Azimuthal angle dependence of HBT radii in Au+Au collisions at RHIC-PHENIX

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The 12th Asia Pacific Physics Conference

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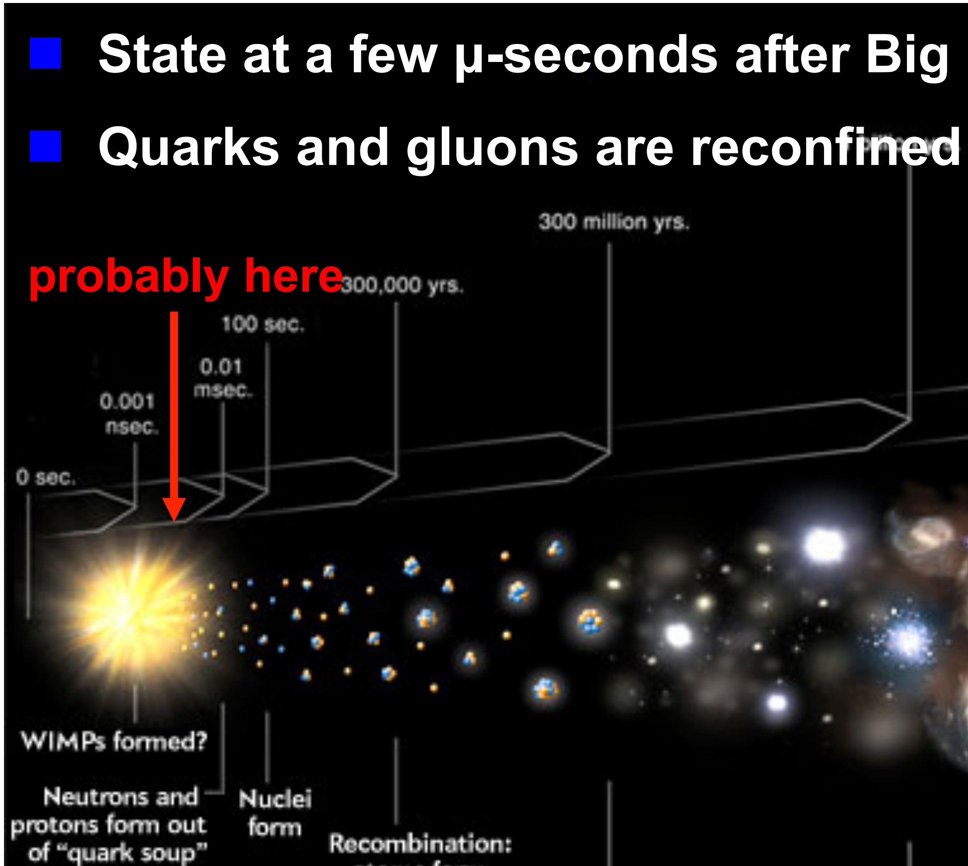
PHENIX

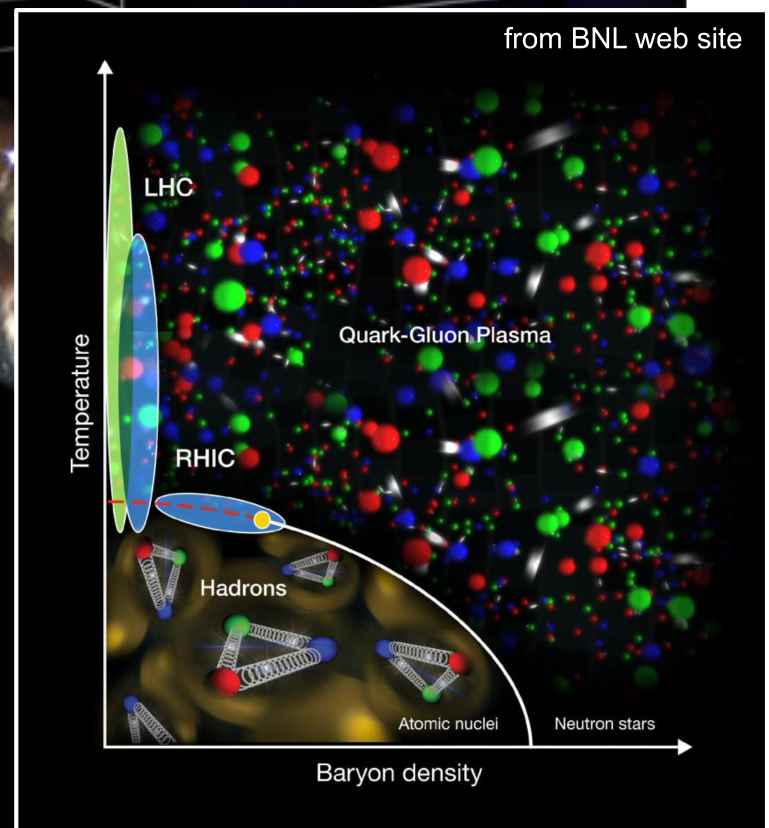
Quark Gluon Plasma (QGP)

http://www.scientificamerican.com/

- State at a few μ-seconds after Big Bang
- Quarks and gluons are reconfined from hadrons

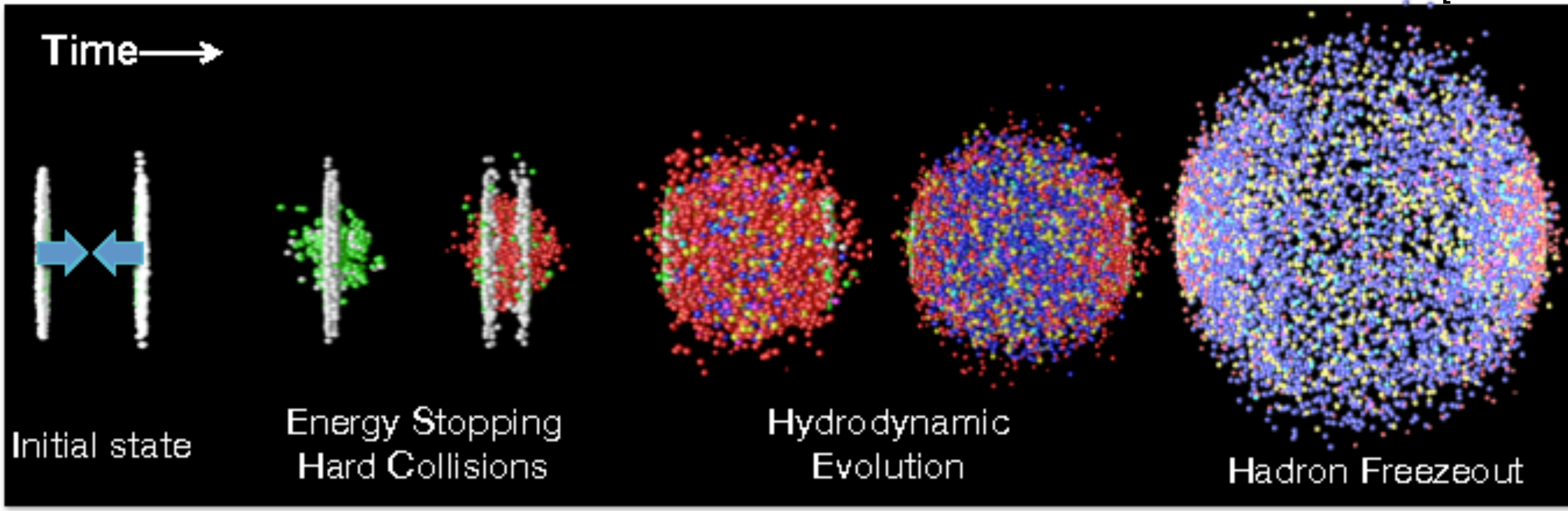


- QGP will be created at extreme temperature and energy density
- Relativistic heavy ion collisions is a unique way to study the QGP



Space-Time evolution in HI collisions

arXiv:1201.4264 [nucl-ex]



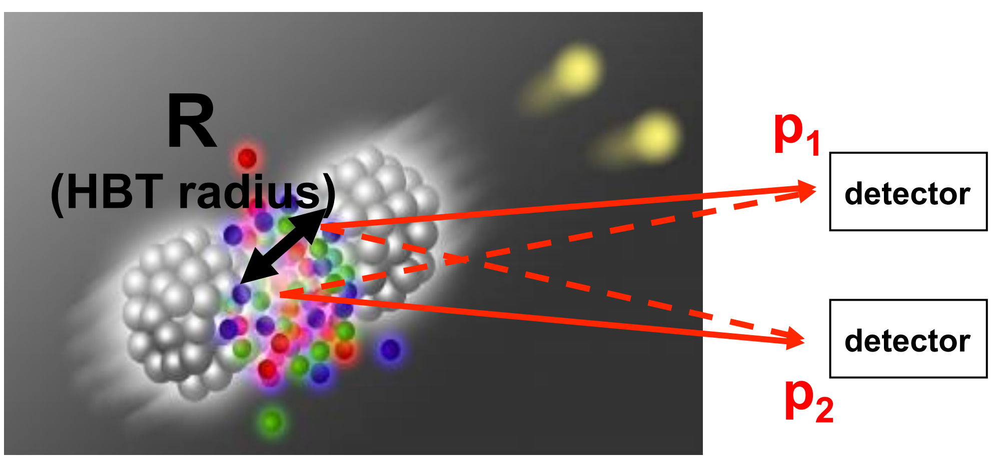
- **Space-time extent at freeze-out reflects the properties of system evolution, such as the phase transition, hydrodynamic expansion and hadron rescattering etc.**
- **HBT interferometry is a powerful tool to study the space-time evolution in Heavy Ion collisions.**

