Azimuthal angle dependence of HBT radii with respect to the Event Plane in Au+Au collisions at PHENIX

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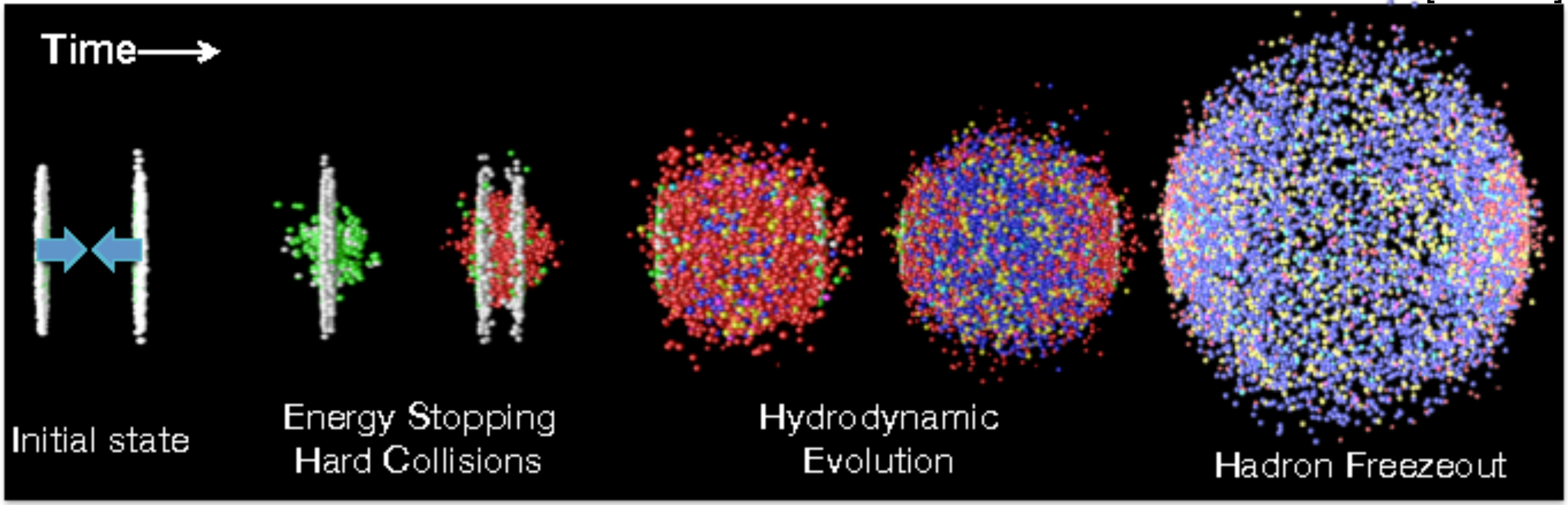
PHENIX

Space-Time evolution in HI collisions

arXiv:1201.4264 [nucl-ex]



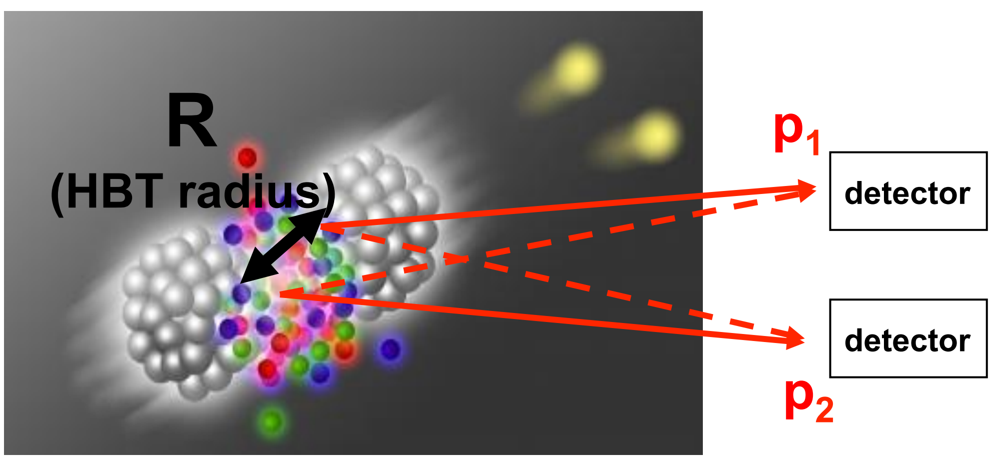
- **Space-time extent at freeze-out reflects the characteristics of system evolution, such as the strength of the expansion, the expansion time, hadron rescattering, and so on.**
- **HBT interferometry is a powerful tool to study the space-time evolution in Heavy Ion collisions.**

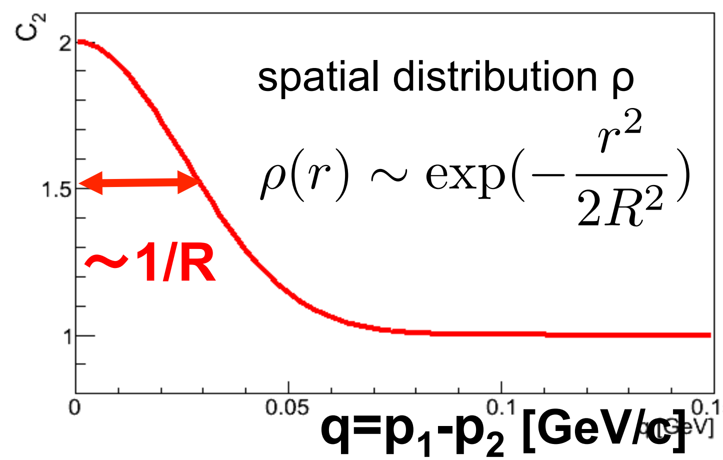
HBT Interferometry

- 1956s, R. Hanbury Brown and R. Twiss measured the angular diameter of Sirius.
- 1960, Goldhaber *et al*. correlation among identical pions in $p+\bar{p}$
- Quantum interference between two identical particles

wave function for 2 bosons(fermions) : $\Psi_{12} = \frac{1}{\sqrt{2}}[\Psi(x_1,p_1)\Psi(x_2,p_2) \pm \Psi(x_2,p_1)\Psi(x_1,p_2)]$

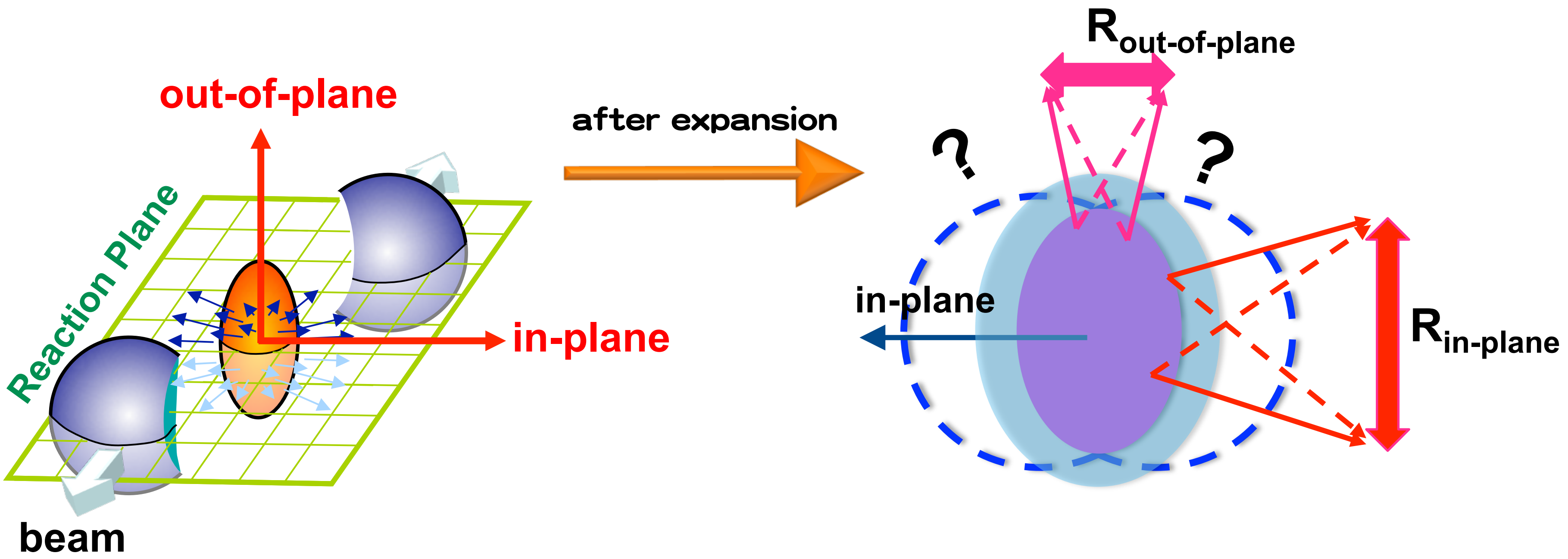
$$C_2 = \frac{P(p_1,p_2)}{P(p_1)P(p_2)} \approx 1 + |\tilde{\rho}(q)|^2 = 1 + \exp(-R^2q^2)$$



