How to measure flow and the reaction plane?

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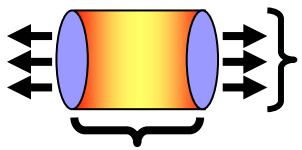
Outline

- **Intro**
- **Definitions of Flow and Reaction Plane**
- **Calculating Reaction Plane**
- **Calculating RP dispersion**
- **v2 from RP**
- **Discussion of Non-flow effects**
- **Typical PHENIX results**

Heavy Ion Collisions at RHIC

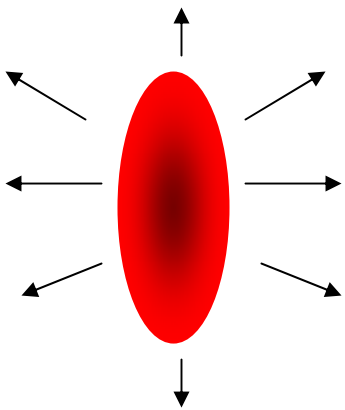
Energy deposition



$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

Pressure gradients

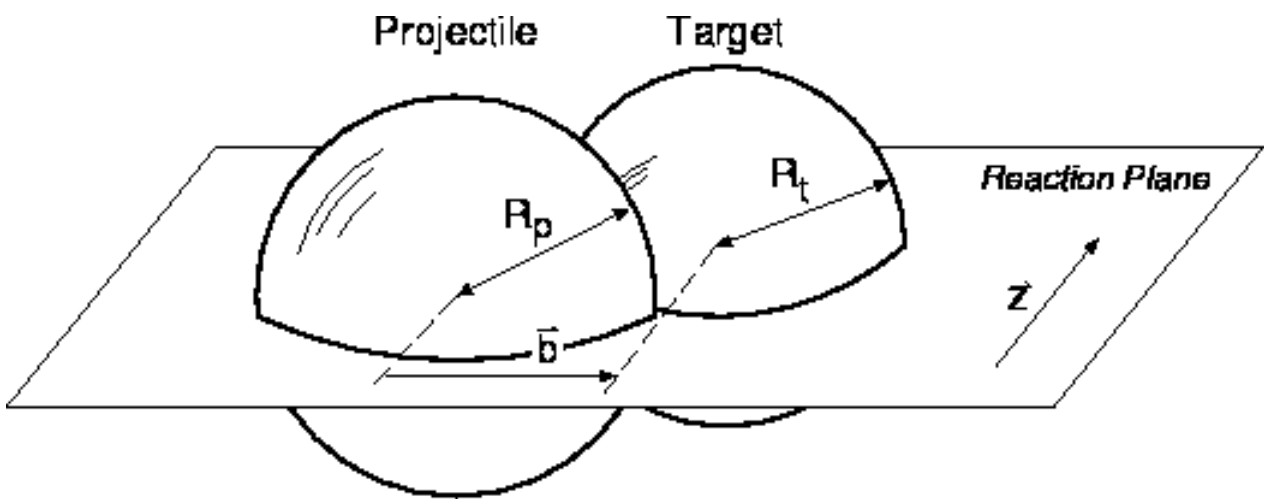
$$\left(P = \rho^2 \cdot \left(\partial\varepsilon / \partial\rho \right)\Big|_{s/\rho} \right)$$



Pressure gradients lead to azimuthal anisotropy of particle emission i.e. flow

The Reaction Plane

The reaction plane is determined by the impact parameter and the beam direction



Flow

Flow is a term used to describe the azimuthal distribution of particles with respect to the reaction plane. :

$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} c_n \cos n\phi\right)$$

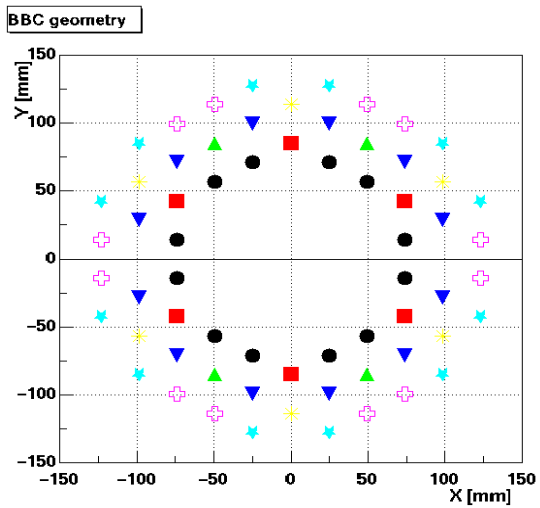
where $c_n = \langle \cos n\phi \rangle$

Flow is usually quantified by c_2 (commonly called v_2)

Question Break

Calculation of BBC Reaction Plane ψ

BBC geometry



Need to take into account asymmetry in PMT charge distribution

Shift Correction

Calculate Ax ,Sx i.e first and second moments of $\sum ADC_i \cos n\phi_i$

Calculate Ay ,Sy i.e first and second moments of $\sum ADC_i \sin n\phi_i$

(Sum over particles, average over events)

Bx = ($\sum ADC_i \cos n\phi_i$ **- Ax)/Sx**

By = ($\sum ADC_i \sin n\phi_i$ **- Ay)/Sy**

tan nψ_0^{cal} **= By/Bx**

Flattening Correction

Because of non-uniform acceptance the RP distribution is not flat. One needs to obtain a flattening correction $\Delta\psi_c$

