Bulk Properties in Au+Au Collisions at $\sqrt{s_{NN}}$ = 9.2 GeV in STAR Experiment at RHIC

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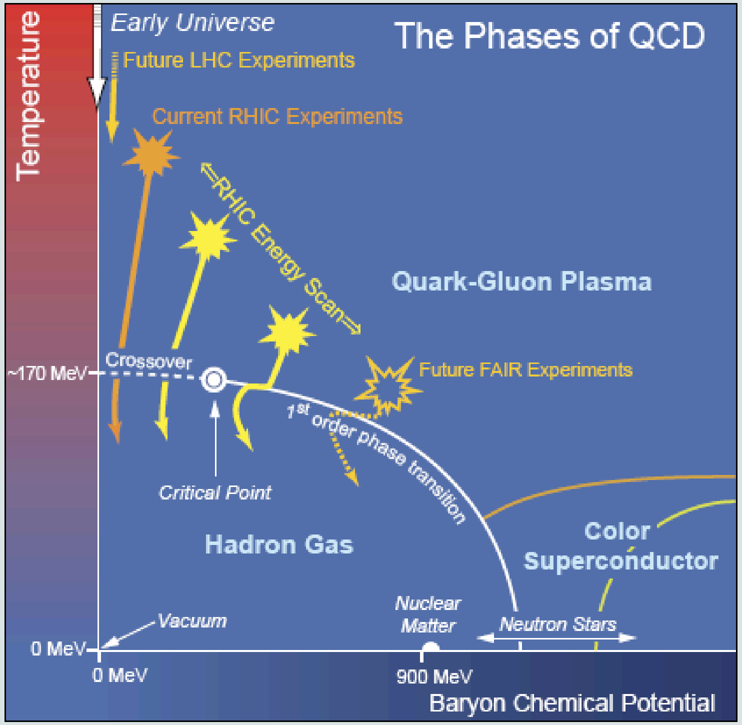
Outline:

- ✓ Motivation
- ✓ STAR Experiment and Collisions at $\sqrt{s_{NN}}$ = 9.2 GeV
- ✓ Results and Systematics : PID Spectra, Ratios, v_1, v_2 and $C_2(Q)$
- ✓ Summary and Outlook (Critical Point Search at RHIC)

Motivation



Schematic QCD phase diagram for nuclear matter. The solid lines show the phase boundaries for the indicated phases. The solid circle depicts the critical point. Possible trajectories for systems created in the QGP phase at different accelerator facilities are also shown.

NSAC 2007 Long-range Plan

QCD phase diagram through experiments -

- ✓ QCD phase boundary
- ✓ QCD critical point

Plan :

Access to phase diagram

- ✓ T and μ_B varies with $\sqrt{s_{NN}}$
- ✓ T and μ_B measured from spectra and ratios of produced particles

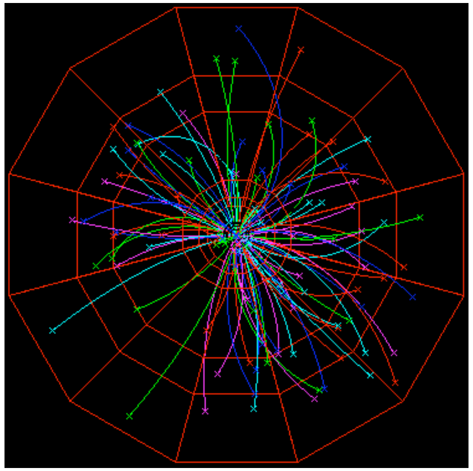
Signatures

- ✓ For locating different phases
- ✓ For locating critical point

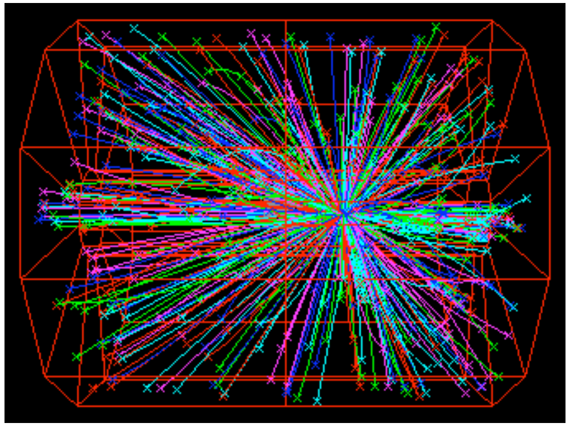
Aim of this talk is to discuss results from successful data taking in STAR with the Au+Au collisions at 9.2 GeV and demonstrate our readiness for the future Critical Point Seacrh program at RHIC

