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Identified particle production and freeze-out properties in heavy-ion collisions in RHIC BES program

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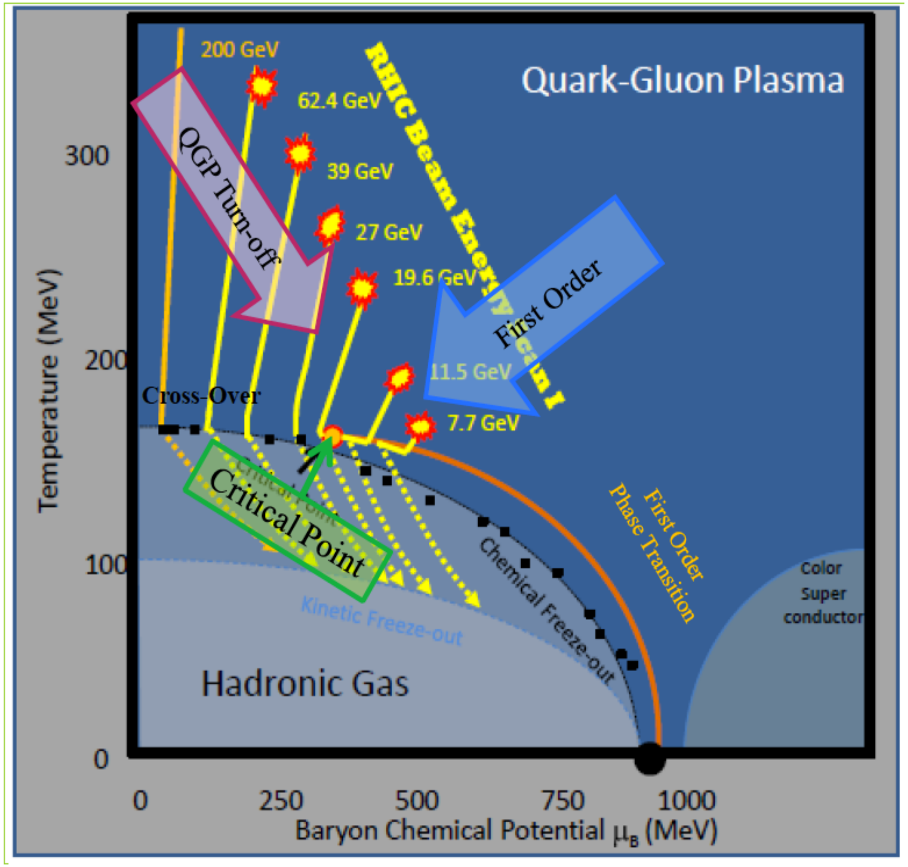
Outline

- Motivation
  Beam Energy Scan (BES) Program in STAR at RHIC
- STAR Detector System
- Particle Identification
- Transverse Momentum Spectra
- Energy and Centrality Dependence of Identified Particle Yields and Ratios
- Freeze-out
- Summary

Motivation



QCD Phase Diagram

STAR BES proposal: arXiv:1007.2613

The main goals of

RHIC Beam Energy Scan (BES) program

Turn-off of QGP signatures

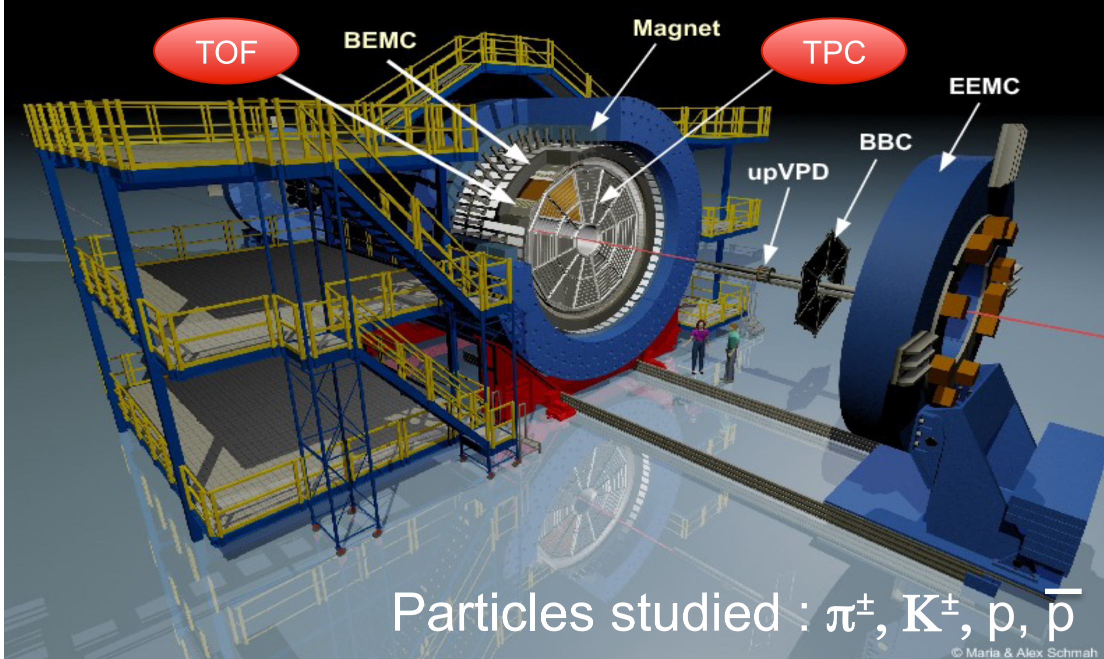
First-order phase transition

Critical Point and QCD phase boundary

T_{ch} , μ_B

The Solenoidal Tracker At RHIC (STAR)

Full azimuthal particle identification.