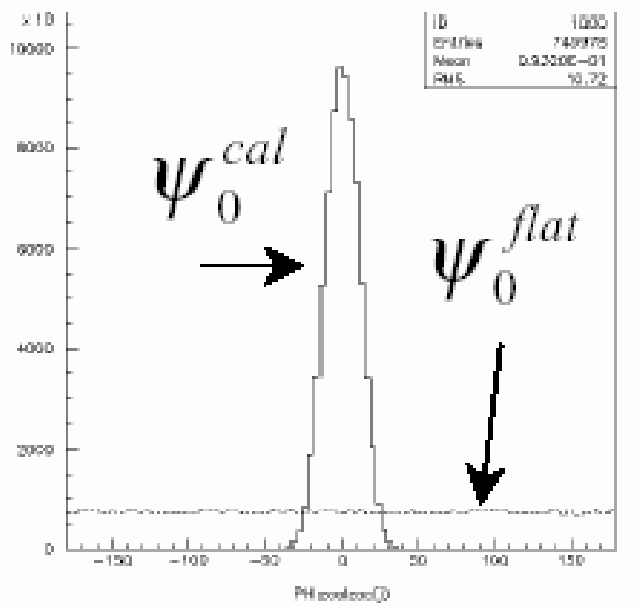
$$\psi_0^{flat} = \psi_0^{cal} + \Delta\psi_c$$

Flattening Correction (contd.)

$$\Delta\psi_c = \sum_n \left(A_n \cos(2n\psi_0^{cal}) + B_n \sin(2n\psi_0^{cal}) \right)$$

$$A_n = -\frac{2}{n}\left\langle \sin(2n\psi_0^{cal}) \right\rangle$$

$$B_n = \frac{2}{n}\left\langle \cos(2n\psi_0^{cal}) \right\rangle$$



Question Break

Reaction Plane Dispersion

A vector Q can be associated with the Reaction Plane

$$\mathbf{Q} = \sum_{k=1}^{N} w_k \, \mathbf{u}_k$$

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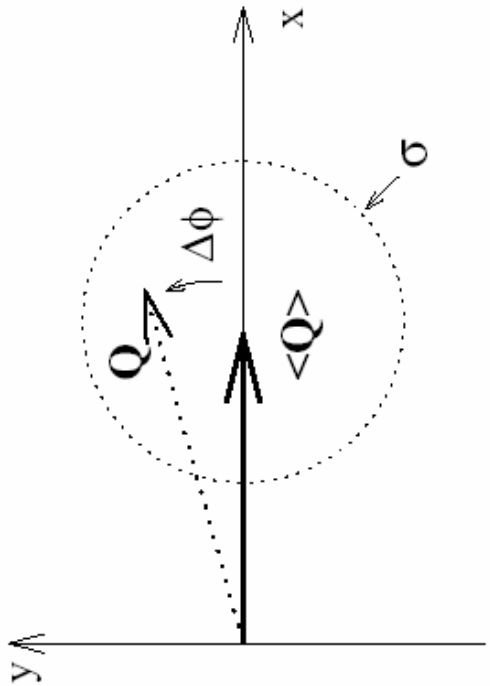
where the sum runs over all the detected particles in the event. $\mathbf{u_k}$ is the unit vector parallel to the transverse momentum of the particle, and w_k is a weight which may depend on the type of particle, its rapidity and transverse momentum.

Reaction Plane Dispersion (contd.)

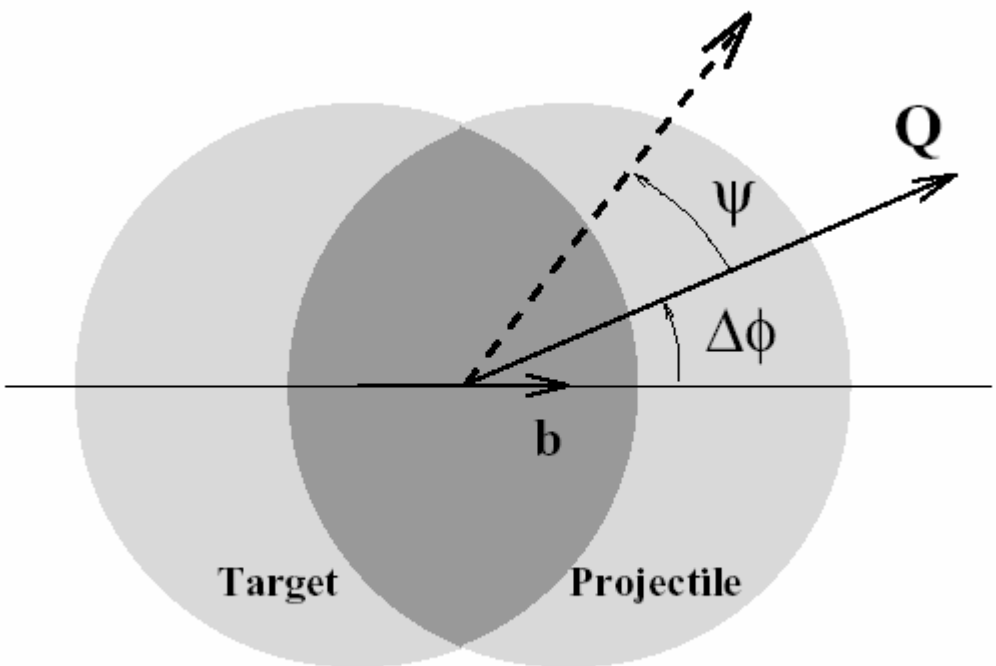
The central limit theorem shows that, for a given magnitude and orientation of the true impact parameter, the fluctuations of Q around its average value, <Q>, are Gaussian.



