Possible Evidence of Thermalization at RHIC

Outline

Why we need to address the issue of thermalization

What are the characteristic signatures of thermalization

What have we learned so far at RHIC

Bedanga Mohanty
VECC,Kolkata

Thermalization : Why Address This Topic ?

(A) To establish Quark-Gluon Plasma (QGP)

“For our purposes here, we take the QGP to be a (locally) thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes.”

STAR Collaboration : Nucl. Phys. A 757 (2005) 102

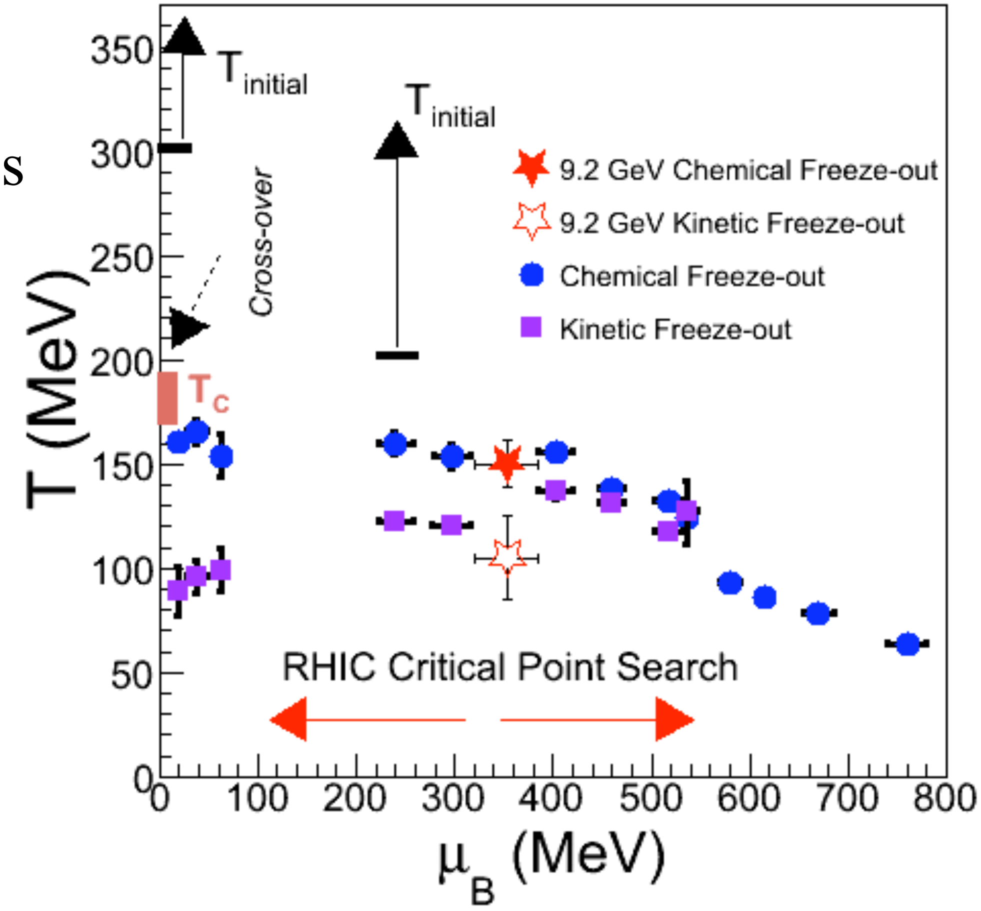
Thermalization : Why Address This Topic ?

(B) To explore the QCD Phase Diagram

Phase diagram is a type of graph used to show the equilibrium conditions between the thermodynamically distinct phases

Temperature in the phase diagram has a meaningful definition for a system in thermal equilibrium

One of the goals of HI program is to "Establish the QCD Phase Diagram"



STAR : 0909.4131

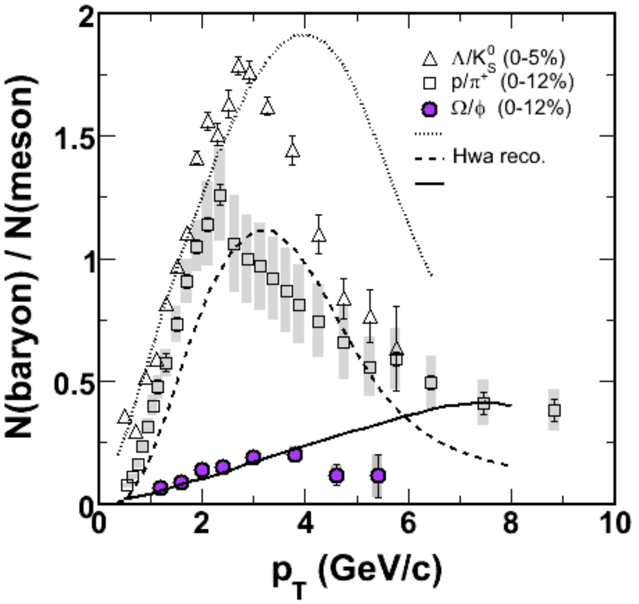
Thermalization : Why Address This Topic ?

(C) To understand several physics conclusions at RHIC

Most theories in our field are based on assumption of thermal equilibrium or close to thermal equilibrium

(1)

STAR : Phys. Rev. Lett. 99 (2007) 112301



Recombination/ coalescence

(2) Lattice QCD assumes thermalization and provides EOS for many phenomenology/theoretical work

(3)

Boltzman equation for homogenous system, no external force and with relaxation time approximation

$-df/dt = f - f_0/\tau_{relax}$

$f = f_0 + (f_i - f_0) \exp(-\Delta t/\tau_{relax})$

$f \dashrightarrow f_0$ (equilibrium dist) if $\Delta t >> \tau_{relax}$

Most models now days work with conditions near equilibrium.

Thermalization

In physics, thermalization is the process of particles reaching thermal equilibrium through mutual interaction.

In general the natural tendency of a system is towards
a state of equipartition of energy or uniform temperature.
This raises the system’s entropy.

Basic Features Of A Thermalized System

What happens when we have a thermalized system :

(A) Maximum Entropy - $dS/dt = 0$; S : Entropy, t : real time

(Very ideal case : Processes are reversible -Initial <===> Final)

-- *To show experimentally is challenging (impossible?)*

(B) Momentum-Space distributions reach equilibrium values

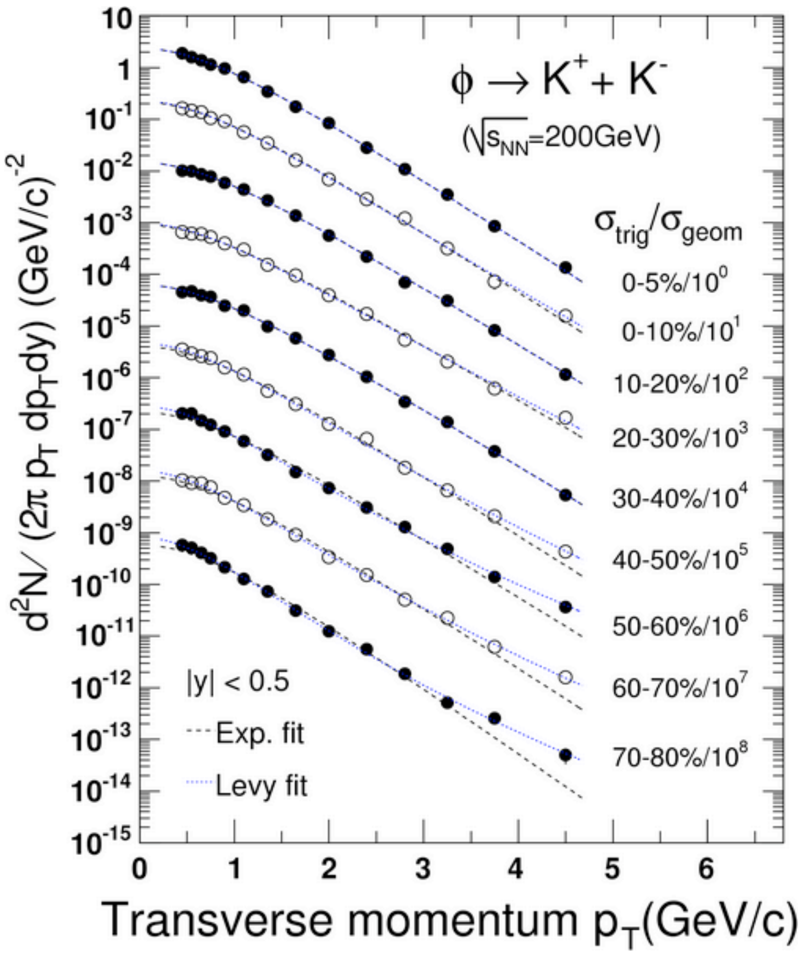
-- *Can we access this experimentally ?*

(C) Interactions among constituents are large or saturate.

-- *Can we demonstrate this experimentally ?*

Kinetic Freeze-out Distributions

Exponential distribution does not necessarily mean we have a thermal system.



