate volume dependence

Fluctuations




➤ Moments can be calculated as derivatives of the pressure

*STAR Collaboration (L. Adamczyk et al.), PRC (2017), PLB (2018)*

# Chemical Freeze-out Parameters

- Utilize Hadron Resonance Gas Model to perform thermal fits of yields and analyses of net-particle fluctuations including strangeness neutrality
- Investigate influence of number of states on freeze-out parameters

## Particle yields

THERMAL-FIST: A package for heavy-ion collisions and hadronic equation of state

$$\frac{\chi^2}{N_{\mathrm{dof}}} = \frac{1}{N_{\mathrm{dof}}} \sum_{i=1}^{N} \frac{\left(N_i^{\mathrm{exp}} - N_i^{\mathrm{HRG}}\right)^2}{\sigma_i^2}$$

$$\langle N_i \rangle = V\, n_i + V \sum_R \langle n_i \rangle_R\, n_R$$

## Fluctuations

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

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

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

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

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

*V. Vovchenko and H. Stöcker, Thermal-FIST, Comp. Phys. Comm. (2019)*

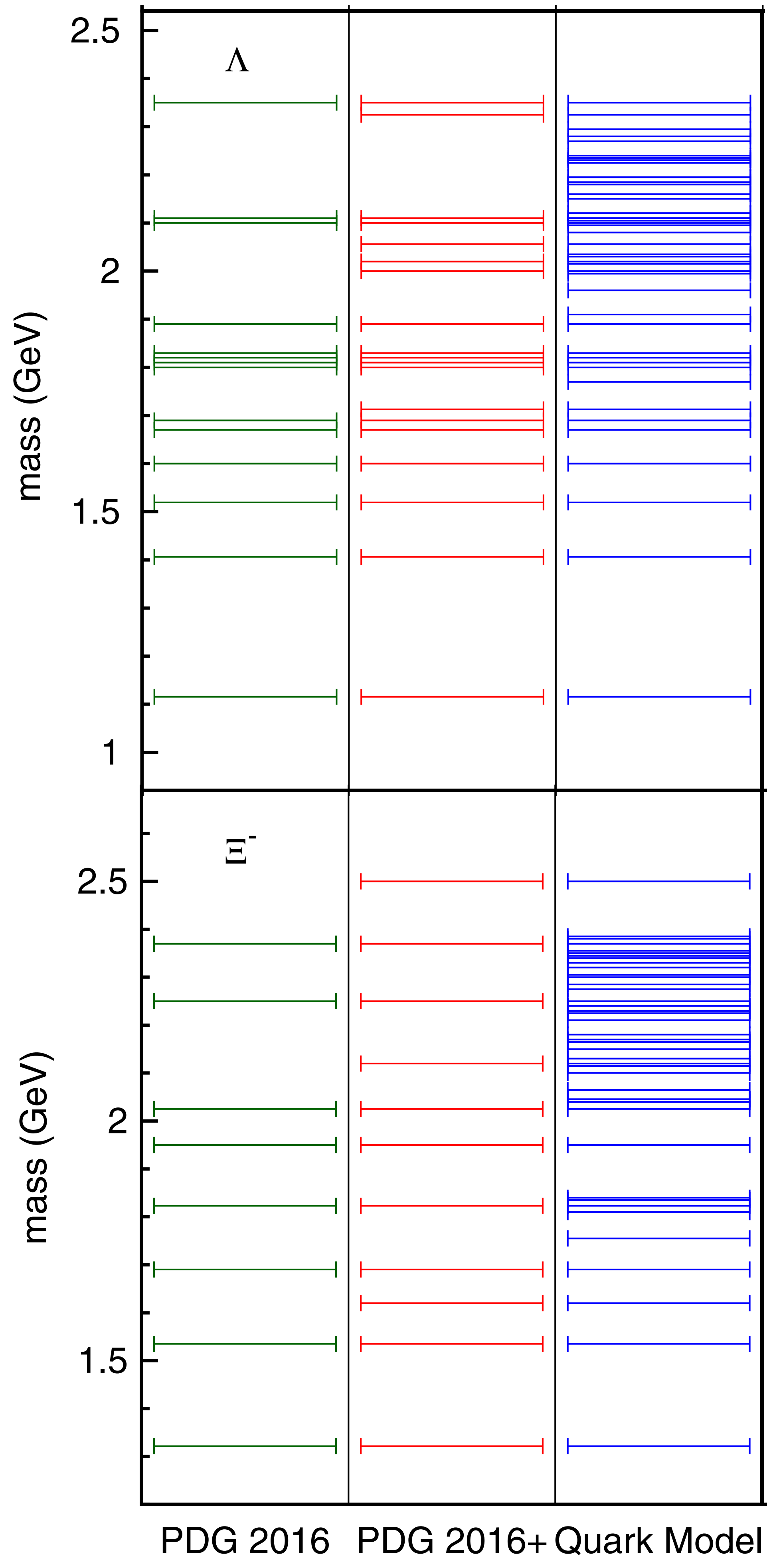
# Hadronic States in HRG Model

- Pressure in HRG model depends on resonances included in the calculation:

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

- **PDG2005**: 142 species
- **PDG2016**: 608 species
- **PDG2016+**: 738 species (all experimentally observed particles, i.e. *,**,***,****)
- **QM**: 1517 species (all states predicted by the Quark Model)

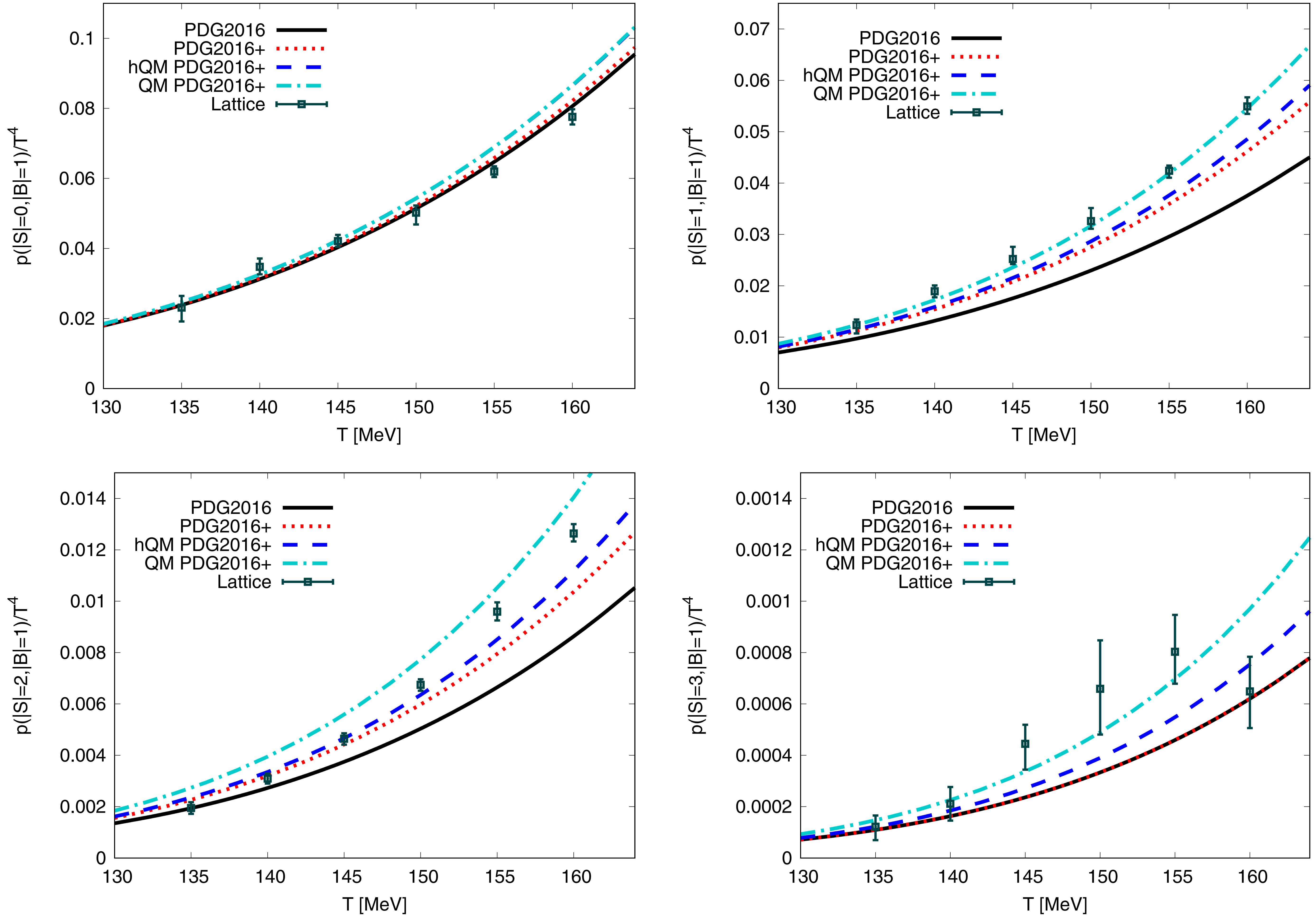
| | | |
|---|---|---|
| $p$ | $1/2^+$ | **** |
| $n$ | $1/2^+$ | **** |
| $N(1860)$ | $5/2^+$ | ** |
| $N(1875)$ | $3/2^-$ | *** |
| $\Delta(1232)$ | $3/2^+$ | **** |
| $\Delta(1750)$ | $1/2^+$ | * |




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

# HRG Partial Pressures Confront LQCD

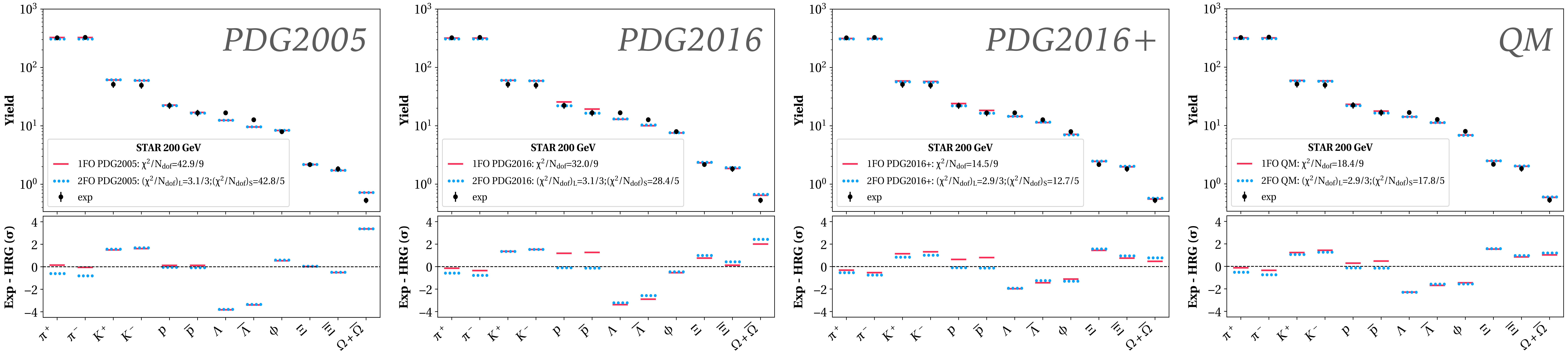
- Determine which particle list best matches Lattice QCD (LQCD) by breaking pressure into various sectors of baryon number and strangeness




P. Alba et al, PRD (2017)

# Thermal Fit Analyses

- Systematic study: chemical freeze-out dependence on number of resonances
- Flavor hierarchy investigation
    - Single freeze-out (1FO): simultaneous fit of all particles
    - Two flavor freeze-out (2FO): fit light and strange particles separately




