BNL-94704-2011
Formal Report

Proceedings of RIKEN BNL Research Center Workshop Volume 102

Initial State Fluctuations and Final-State Particle Correlations

February 2-4, 2011

Organizers: A. Dumitru, D. Molnar and F. Wang

RIKEN BNL Research Center

Building 510A, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

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 Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002 and again in 2007. 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.

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consists of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~100 graduates of which 27 theorists and 14 experimenters have attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. In most cases all the talks are made available on the RBRC website. In addition, highlights to each speaker's presentation are collected to form proceedings which can therefore be made available within a short time after the workshop. To date there are one hundred and one proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998. The next generation computer in this sequence, QCDCQ (400 Teraflops), will become operational in the summer of 2011.

N. P. Samios, Director
February 2011

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

INTRODUCTION

The RIKEN BNL Research Center workshop on "Initial State Fluctuations and Final-State Particle Correlations" was held successfully at Brookhaven National Laboratory on February 2-4, 2011.

The workshop was motivated by rich structures in the experimental particle correlation measurements and the suggestion that those structures may be fingerprints of initial state fluctuations. Experimental data on two-particle correlations have revealed a long-range pseudo-rapidity correlation in heavy-ion collisions at RHIC and in high-multiplicity proton-proton collisions at the LHC, called the "ridge". The ridge is present whether a high transverse momentum (pt) trigger particle is required or not. The basic principle of causality and the approximate correspondence of pseudo-rapidity and space-time rapidity require that such long-range correlations originate from the initial stage of the collision.

In addition, two-particle correlations with a high-pt trigger particle exhibit a broadened and double-peaked structure on the away side in heavy-ion collisions, in contrast to observations for minimum-bias p+p collisions which instead exhibit di-jet peaks. Three-particle correlations suggest that the away-side double-peak correlation is due to conical emission of correlated hadrons.

Various theoretical explanations for the long-range correlations were discussed at the workshop; most notably, the formation of approximately boost invariant color flux tubes. To explain the ridge in heavy-ion collisions, transverse hydrodynamic flow is required. On the other hand, Mach-cone shock waves and non-vanishing "triangularity" of the initial geometry have been proposed to explain the conical emission on the away side. Several speakers showed that initial energy density fluctuations which evolve hydrodynamically give rise to features in two-particle correlations that are qualitatively consistent with the data. Fluctuations in the overlap geometry of participating nucleons can give rise to higher moments of the flow; in particular, a large "triangular flow" can yield features like the near-side ridge and away-side double-peak in the two-particle correlations.

The purpose of the workshop was to bring together experts, both theorists and experimentalists, to examine all aspects of the experimental data and of current theoretical approaches, both on pt-triggered and untriggered particle correlations. Some of the questions to be addressed at the workshop were:

- What do we learn about the properties of the dense medium and of the initial state from multi-particle correlations? What quantitative information can one extract from comparisons of models to data?
- What do we learn about the properties of the dense medium and of the initial state from multi-particle correlations? What quantitative information can one extract from comparisons of models to data?
- How well do the initial fluctuation models describe both the pt-triggered and untriggered two-particle correlation data?
- Do the ridges observed in pt-triggered and untriggered correlations originate from the same physics?
- How can experiments separate triangular flow and non-flow?

Approximately 70 theorists and experimentalists gathered at the workshop. There were 7 experimental overview talks and 18 theoretical talks. There were many focused and intense discussions. The talks and the discussions were very helpful to sharpen our thinking and improve our understanding. While differences of opinions of course still exist, there was a general consensus on the following points:

- Initial fluctuations in the collision geometry and energy density are naturally expected.
- These initial fluctuations can generate event-by-event harmonic "flows" of any order. The first four to five harmonic orders appear to be important while higher harmonics are damped by coarse graining effects.
- Decomposing final-state particle correlations into Fourier harmonics is helpful but offers only partial insight into the physics. The question about mixing of flow and nonflow contributions to various harmonics has to be taken up.
- The physics of the initial-state long-range fluctuations is of fundamental interest on its own.

Are the correlations a manifestation of high-energy QCD evolution, and perhaps of semi-hard flux tubes of longitudinal color-electric and magnetic fields? Are they high energy density hot spots? Are flux tube fluctuations and hot spots the same thing? Should their effects on final state measurements be considered as hydrodynamic flow or as intrinsic correlations? Do the correlations arise at leading order in Nc? Is the Balitsky-Kovchegov equation sufficient to understand two-particle correlations or is it necessary to consider evolution of more general n-point functions? These were some of the questions that were brought up at the workshop and which are expected to advance our understanding through future work.

The workshop participants generally expressed that the workshop was very timely and seeded further development. We were somewhat unlucky with the East Coast weather that delayed several participants but, nevertheless, we had a good program and discussions. Special thanks to all speakers and participants for making the workshop so successful; to our workshop coordinator, Pamela Esposito, for her tireless efforts and professional planning; and, of course, to everybody at RBRC for "making it possible."

Adrian Dumitru, Denes Molnar, Fuqiang Wang

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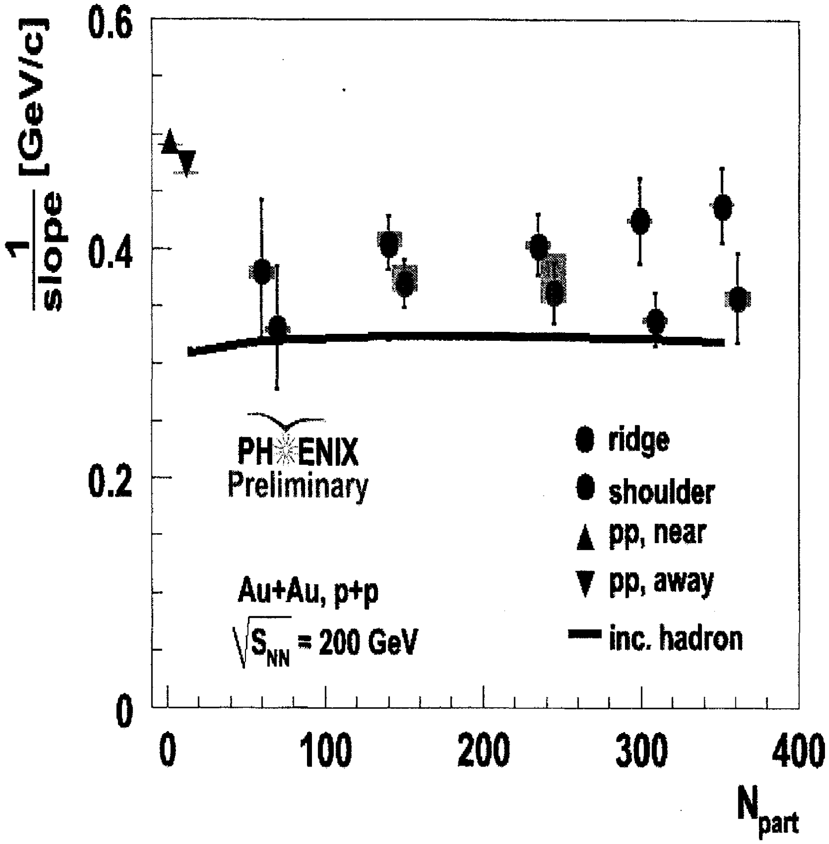
Overview on two particle correlations from PHENIX

John Chin-Hao Chen
Stony Brook University

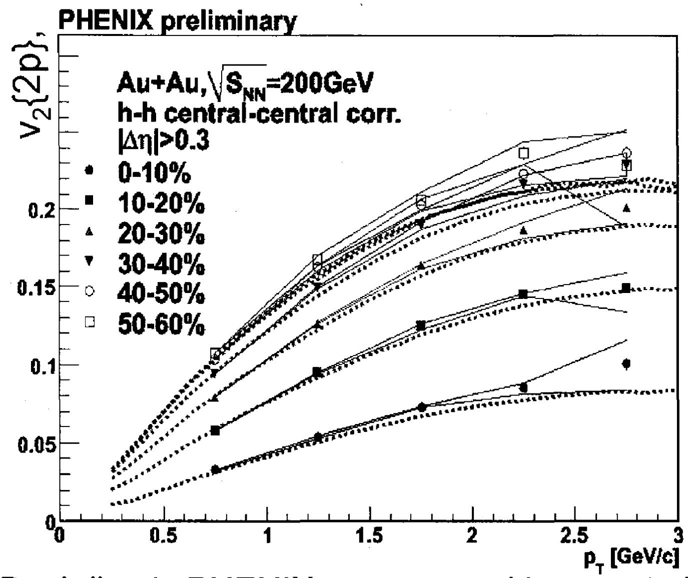
RIKEN Workshop
02/02/2011

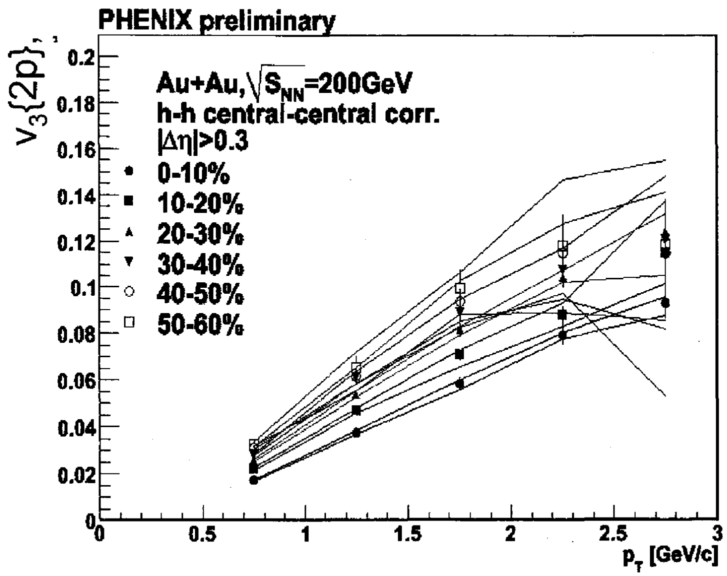
Shoulder & ridge p_T spectra vs. p+p



- Both are softer than hard scattering.
- Ridge harder than shoulder?
- Shoulder not quite as soft as inclusive hadrons.
- Not identical to the bulk.

$v_2\{2p\}$, $v_3\{2p\}$ from two particle correlations

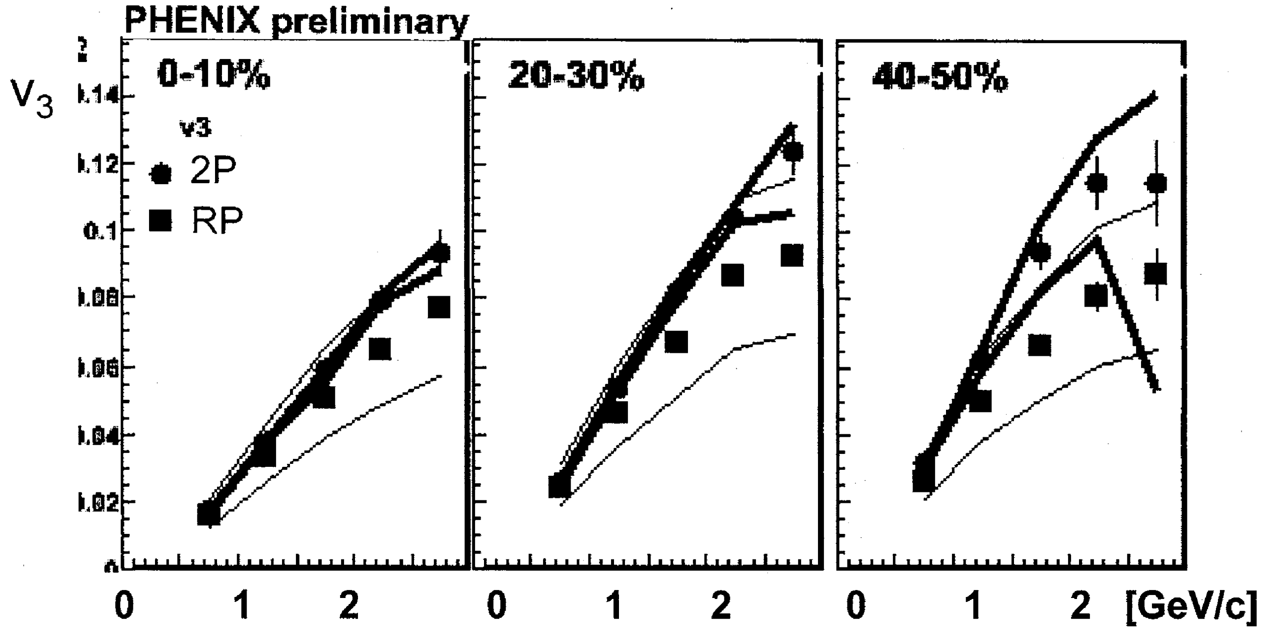




Dash line is PHENIX v_2 measured by event plane
Phys. Rev. Lett. 105, 062301 (2010)

- $v_2\{2p\}$ agrees with previous PHENIX measurements at low p_T
- $v_3\{2p\}$
  - Nonzero
  - Increases with p_T (NB: may have non-flow effects in this method)
  - Increases with centrality

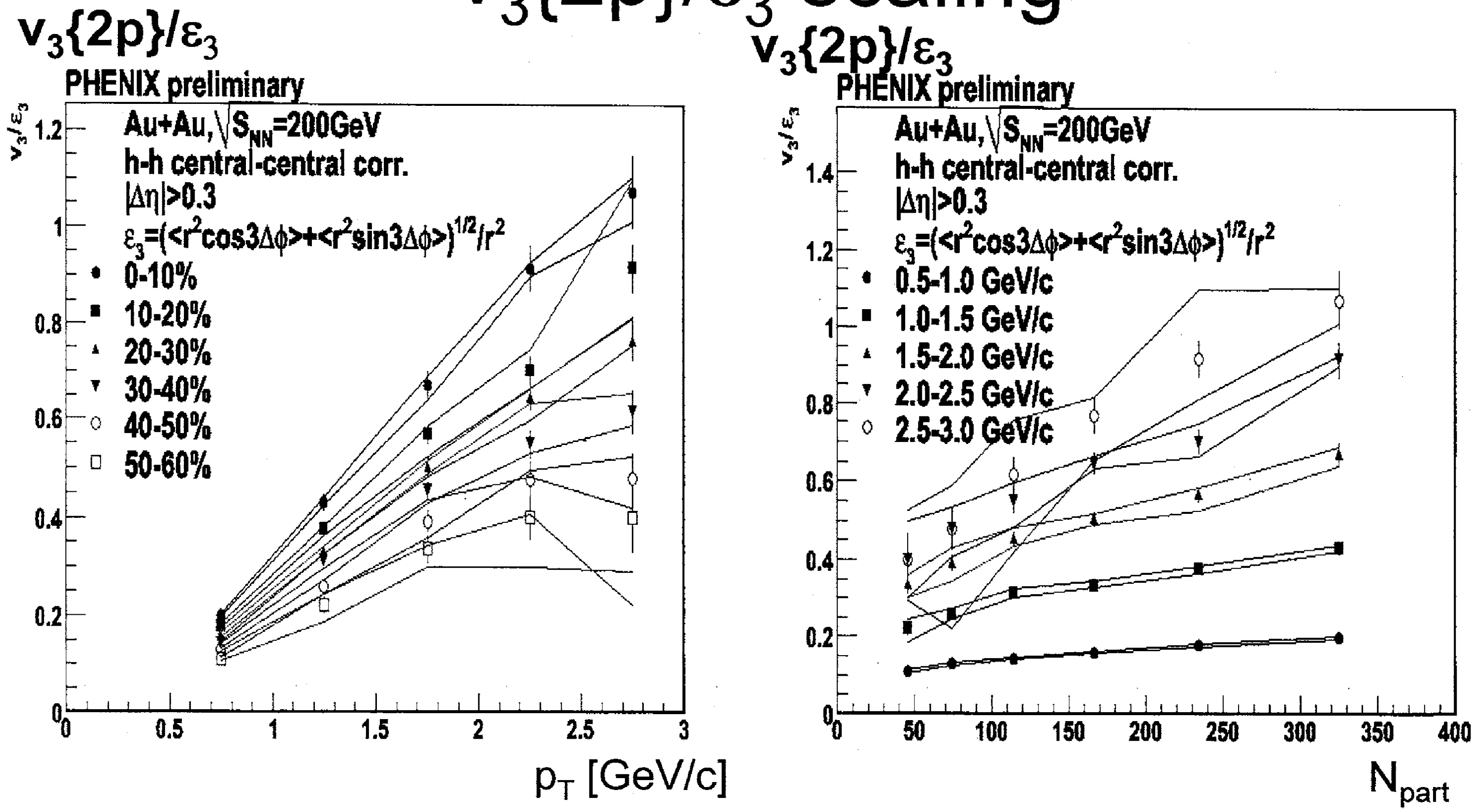
Compare with v_3 measured by ψ_3



Red: event plane method (ψ_3). Black: 2 particle correlation

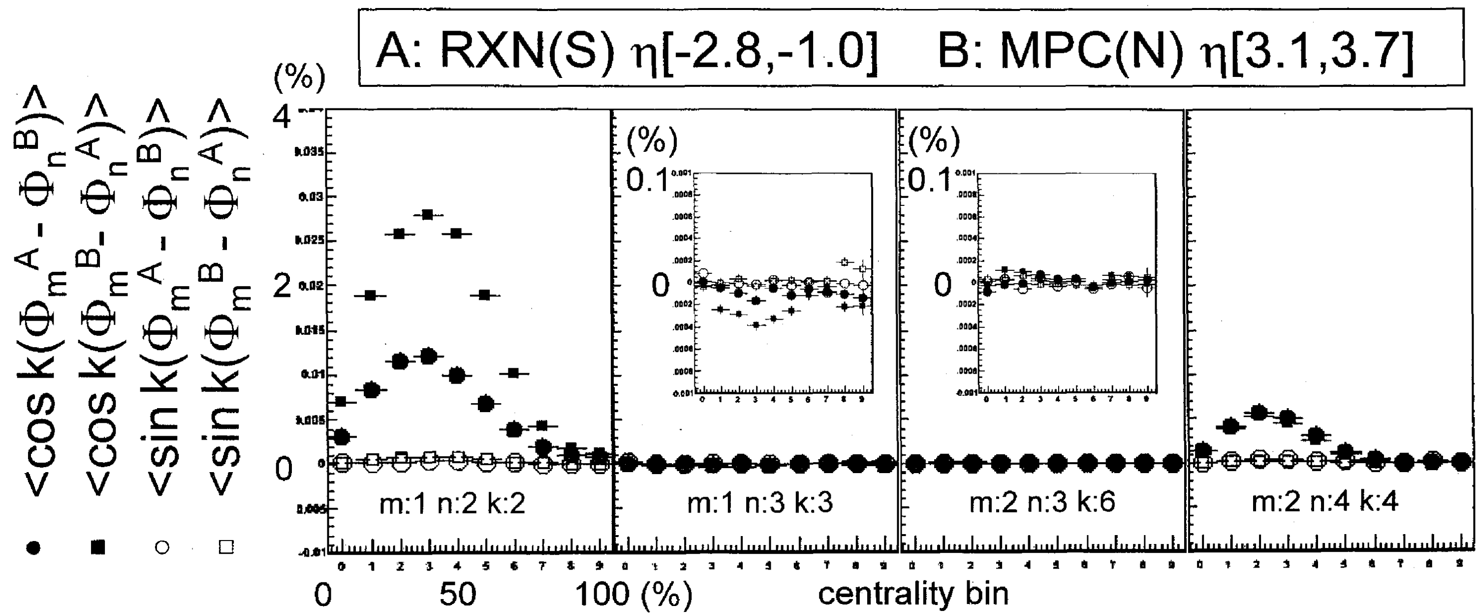
Agree at low p_T, non-flow (i.e jet) effects at high p_T

$v_3\{2p\}/\varepsilon_3$ scaling



- ε_3 = sqrt(<r^2cos3ϕ>^{2}+ <r^2sin3ϕ>^{2})/r^2
- Similar trend as v_2

Correlation between event plane Φ_n

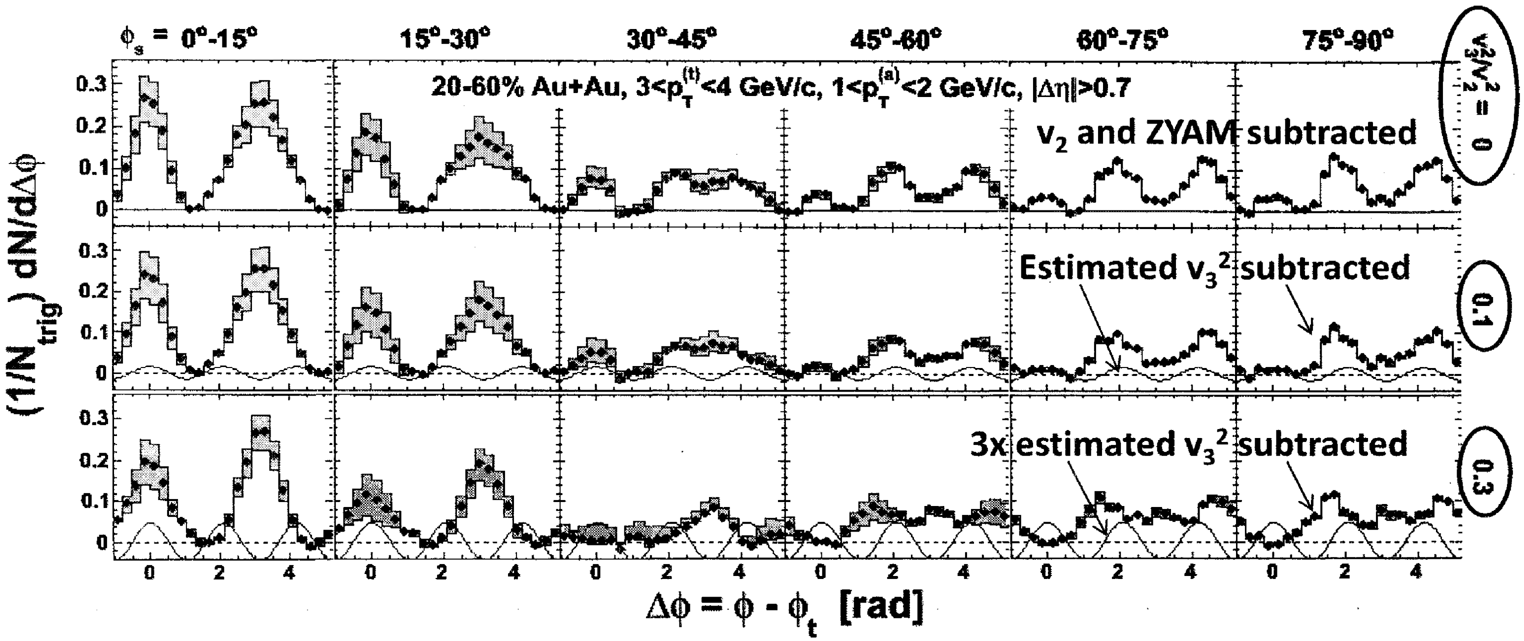


- clear correlation in Φ1–Φ2 , Φ2–Φ4
- weak correlation in Φ1–Φ3
- no visible correlation in Φ2–Φ3

How Much Is Medium Flow, How Much Is Jet-medium Interaction: An Experimental Perspective

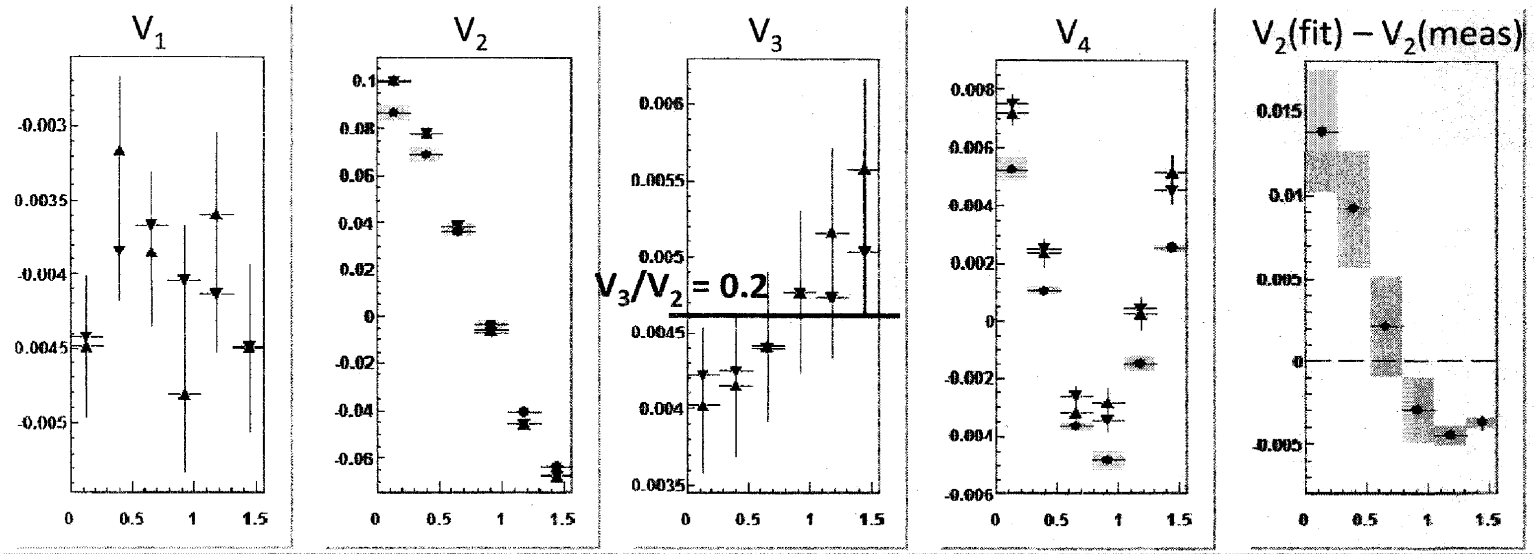
Fuqiang Wang
Purdue University

Effect of v_3 from models



- Dramatic change with trigger ϕ_t – EP, while v_3 effect is independent.
- Large $\Delta\eta$: near-side dominated by ridge. Ridge decreases with ϕ_t – EP.
- $v_3^2/v_2^2 \approx 0.1$ (20-60% centrality) from AMPT (Alver et al.), UrQMD (Petersen et al.): insignificant compared to data.
- Even with 3x larger v_3^2, novel structure remains (and near-side concaved).

Fourier Fit Harmonic Parameters



RP-dep. w/o direction dependence
RP-dep. w/ direction dependence

$V_3/V_2 = 0.1$

Measured central value:
v_2(assoc.)*v_2(trig)=0.023

Difference between fitted harmonics and measured flow is jet-correlation signal (nonflow).

What are the Fourier Harmonics?

- Two-particle Correlation $\equiv V_n\{2\}$ = flow + nonflow

Indirect correlation (flow background):

$$1 + 2V_{1,flow}\cos(\Delta\phi) + 2V_{2,flow}\cos(2\Delta\phi) + 2V_{3,flow}\cos(3\Delta\phi) + 2V_{4,flow}\cos(4\Delta\phi)$$

Direct correlation (nonflow signal):

$$1 + 2V_{1,nf}\cos(\Delta\phi) + 2V_{2,nf}\cos(2\Delta\phi) + 2V_{3,nf}\cos(3\Delta\phi) + 2V_{4,nf}\cos(4\Delta\phi)$$

- To interpret the fitted Fourier harmonics *solely* as flow is a leap of faith, not a due scientific process.

  DATA – Fitted Harmonics $V_n\{2\} \equiv$ ZERO signal, by definition.

  Assume nonflow=0 → then signal=0, i.e. Result = Assumption.

Path forward

Indirect correlation (flow background):

$$1 + 2V_{1,flow}\cos(\Delta\phi) + 2V_{2,flow}\cos(2\Delta\phi) + 2V_{3,flow}\cos(3\Delta\phi) + 2V_{4,flow}\cos(4\Delta\phi)$$

Direct correlation (nonflow signal):

$$1 + 2V_{1,nf}\cos(\Delta\phi) + 2V_{2,nf}\cos(2\Delta\phi) + 2V_{3,nf}\cos(3\Delta\phi) + 2V_{4,nf}\cos(4\Delta\phi)$$

Flow (background) and nonflow (signal) may or may not have the same functional form. Even if same shape, we should be able to tell them apart, because flow is related to RP, nonflow is not.

- From single measurement of two-particle correlation, one cannot determine two unknowns: flow and nonflow correlation.
- Need external information: flow measurements from two- and four-, and six-particle correlations.

Summary

- Two-particle correlations contain both flow and nonflow

  CORREL SIGNAL + CORREL BKGD = NONFLOW + FLOW

  Two-particle correlation alone cannot separate the two.

- Need external measurements of flow and nonflow
  - v_2: flow + nonflow
  - v_3: flow + nonflow
  - Other harmonics

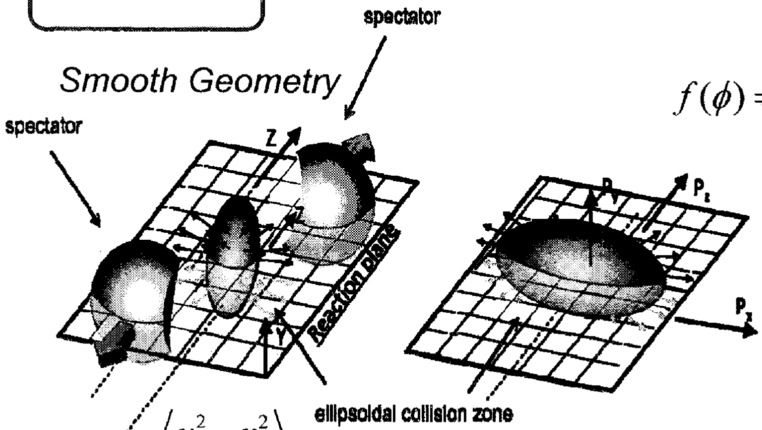
  Hopeful by 2-, 4-, and 6-particle correlations.

Initial Eccentricity Fluctuations and their Relation to Higher-order Flow Harmonics

Roy A. Lacey
Chemistry Dept.,
Stony Brook University

Flow

Smooth Geometry



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

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

$$\sim 5-15\ \frac{GeV}{fm^3}$$

$$\left(\mathrm{P} = \rho^2 \cdot \left(\partial \varepsilon_{Bj} / \partial \rho \right) \Big|_{s/\rho} \right)$$

$$f(\phi) = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{+\infty} v_n \cos(n\phi - n\psi_n) \right)$$

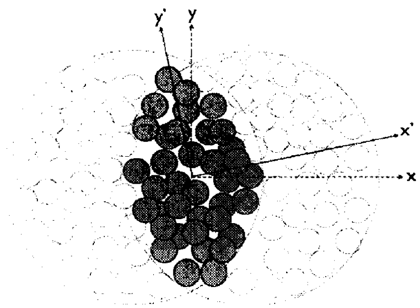
$$\langle e^{in\phi} \rangle \equiv \int_0^{2\pi} e^{in\phi} f(\phi) d\phi = v_n e^{in\psi_n}$$

$$v_n = \left\langle e^{in(\phi_p - \Psi_{RP})} \right\rangle, \quad n = 2, 4, ..,$$

For *smooth profile* $\phi \to \phi + \pi$

Odd harmonics = 0

Flow



Important Consequences for:

Decomposition of correlation functions

- *The Ridge ?*
- *Shoulder ?*
- *Mach Cones ?*

The initial collision geometry is "lumpy"

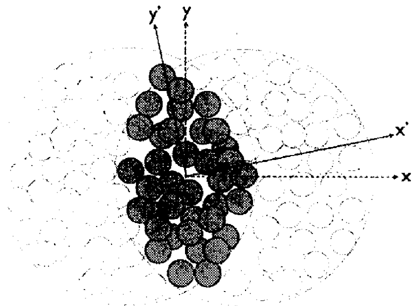
No particular symmetry
$V_{n+1} \neq 0$ (event-by-event)

Do higher-order flow harmonics (odd & even) provide a constraint for the extraction of ϵ and η/s?

Eccentricity Moments

$$S_{nx} \equiv S_n \cos(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\cos(n\phi)$$

$$S_{ny} \equiv S_n \sin(n\Psi_n^*) = \int d\mathbf{r}_\perp \rho_s(\mathbf{r}_\perp)\omega(\mathbf{r}_\perp)\sin(n\phi)$$



$$\omega(\mathbf{r}_\perp) = \mathbf{r}_\perp^{\;2}$$

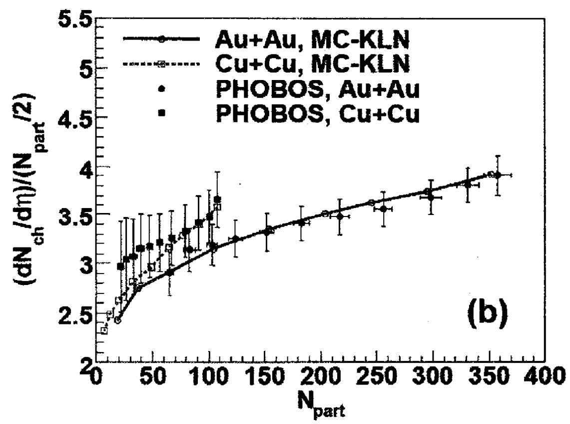
$$\rho_s(\mathbf{r}_\perp) \propto \left(\frac{(1-\alpha)}{2}\frac{dN_{\text{part}}}{d^2\mathbf{r}_\perp} + \alpha \frac{dN_{\text{coll}}}{d^2\mathbf{r}_\perp} \right)$$

For Glauber calculations

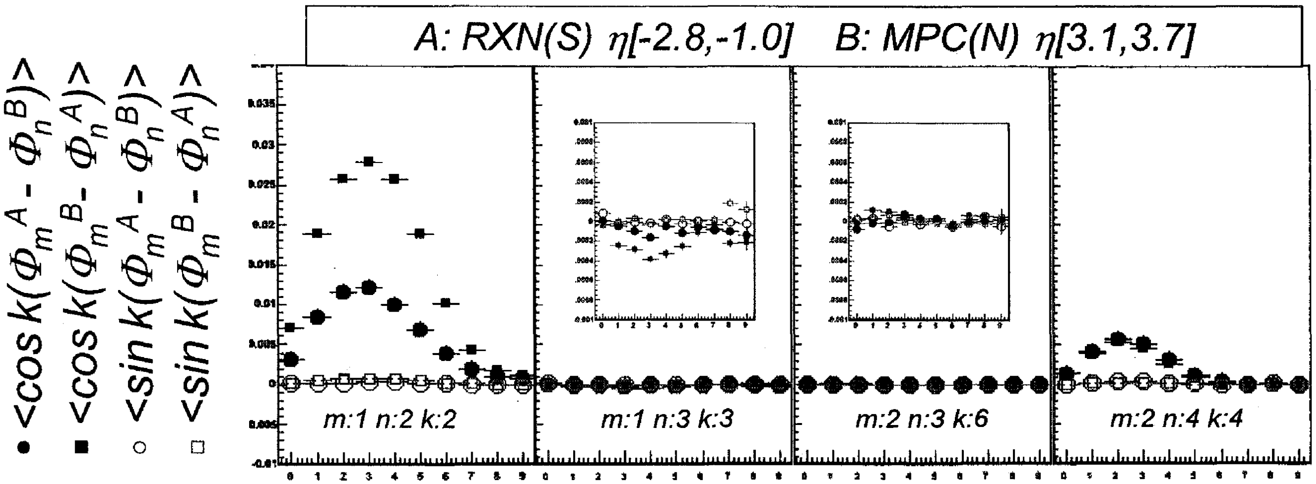
$$\Psi_n^* = \frac{1}{n}\tan^{-1}\left(\frac{S_{ny}}{S_{nx}}\right)$$

$$\varepsilon_n^* = \left\langle \cos n(\phi - \Psi_n^*) \right\rangle$$

$$\varepsilon_n = \left\langle \cos n(\phi - \Psi_m^*) \right\rangle \quad n \neq m.$$



Correlation between ψ_n Planes?

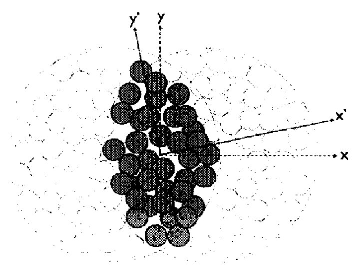


- clear correlation between $\Phi_1 - \Phi_2$, $\Phi_2 - \Phi_4$
  - weak correlation between $\Phi_1 - \Phi_3$
- no visible correlation between $\Phi_2 - \Phi_3$

The vexing issue as to whether or not Φ_2 and Φ_3 are correlated is now settled!

