Measurement of Quantum Interference of Two Identical Particles with respect to the Event Plane in Relativistic Heavy Ion Collisions at RHIC-PHENIX

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outline

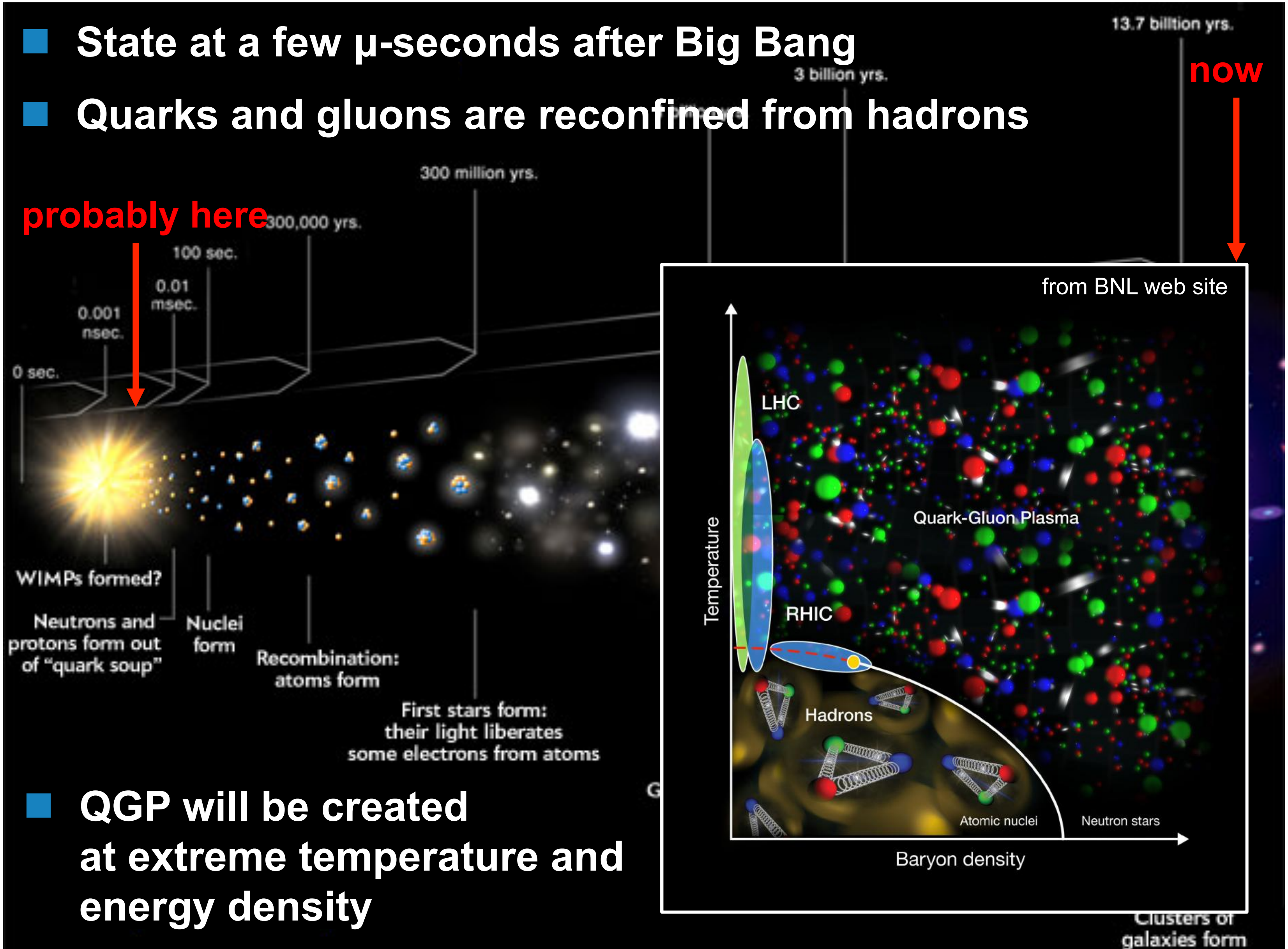
- **Introduction**
  - HBT Interferometry
  - Motivation
- **Analysis**
  - PHENIX Detectors
  - Analysis Method for HBT
- **Results & Discussion**
  - HBT measurement with respect to 2^{nd}-/3^{rd}-order event plane
  - Blast-wave model
  - Monte-Carlo simulation
- **Summary**

Introduction

Quark Gluon Plasma (QGP)

http://www.scientificamerican.com/

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

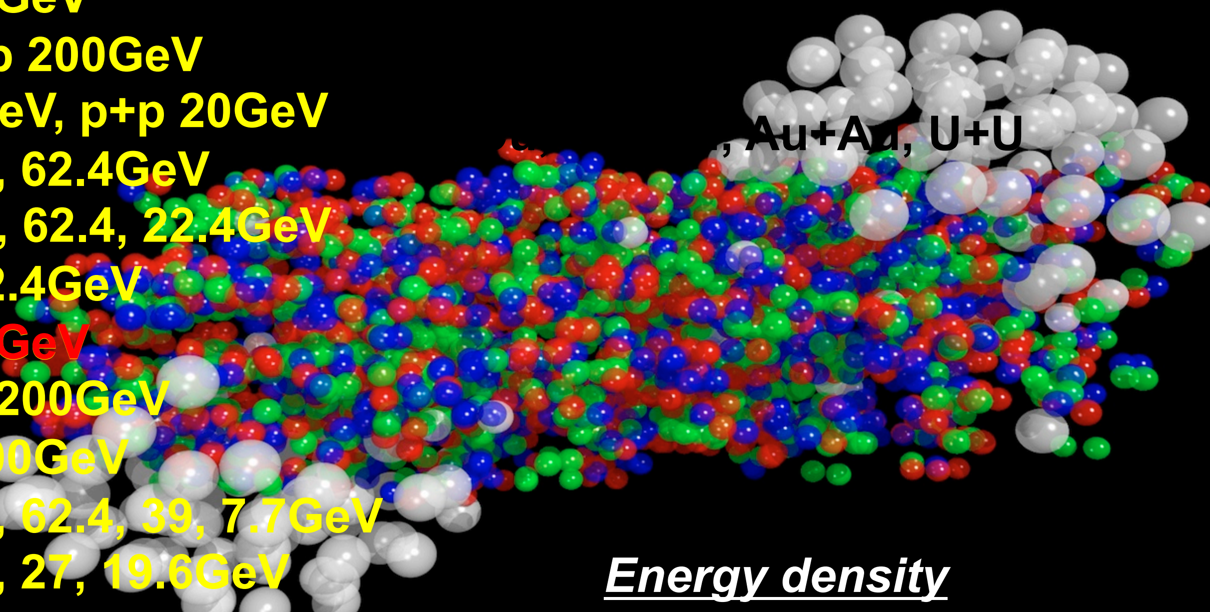


- QGP will be created at extreme temperature and energy density

Relativistic Heavy Ion Collisions

- **Relativistic Heavy Ion Collider is an unique tool to create QGP.**

Year	Species/Energy
2001	Au+Au 130GeV
2002	Au+Au, p+p 200GeV
2003	d+Au 200GeV, p+p 20GeV
2004	Au+Au 200, 62.4GeV
2005	Cu+Cu 200, 62.4, 22.4GeV
2006	p+p 200, 62.4GeV
2007	Au+Au 200GeV
2008	d+Au, p+p 200GeV
2009	p+p 200, 500GeV
2010	Au+Au 200, 62.4, 39, 7.7GeV
2011	Au+Au 200, 27, 19.6GeV
2012	U+U 193GeV, Cu+Au 200GeV

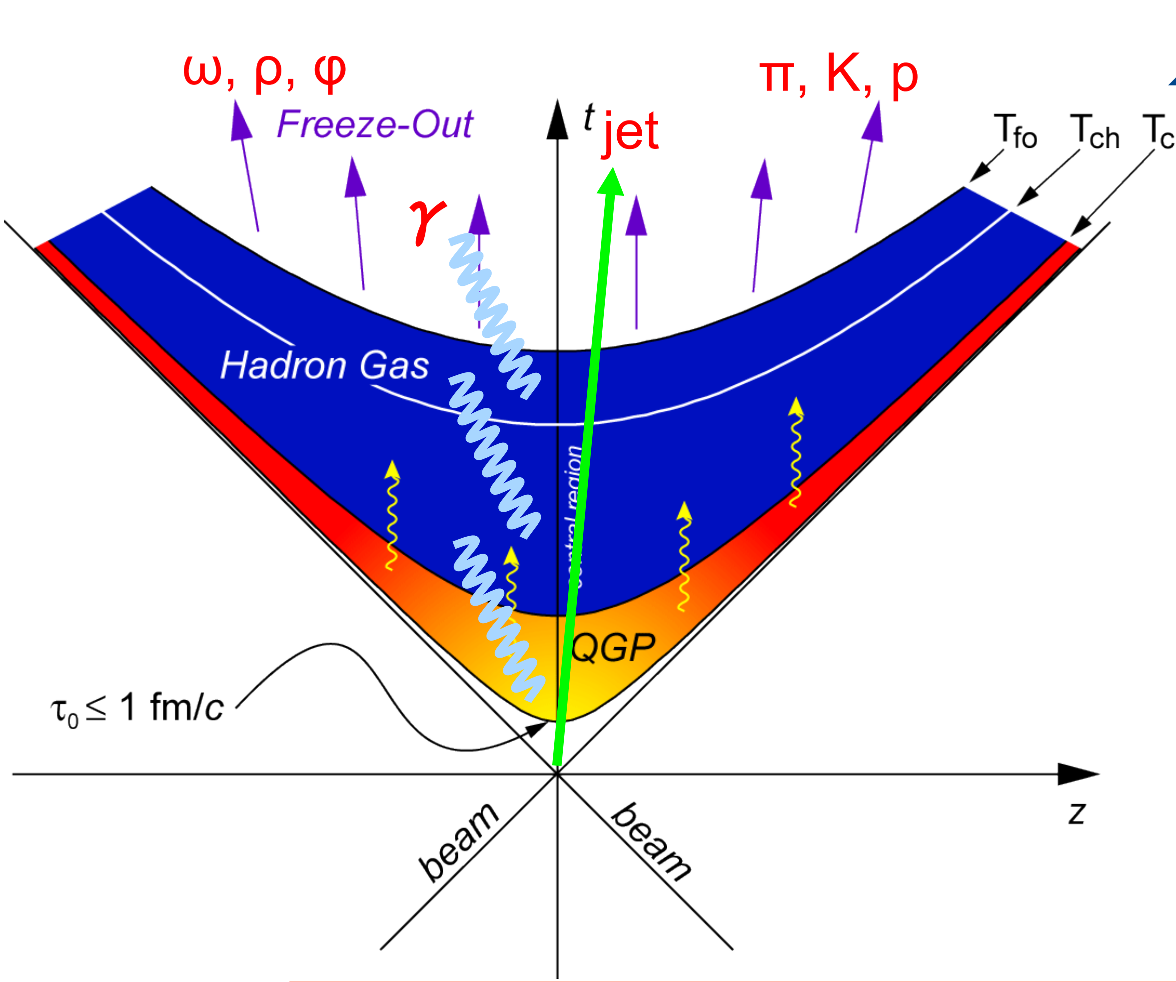


Energy density

- Lattice QCD calculation
  $T_c \sim 170$ MeV
  $\varepsilon_c \sim 1$ GeV/fm^3

- Au+Au 200GeV @RHIC
  $\varepsilon_{Bj} \sim 5$ GeV/fm$^3 > \varepsilon_c$

Space-Time Evolution



5. Thermal freeze-out

4. Chemical freeze-out

3. Phase transition
Hadronization

2. Partonic thermalization
QGP state

1. Collision occurs

How fast the system thermalizes and evolves?
How much the system size?
What is the nature of phase transition?

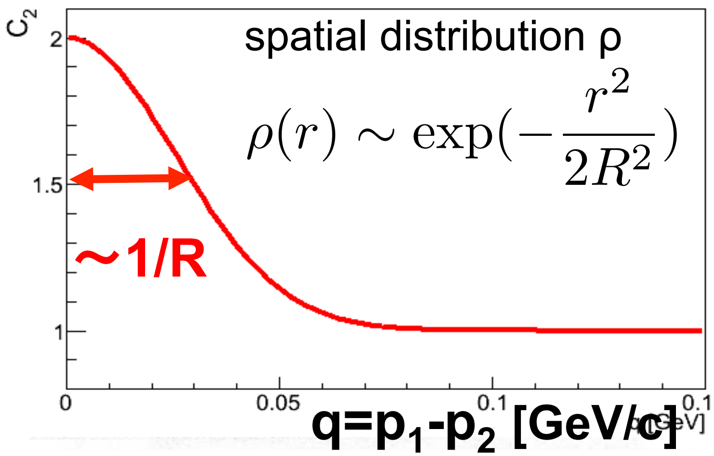
HBT Interferometry

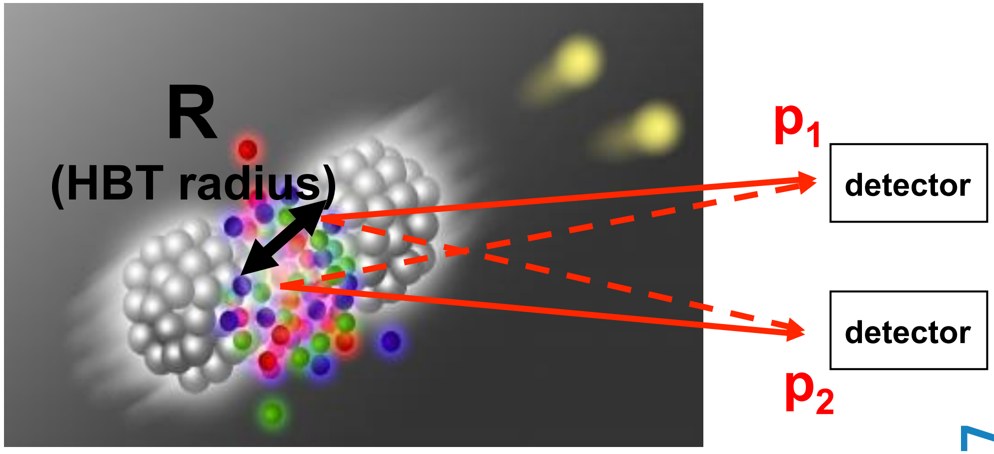
HBT effect is quantum interference between two identical particles.

- **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.

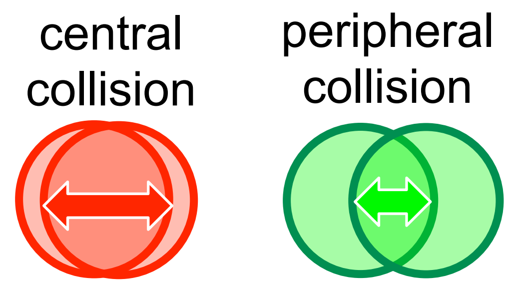
wave function for 2 bosons(fermions) : $\Psi_{12} = \frac{1}{\sqrt{2}}[\Psi(x_1,p_1)\Psi(x_2,p_2) \pm \Psi(x_2,p_1)\Psi(x_1,p_2)]$

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





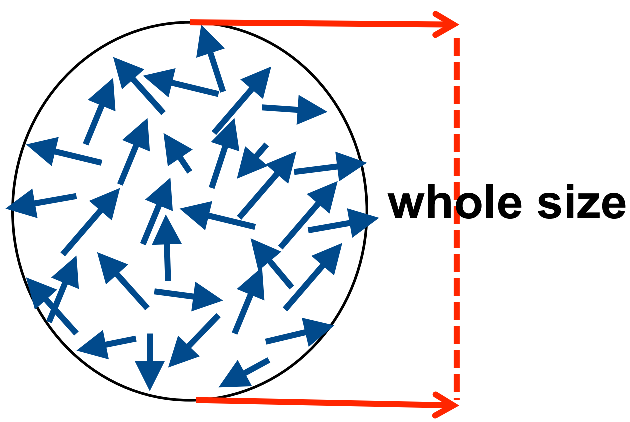
What do HBT radii depend on ?



- **Centrality dependence**
- **Average transverse momentum (k_T) dependece**
  - ✧ **static** source: measuring the **whole size**
  - ✧ **expanding** source: measuring the size of "**emission region**"
    Collective expansion makes "x-p correlation".

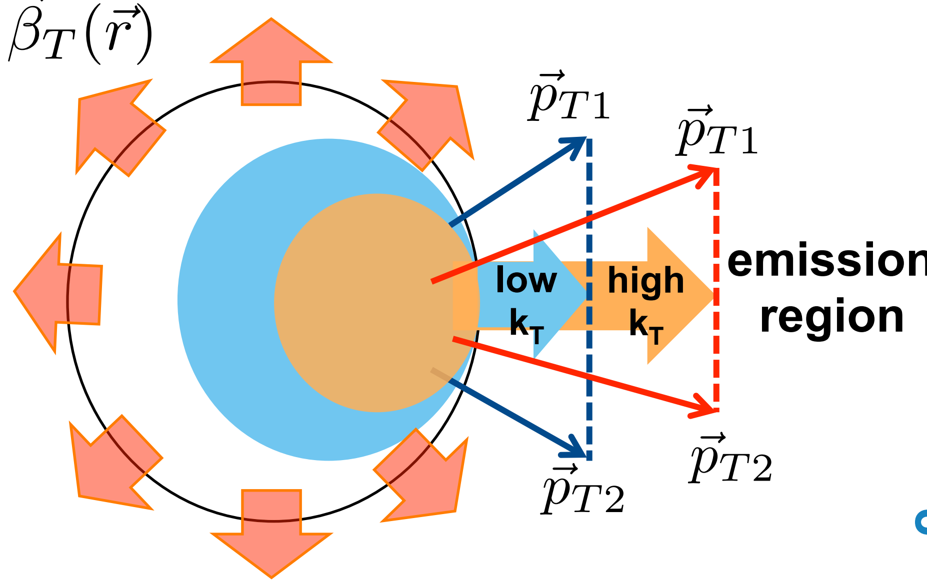
$$\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2})$$

static



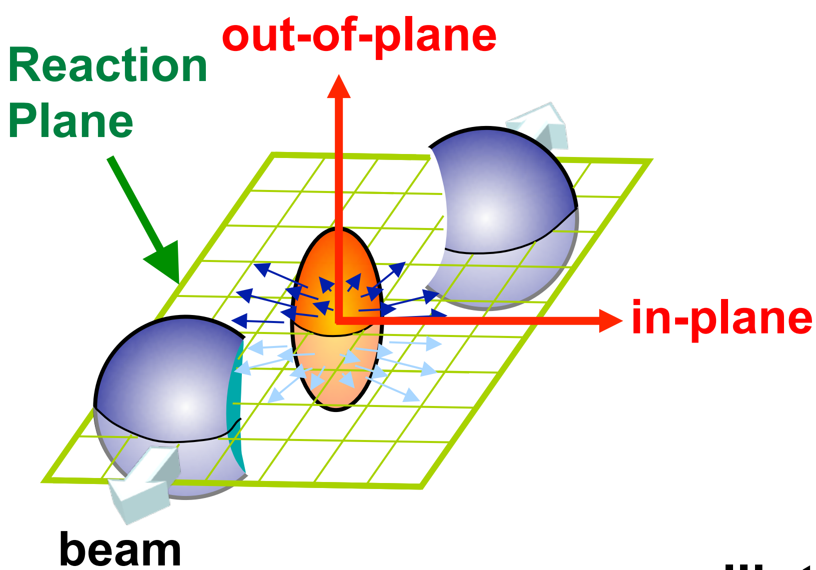
expanding

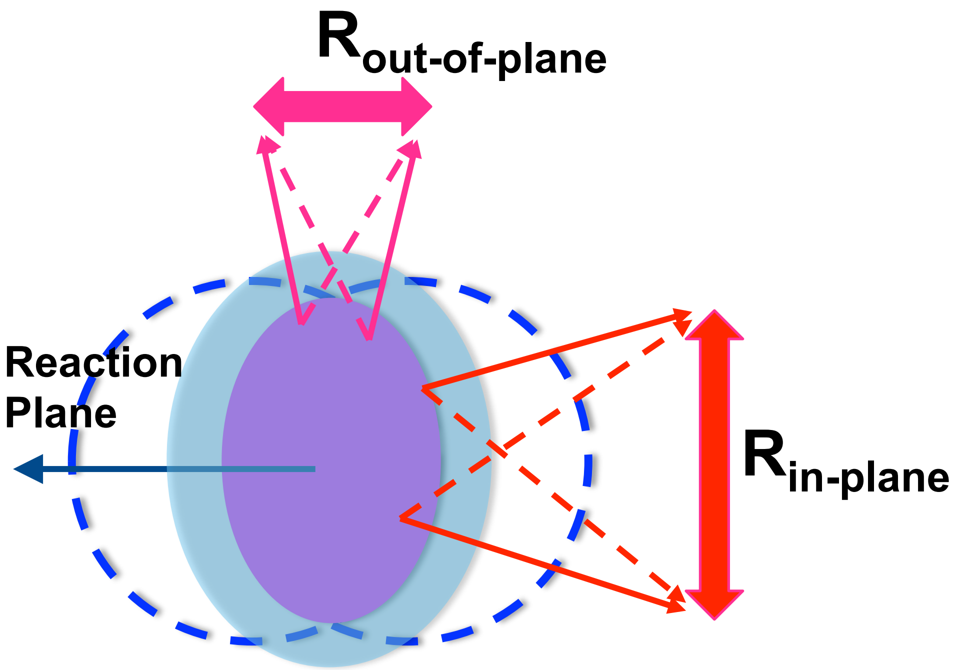
$$\vec{\beta}_T = \vec{\beta}_T(\vec{r})$$



Azimuthal angle dependence

- **HBT w.r.t Reaction Plane give us source shape at freeze-out.**
  - ✧ RP defined by beam axis and vector between centers of colliding nuclei
- **Final eccentricity is determined by initial eccentricity, pressure gradient(velocity profile) and expansion time etc.**
  - ✧ Initial anisotropy causes momentum anisotropy(v_2)





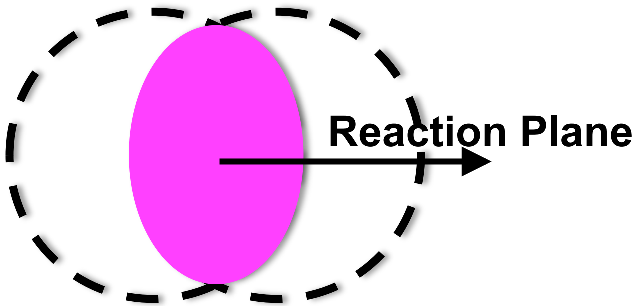
elliptical shape : $R_{in\text{-}plane} \neq R_{out\text{-}of\text{-}plane}$

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

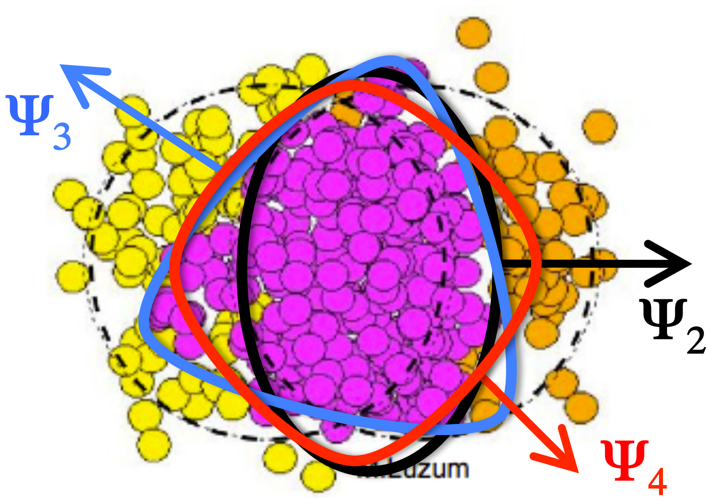
Higher Harmonic Flow and Event Plane

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

smooth picture



fluctuating picture



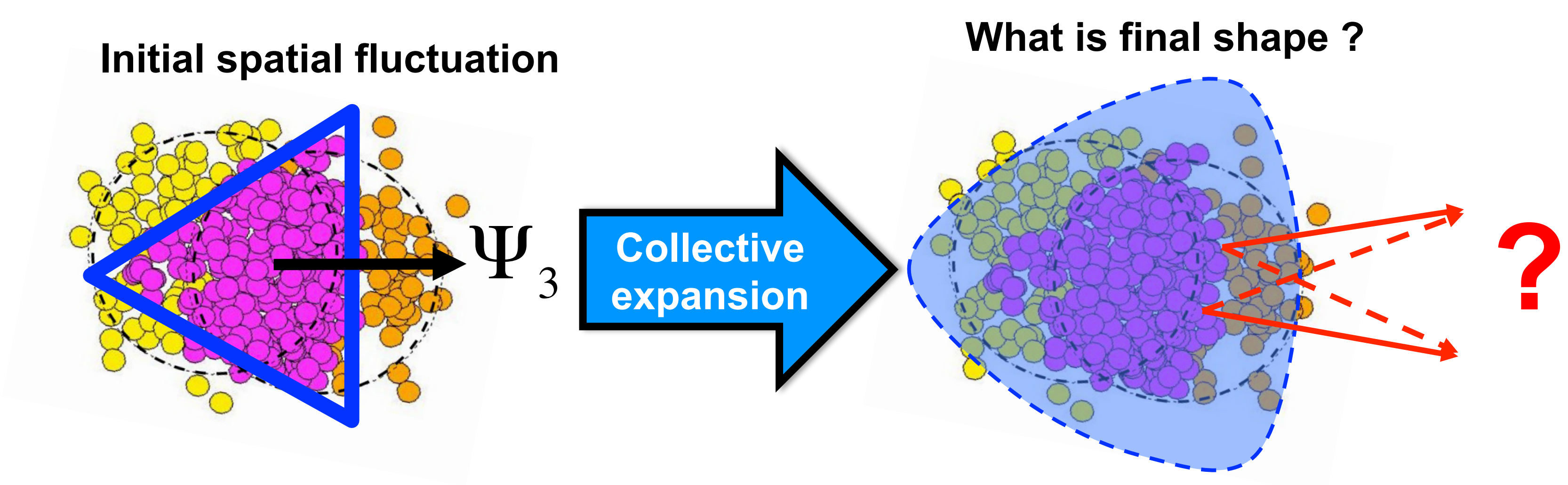
$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos 2(\phi - \Psi_2) + 2v_3\cos 3(\phi - \Psi_3) + 2v_4\cos 4(\phi - \Psi_4)$$

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

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

Motivation

- **Study the properties of space-time evolution of the heavy ion collision via azimuthal HBT measurement.**
  - ✧Measurement of charged pion/kaon HBT radii with respect to 2nd-order event plane, and comparison of the particle species
  - ✧Measurement of HBT radii with respect to 3rd-order event plane to reveal the detail of final state and system evolution.