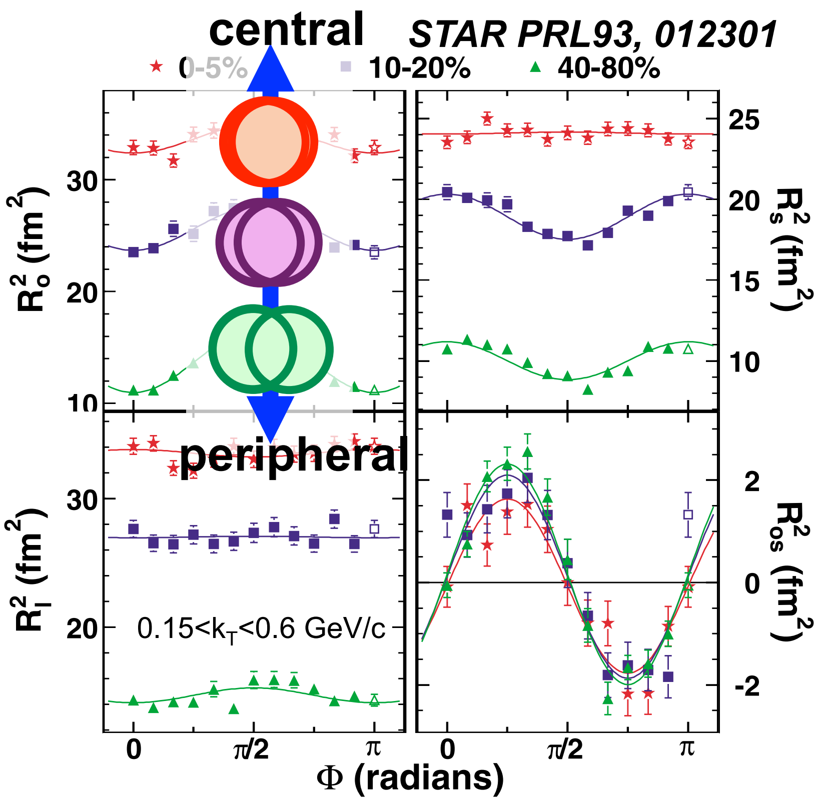


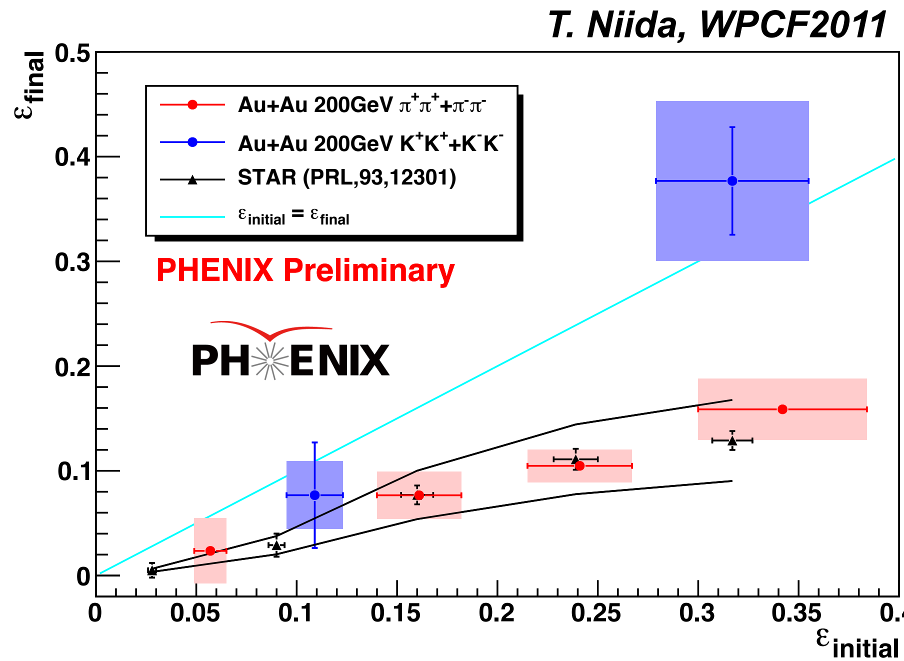
Azimuthal angle dependence

- Angle dependence of HBT radii relative to Reaction Plane reflects the source shape at kinetic freeze-out.
- Initial spatial anisotropy causes momentum anisotropy (flow anisotropy)
  - ✧One may expect in-plane extended source at freeze-out
- Final source eccentricity will depend on initial eccentricity, flow profile, expansion time, and viscosity etc.



HBT radii w.r.t Reaction Plane at RHIC

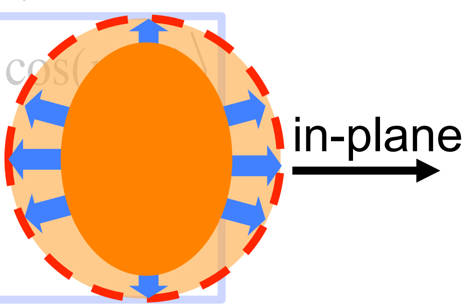




PRC70, 044907 (2004)

$$R_{s,n}^2 = \langle R_{s,n}^2(\Delta\phi)\cos(\cdots)\rangle$$

$$\varepsilon_{final} = 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

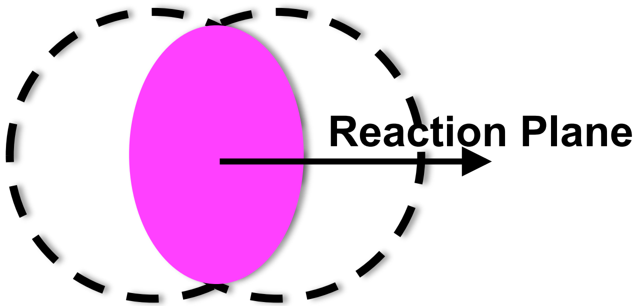


- $\varepsilon_{final} \approx \varepsilon_{inital}/2$
- **Strong expansion to in-plane, but still elliptical shape.**