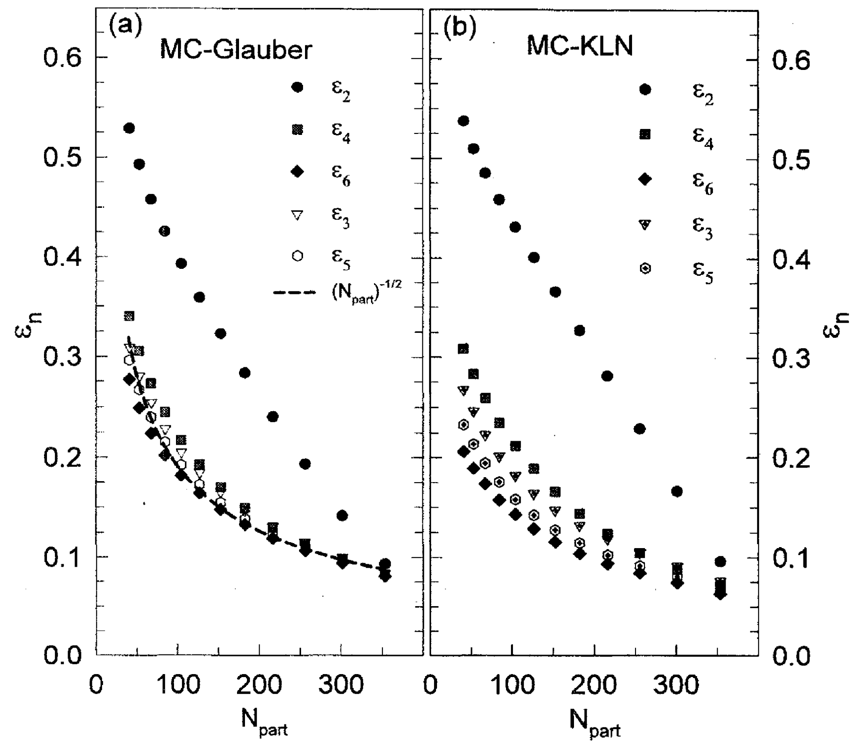
All arguments for a correlation [and their possible implication] are now irrelevant!

Eccentricity Moments



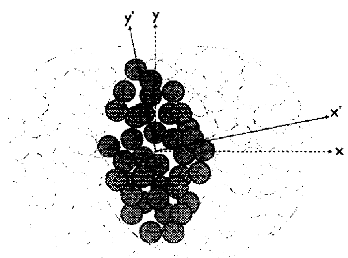
$$\omega(\mathbf{r}_\perp) = \mathbf{r}_\perp^{\,2}$$

Fluctuations dominate Higher-order moments



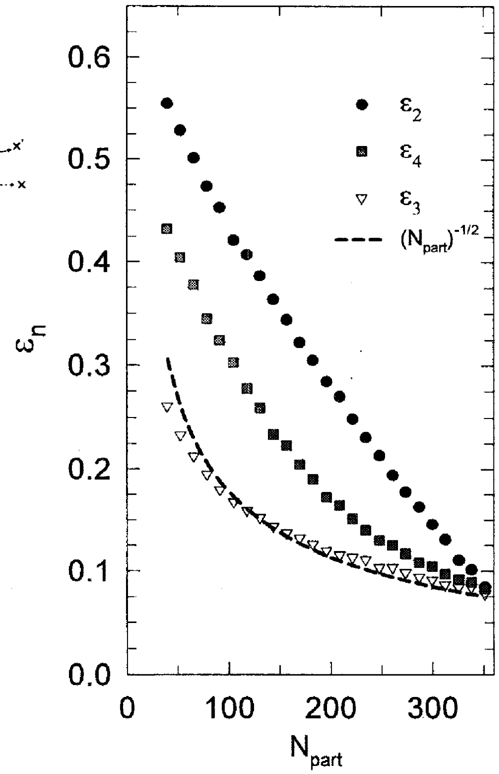
Model dependence of eccentricity

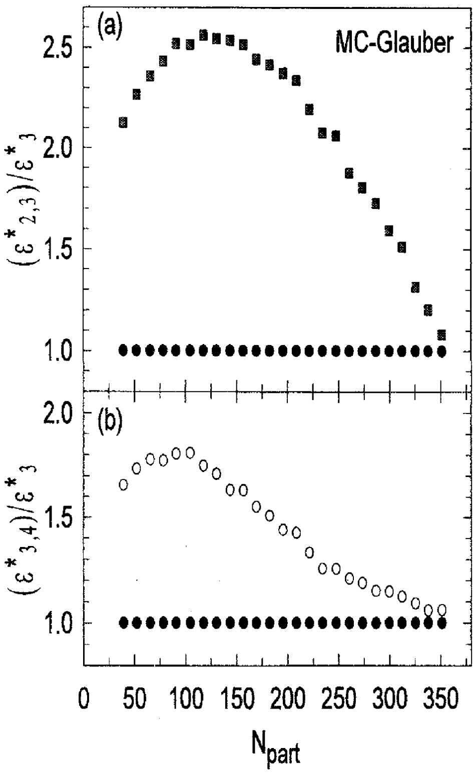
Eccentricity Moments



$$\omega(\mathbf{r}_\perp) = \mathbf{r}_\perp^{\ n}$$

Staig & Shuryak
arXiv:1008.3139

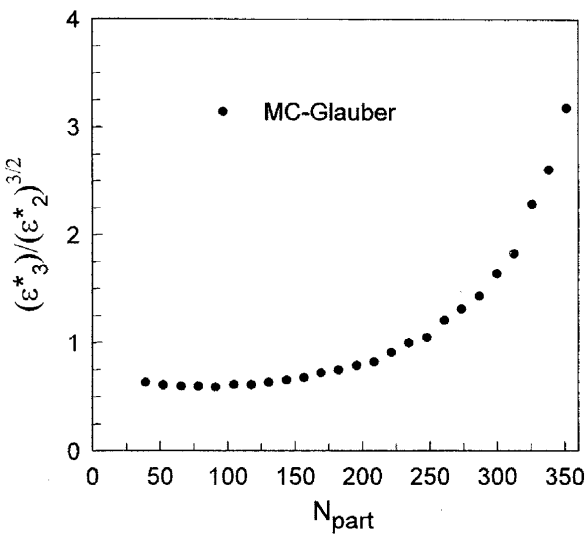


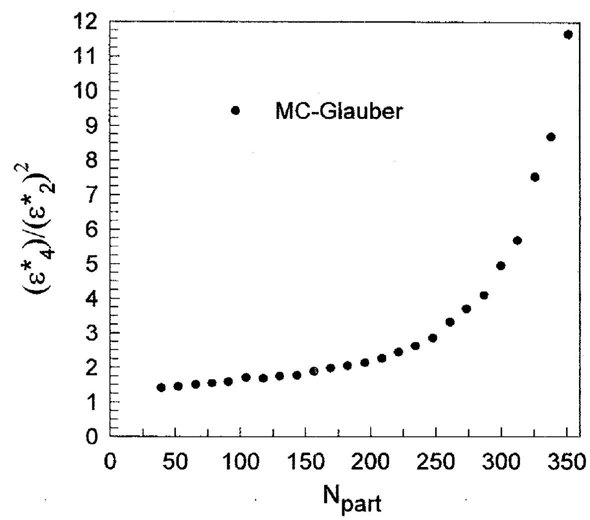


eccentricity differences depend on weighting

Eccentricity Moments

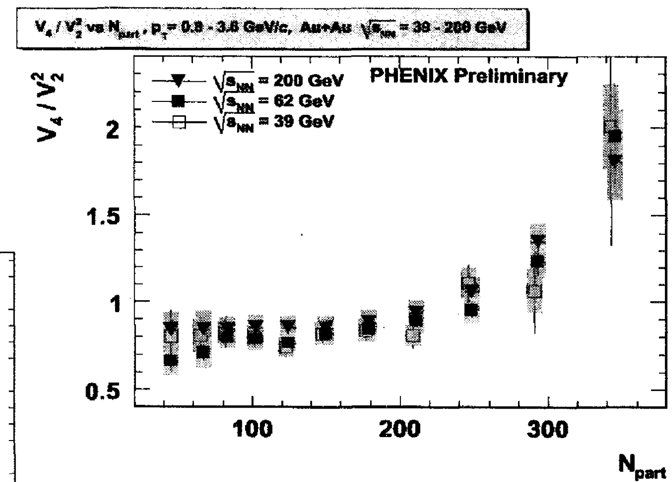
$$\omega(\mathbf{r}_{\perp}) = \mathbf{r}_{\perp}^{\,n}$$

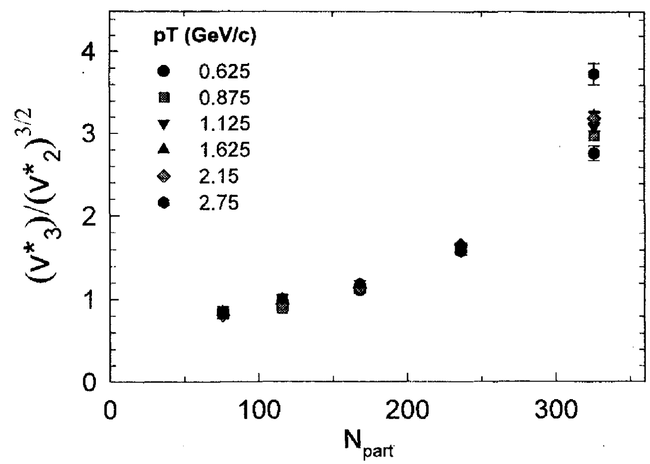


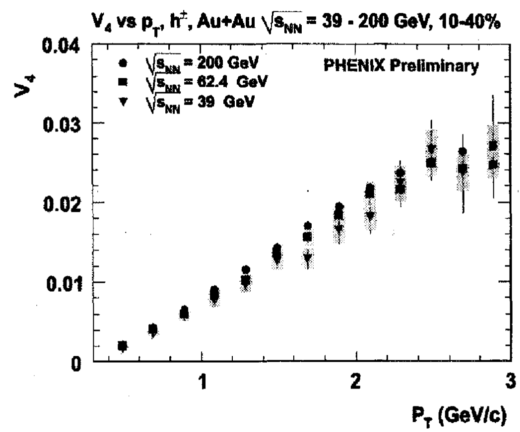


Sizeable model dependent eccentricity differences

Hints from Data







Eccentricity fluctuations are important!

Initial state fluctuations, 2-particle correlations and hydrodynamic flow

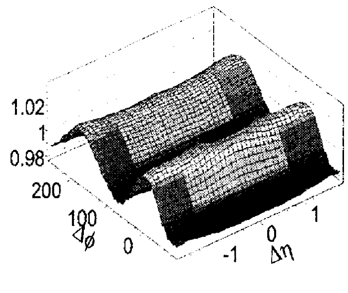
The system-size dependence of elltiptic flow and event-by-event flow fluctuations, as well as theoretical considerations, support the idea of event-by-event fluctuations in the geometry and/or energy-density distributions in the initial state of heavy-ion collisions. In transport models and hydrodynamic calculations, such fluctuations naturally lead to higher order Fourier components of the final state azimuthal distributions. This is reflected in two-particle correlation functions and contributes to phenomena that were previously regarded as distinct from those related to hydrodynamic flow (ridge, cone, head, shoulder, etc). We argue that a consistent treatment of all flow components is necessary before attempting to attribute observed correlation structures to the presence of novel/unexplained "non-flow" correlations.

Gunther Roland

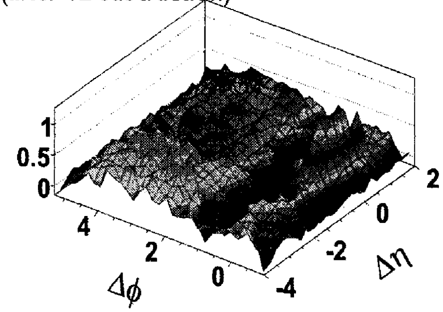
MIT

Higher Order Correlations

Inclusive correlations

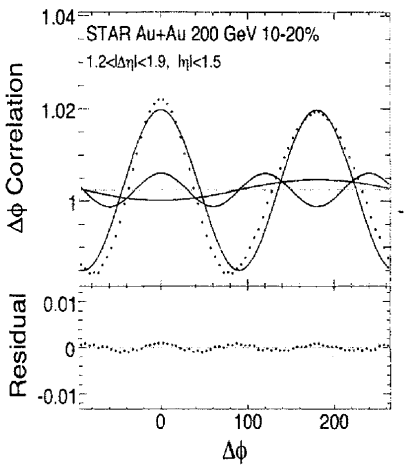


Triggered correlations
(after v2 subtraction)

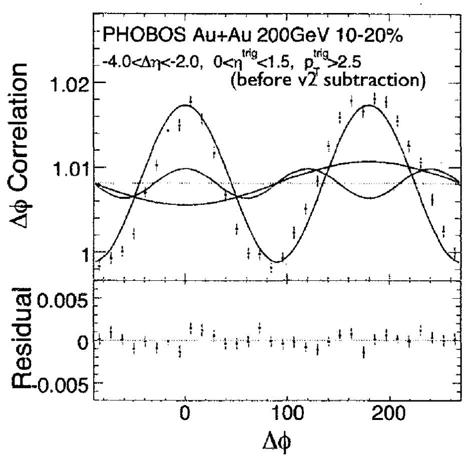


Burak Alver, GR, arXiv:1003.0194 (PRC in press)

arXiv:0806.0513



PRL 104, 06230 (2010)



n.b. Ψ2 and Ψ3 are uncorrelated (for b < 10fm*)
- triangular flow is not visible in v_2 event plane analysis

* correlation for large b pointed out by J. Nagle

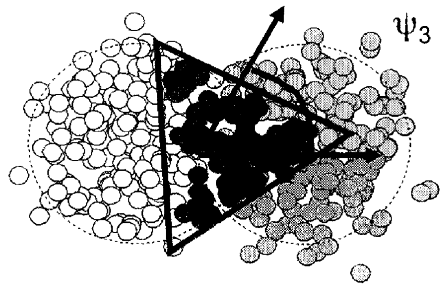
Published correlation data (STAR, PHOBOS) also show v_1, v_3, v_4 components!

Flow contribution to long-range "ridge" and "broad away-side"

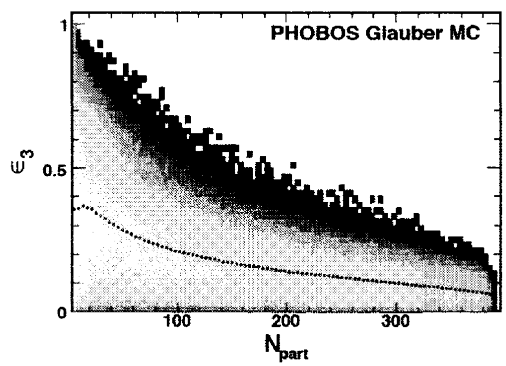
This is purely a fluctuation effect - no fluctuations, no v_3!

Triangular flow

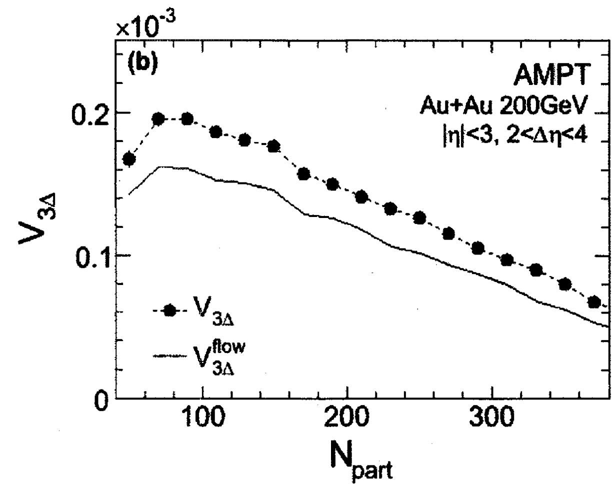
Participant Triangularity



$$\varepsilon_3 = \frac{\sqrt{\left\langle r^2 \cos(3\phi)\right\rangle^2 + \left\langle r^2 \sin(3\phi)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$

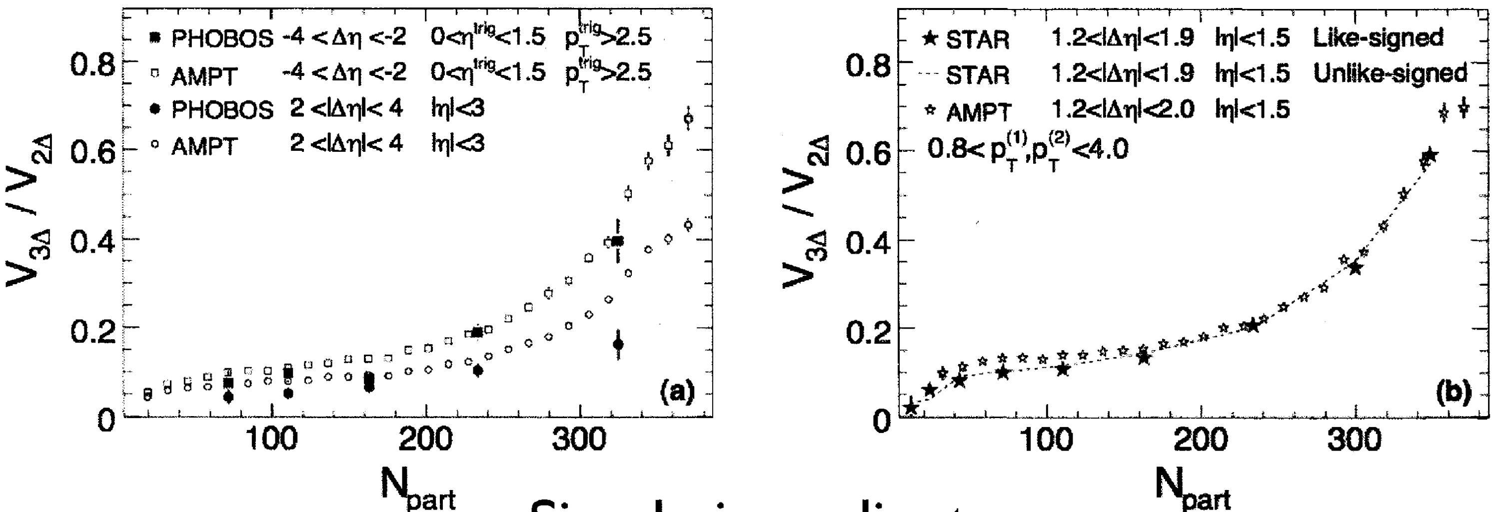


Burak Alver, GR, arXiv:1003.0194, PRC



Just like elliptic flow reflects event-by-event eccentricity, “triangular flow” (v_3) reflects event-by-event “triangularity” (ε_3)

Comparison to published data



Simple ingredients:

Eccentricity, triangularity from MC Glauber

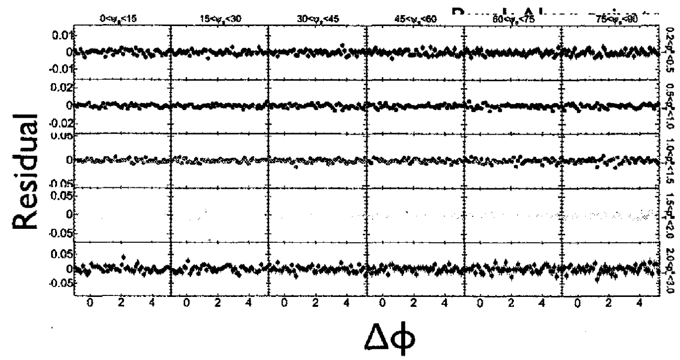
V_2 vs ε_2 and V_3 vs ε_3 from AMPT (per centrality bin)

Stunning agreement with data*

*first version of our paper had a mistake in the pT range for STAR agreement went from "good" to "ridiculous"

Fourier Components of STAR ϕ_s data

Data from STAR
arXiv:1010.0690



Fourier coefficients v_1, v_2, v_3, v_4 exhaust information content of C.F.'s vs ϕ_s
Smooth evolution of v_n with e.g Φ_s

This does not mean that all correlations are from Glauber+Flow

But all components have contributions from Glauber+Flow

Use Fourier decomposition as basis for discussion in which flow contributions can be expressed/calculated easily?

Summary

- Experimental evidence for Glauber-like geometry fluctuations
- Flow is more than just v_2
- Can we make data/theory comparisons more "efficient"?
  - Fourier decomposition vs ridge, cone, shoulder, head etc
  - Shift the data/theory interface to "unsubtracted" C.F. level?
- Evidence for long-range non-flow in pp?

Ridges in Hydrodynamic Approach☆

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Abstract

Event-by-event hydrodynamics, with fluctuating initial conditions, has shown to nicely reproduce several features of experimentally observed quantities in high-energy nuclear collisions. Here we discuss how it may help to understand, in a *unified* way, the various structures observed in the long-range two-particle correlations.

Keywords: Hydrodynamic model, fluctuating initial conditions, ridge effect

☆A part of this paper has been published in the Proceedings of the 40th International Symposium on Multiparticle Dynamics, 21-25 September 2010, University of Antwerp (Belgium) [1]

Preprint submitted to Elsevier *February 8, 2011*

1. Introduction

In hydrodynamic approach of nuclear collisions, it is assumed that, after a complex process involving microscopic collisions of nuclear constituents, at a certain early instant a hot and dense matter is formed, which would be in local thermal equilibrium. This state is characterized by some *initial conditions* (IC), usually parametrized as smooth distributions of thermodynamic quantities and four-velocity (see, for instance, [2, 3]). However, since our systems are small, *important event-by-event fluctuations* are expected in real collisions. Also, if the thermalization is verified at very early time, they should be *very bumpy*. In previous works, we introduced *fluctuating IC* in hydrodynamics [4, 5], by using NEXUS event generator [6], and showed important effects on several observables. In this paper, we briefly survey some of the previous results [4, 7, 8, 9] and then discuss more recent results on long-range two-particle correlations.

2. Some consequences of fluctuating initial conditions

In Figure 1, we show the energy-density distribution in a typical event of fluctuating IC, generated by NeXuS [6] for a central Au+Au collision at 200A GeV. Observe that the distribution is very bumpy, as expected in real collisions, having a tubular structure in η.

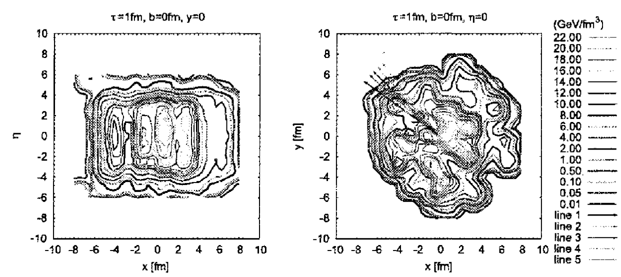

Figure 1: NEXUS Fluctuating Initial Conditions.

Some consequences of such high-energy-density spots have been discussed in [7]. Because of high concentration of energy in small regions, each tube would suffer a violent explosion, expanding isotropically (in transverse directions). If such a tube is at the surface of the matter, certainly the outgoing part of this matter would appear, producing high-p_T particles, which would be isotropically distributed in the momentum space. Thus, first we expect that high-p_T part of the p_T spectra is enhanced when fluctuating IC are used in our computations, in comparison with the results with averaged (smooth) IC. In the second place, we expect that the elliptic flow coefficient $< v_2 >$ suffers reduction as we go to high-p_T region, due to the additional high-p_T isotropic components included now. Here, we are talking about effects of hot spots and not of the fluctuation, which makes v_2 coefficient larger in more central windows because it makes the eccentricity bigger [10]. As for the η dependence of v_2, we know that the average matter density decreases as $|\eta|$ increases as reflected in the η distribution of charged particles, so when such a blob is formed in the large-$|\eta|$ regions, its effects appear more enhanced. Therefore, we expect considerable reduction of v_2 in those regions. All these features have explicitly been verified in [7]. Another effect of small high-energy-density spots in the IC is manifested in the smaller HBT radii, as compared with the case of the smooth averaged IC. [9]. This has been shown both by using the Cooper-Frye prescription [11], and by the continuous-emission one [12].

Besides the effects of high-energy-density spots, fluctuations of IC imply evidently fluctuations of the resulting observable quantities. Such fluctuations become quite large in the anisotropic-flow parameter v_2 [13, 8], as has been effectively verified by experiments [14, 15].

3. Two-particle correlations in hydrodynamic approach

One of the most striking results in relativistic heavy-ion collisions is the existence of structures in the two-particle correlations [16, 17, 18, 19, 20, 21] plotted as function of the pseudorapidity difference $\Delta\eta$ and the angular spacing $\Delta\phi$. The so-called ridge has a narrow $\Delta\phi$ located around zero and a long $\Delta\eta$ extent. The other structure located opposite to the trigger has a single or double hump in $\Delta\phi$; its $\Delta\eta$ extent is not well established. In an earlier work, [22], we presented evidence that hydrodynamic approach reproduces all such structures in heavy-ion collisions. In [22], the events computed by using the hydrodynamic code SPheRIO [5], starting from event-by-event fluctuating IC, generated by NeXus [6], were analyzed in a similar way to the experimental ones, in particular the ZYAM method was used to remove effects of elliptic flow. We later developed a different method to remove elliptic flow from our data and checked that all structures are indeed exhibited and other features well reproduced (dependence on the trigger- or associated-particle transverse momentum, centrality, in-plane/out-of-plane trigger, etc) [23, 24, 25, 26].

3.1. Mechanism of ridge formation - one-tube model

As seen in Fig. 1, each NEXUS IC is very complicated, so difficult to visualize how various structures in the two-particle correlations are generated. In order to clarify the origin of the ridge structures, we introduced in [23] a simplified model which would allow to follow closely the time development of the fluid in the vicinity of one of the high-energy-density tubes. Evidently, only those tubes located close to the surface of the hot matter can contribute to the correlations. Thus, in our simplified model, we replace the complex bulk of the hot matter by the average over many events, leaving just one typical tube close to the surface, like the one on the *line 1* of Fig. 1, right. To simplify the computation, the longitudinal expansion is assumed boost-invariant and the transverse expansion is computed numerically (see details in [23]).

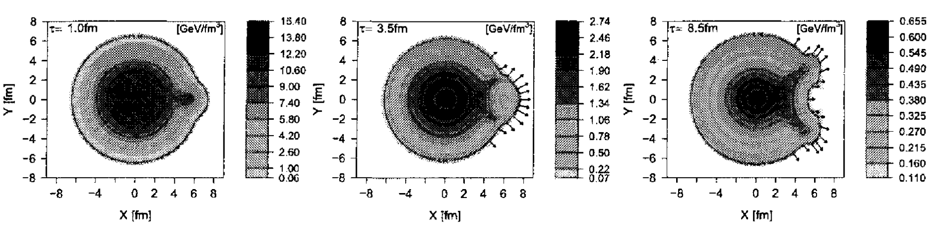

Figure 2: Temporal evolution of energy density for the one-tube model (times: 1.0, 3.5 and 8.5 fm). Arrows indicate fluid velocity on the freeze out surface, thicker curve labeled by the freeze out temperature 0.14 GeV

Figure 2 shows the temporal evolution of the hot matter in this model. As seen, pressed by the violent expansion of the high-energy-density tube, the otherwise isotropic radial flow of the background is deflected and guided into two well defined directions, symmetrical with respect to the initial tube position. Notice that the flow is clearly non-radial in these regions. The resultant single-particle angular distributions for two different p_T-intervals are plotted in Fig. 3, left. As expected they show symmetrical two-peak structures. From this plot, we can easily guess how the two-particle angular correlation will be. The trigger particle is more likely to be in one of the two peaks. We first choose the left-hand side peak. The associated particle is more likely to be also in this peak i.e. with $\Delta\phi = 0$ or in the right-hand side peak with $\Delta\phi \sim +2$. If we choose the trigger particle in the right-hand side peak, the associated particle is more likely to be also in this peak i.e. with $\Delta\phi = 0$ or in the left-hand side peak with $\Delta\phi \sim -2$. So the final two particle angular correlation must have a large central peak at $\Delta\phi = 0$ and two smaller peaks respectively at $\Delta\phi \sim \pm 2$. Figure 3 (right) shows that this is indeed the case. We have checked that this structure is robust by studying the effect of several parameters of the model [23].

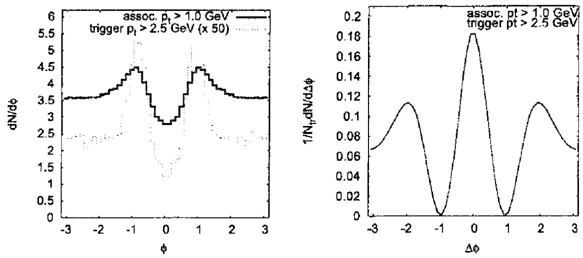

Figure 3: Angular distributions of particles in some different p_T intervals (left) and resulting two-particle correlations (right), in the one-tube model.

As stressed above, the *one-tube boost-invariant model* has been introduced just to clarify the mechanism of ridge-structure formation. However, it is remarkable that this simple model can describe well so many characteristics observed in experiments. For a more realistic simulation, we should consider more complex events such as NeXus events and average over the fluctuations. For an event like the one shown in Fig. 1, only the outer tubes need to be considered. The shape of the two-particle correlations for a single tube (in particular the peak spacing) is relatively independent of its features so the various tubes will contribute with rather similar two-peaks emission pattern at various angles in the single-particle angular distribution. For this single event, the two-particle correlation has a well-defined main structure similar to that of a single tube (Fig. 3) surrounded by several other peaks and depressions due to trigger and associated particles coming from different tubes. When averaged over many randomly fluctuating events these interference terms disappear and only the main one-tube like structure is left. The main advantage of this interpretation of ridge structures is that it involves essentially only the surface of the hot matter. The complexity of the kernel does not influence.

3.2. In-plane/out-of-plane effect

Data have been obtained of two-particle correlation in non-central (20-60% centrality) Au+Au collisions at 200 *A* GeV, fixing the azimuthal angle (ϕ_S) of the trigger particle [27]. As seen in Fig. [4], what is remarkable in these data is the change of the away-side structure from a single-hump one to a double-hump one as ϕ_S goes from 0^o (in-plane) to 90 (out-of-plane) with respect to the event plane. This behavior is more clearly seen in higher-p_T data. We have already discussed this kind of correlation in some previous publications [23, 24]. Here, we present a more quantitative comparison with data.

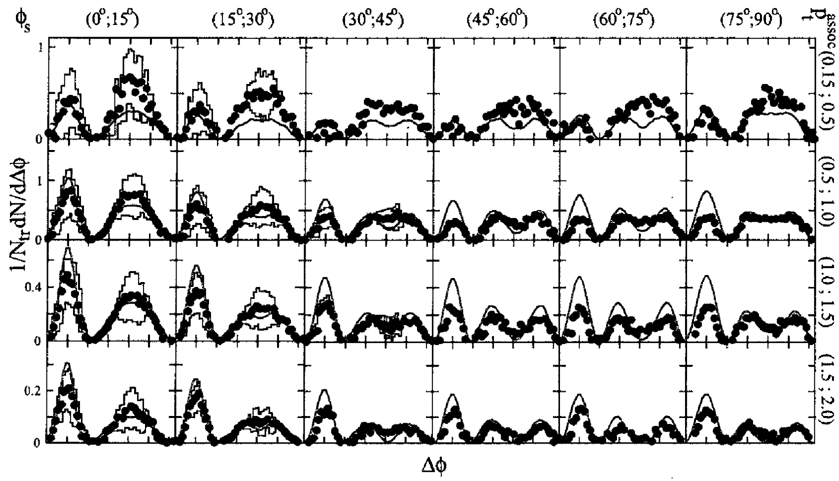

Figure 4: Results of in-plane/out-of-plane effect computed with NeXSPheRIO (solid curve), for 20-60% centrality Au+Au collisions at 200A GeV. The data points are from STAR Collab. [27] with $3 < p_T^{trigg} < 4$ GeV. Histograms and dashed lines are the systematic uncertainties quoted there.

This behavior can be understood also in our one-tube model. However, in this case, we have to replace the symmetrical background of Fig. 2 with an elliptical one as shown in Fig. 5, left. Computing the single-particle angular distributions for different tube position, we see that when ϕ_{tube} approaches 90^o, the elliptic flow is enhanced as shown in Fig. 5, middle, because of the additional increase in the assymmetry caused by the high-energy tube. This excess of back-to-back correlation, as compared with the average, is the origin of one-peak structure in the awayside for the case of in-plane triggers. Such a kind of effect does not exist for the out-of-plane triggers.

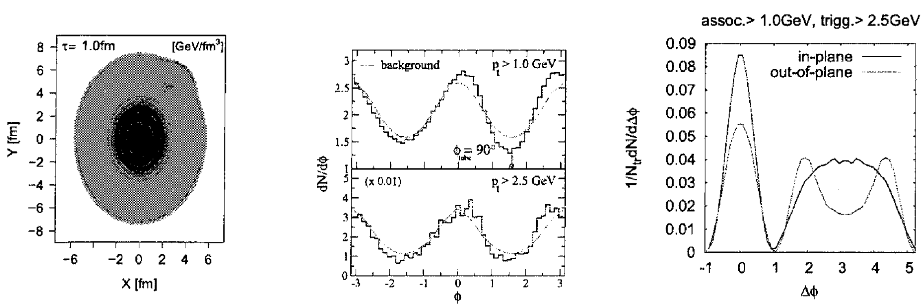

Figure 5: Left: One-tube model for non-central (20-60%) collisions. Middle: Single-particle angular distributions for two different p_T intervals, with $\phi_{tube} = 90^o$ (histograms). The solid curves represent the ones averaged over the tube position ϕ_{tube}. Right: Two-particle correlations, computed with one-tube model, integrated over the tube position for the in-plane (red/grey line) and out-of-plane (blue/black) triggers.

See more details on the in-plane/out-of-plane effect within one-tube model, in the contribution by R. Andrade to the ISMD2010 Proceedings [28].

4. Conclusions

Hydrodynamic approach starting from e-b-e fluctuating initial conditions, with high-energy-density tubes, has shown to reproduce several features of experimentally observed quantities. With regard to the long-range two-particle correlations, it gives a *unified* picture for the nearside and awayside structures as observed experimentally. A high-density tube located close to the surface of the hot matter divides the flow coming from inside into two currents, producing two-peak angular distribution. This two-peak distribution is the origin of both the nearside and the awayside ridges. In non-central collisions ($20 \sim 60\%$ centralities), tubes close to 90^o with respect to the event plane enhance the elliptic flow, producing additional back-to-back correlations with the in-plane triggers ($\phi_S \sim 0^o$). Such an effect does not exist in the case of out-of-plane triggers ($\phi_S \sim 90^o$).

5. Acknowledgments

We acknowledge funding from FAPESP and CNPq.

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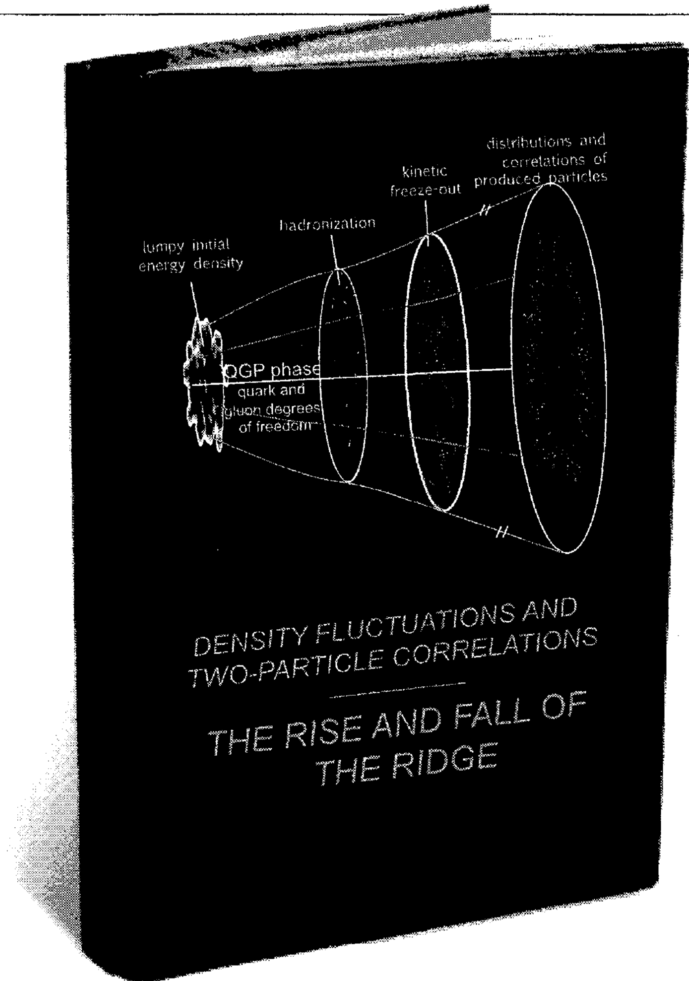


The Rise and Fall of the Ridge in Heavy Ion Collisions

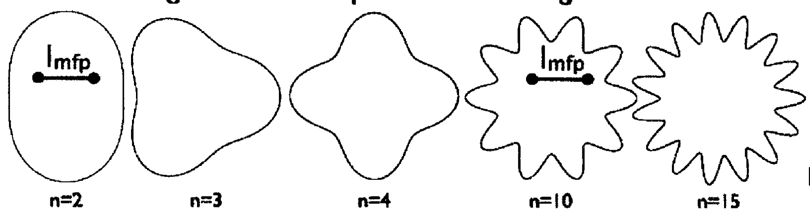
Based on arxiv:1102.1403

Paul Sorensen

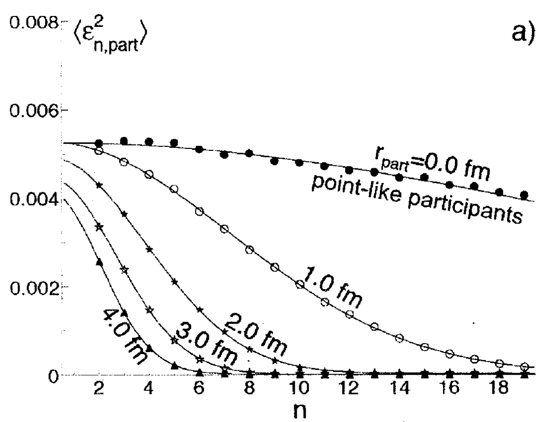
I show how the fluctuations in initial eccentricity can explain the centrality dependence of two-particle correlations. The success of this picture in describing the ridge yield vs centrality in detail demonstrates that the ridge is dominated by density fluctuations in the initial overlap region which are long-range in rapidity, consistent with glasma flux-tubes for example.