STAR Experiment and Collisions at $\sqrt{s_{NN}} = 9.2$ GeV

- ✓ Collisions recorded in STAR Time Projection Chamber

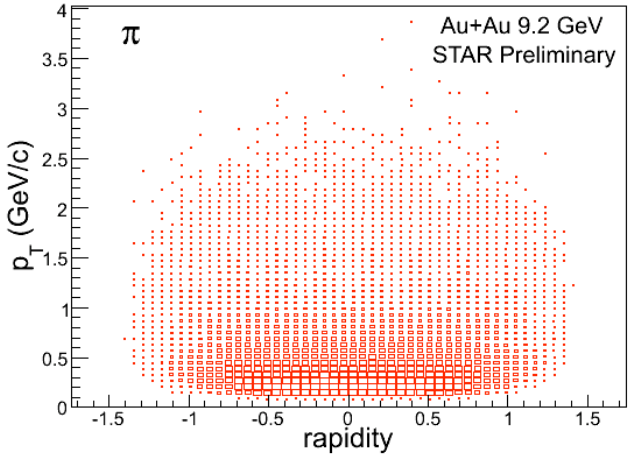


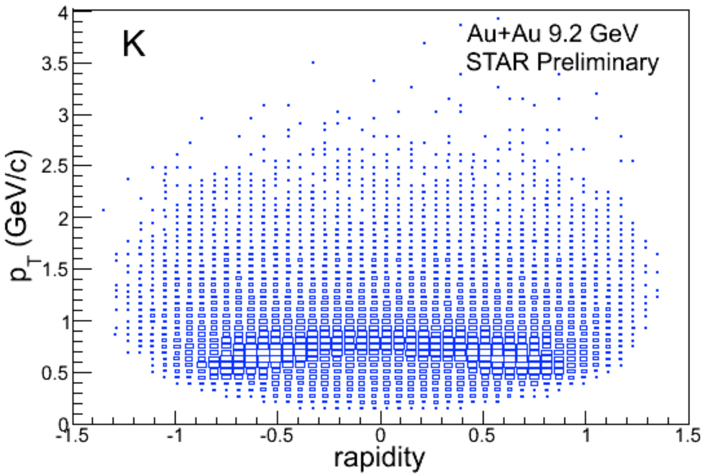
Non-central Collision

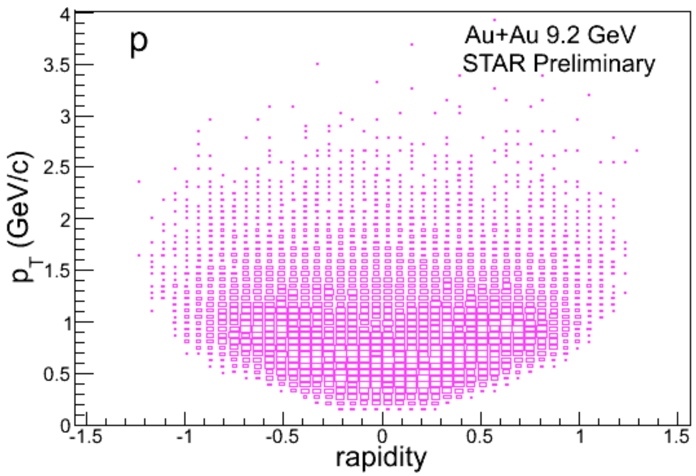


Central Collision

- ✓ Collider experiment : Uniform acceptance for all beam energies







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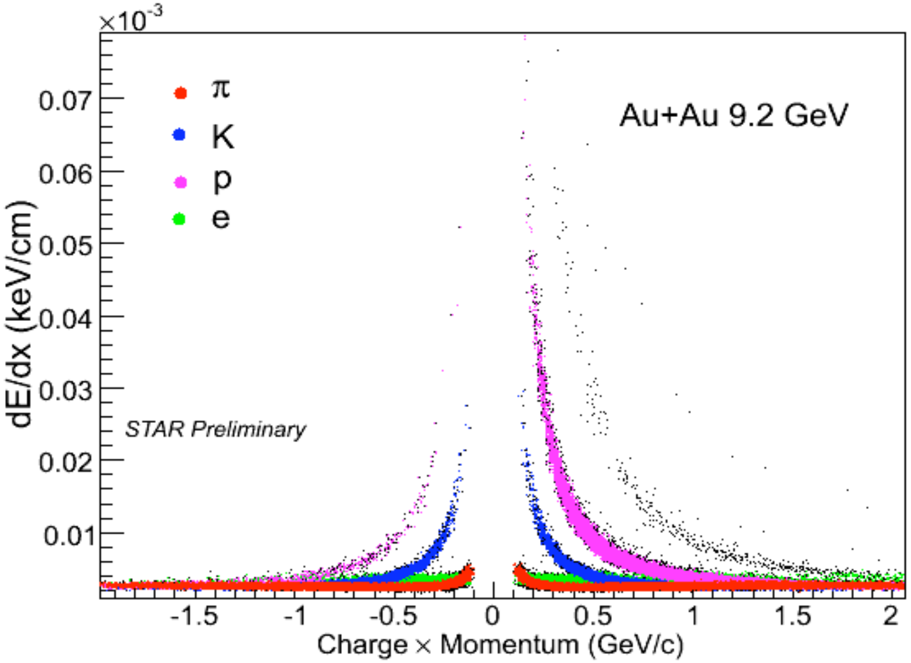
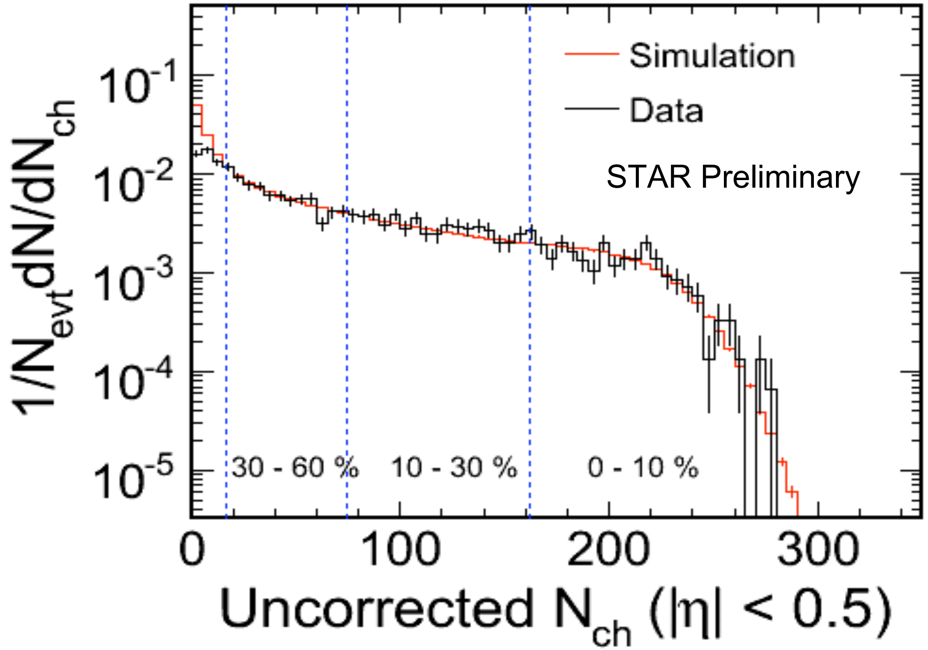
✓ Excellent Particle Identification