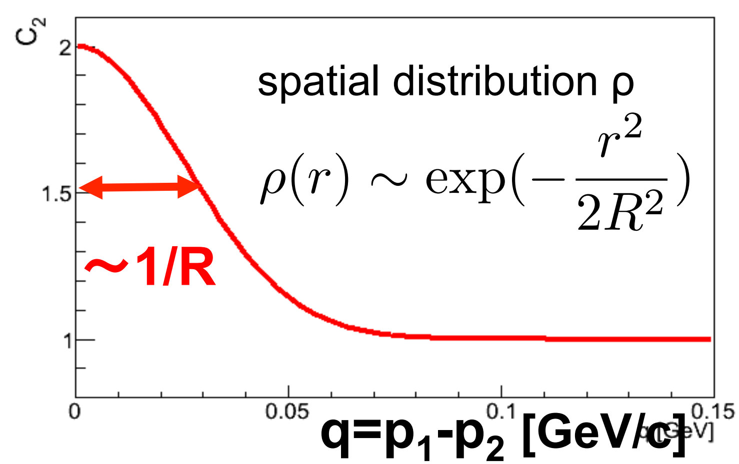
HBT Interferometry

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

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

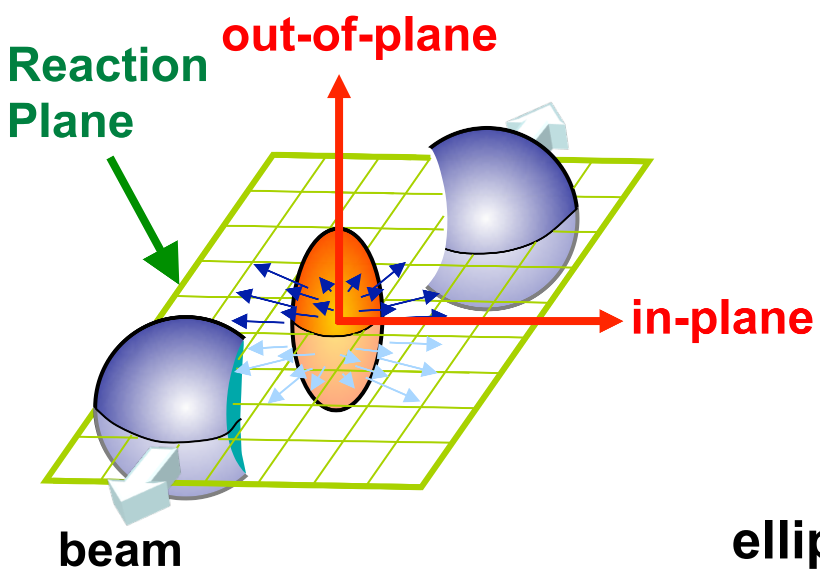
$$C_2 = \frac{P(p_1,p_2)}{P(p_1)P(p_2)} \approx 1 + |\tilde{\rho}(q)|^2 = 1 + \exp(-R^2q^2)$$

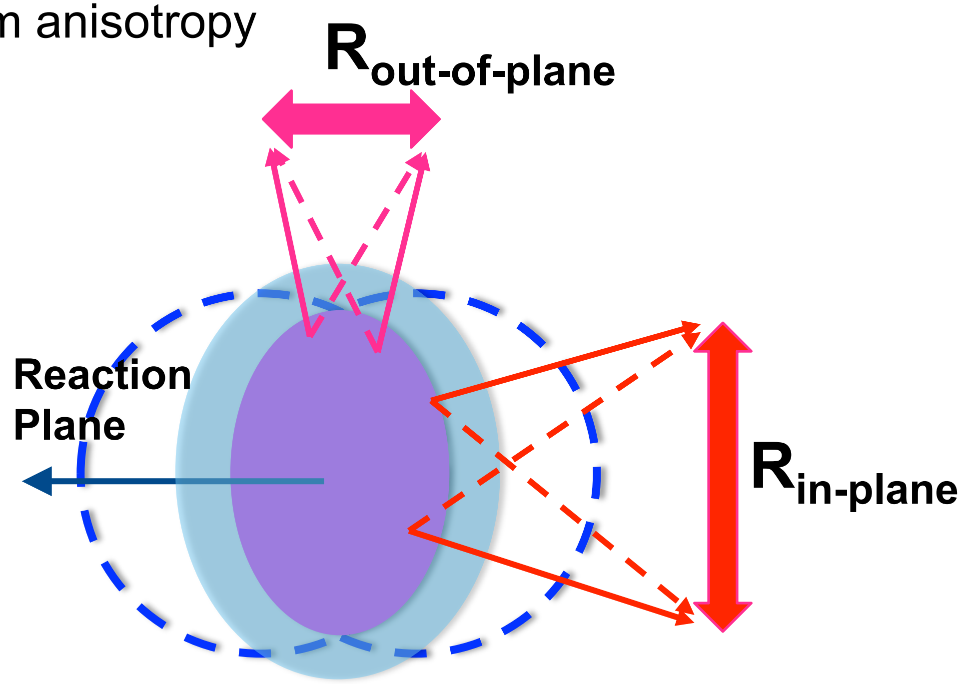




Azimuthal angle dependence

- **HBT w.r.t Reaction Plane give us source shape at freeze-out.**
  - ✧ R.P defined by beam axis and vector between centers of colliding nuclei
- **Final eccentricity is determined by initial eccentricity, velocity profile and expansion time etc.**
  - ✧ Initial anisotropy causes momentum anisotropy



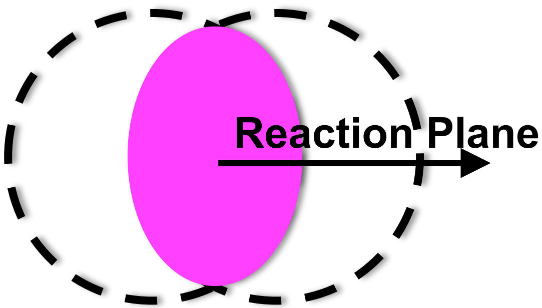


elliptical shape : $R_{in\text{-}plane} > R_{out\text{-}of\text{-}plane}$
spherical shape : $R_{in\text{-}plane} = R_{out\text{-}of\text{-}plane}$

Higher Harmonic Flow and Event Plane

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

<u>smooth picture</u>

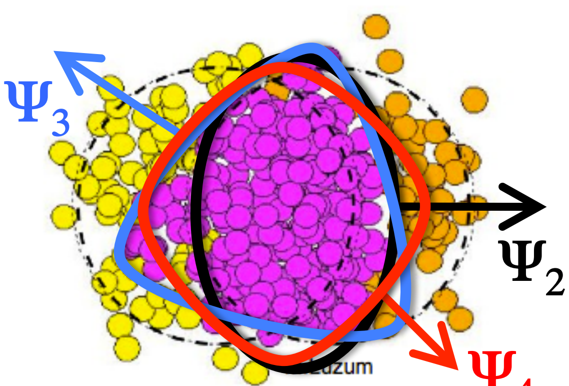


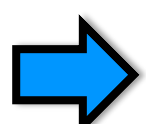
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2) + 2v_3 \cos 3(\phi - \Psi_3) + 2v_4 \cos 4(\phi - \Psi_4)$$

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

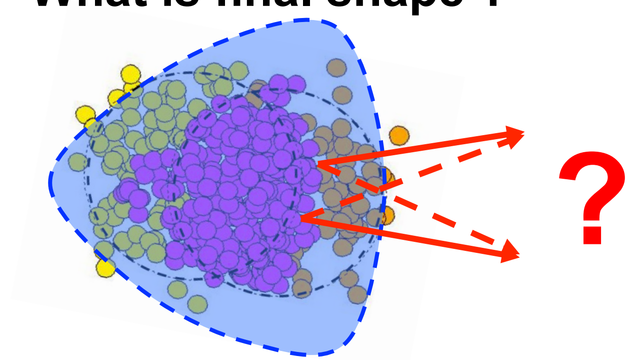
v_n : strength of higher harmonic flow
Ψ_n : higher harmonic **Event plane**
φ : azimuthal angle of emitted particles

<u>fluctuating picture</u>

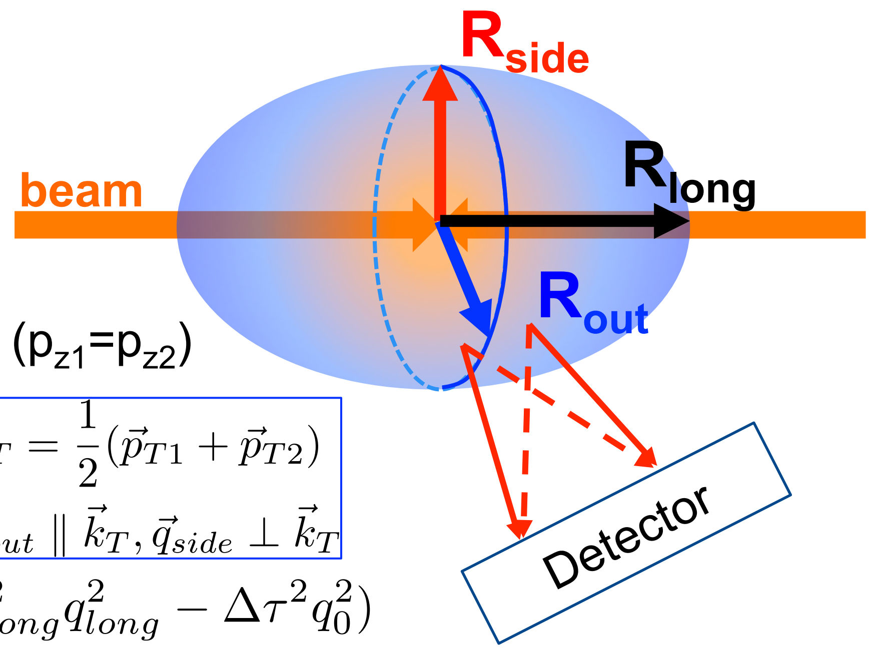




What is final shape ?



3D HBT radii



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

$$\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2})$$

$$\vec{q}_{out} \parallel \vec{k}_T,\ \vec{q}_{side} \perp \vec{k}_T$$

$$C_2 = 1 + \lambda G$$

$$G = \exp(-\mathbf{R}^2\mathbf{q}^2)$$

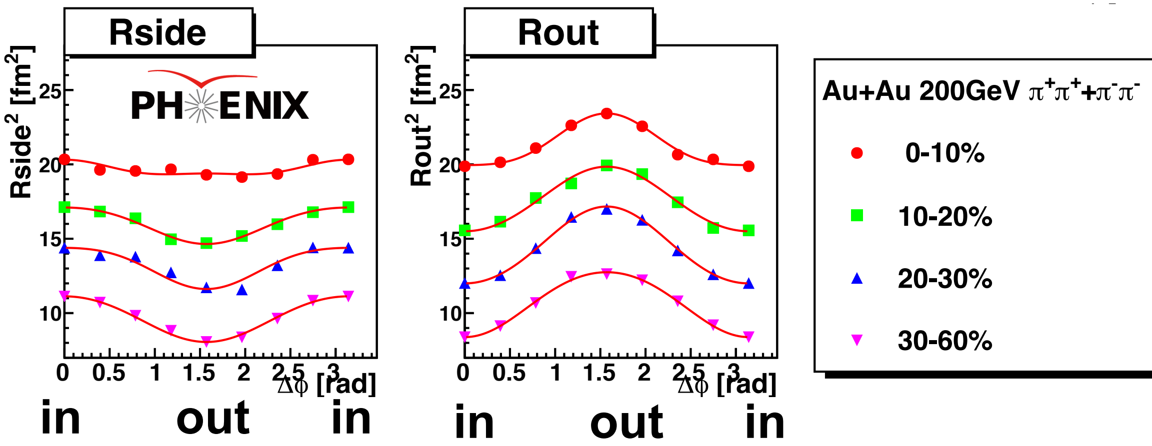
$$= \exp(-R^2_{side}q^2_{side} - R^{*2}_{out}q^2_{out} - R^2_{long}q^2_{long} - \Delta\tau^2 q_0^2)$$

$$\overset{\text{LCMS}}{\approx} \exp(-R^2_{side}q^2_{side} - \underbrace{(R^{*2}_{out} + \beta_T \Delta\tau^2)}_{=R_{out}^2} q^2_{out} - R^2_{long}q^2_{long})$$

$$G = \exp(-R^2_{side}q^2_{side} - R^2_{out}q^2_{out} - R^2_{long}q^2_{long} - 2R^2_{os}q_{side}q_{out})$$

