Detailed HBT measurement with respect to Event plane and collision energy in Au+Au collisions

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Quark Matter 2012

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outline

- Introduction of HBT
- Azimuthal HBT w.r.t v_2 plane
- Azimuthal HBT w.r.t v_3 plane
- Low energy at PHENIX
- Summary

What is HBT ?

- **Quantum interference between two identical particles**
- **Hadron HBT can measure the source size at freeze-out**
  (not whole size but homogeneity region in expanding source)

$$C_2 = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1) \cdot P(\vec{p}_2)}$$

$P(p_1)$: Probability of detecting a particle
$P(p_1,p_2)$: Probability of detecting pair particles

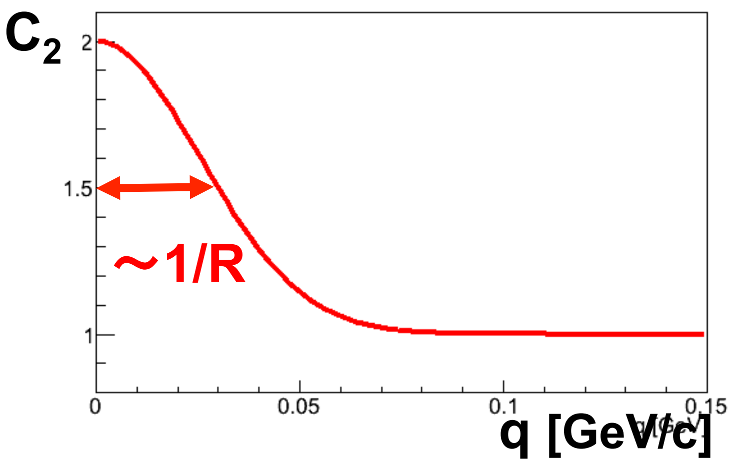
$$= 1 + \left|\tilde{\rho}(q)\right|^2 = 1 + \exp(-R_{inv}^2 q_{inv}^2)$$

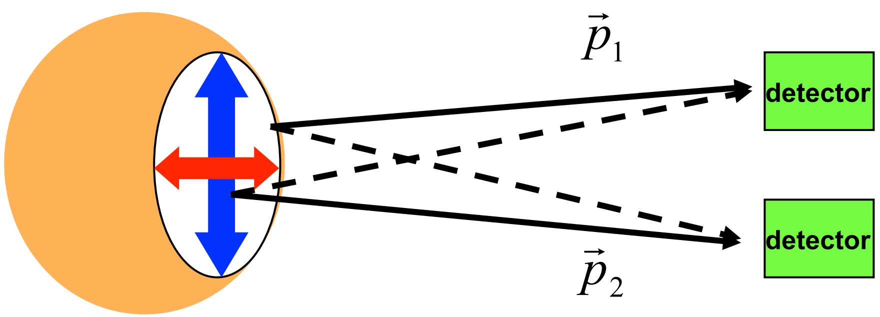
assuming gaussian source

$$\vec{q} = \vec{p}_1 - \vec{p}_2$$

$$\vec{k}_T = \frac{\vec{p}_1 + \vec{p}_2}{2}$$

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

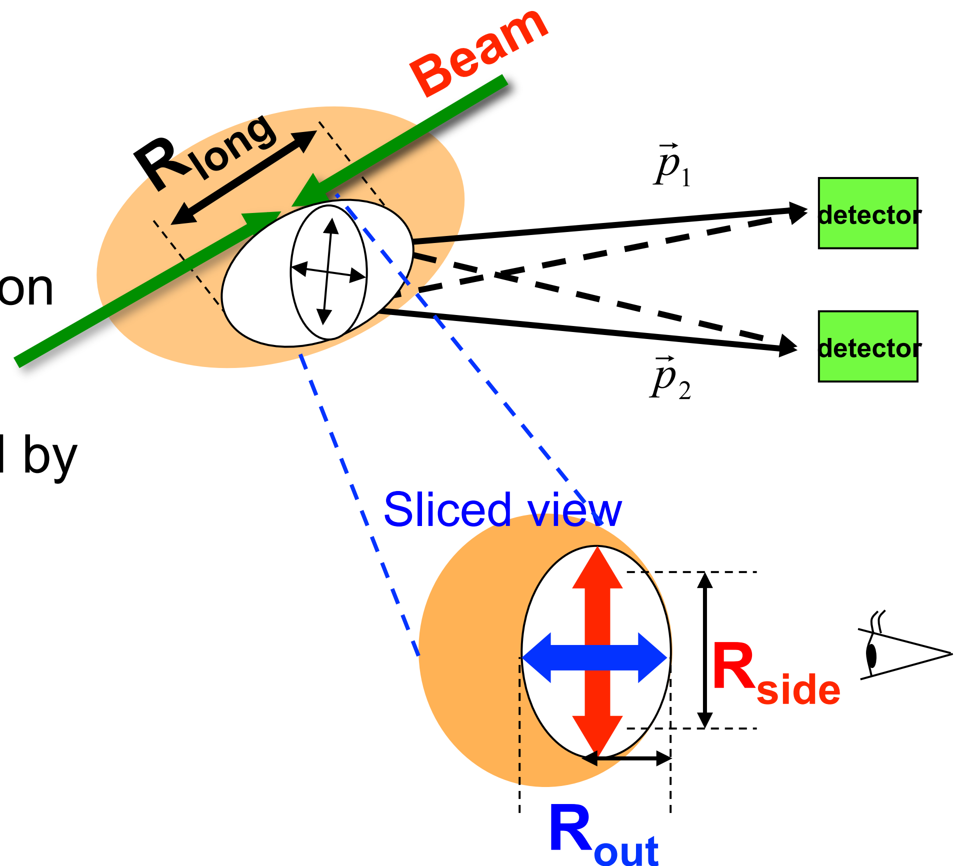




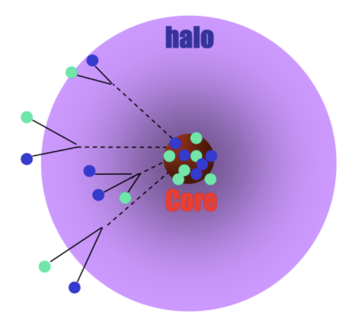
3D HBT radii

- **"Out-Side-Long" system**
  - ✧ Bertsch-Pratt parameterization
- **Core-halo model**
  - ✧ Particles in core are affected by coulomb interaction

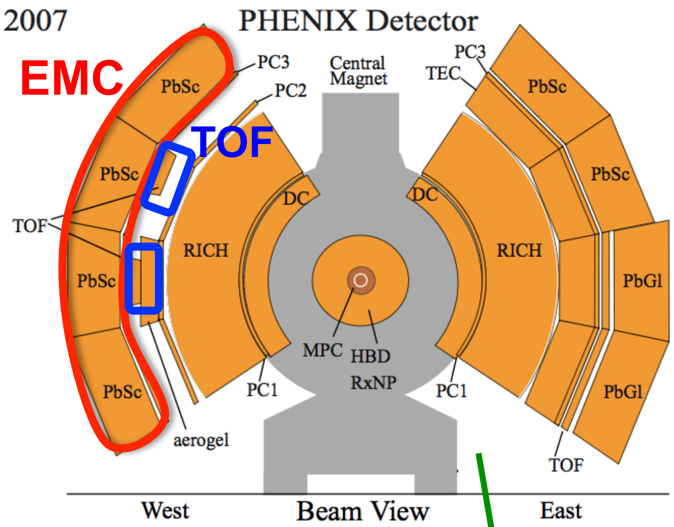
$$C_2 = C_2^{core} + C_2^{halo}$$
$$= N[\lambda(1+G)F] + [1-\lambda]$$
$$G = \exp(-R_{inv}^2 q_{inv}^2)$$
$$= \exp(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2 - 2R_{os}^2 q_{side} q_{out})$$

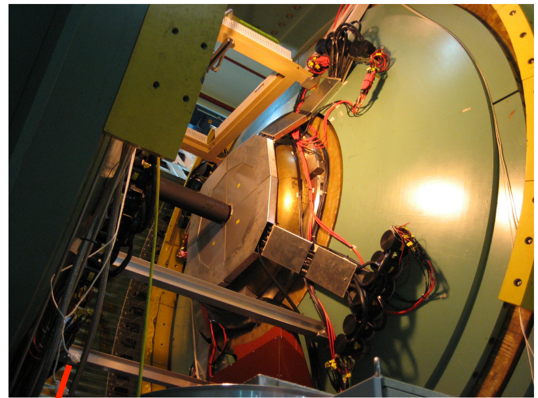


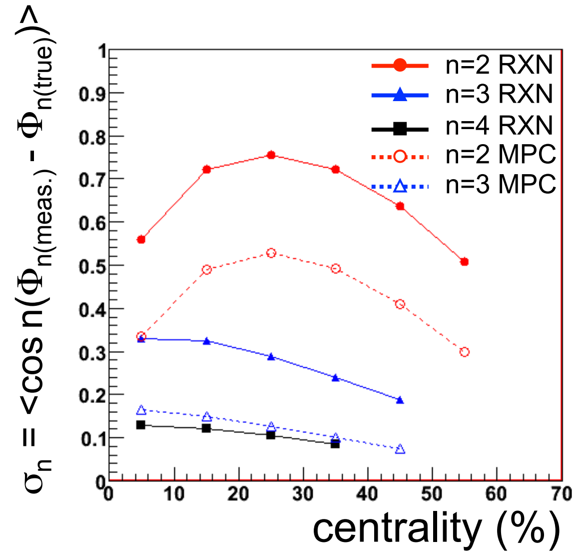
R_{long}: Longtudinal size
R_{side}: Transverse size
R_{out}: Transverse size + emission duration
R_{os}: Cross term between Out and Side

