Measurements of Quantum Interference of Two Identical Particles with respect to the Event Plane in Au+Au Collisions at $\sqrt{s_{NN}}$=200 GeV at RHIC-PHENIX

（ **RHIC-PHENIX**実験 **200 GeV** 金＋金衝突における
同種2粒子を用いた量子力学的干渉効果の反応平面依存性の測定）

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outline

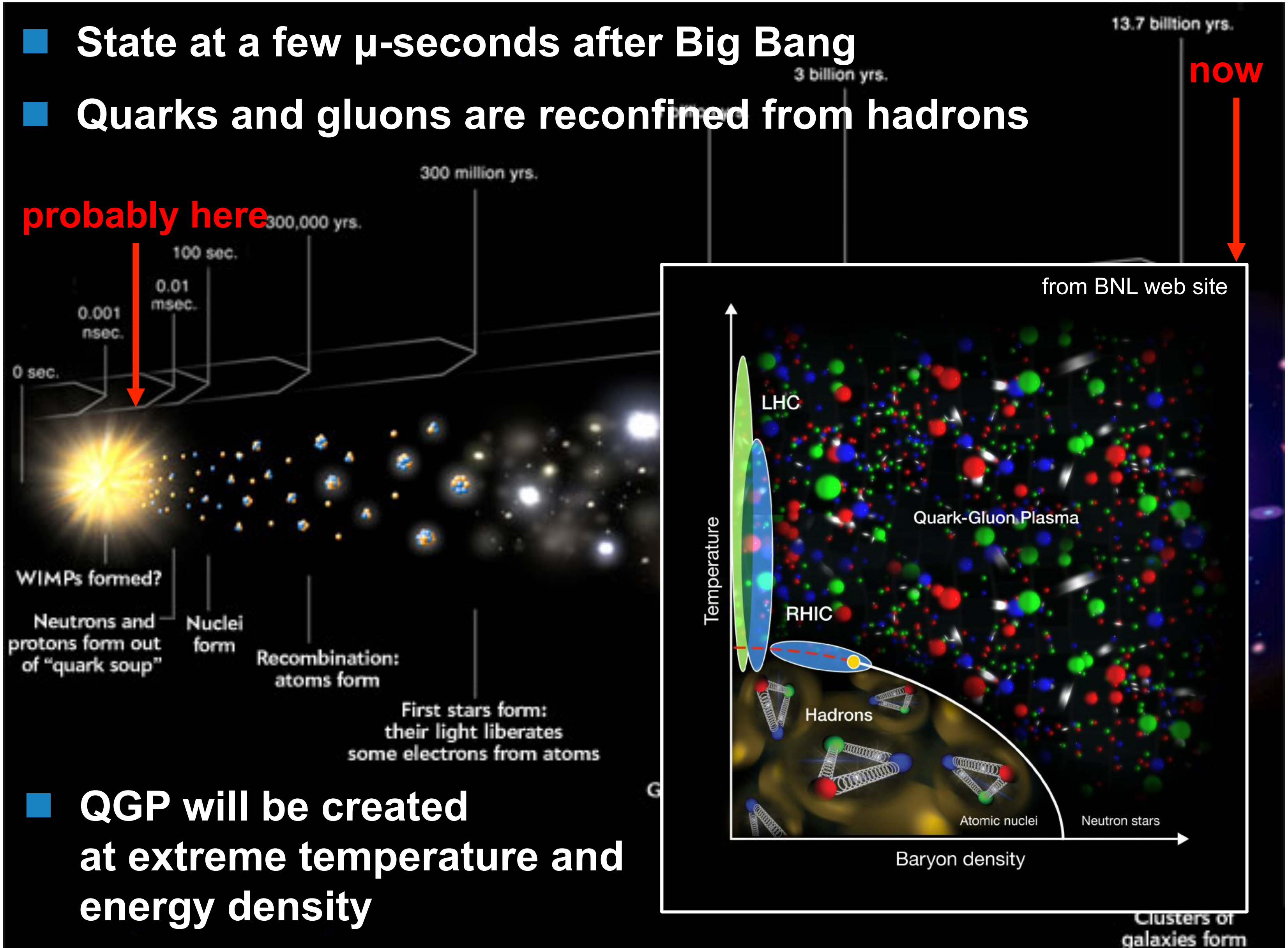
- **Introduction**
  - Hanbury-Brown&Twiss Interferometry (HBT)
  - Motivation
- **Experiment/Analysis**
  - PHENIX Detectors
  - Data selection
  - Analysis Method for HBT
- **Results/Discussion**
  - HBT measurement with respect to the event plane
  - Blast-wave model
  - Monte-Carlo simulation
- **Summary/Conclusions**

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

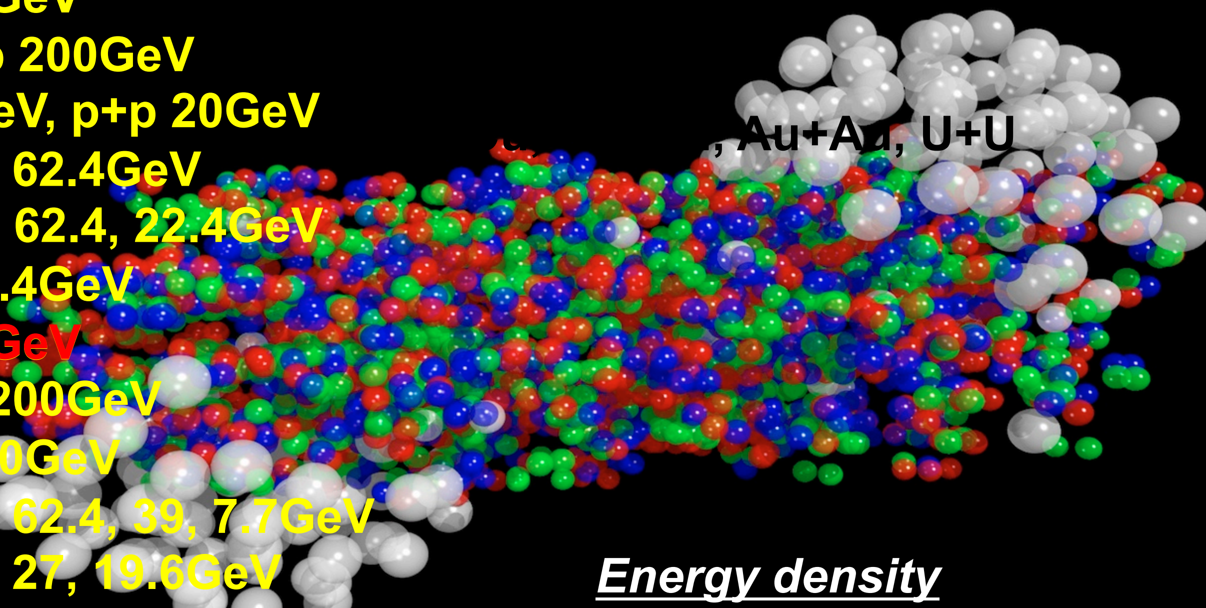


- QGP will be created at extreme temperature and energy density

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

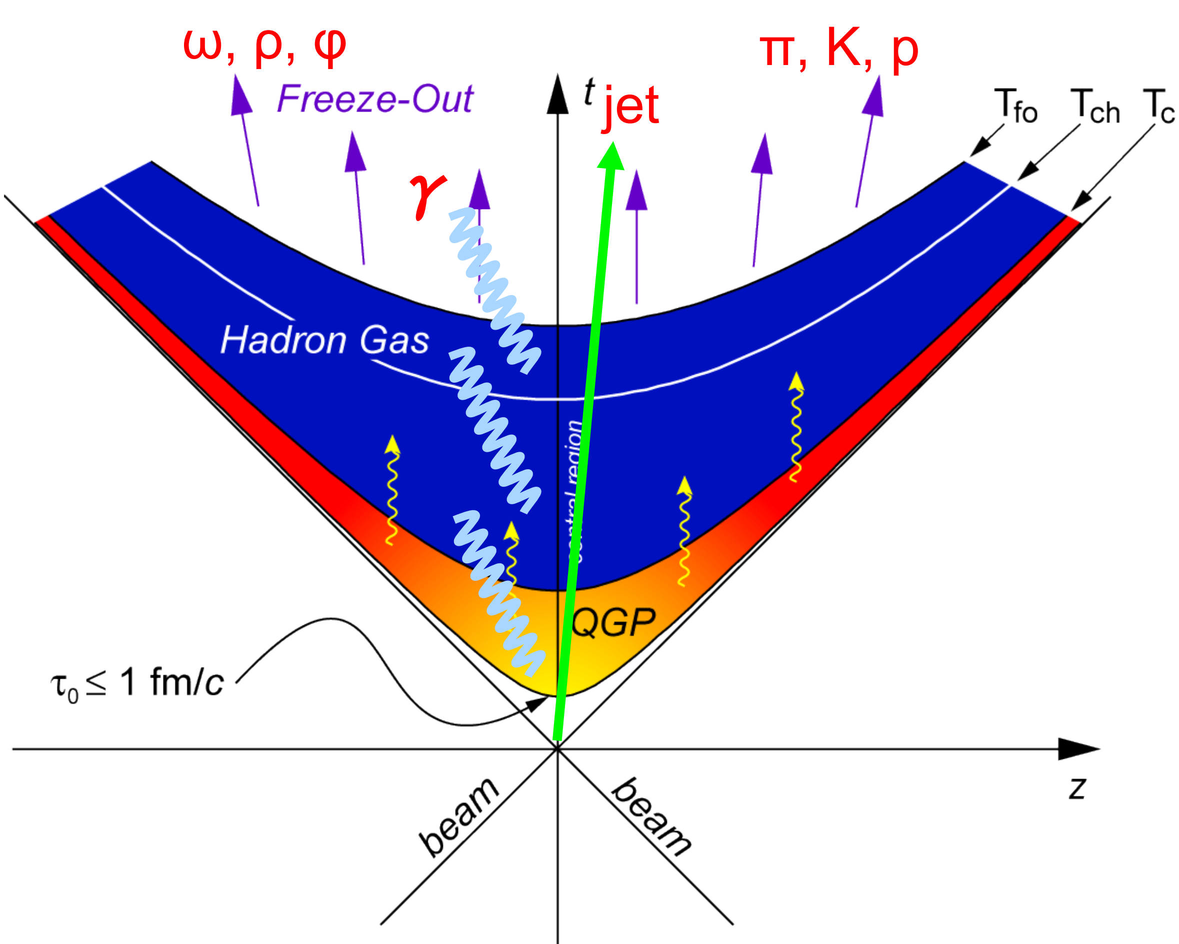
$T_c \sim 170$ MeV

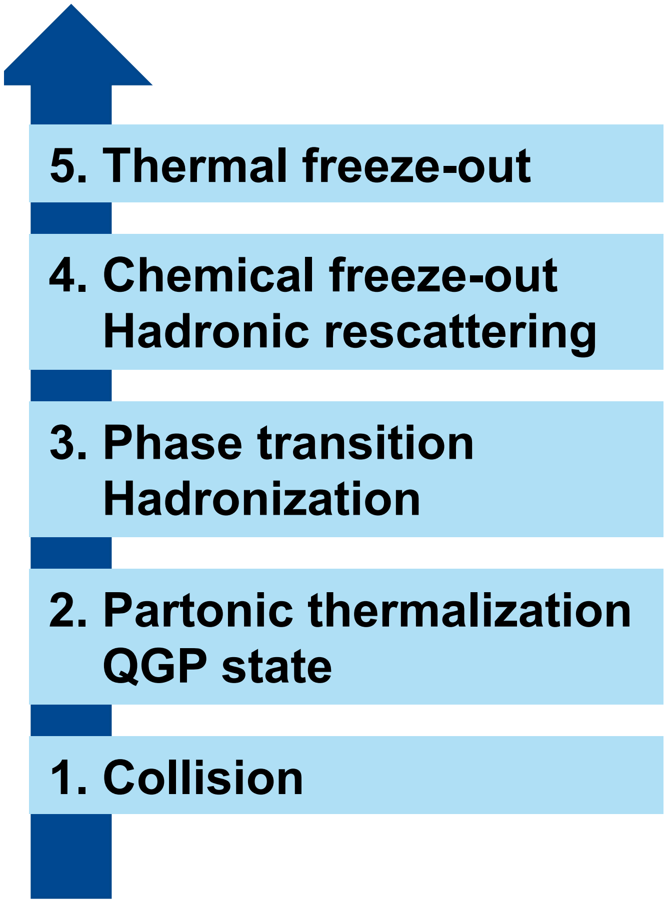
$\varepsilon_c \sim 1$ GeV/fm^3

○ Au+Au 200GeV @RHIC

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

Space-Time Evolution

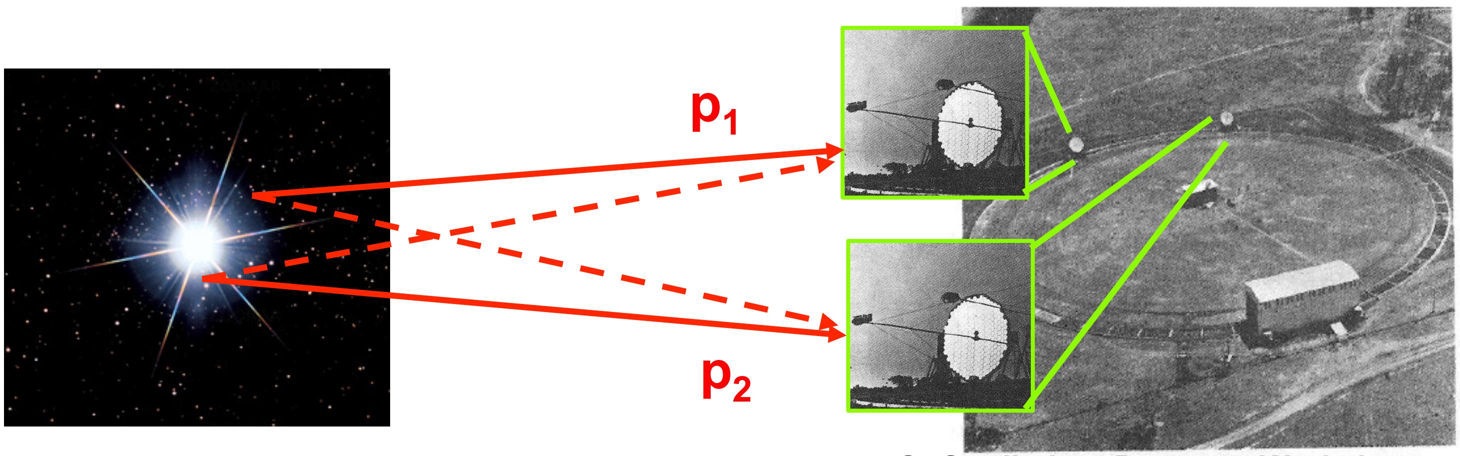




How fast the system evolves?
How much the system size and shape?
Study a detailed space-time picture of evolution of the QGP

HBT Interferometry

- **R. Hanbury Brown and R. Twiss**
  - ✧In 1956, the angular diameter of Sirius was measured.
  - ✧HBT effect is ***quantum interference*** between two identical particles.



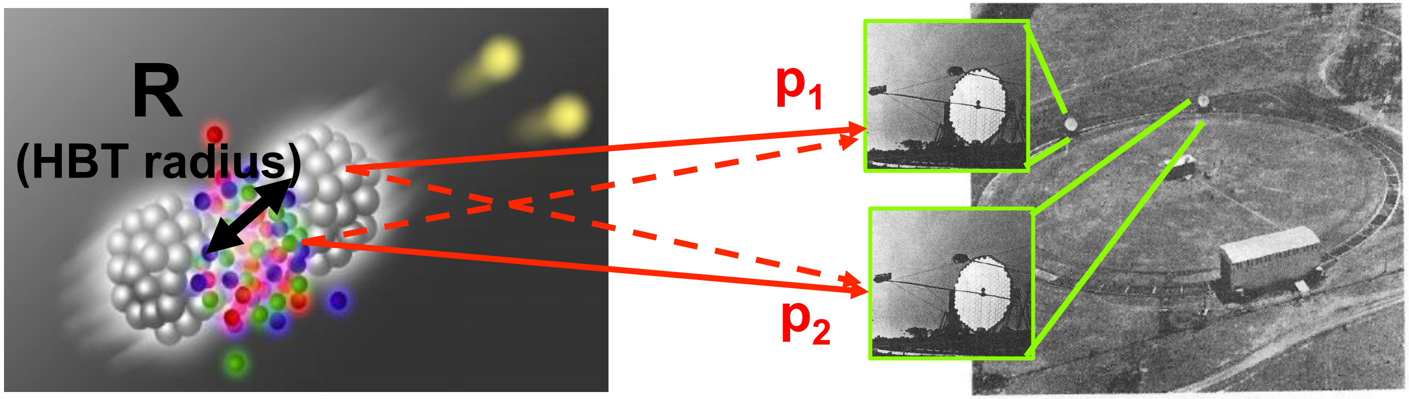
G. Goldhaber, Proc. Int. Workshop on Correlations and Multiparticle production(1991)

wave function of 2 bosons(fermions) : $\Psi_{12} = \frac{1}{\sqrt{2}}[\Psi_1(p_1)\Psi_2(p_2) \pm \Psi_2(p_1)\Psi_1(p_2)]$

Correlation function C_2 : Ratio of probabilities to detect 2 particles and 1 particle

$$C_2 = \frac{P_{12}}{P_1 P_2}$$

HBT Interferometry



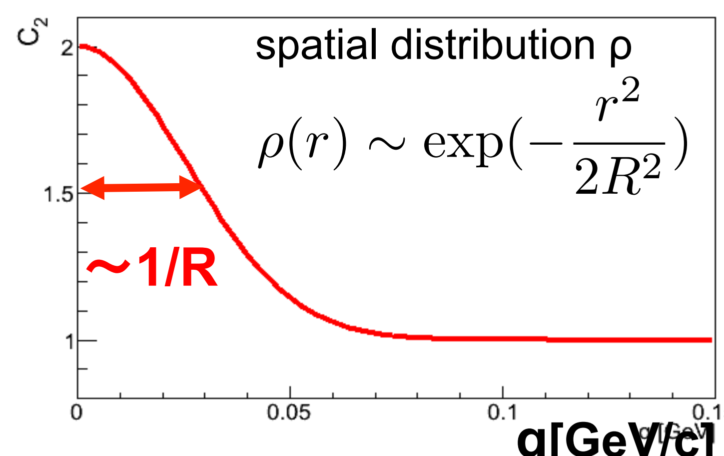
(assuming plane wave)

$$P_{12} \propto [e^{-ip_1\cdot(x_A-x_1)}e^{-ip_2\cdot(x_B-x_2)} + e^{-ip_2\cdot(x_A-x_2)}e^{-ip_1\cdot(x_B-x_1)}]^2$$
$$= [2 \pm e^{-ix_1(p_2-p_1)}e^{ix_2(p_2-p_1)} \pm e^{ix_1(p_2-p_1)}e^{-ix_2(p_2-p_1)}]$$
$$\propto 1 \pm \cos[(x_2-x_1)\cdot(p_2-p_1)]$$

→ **HBT correlation**

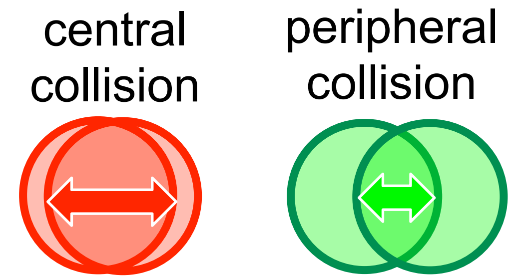
$$C_2 = \frac{P_{12}}{P_1P_2} = \frac{\int dx_1 dx_2 \rho(x_1)\rho(x_2)\left|\Psi_{12}\right|^2}{\int dx_1\rho(x_1)\left|\Psi_1\right|^2 \int dx_2\rho(x_2)\left|\Psi_2\right|^2}$$
$$= 1 \pm \left|\int dx \rho(x) e^{ix(p_2-p_1)}\right|^2$$
$$= 1 + |\tilde{\rho}(q)|^2$$
$$\approx 1 + \exp(-R^2q^2)$$

$\tilde{\rho}(q)$: Fourier transform of ρ(r), $q = p_2 - p_1$



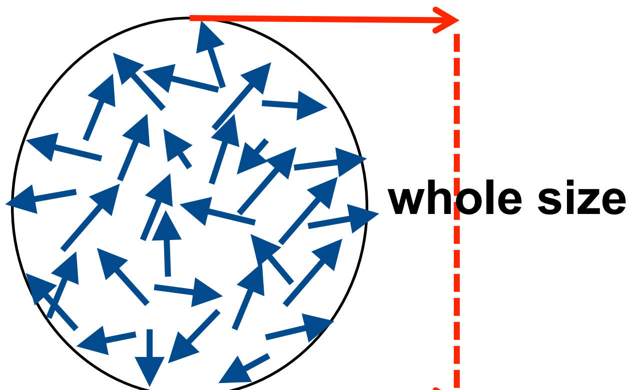
What do HBT radii depend on ?

- **Centrality dependence**
- **Transverse momentum (k_T) dependence**
  - ✧ static source: whole source is measured.
  - ✧ **expanding source**: Size of "**emission region**" is measured.
    Collective expansion makes "x-p correlation".



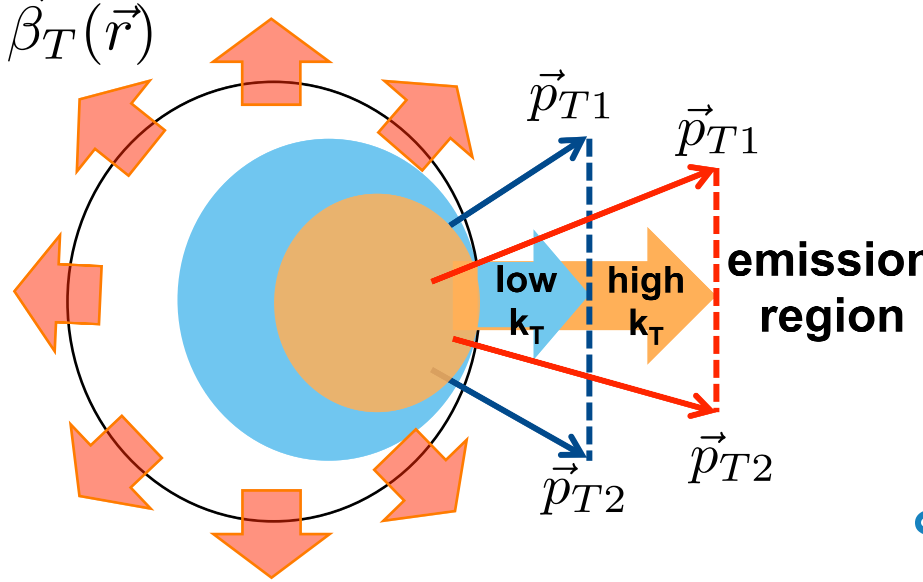
$$\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2})$$

static



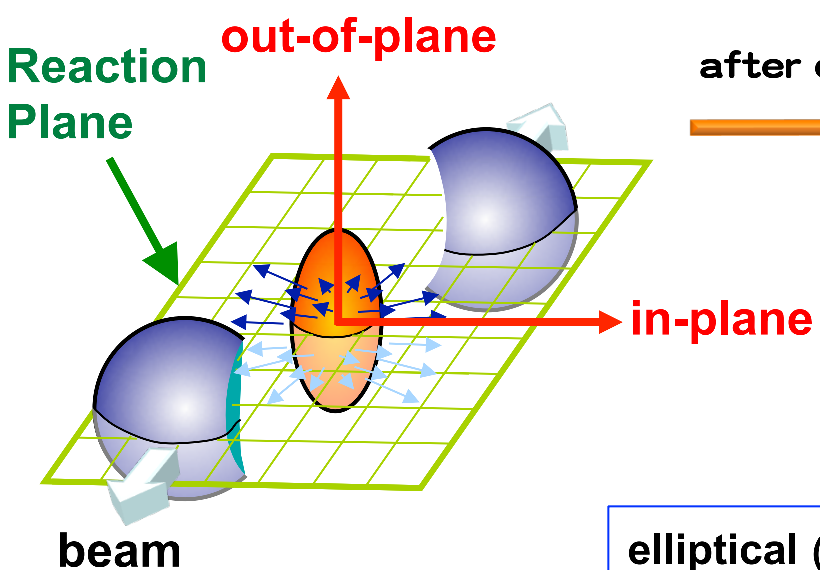
expanding

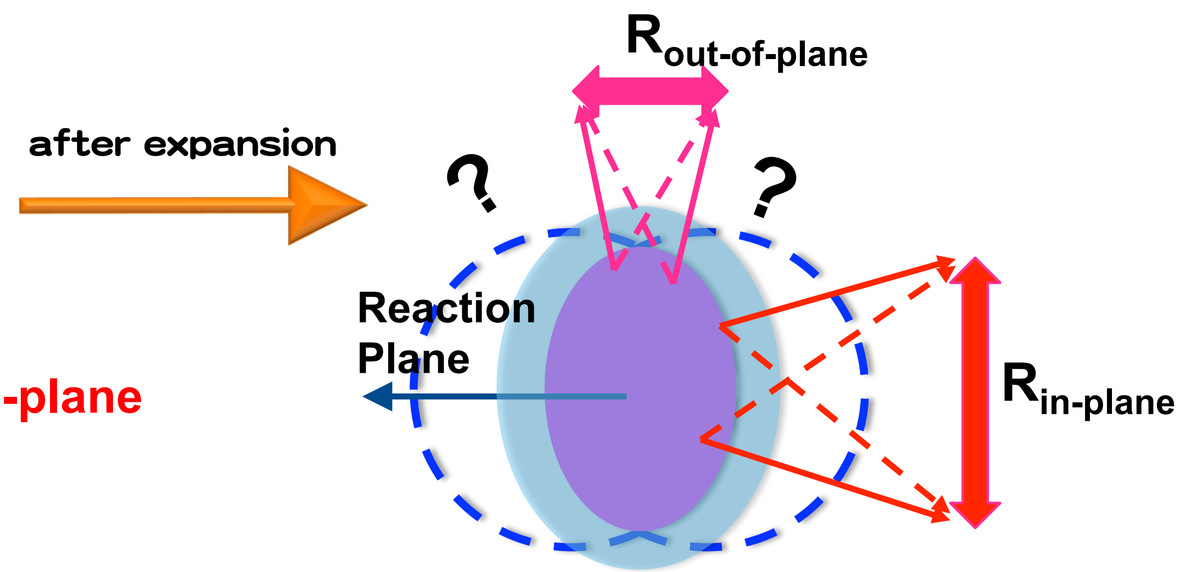
$$\vec{\beta}_T = \vec{\beta}_T(\vec{r})$$



Azimuthal angle dependence

- **Angle dependence of HBT radii w.r.t Reaction Plane reflects the source shape at freeze-out.**
  - ✧ **R.P** is defined by beam axis and a vector between centers of colliding nuclei
- **Initial spatial anisotropy causes momentum anisotropy (flow anisotropy)**
- **Final source eccentricity will be determined by initial eccentricity, flow profile, expansion time, and viscosity etc.**



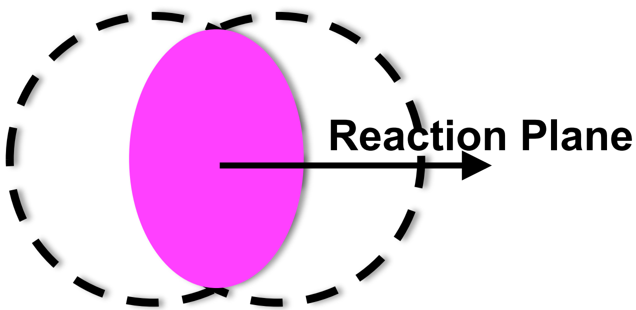


elliptical (out-of-plane extended)	:	$R_{in\text{-}plane} > R_{out\text{-}of\text{-}plane}$
spherical	:	$R_{in\text{-}plane} = R_{out\text{-}of\text{-}plane}$
elliptical (in-of-plane extended)	:	$R_{in\text{-}plane} < R_{out\text{-}of\text{-}plane}$

