Relativistic Heavy-Ion Collisions

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Outline

- Introduction
- Two most important observables
  - "Large" collective flow
  - Jet quenching
- Other important observables
  - Constituent quark scaling
  - Ratios of particle abundances
  - Sequential melting of heavy quarkonia
  - Strangeness enhancement
- Role of fluid dynamics — Fluctuating initial conditions
- RHIC and LHC comparison
- LHC heavy-ion highlights
- Take-home message

Fascinating area of research

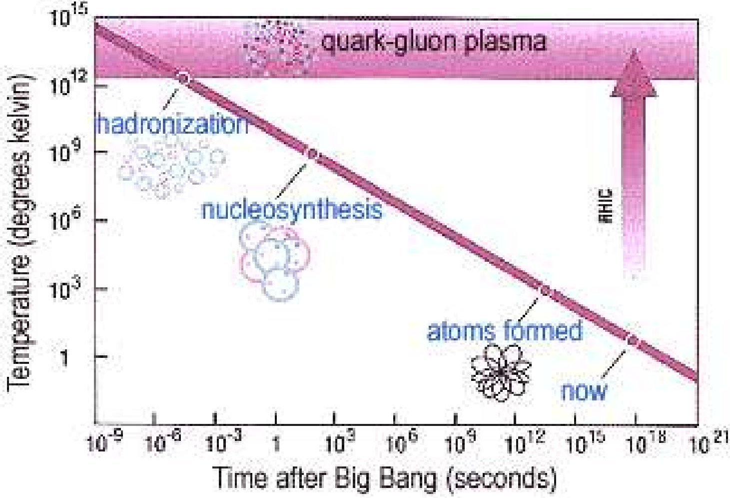
- At the interface of particle physics & high-energy nuclear physics
- Draws heavily from QCD: pert as well as non-pert
- Overlaps with thermal field theory, relativistic fluid dynamics, kinetic or transport theory, quantum collision theory, apart from statistical mechanics & thermodynamics
- QGP at high T & vanishing μ_B is of cosmological interest
- QGP at low T & large μ_B is of astrophysical interest
- Black hole - fluid dynamics connection: String theory

The science of the “small” – the elementary particle physics –

is deeply intertwined with

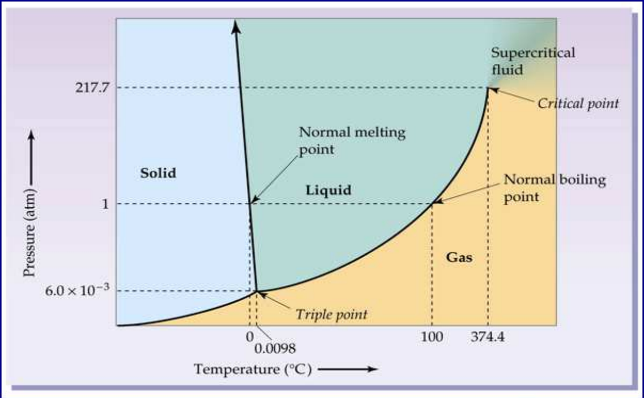
the science of the “large” – cosmology – the study of the origin and evolution of the universe.

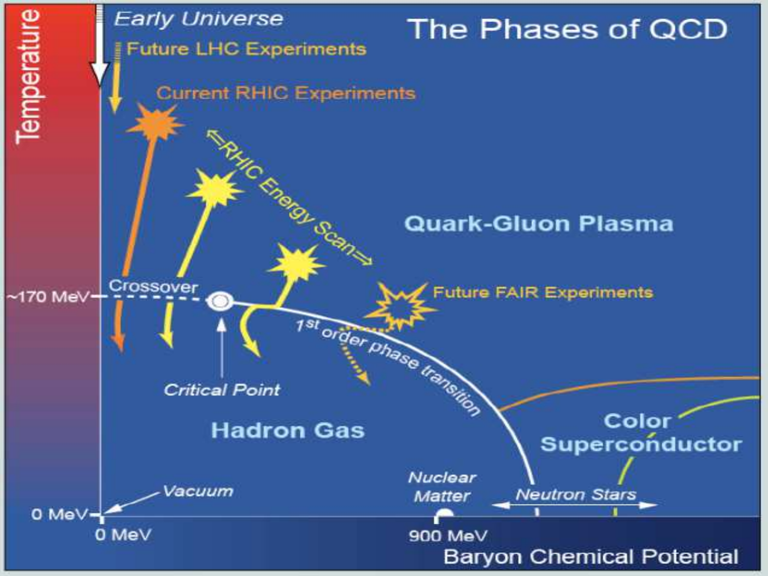
The Big Bang and The Little Bang



Temperature history of the universe

Phase Diagram of Water




Early Universe
The Phases of QCD
Future LHC Experiments
Current RHIC Experiments
Temperature
⇐RHIC Energy Scan⇒
Quark-Gluon Plasma
Future FAIR Experiments
~170 MeV
Crossover
1^{st} order phase transition
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Vacuum
Neutron Stars
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

