The characterisation of the Quark Gluon Plasma

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Using the geometry

• **Use geometry as a control parameter**
  
  • anisotropic flow
    
    • use to constrain initial conditions and the transport parameters of the created system
  
  • use the geometry to learn about parton energy loss and the opacity of the system

Due to event-by-event fluctuations of the initial conditions not only $v_2$ but also higher harmonics are generated $v_3, v_4$ etc
Anisotropic Flow

- Our constraints on transport parameters come from the comparison between anisotropic flow measurements and viscous hydrodynamic model and parton energy loss calculations.
- Why do we believe these constraints?
Anisotropic Flow

1) superposition of independent p+p:
- momenta pointed at random relative to symmetry plane

\[ v_2 = \langle \cos 2(\phi - \Psi_R) \rangle = 0 \]

2) evolution as a bulk system
- pressure gradients (larger in-plane) push bulk “out” \( \rightarrow \) “flow”
- “zero” pressure in surrounding vacuum
- more, faster particles seen in-plane

b \approx 4 \text{ fm}

b \approx 6.5 \text{ fm}
Anisotropic Flow (momentum space)

- Use geometry as a control parameter
- If the constituents interact they convert the coordinate space asymmetries into momentum space asymmetries
- The $v_n$ coefficients provide information about the initial state anisotropies, the transport parameters and the EoS, and can be used to constrain them
- Viscous hydro is very successful in describing the measured $v_n$

\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{+\infty} v_n \cos[n(\phi - \Psi_n)]
\]
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However, these are many important physics parameters; how to constrain all of them to better precision?

Experimentally we can use within one experiment detailed measurements of the energy dependence of the $v_n$ to constrain the temperature dependence of the parameters on which they depend the most.

In addition we can use detailed cumulant measurements to constrain the p.d.f. of the $v_n$ and with that constrain the initial spatial distributions.

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Anisotropic Flow: $\eta/s$

- The difference between $v_2\{2\}$ and $v_2\{4\}$ depends on the $v_2$ event-by-event fluctuations (later in this talk) and provide a constraint on the $v_n$ p.d.f.
- A small increase between 2-10% for the $v_n$ is observed from 2.76 to 5.02 TeV.
- The two parameterisations of $\eta/s$ which describe the data indicate no or a small dependence on temperature.
Anisotropic Flow

- The dependence of $v_n$ on transverse momentum provides more differential information.
- At low transverse momentum the data can be interpreted in a "hydrodynamical" picture while at high-$p_t$ the dominant mechanism is though to be path length dependent energy loss of high energetic partons.
- The $v_2$ coefficients dominates over all transverse momenta except for the most central collisions.
- The $v_2$ is significant up to the highest transverse momenta.
Anisotropic Flow: $\eta/s$

- The ratios between $v_n$ at 5.02 and 2.76 TeV are consistent with unity
- The increase in integrated $v_n$ due to increase in $<p_t>$ (due to radial flow in hydro picture)
- Also consistent with almost no change of $\eta/s$ between the two beam energies

\[\frac{v_{2}(2,|\eta|>1)}{v_{2}(6.02\,\text{TeV}) / v_{n}(2.76\,\text{TeV})} / v_{n}(2.76\,\text{TeV}) \]

\[\frac{v_{2}(4)}{v_{2}(6.02\,\text{TeV}) / v_{n}(2.76\,\text{TeV})} / v_{n}(2.76\,\text{TeV}) \]

\[v_{3}(2,|\eta|>1) \]

\[v_{4}(2,|\eta|>1) \]

5-10 %
20-30 %
40-50 %
Anisotropic Flow; compared to models

- Models use IP-Glasma, AMPT-IC or TRENTo initial conditions and all use UrQMD for the hadronic phase
- All models qualitatively describe the low-$p_t$ data
- The measurement of $v_n(p_t)$ by itself is not enough to constrain the initial conditions
- At large $p_t$ the azimuthal asymmetries are thought to be due to path length dependent parton energy loss
- The model compared to the data uses an event-by-event hydro description ($v$-USPhydro) and jet quenching model (BBMG)
- Tested is a linear $dE/dx \sim L$ and quadratic energy loss
- The $v_2$ at large $p_t$ is compatible with linear energy loss

