Identified Hadron Production from the RHIC Beam Energy Scan Program

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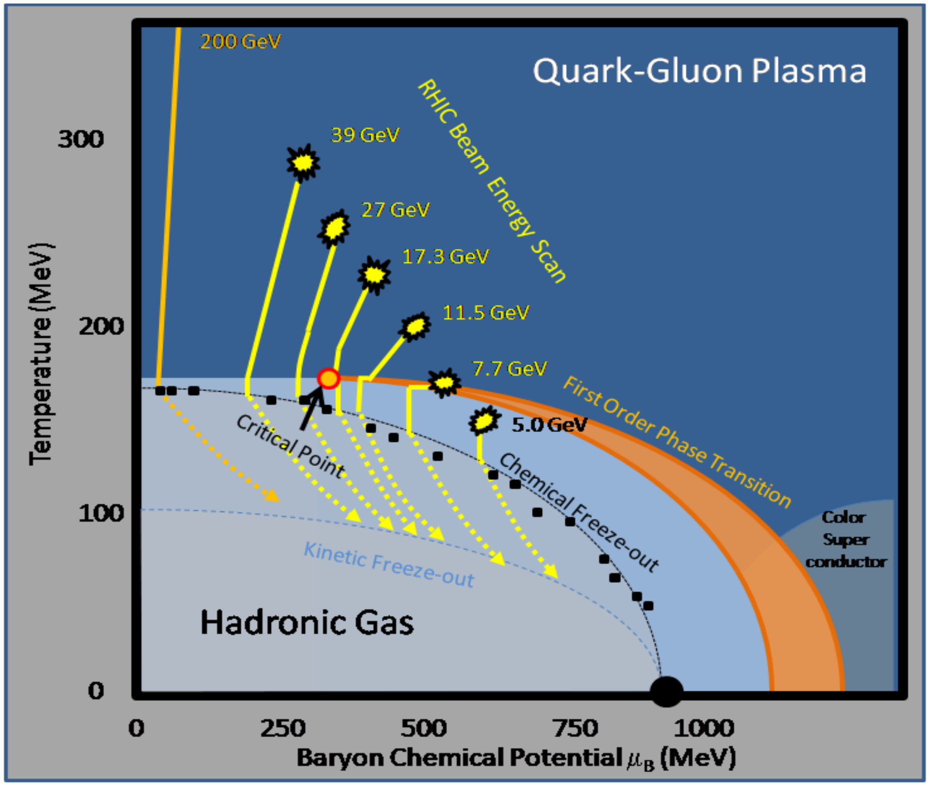
Outline:

- Motivation
- Identified hadron yields and average m_T
- Particle ratios
- Freeze-out parameters
- Nuclear modification factor R_{AA} (from PHENIX)
- Summary

Motivation-I

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:

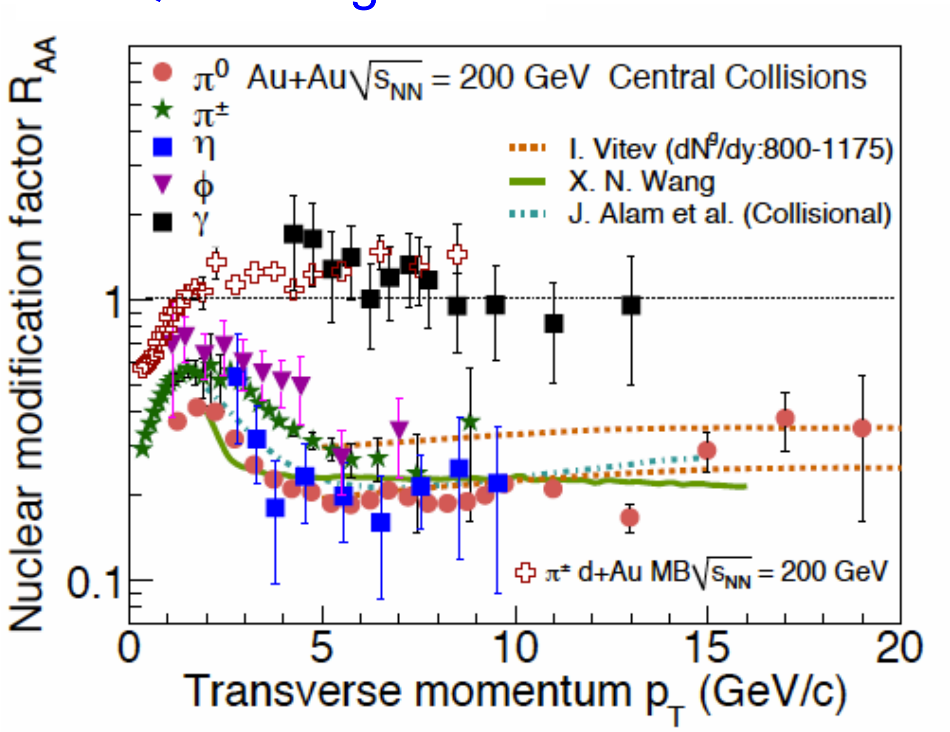
- Search for the phase boundary

- Search for the possible QCD Critical Point

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 $<\beta>$)

Motivation-II

Jet Quenching:



STAR: PRL 97, 152301 (2006); PLB 655, 104 (2007); PLB 637, 161 (2006).
PHENIX: PRC 83,024909 (2011); PRC 82, 011902 (R) (2010); PRL 101, 232301 (2008);PRL 96, 202301 (2006).

$$R_{AA} = \frac{dN_{AA}/d\eta d^2 p_T}{T_{AB} d\sigma_{NN}/d\eta d^2 p_T}$$

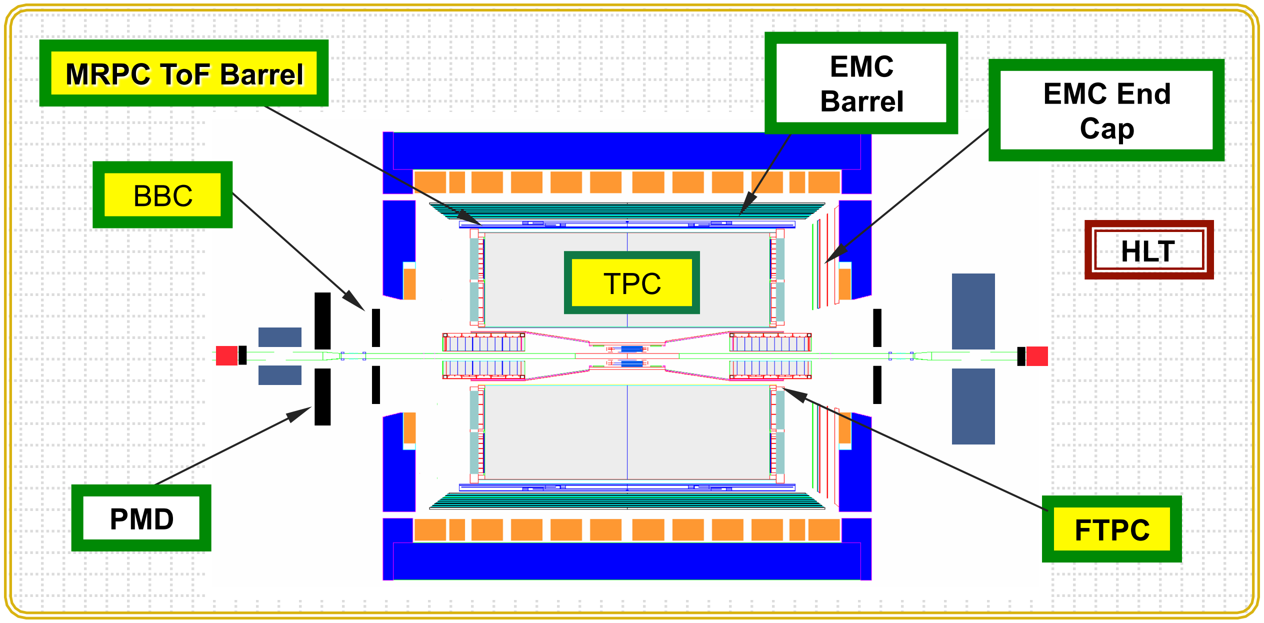
$$T_{AB} = N_{binary}/\sigma_{inelastic}^{pp}$$

