Recent progress at RHIC (assessment of results from the first three years of RHIC running)

Raimond Snellings

For the STAR Collaboration

Introduction

- 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
  - Time scale: collaboration discussion June 12th , available to the public mid-June
- The outline of this talk (given):
  - What we have learned so far in the heavy-ion program at RHIC (from STAR's perspective)
    - The enormous success of the first RHIC years makes it impossible to summarize all the beautiful results from STAR and what we learned from them in just 15 min
  - What are unanswered questions/issues which could be addressed in the future RHIC program over the next 5-10 years or at the LHC (see Tim Hallman's talk).

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

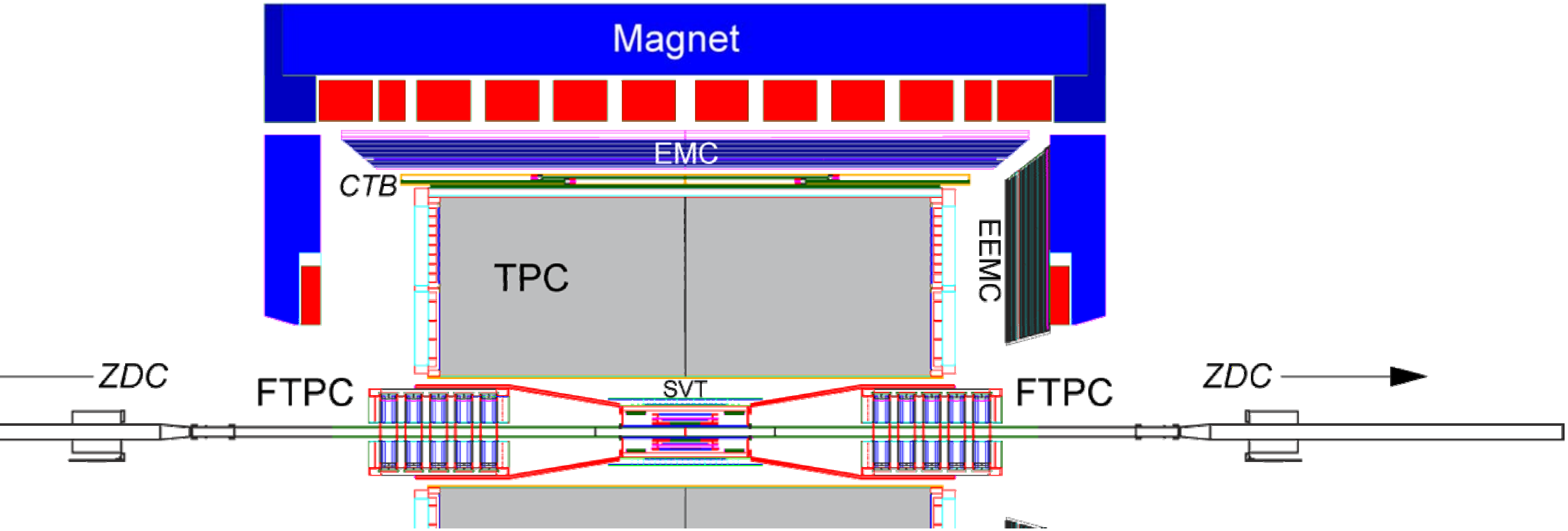
India:
Bhubaneswar, Jammu, IIT-Mumbai, Panjab, Rajasthan, VECC

Netherlands:
NIKHEF

Poland:
Warsaw University of Technology

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

Switzerland:
University of Bern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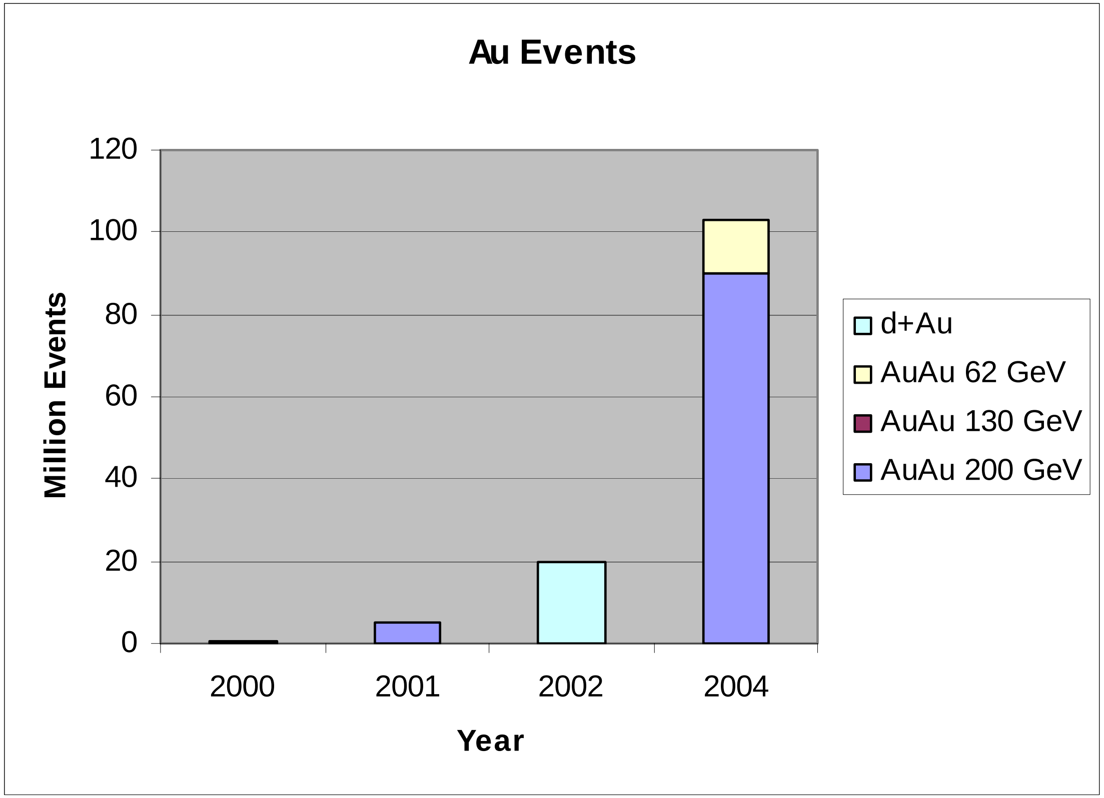
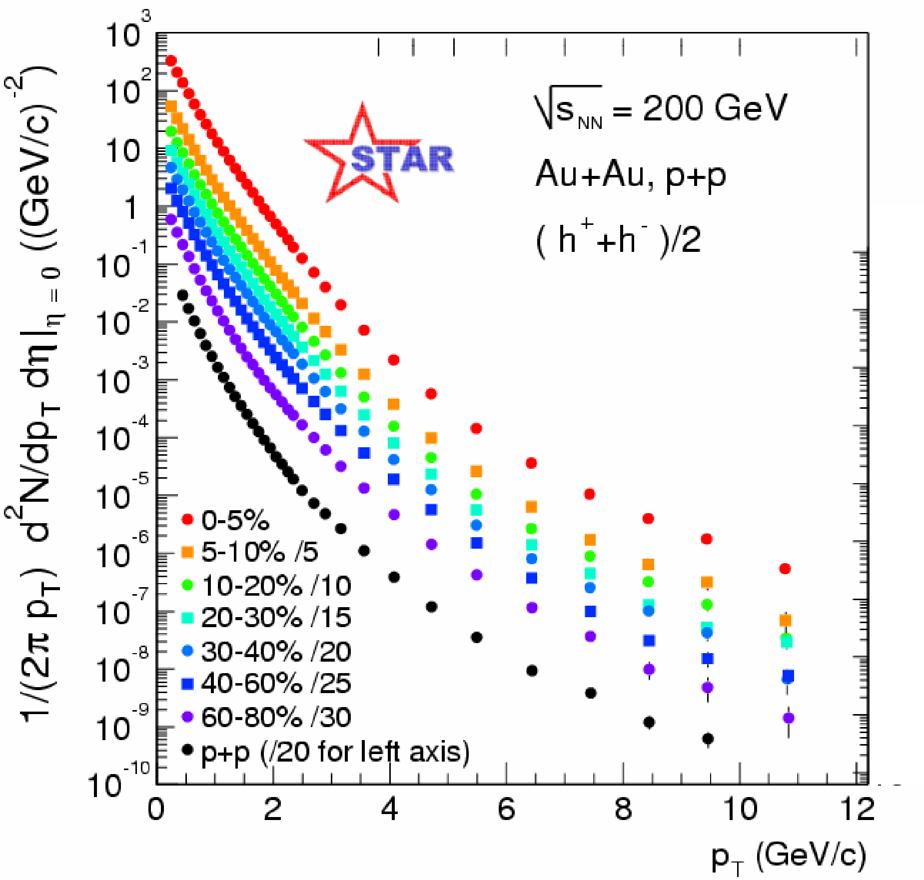
Au+X Datasets