*See also: R. Bellwied et al, arXiv: 2009.14781*

*P. Alba, JS et al, PRC (2020)*

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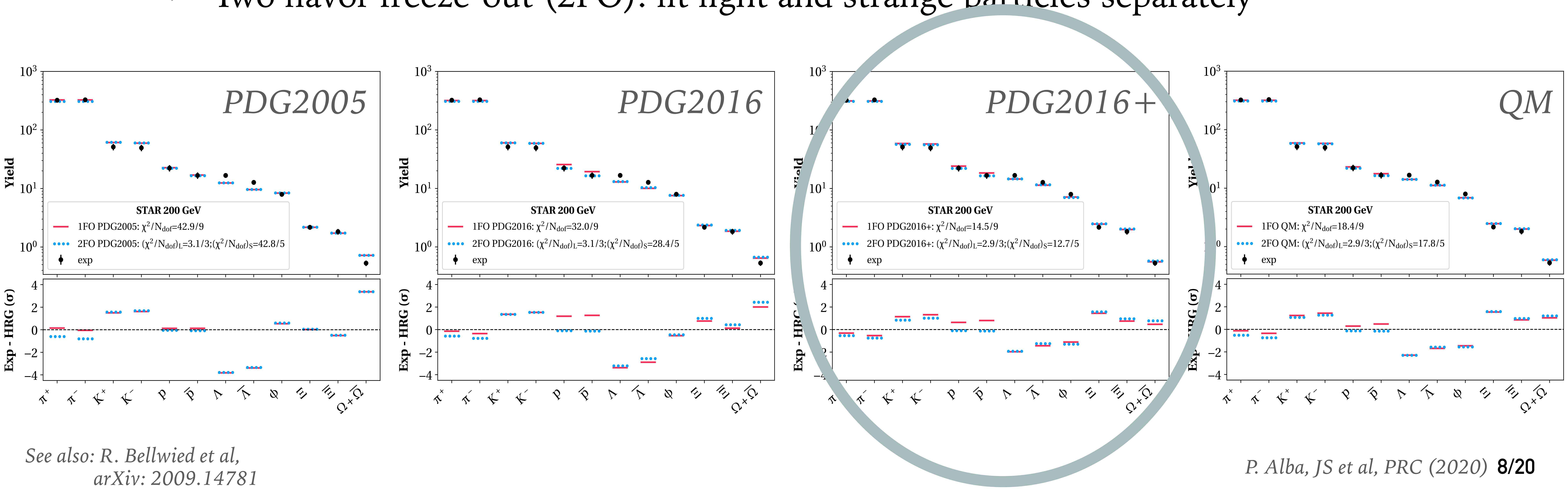
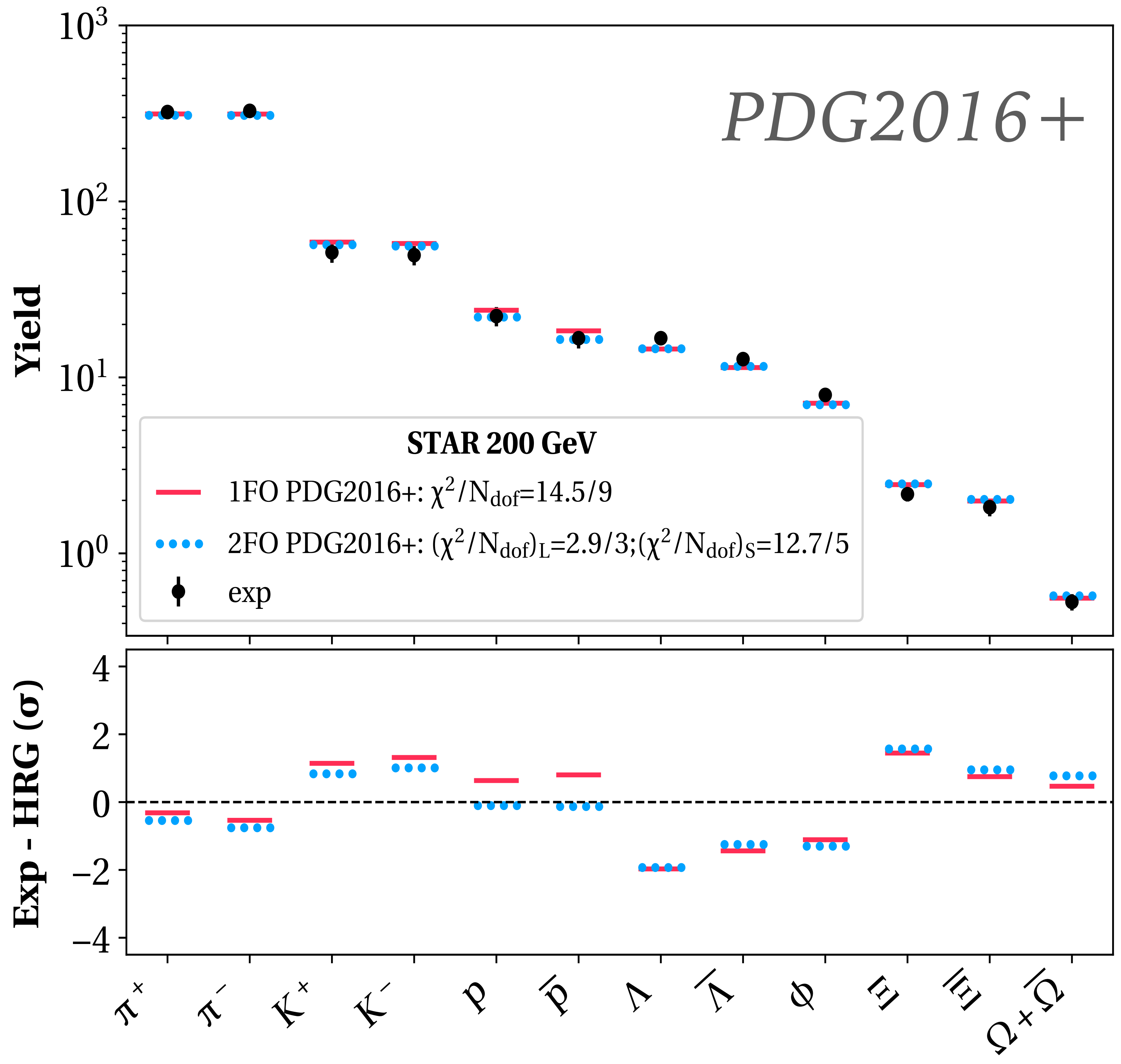


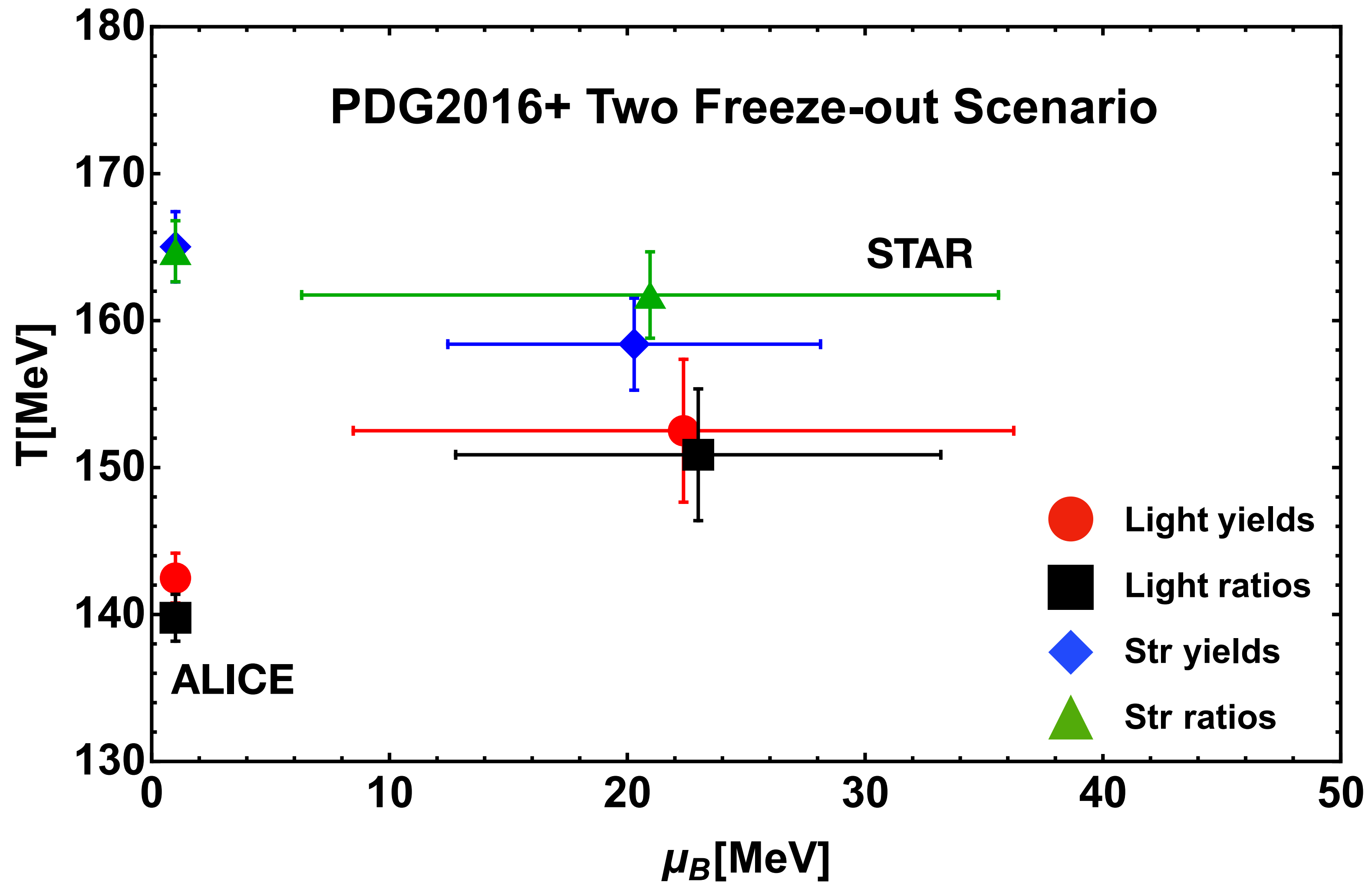

*See also: R. Bellwied et al, arXiv: 2009.14781*

*P. Alba, JS et al, PRC (2020)*

# Light v. Strangeness Freeze-out: Yields

- ➤ Unique chemical freeze-out parameters for light and strange even with many states
- ➤ Separating into light and strange particles produces an overall better fit




Separation between light and strange freeze-out temperatures:

$T_{l,STAR} \simeq 150$ MeV

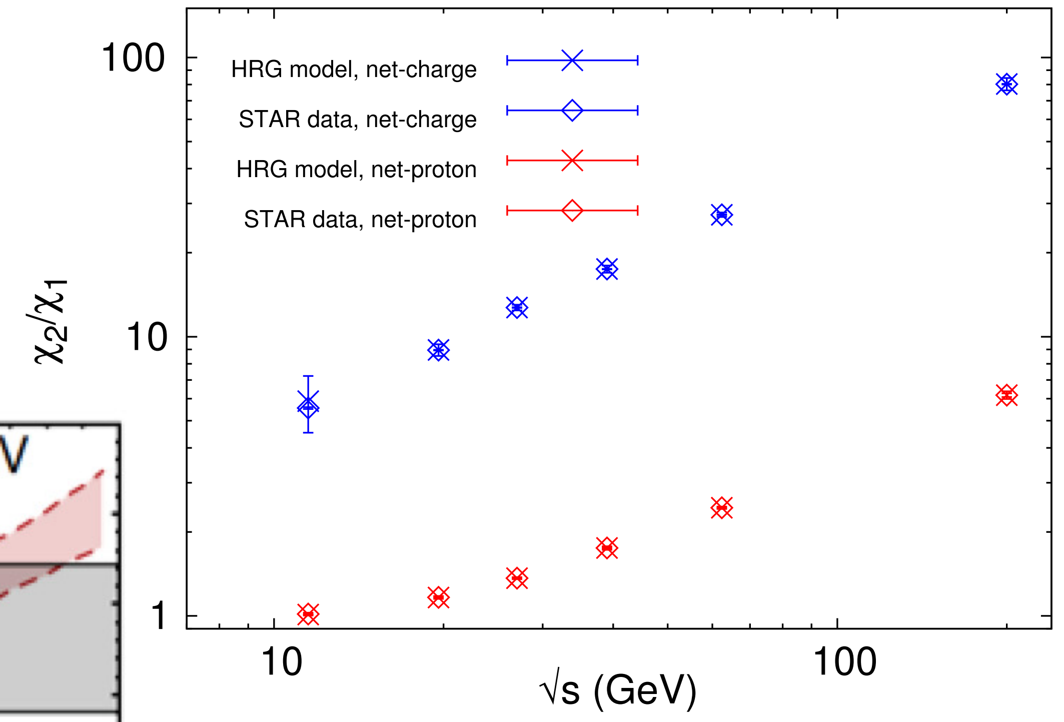
$T_{s,STAR} \simeq 160$ MeV

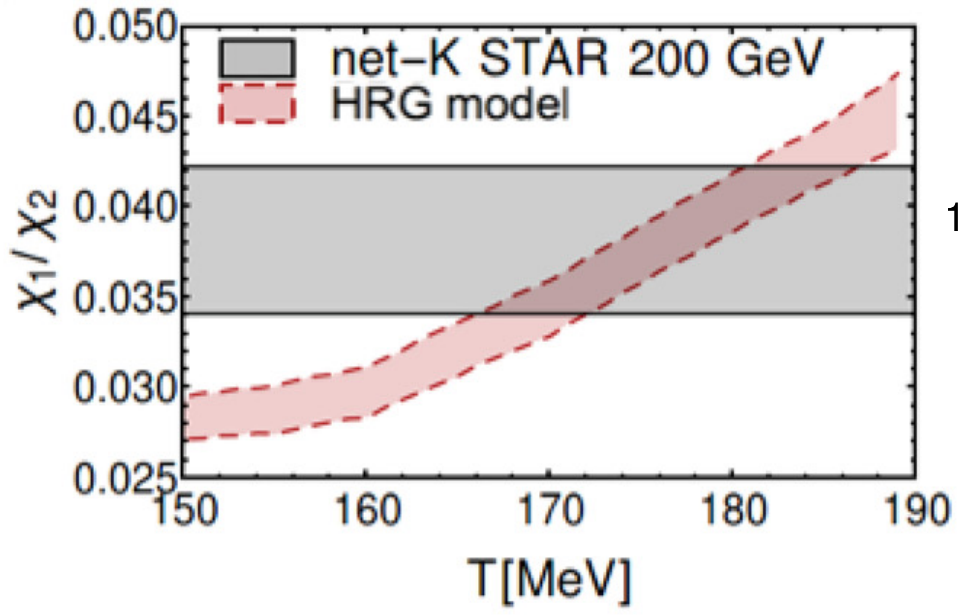
*See also: J. Steinheimer et al, PRL (2013)*
*F. Beccatini et al, PRL (2013)*
*A. Bazavov et al, PRL (2014)*
*G. Aarts et al, PRD (2019)*
*A. Andronic et al, Phys.Lett. B (2019)*