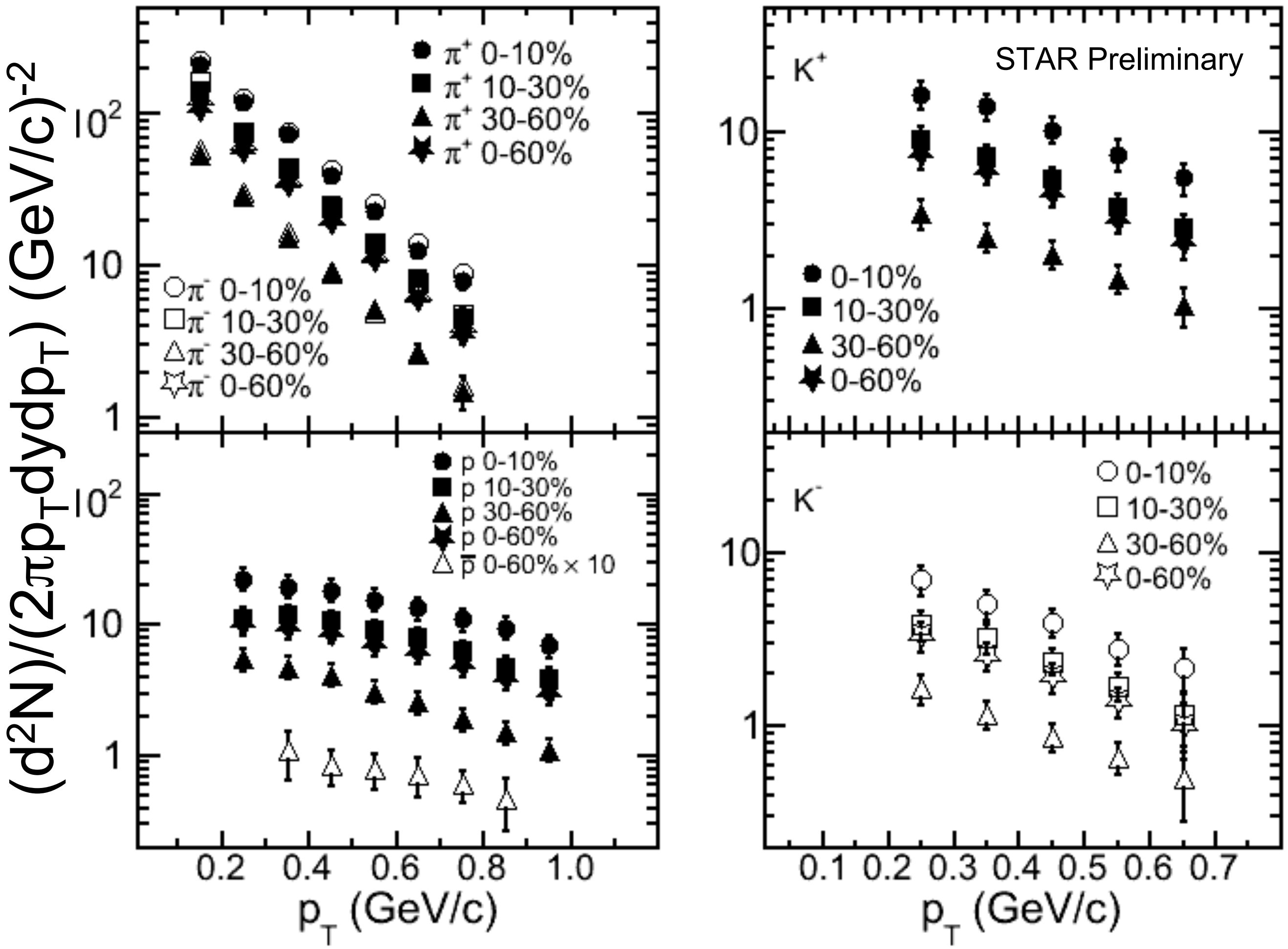
✓ Collision Centrality Selection



✓ Analysis based on ~ 3000 good events collected at ~ 0.6 Hz in year 2008

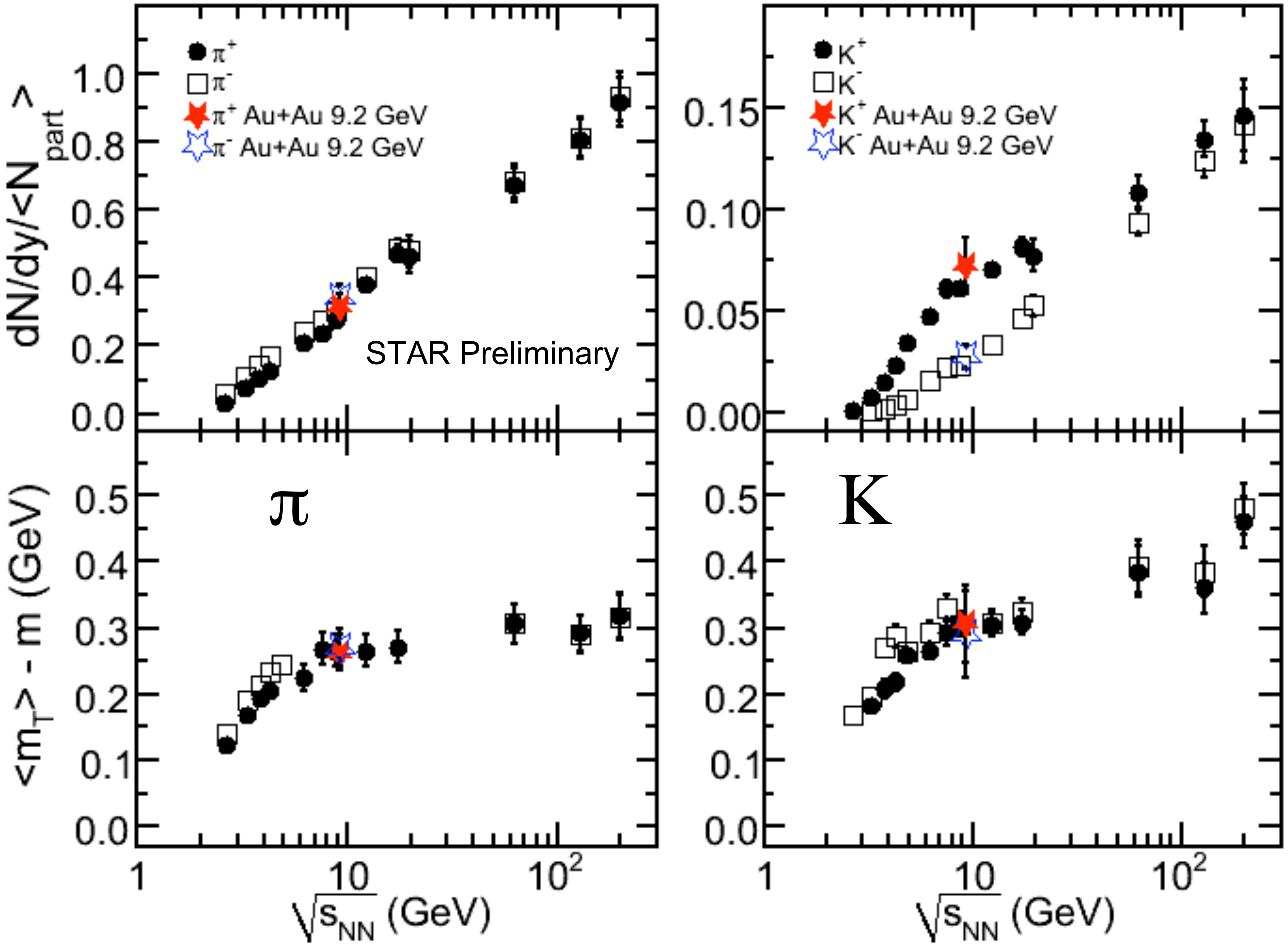
% cs	: N_{part}
0 - 10%	: 318
10 - 30%	: 203
30 - 60%	: 89

Identified Hadron Spectra at Mid-Rapidity



- ✓ The slope of the spectra follows - $p < K < \pi$
- ✓ Spectra characterized by dN/dy and $<m_T>$
- ✓ We measure within our p_T acceptance at mid-rapidity-
  - ~ 82 % of total π produced
  - ~ 47 % of total K produced
  - ~ 75 % of total p produced

Yield and $\langle m_T \rangle$ - Mesons at Mid-Rapidity



- ✓ Yield and $\langle m_T \rangle$ beam energy dependence consistent with the published data
- ✓ Assuming a thermo-dynamic system :

  T ~ $\langle m_T \rangle$ - m

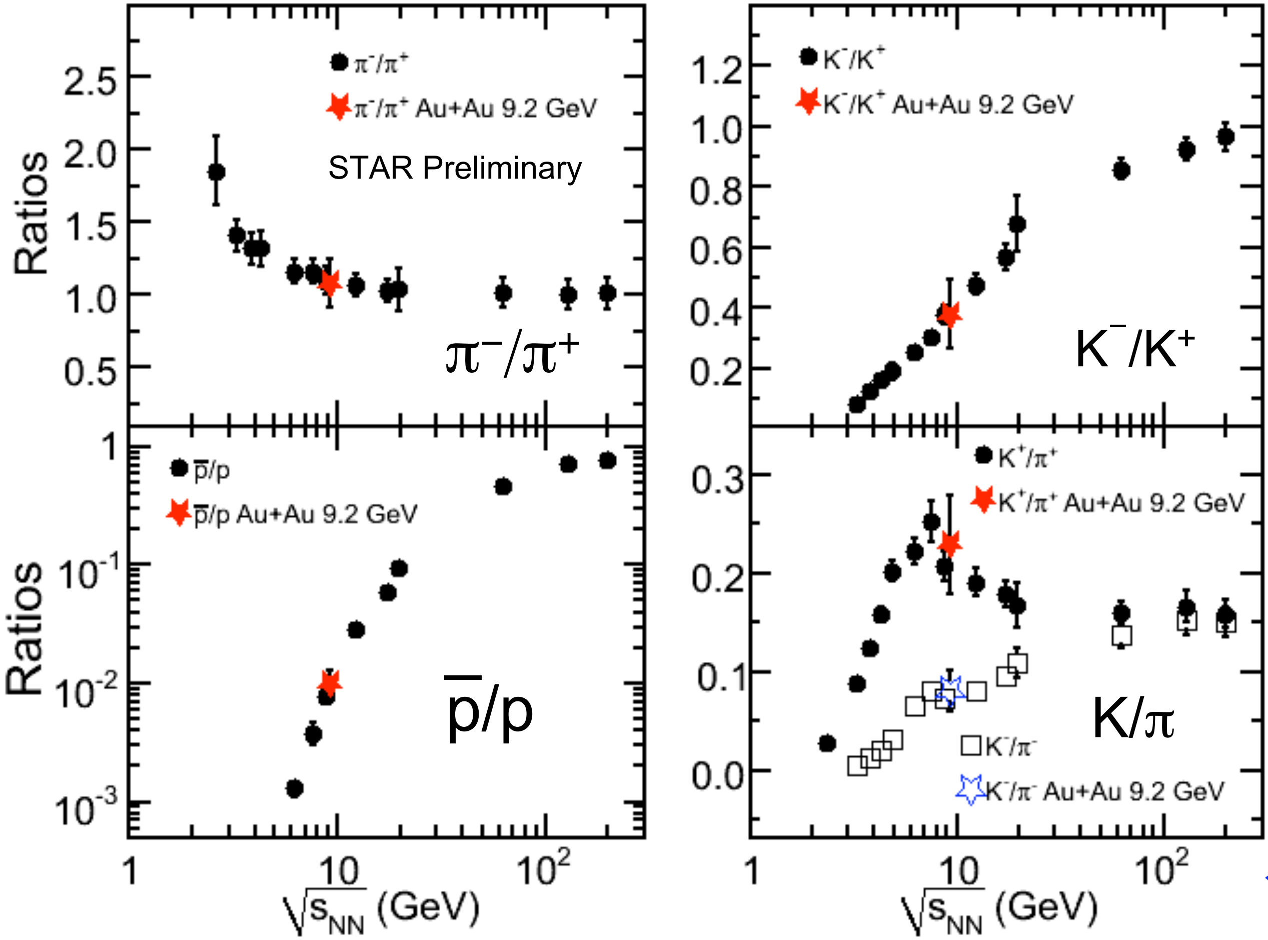
  entropy ~ dN/dy

  α log($\sqrt{s_{NN}}$)

