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

Lokesh Kumar (for the STAR Collaboration)

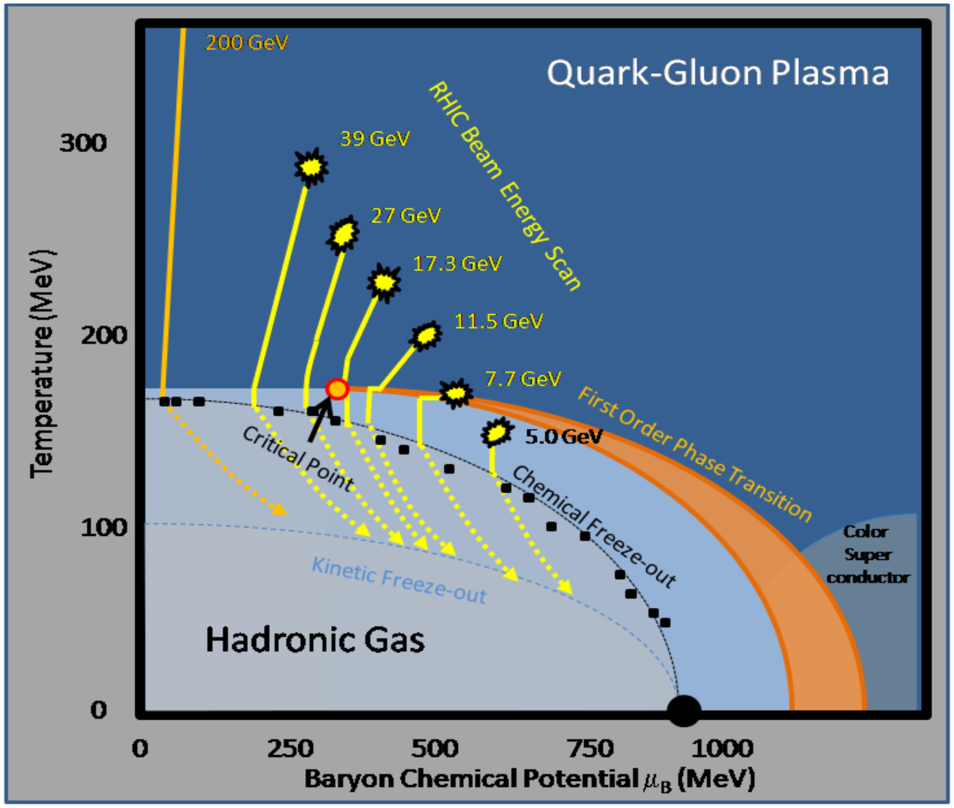
Kent State University

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

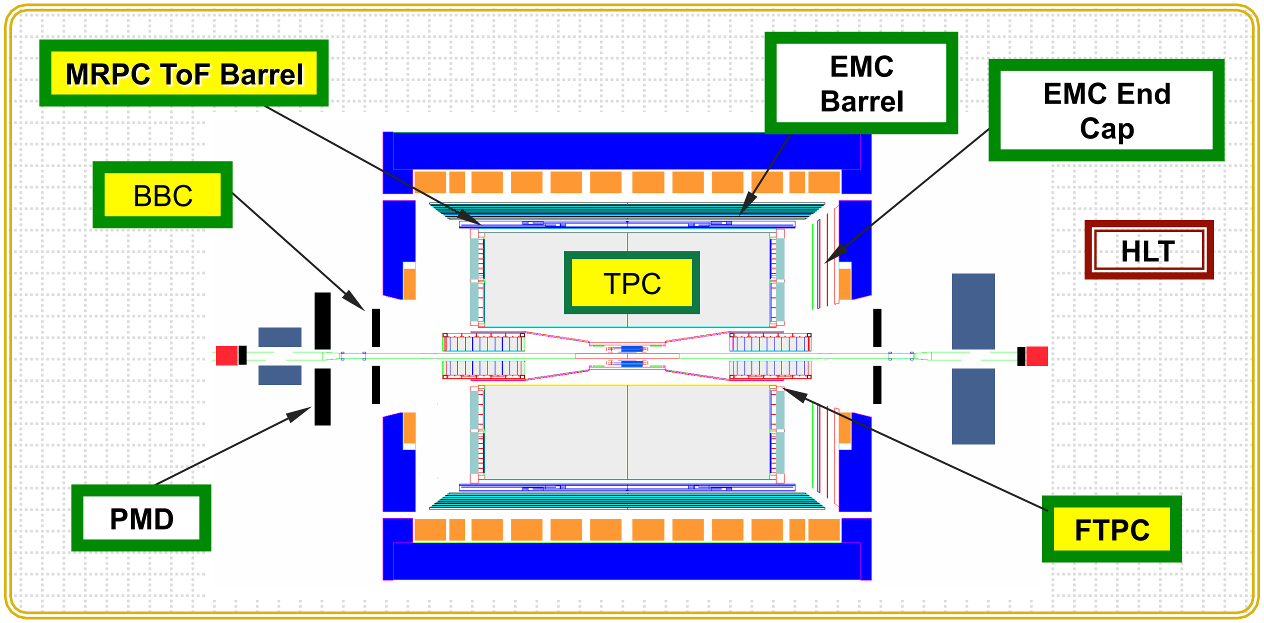
- Goal of RHIC BES program:

- Search for the phase boundary

- Search for the possible QCD Critical Point

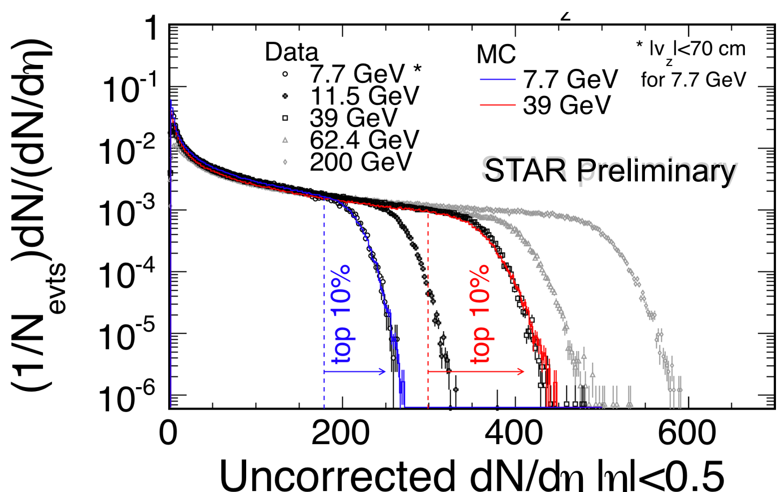
In this presentation we will discuss the bulk properties of the matter through the measurements of particle yields, average p_T, particle ratio and freeze-out parameters

