Detailed HBT measurement with respect to the Event plane in Au+Au 200 GeV collisions at PHENIX

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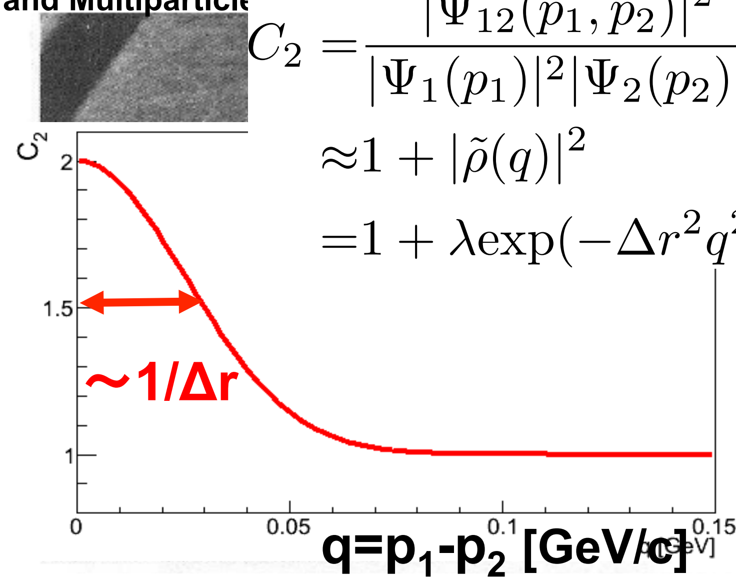
日本物理学会第68回年次大会

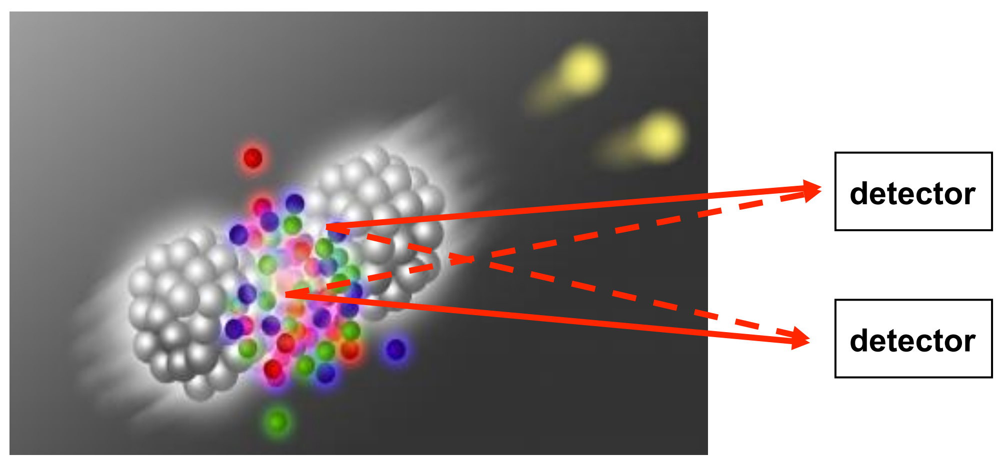
HBT Interferometry

- **HBT effect is quantum interference between two identical particles.**
- **R. Hanbury Brown and R. Twiss**
  - ✧In 1956, they measured the angular diameter of Sirius.
- **Goldhaber *et al*.**
  - ✧In 1960, they observed the correlations among identical pions in p+anti-p collision independent of HBT.

G. Goldhaber, Proc. Int. Workshop on Correlations and Multiparticle

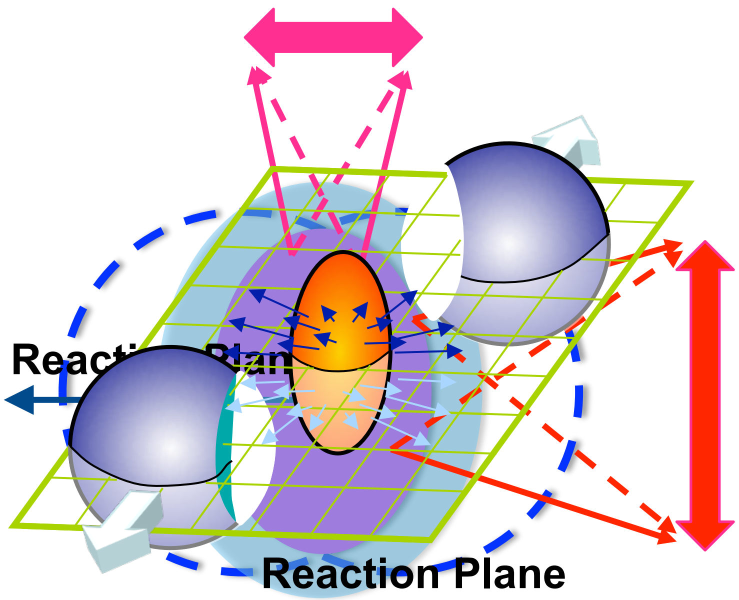
$$C_2 = \frac{|\Psi_{12}(p_1, p_2)|^2}{|\Psi_1(p_1)|^2 |\Psi_2(p_2)|^2} \approx 1 + |\tilde{\rho}(q)|^2 = 1 + \lambda \exp(-\Delta r^2 q^2)$$

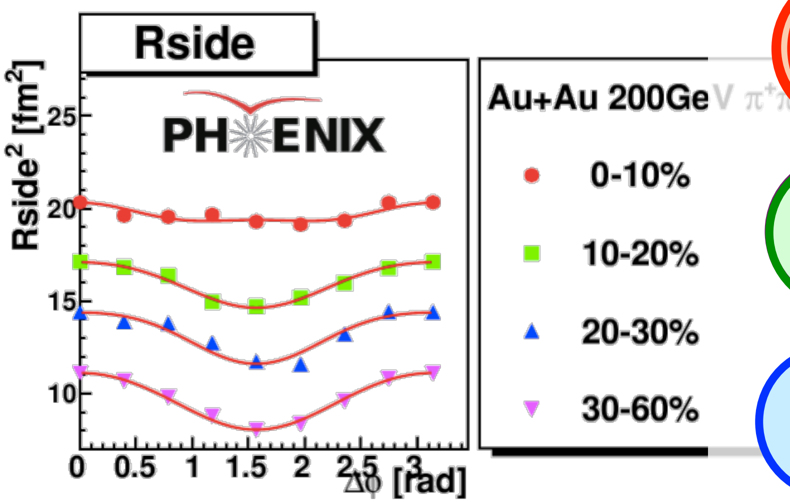


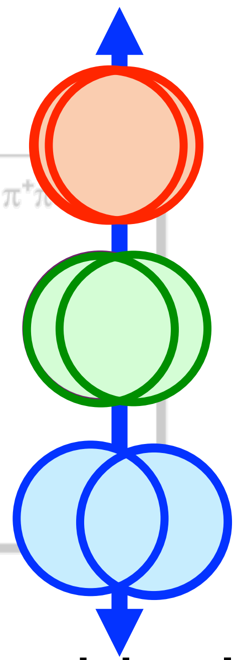


HBT with respect to Reaction Plane

- Azimuthal HBT can give us the source shape at freeze-out.
- Final eccentricity is determined by initial eccentricity, velocity profile and expansion time.
- Very useful tool to investigate space-time evolution in HI !

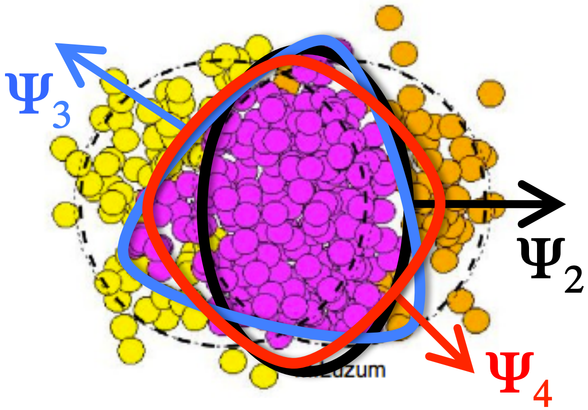






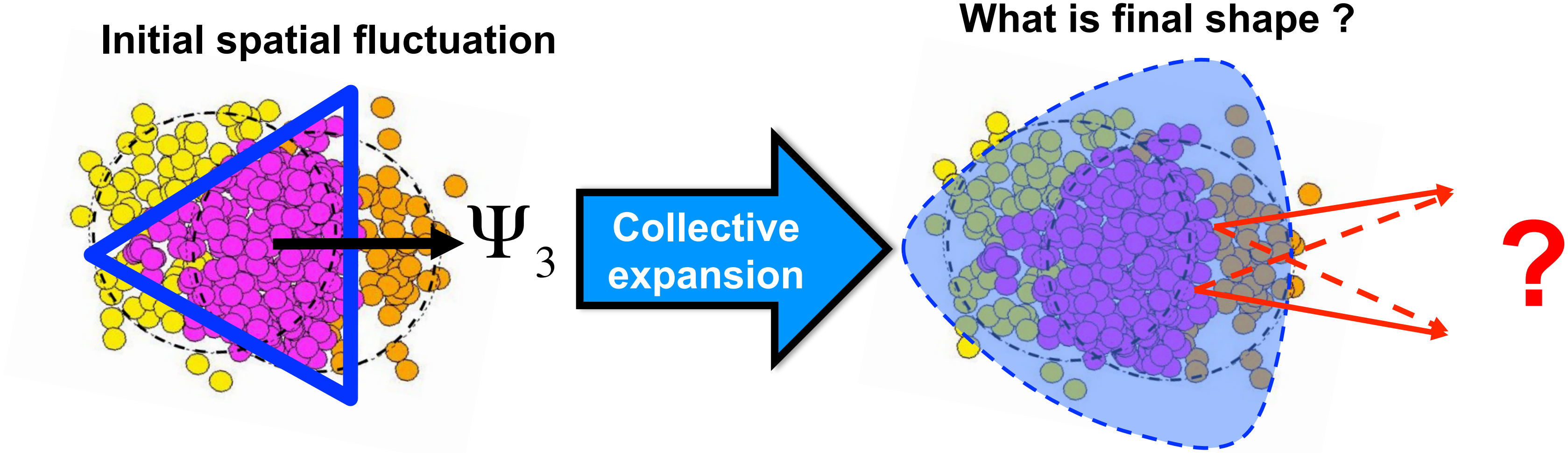
Azimuthal HBT w.r.t 3rd-order event plane

