First Joint ICTP-Trieste/ICTP-SAIFR
School on Particle Physics

Analysis of Collective Flow in Heavy Ion Collisions

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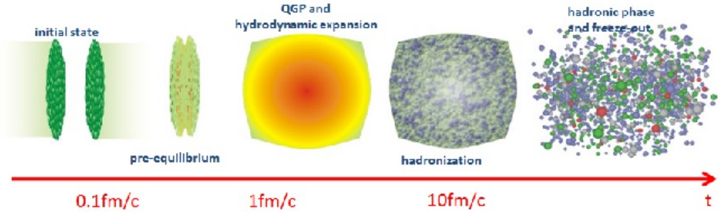
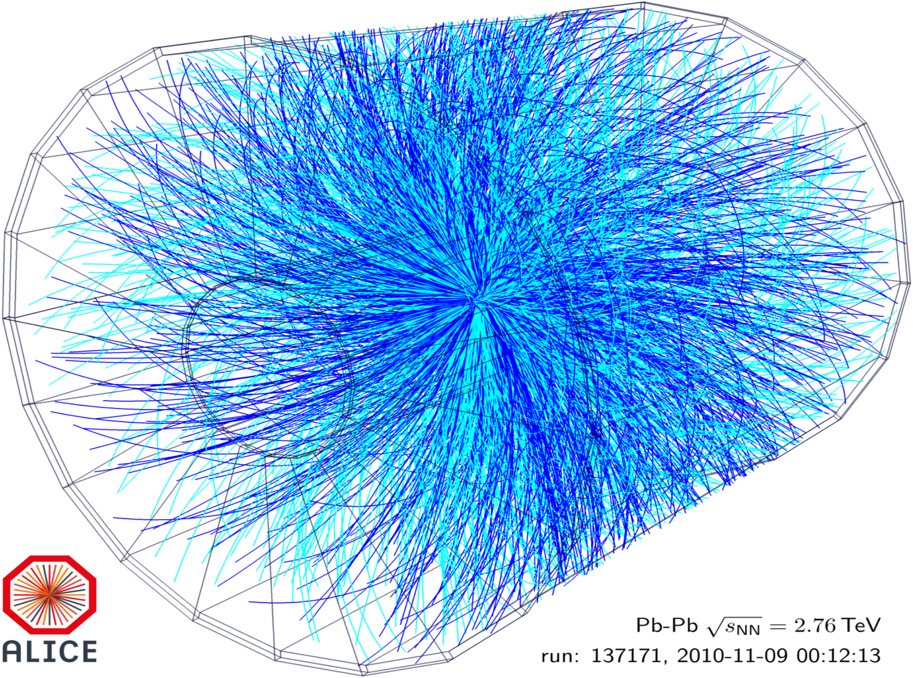
Heavy Ion Collisions

Nuclei collisions help us investigate QCD. The matter in a collision passes through a Quark Gluon Plasma (QGP) phase. The QGP is believed to be one of the early stages of the universe.



From *Qin, Guang-You Int. J. Mod. Phys. E24 (2015) no.02, 1530001*

Only the final particles produced in the collision are measured. So a model of the intermediate state is needed.



From *https://cds.cern.ch/record/2032743*

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Relativistic Hydrodynamics

To describe the QGP we use the relativistic hydrodynamics equations.

$$\partial_\mu T^{\mu\nu} = 0 \tag{1}$$

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu - p g^{\mu\nu} \tag{2}$$

where $g^{\mu\nu}$ is the Minkowski metric, ϵ is the energy density, p is the pressure and u^μ the four velocity of the fluid.
Using initial conditions for the energy-momentum tensor and an equation of state, we can solve the equations (numerically) and evolve the fluid until it reaches the a freezeout temperature, when the evolution stops and particles are emitted.