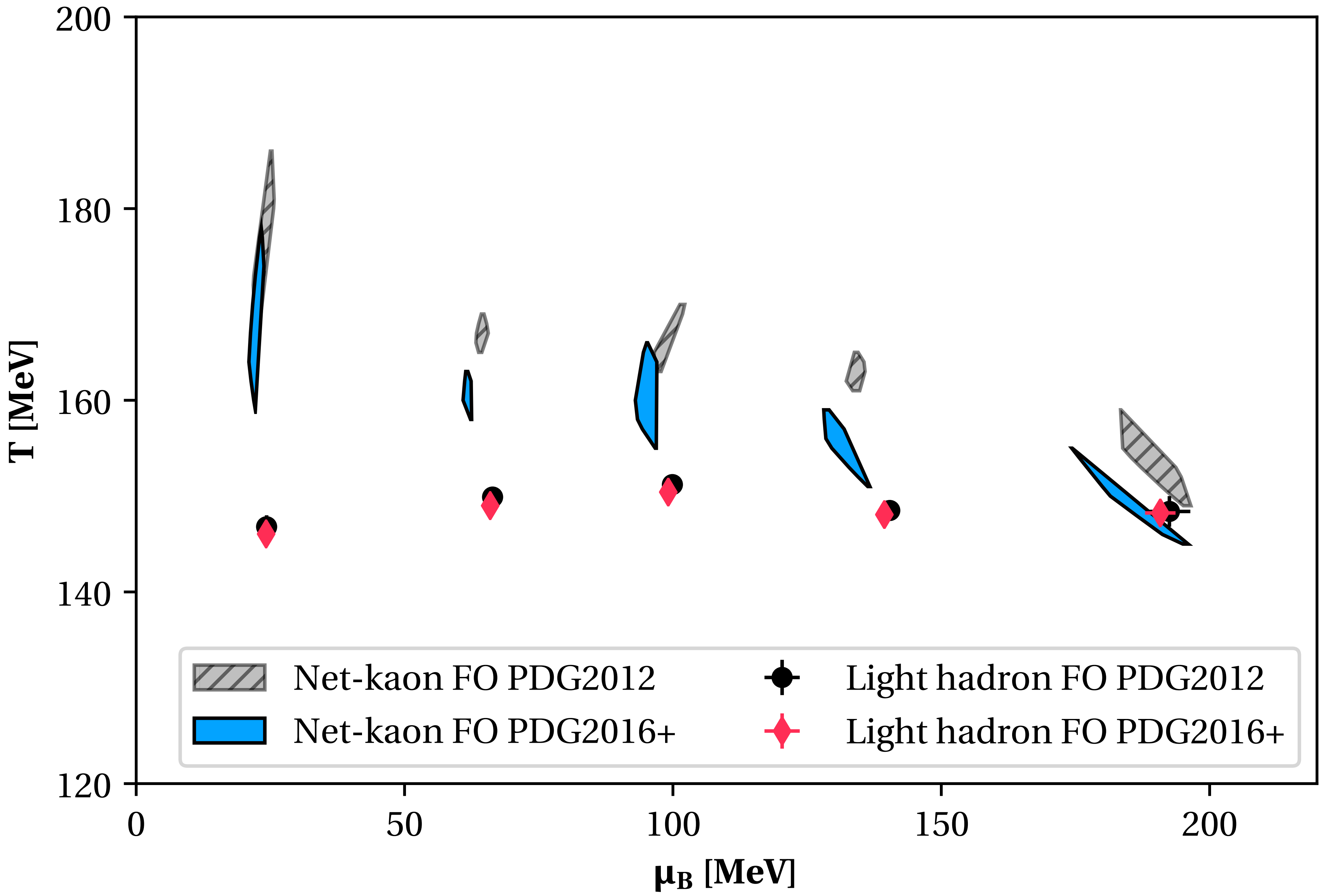
*P. Alba, JS et al, PRC (2020)*
*R. Bellwied at al, arXiv: 2009.14781*

# Light v. Strangeness Freeze-out: Fluctuations

- Freeze-out parameters calculated via net-particle fluctuations are *different* for p and K
  - Light freeze-out determined by combined fit of $\chi_1^p/\chi_2^p$ and $\chi_1^Q/\chi_2^Q$
  - Calculate $\chi_1^K/\chi_2^K$ along the Lattice QCD isentropes



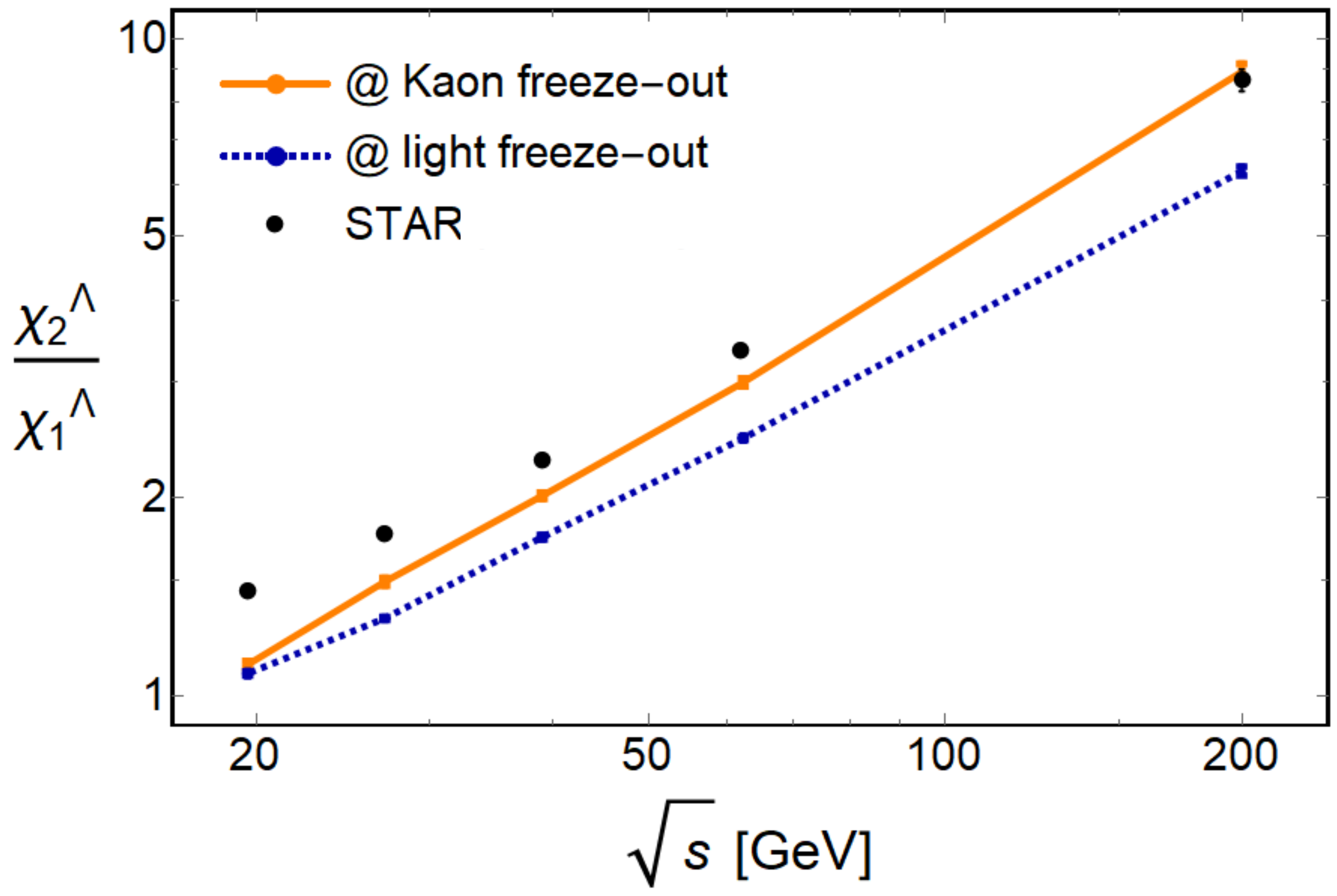




*See also: M. Bluhm and M. Nahrgang, Eur. J. Phys. (2019)*

*P. Alba et al, Phys.Lett. B (2014)*
*R. Bellwied, JS et al, PRC (2019)*
*P. Alba, JS et al, PRC (2020)*

# Light v. Strangeness Freeze-out: Fluctuations

- Freeze-out curves for light particles and net-kaons compared to net-$\Lambda$ fluctuations shows this strange baryon prefers to freeze-out with strange particles

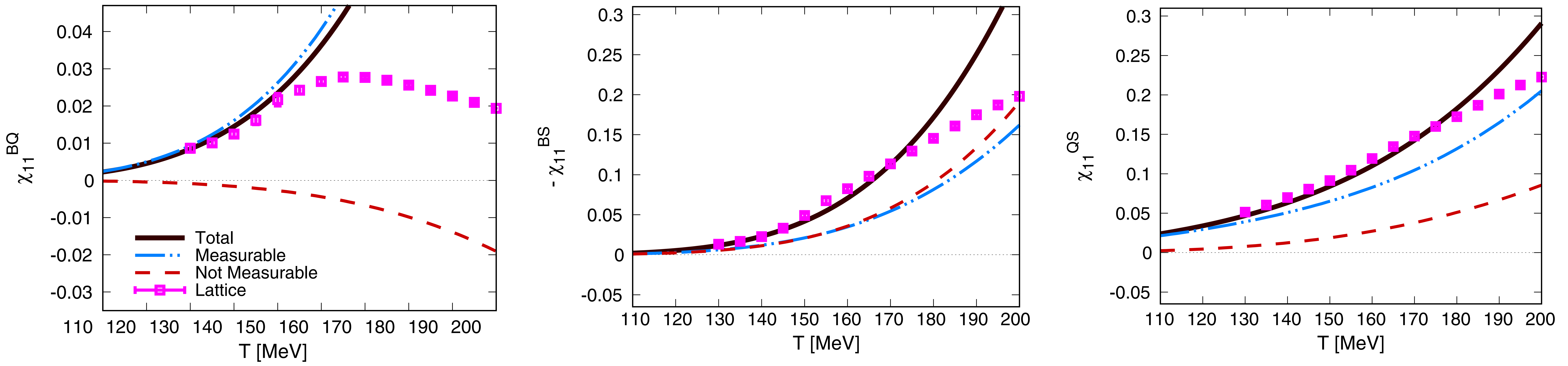



R. Bellwied, JS et al, PRC (2019)
STAR Collaboration (J. Adam), PRC (2020)

# III. Cross-correlators

# Off-diagonal Correlators of Conserved Charges

- The contribution of individual species to correlators on the lattice can be determined by comparing to the HRG model
- Main goal: develop proxies for correlators of conserved charges that can be measured experimentally

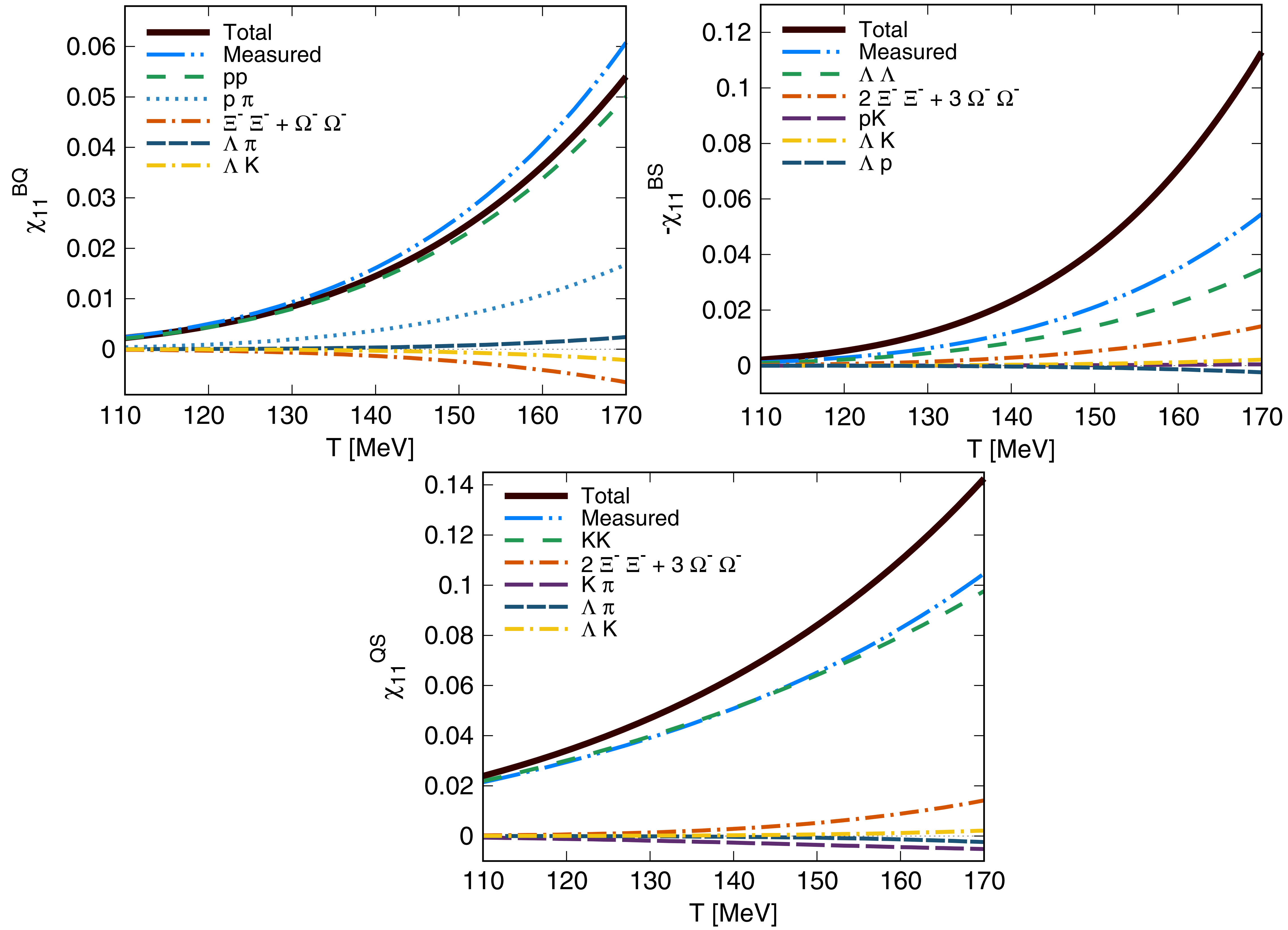



Measurable: $\pi^+$, $\pi^-$, $K^+$, $K^-$, $p$, $\bar{p}$, $\Lambda$, $\bar{\Lambda}$, $\Xi^-$, $\Xi^+$, $\Omega^-$, $\Omega^+$