N_{binary} : Number of binary collisions

- Large suppression of high p_T meson production in central Au+Au collisions
- No suppression in d+Au experiment
- Similar suppression in π, η and ϕ: *suppression is at partonic level*
- No suppression for direct photons: *final state effect*

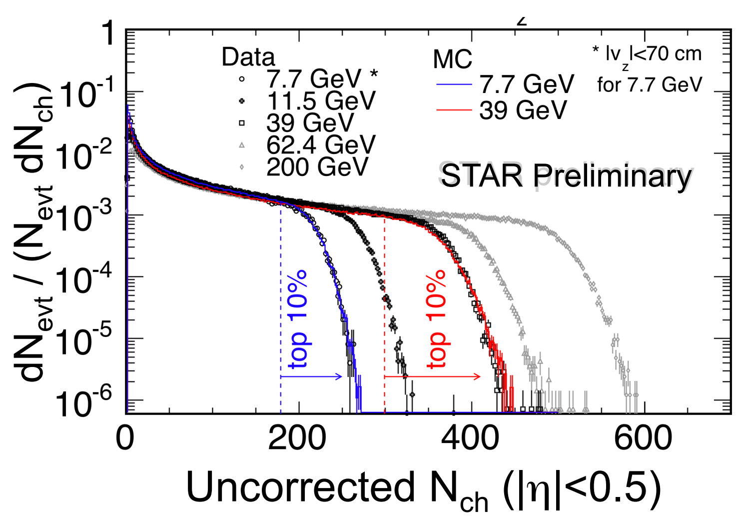
What is the energy dependence of R_{AA} for the BES data ??

STAR: 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%

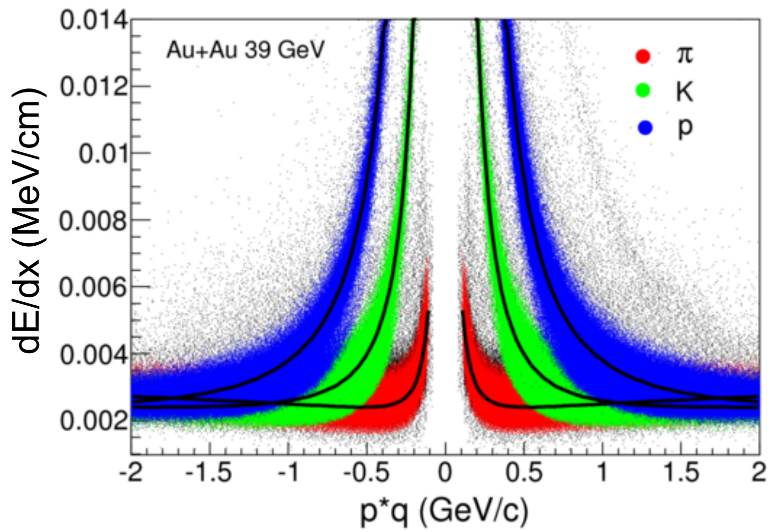


$\sqrt{s_{NN}}$ (GeV)	Good events (proposed) Million MB
5.0	
7.7	~5(5) - 2010
11.5	~11 (5) - 2010
19.6	~17 (15) - 2011
27	~130 (150) - 2011
39	~170 (25) - 2010

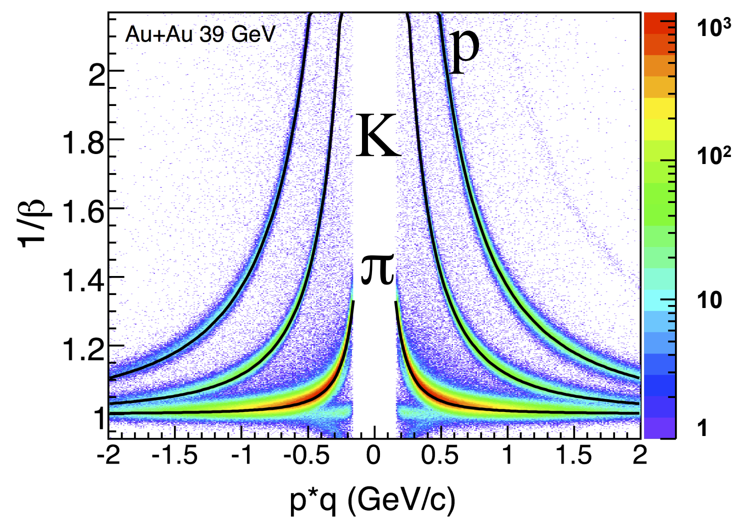
STAR: $\pi^{+/-}$, $K^{+/-}$ and p/$\bar{p}$ Identification