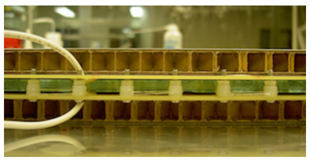


My Activity

3 years later (Something happened!!)

2006(M1) **2007(M2)** **2010(D1)**

MRPC construction



RXNP construction

Installed MRPC&RXNP

Azimuthal HBT analysis using Run4 data

Di-jet Calorimeter construction for ALICE

Summer Challenge @KEK

Shift taking @CERN

Start azimuthal HBT analysis using Run7 data

2011(D2) **2012(D3)** **2013(D4)**

Talk WPCF2011 | ***Talk JPS fall*** | ***Talk JPS spring*** | ***Talk HIC in LHC*** | ***Talk QM2012*** | ***Poster Radon Workshop*** | ***Talk JPS spring***

Summer Challenge @KEK

Shift taking & Detector Expert for Run11 @BNL

preliminary result
Centrality dependence of π/K HBT w.r.t Ψ_2

preliminary result
m_T dependence of π HBT w.r.t Ψ_2

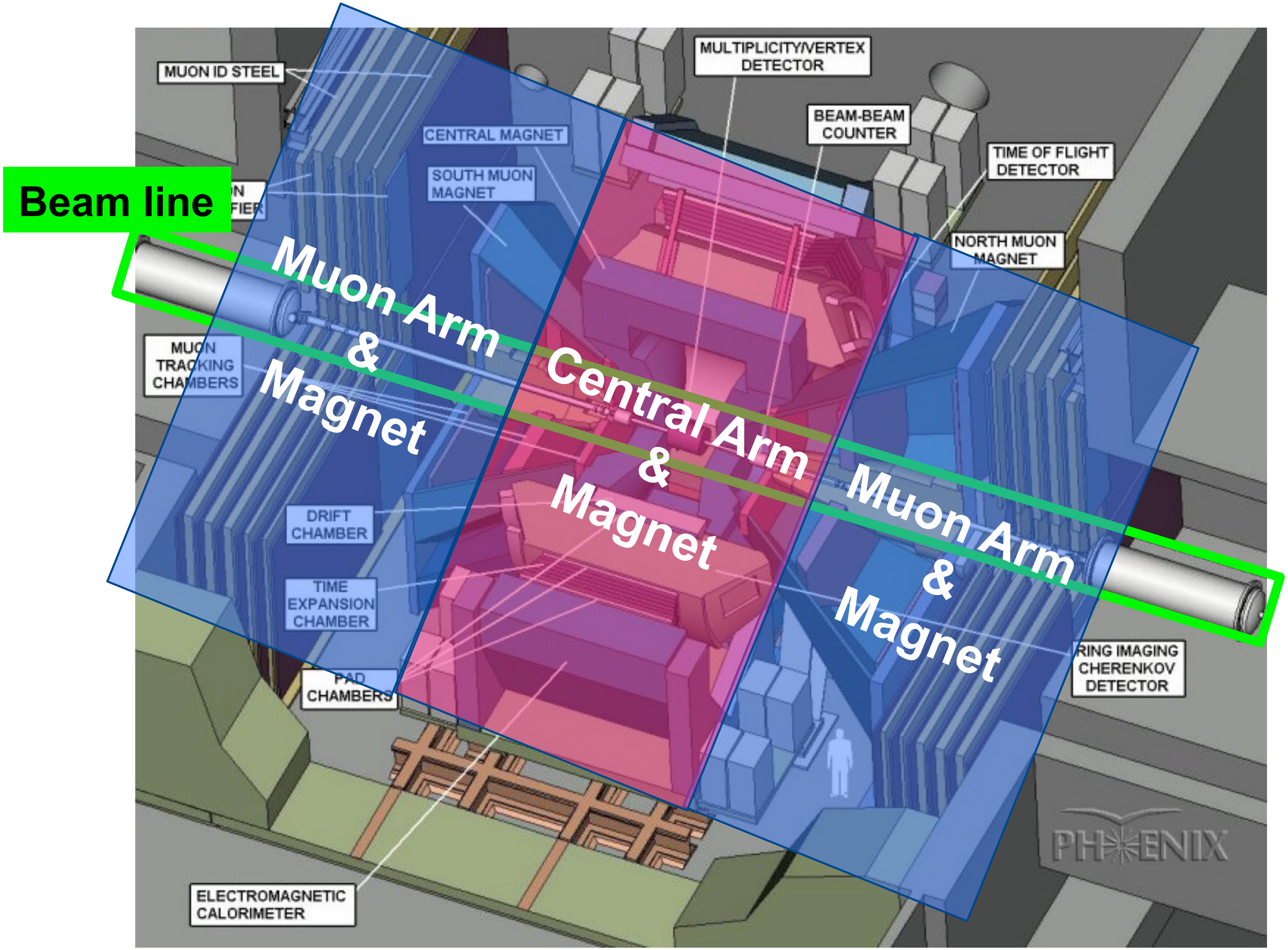
Summer Challenge @KEK

Shift taking & Detector Expert for Run12 @BNL

preliminary result
Centrality dependence of π HBT w.r.t Ψ_3

Analysis

PHENIX Experiment



PHENIX Detectors

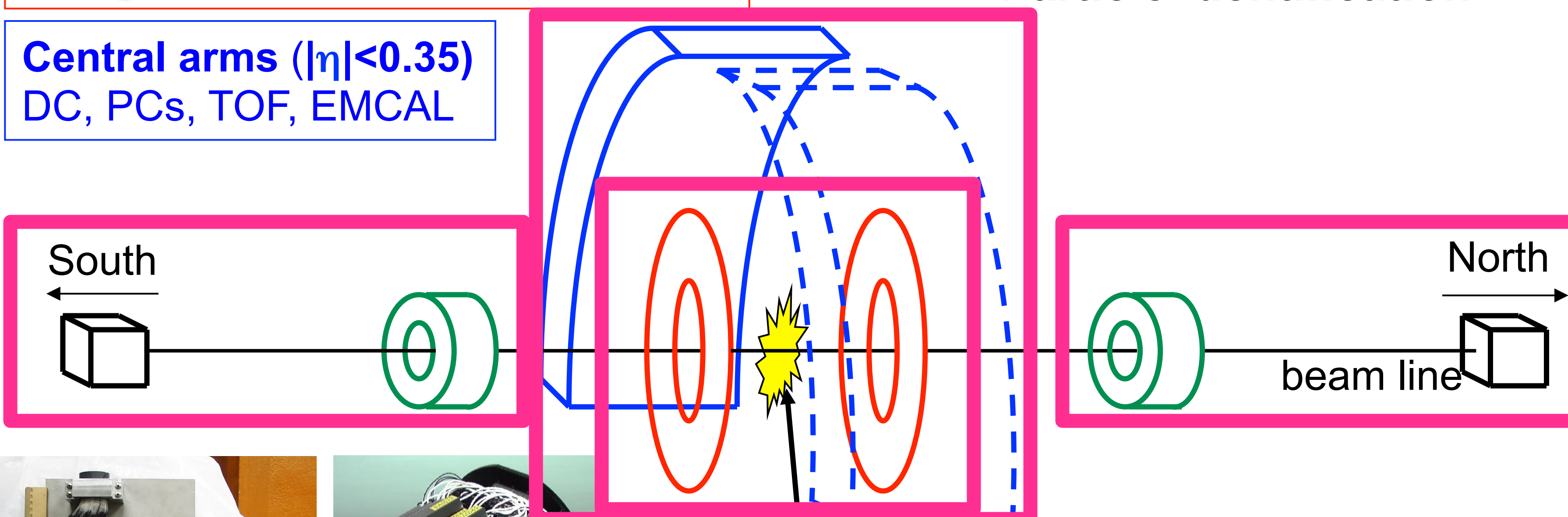
Beam-Beam Counter (|η|=3~4)
Quartz radiator+64PMTs

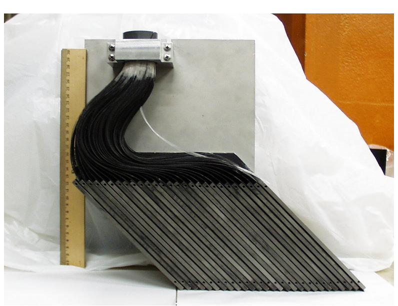
Zero Degree Calorimeter
Spectator neutron energy

Reaction Plane Detector (|η|=1~2.8)
2 rings of 24 scintillators

Central arms (|η|<0.35)
DC, PCs, TOF, EMCAL

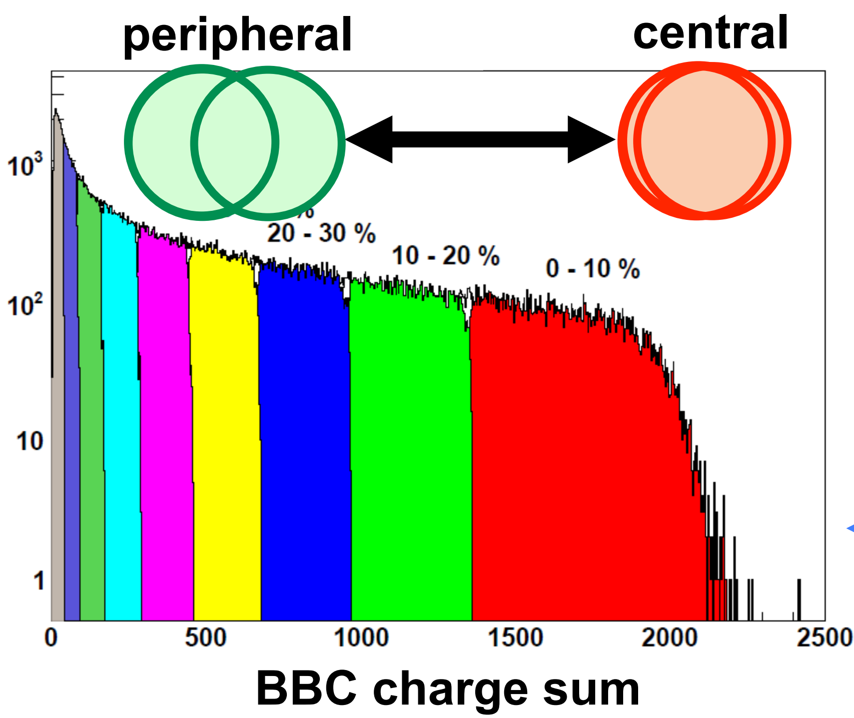
- ⇒ **Minimum Bias Trigger**
- ⇒ **Start time**
- ⇒ **Collision z-position**
- ⇒ **Centrality**
- ⇒ **Event Planes**
- ⇒ **Tracking, Momentum**
- ⇒ **Particle Identification**

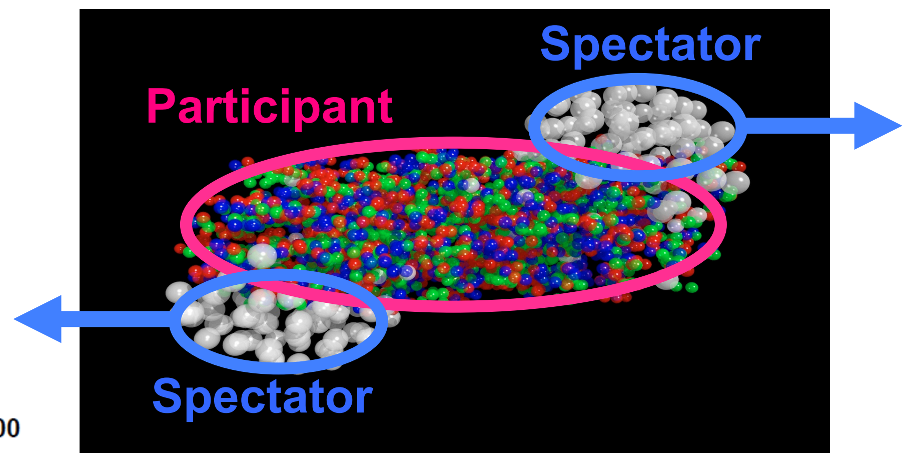




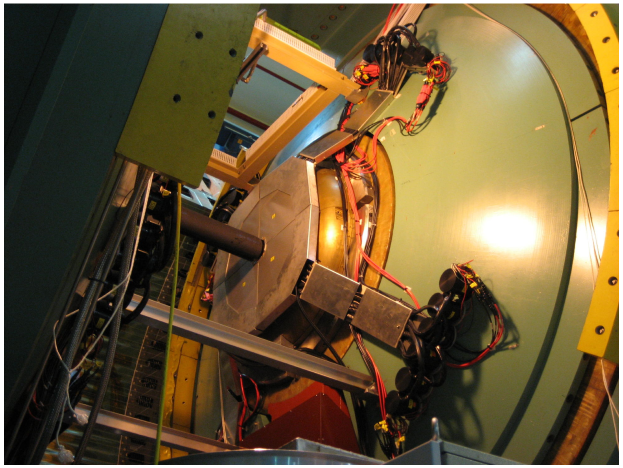
Centrality

- **Centrality is used to classify events instead of impact parameter.**
  - ✧ impact parameter ∝ multiplicity
  - ✧ BBC measures charged particles from participant.
  - ✧ centrality is defined in terms of a percentile
    0%: most central   92%:most peripheral

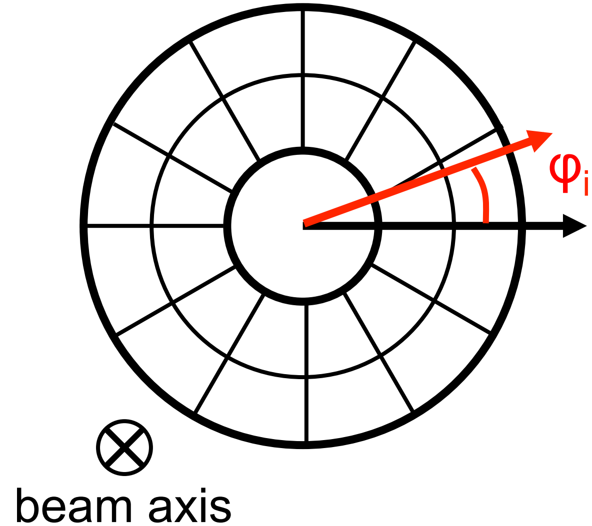


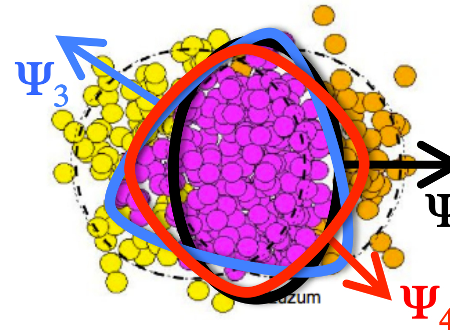


Event Plane

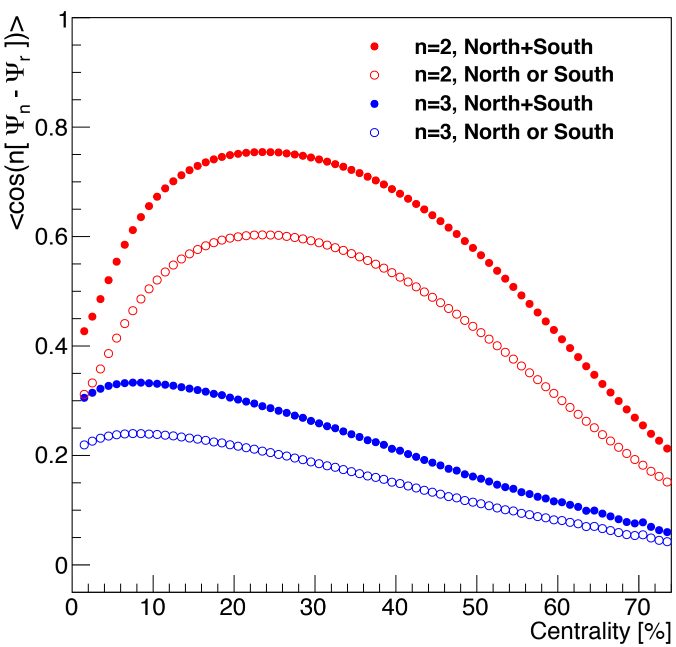


24 scintillator segments





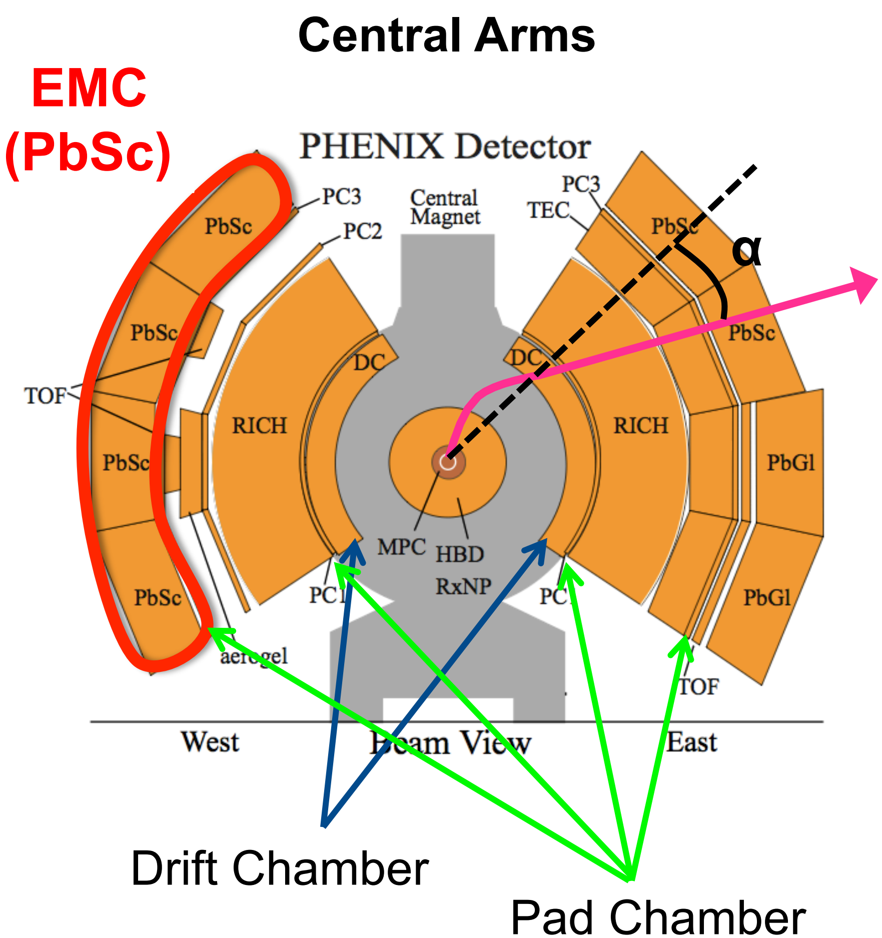
Resolution of Event planes



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

- **Event plane was determined by Reaction Plane Detector**
  - ✧Resolution: $<\cos(n(\Psi_n-\Psi_{real}))>$
    n=2 : ~ 0.75
    n=3 : ~ 0.34
- **Determined by anisotropic flow itself**

Track Reconstruction



- **Drift Chamber**
  - ✧Momentum determination

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

K: field integral
α: incident angle

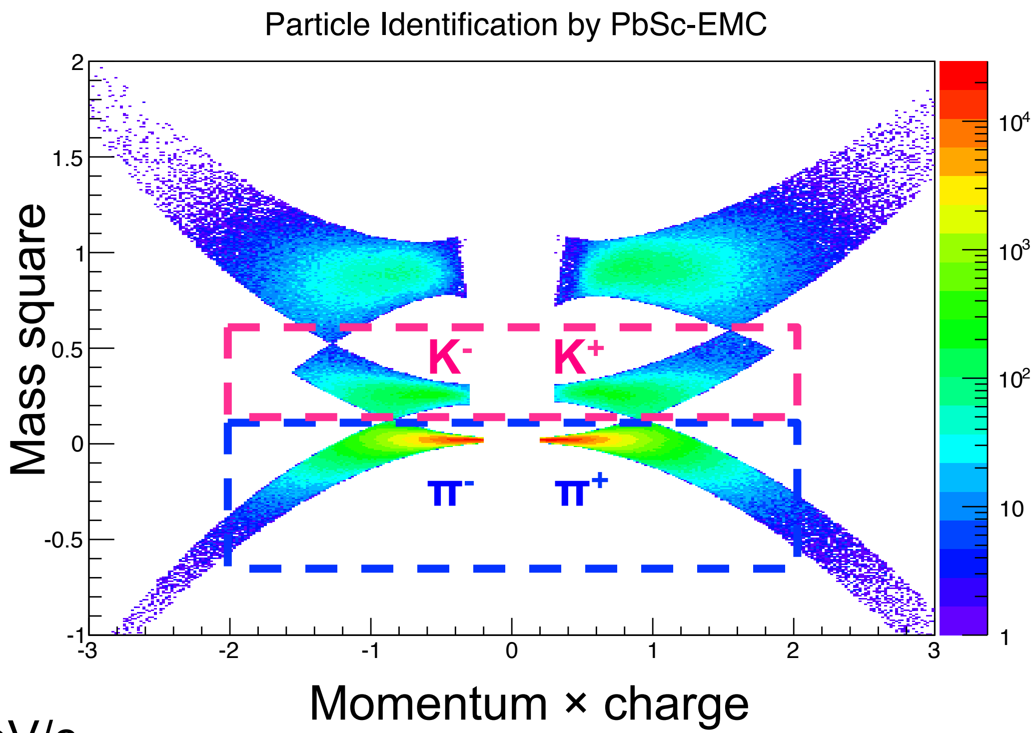
- **Pad Chamber (PC1)**
  - ✧Associate DC tracks with hit positions on PC1
    - ✓ p_z is determined
- **Outer detectors (PC3,TOF,EMCal)**
  - ✧Extend the tracks to outer detectors

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.

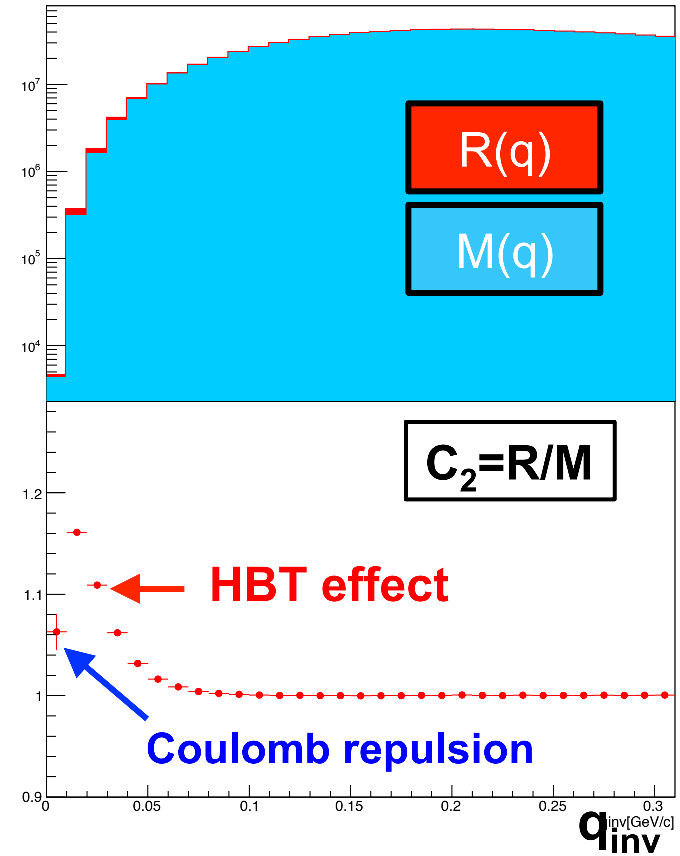
$$C_2 = \frac{R(\mathbf{q})}{M(\mathbf{q})}$$

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

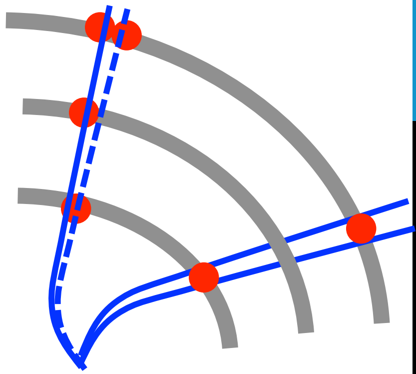
  - Real pairs include HBT effects, Coulomb interaction and detector inefficient effect.

    Mixed pairs doesn't include HBT and Coulomb effects.

relative momentum dist.

