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FORMAL REPORT

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Collective Flow and QGP Properties

November 17-19, 2003

Organizers

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

During the first year, the Center had only a Theory Group. In the second year, an Experimental Group was also established at the Center. At present, there are seven Fellows and seven Research Associates in these two groups. During the third year, we started a new Tenure Track Strong Interaction Theory RHIC Physics Fellow Program, with six positions in the first academic year, 1999-2000. This program had increased to include ten theorists and one experimentalist in academic year, 2001-2002. With recent graduations, the program presently has eight theorists and two experimentalists. Beginning last year a new RIKEN Spin Program (RSP) category was implemented at RBRC, presently comprising four RSP Researchers and five RSP Research Associates. In addition, RBRC has four RBRC Young Researchers.

The Center also has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are fifty-four proceeding volumes available.

The construction of a 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998. A 10 teraflops QCDOC computer in under development and expected to be completed in JFY 2003.

T. D. Lee
November 22, 2002

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

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Collective flow and QGP properties
Summary of the RIKEN BNL workshop

Nu Xu, E. Shuryak, P.F. Kolb, U. Heinz, S. Esumi, and S. Bass

December 15, 2003

The first three years of RHIC physics, with Au+Au collisions induced at 65, 130 and 200 GeV per nucleon pair, produced dramatic results, particularly with respect to collective observables such as transverse flow and anisotropies in transverse momentum spectra. It has become clear that the data show very strong rescattering at very early times of the reaction, strong enough in fact to be described by the hydrodynamic limit. Therefore, with today's experiments, we are able to investigate the equation of state of hot quark gluon matter, discuss its thermodynamic properties and relate them to experimental observables. At this workshop we came together to discuss our latest efforts both in the theoretical description of heavy ion collisions as well as most recent experimental results that ultimately allow us to extract information on the properties of RHIC matter. About 50 participants registered for the workshop, but many more dropped in from the offices at BNL. The workshop lasted for three days, of which each day was assigned a special topic on which the talks focused. On the first day we dealt with the more general question what the strong collective phenomena observed in RHIC collisions tell us about the properties and the dynamics of RHIC matter. The second day covered all different aspects of momentum anisotropies, and interesting new experimental results were presented for the first time. On the third day, we focused on the late fireball dynamics and the breakdown of the assumption of thermalization. New experimental observables were discussed, which will deliver more information of how the expanding fireball breaks up, once the frequent interaction ceases.

Bulk features of RHIC matter and its dynamical description:

Data from RHIC indicate strong collective phenomena, which are particularly apparent in the slopes of the transverse momentum spectra and their azimuthal dependence in non-central collisions. Edward Shuryak discussed how we could understand the liquid-like dynamical behaviour of quark-gluon matter in terms of strong Coulomb-like interactions in the plasma above the critical temperature T_c. As the strong coupling constant runs up to values $\alpha_s \sim 1$, these interactions generate a sequence of quasi-bound states with almost vanishing energy which have large scattering lengths. This shortens the mean-free path in the medium and can lead to very low viscosity. Quantitative estimates on the viscosity coefficient of RHIC matter based on a variety of different scaling assumptions for the scattering cross-sections were presented by Derek Teaney. He also showed first case studies in which viscosity effects are treated dynamically in the hydrodynamic evolution. Further progress in hydrodynamic modeling was presented by Chiho Nonaka, who studied the dynamical consequences of the existence of a chiral critical point in the equation of state. It was shown that for an adiabatic evolution the critical point acts as a focussing point, attracting the system's evolution in the thermodynamic plane spanned by temperature and chemical potential. Hydrodynamic studies also progressed further in the rapidity direction: Tetsufumi Hirano presented comparisons of hydrodynamic calculations with experimental data on elliptic flow at finite rapidity from the PHOBOS collaboration, concluding that at finite rapidity, particle freeze-out might occur at higher temperatures. Recent data on the rapidity dependence of directed flow at SPS and RHIC were discussed from a hydrodynamic viewpoint by Laszlo Csernai, in particular around the midrapidity region, where the existence of a third flow component appears to be well established at SPS energies. The influence of fluctuations in the initial configuration on the dynamical evolution and final state observables was discussed by Frederique Grassi in terms of the NeXSPherIO model.

The microscopic dynamics and its implication for the hydrodynamic treatment of the reaction was addressed by Denes Molnar. Detailed comparisons of microscopic and hydrodynamic calculations with well defined, equivalent initial conditions will allow to tell whether the microscopic scattering is in fact strong enough to reach the hydrodynamic limit. More microscopic studies were presented by Che-Ming Ko, who presented recent results from AMPT, a multi phase transport model. To achieve the large collective effects exhibited in the data, a process of string melting is induced. Although this process softens the equation of state, the parton density increases so strongly that the required scattering rates are achieved. Finally, Steffen Bass addressed the issue of baryon transport from the viewpoint of a parton cascade (VNI/BMS).

Often, the shapes of the particle spectra are characterized in terms of a temperature and a transverse flow velocity at freeze-out. Ulrich Heinz cautioned that the extraction of these parameters is subject to systematic uncertainties resulting from often uncontrolled model assumptions on the shape of the freeze-out surface and the density and velocity profiles. With today's accurate data, these systematic errors might be larger than the statistical errors of the data themselves and can lead to misinterpretation unless the models used in the fit are constrained by physical consistency with a fully dynamical picture. Nevertheless, Wojchiech Broniowski showed that a large number of observables can be described within one small set of parameters. Peter Steinberg summarized the indications for the longitudinal Bjorken flow, and pointed out that there is actually no strong evidence that even a small region around midrapidity would be approximately boost invariant. In contrast, he argued that today's data could also be interpreted in terms of the Landau-scenario. More experimental and theoretical efforts are required to make a case for the often assumed Bjorken scenario.

Momentum anisotropies:

The strong correlations observed in the data can be of global, collective origin (flow) or be in parts due to other sources, such as decays of heavy resonances or jets. Sergei Voloshin stressed the importance to disentangle the different contributions of collectivity in the data. To this cause Jean-Yves Ollitrault presented a new method to analyze momentum anisotropies, particularly the elliptic deformation, with the formalism of 'Yang-Lee zeroes'. N.N. Ajitanand demonstrated the application of the cumulant method to PHENIX data with a particular emphasis on excluding jet-like correlations. The effect of jets and their contribution to the v_2-signal was further investigated by ShinIchi Esumi.

Peter Kolb showed that anisotropies of higher orders (beyond the elliptic deformation) are significant and observable at RHIC and studied the information content that they might bear. First results on v_4, the fourth order harmonic coefficient of the azimuthally sensitive particle spectra have been presented by Art Poskanzer for the first time at this meeting. As it turns out those results show the features expected from the hydrodynamic calculations and are of the predicted magnitude. Aihong Tang presented first results from the STAR collaboration on directed flow, and for the first time delivered the experimental proof that v_2 is in fact positive, i.e. directed into the reaction plane. Other results presented included detailed spectral information, including the anisotropies of Kaons and Lambdas (Paul Sorensen) as well as Omega baryons and Cascades (Kai Schweda). Those anisotropies are large and indicate a common, large flow anisotropy already on the partonic level. Rainer Fries illustrated how those results at intermediate transverse momenta can be interpreted in terms of recombination of partons with a common anisotropic flow modification. Results on v_2 of neutral pions, which is measured up to large transverse momenta and is consistent with the anisotropy of charged pions at small p_T, were presented by Masashi Kaneta. In this talk also first results on photon v_2 were presented, which again turn out to be of similar magnitude than the anisotropies of hadrons, showing no sign of direct photons. Shingo Sakai presented recent results on deuteron elliptic flow, which again is consistent with expectations from flow, nucleon coalescence and quark coalescence. Also first results on electron anisotropies have been presented. Steve Manly presented PHOBOS results on the rapidity dependence of anisotropic flow, pointing out the rapid decrease of the anisotropy at forward and backward rapidities. In a theoretical study, Pasi Huovinen analyzed the influence of the freeze-out criterion on the elliptic anisotropy, in particular on the mass splitting effect in the momentum dependence of elliptic flow. First improvements to the traditional Cooper Frye description of freeze-out of particles on a constant temperature surface lead to a reduction of the resulting mass splitting. A more realistic treatment of freeze-out might therefore require still stronger pressure gradients than applied in traditional hydrodynamic calculations.

Information from the final stages:

The reasons for the hydrodynamic success in the description of momentum observables but failure in the geometric observables (HBT) start to become more apparent and were summarized by Scott Pratt. In particular modifications of the dynamics, such as a relaxation of the assumption of boost invariance and inclusion of non-ideal effects would improve the agreement with data. Zi-Wei Lin pointed out that large positive x-t correlations reduce the $R_{\text{out}}/R_{\text{side}}$ ratio, and that it is important to compare the correlation functions of theoretical calculations and experimental results, rather than parameters extracted from Gaussian fits or geometric sizes of the emission regions. Pure blast wave fits, as illustrated by Boris Tomasik, lead to parameters that cannot be easily interpreted intuitively and seem to be inconsistent with the model assumptions of a thermalized fluid on which the fits are based.

Members of the STAR collaboration reported progress in experimental techniques. Fabrice Retière presented the latest analysis of correlations in non-identical particle pairs, which allows to probe the asymmetry of particle emission resulting from their different masses. The interpretation of the data is in agreement with hydrodynamic expectations that, due to the radially increasing flow profile, lighter particles are emitted from regions further outside of the fireball than heavier particles with the same velocity. Non-central collisions also allow for an HBT analysis with sensitivity to the reaction plane. As discussed by Dan Magestro, the data clearly show that the source shape at freeze out is less deformed than the shape of the initial geometry, but also that at freeze-out the source is still elongated in the direction perpendicular to the reaction plane. The time required for changing the initial deformation to the final one is at least 9 fm/c. From the final state multiplicity Subrata Pal inferred the entropy in the final state and employing the principle of entropy conservation, gave limits for the entropy per unit rapidity in the initial state. The resulting value is in agreement with expectations from lattice QCD, but can hardly be reached in a pure hadronic gas.

Summary:

There were very many lively discussions throughout the workshop which will certainly continue long after the workshop formally ended. The transparencies of all the talks are posted on the web-page of the meeting at *http://tonic.physics.sunysb.edu/flow03*

Acknowledgments:

We would like to thank RBRC and BNL for financial support, and Pamela Esposito for her professional engagement which lead to the success of this workshop.

Hydrodynamics, freeze-out, and blast wave fits to flow spectra

Ulrich Heinz

Physics Department, The Ohio State University, Columbus, OH 43210

Hydrodynamics is the natural language to study collective flow in relativistic heavy-ion collisions. It allows to relate observed flow phenomena to the equation of state of the expanding matter. Hydrodynamics itself does not describe the transition to free-streaming particles at the end of the evolution. It must therefore be supplemented by a kinetic freeze-out criterium. At SPS and RHIC energies, freeze-out occurs dynamically and is controlled by a competition of the local scattering rate with the expansion rate. I show estimates for these expansion rates at SPS and RHIC and comment on the implications for the centrality dependence of freeze-out parameters.

The calculation of hadron momentum spectra from hydrodynamic output proceeds via the Cooper-Frye prescription. I show and discuss the corresponding analytical formula for the spectra for the case of longitudinal bost-invariance. I also show how to calculate elliptic flow from the Cooper-Frye formula. I discuss the effect of radial flow on the spectra and argue that characterizing flow spectra by a single slope is dangerous and can be misleading. As point in case I discuss the shape of the spectra of Ω baryons at SPS and RHIC. I then discuss the application of the Cooper-Frye formula in so-called blast wave model fits to experimental spectra. I show that such fits have systematic uncertainties resulting from details of the model assumptions. Aspects which matter are the radial velocity distribution in the fireball at freeze-out, the shape of the freeze-out hypersurface, the effects from resonance decays, and non-equilibrium chemical potentials at temperatures below the chemical freeze-out point. Each of these aspects is discussed in some detail. I show that for meaningful blast wave fits it is important to implement as much reasonable physics into the blast wave model as possible. I demonstrate that neglecting resonance decays biases the fit towards lower freeze-out temperatures and larger flow while putting the wrong shape for the freeze-out surface can bias the fits towards higher freeze-out temperatures with less flow.

I emphasize some of the dynamical consistency relations between freeze-out parameters that result from full hydrodynamical calculations. I show that such calculations give an excellent description of all hadron spectra at RHIC.

Cooper – Frye algorithm:

Boltzmann approximation: keep only $n=1$ term:
(⟶ good for all hadrons except pions!)

$$\frac{dN}{dy\, m_\perp dm_\perp} = \frac{g}{\pi^2}\int_0^\infty r\,dr\, \underset{\sim}{n(r)} \left[m_\perp K_1\!\left(\frac{m_\perp \operatorname{ch}\rho}{T}\right) I_0\!\left(\frac{p_\perp \operatorname{sh}\rho}{T}\right) - p_\perp \frac{\partial \tau_f}{\partial r} K_0\!\left(\frac{m_\perp \operatorname{ch}\rho}{T}\right) I_1\!\left(\frac{p_\perp \operatorname{sh}\rho}{T}\right)\right]$$

↑ radial density profile

(Schnedermann, Sollfrank, Heinz, PRC 48 (93) 2462)

(independent of y ⟷ boost invariance)

Looks ≈ exponential in $m_\perp$ with inverse slope T_{slope}:

$$\frac{dN}{m_\perp dm_\perp} \sim e^{-m_\perp / T_{slope}(m_\perp)}$$ ⟵ ! not really exponential!

Two important limits:

- Nonrelativistic, $p_\perp \ll m_0$: $T_{slope} \approx T_f + \frac{1}{2} m_0 \langle v_\perp \rangle^2$ (exact for Gaussian $n(r)$ + linear $v_\perp(r)$)
- Relativistic, $p_\perp > m_0$: $T_{slope} \approx T_f \sqrt{\frac{1+\langle v_\perp\rangle}{1-\langle v_\perp\rangle}}$ "blueshift"

Strong Collective Expansion – "The Little Bang"

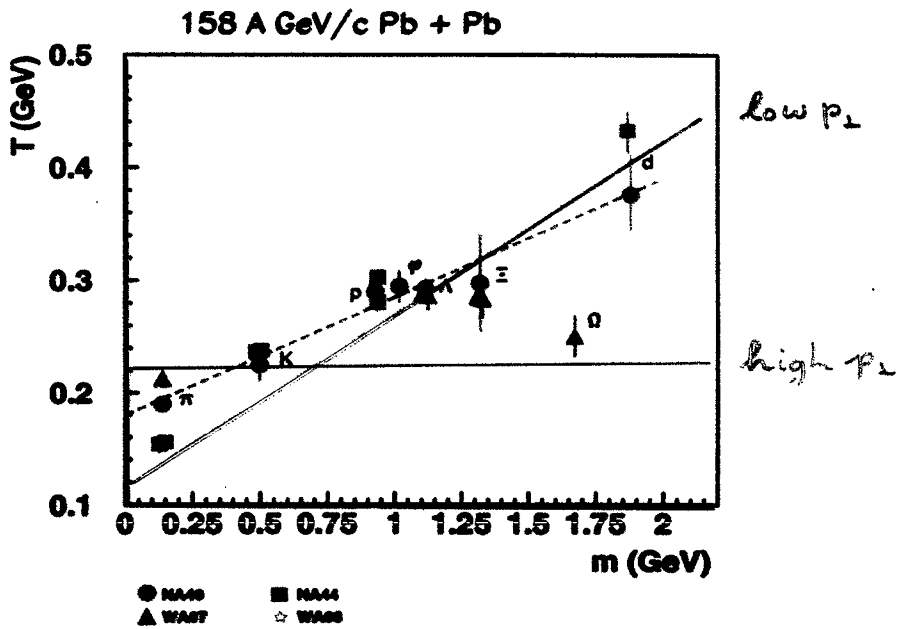
$T_f = 120$ MeV

$\langle v_\perp \rangle = 0.55c$

— $T_{eff} = T_f \sqrt{\frac{1+\langle v_\perp \rangle}{1-\langle v_\perp \rangle}}$

— $T_{eff} = T_f + \frac{1}{2} m \langle v_\perp \rangle^2$

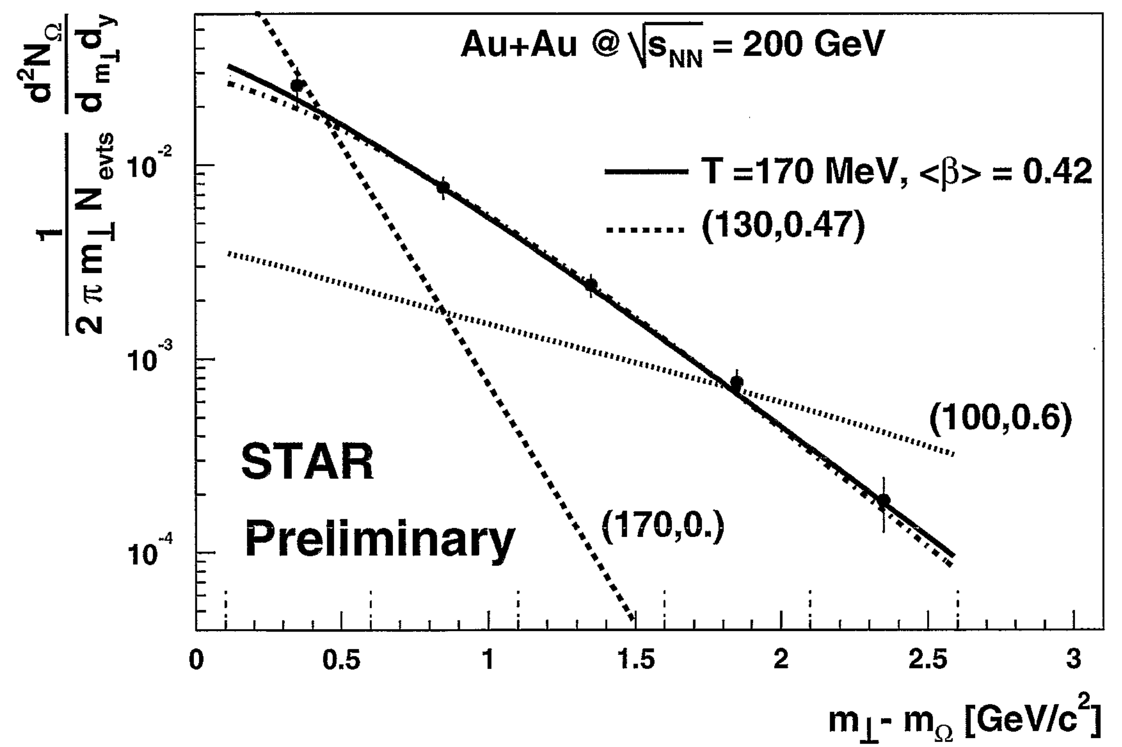
mass dependence of inverse slopes



Simultaneous analysis of slope of this plot and two-particle correlations yields expansion velocity $\langle v_\perp \rangle \approx 0.55\,c$ at hadronic decoupling.

Blast wave fits to Omega spectra:

Au+Au @ $\sqrt{s} = 200\,A$ GeV [C. Suire (STAR), NPA 715 (2003) 470c]:



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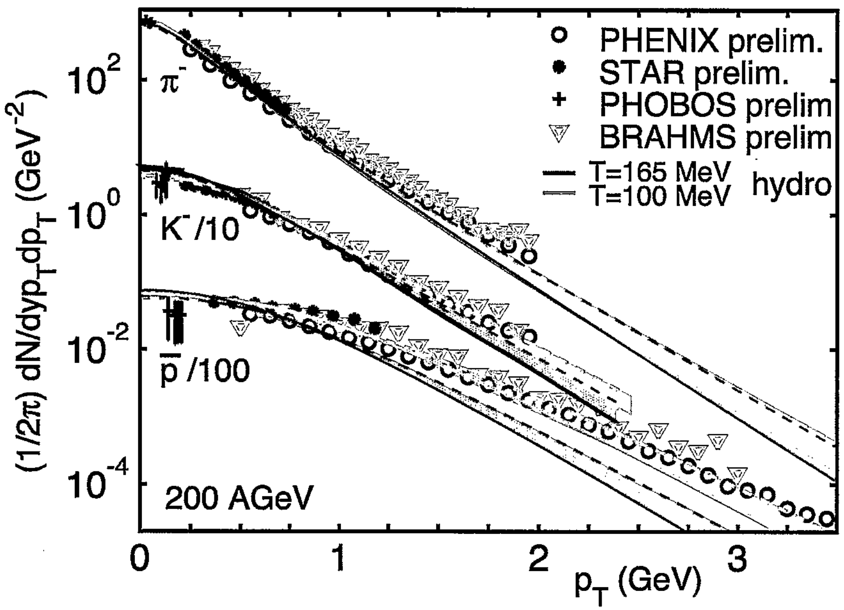
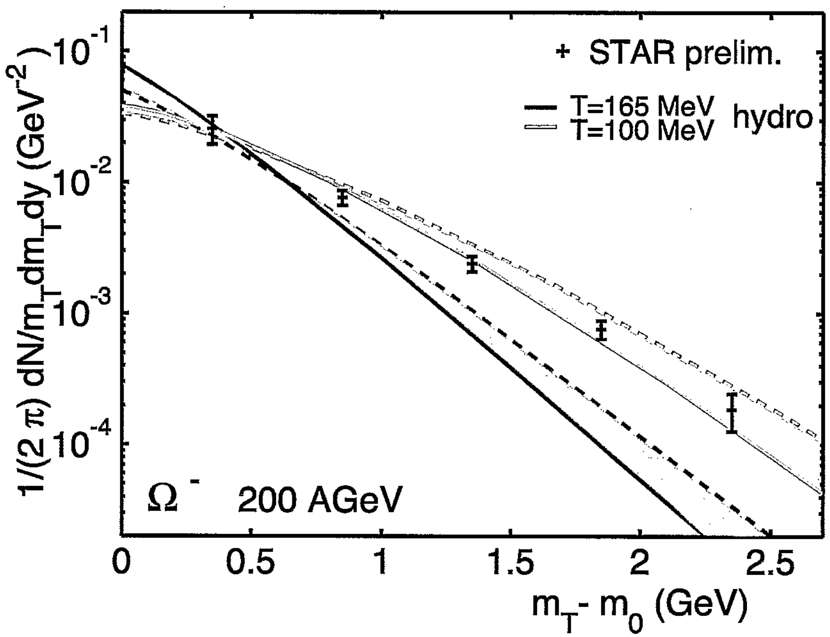
200 A GeV Au+Au spectra and hydrodynamics (I)

hydro: Kolb & Rapp, PRC 67 (2003) 044903



C. Suire (STAR), NPA 715 (2003) 470c



Hydro parameters: $\tau_{\rm eq} = 0.6\,{\rm fm}/c$, $s_0 \equiv s_{\rm max}(b{=}0) = 110\,{\rm fm}^{-3}$, $s_0/n_0 = 250$

$T_{\rm chem} = T_{\rm crit} = 165\,{\rm MeV}$, $T_{\rm dec} = 100\,{\rm MeV}$

Note:
- Hydro does not create enough radial flow already at T_c to describe baryon spectra
- Multistrange baryons seem to fully participate in continued radial flow build-up during late hadronic phase!

Conclusions:

- Blast wave fits have not only statistical, but also systematic errors, due to assumptions on the details of the blast wave model. Good data quality implies that these days the systematic uncertainties dominate!
- Blast wave fits must include resonance feeddown contributions in a selfconsistent way, taking into account non-equilibrium chemical potentials at $T < T_{\rm chem}$.
  Neglecting decay pions biases the fits towards lower temperatures.
- Blast wave fits must take into account the shape of the freeze-out surface.
  Assuming freeze-out at constant proper time $\tau = \sqrt{t^2 - z^2 - r_\perp^2}$ biases the fits towards larger temperatures and less flow.
- Blast wave fits should explore the sensitivity to the flow-velocity distribution $dN/dv_\perp$ and include this in the systematic error.
- Blast wave fits are not the end, but the beginning of a dynamical understanding. They are only meaningful if the fit parameters are dynamically consistent. If they aren't, the fits should not be overinterpreted, but taken as an indication that more thought is needed.

Viscosity In Heavy Ion Collisions

Derek Teaney

November 24, 2003

- The first slide estimates the domain of applicability of hydrodynmaics. Here, I define the *Sound Attenuation Length*, $\Gamma_s \equiv \eta/(e+p)$. Γ_s should be small compared to the smallest typical inverse gradient in the system. For a Bjorken expansion this is simply the Bjorken time $\tau = \sqrt{t^2 - z^2}$. Γ_s is of order of the transport mean free path.

- The next slide garners estimates of the viscosity from the litterature. The perturbative estimate of the viscosity is approximately four times larger than an estimate based upon strongly coupled $N = 4$ Supersymmetric Yang Mills [1]. The $N = 4$ result is in turn is approximately four times larger than the viscosity which is needed by to reproduce the observed elliptic elliptic flow with a classical Boltzmann equation [2] .

- The next two slides estimate how Γ_s/τ evolves as a function of time.

- Finally based upon the arguements given in [3], I estimate that the thermal spectrum can not extend further than $p_T \approx 1.8\, GeV$. The experimental spectrum shows a strong power law beyond this value of transverse momentum.

References

[1] G. Policastro, D. T. Son, A. 0. Starinets, Phys. Rev. Lett. **87**, 081601 (2001) ; JHEP **0209**, 043 (2002);

[2] D. Molnar and M. Gyulassy, Nucl. Phys. A **697**, 495 (2002).

[3] D. Teaney, Phys. Rev. C **68**, 034913 (2003).

How valid is Hydro? How much Entropy is produced?

$$\frac{d(\tau s)}{d\tau} = 0 \qquad \text{(Ideal Case)}$$
$$\frac{d(\tau s)}{d\tau} = \frac{\frac{4}{3}\eta+\sigma}{\tau T} \qquad \text{(Viscous Case)}$$

For hydrodynamics to be valid, the entropy produced over the time scale of the system, τ , must be small compared to the total :

$$\tau \, \frac{\frac{4}{3}\eta + \sigma}{\tau T} \, \frac{1}{\tau s} \equiv \Gamma_s \frac{1}{\tau} \ll 1$$

where $\Gamma_s \equiv \frac{\frac{4}{3}\eta+\sigma}{e+p}$ is the *Sound Attenuation Length*. Note $(sT = e + p)$.

Estimates of Shear Viscosity:

$$\underbrace{T^{00} + T^{zz}}_{\text{indep. of Bag Const.}} = (e+p) + \eta \left\langle \partial^z v^z \right\rangle$$

$$\sim (e+p) \left[1 + \underbrace{\ell_{m.f.p.}}_{1/(n\sigma_0)} \left\langle \partial^z v^z \right\rangle \right]$$

Using $e + p \sim nT$, then find:

$$\Gamma_s \sim \ell_{m.f.p.} \quad \text{and} \quad \eta \sim (d.of.)\frac{T}{\sigma_0} \quad \text{and} \quad \frac{\Gamma_s}{\tau} \sim \frac{\ell_{m.f.p.}}{\tau} \ll 1$$

Estimates of η for the QGP and Heavy Ion Collisions

Perturbative QCD – Arnold, Moore, Yaffe.

- $\eta \approx 86\ T^3 \frac{1}{g^4 \log(1/g)}$. Based upon kinetic theory of quarks and gluons.
  Estimate: (d.o.f) $= 36$ and $\sigma_0 \sim \frac{g^4}{T^2} 4$ then $\eta \sim 36\, \frac{T^3}{g^4}$.
  Set $\alpha_s \to 1/2$ and $\log(1/g) \to 1$

$$\left(\frac{\Gamma_s}{\tau}\right) \approx 0.18 \frac{1}{\tau T} \tag{1}$$

- Leading order. $\eta \approx 150\, T^3 \frac{1}{g^4}$ then

$$\left(\frac{\Gamma_s}{\tau}\right) \approx 0.4 \frac{1}{\tau T}$$

Strongly Coupled conformal N=4 SYM – Son, Starinets, Policastro

- No kinetic theory exists. Like most real liquids.

$$\left(\frac{\Gamma_s}{\tau}\right) = \frac{1}{3\pi} \frac{1}{\tau T} \approx 0.11 \frac{1}{\tau T} \tag{2}$$

Phenomenology – Molnar

Found could fit elliptic flow $v_2(p_T)$ only when

- $\frac{dN}{d\eta} = 1000$, $\sigma_0 = 10 \div 20$, and $\tau_o = 0.1$ fm.

$$\Gamma_s = 0.421 \frac{1}{n\sigma_0} \qquad \left(\frac{\Gamma_s}{\tau}\right) = 0.02 \div 0.04 \tag{3}$$

- Constant cross section. Independent of time!

Thermalization: How does Γ_s/τ evolve?

1. Bjorken Expansion | Scale Invariant Cross Section: $\sigma \sim \frac{\alpha_s^2}{T^2}$

- When Entropy is conserved: $T \sim \frac{1}{\tau^{1/3}}$

$$\frac{\Gamma_s}{\tau} \sim \frac{\#}{\tau T} \sim \# \frac{1}{\tau^{2/3}}$$

- When $\frac{dE}{dy}$ is conserved (entropy is produced): $T \sim \frac{1}{\tau^{1/4}}$

$$\frac{\Gamma_s}{\tau} \sim \frac{\#}{\tau T} \sim \# \frac{1}{\tau^{3/4}}$$

$\Longrightarrow$ rapid to rapid++ thermalization

2. Bjorken Expansion | Constant Cross Section: $\sigma = \sigma_0$

- When Entropy is Conserved: $\tau n \sim$ Const

$$\frac{\Gamma_s}{\tau} \sim \frac{\ell_{m.f.p.}}{\tau} \sim \frac{1}{\tau n \sigma_0} \sim \text{Const}$$

- When $\frac{dE}{dy}$ is conserved (entropy is produced): $\tau n \sim \tau^{1/4}$

$$\frac{\Gamma_s}{\tau} \sim \frac{\ell_{m.f.p.}}{\tau} \sim \frac{1}{\tau n \sigma_0} \sim \frac{1}{\tau^{1/4}}$$

$\Longrightarrow$ Constant to slow thermalization

Spherical Expansion | Scale Invariant Cross Section: $\sigma \sim \frac{\alpha_s^2}{T^2}$

- Entropy conservation: $(sV) \sim$ Const and $s \sim T^3$. Then $T \sim \frac{1}{\tau}$.

$$\frac{\Gamma_s}{\tau} \sim \frac{\#}{\tau T} \sim \text{Const}$$

- Energy conservation: $(eV) \sim$ Const and $e \sim T^4$ $T \sim \frac{1}{\tau^{3/4}}$

$\Longrightarrow$ Constant to slow thermalization

Spherical Expansion | Constant Cross Section: σ_0

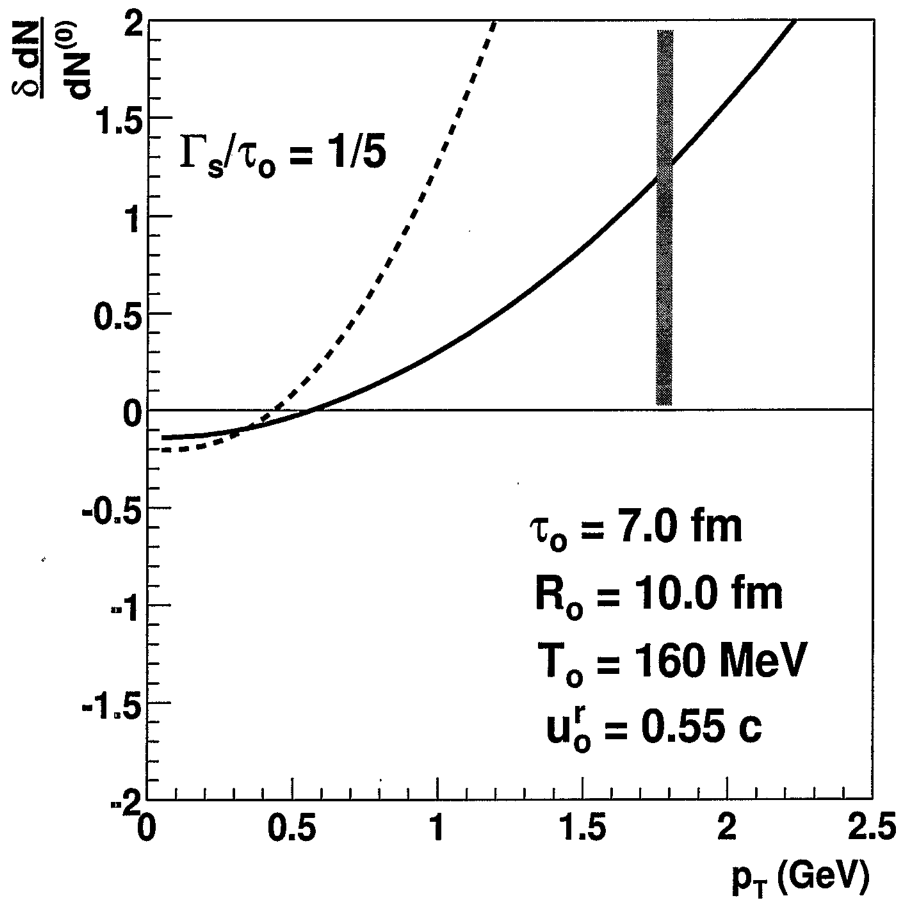
- Entropy Conservation: $(nV) \sim$ Const. $n \sim \frac{1}{\tau^3}$

$$\frac{\Gamma_s}{\tau} \sim \frac{\ell_{m.f.p.}}{\tau} \sim \frac{1}{\tau\, n\sigma_0} \sim \frac{\tau^2}{\sigma_0}$$

- Energy Conservation: $(eV) \sim$ Const. and $n \sim T^3 \sim 1\tau^{9/4}$

$$\frac{\Gamma_s}{\tau} \sim \frac{\ell_{m.f.p.}}{\tau} \sim \frac{1}{\tau\, n\sigma_0} \sim \frac{\tau^{5/4}}{\sigma_0}$$

$\Longrightarrow$ rapid++ to rapid breakup.



$$\frac{\delta dN}{dN^{(0)}} \equiv \frac{\frac{dN^{(1)}}{p_T\, dp_T\, dy}}{\frac{dN^{(0)}}{p_T\, dp_T\, dy}}$$

The maximum possible p_T accessible to Hydrodynamics is ~ 1.8 GeV – A couple of times T_{eff} .

Why the Quark-Gluon Plasma is so perfect liquid?

Edward Shuryak, Stony Brook

The hydrodynamics works very well, quantitatively describing for various secondaries: • The radial flow, • elliptic flow, v_2, v_4 ...

- Huge predictive power. If $l_{m.f.p.} << L$ it is the theory not the model
- The extracted EoS agrees well with the expected EoS from the theory/lattice
- However transport properties such as viscousity, mean free path are strongly overestimated by pQCD: they are surprisingly small: Why?
- Rethinking the QGP at $T = (1-3)T_c$: large cross sections at the zero-binding lines (ES+I.Zahed-03)
- New amasing connections to trapped ultracold (Li) atoms
- A strongly coupled plasma: the AdS/CFT duality =>

at the supercritical coupling $g^2 N_c >> 1$ it is the most perfect fluid known. New light bound states discovered in this problem as well (ES+I.Zahed-03b)

Why some hadrons may survive above T_c?

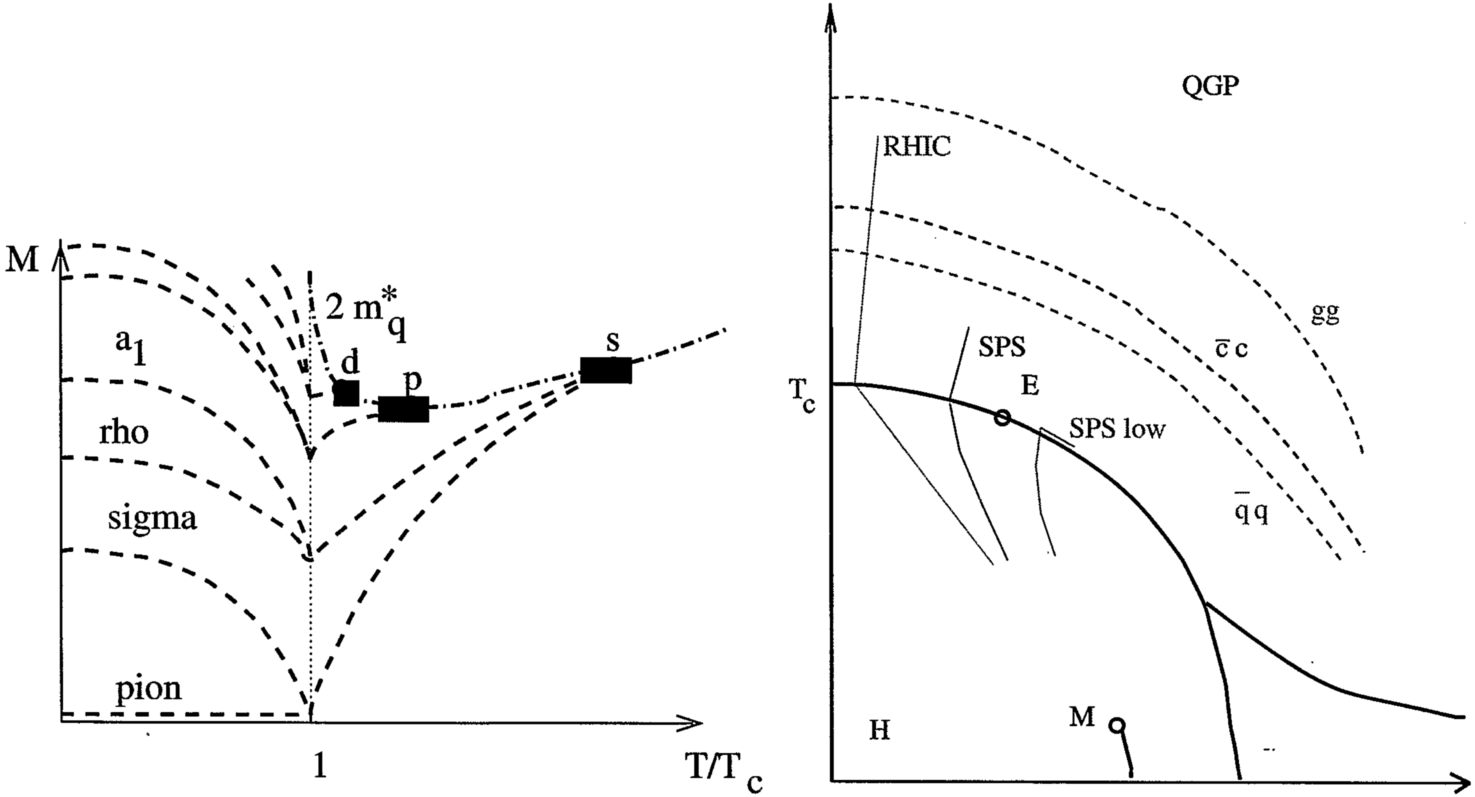
ES and I.Zahed,hep-ph/0307267

- **The loophole in the old argument: α_s kept frozen in the QGP as in-vacuum, at $\alpha_s \sim 1/3$.)**
- **New idea: at $T > T_c$ the charge continues to run to larger values, stopped by the Debye screening only. $\alpha_s \sim 1$ is reached**

G.Brown,C.H.Lee, M.Rho and ES, in progress $\bar{q}q$ bound states for $T_c < T < T_{zerobinding}$: relativistic effects $(1 - \vec{v}_1\vec{v}_2)+$ spin-spin, plus the nonperturbative forces due to instanton-antiinstanton molecules provide massless σ, π at $T => T_c$

- **The main idea: large (unitarity limited) cross sections at the endlines => "sticky molasses"**

ES and I.Zahed,hep-ph/0307267

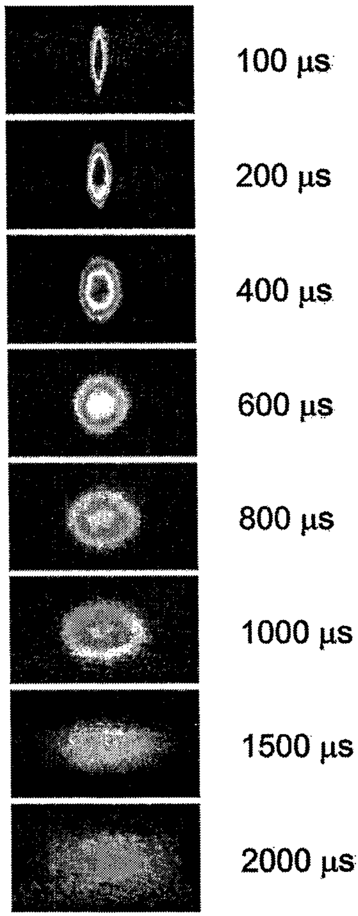


A general view of the endlines for $\bar{q}q$ and also colored composites like qg, gg. Another famous colored dimer is the qq, the Cooper pair of color superconductivity

Elliptic flow with trapped Li^6 atoms:

K.M.O'Hara et al, Science 298,2179, 2002

T.Bourdel et al, PRL 91 020402 , July 11 2003



Magnetic field $B \sim 800G$ shifts (via the Feschbach resonance $|f = 1/2, m_f = 1/2 >\!<=>\! |f = 1/2, m_f = -1/2>$) and makes the 38-th vibrational Li_2 state to exactly zero energy => infinite scattering length a, very large size and lifetime ~ 1 sec.

Normally gas is transparent, $l \ll L$, and expands without collisions isotropically

But in the strong coupling regime $l \ll L$ it explodes hydrodynamically !, see the figure

Cross section can be changed by many orders of magnitude, but the EoS changes by $\sim 20\%$ only ! (like in QGP and CFT... why?)

The theory of viscosity

• Developed for long time in the weak coupling perturbative framework large, $\eta/T^3 \sim const/g^4 log(1/g) >>> 1, const \sim 100$ at small $g <<$ 1

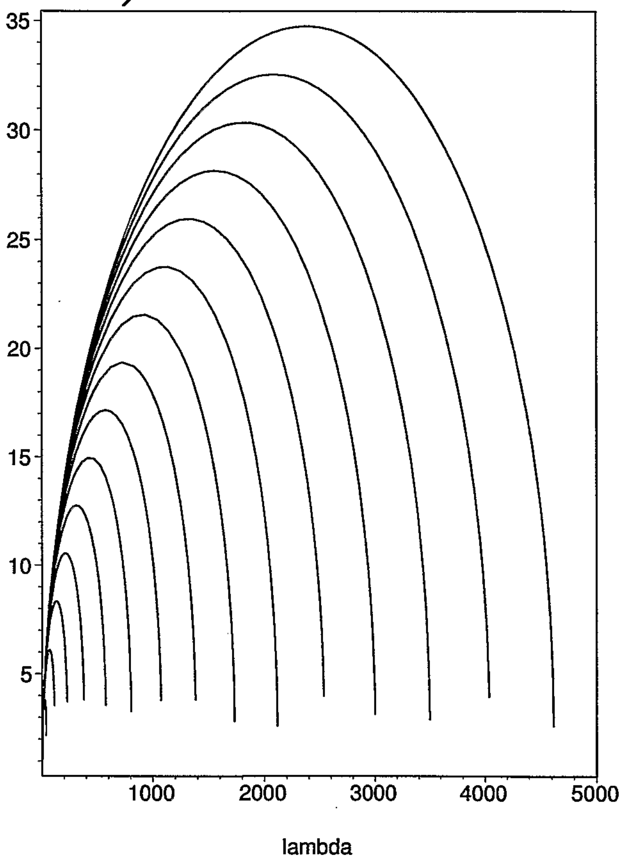
If so, $l \sim few\, fm$ and no hydro at RHIC ! (Recall the Gyulassy-Molnar plot here)

• However, in the strong coupling ($\mathcal{N}$ = 4 supersymmetric Yang-Mills or CFT) Polycastro, Son, Starinets, Phys. Rev. Lett. **87** (2001) 081601 (not in QCD!) their value for the sound attenuation length $T\Gamma_s = \frac{4}{3}\frac{\eta}{s} = \frac{1}{3\pi}$. If used for RHIC QGP $\Gamma_s \sim .1\, fm$ If so, excellent hydro, but no parton cascades...

Son and Starinets (03) found several gravity backgrounds in which similar calculation is possible and found the same $\frac{\eta}{s} = \frac{1}{4\pi}$ which is conjectured to be the universal lower bound for the most perfect liquid. The best known liquid, He^4 at high pressure, has $\frac{\eta}{s \sim 1}$, water at notmal conditions about 40.

• The main idea: the modified Coulomb law can be used even for relativistic bound states, with $v \sim 1$.

• Using a Klein-Gordon eqn $(E-V)^2 - m^2 = p^2, V = -C/r$ with a Coulomb potential, by WKB or exactly, one can find the spectrum. (Known from about 1930).



$$V = -\frac{C}{r}$$
$$E_{nl} =$$
$$m\left[1+\left(\frac{C}{n+1/2+\sqrt{(l+1/2)^2-C^2}}\right)^2\right]^{-1/2}$$

C - nonrelat. atoms, Balmer series... New regime at large $C >> 1$: families of relativistic deeply bound states, with large orbital momentum balancing the supercritical Coulomb

What the parton cascade tells us about RHIC

Dénes Molnár, The Ohio State University, Columbus, OH, USA

- What we learned:
  - large v_2 at RHIC indicates at least pQCD opacities (and possibly much larger)
  - absolutely amazing why hydro works - **even 45mb is not enough**
  - hydro and transport v_2 seem robust against initial τ_0 (much less so for spectra)

- Open issues (my incomplete list):
  - map out initial conditions - e.g., formation time?, initial condition models?
  - better understanding of microscopic dynamics
    develop and test various dynamical models/limits, make codes available (OSCAR)
    3+1D inelastic transport, viscous hydro, 3+1D ideal hydro, 3+1D Yang-Mills, strongly coupled, highly-correlated systems, ...
  - refine/further test hadronization models - e.g., parton coalescence
  - several puzzles still: $\frac{dE_T}{dN}(b) = const$; v_2 vs quenching, HBT, high-p_T correlations

Covariant parton transport theory

Pang, Zhang, Gyulassy, D.M., Vance, Csizmadia, Pratt, Cheng, ...

Simplest Lorentz-covariant nonequilibrium dynamical framework

- **dynamics governed by the mean free path:** $\lambda(s,x) = 1/\sigma(s)n(x)$
  - **interpolates between ideal hydro** $\lambda = 0$ **and free streaming** $\lambda = \infty$
- **natural decoupling,** $\lambda(t \to \infty) \to \infty \quad \leftrightarrow$ **no need for sudden Cooper-Frye**

20

Nonlinear 6+1D transport equation:

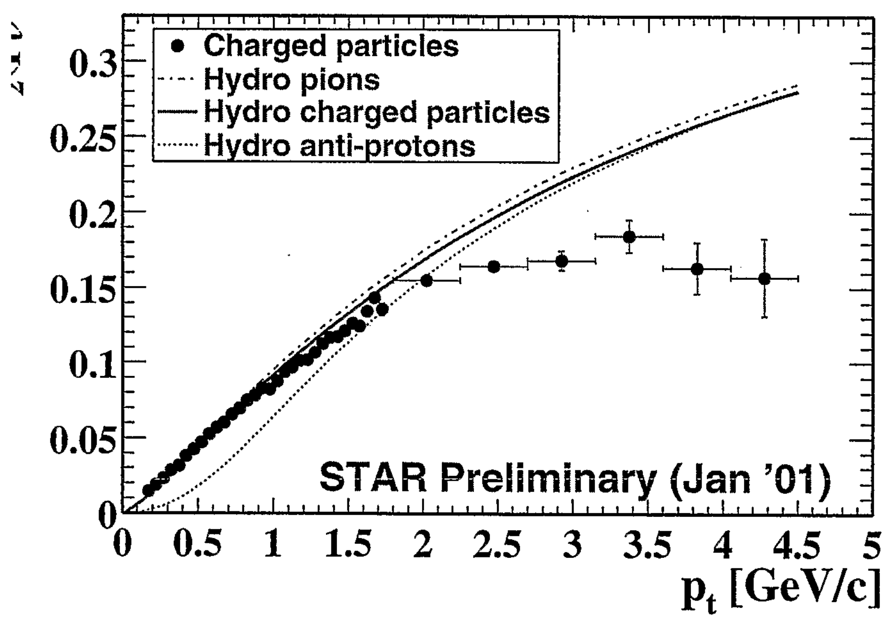
$$p^\mu \partial_\mu f_i(x,\vec{p}) = \overbrace{S_i(x,\vec{p})}^{\text{source}} + \overbrace{C_i^{el.}[f](x,\vec{p})}^{2\to 2\ (\text{ZPC, GCP}, \ldots)} + \overbrace{C_i^{inel.}[f](x,\vec{p})}^{2 \leftrightarrow 3\ (\text{MPC})} + \ldots$$

solvable numerically $\to$ **only a few covariant algorithms: ZPC, MPC, Bjorken-**τ**, ...**

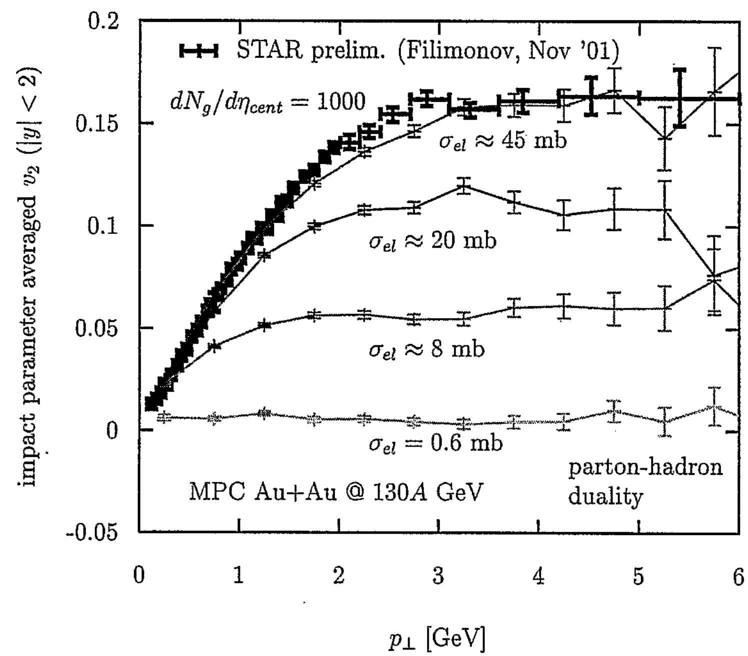
Real dynamical parameter: transport opacity [see NPA 697, 495 ('02)]

$$\chi \equiv \langle n_{coll} \rangle \sigma_{tr}/\sigma_{el} \quad \propto \quad \sigma_{tr} \times dN/d\eta$$

ideal hydro (Kolb, Heinz, Snellings) **transport** (D.M. & Gyulassy)



? =

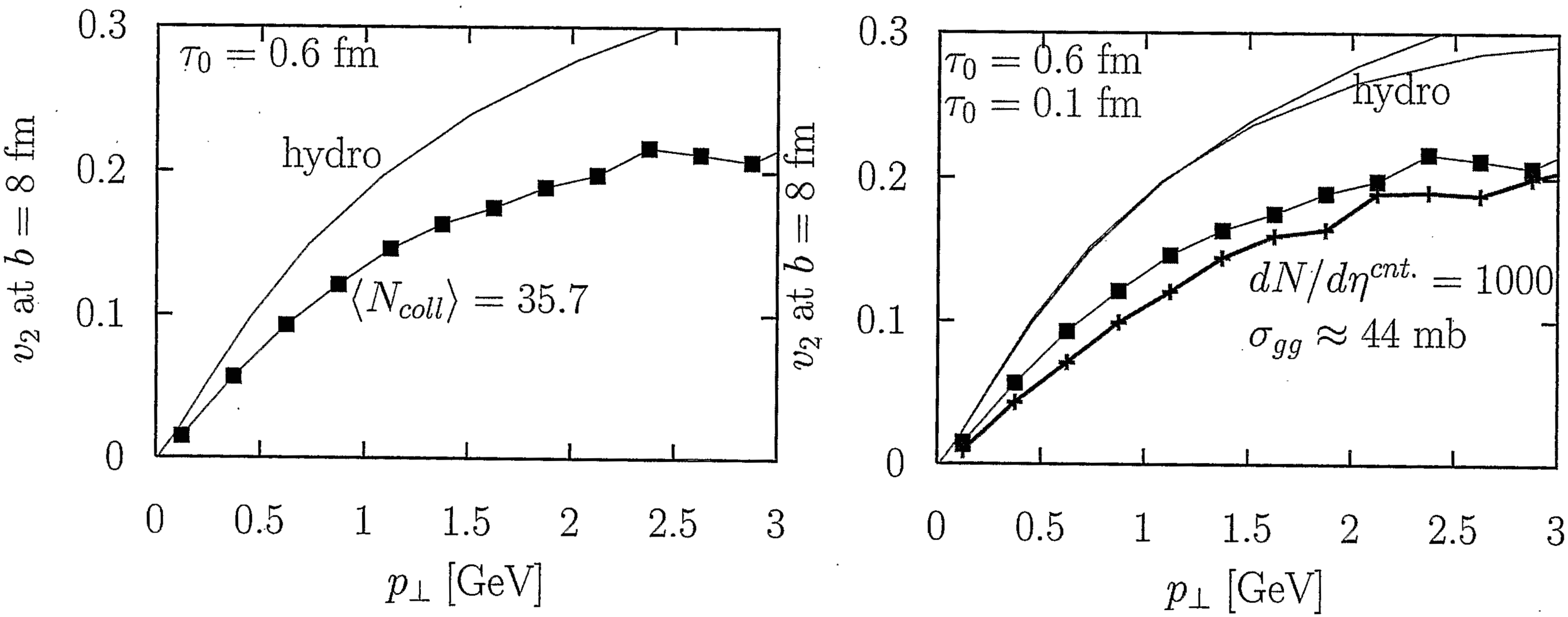


⇒ **so, extreme 15x perturbative opacities justify hydro?**

Apples-to-apples elliptic flow (2)

Now same hydro and transport initconds but $\tau_0 = 0.6$ fm$/c$, scaled $T_0 \sim \tau_0^{-1/3}$

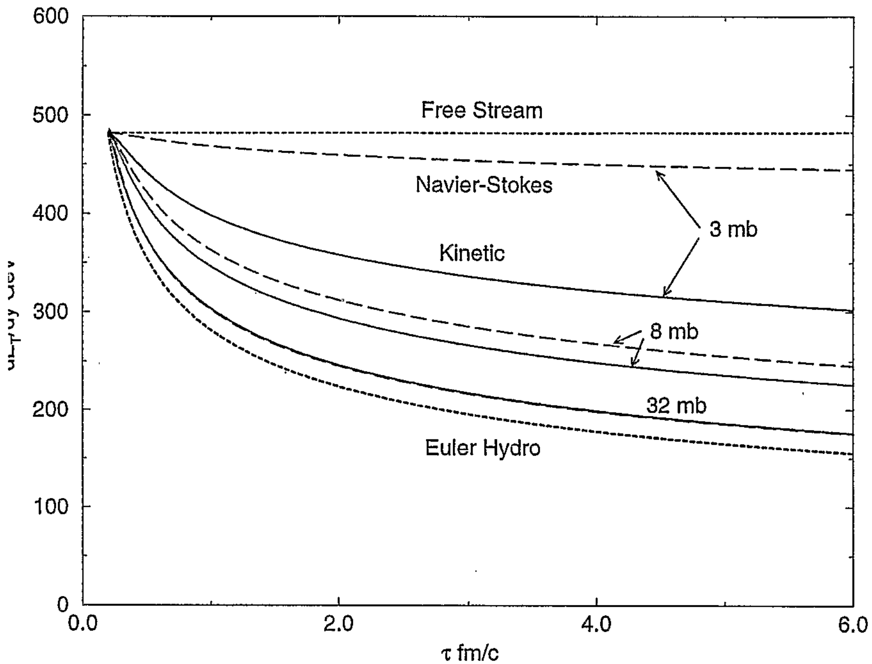
D.M. & Huovinen ('03):



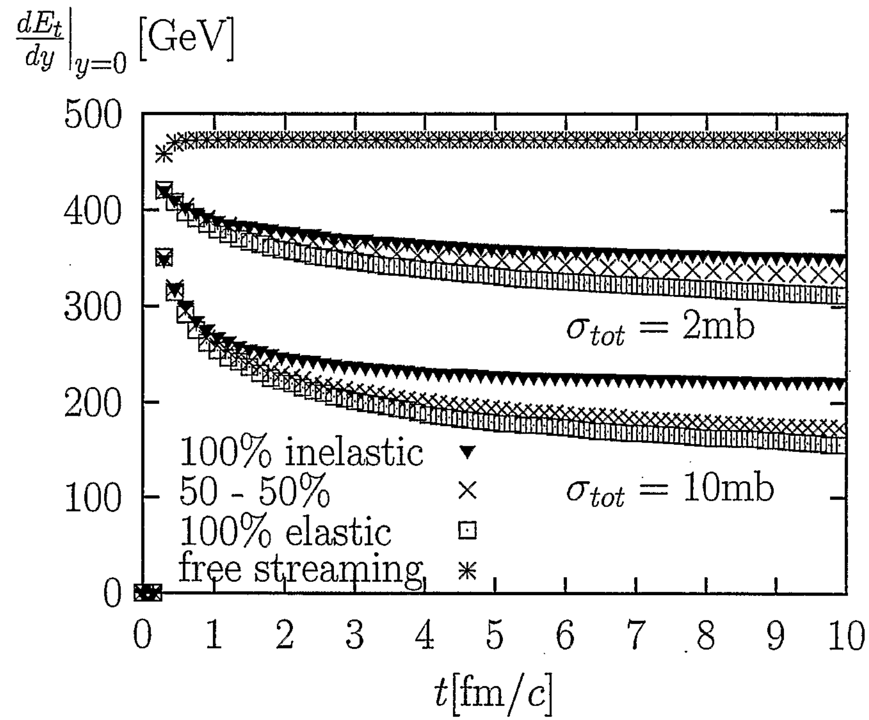
$\Rightarrow$ **large dissipation, transport v_2 is 30-50% reduced relative to hydro**

$\Rightarrow$ **remarkably little sensitivity to initial time**

pure $2 \to 2$ (Zhang & Gyulassy):



$2 \leftrightarrow 3$ **vs** $2 \to 2$ (D.M. & Gyulassy):



$p\,dV$ **work increases with opacity demonstrated approach to Navier-Stokes**

- **elastic and inelastic channels have similar transport effect**

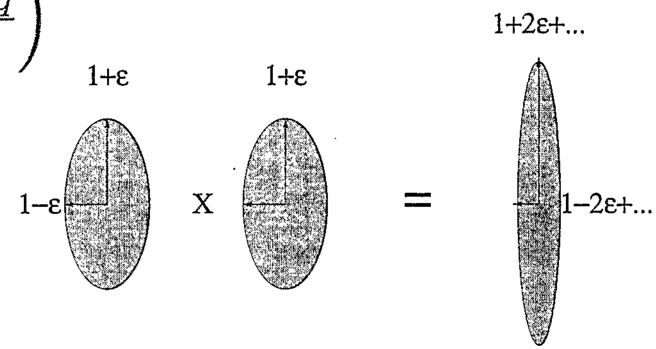
$\Rightarrow$ **effect of** $2 \leftrightarrow 3$ **is roughly a doubling of** $2 \to 2$ **cross section**

Hope looks gone: **there is room for** $2 - 3\times$ **larger opacities but not** $15\times$

Coalescence amplifies elliptic flow

[D.M & Voloshin, PRL 91 ('03)]

narrow wave fn. limit ($\vec{q} = 0$): $\frac{dN_M}{d\phi} \propto \left(\frac{dN_q}{d\phi}\right)^2$



$$v_2^M(p_\perp) \approx v_2^a(\frac{p_\perp}{2}) + v_2^{\bar{a}}(\frac{p_\perp}{2})$$
$$v_2^B(p_\perp) \approx v_2^a(\frac{p_\perp}{3}) + v_2^b(\frac{p_\perp}{3}) + v_2^c(\frac{p_\perp}{3})$$

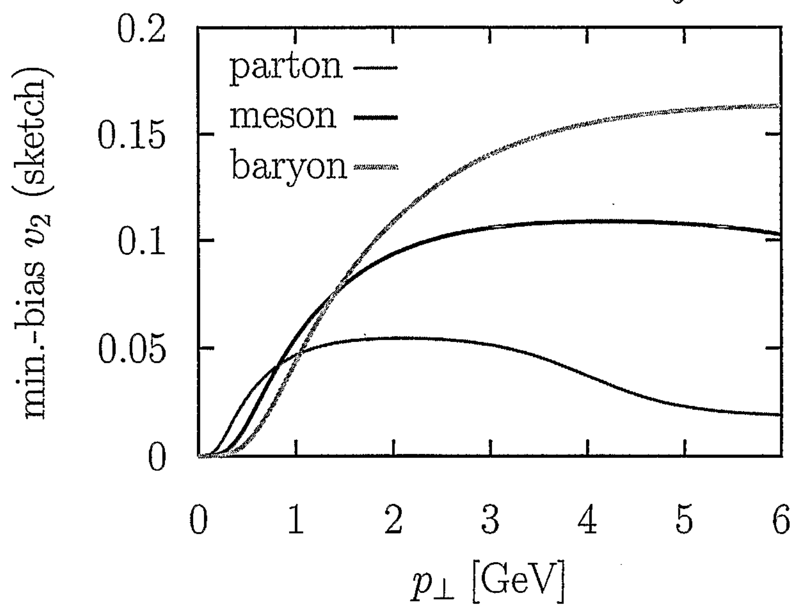
$\Rightarrow$ **hadron flow amplified at high $p_\perp$**

if all quarks have same v_2:

$3\times$ **for baryons**

$2\times$ **for mesons**

" $v_2^h(p_\perp) \approx n \times v_2^q(p_\perp/n)$ "



- **this KEY EFFECT solves opacity puzzle (much smaller parton v_2 needed)**

Transport Model Description of Flow

Che-Ming Ko
Texas A&M University

A multiphase transport model that includes both initial partonic and final partonic interactions has been shown to describe the rapidity and transverse momentum distributions as well as two-particle correlations in heavy ion collisions at RHIC. Large elliptic flow is obtained if scatterings of soft partons from melted strings are included. Taking into account their radiative energy loss in the partonic phase, minijet partons also acquire appreciable elliptic flow. Using the quark coalescence for hadron production, both the observed elliptic flow of identified hadrons and large baryon to pion ratio at intermediate transverse momenta can be explained. The quark coalescence model also predicts that the elliptic flow of charmed meson and J/psi are sensitive to that of charm quarks.

