Zakopane School, June 12, 2011

Hydrodynamic Approach to Relativistic Heavy Ion Collisions

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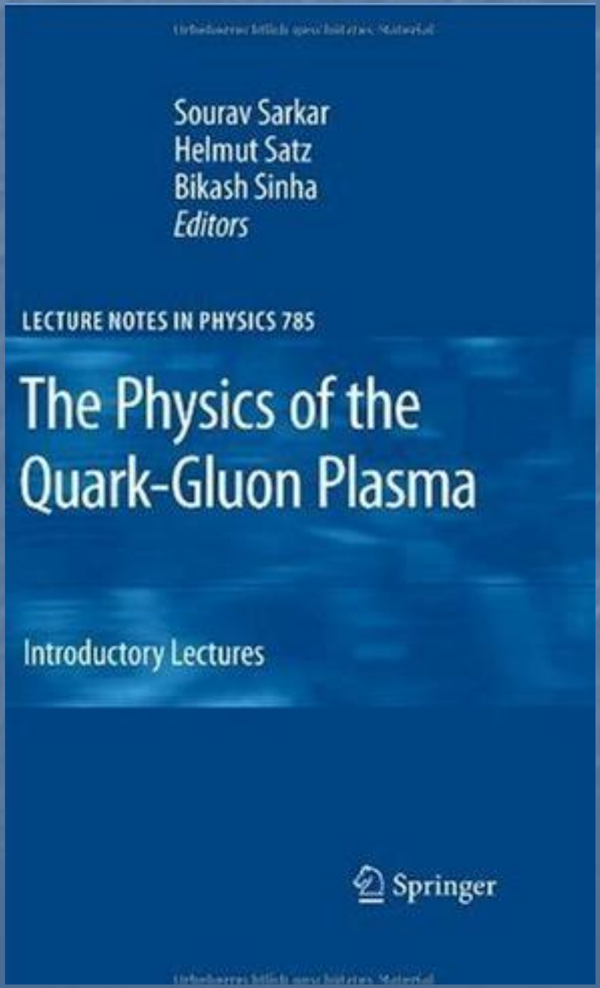
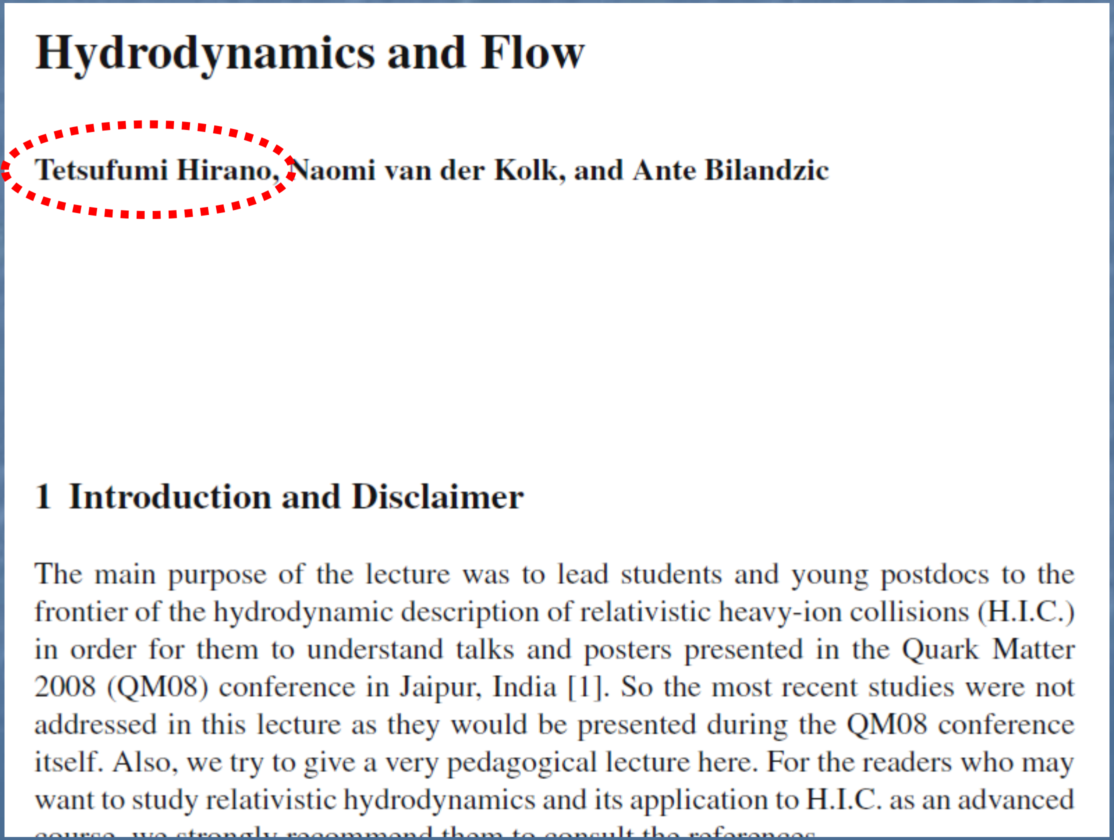
Advertisement: Lecture Notes



Chapter 4



Hydrodynamics and Flow

Tetsufumi Hirano, Naomi van der Kolk, and Ante Bilandzic

1 Introduction and Disclaimer

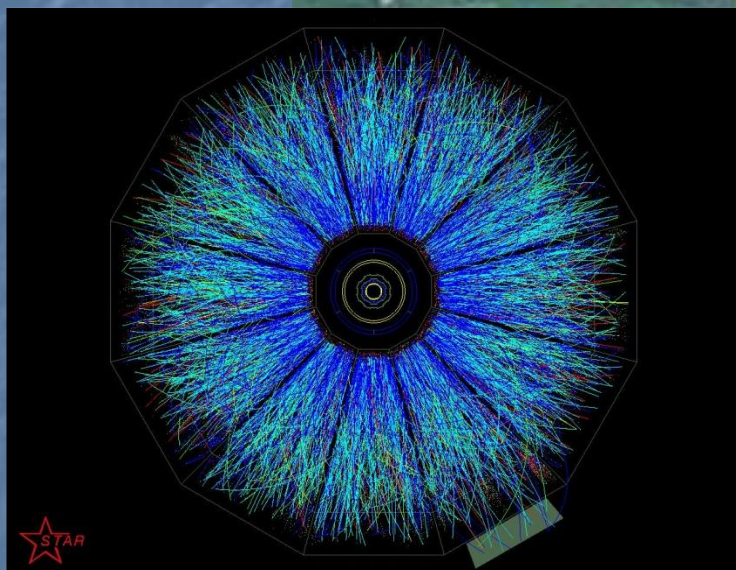
The main purpose of the lecture was to lead students and young postdocs to the frontier of the hydrodynamic description of relativistic heavy-ion collisions (H.I.C.) in order for them to understand talks and posters presented in the Quark Matter 2008 (QM08) conference in Jaipur, India [1]. So the most recent studies were not addressed in this lecture as they would be presented during the QM08 conference itself. Also, we try to give a very pedagogical lecture here. For the readers who may want to study relativistic hydrodynamics and its application to H.I.C. as an advanced

Two Lectures

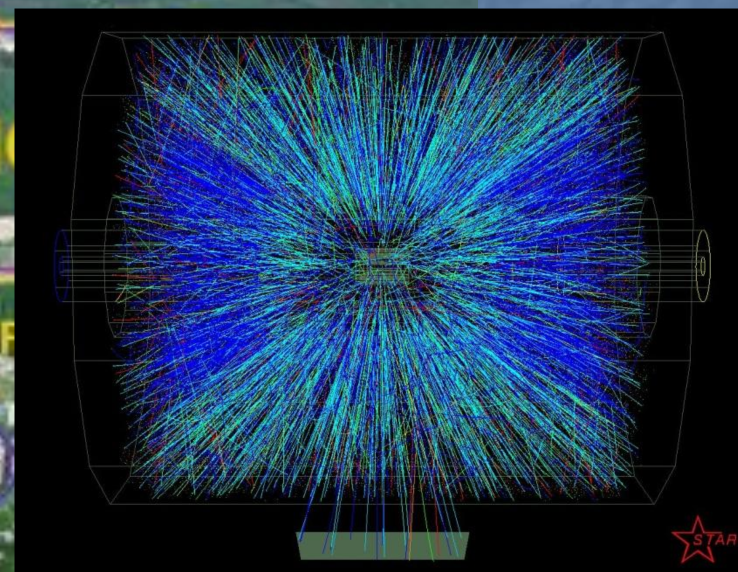
1. Basic aspects of relativistic heavy ion collisions and latest results at LHC
2. Hydrodynamic analysis of relativistic heavy ion collisions at RHIC and LHC

