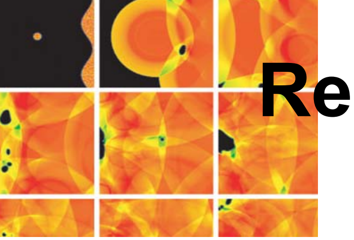


Recent results from STAR experiment in Au+Au collisions at $\sqrt{s_{NN}}$ = 9.2 GeV

Debasish Das

UC Davis

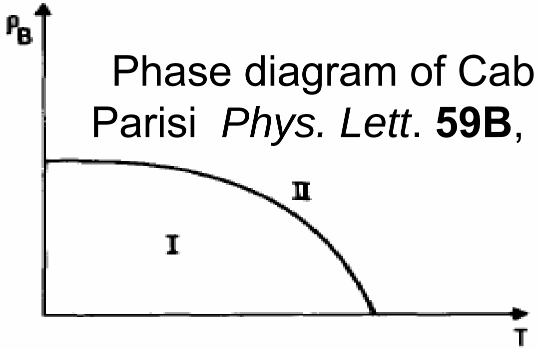
(For the **STAR Collaboration**)

Outline

- ✓ Phase Diagram and its Evolution
- ✓ STAR Experiment
- ✓ Results and Systematics vs. Collision Energies:
  - Identified particle spectra, ratios, collective flow and pion HBT
- ✓ Summary and Outlook (RHIC Energy Scan)

Winter Workshop 2009

Phase Diagram of Nuclear Matter



Phase diagram of Cabibbo and Parisi *Phys. Lett*. **59B**, 67 (1975)

Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Arguments using asymptotic freedom by J. Collins and M. Perry, *Phys. Rev. Lett*. , **34**, 1353 (1975)

that at high baryon number density matter would form a gas of weakly interacting quarks.

Our basic picture then is that matter at densities higher than nuclear consists of a quark soup. The quarks become free at sufficiently high density.

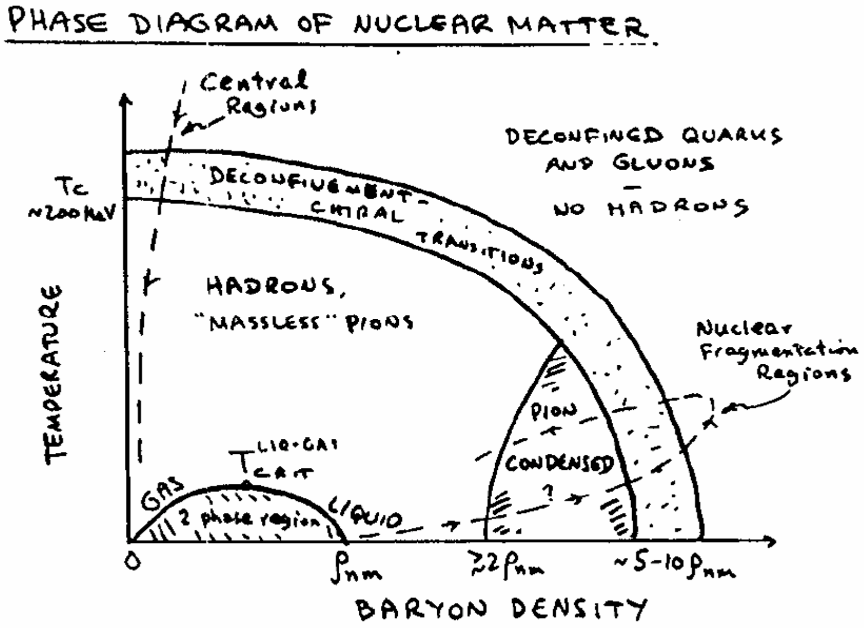
“**True Phase diagram maybe substantially more complex**”

Our curiosity driven to understand the parton degrees of freedom

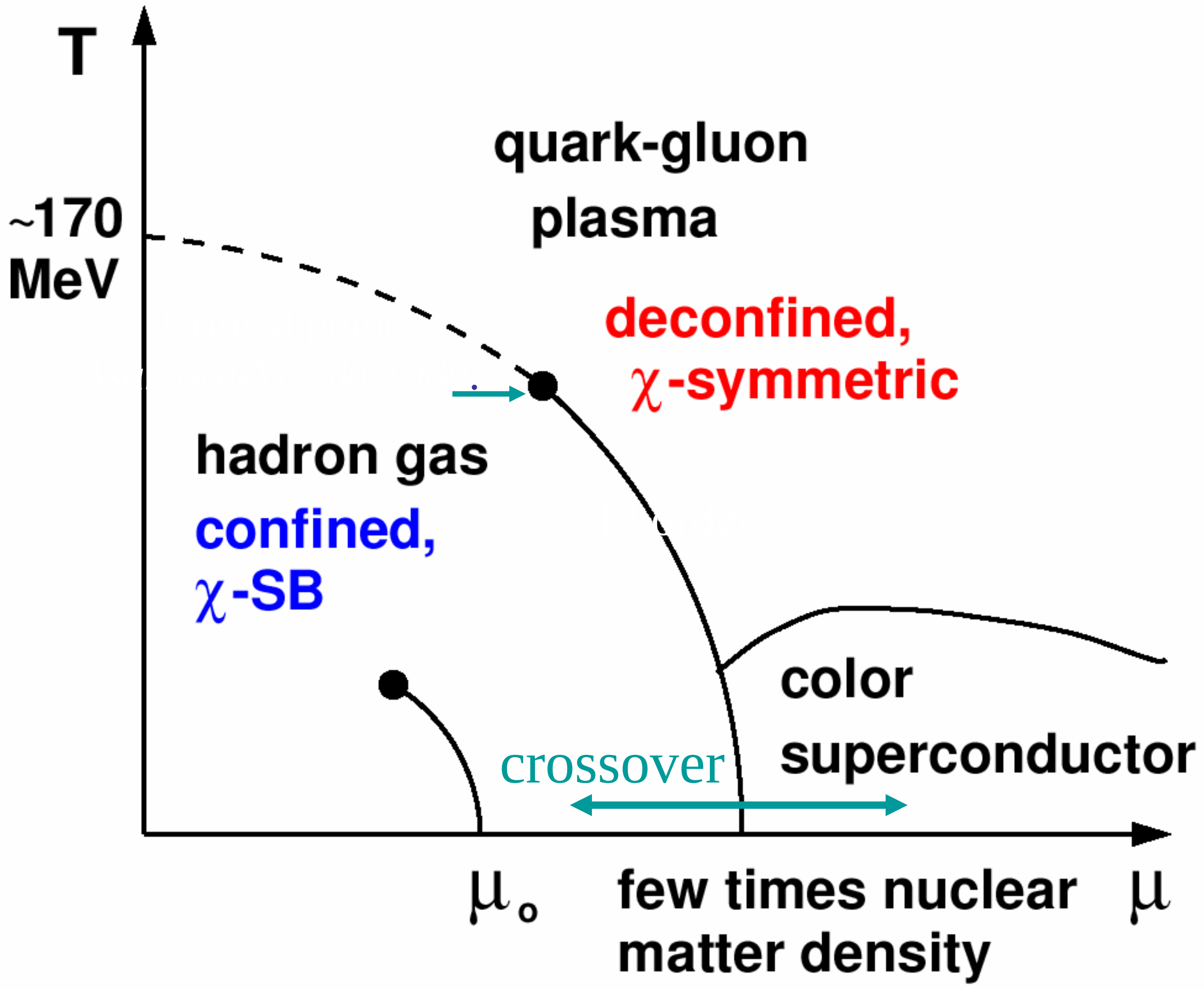
Phase diagram of Baym from

1983 NSAC Long Range Plan

(L.McLerran J.Phys.G35:104001,2008.)



Phase diagram of equilibrated Quark Gluon Plasma



T

~170 MeV

quark-gluon plasma

deconfined, χ-symmetric

hadron gas

confined, χ-SB

color superconductor

crossover

μ_o

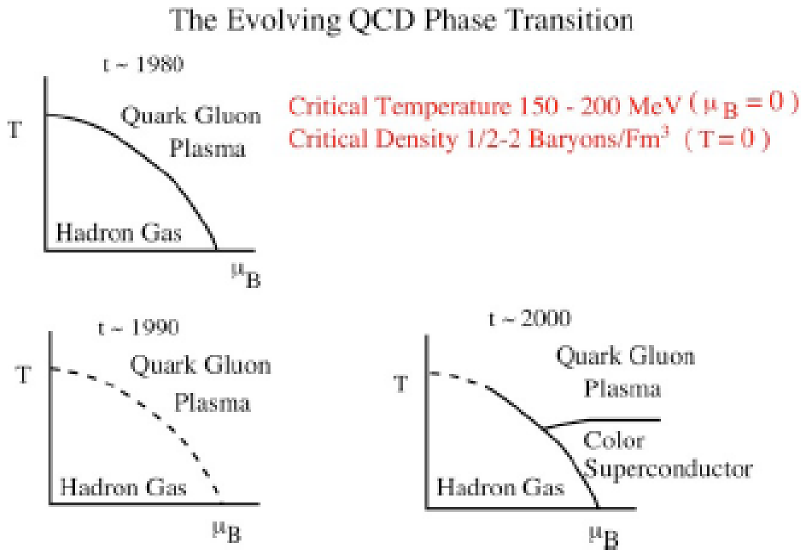
few times nuclear matter density

μ

Courtesy : G.Baym QM2008

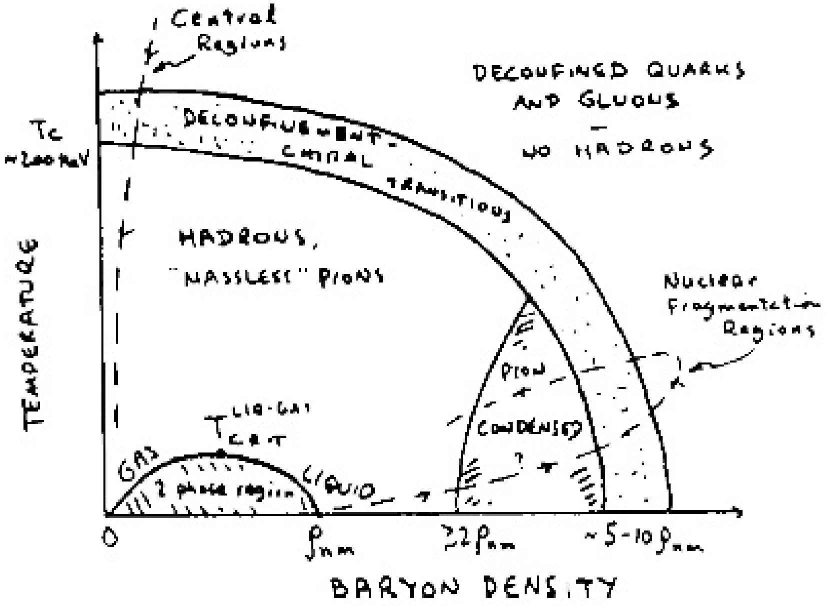
Karsch & Laermann, 2003

Phase Diagram of QCD and its evolution

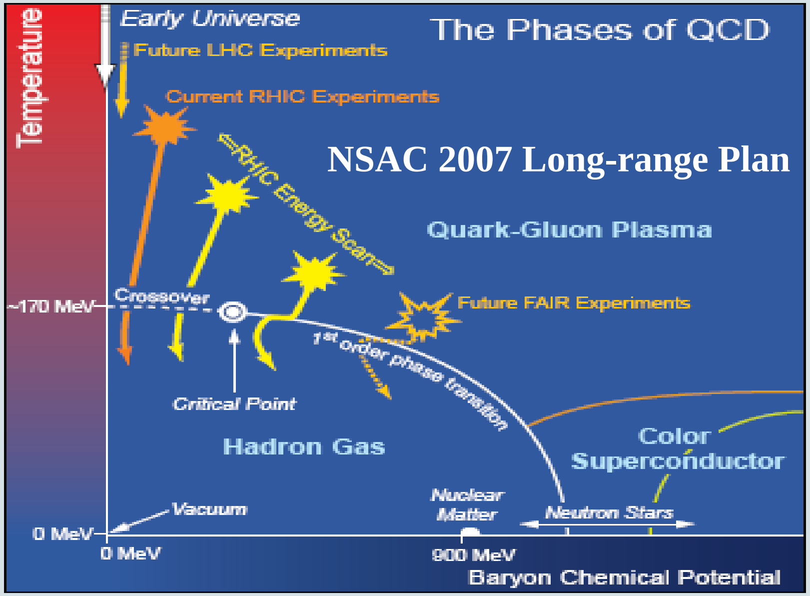


Critical Temperature 150 - 200 MeV ($\mu_B = 0$)
Critical Density 1/2-2 Baryons/Fm^3 (T = 0)

(L.McLerran J.Phys.G35:104001,2008.)



