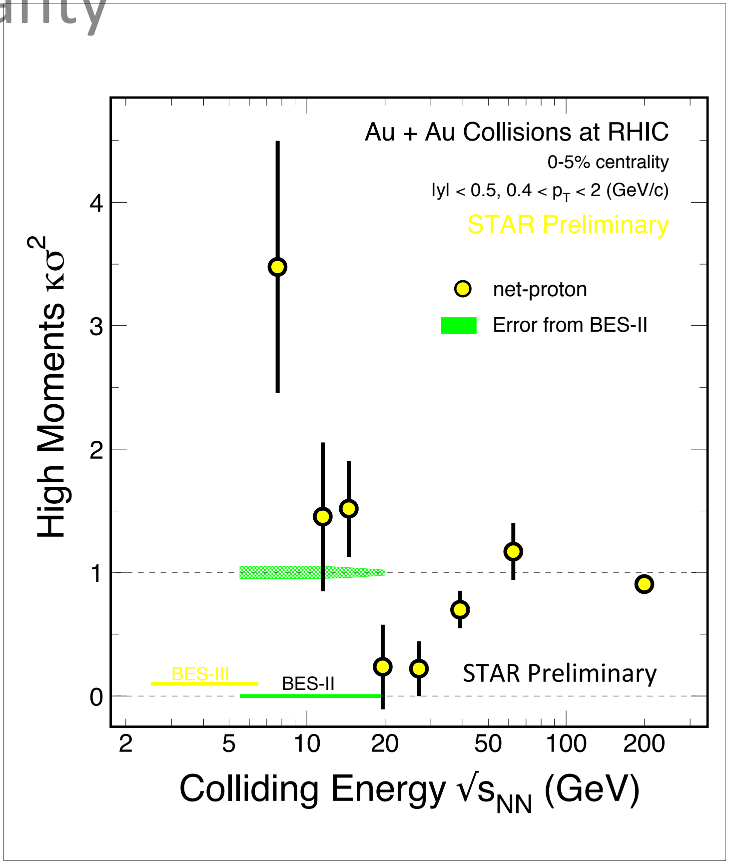
Discussion on Freeze-out dynamics at RHIC Beam Energy Scan Program

Bedanga Mohanty
(NISER)

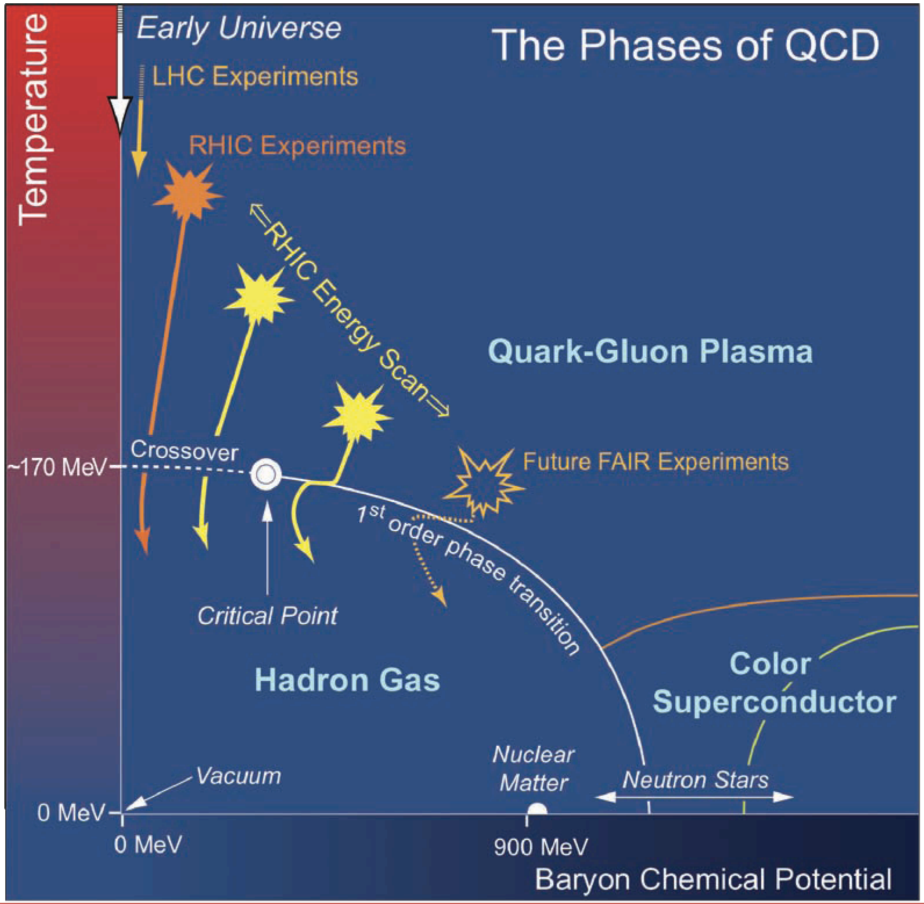


Outline:

RHIC BES Program – interesting results
Chemical Freeze-out properties and systematics
Kinetic Freeze-out properties
Summary

Which part of the QCD Phase Diagram we are probing ?

Goals of Beam Energy Scan Program



Study the phase structure of QCD phase diagram

How :
Vary beam energy to change temperature & baryon chemical potential

SN0493 and SN0598

- Consolidate the signals of quark-hadron transition observed at top RHIC energies
- Look for signatures of possible 1st order phase transition
- Look for signatures of possible critical point

RHIC Beam Energy Scan−Phase I

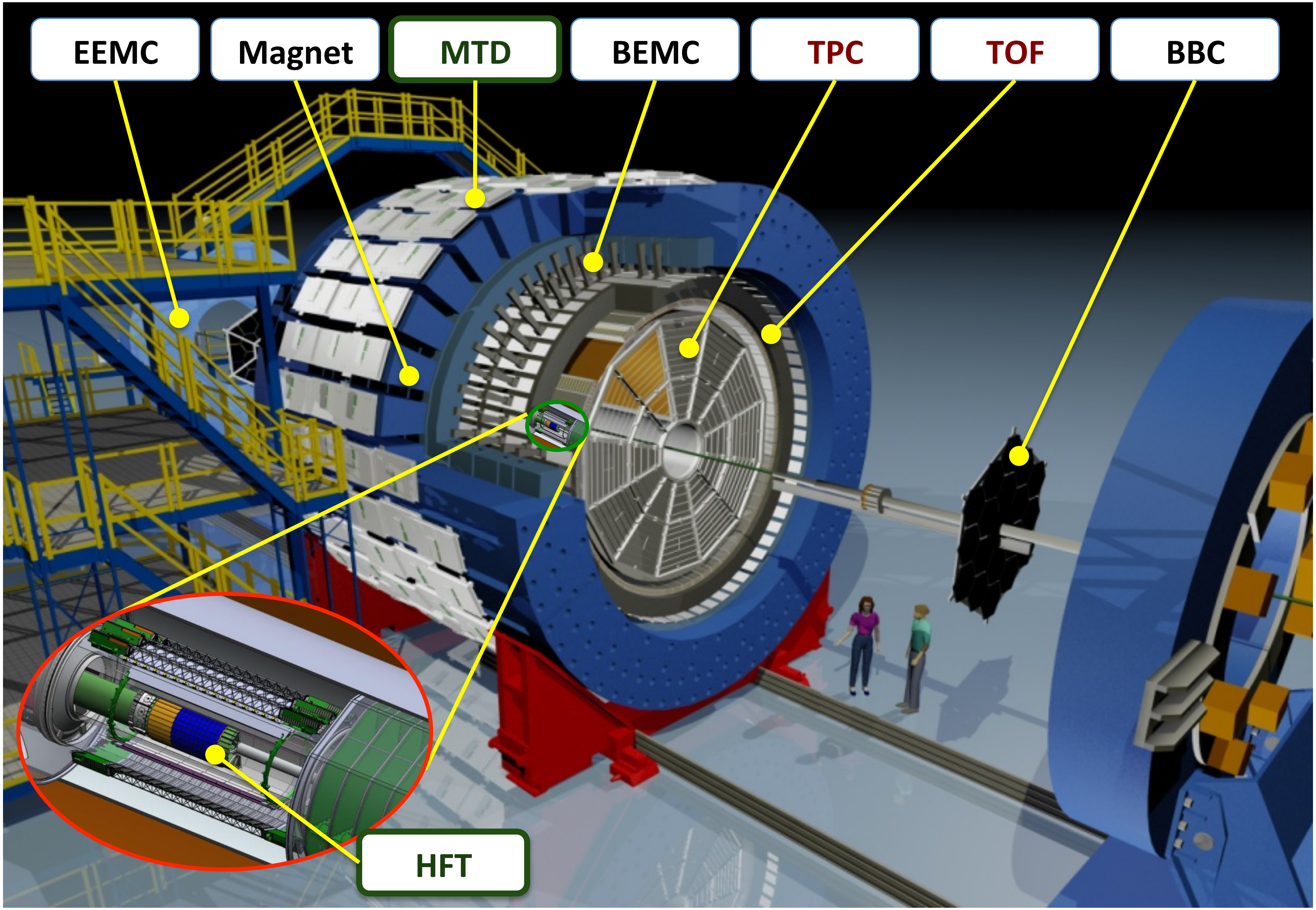
SN0598

$\sqrt{s}$ (GeV)	Statistics(Millions) (0-80%)	Year	μ_B (MeV)	T (MeV)	μ_B /T
7.7	~4	2010	420	140	3.020
11.5	~12	2010	315	152	2.084
14.5	~ 20	2014	266	156	1.705
19.6	~36	2011	205	160	1.287
27	~70	2011	155	163	0.961
39	~130	2010	115	164	0.684
62.4	~67	2010	70	165	0.439
200	~350	2010	20	166	0.142

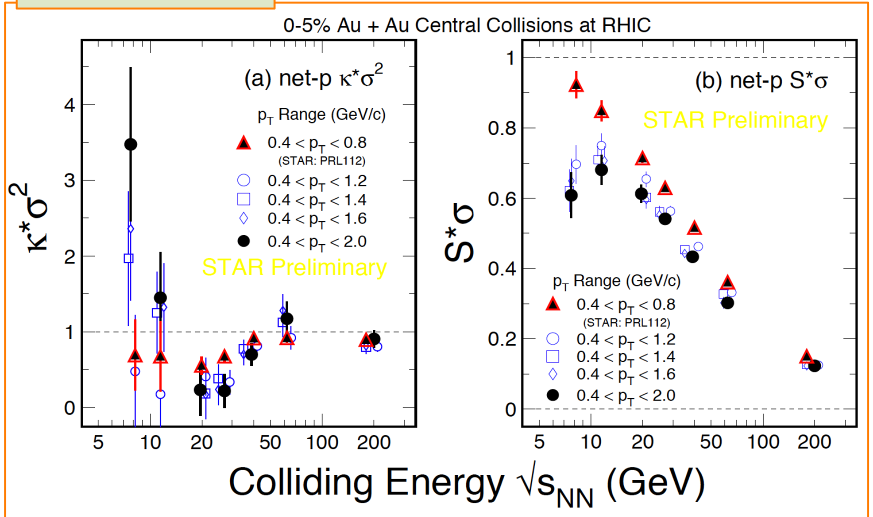
μ_B, T : J. Cleymans et al., Phys. Rev. C 73, 034905 (2006).