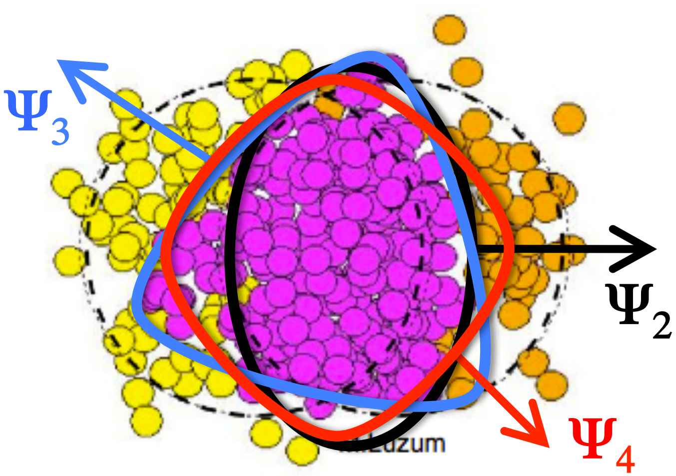
Higher Harmonic Flow and Event Plane

- **Initial density fluctuations cause higher harmonic flow v_n**
- **Azimuthal distribution of emitted particles:**

smooth picture



fluctuating picture



$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos 2(\phi - \Psi_2) + 2v_3\cos 3(\phi - \Psi_3) + 2v_4\cos 4(\phi - \Psi_4)$$

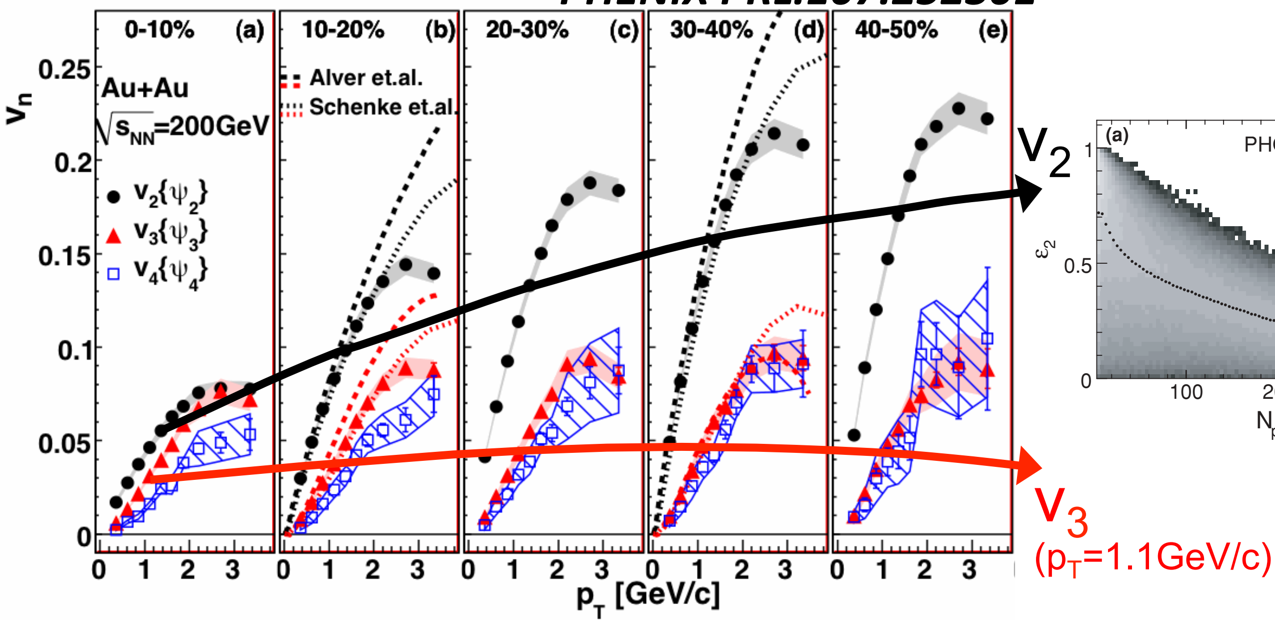
$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$

v_n : strength of higher harmonic flow
Ψ_n : higher harmonic event plane
φ : azimuthal angle of emitted particles

Centrality dependence of v_n and initial ε_n

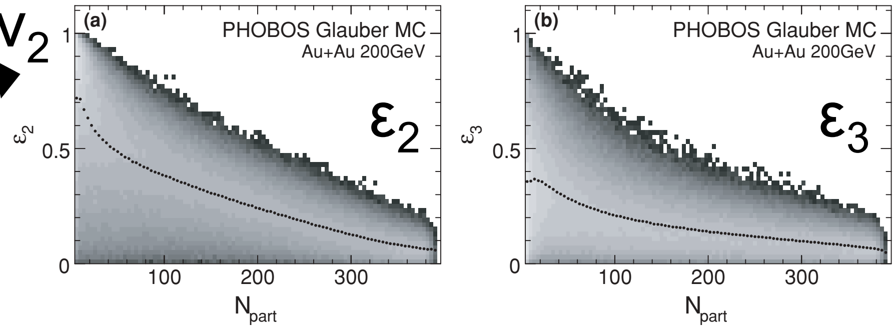
Higher harmonic flow v_n

PHENIX PRL.107.252301



Initial source anisotropy ε_n

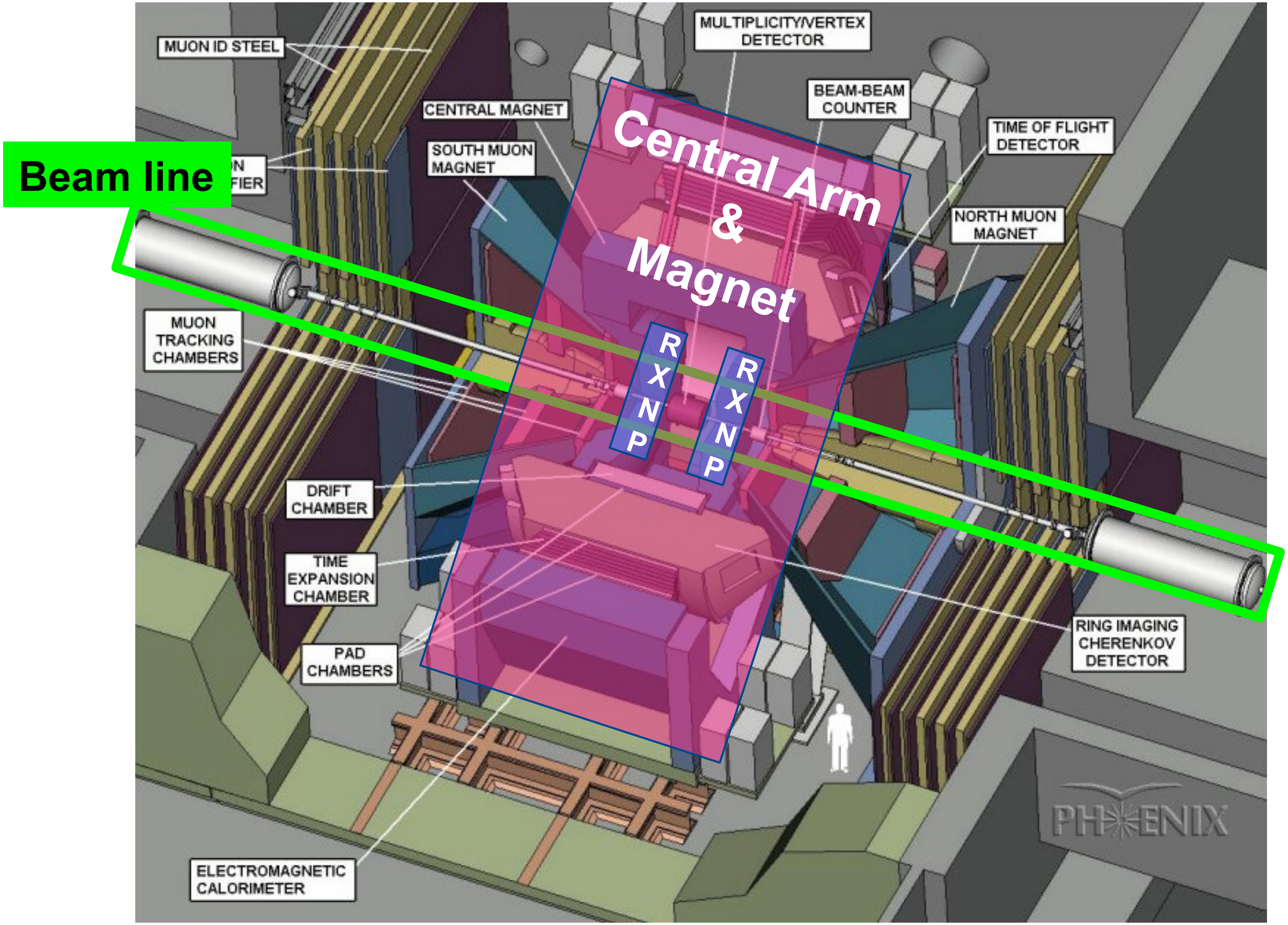
PRC.81.054905



- Weak centrality dependence of v_3 unlike v_2
- Initial ε_3 has finite values and weaker centrality dependence than ε_2

