Identified Hadron Production from the RHIC Beam Energy Scan Program in the STAR Experiment

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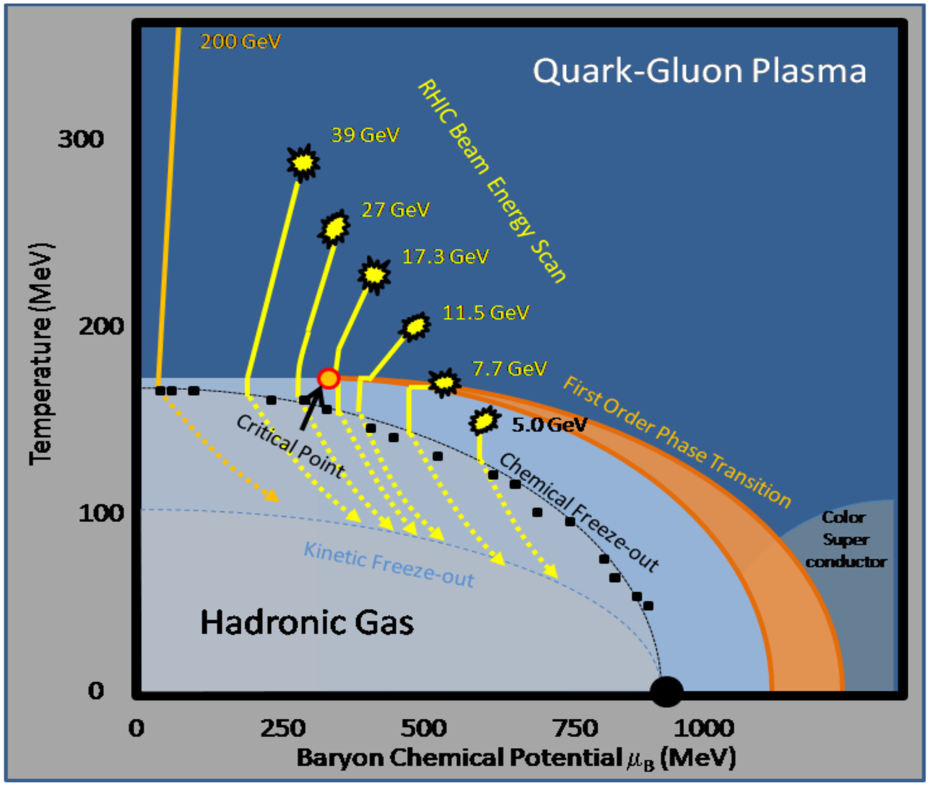
Outline:

- Motivation
- Identified hadron yields and average m_T
- Particle ratios
- Freeze-out parameters
- Summary

Motivation

QCD Phase Diagram (Hadrons-Partons):



http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493: arXiv:1007.2613

- Experimental study: Heavy-ion collisions at varying beam energies

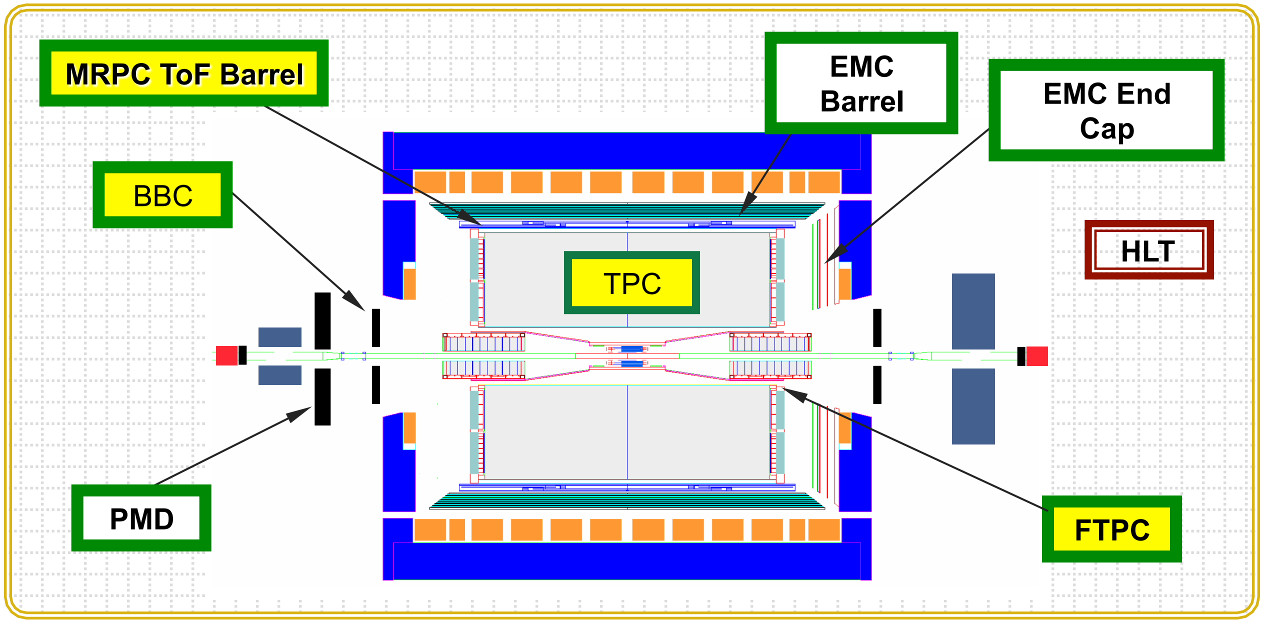
- Goal of RHIC BES program:

- Search for the phase boundary

- Search for the possible QCD Critical Point

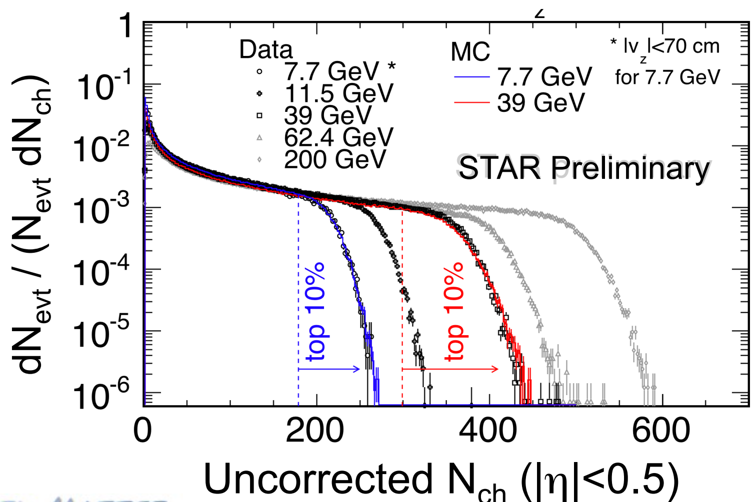
In this presentation we will discuss the bulk properties of the matter through the measurements of particle yields, average p_T, particle ratios and freeze-out parameters (T_{ch}, μ_B, T_{kin} and $<\beta>$)

