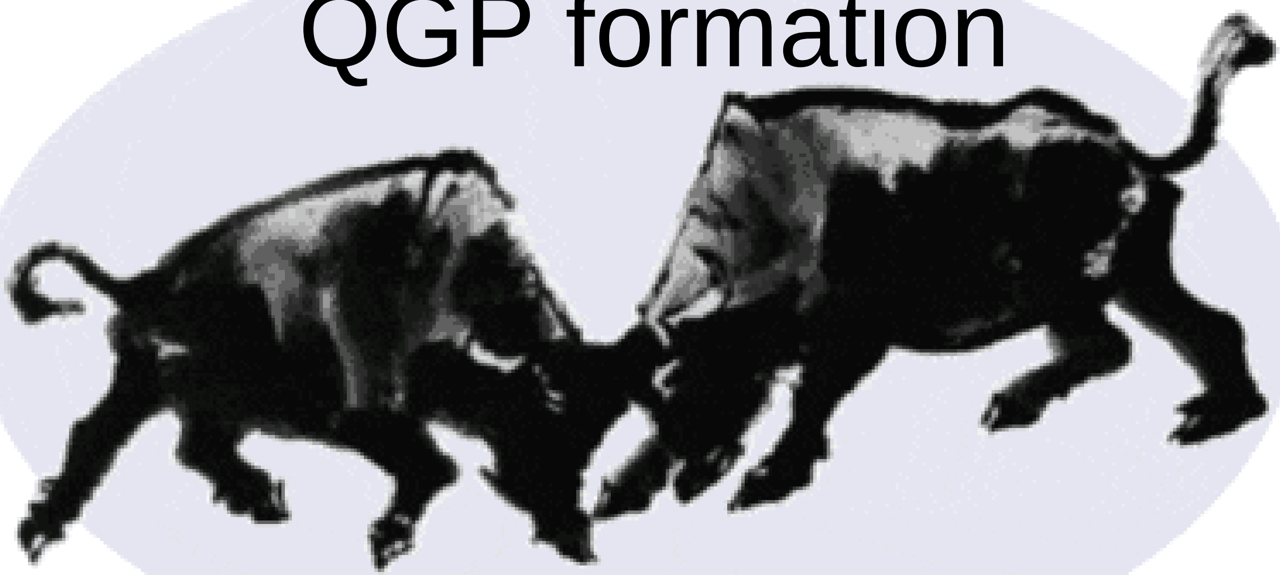
A critical assessment of evidence obtained in the first three years of RHIC running for QGP formation



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Raimond Snellings

For the STAR Collaboration

Introduction

- The main goal of RHIC is to search for QGP formation in the laboratory and study the properties of this state of matter
- We are in the process of assessing what the overall quality of evidence is for the formation of a QGP, based on the data obtained in three successful years of RHIC running (while being close to the end of run 4, the most successful run to date where an *order of magnitude more* data became available)
  - Time scale: collaboration discussion June 12^{th} , available to the public mid-June
- The outline of this talk:
  - Present some of the striking measurements obtained at RHIC so far
  - In our ongoing effort to interpret these striking observation; present questions to the (theory) community which we would like to see discussed in more detail. This will allow us to do a better assessment of the implications of these measurements for the write-up of our whitepaper

The STAR Collaboration: 51 Institutions, ~ 500 People

U.S. Labs:
Argonne, Lawrence Berkeley, and Brookhaven National Labs

U.S. Universities:
UC Berkeley, UC Davis, UCLA, Caltech, Carnegie Mellon, Creighton, Indiana, Kent State, MIT, MSU, CCNY, Ohio State, Penn State, Purdue, Rice, Texas A&M, UT Austin, Washington, Wayne State, Valparaiso, Yale

Brazil:
Universidade de Sao Paolo

China:
IHEP - Beijing, IPP - Wuhan, USTC, Tsinghua, SINR, IMP Lanzhou

Croatia:
Zagreb University

Czech Republic:
Nuclear Physics Institute

England:
University of Birmingham

France:
Institut de Recherches Subatomiques Strasbourg, SUBATECH - Nantes

Germany:
Max Planck Institute – Munich
University of Frankfurt

India:
Bhubaneswar, Jammu, IIT-Mumbai, Panjab, Rajasthan, VECC

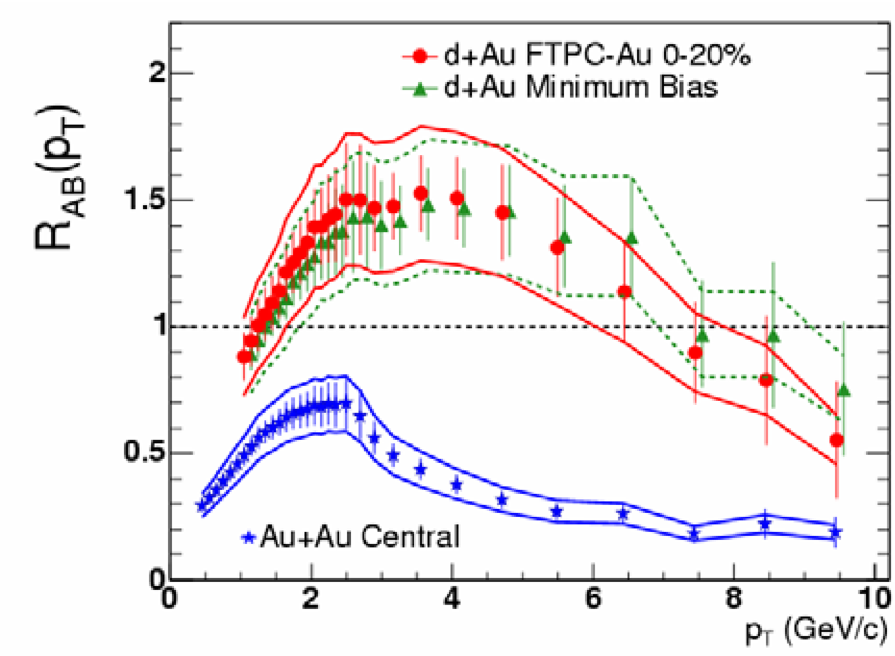
Netherlands:
NIKHEF

Poland:
Warsaw University of Technology

Russia:
MEPHI – Moscow, LPP/LHE JINR – Dubna, IHEP – Protvino

Switzerland:
University of Bern

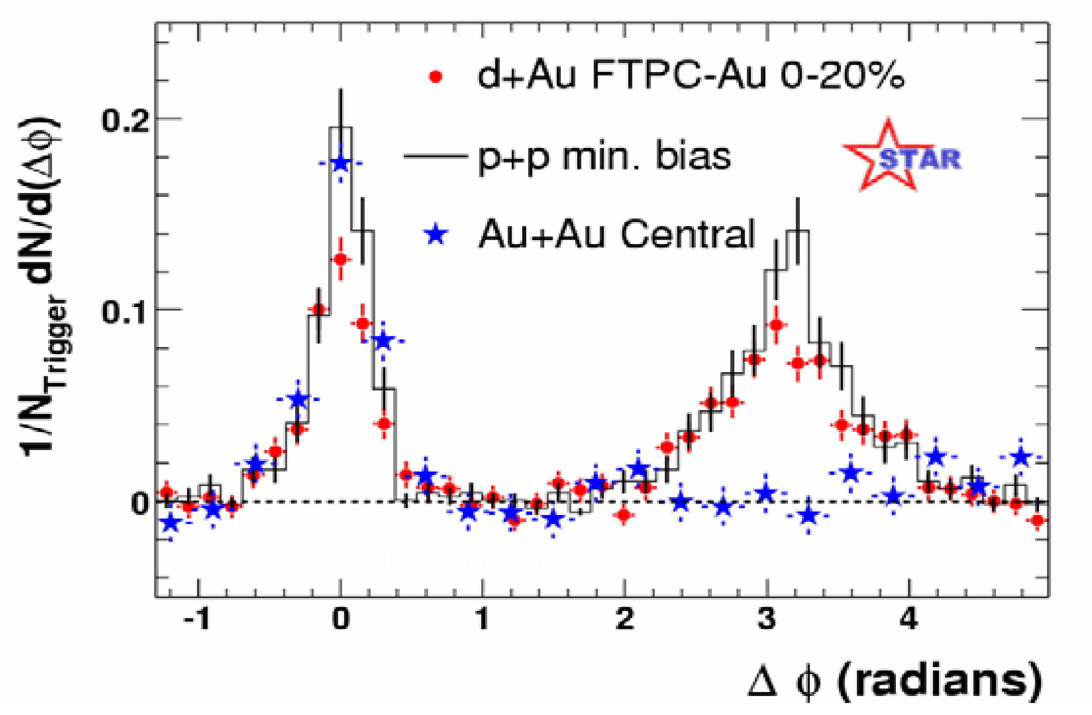
Suppression of the particle yield at high transverse momenta



- Suppression of particle yield is a final state effect!
- Consistent with expectations from parton energy loss in a dense medium!