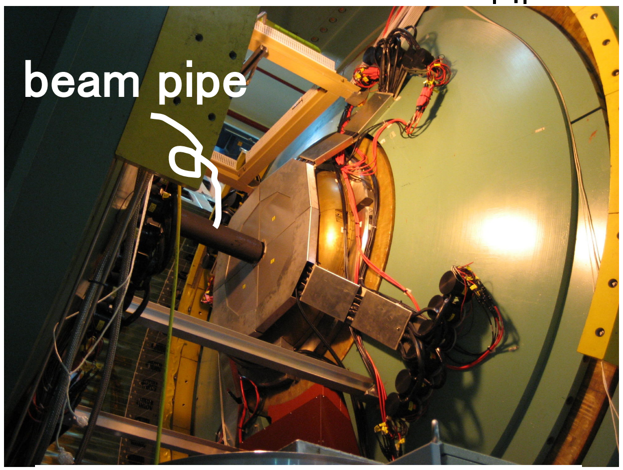
Triangular component in source shape exists at final state?
➡Measurement of HBT radii relative to Ψ_3

PHENIX Experiment

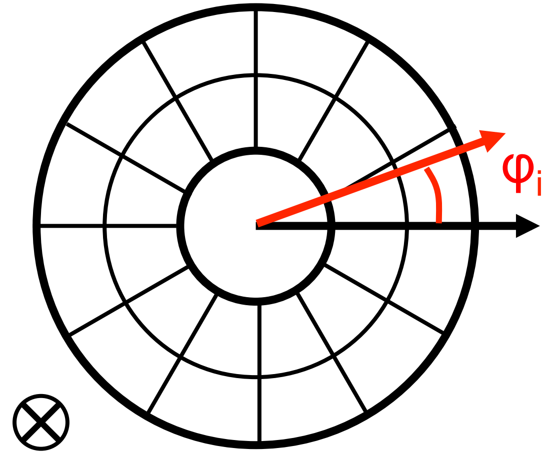


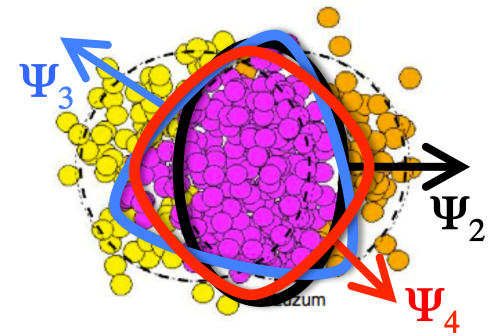
Event Plane Determination

1<|η|<2.8

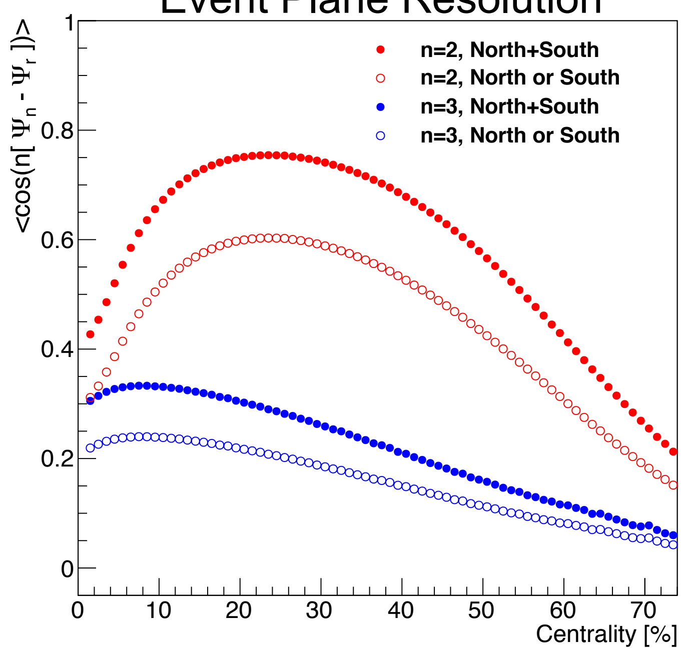


24 scintillator segments





Event Plane Resolution



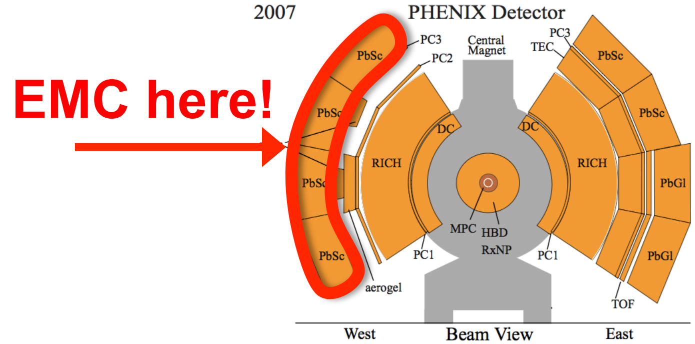
- **Determined by anisotropic flow itself**

$$\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{\Sigma w_i \cos(n\phi_i)}{\Sigma w_i \sin(n\phi_i)}\right)$$

- **Event plane is determined by Reaction Plane Detector (RXNP)**

✧Resolution: $<\cos(n(\Psi_n - \Psi_{real}))>$
n=2 : ~ 0.75
n=3 : ~ 0.34

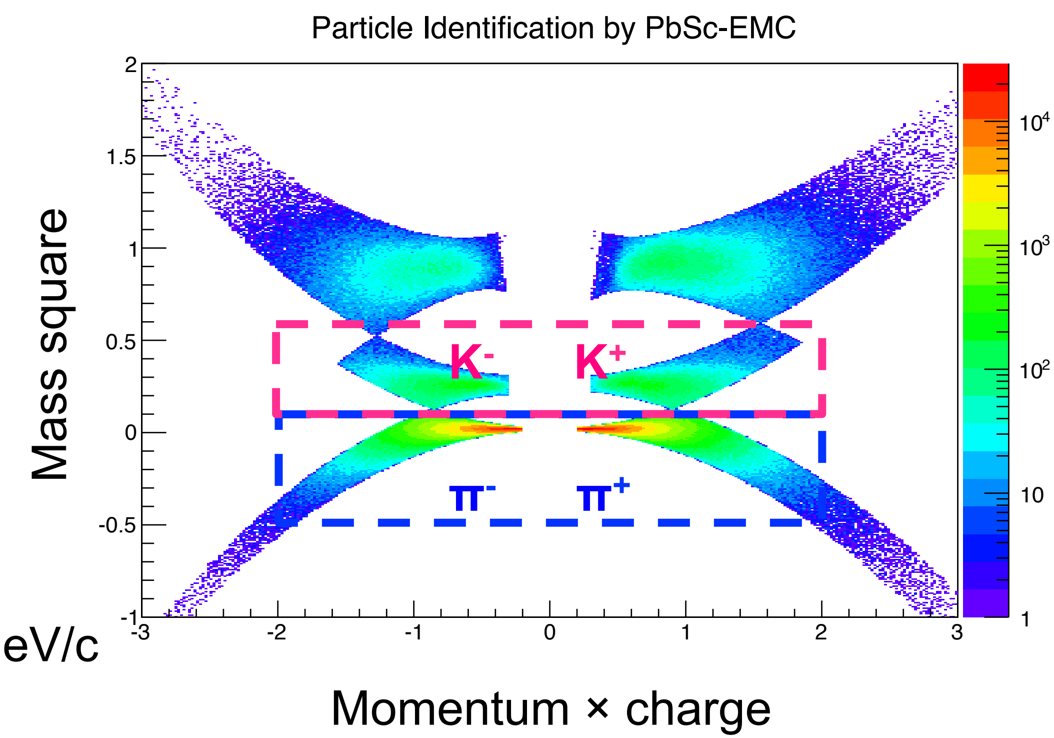
Particle IDentification



- **EMC-PbSc is used.**
  - ✧ timing resolution ~ 600 ps
- **Time-Of-Flight method**

