Elliptic flow phenomenon at ATLAS

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Outline

• Geometry of collisions and centrality
• Basic picture and $v_2$
• More realistic picture – $v_n$
  – characteristics of $v_n$
  – cumulant method and two particle correlations
  – direct flow
• Event plane correlations
• Measuring the flow event-by-event
  – event by event $v_n$
  – extracting the medium response
• The flow and the ridge in p+Pb
• The flow and jets
Centrality of the collision

- Centrality can be quantified using the energy deposited in forward calorimeters (FCal) in percentiles of the total cross-section.
- Correlation between $E_T$ at different $\eta$ is due to the total amount of matter involved in the collision.

[Graph showing the relationship between centrality and energy deposited in forward calorimeters.]
Centrality of the collision

The most peripheral collision

The most central collision

- Centrality can be quantified using the energy deposited in forward calorimeters (FCal) in percentiles of the total cross-section.

- Correlation between $E_T$ at different $\eta$ is due to the total amount of matter involved in the collision.
• Pressure gradients lead to the azimuthal anisotropy

\[ \frac{dN}{d\phi} = N_0 \left( 1 + 2v_2 \cos 2(\phi - \Phi^{RP}) \right) \quad v_2 = \left\langle \cos 2(\phi - \Phi^{RP}) \right\rangle \]

• Initial shape of the interaction region reflected by the elliptic flow, \( v_2 \).
Baseline $v_2$ result

**ATLAS** Preliminary

- Elliptic flow is maximal in mid-peripheral collisions
- Elliptic flow is reduced:
  - in the most central collisions (no initial spacial anisotropy)
  - in the most peripheral collisions (no collectivity)

Very good description by hydrodynamical model – basic evidence for a presence of strongly coupled matter that behaves like an almost perfect, non-viscous fluid (since 2001).

PLB 707 (2012) 330 & ATLAS-CONF-2012-117

Huovinen et al. PLB 503 (2001) 58

03/18/14
More realistic picture

- Pressure gradients lead to the azimuthal anisotropy

\[
\frac{dN}{d\phi} = N_0 \left( 1 + 2v_1 \cos(\phi - \Phi_1) + 2v_2 \cos 2(\phi - \Phi_2) + 2v_3 \cos 3(\phi - \Phi_3) + \ldots \right)
\]

- Initial shape of the interaction region (elliptic flow, \(v_2\))
- Initial spatial fluctuations of interacting nucleons (higher orders, \(v_n\))

... Fourier harmonics
Summary of $v_n$ results

$v_n$ coefficients rise and fall with centrality – reflects the geometry of collision.

$v_n$ coefficients rise and fall with $p_T$ – reflects the hydrodynamic response.

$v_n$ coefficients are ~flat with rapidity – reflect global events shape (in contrast to RHIC observation, see e.g. PHOBOS, PRC 72 (2005), 051901)
Summary of $v_n$ results

Gale et al., PRL 110 (2013), 012302
ATLAS data, PRC 86 (2012), 014907

$v_n$ results allow to put constrains on $\eta/s$ ratio

$v_n$ results allow to put constrains on initial geometry modeling
Cumulant method for flow determination

- $v_2$ can be extracted using different methods, e.g. event plane versus cumulant method
- Cumulant method can reduce a non-flow contribution by calculating multi-particle cumulants:

$$\langle \exp[2i(\phi_1 - \phi_2)] \rangle \rightarrow v_2\{2\}$$
$$\langle \exp[2i(\phi_1 + \phi_2 - \phi_3 - \phi_4)] \rangle \rightarrow v_2\{4\}$$

- EP method usually between two cumulants
Two particle correlations for flow determination

\[ C(\Delta \phi, \Delta \eta) = \frac{N_{\text{same evnt}}(\Delta \phi, \Delta \eta)}{N_{\text{mixed evnts}}(\Delta \phi, \Delta \eta)} \]

Two particle correlation function

\[ \frac{dN_{\text{pairs}}}{d\Delta \phi} \propto 1 + 2 \sum_n (v_{n,n} \cos n\Delta \phi) \]