A multiphase transport model

- Initial conditions: HIJING
  Hard minjet partons and soft strings

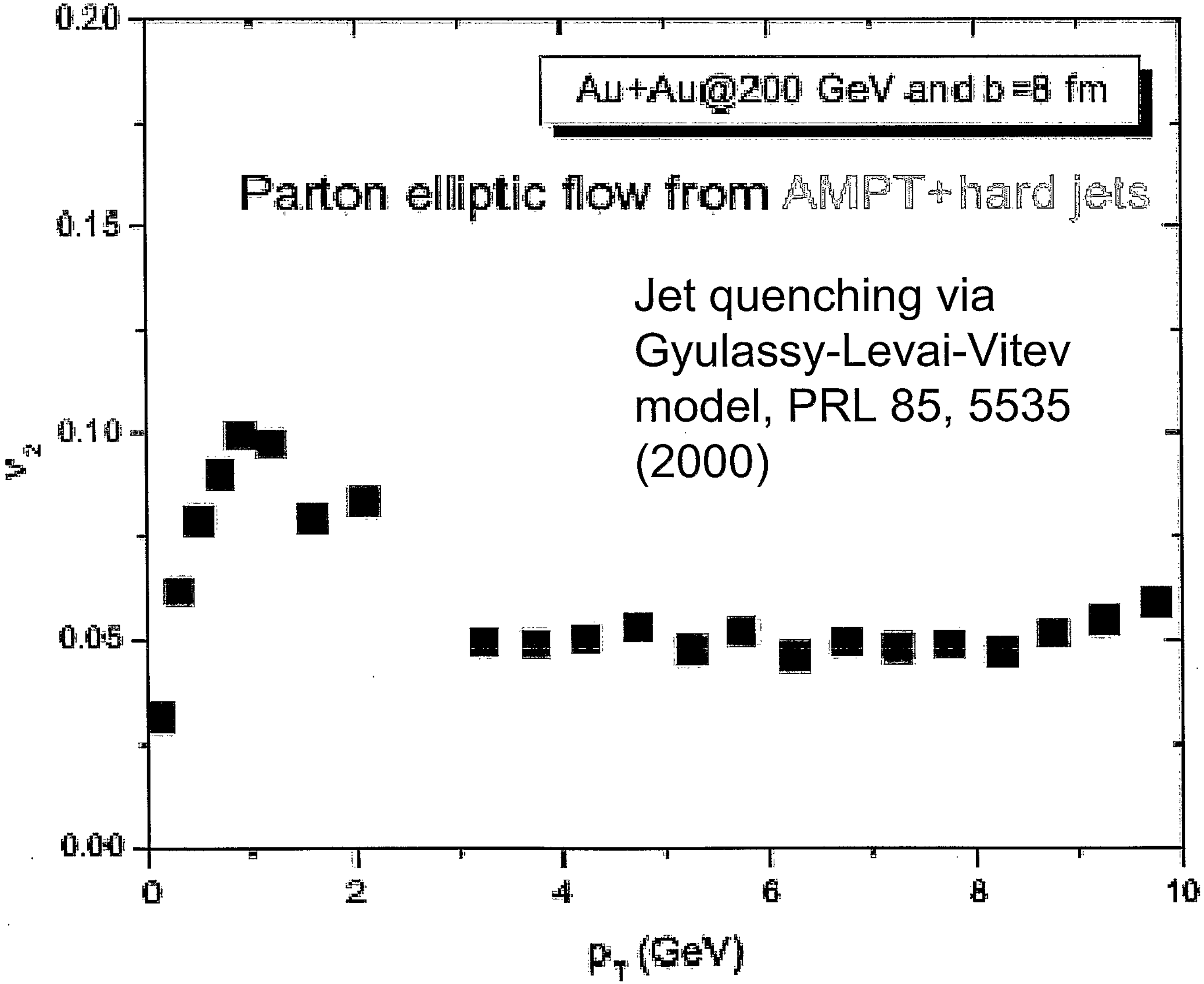
- Parton evolution: ZPC
  Default: Minijet partons
  String melting: Minijet partons and soft partons

- Hadronization:
  Default: Lund string model
  String melting: quark coalescence or recombination

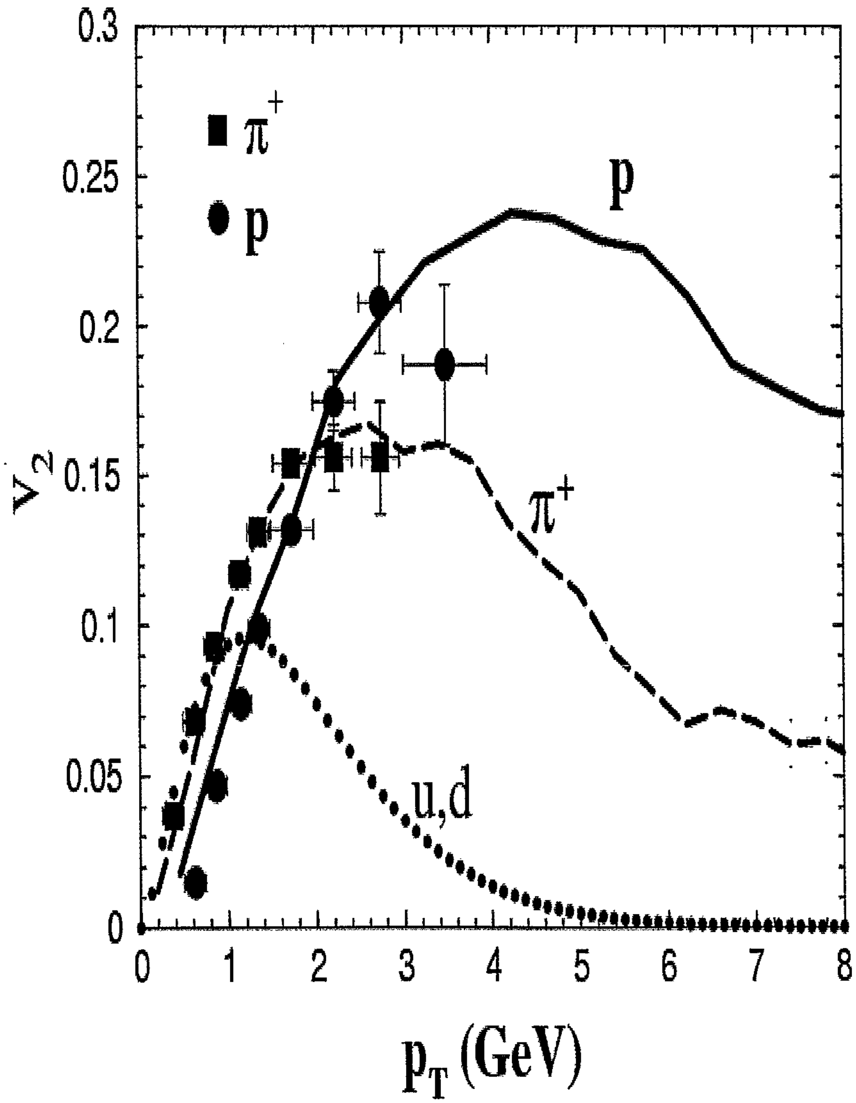
- Hadronic transport: ART

Z.W. Lin, S. Pal, B. Zhang, B.A. Li, and C.M. Ko: PRC 61, 067901 (00); 64, 041901 (01); NPA 698, 375c (02)

Parton elliptic flow



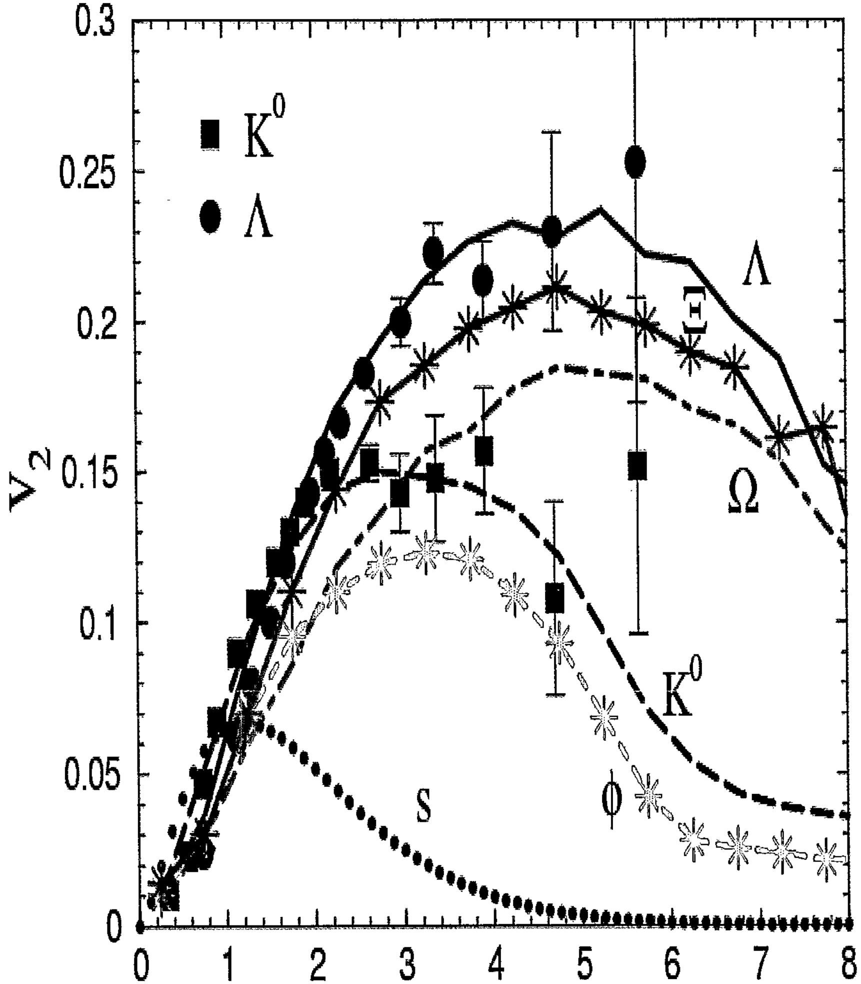
Elliptic flows of pions and protons



Quark coalescence model:
V. Greco, C.M. Ko, P. Levai: PRL 90, 202102 (2003); PRC 68, 034904 (2003)

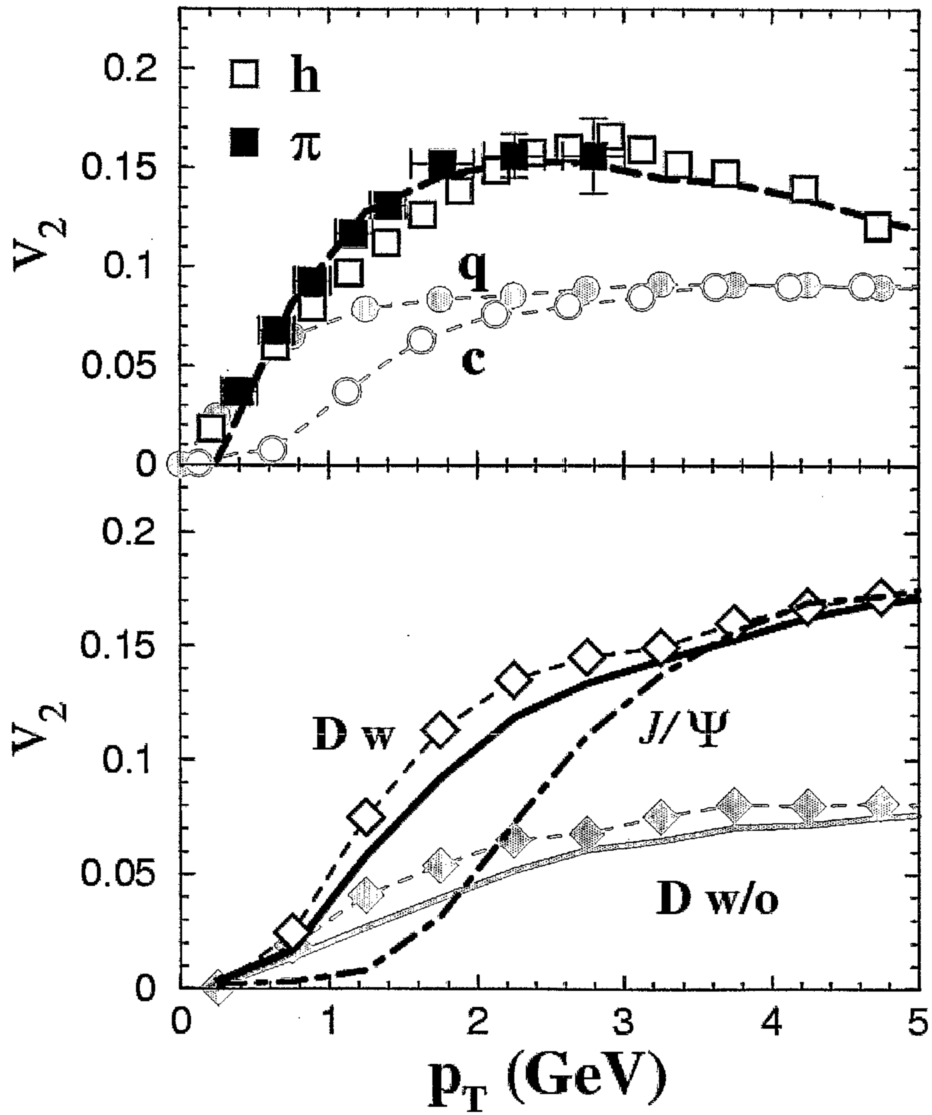
- Elliptic flow of light quarks is extracted from fitting measured pion elliptic flow
- Au+Au @ 200 AGeV
- Proton elliptic flow is then predicted and agrees with data (STAR)

Elliptic flows of kaons, lambdas and omegas



- Au+Au @ 200 AGeV
- Elliptic flow of strange quarks is extracted from fitting measured kaon elliptic flow.
- Predicted lambda elliptic flow agrees with data (STAR)
- Omega elliptic flow is predicted to be smaller than that of lambda

Charm flow



Solid red: With light quark flow but without charm quark flow; resulting electron flow is given by filled diamonds.

Solid blue: With both light and charm quark flows; resulting electron flow is given by open diamonds.

Dash-dotted: Charmonium flow due to charm quark flow

Multi module modeling of heavy ion collisions

L.P. Csernai, A. Anderlik, Cs. Anderlik, Ø. Heggø-Hansen, E. Molnár, A. Nyiri, D. Röhrich, K. Tamousiunas (U of Bergen); V.K. Magas (U of Valencia); A. Keranen, J. Manninen (U of Oulu); D.D. Strottman, B. Schlei (Los Alamos National Lab.); F. Grassi, Y. Hama, (U of Rio de Janeiro); T. Kodama, H. Stöcker, W. Greiner (U of Frankfurt)

A modular computational simulation model is presented Made from different models for different stages of a heavy Ion reaction. These computational modules are coupled to Each other by standardized interfaces (on physical bases). This enables us to use several alternative modules at each stage. Our aim is to describe and analyse collective flow phenomena. We pay particular attention to the initial and final stages of the reaction.

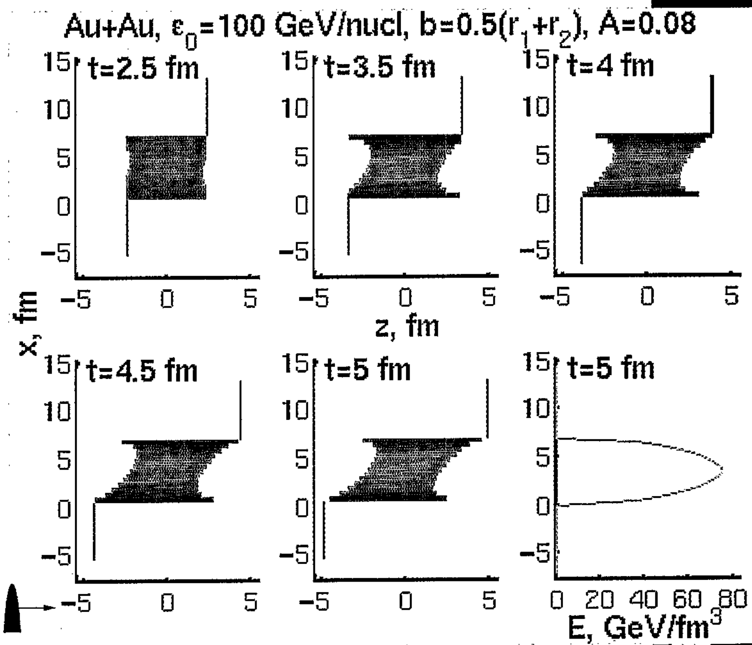
Recent v_1 data indicate that the experimental possibility is present to find the full information on collective flow phenomena in heavy ion reactions. The causes and the connections between the observables and model assumptions will be discussed.

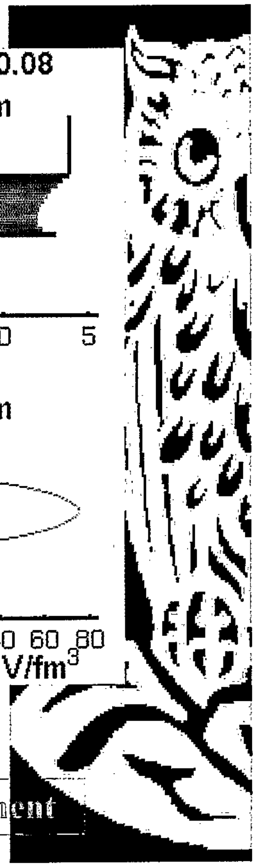
The initial, non-equilibrium stage is described by a Fire-streak model, where each streak develops according to a Coherent Yang-Mills field model. The details (e.g. space-time extent) of the initial stage are tested now based on the measurable outcome.

The subsequent 3D CFD model, based on the PIC method, is now upgraded to RHIC energies. Contrary to earlier lower energy works, we use a QCD Bag Model EoS for the whole fluid dynamical stage, but we allow for final supercooling.

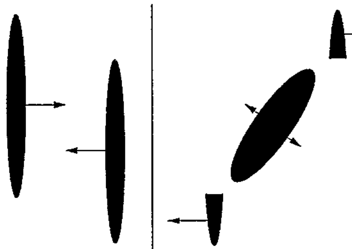
The final stages include the (i) determination of the Freeze-Out (FO) surface, the (ii) sudden hadronization and FO of the plasma by satisfying all conservation and entropy increase laws, and the (iii) calculation of post FO measurables. We have worked extensively on this stage, calculated the statistical eq. for final hadron abundances, FO probabilbity distribution in the phase-space and in the space-time, the resulting, non-equilibrium phase-space distributions and the measurable consequences of these. Preliminary results for measurables are calculated for time-like FO hypersurfaces, with standard, eq. distributions.

Initial state





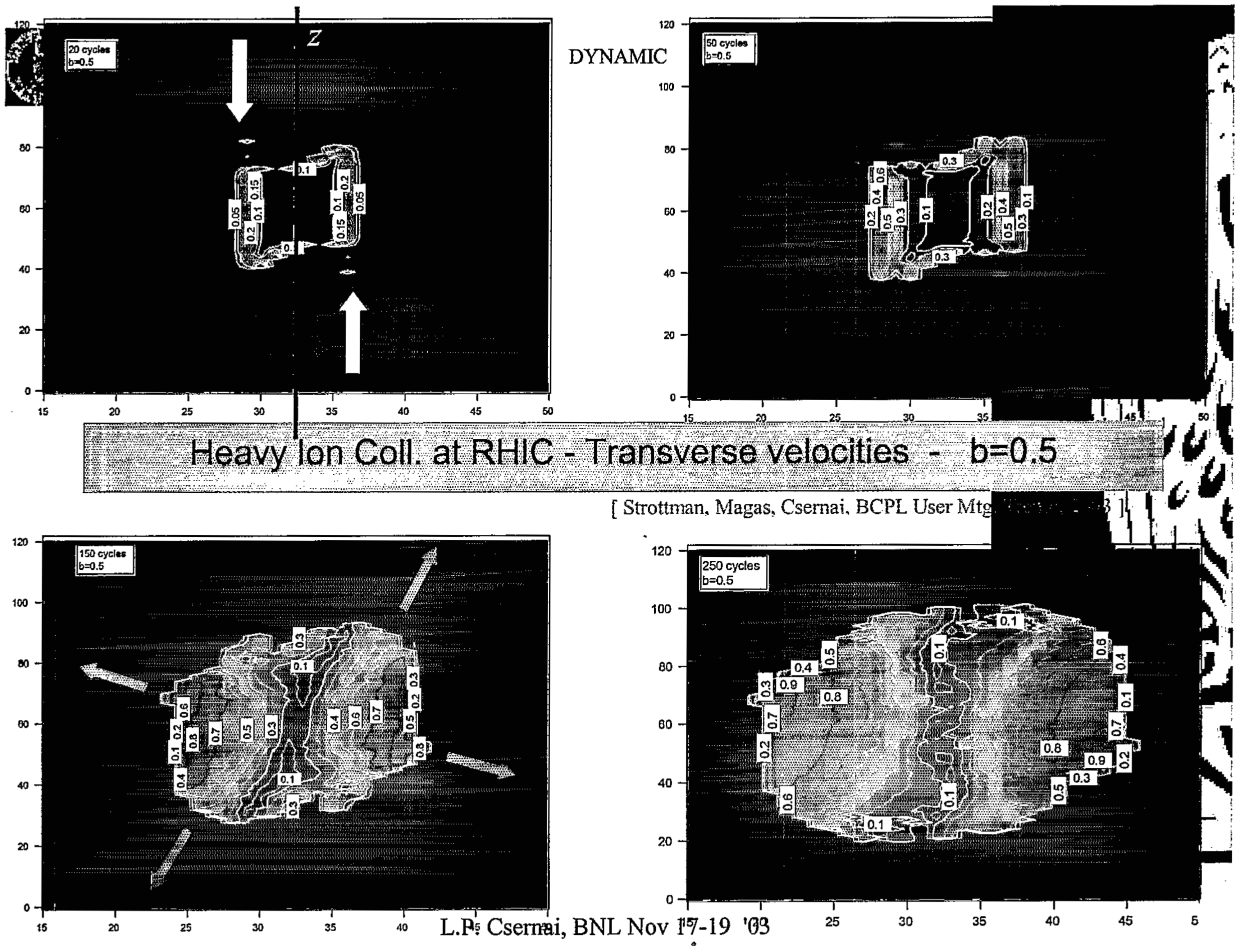
3rd flow component



Before collision

Tilted initial Landau's disk

L.P. Csernai, BNL Nov 17-19 '03


Heavy Ion Coll. at RHIC - Transverse velocities - b=0.5
DYNAMIC
Z
20 cycles
b=0.5
50 cycles
b=0.5
150 cycles
b=0.5
250 cycles
b=0.5
[Strottman, Magas, Csernai, BCPL User Mtg
L.P. Csernai, BNL Nov 17-19 '03

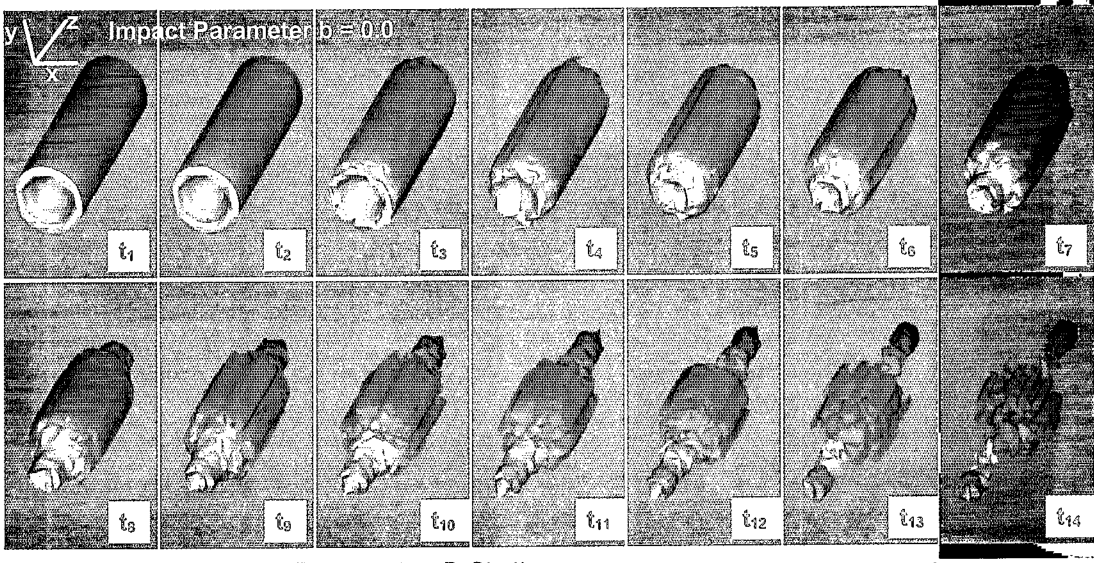
Freeze-Out Hyper-Surface Extraction with Digital Image Processi... iques

Time-Sequence of FOHS Projections

10 times elongated !!

[Bernd R. Schlei (T-1) - LA-UR-03-3

VESTA Rendering of FOHS in 3+1 D Hydrodynamics at fixed Times (t_1 < ... < t

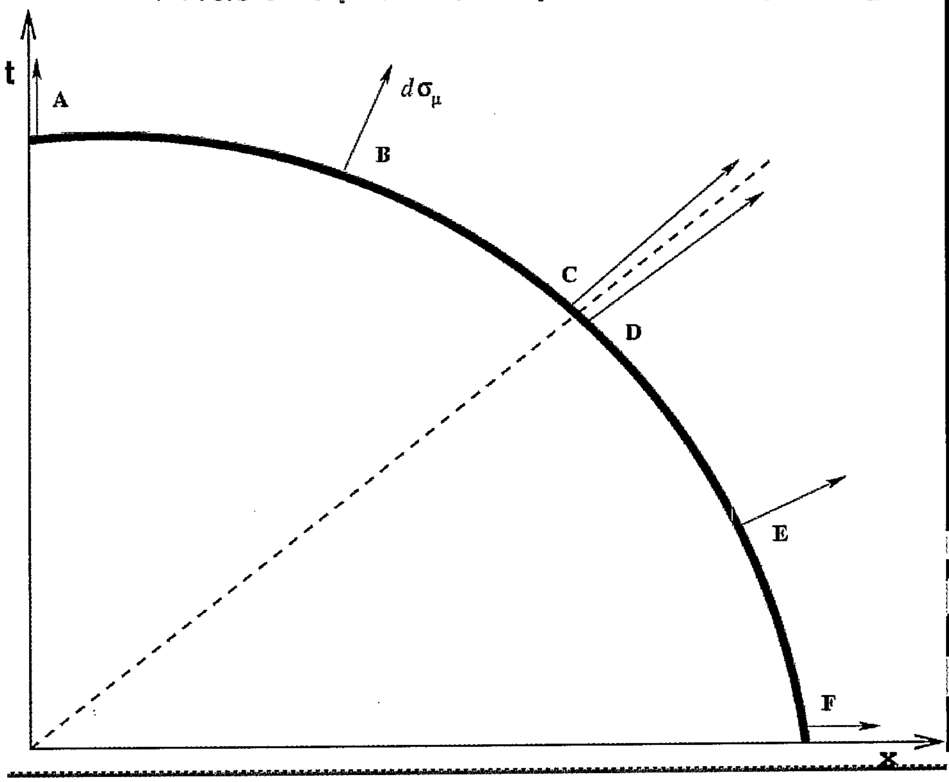


3+1 D Hydrodynamic Density Data, courtesy D. Strottman, Theoretical Division, Los Alamos National Laboratory.

Los Alamos

L.P. Csernai, BNL Nov 17-19 '03

Phase-Space FO probability



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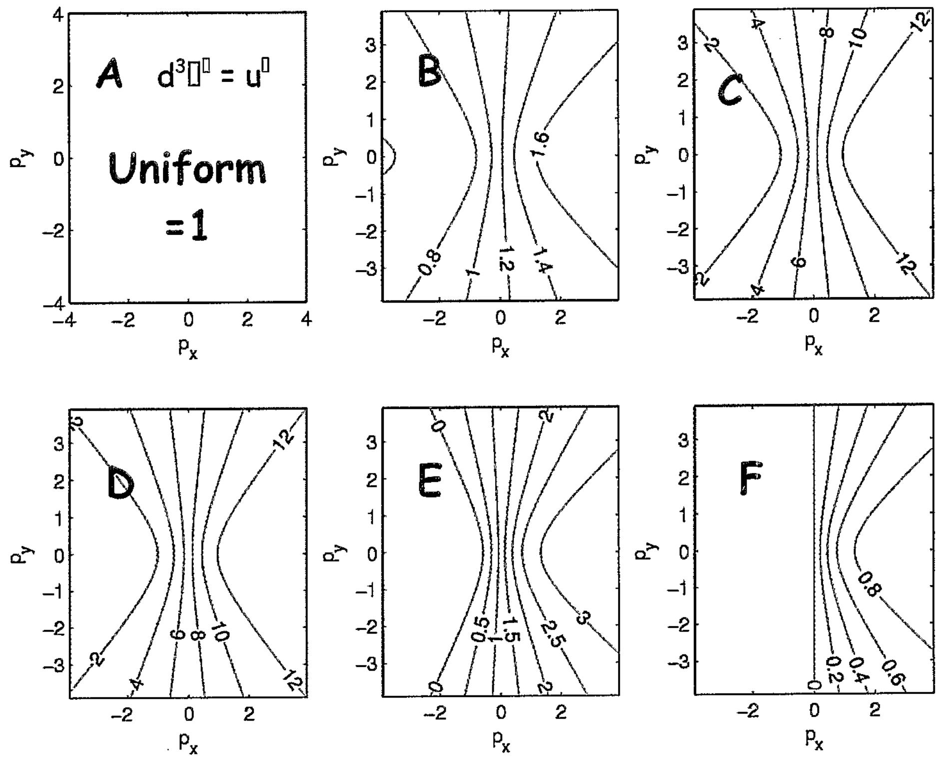
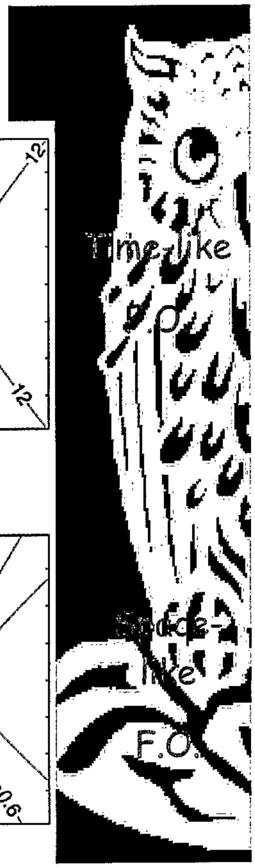
Phase-Space FO probability





L.P. Csernai, BNL Nov 17-19 '03

Results obtained with NeXSPheRIO

Frédérique Grassi

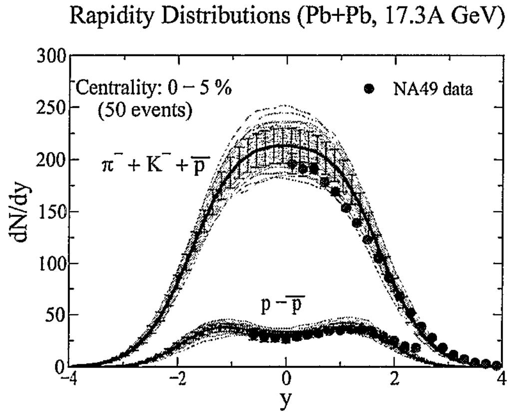
Instituto de Física-Univ. de São Paulo-Brazil

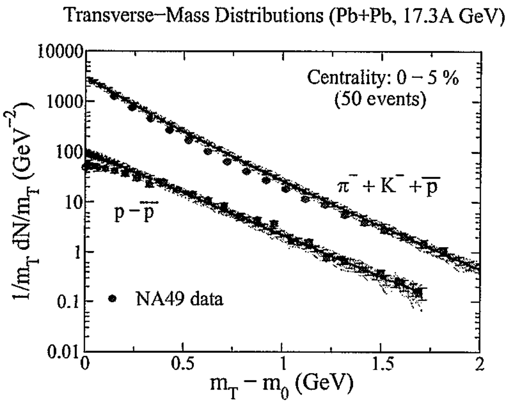
Smoothed Particle Hydrodynamics

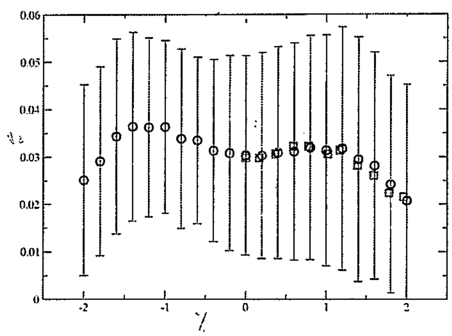
Main ingredients

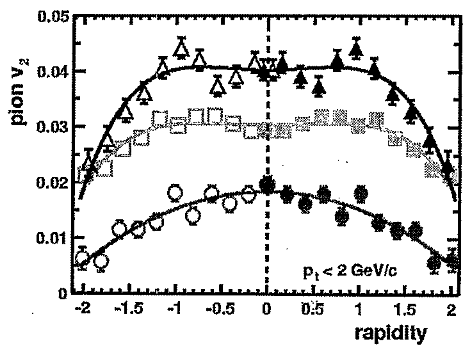
- Method originally developped in astrophysics adapted to relativistic heavy ion collisions by C.E.Aguiar, T.Kodama, T.Osada & Y.Hama, J.Phys.G27(2001)75
- Advantage: incorporate any geometry in the initial conditions (in particular can be used to model event-by-event physics)
- Fluid divided in small volumes called "particles"
- Hydro. eq. become ordinary differential eq. for "particle" motion
- Each "particle" has attached to it, conserved numbers: entropy and baryon number

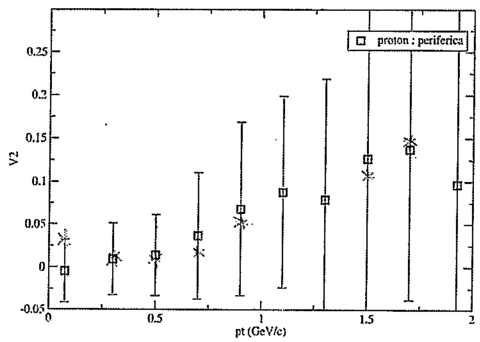
Pb+Pb (158A GeV) spectra

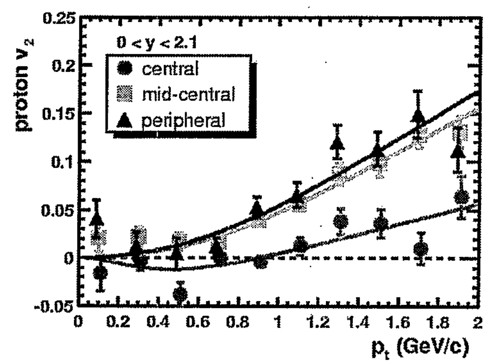










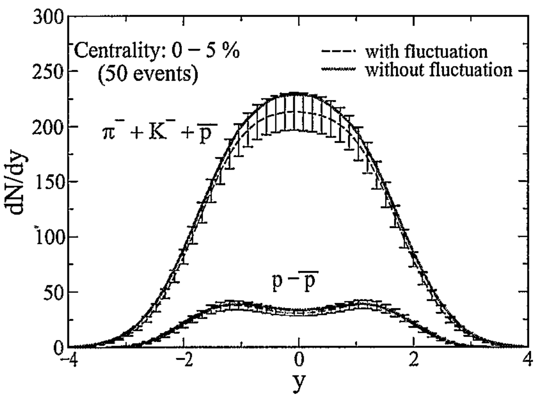


Conclusion: - sizable fluctuations event to event

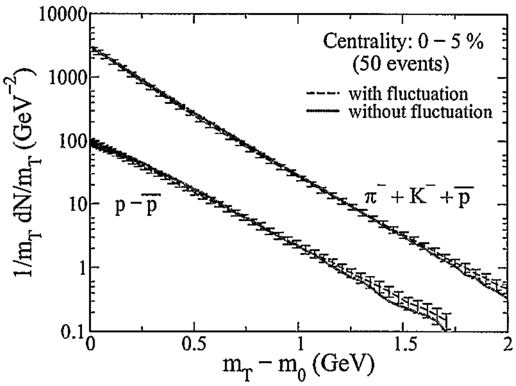
- average on events agrees with data

Averaging I.C. vs. averaging final spectra

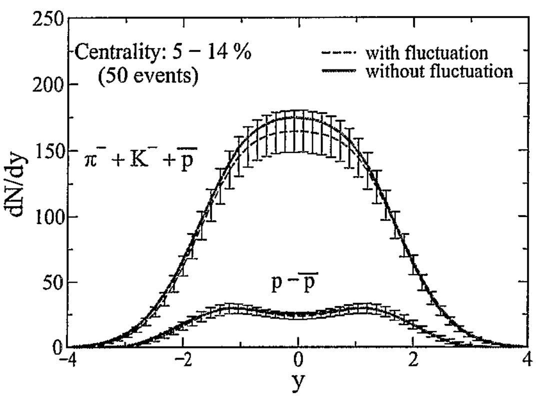
Rapidity Distributions (Pb+Pb, 17.3A GeV)



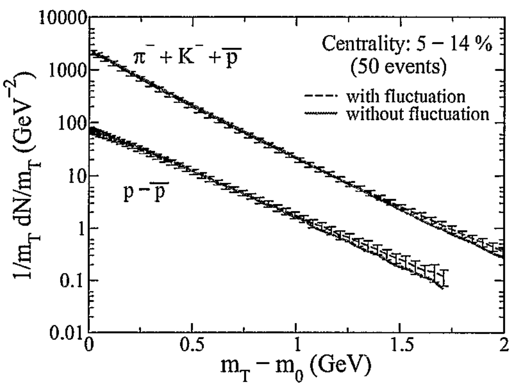
Transverse–Mass Distributions (Pb+Pb,17.3A GeV)



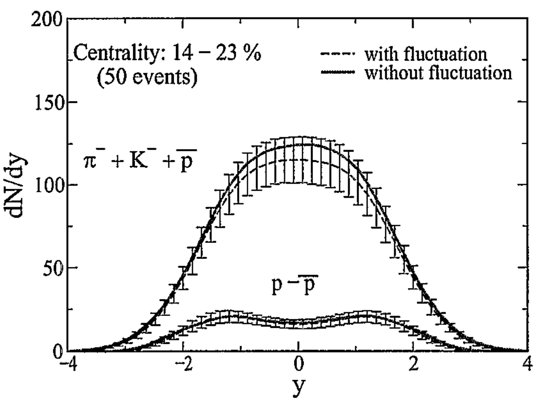
Rapidity Distributions (Pb+Pb, 17.3A GeV)



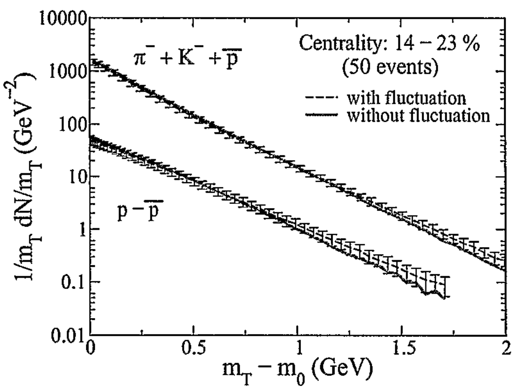
Transverse–Mass Distributions (Pb+Pb, 17.3A GeV)



Rapidity Distributions (Pb+Pb, 17.3A GeV)



Transverse–Mass Distributions (Pb+Pb, 17.3A GeV)

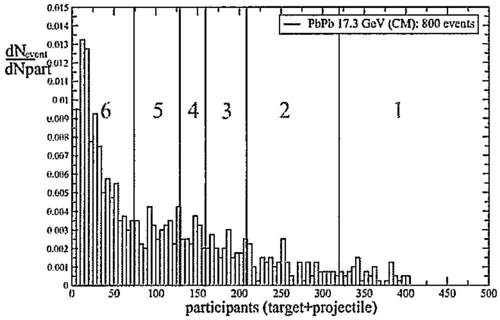


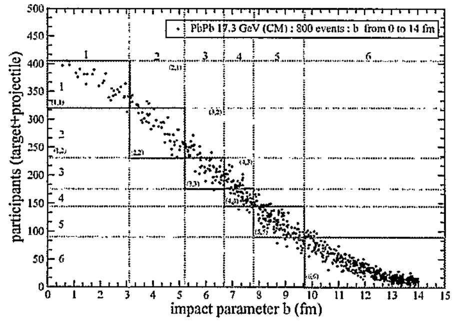
Nb. of participants vs. impact parameter

Centrality windows are defined
- in experiments, using E_{ZDC}, participant number, multiplicities
- in hydro, using impact parameter (generally)

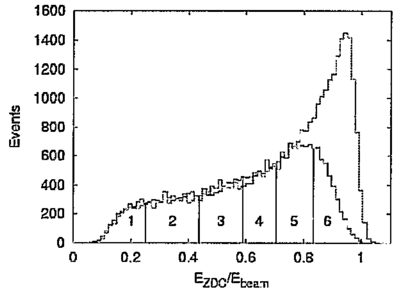
$\rightarrow$ is it comparable?

Run NexSPheRIO 800 times

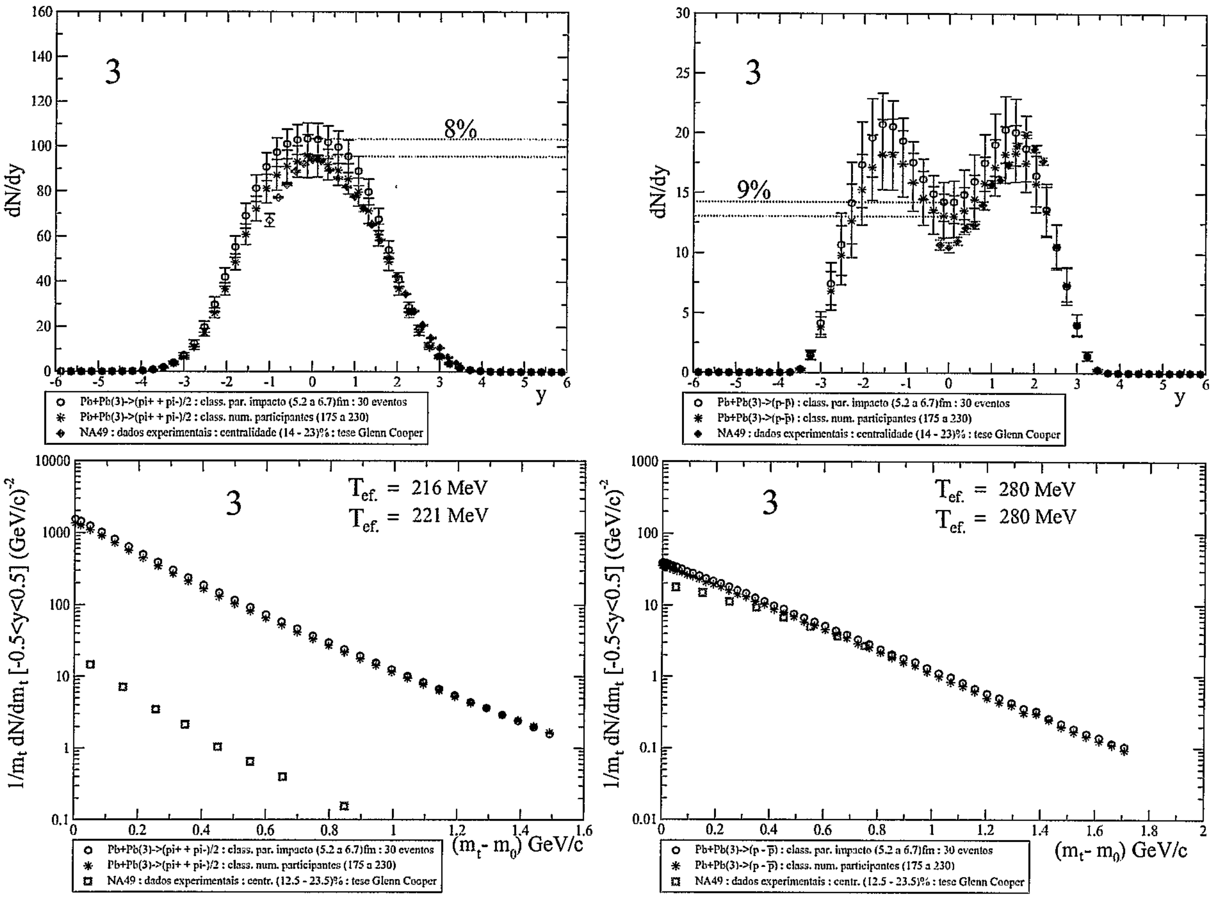




Choice of windows made to approximate NA49 choice

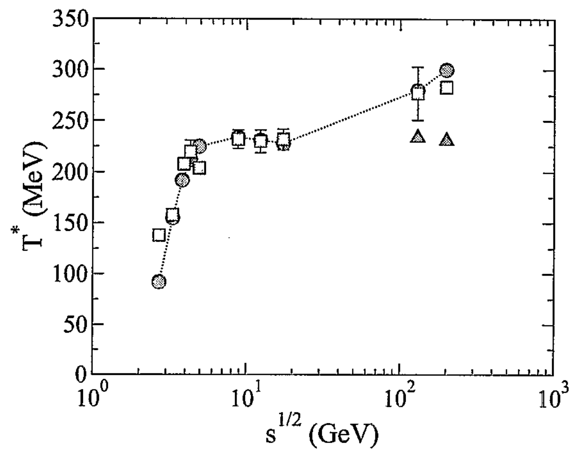


Different particle distributions expected for a window in N_{part} and the corresponding window in b, because mean number of participants are different.



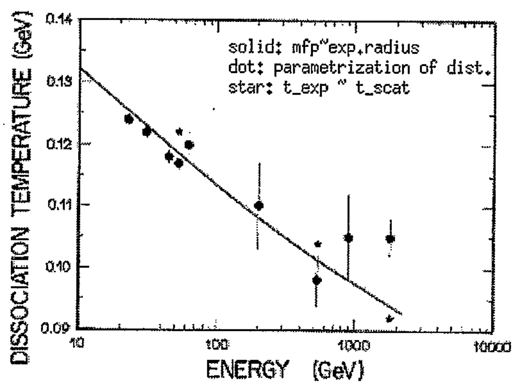
3
8%
dN/dy
y
Pb+Pb(3)->(pi+ + pi-)/2 : class. par. impacto (5.2 a 6.7)fm : 30 eventos
Pb+Pb(3)->(pi+ + pi-)/2 : class. num. participantes (175 a 230)
NA49 : dados experimentais : centralidade (14 - 23)% : tese Glenn Cooper
3
9%
dN/dy
y
Pb+Pb(3)->(p-p̄) : class. par. impacto (5.2 a 6.7)fm : 30 eventos
Pb+Pb(3)->(p-p̄) : class. num. participantes (175 a 230)
NA49 : dados experimentais : centralidade (14 - 23)% : tese Glenn Cooper
3
T_ef. = 216 MeV
T_ef. = 221 MeV
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
(m_t- m_0) GeV/c
Pb+Pb(3)->(pi+ + pi-)/2 : class. par. impacto (5.2 a 6.7)fm : 30 eventos
Pb+Pb(3)->(pi+ + pi-)/2 : class. num. participantes (175 a 230)
NA49 : dados experimentais : centr. (12.5 - 23.5)% : tese Glenn Cooper
3
T_ef. = 280 MeV
T_ef. = 280 MeV
1/m_t dN/dm_t [-0.5<y<0.5] (GeV/c)^-2
(m_t- m_0) GeV/c
Pb+Pb(3)->(p - p̄) : class. par. impacto (5.2 a 6.7)fm : 30 eventos
Pb+Pb(3)->(p - p̄) : class. num. participantes (175 a 230)
NA49 : dados experimentais : centr. (12.5 - 23.5)% : tese Glenn Cooper

Eff. temperature of K^+



Conclusion: decreasing $T_{f.o.}(\sqrt{s})$ is required by data, it implies
$\rightarrow$ longer expansion time IN THE HADRONIC PHASE for increasing $\sqrt{s}$
$\rightarrow$ larger effective temperature $T_{eff}^{K^+}(\sqrt{s})$
$=$ different from common vue that longer expansion time in the QGP phase is responsible for increase in $T_{eff}^{K^+}(\sqrt{s})$

Decreasing $T_{f.o.}(\sqrt{s})$ predicted in the past: see Hama & Navarra Z.Phys.C53(1992)501 and Navarra, Nemes, Ornik & Paiva, Phys.Rev.C45(1992)R2552



SUMMARY

NeXSPheRIO combines initial conditions given by NeXus with a hydrodynamical solution provided by SPheRIO.

- Predictions for rapidity spectra and transverse mass distributions of pions and $p-\bar{p}$ agree with S+S, Pb+Pb at CERN and Au+Au from RHIC (except perhaps the most central window at RHIC).

  Under progress: elliptic flow, HBT

- Fluctuations in initial conditions from event to event lead to large fluctuations in rapitidy distributions

- Using averaged initial conditions leads to higher rapitidy distributions than running various events and then making the average of their individual rapitidy distribution (as happens experimentally)

- Using a classification of centrality windows in participant number (as obtained e.g. experimentally) rather than in impact parameter (as doable in hydrodynamics) lead to up to 12 % difference in rapitidy distributions.

- Increase in $T^{K^+}_{eff}(\sqrt{s})$ seems related to decrease of $T_{f.o.}(\sqrt{s})$ and larger expansion in HADRONIC PHASE rather than larger expansion in QGP phase.

Particle spectra and correlations in a thermal model

Wojciech Broniowski

H. Niewodniczański Institute of Nuclear Physics, Cracow, Poland

Predictions of the thermal model with **single freeze-out**, **flow**, and **resonance decays** are presented. The radical simplification of the single freeze-out, where $T_{\text{chem}} = T_{\text{kin}}$, has gained support from the RHIC HBT results ($R_{\text{out}}/R_{\text{side}} \sim 1$, $R_{\text{side}}(\phi)$ elongated out of the reaction plane, abundant resonances seen in correlations). It complies to the **explosive scenario** at RHIC, where the duration of the hadronic phase is short. An important ingredient of our approach is a complete treatment of resonances, important due to the Hagedorn-like exponential growth of the number of states with their mass. The resonances contribute to the yields of stable particles, increase the slopes of the $p_\perp$ spectra, as well as are an important source of correlations. The boost-invariant freeze-out hypersurface is detemined by the condition $\tau^2 = t^2 - r_z^2 - r_x^2 - r_y^2 = \text{const}$ with the constrain on the transverse size, $\sqrt{r_x^2 + r_y^2} < \rho_{\text{max}}$. The assumption of boost-invariance is good in the mid-rapidity region. The flow is assumed in the Hubble-like form, with $u^\mu = x^\mu/\tau$. The model has altogether four parameters. The two thermal parameters, the temperature and the baryon chemical potential, are determined from ratios of particle yields. The two geometric parameters, namely the invariant time τ and the transverse size ρ_{max}, are fixed with the help of $p_\perp$ spectra, with τ^3 controlling the overall normalization and ρ_{max}/τ determining the slope.

We show in detail the prediction of the model on the **$p_\perp$-spectra** of various particles, including resonances, and at various centralities. The parameterization of the experimental data in terms of the geometric parameters is impressive, with the resulting average flow velocity of ~ 0.5. Systematics in centrality is given.

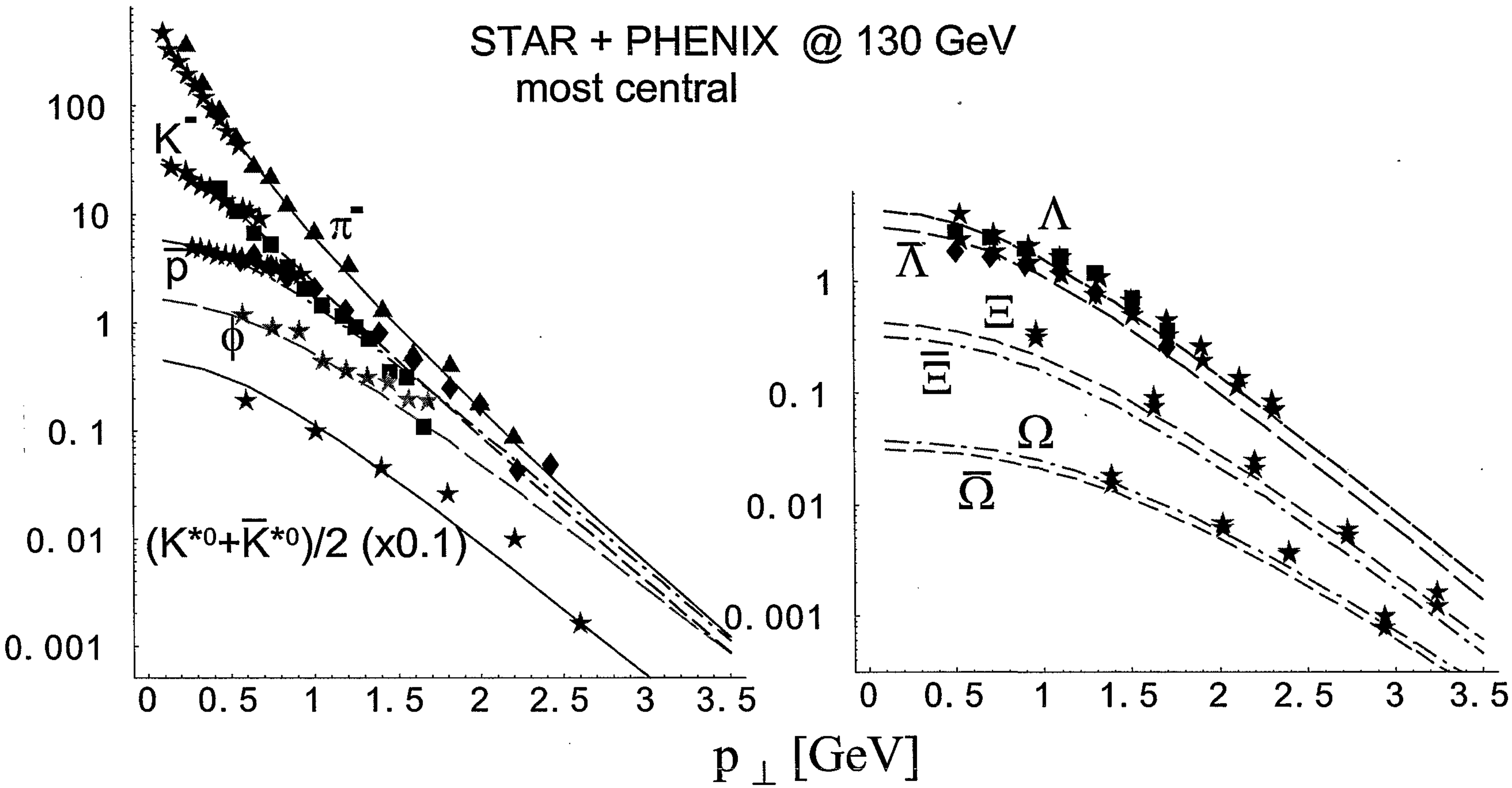
In addition, we have analyzed the $\pi^+\pi^-$ **invariant-mass correlations**, and the **balance functions**. The resonance decays are an important source of these correlations and their inclusion allows for the understanding quantitative description of the data.

We also mention briefly the model results for the pionic **HBT radii**, in particular the feature $R_{\text{out}}/R_{\text{side}} \sim 1$, and for the **elliptic-flow** coefficient, v_2.

In conclusion, **the simple thermal approach works surprisingly well for soft physics, $p_\perp < 2$ GeV.**

Based on:
WB + Wojciech Florkowski, PRL 87 (2001) 272302; PRC 65 (2002) 064905
WB+ Anna Baran + WF, Acta Phys. Polon. B33 (2002) 4235
WB+ WF+ Brigitte Hiller, PRC 68 (2003) 034911
Piotr Bożek+ WB+WF, `nucl-th/0310062`

Results for the transverse-momentum spectra



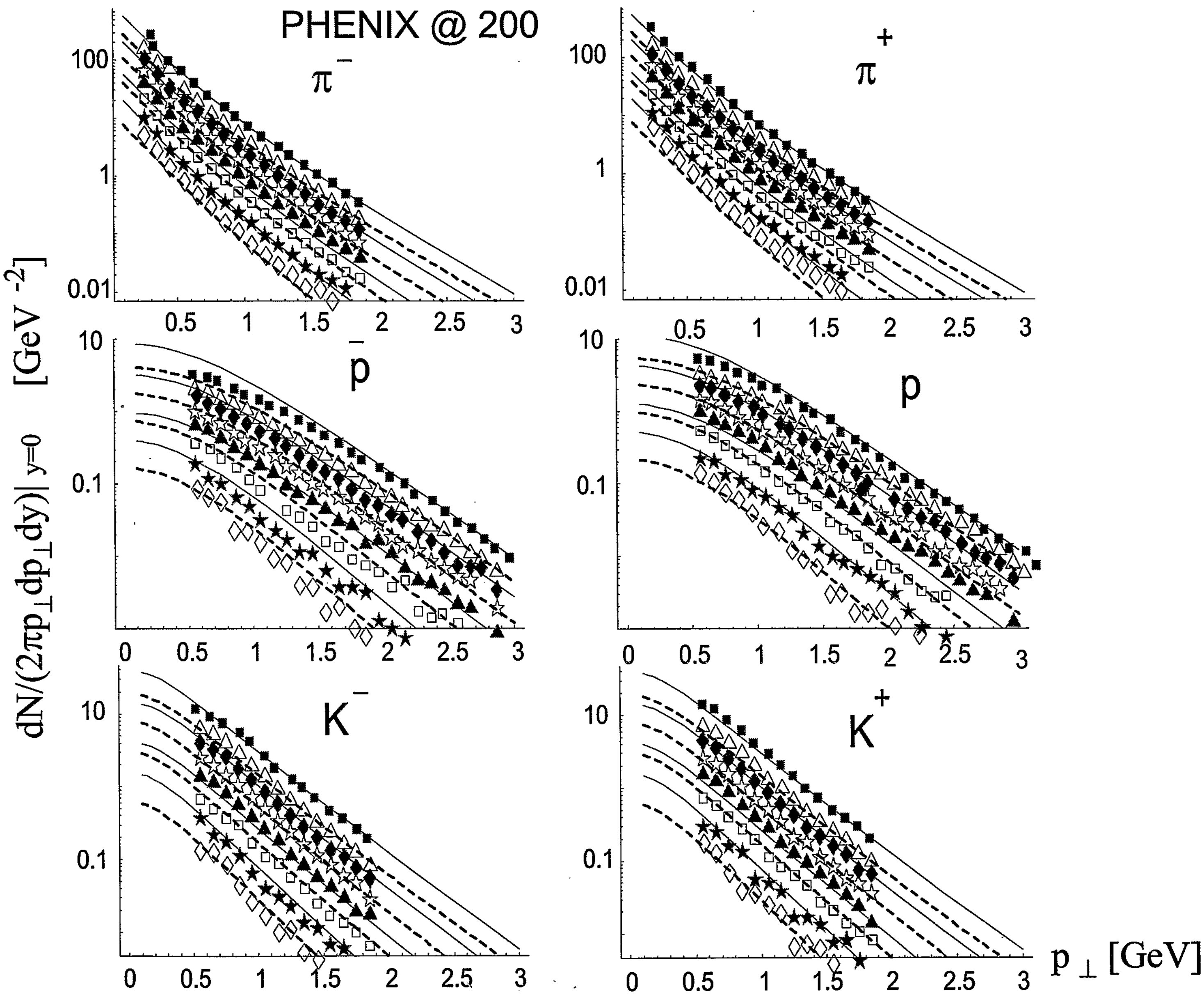
($T = 165$ MeV)

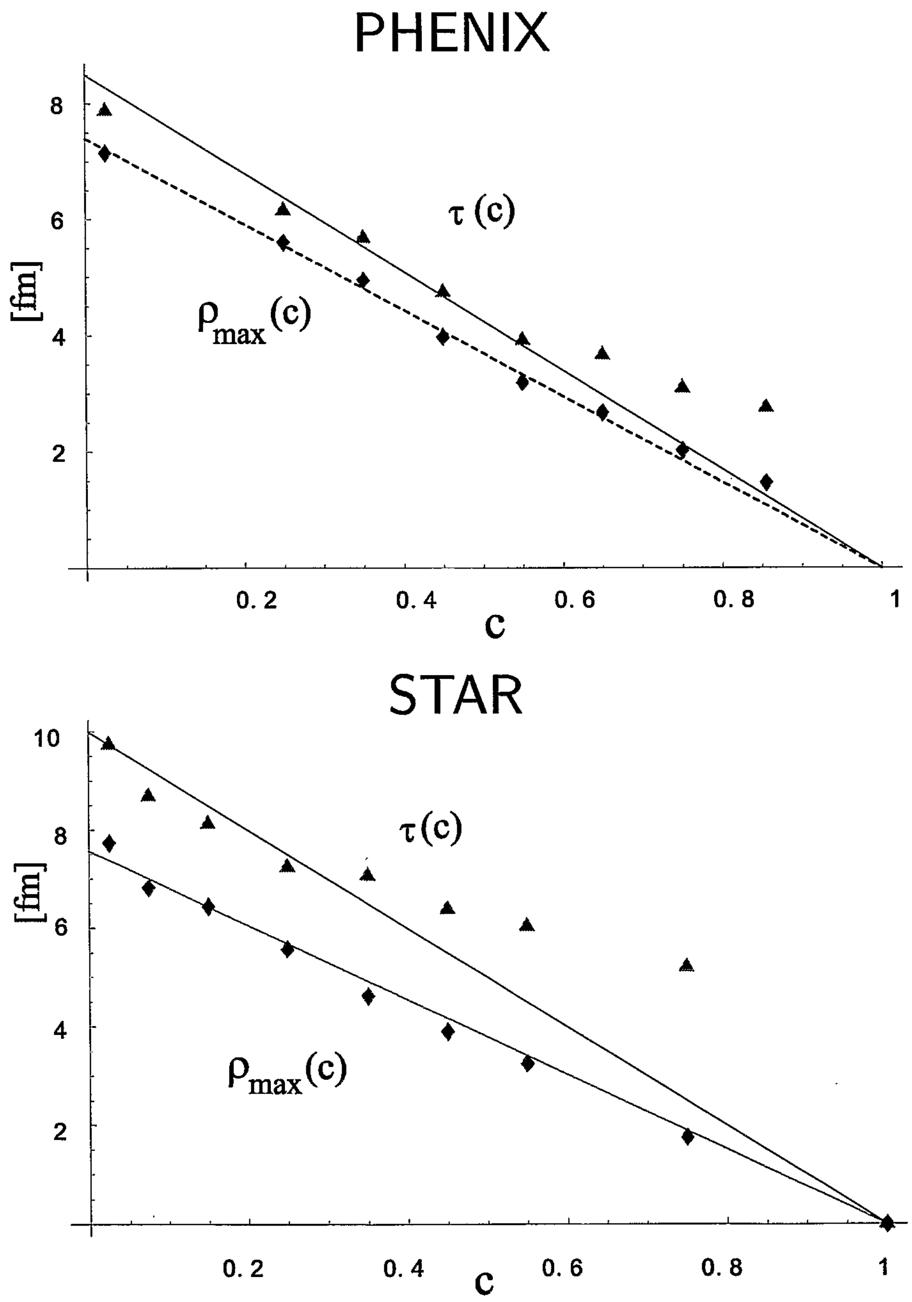
ϕ – very weak interactions, serves as a thermometer

K^* – resonance, lower T would lead to much less K^*'s

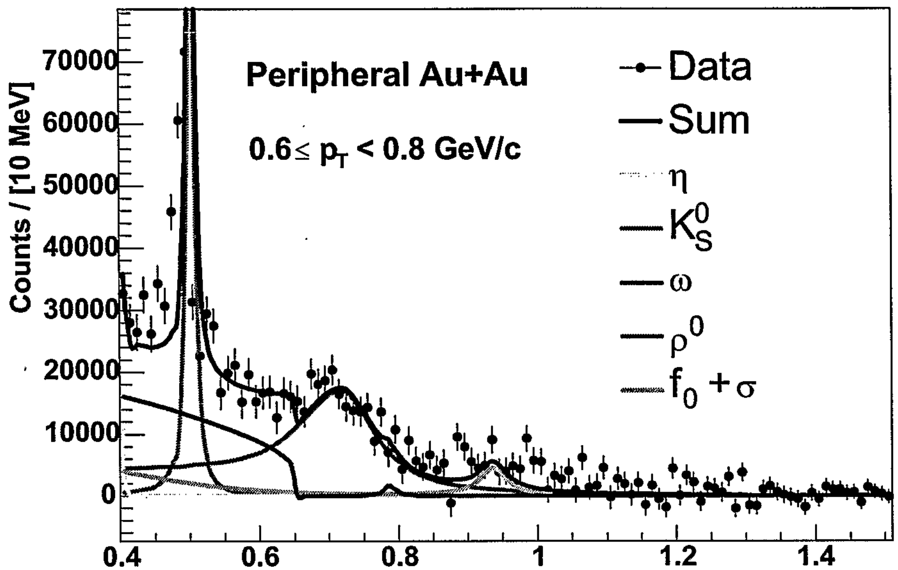
(experimental Ξ's went down by $\sim$ a factor of 2)

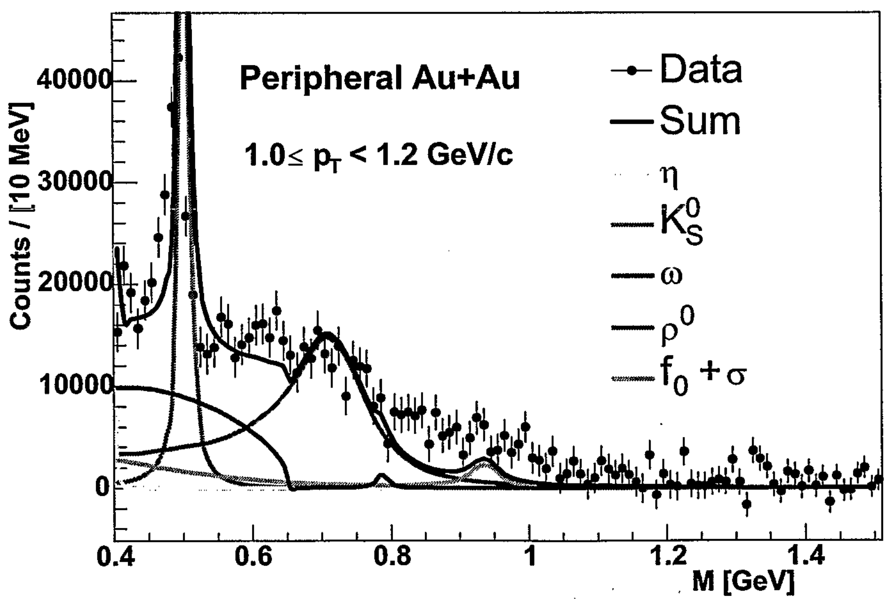
No special treatment of Ω's


PHENIX @ 200
π⁻
π⁺
p̄
p
K⁻
K⁺
dN/(2πp⊥dp⊥dy)| y=0 [GeV -2]
p ⊥ [GeV]


PHENIX
8
6
4
2
[fm]
τ (c)
ρmax(c)
0.2
0.4
0.6
0.8
1
c
STAR
10
8
6
4
2
[fm]
τ(c)
ρmax(c)
0.2
0.4
0.6
0.8
1
c

$\pi^+\pi^-$ pairs from STAR

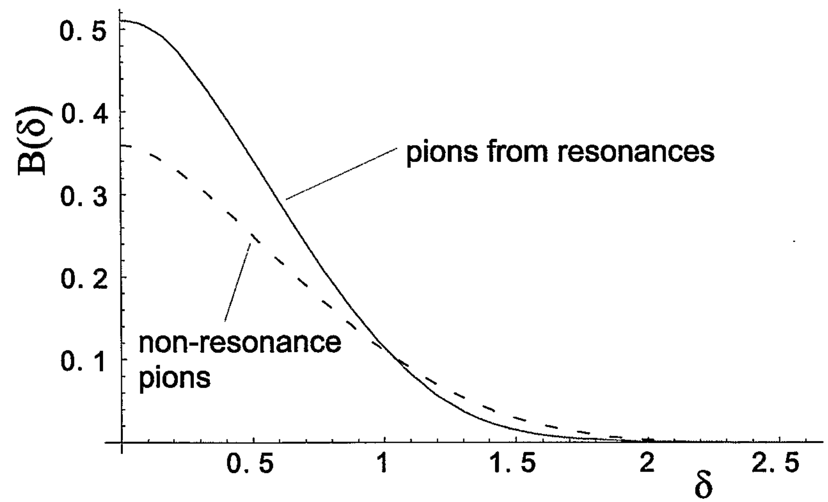




(prepared by P. Fachini)

Balance functions in the thermal model

$$B(\delta, Y) = B_{\mathrm{R}}(\delta, Y) + B_{\mathrm{NR}}(\delta, Y)$$



"Proceedings": Landau Hydrodynamics & RHIC Phenomenology

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Peter Steinberg
Brookhaven National Laboratory

Workshop on Collective Flow & QGP Properties
November 17-19, 2003

The “Landau Solution”

- **Many authors refined original ideas**
  - **This is how things ended up by early 1980’s**
- **Universal Entropy**