Strong suppression of the back to back correlation in central Au+Au

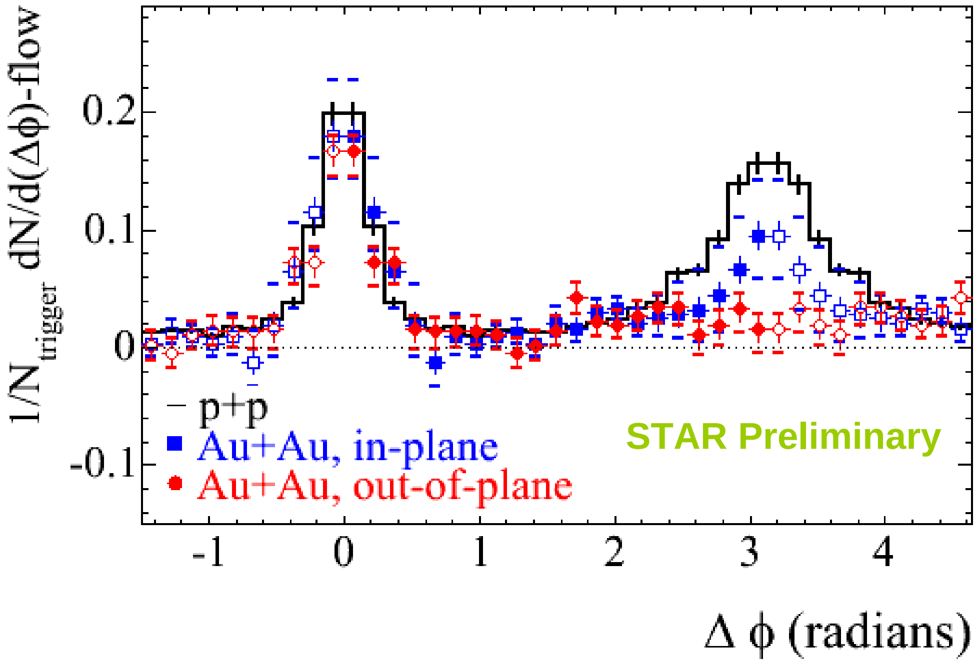
- Back to back supression is a final state effect
- Consistent with expectations of parton energy loss in a dense medium



Trigger particle range 4-6 GeV/c, associated range > 2 GeV/c

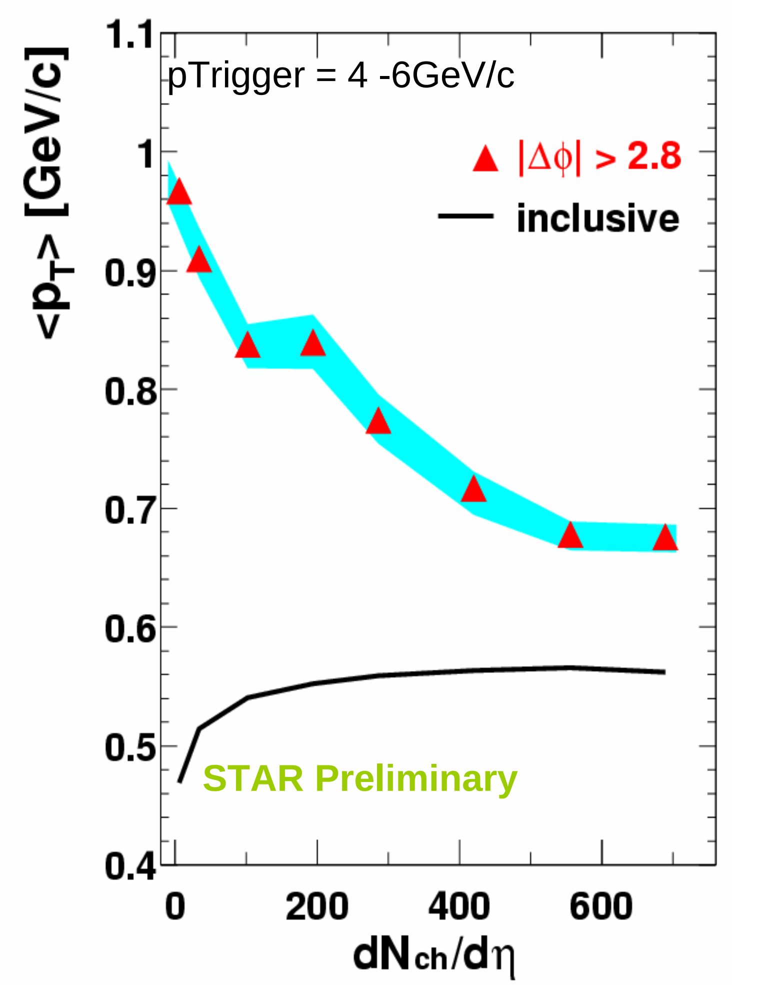
Back to back correlations versus the reaction plane

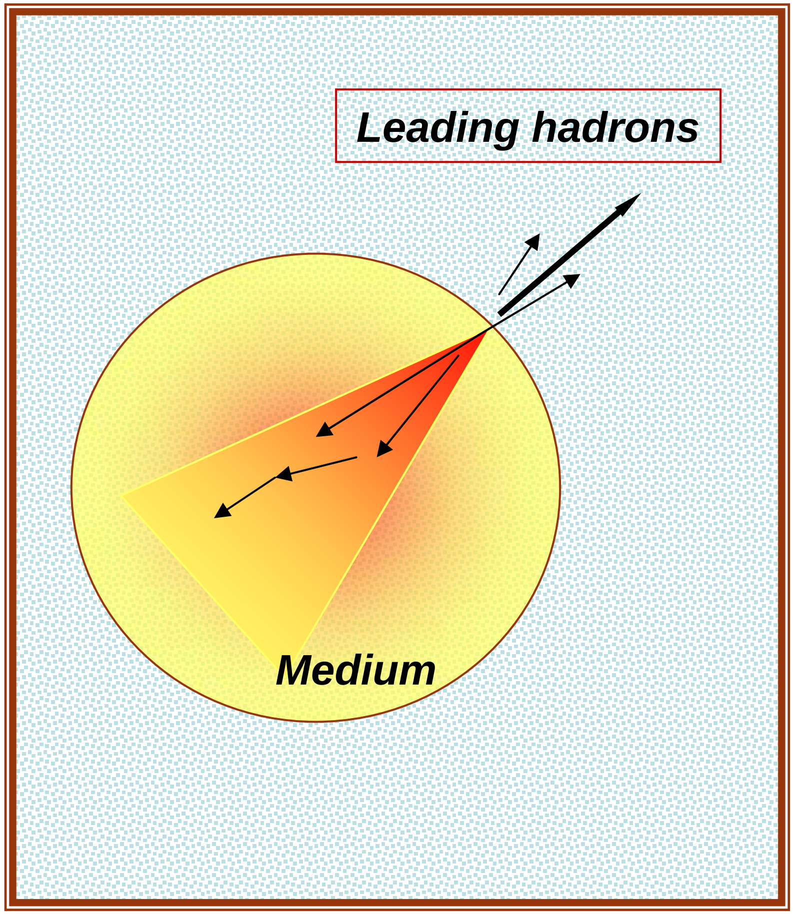
Au+Au centrality:
20-60%



- The back to back correlation depends on the average distance traveled through the medium!