All errors are statistical and systematic added in quadrature

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

Beam Energy Dependence of Particle Ratios at Mid-Rapidity



- ✓ Total number of events for Au+Au 9.2 GeV ~ 3000
- ✓ The ratios follow the general $\sqrt{s_{NN}}$ trend
- ✓ $\pi^-/\pi^+ \sim 1$: similar source of production for π^+ and π^-
- ✓ $K^-/K^+ \sim 0.4$: ~ 60% of K^+ from associated production with Λ
- ✓ K/π ratio reflects strangeness enhancement in heavy ion collisions
- ✓ pbar/p << 1 : Large baryon stopping, Large net protons and High μ_B

E802(AGS) : PRC 58 (1998) 3523, PRC 60 (1999) 044904, PRC 62 (2000) 024901, PRC 68 (2003) 054903

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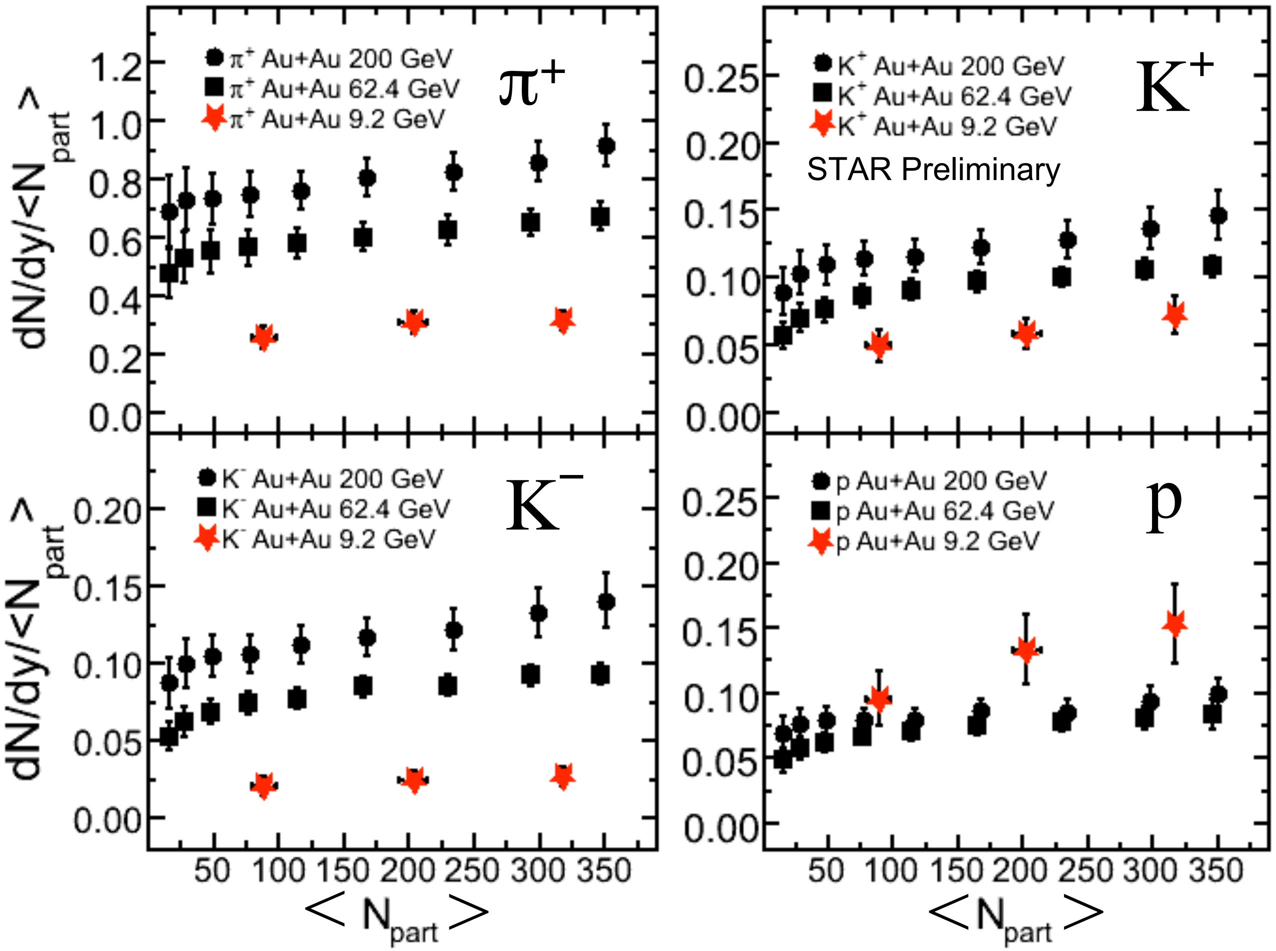
STAR : PRC 79 (2009) 034909, arXiv: 0903.4702

Centrality and Energy Dependence of Yield at Mid-Rapidity



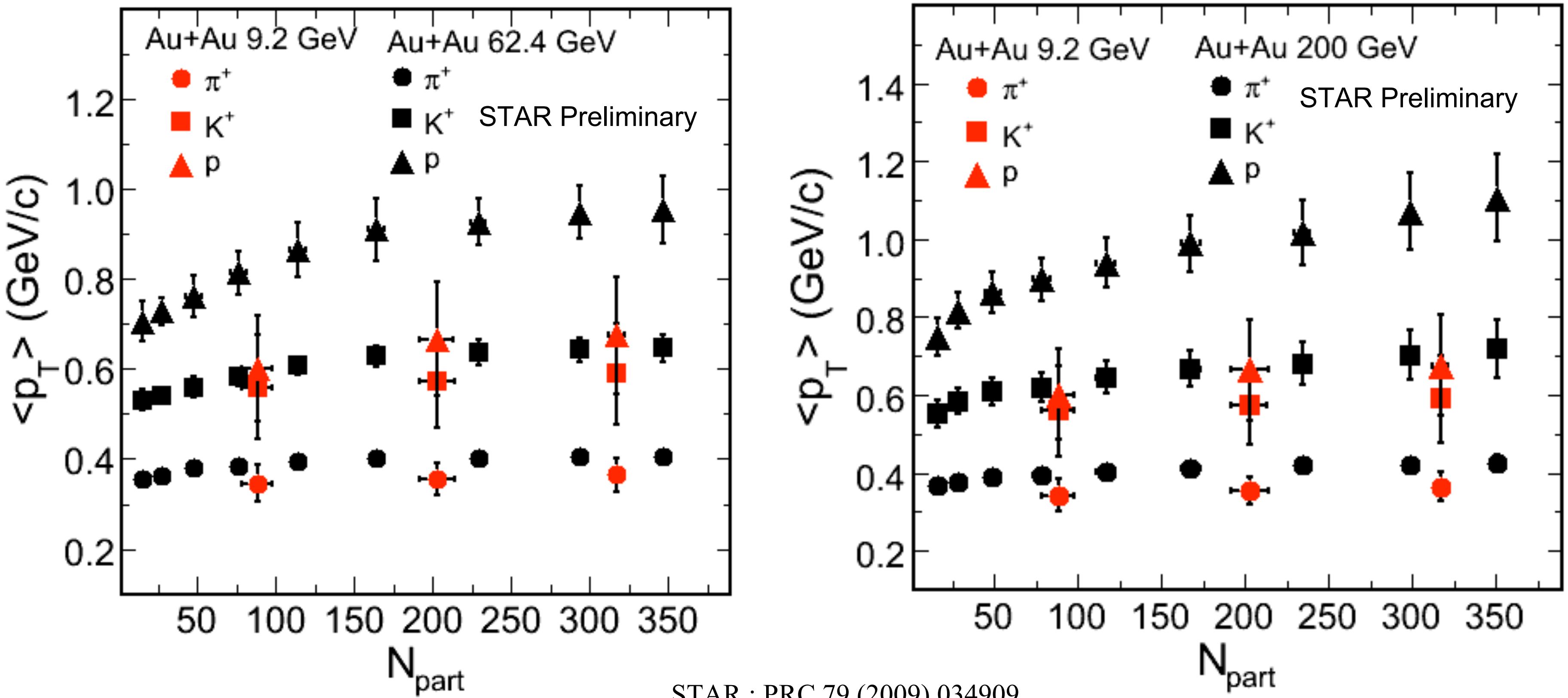
- ✓ Dependence of yield on N_{part} similar to higher energies

