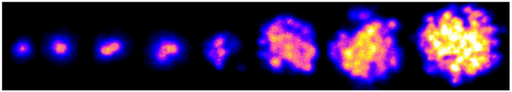
Lecture 26
Small systems (part I)



So far, we have studied the QGP in nucleus-nucleus collision. But is it possible to create it in p+A or p+p? What is the size of smallest QGP droplet created?

Two-particle correlations in $\Delta\phi$ and $\Delta\eta$

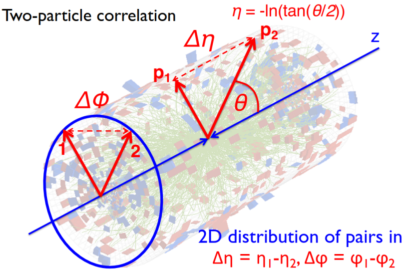
- In lectures 15 and 16, we saw that the momentum distribution can be written

$$E\frac{d^3N}{dp^3} = \frac{d^3N}{dyd^2p_\perp} =$$
$$\frac{d^2N}{2\pi dyp_\perp dp_\perp}\left[1+\sum_{n=1}^{\infty} 2v_n(p_\perp,y)\cos(n(\phi_p-\psi_n(p_\perp,y)))\right]$$

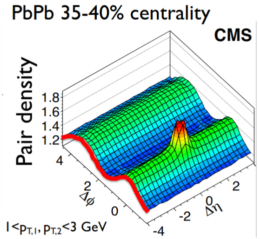
so that $v_m(p_\perp,y) = \frac{\int d\phi_p \cos(m(\phi_p-\psi_m))\frac{d^3N}{m_\perp dm_\perp d\phi_p dy}}{\int d\phi_p \frac{d^3N}{m_\perp dm_\perp d\phi_p dy}}$

and $\psi_m(p_\perp,y) = (1/m)\arctan\frac{\int d\phi_p \sin(m\phi_p)\frac{d^3N}{m_\perp dm_\perp d\phi_p dy}}{\int d\phi_p \cos(m\phi_p)\frac{d^3N}{m_\perp dm_\perp d\phi_p dy}}$

- Similarly, one can measure the two-particle correlation and plot it for exemple as function of $\Delta\phi$ and $\Delta\eta$, or just $\Delta\phi$, and write a Fourier expansion.

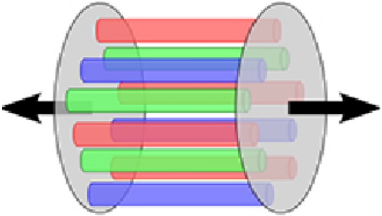


- These two-particle correlations were in fact fundamental to establish the importance of initial fluctations (NeXSPheRIO PRL 103 (2009) 242301) and higher order flow harmonics (Alver and Roland PRC 81 (2010) 054905)
- This is a modern exemple of what is seen in a centrality bin:



- The general angular shape (red curve) is due largely to elliptic flow
- The peak is attributed to jet fragmentaiton, Bose-Einstein correlation.
- The away-side ridge could come from away-side jet
- How about the near-side ridge (long-range correlation)?

• The long-range correlations are due to the longitudinal extent of the fluctuations (color tubes) in the initial conditions + hydro expansion:



Even though particles are independent they are correlated by the fluid expansion

• How does one compute two-particle correlations?

For a given event, the number of pairs with momentum $\vec{p}_a, \vec{p}_b$ is:

$\frac{dN_{pairs}}{d^3p_a d^3p_b} \overset{hydro}{=} \frac{dN}{d^3p_a} \frac{dN}{d^3p_b}$

We assumed that particles were independent, no jets, decays, etc

Selecting pairs in a certain $\Delta\phi - \Delta\eta$ interval and averaging on all events in a centrality class:

$\frac{dN_{pairs}}{d\Delta\phi d\Delta\eta}|_{centr} \propto 1 + 2\sum V_{n\Delta}(p_{\perp a}, \eta_a, p_{\perp b}, \eta_b)\cos(n\Delta\phi)$

where

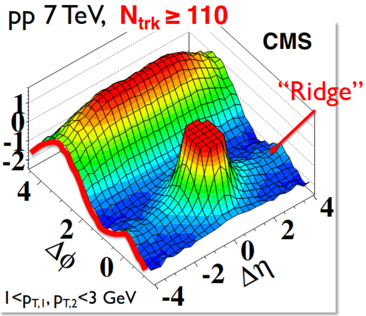
$$\begin{aligned} V_{n\Delta}(p_{\perp a}, \eta_a, p_{\perp b}, \eta_b) &= << \cos n(\phi_a - \phi_b) >_{pairs/1ev.} >_{events} \\ &= < v_n^a v_n^b \cos\left[n(\psi_n^a - \psi_n^b)\right] >_{events} \end{aligned}$$

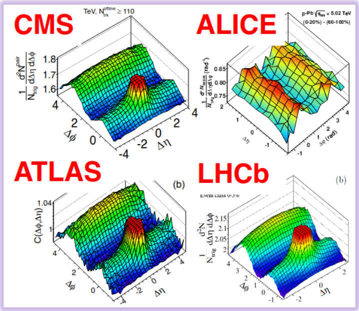
$V_{n\Delta}$ is related to what happens to the particles individually.

It reflects initial conditions and hydro expansion.