Physics of Relativistic Heavy Ion Collisions

Fate of Smashing Two Nuclei



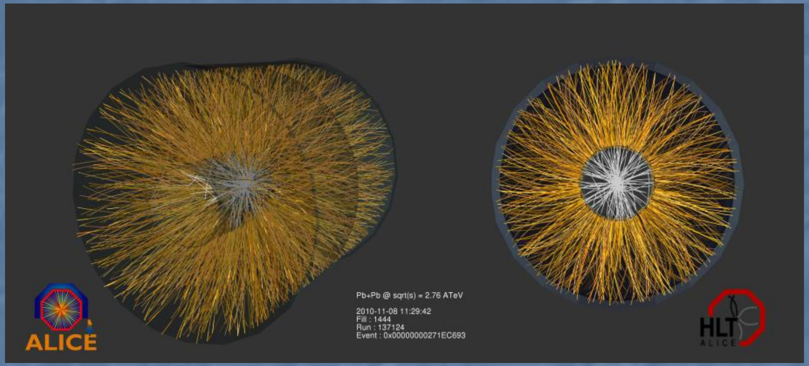
Front View

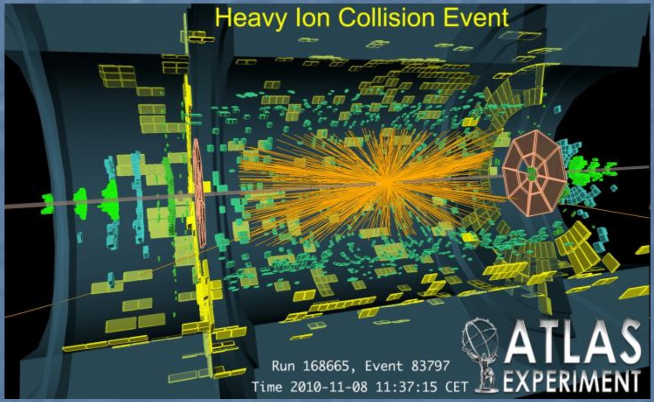


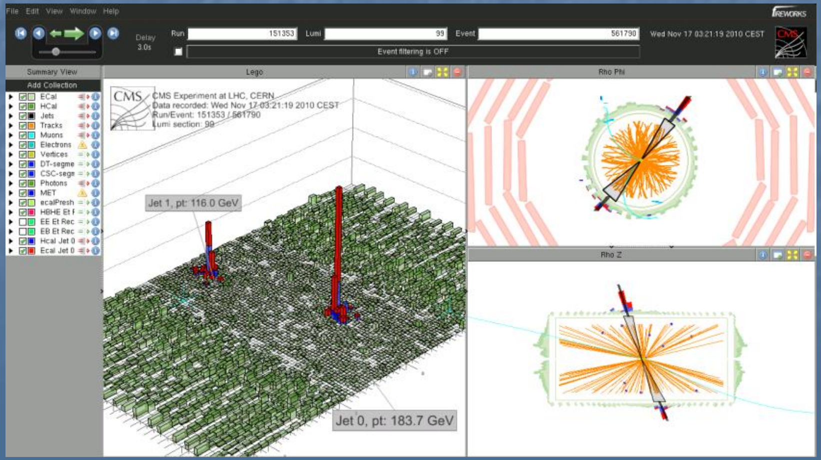
Side View

Multiplicity of charged hadrons ~ 700 per unit rapidity in a head-on collision at sqrt(s_{NN})=200 GeV

New Era Just Started!





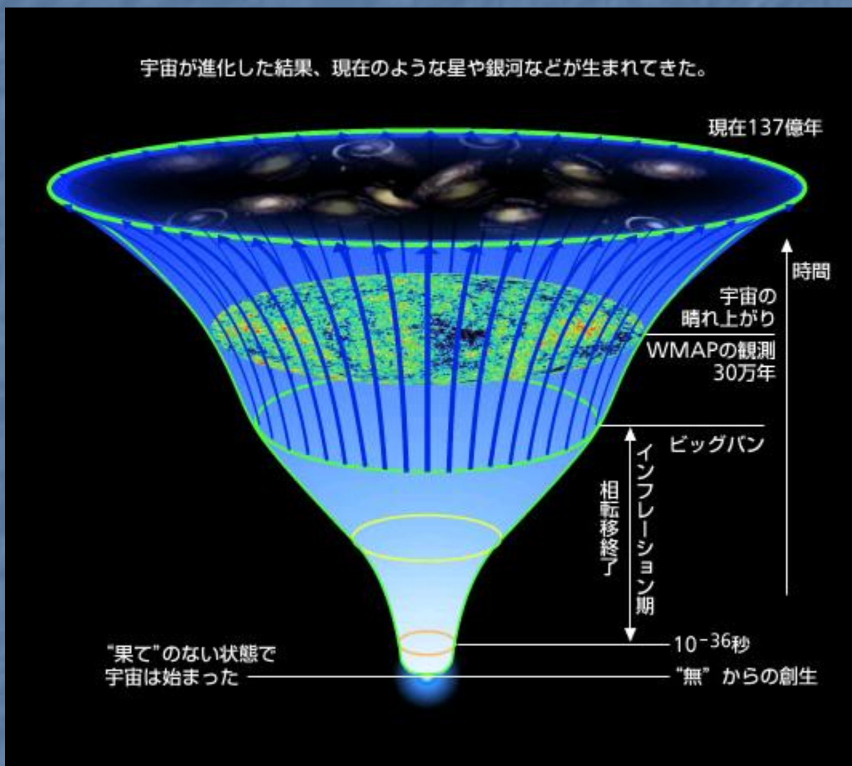


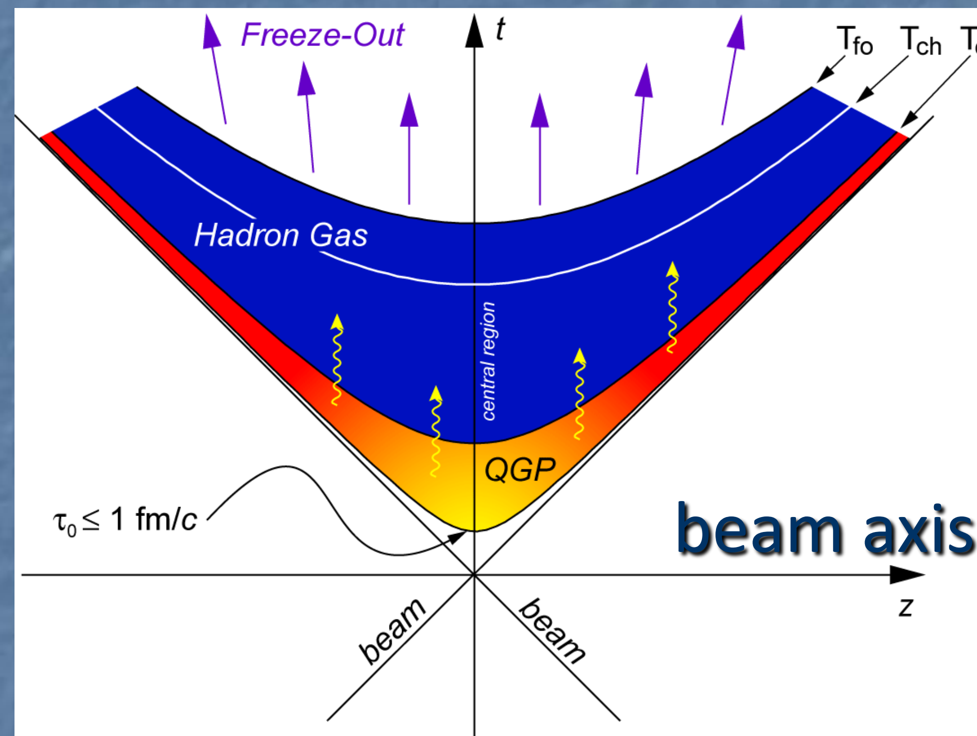
Multiplicity of charged hadrons ~ 1600 per unit rapidity in a head-on collision at $\mathrm{sqrt}(s_{NN})$=2.76 TeV

Primary Goals of Heavy Ion Collisions at Ultrarelativistic Energies

- Understanding of QCD matter under extreme conditions, quark gluon plasma (high T and low n_B)
  - Confinement, chiral symmetry breaking
  - Relevant to early universe
  - Properties of matter under extreme conditions governed by strong interaction
  - Unique opportunity

Big Bang vs. Little Bang





3D Hubble expansion

Nearly 1D Hubble expansion*
+ 2D transverse expansion

Figure adapted from
http://www-utap.phys.s.u-tokyo.ac.jp/~sato/index-j.htm

*Bjorken('83)

Big Bang vs. Little Bang (contd.)

	Big Bang	Little Bang
Time Scale	10^{-5} sec >> m.f.p./c	10^{-23} sec ~ m.f.p./c
Expansion Rate	$10^{5\text{-}6}$/sec	$10^{22\text{-}23}$/sec

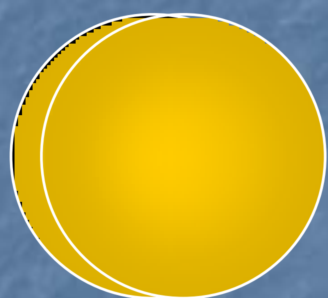
→ Local thermalization is not trivial in heavy ion collisions.

Spectrum	Red-shifted (CMB)	Blue-shifted (hadrons)

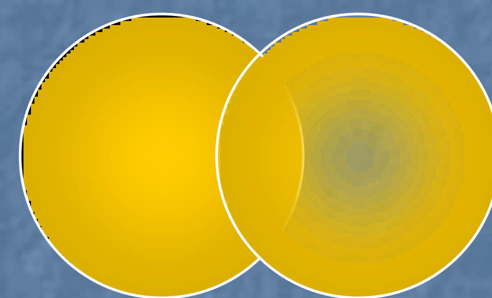
→ Collective flow is a key to see whether local thermalization is achieved.

Jargon: Centrality

"Centrality" characterizes a collision and categorizes events.



