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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TAC seminar, Dec 20th/2012

outline

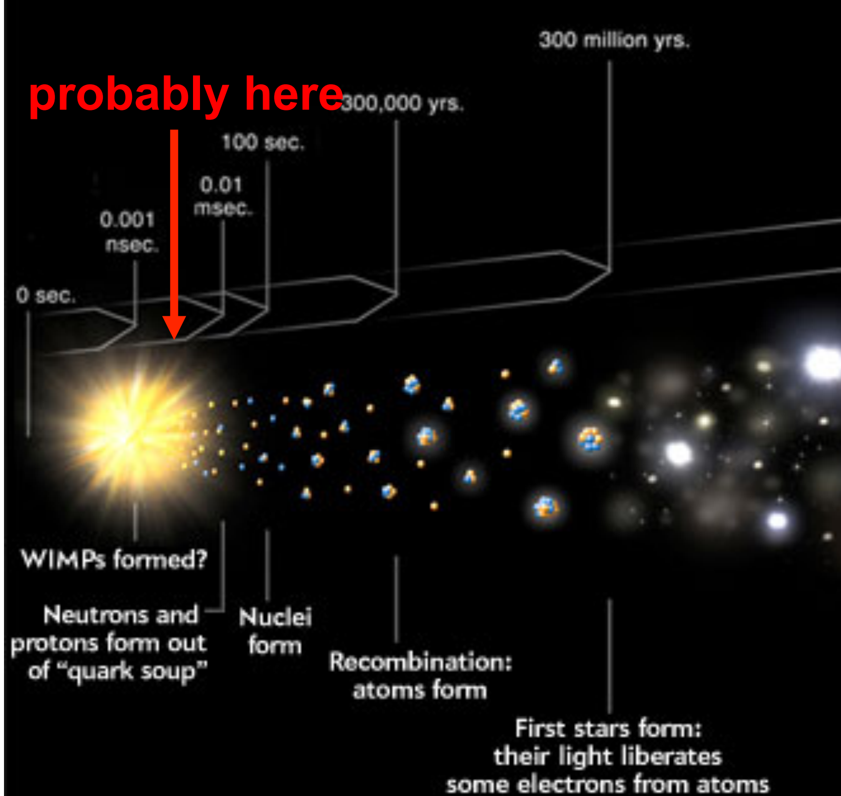
- **Introduction**
  - HBT Interferometry
  - Motivation
- **Analysis**
  - PHENIX Detectors
  - Analysis Method
- **Results & Discussion**
  - HBT measurement with respect to 2nd-/3rd-order event plane
  - Blast-wave model
- **Summary**

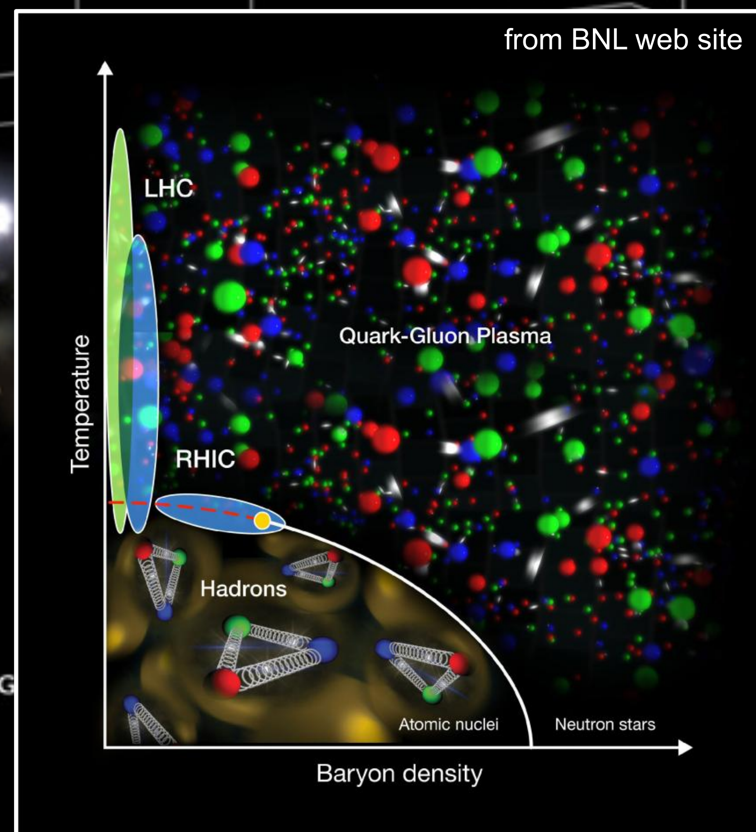
Introduction

Quark Gluon Plasma (QGP)

http://www.scientificamerican.com/

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

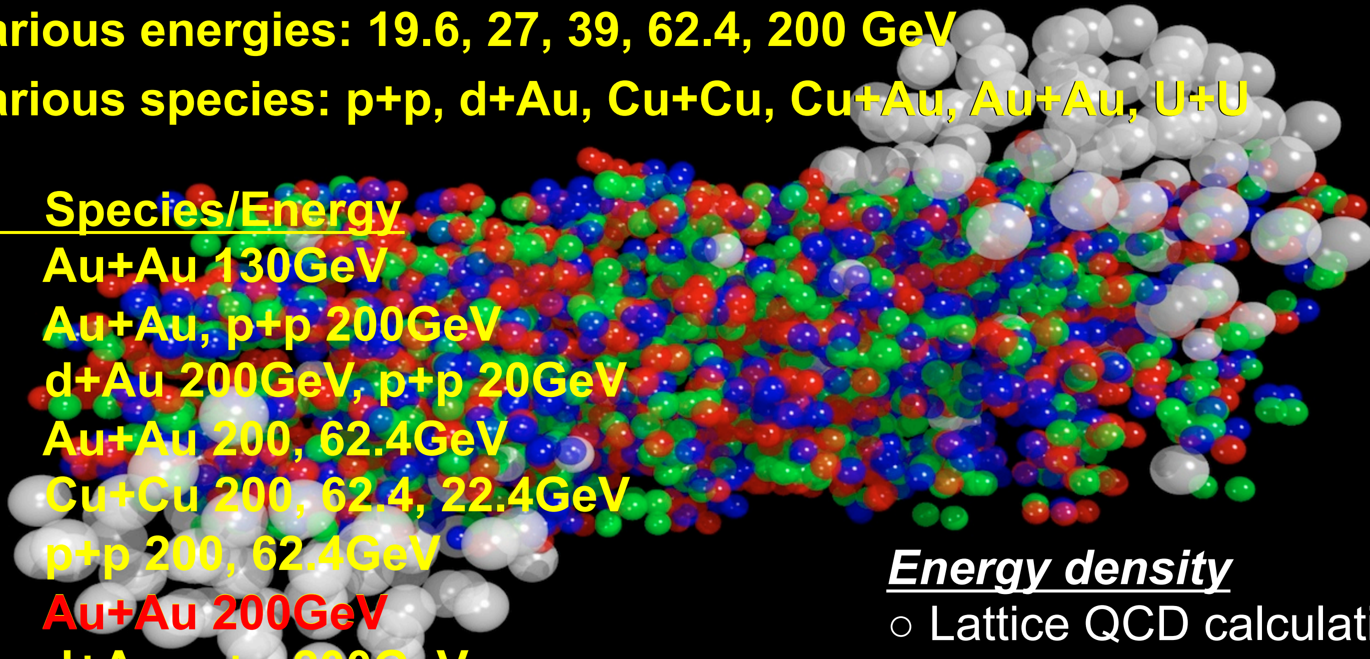




- QGP will be created at extreme temperature and energy density

Relativistic Heavy Ion Collisions

- **Relativistic Heavy Ion Collider is an unique tool to create QGP.**
  - ✧Brookhaven National Laboratory in U.S.A
  - ✧Two circular rings (3.8 km in circumstance)
  - ✧Various energies: 19.6, 27, 39, 62.4, 200 GeV
  - ✧Various species: p+p, d+Au, Cu+Cu, Cu+Au, Au+Au, U+U



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

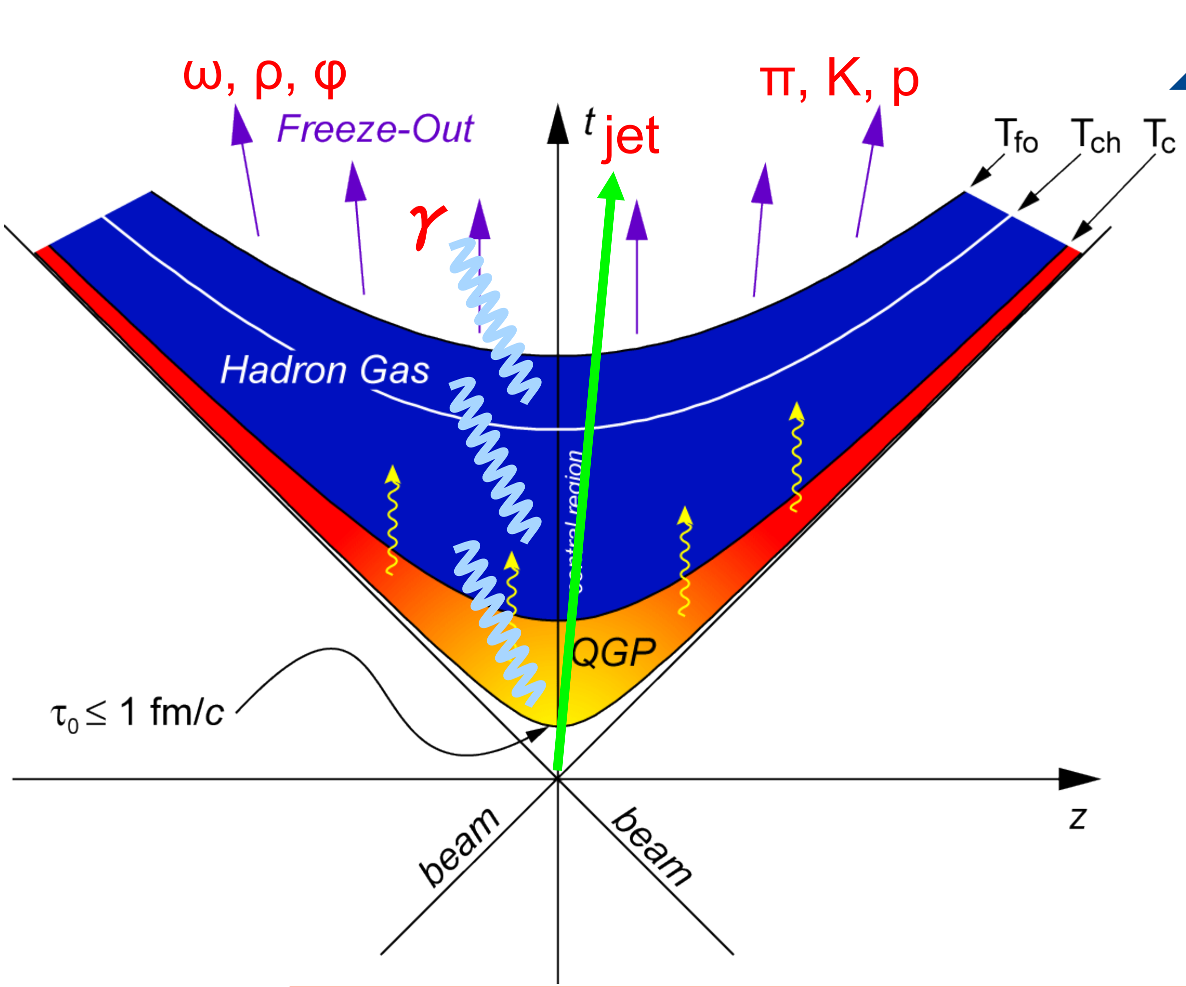
$T_c \sim 170$ MeV

$\varepsilon_c \sim 1$ GeV/fm^3

○ Au+Au 200GeV @RHIC

$\varepsilon_{Bj} \sim 5$ GeV/fm$^3 > \varepsilon_c$

Space-Time Evolution



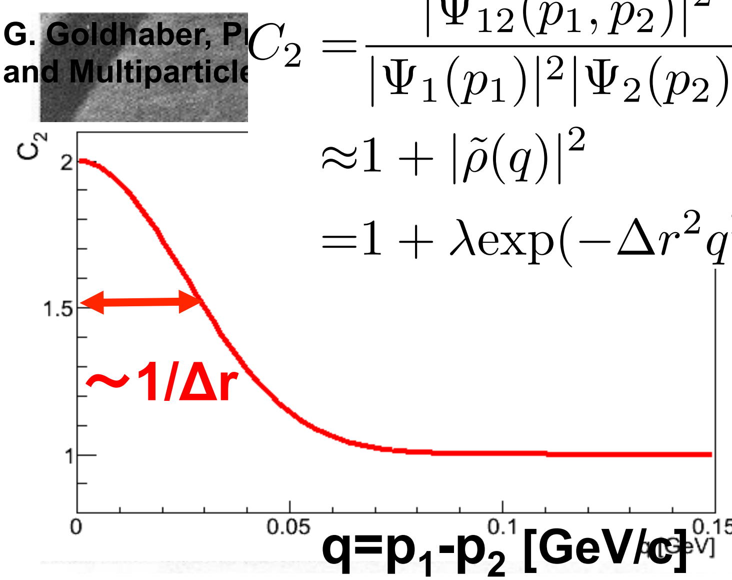
5. Thermal freeze-out
4. Chemical freeze-out
3. Phase transition
   Hadronization
2. Partonic thermarization
   QGP state
1. Collision occurs

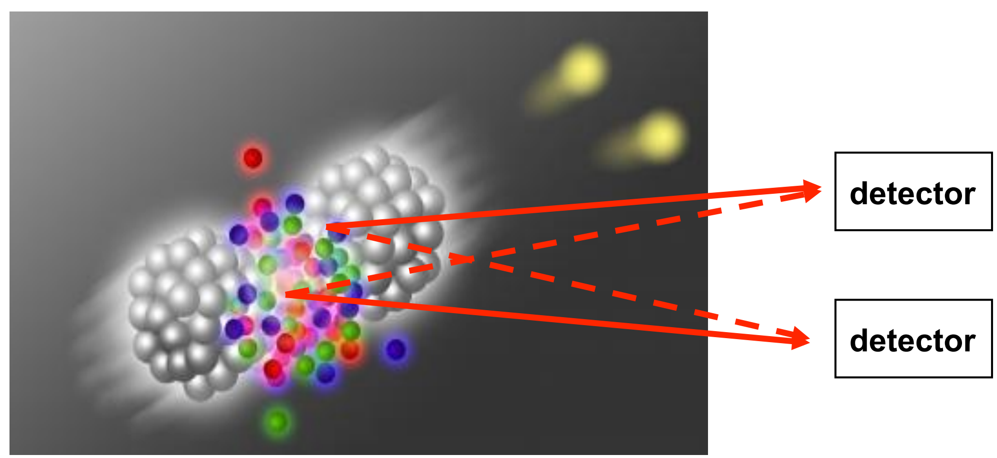
How fast the system thermalizes and evolves?
How much the system size?
What is the nature of phase transition?

HBT Interferometry

- **HBT effect is quantum interference between two identical particles.**
- **R. Hanbury Brown and R. Twiss**
  - ✧In 1956, 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.

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



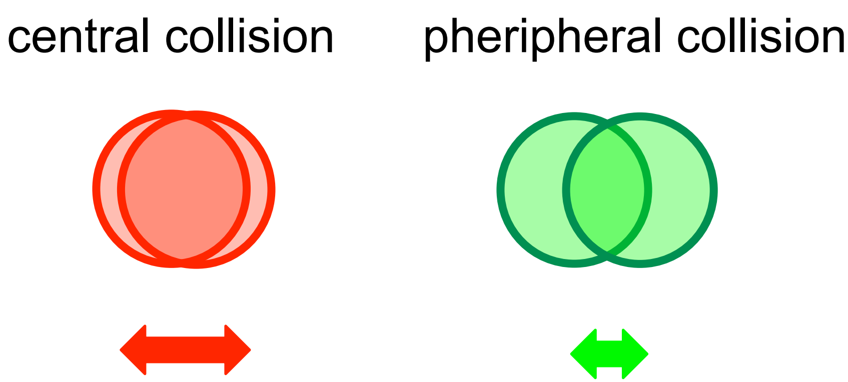


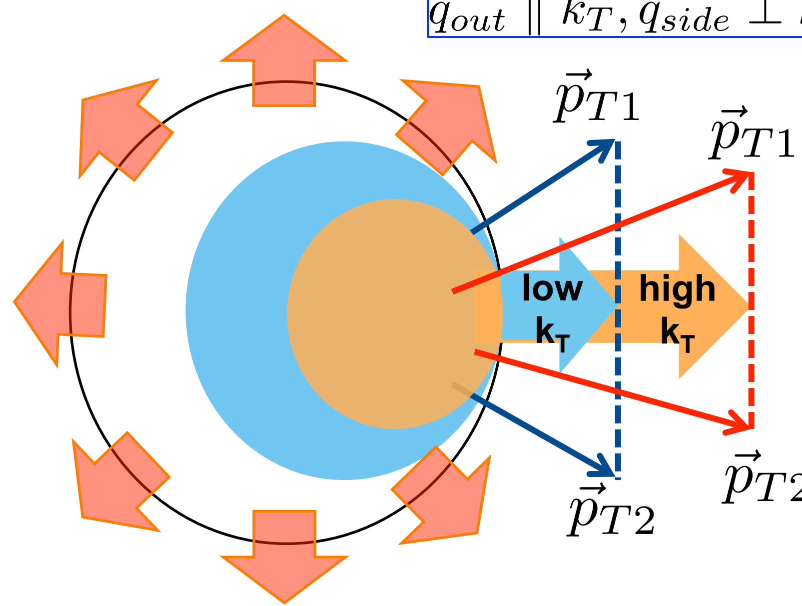
What does HBT radii depend on ?