Where does the energy go?



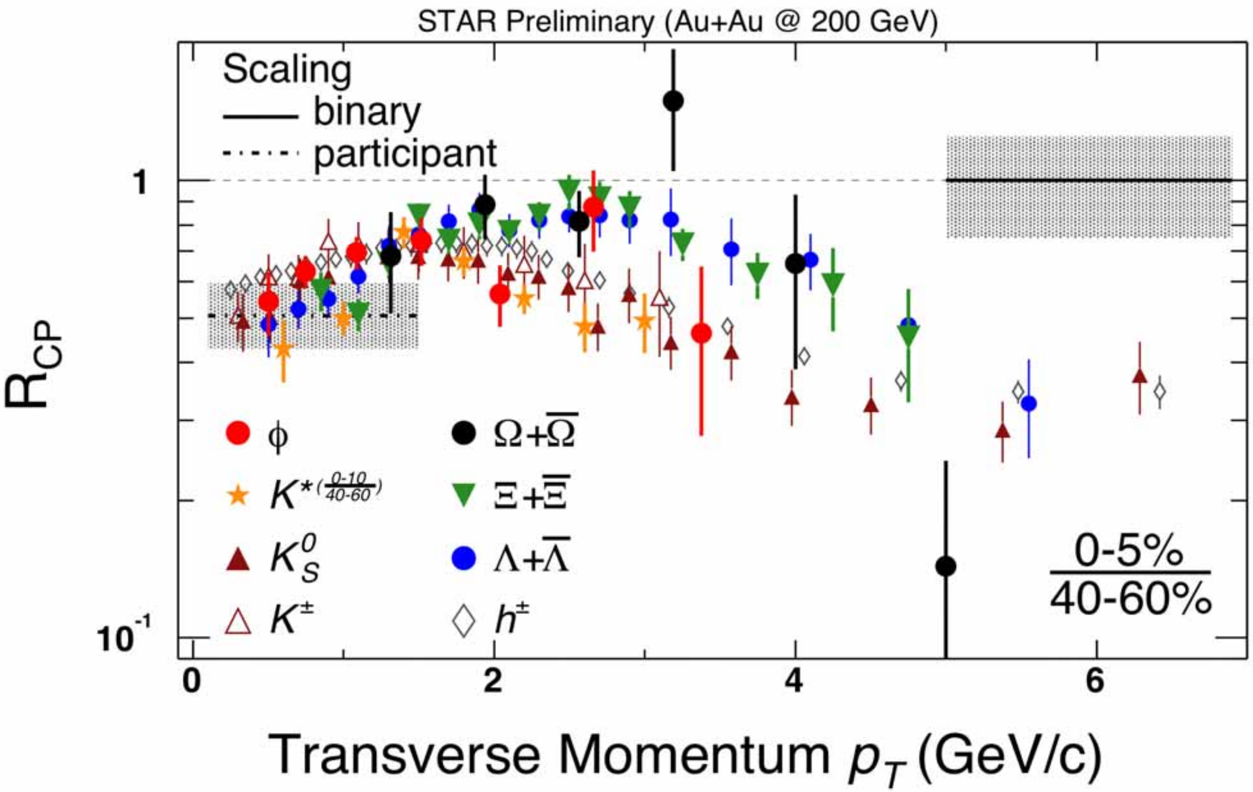


Discovery of the suppression phenomena at RHIC

- The observed strong suppression can be described efficiently by parton energy loss in matter starting with large energy and gluon densities

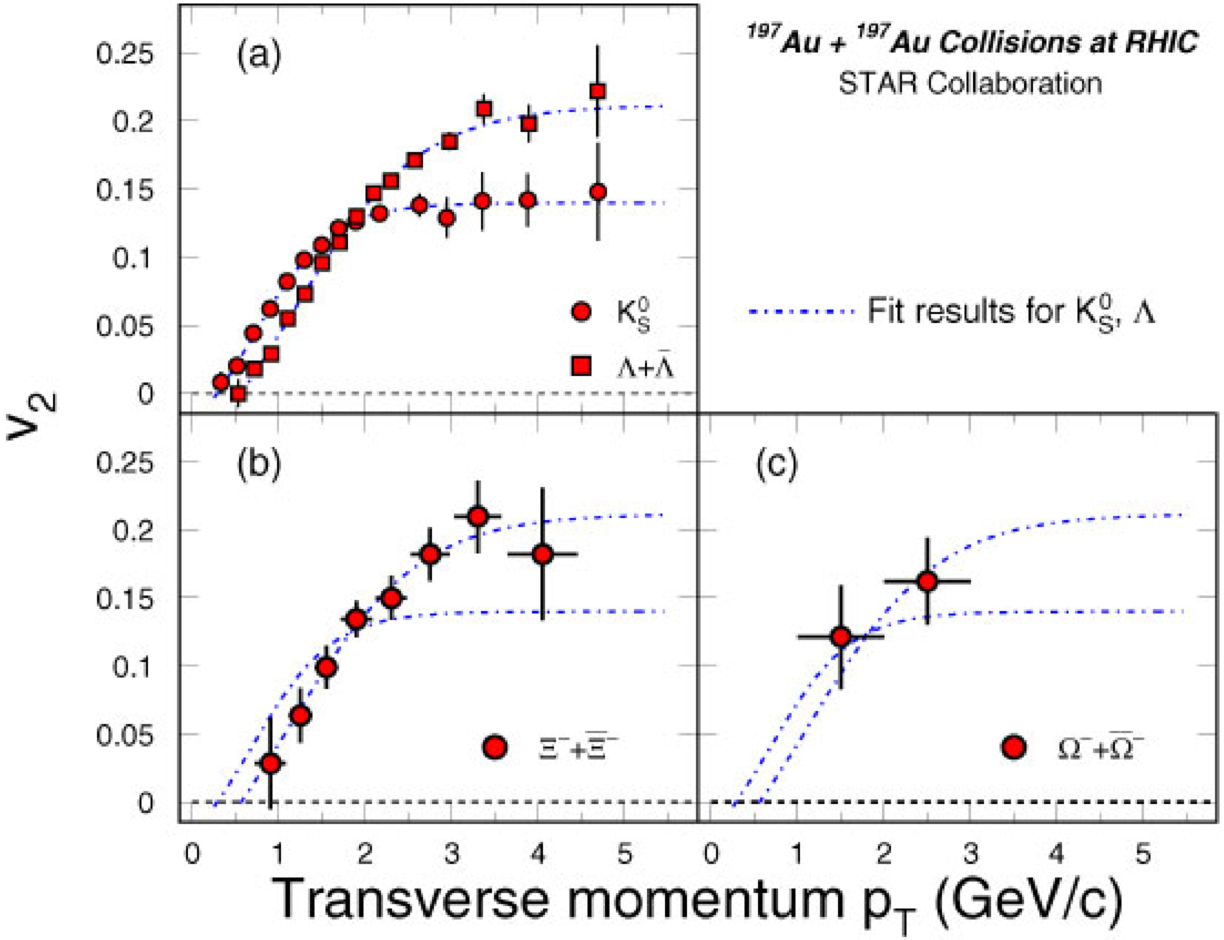
- Does the magnitude of parton energy loss inferred from these observations ***demand*** an explanation in terms of traversal through deconfined matter?
  - What are the uncertainties due to factorization in-medium, in-medium fragmentation versus vacuum fragmentation?
  - How are possible uncertainties amplified due to the longitudinal (and also transverse) expansion of the system?
- Can we ***prove*** from the inferred densities that deconfined matter has been created?