Data Set and Detectors Used



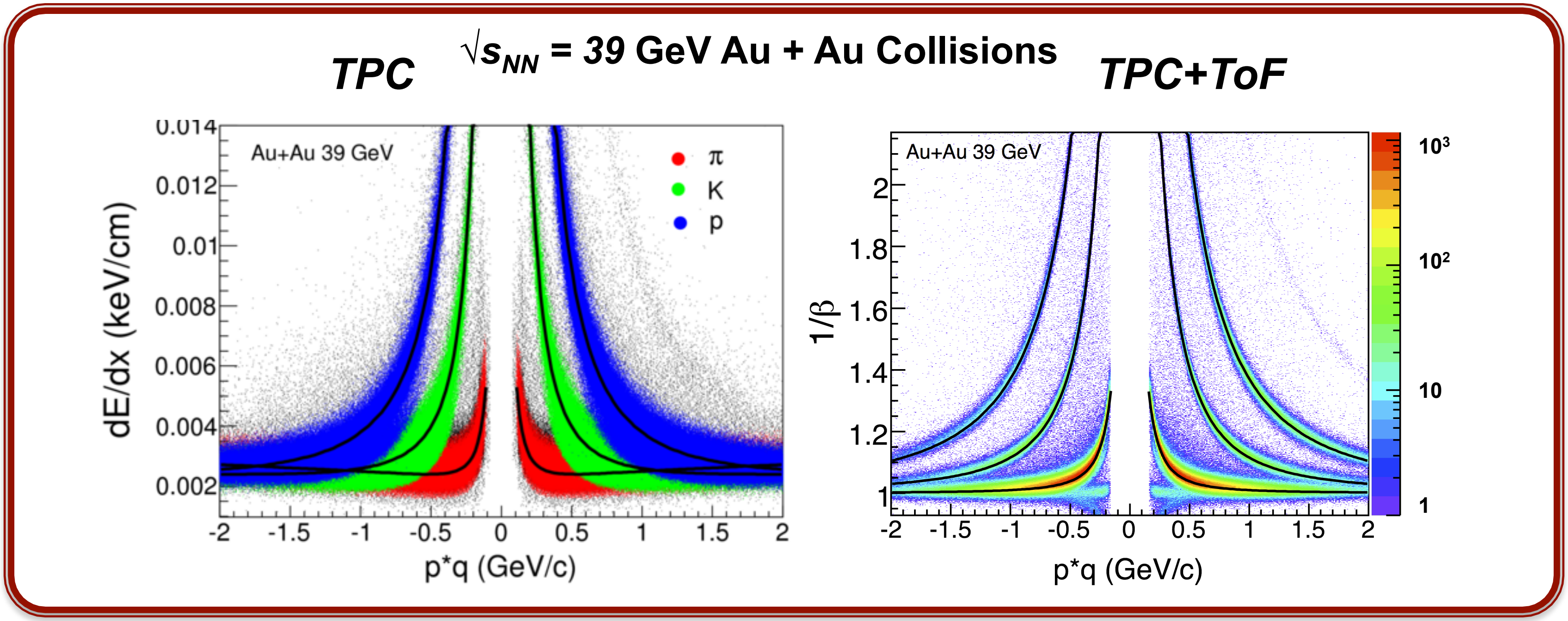
Particle identification over 2π in azimuthal angle and more than two units in rapidity

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)	Events taken (proposed) Million MB
5.0	
7.7	5(5)
11.5	7.5 (5)
19.6	84 (15)
27	(150 @ 400 Hz)
39	250 (25)

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



z = log(dedx_m/dedx_th)