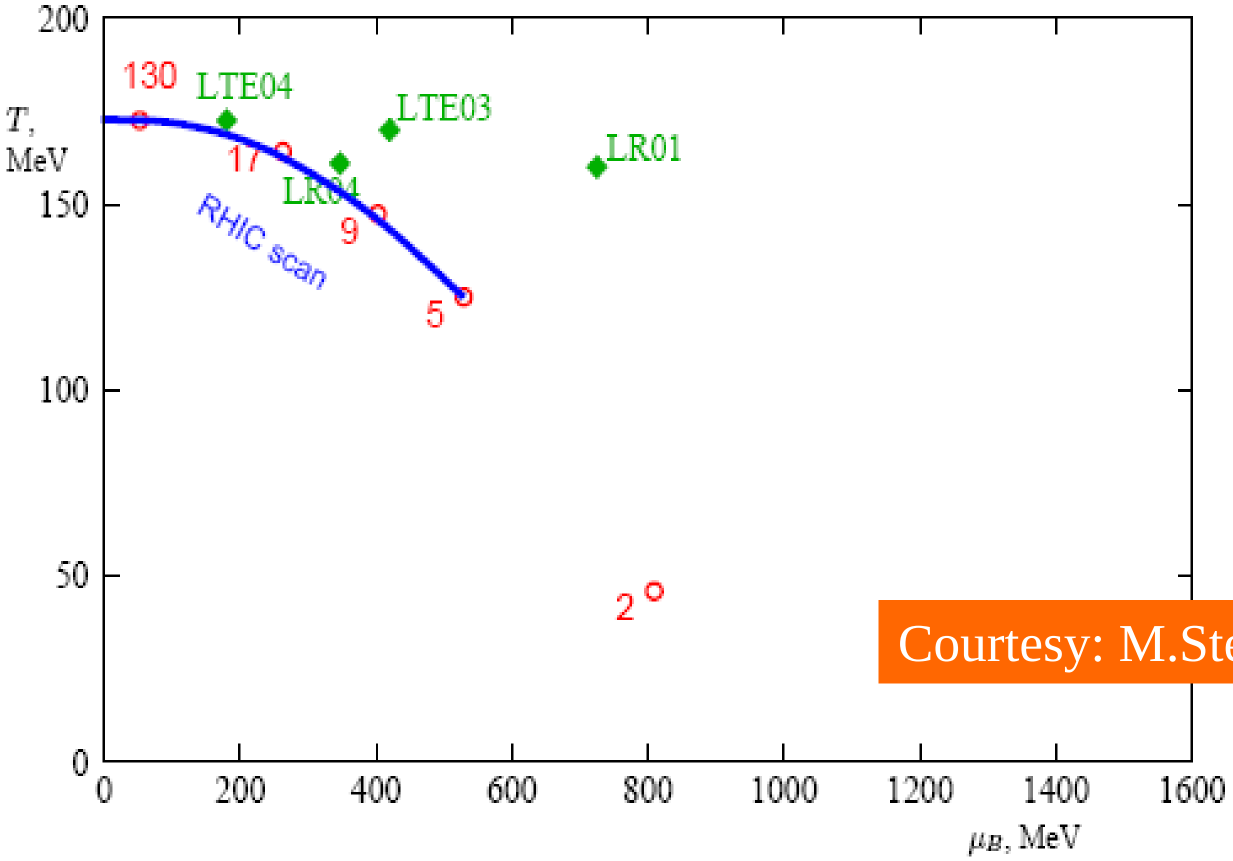
Phase diagram of Baym from **1983 NSAC Long Range Plan** (L.McLerran J.Phys.G35:104001,2008.)



NSAC 2007 Long-range Plan

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.

Scope of this talk



Courtesy: M.Stephanov,QM2008

Here in this talk :

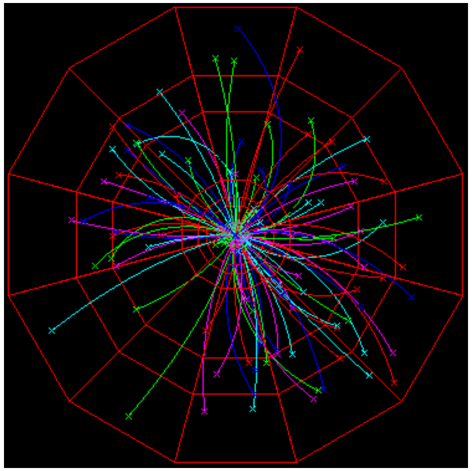
✓Discuss the results from successful data taking in STAR with the Au+Au collisions at 9.2 GeV

✓ Show our preparedness for the future Beam Energy Scan program at RHIC

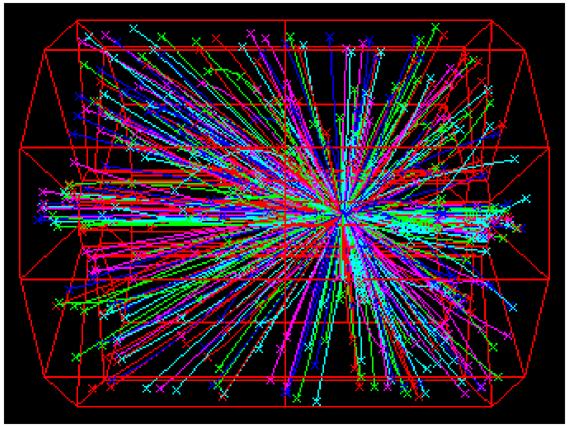
Collisions at $\sqrt{s_{NN}}$ = 9.2 GeV @ STAR

Collisions recorded in STAR at $\sqrt{s_{NN}}$ = 9.2 GeV

Time Projection Chamber

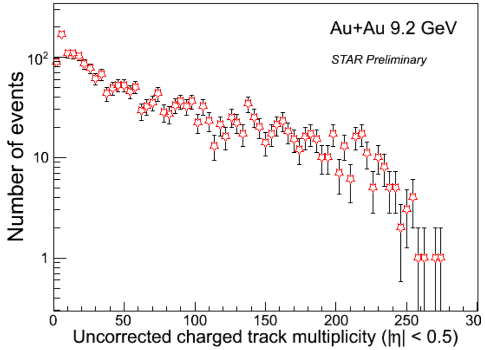


Non-central Collision

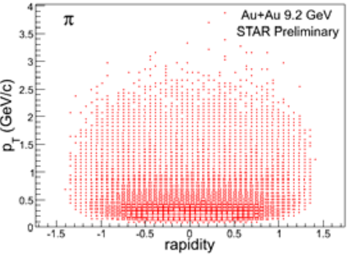


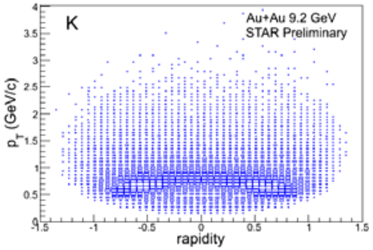
Central Collision

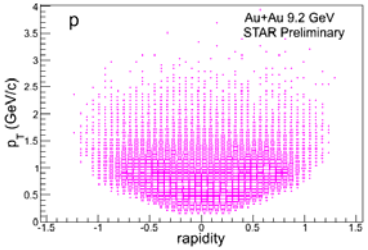
Collected ~ 3000 events in year 2008



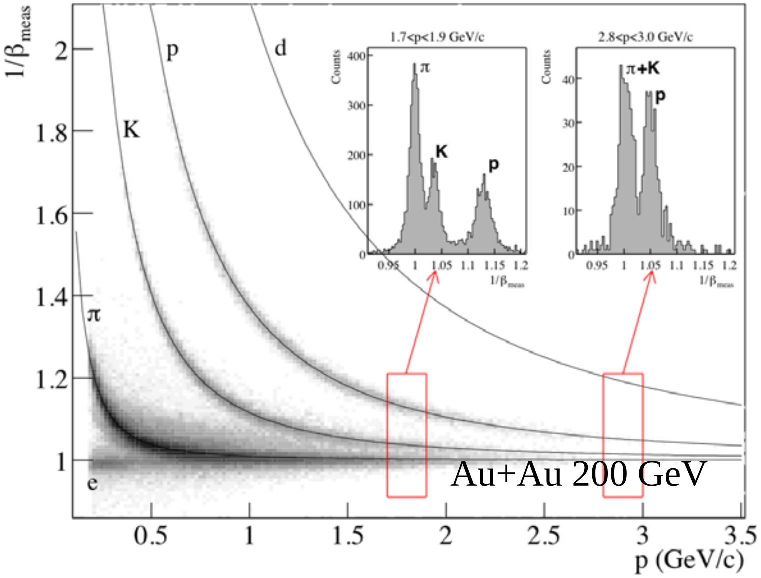
Collider experiment : Uniform Acceptance



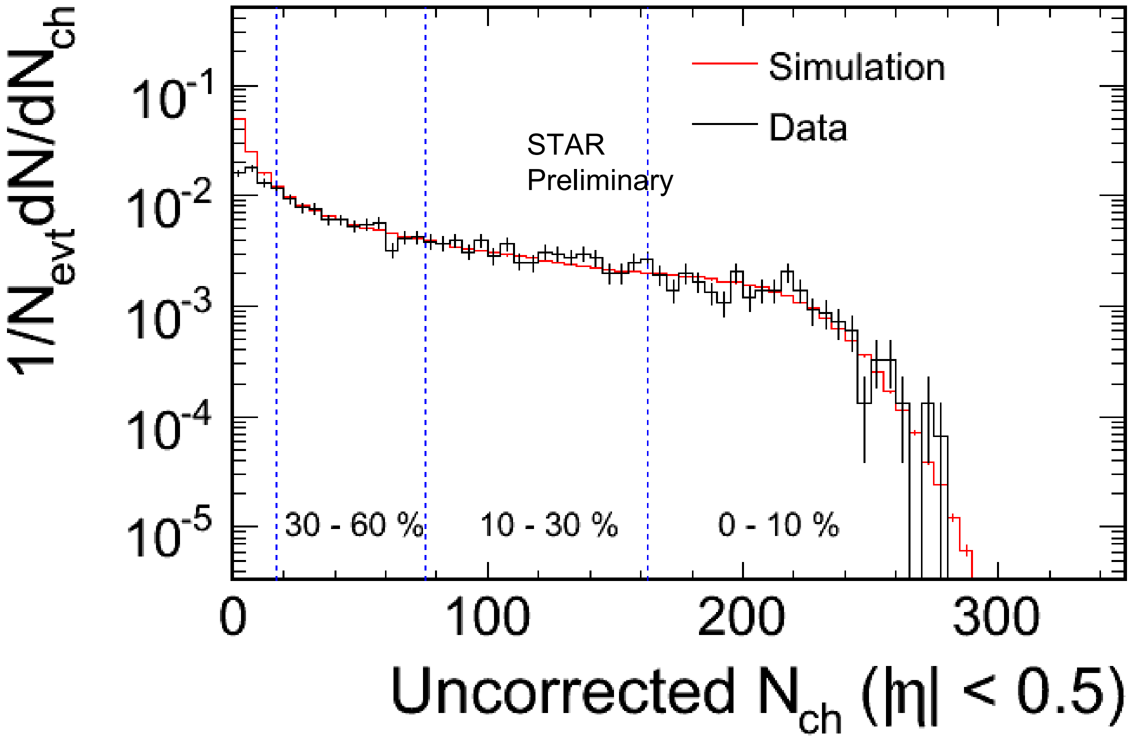




Excellent Particle Identification



Collision Centrality Selection



% cs : N_{part}

0 - 10% : 318

10 - 30% : 203

30 - 60% : 89

Monte-Carlo Glauber Model :

