Chemical and Kinetic Freeze-out Condition From Heavy-ion Collisions at STAR at RHIC

Lokesh Kumar
Panjab University Chandigarh

(for the STAR Collaboration)

Workshop on the QCD Phase Structure at High Baryon Density Region

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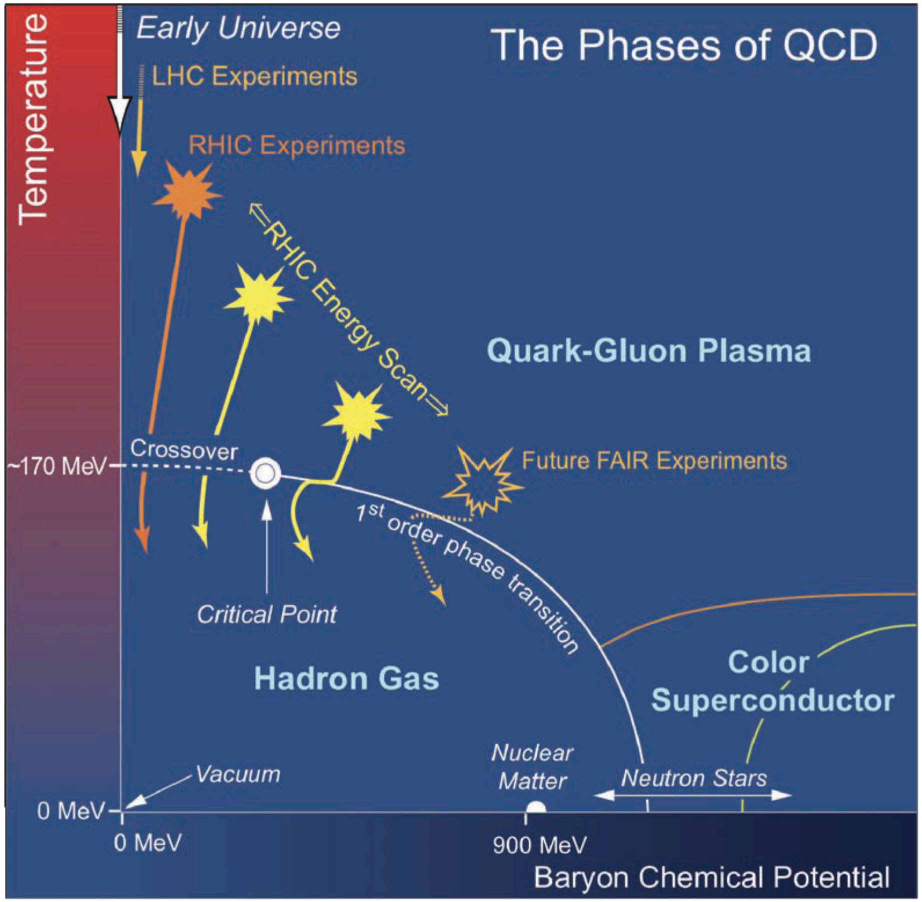
Outline

- Introduction & motivation
- Latest results on yields, ratios, and freeze-out at Au+Au 14.5 GeV (STAR: arXiv: 1908.03585 [nucl-ex]) and U+U 193 GeV (Final publication stage)
- Chemical and kinetic freeze-out parameters using data from STAR experiment
- How iTPC upgrade will help in precision measurement of freeze-out parameters?
- Summary

High-Energy Heavy-Ion Collisions (HICs)

The QCD phase diagram -- Phase diagram of strong interactions

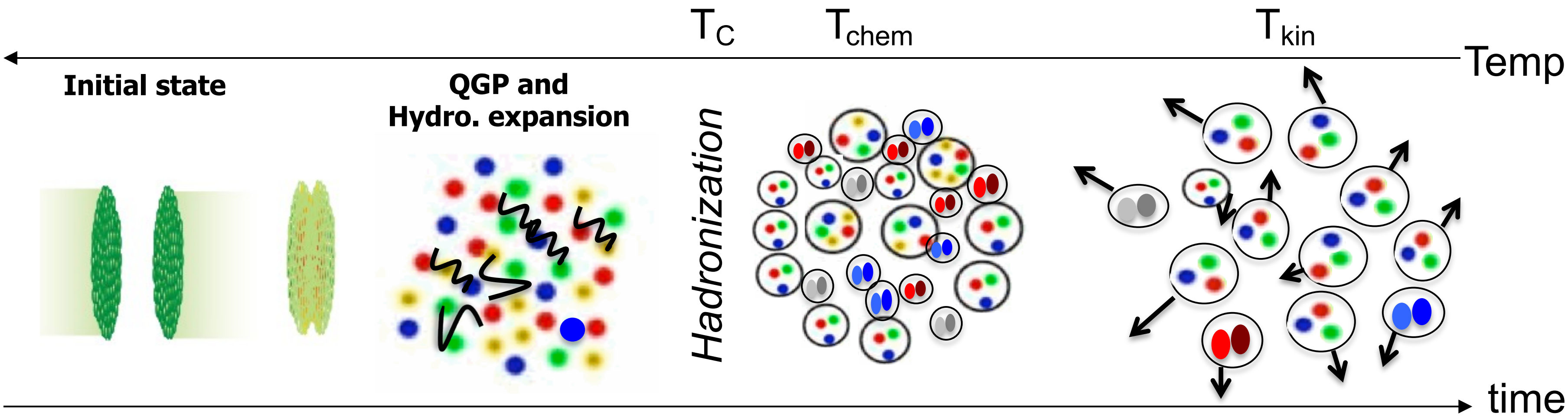


- Understand particle production
- Freeze-out dynamics
- Study QGP properties
- Explore the QCD phase diagram
  -- Search for the signals of phase boundary
  -- Search for the possible QCD Critical Point
  -- Search for the first-order phase transition line

The x and y axes depend on the collision energy of the heavy-ions

Evolution of High-Energy HICs

Time Evolution of Heavy-ion Collisions:



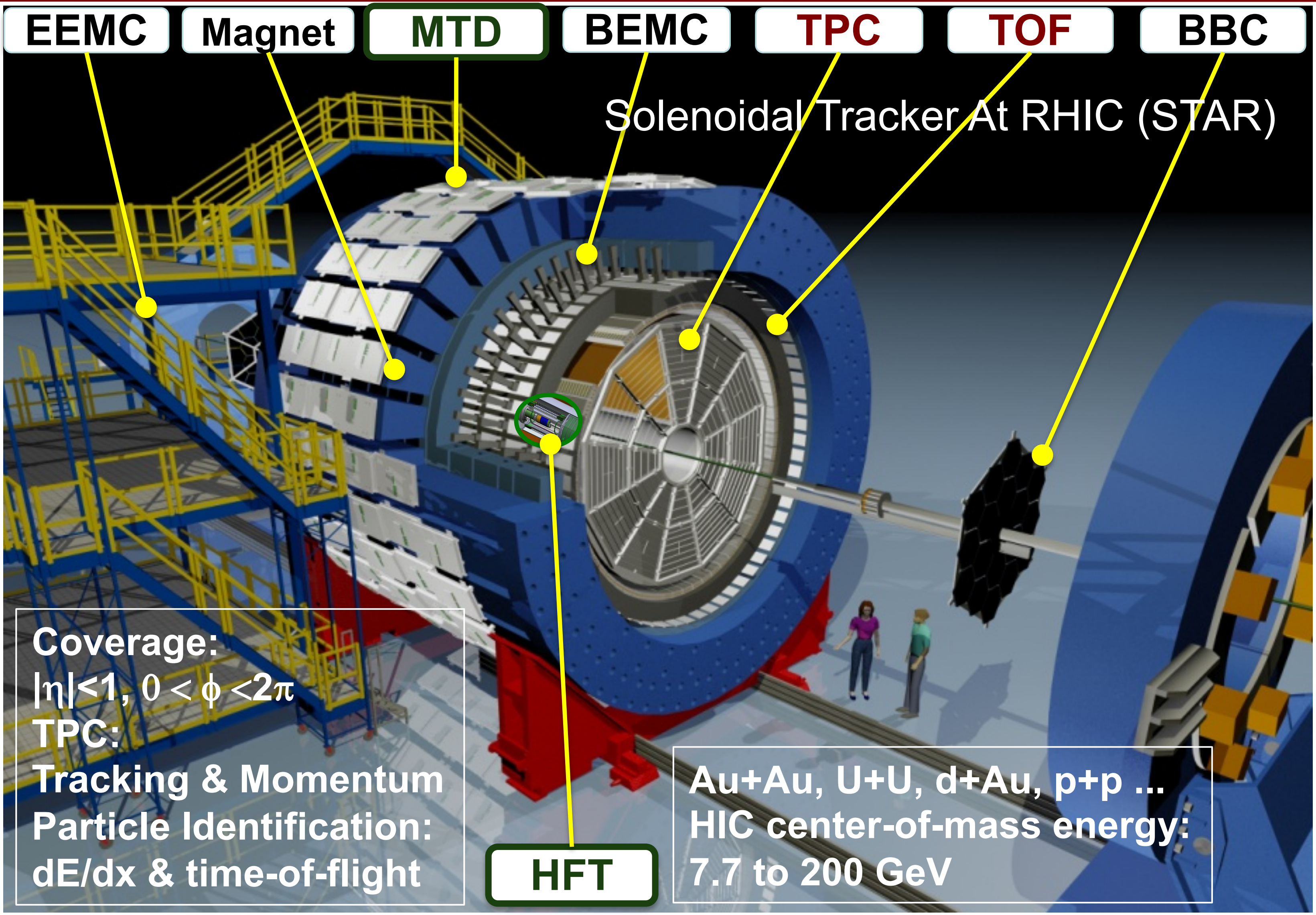
Colliding ions	Deconfined state	Chemical freeze-out	Kinetic freeze-out
		✧ Inelastic collisions cease ✧ Particle yield fixed	✧ Elastic collisions cease ✧ Spectral shape fixed

Freeze-out (FO) parameters:

- Statistical thermal model: T_{ch} and μ_B
- Blast-wave model: T_{kin} and $<\beta>$

Particle Yields and **Ratios:** provide Information about QCD phase diagram

The STAR Detector



Coverage:
$|\eta|<1$, $0 < \phi < 2\pi$
TPC:
Tracking & Momentum
Particle Identification:
dE/dx & time-of-flight