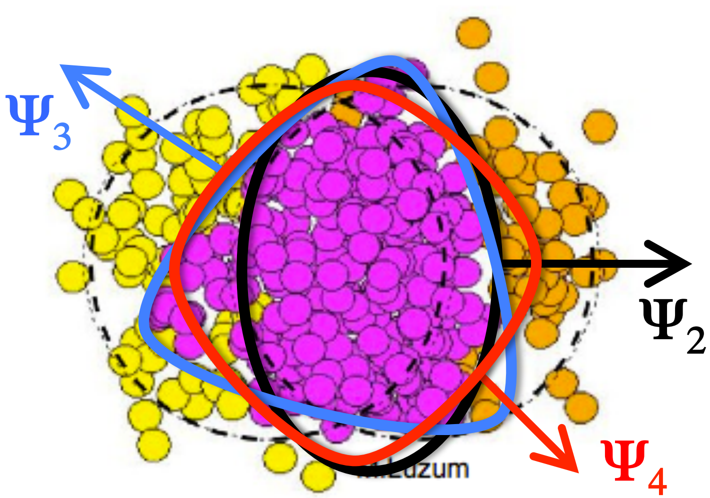
Higher Harmonic Flow and Event Plane

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

smooth picture



fluctuating picture



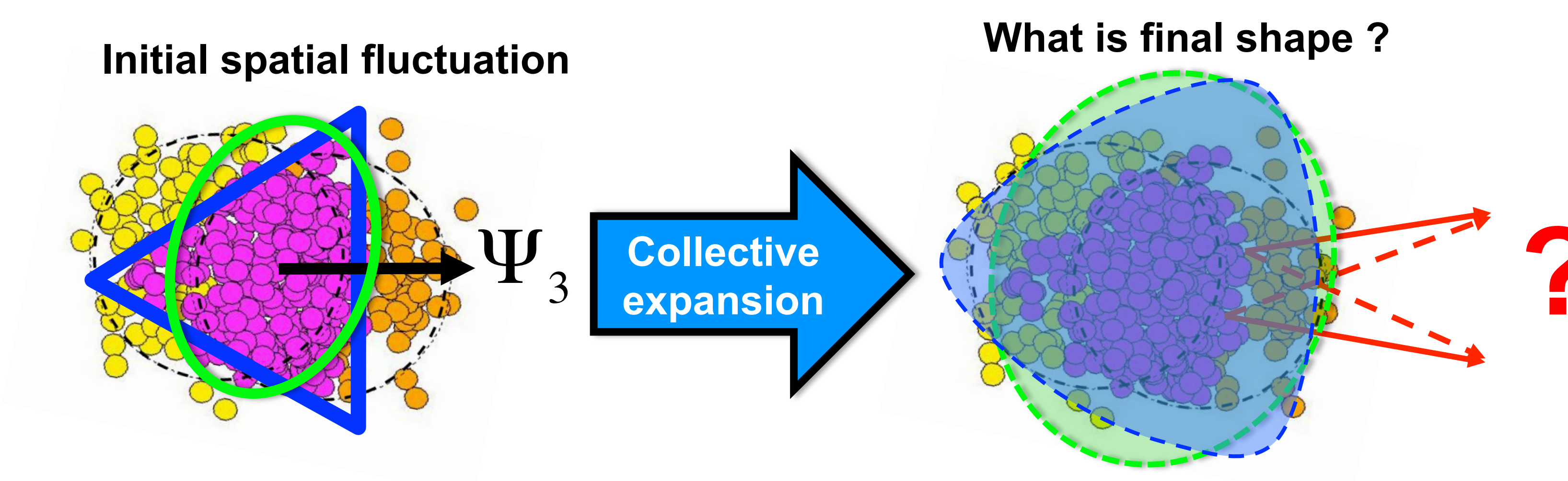
$$\frac{dN}{d\phi} \propto 1 + 2\boxed{v_2}\cos 2(\phi - \boxed{\Psi_2}) + 2\boxed{v_3}\cos 3(\phi - \boxed{\Psi_3}) + 2\boxed{v_4}\cos 4(\phi - \boxed{\Psi_4})$$

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

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 in the heavy ion collisions via azimuthal HBT measurement.**
  - ✧Measurement of charged pion HBT radii with respect to 2^{nd} and 3^{rd}-order event planes to reveal the detail of final state and space-time evolution of the system.
  - ✧Study particle species dependence by comparison of charged pion and kaon HBT radii

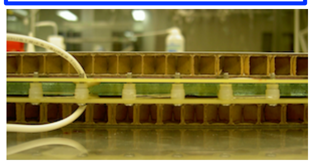


My Activities

3-years vacuum (It's mystery!)

2006(M1) **2007(M2)** **2010(D1)** **2011(D2)**

MRPC construction



RXNP construction

Installed MRPC&RXNP

Azimuthal HBT analysis using Run4 data

Di-jet Calorimeter construction for ALICE

Summer Challenge (SC) @KEK

Shift taking @CERN

Start azimuthal HBT analysis using Run7 data

Talk WPCF2011

2012(D3) **2013(D4)**

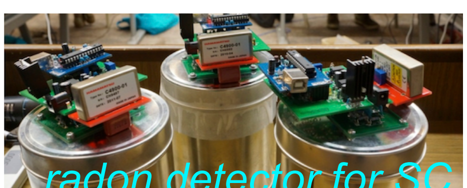
Talk JPS fall · ***Talk JPS spring*** · ***Talk HIC in LHC*** · ***Talk QM2012*** · ***Poster Radon Workshop*** · ***Talk JPS spring*** · ***Talk APPC12***

SC @KEK **SC @KEK** **SC @KEK**

Shift taking & Detector Expert for Run11 @BNL

Shift taking & Detector Expert for Run12 @BNL

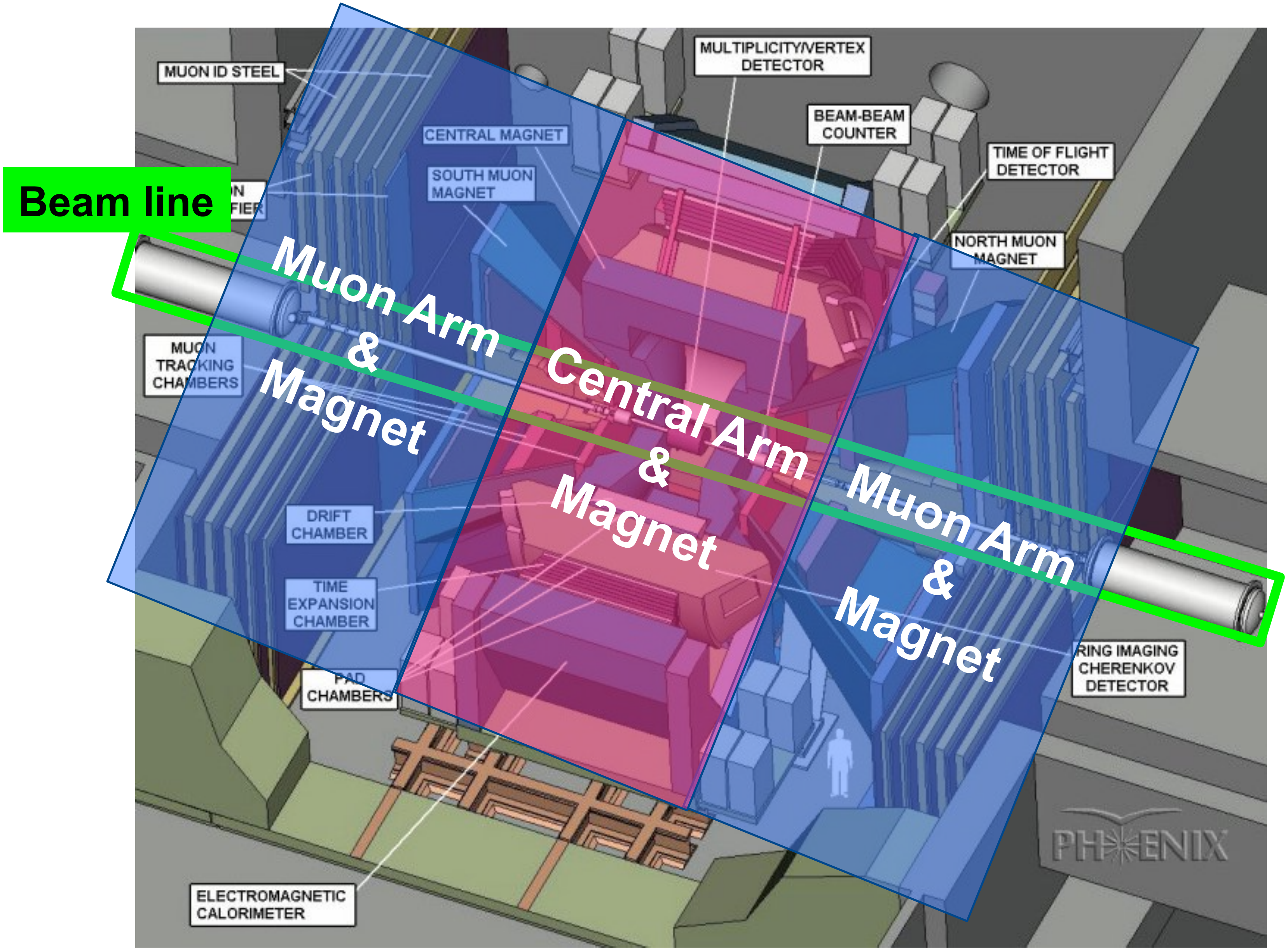
Work for Run13 @BNL



★ preliminary result for π/K HBT w.r.t Ψ_2
★ preliminary result for π/K HBT w.r.t Ψ_3
☆ Working for publication now

Experiment/ Analysis

PHENIX Experiment



Roles of Detectors

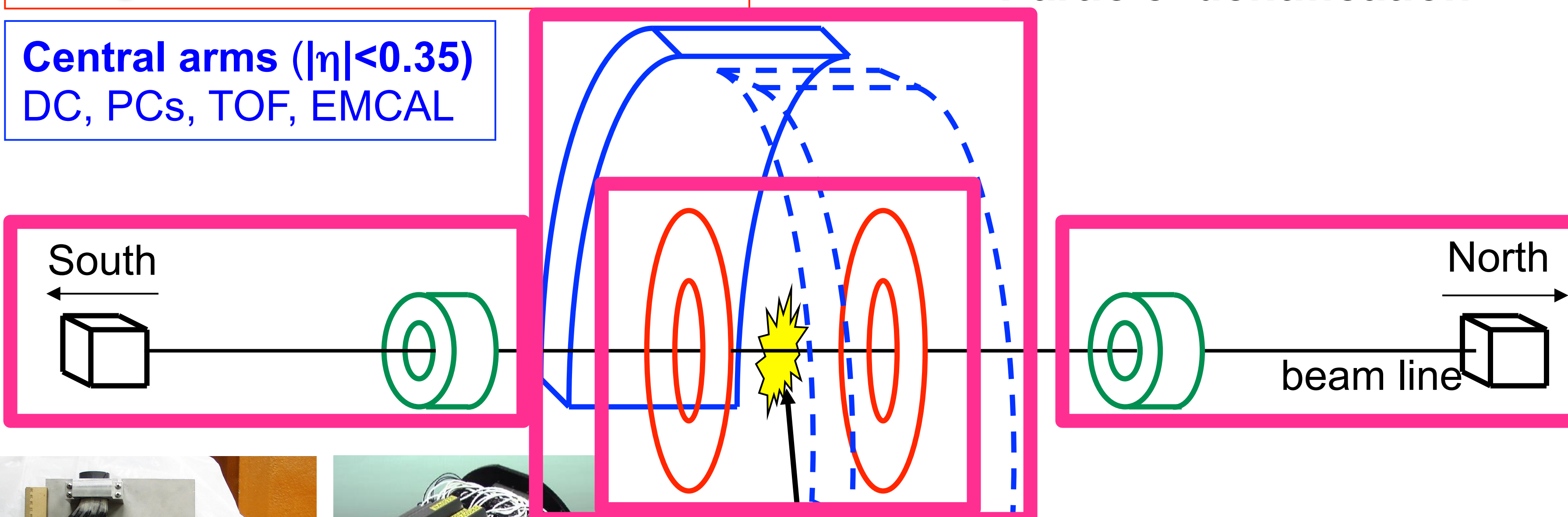
Beam-Beam Counter (|η|=3~4)
Quartz radiator+64PMTs

Zero Degree Calorimeter
Spectator neutron energy

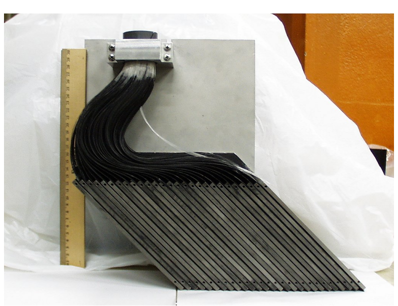
Reaction Plane Detector (|η|=1~2.8)
2 rings of 24 scintillators

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

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

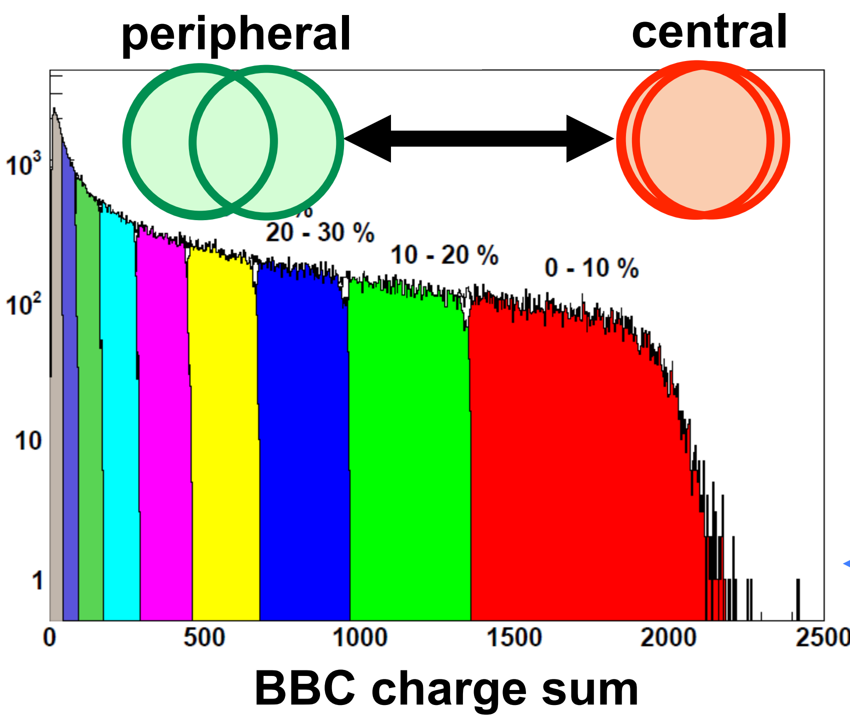


collision point

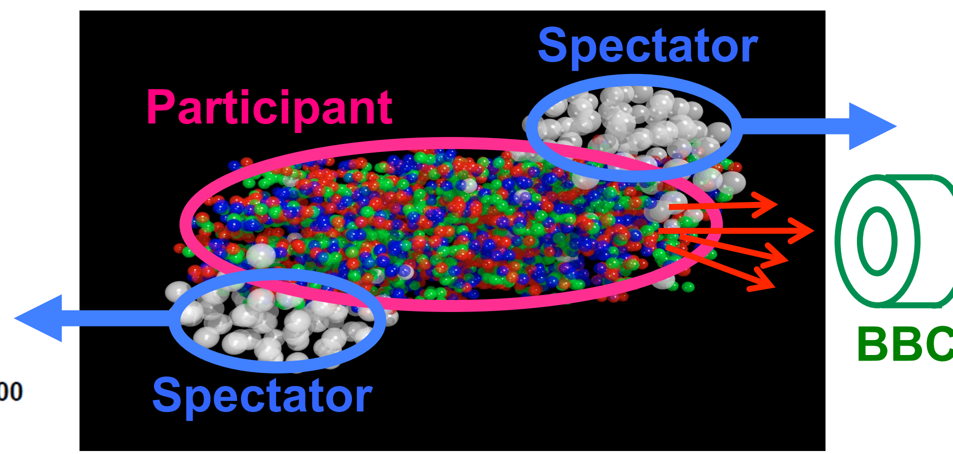


Collision Centrality

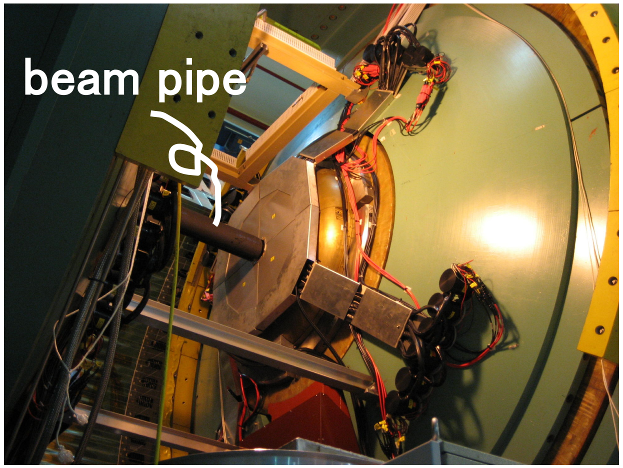
- **Centrality is used to classify events instead of impact parameter.**
  - impact parameter ∝ multiplicity ∝ charge sum at BBC
  - 0% : head-head collision
    92% : most peripheral collisions

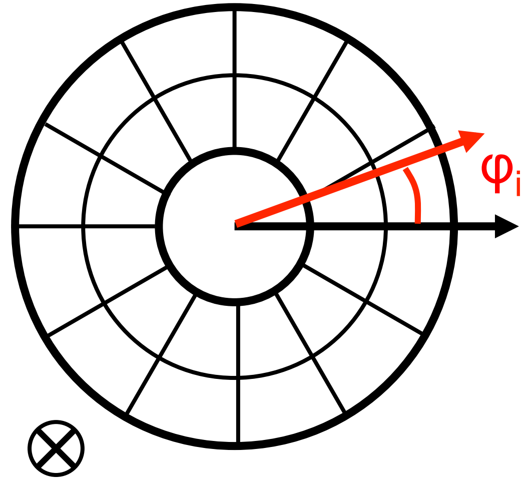


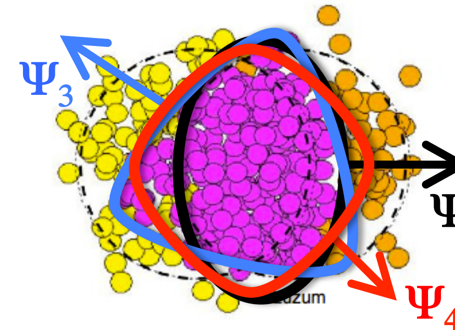
quartz radiator
+64PMTs



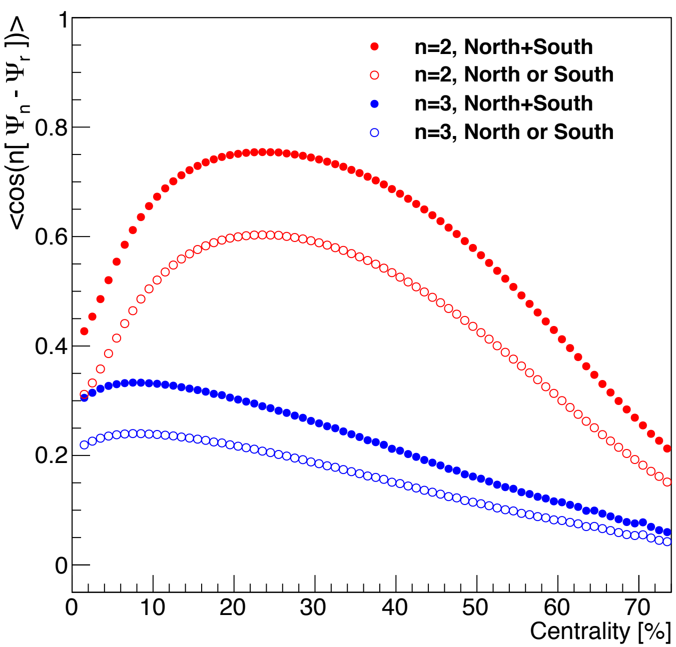
Event Plane







Resolution of Event planes



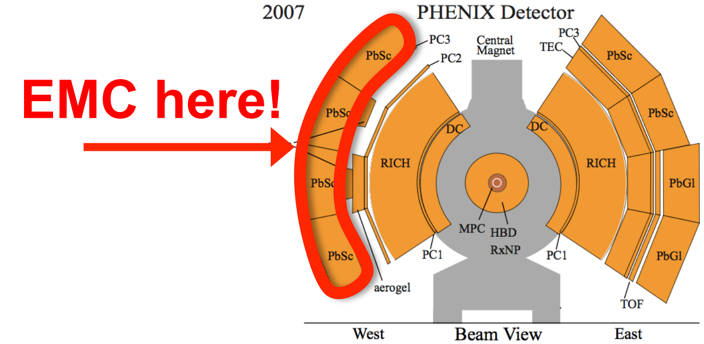
$$\Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{\Sigma w_i \cos(n\phi_i)}{\Sigma w_i \sin(n\phi_i)}\right)$$

- **Event plane was determined by Reaction Plane Detector (RXNP)**

  ✧Resolution: <cos(n(Ψ_n-Ψ_{real}))>
  n=2 : ~ 0.75
  n=3 : ~ 0.34

- **Determined by anisotropic flow itself**

Particle IDentification



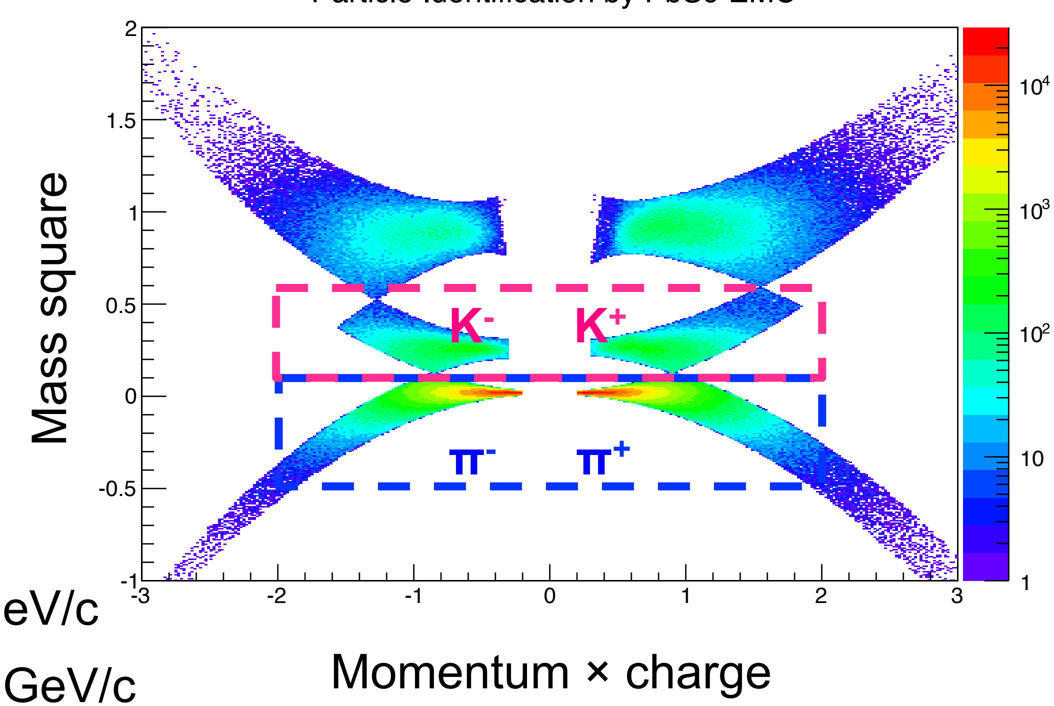
- **EMC-PbSc is used.**
  - ✧ timing resolution ~ 600 ps
- **Time-Of-Flight method**

$$m^2 = p^2 \left(\left(\frac{ct}{L} \right)^2 - 1 \right)$$

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

Particle Identification by PbSc-EMC



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.

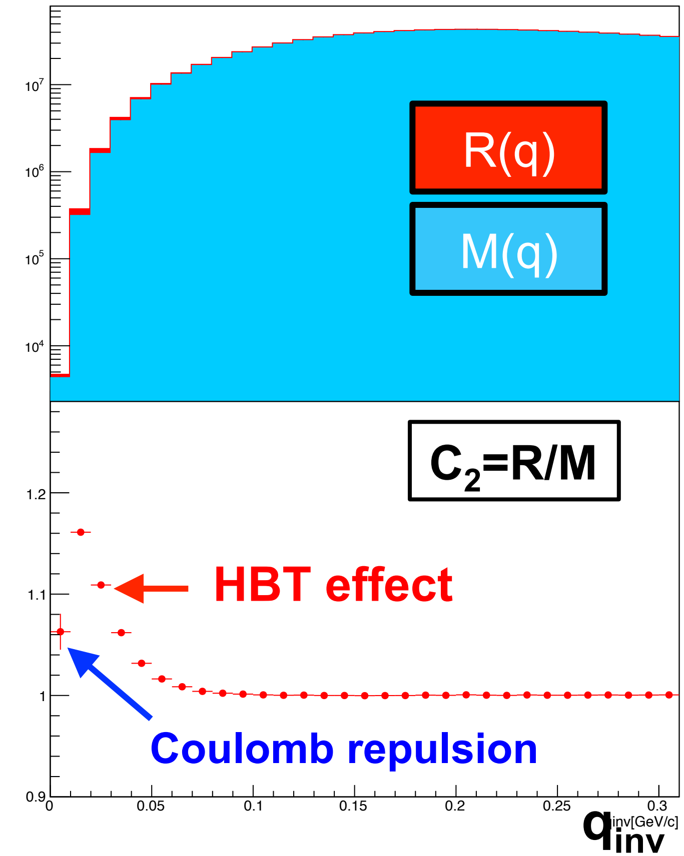
$$C_2 = \frac{R(\mathbf{q})}{M(\mathbf{q})}$$

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

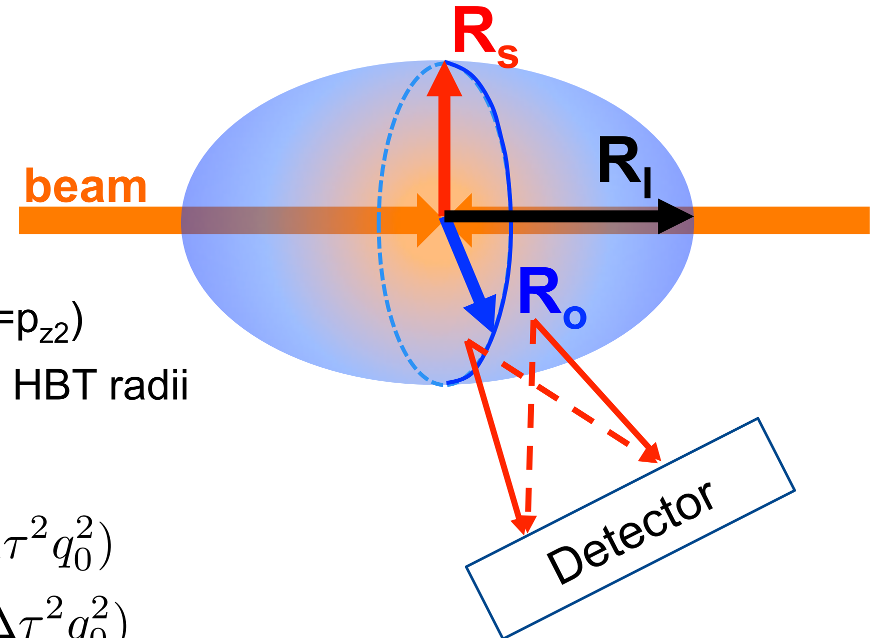
- ✧ Real pairs include HBT effects, Coulomb interaction and detector inefficient effect.

  Mixed pairs doesn't include HBT and Coulomb effects.

relative momentum dist.