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

TPC



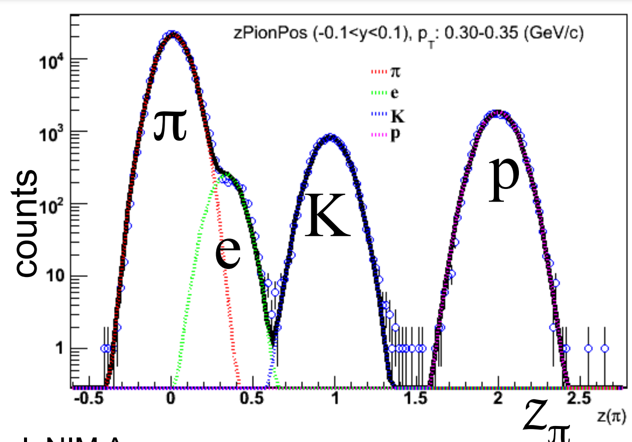
TPC+ToF

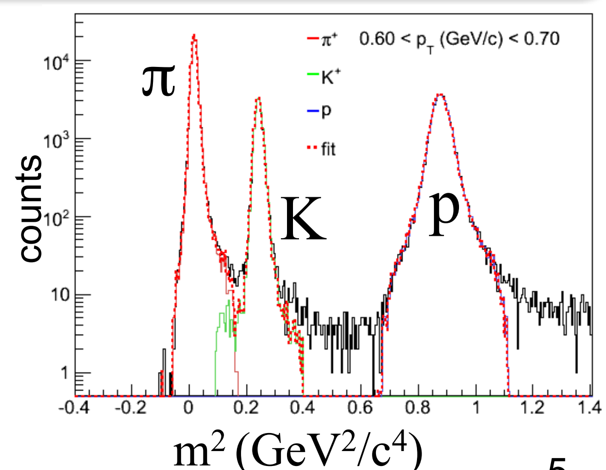


$$z = \log\left(\frac{(dE/dx)_{meas.}}{(dE/dx)_{theory}}\right)$$

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

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





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

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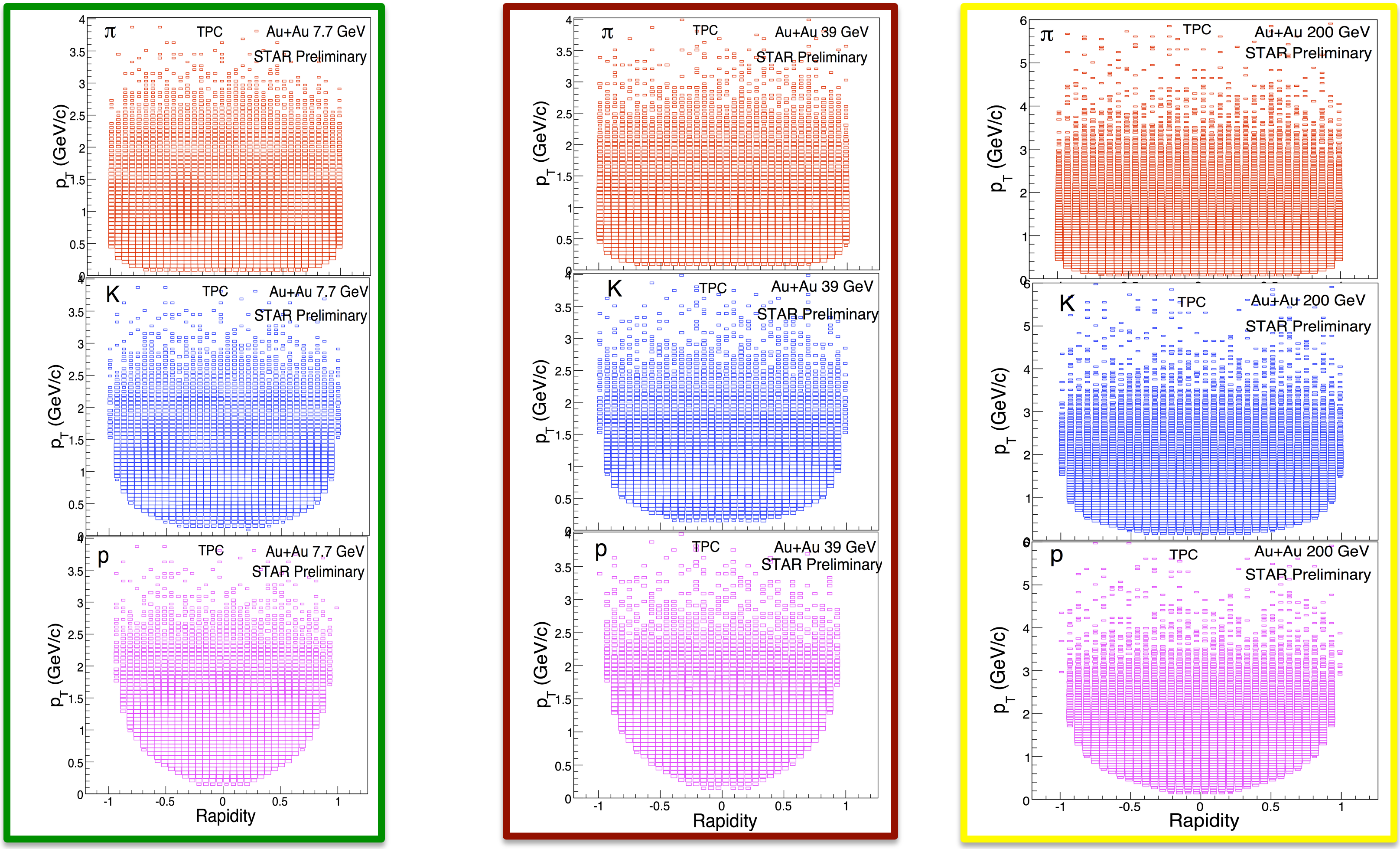
STAR: Large and Uniform Acceptance

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

π:

K:

p:

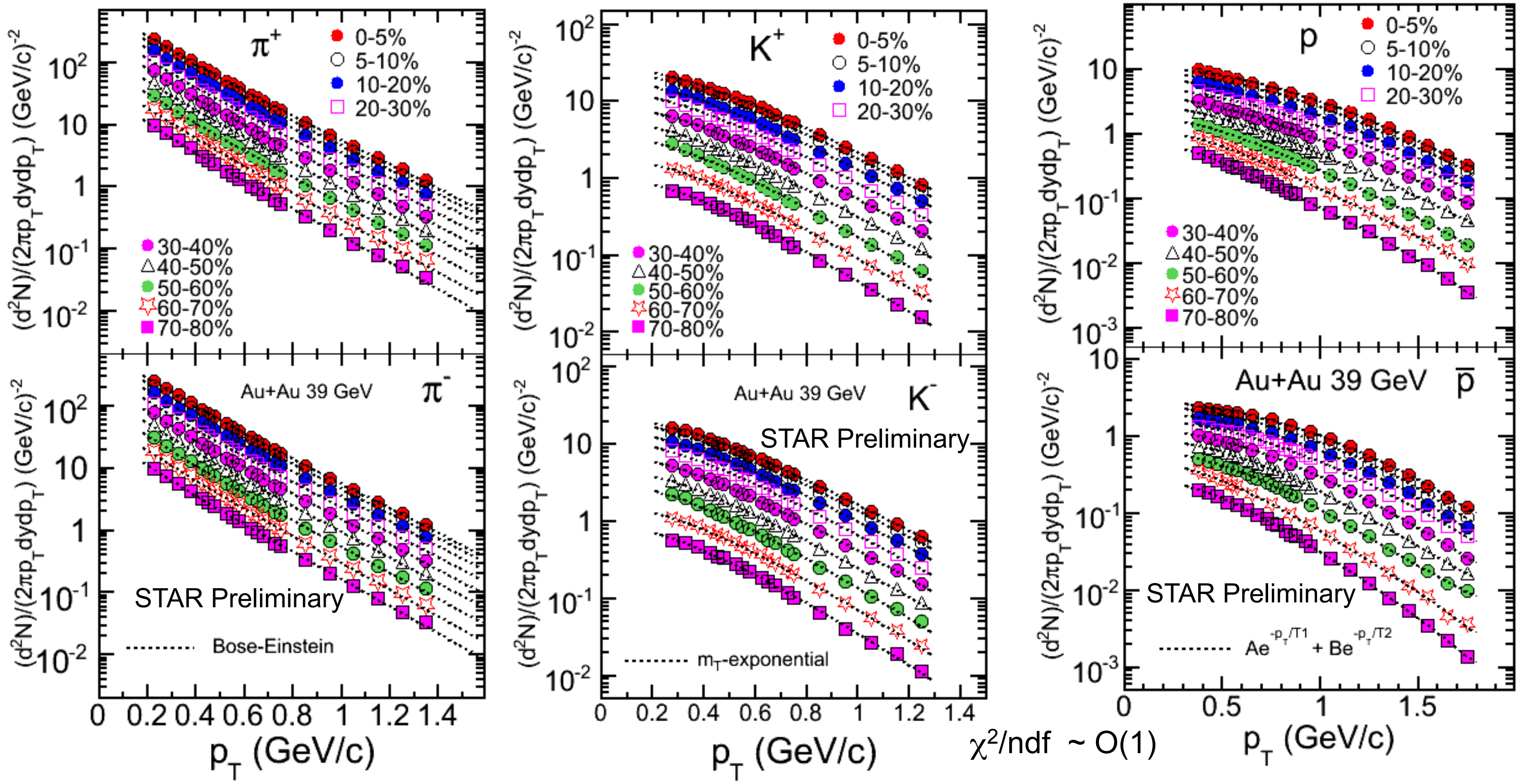


- ➢ Similar acceptance at midrapidity - Crucial for all analyses

Results: Identified hadrons measurements from STAR

Invariant Yield

Au+Au 39 GeV:



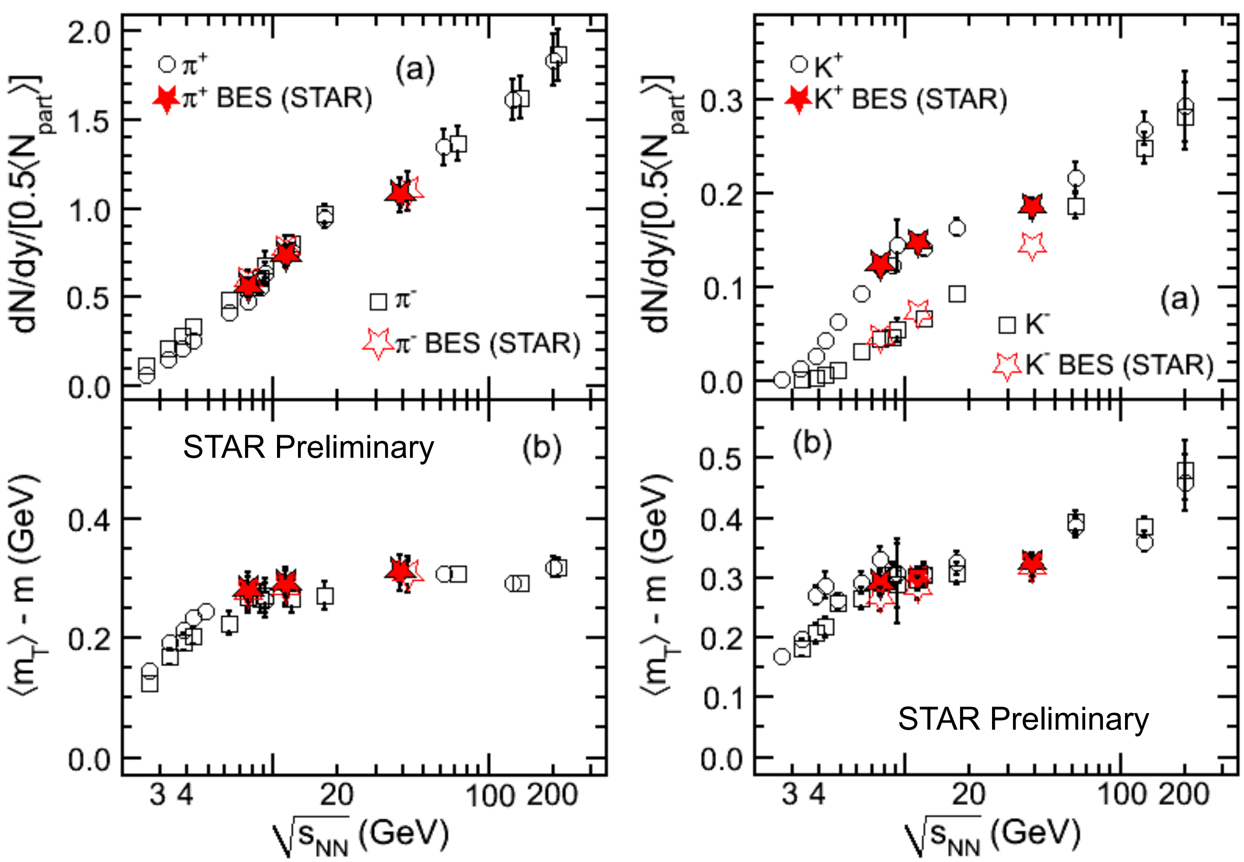
We measure ~ 70-80% of π, K and p within our p_T acceptance at mid-rapidity

Similar measurements are carried out for 7.7 and 11.5 GeV collisions

Energy Dependence of Yields & $<m_T>$

Midrapidity and central collisions

Errors: statistical and systematic added in quadrature



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

- Assuming a thermodynamic system:

  T ~ $<m_T>$ - m

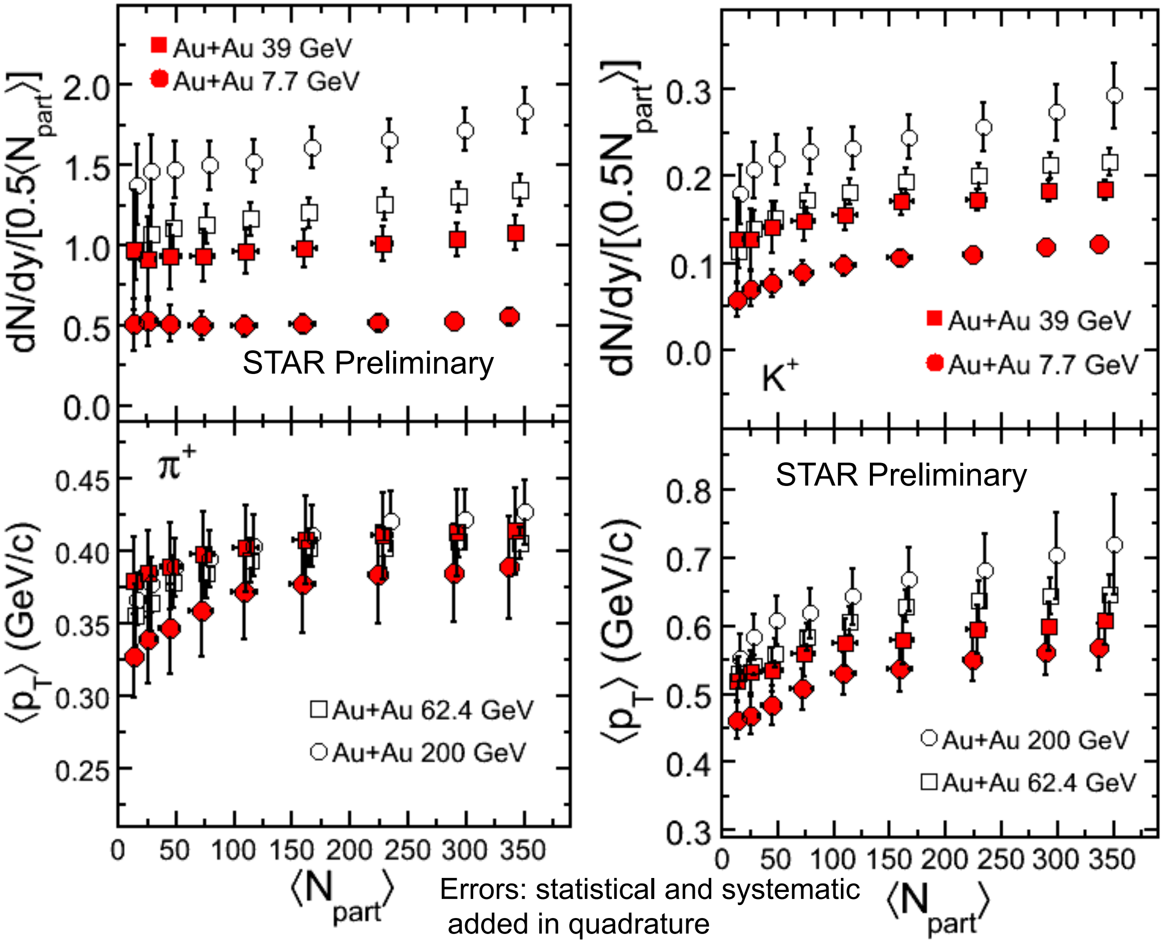
  entropy ~ dN/dy

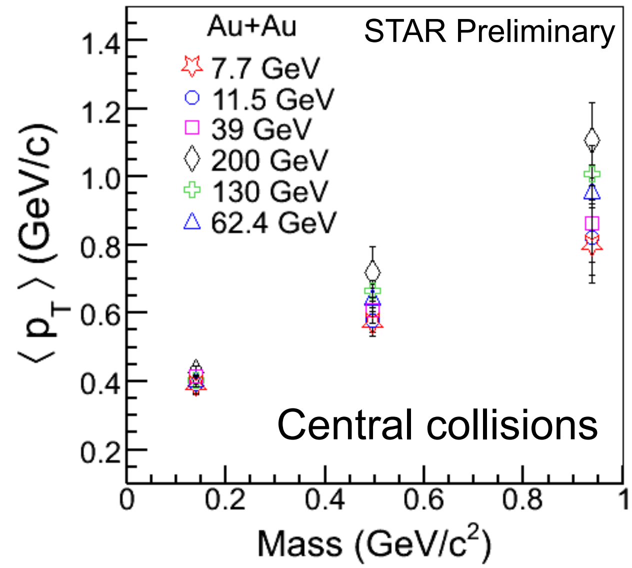
  $\propto \log(\sqrt{s_{NN}})$

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
- $<m_T>$ - m remains constant for BES energies (7.7, 11.5, and 39 GeV)

Centrality Dependence of Yields & $<p_T>$





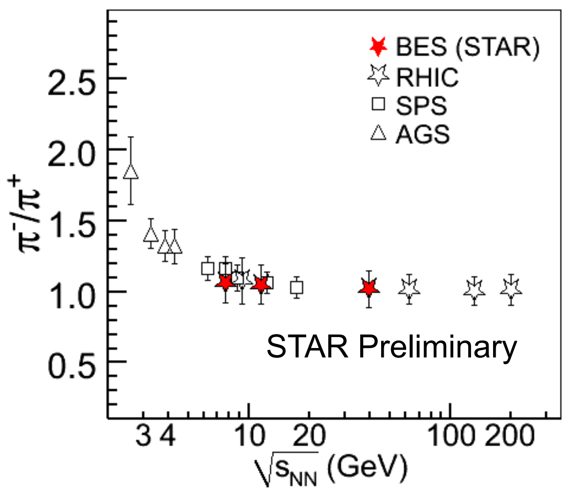
✧ $dN/dy/0.5N_{part}$ ~ constant for π as function of centrality at 7.7 GeV. For other energies and kaons, it increases with centrality.