- **Centrality**
  - ✧ HBT radii depends on the size of collision area.
- **Average pair momentum k_T**
  - ✧ Case of “static source”: measuring the whole size
  - ✧ Case of “expanding source” : measuring “homogeneity region”

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

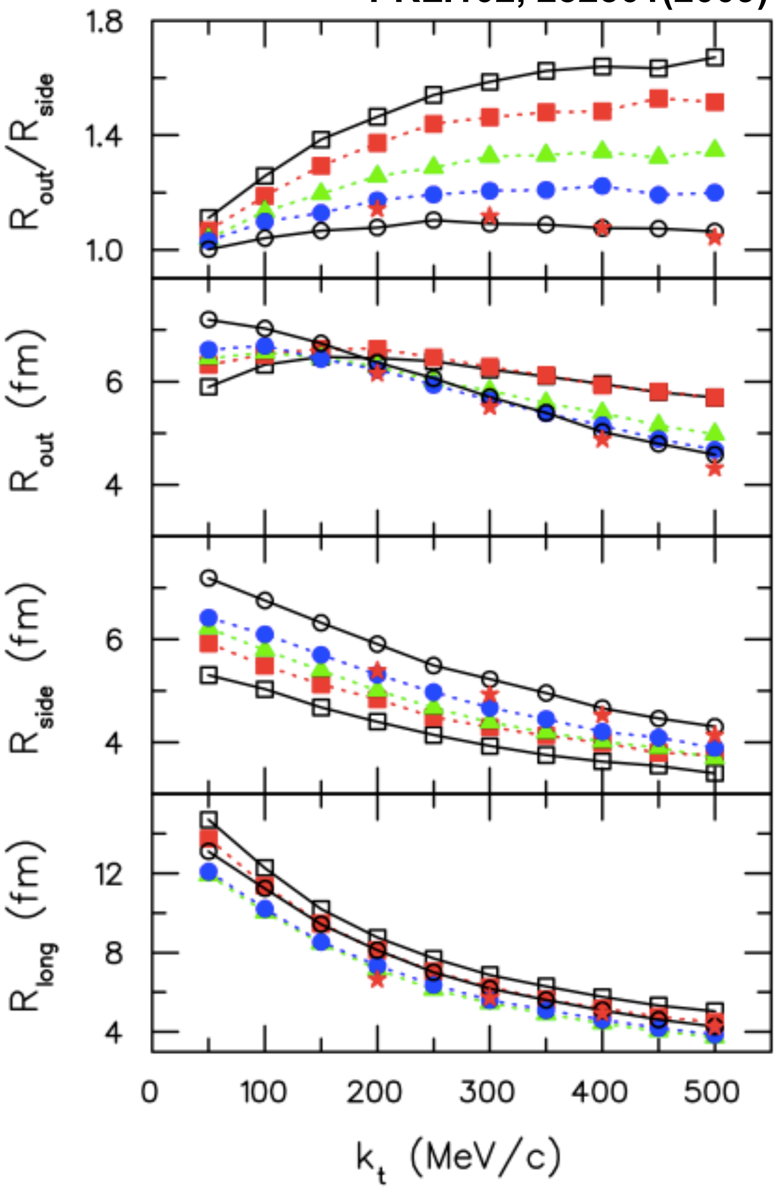
$$\vec{q}_{out} \parallel \vec{k}_T, \vec{q}_{side} \perp \vec{k}_T$$





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

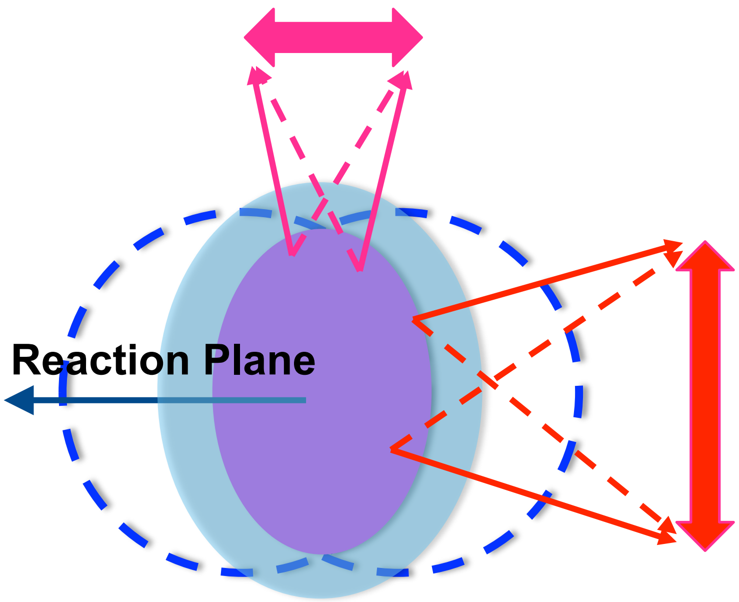
● Adding viscosity

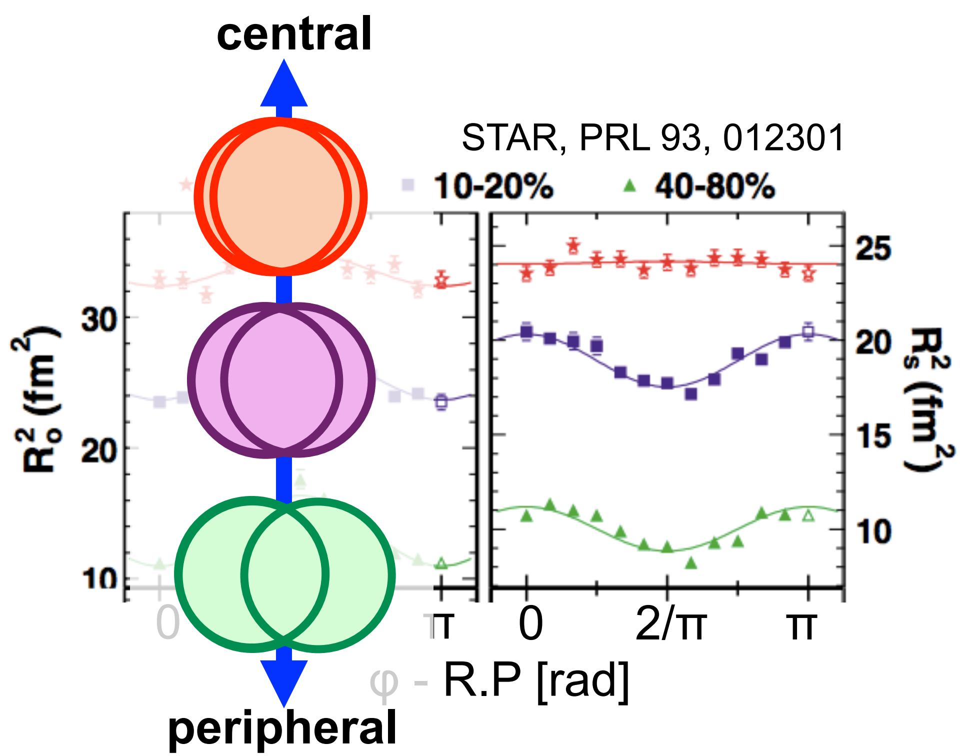
○ Including all features

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

HBT with respect to Reaction Plane

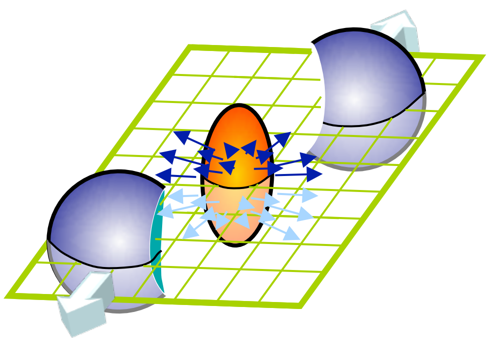
- Azimuthal HBT can give us the source shape at freeze-out.
- Final eccentricity is determined by initial eccentricity, pressure gradient(velocity profile) and expansion time etc.



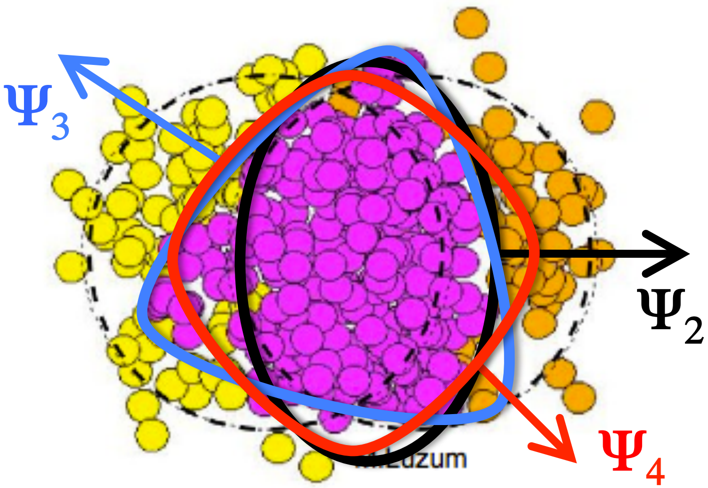


Higher Harmonic Flow and Event Plane

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



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

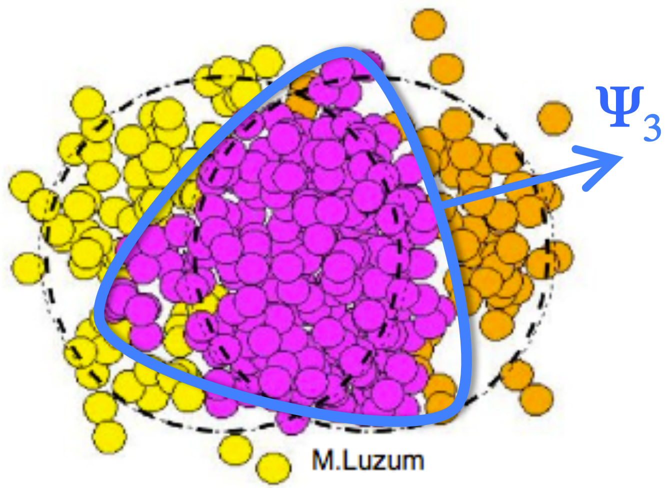


$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$

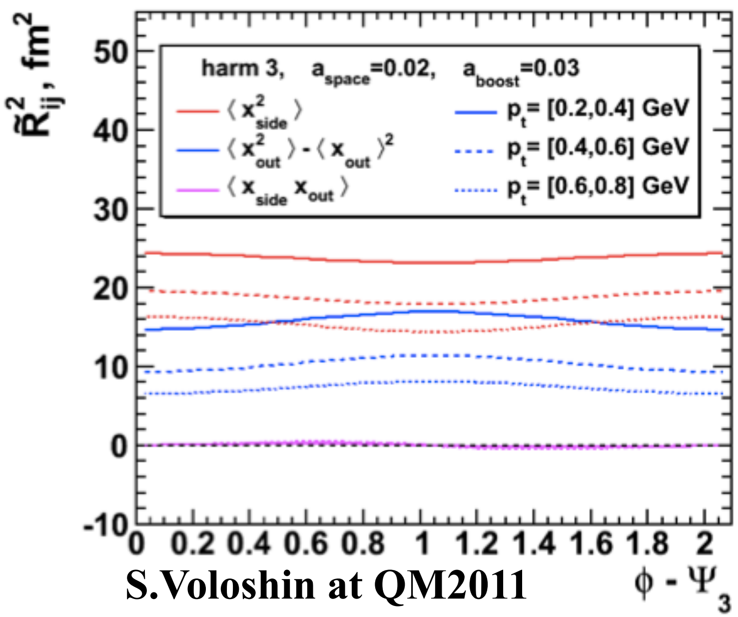
v_n : Strength of higher harmonic flow
Ψ_n : Higher harmonic event plane
φ : Azimuthal angle of emitted particles

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], $\rho = r'\rho_{max}(1+\cos(n\varphi))$

Motivation

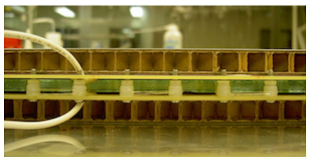
- **Study the properties of time-space evolution of the heavy ion collision via azimuthal HBT measurement.**
  - ✧Measurement of charged pion/kaon HBT radii with respect to 2nd-order event plane, and Comparison of the particle species
  - ✧Measurement of HBT radii with respect to 3rd-order event plane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

My Activity

3 years later

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

MRPC construction



RXNP construction

Installed MRPC&RXNP

Azimuthal HBT analysis using Run4 data

Di-jet Calorimeter construction

Summer Challenge @KEK

Shift taking @CERN

Start azimuthal HBT analysis using Run7 data

2011(D2) **2012(D3)**

Talk WPCF2011

Talk JPS fall

Talk JPS spring

Talk HIC in LHC era

Talk QM2012

Poster Radon Workshop

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

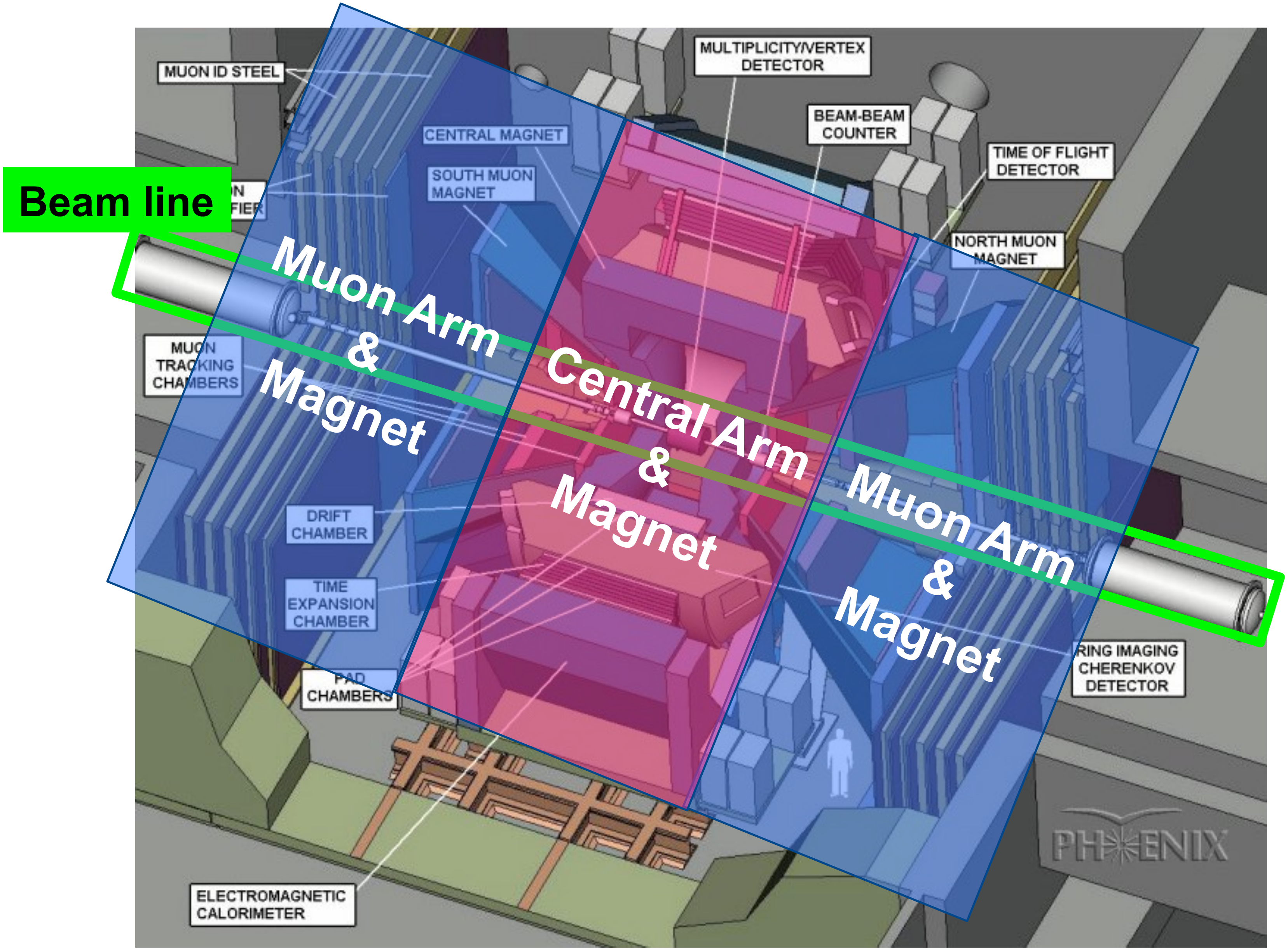
Summer Challenge @KEK

Shift taking & Detector Expert for Run12 @BNL

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

Analysis

PHENIX Experiment



PHENIX Detectors

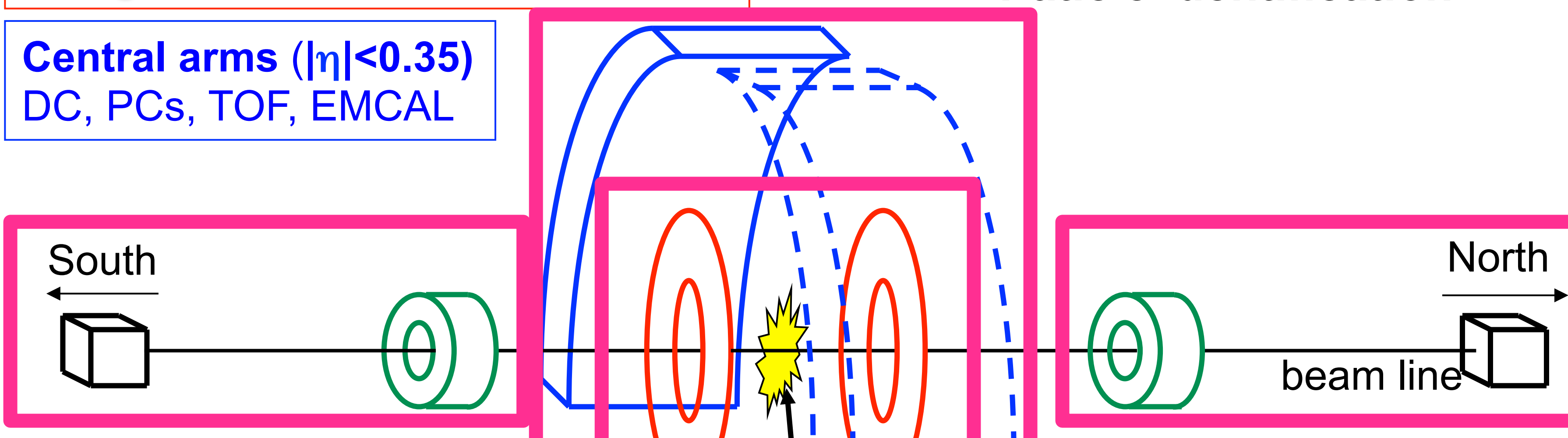
Beam-Beam Counter (|η|=3~4)
Quartz radiator+64PMTs

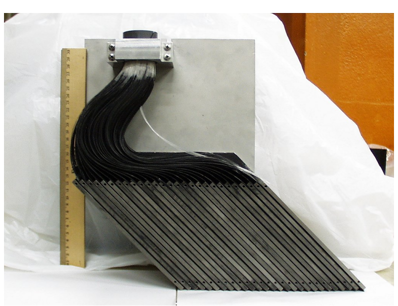
Zero Degree Calorimeter
Spectator neutron energy

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

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

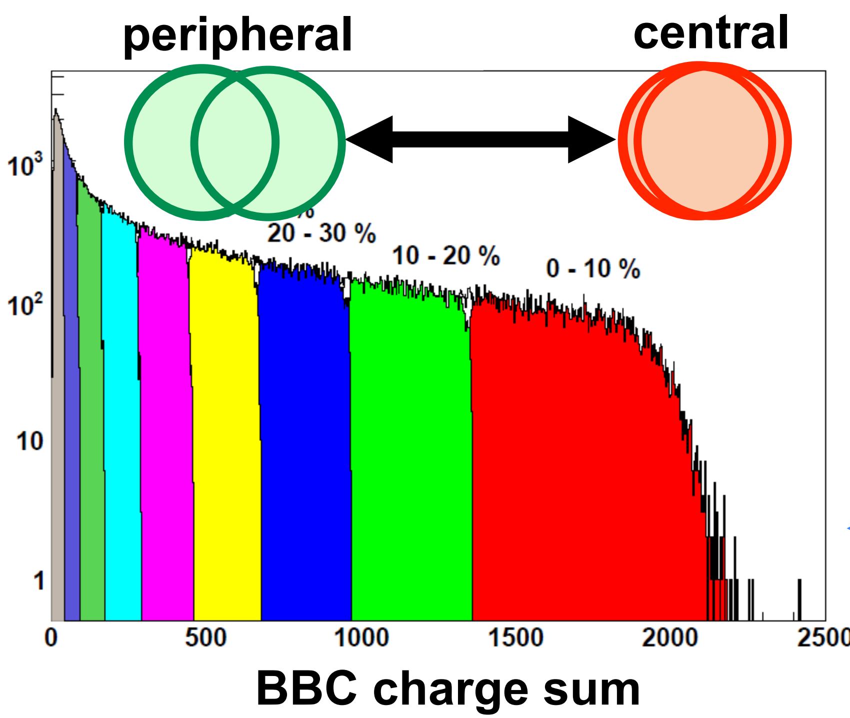
- ⇒ **Minimum Bias Trigger**
- ⇒ **Start time**
- ⇒ **Collision z-position**
- ⇒ **Centrality**
- ⇒ **Event Planes**
- ⇒ **Tracking, Momentum**
- ⇒ **Paticle Identification**