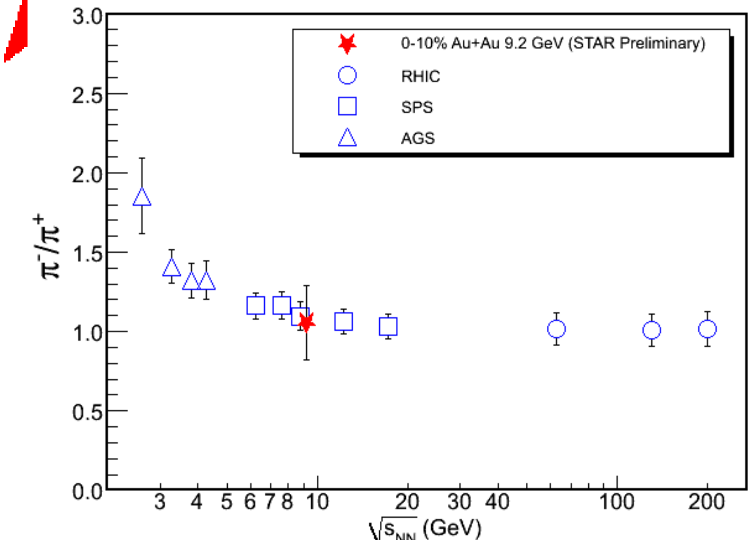
✓ $\sigma_{NN} = 31.5$ mb

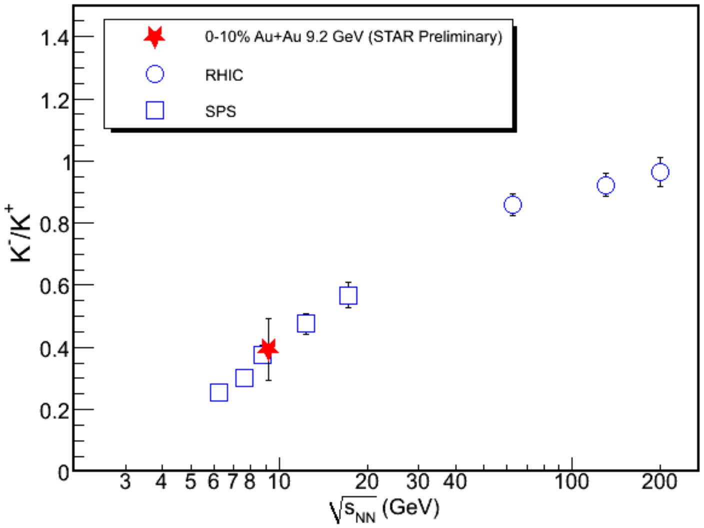
Negative Binomial Distribution fitted to the data

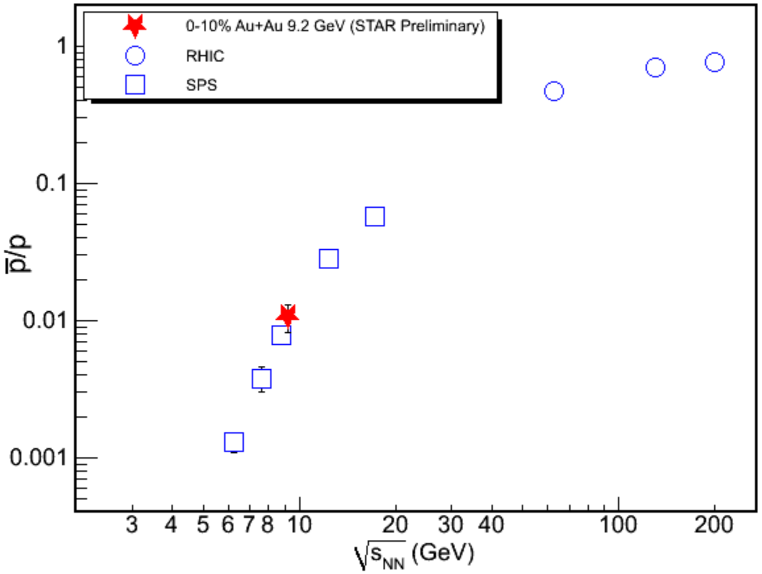
Fraction of hard component, $x = 0.11$

NBD parameters : $\mu = 1.12$, $k = 2.1$

Anti-particle to Particle ratios at mid-rapidity







The ratios follow the $\sqrt{s_{NN}}$ trend
pbar/p << 1 : Large baryon stopping
Large net protons
High μ_B
$K^-/K^+ \sim 0.4$: ~ 60% K^+ by associated
production with Λ
$\pi^-/\pi^+ \sim 1$: similar source of production
for π^+ and π^-

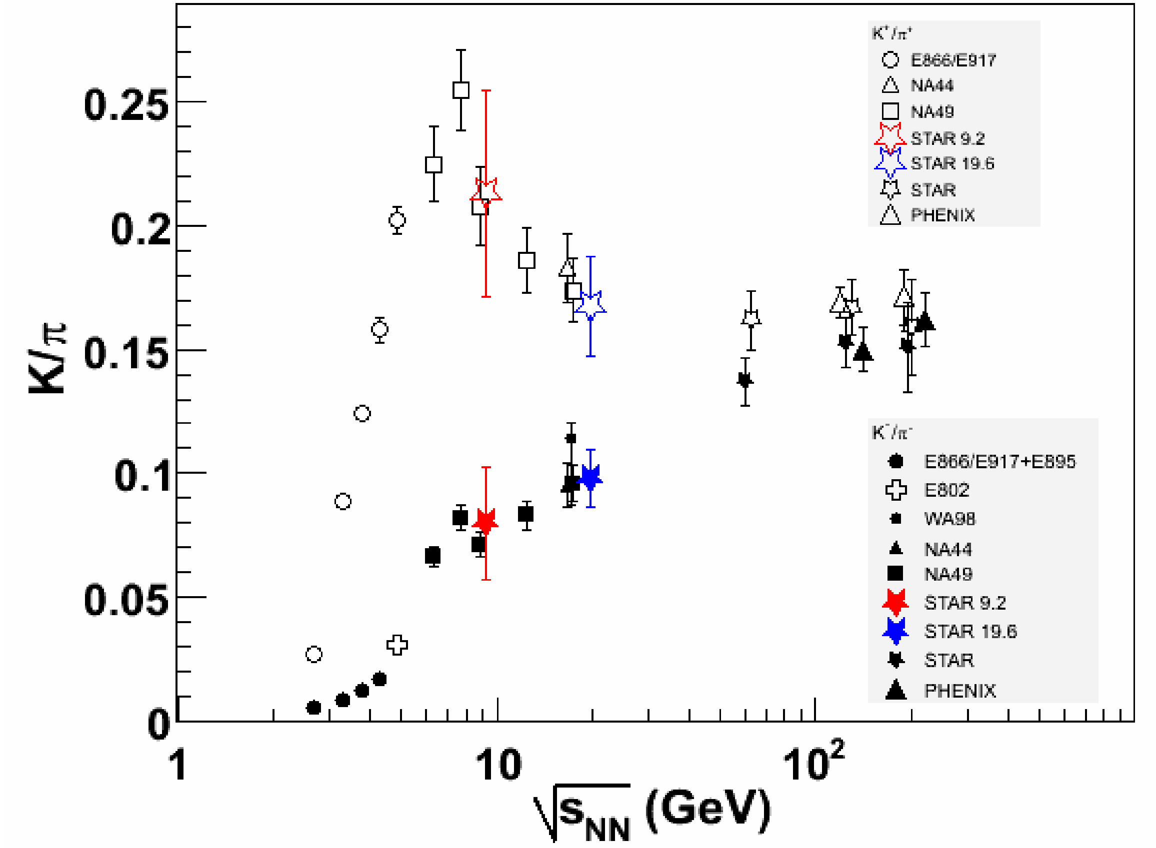
✓ At low energy pions are dominantly produced from Δ resonance

NA49 : PRC 66 (2002) 054902,
PRC 77 (2008) 024903,
PRC 73 (2006) 044910
STAR : ArXiv : 0808.2041;

L.Kumar arXiv:0812.4099 SQM-2008

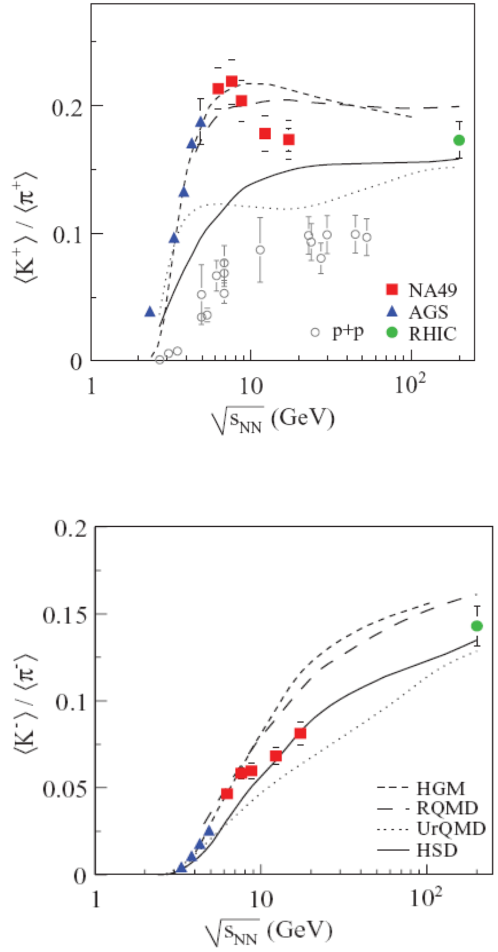
AGS : PRC 58 (1998) 3523, PRC 60 (1999) 044904,
PRC 62 (2000) 024901, PRC 68 (2003) 054903

Beam Energy Dependence of Particle Ratios



E802 PRL81, 2650 (1998); E866 PLB476, 1 (2000); E917 PLB490, 53 (2000); NA44 PLB471, 6 (1999)
WA98 PRC67, 104906 (2003); NA49 PRC66, 054902 (2002); NA49 EPJC33, S621 (2004) ;
NA49 arXiv:0710.0118v2; PHENIX PRC69, 034909 (2004); PHENIX PRL88, 242301 (2002)

STAR : ArXiv : 0808.2041;