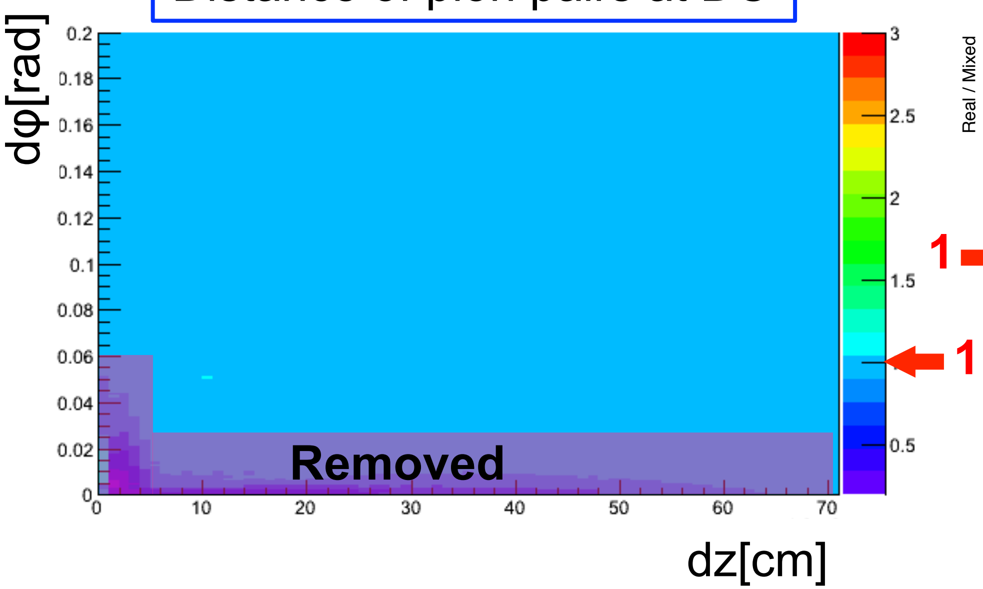


Pair Selection

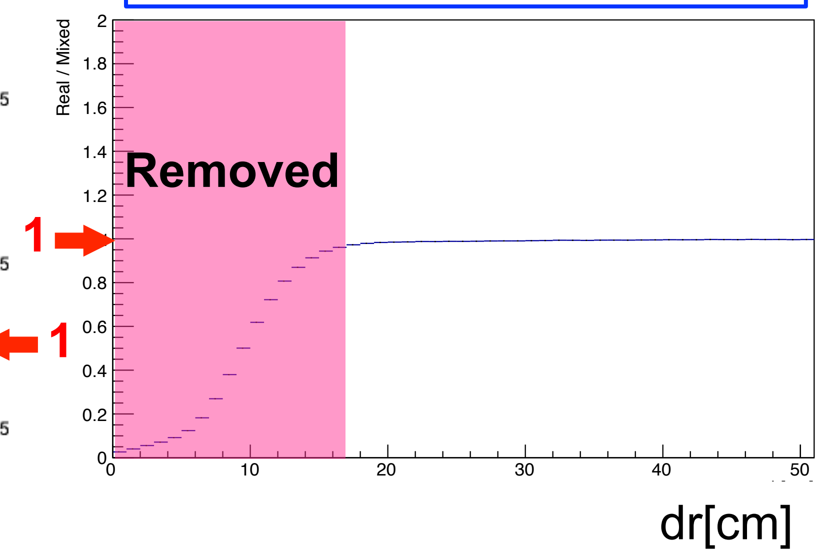


- **Ghost Tracks**
  - ✧A single particle is reconstructed as two tracks
- **Merged Tracks**
  - ✧Two particles is reconstructed as a single track

Distance of pion pairs at DC



Distance of pion pairs at EMC



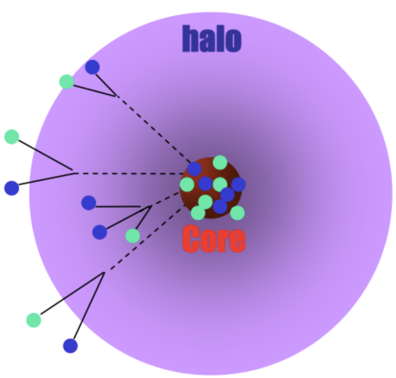
Coulomb Interaction

- **Coulomb repulsion for like-sign pairs reduces pairs at low-q.**
  - ✧ Estimated by Coulomb wave function

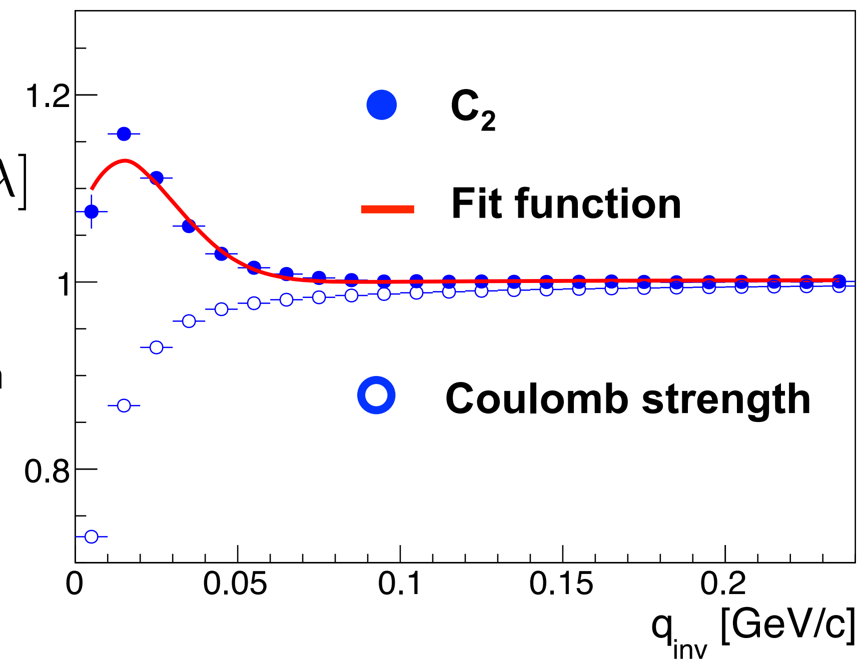
$$\left[-\frac{\hbar^2\nabla^2}{2\mu}+\frac{Z_1Z_2e^2}{r}\right]\Psi(r)=E\Psi(r) \qquad \gamma=\frac{me^2}{\hbar^2 q}Z_1Z_2$$

- **The correction was applied in fit function for C_2**
  - ✧ Core-Halo model

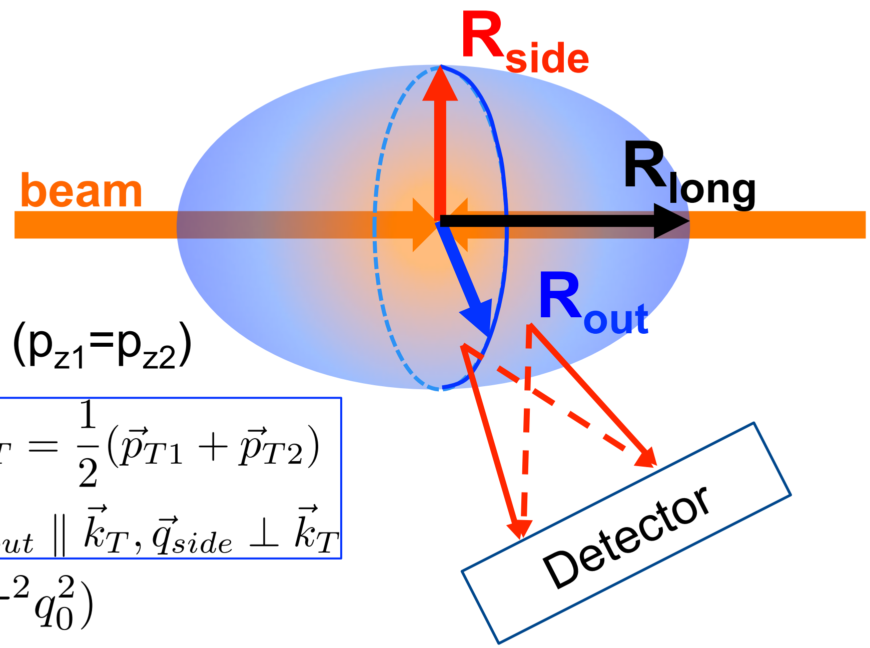
$$\begin{aligned}C_2 &= C_2^{core}+C_2^{halo}\\ &= N[\lambda(1+G)F_{coul}]+[1-\lambda]\end{aligned}$$



F_{coul} : Coulomb term
G : Gaussian term



3D HBT radii



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

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

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

$$C_2 = 1 + \lambda G$$

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

$$= \exp(-R_x^2 q_x^2 - R_y^2 q_y^2 - R_z^2 q_z^2 - \Delta\tau^2 q_0^2)$$

$$= \exp(-R_{side}^2 q_{side}^2 - R_{out}^{*2} q_{out}^2 - R_{long}^2 q_{long}^2 - \Delta\tau^2 q_0^2)$$

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

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

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

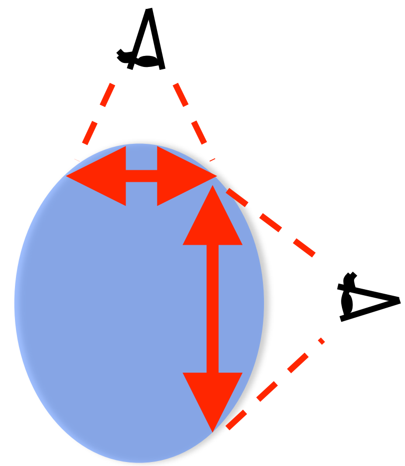
What do R_s and R_o represent ?

- R_s is **"width"** of source
- R_o is **"depth"** of source

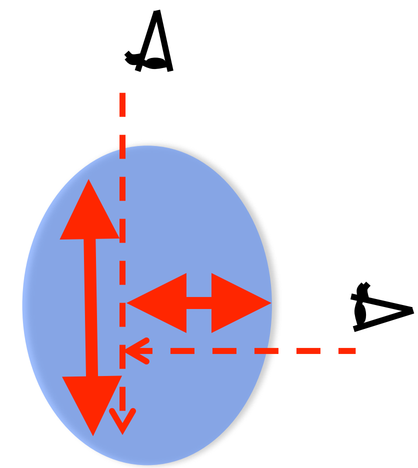
$$\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2})$$

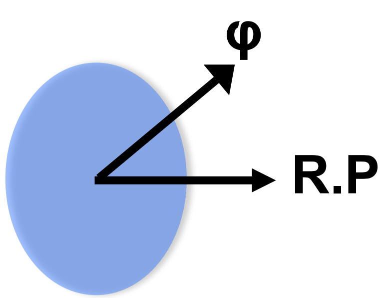
$$\vec{q}_{out} \parallel \vec{k}_T, \vec{q}_{side} \perp \vec{k}_T$$

R_{side}

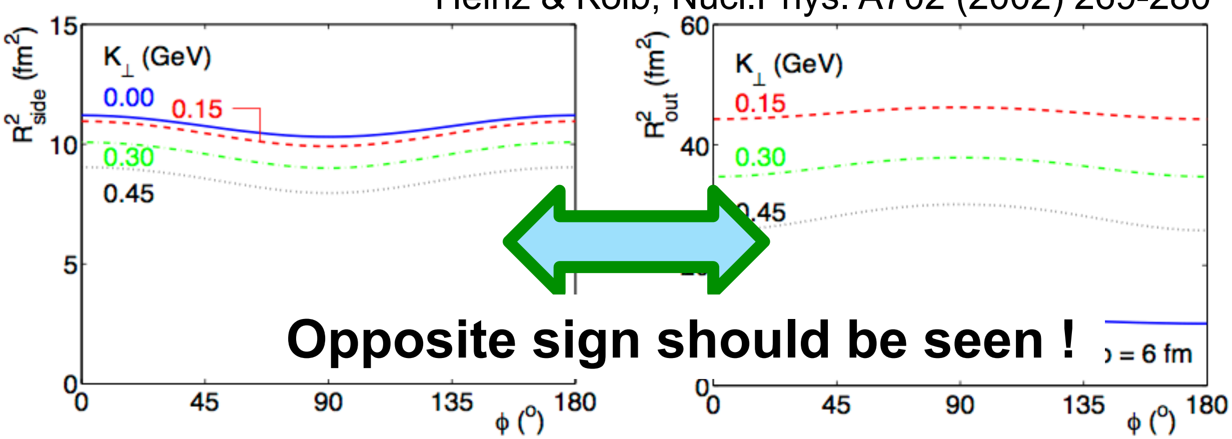


R_{out}





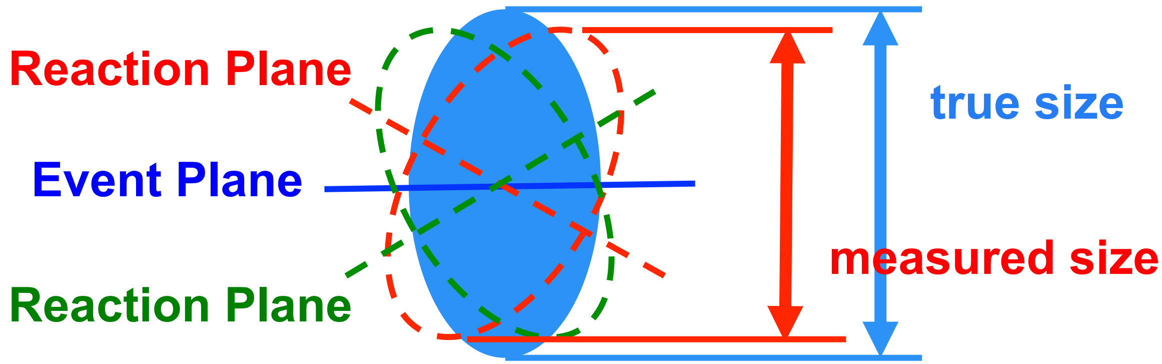
Heinz & Kolb, Nucl.Phys. A702 (2002) 269-280



Opposite sign should be seen !

Correction of Event Plane Resolution

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

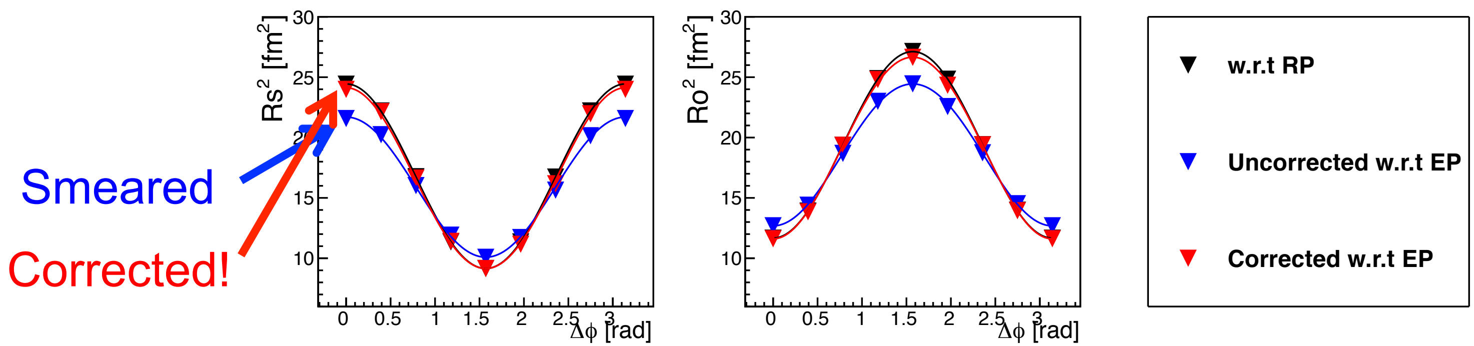


- **Resolution correction**
  - ✧correction for q-distribution
    PRC.66, 044903(2002)
  - ✧Check by simulation

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

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

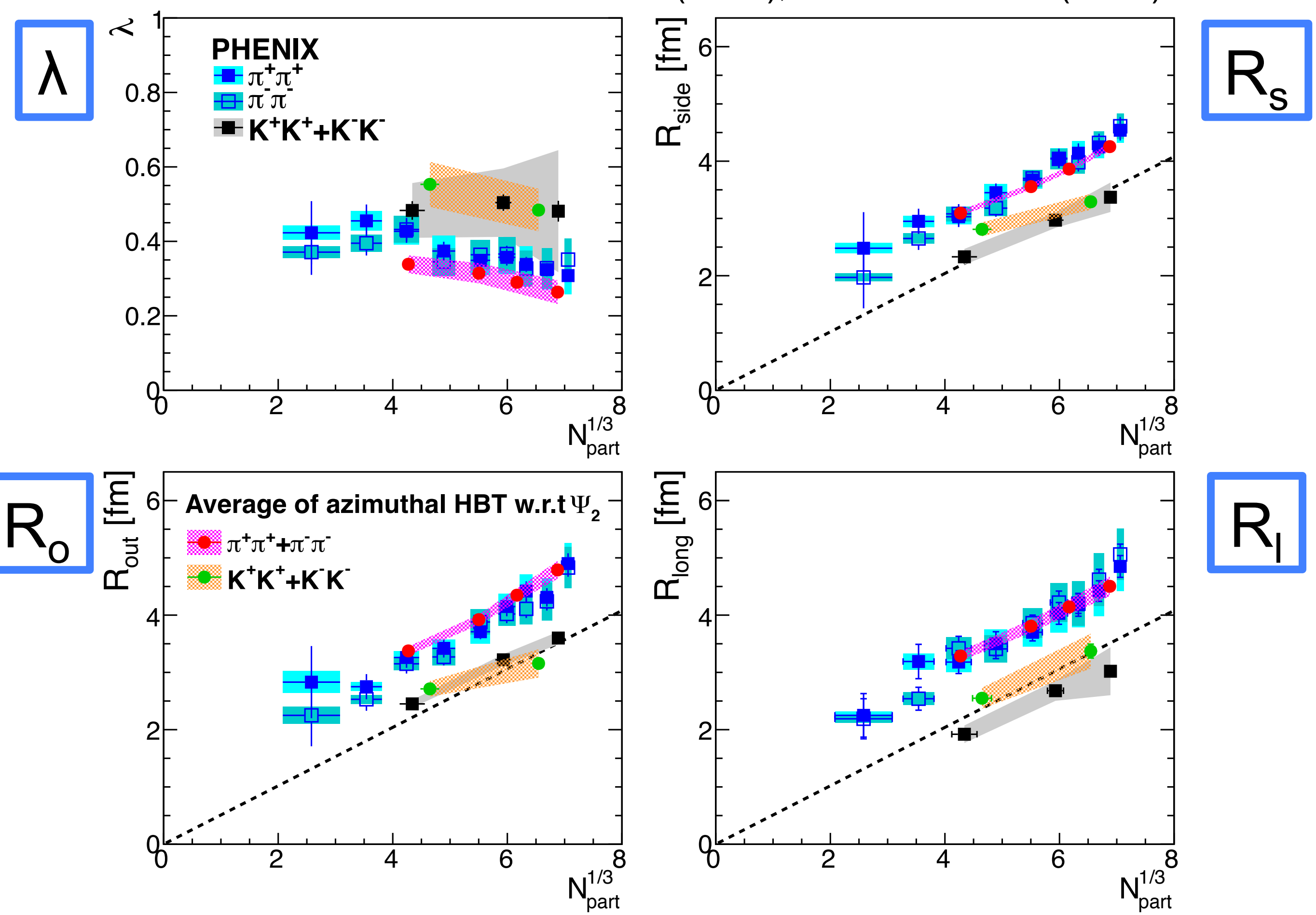
event plane resolution



Consistency check with the past result

- **Extracted HBT radii are compared to PHENIX data.**

PRL93.152302(2004), PRL103.142301(2009)

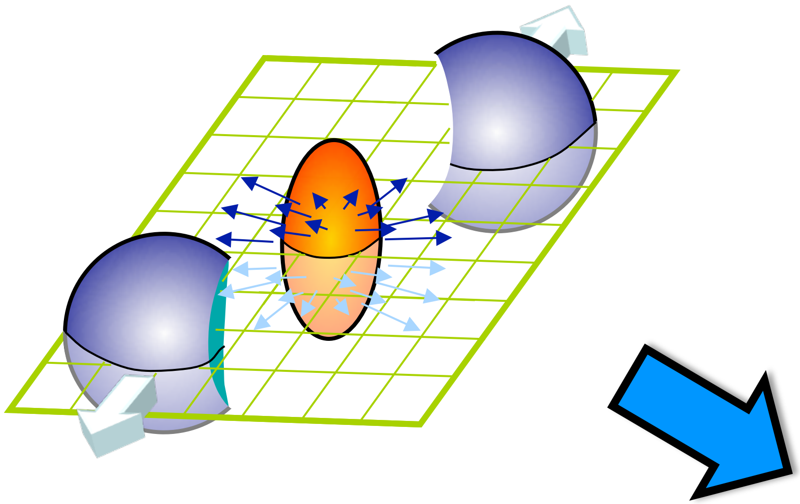


Both my result and PHENIX result are consistent within systematic error.

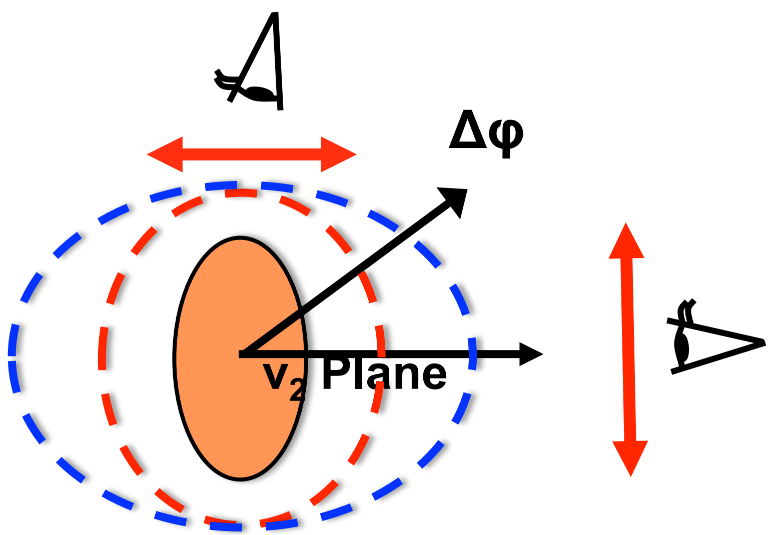
Results
&
Discussion

Azimuthal HBT w.r.t 2nd order event plane

Initial spatial eccentricity

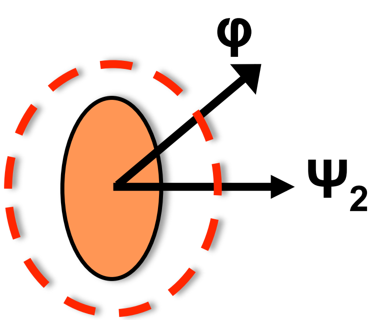


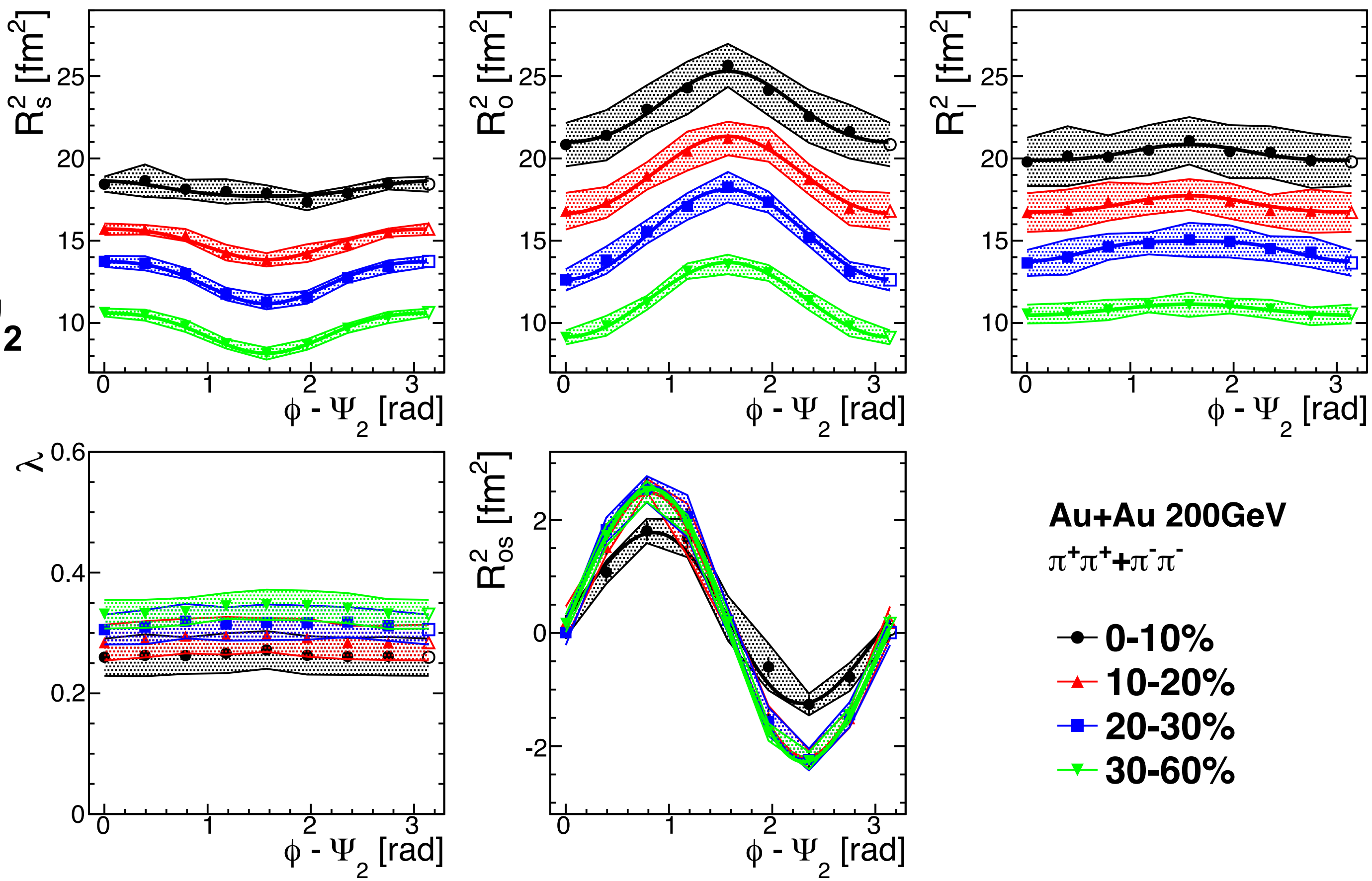
What is final eccentricity ?