STAR : PRL 99 (2007) 112301

Multi-particle production process

(no assumption of thermalization)

$dN/dyd^2p_T \sim \mathrm{Exp}\,(-p_T/E/2N)^*$

From multi-particle phase space factor

Thermal system

$dN/dyd^2p_T \sim \mathrm{Exp}\,(-p_T/E/3N)$

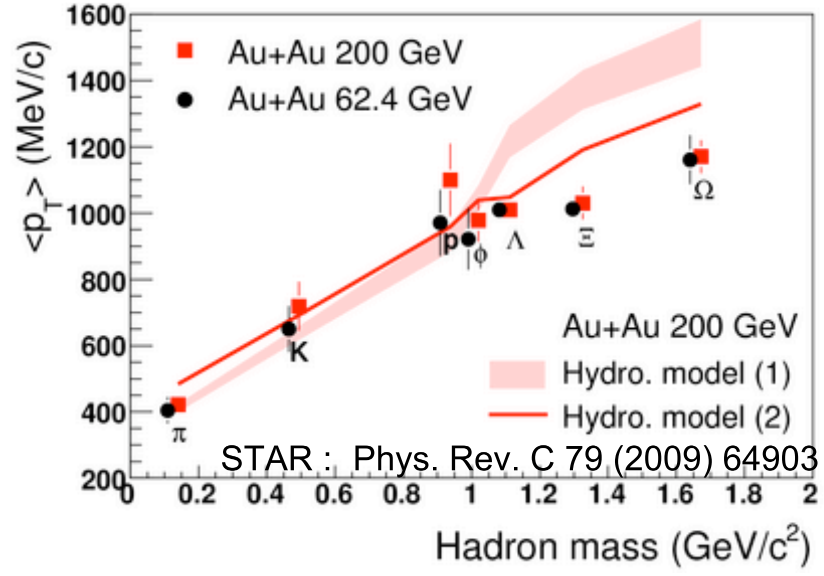
Factor of 3/2 : invariant momentum space (d^3p/E) not equal to Thermodynamic Momentum space (d^3p).

Experimentally difficult to distinguish the two.

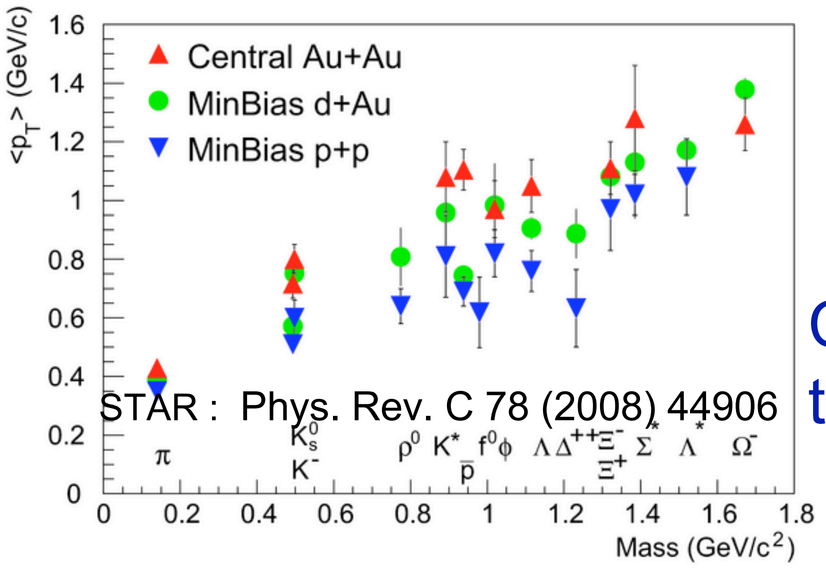
*Assumption : average matrix element square is not strongly p_T dependent.

Kinetic Freeze-out Distributions

Slope of p_T distribution : Two contributions - Random part +
Collective part



STAR : Phys. Rev. C 79 (2009) 64903



STAR : Phys. Rev. C 78 (2008) 44906

Random Part ~ E/N
Intensive quantity independent of system size

Collective part can also occur for systems away from equilibrium

Indicates final state interactions, which will eventually drive system towards equilibrium.

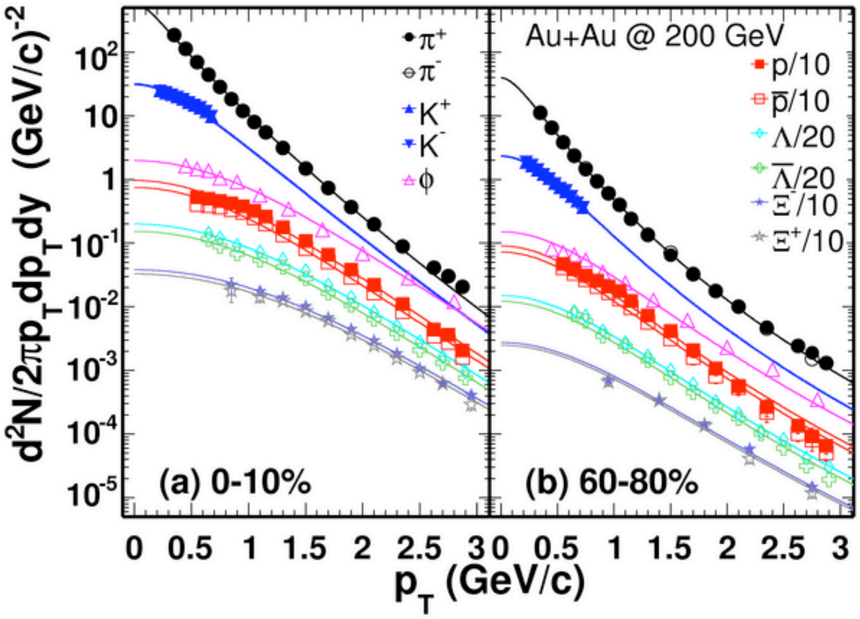
$\tau_{scattering} < \tau_{expansion}$

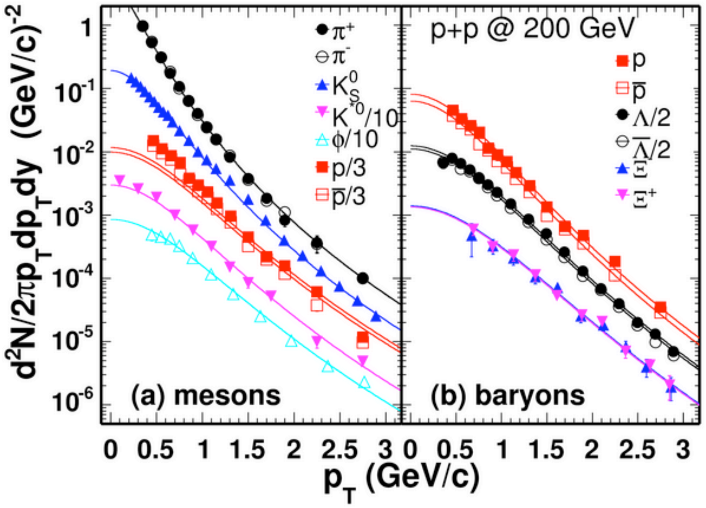
Comparison with pp and dAu leads to interpretations being inconclusive ?

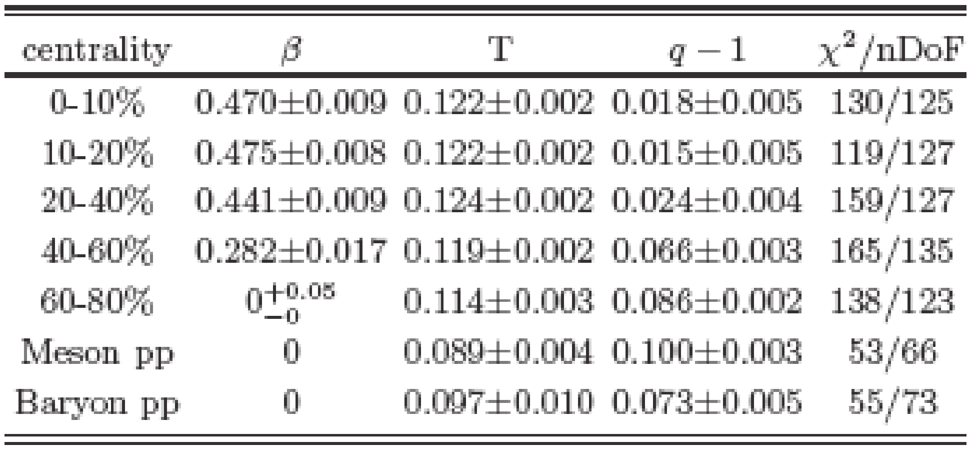
Kinetic Freeze-out Distributions

$$\frac{d^2N}{2\pi m_T dm_T dy} \propto (1+\frac{q-1}{T}m_T)^{-1/(q-1)}$$

m_T-exponential Boltzman distribution re-written as m_T power law. q characterizes degree of equilibrium -- Tallis statistics







centrality	β	T	$q-1$	χ^2/nDoF
0-10%	0.470±0.009	0.122±0.002	0.018±0.005	130/125
10-20%	0.475±0.008	0.122±0.002	0.015±0.005	119/127
20-40%	0.441±0.009	0.124±0.002	0.024±0.004	159/127
40-60%	0.282±0.017	0.119±0.002	0.066±0.003	165/135
60-80%	$0^{+0.05}_{-0}$	0.114±0.003	0.086±0.002	138/123
Meson pp	0	0.089±0.004	0.100±0.003	53/66
Baryon pp	0	0.097±0.010	0.073±0.005	55/73