Particles studied : $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$

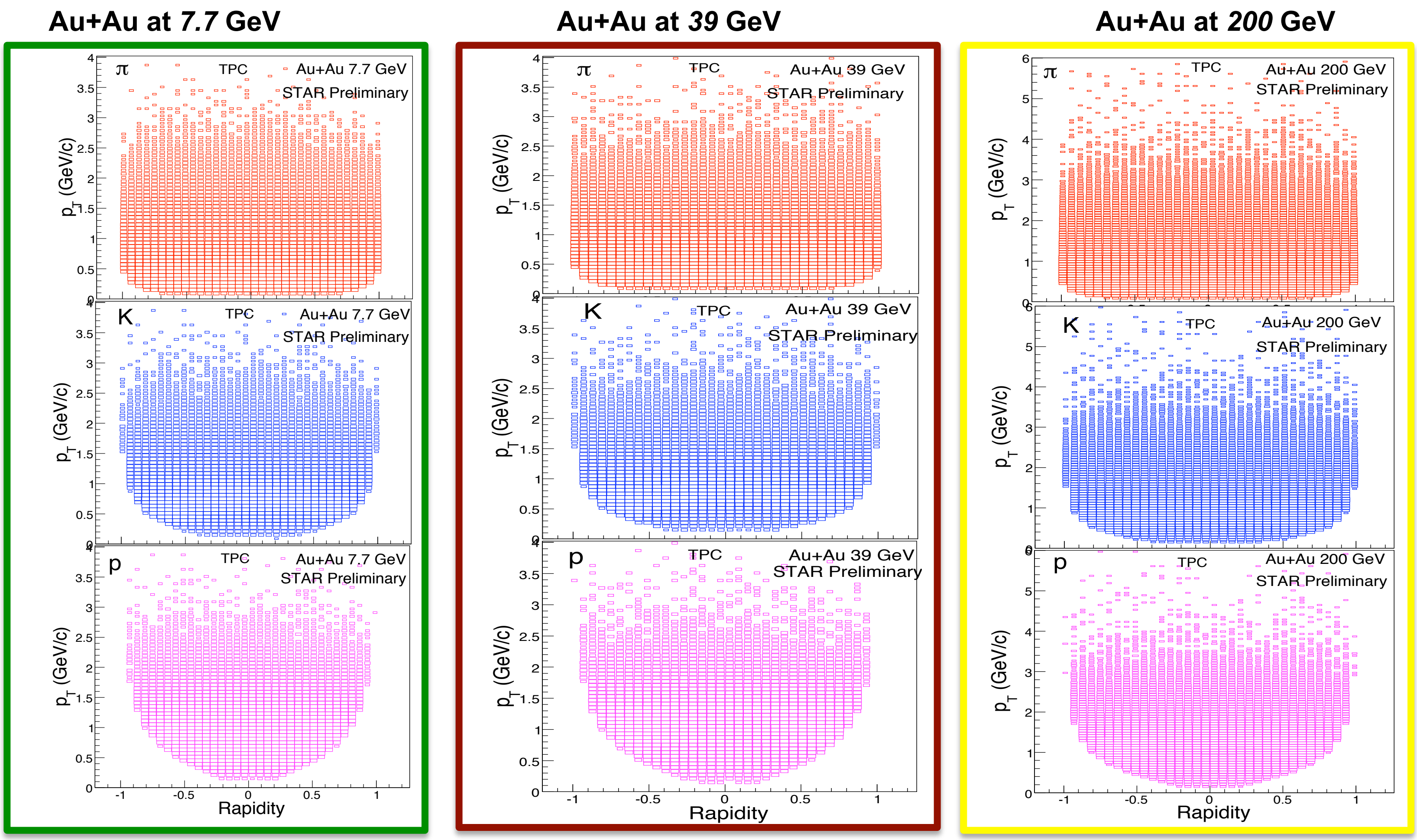
Year	Energy (GeV)	Events (Millions)
2010	39	130
2011	27	70
2011	19.6	36
2014	14.5	20
2010	11.5	12
2010	7.7	4

Large coverage $0 < \Phi < 2\pi$, $|\eta| < 1.0$

Excellent particle identification capabilities (TPC and TOF)

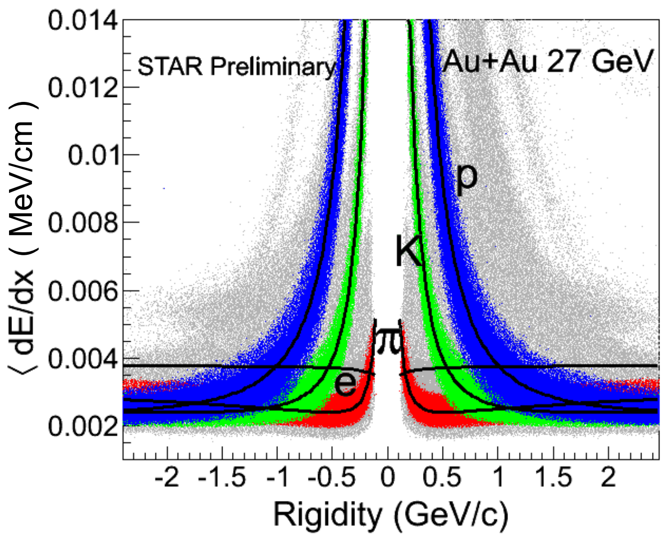
Uniform transverse momentum (p_T) and rapidity acceptance

STAR PID for (π, K, p)