Centrality dependence of pion HBT radii w.r.t Ψ_2

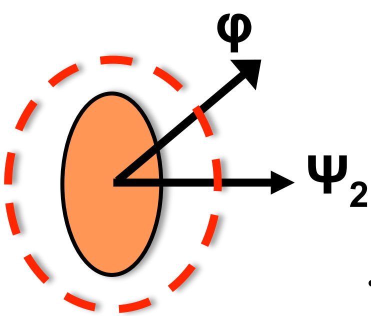
- **Oscillation are seen for R_{side}, R_{out}, $R_{os.}$**
- **R_{out} has stronger oscillation than R_{side} in all centrality.**
  - ✧Flow anisotropy? or Emission duration depend on azimuthal angle?
  - ✧Difference of “width” and “depth”?

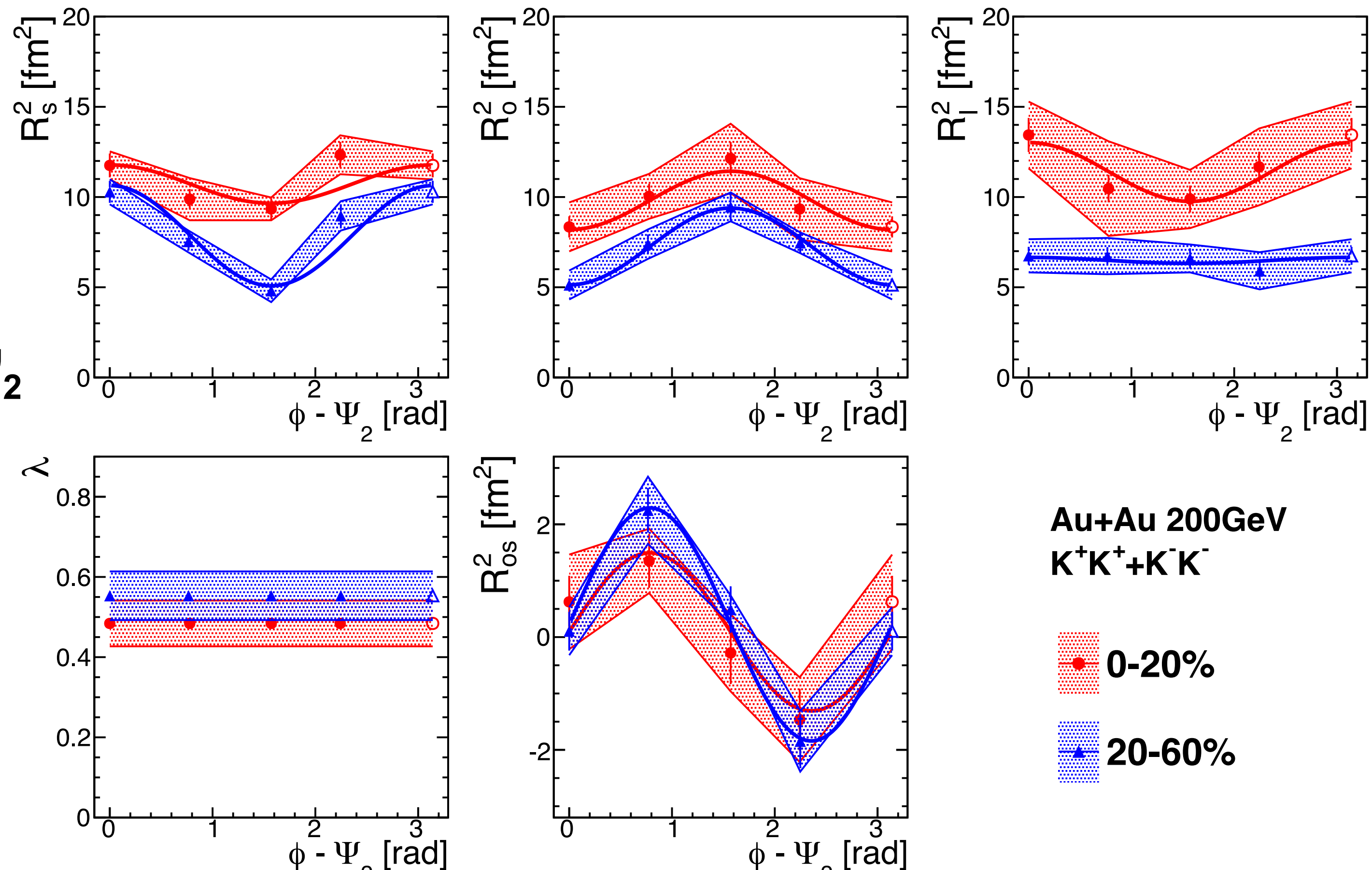




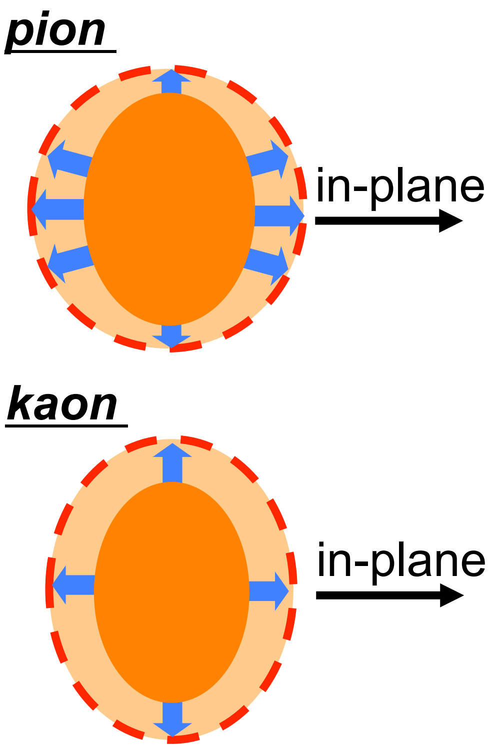
Centrality dependence of kaon HBT radii w.r.t Ψ_2

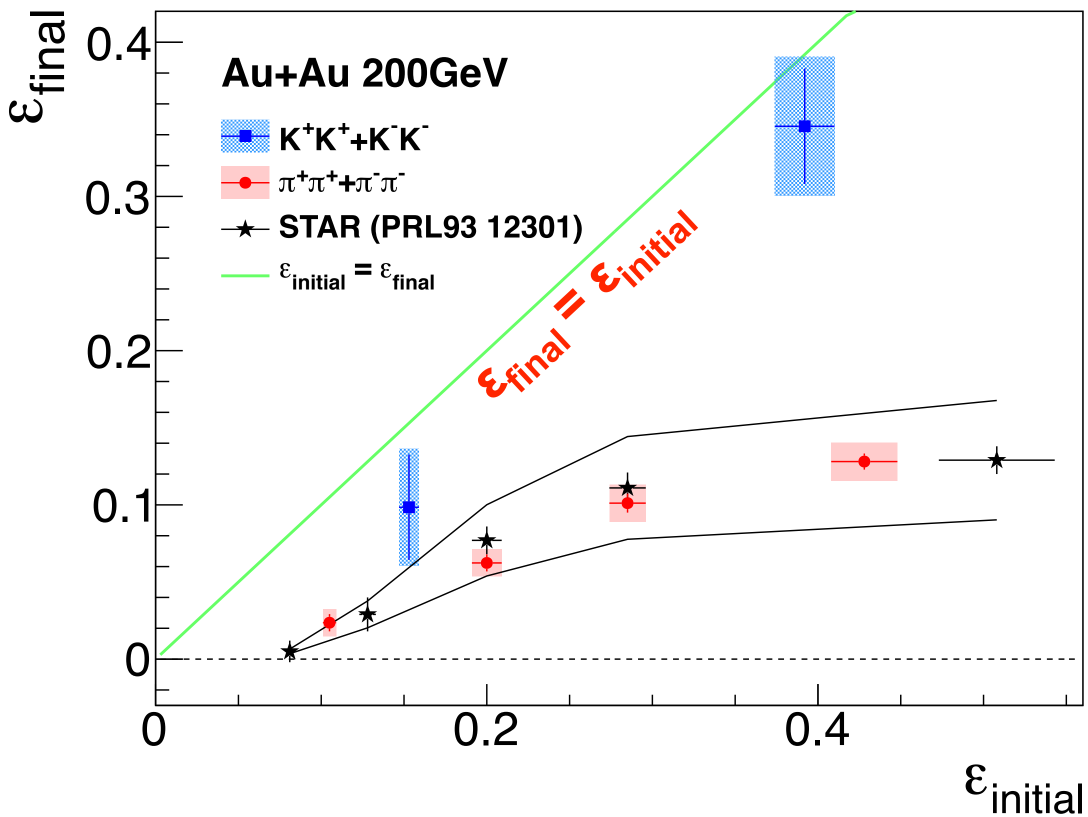
- **Result of charged kaons show similar trends!**





Eccentricity at freeze-out

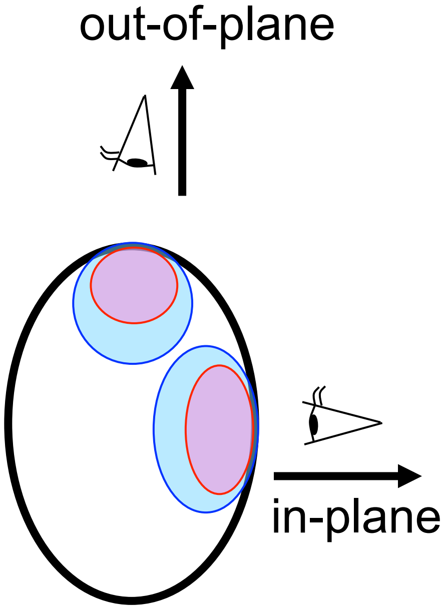


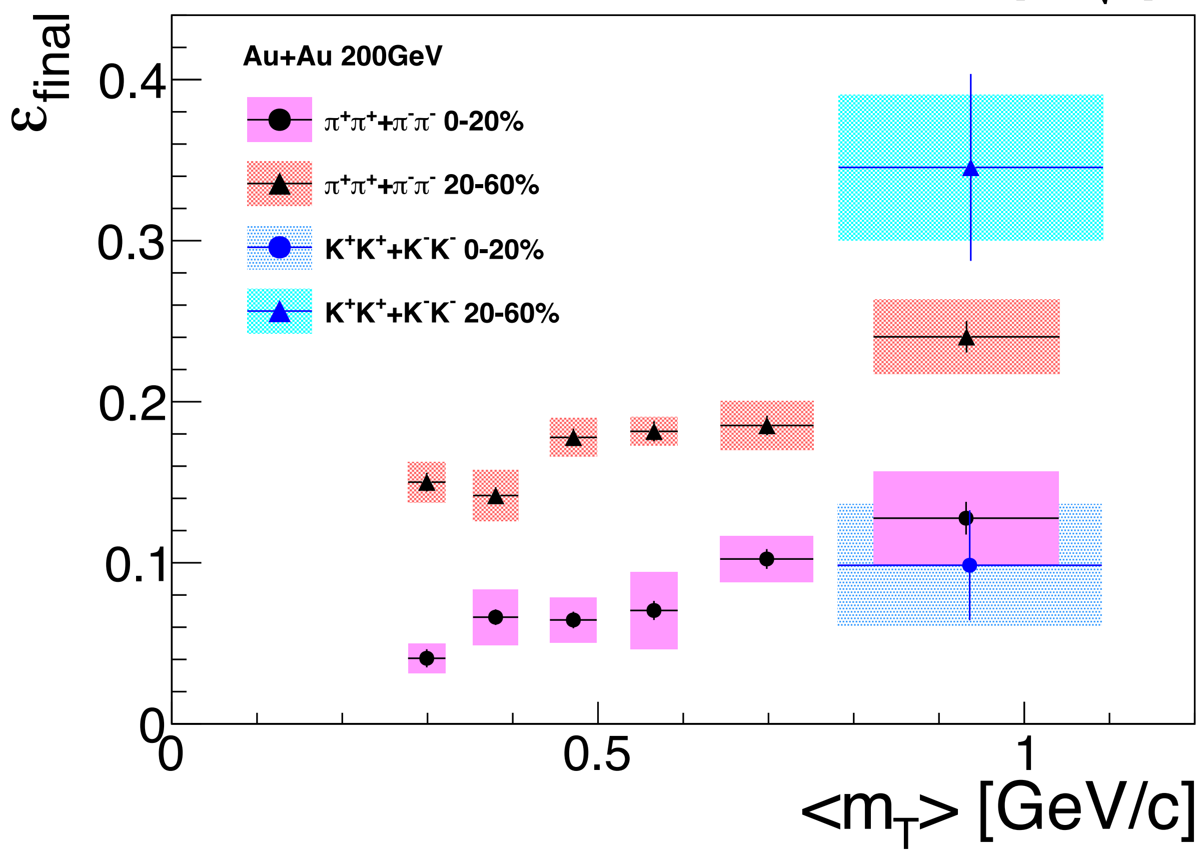


- **$\varepsilon_{final} \approx \varepsilon_{initial}/2$ for pion**
  - ✧ Consistent with STAR result.
  - ✧ This Indicates that source expands to in-plane direction, and still elliptical shape.
- **$\varepsilon_{final} \approx \varepsilon_{initial}$ for kaon**
  - ✧ Kaon may freeze-out sooner than pion because of less cross section.
  - ✧ Due to the difference of m_T between π/K ?

m_T dependence of ε_{final}

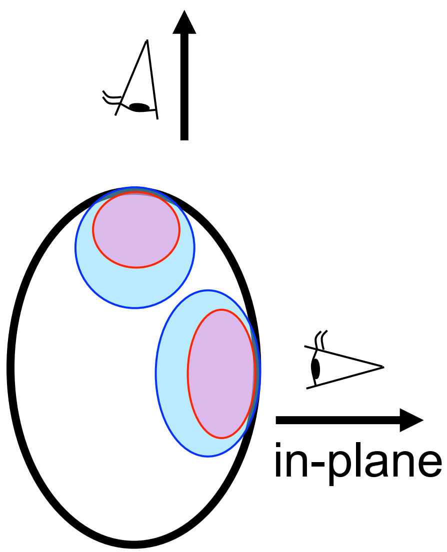
$$m_T = \sqrt{k_T^2 + m^2}$$

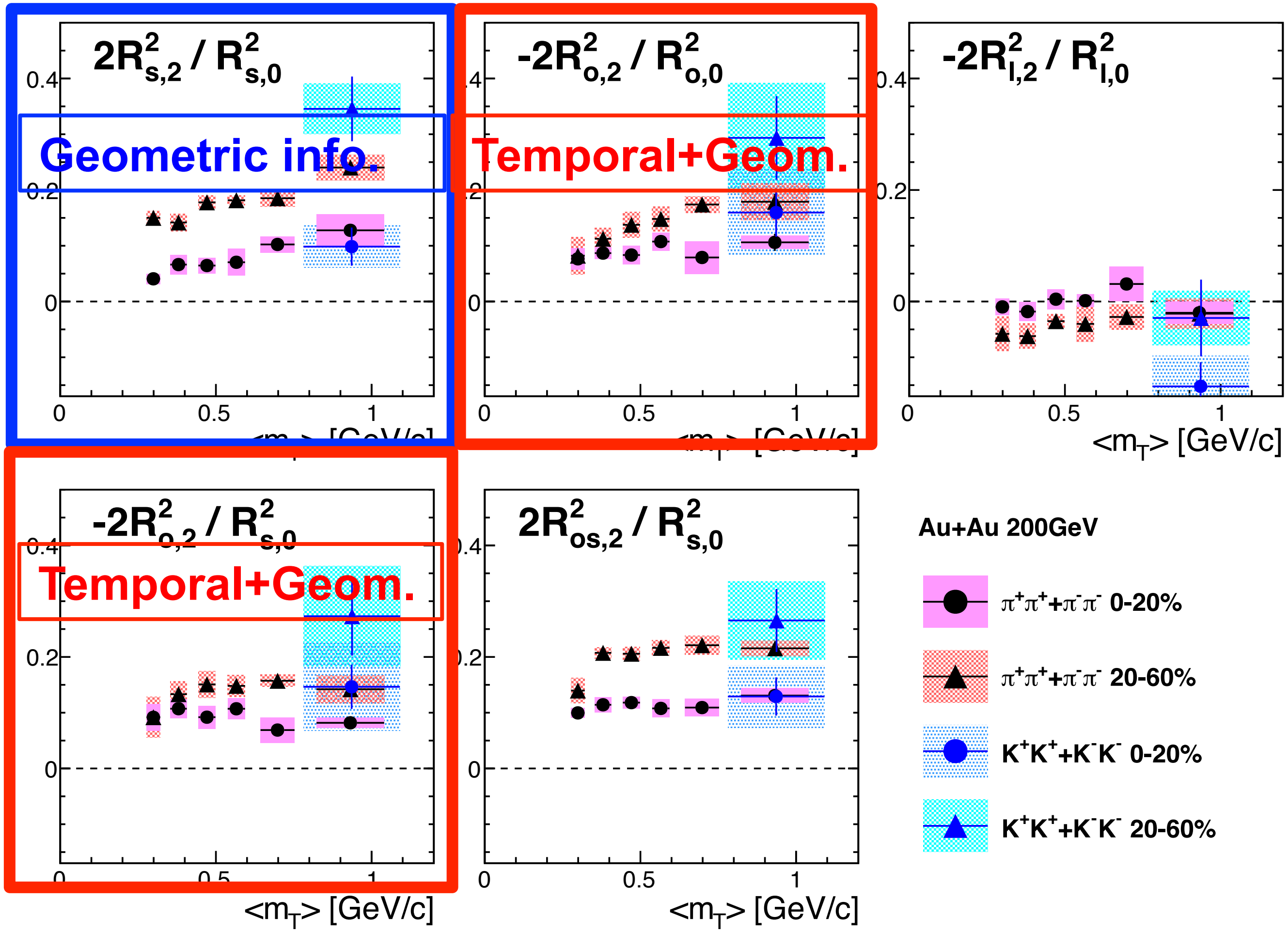




- **ε_{final} of π increases with m_T in most/mid-central collisions**
  - ✧Looking at the variation of the shape of the emission region ?
- **Still difference between π/K in 20-60% even at the same m_T**
  - ✧Indicates sooner freeze-out time of K than π ?

m_T dependence of relative amplitude



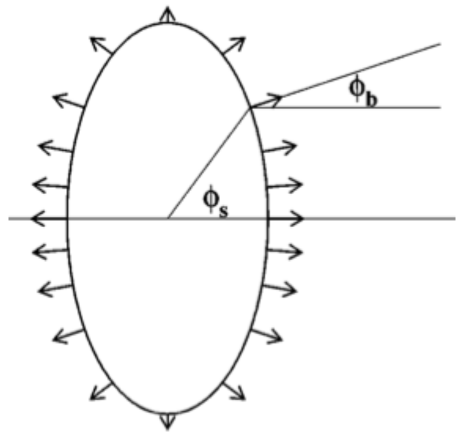


- **Relative amplitude of R_{side} and R_{out} show m_T dependence**
  - ✧R_o in 0-20%doesn't depend on m_T ?
- **Difference between π/K is similar for other parameters**

Interpretation by Blast wave model

PRC 70, 044907 (2004)

- **Hydrodynamic model assuming radial flow**
  - ✧Well described at low p_T for p_T spectra & elliptic flow
  - ✧Assuming freeze-out takes place for all hadrons at the same time
  - ✧Freeze-out condition is treated as free parameters.



<u>7 free parameters</u>

* box profile is assumed as spatial density

T_f	: temperature at freeze-out
ρ_0, ρ_2	: transverse rapidity
R_x, R_y	: transverse sizes (shape)
$\tau_0, \Delta\tau$	: system lifetime, emission duration

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

$$\rho(r,\phi) = \tilde{r}[\rho_0 + \rho_2 \cos(2\phi)]$$

$$\tilde{r} = \sqrt{(\frac{r\cos(\phi)}{R_x})^2 + (\frac{r\sin(\phi)}{R_y})^2}$$

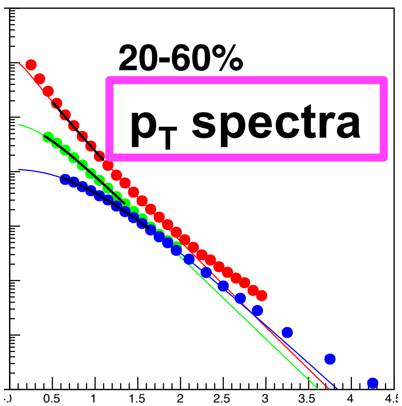
✧ Assuming a Gaussian distribution peaked at τ_0 and with a width $\Delta\tau$, and source size doesn't change with τ.

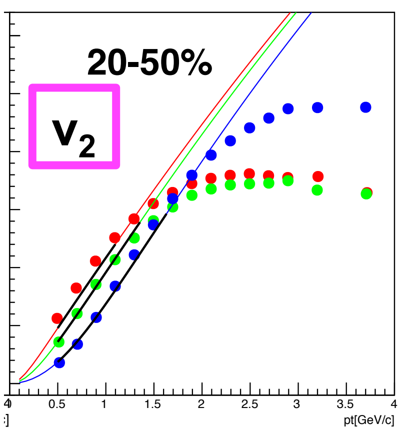
$$\frac{dN}{d\tau} \sim \exp\left(-\frac{(\tau-\tau_0)^2}{2\Delta\tau^2}\right)$$

✧ Spatial(R_y/R_x) and flow(ρ_2) anisotropy make HBT oscillation.

Fit by Blast wave model

- **Transverse momentum distribution (p_T spectra) and v_2 are used to reduce parameter.**



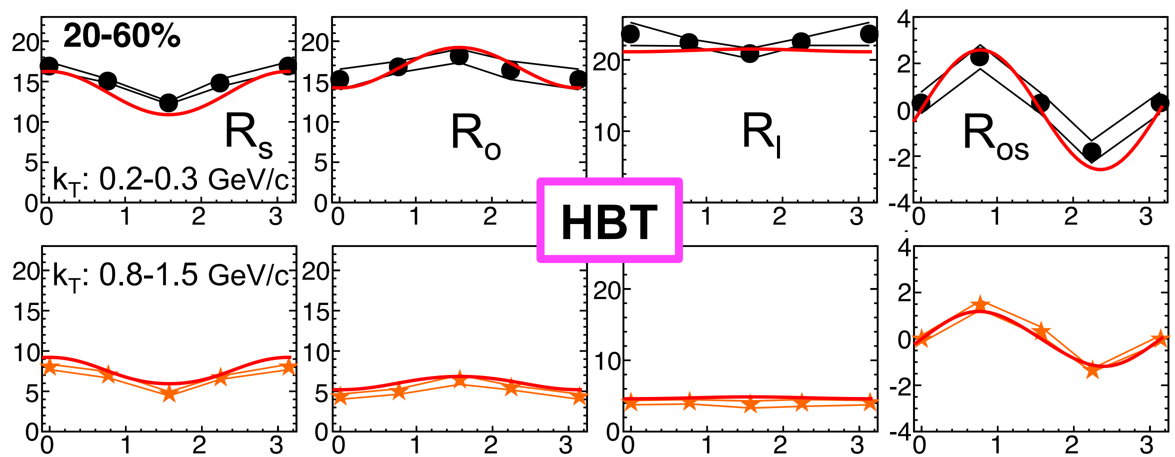


1. Fit p_T spectra to obtain T_f and ρ_0

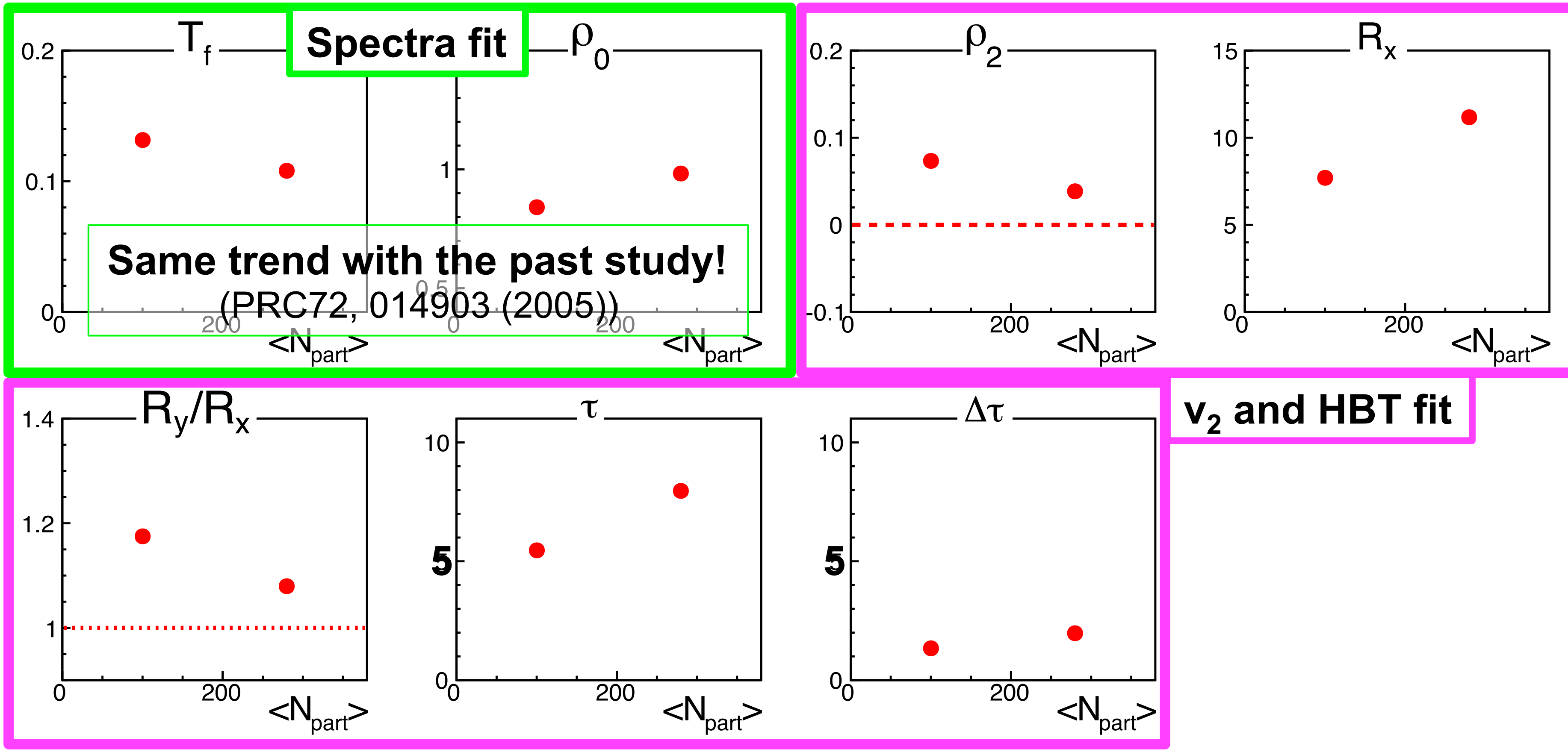
- spectra data from PHENIX (PRC69,034909(2004))

2. Fit v_2 and HBT radii for all k_T simultaneously

- ρ_2, R_x, R_y, τ_0, $\Delta\tau$ are obtained.