Why Are Higher Harmonics Interesting?

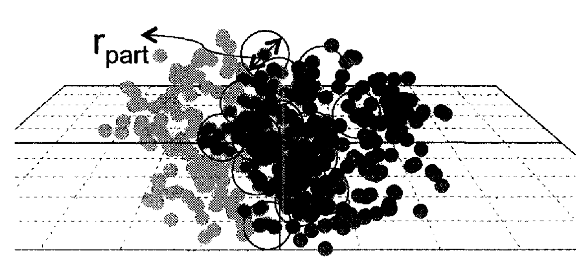
Higher harmonics probes smaller length-scales.



Á. Mócsy
Hard Probes 2010



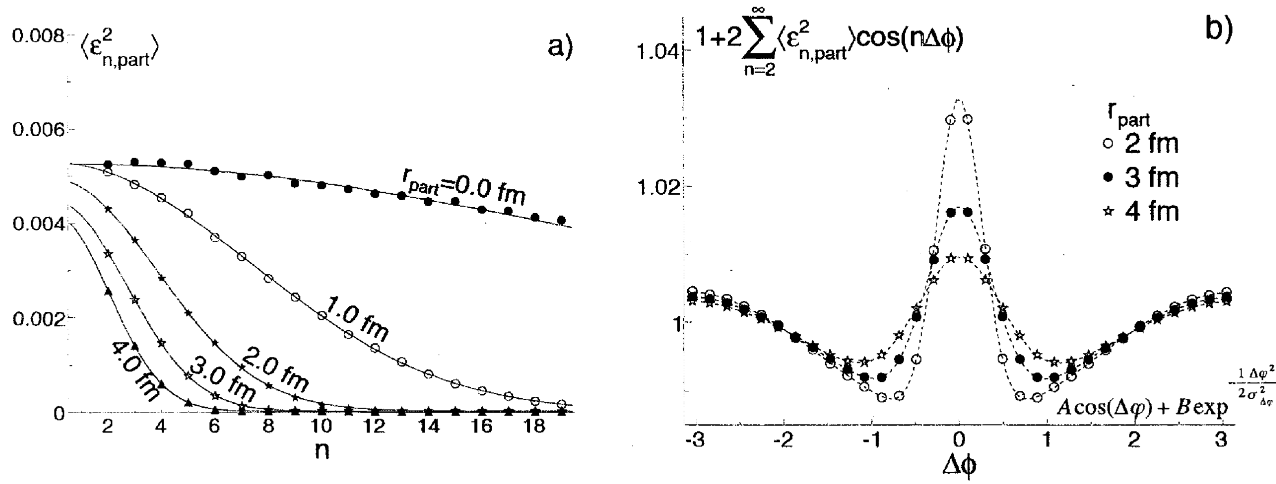
Monte Carlo Glauber



Geometry fluctuations yield $\langle \varepsilon^2_{n,part} \rangle > 0$ for even and odd harmonics

ε_{part} drops faster with n as the participants are smeared out more: drop is described well by Gaussian curves

Converted Into Correlations



Gaussian shape of $\langle \varepsilon^2_{n,part} \rangle$ should give rise to Gaussian vs $\Delta\varphi$

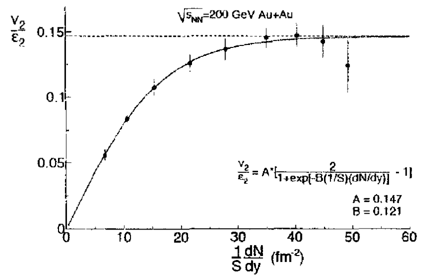
Shift to center of mass $\langle x \rangle = \langle y \rangle = 0$ means $\langle \varepsilon_{1,part} \rangle = 0$. This leads to a negative $\cos(\Delta\varphi)$ term

$-\cos(\Delta\varphi)$ term should have the same centrality dependence as the near-side peak (as seen in data)

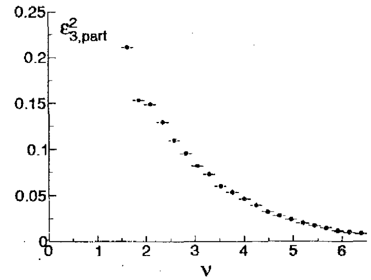
Predicting the 'Minijet' A_1 from Fluctuations

Are correlations really dominated by the initial lumpiness?

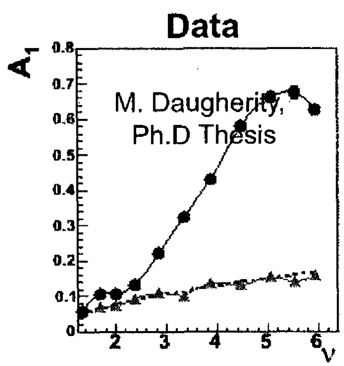
1) take conversion efficiency from $c=(v_2/\varepsilon_2)^2$

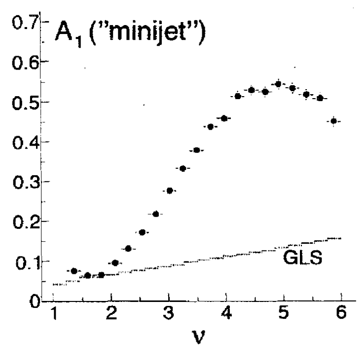


2) take initial eccentricity from Monte-Carlo Glauber



3) convert <cos(3Δφ)> into equivalent Gaussian Amplitude

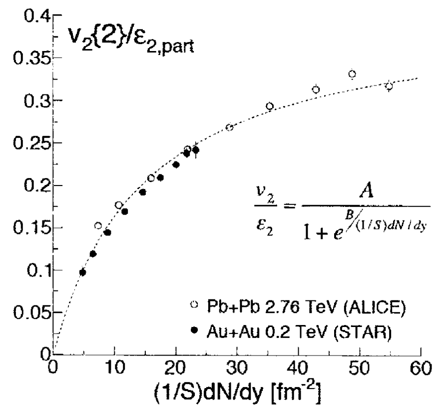




prediction for "minijet" amplitude from density fluctuations

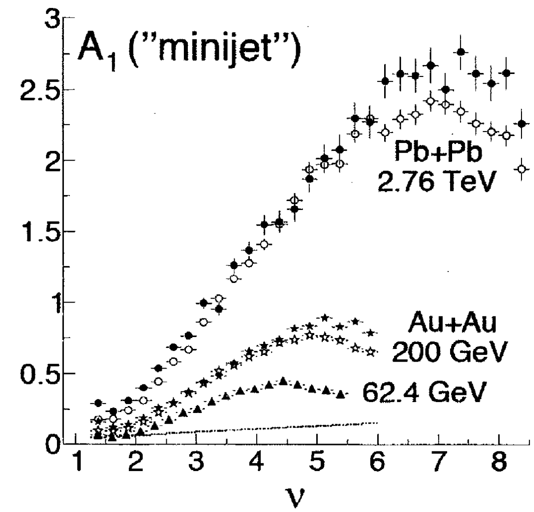
$$A_1 = \rho_0 c \varepsilon^2_{part,3} / 0.039$$

LHC Predictions: Results



ALICE: Phys. Rev. Lett. 105, 252302 (2010)
STAR: Phys. Rev. C 72, 014904 (2005)

Fit function from Knudsen number analysis
Drescher, et. al. Phys. Rev. C 76:024905, 2007
A=0.412, B=15.2



A_1 (ridge amplitude) will be much larger at the LHC: *driven by multiplicity and flow*

"Rise and fall of the ridge will be present at all energies: *it's a feature of the nuclear geometry*

Conclusions

Several pieces of evidence now demonstrate that the low p_T ridge comes from initial geometry

- The amplitude of the "minijet" peak can be predicted from participant eccentricity
- The correspondence of the near-side amplitude and the away-side –cos term can be explained
- Narrowing in azimuth explained by flow

Predictions provided for LHC as a check of this explanation

$v_n\{2\}^2/\varepsilon^2_{part,n}$ is an observable rich in information about the system created in heavy-ion collisions (*eg.* mean-free-path)

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Event-by-event Hydrodynamic Description of Anisotropic Flow and Correlations at RHIC and LHC

I present results for the elliptic and triangular flow coefficients in Au+Au collisions at $\sqrt{s} = 200\ \mathrm{AGeV}$ and $\sqrt{s} = 2.76\ \mathrm{ATeV}$ using event-by-event (3+1)D viscous hydrodynamic simulations. I study the effect of initial state fluctuations and finite viscosities on the flow coefficients v_2 and v_3 as functions of transverse momentum and pseudo-rapidity. Fluctuations are essential to reproduce the measured centrality dependence of elliptic flow. I also present first results on final state $\Delta\eta - \Delta\phi$ correlations from D=3+1 viscous hydrodynamic simulations. Using initial "hot tubes" leads to a ridge and double bump structure on the away-side after subtracting the elliptic flow contribution.

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MUSIC

MUScl for Ion Collisions:

B. Schenke, S. Jeon, and C. Gale Phys. Rev. **C82**, 014903 (2010), arXiv:1004.1408

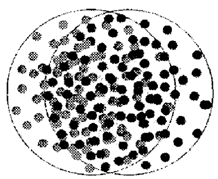
MUSCL = Monotonic Upstream Centered Scheme for Conservation Laws

- 3+1 dimensions and $\tau - \eta$ coordinates
- Finite shear viscosity (2^{nd} order Israel Stewart) and ideal
- Event-by-event!
- Kurganov Tadmor algorithm.
  (Low numerical viscosity, good for large gradients)
- Cooper-Frye freeze-out
  with sophisticated freeze-out surface construction
- Includes different equations of state including the latest from Huovinen and Petreczky (Lattice-QCD)
  P. Huovinen and P. Petreczky, Nucl. Phys. **A837**, 26-53 (2010)

Event-by-event!

Initialization:

- Sample Woods-Saxon distributions
  to determine all nucleon positions
- Overlap those distributions using impact parameter b



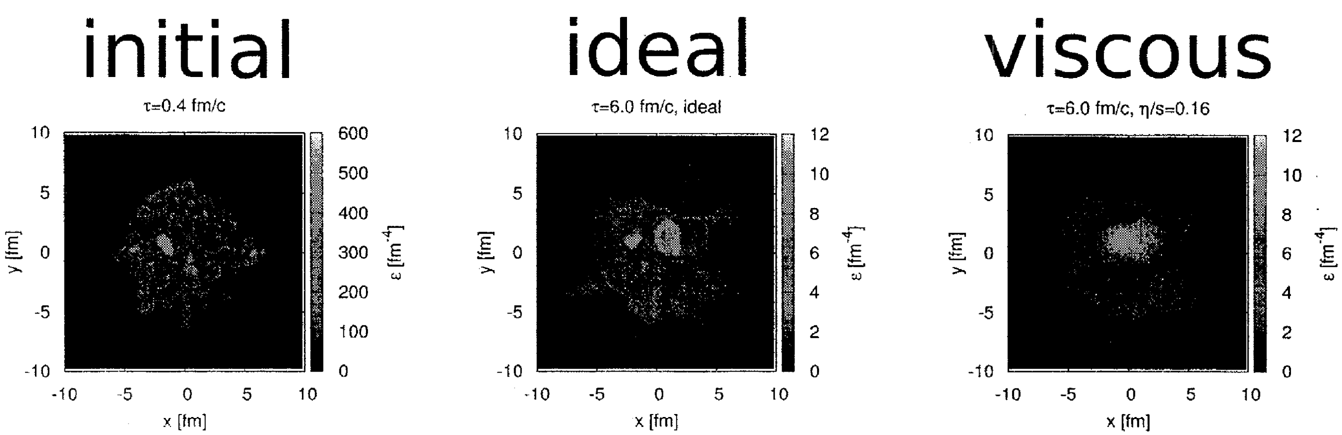
b is sampled from $P(b)db = 2bdb/(b_{\mathrm{max}}^2 - b_{\mathrm{min}}^2)$

- Nucleon-nucleon collision occurs if distance is $< \sqrt{\sigma_{NN}/\pi}$
- At position of collision add 2D-Gaussian energy density distribution with width σ_0.
  For now we use $\sigma_0 = 0.4\,\mathrm{fm}$.
  Assume elongated hot spots in rapidity, "hot tubes".

Viscosity in event-by-event simulations

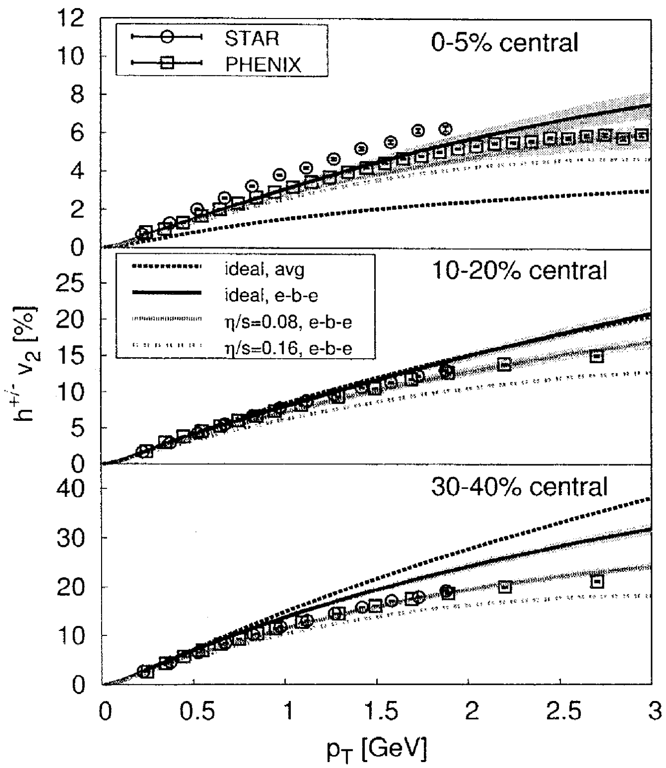
We can see the effect of viscosity in event-by-event simulations!

B. Schenke, S. Jeon, and C. Gale, Phys. Rev. Lett. 106, 042301 (2011)



beam direction ⊗ ⊙

Flow results from e-b-e viscous MUSIC



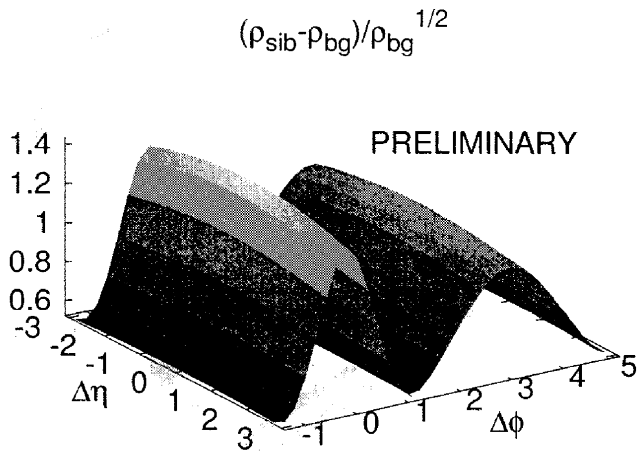
B. Schenke, S. Jeon, and C. Gale, PRL 106, 042301 (2011)

- event-by-event fluctuations important!
  (average initial conditions give wrong centrality dependence)
- Viscosity is **very low**.
  The lower bound of viscosity/entropy density conjectured from AdS/CFT duality is
  $\eta/s = 1/4\pi \approx 0.08$

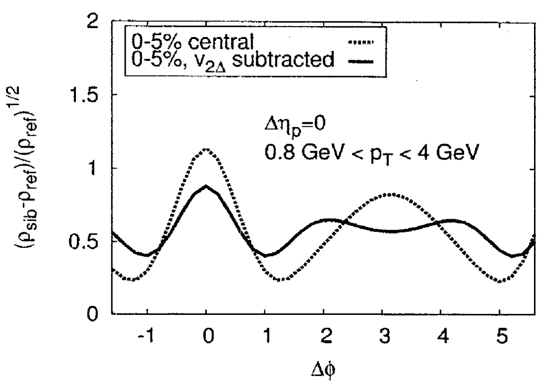
Experimental data: J. Adams et al. (STAR), Phys.Rev.C72, 014904 (2005)
A. Adare et al. (PHENIX), Phys.Rev.Lett.105, 062301 (2010)

Correlations

Untriggered $\Delta\eta - \Delta\phi$ correlations from viscous hydro.



Fourier decomposition, subtract the elliptic flow component:



Hot spots, harmonic flow, dihadron and γ-hadron correlations in high-energy heavy-ion collisions

Guo-Liang Ma

Shanghai Institute of Applied Physics,
Chinese Academy of Sciences

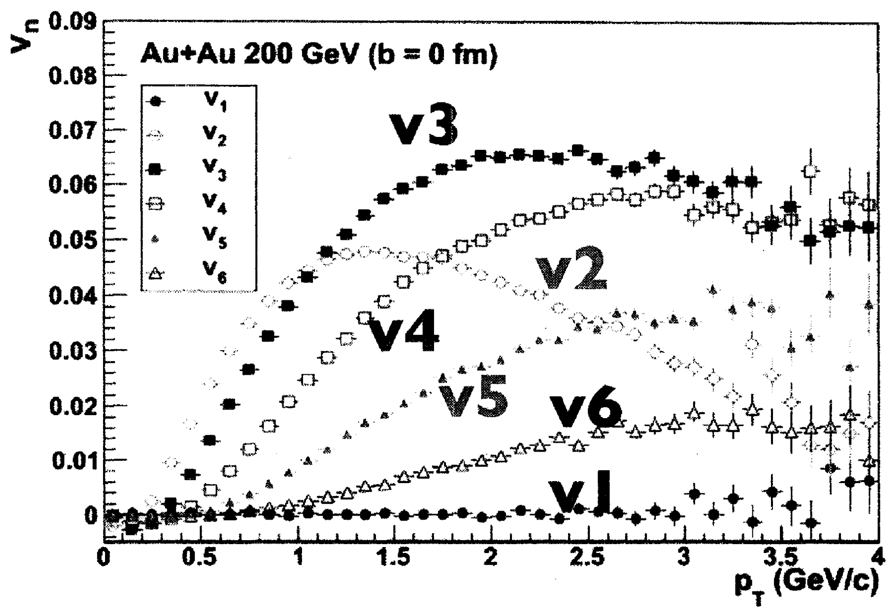
Abstract: Collective expansion due to parton rescattering will translate the initial geometric irregularities into harmonic flow in momentum space. The harmonic flows significantly enhance double-peak structure for di-hadron correlation. The current measured di-hadron correlation should consists of to three main parts: harmonic flow background, hot spots and jet-medium interaction. Hot spots look like tubes, which generate ridge-like structure longitudinally in Au+Au collision at RHIC energy. γ-hadron correlation is weaker than di-hadron correlation for double-peak structure, which is proposed as a golden probe to study jet-medium interaction because of zero flow for γ.

This work is in collaboration with Hanlin Li, Fuming Liu, Xin-Nian Wang and Yan Zhu, based on arXiv: 1006.2893 and 1011.5249.

RBRC Workshop, BNL, Feb. 2-4, 2011

SINAP 中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

different flow components as function of p_T



$$\psi_2 = \frac{\mathrm{atan2}(\langle r^2 \sin(2\phi_{part})\rangle, \langle r^2 \cos(2\phi_{part})\rangle) + \pi}{2}$$

$$v_2 = \langle \cos(2(\phi - \psi_2))\rangle.$$

$$\psi_3 = \frac{\mathrm{atan2}(\langle r^2 \sin(3\phi_{part})\rangle, \langle r^2 \cos(3\phi_{part})\rangle) + \pi}{3}.$$

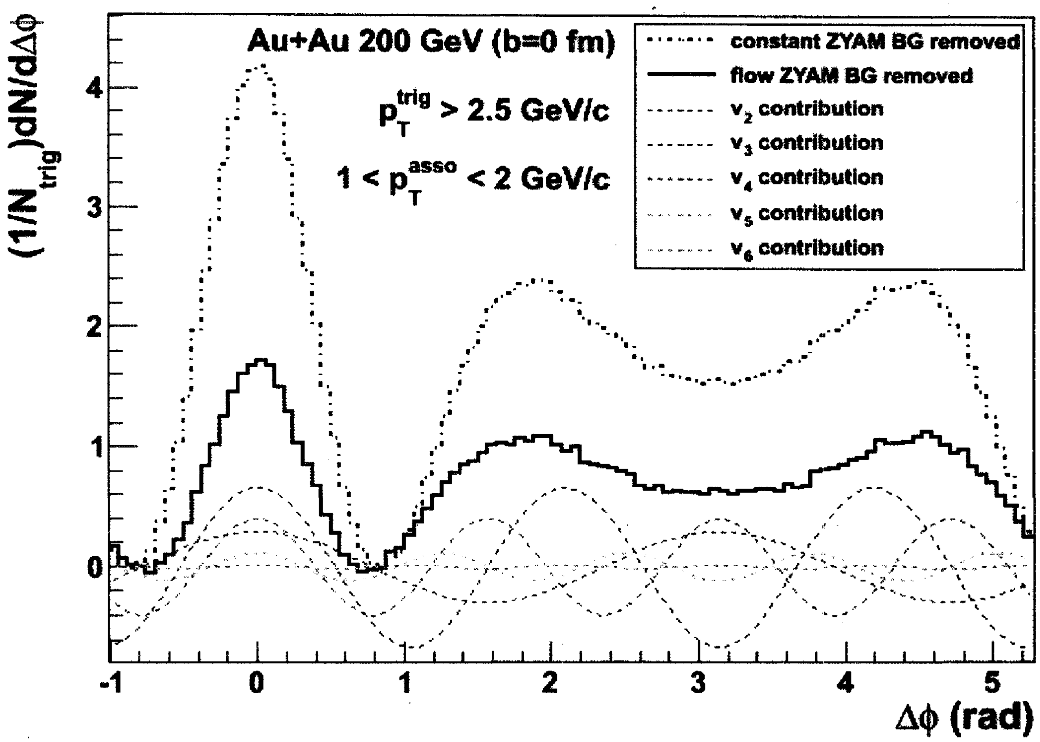
$$v_3 \equiv \langle \cos(3(\phi - \psi_3))\rangle,$$

$$\vdots$$

Note: ψ_2 and ψ_3 is the minor axis of participant eccentricity and triangularity, instead of reaction plane axis, which makes v2 and v3 nonzero even for b=0 fm Au+Au collisions.

•The initial geometry asymmetry induces elliptic and triangular flow etc., even for most central Au+Au collisions (b=0fm).

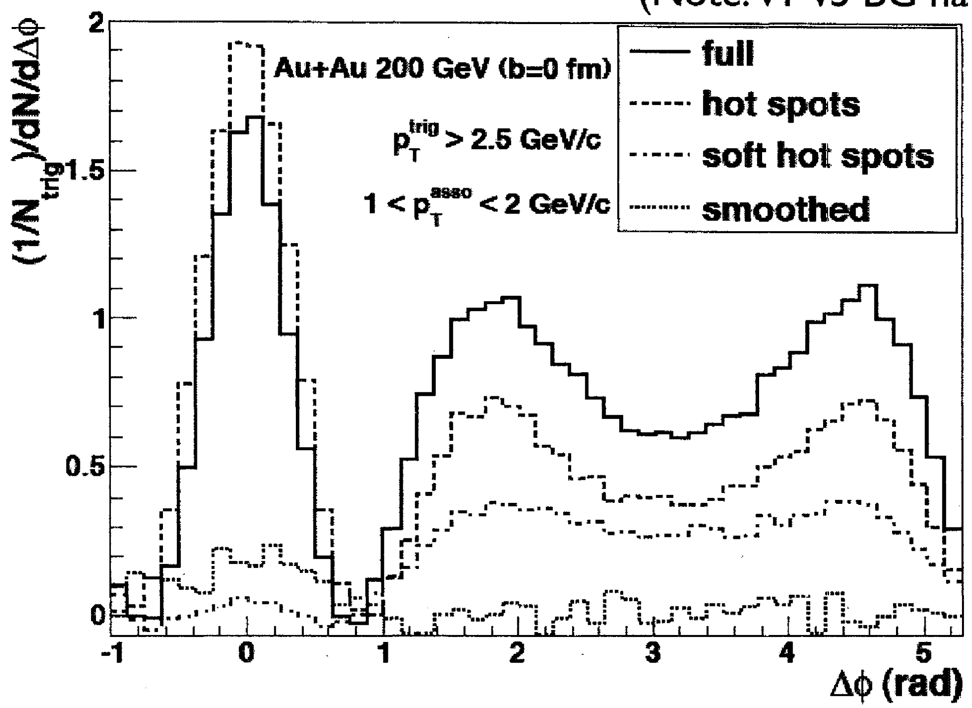
di-hadron correlation and flow v_n BG (n=2,3,4...)



- v_n BG significantly affects the shape and magnitude of di-hadron correlation.

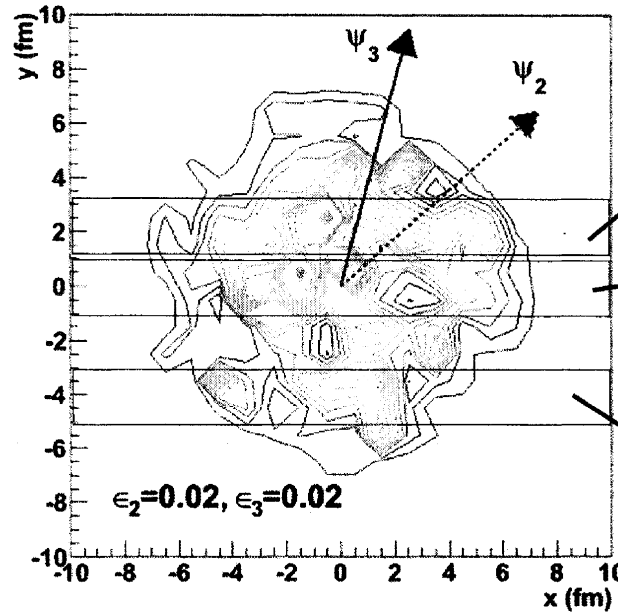
di-hadron correlations in different mechanisms

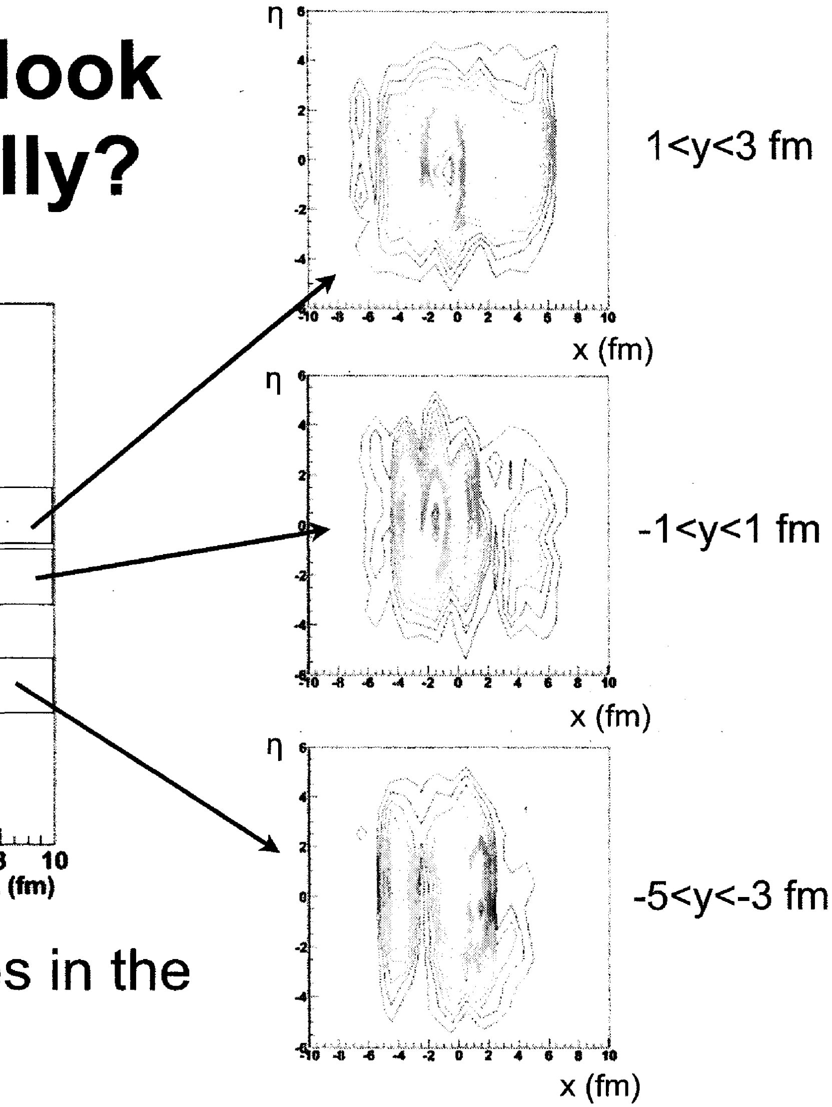
(Note: v1-v5 BG have been removed)



- Hot spots can form a double hump on away side, but the magnitude is less than that of full jet by about 40%.
- Soft hot spots, which consist of soft partons from strings, present a weak double hump.
- The dihadron correlation from smoothed initial condition becomes almost flat.
- It is difficult to extract dihadron correlation from dijets (and jet-induced medium excitation) alone.

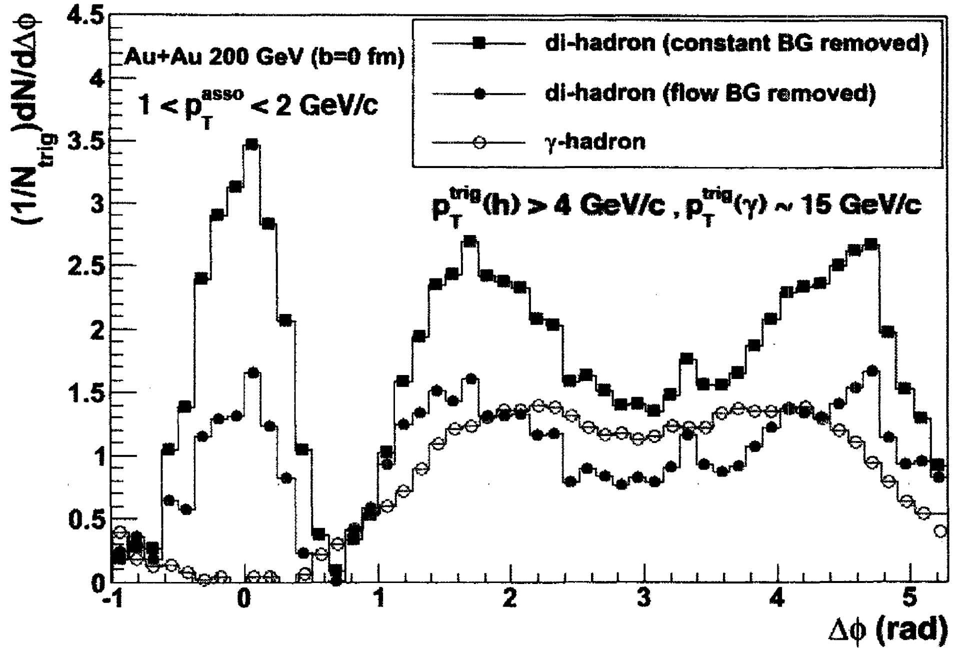
What hot spots look like longitudinally?





•Hot spots look like tubes in the longitudinal direction.

dihadron and γ-hadron



•Di-hadron correlation (full) becomes less but still different from γ-hadron correlation after removing v_n flow BG.