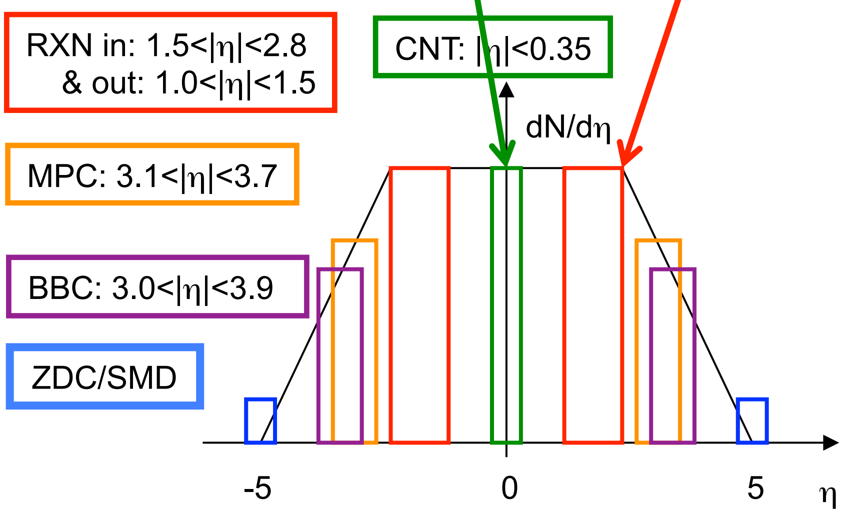


Measurement by PHENIX Detectors







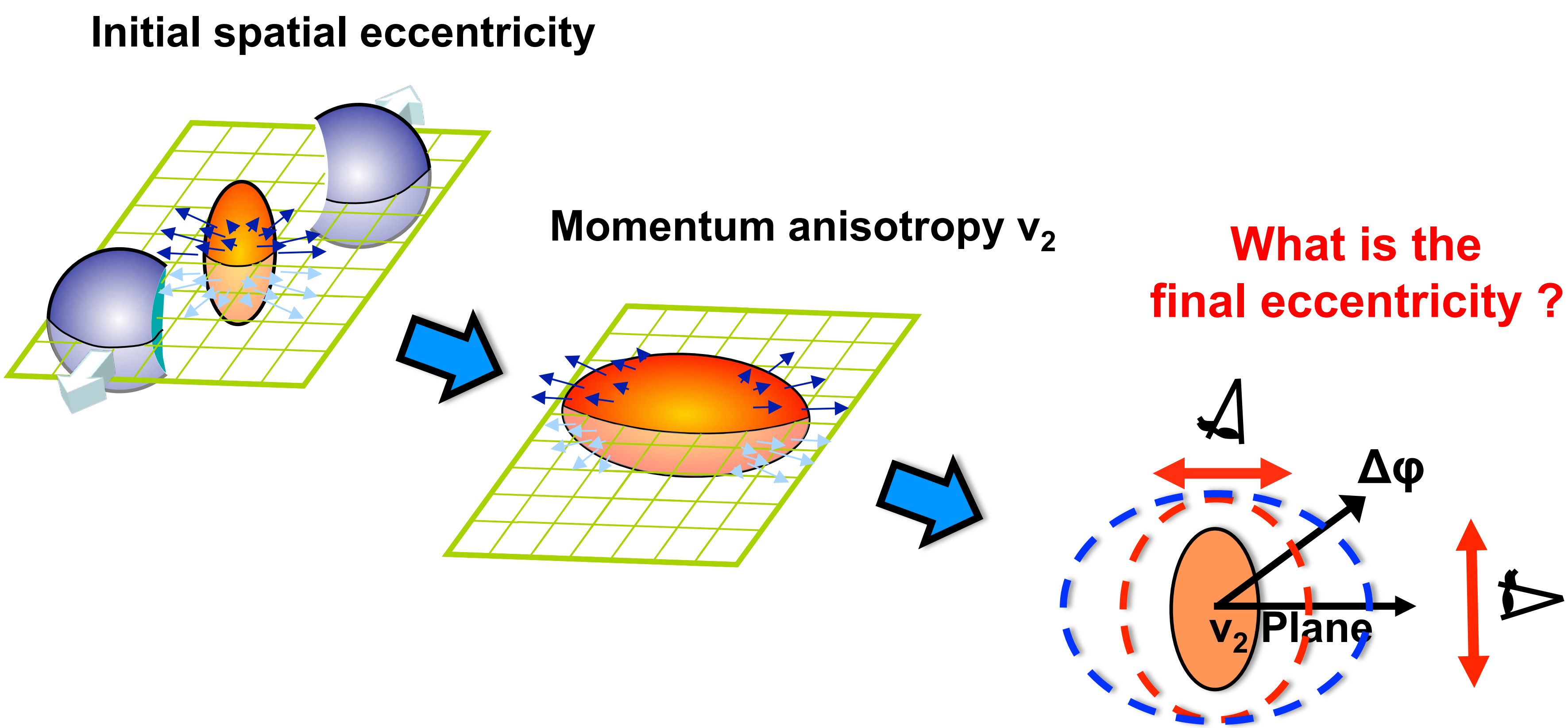


$$C_2 = \frac{R(q)}{M(q)}$$

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

Azimuthal HBT w.r.t v_2 plane



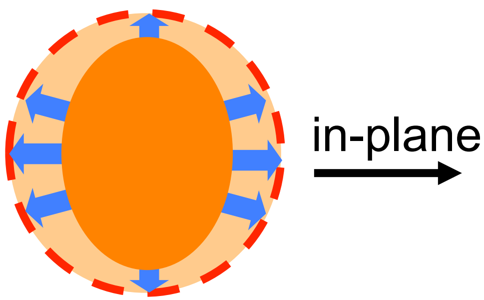
- **Final eccentricity can be measured by azimuthal HBT**
  - ✧It depends on initial eccentricity, pressure gradient, expansion time, and velocity profile, etc.
  - ✧Good probe to investigate system evolution

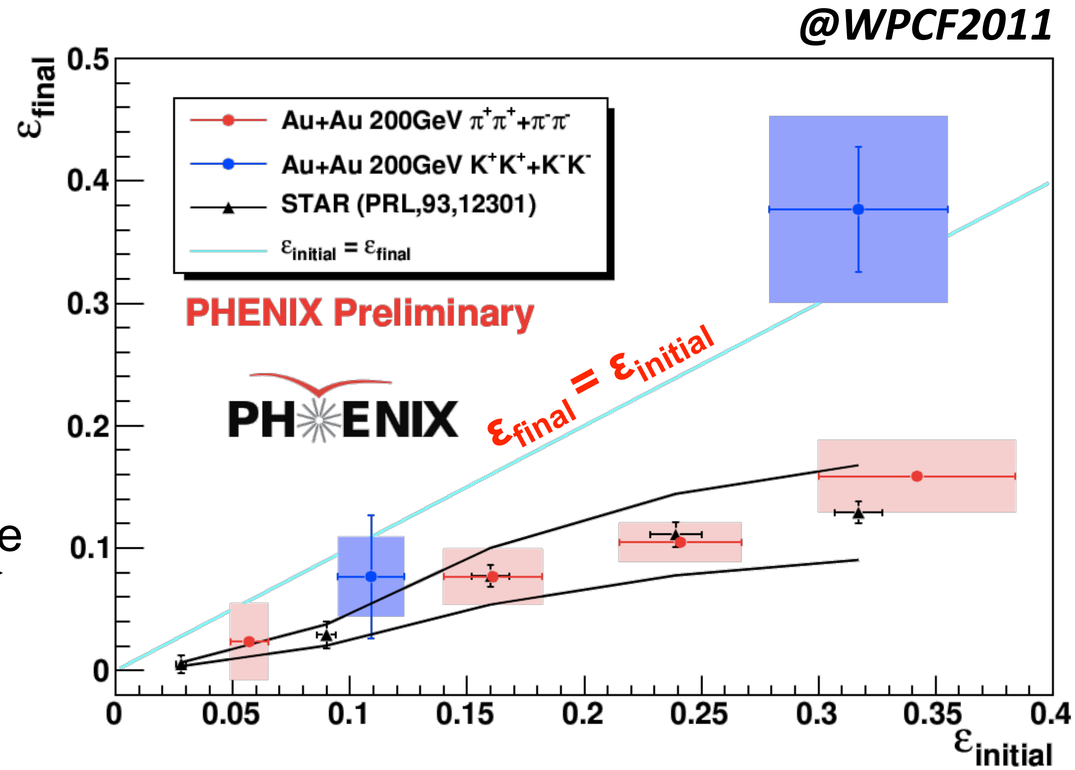
Eccentricity at freeze-out

R_s^2 PRC70, 044907 (2004)

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

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

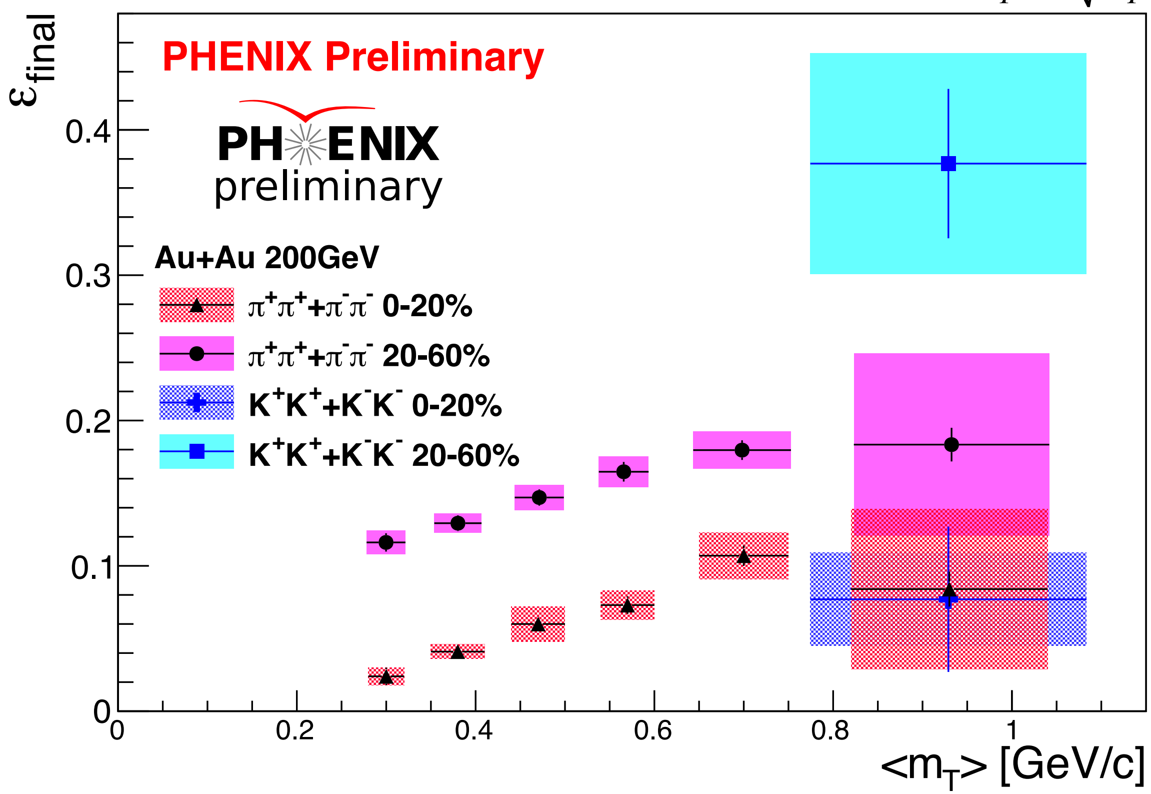




- $\varepsilon_{final} \approx \varepsilon_{initial}/2$ **for pion**
  - Indicates that source expands to in-plane direction, and still elliptical shape
  - PHENIX and STAR results are consistent
- $\varepsilon_{final} \approx \varepsilon_{initial}$ **for kaon**
  - Kaon may freeze-out sooner than pion because of less cross section
  - Need to check the difference of m_T between π/K?

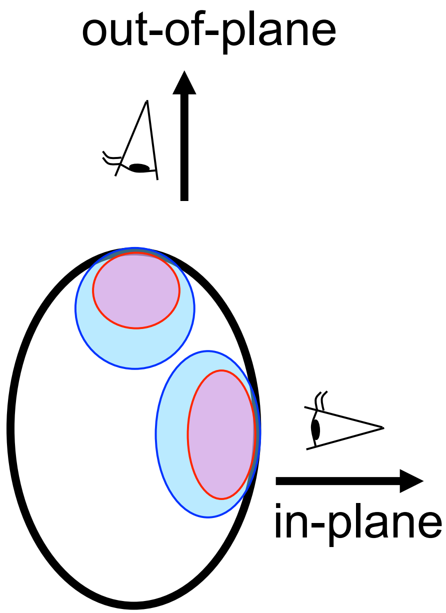
m_T dependence of ε_{final}

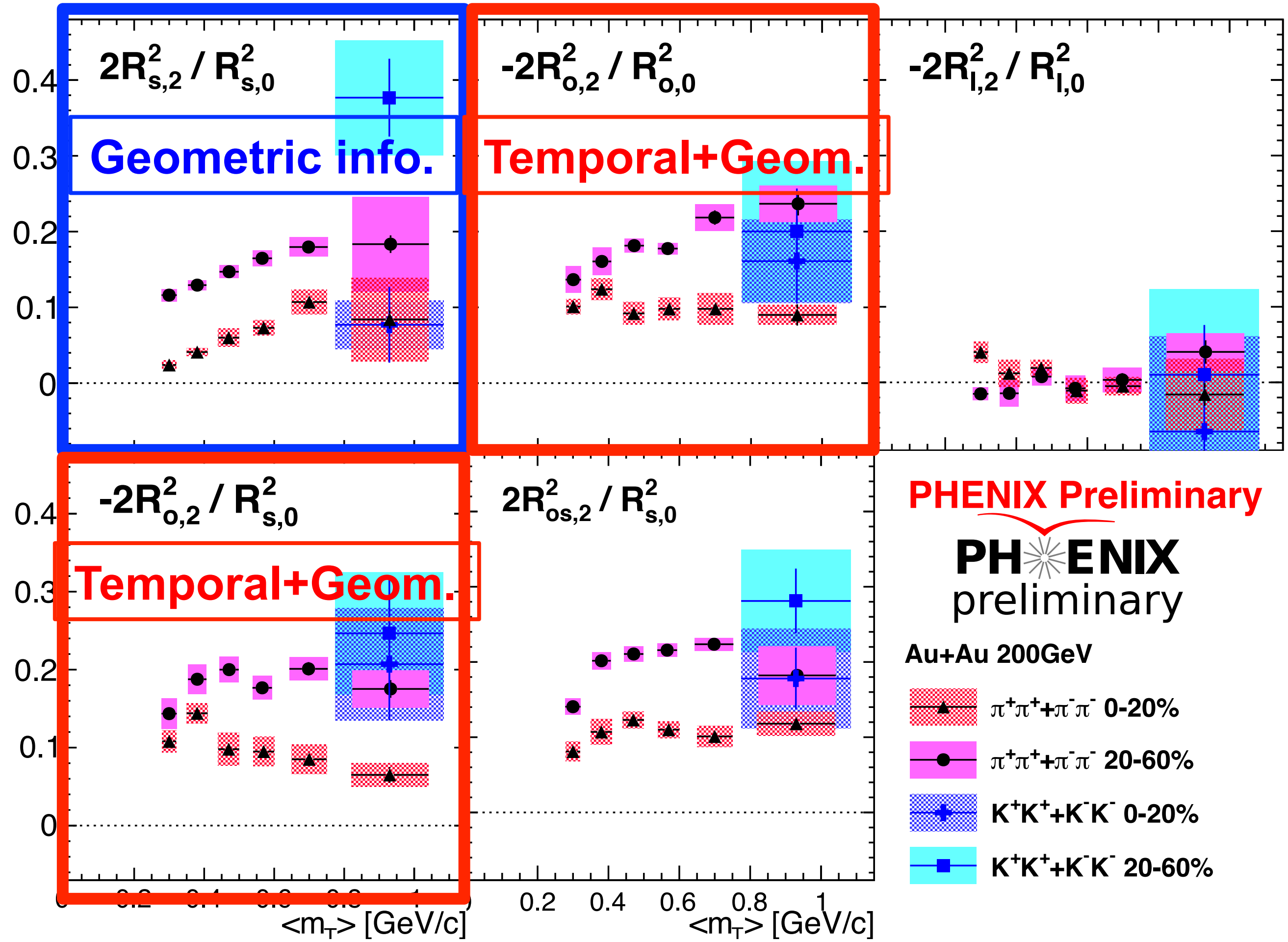
$$m_T = \sqrt{k_T^2 + m^2}$$



- 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 ?