STAR : PRC 79 (2009) 034909

- ✓ π, K yield in 9.2 GeV is lower than that 200 and 62.4 GeV

- ✓ proton yield in 9.2 GeV is greater than that in 200 and 62.4 GeV
  - Significant baryon stopping at mid-rapidity at low energies

Centrality and Energy Dependence of $\langle p_T \rangle$

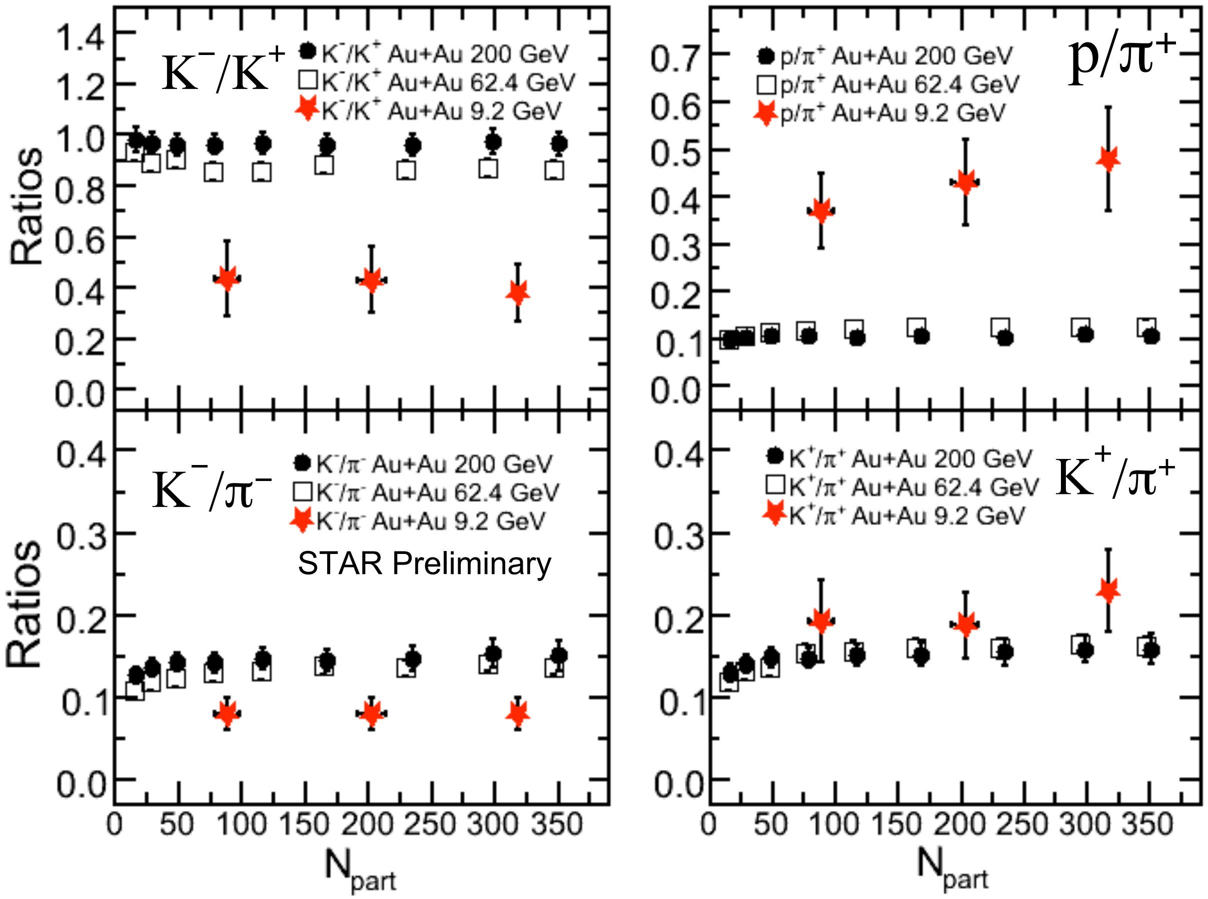


STAR : PRC 79 (2009) 034909

✓ $\langle p_T \rangle$ increases with mass of particle - reflects collectivity in radial direction

✓ $\langle p_T \rangle$ for π, K and p in 9.2 GeV is lower than those in 200 and 62.4 GeV
- Difference is maximum in case of proton (Due to small radial flow in 9.2 GeV)

Centrality and Energy Dependence of Particle Ratios

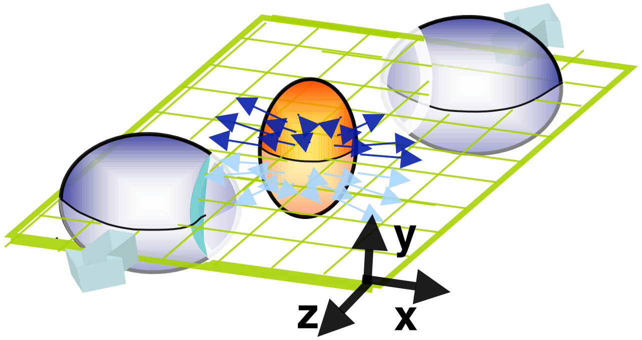


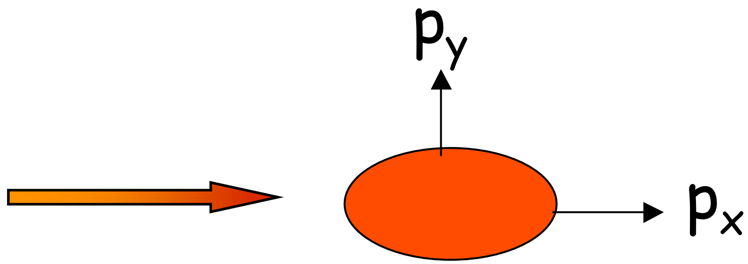
- ✓ K^-/K^+ is lower in 9.2 GeV compared to that in 200 and 62.4 GeV
- ✓ p/π^+ in 9.2 GeV is greater compared to 200 and 62.4 GeV
  - shows large baryon stopping at low energy
- ✓ K^-/π^- in 9.2 GeV is lower than in 200 and 62.4 GeV

STAR : PRC 79 (2009) 034909

- ✓ K^+/π^+ is higher in 9.2 GeV compared to that in 200 and 62.4 GeV
- ✓ Ratios seem to be almost independent of collision centrality studied for all energies

Azimuthal Anisotropy Measurements





$$\phi = \mathrm{atan}\frac{p_y}{p_x}$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

initial spatial anisotropy

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

anisotropy in momentum space

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2v_1\cos(\phi - \Psi_R) + 2v_2\cos(2(\phi - \Psi_R)) + \ldots\right)$$

directed (↑ v_1) **elliptic** (↑ v_2)

$$v_n = \langle \cos(n(\phi - \psi_n)) \rangle = \langle e^{in(\phi - \psi_n)} \rangle$$