λ	: chaoticity
R_{side}	: **transverse HBT radius**
R_{out}	: **transverse HBT radius + Δτ (emission duration)**
R_{long}	: longitudinal HBT radius
R_{os}	: cross term for φ-dependent analysis

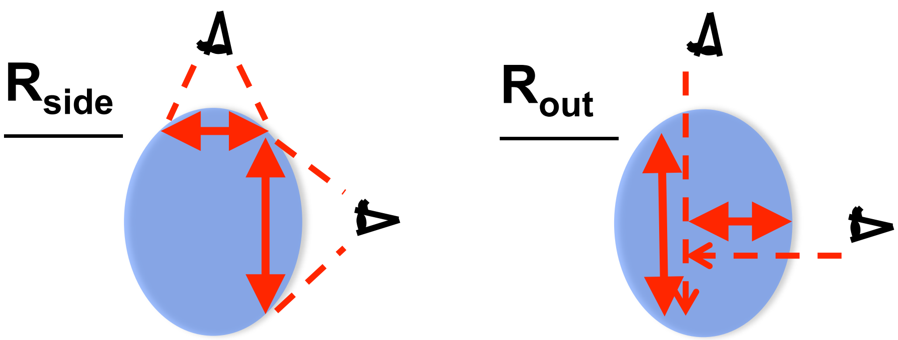
HBT radii w.r.t 2^{nd}-order event plane

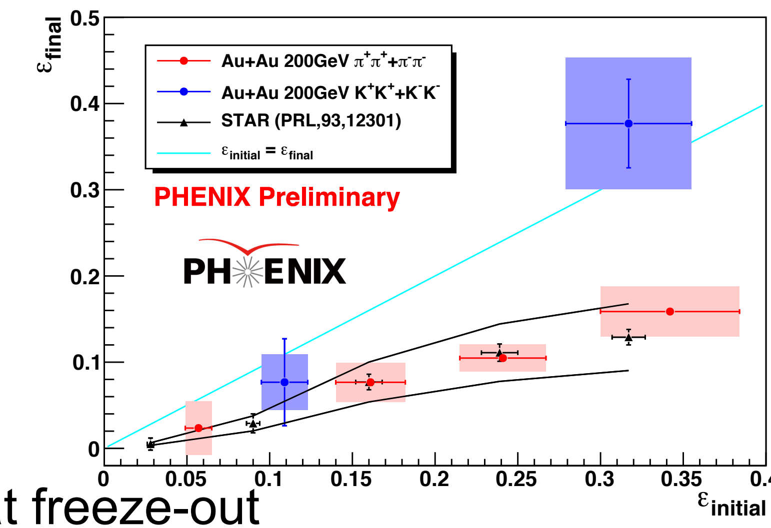


PRC70, 044907 (2004)

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

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

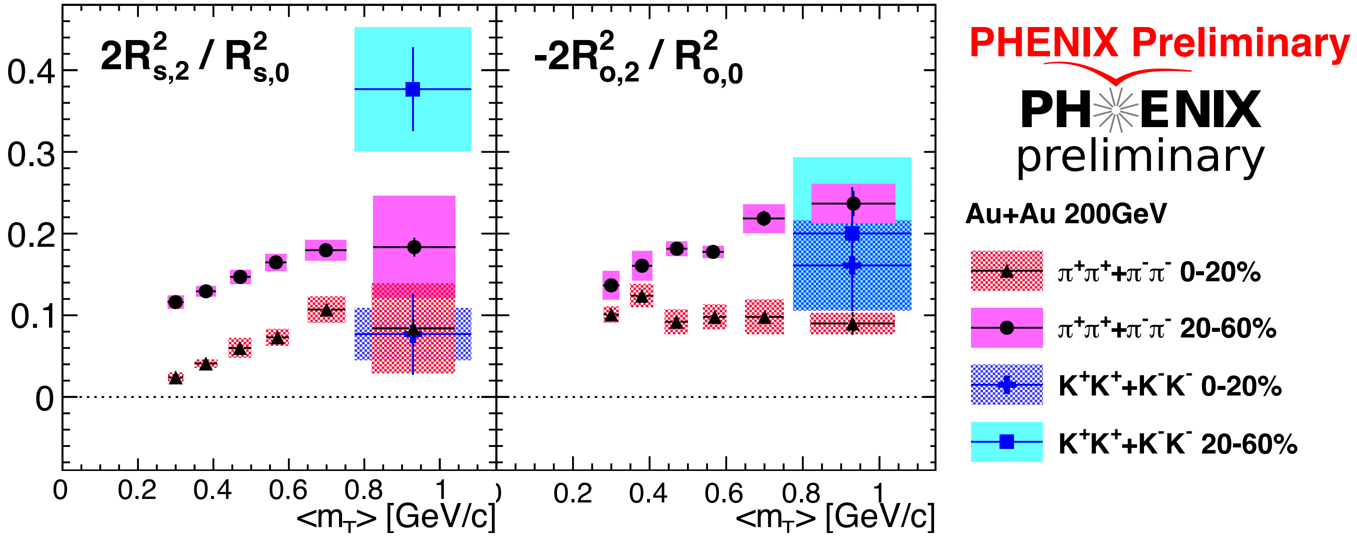


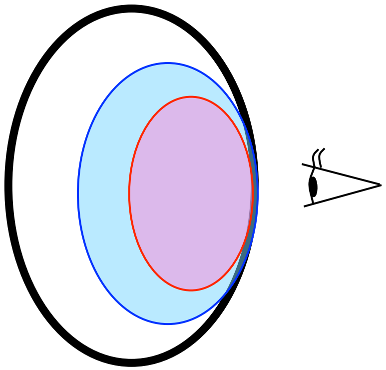


- $\varepsilon_{final} \approx \varepsilon_{initial}/2$ **for pion**
  - ✧expansion to in-plane, but still elliptical at freeze-out
  - ✧consistent with STAR experiment
- $\varepsilon_{final} \approx \varepsilon_{initial}$ **for kaon**
  - ✧emission region we're looking at is different?

m_T dependence

- **HBT does not measure the whole size but the emission region for expanding source**
  - ✧HBT radii depend on pair transverse momentum mass m_T
  - ✧Kaon has higher m_T than pion
- **$R_{s,2}^2/R_{s,0}^2$ shows difference even at the same m_T in 20-60%**
  - ✧m_T scaling works well for average radius of π/K (PRL103.142301(2009))
  - ✧Different freeze-out dynamics for both species ?

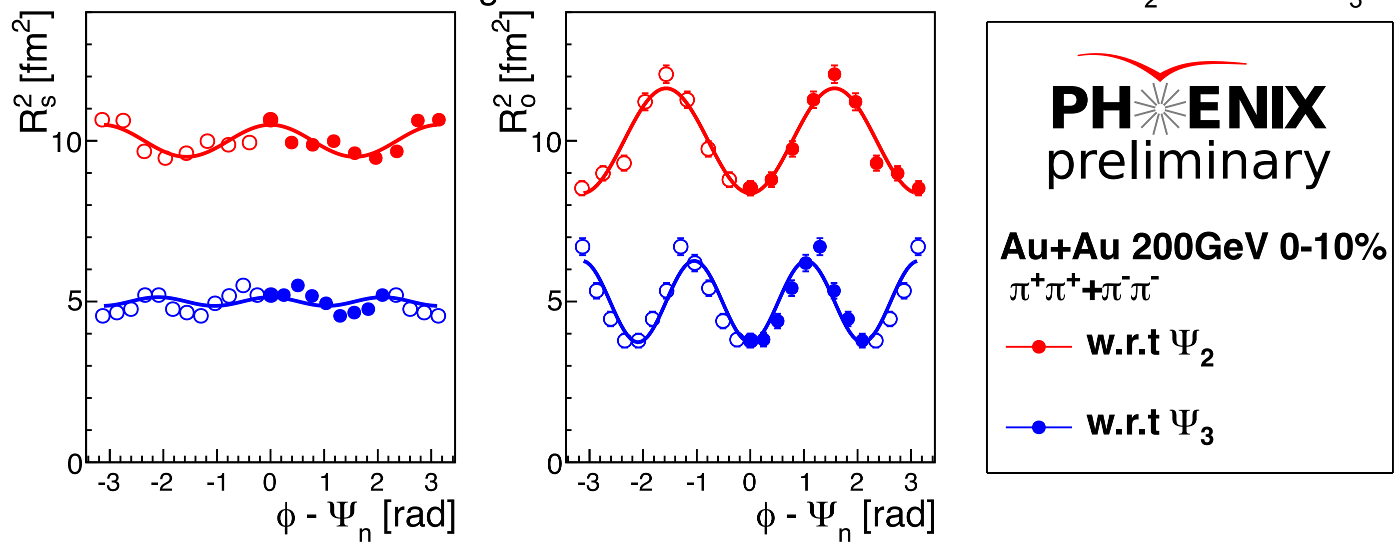




$$m_T = \sqrt{k_T^2 + m^2}$$

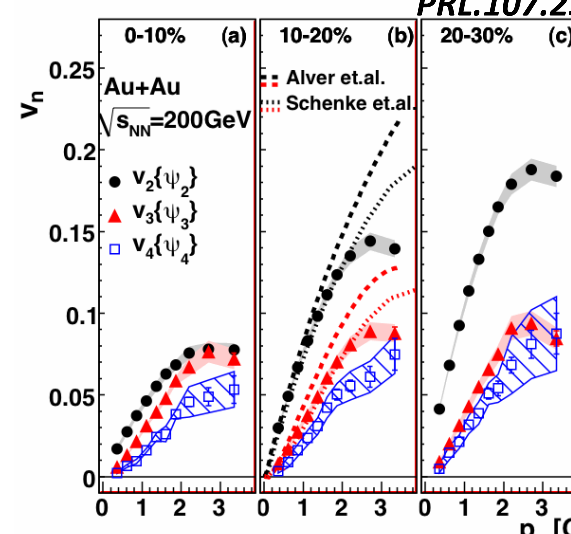
HBT radii w.r.t 3rd-order event plane

Average of radii is set to "10" or "5" for w.r.t Ψ_2 and w.r.t Ψ_3



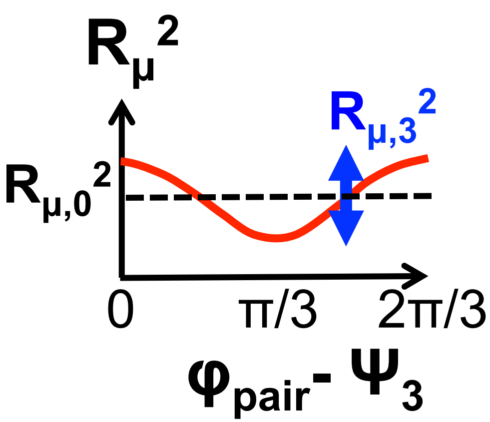
- R_{out} clearly shows a finite oscillation w.r.t Ψ_3 in most central event
  - ✧Strength w.r.t Ψ_3 is comparable to w.r.t Ψ_2
- What make this R_o oscillation?
  - ✧Triangular spatial shape?
  - ✧Triangular flow?
    - ✓ v_3 is comparable to v_2 in most central
  - ✧Emission duration?

