Anisotropic Flow at the LHC as measured by ALICE

Raimond Snellings
1) Elliptic Flow
2) What do we learn from various particle species?
3) Higher harmonics
4) What’s next?
In a Heavy Ion Collision

an anisotropic system is created
Elliptic Flow

- the system in coordinate space configuration is anisotropic (for a non-central collision almond shape). However, initial momentum distribution isotropic (spherically symmetric)
- interactions among constituents generate a pressure gradient which transforms the initial coordinate space anisotropy into the observed momentum space anisotropy $\rightarrow$ anisotropic flow
- self-quenching $\rightarrow$ sensitive to early stage

$$v_2 = \langle \cos 2\phi \rangle$$
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$
Elliptic flow is large

Ideal hydro gets the magnitude for more central collisions
RHIC Scientists Serve Up “Perfect” Liquid
New state of matter more remarkable than predicted -- raising many new questions
April 18, 2005

Hunting the Quark Gluon Plasma
RESULTS FROM THE FIRST 3 YEARS AT RHIC
ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS
April 18, 2005

Fig. A
Fig. B
The Perfect Liquid?

What to expect at the LHC: still the perfect liquid or approaching a viscous ideal gas?
The Perfect Liquid?

CERN, November 26, 2010:
‘the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid).’
First LHC $v_2$ measurement

1) not in line with expectations from pure ideal hydro (measured $v_2$ increased too much)

2) not in line with simple triangular scaling

3) in line with expectations from models incorporating viscous corrections (viscous hydro, parton cascades, hybrid models)
Elliptic flow as function of transverse momentum does not change much from RHIC to LHC energies, can we understand that?
Charged particle flow sums contributions of different mass particles which do individually change significantly as function of beam energy according to hydro. This prediction we can test.
Mass dependence of $v_2(p_T)$

Centrality dependence clearly shows the effect of increasing radial flow.
viscous hydro does capture energy dependence but fails quantitatively for the protons in more central collisions (both for RHIC and the LHC!)
Mass dependence of $v_2(p_t)$


Hybrid calculations (VISHNU) fix the more central collisions
Is there a strong contribution from the hadronic phase?
The phi meson is also not described by pure viscous hydro
The multi-strange baryons are closer to viscous hydro
Is this in line with expectations from an hadronic contribution?
The phi meson follows at low-\(p_t\) the mass scaling while at intermediate \(p_t\) follows the pions as would be expected in a reco picture. No KET scaling observed.
Viscous hydro and many (most?) models do not show a universal scaling versus KET. In a simple blast-wave model how well the scaling works depends on the magnitude of the transverse flow.
At low $p_t$ the mass ordering of the breaking of the KET scaling in the data is in agreement with that in viscous hydro.
Anisotropic Flow

Azimuthal distributions of particles measured with respect to the reaction plane (spanned by impact parameter vector and beam axis) are not isotropic.

\[
E \frac{d^3N}{d^3 \vec{p}} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2\nu_n \cos \left( n (\phi - \Psi_{RP}) \right) \right)
\]

\[
\nu_n = \langle \cos n(\phi - \Psi_{RP}) \rangle
\]

harmonics \( \nu_n \) quantify anisotropic flow

S. Voloshin and Y. Zhang (1996)
\textbf{\(v_n\) is not an observable}

\[ \langle v_n \rangle = \langle \langle e^{in(\phi_1-\Psi_n)} \rangle \rangle \]

- since the common symmetry planes cannot be measured event-by-event, we measure quantities which do not depend on it's orientation: multi-particle azimuthal correlations

\[
\langle \langle e^{in(\phi_1-\phi_2)} \rangle \rangle = \langle \langle e^{in(\phi_1-\Psi_n-(\phi_2-\Psi_n))} \rangle \rangle \\
= \langle \langle e^{in(\phi_1-\Psi_n)} \langle e^{-in(\phi_2-\Psi_n)} \rangle \rangle \\
= \langle v_n^2 \rangle 
\]

- assuming that only correlations with the symmetry plane are present - not a very good assumption (jets, resonances, etc)!
• If $v_2$ fluctuates

$$\langle v_2 \rangle \neq \sqrt{\langle (v_2)^2 \rangle}$$

• If

$$v_2 \propto \varepsilon$$

• $\rightarrow$ fluctuations in the initial conditions change our various observables related to $v_2$

eccentricity fluctuations and its possible effect on $v_2$ measurements:
participant eccentricity
Flow Fluctuations

when (2-particle) nonflow is corrected for or negligible!