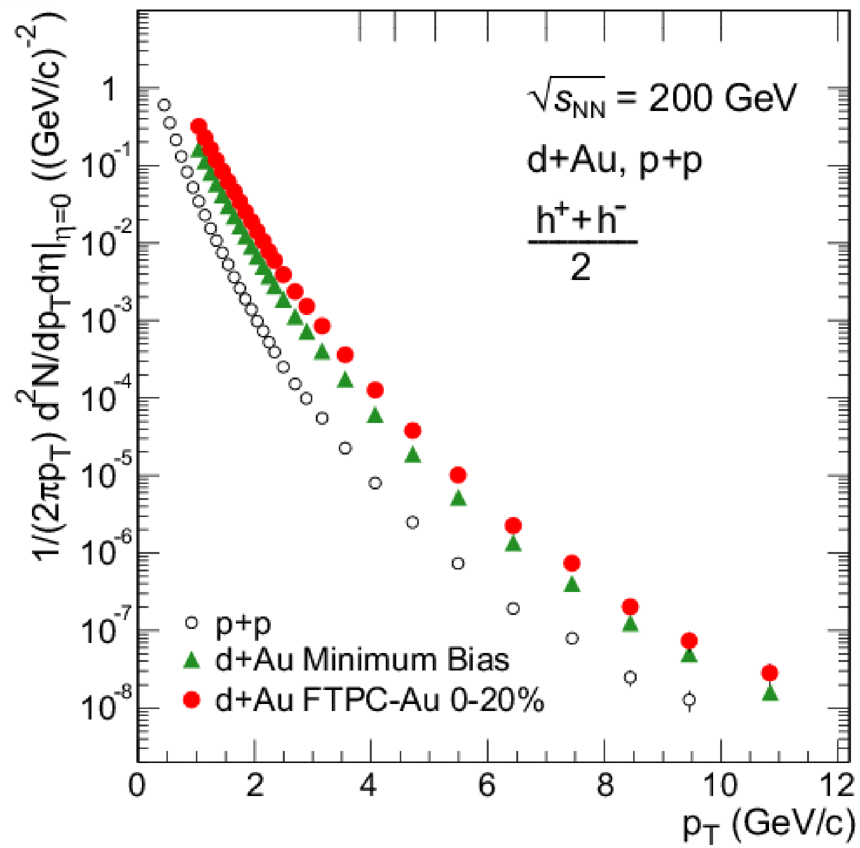
- ❑ This year: extremely successful run, all BUR goals substantially met
- ❑ Greater than order of magnitude increase in dataset

Leading particle spectra

Au+Au

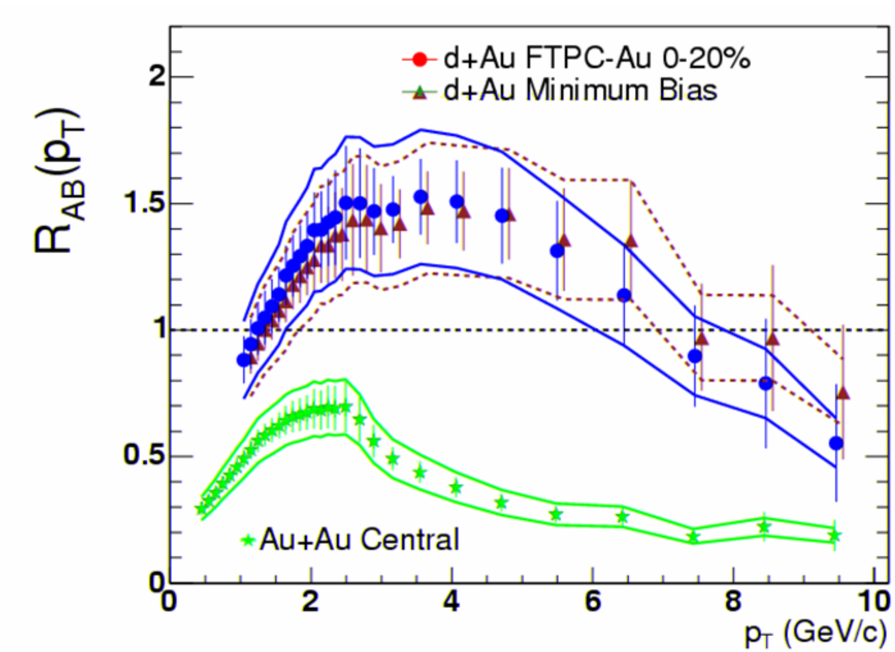


d+Au



Charged hadron p_T distributions measured up to 12 GeV in Au+Au, d+Au and p+p reference

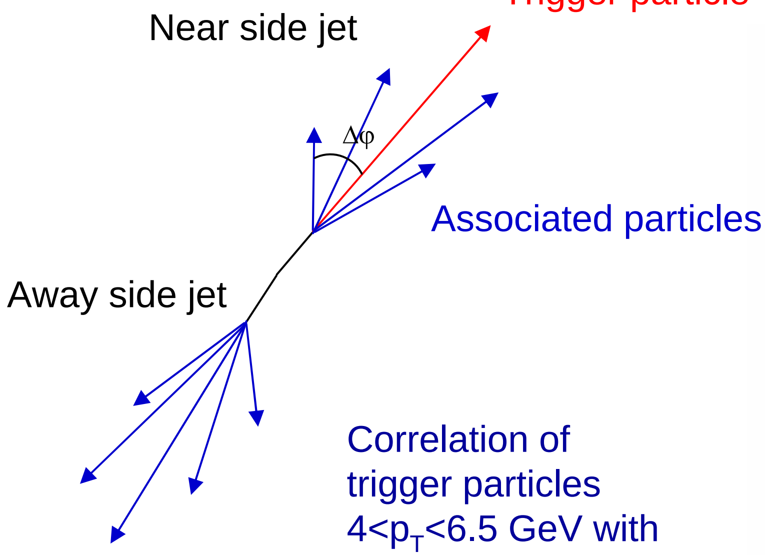
Suppression of the particle yield at high transverse momenta



$$R_{AB} = \frac{dN_{AB} / dp_T}{\langle N_{bin} \rangle dN_{pp} / dp_T}$$

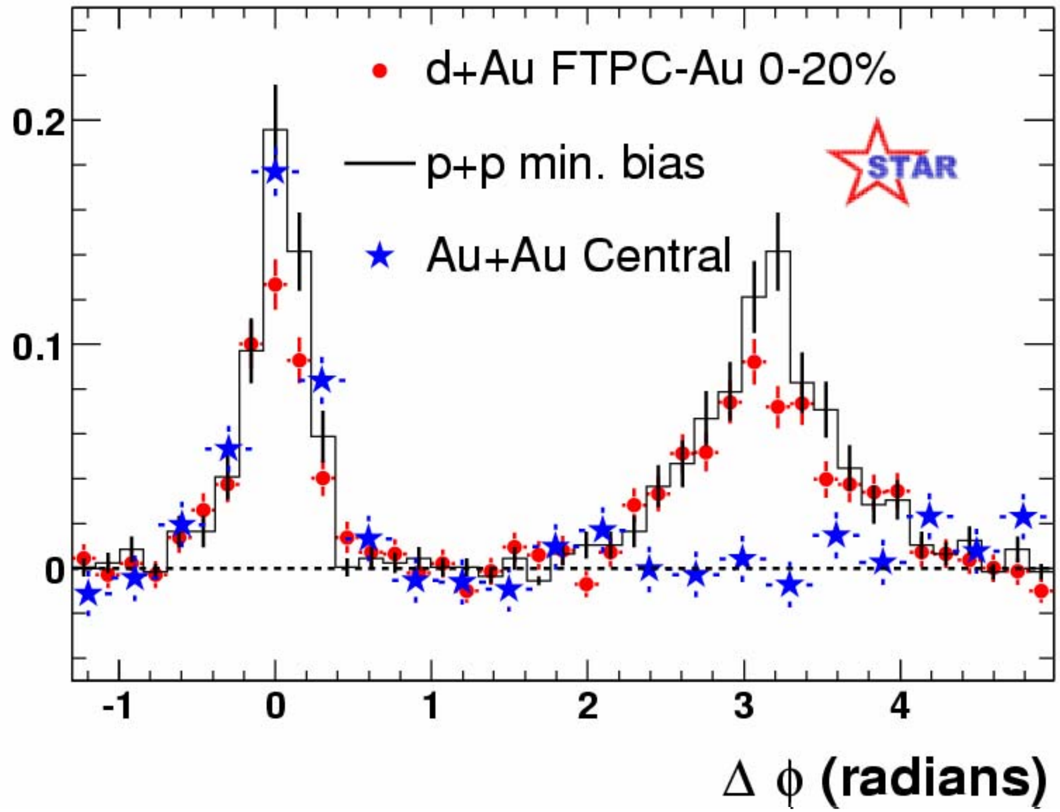
- Suppression of particle yield is a final state effect!
- Consistent with expectations from parton energy loss in a dense medium!