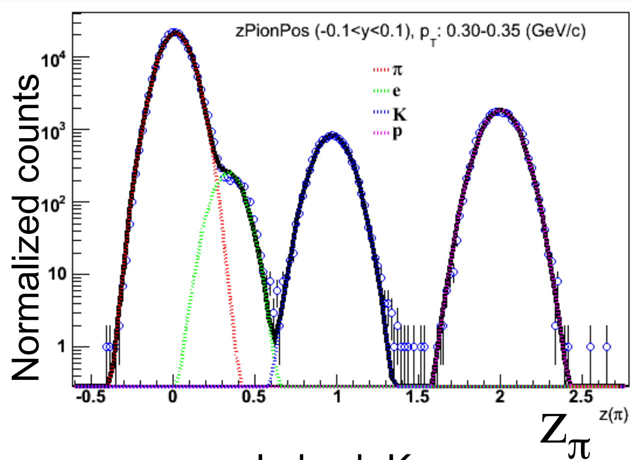
$m^2 = p^2 * [(tof*c/L)^2 - 1]$,

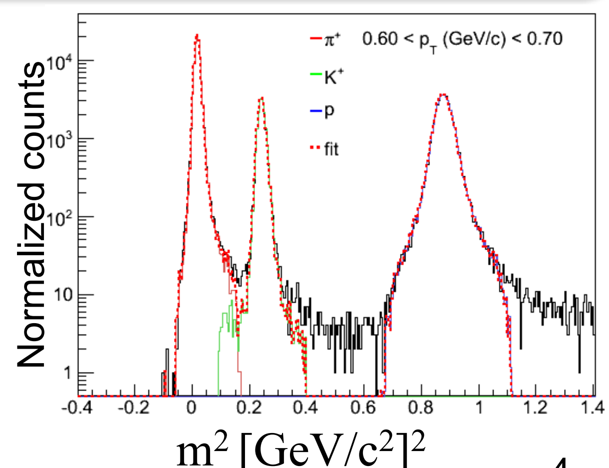
p= momentum

tof=time of flight

c=velocity of light

L=path length

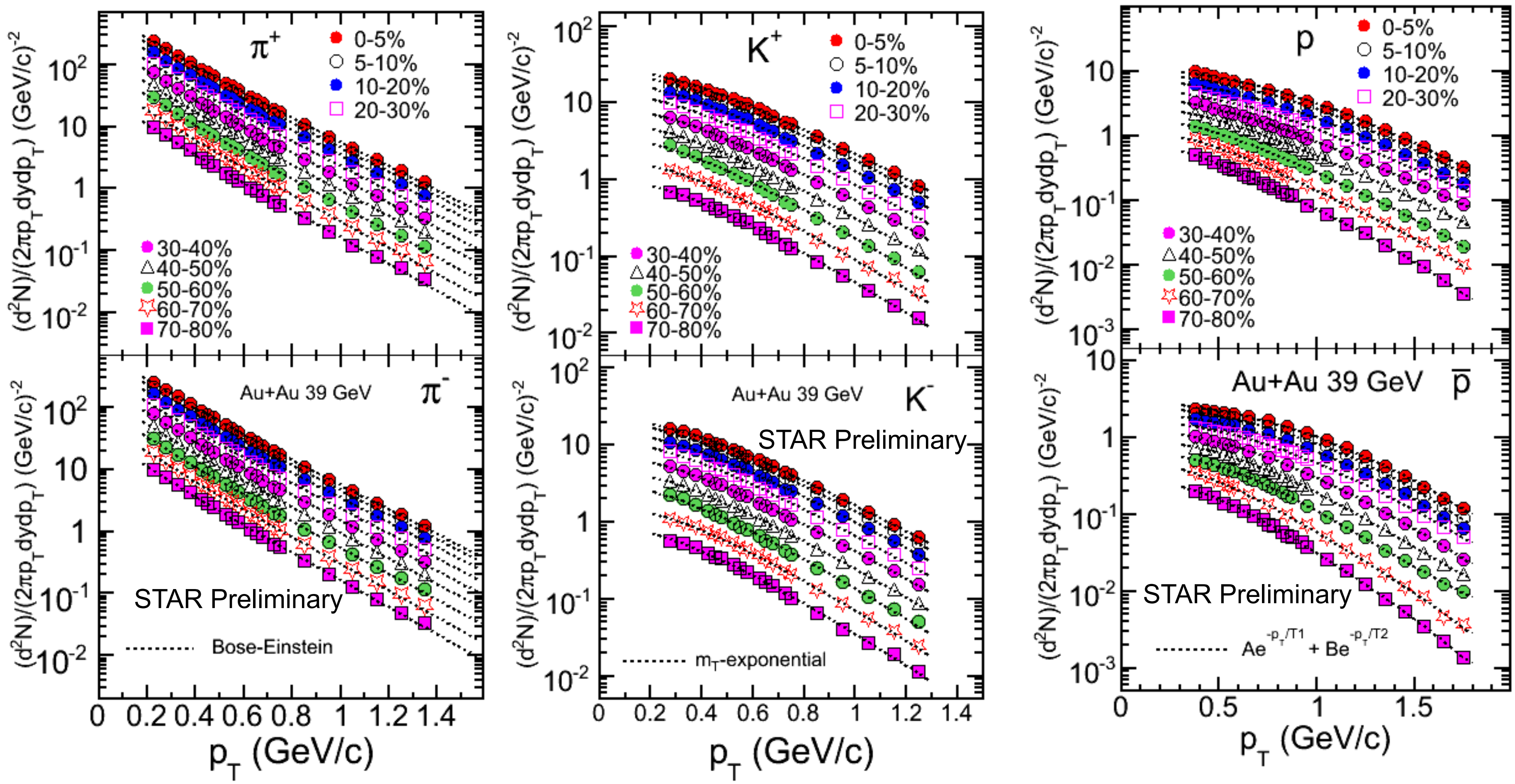




Lokesh Kumar

Invariant Yield

Au+Au 39 GeV:



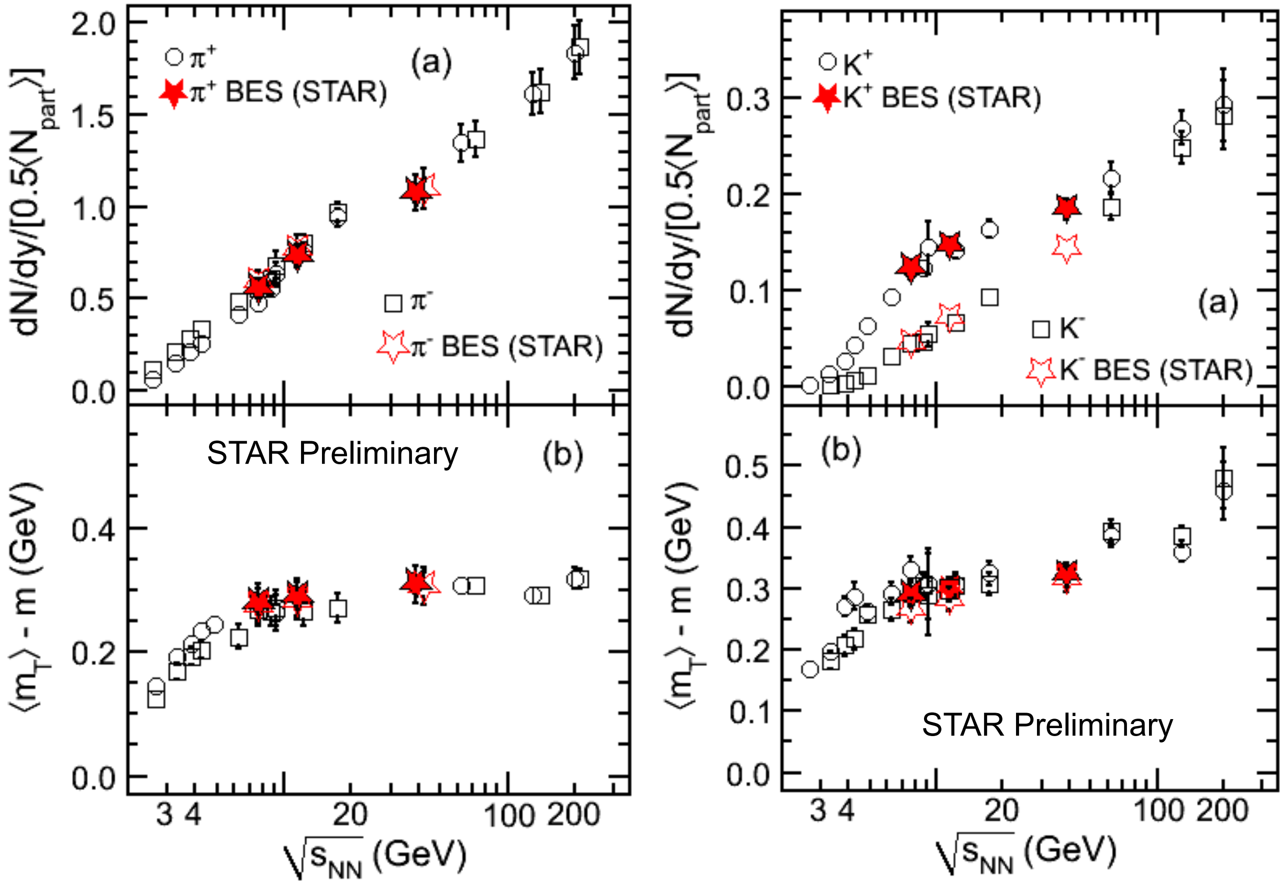
We measure ~ 70-77% of π, K and p within our p_T acceptance at mid-rapidity