The near-side long range correlation structure in two particle number correlations at RHIC

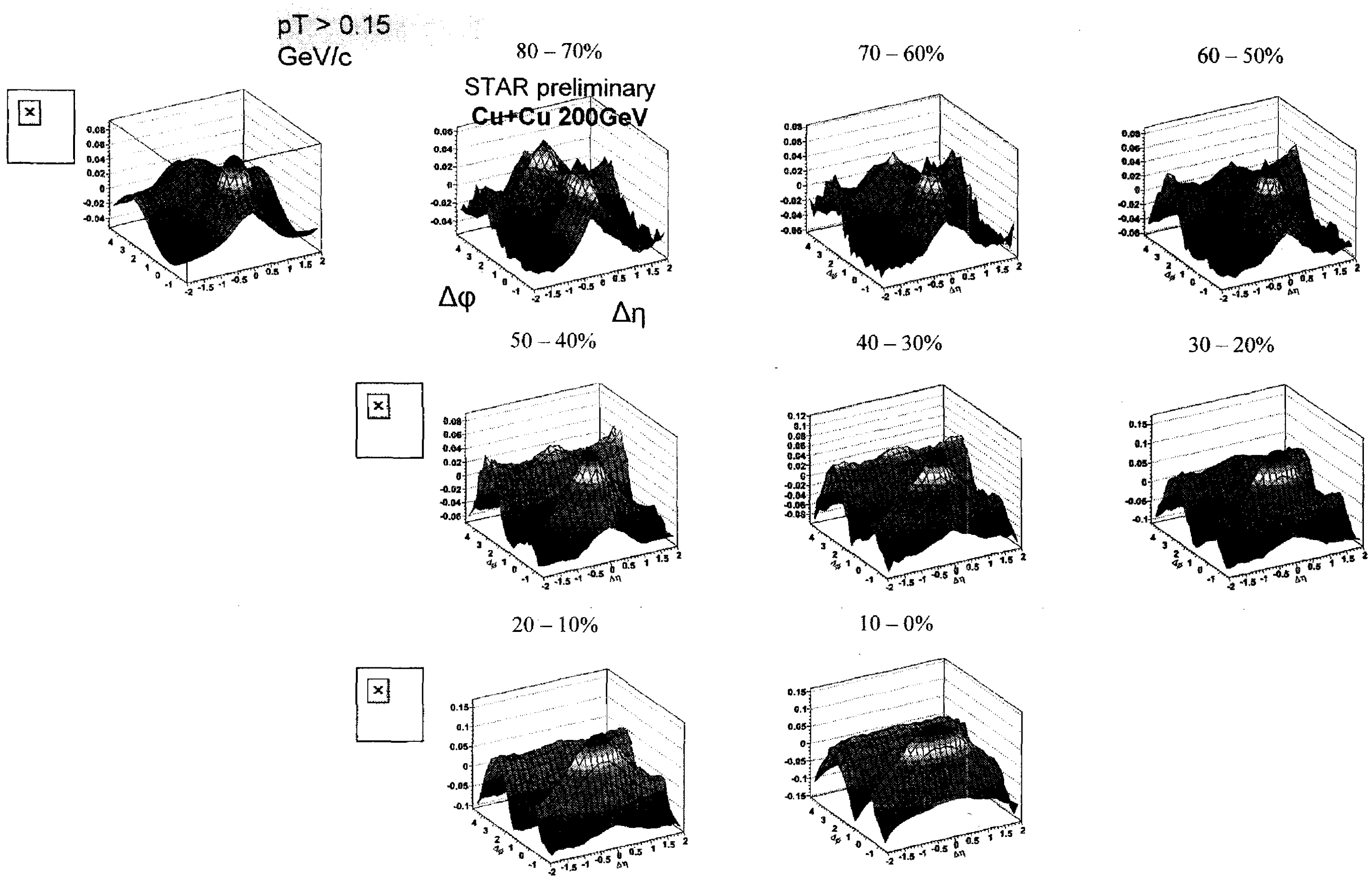
L. C. De Silva

for the STAR collaboration

University of Houston

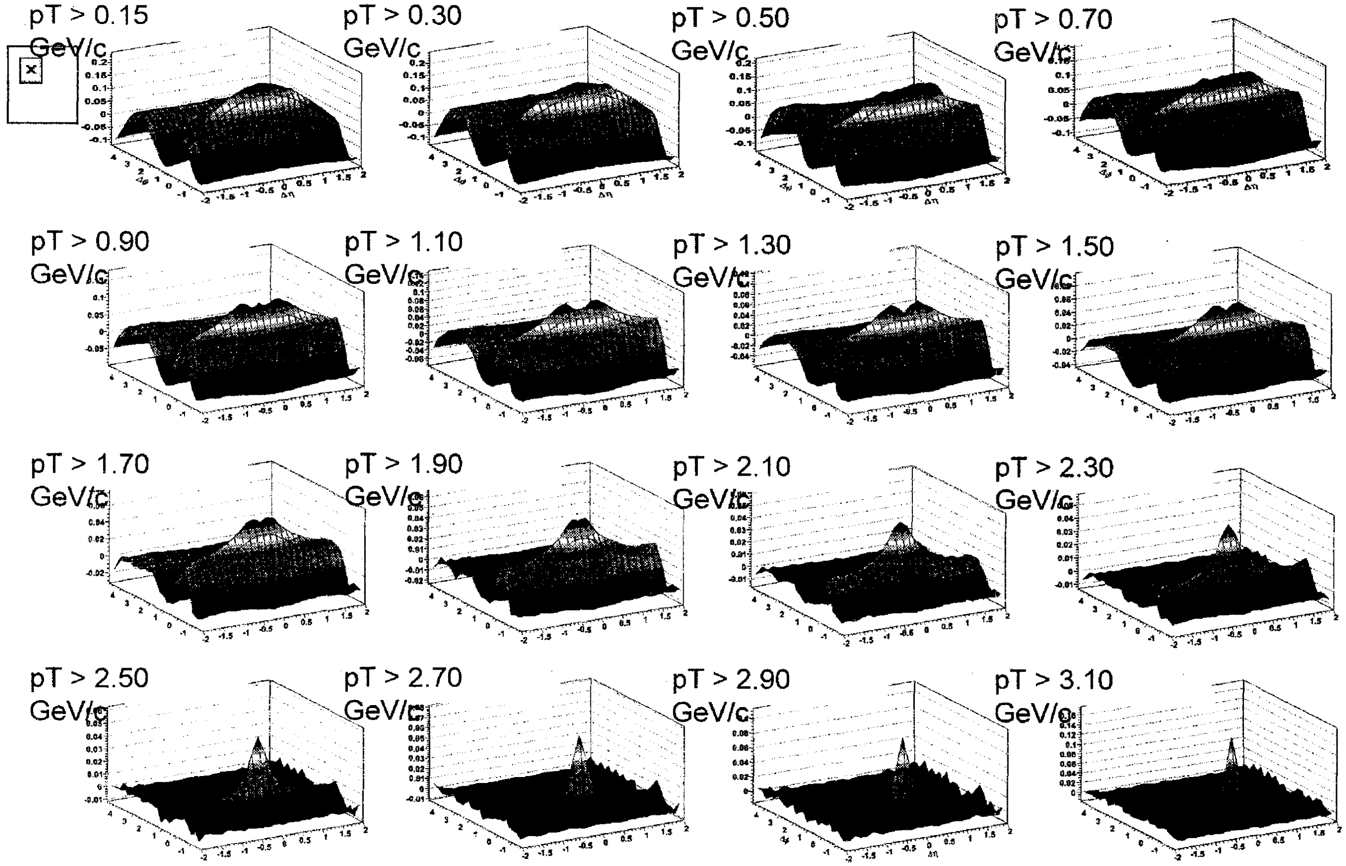
- Motivation of study
  - Triggered and un-triggered data in 200GeV Au+Au collisions
- Data and cuts
- Correlation measure
- Centrality dependent evolution
- Momentum dependent evolution
- Fit function and alterations
- Comparison to theory
- Summary

Untriggered correlation plots – centrality evolution



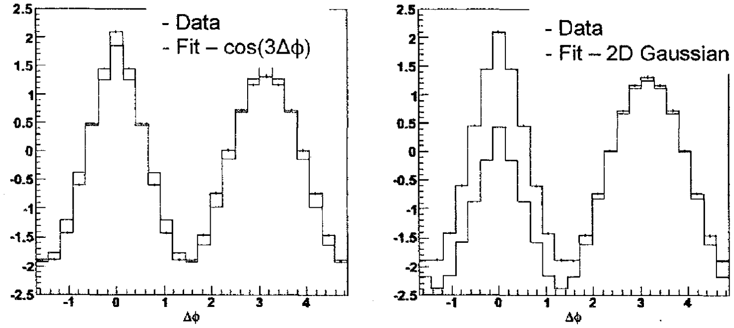
STAR preliminary

Au+Au 200GeV : 0–10%



- Disappearance of long range correlation ("ridge") at high pT
- Emergence of "Jet" like (unmodified jet?) at high pT

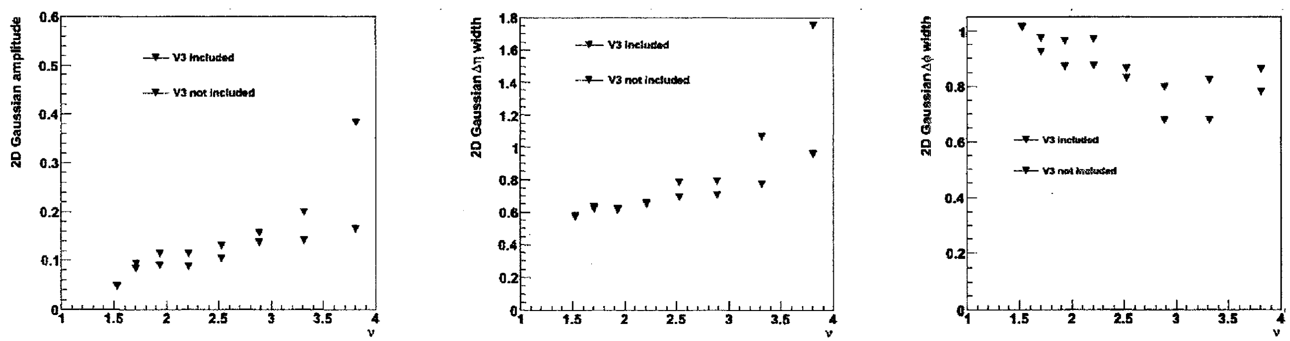
Do we need v_3 to describe the same side structure



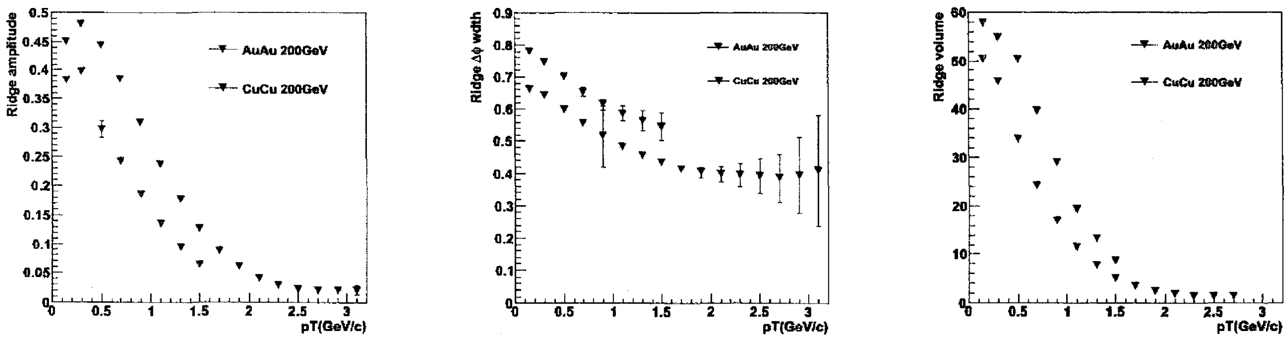
[redacted]

STAR preliminary
Cu+Cu 200GeV

- The projections indicate that the v_3 contribution to the long range correlation on the same side is relatively small compared to a 2D Gaussian
- Furthermore the centrality dependence indicate that the v_3 contribution is less relevant in more peripheral bins
- The sharp amplitude and $\Delta\eta$ width evolution follow a smoother evolution when v_3 taken in to account



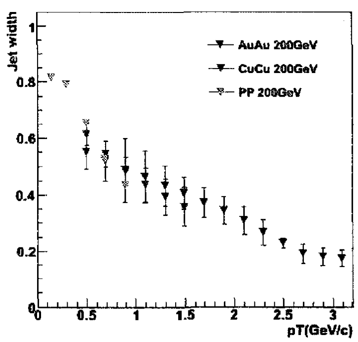
Asymmetric 2D Gaussian momentum dependence



STAR preliminary
Au+Au 200GeV

- Both systems follow similar trends
- Au+Au 200GeV data show that the “ridge” yield approaches zero at high pT

Symmetric 2D Gaussian momentum dependence



- Extracted width indicates that the observed “jet” like peak could be in fact an unmodified jet peak

- Further studies are required (amplitude, volume and efficiency corrections) to draw any conclusions

Summary and conclusions

- Centrality dependence
  - Determined a complex fit function to account for all the contribution to the two particle correlation structure (Triggered + untriggered, same side and away side)
  - Tested the applicability of a v_3 term to describe the $\Delta\eta$ elongated correlation structure on the same side ("ridge")
  - v_3 contribution on the long range structure is relatively small, an asymmetric 2D Gaussian alone can describe the same side structure within STAR acceptance
  - Little evidence on away side for a v_3 term (no double hump structure in residuals)
  - CGC + radial flow model which yield an asymmetric 2D Gaussian describes the data in terms of amplitude and $\Delta\phi$ width
  - The inclusion of a v_3 leads to a non zero v_2 term in central collisions
- Momentum dependence
  - We observe the emergence of a symmetric jet like peak (unmodified?) on the same side
  - The relative jet yield gets much larger compared to the ridge at high pT – long range correlation amplitude drops by an order of magnitude
  - In the CGC + radial flow picture the jet-bulk correlation contribution seems to be small (mostly jet-jet and bulk-bulk correlations)

Conical correlations phenomenology

Giorgio Torrieri[a], Barbara Betz[b], Miklos Gyulassy[b]

[a] FIAS, JW Goethe Universitat, Frankfurt, Germany

[b] Physics department, Columbia University, New York

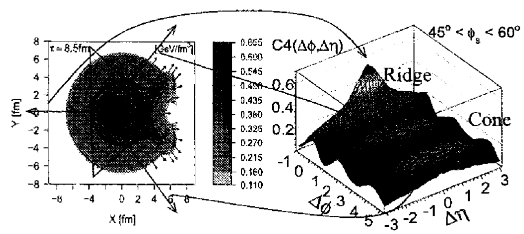
After motivating the study of hard-soft correlations in terms of Mach cones, we give an overview of other physical processes capable of producing such correlations. We then attempt to devise experimental observables capable of distinguishing between these scenarios

Experiment:If we lower trigger, away-side peak reappears and it looks like a Mach cone!But...

- Hydrodynamics, even perfect hydrodynamics, is not enough to get a Mach cone. "Textbook" Mach-cone an unrealistic semplification
  - Collective flow
  - Energy deposition
  - Non-linear corrections
  - Freeze-out

- Alternative explanations do exist
  - Fluctuations of the jets
  - Fluctuations of the background focused by transverse flow
  - Freezeout

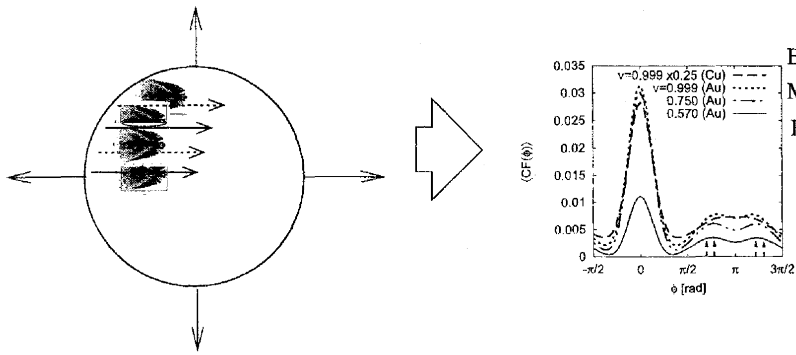
Hotspots can be parametrized as triangular flow B.Alver,G.Roland



Ridges and cones in this scenario come from "fake" jets!

- No heavy quark correlations
- No dijet correlations (trigger bias?
- Correlations disappear if trigger p_T increased (trigger bias?)

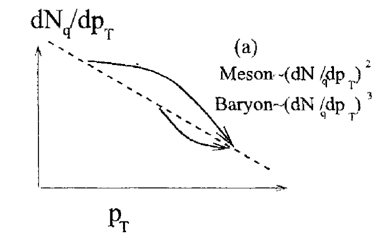
Barbara Betz, Jorge Noronha, GT , Miklos Gyulassy, Dirk H. Rischke, Phys.Rev.Lett.105:222301,2010.
Sum over jet paths can generate conical signal where there was none

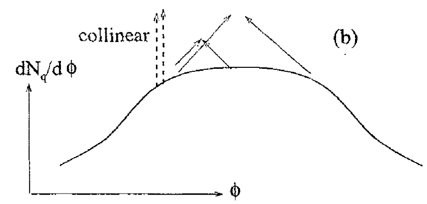


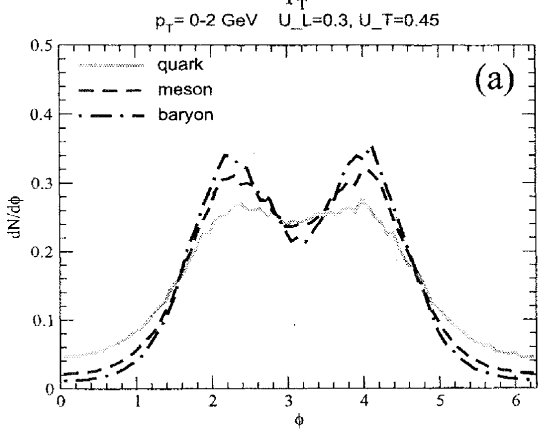
B Betz, J Noronha, GT
M Gyulassy, D Rischke
PRL105:222301

But cone nevertheless fake: Mach's law is NOT obeyed. A "subsonic" heavy quark jet also generates a cone

Coalescence can also generate conical signal where there was none

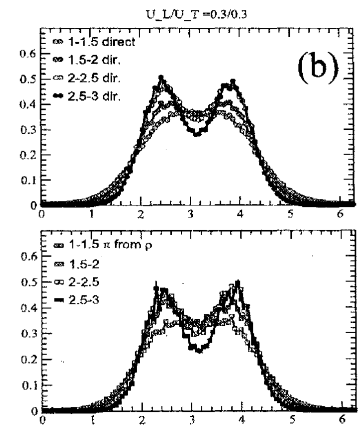






Coalescence
vs
Resonance
decay

direct pions
vs
$\rho \longrightarrow \pi\pi$



G.Torrieri
V.Greco
NPA830:785
arXiv:0909.3366

A "phenomenological" summary table

Signature	Real Mach	Flow fluct	Jet fluct	reco
Heavy quarks	O	×	O	O
Mach's law	O	×	×	×
Dijets	Trigger Bias?	×	O	×
p_T^{high}	Trigger Bias?	×	O	×
Meson/Baryon	×	×	×	O
3-particles	O	O	×	×
Mach cones, $v_{heaby\ \ quark\ \ jet} \leq c_s$	×	O	O	O

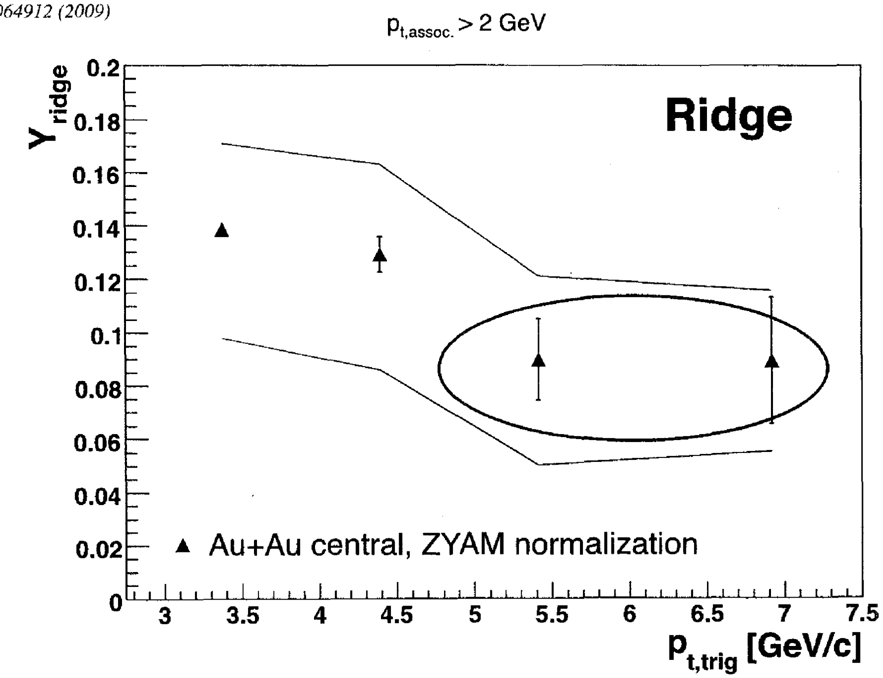
Joern Putschke (Yale University)

The “high-p_T” ridge at RHIC

A summary of measurements concerning the high-p_T ridge at RHIC were presented with an emphasis on the possible connection of the ridge properties with pQCD jet properties. 2+1 triggered correlation studies imply that if one selects a high-p_T “di-jet” neither ridge nor mach-cone like effects are measured on the near- and the away-side. Collision energy dependent ridge measurements (62 vs. 200 GeV) revealed that the ridge to jet ratio seems to be independent on energy. The reduced jet-like yield at 62 GeV is explained in terms of jet kinematics. Furthermore the ridge yield as function of collision energy seems to scale with R_{AA}. Overall the combination of system-size and collision energy dependent ridge measurements should be able to constrain further the origin of the ridge phenomena.

Ridge yield vs. $p_{t,trig}$ in Au+Au

STAR Phys. Rev. C80:064912 (2009)



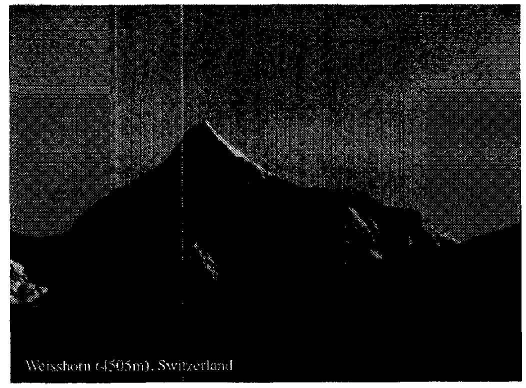
66

Ridge yield persists to highest trigger p_t ⇒ correlated to jet production

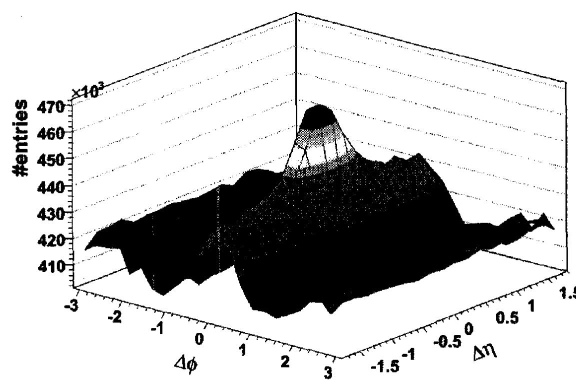
Ridge only in Au+Au (not present in p+p or d+Au or peripheral Au+Au)

Ridge characteristics

- ridge approx. independent on $\Delta\eta$
- ridge persists up to highest trigger p_t
  $\Rightarrow$ correlated to jet production
- ridge spectrum ~ "bulk-like"
- ridge energy roughly a few GeV (not shown)
- no significant PID trigger dependence (not shown)
- B/M (p/π, Λ/K^0_S) ratio in ridge ~ inclusive B/M ratio
- jet di-hadron fragmentation function
  after subtracting the ridge contributions
  comparable to d+Au



STAR Au+Au 0-10%, RHIC, US (~0m)



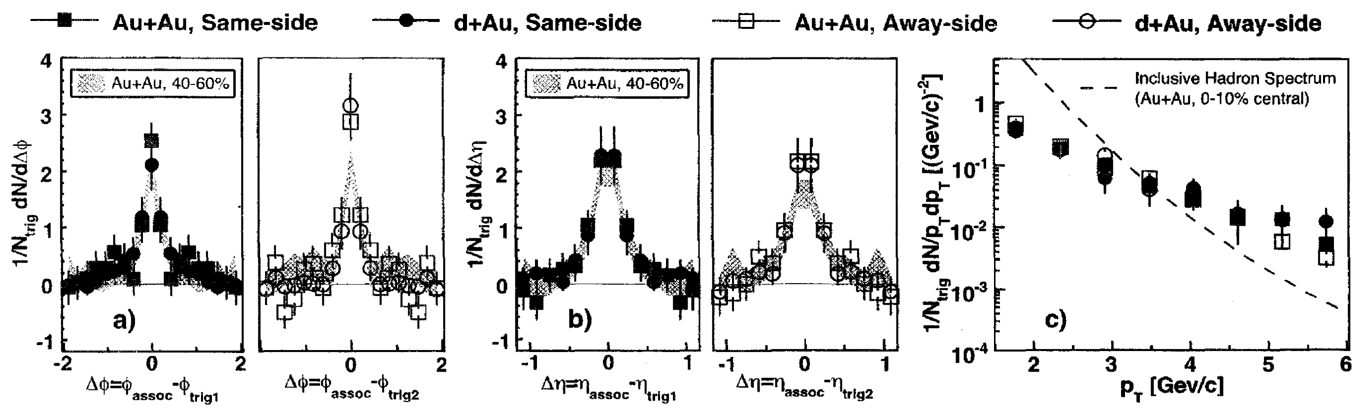
<u>**Interesting from the high-p_T point of view:**</u>

Are we seeing vacuum fragmentation after energy loss on the near-side in central Au+Au collisions with the lost energy deposited in the ridge ?

Di-jet (2+1) correlations in Au+Au

STAR to be published (2011)

T1: p_T>5GeV/*c*   T2: p_T>4GeV/*c*   A: p_T>1.5GeV/*c*



Di-jet measurements suggest that neither the widths in $\Delta\eta$ and $\Delta\phi$ (ridge/mach cone) are modified nor the yields are suppressed and comparable to d+Au

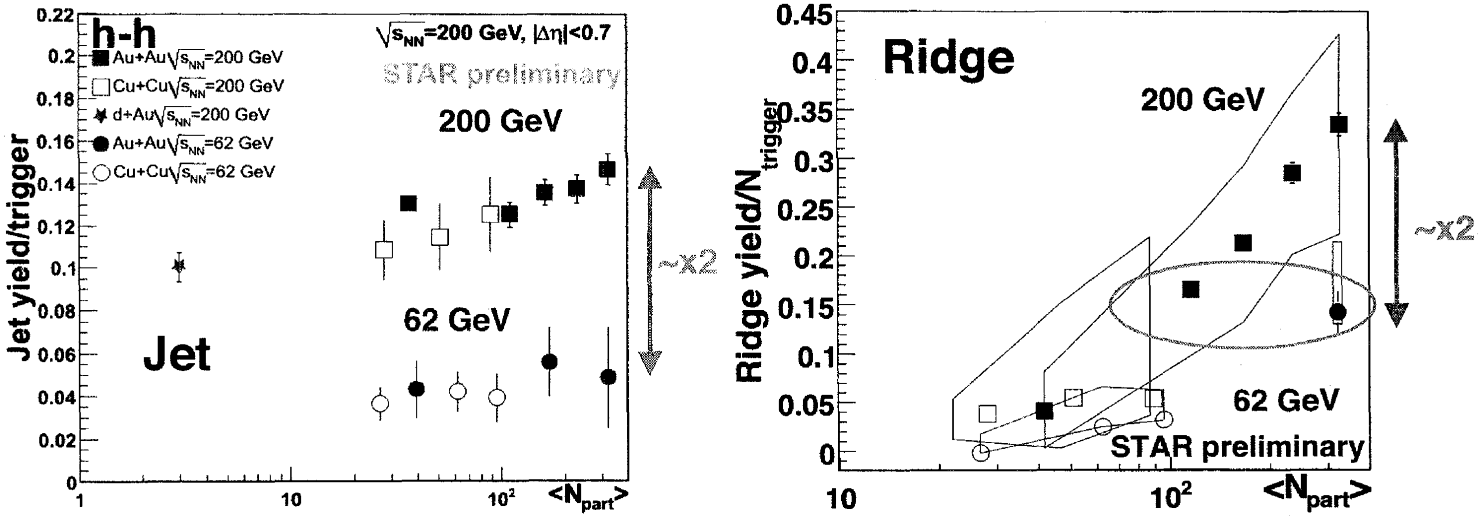
Surviving (di-jet) pairs at high p_t seem to favor conditions with small energy loss

⇒ Ridge correlated with energy loss !(?)

Energy dependence: Jet/Ridge 62 vs. 200 GeV

C. Nattrass (STAR), QM'2008 (to be published)

3.0 GeV/c < $p_T^{trigger}$ 6.0 GeV/c; 1.5 GeV/c < $p_T^{associated}$ < $p_T^{trigger}$



- **Jet yield significantly smaller in 62 GeV vs. 200 GeV**
- **Ridge yield also suppressed in 62 GeV vs. 200 GeV**
- **Ridge/Jet ratio comparable in 62 and 200 GeV**

Remark: Significantly increased statistics in Au+Au 62 GeV on tape! Also 39 GeV available + LHC!

Ridge 62 vs. 200 GeV in the context of jet quenching

Jet/Ridge ratio approx. independent on collision energy !

Suppressed jet yield in 62 GeV described by pQCD kinematics

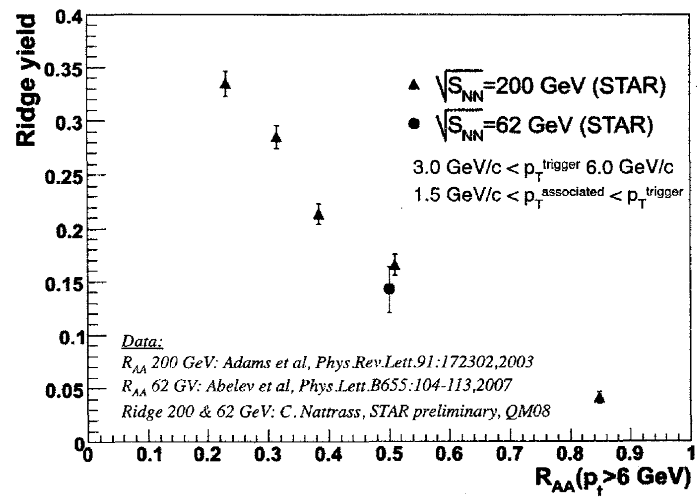
⇒ Ridge correlated with pQCD jet properties/quenching and trigger bias !?

<u>OR</u> just coincidence !?

Does the ridge scales with a quantity closer related to energy loss ? R_{AA} ?

At same $\sqrt{s}$ and similar N_{part}
Ridge(CuCu)=Ridge(AuAu)
and R_{AA}(CuCu)=R_{AA}(AuAu)

But at similar N_{part} for AuAu
Ridge(62)≠Ridge(200), but
R_{AA}(62)≠R_{AA}(200)



Ridge yield seems to scale with R_{AA}→ Ridge caused by/scales with jet-quenching/parton energy loss !(?)

<u>Not so fast:</u> so does dN/dy (background) vs $\sqrt{s}$ ...

Discussion

System-size at same $\sqrt{s}$ and similar N_{part} :

Jet/Ridge(CuCu)=Jet/Ridge(AuAu)

Jet(CuCu)=Jet(AuAu)

Ridge(CuCu)=Ridge(AuAu)

dN/dy(CuCu)=dN/dy(AuAu)

v_2(CuCu)≠v_2(AuAu) (~x2)

(also expected for v_n terms)

Similar R_{AA} and dN/dy
<u>but</u> different geometry (v_n)!
If Ridge is purely background (v_n)
→ Ridge yield should be different !?

Energy dependence at similar N_{part} :

Jet/Ridge(200)=Jet/Ridge(62)

Jet(200)≠Jet(62) (pQCD) (x2)

Ridge(62)≠Ridge(200) (~x2)

dN/dy(62)≠dN/dy(200) (~x1.5)

v_2(62)=v_2(200)

(also expected for v_n terms)

At similar R_{AA}:

Jet/Ridge(200)≠Jet/Ridge(62)

Jet(200)≠Jet(62) (pQCD) (x2)

Ridge(62)=Ridge(200)

dN/dy(62)=dN/dy(200)

v_2(62)≠v_2(200) (different N_{part})

Can we test this (Jet&Ridge) at LHC dN/dy > 2x but R_{AA} similar and more precise at 62 (and 39) GeV at RHIC!?

Ridges and Di-jets from Color Glass Condensate

Jamal Jalilian-Marian

We consider 2-hadron correlations in high energy pp, pA and AA collisions using the Color Glass Condensate formalism. The predictions of the formalism in qualitative agreement with the data. It is shown that the dipole approximation fails and one needs to solve the JIMWLK equation.

CGC: QCD at high gluon density

multiple scatterings → **p_t broadening**

"Cronin" effect

evolution with ln (1/x) → **suppression**

"Leading twist" nuclear shadowing

effective degrees of freedom:
Wilson line $V(x_t)$ re-sums multiple scatterings

CGC observables are expressed in terms of

$$< \mathrm{Tr}\, V \cdots V^{\dagger} >$$ → ***satisfy the JIMWLK equation: Re-sums ln 1/x***

<...> = average over color charges (Gaussian weight)

Di-jet correlations: pA

$O_2(r,\bar{r}) \equiv Tr V_r V_{\bar{r}}^\dagger$ ⟵ **F2 in DIS, single hadron in pA**

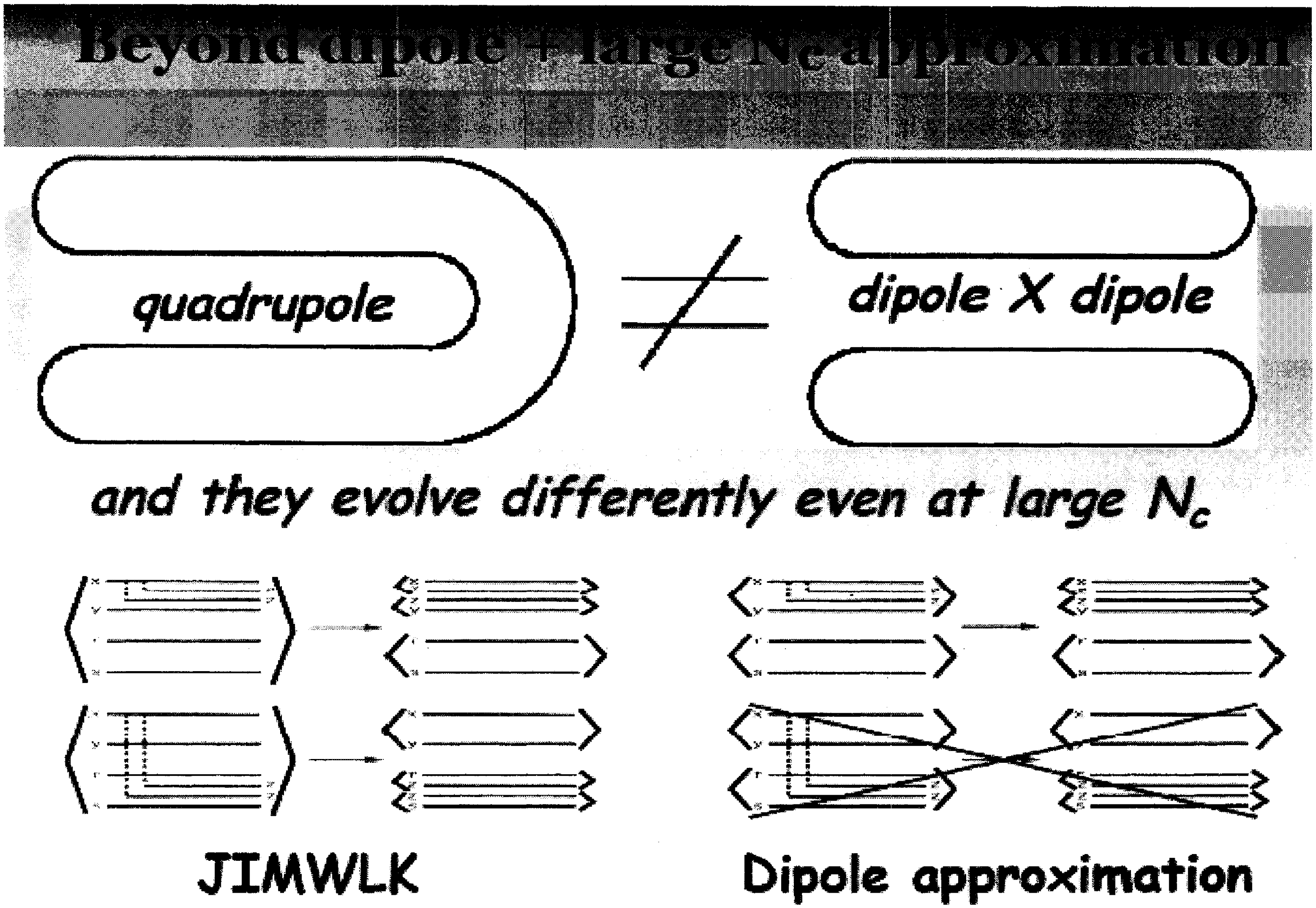
$$O_4(r,\bar{r}:s) \equiv Tr V_{\bar{r}}^\dagger\, t^a\, V_r\, t^b\, [U_s]^{ab} = \frac{1}{2}\left[Tr V_{\bar{r}}^\dagger V_s\; Tr V_r V_s^\dagger - \frac{1}{N_c} Tr V_{\bar{r}}^\dagger V_r\right]$$

$$O_6(r,\bar{r}:s,\bar{s}) = Tr V_r V_{\bar{r}}^\dagger\, t^a\, t^b\, [U_s U_{\bar{s}}^\dagger]^{ba} = \frac{1}{2}\left[Tr V_r V_{\bar{r}}^\dagger V_{\bar{s}} V_s^\dagger\; Tr V_s V_{\bar{s}}^\dagger - \frac{1}{N_c} Tr V_r V_{\bar{r}}^\dagger\right]$$

Dipole + large Nc approximation?

$$\langle O_4(r,\bar{r}:s)\rangle \simeq \langle O_2(r-s)\rangle\,\langle O_2(s-\bar{r})\rangle$$

$$\langle O_6(r,\bar{r}:s,\bar{s})\rangle \simeq \langle O_2(r-s)\rangle\,\langle O_2(\bar{r}-\bar{s})\rangle\,\langle O_2(s-\bar{s})\rangle + \langle O_2(r-\bar{r})\rangle\,\langle O_2(\bar{s}-s)\rangle\,\langle O_2(s-\bar{s})\rangle$$


Beyond dipole + large Nc approximation
quadrupole
dipole X dipole
and they evolve differently even at large N_c
JIMWLK
Dipole approximation

JIMWLK: Beyond dipole + large Nc

$$\frac{d}{dy}\langle O_6(r,\bar r : s,\bar s)\rangle = -\frac{N_c\,\alpha_s}{2(2\pi)^2}\int d^2z \Big\langle 2\,\Big[\frac{(r-s)^2}{(r-z)^2(s-z)^2}+\frac{(r-\bar r)^2}{(r-z)^2(\bar r-z)^2}+\frac{(\bar r-\bar s)^2}{(\bar r-z)^2(\bar s-z)^2}$$

$$+3\,\frac{(s-\bar s)^2}{(s-z)^2(\bar s-z)^2}\Big]\,O_6(r,\bar r : s,\bar s) - \frac{1}{N_c}\Big[$$

$$\Big[\frac{(r-\bar r)^2}{(r-z)^2(\bar r-z)^2}+\frac{(r-s)^2}{(r-z)^2(s-z)^2}-\frac{(s-\bar r)^2}{(s-z)^2(\bar r-z)^2}\Big]\,Tr V_z V_r^\dagger V_s V_{\bar s}^\dagger\;\; Tr V_r V_z^\dagger\;\; Tr V_s V_{\bar s}^\dagger$$

$$+\Big[\frac{(r-\bar r)^2}{(r-z)^2(\bar r-z)^2}+\frac{(\bar r-\bar s)^2}{(\bar r-z)^2(\bar s-z)^2}-\frac{(r-\bar s)^2}{(r-z)^2(\bar s-z)^2}\Big]\,Tr V_r V_z^\dagger V_{\bar s} V_s^\dagger\;\; Tr V_z V_{\bar r}^\dagger\;\; Tr V_s V_{\bar s}^\dagger$$

$$+\Big[\frac{(r-s)^2}{(r-z)^2(s-z)^2}+\frac{(s-\bar s)^2}{(s-z)^2(\bar s-z)^2}-\frac{(r-\bar s)^2}{(r-z)^2(\bar s-z)^2}\Big]\,Tr V_r V_{\bar r}^\dagger V_{\bar s} V_z^\dagger\;\; Tr V_z V_s^\dagger\;\; Tr V_s V_{\bar s}^\dagger$$

$$+\Big[\frac{(\bar r-\bar s)^2}{(\bar r-z)^2(\bar s-z)^2}+\frac{(s-\bar s)^2}{(s-z)^2(\bar s-z)^2}-\frac{(\bar r-s)^2}{(\bar r-z)^2(s-z)^2}\Big]\,Tr V_r V_{\bar r}^\dagger V_z V_s^\dagger\;\; Tr V_{\bar s} V_z^\dagger\;\; Tr V_s V_{\bar s}^\dagger$$

$$+2\,\frac{(s-\bar s)^2}{(s-z)^2(\bar s-z)^2}\,Tr V_r V_{\bar r}^\dagger V_{\bar s} V_s^\dagger\;\; Tr V_s V_z^\dagger\, Tr V_z V_{\bar s}^\dagger\; +$$

$$\Big[\frac{(\bar r-s)^2}{(\bar r-z)^2(s-z)^2}-\frac{(\bar r-\bar s)^2}{(\bar r-z)^2(\bar s-z)^2}-\frac{(r-s)^2}{(r-z)^2(s-z)^2}+\frac{(r-\bar s)^2}{(r-z)^2(\bar s-z)^2}\Big]\,Tr V_r V_s^\dagger\;\; Tr V_{\bar r}^\dagger V_{\bar s}\;\; Tr V_s V_{\bar s}^\dagger$$

$$+\Big[\frac{(\bar r-s)^2}{(\bar r-z)^2(s-z)^2}+\frac{(r-\bar s)^2}{(r-z)^2(\bar s-z)^2}-\frac{(r-\bar r)^2}{(r-z)^2(\bar r-z)^2}-\frac{(s-\bar s)^2}{(s-z)^2(\bar s-z)^2}\Big]\,Tr V_r V_{\bar r}^\dagger\, Tr V_{\bar s} V_s^\dagger\;\; Tr V_s V_{\bar s}^\dagger$$

+ terms suppressed by $\mathrm{O}(\frac{1}{\mathrm{N_c^2}})$

JIMWLK: Beyond dipole + large Nc

2-hadron correlations pose new challenges to CGC
but
every challenge can become an opportunity

How large are the terms missed by dipole approximation ?