Identified particles at intermediate to high-p_t



- Two groups, baryons and mesons
- At ~5 GeV/c baryons and mesons seem to approach each other
- Suggesting relevance of constituent quarks for hadron production
- Coalescence/recombination provides a description between ~1.5-5 GeV/c

Elliptic flow at intermediate to high-p_t



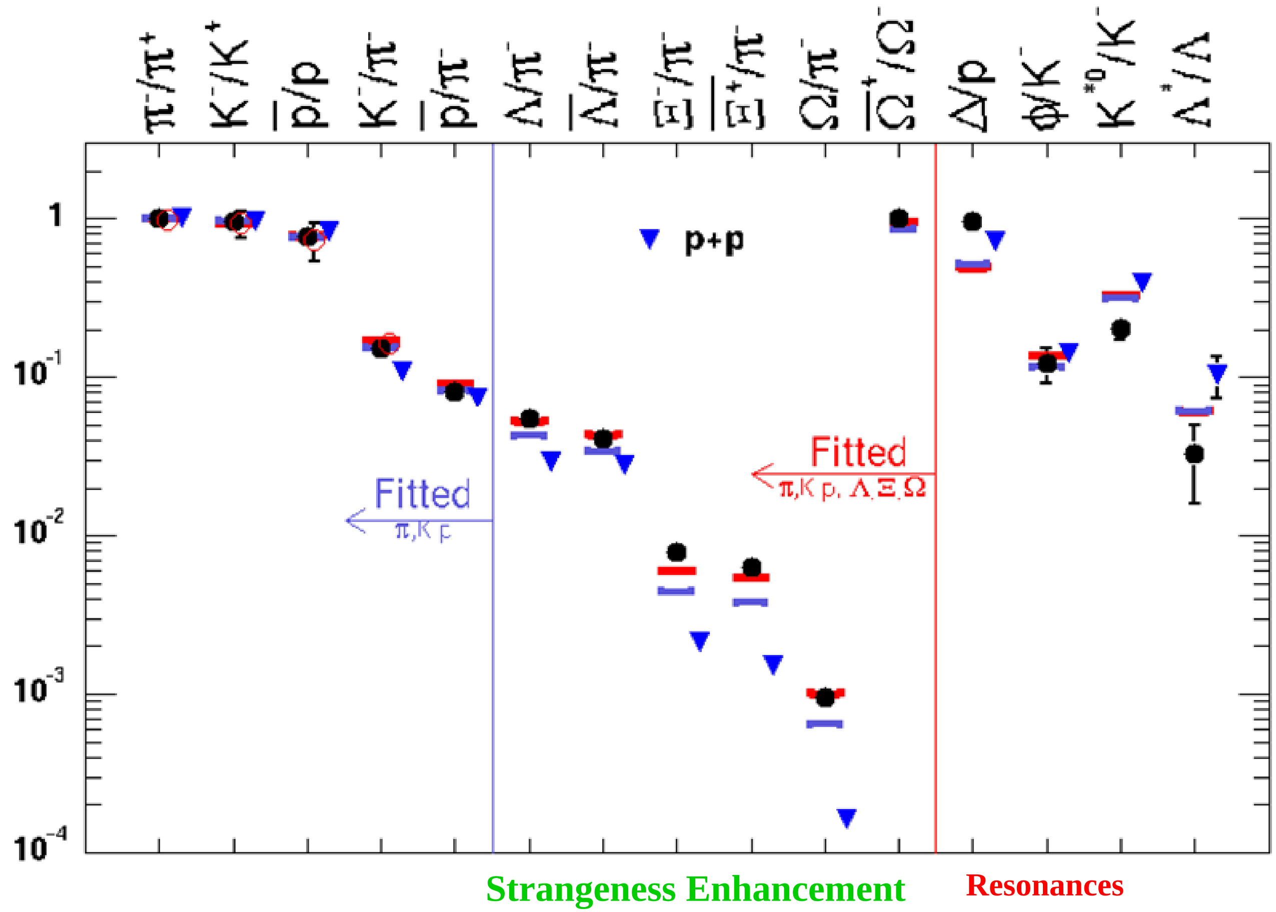
- Two groups, baryons and mesons
- Suggesting relevance of constituent quarks for hadron production
- Coalescence/recombination provides a description between 1.5-5 GeV/c

Identified particles at intermediate to high-p_t

- Baryons and mesons scaling is suggestive of importance of constituent quark degree of freedom in hadronization and suggestive of collective flow at the constituent quark level
- This scaling is compactly described in a coalescence/recombination model

- Aside from providing an organizing principle, what predictive power do these models have? Can they predict the correct centrality-dependence of these ratios, or meson vs. baryon correlations (angular or otherwise) at moderate p_t? Does it also still work when applied on models with a more complete space-time evolution?

Particle yields

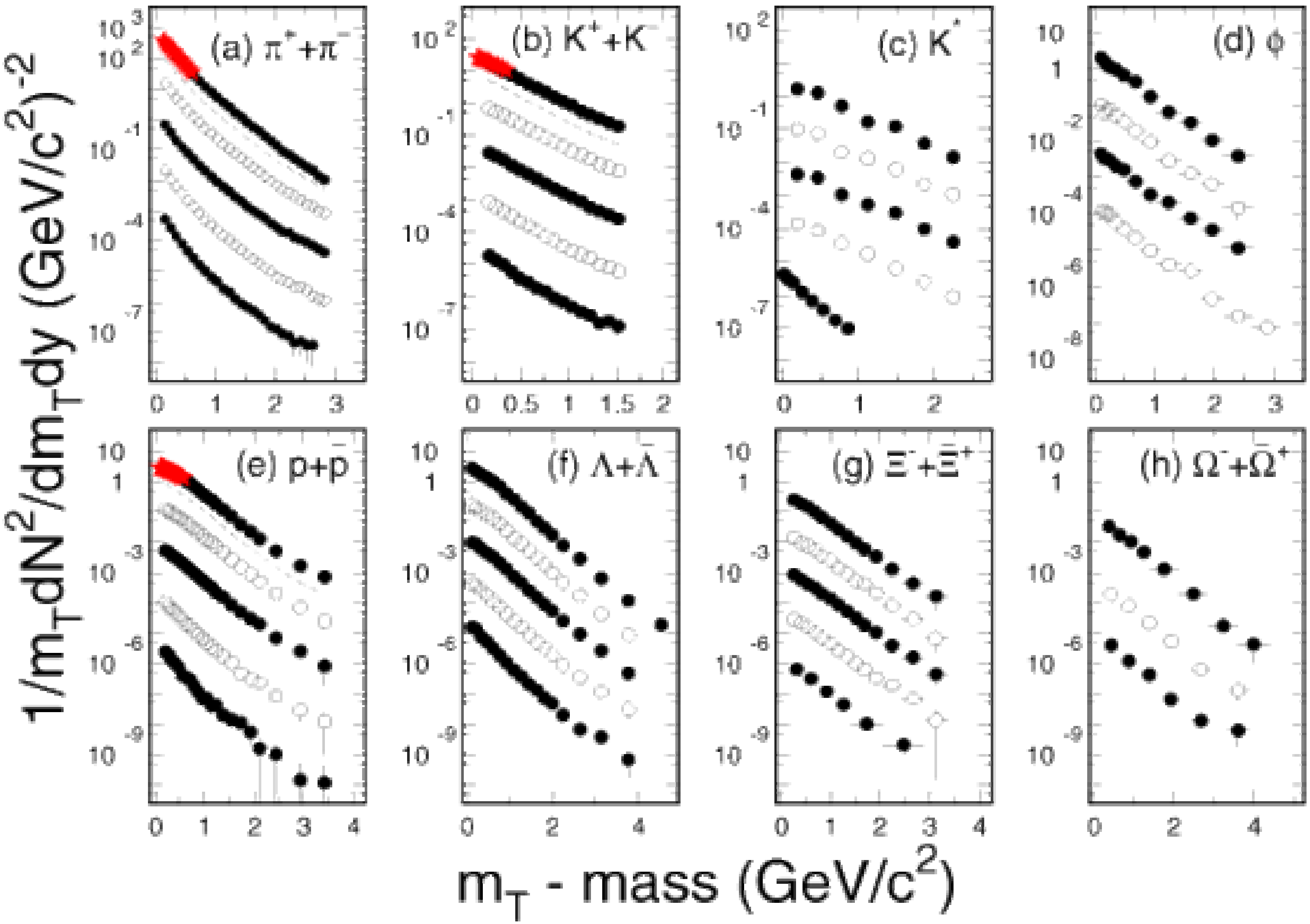


STAR
O PHENIX

- Chemical freeze-out 160 +/- 10 MeV, close to expected critical temperature, particle ratios similar in pp for most abundant species
- Deviations of the resonance yields compared to thermal model predictions indicative of hadronic phase after chemical freeze-out