QGP Definition

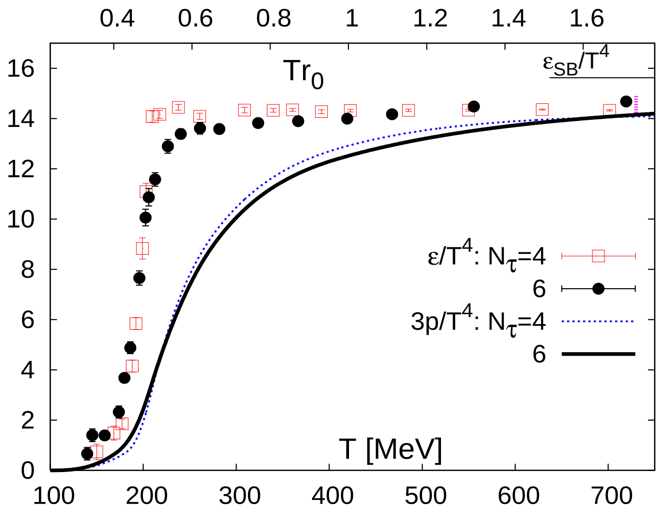
Quark-Gluon Plasma (QGP): This is defined as a (locally) thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that they propagate over *nuclear*, rather than merely *nucleonic*, volumes.

Two essential ingredients:

1. Degrees of freedom should be quarks and gluons
2. Matter should have attained (local) thermal equilibrium

- Big idea: To map out (quantitatively) QCD phase diagram.
- Theoretical tools: Lattice QCD, phenomenological models, effective theories.
- Experimental tools: Relativistic heavy-ion collisions:
  SPS (CERN), RHIC (BNL), LHC (CERN). Upcoming lower-energy facilities: FAIR (GSI) & NICA (JINR).

Lattice QCD result for EOS



Nearly realistic *u*, *d*, *s* masses. From Cheng et al. (2008).

General Philosophy

- Collision of two nuclei or two CGC plates
- Deposition of kinetic energy & formation of glasma
- Liberation of partons from glasma
- (Near) thermalization of partons: Formation of QGP
- Hydrodynamic expansion, cooling, dilution
- Hadronization — Kinetic theoretical expansion
- Chemical freezeout: inelastic processes stop
- Kinetic freezeout: elastic scatterings stop
- Detection of particles — Extraction of QGP properties

Standard Model of URHICs

- Initial state: Glauber model or Colour-Glass Condensate
- Intermediate evolution: Rel. second-order hydrodynamics
- End evolution: Rel. transport theory leading to a freeze-out
- Final state: Detailed measurements (single-particle inclusive, two-particle correlations, etc.) are available.

Aim: To achieve a quantitative understanding of the properties of quark-gluon plasma (QGP), e.g., its EOS, Transport coeffs.

Major problems: Correct initial-state model? Event-by-event fluctuations in the initial state.

Two most important observables in rhics

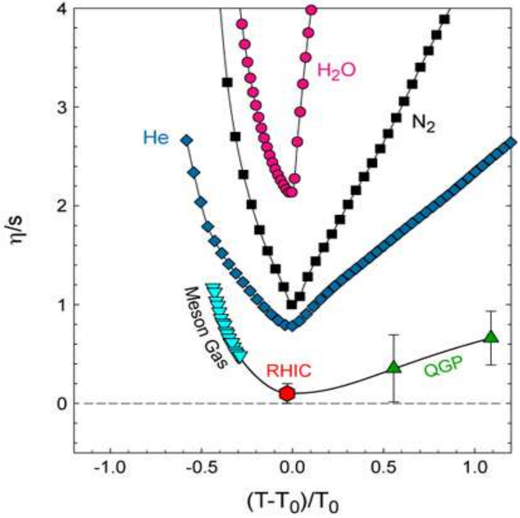
(1) Elliptic flow and (2) Jet quenching.

Observation of a "large" elliptic flow led to the claim of formation of an almost perfect fluid – strongly coupled QGP (sQGP) – at RHIC $\Rightarrow$ (local) equilibration of matter.

A natural explanation of the observed jet quenching is in terms of a dense & coloured (hence partonic, not hadronic) medium.

Recall the definition of QGP.

