Introduction to Relativistic Heavy Ion Physics

Lecture 3: Approaching Perfection

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Reminder- From Lecture 2

- A new state of matter (QGP?) is formed in Au+Au collisions at RHIC
  - Densities 30-60 x normal nuclear density
  - Inferred temperature ~ 2 x that required for phase transition to QGP

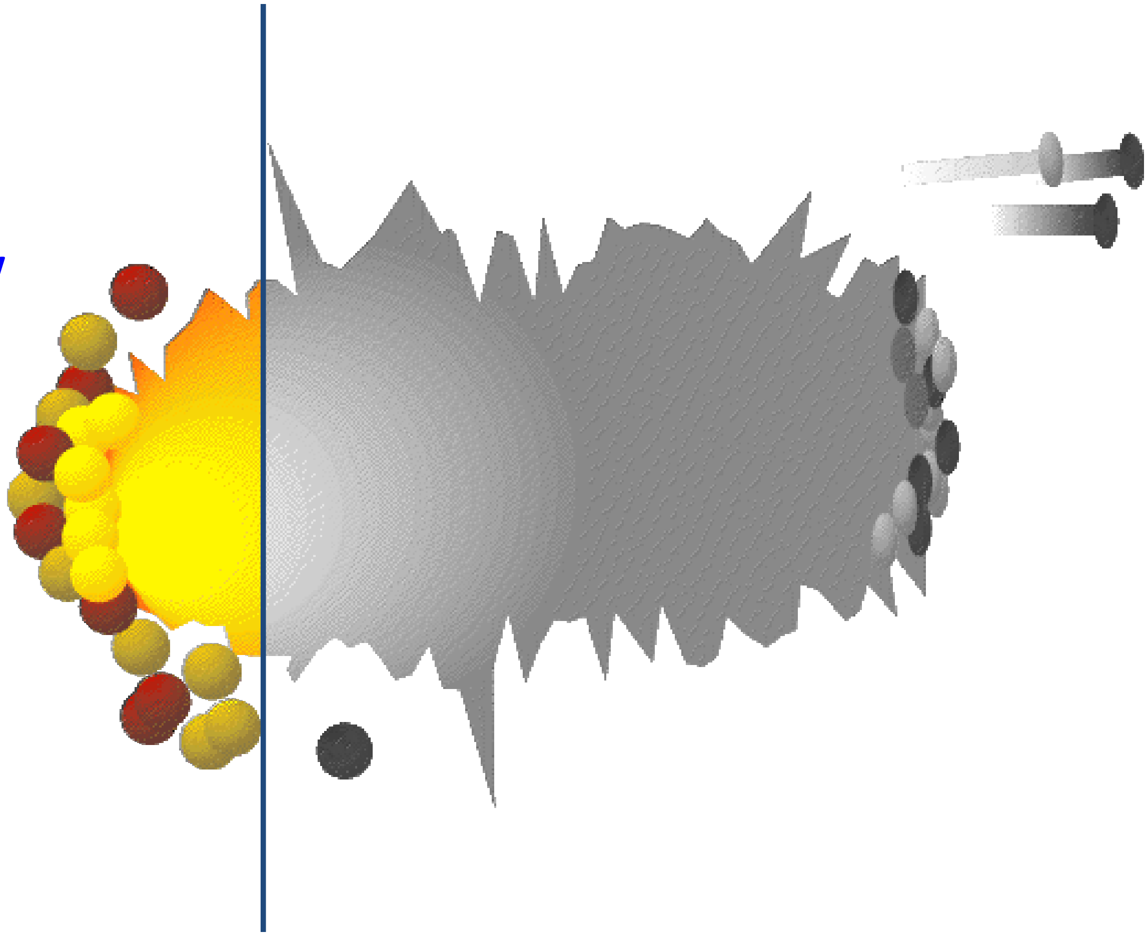
- Today: Is it fluid ?
  - Why it's nearly perfect
  - Why it can't be perfect

Initial State

Does this tremendously hot and dense material behave as a fluid?

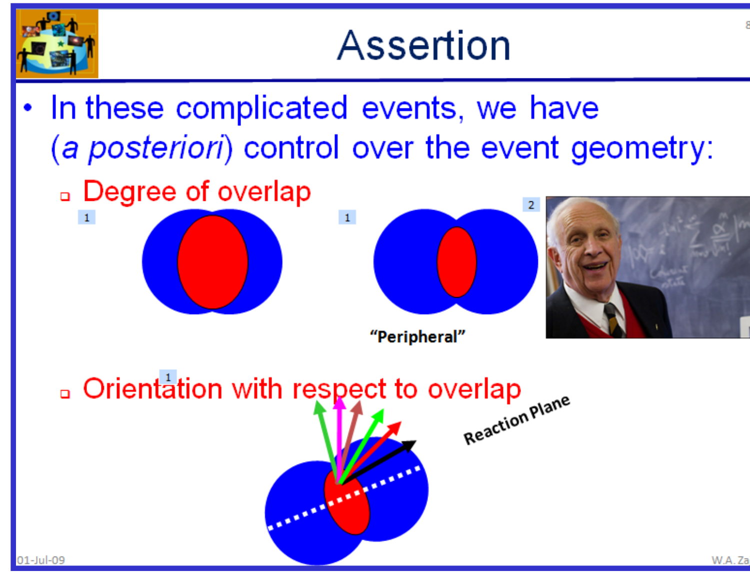
3. Initial State

Hydrodynamic flow
from
initial spatial
asymmetries

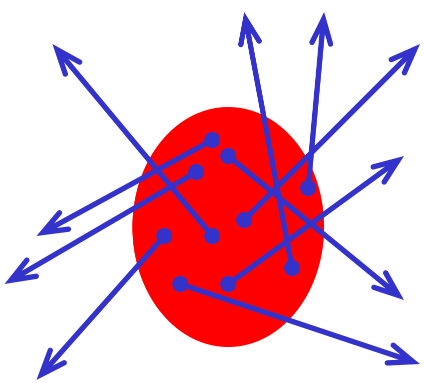


Recall Assertion

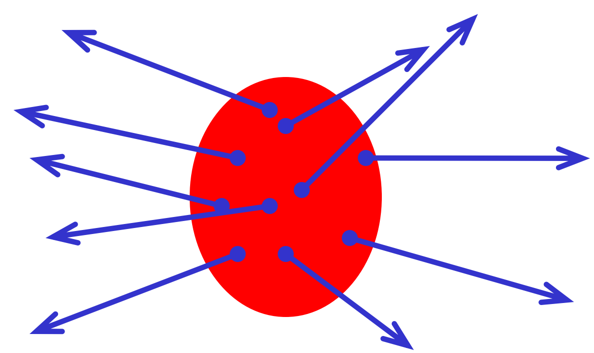
- We have (*a posteriori*) control over the event geometry:



  - Two possible scenarios:



“Free” quarks and gluons

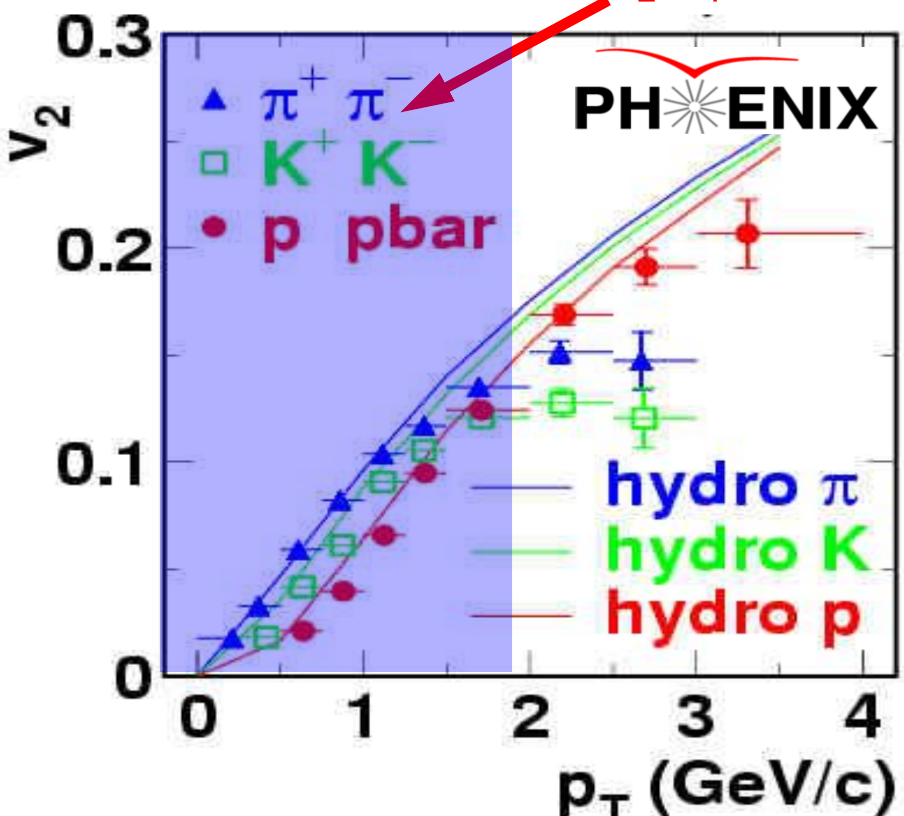


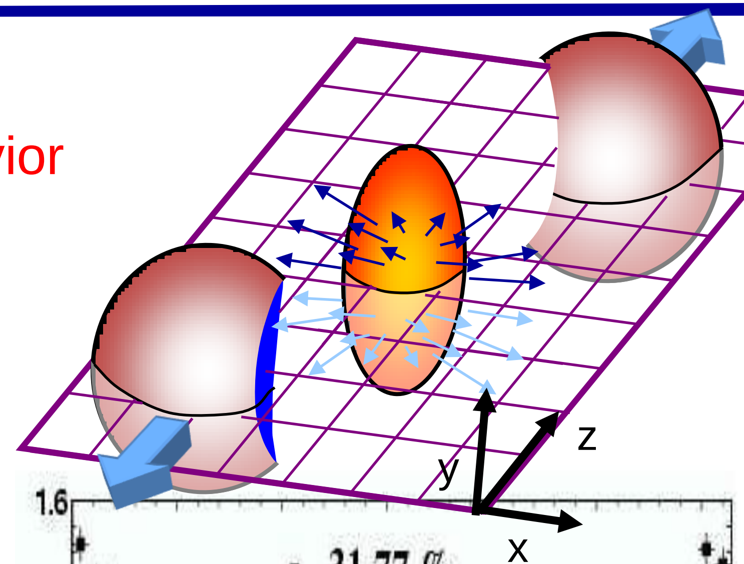
“Strongly-coupled” quarks and gluons

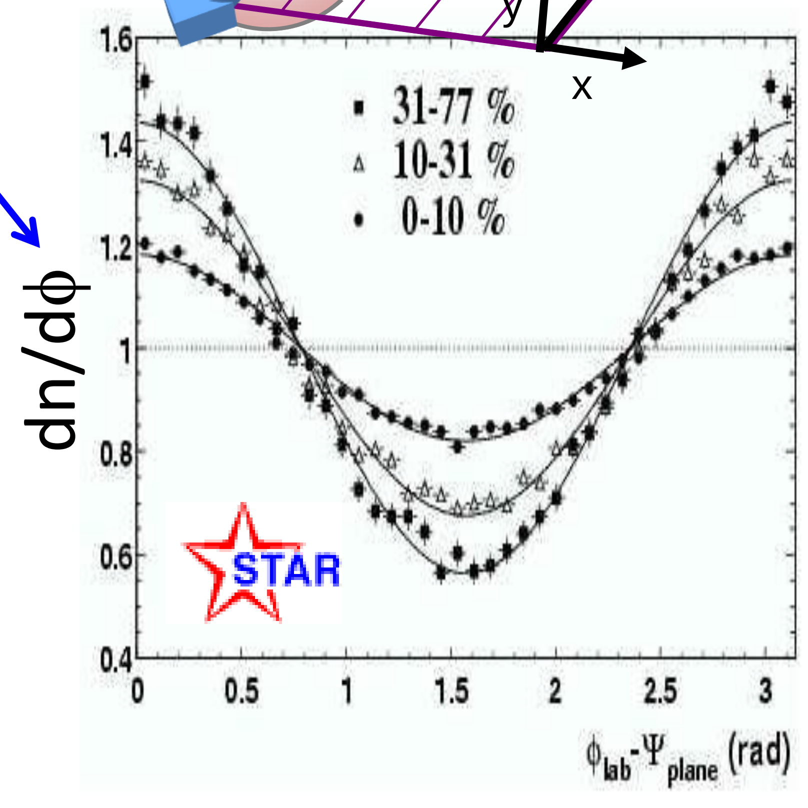
Motion Is Hydrodynamic

- When does thermalization occur?
  - Strong evidence that final state bulk behavior reflects the initial state geometry
- Because the initial *azimuthal asymmetry* persists in the final state