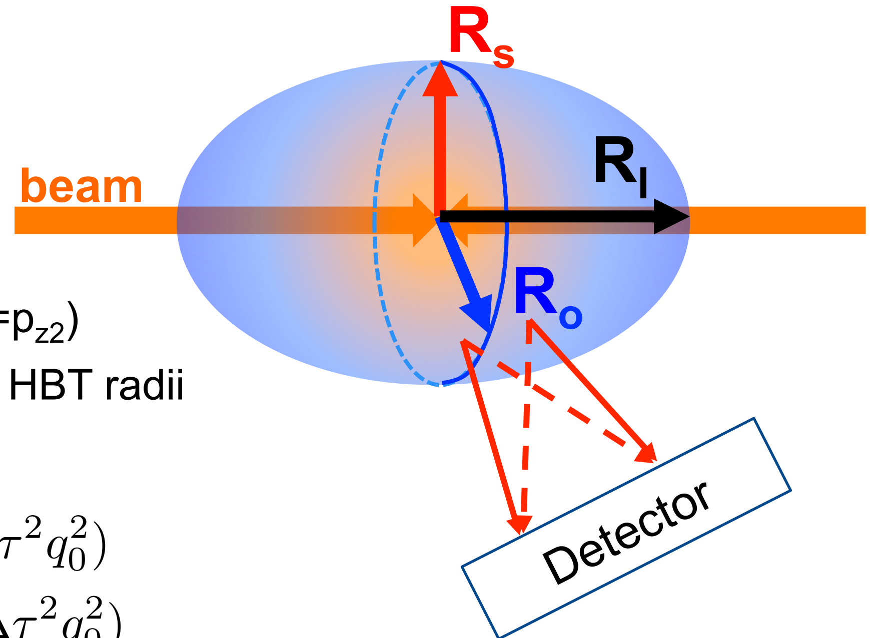
$$m^2 = p^2\left(\left(\frac{ct}{L}\right)^2 - 1\right)$$

p: momentum L: flight path length
t: time of flight



- **Charged π within 2σ**
  - ✧ π/K separation up to ~1 GeV/c

3D-Analysis



- **"Out-Side-Long" frame**
  - ✧ Bertsch-Pratt parameterization
  - ✧ Longitudinal Center of Mass System ($p_{z1}=p_{z2}$)

$C_2 = 1 + \lambda G$ λ : chaoticity R_μ : HBT radii

$$G = \exp(-\mathbf{R}^2\mathbf{q}^2)$$
$$= \exp(-R_x^2 q_x^2 - R_y^2 q_y^2 - R_z^2 q_z^2 - \Delta\tau^2 q_0^2)$$
$$= \exp(-R_s^2 q_s^2 - R_o^{*2} q_o^2 - R_l^2 q_l^2 - \Delta\tau^2 q_0^2)$$
$$\overset{\text{LCMS}}{\approx} \exp(-R_s^2 q_s^2 - (\underbrace{R_o^{*2} + \beta_T^2 \Delta\tau^2}_{=R_o^2}) q_o^2 - R_l^2 q_l^2)$$

$$\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2})$$
$$\vec{q}_o \parallel \vec{k}_T, \quad \vec{q}_s \perp \vec{k}_T$$

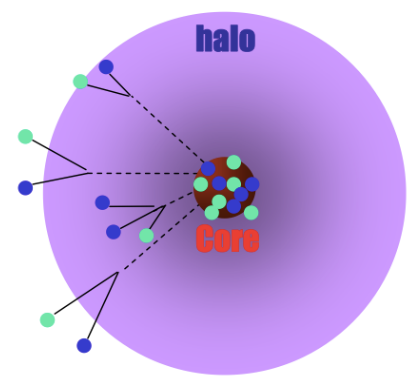
including cross term

$$G = \exp(-R_s^2 q_s^2 - R_o^2 q_o^2 - R_l^2 q_l^2 - 2R_{os}^2 q_s q_o)$$

- **Core-Halo model**

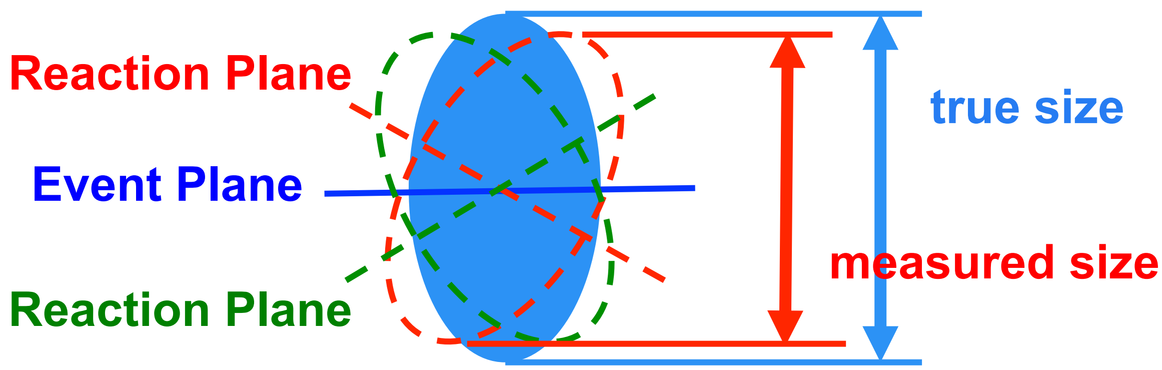
$$C_2 = C_2^{core} + C_2^{halo}$$
$$= N[\lambda(1+G)F_{coul}] + [1-\lambda]$$

N: normalization factor
F_{coul}: Coulomb correction factor



Correction of Event Plane Resolution

- **Smearing effect by finite resolution of the event plane**



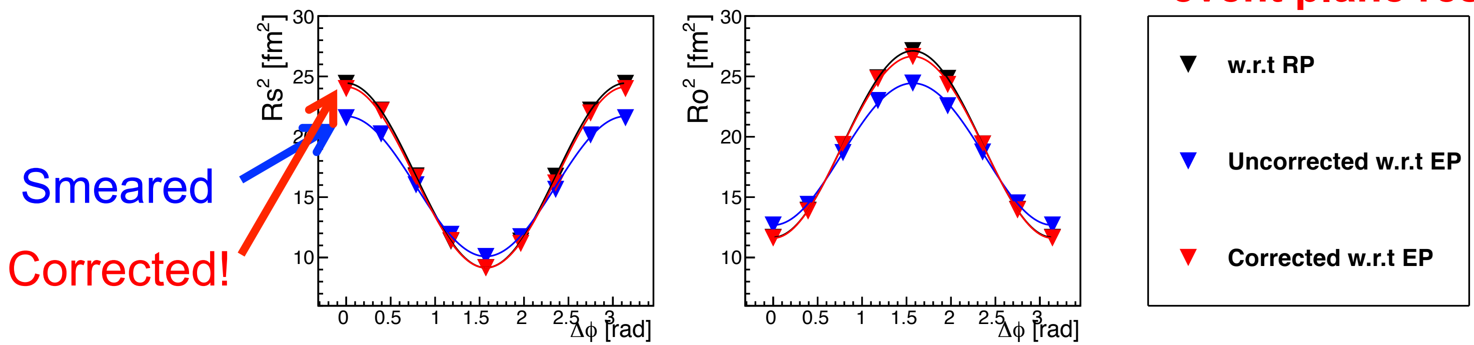
- **Correction for q-distribution**

$$A_{crr}(q,\Phi_j) = A_{uncrr}(q,\Phi_j) + 2\Sigma\zeta_{n,m}[A_c\cos(n\Phi_j) + A_s\sin(n\Phi_j)]$$