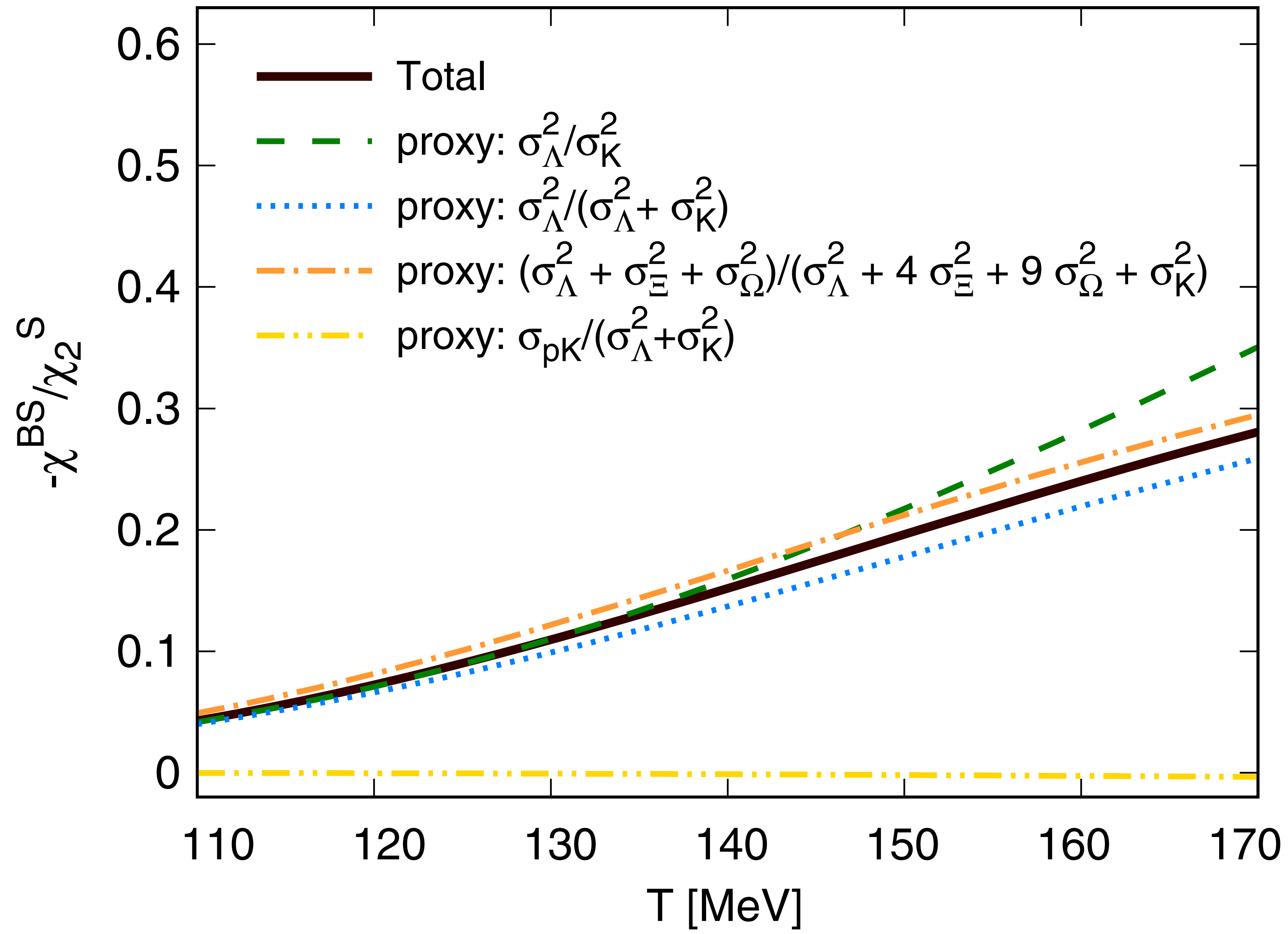
*R. Bellwied, JS et al, PRD (2020)* 

# Off-diagonal Correlators of Conserved Charges

- In reality, there are only a few terms that makeup the overwhelming majority of a correlator
- Determine proxy by constructing ratios with the most dominate species



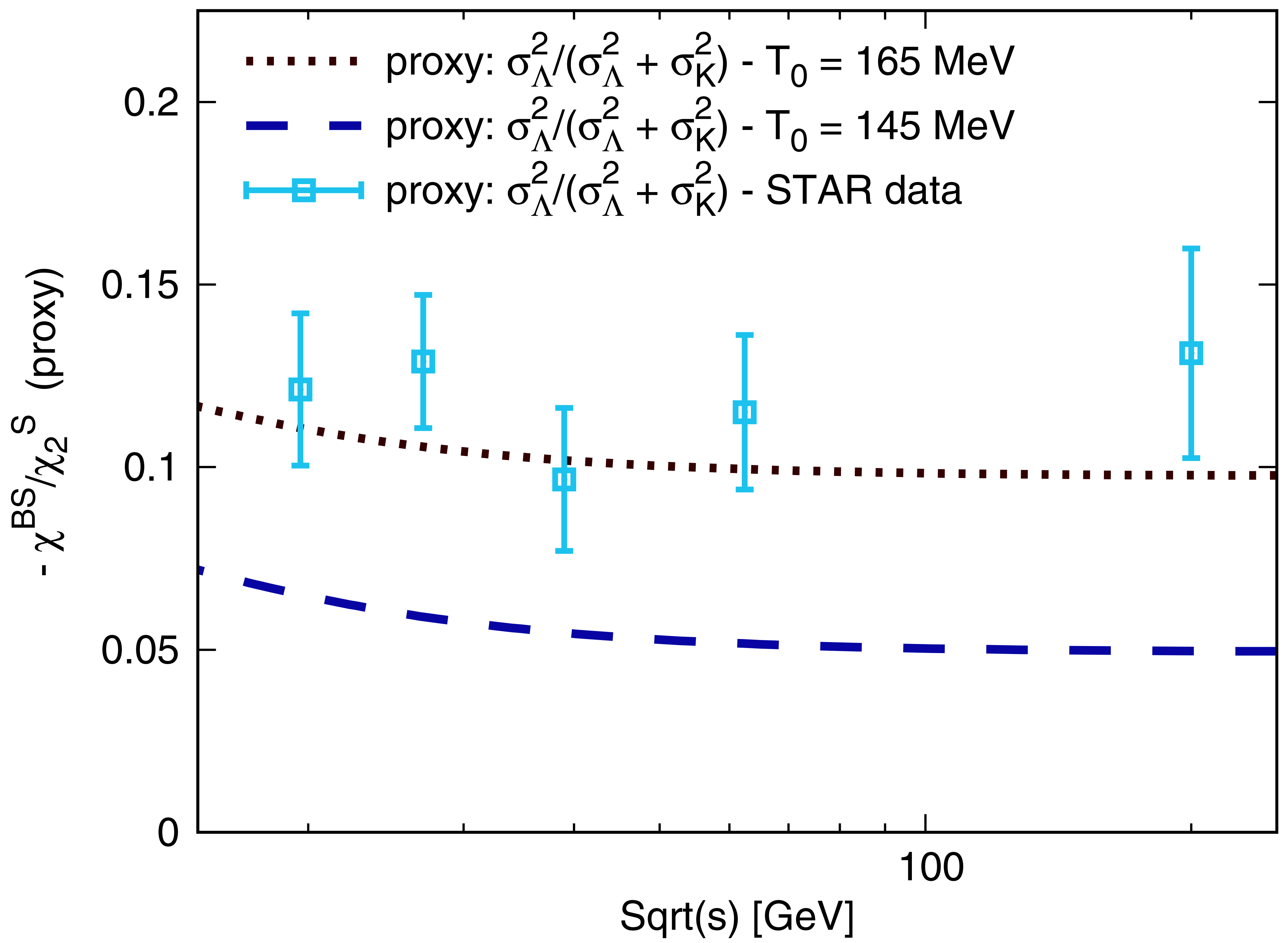

Proxy to measure **baryon-strangeness correlator**




*R. Bellwied, JS et al, PRD (2020)*

# Cross-correlators at Freeze-out

- The baryon-strangeness correlator can test the flavor hierarchy
  - Lines show parametrization of proxy on upper and lower bounds of crossover
  - Experimental data favor higher temperature

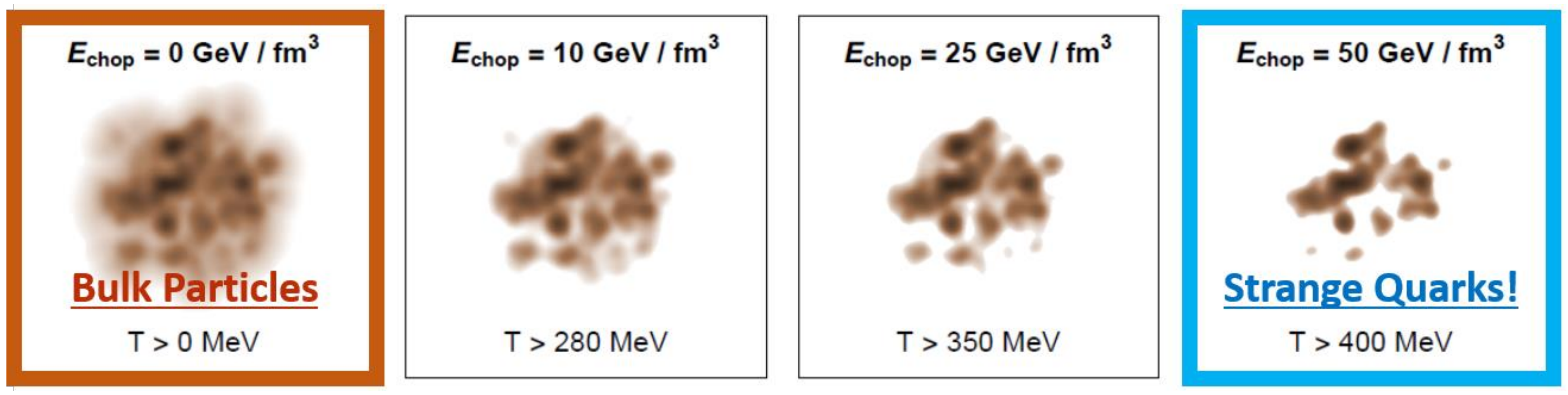


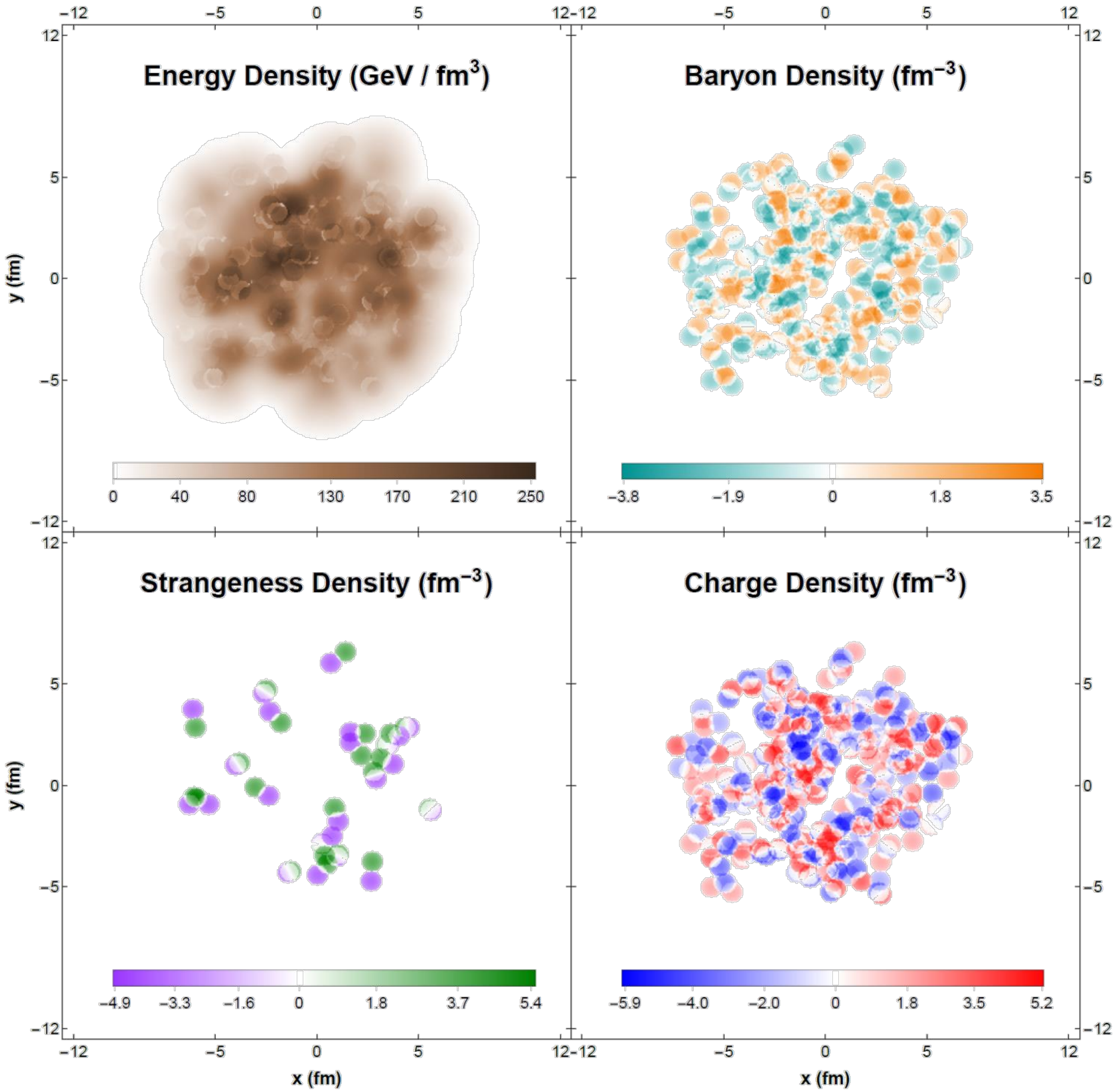

*R. Bellwied, JS et al, PRD (2020)*
*STAR Collaboration (J. Adam), PRC (2020)*

# IV. BQS Modeling

# BQS Initial Conditions

- ➤ Initial densities for each conserved charge can be constructed by re-sampling the initial energy density to map gluon density to $q\bar{q}$ production
- ➤ Baryon and charge densities largely mirror energy density
- ➤ Strangeness density is related to distribution of hot spots