Data Set and Detectors Used



Particle identification over 2π in azimuthal angle and more than two units in rapidity

Au+Au Collisions:
7.7, 11.5 and 39 GeV
$|y| < 0.1$
$p_T > 0.1$ GeV/c
Centrality: 0-80%

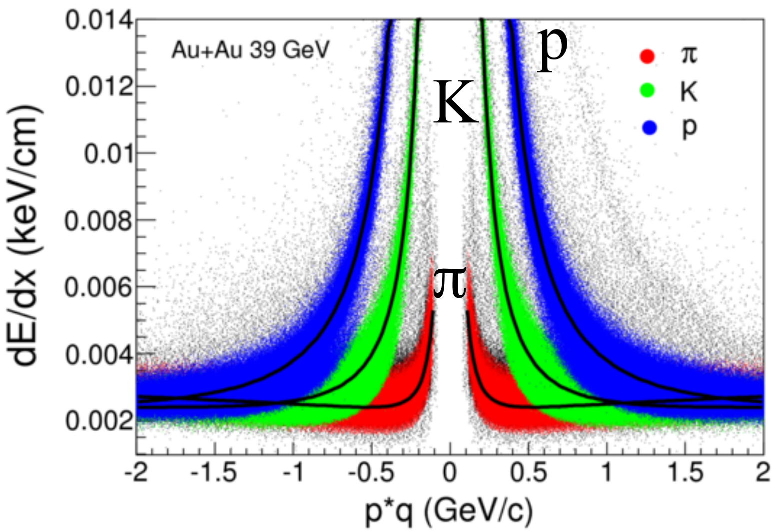


$\sqrt{s_{NN}}$ (GeV)	Good events (proposed) Million MB
5.0	
7.7	~5(5)
11.5	~11 (5)
19.6	~17 (15)
27	(150 @ 400 Hz)
39	~170 (25)

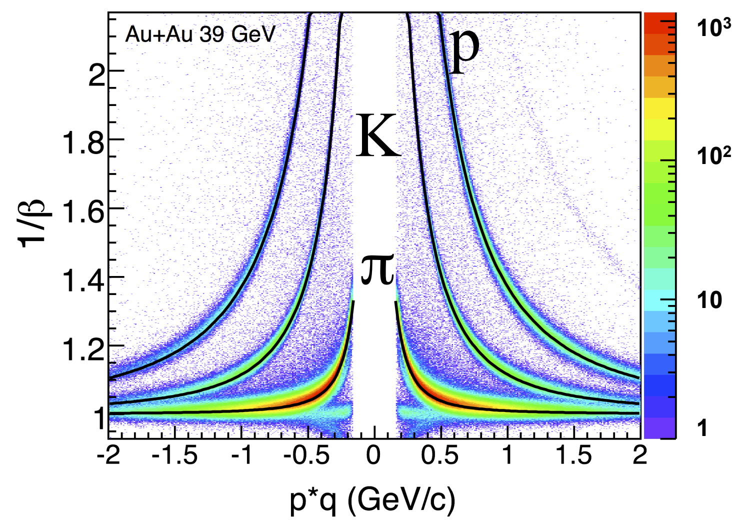
$\pi^{+/-}$, $K^{+/-}$ and $p/\bar{p}$ Identification

$\sqrt{s_{NN}}$ = 39 GeV Au + Au Collisions

TPC



TPC+ToF

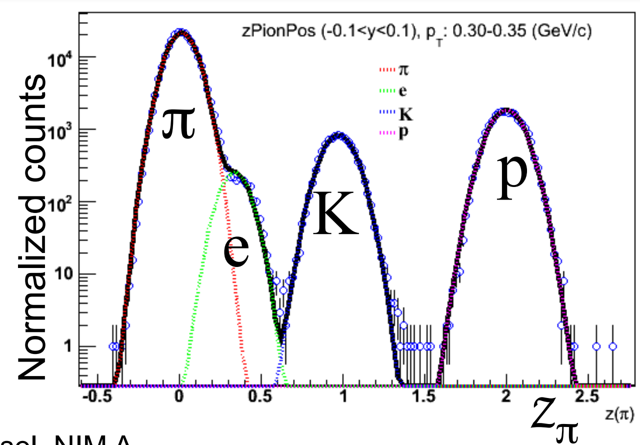


$$z = \log\left(\frac{(dE/dx)_{meas.}}{(dE/dx)_{theory}}\right)$$

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

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

H. Bichsel, NIM A. 562 (2006) 154



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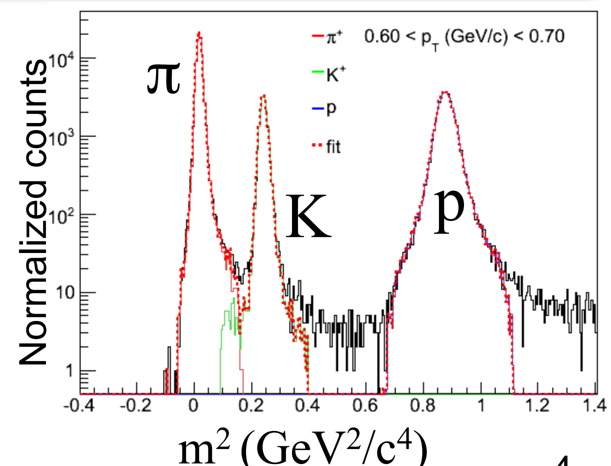