m_T dependence of relative amplitude

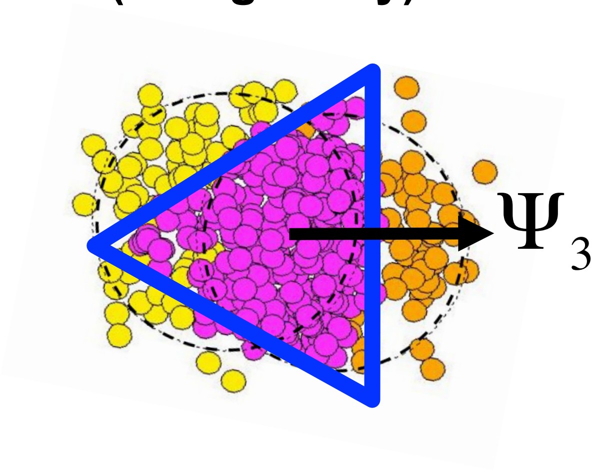




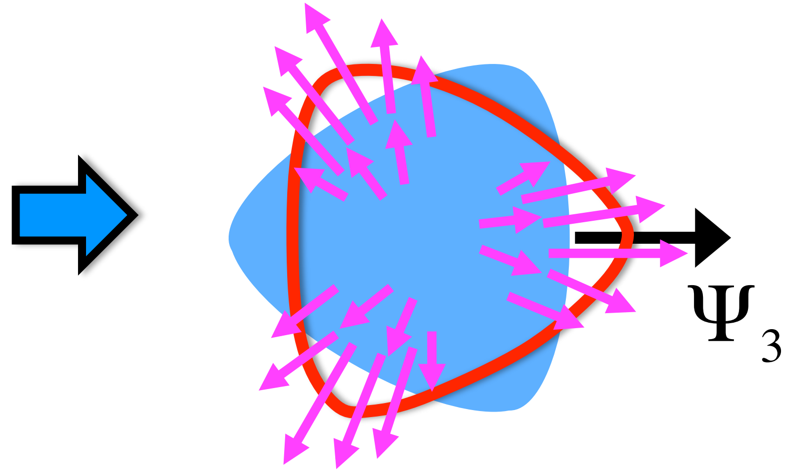
- **Relative amplitude of R_{out} in 0-20% doesn't depend on m_T**
  - ✧Does it indicate emission duration between in-plane and out-of-plane is different at low m_T?

Azimuthal HBT w.r.t v_3 plane

Initial spatial fluctuation (triangularity)



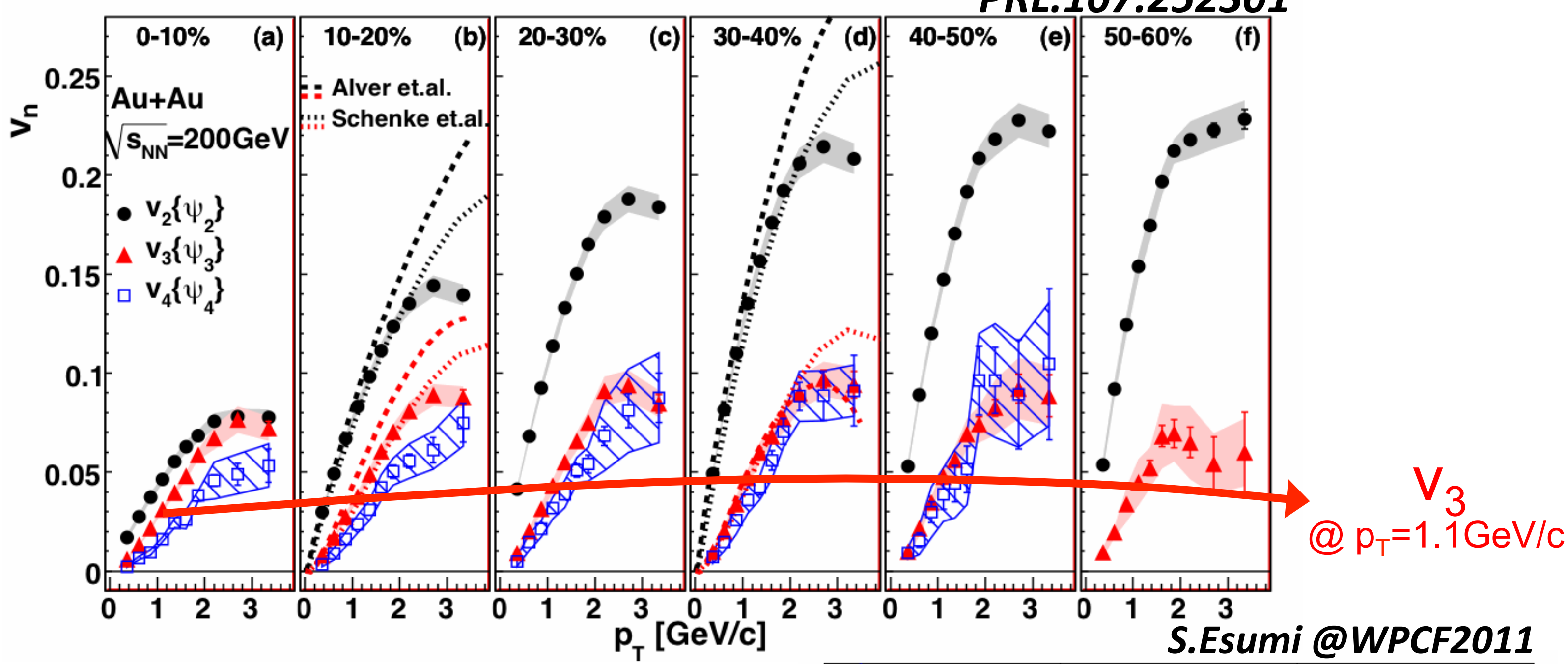
Momentum anisotropy triangular flow v_3



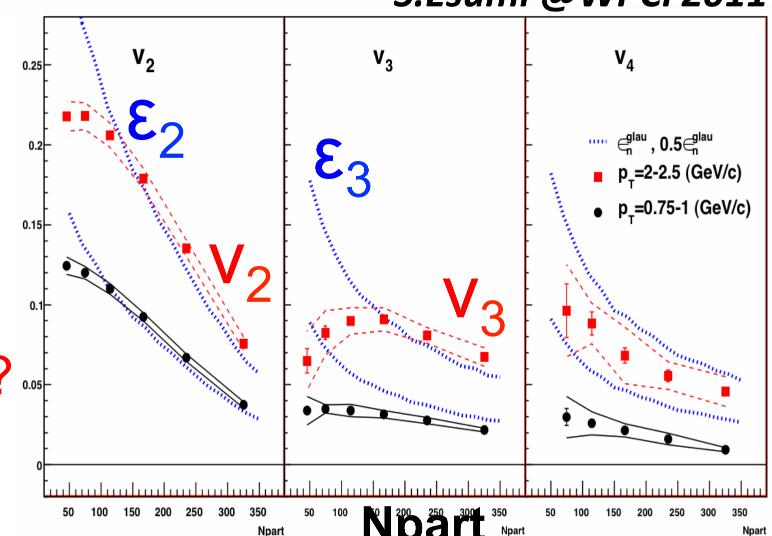
- **Final triangularity could be observed by azimuthal HBT w.r.t v_3 plane(Ψ_3) if it exists at freeze-out**
  - ✧Related to initial triangularity, v_3, and expansion time, etc.
  - ✧Detailed information on space-time evolution can be obtained

Centrality dependence of v_3 and ε_3

PRL.107.252301



S.Esumi @WPCF2011

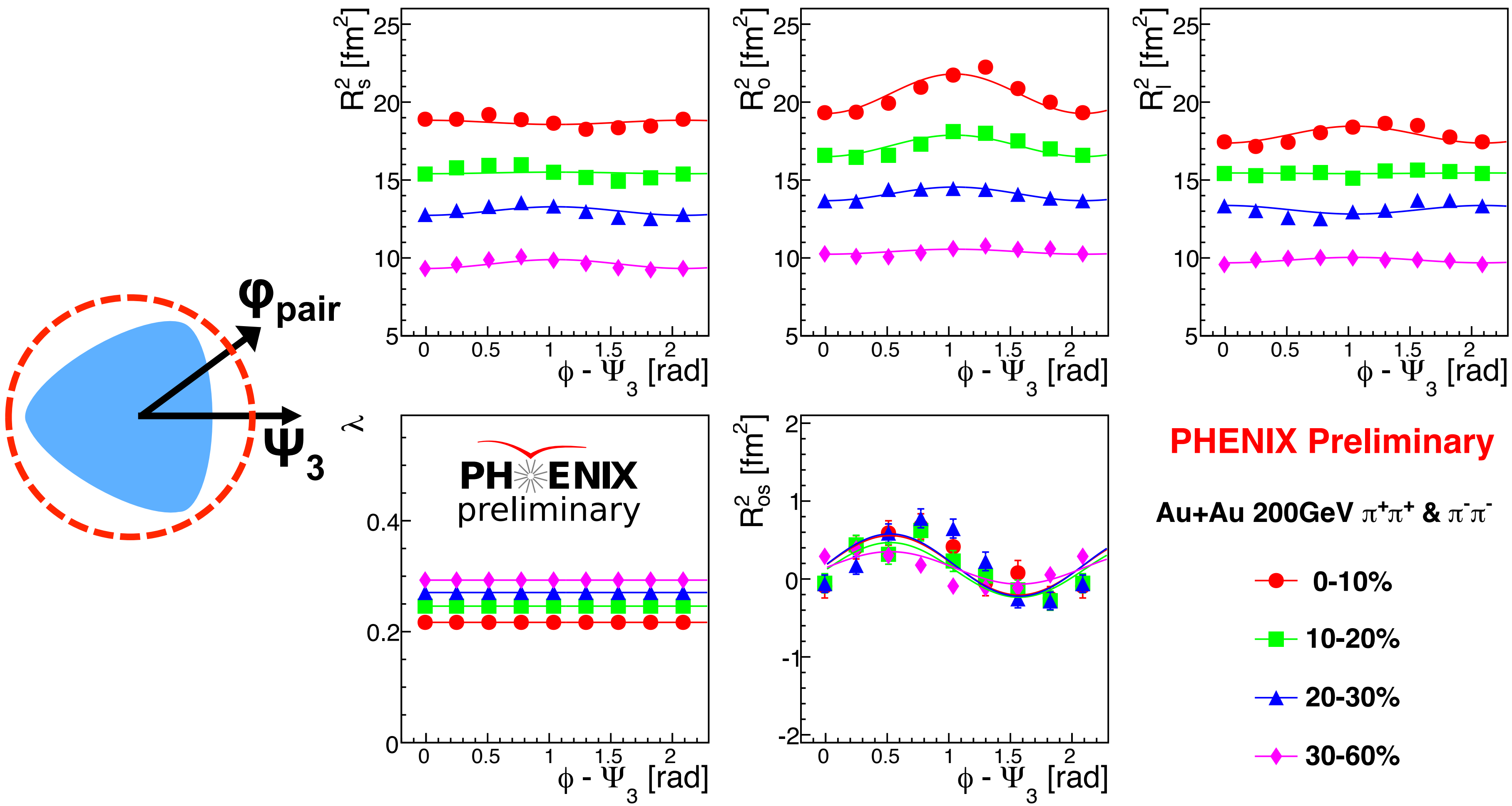


- **Weak centrality dependence of v_3**
- **Initial ε_3 has centrality dependence**

🍙 Final ε_3 has any centrality dependence?