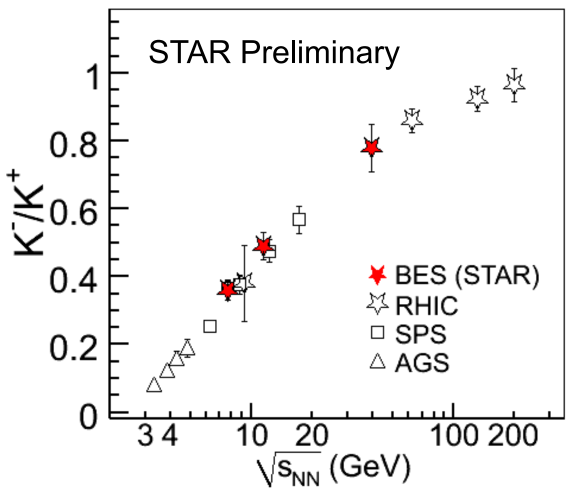
✧ $<p_T>$ increases with centrality – collectivity increases with centrality

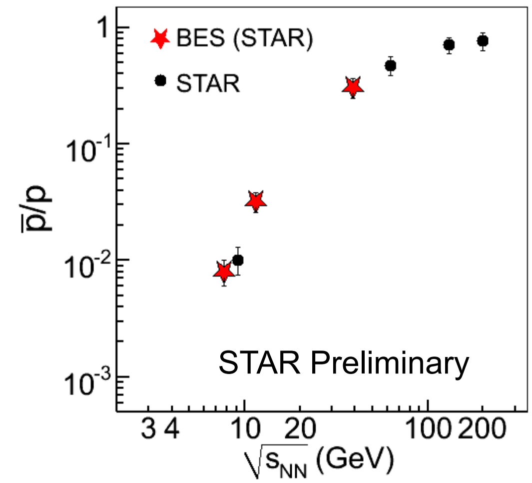
✧ $<p_T>$ for π seems to be similar from 39 GeV to 200 GeV

✧ $<p_T>$ increases with mass of the particle

Anti-Particle to Particle Ratios

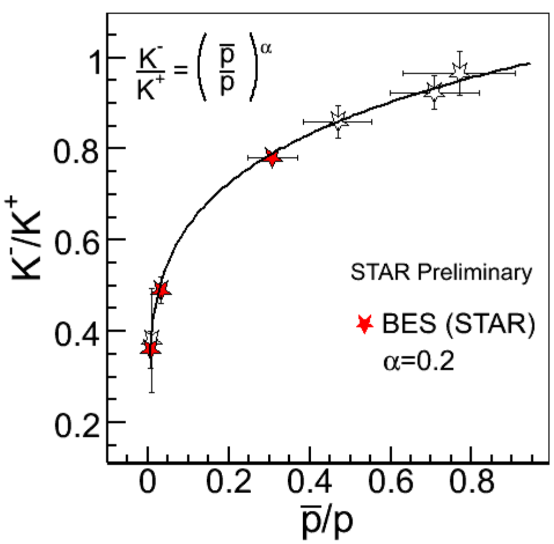






Midrapidity and central collisions

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

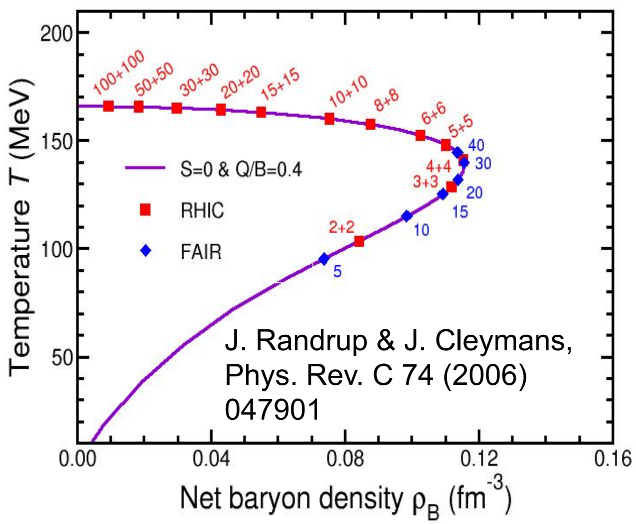
Correlation between K^-/K^+ and $\bar{p}/p$:

- Follows power law behavior
- Shows how the kaon production is related to net-baryon density.

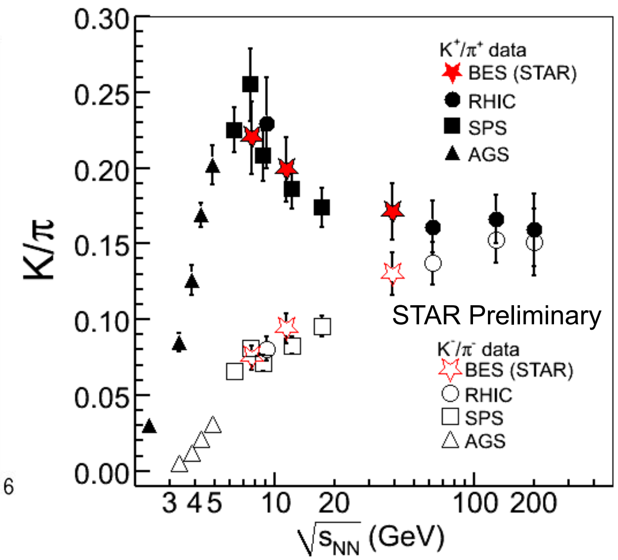
BRAHMS: PRL 90, 102301 (2003)
J. Cleymans et al. ZPC 57, 135 (1993)

Particle Ratios

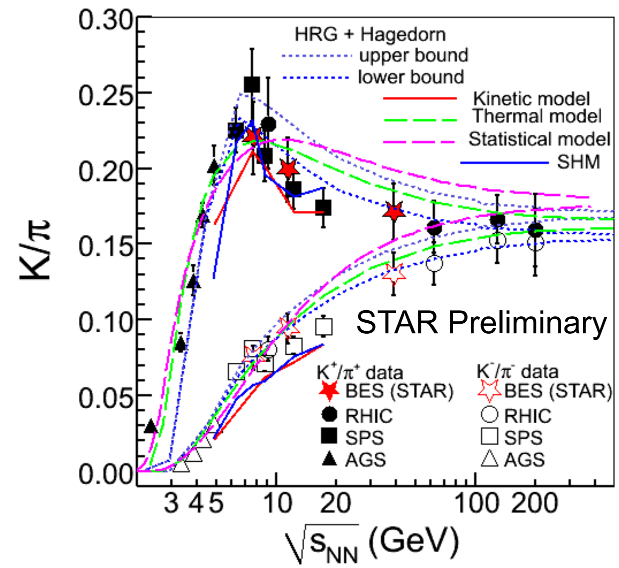
The maximum net-baryon density at freeze-out: **$\sqrt{s_{NN}}$ ~ 8 GeV**



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.