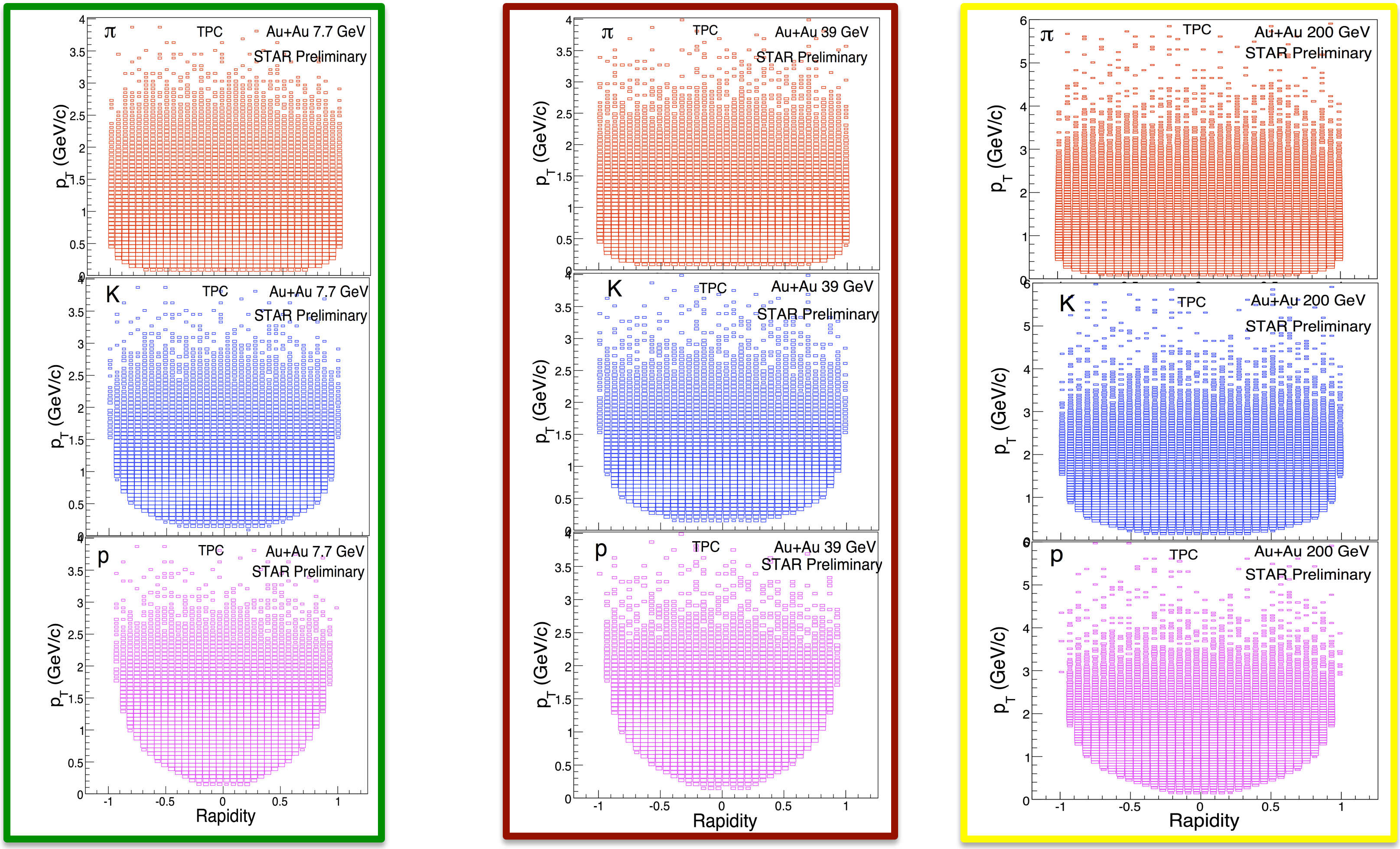
Large and Uniform Acceptance

Au+Au 7.7 GeV: Au+Au 39 GeV: Au+Au 200 GeV:

π:

K:

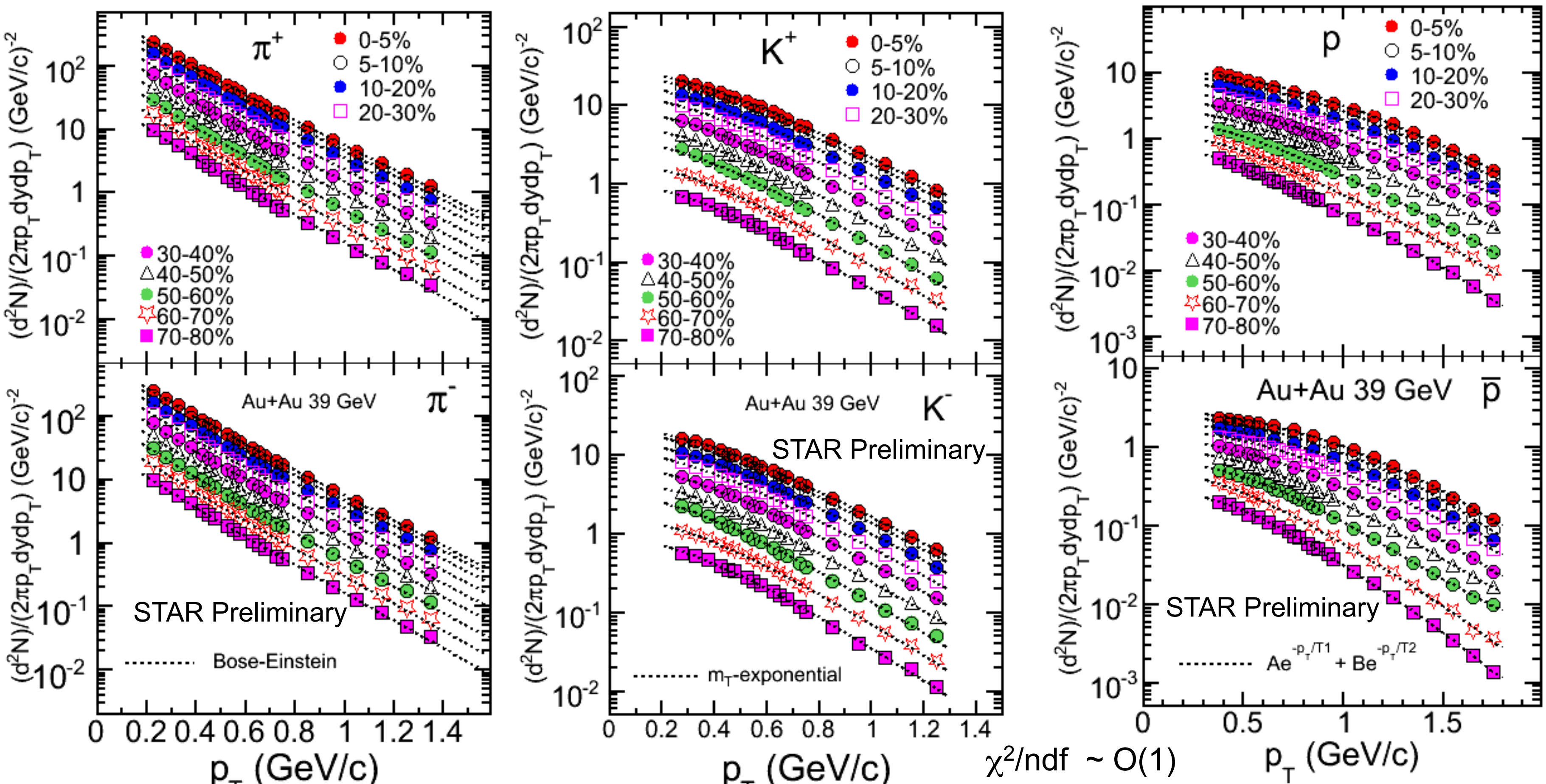
p:



- Similar acceptance at midrapidity - Crucial for all analyses

Invariant Yield

Au+Au 39 GeV:



We measure ~ 70-80% of π, K and p within our p_T acceptance at mid-rapidity

Similar measurements are carried out for 7.7 and 11.5 GeV collisions

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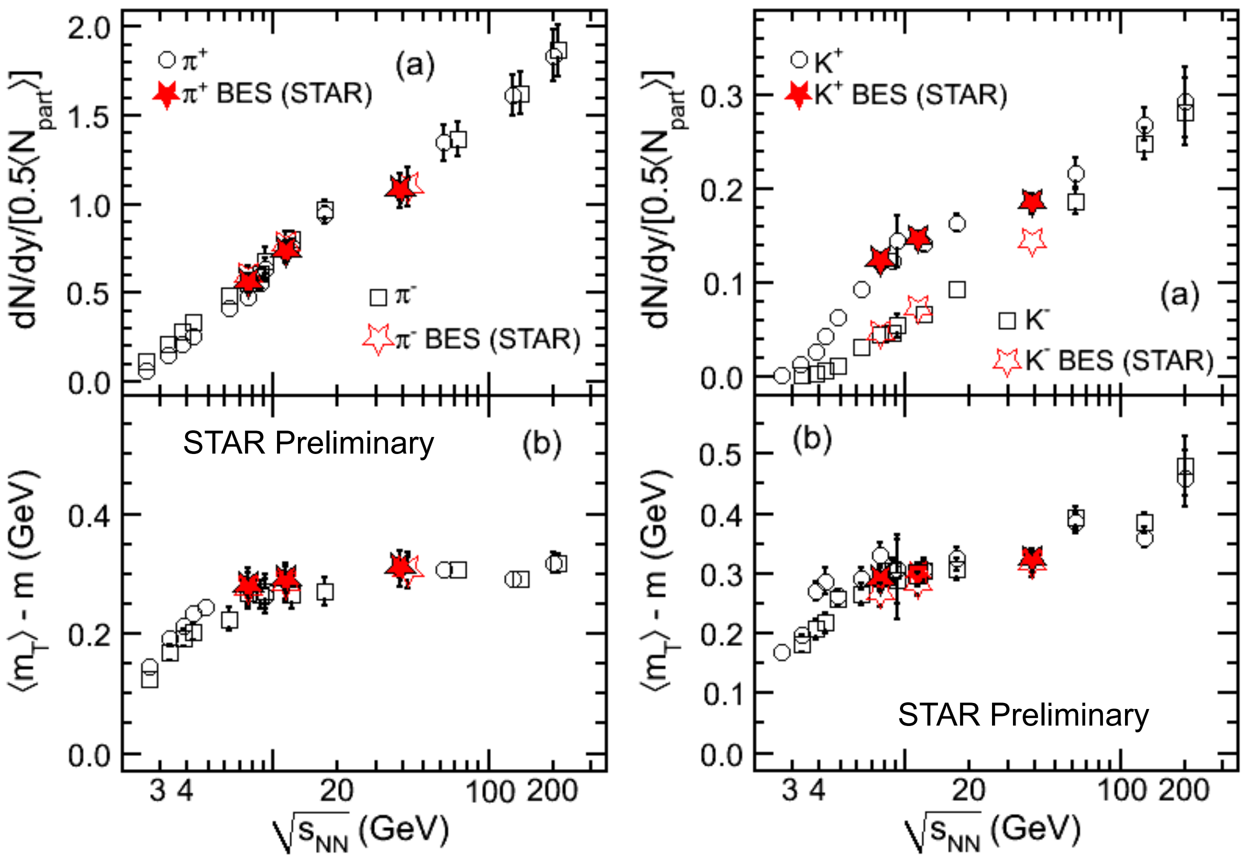
Energy Dependence of Yields & $\langle m_T \rangle$

Midrapidity and central collisions

Errors: statistical and systematic added in quadrature



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

- Assuming a thermodynamic system:

$T \sim \langle m_T \rangle - m$

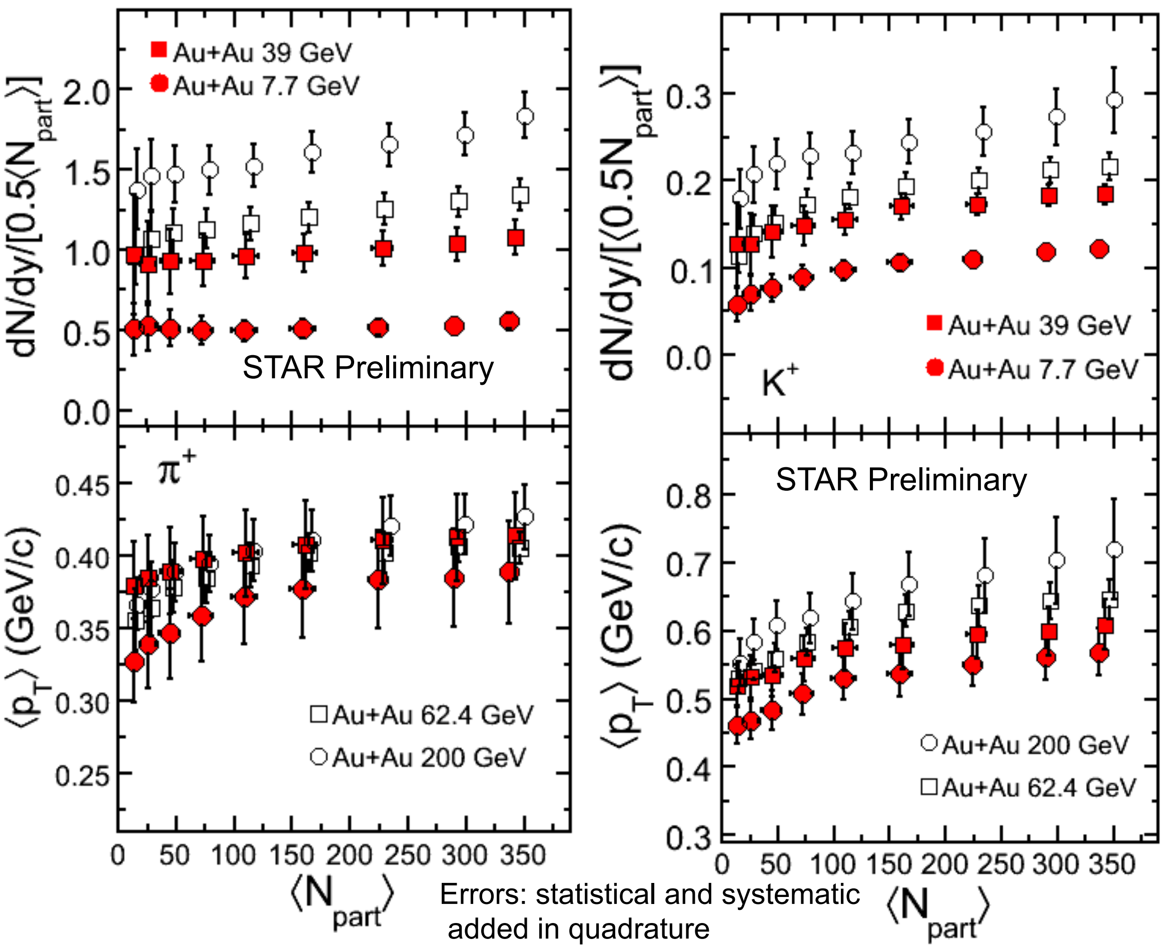
entropy ~ dN/dy

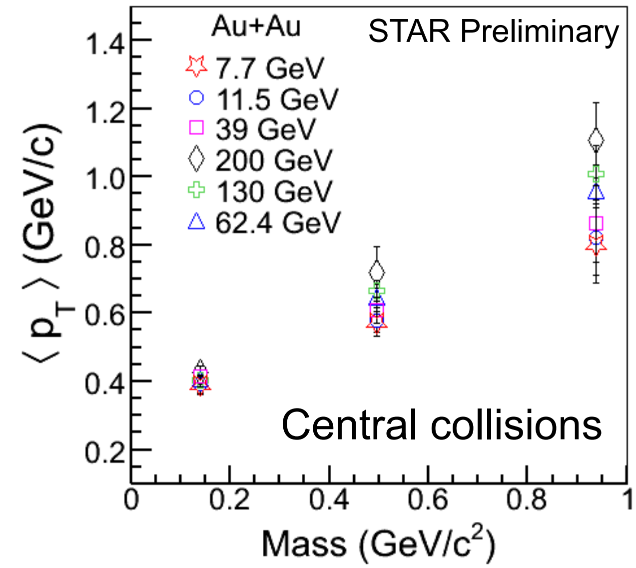
$\propto \log(\sqrt{s_{NN}})$

References for other energies:
NA49 : PRC 66 (2002) 054902, PRC 77 (2008) 024903, PRC 73 (2006) 044910
STAR : PRC 79 (2009) 034909, arXiv: 0903.4702; PRC 81 (2010) 024911
E802(AGS) : PRC 58 (1998) 3523, PRC 60 (1999) 044904
E877(AGS) : PRC 62 (2000) 024901
E895(AGS) : PRC 68 (2003) 054903

- Results consistent with the published energy dependence
- $\langle m_T \rangle$ - m remains constant for BES energies

Centrality Dependence of Yields & $<p_T>$



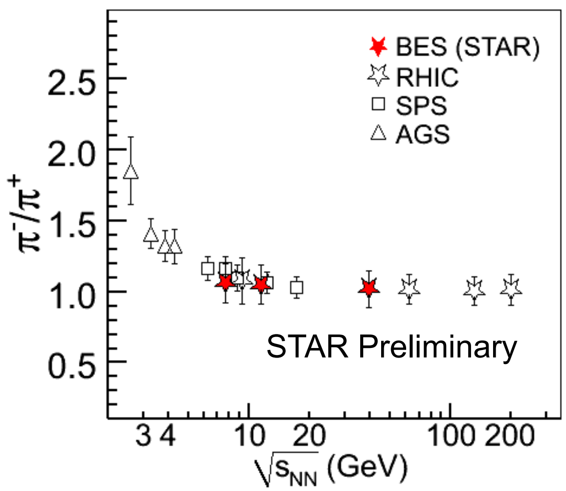


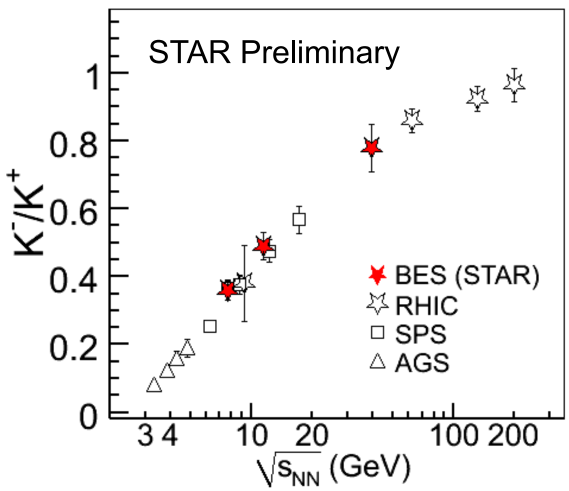
✧ $dN/dy/0.5N_{part}$ ~ constant for π as function of centrality at 7.7 GeV. For other energies and kaons, it increases with centrality.

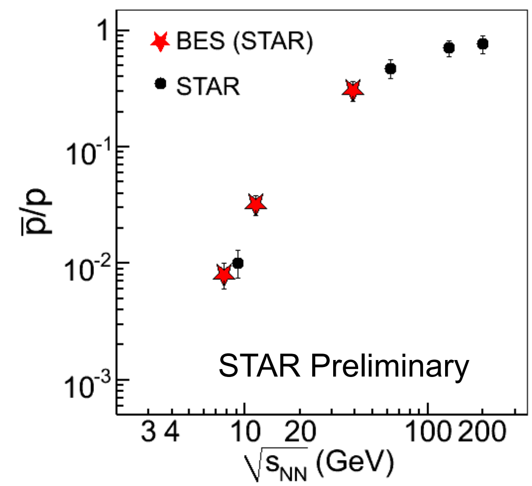
✧ $<p_T>$ increases with centrality – collectivity increases with centrality

✧ $<p_T>$ for π seems to be similar from 39 GeV to 200 GeV
✧ $<p_T>$ increases with mass of the particle

Anti-Particle to Particle Ratios

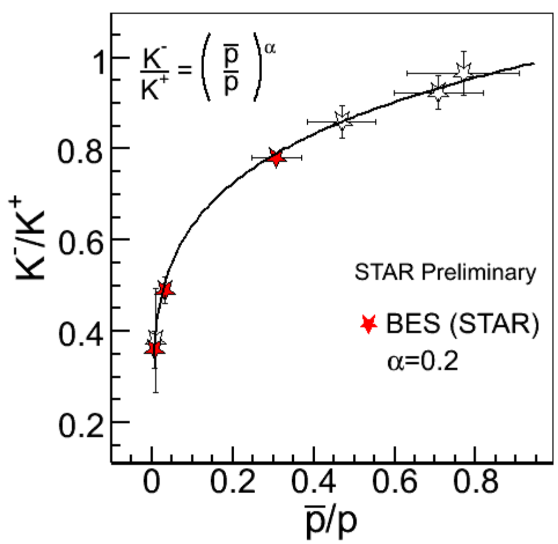






Midrapidity and central collisions

Errors: statistical and systematic added in quadrature



- Results consistent with the published energy dependence
- π^-/π^+ ratio ~ 1.1 at 7.7 GeV: resonance decay (Δ)
- $K^-/K^+ \sim 0.4-0.5$: associated production at 7.7-11.5 GeV
- $\bar{p}/p \ll 1$ at 7.7-11.5 GeV: large baryon stopping