Au+Au, U+U, d+Au, p+p ...
HIC center-of-mass energy:
7.7 to 200 GeV

Particle Identification

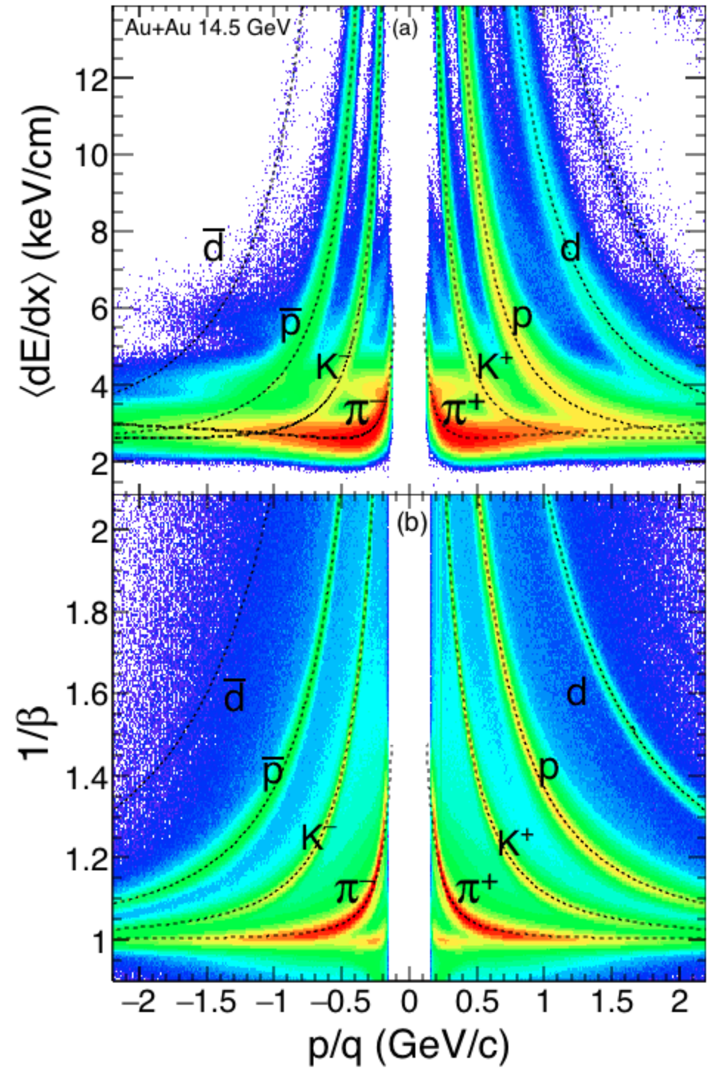
Charged particles [π, K, p, and light (anti) nuclei] identified via --

(a) Ionization energy loss:
- $< dE/dx > \sim A / \beta^2 = A (1 + \mathbf{m^2} / p^2)$

(b) Time-of-flight:
- $< \tau > = L / \beta = L (1 + \mathbf{m^2} / p^2)^{1/2}$

Momentum $p = \gamma \beta m$

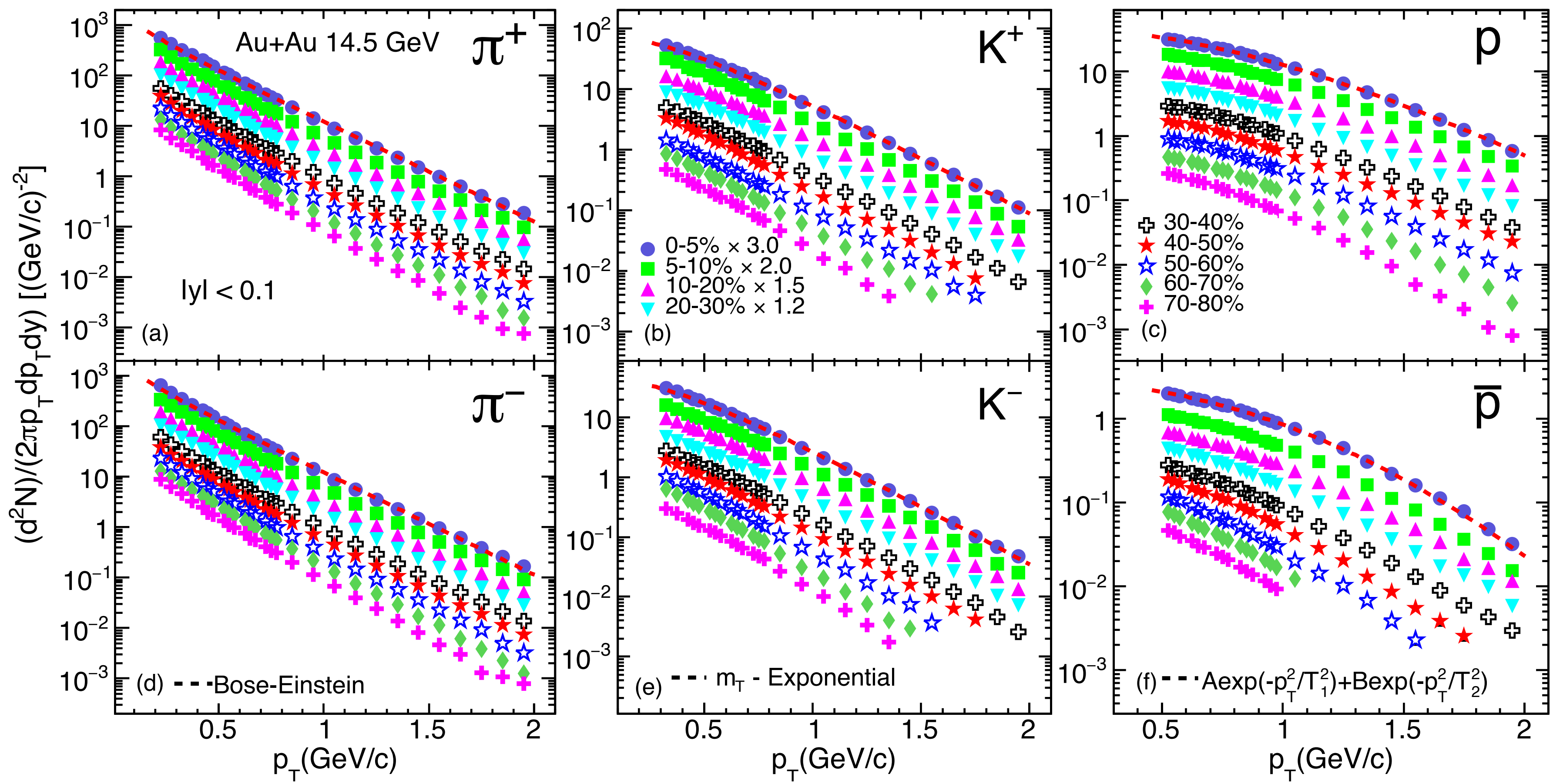
Strange particles (Λ, K0s, Ξ, Ω,….)
Resonances (K*, ϕ, ρ…..)
Heavy-flavor (Ds,Bs,J/Ψ,Υ…...)
…
through --
(c) decay kinematics/ invariant mass



Transverse Momentum Distribution

Au+Au @ 14.5 GeV

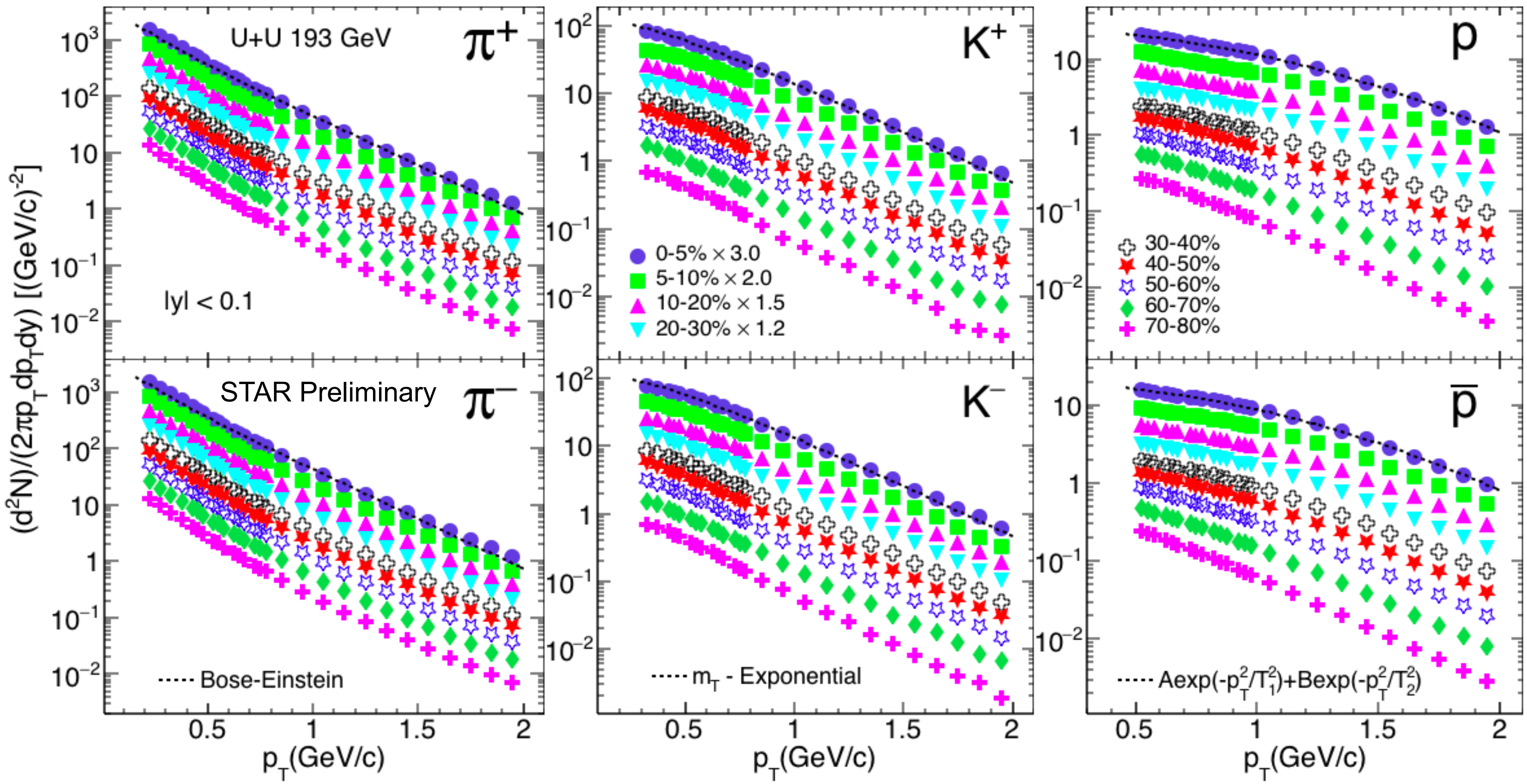
STAR: arXiv: 1908.03585 [nucl-ex]



Integrating over full p_T range gives particle yield (dN/dy)