Meaning of "the most perfect fluid"



Constant-pressure curves

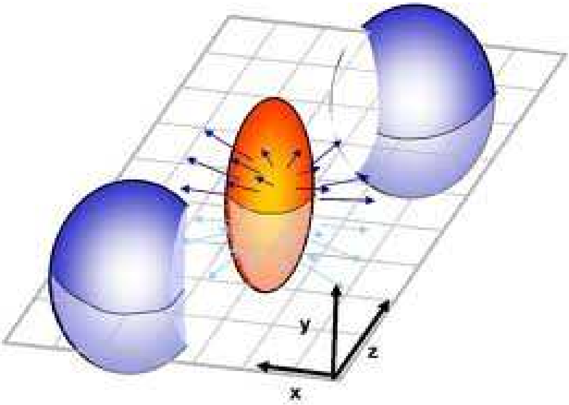
Meson gas: χPT
(50 % error not shown)

QGP: LGT calc. of Nakamura & Sakai

From Lacey et al. (PRL 2007).

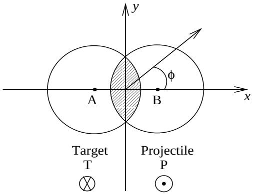
Note: η/s. Note: Liquids & gases behave differently.

Non-central Collision & Reaction Plane



Beam or longitudinal direction: z, Impact parameter vector: x, Reaction plane: xz, Transverse or azimuthal plane: xy.

Non-central Collision & Anisotropic Flow



Triple differential invariant distribution of particles emitted in $|f\rangle$

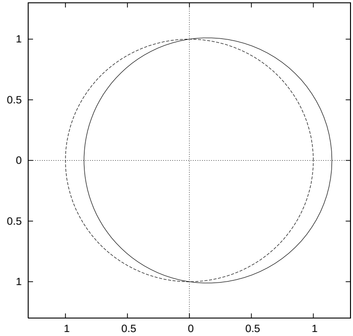
$$
\begin{aligned}
E\frac{d^3N}{d^3p} &= \frac{d^3N}{p_T dp_T dy d\phi} \\
&= \frac{d^2N}{p_T dp_T dy}\frac{1}{2\pi}\left[1+\sum_1^{\infty} 2v_n \cos n(\phi-\Psi^R)\right], \qquad (1)
\end{aligned}
$$

where y: rapidity, ϕ: measured w.r.t. the reaction plane.

v_1: Directed Flow, v_2: Elliptic Flow.

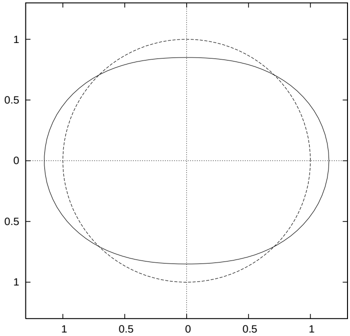
Fluctuations $\Rightarrow$ Eq. (1) needs generalization. Later.

Why "Directed Flow" ?



Polar plot $r = 1 + 2v_1 \cos\phi$ for a small (a few %) v_1.
Appears shifted in one direction. Hence Directed Flow.

Why "Elliptic Flow" ?

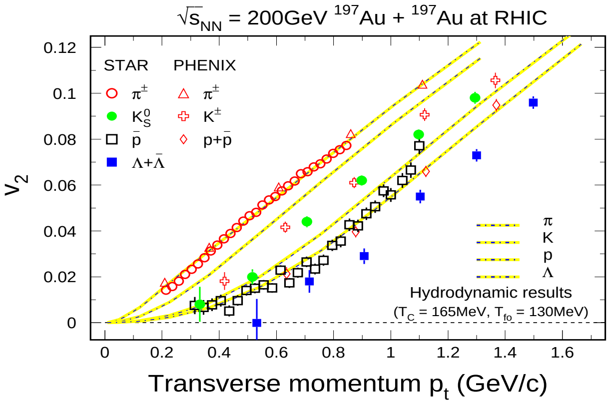


Polar plot $r = 1 + 2v_2 \cos 2\phi$ for a small (a few %) v_2.
Looks like an ellipse. Hence Elliptic Flow.