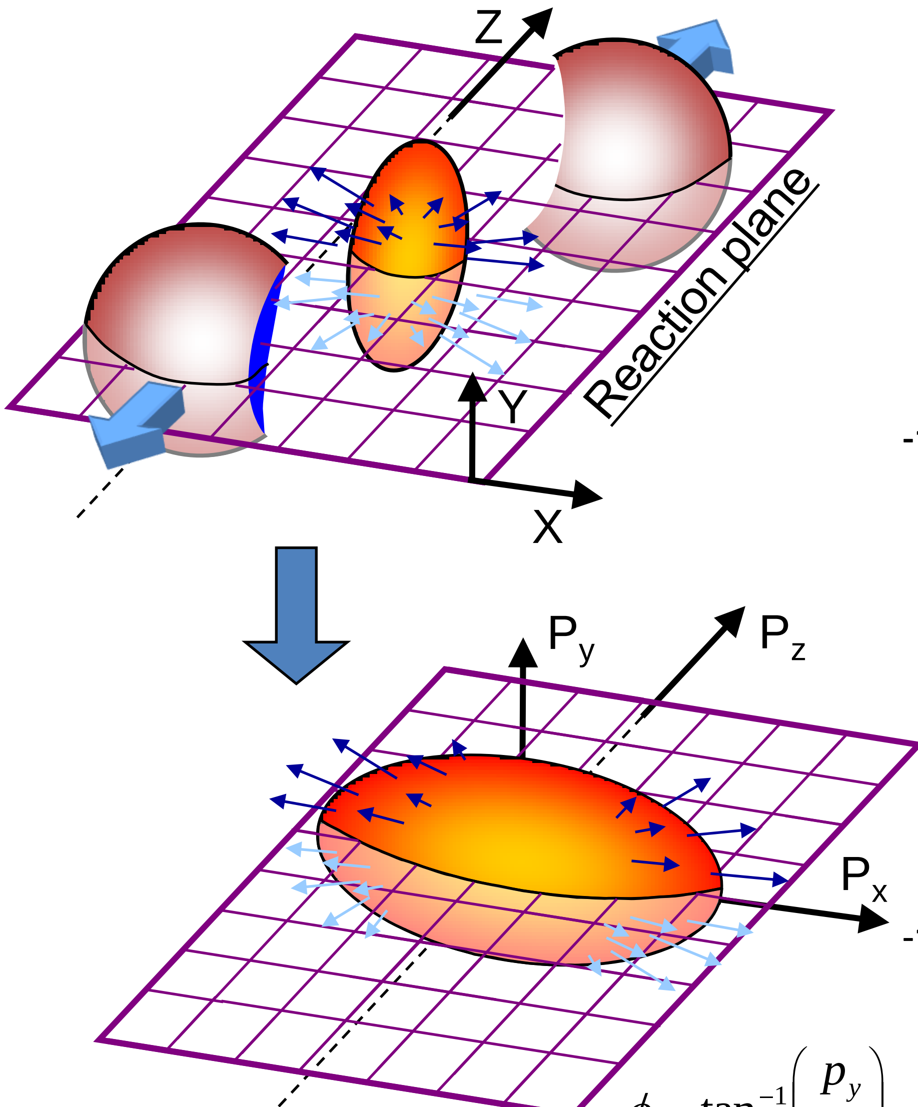
$$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$$