Transverse Momentum Distribution

U+U @ 193 GeV



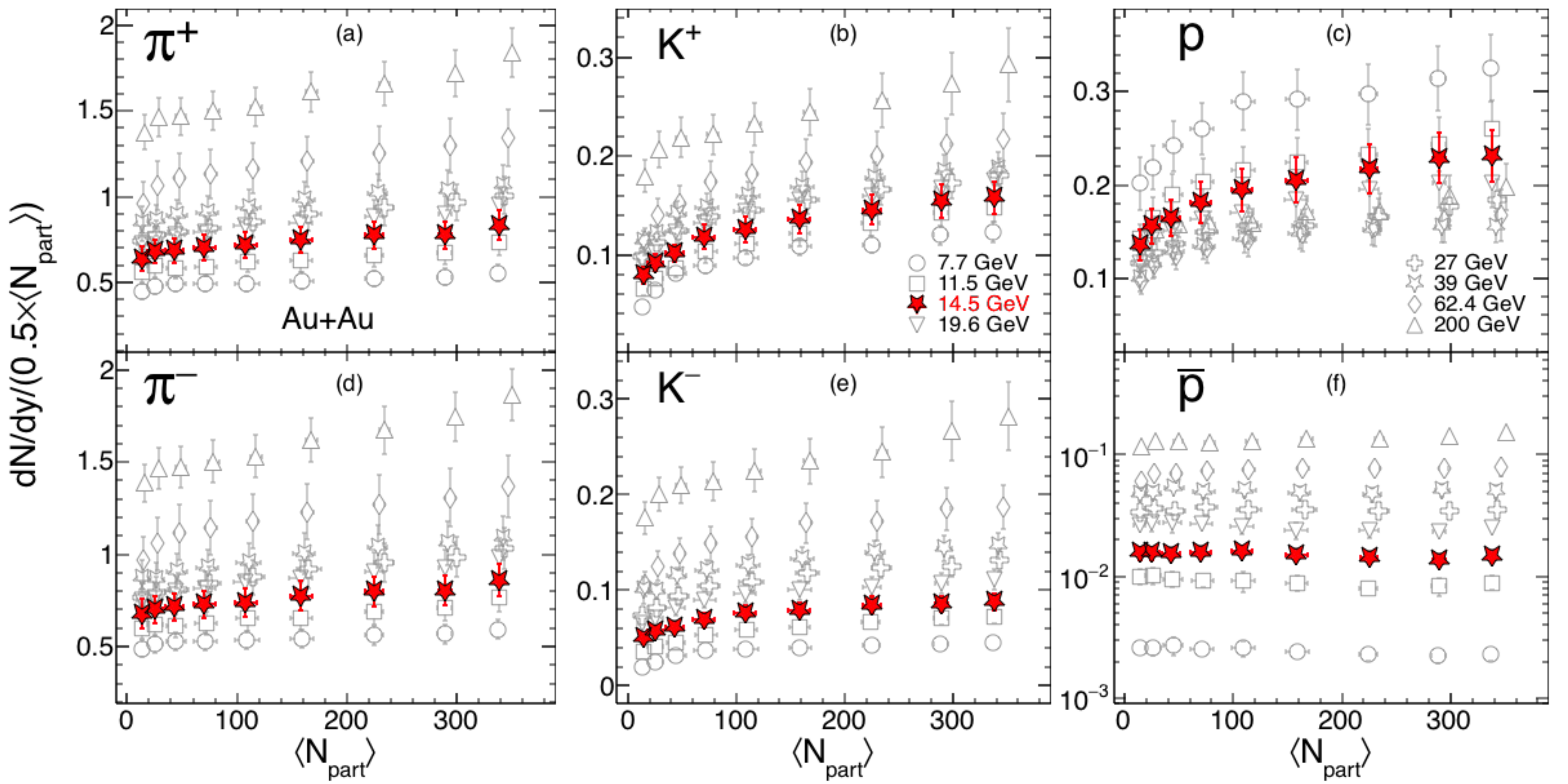
Integrating over full p_T range gives particle yield (dN/dy)

Particle Yields

STAR: PRC **96**, 044904 (2017)

Au+Au @ 14.5 GeV

STAR: arXiv: 1908.03585 [nucl-ex]

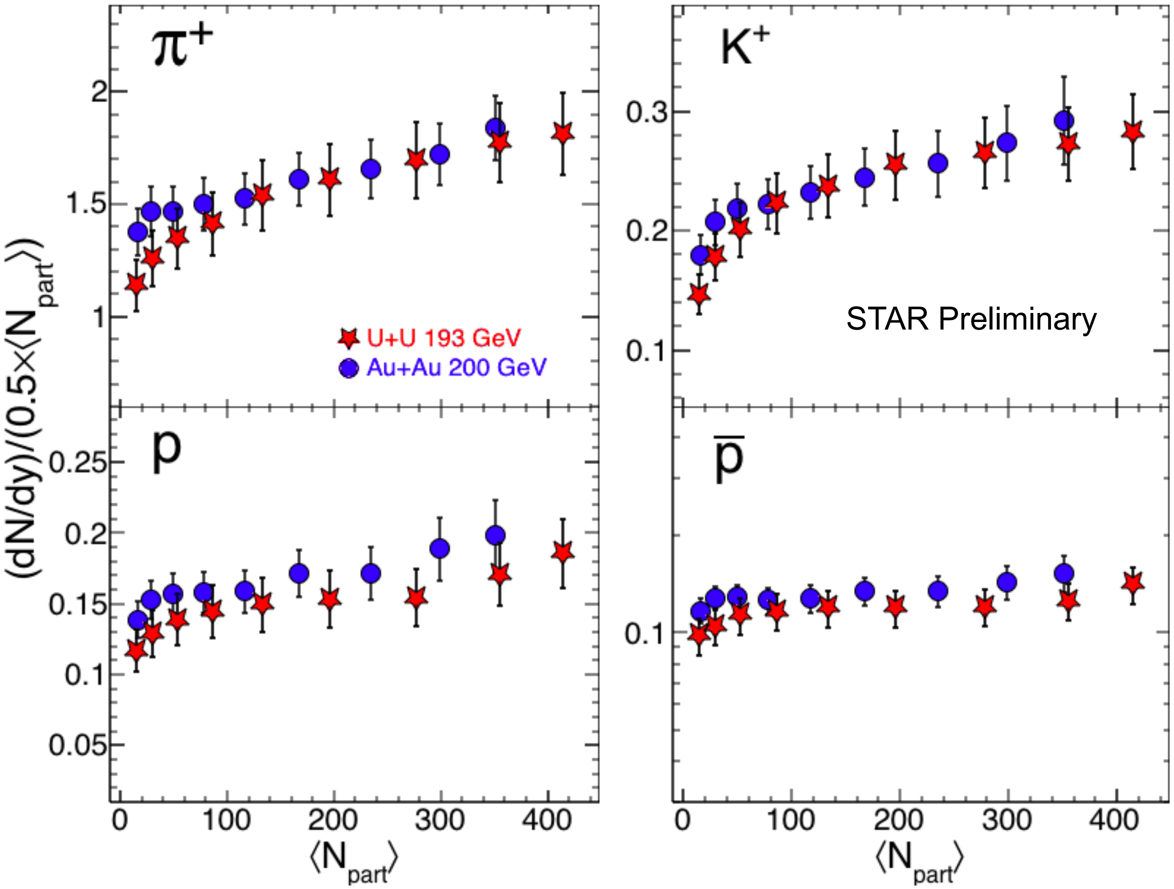


Yields @ 14.5 GeV:

-- Increase from peripheral to central collisions (except for $\bar{p}$)

-- Fall in the energy dependence trend

Particle Yields

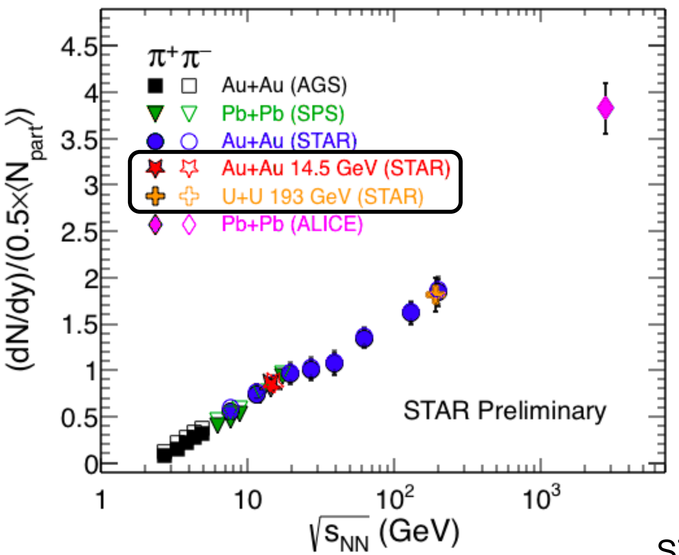


U+U @ 193 GeV

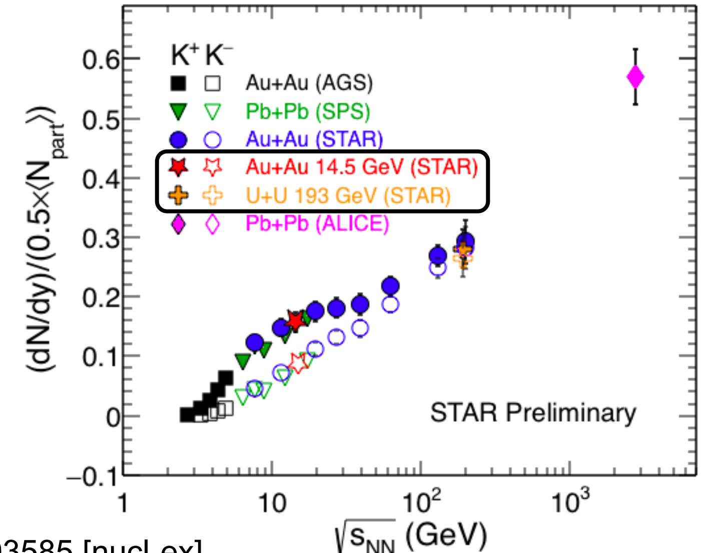
- Yields are mostly consistent with Au+Au 200 GeV at similar N_{part} within systematic uncertainties
- Centrality dependence is extended beyond $N_{part} > 400$

- Yields increase from peripheral to central collisions

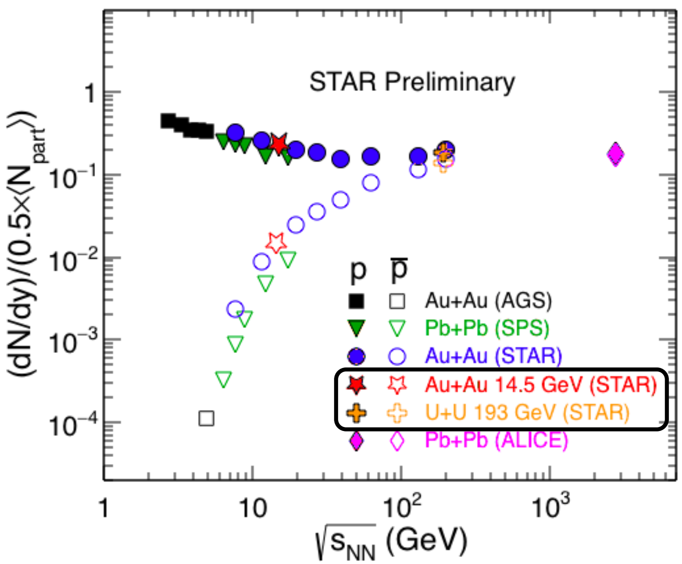
Energy Dependence: Yields



STAR: PRC **96**, 044904 (2017)