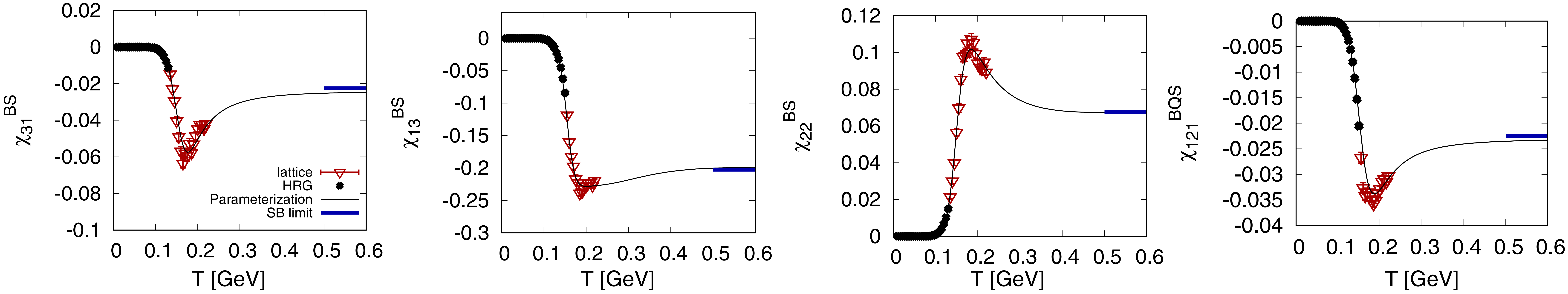




ICCING: M. Martinez et al, arXiv: 1911.12454;1911.10272

# BQS EoS

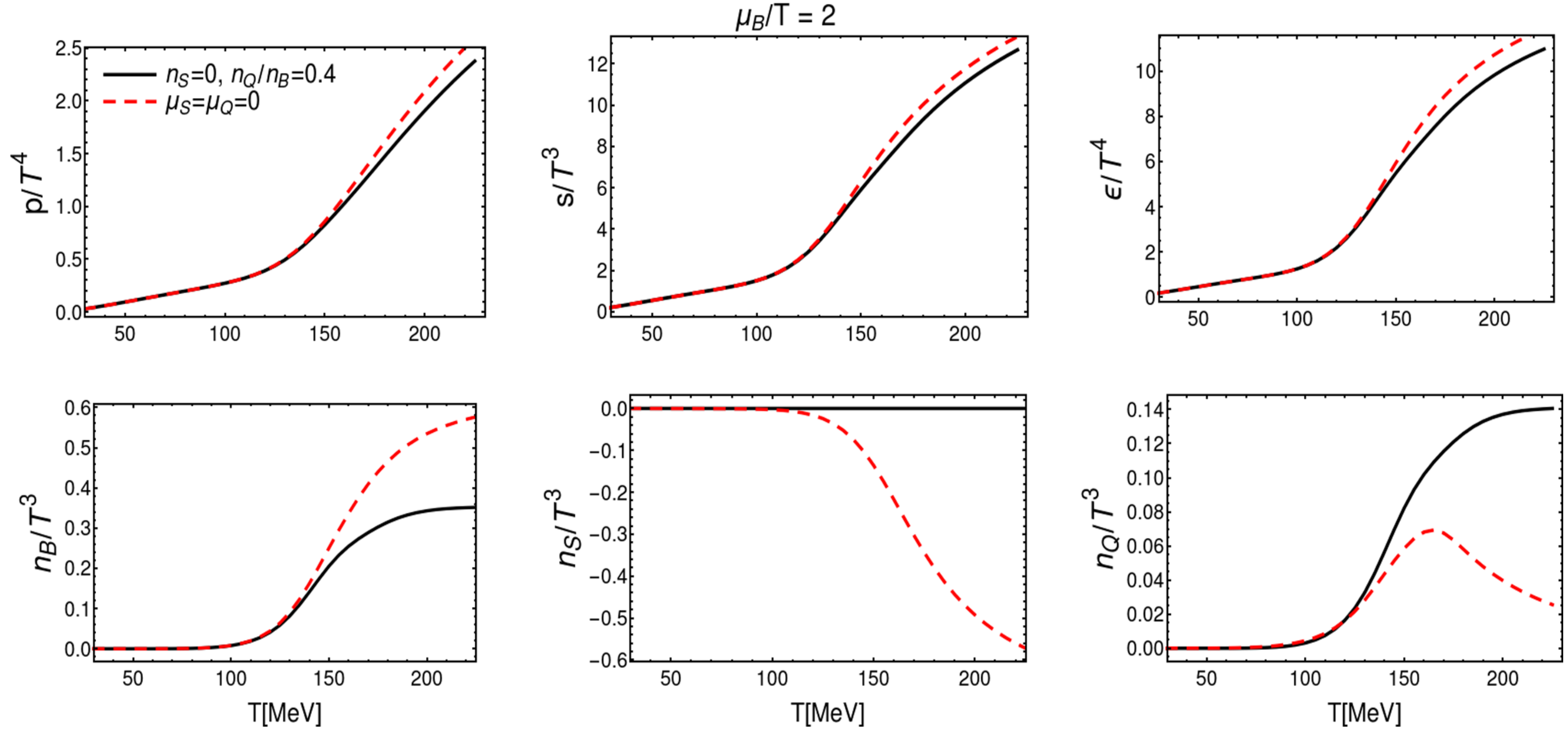
- Reconstruct the QCD equation of state from all diagonal and off-diagonal Taylor expansion coefficients up to $\mathcal{O}(\mu_B^4)$

$$\frac{P(T,\mu_B,\mu_Q,\mu_S)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{ijk}^{BQS}(T) \left(\frac{\mu_B}{T}\right)^j \left(\frac{\mu_Q}{T}\right)^k \left(\frac{\mu_S}{T}\right)^i$$

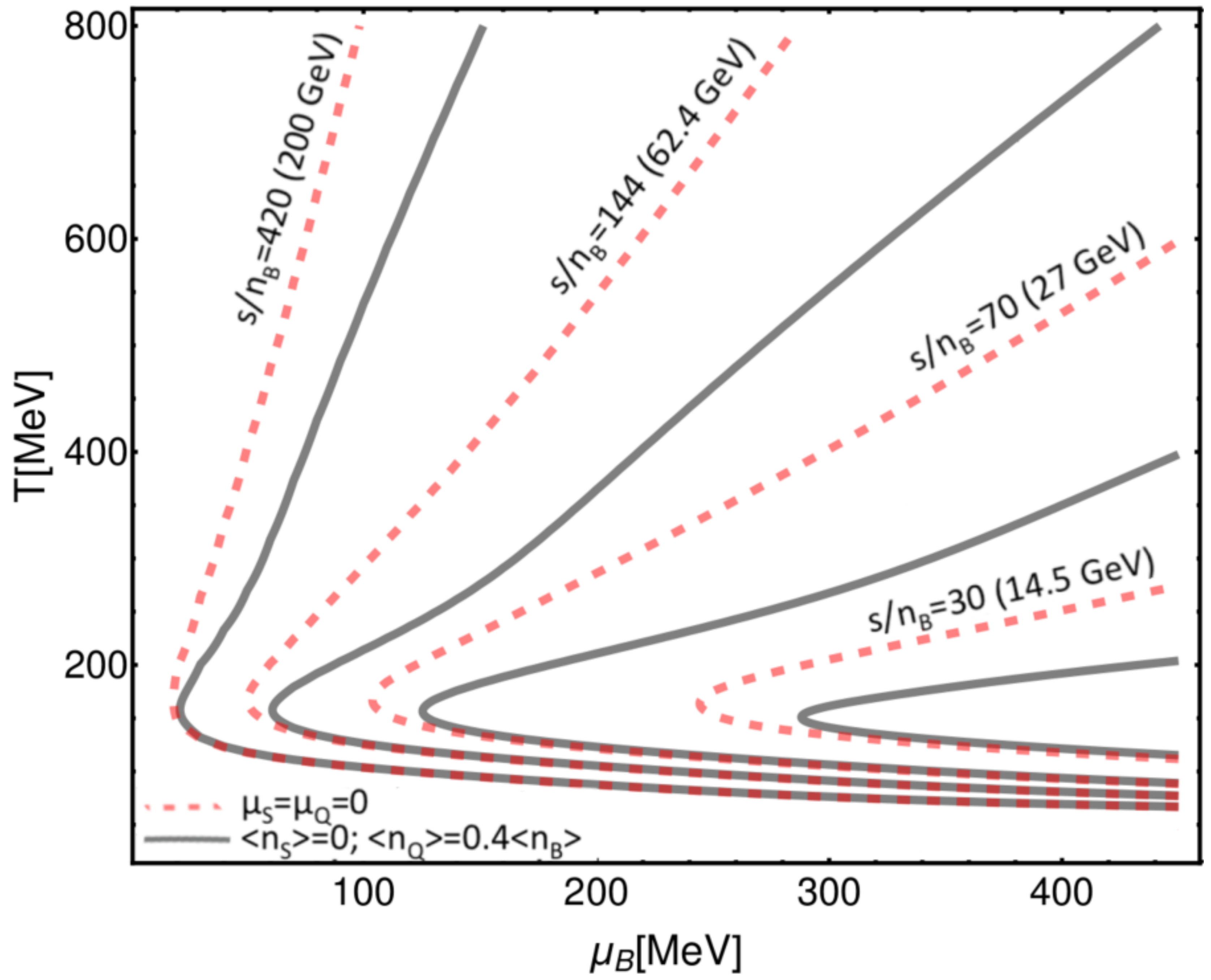


# BQS EoS

➤ Charge conservation conditions can be applied in BQS EoS




Isentropic trajectories stress importance of BQS modeling for heavy-ion phenomenology

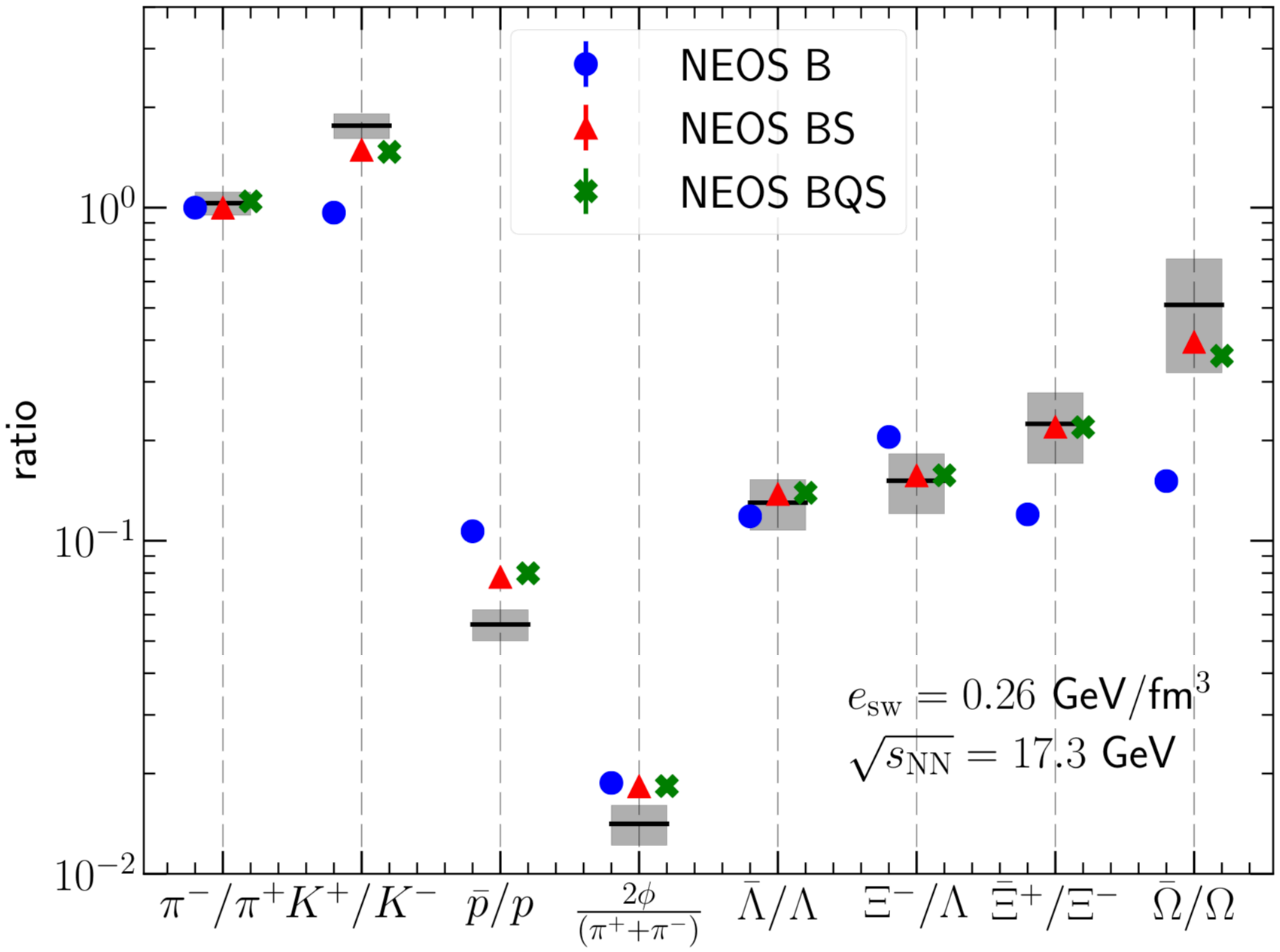



*See also: A. Monnai et al, PRC (2019)*

*J. Noronha-Hostler, JS et al, PRC (2019)*

# BQS EoS

- Full dynamical modeling with successive additions of charge conservation conditions increases agreement of predicted particle ratios with experimental data
  - Including only baryon number is not sufficient
  - Strange baryons especially affected
  - Small difference after adding Q



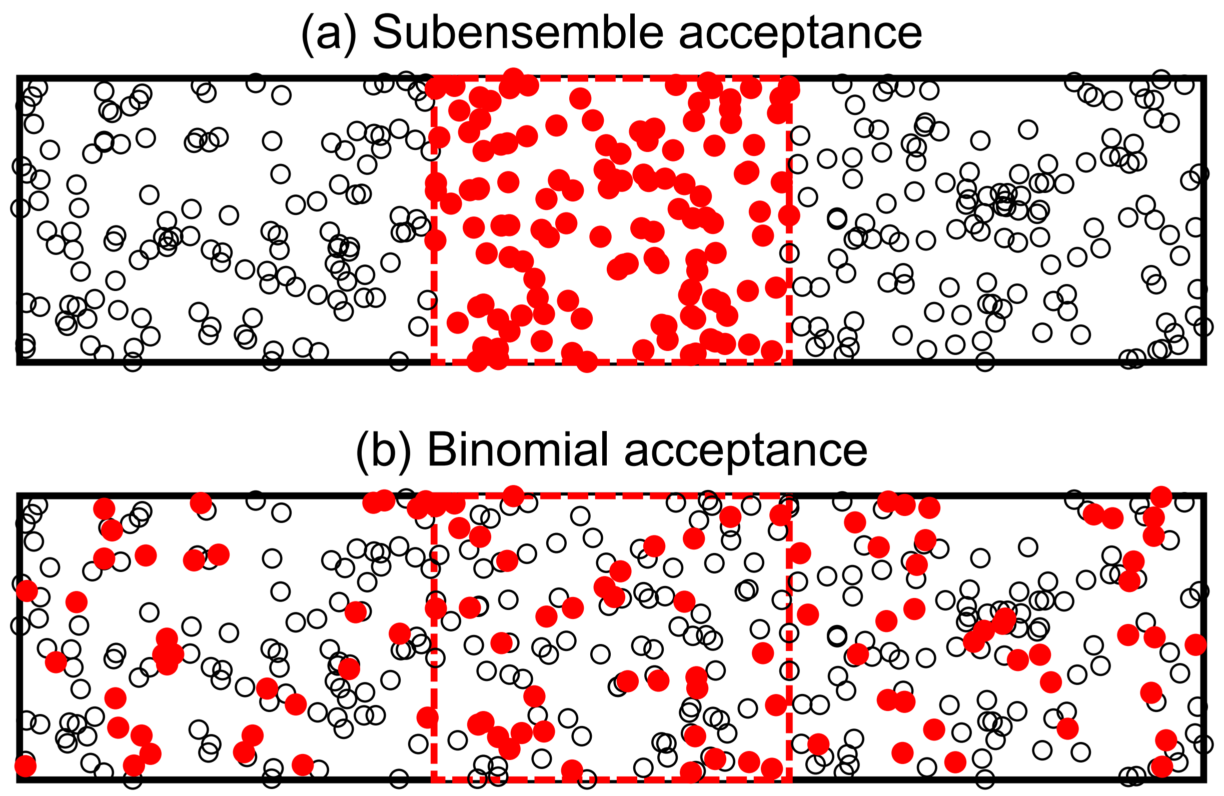
# BQS Conserved Fluctuations

- Using the subensemble acceptance method, the conservation effects can be studied for all QCD charges