Suggests no collectivity in pp and peripheral Au+Au collisions

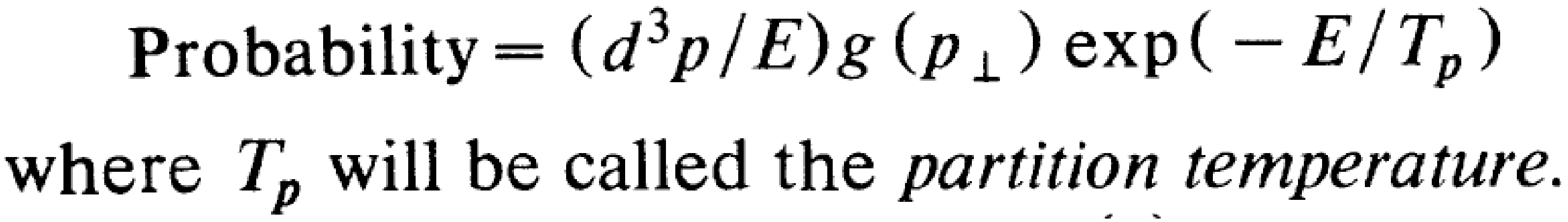
Z. Tang et al., Phys.Rev.C79:051901,2009.

Single Particle Momentum Distribution

T.T. Chou, C. N. Yang and E. Yen

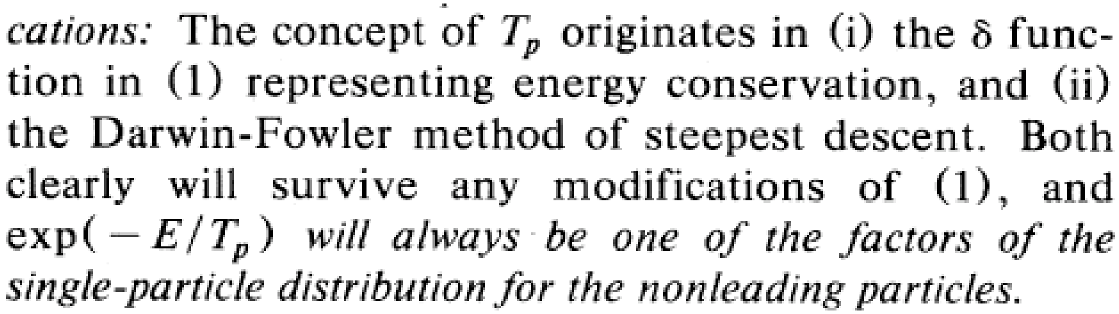
Phys. Rev. Lett. 54, 510–513 (1985)

> “A concept of partition temperature is introduced in high-energy collisions. It is a natural mathematical consequence of the Darwin-Fowler method, and neither requires nor implies thermal equilibrium. A collision at a given incoming energy is described as an incoherent superposition of collisions with different partition temperatures.”



$$\text{Probability} = (d^3p/E)\,g(p_\perp)\exp(-E/T_p)$$

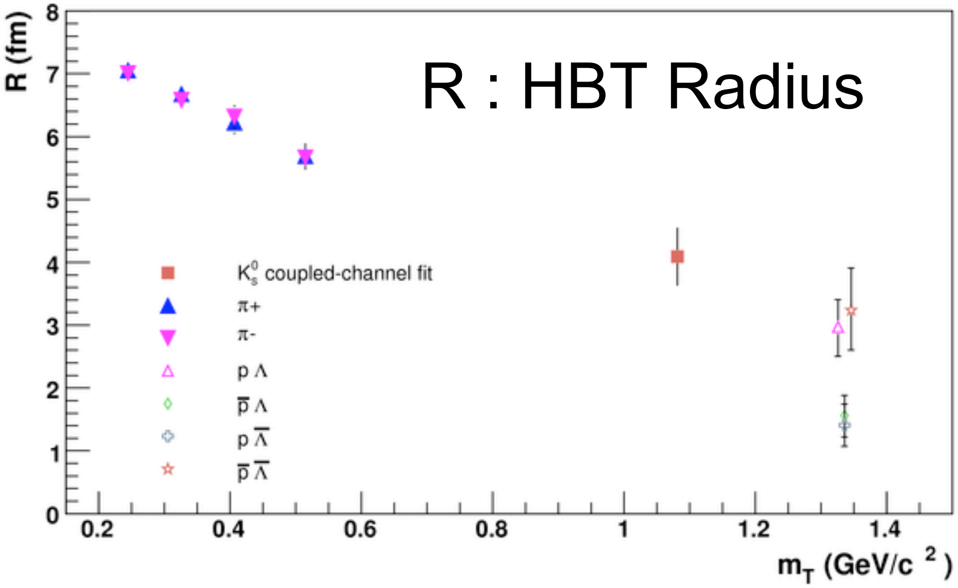
where T_p will be called the *partition temperature.*

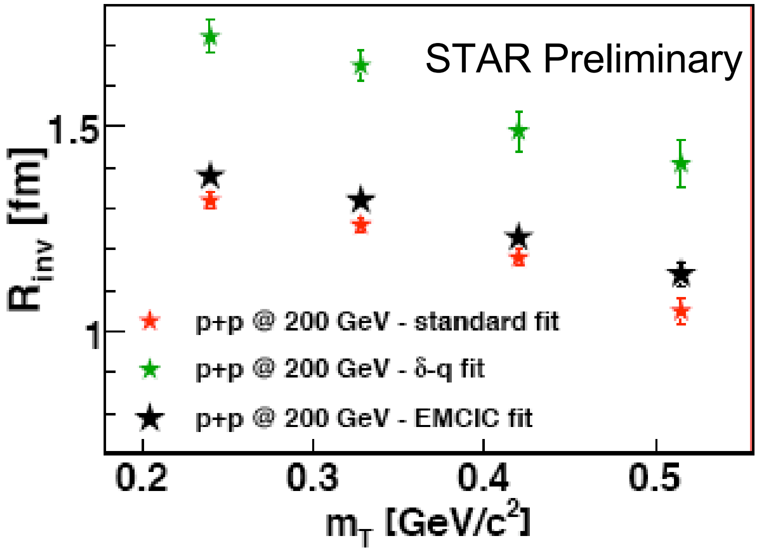


cations: The concept of T_p originates in (i) the δ function in (1) representing energy conservation, and (ii) the Darwin-Fowler method of steepest descent. Both clearly will survive any modifications of (1), and $\exp(-E/T_p)$ *will always be one of the factors of the single-particle distribution for the nonleading particles.*