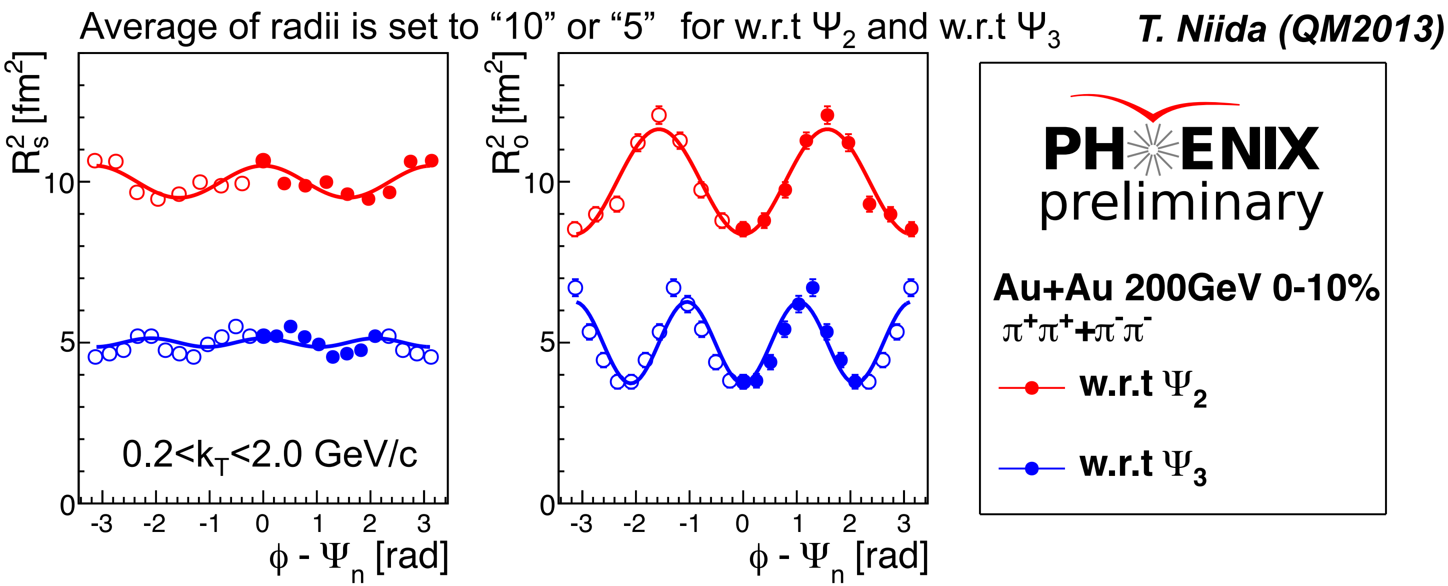
$$\zeta_{n,m} = \frac{n\Delta/2}{\sin(n\Delta/2)\langle\cos(n(\Psi_m - \Psi_{real}))\rangle}$$

event plane resolution

  - ✧PRC.66, 044903(2002)
    - ✓ model-independent correction
  - ✧Checked by MC-simulation



HBT radii w.r.t 3rd-order event plane



- **R_o clearly shows a finite oscillation w.r.t Ψ_3 in most central event, while R_s does not show such a oscillation.**
- **What makes this R_o oscillation**

□ $\Delta\tau$ depends on azimuthal angle?

Note: R_o is sensitive to $\Delta\tau$ & β_T

$$C_2 = 1 + \lambda \exp(-R_s^2 q_s^2 - R_o^2 q_o^2 - R_l^2 q_l^2 - 2R_{os}^2 q_o q_s)$$

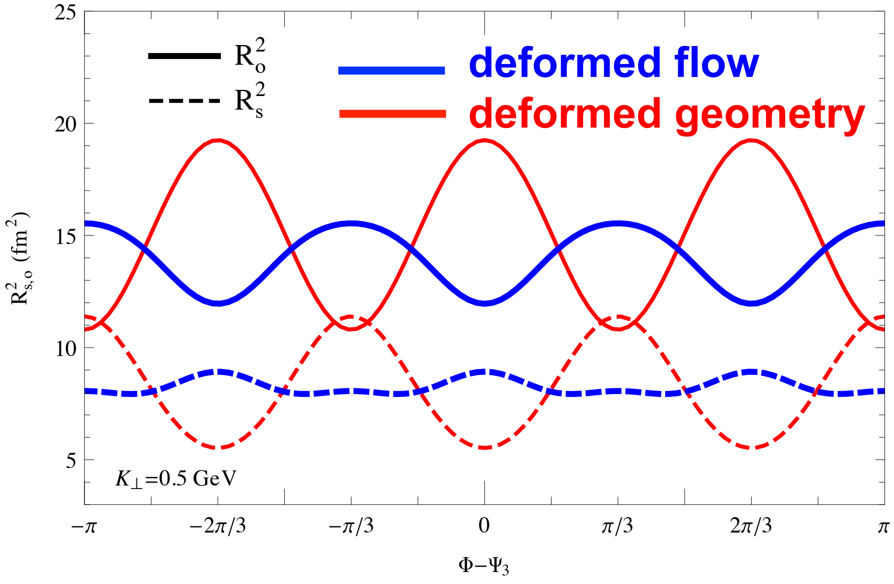
$$R_o^2 = R_o^{*2} + \beta_T^2 \Delta\tau^2$$

□ effect of flow anisotropy?

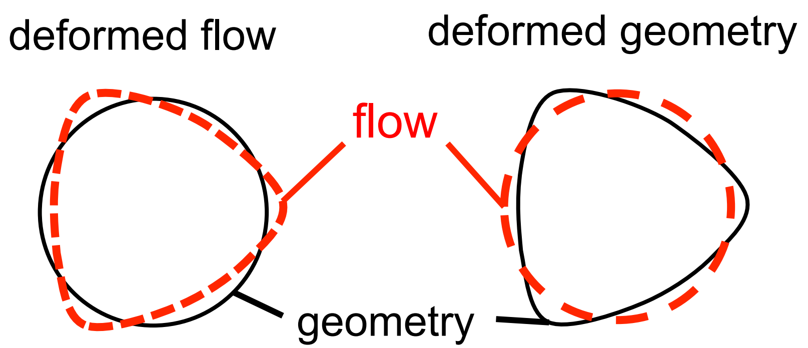
□ difference of "width" and "thickness"?