Di-hadron correlations



Correlation of trigger particles $4<p_T<6.5$ GeV with associated particles $2<p_T<p_{T,trig}$

Adler *et al.*, PRL90:082302 (2003)



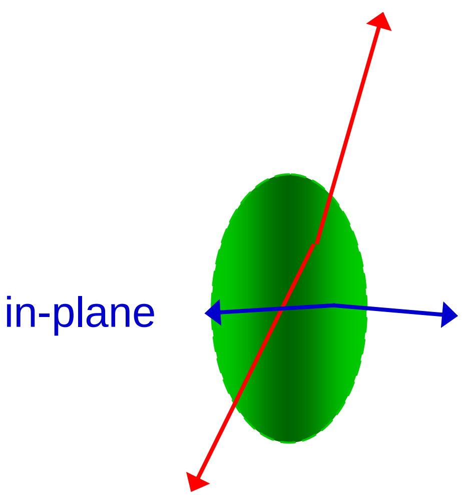
p+p, peripheral Au+Au: 2 jets

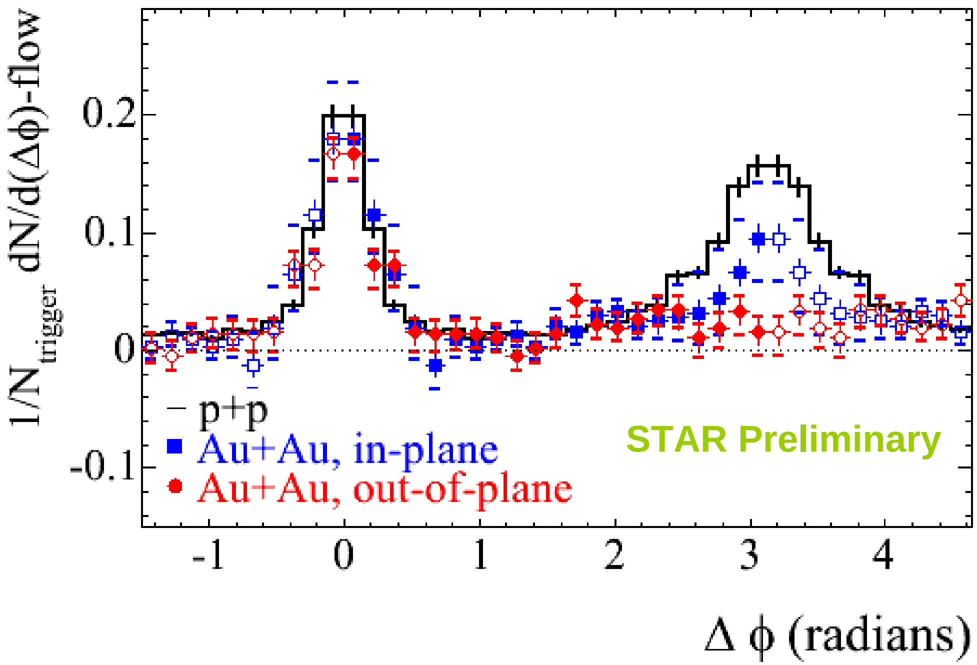
Central Au+Au: no away-side jet

d+Au control: 2 jets

- Back to back suppression is a final state effect, consistent with expectations of parton energy loss in a dense medium

Back to back correlations versus the reaction plane





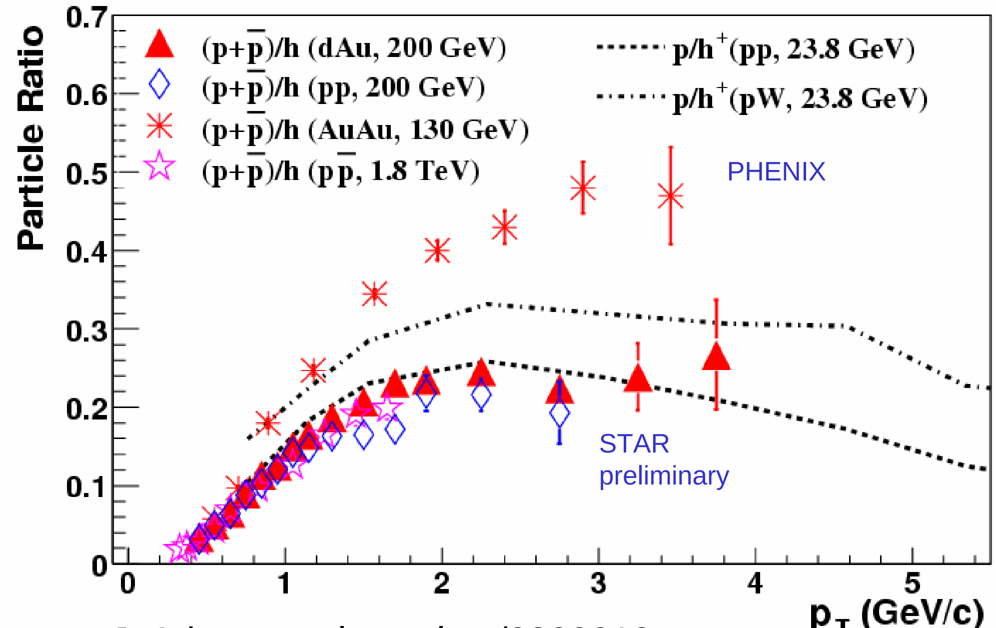
Au+Au centrality:
20-60%

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

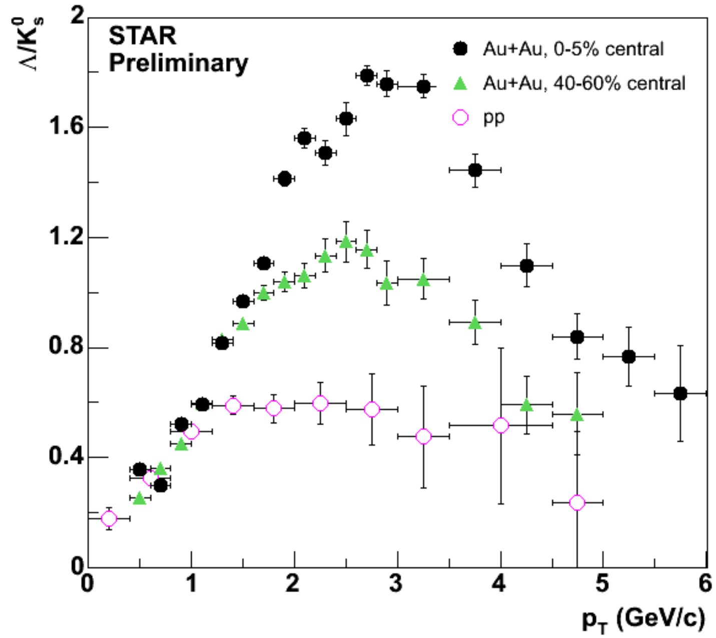
Discovery of the suppression phenomena at RHIC

- The observed high-p_t phenomena can be described efficiently by parton energy loss in matter starting with large energy and gluon densities
  – Large observed suppression of the particle yield
  – The suppression of the back to back correlation (broadening at low-p_t)
  – The large elliptic flow
  – The path length dependence of the back to back azimuthal correlation

