Characterizing Jets in Heavy Ion Collisions by Flow Method

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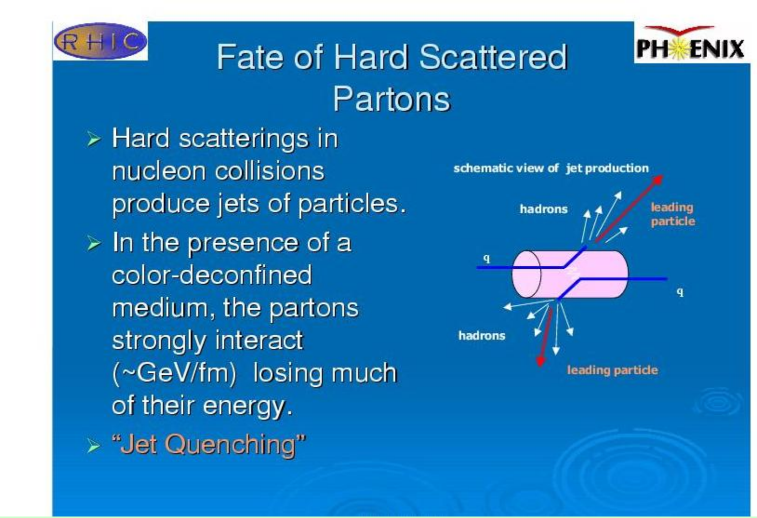
Outline

Introduction

- At RHIC and LHC, jet production is considered to be an efficient probe for the formation of QGP
- The STAR experiment has published the results on v_2 as a function of p_t, at large p_t, v_2 stops growing and shows a saturation
- That indicates jet fragmentation, jet quenching and strong parton energy loss in QGP
- *Energy loss of fast partons in a QGP $\not\Rightarrow$ jet quenching*

Jets in HIC


RHIC
PHENIX
Fate of Hard Scattered Partons
Hard scatterings in nucleon collisions produce jets of particles.
In the presence of a color-deconfined medium, the partons strongly interact (~GeV/fm) losing much of their energy.
"Jet Quenching"
schematic view of jet production
hadrons
leading particle
q
q
hadrons
leading particle

From Flow coefficients

- The flow coefficients are nothing but the Fourier coefficients of the azimuthal distribution of particles produced in heavy ion collisions. These determined by doing Fourier analysis of the collisions data. Thus, given a normalized distribution of particles, $P(\phi)$ in azimuthal angle, we can expand in Fourier series

$$P(\phi) = \frac{1}{2\pi} \sum_{m=0}^{\infty} v_m \cos m(\phi - \phi_m). \tag{1}$$

- The flow coefficients v_m are then

$$v_m = \int_0^{2\pi} d\phi P(\phi) \cos m(\phi - \phi_m), \tag{2}$$

with $v_0 = 1$ because $P(\phi)$ is normalized.

- In the experiments, ϕ_m is not known and inaccuracies determination of ϕ_m from the data. Therefore convenient to eliminate ϕ_m and determine the flow coefficients by using two-particle correlation method

$$v_m^2 = \int d\phi_1 d\phi_2 P(\phi_1) P(\phi_2) \cos m(\phi_1 - \phi_2). \qquad (3)$$

- The definition of the flow in eq(2) is not weighted by any physical quantity. One can define flow of a physical quantity by weighting the averages by the corresponding physical quantity. Thus, the transverse momentum flow v_{m,p_T} is

$$v_{m,p_T} = \int_0^{2\pi} \int_0^{\infty} d\phi dp_T p_T P(\phi, p_T) \cos m(\phi - \phi_m), \qquad (4)$$

- Eliminate ϕ_m and determine the transverse momentum flow as

$$v^2_{m,p_T} = \int d\phi_1 d\phi_2 dp_{T1} dp_{T2} p_{T1} p_{T2} P(\phi_1) P(\phi_2) \times \cos m(\phi_1 - \phi_2). \quad (5)$$

- For a given particle distribution in an experiment, the flow coefficients are determined by

$$v^2_m = \frac{1}{N^2} \sum_{i,j} \cos(\phi_i - \phi_j) \quad (6)$$

and

$$v^2_{m,p_T} = \frac{1}{N^2} \sum_{i,j} p_{T,i} p_{T,j} \cos(\phi_i - \phi_j), \quad (7)$$

where N is the number of particles in the event and $p_{T,i}$ is the transverse momentum of i^{th} particle.