Possible explanation

PRC88, 044914 (2013)

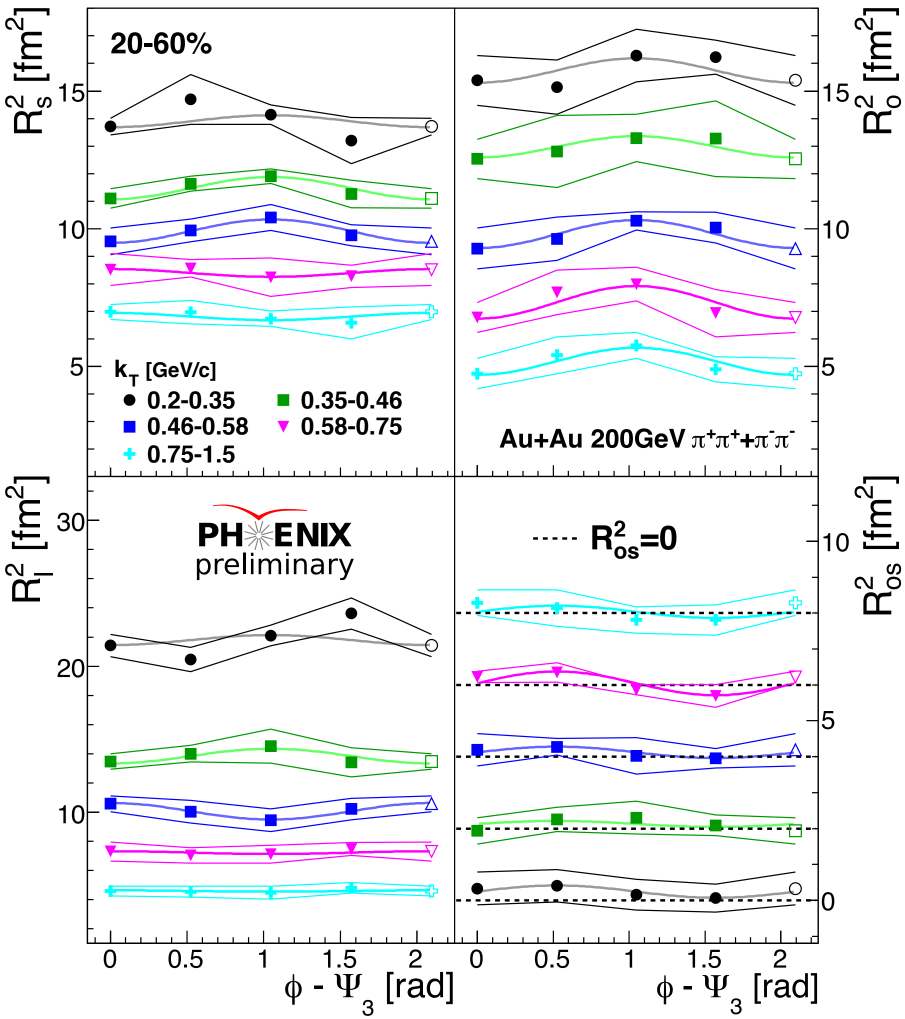


- **HBT radii w.r.t Ψ_3 with Gaussian model**
  - ✧C. Plumberg *et al.*, PRC88, 044914 (2013)
  - ✧***Next talk: C. Plumberg***
- **with/without triangularly deformed flow/geometry**



- **"Deformed flow" shows finite R_o oscillation and very small R_s oscillation**
- **Qualitatively agreement with the data seen in most-central collisions**

k_T dependence of HBT radii w.r.t Ψ_3

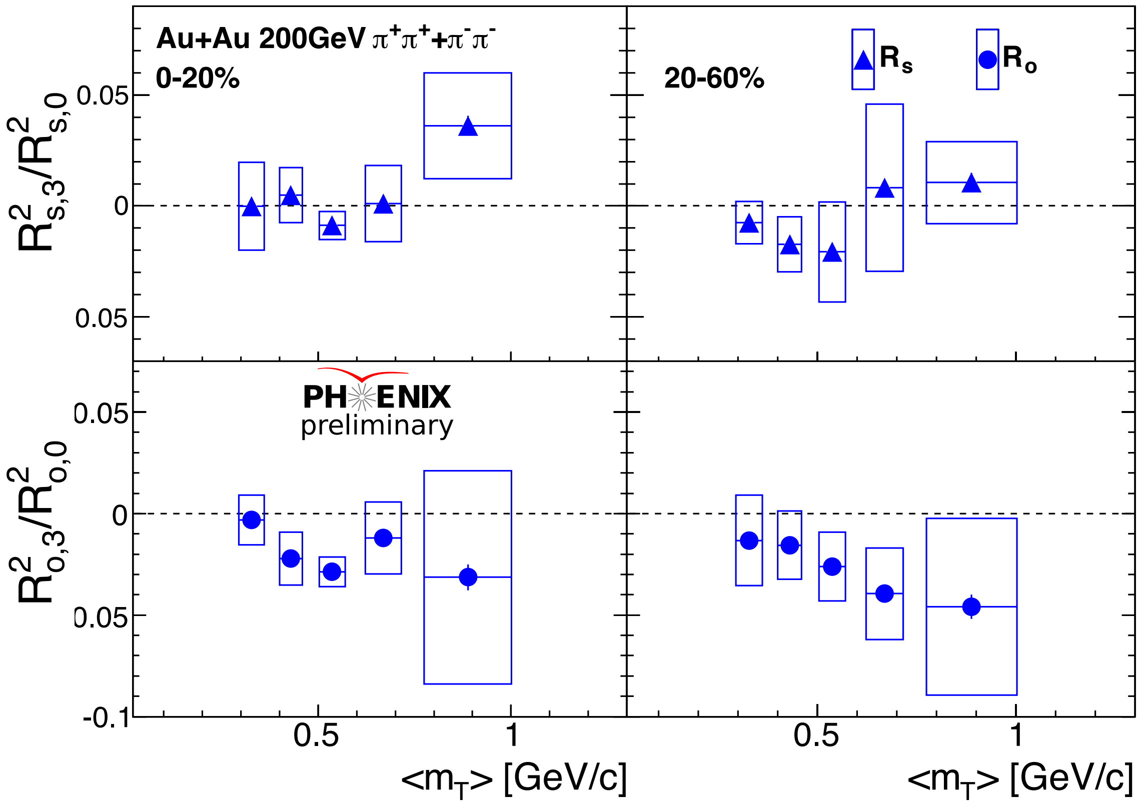


- **Charged pions in Au+Au 200 GeV**
  - ✧20-60% centrality
  - ✧5 k_T bins within 0.2-1.5 GeV/c
- **Fitted with the following Eq.:**

$$R_\mu^2 = R_{\mu,0}^2 + 2R_{\mu,3}^2 \cos[3(\phi - \Psi_3)]$$
$$R_{os}^2 = 2R_{os,3}^2 \sin[3(\phi - \Psi_3)]$$
$$\mu = s, o, l$$

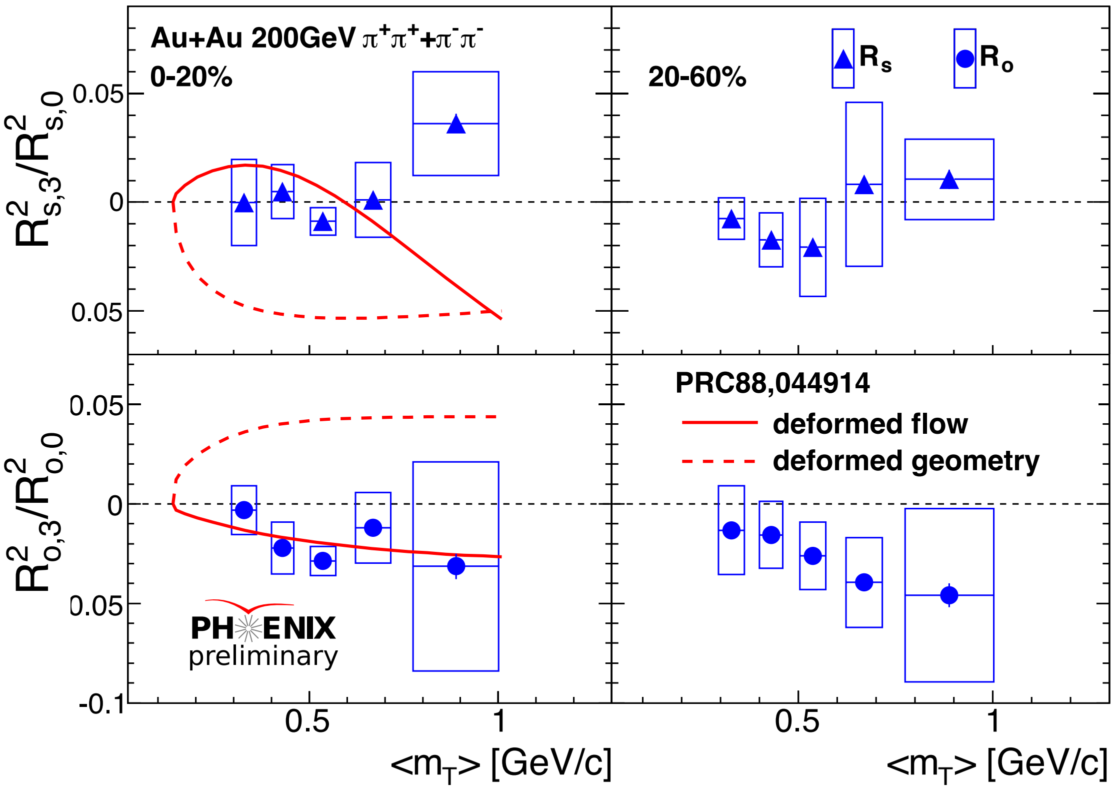
- **No clear k_T dependence for R_s**
- **Same sign of the R_o oscillation in all k_T bins**