Baryon Enhancement

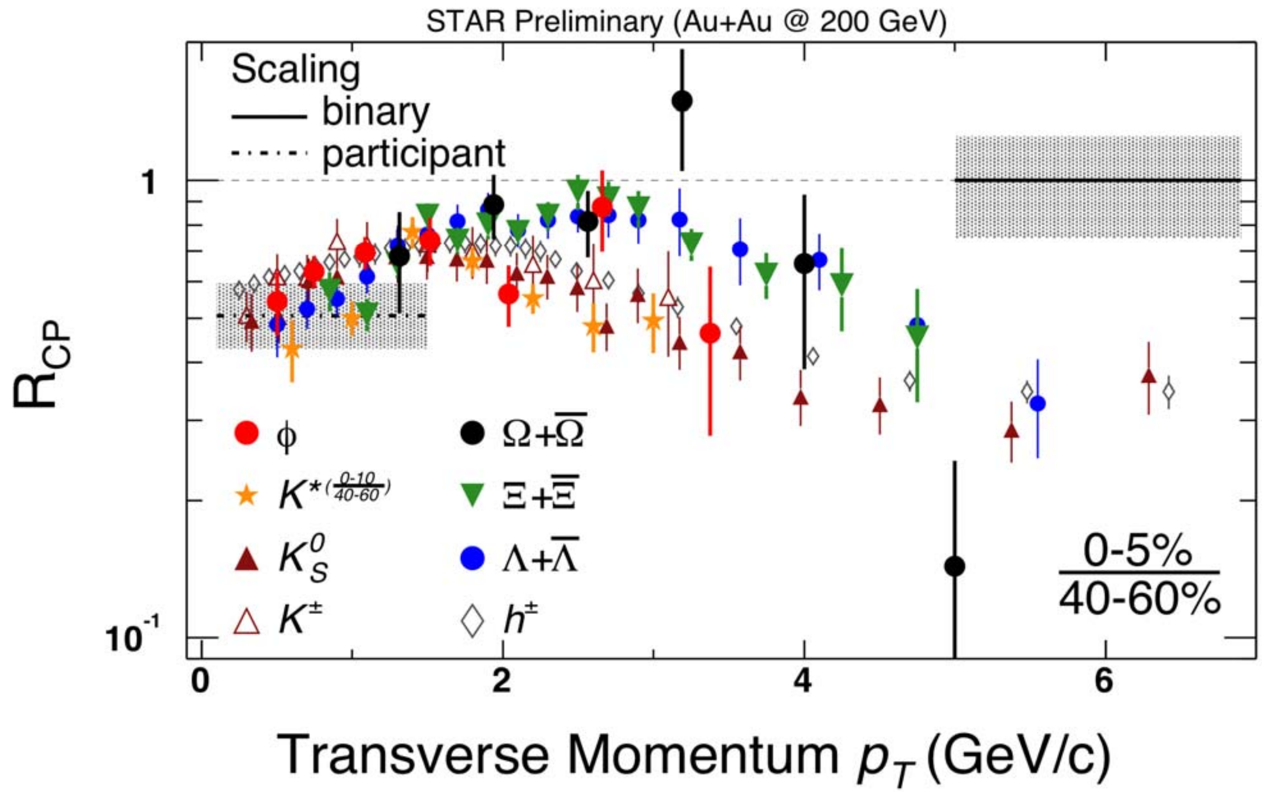


J. Adams et al., nucl-ex/0309012



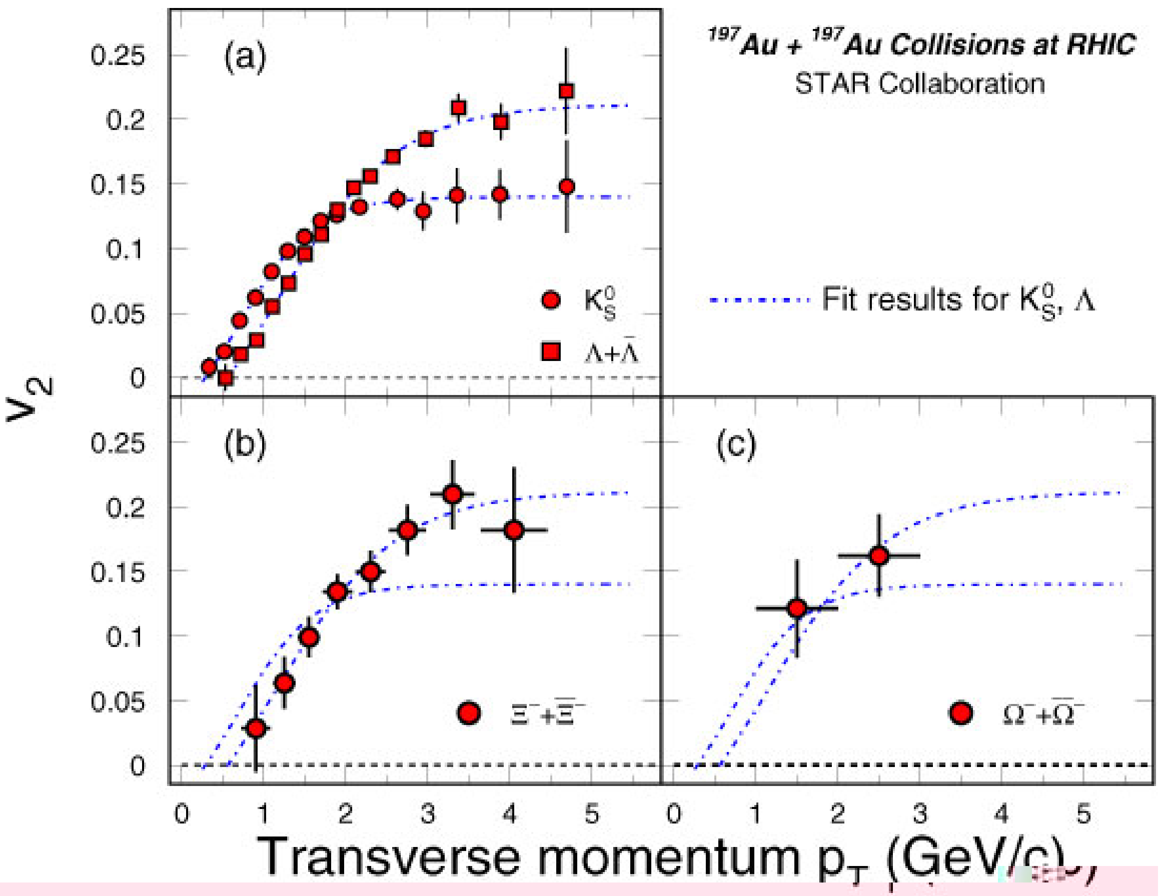
- ❑p+pbar/h enhancement in Au + Au; Not fully explained by Cronin effect
- ❑ Strong baryon/meson modification in Au + Au also in Λ/K^0_s ratio
- ❑ Simple fragmentation picture fails for p_T less than ~6 GeV/c

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

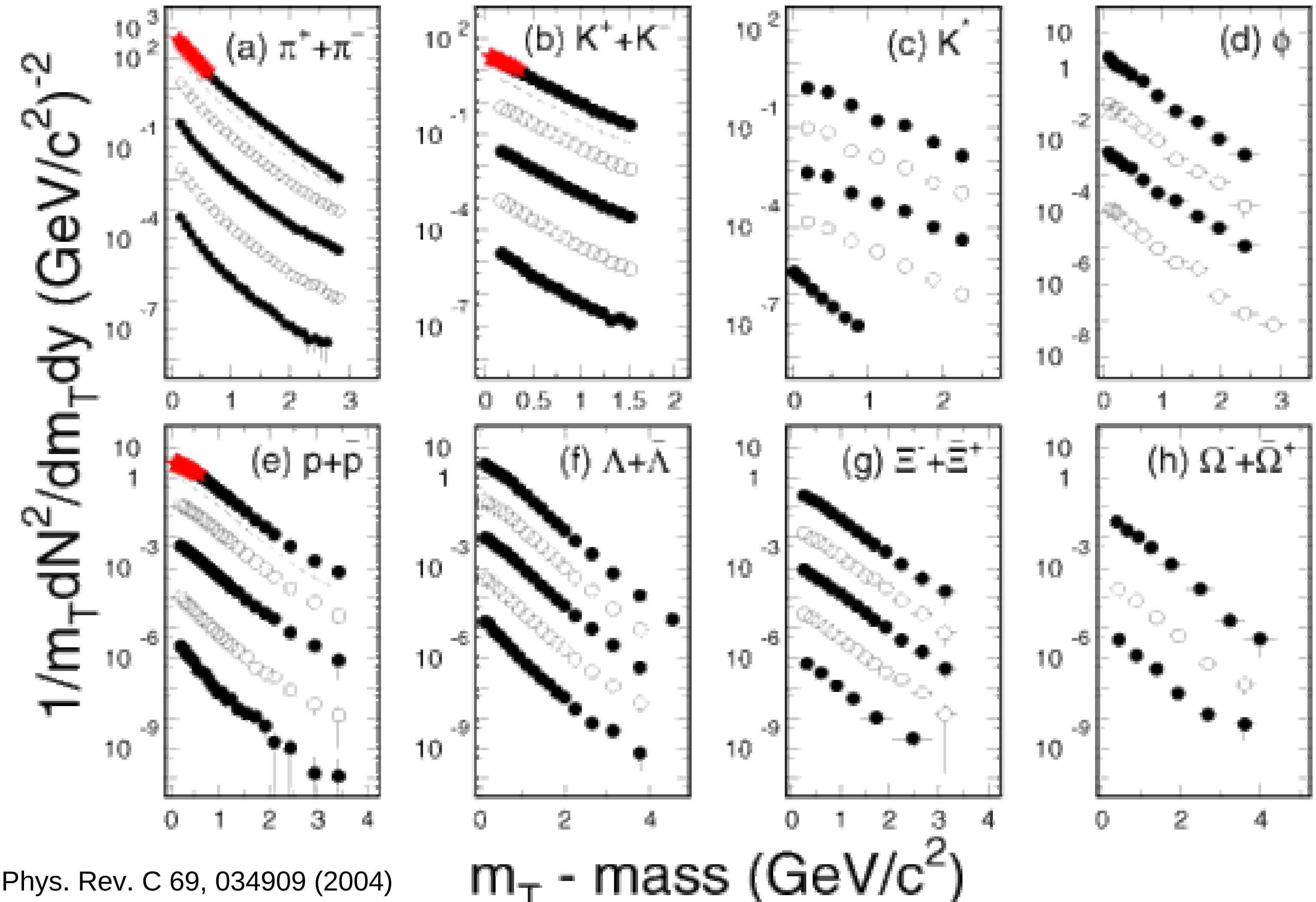
Elliptic flow at intermediate to high-p_t



- Two groups, baryons and mesons
- Suggesting relevance of constituent quarks for hadron production
- Coalescence/recombination provides a description between 1.5-5 GeV/c – suggestive of collective flow at the constituent quark level