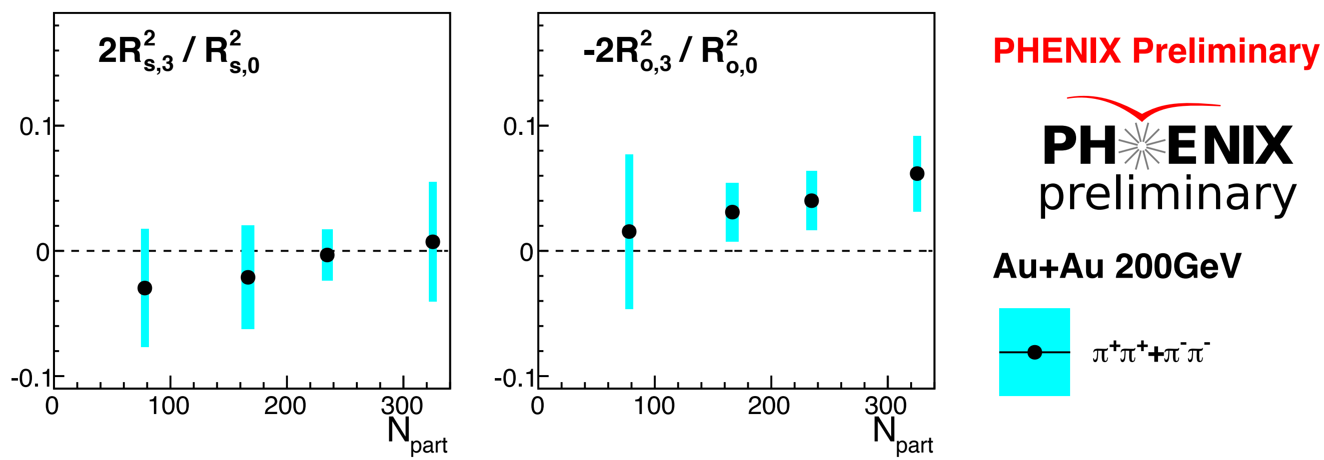
PRL.107.252301



Centrality dependence of relative amplitudes

- Oscillation of R_s shows is almost zero within systematic error
  - ✧ Slightly negative value in peripheral ?
- R_o has finite oscillation except peripheral event

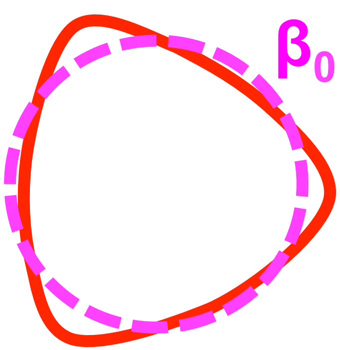




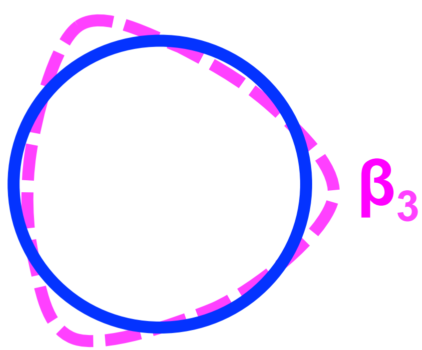
Possible explanation of R_o oscillation

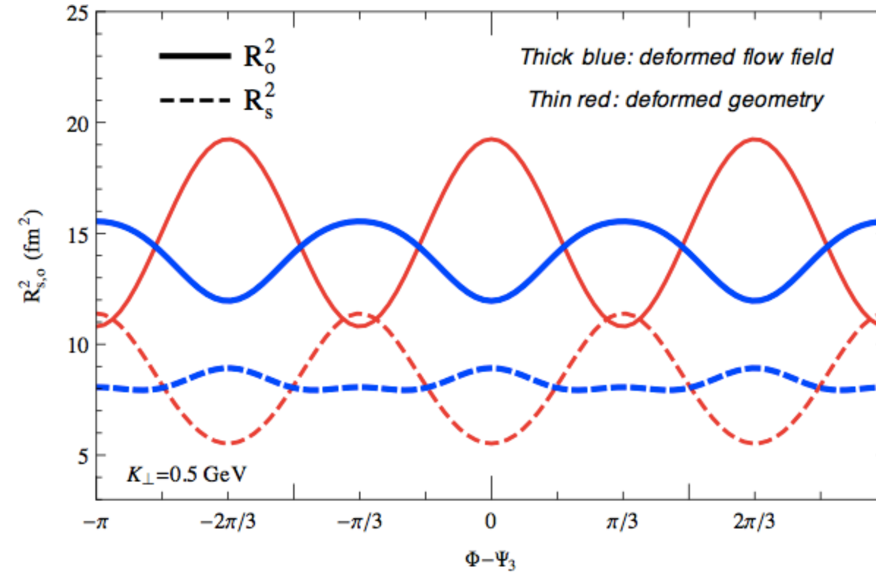
- **HBT w.r.t Ψ_3 with toy model have been reported in arXiv:1306.1485[nucl-ex] (2013)**
  - ✧assuming Gaussian source with triangular geometric deformation and triangular flow

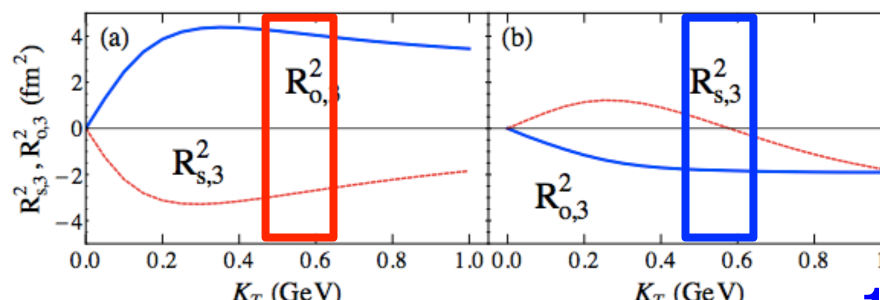
triangular source
without flow anisotropy



spherical source
with flow anisotropy







- ✦ Close to “flow dominated” case ?
- ✦ Need to check the k_T dependence to constraint ε_3/β_3

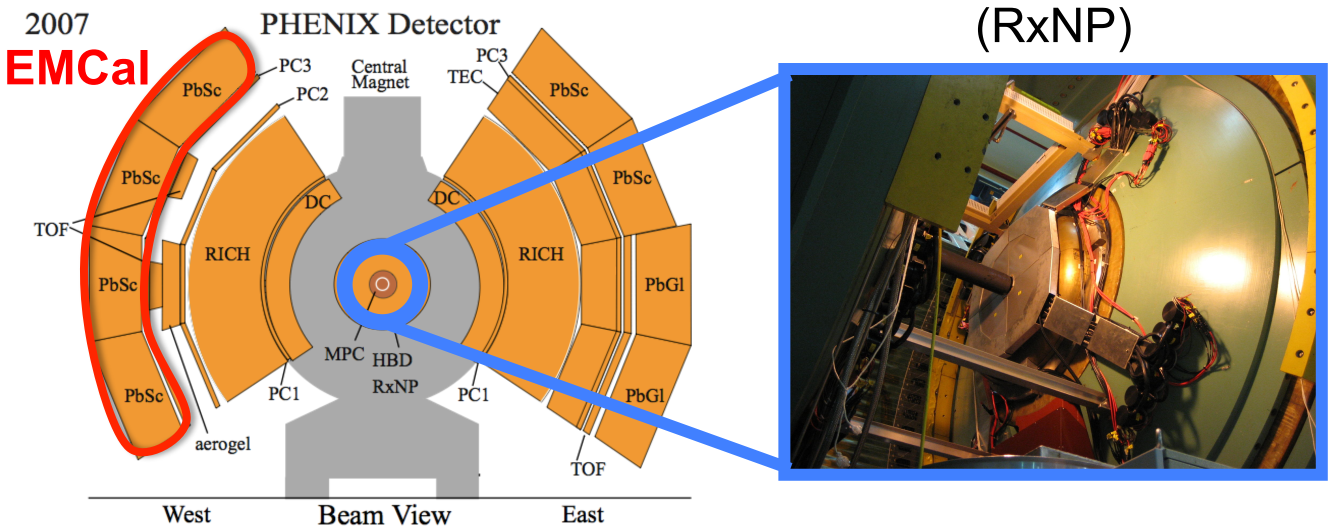
Summary

- **Azimuthal angle dependence of HBT radii with respect to 2^{nd}- and 3^{rd}-order event plane have been presented.**
  - ✧Final eccentricity of kaons shows higher value that of pion even at the same m_T
  - ✧Oscillation of R_o w.r.t Ψ_3 have been observed in most central event, while R_s doesn't show any signal beyond systematic error
    - ✓ R_o oscillation may be explained by triangular flow
- **Outlook**
  - ✧k_T dependence of oscillation amplitudes w.r.t Ψ_3 will be measured, which will provides us information on the relative magnitude of geometrical and flow anisotropy

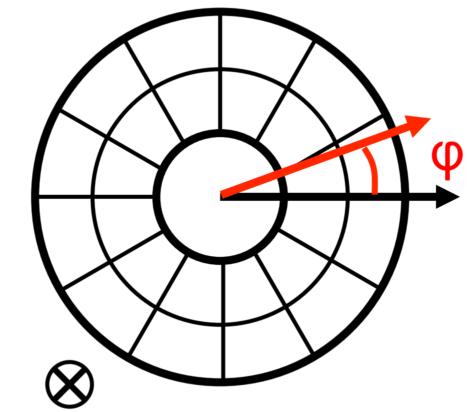
Back up

PHENIX Detectors

Reaction Plane Detector (RxNP)