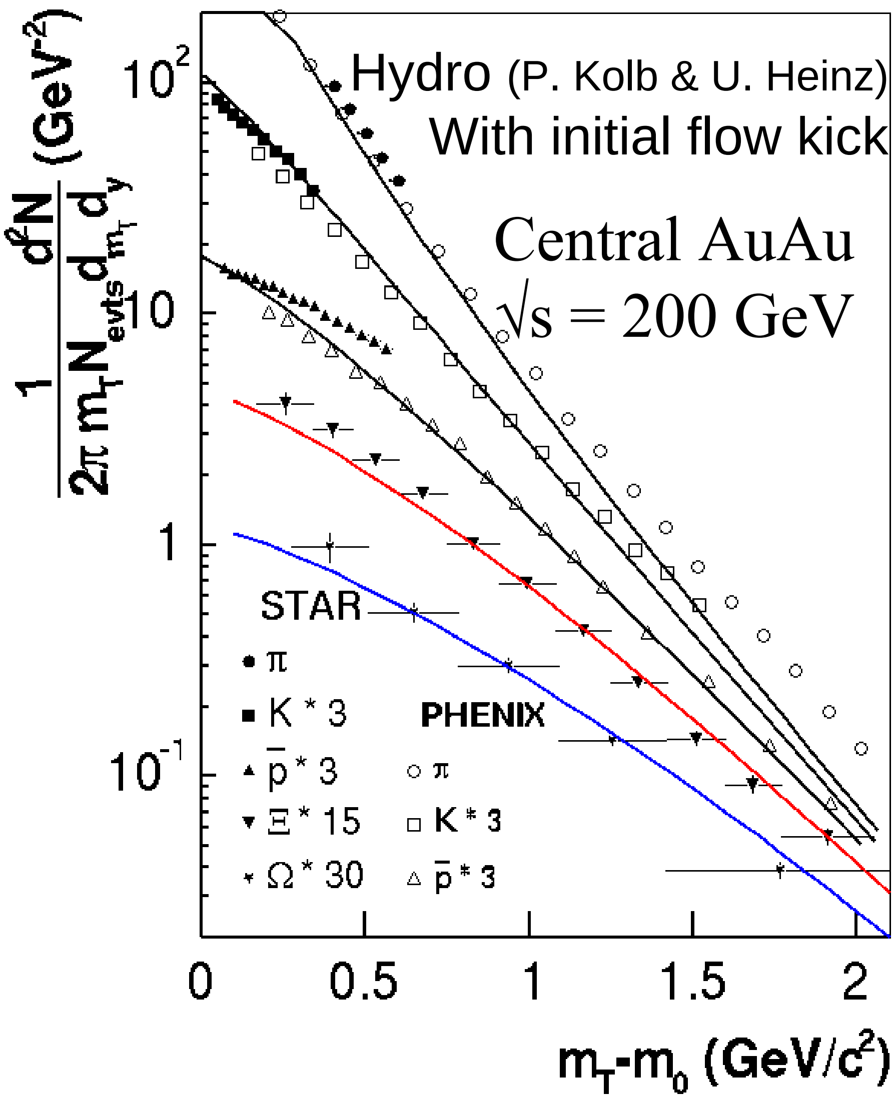
Identified particle spectra

STAR and PHENIX data



PHENIX Phys. Rev. C 69, 034909 (2004)

Identified particle spectra

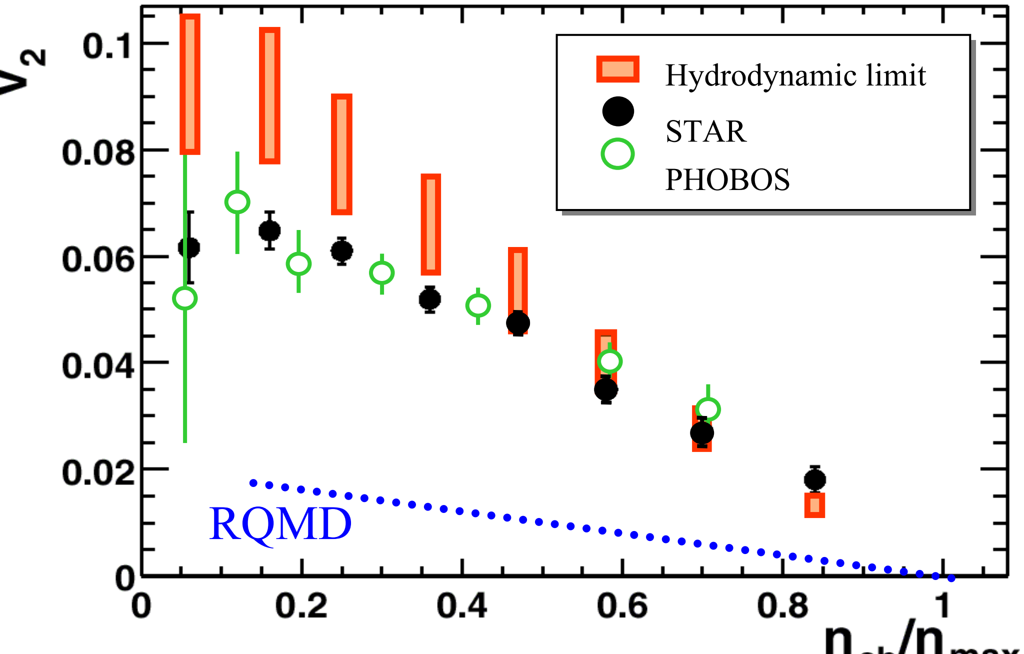


- Mass dependence of particle spectra described reasonably well by ideal hydrodynamics

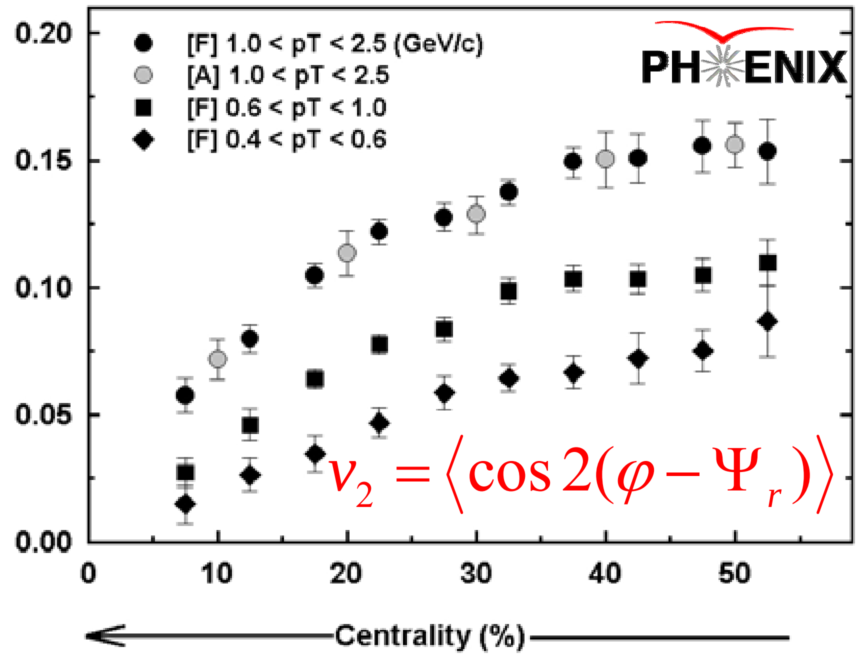
Charged hadron elliptic flow

PHOBOS: Phys. Rev. Lett. **89**, 222301 (2002)
STAR: Phys. Rev. Lett. **86**, 402 (2001)