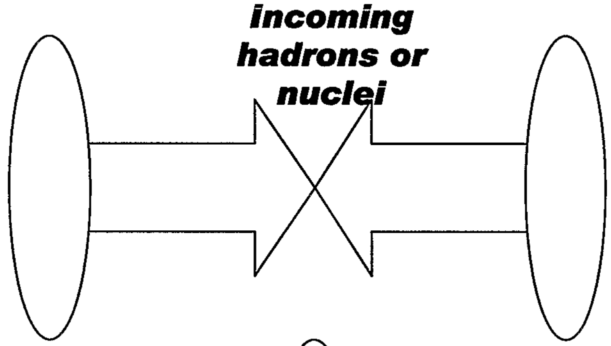
$$N_{ch} \sim Ks^{1/4}$$

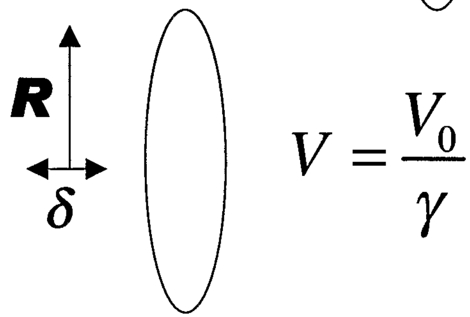
- **Gaussian Rapidity Distributions**

$$\frac{dN}{dy} = Ks^{1/4}\frac{e^{-y^2/2L}}{\sqrt{2\pi L}} \quad L = \ln\left(\frac{\sqrt{s}}{2m_p}\right) = \ln(\gamma) = \sigma_y^2$$

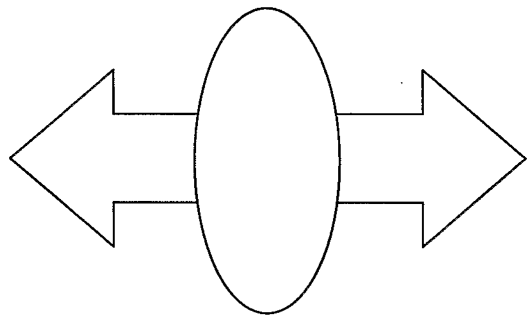
- **Thermal p_T spectra**

$$\frac{dN}{p_T dp_T} = \exp(-p_T/T)$$



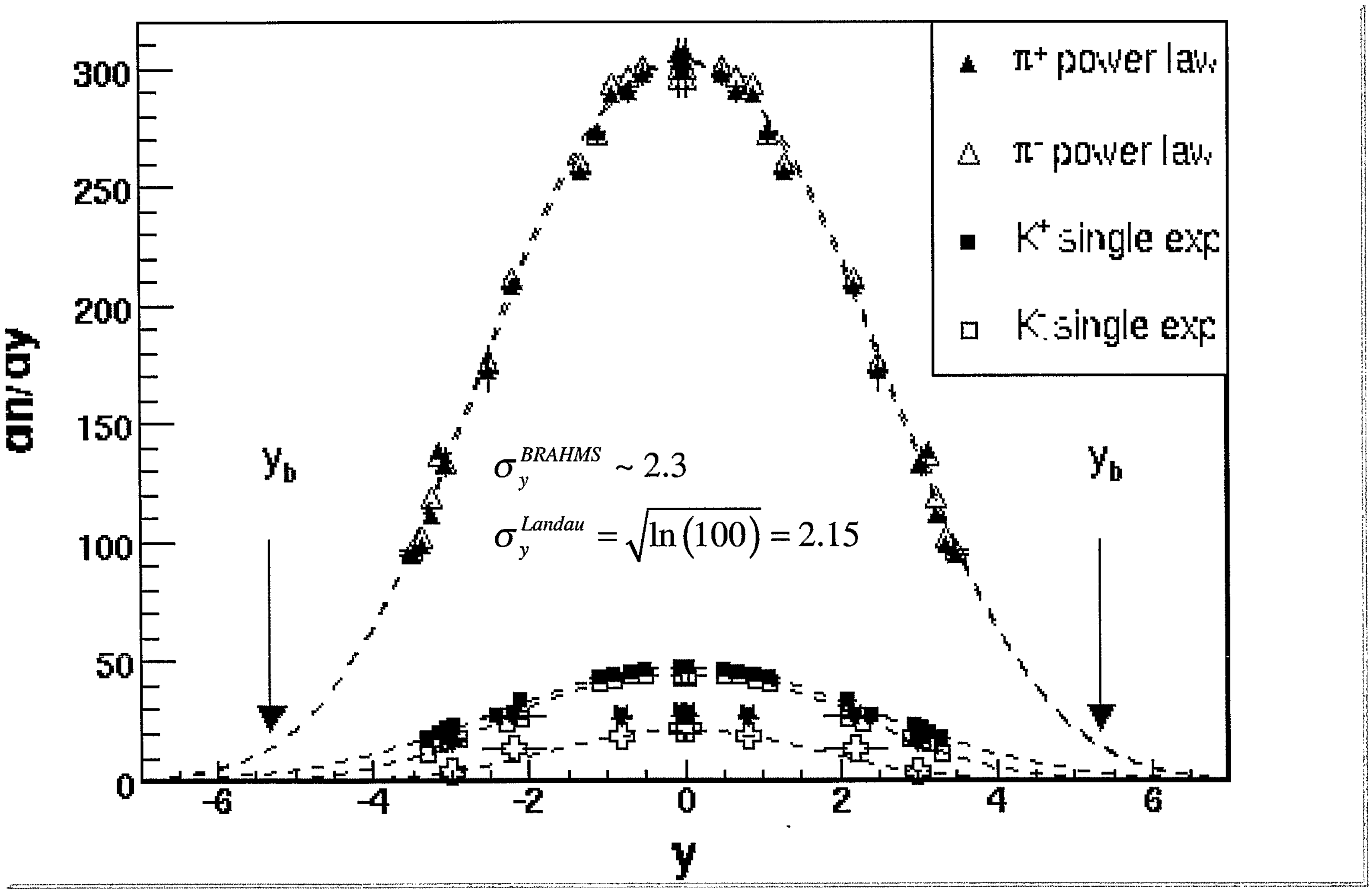


Full stopping



Longitudinal explosion

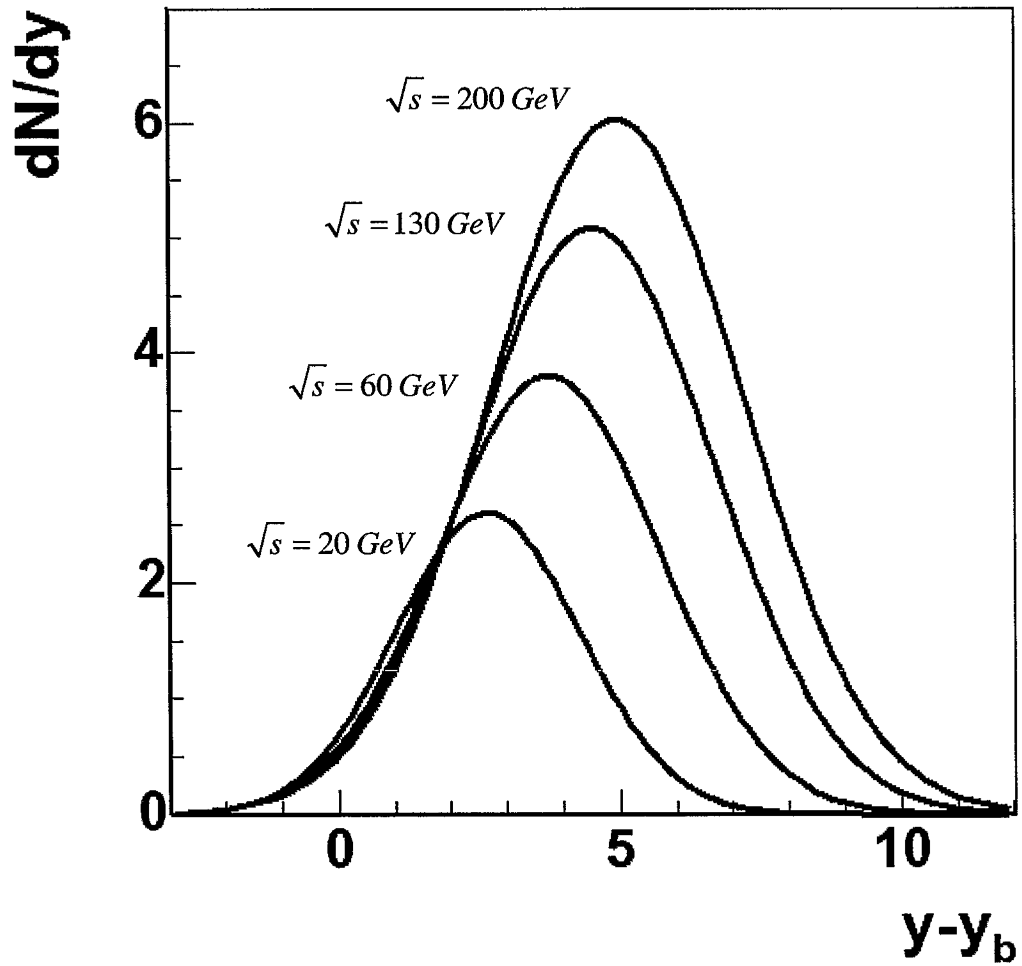
Coincidence #1: BRAHMS dN/dy



BRAHMS Preliminary 2003

Coincidence #2: Scaling

Limiting fragmentation (x scaling) somehow "built-in"



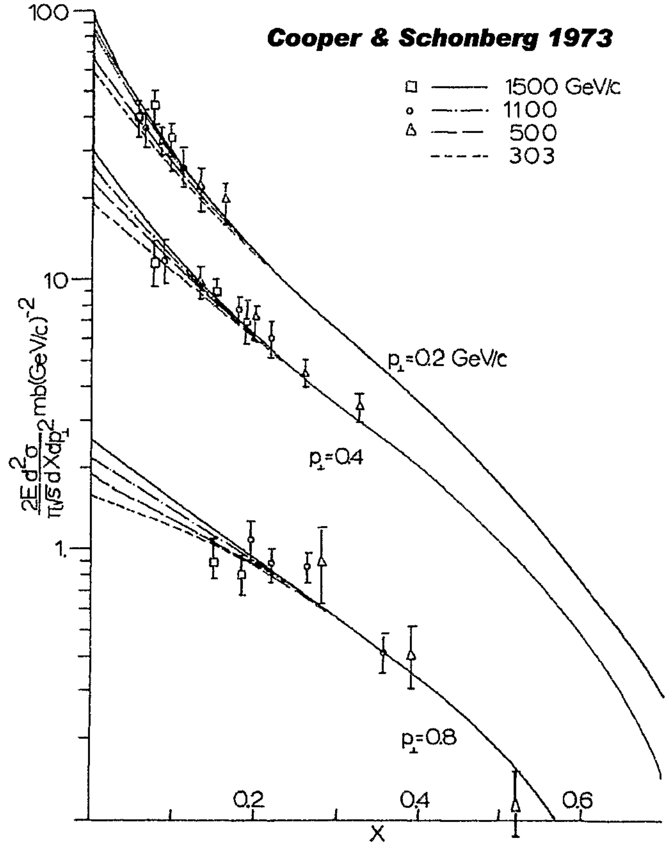
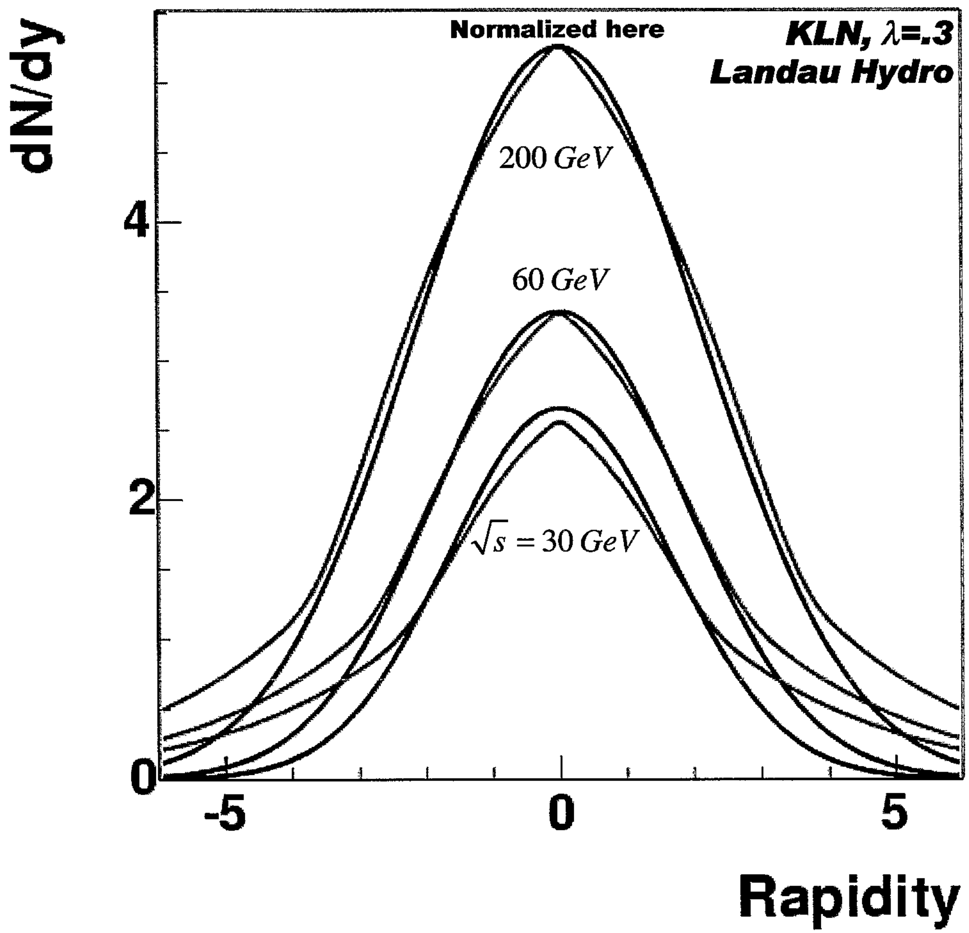


FIG. 3. Invariant inclusive π^+ differential cross section, $2\pi^{-1}E^*d^2\sigma/dx\sqrt{s}\,dp_\perp^2$ at 303, 500, 1100, and 1500 GeV/c, as a function of $x=2p_{\|}^*/\sqrt{s}$. Data points are the same as in Fig. 2(a).

Coincidence #3: KLN



Compare dN/dy

"Default" KLN parameters (normalize @ 200 GeV peak)

Scale in similar fashion both height & width

This was a surprise.

Of course different KLN parameters can make the agreement worse

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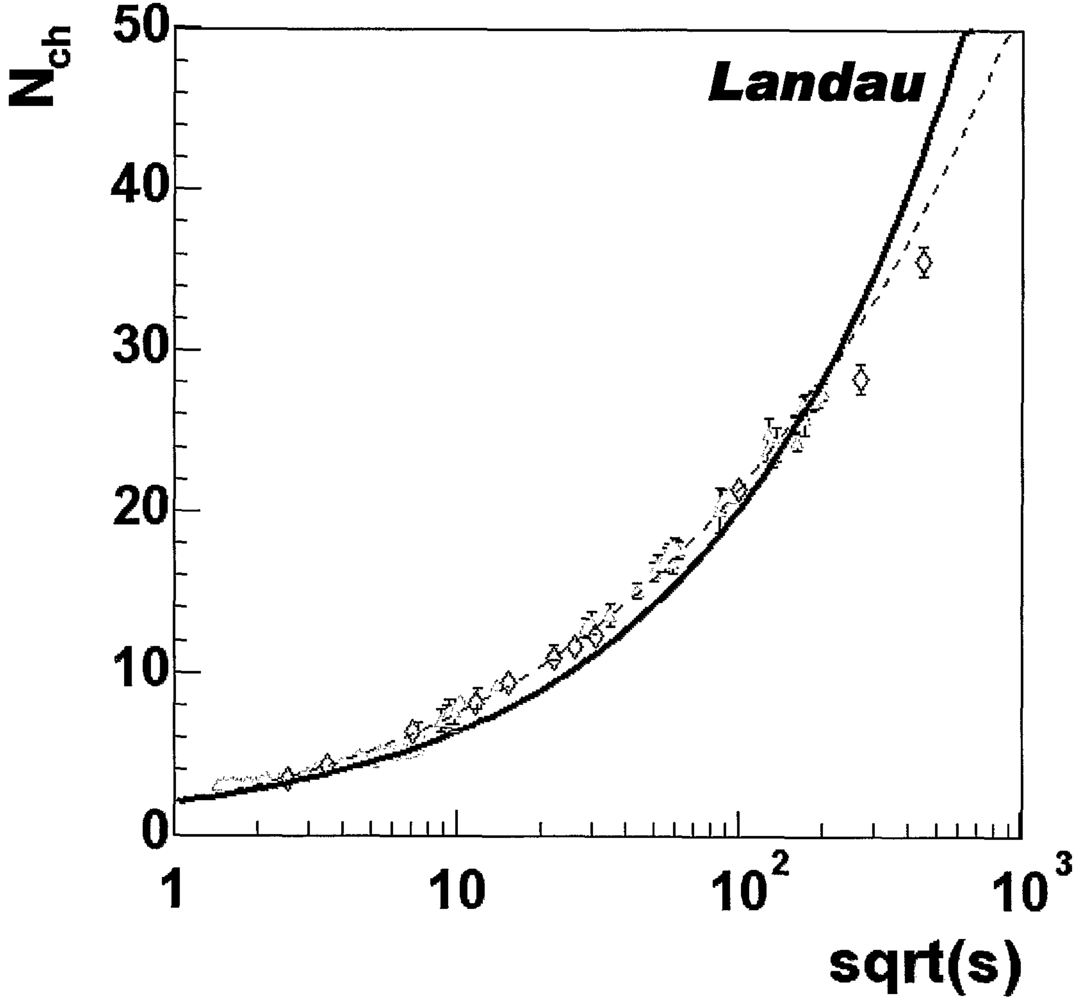
Coincidence #4: Landau vs. Mueller



Landau "better" at low energies

MLLA QCD better at higher energies (esp. including pp@√s/2)

Difference increases dramatically at higher energies (LHC day-1 important)

Oddity: slower increase from pQCD is like

$$c_s^2 > 1/3$$

Coincidence #5: RHIC pp Data

- **<u>One</u> parameter fit to STAR & PHENIX pp data**
  - **L = 0.570±.001 (STAR)**
  - **L = 0.541±.001 (PHENIX)**

- **Power-law has <u>two</u>:**

$$\left(1+\frac{p_T}{p_0}\right)^n$$

- **Not sure if or how this formula works with A+A**
  - **Mass dependence of y_T**

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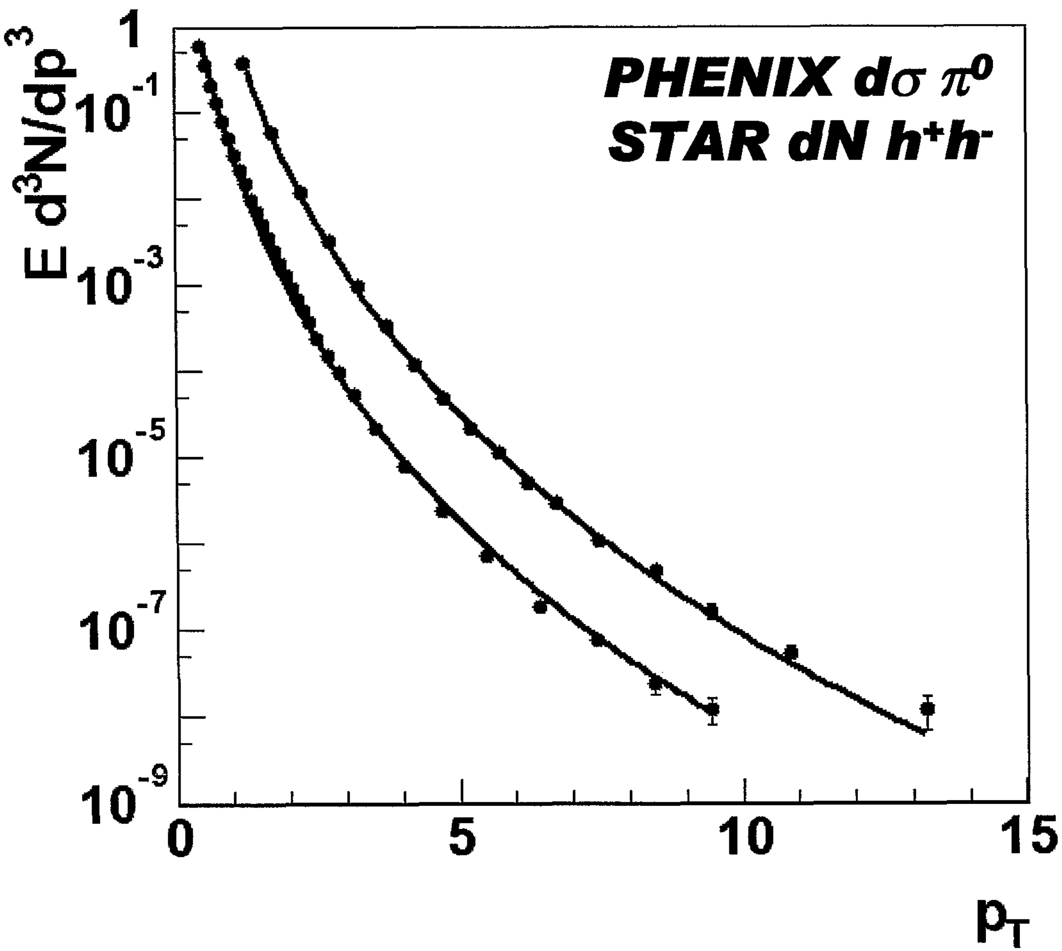


$$\frac{dN}{p_T dp_T} = C\exp\left(-y_T^2/2L\right) \qquad y_T = \frac{1}{2}\ln\left(\frac{m_T+p_T}{m_T-p_T}\right)$$

Net baryon density in $Au + Au$ collisions at RHIC

Steffen A. Bass

RIKEN-BNL Research Center and Duke University

First experiments at the Relativistic Heavy Ion Collider (RHIC) have shown that the matter created in the central rapidity region contains a significant excess of baryons over antibaryons. While a slight baryon excess was not unexpected, the magnitude of the net baryon multiplicity density $dN_{\mathrm{B}-\overline{\mathrm{B}}}/dy \approx 19 \pm 2$ at $\sqrt{s}_{NN} = 130$ GeV and $\approx 14 \pm 4$ at $\sqrt{s}_{NN} = 200$ GeV is higher than what many theoretical models had predicted. In particular models in which the deposition of energy at midrapidity is driven by quasiclassical glue fields or fragmenting color flux tubes, which produce quarks and anti-quarks in equal abundance, underpredicted the data.

In this talk I show that the parton cascade model predicts a net baryon excess at mid-rapidity in Au+Au collisions at RHIC, which is in qualitative agreement with the measured values. Two mechanisms are driving this excess: One is the presence of a net baryon density in the initial state parton distributions at Bjorken-x around 0.01 reflecting the size of the valence quark component in this range of x. The other important factor is the rescattering among partons, which transports more partons, and hence additional net baryon number, to mid-rapidity. This transport mechanism increases the net baryon number density well into the range of measured values.

The transverse momentum distribution of net quarks (quarks minus antiquarks) is calculated as well at two different rapidities. Parton re-scattering and fragmentation is seen to lead to a substantial difference in the slopes of these distributions between mid- and forward-rapidities, in qualitative agreement with the corresponding data for the net baryon distribution.

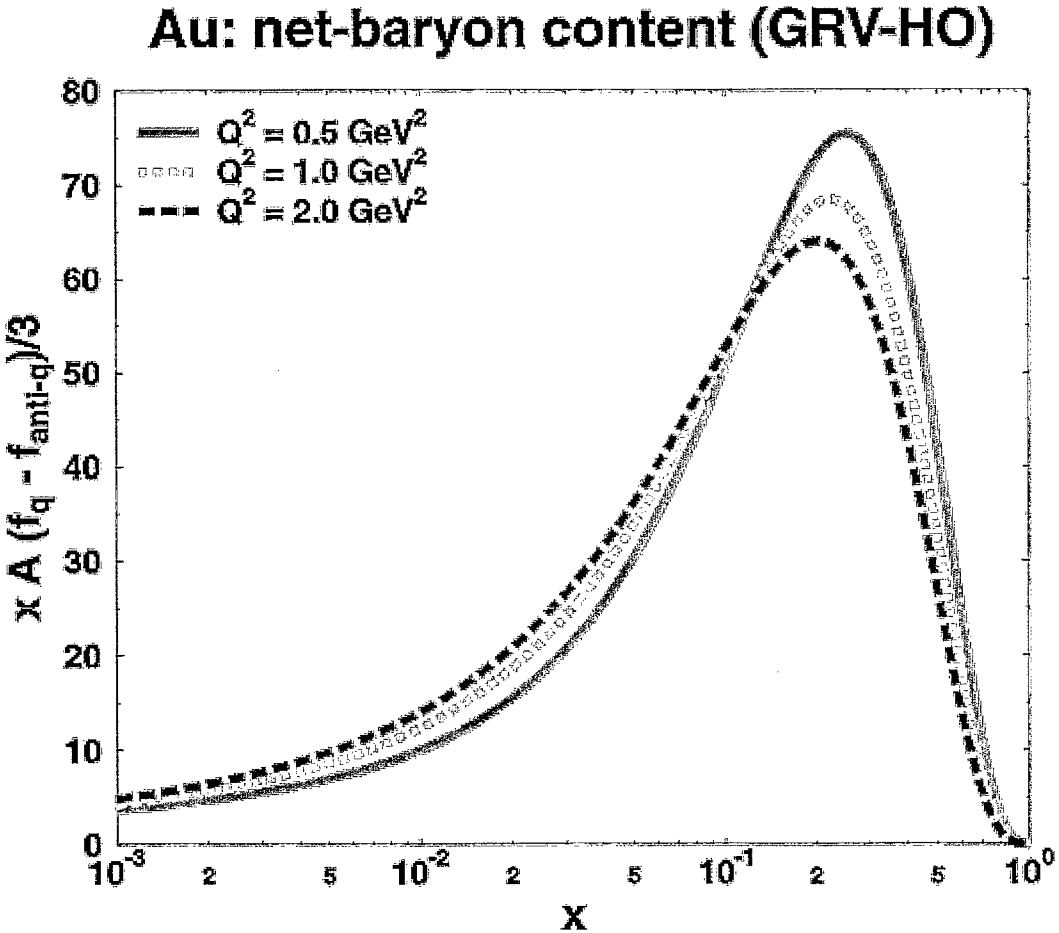
Basic Principles of the PCM

- degrees of freedom: quarks and gluons
- classical trajectories in phase space (with relativistic kinematics)
- initial state constructed from experimentally measured nucleon structure functions and elastic form factors
- an interaction takes place if at the time of closest approach d_{min} of two partons

$$d_{\min} \leq \sqrt{\frac{\sigma_{tot}}{\pi}} \quad \text{with} \quad \sigma_{tot} = \sum_{p_3,p_4} \int \frac{d\sigma\left(\sqrt{\hat{s}}; p_1, p_2, p_3, p_4\right)}{d\hat{t}} d\hat{t}$$

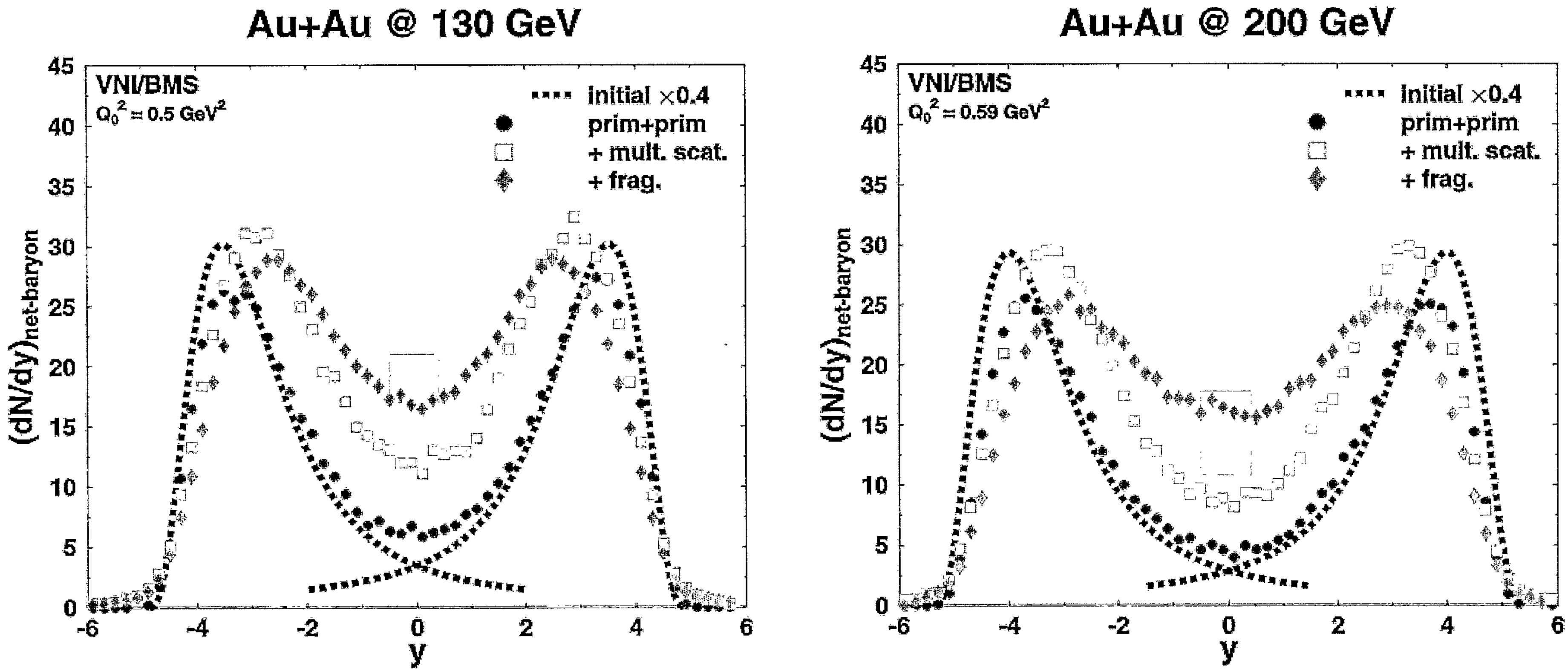
- system evolves through a sequence of binary (2→2) elastic and inelastic scatterings of partons and initial and final state radiations within a leading-logarithmic approximation (2→N)
- binary cross sections are calculated in leading order pQCD with either a momentum cut-off or Debye screening to regularize IR behaviour
- guiding scales: initialization scale Q_0, p_T cut-off p_0 / Debye-mass μ_D, intrinsic k_T, virtuality > μ_0

Stopping at RHIC: Initial or Final State Effect?



- net-baryon contribution from initial state (structure functions) is non-zero, even at mid-rapidity!
  - ➢initial state alone accounts for $dN_{net\text{-}baryon}/dy \approx 5$
- is the PCM capable of filling up mid-rapidity region?
- is the baryon number transported or released at similar x?

Stopping at RHIC: PCM Results

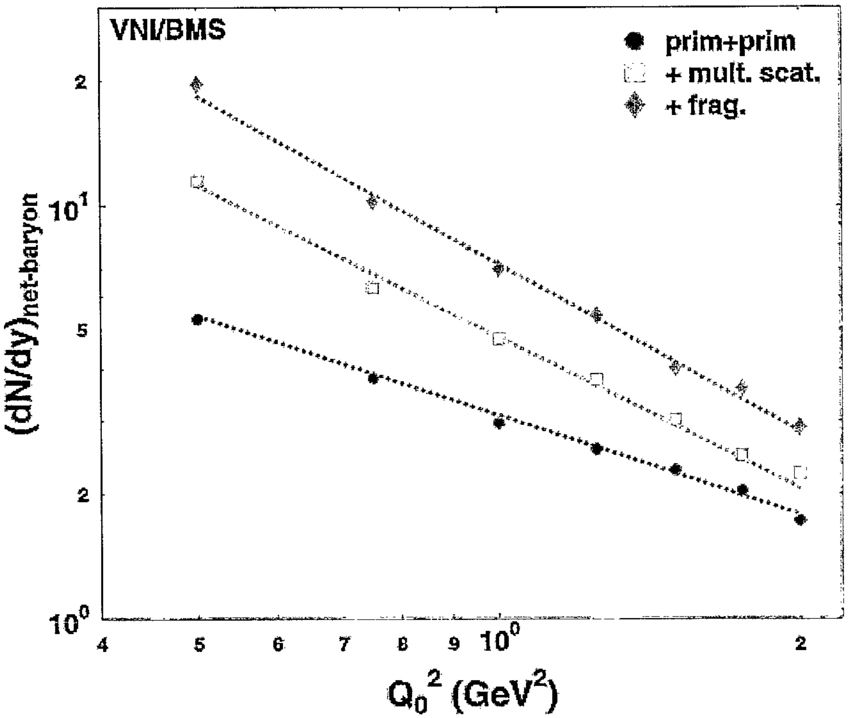


- primary-primary scattering releases baryon-number at corresponding y
- multiple rescattering & fragmentation fill up mid-rapidity domain

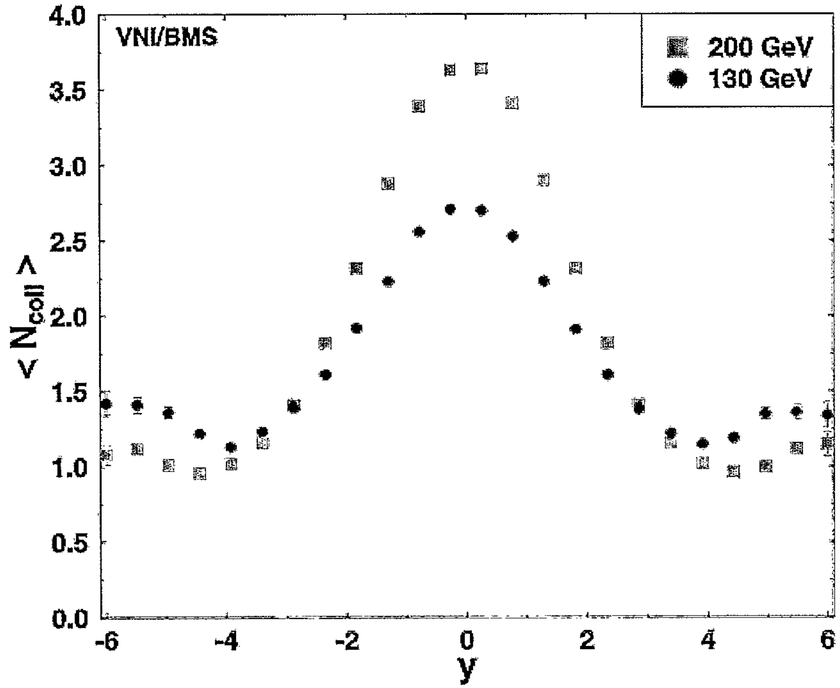
➢ initial state & parton cascading can fully account for data!

Stopping: Dynamics & Parameters

Au+Au @ 200 GeV



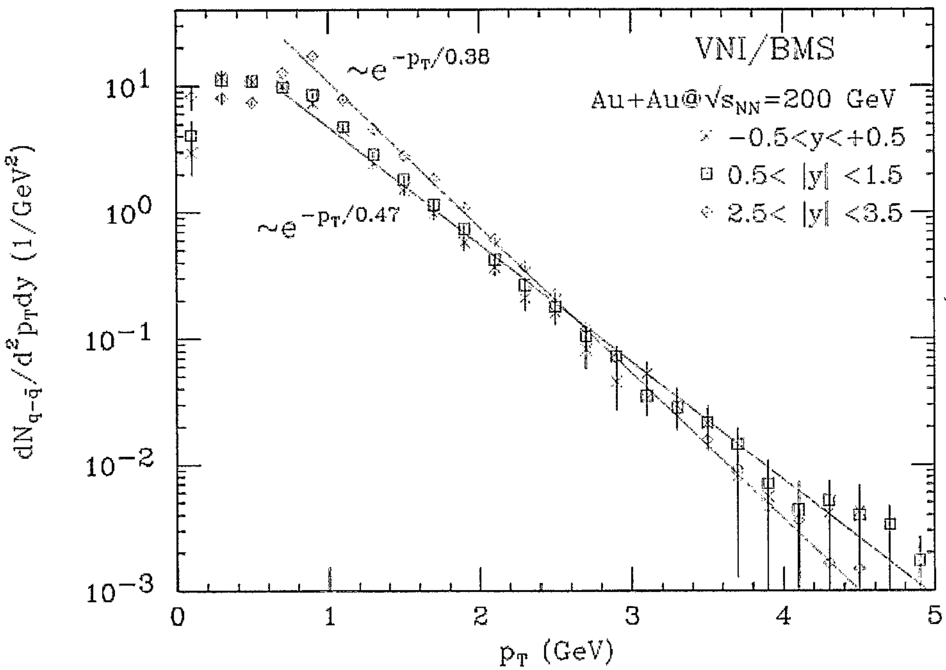
Au+Au @ RHIC

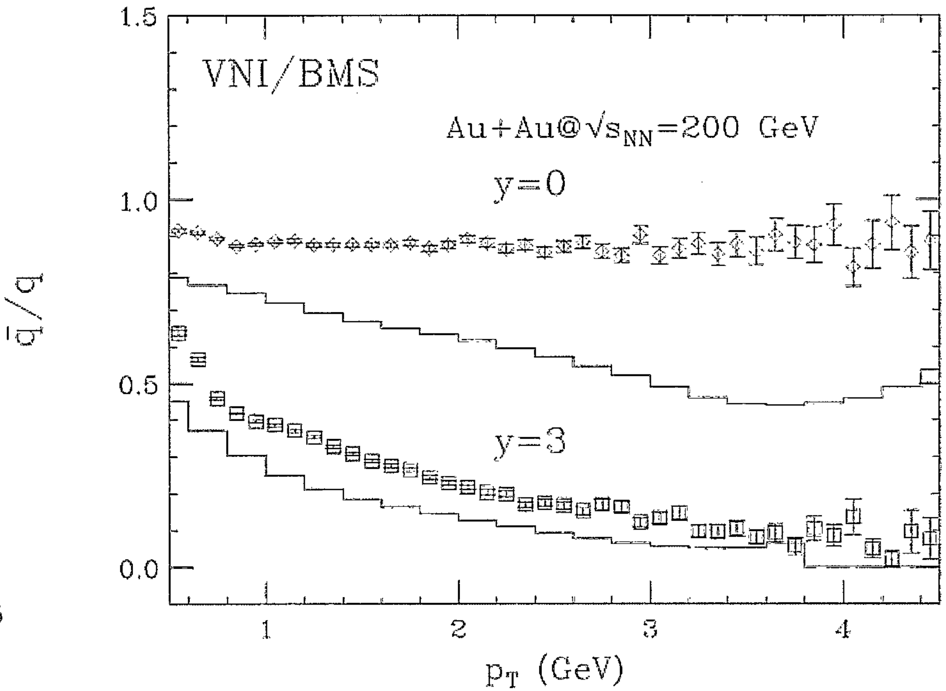


- net-baryon density at mid-rapidity depends on initialization scale and cut-off Q_0
- collision numbers peak strongly at mid-rapidity

Bass, Mueller, Srivastava *RHIC Physics with the Parton Cascade Model*

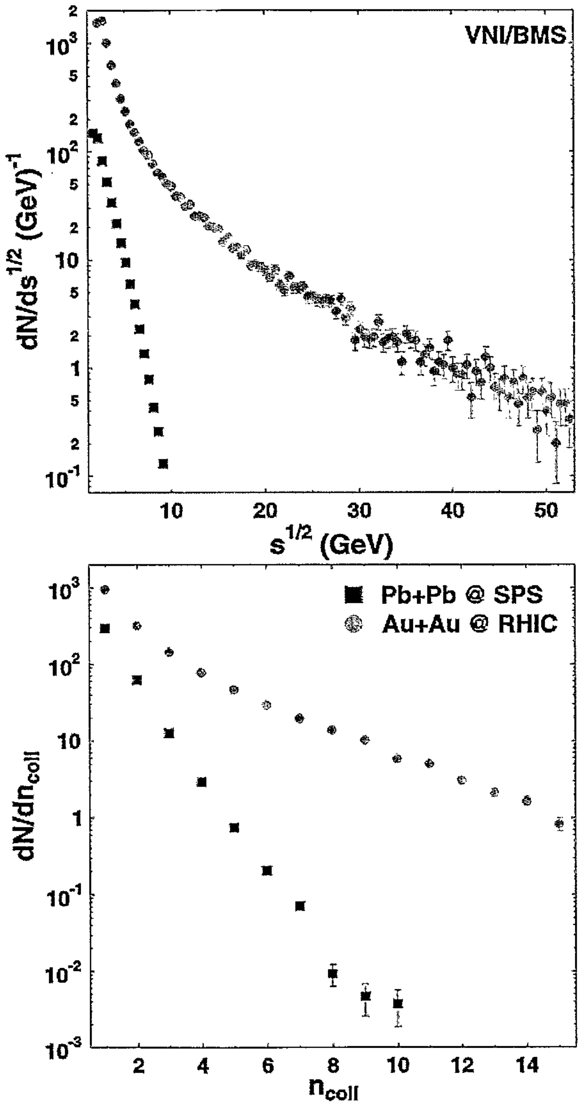
p_t dependence of net-quark dynamics





- slope of net-quark p_t distribution shows rapidity dependence
- qbar/q ratio sensitive to rescattering
- forward/backward rapidities sensitive to different physics than y_{CM}

SPS vs. RHIC: a study in contrast



Bass, Mueller, Srivastava

	SPS	RHIC
cut-off p_t^{min} (GeV)	0.7	1.0
# of hard collisions	255.0	3618.0
# of fragmentations	17.0	2229.0
av. Q^2 (GeV^2)	0.8	1.7
av. (GeV)	2.6	4.7

- perturbative processes at SPS are negligible for overall reaction dynamics
- sizable contribution at RHIC, factor 14 increase compared to SPS

PCM: status and the next steps ...

results of the last year:

- *Parton Rescattering and Screening in Au+Au at RHIC*
- Phys. Lett. **B551** (2003) 277
- *Light from cascading partons in relativistic heavy-ion collisions*
- Phys. Rev. Lett. **90** (2003) 082301
- *Semi-hard scattering of partons at SPS and RHIC : a study in contrast*
- Phys. Rev. **C66** (2002) 061902 Rapid Communication
- *Net baryon density in Au+Au collisions at the Relativistic Heavy Ion Collider*
- Phys. Rev. Lett. **91** (2003) 052302
- *Transverse momentum distribution of net baryon number at RHIC*
- Journal of Physics **G29** (2003) L51-L58

the next steps:

- inclusion of gluon-fusion processes: analysis of thermalization
- investigation of the microscopic dynamics of jet-quenching
- heavy quark production: predictions for charm and bottom
- hadronization: develop concepts and implementation

Momentum anisotropies – probing the detailed dynamics

Peter Kolb

Department of Physics and Astronomy, SUNY Stony Brook, Stony Brook, NY 11794-3800, USA

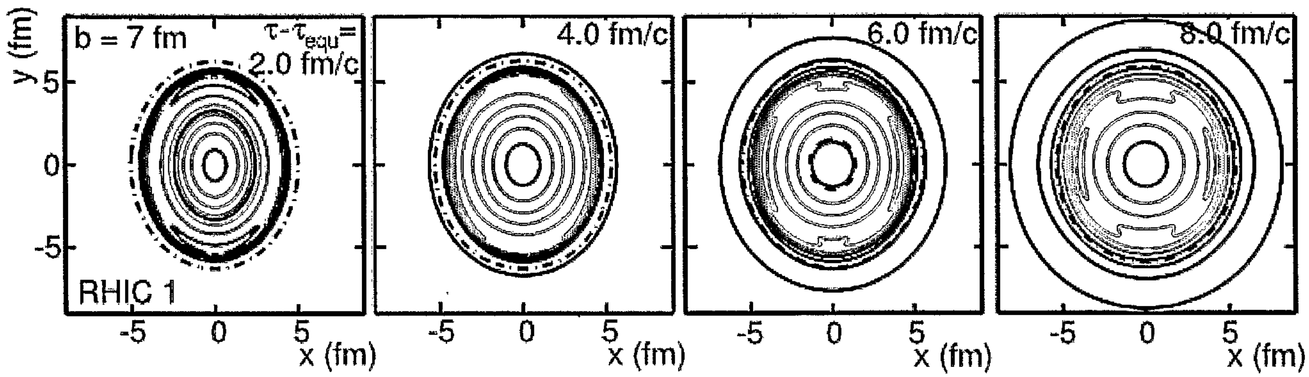
Non-central collisions of large nuclei such as Au feature a strongly deformed overlap region. This geometric eccentricity drives an anisotropic evolution of the region of initial energy deposition, which ultimately manifests itself in an anisotropic particle distribution pattern in the transverse plane perpendicular to the beam axis. This is usually classified in terms of the Fourier expansion of the transverse momentum spectra. As the initial geometric eccentricity with anisotropic pressure gradients leads to an anisotropic motion of the expanding matter, the driving source of the generation of momentum anisotropy reduces itself and eventually even vanishes. Different approaches to model this dynamics agree that this transition of geometric to momentum anisotropy happens on a timescale that is comparable to the livetime of the plasma stage of the reaction. Probing momentum anisotropies thus means probing the system at temperatures beyond the critical temperature.

Today, the analysis of momentum anisotropies has been restricted to the first order of the deformation – the elliptic coefficient v_2. Following the arguments of [1] I will show that higher order anisotropies can also achieve significantly large values, particularly at large transverse momenta. Gaining knowledge about those higher order corrections will ultimately deliver the full picture of transverse momentum spectra, triple differentially in rapidity, momentum and azimuthal angle.

With the help of a full hydrodynamic calculation I show that higher order anisotropies can achieve significant values, which make them accessible todays experiments. Then, along the lines of the blast-wave approximation I illustrate the high sensitivity of the higher anisotropies to the flow field generated by the collective expansion, and point out an extremely strong correlation of small flow variations and higher order anisotropies in the particle spectra. These small flow anisotropies are in turn expected to be very sensitive on details of the transverse dynamics and thus also on details of the underlying model calculations. Finally I will analyze anisotropies in the high momentum region from a model that assumes extreme jet quenching within the overlap region. Within the assumptions taken in this model, an intriguing centrality dependencies of the saturation values of higher flow anisotropies at large transverse momenta is predicted.

Higher order anisotropies thus have a promising future to strongly constrain input parameters of model calculations and will allow us to make more quantitative statements on the nuclear equation of state at extreme energies as well as thermalization processes and their duration.

[1] Peter F. Kolb, Phys. Rev. C 68 (2003) 031902(R)



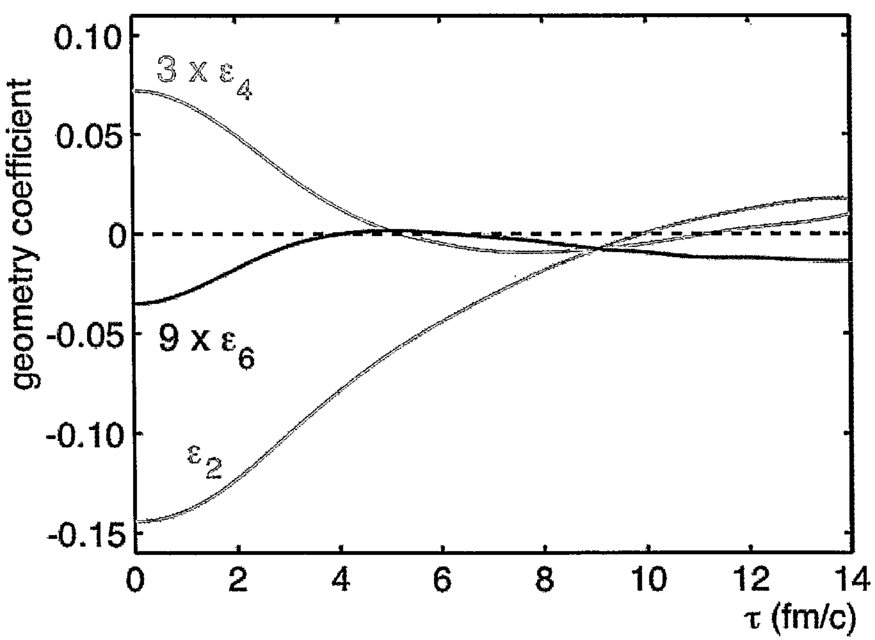
quantify anisotropies

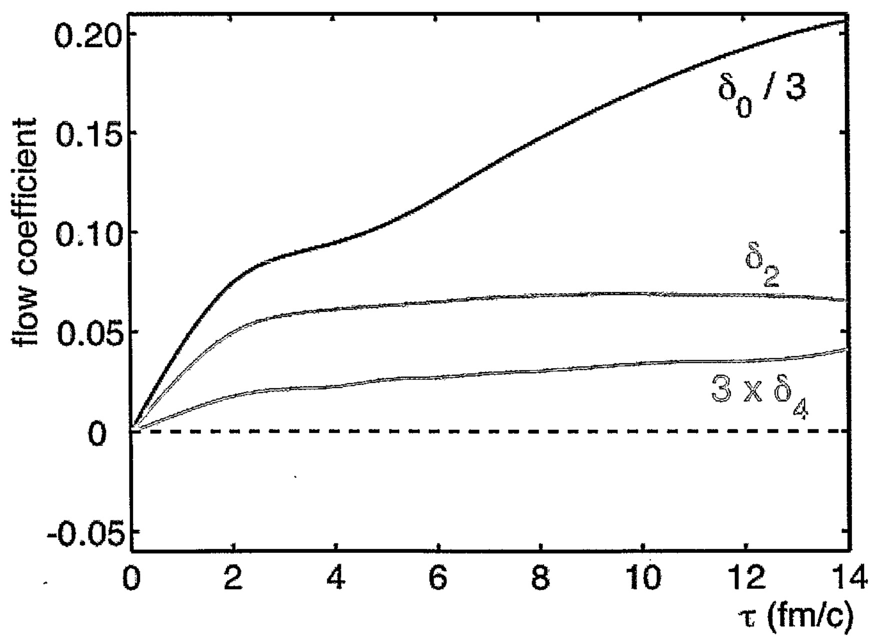
coordinate space

$$\epsilon_n(\tau) = \langle \cos(n\varphi) \rangle$$

momentum space

$$\delta_n(\tau) = \langle v_T \cos(n\varphi_v) \rangle$$

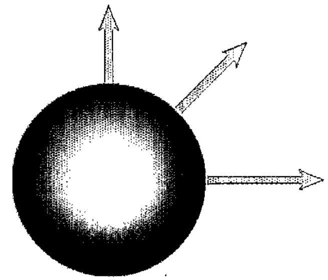




Blast wave parametrization for non-central collisions

Generalization of: Huovinen, PFK, Heinz, Ruuskanen, Voloshin, PLB 503 (01) 58

Radial rapidity-field with angular modulation:



$$\rho(r,\varphi_s) = \rho_0(r)\,(1 + 2f_2\cos(2\varphi_s)) \\ + 2f_4\cos(4\varphi_s) \\ + 2f_6\cos(6\varphi_s)\ldots$$

Freeze-out on azimuthally symmetric hypersurface of temperature *T*:

$$\frac{dN}{dyp_Tdp_Td\varphi_p} \propto \sum_{k=1}^{\infty}(\pm)^{k+1}\int rdrd\varphi_s\tau_f\, e^{k\alpha(\varphi_s+\varphi_p)\cos(\varphi_s)}\,\mathrm{K}_1(k\beta(\varphi_s+\varphi_p))$$

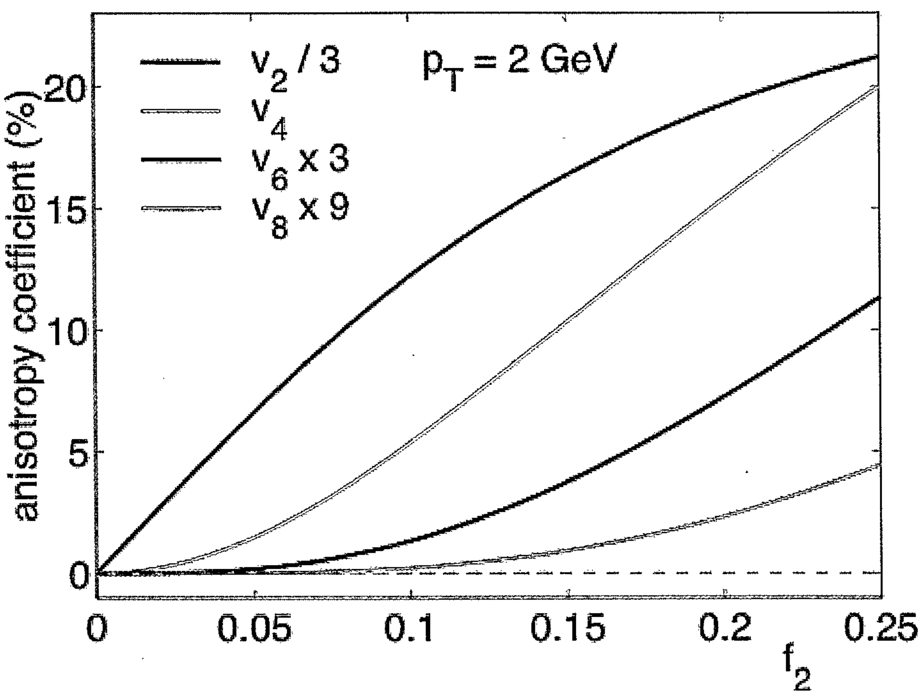
$$\alpha = p_T/T\sinh\rho \qquad \beta = m_T/T\cosh\rho$$

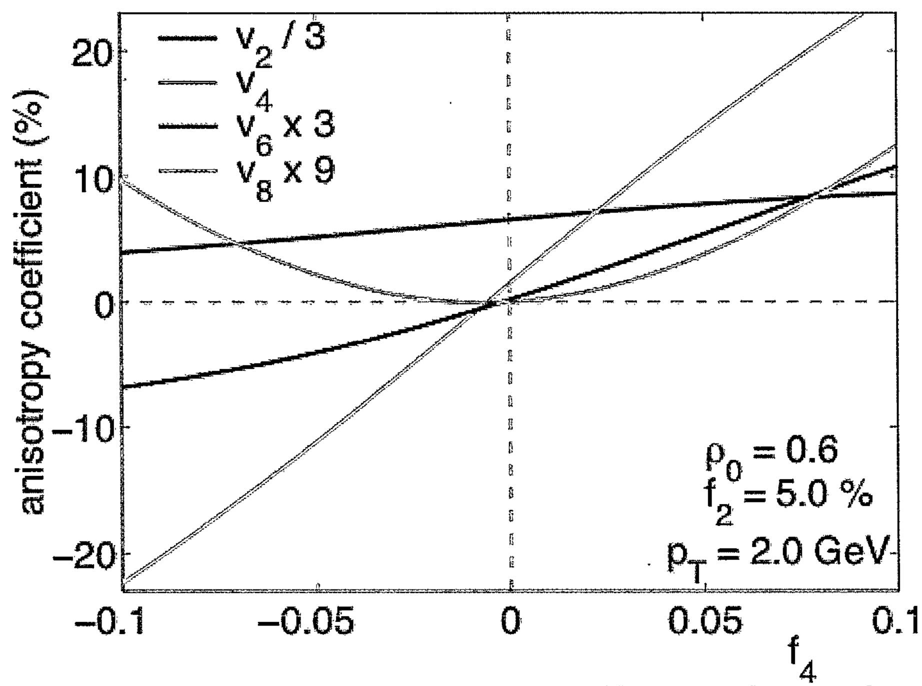
Collapse of the radial integration onto shell:

$$v_n(p_T) = \frac{\sum(\pm)^{k+1}\int d\phi\cos(n\phi)\,\mathrm{I}_n(k\alpha(\phi))\,\mathrm{K}_1(k\beta(\phi))}{\sum(\pm)^{k+1}\int d\phi\,\mathrm{I}_0(k\alpha(\phi))\,\mathrm{K}_1(k\beta(\phi))}$$

SENSITIVITY ON f_2 AND f_4

at some fixed transverse momentum (here p_T =2 GeV)





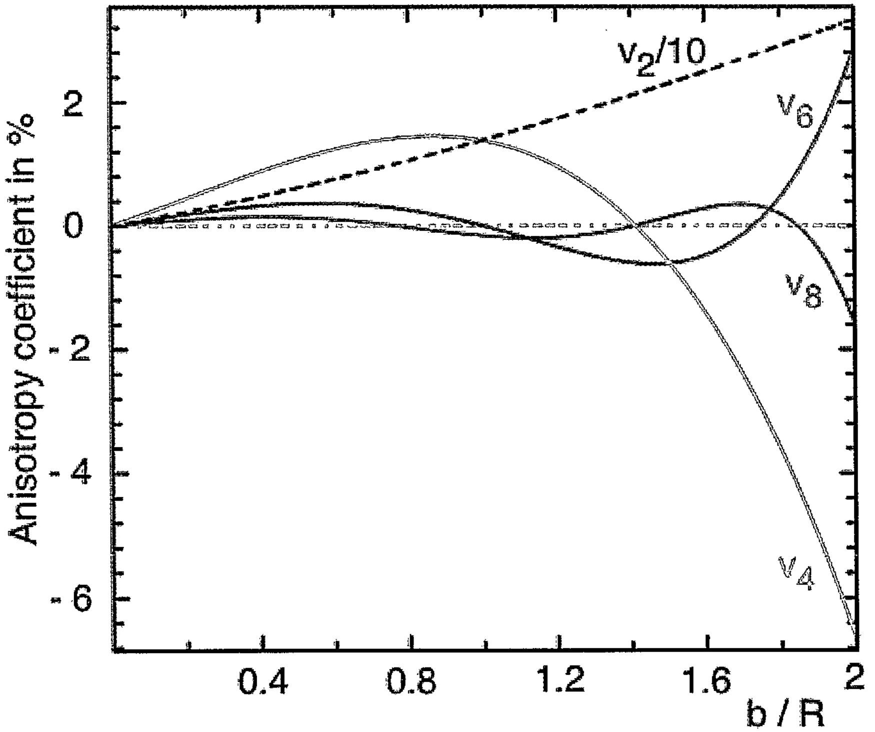
A purely elliptic flow anisotropy produces a small quadrupole moment after folding with the thermal distriution...

... an additional small quadropole distortion in the flow field yields a large quadrupole moment in the particle distribution

Limiting Anisotropies versus Centrality

PFK, Phys. Rev. C 68 (2003) 031902(R)

$$\alpha = \arccos \frac{b}{2R} \qquad v_n = (-1)^{n/2} \frac{1}{1-n^2} \frac{\sin(n\alpha)}{n\alpha}$$



$$v_2 = \frac{\sin(2\alpha)}{6\,\alpha}$$

$$v_4 = -\frac{\sin(4\alpha)}{60\,\alpha}$$

$$v_6 = \frac{\sin(6\alpha)}{210\,\alpha}$$

$$v_8 = -\frac{\sin(8\alpha)}{504\,\alpha}$$

Extreme jet-quenching leads to interesting centrality dependence!

This picture predicts a peanut like distribution as well!

Summary: Why Study Higher Harmonics ?

Get a full picture of the transverse momentum spectrum

$$\frac{dN}{p_T dp_T dy d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2\,v_2\cos(2\varphi) + 2\,v_4\cos(4\varphi) + 2\,v_6\cos(6\varphi) + \ldots\right)$$

Ideally, triple differentially for different centrality classes: $v_n(p_T, y; b)$

with odd coefficients at $y \neq 0$

Anisotropies are

- generated early in the evolution

  ⇒ probe the hottest stages

- very sensitve on details of the dynamics

  ⇒ will allow very quantitative statements

BROOKHAVEN
NATIONAL LABORATORY

NIKHEF

Directed and elliptic flow from Au+Au collisions at 200 GeV and azimuthal correlations in p+p and d+Au collisions at 200 GeV

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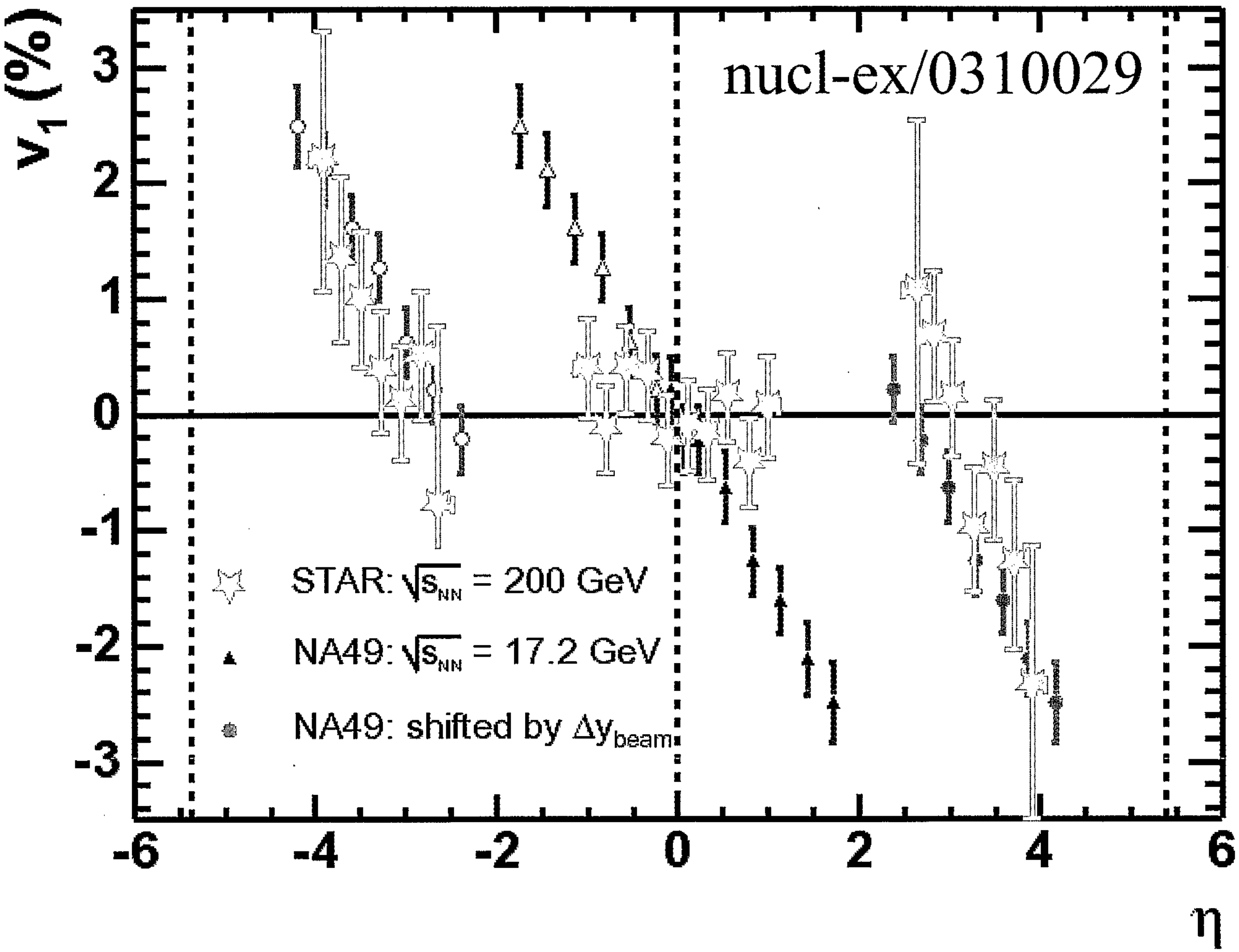
Aihong Tang for the STAR Collaboration

Directed flow at RHIC

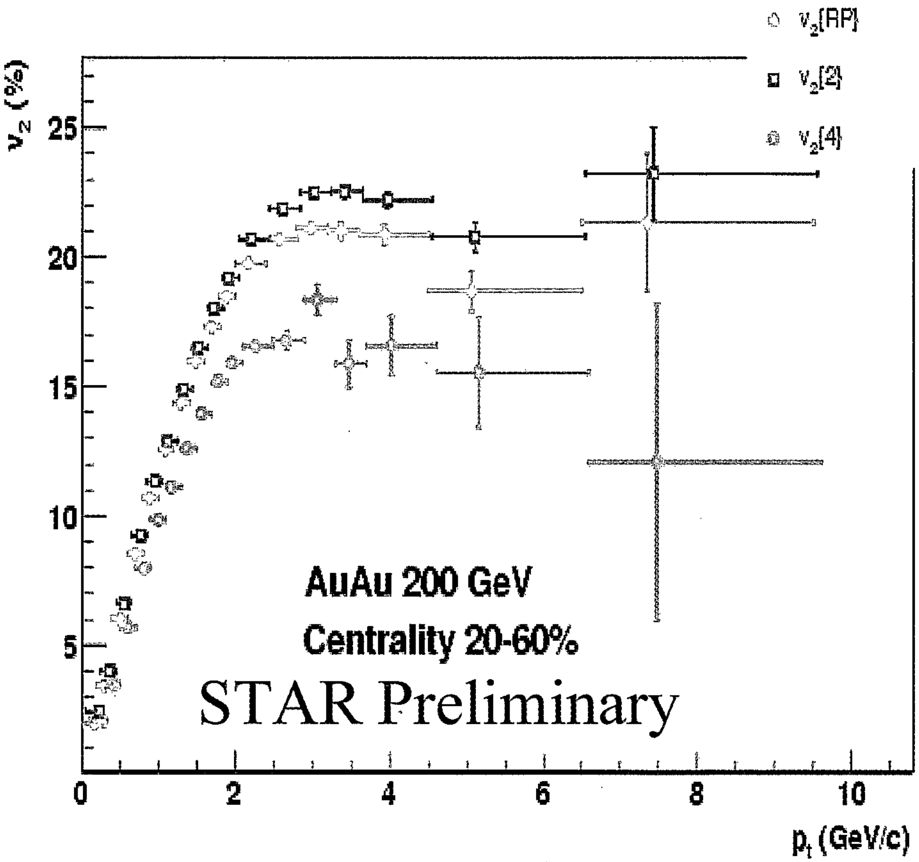


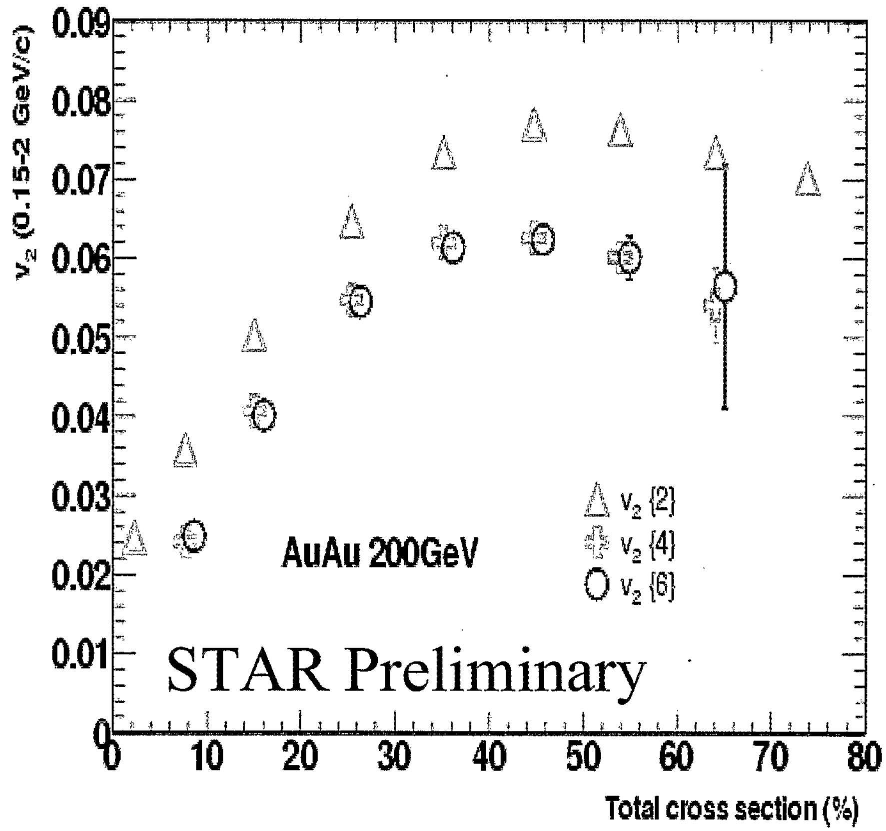
In-plane elliptic flow confirmed

Consistent with a "limiting fragmentation" hypothesis.