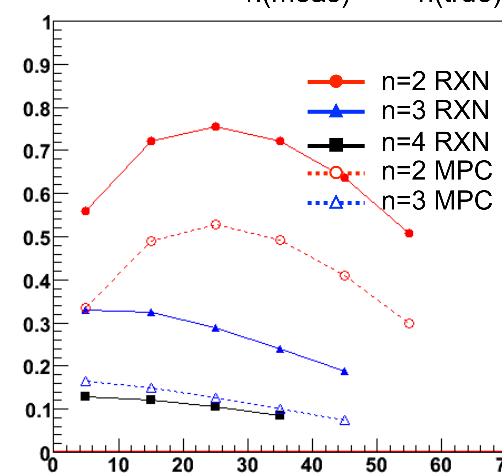
24 scintillator segments



beam axis

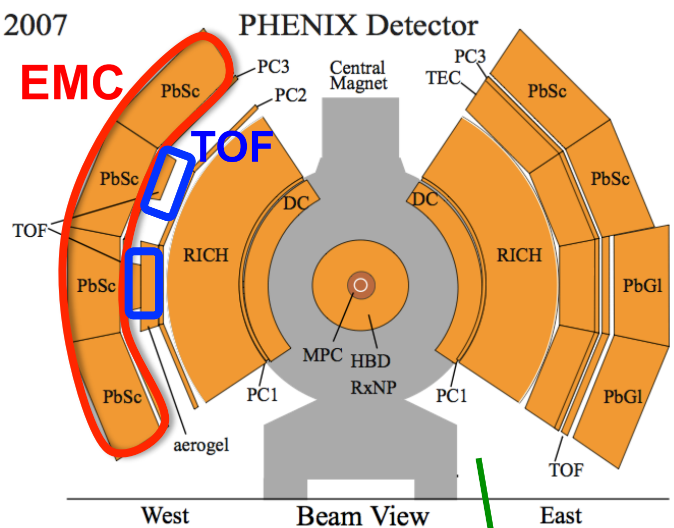
$$\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{\Sigma w_i \cos(n\phi_i)}{\Sigma w_i \sin(n\phi_i)}\right)$$

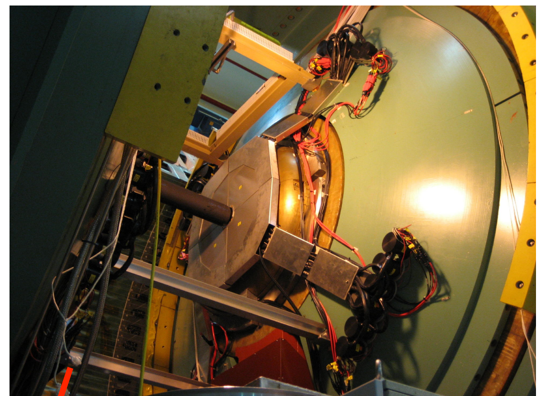
$Res(\Psi_n)$
$= \langle \cos n(\Psi_{n(meas)} - \Psi_{n(true)}) \rangle$

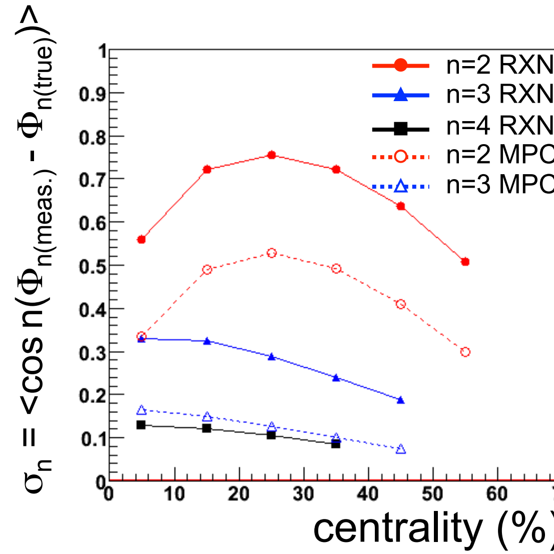


- ☆ Particle Identification by EMCal
  - ✦ π/K separation up to ~1GeV
- ☆ Centrality by Beam-Beam Counter
  - ✦ measure charge sum from participants
- ☆ Event plane Ψ_n determined by RxNP
  - ✦ $Res(\Psi_2)$ ~0.75, $Res(\Psi_3)$ ~0.32

PHENIX Detectors

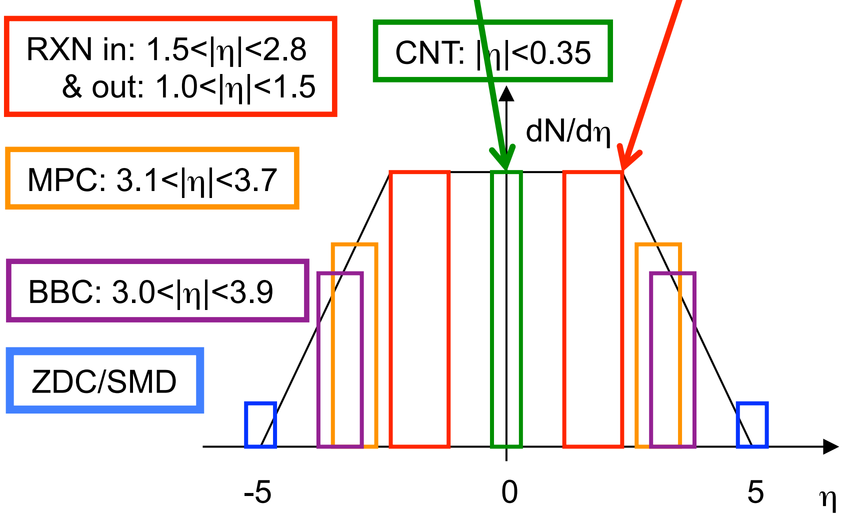






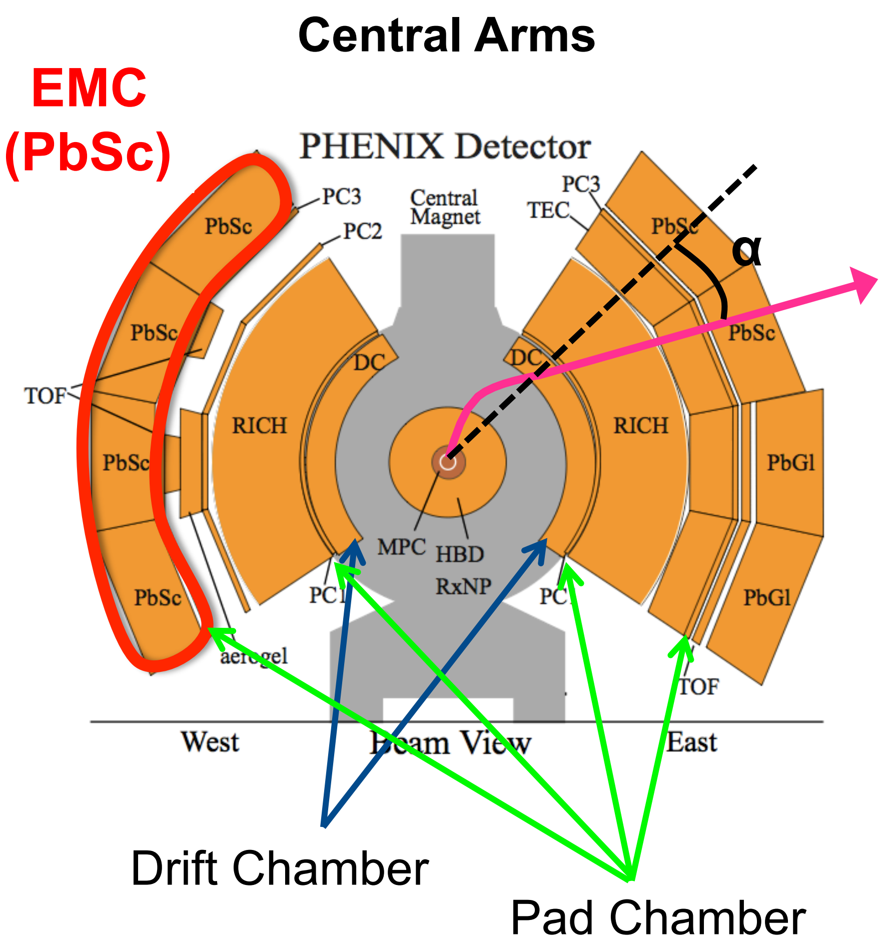
$$C_2 = \frac{R(q)}{M(q)}$$

R(q),M(q):
relative momentum dist.
for real and mixed pairs



- ☆ PID by EMC&TOF
  - ⇨ charged π/K are selected
- ☆ Ψ_n by forward detector RXN

Track Reconstruction



- **Drift Chamber**
  - ✧Momentum determination

$$p_T \simeq \frac{K}{\alpha}$$

K: field integral
α: incident angle

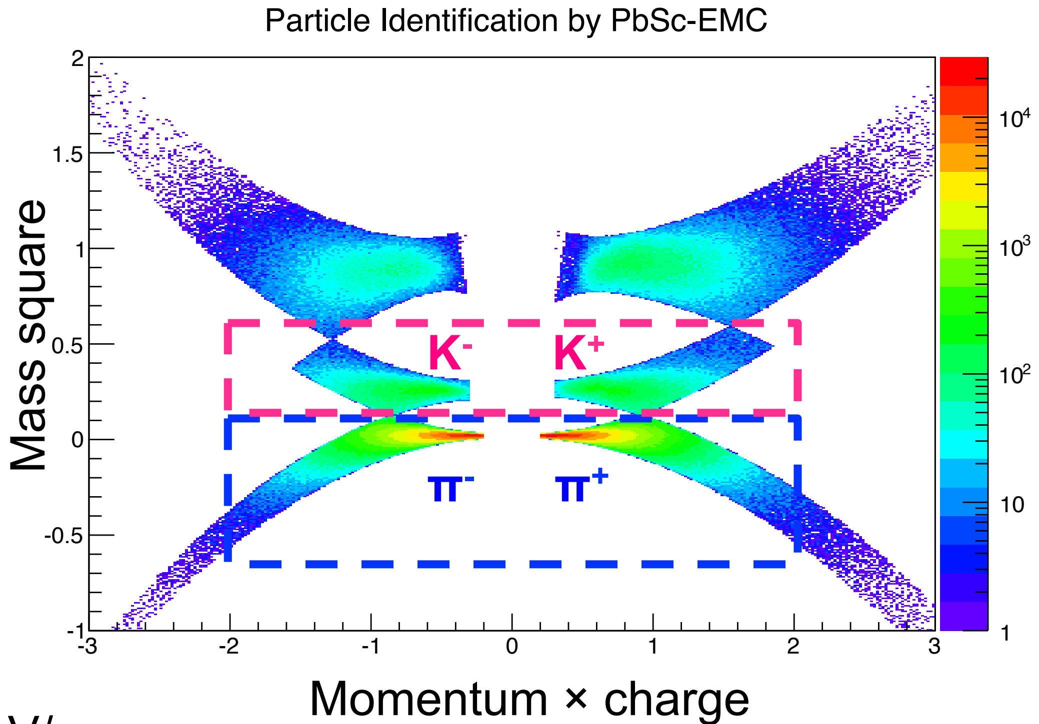
- **Pad Chamber (PC1)**
  - ✧Associate DC tracks with hit positions on PC1
    - ✓ p_z is determined
- **Outer detectors (PC3,TOF,EMCal)**
  - ✧Extend the tracks to outer detectors

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/K within 2σ**
  - ✧π/K separation up to ~1 GeV/c
  - ✧K/p separation up to ~1.6 GeV/c

Correlation Function

- **Experimental Correlation Function C_2 is defined as:**
  - ✧ R(q): **R**eal pairs at the same event.
  - ✧ M(q): **M**ixed pairs selected from different events.