One jet

- Assume that the background particles N_b and a jet N_J number of particles are distributed uniformly.
- Thus, the probability distribution of $N = N_b + N_j$ particles

$$P(\phi, p_T) = \frac{N_b}{N} P_b(\phi, p_T) + \frac{N_j}{N} P_j(\phi, p_T), \tag{8}$$

where

$$P_b(\phi, p_T) = \frac{1}{2\pi} f_B(p_T) \quad \text{for} \;\; 0 < \phi < 2\pi$$

and

$$P_j(\phi, p_T) = \frac{1}{\Delta\phi} f(p_T), \quad \text{for} \;\; \phi_0 - \Delta\phi/2 < \phi < \phi_0 + \Delta\phi/2.$$

- The transverse momentum distributions of background and jet particles have been normalized to unity. Thus $\int f(p_T)dp_T = \int f_B(p_T)dp_T = 1$. For this distribution, the expression for flow coefficients v_m is

$$\begin{aligned} v_m^2 &= \int d\phi_1 d\phi_2 dp_{T1} dp_{T2} P(\phi_1, p_{T1}) P(\phi_2, p_{T2}) \cos m(\phi_1 - \phi_2) \\ &= \int d\phi_1 d\phi_2 dp_{T1} dp_{T2} P(\phi_1, p_{T1}) P(\phi_2, p_{T2}) \\ &\times (\cos(m\phi_1)\cos(m\phi_2) + \sin(m\phi_1)\sin(m\phi_2)) \\ &= \frac{N_j^2}{N^2}\Big[\int d\phi_1 dp_{T1} P_j(\phi_1, p_{T1}) \cos m(\phi_1 - \phi_0)\Big]^2 \\ &= \frac{N_j^2}{N^2}\Big[j_0(m\Delta\phi/2)\Big]^2. \end{aligned} \quad (9)$$

➥ If the jet angle $\Delta\phi$ is small, then expand the cosine function in powers of $\phi_1 - \phi_0$,

$$v_m^2 = \frac{N_j^2}{N^2}\left[1 - \frac{m^2\Delta\phi^2}{12} + \mathcal{O}(m^4)\right]. \tag{10}$$

➥ For this distribution, the variance $\sigma = \sqrt{(\phi_{av}^2) - (\phi_{av})^2} = \frac{\Delta\phi}{\sqrt{12}}$. In fact, for general azimuthal distribution function, we can show that

$$v_m^2 = \frac{N_j^2}{N^2}\left[1 - m^2\sigma^2 + \mathcal{O}(m^4)\right], \tag{11}$$

➥ Assume that the jet particles are distributed according to a probability distribution function which is symmetric about ϕ_0.

➥ Following the same methodology, the expression for p_T-weighted flow coefficients can be determined. One can write

$$v^2_{m,p_T} = \frac{N_j^2 < p_T >^2}{N^2}\Big[j_0(m\Delta\phi/2)\Big]^2 = \frac{N_j^2 < p_T >^2}{N^2}\Big[1 - \frac{m^2\Delta\phi^2}{12} + \mathcal{O}(m^4)\Big] = \frac{N_j^2 < p_T >^2}{N^2}\Big[1 - m^2\sigma^2 + \mathcal{O}(m^4)\Big], \quad (12)$$

where $< p_T > = \int dp_T p_T f(p_T)$ is the average transverse momentum carried by a particle in the jet. Thus $N_j < p_T >$ gives the total transverse momentum of the jet.

Two jets

➥ Consider two jets emitted at azimuthal angles ϕ and $\phi + \pi$. We expect that a hard parton scattering would produce such jets having equal and opposite jet momenta.

➥ To consider such a situation, following particle distribution function $P(\phi, p_T)$ is chosen.

$$P(\phi, p_T) = \frac{N_b}{N} P_b(\phi, p_T) + \frac{N_{j1}}{N} P_{j1}(\phi, p_T) + \frac{N_{j2}}{N} P_{j2}(\phi, p_T), \quad (13)$$

where

$$\begin{aligned} P_b(\phi, p_T) &= \frac{1}{2\pi} f_B(p_T) \quad \text{for } \ 0 < \phi < 2\pi \\ P_{j1}(\phi, p_T) &= \frac{1}{\Delta\phi} f_1(p_T) \quad \text{for } \ \phi_0 - \Delta\phi_1/2 < \phi < \phi_0 + \Delta\phi_1/2 \\ P_{j2}(\phi, p_T) &= \frac{1}{\Delta\phi} f_2(p_T) \ \text{for } \ \phi_0 - \Delta\phi_2/2 < \phi + \pi < \phi_0 + \Delta\phi_2/2. \end{aligned} \tag{14}$$