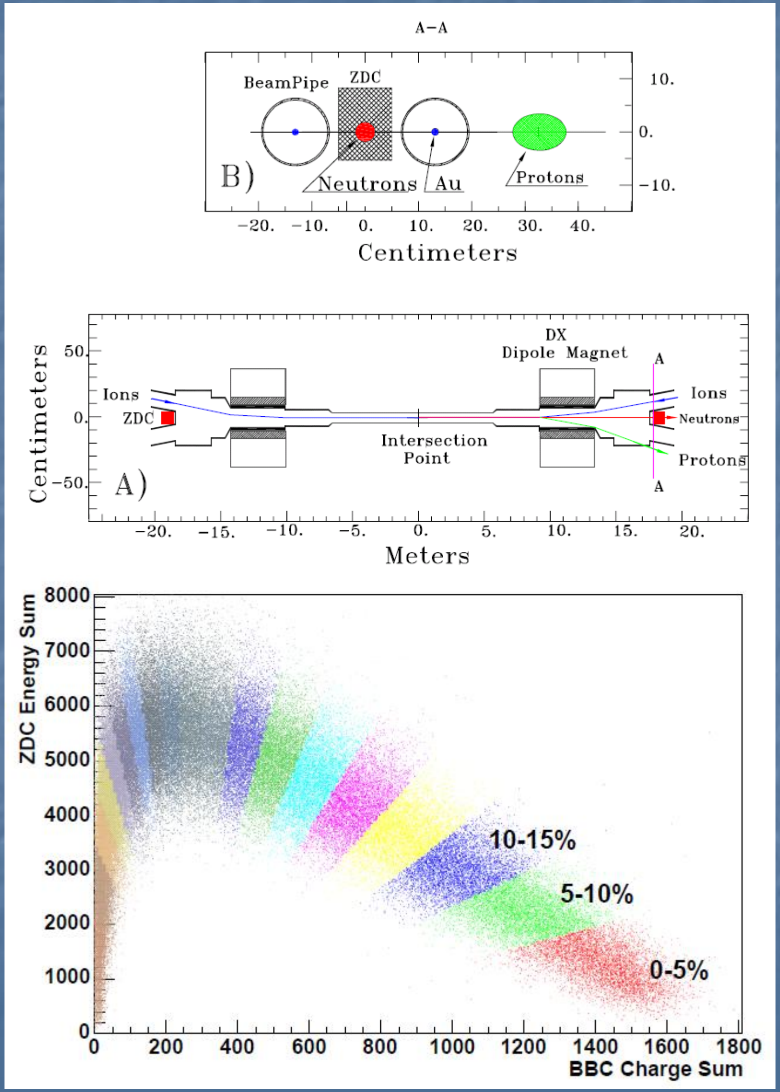
central event



peripheral event

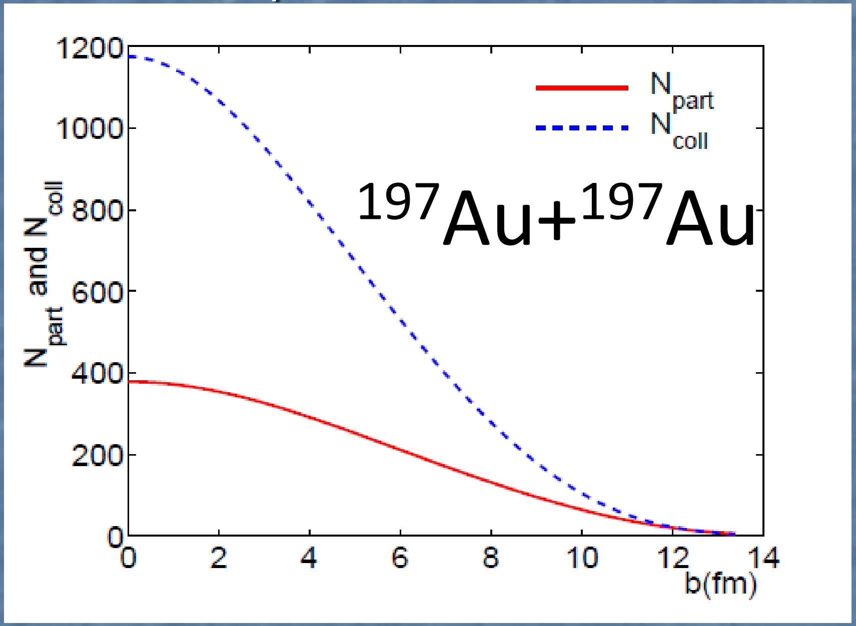
Participant-Spectator picture is valid

How to Quantify Centrality



PHENIX: Correlation btw. BBC and ZDC signals

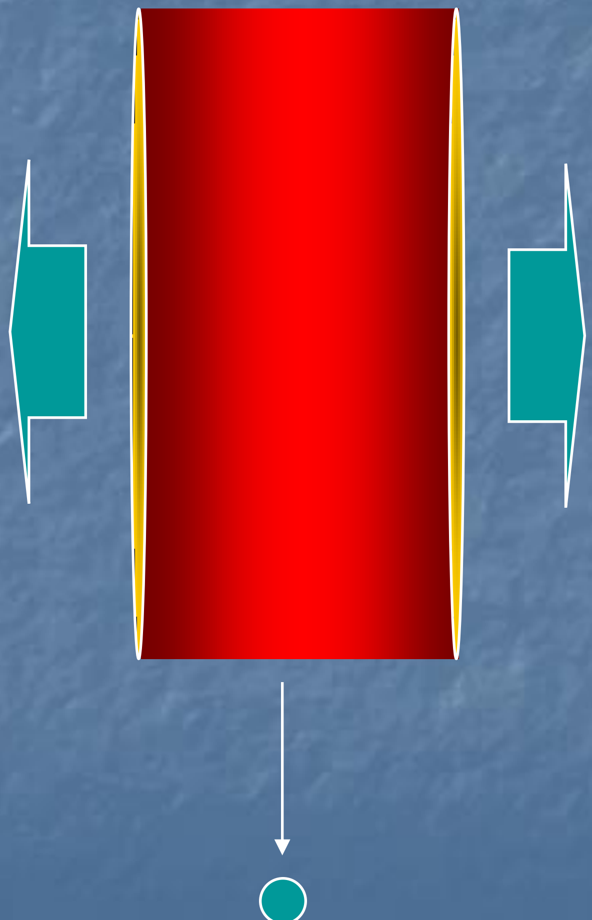
N_{part} and N_{coll}



N_{part}: The number of participants
N_{coll}: The number of binary collisions
N_{part} and N_{coll} as a function of impact parameter

Basic Checks of Exp. Data at RHIC

Sufficient Energy Density?



Bjorken('83)

Bjorken energy density

$$\epsilon_{\mathrm{Bj}}(\tau) = \frac{\langle m_T \rangle}{\tau \pi R^2} \frac{dN}{dy}$$

total energy
(observables)

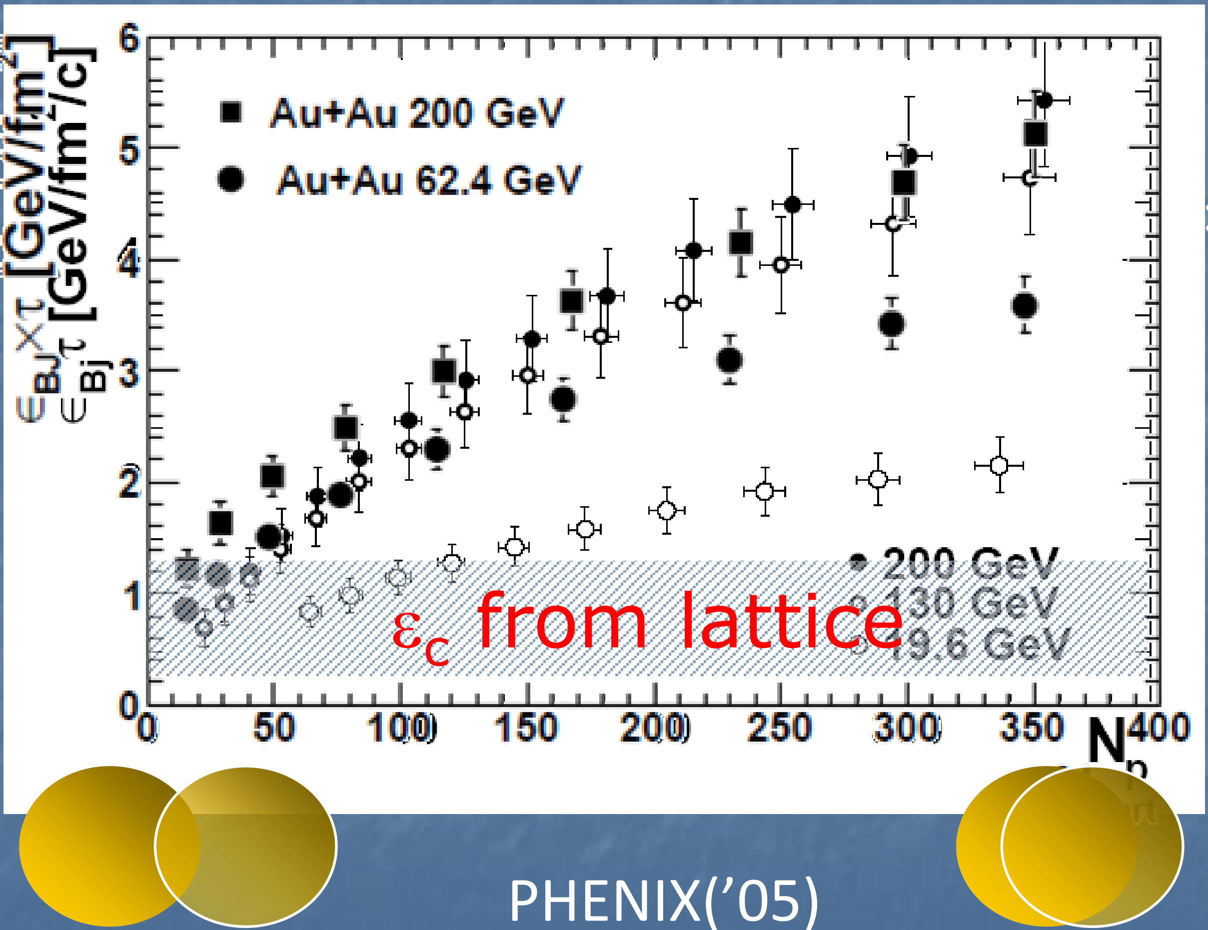
τ: proper time

y: rapidity

R: effective transverse radius

m_T: transverse mass

Estimated Energy Density at RHIC



$$\epsilon_{Bj}(\tau) = \frac{\langle m_T \rangle}{\tau \pi R^2} \frac{dN}{dy}$$

Well above ε_c from lattice simulations in central collision at RHIC

PHENIX('05)
STAR('08)