- **Higher-order flow v_n and Event plane Ψ_n**

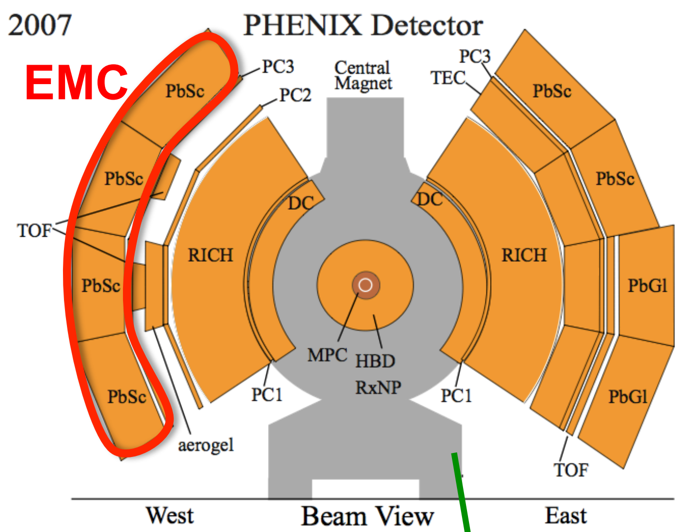


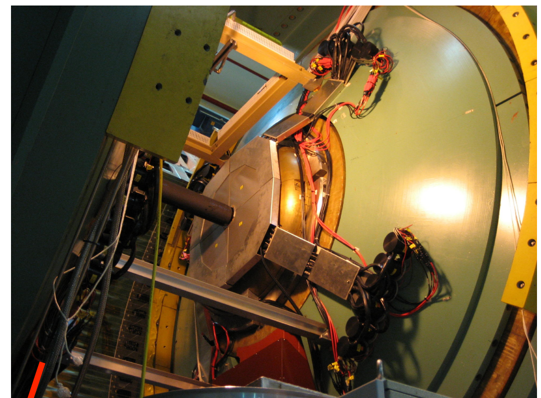
$$\frac{dN}{d\phi} \propto 1+2v_2\cos2(\phi-\Psi_2)$$
$$+2v_3\cos3(\phi-\Psi_3)$$
$$+2v_4\cos4(\phi-\Psi_4)$$
$$v_n = \langle \cos n(\phi-\Psi_n)\rangle$$

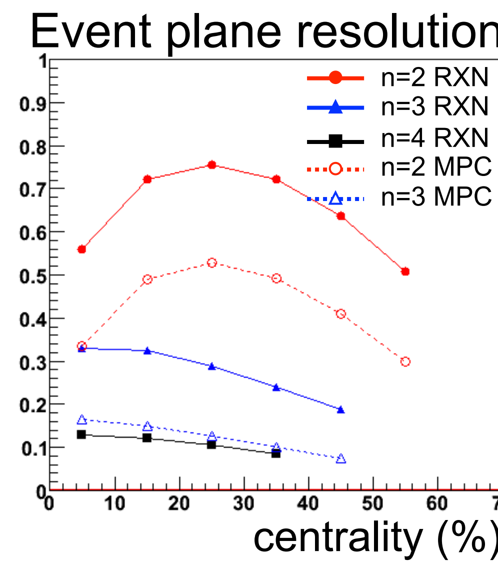
- **Is the deformation due to initial fluctuations is preserved until freeze-out?**

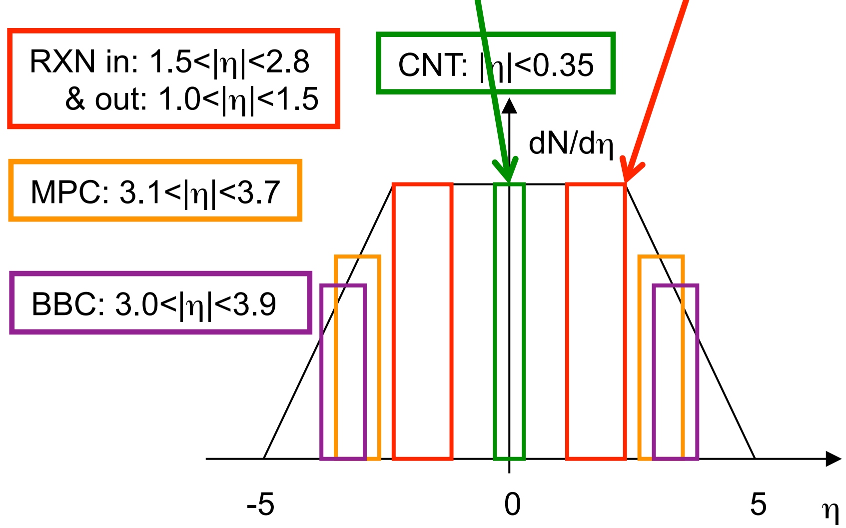


Measurement by PHENIX Detectors









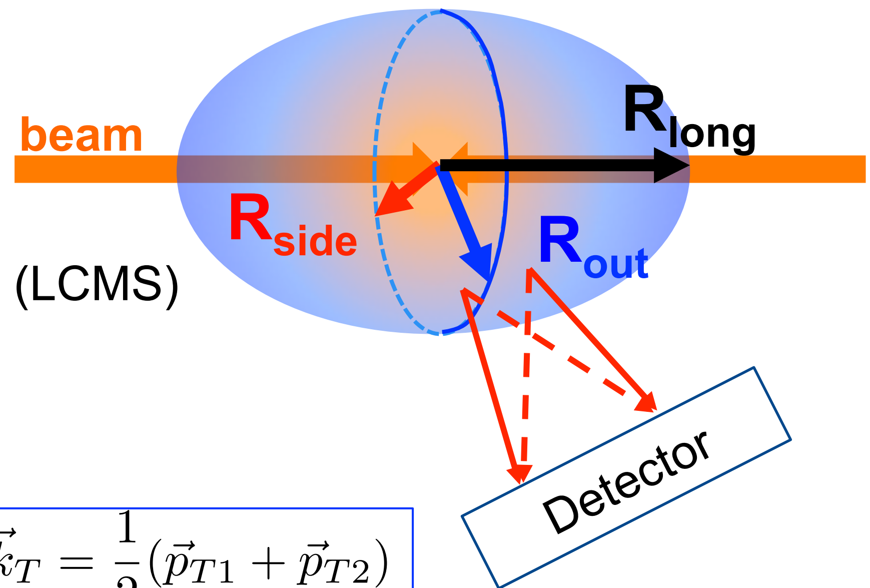
- ☆ PID by EMC-PbSc
  - ⇨ select charged π
- ☆ Ψ_n by forward detector RXN
- ☆ Correlation function C_2

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

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

3-dimensional HBT analysis

- **"Out-Side-Long" system**
  - ✧ Bertsch-Pratt parameterization
    - ✓ **L**ongitudinally **C**o-**M**oving **S**ystem (LCMS)
- **Core-halo model**
  - ✧ To deal with Coulomb interaction



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

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

$$\begin{aligned} C_2 &= C_2^{core} + C_2^{halo} \\ &= N[\lambda(1+G)F] + [1-\lambda] \end{aligned}$$

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

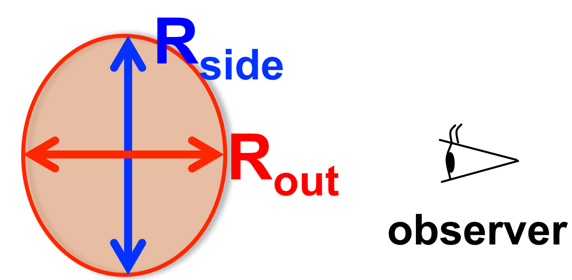
λ : chaoticity

R_{side} : transverse size

R_{out} : transverse size + emission duration

R_{os} : cross term between "out" and "side"