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:

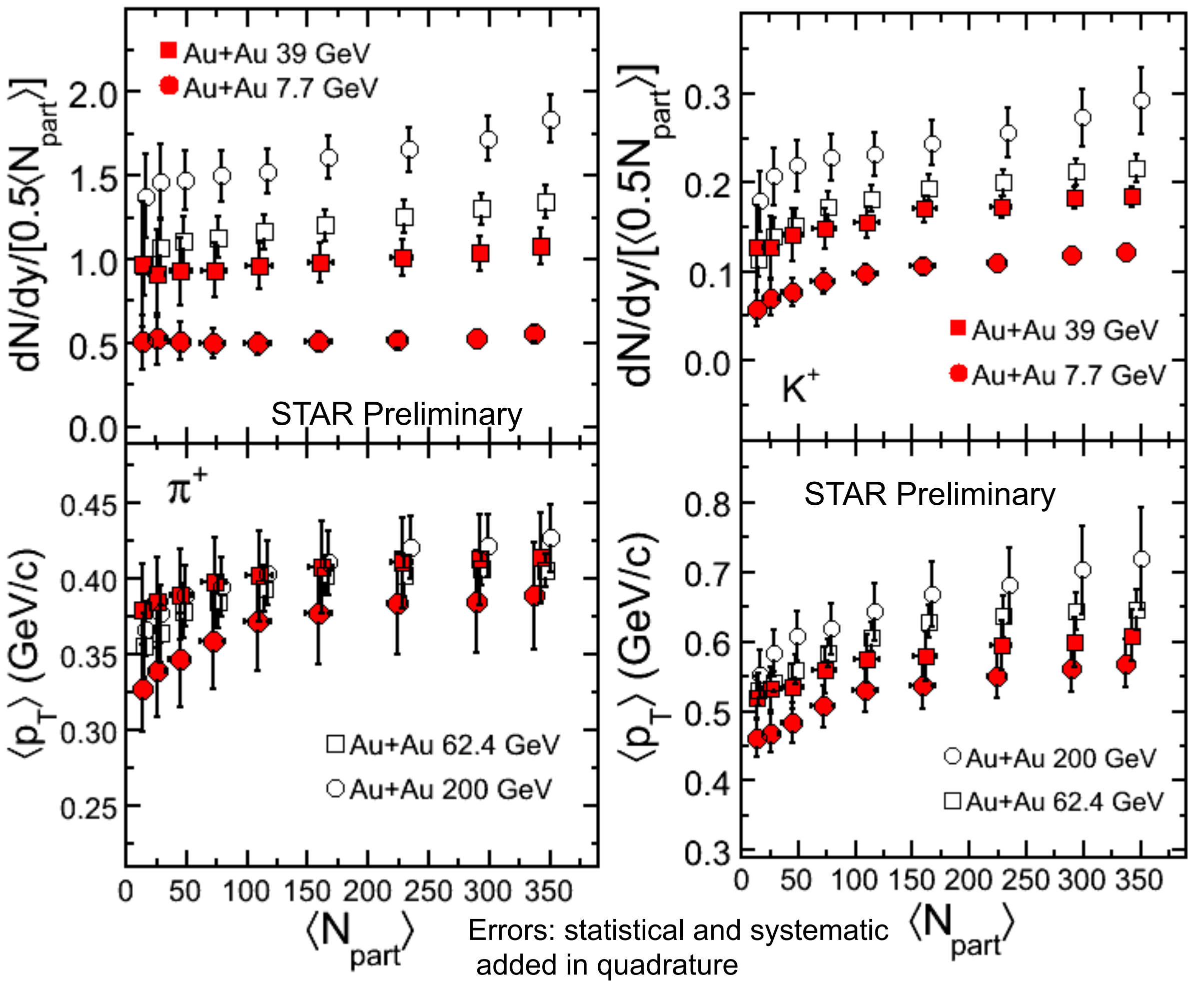
$T \sim <m_T> - m$

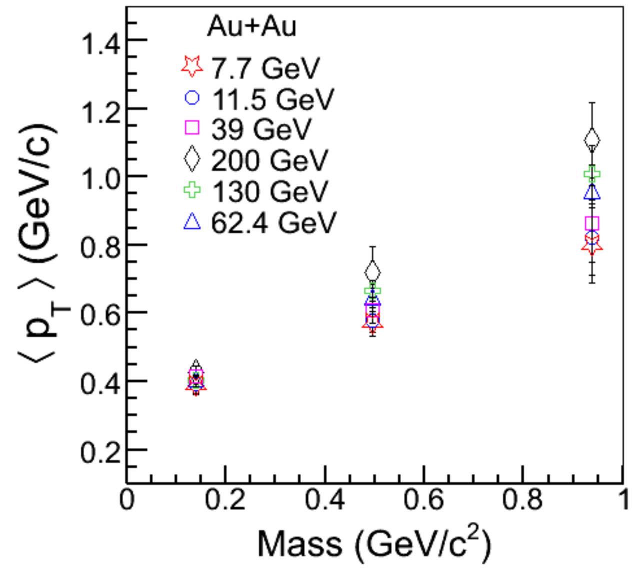
entropy ~ dN/dy $\propto \log(\sqrt{s_{NN}})$

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

Centrality Dependence of Yields & $<p_T>$





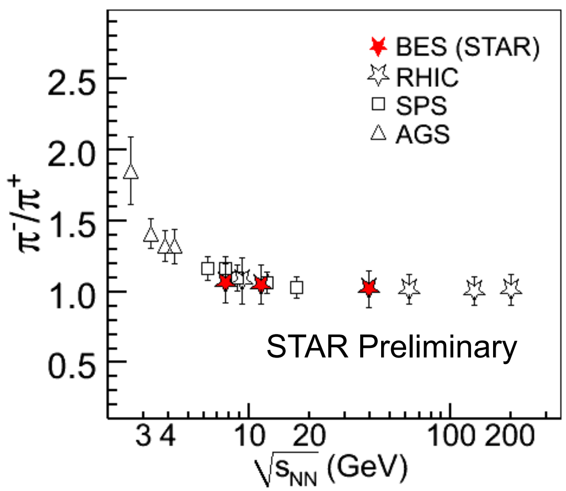
✧ dN/dy/0.5N_{part} ~ constant for π as function of centrality at 7.7 GeV. For other energies and kaons, it increases with centrality.