PHENIX: Phys. Rev. Lett. 89, 212301 (2002)

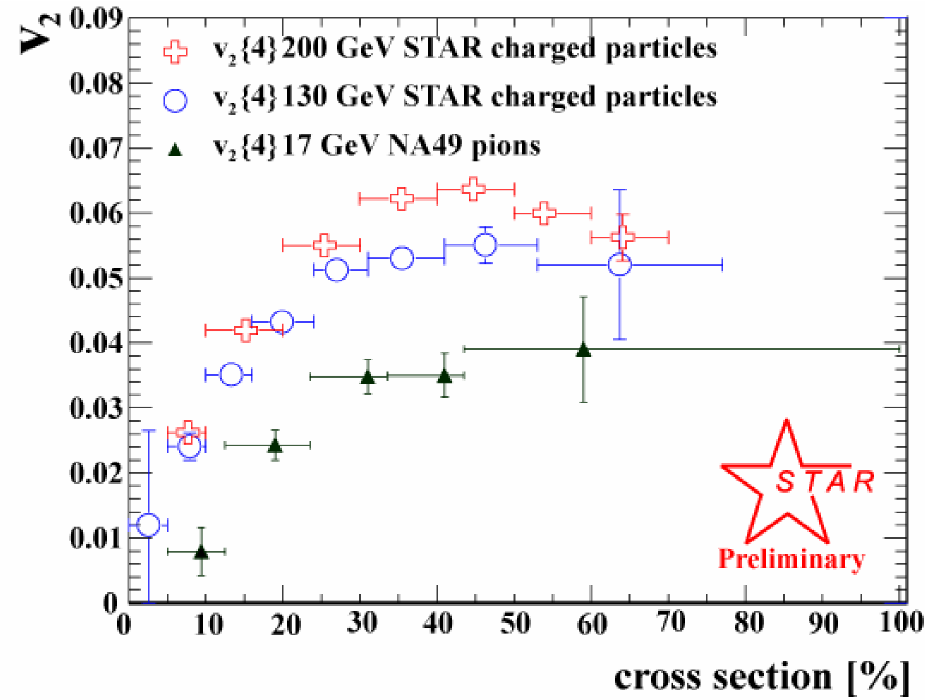


Compilation and Figure from M. Kaneta

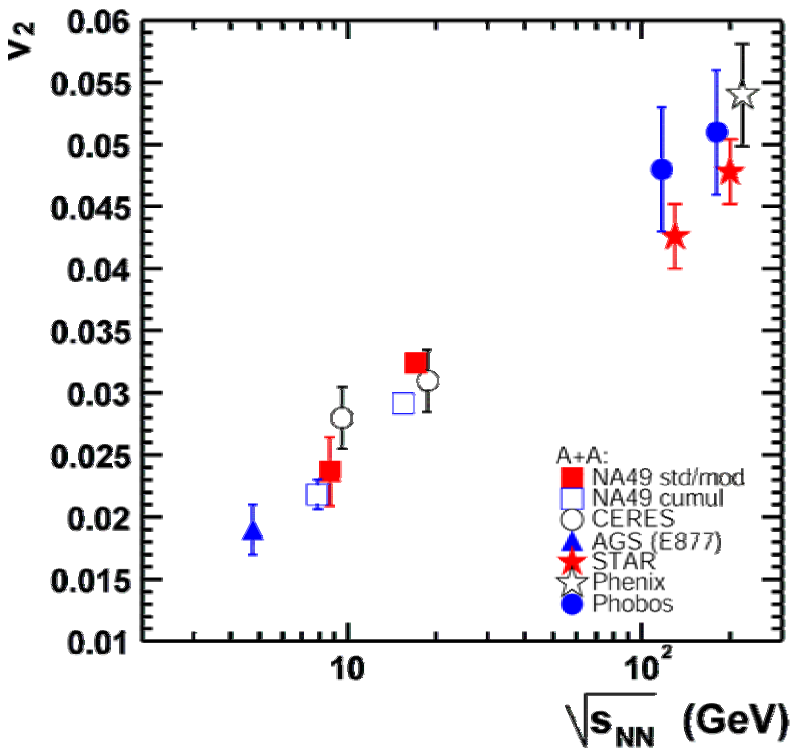


First time in Heavy-Ion Collisions a system created which at low p_t is in quantitative agreement with ideal hydrodynamic model predictions for v_2 up to mid-central collisions