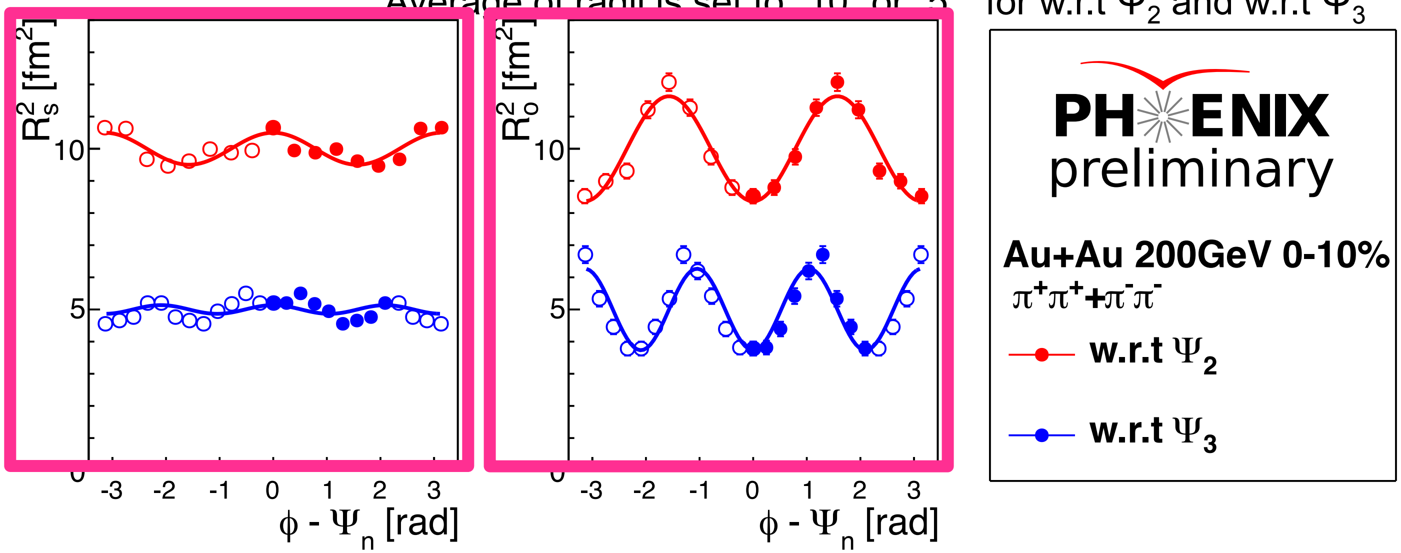
R_{long} : longtudinal size



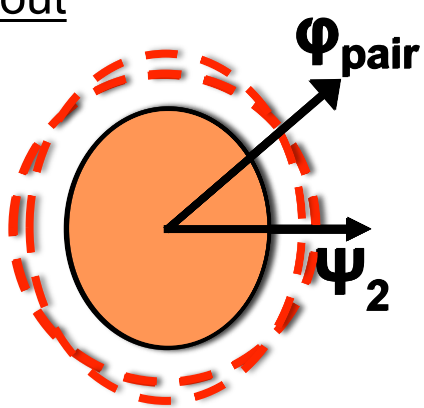
Comparison of 2nd and 3rd order component

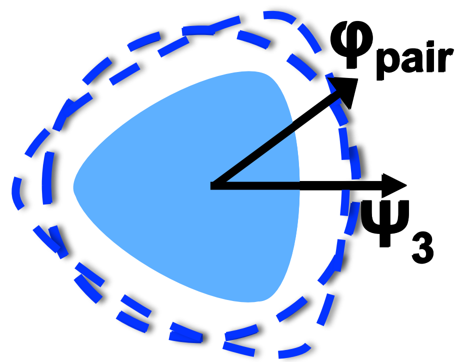
- **In 0-10%, R_{out} have stronger oscillation for Ψ_2 and Ψ_3 than R_{side}**
  - ✧ Does the emission duration depend on azimuthal angle ?
  - ✧ Different sensitivity for possible sources to make the oscillation ?

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



Rout

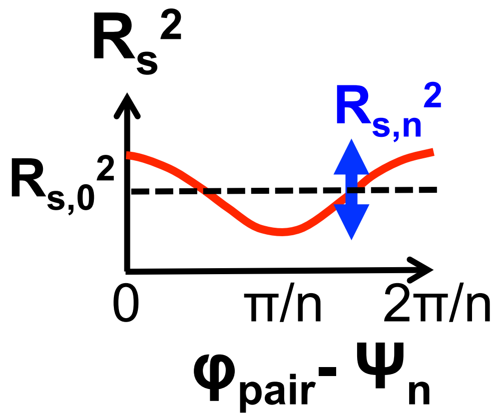




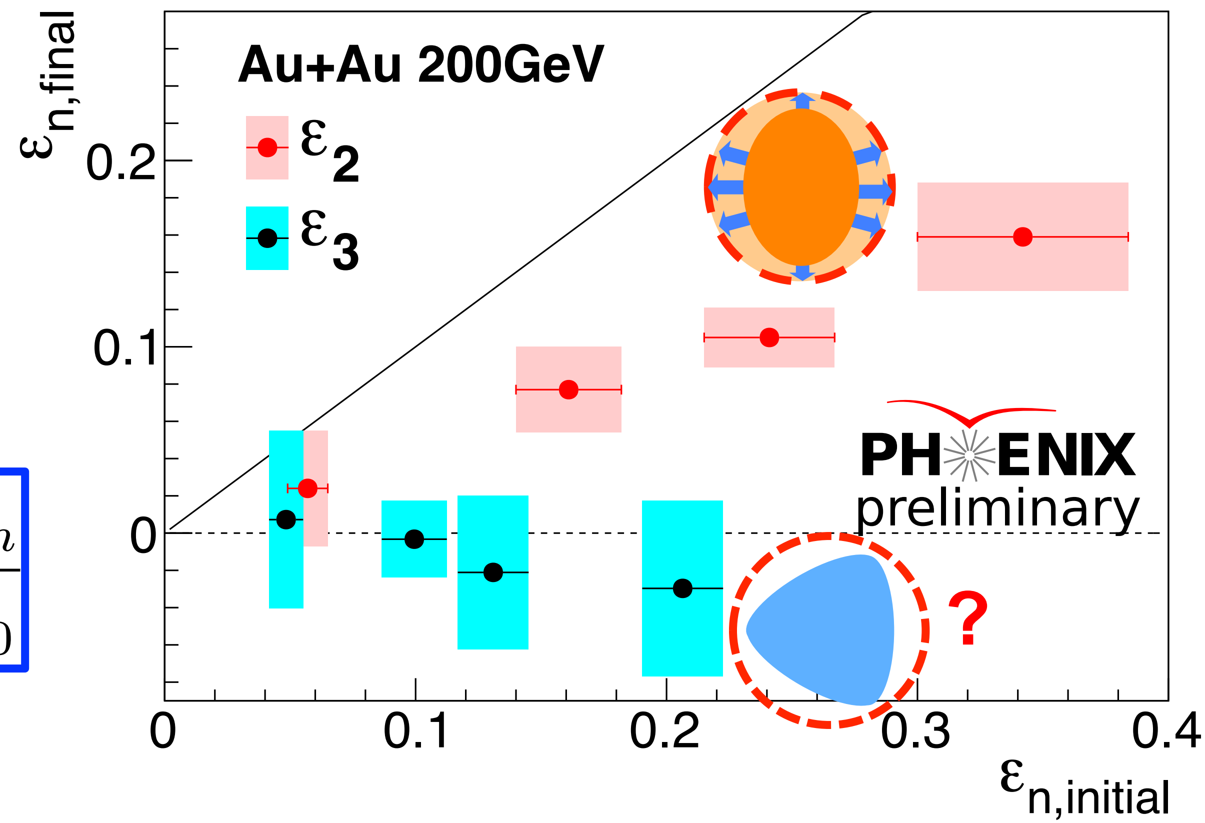
Rside

Oscillation of R_s

- **Relative amplitude of R_s for 2nd-order is used to represent "Eccentricity" at freeze-out**
  - ✧ Strong expansion to in-plane direction, but still elliptical shape !



$$\varepsilon_{n,final} = 2\frac{R^2_{s,n}}{R^2_{s,0}}$$



☆ Relative amplitudes for 3rd-order show zero~negative.
What does it indicate? Zero triangularity?

Simulation for Triangular shape

- **Main possible sources to make Ψ_3 dependence of HBT radii**
  - ✧ Spatial triangular shape in expanding source
  - ✧ Triangular flow v_3

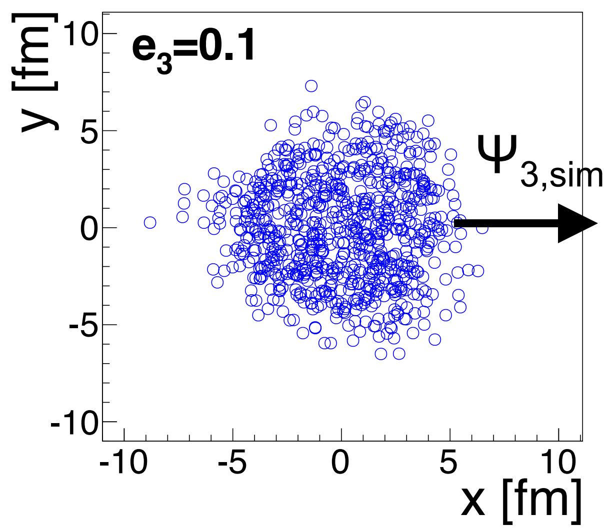
- **Setup of Monte-Carlo Simulation**
  - ✧ Assuming Woods-Saxon distribution
  - ✧ Triangular shape controlled by "e_3"
  - ✧ Triangular flow controlled by "β_3"
    - ✓ β_0 for radial flow is fixed as 0.8.

$$R_{xy} = R(1 - e_3 \cos(3\Delta\phi))$$

$$\beta_T = \tanh(\rho)$$

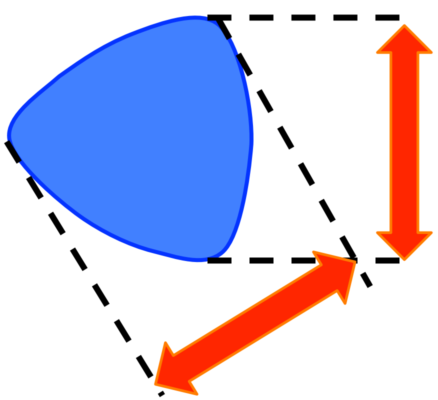
$$\rho = \tanh^{-1}[\beta_0 + \beta_3 \cos(3\Delta\phi)](\frac{r_{xy}}{R_{xy}})$$