T . Niida Quark Matter 2012, Aug.14, 2012

Azimuthal HBT radii w.r.t Ψ_3

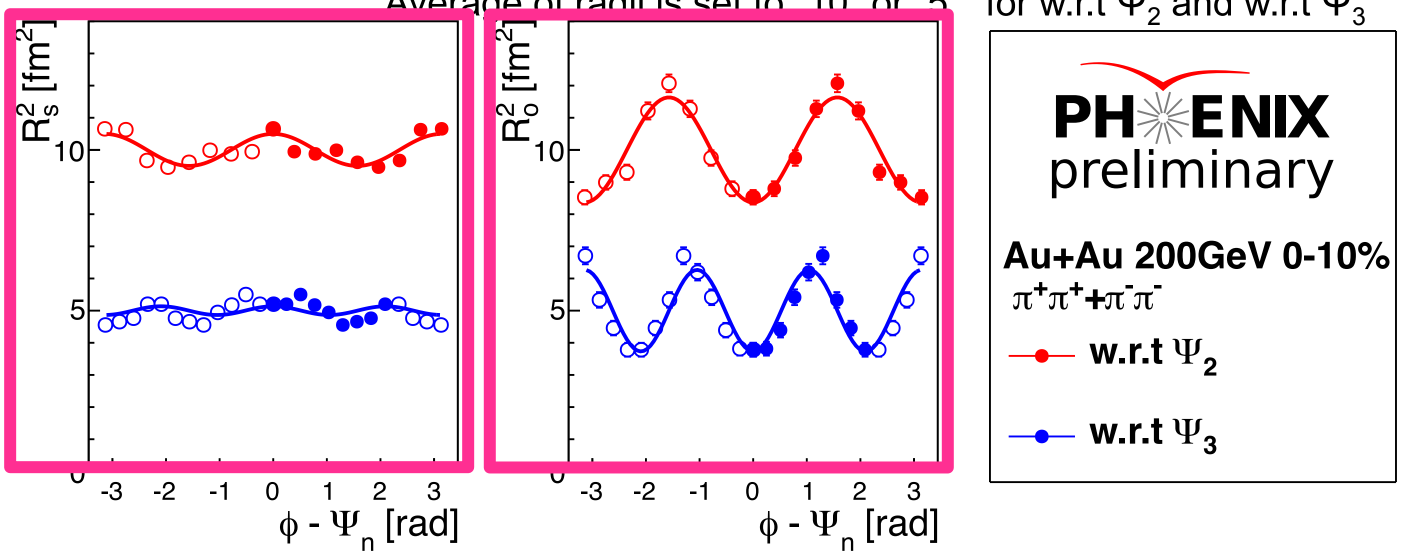


- R_{side} is almost flat
- R_{out} have a oscillation in most central collisions

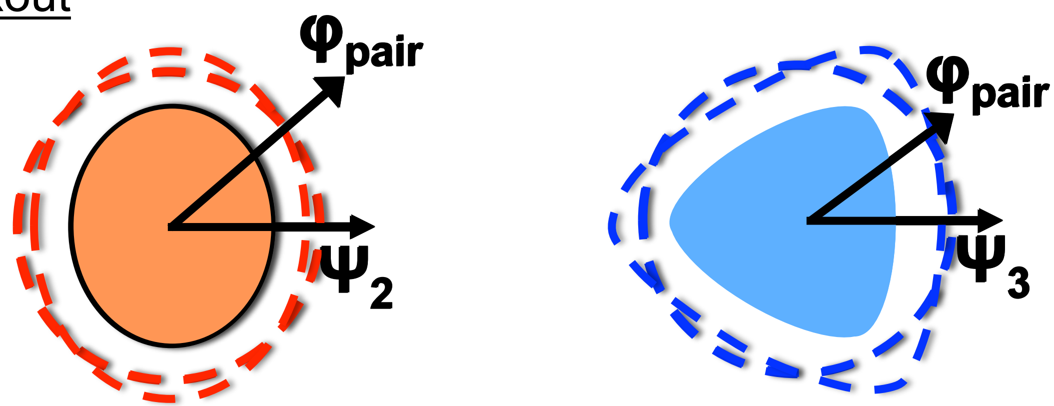
Comparison of 2nd and 3rd order component

- In 0-10%, R_{out} have stronger oscillation for Ψ_2 and Ψ_3 than R_{side}
  - ✧ Its oscillation indicates different emission duration between 0°/60° w.r.t Ψ_3

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



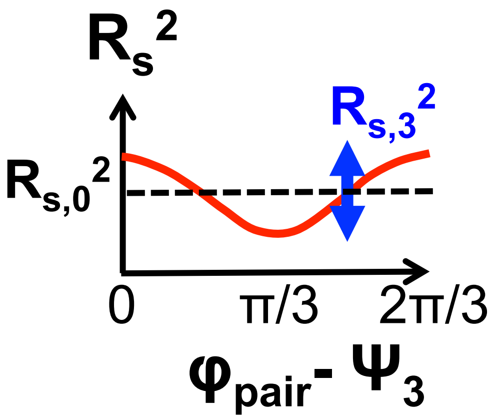
Rout



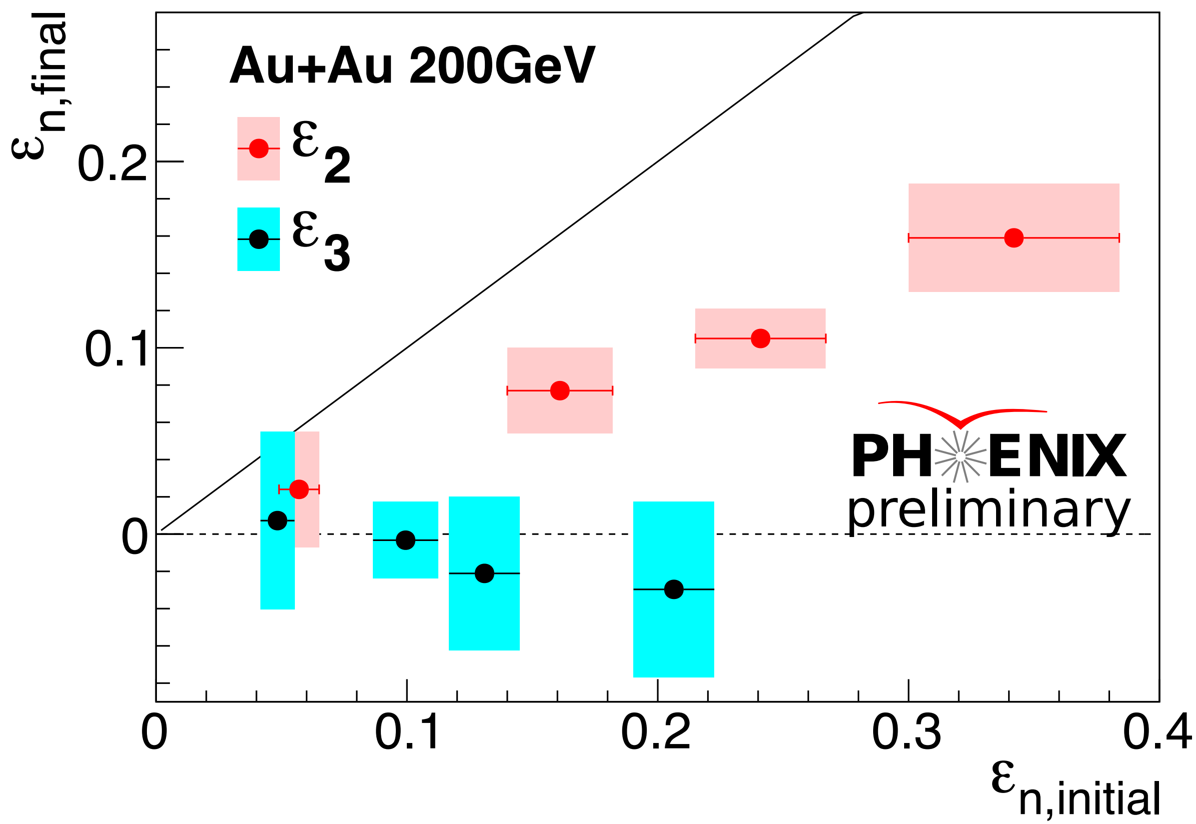
Rside

Triangularity at freeze-out

- **Relative amplitude is used to represent "triangularity" at freeze-out**



$$\varepsilon_{3,final} = 2\frac{R_{s,3}^2}{R_{s,0}^2}$$



☆Triangular component at freeze-out seems to vanish for all centralities within systematic error

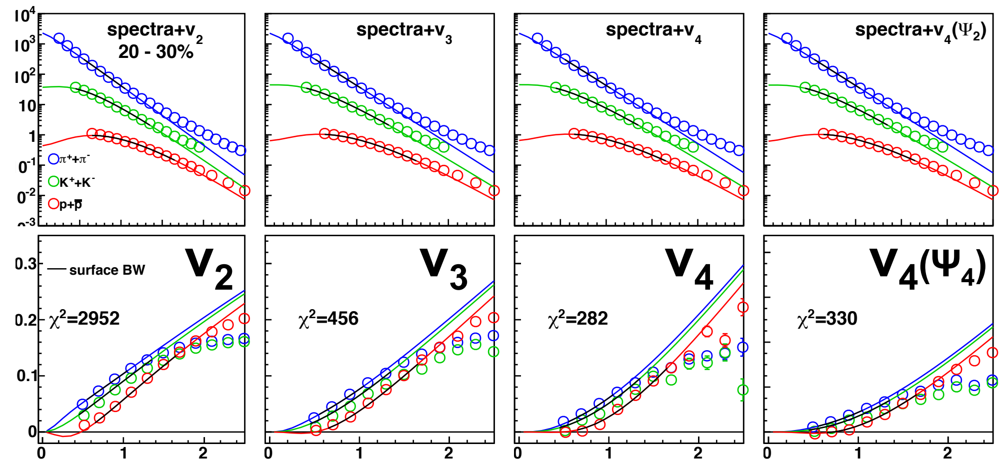
Spatial anisotropy by Blast wave model

Poster, Board #195
Sanshiro Mizuno

- **Blast wave fit for spectra & v_n**
  - ✧Parameters used in the model

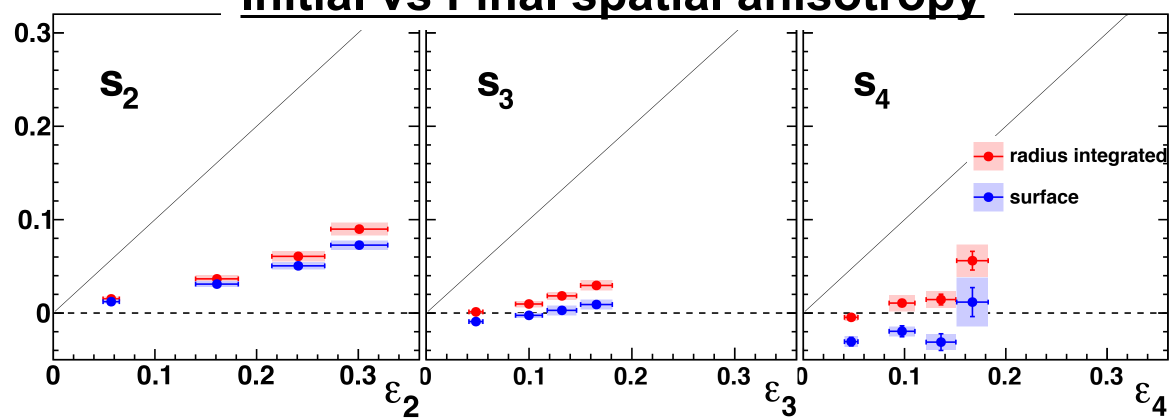
    T_f : temperature at freeze-out
    ρ_0 : average velocity
    ρ_n : anisotropic velocity
    s_n : spatial anisotropy