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Fourier Expansion

The distribution of particles can be expanded in a Fourier series:

$$\frac{dN}{p_T dp_T \, d\eta \, d\phi} = \frac{dN}{2\pi \, p_T dp_T \, d\eta} \sum_{n=-\infty}^{\infty} V_n(p_T, \eta) e^{in\phi} \tag{3}$$

$$V_n(p_T, \eta) = v_n(p_T, \eta) e^{in\psi_n(p_T, \eta)} = \frac{1}{N(p_T, \eta)} \sum_j e^{in\phi_j} \tag{4}$$

v_n is called the anisotropic flow and Ψ_n the event plane.
Here, the sum is over particles in a given interval of p_T and η in one event.
Also of use, is the Flow Vector:

$$Q_n(p_T, \eta) \equiv \sum_j e^{in\phi_j} \tag{5}$$

Two-Particle Correlation

The distribution of particle pairs is determined by the single particle distribution, if non-flow effects are neglected:

$$\frac{dN_{\text{pairs}}}{d^3p_a d^3p_b} \approx \frac{dN}{d^3p_a}\frac{dN}{d^3p_b}. \tag{6}$$

It can also be expanded in a Fourier series:

$$\left\langle \frac{dN_{\text{pairs}}}{d^3p_a d^3p_b} \right\rangle \propto \sum_n V_{n\Delta}(p_a, p_b) e^{in(\phi_a - \phi_b)}, \tag{7}$$

$$V_{n\Delta}(p_a, p_b) = \langle V_n(p_a) V_n^*(p_b) \rangle = \langle v_n(p_a) v_n(p_b) e^{in(\psi_{a_n} - \psi_{b_n})} \rangle. \tag{8}$$

Here, the brackets indicate an average over events.

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Principal Component Analysis

Writing $V_{n\Delta}$ in terms of the flow vector Q_n, since the event plane is random, $\langle Q_n \rangle$ is zero for $n > 0$ and the two-particle correlation coefficient can be interpreted as a covariance function:

$$\left\langle \Big(Q_n(p_a) - \langle Q_n(p_a) \rangle\Big)\Big(Q_n(p_b) - \langle Q_n(p_b) \rangle\Big) \right\rangle \\ = \langle Q_n(p_a) Q_n^*(p_b) \rangle = V_{n\Delta}(p_a, p_b) \tag{9}$$

$V_{n\Delta}$ can be written in terms of its eigenvectors Φ_α:

$$V_{n\Delta}(p_a, p_b) = \langle Q_n(p_a) Q_n^*(p_b) \rangle = \sum_\alpha \lambda_\alpha \Phi_\alpha(p_a) \Phi_\alpha(p_b) \tag{10}$$

Principal Component Analysis

And so the modes can be defined as:

$$V_n^{(\alpha)}(p) \equiv \sqrt{\lambda_\alpha}\Phi_\alpha(p). \tag{11}$$

Since the flow coefficients, V_n, are the variance (noise) of Q_n they can be expressed by the eigenvectors of the covariance matrix. And if there is only one mode, it must be equal to V_n. So, the first component, with the highest eigenvalue, should be the anisotropic flow and the others must be related to fluctuations.
To compare to the usual flow coefficients, the modes are normalized by $\langle V_0 \rangle$.