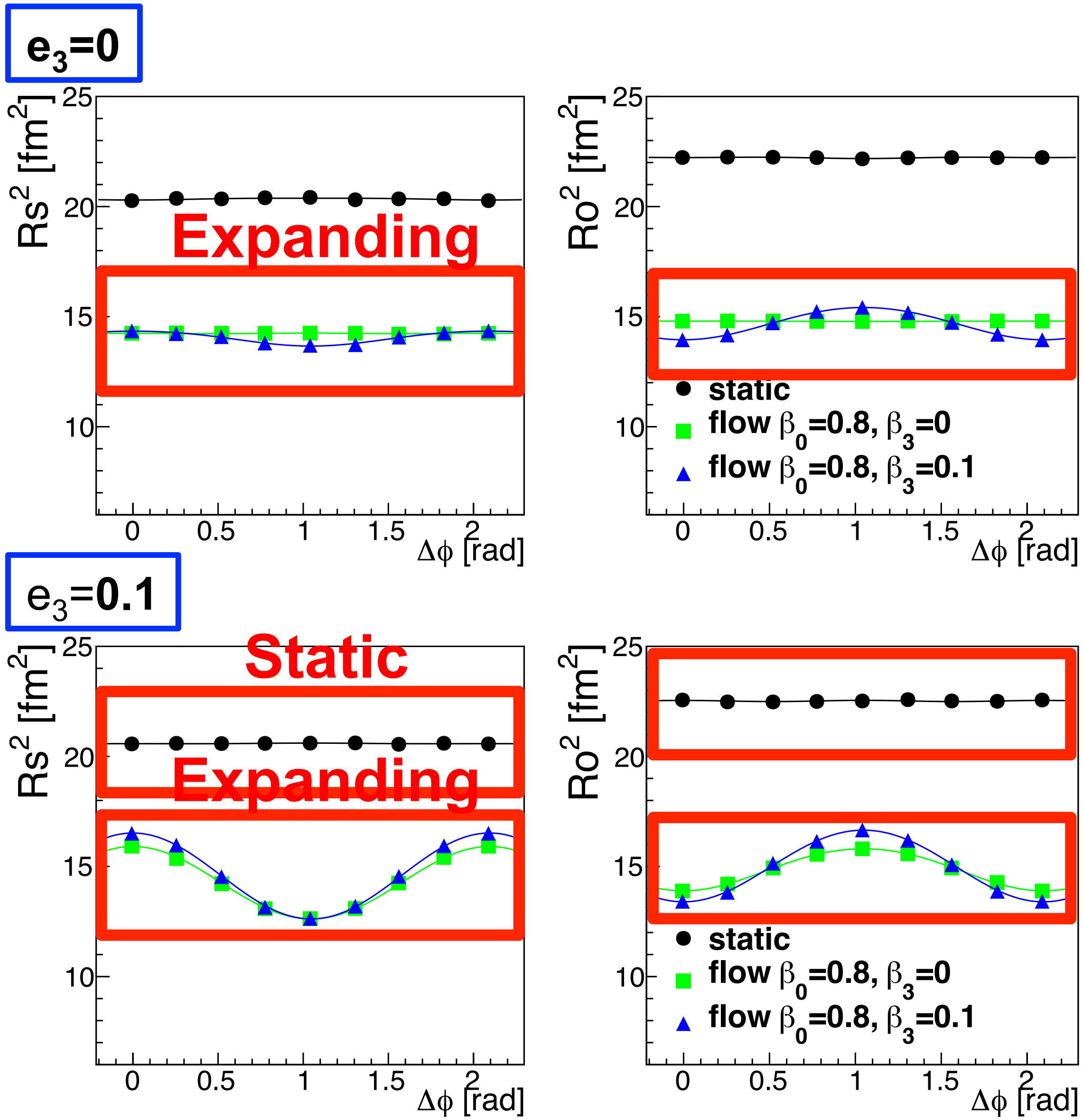
  - ✧ HBT correlation: 1+cos(Δr×Δp)
  - ✧ p_T spectra with T_f = 160 MeV
  - ✧ No Coulomb interaction, no opacity



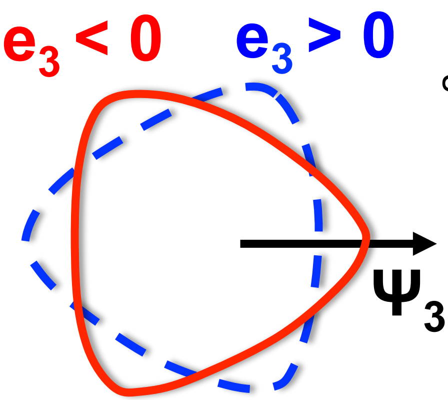
Simulation Results

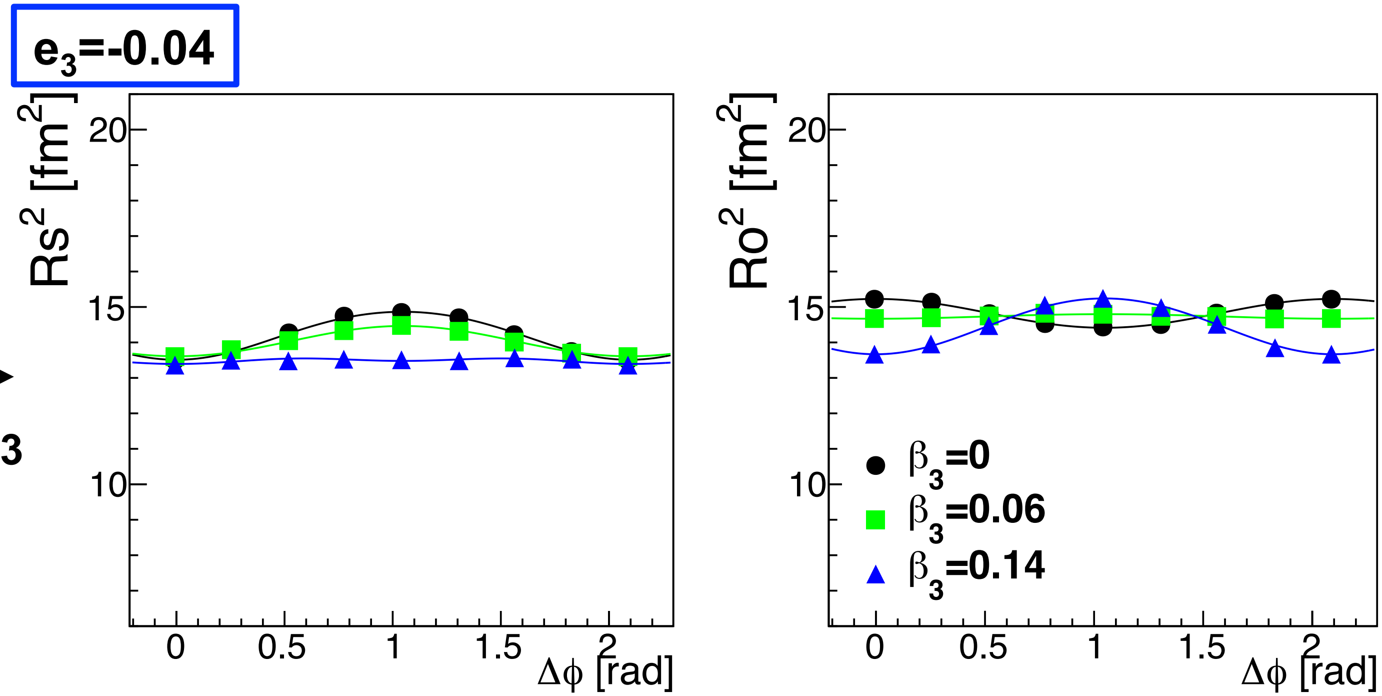
- **Static source**
  - ✧ No oscillation for triangular shape
- **Expanding source**
  - ✧ Triangular shape
    - ✓ Oscillation appears !
  - ✧ Spherical shape
    - ✓ β_3 makes oscillation !





Simulation Results





- **Oscillation is determined by triangular shape and β_3**
- **Zero oscillation does not necessarily indicate the spherical source**
  - ✧ Data is close to the situation with e_3<0 and finite β_3
  - ✧ Negative e_3 may indicate that initial triangular deformation is modified by triangular flow

Summary

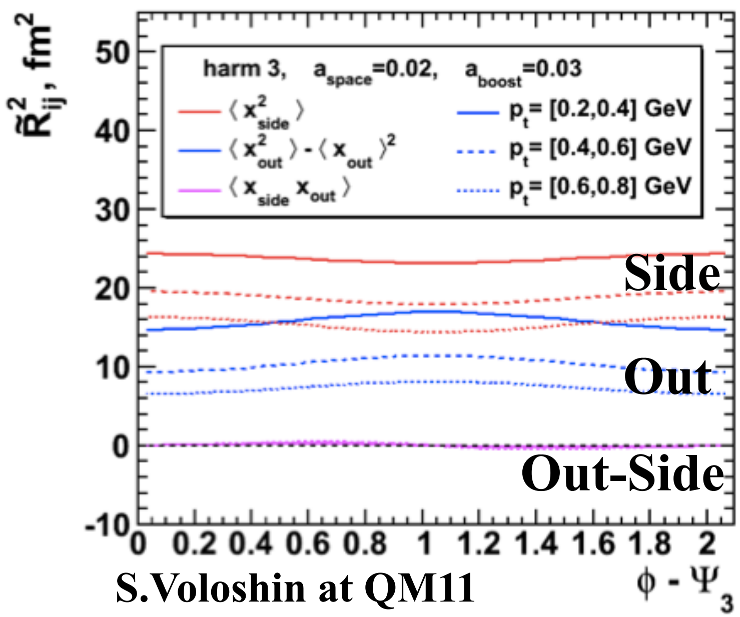
- **Azimuthal HBT radii w.r.t v_3 plane**
  - ✧First measurement of Ψ_3 dependent HBT radii have been presented.
  - ✧Oscillation of R_s is very weak, almost zero or slightly negative sign.
  - ✧R_o clearly has finite oscillation in most central collisions.
    - ☛ Different emission duration for azimuthal angle ?

- **Monte-Carlo simulation of HBT for triangular source**
  - ✧Ψ_3 dependence of HBT radii will be determined by the balance of triangular flow and spatial triangularity.
  - ✧Data in 0-10% is close to the source with negative e_3 and finite β_3. Initial triangular deformation may be modified by triangular flow.