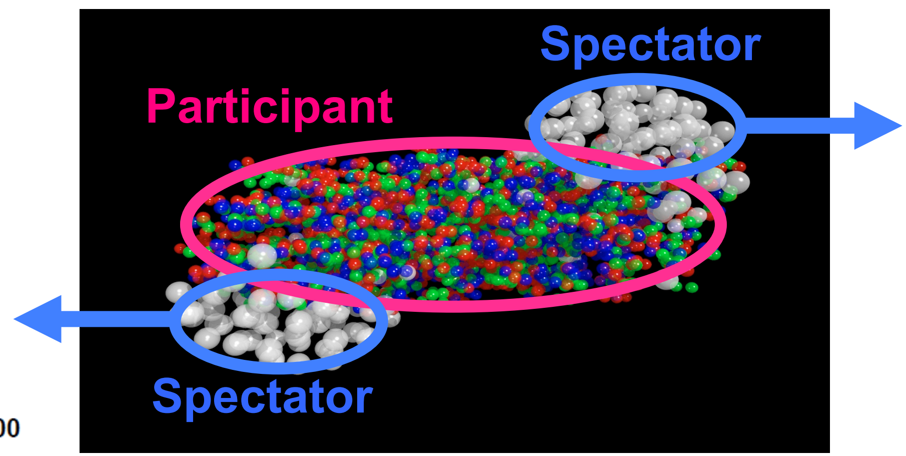




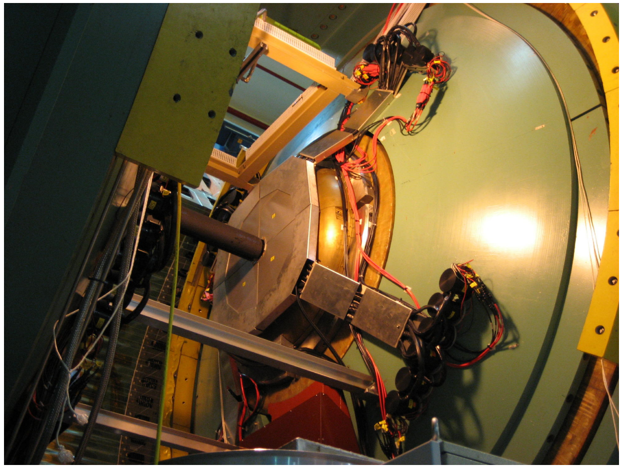
Centrality

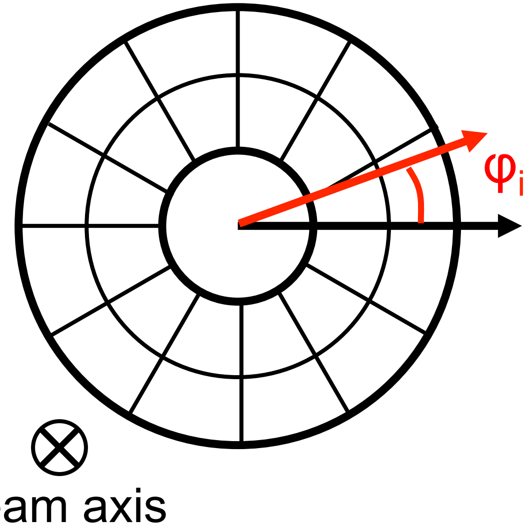
- **Centrality is used to classify events instead of impact parameter.**
  - ✧ 0% to 100% ←→ central to peripheral collision
- **BBC measures charged particles coming from participant.**

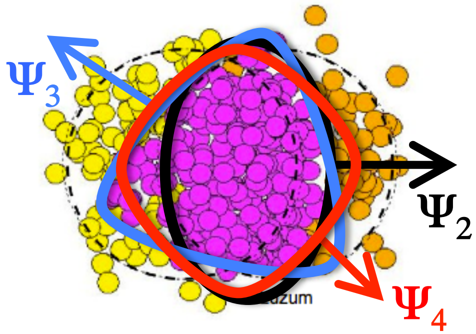


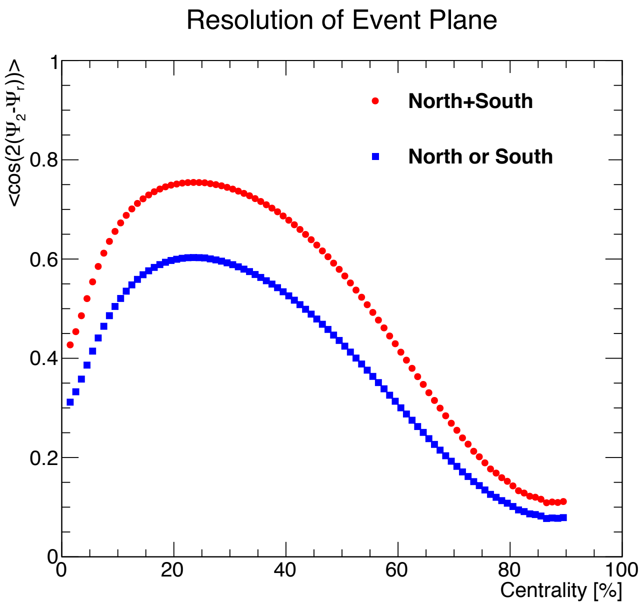


Event Plane







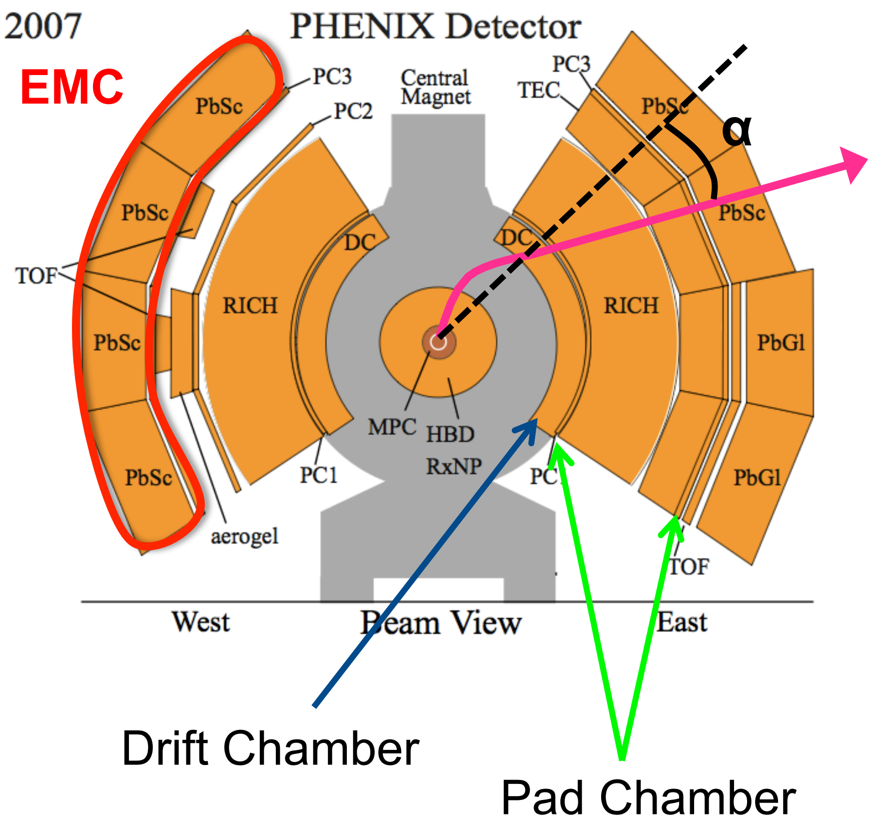


$$\Psi_n = \frac{1}{n} arctan\left(\frac{\Sigma w_i cos(n\phi_i)}{\Sigma w_i sin(n\phi_i)}\right)$$

- **Event plane was determined by Reaction Plane Detector**
  - Resolution: <cos(n(Ψ_n-Ψ_{real}))>
    n=2 : ~ 0.75
    n=3 : ~ 0.34

Track Reconstruction

Central Arms



- **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
- **Outer detectors (PC3,TOF,EMCal)**
  - ✧Extend the tracks to outer detectors

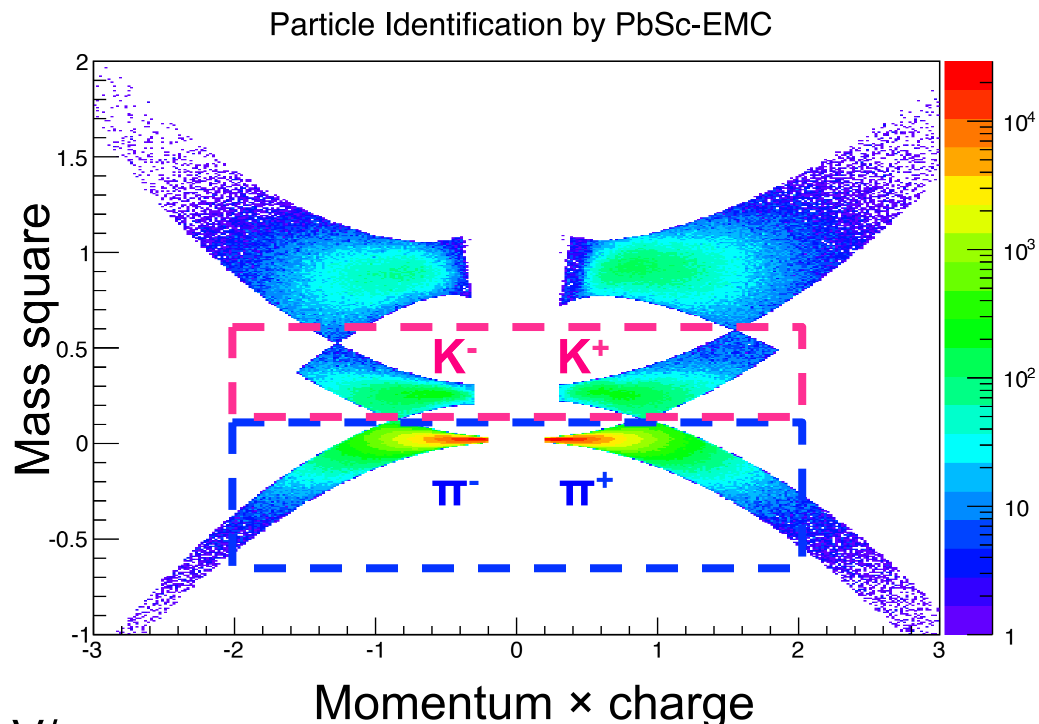
Particle IDentification

- **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

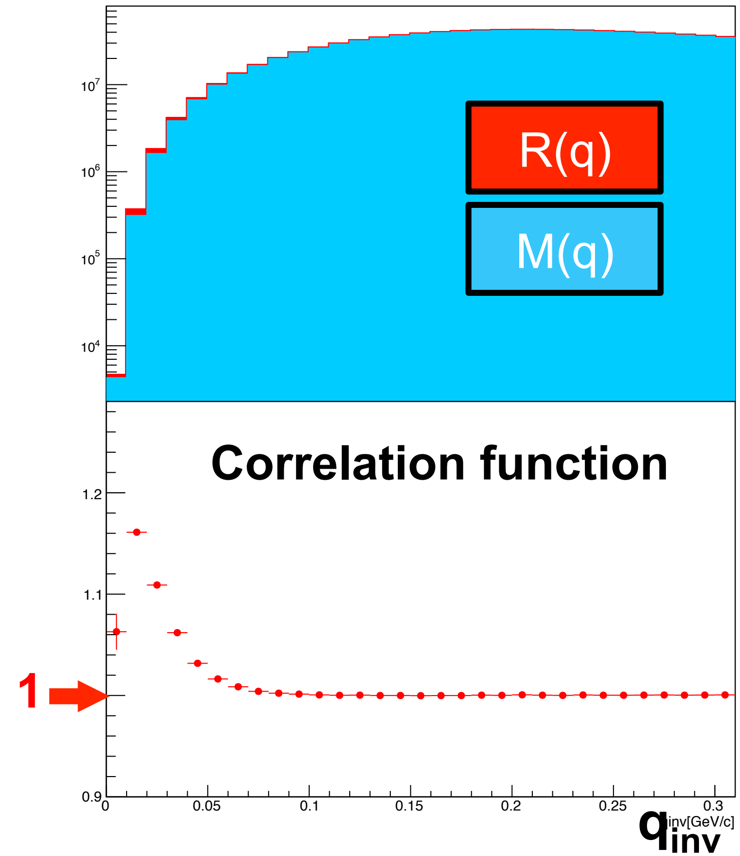


Correlation Function

- **Experimental Correlation Function C_2 is defined as:**
  - ✧ R(q): Real pairs at the same event.
  - ✧ M(q): Mixed pairs selected from two different/similar events.

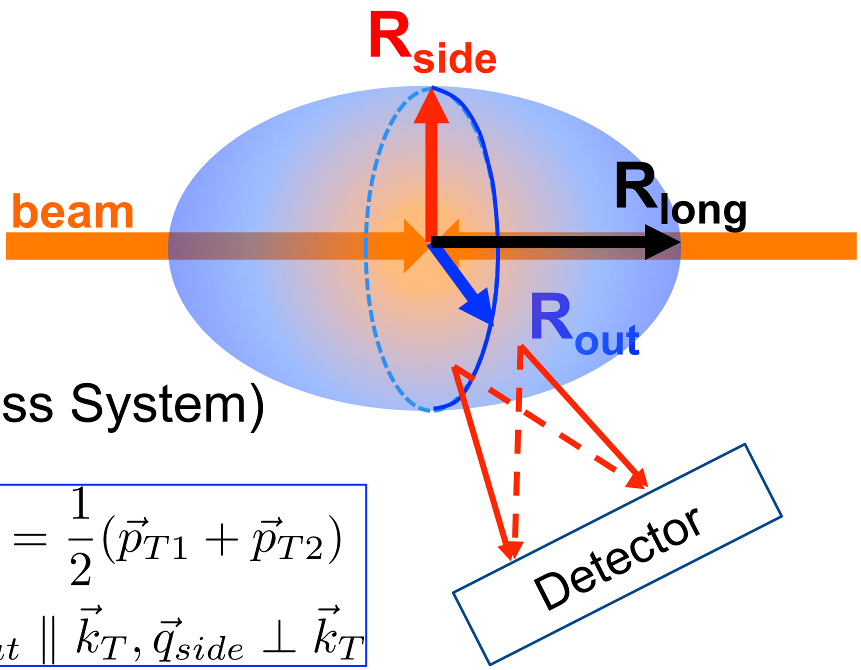
$$C_2 = \frac{R(\mathbf{q})}{M(\mathbf{q})}$$

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



- ✧ R(q) includes HBT effects, Coulomb interaction and detector inefficient effect, while M(q) doesn’t include HBT, Coulomb.

3D HBT radii



- **"Out-Side-Long" system**
  - ✧ Bertsch-Pratt parameterization
  - ✧ LCMS(Longitudinal Center of Mass System) frame is used.

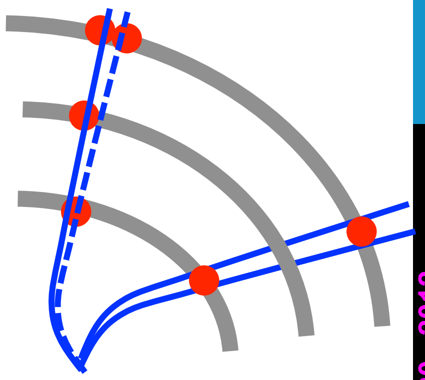
$$\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2})$$
$$\vec{q}_{out} \parallel \vec{k}_T, \vec{q}_{side} \perp \vec{k}_T$$

$$C_2 = 1 + \lambda G$$
$$G = \exp(-R_{inv}^2 q_{inv}^2)$$
$$= \exp(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2 - 2R_{os}^2 q_{side} q_{out})$$

λ : chaoticity
R_{side} : transverse size
R_{out} : transverse size + emission duration
R_{os} : cross term between "out" and "side"
R_{long} : longtudinal size

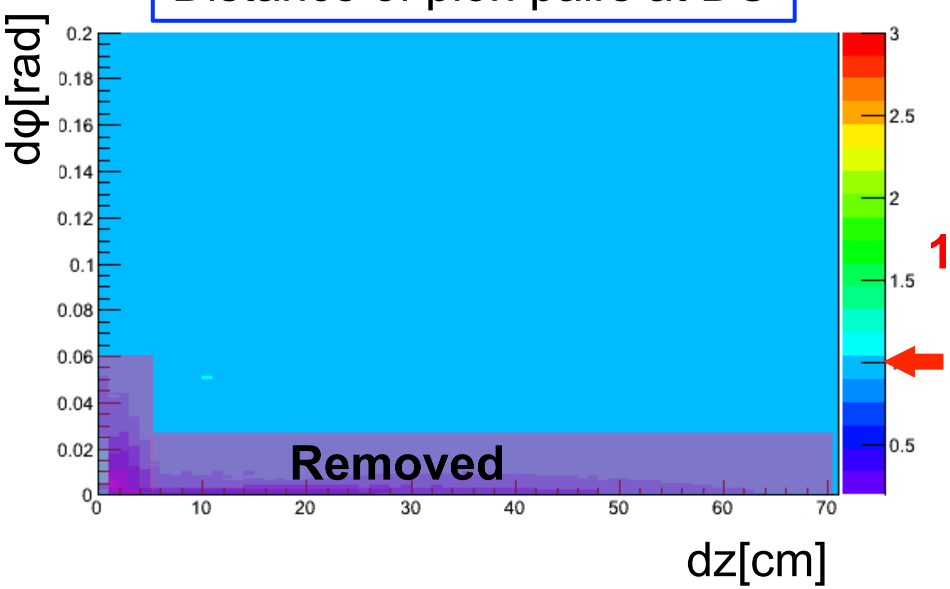
R_{out} includes temporal information on emission duration of particles!

Pair Selection

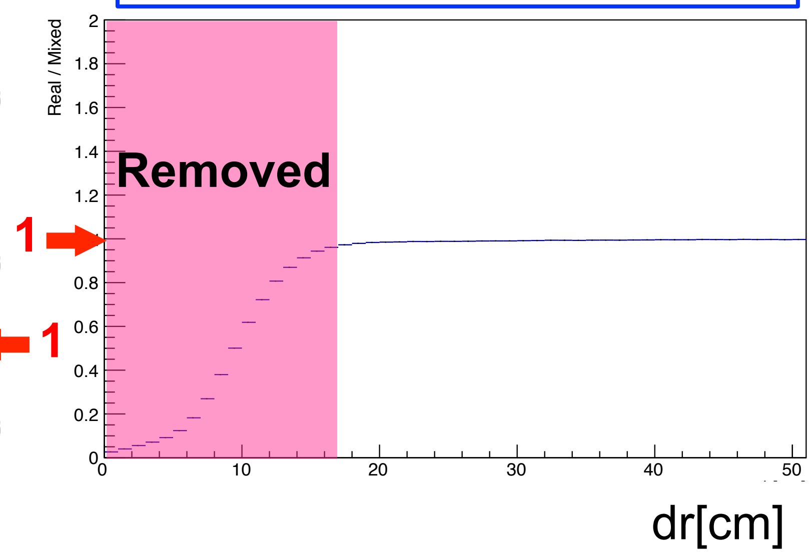


- **Ghost Tracks**
  - ✧A single particle is reconstructed as two tracks
- **Merged Tracks**
  - ✧Two particles is reconstructed as a single track

Distance of pion pairs at DC



Distance of pion pairs at EMC



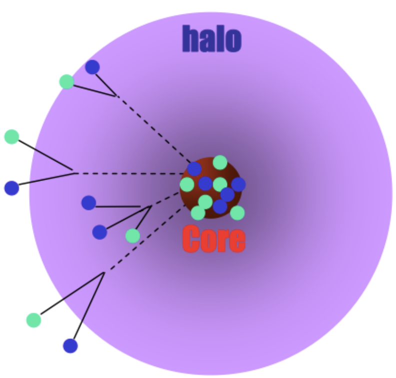
Coulomb Interaction

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

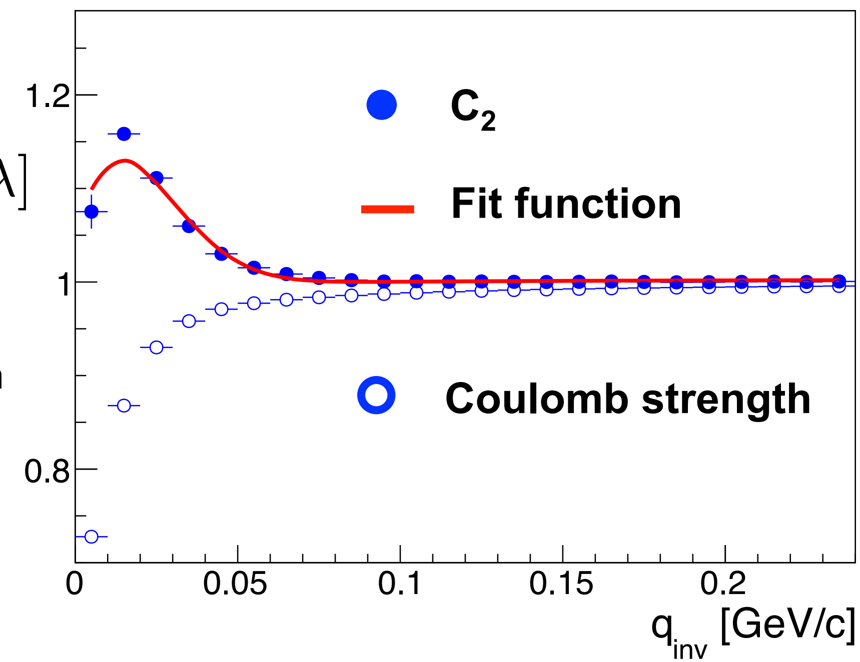
$$\left[-\frac{\hbar^2\nabla^2}{2\mu}+\frac{Z_1Z_2e^2}{r}\right]\Psi(r)=E\Psi(r) \qquad \gamma=\frac{me^2}{\hbar^2 q}Z_1Z_2$$