Shows no sign of a "wiggle" (also does not exclude the magnitude as predicted)

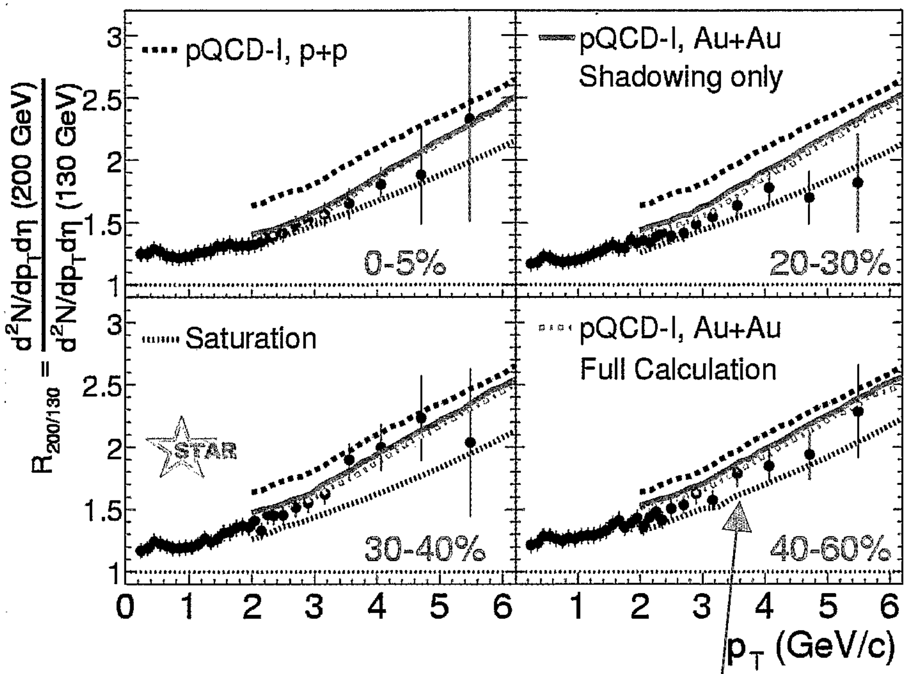
High pt v2 and correlation : the test of jet quenching



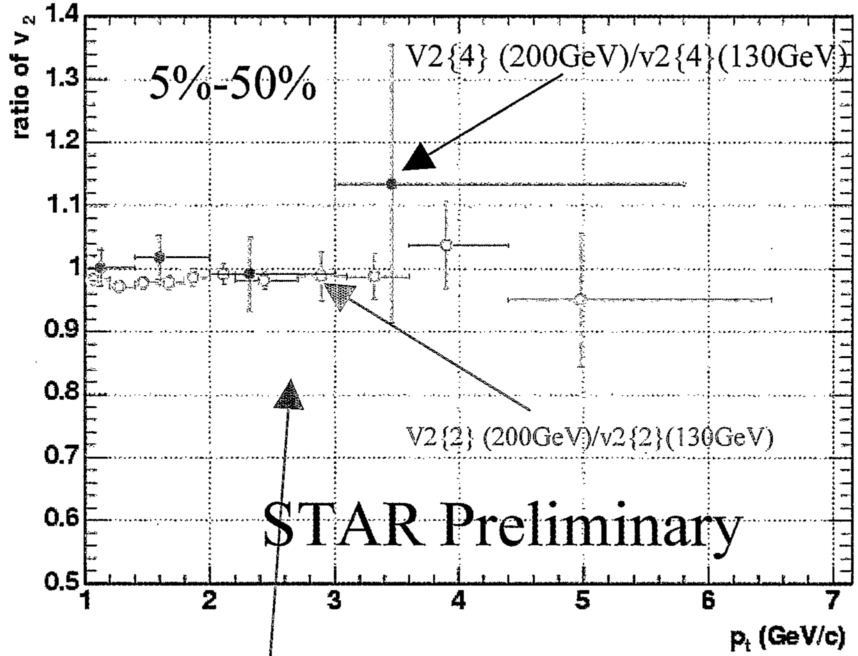


Significant v2 up to ~7 GeV/c in pt, the region where hard scattering begins to dominate. Nonflow from 4 particle correlation, v{6}-v{4} is negligible.

High pt v2 and correlation : the test of jet quenching 200 GeV/130 GeV

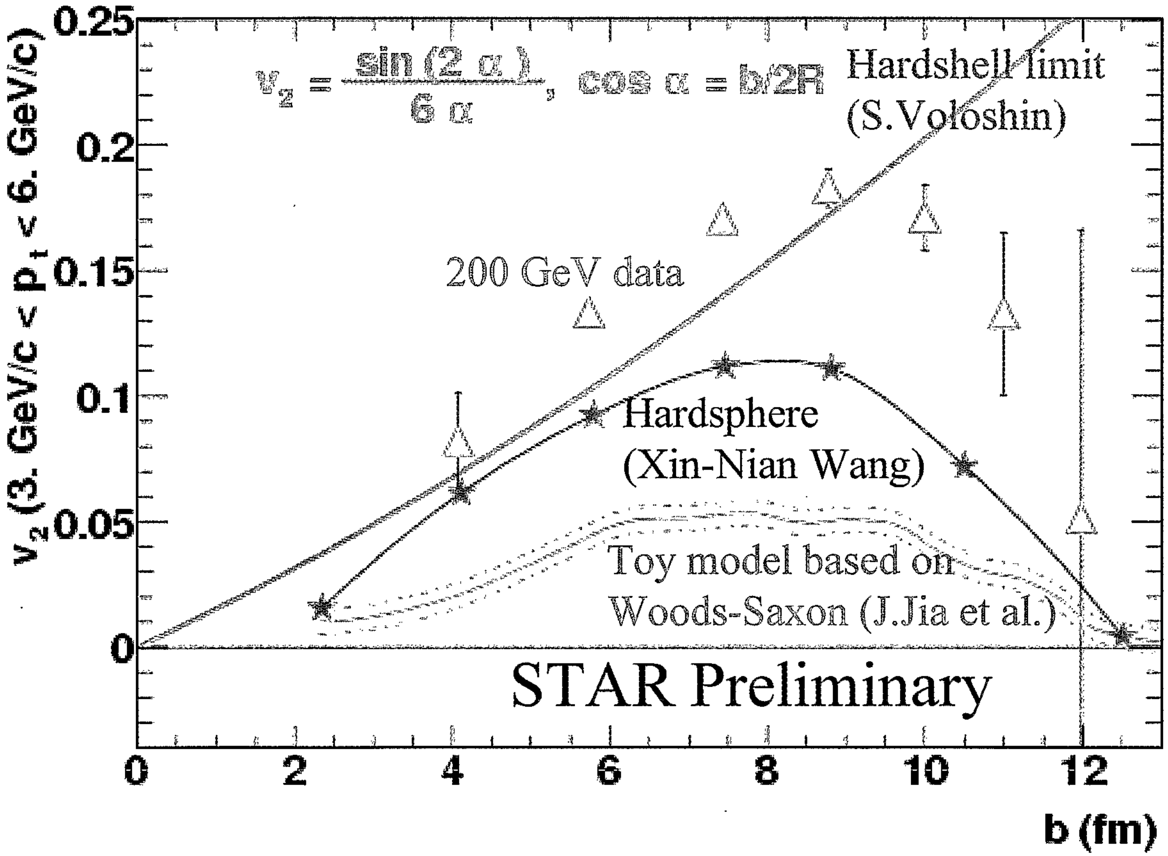


Nucl-ex/0305015

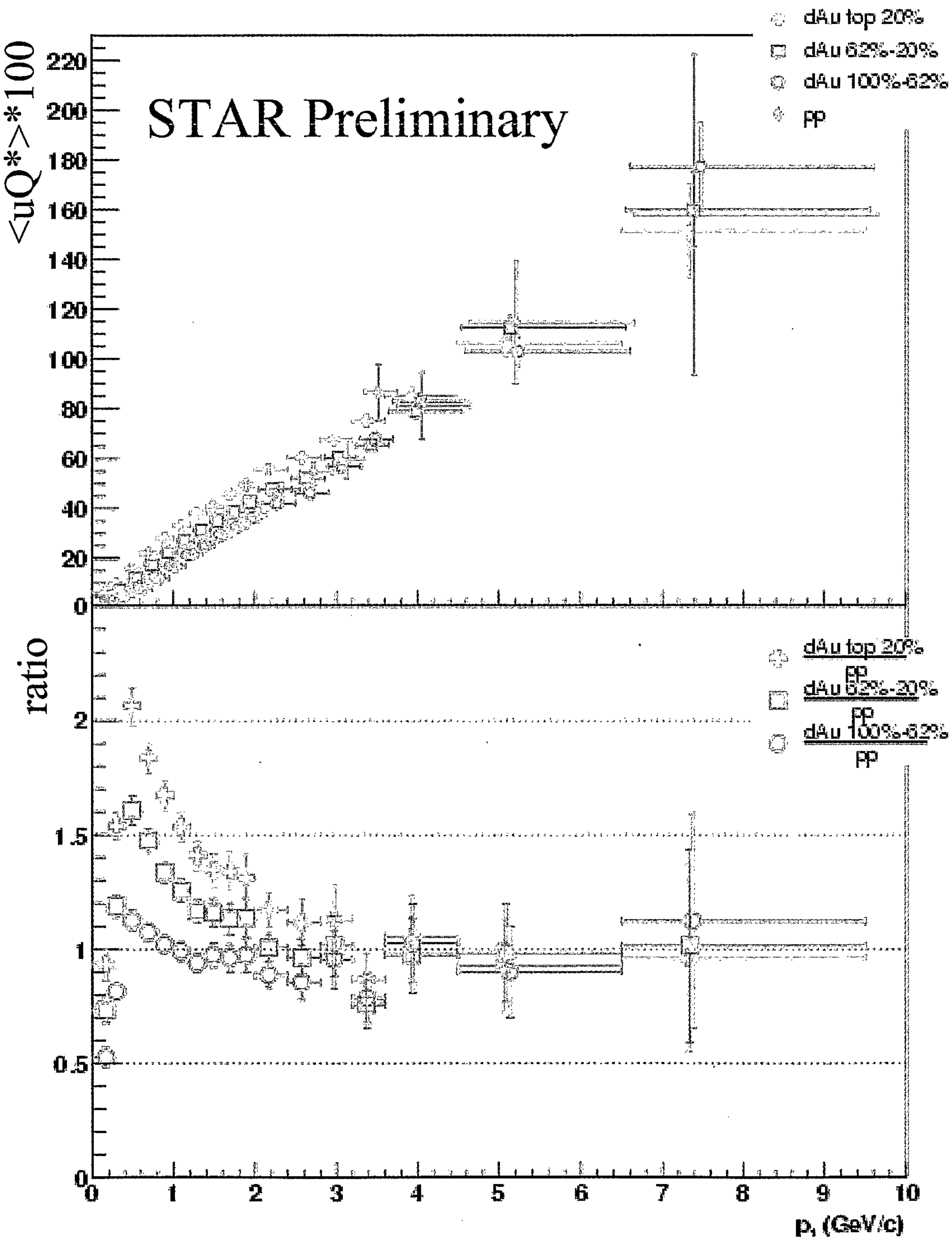


Yields increases but v2 stays the same consistent with "jet quenching" picture.

High pt v2 and correlation : the test of jet quenching



V2 from middle central collisions exceeds the upper limit set by hard shell emission - why ? Coalescence?



Is there "elliptic flow" in dAu collisions ?

V1 Conclusions

- V1 from 3 particle cumulant analysis confirms the *in-plane* elliptic flow
- V1 at RHIC supports the "limiting fragmentation" hypothesis.
- V1 is found to be flat at middle rapidity -> consistent with theoretical predictions.

V2 Conclusions

- Sizable v2 is found up to 7 GeV/c in pt.
- Nonflow contribution to 4 particle correlations is negligible.
- V2 at moderate pt increases little from 130 GeV to 200 GeV, while yields increases significantly -> qualitatively consistent with geometrical v2
- V2 at moderate pt is too high to be explained by "jet quenching" alone.
- Back-to-back suppression is larger in the out-of-plane direction

Conclusion of azimuthal correlation in dAu

- Some azimuthal asymmetry is developed at low pt in dAu collisions, could be due to multiple hadronic rescattering.
- As expected, such azimuthal asymmetry is not found in Hijing due to the fact that Hijing does not have collectivity.

Azimuthal Anisotropy: The Higher Harmonics

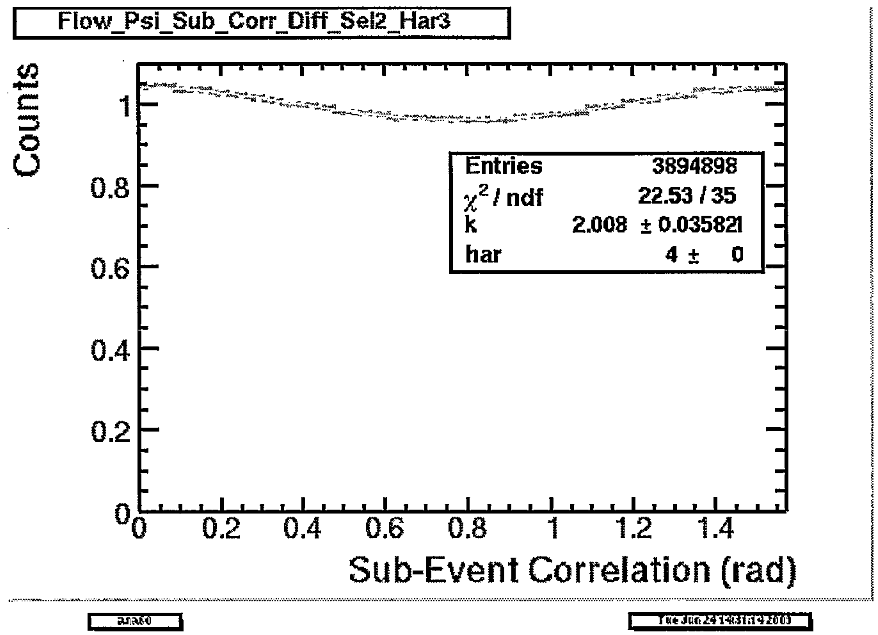
Art Poskanzer for the STAR Collaboration

We report the first observations of the fourth harmonic (v4) in the azimuthal distribution of particles at RHIC. The measurement was done taking advantage of the large elliptic flow (v2) generated at RHIC. The integrated v4 is about a factor of 10 smaller than v2. For the sixth (v6) and eighth (v8) harmonics upper limits on the magnitudes are reported.

STAR

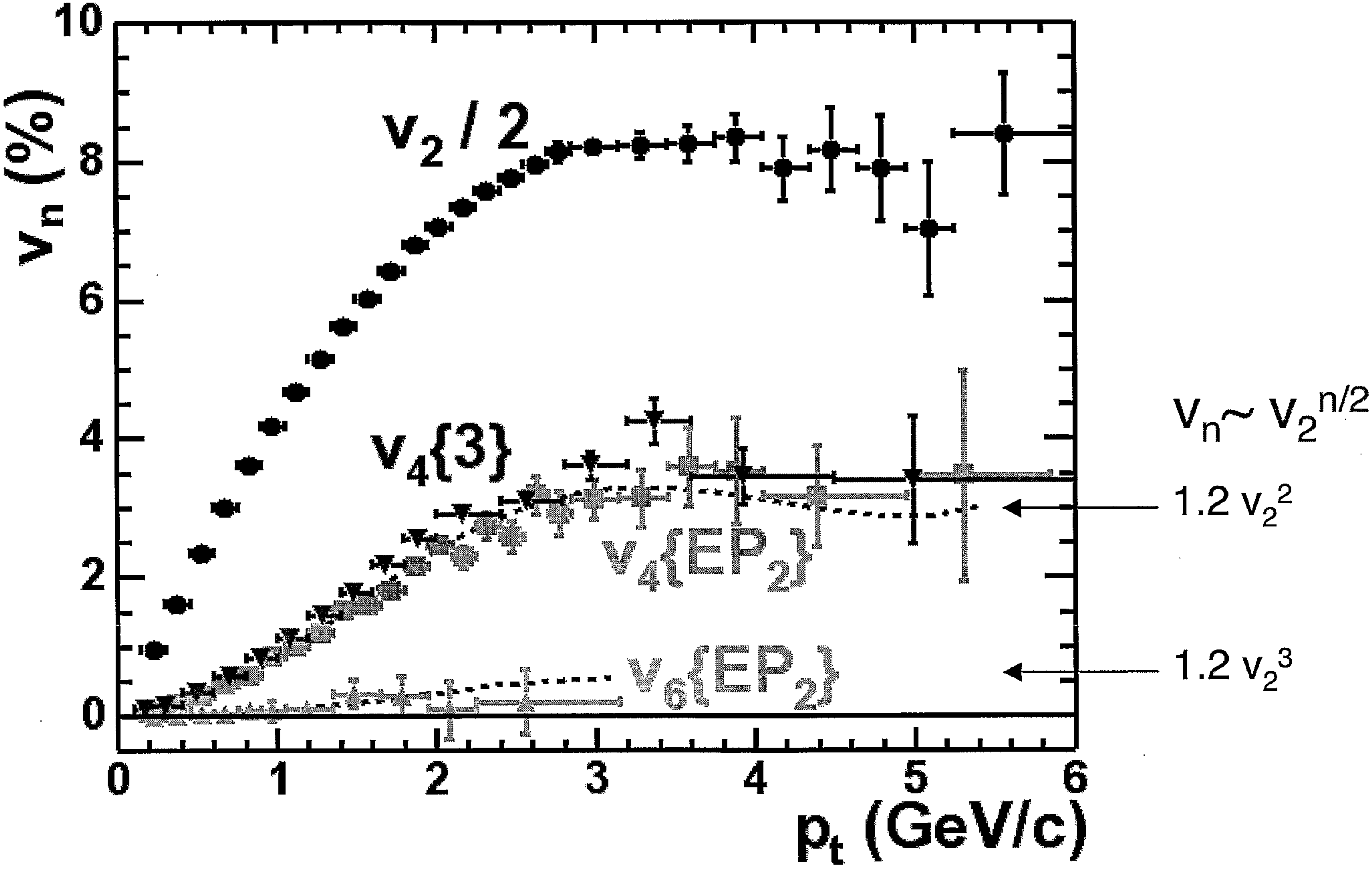
v_2 determines the reaction plane

- v_1 (Aihong Tang), v_4 v_6 and v_8 using **second** harmonic particles
- Possible because v_2 is so large at RHIC and event plane resolution is so good in STAR



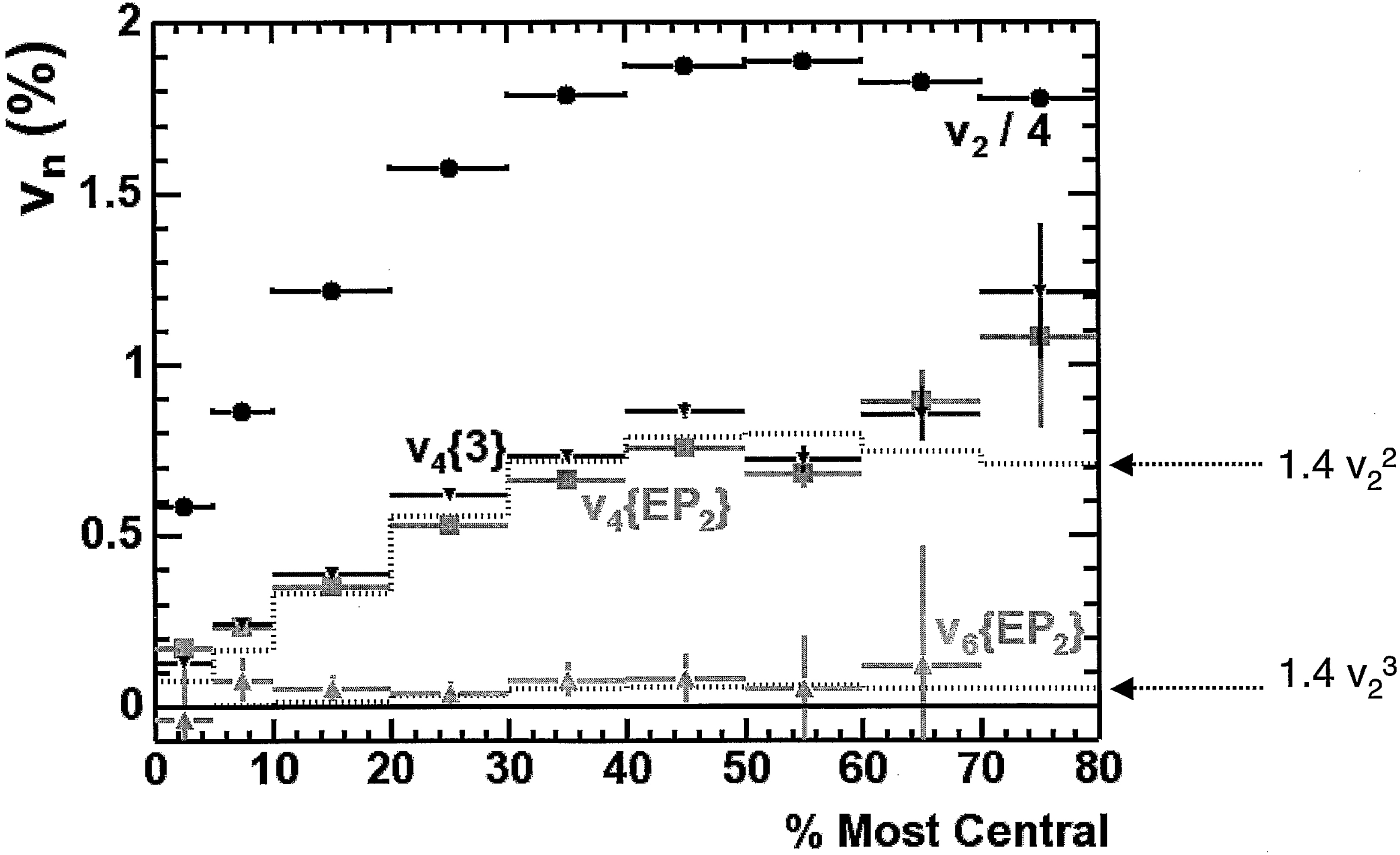
4^{th} harmonic of one subevent relative to 2^{nd} harmonic of other subevent:
v_4 positive

$v_4(p_t)$



v2 / 2
v4{3}
v4{EP2}
v6{EP2}
vn (%)
pt (GeV/c)
0
2
4
6
8
10
0
1
2
3
4
5
6
vn~ v2n/2
1.2 v22
1.2 v23

v_4(centrality)



Poskanzer and Tang

STAR

v triply integrated
in MTPC

v	%
2	5.18 +/- 0.005
4	0.44 +/- 0.009
6	0.043 +/- 0.037
8	-0.06 +/- 0.14

Two sigma upper limit is 0.1% (for v = 6)

Conclusions

- v_4 compared to v_2
  - Integrated, a factor of 12 smaller
  - v_2^2 scaling
- v_6
  - Probably another factor of 10 smaller
  - Consistent with v_2^3 scaling
- Hydro, sensitive to initial conditions
  - v_4 fits very well
  - v_6 is zero instead of negative from hydro
- Waist
  - v_4 larger than needed to remove the waist
- $v_4\{EP_4\}$
  - 3x high because of either fluctuations or nonflow

Update on flow studies with Phobos

Steve Manly (University of Rochester) representing the PHOBOS collaboration

Abstract

Several different techniques used by PHOBOS to measure directed and elliptic flow are described. Most of the methods correlate a reaction plane and $v_1(v_2)$ measured in widely separated regions of the detector in pseudorapidity. Recent BRAHMS and (preliminary) STAR results on $dN/d(p_T)$ and $v_2(p_T)$ in the forward region are convoluted with reasonable assumptions and found to yield an average v_2 at $\eta \sim 2.2$ which is consistent with the published PHOBOS $v_2(\eta)$ data. The drop in v_2 as a function of η appears to be driven by the change in the slope of $v_2(p_T)$ as a function of η. PHOBOS is in the process of finalizing track and hit-based results at 200 GeV and hopes to release preliminary results on directed flow in Au-Au collisions at three energies soon.

PHOBOS flow analyses based on subevent technique

Poskanzer and Voloshin, Phys. Rev. C58 (1998) 1671.

Azimuthal symmetry is critical

Strategies:

Hit-based analyses

- **Avoid the holes – Offset vtx method** →
- **Use the holes – Full acceptance method** →
- **Use a different type of analysis, such as cumulants**

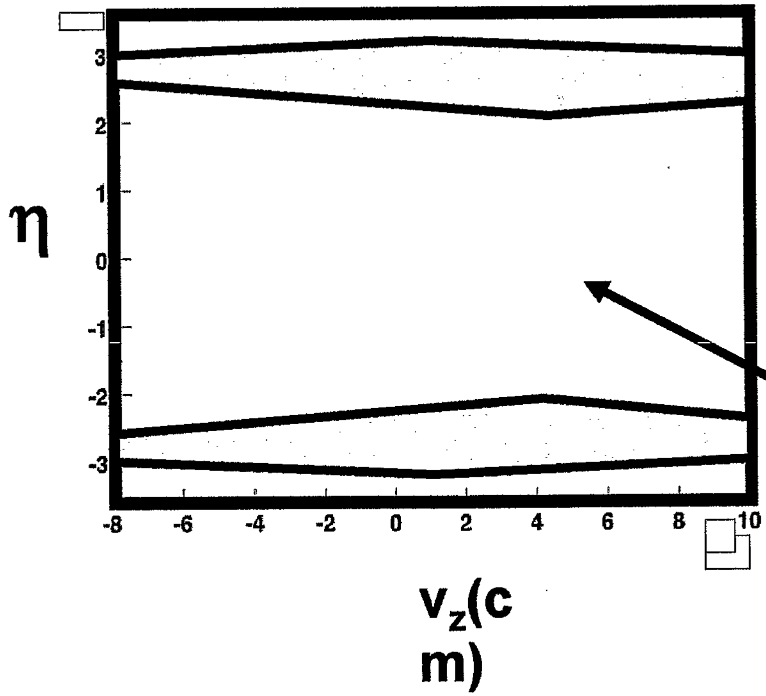
Track-based analysis:

Avoids holes for reaction plane determination

Uses tracks passing into spectrometer

A question to this workshop:

Are there non-flow correlations that stretch across 3-6 units of η?



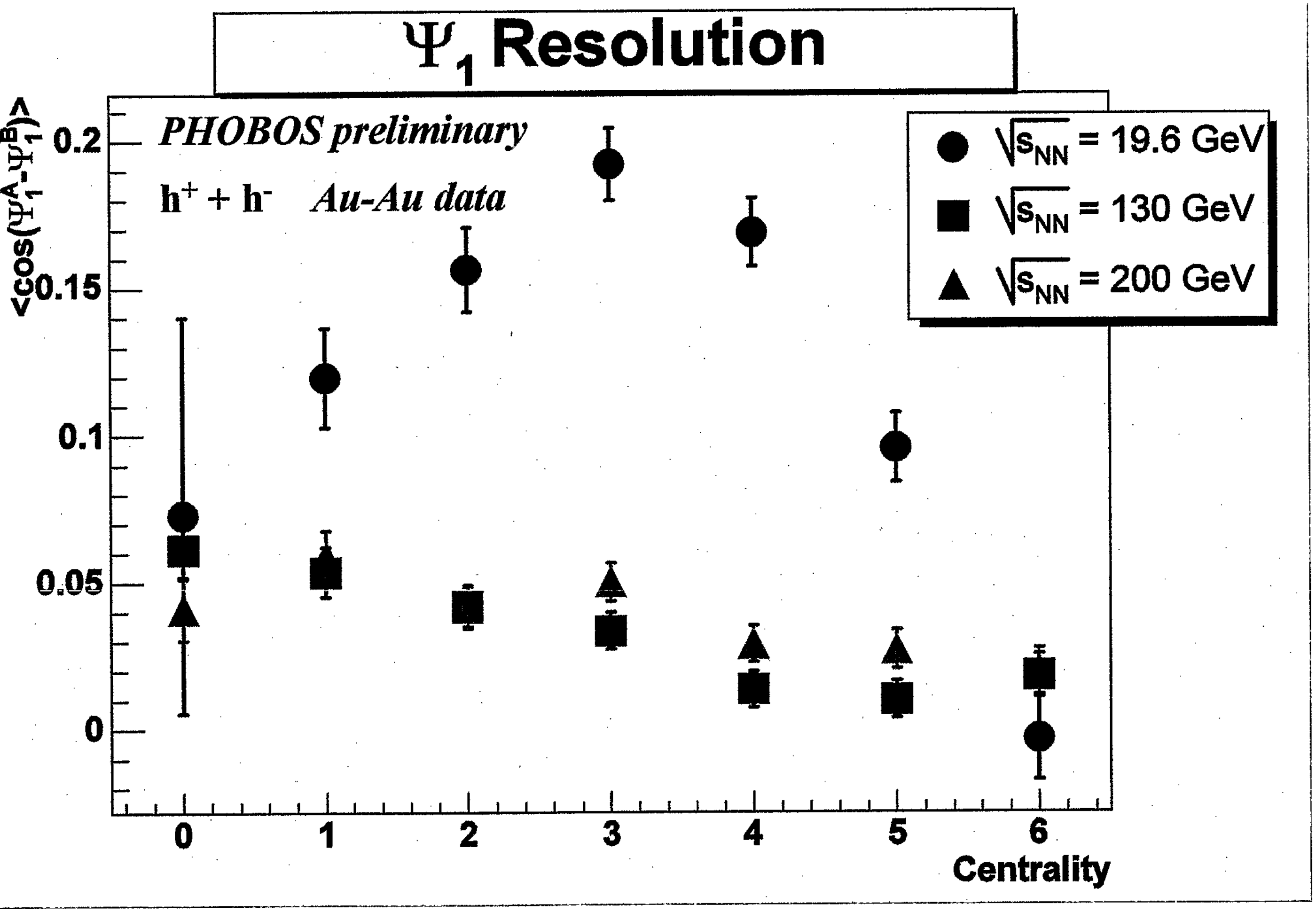
Full acceptance v_1: $\eta_{sep}=6$

Full acceptance v_2: $\eta_{sep}=5.2$

Offset vertex v_2: $\eta_{sep}=0.2\text{-}1.0$

Track-based analysis

Preliminary directed flow sensitivity



Flow at PHOBOS: What's new?

200 GeV analyses

- Finalizing systematics
- Plan to release soon final results in 3 bins of centrality

Directed flow (v1)

- Still optimizing analysis and working to understand fine points of data analysis using mid-z technique
- Goal is to release preliminary $v_1(\eta)$ at 19.6, 130 and 200 GeV for Quark Matter

Rapidity Dependence of Elliptic Flow from Hydrodynamics

Tetsufumi Hirano

RIKEN BNL Research Center

(Collaboration with Yasushi Nara, Univ. of Arizona)

Rapidity Dependence of Elliptic Flow from Hydrodynamics

Tetsufumi Hirano* and Yasushi Nara**
*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973
**Department of Physics, University of Arizona, Tucson, Arizona 85721

The azimuthal anisotropy of particle momentum (v_2) is believed to be sensitive to the dynamics and the degree of equilibration of the system produced in high-energy heavy-ion collisions. In past years, $v_2(p_T)$ is observed by STAR and PHENIX [1] and found to be consistent with hydrodynamic results in low p_T region (p_T<1.5GeV/c) near midrapidity [2,3]. v_2 as a function of pseudorapidity η was also measured by the PHOBOS Collaboration [4]. This shows the strong pseudorapidity dependence: $v_2(\eta)$ has a maximum at midrapidity and rapidly decreases with rapidity. On the other hand, hydrodynamic simulations in full three dimensional space gave a mild dependence on rapidity and overestimate the data in forward/backward rapidity regions [3]. This suggest that the hydrodynamic picture is valid only near midrapidity.

In this talk, we revisit the rapidity dependence of v_2 within the hydrodynamic approach by emphasizing on the improvement of initial conditions. In asymmetric collisions like S+Au at SPS energies, hydrodynamic initialization using local rapidity shift is very useful to reproduce the asymmetric shape of rapidity distribution [5]. When this prescription is extended to non-central collisions where there is a difference of thickness between two colliding nuclei at a transverse coordinate, the initial energy density in the reaction plane is slightly tilted from collision axis. This causes the so-called third flow [6] and results in large elliptic flow in forward rapidity region. This is the reason why the previous results overestimate the PHOBOS data. In the conventional hydrodynamic approach, the space-time rapidity dependence of initial distribution is taken so as to reproduce the observed (pseudo-)rapidity distribution. The initial condition has an ambiguity since some initial conditions leads to reproduce the data within error bars. We tune the initial condition again without using the local rapidity shift and obtain the pseudorapidity dependence of elliptic flow in Au+Au collisions at 200A GeV. We find $v_2(\eta)$ grows with the thermal freezeout temperature. We reproduce the PHOBOS data by choosing $T^{\rm th}$=140MeV.

It is much better to take an initial condition from a model calculation which is relevant at the earliest stage relativistic heavy ion collisions. At very high energies, the initial gluon distribution in a hadron/nucleus saturates in low k_T region [7]. Kharzeev and Levin [8] simply parametrized initial gluon distribution in a nucleus from the saturation picture. This works very well for description of rapidity and centrality dependences of particle multiplicity. But this calculation does not take into account final interactions. We use this model as an initialization of fluid, perform hydrodynamic simulation, and obtain the final spectra [9]. Even we take account of final state interaction through hydrodynamic evolution, this initial condition works very well for pseudorapidity distributions. We roughly reproduce the PHOBOS data.

Reference

[1] K.H. Ackermann *et al.* (STAR), Phys.Rev.Lett.86, 402 (2001); K.Adcox *et al.* (PHENIX), Phys. Rev.Lett.89, 212301 (2002).
[2] B.B. Back *et al.* (PHOBOS), Phys.Rev.Lett.89, 222301 (2002).
[3] P. Huovinen *et al.*, Phys.Lett.B500, 232 (2001)
[4] T. Hirano, Phys.Rev.C65, 011901(2002).
[5] J. Sollfrank *et al.*, Eur.Phys.J C6, 525 (1999).
[6] L.P. Csernai and D. Rohrich, Phys.Lett.B458, 454 (1999).
[7] L.V. Gribov, E.M. Levin, M.G. Ryskin, Phys.Rep.100, 1 (1983).
[8] D. Kharzeev and E. Levin, Phys.Lett.B523, 79 (2001).
[9] T. Hirano and Y. Nara, in preparation.

Introduction

$v_2(y)$ is supposed to reflect global dynamics…

→ How obtain by hydrodynamics?

Non-central coll. → No cylindrical sym.

Non-Bjorken behavior → No scaling ansatz

High energy collisions (@RHIC) → No Cartesian coordinate?

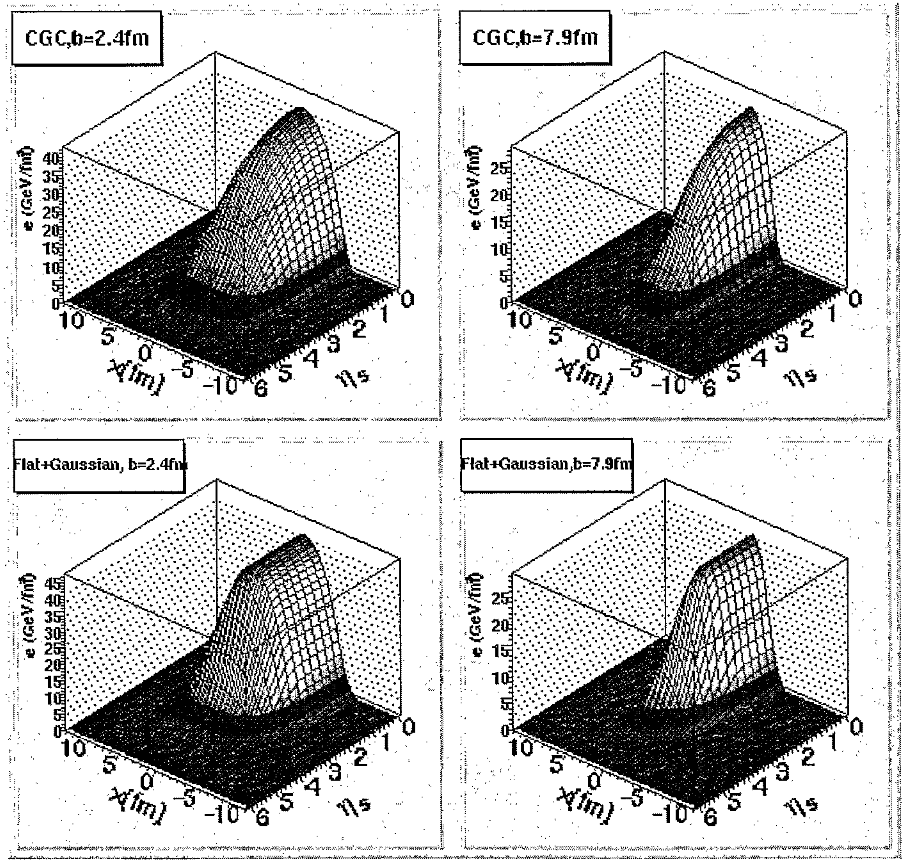
⇓

Need **full** 3D hydro simulations in τ-η coordinate

T.H., PRC65,011901(2002).

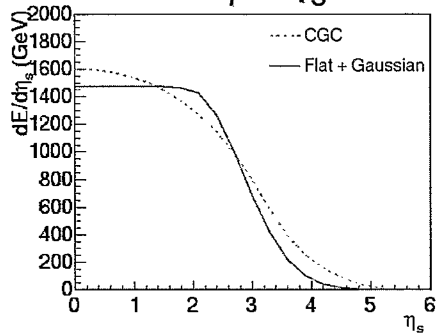
From Experimental Point of View
Need broad acceptance in longitudinal direction
See S.Manly's talk

Initial Energy Density Distribution and $dN_{ch}/d\eta$

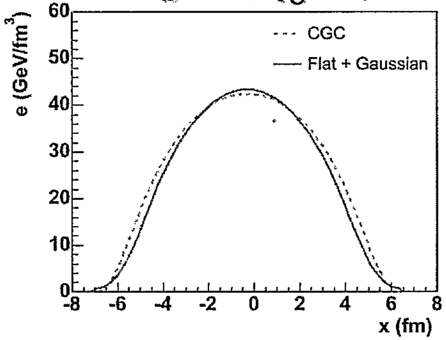


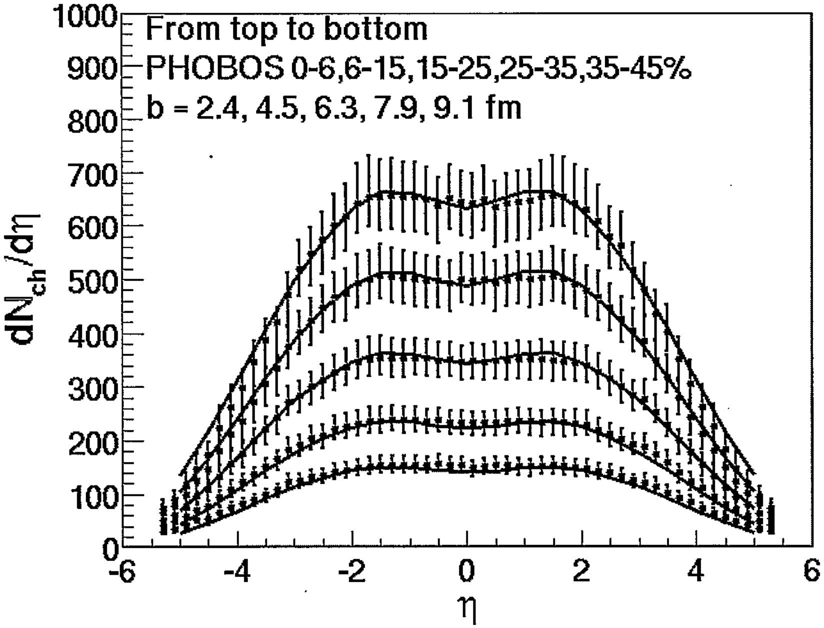
b=2.4fm

$dE_T/d\eta_s$

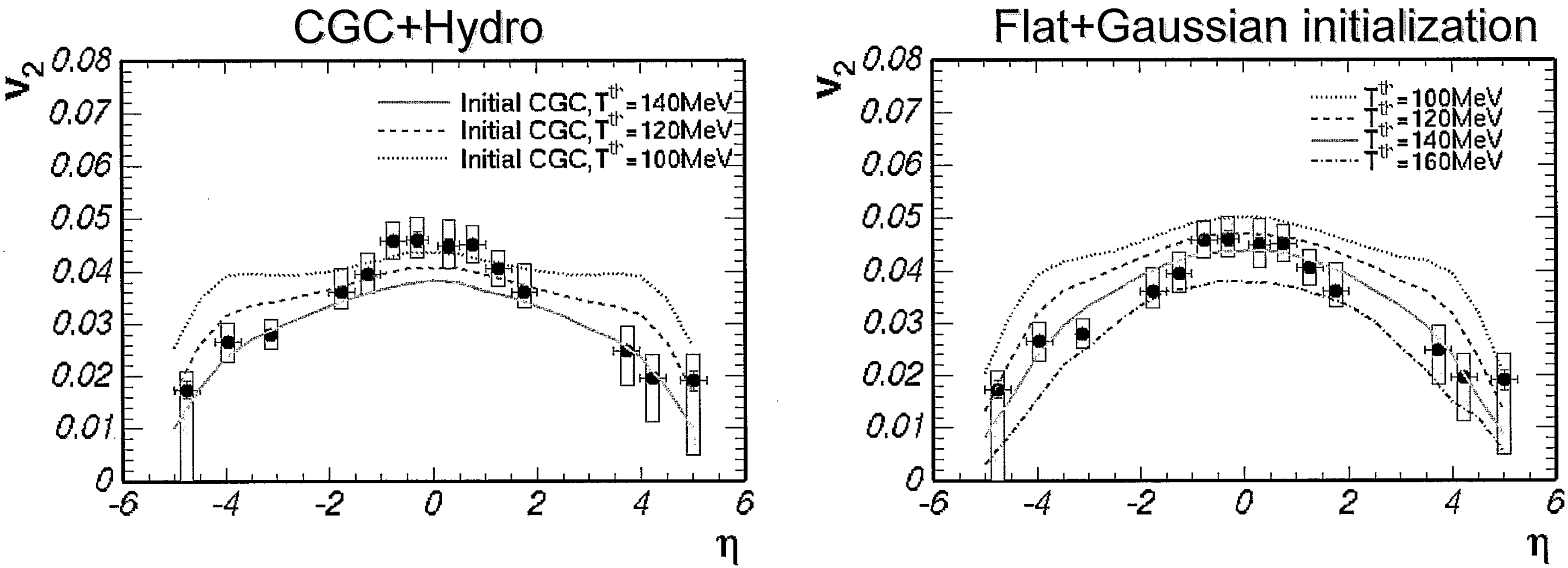


$e(y=0, \eta_s=0)$





$v_2(\eta)$ from CGC+Hydro



- Slightly suppressed near midrapidity region
  - Pressure gradient in longitudinal direction
  - Pressure gradient in transverse direction

  →Stronger longitudinal flow and weaker transverse flow in CGC+hydro case than in flat+Gaussian case.

Summary & Discussion

- There IS a solution for $v_2(\eta)$ from hydrodynamics.
- Further systematic studies are needed.
  - Initial condition? T^{th} dependence ? EOS ?
- CGC+hydro(+jet) model ("Improvement" of I.C.)

- Consistency check

→ $<p_T>$(y) & p_T spectra in forward rapidity (BRAHMS data)

  - T^{th} depends on particle species ? T^{th} ~80-100MeV from proton slope? (← If so, need hadron cascade)
  - T^{th} depends on rapidity ? (←BRAHMS data)

Jean-Yves Ollitrault

Service de physique théorique

CEA Saclay, France

Analyzing v_2 with Lee-Yang zeroes

Analyzing v_2 with Lee-Yang zeroes

I present a new method to analyze elliptic flow at RHIC. I will argue that this method is the most reliable to analyze anisotropic flow. It is similar to methods based on cumulants of four or six particle correlations, which have already been implemented by the STAR collaboration at RHIC. Here, the idea is to study directly the genuine correlation (or cumulant) between a large number of particles, not just four or six. This naturally provides the best separation between correlations due to flow (which are collective) and nonflow effects (which involve fewer particles).

This new method is not only more accurate, but also simpler to implement than previously used cumulant methods. It is formally elegant, and analogous to the famous theory of phase transition by Lee and Yang. It is the first application of this theory to the analysis of experimental data.

The only limitation of this method is statistical errors, which can be significantly larger than with other methods if the detector acceptance is not large enough. With the STAR detector, however, the statistical error should be the same, or even slightly smaller, than with four-particle cumulants for a mid-central Pb-Pb collision. The method will also be easily applicable at LHC.

Details about this method are given in a letter, nucl-th/0307018, and a longer paper, nucl-th/0310016, both written in collaboration with R.S. Bhalerao and N. Borghini.

A new simple recipe to analyze v_2

Define

sum over particles seen in the event

$$\downarrow$$

$$Q \equiv \sum_j \cos 2\phi_j$$

$$\uparrow$$

azimuthal angles measured in the laboratory

The relevant information is contained in the probability distribution of Q, $p(Q)$. But where ?

A histogram mixes relevant+irrelevant information.

E877 hep-ex/9405003

Rather compute the Fourier transform of the distribution (it's even easier than a histogram!)

$$G(ir) \equiv (1/N_{\text{evts}}) \sum_{\text{evts}} e^{irQ}$$

The first minimum of $|G(ir)|$, at $r = r_0$ is

- directly related to $v_2 = 2.405/Mr_0$
  (M = mean event multiplicity)
- insensitive to nonflow correlations

(note that the $\sin 2\phi_j$ are not needed here)

Generating functions [1]: definitions

Define

$$G(z) \equiv \left\langle \exp\left(z \sum_{j=1}^{M} \cos 2\phi_j \right) \right\rangle$$

$\langle ... \rangle$ = average over events,
$\sum_j$ = sum over particles in an event.

Or, equivalently

$$\tilde{G}(z) \equiv \left\langle \prod_{j=1}^{M} (1 + z \cos 2\phi_j) \right\rangle$$

(everywhere in this talk, $\tilde{G}$ can be used instead of G)

Cumulants c_k are defined by

$$\ln G(z) = \sum_{k=1}^{+\infty} c_k \frac{z^k}{k!}$$

Naive order of magnitude: $c_k \sim M^k$
(M = event multiplicity)

Generating functions [4]: zeroes

Nonflow $c_k \propto M$
Flow $c_k \propto M^k$

Identify the flow: construct c_k for large k

$$\ln G(z) = \sum_{k=1}^{+\infty} c_k \frac{z^k}{k!}$$

How do I compute the asymptotic behaviour of the coefficients of a power-series expansion ?

Hint :

$$\ln\left(1 - \frac{z}{z_0}\right) = \sum_{k=1}^{+\infty} \frac{z^k}{k {z_0}^k}$$

The asymptotic behaviour of c_k is completely determined by z_0, i.e. the zero of the function in the log.

This is a general result : the first zero of $G(z)$ in the complex plane completely determines large-order cumulants.

Very generally, studying collective motion amounts to finding the zero of the generating function $G(z)$ which is closest to the origin in the complex plane of z.

Generating functions [5]: zeroes

Where is the first zero ?

$$G(z) = I_0(zMv_2) \times \cdots$$

Zeroes are on the imaginary axis. The first is at

$$z_0 = \frac{2.405\, i}{Mv_2}.$$

Determine z_0 experimentally, thus obtain v_2.

In practice $G(z)$ is obtained from an average over a finite number of collisions, and the detector is not perfectly isotropic:
→ The zeroes of $G(z)$ don't lie exactly on the imaginary axis.
→ Rather than the first zero, we determine the first minimum of $|G(z)|$ on the imaginary axis.

Until now, we have only used the $\cos 2\phi_j$. In order to use also the information on $\sin 2\phi_j$,

- We repeat the whole procedure with $\cos 2(\phi_j - \theta)$ where θ is a fixed angle → we obtain an estimate of v_2 for each value of θ;
- We average the result over the values of θ.

Summary and perspectives

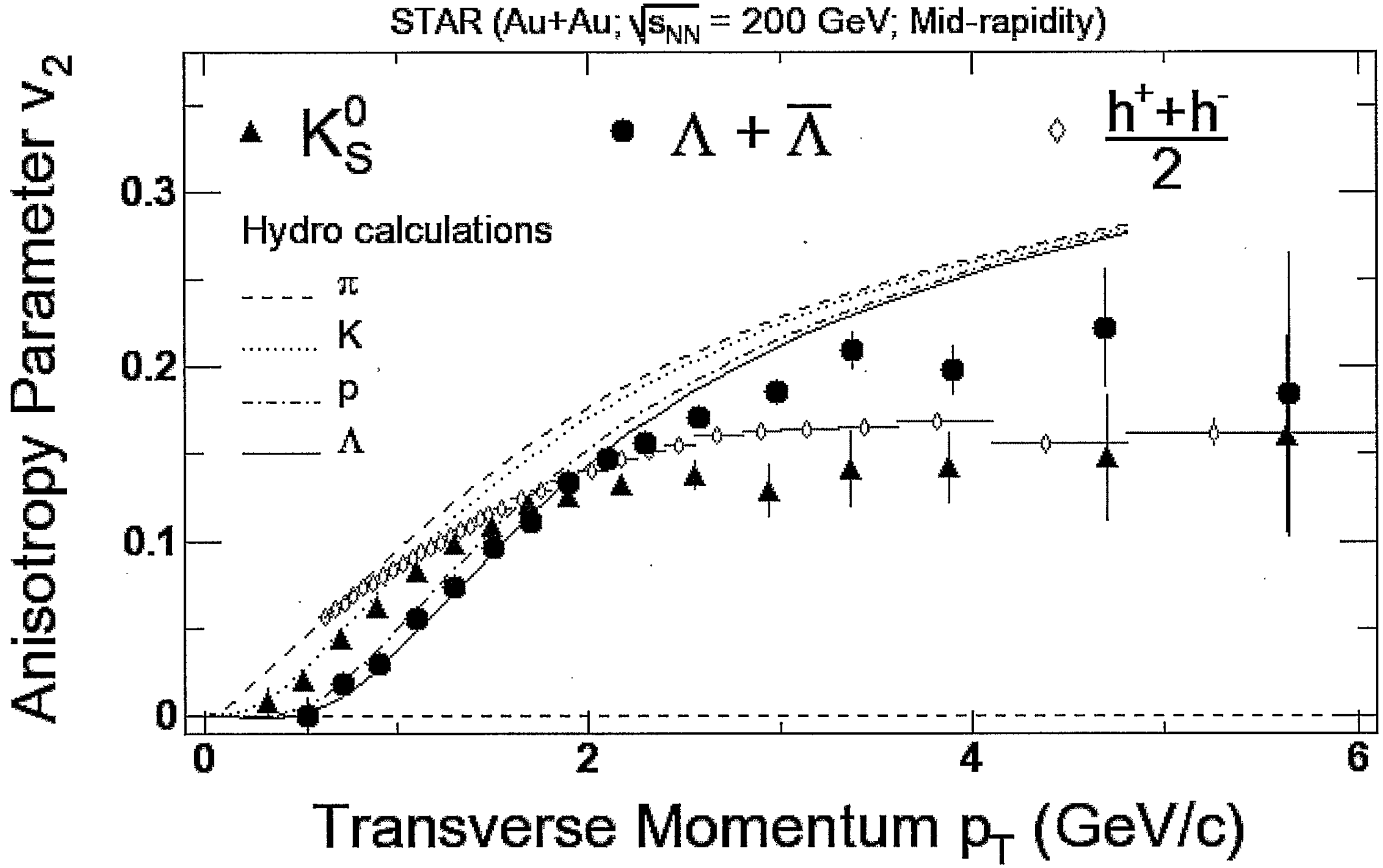
- First application of Lee-Yang theory to experimental data
- Isolate directly genuine collective behavior in heavy ion collisions.
- Simple to implement
- Can be used with azimuthally asymmetric detector (not shown here)
- For STAR, statistical errors will not be larger than with 4-particle cumulants
- Could be extended to other observables in order to look for critical fluctuations

Paul Sorensen
Lawrence Berkeley National Laboratory

Particle production at low, intermediate, and high transverse momentum: what we're learning about heavy-ion collisions and hadronization of bulk partonic matter from measurements of identified particle production

Measurements of identified particles over a broad p_T range may provide strong evidence for the existence of a thermalized partonic state in heavy-ion collisions (\textit{i.e.} a quark-gluon plasma). Of particular interest are the centrality dependence and the azimuthal anisotropy in the yield of baryons and mesons at intermediate p_T. The first measurements of v_2 and the number-of-binary-collisions scaled centrality ratio R_{CP} for K_S^0 and $\Lambda+\bar{\Lambda}$ production in Au+Au collisions at RHIC are presented. These measurements from the STAR detector establish the particle-type dependence of v_2 and R_{CP} within $0.4 < p_T < 6.0$. At intermediate p_T (1.5--4.5 GeV/c) v_2 of K_S^0 and $\Lambda+\bar{\Lambda}$ is shown to follow a number-of-constituent-quark scaling with v_2^{kaon}(p_T/2)/2 = v_2^{lambda}(p_T/3)/3. R_{CP} shows that lambda production at intermediate p_T increases more rapidly with system size than kaon production: consistent with multi-parton dynamics in particle production. At $p_T = 5.5$ GeV/c lambda, kaon, and charged hadron production are suppressed by a similar factor ($R_{CP} \approx 0.33$): establishing the extent of the centrality dependent baryon enhancement. The particle- and p_T-dependence of v_2, and R_{CP} are consistent with expectations based on hadronization of bulk partonic matter by coalescence. As such, the constituent-quark-number scaled v_2 may reflect the anisotropy established in a partonic stage providing strong evidence for the existence of a quark-gluon plasma in Au+Au collisions at RHIC.

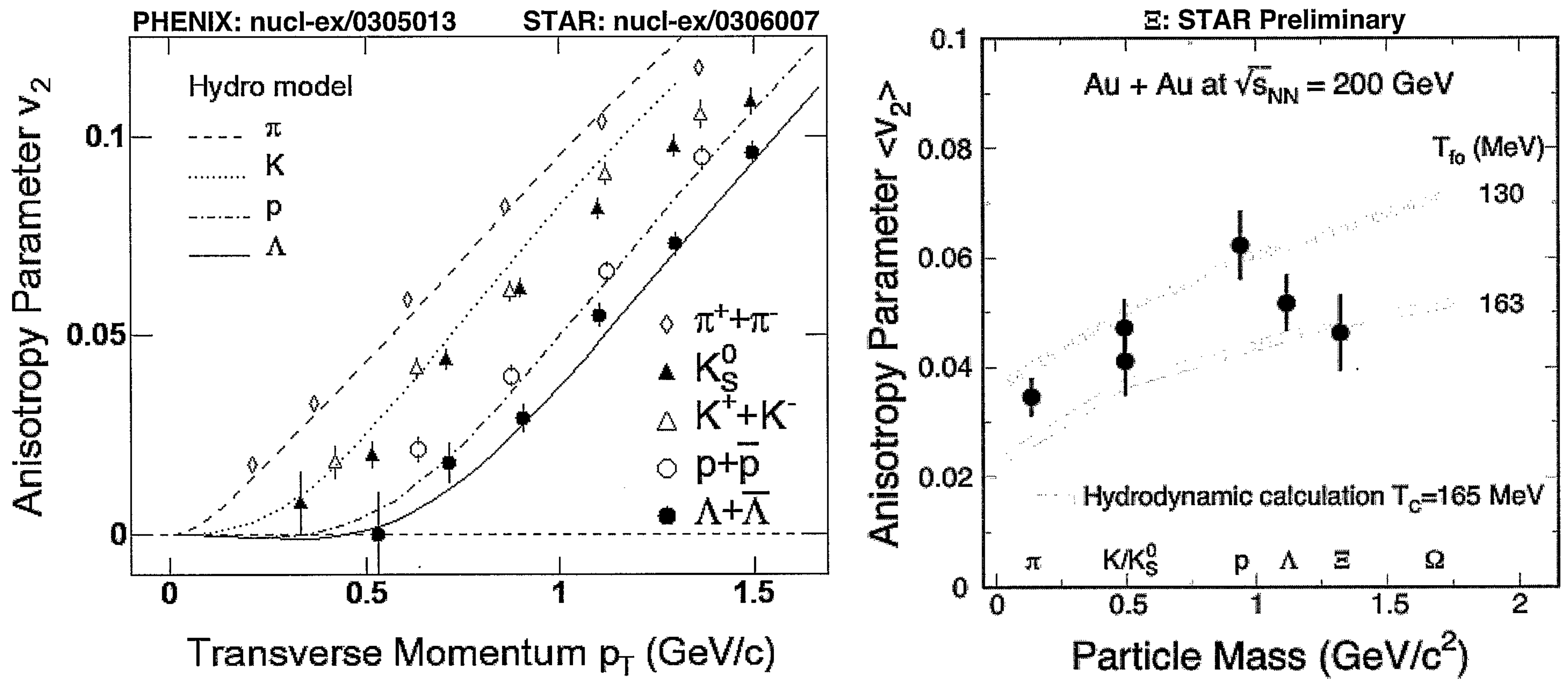
Min-bias identified particle v_2 at 200 GeV



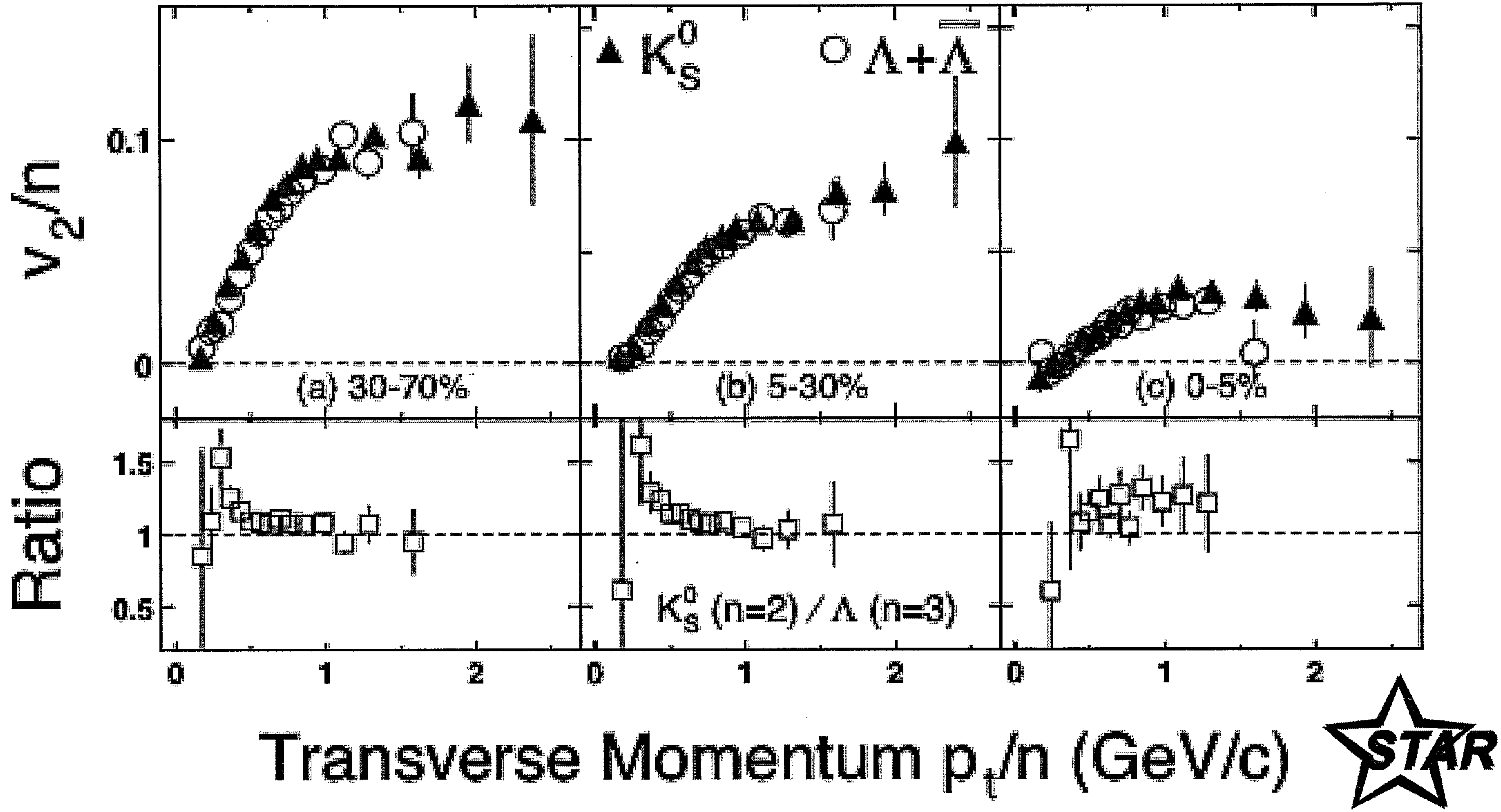
•v_2 appears to saturate at ~0.13 for K_S and ~0.20 for Λ with the saturation setting in at different p_T.

•Conversion of coordinate to momentum anisotropy: at or near the hydrodynamic limit (zero path length/totally opaque).