14.5 results shown at QM2015, follows common trends with respect to yields and ratios of produced particles

STAR Detector System



CP Search

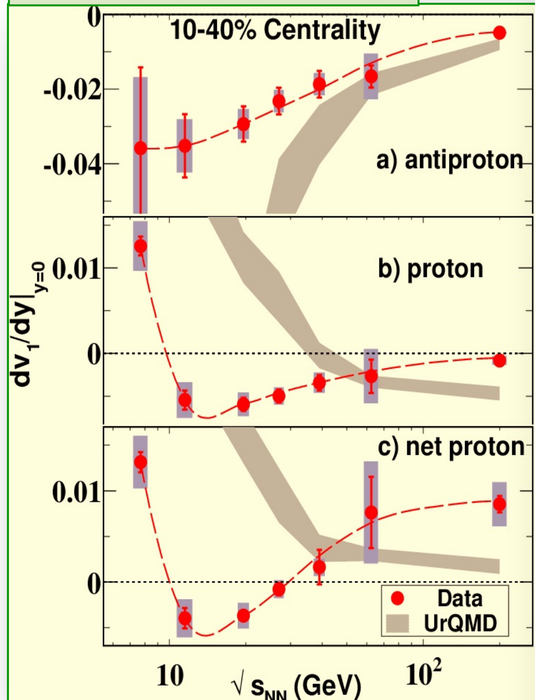


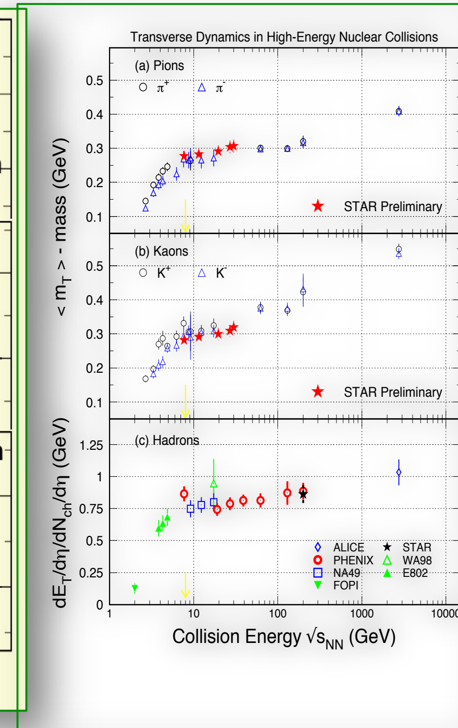
STAR: *PRL103, 251601(09)*
PRL113, 052302(14)

STAR: ***PRL112**, 32302(14)*
STAR: ***PRL113**,092301(14)*

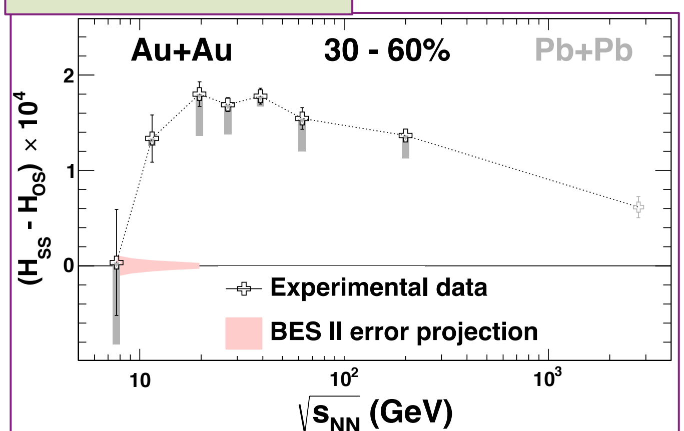
Phys.Rev.Lett. 112 (2014) 162301; SN0598