The surprise

The same ridge structure is seen in **high multiplicity** p+p and p+A collisions

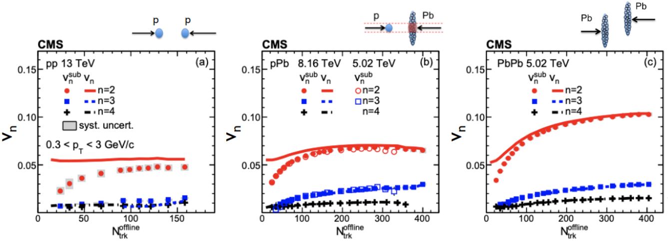




Does hydro apply to these as well?

Anisotropic flow

• To answer this, we can look at the single particle angular distribution and check if there is anisotropic flow



PRL 120, 092301 (2018)

All systems exhibit collective flow (at high multiplicty for p+p and p+A)

• If there is a collective motion, one expects that groups of particles should be flowing together, not just pairs
$\rightarrow$ One can study multiparticle correlations generalizing slide 5

$$<< \cos\left(n_1\phi_1^{a_1} + n_2\phi_2^{a_2} + ... + n_m\phi_m^{a_m}\right) >_{m-part/1ev.}>_{events}=< v_{n_1}^{a_1} v_{n_2}^{a_2}...v_{n_m}^{a_m} \cos\left(n_1\psi_{n_1}^{a_1} + n_2\psi {n_2}^{a_2} + n_m\psi_{n_m}^{a_m}\right) >_{events}$$

with $\sum n_i = 0$ and a_i represents a bin in phase space.

It is possible to suppress non-flow correlations by considering particular combinations of correlations also called cumulants:

Borghini, Dinh and Ollitrault nucl-th/0007063

For exemple, the first momentum integrated cumulants satisfy:

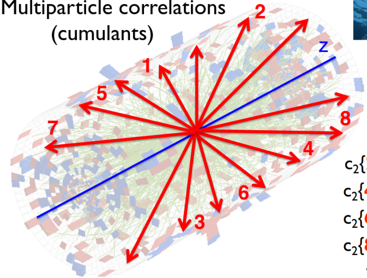
$$v_n\{2\}^2 \overset{flow}{\sim} < v_n^2 >$$

$$v_n\{4\}^4 \overset{flow}{\sim} 2 < v_n^2 >^2 - < v_n^4 >$$

For a review, see e.g. Luzum and Petersen 1312.5503

Collective or NOT?

Multiparticle correlations (cumulants)



$c_2\{2\} \sim (v_2\{2\})^2$

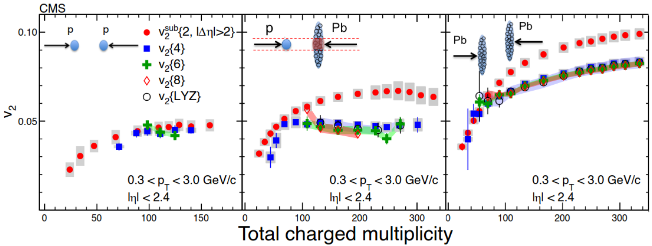
$c_2\{4\} \sim (v_2\{4\})^4$

$c_2\{6\} \sim (v_2\{6\})^6$

$c_2\{8\} \sim (v_2\{8\})^8$

……

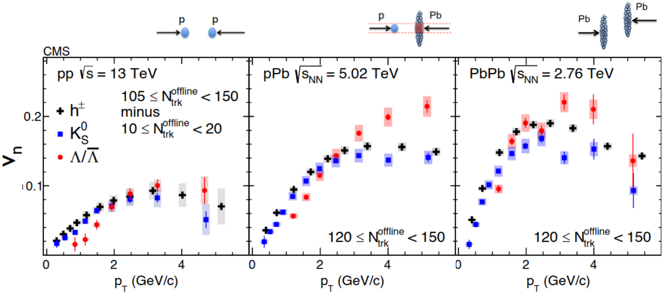
Hydrodynamics flow: $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \ldots \approx v_2\{\infty\}$



$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \ldots \approx v_2\{\infty\}$

• Mass ordering (lecture 15) is also satisfied in high multiplicity p+p and p+A collisions

Heavier particles get a larger momentum boost from the common fluid velocity and so shifted toward higher $p_\perp$



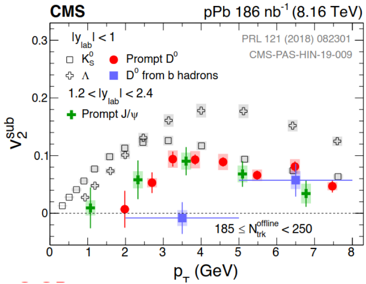
Challenge

Show that (cf. slide 5)

$\cos n(\phi_a - \phi_b) >_{pairs/1ev.} = v_n^a v_n^b \cos\left[n(\psi_n^a - \psi_n^b)\right]$

Homework

Can you interpret the behavior of the green and red points? (at low $p_\perp$)



Other references on this topic

- J.L.Nagle and W.A.Zajc "Small System Collectivity in Relativistic Hadronic and Nuclear Collisions" Annual Review of Nuclear and Particle Science 68 (2018) 211) (very clear and interesting)
- W.Busza, K. Rajagopal and W.van der Schee "Heavy Ion Collisions: The Big Picture, and the Big Questions" Annual Review Nuclear and Particle Science 68 (2018) 211 (somewhat of a complement to above reference)
- S. Schlichting and D. Teaney "The First fm/c of Heavy-Ion Collisions" Annual Review Nuclear Particle Science 69 (2019) 447
- C. Loizides "Experimental overview on small collision systems at the LHC" Nuclear Physics A 956 (2016) 200 (a little obsolete, but interesting)