    ✓ s_2 and s_3 correspond to final eccentricity and triangularity



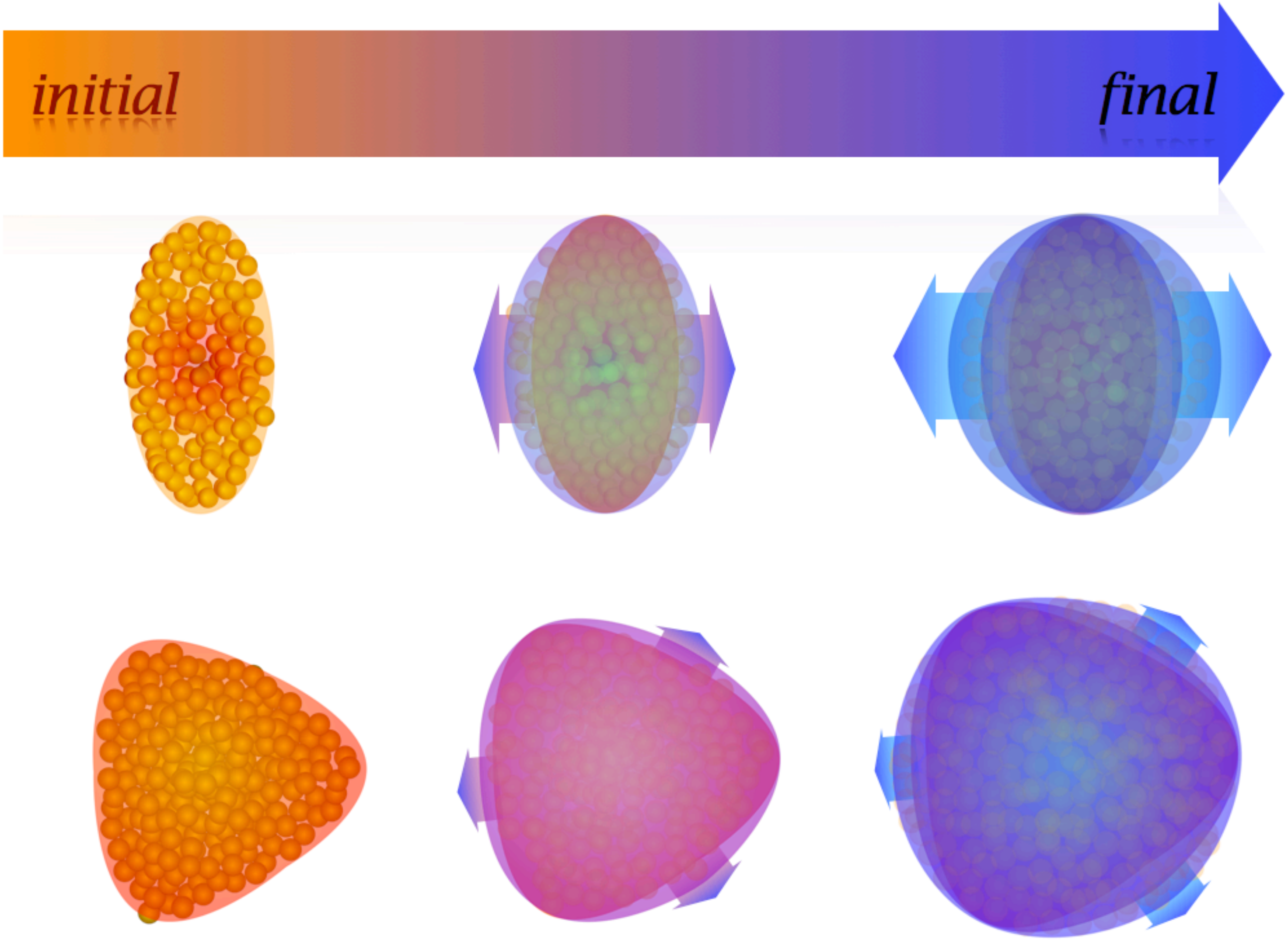
Initial vs Final spatial anisotropy

- ✧s_2 increase with going to peripheral collisions
- ✧s_3 is almost zero

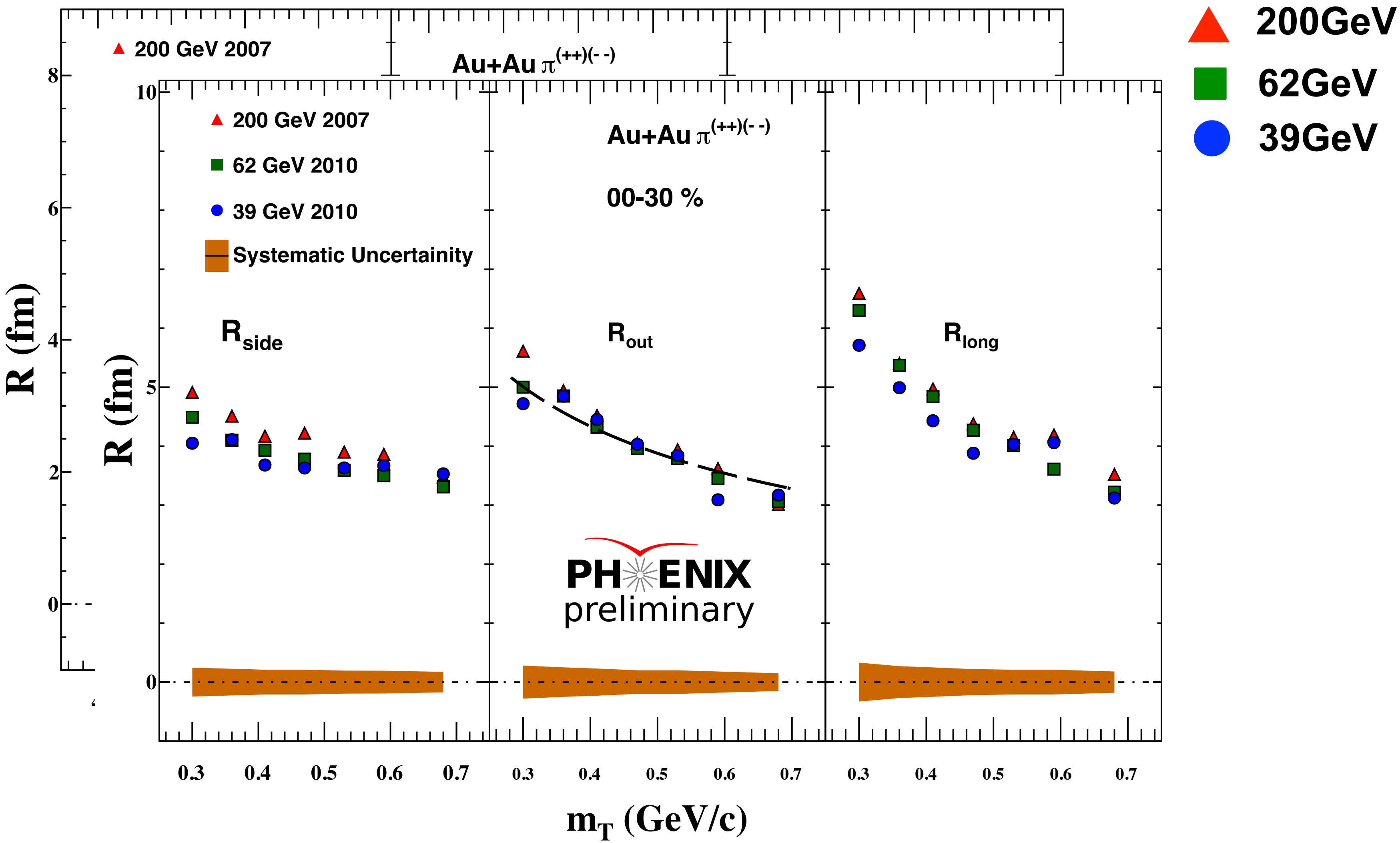


☞ Similar results with HBT

Image of initial/final source shape



Low energy at PHENIX

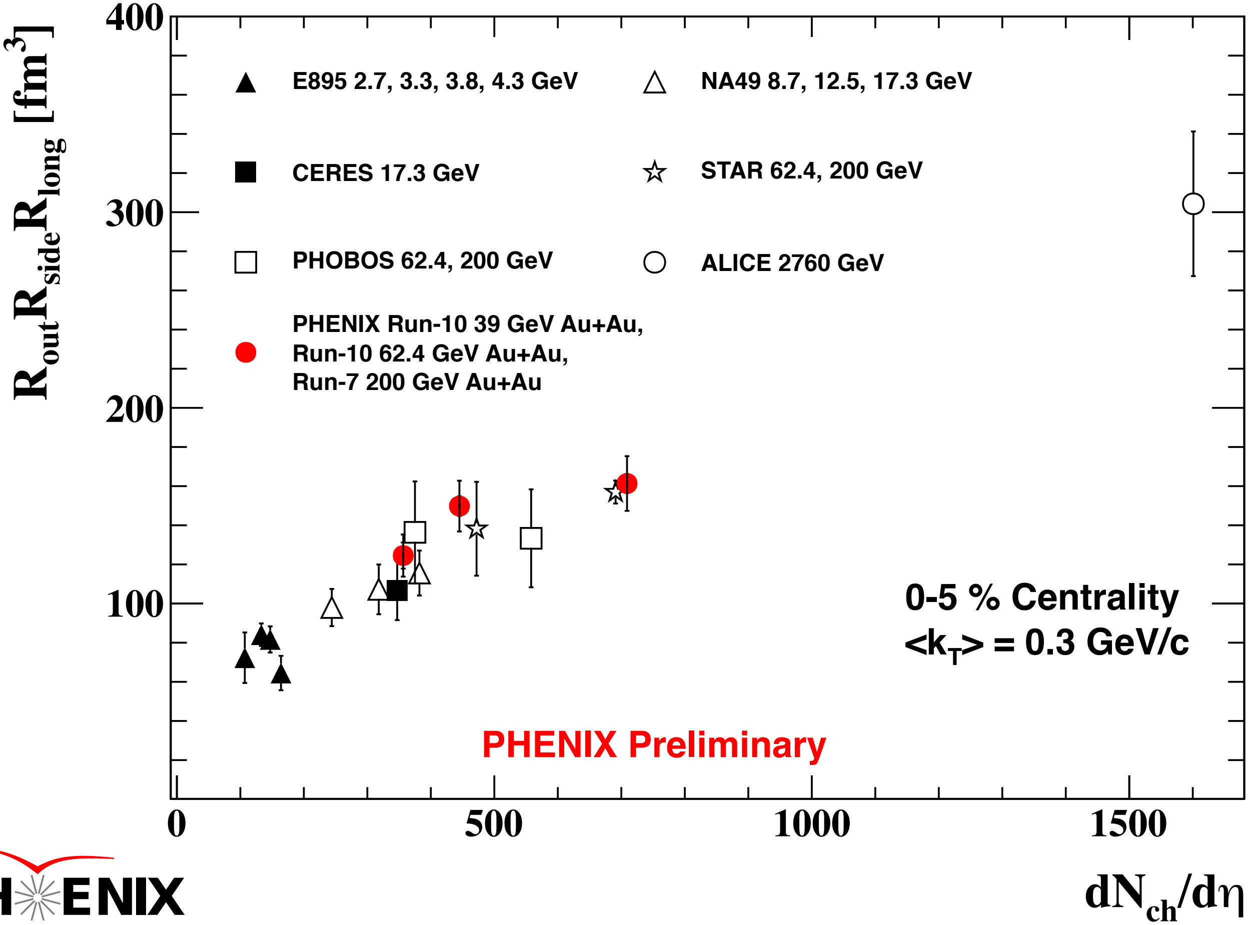


- No significant change beyond systematic error in 200GeV, 62GeV and 39GeV for centrality and m_T dependence

Volume vs Multiplicity

- Product of 3D HBT radii shows the volume of homogeneity regions
- Consistent with global trends

Poster, Board #246
Alex Mwai



PHENIX preliminary

Summary

- **Azimuthal HBT radii w.r.t v_2 plane**
  - ✧Final eccentricity increases with increasing m_T, but not enough to explain the difference between π/K
    - ☛ Difference may indicate faster freeze-out of K due to less cross section
  - ✧Relative amplitude of R_{out} in 0-20% doesn't depend on m_T
    - ☛ It may indicate the difference of emission duration between in-plane and out-of-plane
- **Azimuthal HBT radii w.r.t v_3 plane**
  - ✧First measurement of final triangularity have been presented. It seems to vanish at freeze-out by expansion.
  - ✧while Rout clearly has finite oscillation in most central collisions
    - ☛ It may indicate the difference of emission duration between $\Delta\varphi$=0°/60° direction
- **Low energy in Au+Au collisions**
  - ✧No significant change between 200, 62 and 39 [GeV]
  - ✧Volume is consistent with global trends

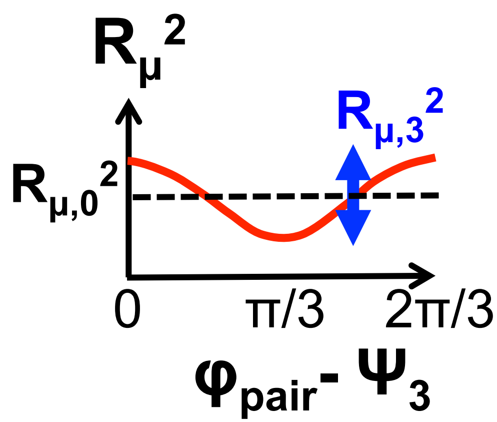
Thank you for your attention!