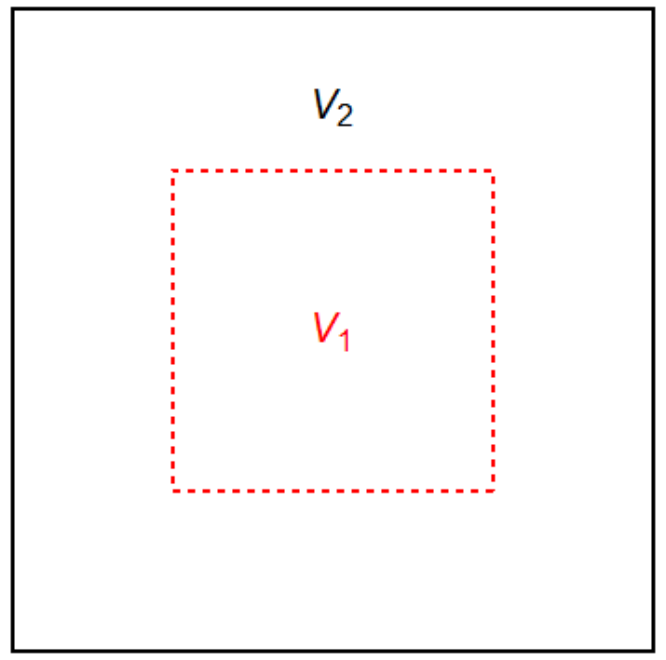
B conserved: $\kappa_4[B^1] = \alpha V T^3 \beta \left[ (1-3\alpha\beta)\,\chi_4^B - 3\,\alpha\,\beta\,\frac{(\chi_3^B)^2}{\chi_2^B} \right]$

BQS conserved: $$\kappa_4[B^1] = \alpha V T^3 \beta \Big[ (1-3\alpha\beta)\,\chi_4^B - \frac{3\alpha\beta}{D[\hat\chi_2]} \times \Big\{ (\chi_3^B)^2[\chi_2^Q\chi_2^S - (\chi_{11}^{QS})^2] + (\chi_{21}^{BQ})^2[\chi_2^B\chi_2^S - (\chi_{11}^{BS})^2] + (\chi_{21}^{BS})^2[\chi_2^B\chi_2^Q - (\chi_{11}^{BQ})^2] - 2\chi_3^B\chi_{21}^{BQ}(\chi_2^S\chi_{11}^{BQ} - \chi_{11}^{BS}\chi_{11}^{QS}) - 2\chi_3^B\chi_{21}^{BS}(\chi_2^Q\chi_{11}^{BS} - \chi_{11}^{BQ}\chi_{11}^{QS}) \Big\} \Big]$$

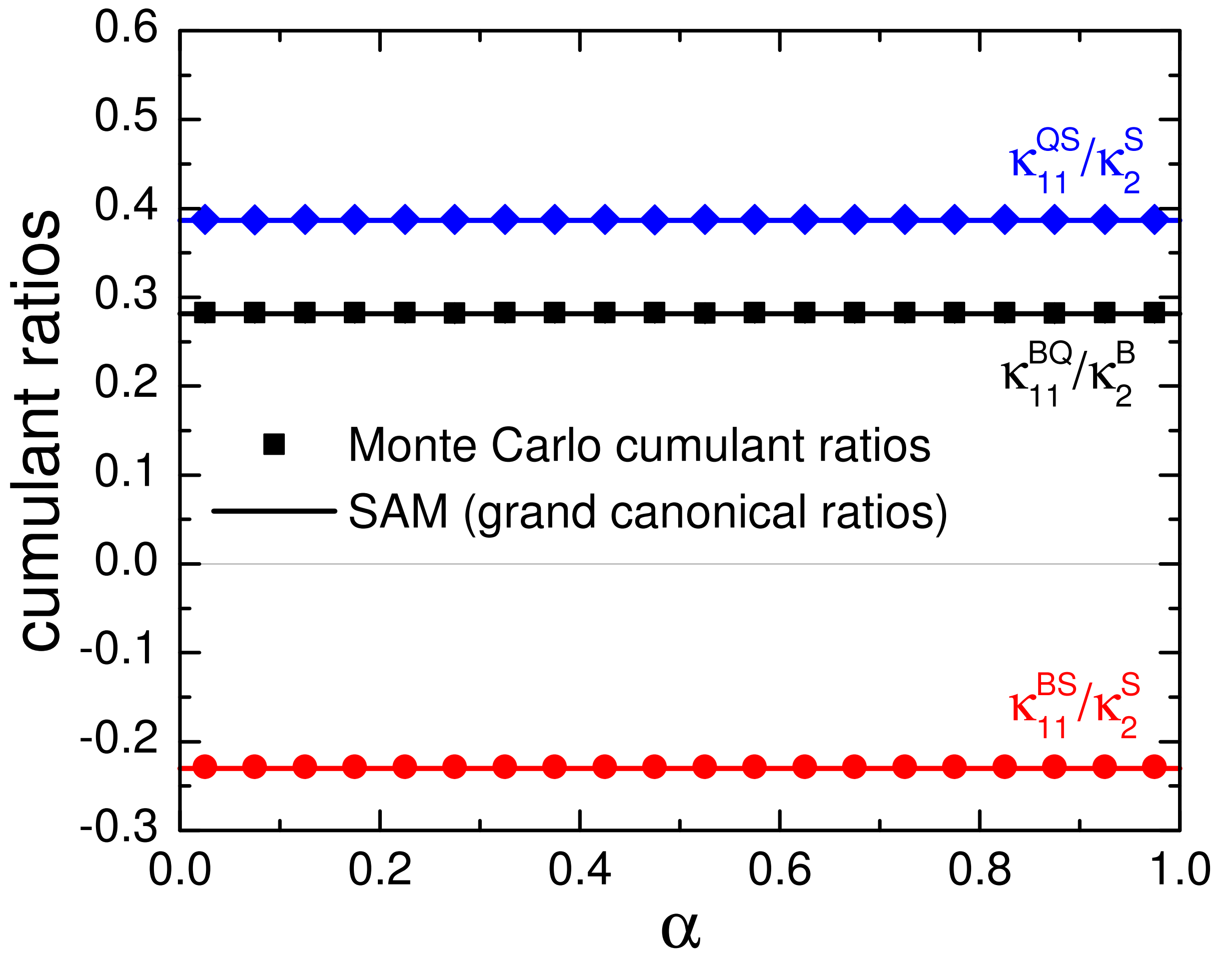
$$D[\hat\chi_2] = \chi_2^B\chi_2^Q\chi_2^S + 2\chi_{11}^{BQ}\chi_{11}^{BS}\chi_{11}^{QS} - \chi_2^B(\chi_{11}^{QS})^2 - \chi_2^Q(\chi_{11}^{BS})^2 - \chi_2^S(\chi_{11}^{BQ})^2$$