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

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

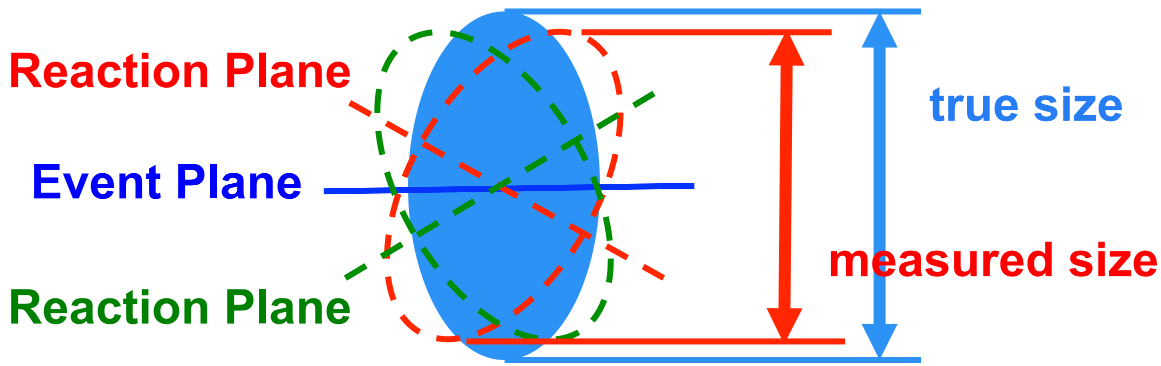


F_{coul} : Coulomb term
G : Gaussian term



Correction of Event Plane Resolution

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



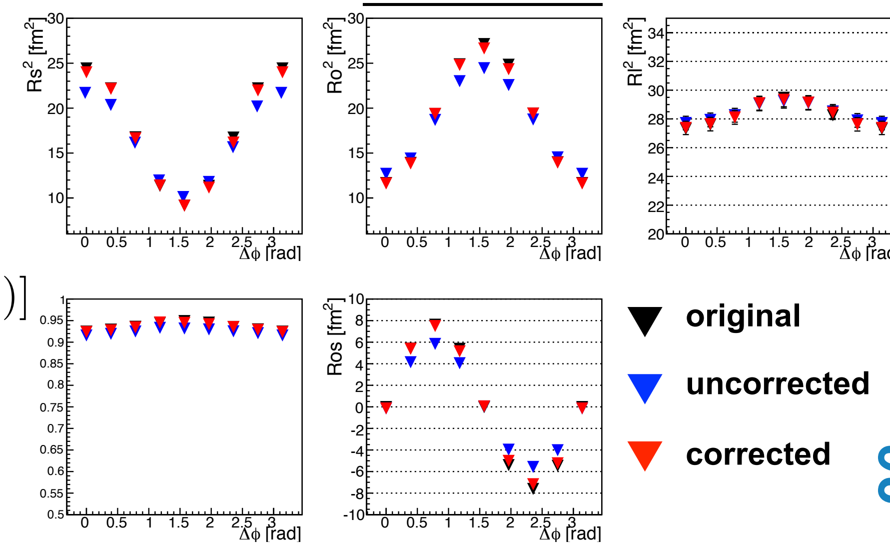
- **Resolution correction**
  - ✧correction for q-distribution
    PRC.66, 044903(2002)

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

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

event plane resolution

simulation



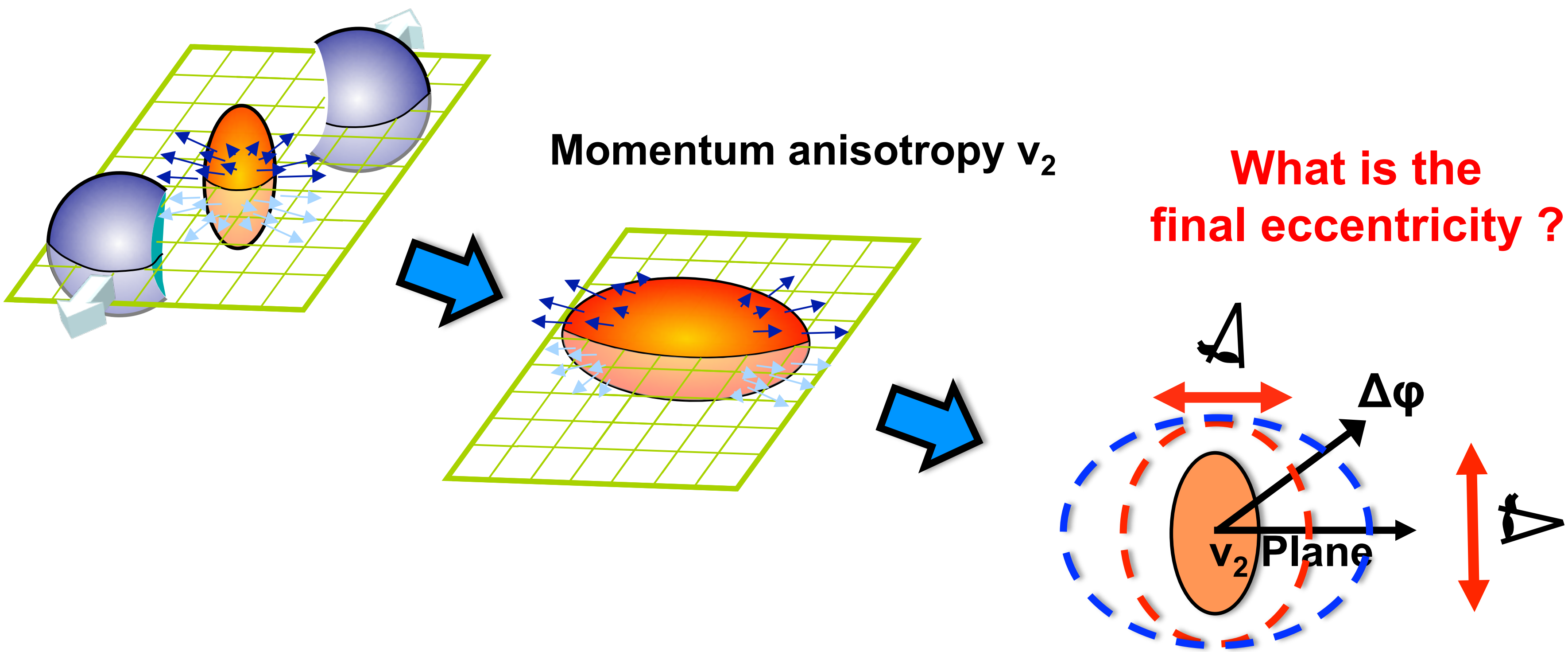
Results & Discussion

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

Initial spatial eccentricity

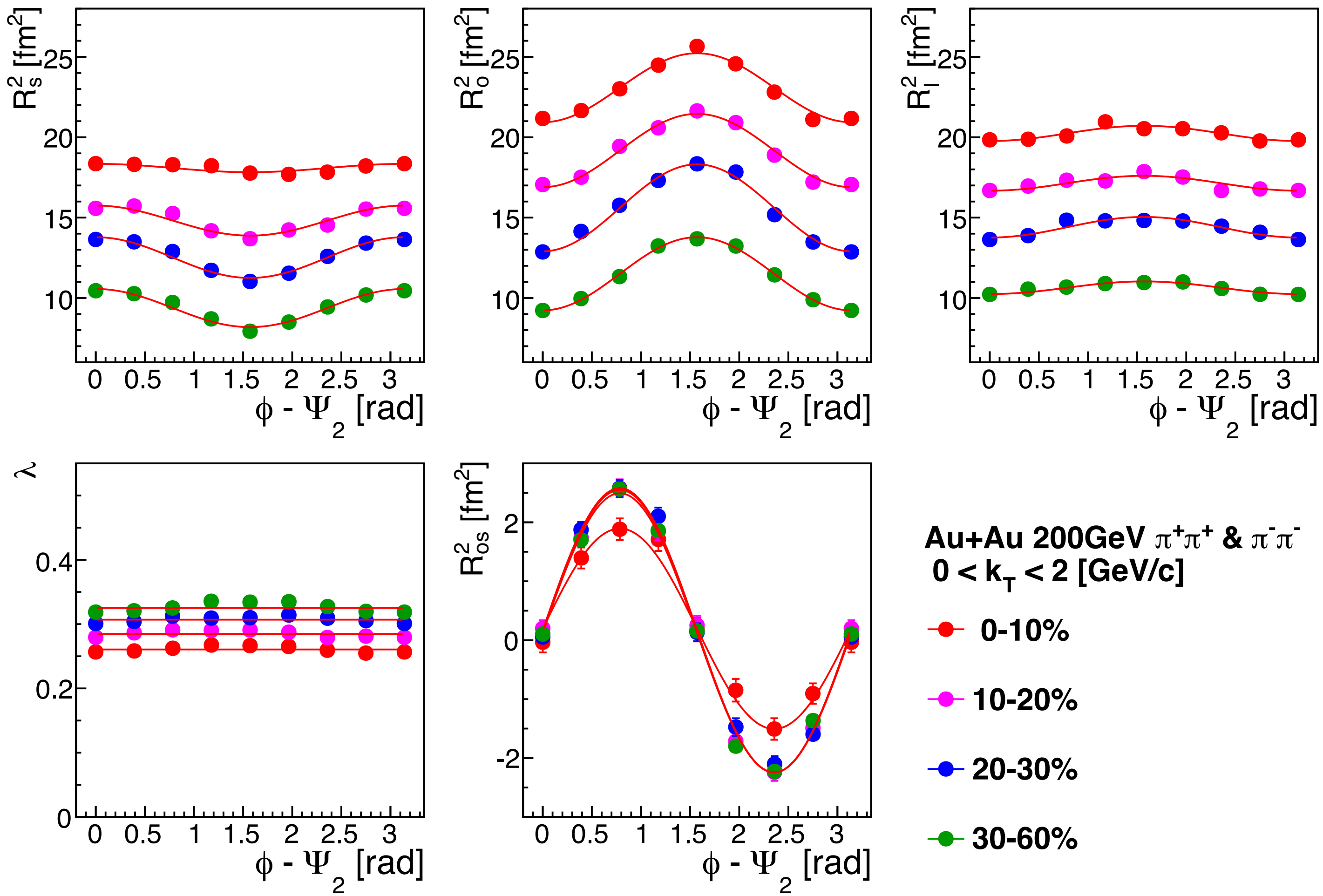
Momentum anisotropy v_2

What is the final eccentricity ?



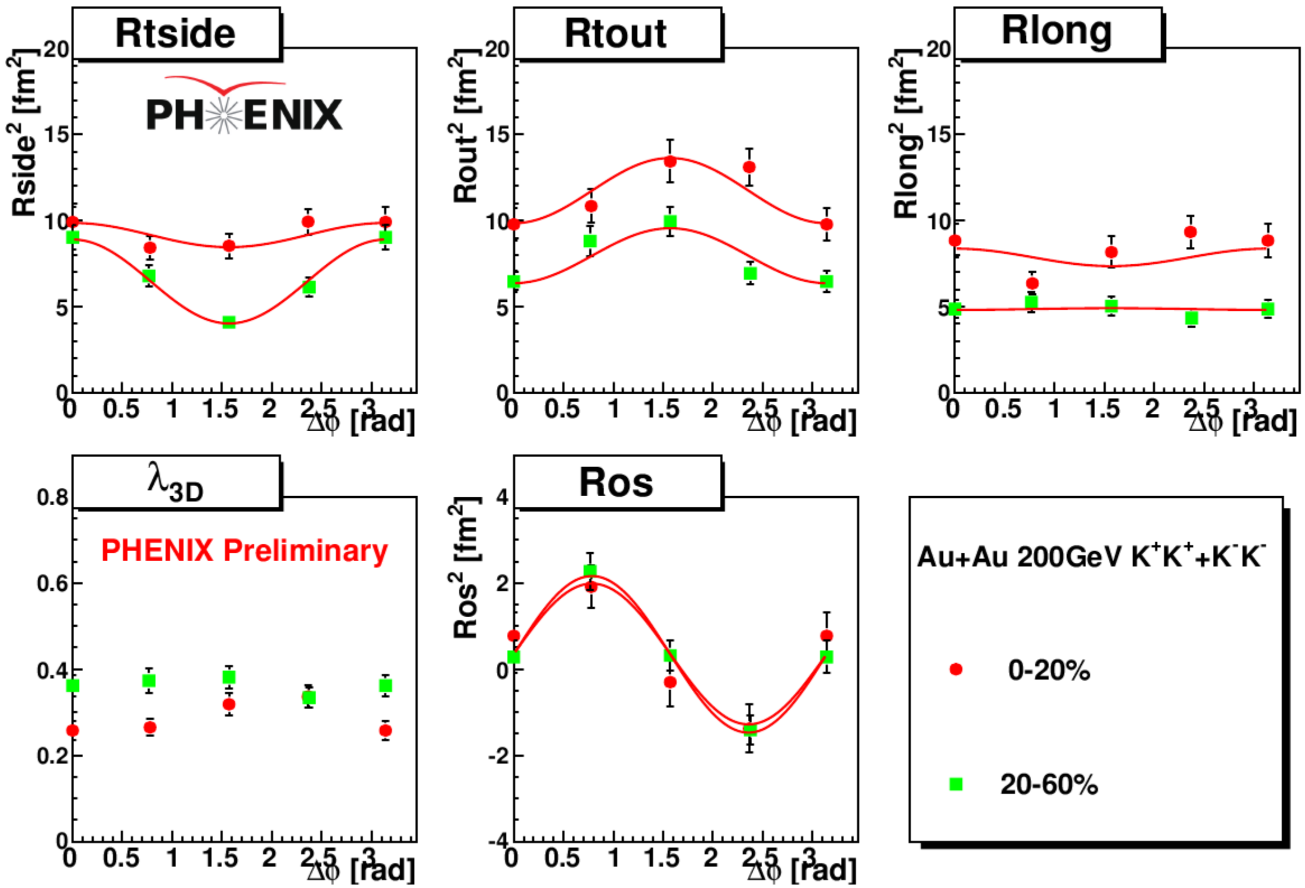
Centrality dependence of pion HBT radii w.r.t Ψ_2

- Oscillation are seen for R_{side}, R_{out}, $R_{os.}$
- R_{out} has strong oscillation in all centrality.

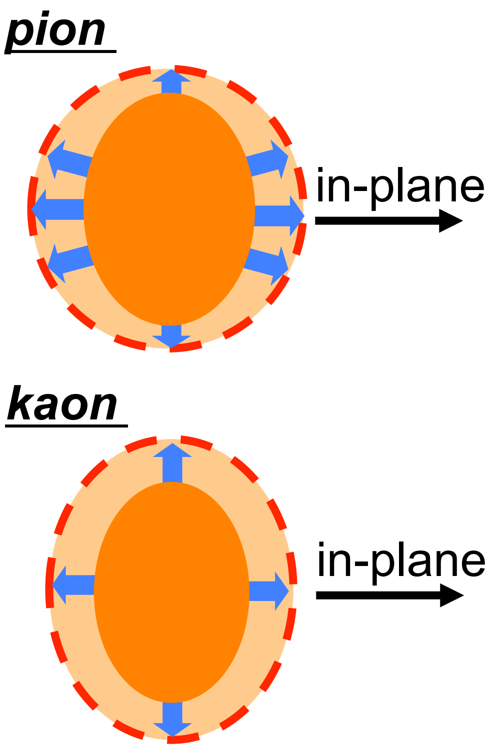


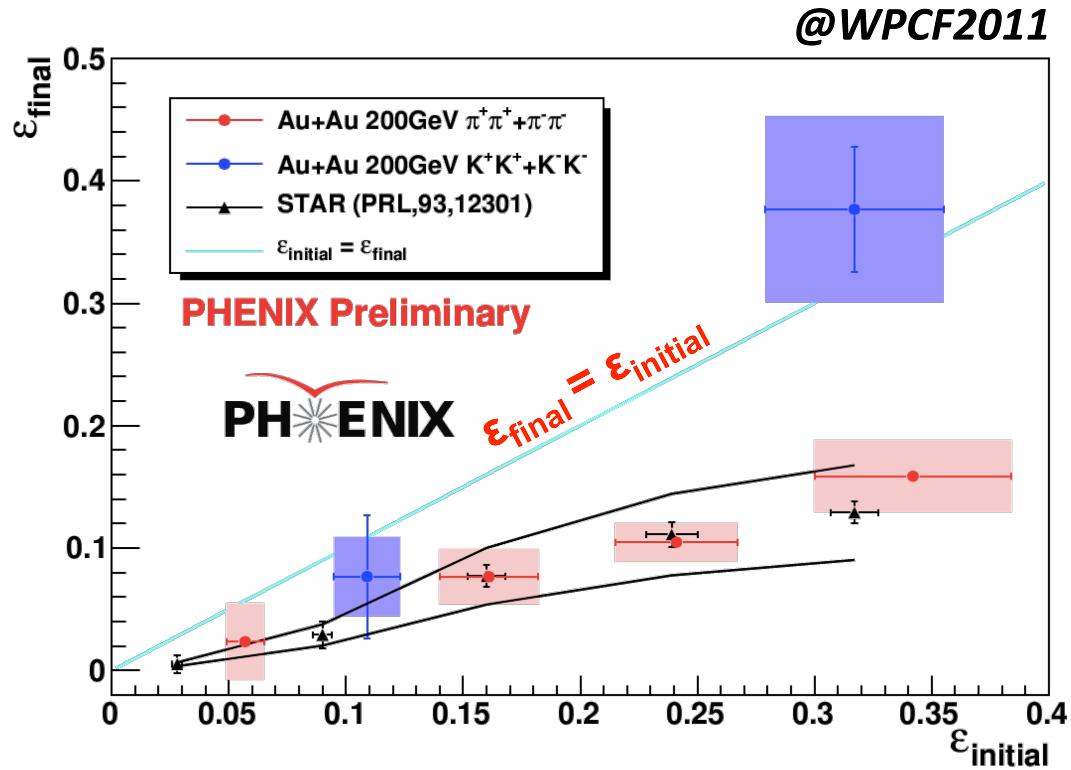
Centrality dependence of kaon HBT radii w.r.t Ψ_2

- charged kaons also have similar trends!