➥ Note the number of jet particles, their opening angles and momentum distributions assumed to be different for the two jets. The computation of the flow coefficients carried out in the same fashion as

$$v_m^2 = \frac{1}{N^2}\Big[N_{j1} j_0(\frac{m\Delta\phi_{j1}}{2}) + (-1)^m N_{j2} j_0(\frac{m\Delta\phi_{j2}}{2})\Big]^2 \qquad (15)$$

and

➥

$$v_{m,p_T}^2 = \frac{1}{N^2}\Big[< p_{T,1} > j_0(\frac{m\Delta\phi_{j1}}{2}) +(-1)^m < p_{T,2} > j_0(\frac{m\Delta\phi_{j2}}{2})\Big]^2. \qquad (16)$$

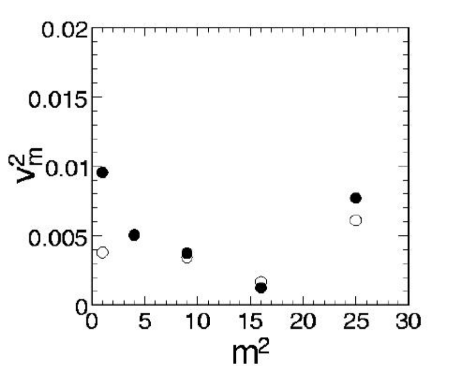
➥ First, for two jet case, the flow coefficients for even m are significantly larger than those for odd m. Particularly, if the two jets have similar opening angles and numbers of jet particles, the odd flow coefficients (close to zero) and much smaller than the even coefficients.

➥ On the other hand, if the opening angle of one of the jets is broadened significantly, the corresponding Bessel function would decrease rapidly with m and the pattern would look more like a single jet case.

Calculations and Results

- The analysis is done for the number of jet particles varying from 10 to 20, the opening angle between $\pi/6$ and $\pi/4$ radians. The analyzes are done by using a p_T cut of 0.5, 0.75 and 1 GeV for background particles.
- The dynamical elliptical flow is observed to be of the order of $10 - 15\%$. Since we are determining v_m^2, the contribution of dynamical elliptic flow to v_2^2 is $\sim 0.01 - 0.02$.
- For an event with N particles, we compute the flow coefficients $v_m^2 = \frac{\sum_{i,j} \cos(m(\phi_i - \phi_j))}{N^2}$. Fitting a curve $b - cm^2$ to these values by minimizing χ^2, we obtain the number of jet particles ($N_j^2 = bN^2$) and the jet opening angle ($\Delta\phi^2 = 12cN^2/N_j^2 = 12c/b$).

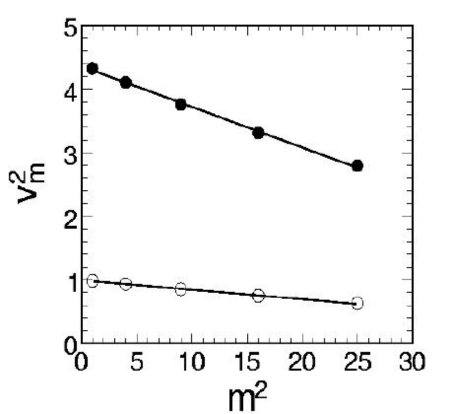
Case of no jet



☞ The closed (open) symbols are for with (without) p_T weight, the value of p_T cut used is 0.75 GeV.

☞ The flow coefficients are generally smaller than 0.005 and 0.015 for constant weight and p_T weighted coefficients respectively.

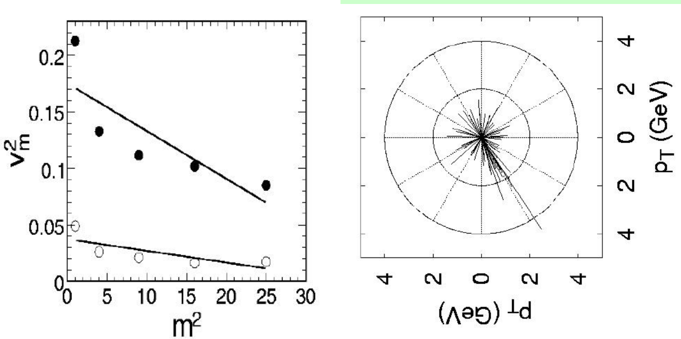
Case of only jet



☞ opening angle is $\pi/6$ and number of jet particles is 10

☞ The values of flow coefficients are large in comparison with the events having only background particles.