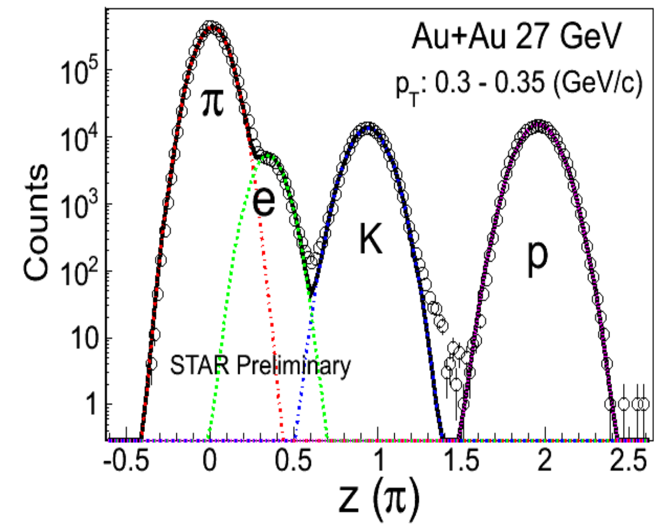
Similar acceptance at mid-rapidity

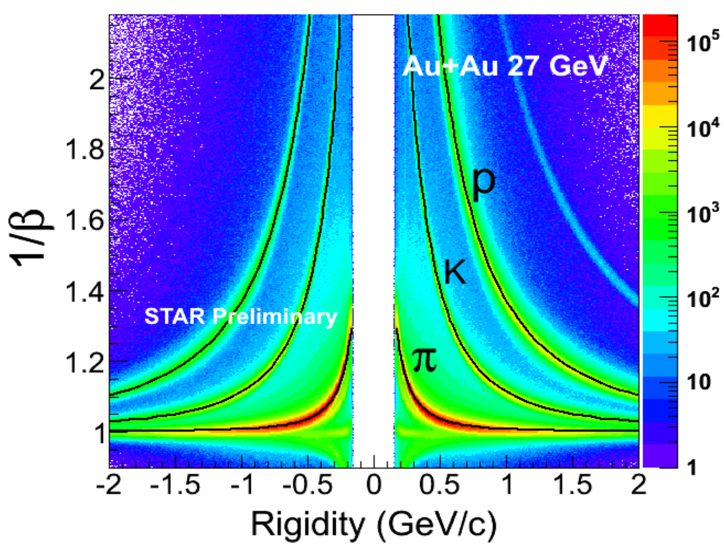
Particle Identification



TPC

$$z = \log\left(\frac{(dE/dx)_{meas.}}{(dE/dx)_{theory}}\right)$$

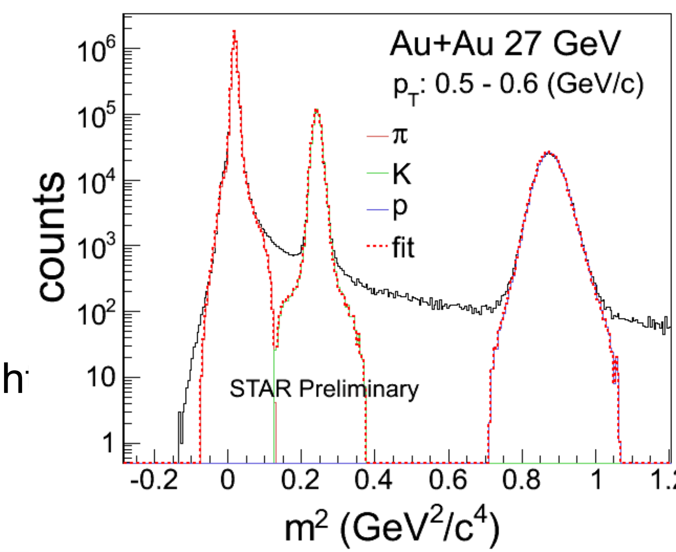




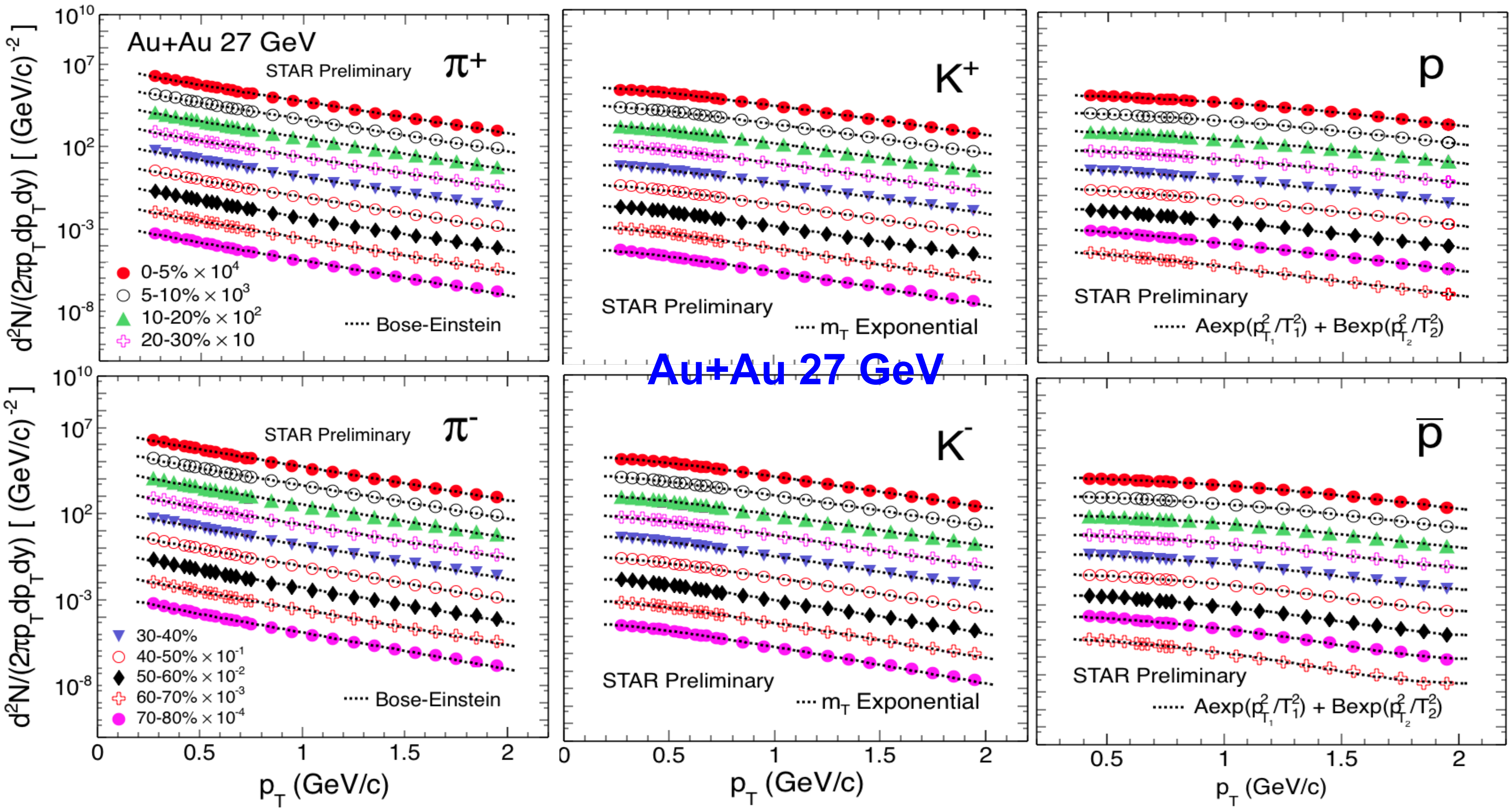
TPC+TOF

$$m^2 = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

p = momentum
t = time-of-flight
c = velocity of ligh
L = path length

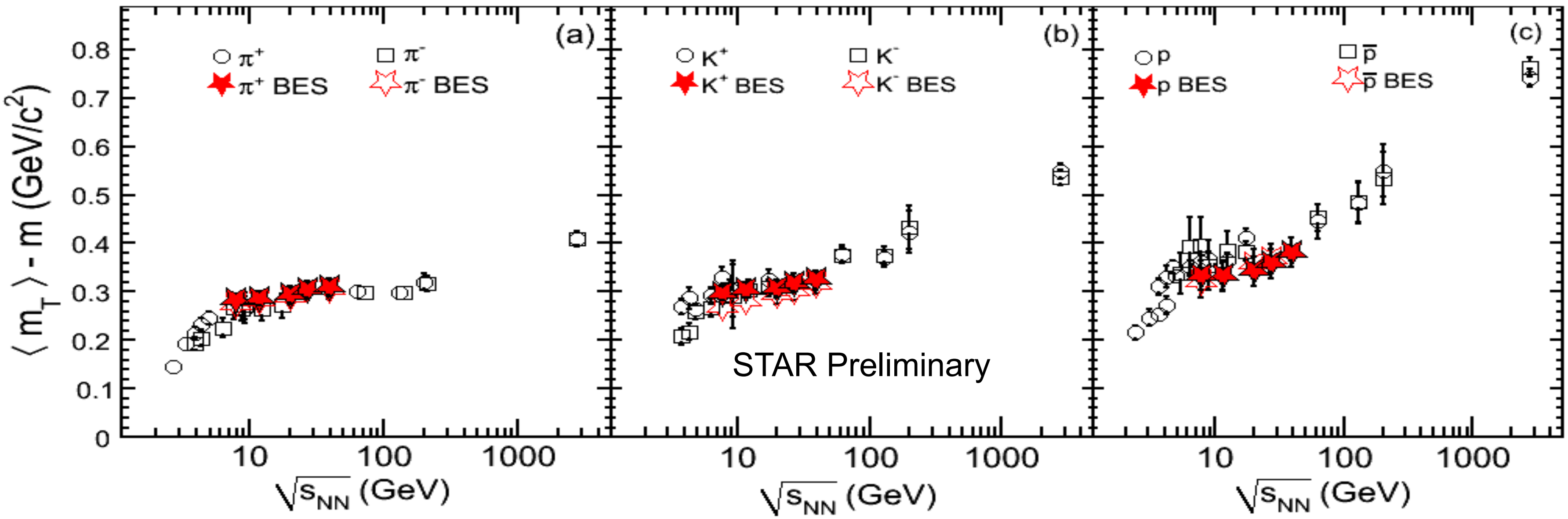


Transverse Momentum Particle Spectra



- Characterized through dN/dy, <p_T> or <m_T>