in limit of "small" (not necessarily Gaussian) fluctuations

\[ v_n^2 \{ 2 \} = \bar{v}_n^2 + \sigma_v^2 \]
\[ v_n^2 \{ 4 \} = \bar{v}_n^2 - \sigma_v^2 \]
\[ v_n^2 \{ 2 \} + v_n^2 \{ 4 \} = 2\bar{v}_n^2 \]
\[ v_n^2 \{ 2 \} - v_n^2 \{ 4 \} = 2\sigma_v^2 \]

in limit of only (Gaussian) fluctuations

\[ v_n \{ 4 \} = 0 \]
\[ v_n \{ 2 \} = \frac{2}{\sqrt{\pi}} \bar{v}_n \]
\[ v\{2\} = \langle v \rangle + \frac{1}{2} \frac{\sigma_v^2}{\langle v \rangle} \]
\[ v\{4\} = \langle v \rangle - \frac{1}{2} \frac{\sigma_v^2}{\langle v \rangle} \]
\[ v\{6\} = \langle v \rangle - \frac{1}{2} \frac{\sigma_v^2}{\langle v \rangle} \]
\[ v\{8\} = \langle v \rangle - \frac{1}{2} \frac{\sigma_v^2}{\langle v \rangle} \]

Clear separation between \( v_2\{2\} \) and higher order cumulants
Higher order cumulant \( v_2 \) estimates are consistent within uncertainties
For more central collisions the data is between MC Glauber and MC-KLN CGC

\[\sigma_{v_n} \approx \left[ \frac{1}{2} \left( v_n^2 \{2\} - v_n^2 \{4\} \right) \right]^{\frac{1}{2}}\]

\[\frac{\sigma_{v_n}}{v_n} \approx \left( \frac{v_n^2 \{2\} - v_n^2 \{4\}}{v_n^2 \{2\} + v_n^2 \{4\}} \right)^{\frac{1}{2}}\]
The $v_2$ fluctuations are very similar as function of $\eta$ and $p_t$.

- Color electric-magnetic fields after the collision are purely longitudinal: Flux Tube picture
- In the CGC, multiplicities rise proportional to the (local) saturation scale
- Correlation length in rapidity
- Correlation length in the transverse plane:
  - Flux tubes
  - Glasma flux tubes
- "flux tubes" extending between the projectiles:
  - The flux tubes fill up the entire volume
- Correlation length in rapidity:
- Correlation length in the transverse plane:
  - The initial chromo-

Summary

- Modeling the initial state of HIC
- Classical fields
- Bookkeeping
- Introduction
- ⇥
- ⇥

François Gelis – 2007 Lecture III / IV – Hadronic collisions at the LHC

- Lappi, McLerran (2006) ⇥
- Initial Glasma fields
- Summary
- Matching to hydro
- Glasma fields
- Factorization
- CGC
- Leading Logs
- Leading Order
- Stages of AA collisions
- Color Glass Condensate
- Why small-x gluons matter
- Grazing
- Staggered

\[
\frac{(v_2^2)\cdot(v_2^4)}{(v_2^4)\cdot(v_2^4)}
\]

\[
\frac{(v_2^2)\cdot(v_2^4)}{(v_2^4)\cdot(v_2^4)}
\]

\[
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\]

\[
\frac{(v_2^2)\cdot(v_2^4)}{(v_2^4)\cdot(v_2^4)}
\]
Initial conditions and $v_n$

Initial spatial geometry not a smooth almond (for which all odd harmonics are zero due to reflection symmetry) may give rise to higher odd harmonics versus their planes of symmetry.

\[
\frac{2\pi}{N} \frac{dN}{d\phi} = 1 + \sum_{n=2,4,6,\ldots}^{\infty} 2v_n \cos n(\phi - \Psi_R)
\]

\[
\frac{2\pi}{N} \frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi_n)
\]
Shear Viscosity

Initial conditions
ideal hydro $\eta/s=0$
viscous hydro $\eta/s=0.16$

Larger $\eta/s$ clearly smoothes the distributions and suppresses the higher harmonics (e.g. $v_3$)

The $v_3$ with respect to the reaction plane determined in the ZDC and with the $v_2$ participant plane is consistent with zero as expected if $v_3$ is due to fluctuations of the initial eccentricity. The $v_3\{2\}$ is about two times larger than $v_3\{4\}$ which is also consistent with expectations based on initial eccentricity fluctuations.