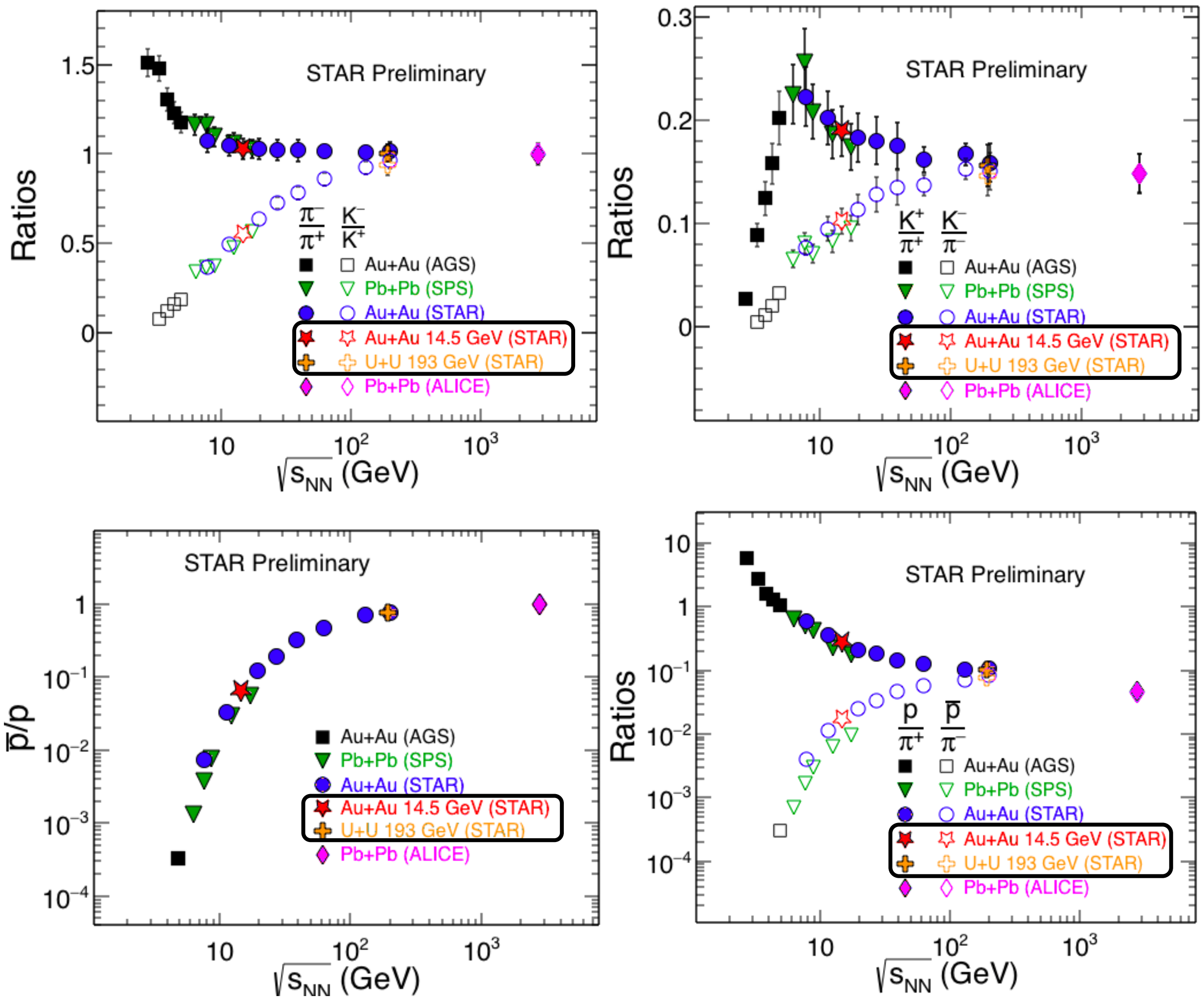
STAR: arXiv:1908.03585 [nucl-ex]



- Yields increase as a function of collision energy except for protons
- *Au+Au 14.5 GeV and U+U 193 GeV fit well in the trend*
- **Higher energies:** Similar (pair) production of particle and anti-particle

Lower energies: $\pi^- > \pi^+$, $K^+ > K^-$, $p > \bar{p}$

Energy Dependence: Ratios



STAR: PRC **96**, 044904 (2017) STAR: arXiv: 1908.03585 [nucl-ex]

- Ratios show interesting trends for energy dependence
- *Au+Au 14.5 GeV and U+U 193 GeV fit well in the trend*
- **Higher energies:** Similar (pair) production of particle and antiparticle

Lower energies:

$\pi^- > \pi^+$, $K^+ > K^-$, $p > \bar{p}$

Chemical Freeze-out

Inelastic collisions among the particles cease; the particle yields and ratios gets fixed

Statistical thermal model: J. Cleymans et al., Comp. Phys. Comm. **180**, 84 (2009)

$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu} = \frac{VTm_i^2 g_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm1)^{k+1}}{k}\left(e^{\beta k\mu_i}\right)K_2\left(\frac{km_i}{T}\right)$$

(Grand canonical ensemble)

$\beta \cong 1/T$; -1(+1) for fermions (bosons),
Z - partition function;
m_i - mass of hadron species i;

V - volume; T - Temperature;
K_2 - 2^{nd}-order Bessel function;
g_i - degeneracy; μ_i - chemical potential

Model Features: Assumes
- ❑ Non-interacting hadrons and resonances
- ❑ Thermodynamically equilibrium system

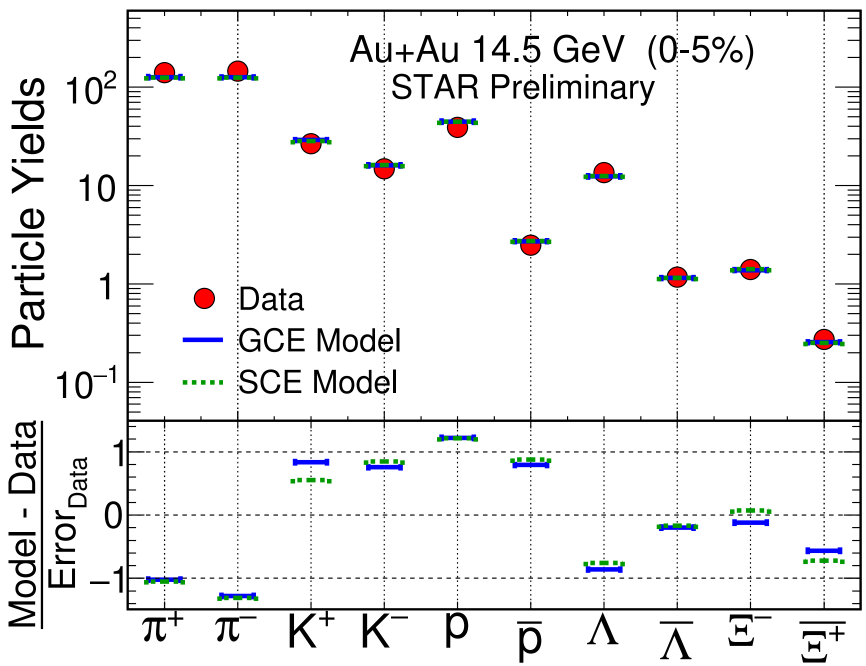
Experimental particle yields or ratios are input to the thermal model to extract the freeze-out parameters, mainly, T_{ch} and μ_B

Thermal Model Fits

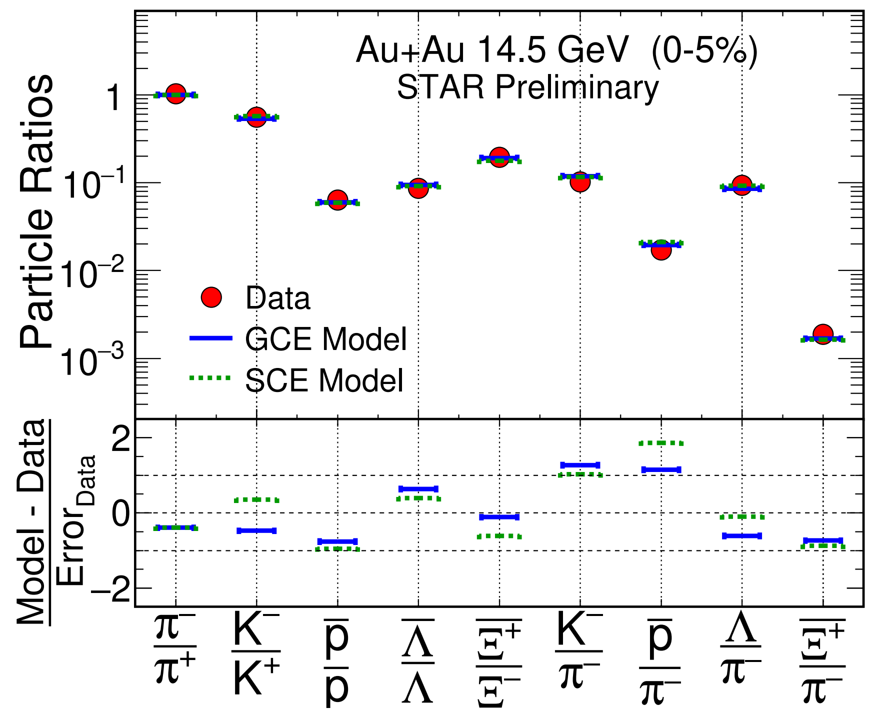
Au+Au @ 14.5 GeV

D. Mishra (STAR Collaboration)
Nucl. Phys. A 956, 292 (2016)

Thermal model fit: Grand Canonical / Strangeness Canonical Ensemble using Yield and Ratios Fits



STAR: arXiv: 1908.03585 [nucl-ex]



- Good description by statistical thermal model
- Results are consistent between different studied cases