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Anisotropic Flow Fluctuations: Constraints on Initial Conditions

\[ v_n(2) = \sqrt[3]{\langle v_n^2 \rangle} \]
\[ v_n(4) = \sqrt[4]{2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle} \]
\[ v_n(6) = \sqrt[6]{\langle v_n^6 \rangle - 9\langle v_n^2 \rangle^2(v_n^4) + 12\langle v_n^2 \rangle^3} \]
\[ v_n(8) = \sqrt[8]{\langle v_n^8 \rangle - 16\langle v_n^2 \rangle\langle v_n^6 \rangle - 18\langle v_n^4 \rangle^2 + 144\langle v_n^2 \rangle^2\langle v_n^4 \rangle^2 - 144\langle v_n^2 \rangle^4} \]

The different estimates of \( v_2 \) are sensitive to the moments of the \( v_2 \) distribution, if \( v_2(4)=v_2(6)=v_2(8) \) the distribution is a Bessel-Gaussian p.d.f.
A fine splitting is observed which is centrality dependent showing the non Bessel Gaussian contribution.

The splitting does not depend on the $p_T$ range used and collision energy.

The results agree well with model calculations as well as with ATLAS results based on a different technique.
Anisotropic Flow Fluctuations: Constraints on Initial Conditions

\[ \gamma_1 = \frac{\langle (v_n\{RP\} - \langle v_n\{RP\} \rangle)^3 \rangle}{\langle (v_n\{RP\} - \langle v_n\{RP\} \rangle)^2 \rangle^{3/2}} \]

\[ \gamma_1^{\text{exp}} = -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\})^{3/2}} \]

\[ v_2\{6\} - v_2\{8\} = \frac{1}{11}(v_2\{4\} - v_2\{6\}) \]

The standardised skewness can be estimated using the multi-particle cumulants.

This experimental estimate depends on the fact that the higher order moments, e.g. kurtosis, are small, which can be tested.
A fine splitting is observed between $v_2\{8\}$ and $v_2\{6\}$.

Can be contributed to the skewness of the p.d.f.

Higher order contributions are constrained in the equality

$$v_2\{6\} - v_2\{8\} = \frac{1}{11}(v_2\{4\} - v_2\{6\})$$
Anisotropic Flow Fluctuations: Constraints on Initial Conditions

\[ \gamma_1^{\exp} = -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}} \]

- A negative skewness is observed as expected due to the constrains on \( \varepsilon_2 \) between 0-1
- The skewness agrees well with model calculations and increases towards peripheral collisions due to the constraint of 1
Anisotropic Flow Fluctuations: Constraints on Initial Conditions

\[ P(\varepsilon_2) = \frac{1}{k_2} 2\alpha \varepsilon_2 (1 - \varepsilon_2^2)^{\alpha - 1} (1 - \varepsilon_0^2)^{\alpha + 1/2} \frac{1}{\pi} \int_0^\pi \left(1 - \varepsilon_2 \varepsilon_0 \cos \varphi \right)^{-2\alpha - 1} d\varphi \]

The elliptic power distribution can be used to describe the underlying p.d.f. of \( \varepsilon_2 \).

The parameter \( \alpha \) qualifies the magnitude of the flow fluctuations, \( \varepsilon_0 \) the mean eccentricity in the reaction plane and \( k_2 \) the proportionality between \( \varepsilon_2 \) and \( v_2; \ v_2 = k_2 \varepsilon_2 \).
Anisotropic Flow p.d.f.: Constraints on Initial Conditions

\[ P(\varepsilon_2) = \frac{1}{k_2} 2\alpha \varepsilon_2 (1 - \varepsilon_2^2)^{\alpha-1} (1 - \varepsilon_0^2)^{\alpha+1/2} \frac{1}{\pi} \int_0^\pi (1 - \varepsilon_2 \varepsilon_0 \cos \varphi)^{-2\alpha-1} d\varphi \]
Summary

• Anisotropic flow is precisely measured at the LHC as function of collision energy using multi-particle cumulants
• The underlying p.d.f. of $v_2$ can be determined with high precision using the cumulants and are used to constrain the initial conditions
• Viscous hydrodynamical calculations with these initial conditions describe well the centrality, energy and collision system dependence of the $v_n$
• The measurements provide strong constrains on the temperature dependence of the transport coefficients and the path length dependence of parton energy loss
Thanks!