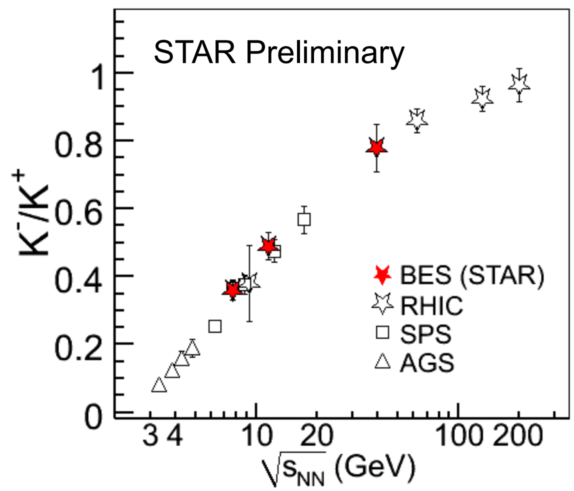
✧ $<p_T>$ increases with centrality – collectivity increases with centrality

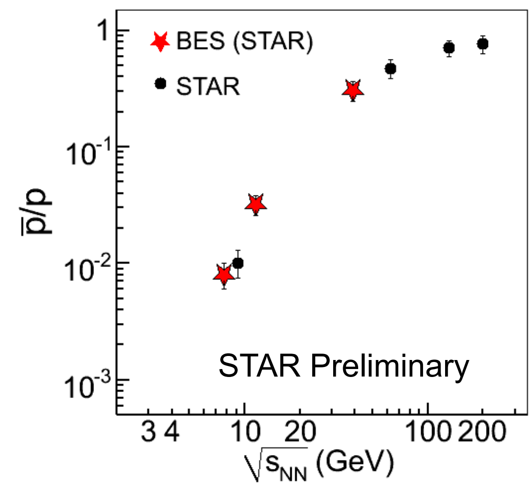
✧ $<p_T>$ for π seems to be similar from 39 GeV to 200 GeV

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

Anti-Particle to Particle Ratios

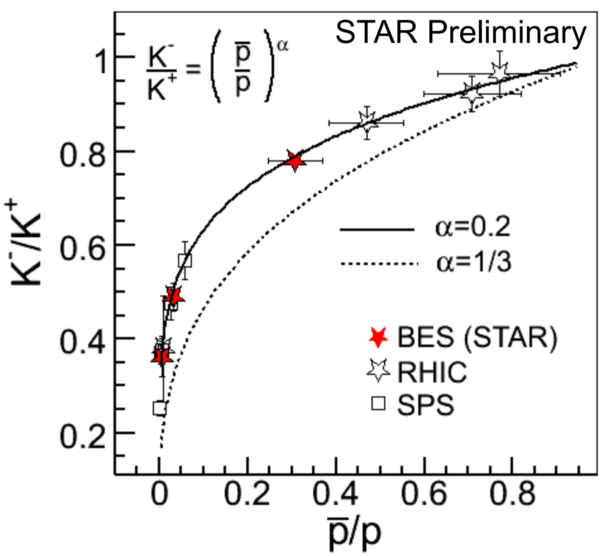






Midrapidity and central collisions

Errors: statistical and systematic added in quadrature



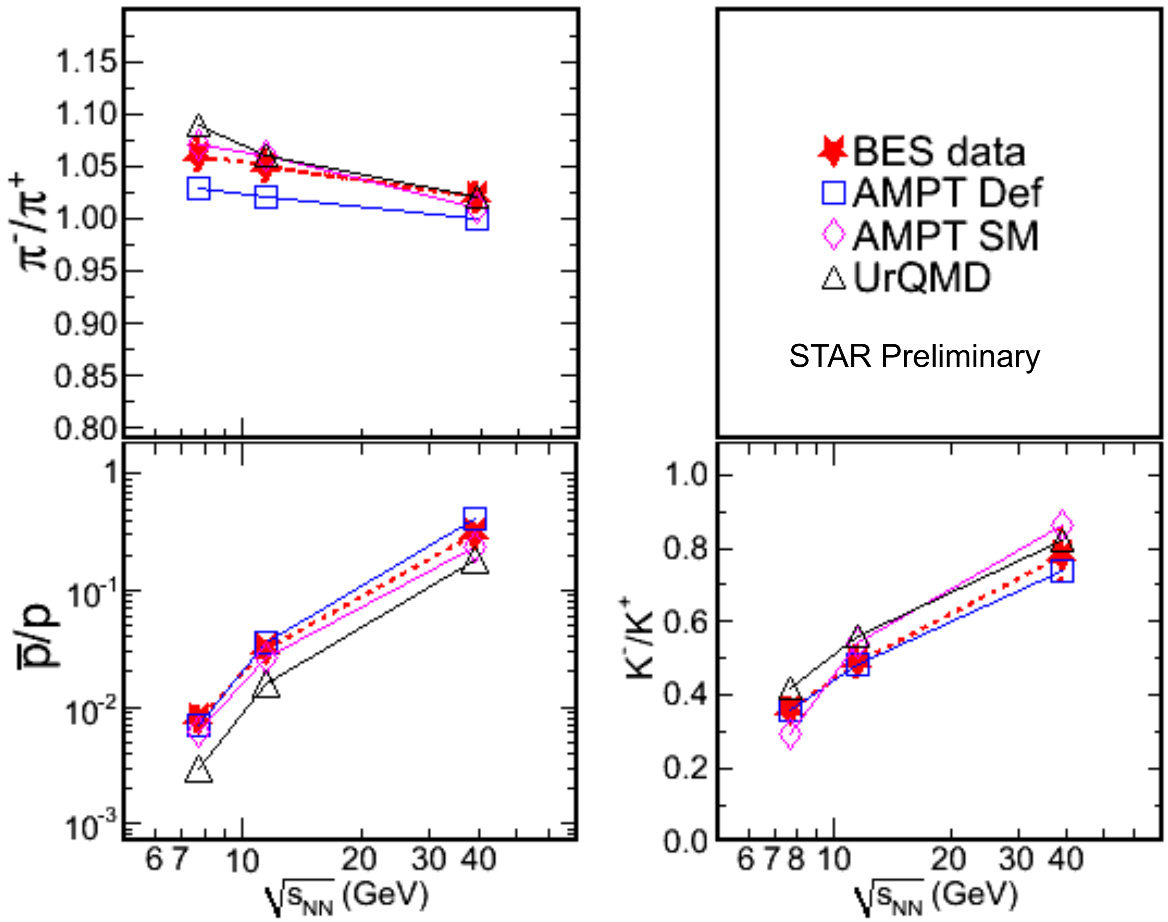
- ➢Results consistent with the published energy dependence
- ➢ π^-/π^+ ratio ~ 1.1 at 7.7 GeV: resonance decay (Δ)
- ➢ $K^-/K^+ \sim 0.4-0.5$: associated production at 7.7-11.5 GeV
- ➢ pbar/p << 1 at 7.7-11.5 GeV: large baryon stopping