Energy Dependence of $<m_T> - m$



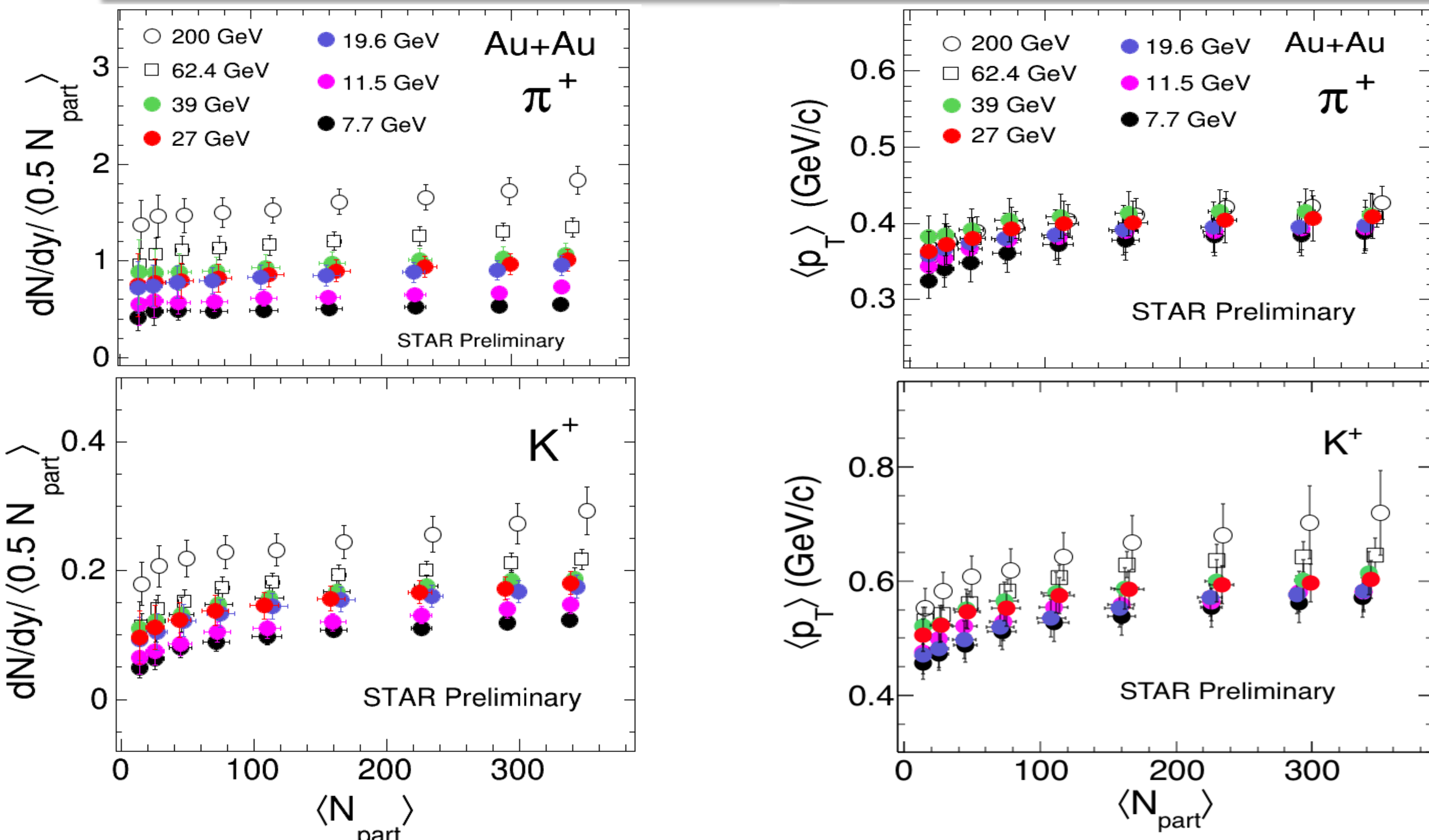
$$m_T = \sqrt{(p_T^2 + m^2)}$$

NA49 : PRC 66 (2002) 054902, PRC 77 (2008) 024903, PRC 73 (2006) 044910 ; STAR : PRC 79 (2009) 034909, PRC 81, 024911 (2010); E802(AGS) : PRC 58 (1998) 3523, PRC 60 (1999) 044904; E877(AGS) : PRC 62 (2000) 024901 E895(AGS) : PRC 68 (2003) 054903; ALICE: PRL109, 252301 (2012), PRC 88, 044910 (2013)

- $<m_T> - m$ is related to the temperature of the system and Entropy ~ dN/dy α log($\sqrt{s_{NN}}$) L. Van Hove, Phys. Lett. B 118, 138 (1982)