What is their energy dependence ?

What is the role of non-Gaussian (quartic) initial conditions ?

need to solve JIMWLK equation

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Away-side Hadron Correlations from NLO pQCD

Alejandro Ayala

Instituto de Ciencias Nucleares, UNAM

In collaboration with J. Jalilian-Marian, J. Magnin, A. Ortiz, G. Paic, M.E. Tejeda-Yeomans

PRL 104, 042301 (2010) and in progress

pQCD: Au+Au vs p+p

- In Au+Au average p_T larger in shoulders than in head
- Q: Are shoulders more jet-like than head?
- Q: Can it happen that in Au+Au there is a chance to observe events where the structure on the away side has two jets (originating from a pQCD process) instead of only one?
- Q: If so, why such events are not seen in p+p?

Use modified pff's in AuAu collisions

to get medium induced energy loss effects into $2 \to \{2,\ 3\}$ xsecs
we use modified pff proposed by Zhang et al [PRL98 (2007)]:

$$D_{h/i}(z_i, \mu^2)$$
$$= (1 - e^{-\langle \frac{L}{\lambda} \rangle}) \left[\frac{z_i'}{z_i} D^0_{h/i}(z_i', \mu^2) + \langle \frac{L}{\lambda} \rangle \frac{z_g'}{z_i} D^0_{h/g}(z_g', \mu^2) \right] + e^{-\langle \frac{L}{\lambda} \rangle} D^0_{h/i}(z_i, \mu^2)$$

$z_i' = \frac{h_t}{(b_{ti} - \Delta E_i)}$ rescaled momentum fraction of the leading parton with flavor i

$z_g' = \langle \frac{L}{\lambda} \rangle \frac{b_t}{\Delta E_i}$ rescaled momentum fraction of the radiated gluon

$\langle \frac{L}{\lambda} \rangle$ average number of scatterings

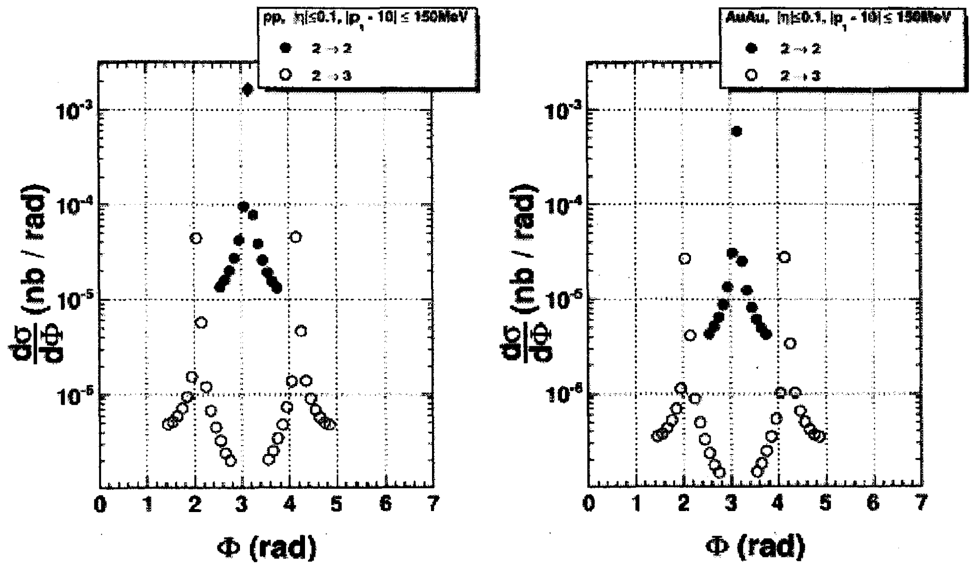
average radiative parton energy loss

$$\Delta E \propto \langle \frac{dE}{dL} \rangle_{1d} \int_{\tau_0}^{\infty} d\tau \Delta\tau\, \rho_g(\tau, \vec{r}_t + \vec{n}\tau)$$

most central collisions: $\vec{b}_\perp = 0$

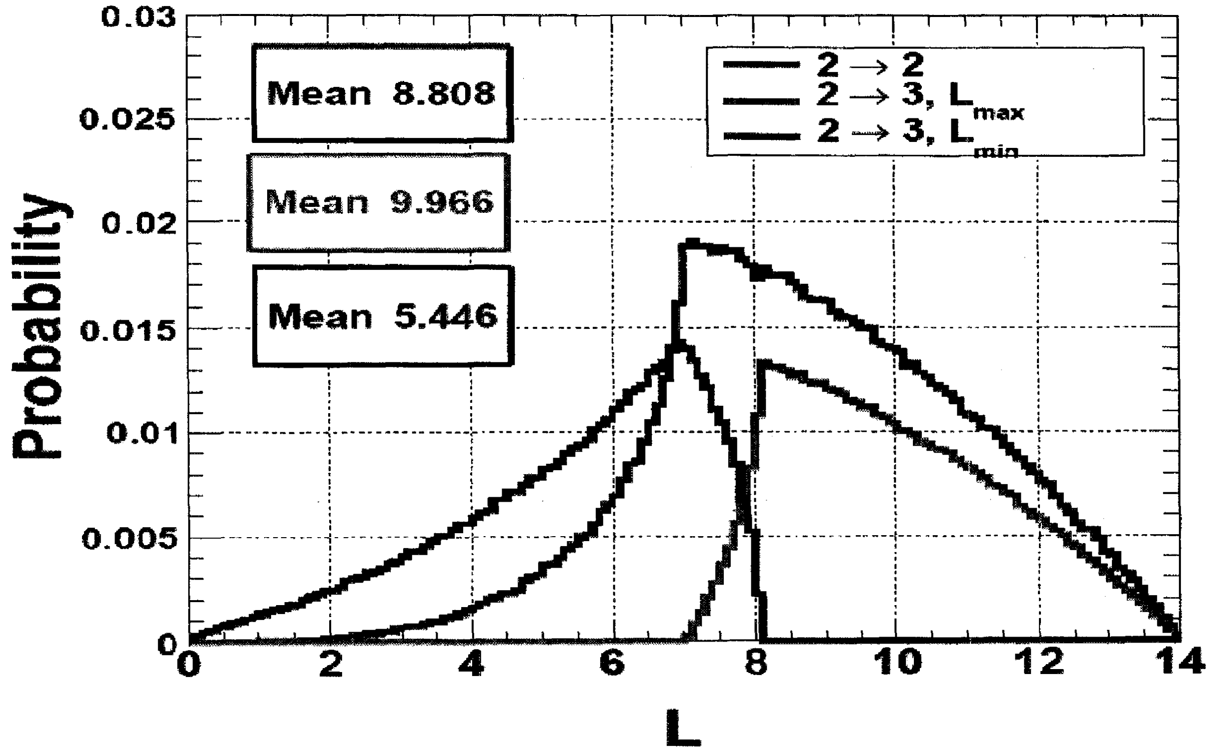
the xsections

2 ►2 and 2 ►3 angular distribution of the away side hadron(s)



$$\frac{\text{AuAu}:\ \frac{2\to3}{2\to2}}{\text{pp}:\ \frac{2\to3}{2\to2}} \sim 2.26$$

path length dependence: 2--> 2 vs. 2 --> 3



Conclusions

- We computed x-sect. for three hadron production + energy loss to look for shape of away side in Au+Au
- AuAu/pp larger in $2 \longrightarrow 3$ than in $2 \longrightarrow 2$
- Different path lengths of away side partons.
- Events with three jets should exists and one could look for them. Three particle correlation analysis.

Hydrodynamical evolution based on flux tube initial conditions: Ridges in AA and pp scattering

K. Werner[(a)], Iu. Karpenko[(a,b)], T. Pierog[(c)], M. Bleicher[(d)], K. Mikhailov[(e)]
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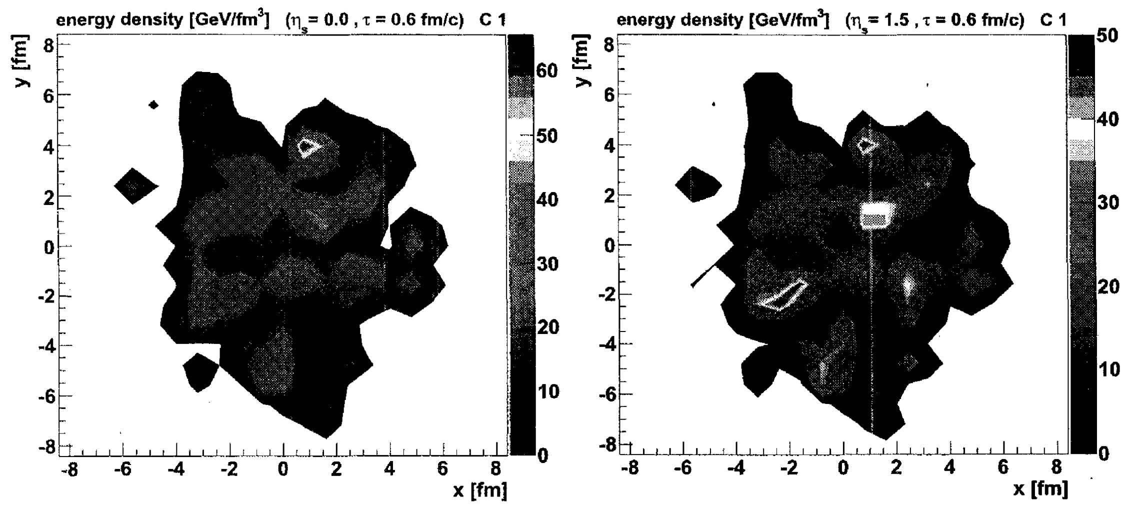
[(b)] *Bogolyubov Institute for Theoretical Physics, Kiev 143, 03680, Ukraine*
[(c)] *Karlsruhe Institute of Technology (KIT), Institut fuer Kernphysik, Germany*
[(d)] *Frankfurt Institute for Advanced Studies (FIAS), Johann Wolfgang Goethe Universitaet, Frankfurt am Main, Germany* and
[(e)] *Institute for Theoretical and Experimental Physics, Moscow, 117218, Russia*

One of the most important experimental results for AuAu scattering at RHIC is the observation of a so-called "ridge" structure in the two particle correlation function versus the pseudorapidity difference $\Delta\eta$ and the azimuthal angle difference $\Delta\phi$. One finds a strong correlation around $\Delta\varphi = 0$, extended over many units in $\Delta\eta$. We show that a hydrodynamical expansion based on flux tube initial conditions leads in a natural way to the observed structure. To get this result, we have to perform an event-by-event calculation, because the effect is due to statistical fluctuations of the initial conditions, together with a subsequent collective expansion. More recently, very similar "ridge" structures have been observed in proton-proton scattering at the LHC. Again, a hydrodynamic calculation based on flux tube initial conditions explains the phenomenon. This is a strong point in favour of a fluid-like behavior even in *pp* scattering, where we have to deal with length scales of the order of 0.1 fm.

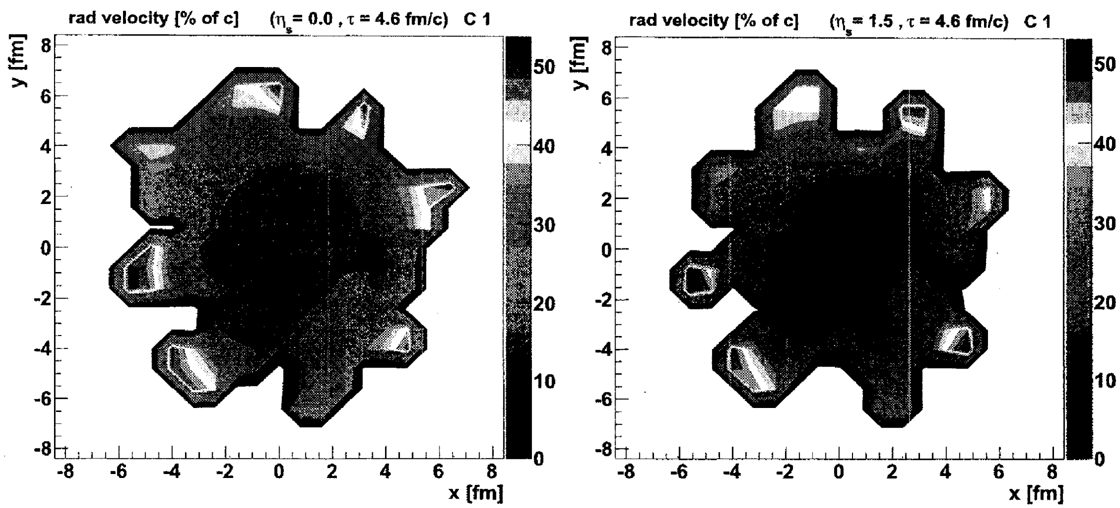
After checking successfully hundreds of particle spectra in AuAu, we study

Interesting EbE features:

Bumpy structure of energy density in transverse plane,
but **translational invariance**

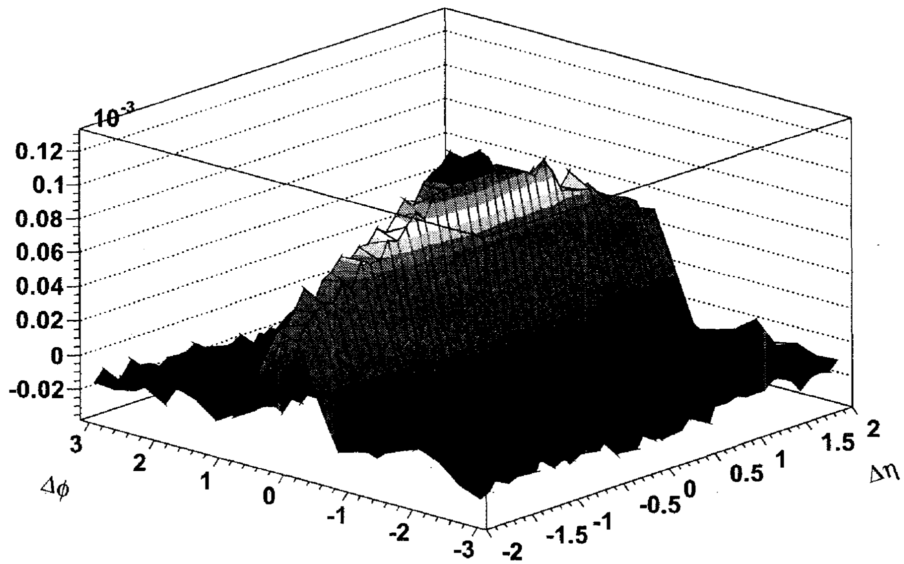


Leads to **translational invariance of transverse flows**



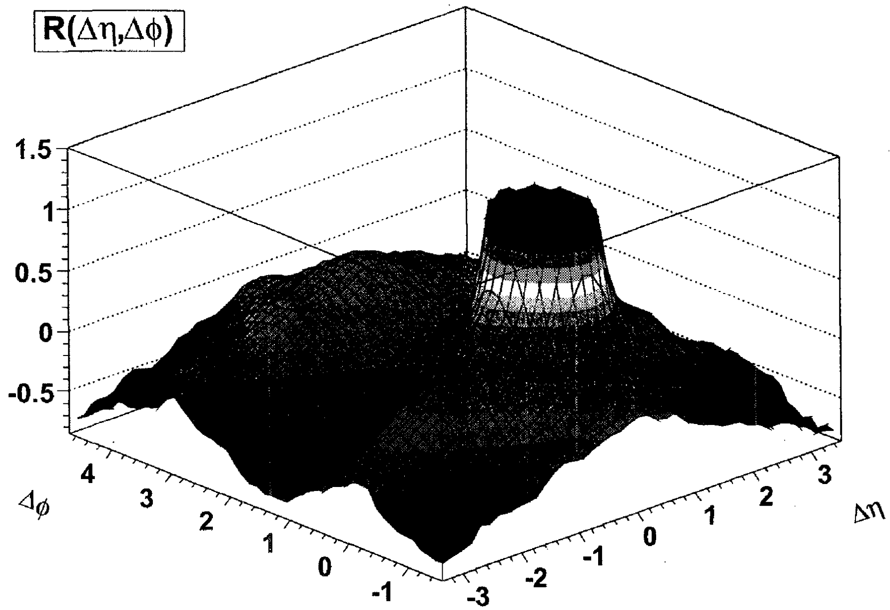
give the same collective push
to particles produced at different values of η_s
at the same azimuthal angle

=> **ridge**-structure in the dihadron correlation $dN/d\Delta\eta\, d\Delta\phi$ **for free**



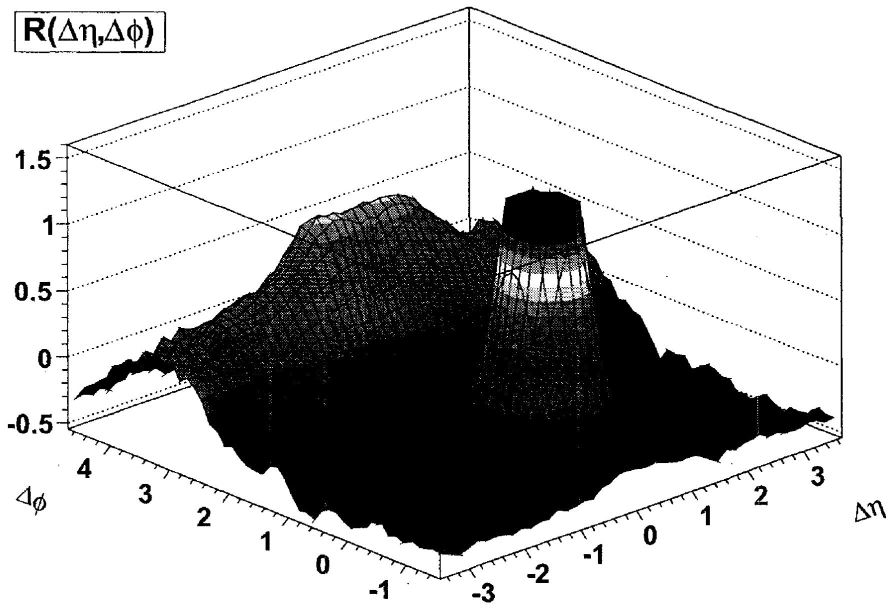
trigger particles with transverse momenta between 3 and 4 GeV/c,
assoc particles with transverse momenta between 2 GeV/c and p_t of the trigger,
in central Au-Au collisions at 200 GeV

Our calculation provides a similar ridge structure in pp@7TeV
using particles with $1 < p_t < 3\text{GeV/c}$, for high multiplicity events



close in form and magnitude compared to the CMS result
(5.3 times mean multipl., compared to 7 in CMS)

Calculation without hydro => NO RIDGE



hydrodynamical evolution “makes” the effect! HOW?

ON ANGULAR CORRELATIONS IN GLUON EMISSION.

Alex Kovner

University of Connecticut

We present a general, model independent argument demonstrating that gluons produced in high energy hadronic collision are necessarily correlated in rapidity and also in the emission angle. The strength of the correlation depends on the process and on the structure/model of the colliding particles. In particular we argue that it is strongly affected (and underestimated) by factorized approximations frequently used to quantify the effect.

with Misha Lublinsky

NAIVE PICTURE OF EIKONAL GLUON PRODUCTION

LONG RANGE RAPIDITY CORRELATIONS COME FOR FREE WITH BOOST INVARIANCE

INCOMING $|P>$ IS BOOST INVARIANT: EXACTLY THE SAME GLUON DISTRIBUTIONS AT Y_1 AND Y_2. AND THEY SCATTER ON EXACTLY THE SAME TARGET

WHAT HAPPENS AT Y_1, HAPPENS ALSO AT Y_2

TRUE **CONFIGURATION BY CONFIGURATION** IF THERE IS A "'CLASSICAL"' AVERAGE FIELD IN THE PROJECTILE - FLUCTUATIONS ARE SMALL. BUT EVEN OTHERWISE ONE CERTAINLY EXPECTS SOME LONG RANGE CORRELATIONS IN RAPIDITY.

IF IT IS PROBABLE TO PRODUCE A GLUON AT Y_1, IT IS ALSO PROBABLE TO PRODUCE GLUON AT Y_2

BUT EXACTLY BY THE SAME LOGIC THERE MUST BE ANGULAR CORRELATIONS: IF THE FIRST GLUON IS MOST LIKELY TO BE SCATTERED TO THE RIGHT, THE SECOND GLUON **AT THE SAME IMPACT PARAMETER** WILL BE ALSO SCATTERED TO THE RIGHT

TWO GLUON INCLUSIVE PRODUCTION

WE NEGLECT THE EVOLUTION BETWEEN THE TWO PRODUCED GLUONS

AND ALSO ASSUME DILUTE PROJECTILE

KEEP ONLY "'CLASSICAL"' TERM

$$\frac{dN}{d^2pd^2kd\eta d\xi} =< A^{ab}(k,p)A^{*ab}(k,p) >_{P,T}$$

WITH

$$A^{ab}(k,p) = \int_{u,z} e^{ikz+ipu}$$

$$\int_{x_1,x_2} \Big\{ f_i(z-x_1)\,[S(x_1) - S(z)]^{ac}\,\rho^c(x_1)\Big\}\Big\{ f_j(u-x_2)\,[S(u) - S(x_2)]^{bd}\,\rho^d(x_2)\Big\}$$

SQUARING THE AMPLITUDE

$$\sigma^4 = \int_{z,\bar{z},u,\bar{u},x_1,\bar{x}_1,x_2\bar{x}_2} e^{ik(z-\bar{z})+ip(u-\bar{u})}\vec{f}(\bar{z}-\bar{x}_1)\cdot\vec{f}(x_1-z)\,\vec{f}(\bar{u}-\bar{x}_2)\cdot\vec{f}(x_2-u)$$

$$\times\Big\{\rho(x_1)[S^\dagger(x_1) - S^\dagger(z)][S(\bar{x}_1) - S(z)]\rho(\bar{x}_1)\Big\}\,\Big\{\rho(x_2)[S^\dagger(u) - S^\dagger(x_2)][S(\bar{u}) - S(\bar{x}_2)\rho(\bar{x}_2)\Big\}$$

DDGJLV ARGUE FOR POSITIVE ANGULAR CORRELATIONS

INDEED DETAILS DON'T MATTER

$$\sigma^4 = \langle \sigma_1(k)\sigma_1(p) >$$

CONFIGURATION BY CONFIGURATION (FOR FIXED CONFIGURATION OF PROJECTILE CHARGES ρ AND FIXED TARGET FIELDS S)

$$\sigma_1(k) = \int_{z,\bar{z},x_1,\bar{x}_1} e^{ik(z-\bar{z})} \vec{f}(\bar{z}-\bar{x}_1)\cdot\vec{f}(x_1-z) \left\{\rho(x_1)[S^\dagger(x_1) - S^\dagger(z)][S(\bar{x}_1) - S(z)]\rho(\bar{x}_1)\right\}$$

$\sigma_1(k)$ IS A NONTRIVIAL REAL FUNCTION OF k, WHICH HAS A MAXIMUM AT SOME VALUE $k = q_0$. CLEARLY THEN THE TWO GLUON PRODUCTION PROBABILITY CONFIGURATION BY CONFIGURATION HAS A MAXIMUM AT

$$k = p = q_0$$

THE VALUE OF q_0 DEPENDS ON CONFIGURATION, BUT THE FACT THAT k AND p ARE THE SAME DOES NOT.

HOW BIG IS THE EFFECT?

TRANSVERSE CORRELATION LENGTH IN THE HADRON $L = \frac{1}{Q_s}$

TO BE CORRELATED THE TWO GLUONS HAVE TO BE IN THE SAME INCOMING STATE AND HAVE TO SCATTER OF THE SAME TARGET FIELD HAVE TO SIT WITHIN $\Delta X < L_{min}$ OF EACH OTHER.

THE CORRELATED PRODUCTION $\propto S/Q_s^2$,

WHILE THE TOTAL MULTIPLICITY $\propto S$

$$\left[\frac{d^2N}{d^2pd^2k} - \frac{dN}{d^2k}\frac{dN}{d^2p}\right] / \frac{dN}{d^2k}\frac{dN}{d^2p} \sim \frac{1}{(Q_s^{max})^2 S_{min}}\,.$$

CONCLUSIONS

GLUON PRODUCTION AT HIGH ENERGY LEADS NATURALLY TO RAPIDITY CORRELATIONS (TRIVIALLY) AND ANGULAR CORRELATIONS (A LITTLE LESS TRIVIALLY). THERE JUST HAVE TO BE MANY GLUONS SO THAT MORE THAN ONE IS PRODUCED AT FIXED IMPACT PARAMETER (WITHIN $\Delta b \sim \frac{1}{Q_s}$)

CORRELATIONS EXIST CONFIGURATION BY CONFIGURATION AND THEREFORE GAUSSIAN AVERAGING VERY LIKELY UNDERESTIMATES THEM. **THERE IS NO REASON NOT TO HAVE CORRELATIONS AT LEADING ORDER IN** $1/N_C$.

"'CLASSICAL"' TERM LEADS TO THE STRONGEST CORRELATIONS - THUS WE MAY EXPECT STRONGEST CORRELATIONS FOR NUCLEUS PROJECTILE WHERE IT DOMINATES. ON THE OTHER HAND EFFECT BECOMES WEAKER WITH INCREASING Q_S. SO MAYBE ACTUALLY THE OTHER WAY ROUND - IT IS STRONGEST FOR $p-p$ IN A LIMITED RANGE OF ENERGIES?

Fluctuating Hydrodynamics at RHIC

Derek Teaney

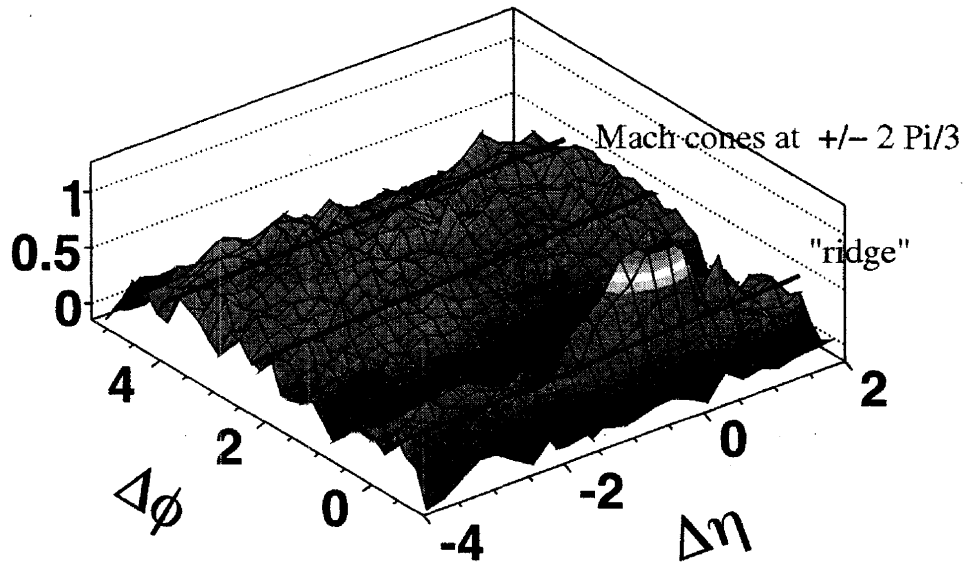
SUNY Stonybrook and RBRC Fellow

STONY BROOK
STATE UNIVERSITY OF NEW YORK

- In collaboration with Yan Li – http://arxiv.org/abs/1010.1876

Interesting Two Particle Correlations at RHIC

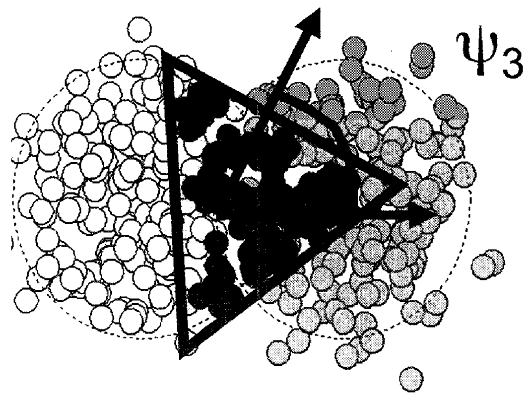
- After flow subtraction see additional structures $p_T^{\mathrm{trig}} > 2.5\,\mathrm{GeV}$
  - known as the “ridge” and the “shoulder” and the “mach cone” at $\pm 2\pi/3$



These structures are well described by $\cos(\Delta\phi)$ and $\cos(3\Delta\phi)$

Triangularity explanation

- Many precursors – Takashi et al, Sorenson, AMPT predictions
- I will follow Alver & Roland
- On an event by event basis the initial energy density can be skewed



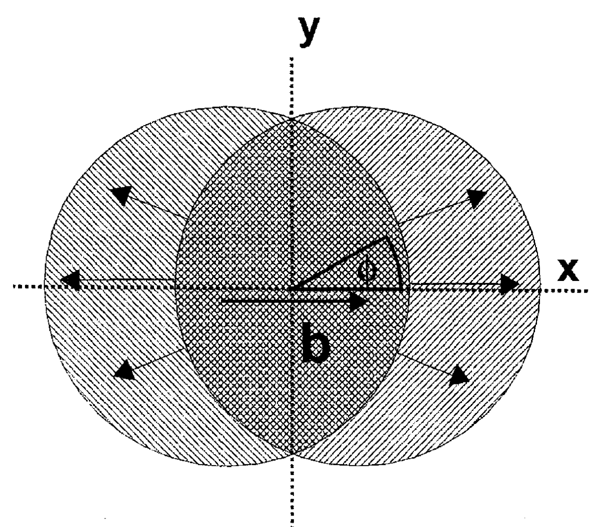
The triangular shape causes the distribution a triangular hydrodynamic response

Outline:

1. Classify geometric fluctuations with cumulants
2. Determine the initial cumulants and their *correlations* with glauber
3. Calculate the hydrodynamic response to these cumulants

Give predictions

Dependence on the smooth initial geometry



How sensitive are we to the smooth initial geometry?

Conclusions

- Fluctuations are fun – a new testing ground for hydro.
- Once we understand we can use it to constrain η/s
- Good stuff from my student Yan Li
  - Viscosity
  - Non-linear corrections
  - Multiple v_2 planes from higher cumulants

Main message for today: measure $\langle \cos(\phi_\alpha - 3\phi_\beta + 2\Psi_{PP}) \rangle$!

Find the hot spots!

From geometry fluctuations to harmonic flows

Guang-You Qin

Duke University

A systematic study of initial collision geometry fluctuations in relativistic heavy ion collisions is presented. Within an event-by-event framework, the time evolution of multipole moments of collision geometry through different stages of fireball history and the correlation of the final harmonic flows to the initial geometric anisotropies are analyzed. It is found that although all initial spatial anisotropies are of the same magnitude, only the lowest few flow coefficients survive after hydrodynamic evolution. The correlation between odd and event moments is quantitatively studied found to be small. The study sheds lights on how multipole moments of initial collision geometry relate to measurable collective flows of the hadronic final state and allows for improved constraints on the determination of various transport properties of hot QCD matter produced in high energy nuclear collisions.

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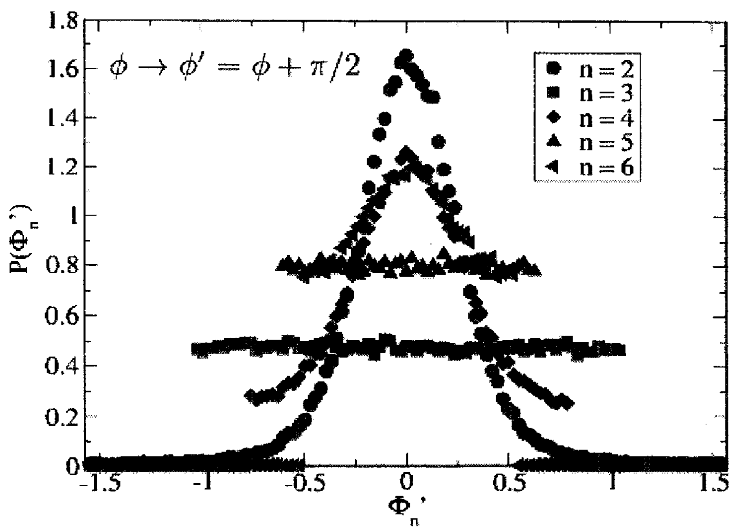
Initial state fluctuations

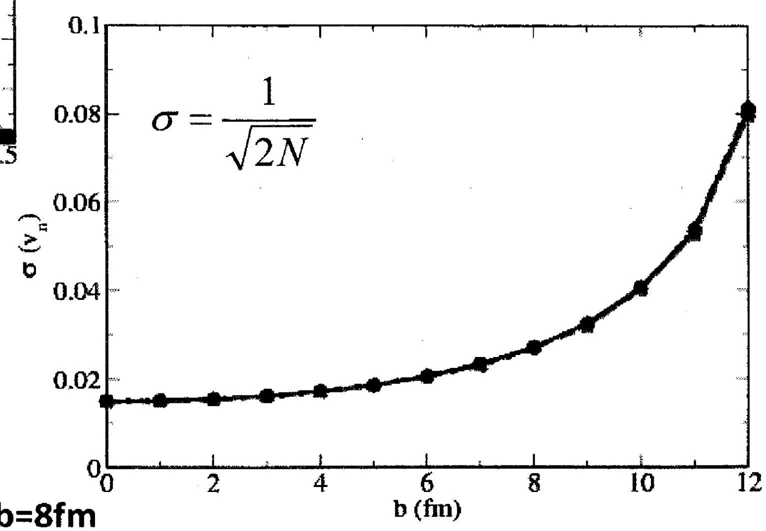


Initial momentum anisotropy v_n are fluctuating (larger for smaller system)

Both initial geometry fluctuations and initial v_n fluctuations contribute to final flow fluctuations

Even moments are strongly correlated with RP, with one maximum along y direction

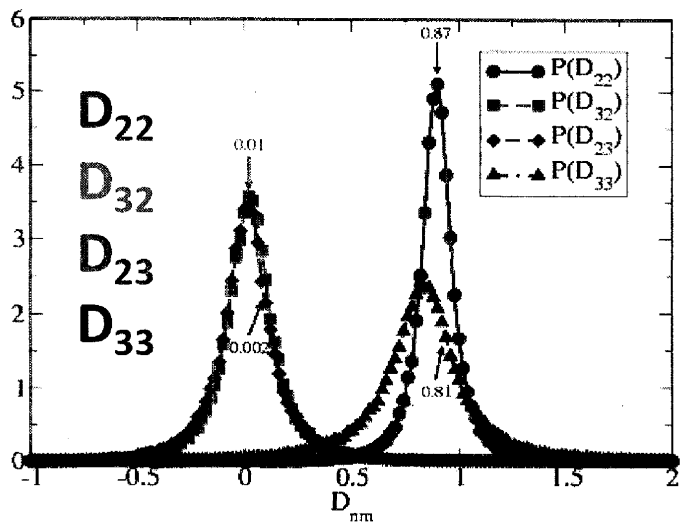
Odd moments are not correlated with RP



b=8fm

Pre-equilibrium phase

$$(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}}) f(\mathbf{x}, \mathbf{p}, t) = C[f]$$

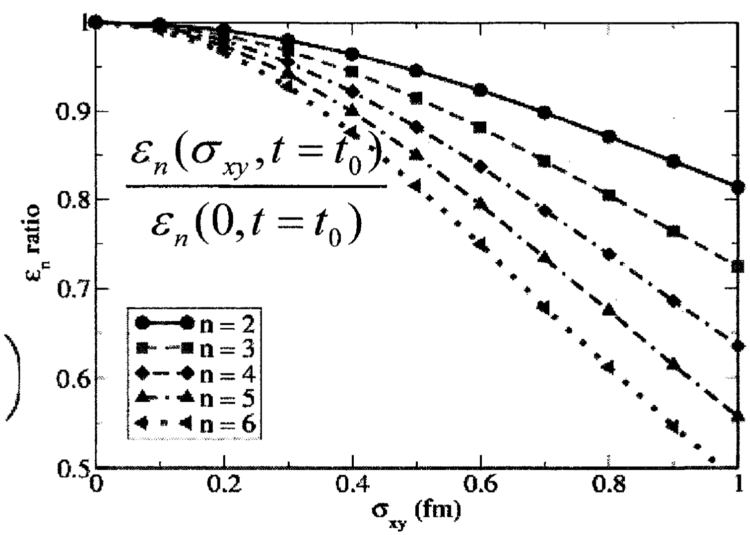


$$\begin{pmatrix} \epsilon_2(t_0) \\ \epsilon_3(t_0) \end{pmatrix} = \begin{pmatrix} D_{22}(t_0) & D_{23}(t_0) \\ D_{32}(t_0) & D_{33}(t_0) \end{pmatrix} \begin{pmatrix} \epsilon_2(0) \\ \epsilon_3(0) \end{pmatrix}$$