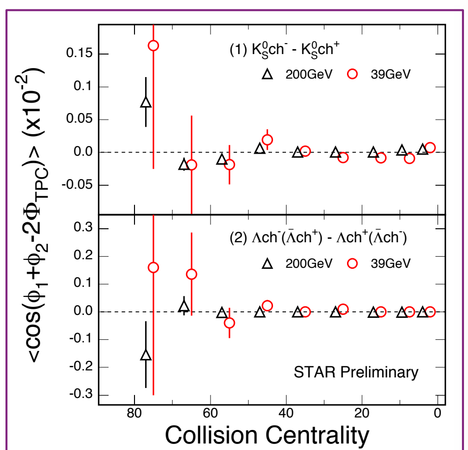
Softening of EOS



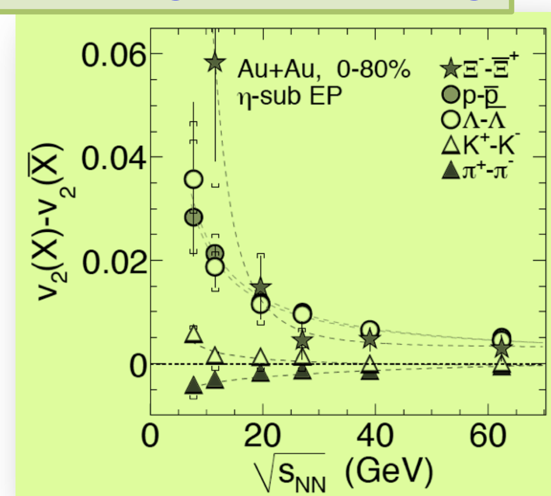


QGP and QCD

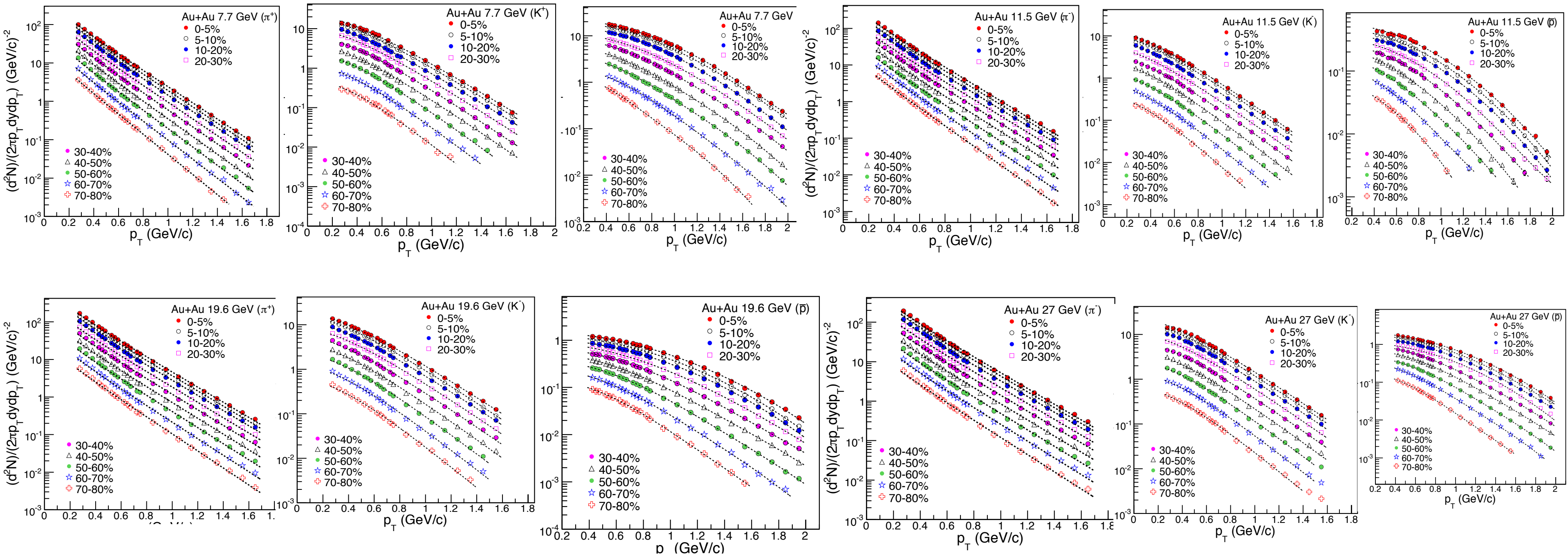


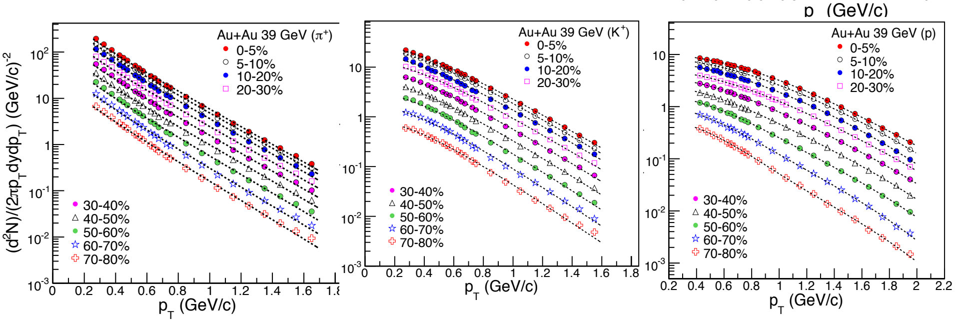


Breaking of NCQ scaling



Invariant Yields - Hadrons





Particles: **π, K, p, Λ , Ξ , Φ, Ω**

Kinematics: Midrapidity : +/- 0.5

p_T range : 0.15 - 2 GeV/c

Uniform coverage y vs. p_T

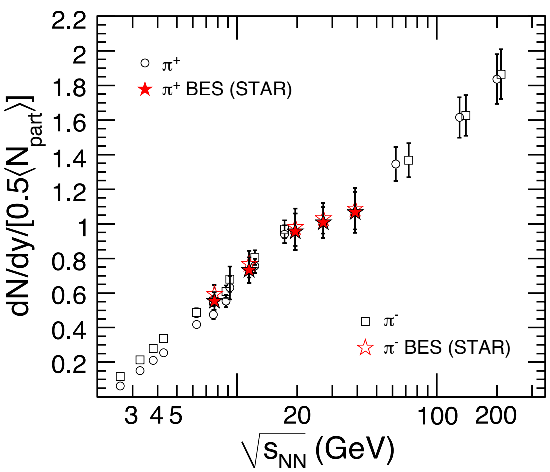
Collision System: Au+Au

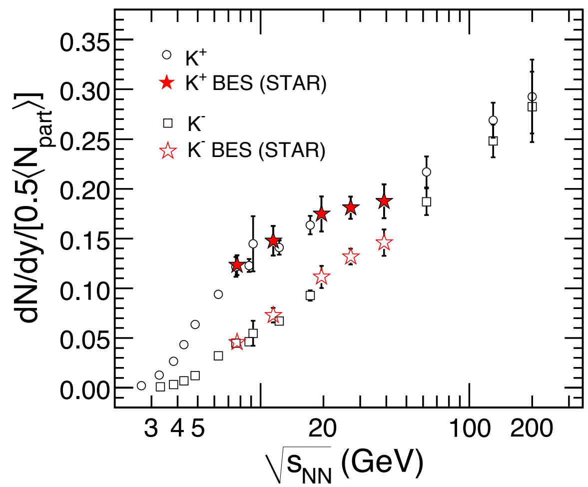
Beam Energy: 7.7, 11.5, 19.6, 27, 39, 62.4, 200 GeV

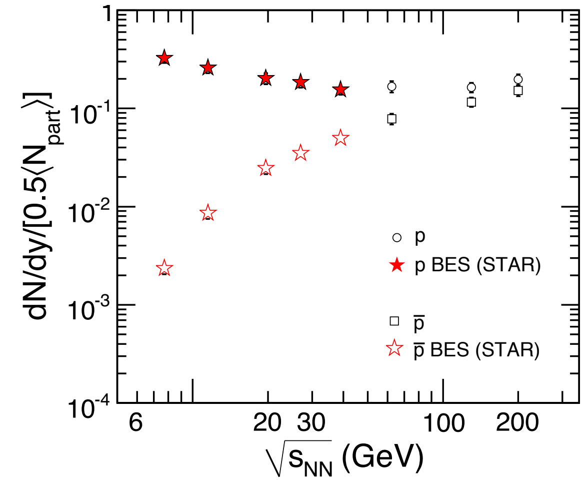
Collision Centrality: 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%

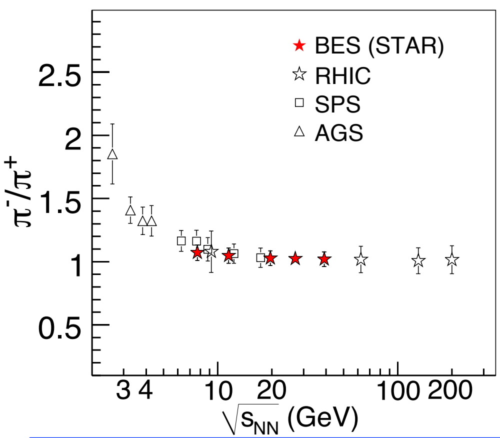
Data: STAR preliminary QM2014

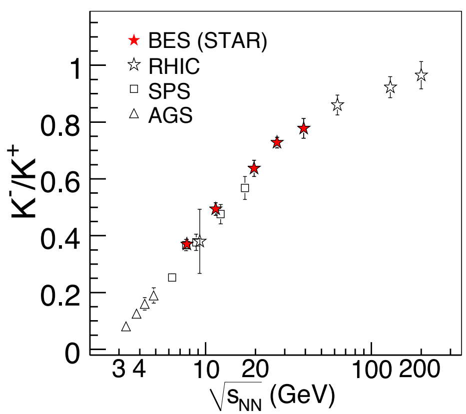
Yields and Ratios (Representative)

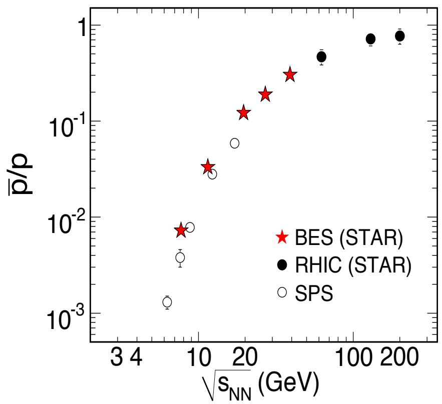


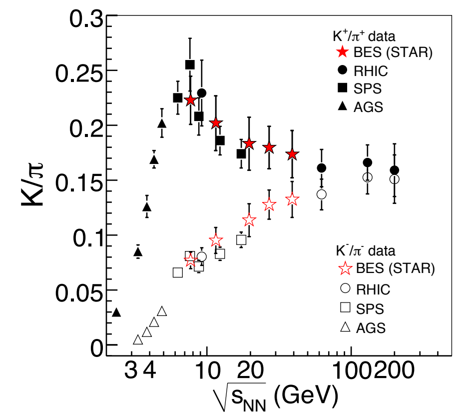












Reflects: Dominance of pair production at high energy end
Associated production for kaons at lower energy end
Resonances play important role
Baryon to meson dominated systems

Data for systematic study of freeze-out properties

Data: STAR preliminary QM2014

Chemical Freeze-out

Chemical Freeze-out : Inelastic collision ceases
Particle yields get fixed

★**THERMUS** : Statistical thermal model
Ensemble used – Grand Canonical and Strangeness Canonical

For Grand Canonical: Quantum numbers (*B, S, Q*) conserved on average

$$n_i = \frac{T m_i^2 g_i}{2\pi^2} \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k} \left(e^{\frac{k\mu_i}{T}} \right) K_2 \left(\frac{k m_i}{T} \right)$$

To consider incomplete strangeness equilibration:

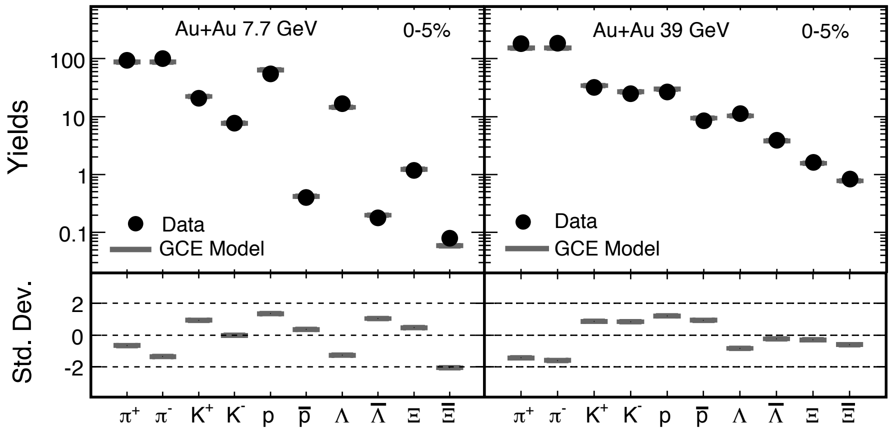
$$n_i \rightarrow n_i \gamma_S^{|S_i|}$$

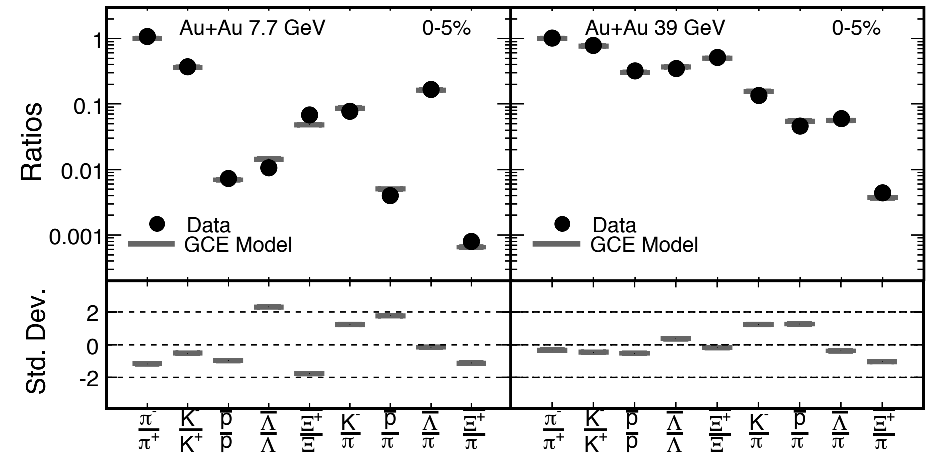
For Strangeness Canonical: Strangeness quantum number (*S*) conserved exactly

Extracted thermodynamic quantities: T_{ch}, μ_B, μ_s and γ_S (strangeness saturation factor)

•Thermus, S. Wheaton & Cleymans, Comput. Phys. Commun. 180: 84-106, 2009.