Reaction Plane Dispersion (contd.)

Due to the RP dispersion the measured angle ψ is different from the true angle ϕ.

$$\psi = \phi - \Delta\phi$$



Reaction Plane Dispersion (contd.)

Since ϕ and $\Delta\phi$ are statistically independent we have

$$\langle \cos n\psi \rangle = \langle \cos n\phi \rangle \langle \cos n\Delta\phi \rangle$$

i.e. measured harmonic = true harmonic * RP dispersion

The distribution of $\Delta\phi$ is given by

$$\frac{dN}{\Delta\phi} = \frac{1}{\pi} \exp(-\chi^2) \left\{ 1 + z\sqrt{\pi}\,[1 + \mathrm{erf}(z)] \exp(z^2) \right\} .$$

where $z = \chi \cos \Delta\phi$

Calculation of Reaction Plane Dispersion

The reaction plane dispersion is calculated by a three step procedure

Step 1: Calculate Reaction Planes for two sub-events

Step 2 : Plot the difference distribution N($\Delta\phi_R$)

$$\Delta\phi_R = |\psi 1 - \psi 2|$$

Calculation of Reaction Plane Dispersion (contd.)

Step 3 : From the theory of the RP dispersion it can be shown that N is described by the function :

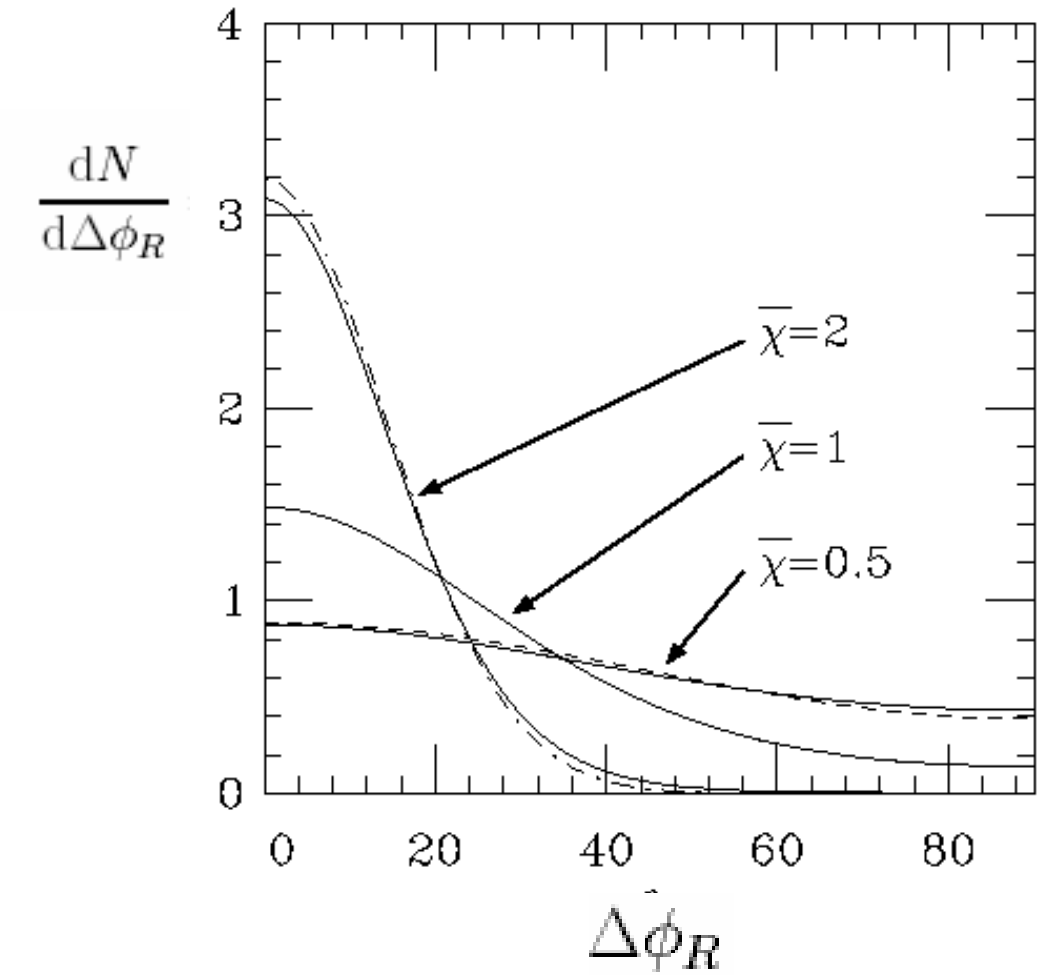
$$\frac{\mathrm{d}N}{\mathrm{d}\Delta\phi_R} = \frac{\mathrm{e}^{-\chi_I^2}}{2}\left\{\frac{2}{\pi}(1+\chi_I^2) + z\left[I_0(z) + \mathbf{L}_0(z)\right] + \chi_I^2\left[I_1(z) + \mathbf{L}_1(z)\right]\right\}$$