    Event mixing was performed using events with similar z-vertex, centrality, E.P.

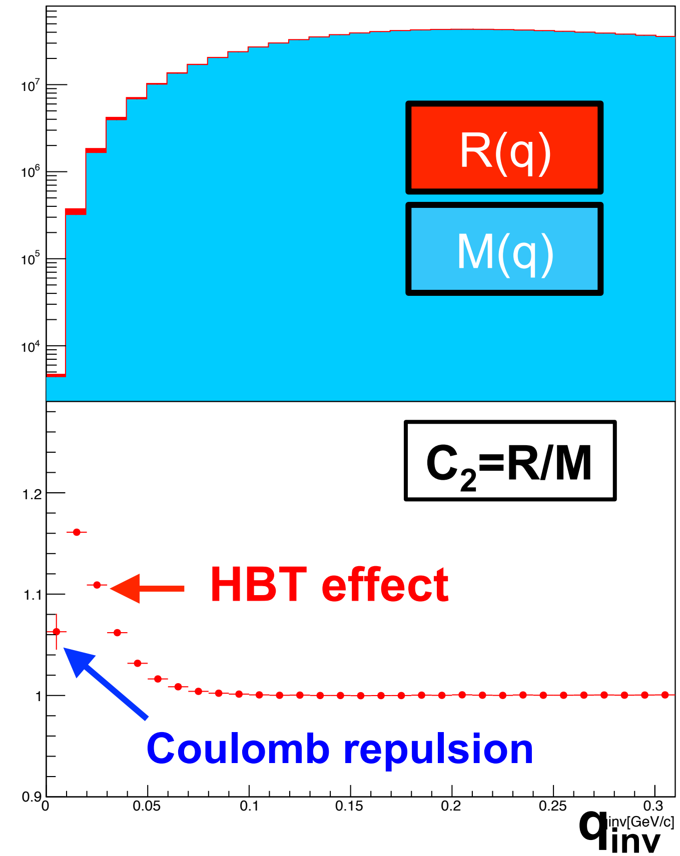
$$C_2 = \frac{R(\mathbf{q})}{M(\mathbf{q})}$$

$$\mathbf{q} = \mathbf{p_1} - \mathbf{p_2}$$

- ✧ Real pairs include HBT effects, Coulomb interaction and detector inefficient effect.

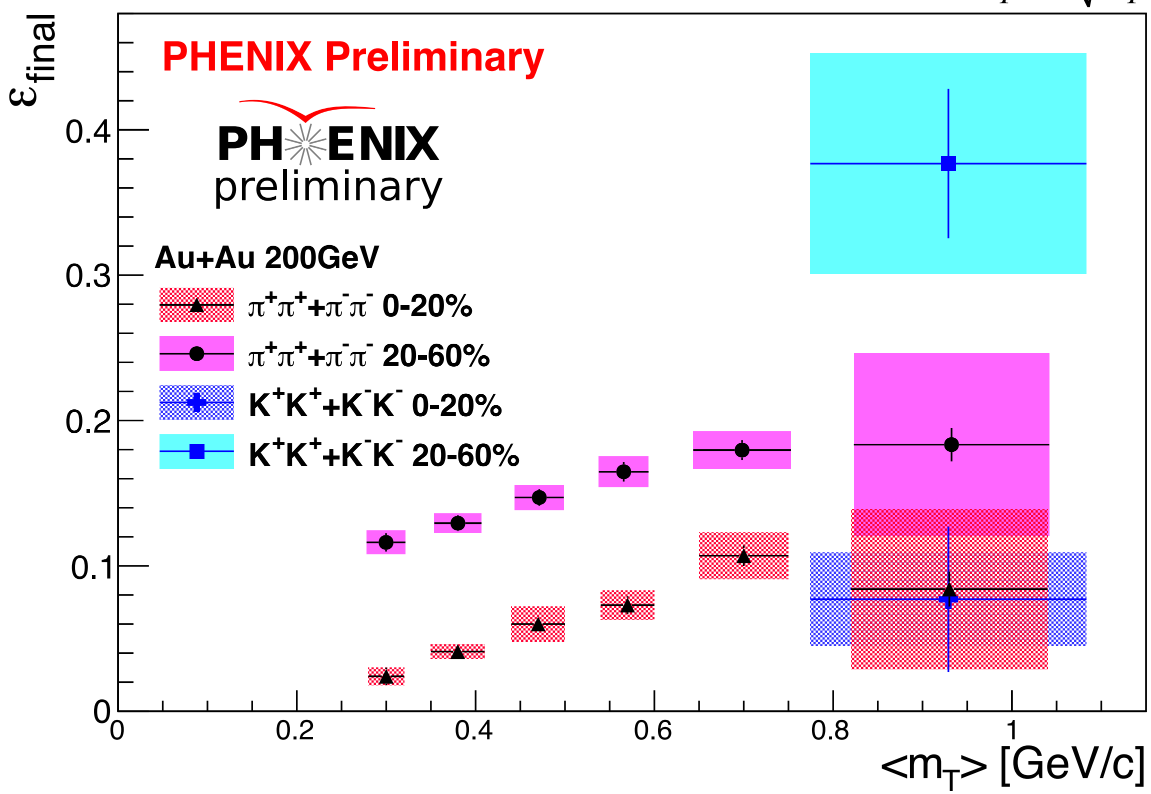
  Mixed pairs doesn't include HBT and Coulomb effects.

relative momentum dist.



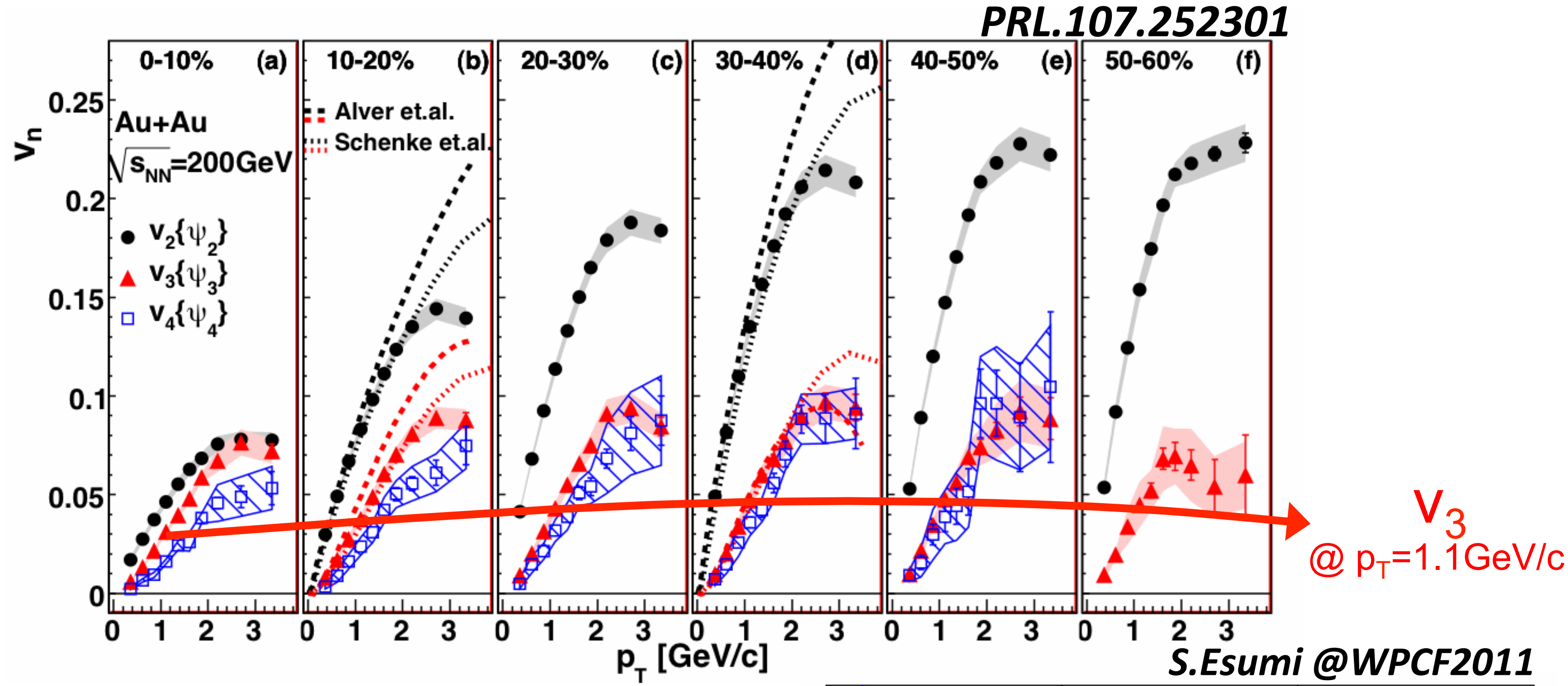
m_T dependence of ε_{final}

$$m_T = \sqrt{k_T^2 + m^2}$$



- ε_{final} of pions increases with m_T in most/mid-central collisions
- There is still difference between π/K for mid-central collisions even in same m_T
  - ✧Indicates sooner freeze-out time of K than π ?