Chemical Freeze-out





Yields

Model Used: THERMUS

Ratios

✓ Particles used : π, K, p, Λ , Ξ

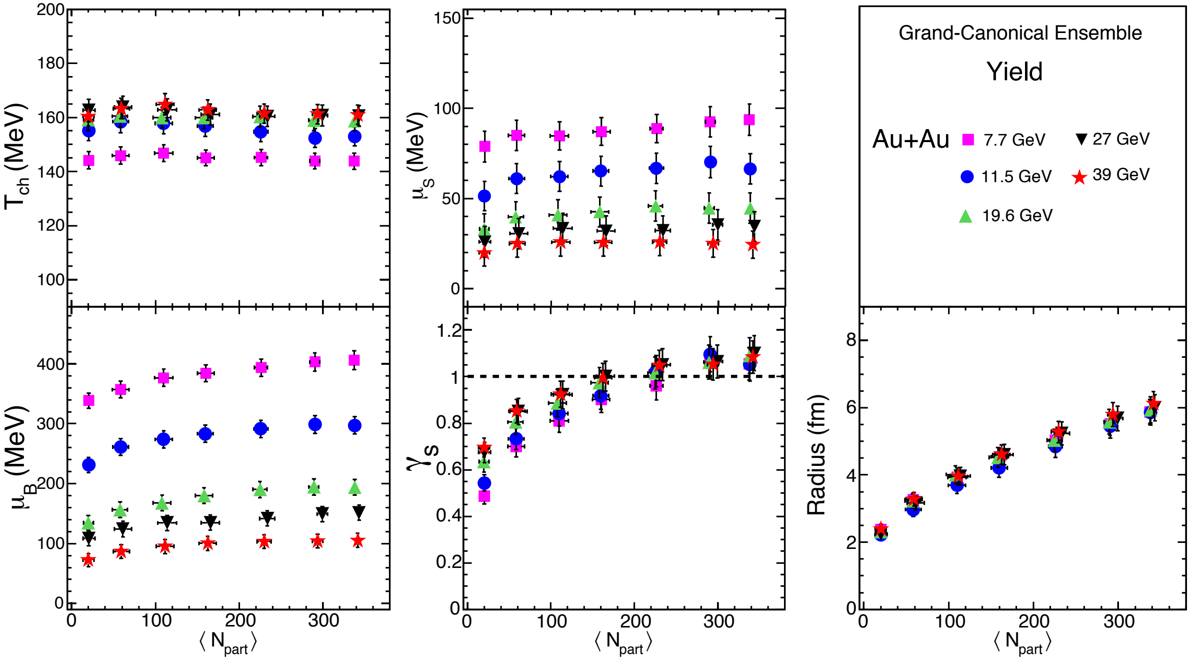
✓ Ensemble used: Grand Canonical
Strangeness Canonical

✓ Fit parameters: chemical freeze-out temperature, T_{ch},
baryon and strangeness chemical potential, μ_B, μ_S,
strangeness saturation factor, γ_S
Charge chemical potential $\mu_Q = 0$

Midrapidity
Protons and anti-proton are inclusive

Data:
STAR preliminary
QM2014

Chemical Freeze-out (GCE)



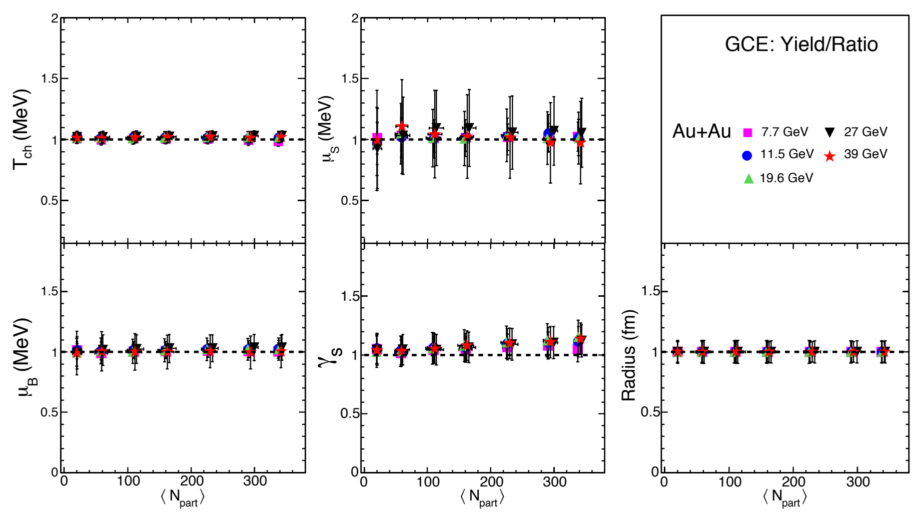
T_{ch} decreases with decrease In beam energy

μ_B increases with decrease in beam energy

μ_S increases with decrease In beam energy

Radius remains similar across BES energies

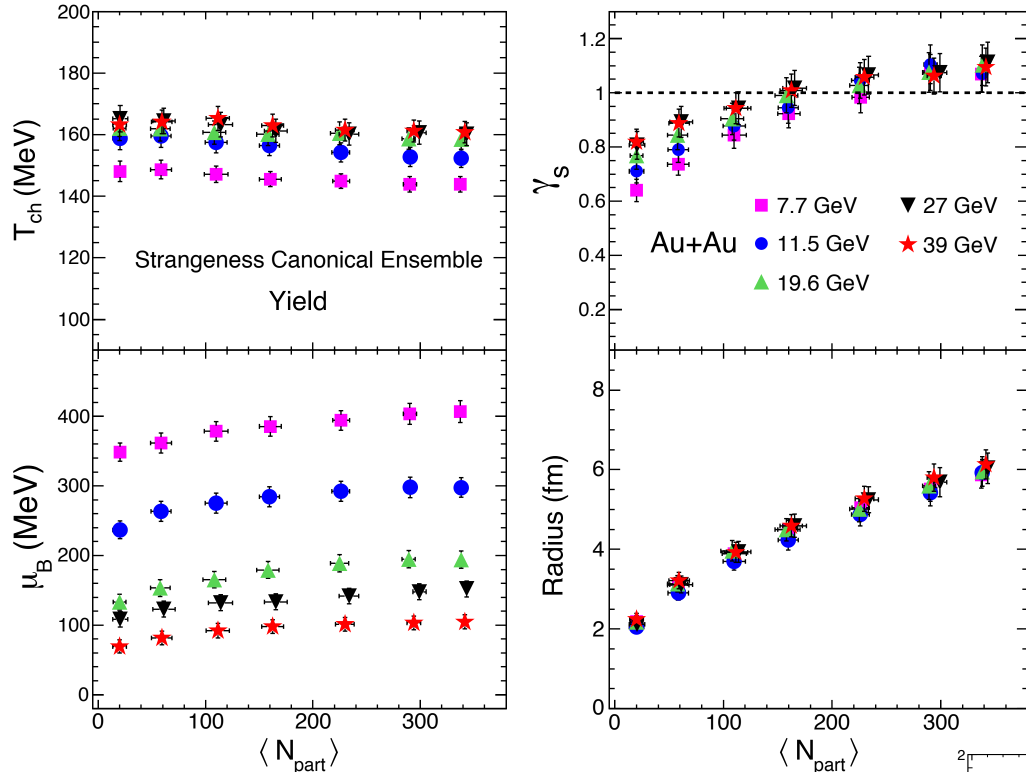
Use of ratio leads to slightly larger γ_s and lower T_{ch}



χ^2/ndf within 2 for all cases

Data: STAR preliminary QM2014

Chemical Freeze-out (SCE)



T_{ch} decreases with decrease
In beam energy

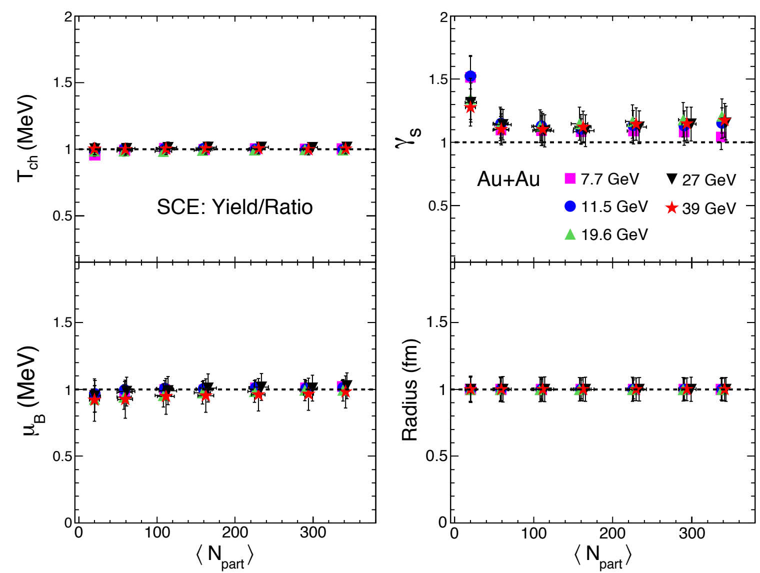
μ_B increases with decrease
in beam energy