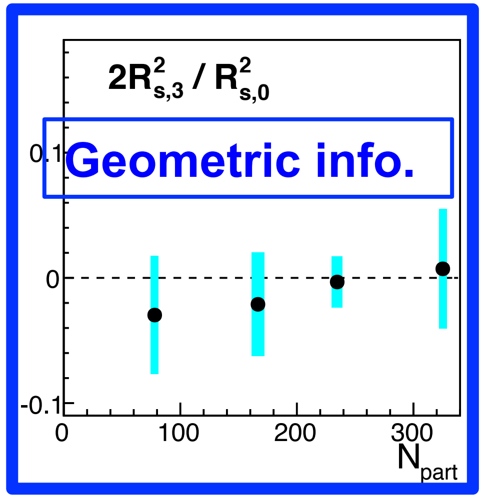
Japanese rice ball
has just “triangular shape” !!

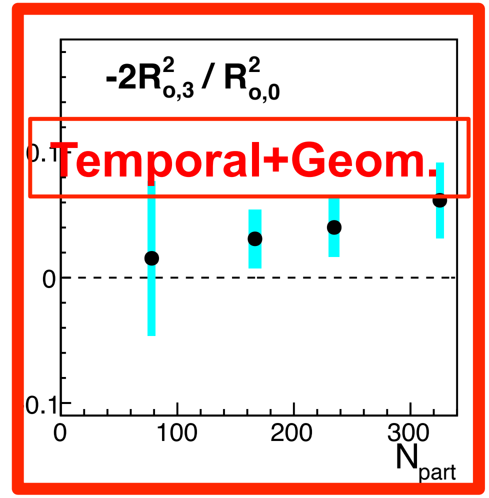
Back up

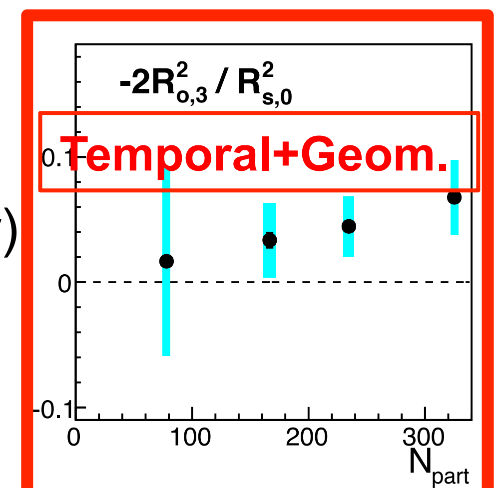
Relative amplitude of HBT radii

- Relative amplitude is used to represent “triangularity” at freeze-out
- Relative amplitude of Rout increases with increasing Npart







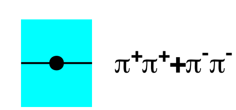


☆ Triangular component at freeze-out seems to vanish for all centralities(within systematic error)