3D-Analysis



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

$C_2 = 1 + \lambda G$ λ : chaoticity R_μ : HBT radii

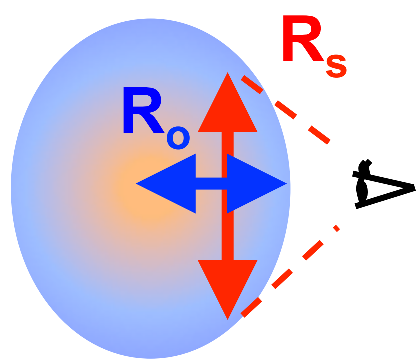
$$G = \exp(-\mathbf{R}^2\mathbf{q}^2)$$
$$= \exp(-R_x^2 q_x^2 - R_y^2 q_y^2 - R_z^2 q_z^2 - \Delta\tau^2 q_0^2)$$
$$= \exp(-R_s^2 q_s^2 - R_o^{*2} q_o^2 - R_l^2 q_l^2 - \Delta\tau^2 q_0^2)$$
$$\overset{\text{LCMS}}{\approx} \exp(-R_s^2 q_s^2 - \underbrace{(R_o^{*2} + \beta_T \Delta\tau^2)}_{=R_o^2} q_o^2 - R_l^2 q_l^2)$$

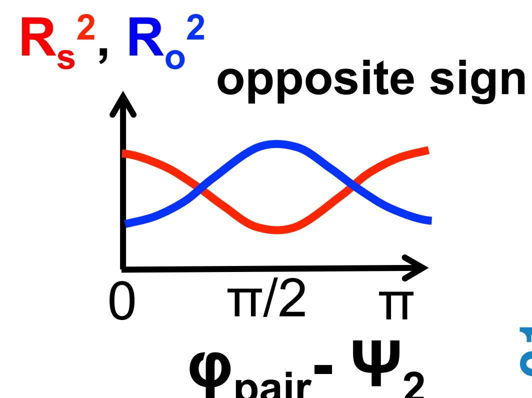
$$\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2})$$
$$\vec{q}_o \parallel \vec{k}_T, \quad \vec{q}_s \perp \vec{k}_T$$

including cross term

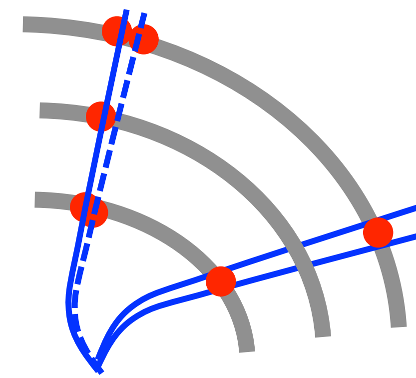
$$G = \exp(-R_s^2 q_s^2 - R_o^2 q_o^2 - R_l^2 q_l^2 - 2R_{os}^2 q_s q_o)$$

- **R_s = "width" of source**
- **R_o = "thickness" of source**





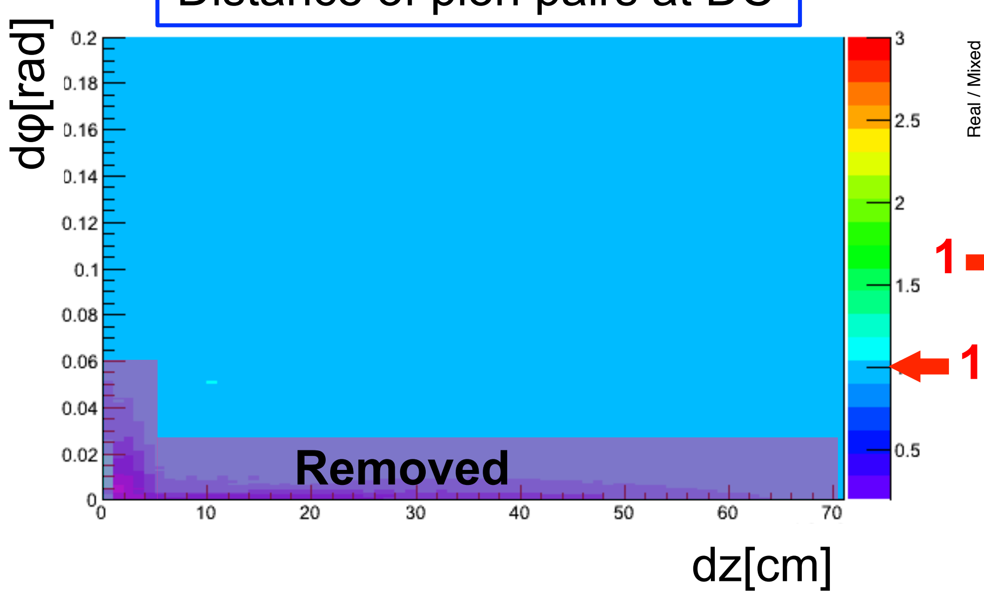
Pair Selection



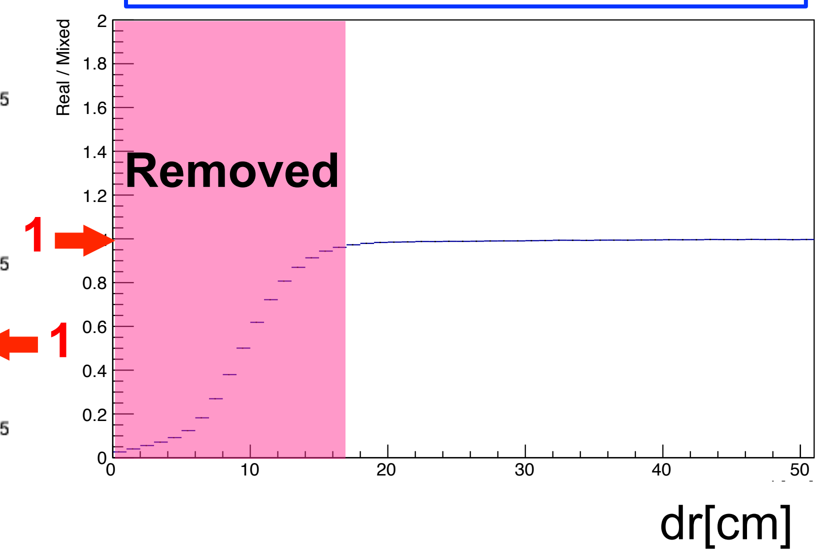
- **Ghost Tracks**
  - ✧A single particle is reconstructed as two tracks
- **Merged Tracks**
  - ✧Two particles is reconstructed as a single track

- **Real/Mixed distribution of relative hit position should be unity in case of no mis-reconstruction and ideal detector efficiency.**

Distance of pion pairs at DC



Distance of pion pairs at EMC



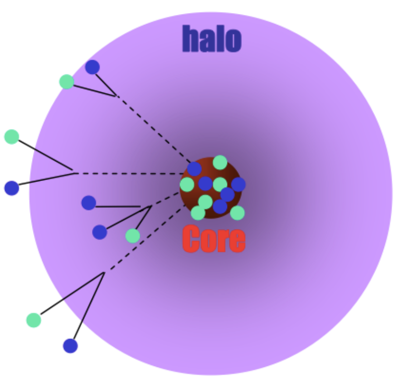
Coulomb Interaction

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

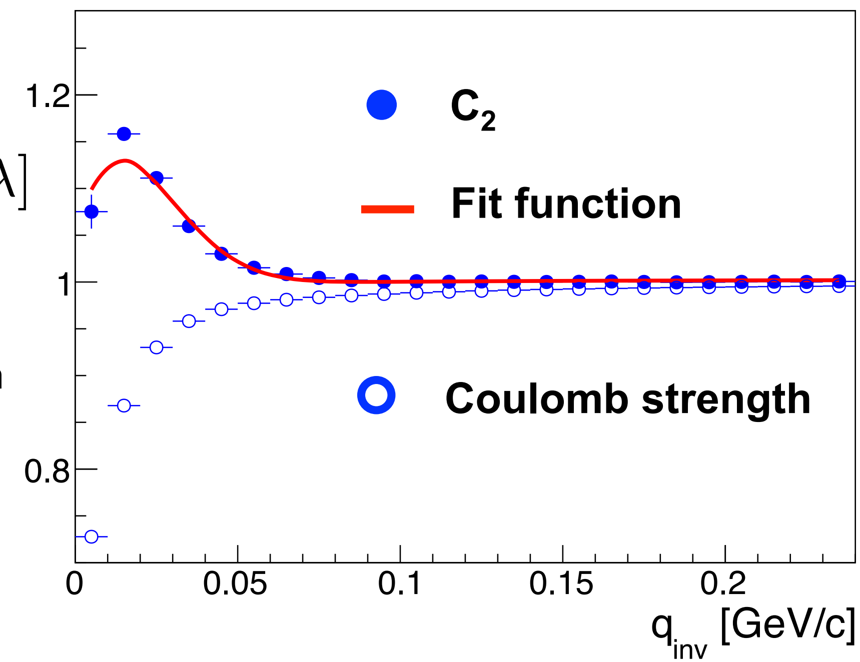
$$\left[-\frac{\hbar^2\nabla^2}{2\mu}+\frac{Z_1Z_2e^2}{r}\right]\Psi(r)=E\Psi(r) \qquad \gamma=\frac{me^2}{\hbar^2 q}Z_1Z_2$$

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

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

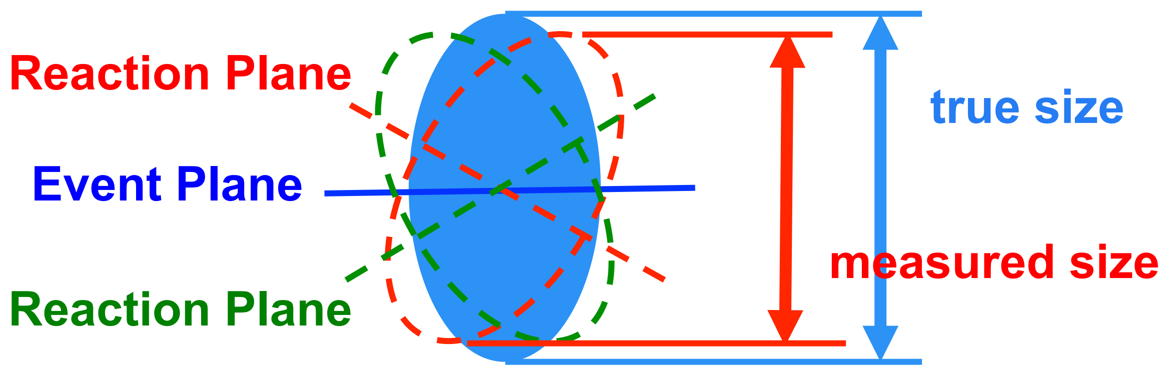


F_{coul} : Coulomb term
G : Gaussian term



Correction of Event Plane Resolution

- Smearing effect by finite resolution of the event plane

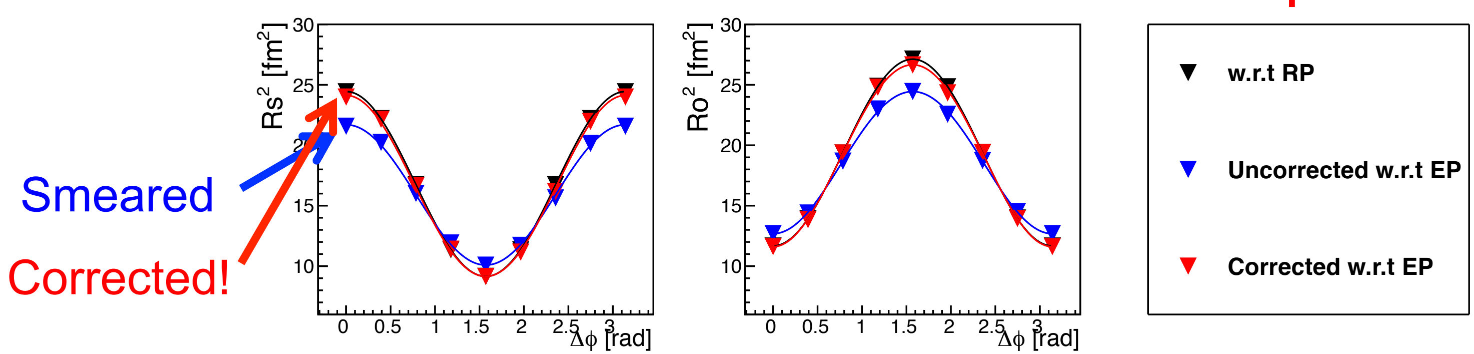


- Resolution correction
  - ✧correction for q-distribution
    PRC.66, 044903(2002)
  - ✧Check by simulation

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

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

event plane resolution



Systematic uncertainties

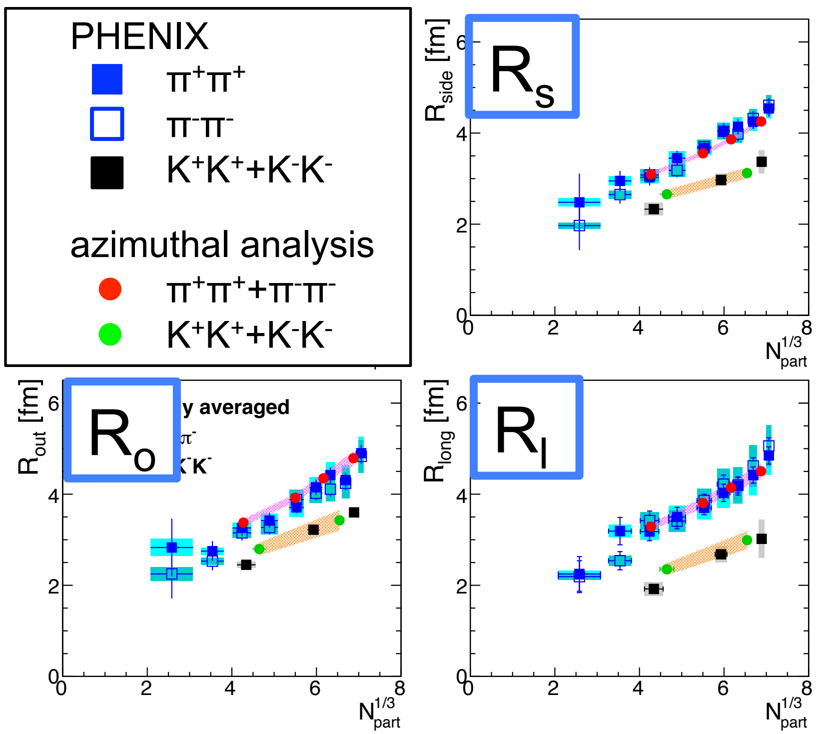
- **Track and Pair selection**
  - Track matching cut at Pad Chamber and EMCal (~5%)
  - PID cut (~2%)
  - Pair selection cut at Drift Chamber and EMCal (~6%)
- **Input source size for the Coulomb interaction (~2%)**
- **Event plane determination (~4%)**
  - Measured with north, south, and both combined RXNP

※ The values within ( ) are for R_{μ}^2 of pions

Consistency check with the previous results

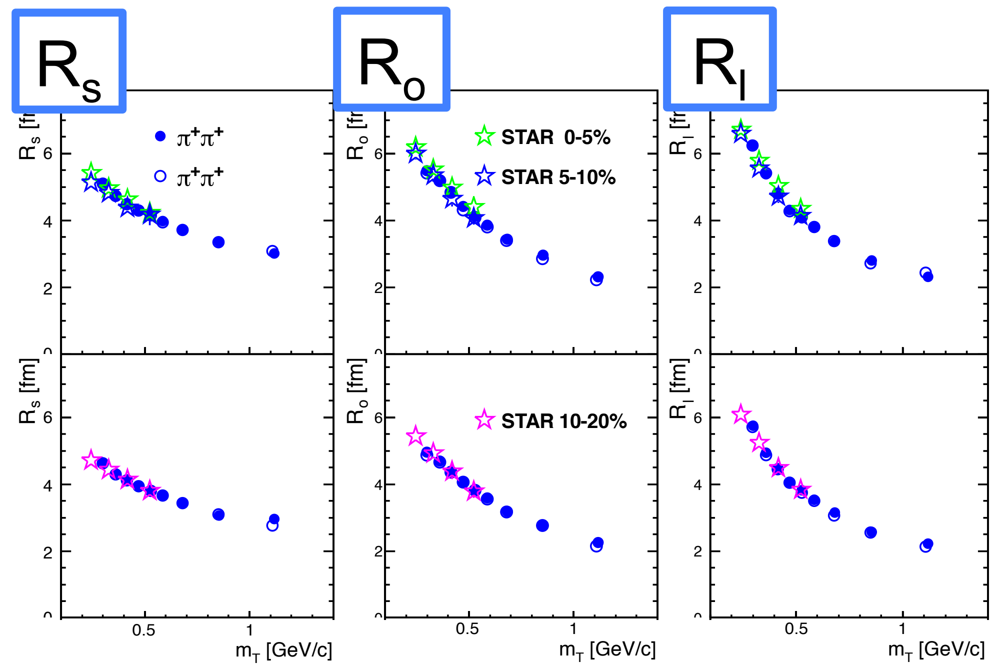
- **Extracted HBT radii are compared to the PHENIX and STAR results.**

Centrality dependence



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

k_T dependence

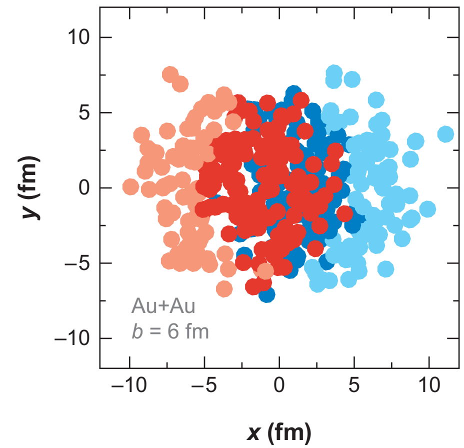


PRC71.044906 (2005)

Consistent with PHENIX and STAR results within systematic errors.

Initial spatial anisotropy

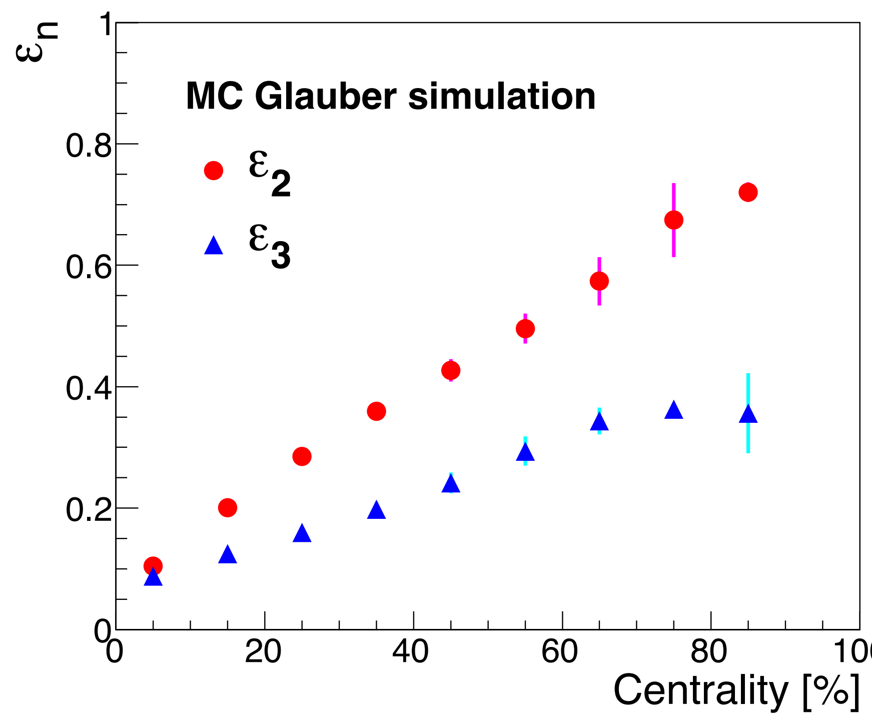
- **Estimated by Monte-Carlo Glauber simulation**
  - ✧ assuming a Woods-Saxon density
  - ✧ collision takes place if $d < \sqrt{\sigma_{nn}/\pi}$
    - ✓ d: distance between nucleons
    - ✓ σ_{nn}: total cross section



$$\varepsilon_n = \frac{\langle r^2 \cos[n(\phi - \Psi_n)]\rangle}{\langle r^2 \rangle}$$

$$\Psi_n = \frac{1}{n}\left[\tan^{-1}\left(\frac{\langle r^2 \sin(n\phi)\rangle}{\langle r^2 \cos(n\phi)\rangle}\right) + \pi\right]$$

- **Centrality dependence of initial ε_2 and ε_3 are seen.**
  - ✧ $\varepsilon_3 \sim \varepsilon_2/2$ at mid-central collision



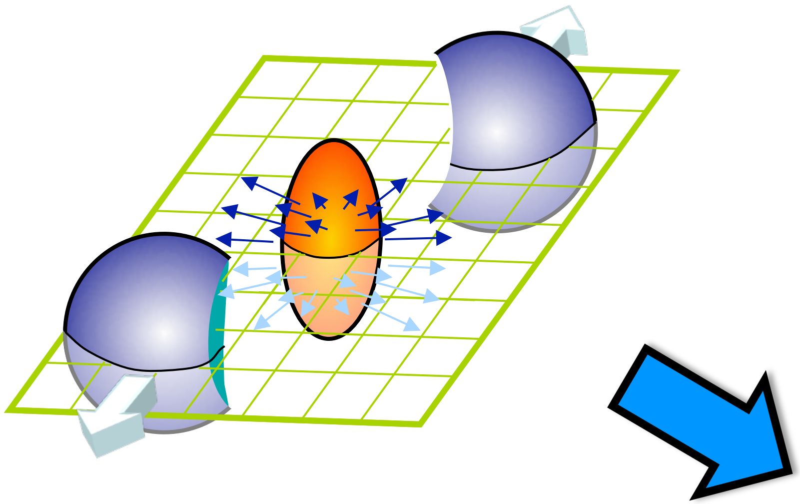
Results/ Discussion

- □ Azimuthal angle dependence w.r.t 2nd-order event plane
- □ Comparison of π/K HBT radii
- □ Blast-wave model fit

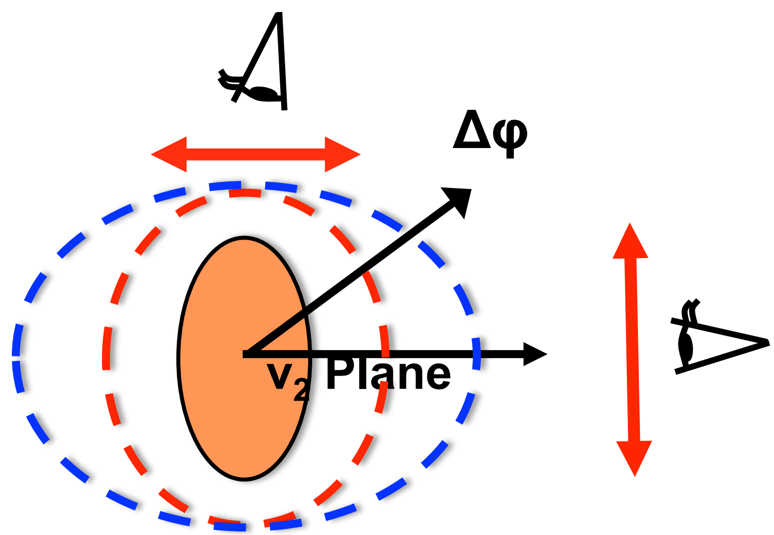
- □ Azimuthal angle dependence w.r.t 3rd-order event plane
- □ Monte-Carlo simulation

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

Initial spatial eccentricity

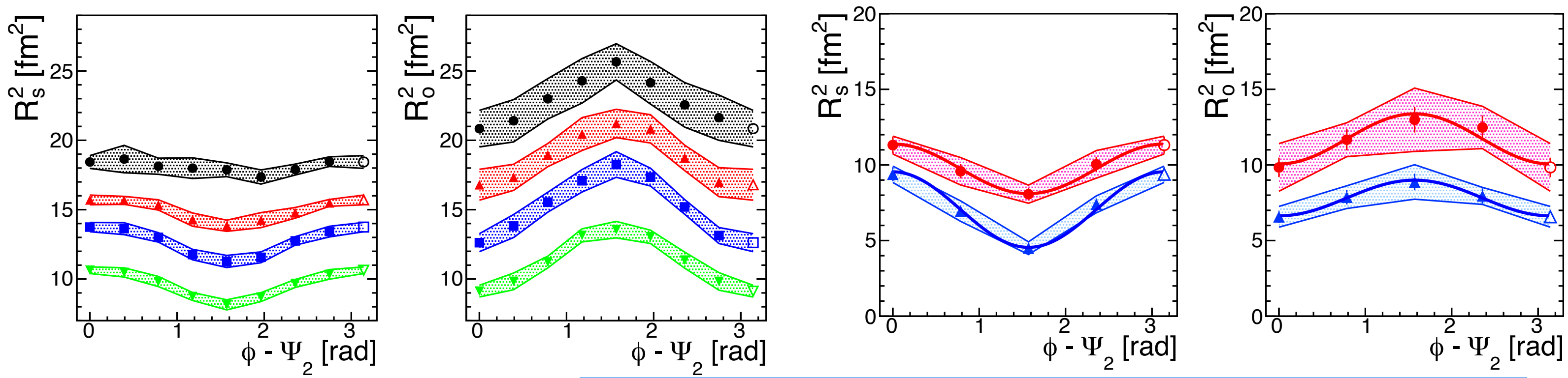


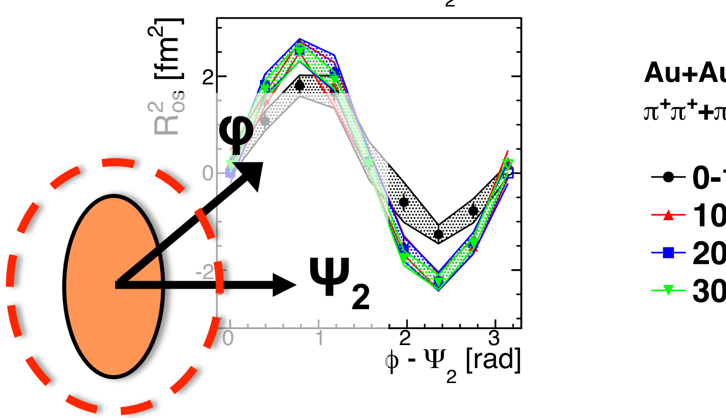
What is final eccentricity ?



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

- **Oscillations of R_s, R_o, and $R_{os.}$ are seen for π/K**
  - ✧Centrality dependence of R_s oscillation is seen.
  - ✧R_o has stronger oscillation than R_s in all centrality.