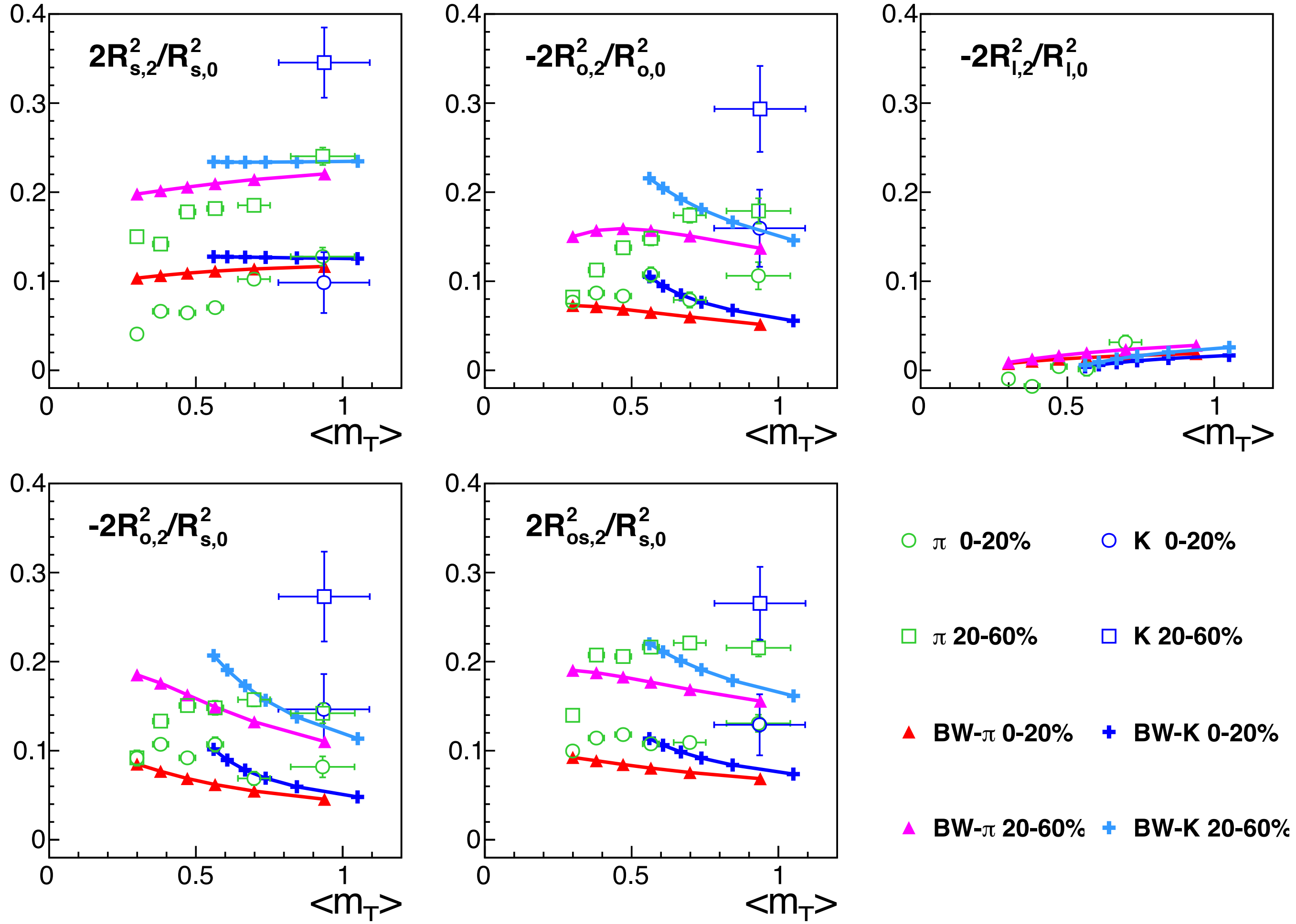
Extracted freeze-out parameters



- **ρ_2 and ellipticity(R_y/R_x) increase with decreasing N_{part}**
  - ✧Reasonable in terms of v_2 and ε_f
- **τ and Δτ increases with increasing N_{part}**
  - ✧Finite emission duration (1~2fm/c)
  - ✧Shorter than typical hydrodynamic freeze-out time (~15fm/c)

Comparison of π and K

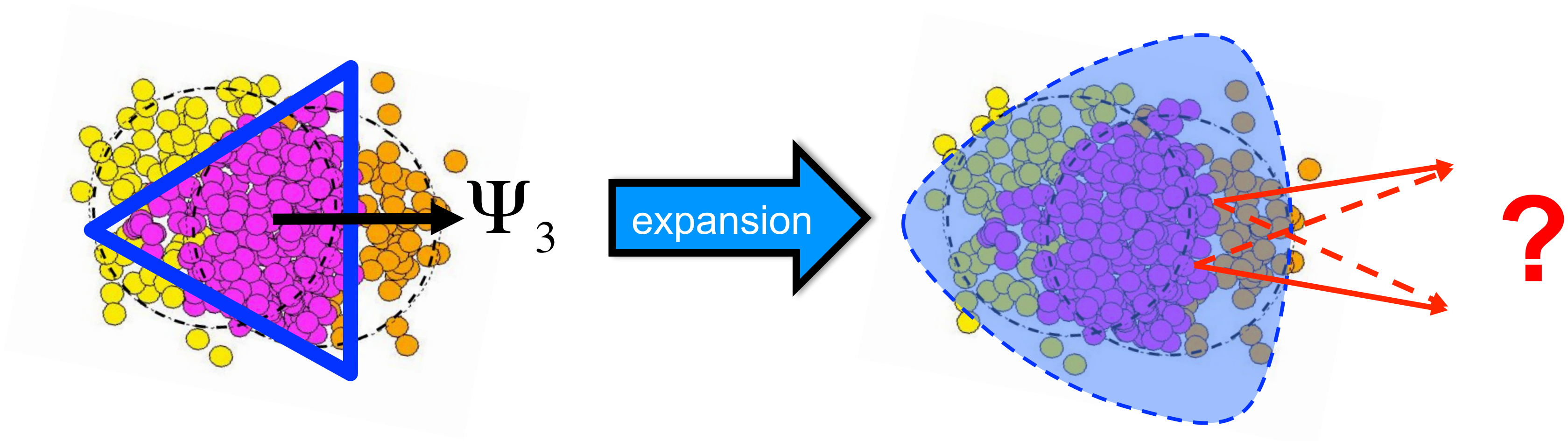
- **π and K was recalculated using extracted parameters**



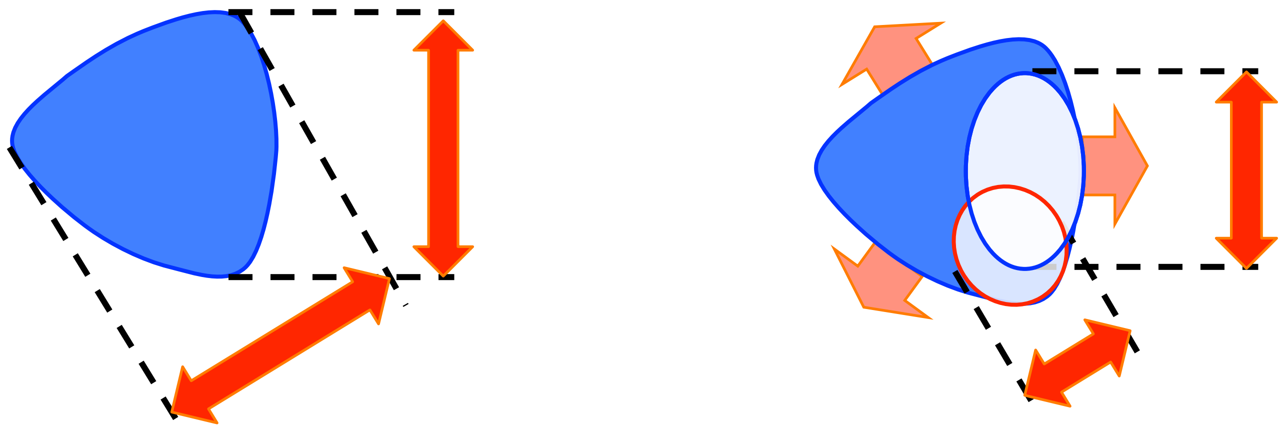
- **Data and BW doesn't match qualitatively for relative amplitudes**
- **Large ε_f of K in 20-60% cannot be explained well by BW**

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

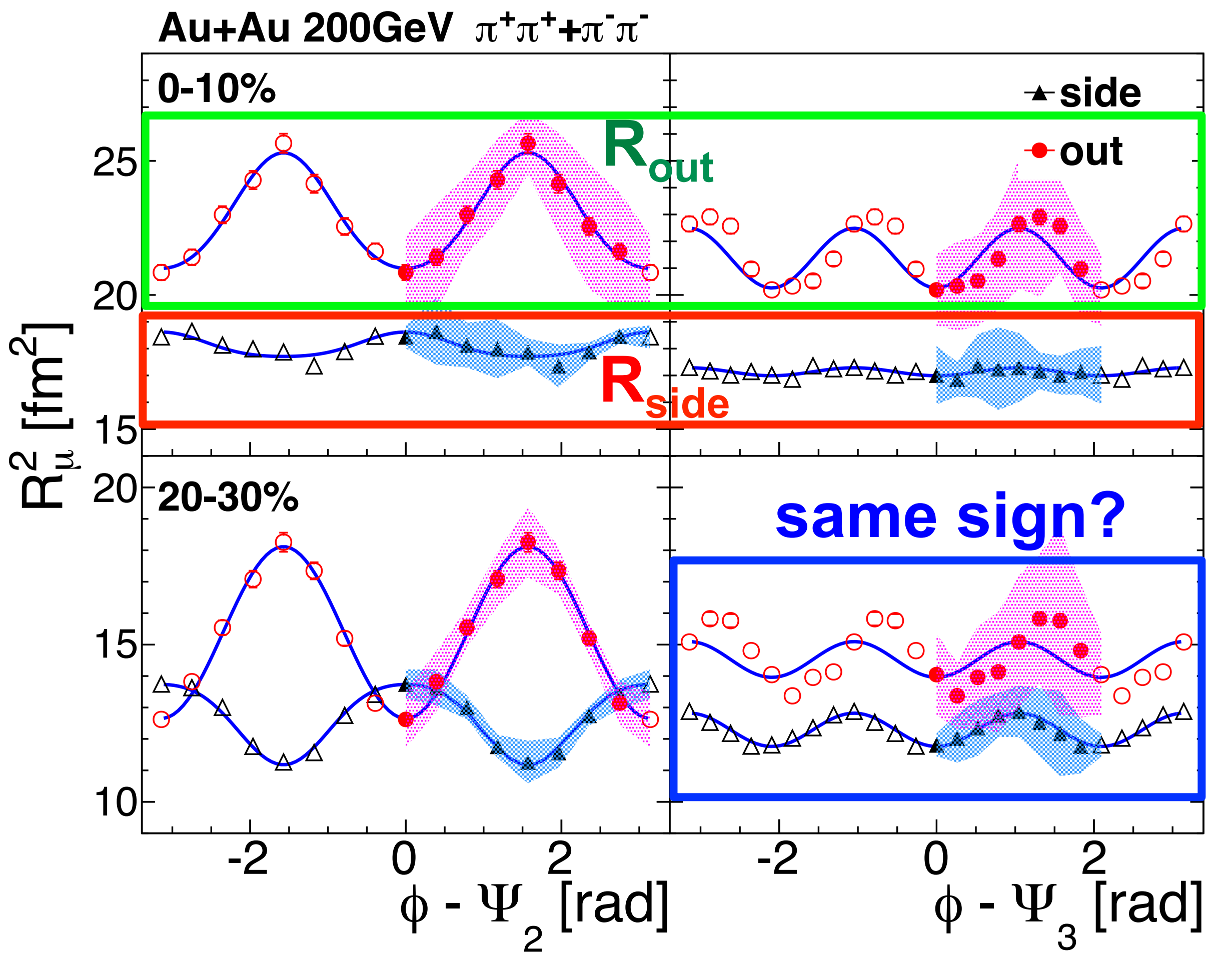
Initial spatial fluctuation **What is final shape ?**

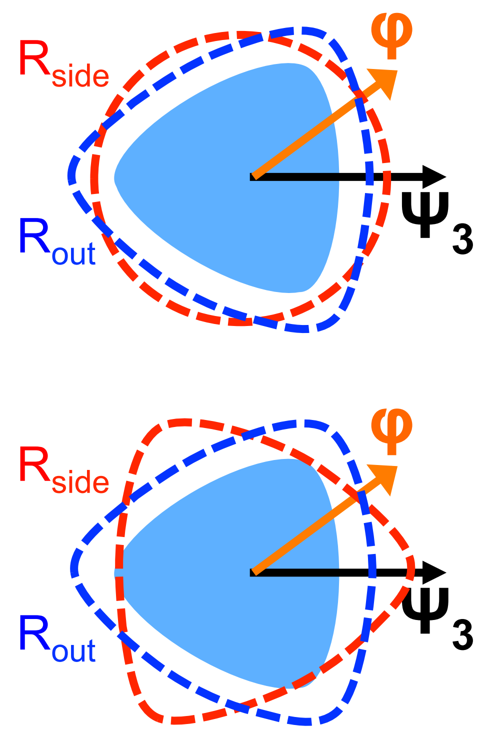


- **Note that no anisotropy is observed by HBT in static source.**



Pion HBT radii w.r.t Ψ_3

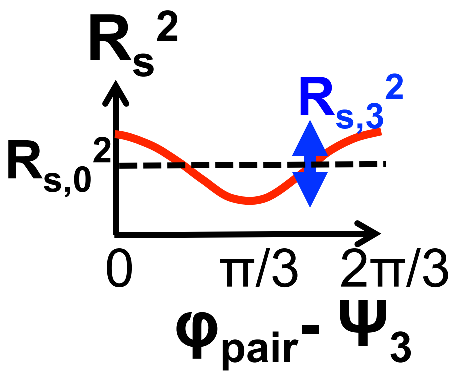


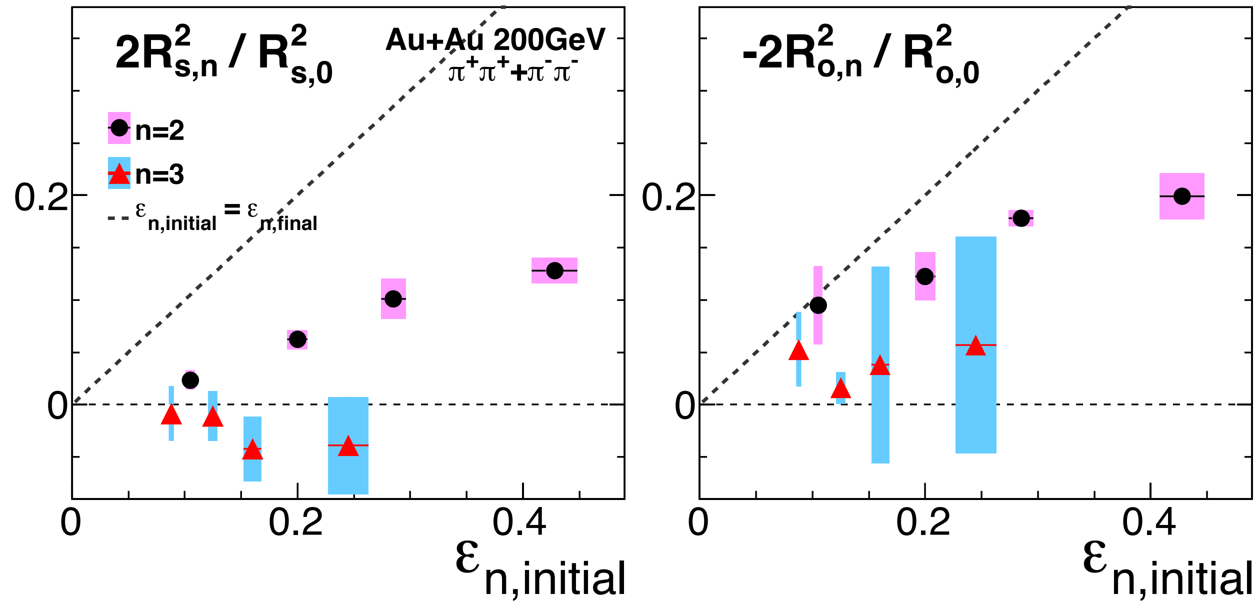


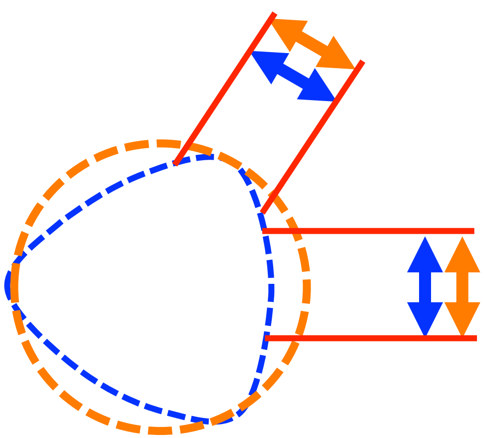
- In 0-10%, R_s is almost flat, while R_o has strong oscillation
  - ✧ Emission duration? Flow anisotropy?
- For n=3, R_s has the same sign to R_o in 20-30%

Relative amplitude of R_{side} and R_{out}

- **Initial ε_n is calculated by Monte-Carlo Glauber simulation**
  - ✧Initial ε_n increases with going to peripheral collisions







- **Variation of HBT radius w.r.t Ψ_3 is very weak compared to the variation w.r.t Ψ_2**
  - ✧$R_{s,3}$ shows zero or slightly negative value
  - ✧$R_{o,3}$ shows zero or slightly positive value

Interpretation by Monte-Carlo simulation

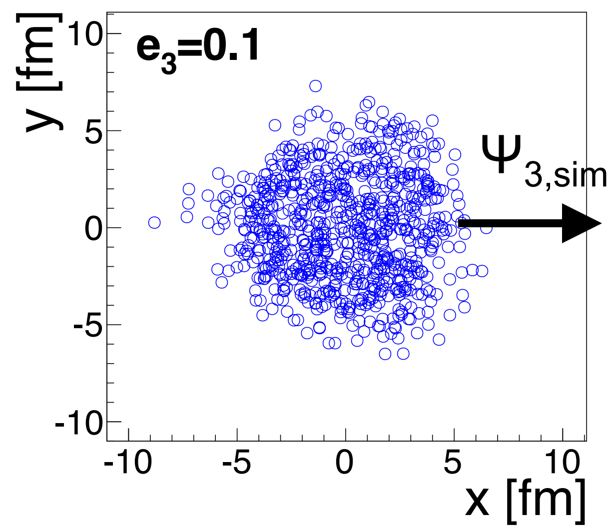
Setup of simulation

- ✧ Spatial distribution
  - ✓ Assuming Woods-Saxon distribution
  - ✓ Spatial shape controlled by **"e_n"**
- ✧ Transverse flow
  - ✓ Radial flow with velocity β_0
  - ✓ Flow anisotropy controlled by **"β_n"**
  - ✓ Boost to radial direction
- ✧ HBT correlation: 1+cos(**Δr • Δp**)
- ✧ m_T distribution with T_f = 160 MeV
- ✧ No Coulomb interaction, no opacity

$$R = R_0(1 - e_n \cos(n\Delta\phi))$$

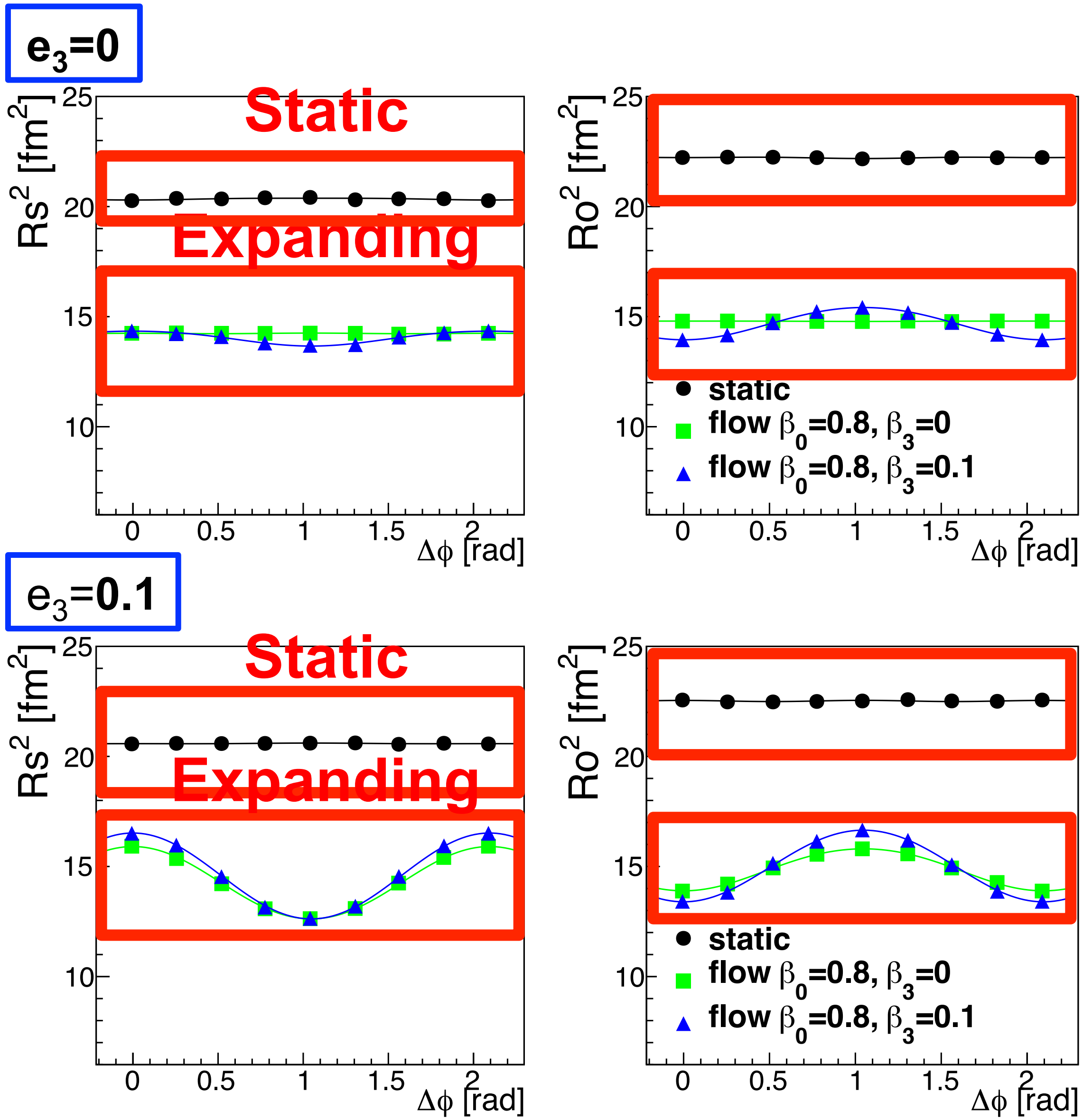
$$\beta_T = \tanh(\rho)$$

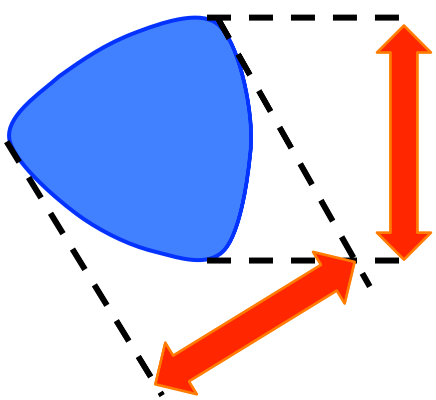
$$\rho = \tanh^{-1}[\beta_0 + \beta_n \cos(n\Delta\phi)](\frac{r}{R})$$



Simulation check

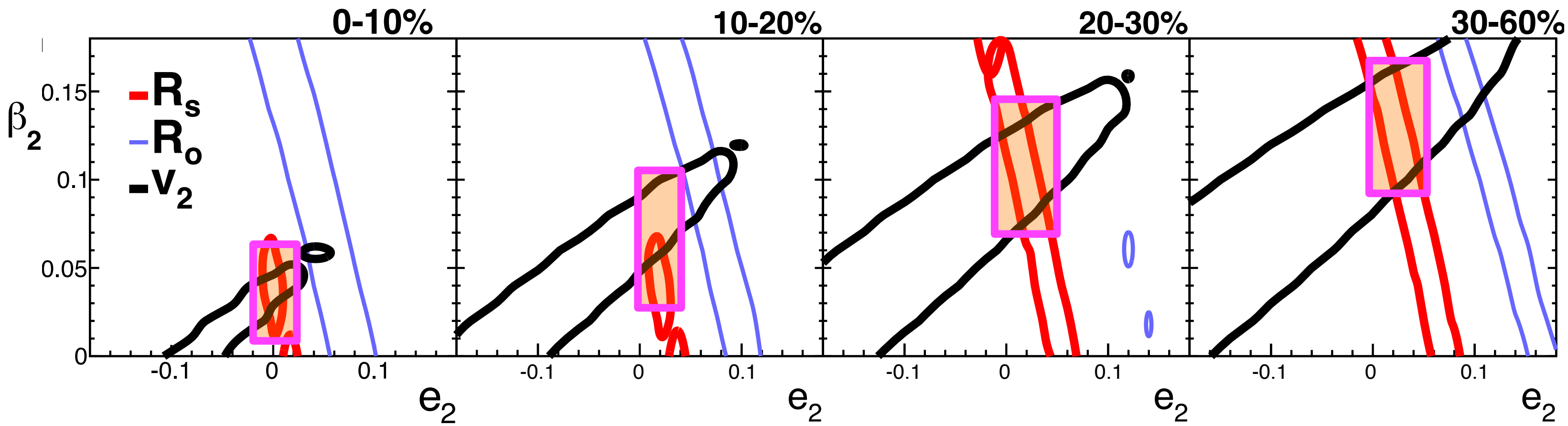
- **Static source**
  - ✧ No oscillation for triangular shape
- **Expanding source**
  - ✧ Triangular shape
    - ✓ Oscillation appears !
  - ✧ Spherical shape
    - ✓ β_3 makes oscillation !