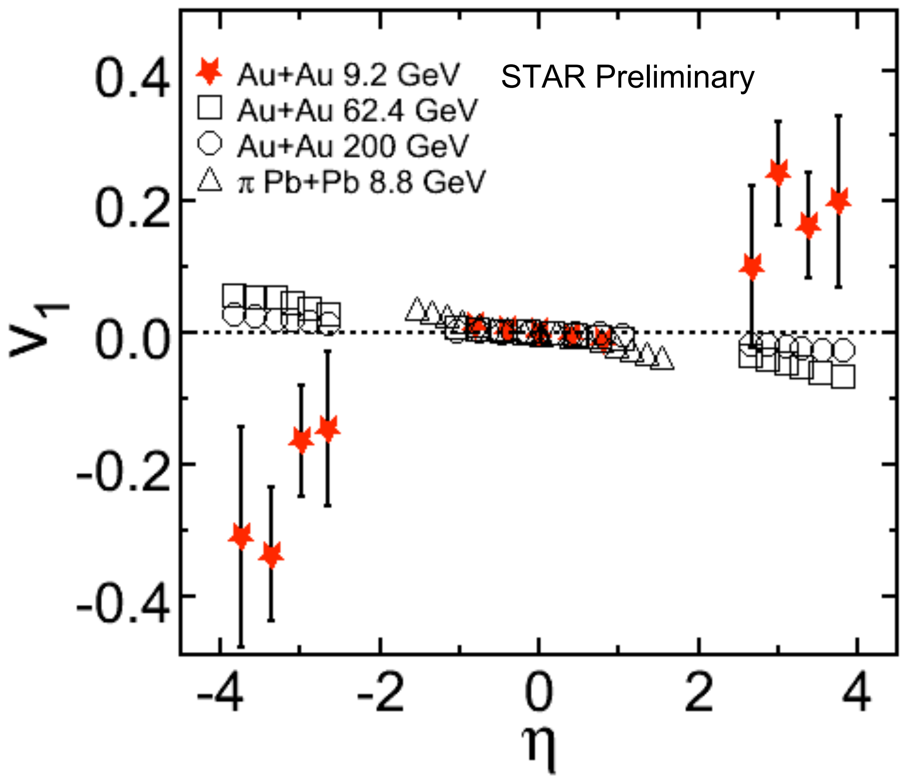
= Correlation to the reaction plane

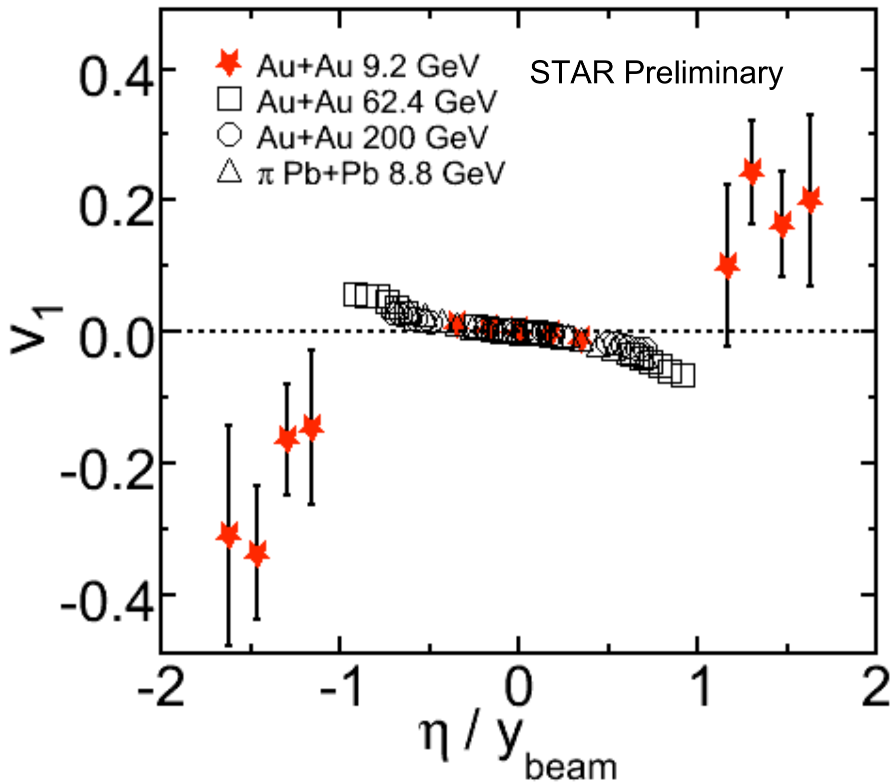
≡"anisotropic flow"

Within the assumptions of hydrodynamical calculations - Azimuthal Anisotropy measurements could be related to Equation Of State

v_1, v_2 = f(p_T, centrality) ~ ΔP = f(T, ε(or V)) –> EOS

Azimuthal Anisotropy - Directed Flow





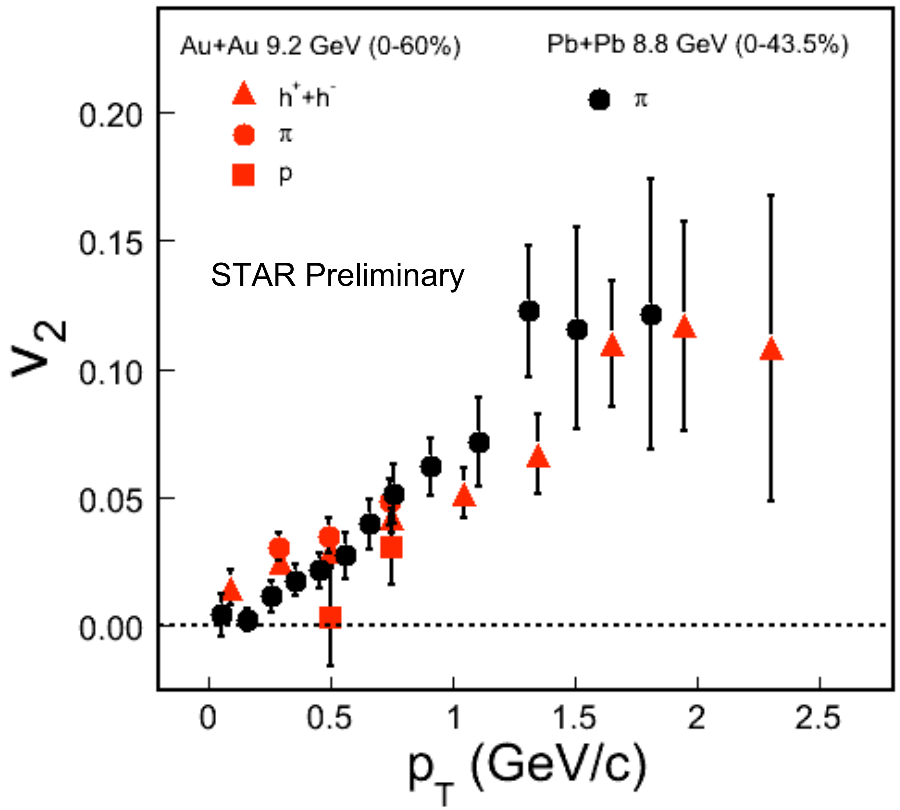
STAR : PRL 92 (2004) 062301

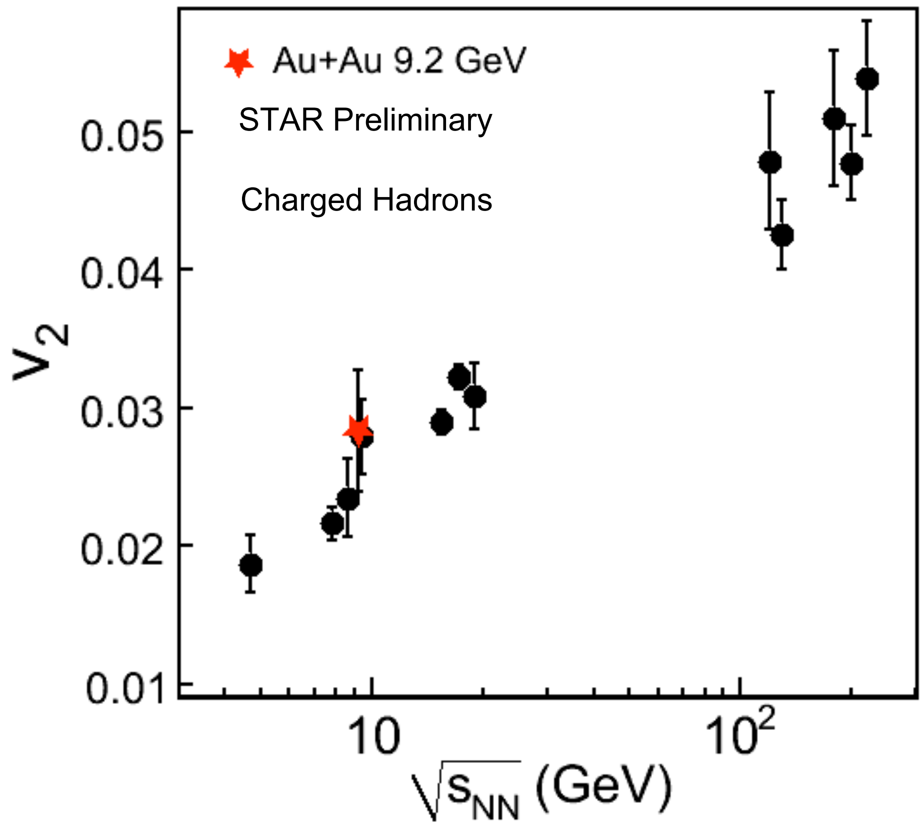
STAR : arXiv:0807.1518[nucl-ex]