Identified particle v_2 at low p_T



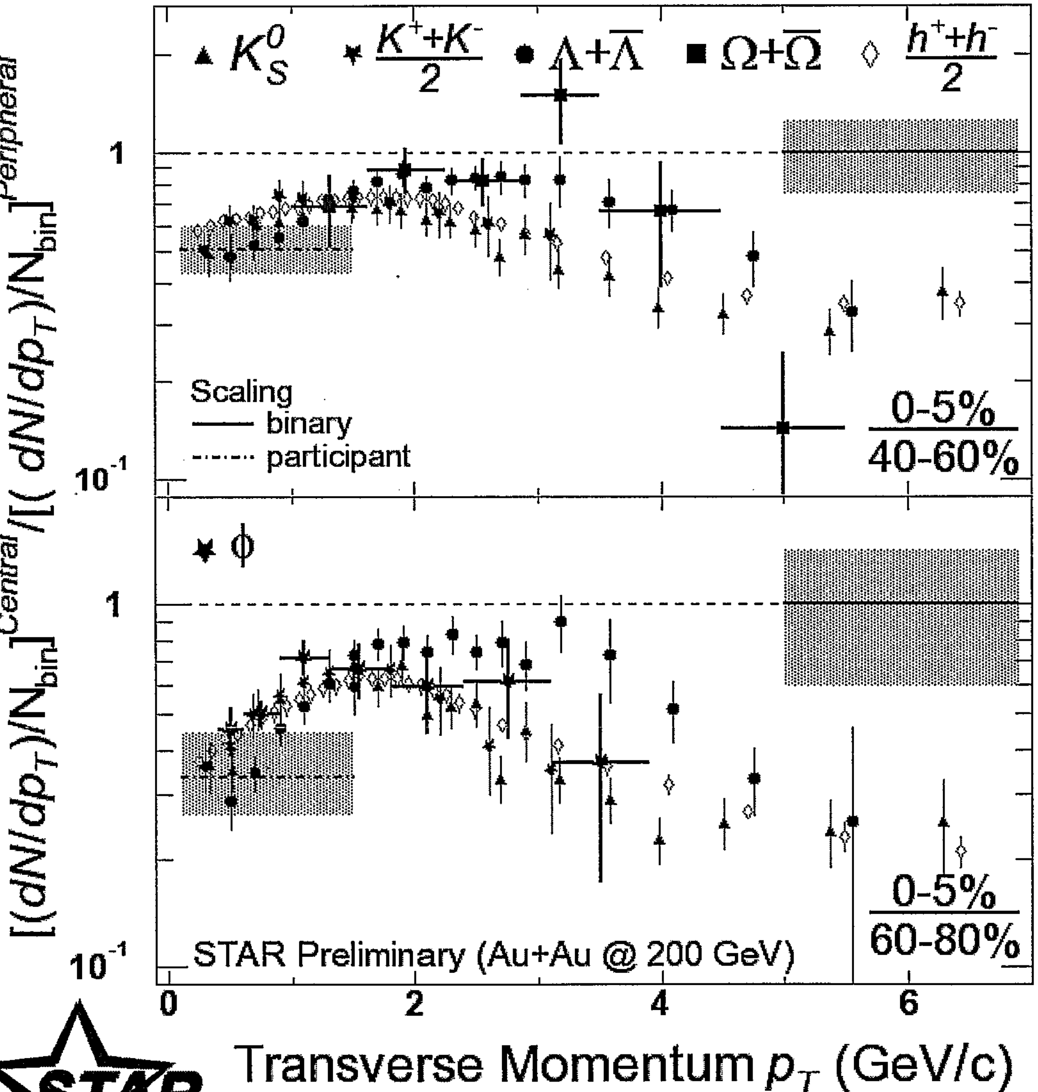
- Hydro models assuming local thermal equilibrium describe the species dependence of v_2 well.
- Increase of integrated v_2 with mass is suggestive of significant collective motion.



Scaling Breakdown Lower limit: $p_T/n<0.6$ GeV/c²
Upper limit: undetermined*

*R_{CP} suggest a breakdown for $p_T/n>1.7$ GeV/c²

System size dependence: R_{CP}



- Total yield in central collisions suppressed w.r.t. scaled peripheral collisions.
- At intermediate p_T however, the baryon yields are increasing more quickly with centrality than meson yields.
- The Λ, K_S, and inclusive yields have the same suppression near 5 GeV/c.

Const. quark no. dependence

- A two-component p_T spectra (exponential and power-law tail):
  - –with $p_{T,cross}$(kaon) ≈ $p_{T,cross}$(pion) ≈ 1–2 GeV/c.
  - –and $p_{T,cross}(\Lambda)$ ≈ $p_{T,cross}$(proton) ≈ 3–4 GeV/c.
- Particle-type dependent nuclear modification at intermediate p_T:
  - –with R_{CP}(kaon) ≈ $R_{CP}(\phi) \leq 0.65$.
  - –and $R_{CP}(\Xi) \approx R_{CP}(\Lambda) \approx R_{CP}$(proton) ≤ 0.95.
- Particle-type dependent elliptic flow:
  - –with most hadrons having the same $v_2/n(p_T/n)$ for p_T above ~1 GeV/c.
- Large baryon to meson ratio (Λ/K_S and p/pion).

These observations:

–Provide insight into how th environments influences hadron formation.

–Provide information on the characteristics of the partonic state.

Further investigation/confirmation is still needed.

An extensive phenomenological study of identified particle yields and v_2 verses system-size can shed light on hadron formation: long-term/high-impact RHIC project.

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Elliptic Flow of Multi-strange Baryons at RHIC – Evidence of Partonic Collectivity

Kai Schweda
Lawrence Berkeley National Laboratory

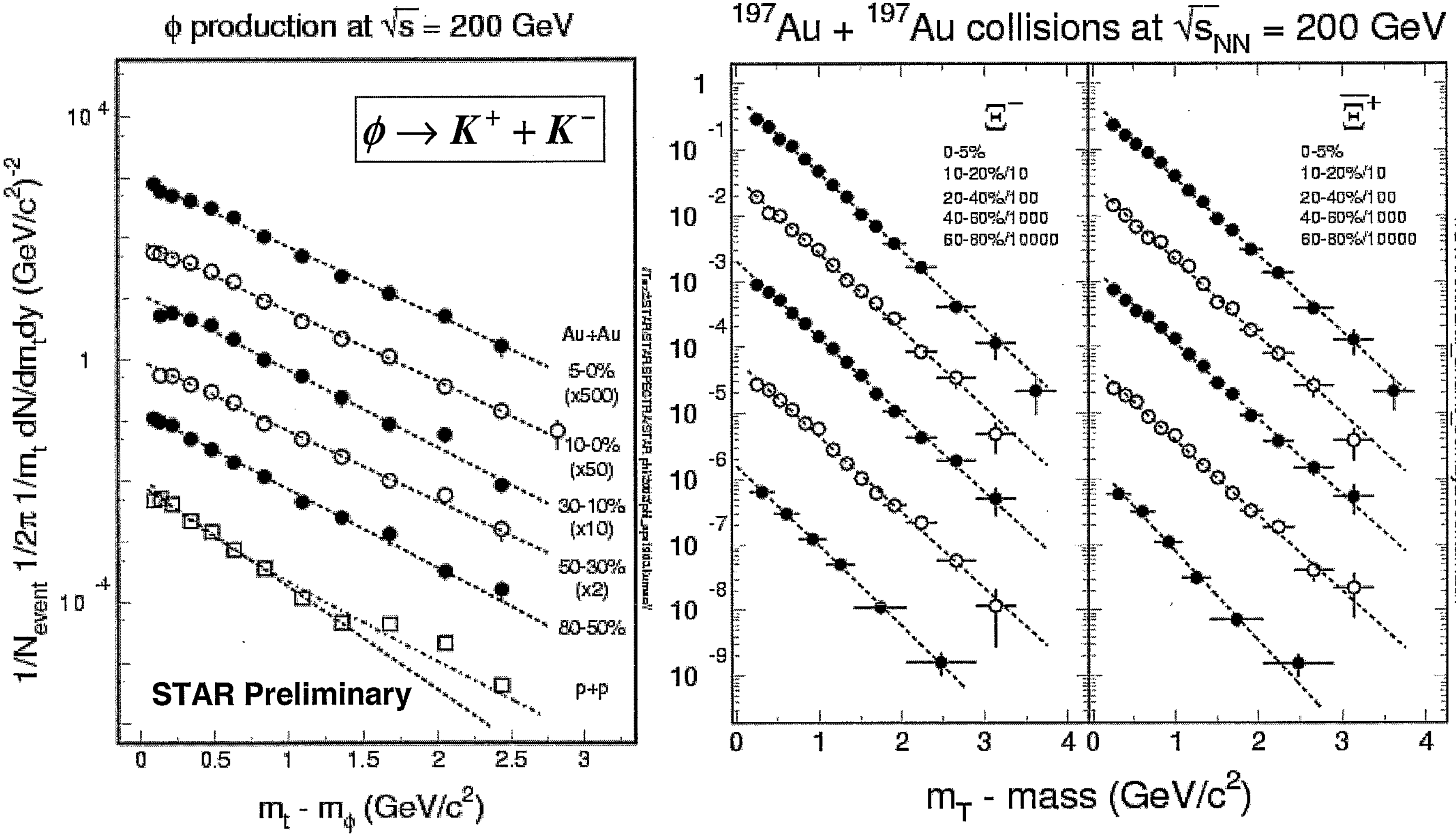
J. Castillo, Y. Cheng, M. Estienne, F. Liu, Z. Liu, H. Long, J. Ma, A. Poskanzer, F. Retiere, H.G. Ritter, P. Sorensen, C. Suire, N.Xu, E. Yamamoto.

Elliptic flow of multi-strange particles - Evidence of partonic collectivity at RHIC

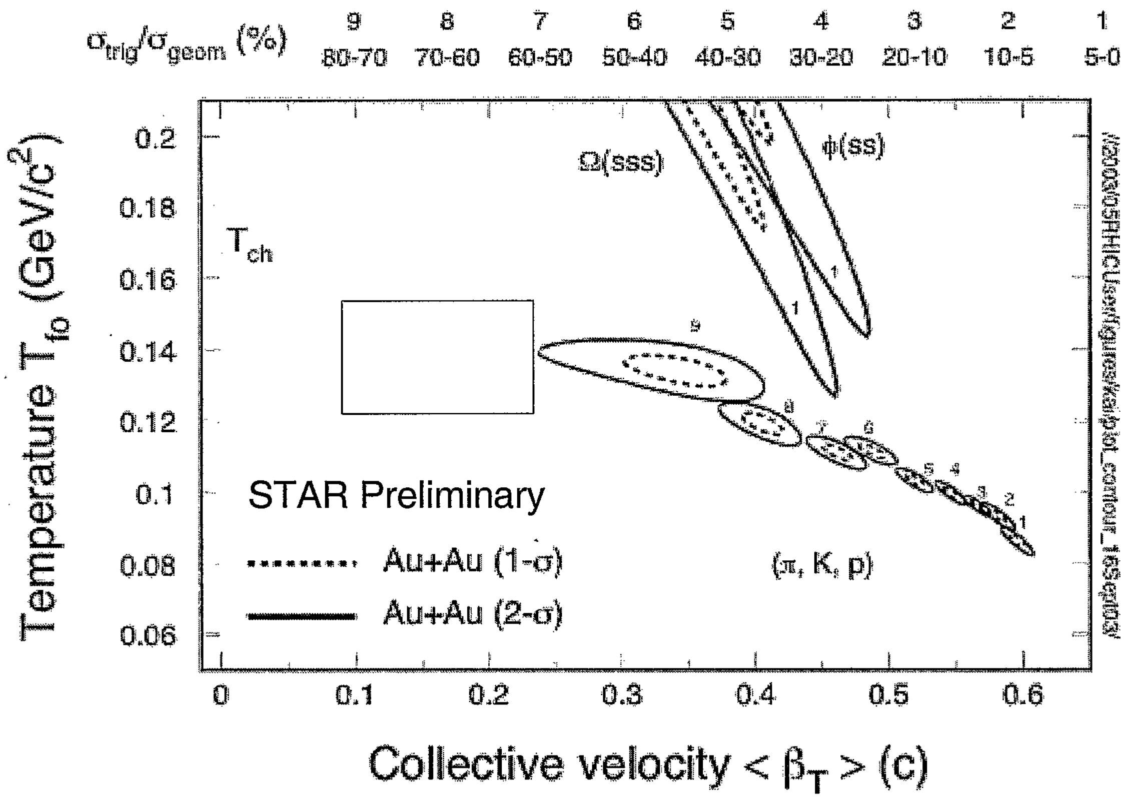
The study of collective expansion plays a key role in understanding the dynamics of nuclear collisions. Collectivity is accumulated during the whole collision history, i.e.
during the postulated partonic stage when quarks and gluons are the relevant degrees of freedom, as well as during the subsequent hadronic stage. From a thermal + transverse radial flow model fit[1] to transverse momentum distributions of non-strange, strange and multi-strange hadrons, we demonstrate how one can possibly disentangle partonic and hadronic contributions to collective expansion. Furthermore, elliptic flow is believed to carry early stage information. We present latest results on the measurement of elliptic anisotropy parameters v_2 of the multi-strange baryons Ξ and Ω from Au+Au collisions at sqrt(sNN) = 200GeV.
These results suggest that collectivity of multi-strange particles is dominantly built up in the pre-hadronic phase.

[1]E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C48, 2462 (1993).

Transverse Momentum Spectra



Kinetic Freeze-out at RHIC



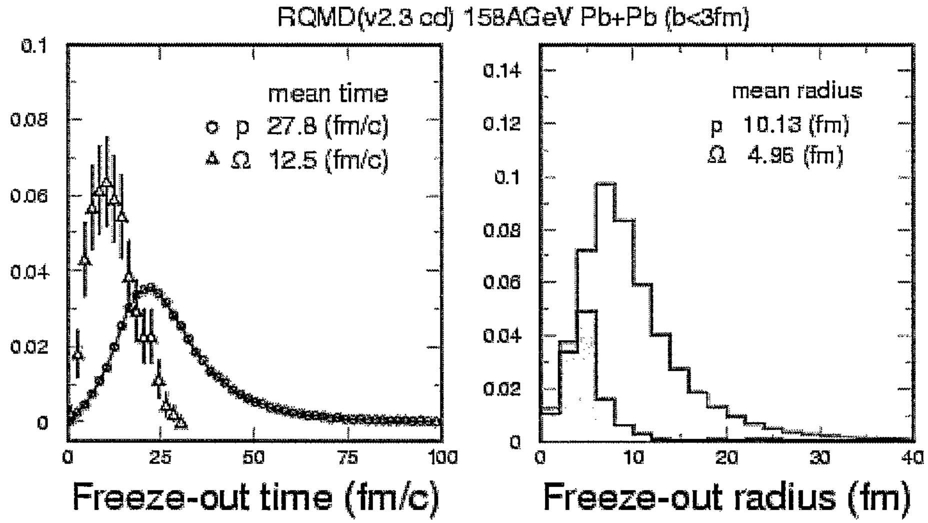
1) Compare to π, K, and p, multi-strange particles ϕ, Ω are found at higher T and lower $<\beta_T>$
⇨⇨ Collectivity prior to hadronization

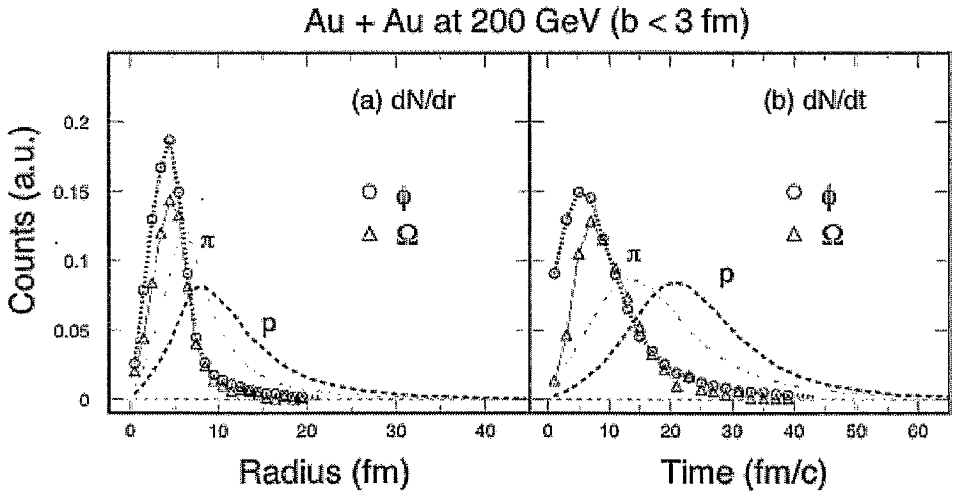
2) Sudden single freeze-out* Resonance decay lower T_{fo} for (π, K, p)
⇨⇨ Collectivity prior to hadronization

Partonic Collectivity !

Data: STAR preliminary Au+Au@200GeV: Nucl. Phys. A715, 129c(2003).
*A. Baran, W. Broniowski and W. Florkowski; nucl-th/0305075

Hadronic-Model Test





- SPS energy:

H. van Hecke, H. Sorge, NX,
Phys. Rev. Lett., **81**, 5764(1998).

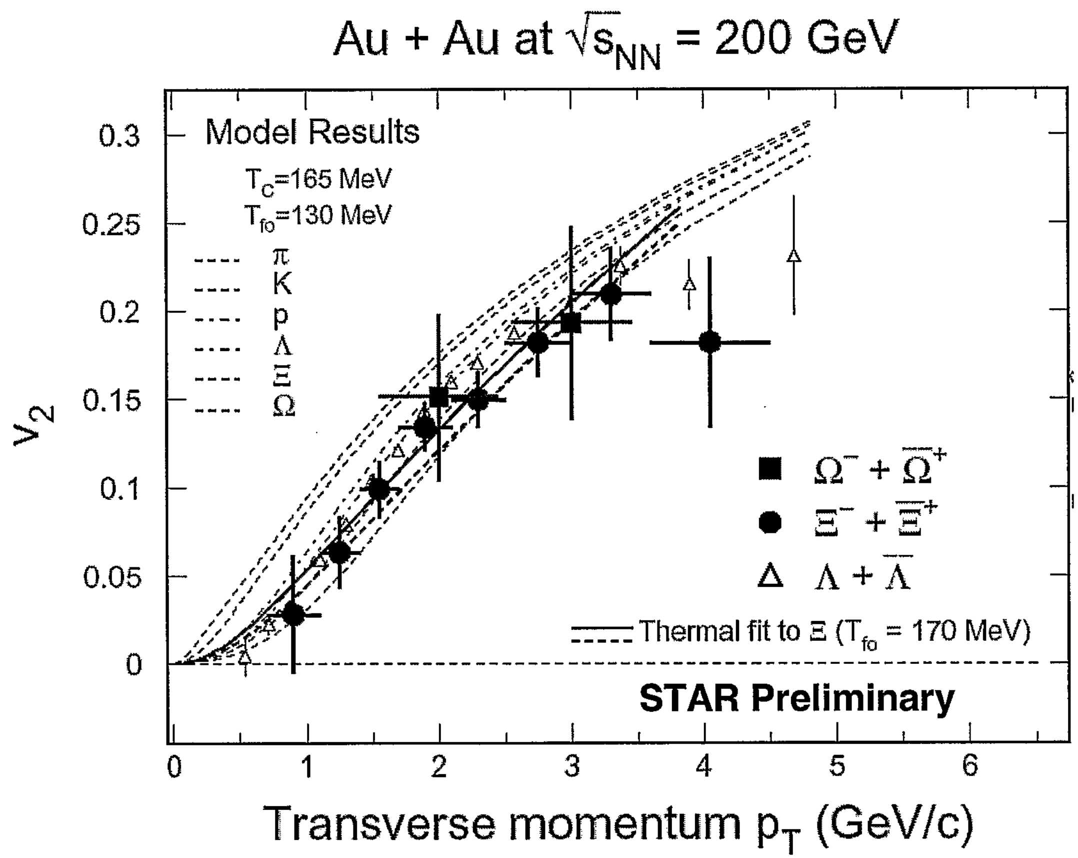
- RHIC energy:

Y. Cheng, F. Liu, Z. Liu, K.S., N. Xu,
Phys. Rev. **C68**, 034901(2003)

Multi-strange hadrons freeze-out early!

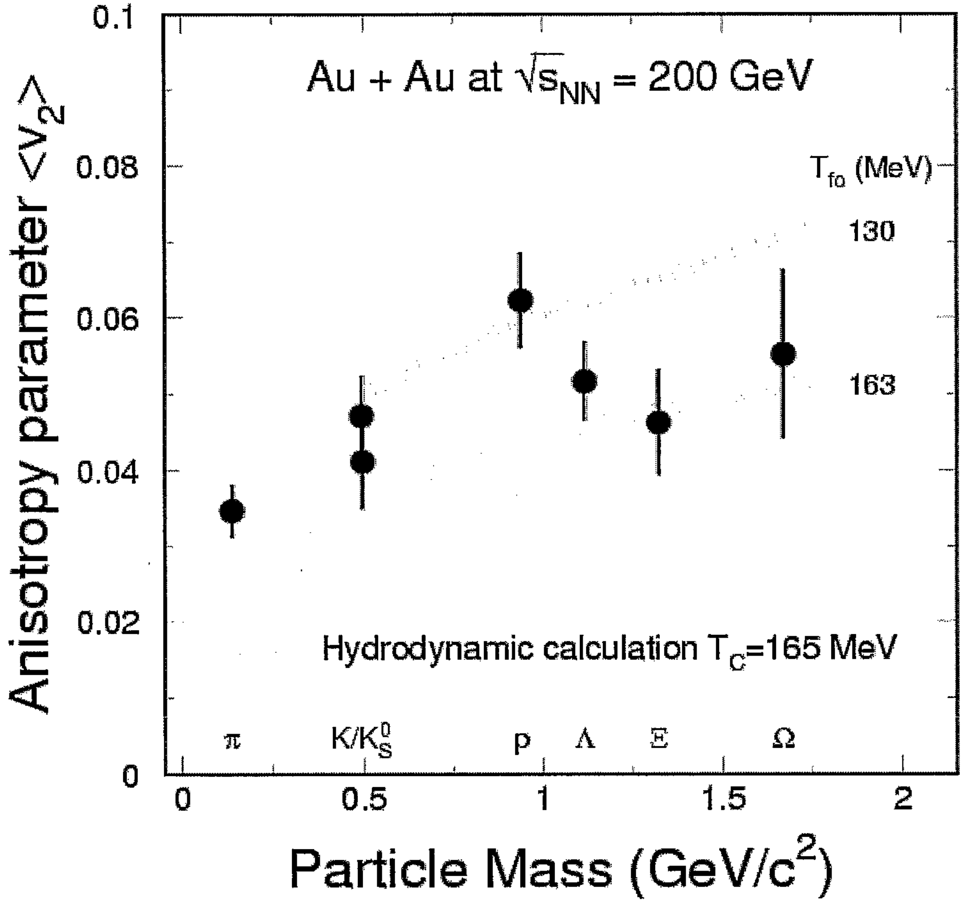
BNL '03, Nov 17 - 19, 2003

Multi-Strange Baryons v_2



- Multi-strange baryons show collectivity !
- ***Partonic collectivity at RHIC!***

v_2 vs Particle Mass



Two lines:

(a) T_{fo} = 130MeV fits π, K, p

(b) T_{fo} = 163 MeV fits (multi-)strange baryons

⇒ multi-strange baryons freeze out earlier

Y. Kondo, O. Morimatsu, nucl-th/0308023

T. Doi, Y. Kondo and M. Oka, hep-ph/0311117

π^0 and Photon v_2 Study in $\sqrt{s_{NN}} = 200$ GeV Au+Au Collisions

Masashi Kaneta*
for the PHENIX collaboration

The event anisotropy analysis is one of powerful tools to study properties of early stage in high energy heavy ion collisions. Because it is reflect information of collision dynamics in early stage after heavy ion collisions. The recent results of event anisotropy analysis suggest us to finite v_2 (second harmonic coefficient of Fourier expansion of azimuthal distributions) until several GeV/c of transverse momentum (p_T). Due to particle identification method a measurement of charged π, K, and p has a limit of p_T (<several GeV/c, so far)[1]. On the other hand, the π^0 measurement using Electro-Magnetic Calorimeter (EMC) can reach very high p_T (>10GeV/c)[2, 3]. The PHENIX is almost unique experiment to measure high transverse momentum π^0 in relativistic heavy ion collisions at RHIC. We will report results of $\pi^0 andphotonv_2$ analysis as a function of centrality and p_T from $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions data.

References

[1] K. Adcox et al. (PHENIX): nucl-ex/0307010

[2] S.S. Adler et al. (PHENIX): hepl-ex/0304038

[3] S.S. Adler et al. (PHENIX): Phys. Rev. Lett. **91**, 072301 (2003)

*RIKEN-BNL Research Center, Brookhaven National Laboratory, Bldg. 510A, Upton, NY 11973-5000

π^0 and Photon v_2 Study in $\sqrt{s_{NN}}$ = 200GeV Au+Au Collisions

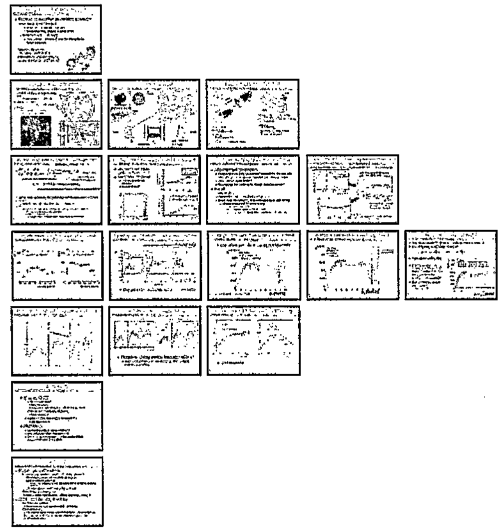
KANETA, Masashi
金田雅司

Hisayuki Torii
ShinIchi Esumi
Saskia Mioduszewski
Edouard Kistenev

for the PHENIX Collaboration
RIKEN-BNL Research Center

Overview

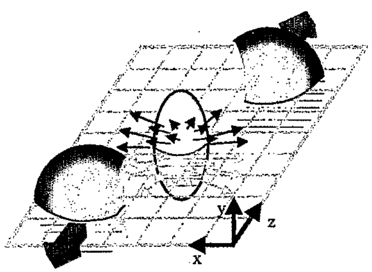
- Introduction
- PHENIX
- Analysis
- π0 v_2
- Photon v_2
- Summary
- Outlook



Why Event Anisotropy?

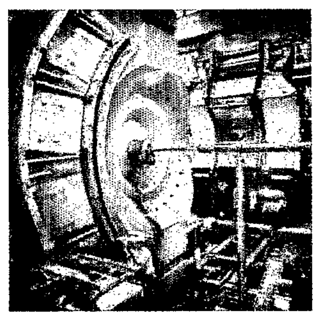
- Because of sensitive to collision geometry
  - In low p_T (~<2 GeV/c)
    - Pressure gradient of early stage
    - Hydrodynamical picture is established
  - In high p_T (>~2 GeV/c)
    - Energy loss in dense medium (Jet Quenching)
    - Partonic flow(?)

Here we focus on ellipticity of azimuthal momentum distribution, v_2 (second Fourier coefficient)

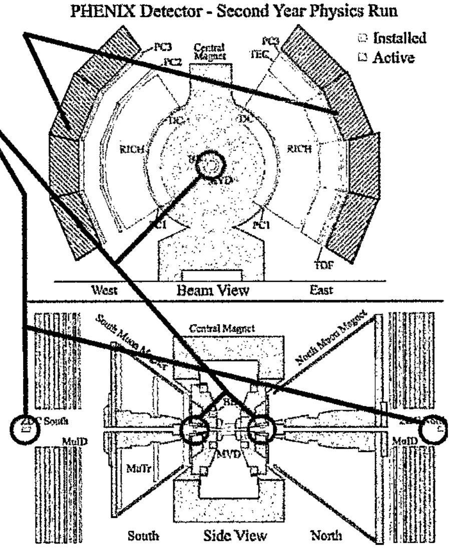


PHENIX Experiment

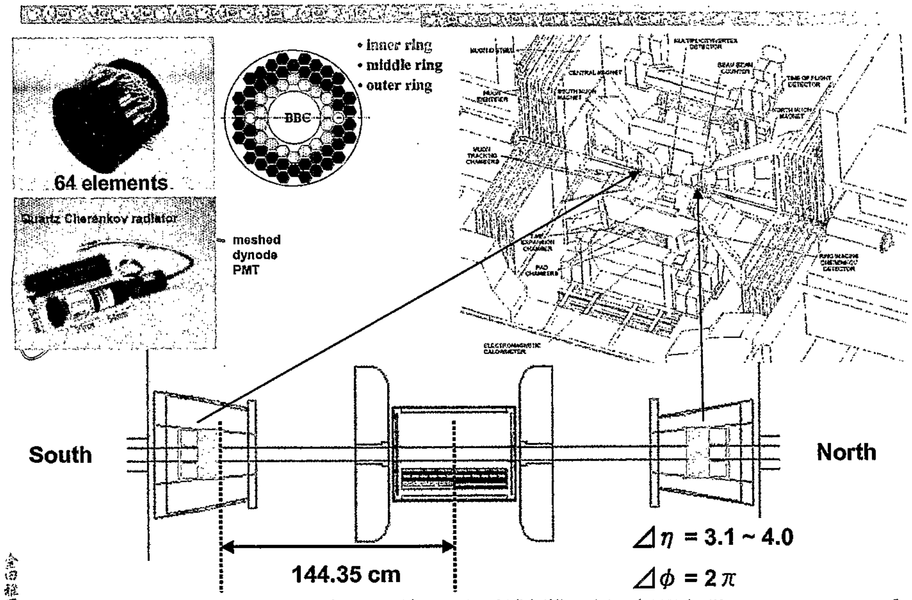
- Lead Scintillator and Lead Glass EMCs
  - Gamma measurement ($\pi^0 \rightarrow \gamma\gamma$)
- BBCs and ZDCs
  - Collision centrality determination
- BBCs
  - Reaction plane determination and
  - Its resolution correction



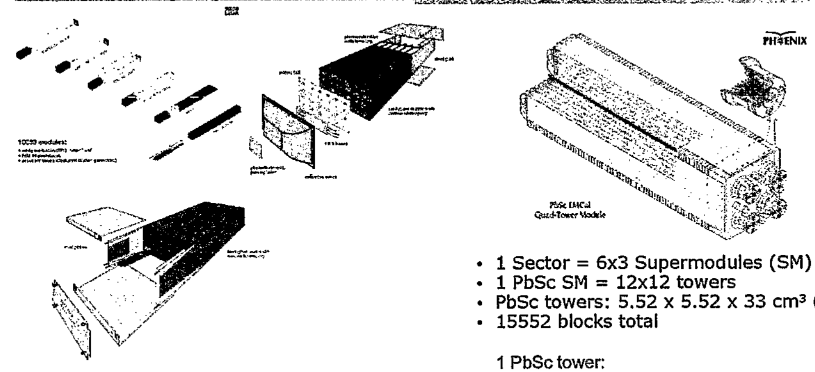
PHENIX Detector - Second Year Physics Run



BBC in PHENIX



PbGl and PbSc EMC's



- 2 Sectors PbGl
- 1 PbGl Sector
  - 16x12 supermodules (SM)
- 1 PbGl SM
  - 6x4 towers
  - Separate reference system
- 1 FEM
  - Reads out 2x3 supermodules or 12x12 towers

- 1 Sector = 6x3 Supermodules (SM)
- 1 PbSc SM = 12x12 towers
- PbSc towers: 5.52 x 5.52 x 33 cm³ (18 X_0)
- 15552 blocks total

1 PbSc tower:
- 66 sampling cells
- 1.5 mm Pb, 4 mm Sc
- Ganged together by penetrating wavelength shifting fibers for light collection
- Readout: FEU115M phototubes

Method of π^0 and Photon v_2 Measurement

$$E\frac{dN^3}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+\sum_{n=1}^{\infty}2\,v_n^{measured}\cos[n(\phi-\Psi_r)]\right)\quad \text{where } n=1,2,3,....$$

event anisotropy parameter measured (for $v_n^{measured}$); azimuthal angle of the particle (for ϕ); reaction plane angle (for Ψ_r)

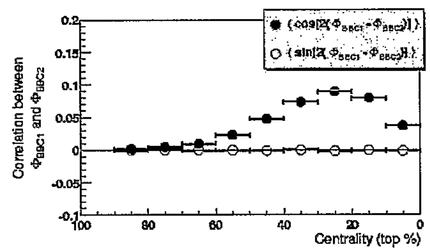
$$v_n^{real} = v_n^{measured} / \text{(reaction plane resolution)}_n$$

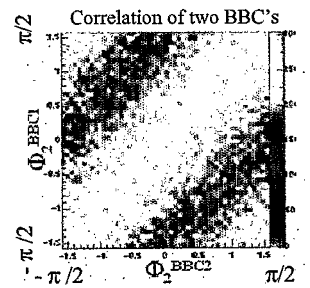
Note: the detail of reaction plane definition will be found in **nucl-ex/0305013**

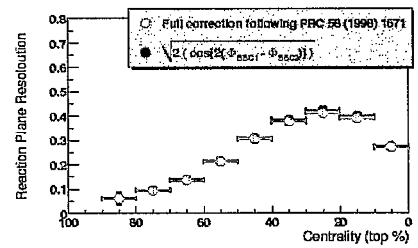
- Define reaction plane by charged multiplicity on Beam-Beam Counters
- Photon
  - Obtained second harmonic coefficient from $<\cos[2(\phi-\Phi_r)]>$
- π^0
  - π^0 reconstruction and subtract background (combinatorial and the others)
    - For each p_T, azimuthal angle, centrality
  - Commbine both information
    - Counting number of π^0 as a function of $\phi-\Phi_r$ and fit by the formula

Reaction Plane Defined by BBC's

- BBC north and south (η=3.1-4.0) are used
- Resolution calculation
  - Two sub-events are selected
  - North and south





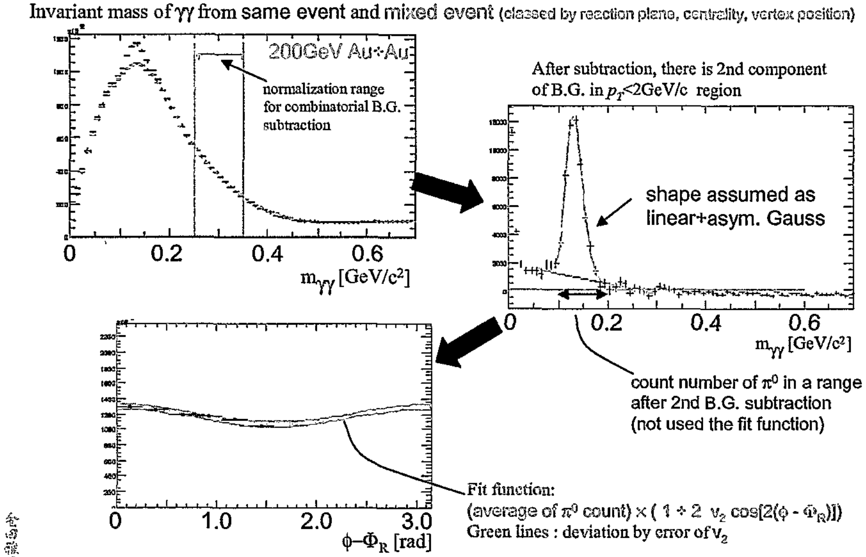


Photon and π^0 Identification

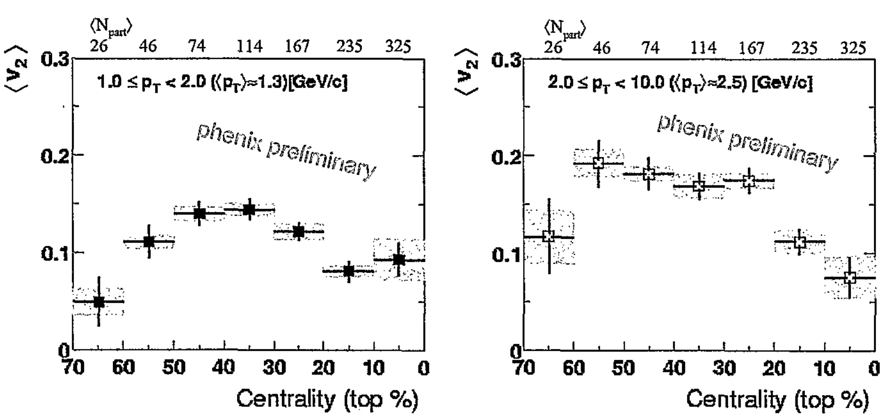
- Requirement for photon
  - Dead and noisy EMC towers are removed for the analysis
  - PID cuts: $\chi^2<3$ for photon probability to shower shape
  - |TOF| cut to reject hadron
  - No charged track hit within cluster isolation window
- For π^0
  - Photon ID, plus
  - Asymmetry cut: $|E_1-E_2| / (E_1+E_2) < 0.8$
  - Combinatorial background is estimated by event mixing
    - Classes categorized for event mixing
      - centrality : every 10%
      - BBC Z Vertex : every 10cm in ±30cm
      - reaction plane direction in PHENIX detector : 24 bins in $\pm\pi$

Example Plots from the π^0 v_2 Analysis Procedure

Invariant mass of $\gamma\gamma$ from same event and mixed event (classed by reaction plane, centrality, vertex position)

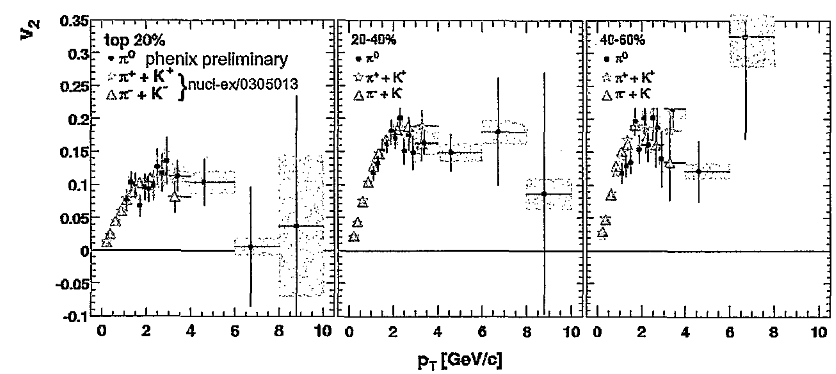


$\langle v_2 \rangle$ vs. Centrality from 200GeV Au+Au



v_2 vs. p_T vs. Centrality from 200GeV Au+Au

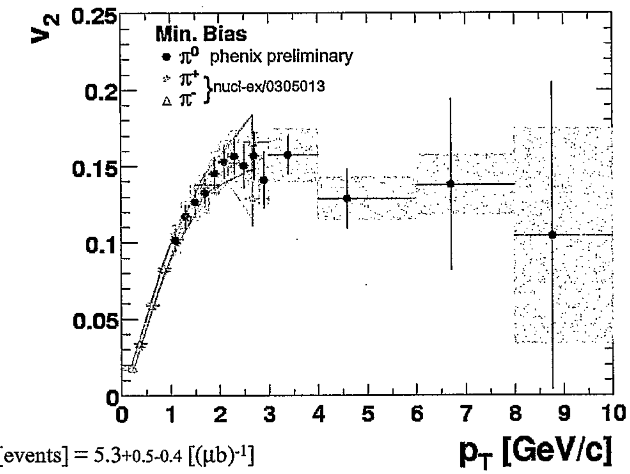
Statistical error is shown by error bar
Systematic error from π^0 count method and reaction plane determination is shown by gray box
The charged π and K v_2 are shown only with statistical errors



- Charged π+K v_2 consistent with π^0 v_2 in p_T<4GeV/c

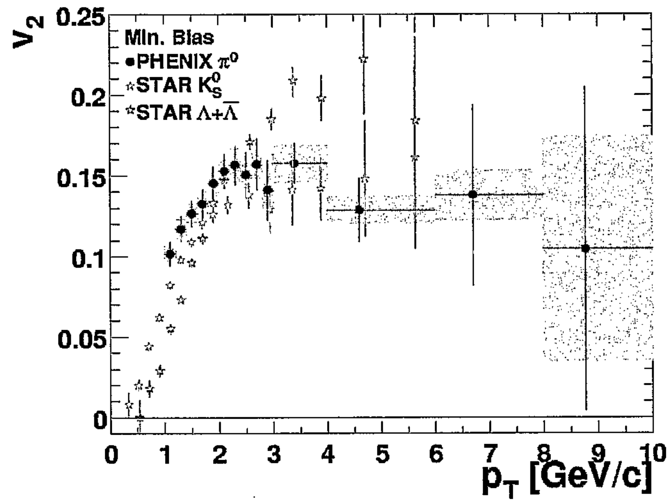
v_2 vs. p_T (Minimum Bias) from 200GeV Au+Au

- Identified particle v_2 up to p_T=10GeV/c



36.3×10^6 [events] = $5.3^{+0.5}_{-0.4}$ [$(\mu b)^{-1}$]

Comparison with K^0_S and Λ (STAR)



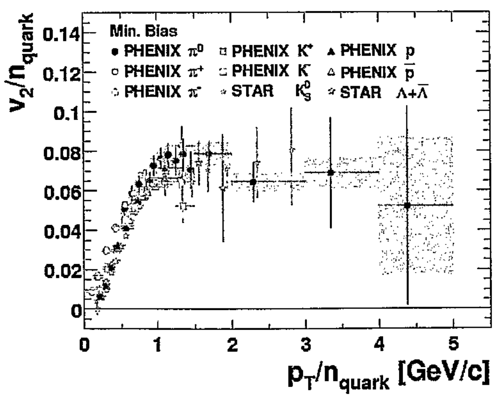
STAR data from nucl-ex/0306008

Quark Coalescence?

- Phys. Rev. Lett. 91 (2003) 092301, D.Molnar and S.A. Voloshin
- $q\bar{q}\rightarrow$meson, $qqq(\bar{q}\bar{q}\bar{q})\rightarrow$Baryon

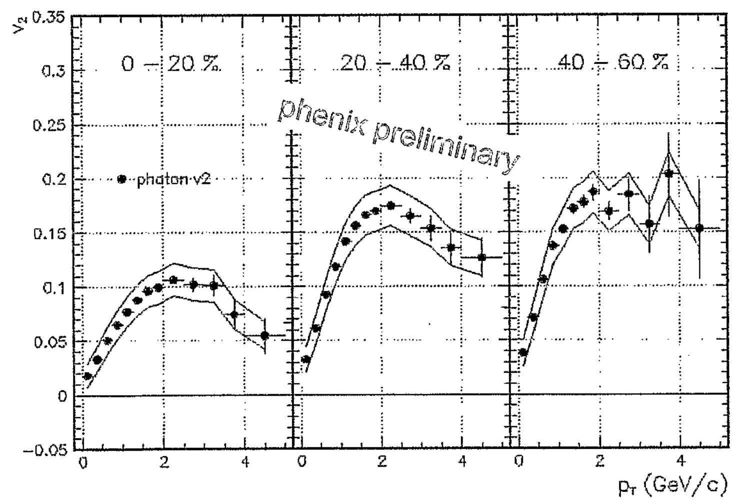
$$v_{2,M}(p_\perp) \approx 2v_{2,q}\left(\frac{p_\perp}{2}\right), \qquad v_{2,B}(p_\perp) \approx 3v_{2,q}\left(\frac{p_\perp}{3}\right),$$

- How data looks like?
- Non-strange and strange meson and baryon seems to be merged around p_T/n_{quark} ≈1-3GeV/c
- But we need more statistics to conclude it

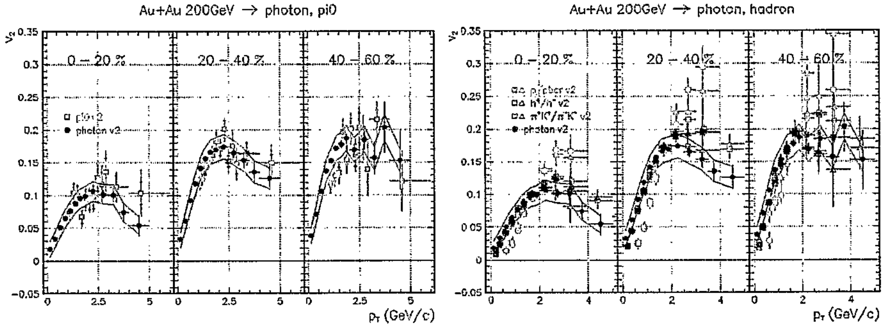


Photon v_2 from 200 GeV Au+Au

Au+Au 200GeV ⟶ photon

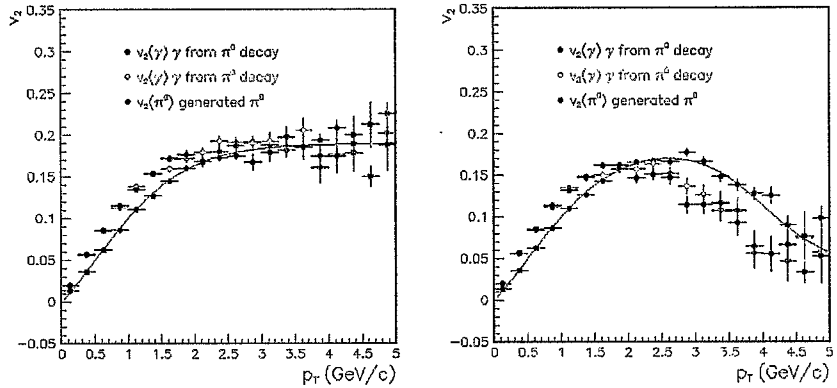


Photon v_2 and Hadron v_2



- Photon v_2 shows similar tendency with π^0
  - need more statistics to see photon v_2 after π^0 (and also η) decay effect

π^0 Decay Effect for Photon v_2



- Tool is ready

Summary

- π^0 v_2 at RHIC
  - First measurement
    - In p_T=1-10 GeV/c
    - v_2 of the highest p_T from identified particle
  - Charged π v_2 consistent with π^0 v_2
    - In p_T=1-3GeV/c
  - Minimum bias data shows non-zero π^0 v_2
    - Up to p_T~8 GeV/c
- Photon v_2
  - increasing with p_T up to ~2GeV/c
  - and saturated then decreasing(?)
  - We hope to see photon v_2 after decay effect subtraction with more data

Outlook

- Feature plan of analysis
  - Using high p_T gamma trigger in run2 Au+Au data
    - We will have about twice statistics in high p_T
    - need to study trigger bias
      - therefore, present analysis results are from minimum bias trigger events
  - η v_2 will be also available by same method
  - PHENIX has photon v_2 also
  - Photon v_2 after hadron decay effect, especially low p_T!
- RHIC run4 Au+Au, it will be
  - Much more statistics
    - Detail study of v_2 shape around p_T=2-4GeV/c
  - Much higher p_T
    - We want to know where is the end of finite v_2 in very high p_T
  - Also capability of photon measurement in low p_T by conversion finding

Electron and identified hadron v_2 to look for hadronic or partonic origin of elliptic flow

Shingo Sakai

for the PHENIX Collaboration

Univ. of Tsukuba

(Institute of Physics, Univ. of Tsukuba
1-1-1 Tennoudai, Tsukuba, Ibaraki 305 Japan)

The elliptic flow (v_2: second harmonic of Fourier expansion of azimuthal distribution) is believed to be reflect to the early pressure gradient in the collision zone at low p_t region and partonic energy loss in the dense medium at high p_t region. Therefore it is one of the important observable that helps us to understand the early stage of unclear-nuclear collisions. The transverse momentum dependence of the v_2 for the different particle species could possibly provide further information of the collisions dynamics and also provide of the origin of the elliptic flow; hadronic or partonic flow.

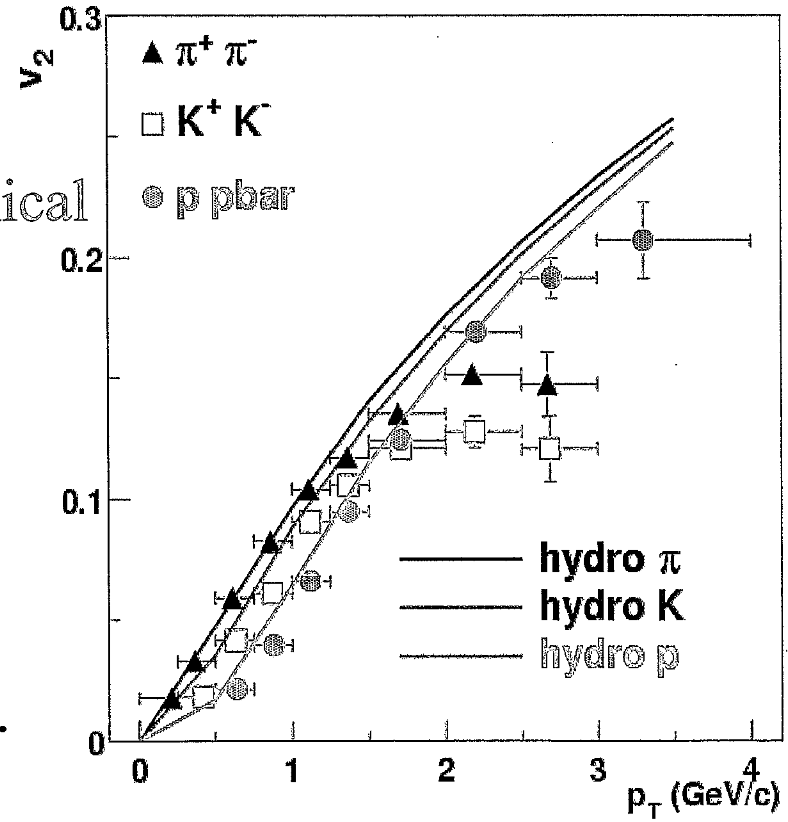
In this presentation, we' ll show the transverse momentum dependence of hadrons $v_2(\pi, K, p, d)$ at 200 GeV Au+Au collisions in the PHENIX experiment at RHIC and discuss the trend comparing with hydro and coalescence model. And we' ll also show the electron v_2 because the high p_t electron v_2 can carry information about the anisotropy of the parent charmed mesons.

Comparison with hydro model

- $p_T < 2.0$ GeV/c
  - Clear mass dependence

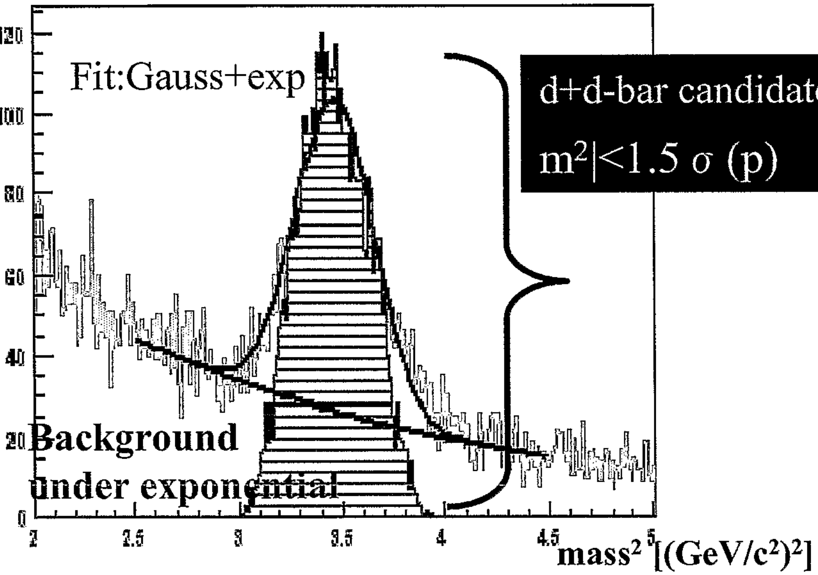
    $v_2(\pi) > v_2(K) > v_2(p)$

    Consistent with hydrodynamical model.
- $p_T > 2.0$ GeV/c
  - $v_2(p) > v_2(\pi)$
  - Clear departure from hydrodynamical behavior is observed.
  - Saturation at intermediate p_T.



How about heavier particle ? (deuteron v_2)

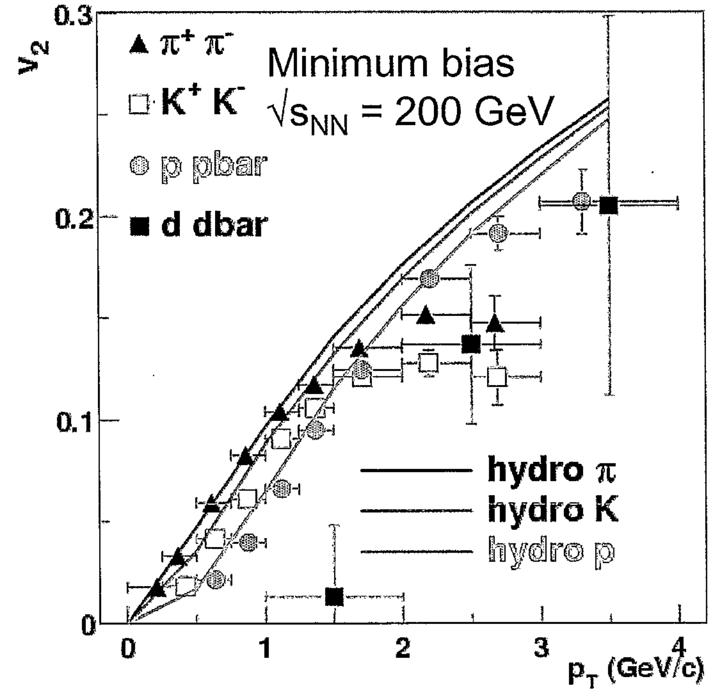
m² distribution(1.0<p_t(GeV/c)<2.0)



v_2 of d+d-bar is estimated by subtracting backgrounds.

$$\frac{dN^{corr}}{d\phi} = \frac{dN^{cand}}{d\phi} - \frac{dN^{bg}}{d\phi}$$

PHENIX PRELIMINARY



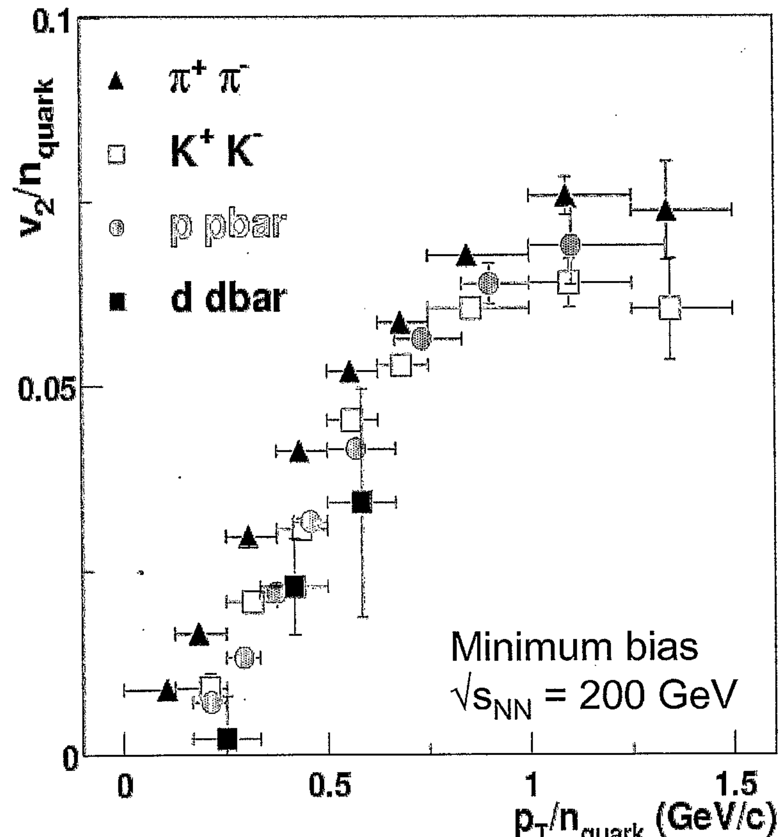
Clear mass dependence at low pt ;

deuteron v_2 is smaller than proton v_2

hadron or quark flow ?

Deuteron : coalescence of proton and neutron.

But if it's scaled with quark numbers • • •



hadron mass dependence seems to be remaining even after n_{quark} scaling.

It might suggest that there are two different flows (quark flow and hadron flow) before and after phase-transition or chemical freeze-out.

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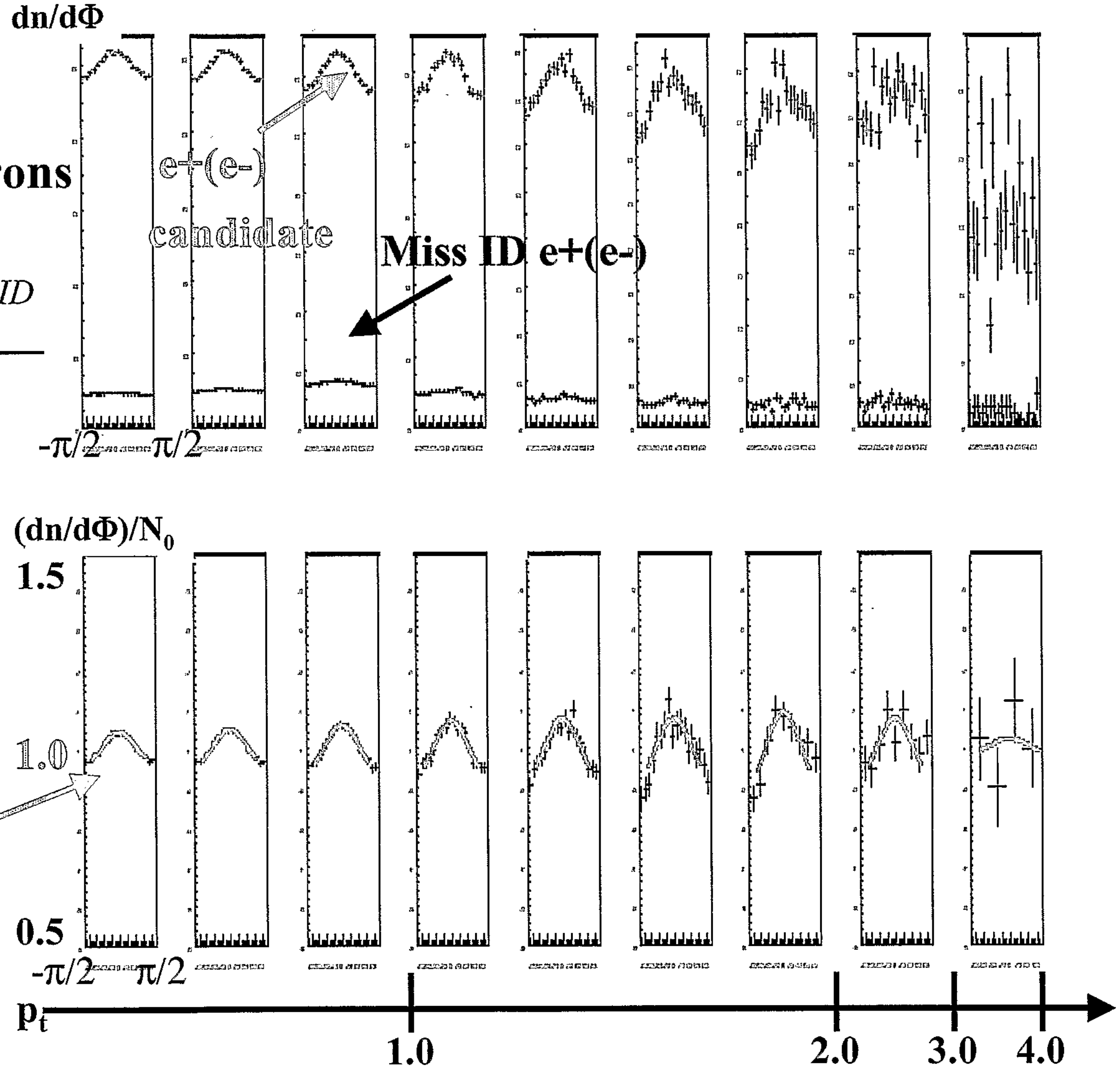
dn/dΦ distribution

v_2^e is corrected by subtracting miss ID of electrons

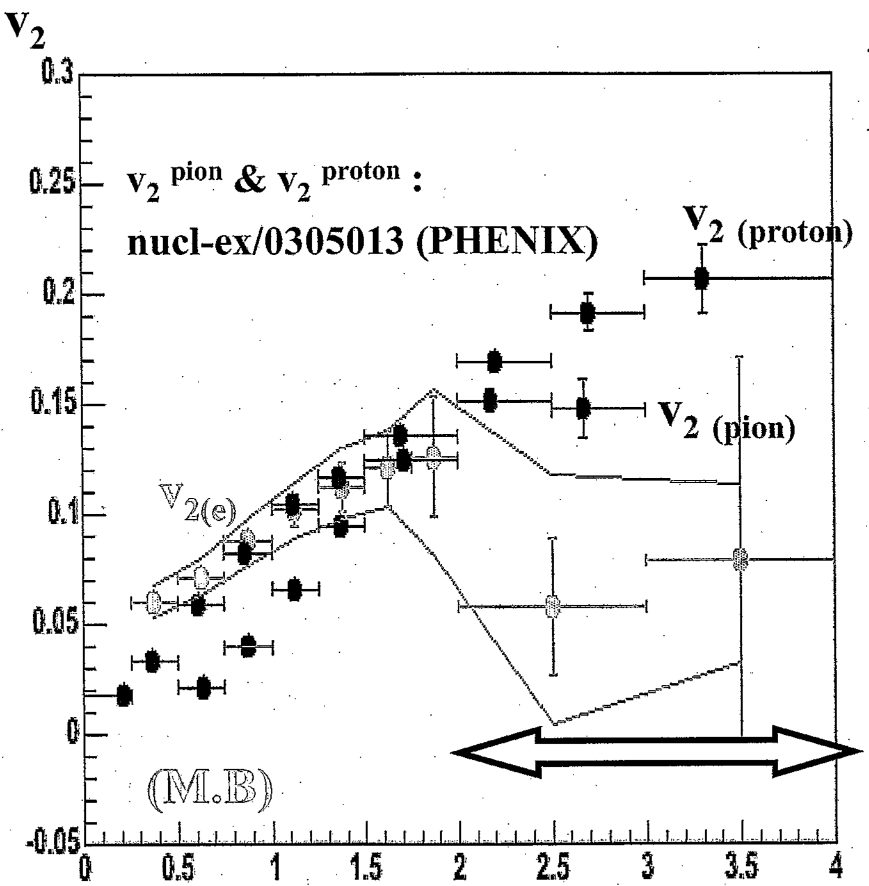
$$\frac{dN^{corr}}{d\phi} = \frac{dN^{cand}}{d\phi} - \frac{dN^{missID}}{d\phi}$$

cand --- dn/dphi of candidate (detected RICH) e+(e-)
miss ID --- dn/dphi of miss ID e+(e-)



dn/dΦ of after subtract Miss ID e+(e-)

Comparison with v_2 of hadrons



p_t[GeV/c]

higher statistics needed.

x30 statistics expected in run4.

<<Low p_t (p_t<1.0GeV/c)>>

$v_{2(e)}$ is larger than $v_{2(pion)}$ & $v_{2\ (proton)}$

-> dominant pi0 decay

- small decay angle
- decay from higher p_t

<<High p_t (p_t>2.0GeV/c)>>

$v_{2(e)}$ seems to be smaller than $v_{2\ (pion)}$

particular interest because of the contributions from heavy-quark (c/b) decays !(but the data include another sources now)

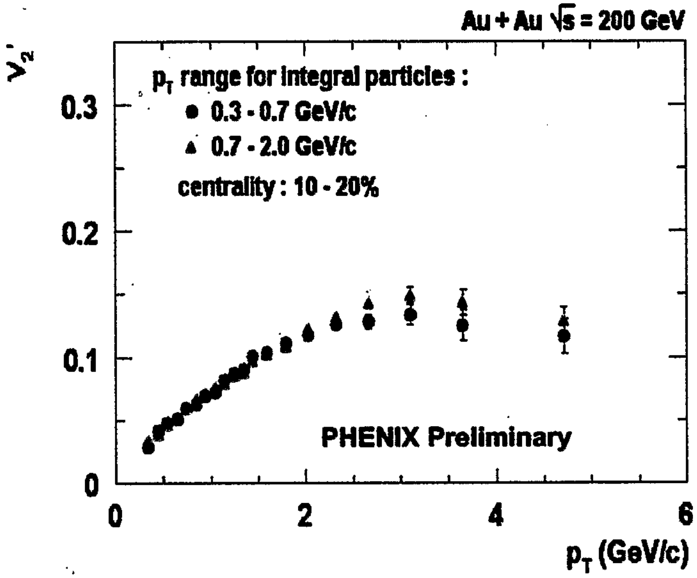
Azimuthal Correlation Studies via Correlation Functions and Cumulants

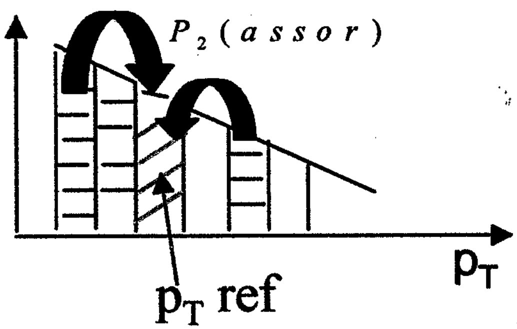
N. N. Ajitanand
SUNY, Stony Brook

The azimuthal anisotropy (v2) of charged hadrons measured in Au+Au collisions ($\sqrt{s_{NN}} = 200GeV$) by PHENIX has been quantified via cumulants. The second order cumulant v2 obtained as a function of pT and centrality show scaling behavior consistent with an eccentricity driven anisotropy. The similarity of v2 obtained by correlating high pT hadrons with relatively low and relatively high pT partners suggests that jets are correlated with the reaction plane.

Assorted azimuthal correlations are shown for high pT leading hadrons with flavor-identified partners of lower pT. In Au +Au collisions the correlations for associated baryons are noticeably more symmetric than for associated mesons indicating significantly lower contributions into the baryon branch of the jet fragmentation. In contrast, in d + Au collisions both types of associated particle correlations show sizeable asymmetries. A method developed to extract jet yields and jet properties through a de-convolution of the correlation functions, is also discussed.