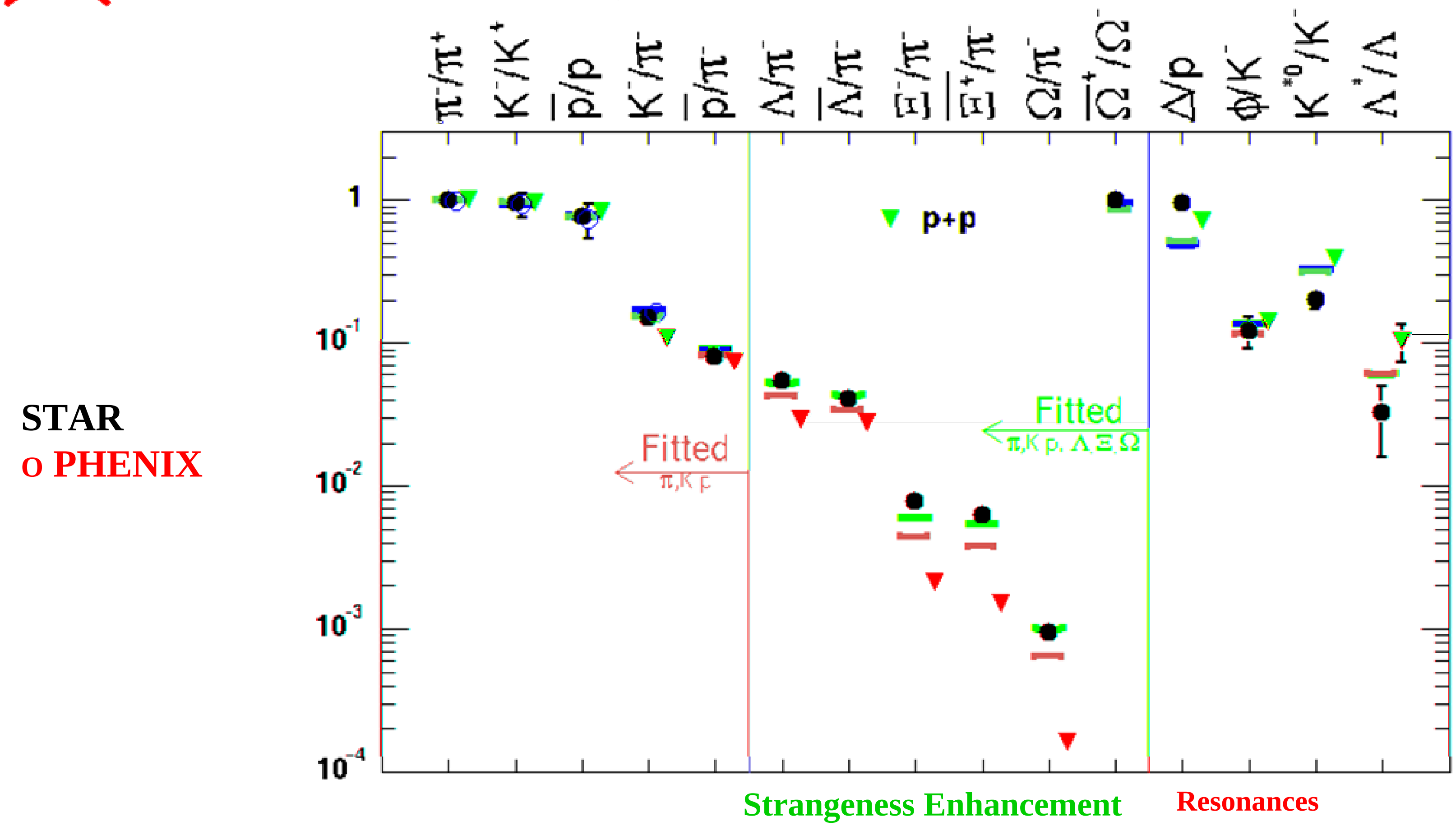
Identified particle spectra

STAR and PHENIX data



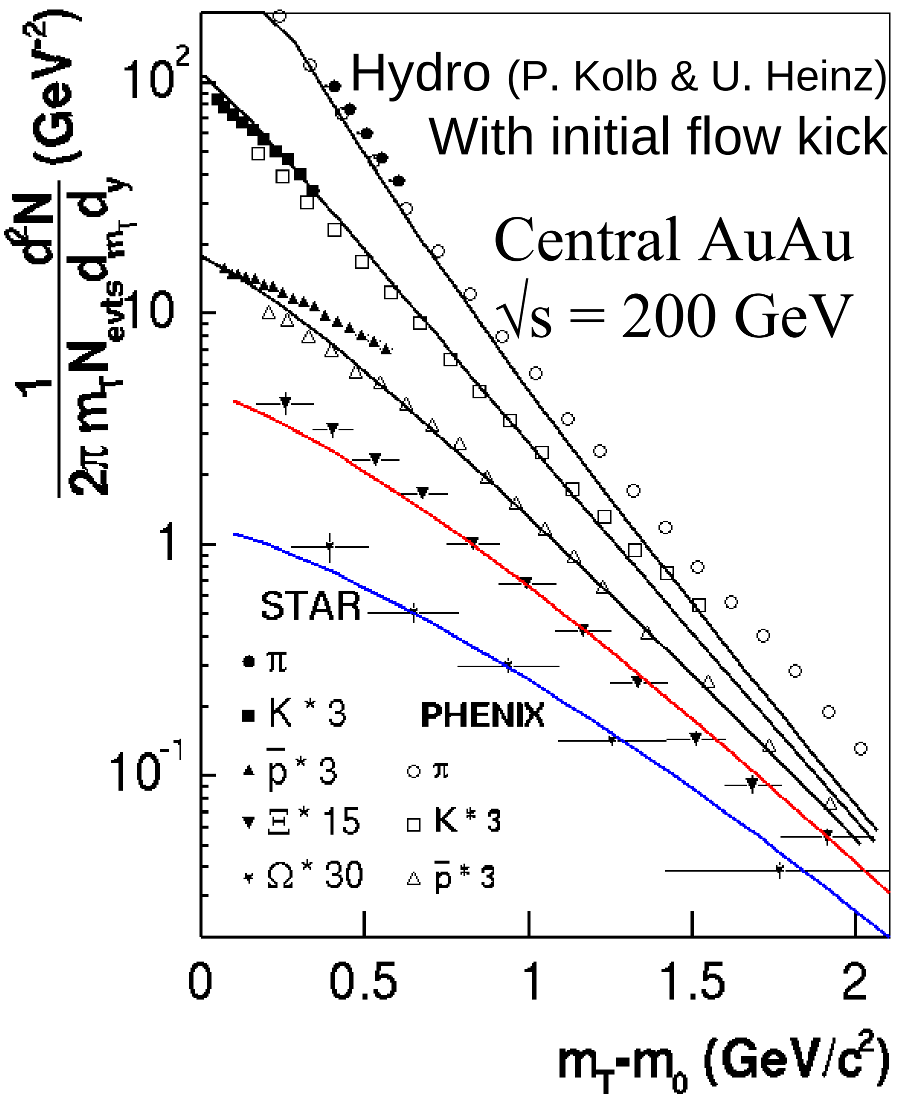
PHENIX Phys. Rev. C 69, 034909 (2004)

Particle yields/thermal model



- 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

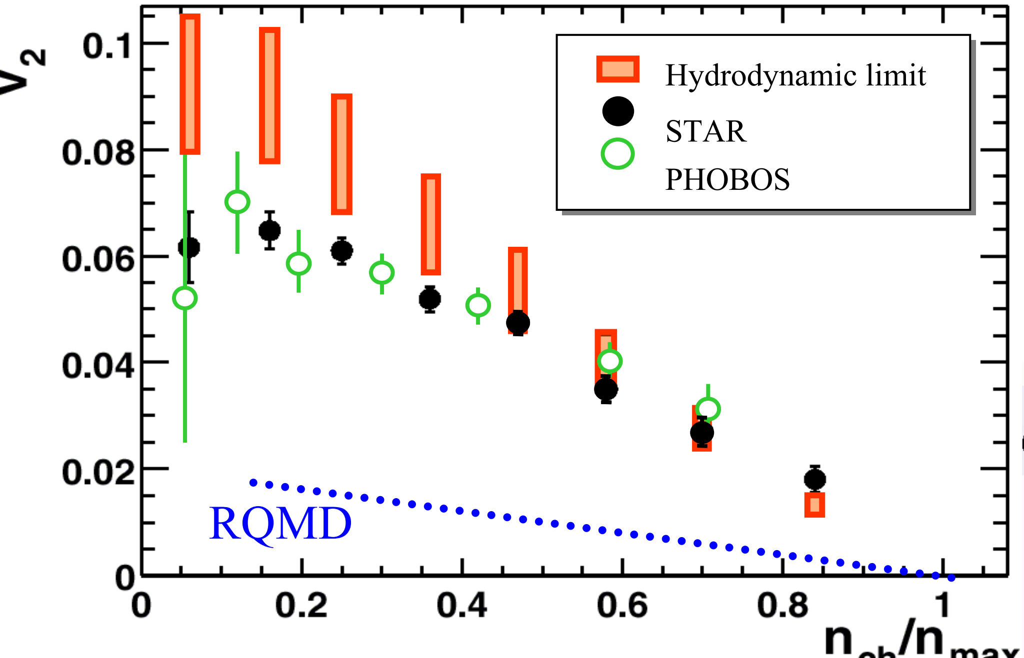


- Mass dependence of particle spectra described reasonably well by ideal hydrodynamics