where $z = \chi_I^2 \cos\Delta\phi_R$

I and L are Modified Bessel and Struve Functions

χ_I^2 can be obtained by a simple fit to the data

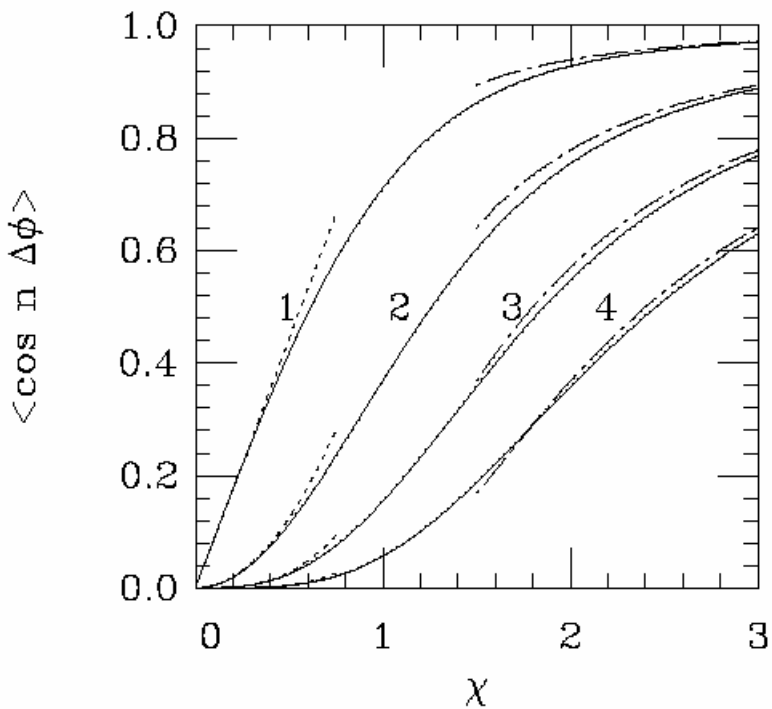
Calculation of Reaction Plane Dispersion (contd.)



Calculation of Reaction Plane Dispersion (contd.)

The RP dispersion is given by

$$\langle \cos n\Delta\phi \rangle = \frac{\sqrt{\pi}}{2}\chi e^{-\chi^2/2}\left[I_{\frac{n-1}{2}}\left(\frac{\chi^2}{2}\right) + I_{\frac{n+1}{2}}\left(\frac{\chi^2}{2}\right)\right]$$

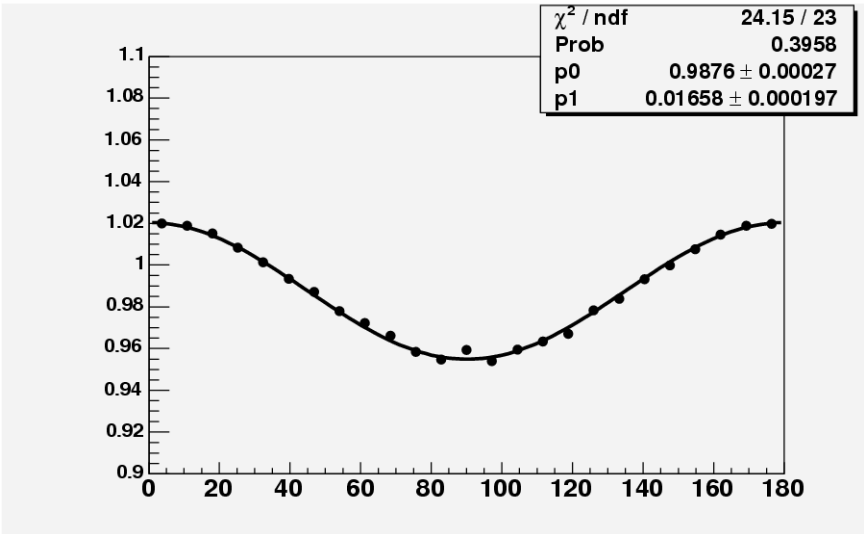


Question Break

v2 from BBC RP

Step 1 Obtain the azimuthal distribution of central arm particles wrt the flattened BBC RP