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

Comparison with Models

Midrapidity and central collisions

UrQMD- Ultrarelativistic Quantum Molecular Dynamics
AMPT- A Multiphase Transport Model



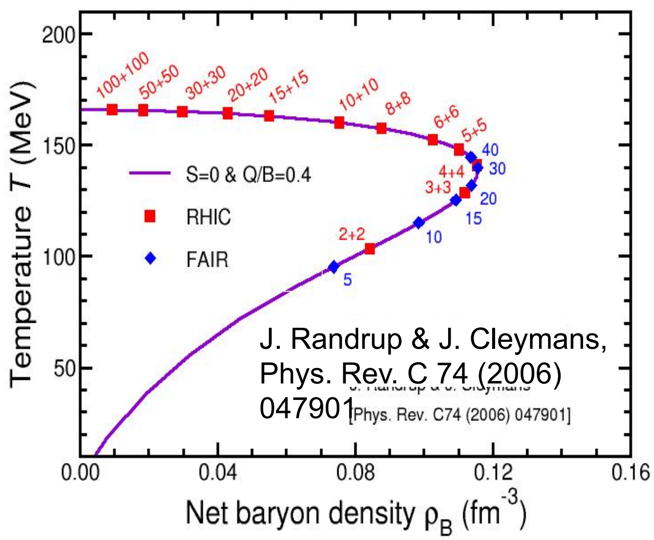
Models show similar trend as data

UrQMD gives lower values compared to data for pbar/p ratio

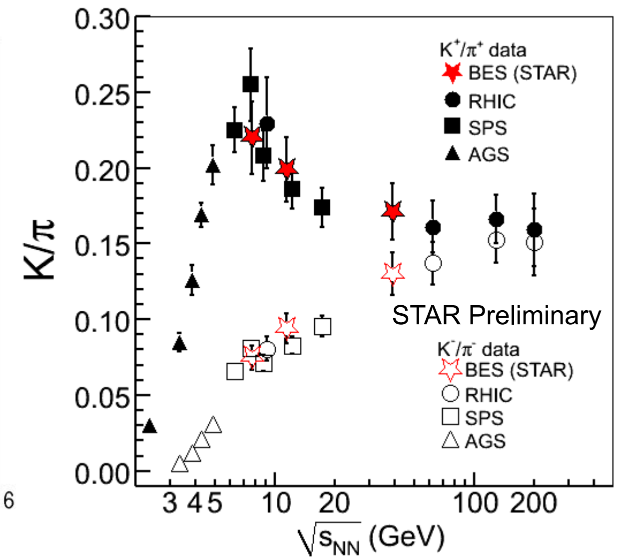
S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998);M. Bleicher et al., J. Phys. G 25, 1859 (1999).
Z.-W. Lin et al. Phys. Rev. C 65, 034904 (2002); Z.-W.Lin et al. bid. 72, 064901(2005);
L.-W. Chen et al., Phys. Lett. B 605, 95 (2005).

Particle Ratios

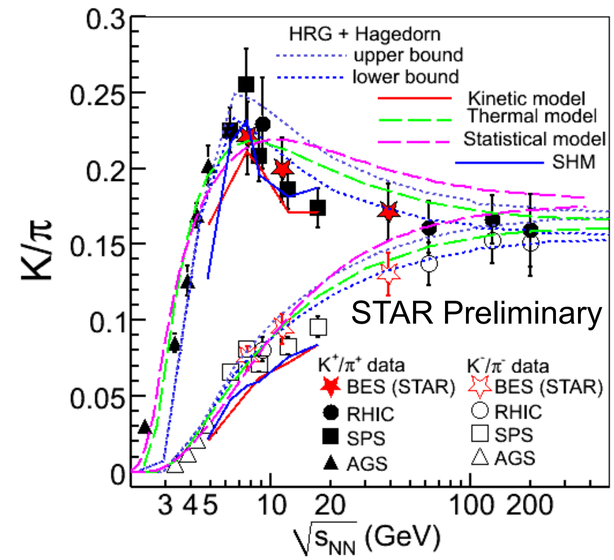
The maximum baryon density at freeze-out: $\sqrt{s_{NN}}$ ~ 8 GeV