* \( v_{n,n} \) accessible via discreet Fourier transform

\[ v_{n,n} = \langle \cos(n\Delta \phi) \rangle = \frac{\sum_m \cos(n\Delta \phi_m)C'(\Delta \phi_m)}{C'(\Delta \phi_m)} \]

* Ridge like structures (often attributed to response of the medium to jet) can be generated by flow harmonics (\( v_{1,1} - v_{6,6} \))
Two particle correlations for flow determination

- $v_{n,n}$ should factorize in $p_T$ regions dominated by effects from initial spatial asymmetries

\[
v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a) v_n(p_T^b) \quad \rightarrow \quad v_n(p_T) = \sqrt{v_{n,n}|_{p_T^a=p_T^b}}
\]

... can be tested
Two particle correlations give direct flow - $v_1$

- Direct flow can be accessed from two particle correlation measurement.
- Direct flow involves momentum conservation.
- Direct flow of the same magnitude as triangular flow.
Event plane correlations

Event planes predicted to be correlated. Correlations of two event planes can be completely described by

$$\frac{dN_{\text{evts}}}{d(k(\Phi_n - \Phi_m))} \propto 1 + 2 \sum_{j=1}^{\infty} V_{n,m}^j \cos jk(\Phi_n - \Phi_m)$$

$$V_{n,m}^j = \langle \cos jk(\Phi_n - \Phi_m) \rangle$$

- Can be generalized to multi-plane correlators, e.g. three-plane correlator.

Measured correlators:

\[
\begin{align*}
\langle \cos 4(\Phi_2 - \Phi_4) \rangle & \quad \langle \cos 6(\Phi_2 - \Phi_6) \rangle \\
\langle \cos 8(\Phi_2 - \Phi_4) \rangle & \quad \langle \cos 6(\Phi_3 - \Phi_6) \rangle \\
\langle \cos 12(\Phi_2 - \Phi_4) \rangle & \quad \langle \cos 12(\Phi_3 - \Phi_4) \rangle \\
\langle \cos 6(\Phi_2 - \Phi_3) \rangle & \quad \langle \cos 10(\Phi_2 - \Phi_5) \rangle \\
\end{align*}
\]

\[
\begin{align*}
\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle & \quad \langle \cos(-8\Phi_2 + 3\Phi_3 + 5\Phi_5) \rangle \\
\langle \cos(2\Phi_2 + 4\Phi_4 - 6\Phi_6) \rangle & \quad \langle \cos(-10\Phi_2 + 4\Phi_4 + 6\Phi_6) \rangle \\
\langle \cos(2\Phi_2 - 6\Phi_3 + 4\Phi_4) \rangle & \quad \langle \cos(-10\Phi_2 + 6\Phi_3 + 4\Phi_4) \rangle \\
\end{align*}
\]
Event plane correlations

• Correlation of event planes due to fluctuations of initial geometry and non-linear mixing of different harmonic in the final state
• Data can be reproduced by AMPT model (= Glauber with initial geometry fluctuation + parton and hadron transport model to model the final state)
• Example: strong correlation between $\Phi_2$ and $\Phi_4$, significant correlation of $\Phi_2$ and $\Phi_3$

arXiv:1403.0489
Flow can be accessed event by event

Significant event by event fluctuations => can access the flow on the event by event basis
Flow can be accessed event by event.

Significant event by event fluctuations => can access the flow on the event by event basis.
Flow can be accessed event by event

Many “little bangs” with local fluctuations

- Fourier series for particle anisotropies can be calculated for each event

\[ \frac{dN}{d\phi} \propto 1 + \sum_n (v_{n,x} \cos n\phi + v_{n,y} \sin n\phi) \]

\[ v_n = \sqrt{v_{n,x}^2 + v_{n,y}^2} \]

- \( v_n \) contains more information than previously shown \(<v_n>\)

- Information can be extracted in terms of probability distributions:

\[ \frac{dN}{d\phi} \propto 1 + \sum_n v_n \cos n(\phi - \Phi_n) \]

\[ p(v_n) \rightarrow p(\Phi_n, \Phi_m) \]

U, Heinz, J.Phys.Conf.Ser. 455 (2013) 012044
Event-by-event $v_n$ distributions

Probability distributions for $v_2$, $v_3$, $v_4$ in different centrality ranges.
Event-by-event $v_n$ distributions

Probability distributions for $v_2$, $v_3$, $v_4$ have the same shape irrespective of $p_T$. 