Step 2 Fit the distribution with a second harmonic function



Fit to data

Step 3 True v2 = Fit v2 / RP dispersion

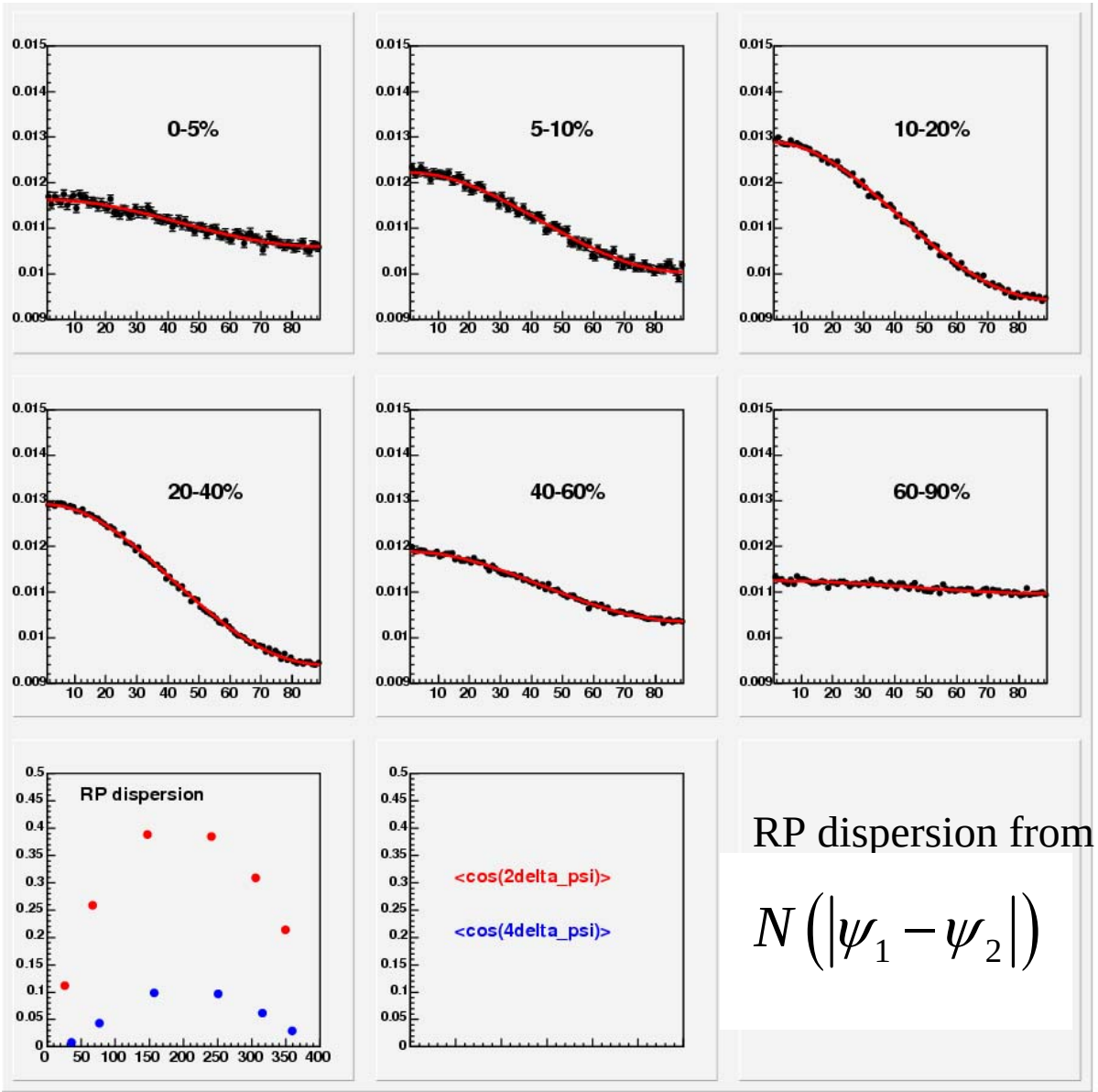
Non-flow effects

Presence of an-harmonic clusters in BBC can change the measured RP substantially. The large eta gap between N and S BBC reduces jet effects

Jets in the central arm, if they are **uncoupled** to the RP, will dilute the measured v2. Possible reason for leveling off of v2 at high pt where jet fraction is higher

Jets coupled to RP an-harmonically will spoil the chi-square of the harmonic fit.