Importance of the anisotropic or azimuthal flow

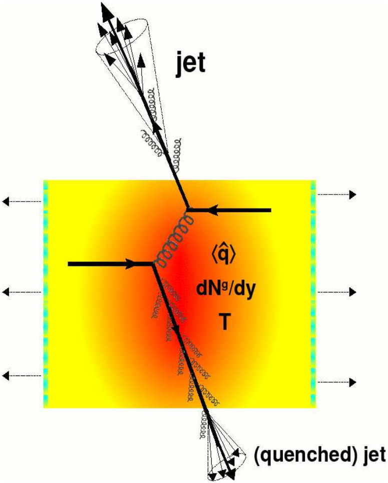
- Sensitive to the early history of the collision because of the self-quenching expansion.
- Signature of pressure at early times, or
- Measure of the degree of thermalization of the quark-gluon matter formed in rhics – (central issue).
- Observation of a "large" elliptic flow at RHIC led to the claim of formation of an almost perfect fluid.
  Strongly coupled QGP $\Rightarrow$ (local) equilibration of matter.

“Large” Elliptic Flow — Success of Ideal Hydro



Minimum-bias data, Oldenberg (STAR), nucl-ex/0412001.
Solid lines: Huovinen et al. (2001, -04), EoS-Q. Mass ordering.

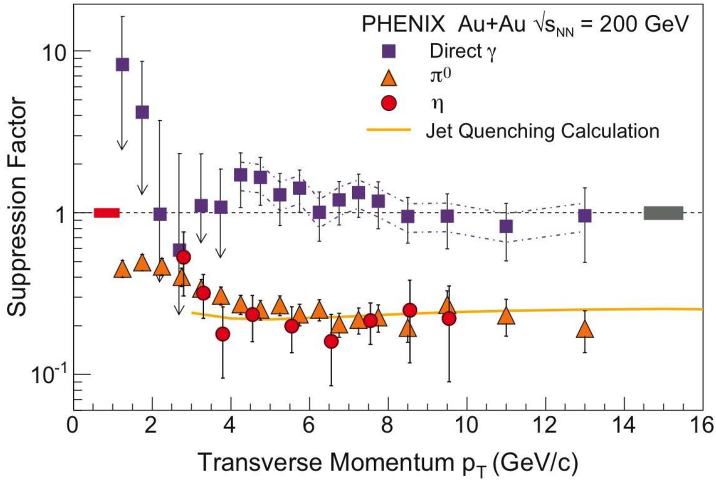
Jet Quenching



- Jet quenching is seen in inclusive single-particle spectra and in dihadron correlations.

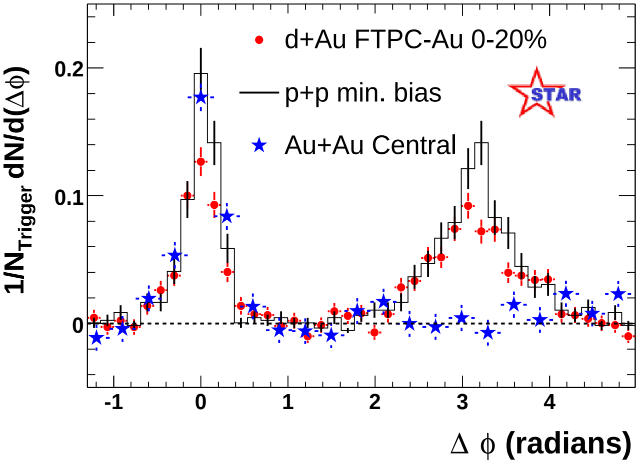
- Direct jet reconstruction is possible but very difficult at RHIC, relatively easy at LHC.

Jet Quenching (single-particle inclusive yield)



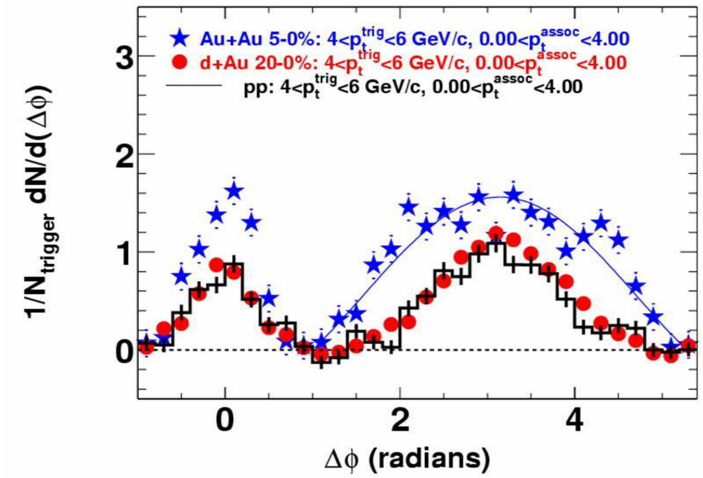
R_{AA} vs p_T. Central collisions. Suppression is a final-state effect. Energetic partons lose energy as they traverse the medium. Calc. by Gyulassy, Levai, Vitev. $dN^g/dy = 1150$.