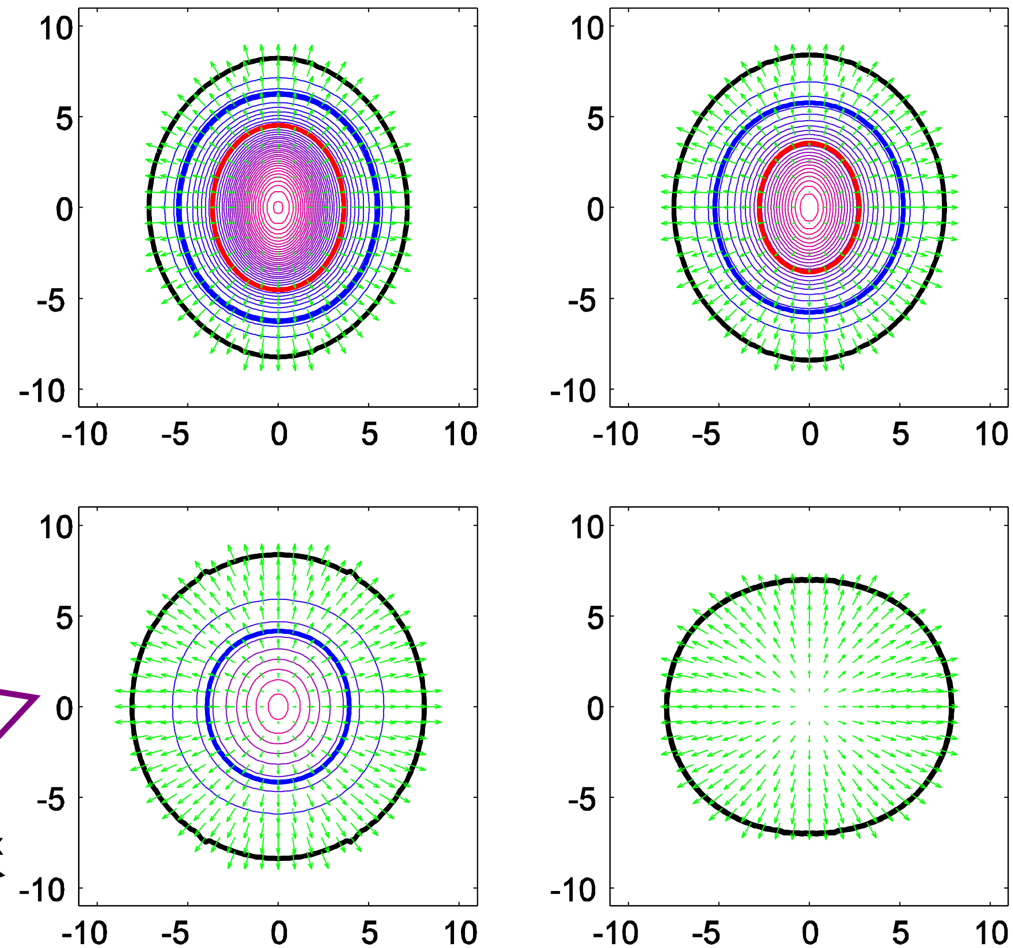




Flow In Pictures

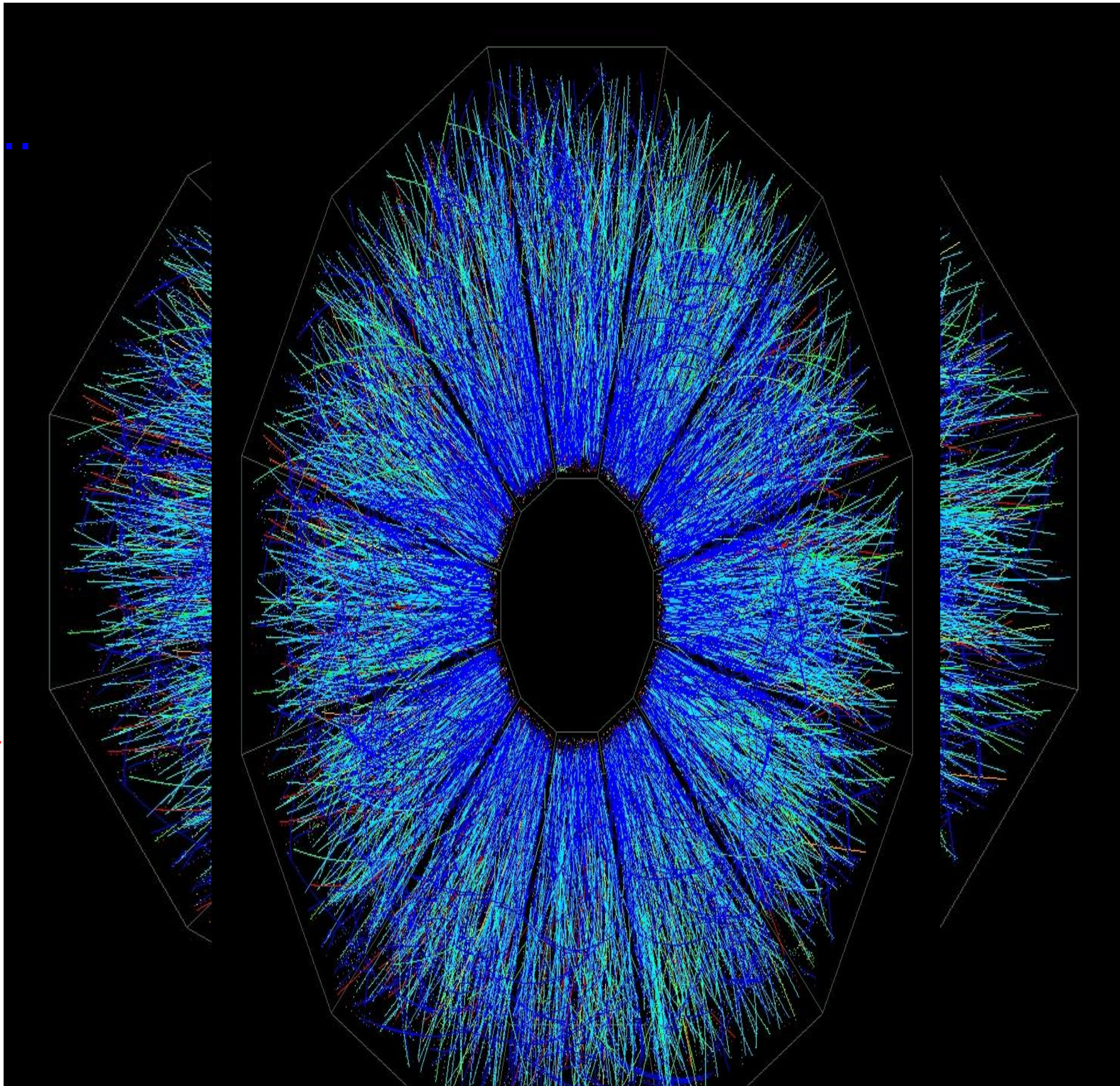


$$\phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$



The Flow" Is *Large*

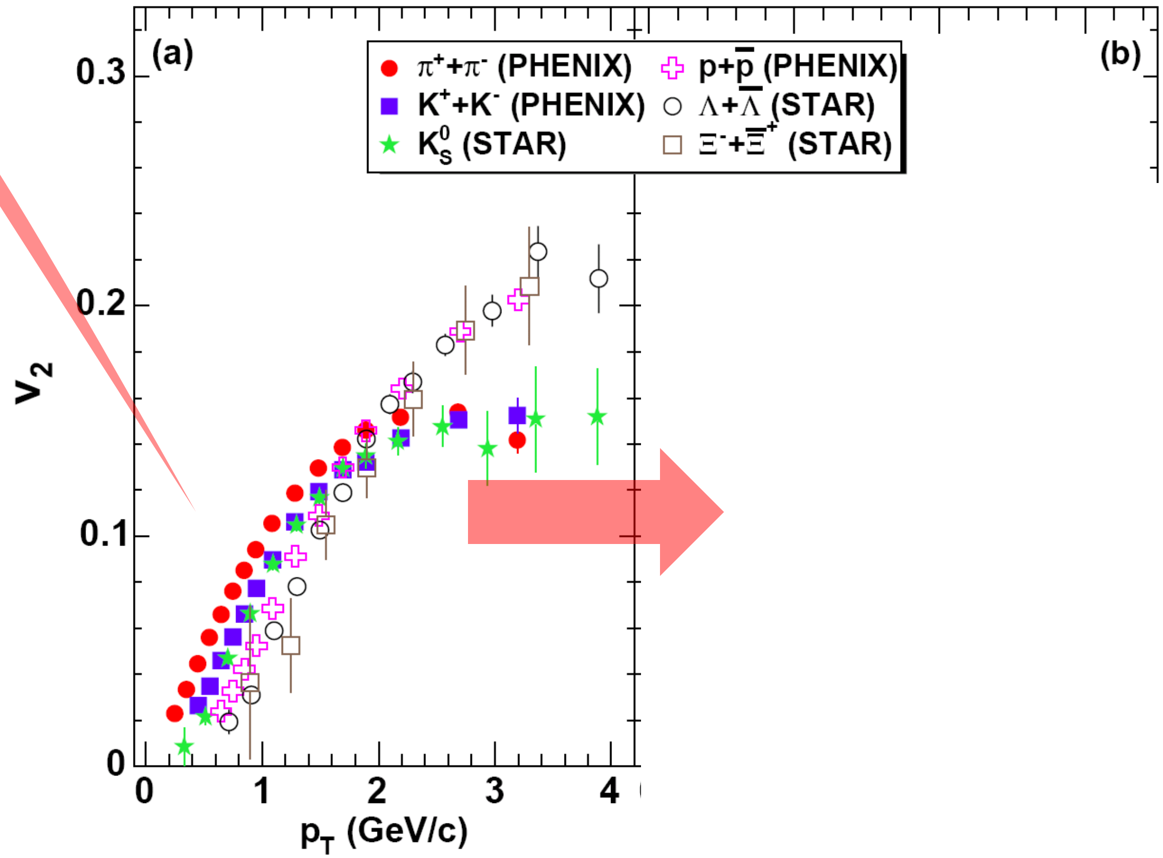
- Value of v_2 in
  dn/dϕ
  $\sim 1 + 2\, v_2 \cos(2\,\phi) + ..$
  saturates
  at ~ 0.2
- Hydrodynamic calculations
  show this modulation is
  - characteristic of *a state of matter*
  - established in the earliest (geometrically asymmetric) stage of the collision
  - at τ < ~ 1 fm/c with energy density $\varepsilon > 5$ GeV / fm^3



The Flow Is ~*Perfect*

- The "fine structure" $v_2(p_T)$ for different mass particles shows good agreement with ideal ("perfect fluid") hydrodynamics

$$KE_T \equiv \sqrt{m^2 + p_T^2}$$



- Roughly: $\partial_\nu T^{\mu\nu} = 0 \rightarrow$ Work-energy theorem

  $\rightarrow \int \nabla P \, d(vol) = \Delta E_K \cong m_T - m_0 \equiv \Delta KE_T$

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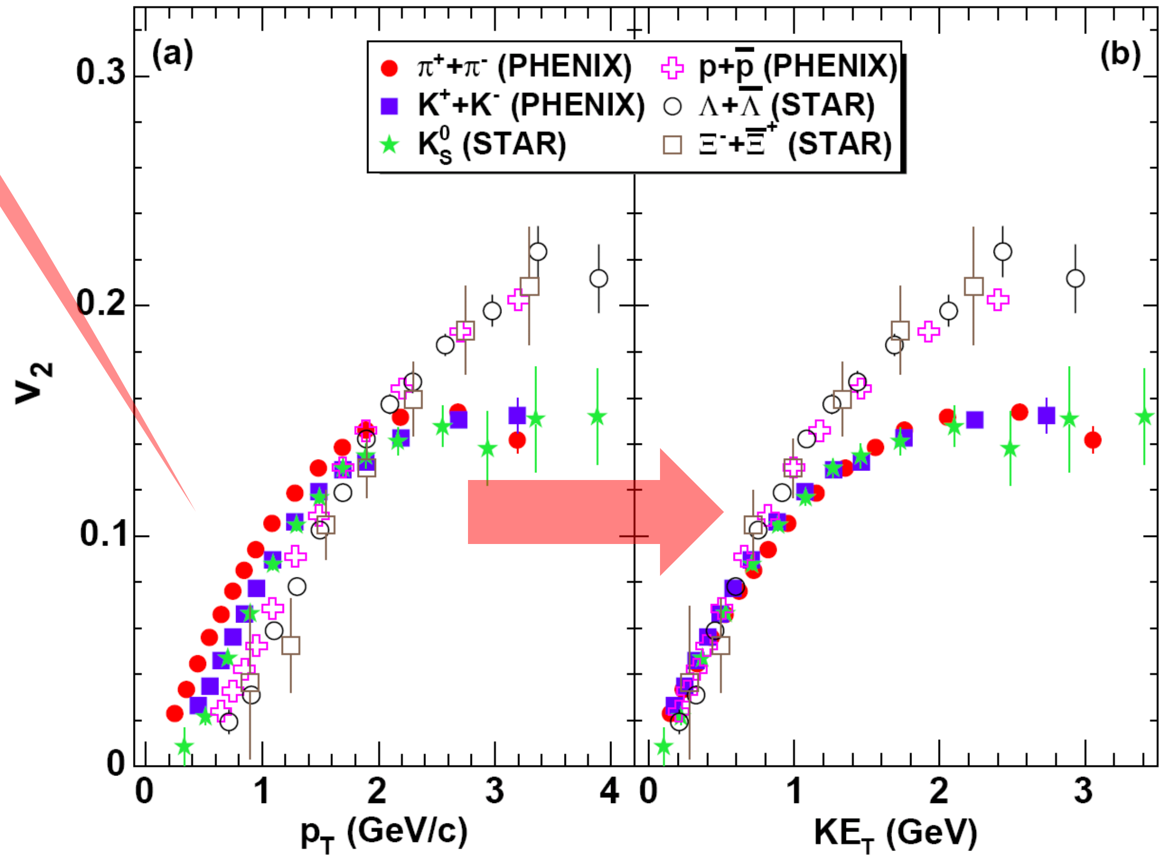
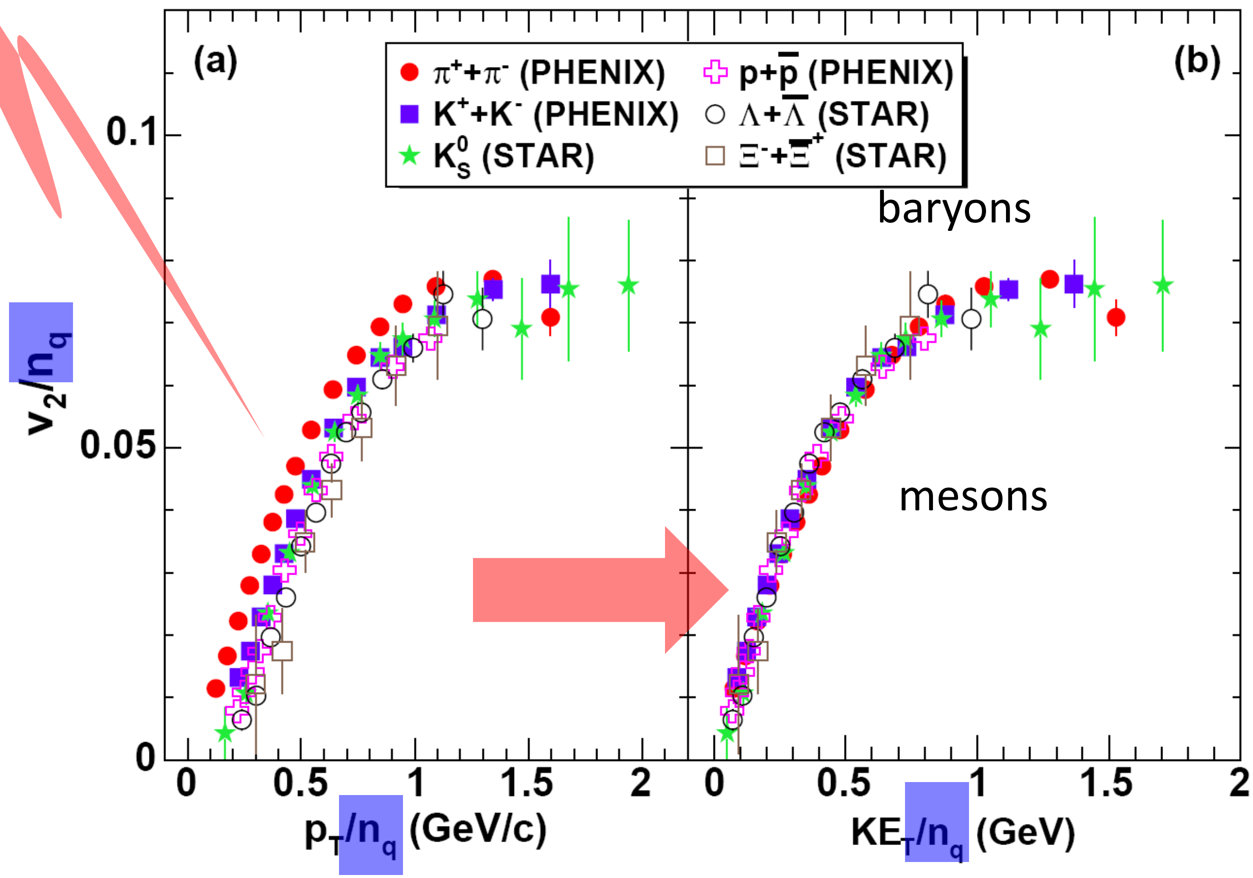


- Roughly: $\partial_\nu T^{\mu\nu} = 0 \rightarrow$ Work-energy theorem

  $\rightarrow \int \nabla P \, d(\text{vol}) = \Delta E_K \cong m_T - m_0 \equiv \Delta KE_T$

The Flow Knows Quarks

- The "fine structure" $v_2(p_T)$ for different mass particles shows good agreement with ideal ("perfect fluid") hydrodynamics