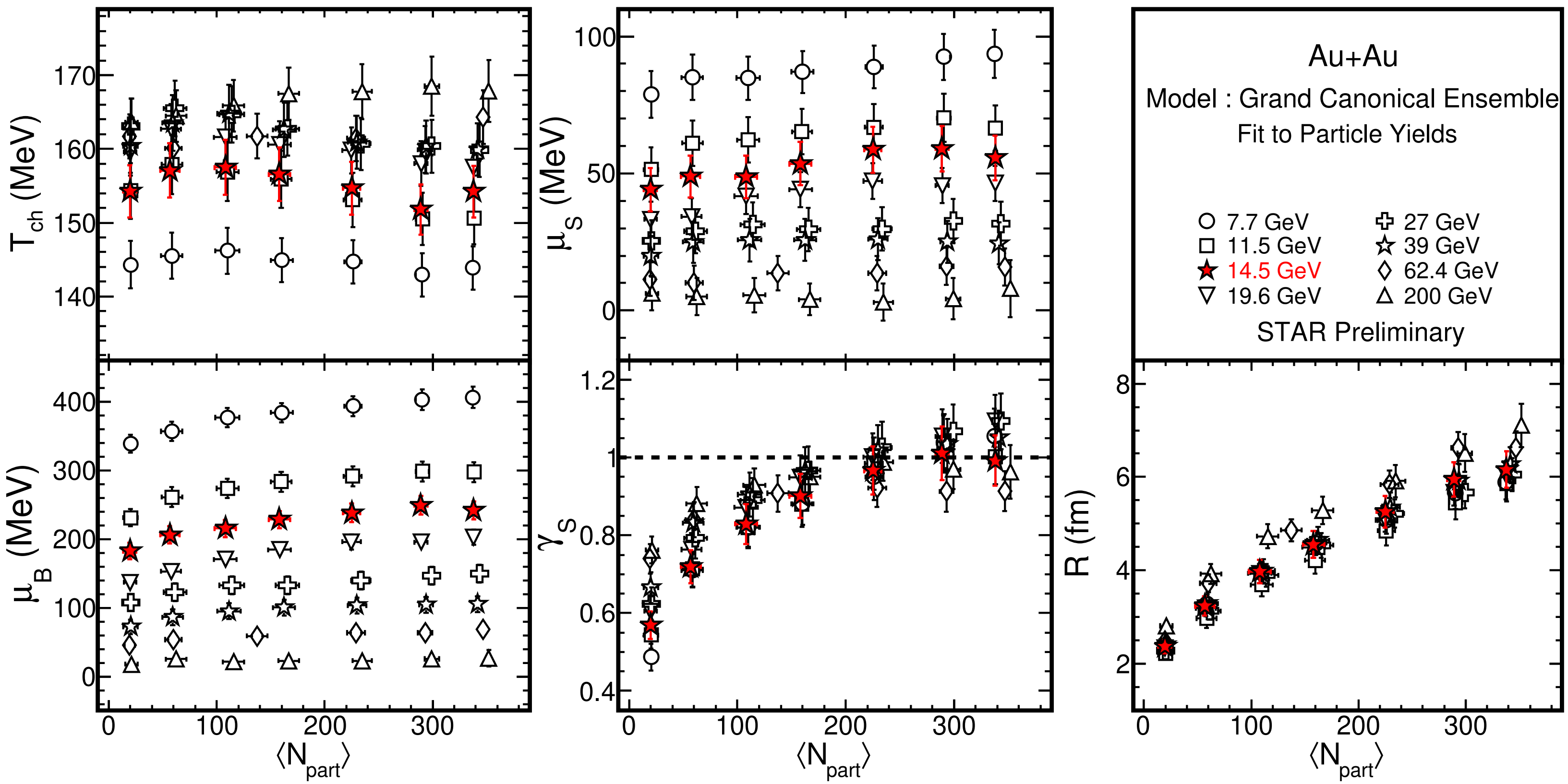
CFO Parameters

STAR: PRC **96**, 044904 (2017)

Au+Au @ 14.5 GeV

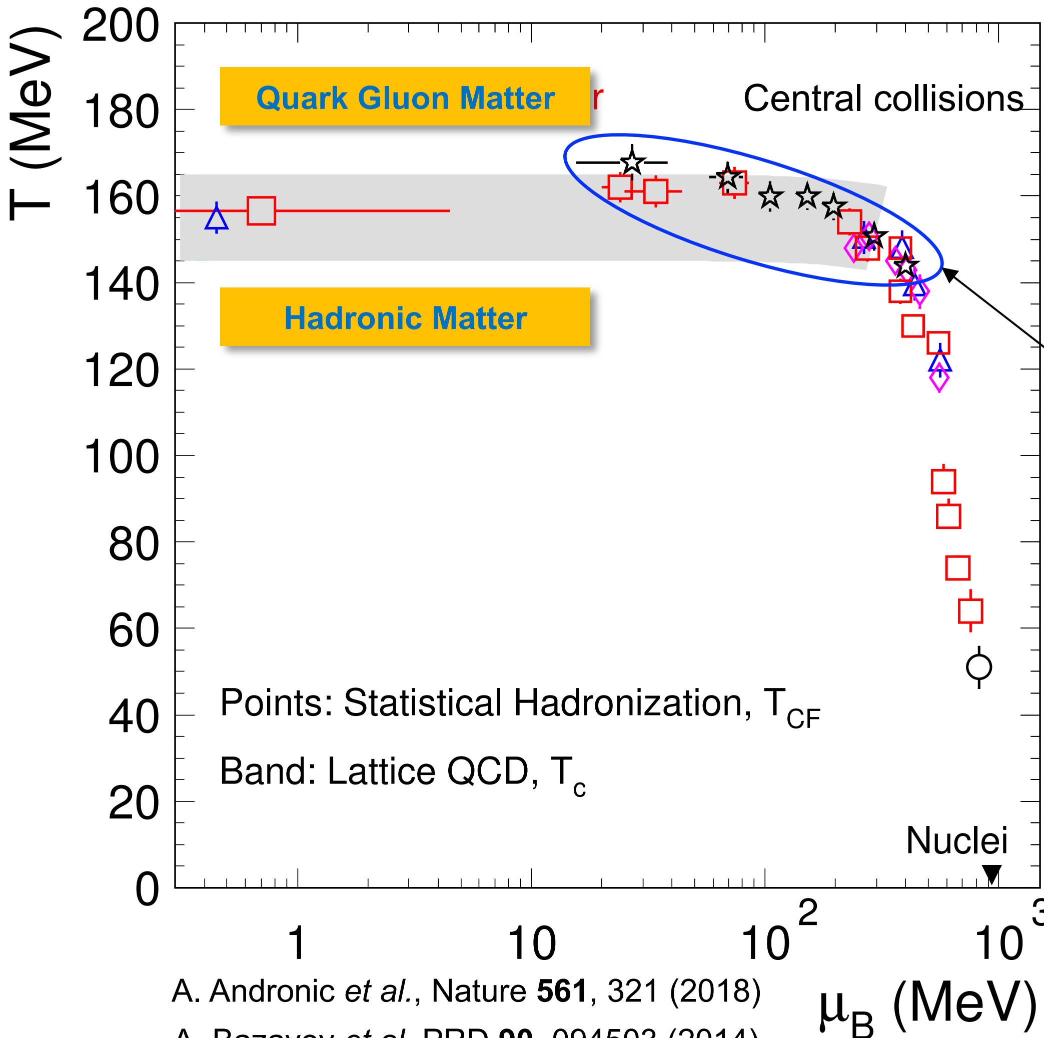
D. Mishra (STAR Collaboration)
Nucl. Phys. A 956, 292 (2016)

Thermal model fit: Grand Canonical Ensemble using yield fits



14.5 GeV CFO parameters follow energy dependence trend

CFO Results – Comparison with T_C



A. Andronic *et al.*, Nature **561**, 321 (2018)
A. Bazavov *et al.* PRD **90**, 094503 (2014)
S. Borsanyi *et al.* JHEP **1208**, 053 (2012)

- The experimentally measured phase diagram
- These points constitute the freeze-out curve
- ***STAR results cover a large range of μ_B***
- CFO parameters from thermal model are consistent with recent lattice calculations of T_c
  -- *Transition temperature is close to freeze-out temperature?*

CFO Results Using Models

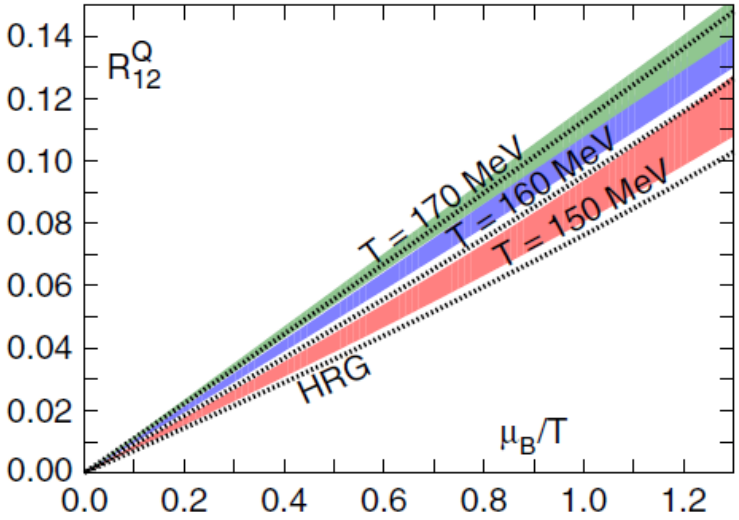
Relation of Lattice QCD observables with experimental observables:

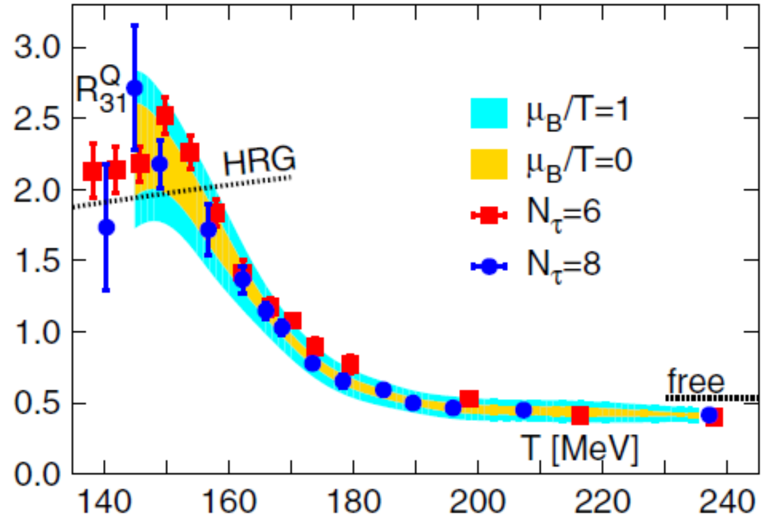
The volume-independent ratios of susceptibilities from lattice QCD are related to the moments of conserved quantities from the experiment ---

$$R_{12} = \frac{\chi_1}{\chi_2} = \frac{\mu}{\sigma^2}$$

A. Bazavov *et al.* Phys. Rev. Lett. 109, 192302 (2012)

$$R_{31} = \frac{\chi_3}{\chi_1} = \frac{S\sigma^3}{\mu}$$





Using R_{12} and R_{31} at a given experimental energy, allows to extract freeze-out parameters – T_{ch} and μ_B