Kinetic Freeze-out Distributions

STAR : Phys. Rev. C 74 (2006) 54902





Ideal hydrodynamics

$R_x \sim 1/\sqrt{m_T}$

Viscosity breaks scaling

$R^2_L \sim \tau_0\ T/m_T - 19/16\ \Gamma_s/\tau_0$

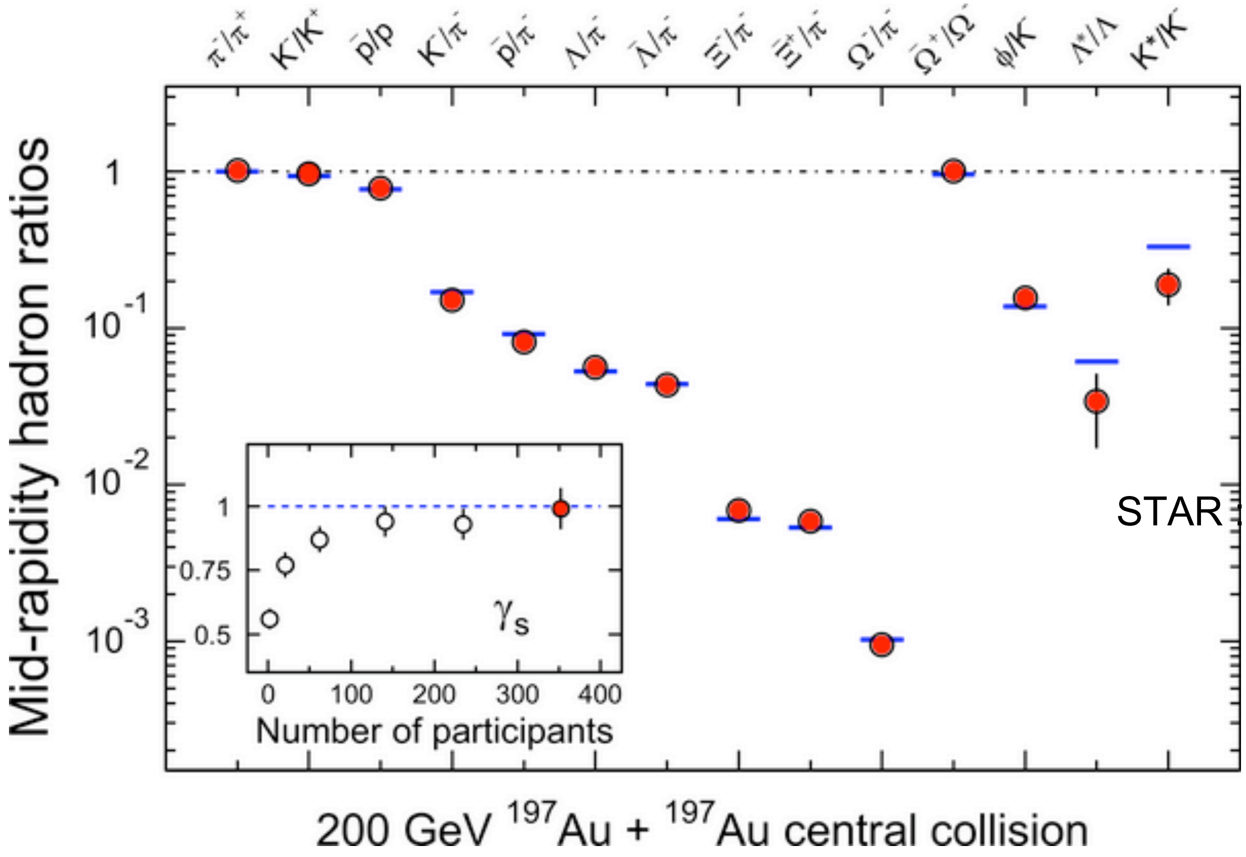
Γ_s : Sound attenuation length

τ_0 - Initial time

Both Au+Au and p+p
show scaling with $1/\sqrt{m_T}$

Conclusions inconclusive ?

Chemical Freeze-out Distributions



T_{ch} = 163 ± 4 MeV

μ_B = 24 ± 4 MeV

STAR : Phys. Rev. C 79 (2009) 34909

$$n_i(T,\mu_i) \sim \exp\left(\frac{\mu_i - m_i}{T}\right)$$

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

In central collisions, thermal model fit well with γ_S = 1. The system is thermalized at RHIC ?

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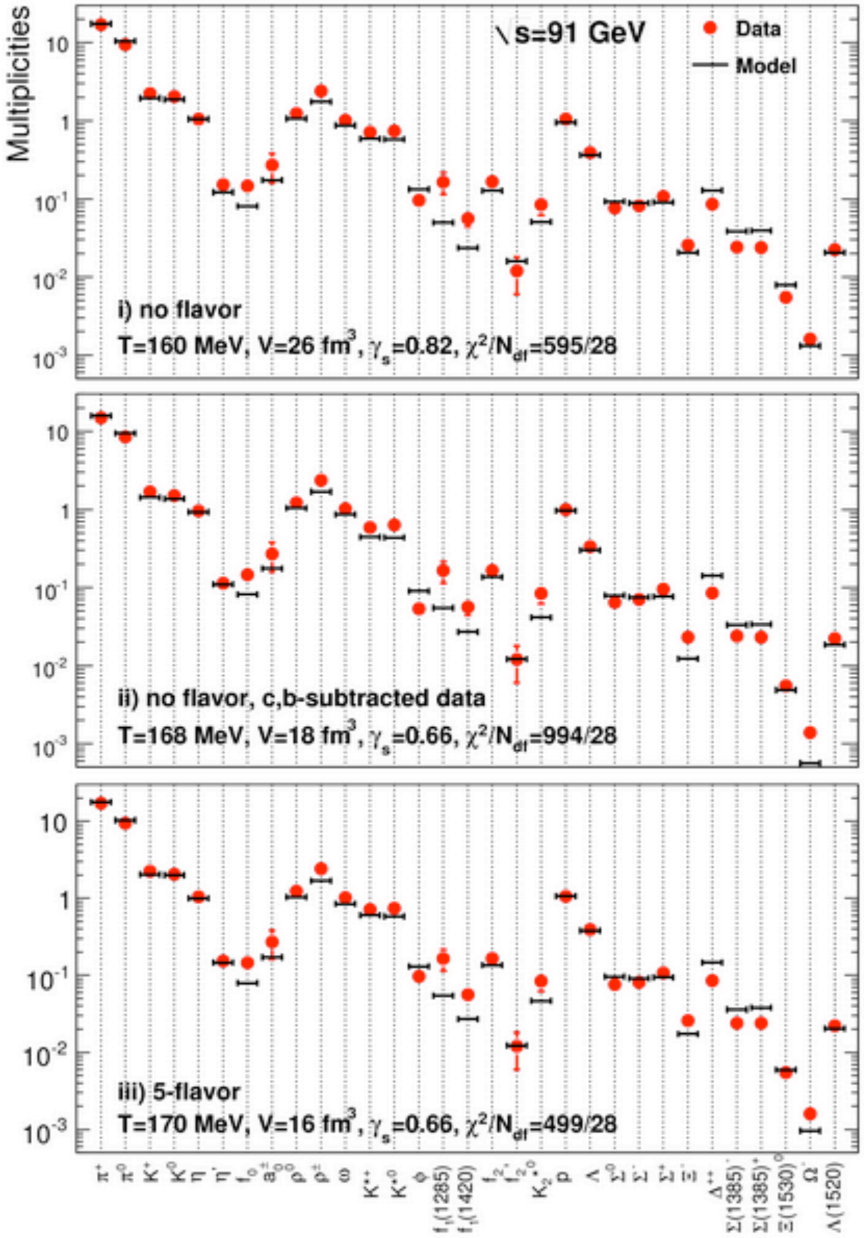
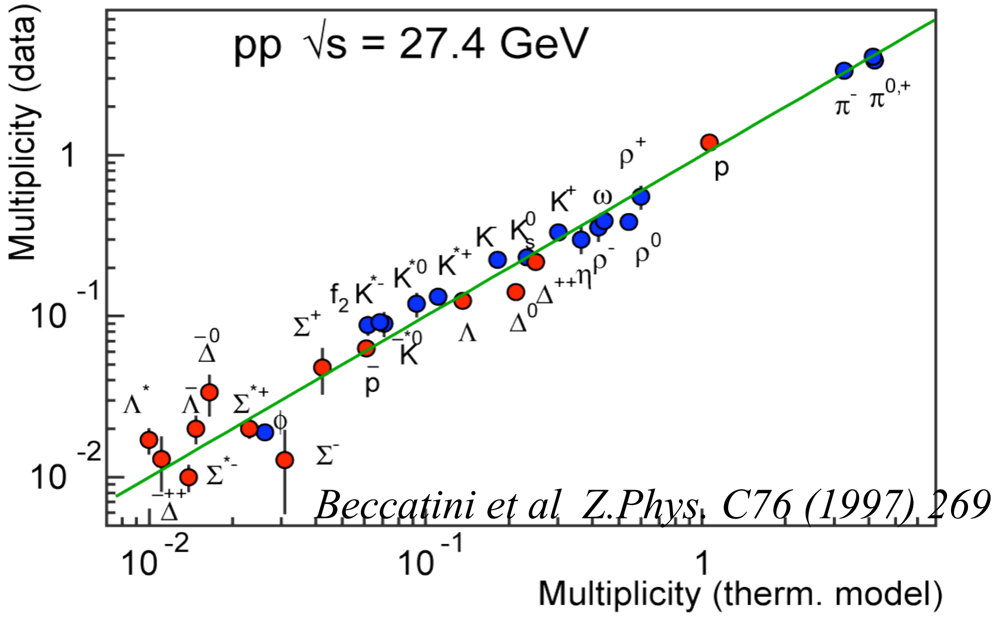
Freeze-out Distributions in e^+e^- and pp



Thermal description of hadron production in e+e- collisions.

A. Andronic, et al., arXiv:0804.4132

The fits to e^+e^- are actually bad!