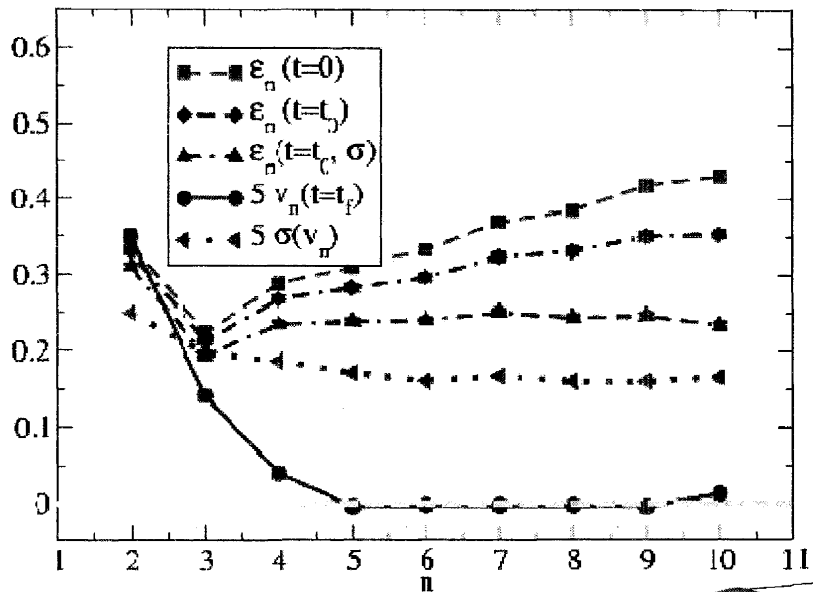
t_0=0.6fm/c, b=8fm

Free streaming smears the spatial anisotropies (larger for higher moments)
Weak correlations between odd and even moments

Gaussian smearing increase fluctuation size, reduce the spatial anisotropies (larger for higher moments)



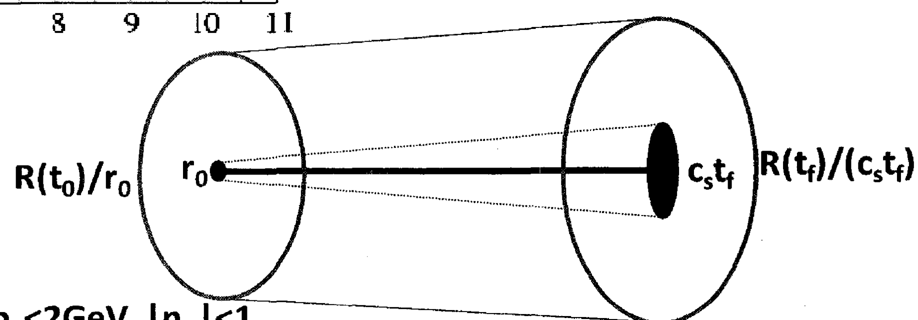
From initial anisotropy to final flow



Initial e_n the same magnitude

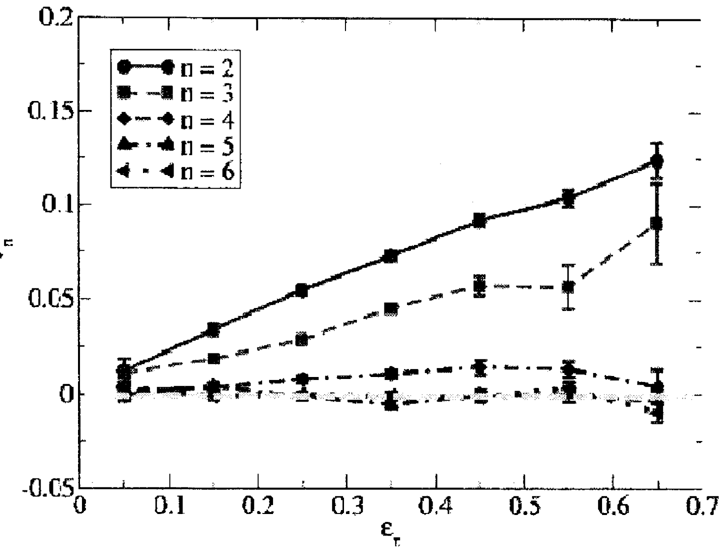
High order v_n are quenched after hydro

All final v_n fluctuations still present



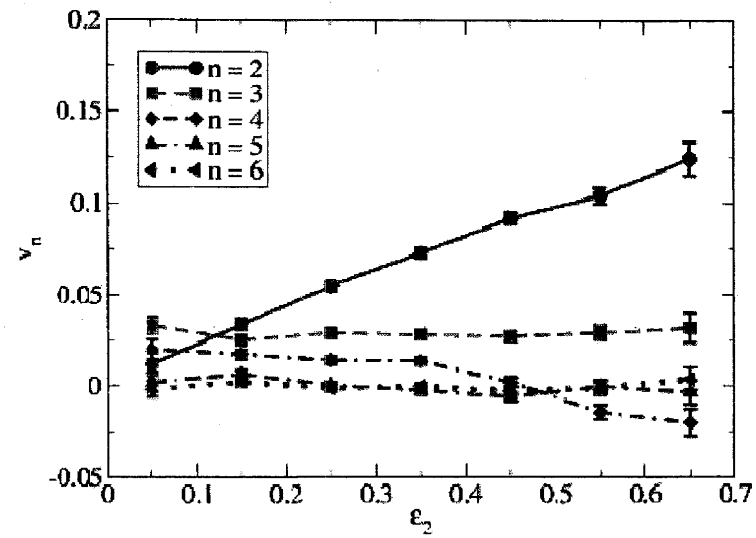
Au+Au @ 200GeV b=5-10fm, p_T<2GeV, $|\eta_p|$<1

Response of v_n to e_m



Essentially linear response of v_n to e_n (weaker response for higher moments)

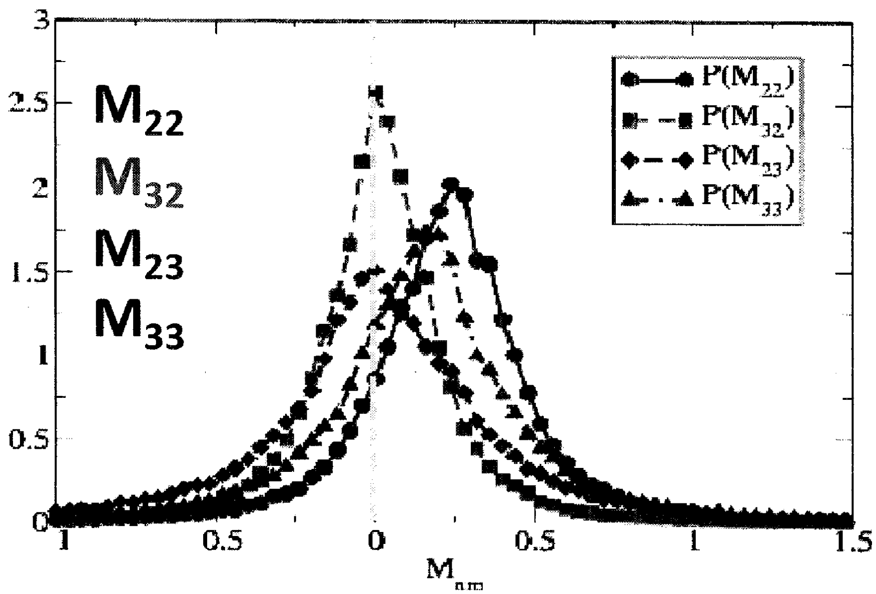
Weak response between mixed moments

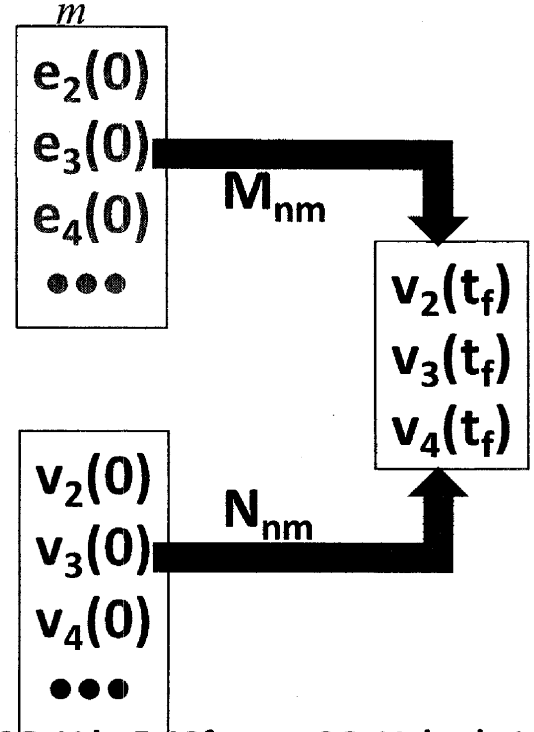


Au+Au @ 200GeV b=5-10fm, p_T<2GeV, $|\eta_p|$<1

Transformation (response) matrix

$$v_n(t=t_f)=\sum_m M_{nm}\varepsilon_m(t=0)+\sum_m N_{nm}v_m(t=0)$$





$$\begin{pmatrix} v_2 \\ v_3 \end{pmatrix} = \begin{pmatrix} M_{22} & M_{23} \\ M_{32} & M_{33} \end{pmatrix} \begin{pmatrix} \epsilon_2 \\ \epsilon_3 \end{pmatrix}$$

Au+Au @ 200GeV b=5-10fm, p_T<2GeV, $|\eta_p|$<1

Initial State Fluctuations and Triangular Flow

- Hannah Petersen, Duke University
  in collaboration with G. Qin, S.A. Bass, B. Mueller, C. Coleman-Smith, R. Wolpert

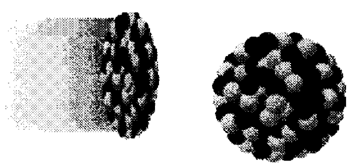
We present a systematic study of the granularity of the initial state of hot and dense QCD matter produced in ultra-relativistic heavy-ion collisions and its influence on bulk observables like particle yields, m_T spectra and elliptic flow. For our investigation we use a hybrid transport model, based on (3+1)d hydrodynamics and a microscopic Boltzmann transport approach. The initial conditions are generated by a non-equilibrium hadronic transport approach and the size of their fluctuations can be adjusted by defining a Gaussian smoothing parameter σ.
As a response to the initial triangularity ε_3 of the collision zone, v_3 is computed in a similar way to the standard event-plane analysis for elliptic flow v_2. It is found that the triangular flow exhibits weak centrality dependence and is roughly equal to elliptic flow in most central collisions. We also explore the transverse momentum and rapidity dependence of v_2 and v_3 for charged particles as well as identified particles. All the expected features (weak centrality dependence, flatness in pseudorapidity v_3 is smaller than v_2) can be observed including fluctuating flux tube initial conditions, and ideal hydrodynamic evolution and a hadronic afterburner.

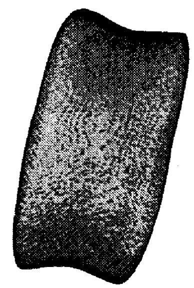
Refs: arXiv:1012.4629 & Phys.Rev. C82 (2010) 041901

Hybrid Approach

- Use advantages of **transport** and **hydrodynamics** and create combined model
- The idea here: Fix the hydro evolution and freeze-out

  → learn something about the influence of different **initial conditions**





1) Non-equilibrium initial conditions via UrQMD

2) Hydrodynamic evolution

3) Freeze-out via hadronic cascade (UrQMD)

(H.P. et al., PRC 78:044901, 2008, arXiv: 0806.1695)

UrQMD-3.3p1 is available at http://urqmd.org

Initial State at RHIC

- Energy-, momentum- and baryon number densities are mapped onto the hydro grid using for each particle

$$\epsilon(x,y,z) = \left(\frac{1}{2\pi}\right)^{\frac{3}{2}} \frac{\gamma_z}{\sigma^3} E_p \exp - \frac{(x-x_p)^2 + (y-y_p)^2 + (\gamma_z(z-z_p))^2}{2\sigma^2}$$

- Main parameters are σ and t_{start}, $|y|<2$
- Smooth but still event-by-event in contrast to averaging over many fluctuating initial conditions

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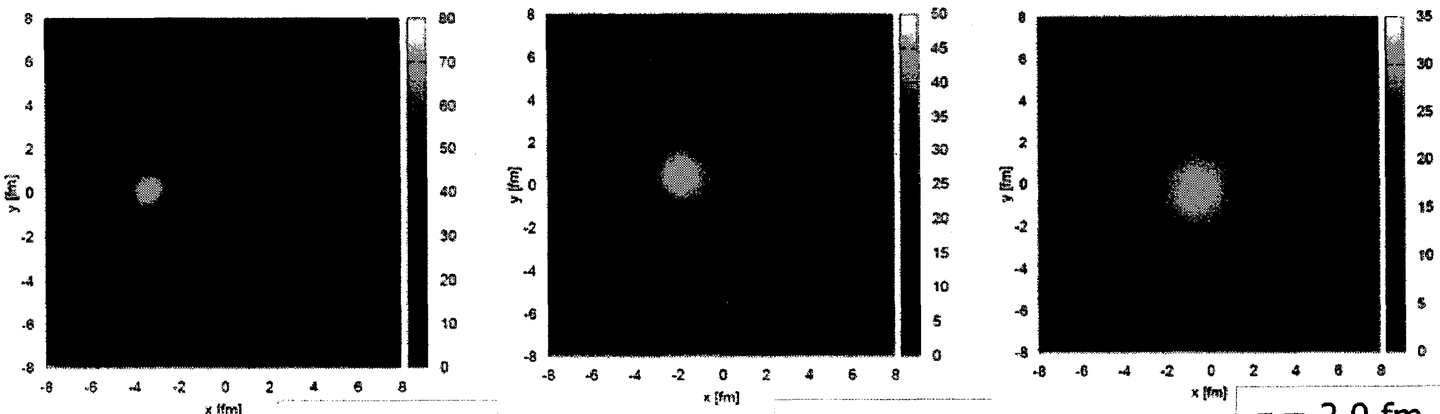
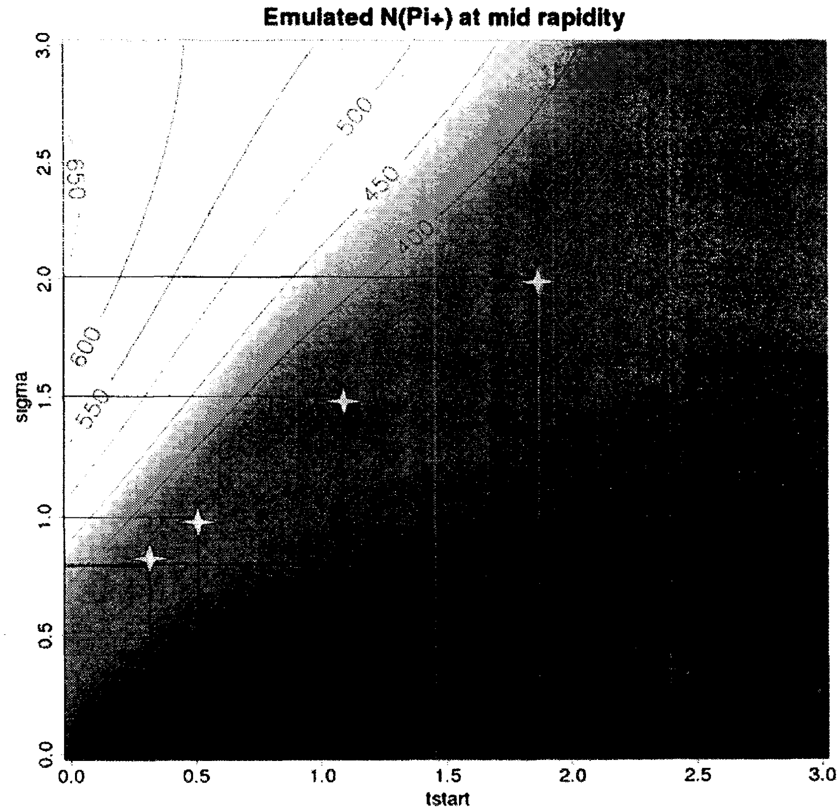


σ = 0.8 fm σ = 1.0 fm σ = 2.0 fm

H.P. et al, arXiv: 1008.3846

Parameter Sensitivity Tests



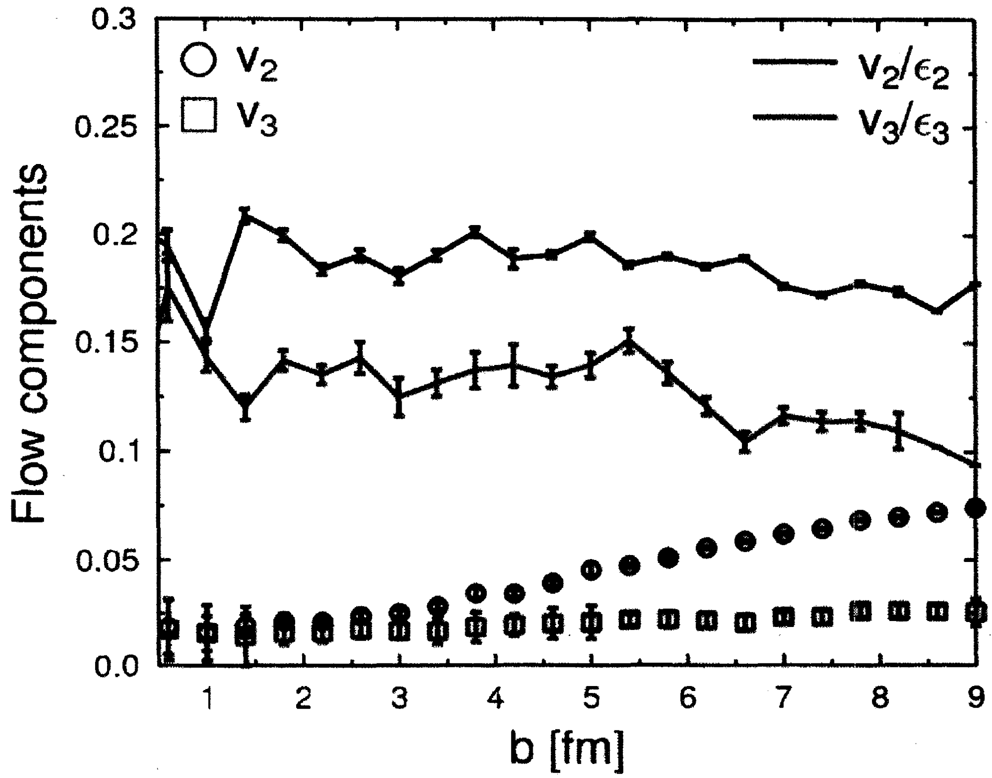
- Sophisticated statistical analysis
- **Emulator** predicts results of calculations for parameter sets by means of advanced statistics
- Number of pions in the t_{start}- σ plane

→ Determine reasonable **combinations** of parameters

Thanks to Chris Coleman-Smith, MADAI collaboration

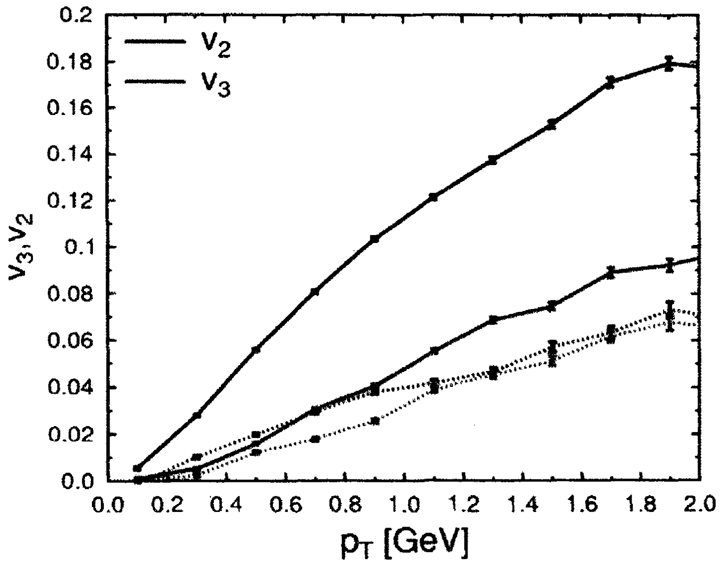
(H.P. et al., arXiv: 1012.4629)

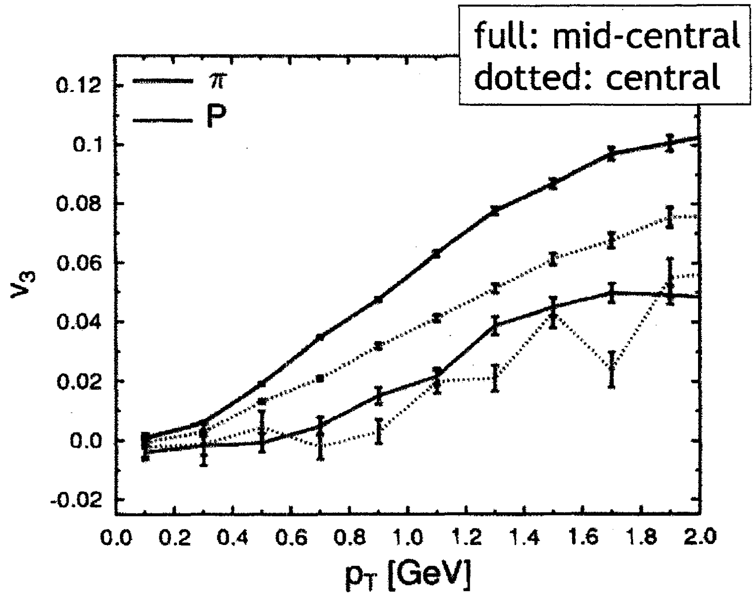
Centrality Dependence



- Hydrodynamic response **stronger** for elliptic flow
- Triangular flow exhibits only **weak** centrality dependence

Tranverse Momentum Dependence





- Central Collisions: $v_2 \approx v_3$
- Mid-central collisions: $v_2 \approx 2 \cdot v_3$
- Mass splitting for identified particles

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COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

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Jets and Fluctuating Initial Conditions

While the 2nd Fourier harmonics of jet quenching have been thoroughly explored in literature and shown to be insensitive to the underlying jet path-length dependence of energy loss and differences between the mean eccentricity predicted by Glauber and CGC/KLN models of initial conditions, the sensitivity of higher harmonics has remained relatively unexplored. We demonstrate that those higher-jet harmonics are remarkably insensitive to the initial conditions and show that higher powers of the path-length dependence will lead to a saturation effect for all Fourier harmonics. However, the different $v_n(N_{part})$ vs. $v_n^{I_{AA}}(N_{part})$ correlations between the moments of monojet and dijet nuclear modification factors remain the most sensitive probe to differentiate between Glauber and CGC/KLN initial state geometries.

R_{AA} and v_2

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

- Considering the generic energy-loss model

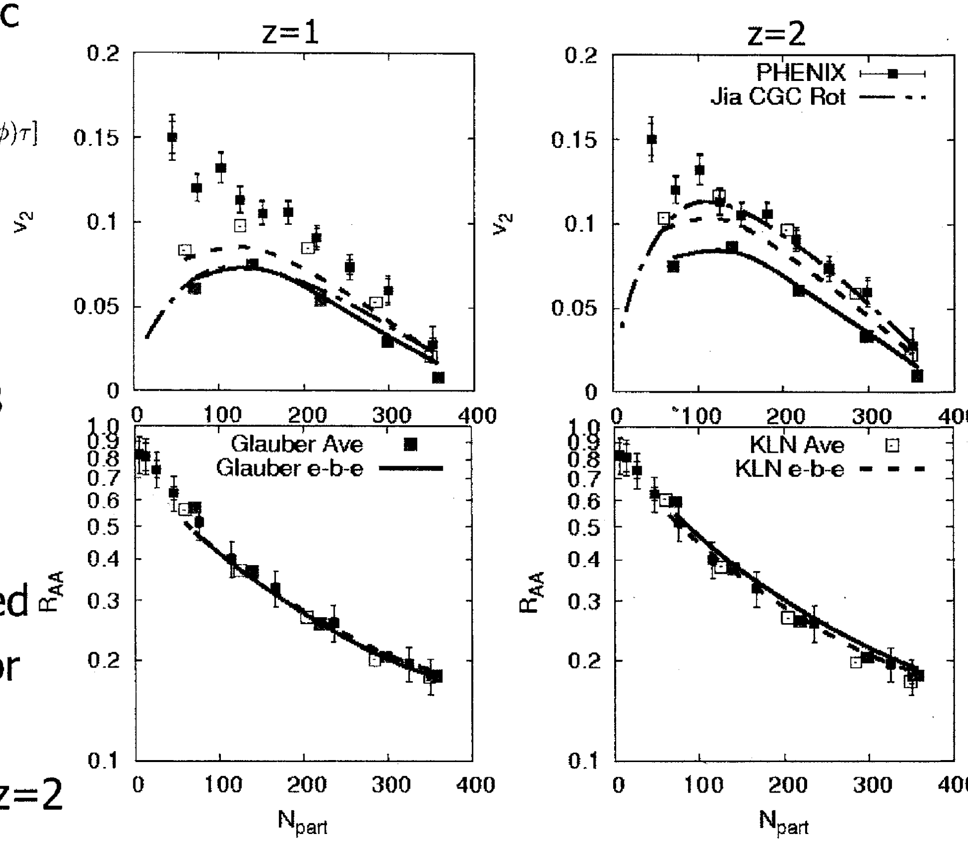
$$\frac{dE}{dx}(x_0,\phi,\tau) = -\kappa P^a \tau^z T^{z-a+2}[x_0 + \hat{n}(\phi)\tau]$$

  - $\Delta E \sim P^a$, a=0.3
  - $\Delta E \sim l^z$, z=m

→ Having fixed κ for $R_{AA}(N_{part}=350) \sim 0.18$ $R_{AA}(N_{part})$ can be reproduced

→ z=1: v_2 not reproduced
z=2: v_3 reproduced for CGC initial cond.

→ match Jia's curve for z=2 with a=0.3



Glauber: B.Betz et.al., to be published
CGC: H. Drescher et. al., PRC **76** (2007) 024905

R_{AA} vs. I_{AA}, and v_n vs. v_n^{IAA}

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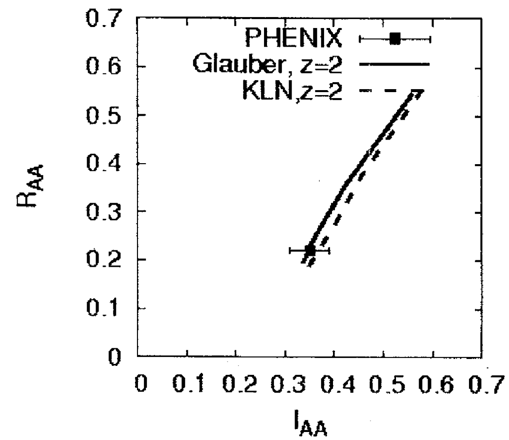
- Extend to dijet analysis,

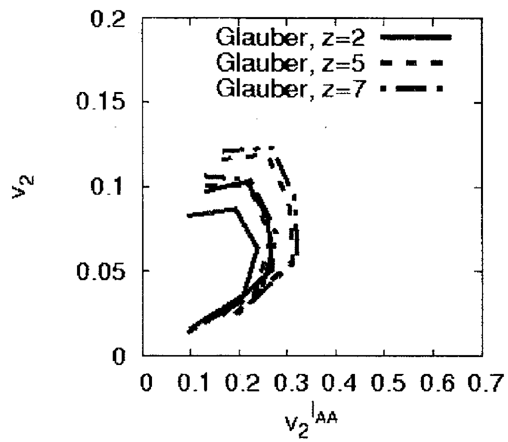
  but considering $\kappa_{away} = \kappa$

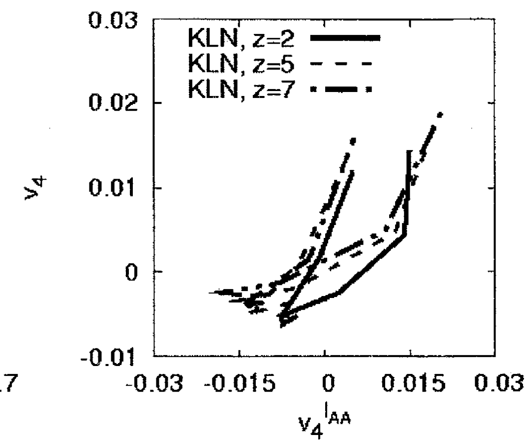
→ In contrast to Jia's model, we fit the R_{AA} vs. I_{AA}



- v_n vs. v_n^{IAA}:

  - clear shift between Glauber and CGC model
  - saturation effect for larger z=m





Higher Harmonics

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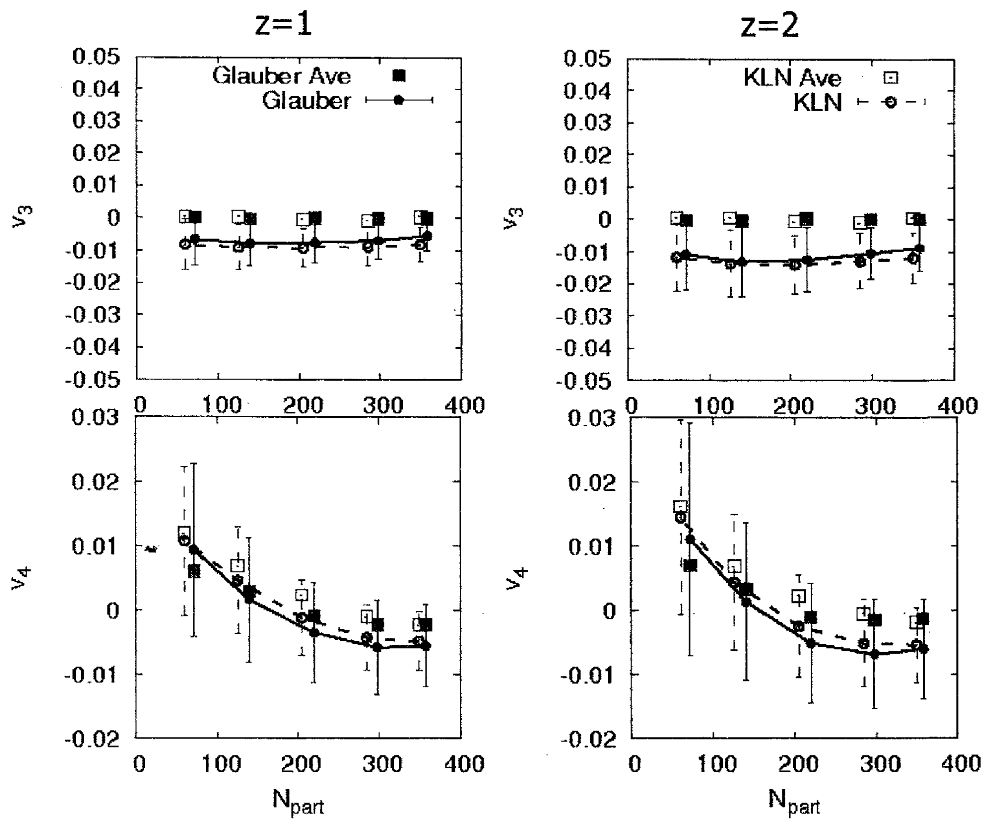
- $v_3 \neq 0$ event-by-event,
- v_4 similar for average and event-by-event initial conditions

→ Not suitable to distinguish between Glauber and CGC initial conditions



➔ Higher harmonics are more sensitive to local gradients, but also to event-by-event fluctuations → larger $v_{3,4}$ fluctuations

Path-length dependence

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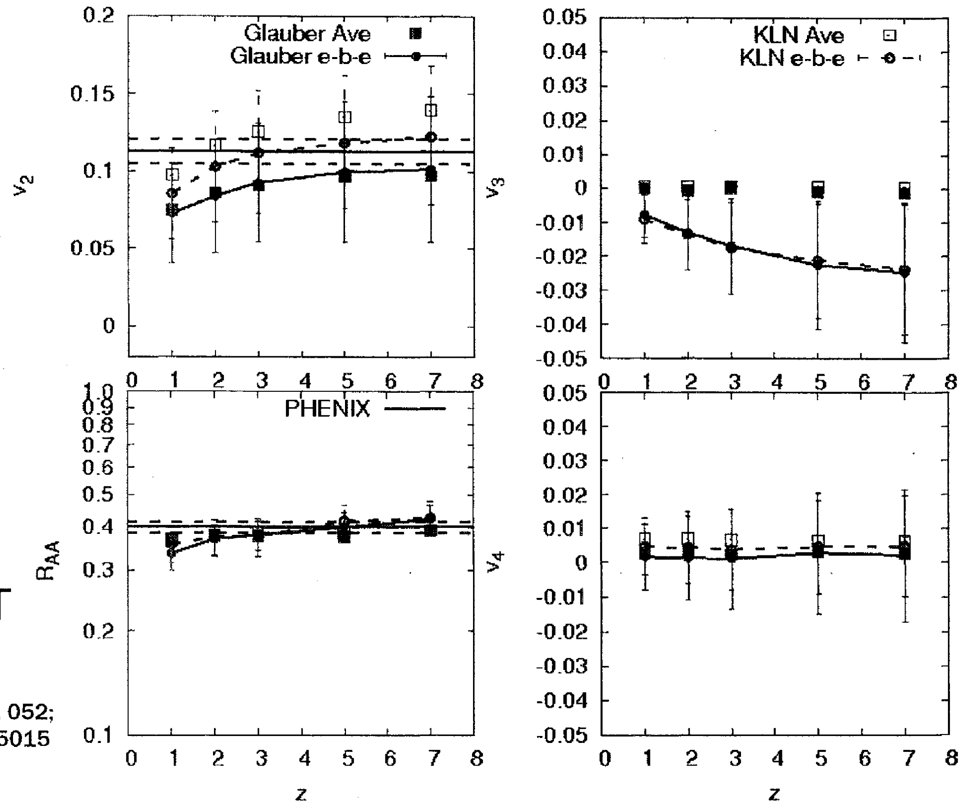
- Study the path-length dependence at b=8fm:
  - Once R_{AA} is fixed via κ,
  - sensitivity remains mostly for v_2 and v_3

➔ saturation effect occurs for larger z

→ described by AdS/CFT off-shell partons

S. Gubser et. al., JHEP **0810** (2008), 052;
P. Chesler et.al., PRD **79** (2009) 125015



- Measurement of virtuality in jet-photon collisions & $v_{2,3}$ could lead to signature of AdS/CFT dynamics & microscopic mechanism of energy loss.

Conclusions

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- Introduced a generic energy loss model, exploring $\Delta E \sim P^a$ and l^z
- Investigated higher Fourier harmonics of jet quenching

  ➔ Showing that they are *remarkably insensitive* to the Glauber and CGC model initial conditions

- Studied the path-length dependence for larger exponents

  → while z=2 reproduces the measured v_2 well, a *saturation effect* occurs for larger exponents

  ➔ favoring an AdS/CFT energy loss

➔ It is necessary to always determine the mean and the with of correlation!

COLLECTIVE FLOW AND LONG-RANGE CORRELATIONS IN HEAVY-ION COLLISIONS

Matthew Luzum

Institut de physique théorique
CEA/Saclay, France

February 3, 2010

Summary: Making use of recently released data on dihadron correlations by the STAR collaboration, I analyze the long-range ("ridge-like") part of these data and show that the dependence on both transverse momentum as well as orientation with respect to the event plane are consistent with correlations expected from only collective flow. In combination with previously analyzed centrality-dependent data, they provide strong evidence that only collective flow effects are present at large relative pseudorapidy. Based on arXiv:1011.5773 [nucl-th].

DOES COLLECTIVE FLOW EXPLAIN LONG-RANGE CORRELATION?

QUESTION:

What is the collective flow contribution to dihadron correlations at large $|\Delta\eta|$?