We observe significant $v_3$ and $v_4$ which compared to $v_2$ has a different centrality dependence (strong constrain for $\eta/s$).
We observe as for $v_2$ that $v_3\{4\}$ and $v_3\{6\}$ agree within errors and the difference of about a factor 2 between $v_3\{2\}$ and $v_3\{4\}$ and $v_3\{6\}$ matches that observed in Glauber calculations (indication of the number of sources?)

We can now even measure the $p_T$ dependence of $v_3$ using higher order cumulants
Correlations between $v_n$

The 5 particle cumulants allow us to cleanly measure if there is a correlations between the various planes
Conclusions

• Elliptic flow measurements provided strong constraints on the bulk properties of hot and dense matter produced at RHIC and LHC energies and have led to the new paradigm of the QGP as the so called perfect liquid

• At the LHC we observe even stronger flow than at RHIC which is expected for almost perfect fluid behavior

• Viscous hydro calculations fail to describe proton $v_2$ while hybrid models do a much better job

• Does this hadronic contribution also explain the $v_2$ of the phi meson and multi-strange baryons?

• At the LHC KET scaling is broken (but was it ever a well founded scaling?)

• $v_2$ fluctuations are in qualitative agreement with expectations from Glauber models and rather independent of $\eta$ and $p_t$

• The measurements of $v_3$ and higher $v_n$'s at RHIC and at the LHC indicate that these flow coefficients behave as expected from a created system which has a small $\eta/s$

• The fluctuations can be used to do “event shape engineering” which provides new ways to compare to models
multi-particles

ALICE PRELIMINARY

Pb-Pb $\sqrt{s_{\text{NN}}} = 2.76$ TeV
$|\eta| < 0.8 \quad 0.2 \leq p_T^{(bc)} < 5$ GeV/c

$\langle \cos(\phi_a - 3\phi_b + 2\phi_c) \rangle$

$\times 10^{-6}$

$ -50 \quad -40 \quad -30 \quad -20 \quad -10 \quad 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 70$

$p_T^{(a)}$ (GeV/c)

$0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5$

5-particle cumulant

$\langle \cos(3\phi_1 + 3\phi_2 - 2\phi_3 - 2\phi_4 - 2\phi_5) \rangle$

$\langle \cos(2\phi_1 + 2\phi_2 - 2\phi_3 - 2\phi_4 - 2\phi_5) \rangle$

$\langle \cos(3\phi_1 + 2\phi_2 - 2\phi_3 - 2\phi_4 - 2\phi_5) \rangle$

$\langle \cos(3\phi_1 - 2\phi_2 - 3\phi_3) \rangle$

$\langle \cos(3\phi_1 - 2\phi_2 - 3\phi_3) \rangle$

$\langle \cos(3\phi_1 - 2\phi_2 - 3\phi_3) \rangle$

Pb-Pb $\sqrt{s_{\text{NN}}} = 2.76$ TeV
$|\eta| < 0.8 \quad 0.2 \leq p_T < 5$ GeV/c

$\times 10^{-6}$

$0 \quad 0.1 \quad 0.2 \quad 0 \quad 0.1 \quad 0.2 \quad 0.3$

centrality percentile

$0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 70$

ALICE PRELIMINARY

ALI-PREL-29333

ALI-PREL-29328
v2 and v3
Event shape engineering

Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

\(|\eta|<0.8\) 10-20%

\(v_2[EP](SE)/v_2[EP](\text{No q}_2 \text{ selection})\)

5% high \(q_2\) (VZERO-A)

10% low \(q_2\) (VZERO-A)

ALICE PRELIMINARY
Flow Fluctuations

\[ v\{2\} = \langle v \rangle + \frac{1}{2} \frac{\sigma_v^2}{\langle v \rangle} \]

\[ v\{4\} = \langle v \rangle - \frac{1}{2} \frac{\sigma_v^2}{\langle v \rangle} \]

\[ v\{6\} = \langle v \rangle - \frac{1}{2} \frac{\sigma_v^2}{\langle v \rangle} \]

\[ v\{8\} = \langle v \rangle - \frac{1}{2} \frac{\sigma_v^2}{\langle v \rangle} \]

- for \( \sigma_v \ll \langle v \rangle \) this is a general result to order \( \sigma^2 \)