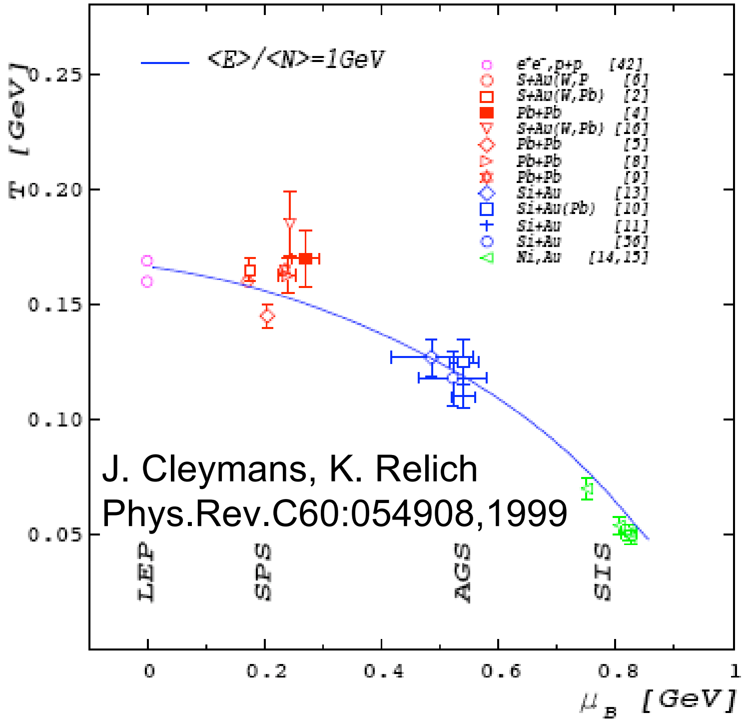
Beccatini et al Z.Phys. C76 (1997) 269

Chemical Freeze-out Distributions

(A) Assumptions :

1. μ,T are constant along freeze-out hyper surface
2. Simultaneous freeze-out
   (but mean free path different for different particles)
3. Flow 4-velocity common to all particle species
4. Hadron masses and decay widths do not change with T

(B) Fits also to e^+e^-,pp, pA



J. Cleymans, K. Relich
Phys.Rev.C60:054908,1999

(C)Multi-particle production

$$E d\sigma/d^3p_1 \sim F(P-p_1) < | M (P, p_1 \ldots p_N)|^2>$$

Phase space
+ Conservation
$\sim \mathrm{Exp}(-p_{T1}/T_{slope})$

Matrix element
For 2->N process

Fugacity
$\sim \exp(\mu/T)$
Decides yields

Equilibrium picture not unique

Loss of correlation due to interactions

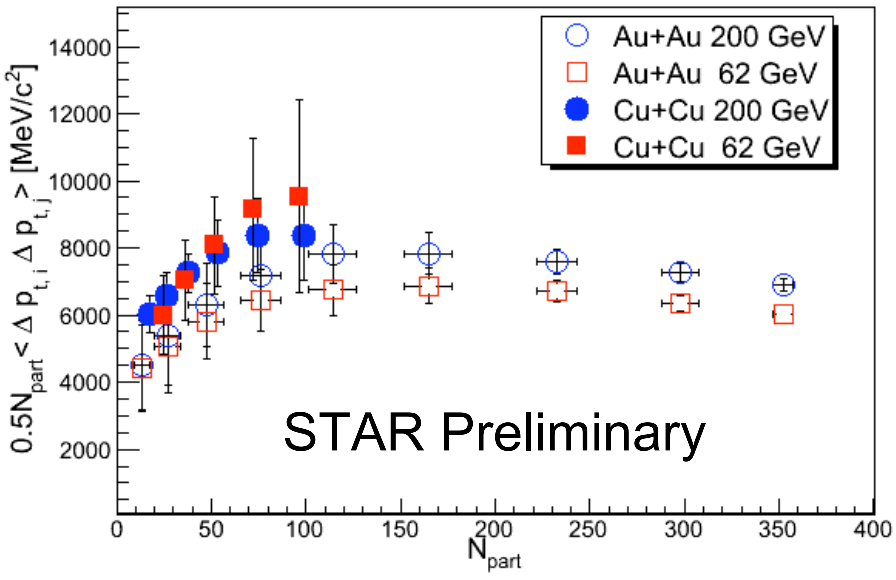
For a thermal system :

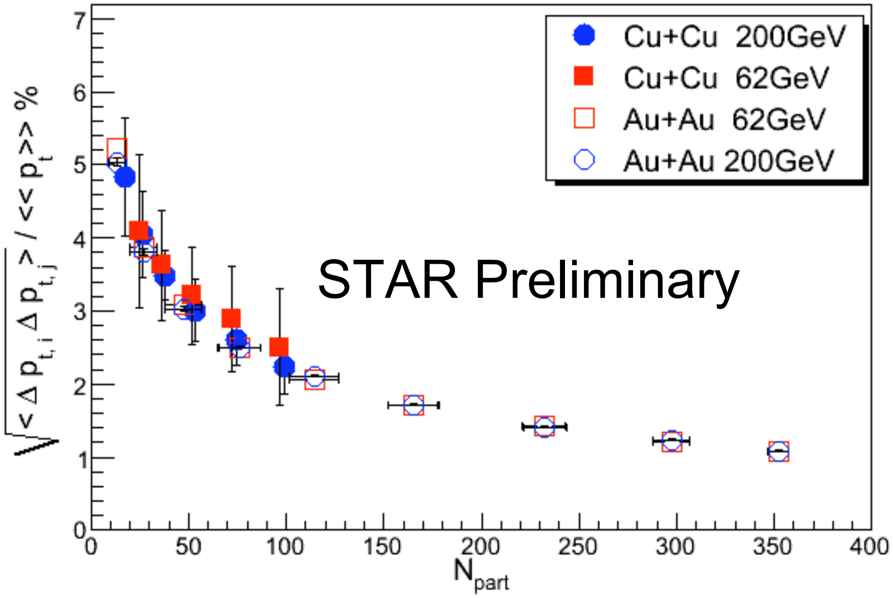
Correlations (in momentum) reach equilibrium values

Physical observables which are sensitive to interactions -

Such as : Average elliptic flow saturate with density
Momentum correlations saturate with density

L. Kumar : QM2008; STAR : Phys. Rev. C 72 (2005) 044902





Hints available : But we have we ruled out other physical processes (jets/minijets ?; PLB 567 (2003) 184)

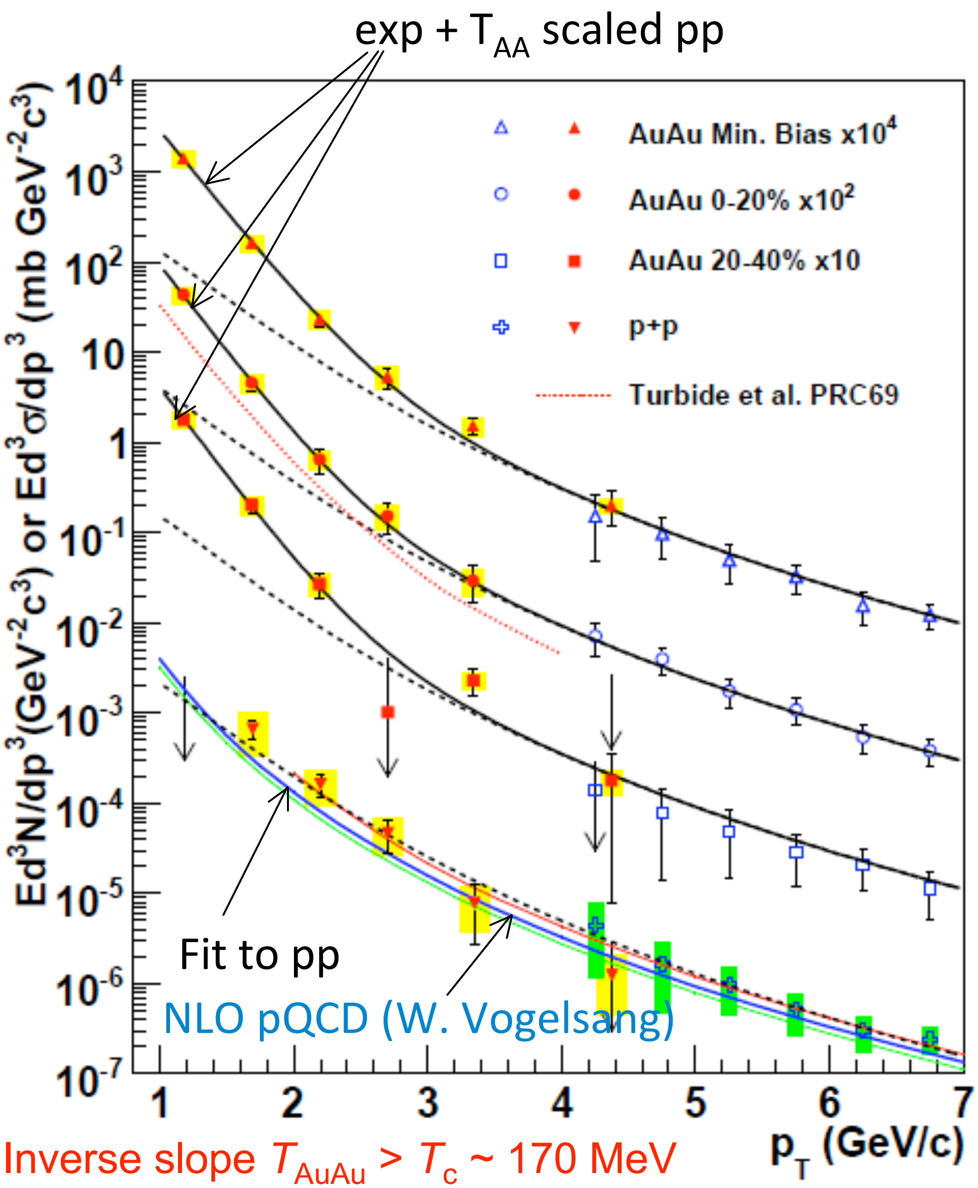
Freeze-Out Distributions

By definition a state in thermodynamic equilibrium has no knowledge of past

May be we should look at early time distributions to see if the partonic matter attended a thermalized state

Direct photon spectra

PHENIX: PRL, 104, 132301 (2010)