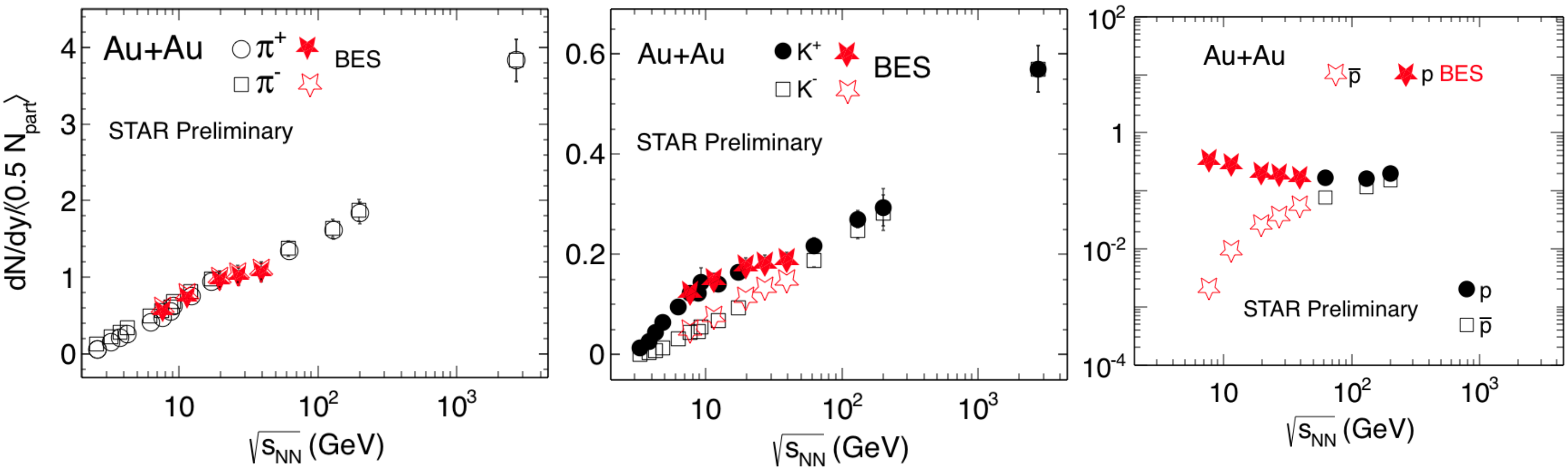
- The saturation of $<m_T> - m$ around BES energies.

Centrality Dependence of dN/dy and <pT>



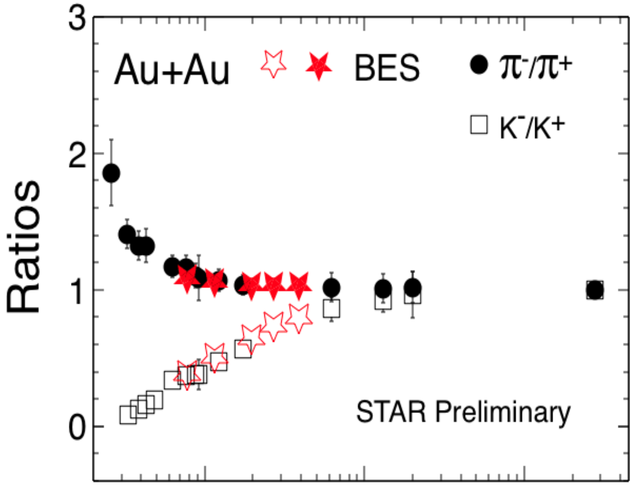
$<p_T>$ increases with centrality ⟶ collectivity increases with centrality

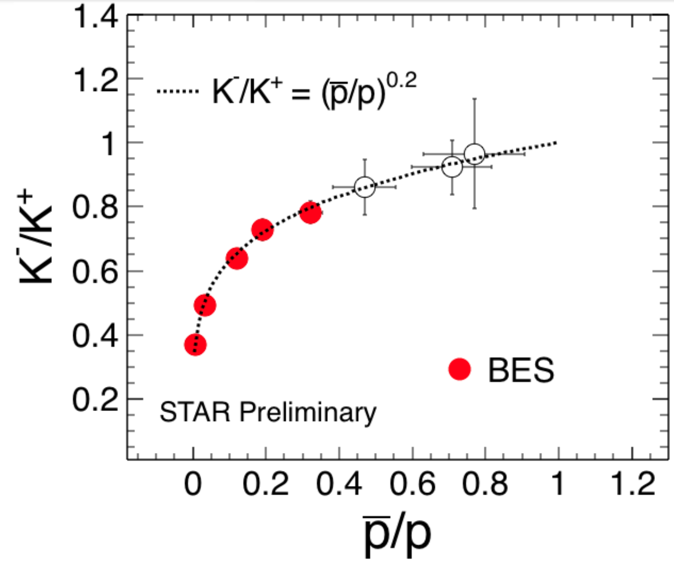
Energy Dependence of Particle Yields



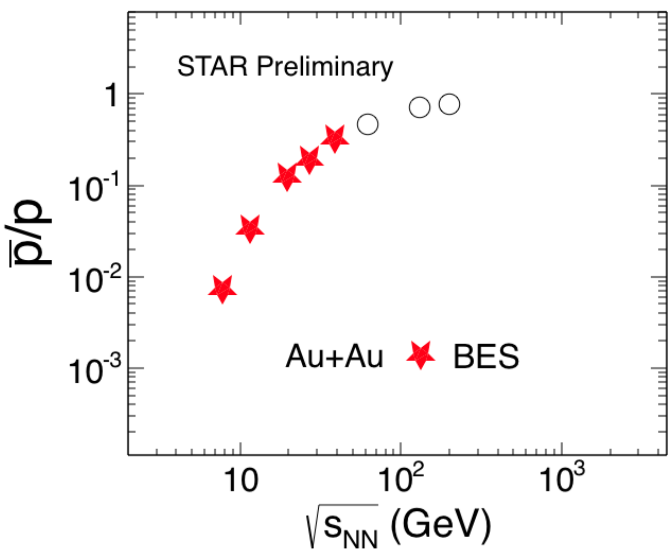
- The energy dependence of yields per participating nucleon pair for $\pi^{\pm}$, $K^{\pm}$, p, and $\bar{p}$ in all BES energies follow the general energy dependence trend of dN/dy with other energies.