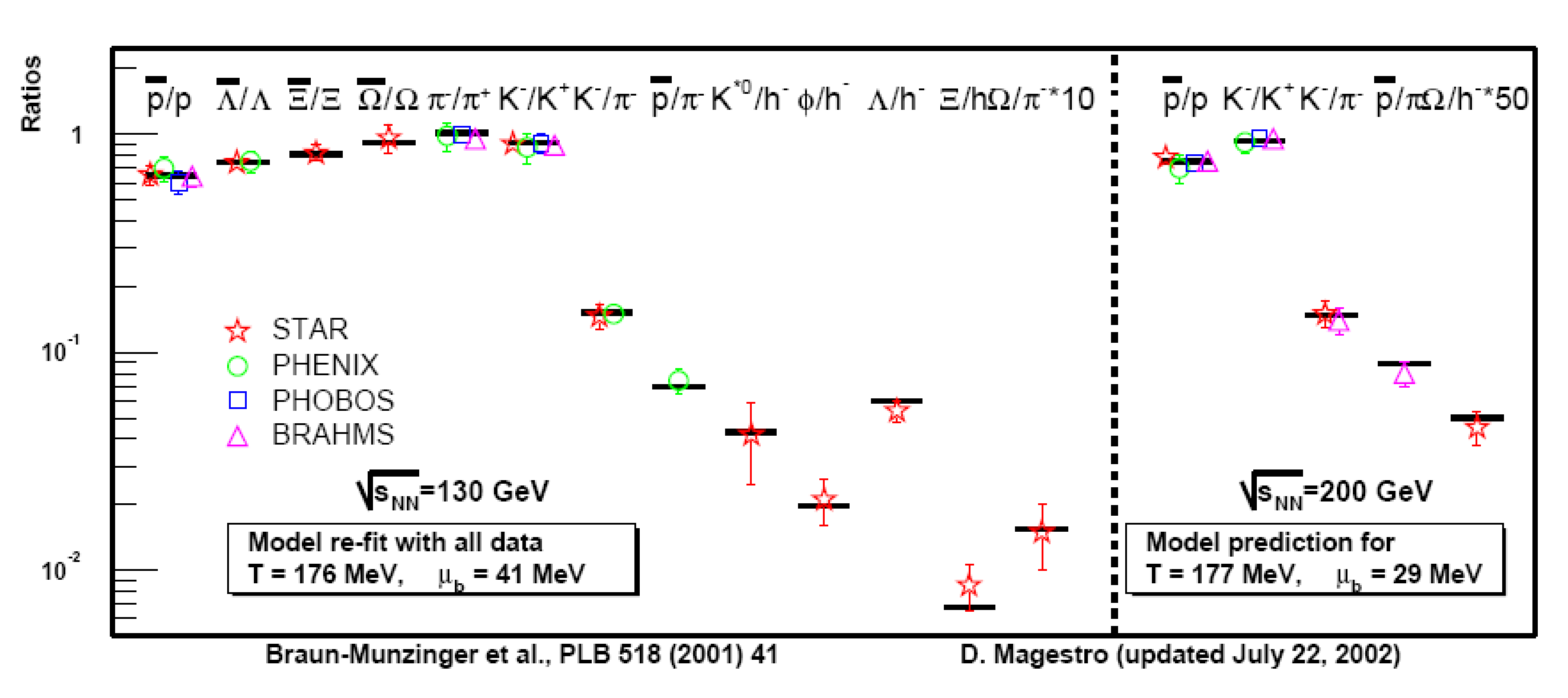
Matter in (Chemical) Equilibrium?

$$n_i(T,\mu) \;=\; \frac{g}{2\pi^2}\int_0^\infty \frac{p^2dp}{\exp[(E_i-\mu_i)/T]\pm 1}$$

$$\langle N_i\rangle = V\left[\underbrace{n_i^{\text{th}}(T,\mu)}_{\text{direct}} + \underbrace{\sum_R \Gamma_{R\to i}n_R(T,\mu)}_{\text{Resonance decay}}\right]$$

Two fitting parameters: T_{ch}, μ_B

Chemical Freezeout Temperature

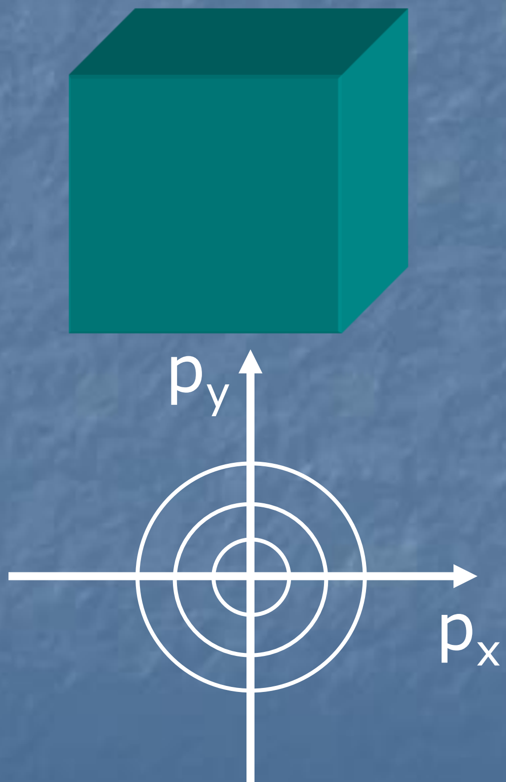


$T=177\mathrm{MeV},\ \mu_B = 29\ \mathrm{MeV}$

⇨ Close to T_c from lattice

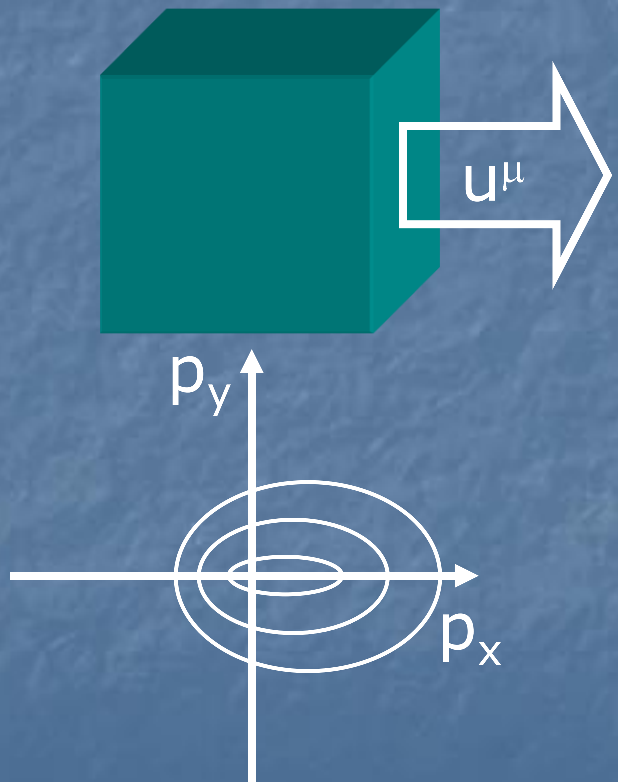
Matter in (Kinetic) Equilibrium?

Kinetically equilibrated matter at rest



Isotropic distribution

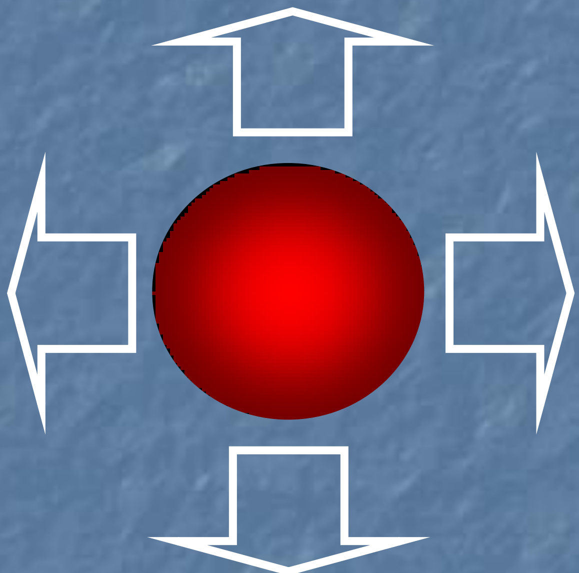
Kinetically equilibrated matter at finite velocity



Lorentz-boosted distribution

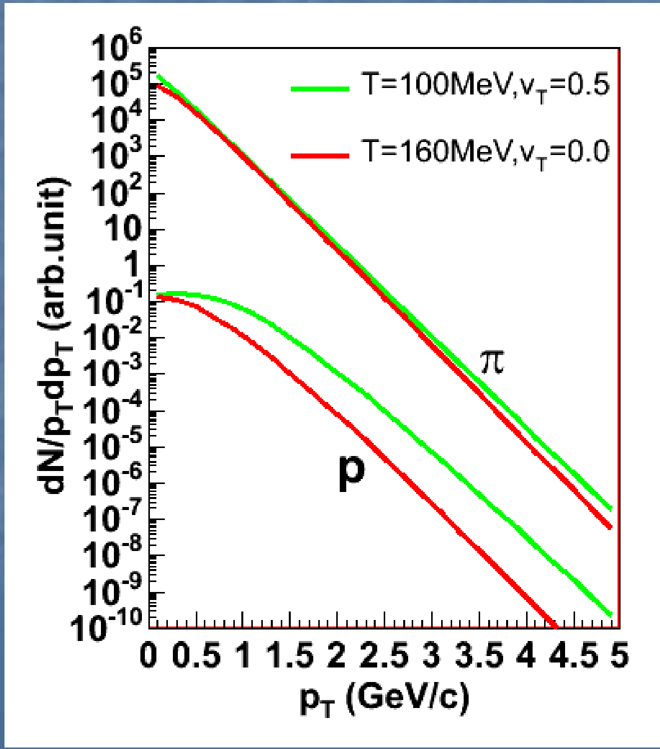
Radial Flow

Kinetic equilibrium
inside matter

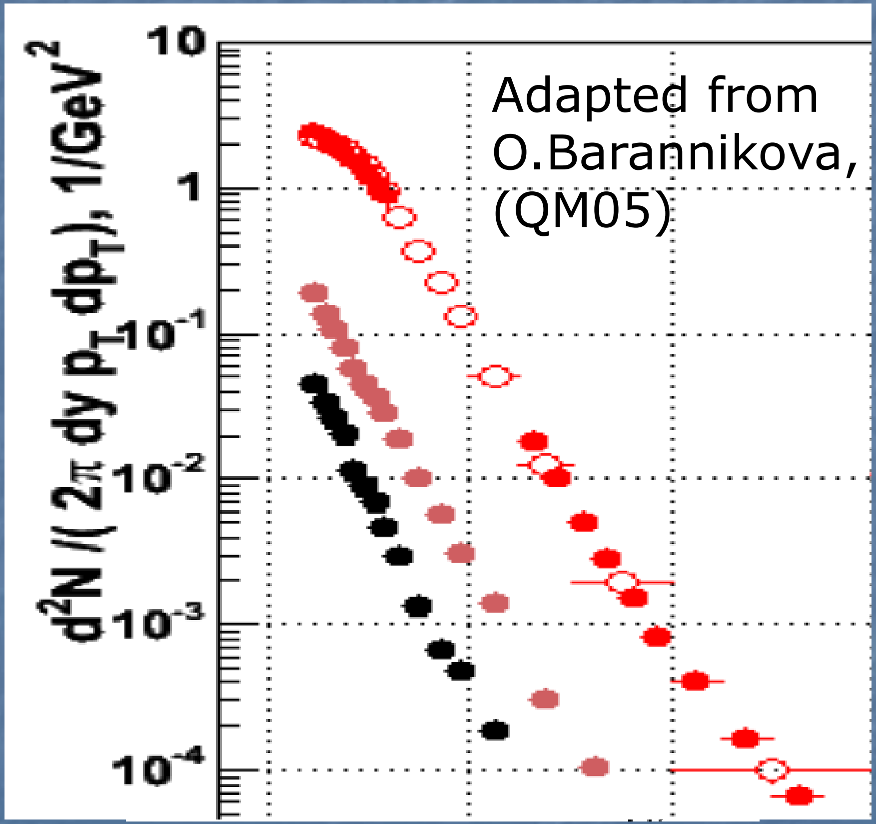


Pressure gradient
→ Driving force of flow
→ Flow vector points to
radial direction

Blast wave model
(thermal+boost)
e.g. Sollfrank et al.('93)



Spectral change is seen in AA!