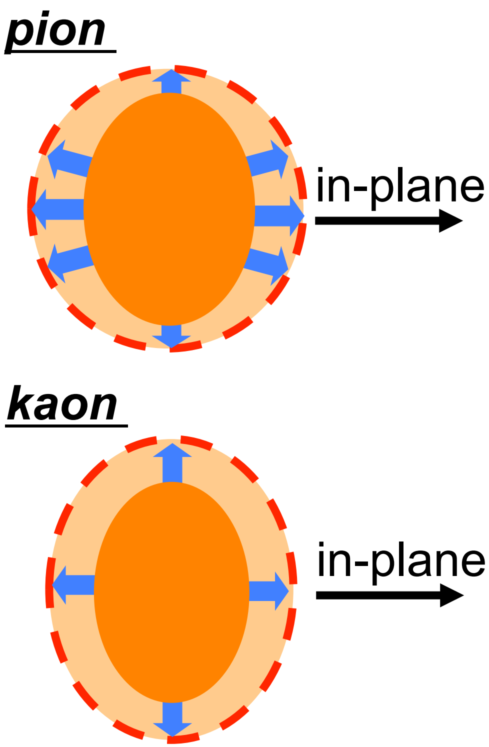
Note: R_o inherently depends on β_T & Δτ

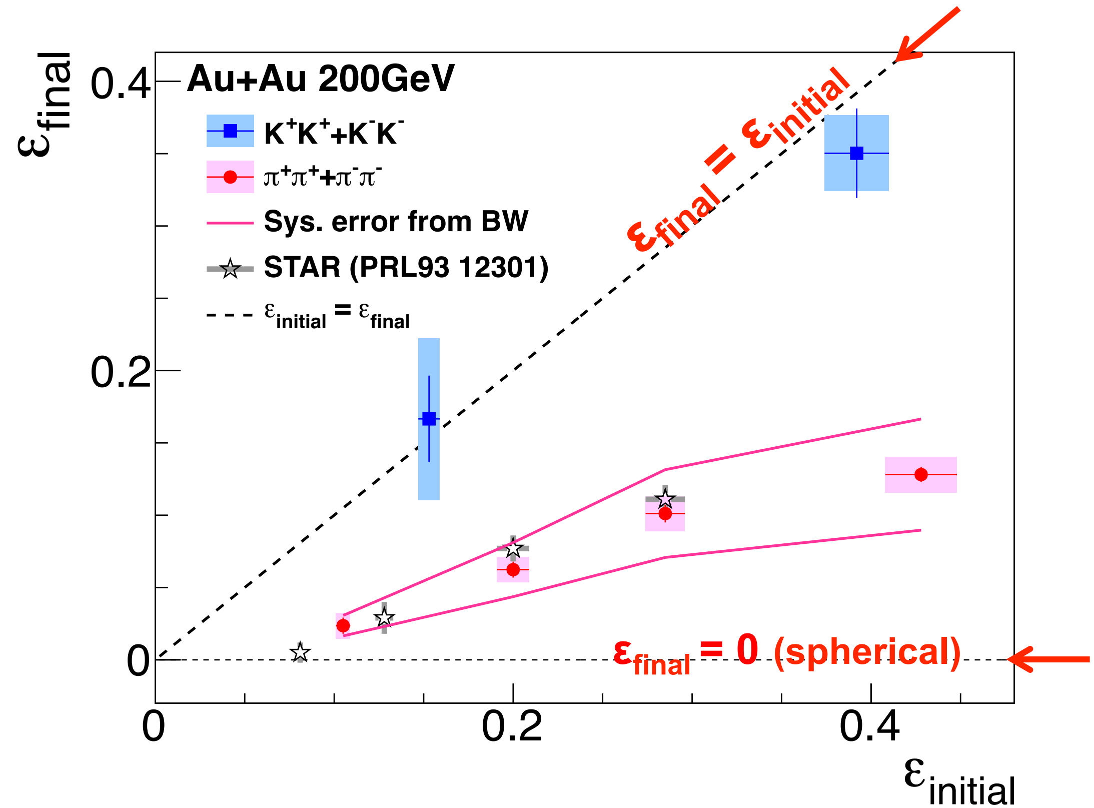
$$C_2 = 1 + \lambda \exp(-R_s^2 q_s^2 - R_o^2 q_o^2 - R_l^2 q_l^2 - 2R_{os}^2 q_o q_s)$$
$$R_o^2 = R_o^{*2} + \beta_T \Delta\tau^2$$

- □ effect of flow anisotropy?
- □ Δτ depend on azimuthal angle?
- □ difference of "width" and "thickness"?

→Study with Blast-wave model

Eccentricity at freeze-out

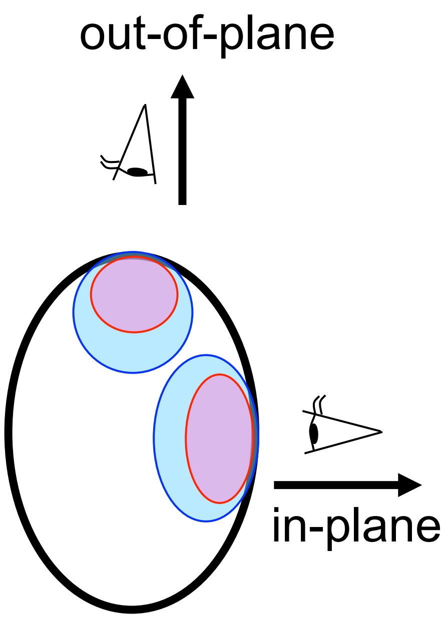


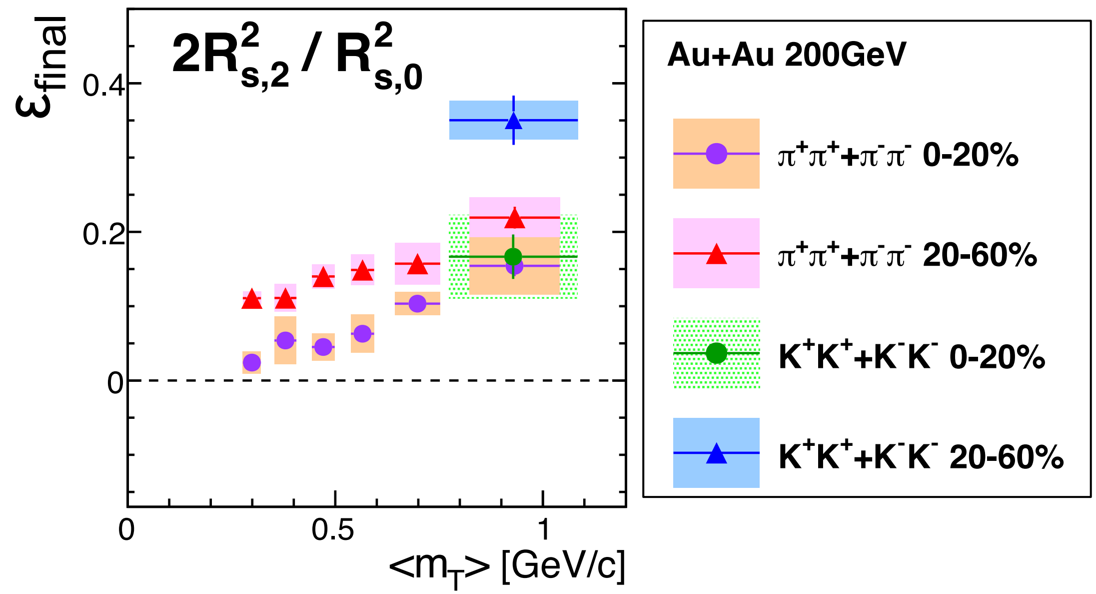


- **$\varepsilon_{final} \approx \varepsilon_{initial}/2$ for pion**
  - Consistent with STAR result.
  - This Indicates that source expands to in-plane direction, and still elliptical shape.
- **$\varepsilon_{final} \approx \varepsilon_{initial}$ for kaon**
  - Kaon may freeze-out sooner than pion due to less cross section ?
  - Is the emission region different due to the different m_T ?

m_T dependence of ε_{final}

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

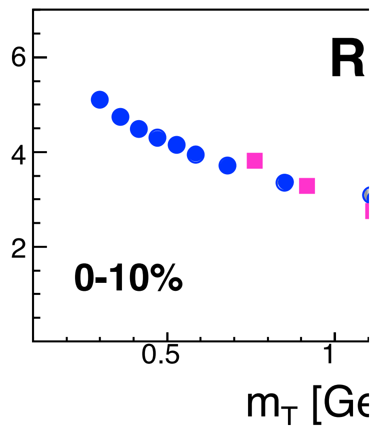


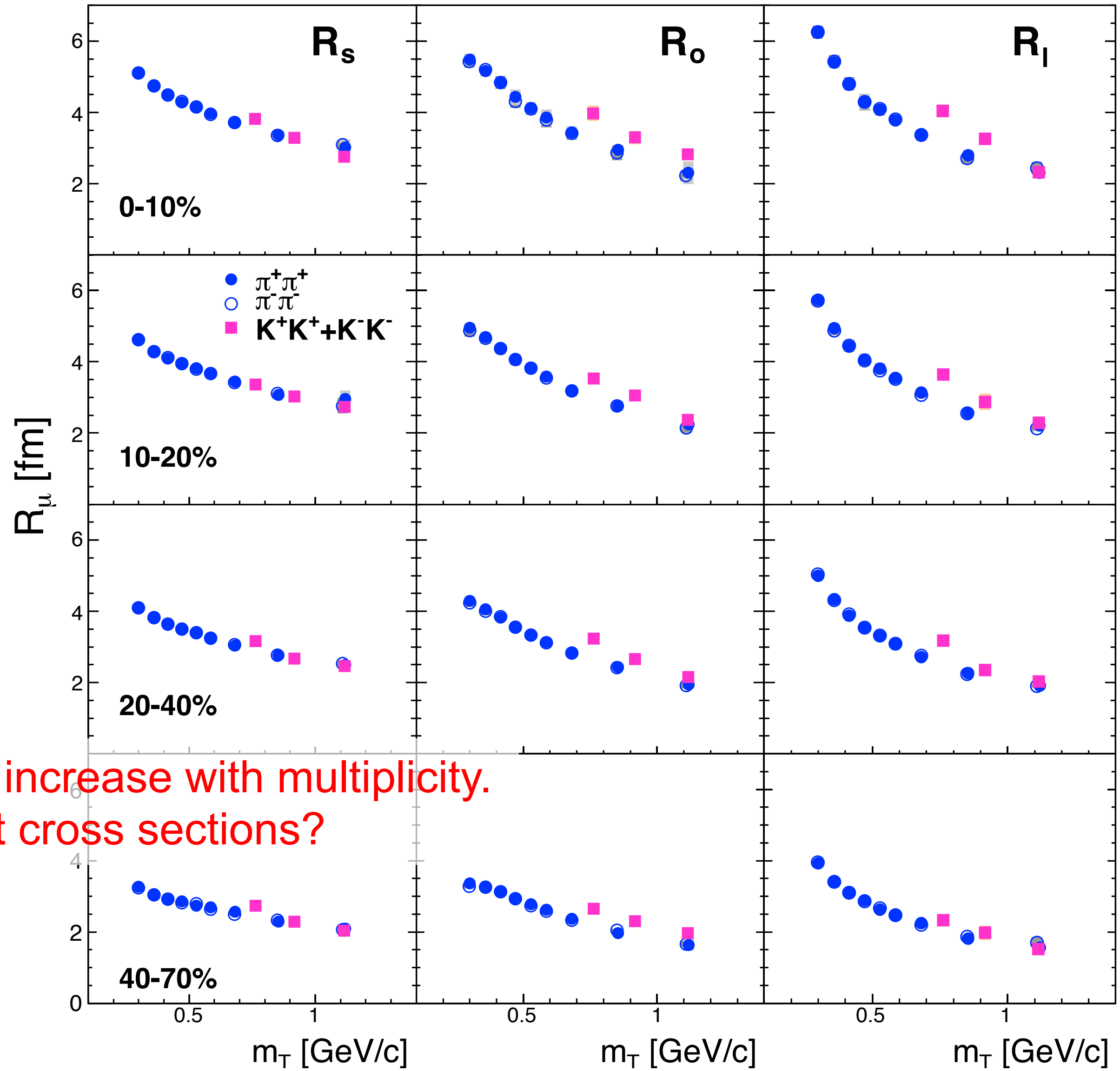


- **ε_{final} of π increases with m_T**
  - ✧It would reflect the variation of the emission region.
- **Still difference between π/K in 20-60% even at the same m_T**
  - ✧Indicates sooner freeze-out time of K than π ?
  - ✧How about the average radii ?

Comparison of π/K HBT radii (1)

- Difference can be s
- Charged kaons hav

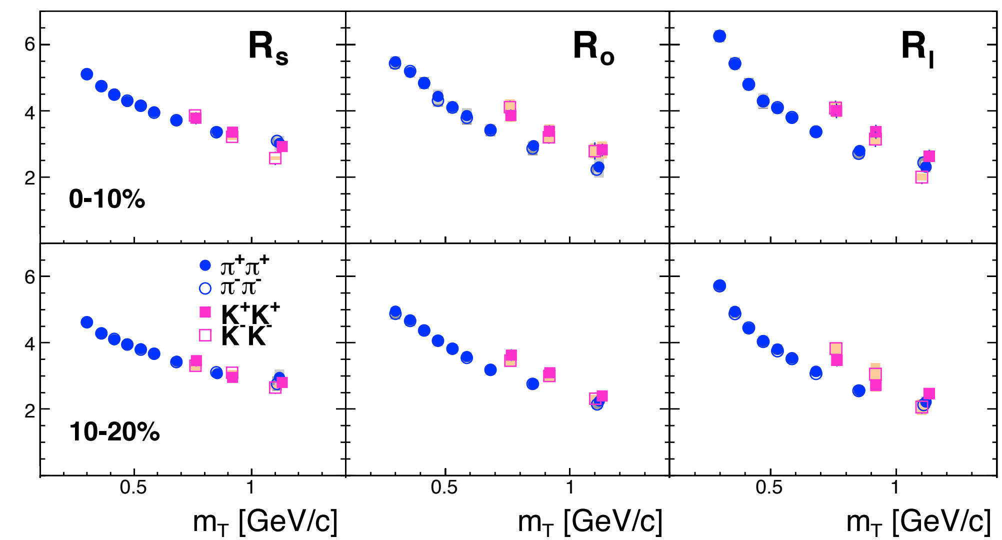




Difference seems to increase with multiplicity.
Effect of the different cross sections?

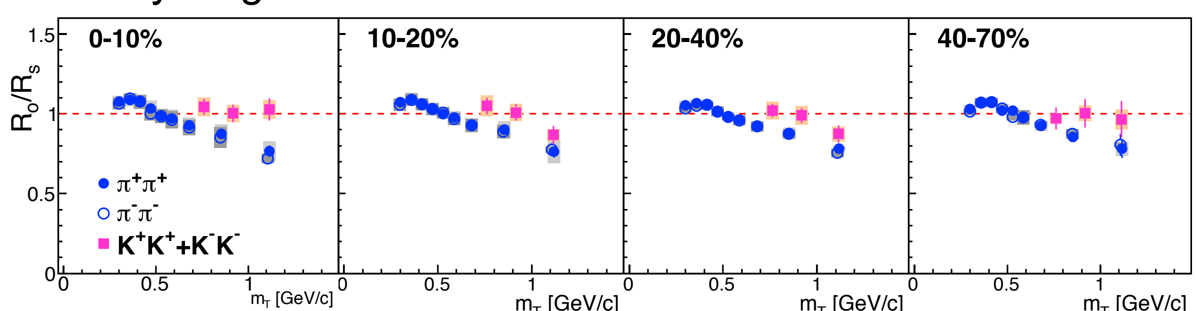
Comparison of π/K HBT radii (2)

- **Comparison of positive and negative kaons**
  - ✧K^+ have less σ_{total} on nucleons than K^-
    $\sigma(K^-)/\sigma(K^+) \approx 5$ at p≈0.3[GeV/c] ($\sigma(K^-)/\sigma(\pi^-) \approx 2$)



- **No significant difference between both kaons**
  - ✧π/K difference may not be explained by the effect of hadronic rescattering.

- **R_o/R_s for the emission duration**
  - ✧No centrality and m_T dependence
  - ✧K>π : relatively longer emission duration of K ?

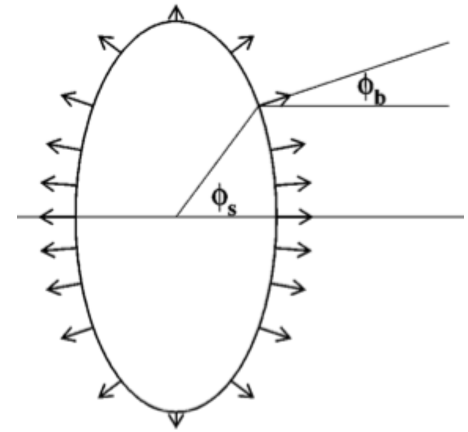


Further discussion will be done later.

Interpretation by Blast wave model

PRC 70, 044907 (2004)

- **Hydrodynamic model parameterized with freeze-out conditions**
  - ✧Thermal equilibrium + collective expansion
  - ✧Freeze-out takes place for all hadrons at the same time
  - ✧Well reproduced p_T spectra & elliptic flow at low p_T



Free parameters which chracterize freeze-out

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

* box profile is assumed as spatial density

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

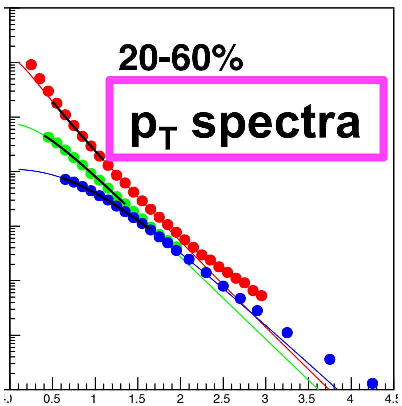
$$\rho(r,\phi) = \tilde{r}[\rho_0 + \rho_2 \cos(2\phi)]$$

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

- **Motivation of BW study**
  - ✧Are π/K HBT results reproduced by the same freeze-out parameters?
  - ✧Extract the temporal information

Fit by Blast-wave model

- **Transverse momentum distribution (p_T spectra) and elliptic flow v_2 are used to effectively reduce the BW parameters.**

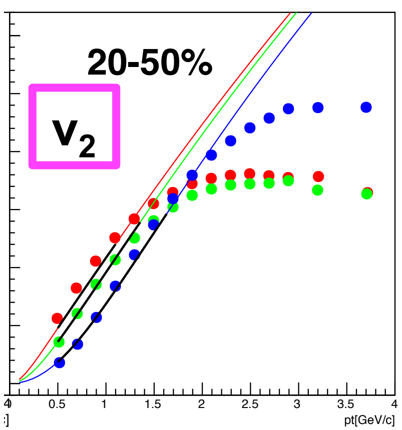


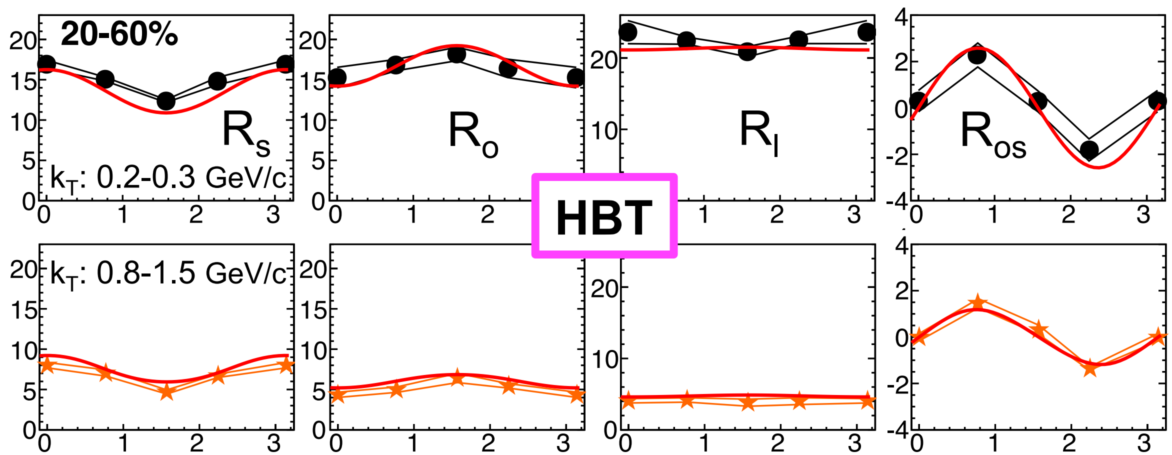
1. Fit p_T spectra to obtain T_f and ρ_0

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

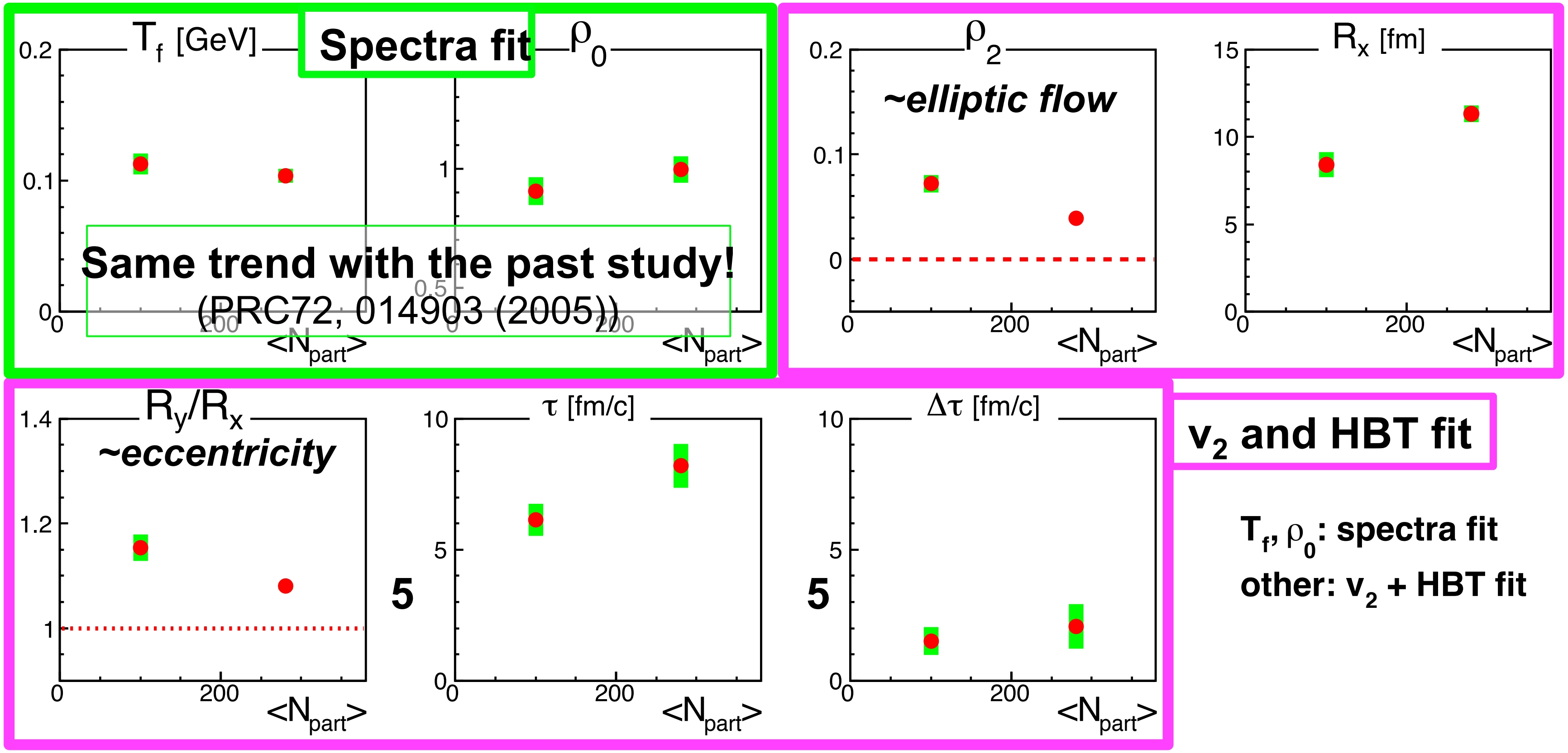
2. Fit v_2 and HBT radii for all k_T simultaneously

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





Extracted freeze-out parameters

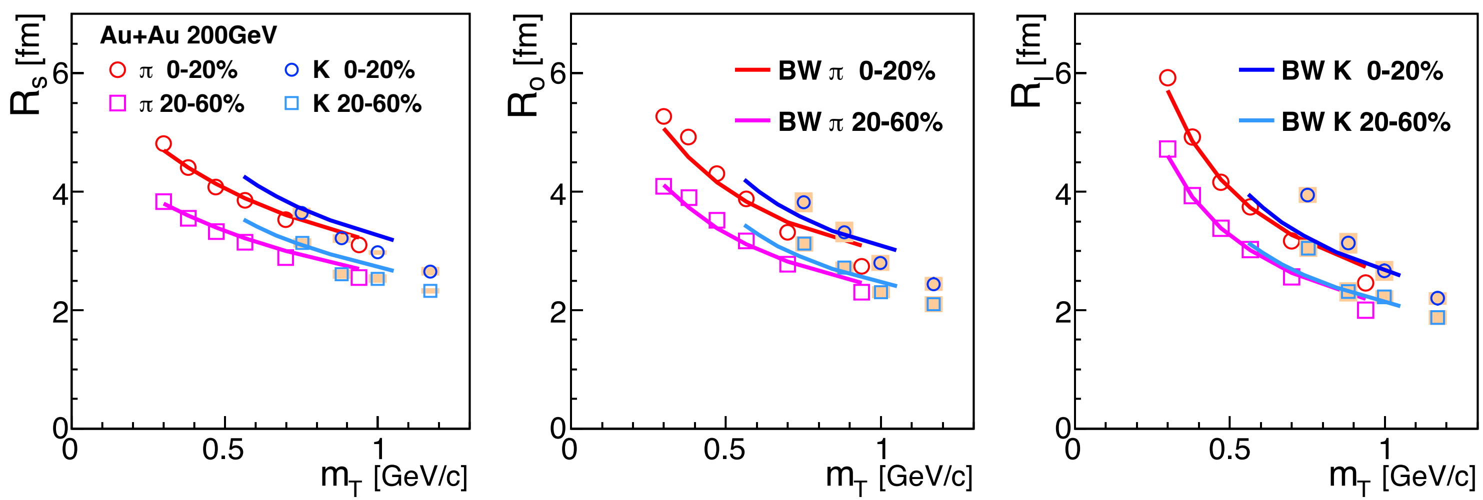


T_f, ρ_0: spectra fit
other: v_2 + HBT fit

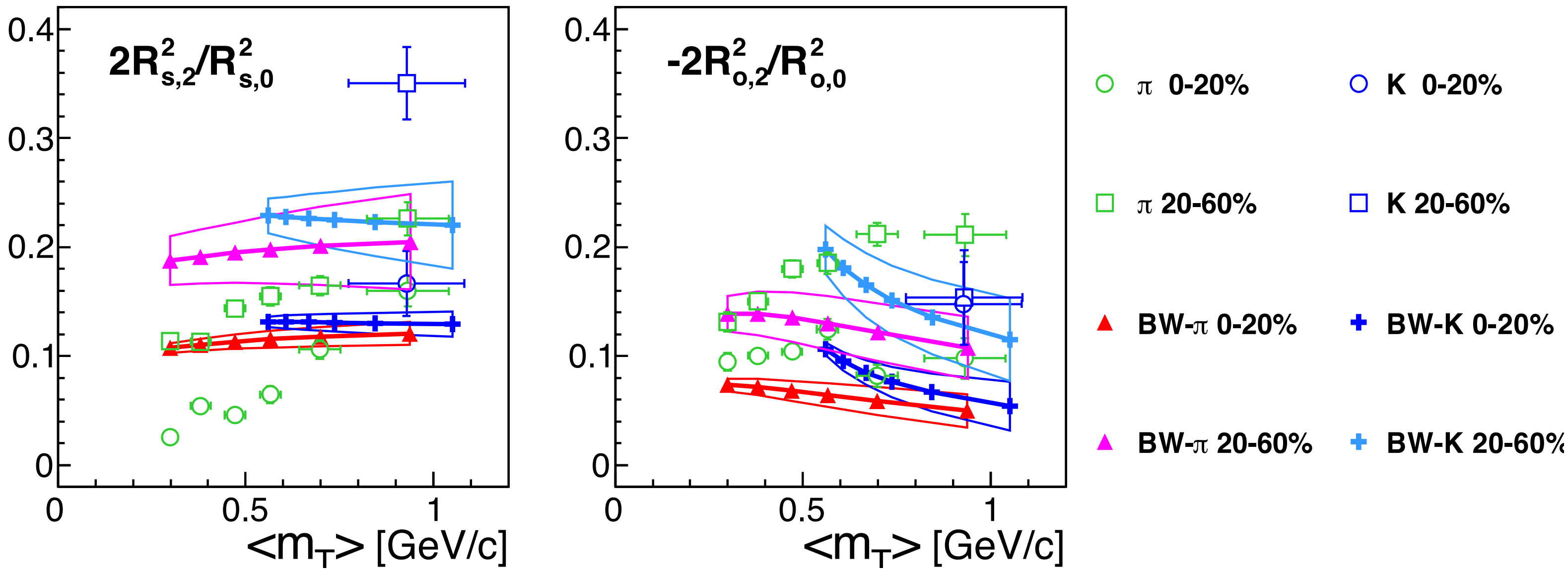
- **ρ_2 and ellipticity(R_y/R_x) increase with decreasing N_{part}**
  - ✧Reasonable in terms of v_2 and ε_f
- **τ and Δτ increases with increasing N_{part}**
  - ✧Freeze-out time: 6~8 fm/c, Emission duration: 1.5~2fm/c
    - ✓ Similar value (τ=8.6, <Δτ>=2) in Source imaging+Therminator model(PRC100.232301)

Comparison of mean radii between π/K

- **Mean HBT radii of π are reproduced well by BW, but not for K**
  - ✧Using fit parameters obtained by fitting pion HBT radii
  - ✧BW also expects larger radii of K in R_s and R_l
- **Indicate different freeze-out mechanism?**
  - ✧e.g Freeze-out time or/and emission duration are different?