Midrapidity and central collisions



Errors: statistical and systematic added in quadrature



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

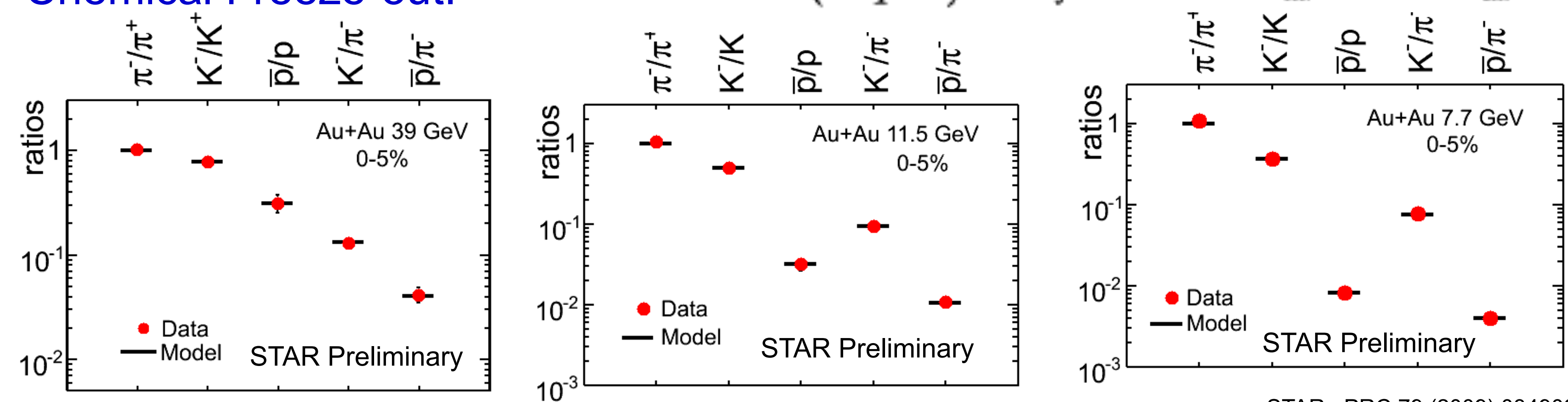
J. Cleymans et al., Eur. Phys. J. A 29, 119 (2006); A. Andronic et al., Phys. Lett B 673, 142 (2009); J. Rafelski, et al. J. Phys. G 35, 044011 (2008); B. Tomasik et al., Eur. Phys. J. C 49, 115 (2007) S. Chatterjee et al., Phys. Rev. C 81, 044907 (2010)

- 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:

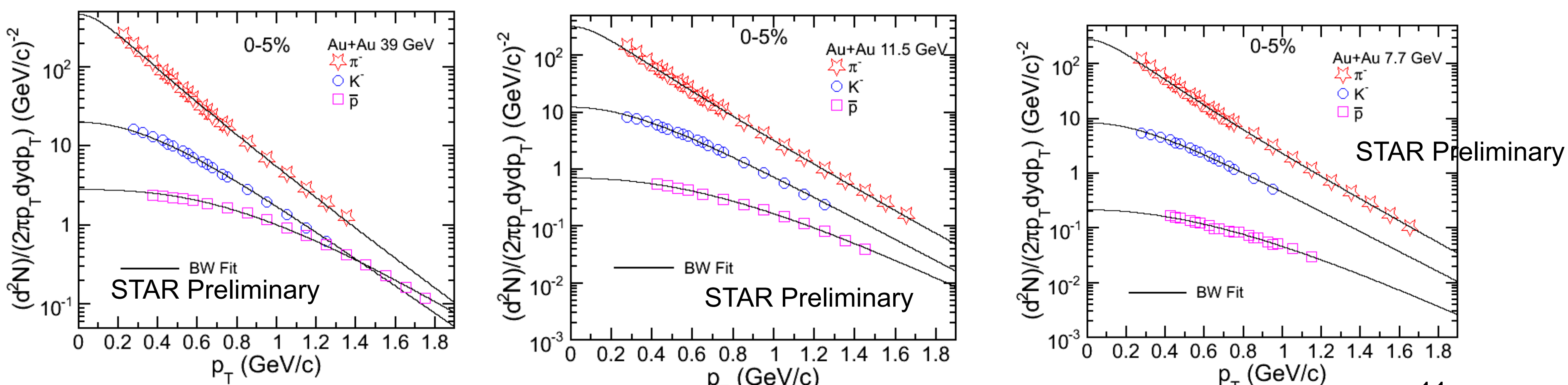
$$n_i(T,\mu_i) \sim \exp\left(\frac{\mu_i - m_i}{T}\right) \qquad \frac{N_i}{N_j} \sim \exp\left(\frac{\mu_{i,\mathrm{ch.}} - \mu_{j,\mathrm{ch.}}}{T_{\mathrm{ch.}}} - \frac{m_i - m_j}{T_{\mathrm{ch.}}}\right)$$



STAR : PRC 79 (2009) 034909
STAR : NPA 757 (2005) 102

Kinetic Freeze-out:

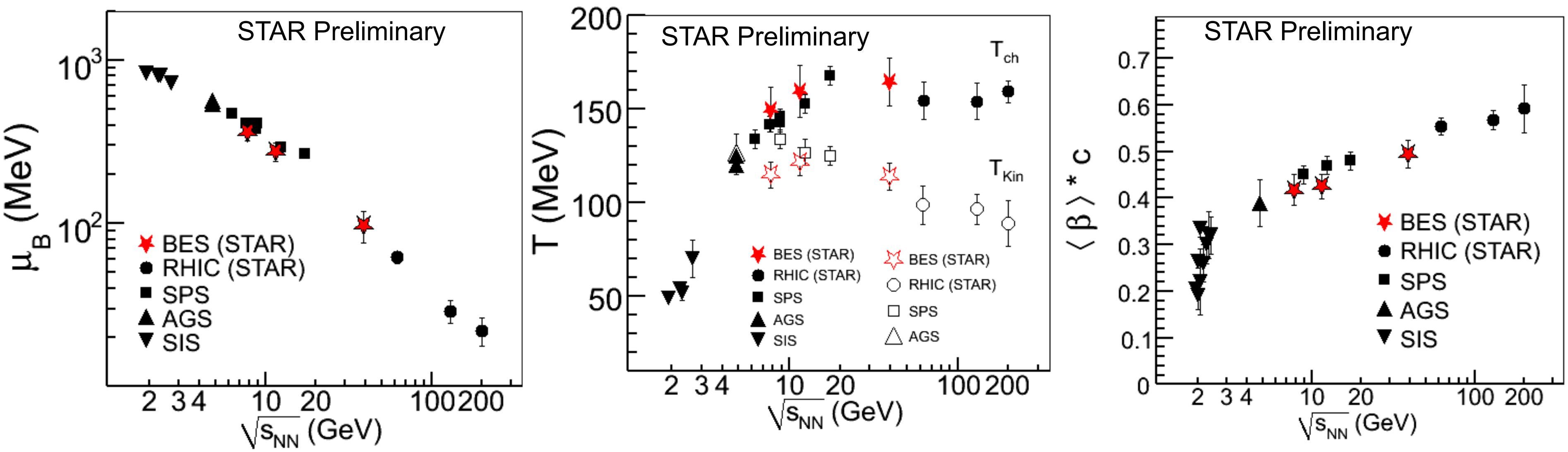
$$\frac{dN}{p_T dp_T} \propto \int_0^R r\,dr\,m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$