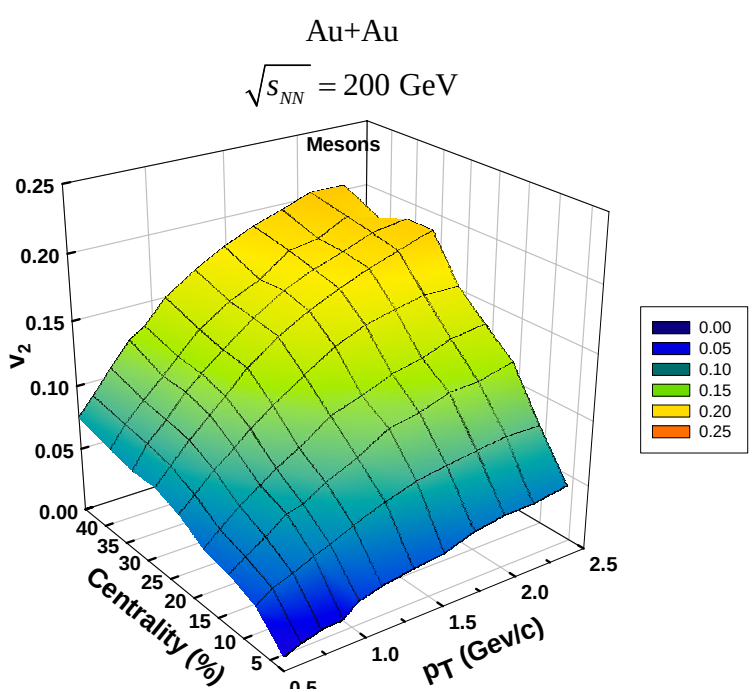
RP Dispersion Plots from Data

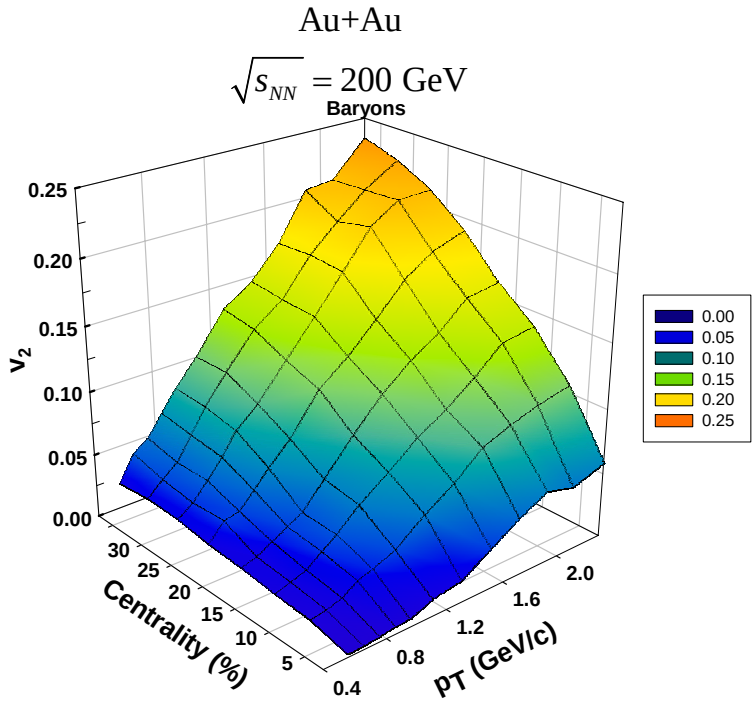


RP dispersion from

$$N\left(\left|\psi_1 - \psi_2\right|\right)$$

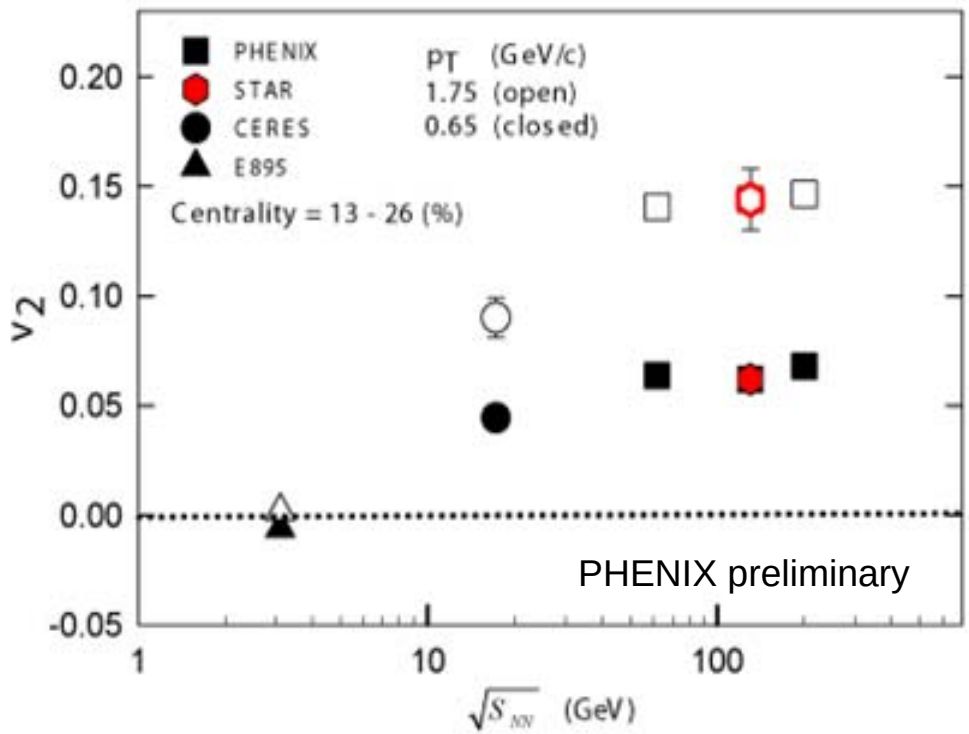
v2 vs centrality,pt and flavor from PHENIX





Flow dominates at low pT at RHIC

Recent v2 excitation function – PPG047



Using RP to extinguish flow !

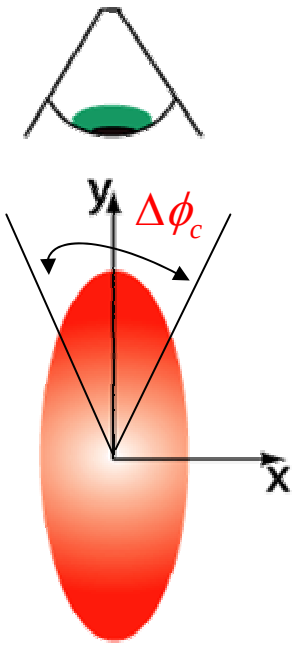
Two particle azimuthal correlions are used to study jets

But these correlations contain the effects of BOTH flow and jets

In order to study jet modification it is necessary to eliminate the effects of flow