Cumulant Analysis: Dependence on integral p_T range

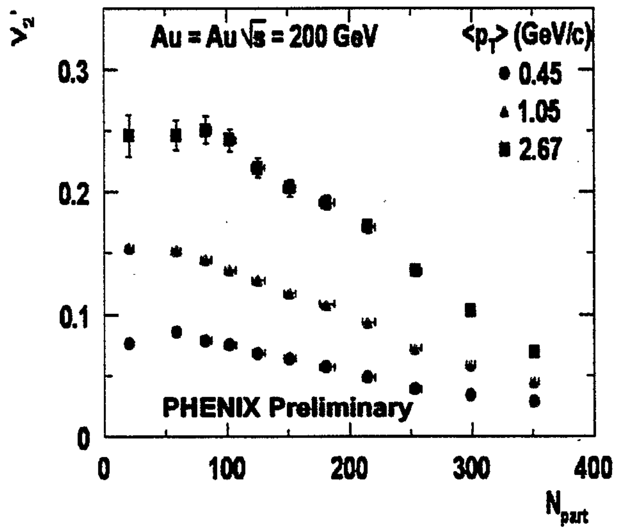


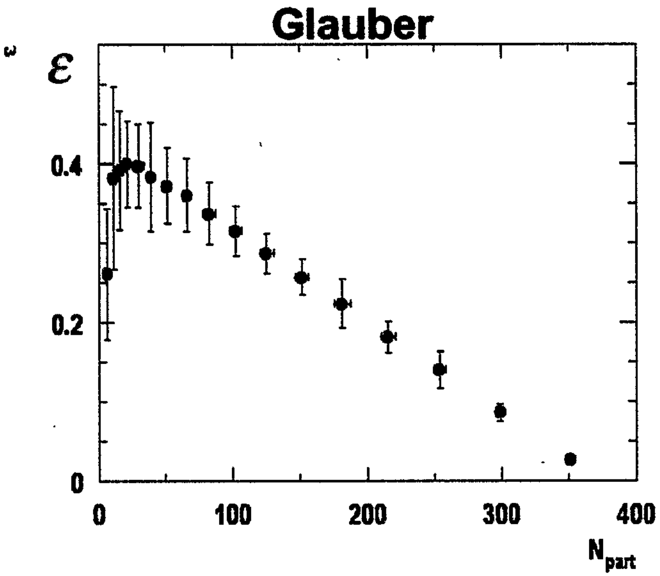


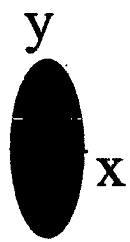
- ***No significant dependence on integral p_T of reference***

N. N. Ajitanand, SUNY Stony Brook

Cumulant Analysis: Centrality Dependence







eccentricity

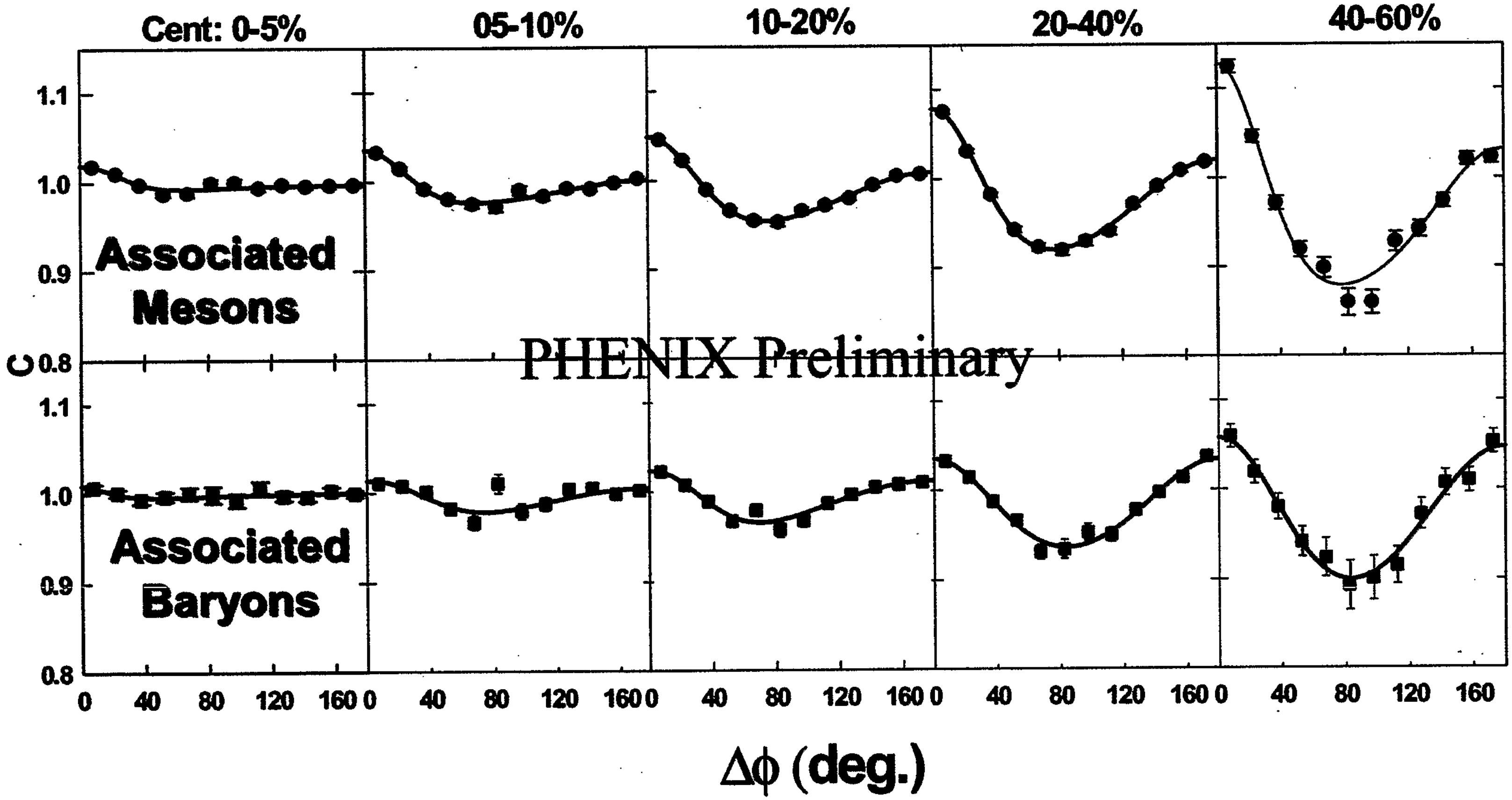
$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Anisotropy driven by eccentricity : v_2 scales with N_{part}

Assorted Correlation Functions

$2.5 < pT_{LH} < 4.0$ GeV/c

$1.0 < pT_{A_{M/B}} < 2.5$ GeV/c

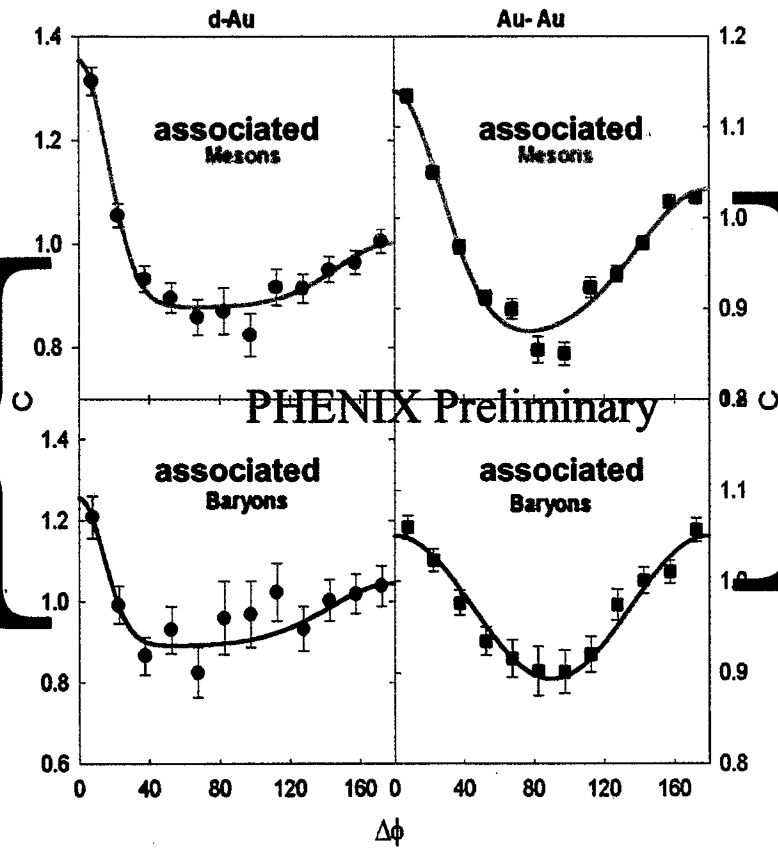


Noticeable differences in the asymmetries For associated baryons and mesons

N. N. Ajitanand, SUNY Stony Brook

Assorted Correlation Functions

- Similar asymmetry trends for associated mesons & baryons in d+Au



- Dissimilar trends for associated mesons and baryons in Au+Au

De-convolution of Correlation Function Necessary

N. N. Ajitanand, SUNY Stony Brook

Collective flow and QGP properties
Brookhaven, November 17–19, 2003

FREEZE-OUT AND ELLIPTIC ANISOTROPY

Pasi Huovinen
University of Jyväskylä

Freeze-out

- When/where particles scatter the last time
- Loosely speaking: "when mean free path is larger than system size"
- Mean free path depends strongly on temperature $\rightarrow$ simple approximation: freeze-out at constant temperature/energy density
- Dynamical criterion (Bondorf *et al.* NPA296 (1978)): Freeze-out when expansion rate equals scattering rate:

$$\xi = \frac{\tau_{exp}}{\tau_{scat}} \approx 1$$

- Expansion time:

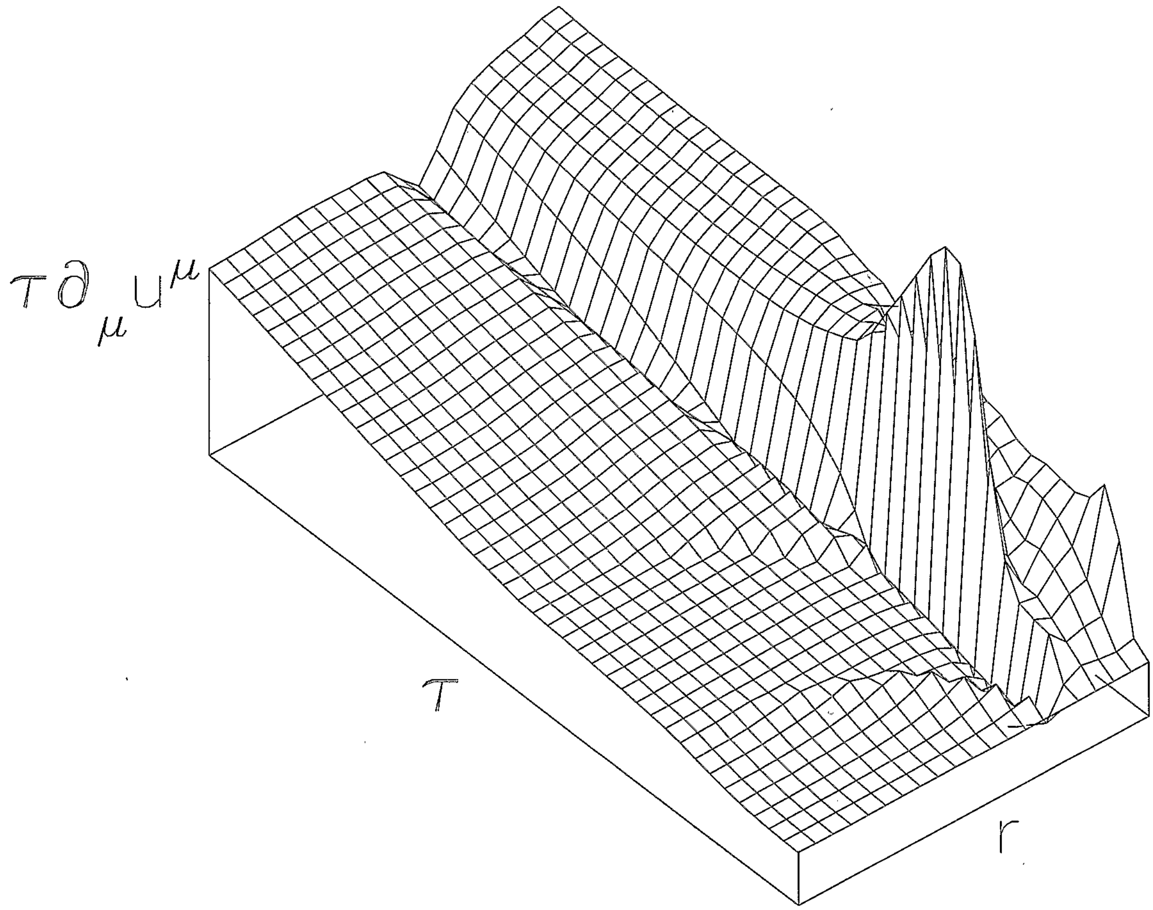
$$\tau_{exp} = \frac{1}{\partial_\mu u^\mu}$$

- Scattering rate of pions from Prakash *et al.* Phys. Rep. 227 (1993).

$$\tau_{\pi\pi}^{-1} \approx 16 \left(\frac{T}{100\,\mathrm{Me}V}\right)^4 \mathrm{Me}V$$

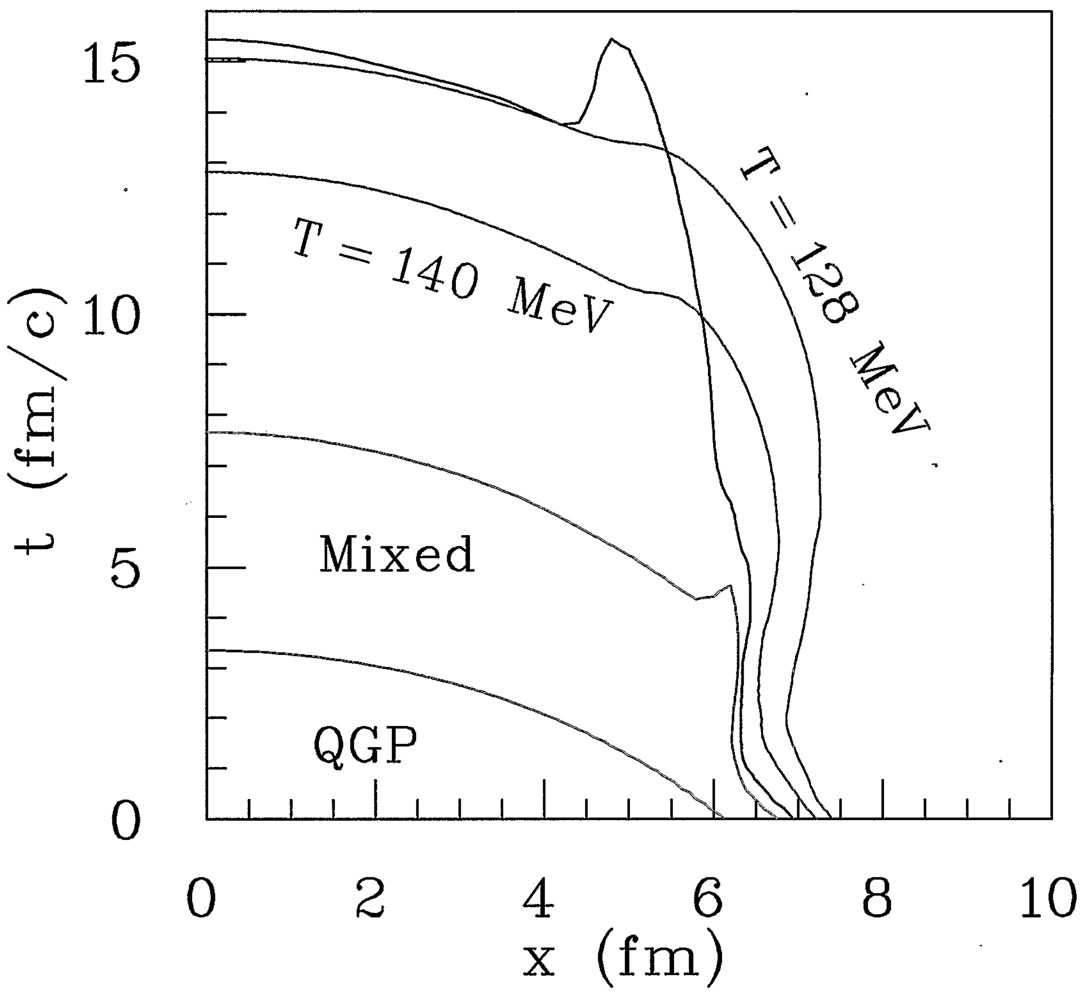
Parametrization by Daghigh & Kapusta, PRD65 (2002)

Expansion rate in almost central collision



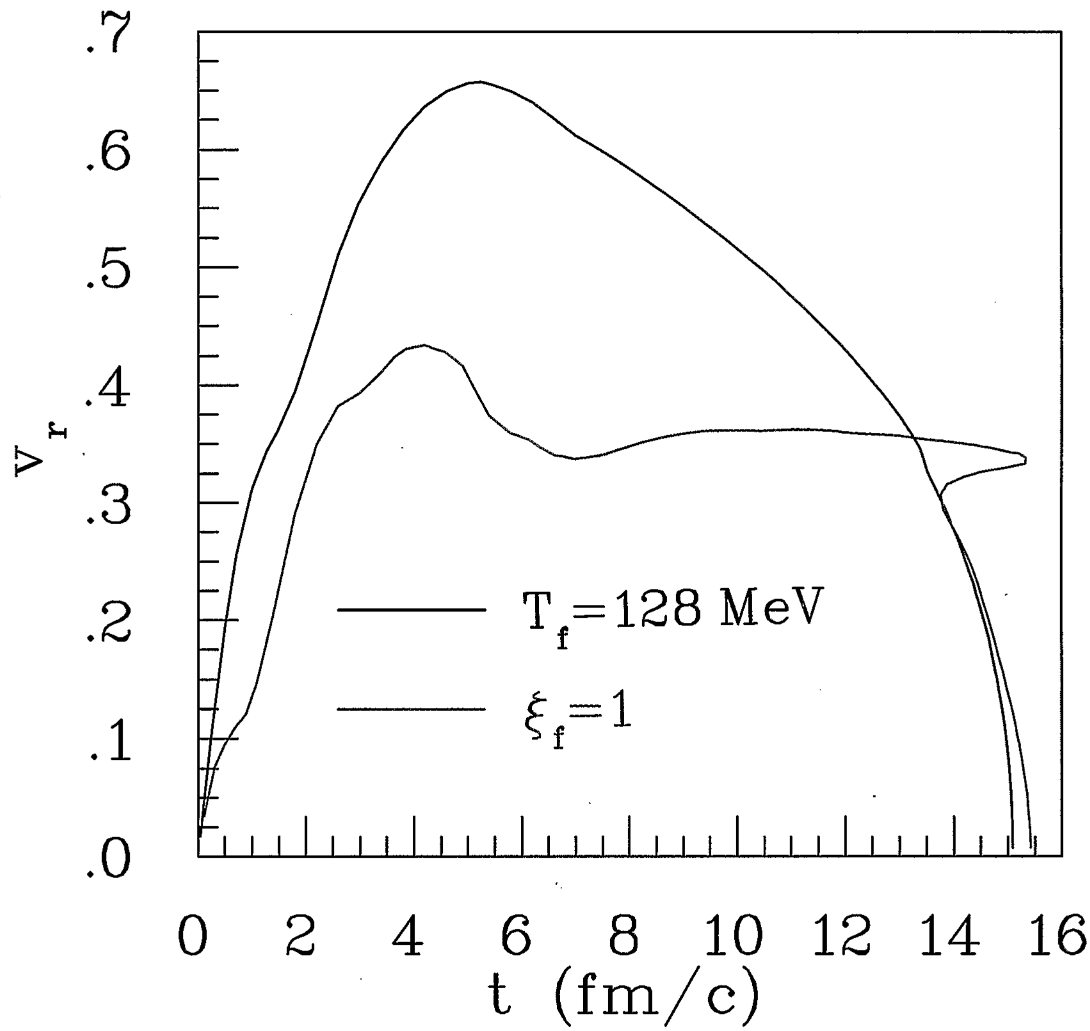
- Expansion rate $\partial_\mu u^\mu$ multiplied by time to remove "trivial" longitudinal expansion
- Rarefaction shock wave in the early stage
- "Valley of slow expansion" has its origin in mixed phase but it even after the system is completely hadronized

Freeze-out and constant temperature surfaces in xt-plane



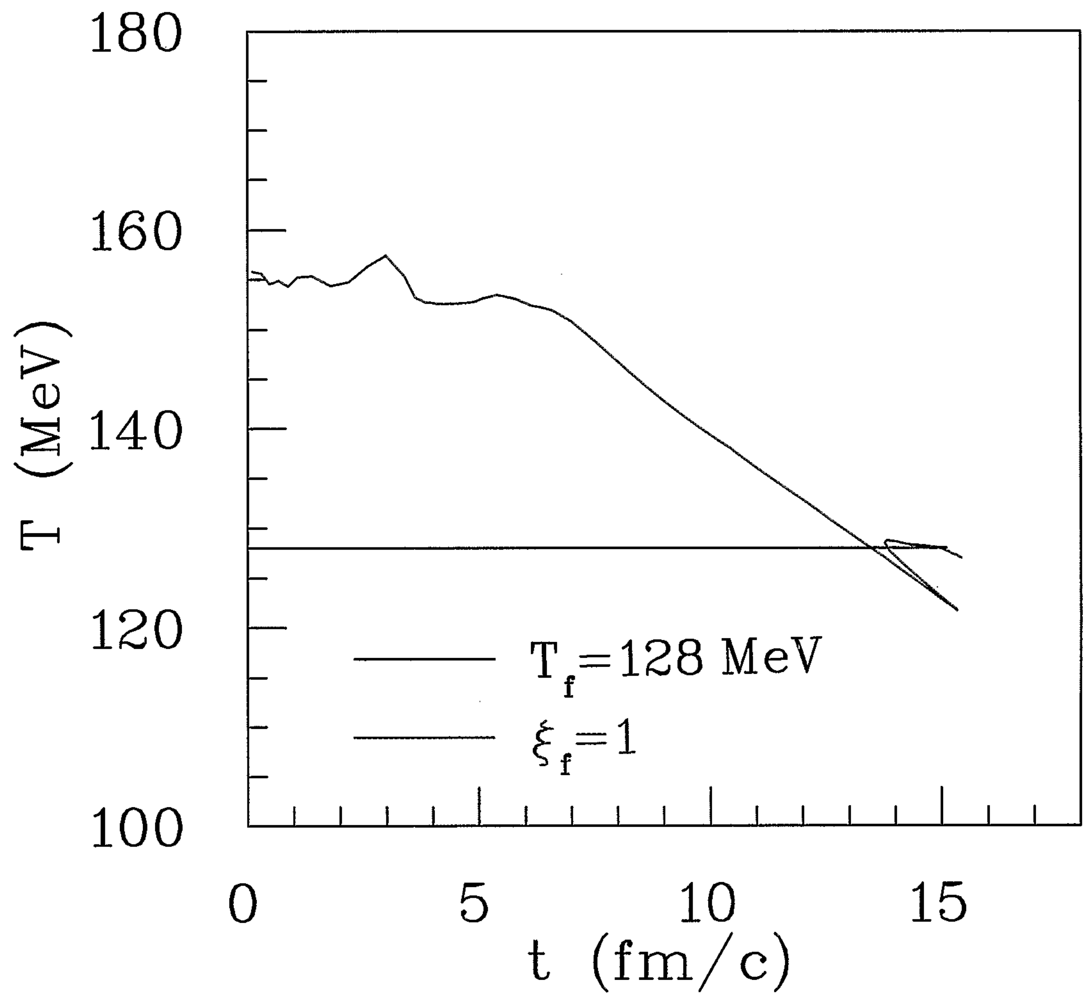
- Change in size small
- Most particles emitted in almost constant temperature

Transverse flow velocity on freeze-out surface as function of time



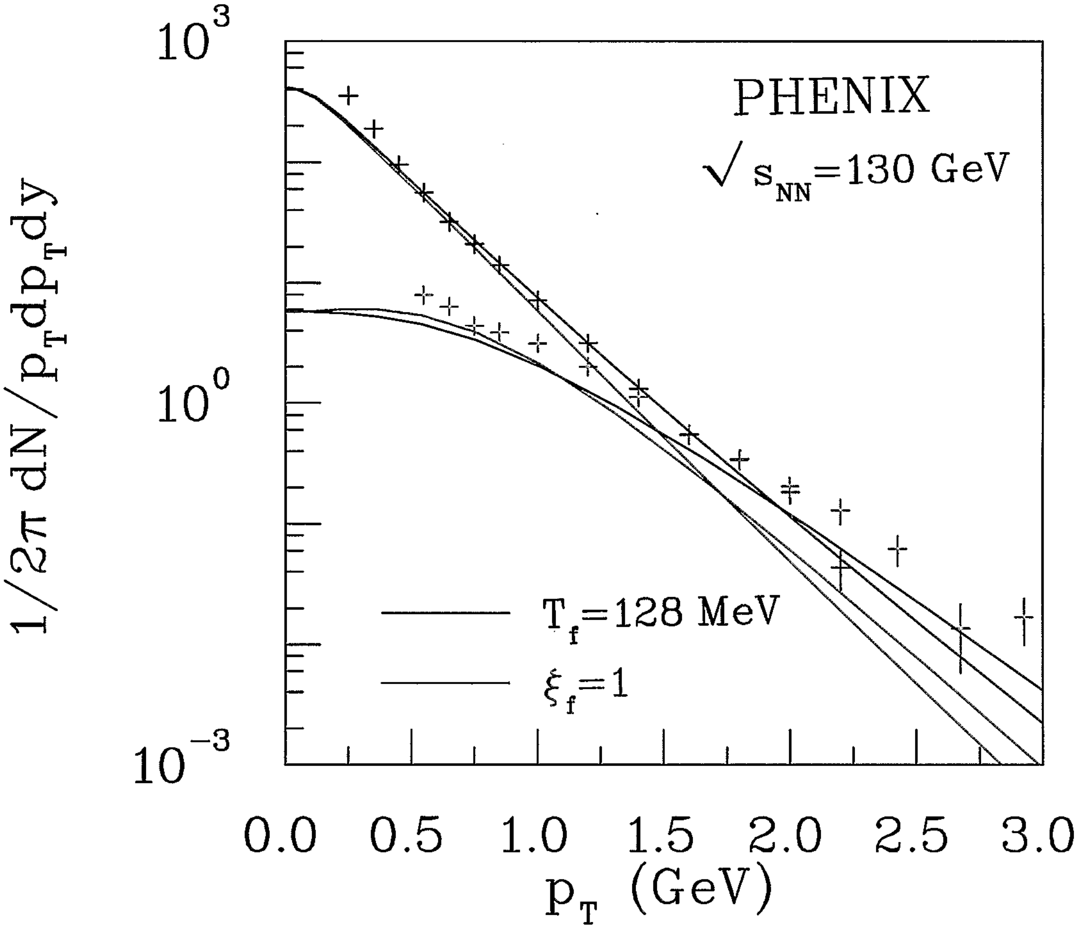
- Maximum flow velocity cut by almost a factor of two!

Temperature on freeze-out surface as function of time

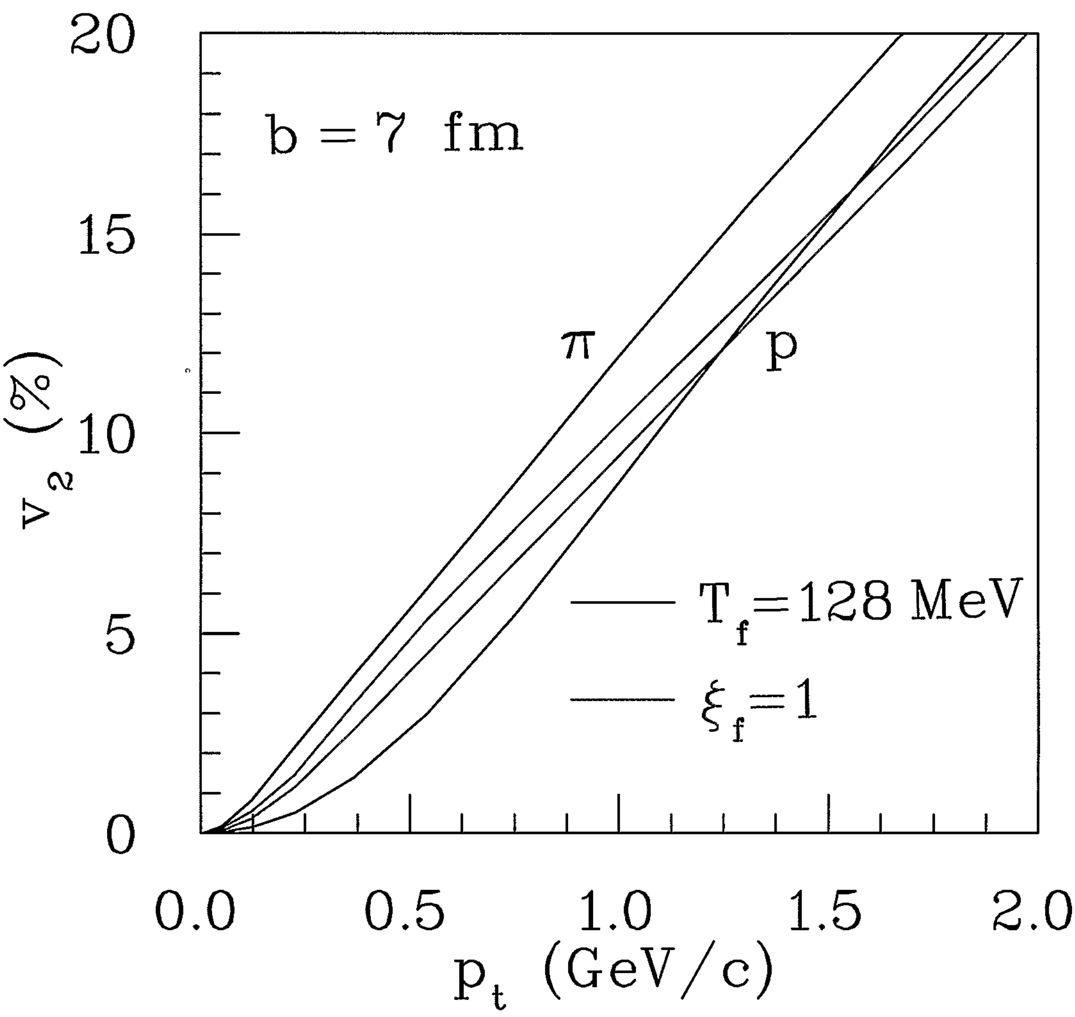


- Average temperature ~ 140 MeV

Pion and antiproton p_T spectra for most central collisions

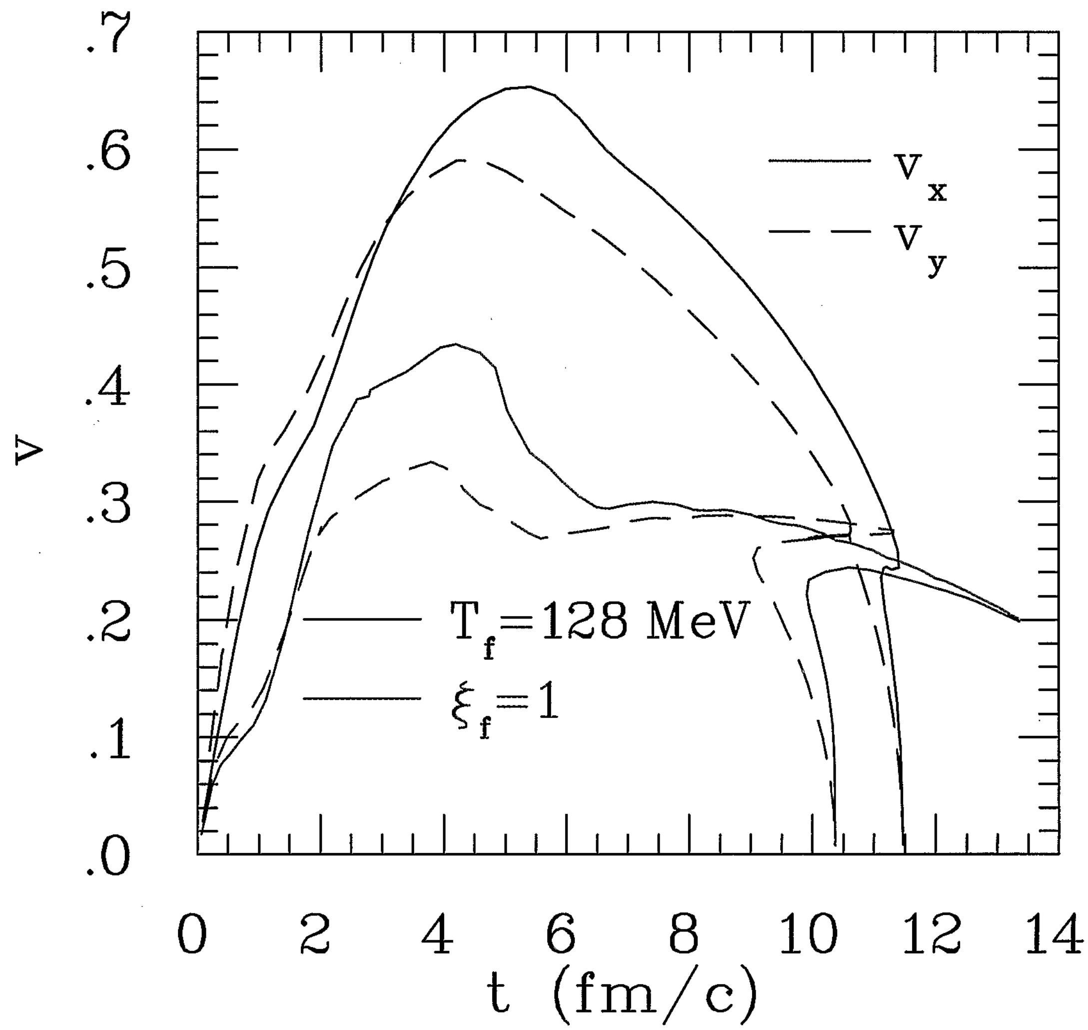


Pions and protons $v_2(p_t)$ in $b = 7$ fm collision



- Pion and proton v_2 close!
- Sign of shape, not flow anisotropy

Transverse flow velocity in in-plane and out-of plane directions

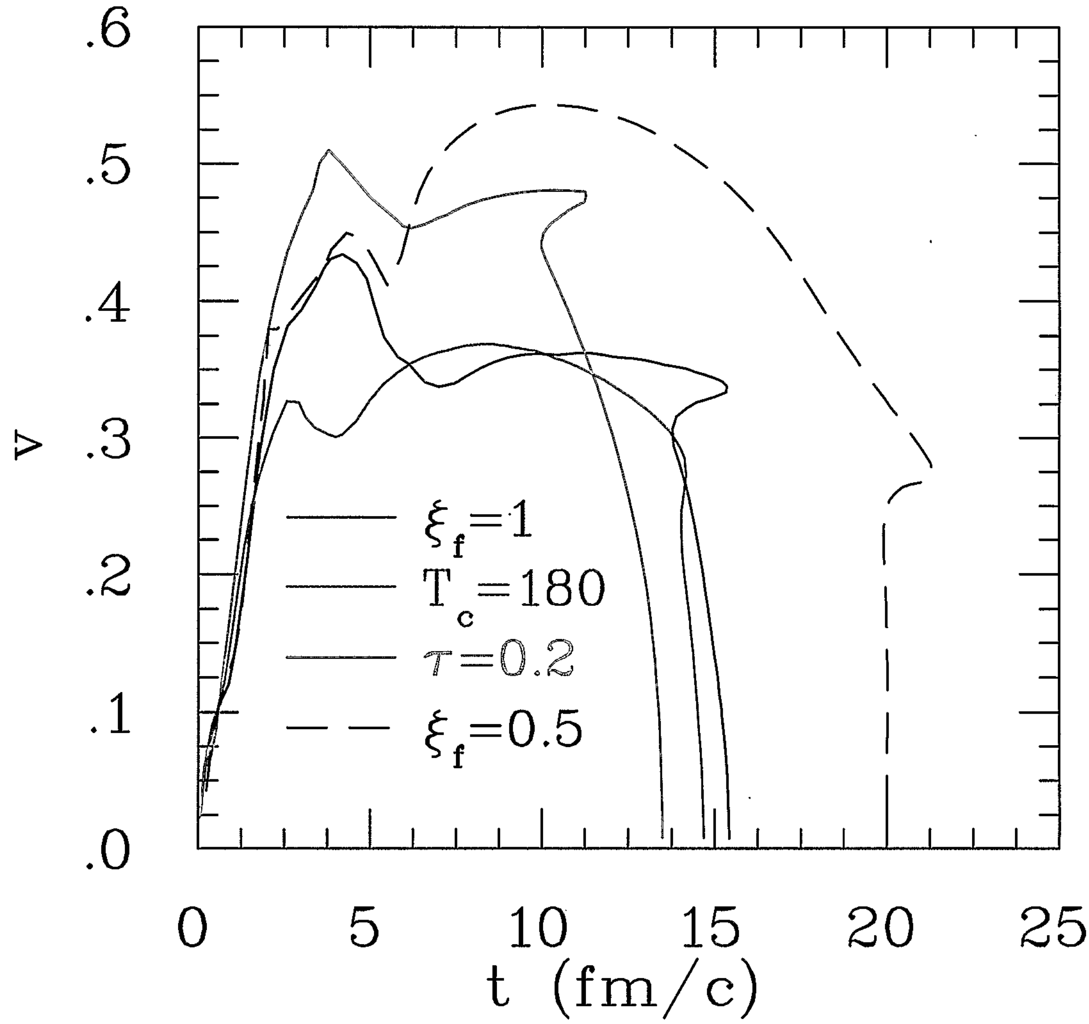


- Flow velocity in-plane and out-pf-plane almost similar after hadronization shock disappears

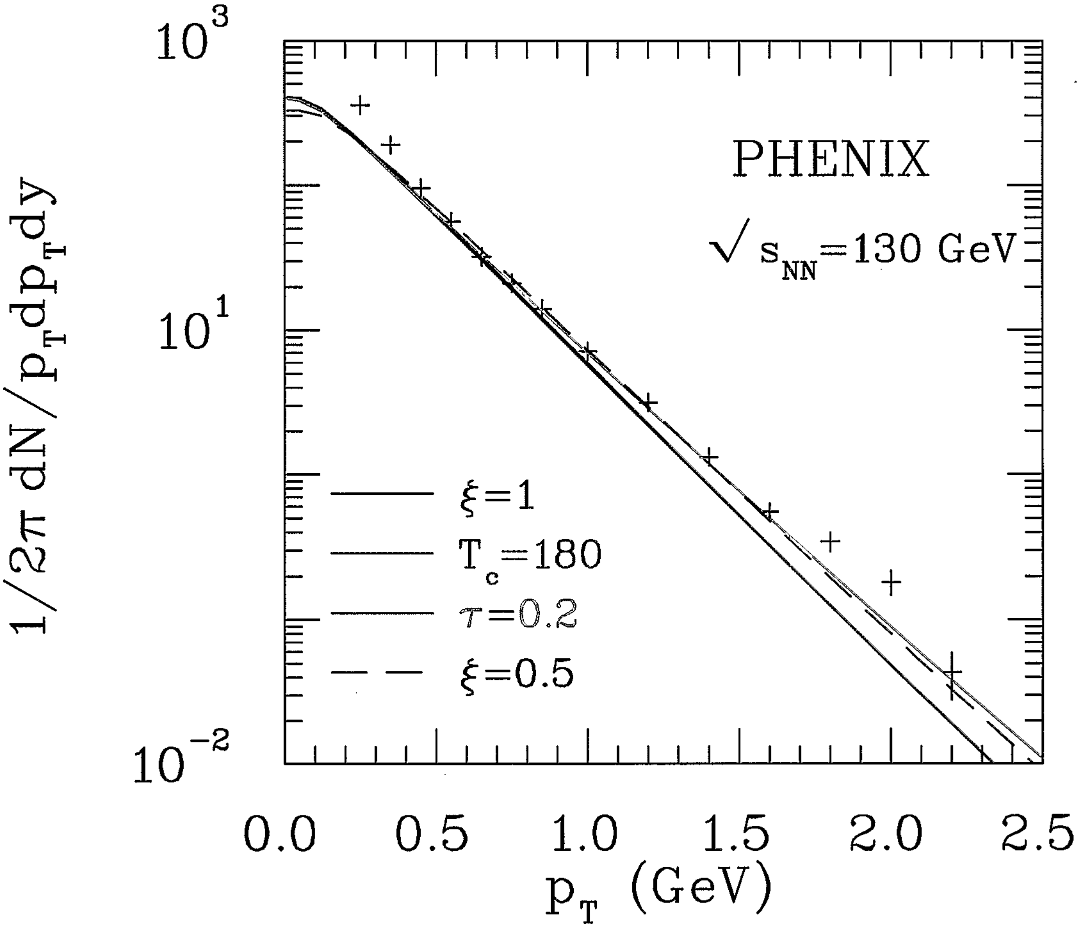
How to create more flow?

- Stiffer EoS
  - higher $T_c \rightarrow T_c = 180$ MeV instead of 165 MeV
- Steeper initial gradients
  - Participant vs. binary collisions scaling
- Shorter initial time
  - $\tau_0 = 0.2$ fm/c instead of 0.6 fm/c
- Later freeze-out
  - $\xi = 0.5$ instead of 1

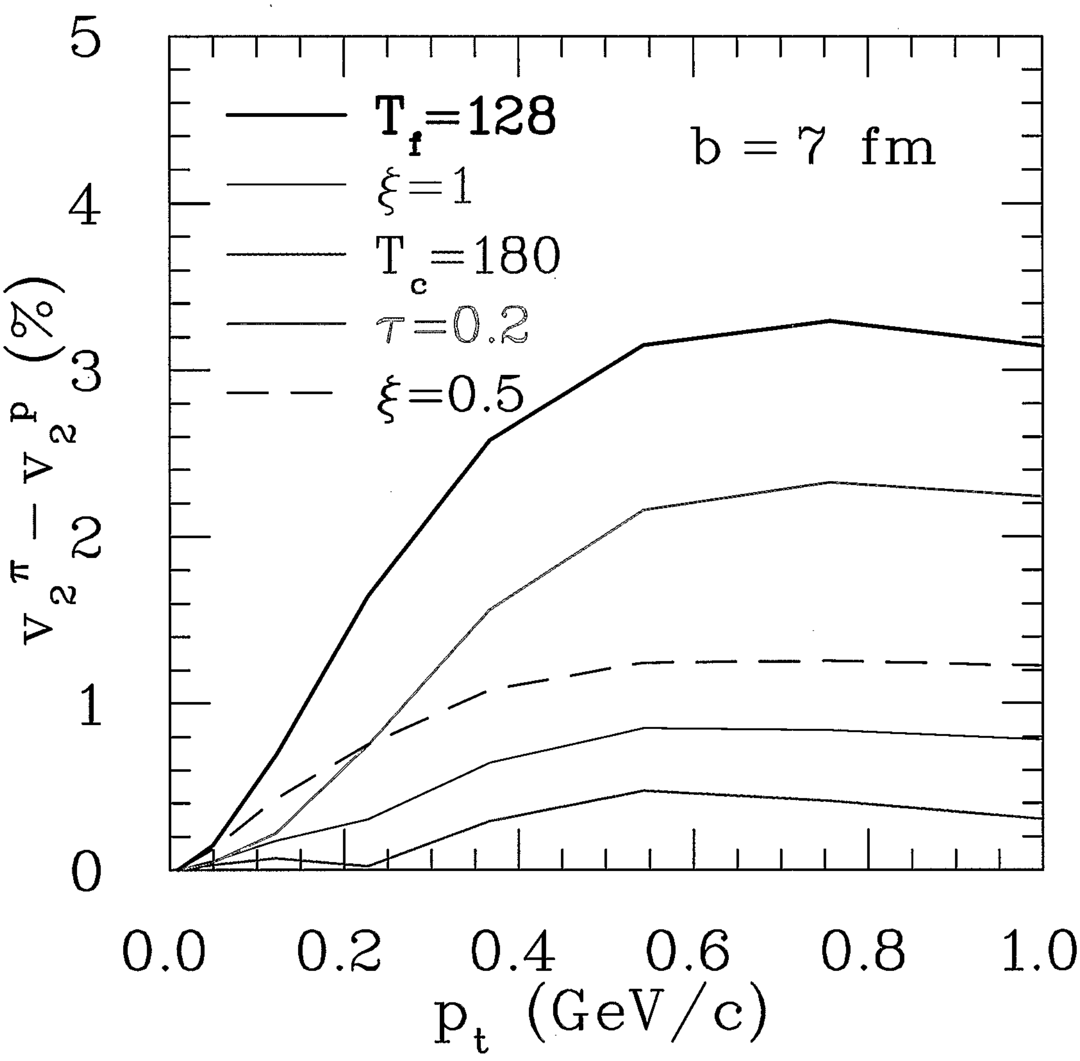
The effect of EoS, initial state and ξ_f on transverse flow velocity



The effect of EoS, initial state and ξ_f on pion p_T spectrum



Difference between pion and proton $v_2(p_T)$



Summary

- Freeze-out at constant temperature/density is over-idealization
- But freeze-out where expansion and scattering rates are equal does not fit the data!
  - seem to need larger scattering rates in hadron gas
- Possible solutions
  - scattering rate wrong?
  - EoS with smooth crossover → no shock → smoother expansion?
  - EoS with smaller T_c?
  - Continuous freeze-out from 4-volume?

The HBT Puzzle at RHIC

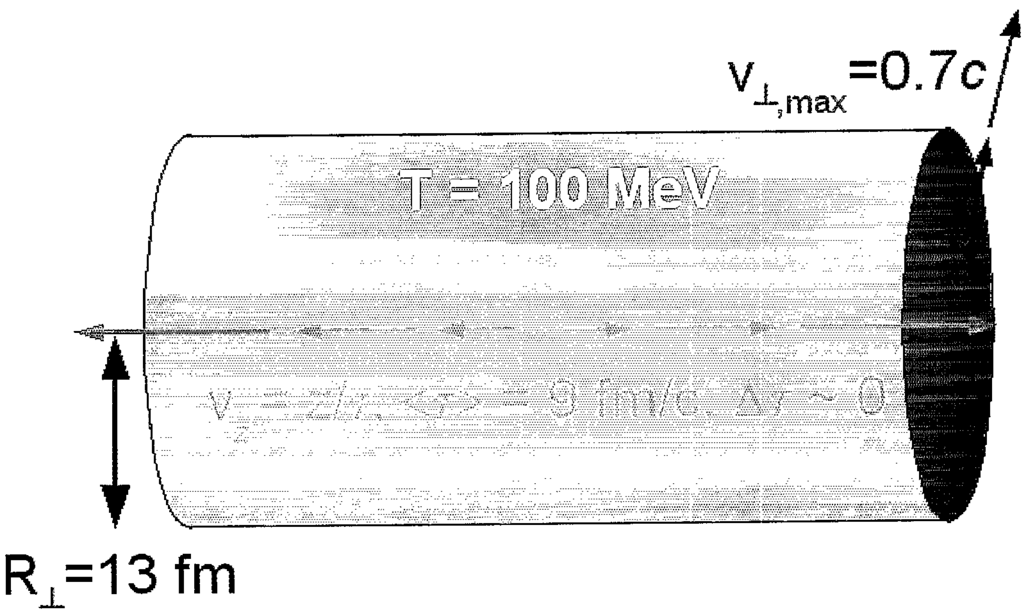
Scott Pratt, Michigan State University

After reviewing the fundamentals of HBT, I will discuss two-pion correlations at RHIC and explain why they seem to defy explanation. Although they can be well fit with blast-wave parameters, the blast-wave configuration is difficult to reach. The large transverse size (13 fm) must be reached in a remarkably short time (~10 fm/c) which would require instantaneous acceleration of the fireball from rest to the fit edge velocity of 0.7 *c*. Furthermore, surface emission must be damped to explain $R_{out}/R_{side} \sim 1$. I will review the robustness of the HBT formalism and provide some rough ideas for what changes in the dynamics might help explain the measurement. Finally, I will present alternative means for measuring the space-time parameters of the source using non-identical particles.

OUTLINE

- Brief review
- What is the HBT Puzzle?
- Can we blame theorists?
- Can we blame experimentalists?
- Are we leaving something out of the dynamics?
- Alternative "HBT" Methods

Blast Wave Parameters



Unphysical acceleration??

Invalid formalism??

$$C(\vec{v},\vec{q}) = \int d^3r\, g(\vec{v},\vec{r}) \left|\psi(\vec{q},\vec{r})\right|^2$$

1. Higher-order symmetrization S.P. PLB(93)•Only important at low q, where $f_{max} > 1$

2. Independent emission

•Should be good for large sources at moderate p_t

3. Equal-time approximation

•**Not an issue for pure HBT**

•Testable with classical trajectories for Coulomb

4. Smoothness

•Not an issue for pure HBT with large sources S.P., PRC(2000)

5. Interact only two-at-a-time

•Assumes "Hard" Interactions with 3rd body

•Mean Field effects cancel in Glauber approximation R.Lednicky et al., PLB(96)

No distortions greater than 10% from approximations (so far)

Shortcomings of Hydro Treatments

1. Lack of viscosity
- Underpredicts transverse acceleration
- Underpredicts lifetime ($v_{therm,z}$ would shrink)
2. Assume boost invariance
- Should cut off tails of source at large z
- Neglects longitudinal acceleration
3. "Emissivity" between phases
- Shock wave treatments assume maximum burn rate
4. Neglect mass shifts
- Underpredicts phase space density

Alternate Measurement of $R_{out}/R_{long}/R_{side}$

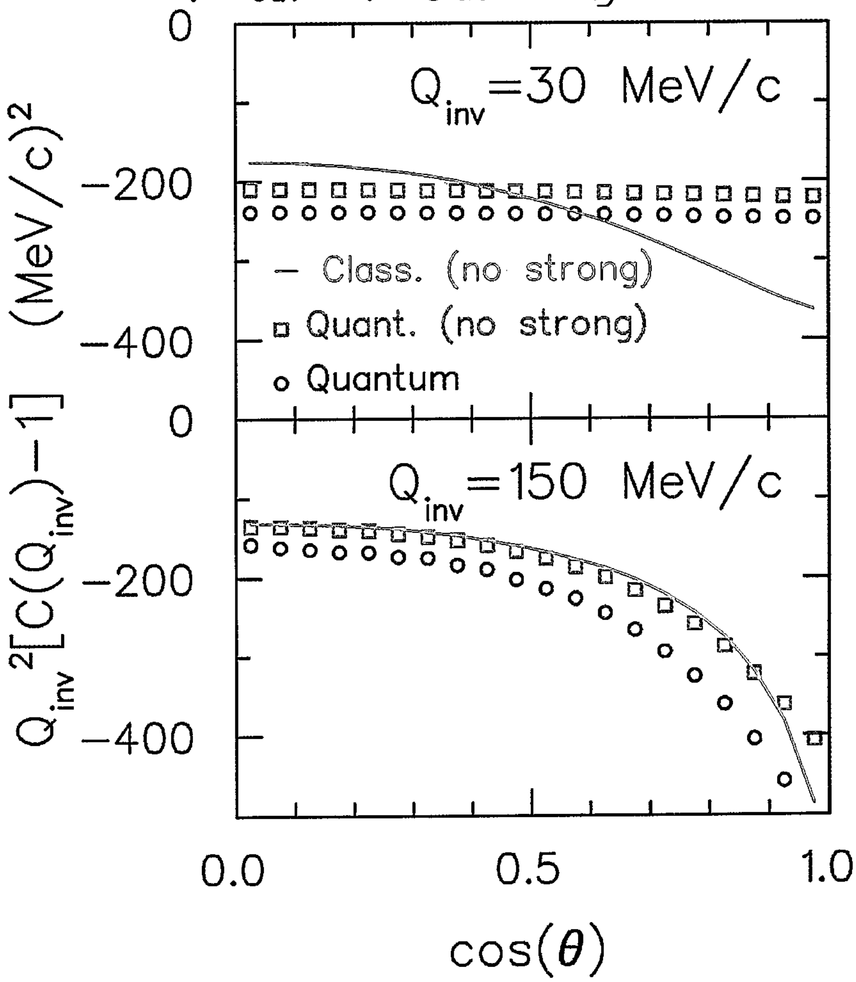
S.P. and S.Petriconi, PRC(2000)

Any $\cos(\theta_{qr})$ dependence in $|\phi(q,r,\cos\theta)|^2$ provides leverage for determining shape

For *r* outside interaction range ε,

$$\psi(\vec{q},\vec{r}) = \psi_0(\vec{q},\vec{r}) + \frac{1}{qr}\sum_\ell (2\ell+1) i^\ell P_\ell(\cos\theta)\left(e^{-2i\delta}-1\right)\varphi_\ell^{in}(q,r)$$

pK Correlations, R_{out}=8, R_{side}=R_{long}=4 fm



Summary

- HBT Puzzle remains elusive
- Theorists must:

-Finish checking validity of HBT formalism

-Add features to "hydro" treatments (viscosity, emissivity, non-Bjorken IC)

-Further investigate non-idenctical particles

- Experimentalists should:

-Finish analyses of KK interferometry

-Perform shape analyses with non-identical particles

The freeze-out state at RHIC

Boris Tomášik

The Niels Bohr Institute

Collective flow and QGP properties
RIKEN-BNL workshop
November 19, 2003

By using the method of HBT interferometry in combination with examining the single-particle p_t spectra one can infer information about the final state (the freeze-out) of the fireball. In particular, it is possible to determine the temperature at the kinetic freeze-out and the strength of the transverse expansion. These two quantities are always correlated when looking at spectra and/or HBT individually.

On the other hand, freeze-out is a result of a "competition" of these two quantities. Indeed, particles decouple from the fireball when the rate at which the matter density drops becomes appreciably higher than the scattering rate. The former is determined by transverse expansion, the latter by temperature. Thus it makes sense to ask whether a combination of T and $\langle v_t \rangle$ inferred from a (model) fit to data is reasonable.

I apply the so-called blast-wave model in fitting the pion, kaon, and (anti)proton spectra as measured by PHENIX collaboration at $\sqrt{s} = 130\,A\text{GeV}$ and the HBT radii measured by PHENIX and STAR at the same energy. The important assumptions of the model are that i) all particle species decouple at the same time rather quickly; ii) the radial density distribution of the fireball is uniform; iii) there is a boost-invariant longitudinal expansion; iv) and there is transverse expansion. The model assumes thermal equilibrium; but alternatively temperature can be understood as a measure of coupling between particle momentum and the position from which is is emitted: the lower the temperature the stronger the coupling.

All observables—the six spectra and the HBT radii—are fitted separately. If the model is good, the fit results will be compatible. Incompatible fit results point to a failure of some assumptions of the model.

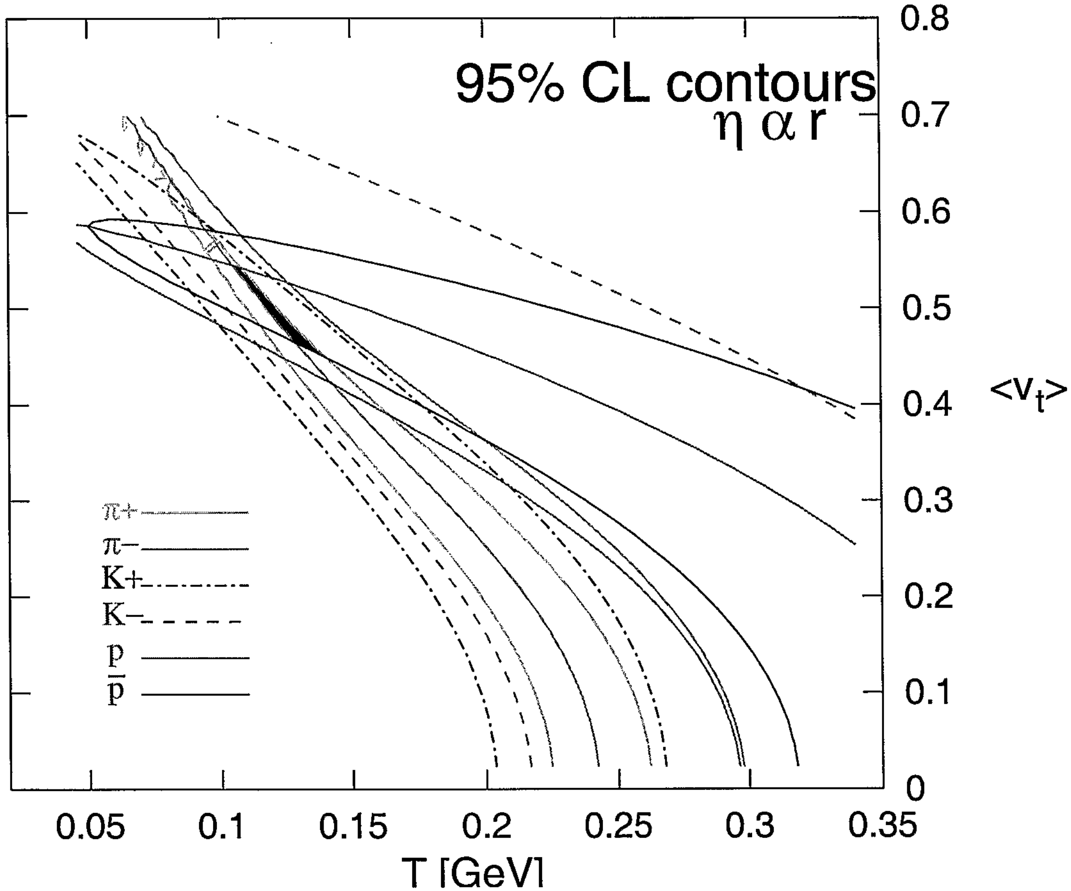
There is an overlap between the results on T and $\langle v_t \rangle$ from fitting spectra of different species at 95% confidence level. (There is no overlap of 1σ contours.) With a slight dependence on the choice of transverse flow profile and of the chemical potentials it is at temperatures 100–140 MeV and transverse flows 0.42–0.58c.

When fitting the HBT radii, it turns out that the data from the two collaborations are somewhat different: the $M_\perp$ slope of R_s is steeper in PHENIX data than in those from STAR. Quantitatively, this leads to a disagreement of the 1σ contours from fits in T and $\langle v_t \rangle$; however at 95% confidence level one already has an overlap. Here one profits from large error bars. If $\pi^+\pi^+$ HBT radii from both collaborations are fitted together, the 95% confidence interval in T and $\langle v_t \rangle$ has only a tiny overlap with that from the fits to spectra. The model, as it is formulated here, is *almost* excluded.

A striking result is obtained, if one looks for the *best* fit to the HBT radii. This is always obtained for very low values of the temperature parameter: 30–40 MeV. In such a case the place of particle emission is extremely strongly correlated with the momentum and one indeed reproduces the steep slope of R_s and R_l. Similar results are obtained from fitting the HBT radii from RHIC at 200 AGeV and from the SPS data.

This should *not* be interpreted as an evidence for very low freeze-out temperature!!! Instead, the model is pushed into a domain where its physical interpretation looses its meaning and the quantitative results probably indicate a different mechanism of particle emission. I think that a possible solution might be a fireball with continuous emission of particles. It turns out that it is easier for a high-p_t particle to escape the fireball than it is for a low-p_t one. Thus particles at higher p_t could escape earlier while the fireball is smaller, while those at low p_t would come from a big source. This could serve as an additional effect to generate the $M_\perp$ dependence of the HBT radii.

Fits to spectra with $\alpha = 1$ and $\mu = 0$



- resonances included according to temperature and $\mu = 0$
- no overlap at 1σ level!
- $T \approx 105 - 140\text{MeV}$
  $\langle v_t \rangle \approx 0.45 - 0.54$

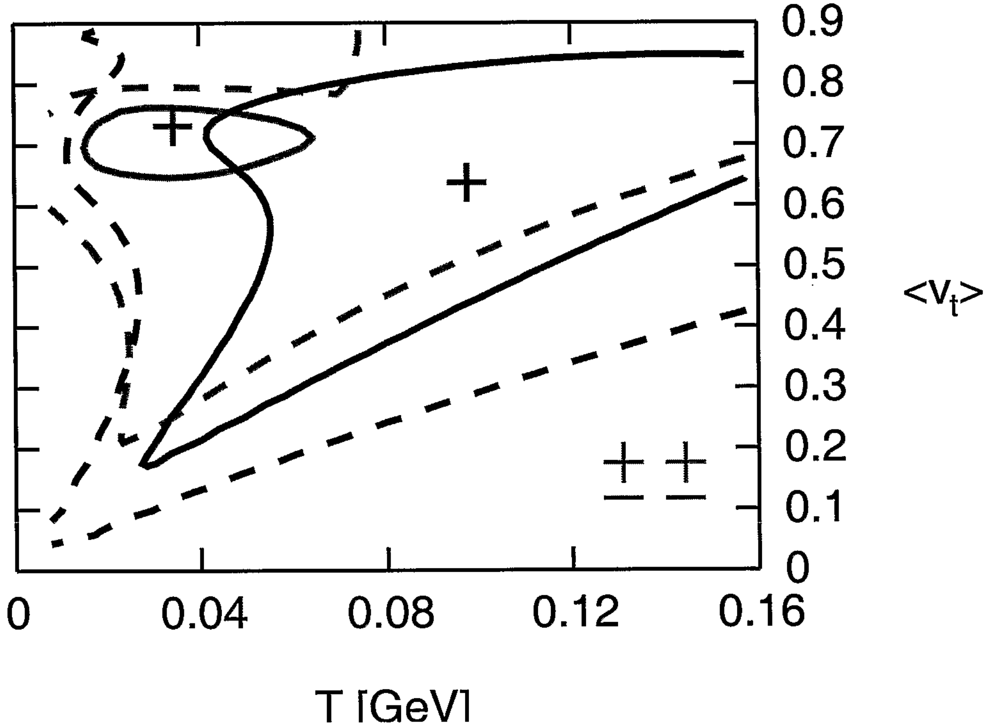
Conclusions from fits to HBT radii at RHIC 130

- PHENIX data push towards strong transverse flow

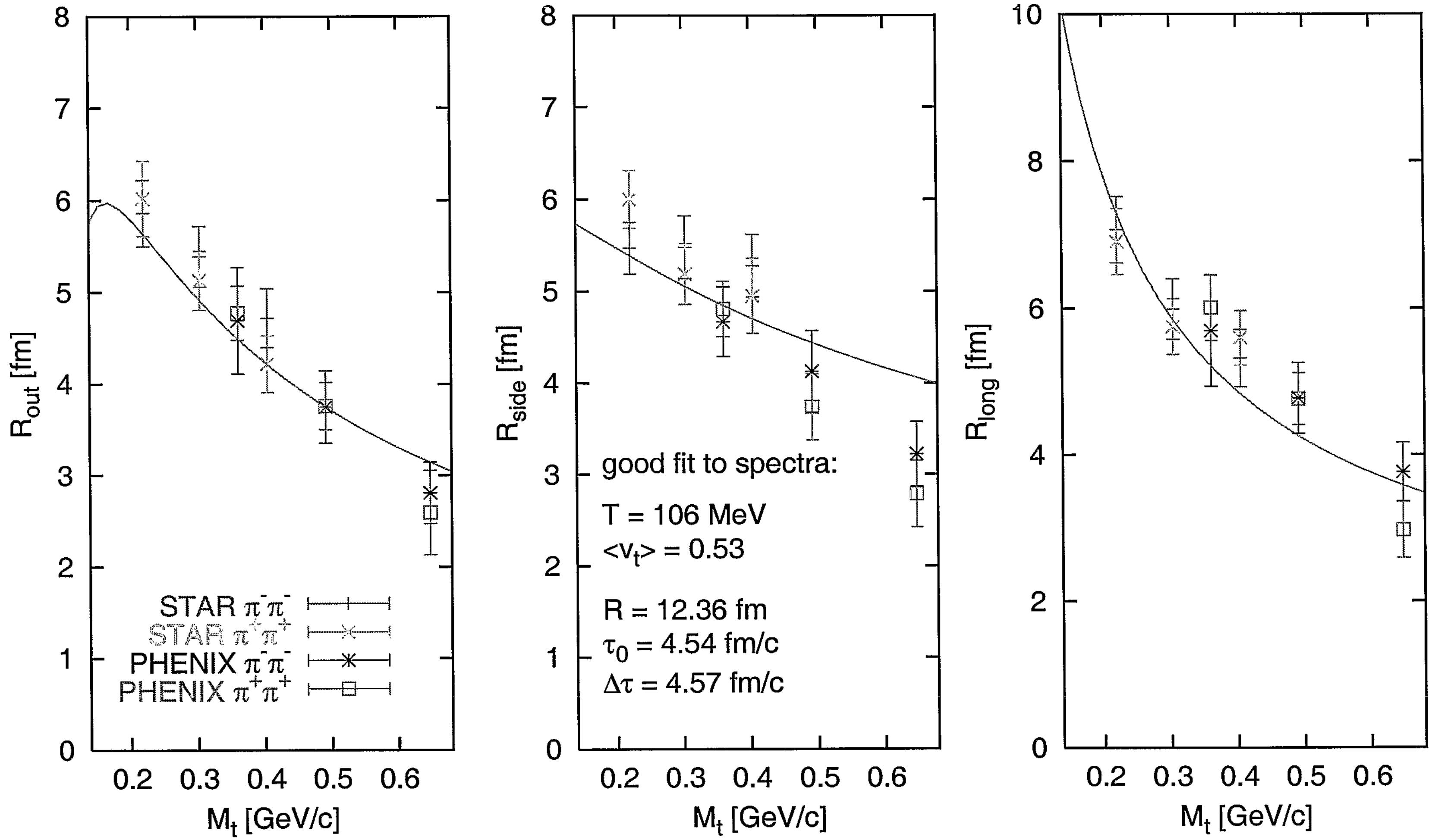
- weak-expansion-low-temperature region excluded: only tiny overlap with 95% CL from spectra!