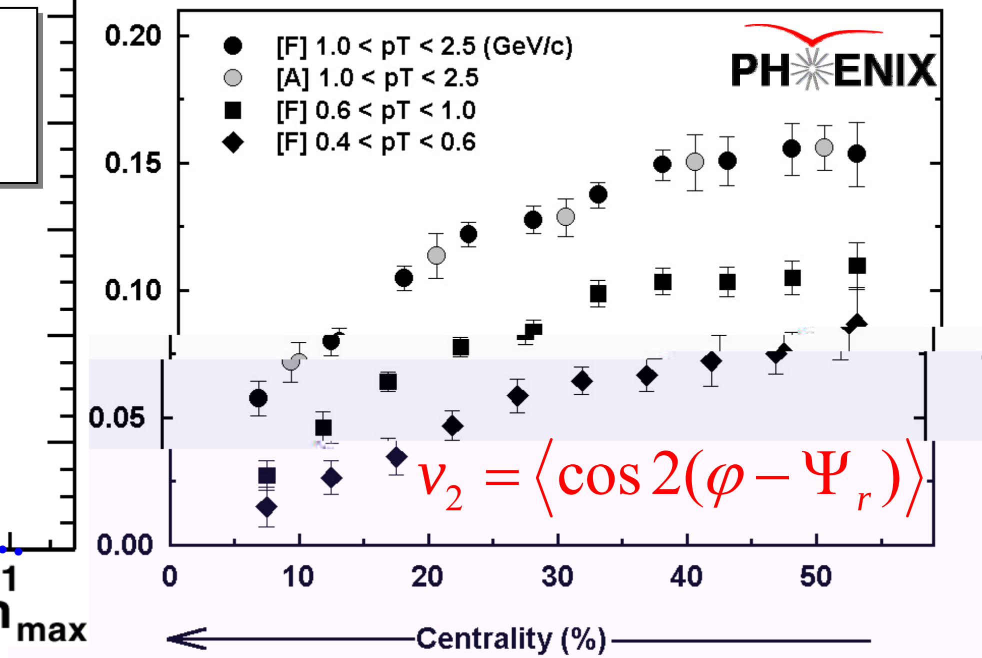
Charged hadron elliptic flow

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

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

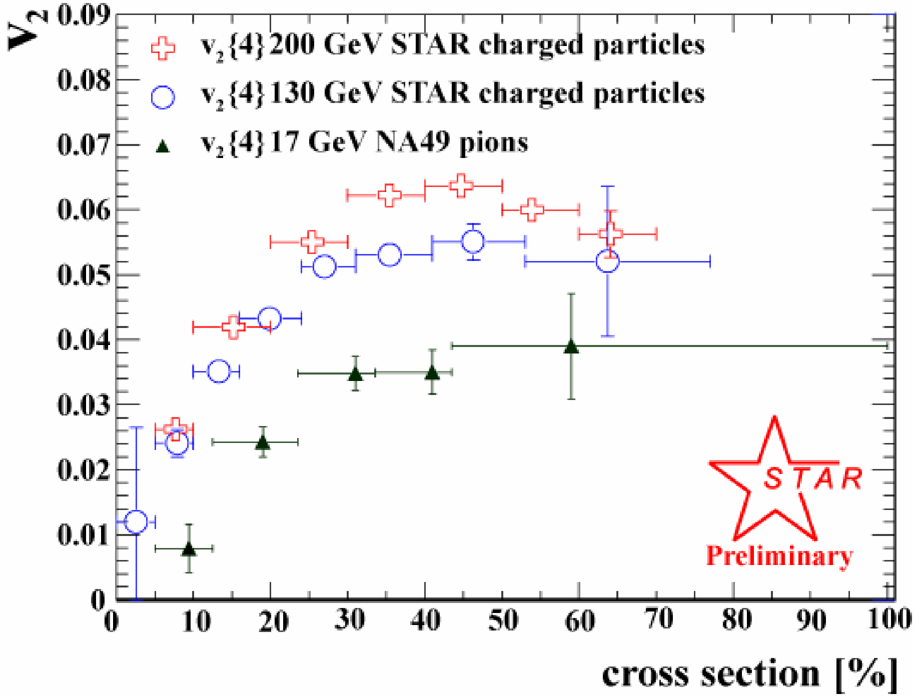


Compilation and Figure from M. Kaneta

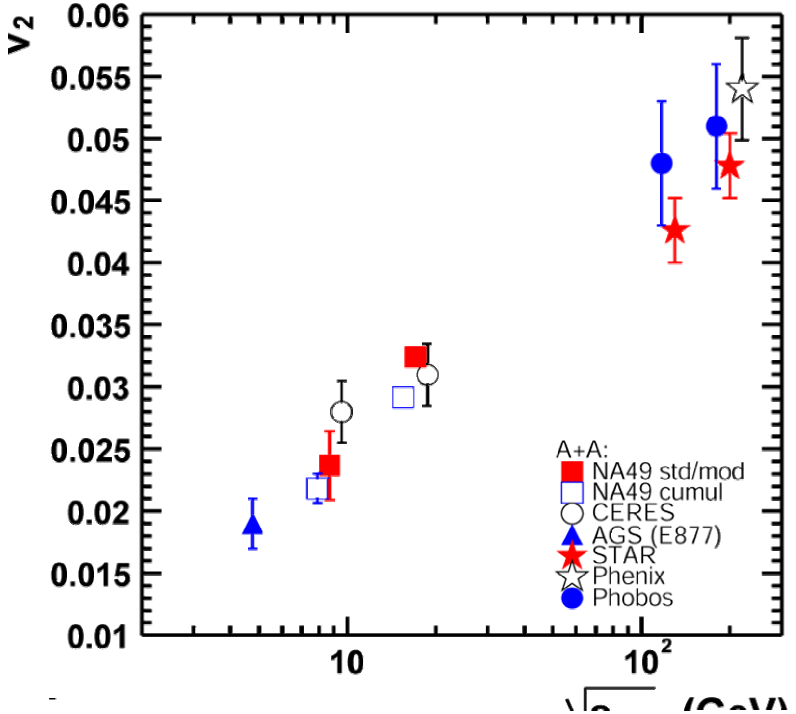


First time in Heavy-Ion Collisions a system created which at low p_t is in quantitative agreement with ideal hydrodynamic model predictions for v_2 up to mid-central collisions