v2 extinction for constrained correlations

Out-of-plane



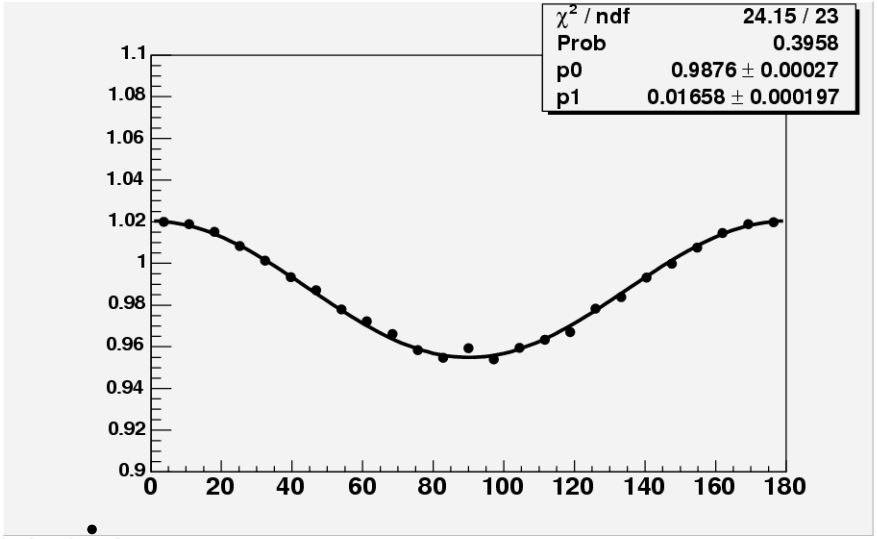
In-plane

v_2^{out} **is given by :**

$$v_2^{out} = \left(\frac{2v_2(\Delta\phi_c) - \sin(2\Delta\phi_c)\langle\cos(2\Delta\Psi_R)\rangle + \frac{v_2}{2}\sin(4\Delta\phi_c)\langle\cos(4\Delta\Psi_R)\rangle}{2(\Delta\phi_c) - 2v_2\sin(2\Delta\phi_c)\langle\cos(2\Delta\Psi_R)\rangle} \right)$$

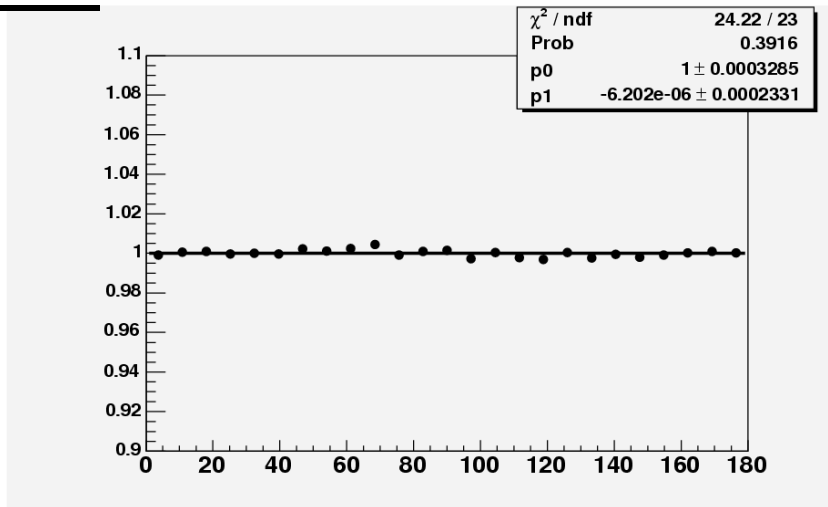
By a proper choice of $\Delta\phi_c$ **it is possible to make** v_2^{out} **= 0 i.e. extinguish flow !**

Demonstration of v2 extinction via simulation



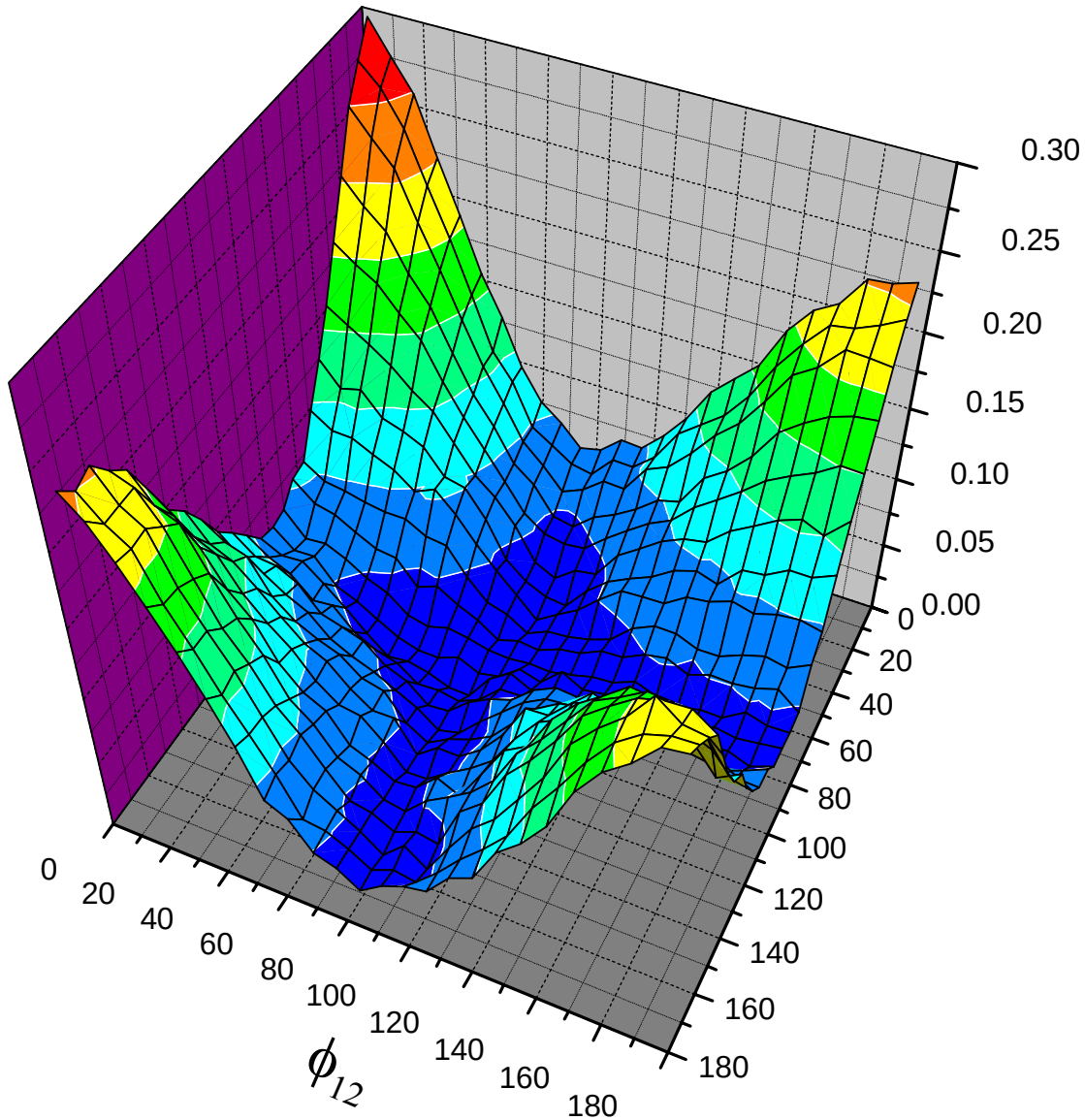
$\Delta\phi$ distribution without extinction