Back up

Model Calculations

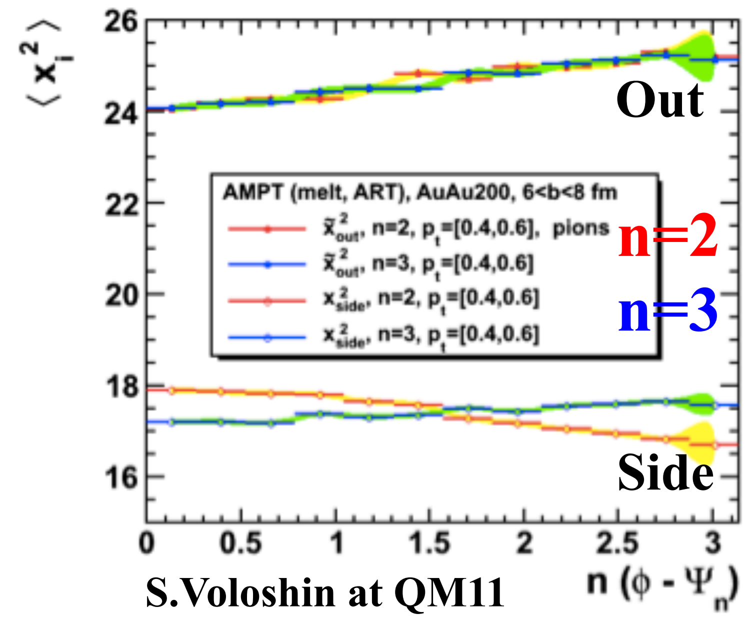
Blast-wave model



S.Voloshin at QM11

T=100[MeV], $\rho = r' \rho_{max}(1+\cos(n\varphi))$

AMPT



S.Voloshin at QM11

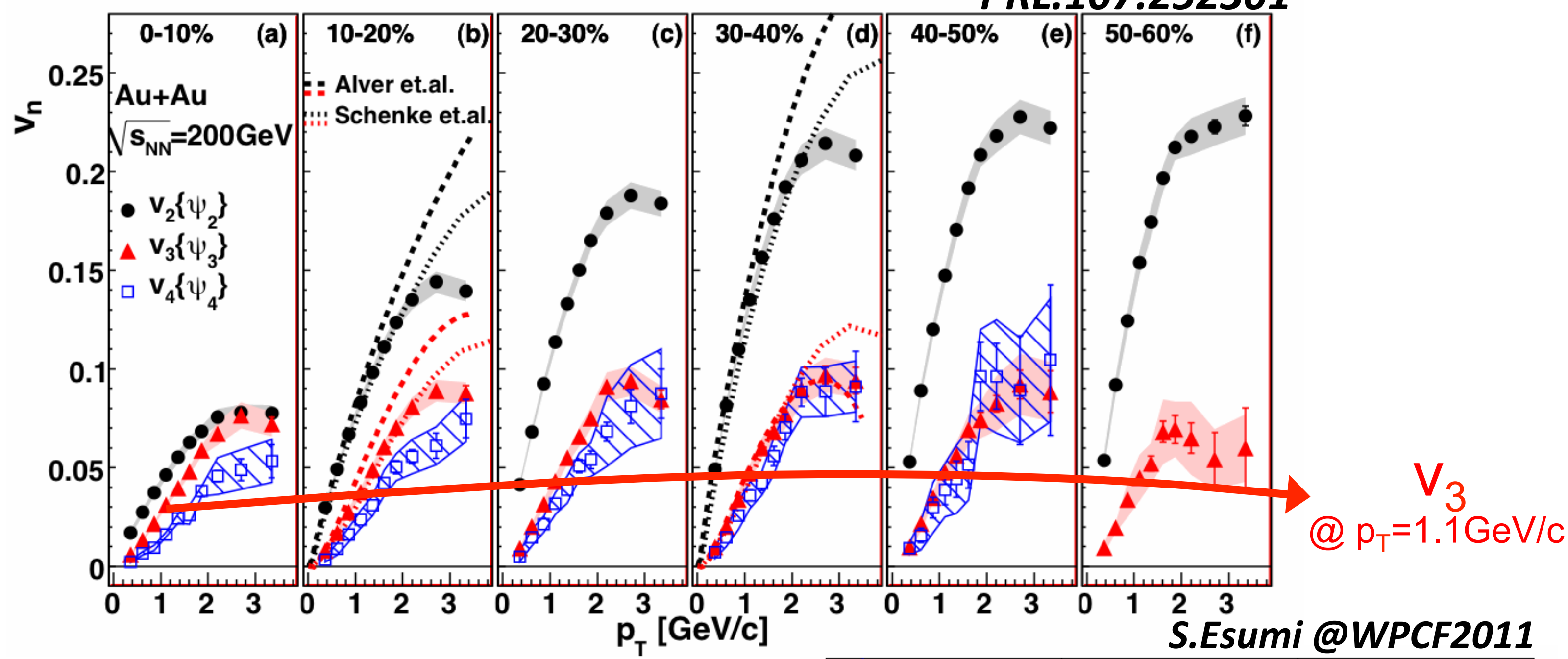
Both models predict weak oscillation will be seen in R_{side} and R_{out}.

BW ▷▶ Opposite sign of R_{side} and R_{out}

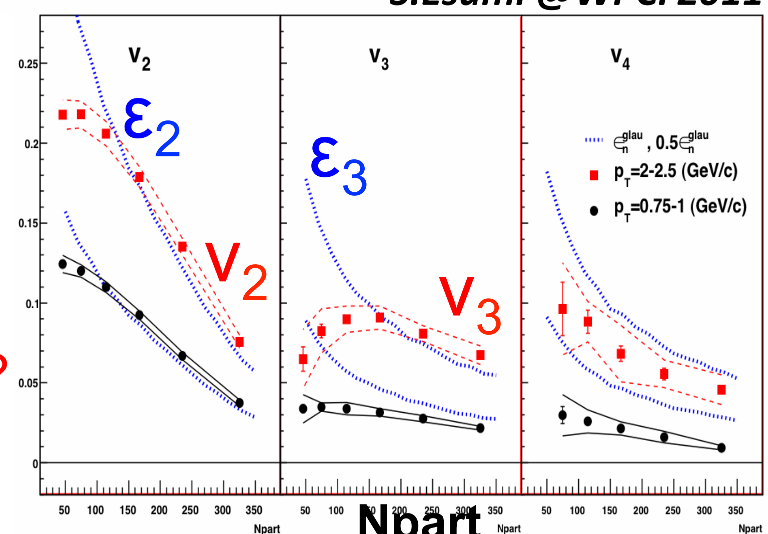
AMPT ▷▶ Same sign of R_{side} and R_{out}

Centrality dependence of v_3 and ε_3

PRL.107.252301



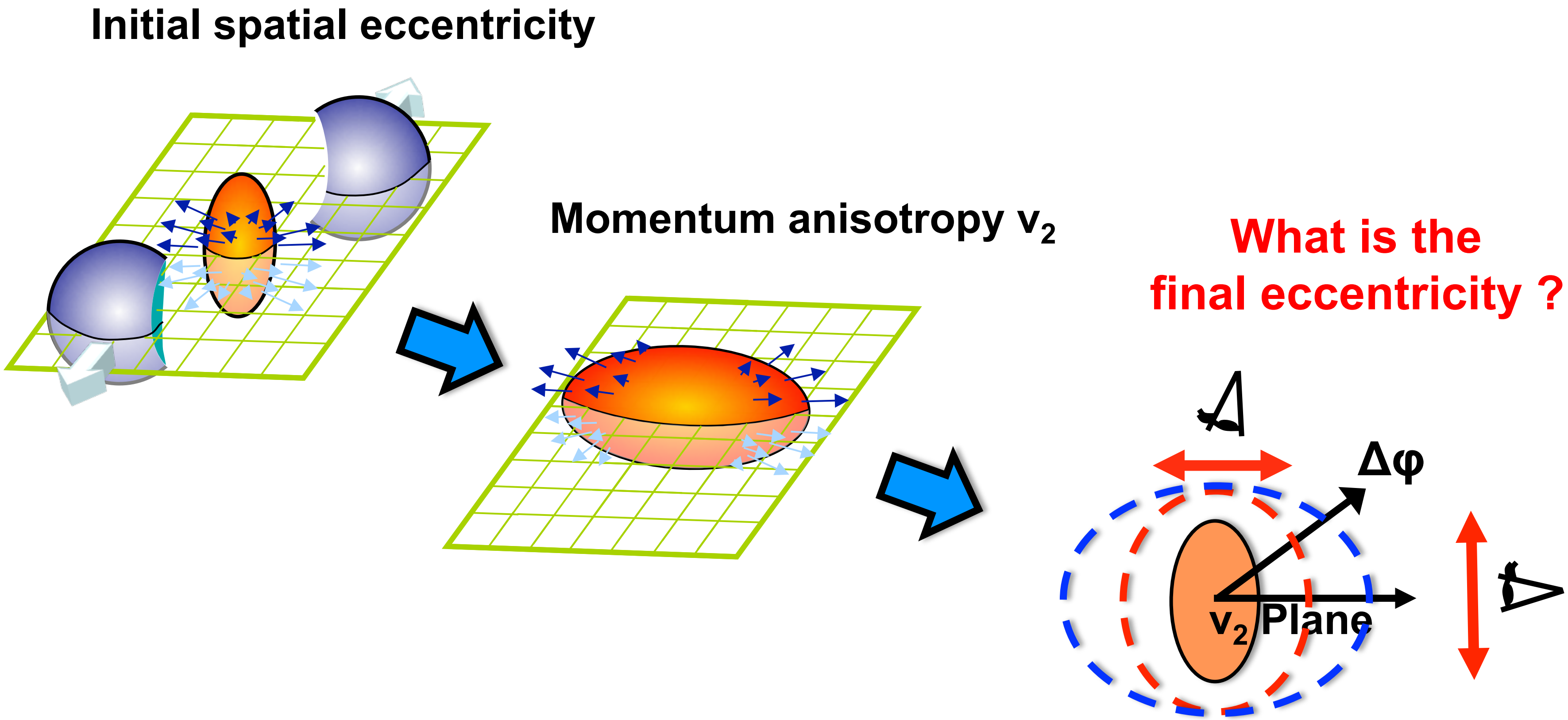
S.Esumi @WPCF2011



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

Final ε_3 has any centrality dependence?