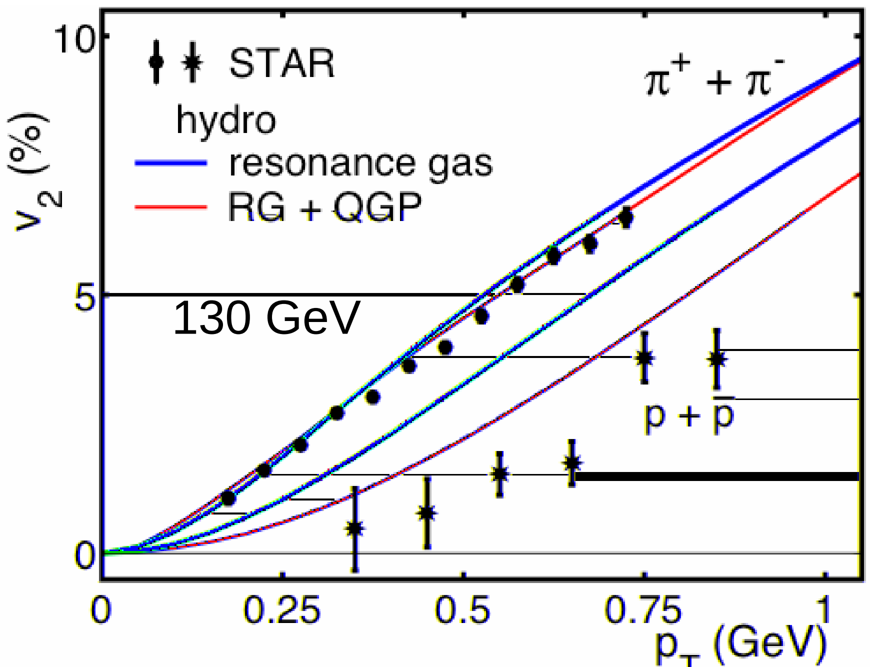
Energy dependence of v_2

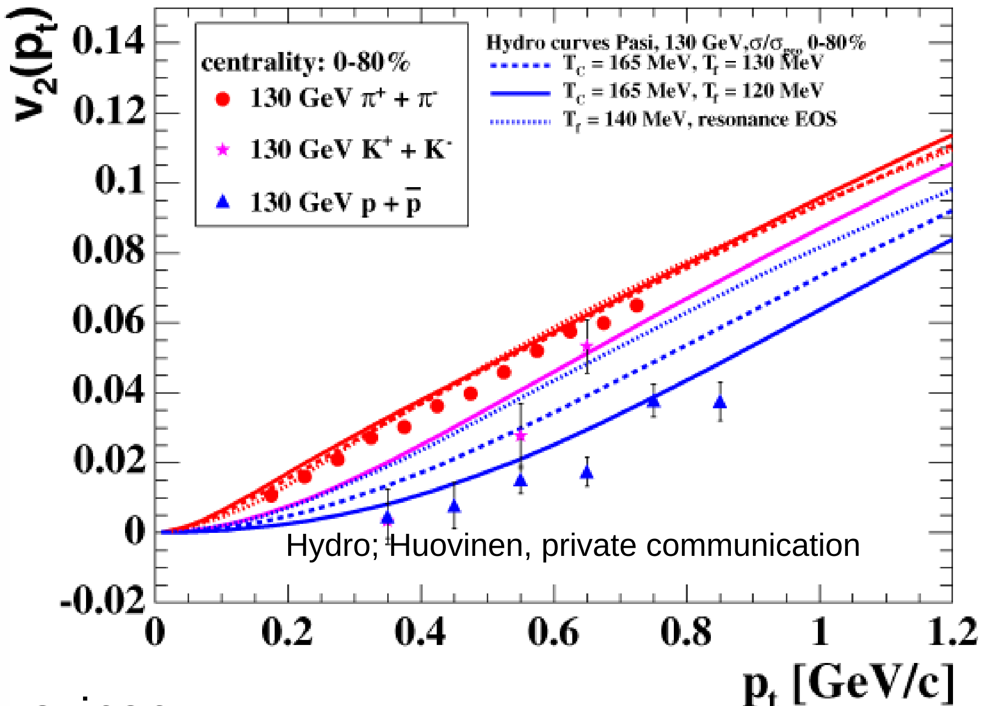


NA49 Phys.Rev. C68 (2003) 034903



$v_2(m,p_t)$

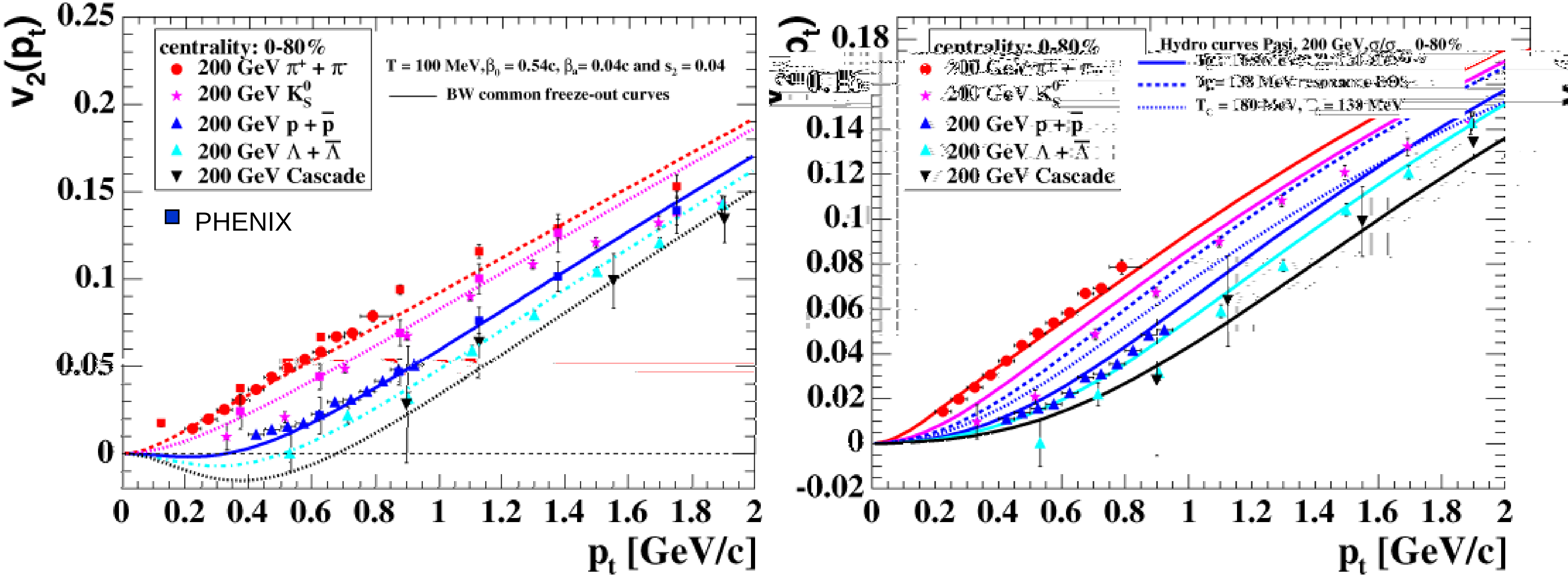




Hydro calculations: Kolb, Heinz and Huovinen

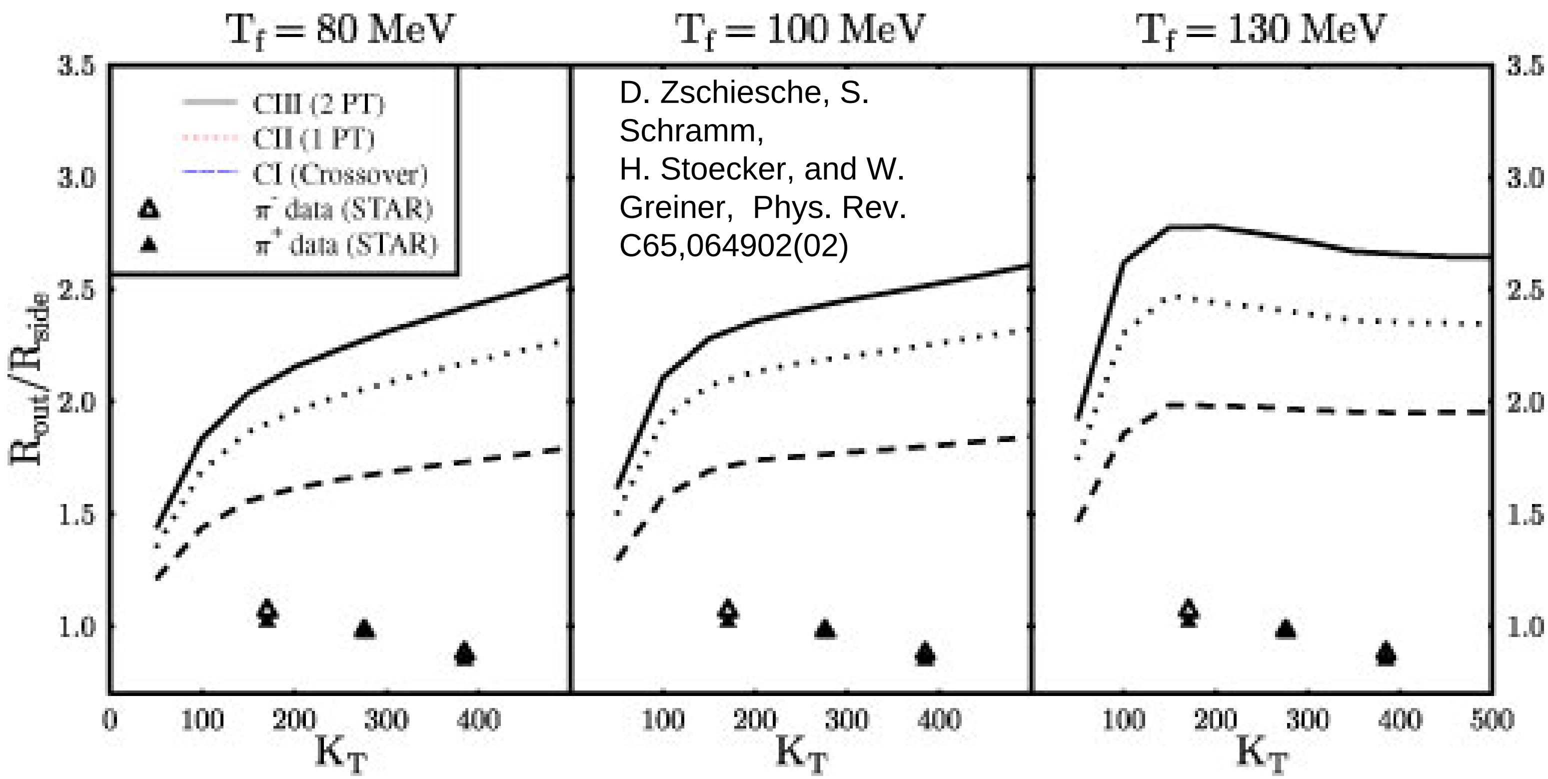
- Clear mass dependence; signature of collective flow (not only in hydro)
- Hydrodynamics gives reasonable description of various mass particles at low transverse momenta
- Hydro calculation constrained by particle spectra

$v_2(m,p_t)$



- Consistent measurements from PHENIX and STAR
- Blast-wave fit as well as full hydro calculation gives reasonable description of mass dependence from pions to cascade

Space-time information



- Dynamical models which describe the relatively well the spectra and elliptic flow give a rather poor description of the HBT "radii"

The first three years of RHIC

- A lot of progress made in the first three years of RHIC running
  - Large volumes of high quality heavy-ion and reference data
  - Consistent results from all RHIC experiments
  - Significant advances in theoretical treatment – many of the striking results have been described and sometimes even predicted to a reasonable quantitative level
- At higher p_t: strong suppression phenomena
  - Confirmation of theory predictions and evidence of high densities
  - How are the uncertainties, of the density for example, amplified by the expansion of the system? Does this observation demand and explanation in terms of traversal through deconfined matter?
- At intermediate p_t: baryon meson scaling in v_2 and R_{cp}
  - Described by coalescence/recombination model – constituent quark collectivity
  - What about predictive power? Centrality dependence of scaling, correlations and dynamical treatment?
- At low-p_t: strong collective behavior, manifest in all observables
  - Collisions at RHIC energies appear to have attained conditions which simplify the theoretical treatment at lower p_t – ideal fluid expansion and approximate local thermalization
  - Unique QGP EOS? How does the HBT “puzzle” fit in?

Questions from RBRC

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

- 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?

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))

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?

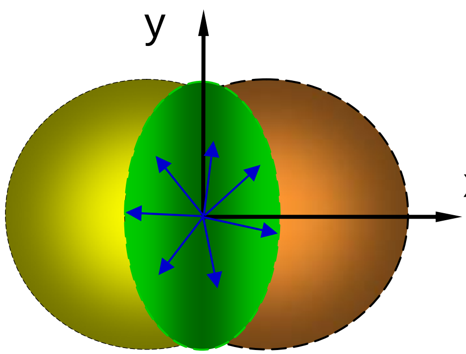
Initial conditions (CGC)

- 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

Critical behavior?