Parameter Search of β_2 vs e_2

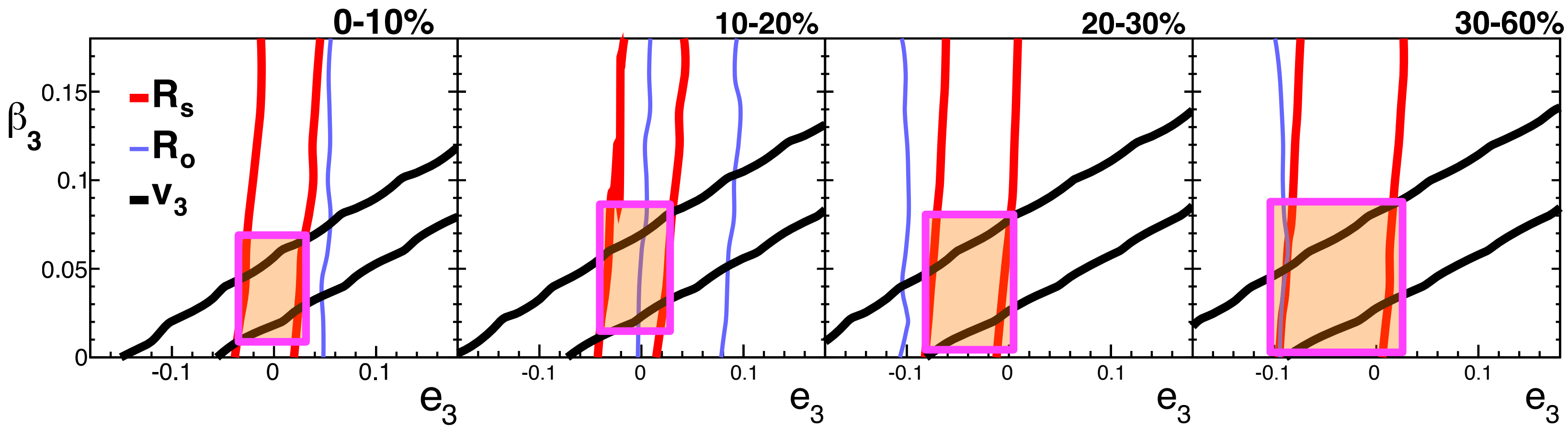
- **Difference between data and simulation are shown as contour plot**
  - ✧ Contour lines for R_μ are set to be larger than the systematic error of data.



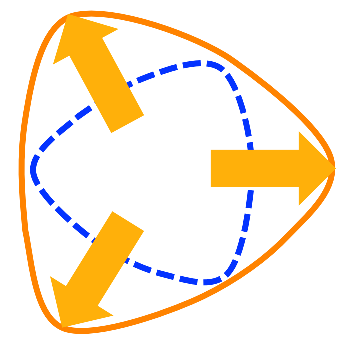
- **Overlap of v_2 and R_s indicates $e_2 \geqq 0$.**
  - ✧ Centrality dependences of β_2 and e_2 are similar to ρ_2 and R_y/R_x in BW.
- **Regions of R_s and R_o don't match.**
  - ✧ Strong oscillation of R_o cannot be explained by flow and geometry ?
  - ✧ Related to the emission duration ?

Parameter Search of β_3 vs e_3

- **Difference between data and simulation are shown as contour plot**
  - ✧ Contour lines for R_μ are set to be the systematic error of data.



- **Overlap of v_3 and R_s indicates $e_3 \leqq 0$.**
  - ✧ Centrality dependence of β_3 is similar to that of v_3.
- **Negative e_3 indicates the opposite shape to initial shape**



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

Summary(1)

- **Azimuthal HBT radii w.r.t 2nd-order event plane**
  - ✧ε_{final} of π is ~$\varepsilon_{initial}/2$, which indicates the strong expansion to in-plane direction and still elliptical shape.
  - ✧ε_{final} of π 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.
  - ✧Strong oscillation of R_{out} was seen in central event.
    Relative amplitude of R_{out} in 0-20% doesn't depend on m_T.
    - ☛ Related to flow anisotropy or emission duration depending on azimuthal angle.
- **Blast-wave model**
  - ✧Blast-wave fit for pion HBT using p_T spectra and v_2
  - ✧Extracted system lifetime is shorter than hydrodynamic calculations.
    Finite emission duration
  - ✧m_T dependence of π and the difference between π&K cannot be explained well by BW with extracted parameters
    - ☛ Need to compare a realistic model (3D-hydro+cascade?)

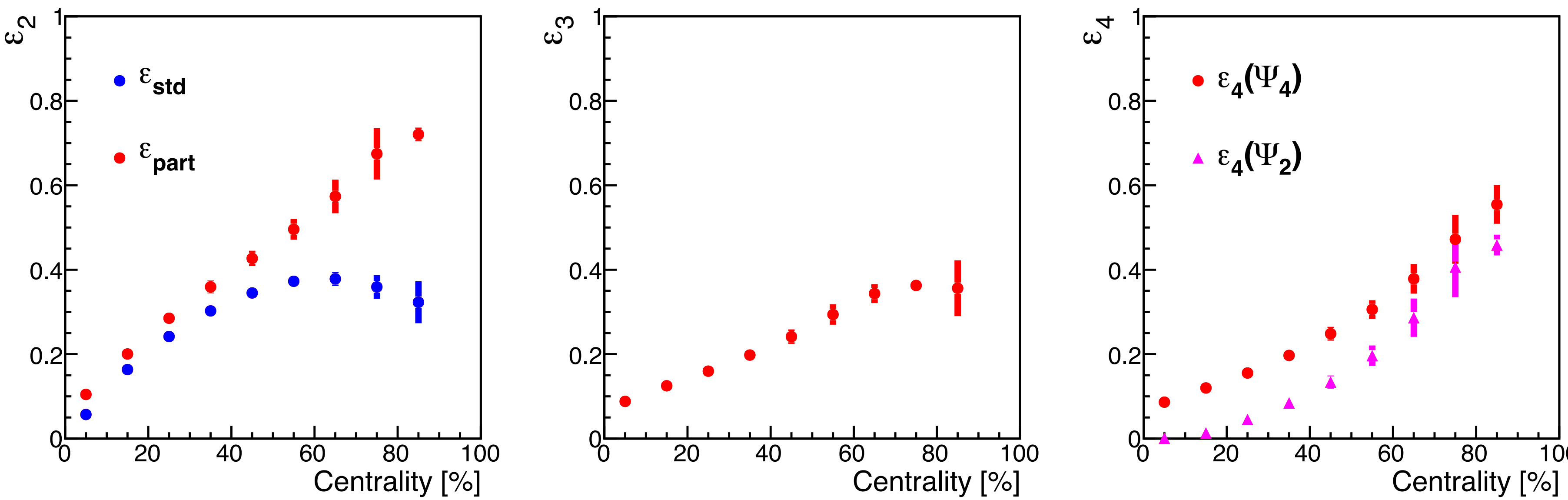
Summary(2)

- **Azimuthal HBT radii w.r.t 3rd-order event plane**
  - ✧First measurement of azimuthal HBT w.r.t 3rd-order event plane
  - ✧Relative amplitudes of R_{side} seem to have zero~negative value, while those of R_{out} have zero~positive value.
- **Monte-Carlo simulation**
  - ✧Elliptical and triangular source was simulated changing the strength of spatial(e_n) and flow(β_n) anisotropy.
  - ✧Parameter search was performed comparing data to simulation.
    - ✓ Searched e_2 and β_2 show similar trend with Blast-wave fit result.
    - ✓ Searched e_3 and β_3 indicates that the sign of initial triangular anisotropy may be changed by triangular flow.
  - ✧Need to compare with a event-by-event hydrodynamic model for the comprehensive understanding of the data.

Back up

Initial spatial anisotropy by Glauber model

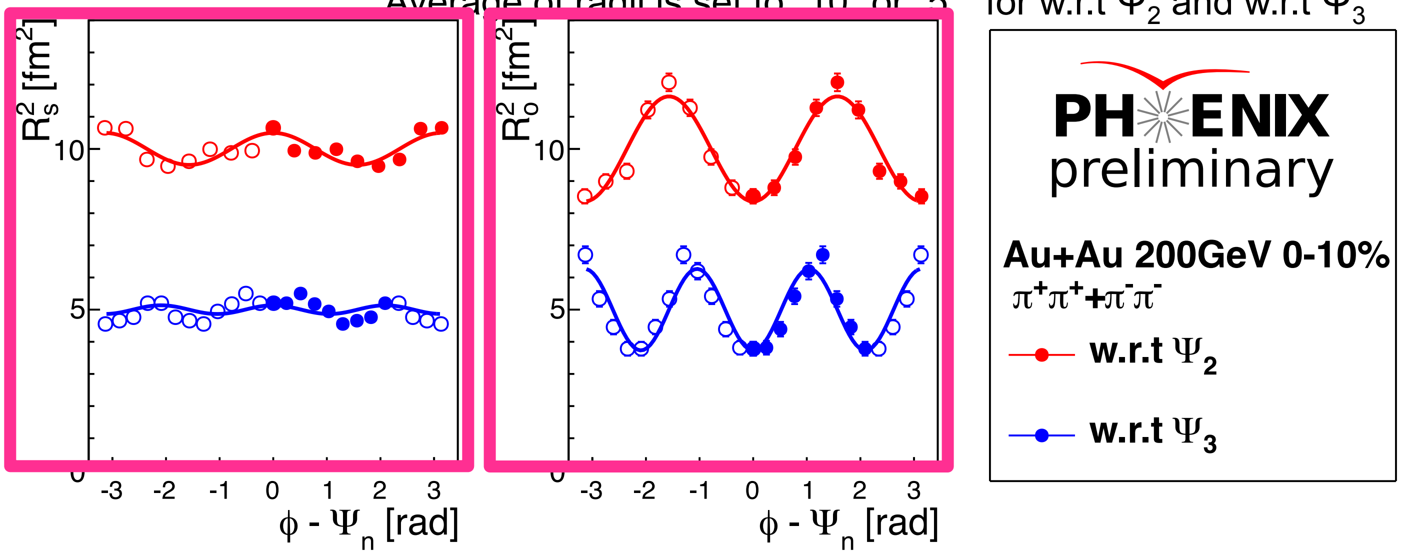
- **Initial eccentricity and triangularity increase with centrality going from central to peripheral.**



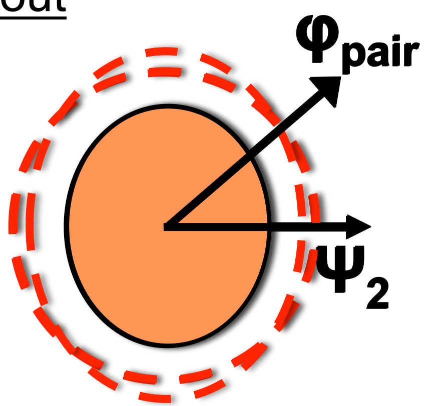
Comparison of 2nd and 3rd order component

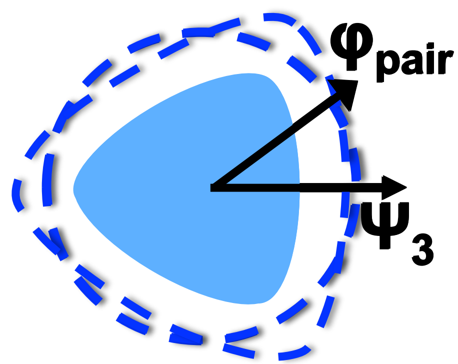
- **In 0-10%, R_{out} have stronger oscillation for Ψ_2 and Ψ_3 than R_{side}**
  - ✧This oscillation indicates different emission duration between 0°/60° w.r.t Ψ_3 ? or depth of the triangular shape ?

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



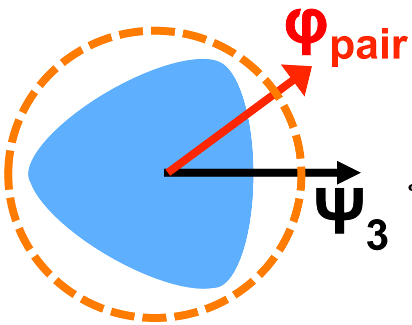
Rout

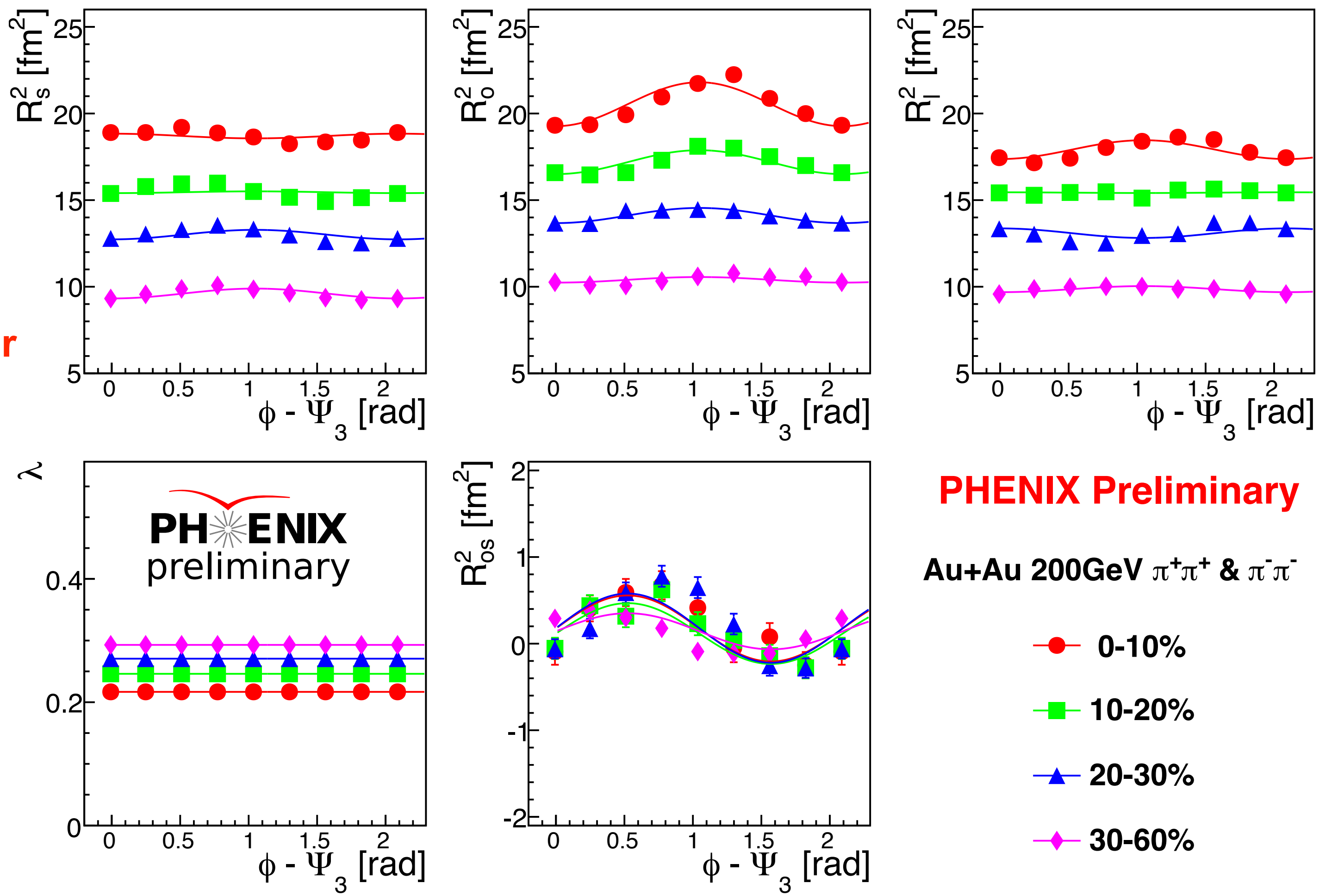




Rside

Azimuthal HBT radii w.r.t Ψ_3

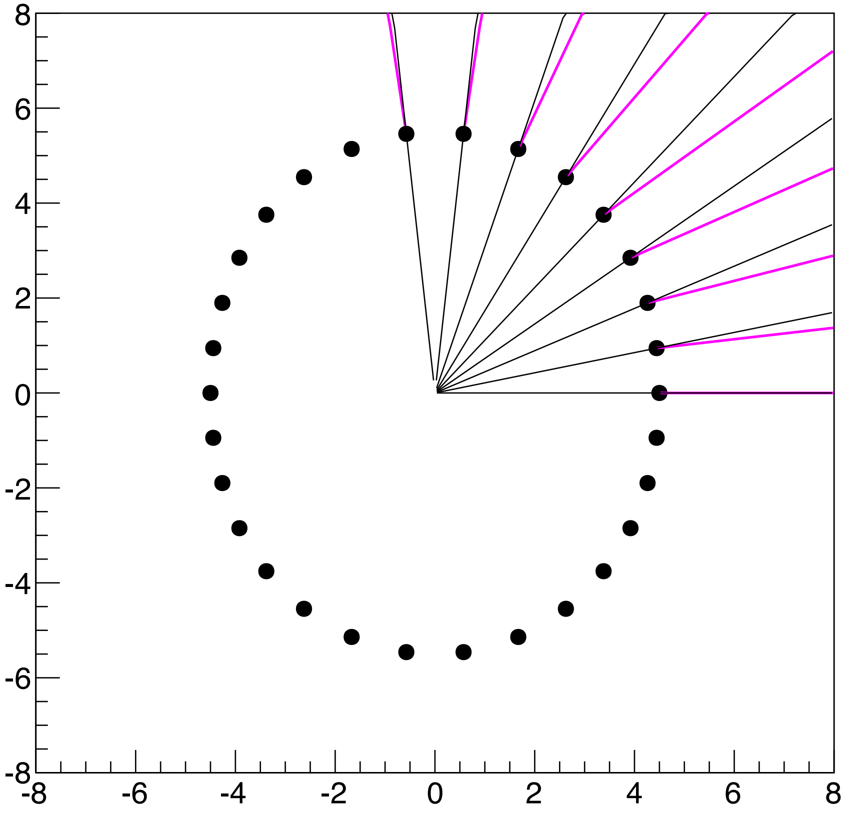


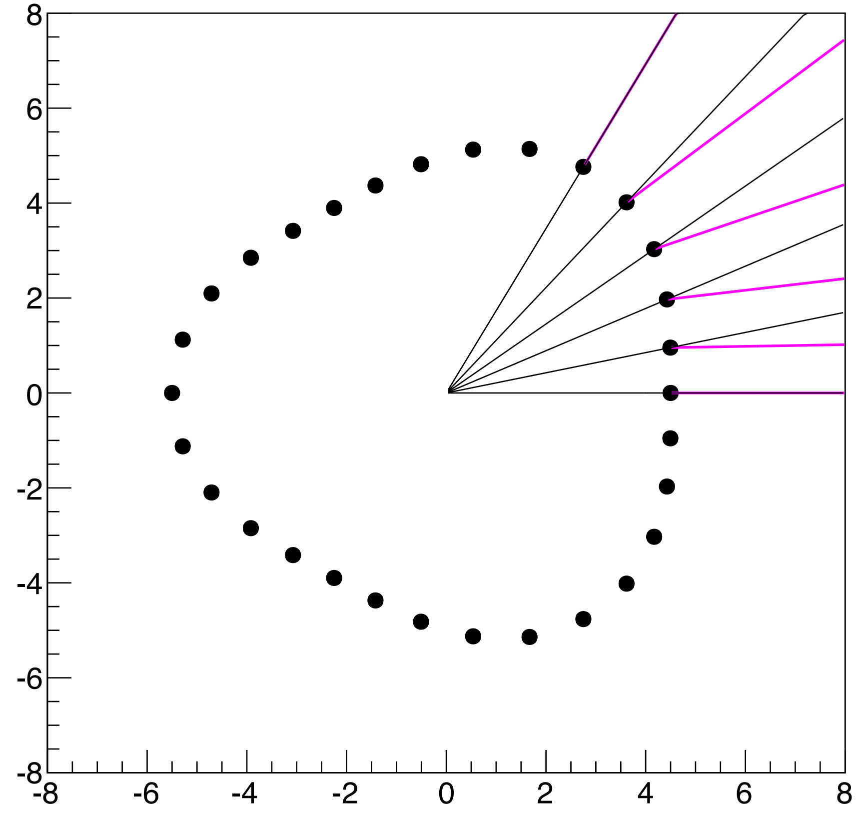


- R_{side} is almost flat
- R_{out} have a oscillation in most central collisions

Boost angle

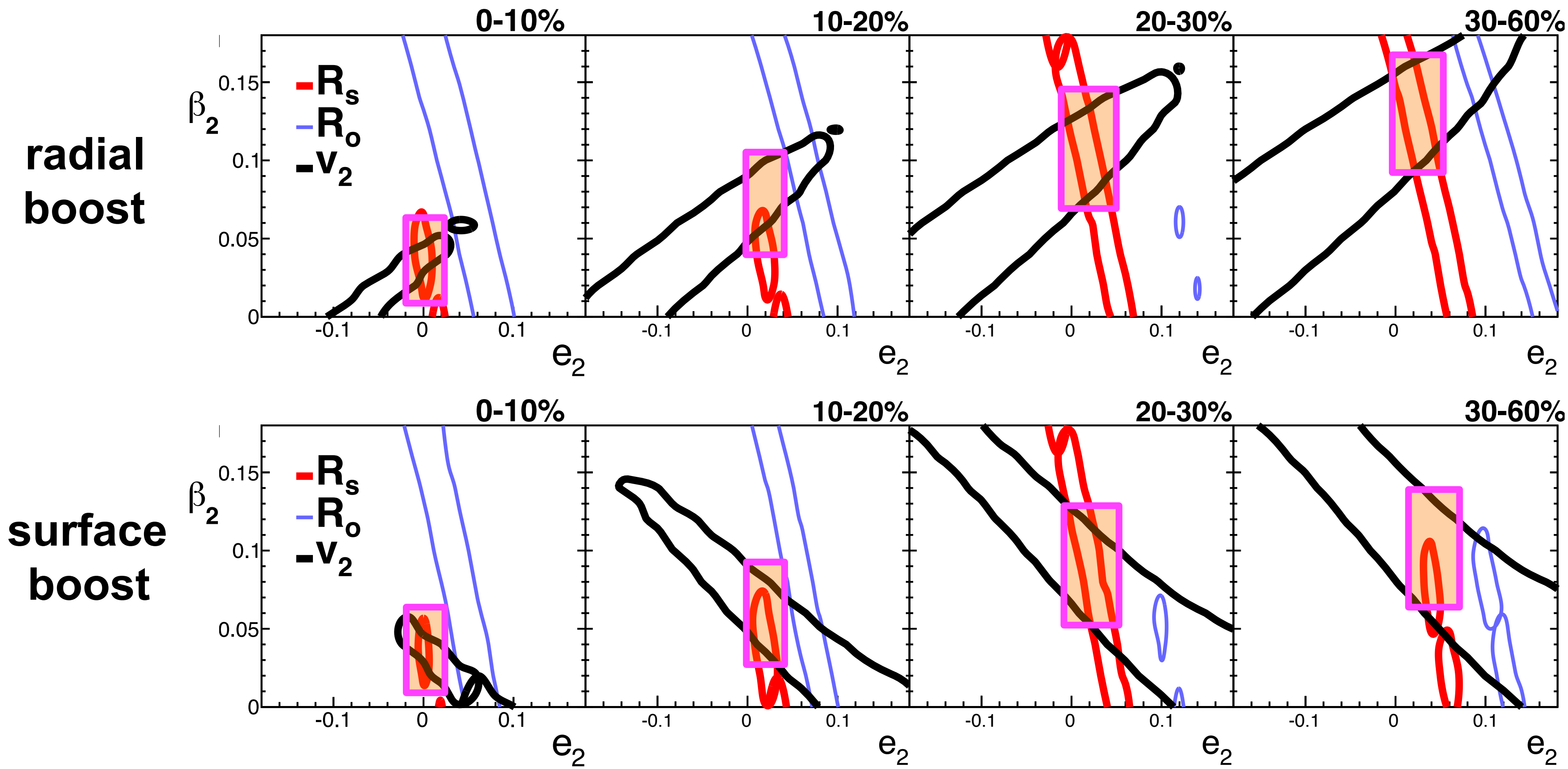
- **Boost angle is set to be :**
  - ✧radial direction of the particle position (**radial boost**)
  - ✧perpendicular to the surface which is similar condition with BW (PRC70, 044907 (2004)) (**surface boost**)