QUARK MATTER ANNECY 2011

Lokesh Kumar

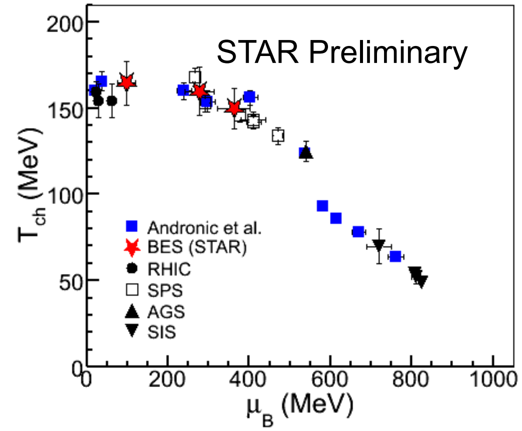
Energy Dependence of Freeze-out Parameters

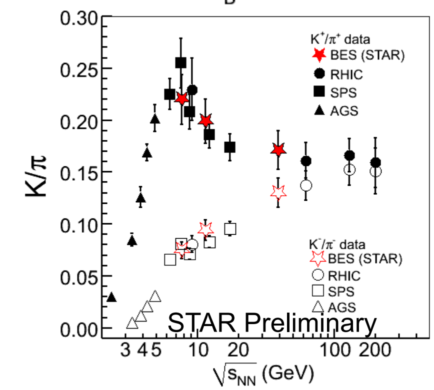


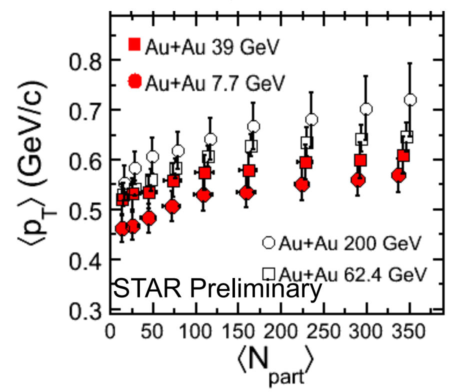
- Chemical potential decreases with energy: net-baryon density increases towards low energies
- Chemical freeze-out temperature increases with energy at low energies and becomes almost similar at higher energies
- Kinetic freeze-out temperature decreases with energy after $\sqrt{s_{NN}}$ ~ 7.7 GeV
-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

Summary

- ✓ Highly successful BES program at RHIC
- ✓ Presented various bulk properties of matter for Au+Au collisions at $\sqrt{s_{NN}}$ =7.7, 11.5, and 39 GeV on invariant yield, dn/dy, $<m_T>$, particle ratios, and freeze-out parameters
- ✓ For central collisions: $<m_T>$-m remains constant for BES energies
- ✓ $<p_T>$ of hadrons increases with collision centrality and mass indicating increase in collectivity
- ✓ $K^-/K^+ \sim (\text{pbar}/p)^{0.2}$ indicating kaon production is correlated with net baryon density
- ✓ K/p ratio presented to study strangeness enhancement. Beam energy dependence seems to be best explained using HRG+Hagedorn model
- ✓ Chemical freeze-out parameters: T_{ch} increases and μ_B decreases with energy.
- ✓ Kinetic freeze-out parameters: $<\beta>$ increases and T_{kin} decreases with energy







Thanks

Thanks to STAR Collaboration

Argonne National Laboratory, Argonne, Illinois 60439
Brookhaven National Laboratory, Upton, New York 11973
University of California, Berkeley, California 94720
University of California, Davis, California 95616
University of California, Los Angeles, California 90095
Universidade Estadual de Campinas, Sao Paulo, Brazil
University of Illinois at Chicago, Chicago, Illinois 60607
Creighton University, Omaha, Nebraska 68178
Czech Technical University in Prague, FNSPE, Prague, 115 19, Czech Republic
Nuclear Physics Institute AS CR, 250 68 \v{R}e\v{z}/Prague, Czech Republic
University of Frankfurt, Frankfurt, Germany
Institute of Physics, Bhubaneswar 751005, India
Indian Institute of Technology, Mumbai, India
Indiana University, Bloomington, Indiana 47408
Alikhanov Institute for Theoretical and Experimental Physics, Moscow, Russia
University of Jammu, Jammu 180001, India
Joint Institute for Nuclear Research, Dubna, 141 980, Russia
Kent State University, Kent, Ohio 44242
University of Kentucky, Lexington, Kentucky, 40506-0055
Institute of Modern Physics, Lanzhou, China
Lawrence Berkeley National Laboratory, Berkeley, California 94720
Massachusetts Institute of Technology, Cambridge, MA
Max-Planck-Institut f\"ur Physik, Munich, Germany
Michigan State University, East Lansing, Michigan 48824
Moscow Engineering Physics Institute, Moscow Russia
NIKHEF and Utrecht University, Amsterdam, The Netherlands
Ohio State University, Columbus, Ohio 43210
Old Dominion University, Norfolk, VA, 23529
Panjab University, Chandigarh 160014, India
Pennsylvania State University, University Park, Pennsylvania 16802
Institute of High Energy Physics, Protvino, Russia
Purdue University, West Lafayette, Indiana 47907
Pusan National University, Pusan, Republic of Korea
University of Rajasthan, Jaipur 302004, India
Rice University, Houston, Texas 77251
Universidade de Sao Paulo, Sao Paulo, Brazil
University of Science \& Technology of China, Hefei 230026, China
Shandong University, Jinan, Shandong 250100, China
Shanghai Institute of Applied Physics, Shanghai 201800, China
SUBATECH, Nantes, France
Texas A\&M University, College Station, Texas 77843
University of Texas, Austin, Texas 78712
University of Houston, Houston, TX, 77204
Tsinghua University, Beijing 100084, China
United States Naval Academy, Annapolis, MD 21402
Valparaiso University, Valparaiso, Indiana 46383
Variable Energy Cyclotron Centre, Kolkata 700064, India
Warsaw University of Technology, Warsaw, Poland
University of Washington, Seattle, Washington 98195
Wayne State University, Detroit, Michigan 48201
Institute of Particle Physics, CCNU (HZNU), Wuhan 430079, China
Yale University, New Haven, Connecticut 06520
University of Zagreb, Zagreb, HR-10002, Croatia

Back-up