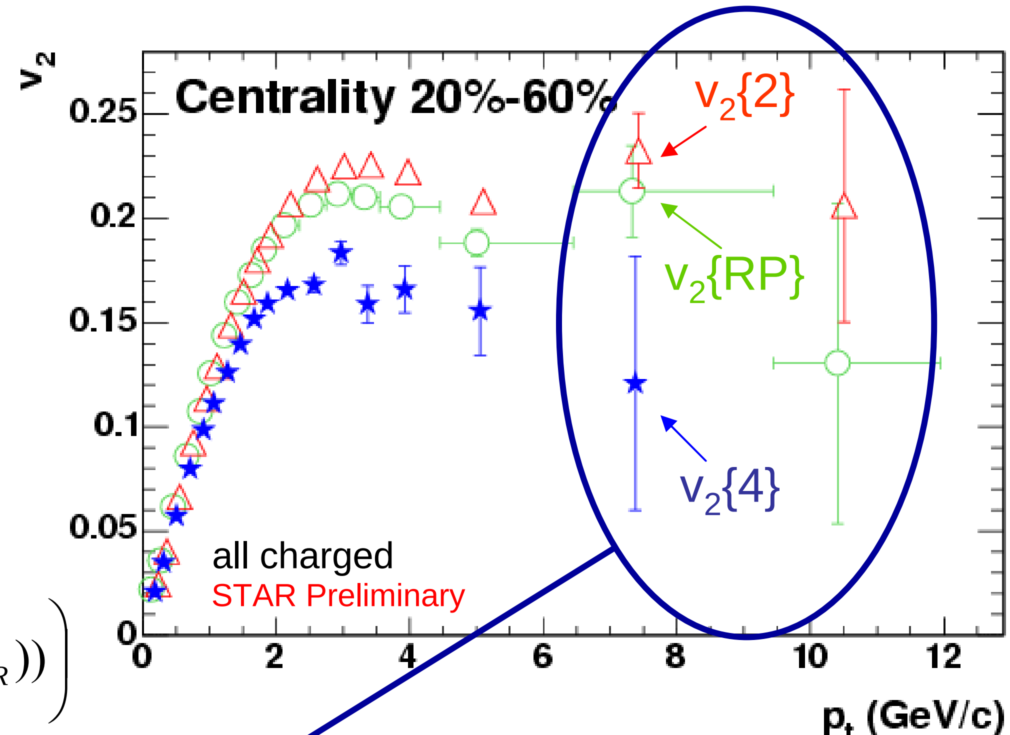
- Is it naïve to expect non-monotonic behavior?
- Can we make a convincing QGP discovery claim without a rapid change in an observable characteristic of a phase transition?
  - Where is the smoking gun?
- Can we predict, based on what we now know from SPS and RHIC, at what energies or under what conditions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

Elliptic Flow



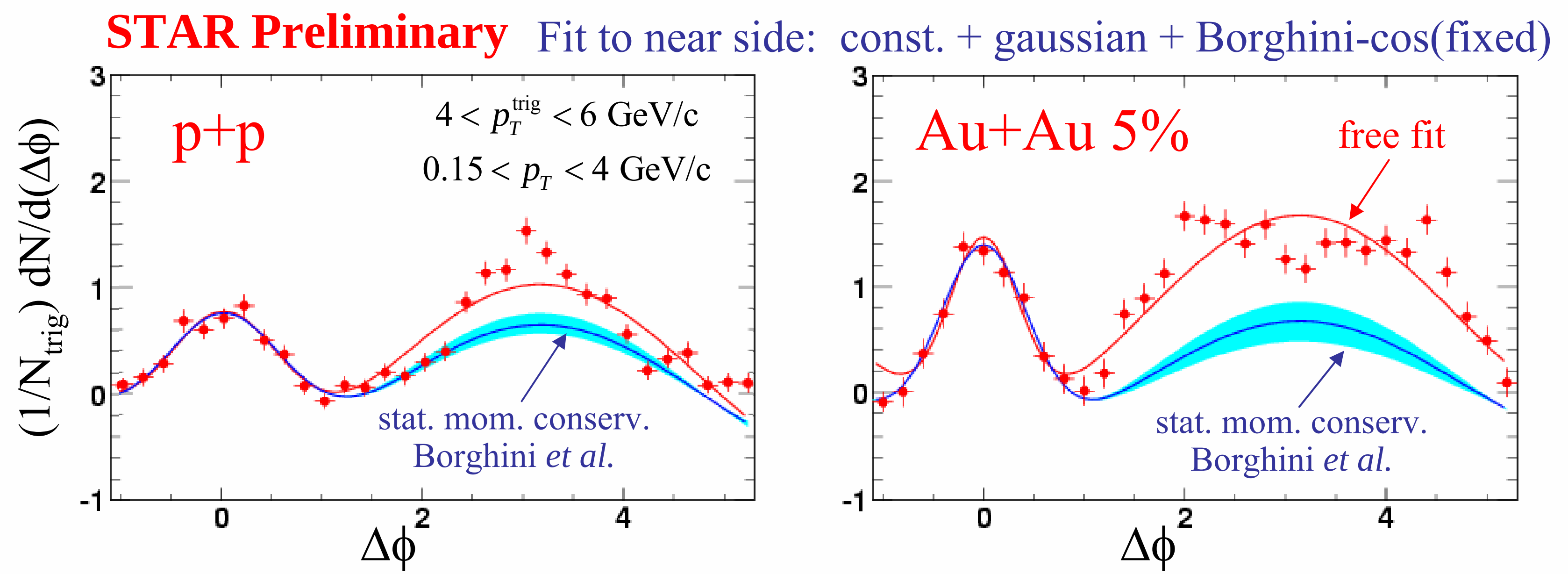
$$\phi = \operatorname{atan} \frac{p_y}{p_x}$$

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t}\left(1+2\sum_n v_n \cos(n(\phi-\Psi_R))\right)$$



Finite (large) v_2 observed up to largest measured p_T, indicates strong absorption by the medium

Low-p_T recoil

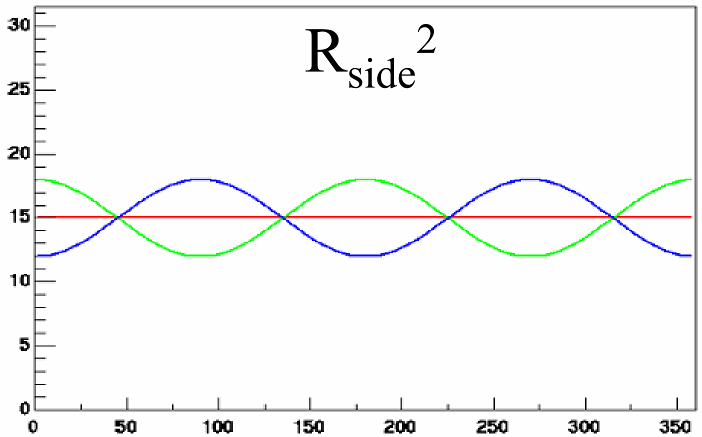


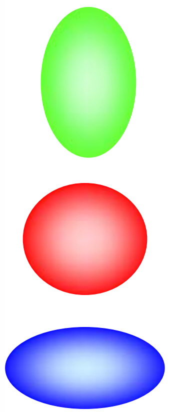
Borghini *et al.* PRC 62, 034902 (2000):

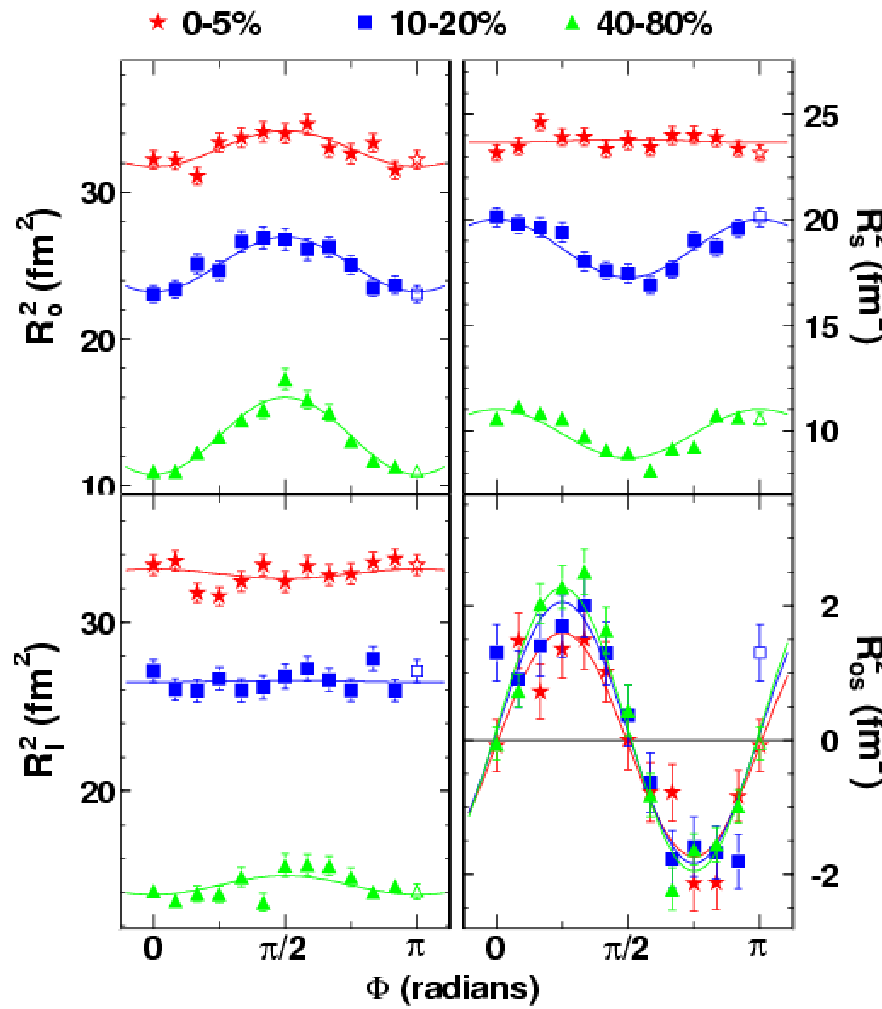
$$\frac{dN}{d(\Delta\varphi)} = -\frac{P_{T,jet}}{\pi}\frac{\sum p_{T,meas}}{\sum p_{T,all}}\cos(\Delta\varphi)$$

Away side close to
'statistical momentum balance'

Space-time information







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