Eccentricity at freeze-out

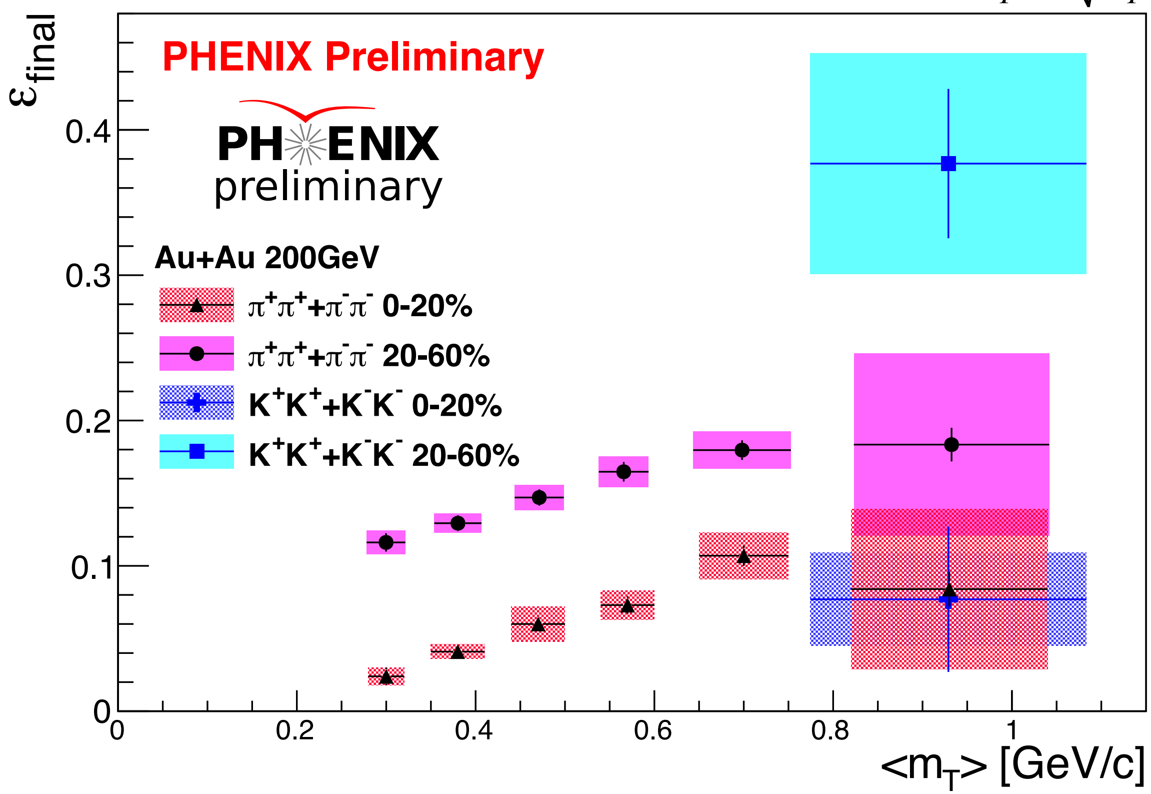




- **$\varepsilon_{final} \approx \varepsilon_{initial}/2$ for pion**
  - This Indicates that source expands to in-plane direction, and still elliptical shape.
  - PHENIX and STAR results are consistent.
- **$\varepsilon_{final} \approx \varepsilon_{initial}$ for kaon**
  - Kaon may freeze-out sooner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

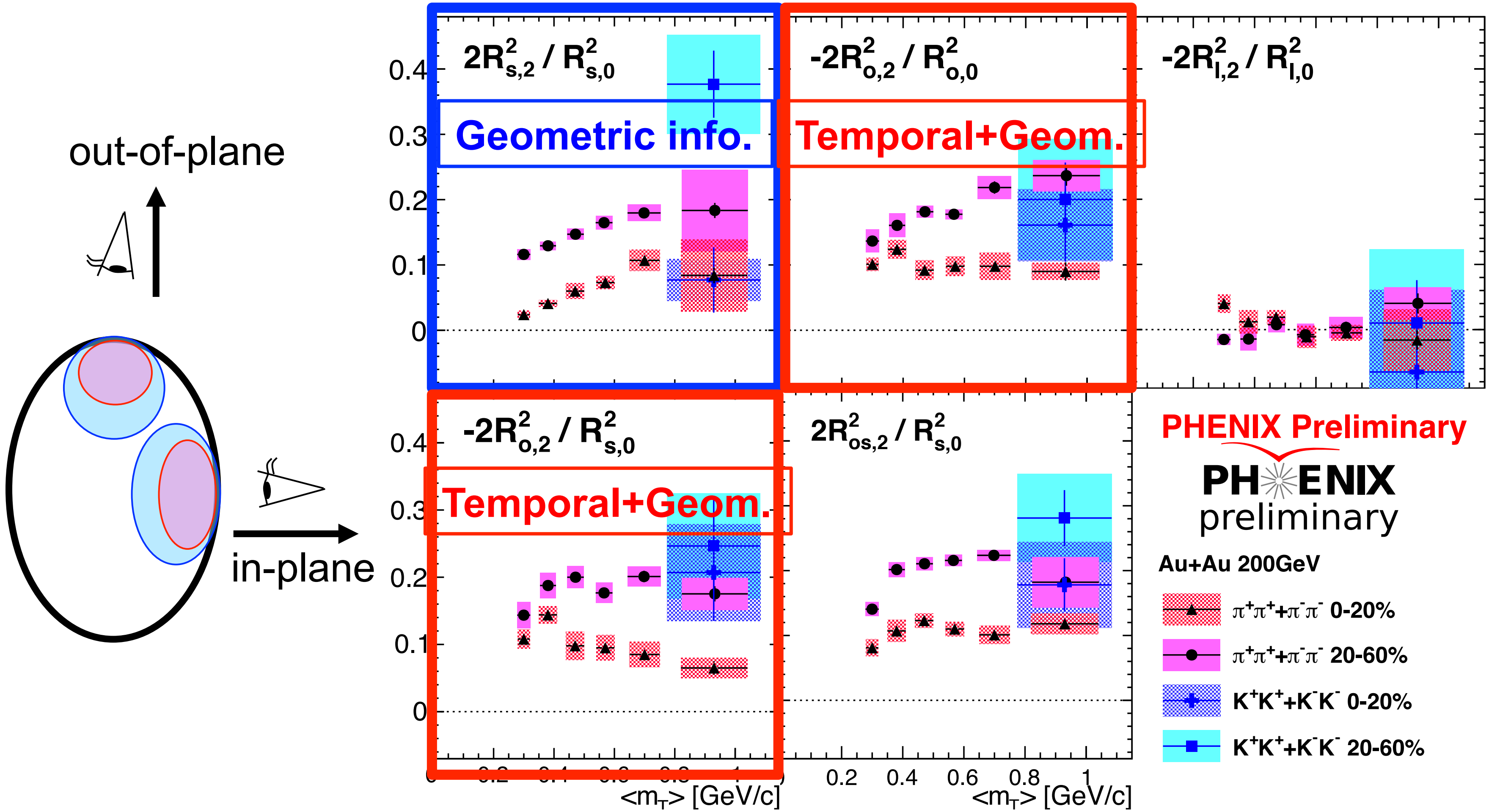
m_T dependence of ε_{final}

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



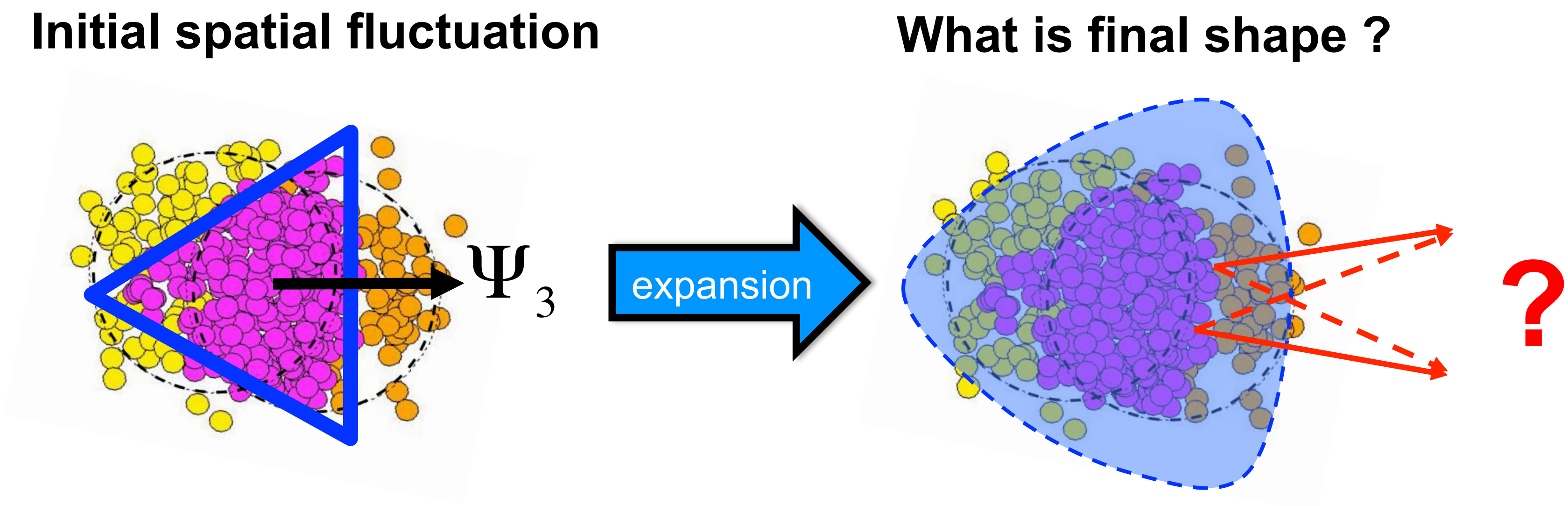
- **ε_{final} of pions increases with m_T in most/mid-central collisions**
- **Still difference between π/K in 20-60% even at the same m_T**
  - ✧Indicates sooner freeze-out time of K than π ?

m_T dependence of relative amplitude

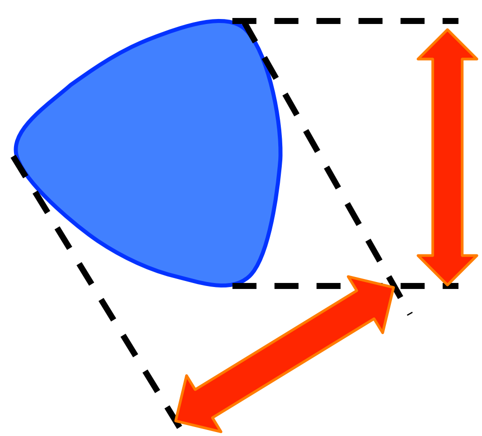


- **Relative amplitude of R_{out} in 0-20% doesn't depend on m_T**
  - ✧Does it indicate the difference of emission duration between in-plane and out-of-plane at low m_T?

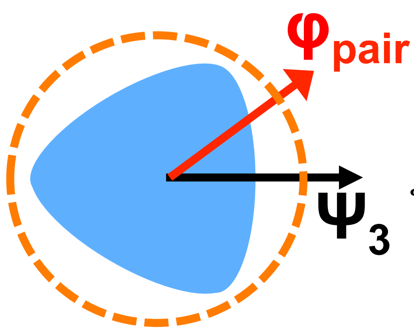
Azimuthal HBT w.r.t 3rd order event plane

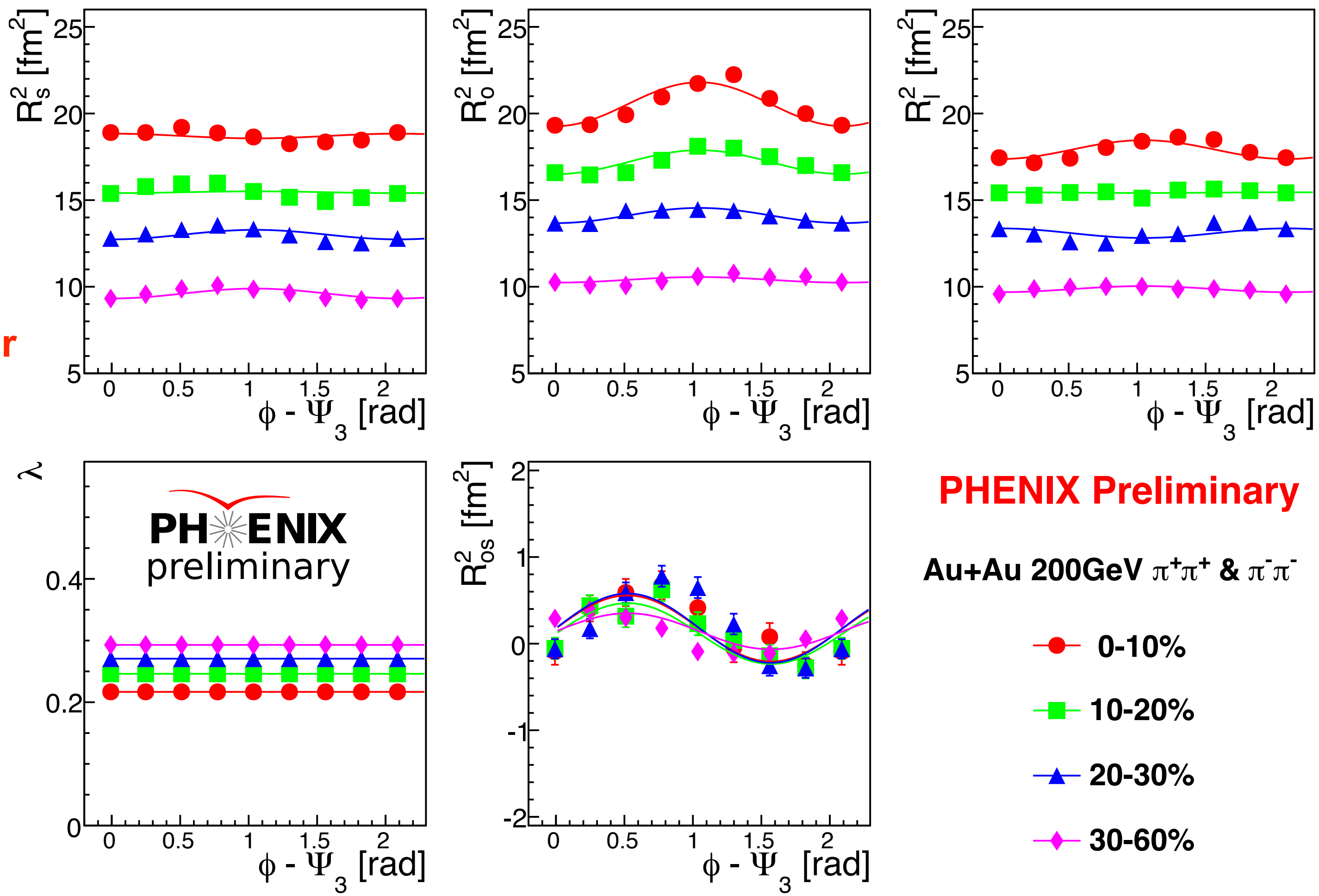


- Note that no anisotropy is observed by HBT in static source.



Azimuthal HBT radii w.r.t Ψ_3



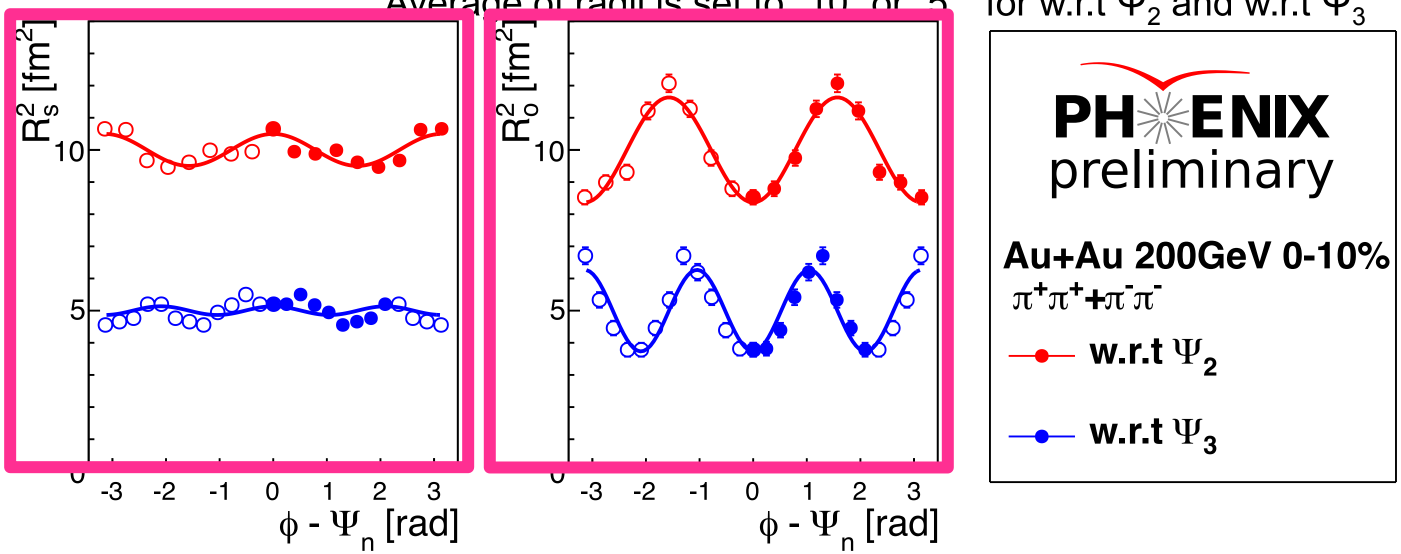


- R_{side} is almost flat
- R_{out} have a oscillation in most central collisions

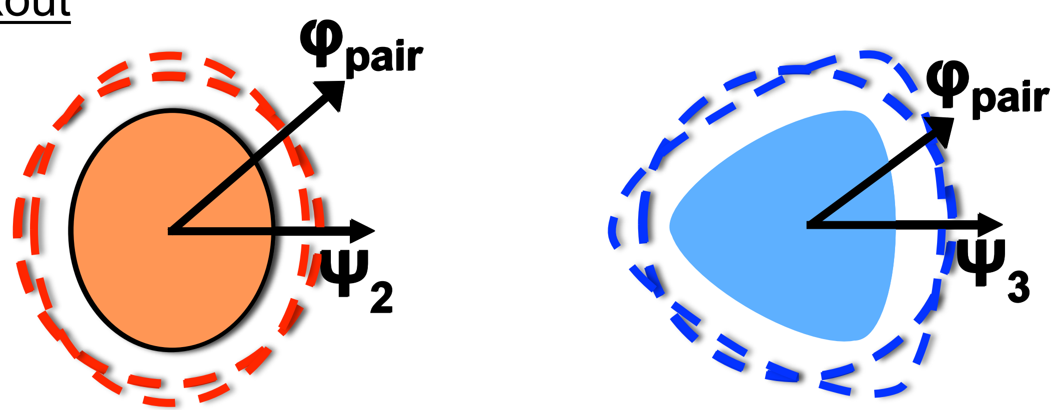
Comparison of 2nd and 3rd order component

- **In 0-10%, R_{out} have stronger oscillation for Ψ_2 and Ψ_3 than R_{side}**
  - ✧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



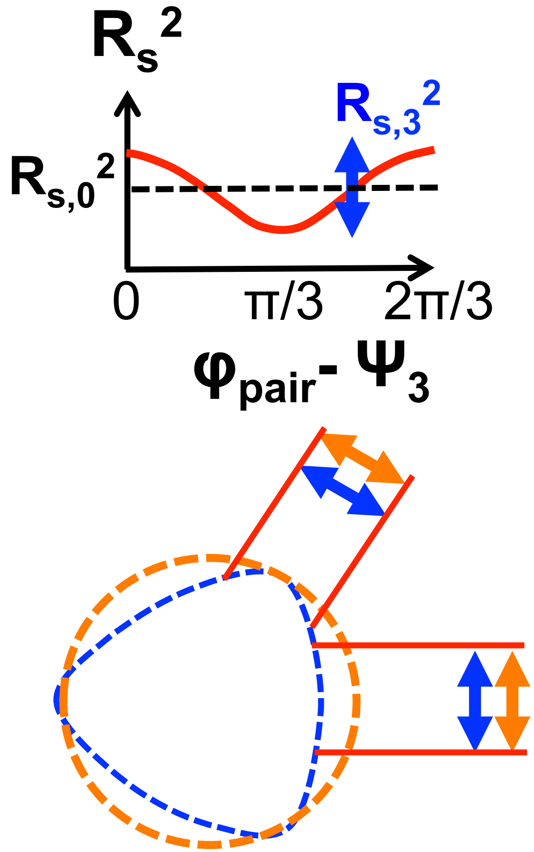
Rout

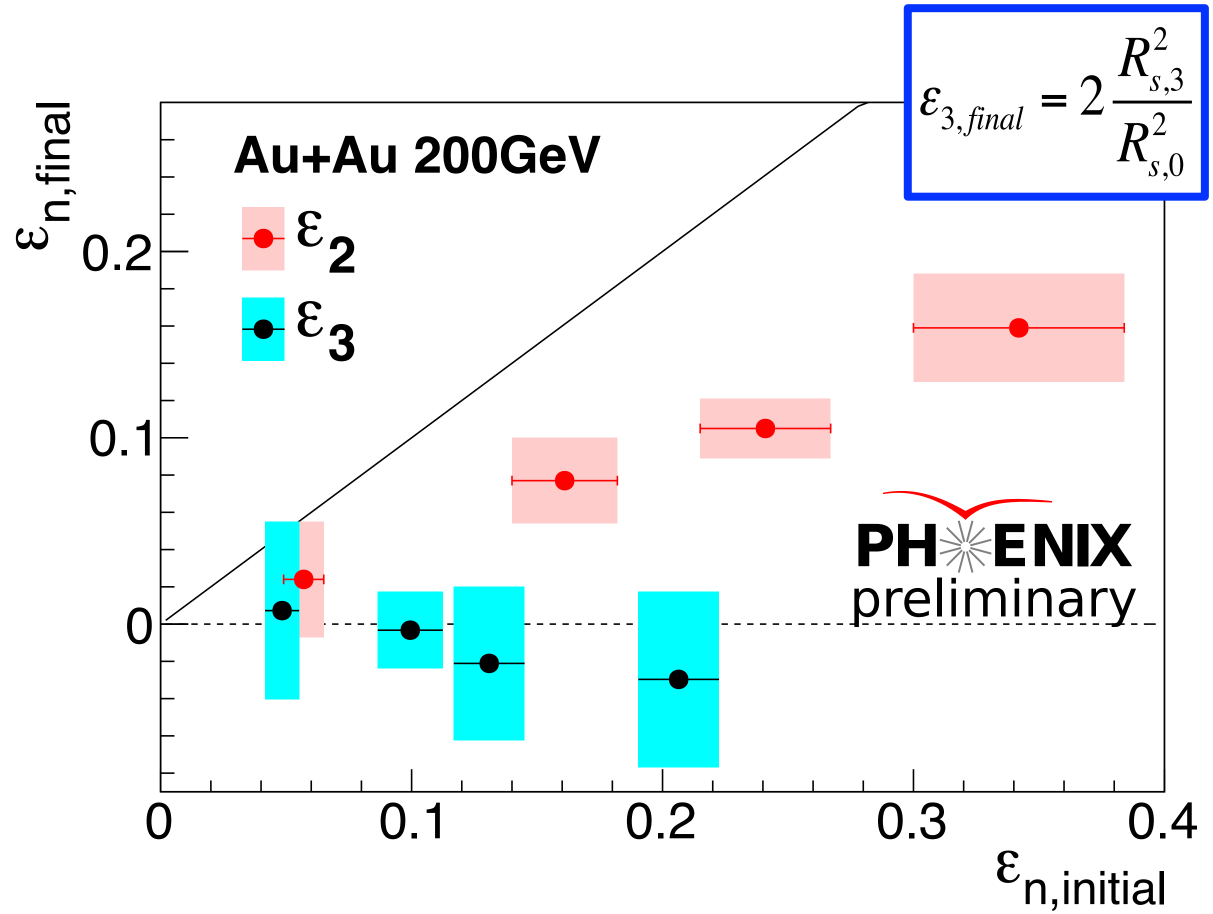


Rside

Relative amplitude of R_{side}

- Relative amplitude of R_{side} w.r.t Ψ_3 is zero within systematic error.