Jet Quenching (dihadron angular correlations)



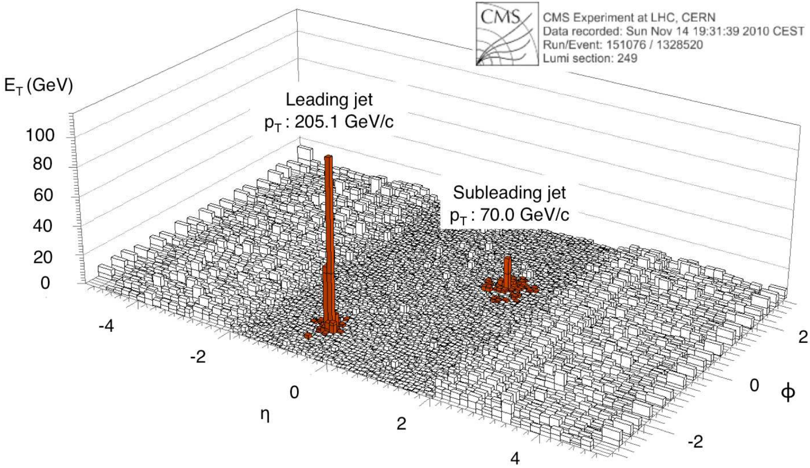
Trigger particle $p_T > 4$ GeV. Associated particle $p_T > 2$ GeV. [nucl-ex/0306024].

Jet Quenching (dihadron angular correlations)



Broadened jet shape due to medium-induced gluon radiation [nucl-ex/0501016].

Jet Quenching at CMS – Unbalanced-dijet event

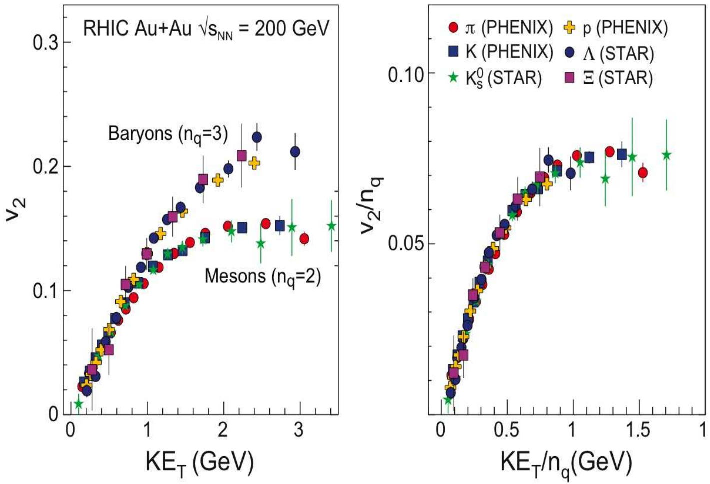


Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV. Summed E_T in e.m. and hadron calorimeters. [nucl-ex/1102.1957]

Various p_T regimes and corresponding observables

- Low-p_T regime: $0 \lesssim p_T \lesssim 1.5$ GeV/c
  Collective flows
- Medium-p_T regime: $1.5 \lesssim p_T \lesssim 5$ GeV/c
  Constituent quark scaling
- High-p_T regime: $p_T \gg 5$ GeV/c
  Jet quenching

Constituent Quark Scaling



Left: 2 distinct branches. Right: universal curve.

Flow is developed at the quark level.

Hadronization occurs by quark recombination or coalescence.

Other important observables

- Ratios of particle abundances: constrain models of particle production.
- Strangeness enhancement: (1) Although $m_s \gg m_{u,d}$, production of $s, \bar{s}$ becomes easy at $T > m_s$ (2) Large gluon density in QGP helps $g\bar{g} \rightarrow s\bar{s}$ (3) Mass of the lightest strange hadron $\gg m_s$. Hence mass threshold for strangeness production is much higher in the hadron scenario than in the QGP scenario.
- Sequential melting of heavy quarkonia: Colour Debye screening of attraction between Q and $\bar{Q}$ in QGP.