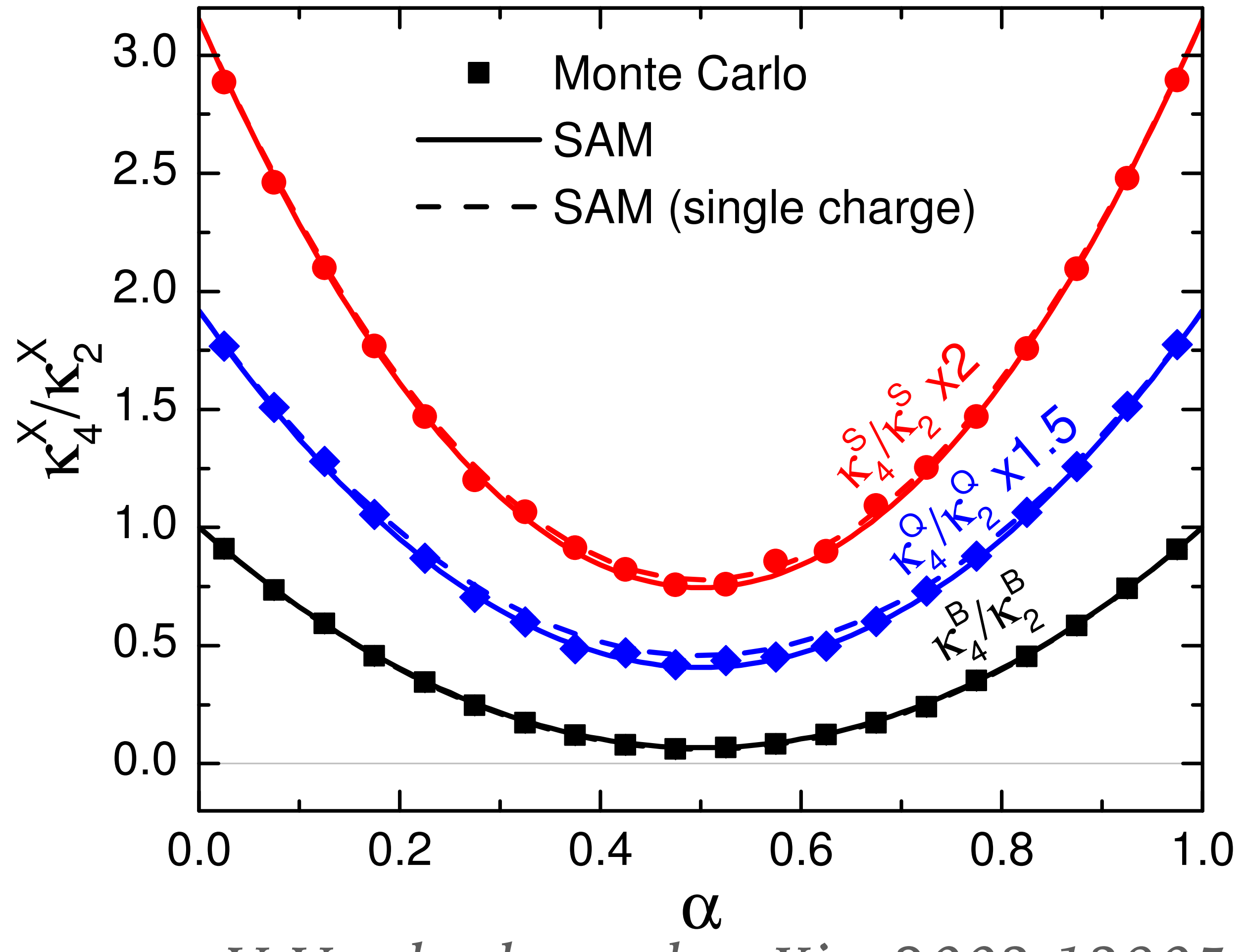



$\alpha \equiv V_1/V \equiv \Delta Y_{acc}/\Delta Y_{4\pi} \lesssim 0.2$




$\beta \equiv 1 - \alpha$




*V. Vovchenko et al, arXiv: 2003.13905, JHEP (2020)*

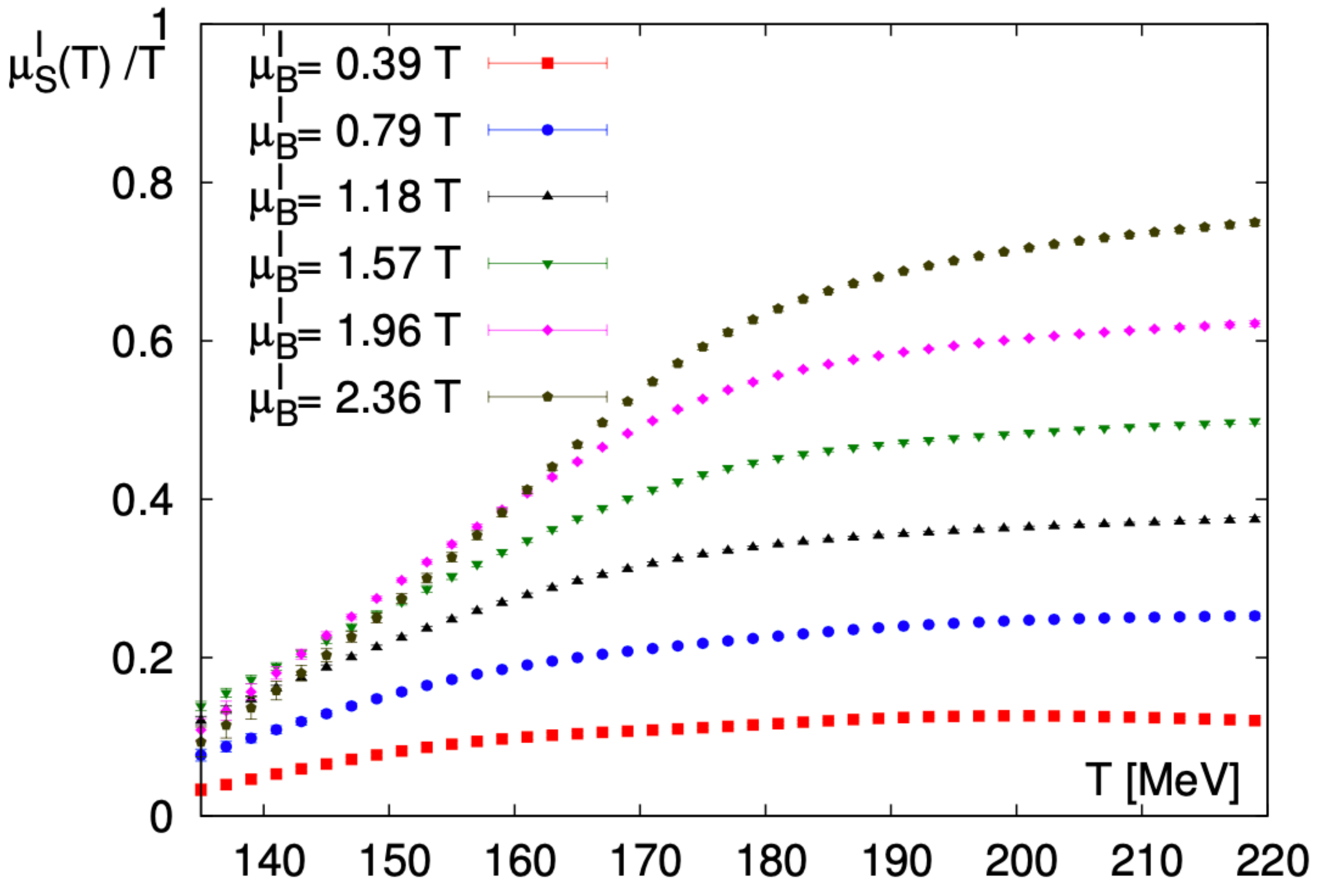
# V. Conclusions

# Conclusions

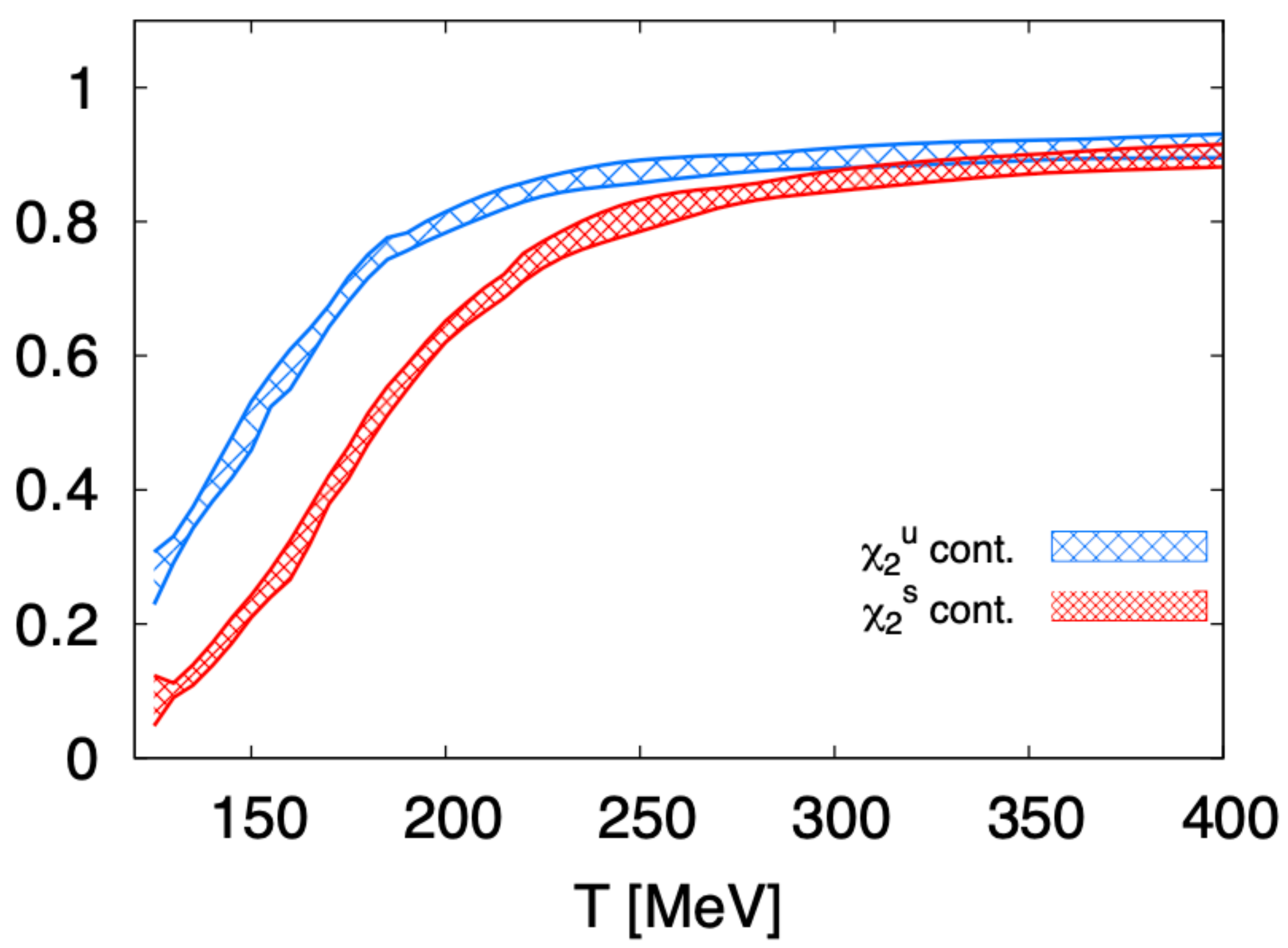
- Evidence for a light v. strange flavor hierarchy at chemical freeze-out from:
  - Thermal fits with separate light and strange freeze-out parameters,
  - Net-K and net-$\Lambda$ fluctuations yield higher freeze-out temperatures
- Many models can now incorporate all BQS conserved charges:
  - ICCING provides initial densities for all charges
  - BQS EoS provides strangeness neutrality, matching experimental situation
  - Charge conservation effects for BQS can now be corrected for any EoS
  - …more exciting developments out there!