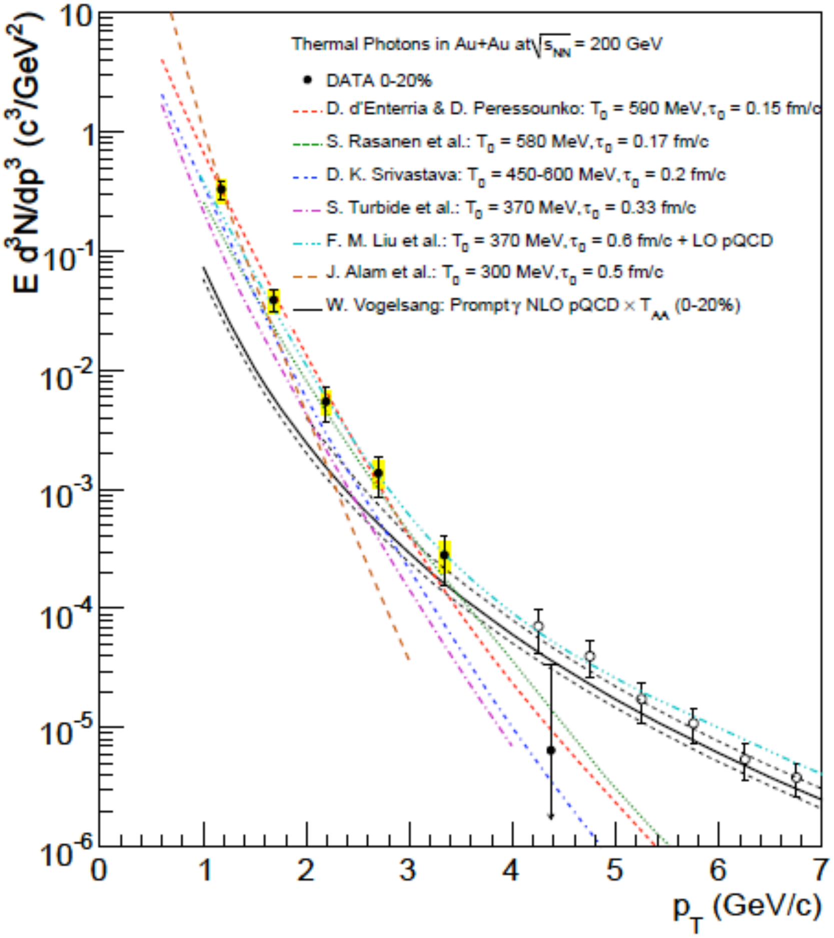


exp + T_{AA} scaled pp

Fit to pp

NLO pQCD (W. Vogelsang)

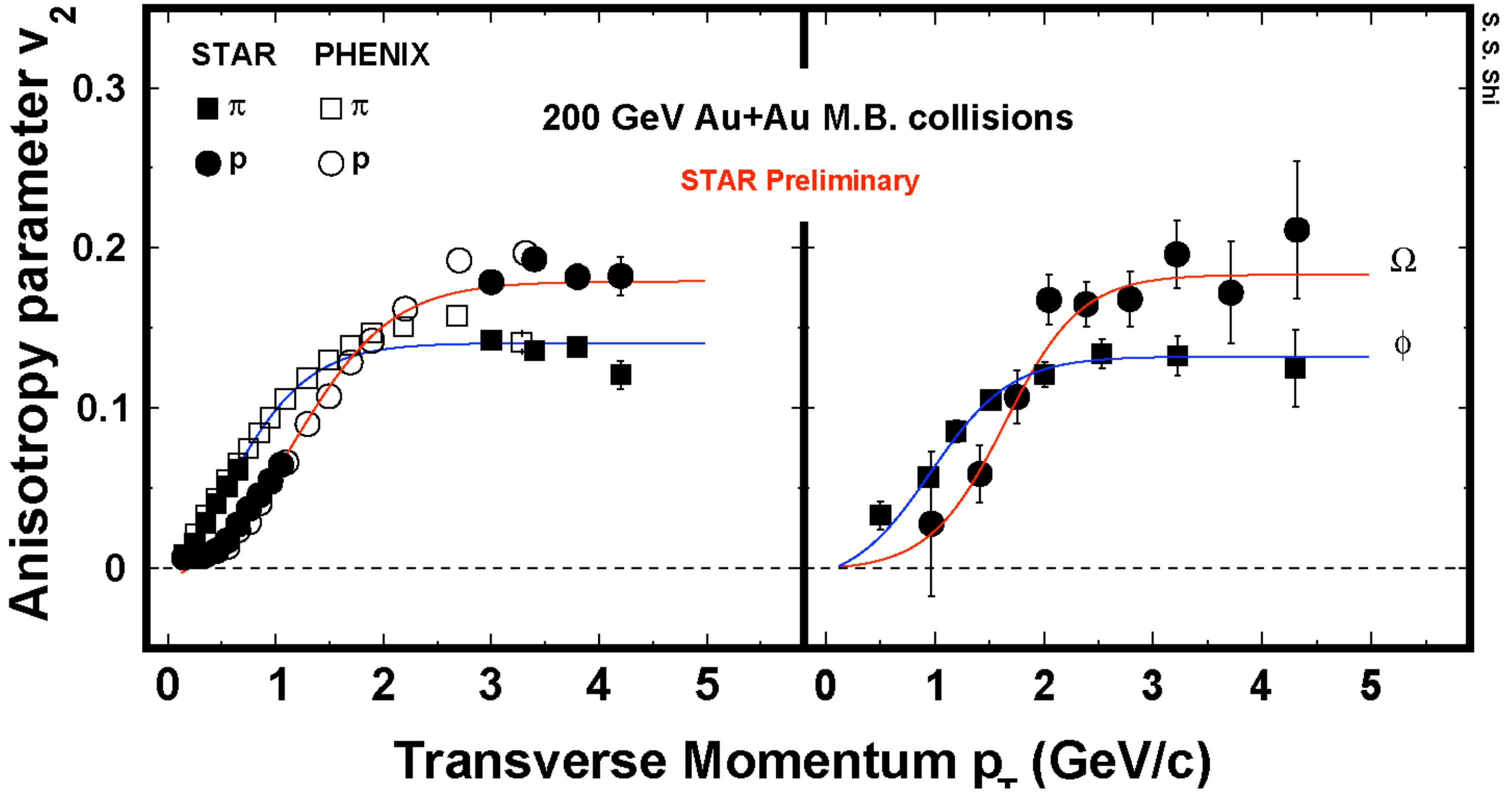
Inverse slope $T_{AuAu} > T_c \sim 170$ MeV



Hydrodynamical models assuming thermal equilibrium able to explain the observation

Early time Collectivity

Substantial portion of elliptic flow developed early



Low p_T : Heavier hadrons lower flow (~ hydrodynamic pattern)

High p_T : Flow grouped along baryon-meson lines (~ Hadronization by partonic recombination)

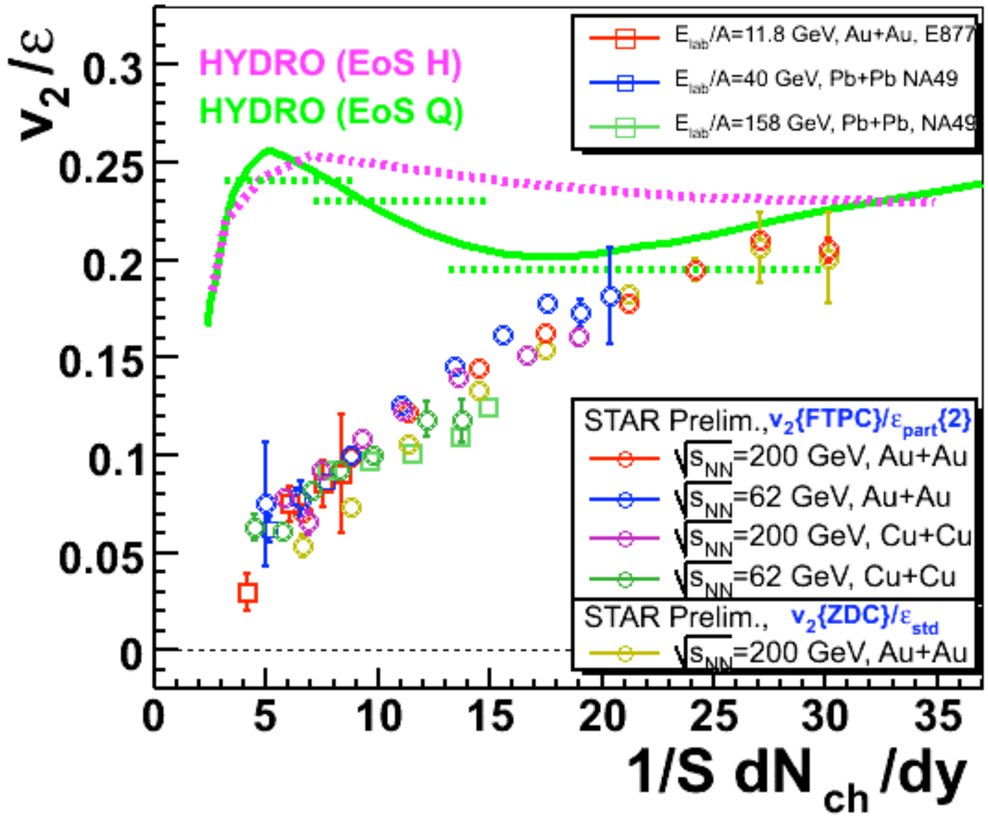
All p_T : Flow similar for hadrons with strange and light quark (~ developed at partonic stage)