Azimuthal HBT w.r.t v_2 plane

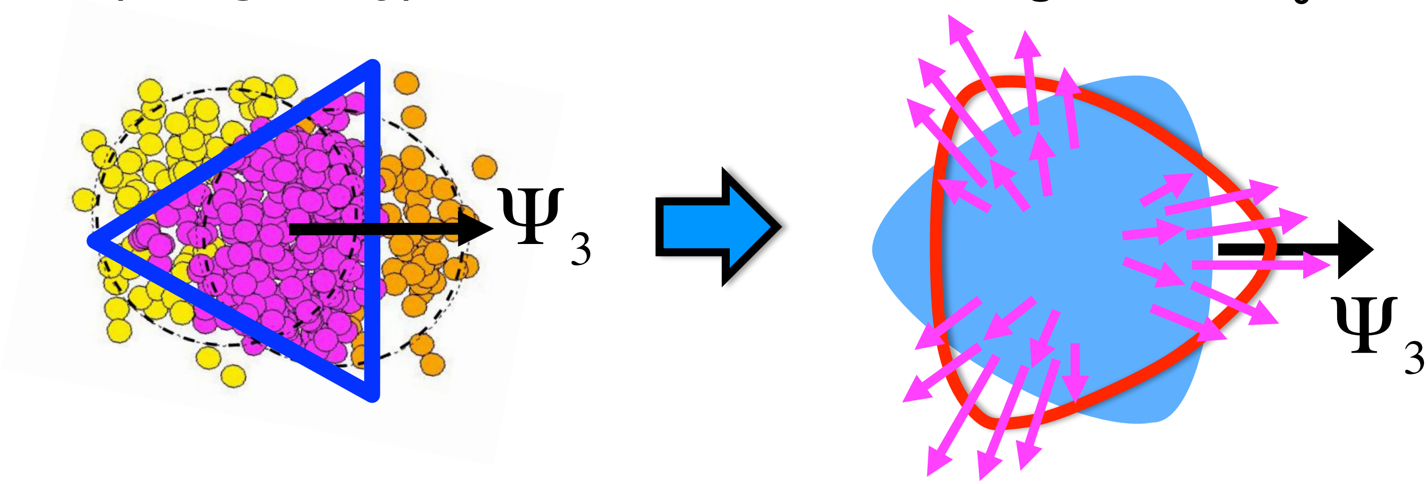


- **Final eccentricity can be measured by azimuthal HBT**
  - ✧It depends on initial eccentricity, pressure gradient, expansion time, and velocity profile, etc.
  - ✧Good probe to investigate system evolution

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

3D HBT radii

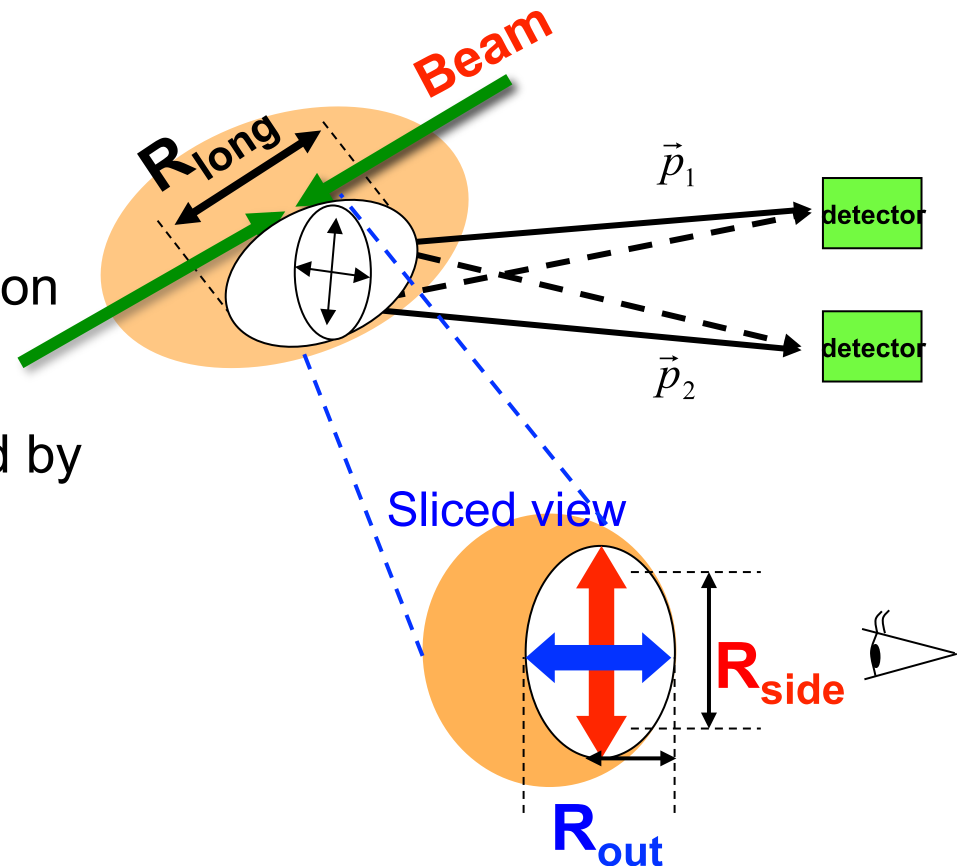
- **"Out-Side-Long" system**
  - ✧ Bertsch-Pratt parameterization
- **Core-halo model**
  - ✧ Particles in core are affected by coulomb interaction

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

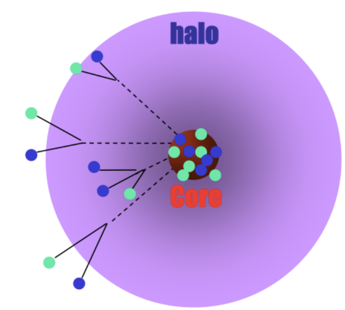
$$= N[\lambda(1+G)F] + [1-\lambda]$$

$$G = \exp(-R_{inv}^2 q_{inv}^2)$$

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



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



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

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

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

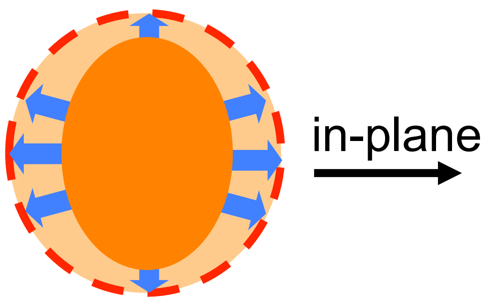
$$G = \exp(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2 - 2R_{os}^2 q_{side} q_{out})$$

Eccentricity at freeze-out

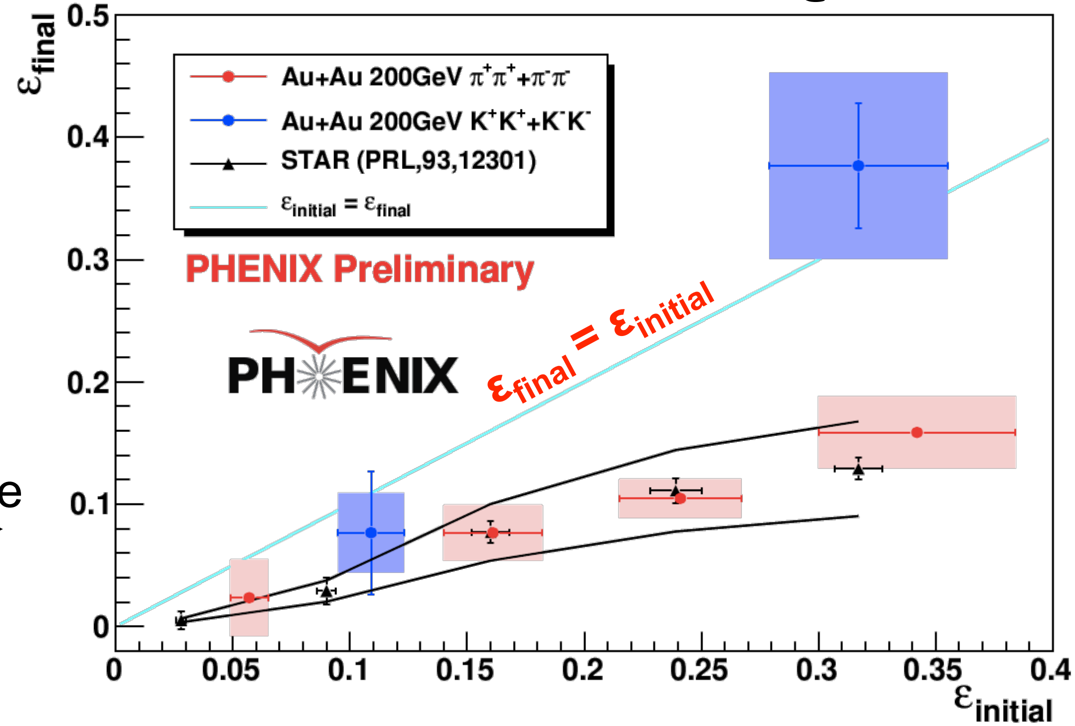
R_s^2 PRC70, 044907 (2004)