PHENIX Preliminary

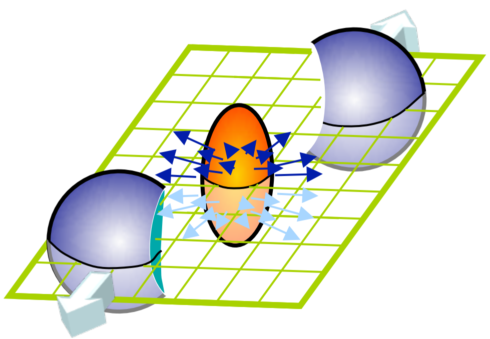
PHENIX preliminary

Au+Au 200GeV

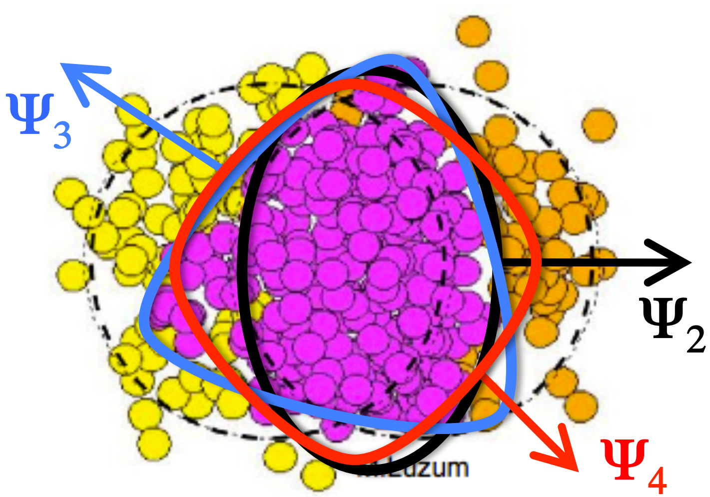


Higher harmonic event plane

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



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

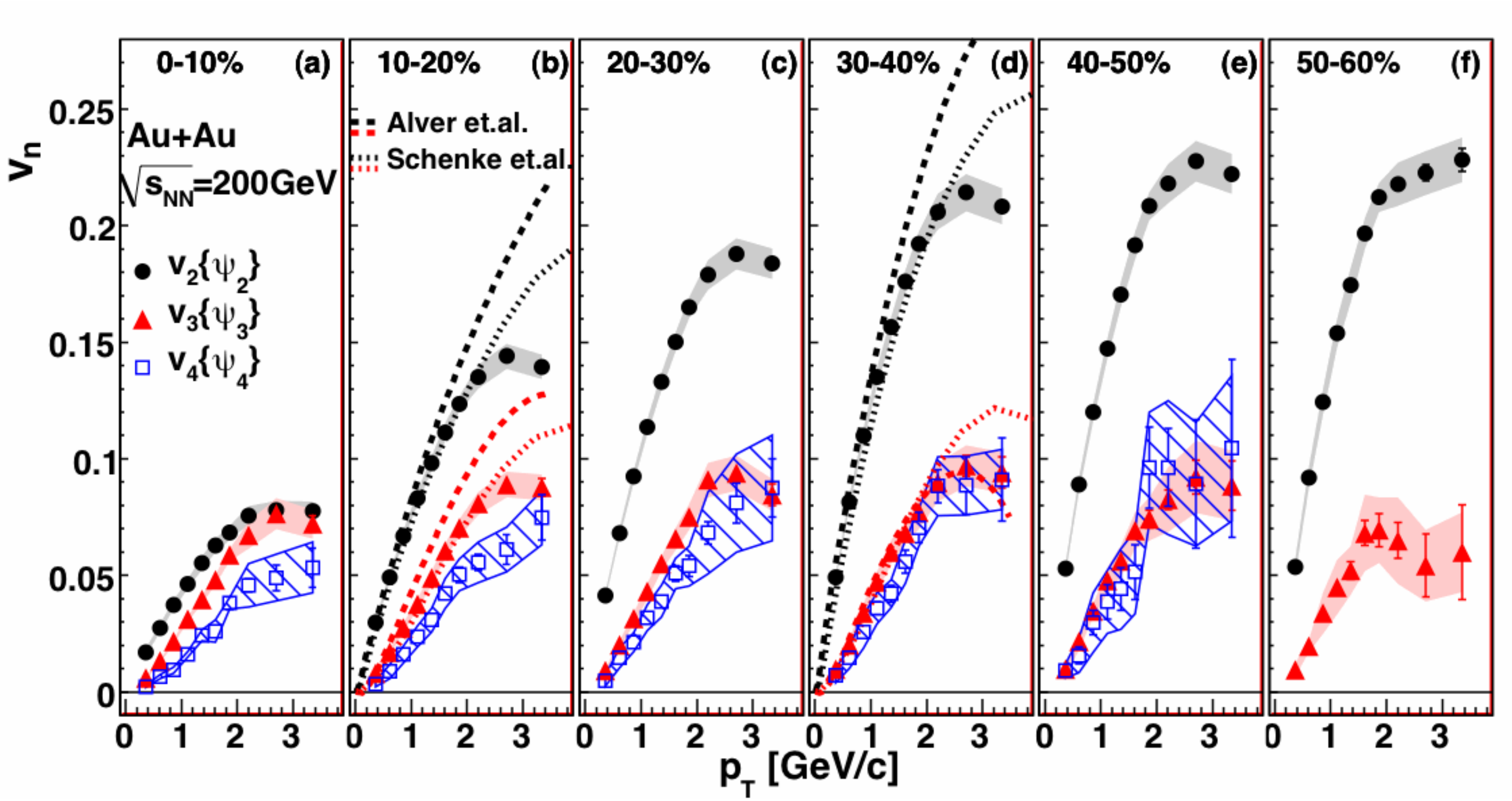


$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$

Ψ_n : Higher harmonic event plane
ϕ : Azimuthal angle of emitted particles

Charged hadron v_n at PHENIX

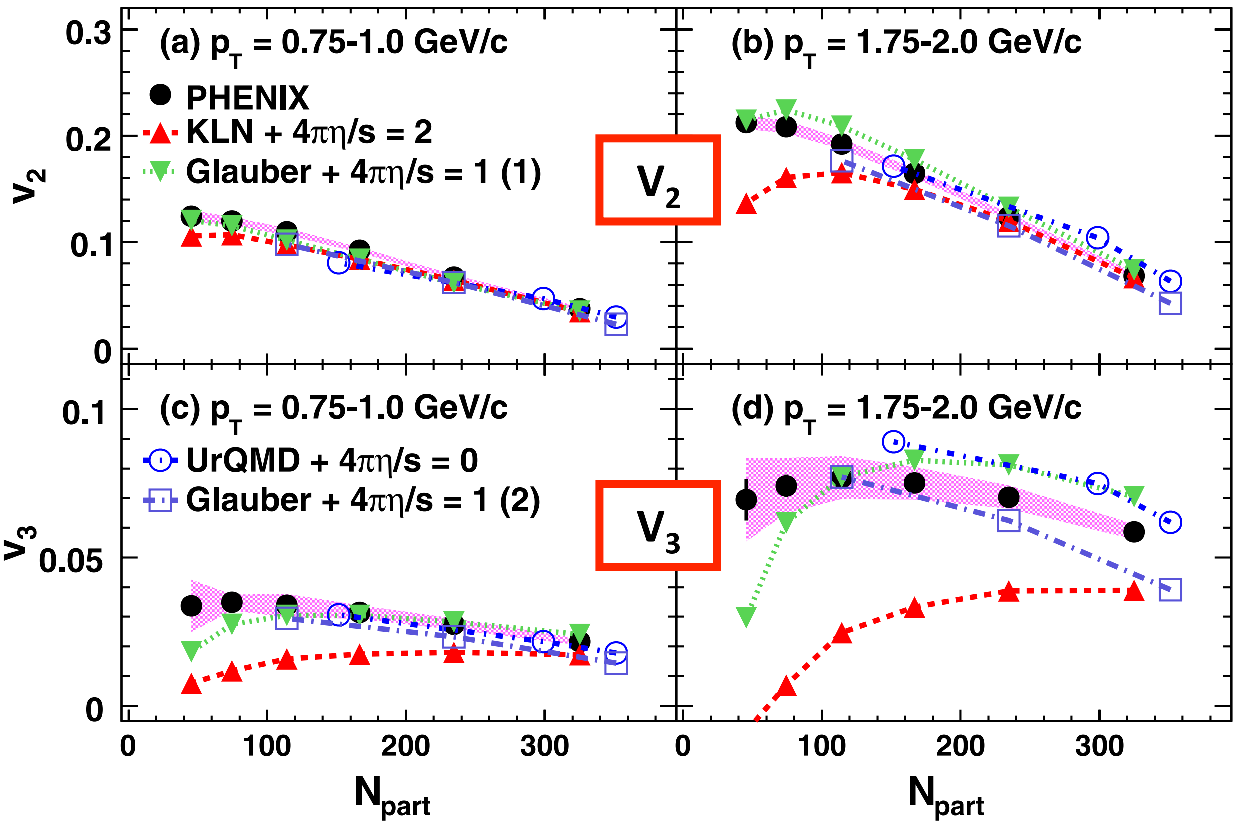
PRL.107.252301



- 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

v_3 breaks degeneracy

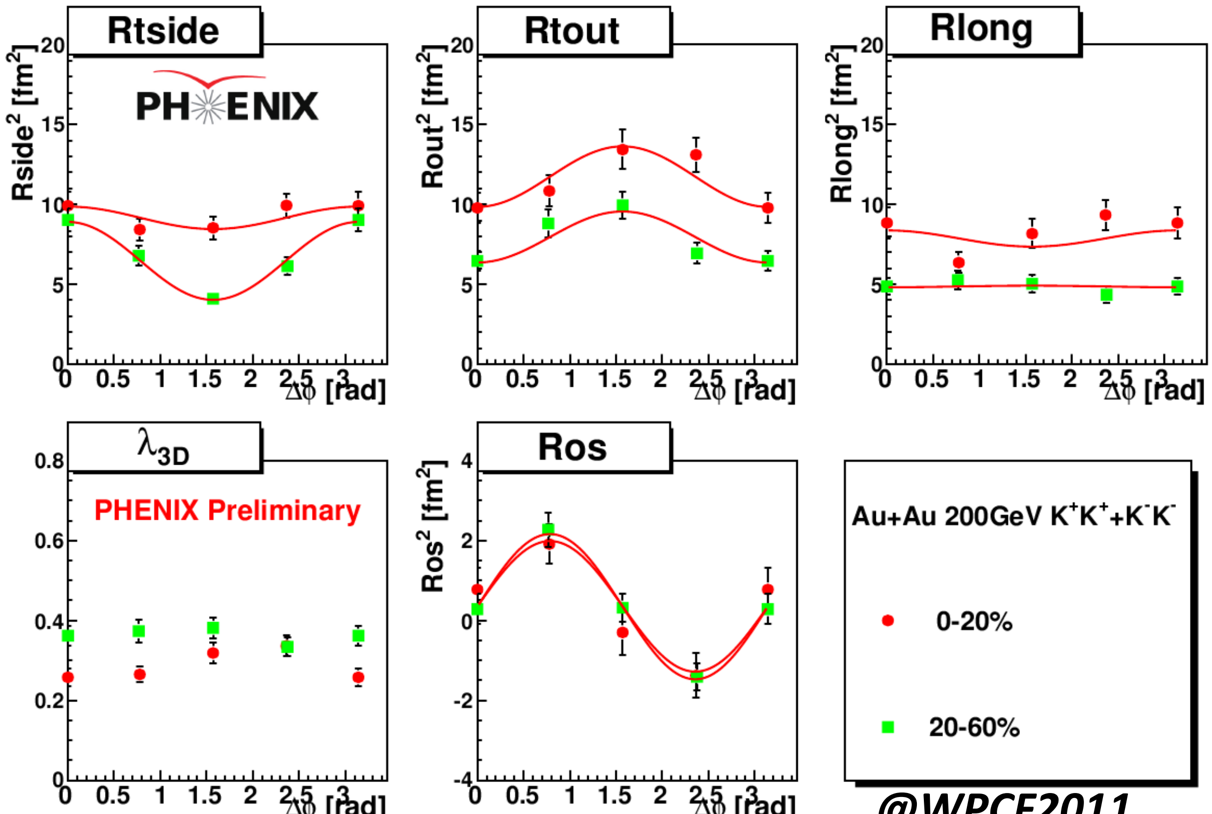
PRL.107.252301



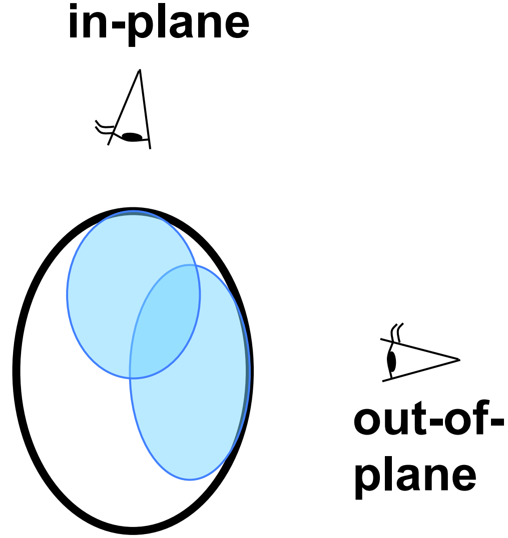
- v_3 provides new constraint on hydro-model parameters
  - ✧ Glauber & 4πη/s=1 : works better
  - ✧ KLN & 4πη/s=2 : fails

Azimuthal HBT radii for kaons

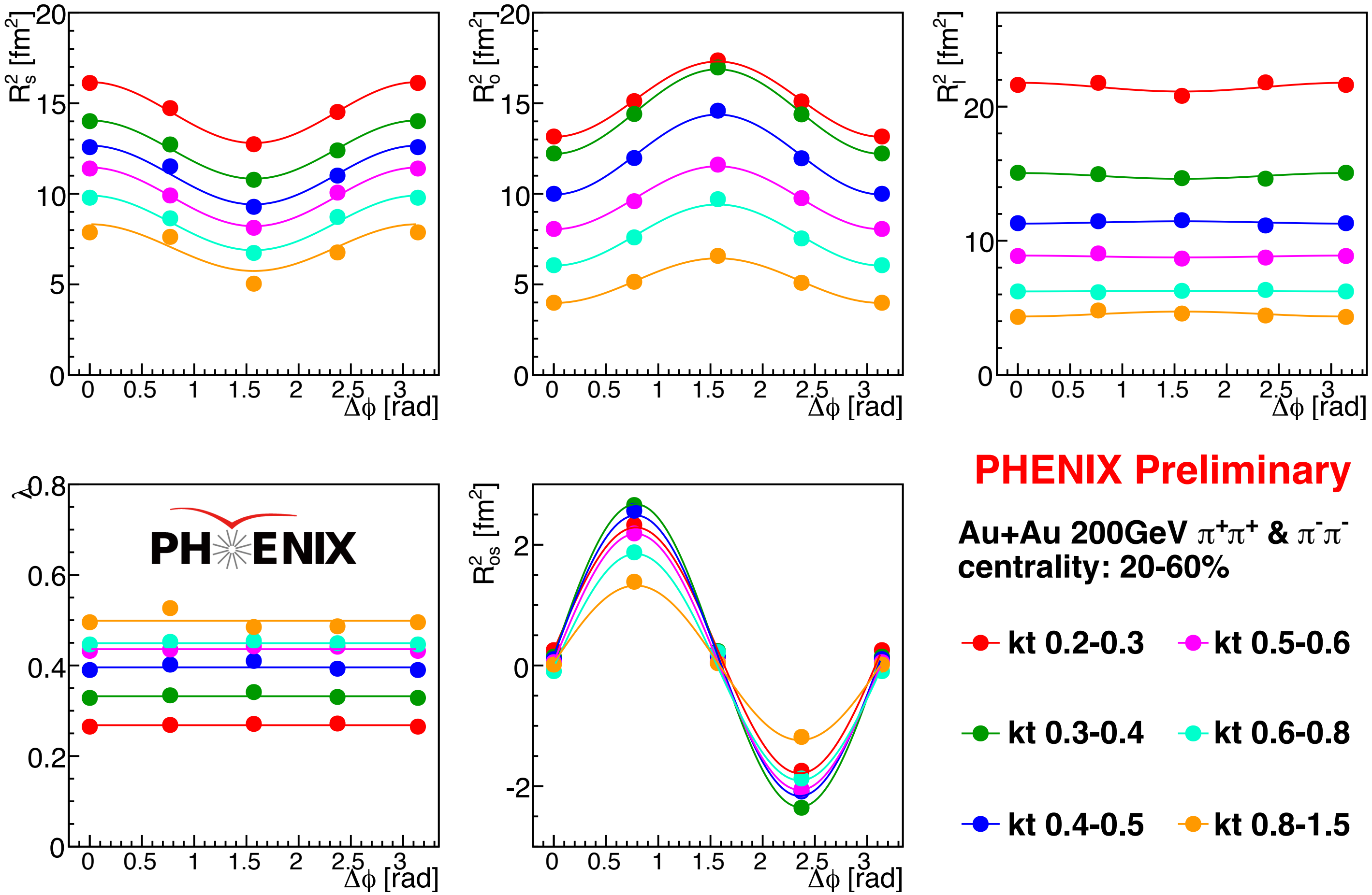
- Observed oscillation for R_{side}, R_{out}, R_{os}
- Final eccentricity is defined as $\varepsilon_{final} = 2R_{s,2} / R_{s,0}$
  - $R^2_{s,n} = \langle R^2_{s,n}(\Delta\phi)\cos(n\Delta\phi)\rangle$ PRC70, 044907 (2004)

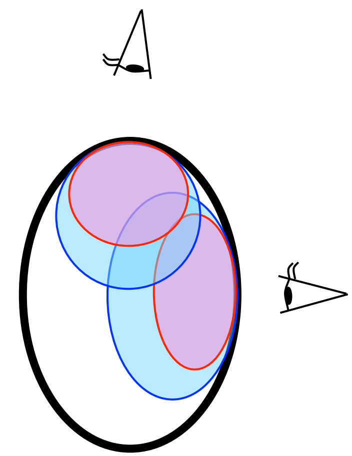


@WPCF2011



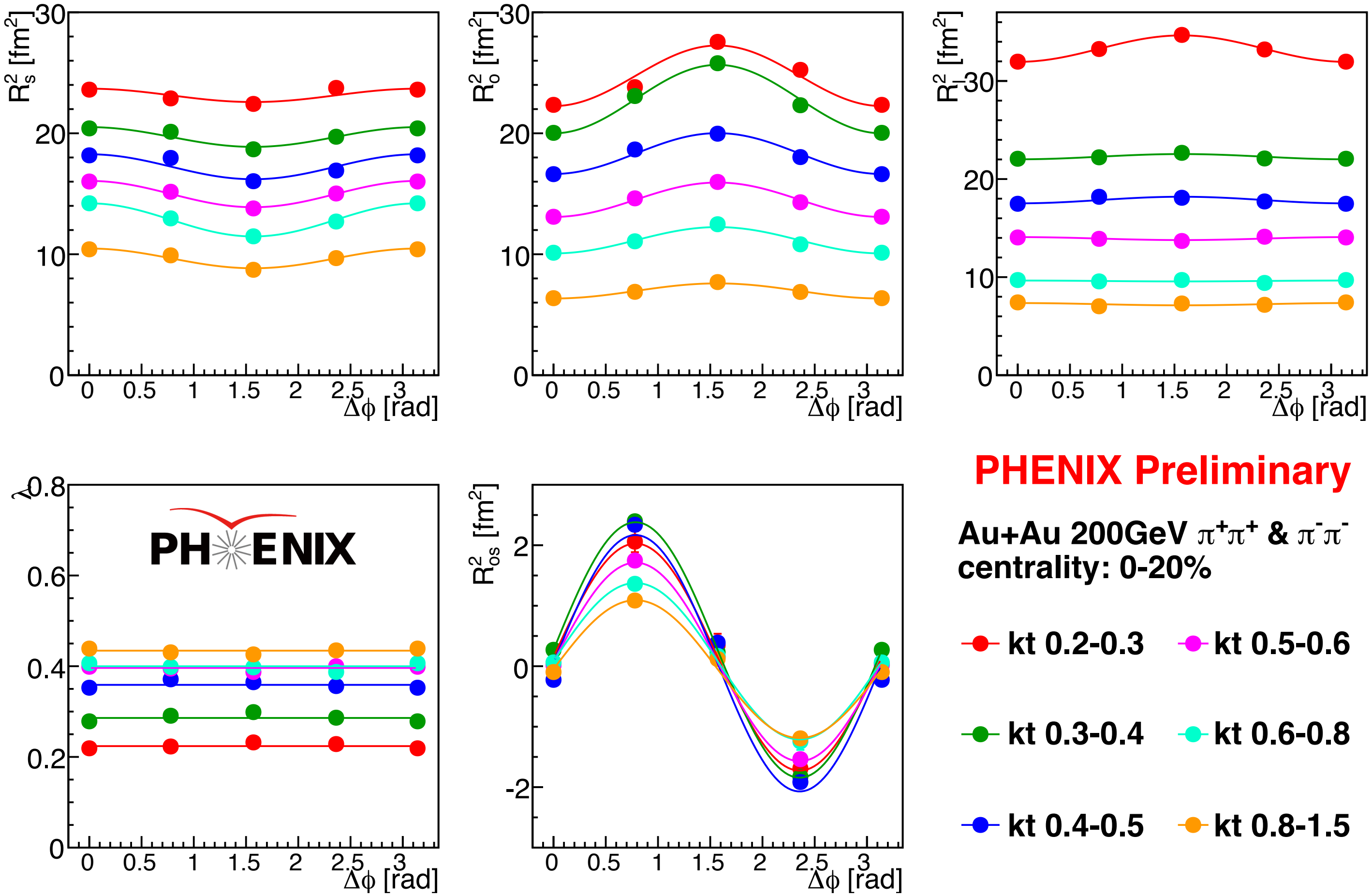
k_T dependence of azimuthal pion HBT radii in 20-60%