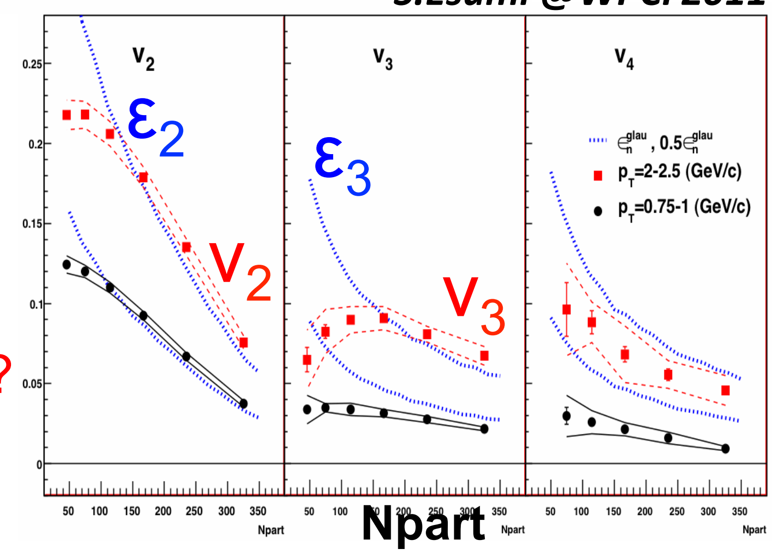
Centrality dependence of v_3 and ε_3



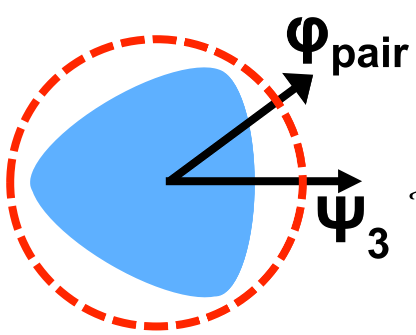
S.Esumi @WPCF2011

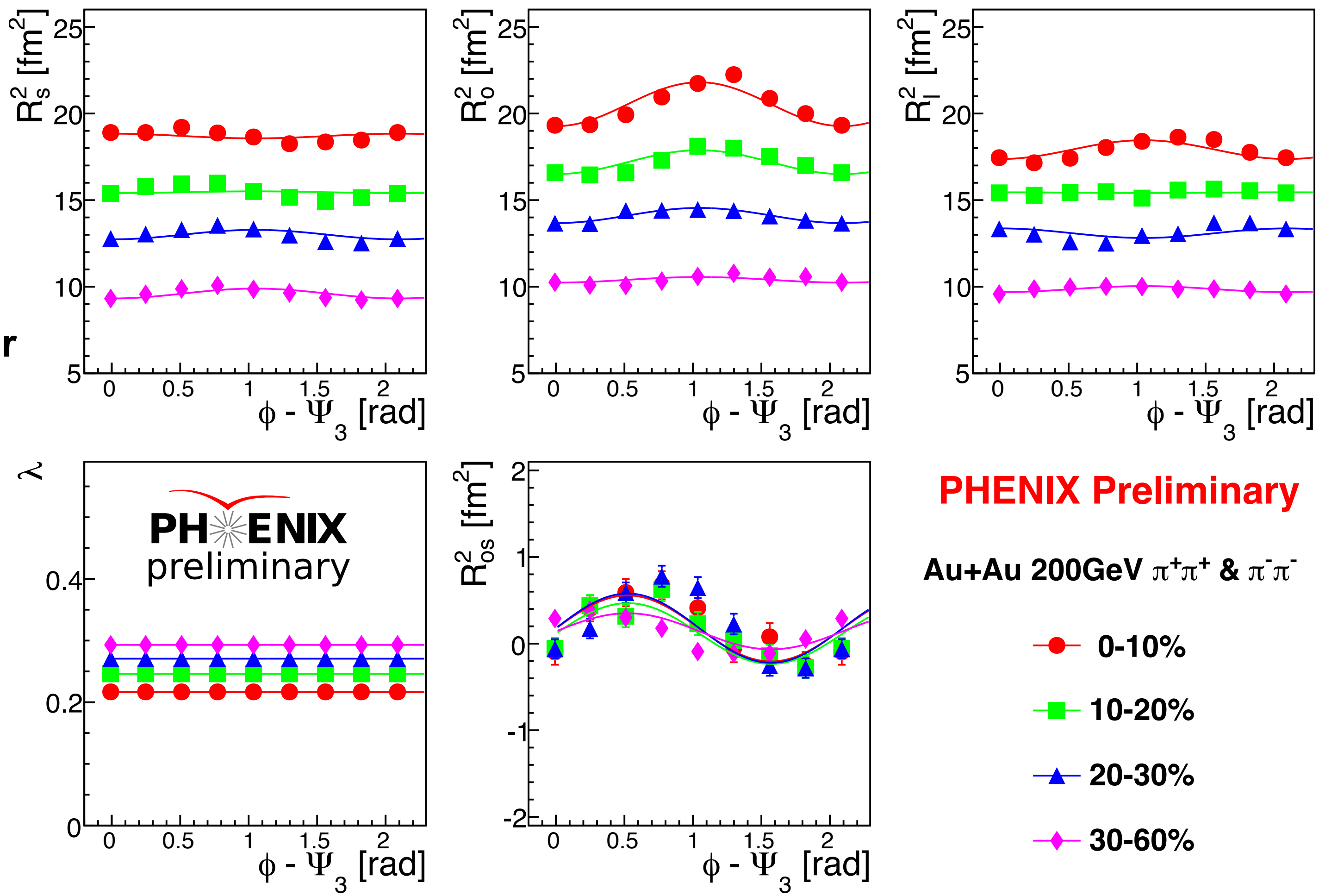
- Weak centrality dependence of v_3
- Initial ε_3 has centrality dependence

Final ε_3 has any centrality dependence?