μ_S increases with decrease
In beam energy

Radius remains similar across
the BES energies

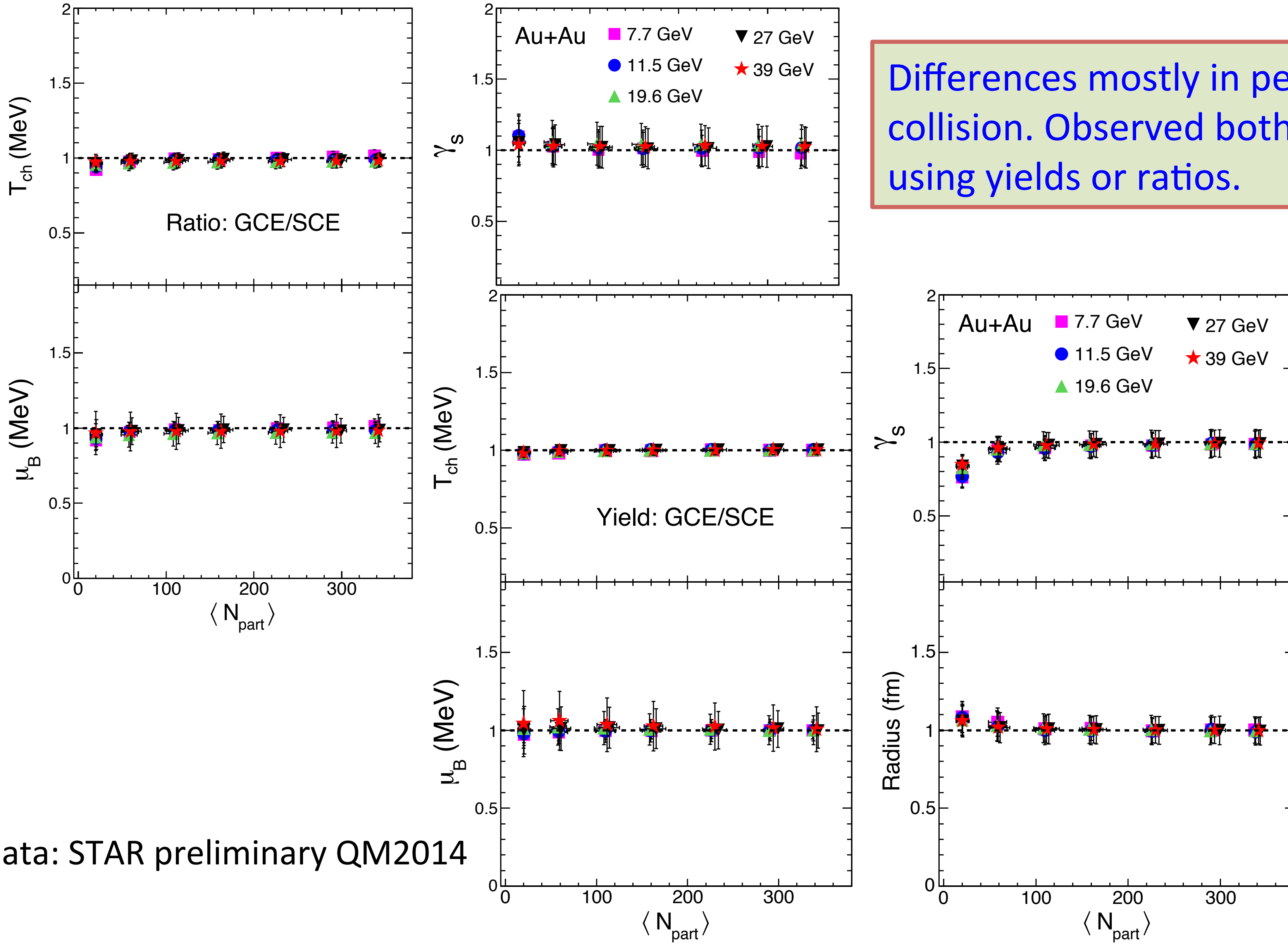
Use of ratio leads to slightly
larger γ_s and lower T_{ch}

χ^2/ndf within 2 for all cases



Data: STAR preliminary QM2014

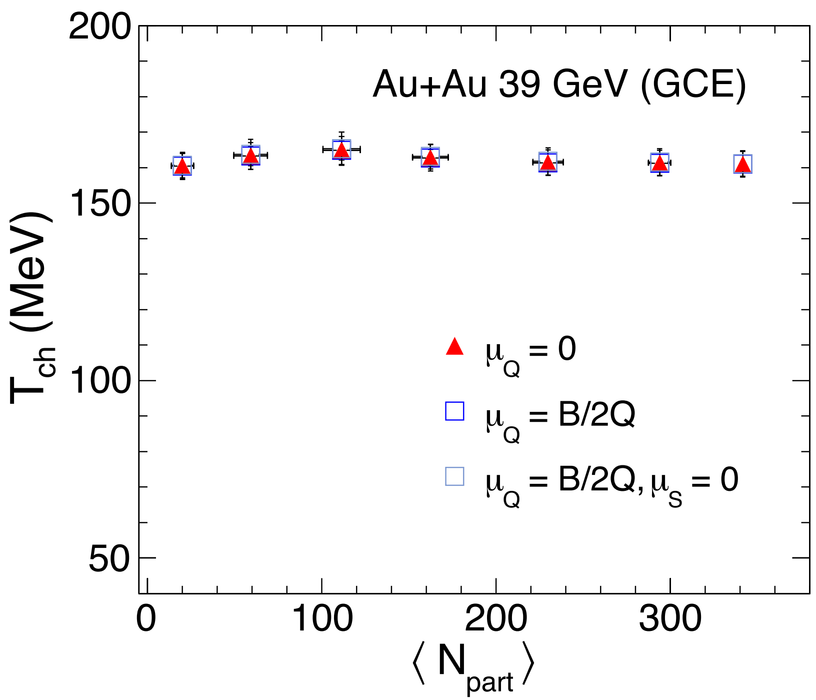
Chemical Freeze-out (GCE Vs. SCE)

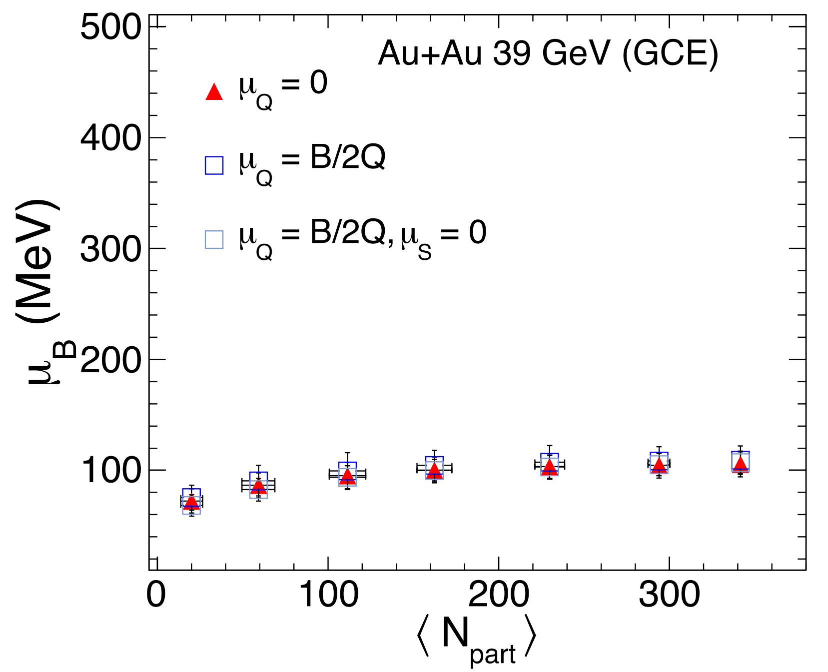


Differences mostly in peripheral collision. Observed both when using yields or ratios.

Data: STAR preliminary QM2014

Chemical Freeze-out : Constrain on μ_Q





- **THERMUS**
- **Grand Canonical Ensemble**
- Particles used:

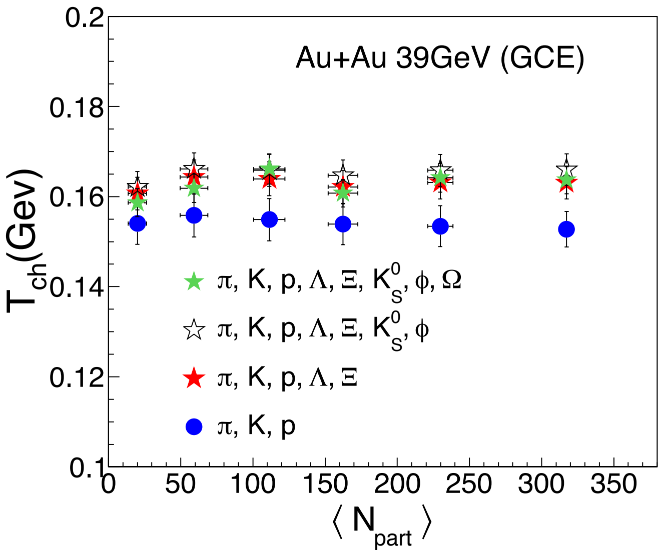
  π, K, p, Λ , Ξ

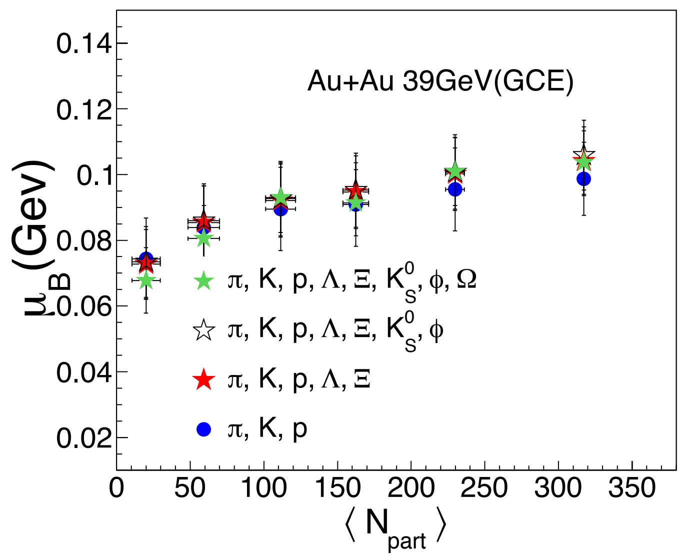
- Different conditions on parameters
  1. $\mu_Q = 0$,
  2. $\mu_Q = B/2Q$
  3. $\mu_Q = B/2Q$, $\mu_s = 0$