PRC 77 (2008) 024903

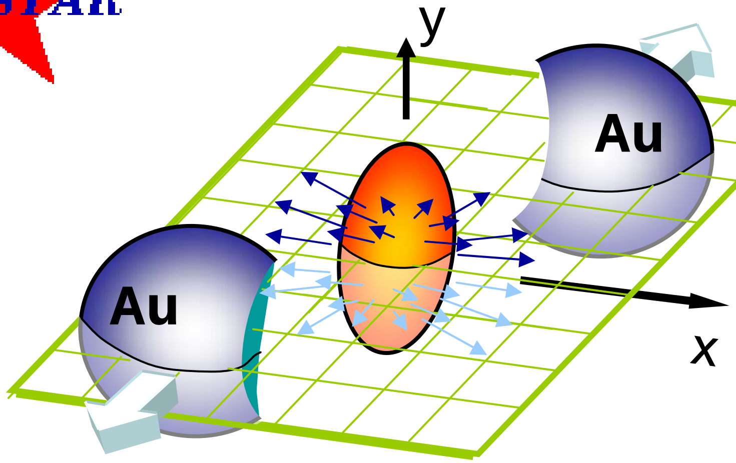
L.Kumar; arXiv:0812.4099 SQM-2008

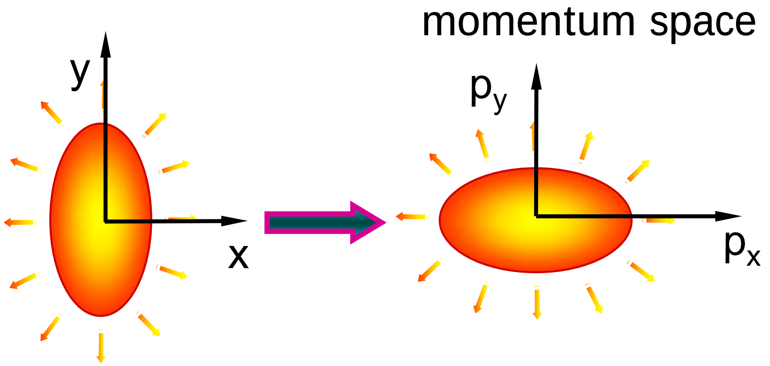
D.Cebra – QM2008

These ratios follow the observed beam energy dependence

K/π ratios reflect strangeness production in heavy ion collisions

Azimuthal Anisotropy Measurements





$$\frac{dN}{d\phi} = a_0\left[1 + 2\sum_{n=1}^{\infty} v_n cos(n\phi)\right]$$

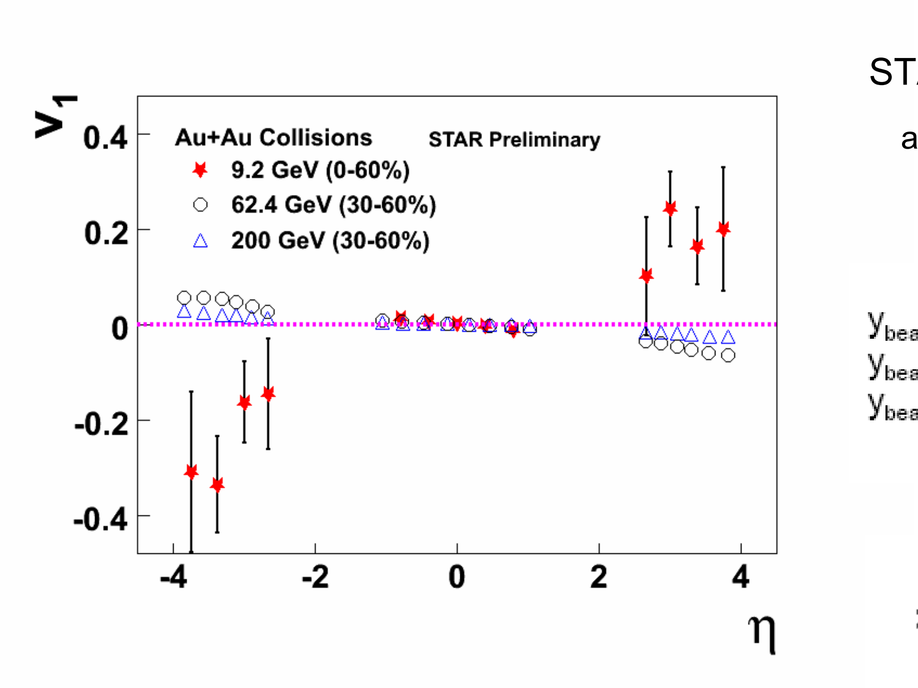
$$\phi = \text{atan}\frac{p_y}{p_x}$$ → azimuthal angle between the momentum of the particle and the reaction plane

Amplitudes of the 1st and 2nd harmonics in the Fourier expansion of the azimuthal distribution respectively ← 1st two coefficients:

- v_1 → **directed flow**
- v_2 → **elliptic flow**

Initial spatial anisotropy → **Strong pressure gradients** → **Azimuthal anisotropy** → **Sensitivity to EOS of nuclear matter**

Azimuthal Anisotropy - (v_1)

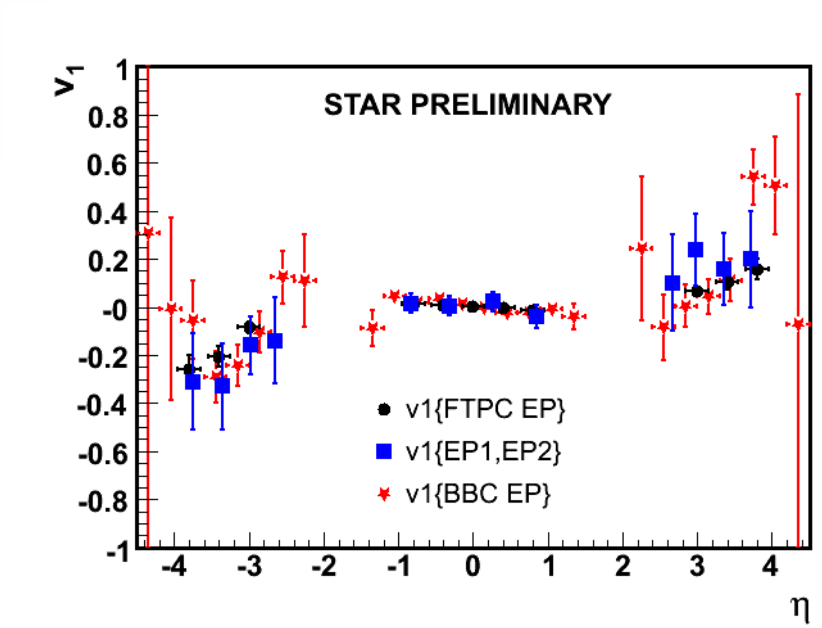


STAR : PRL 92 (2004) 062301

arXiv:0807.1518[nucl-ex]

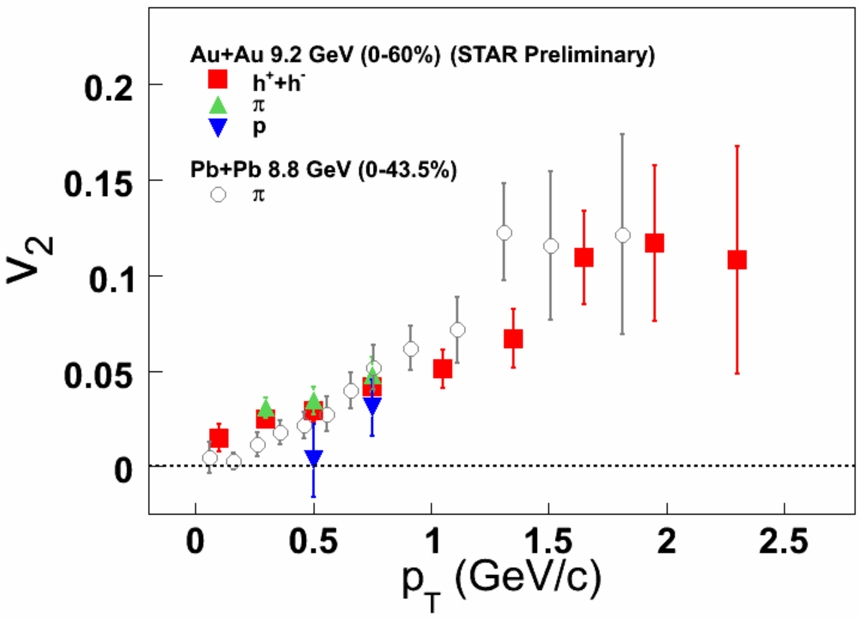
y_{beam} for 9.2 GeV ~ 2.3
y_{beam} for 200 GeV ~ 5.4
y_{beam} for 62.4 GeV ~ 4.2

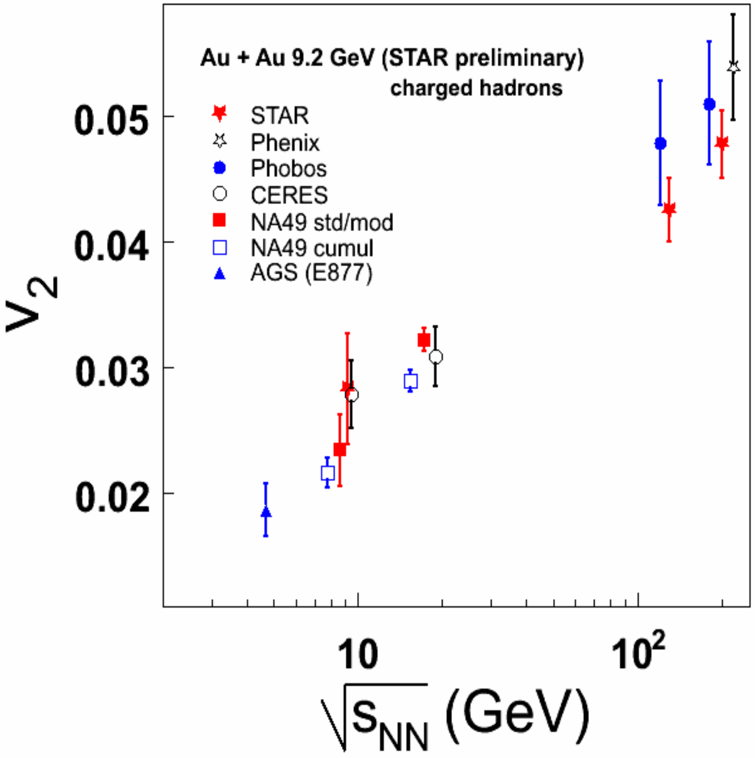
compared to Au+Au 200 and 62.4 GeV ,
v_1 for Au+Au 9.2 GeV shows different trend



3 independent analyses , results within errors

Azimuthal Anisotropy - (v_2)





Au+Au 9.2 GeV : $|\eta|<1$,

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

Particle Momentum correlations (HBT)

Relative momentum between pions is a **vector** $\vec{q} = (\vec{p}_1 - \vec{p}_2)$