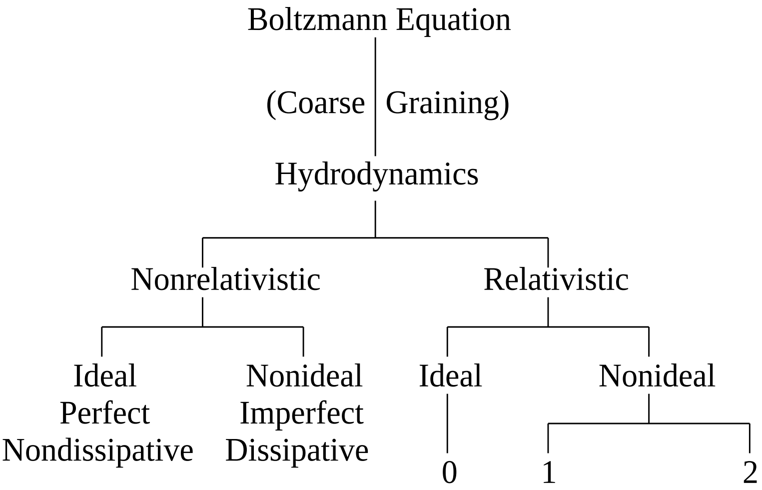
Fluid Dynamics / Hydrodynamics — what, where, why

- Kinetic/Transport Theory: Microscopic theory.
- Fluid Dynamics: Effective theory that describes the slow, long-wavelength motion of a fluid close to equilibrium.
- A set of coupled partial differential equations for $n, \ \epsilon, \ P, \ u^{\mu}$, dissipative fluxes. In addition: transport coefficients & relaxation times also occur.
- Powerful technique: Given initial conditions & EoS, hydro predicts evolution of the matter.
- Limitation: applicable at or near (local) thermodynamic equilibrium only.
- Applications in cosmology, astrophysics, physics of high-energy heavy-ion collisions, ...

Hydrodynamics in HE Heavy-Ion Collisions

- Calc. of charge multiplicity, p_T spectra of hadrons, anisotropic flows v_n, and femtoscopic radii.
- Also calc. of jet quenching, J/ψ melting, thermal γ, ℓ^2, etc.
- Thus hydro plays a central role in modeling rhics.

Coarse-Graining of the Boltzmann equation

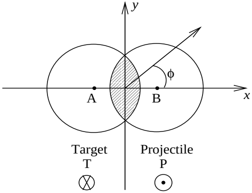


2: Currently under intense investigation

Zeroth-, First-, Second-Order Hydrodynamics

- The theory is formulated as an order-by-order expansion in gradients of hydrodynamic velocity u^μ.
- Zeroth order: Ideal hydrodynamics.
- First order: Relativistic Navier-Stokes theory — parabolic equation — acausal behaviour — rectified in second-order Israel-Stewart theory.
- Second order: Israel-Stewart

Traditional Hydrodynamic Calculations



- Shaded area: overlap of two (smooth) Woods-Saxon distributions.
- Initial energy (or entropy) density $\epsilon(x, y)$: Smooth.
- Single-particle spectra, directed & elliptic flows are calculated assuming smooth initial conditions.
- $v_1(y) = -v_1(-y)$. Hence v_1 vanishes at mid-rapidity.

However, the reality is not so simple.

Initial geometry is not smooth.

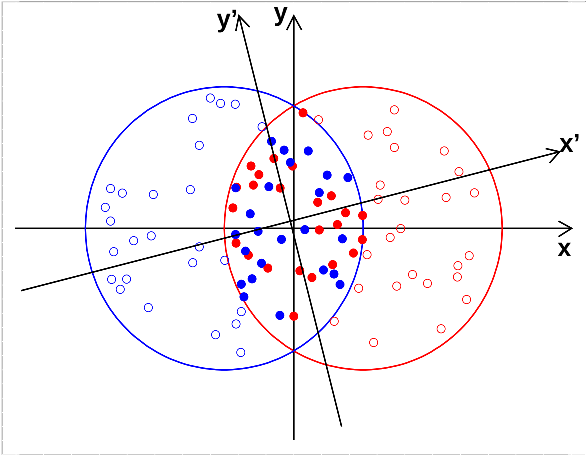
Why?

Event-to-event fluctuations in nucleon positions

Basic idea: Collision time-scale is so short that each incoming nucleus sees nucleons in the other nucleus in a frozen configuration.

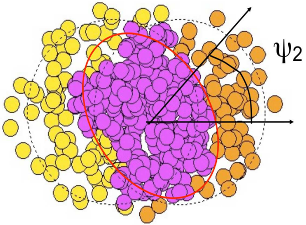
Fluctuations in N positions (and hence in NN collision points) result in fluctuations in the shape & orientation of the overlap zone.

Event-to-event fluctuations in nucleon positions

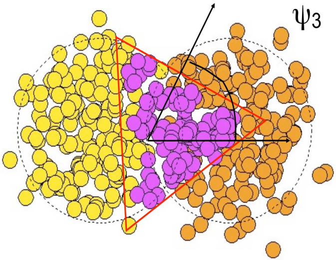


"Snapshot" of nucleon positions at the instant of collision. Due to event-to-event fluctuations, the overlap zone could be shifted & tilted w.r.t. the (x, y) frame. $x'y'$: principal axes of inertia.