Energy Dependence of Particle Ratios





BRAHMS: PRL 90, 102301 (2003)
Becattini et al. PRC 64, 024901 (2001)

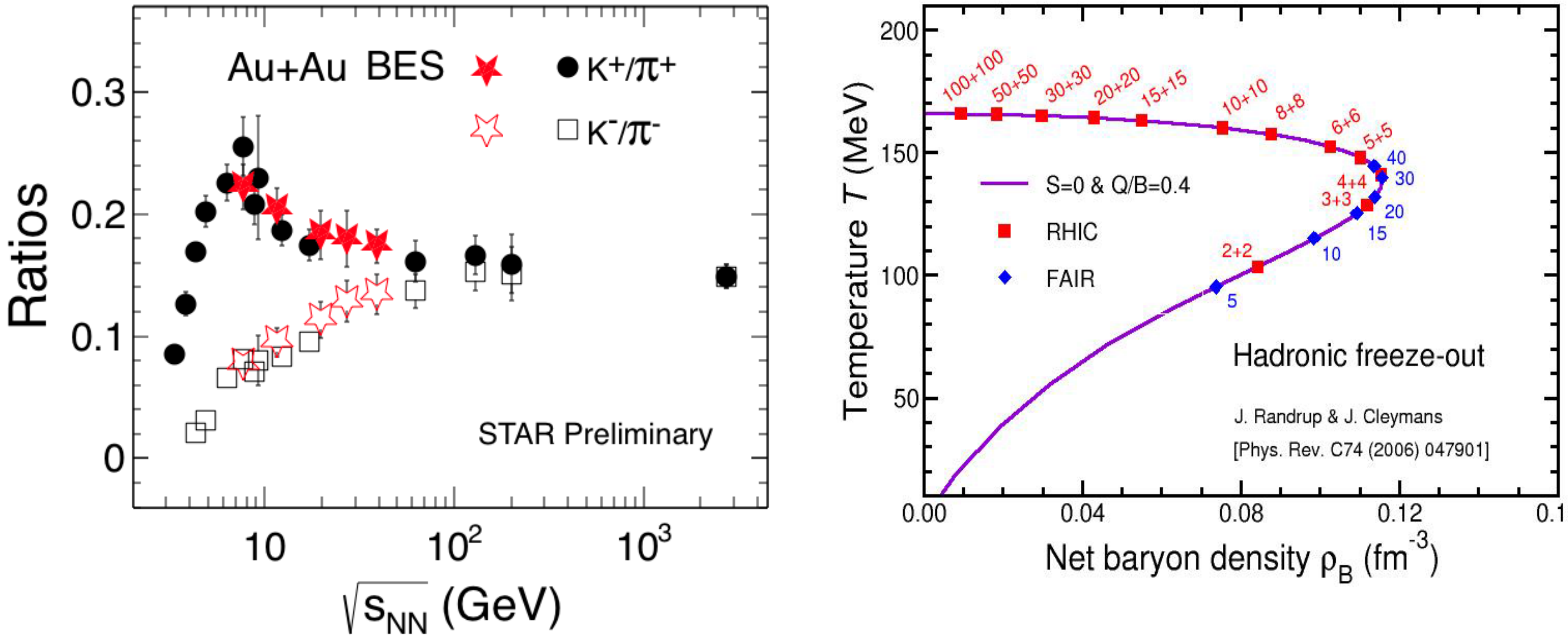


- Particle ratios at BES energies follows a systematic trend with beam energy

Pion ratio at low energies - resonance decays
Kaon ratio at lower energies - associated production
Proton ratio at low energies - large baryon stopping

- Correlation between kaon and baryon ratio follows a power law behavior

Energy Dependence of Particle Ratios



- Maximum net baryon density at freeze-out $\sqrt{s_{NN}}$ ~ 8 GeV
- K/π ratio indicates the strangeness enhancement
- K/π ratio at BES energies follow the existing trend

Chemical Freeze-out

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

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

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

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

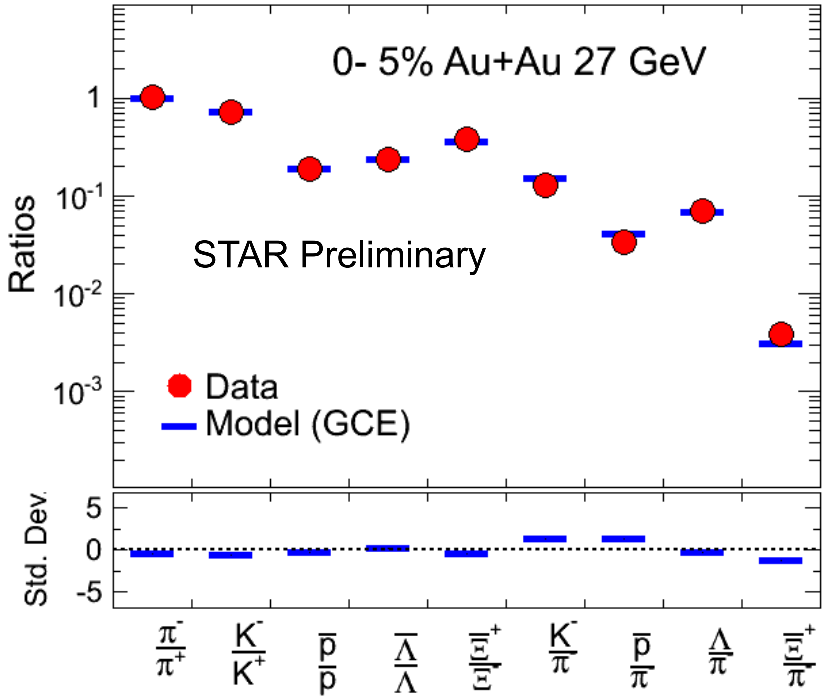
To consider incomplete strangeness equilibration:

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

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

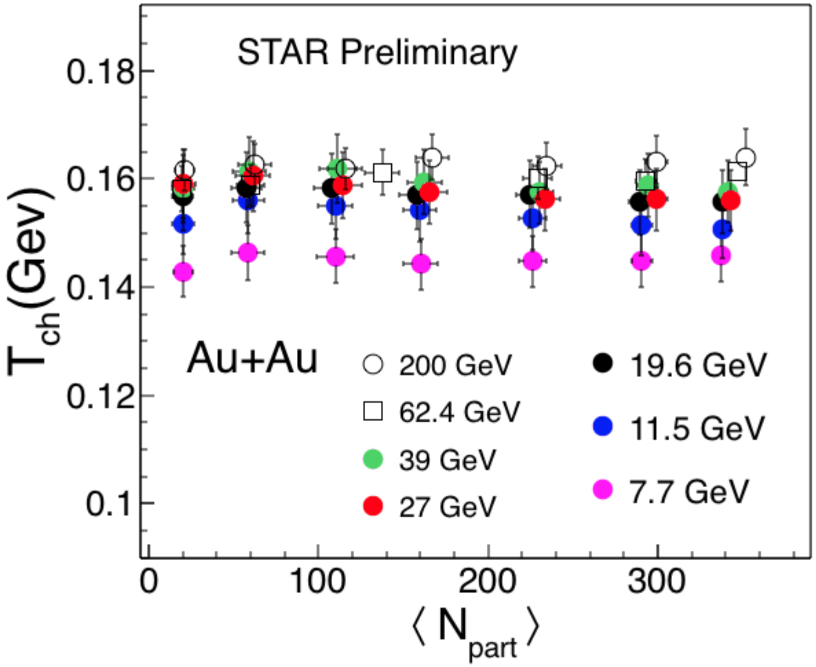


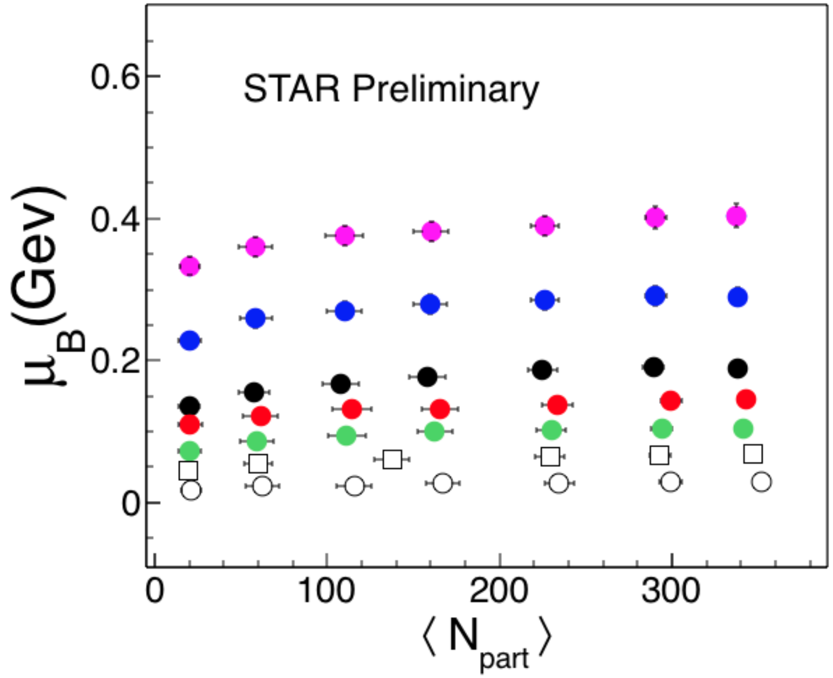
✓ Particles used : π, K, p, Λ , Ξ

✓ Ensemble used: Grand canonical ensemble

✓ Fit parameters: $T_{ch,}$ $\mu_{B,,}$ $\mu_{S,}$, R and γ_S

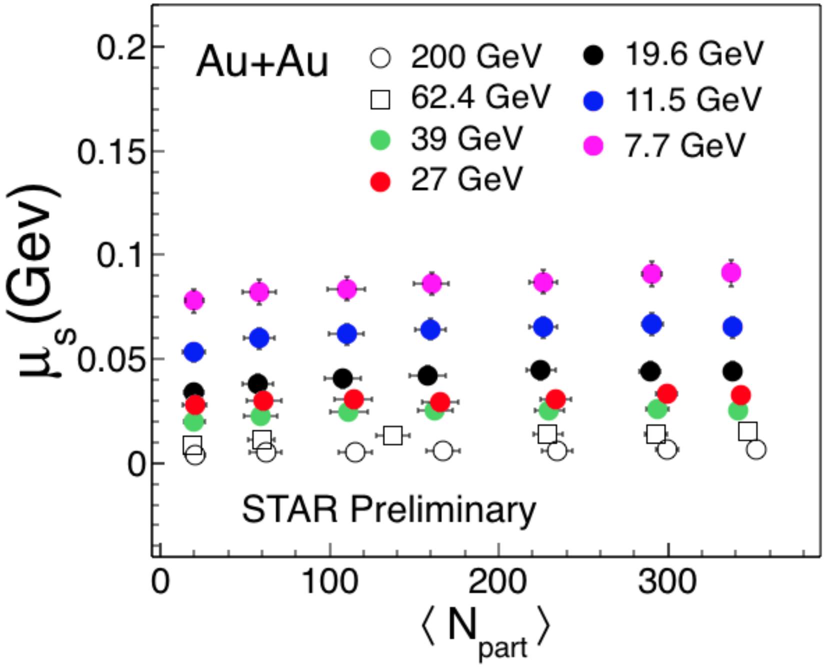
Chemical Freeze-out

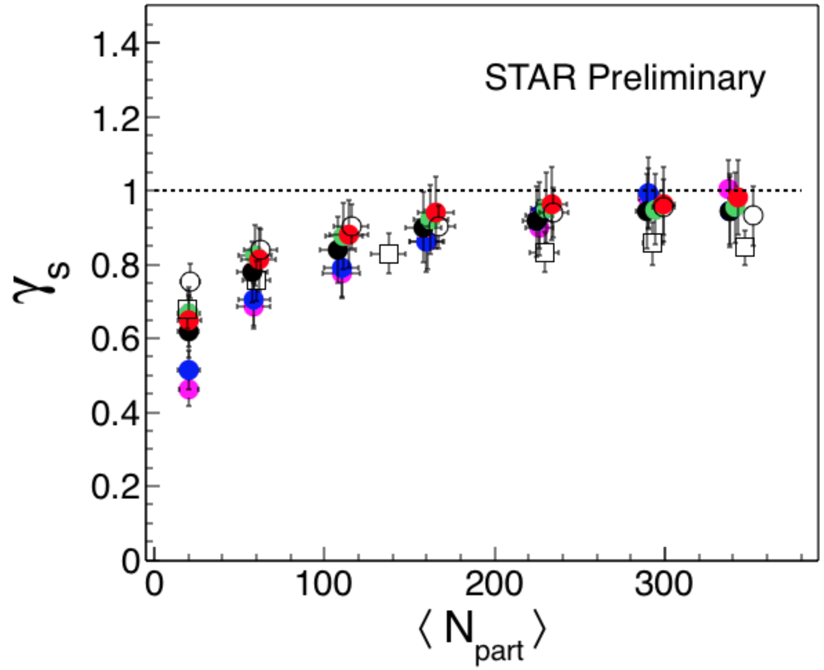




- Particles used in the fit: **π, K, p, Λ , Ξ**
- Freeze-out results shown from : Grand canonical ensemble
- As collision energy increases chemical freeze-out temperature increases
- Baryon chemical potential decreases with increase in collision energy.