CFO Results Using Models

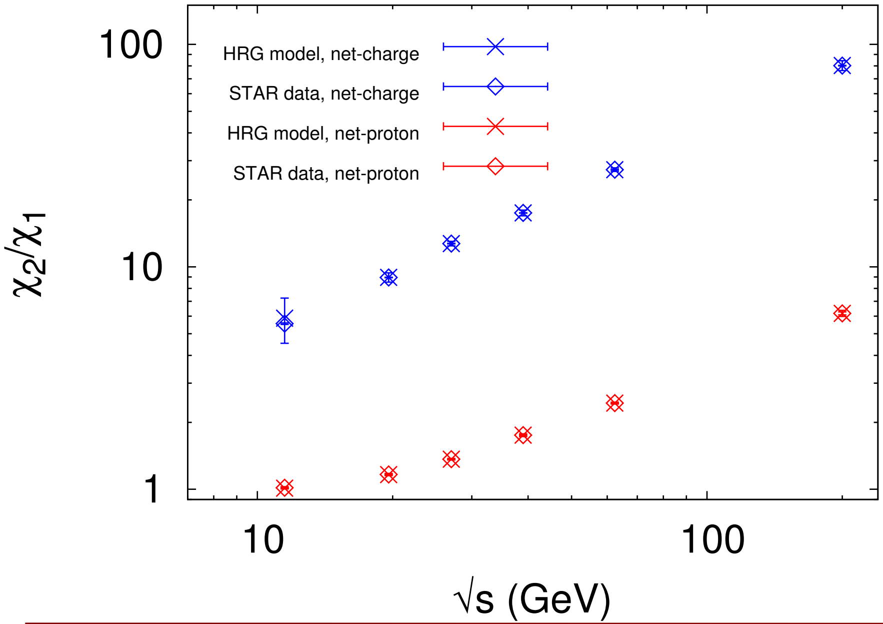
Limitations:

- Experimental kinematic acceptance cannot be taken into account
- Available only for small chemical potentials.

Hadron Resonance Gas (HRG):

- Can be used with similar experimental kinematic acceptance to calculate fluctuation observables
- Allows to expand the range of μ_B

P. Alba *et al.*, Phys. Lett. B738 305, (2014)



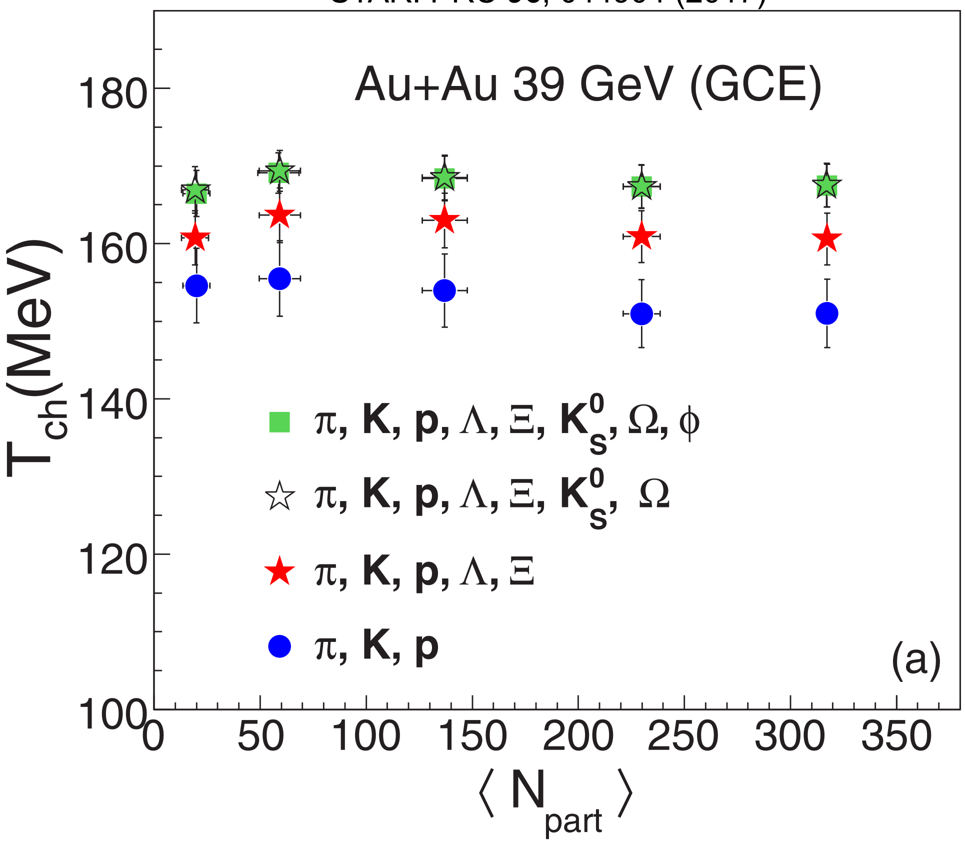
- Model results agree with experimental ratios
- Isospin randomization issue below 11.5 GeV.
- Extracted FO parameters depend on the hadron spectrum included in HRG

S. Chatterjee *et al.* Phys. Rev. C 96, 054907 (2017)

CFO Results – Particle Dependence

Freeze-out parameters dependence on the particle type:

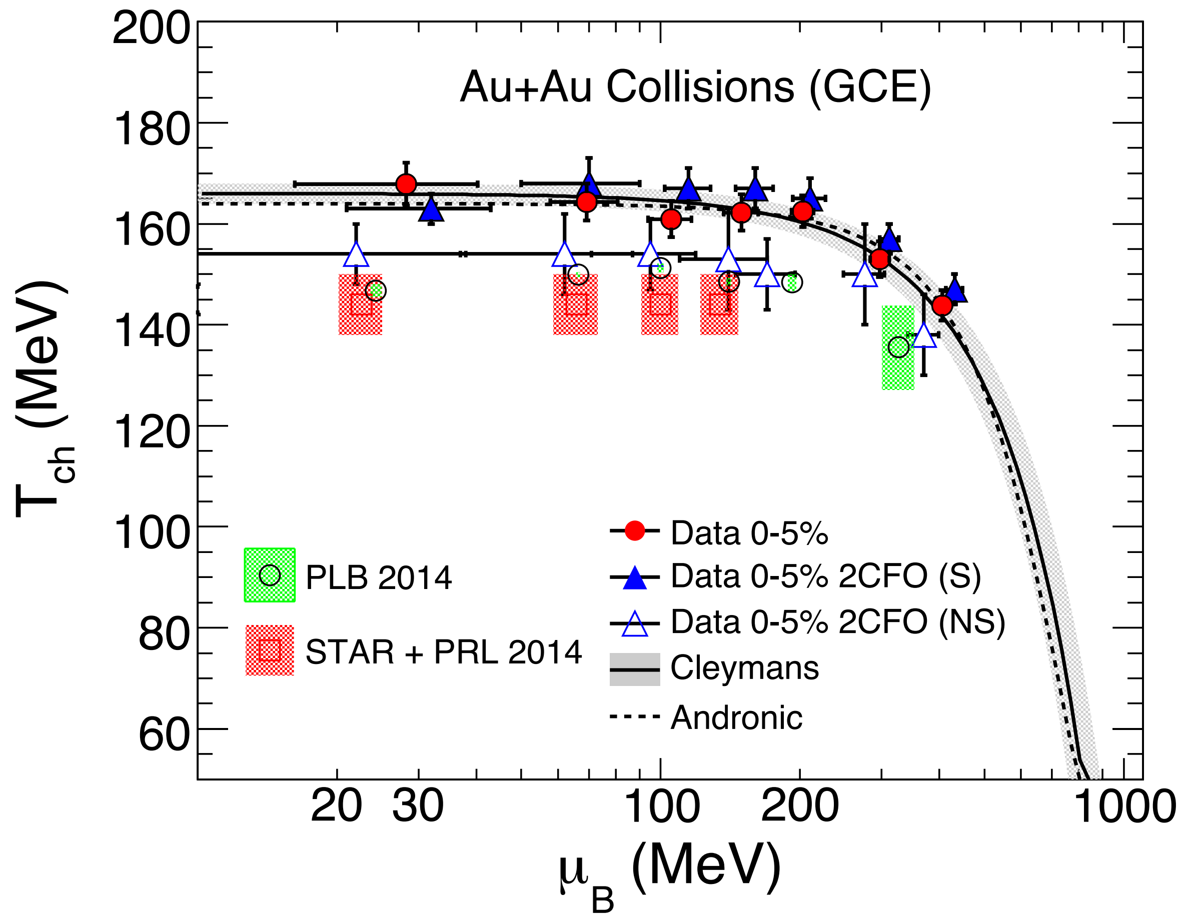
STAR: PRC **96**, 044904 (2017)



- The FO parameters depend on the particle yields fitted in the statistical thermal model
- Strange and non-strange particle yields give different freeze-out temperature
- Massive strange particle yields lead to higher FO temperature

The observation is consistent with 2CFO (separate strange and non-strange) freeze-out models – S. Chatterjee et al. PLB 727, 554 (2013) R. Bellwied et al. PRL 111, 202302 (2013) K. Bugaev et al. EPL 104, 22002 (2013)

Chemical Freeze-out : Summary



Parameterization from Cleymans et al. and Andronic et al. PRC **73**, 034905 (2006) NPA **904**, 543c (2013)

- STAR freeze-out results from THERMUS
  STAR: PRC **96**, 044904 (2017)
- LQCD results obtained by comparing with STAR ratio of susceptibilities
  PRL **113**, 052301 (2014)
- HRG model results from ratio of susceptibilities
  PLB 738, 305 (2014)
- Freeze-out from 2CFO model
  PLB 727, 554 (2013)

Kinetic Freeze-out

Elastic collisions among the particles cease and the momentum distribution gets fixed

Blast-Wave (BW) Model:

$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

E. Schnedermann, J. Sollfrank, and U. W. Heinz, Phys. Rev. C **48**, 2462 (1993).

I_0, K_1: Modified Bessel functions
$\rho(r) = \tanh^{-1}\beta$, r/R: relative radial position; R: radius of fireball
β: transverse radial flow velocity, T_{kin}: Kinetic freeze-out temperature