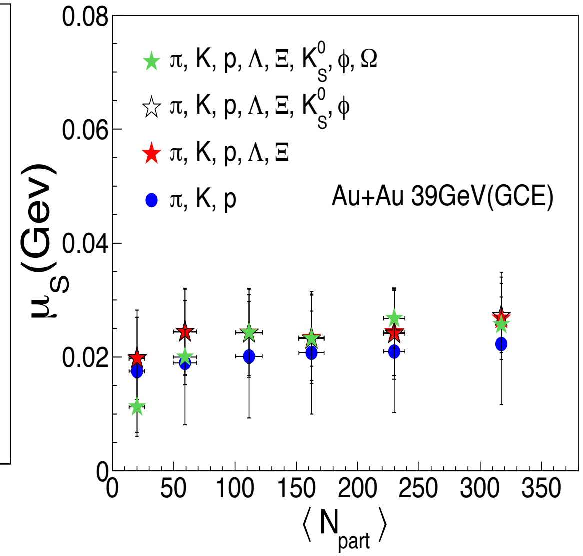
Not much difference observed

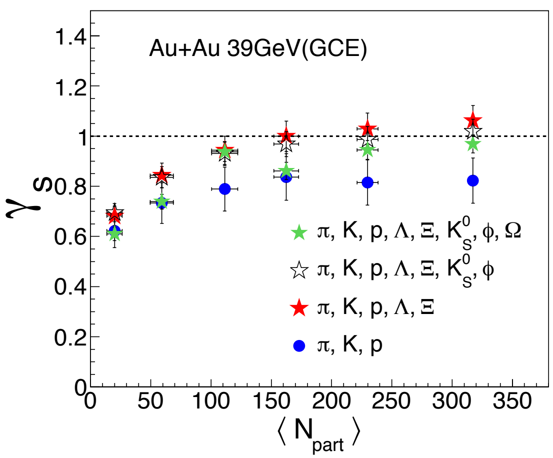
Data: STAR preliminary QM2014

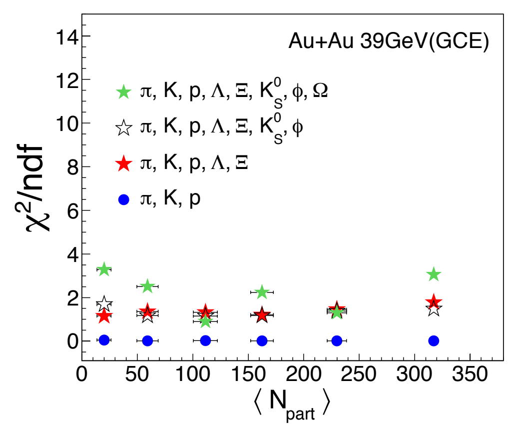
Chemical Freeze-out: Particle Species











- **THERMUS**
- **Grand Canonical Ensemble**
- Particles

  set1: **π, K, p, Λ , Ξ**

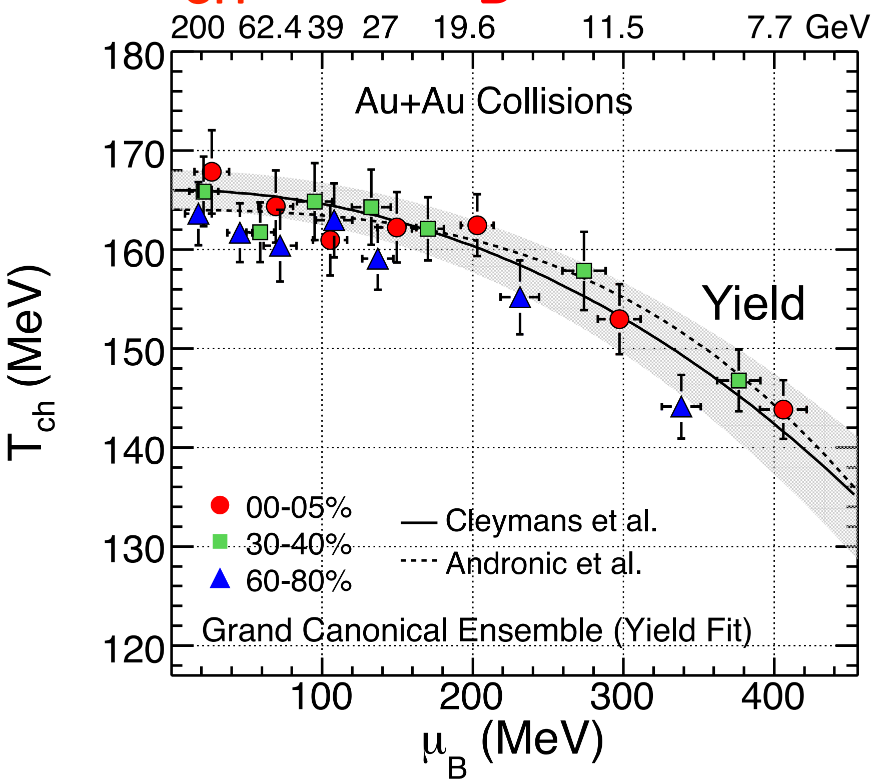
  set2: **π, K, p, Λ , Ξ , Φ, Ω**

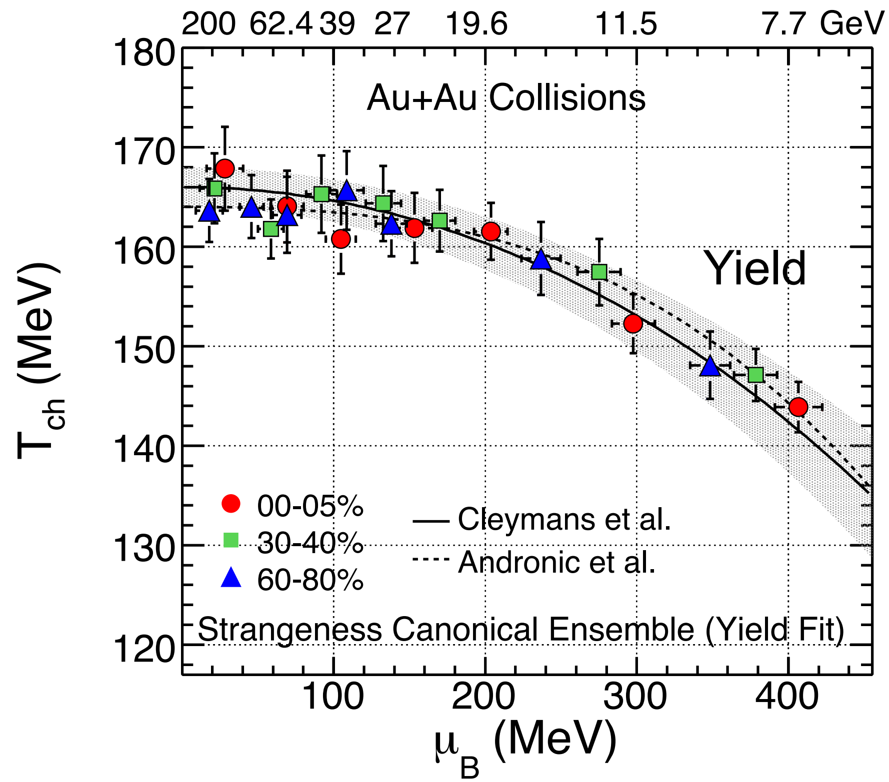
  set3: **π, K, p**

Role of strange hadrons important

Data: STAR preliminary QM2014

T_{ch} vs. μ_B (GCE&SCE: Yields and Ratio)

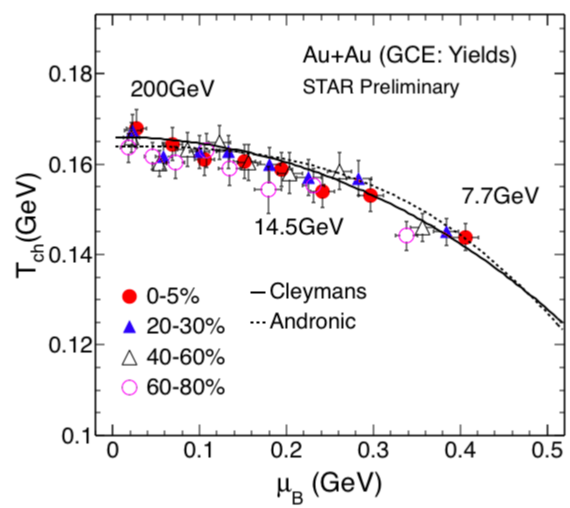




- ✓ Energies: **7.7, 11.5, 19.6, 27,39, 62.4, 200 GeV**
- ✓ Particles used : π, **K, p,** Λ , Ξ
- ✓ Ensemble used: **Grand Canonical**
- ✓ Fit parameters: T_{ch}, μ_B, μ_s and γ_S