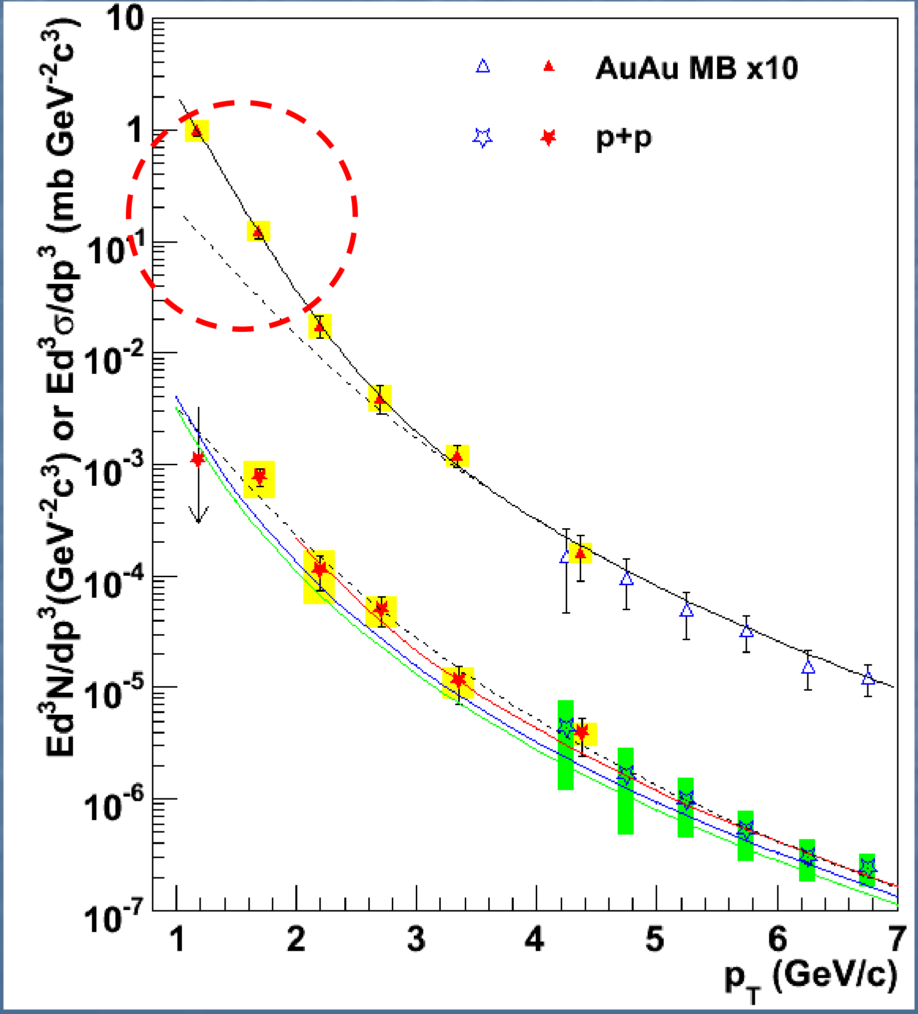


Power law in pp & dAu

Convex to Power law in Au+Au

- "Consistent" with thermal + boost picture
- Large pressure could be built up in AA collisions

Thermalized?



Excess of photon radiation

Thermal radiation?

Consistent with

Inverse slope

T~220±20 MeV

PHENIX, PRL 104, 132301 (2010)

Basic checks cleared

- Energy density can be well above e_c.
- "Temperature" can be extracted.
  - Chemically frozen $T \sim T_c$
  - Space-time averaged $T > T_c$
- High pressure could be built up.

Importance of systematic study
based on dynamical framework

Discovery of nearly perfect fluidity at RHIC

Hydrodynamics for QGP at Work

asahi.com

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宇宙の始まりはしずく？　「クオークは液体」と発表

2005年04月18日23時34分

宇宙誕生の大爆発「ビッグバン」直後に相当する超高温・高密度の状態を再現する実験をしてきた日米などの国際チームは18日、物質を形づくる究極の基本粒子クオークは超高温でバラバラになるが、気体のように自由に跳び回るのでなく、しずくのような液体状態にあったと考えられる、と発表した。理論的に予想外の発見で、宇宙や物質のなりたちを説明するシナリオに影響を与える可能性がある。

The Washington Post

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

新华网
XINHUANET.com

科学家称初生宇宙可能是液体状的而非气体状

www.XINHUANET.com　2005年04月20日 07:43:55　来源：新京报

【字体：大 中 小】【打印本稿】【读后感言】【进入论坛】【推荐 Go 】　【关闭】

本报综合报道 4月18日，在美国佛罗里达州坦帕市举行的美国物理协会会议上，有科学家提出，对粒子碰撞的最新研究结果表明，在宇宙诞生的最初百万分之一秒，宇宙可能是液体状的，而不是像过去所认为的那样是炽热的气体状的。

nature

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

by Mark Peplow
news@nature.com

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

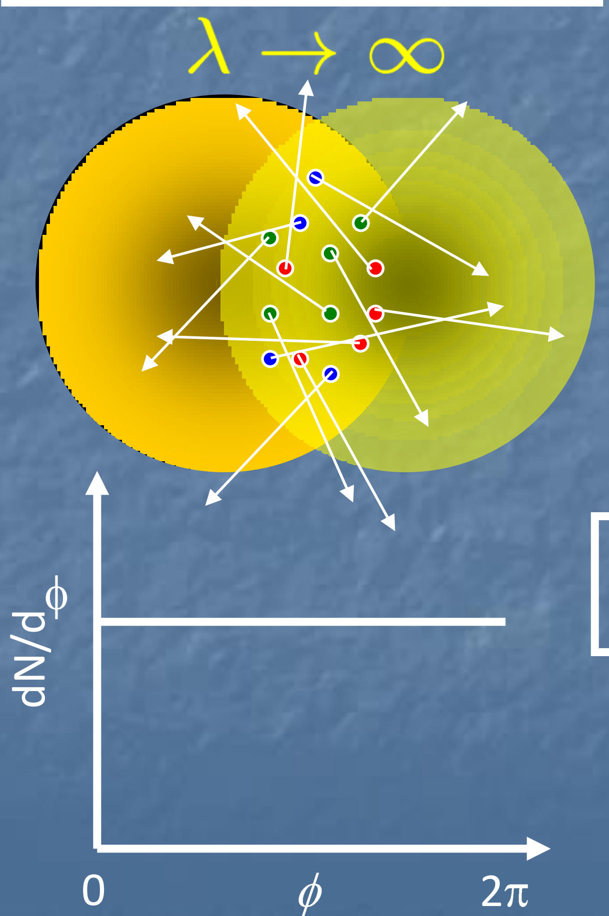
Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

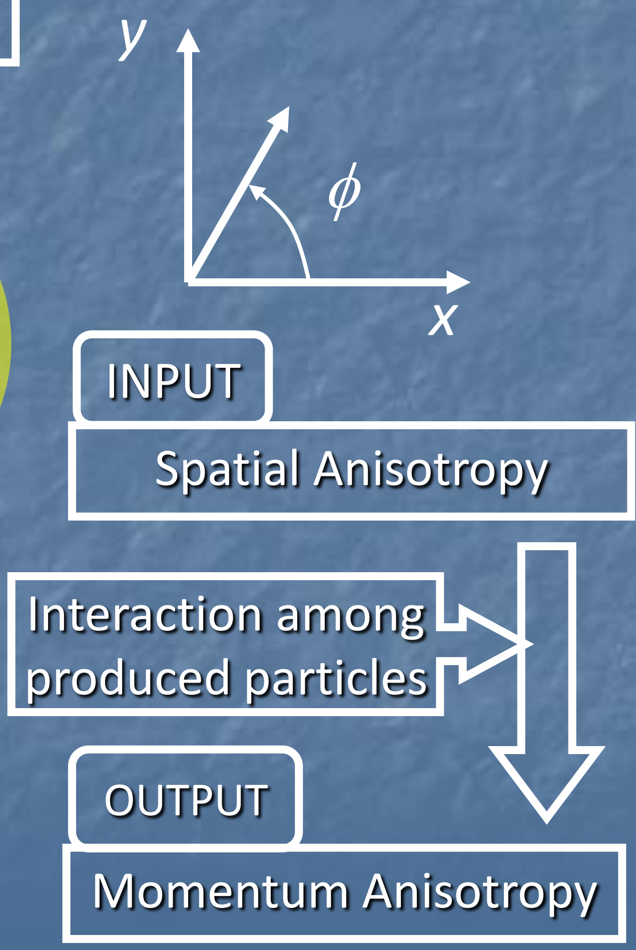
Ollitrault ('92)

What is Elliptic Flow?