Fluctuating Initial Geometry & "New" Flows



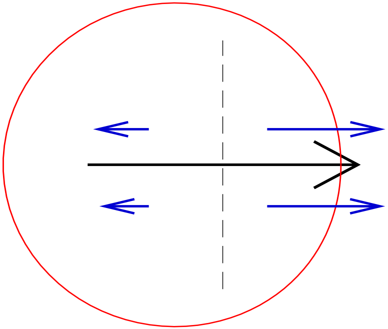
Ellipse
→ elliptic flow $v_2(p_T, y)$



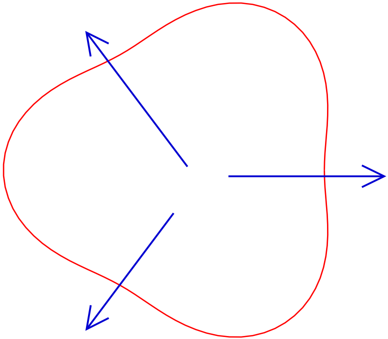
Triangle
→ triangular flow $v_3(p_T, y)$

Fluctuating Initial Geometry & "New" Flows

Systematic harmonic decomposition of the initial geometry



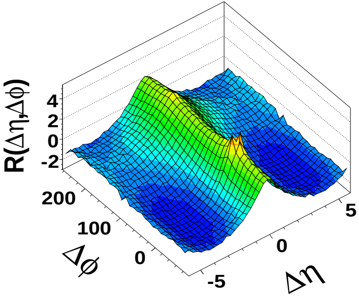
Dipole asymmetry
→ dipolar flow $v_1(p_T, y)$



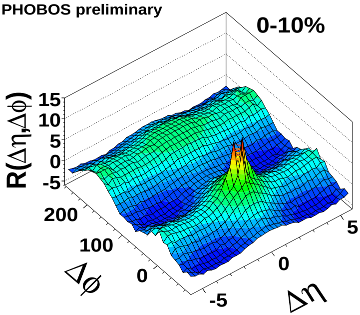
Triangularity
→ triangular flow $v_3(p_T, y)$