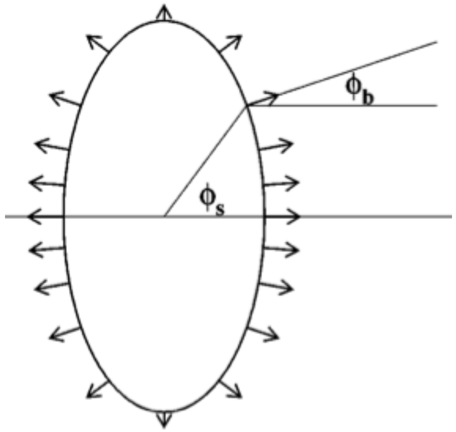


☆ The width of the "homogeneity" seems to be the same between 0°/60° w.r.t Ψ_3 unlike the depth(+emission duration).

Blast wave model

- **Hydrodynamic model assuming radial flow**
  - ✧Well described at low p_T for spectra & elliptic flow
  - ✧Expand to HBT : **PRC 70, 044907 (2004)**
  - ✧Physical parameters are treated as free parameters.

PRC 70, 044907 (2004)



<u>7 free parameters</u>

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 and emission duration

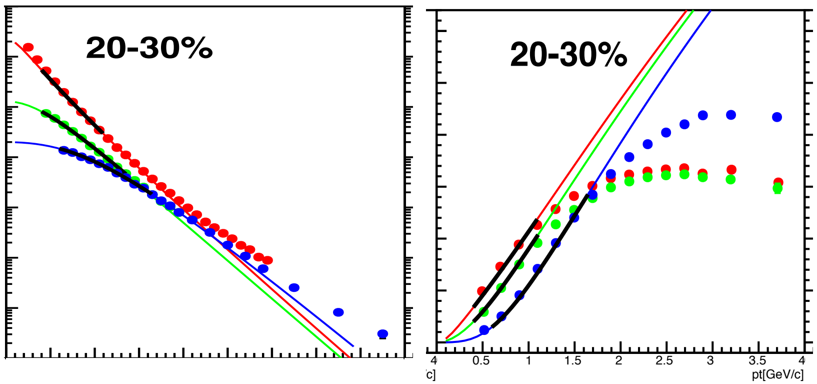
$$\rho(r,\phi) = \tilde{r}[\rho_0 + \rho_2 \cos(2\phi)]$$

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

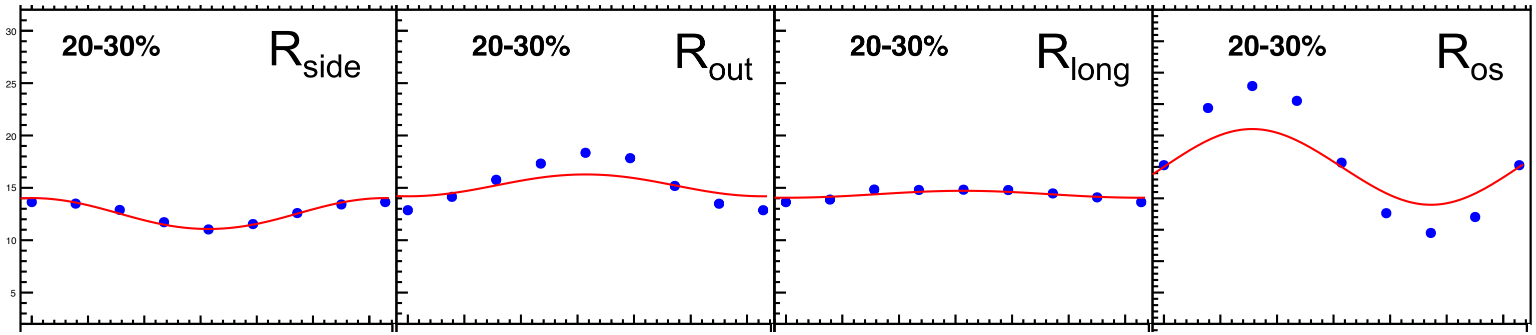
Assuming a Gaussian distribution peaked at τ_0 and with a width $\Delta\tau$, and source size doesn't change with τ.

Fit by Blast wave model

- **Spectra and v_2 are used to reduce parameters.**

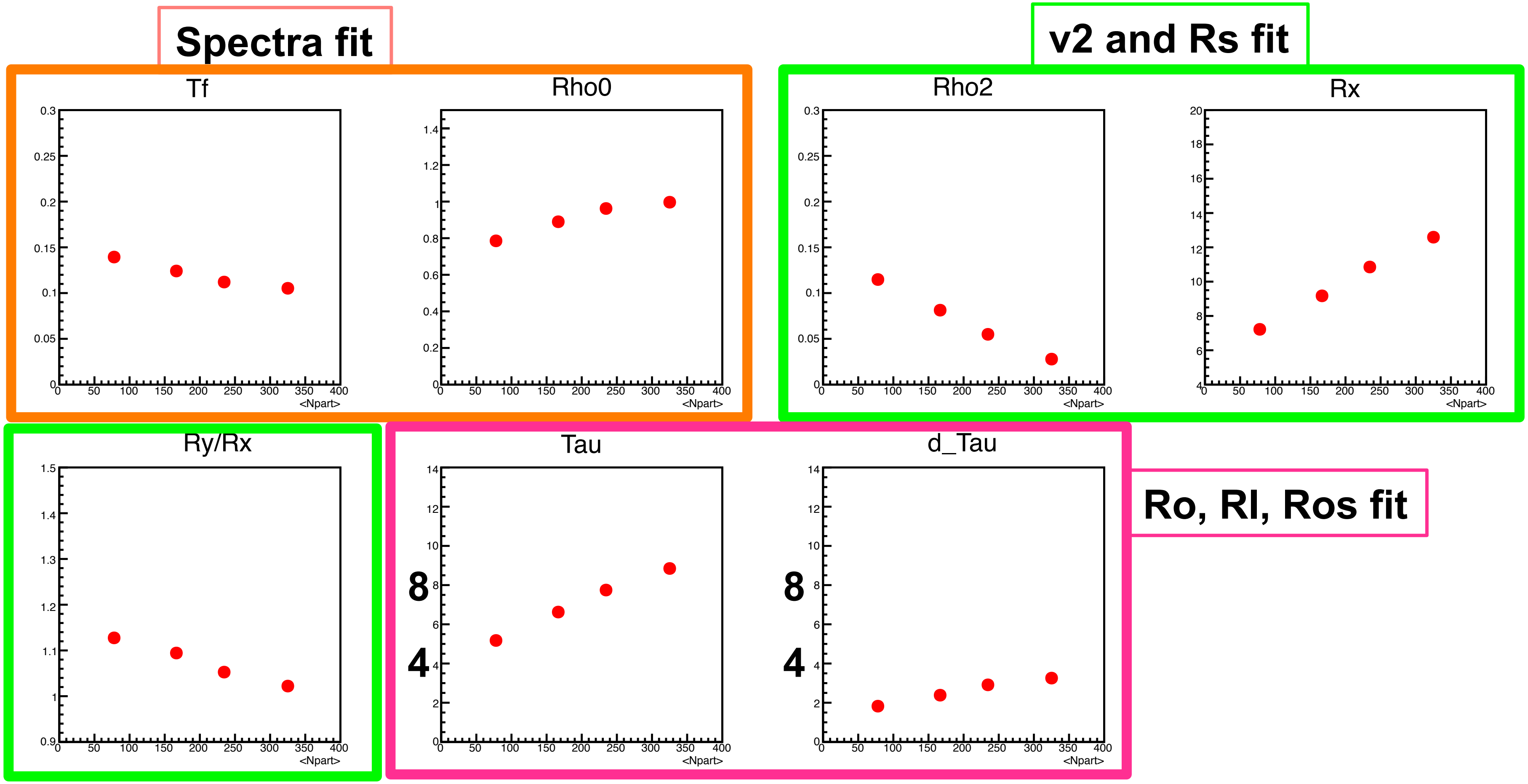


Specta → T_f and ρ_0
v_2 & R_{side} → ρ_2, R_x and R_y
R_{out}, R_{long}, R_{os} → τ_0, $\Delta\tau$



R_{out} and R_{os} doesn't seem to be fitted well.
Need to plot the systematic error.
In this model, $\Delta\tau$ doesn't depend on azimuthal angle.

Extracted freeze-out parameters



- Size(R_x,R_y) and R_y/R_x seem to be valid.
- τ and Δτ increases with going to centrality.

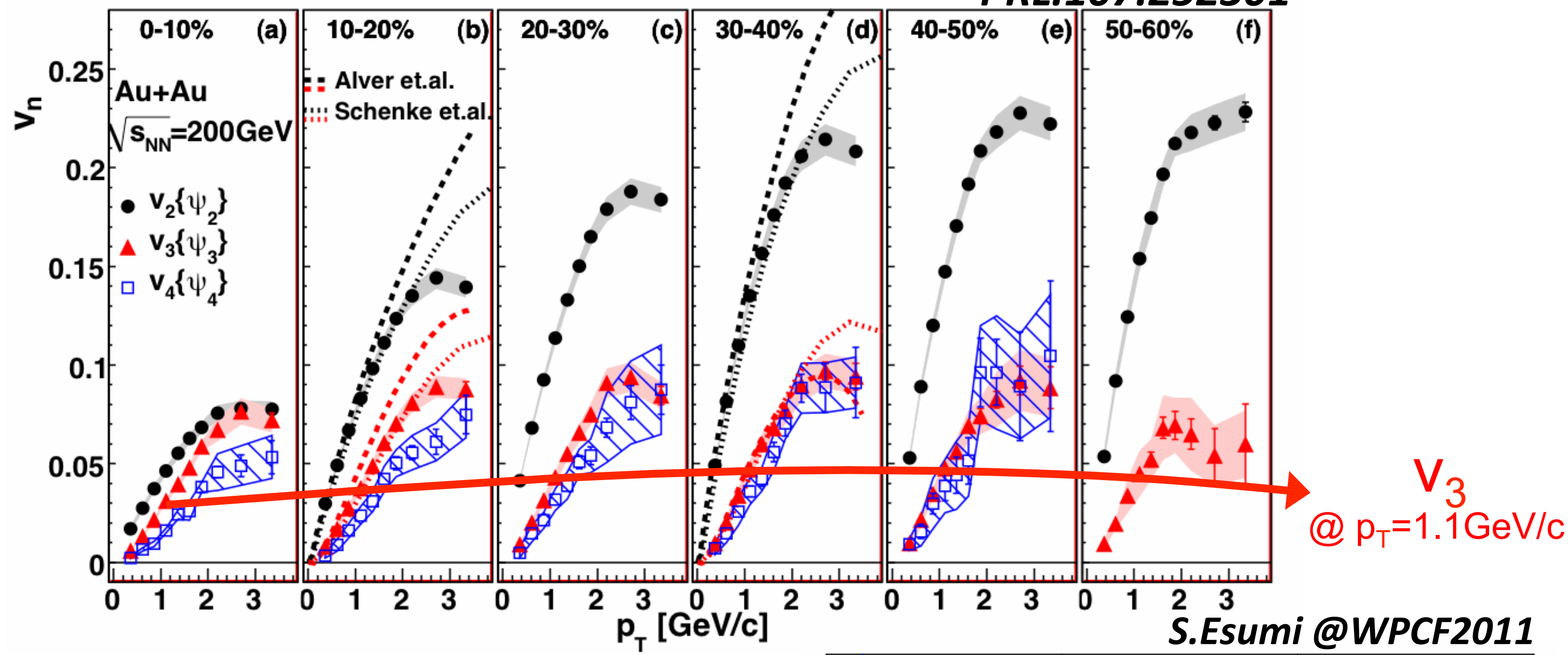
Summary

- **Azimuthal HBT radii w.r.t 2nd–order event 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 $K^{\pm}$ 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 3rd-order event plane**
  - ✧R_{side} doesn't seem to have azimuthal dependence.
  - ✧While R_{out} clearly has finite oscillation in most central collisions.
    - ☛ It may indicate the difference of emission duration between Δφ=0°/60° direction or depth of the triangular shape.
- **Balst wave model**
  - ✧System lifetime and emission duration seems to get longer in central collisions.

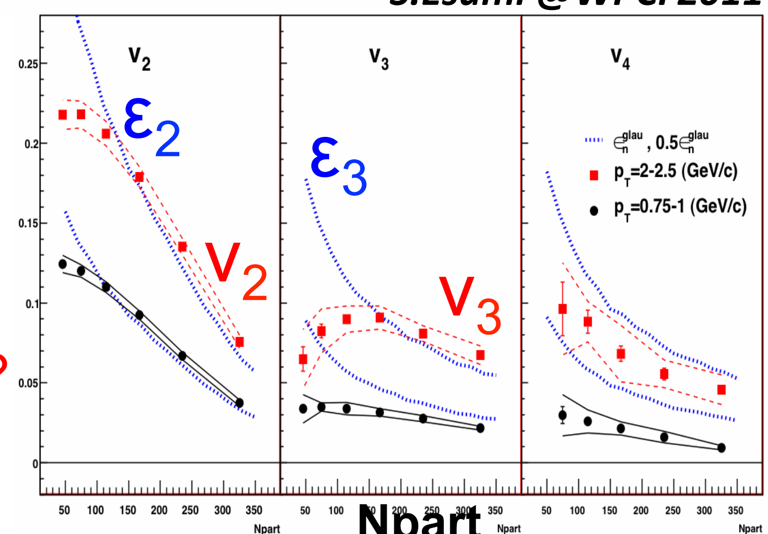
Back up

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?

PHENIX Detectors

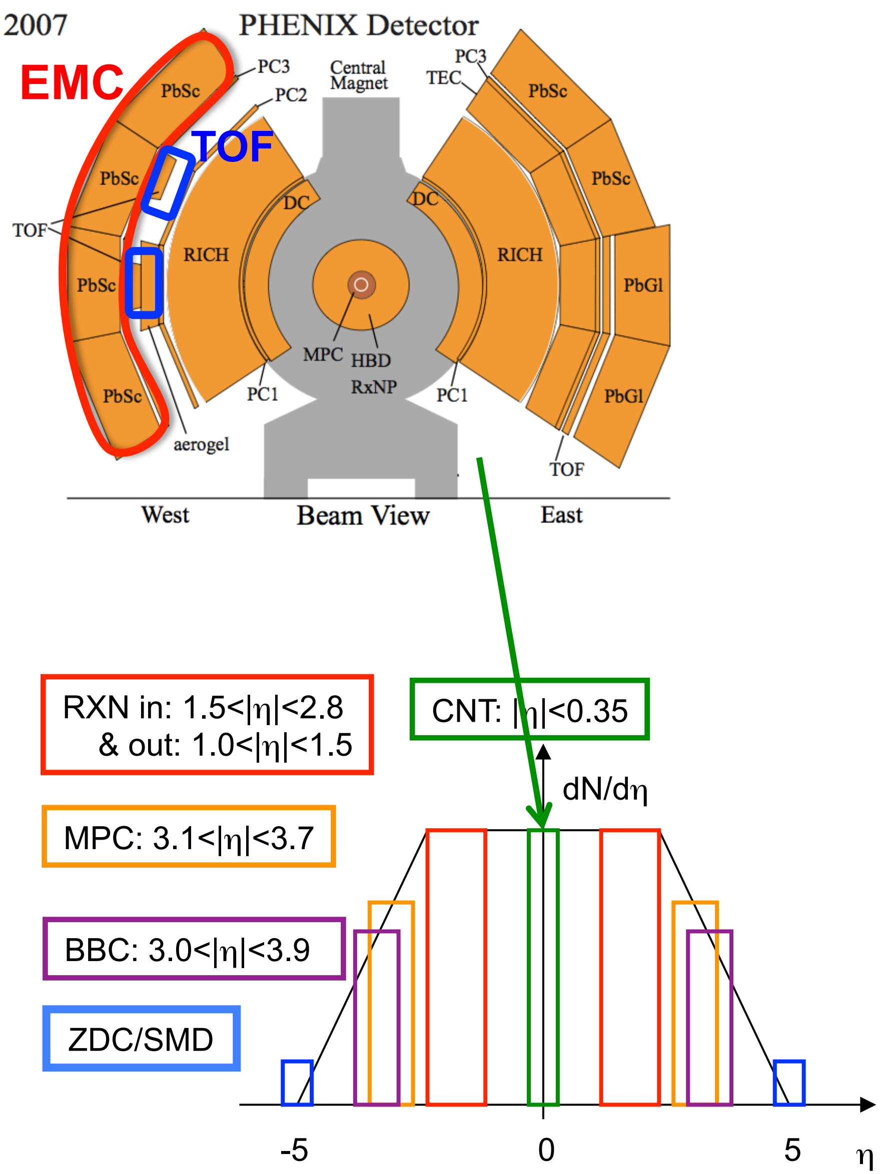
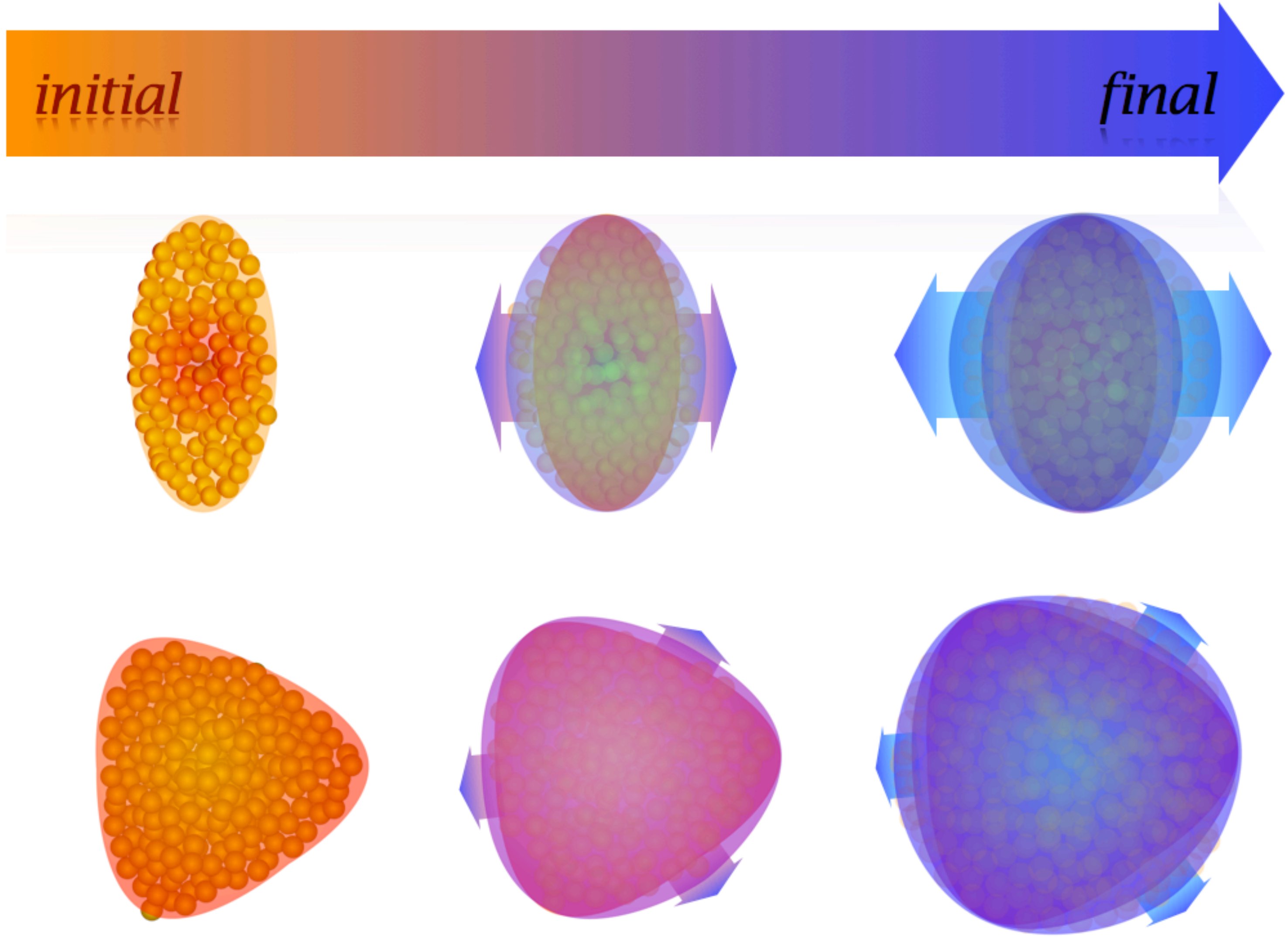