- Can it all be explained by collective flow (à la Alver & Roland, Sorenson, etc.)?
- Can use new STAR data (arXiv:1010.0690) to test, adding information about p_t dependence as well as orientation with respect to the event plane, complementing the previously-studied centrality dependence.
- (Spoiler: yes it can! There is no compelling evidence of non-flow correlations at large $|\Delta\eta|$)

What we expect from collective flow

Collective flow: particles emitted according to 1-particle distribution

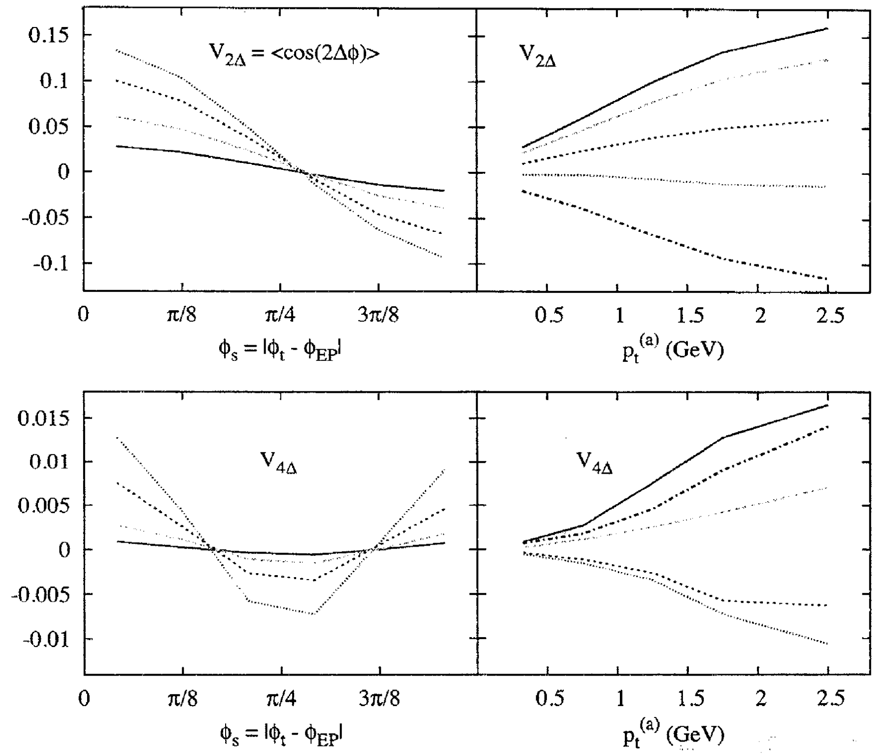
$$\frac{dN}{dY\, d^2p_t} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \psi_n) = \sum_{n=-\infty}^{\infty} v_n e^{in\psi_n} e^{-in\phi},$$

In a given event, 2-particle distribution determined by 1-particle distribution, $P(\phi_1, \phi_2) = P(\phi_1)P(\phi_2)$:

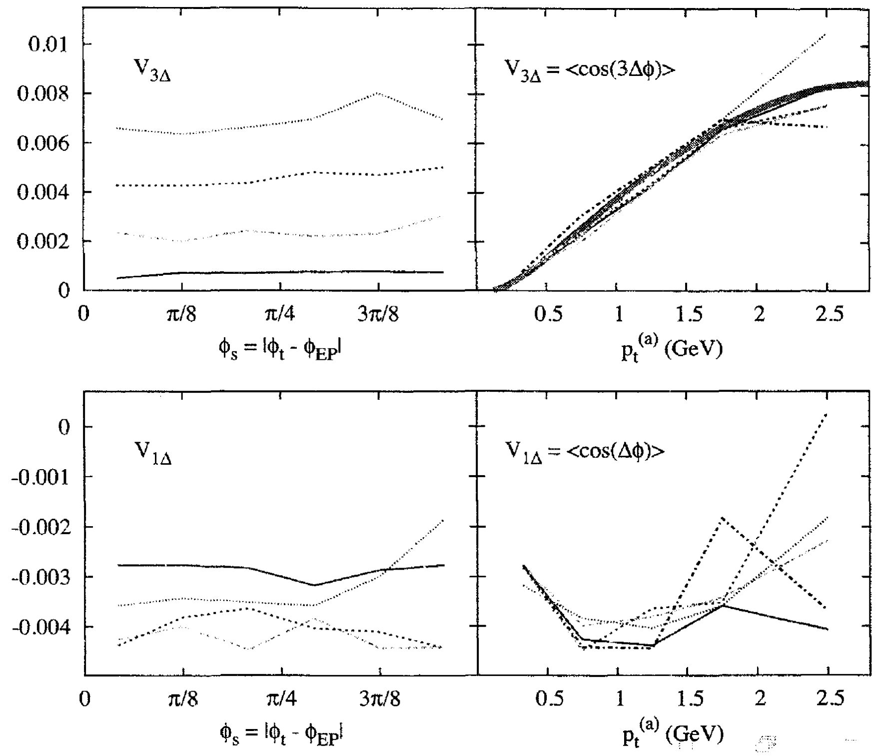
$$\begin{aligned} V_{n\Delta} \equiv & \langle \cos(n\Delta\phi) \rangle = \mathrm{Re}\langle e^{in(\phi_a - \phi_t)} \rangle \\ = & \langle \cos(n\phi_a - n\psi_n) \rangle \langle \cos(n\phi_t - n\psi_n) \rangle \\ \equiv & v_n^{(a)} v_n^{(t)} \end{aligned}$$

As expected from flow, only the first few Fourier componants $V_{n\Delta}$ are non-negligible, and follow the expected behavior with respect to p_t and event plane orientation:

$\langle\cos(2\Delta\phi)\rangle$ — ELLIPTIC FLOW, $\langle\cos(4\Delta\phi)\rangle$ — QUADRANGULAR FLOW



$\langle\cos(3\Delta\phi)\rangle$ — TRIANGULAR FLOW, $\langle\cos(\Delta\phi)\rangle$ — DIRECTED FLOW AND p_t CONSERVATION



SUMMARY

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To be consistent with data, a non-flow signal must have:

1. Odd harmonics with no dependence on ϕ_s
2. A second harmonic with monotonically decreasing dependence on ϕ_s
3. A fourth harmonic that decreases and then increases with ϕ_s
4. p_t dependence that is identical to flow

I.e., it must have all of the same properties as flow

More likely: there are only collective flow correlations at large $\Delta\eta$

The second coming of hydro: The shocks and sounds

Edward Shuryak

Department of Physics and Astronomy, Stony Brook University

•"Tiny Bangs" on top of the "Little Bang", from (i) the initial state fluctuations and (ii) jets.

• Sound horizon and viscous horizon can be determined

• Linear approximation: No need for "event-by-event" hydro, Green function from a point perturbation is analytically found for Gubser flow. V_n/e_n gets oscillatory at higher n.

•Jet/fireball edge should be visible, for large energy loss, if pt is tuned to 2-3 GeV. Perhaps it is already seen, on e-by-e basis!

•Phases of higher harmonics need to be measured, it can be done

•Either by 3-body correlators or 2-body in respect to reaction plane. Conditions $n_1+n_2+n_3=0$ and includes specific comb. Of phases

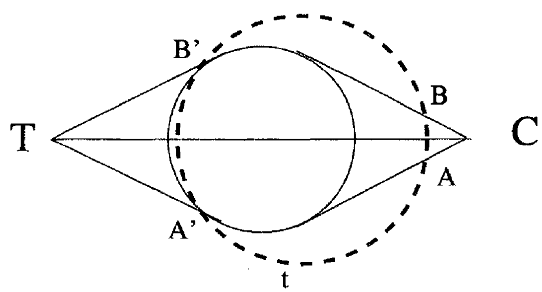
Jet/Fireball Edge should be observable!

Edward Shuryak

Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794

(Dated: January 26, 2011)

Shock/sound propagation from the quenched jets have well-defined front, separating the fireball into regions which are and are not affected. While even for the most robust jet quenching observed this increases local temperature and flow of ambient matter by only few percent at most, strong radial flow increases the contrast between the two regions so that the difference should be well seen in particle spectra at some p_t, perhaps even on event-by-event basis. We further show that the effect comes mostly from certain ellipse-shaped 1-d curve, the intercept of three 3-d surfaces, the Mach cone history, the timelike and spacelike freezeout surfaces. We further suggest that this "edge" is already seen in an event released by ATLAS collaboration.



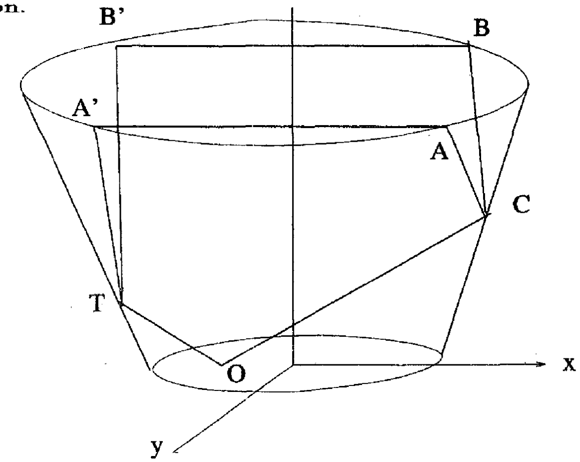
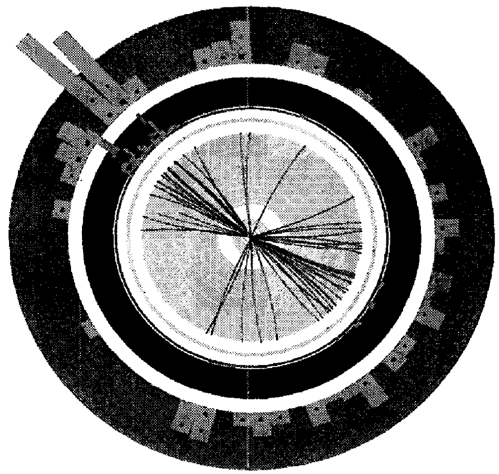


FIG. 1: Schematic shape of the Mach surface in the transverse x, y plane at $z = 0$ and fixed time (upper plot), as well as its shape in 3d including the (proper longitudinal) time (lower plot). Mach surface σ_M is made of two parts, $OCAA'T$ and $OCBB'T$. For more explanations see text.

The angular edge of the jets

$$\Delta\phi = \pm \frac{H s(t, t_f)}{R}$$



- ATLAS event, same a shown above, in which there is no identifiable jet
- Tracks pt>2.6 GeV, cal. E>1GeV/cell
- Note the sharp edge of the away-side perturbation! **Is it a “frozen sound“?**

Two new fundamental scales, describing fluctuations **at freezeout**

(P.Staig,ES)

1.The sound horizon:
radius

$$H_s = \int_0^{\tau_f} d\tau c_s(\tau)$$

2.The viscous horizon:
The width of the circle

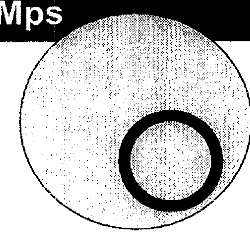
$$\delta T_{\mu\nu}(t) = exp\left(-\frac{2}{3}\frac{\eta}{s}\frac{k^2 t}{3T}\right)\delta T_{\mu\nu}(0)$$

$$k_v = \frac{2\pi}{R_v} = \sqrt{\frac{3Ts}{2\tau_f \eta}} \sim 200 MeV$$

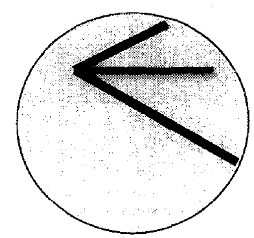
Let us finish this section by pointing our the hierarchy relation between all those four scales which we assume is true

$$R > H_s > R_v > l \qquad (2.8)$$

For the Big Bang it was introduced by Sunyaev-Zeldovich about 40 years ago, was observed in CMB and galaxy correlations, it is about 150 Mps

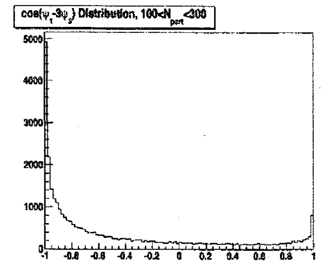


cylinders



cones

Non-central collisions, no integral => n1+2=n2, such as 1+2=3,3+2=5



"tips" => all angles are about 90°

Let us present some details about this case, which will illustrate a general case. Let us make a simplification, writing only the second harmonics in the weight and ignoring small fluctuations in the magnitude and the angle ψ_2 around $\pi/2$ (see Fig.6b)

$$W(\psi_p) = 1 + 2W_2 cos(2(\psi_p - \pi/2)) + ... \quad (4.10)$$

where $W_2 \approx 0.95$.One can then calculate any moments of the 2-body distribution, for example the one corresponding to 1+2=3 term

experiment

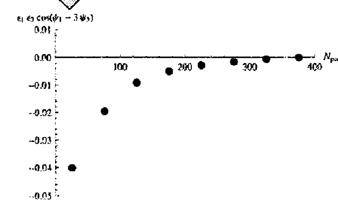
$$\int \frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi} cos\,(\phi_1 - 3\phi_2) < \frac{d^2N}{d\phi_1 d\phi_2} > |_W$$

$$\approx -W_2(\frac{v_1}{\epsilon_1})(\frac{v_3}{\epsilon_3}) < \epsilon_1\epsilon_3 cos(3\psi_3 - \psi_1) >$$

Glauber (or other initial state model)

hydro

we have separated the ratios $v_1/\epsilon_1, v_3/\epsilon_3$ (which are calculable by hydrodynamics) from the subsequent angular bracket containing the initial state deformations and their phases: those are to be averaged over the ensemble of initial conditions. For example, calculated in the Glauber model as explained at the beginning of the paper we obtain



The Fate of the Initial State Fluctuations in Heavy Ion Collisions.
III Sound propagation on top of expanding fireball

Pilar Staig and Edward Shuryak

Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794

(Dated: December 29, 2010)

Comoving coordinates with Gubser flow:

Gubser and Yarom, arXiv:1012.1314

$$\sinh\rho = -\frac{1-q^2\tau^2+q^2r^2}{2q\tau}$$
$$\tan\theta = \frac{2qr}{1+q^2\tau^2-q^2r^2}$$

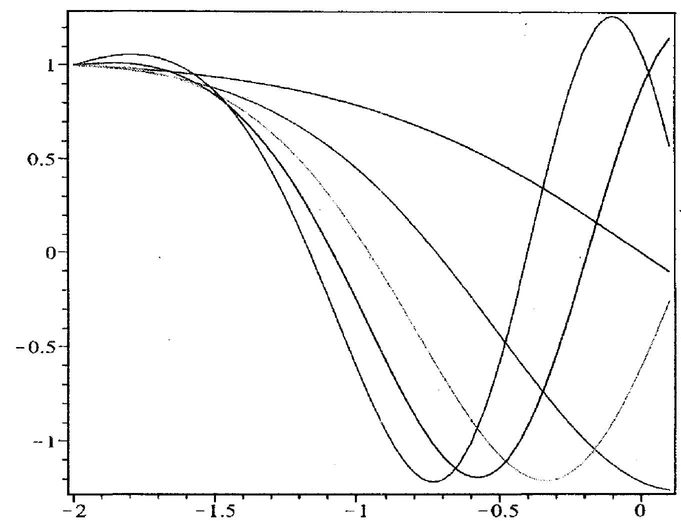
$$\frac{\partial^2\delta}{\partial\rho^2} - \frac{1}{3\cosh^2\rho}\left(\frac{\partial^2\delta}{\partial\theta^2} + \frac{1}{\tan\theta}\frac{\partial\delta}{\partial\theta} + \frac{1}{\sin^2\theta}\frac{\partial^2\delta}{\partial\phi^2}\right) + \frac{4}{3}\tanh\rho\frac{\partial\delta}{\partial\rho} = 0 \qquad (3.16)$$

We have seen that in the short wavelength approximation we found a wave-like solution to equation 3.16, but now we would like to look for the exact solution, which can be found by using variable separation such that $\delta(\rho,\theta,\phi) = R(\rho)\Theta(\theta)\Phi(\theta)$, then

$$R(\rho) = \frac{C_1 P^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho) + C_2 Q^{2/3}_{-\frac{1}{2}+\frac{1}{6}\sqrt{12\lambda+1}}(\tanh\rho)}{(\cosh\rho)^{2/3}}$$
$$\Theta(\theta) = C_3 P_l^m(\cos\theta) + C_4 Q_l^m(\cos\theta)$$
$$\Phi(\phi) = C_5 e^{im\phi} + C_6 e^{-im\phi} \qquad (3.26)$$

where $\lambda = l(l+1)$ and P and Q are associated Legendre polynomials. The part of the solution depending on θ and ϕ can be combined in order to form spherical harmonics $Y_{lm}(\theta,\phi)$, such that $\delta(\rho,\theta,\phi) \propto R_l(\rho)Y_{lm}(\theta,\phi)$.

Different harmonIcs l=1,3,5,7,9



t is actually rho, lhs (rho=-2) is initiation time and r.h.s. is FO time

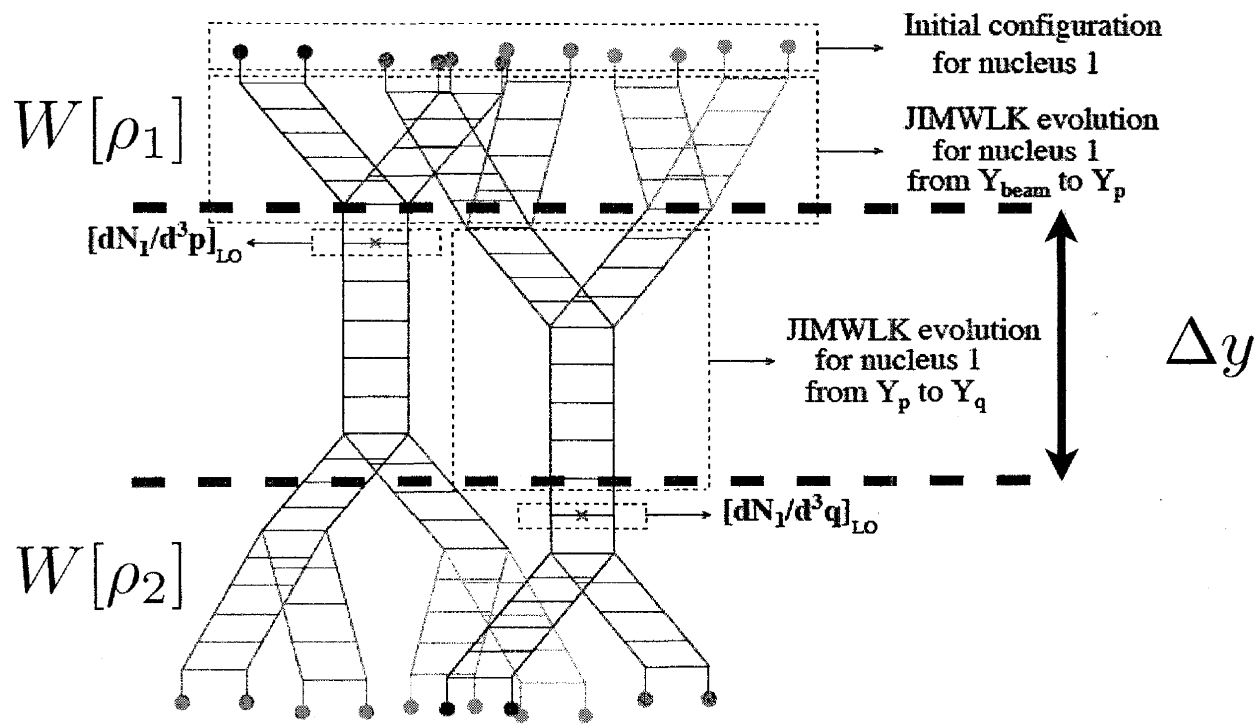
Ridge correlations and high energy QCD evolution

NC STATE UNIVERSITY

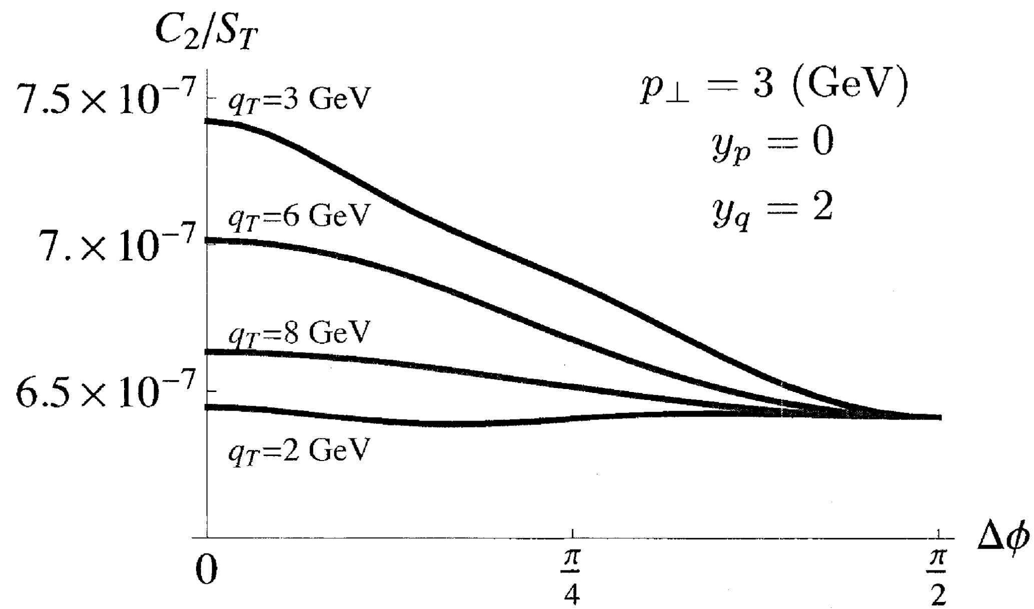
Kevin Dusling

February 4^{th} 2011

Double inclusive gluon production

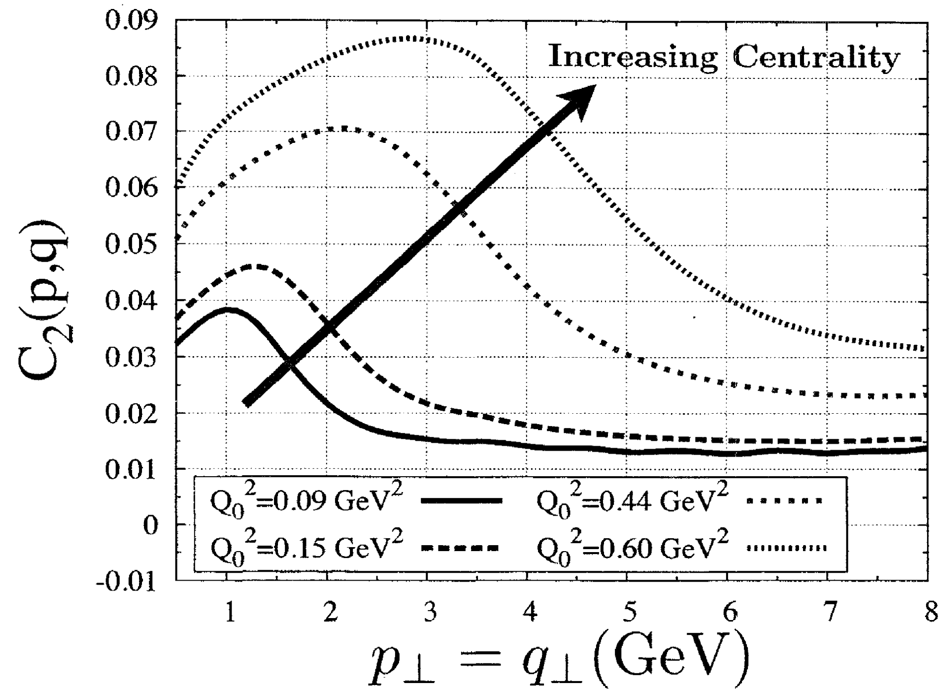


p_T systematics I

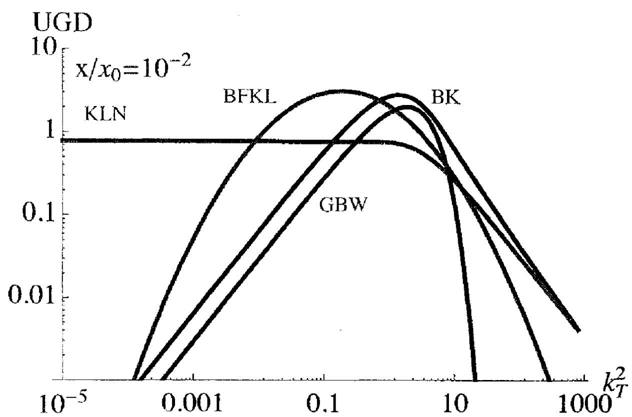


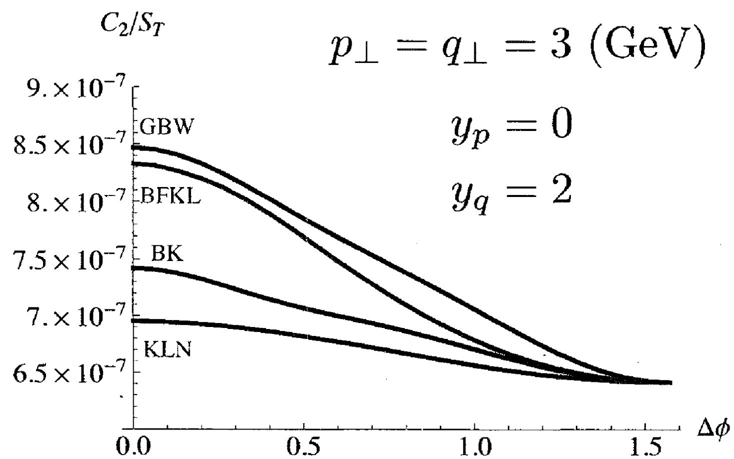
As expected, ridge disappears for $p_\perp \neq q_\perp$.

p_T systematics II



Role of wavefunction





$p_\perp = q_\perp = 3$ (GeV)

$y_p = 0$

$y_q = 2$

Ridge sensitive to diffusiveness of wavefunction

Conclusions

1. Quantum corrections to the nuclear wave function at high energy
   - introduce rapidity dependent corrections to di-hadron correlations
   - lead to angular correlations in multi-gluon production

2. The ridge in proton-proton collisions is a sensitive probe of the universal wavefunction of the proton

Fluctuating Valence Charges and the CGC

Yasushi Nara (Akita International Univ.)
with the collaboration with A. Dumitru

Abstract:
We introduce the Monte-Carlo version of kt-formula to simulate fluctuating Valence charged in CGC. It is important to take into account this fluctuation for centrality dependence of multiplicity. We also consider the effect of impact parameter dependence by assuming the Gaussian shape of nucleon.

- Monte-Carlo version of KLN (MCKLN)
- Eccentricity from CGC (KLN).
- Monte-Carlo version of kt-factorization with rcBK (MCrcBK)
- impact parameter dependent MCrcBK (bMCrcBK)

RIKEN-BNL Research Center Workshop Feb. 2-4, 2011

Monte-Carlo version of KLN (MC-KLN)

- Sample A and B nucleons according to the Woods-Saxon distribution.
- Nucleon-nucleon collision will occur if $(x_i - x_j)^2 + (y_i - y_j)^2 \leq \frac{\sigma_{NN}}{\pi}$
- Local density of nucleons at each grid is obtained by

$$t_A(\boldsymbol{r}_\perp) = \frac{\text{number of nucleons}}{S}$$

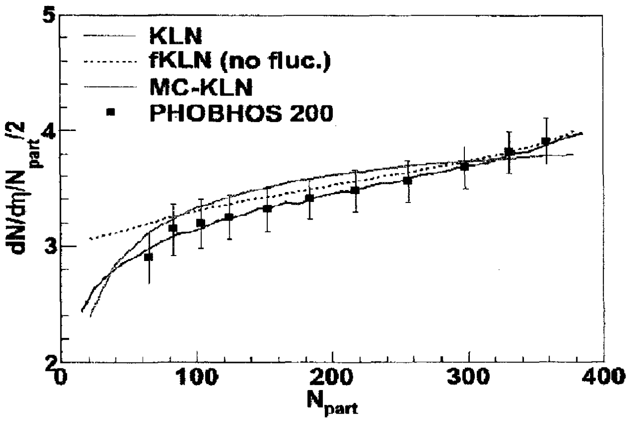
which is used to simulate coherent scattering

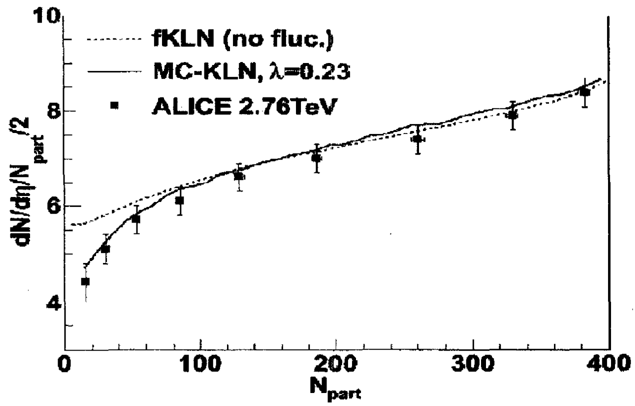
- Saturation scale at a given transverse coordinate is given by

$$Q_{s,A}^2(\boldsymbol{r}_\perp) = 2\text{GeV}^2 \left(\frac{t_A(\boldsymbol{r}_\perp)}{1.53}\right) \left(\frac{0.01}{x}\right)^\lambda$$

- For each generated configuration, we apply the k_t-factorization formula at each transverse grid.

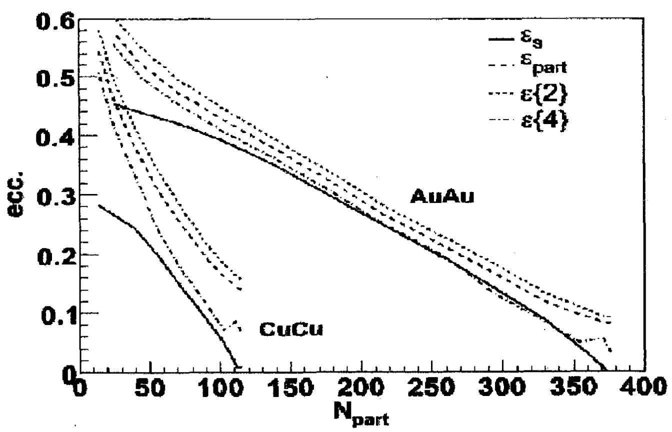
Centrality dependence at y=0





$$\frac{1}{N_{\mathrm{part}}}\frac{dN}{dy} = c\ln\left(\frac{Q_s^2}{\Lambda_{\mathrm{QCD}}^2}\right)$$

The effect of fluctuation is seen in the peripheral collisions (Npart < 200).



MC version of kt-factorization with running coupling BK (rcBK) wave function

implemented by A.Dumitru by using the solution of rcBK from J. L. Albacete.

It is available from

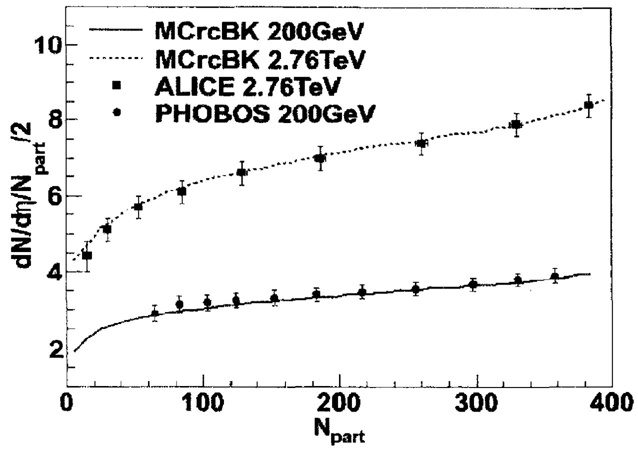
http://physics.baruch.cuny.edu/node/people/adumitru/res_cgc

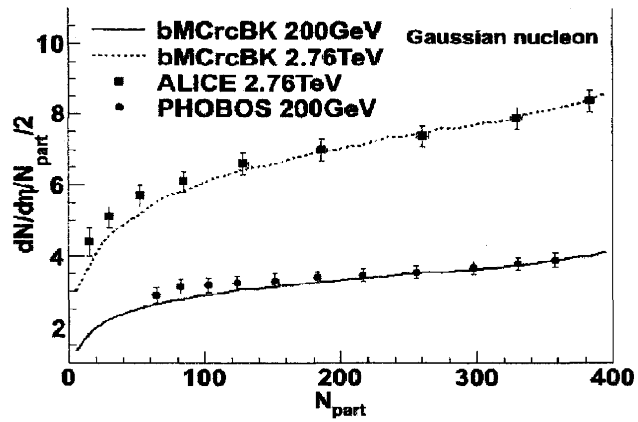
$$\varphi(k,x,b) = \frac{C_F}{\alpha_s(k)\,(2\pi)^3} \int d^2\mathbf{r}\; e^{-i\mathbf{k}\cdot\mathbf{r}}\, \nabla^2_{\mathbf{r}} \mathcal{N}_G(r, Y = \ln(x_0/x), b)$$

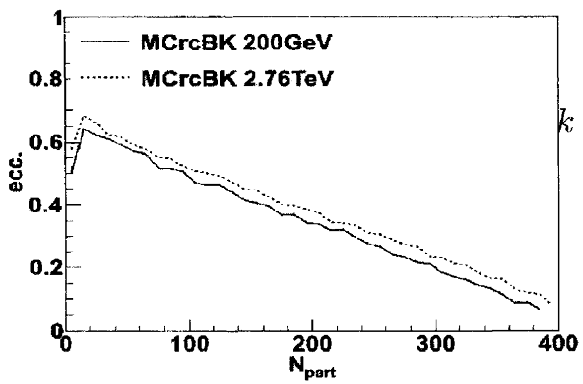
$\mathcal{N}_G$ is related to the quark dipole scattering amplitude from rcBK eq.

$$\mathcal{N}_G(r,x) = 2\,\mathcal{N}(r,x) - \mathcal{N}^2(r,x)\,.$$

MC version of kt-factorization with rcBK wave function







NN collision probability $P(b) = 1 - \exp[-kT_{pp}(b)]$

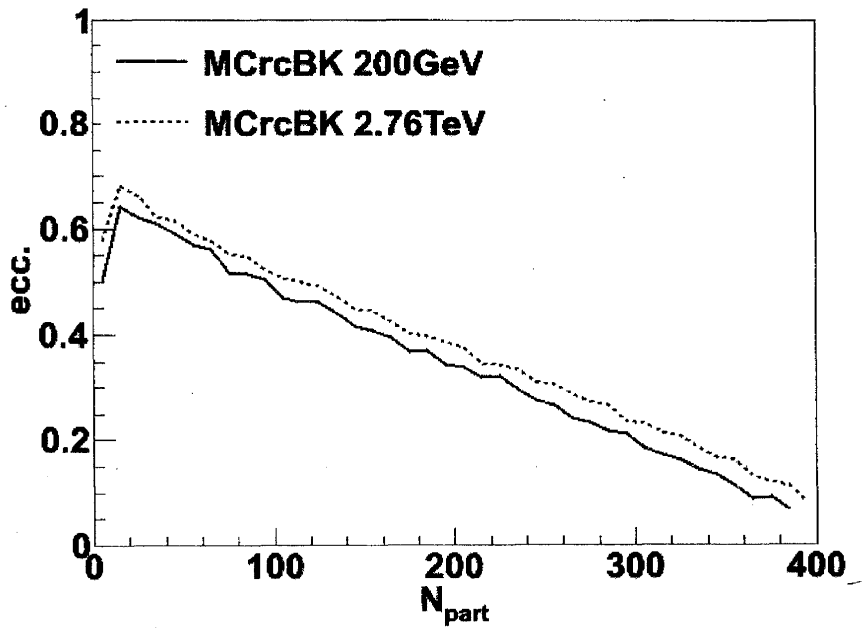
k is fixed by the relation $\sigma_{in} = \int d^2b\,(1 - \exp[-kT_{pp}(b)])$

$$T_{pp}(b) = \int d^2 s T_p(s) T_p(s-b)$$

$$T_p(r) = \frac{1}{2\pi B}\exp[-r^2/(2B)]$$

NN collision probability $P(b) = 1 - \exp[-kT_{pp}(b)]$

eccentricity from MCrcBK



No incident energy dependence for eccentricity

Triangular Flow and Di-hadron Azimuthal Correlations

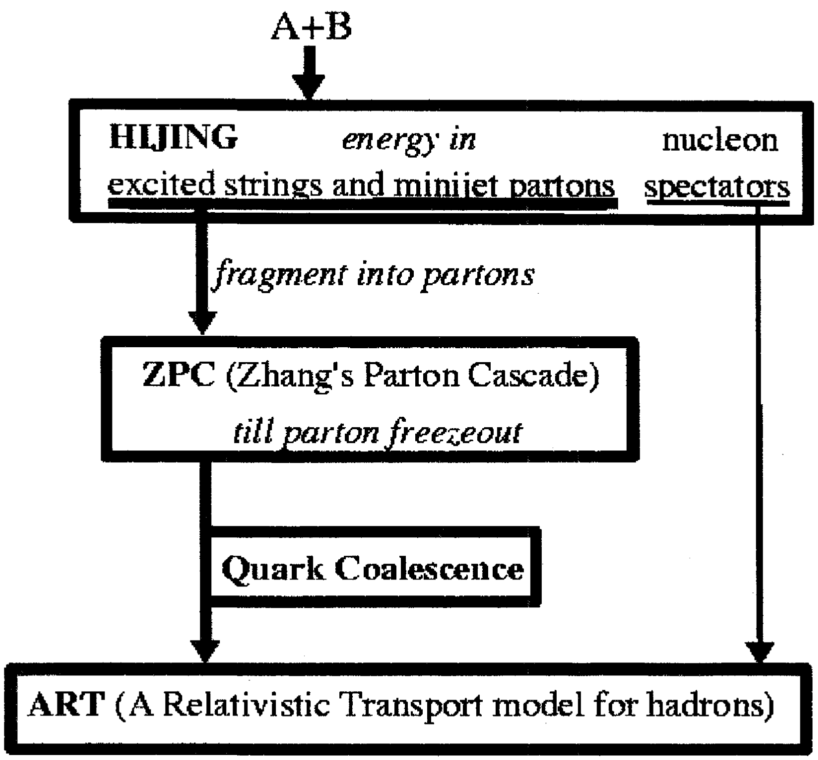
Jun Xu[1]

[1] *Cyclotron Institute, Texas A&M University, College Station, TX 77843-3366, USA*

The di-hadron azimuthal angular correlations in Au+Au collisions at center of mass energy $\sqrt{s_{NN}} = 200$ GeV and impact parameter $b = 8$ fm have been studied by using the AMPT model. The away-side double-peak structure is obtained after subtracting background correlations due to the elliptic flow. Both the near-side peak and the away-side double peaks in the azimuthal angular correlations are significantly suppressed (enhanced) in events of small (large) triangular flow, which are present as a result of fluctuations in the initial collision geometry. After subtraction of background correlations due to the triangular flow, the away-side double peaks change into a single peak with broad shoulders on both sides. The away side of the di-hadron correlations becomes essentially a single peak after subtracting background correlations due to flows up to the 5th order.