Energy dependence of v_2

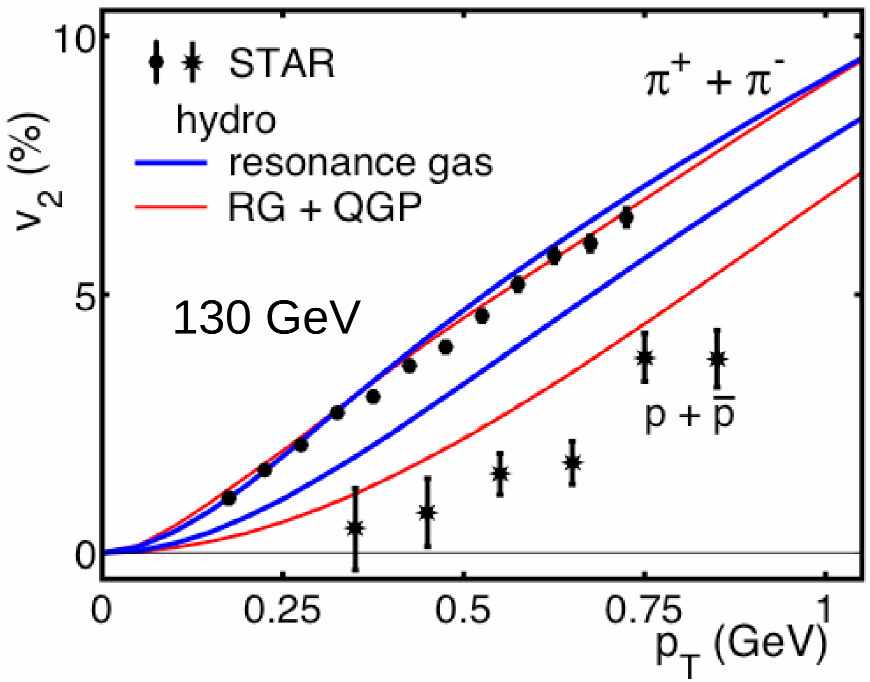


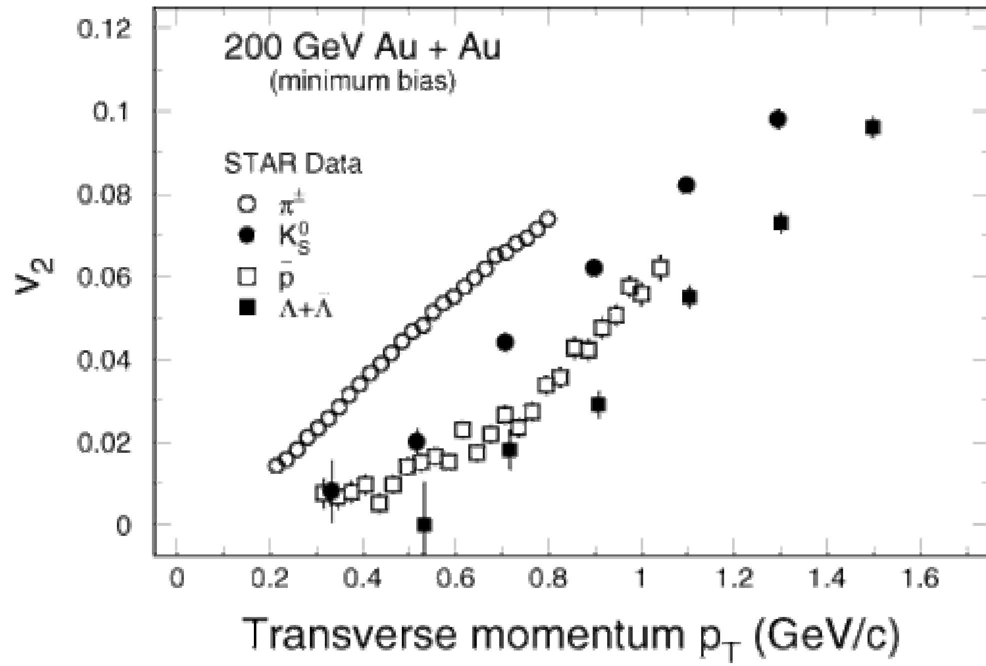
NA49 Phys.Rev. C68 (2003) 034903



- See: Peter F. Kolb and Ulrich Heinz, review for 'Quark Gluon Plasma 3', nucl-th/0305084. Pasi Huovinen, review for 'Quark Gluon Plasma 3', nucl-th/0305064. D. Teany, J. Lauret and E. V. Shuryak, nucl-th/0110037; Phys. Rev. Lett 86, 4783 (2001)
- Rather smooth dependence versus beam energy

$v_2(m,p_t)$





Hydro calculations: Kolb, Heinz and Huovinen

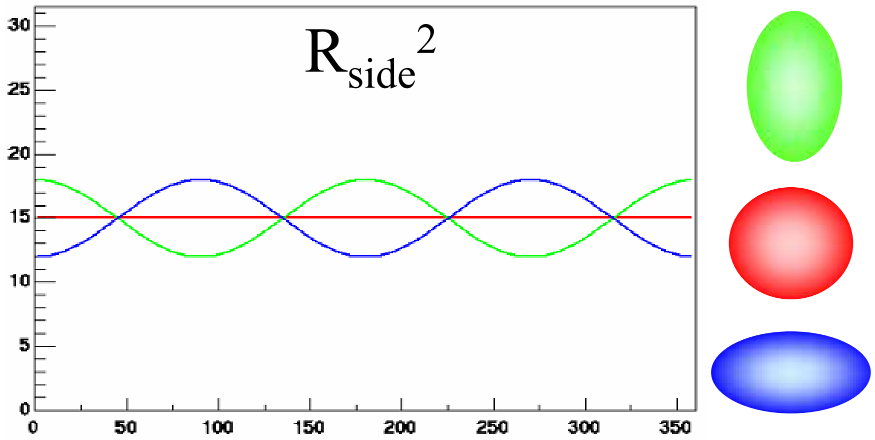
- Clear mass dependence; signature of collective flow (not only in hydro)
- Hydrodynamics gives reasonable description of various mass particles at low transverse momenta
- Hydro calculation constrained by particle spectra

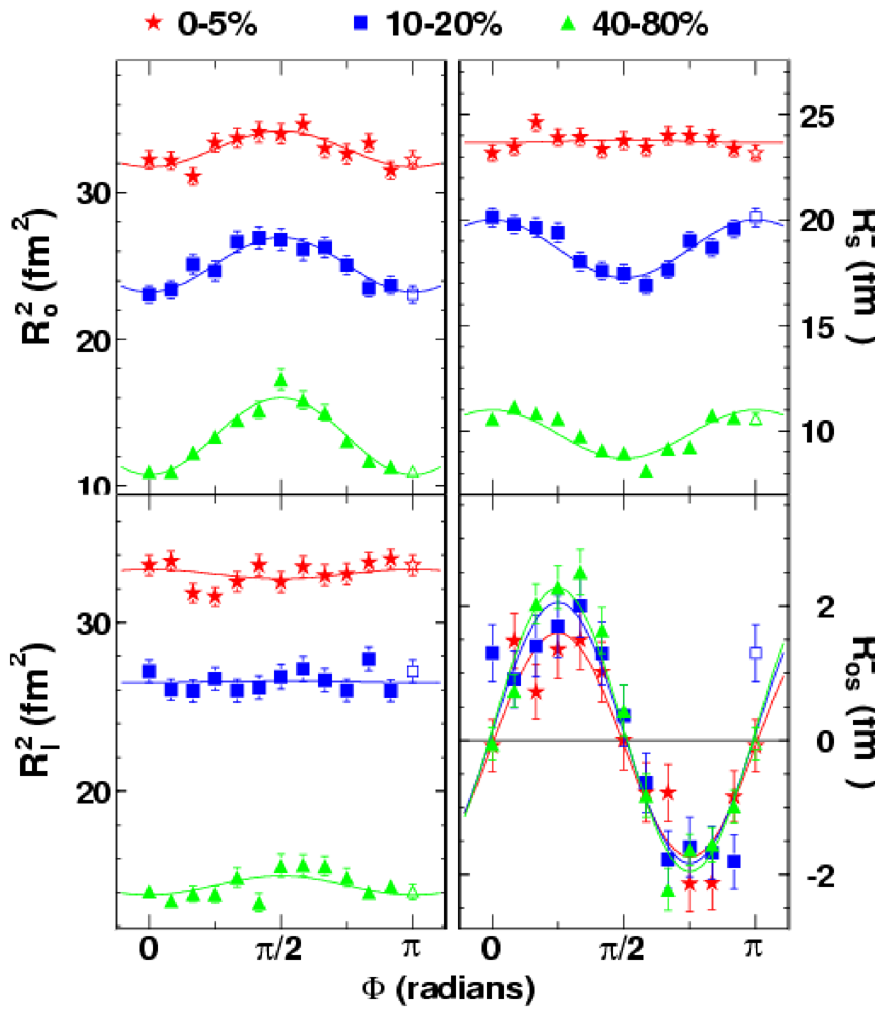
Is the system in approximate local thermal equilibrium?

- The unprecedented success of hydrodynamics calculations assuming ideal relativistic fluid behavior in accounting for RHIC elliptic flow results has been interpreted as evidence for both early attainment of local thermal equilibrium and softening of the equation of state, characteristic of the predicted phase transition.

- How do we know that the observed elliptic flow can not result alternatively from a harder EOS coupled with incomplete thermalization? (D. Teaney, J. Lauret, E.V. Shuryak; Phys. Rev. Lett 86, 4783 (2001))