Image of initial/final source shape

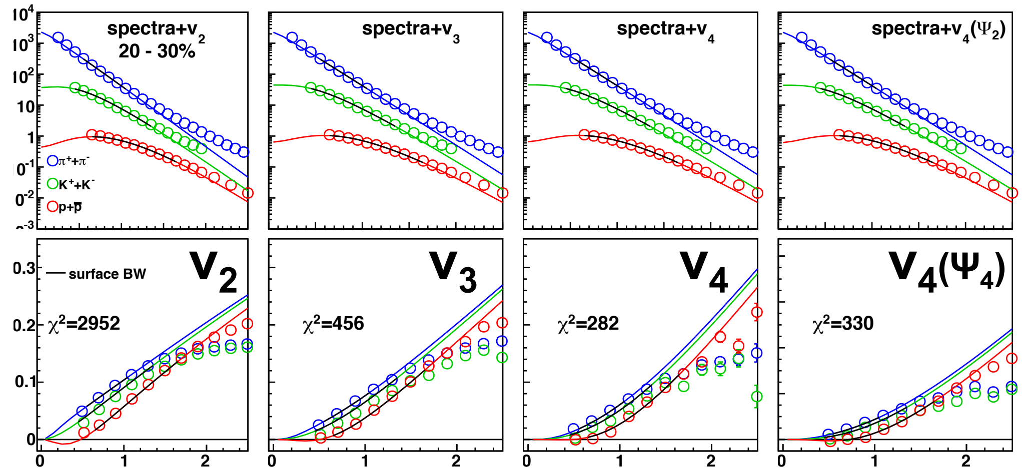


Spatial anisotropy by Blast wave model

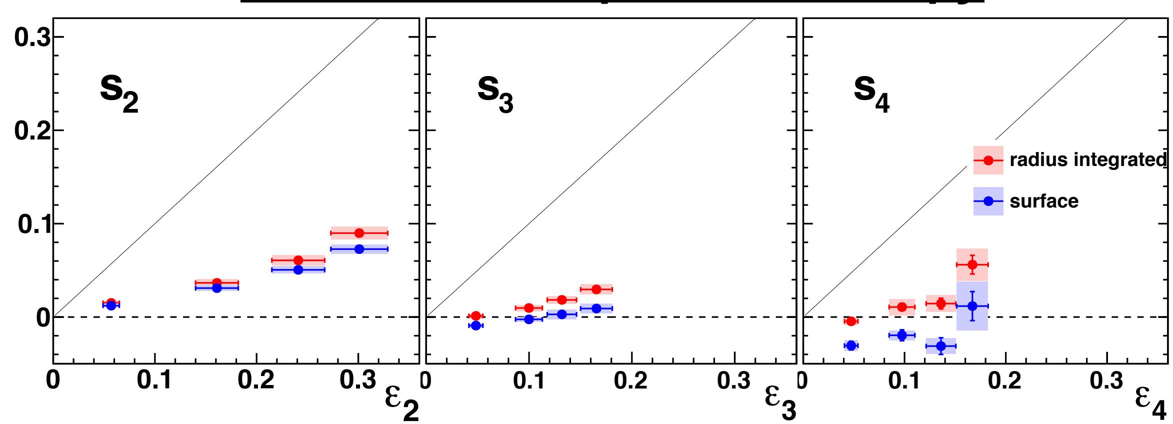
- **Blast wave fit for spectra & v_n**
  - ✧Parameters used in the model

    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



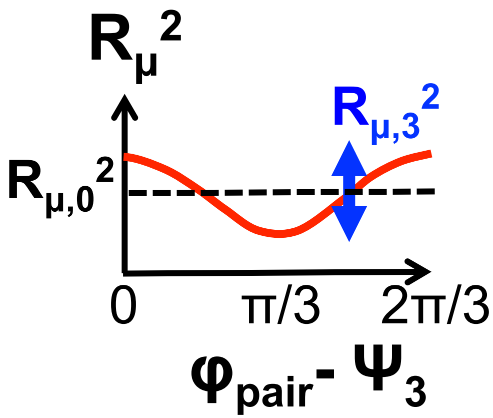
- ✧s_2 increase with going to peripheral collisions
- ✧s_3 is almost zero

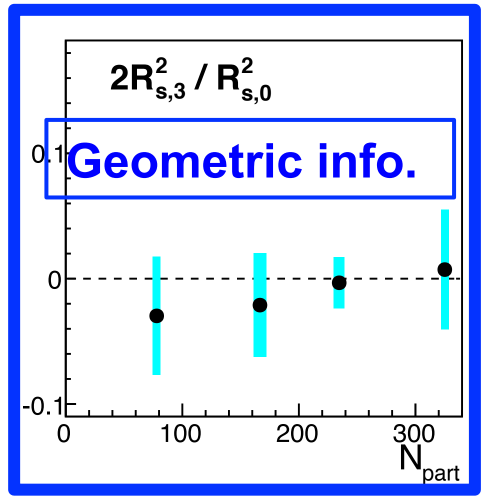
☞Similar results with HBT

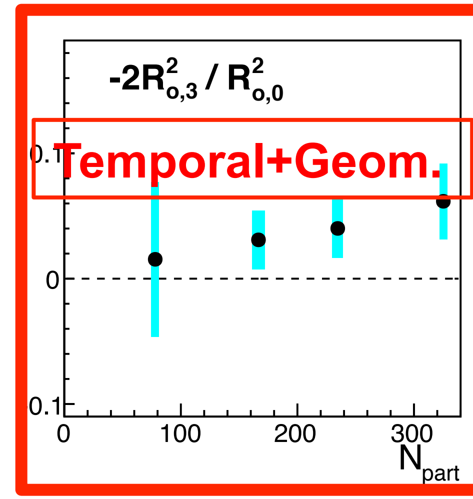
Poster, Board #195
Sanshiro Mizuno

Relative amplitude of HBT radii

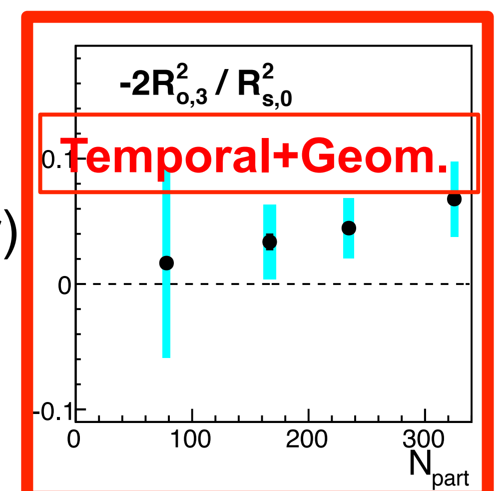
- Relative amplitude is used to represent "triangularity" at freeze-out
- Relative amplitude of Rout increases with increasing Npart







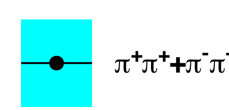
☆ Triangular component at freeze-out seems to vanish for all centralities(within systematic error)



PHENIX Preliminary

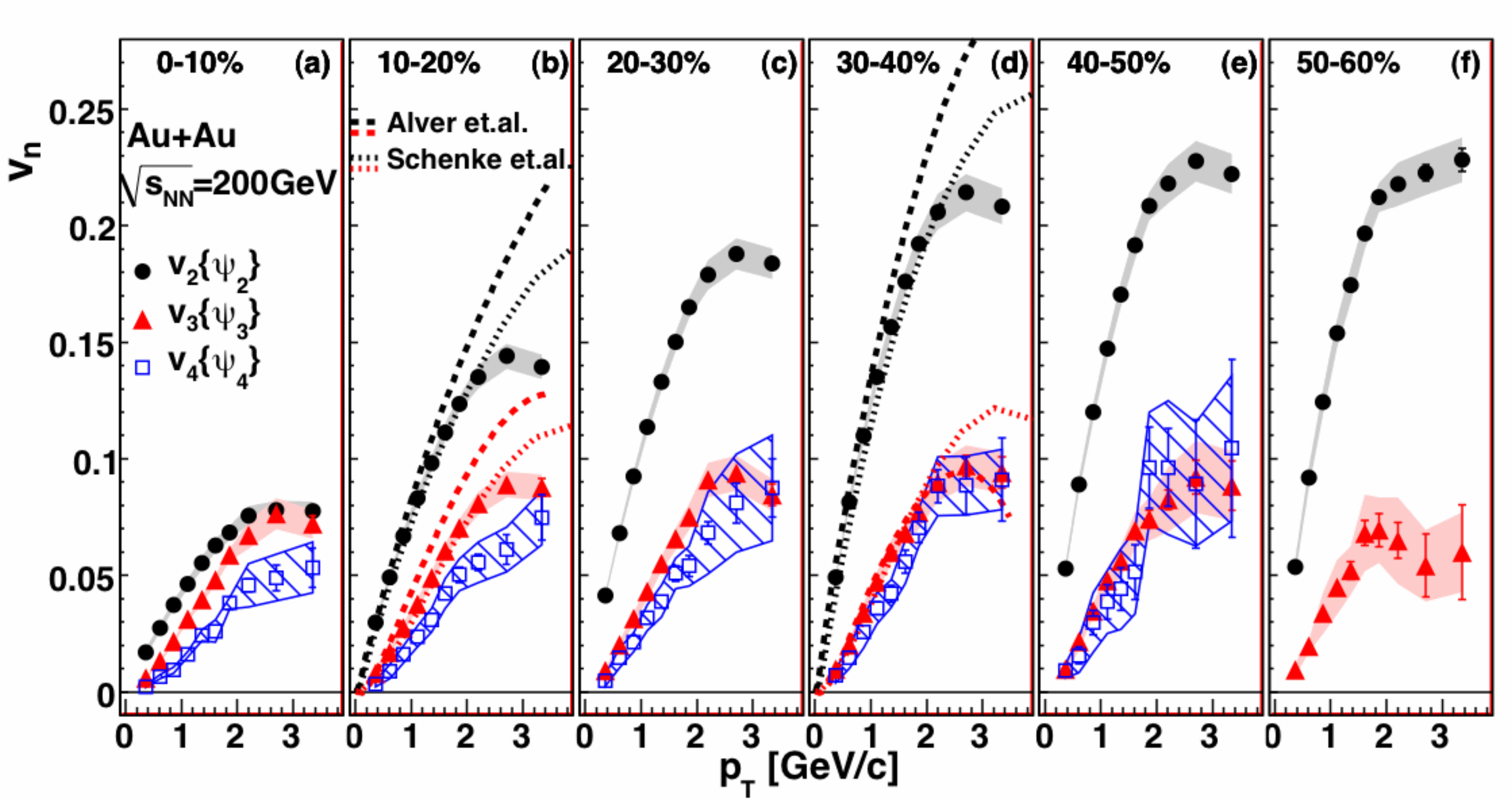
preliminary

Au+Au 200GeV



Charged hadron v_n at PHENIX

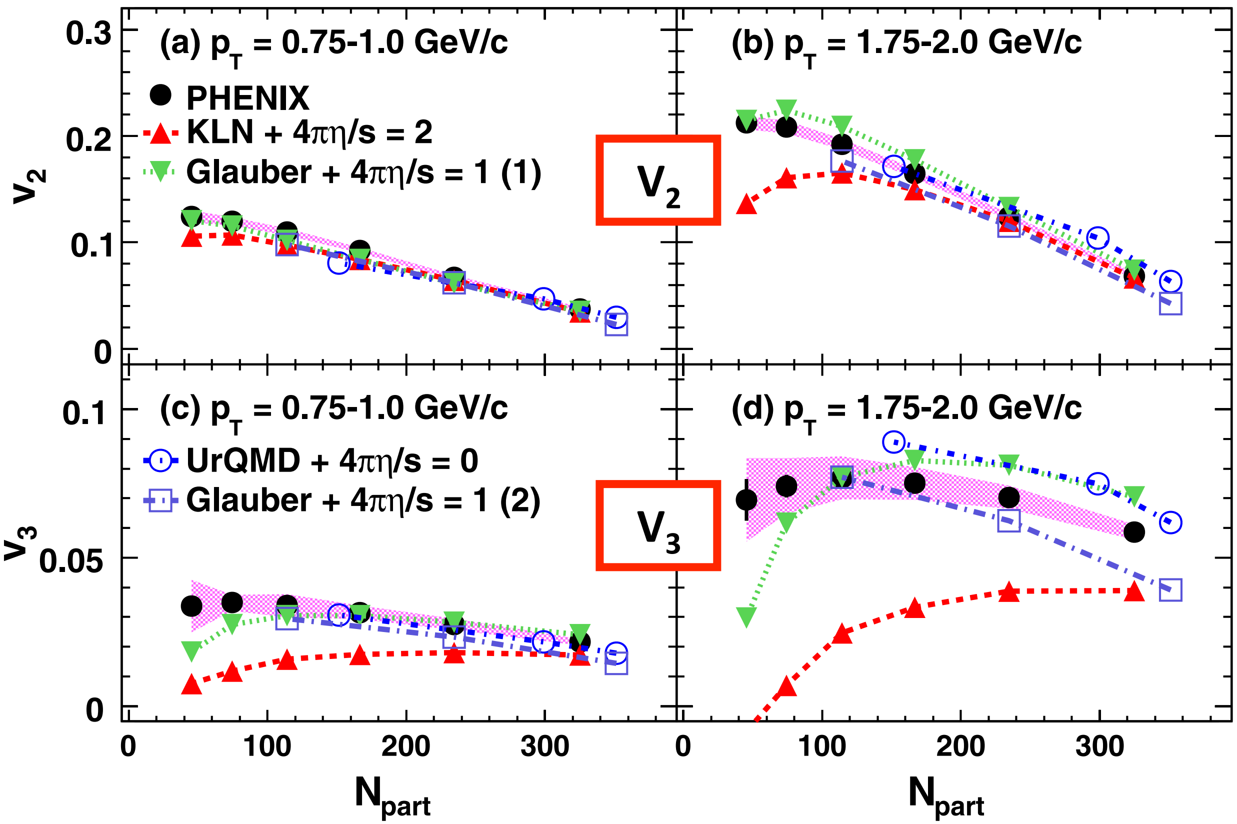
PRL.107.252301



- 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

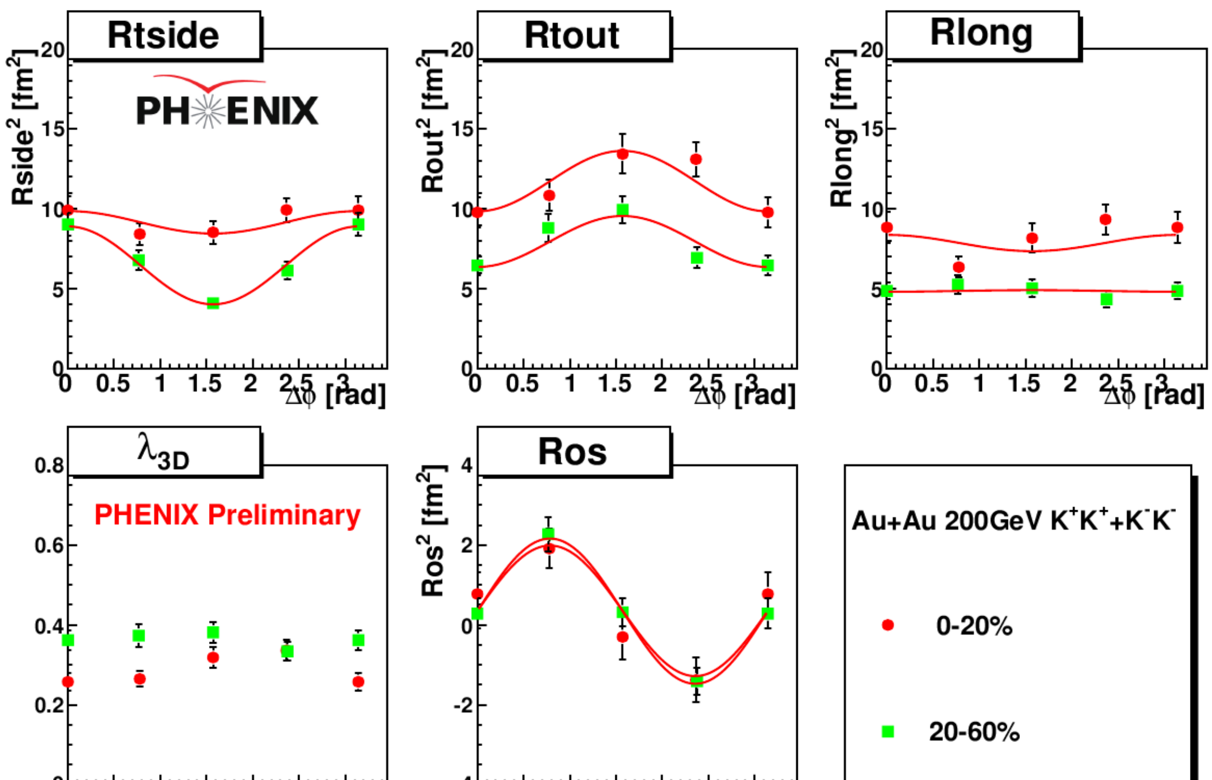
PRL.107.252301



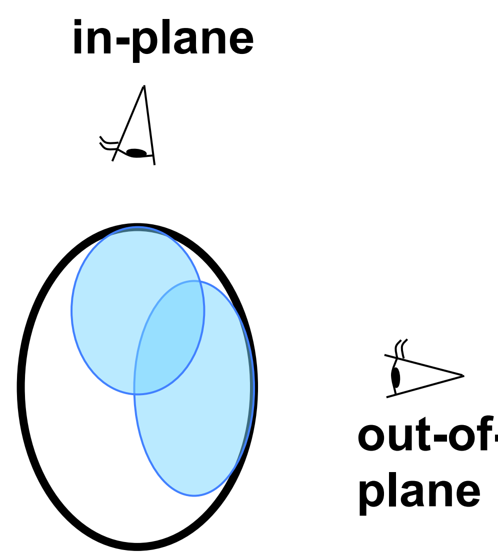
- **v_3 provides new constraint on hydro-model parameters**
  - ✧ Glauber & 4πη/s=1 : works better
  - ✧ KLN & 4πη/s=2 : fails