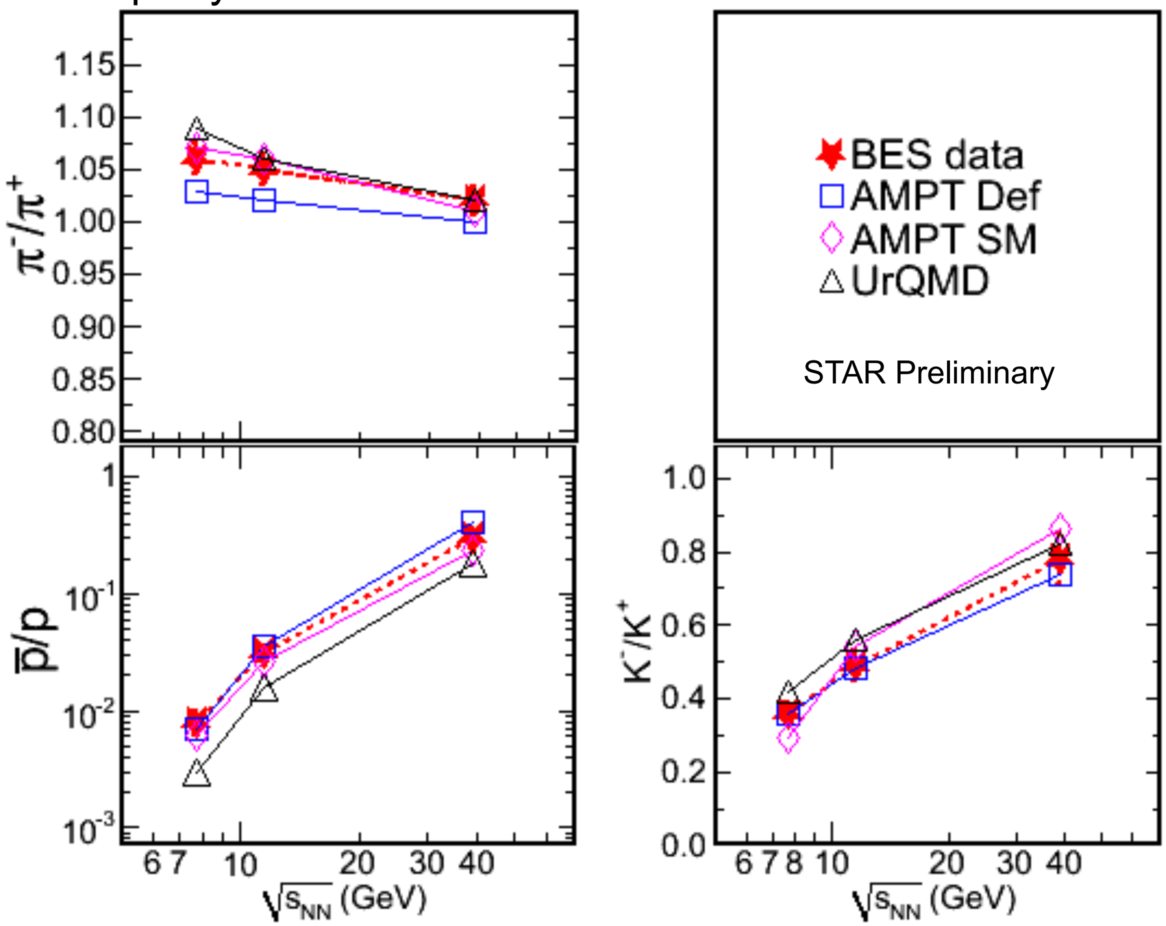
Correlation between K^-/K^+ and $\bar{p}/p$:
- Follows power law behavior
- Shows how the kaon production is related to net-baryon density.

BRAHMS: PRL 90, 102301 (2003)
J. Cleymans et al. ZPC 57, 135 (1993)

Comparison with Models

UrQMD- Ultrarelativistic Quantum Molecular Dynamics (ver. 2.3)
AMPT- A Multiphase Transport Model (Default and String Melting Scenario) (ver. 1.11)

Midrapidity and central collisions



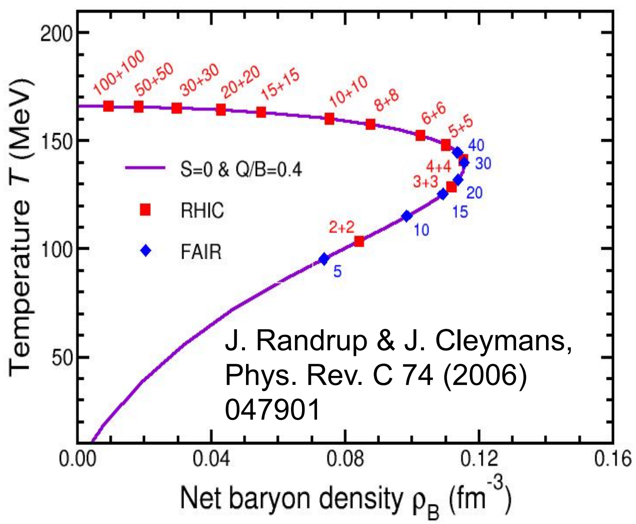
Transport models show similar trend as data

UrQMD gives lower values compared to data for $\bar{p}/p$ ratio

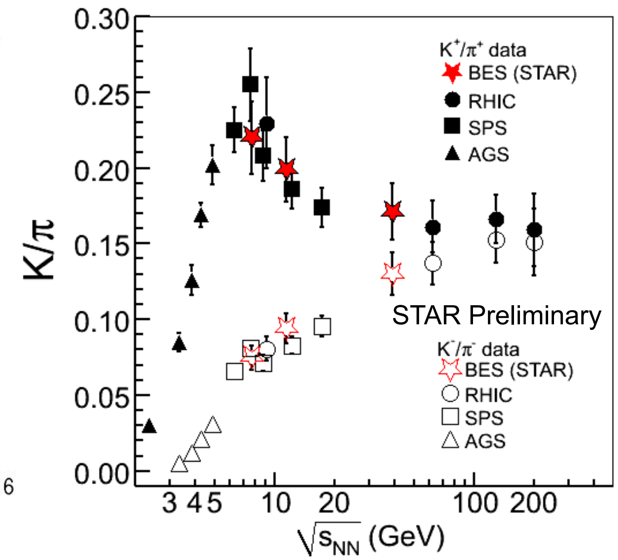
S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998);M. Bleicher et al., J. Phys. G 25, 1859 (1999).
Z.-W. Lin et al. Phys. Rev. C 65, 034904 (2002); Z.-W.Lin et al. bid. 72, 064901(2005);
L.-W. Chen et al., Phys. Lett. B 605, 95 (2005).