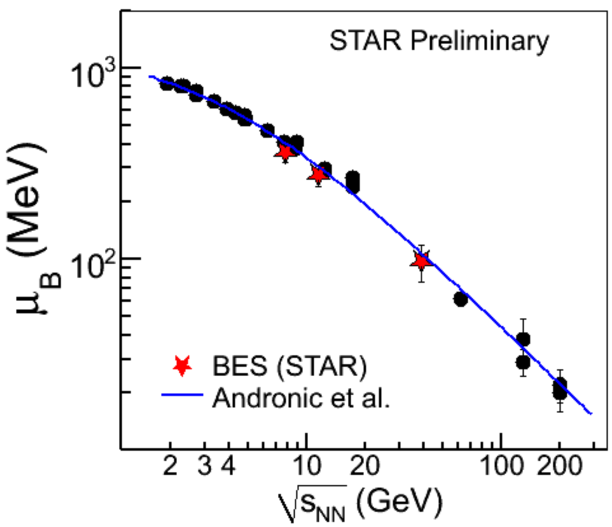
J. Cleymans et al., Eur. Phys. J. A 29, 119 (2006); A. Andronic et al., Phys. Lett B 673, 142 (2009); J. Rafelski, et al. J. Phys. G 35, 044011 (2008); B. Tomasik et al., Eur. Phys. J. C 49, 115 (2007) S. Chatterjee et al., Phys. Rev. C 81, 044907 (2010)

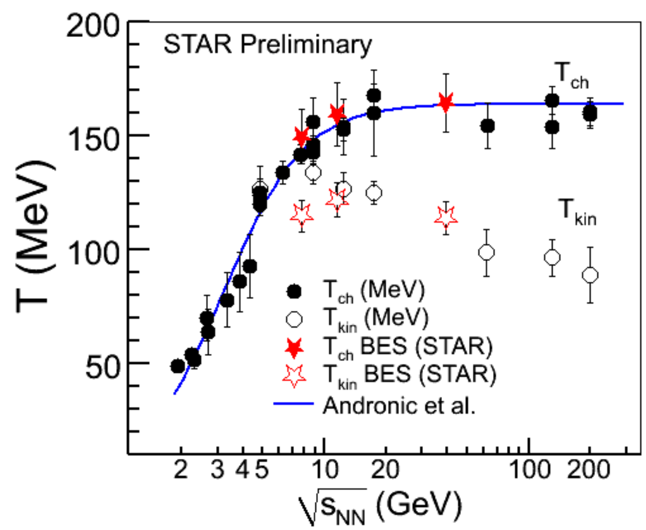
- K/π ratio indicates the strangeness enhancement
- K^+/π^+ vs. $\sqrt{s_{NN}}$ seems to be best explained using HRG+Hagedorn model
- K/π at BES energies are consistent with published energy dependence

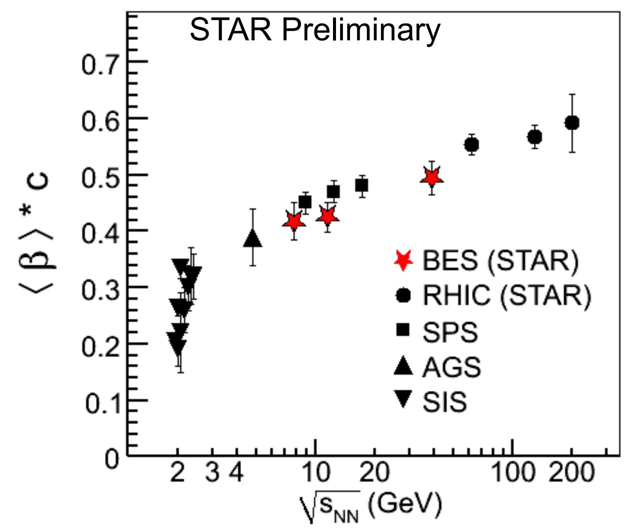
Energy Dependence of Freeze-out Parameters

Spectra and ratios used to obtain freeze-out parameters: μ_B, T_{ch}, T_{kin}, and $<\beta>$

central collisions



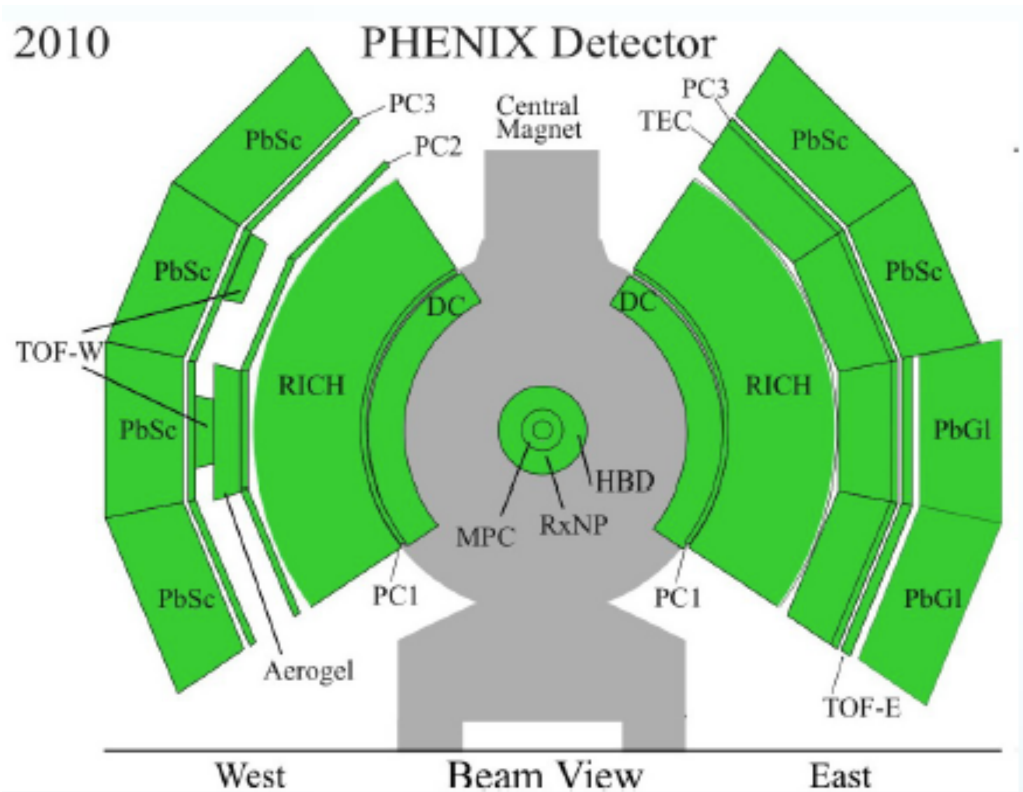


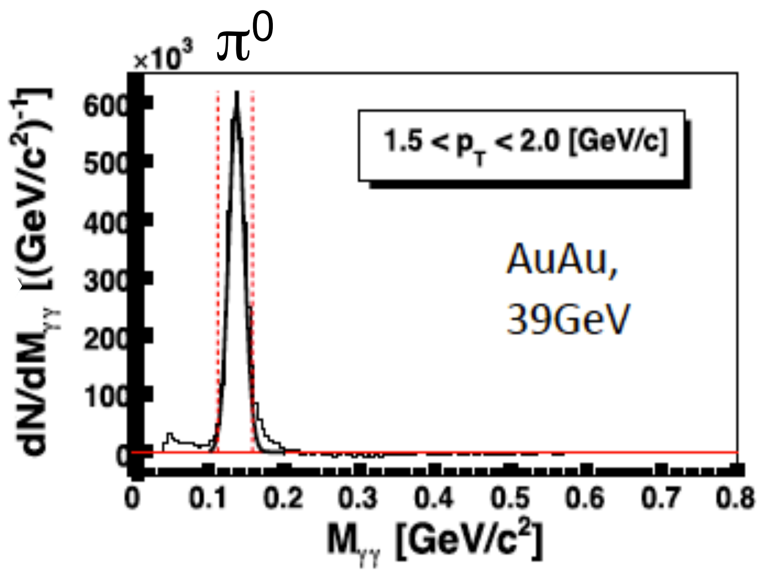


STAR : PRC 79 (2009) 034909 and references therein; STAR : NPA 757 (2005) 102; Andronic et al. NPA 834 (2010) 237