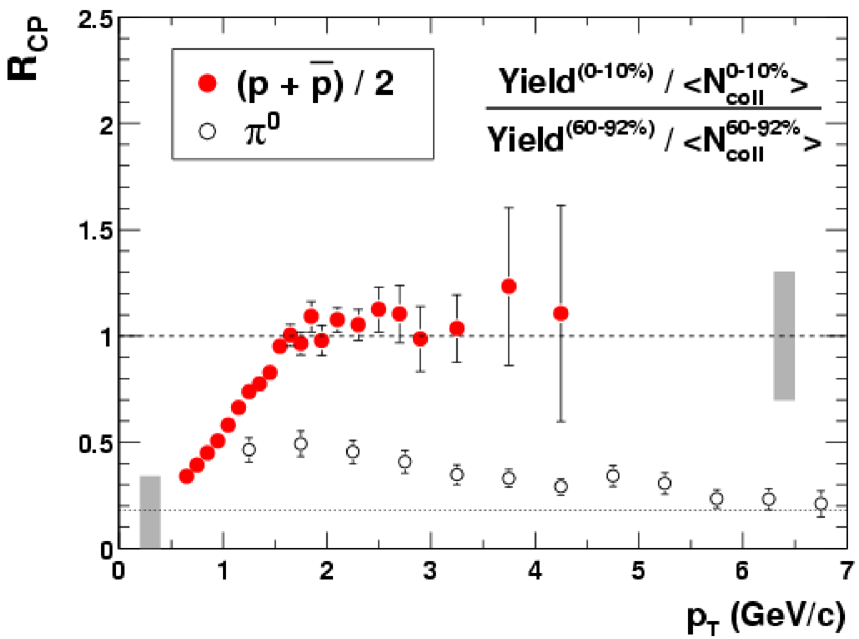
- Scaling flow parameters by *quark content n_q* resolves meson-baryon separation of final state hadrons

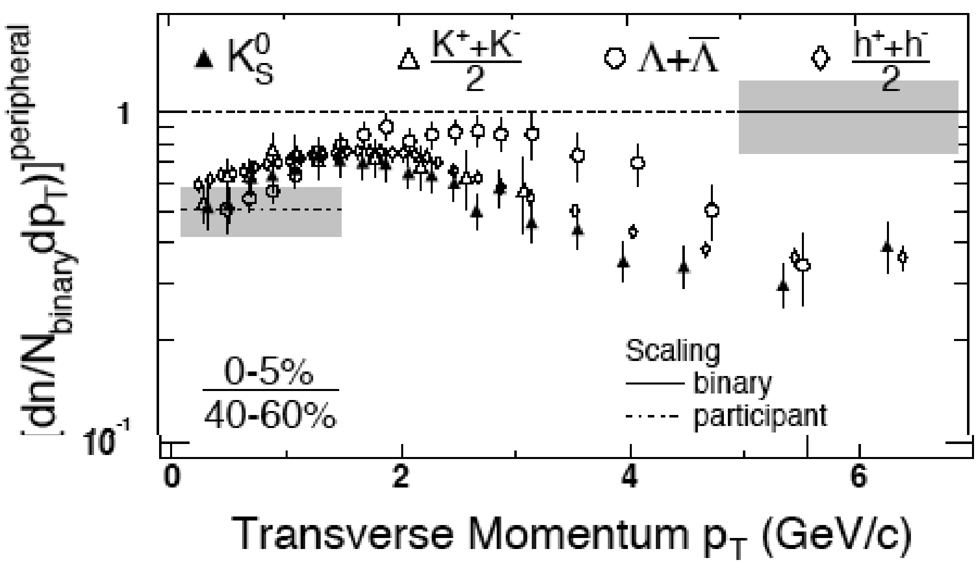
Baryons Are Different

- Results from
  - PHENIX (protons and anti-protons)
  - STAR (lambda's and lambda-bars)

indicate little or no suppression of baryons in the range ~2 < p_T < ~5 GeV/c

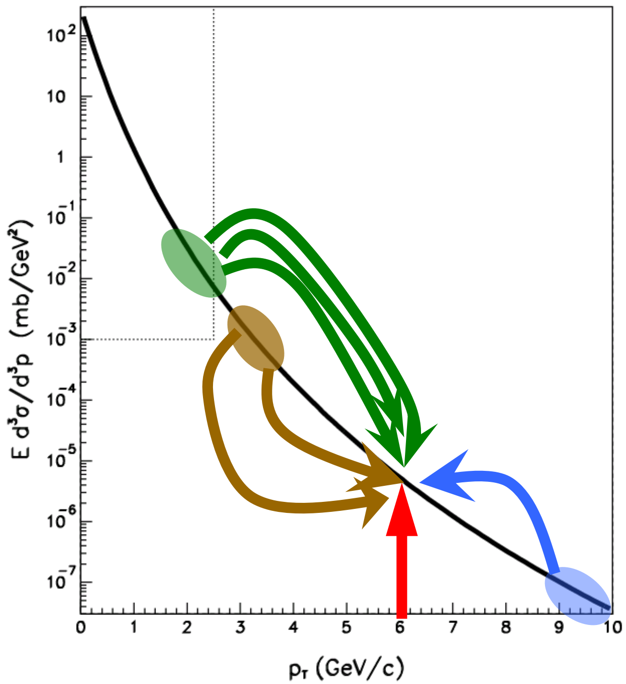
- One explanation: quark recombination (next slide)





Recombination

- The *in vacuo* fragmentation of a high momentum quark to produce hadrons
  competes with the *in medium* recombination of lower momentum quarks to produce hadrons
- Example:
  - Fragmentation: $D_{q \rightarrow h}(z)$
    - produces a 6 GeV/c π from a 10 GeV/c quark
  - Recombination:
    - produces a 6 GeV/c π from *two* 3 GeV/c quarks
    - produces a 6 GeV/c proton from *three* 2 GeV/c quarks



Fries, et al, nucl-th/0301087

Greco, Ko, Levai, nucl-th/0301093

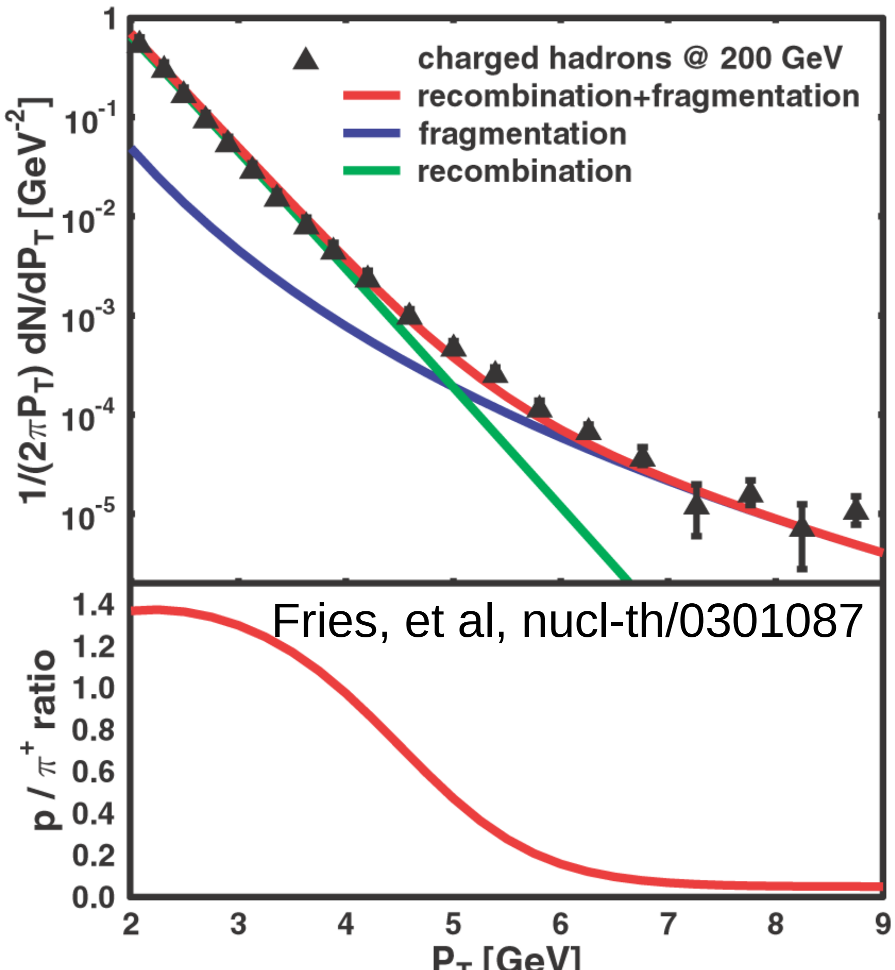
Recombination Meets Data

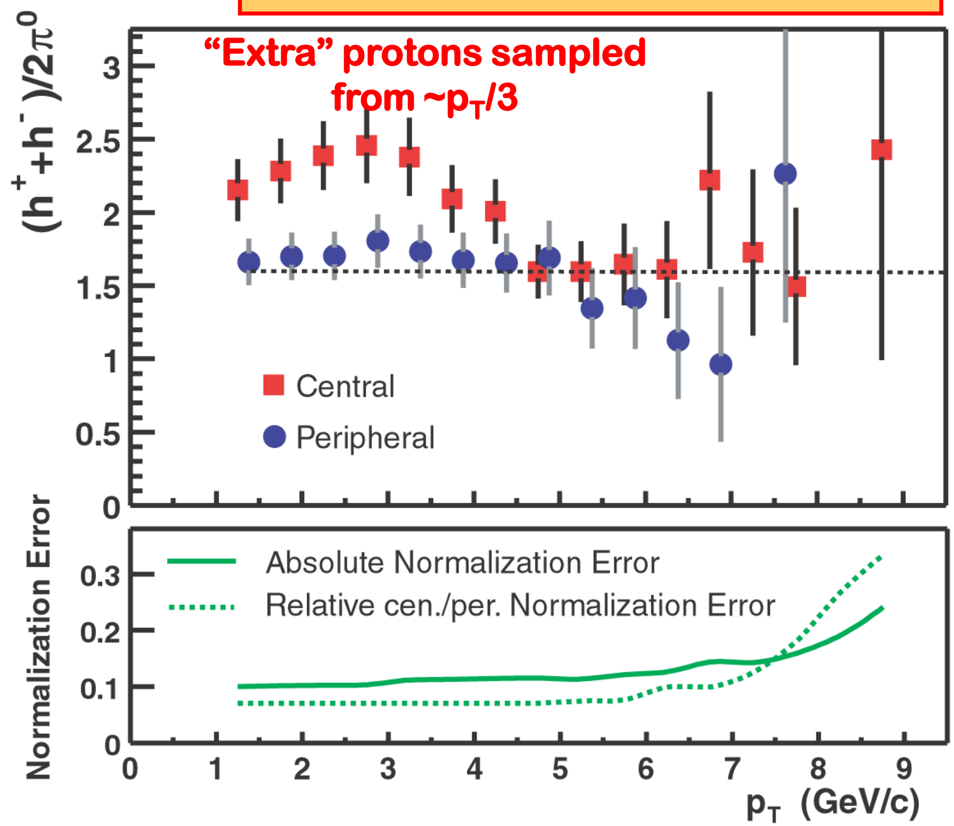
- Provides a “natural” explanation of
  - Spectrum of charged hadrons
  - Enhancements seen in p/π