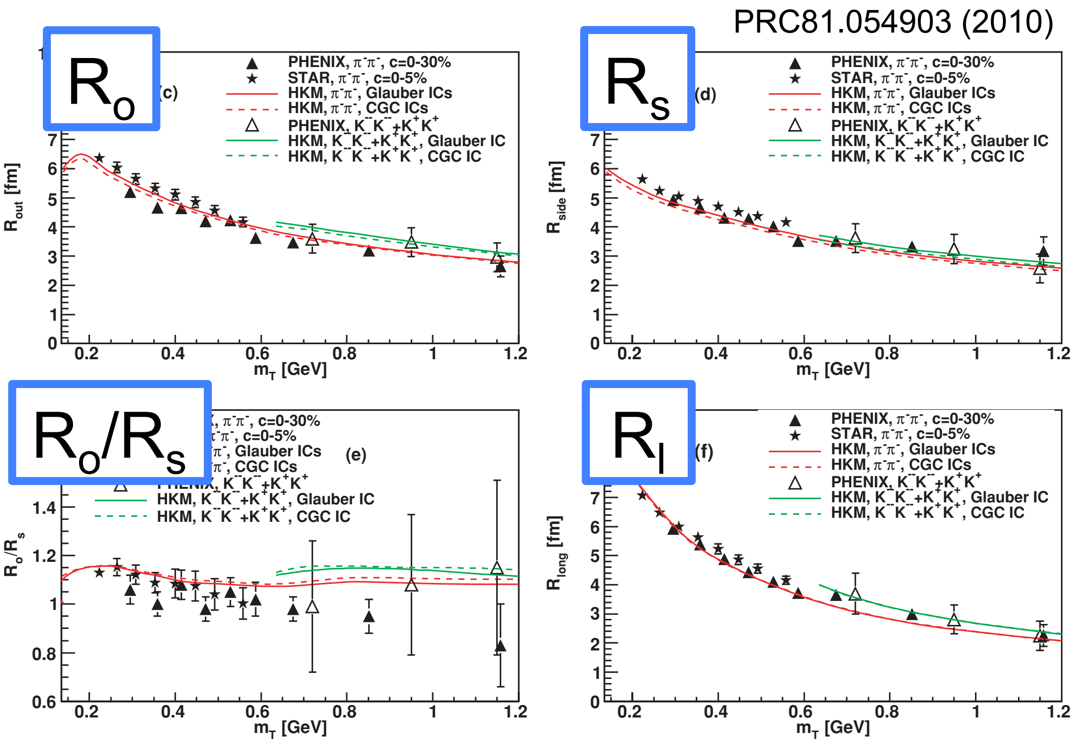


Comparison of oscillation amplitude between π/K



- BW doesn't also reproduce the oscillation amplitudes of R_s^2 quantitatively, and R_o^2 qualitatively.
- Underestimate of R_o oscillation in BW.
  - ✧ϕ-dependent Δτ?
  - ✧Spatial density/flow profile is not appropriate?
- π/K difference in the oscillation cannot be explained by BW.

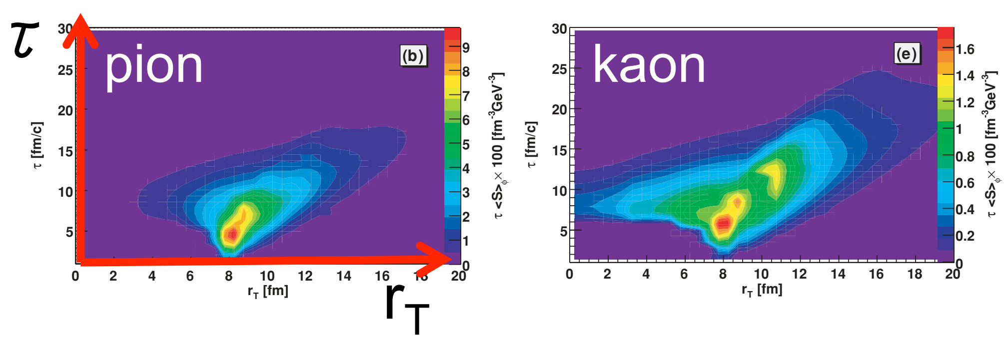
Recent theoretical result



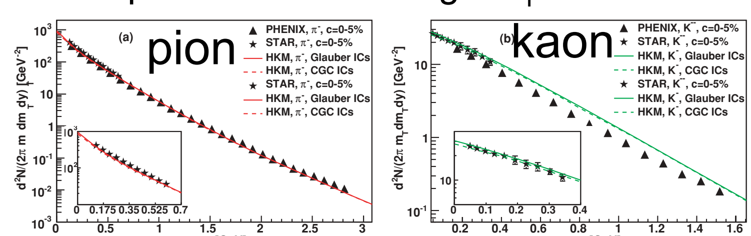
- **HydroKinetic Model**
  - Glauber or CGC
  - crossover transition
  - microscopic transport
  - pre-thermal flow
  - implicitly viscosity

- **Larger R_o and R_l of kaon**
  - ✧Similar trend to the measured ones
  - ✧Majority of kaons leave system later than pions at the same m_T
  - →Longer emission duration ?

Emission function at m_T=0.86GeV/c



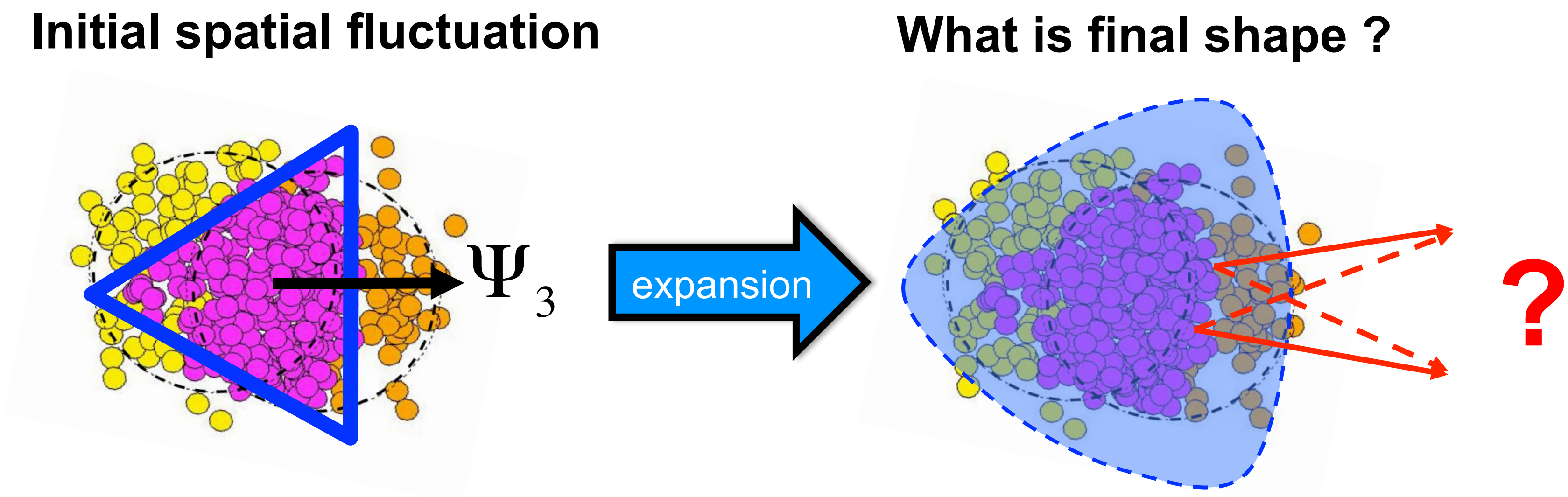
※Note that kaon spectra is not reproduced well at high m_T



Summary-1

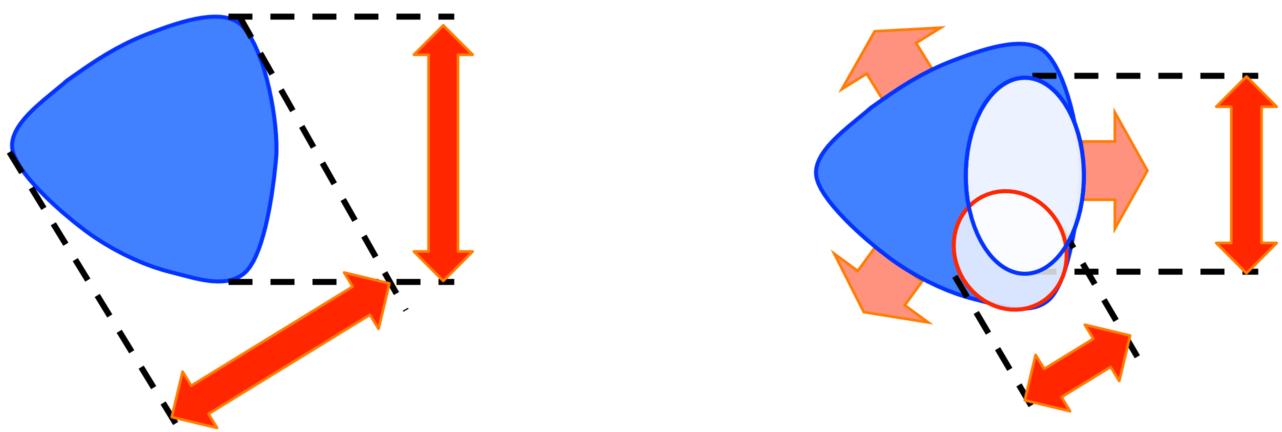
- **Azimuthal HBT radii w.r.t 2^{nd}-order event plane**
  - ✧pion ε_{final} is $\sim\varepsilon_{initial}/2$
    - ✓ Strong expansion to in-plane direction and still elliptical shape.
  - ✧kaon ε_{final} > pion ε_{final} even at the same m_T
  - ✧Stronger oscillation of R_o
- **Comparison of π/K HBT radii**
  - ✧Difference of R_o and R_l in most central collisions
  - ✧No significant difference between K^+K^+ and K^-K^-
- **Study with Blast-wave model**
  - ✧Freeze-out time ~8 fm/c, Δτ ~2fm/c
    - ✓ Consistent with source imaging analysis
  - ✧π/K difference of mean radii is not explained well
  - ✧Oscillation amplitudes is not reproduced well
    - ✓ Stronger R_o oscillation is not explained only by flow anisortopy within BW
- **Comparison with HKM model**
  - ✧Qualitatively consistent with larger R_o&R_l of K
  - ✧Supporting longer emission duration of K from R_o/R_s

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

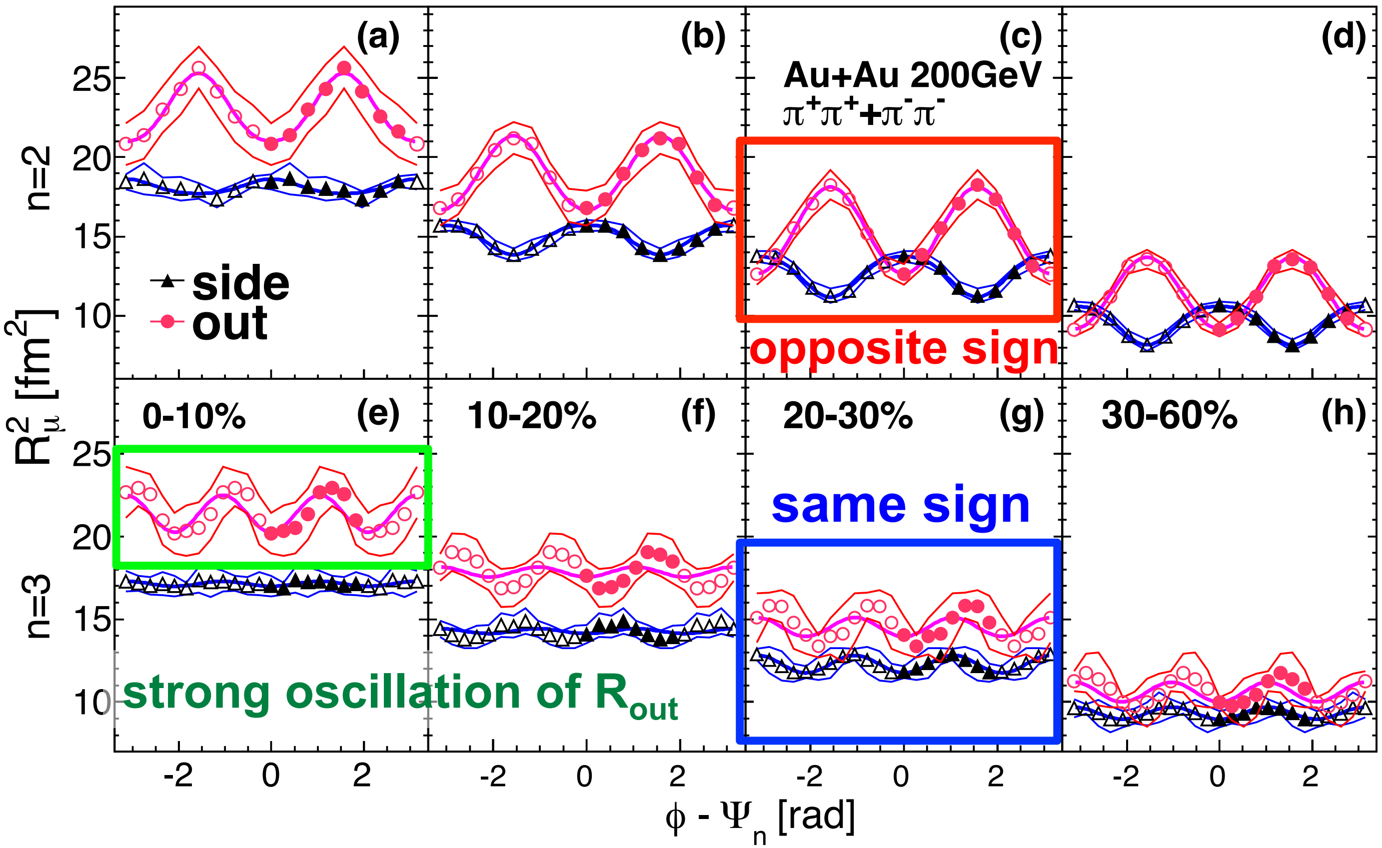


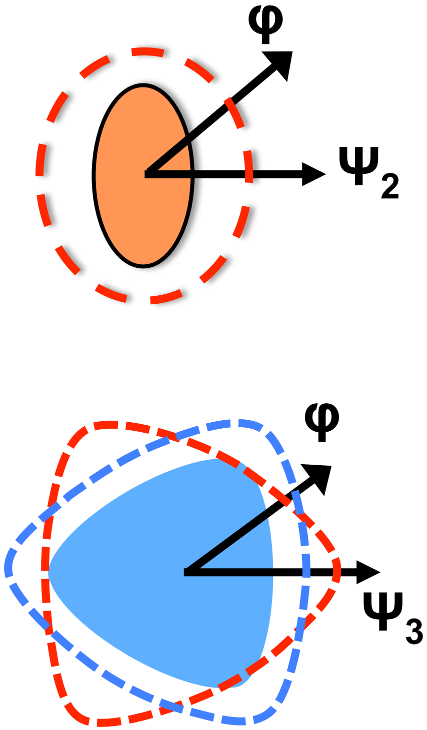
- **Note that anisotropy is not observed in a static source.**

measured size ≈ extent of base of triangle



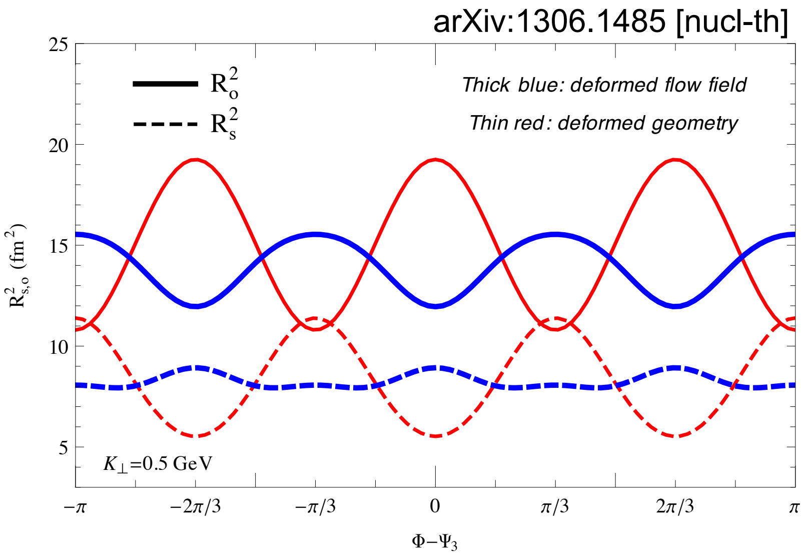
Pion HBT radii w.r.t Ψ_3





- In 0-10%, strong oscillation of R_o is seen as well as 2nd-order
- R_s slightly shows the same sign as R_o in 20-30% unlike 2nd-order

Possible explanation



- **Qualitatively agreement with R_o oscillation and R_s flatness**
- **Comparison of m_T dependence**

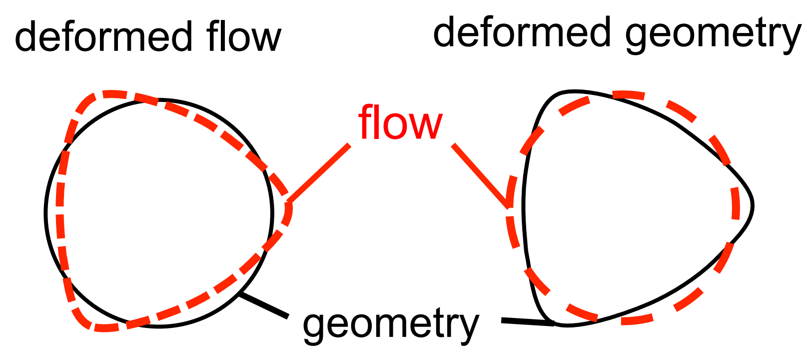
(Model calculations are scaled by 0.3)

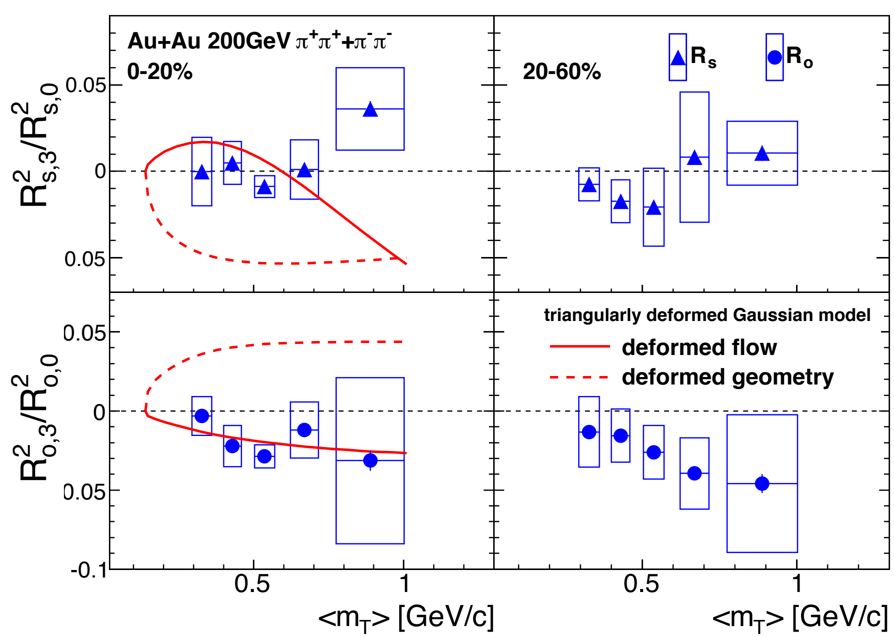
✧Similar trend of m_T dependence of $R_{o,3}{}^2$

✧$R_{s,3}{}^2$ seems to be opposite trend.

✓ negative value at low m_T, and goes up to positive value at higher m_T

- **Gaussian model w/ and w/o deformed flow/geometry**





Interpretation by Monte-Carlo simulation

What does the negative sign of R_s (and the same sign as R_o) mean?
Need to disentangle both effects of the 3rd-order spatial and flow anisotropy!

Setup of simulation

- ✧Similar to BW: thermal motion + transverse boost
- ✧Spatial distribution
  - ✓ Assuming Woods-Saxon distribution
  - ✓ Spatial shape controlled by **"e_3"**

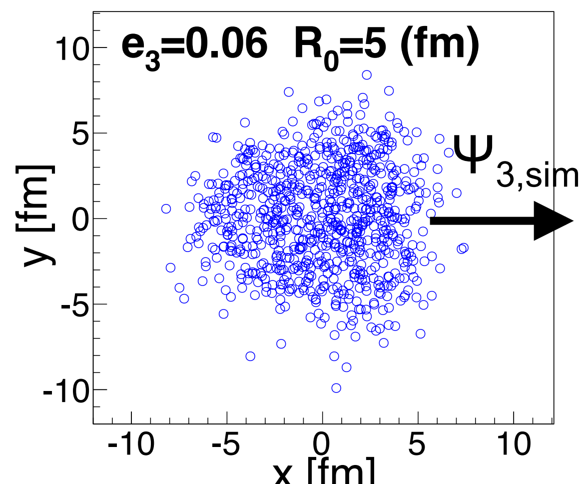
$$R = R_0(1 - e_3 \cos(3\Delta\phi))$$

- ✧Transverse flow
  - ✓ Radial flow with velocity β_0
  - ✓ Flow anisotropy controlled by **"β_3"**
  - ✓ Boost to radial direction

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

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

- ✧ HBT correlation: 1+cos(**Δr • Δp**)
- ✧ No Coulomb interaction, no opacity



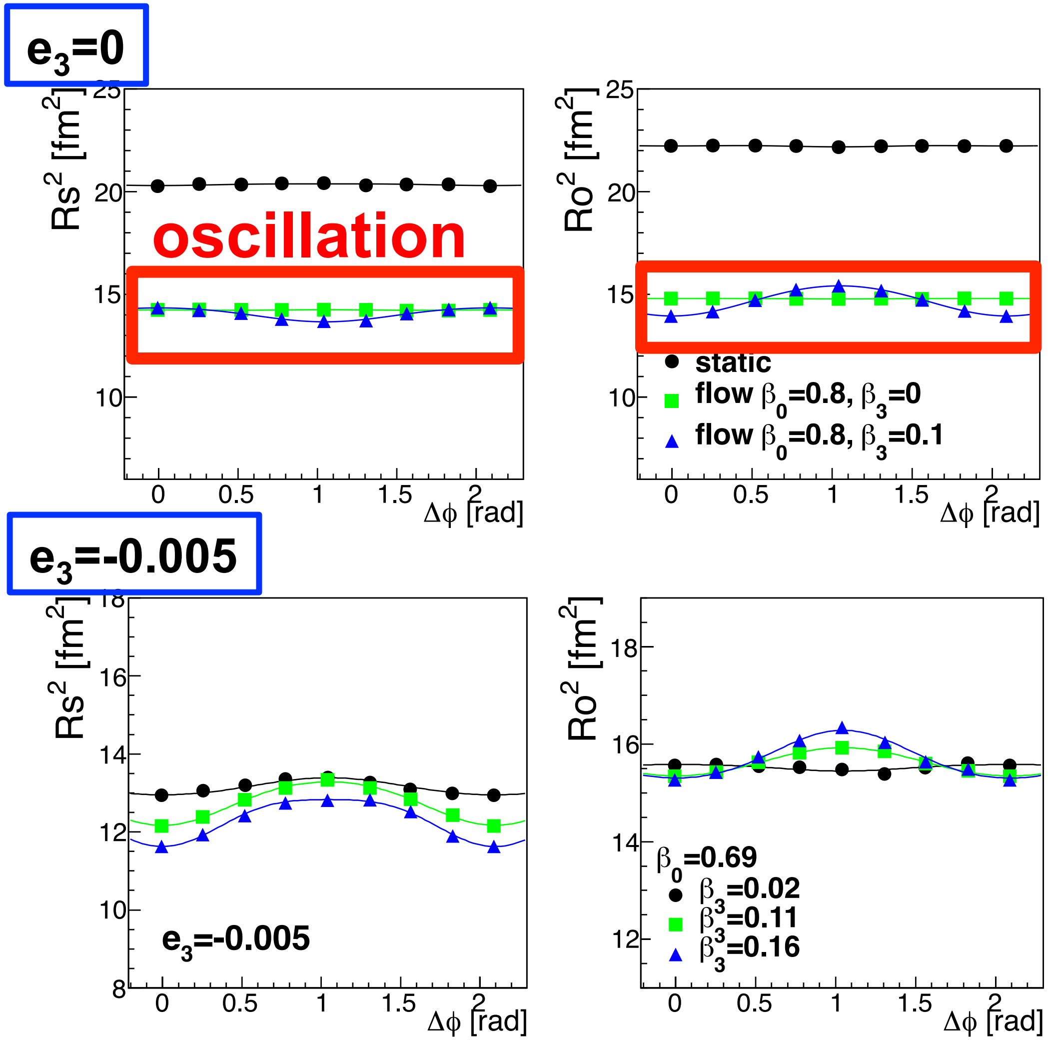
Other parameters

- ✧thermal temperature Tf
- ✧source size R_0
- ✧strength of radial flow β_0
- ✧emission duration Δτ

→ Tuned by pT spectra, average HBT radii

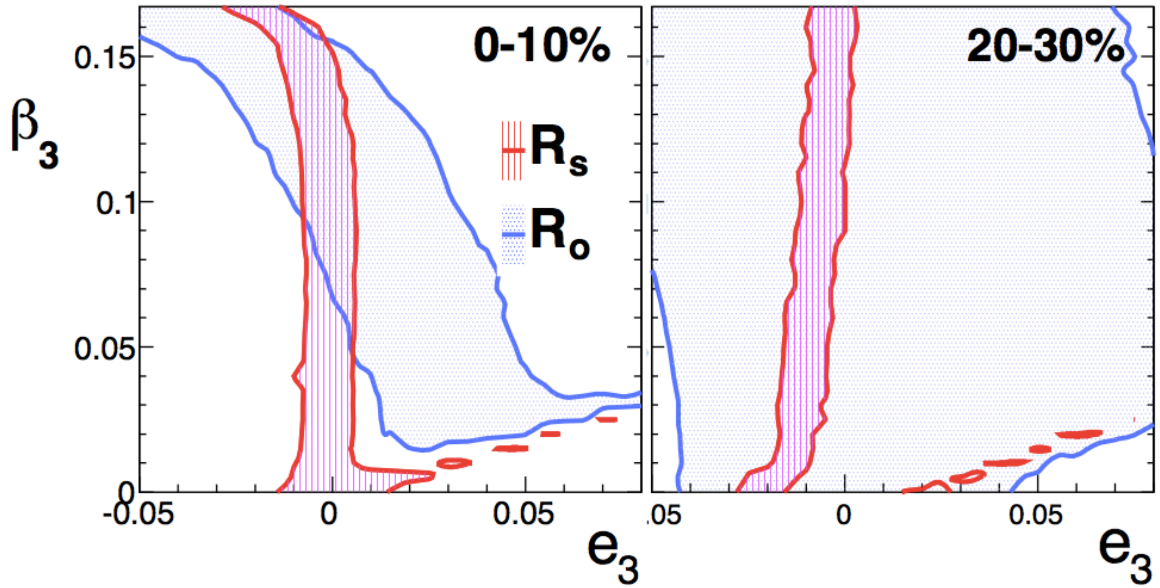
Oscillation of HBT radii in simulation

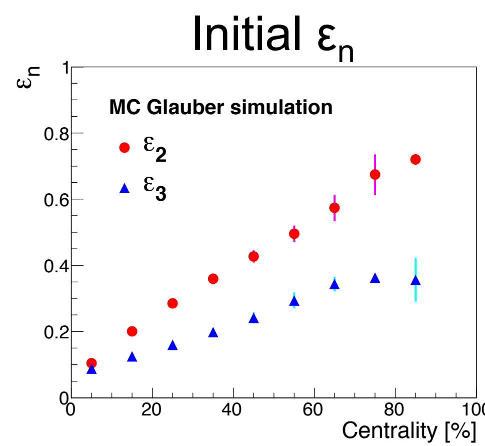
- **Triangular flow makes oscillation even for spherical source.**
- **Amplitude and sign of the oscillation will be determined by the balance of the spatial and flow anisotropy.**