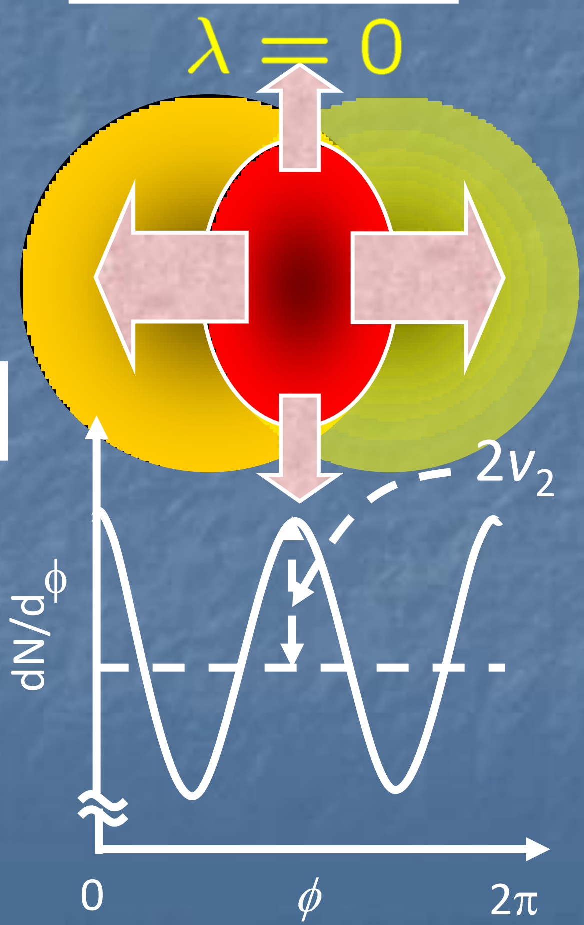
How does the system respond to spatial anisotropy?

No secondary interaction





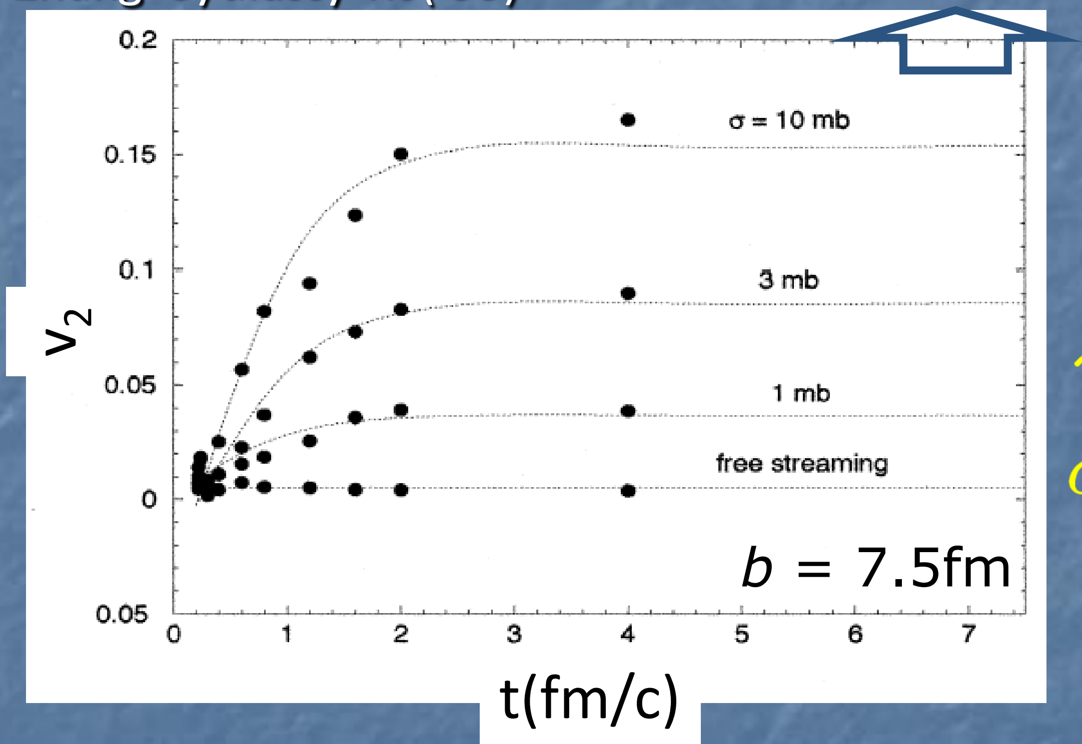
Hydro behavior



Elliptic Flow in Kinetic Theory

Zhang-Gyulassy-Ko('99)

ideal hydro limit



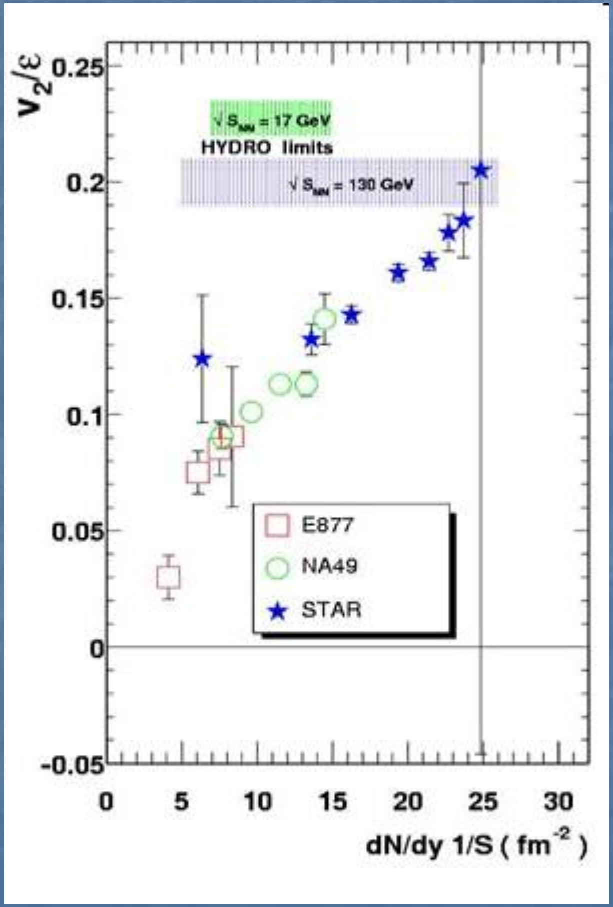
$$\lambda = \frac{1}{\sigma\rho} \propto \eta$$

$\lambda \to 0$: Ideal hydro

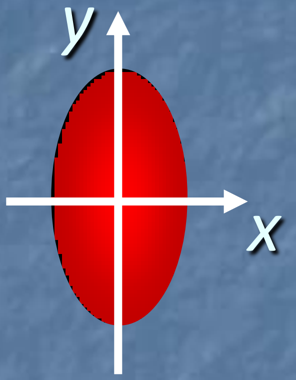
$\sigma \to \infty$: strongly interacting system

v_2 is
- generated through secondary collisions
- saturated in the early stage
- sensitive to cross section (~1/m.f.p.~1/viscosity)

Arrival at Hydrodynamic Limit



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



$$\frac{v_2}{\varepsilon} = \frac{\text{momentum anisotropy}}{\text{spatial anisotropy}}$$

$$= \frac{\text{output}}{\text{input}} = \text{response}$$

Experimental data reach hydrodynamic limit curve for the first time at RHIC.

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

Print-friendly E-mail Article

RHIC Scientists Serve Up "Perfect" Liquid

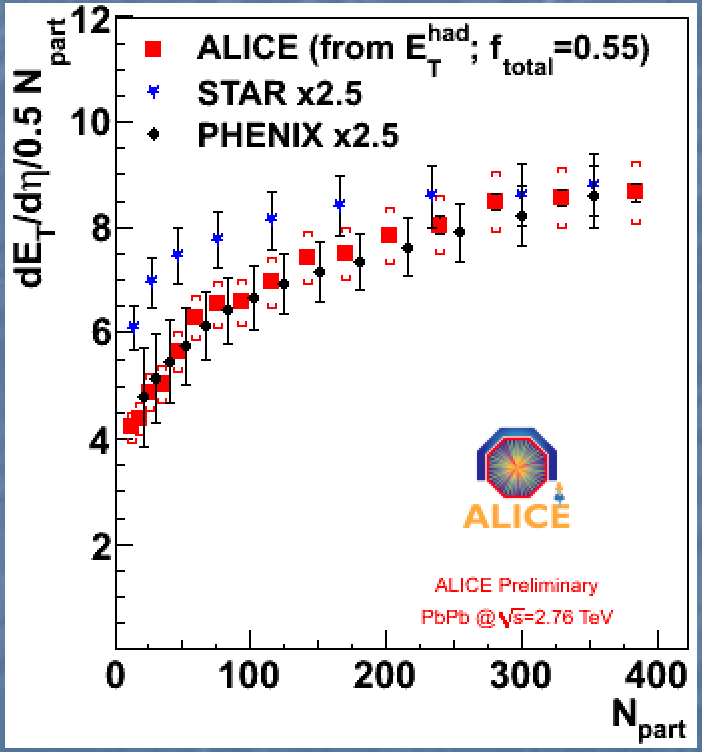
New state of matter more remarkable than predicted -- raising many new questions

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

New Results at LHC

Transverse Energy at LHC



~2.5 times larger than at RHIC

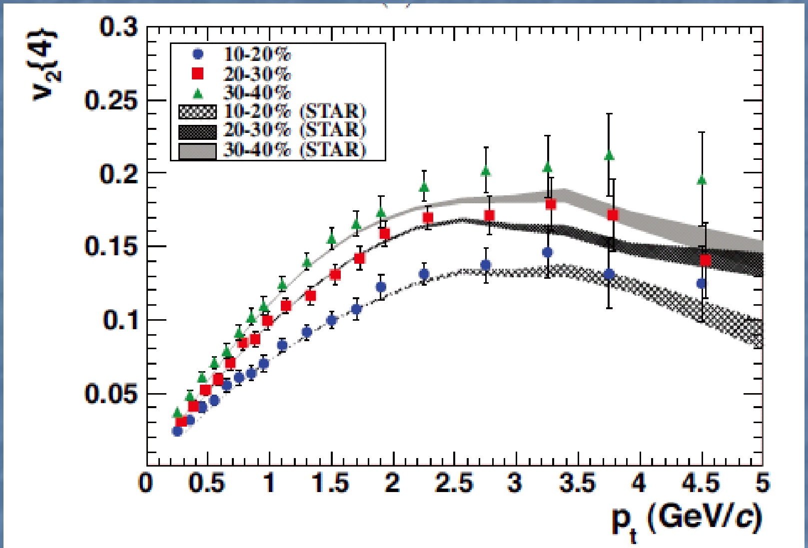
$\varepsilon \sim 16\ \mathrm{GeV/fm^3}$ @LHC