y_{beam} 9.2 GeV ~ 2.3
y_{beam} 200 GeV ~ 5.4
y_{beam} 62.4 GeV ~ 4.2

✓ v_1 for Au+Au 9.2 GeV at higher rapidity is possibly due to spectators

Azimuthal Anisotropy - Elliptic Flow



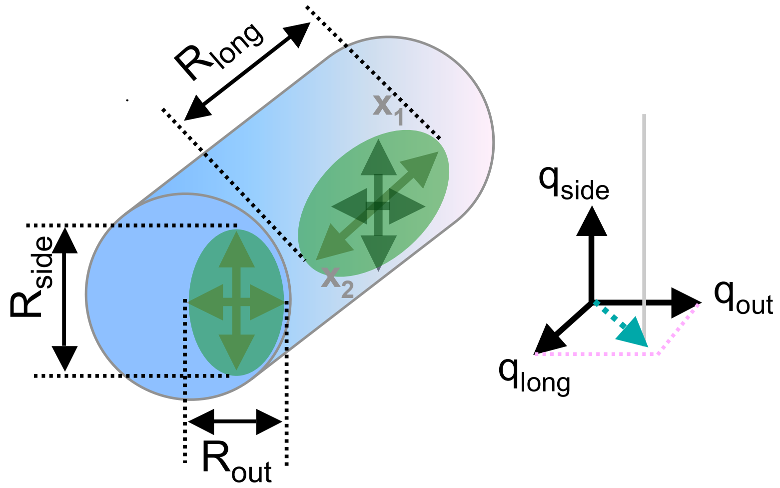


Au+Au 9.2 GeV : |η|<1, only statistical errors are shown

✓ Results comparable to SPS results at similar beam energy

NA49 : PRC 68 (2003) 034903
AGS : PLB 474 (2000) 27
STAR : PRC 77 (2008) 054901 : PRC 75 (2007) 054906, PRC 72 (2005) 014904
PHOBOS : PRC 72 (2005) 051901 : PRL 98 (2007) 242302
PHENIX : PRL 98 (2007) 162301
CERES : NPA 715 (2003) 615

Interferometery Measurements



HBT measurements provides

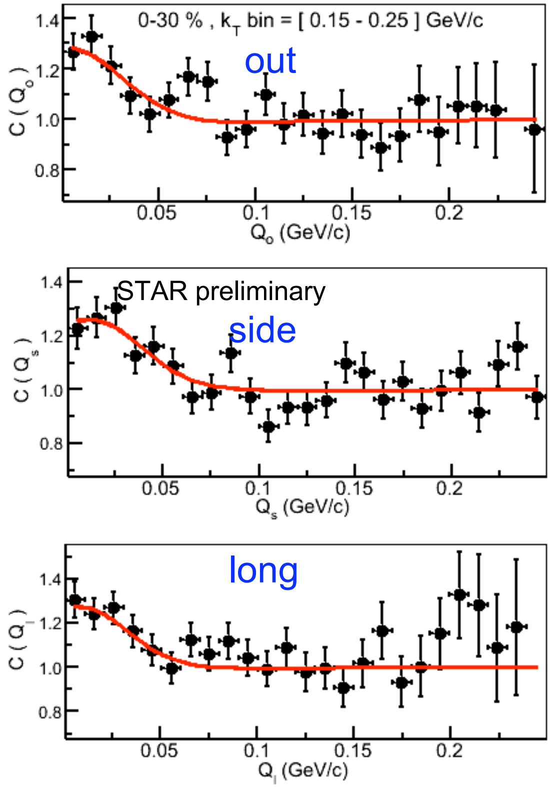
Source dimensions (homogeneity region) - R
Source is chaotic or coherent - λ

R_{out} - spatial + temporal extension of source
R_{side} - only the spatial extension
R_{out} / R_{side} - emission duration of source

$R_{out}/R_{side} >> 1$ for a 1st order phase transition
-- Rischke & Gyulassy, NPA 608, 479 (1996)

Study HBT as a function of Beam Energy ~ energy density

Pion Interferometery Measurements



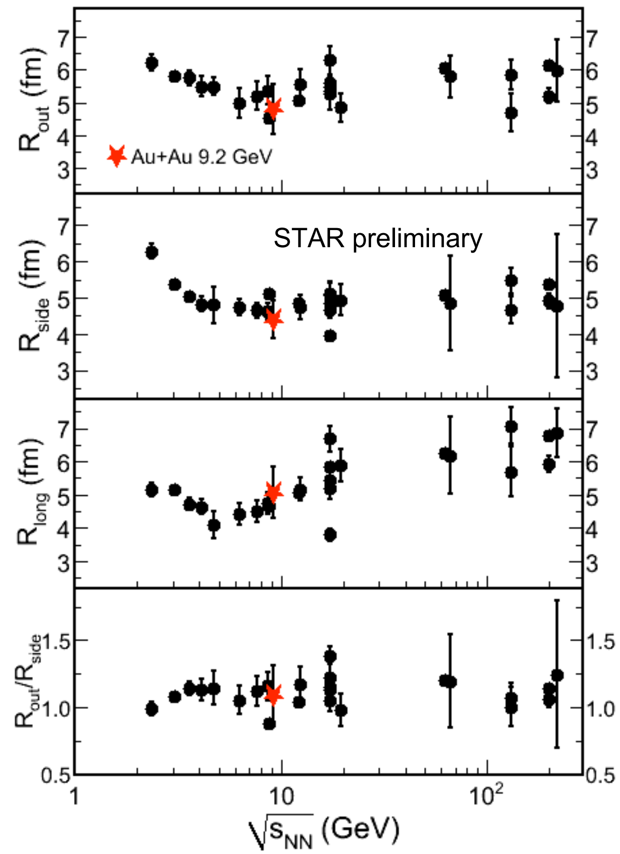
π^-

Centrality : 0 - 30%

Error bars for Au+Au 9.2 GeV are statistical

Systematic errors expected to be < 10 % for each out, side and long

E802 : PRC 66 (2002) 054906
CERES : NPA 714 (2003) 124
E895 PRL 84 (2000) 2798



Source parameters :

Kt bin(GeV/c)	R_{out}(fm)	R_{side}(fm)	R_{long}(fm)	λ
0.15-0.25(GeV/c)	4.81 +/- 0.8	4.41 +/- 0.5	5.06 +/- 0.8	0.548 +/- 0.1

✓ Previously observed trend on beam energy followed

STAR : PRC 71 (2005) 044906, PRL 87 (2001) 082301
PHENIX : PRL 88 (2002) 192302, PRL 93(2004) 152302
PHOBOS : PRC 73 (2006) 031901
WA97 : JPG 27 (2001) 2325