...requires the assumption of a thermalized parton phase... (which) may be appropriately called a

quark-gluon plasma

Fries *et al.*, nucl-th/0301087



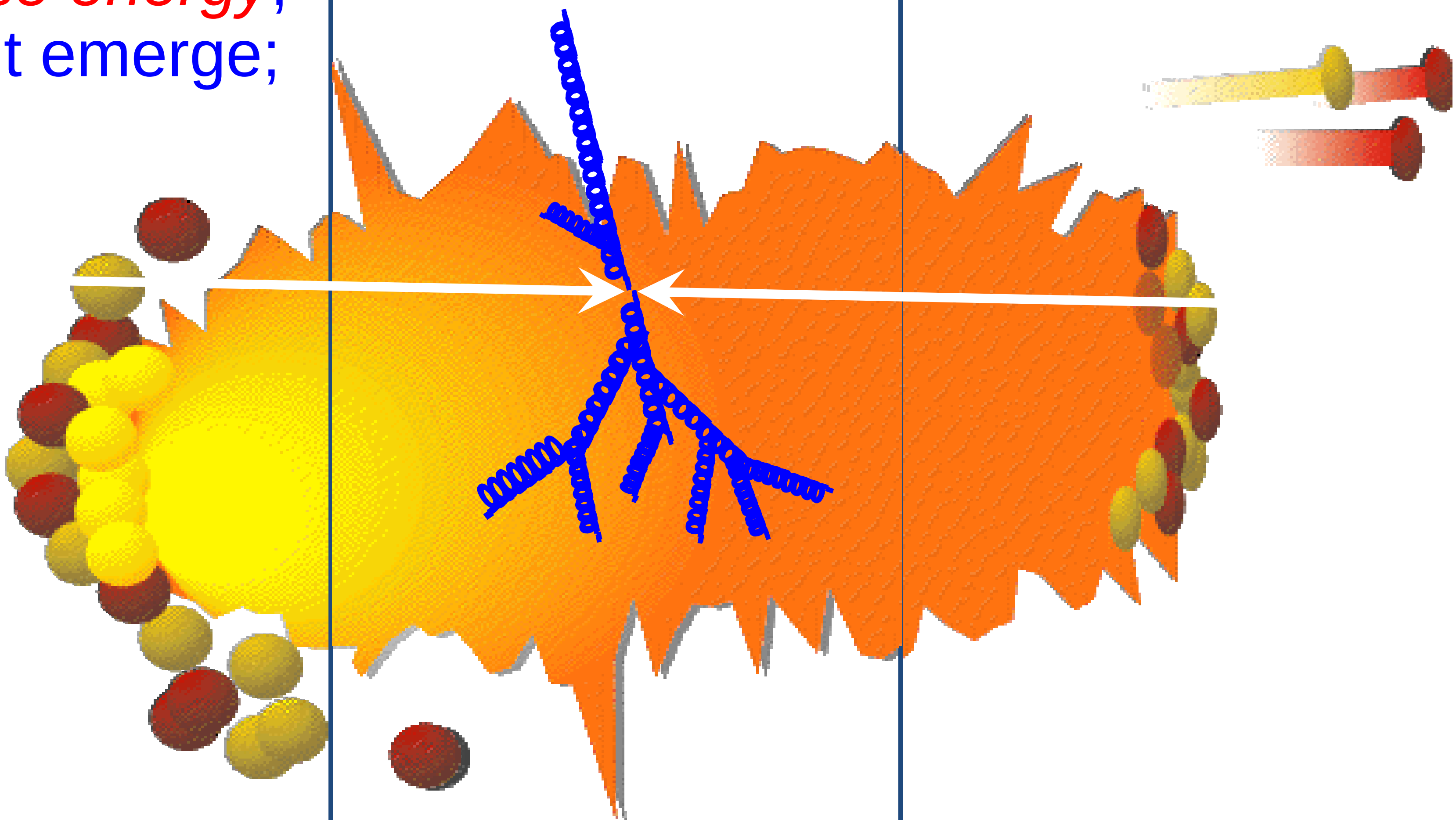


Connecting Soft and Hard Regimes

Scattered partons on the "near side"

lose energy,

but emerge;



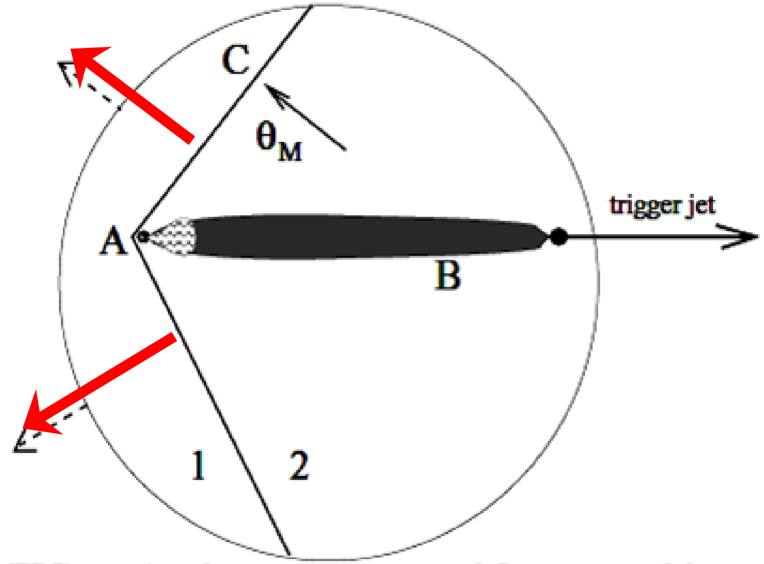
those on the "far side" are totally absorbed → ***Really ?***

Fluid Effects on Jets ?

- Mach cone?
  - ☑ Jets travel faster than the speed of sound in the mediun
  - ☑ While depositing energy via gluon radiation.

➡QCD “sonic boom” (?)

☞To be *expected* in a *dense fluid* which is *strongly-coupled*

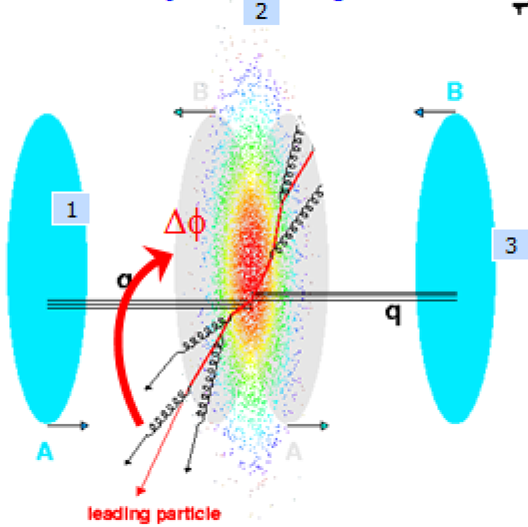


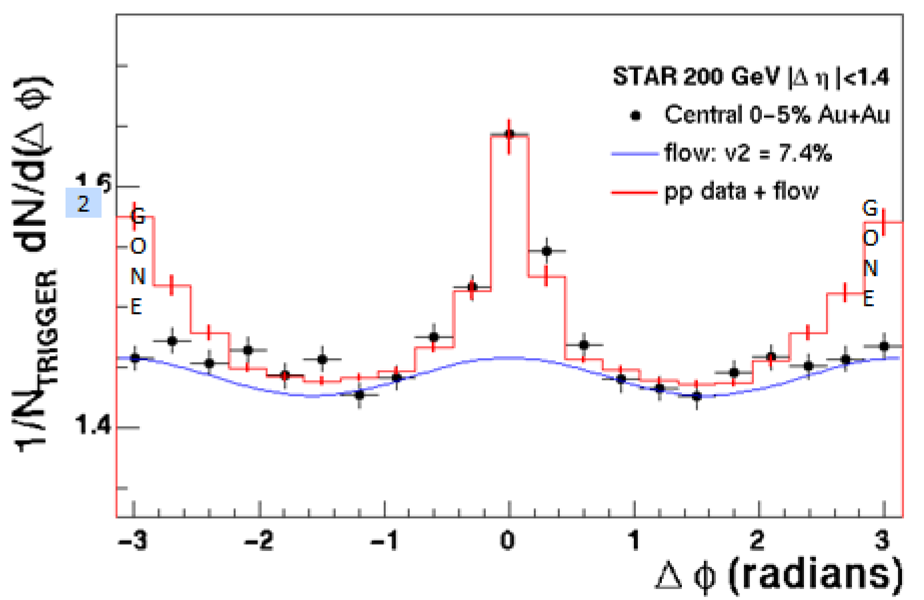
High p_T Parton → Low p_T “Mach Cone”?

- The “*dis*
  high p_T p
- But at lo
  see *re-a*
- and
- “Side-lob
  (Mach c)

The Matter is Opaque

STAR azimuthal correlation function shows ~ complete absence of “away-side” jet





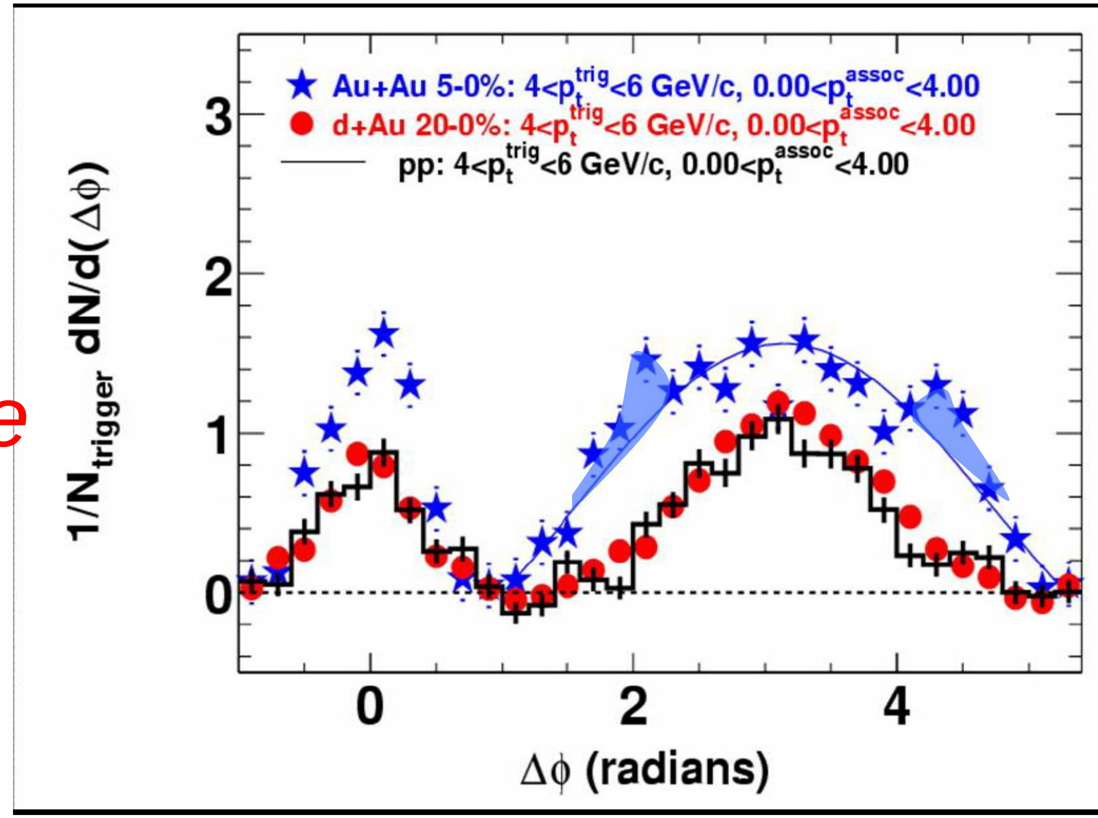
$$C_2(Au+Au) = C_2(p+p) + A^*(1+2v_2^2\cos(2\Delta\phi))$$

That is, “partner” in hard scatter is *absorbed* in the *dense* medium

⇒Density ~ 50 x normal nuclear ε_0

High p_T Parton $\rightarrow$ Low p_T "Mach Cone"?