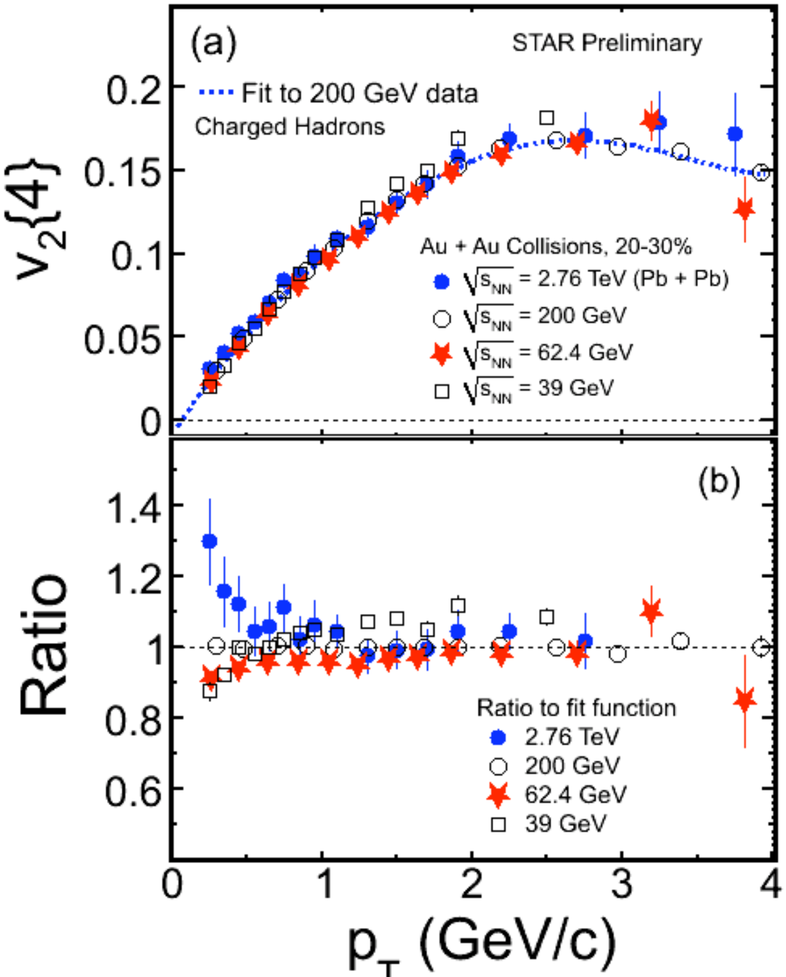
Does this collectivity reflect enough partonic interactions to claim Thermalization ?

Saturation Of Interactions : v_2 Saturate

Part of it in
STAR : Phys. Rev. C 66 (2002) 34904

L. Kumar: ICPAQGP 2010





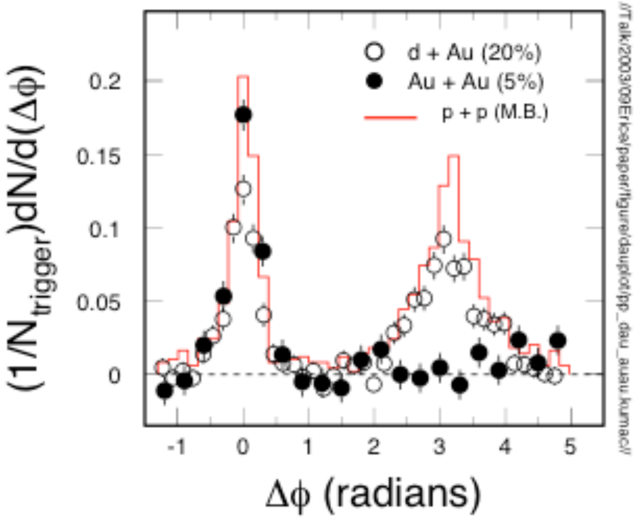
Hints available, but U+U collisions in Run 11 Or LHC Heavy Ion program will hopefully settle the issue

v_2 (39 GeV) ~ v_2 (62.4 GeV) ~ v_2 (200 GeV) ~ v_2 (2.76 TeV)

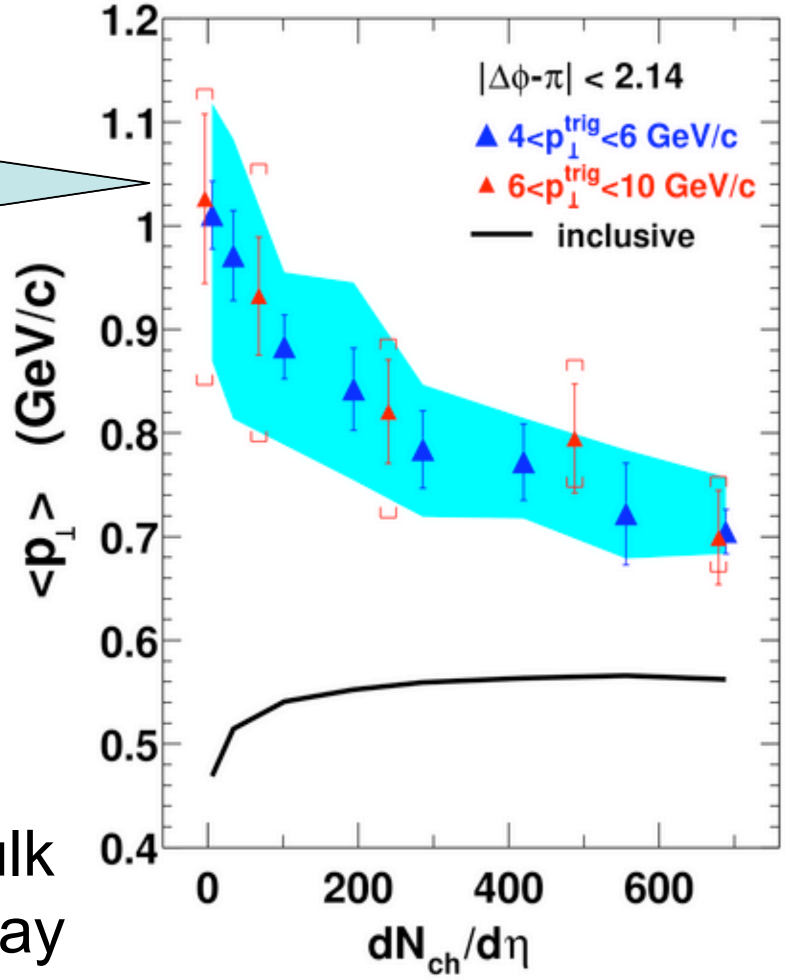
Initial state effect ?

Interactions : Jet and Bulk

Away side associated hadron mean p_T



STAR : Phys. Rev. Lett. 95 (2005) 152301



The away side jet traverses a large amount of matter. The interactions seem to drive particles from the two sources, jet fragmentation and the bulk medium, toward equilibration. This may in turn imply a high degree of thermalization within the medium itself.