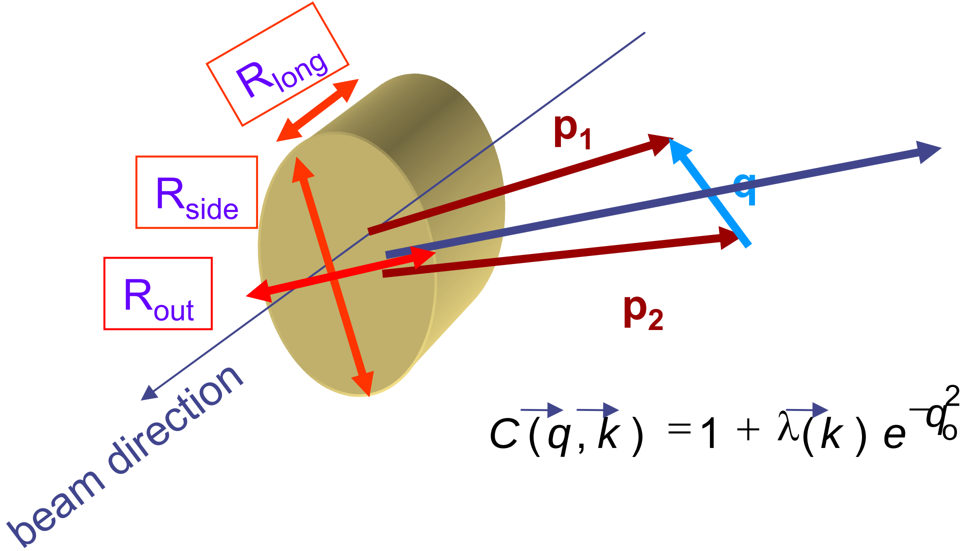
→ can extract 3D shape information

R_{long} – along beam direction

R_{out} – along “line of sight”

R_{side} – ⊥ “line of sight”

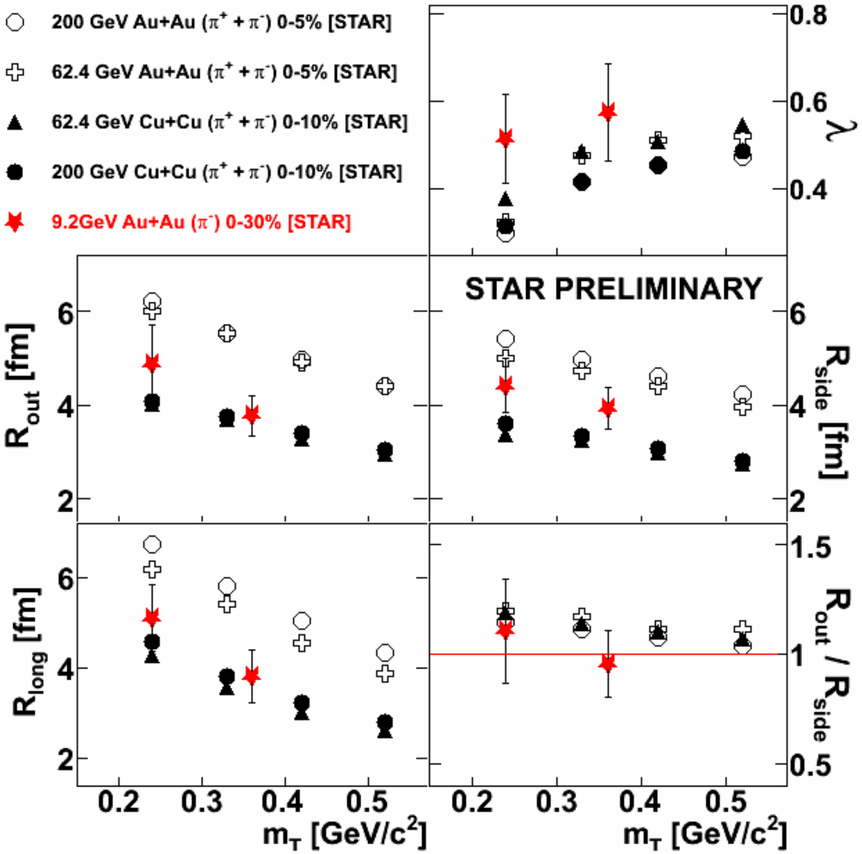
$\vec{K} = 1/2(\vec{p}_1 + \vec{p}_2)$

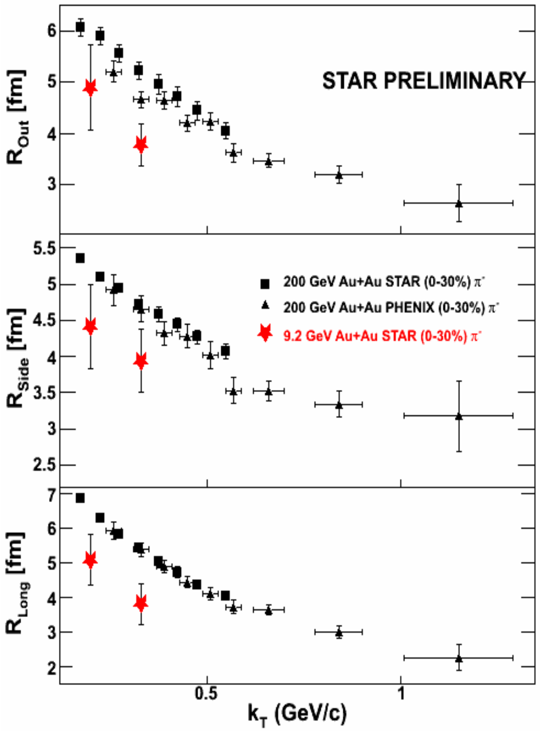


$$C(\vec{q},\vec{k}) = 1 + \lambda(\vec{k})\, e^{-q_{out}^2 R_{out}^2 - q_{side}^2 R_{side}^2 - q_{long}^2 R_{long}^2}$$

m_T dependence of HBT radii

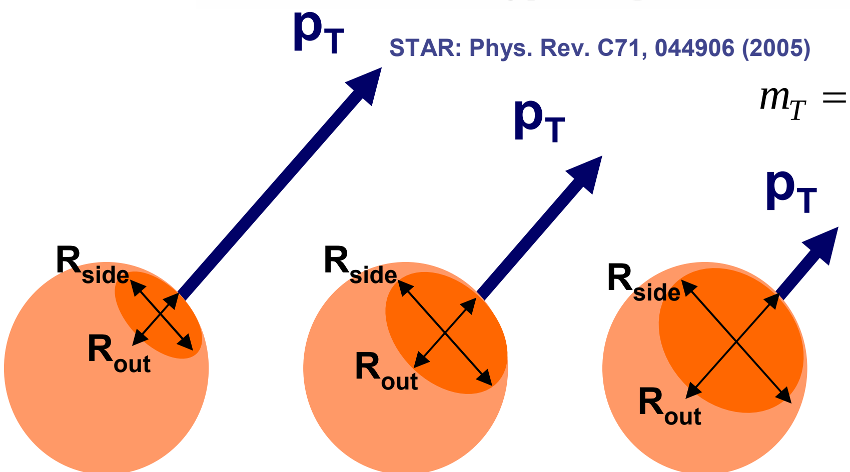
- **HBT radii decrease with m_T:** qualitatively consistent with models with collective flow.
  - Transverse radii → transverse flow
  - R_L → longitudinal flow
- $R_{out} / R_{side} \sim 1$.



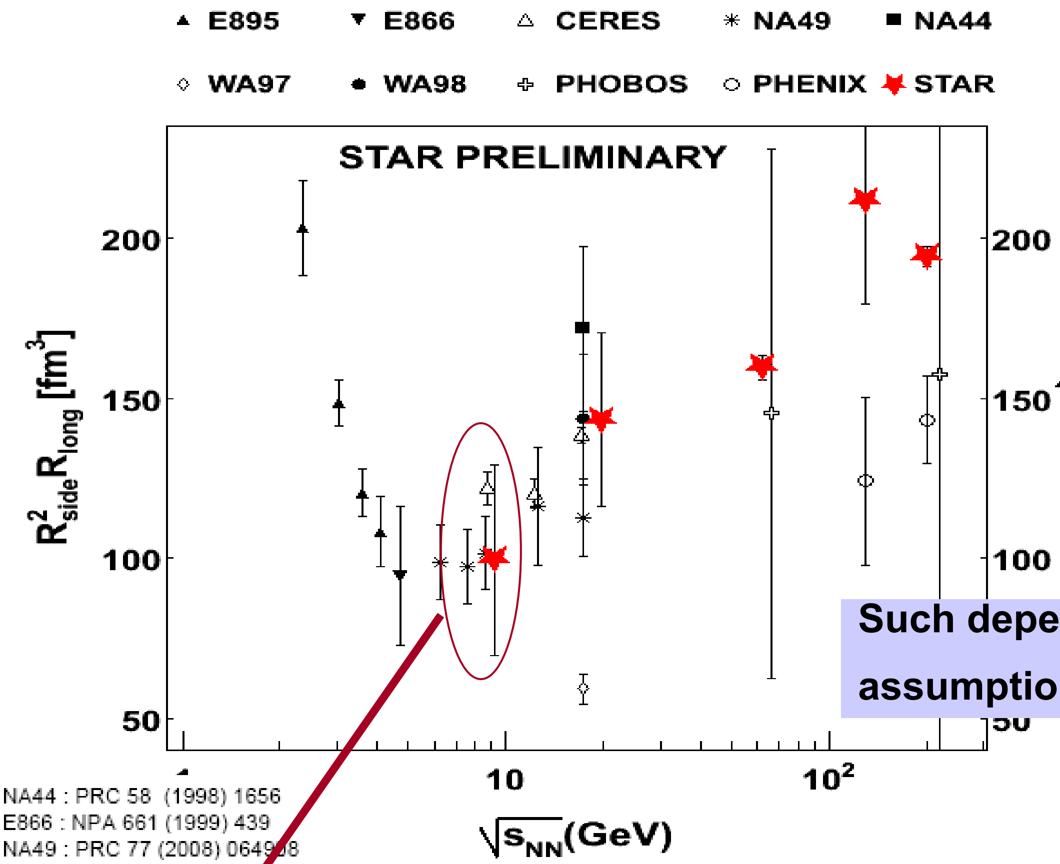


STAR: Phys. Rev. C71, 044906 (2005)

$$m_T = \sqrt{m_\pi^2 + k_T^2}$$



Constant Freeze-out Density



At high energies:
Baryon density << Pion density

freeze out volume
($R_s^2R_L$)

$$\lambda_f = \frac{1}{\rho_f \cdot \sigma} = \frac{V_f}{N \cdot \sigma}$$

Proportional
to $dN_{ch}/d\eta$

Such dependences are consistent with the assumption of mean free path of pions at freeze-out.