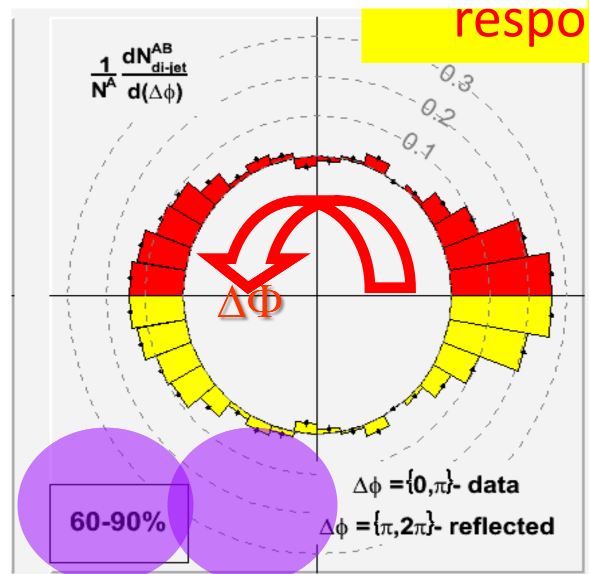
- The "*disappearance*" is that of the high p_T partner
- But at low p_T, see *re-appearance*
- and
- "Side-lobes" (Mach cones?)



Suggestion of Mach Cone

- Modifications to **di-jet** hadron pair correlations in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, **PHENIX Collaboration (S.S. Adler *et al.*)**, Phys Rev Lett 97:052301 2006

ct” fluid response!



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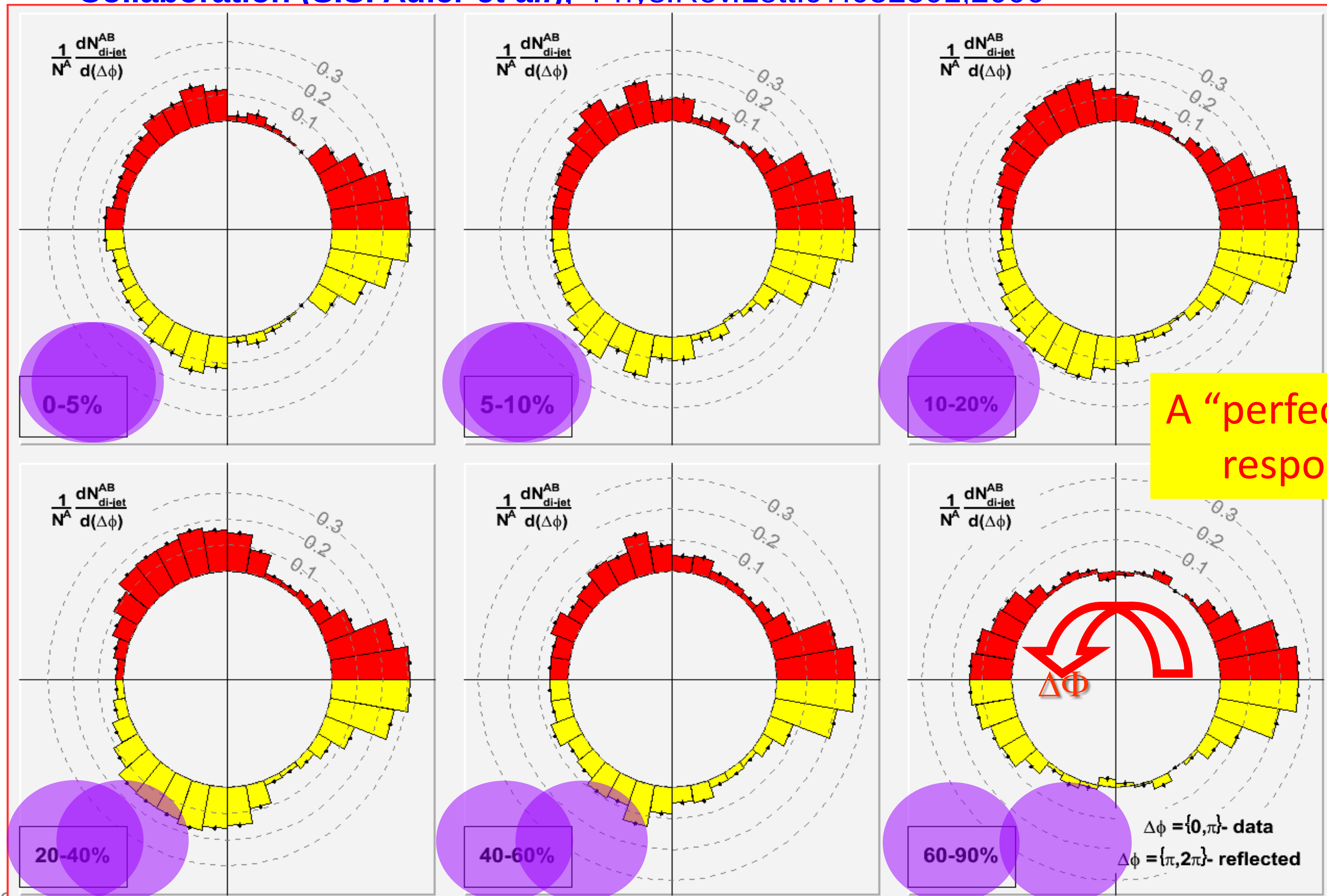

A "perfect" fluid response!

RHIC Success

New Press Release - Mozilla Firefox

e Edit View Go Bookmarks Tools Help

http://www.bnl.gov/bnlweb/pubaf/pr/PR_print.asp?prID=05-38 Go

mozilla.org Latest Builds Lifetime Columbia University ...

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Contact: Karen McNulty Walsh, (631) 344-8350 or Mona S. Rowe, (631) 344-5056

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

Secretary of Energy Samuel Bodman

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

"The possibility of a connection between string theory and RHIC collisions is unexpected and exhilarating," Dr. Orbach said. "String theory seeks to unify the two great intellectual achievements of twentieth-century physics, general relativity and quantum mechanics, and it may well have a profound impact on the physics of the twenty-first century."

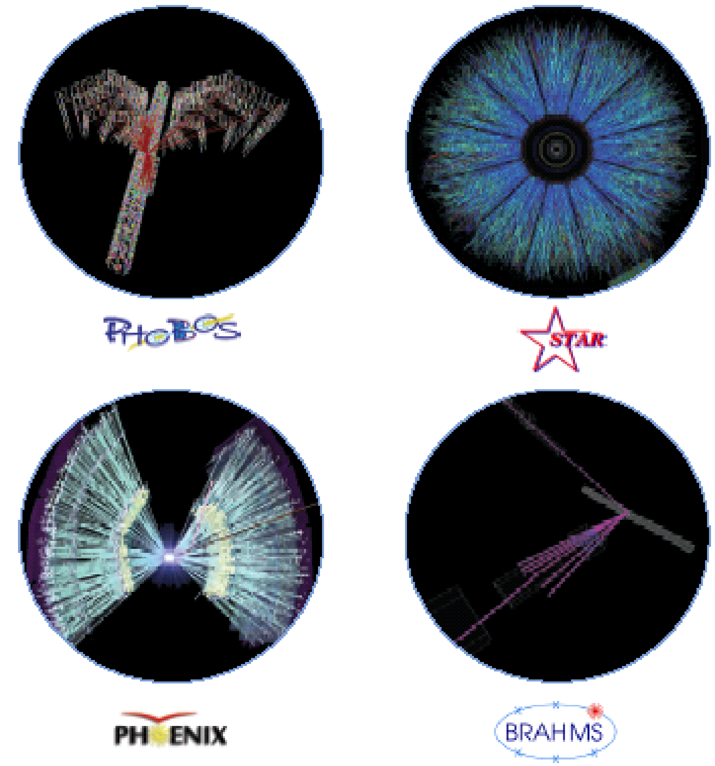
The papers, which the four RHIC collaborations (BRAHMS, PHENIX, PHOBOS, and STAR) have been working on for nearly a year, will be published simultaneously by the journal *Nuclear Physics A*, and will also be compiled in a special Brookhaven report, the Lab announced at the April 2005 meeting

Hunting the Quark Gluon Plasma

Results from the first 3 years at RHIC

Assessments by the experimental collaborations

April 18, 2005

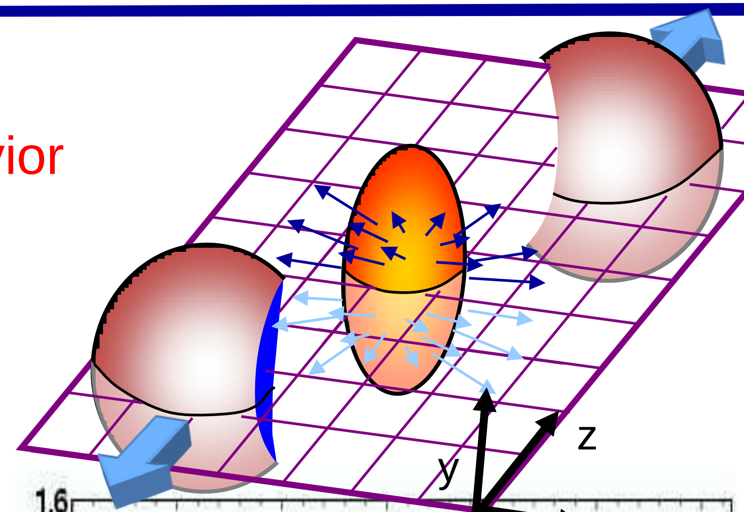


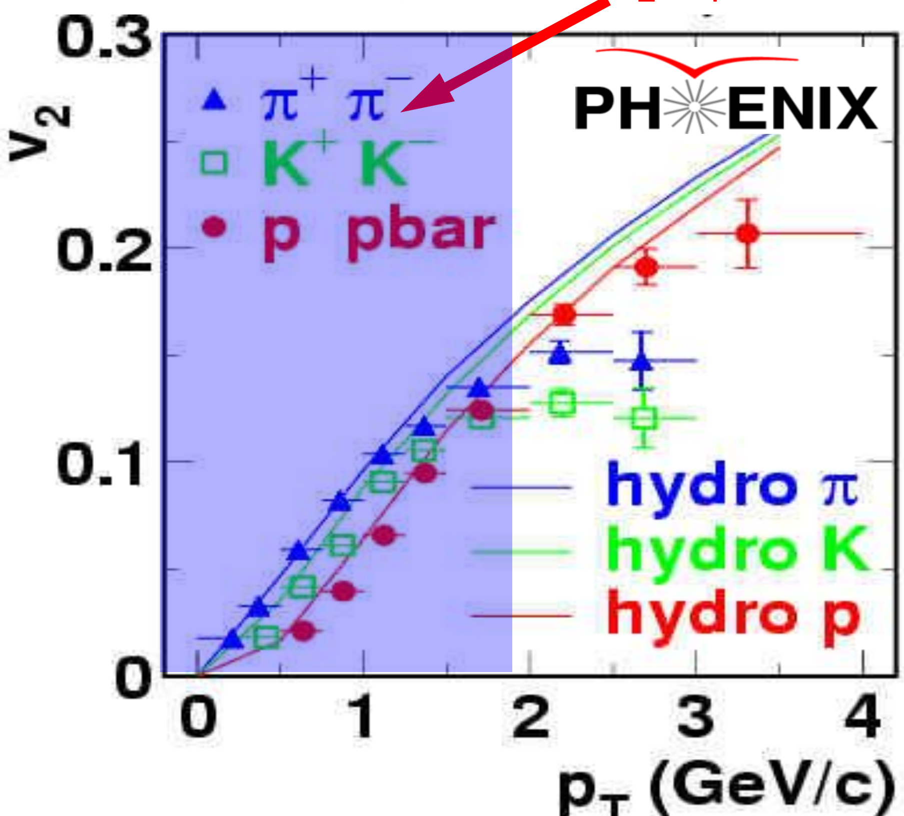
Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