- improvements with chemical potential, other flow profiles, etc to be checked

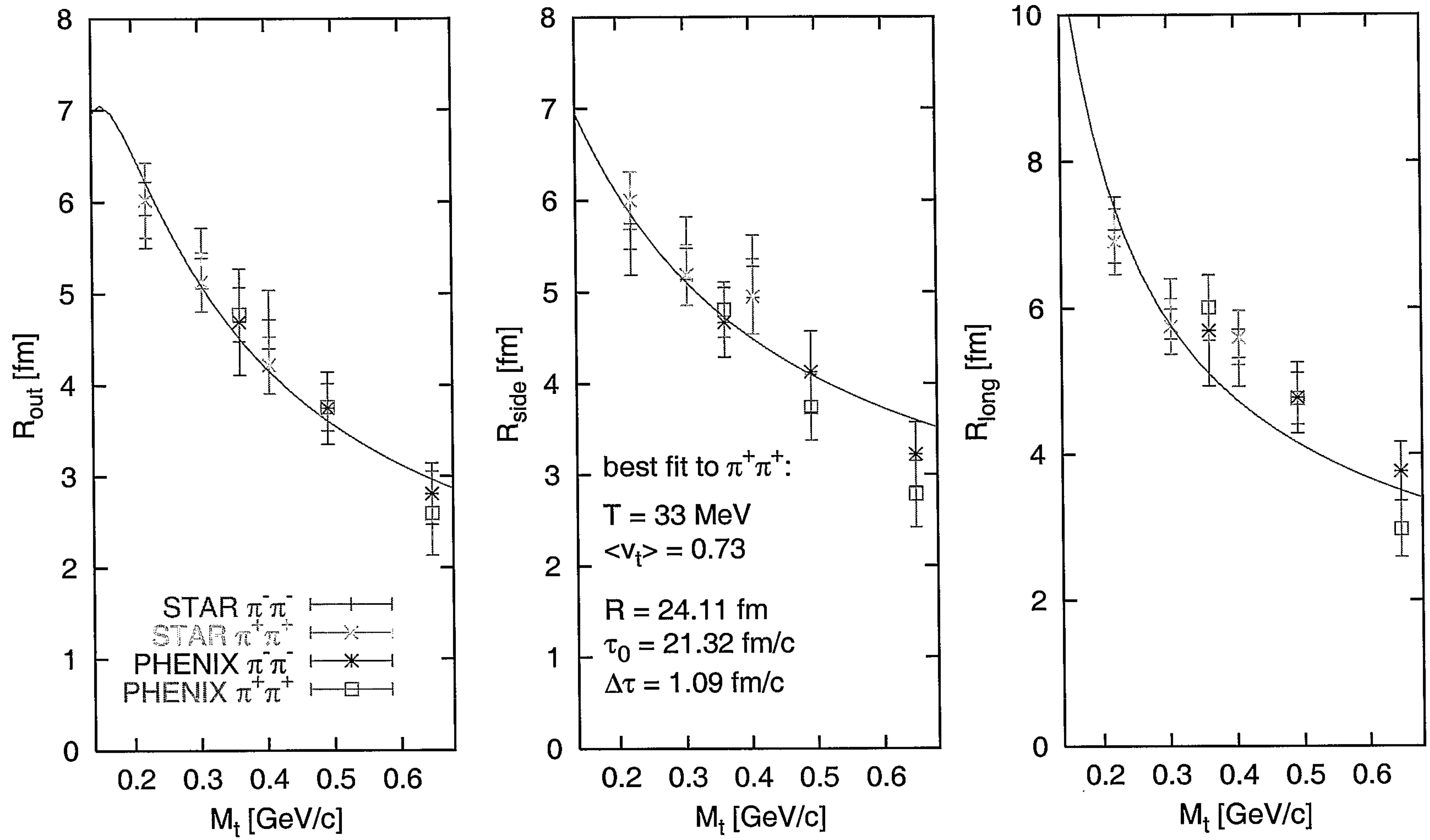
1σ and 95% CL contours from fits to $\pi^+\pi^+$ and $\pi^-\pi^-$ HBT radii from STAR and PHENIX



Model that fits HBT and spectra from RHIC 130



Best model to fit $\pi^+\pi^+$ HBT radii from RHIC 130



Continuous freeze-out

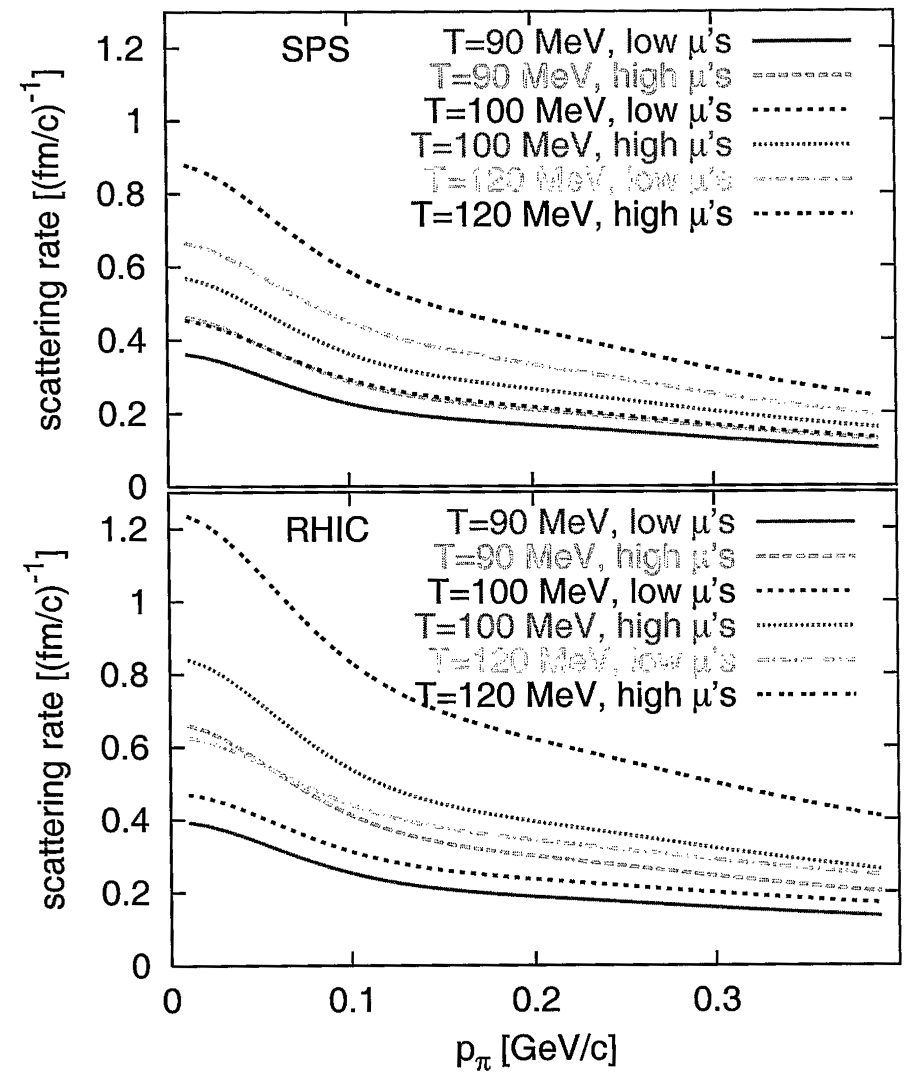
- momentum dependence of the scattering rate

  ⇒ easier decoupling for high momentum particles

  ⇒ sequential freeze-out of different momenta

- temperature dependence of the scattering rate

  ⇒ realistic escape probability at $T \approx 100\,\mathrm{MeV}$

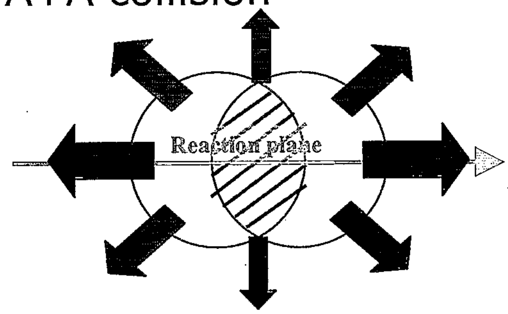


Charged particle v2 and azimuthal pair correlation with respect to the reaction plane at PHENIX

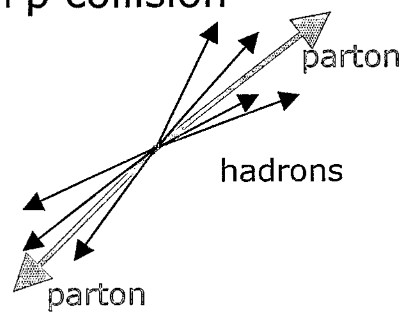
ShinIchi Esumi
for the PHENIX collaboration
Inst. of Physics, Univ. of Tsukuba

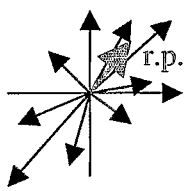
Azimuthal anisotropy "v2" for the charged particle were measured at the RHIC energies and found to be larger than for the lower energy heavy-ion collisions and to be approaching to the hydro-dynamical limit at low pt below 2GeV/c. PHENIX experiment has used two different methods to measure the v2: a) azimuthal correlation and b) with reaction plane at forward rapidity. We here intend to combine those 2 methods to make use of two merits: non smeared shape from a) and geometric orientation of the source from b) by measuring the charged particle azimuthal correlation with respect the different orientation of the reaction plane. This might possibly identify the origin of the large v2 measured at RHIC energy.

A+A collision



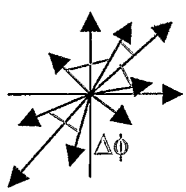
p+p collision





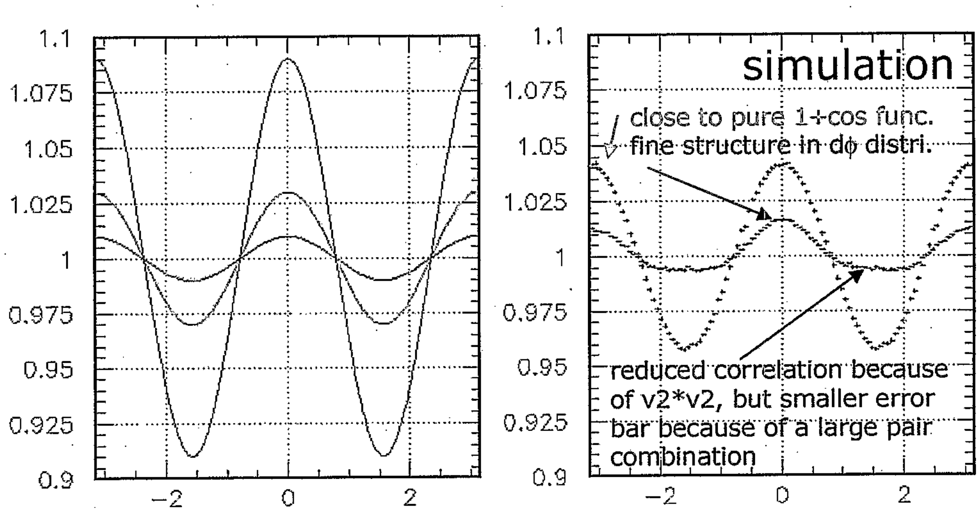
r.p. for a geometrical origin
suffer r.p. resolution (smeared shape)

$$dN/d(\phi-\Phi) = N\,(1 + \Sigma\, 2v_n{}'\cos(n(\phi-\Phi)))$$



no smearing (detailed shape analysis)
event anisotropy shape (no relation to r.p.)

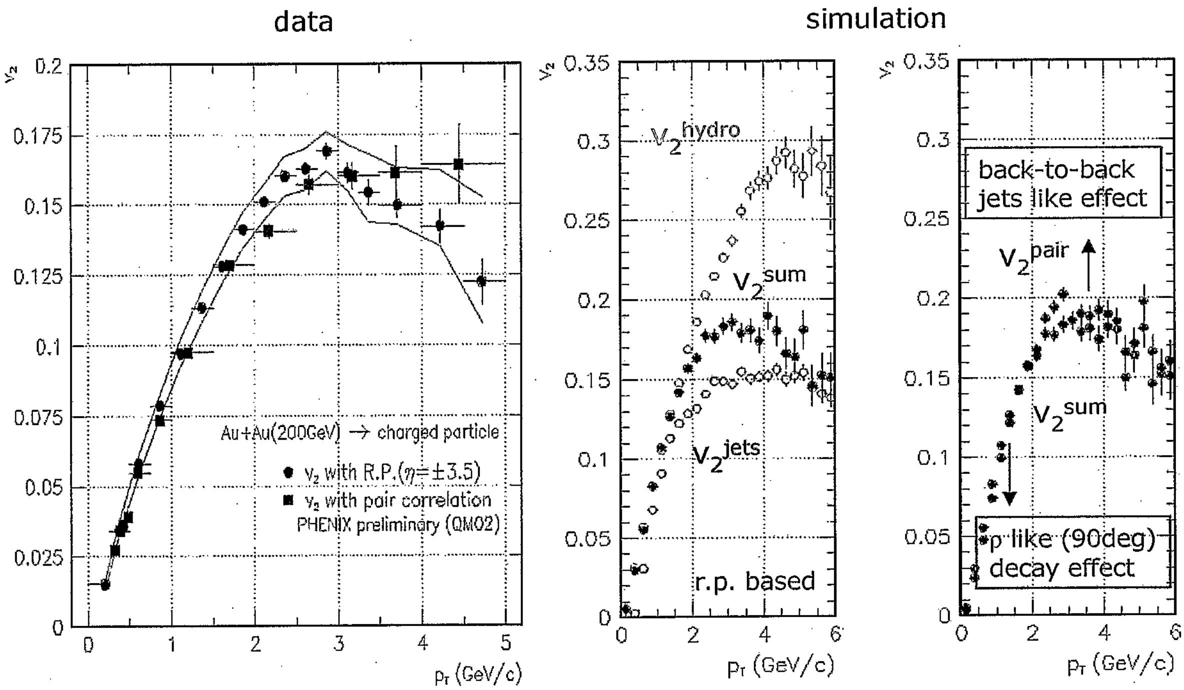
$$N^{real}(\Delta\phi)/N^{mixed}(\Delta\phi) = N\,(1 + \Sigma\, 2v_n{}^2\cos(n(\Delta\phi)))$$

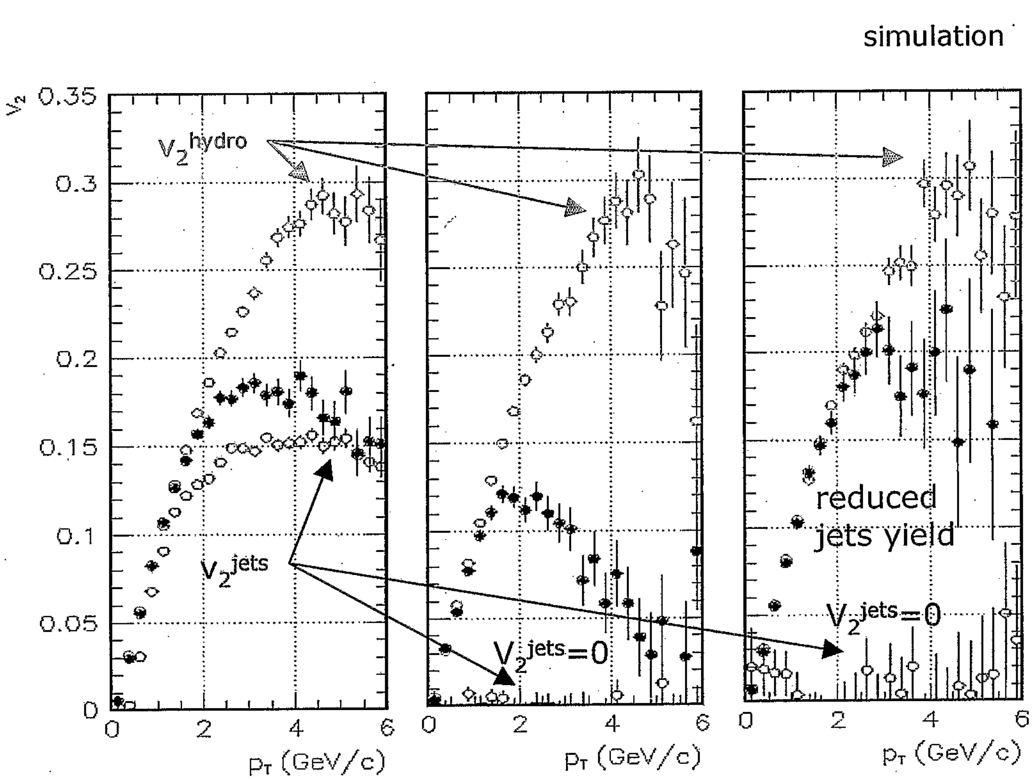


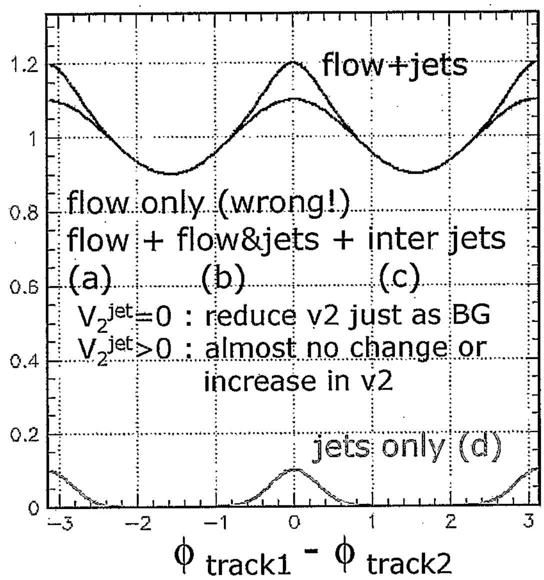
$\phi_{track} - \Phi_{true}$ -> v2

$\phi_{track} - \Phi_{measured}$ -> v2*resolution

$\phi_{track1} - \phi_{track2}$ -> v2*v2


data
simulation
Au+Au(200GeV) → charged particle
v_2 with R.P.(η=±3.5)
v_2 with pair correlation
PHENIX preliminary (QM02)
V_2^{hydro}
V_2^{sum}
V_2^{jets}
r.p. based
back-to-back jets like effect
V_2^{pair}
ρ like (90deg) decay effect
p_T (GeV/c)


simulation
V_2^{hydro}
V_2^{jets}
V_2^{jets}=0
reduced jets yield
p_T (GeV/c)

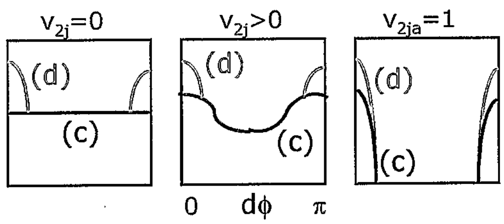


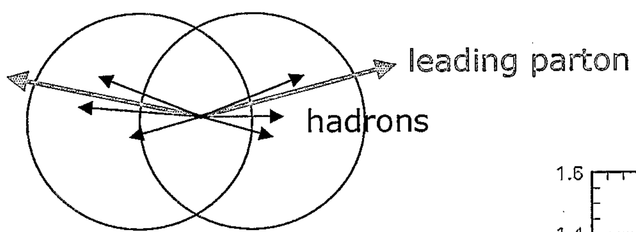
Parameters
- n_f : flow particles
- n_j : # of jet axis with v_{2ja}
- n_p : # of particle per jet
- v_{2f} : v_2 of n_f
- v_{2j} : v_2 of $n_j n_p$

Harmonic part : $1+2p*\cos(d\phi)$
- (a) $p=v_{2f}v_{2f}$: $n_f(n_f-1)$
- (b) $p=v_{2f}v_{2j}$: $n_f n_j n_p$
- (c) $p=v_{2j}v_{2j}$: $n_j(n_j-1)n_p^2$

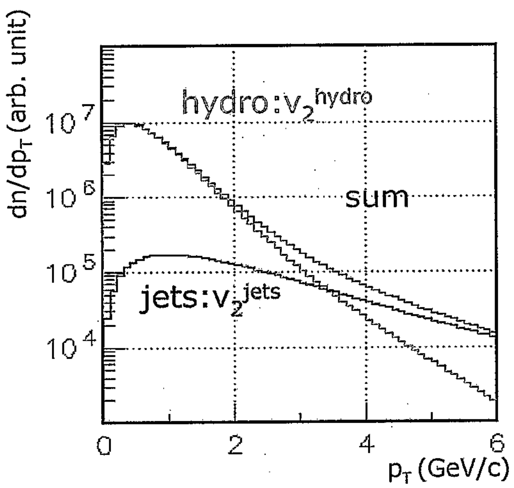
Jet shape : near+far side gauss
- (d) $F(d\phi)$: $n_j n_p(n_p-1)$

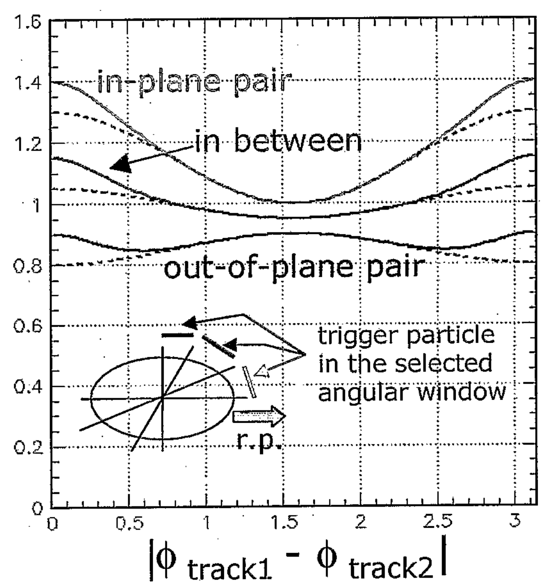
Jet part
- (c)+(d) : $n_j n_p(n_j n_p-1)$



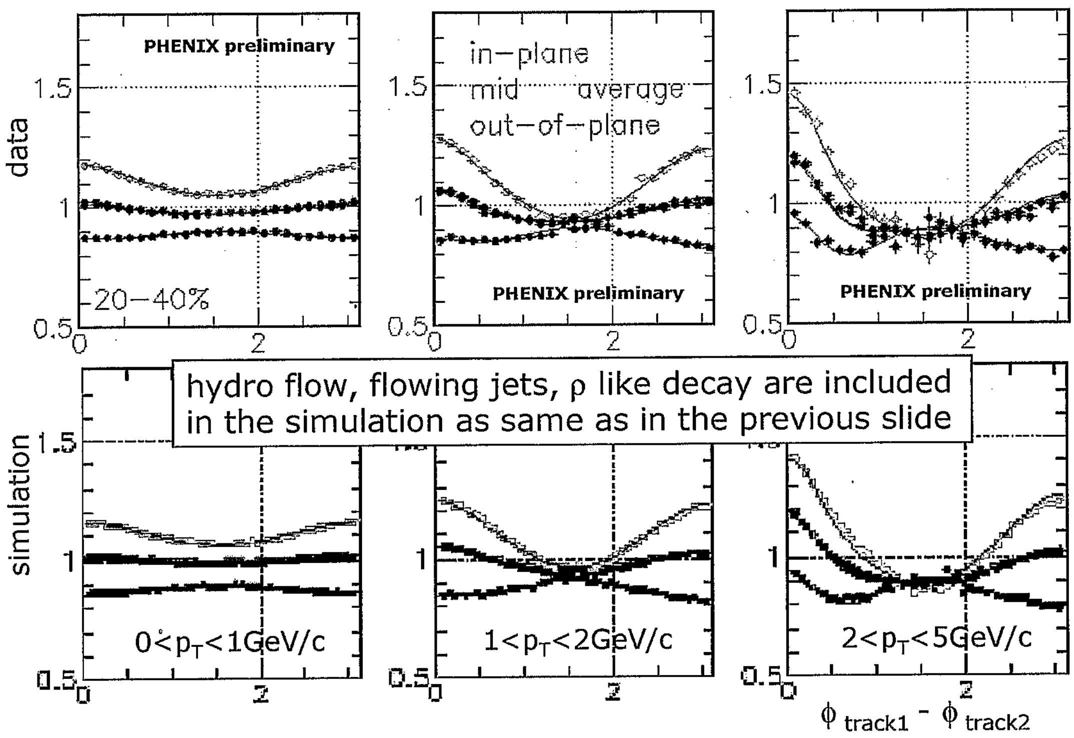


Q: Are jets source of v2?
Q: Does reaction zone make flowing jets?

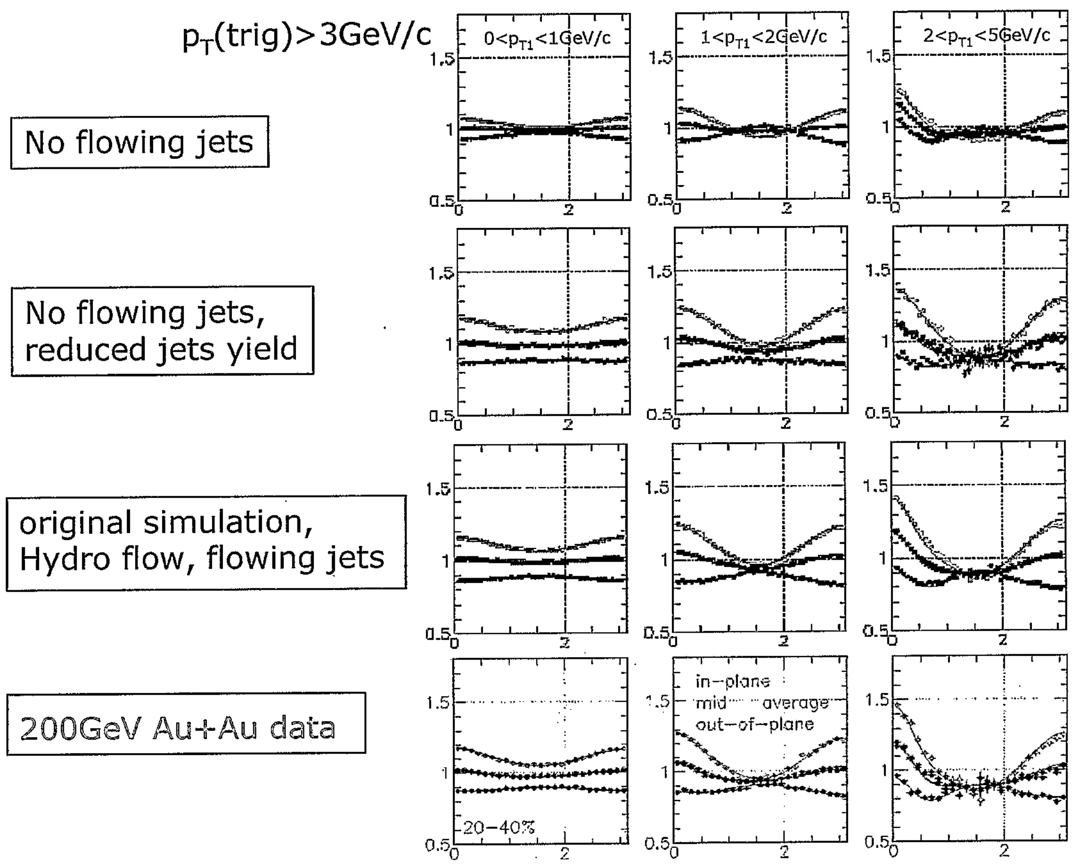


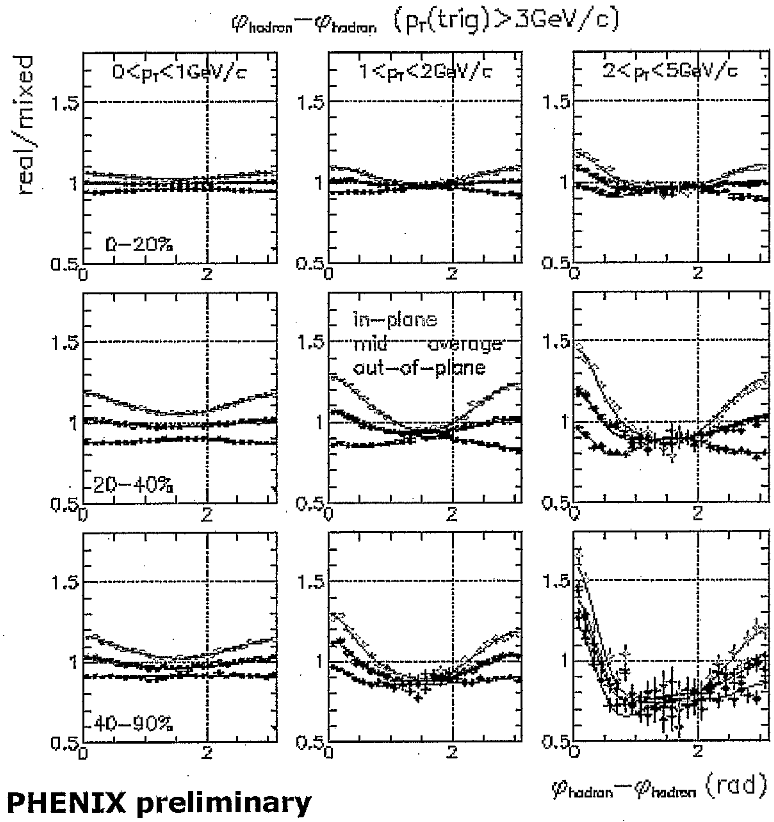


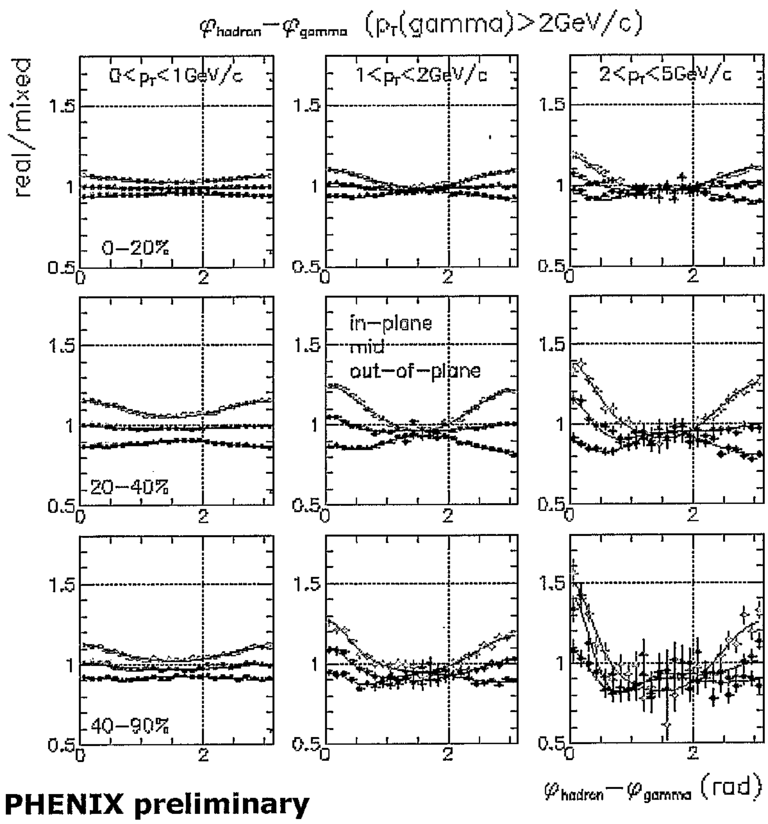
hadron-hadron correlation $(p_T(trig)>3GeV/c)$



$p_T(trig)>3GeV/c$




φhadron−φhadron (pT(trig)>3GeV/c)
real/mixed
0<pT<1GeV/c
1<pT<2GeV/c
2<pT<5GeV/c
0−20%
20−40%
40−90%
in−plane
mid
average
out−of−plane
φhadron−φhadron (rad)
PHENIX preliminary


φhadron−φgamma (pT(gamma)>2GeV/c)
real/mixed
0<pT<1GeV/c
1<pT<2GeV/c
2<pT<5GeV/c
0−20%
20−40%
40−90%
in−plane
mid
out−of−plane
φhadron−φgamma (rad)
PHENIX preliminary

Entropy at RHIC

Subrata Pal[1] and Scott Pratt[2]

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[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan*

The entropy per unit rapidity dS/dy which is approximately conserved between initial thermalization and the final freeze-out can provide considerable insight into matter at the early stage of heavy ion collisions. Viscous effects, shock waves, and hadronization can only increase the entropy so that the entropy at the final state provides an upper bound for the entropy of the initial state. For central heavy ion collisions at the RHIC energy, the entropy rapidity density at freeze-out is extracted from available experimental data for single particle hadronic spectra and hadron source sizes estimated from two-particle interferometry. The estimated total dS/dy is 4451 in the final state. From the measured transverse energy production at RHIC, an average energy density of $\bar{\epsilon} = 4.5$ GeV/fm^3 is obtained for boost invariant longitudinal expansion. Including the effects longitudinal work and longitudinal motion, the resulting entropy density from lattice QCD for a thermalized quark-gluon plasma is consistent with the final state entropy density.

Entropy Rapidity Density

Entropy in Landau quasi-particle approximation

$$S = (2J+1)\int \frac{d^3r d^3p}{(2\pi)^3}\left[-f\ln f \pm (1\pm f)\ln(1\pm f)\right]$$

$$\approx (2J+1)\int \frac{d^3r d^3p}{(2\pi)^3}\left[-f\ln f + f \pm f^2/2\right] \quad \text{for } f \ll 1$$

Phase space density

$$f(\mathbf{r},\mathbf{p},t) = f_{\max}(\mathbf{p})\exp\left(-\frac{x^2}{2R_x^2} - \frac{y^2}{2R_y^2} - \frac{z^2}{2R_z^2}\right)$$

R_i's implicit function of p

No explicit chemical equilibration

Single-particle Spectra and Radii

$$\frac{dN}{d^3p} = (2J+1)\int \frac{d^3r}{(2\pi)^3} f(\mathbf{r},\mathbf{p})$$

$$f_{\max}(\mathbf{p}) = \frac{(2\pi)^{3/2}}{(2J+1)}\frac{dN}{d^3p}\frac{1}{R^3}$$

dS/dy from HBT radii and spectra

Two-particle correlation function (gaussian source)

$$C(\mathbf{K},\mathbf{q}) = \frac{P(\mathbf{p}_1,\mathbf{p}_2)}{P(\mathbf{p}_1)P(\mathbf{p}_2)}$$
$$= 1 + \exp\left(-q_x^2 R_x^2 - q_y^2 R_y^2 - q_z^2 R_z^2\right)$$

$\mathbf{K} = (\mathbf{p}_1 + \mathbf{p}_2)/2$ and $\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2$

In out-side-long frame: **q_l: along beam direction; q_o: parallel to total K_T; q_s: orthogonal to q_l and q_o**

$$C(\mathbf{K},\mathbf{q}) = 1 + \exp\left(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2\right)$$

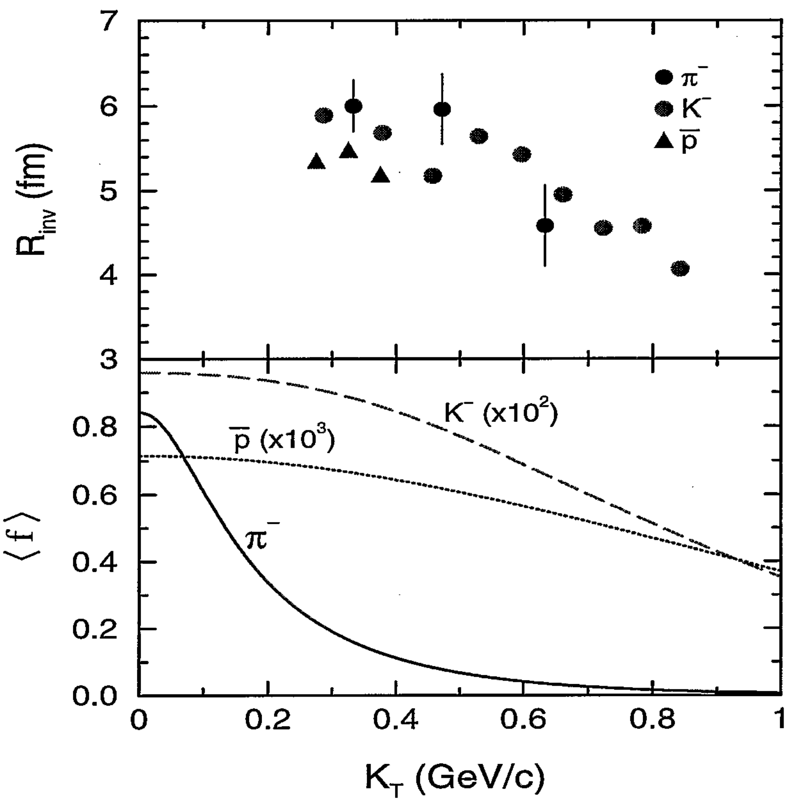
Final state entropy rapidity density

$$\frac{dS}{dy} = \int d^2p_T\, E\frac{dN}{d^3p}\left[\frac{5}{2} - \ln \mathcal{F}(\mathbf{p}) \pm \frac{1}{2^{5/2}}\mathcal{F}(\mathbf{p})\right]$$

$$\mathcal{F}(\mathbf{p}) = \frac{1}{m}\frac{(2\pi)^{3/2}}{(2J+1)}\, E\frac{dN}{d^3p}\frac{1}{R_{\rm inv}^3}, \quad R_{\rm inv}^3 = \frac{E_T}{m}R_o R_s R_l$$

dS/dy in final state can be estimated from HBT radii $R_{\rm inv}$ and s.p. spectra $E\,dN/d^3p$

HBT Radii and Phase Space Density



- π multiplicity at RHIC 70% larger than at SPS
- π radii identical at RHIC and SPS
- High π final phase space density at RHIC
- HBT radii $R_{\text{inv}} = A/\sqrt{m_T}$ for $\pi, K, \bar{p}$ not consistent with one scaling coefficient

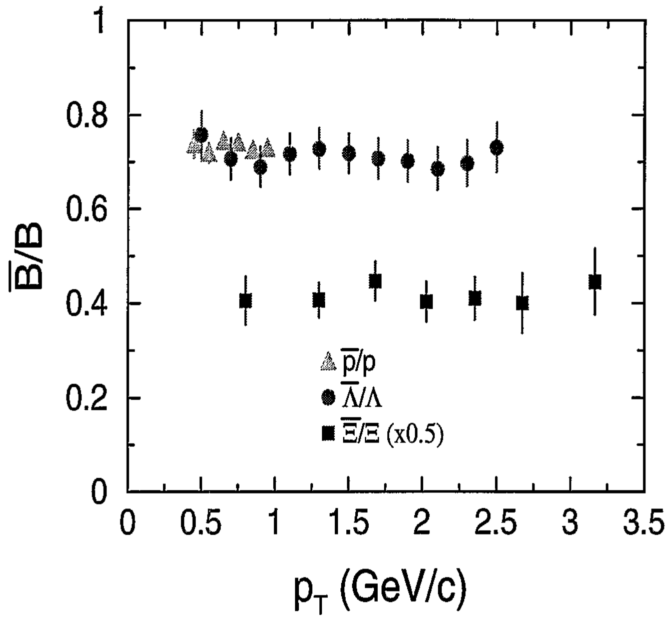
Final State Entropy Rapidity Density

dS/dy of baryons:

$\overline{p}/p = 0.72$, $\overline{\Lambda}/\Lambda = 0.71$

$\overline{\Xi}^+/\Xi^- = 0.83$, $\overline{\Omega}^+/\Omega^- = 0.95$

Slope T and HBT radii of B and $\overline{B}$ assumed same



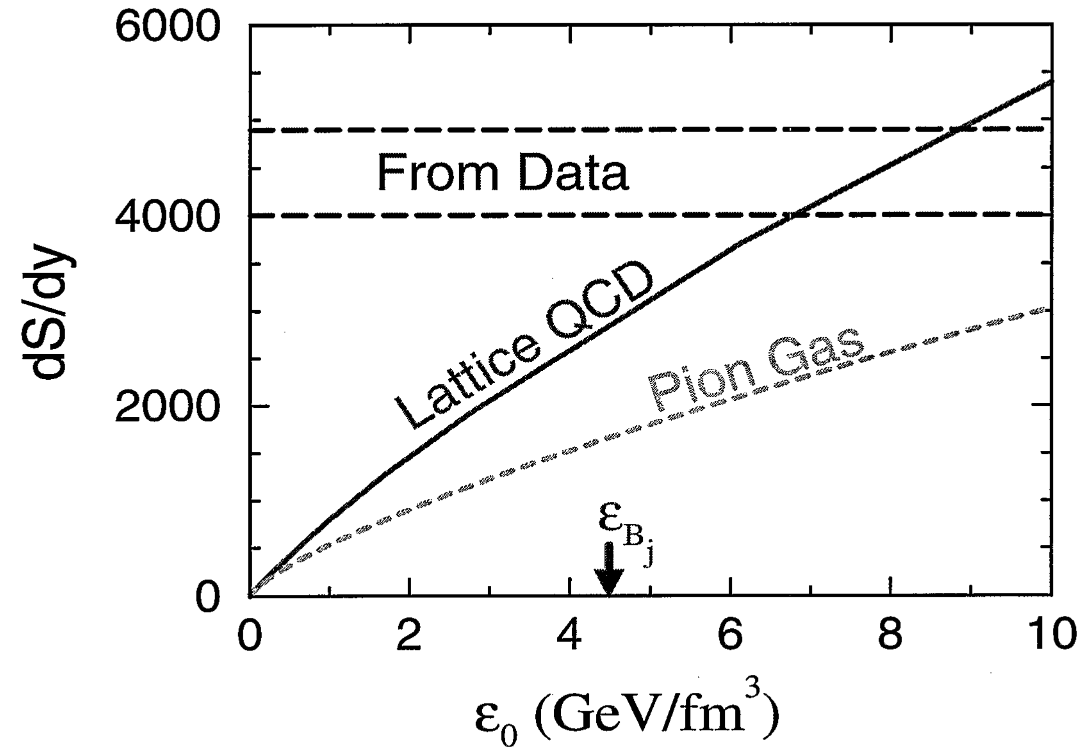
Final State Entropy rapidity density of hadrons

π^-	η (η')	K^- (K^+)	$\overline{p}$ (p)	$\overline{\Lambda}+\overline{\Sigma}^0$ ($\Lambda+\Sigma^0$)	$\overline{\Sigma}^\pm$ ($\Sigma^\pm$)	$\overline{\Xi}^\pm$ ($\Xi^\pm$)	$\overline{\Omega}^+$ (Ω^-)
680	256 (69)	256 (286)	118 (159)	81 (111)	31 (42)	23 (27)	5 (5)

Final State Total $dS/dy = 4451$ (model indep)

- $dS/dy|_\pi < 1/2\ dS/dy|_{\rm tot}$ though mult. $N_\pi \approx 2/3\ N_{\rm tot}$
- Baryons compensate the lack of π entropy

Entropy rapidity density from Lattice QCD



Adding local longitudinal motion, viscosity, transverse flow, longitudinal work result in $\overline{\epsilon(\tau)} \simeq 7 \pm 2$ **GeV/fm**^{3}

⋆ Final state dS/dy consistent with a thermalized QGP at RHIC

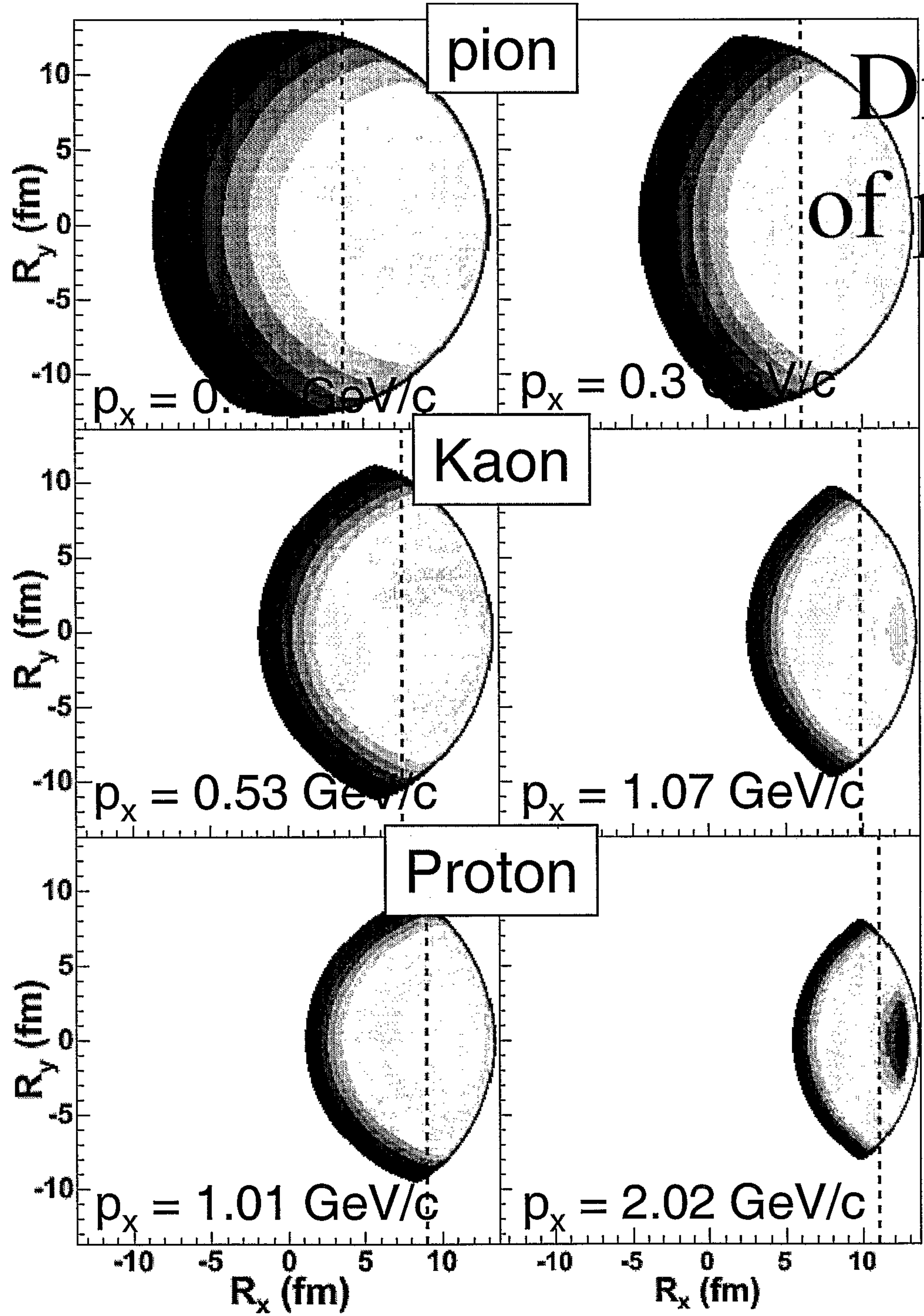
• For a massless gas of quarks and gluons:

$$\varepsilon = \left(N_B + \frac{7}{8} N_F\right) \frac{\pi^2}{30} T^4$$

Fabrice Retière
Lawrence Berkeley National Lab

Flow and non-identical two-particle correlations

The Coulomb and strong interactions induces a correlation between non-identical particles after their kinetic freeze-out, which is used to infer information about the particle freeze-out space-time distribution. This technique allows determining whether or not different particle species are emitted on average at the same space-time location. The STAR data show that the source of pions, kaons and protons are shifted. This shift is consistent with transverse flow as parameterized in the blast-Wave or modeled by RQMD. Pion-kaon, pion-proton and kaon-proton correlation offer an independent confirmation of the presence of strong collective expansion at RHIC. This technique may shed light on time ordering of pion, kaon and proton emission. The latest STAR results suggest a delay emission of protons with respect to the Blast-Wave expectation, which ignores hadronic cross-sections. Furthermore, preliminary results show that the emission pattern of Ξ may be investigated constructing π- constructing π-Ξ correlation functions, correlation functions.



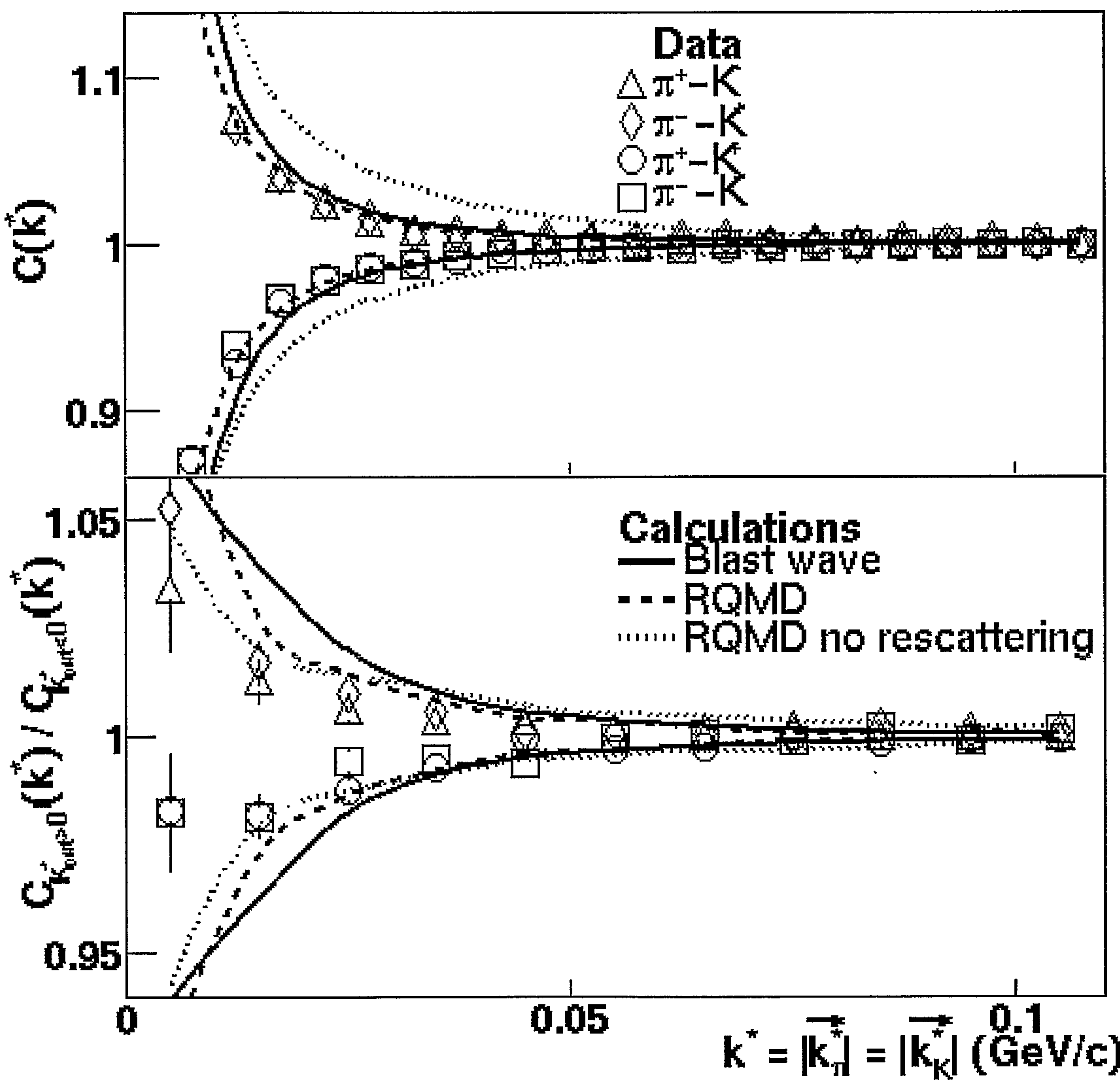
Distribution emission of points in Blast-Wave

Distribution of emission points at a given emission momentum.

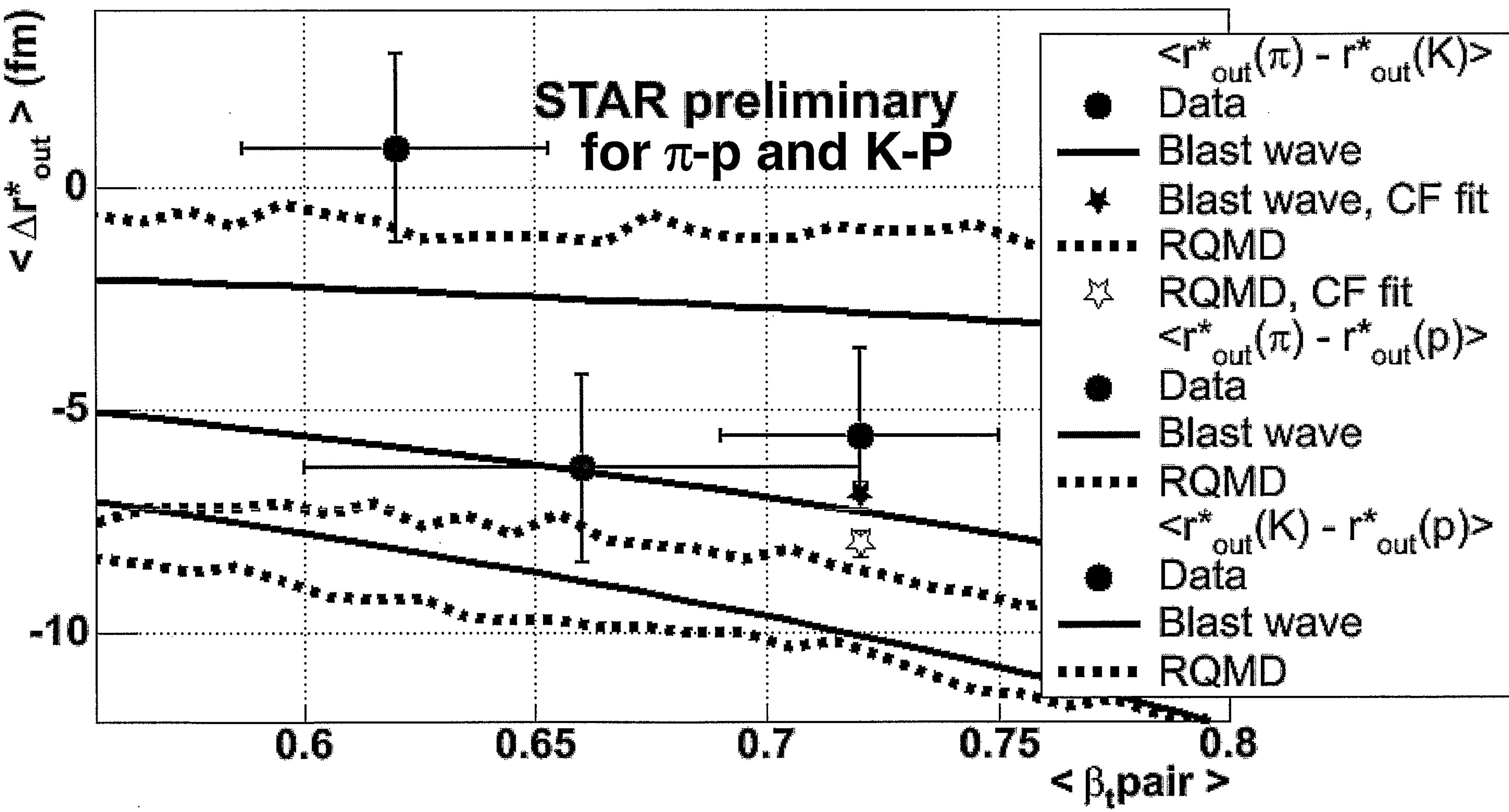
Particles are correlated when their velocities are similar.
Keep velocity constant:
- Left, $\beta_x = 0.73c$, $\beta_y = 0$
- Right, $\beta_x = 0.91c$, $\beta_y = 0$

Dash lines: average emission Radius.
$\Rightarrow \langle R_x(\pi)\rangle < \langle r_x(K)\rangle < \langle R_x(p)\rangle$

STAR data and models

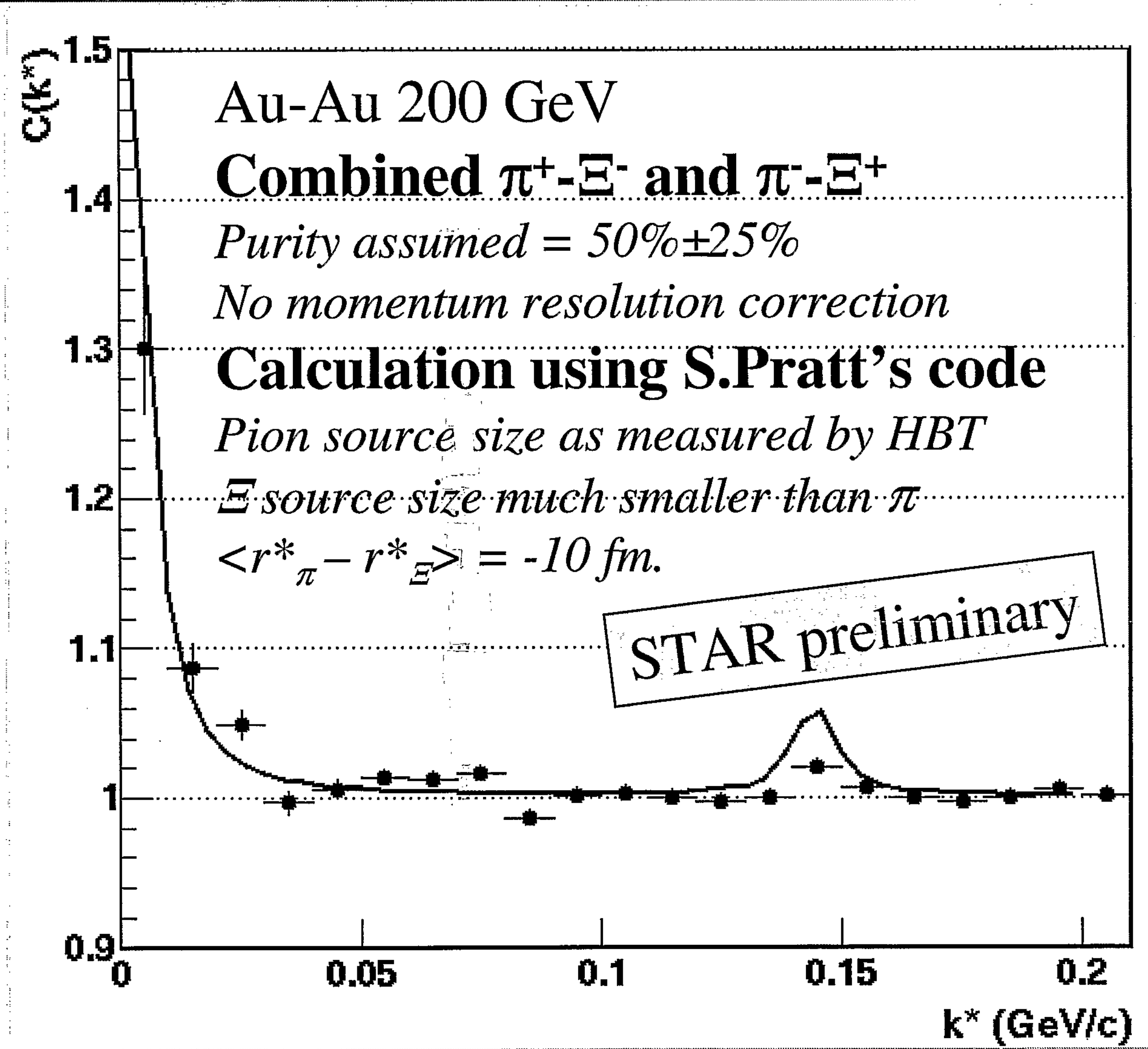


Summary plot



Outlook 2
π-Ξ correlation and collectivity

- Source size and shift from π^--Ξ^- and π^+-Ξ^+
  - Coulomb only
- Do Ξ flow as π?
- Investigate strong interaction in unlike-sign
  - Input onto cross-sections?



Outlook 3
A lot can be done

	$\pi^\pm$	$K^\pm$	K^0_s	$p^\pm$	Λ	$\Xi^\pm$	$\Omega^\pm$	$D^\pm$
$\pi^\pm$	Y1-4							
$K^\pm$	Y1-4	Y1-4						
K^0_s	int. ?	int. ?	Y2-4					
$p^\pm$	Y1-4	Y2-4	int. ?	Y2-4				
Λ	int. ?	int. ?	no stat	Y2-4	Y4			
$\Xi^\pm$	Y2-4	Y4?	no stat	Y4?	no stat	no stat		
$\Omega^\pm$	Y4?	no stat	no stat	no stat	no stat	no stat	no stat	
$D^\pm$	Y7?	no stat	no stat	no stat	no stat	no stat	no stat	no stat

Hope other RHIC experiments join in

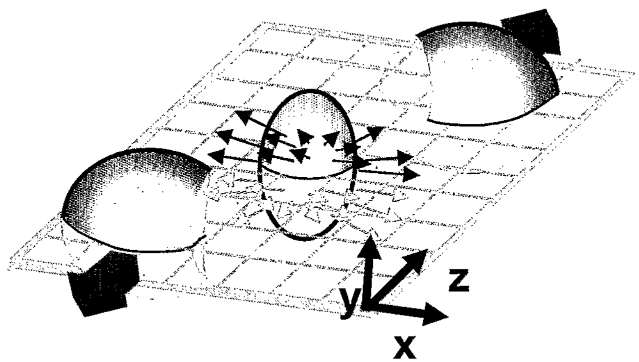
Y1 (2000) = 0.5M central @ 130GeV, Y2 = 2M central @ 200 GeV, Y4 = 50M+ min-bias @ 200 GeV

Probing spatial anisotropy at freeze-out with HBT

Dan Magestro
The Ohio State University

Riken/BNL Flow Workshop, 11/03

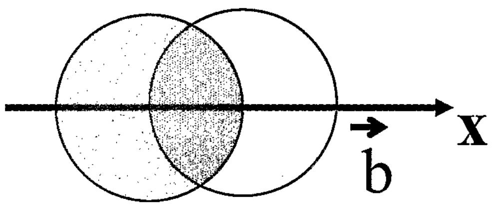
Oscillations of transverse HBT radii relative to the reaction plane allow the investigation of the spatial anisotropy of the freeze-out source. We present results of azimuthally-sensitive HBT in Au+Au collisions from the STAR Experiment at RHIC and show that, taking into account blast-wave studies of the sensitivity of the oscillation amplitudes to the spatial anisotropy of the source, the freeze-out source is out-of-plane extended. This indicates that the source retains some of its initial spatial anisotropy, suggesting short expansion times of the system.

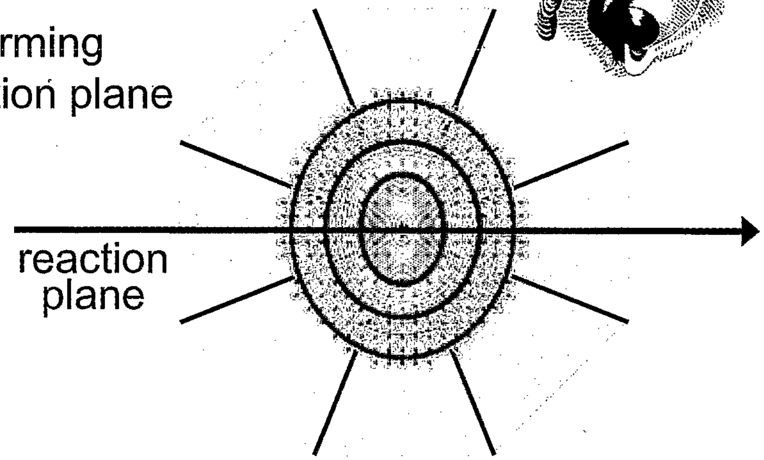


The HBT(Φ) experimental technique

1. Study (transverse) source at different angles by performing <u>two-pion interferometry separately</u> for bins w.r.t. reaction plane

beam into screen



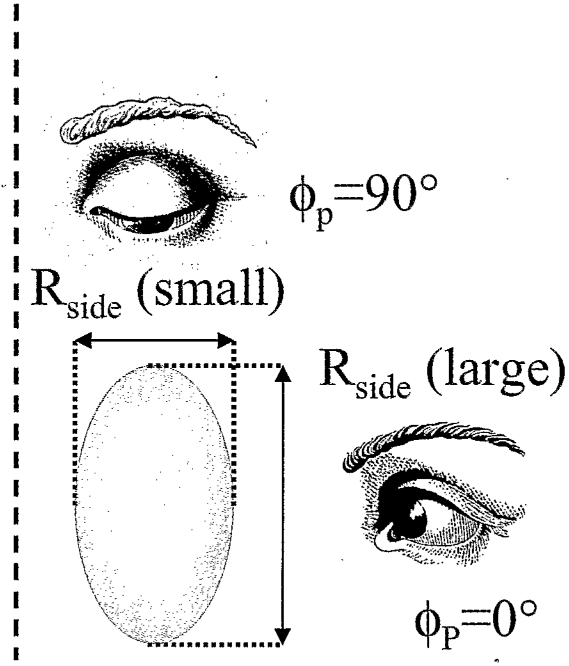


2. Apply HBT formalism for non-central collisions to extract "HBT radii" for each bin

$$C(\vec{q},\Phi) = N\left[\left(1-\lambda(\Phi)\right) + \lambda(\Phi)\cdot K(\vec{q})\cdot e^{-\left[q_o^2R_o^2(\Phi)+q_s^2R_s^2(\Phi)+q_l^2R_l^2(\Phi)+2q_oq_sR_{os}^2(\Phi)\right]}\right]$$

λ fraction of correlated pairs are fit to Coulomb + Gaussian

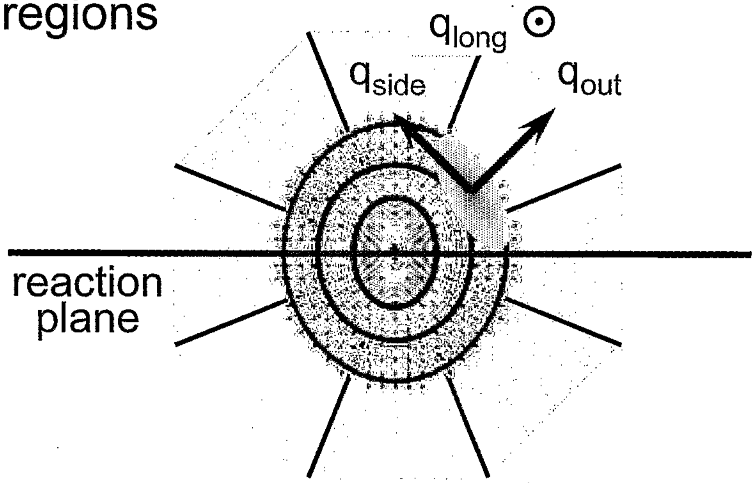
3. Oscillations of radii w.r.t. RP indicate if source is <u>in-plane</u> or <u>out-of-plane</u> extended



Summary of HBT(Φ) procedure

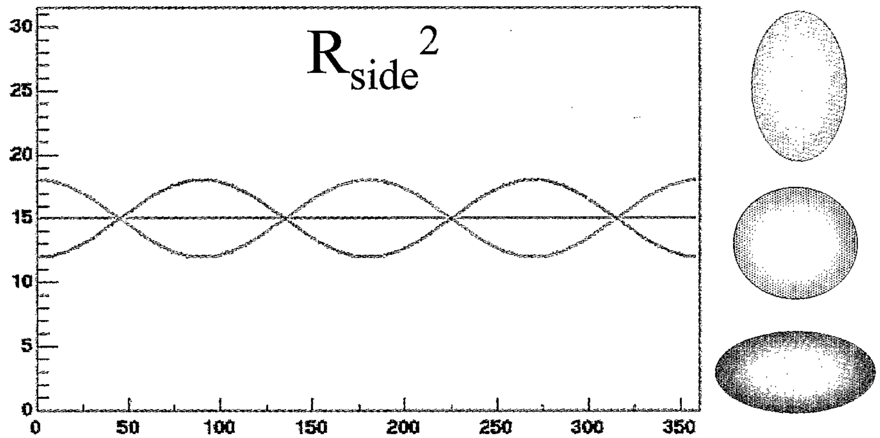
❶ What we measure

HBT radii as a function of emission angle – corresponds to homogeneity regions



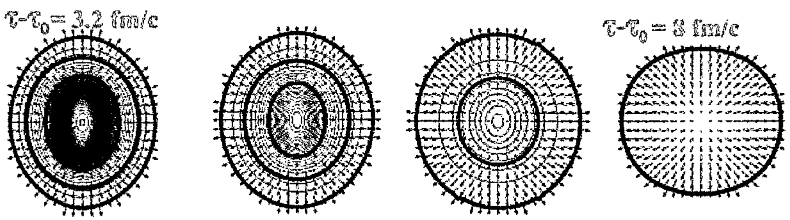
❷ What we expect to see:

2^{nd}-order oscillations in HBT radii analogous to momentum-space (flow)



❸ Why we're interested

The size and orientation of the source at freeze-out places tight constraints on expansion/evolution



❹ What should be remembered

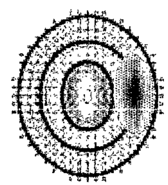
The form of the oscillations (sin vs. cos, harmonics) are governed by geometrical symmetries of the source.