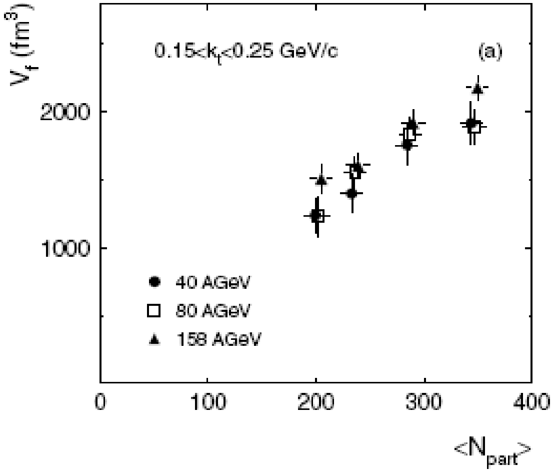
NA44 : PRC 58 (1998) 1656
E866 : NPA 661 (1999) 439
NA49 : PRC 77 (2008) 064908

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

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

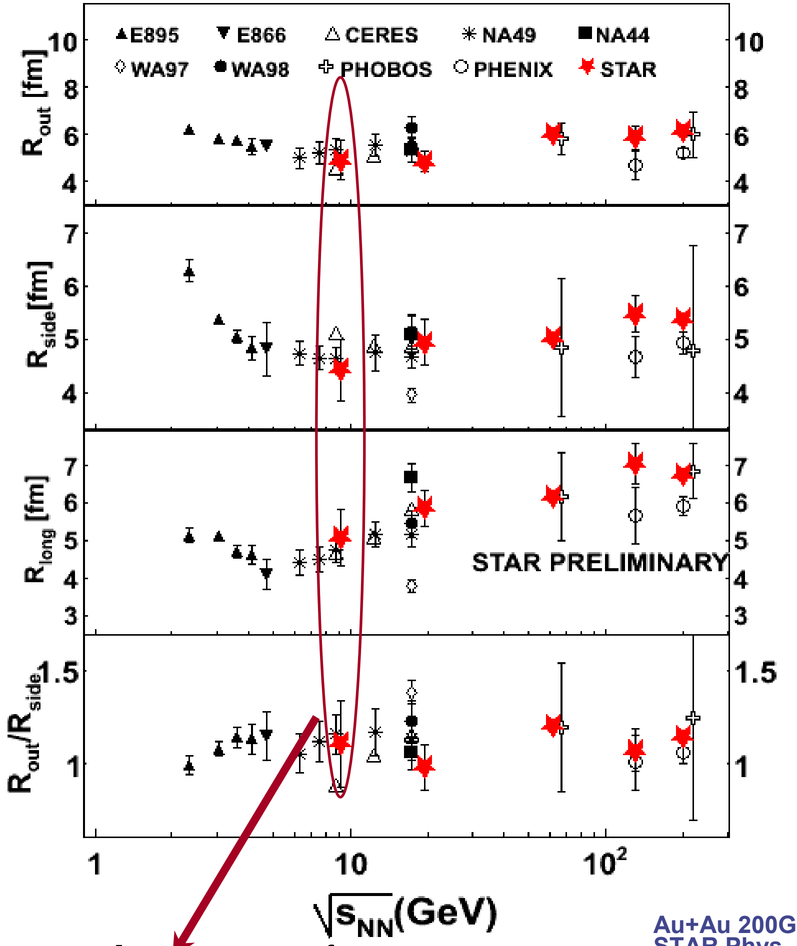
Centrality : 0 - 30% for Au+Au 9.2 GeV

- o **Two distinct domains:** decrease at AGS and rise within SPS and RHIC energies
- o At AGS pion-nucleon term of **N.σ** dominates
- o **Volume estimates at RHIC should scale with $dN_{ch}/d\eta$**

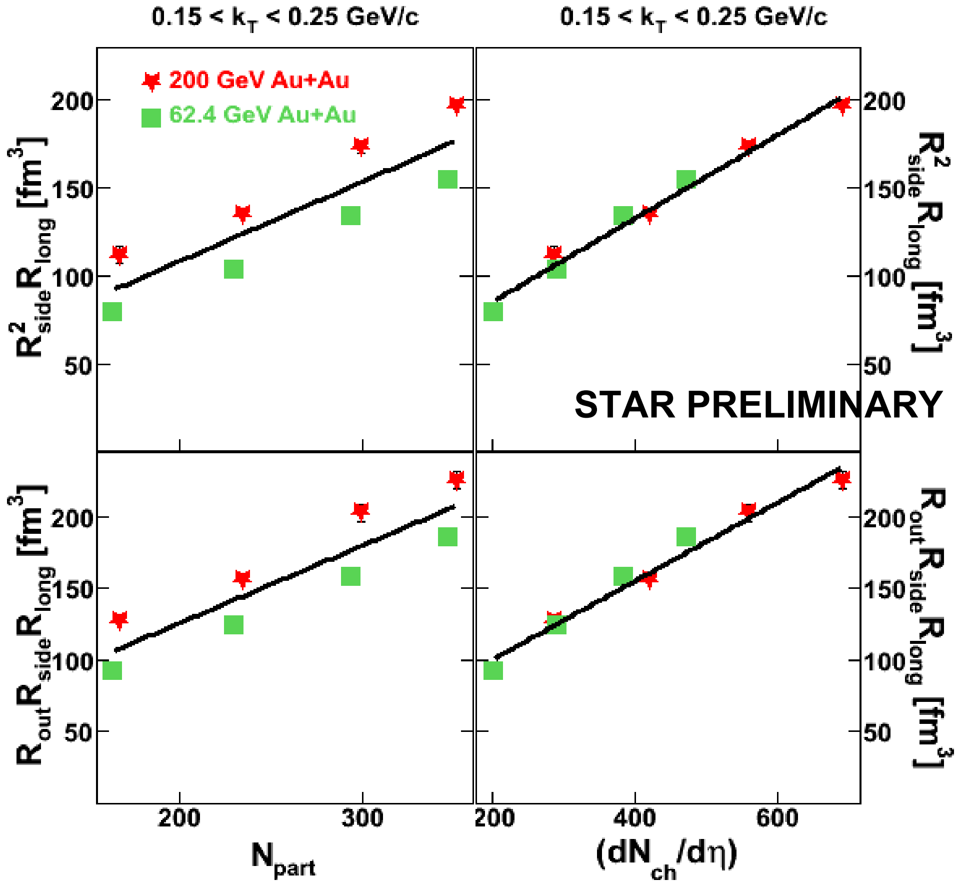


CERES PRL 90, 022301(2003)

Comparative volume estimates with N_{part} and N_{ch}



Centrality : 0 - 30% for Au+Au 9.2 GeV



Au+Au 200GeV results from STAR Phys. Rev. C71, 044906 (2005)

M.Lisa et al.Ann.Rev.Nucl.Part.Sci.55:357-402,2005

- ➢Measurements of Au+Au collisions at same centralities and different energies show different freeze-out volume, which means that N_{part} is not a suitable scaling variable in this case.

- ➢On the other hand charge particle multiplicity seems to be a better scaling variable in the mid-rapidity region of $|\eta| < 0.5$ for the STAR analyses.

Int.J.Mod.Phys.E16:1883-1889,2007

Summary

- **Identified particle spectra** obtained from Au+Au collisions at 9.2 GeV.
  Hadron yields and ratios are similar to SPS experiments at similar beam energies. Higher statistics required for qualitative improvements on SPS results.
- Yield and $<m_T>$ follows previously established beam energy dependence
- Anti-proton to proton ratio ~ 0.01 indicating significant baryon stopping at mid-rapidity in these collisions
- K^-/K^+ ~ 0.4 indicating associated production for K^+

- **Azimuthal Anisotropy (v_1 and v_2)** measurements follow the SPS results from collisions at similar energies

- **Pion interferometry** results follow the established beam energy trends
- The scaling of the apparent freeze-out volume with charged particle multiplicity show the consistency with the hypothesis of a universal mean-free-path at freeze-out. Also confirms with dependence of transverse mass.

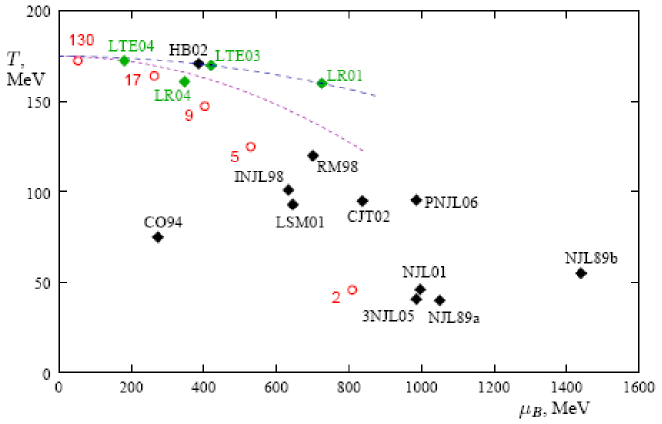
"I never guess. It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts."

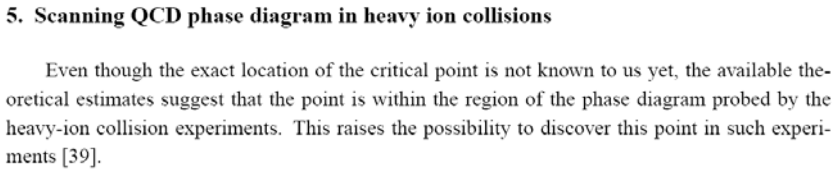
Sir Arthur Conan Doyle, The Sign of Four, A Scandal in Bohemia (Sherlock Holmes)
British mystery author & physician (1859 - 1930)

Proposed Beam Energy Scan Program from STAR

STAR Beam User Request

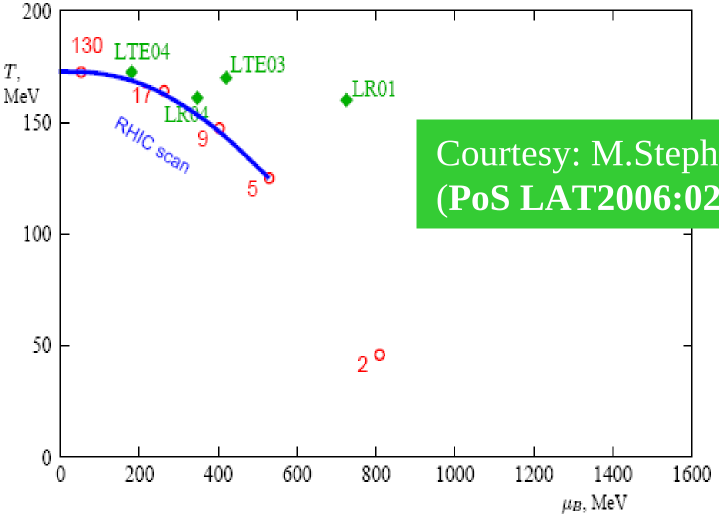
$\sqrt{s_{NN}}$ [GeV]	μ_B [MeV]	Rate [Hz]	Goal [Events]	Duration [Days]
5.0	550	0.5	100K	3
7.7	410	2.6	5M	18
12.3	300	10	10M	10
17.3	229	25	10M	7
27	151	30	20M	14
39	112	50	20M	7





5. Scanning QCD phase diagram in heavy ion collisions

Even though the exact location of the critical point is not known to us yet, the available theoretical estimates suggest that the point is within the region of the phase diagram probed by the heavy-ion collision experiments. This raises the possibility to discover this point in such experiments [39].

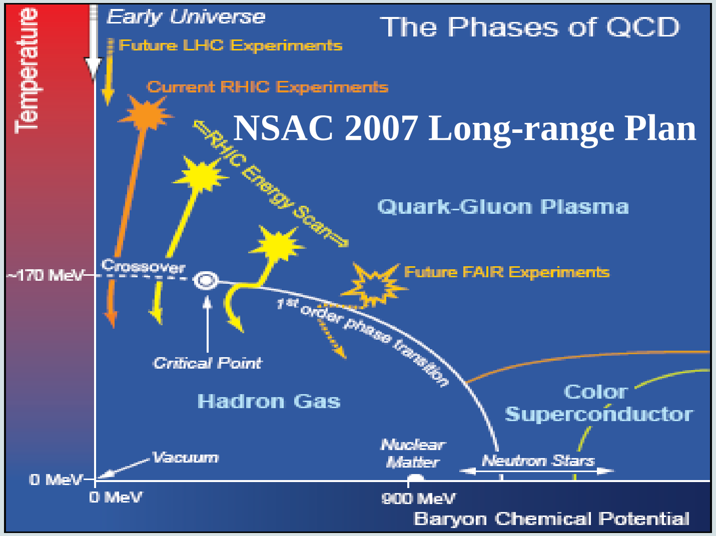


Courtesy: M.Stephanov
(**PoS LAT2006:024,2006**.)

Explore the QCD Phase Diagram!

Outlook

The Beam Energy Scan Program
has started at RHIC !!



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.