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

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

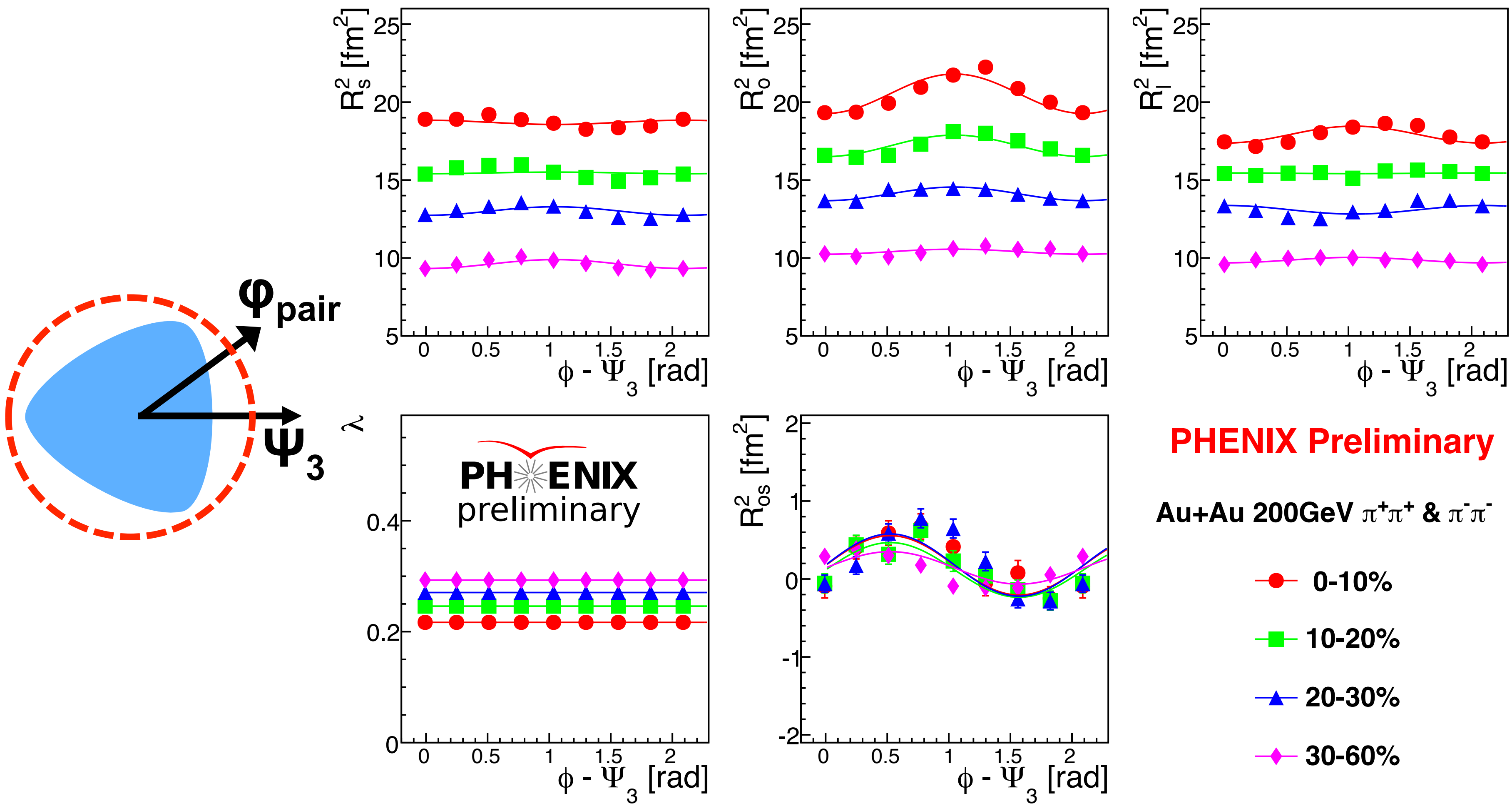


@WPCF2011



- **$\varepsilon_{final} \approx \varepsilon_{initial}/2$ 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?

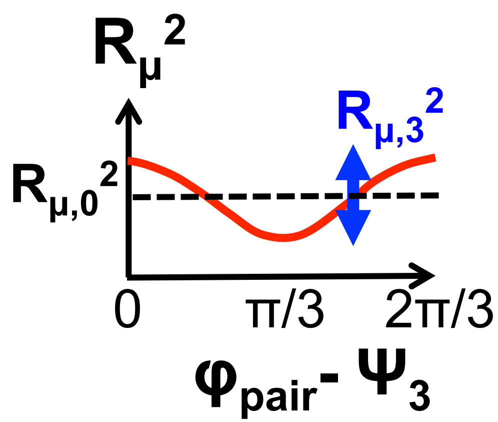
Azimuthal HBT radii w.r.t Ψ_3

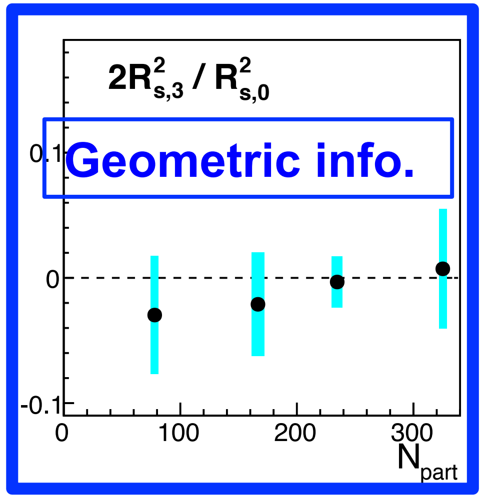


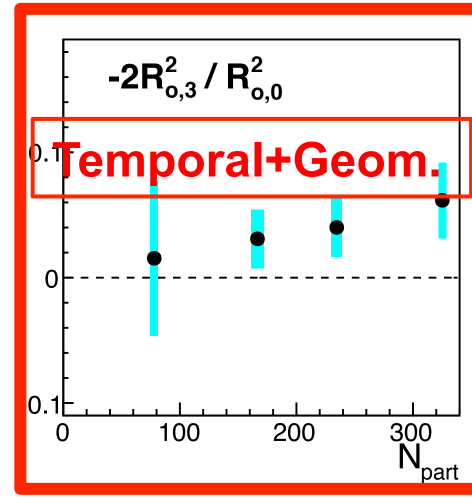
- R_{side} is almost flat
- R_{out} have a oscillation in most central collisions

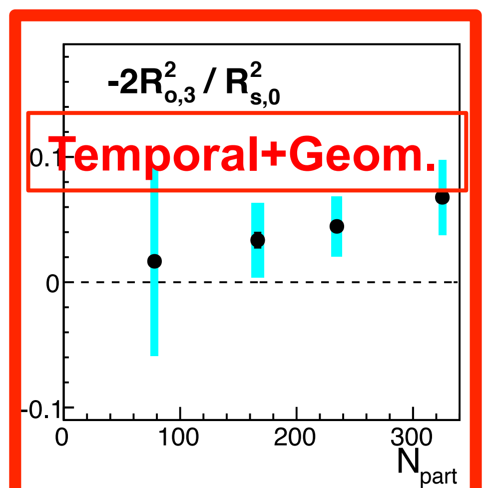
Relative amplitude of HBT radii

- **Similar definition with "final eccentricity"**
- **Relative amplitude of R_{out} increases with increasing N_{part}**





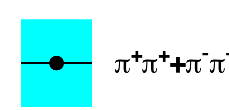




PHENIX Preliminary

PHENIX preliminary

Au+Au 200GeV



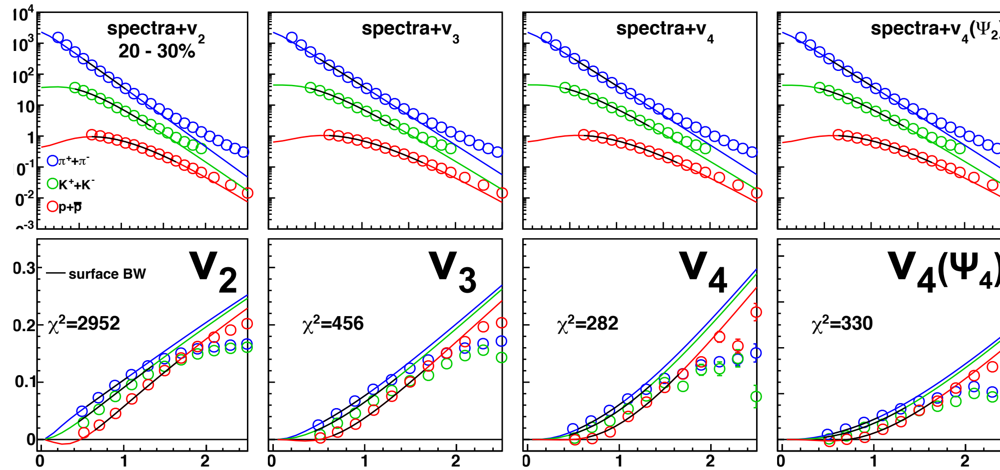
Freeze-out parameters extracted by Blast wave model

S. Mizuno, QM12

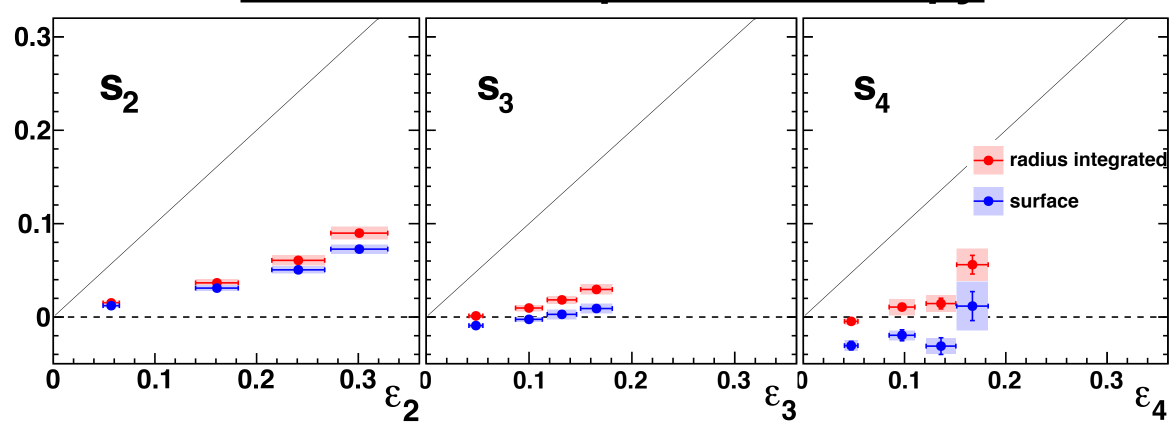
- **Blast wave fit for spectra & v_n**
  - ✧Parameters used in the model