One jet case



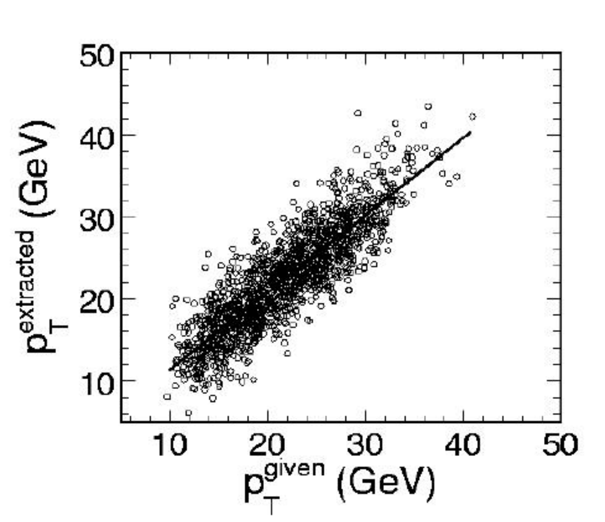
☞ For p_T cut of 0.75 GeV for background particles and 10 jet particles

☞ In the 'wagon-wheel' plot, each line represents a particle in the event and the direction ($\Delta\phi$) and the length (p_T) of the particle, respectively.

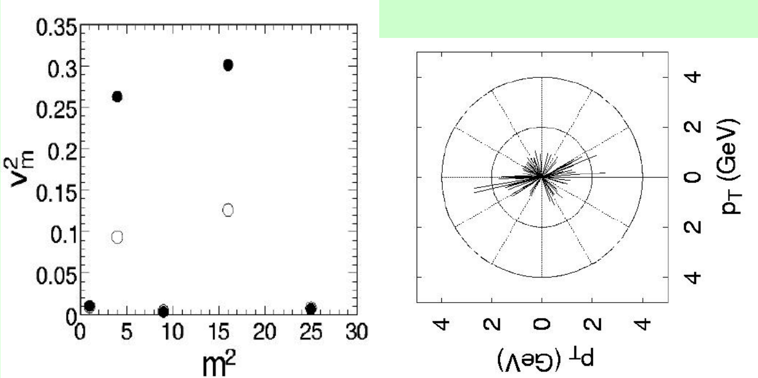
Extracted values

Input # of particles, jet p_T, p_T cut and $\Delta\phi$	extracted # of particles, jet p_T, $\Delta\phi$ (p_T weight), $\Delta\phi$ (w/o p_T weight)
10, 18.26, 1.00, $\pi/6$	10.52, 18.17, 0.43, 0.46
10, 18.26, 0.75, $\pi/6$	11.60, 18.17, 0.46, 0.57
10, 18.26, 0.50, $\pi/6$	14.11, 18.14, 0.56, 0.70
10, 18.26, 1.00, $\pi/4$	10.31, 18.17, 0.54, 0.53
10, 18.26, 0.75, $\pi/4$	11.44, 18.17, 0.53, 0.57
10, 18.26, 0.50, $\pi/4$	14.05, 18.18, 0.54, 0.77
10, 18.26, 1.00, $\pi/8$	10.56, 18.17, 0.39, 0.44
10, 18.26, 0.75, $\pi/8$	11.63, 18.17, 0.45, 0.59

Correlation between input and extracted jet p_T



Two jets case



☞ The closed (open) symbols are for different (same) jet angle of both the jets using p_T cut. In the transverse momenta of the particles in a 'wagon-wheel' plot, two back-to-back jets can be identified in the figure.

Summary and Conclusion

- We have explored the possibility of identifying and characterizing the jet structure in a relativistic heavy ion collisions.
- We have shown that, there is a linear relation between the square of the flow coefficients v_m with m^2 and using this relation it is possible to estimate the number of jet particles, the jet opening angle and the jet transverse momentum.

- We have applied the method to simulated data having zero, one and two jets. We find that these three cases can be distinguished from the pattern of the flow coefficients. For the events with no jet, the flow coefficients are small. For one jet events, the flow coefficients are large and show the linear behavior discussed above. For the two jet case, the odd and even flow coefficients fluctuate with the odd coefficients being small.
- We feel that this method can be used in LHC experiments to isolate collision events having one and two jets and possibly extract the properties of jets.

References

- S. C. Phatak and P. K. Sahu, Phys. Rev. C69, 024901, (2004).
- S. Dash, D. K. Mishra, S. C. Pathak and P. K. Sahu nucl-th/0607014; Submitted to journal.