JHEP 11 (2013) 183
Comparison to theory: Glauber model + CGC

- The eccentricity, $\varepsilon$, distribution rescaled such that $\langle \varepsilon^2 \rangle = \langle v^2 \rangle$. Mapping $p(\varepsilon^2) \leftrightarrow p(v^2)$ to be provided by models.
- (Glauber model – description of geometry of collision; CGC ~ description of initial state of nuclei by saturated gluons)
Ridge in p+Pb

- Discovery of double ridge structure in high multiplicity p+Pb events
- Influence of away-side jet estimated from low multiplicity events
Ridge in p+Pb

- Significant $v_2$ and $v_3$, comparable to Pb+Pb collisions.
- Significant $v_2\{4\} \sim 0.06$ suggests large collective motion.
- $v_2$ values comparable to hydrodynamics.
v$_2$ and high-pt

- $v_2$ > 0 with jets up-to ~200 GeV
- Comparable to $v_2$ of high-pt hadrons measured by CMS
- Clear sensitivity to path length
- Can provide direct restrictions to parton energy loss models

More details in talk by Zvi Citron, Fri 9:10
$v_2$ estimated also in for $Z^0$ boson ... consistent with zero
Conclusions

- Differential $v_2$ and higher order flow harmonics up to $n=6$ measured using various methods in different pt, eta and centrality ranges.
  
  $\Rightarrow$ detailed constrained on geometry models and viscosity/entropy

- Estimates of direct flow from two particle correlations

- Two particle correlations can describe the ridge structure

- Event-by-event fluctuations of the medium and its evolution via measurement probabilities $p(v_n)$ (and $p(\Phi_n)$)
  
  $\Rightarrow$ strong non-linear effects in the hydrodynamic response to initial geometry fluctuations

- Double ridge and flow like phenomena seen in $p+Pb$ collisions

- $v_2$ using jets allows for detailed studies of path-length dependence of parton energy loss
Backup slides
Extracting hydrodynamical response from v2

Model – eccentricity

\[ \tilde{\epsilon}_n = \left( \frac{\langle r^n \cos(n\phi) \rangle}{\langle r^n \rangle}, \frac{\langle r^n \sin(n\phi) \rangle}{\langle r^n \rangle} \right) \]

\[ \tilde{\epsilon}_n = \tilde{\epsilon}_{n,RP} + \Delta_{n,fluc} \]

\[ p(\tilde{\epsilon}_n) \propto \exp\left( -\frac{(\tilde{\epsilon}_n - \tilde{\epsilon}_{n,RP})^2}{2\delta_{\epsilon_n}^2} \right) \]

\[ \tilde{\epsilon}_{n,RP} \rightarrow \text{Mean Geometry} \]

\[ \delta_{\epsilon_n} \rightarrow \text{Fluctuations} \]

Data – flow

\[ \tilde{v}_n = (v_n \cos(n\Phi_n), v_n \sin(n\Phi_n)) \]

\[ \tilde{v}_n = \tilde{v}_{n,RP} + \tilde{p}_{n,fluc} \]

\[ p(\tilde{v}_n) \propto \exp\left( -\frac{(\tilde{v}_n - \tilde{v}_{n,RP})^2}{2\delta_{v_n}^2} \right) \]

\[ \tilde{v}_{n,RP} \rightarrow \text{Mean Geometry} \]

\[ \delta_{v_n} \rightarrow \text{Fluctuations} \]
Comparison to theory:
**IP – Glasma model**

- Modeling of the hydrodynamical response is successful.
- (IP-glasma ~ improved CGC with impact parameter dependent saturation model.)