Comparison of boost angle for β_2 vs e_2

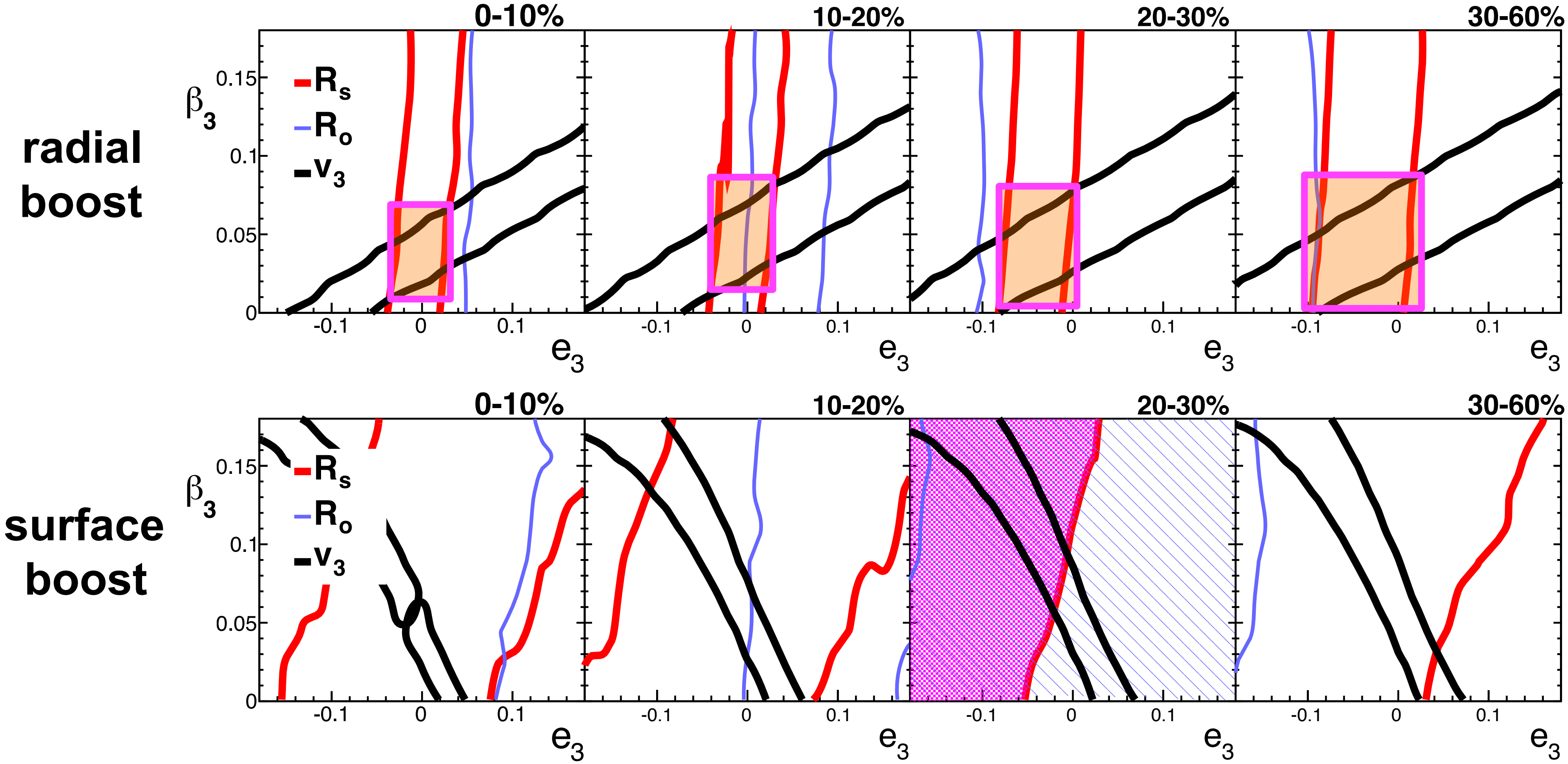
- **Difference between data and simulation are shown as contour plot**
  - ✧ Contour lines for R_μ are set to be larger than the systematic error of data.



Similar trend can be seen between two conditions!!

Comparison of boost angle for β_3 vs e_3

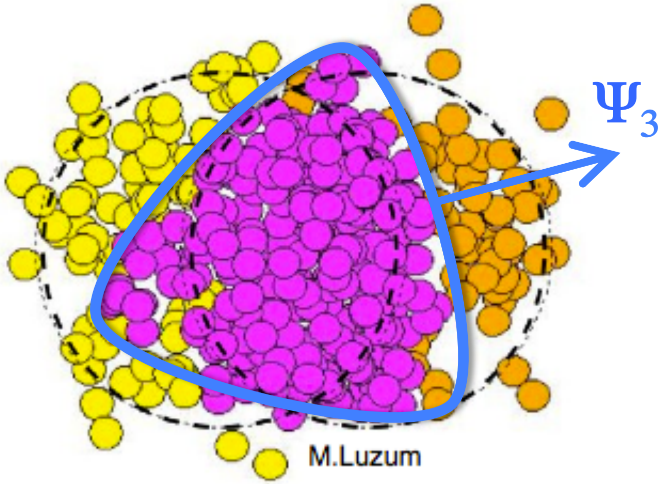
- **Difference between data and simulation are shown as contour plot**
  - ✧ Contour lines for R_μ are set to be larger than the systematic error of data.



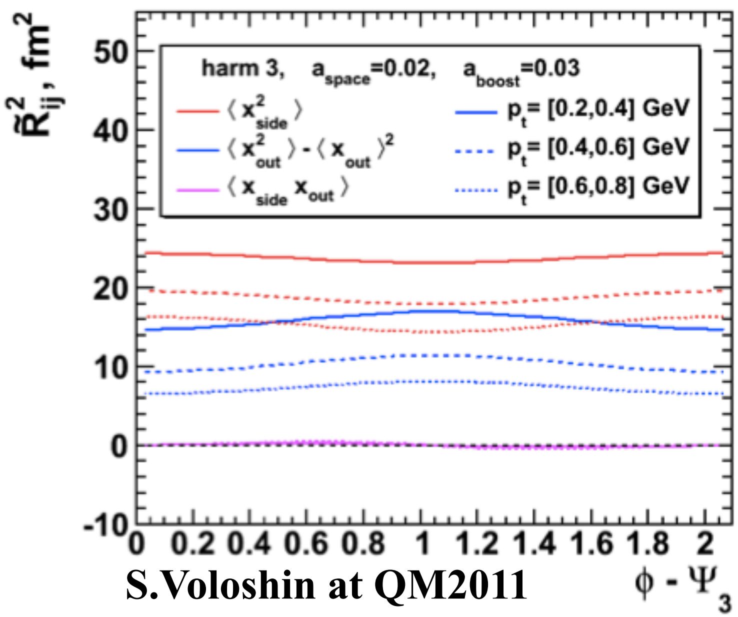
At least, $e_3 \leqq 0$ in 20-30%

HBT vs Higher Harmonic Event Plane

- **The idea is to expand azimuthal HBT to higher harmonic event planes.**
  - ✧may show the fluctuation of the shape at freeze-out.
  - ✧provide more constraints on theoretical models about the system evolution.



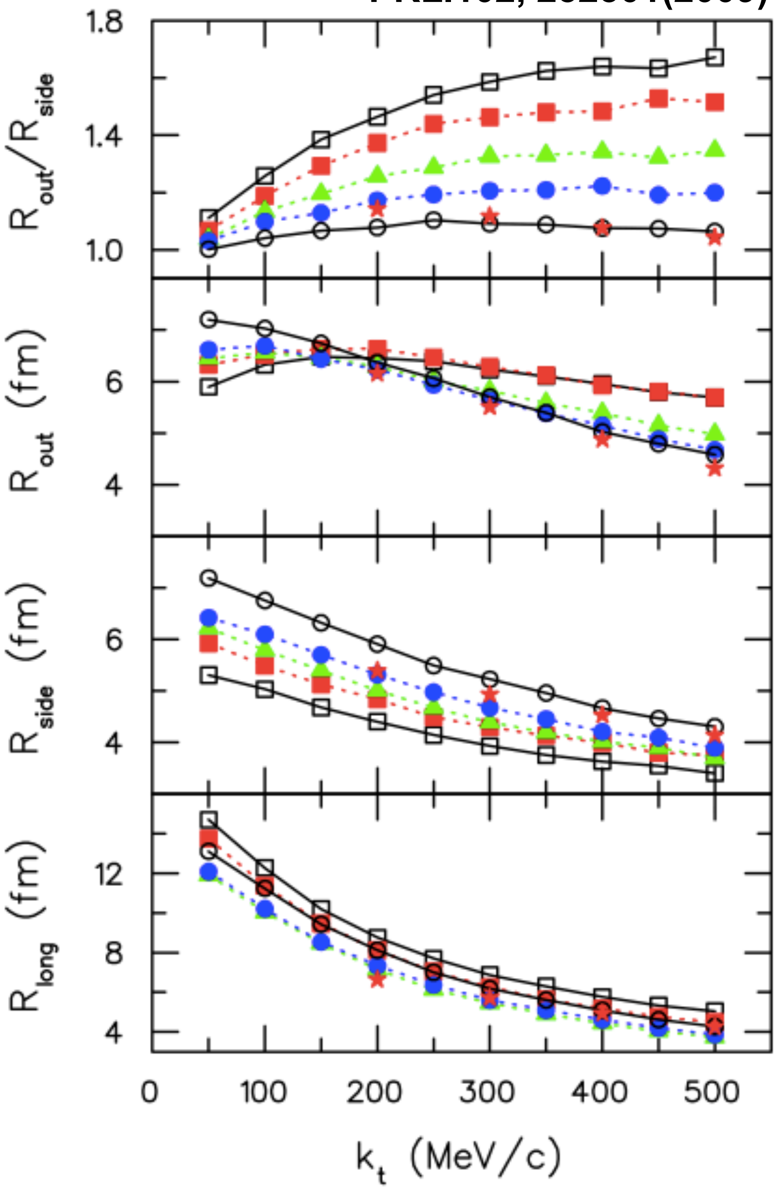
Hydrodynamic model calculation



S.Voloshin at QM2011
T=100[MeV], $\rho=r'\rho_{max}(1+\cos(n\varphi))$

Comparison of models and the past HBT results

PRL.102, 232301(2009)



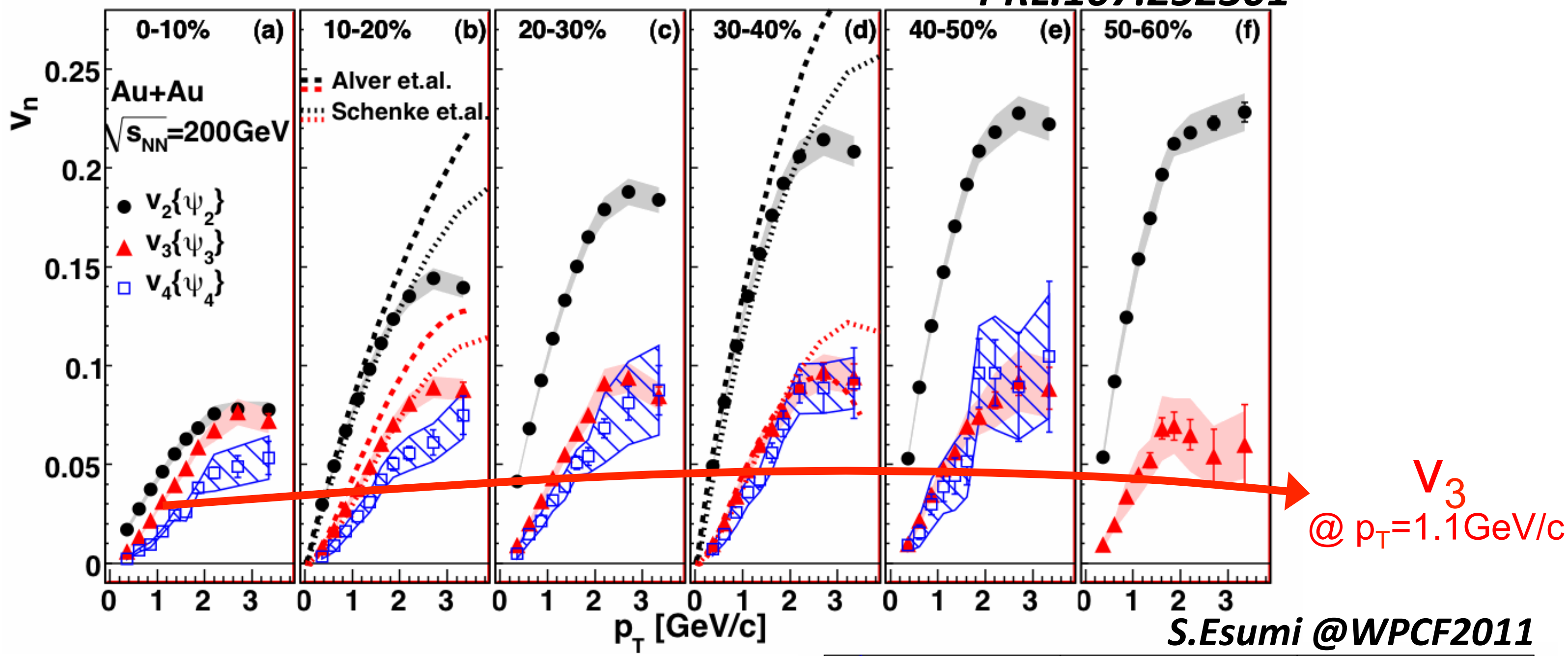
★ STAR, Au+Au 200 GeV

- □ First-order phase transition with no prethermal flow, no viscosity
- ■ Including initial flow
- ▲ Using stiffer equation of state
- ● Adding viscosity
- ○ Including all features

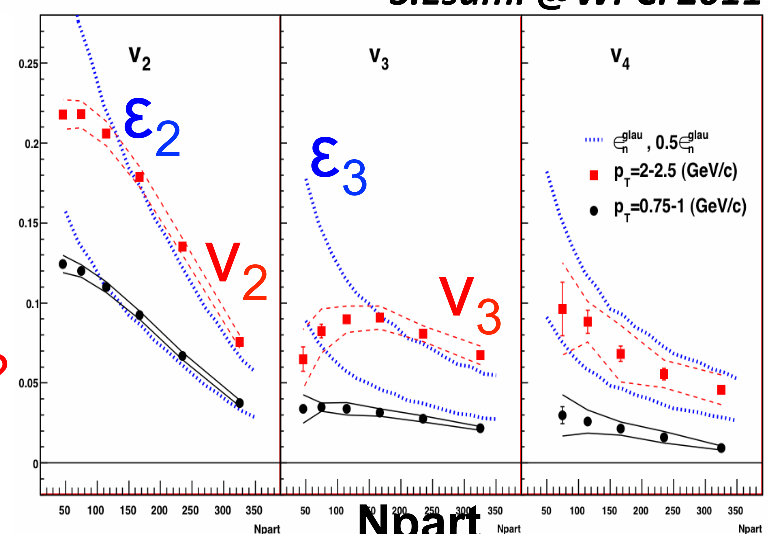
Hydrodynamic model can reproduce the past HBT result!
HBT can provide constraints on the model!

Centrality dependence of v_3 and ε_3

PRL.107.252301



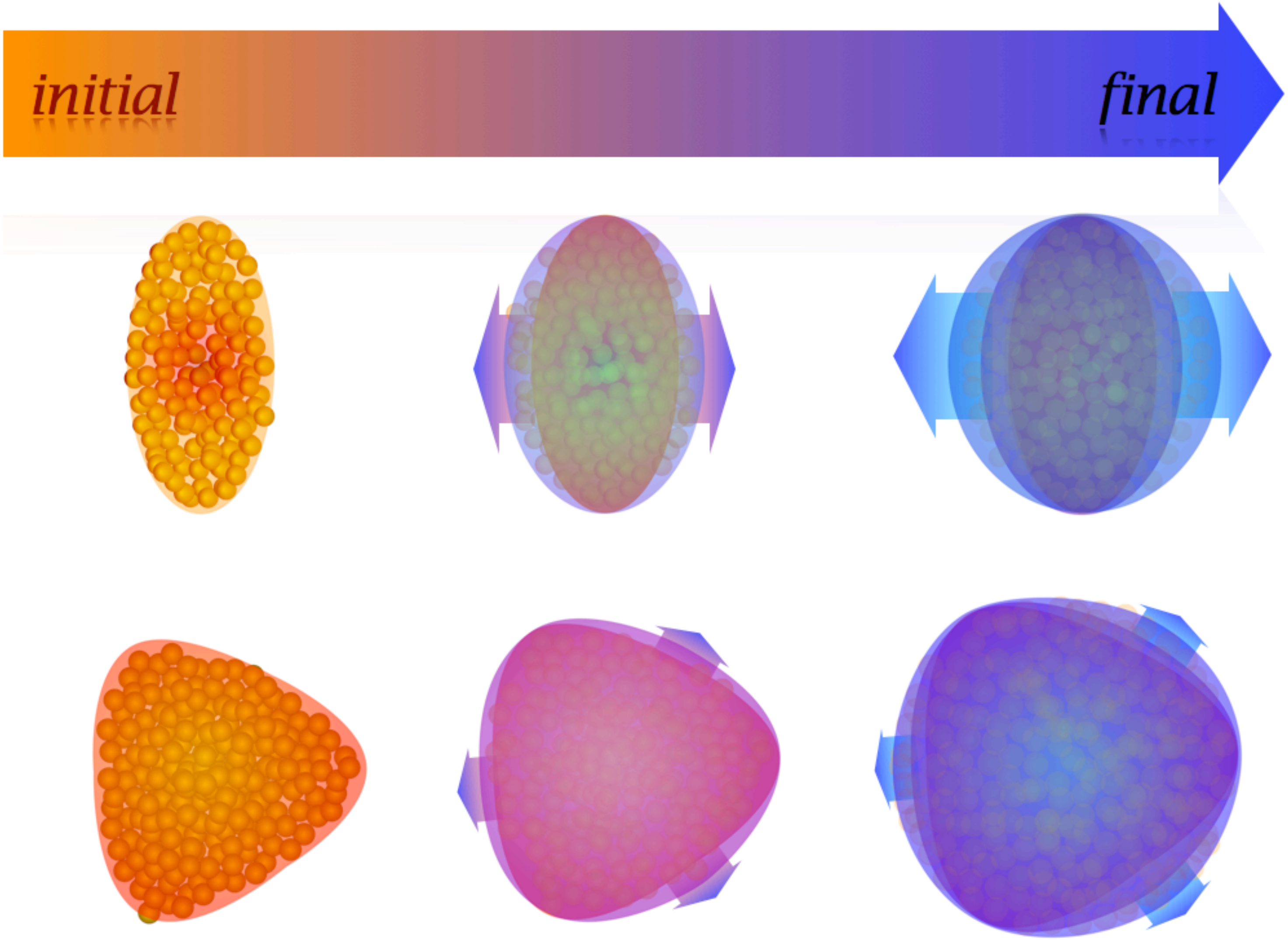
S.Esumi @WPCF2011



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

Final ε_3 has any centrality dependence?

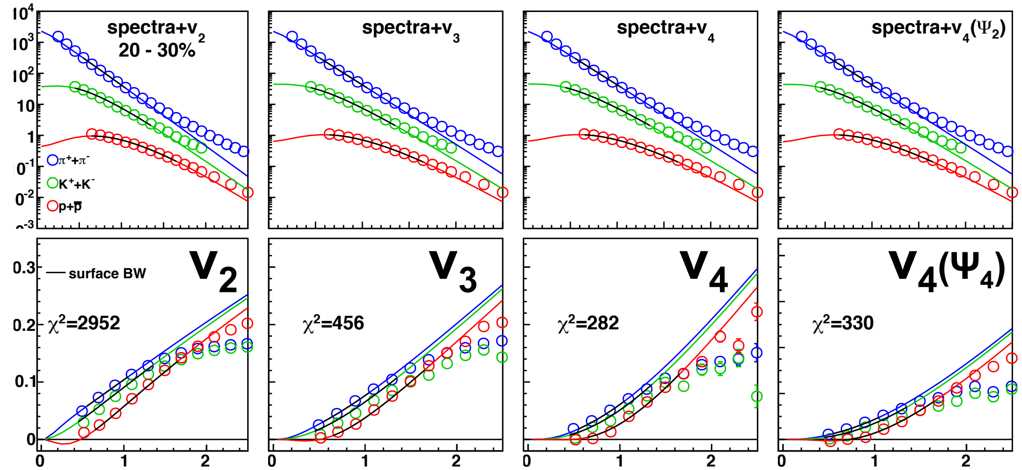
Image of initial/final source shape



Spatial anisotropy by Blast wave model

- **Blast wave fit for spectra & v_n**
  - ✧Used parameters

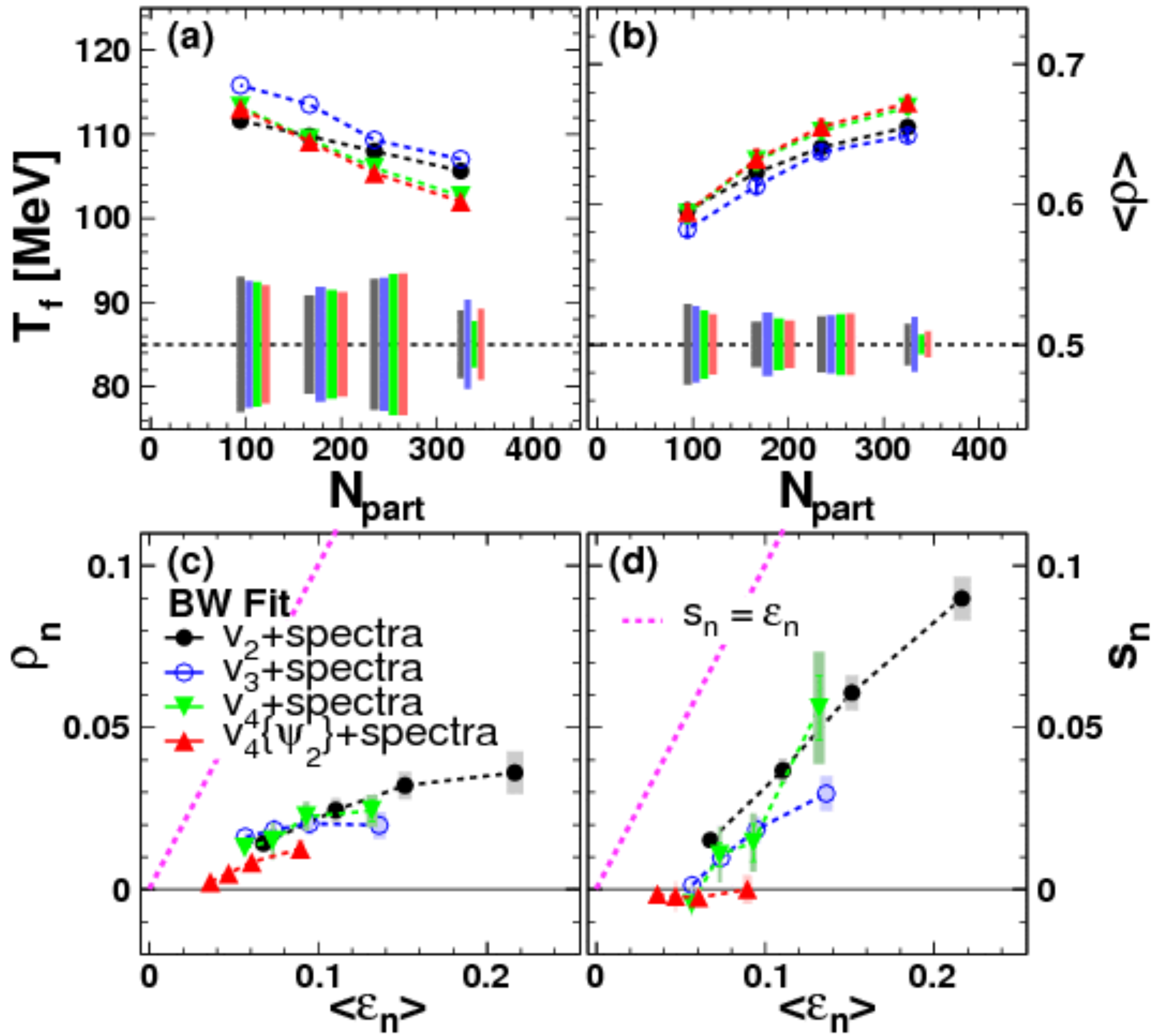
    T_f : temperature at freeze-out
    ρ_0 : radial flow strength
    ρ_n : flow anisotropy
    s_n : spatial density anisotropy