    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

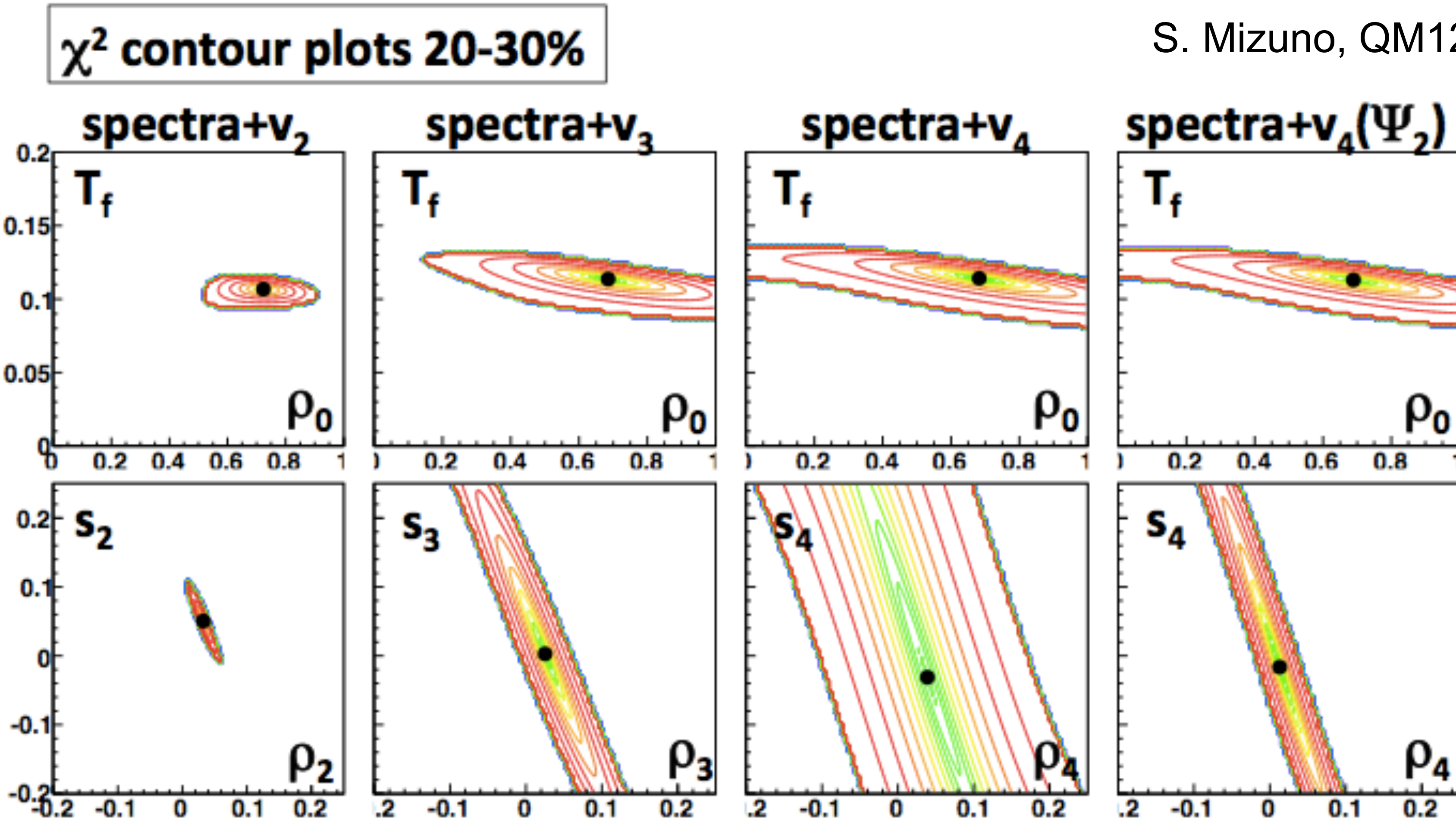


- ✧s_2 increase with going to peripheral collisions
- ✧s_3 is almost zero

☞ Similar results with HBT

Contour plot ρ_n vs s_n

S. Mizuno, QM12

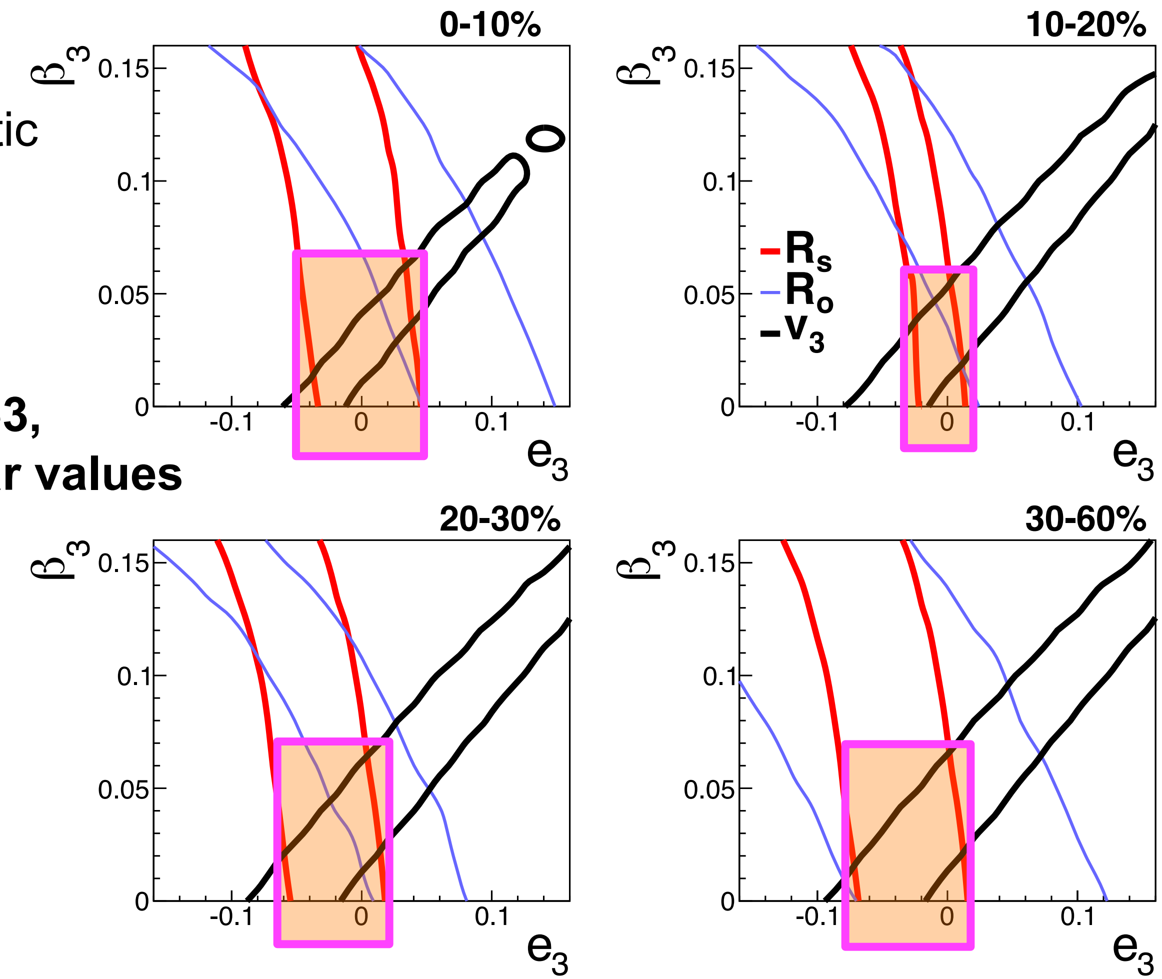


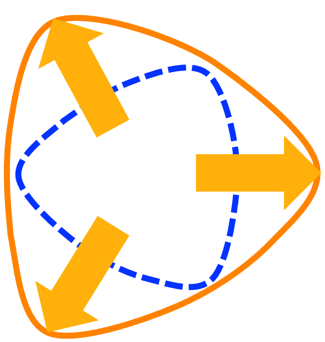
Parameter Search of β_3 vs e_3

- **Difference between data and simulation are shown as contour plot**

- The contours for R_μ represents the systematic error of the data.

- **Overlap of v_3 and R_s indicates 0~negative e3, where β_3 shows similar values in all centralities.**





☆ **v_3 flow may overcome the initial triangular deformation !**

Summary

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  - ✧First measurement of Ψ_3 dependent HBT radii have been presented.
  - ✧Oscillation of R_s is very weak, almost zero or slightly negative sign.
  - ✧R_o clearly has finite oscillation in most central collisions.
    - ☛ Different emission duration for azimuthal angle ?

- **Monte-Carlo simulation of HBT for triangular source**
  - ✧Ψ_3 dependence of HBT radii will be determined by the balance of triangular flow and spatial triangularity.
  - ✧R_s and v_3 indicates that the parameter e_3 has a zero to negative value. Initial triangular deformation may be modified by triangular flow.
  - ✧R_o oscillation doesn't seem to be explained only by e_3 and β_3.
    - ✓ Related to different sensitivity to β_3 between R_s and R_o ?
    - ✓ Different emission duration for azimuthal angle ?