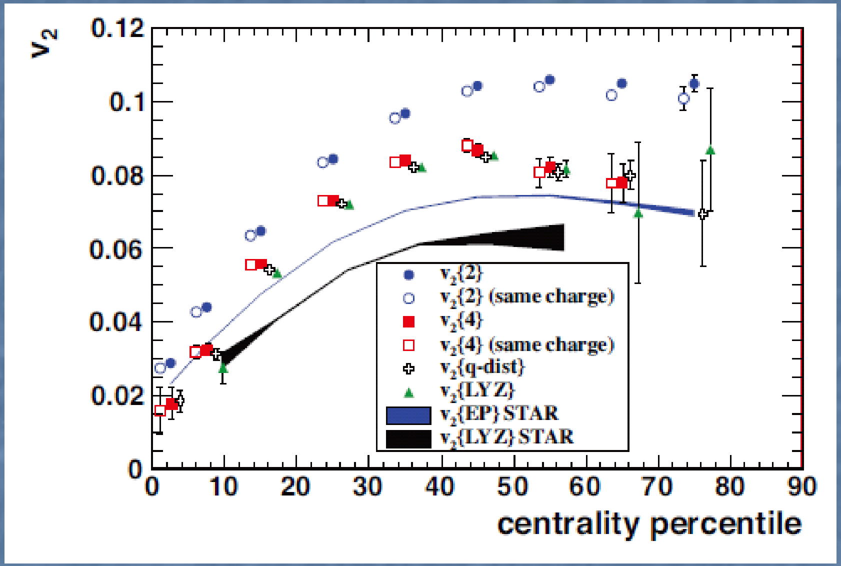
$\varepsilon \sim 5.4\ \mathrm{GeV/fm^3}$ @RHIC

assuming $\tau = 1\ \mathrm{fm}/c$

Adapted from talk by A.Toia(ALICE) at QM2011

Elliptic Flow



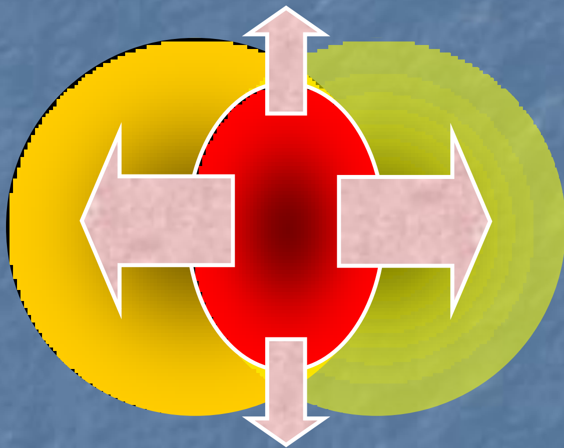


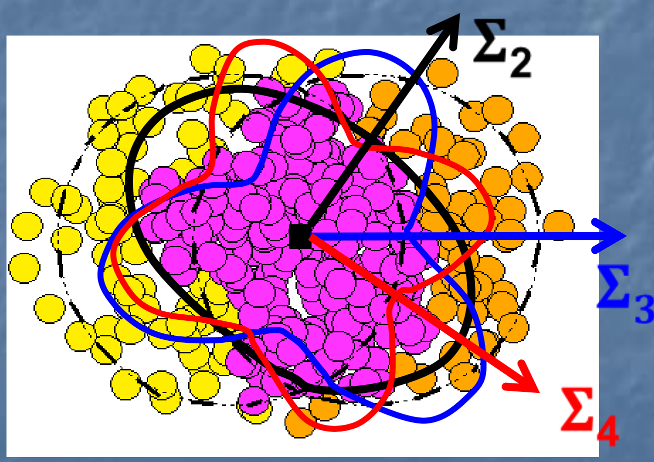
Almost identical to RHIC!?

~30% increase from RHIC to LHC

ALICE, arXiv:1011.3914

Initial Fluctuation



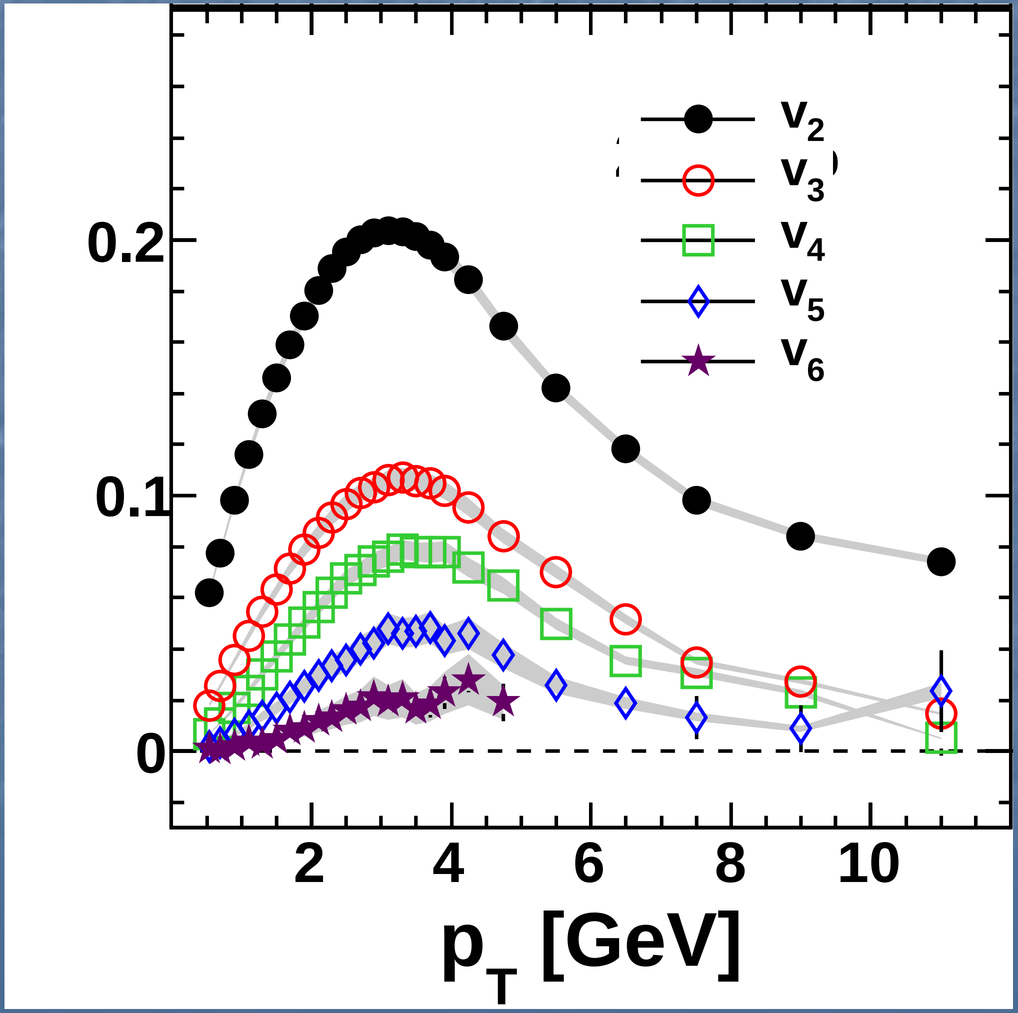


Adapted from talk by J.Jia at QM2011

Ideal situation:
Initial eccentricity drives elliptic flow.

Real situation:
Initial spatial fluctuation causes higher order harmonics.
Profile itself determines "event" planes to respond.