Extracted parameters by different Blast wave model

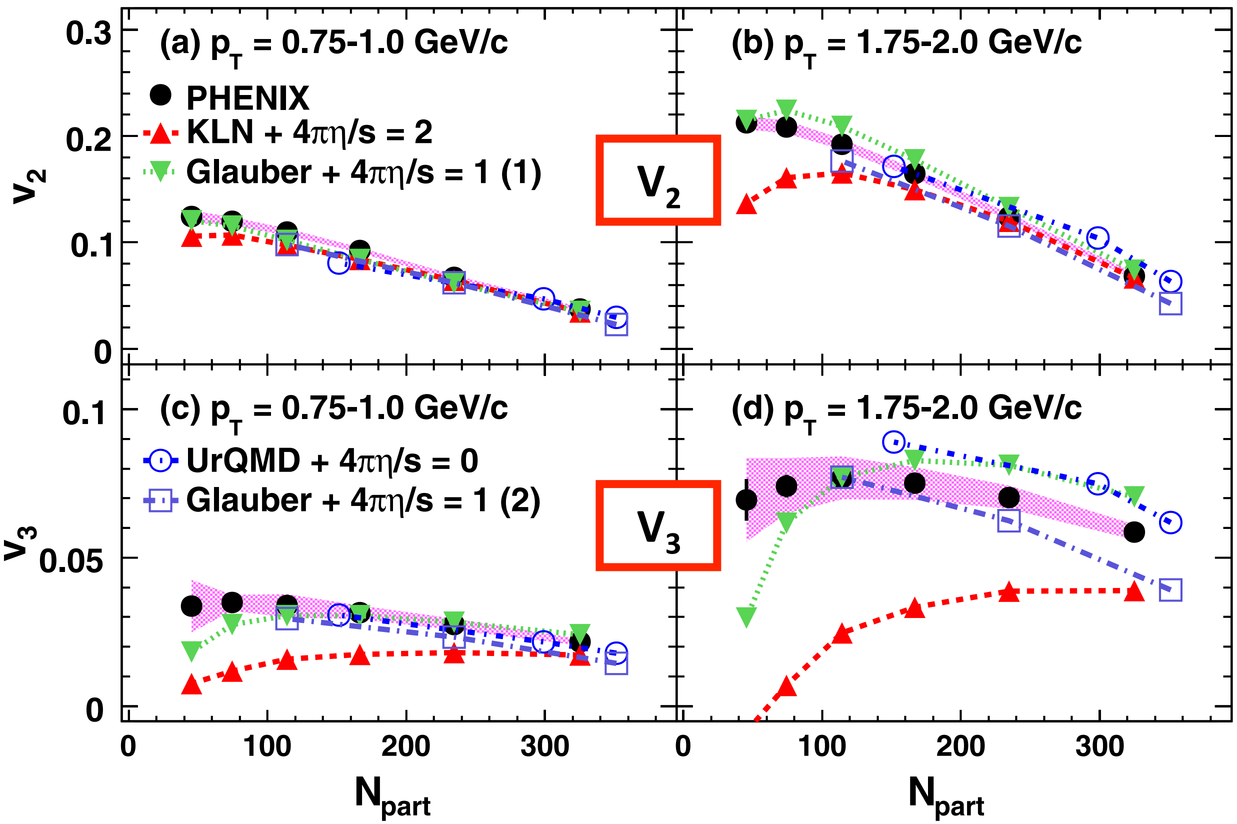
- **Blast wave fit was performed for spectra and v_n**

Flow anisotropy ρ_2 and ρ_3 have similar trend !



v_3 breaks degeneracy

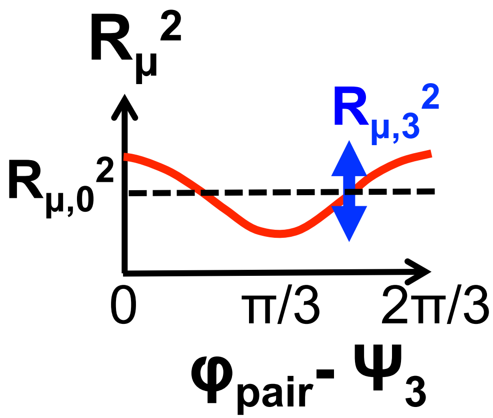
PRL.107.252301

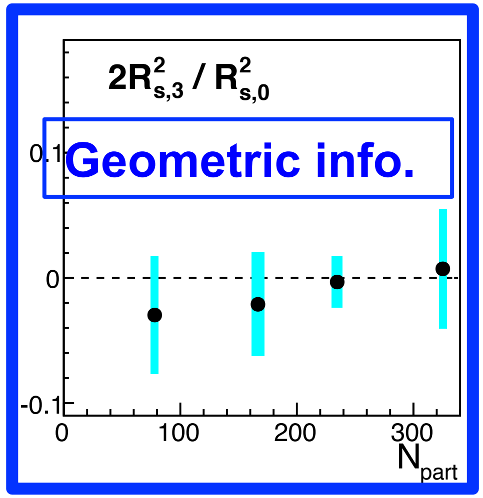


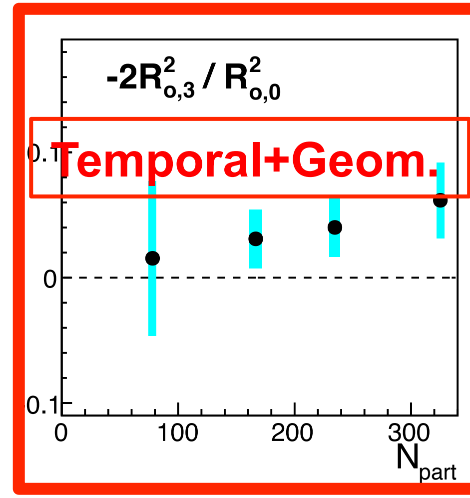
- **v_3 provides new constraint on hydro-model parameters**
  - Glauber & 4πη/s=1 : works better
  - KLN & 4πη/s=2 : fails

Relative amplitude of HBT radii

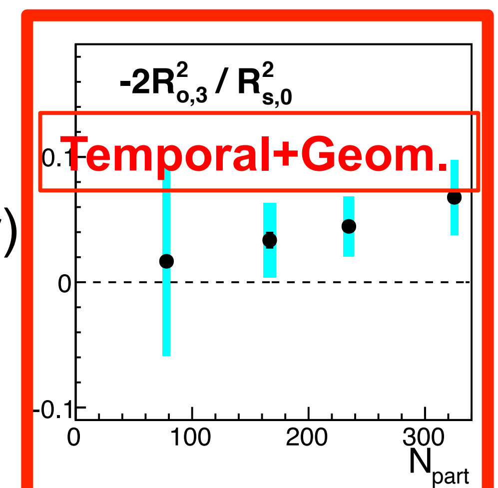
- **Relative amplitude is used to represent "triangularity" at freeze-out**
- **Relative amplitude of Rout increases with increasing Npart**







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



PHENIX Preliminary

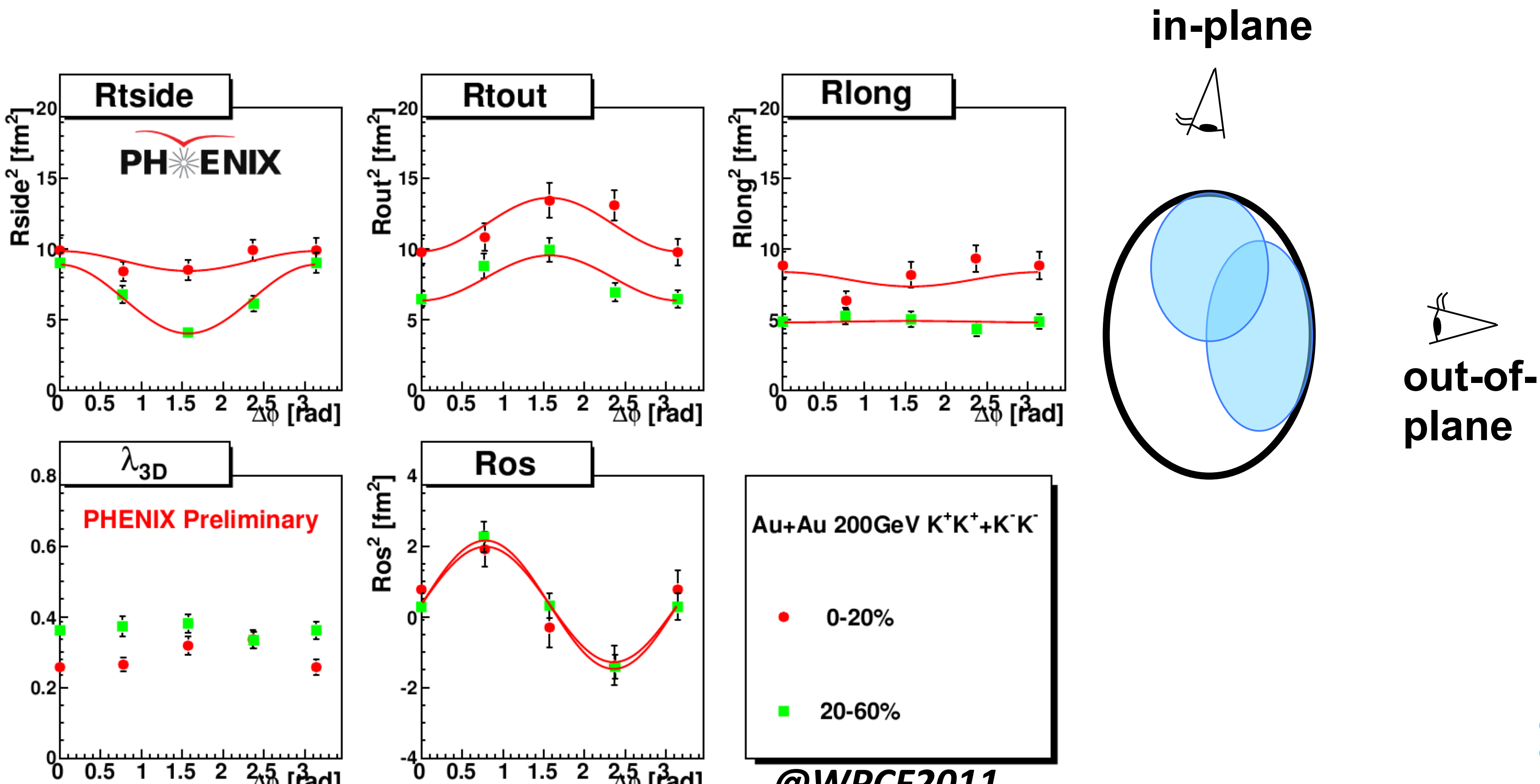
PHENIX preliminary

Au+Au 200GeV

$\pi^+\pi^+ + \pi^-\pi^-$

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)



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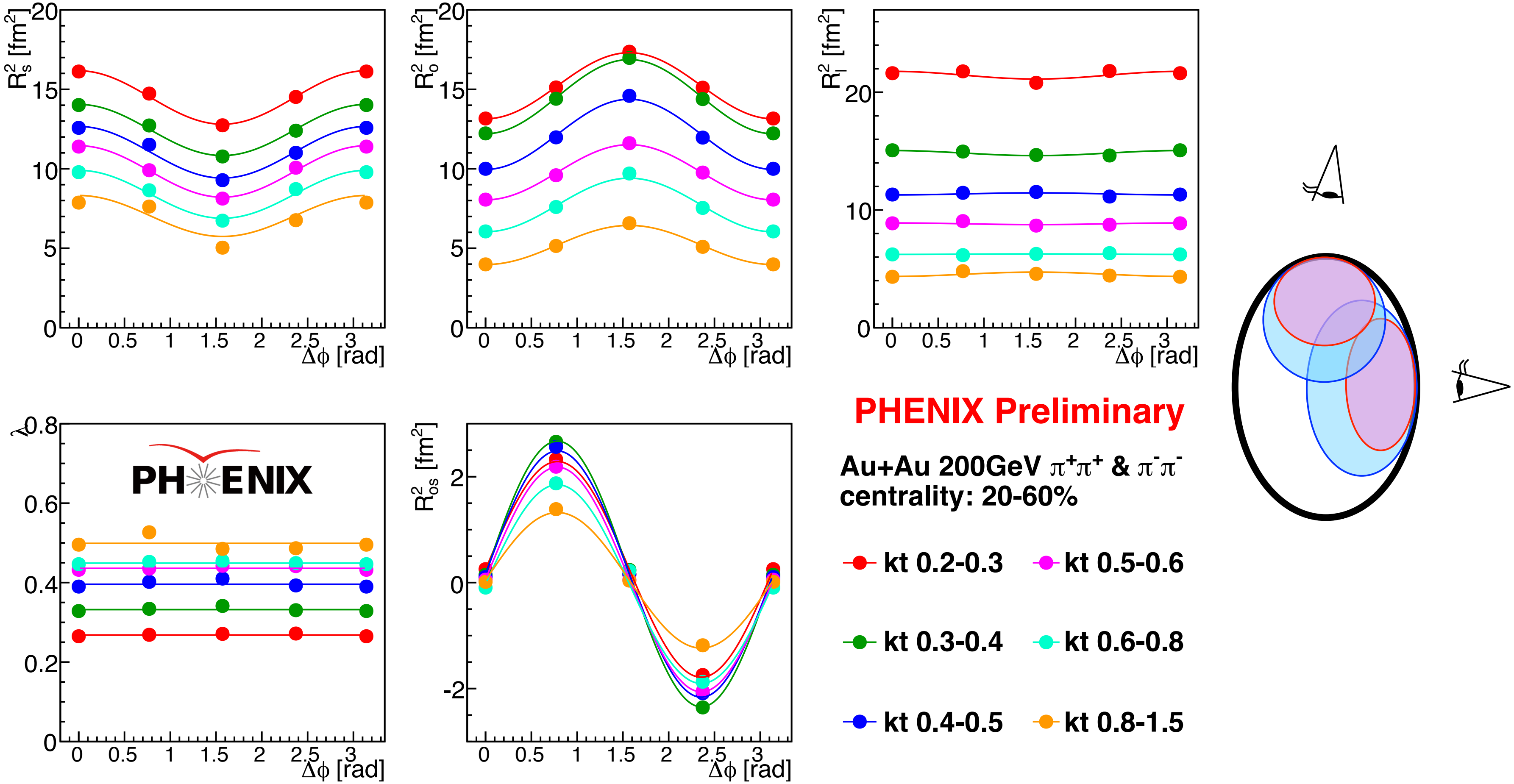
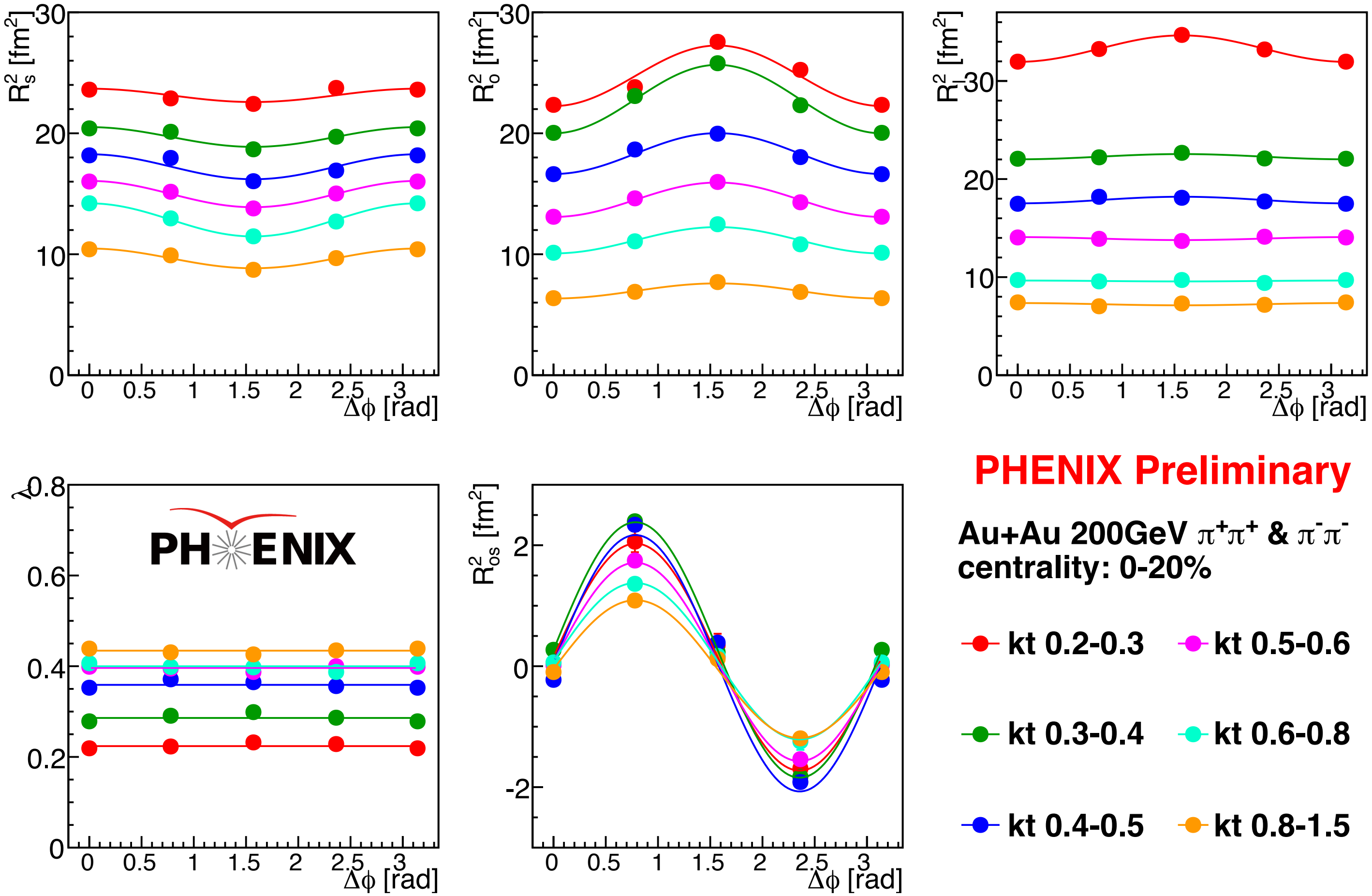
k_T dependence of azimuthal pion HBT radii in 20-60%



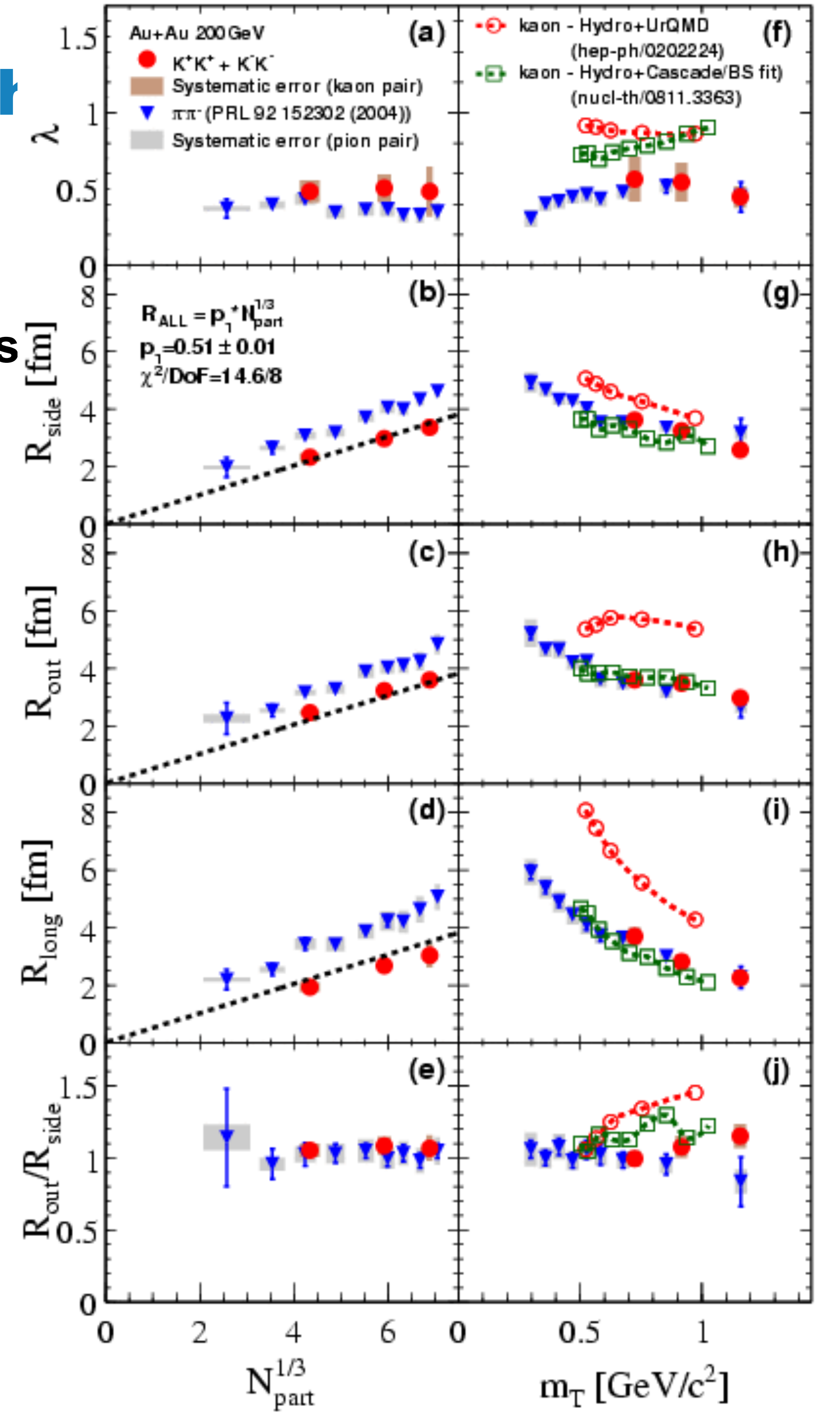
- Oscillation can be seen in R_s, R_o, and R_{os} for each kT regions

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



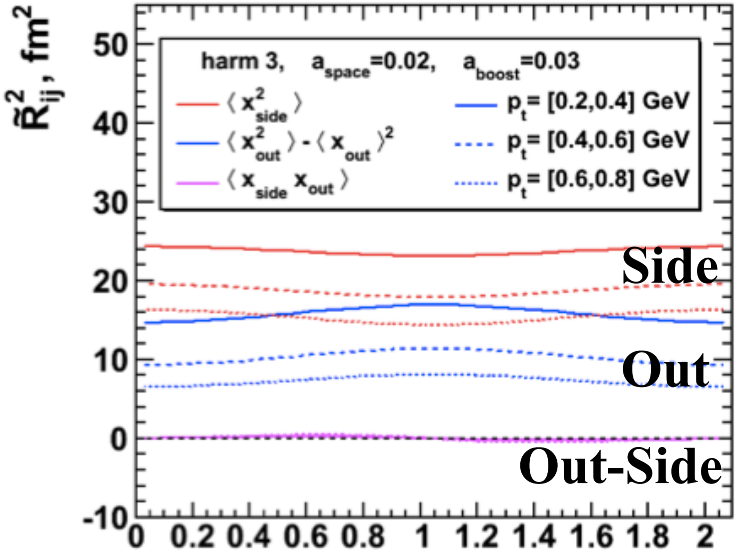
The past HBT Results for ch

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



Model predictions

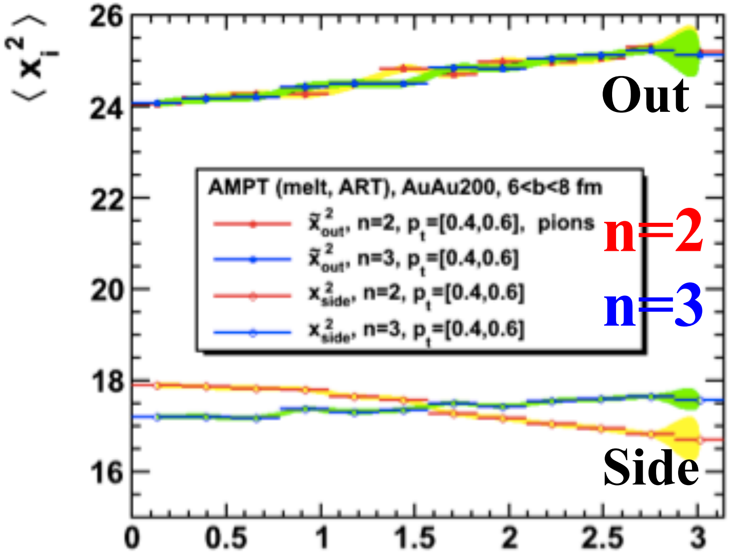
Blast-wave model



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}.