- 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

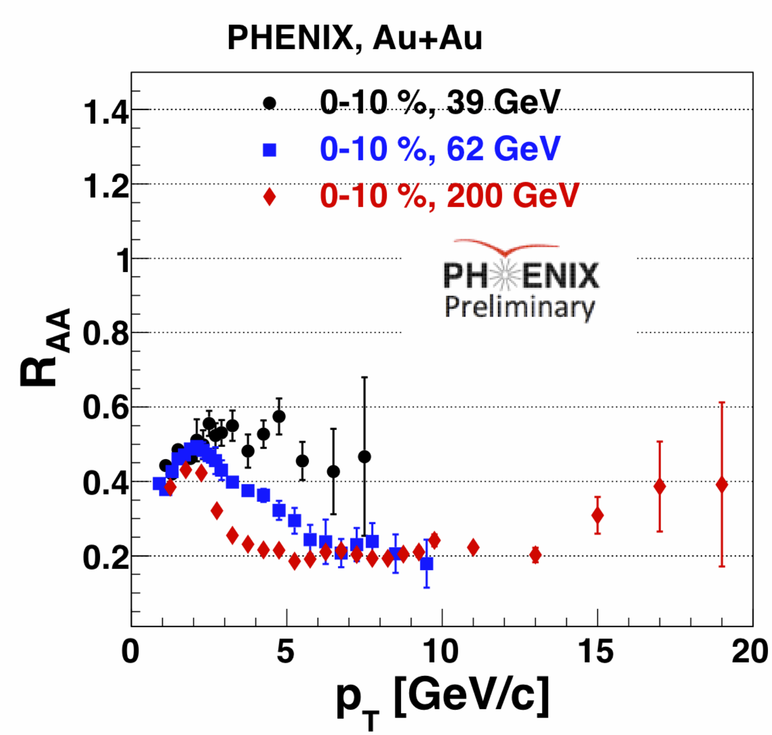
Results: Nuclear modification factor R_{AA} from PHENIX

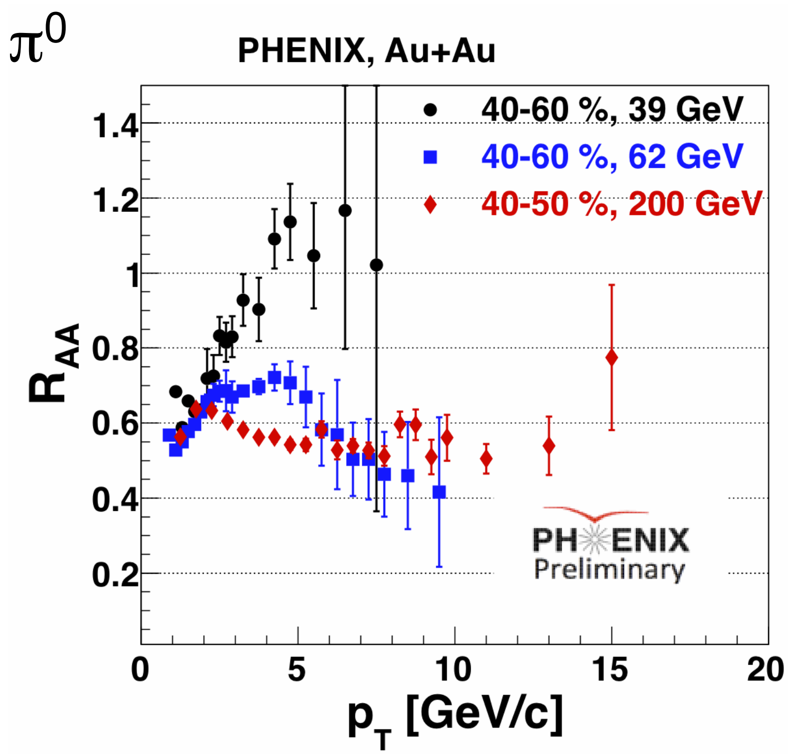




Nuclear Modification Factor R_{AA} or Jet Quenching

QM2011: Norbert Novitzky

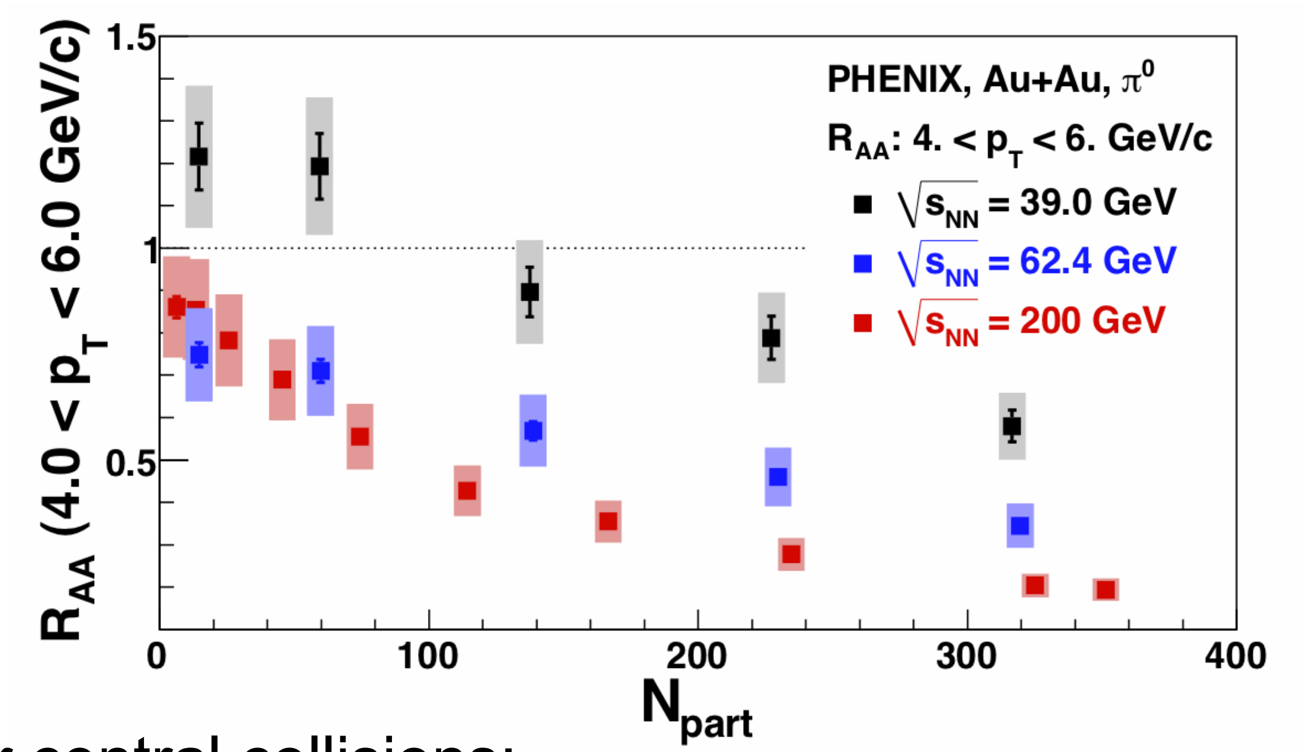




- Central collisions: Strong suppression for $\sqrt{s_{NN}}$ = 39, 62.4 and 200 GeV
- Peripheral collisions: 62.4 and 200 GeV are suppressed but not 39 GeV

p+p reference at 39GeV taken from E0706 taking care of rapidity acceptance difference

Centrality and Energy Dependence of R_{AA}



QM2011: Norbert Novitzky

- For central collisions:

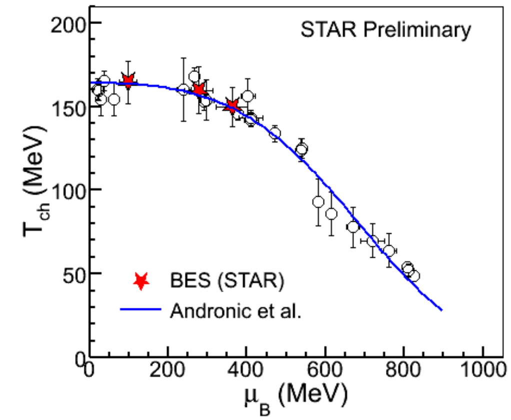
$$R_{AA}\,(39) > R_{AA}\,(62.4) > R_{AA}\,(200)$$

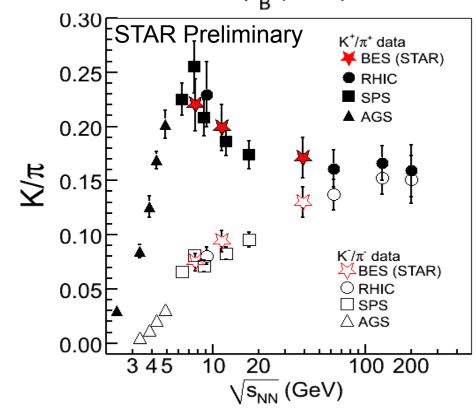
- For peripheral collisions:

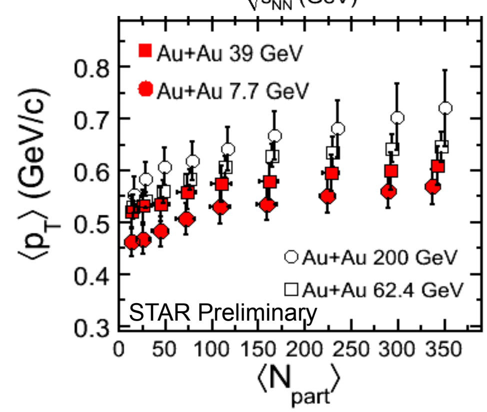
$$R_{AA}\,(62.4) \sim R_{AA}\,(200);\ R_{AA}\,(39) \geq 1$$

Summary

- ❑ Bulk Properties:
  - dN/dy increases with $\sqrt{s_{NN}}$ and consistent with published energy dependence trend. Inverse slopes of spectra follow: $\pi < K < p$
- ❑ 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

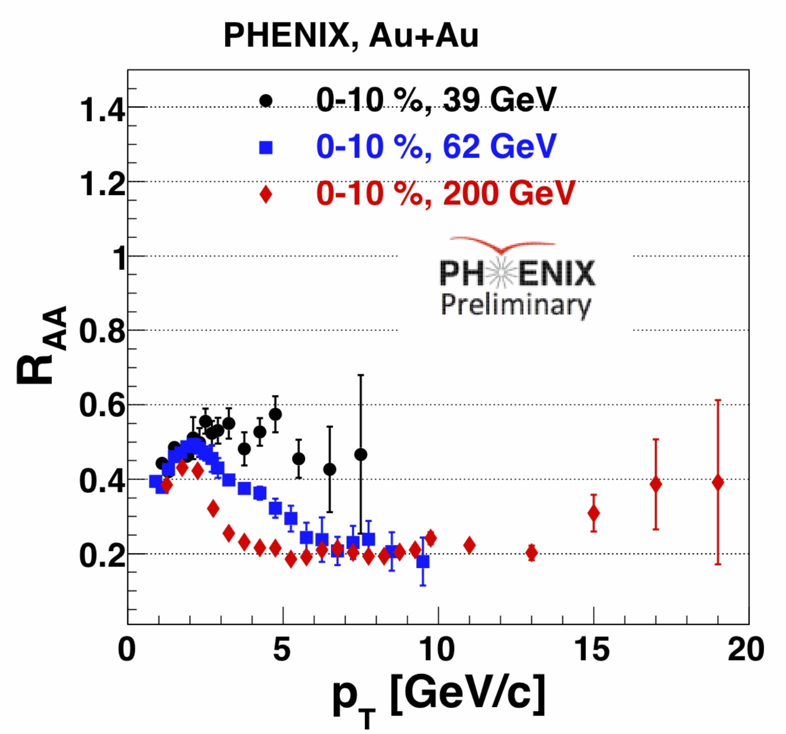






Summary Contd.

- Nuclear modification factor:
  - R_{AA} < 1 is also observed for central Au+Au collisions at $\sqrt{s_{NN}}$ = 39 GeV
  - For 0-10% centrality and p_T:4-6 GeV/c: R_{AA} (39) > R_{AA} (62.4) > R_{AA} (200)



- More results coming from $\sqrt{s_{NN}}$ = 19.6 and 27 GeV collisions

Thank You

Back-up

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

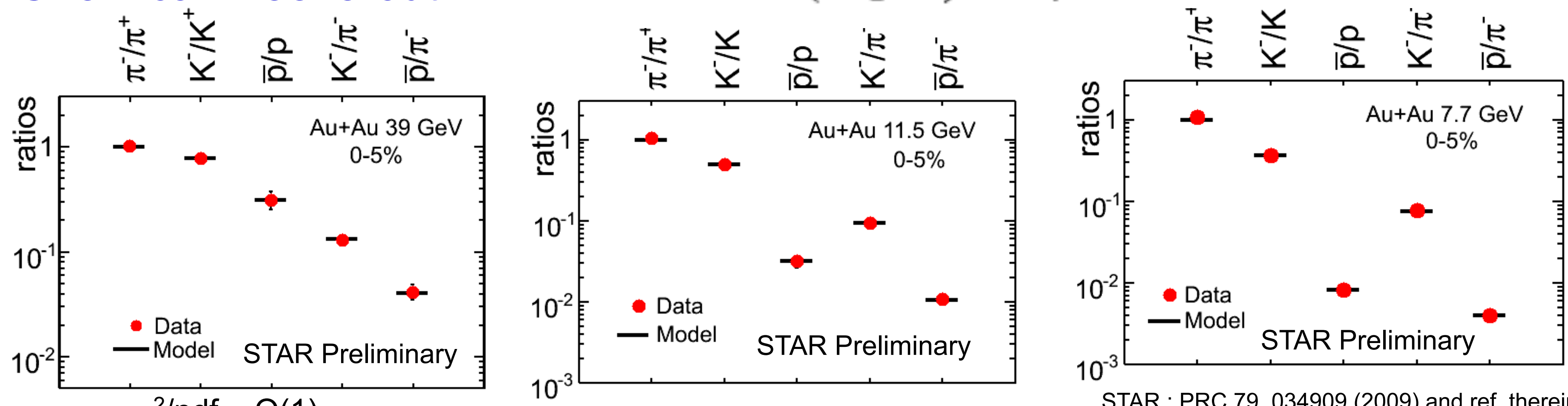
S. Chatterjee, R. M. Godbole, and S. Gupta, Phys. Rev. C 81, 044907 (2010)

- ✓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

Freeze-out Conditions

Chemical Freeze-out:

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



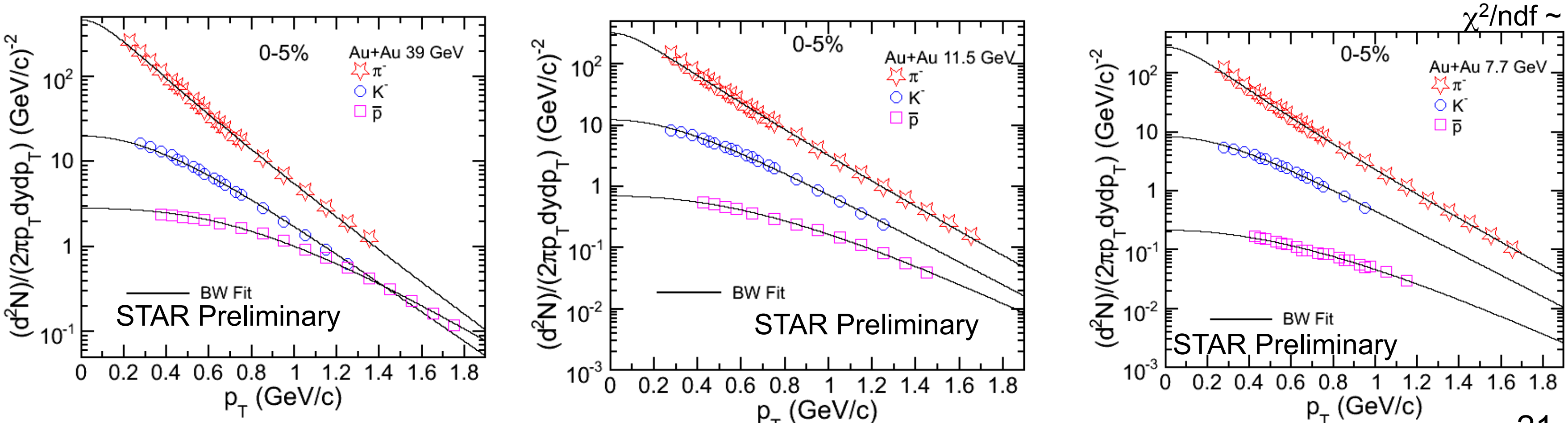
$\chi^2/ndf \sim O(1)$

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).

Kinetic Freeze-out:

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

$\chi^2/ndf \sim O(1)$



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