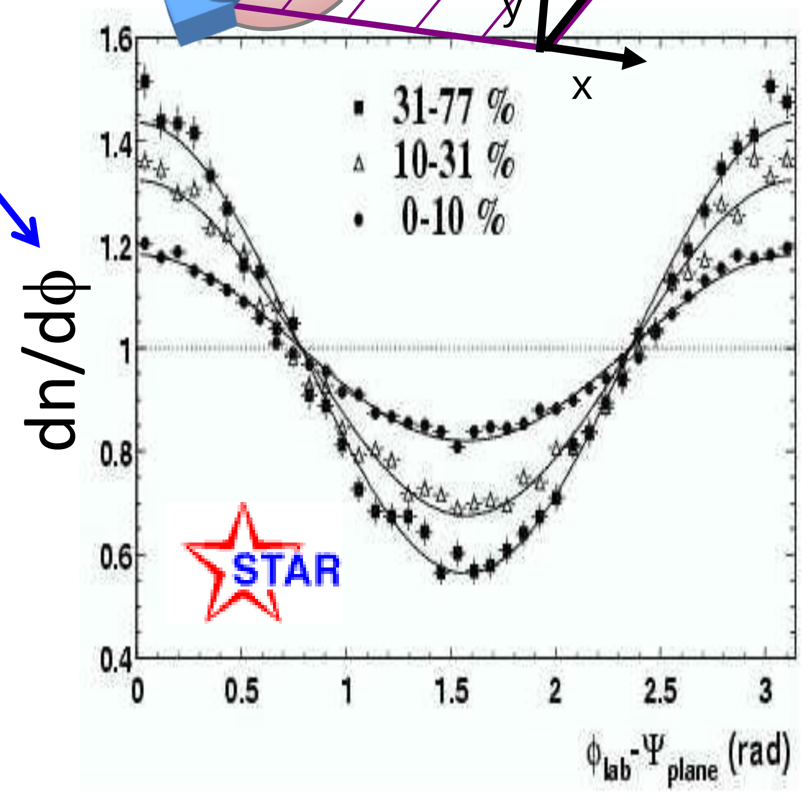
Motion Is Hydrodynamic

- When does thermalization occur?
  - Strong evidence that final state bulk behavior reflects the initial state geometry
- Because the initial *azimuthal asymmetry* persists in the final state

$$dn/d\phi \sim 1 + 2\, v_2(p_T)\cos(2\phi) + \ldots$$

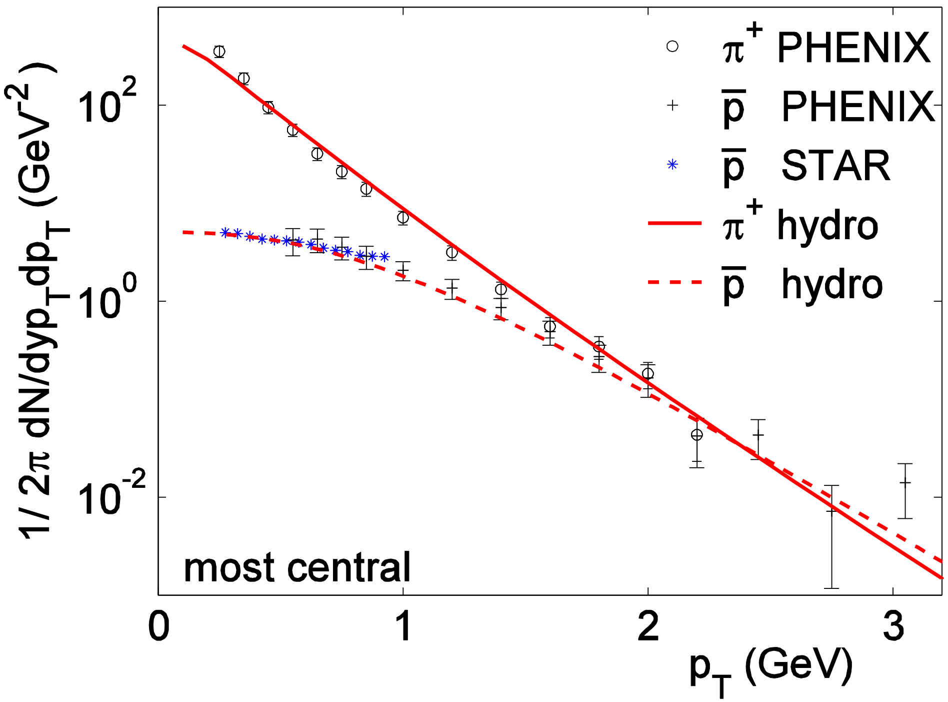


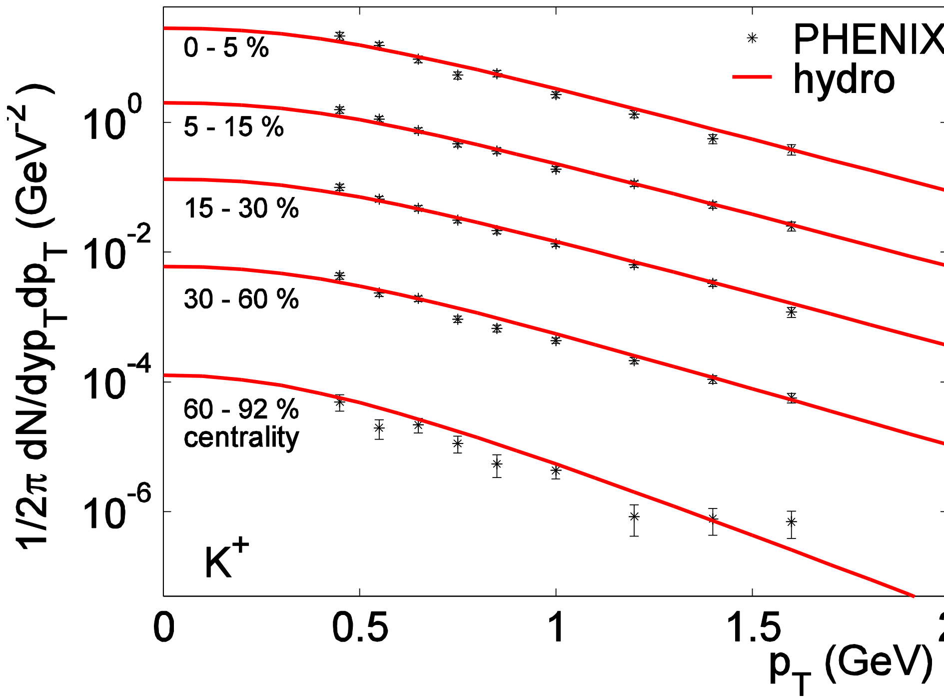




Hydrodynamic Behavior

- Superimposed on the thermal (~Boltzmann) distributions:
  - Collective velocity fields from $\partial_\mu T^{\mu\nu} = 0 \quad , \quad \partial_\mu j_B^{\mu} = 0$
  - Momentum spectra ~ $\frac{dn}{d\vec{p}} \sim \frac{dn(\text{Thermal})}{d\vec{p}} \otimes f_{HYDRO}\left(\vec{v} = \frac{\vec{p}}{m}\right)$
  - 'Test' by investigating description for different mass particles:





- Excellent description of particle production (P. Kolb and U. Heinz, hep-ph/0204061)

Behind The Equations

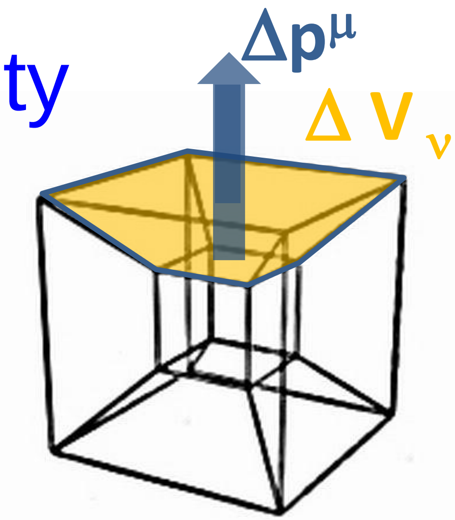
- Q. OK, what does this mean?

$$\partial_\mu T^{\mu\nu} = 0 \quad , \quad \partial_\mu j_B{}^\mu = 0$$

- Answers:
  - $\partial_\mu T^{\mu\nu} = 0 \quad \Leftrightarrow \quad F = ma$
  - $\partial_\mu j_B{}^\mu = 0 \quad \Leftrightarrow$ **baryon number is conserved**

Stress-Energy Tensor Reminder

- $T^{\mu\nu} \equiv \mu$-th component of energy-momentum density in ν-th "direction"



- Examples:
  - $T^{00} = \dfrac{\Delta p^0}{(\Delta V)_0} = \dfrac{\Delta E}{\Delta x_1 \Delta x_2 \Delta x_3} = \text{Energy Density}$
  - $T^{11} = \dfrac{\Delta p^1}{(\Delta V)_1} = \dfrac{\Delta p^1}{\Delta x_0 \Delta x_2 \Delta x_3} = \dfrac{\Delta p^1 / \Delta t}{\Delta x_2 \Delta x_3} = \dfrac{F_1}{A_\perp} = \text{Pressure (in "1" direction)}$
  - $T^{12} = (\text{Force})_1$ per unit area in 2 direction $\equiv$ Shear stress

- Energy-momentum conservation: $\partial_\mu T^{\mu\nu} = 0$

Perfect Fluids

- Defined as
  - Isotropic in fluid rest frame
  - Incapable of supporting a shear stress
- So $T^{00} = \varepsilon$, $T^{ij} = P\,\delta^{ij}$ in the fluid rest frame .
- Q. How to write as proper Lorentz tensor ?:
- A. Use fluid four-velocity u^μ to express as

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - g^{\mu\nu} P$$

Exercise 1: Check this.

Ideal Hydrodynamics

- That is, the hydrodynamics of a perfect fluid:

$$T^{\mu\nu} = (\varepsilon + P)u^{\mu}u^{\nu} - g^{\mu\nu}P \quad ; \quad \partial_{\mu}T^{\mu\nu} = 0$$

$$j_B^{\ \mu} = n_B u^{\mu} \quad ; \quad \partial_{\mu} j_B^{\ \mu} = 0$$

- *Not* enough to solve:
  - ☞ Still need "equation of state"
    - ▸ (could be as simple as P = ε / 3)
  - ❑ Even with E.O.S., still hard without further simplifying assumptions:
    - ♦ Examples:
      - ○ Expansion in 1D only (Landau, Bjorken)
      - ○ Uniform 3D 'Hubble' expansion (Csorgo)

Exercise 2: Verify these statements.