$$v_n^{(\alpha)} = \frac{V_n^{(\alpha)}}{\langle V_0 \rangle} \tag{12}$$

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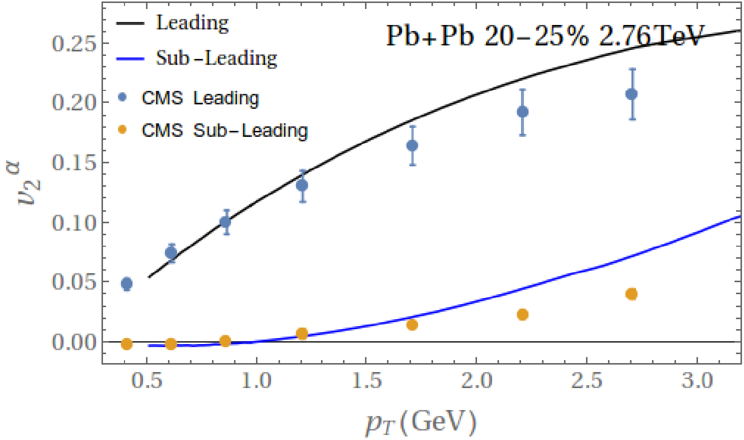
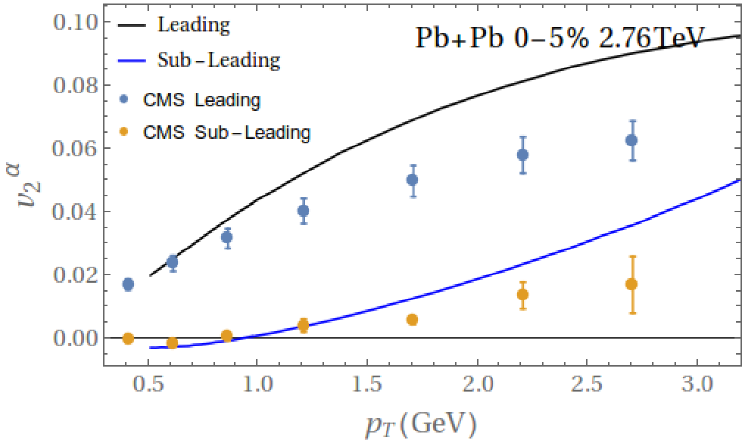
Results



First and second components of v_2 from simulations and CMS data of Pb+Pb collisions at 2.76TeV with 20-25% centrality.

Results



First and second components of v_2 from simulations and CMS data of Pb+Pb collisions at 2.76TeV with 0-5% centrality.

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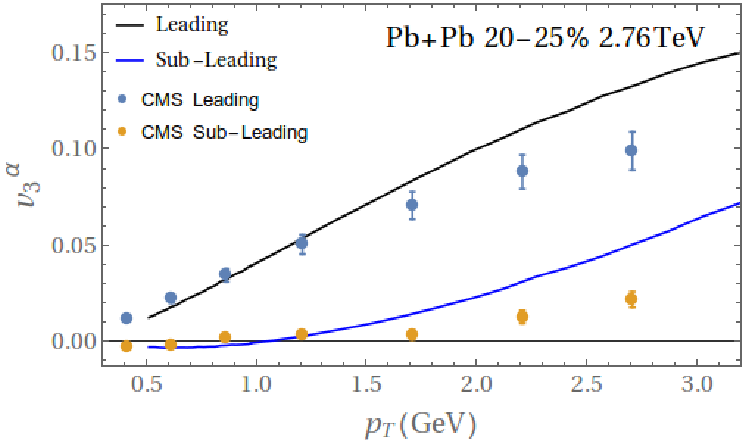

First and second components of v_3 from simulations and CMS data of Pb+Pb collisions at 2.76TeV with 20-25% centrality.

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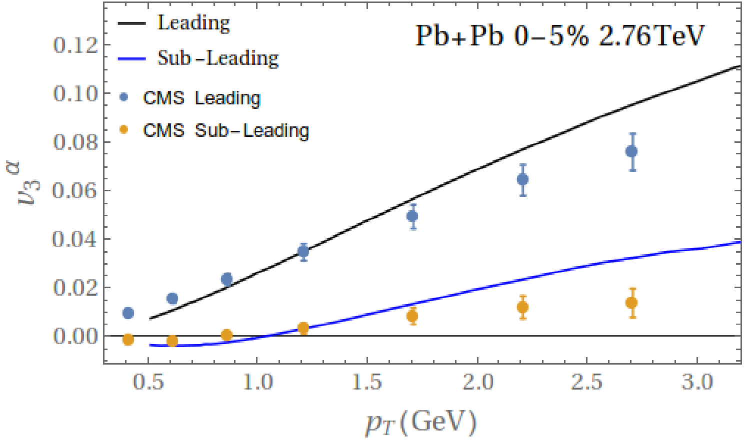

First and second components of v_3 from simulations and CMS data of Pb+Pb collisions at 2.76TeV with 0-5% centrality.

Bibliography

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