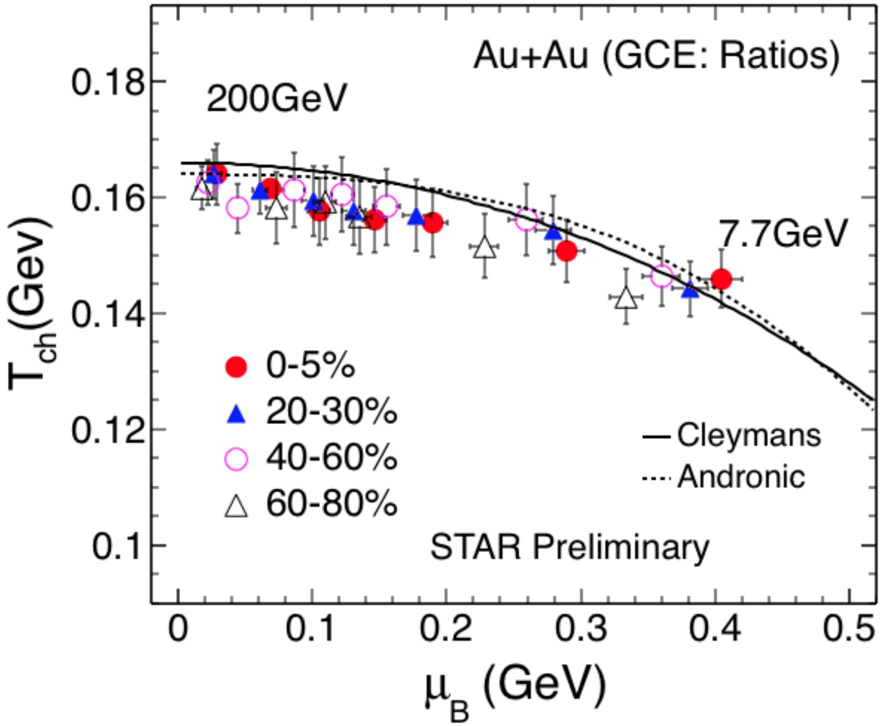
Chemical Freeze-out





- Particles used in the fit : π, **K, p**, Λ , Ξ
- Freeze-out results shown from : Grand canonical ensemble
- Strangeness chemical potential decreases with increase in collision energy
- Strangeness saturation factor increases from peripheral to central collisions for all energies

Chemical Freeze-out: T_{ch} vs. μ_B



Andronic: NPA 834 (2010) 237
Cleymans: PRC 73 (2006) 034905

- ✓ Particles used :
  π, K, p, Λ , Ξ
- ✓ Ensemble used:
  Grand Canonical Ensemble
- ✓ Fit parameters:
  T_{ch}, μ_{B}, μ_s and γ_S (strangeness saturation factor)

> ➢ We observe a centrality dependence of baryon chemical potential (μ_B) at lower energies.

Kinetic Freeze-out

Kinetic Freeze-out : Elastic collision ceases
Transverse momentum spectra get fixed

Blast Wave : Hydrodynamic inspired model

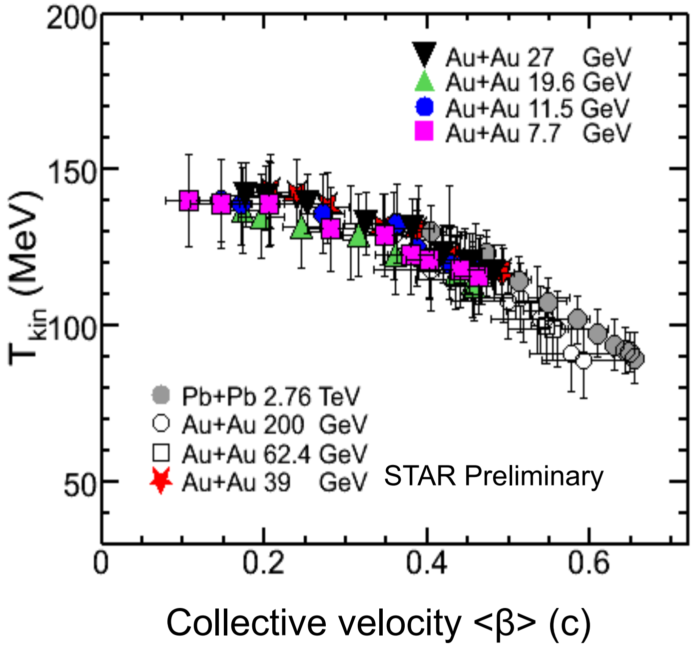
$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

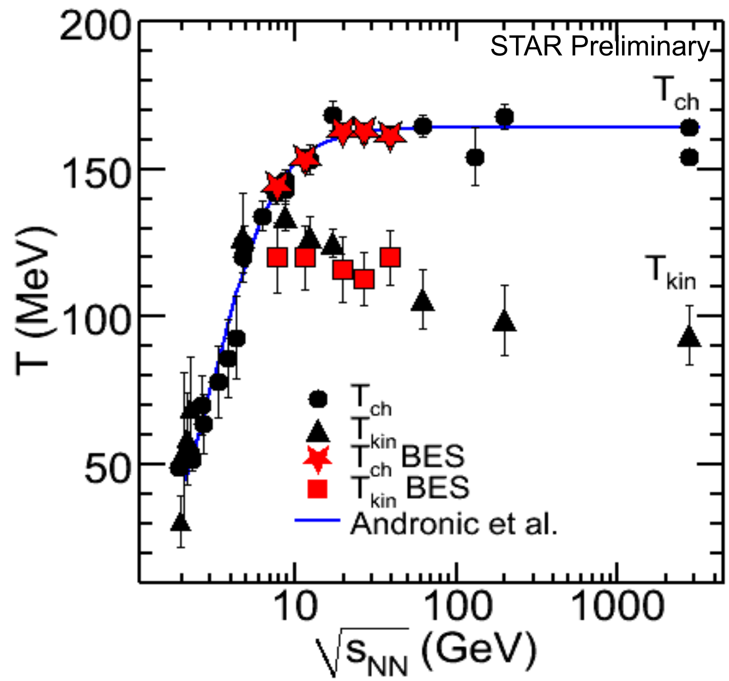
E. Schnedermann et al., Phys. Rev. C 48, 2462 (1993)

Particle spectra are fitted simultaneously

Extracted thermodynamic quantities: T_{kin} and **<β>**

Kinetic Freeze-out





Kinetic Freeze-out:

- Lower value of T_{kin} corresponds to larger collectivity <β>
- Stronger collectivity at higher energy

Summary

- ✓ Successful completion of RHIC Beam Energy Scan Program-I : 7.7, 11.5, 19.6, 27, 39 GeV.
- ✓ Transverse momemtum spectra, centrality and energy dependence of particle yields and ratios are presented.
- ✓ Saturation of <m_T> -m around lower BES energies.
- ✓ Particle ratios are used to extract T_{ch} and μ_B : Study the QCD phase diagram.
- ✓ New measurements at BES energis at RHIC : Extend μ_B range from 20 - 400 MeV of the QCD phase diagram.
- ✓ Chemical Freeze-out: Observation of centrality dependence of baryon chemical potential (μ_B) at lower energies.

WAITING FOR RHIC BES II RESULTS IN SEARCH OF CRITICAL POINT !!!

Thank you