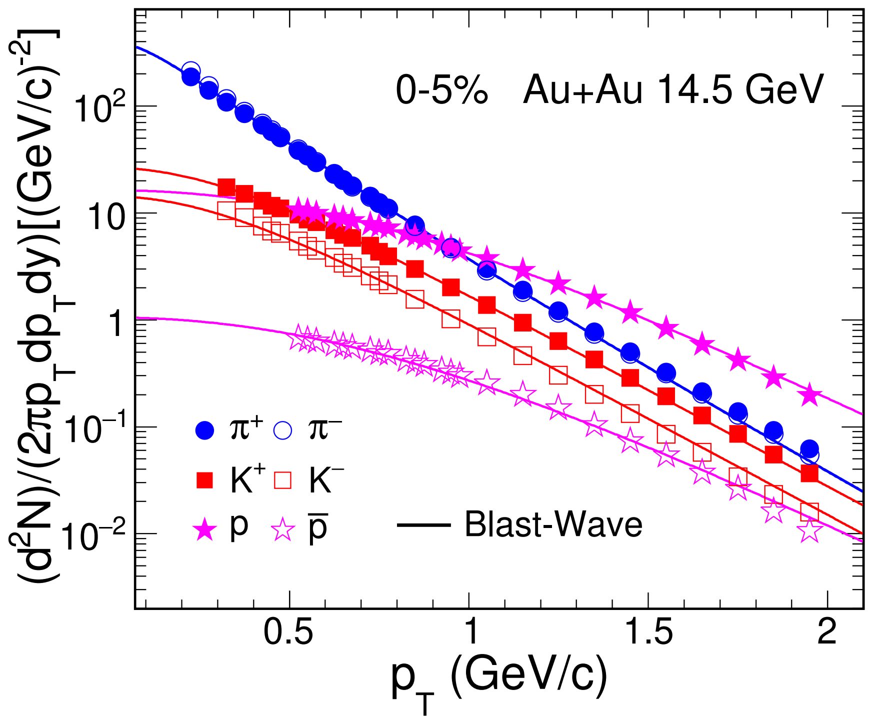
Model Features:

- ❑ Hydrodynamic based model
- ❑ Assumes particles are locally thermal at a kinetic freeze-out temperature and moving with a common radial flow velocity

- ✧ Momentum distributions are fitted simultaneously with BW
- ✧ Two main parameters: T_{kin} and $\langle\beta\rangle$

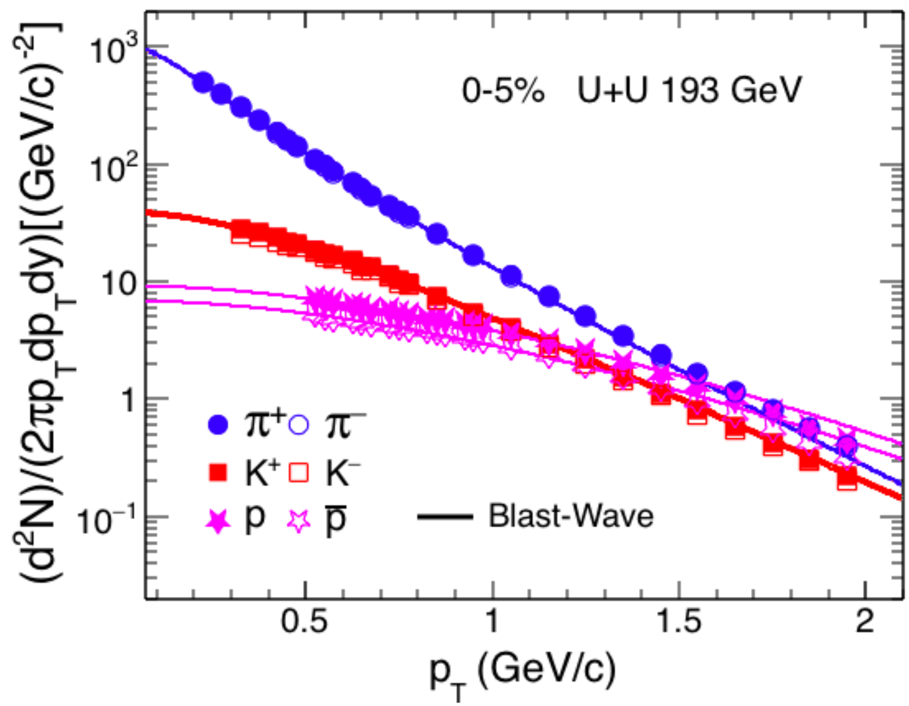
Blast-Wave Fit

Au+Au @ 14.5 GeV



STAR: arXiv: 1908.03585 [nucl-ex]

U+U @ 193 GeV

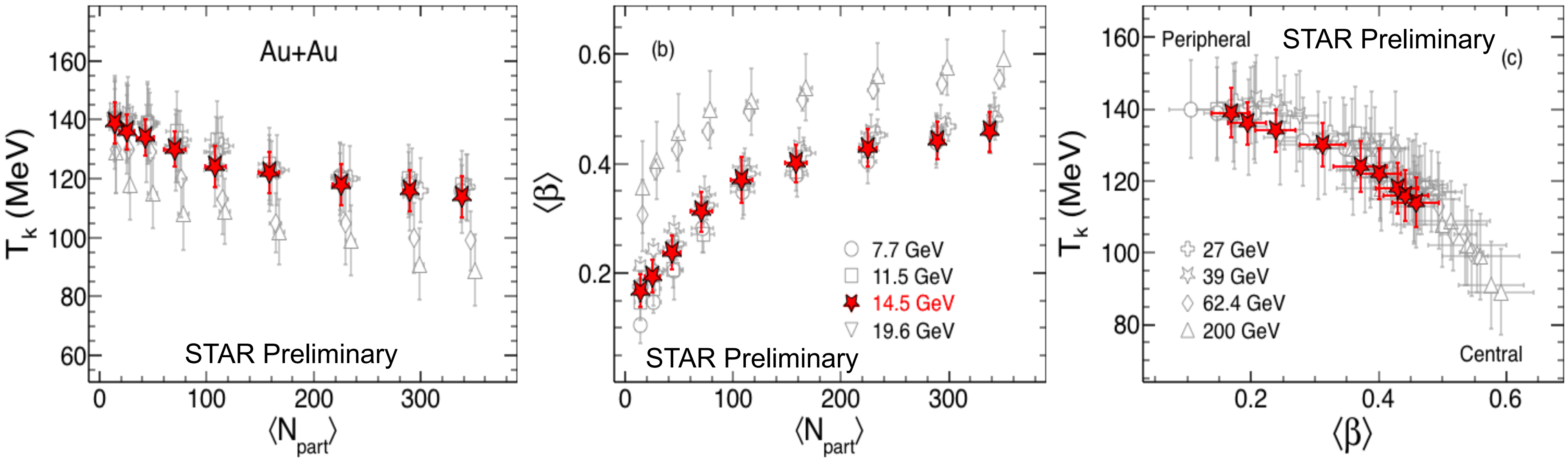


- Blast-wave model well describes the π, K, p spectra simultaneously
- Extracted parameters: T_{kin} and <β>

KFO Parameters

Au+Au @ 14.5 GeV

STAR: PRC **96**, 044904 (2017)
STAR: arXiv: 1908.03585 [nucl-ex]

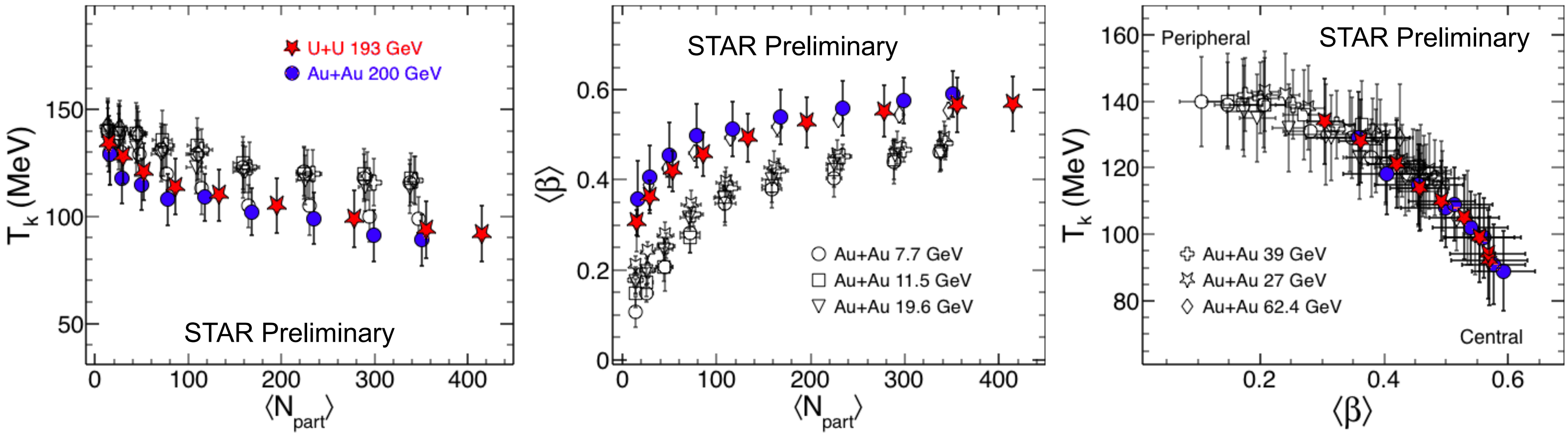


- T_k decreases and β increases from peripheral to central collisions
- Anticorrelation observed between T_k and β
- 14.5 GeV results show similar N_{part} dependence as at other energies

KFO Parameters

U+U @ 193 GeV

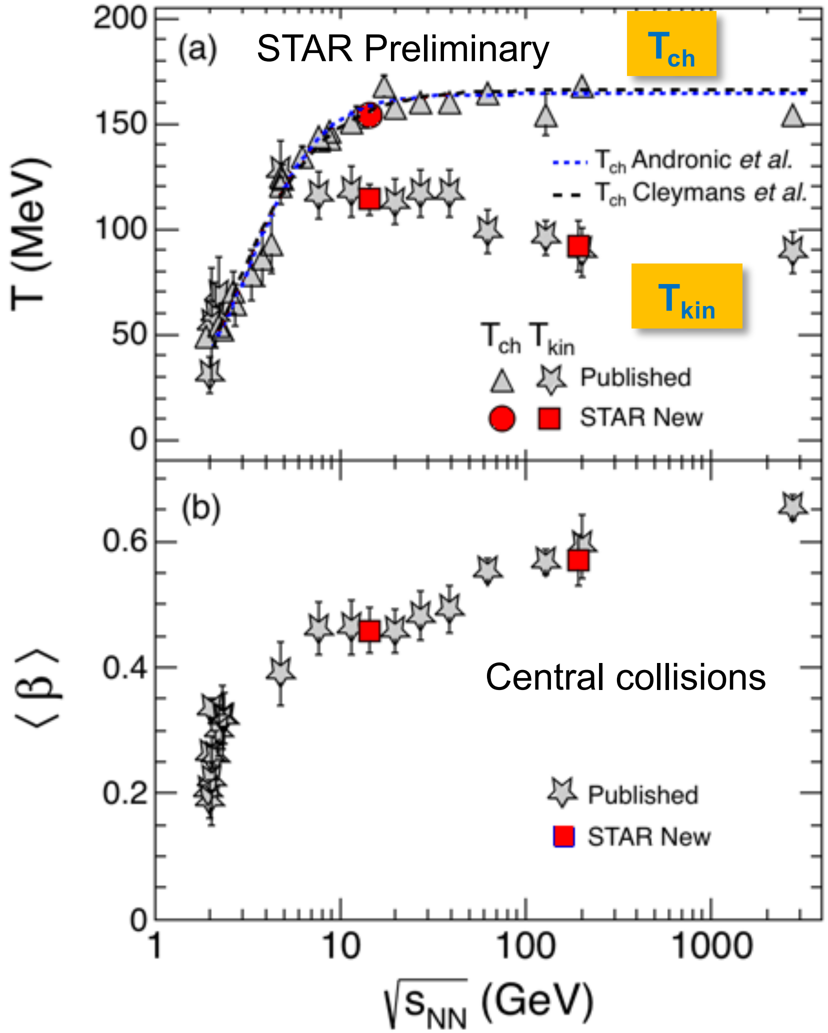
STAR: PRC **96**, 044904 (2017)