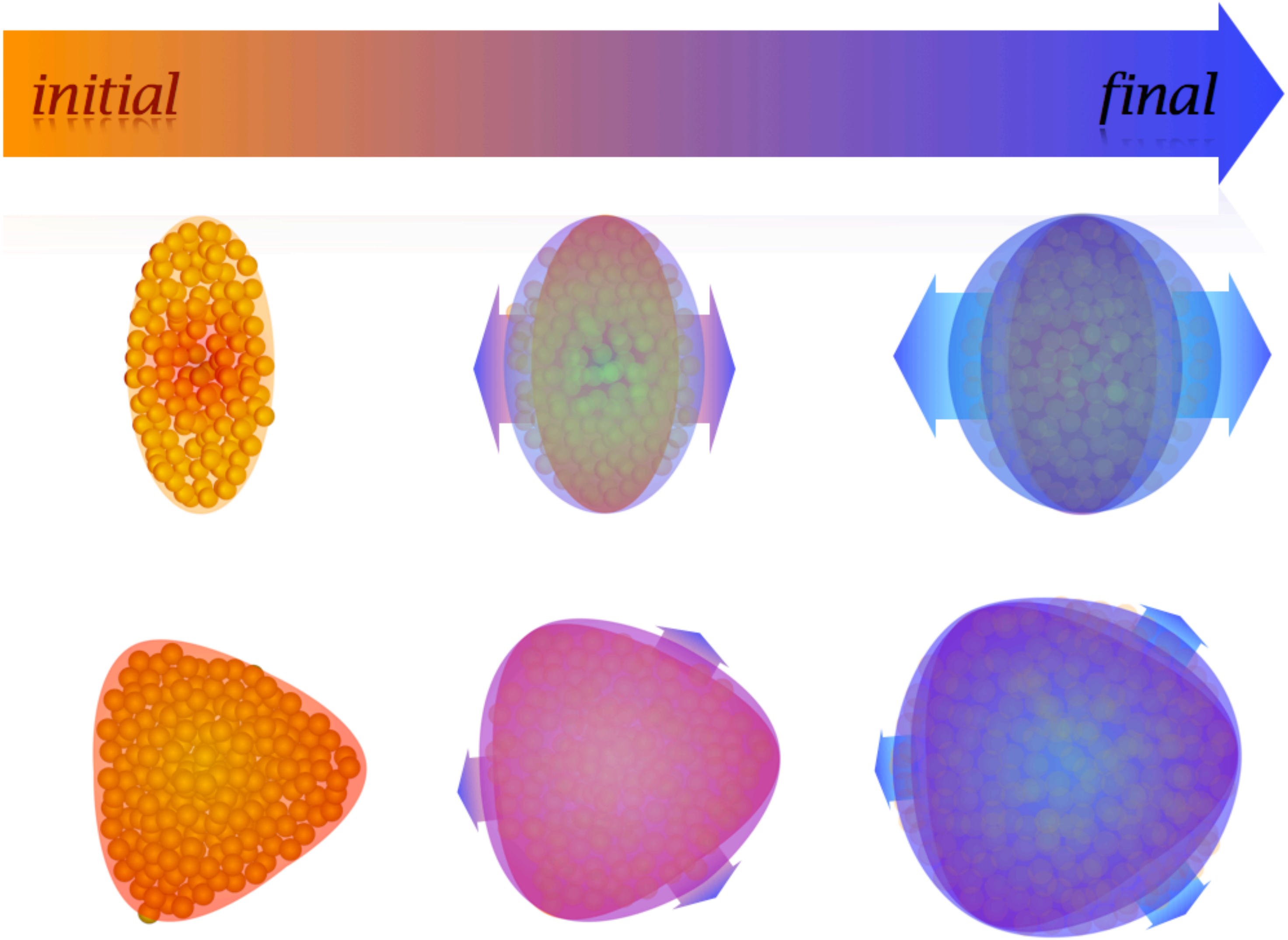
Azimuthal HBT radii w.r.t Ψ_3





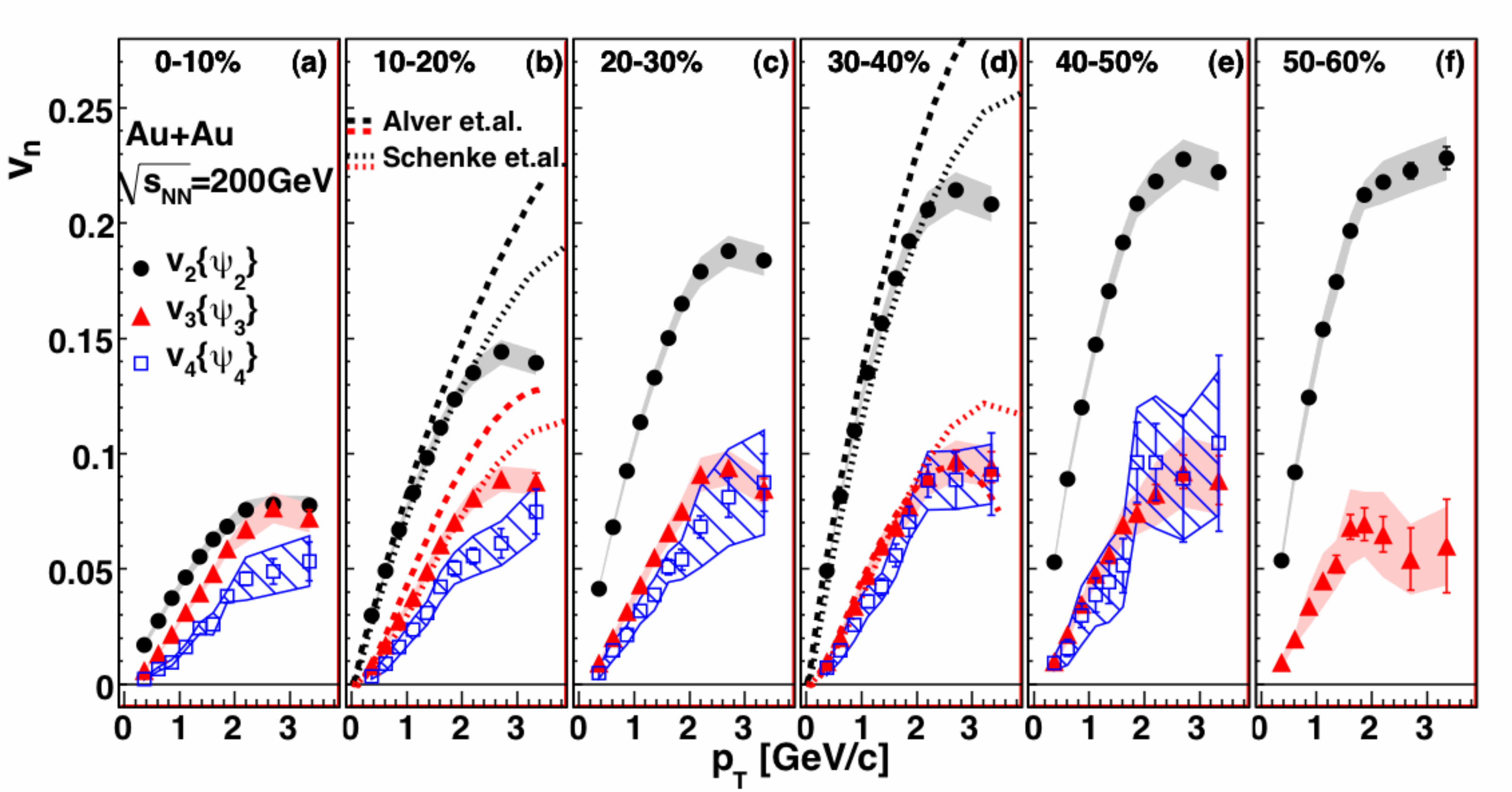
- R_{side} is almost flat
- R_{out} have a oscillation in most central collisions

Image of initial/final source shape



Charged hadron v_n at PHENIX

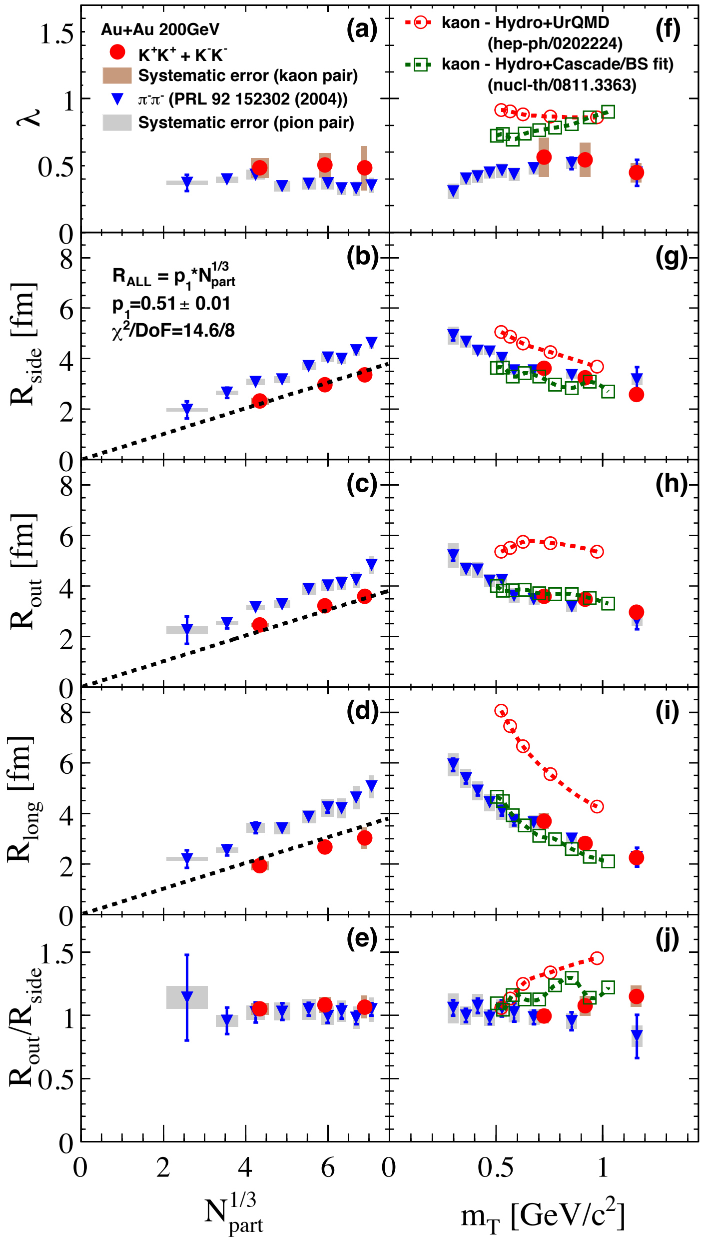
PRL.107.252301



- v_2 increases with increasing centrality, but v3 doesn’t
- v_3 is comparable to v_2 in 0-10%
- v_4 has similar dependence to v_2

The past HBT Results for charged pions and kaons

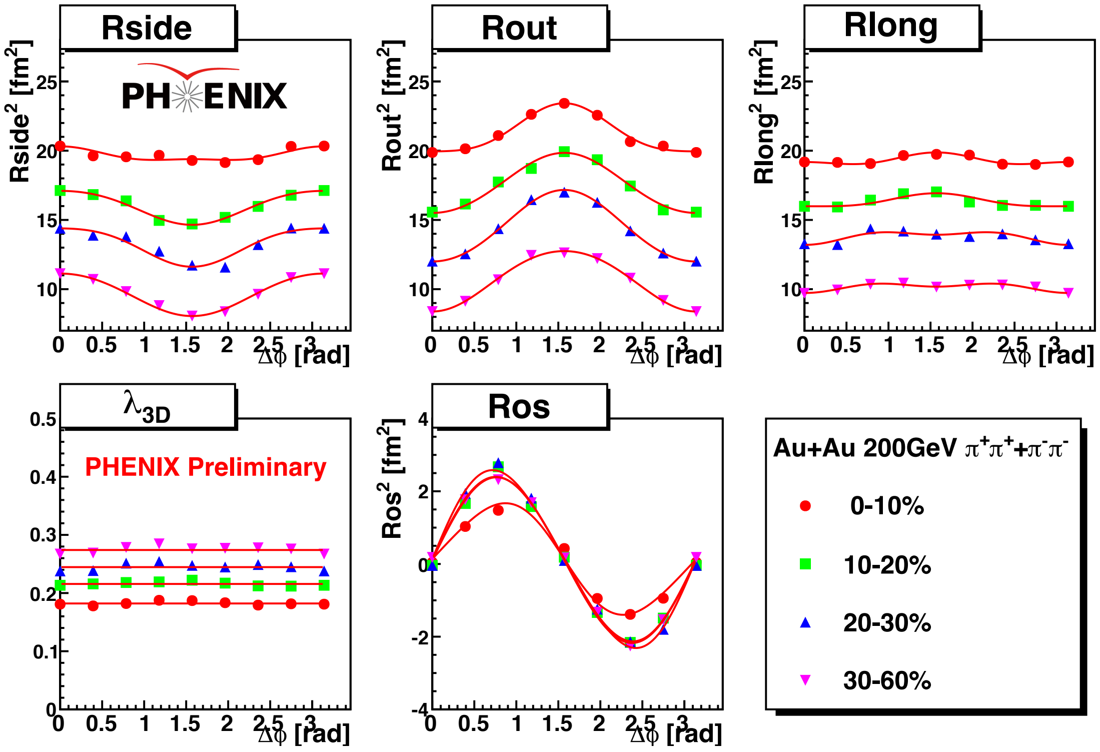
PRL103.142301(2009)

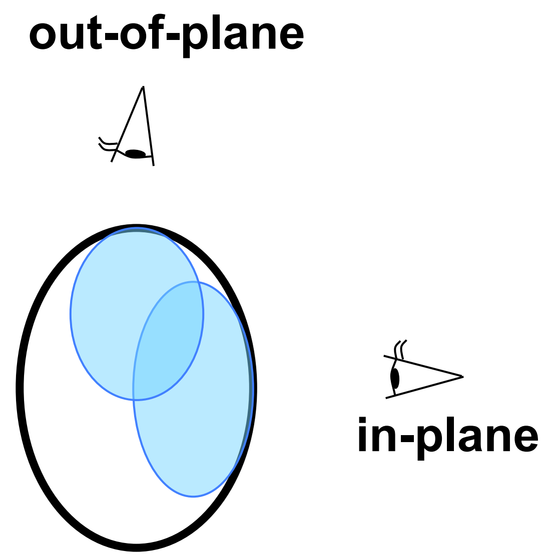


- **Centrality / m_T dependence have been measured for pions and kaons**
  - ✧higher transverse mass m_T for kaons leads to smaller radii compared to pions
    - ✓ pion $\langle m_T \rangle \sim 0.47$ GeV/c
    - ✓ kaon $\langle m_T \rangle \sim 0.89$ GeV/c
  - ✧m_T scaling works well

Azimuthal HBT radii for pions

- Observed oscillation for R_{side}, R_{out}, R_{os}
- Rout in 0-10% has oscillation
  - ✧ Different emission duration between in-plane and out-of-plane?





Azimuthal HBT radii for kaons

- Observed oscillation for R_{side}, R_{out}, R_{os}
- Final eccentricity is defined as $\varepsilon_{final} = 2R_{s,2} / R_{s,0}$
  - ✧ $R^2_{s,n} = \left\langle R^2_{s,n}(\Delta\phi)\cos(n\Delta\phi)\right\rangle$ PRC70, 044907 (2004)