A multiphase transport (AMPT) model with string melting

Structure of AMPT model with string melting



Parton scattering cross section in ZPC:

$$\frac{d\sigma}{dt} = \frac{9\pi\alpha_s^2}{2(t-\mu^2)^2}$$

$$\sigma \approx \frac{9\pi\alpha_s^2}{2\mu^2}$$

Total cross section for parton scattering is set to be 10 mb to compensate for the neglected higher-order inelastic processes.

Total correlation: < >$_{e:}$ average over all events

$$\frac{dN_{pair}}{d\Delta\phi} = \left\langle \int f^{trig}(\phi) f^{asso}(\phi + \Delta\phi) d\phi \right\rangle_e$$

$$= \frac{1}{2\pi}\left[\left\langle N^{trig} N^{asso} \right\rangle_e + 2\sum_{n=2}^{\infty} \left\langle N^{trig} v_n^{trig} N^{asso} v_n^{asso} \right\rangle_e \cos(\Delta\phi) \right]$$

due to jet correlation and anisotropic flow.

Background correlation:

$$\left(\frac{dN_{pair}}{d\Delta\phi}\right)_{back} = \frac{1}{2\pi}\left[\left\langle N^{trig} \right\rangle_e \left\langle N^{asso} \right\rangle_e + 2\sum_{n=2}^{\infty} \left\langle N^{trig} v_n^{trig} \right\rangle_e \left\langle N^{asso} v_n^{asso} \right\rangle_e \cos(n\Delta\phi) \right]$$

$$= \frac{\left\langle N^{trig} \right\rangle_e \left\langle N^{asso} \right\rangle_e}{2\pi}\left[1 + 2\sum_{n=2}^{\infty} \frac{\left\langle N^{trig} v_n^{trig} \right\rangle_e}{\left\langle N^{trig} \right\rangle_e} \frac{\left\langle N^{asso} v_n^{asso} \right\rangle_e}{\left\langle N^{asso} \right\rangle_e} \cos(n\Delta\phi) \right]$$

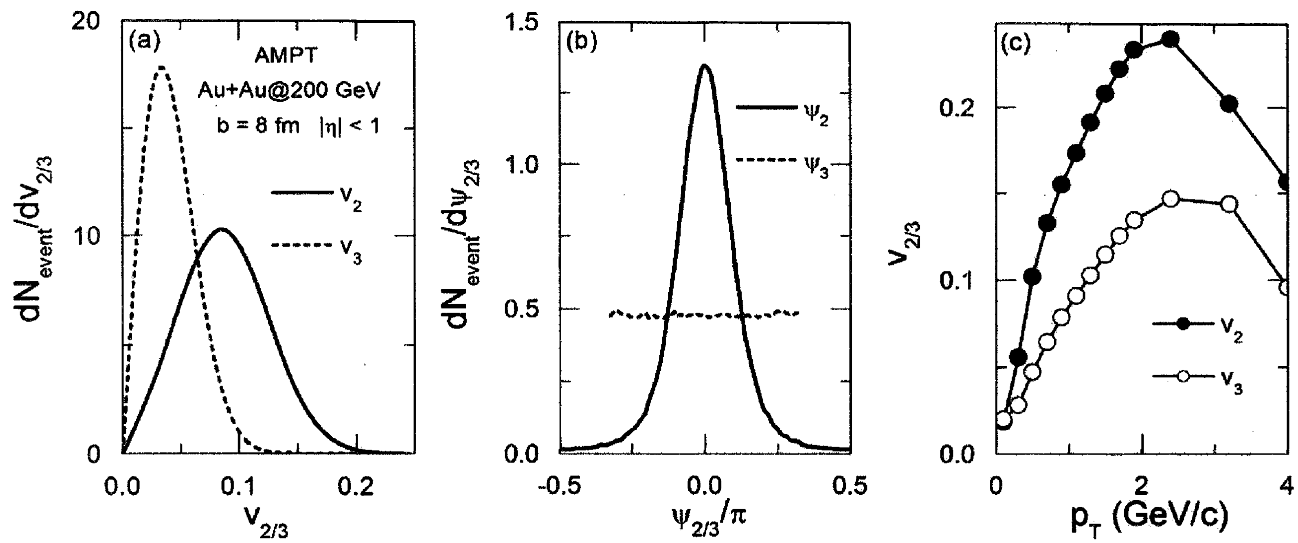
due to anisotropic flow.

Results and discussions

We study Au+Au collisions at $\sqrt{s_{NN}} = 200\,GeV$ with b = 8 fm (about 30% centrality).

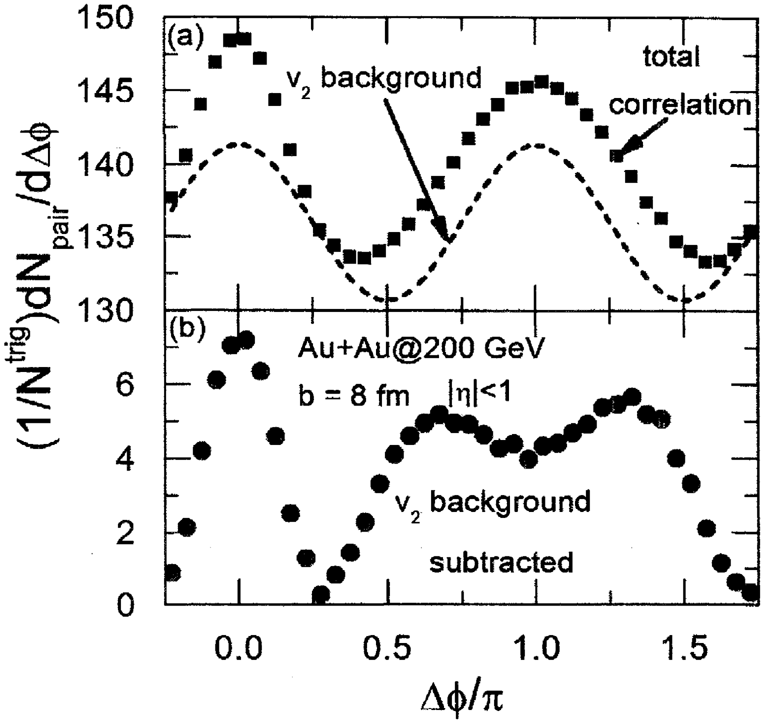
event plane: $\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{\langle \sin(n\phi)\rangle}{\langle \cos(n\phi)\rangle}\right)$ anisotropic flow: $v_n = \langle \cos[n(\phi - \Psi_n)]\rangle$

p_T dependence: $v_n(p_T) = \langle \cos[n(\phi - \Psi_n)]\rangle_{p_T}$ $\quad \langle v_n\rangle_e(p_T) = \frac{\langle N(p_T)v_n(p_T)\rangle_e}{\langle N(p_T)\rangle_e}$



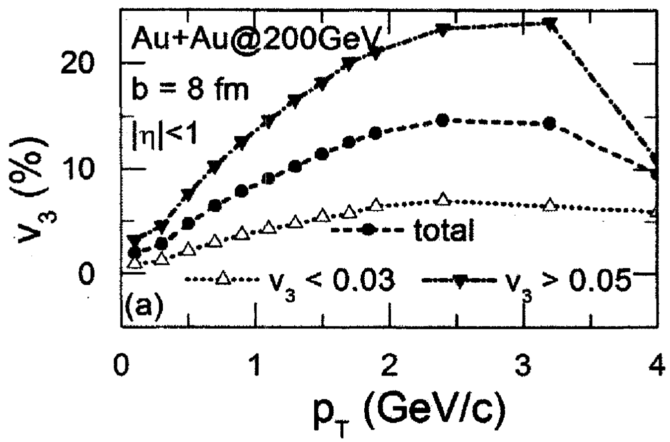
$$0.15\,GeV/c < p_T^{asso} < 2.5\,GeV/c$$

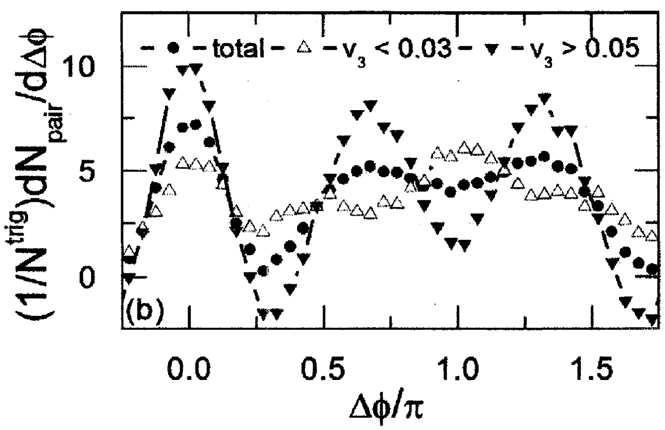
$$2.5\,GeV/c < p_T^{trig} < 6\,GeV/c$$

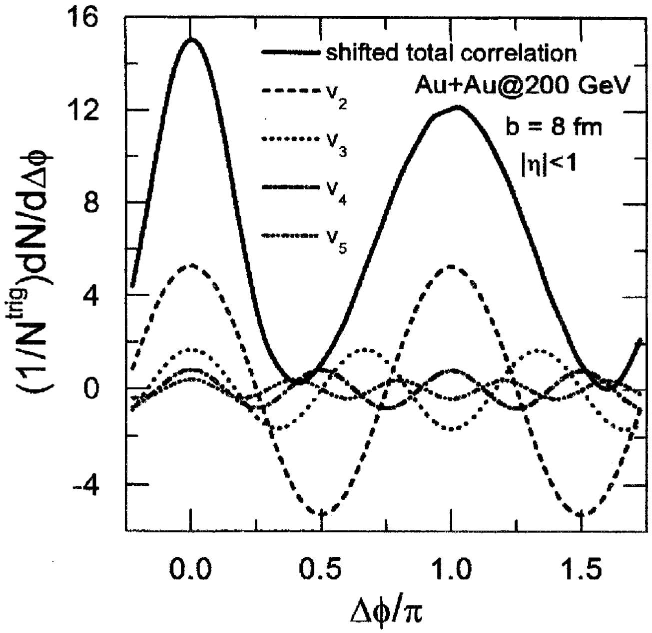


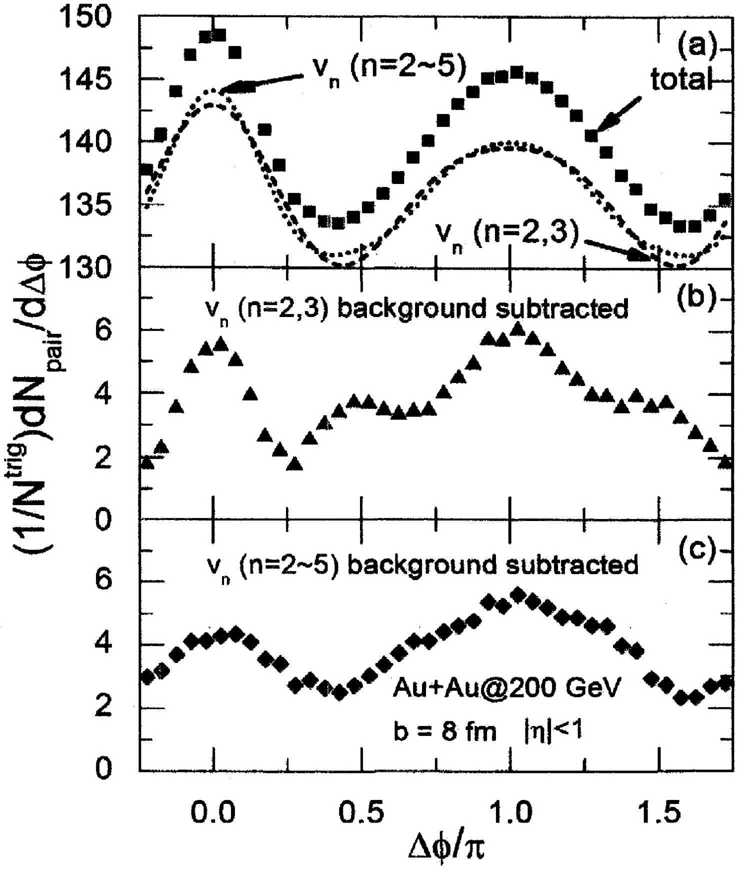
The away-side double peaks are observed after subtracting the background of v_2.

All the peaks are enhanced (suppressed) in events of larger (smaller) v_3 after subtracting the background of v_2.









Higher-order anisotropic flows contribute to the di-hadron correlation.

They should also be subtracted to get back-to-back jet corrrelation.

Event-by-event Shape and Flow Fluctuations in RHIC Fireballs*

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presented at
RBRC Workshop on
Initial-State Fluctuations and Final-State Particle Correlations
Brookhaven National Laboratory, 2-4 February 2011

In collaboration with Zhi Qiu

*Supported by the U.S. Department of Energy (DOE)

Eccentricity definitions:

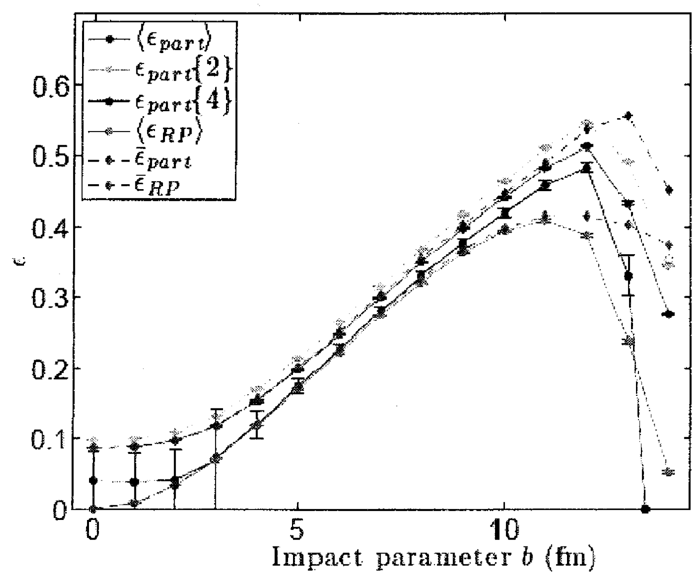
Define event average $\{\dots\}$, ensemble average $\langle\dots\rangle$

Two choices for weight function in event average: (i) Energy density $e(\boldsymbol{x}_\perp; b)$
(ii) Entropy density $s(\boldsymbol{x}_\perp; b)$

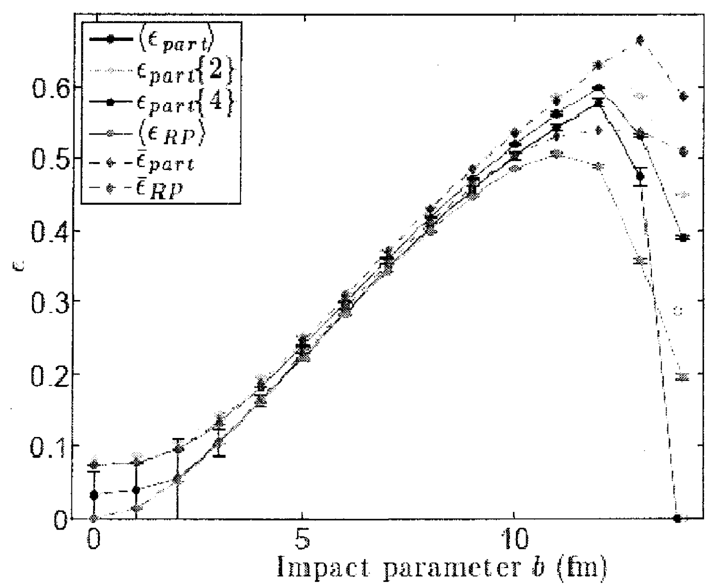
Define $\sigma_x^2 = \{x^2\} - \{x\}^2$, $\sigma_{xy} = \{xy\} - \{x\}\{y\}$, etc.,
where x, y are reaction-plane coordinates ($\boldsymbol{e}_x \parallel \boldsymbol{b}$)

1. Standard eccentricity: $\varepsilon_s \equiv \bar{\varepsilon}_{\rm RP} = \frac{\langle\sigma_y^2 - \sigma_x^2\rangle}{\langle\sigma_y^2 + \sigma_x^2\rangle}$ (calculated from RP-averaged $\langle e\rangle$ or $\langle s\rangle$)
2. Average reaction-plane eccentricity: $\langle\varepsilon_{\rm RP}\rangle = \left\langle\frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}\right\rangle$
3. Eccentricity of the participant-plane averaged source: $\bar{\varepsilon}_{\rm part} = \frac{\sqrt{\langle(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2\rangle}}{\langle\sigma_y^2 + \sigma_x^2\rangle}$
4. Average participant-plane eccentricity: $\langle\varepsilon_{\rm part}\rangle = \left\langle\frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}\right\rangle$
5. r.m.s. part.-plane eccentricity: $\varepsilon_{\rm part}\{2\} \equiv \sqrt{\langle\varepsilon_{\rm part}^2\rangle}$ $\left(= \sqrt{\langle\varepsilon_{\rm part}\rangle^2 + \sigma_\varepsilon^2/2}\right.$ for Gauss. fl.)
6. 4th cumulant eccentricity: $\varepsilon_{\rm part}\{4\} \equiv \left[\langle\varepsilon_{\rm part}^2\rangle^2 - \left(\langle\varepsilon_{\rm part}^4\rangle - \langle\varepsilon_{\rm part}^2\rangle^2\right)\right]^{1/4}$
$\left(= \sqrt{\langle\varepsilon_{\rm part}\rangle^2 - \sigma_\varepsilon^2/2}\right.$ for Gauss. fl.)

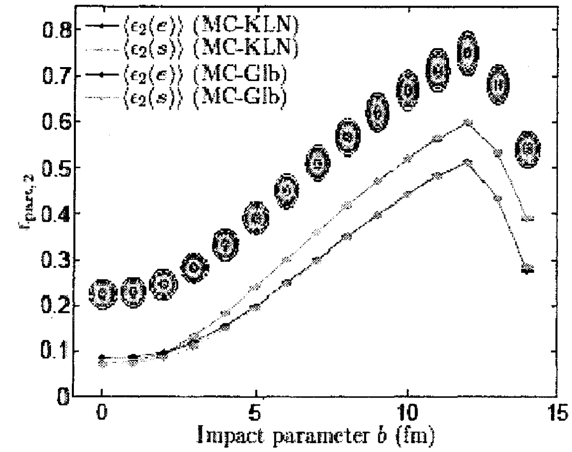
MC-Glauber eccentricities (e-weighted):



MC-KLN eccentricities (e-weighted):

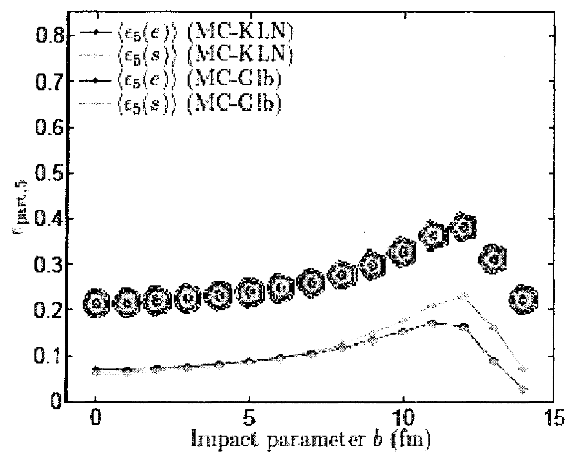


MC-Glauber vs. MC-KLN, e vs. s-weight



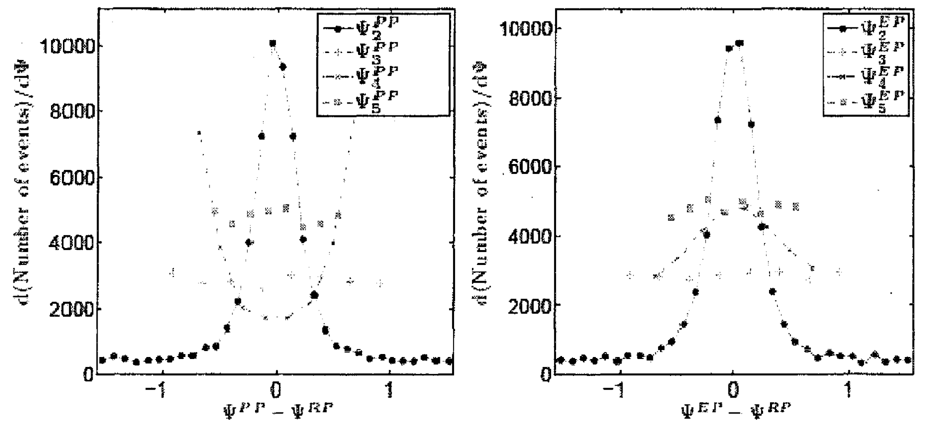
- Contours: $e(r,\phi) = e_0 \exp\left[-\frac{r^2}{2\rho^2}\left(1+\varepsilon_n \cos(n(\phi-\psi_n))\right)\right]$ where $\varepsilon_n e^{in\psi_n} = -\frac{\int r dr d\phi\, r^2 e^{in\phi}\, e(r,\phi)}{\int r dr d\phi\, r^2\, e(r,\phi)}$
- MC-KLN: little difference between eccentricities of energy and entropy density profiles
- MC-Glauber: For near-central collisions, energy density $\sim 20\%$ more eccentric than entropy density
- Except for the two most central bins, MC-KLN gives $\sim 20\%$ larger eccentricity than MC-Glauber

Fifth order harmonic



- Contours: $e(r,\phi) = e_0 \exp\left[-\frac{r^2}{2\rho^2}\left(1+\varepsilon_5 \cos(5(\phi-\psi_5))\right)\right]$ for MC-KLN
- Little difference between MC-Glauber and MC-KLN, except in peripheral collisions
- $\varepsilon_{\text{part},5} \lesssim \varepsilon_{\text{part},2}$ in central collisions, $\varepsilon_{\text{part},5} \sim \varepsilon_{\text{part},3}$ in peripheral collisions
- Little difference between $\langle\varepsilon_5\rangle$ of energy and entropy densities, except for MC-Glauber in most central bins
- At large b, large enough $\langle\varepsilon_5\rangle$ to cause cross-currents in v_5

Flow angle distributions (0–60% centrality):

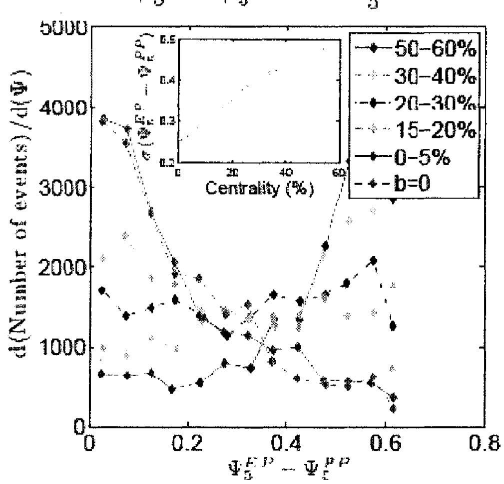


$$\varepsilon_n e^{in\psi_n^{\rm PP}} = -\frac{\int r dr d\phi\, r^2 e^{in\phi} e(r,\phi)}{\int r dr d\phi\, r^2 e(r,\phi)} \qquad \varepsilon_n e^{in\psi_n^{\rm EP}} = -\frac{\int d\phi_p\, e^{in\phi_p} (dN/d\phi_p)}{\int d\phi_p\, (dN/d\phi_p)}$$

- Angles of $\varepsilon_{3,5}$ and $v_{3,5}$ uncorrelated with reaction plane (Qin et al., PRC 82 (2010) 064903)
- v_4-angle $\psi_4^{\rm EP}$ lies (on average) in the reaction plane even though ε_4-angle $\psi_4^{\rm PP}$ points at $\pm\frac{\pi}{4} = \pm 45^\circ \Longrightarrow v_4$ driven mostly by elliptic deformation ε_2, not ε_4.

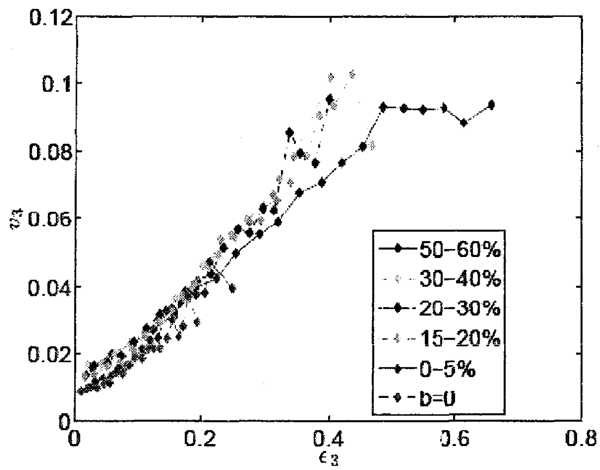
Correlation between flow and eccentricity angles:

$$\psi_5^{\rm EP} - \psi_5^{\rm PP} \mod \frac{\pi}{5}$$



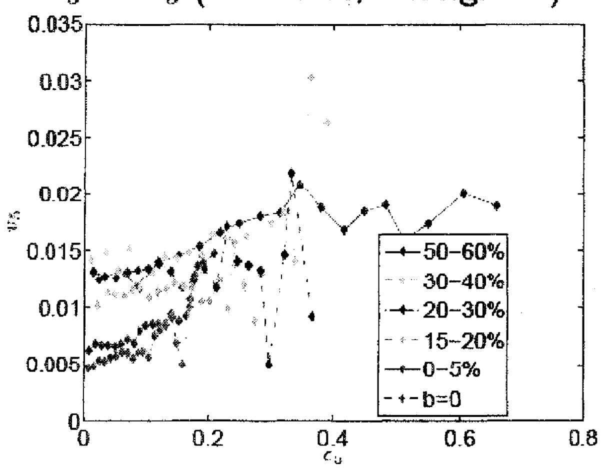
- Near-central collisions: $\psi_5^{\rm EP}$ (weakly) correlated with $\psi_5^{\rm PP} \Longleftrightarrow v_5$ driven by ε_5
- Peripheral collisions: $\psi_5^{\rm EP}$ (weakly) anti-correlated with $\psi_5^{\rm PP} \Longleftrightarrow v_5$ strongly influenced by $\varepsilon_{n\neq5}$
- Mid-central to mid-peripheral: no correlation between $\psi_5^{\rm EP}$ and $\psi_5^{\rm PP}$

Higher harmonic flows and associated eccentricities: v_3 vs. ε_3 (MC-KLN, e-weighted)



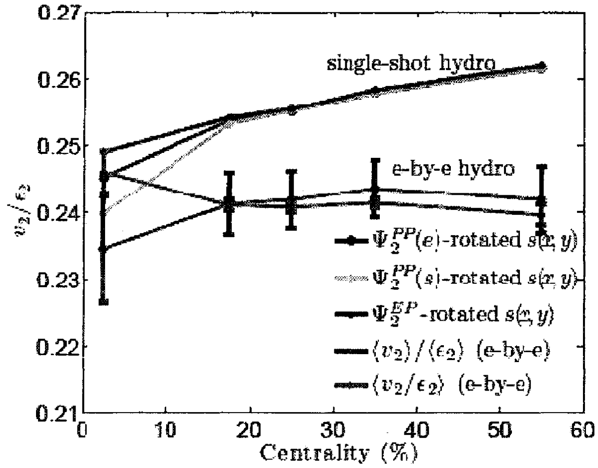
- Slope of $v_3(\epsilon_3)$ and value of v_3/ε_3 depend on centrality class
- Non-zero triangular flow $v_3 \sim 1-2\%$ even for zero triangularity ε_3
  $\Longrightarrow$ other (odd) harmonic eccentricity coefficients feed into v_3

Higher harmonic flows and associated eccentricities: v_5 vs. ε_5 (MC-KLN, e-weighted)



- Correlation between v_5 and ε_5 strongly centrality dependent
- In mid-central and peripheral collisions, v_5 is mostly generated by $\varepsilon_{n\neq5}$
- Even in central collisions, other $\varepsilon_{n\neq5}$ feed into v_5, generating non-zero v_5 for zero ε_5

Eccentricity-scaled elliptic flow (MC-KLN)



- Event-by-event hydro produces **4–6% less** v_2/ε_2 than single-shot hydro w/ smooth averaged initial profile
- This reduces $(\eta/s)_{QGP}$ estimates from data by about $0.02-0.03$
- This reduction in $(v_2/\varepsilon_2)_{ebe}$ may be smaller in viscous hydro; in central collisions, v_2/ε_2 from single-shot hydro is sensitive to initial-state averaging procedure [Note: all ε_2 are e-weighted]

Lessons to remember:

- ε_2 from smooth averaged energy density profile overestimates average eccentricity of peripheral collisions
  $\Longrightarrow$ single-shot hydro gives too much (!) v_2 for $\gtrsim 50-60\%$ centrality

- Eccentricity fluctuations are non-Gaussian for very central and very peripheral collisions

- Standard eccentricity is not a good substitute for $\varepsilon\{4\} \sim v\{4\}$

- Event-by-event hydro gives less v_2/ε_2 than single-shot hydro with averaged initial profile
  $\Longrightarrow$ estimates of $(\eta/s)_{QGP}$ from data comparisons with single-shot hydro somewhat too high.

- Correlation between higher harmonic flows $v_{n\geq 3}$ and their flow angles $\psi^{EP}_{n\geq 3}$ and the corresponding eccentricity coefficients $\varepsilon_{n\geq 3}$ and their angles $\psi^{PP}_{n\geq 3}$ is weak; significant cross-feeding between different harmonic coefficients

Initial State Fluctuations and Final-State Particle Correlations

February 2 – 4, 2011

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Updated 2/2/11

RBRC Workshop

Initial State Fluctuations and Final-State Particle Correlations

Organizers: Adrian Dumitru, Denes Molnar and Fuqiang Wang

Physics Department Large Seminar Room
February 2-4, 2011

	Wednesday (feb 2)	**Thursday (feb 3)**	**Friday (feb 4)**
8:45 – 9:00	Opening (Organizer)[1]	[2]	[3]
9:00 – 9:30	J. Chin-Hao Chen (Overview of dihadron correlations from PHENIX)	J. Putschke (The high-pT ridge at RHIC)	E. Shuryak (Sound Propagation in an Expanding Fireball)
9:30 – 10:00	F. Wang (How much is medium flow, how much is jet-medium interaction: An experimental perspective)	J. Jalilian-Marian (Di-jets and Ridges from CGC)	K. Dusling (Ridge correlations and high energy QCD evolution)
10:00 – 10:30	R. Lacey (Initial eccentricity fluctuations and their relation to higher-order flow harmonics)	A. Ayala (Away-side Hadron Correlations from NLO pQCD)	Y. Nara (Fluctuating Valence Charges and the CGC)
10:30 – 11:00	**Coffee Break**	**Coffee Break**	**Coffee Break**
11:00 – 11:30	G. Roland (Initial State Geometry Fluctuations and 2-particle Correlations)	K. Werner (Hydro Evolution Based on Flux Tube Initial Conditions	Jun Xu (Triangular Flow and Dihadron Azimuthal Correlations)
11:30 – 12:00	Y. Hama (Ridges in Hydro Approach)	A. Kovner (Angular Correlations in Gluon Emission at High Energy)	U. Heinz (Event-by-event Shape and Flow Fluctuations in RHIC Fireballs)
12:00 – 12:30	**Lunch**	**Lunch**	**Lunch**
12:30 – 1:00			
1:00 – 1:30	[4]	[5]	[6]
1:30 – 2:00	P. Sorensen (Dihadron Correlations from Initial State Density Fluctuations)	D. Teaney (Triangularity and Dipole Asymmetry in Heavy Ion Collisions)	Summary (X.N. Wang)
2:00 – 2:30	B. Schenke (Event-by-event hydrodynamic description of anisotropic flow and correlations at RHIC and LHC)	G. Qin (From geometry fluctuations to harmonic flows)	Discussion
2:30 – 3:00	G. Ma (Hot Spots, Harmonic Flow, Dihadron and γ-hadron Correlations in High-energy Heavy-ion Collisions)	H. Petersen (Initial State Fluctuations and Triangular Flow in Event-by-Event Ideal Hydrodynamics)	Discussion
3:00 – 3:30	**Coffee Break**	**Coffee Break**	
3:30 – 4:00	C. De Silva (The Near-side Long Range Correlation Structure in Two Particle Number Correlations at RHIC)	B. Betz (Jets and Fluctuating Initial Conditions)	
4:00 – 4:30	G. Torrieri (Mach cones from fluctuations in initial conditions)	M. Luzum (Collective flow and long-range correlations in heavy ion collisions)	
4:30 – 5:00			
5:00 – 5:30			
5:30 – 6:00		**Dinner for registered participants at Berkner Hall**	

1. Chair: P. Sorensen
2. Chair: R. Venugopalan
3. Chair: A. Dumitru
4. Chair: F. Wang
5. Chair: U. Heinz
6. Chair: A. Dumitru

Additional RIKEN BNL Research Center Proceedings:

Volume 101 – RBRC Scientific Review Committee Meeting, October 27-29, 2010 – BNL-94589-2011
Volume 100 – Summer Program on Nucleon Spin Physics, BNL, July 14-28, 2010
Volume 99 – The Physics of W and Z Bosons, BNL, June 24-25, 2010 – BNL-94287-2010
Volume 98 – Saturation, the Color Glass Condensate and the Glasma: What Have we Learned from RHIC?, BNL – May 10-12, 2010 – BNL-94271-2010
Volume 97 – RBRC Scientific Review Committee Meeting, October 21-22, 2009 – BNL-90674-2009
Volume 96 – P- and CP-Odd Effects in Hot and Dense Matter, April 26-30, 2010 – BNL-94237-2010
Volume 95 – Progress in High-pT Physics at RHIC, March 17-19, 2010 – BNL-94214-2010
Volume 94 – Summer Program on Nucleon Spin Physics at LBL, June 1-12, 2009
Volume 93 – PHENIX Spinfest School 2009 at BNL - July 1-31, 2009. BNL-90343-2009
Link: PHENIXSpinfestSchool2009@BNL
Volume 92 – PKU-RBRC Workshop on Transverse Spin Physics, June 30-July 4, 2008, Beijing, China, BNL-81685-2008
Volume 91 – RBRC Scientific Review Committee Meeting, November 17-18, 2008 – BNL-81556-2008
Volume 90 – PHENIX Spinfest School 2008 at BNL, August 4-8, 2008 - BNL-81478-2008
Volume 89 – Understanding QGP through Spectral Functions and Euclidean Correlators, April 23-25, 2008 – BNL-81318-2008
Volume 88 – Hydrodynamics in Heavy Ion Collisions and QCD Equation of State, April 21-22, 2008 – BNL-81307-2008
Volume 87 – RBRC Scientific Review Committee Meeting, November 5-6, 2007 – BNL-79570-2007
Volume 86 – Global Analysis of Polarized Parton Distributions in the RHIC Era, October 8, 2007 – BNL-79457-2007
Volume 85 – Parity-Violating Spin Asymmetries at RHIC-BNL, April 26-27, 2007 – BNL-79146-2007
Volume 84 – Domain Wall Fermions at Ten Years, March 15-17, 2007 – BNL 77857-2007
Volume 83 – QCD in Extreme Conditions, July 31-August 2, 2006 – BNL-76933-2006
Volume 82 – RHIC Physics in the Context of the Standard Model, June 18-23, 2006 – BNL-76863-2006
Volume 81 – Parton Orbital Angular Momentum (Joint RBRC/University of New Mexico Workshop) February 24-26, 2006 – BNL-75937-2006
Volume 80 – Can We Discover the QCD Critical Point at RHIC?, March 9-10, 2006 – BNL-75692-2006
Volume 79 – Strangeness in Collisions, February 16-17, 2006 – BNL-79763-2008
Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, Dec 12-14, 2005 – BNL-76915-2006
Volume 77 – RBRC Scientific Review Committee Meeting – BNL-52649-2005
Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005
Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005
Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005
Volume 73 – Jet Correlations at RHIC, March 10-11, 2005 – BNL-73910-2005
Volume 72 – RHIC Spin Collaboration Meetings XXXI(January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11, 2005) – BNL-73866-2005
Volume 71 – Classical and Quantum Aspects of the Color Glass Condensate – BNL-73793-2005
Volume 70 – Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic – BNL-73867-2005
Volume 69 – RBRC Scientific Review Committee – BNL-73546-2004
Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004
Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures
Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino Italy – BNL-73534-2004
Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6, 2004) – BNL-73506-2004
Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004
Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004
Volume 60 – Lattice QCD at Finite Temperature and Density – BNL-72083-2004

Additional RIKEN BNL Research Center Proceedings:

Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004
Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized pp Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
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Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
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Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723
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Initial State Fluctuations and Final-State Particle Correlations

February 2-4, 2011

Li Keran

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

<u>Speakers</u>

Alejandro Ayala
L. Chanaka DeSilva
Ulrich Heinz
Roy Lacey
Yasushi Nara
Guangyou Qin
Edward Shuryak
Giorgio Torrieri
Jun Xu
Barbara Betz
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Jamal Jalilian-Marian
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Derek Teaney
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