Fluctuations

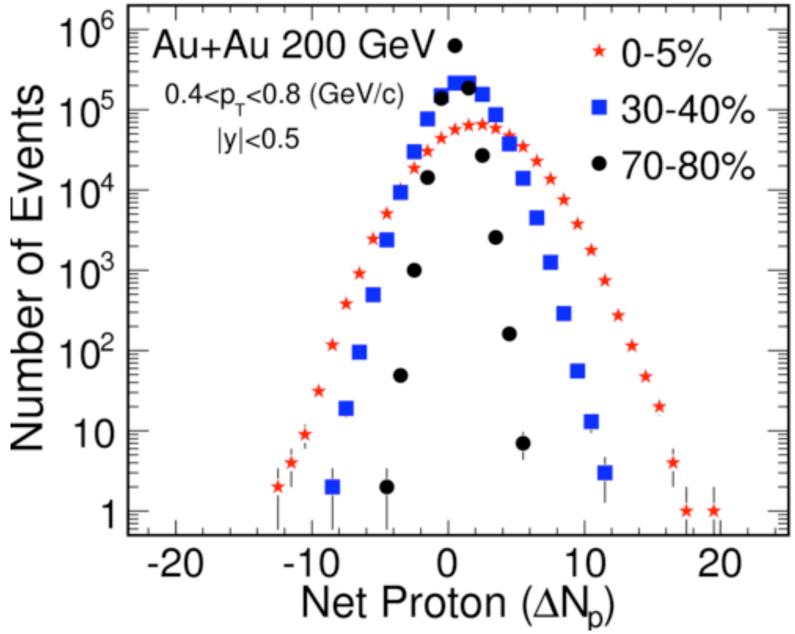
STAR: PRL 105 (2010) 022302

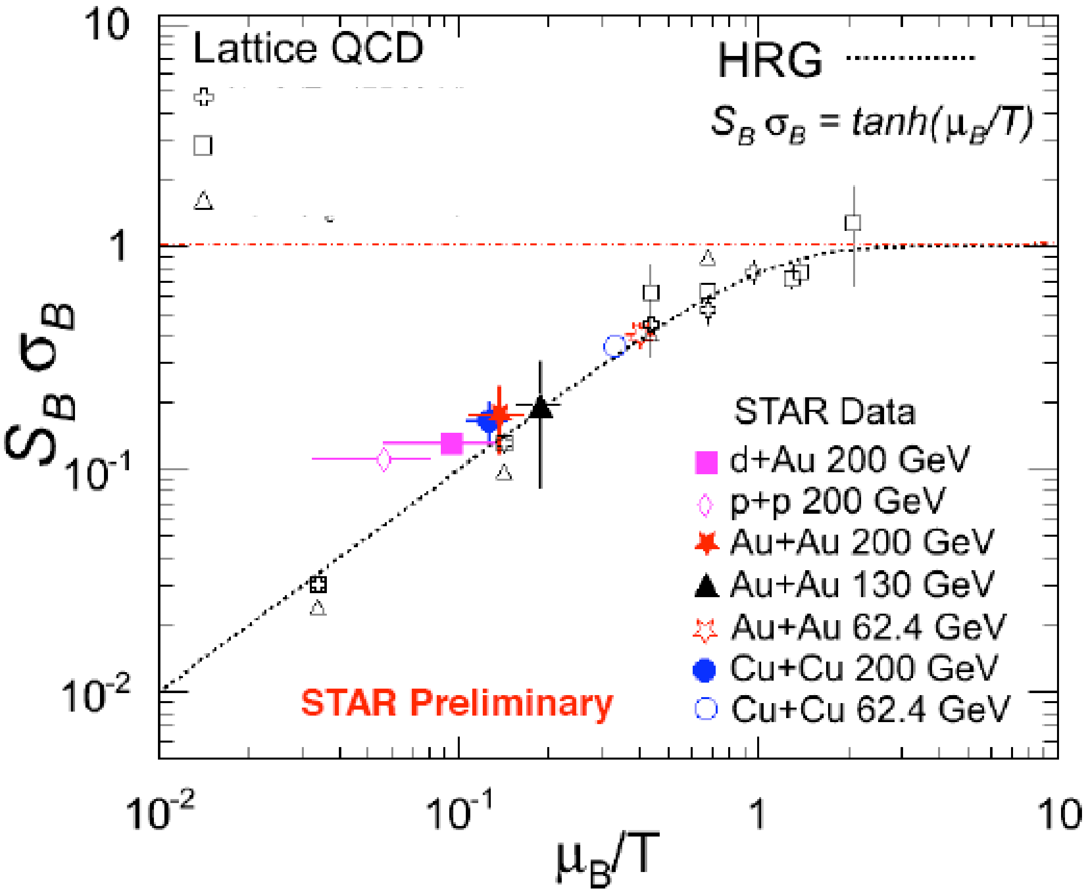
H. Ritter: ICPAQGP 2010

R. Gavai & S. Gupta arXiv:1001.3796

Event-by-event net-proton distribution

Assumptions:
Net-proton ~ net-Baryon
Thermalization
Modelling: Chemical Freeze-out





$$S\,\sigma \sim \chi_B^{(3)}/\chi_B^{(2)}$$

$$\kappa\sigma^2 \sim \chi_B^{(4)}/\chi_B^{(2)}$$

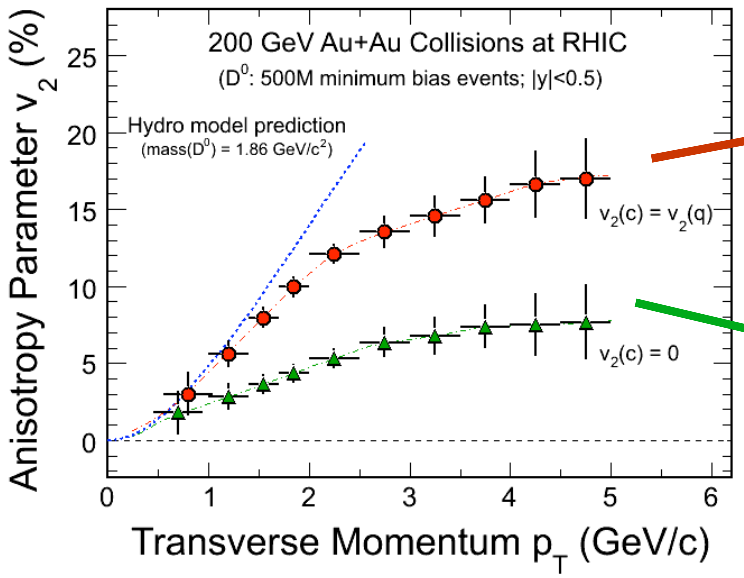
Agreement with Lattice QCD and HRG

Conclusions

Measurements @ top RHIC energies	Thermalization	Remark
PID spectra and mean p_T	Seems to	Not unique, Simple multi-particle production gives same feature. Tallis distribution ?
Particle Ratios	Seems to	Not unique & pp, e^+e^-, pA same
HBT	Seems to	Not unique, pp same behaviour
PID v_2, away side $<p_{T>}$	Could be	Need models to confirm
V_2/ε vs. 1/S dN/dy V_2 vs. p_T	Hints	More measurements, V_2 vs. p_T saturates beyond 39 GeV
Fluctuations	Seems to	Agreement with Lattice QCD and HRG
Direct photon	Seems to	Hydro-based models explain data
p_T Correlations	Hints	Measurements in heavy quark sector

So far difficult to get a direct evidence from experiments.
Cumulative evidences from joint theory-experiment comparisons
is the way to establish thermalization at RHIC or need data from charm sector

Outlook: Possible direct evidence for light quark thermalization



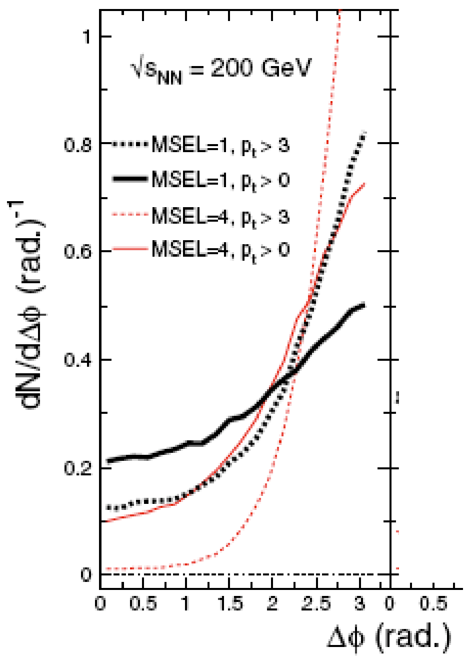
Charm-quark flow

➠ Thermalization of light-quarks!

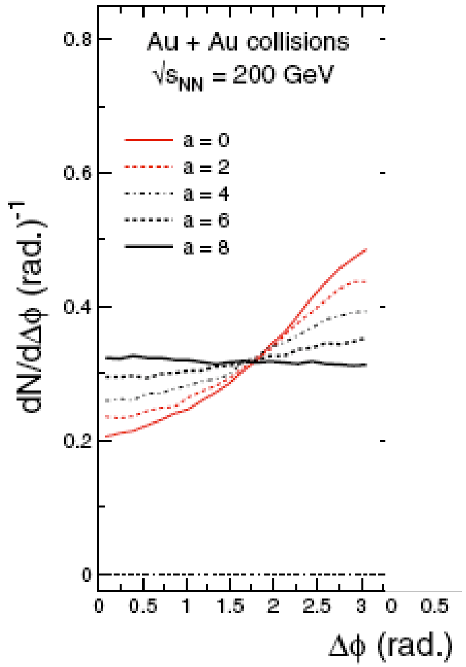
Charm-quark does not flow

➠ Drag coefficients

PRL 100, 152301 (2008)



Loss of correlations in AA relative to pp, best is to look at p_T correlations (arXiv:0908.042)



Pressure, Flow, …

Thermodynamic identity

σ – entropy p – pressure

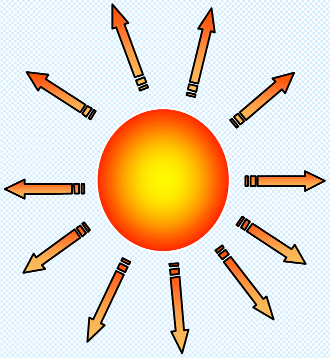
U – energy V – volume

$\tau = k_B T$, thermal energy per dof

$$\tau d\sigma = dU + pdV$$

In A+A collisions, interactions among constituents *and* density distribution lead to:

pressure gradient ⇒ collective flow



⇔ number of degrees of freedom (dof)

⇔ Equation of State (EOS)

⇔ cumulative – *partonic* + *hadronic*