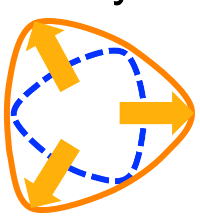
χ^2 minimization for e_3 and β_3

- χ^2 is calculated by difference of relative amplitudes of R_s^2 and R_o^2
  - ✧1σ-contour lines are shown



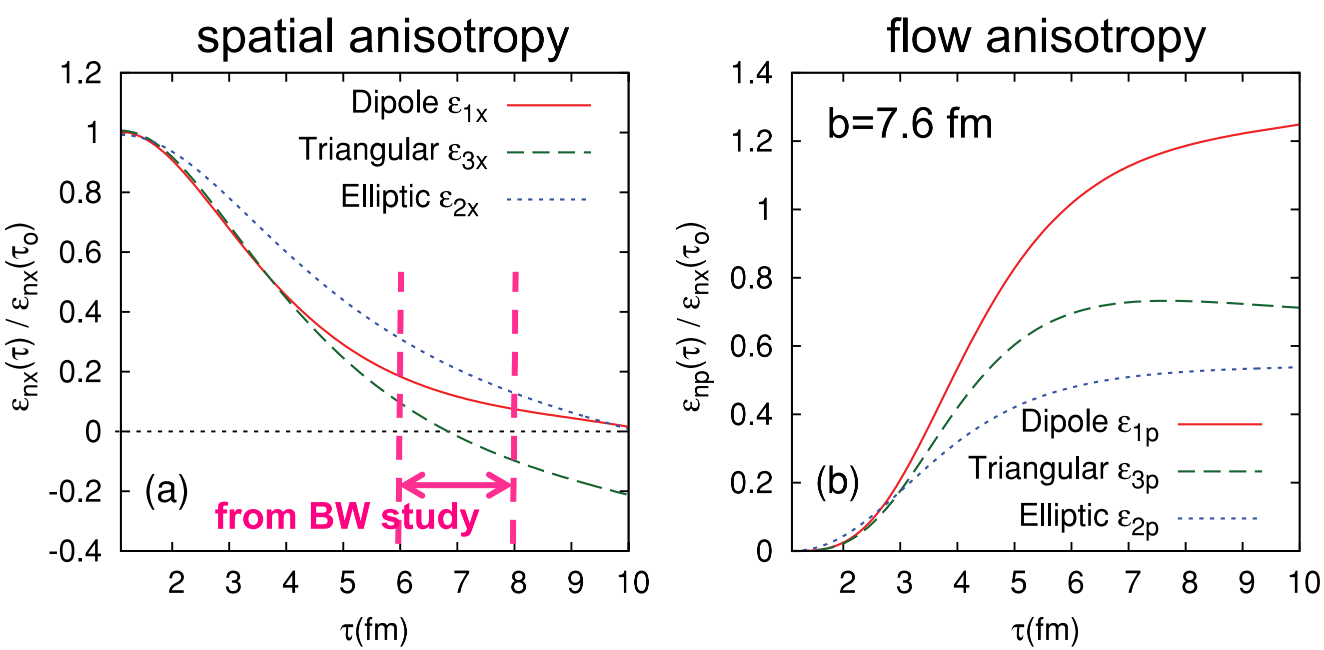


- e_3 is well constrained by R_s, (R_s is less affected by β_3)
  - ✧e_3 is close to zero in 0-10%, and slightly negative in 20-30%
  - ✧That indicates that initial ε_3 is much reduced, and potentially reversed by triangular flow under this simulation



Theoretical expectation for final triangularity

- **Initial Glauber for event-by-event cumulants + ideal hydrodynamics (PRC83.064904 (2011))**
  - ✧For τ >7at fm/c, only ε_3 shows negative value.
  - ✧This model also indicate the possibility of reversed triangularity at freeze-out



Summary-2

- **3^{rd}-order oscillations of HBT radii were observed.**
  - ✧First measurement!
  - ✧Finite R_o oscillation in all centralities
  - ✧Very small R_s oscillation in mid central
- **Comparison with Gaussian model with deformed flow/geometry**
  - ✧m_T dependence of R_o oscillation can be qualitatively explained.
  - ✧R_o oscillation will be mainly driven by triangular flow.
- **Monte-Carlo simulation**
  - ✧R_s oscillation is affected by geometry, not so much by flow.
  - ✧χ^2 minimization was perfomed
    - ✓ geometrical anisotropy e_3 shows zero ~ slightly negative

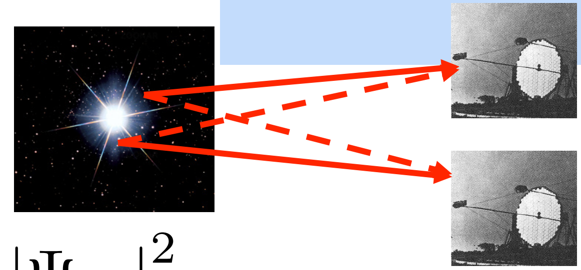
Conclusions

Azimuthal angle dependence of HBT radii was measured w.r.t 2^{nd} and 3^{rd}-order event plane in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

- **Final spatial distribution**
  - ✧Initial eccentricity is diluted, but still out-of-plane extended shape.
  - ✧Initial triangularity is significantly diluted, and potentially reversed.
- **Particle species**
  - ✧Freeze-out mechanism may be different between pions and kaons.
  - ✧Result indicates longer emission duration of kaons, which is opposite to an intuitive expectation in terms of the cross section.

Back up

Correlation function C_2 is defined as:



$$C_2 = \frac{P_{12}}{P_1 P_2} = \frac{\int dx_1 dx_2 \rho(x_1)\rho(x_2) \left|\Psi_{12}\right|^2}{\int dx_1 \rho(x_1) \left|\Psi_1\right|^2 \int dx_2 \rho(x_2) \left|\Psi_2\right|^2}$$

where P_{12} is a possibility to measure two particles, and $P_1(P_2)$ is a possibility to measure one particle. ρ(r) is the spatial distribution of particle emitting source. Assuming the plane wave for the wave function, C_2 is rewritten as:

$$\begin{aligned} P_{12} &\propto [e^{-ip_1\cdot(x_A-x_1)} e^{-ip_2\cdot(x_B-x_2)} + e^{-ip_2\cdot(x_A-x_2)} e^{-ip_1\cdot(x_B-x_1)}]^2 \\ &= [2 \pm e^{-ix_1(p_2-p_1)} e^{ix_2(p_2-p_1)} \pm e^{ix_1(p_2-p_1)} e^{-ix_2(p_2-p_1)}] \\ &\propto 1 \pm \cos[(x_2 - x_1)\cdot(p_2 - p_1)] \end{aligned}$$

→ **correlation term**

$$\begin{aligned} C_2 &= 1 \pm \left| \int dx \rho(x) e^{ix(p_2-p_1)} \right|^2 \\ &= 1 \pm \left|\tilde{\rho}(q)\right|^2 \end{aligned}$$

$\tilde{\rho}(q)$: Fourier transform of ρ(r)
$q = p_2 - p_1$

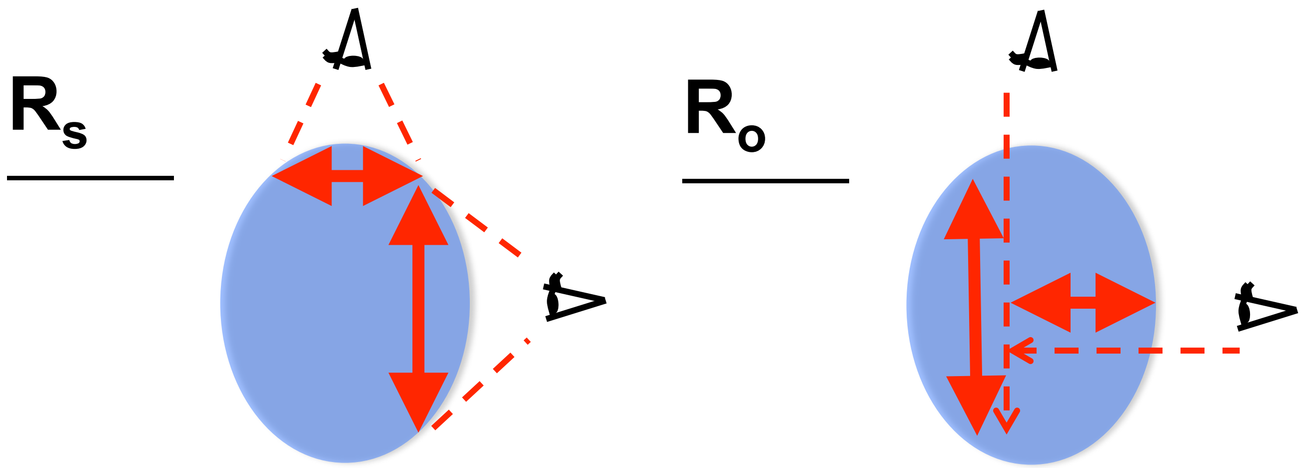
C_2 can be expressed as a function of relative momentum!

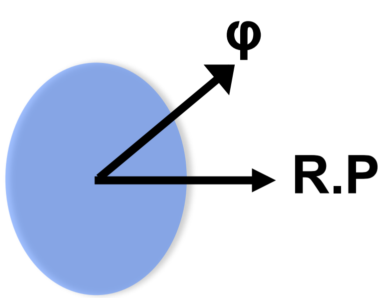
What do R_s and R_o represent ?

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

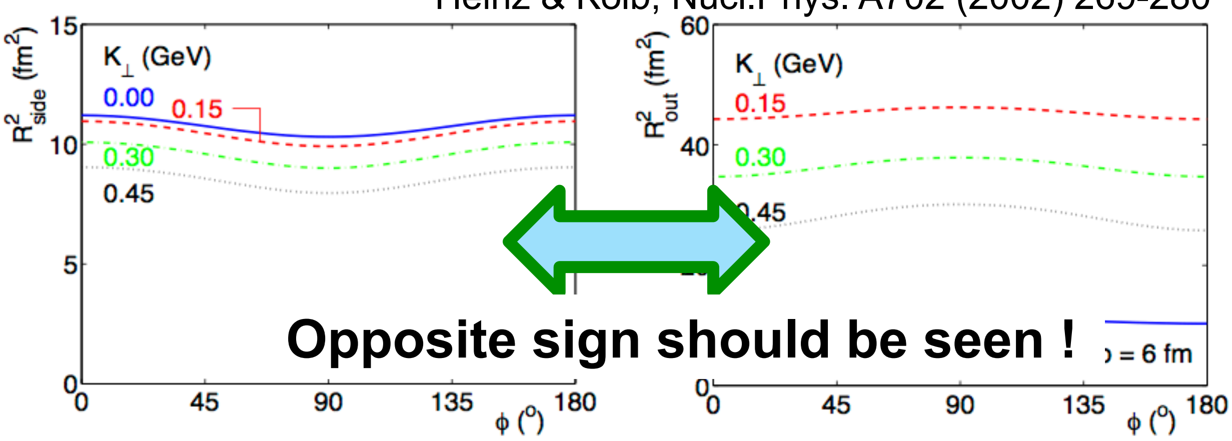
$$\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2})$$

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



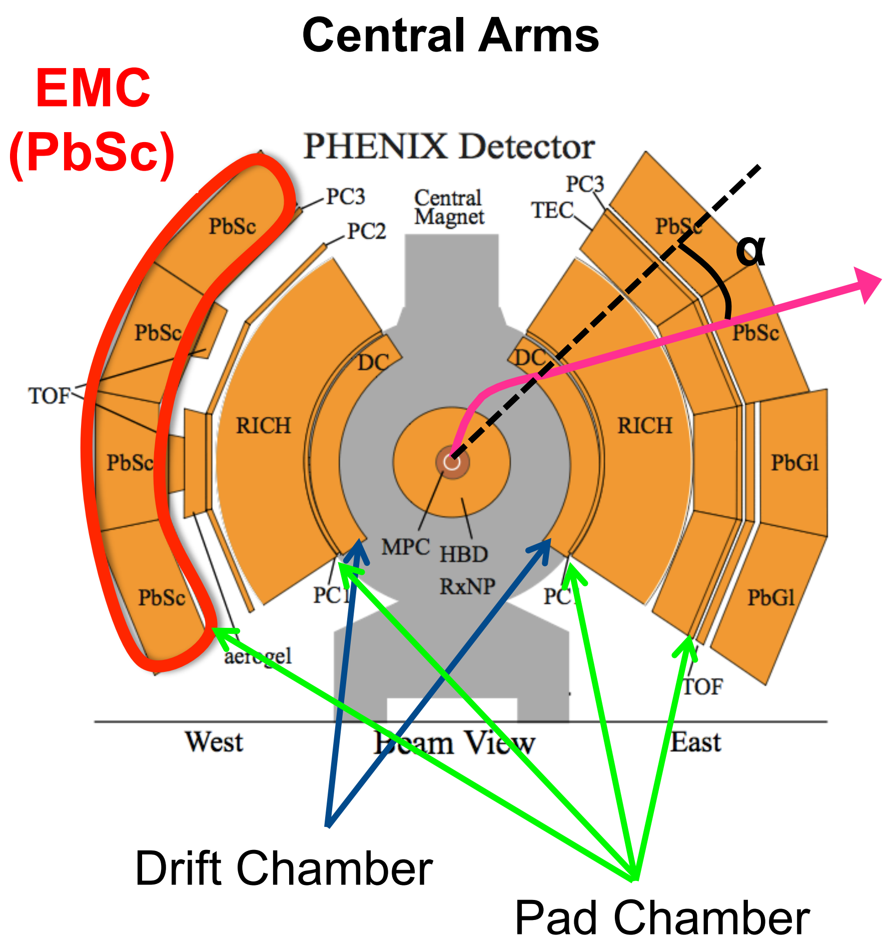


Heinz & Kolb, Nucl.Phys. A702 (2002) 269-280



Opposite sign should be seen !

Track Reconstruction



- **Drift Chamber**
  - ✧Momentum determination

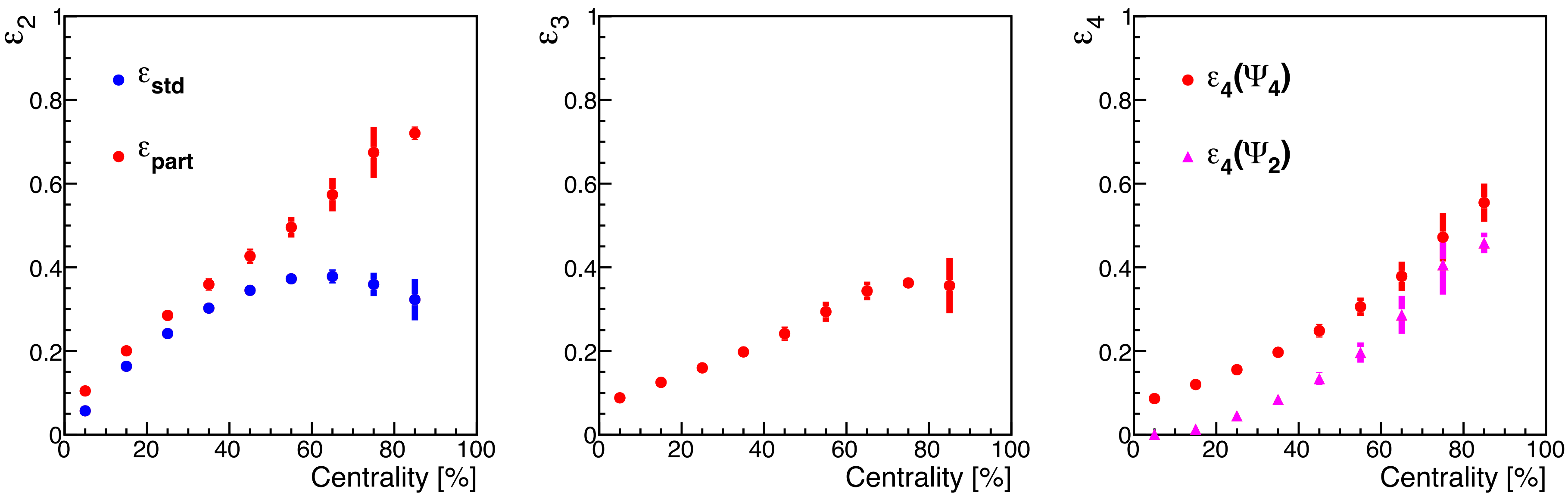
$$p_T \simeq \frac{K}{\alpha}$$

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

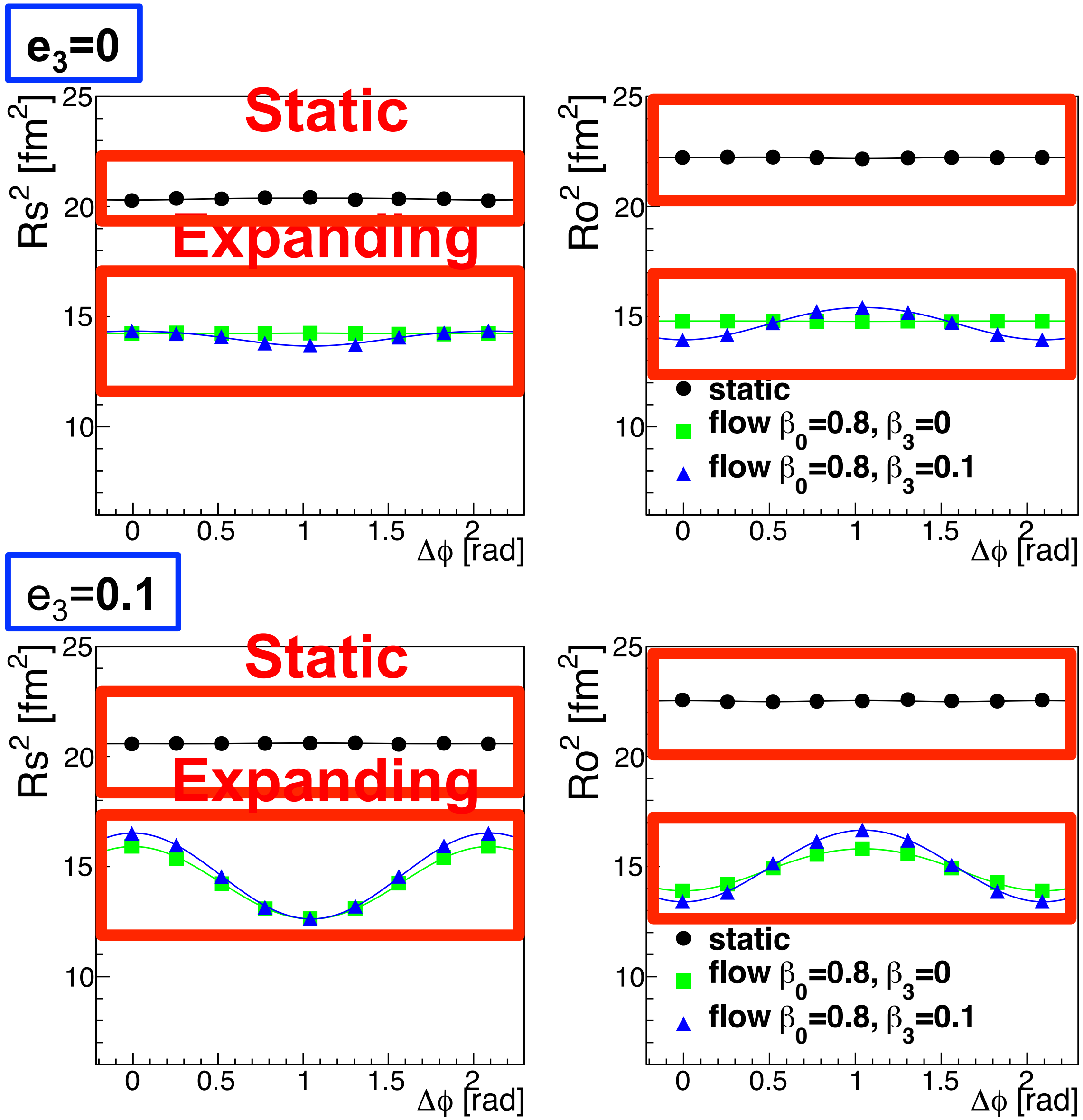
Initial spatial anisotropy by Glauber model

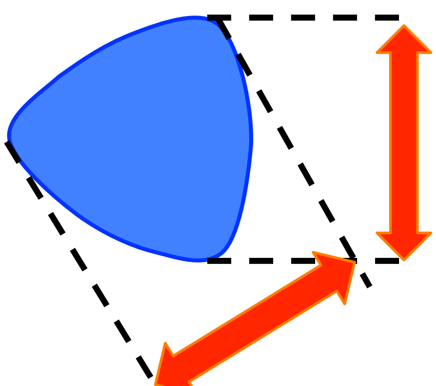
- Initial eccentricity and triangularity increase with centrality going from central to peripheral.



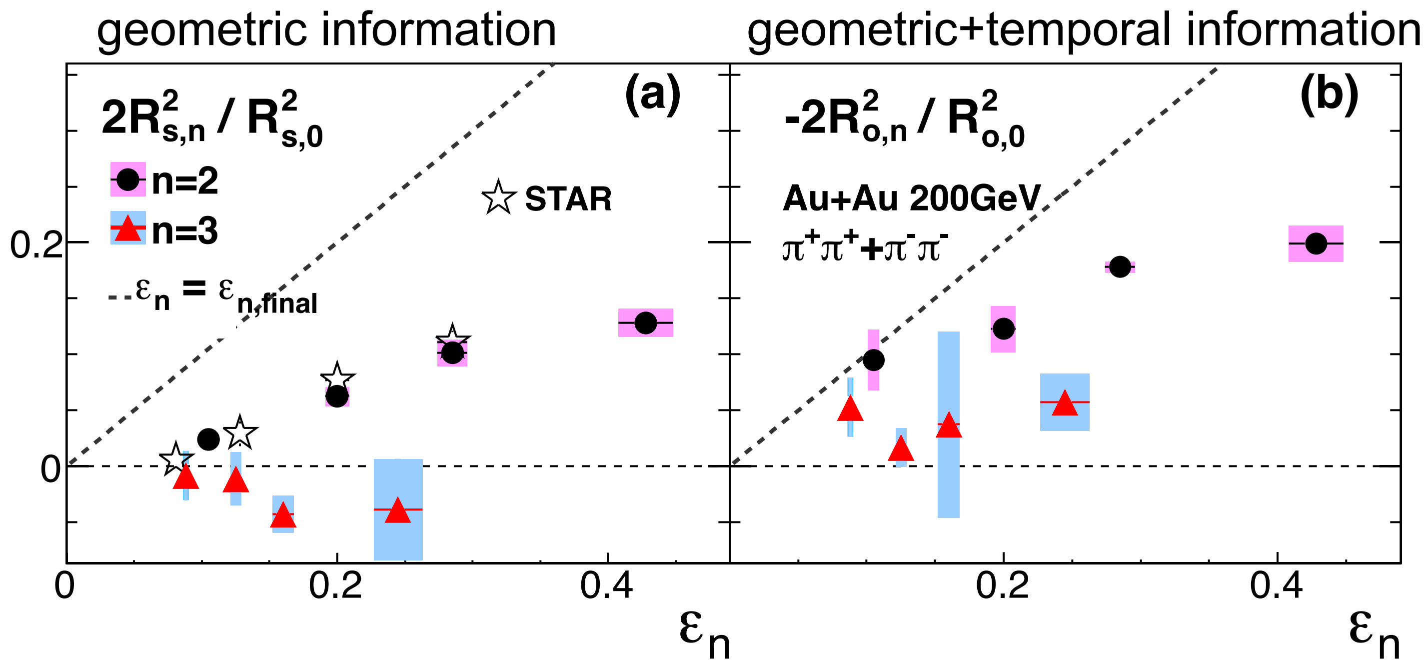
Simulation check

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





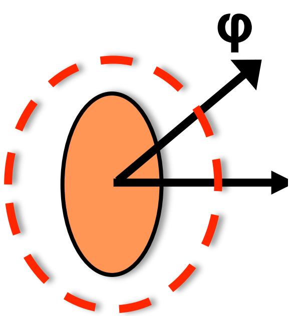
Initial vs Final source eccentricity

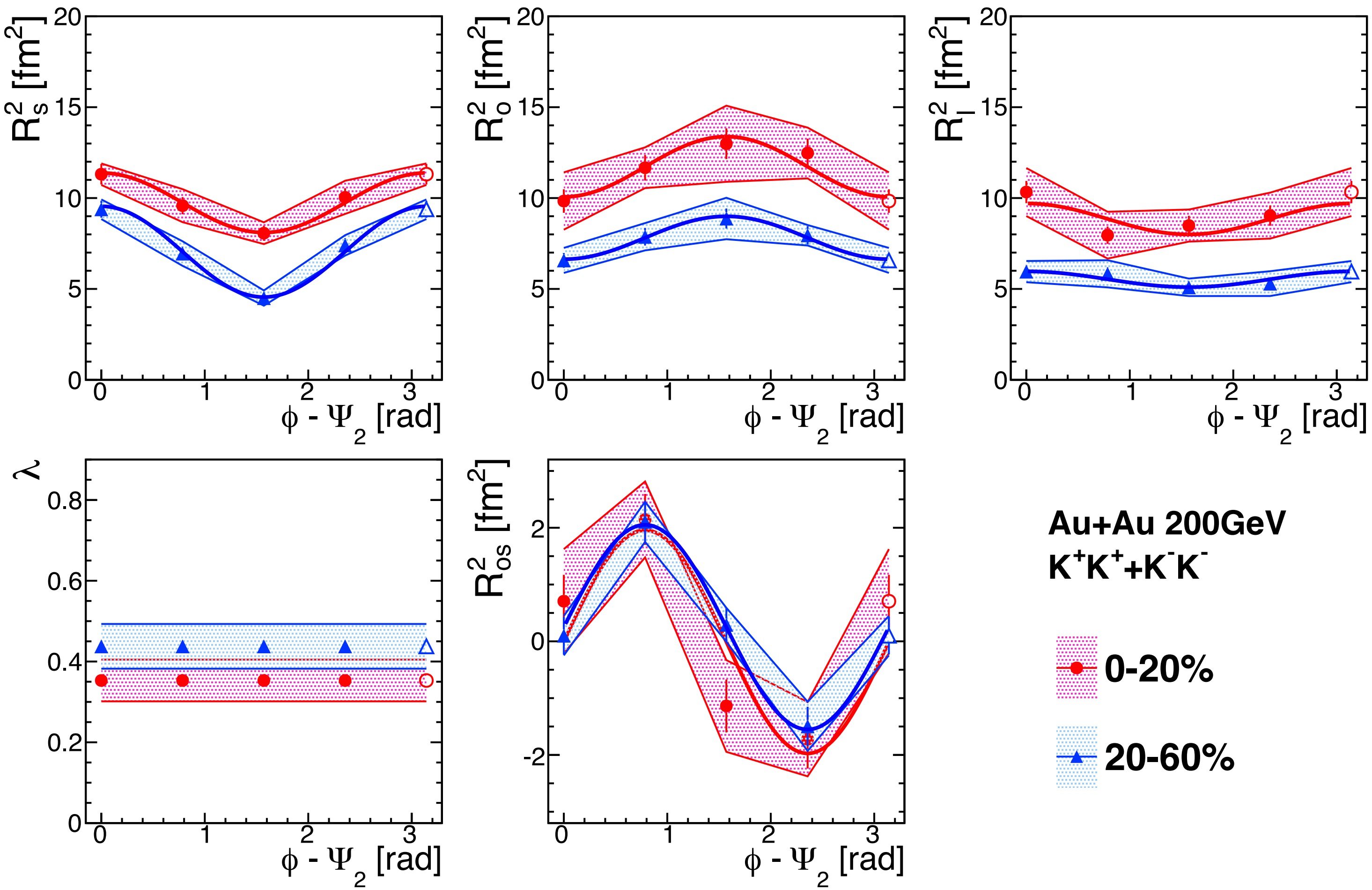


- **2^{nd}-order oscillation is sensitive to final eccentricity**
  - ✧final ε_2 ≈ initial ε_2
  - ✧Strong expansion to in-plane direction, and instant emission
- **3^{rd}-order oscillation affected by spatial and flow anisotropy**
  - ✧Smaller than 2^{nd}-order
  - ✧Initial triangular shape may be reduced by triangular flow