NA44 : PRC 58 (1998) 1656
E866 : NPA 661 (1999) 439
NA49 : PRC 77 (2008) 064908

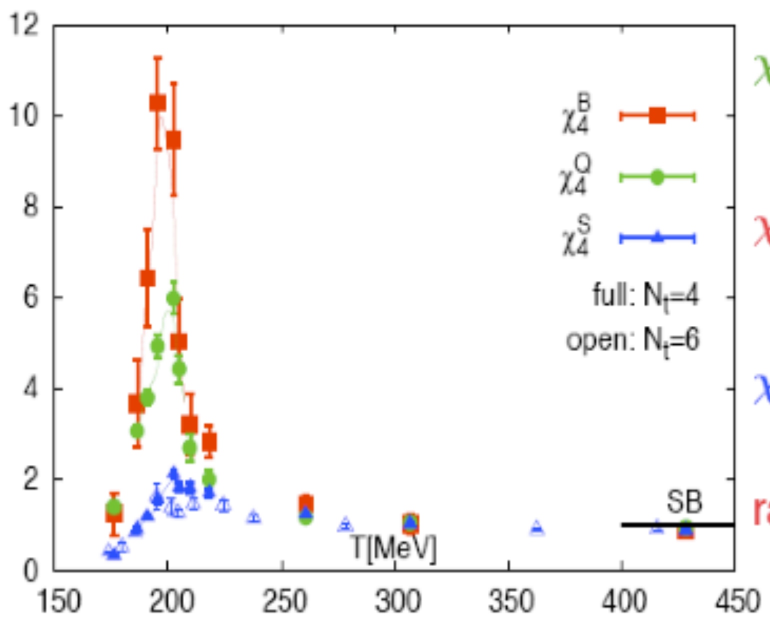
Critical Point Search Program from STAR

Look for QCD critical point -

T.K. Nayak : QM09

✓ One of the key measurements : Fluctuations and studies of higher moments of event by event multiplicity distributions of net-protons

vanishing chemical potentials: RBC-Bielefeld, arXiv:0805.0236



$$\chi_4^Q = \frac{1}{VT^3}\left(\langle Q^4\rangle - 3\langle Q^2\rangle^2\right)$$

$$\chi_4^B = \frac{1}{VT^3}\left(\langle N_B^4\rangle - 3\langle N_B^2\rangle^2\right)$$

$$\chi_4^S = \frac{1}{VT^3}\left(\langle N_S^4\rangle - 3\langle N_S^2\rangle^2\right)$$

rapid approach to SB limit

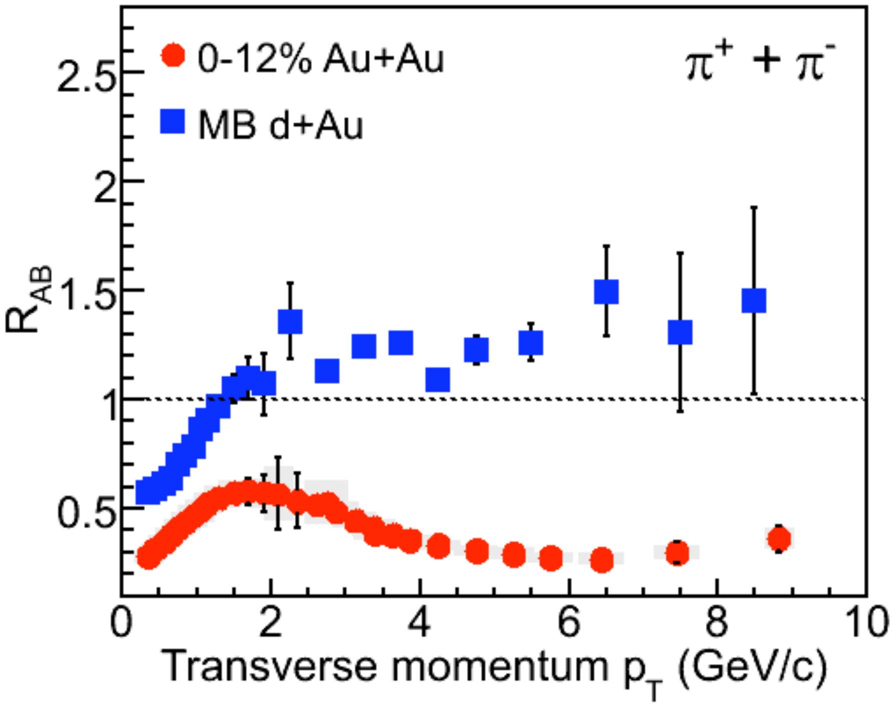
$\Rightarrow$ large light quark number & charge fluctuations across transition region

Look For Onset of Observations at RHIC

Look for onset of several interesting observables -

✓ Onset of high p_T suppression

Y. Xu : QM09

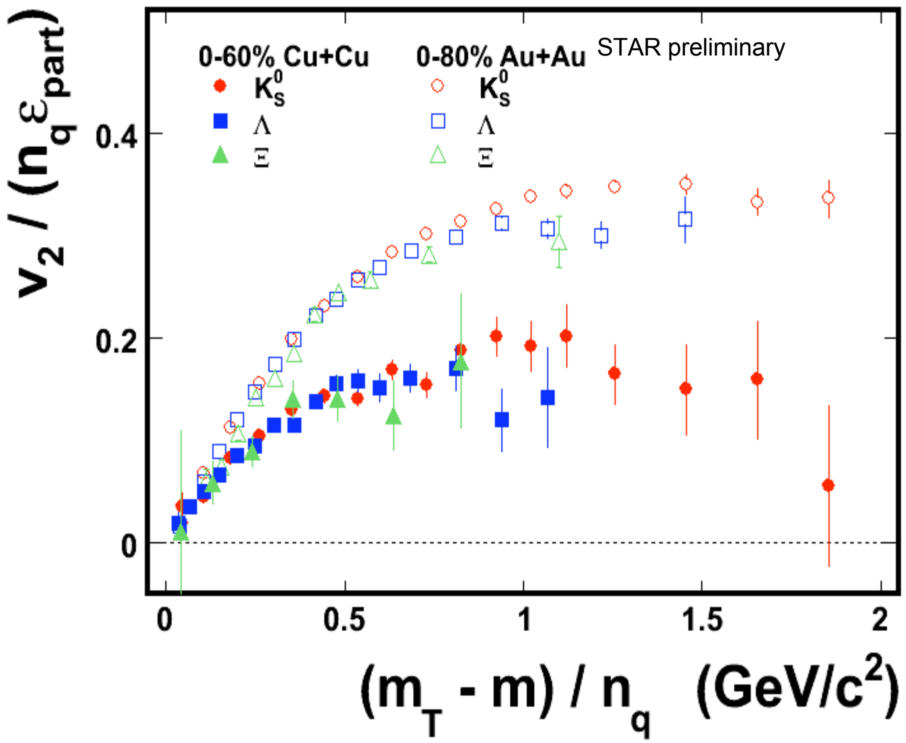


STAR : PLB 655 (2007) 104, PLB 637 (2006) 161,
PRL 97 (2006) 152301

STAR : PRC 77 (2008) 54901

✓ Onset of Number of Constituent Quark scaling in v_2 measurements and strange hadron v_2

S. S. Shi : QM09



Summary

- ✓ Identified particle spectra obtained from Au+Au collisions at 9.2 GeV, centrality and beam energy dependence of the hadron yields and ratios presented.
- ✓ In central collisions anti-proton to proton ratio ~ 0.01 shows significant baryon stopping at mid-rapidity in these collisions
- ✓ In central collisions $K^-/K^+ \sim 0.4$ shows associated production for K^+
- ✓ p/π ratio is higher and K^-/π^- is lower at 9.2 GeV compared to 200 GeV at all collision centralities studied
- ✓ Azimuthal Anisotropy (v_1 and v_2) measurements are similar to those obtained at SPS from collisions at similar energies
- ✓ Pion interferometry results follow the established beam energy trends

These results from the lowest beam energy collisions at RHIC demonstrate STAR experiment's readiness to take up the proposed Critical Point Search Program.

Large and uniform acceptance for all beam energies in a collider set up, excellent particle identification (TPC+TOF) and higher statistics will enable doing qualitative improvement on SPS results.

Critical Point Search Program will allow us to explore the QCD phase diagram and search the onset of several interesting observations at RHIC

Thanks

Thanks to STAR Collaboration

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University of California - Los Angeles
Universidade Estadual de Campinas
Carnegie Mellon University
University of Illinois at Chicago
Creighton University
Nuclear Physics Inst., Academy of Sciences
Laboratory of High Energy Physics - Dubna
Particle Physics Laboratory - Dubna
Institute of Physics. Bhubaneswar
Indian Institute of Technology. Mumbai
Indiana University Cyclotron Facility
Institut Pluridisciplinaire Hubert Curien
University of Jammu
Kent State University
University of Kentucky
Institute of Modern Physics, Lanzhou
Lawrence Berkeley National Laboratory
Massachusetts Institute of Technology
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Michigan State University

Moscow Engineering Physics Institute
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NIKHEF and Utrecht University
Ohio State University
Panjab University. Chandigarh
Pennsylvania State University
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Rice University
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SUBATECH
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University of Zagreb