Pure harmonic

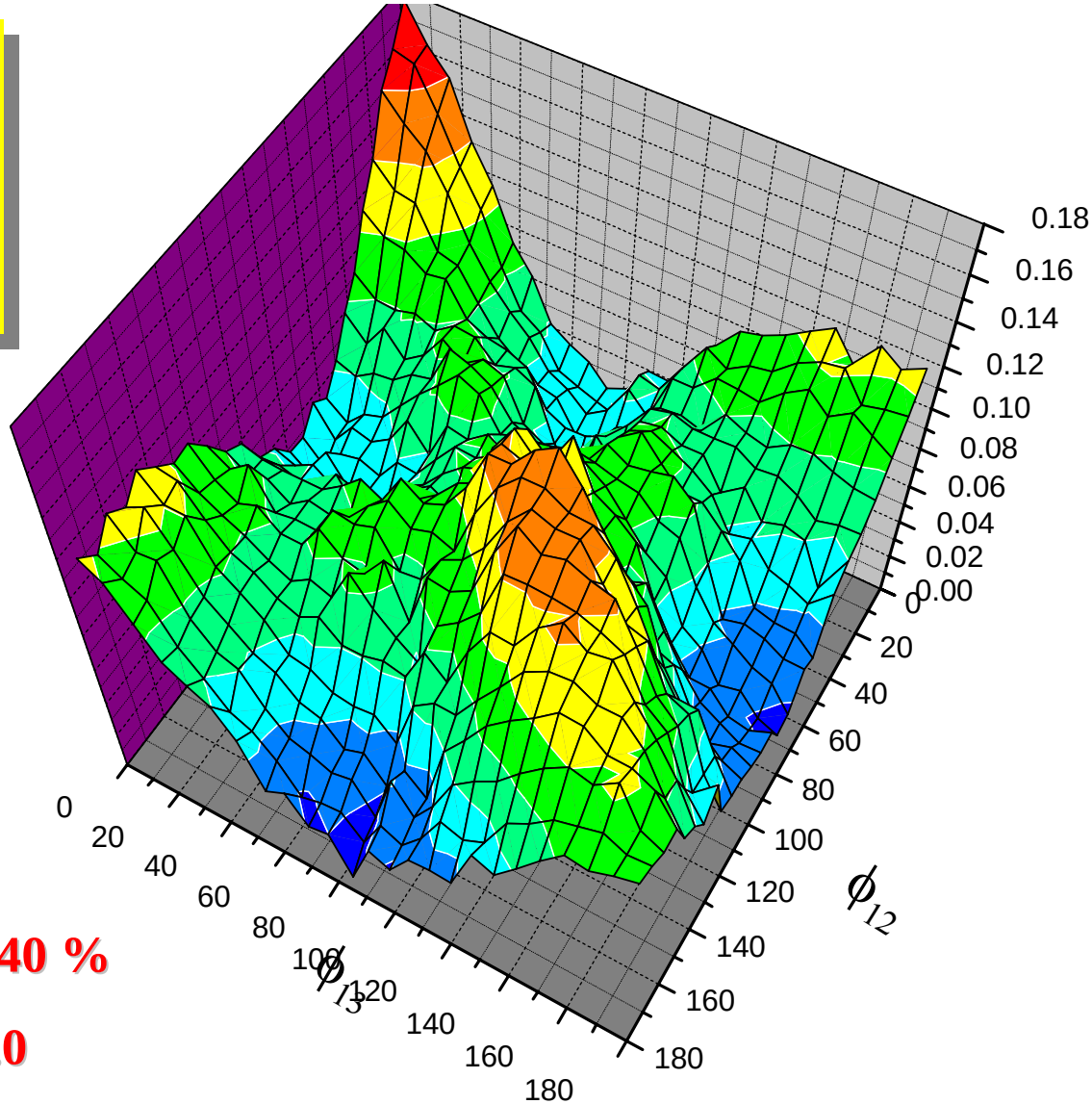


$\Delta\phi$ distribution with extinction

3 particle results For Run- 4 Data Unconstrained



3 particle results For Run- 4 Data



200 GeV Au+Au 20 - 40 %

2.5<pt_leading<4.0

1.0<pt_assoc<2.5

With v2 Extinction

Jet Landscape