Ridge and Shoulder

$R(\Delta\eta, \Delta\phi)$: Inclusive two-particle correlation function

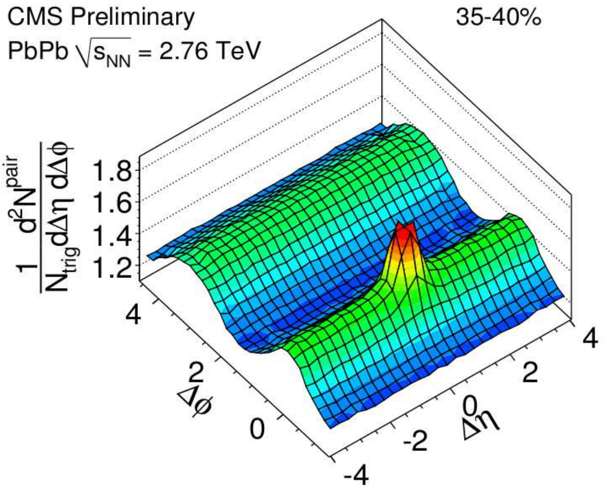


pp, 200 GeV



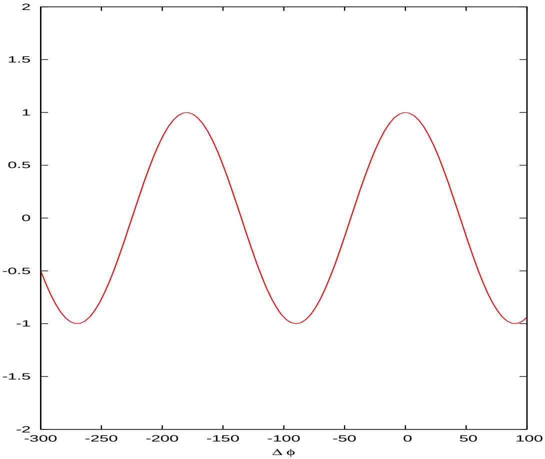
Central Au-Au, 200 GeV

Ridge and Shoulder



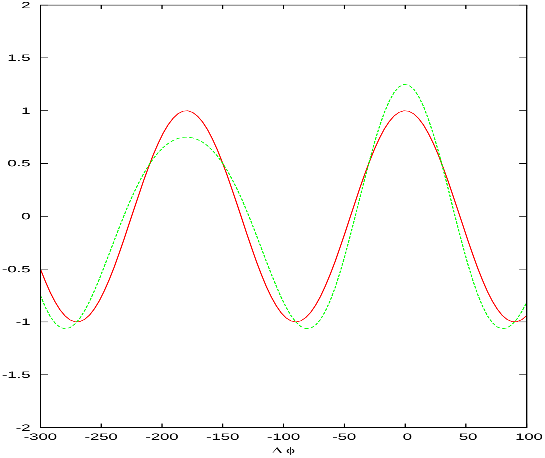
Ridge and Shoulder — Explanation

$\cos(2\Delta\phi)$



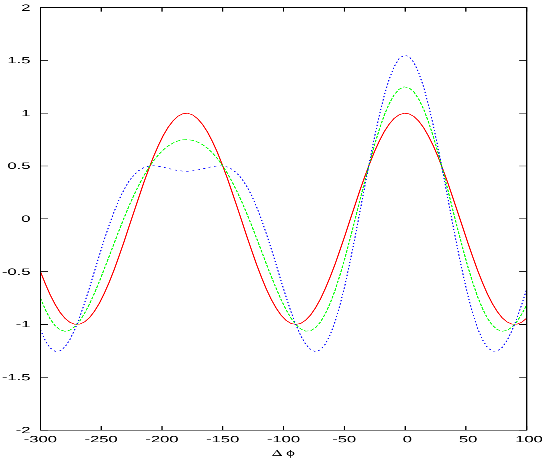
Ridge and Shoulder — Explanation

$$\cos(2\Delta\phi) + 0.25\cos(3\Delta\phi)$$



Ridge and Shoulder — Explanation

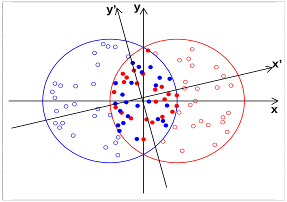
$$\cos(2\Delta\phi) + 0.55\cos(3\Delta\phi)$$



“Old” and “New” flows

- Unlike the “old” directed flow v_1, the “new” v_1 arises due to fluctuations in the initial geometry, does not vanish at mid-rapidity, and is predicted to have no correlation with the reaction plane.
- Triangular flow makes a significant contribution to the “ridge” and “shoulder”.
- Evidence for the “new” v_1 has been seen in the first harmonic, $\langle \cos \Delta\phi \rangle$ of the dihadron correlations at STAR @ RHIC.
- All this provides a strong support to hydrodynamics as the appropriate effective theory for rhics.

Various Planes



- Reaction Plane: xz plane: Plane determined by the impact parameter vector and the beam axis.
- Participant Plane: $x'z$ plane, where $x'y'$ are the principal axes of inertia. (Defn can be generalized to arbitrary n)
- Event Plane: Estimate of the PP, obtained using the final-state momentum distribution ($\mathbf{Q}z$ plane):

$$Q\cos\Psi = \sum_i w_i \cos\phi_i, \qquad Q\sin\Psi = \sum_i w_i \sin\phi_i.$$

(Defn can be generalized to arbitrary n)

Non-central Collision & Anisotropic Flow

Thus each harmonic n may have its own reference angle in the transverse plane. Hence the generalized distribution of particles emitted in $|f\rangle$ is

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_{1}^{\infty} 2v_n \cos n(\phi - \Psi_n)\right).$$

Recent Hydrodynamic Calculations

- Initial energy density: inhomogeneous and fluctuating from event to event. Not smooth.
- Hydrodynamics with smooth initial conditions $\rightarrow$ Hydrodynamics with fluctuating initial conditions. Event-by-event hydrodynamics
- Instead of averaging over initial conditions and then applying hydro, apply hydro first and then average over all outputs.

Comparison of RHIC & LHC heavy-ion collision expts

	RHIC (Au-Au)	LHC (Pb-Pb)	Increase
$\sqrt{s_{NN}}$ (GeV)	200	2760	14
$dN_{ch}/d\eta / \left(\frac{<N_{part}>}{2}\right)$	3.76	8.4	2.2
$\epsilon_{Bj}\tau_i$ (GeV/fm^2)	16/3	16	3
ϵ_{Bj} (GeV/fm^3)	10	30	3
T_i (MeV)	360	470	30%
$V_{f.o.}$ (fm^3)	2500	5000	2
Lifetime (fm)	8.4	10.6	30%
v_{flow}	0.6	0.66	10%
$< p_T >_\pi$	0.36	0.45	25%
Diffl. $v_2(p_T)$			unchanged
p_T-integrated v_2			30%

Hotter, Larger, Longer-Lasting