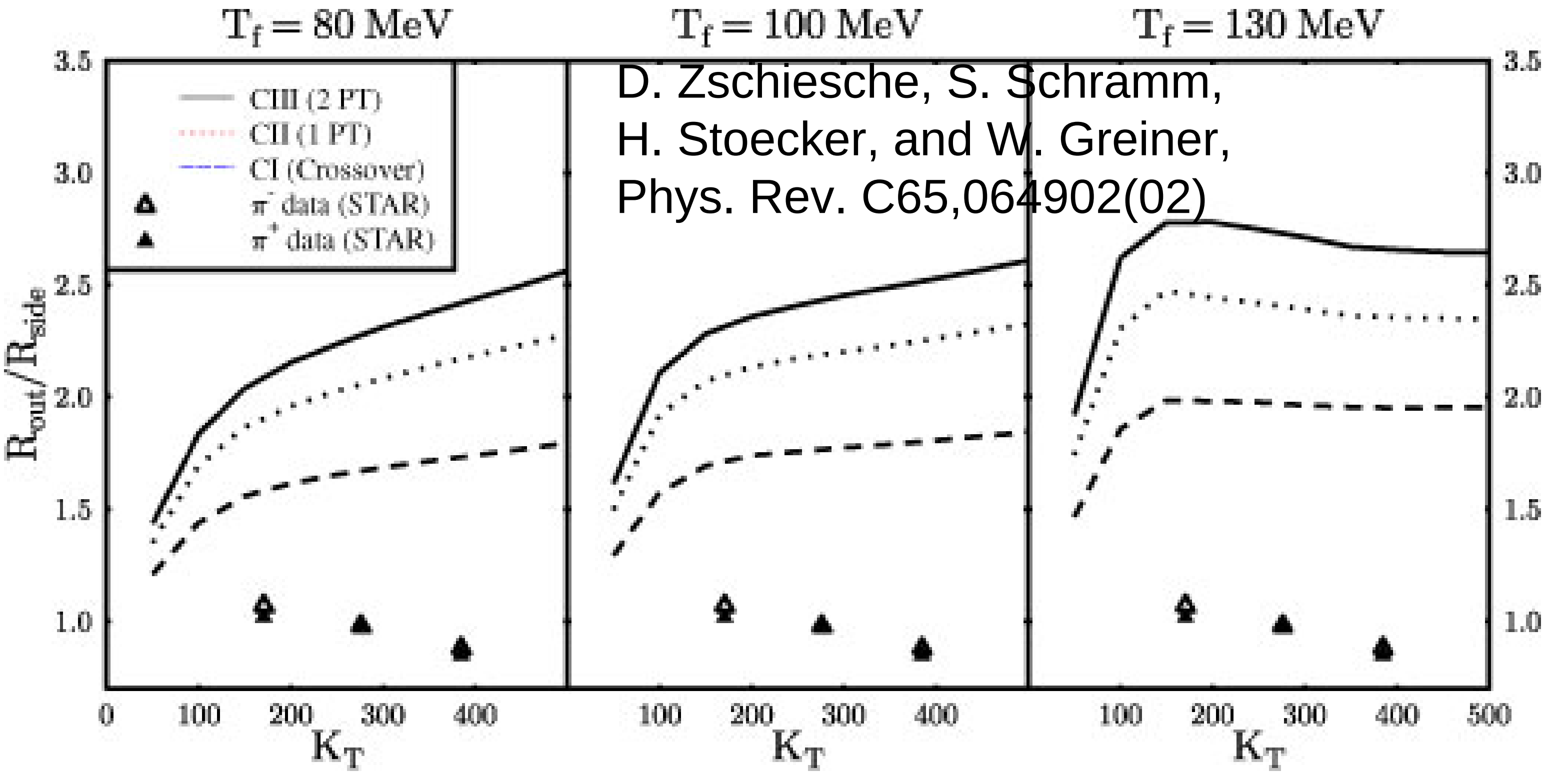
Space-time information





- HBT “radii” show an azimuthal dependence; qualitative centrality dependence fits into picture obtained from v_2 and spectra

Space-time information



D. Zschiesche, S. Schramm,
H. Stoecker, and W. Greiner,
Phys. Rev. C65,064902(02)

- Dynamical models which describe the relatively well the spectra and elliptic flow give a rather poor description of the HBT “radii”
- Key observables like the elliptic flow compared to hydro depend on the time evolution of the system, which seems not completely under control

HBT, spectra and v_2; the soft sector

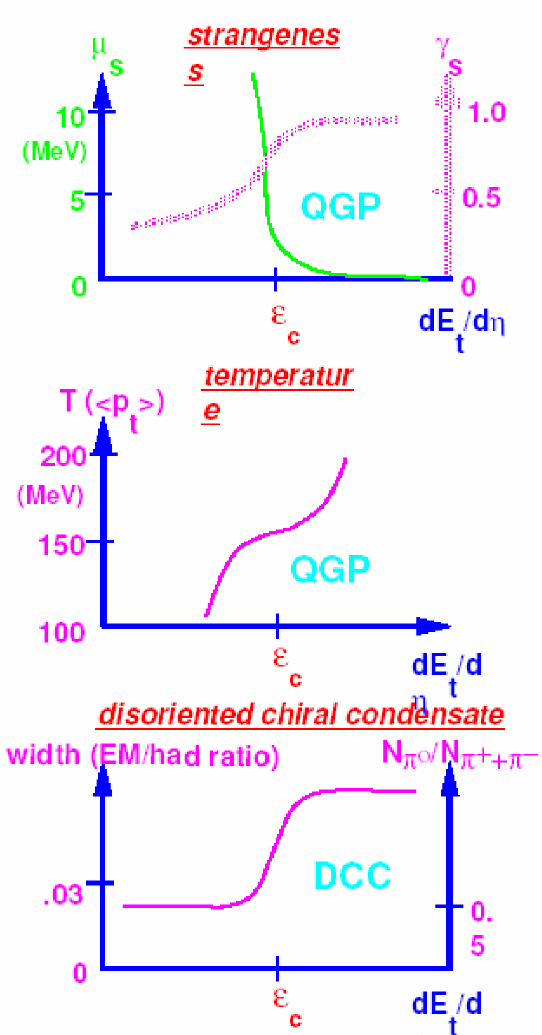
- The indirect evidence for a phase transition in the elliptic flow results comes primarily from the sensitivity in hydrodynamic calculations of the magnitude and hadron mass-dependence of v_2 to the EOS

- How does the level of this EOS sensitivity compare quantitatively to that of uncertainties in the calculations, based the range of adjustable parameters and the failure to describe the spectra, elliptic flow and HBT at the same time?

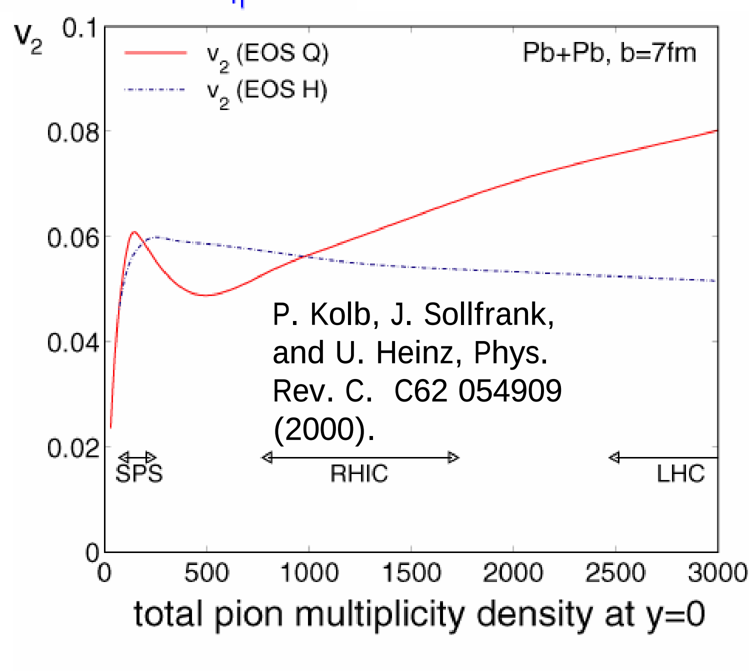
Initial conditions (CGC)

- If there is a truly universal gluon density saturation scale, determined already from HERA *e*-p deep inelastic scattering measurements, why has it been necessary to refit parameters of the saturation scale to RHIC A+A particle multiplicities? Is not the A-dependence of the gluon densities at the relevant Bjorken x-ranges predicted in gluon saturation treatments

Going back in history…
(actually even not so long ago)



Harris & Mueller
AnnRevNuclPartSci ‘96



Critical behavior?

- Is it naïve to expect non-monotonic behavior?
- Can we make a convincing QGP discovery claim without a rapid change in an observable characteristic of a phase transition?
  - Where is the smoking gun?
- Can we predict, based on what we now know from SPS and RHIC, at what energies or under what conditions we produce matter below the critical temperature and which observables from those collisions will show a non-monotonic behavior?

Experimental observations/discoveries

- At RHIC we showed that Au+Au collisions create a medium that is dense, dissipative and exhibits strong collective behavior
  - We observe suppression phenomena in single particle observables and very importantly also in the correlations (large acceptance)
  - We observed baryon meson scaling in v_2 and R_{cp} at ~ 2-5 GeV/c
  - We observe strong collective behavior, manifest in all observables