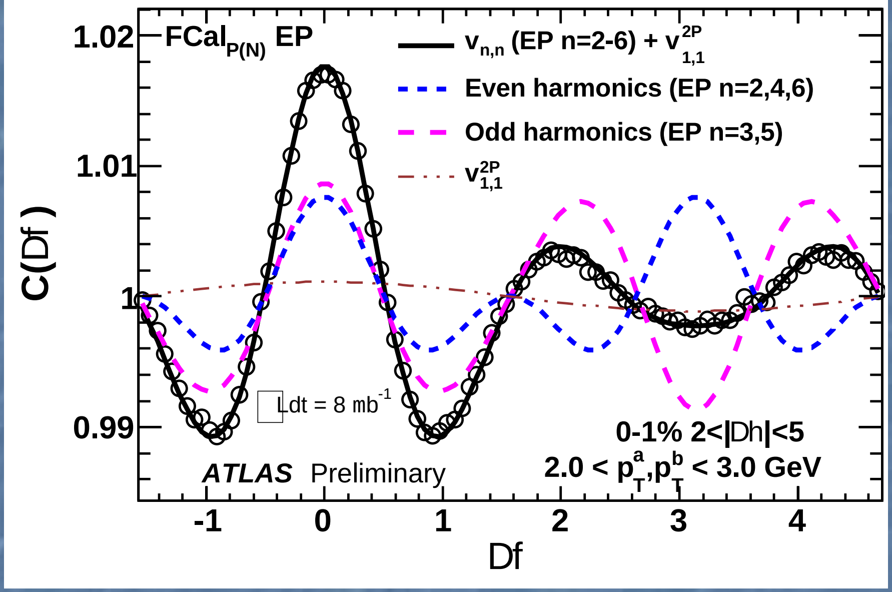
Higher Harmonics in Wide p_T Range



Higher harmonics are measured up to 10 GeV/c

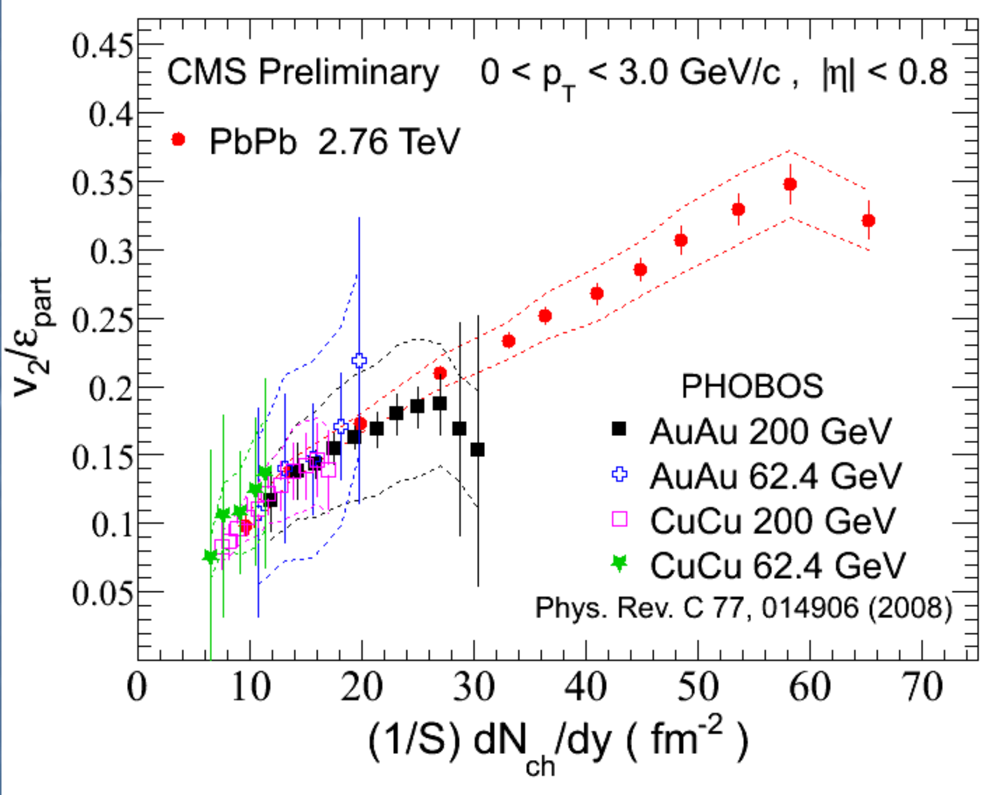
Adapted from talk by J.Jia(ATLAS) at QM2011

Two Particle Correlation



Adapted from talk by
J.Jia(ATLAS) at QM2011

Response to Eccentricity



Linear increase with multiplicity!?

Adapted from talk by J. Velkovska(CMS) at QM2011

Summary of Flow Phenomena

- An almost perfect fluid is created at RHIC for the first time.
  - Concept of strongly interacting quark-gluon many body system is established.
  - How perfect?
- First LHC results just appear!
- Fluctuation and dissipation would be a key to understand the dynamics and, in turn, transport properties of the QGP.

Remarks on this Estimate

- Even e^+e^- or pp data can be fitted well!

  See, e.g., Becattini&Heinz('97)

- What is the meaning of fitting parameters?

  See, e.g., Rischke('02),Koch('03)

- Why so close to T_c?
  - → No chemical eq. in hadron phase!?
  - → Essentially dynamical problem!

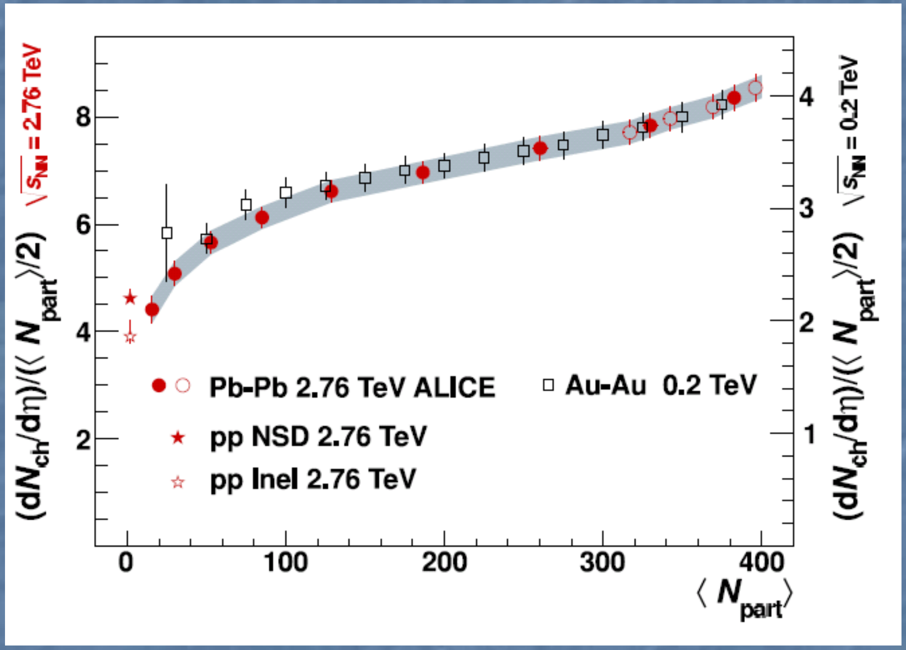
$$\partial \cdot u(x) \Longleftrightarrow \sum_j \langle \sigma_{ij} v_{ij} \rangle \rho_j$$

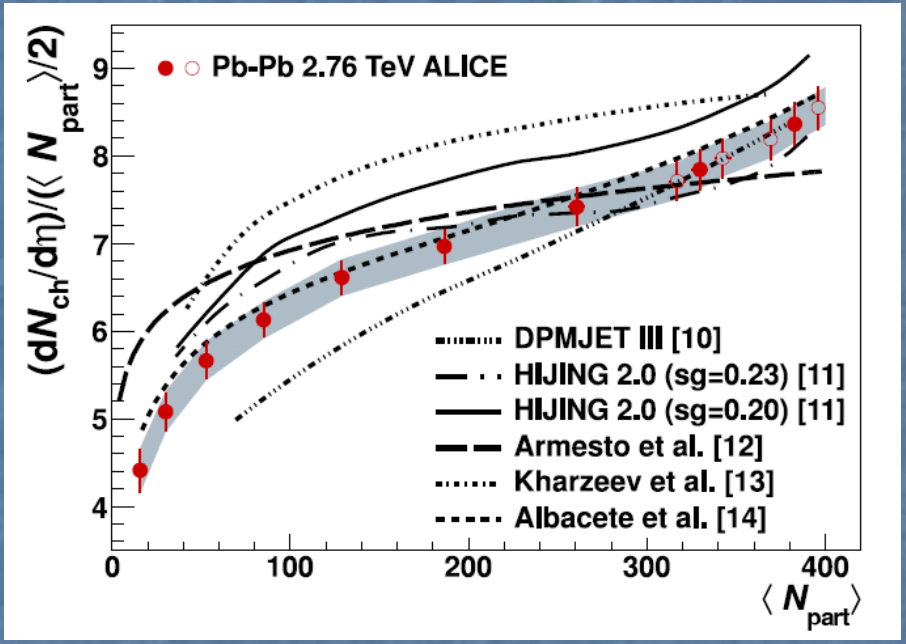
expansion rate ⟺ reaction rate

Remarks on this Estimate

- Not necessary to be thermalized completely
  - Results from hadronic cascade models.
- How is radial flow generated dynamically?
- Finite radial flow even in pp collisions?
  - (T,v_T)~(140MeV,0.2)
  - Is blast wave reliable quantitatively?
- Consistency?
  - Chi square minimum located a different point for f and W
- Flow profile? Freezeout hypersurface? Sudden freezeout?

Multiplicity



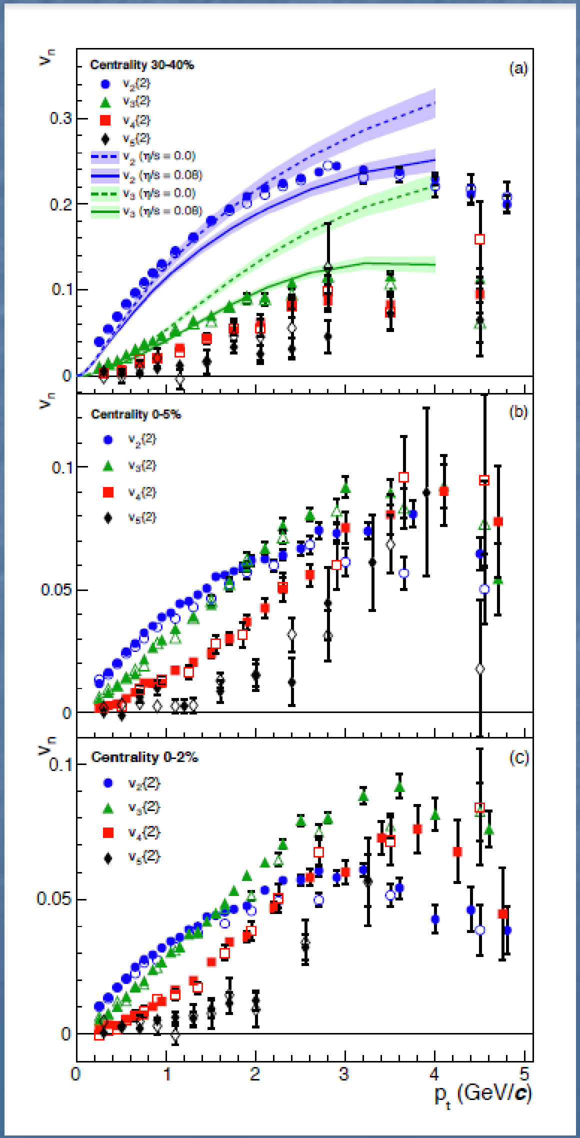


One data point kills most of models

As ~2.1 times many as at RHIC

ALICE, arXiv:1011.3916, arXiv:1012.1657

Higher Order Harmonics



- v_n (n=2,3,4 and 5) are observed at LHC
- v_n (n>3) mainly from initial fluctuation effects
- $v_2 \sim v_3$ in central events

ALICE Collaboration
arXiv:1105.3865