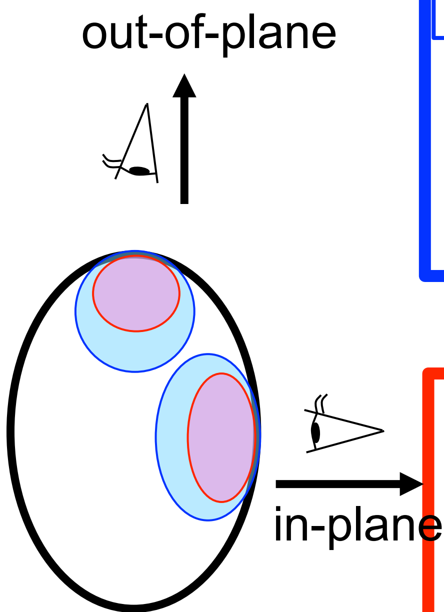
Centrality dependence of kaon HBT radii w.r.t Ψ_2

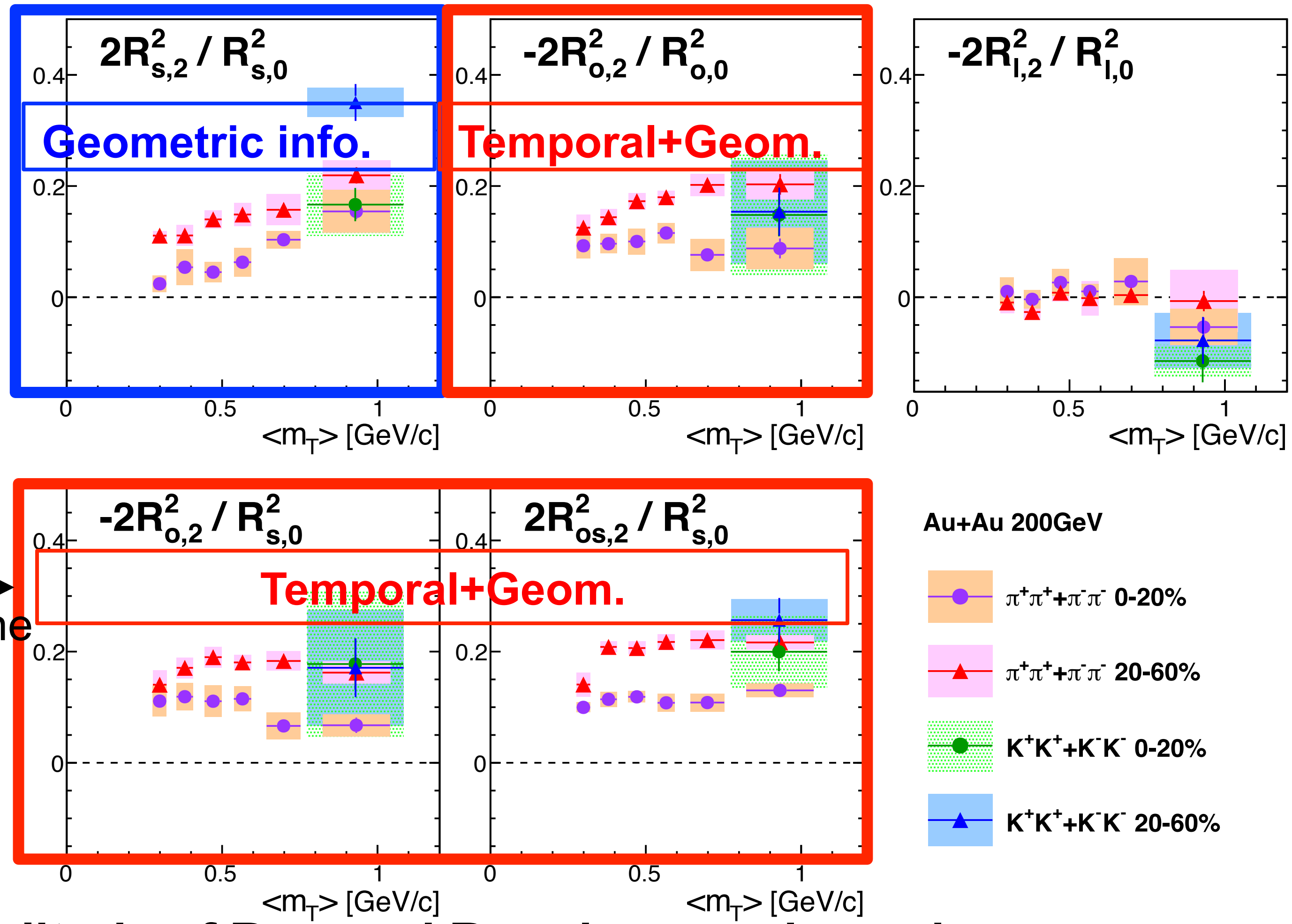
- Result of charged kaons show similar trends!





m_T dependence of relative amplitude

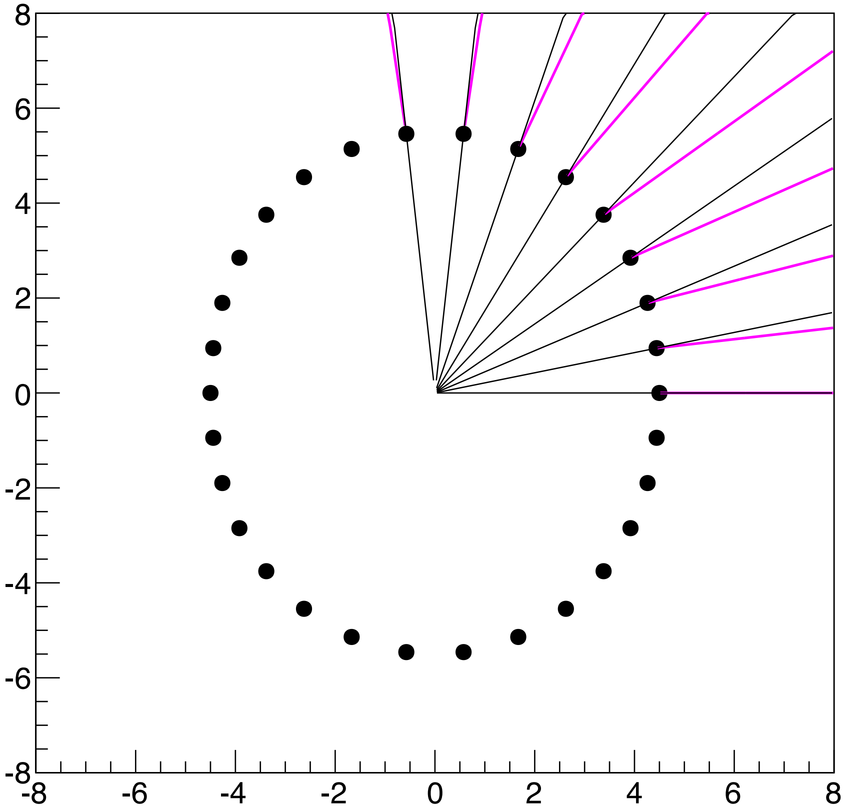


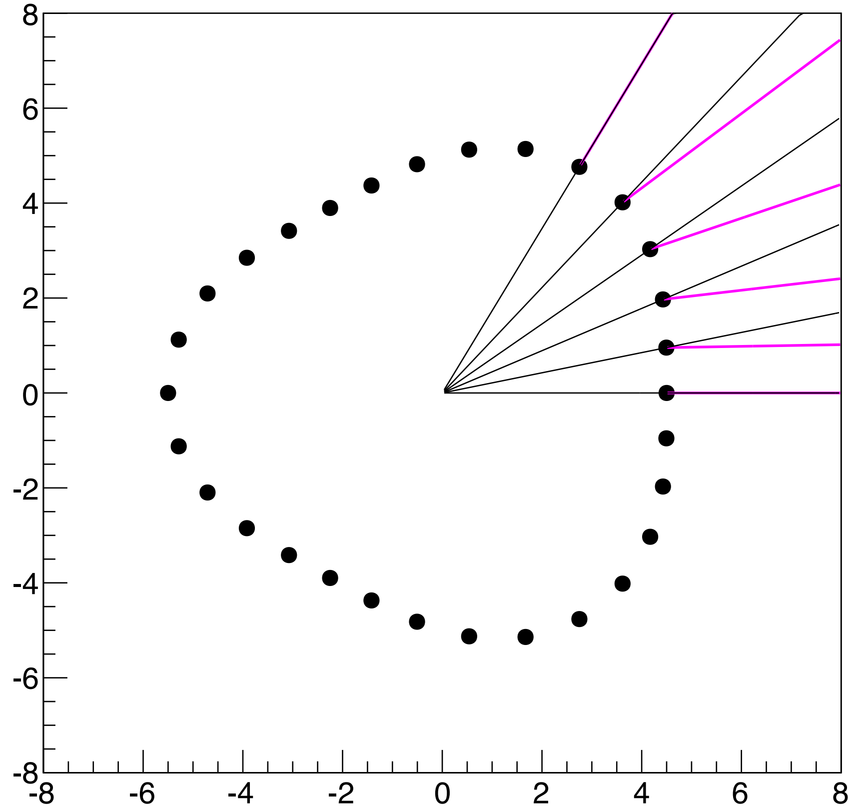


- **Relative amplitude of R_{side} and R_{out} show m_T dependence**
  - ✧R_o in 0-20%doesn't depend on m_T ?
- **Difference between π/K is similar for other parameters**

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**)

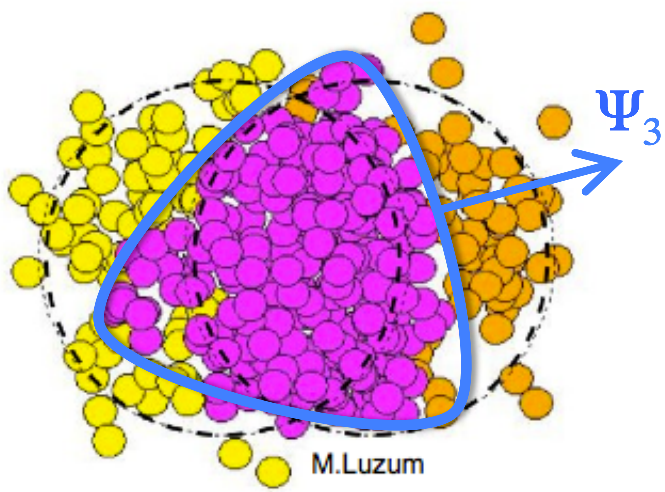




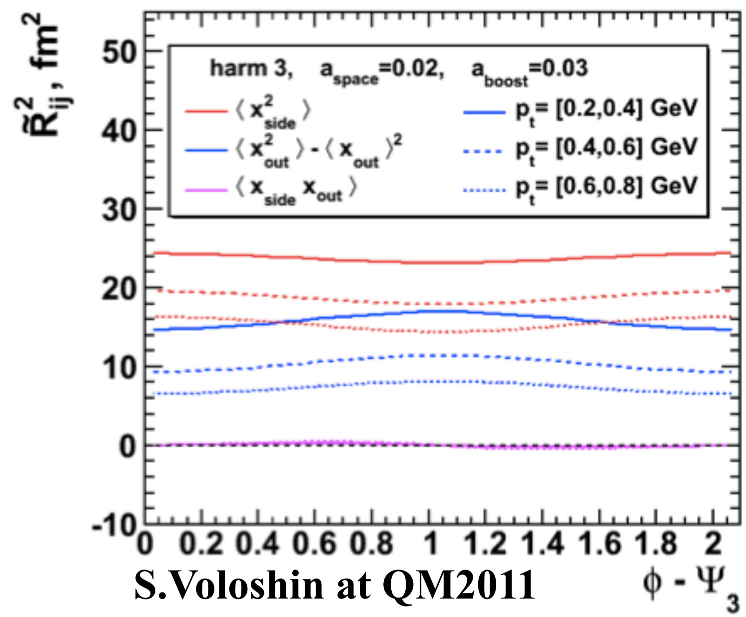
13

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.



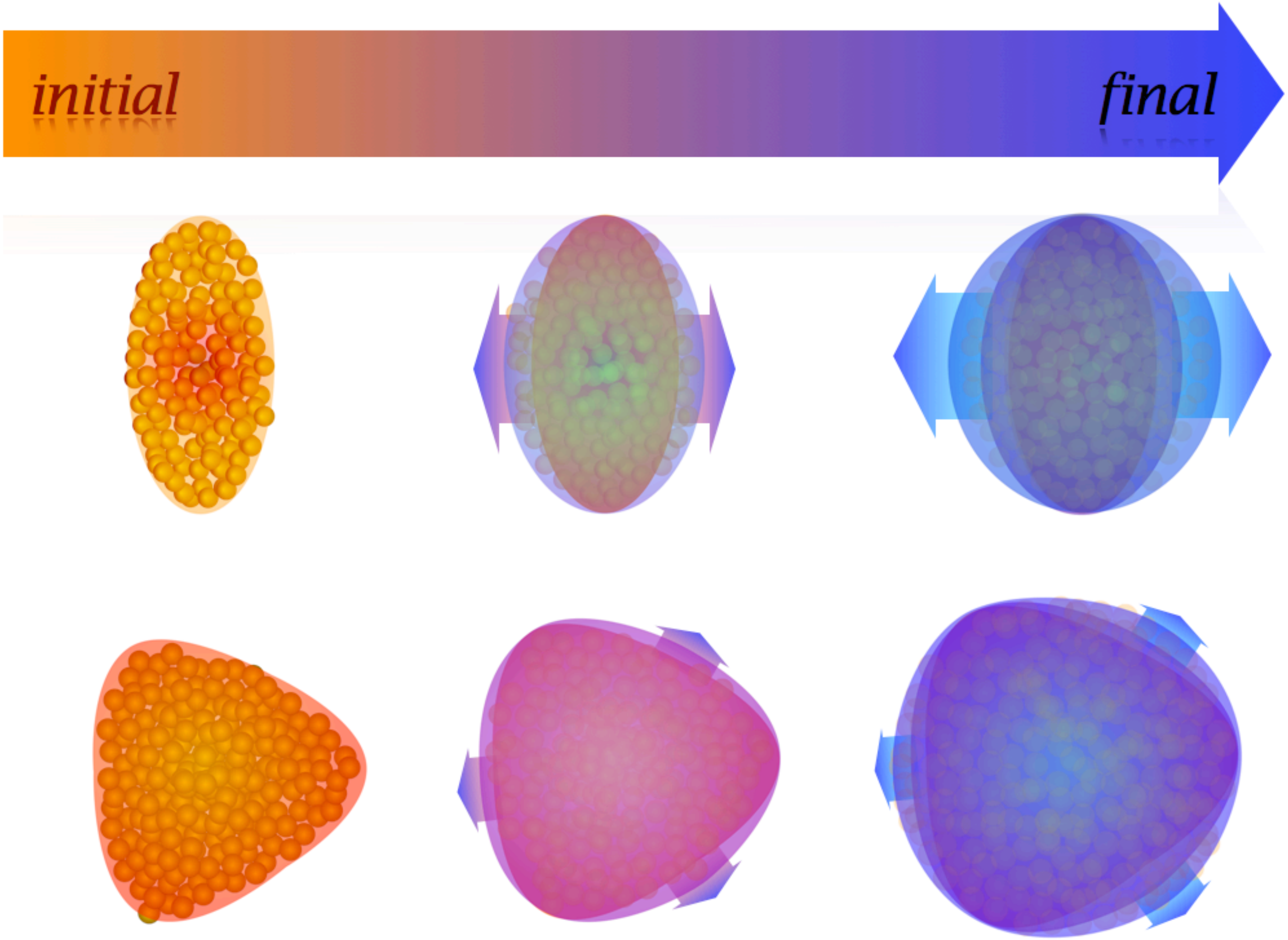
Hydrodynamic model calculation



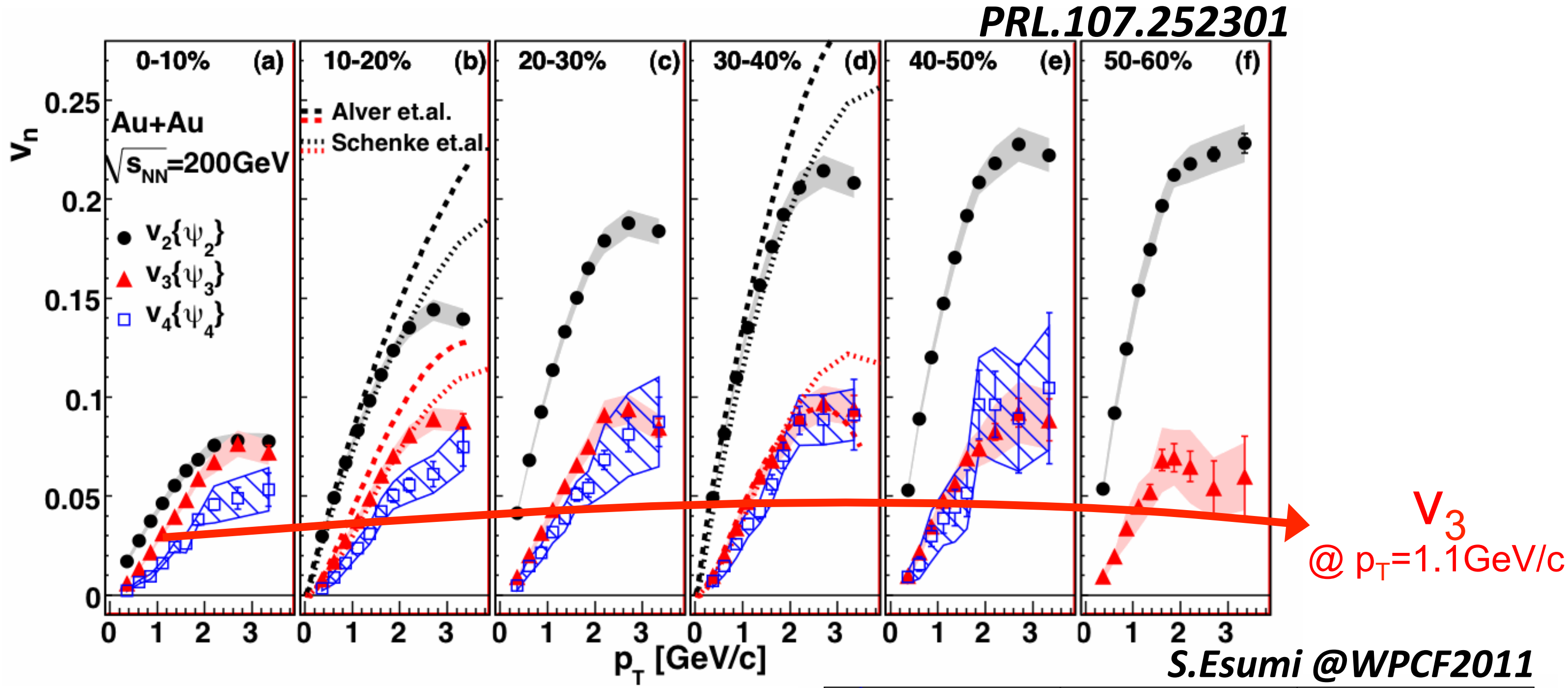
S.Voloshin at QM2011

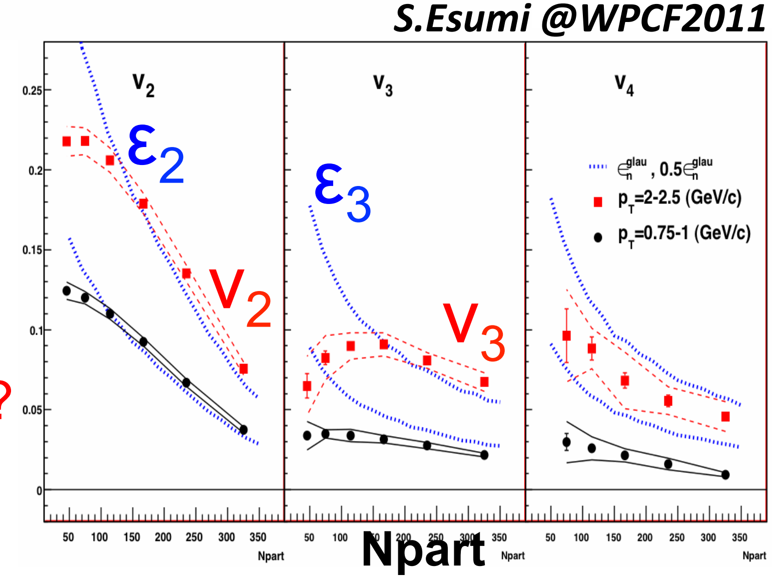
T=100[MeV], $\rho = r' \rho_{max}(1+\cos(n\varphi))$

Image of initial/final source shape



Centrality dependence of v_3 and ε_3



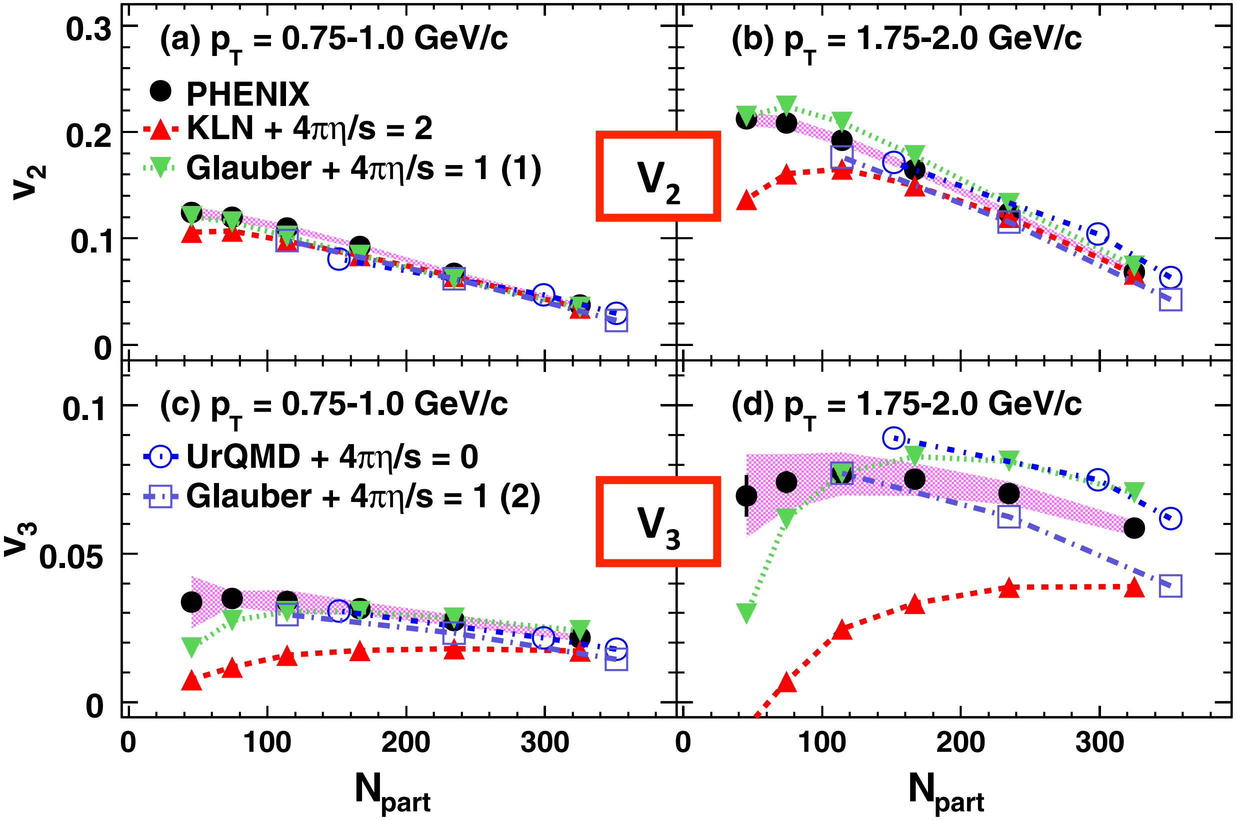


- Weak centrality dependence of v_3
- Initial ε_3 has centrality dependence

Final ε_3 has any centrality dependence?

v_3 breaks degeneracy

PRL.107.252301

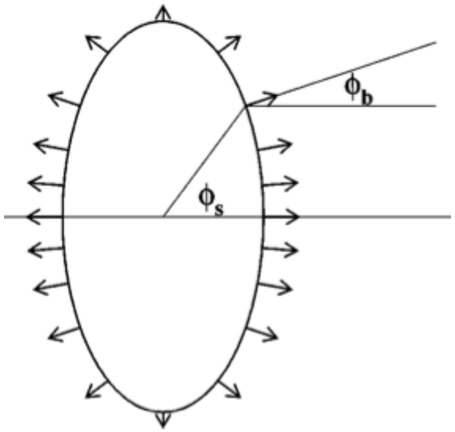


- **v_3 provides new constraint on hydro-model parameters**
  - ✧ Glauber & 4πη/s=1 : works better
  - ✧ KLN & 4πη/s=2 : fails

Interpretation by Blast wave model

- **Hydrodynamic model assuming radial flow**

PRC 70, 044907 (2004)



✧Well described p_T spectra & elliptic flow at low p_T

✧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)
$\tau_0, \Delta\tau$	: freeze-out time, emission duration

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

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

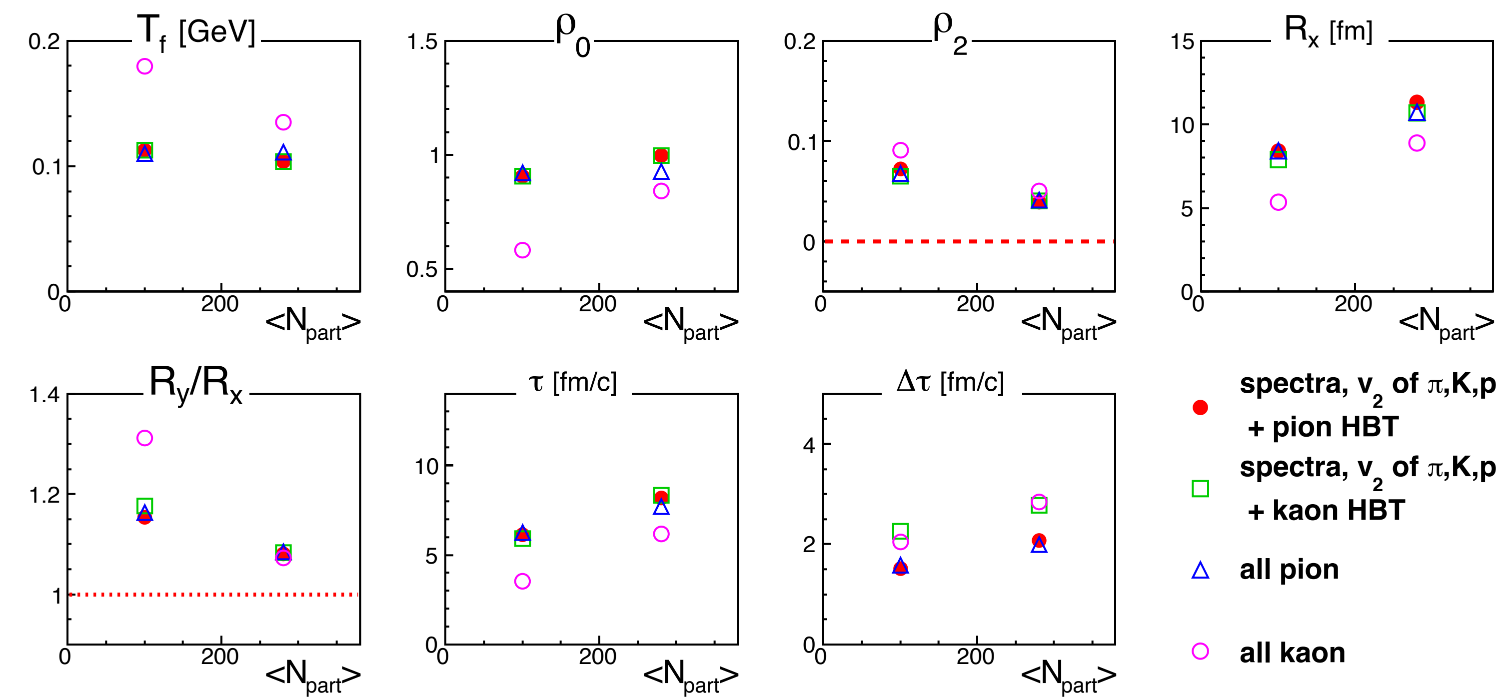
$$\tilde{r} = \sqrt{(\frac{r\cos(\phi)}{R_x})^2 + (\frac{r\sin(\phi)}{R_y})^2}$$

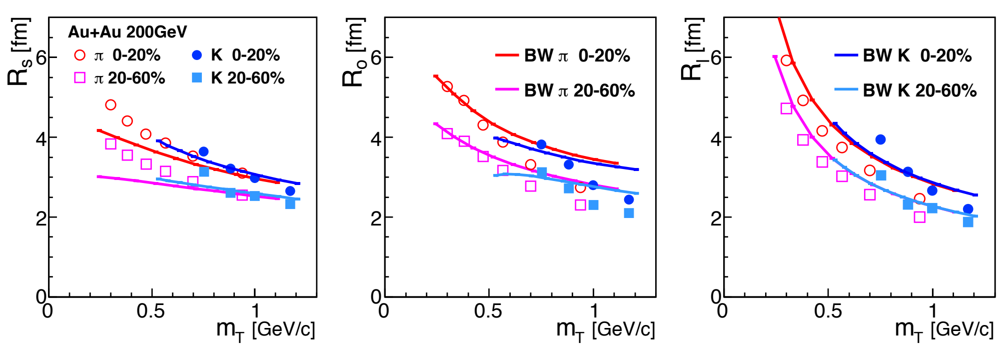
✧ Assuming a Gaussian distribution peaked at τ_0 and with a width $\Delta\tau$, and source size doesn't change with τ.