Particle Ratios

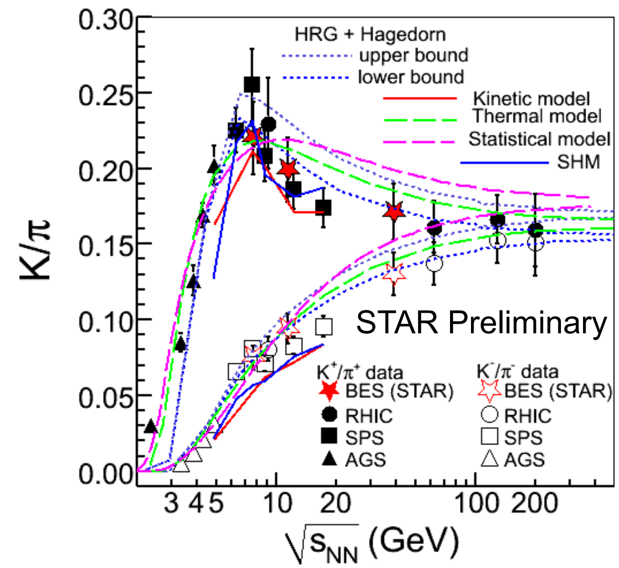
The maximum net-baryon density at freeze-out: **$\sqrt{s_{NN}}$ ~ 8 GeV**



Midrapidity and central collisions



Errors: statistical and systematic added in quadrature



Weak decay contribution for π are estimated from HIJING. Error due to this effect included in final errors.

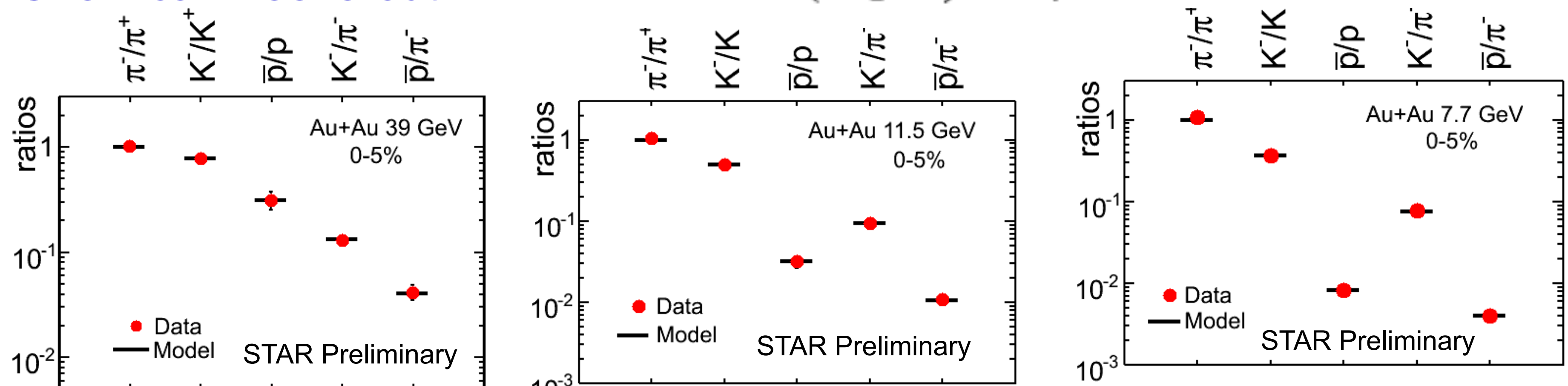
J. Cleymans et al., Eur. Phys. J. A 29, 119 (2006); A. Andronic et al., Phys. Lett B 673, 142 (2009); J. Rafelski, et al. J. Phys. G 35, 044011 (2008); B. Tomasik et al., Eur. Phys. J. C 49, 115 (2007) S. Chatterjee et al., Phys. Rev. C 81, 044907 (2010)

- K/π ratio indicates the strangeness enhancement
- K^+/π^+ vs. $\sqrt{s_{NN}}$ seems to be best explained using HRG+Hagedorn model
- K/π at BES energies are consistent with published energy dependence

Freeze-out Conditions

Chemical Freeze-out:

$$n_i(T,\mu_i) \sim \exp\left(\frac{\mu_i - m_i}{T}\right) \qquad \frac{N_i}{N_j} \sim \exp\left(\frac{\mu_{i,\mathrm{ch.}} - \mu_{j,\mathrm{ch.}}}{T_{\mathrm{ch.}}} - \frac{m_i - m_j}{T_{\mathrm{ch.}}}\right)$$



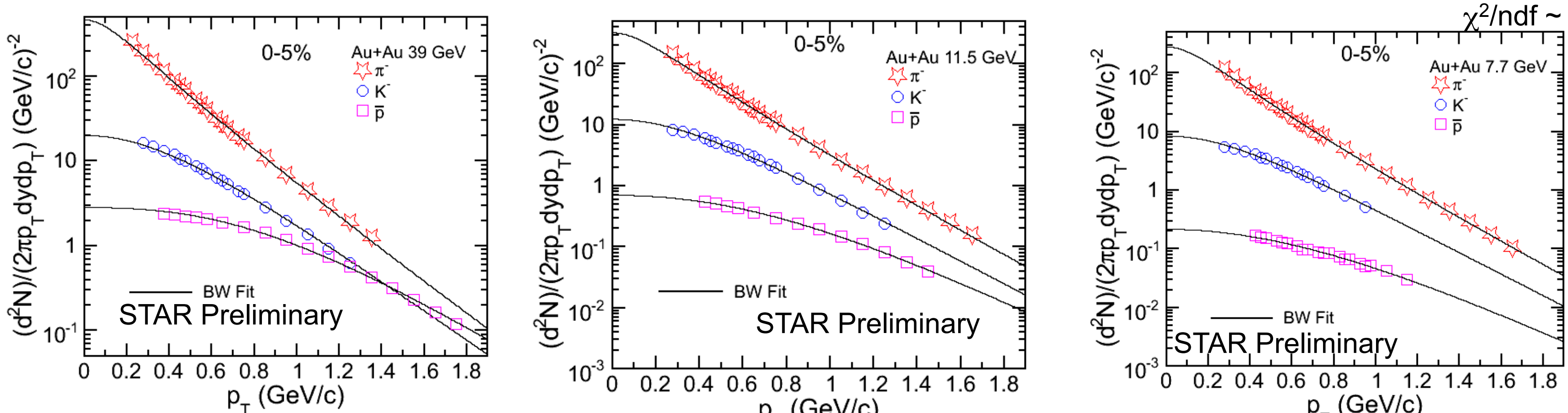
χ^2/ndf ~ O(1)

Kinetic Freeze-out:

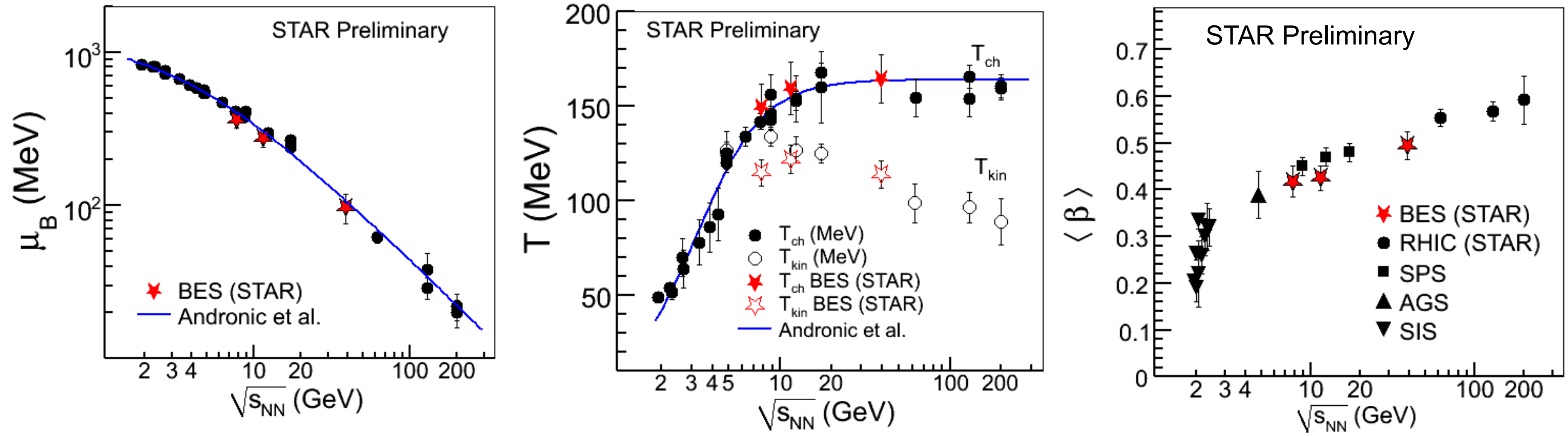
$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

STAR : PRC 79, 034909 (2009) and ref. therein
STAR : NPA 757, 102 (2005).
P. Braun-Munzinger et al. PLB 344, 43 (1995).
E. Schnedermann et al. PRC 48, 2462 (1993).

χ^2/ndf ~ O(1)



Energy Dependence of Freeze-out Parameters

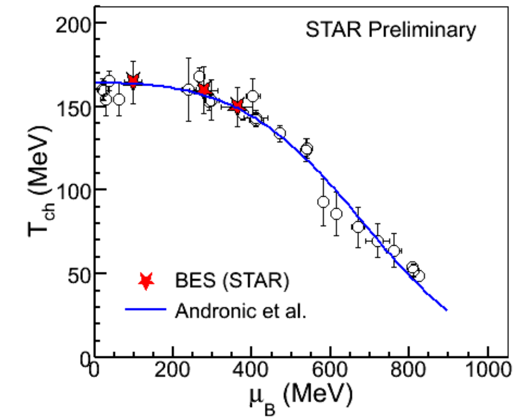


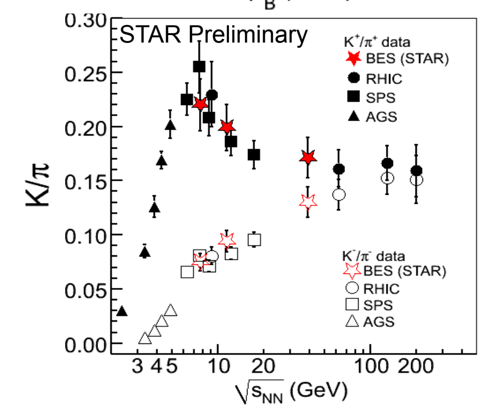
STAR : PRC 79 (2009) 034909 and references therein
STAR : NPA 757 (2005) 102
Andronic et al. NPA 834 (2010) 237

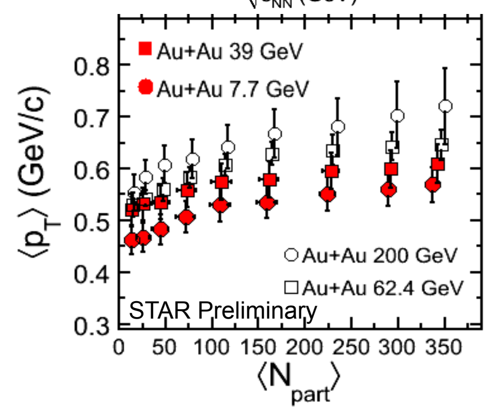
- Baryon chemical potential decreases with energy
- Chemical freeze-out temperature increases with energy at low energies and becomes almost similar at higher energies
- Kinetic freeze-out temperature decreases with energy after $\sqrt{s_{NN}}$ ~ 7.7 GeV
- Average flow velocity increases with energy

Summary

- Bulk Properties:
  - dN/dy increases with $\sqrt{s_{NN}}$ and consistent with published energy dependence trend. Inverse slopes of spectra follow: π < K < p
- Baryon Density:
  - Reflected in energy dependence of K/π ratio
  - K^-/K^+ correlation with $\bar{p}/p$
- Freeze-out Conditions:
  - New measurements extend the μ_B range covered by RHIC data from 20-350 MeV in the phase diagram
  - Collectivity increases with beam energy, centrality and mass







Thanks

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Models: K/π

Statistical Model

J. Cleymans, H. Oeschler, K. Redlich and S. Wheaton, Eur. Phys. J. A 29, 119 (2006)

- ✓Entropy/T^3 as function of collision energy - increases for mesons, and decreases for baryons
- ✓Thus, a rapid change is expected at the crossing of the two curves, as the hadronic gas undergoes a transition from a baryon- dominated to a meson-dominated gas,T=140 MeV, μ_B=410 MeV, energy ~ 8.2 GeV

Statistical Hadronization Model

J. Rafelski, I. Kuznetsova and J. Letessier, J. Phys. G 35, 044011 (2008)

- ✓Strong interactions saturate particle production matrix elements
- ✓Below 7.6 GeV system in chemical non-equilibrium, above over saturation of chemical composition

Hadronic non-equilibrium Kinetic Model

B. Tomasik and E. E. Kolomeitsev, Eur. Phys. J. C 49, 115 (2007)

- ✓Surplus of strange particles are produced in secondary reactions of hadrons genera- -ted in nuclear collisions.
- ✓ Amount of kaons depend on the lifetime of the whole system

Thermal Model

A. Andronic, P. Braun-Munzinger and J. Stachel , Phys. Lett B 673, 142 (2009)

- ✓Includes many higher resonances (m > 2 GeV) and σ-meson which is neglected in most of the models

Hadron Resonance Gas + Hagedorn Model

S. Chatterjee, R. M. Godbole, and S. Gupta, Phys. Rev. C 81, 044907 (2010)

- ✓Assumes a bag of hadron gas. Includes all hadrons up to masses 2 GeV as given in PDG
- ✓Unknown hadron resonances are included through Hagedorn formula
- ✓Assumes that the strangeness in the baryon sector decays to strange baryons and does not contribute to kaon production

Invariant Yields

Au+Au 11.5 GeV   Au+Au 7.7 GeV