- T_k decreases and β increases from peripheral to central collisions
- Anticorrelation observed between T_k and β
- U+U 193 GeV results show similar N_{part} dependence as at other energies and are consistent with 200 GeV
- Centrality dependence is extended beyond N_{part} > 400

Energy Dependence of FO Parameters

STAR: PRC **96**, 044904 (2017)



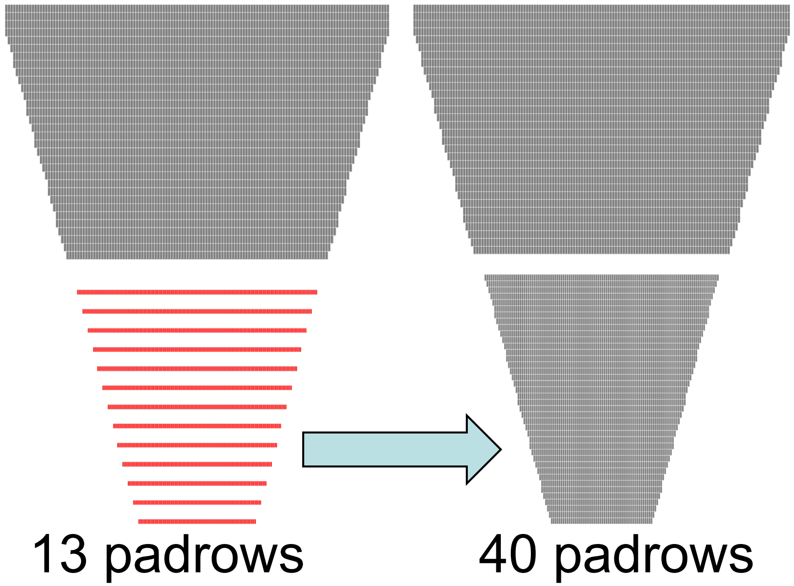
STAR: arXiv: 1908.03585 [nucl-ex]

- Chemical freeze-out temperature increases and then saturates with beam energy
- Kinetic freeze-out temperature decreases while <β> (collectivity) increases with beam energy for central collisions
- *New STAR results (at Au+Au 14.5 GeV and U+U 193 GeV) are consistent with energy dependence*
- Difference between chemical and kinetic freeze-out temperatures increases with beam energy

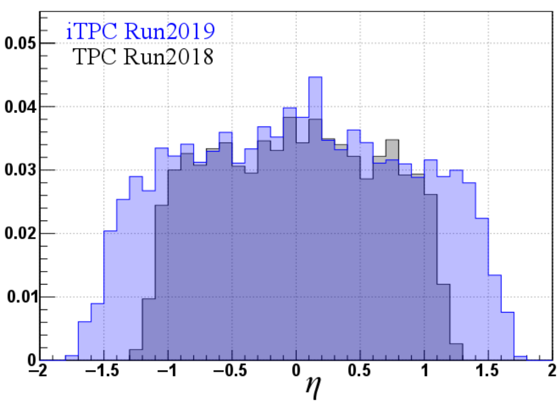
  -- *Suggests system interacts for longer duration at higher collisions energies*

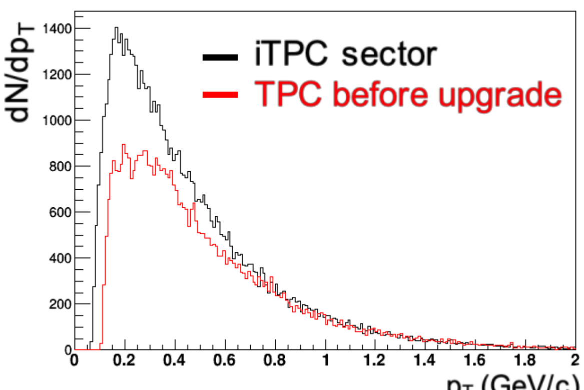
Precision Measurements with iTPC

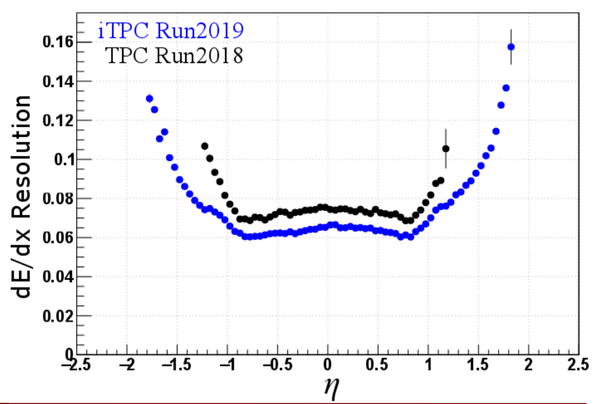
STAR TPC upgrade of inner TPC (iTPC) – Successful data taken in 2019



Quantity	Improvement	
	TPC	iTPC
No. of hits per track	45	72
η coverage	$\|\eta\| < 1.0$	$\|\eta\| < 1.5$
Low p_T acceptance	125 MeV/c	60 MeV/c
Momentum and dE/dx resolution	Improved with iTPC	







Improvement in FO parameters Estimation

- Current systematic uncertainties on the freeze-out parameters are large at STAR
- The systematic uncertainties on the spectra, yields, and ratios depend on track quality, low-p_T extrapolation, momentum and dE/dx resolution
- These uncertainties propagate to the extracted freeze-out parameters
- With improvement in these measurements through iTPC upgrade, it is expected to have reduction in uncertainties on spectra, yields and ratios and hence on freeze-out parameters
- BES-II is expected to provide freeze-out parameters with more precision

Summary

- Latest results on particle yields and ratios from STAR at Au+Au 14.5 GeV and U+U 193 GeV are presented.

  -- *At 14.5 GeV results follow the similar* ***N_{part} dependence*** *as other energies and fit well in* ***energy dependence*** *trend*

  -- *At U+U 193 GeV results follow the similar* ***N_{part} dependence*** *as Au+Au 200 GeV and are* ***consistent*** *with Au+Au 200 GeV at similar N_{part}; centrality dependence is* ***extended*** *beyond N_{part} > 400*

- Chemical and kinetic freeze-out parameters are presented for Au+Au 14.5 GeV

  -- *The results follow similar* ***centrality dependence*** *as other energies and fit well in the* ***energy dependence*** *trend*

- Kinetic freeze-out parameters are presented at U+U 193 GeV

  -- *The results follow similar* ***centrality dependence*** *as Au+Au 200 GeV and are consistent with Au+Au 200 GeV at similar N_{part}*

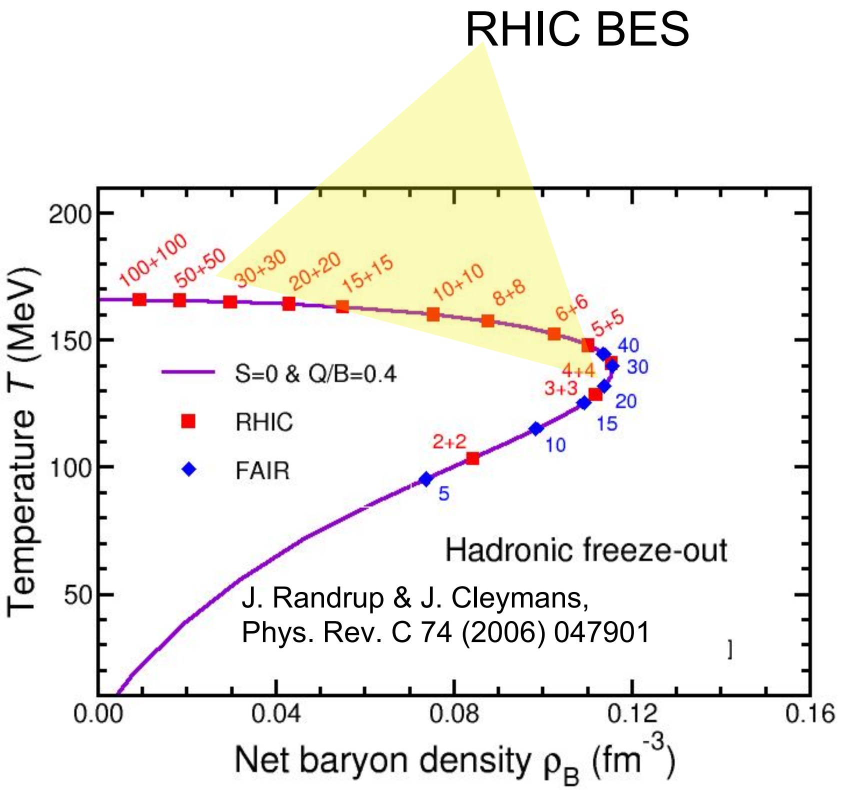
Summary

- STAR FO results suggest to cover a large range of μ_B in the phase diagram
  - -- *The transition temperature from Lattice seems to be close to T_{ch}*
  - -- *Extracted FO parameters from SHM depend on particle type – different values for strange and non-strange hadrons*
  - -- *FO parameters can be extracted using fluctuation of conserved quantities (net-charge and net-proton) from Lattice and HRG models; Results consistent with SHM (non-strange hadrons)*
- BES-II with upgraded iTPC will help in precision measurements of FO parameters at STAR at RHIC

Thank You

Back up

Maximum Baryon Density



Phys.Lett. B738 (2014) 305-310

Ensembles: Heavy-ion Experiments

Statistical Thermal Model: THERMUS Package J. Cleymans et al., Comp. Phys. Comm. 180, 84 (2009)

Grand Canonical Ensemble: The energy and quantum numbers or particle numbers are conserved on average through the temperature and chemical potentials.

-- Widely used in high energy heavy-ion collisions

-- Chemical potential for particle species *i* is given by:

$$\mu_i = B_i\mu_B + Q_i\mu_Q + S_i\mu_S$$

B_i, Q_i, S_i : baryon, charge, strangeness number

Strangeness Canonical Ensemble: The strangeness (S) in the system is fixed exactly by its initial value of *S*, while the baryon and charge contents are treated grand-canonically.

-- At lower energies, low production of strange particles requires canonical treatment of strangeness

-- Chemical potential for particle species *i* is given by

$$\mu_i = B_i\mu_B + Q_i\mu_Q$$