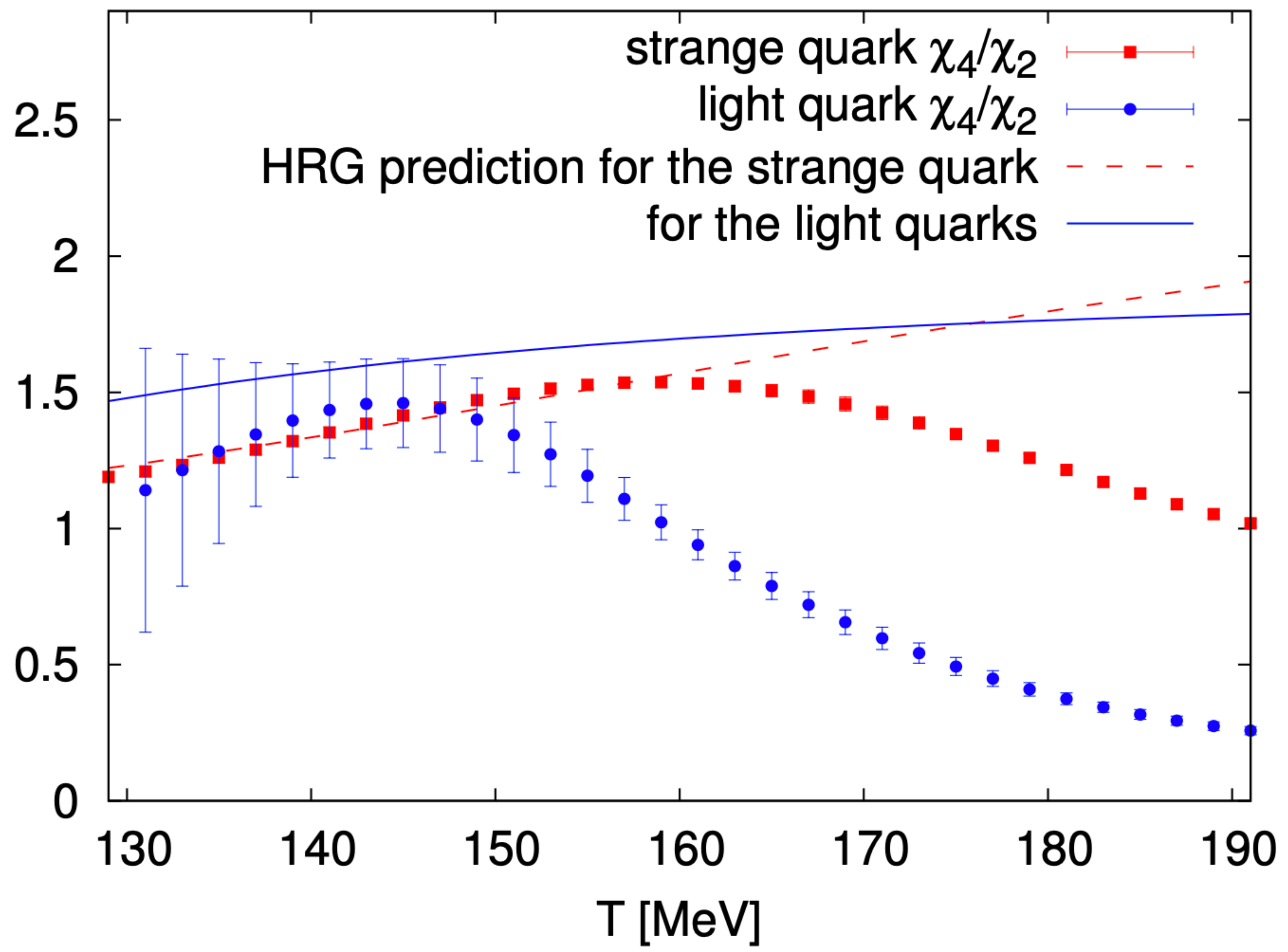
# Back-up Slides

# Strangeness neutrality on the lattice

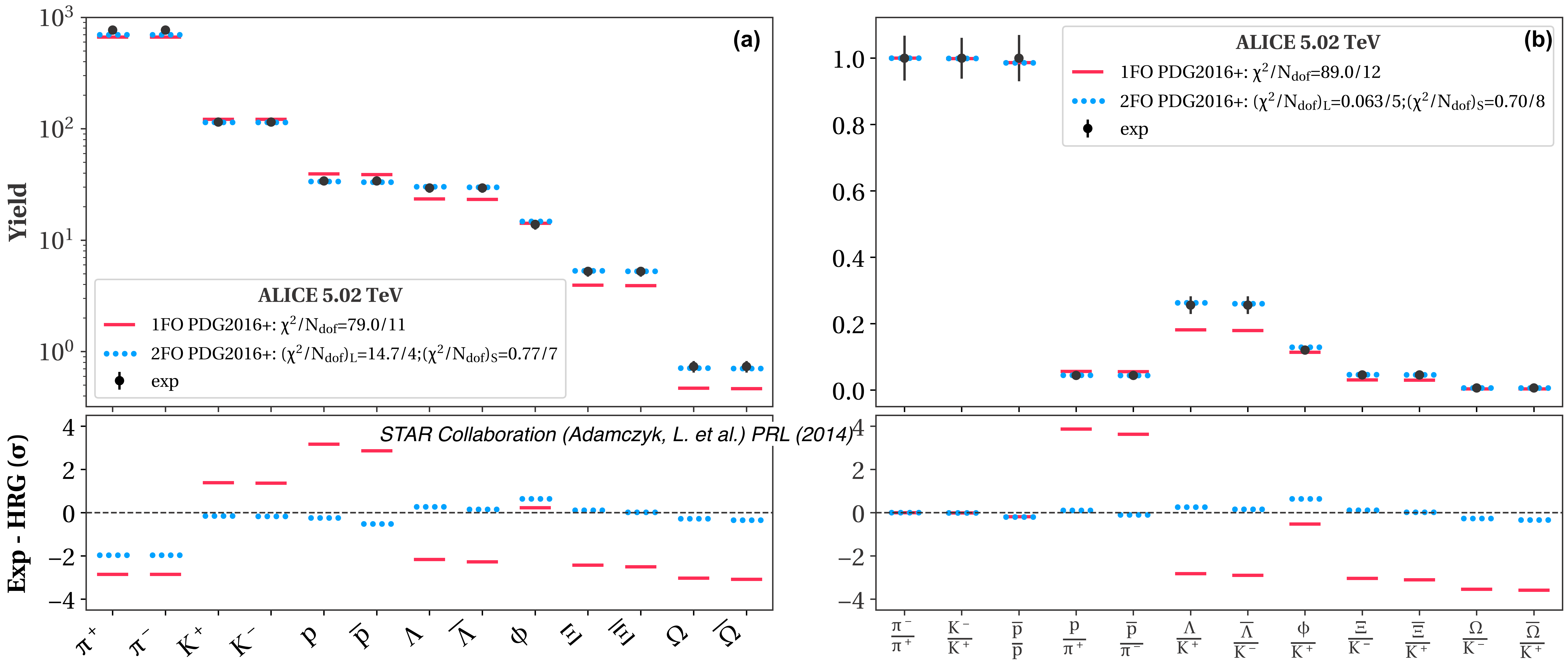


# Indications of Flavor Hierarchy

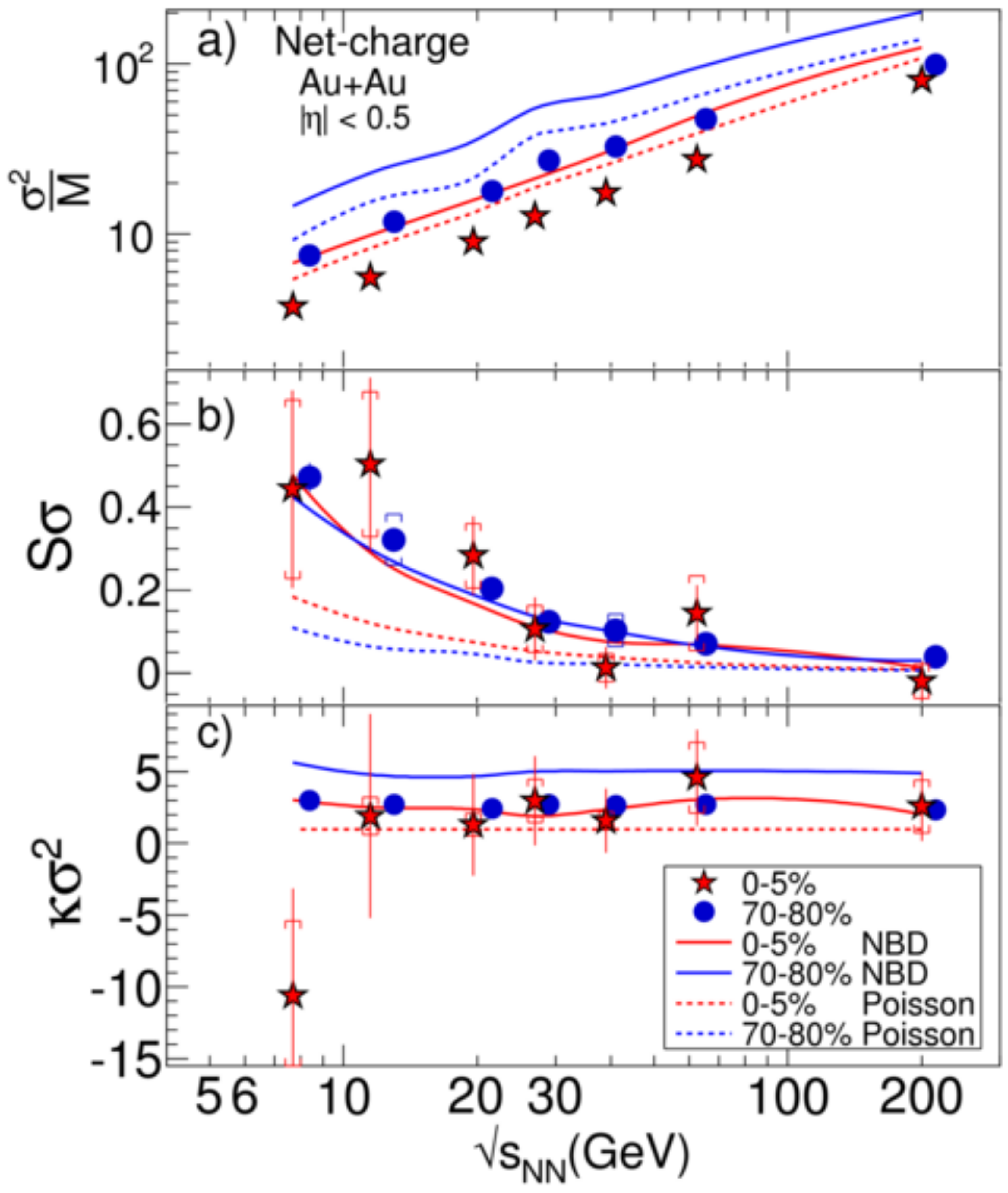


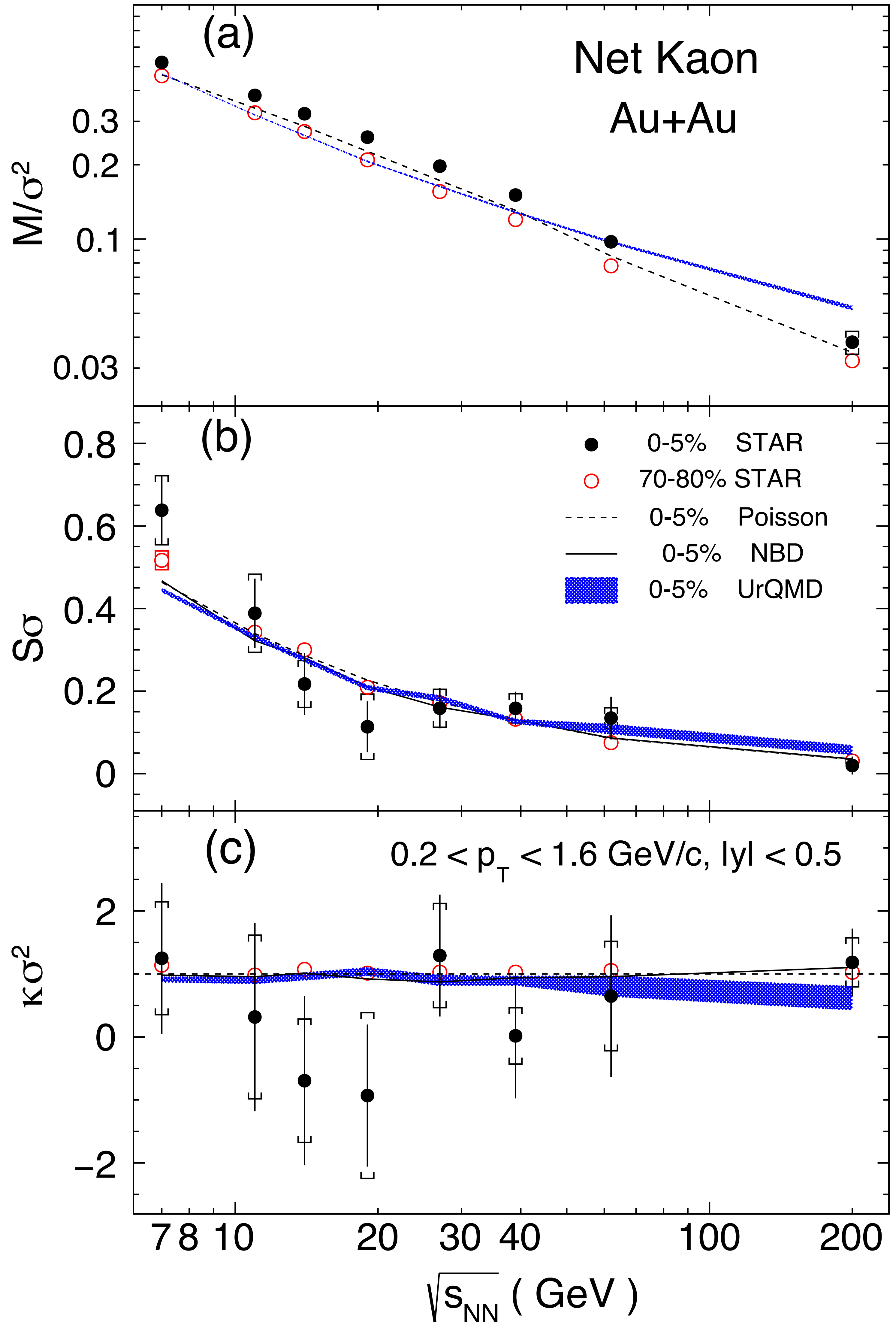



# Thermal Fits for ALICE



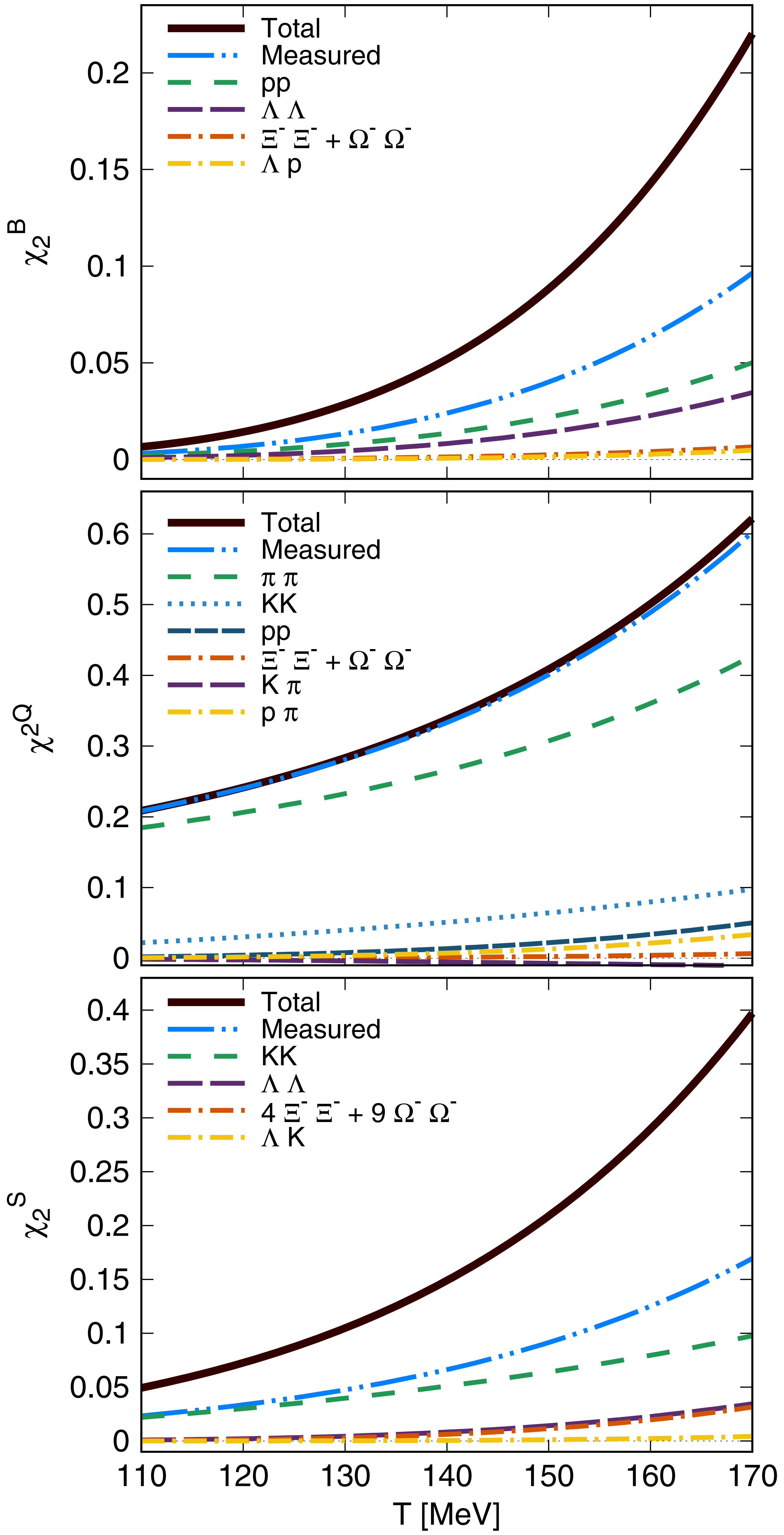
# Net-particle Fluctuations from STAR

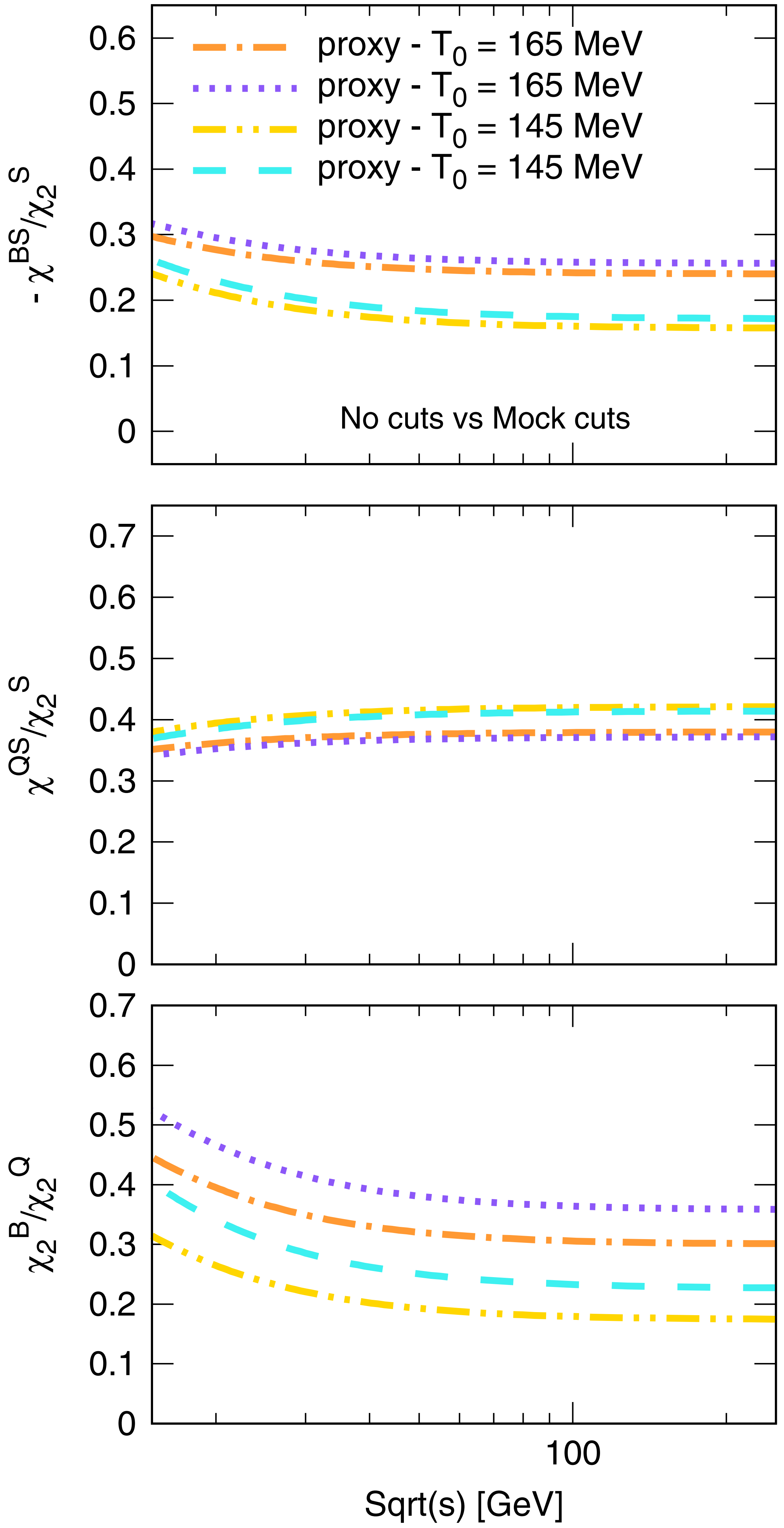


# Cross-correlators

- Diagonal correlators
- Effect of acceptance cuts on the proxies



# ICCING Sampling Algorithm