Azimuthal HBT radii for kaons

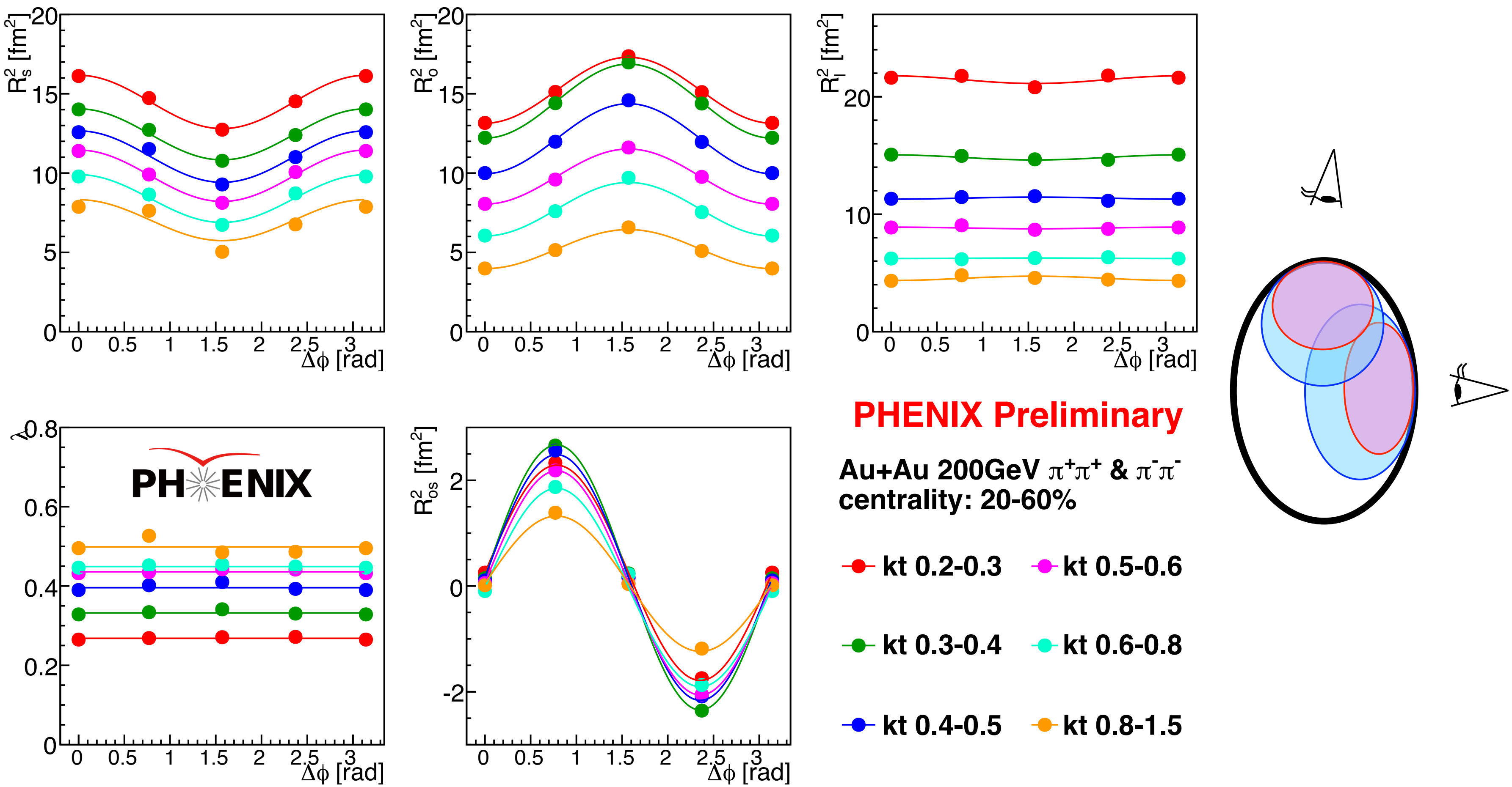
- Observed oscillation for R_{side}, R_{out}, R_{os}
- Final eccentricity is defined as $\varepsilon_{final} = 2R_{s,2} / R_{s,0}$
  - $R_{s,n}^2 = \langle R_{s,n}^2(\Delta\phi)\cos(n\Delta\phi) \rangle$ PRC70, 044907 (2004)



@WPCF2011

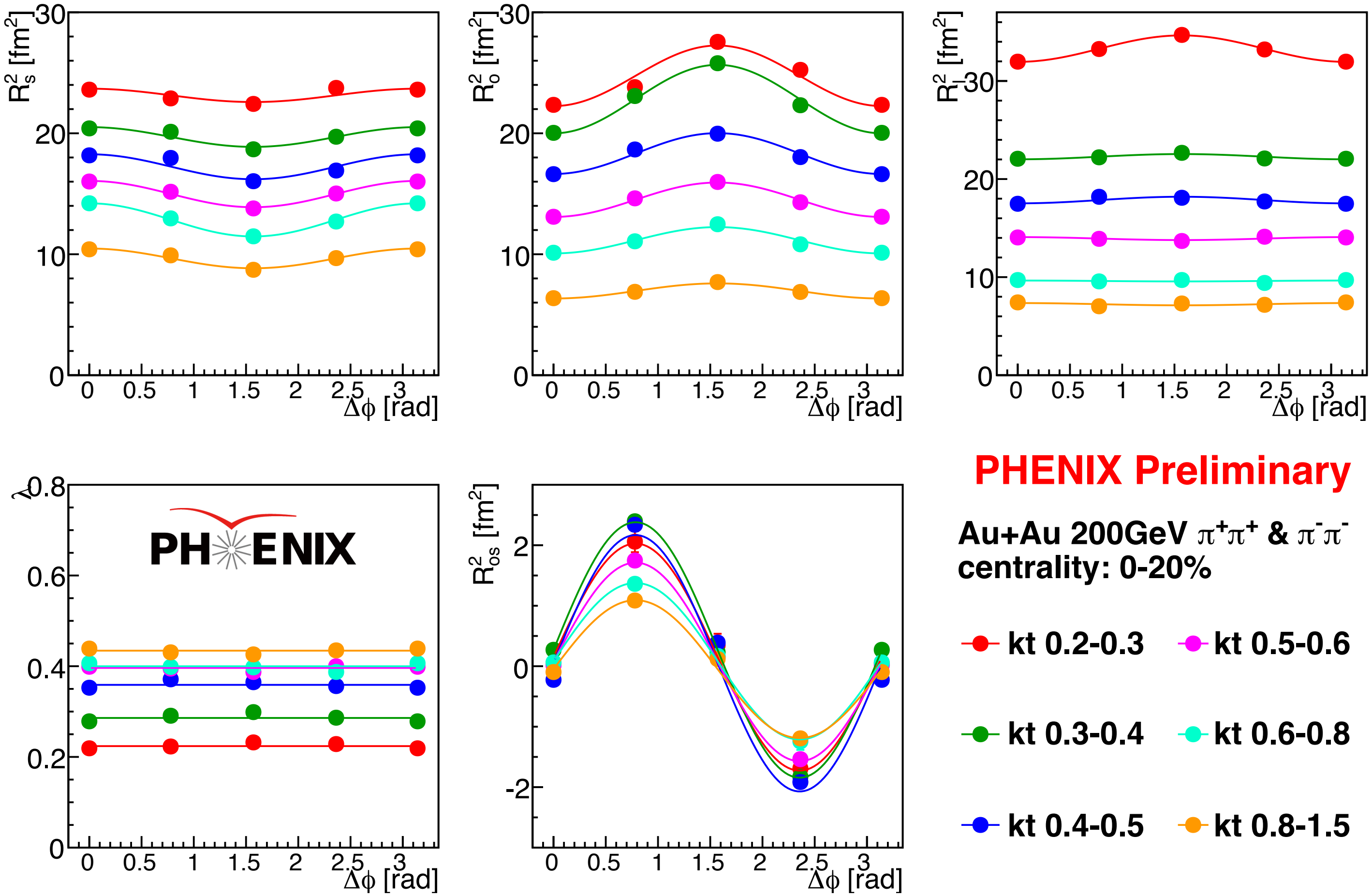


k_T dependence of azimuthal pion HBT radii in 20-60%



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

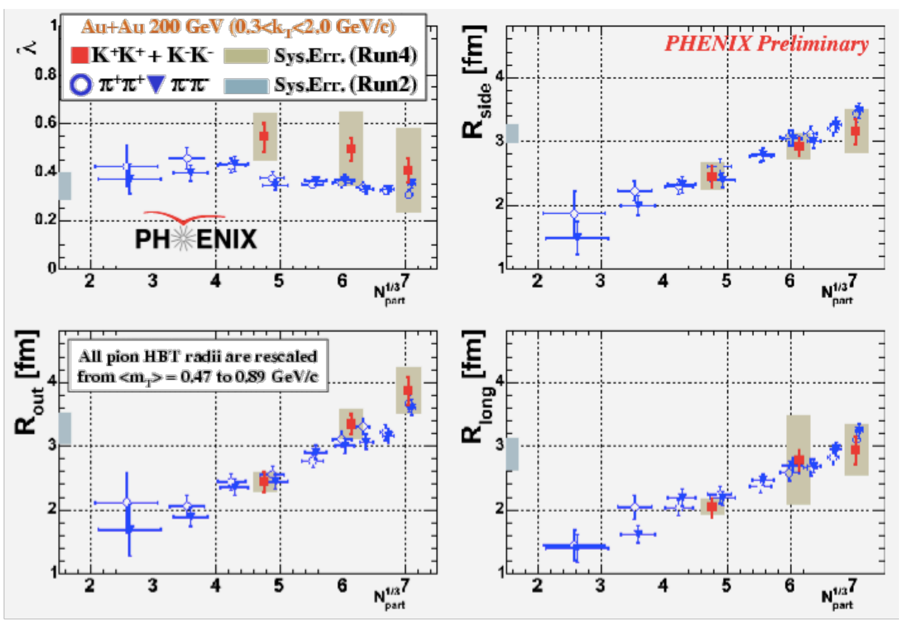
k_T dependence of azimuthal pion HBT radii in 0-20%



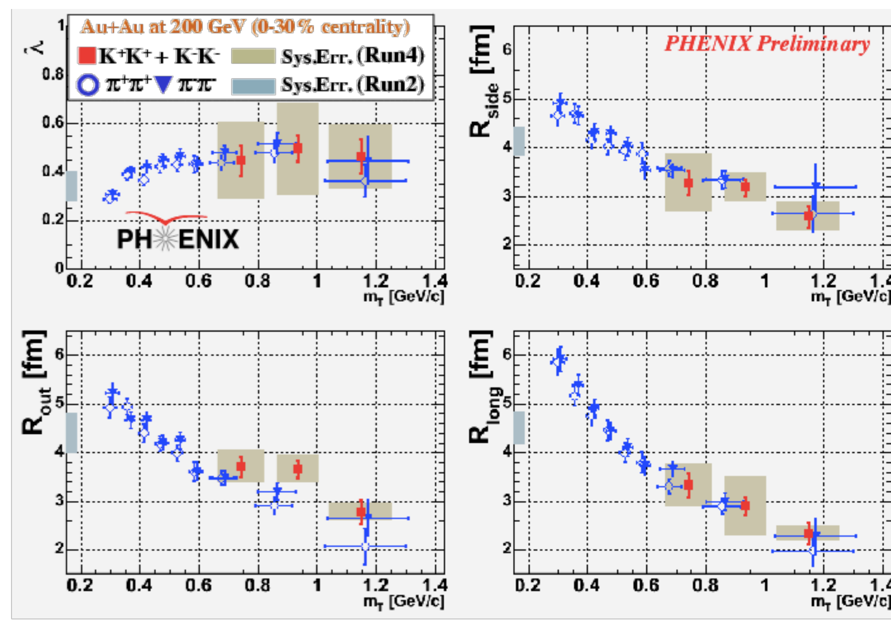
The past HBT Results for charged pions and kaons

- **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

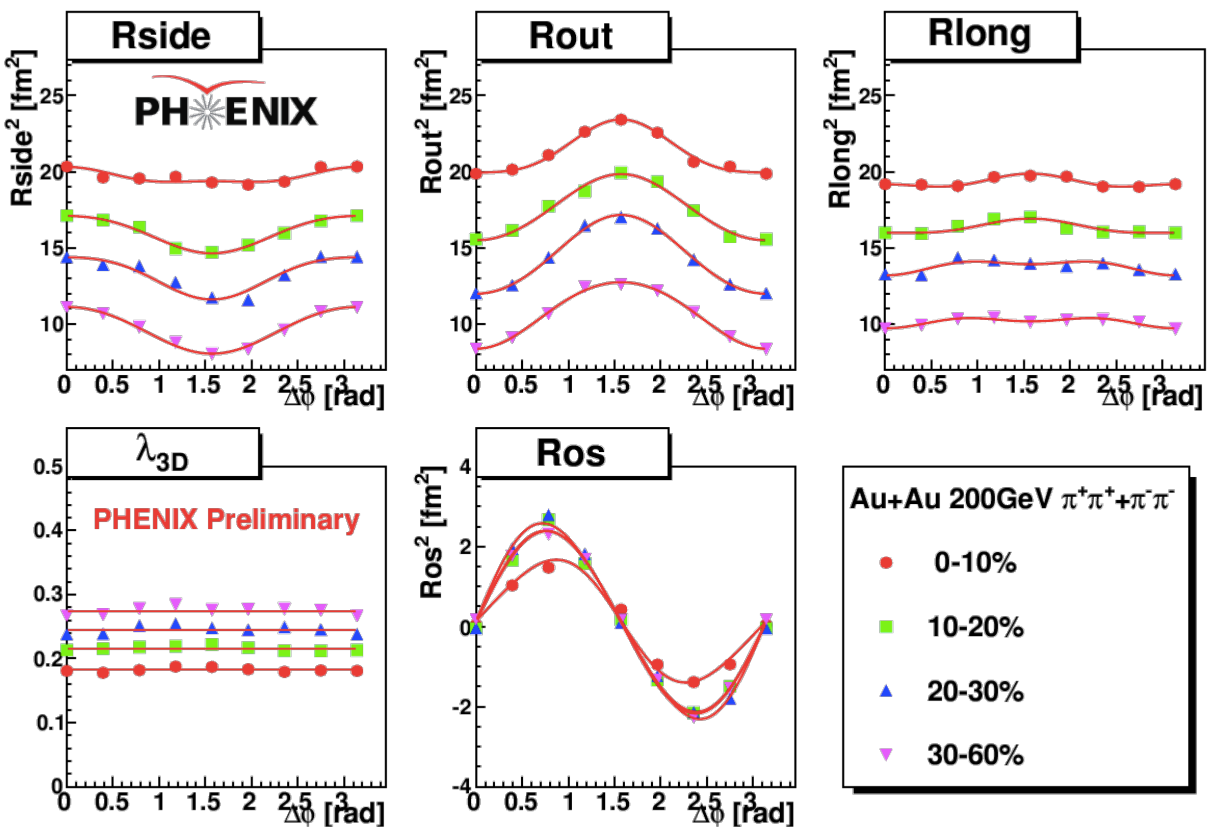
$$C_2 = C_2^{core} + C_2^{halo}$$

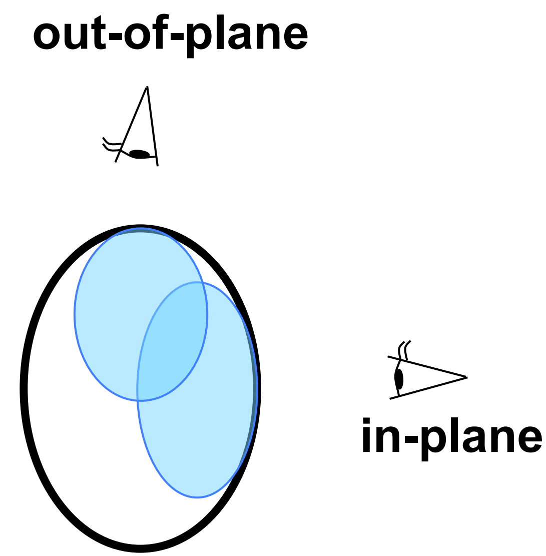
$$= N[\lambda(1+G)F] + [1-\lambda]$$

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

Azimuthal HBT radii for pions

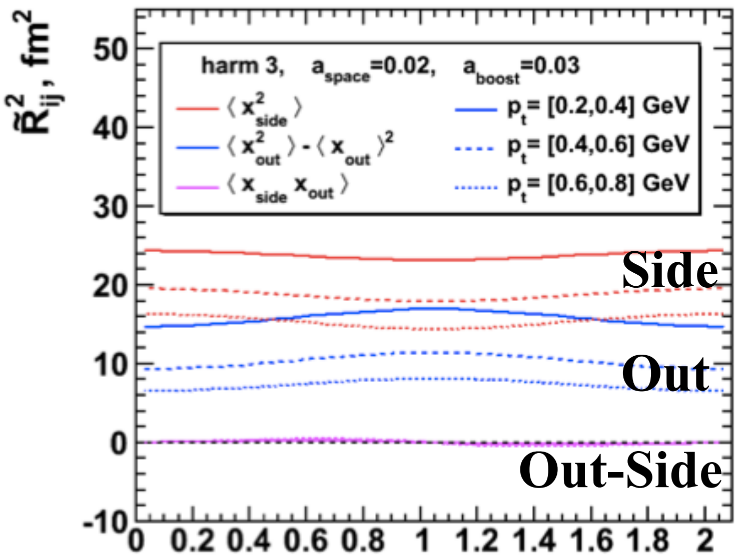
- Observed oscillation for R_{side}, R_{out}, R_{os}
- Rout in 0-10% has oscillation
  - ✧ Different emission duration between in-plane and out-of-plane?





Model predictions

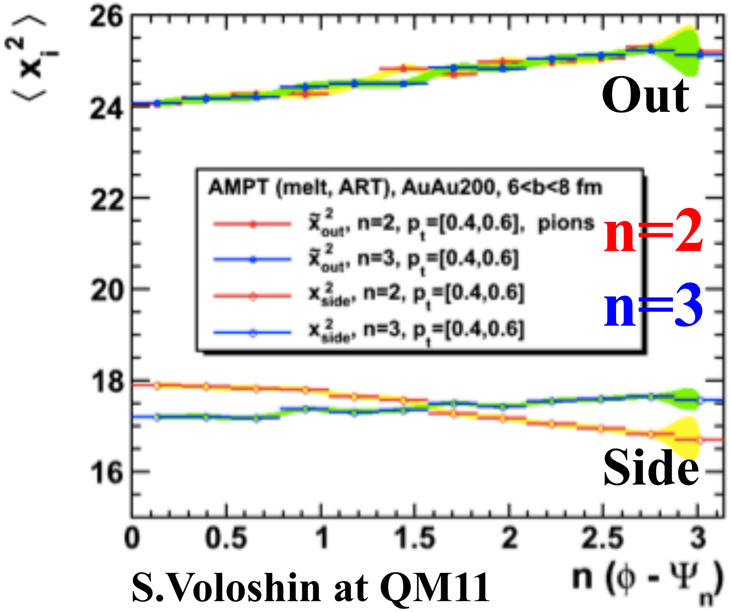
Blast-wave model



S.Voloshin at QM11

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

AMPT



S.Voloshin at QM11

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