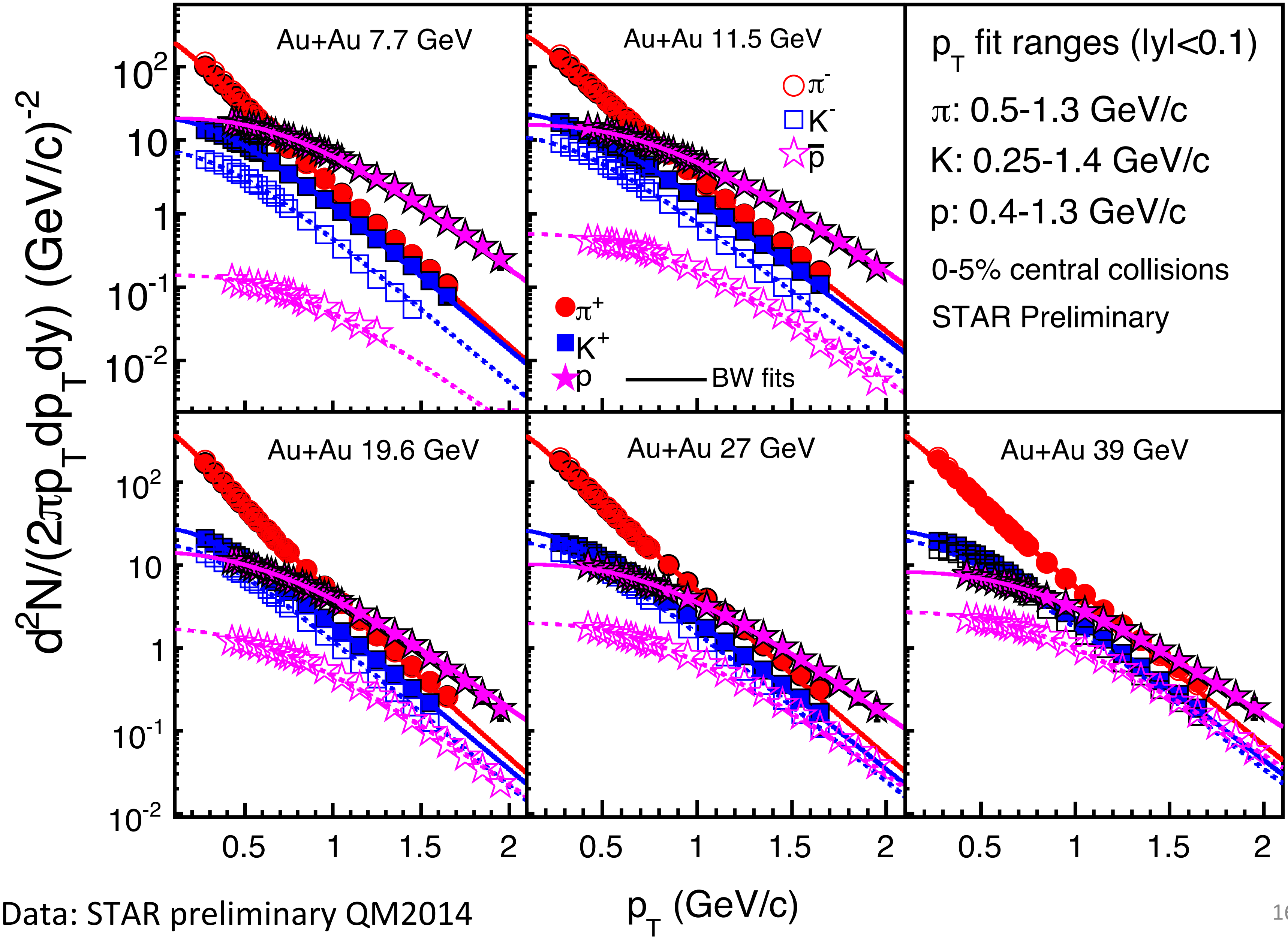
Protons and anti-protons are inclusive

T_{Ch} : 145 MeV – 165 MeV
μ_B : 415 MeV - 20 MeV



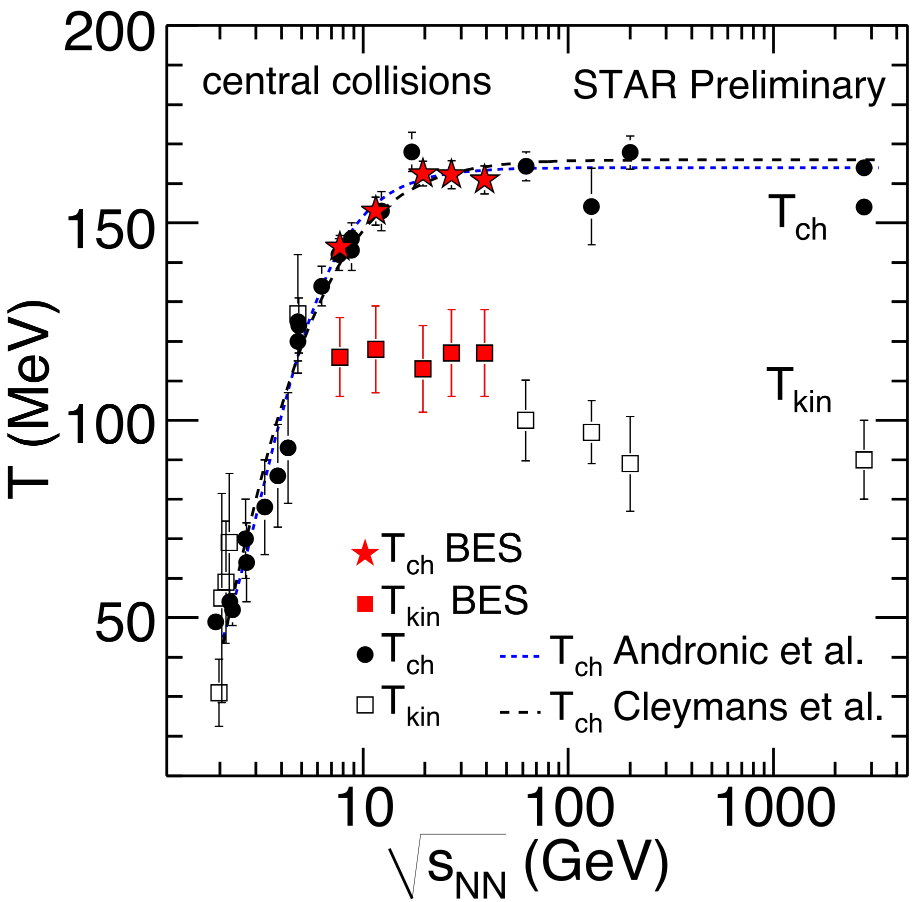
Data:
STAR QM2015

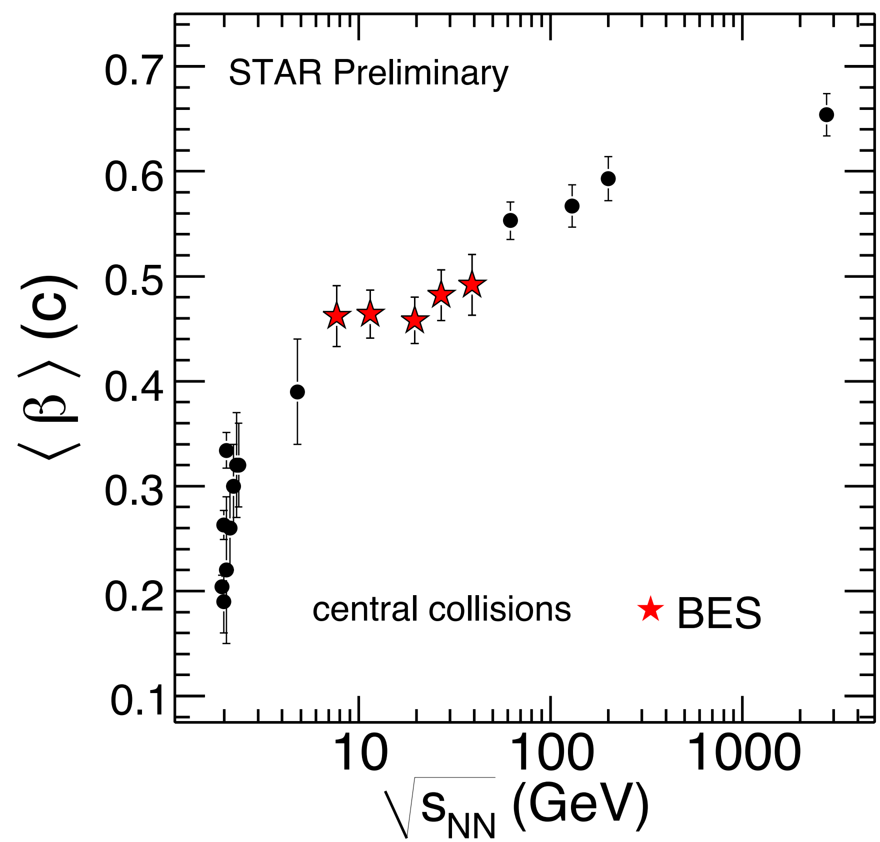
Kinetic Freeze-out (Blast-Wave Model fits)