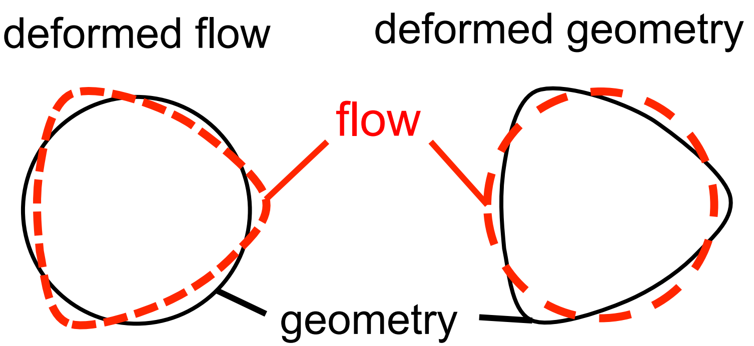
m_T dependence of 3rd-order oscillation amplitudes



- $R_{s,3}^2$ are around zero, and does not show any clear m_T dependence.
- $R_{o,3}^2$ has finite negative values in both centrality
  - ✧In 20-60%, it seems to decrease with $m_{T.}$

Comparison with the 3rd-order Gaussian model



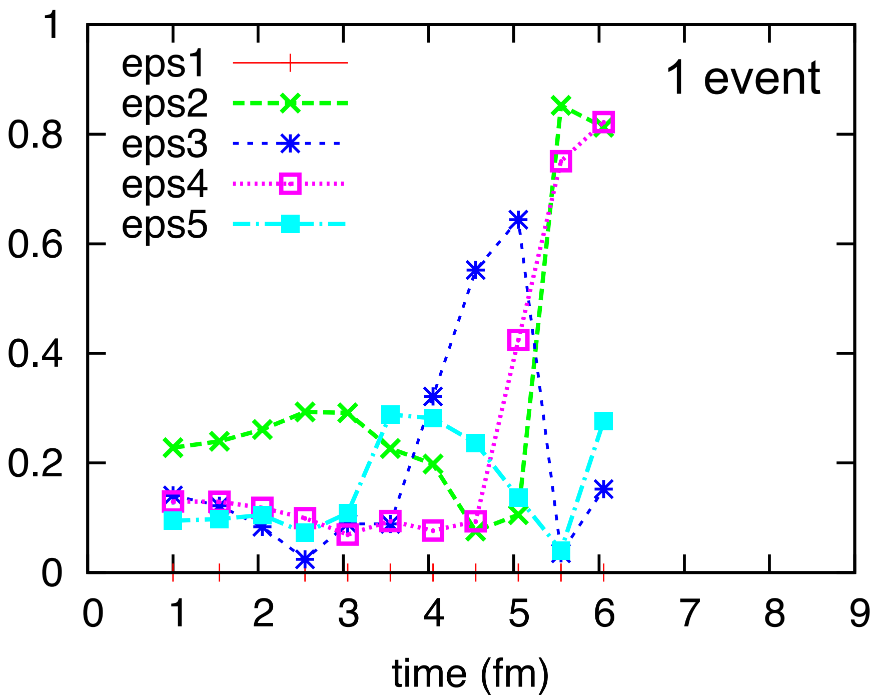


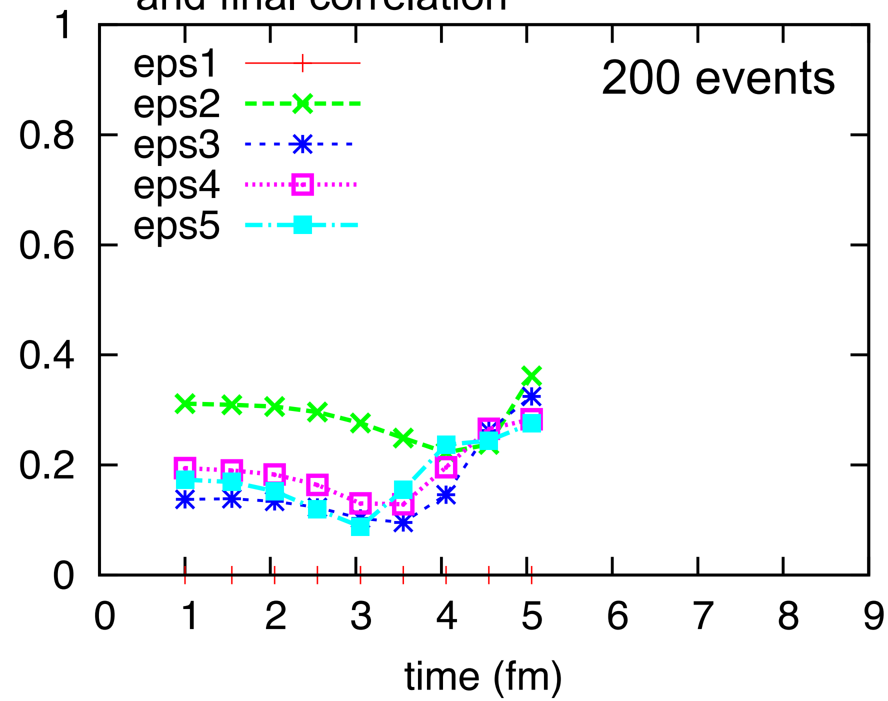
- **Trend of $R_{o,3}^2$ seems to be explained by "deformed flow" in both centralities.**
  - ✧Note that model curves are scaled by 0.3 for the comparison with the data
- **$R_{s,3}^2$ seems to show a slight opposite trend to "deformed flow".**
  - ✧Zero~negative value at low m_T, and goes up to positive value at higher m_T
- **Contribution from spatial anisotropy seems to be small.**

Time evolution of spatial anisotropy

- **MC-KLN + Hydrodynamic model**
  - ✧Parameters are not tuned.
- **15-20% centrality**

C. Nonaka, Aug. 2013,
@2nd workshop on initial fluctuations and final correlation





- **Inflection points represent that the n^th-order deformation of the source turns over.**
- **Interesting that ε_3 turns over earlier than ε_2.**

Summary

- **Azimuthal angle dependence of HBT radii with respect to 3rd-order event plane have been presented.**
  - ✧Finite oscillation of R_o^2 and very weak oscillation of R_s^2 seen in most central event may be explained by the triangular flow anisotropy rather than spatial anisotropy.
  - ✧$R_{o,3}^2$ shows a monotonic decrease with m_T.
    - ✓ Similar trend to “deformed flow” model
  - ✧$R_{s,3}^2$ does not show any clear m_T dependence, but seems to have opposite trend to “deformed flow” model.
- **The result indicate that initial triangularity may be significantly diluted.**

Thank you for your attention!