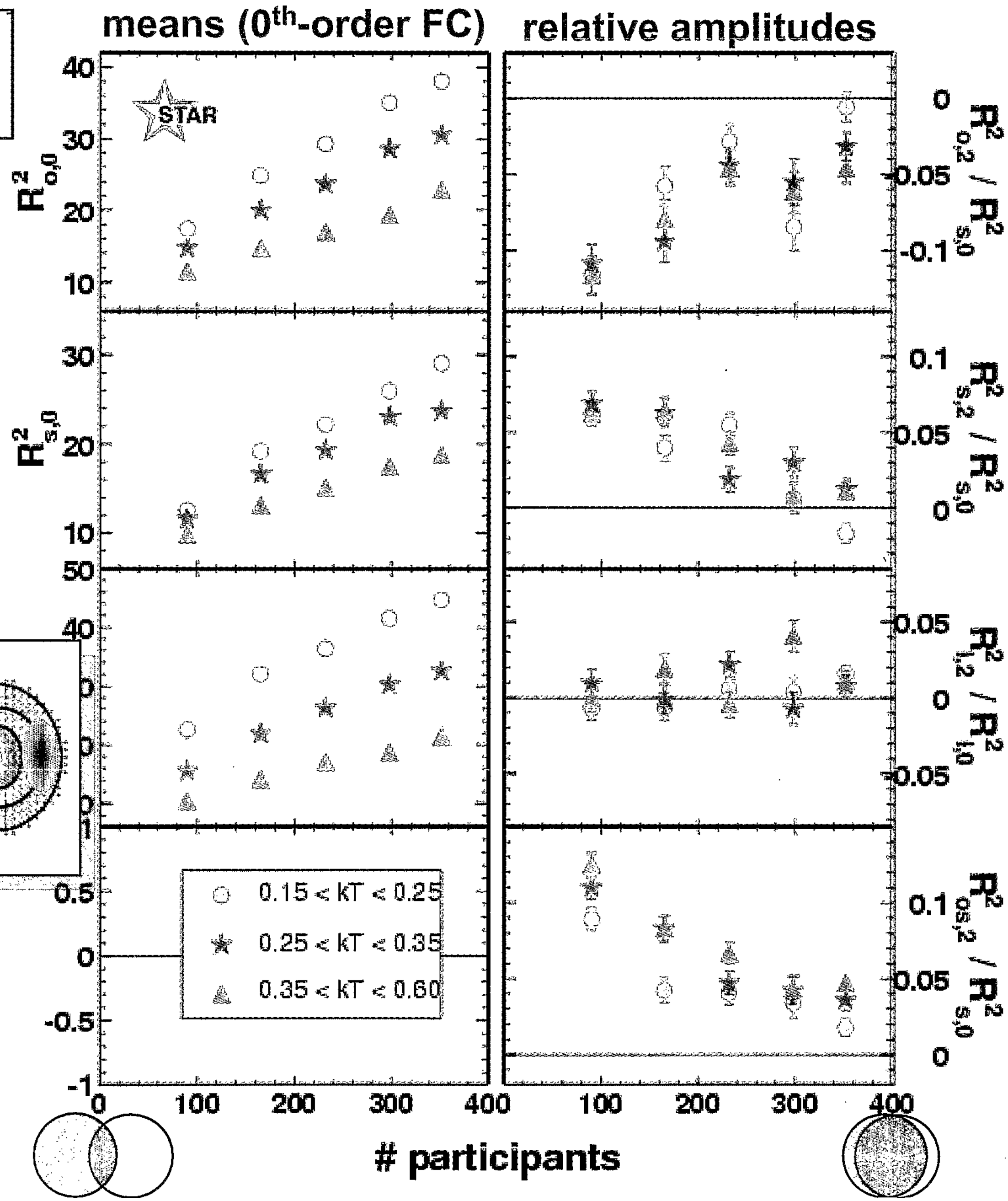
Fourier coefficients of HBT(Φ) oscillations

$$R^2_{\mu,n}(k_T) = \begin{cases} \langle R^2_\mu(k_T,\phi_p)\cos(n\phi_p)\rangle & (\mu = o, s, l) \\ \langle R^2_\mu(k_T,\phi_p)\sin(n\phi_p)\rangle & (\mu = os) \end{cases}$$

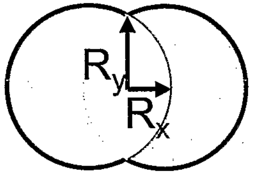
- Relative amplitudes increase in magnitude as centrality decreases
- **Source at freeze-out reflects initial spatial anisotropy!**

- Next step:
  Relate the relative amplitudes from HBT(Φ) to eccentricity of source at freeze-out





Evolution of source eccentricity

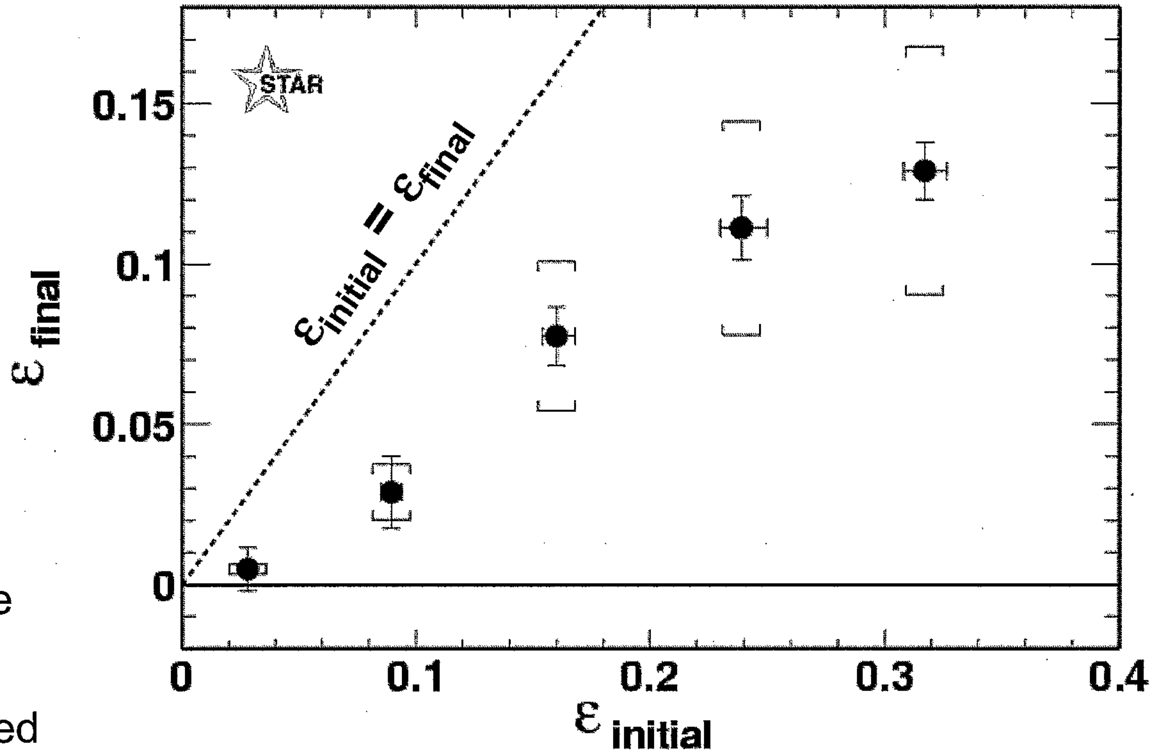


Initial eccentricity

- Estimate $\varepsilon_{initial}$ from nuclear overlap model
- Weight events by ≈ # pairs

Final eccentricity

- **HBT(Φ)**: Estimate ε_{final} from relative amplitudes ($\varepsilon_{final} = 2\, R_{s,2}^2/R_{s,0}^2$)
- **Blast-wave**: Relative amplitudes are driven by spatial anisotropy
- 30% sys. error assigned to ε_{final} based on variation of rel. amplitudes with other b-w parameters

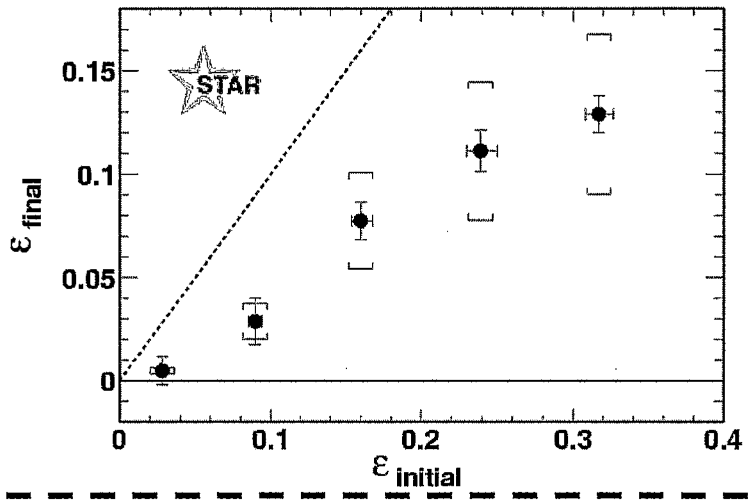


- Monotonic relationship between $\varepsilon_{initial}$ and ε_{final}
- Freeze-out spatial anisotropy reflects greater initial spatial anisotropy

HBT(Φ): Physics interpretation

Out-of-plane sources at freeze-out

- Indicate pressure and/or expansion time was not sufficient to quench initial shape



But from v_2 measurements we know...

- Strong in-plane flow → significant pressure build-up in system

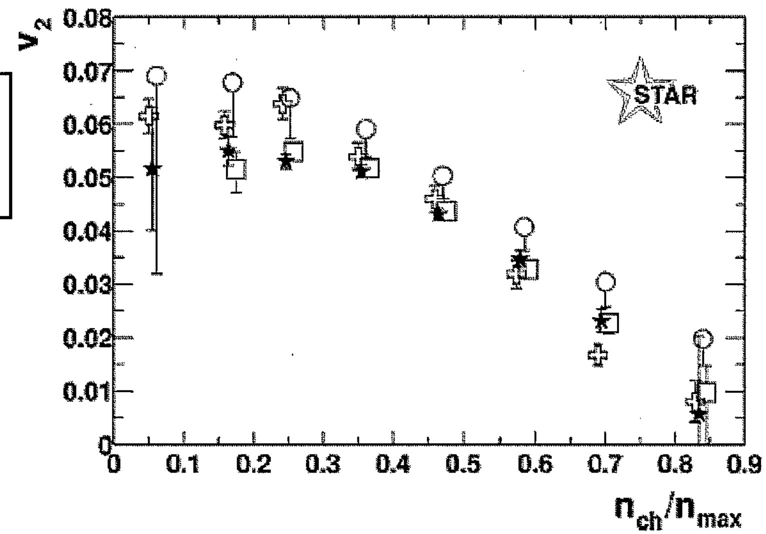


FIG. 13. Measured elliptic flow vs centrality for Au+Au at $\sqrt{s_{NN}}$= 130 GeV. The circles show the conventional v_2 with estimated systematic uncertainty due to nonflow [37], the stars show the fourth-order cumulant v_2 from the generating function, the crosses show the conventional v_2 from quarter events, and the squares show the fourth-order cumulant v_2 from the four-subevent method.

∴ Short expansion time plays dominant role in out-of-plane freeze-out source shapes

Short system lifetime consistent with blast-wave fits to spectra/v_2 & "standard" HBT radii

- However, late-stage contributions to v_2 signal, though likely quite weak, cannot be exlcuded
- In framework of Teaney *et al* (Hydro+RQMD), late-stage rescattering stage is short-lived...

Strong and positive x-t correlation and its effect on Rout/Rside

Zi-Wei Lin

The Ohio State University

Summary:

We study pion HBT at RHIC energies using a multi-phase transport (AMPT) model. Strong and positive x-t correlations, found previously at the final hadronic freezeout, are already present at the end of the partonic stage and when hadrons are first formed. This positive x-t term tends to reduce Rout and thus Rout/Rside, when they are evaluated from the variance of the emission function.

Moreover, values of Rout/Rside evaluated from Gaussian fits to the 3-d correlation function C(Q) are found to be smaller and consistent with 1, even when the value of Rout/Rside from the emission function is well above 1. Further studies are needed to understand this.

Why x-t correlation may be important?

Spatial-size *x-t correlation* *duration-time*

$$R_{\rm out}^2 = D_{x_{\rm out},x_{\rm out}} - 2\, D_{x_{\rm out},\beta_\perp t} + D_{\beta_\perp t,\beta_\perp t}$$

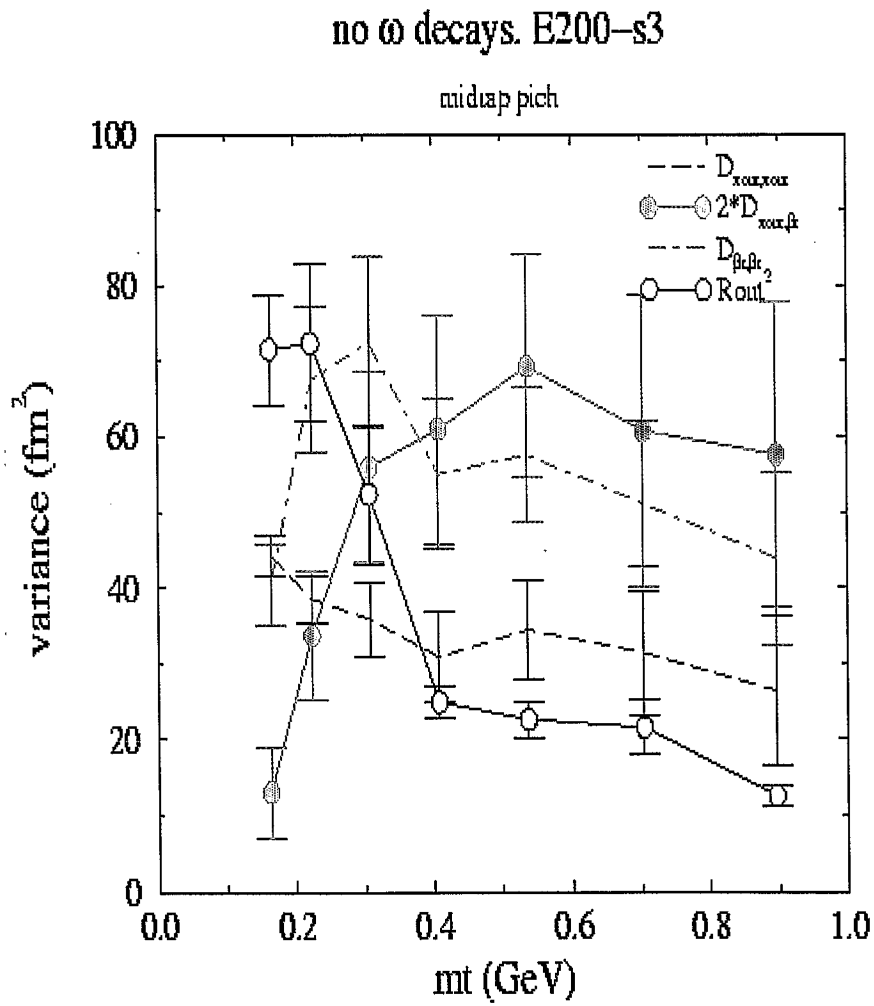
$$R_{\rm side}^2 = D_{x_{\rm side},x_{\rm side}}$$

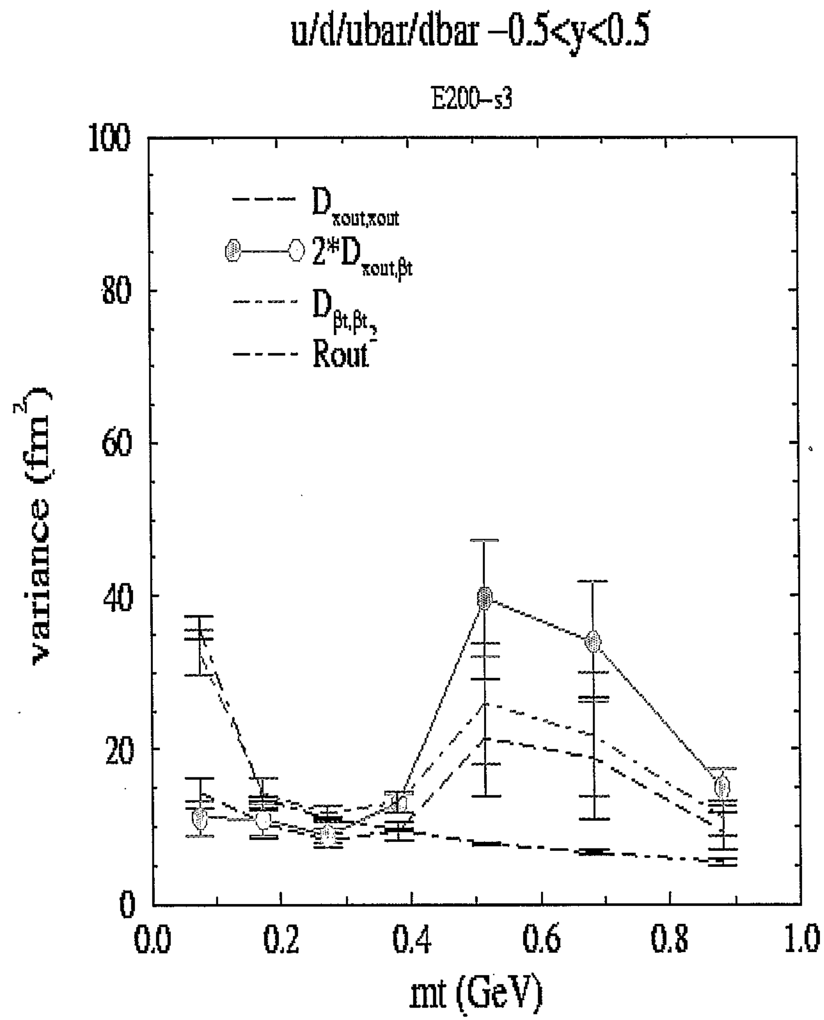
Magnitude and sign of x-t correlation
are important for Rout, Rout/Rside,
& extraction of duration-time

197

x-t correlation for pions

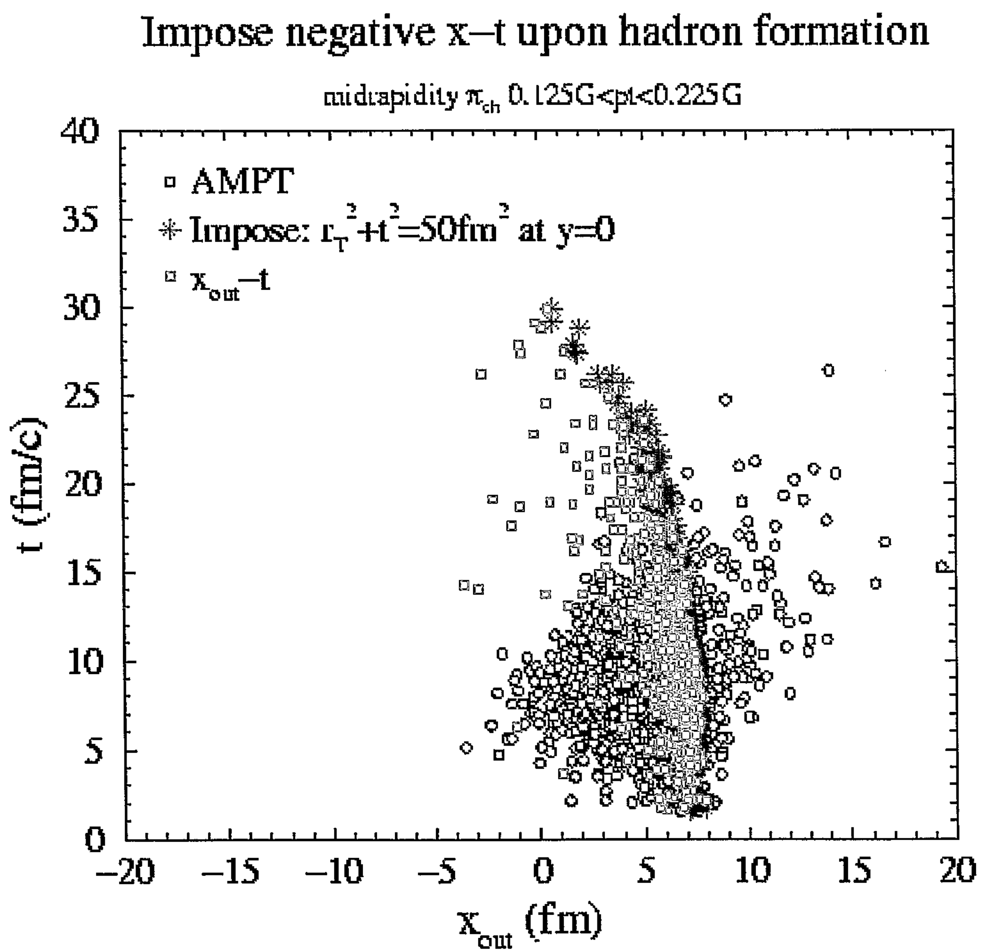
Already present for quarks





Au+Au at 200AGeV (b=0 fm)

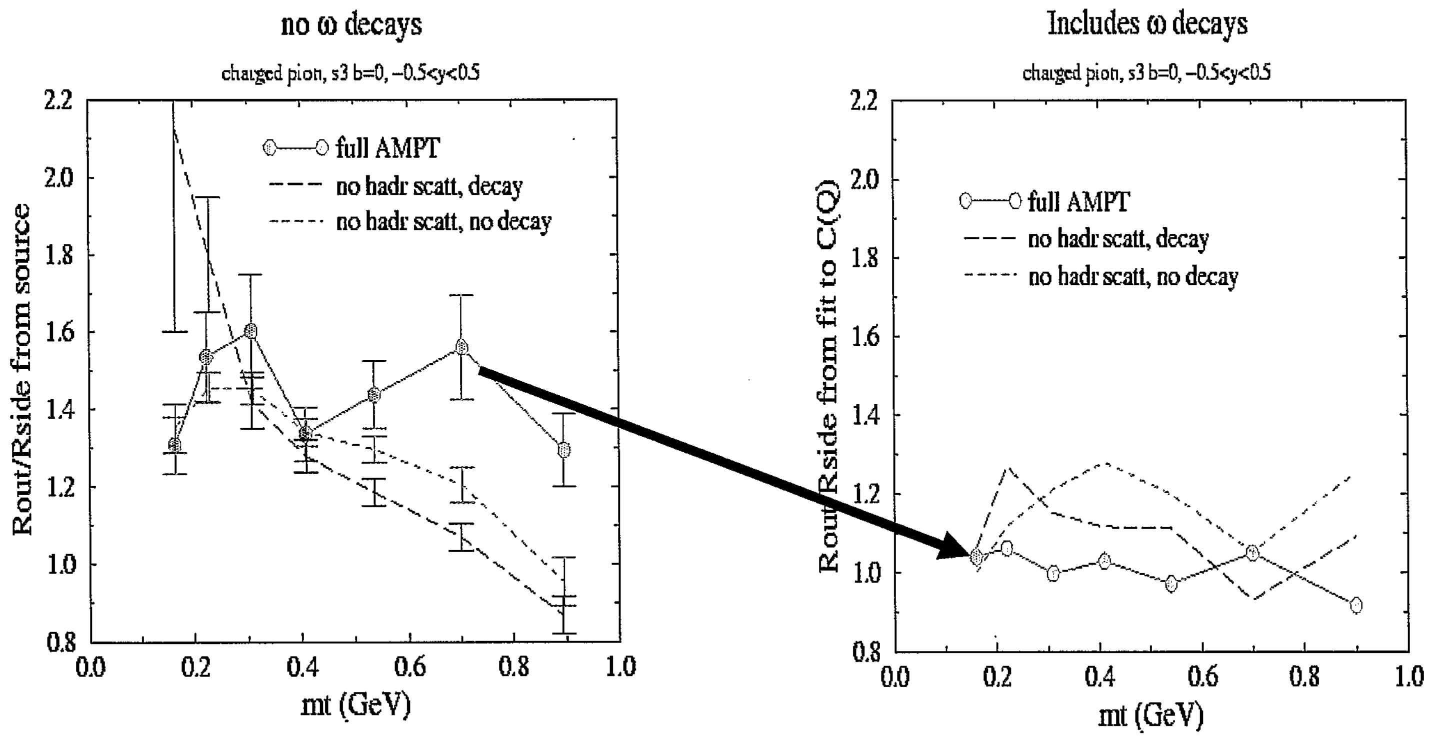
Can an initial negative x-t correlation survive later?



Negative x-t term expected at RHIC energies from Cooper-Frye used in hydro models

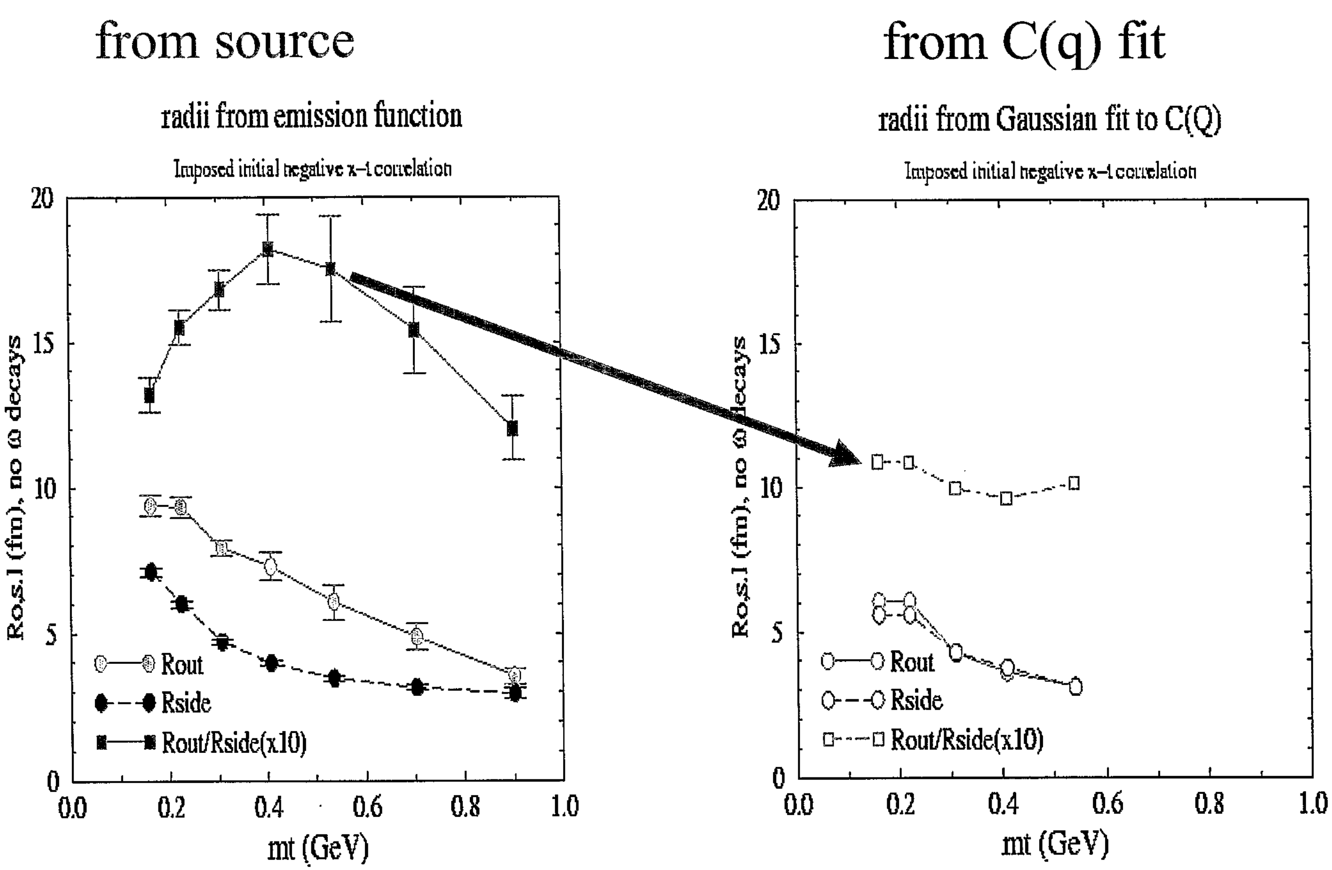
AMPT: Au+Au at 200AGeV at b=0 fm, 3mb

from source | from C(q) fit



big decrease for fitted Rout, Rout/Rside

With an initial negative x-t correlation at hadron formation



huge decrease for fitted Rout, Rout/Rside

Recombination and Fragmentation from a Dense Parton Phase

RAINER J. FRIES

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Experiments at RHIC show a large suppression of high-P_T particles in central Au+Au collisions. This jet quenching results from a strong energy loss of fast partons traveling through the hot medium created in these collisions. Particle creation at high P_T (i.e. $P_T > 2$ GeV) is usually described by perturbative QCD (pQCD). The strong energy loss, however, suppresses this hard particle production and enables soft particle production mechanisms to dominate even at intermediate transverse momentum. At RHIC energies this intermediate region can extend as far as $4 \ldots 6$ GeV in transverse momentum.

A suitable description of hadron production in this region is possible by assuming a recombination mechanism of constituent quarks at the phase transition. A quark-antiquark pair can form a meson, three quarks can form a baryon. If P_T is larger than the mass of the hadron, the calculation becomes independent of the shape of the hadronic wave function for an exponential parton spectrum, making this a quite universal description. One can show that recombination is more effective for exponential spectra, while power-law spectra favor (pQCD) fragmentation. Calculations using a combination of recombination from a thermal parton phase and pQCD fragmentation yield excellent agreement with experimental data on hadron production for $P_T > 2$ GeV. In particular, the anomalously large baryon/meson ratio, and the particle dependence of nuclear suppression can be explained.

Recombination predicts a simple scaling law for elliptic flow,

$$v_2(P_T) = n v_2^{part}(P_T/n) \tag{1}$$

where n is the number of valence partons in the hadron, $n = 2$ for mesons, $n = 3$ for baryons, $n = 6$ for deuterons. v_2^{part} is the elliptic flow in the parton phase before hadronization. Experimental data from STAR and PHENIX impressively confirm this scaling law, therefore supporting the hypothesis of a universal elliptic flow in the parton phase.

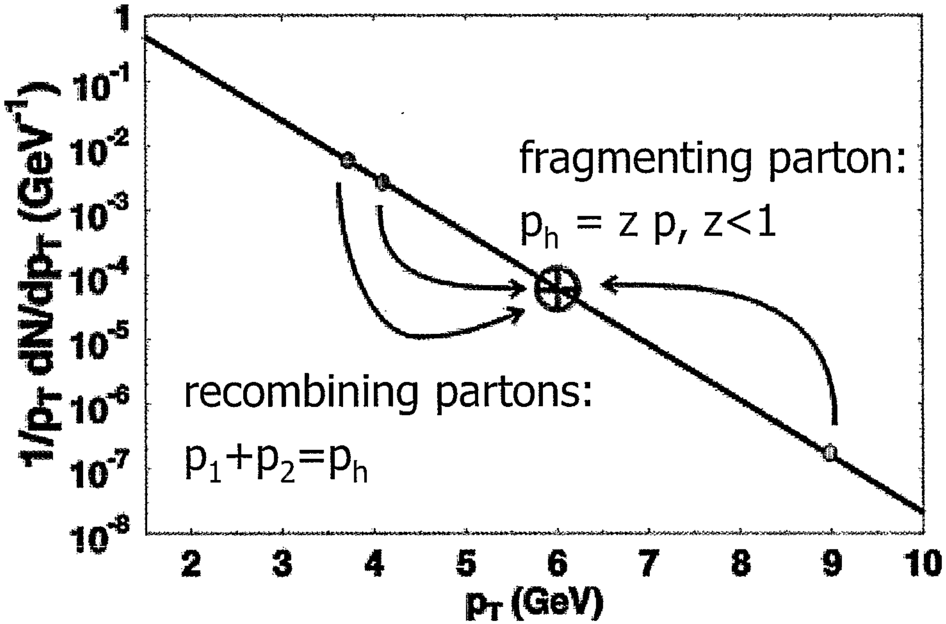
[1] R. J. Fries, B. Müller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. **90**, 202303 (2003); Phys. Rev. C 68, 044902 (2003); nucl-th/0305079.

[2] C. Nonaka, R. J. Fries and S. A. Bass, nucl-th/0308051.

Recombination vs Fragmentation

- for exponential parton spectrum, recombination is more effective than fragmentation
- baryons are shifted to higher p_t than mesons, for same quark distribution

➢ understand behavior of protons!



Recombination formalism II

- choose a hypersurface Σ for hadronization
- use local light cone coordinates (hadron defining the + axis)
- $w_a(r,p)$: single particle distribution functions for quarks at hadronization
- Φ_M & Φ_B: light-cone wave-functions for the meson & baryon respectively
- x, x' & $(1-x)$: momentum fractions carried by the quarks
- integrating out transverse degrees of freedom yields:

$$E\frac{dN_M}{d^3P} = \int_\Sigma d\sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha,\beta} \int dx\, w_\alpha(R, xP^+)\, \overline{w}_\beta(R,(1-x)P^+) \left|\overline{\phi}_M(x)\right|^2$$

$$E\frac{dN_B}{d^3p} = \int_\Sigma d\sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha,\beta,\gamma} \int dx\,dx'\, w_\alpha(R, xP^+)\, w_\beta(R, x'P^+)\, w_\gamma(R,(1-x-x')P^+) \left|\overline{\phi}_B(x,x')\right|^2$$

Recombination + Fragmentation

- Fragmentation of perturbative partons dominates at high p_t.
- Recombination kicks in at 4-6 GeV at RHIC energies.
- Our description of recombination fails when Λ/P_T and m/P_T corrections become large (from 1-2 GeV on at RHIC).
- But: recombination will still be the dominant hadronization mechanism. Take into account binding energies, mass effects.

Parton Number Scaling of Elliptic Flow

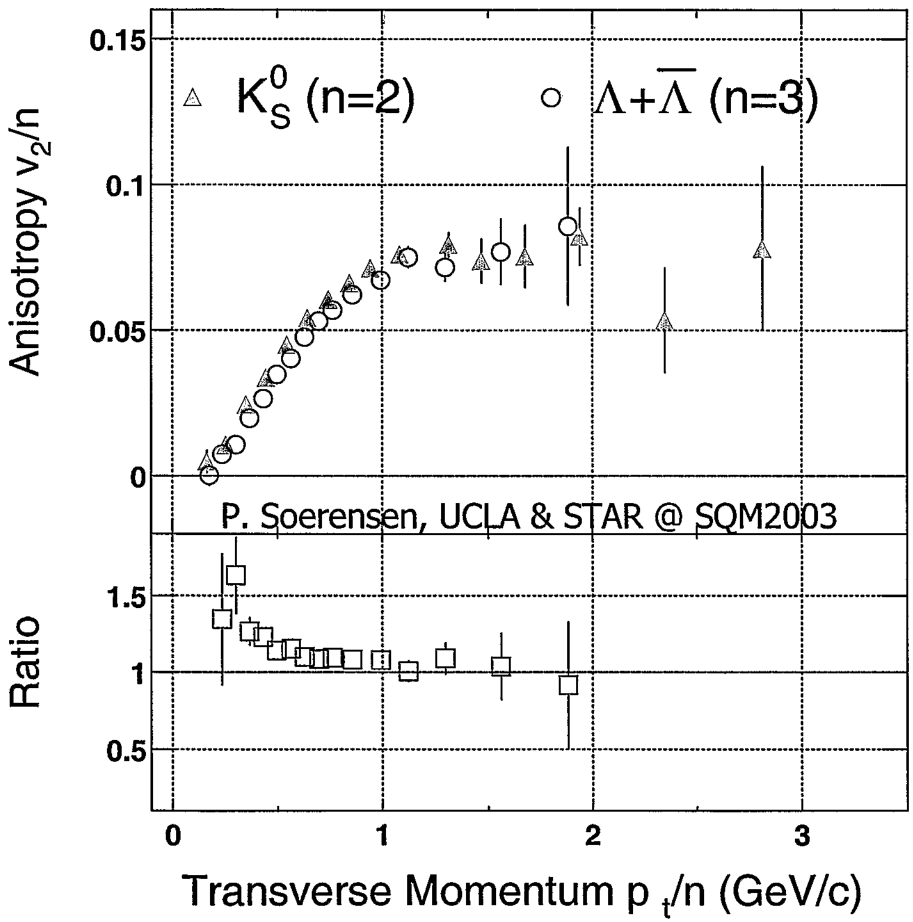
- in the recombination regime, meson and baryon v_2 can be obtained from the parton v_2 in the following way:

$$v_2^M(p_t) = \frac{2v_2^p\left(\frac{p_t}{2}\right)}{1+2\left(v_2^p\left(\frac{p_t}{2}\right)\right)^2} \quad \text{and} \quad v_2^B(p_t) = \frac{3v_2^p\left(\frac{p_t}{3}\right)+3\left(v_2^p\left(\frac{p_t}{3}\right)\right)^3}{1+6\left(v_2^p\left(\frac{p_t}{3}\right)\right)^2}$$

➢ neglecting quadratic and cubic terms, one finds a simple scaling law:

$$v_2^M(p_t) = 2v_2^p\left(\frac{p_t}{2}\right) \quad \text{and} \quad v_2^B(p_t) = 3v_2^p\left(\frac{p_t}{3}\right)$$

Parton Number Scaling of v_2



- in leading order of v_2, recombination predicts:

$$v_2^M(p_t) = 2v_2^p\left(\frac{p_t}{2}\right)$$

$$v_2^B(p_t) = 3v_2^p\left(\frac{p_t}{3}\right)$$

> ➢ smoking gun for recombination
>
> ➢ measurement of partonic v_2 !

Rainer J. Fries *Recombination & Fragmentation*

Hydrodynamical evolution near the QCD critical end point

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Recently, the possibility of the existence of a critical end point (CEP) in the QCD phase diagram has attracted a lot of attention and several experimental signatures have been proposed. Berdnikov and Rajagopal discussed the growth of the correlation length near the CEP in heavy-ion collision from the schematic argument. However, there has seen, so far, no quantitative study on the hydrodynamic evolution near CEP. Here we quantitatively evaluate the effect of the critical end point on the observables using the hydrodynamical model. First, we construct an equation of state (EOS) with CEP. We assume that an EOS with CEP is consist of two parts, a singular part near CEP and a non-singular part which is usual EOS of QGP phase or hadron gas. We formulate the singular part of EOS near CEP under assumption that it belongs to the same universality class as the 3-d Ising model. From the EOS with CEP we found that CEP is an attractor of n_B/s trajectories in T-μ plane, which is very different from an EOS of Bag model which is used in usual hydrodynamical models. This suggests that the effect of CEP can appear strongly in the time evolution of system and the experimental observables. Next we investigate the time evolution and the behavior of correlation length near CEP along n_B/s trajectories. We show the correlation length in equilibrium $\xi_{\rm eq}$ near the critical point. Due to the focusing effect, n_B/s trajectories are attracted to CEP, which causes the fact that trajectories pass through the region where $\xi_{\rm eq}$ large. Using Bjorken's scaling solution, we analyze the time evolution of correlation length ξ along n_B/s trajectories. At the beginning of time evolution, ξ becomes much smaller than $\xi_{\rm eq}$. However, here, the important point is that ξ becomes larger than $\xi_{\rm eq}$ at kinetic freeze-out temperature. In 3-d calculation, the difference between $\xi_{\rm eq}$ and ξ may become large due to transverse expansion. Finally we discuss the consequences of CEP in experimental results such as fluctuations and the kinetic freeze-out temperature. The relative low freeze-out temperature at RHIC to that at SPS implies the consequence of CEP. The EOS with CEP gives the natural explanation to the behavior of kinetic freeze-out temperature in an energy scan.

EOS with CEP

- **How to Construct EOS with CEP?**
  - Assumption

    Critical behavior dominates in a large region near end point
  - Near QCD end point singular part of EOS

3d Ising Model ⟷ **QCD**

Same Universality Class

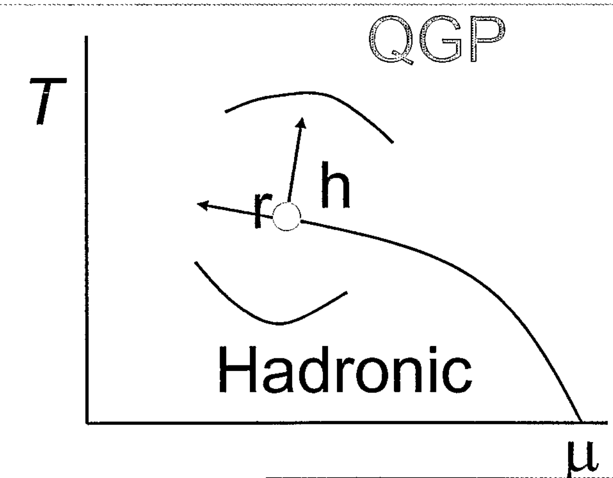
$r = \frac{T - T_C}{T_C}$

h: extermal magnetic field

$(r, h) \longleftrightarrow (T, \mu)$

$T, \ \mu$

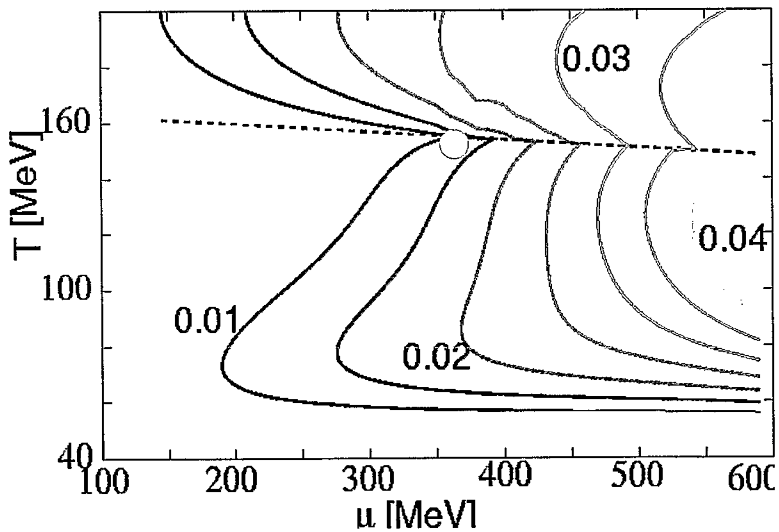
  - Mapping $(r, h) \longleftrightarrow (T, \mu)$
  - Matching with known *QGP* and *Hadronic* entropy density
  - Thermodynamical quantities



Comparison with Bag + Excluded Volume EOS

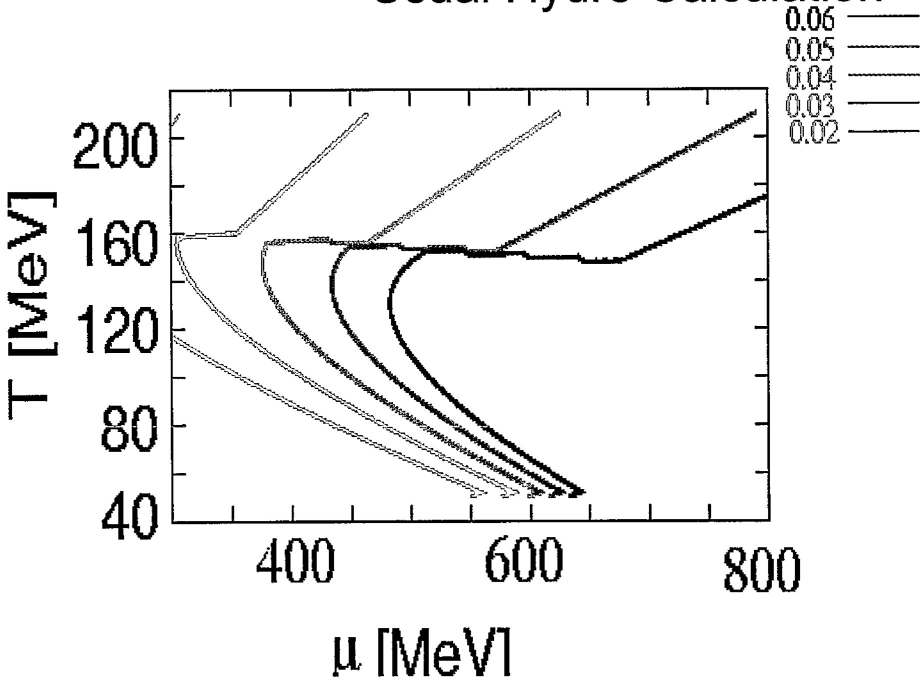
- n_B/s trajectories in T- μ plane

With End Point



Focused

Bag Model +
Excluded Volume Approximation
(No End Point)
= Usual Hydro Calculation



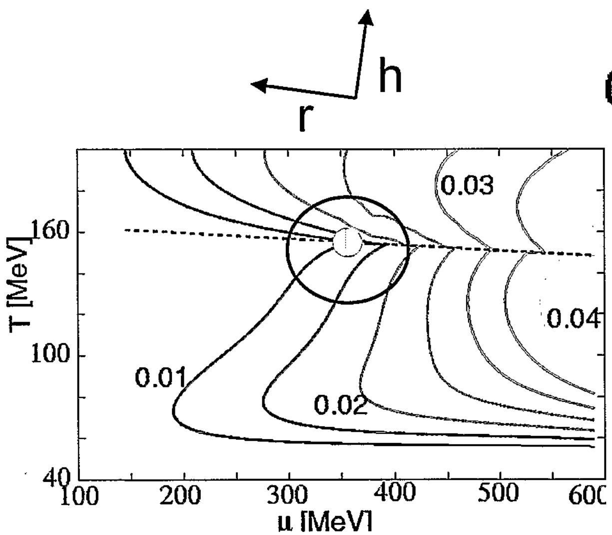
Not Focused

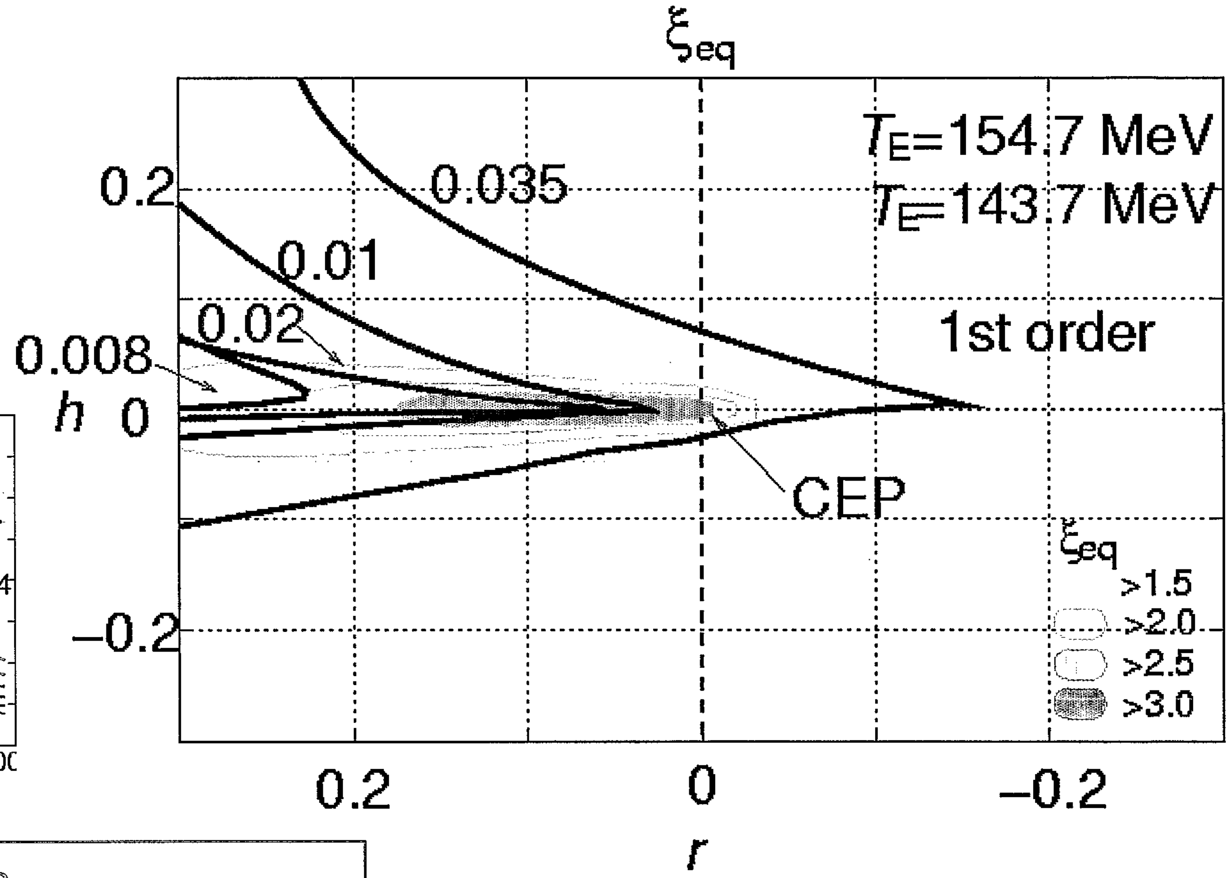
Correlation Length (I)

- ξ_{eq}

Widom's scaling low

$$\xi_{eq}^2(r,M) = f^2 M^{-2\nu/\beta} g\left(\frac{|r|}{|M|^{1/\beta}}\right)$$





- Max. ξ_{eq} depends on n_B/s.
- Trajectories pass through the region where ξ_{eq} is large. (focusing)

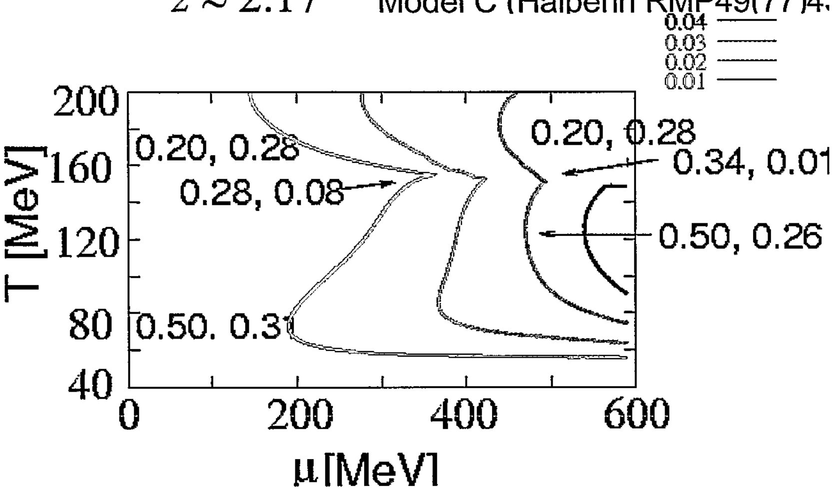
Correlation Length (II)

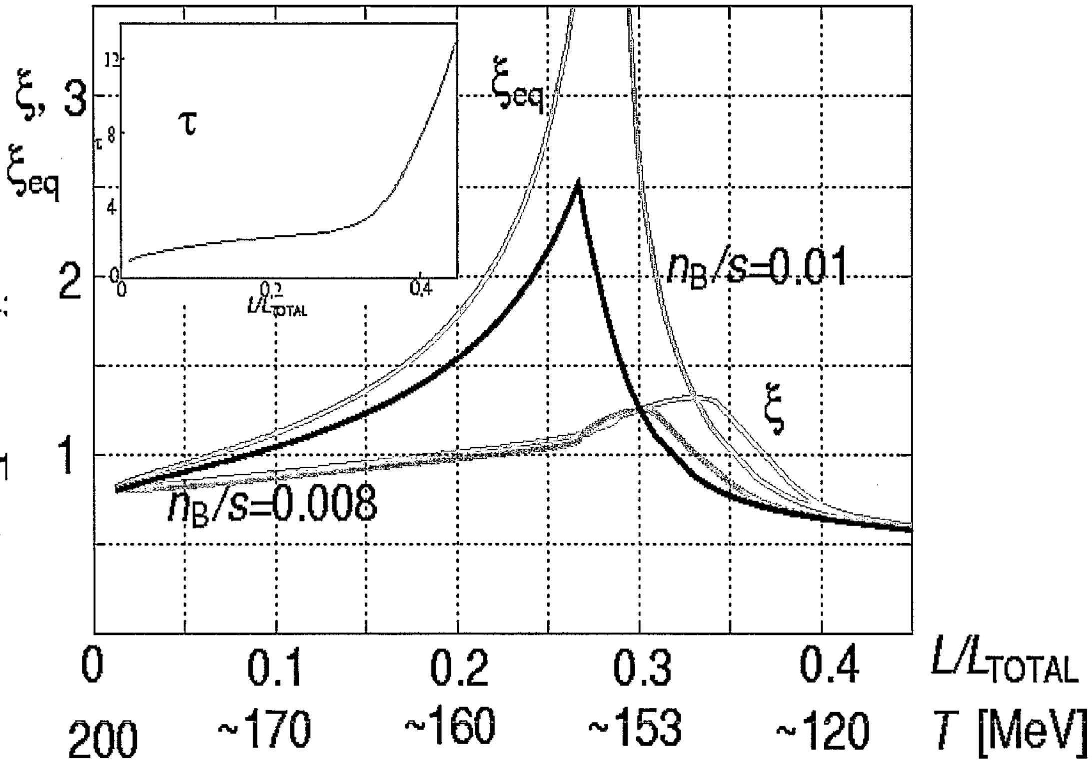
- ξ : time evolution (1-d)

$$\frac{d}{d\tau}m_\sigma(\tau) = -\Gamma[m_\sigma(\tau)]\left(m_\sigma(\tau) - \frac{1}{\xi_{eq}(\tau)}\right)$$

$$\Gamma(m_\sigma) = \frac{a}{\xi_0}(m_\sigma\xi_0)^z,\quad m_\sigma(\tau) = 1/\xi(\tau)$$

$z \approx 2.17$ Model C (Halperin RMP49(77)4:

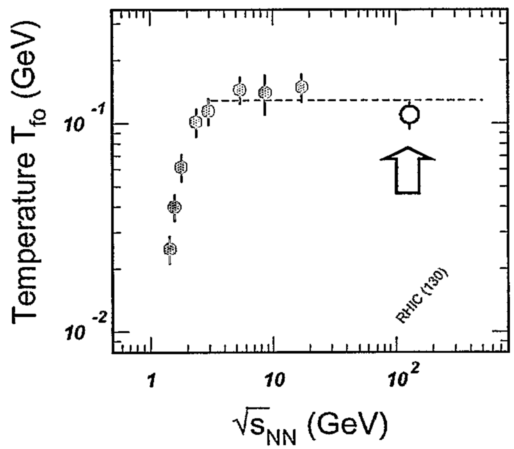




- ξ is larger than ξ_{eq} at Tf.
- Differences among ξs on n_B/s are small.
- In 3-d, the difference between ξ_{eq} and ξ becomes large due to transverse expansion.

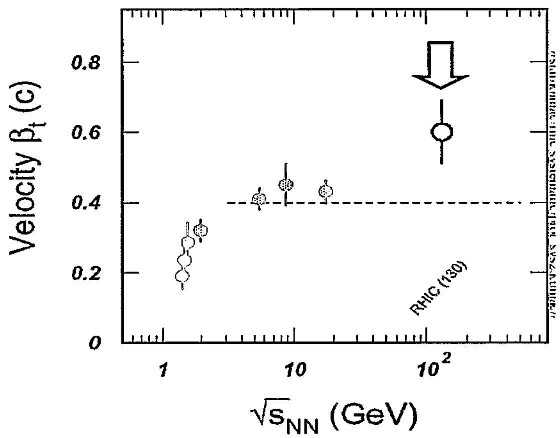
Consequences in Experiment (II)

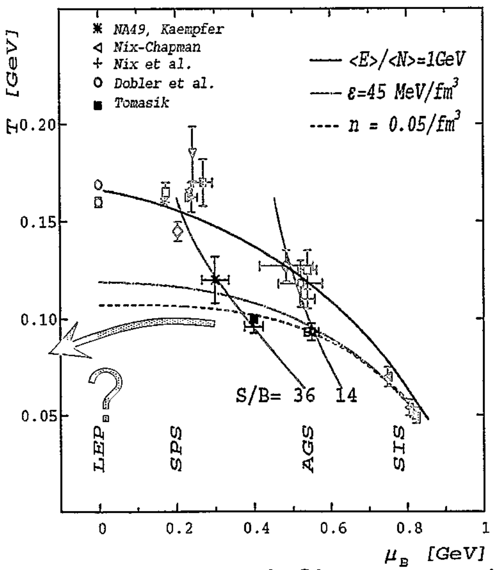
■ Kinetic Freeze-out Temperature



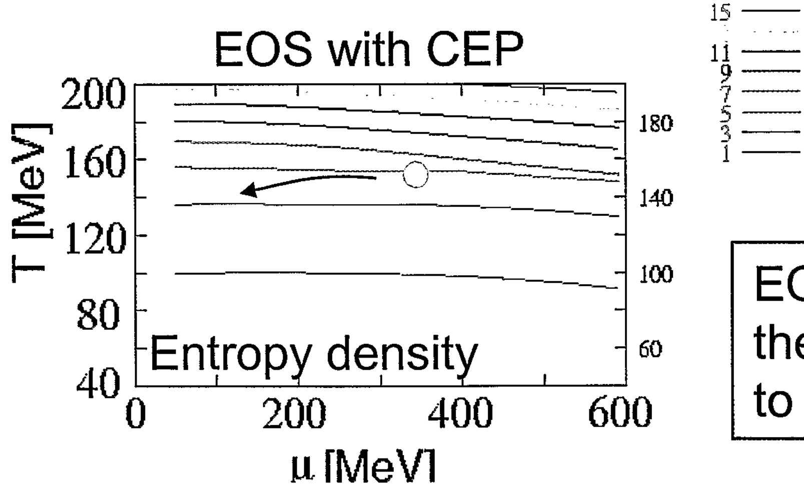
Low T_f comes from large flow.

Xu and Kaneta, nucl-ex/0104021(QM2001)





J. Cleymans and K. Redlich, PRC, 1999



EOS with CEP gives the natural explanation to the behavior of T_f.

COLLECTIVE FLOW AND QGP PROPERTIES

A RIKEN BNL Research Center Workshop
November 17-19, 2993

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COLLECTIVE FLOW AND QGP PROPERTIES
RIKEN-BNL Workshop
November 17-19, 2003

BNL Physics Department, Building 510, Large Seminar Room

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Monday, November 17:

9.00 – 9.05	Introduction and Welcome
9.05 – 9.40	**Ulrich Heinz** : Hydrodynamics, freeze-out and blast wave fits to flow spectra
9.40 – 10.15	**Derek Teaney** : Viscosity in heavy ion collisions
10.15 – 10.35	*Coffee Break*
10.35 – 11.10	**Edward Shuryak** : Why the QGP is a good liquid
11.10 – 11.45	**Denes Molnar** : What the parton cascade tells us about RHIC
11.45 – 12.20	**Che Ming Ko** : Transport model description of flow
12.20 – 13.20	*Lunch*
13.20 – 13.55	**Laszlo Csernai** : Multi module modelling of heavy ion collisions
13.55 – 14.30	**Frederique Grassi** : Results obtained with the hydrodynamical model NeXSPherIO
14.30 – 15.05	**Wojciech Broniowski** : Particle spectra and correlations in a thermal model
15.05 – 15.35	*Coffee Break*
15.35 – 16.10	**Peter Steinberg** : Landau hydrodynamics and RHIC phenomena
16.10 – 16.45	**Steffen Bass** : Baryon number transport
16.45 – 17.20	**Sergei Voloshin** : Anisotropic flow: trends and questions
18.30	*Dinner at Brookhaven Center*

Tuesday, November 18:

9.00 – 9.35	**Peter Kolb** : Momentum anisotropies - exploring the detailed dynamics
9.35 – 10.10	**Aihong Tang** : Directed and elliptic flow in Au+Au collisions at 200 GeV and azimuthal correlations in p+p and d+Au collisions at 200 GeV
10.10 – 10.30	*Coffee Break*
10.30 – 11.05	**Art Poskanzer** : Azimuthal anisotropy: The higher harmonics
11.05 – 11.40	**Steve Manly** : Update on flow studies with PHOBOS
11.40 – 12.15	**Tetsufumi Hirano** : Rapidity dependence of elliptic flow from hydrodynamics
12.15 – 13.15	*Lunch Break*
13.15 – 13.50	**Jean-Yves Ollitrault** : Analyzing v2 with Lee-Yang zeroes
13.50 – 14.25	**Paul Sorensen** : Identified particle production at intermediate pT
14.25 – 14.55	*Coffee Break*
14.55 – 15.30	**Kai Schweda** : Elliptic flow of multistrange baryons at RHIC – evidence of partonic collectivity
15.30 – 16.05	**Masashi Kaneta** : pi0 and photon v2 study in 200 AGeV Au+Au collisions
16.05 – 16.40	**Shingo Sakai** : Electron v2 and identified hadron v2 to look for origin of hadronic or partonic elliptic flow
16.40 – 17.15	**N.N. Ajitanand** : Azimuthal correlation studies via correlation functions and cumulants
17.15– 17.50	**Pasi Huovinen** : The effect of freeze-out on elliptic anisotropy

Wednesday, November 19:

8.30 – 9.05	**Scott Pratt** : 50 ways to image the final state
9.05 – 9.40	**Boris Tomasik** : Freeze-out state at RHIC
9.40 – 10.15	**ShinIchi Esumi** : Charged particle v2 and pair correlation w.r.t. R.P. at PHENIX
10.15 – 10.30	*Coffee Break*
10.30 – 11.05	**Subrata Pal** : Entropy at RHIC
11.05 – 11.40	**Fabrice Retiere** : Flow and non-identical two-particle correlations
11.40 – 12.15	**Dan Magestro** : Probing spatial anisotropy at freeze-out with HBT
12.15 – 13.15	*Lunch Break*
13.15 – 13.50	**Zi-Wei Lin** : Strong and positive x-t correlation and its effect on Rout/Rside
13.50 – 14.25	**Rainer Fries** : Recombination and fragmentation from a dense parton phase
14.25 – 15.00	**Chiho Nonaka** : Hydrodynamics near a critical end point
15.00 – 15.30	*Coffee Break – END OF WORKSHOP*

Additional RIKEN BNL Research Center Proceedings:

Additional RIKEN BNL Research Center Proceedings:

Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574
Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560
Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299
Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559
Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116
Volume 10 – Physics of Polarimetry at RHIC – BNL-65926
Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762
Volume 8 – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634
Volume 7 – RHIC Spin Physics – BNL-65615
Volume 6 – Quarks and Gluons in the Nucleon – BNL-65234
Volume 5 – Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density – BNL-65105
Volume 4 – Inauguration Ceremony, September 22 and Non -Equilibrium Many Body Dynamics – BNL-64912
Volume 3 – Hadron Spin-Flip at RHIC Energies – BNL-64724
Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723
Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

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Inside Back Cover

RIKEN BNL RESEARCH CENTER

Collective Flow and QGP Properties

November 17-19, 2003

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

Speakers:

N. Ajitanand
R. Fries
M. Kaneta
S. Manly
A. Poskanzer
E. Shuryak
B. Tomasik
S. Bass
F. Grassi
C.-M. Ko
D. Molnar
S. Pratt
P. Sorensen
S. Voloshin
W. Broniowski
U. Heinz
P. Kolb
C. Nonaka
F. Retiere
P. Steinberg
L. Csernai
T. Hirano
Z.-W. Lin
J.-Y. Ollitrault
S. Sakai
A. Tang
S.-I. Esumi
P. Huovinen
D. Magestro
S. Pal
K. Schweda
D. Teaney

Organizers: S. Bass, S. Esumi, U. Heinz, P. Kolb, E. Shuryak, N. Xu