- Oscillation can be seen in R_s, R_o, and R_{os} for each kT regions

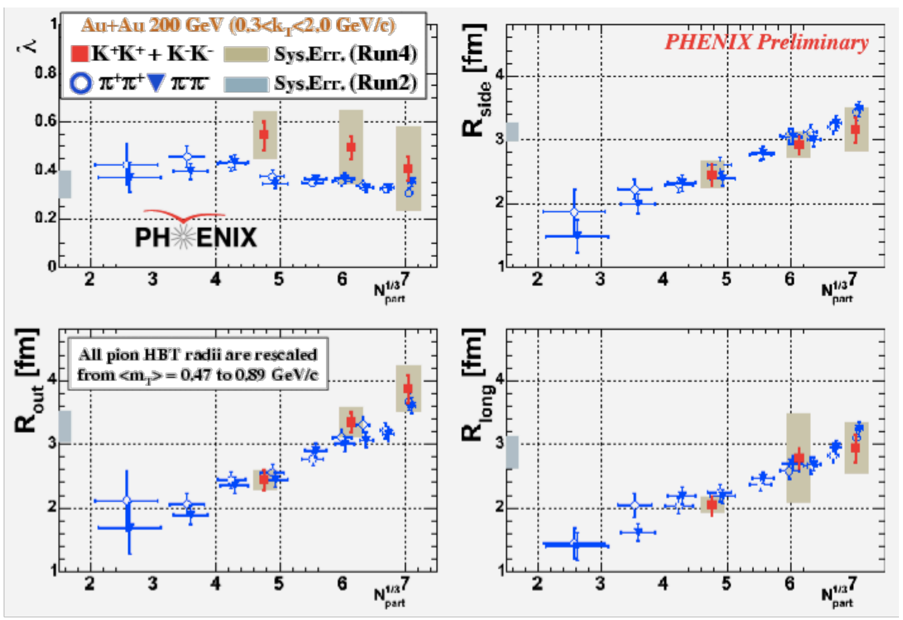
k_T dependence of azimuthal pion HBT radii in 0-20%



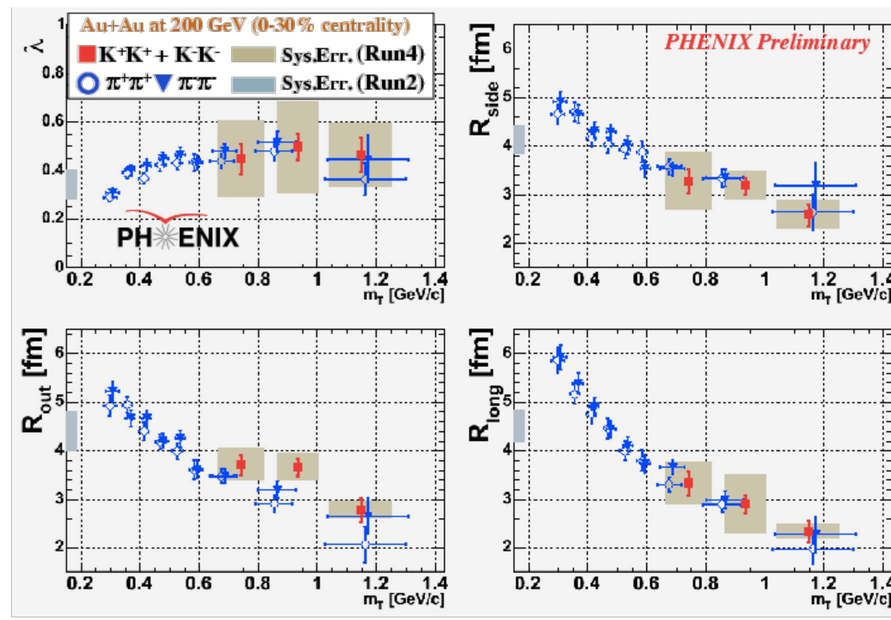
The past HBT Results for charged pions and kaons

- **Centrality / m_T dependence have been measured for pions and kaons**
  - ✧ No significant difference between both species

centrality dependence



m_T dependence



Analysis method for HBT

- **Correlation function**

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

  - Ratio of real and mixed q-distribution of pairs
    q: relative momentum

- **Correction of event plane resolution**
  - U.Heinz et al, PRC66, 044903 (2002)
- **Coulomb correction and Fitting**
  - By Sinyukov's fit function
  - Including the effect of long lived resonance decay

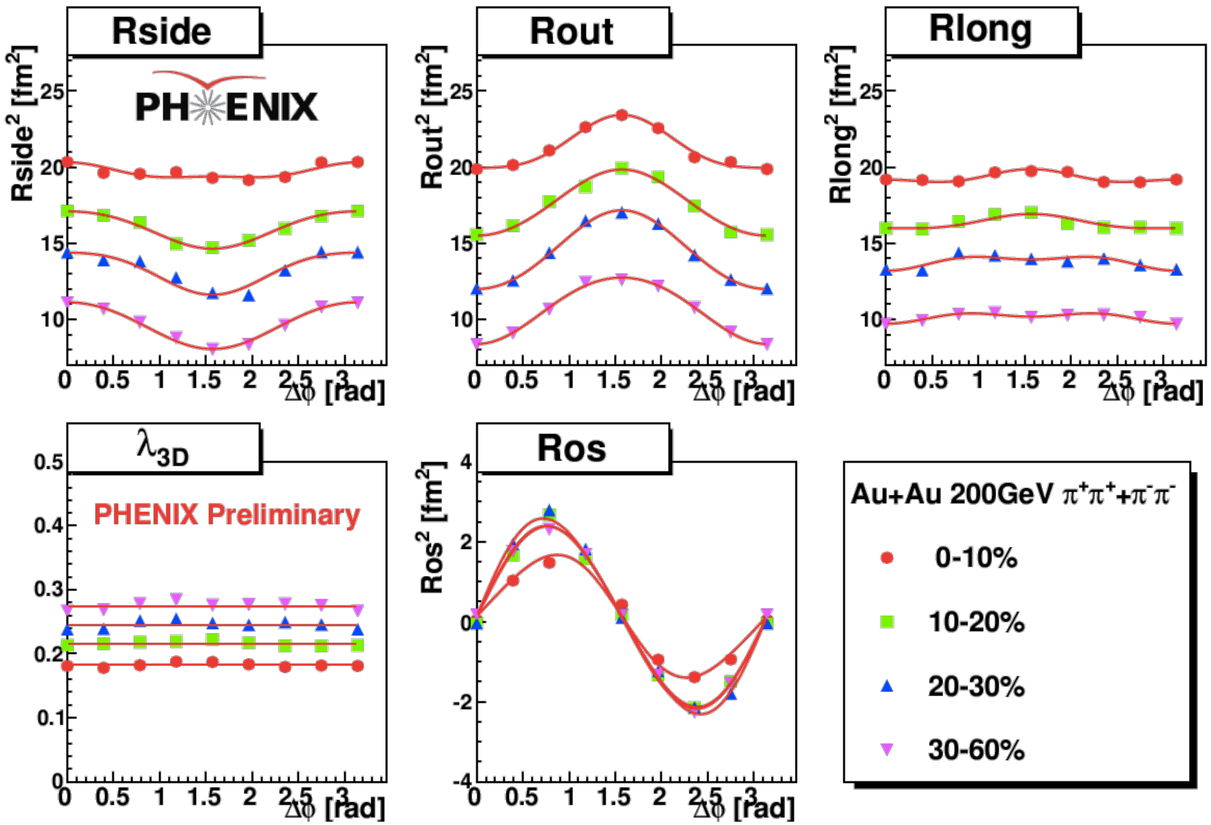
$$C_2 = C_2^{core} + C_2^{halo}$$

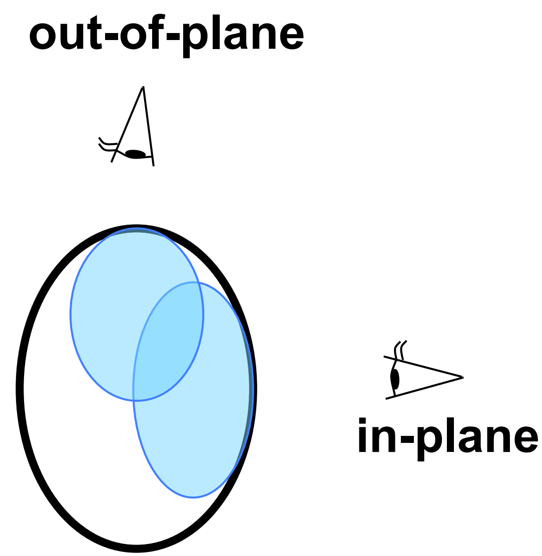
$$= N[\lambda(1+G)F] + [1-\lambda]$$

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

Azimuthal HBT radii for pions

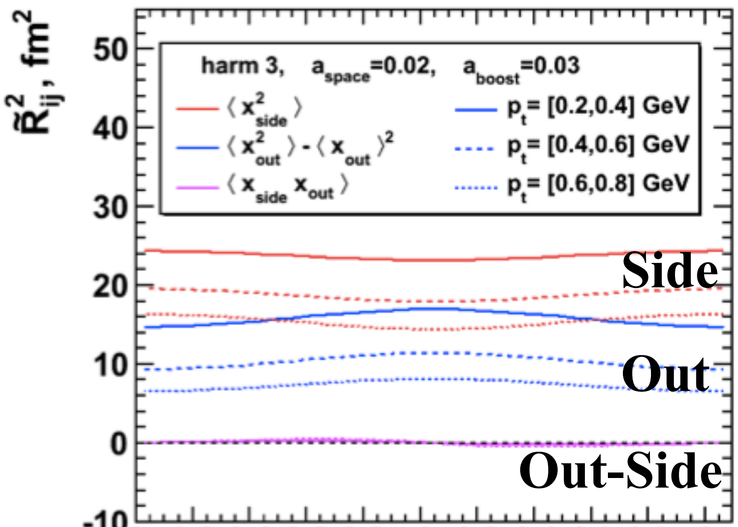
- Observed oscillation for R_{side}, R_{out}, R_{os}
- Rout in 0-10% has oscillation
  - ✧ Different emission duration between in-plane and out-of-plane?





Model predictions

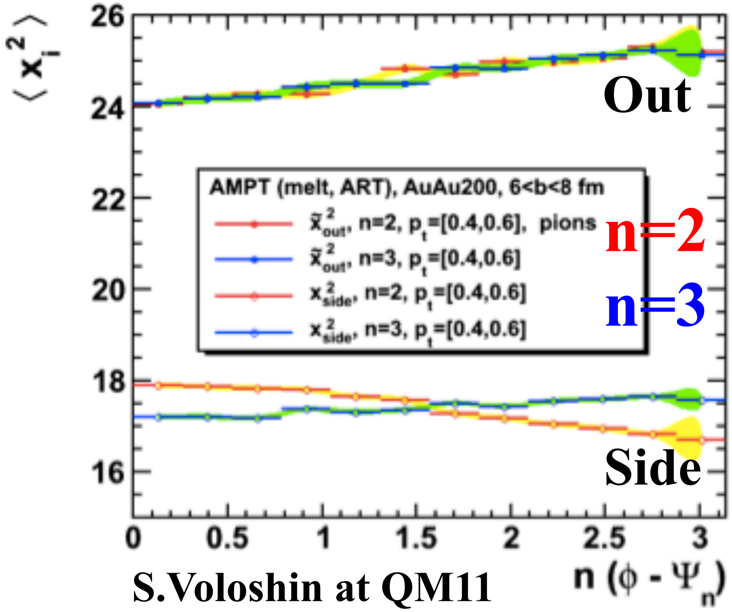
Blast-wave model



S.Voloshin at QM11

T=100[MeV], ρ=r'ρ_{max}(1+cos(nφ))

AMPT



S.Voloshin at QM11

Both models predict weak oscillation will be seen in R_{side} and R_{out}.