Data: STAR preliminary QM2014

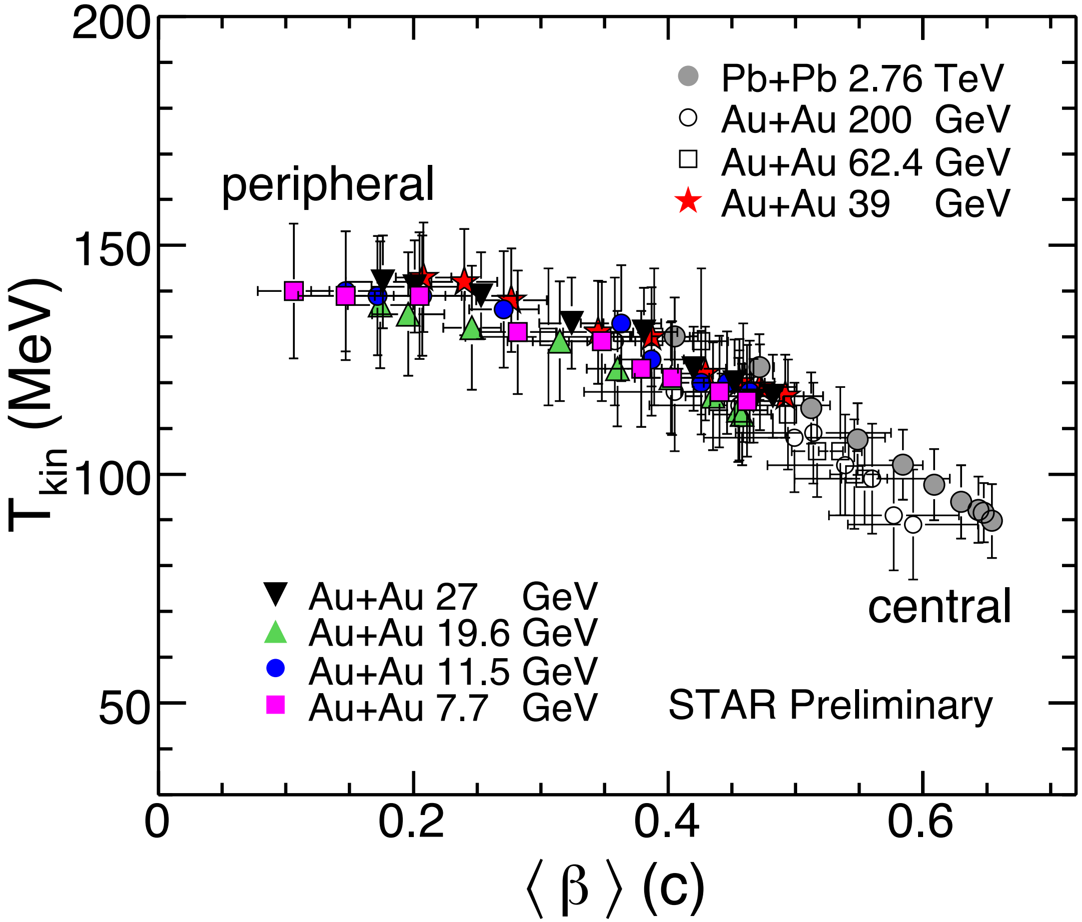
Kinetic Freeze-out Parameters



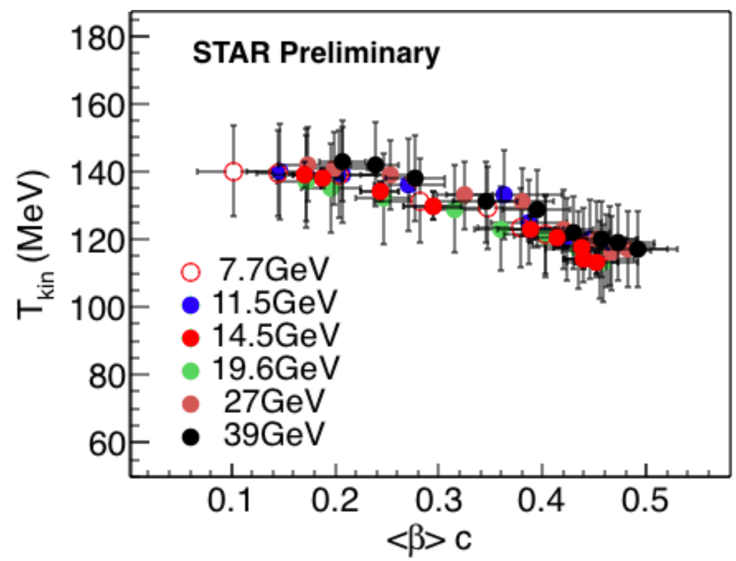


- The separation between T_{ch} and T_{kin} increases with increasing energy.
- The expansion velocity is observed to be constant around 7.7 and 19.6 GeV.

Kinetic Freeze-out Parameters Correlation

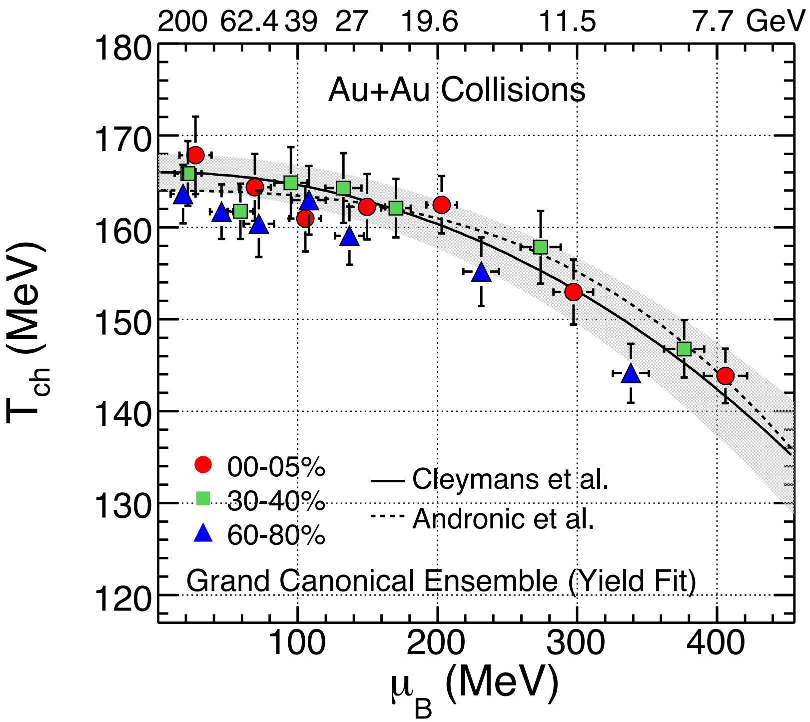


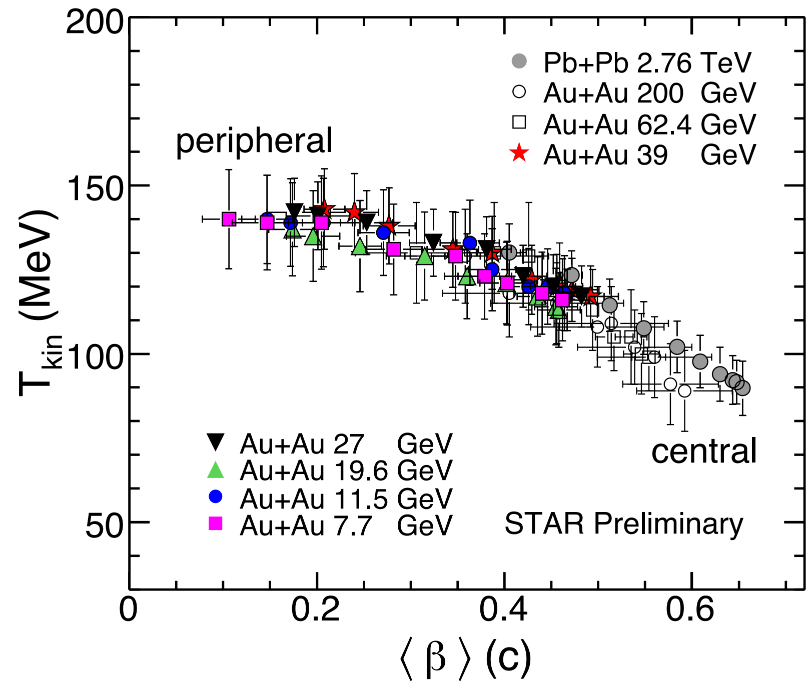
STAR: QM2015



Anti-Correlation observed.
Central collisions: larger collectivity and smaller de-coupling temperature.
Peripehral collisions: smaller collectivity and larger de-coupling temperature.

Freeze-out Results Summary





Chemical Freeze-out: (GCE)

- Central collisions
- BES-I:

$20 < \mu_B < 420$ MeV

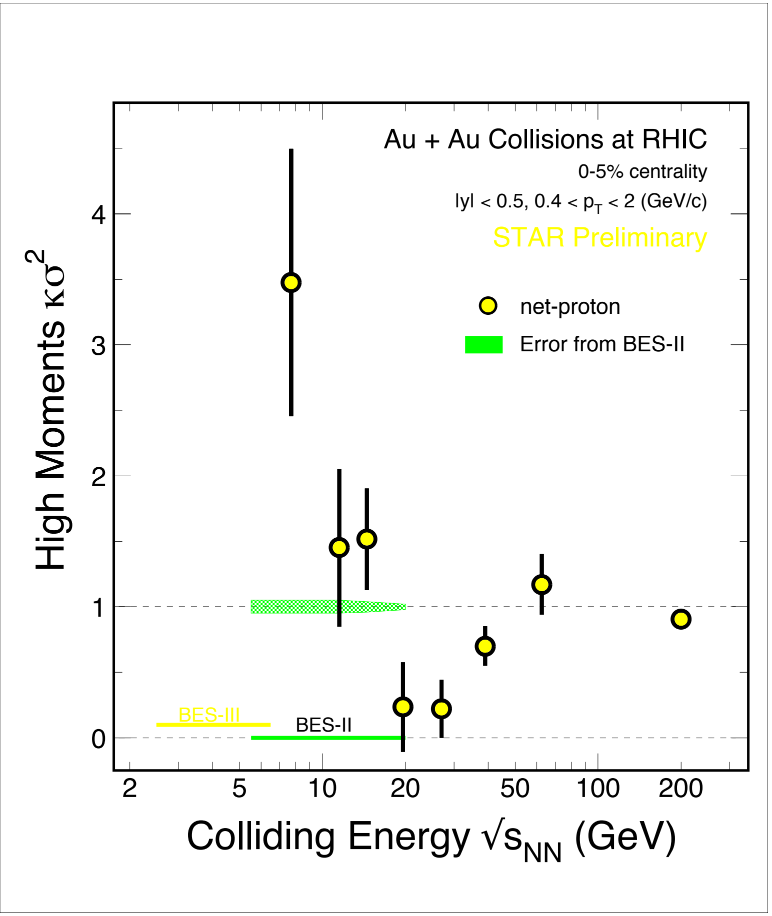
T_{ch} variation is small

Kinetic Freeze-out:

- Central collisions: lower value of T_{kin} and larger collectivity β
- Stronger collectivity at higher energy

BES program allows for exploring the interesting part of (μ_B : 20 – 420 MeV) the QCD phase diagram.

Some issues we can try to address



1. Can one claim existence of CP region in QCD Phase Diagram ?

***1(a) If Yes:** What representation of results is required ?*

***1(b) If No:** What additional checks and measurements needed from experiment ?*
What theoretical results needs to be obtained or compared with ?

2. **Should we study C_6 at higher energies ?**

3. Can experiment and theory colleagues together jointly get the physics conclusion out for this result ?

Experimentally look at next set of Observables (till BES-II)

Mixed Cumulants

$$\chi^n_{xy} = \frac{d^{n+m}[P(T,\mu)/T^4]}{d(\mu_x/T)^n d(\mu_y/T)^m}$$

Correlations between Baryon number and Strangeness number .....

Observables for CP:

$\kappa_{3p}\kappa_{2\pi}^{3/2}/\kappa_{3\pi}\kappa_{2p}^{3/2}$
$\kappa_{4p}\kappa_{2\pi}^{2}/\kappa_{4\pi}\kappa_{2p}^{2}$
$\kappa_{4p}^{3}\kappa_{3\pi}^{4}/\kappa_{4\pi}^{3}\kappa_{3p}^{4}$
$\kappa_{2p2\pi}^{2}/\kappa_{4\pi}\kappa_{4p}$
$\kappa_{2p1\pi}^{3}/\kappa_{3p}^{2}\kappa_{3\pi}$

too are parameter-independent. So, the last five ratios in the table have no ξ-dependence, no dependence on the four poorly known parameters, and no n_p-dependence. This means that, after we subtract the Poisson contribution to each of the cumulants involved, we can make a robust prediction for the ratios of the contributions of critical fluctuations. We find that these five ratios are all precisely 1.

Phys. Rev. D 82 (2010) 074008