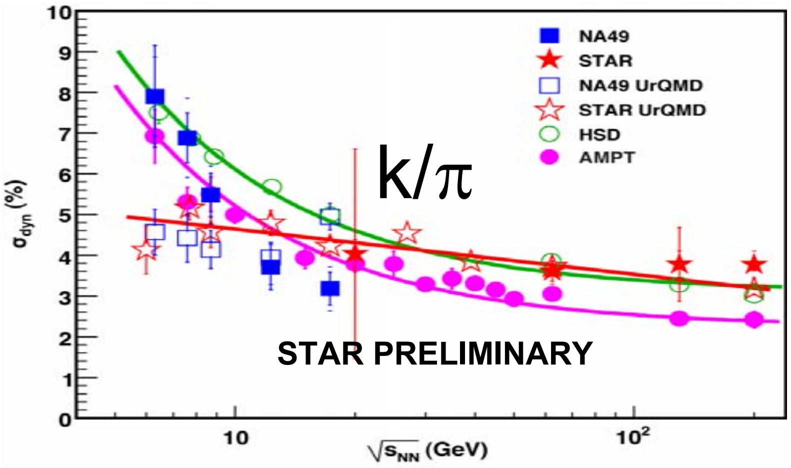
STAR’s Plan : Run 10 RHIC Beam Energy Scan

Several crucial measurements, which
we pursue in STAR, need to be affirmed
to understand the existence of critical point

The Observables and Interests:

(a) Number of quark scaling in v2
(b) Strong Parity violations
(c) Higher Moments of net-proton
(d) Fluctuations in hadron ratios

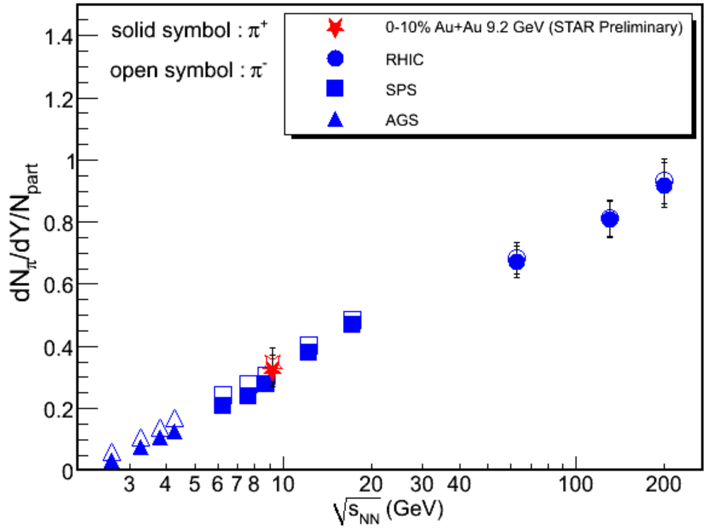
(a) and (b) : disappearance
(c) and (d) : appearance

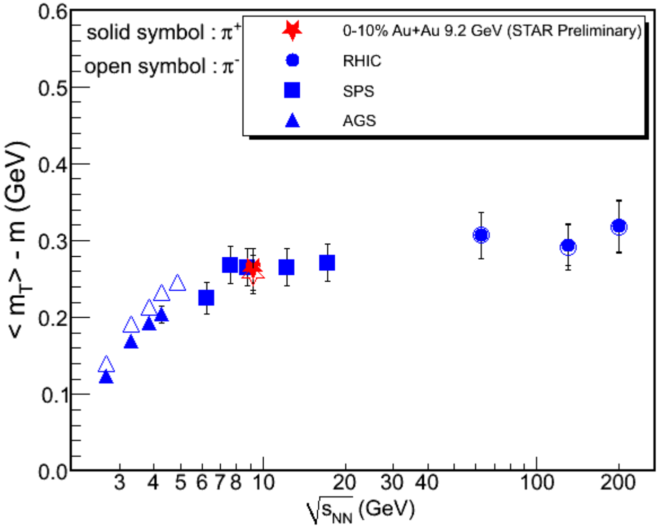


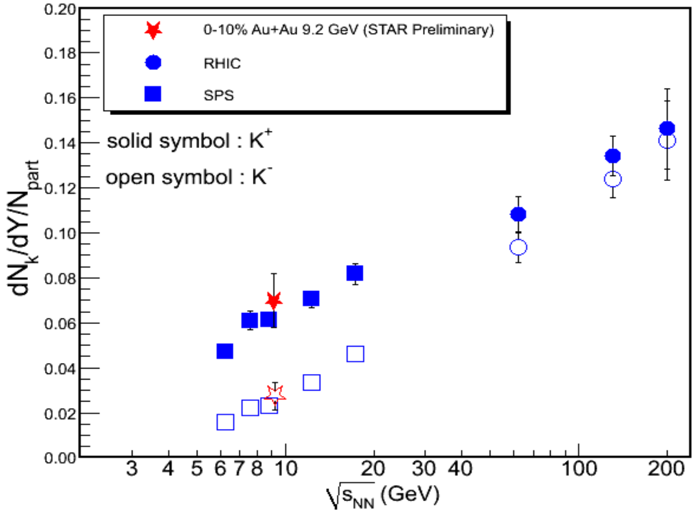
We need experimental evidence for the understanding of
either the critical point or 1st order transition which is important to
map the **QCD Phase Diagram**.

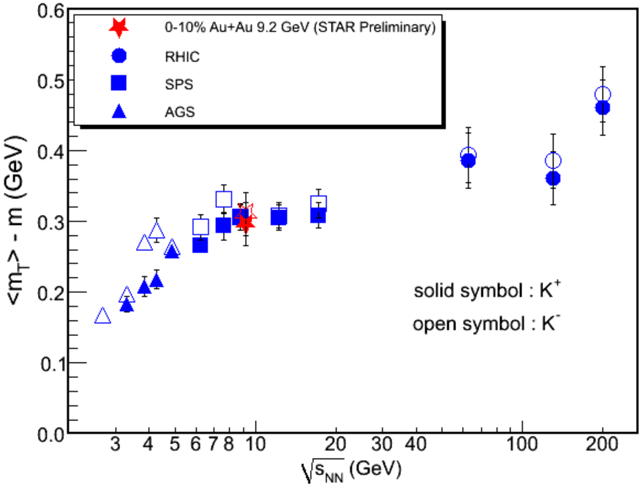
BACK UP SLIDES

Yield and Slope - Mesons at mid-rapidity







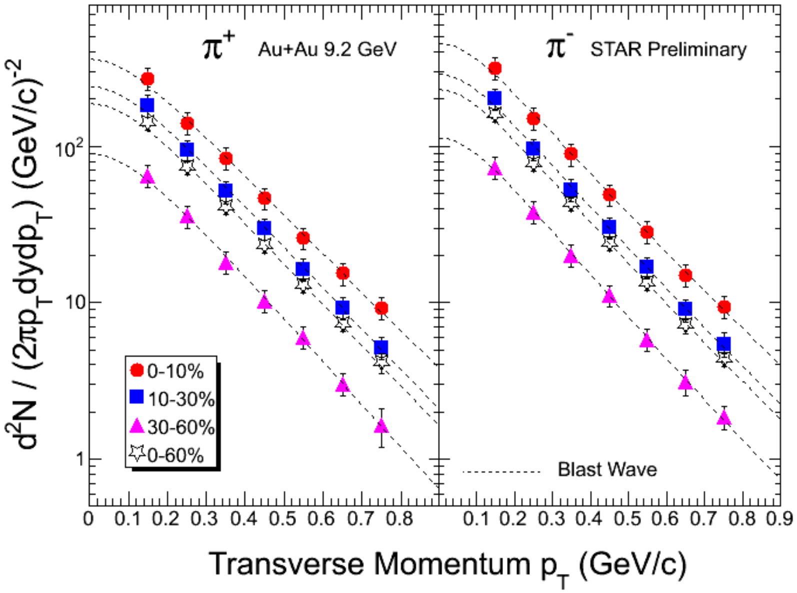


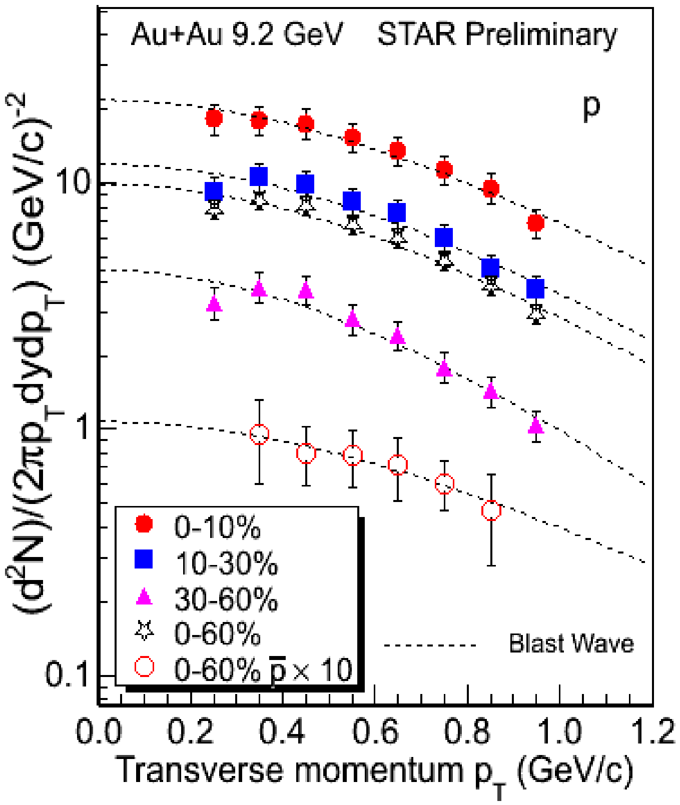
NA49 : PRC 66 (2002) 054902, PRC 77 (2008) 024903, PRC 73 (2006) 044910
STAR : ArXiv : 0808.2041;
AGS : PRC 58 (1998) 3523, PRC 60 (1999) 044904, 064901,
PRC 62 (2000) 024901, PRC 68 (2003) 054903

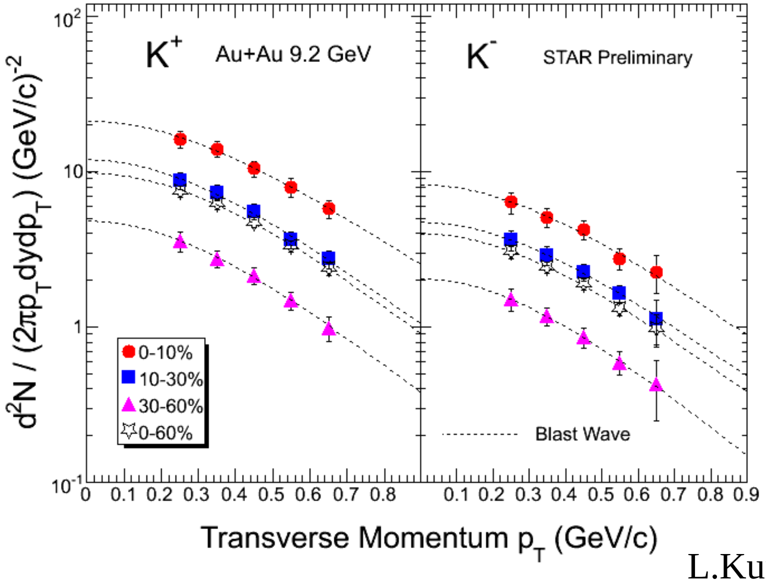
Yield and Slope consistent with the dependence on beam energy trend

L.Kumar arXiv:0812.4099 SQM-2008

Identified hadron spectra at mid-rapidity







We measure from Model Fits:

~ 82 % of total π produced
~ 47 % of total K produced
~ 75 % of total p produced

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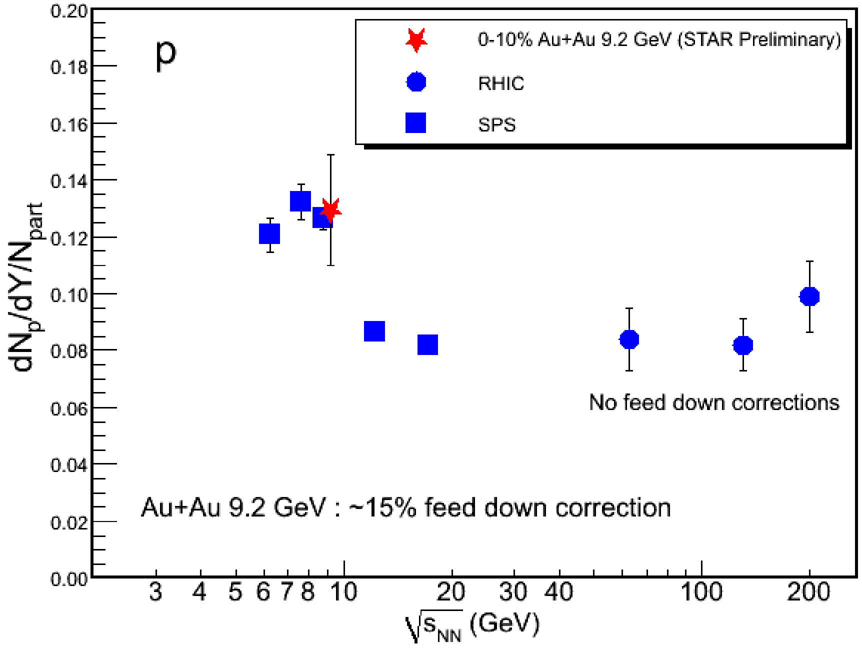
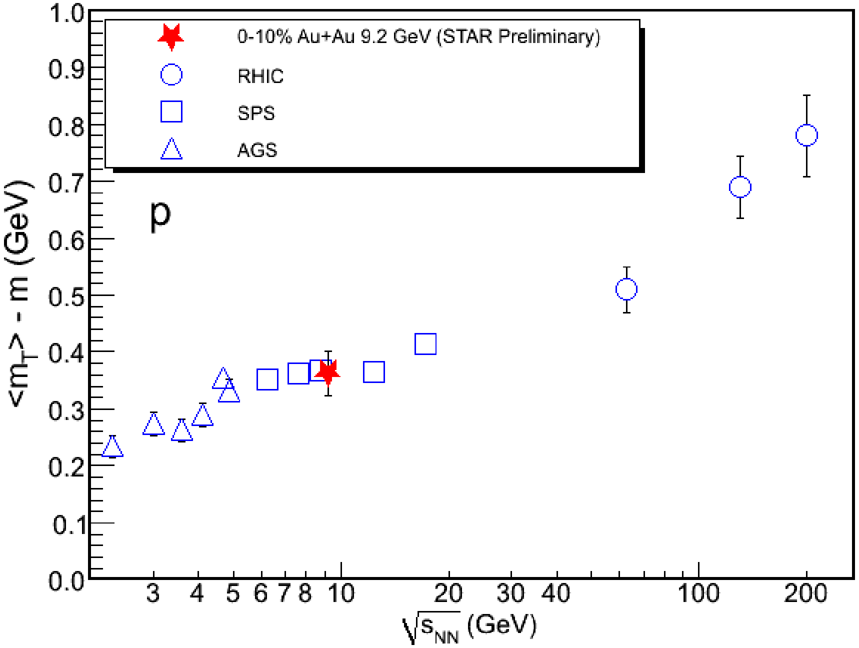
Yield and Slope - Baryons at mid-rapidity



No feed down corrections

Au+Au 9.2 GeV : ~15% feed down correction

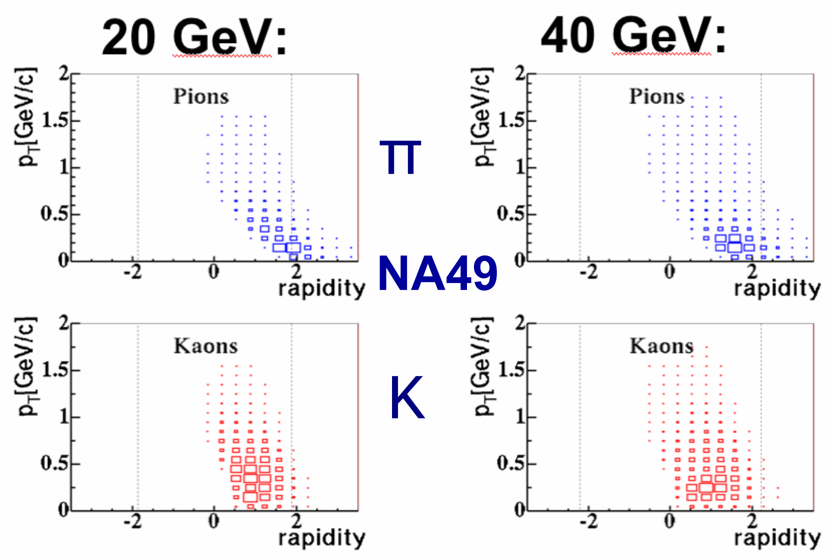


Both the yield and $\langle m_T \rangle$ are close to the SPS results at similar energies

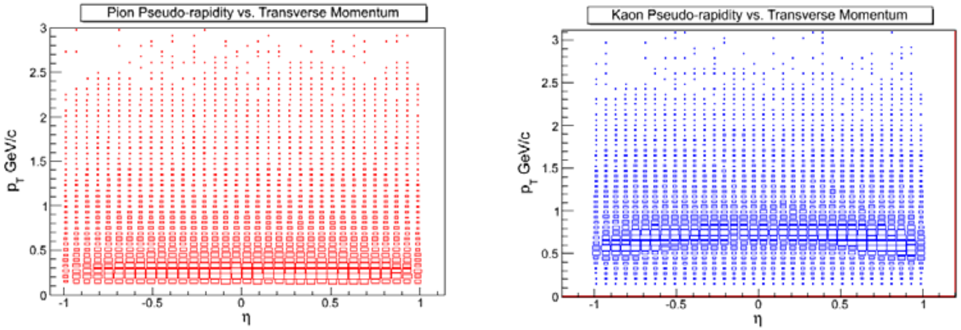
NA49 : PRC 66 (2002) 054902, PRC 77 (2008) 024903, PRC 73 (2006) 044910
STAR : ArXiv : 0808.2041;
AGS : PRC 58 (1998) 3523, PRC 60 (1999) 044904, 064901,
PRC 62 (2000) 024901, PRC 68 (2003) 054903

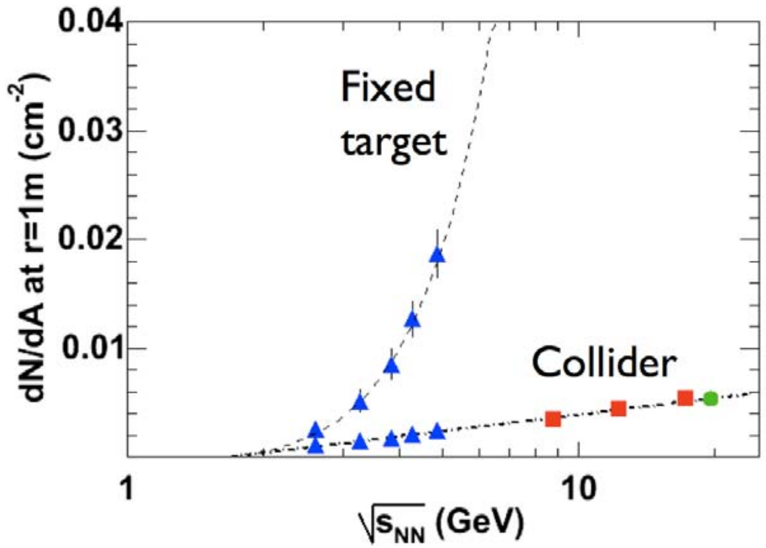
Colliders are a great choice for E-scan

Acceptance



π **STAR** **K**



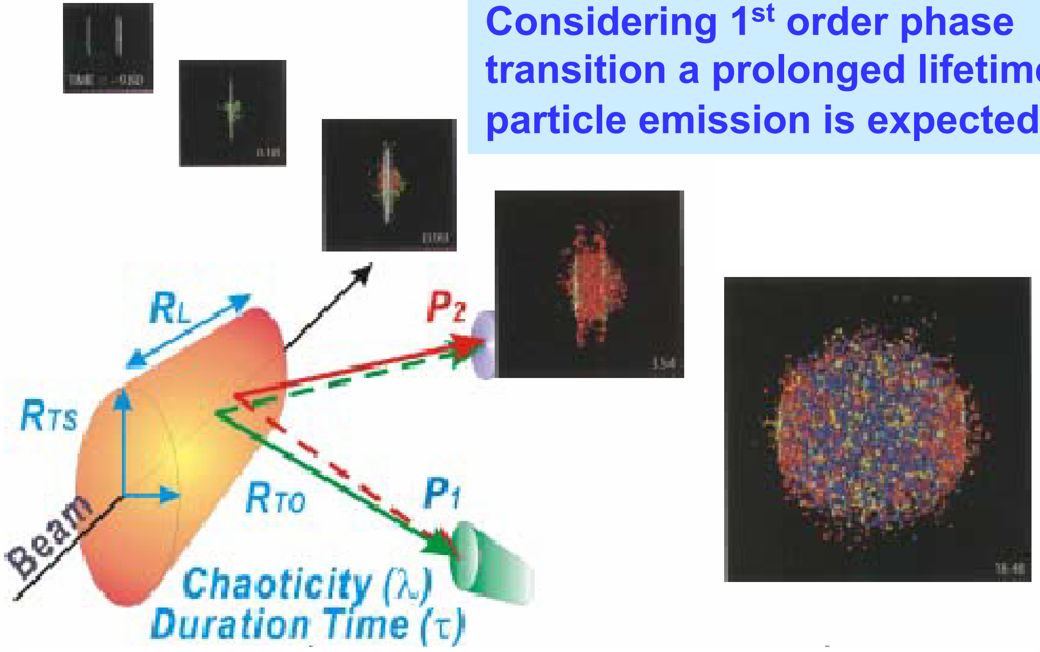


- Occupancy for collider detectors is much less dependent on beam energy
- Less problems with track merging, charge sharing hits etc..

Better control of systematics

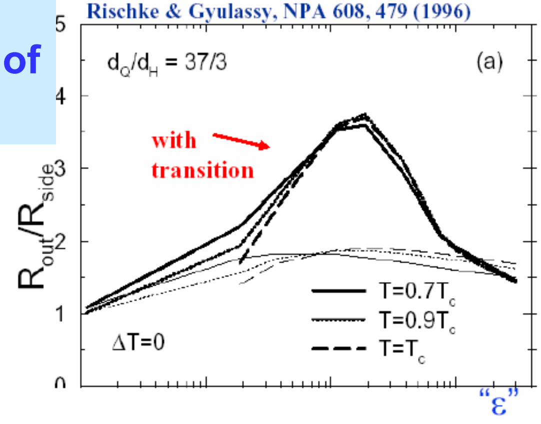
HBT studies : Signature of QGP

Considering 1st order phase transition a prolonged lifetime of particle emission is expected.



3D 1-fluid Hydrodynamics

Rischke & Gyulassy, NPA 608, 479 (1996)



Quark Gluon Plasma

"Ionize" nucleons with heat

"Compress" them with density

New state(s?) of matter

$$\frac{R_{OUT}}{R_{SIDE}} \leftrightarrow \tau$$

It is obvious for a static source, but our source is expanding..