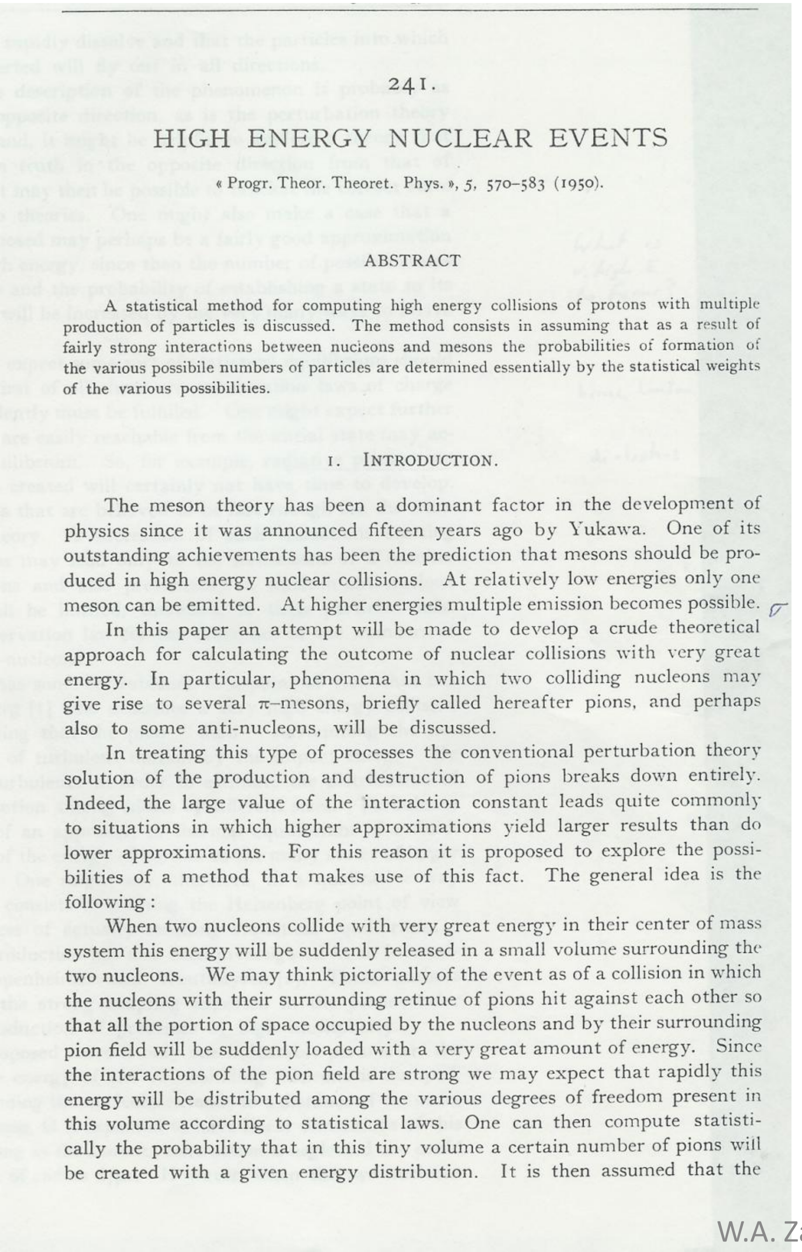
Innocuous Question

- Why ideal hydrodynamics ?
- (The fluid version of the frictionless plane)

- Answers:
  - It works
  - Non-ideal *very* hard to do relativistically
  - But for *relativistic* fluids, argument from Landau justifying ideal hydrodynamics (to follow)

Fermi 1950

- Fermi (1950)
  - "High Energy Nuclear Events", Prog. Theor. Phys. 5, 570 (1950)
  - Lays groundwork for statistical approach to particle production in strong interactions:
    - "Since the interactions of the pion field are *strong*, we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to statistical laws."
    - (Emphasis added by WAZ)



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HIGH ENERGY NUCLEAR EVENTS

« Progr. Theor. Theoret. Phys. », 5, 570–583 (1950).

ABSTRACT

A statistical method for computing high energy collisions of protons with multiple production of particles is discussed. The method consists in assuming that as a result of fairly strong interactions between nucleons and mesons the probabilities of formation of the various possibile numbers of particles are determined essentially by the statistical weights of the various possibilities.

1. INTRODUCTION.

The meson theory has been a dominant factor in the development of physics since it was announced fifteen years ago by Yukawa. One of its outstanding achievements has been the prediction that mesons should be produced in high energy nuclear collisions. At relatively low energies only one meson can be emitted. At higher energies multiple emission becomes possible.

In this paper an attempt will be made to develop a crude theoretical approach for calculating the outcome of nuclear collisions with very great energy. In particular, phenomena in which two colliding nucleons may give rise to several π–mesons, briefly called hereafter pions, and perhaps also to some anti-nucleons, will be discussed.

In treating this type of processes the conventional perturbation theory solution of the production and destruction of pions breaks down entirely. Indeed, the large value of the interaction constant leads quite commonly to situations in which higher approximations yield larger results than do lower approximations. For this reason it is proposed to explore the possibilities of a method that makes use of this fact. The general idea is the following:

When two nucleons collide with very great energy in their center of mass system this energy will be suddenly released in a small volume surrounding the two nucleons. We may think pictorially of the event as of a collision in which the nucleons with their surrounding retinue of pions hit against each other so that all the portion of space occupied by the nucleons and by their surrounding pion field will be suddenly loaded with a very great amount of energy. Since the interactions of the pion field are strong we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to statistical laws. One can then compute statistically the probability that in this tiny volume a certain number of pions will be created with a given energy distribution. It is then assumed that the

Landau 1955

- Landau (1955)
  significant extension
  of Fermi's statistical model
- Considers fundamental roles of
  - hydrodynamic evolution
  - entropy
    - "The defects of Fermi's theory arise mainly because the expansion
      of the compound system
      is not correctly taken
      into account…
      (The) expansion of the system can be considered on the basis of
      relativistic hydrodynamics."

88. A HYDRODYNAMIC THEORY OF MULTIPLE FORMATION OF PARTICLES

1. INTRODUCTION

Experiment shows that in collisions of very fast particles a large number of new particles are formed in multi-prong stars. The energy of the particles which produce such stars is of the order of 10^{12} eV or more. A characteristic feature is that such collisions occur not only between a nucleon and a nucleus but also between two nucleons. For example, the formation of two mesons in neutron–proton collisions has been observed at comparatively low energies, of the order of 10^9 eV, in cosmotron experiments[1].

Fermi[2,3] originated the ingenious idea of considering the collision process at very high energies by the use of thermodynamic methos. The main points of his theory are as follows.

(1) It is assumed that, when two nucleons of very high energy collide, energy is released in a very small volume V in their centre of mass system. Since the nuclear interaction is very strong and the volume is small, the distribution of energy will be determined by statistical laws. The collision of high-energy particles may therefore be treated without recourse to any specific theories of nuclear interaction.

(2) The volume V in which energy is released is determined by the dimensions of the meson cloud around the nucleons, whose radius is $\hbar/\mu c$, μ being the mass of the pion. But since the nucleons are moving at very high speeds, the meson cloud surrounding them will undergo a Lorentz contraction in the direction of motion. Thus the volume V will be, in order of magnitude,

$$V = \frac{4\pi}{3}\left(\frac{\hbar}{\mu c}\right)^3 \frac{2Mc^2}{E'}, \qquad (1.1)$$

where M is the mass of a nucleon and E' the nucleon energy in the centre of mass system.

(3) Fermi assumes that particles are formed, in accordance with the laws of statistical equilibrium, in the volume V at the instant of collision. The particles formed do not interact further with one another, but leave the volume in a "frozen" state.

С. З. Беленький и Л. Д. Ландау, Гидродинамическая теория множественного образования частиц, *Успехи Физических Наук*, **56**, 309 (1955).
S. Z. Belenkij and L. D. Landau, Hydrodynamic theory of multiple production of particles, *Nuovo Cimento*, Supplement, **3**, 15 (1956).

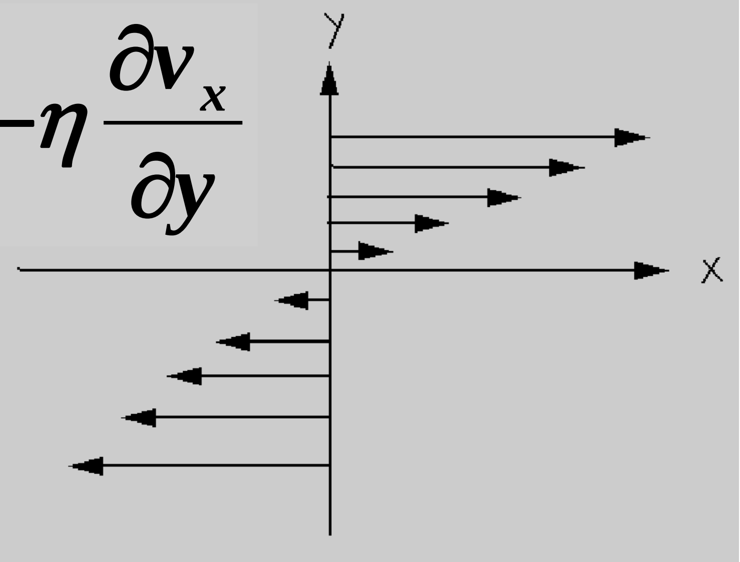
Perfection ←→ (No) Viscosity

- Isotropic in rest frame

➔ No shear stress

➔ no viscosity, $\eta = 0$

$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$



- Primer:
  - Remove your organic prejudices
  - Viscosity ~ mean free path

  - Small viscosity ➔ Small λ_{mfp}
  - *Zero* viscosity ➔ $\lambda_{mfp} = 0$ (!)

Landau on Viscosity

1) Use of hydro relies on $R/\lambda >> 1$

2) Negligible viscosity η equivalent to large Reynolds number $\mathcal{R}e \equiv \rho V R / \eta >> 1$

$$\rho V R / \eta \sim V\, R / v_{th}\, \lambda$$

but for a *relativistic* system

$$V \sim v_{th}$$

so

$$\mathcal{R}e >> 1 \Rightarrow R / \lambda >> 1 \text{ ; see \#1}$$

and statistical equilibrium is set up.
(2) The second stage of the collision consists in the expansion of the system. Here the hydrodynamic approach must be used, and the expansion may be regarded as the motion of an ideal fluid (zero viscosity and zero thermal con-

† The conditions of applicability of thermodynamics and hydrodynamics are comprised in the requirement $l/L \ll 1$, where l is the "mean free path" and L the least dimension of the system.

† This may be made clear by the following qualitative arguments. If viscosity and thermal conductivity are to be negligible, the Reynolds number LV/lv must be much greater than unity. Here L is the least dimension of the system, V the "macroscopic" velocity, v the "molecular" velocity and l the mean free path. Since V and v are of the order of c, the condition $R \gg 1$ corresponds to $l/L \ll 1$.

Summary- Lecture 3

- Strong evidence that initial-state spatial asymmetry appears as final-state “flow” .
- The flow properties of QGP in Au+Au collisions at top RHIC energy is roughly consistent with perfect fluid (η=0) hydrodynamics:
  - Particle mass dependence of $v_2(p_T)$
  - Scaling of same with KE_T
- Theoretical argument (Landau) suggests applicability of hydrodynamics to relativistic systems is approximately equivalent to requiring perfect fluid behavior.