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

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

pion BW fit vs kaon BW fit

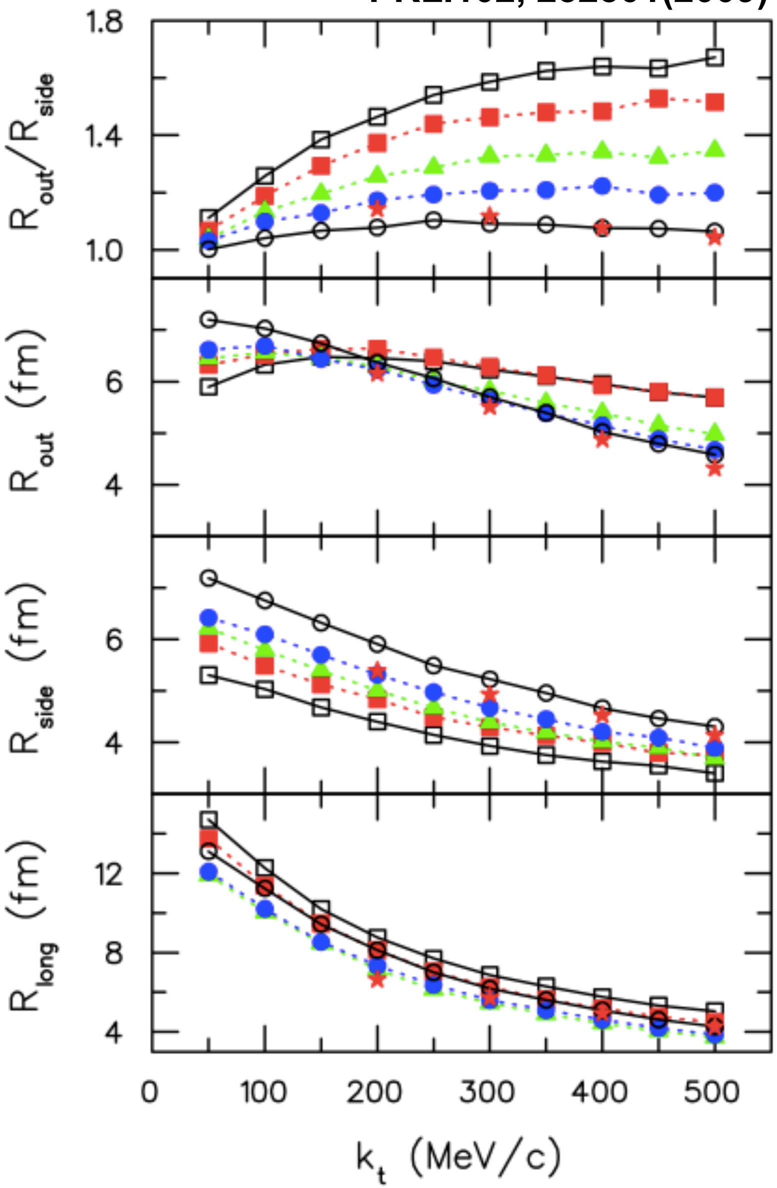




- Fit only for kaon data shows longer Δτ, while m_T dependence of mean radii is not reproduced.
  - ✧ azimuthal kaon data used in the fit has only a data point in k_T.

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

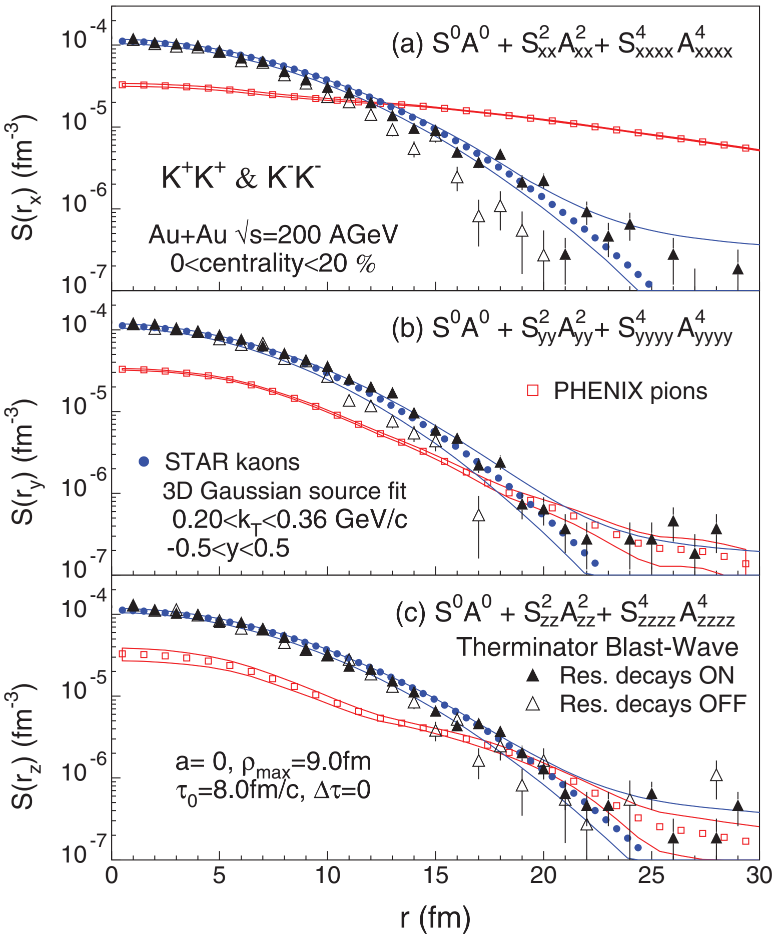
▲ Using stiffer equation of state

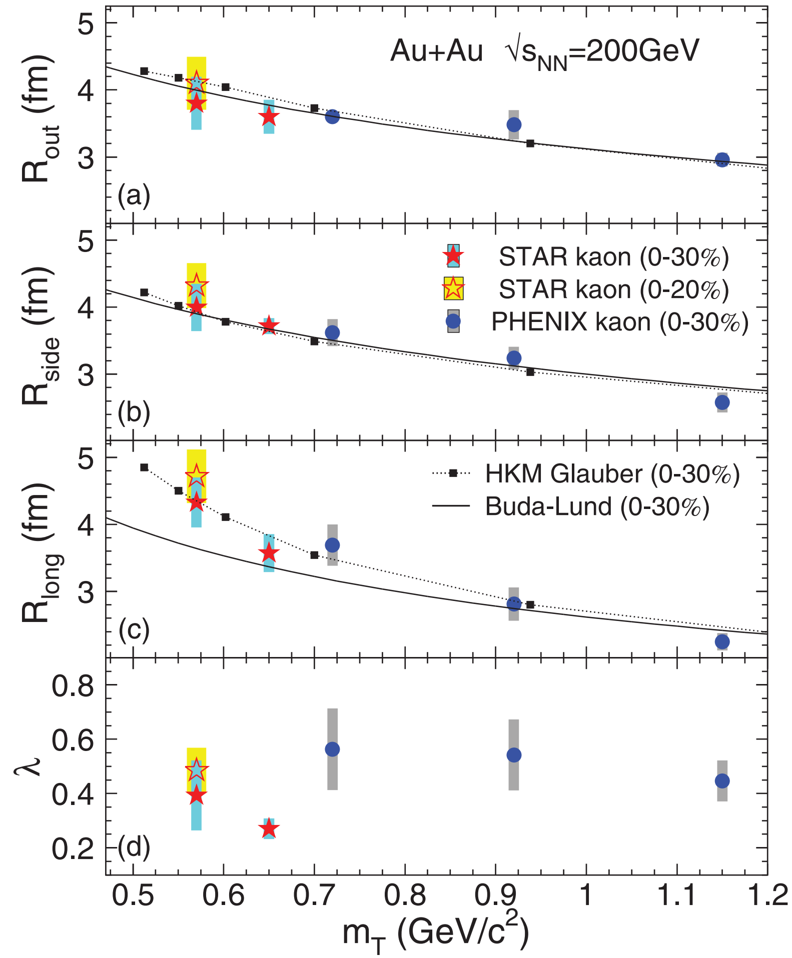
● Adding viscosity

○ Including all features

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

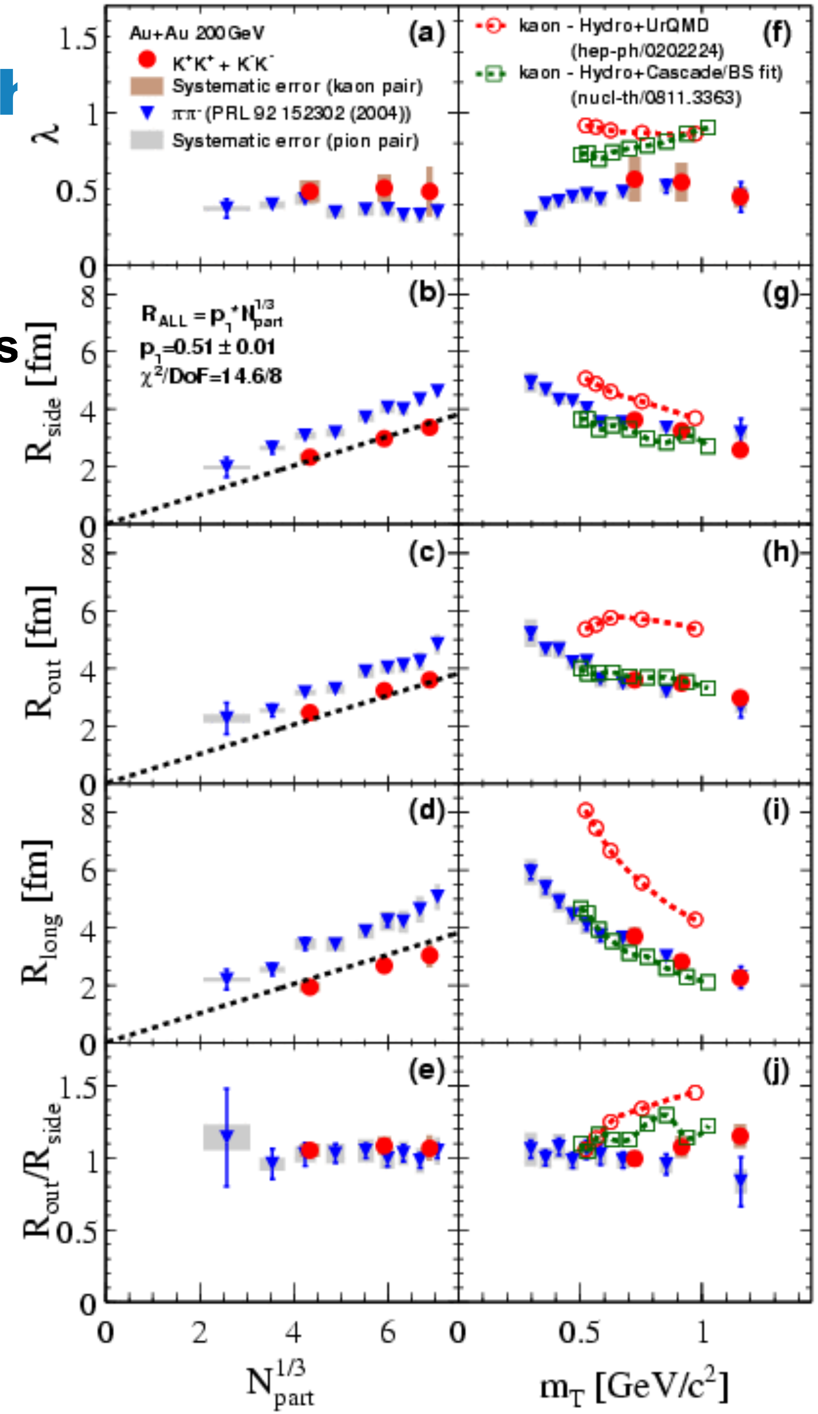
Imaging analysis from STAR





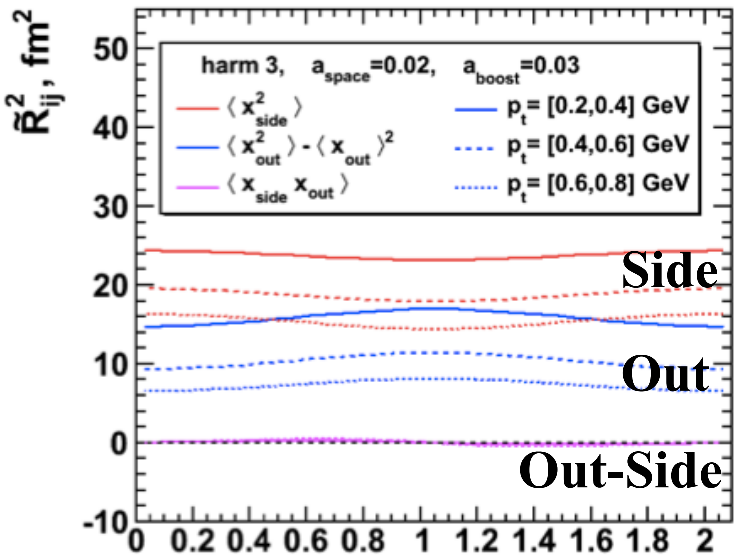
The past HBT Results for ch

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



Model predictions

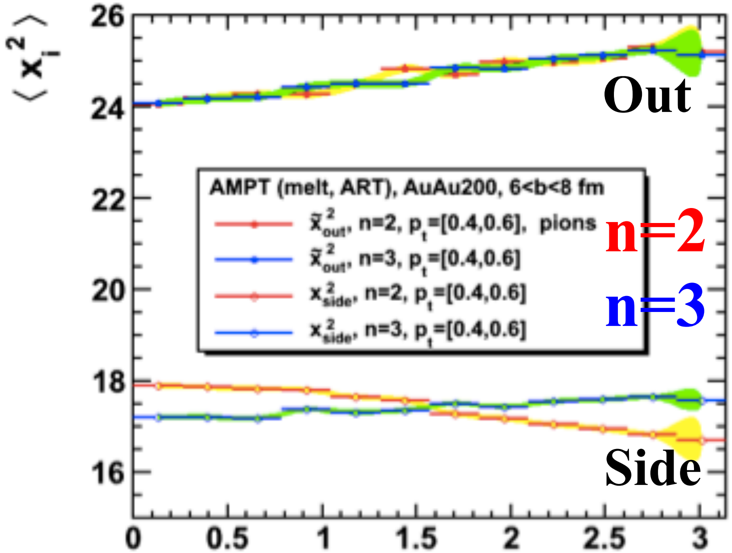
Blast-wave model



S.Voloshin at QM11 $\phi - \Psi_3$

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

AMPT

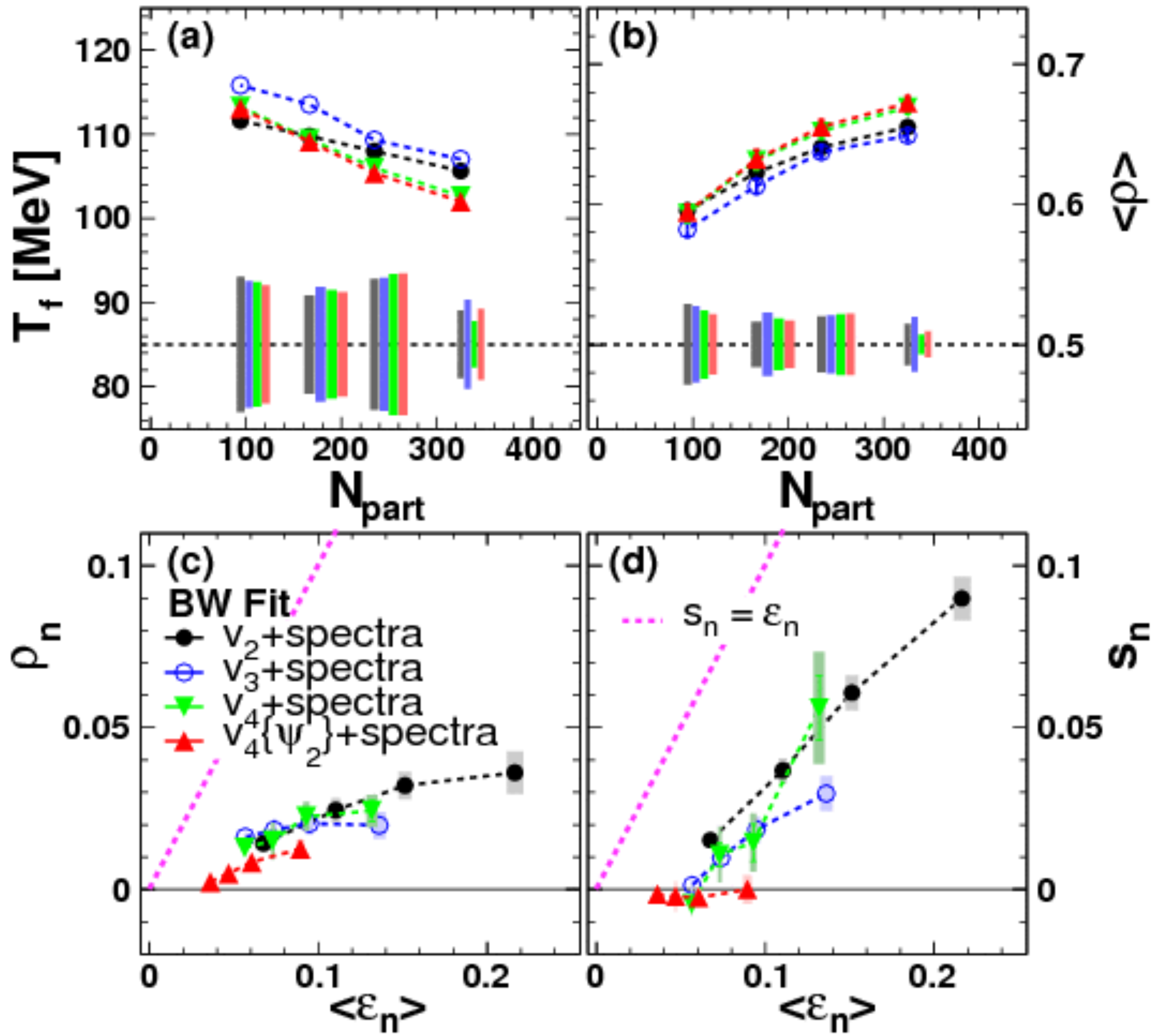


S.Voloshin at QM11 $n(\phi - \Psi_n)$

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

Extracted parameters by different Blast wave model

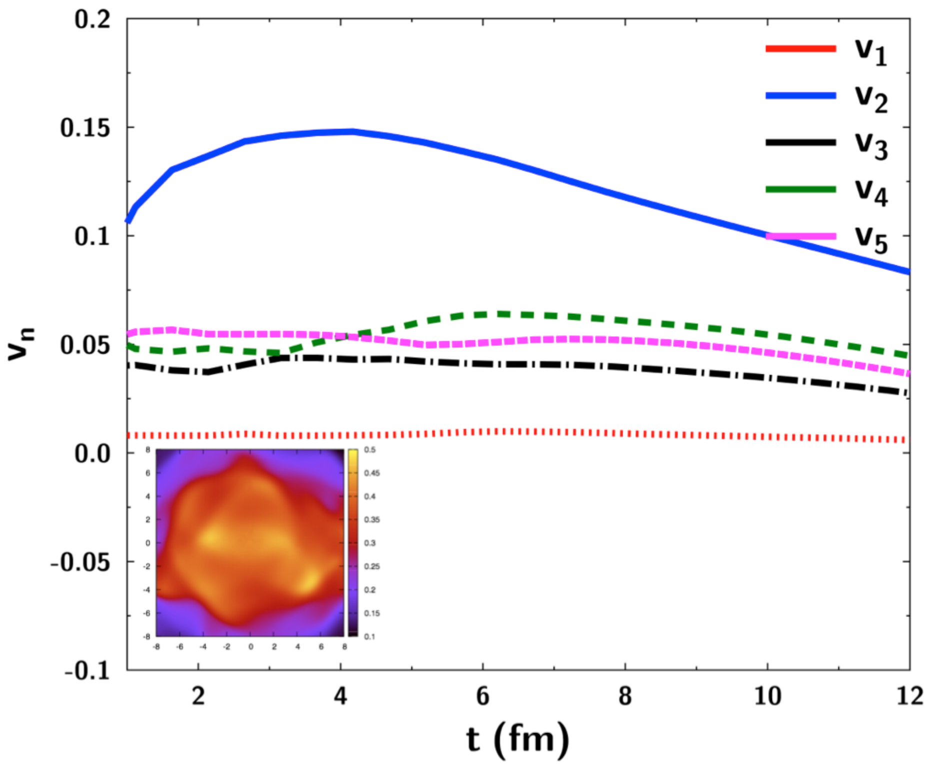
- Blast wave fit was performed for spectra and v_n



Flow anisotropy ρ_2 and ρ_3 have similar trend !

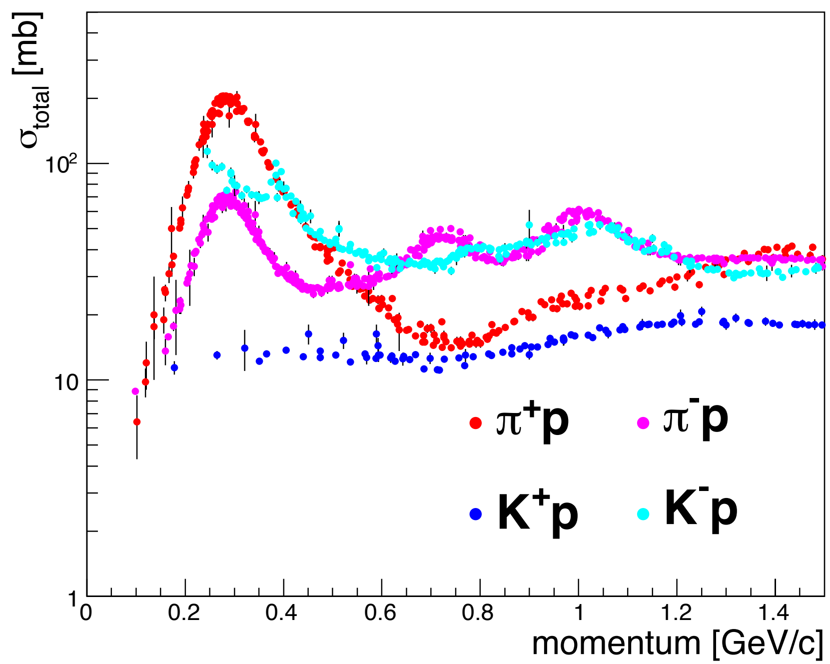
Time evolution of higher harmonic flow

Ideal hydrodynamic calculation
(Nonaka, correlation 2013)



Interaction cross section

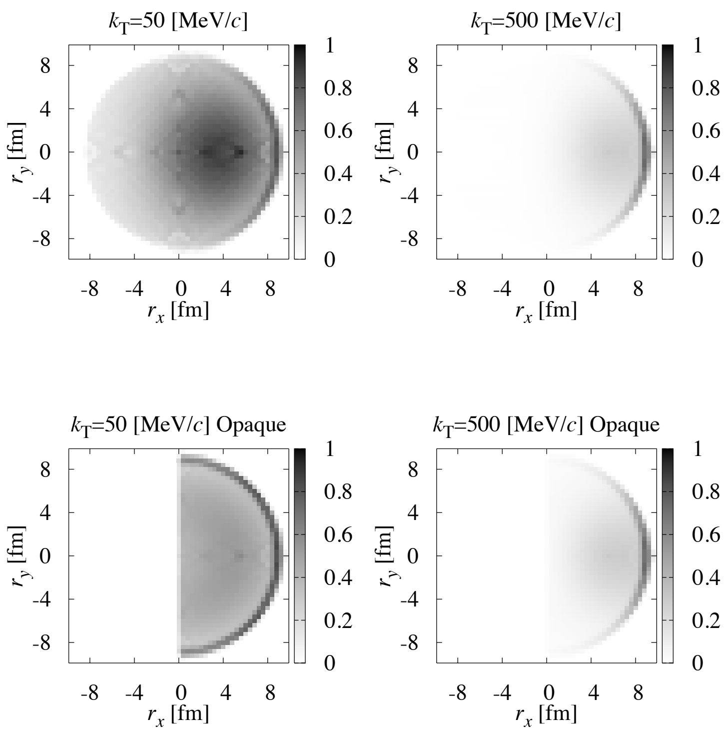
- **Try looking at HBT radii for K^+K^+ and K^-K^- separately because they have different interaction cross section on nucleons.**
- **If π/K difference is due to the hadron rescattering with different cross sections, the difference may be also seen in positive and negative kaon pairs.**

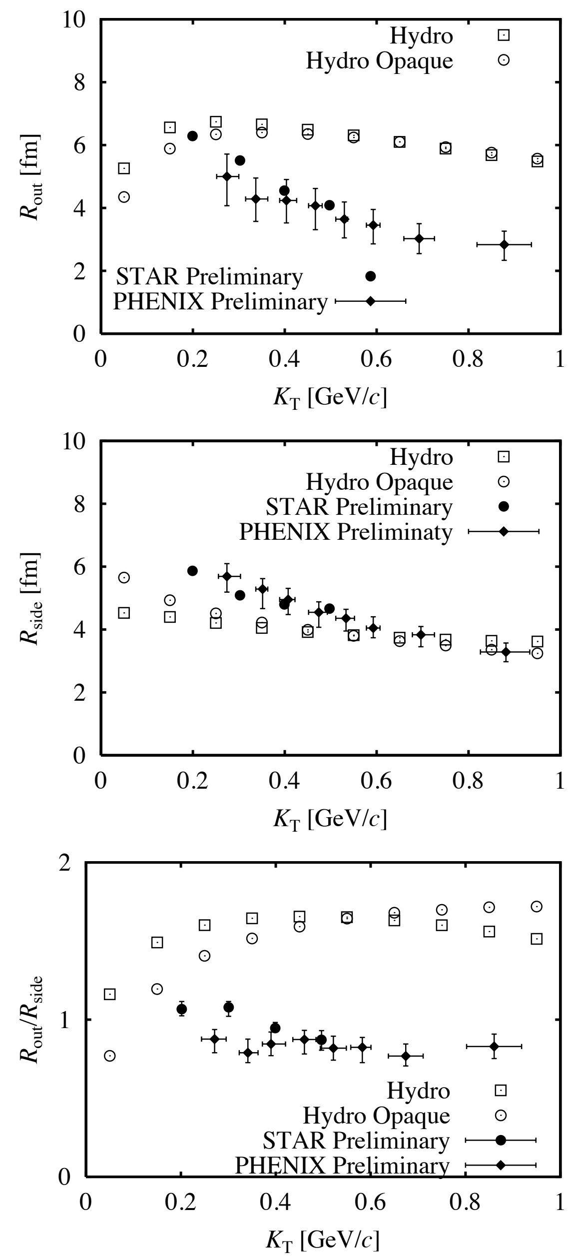


0.8 ~ 1.0 GeV/c
(π) = 0.69 ~ 1.1, k_T(K) = 0.5 ~ 1.0
(p_{T1}+p_{T2})/2)

Effect of Opacity

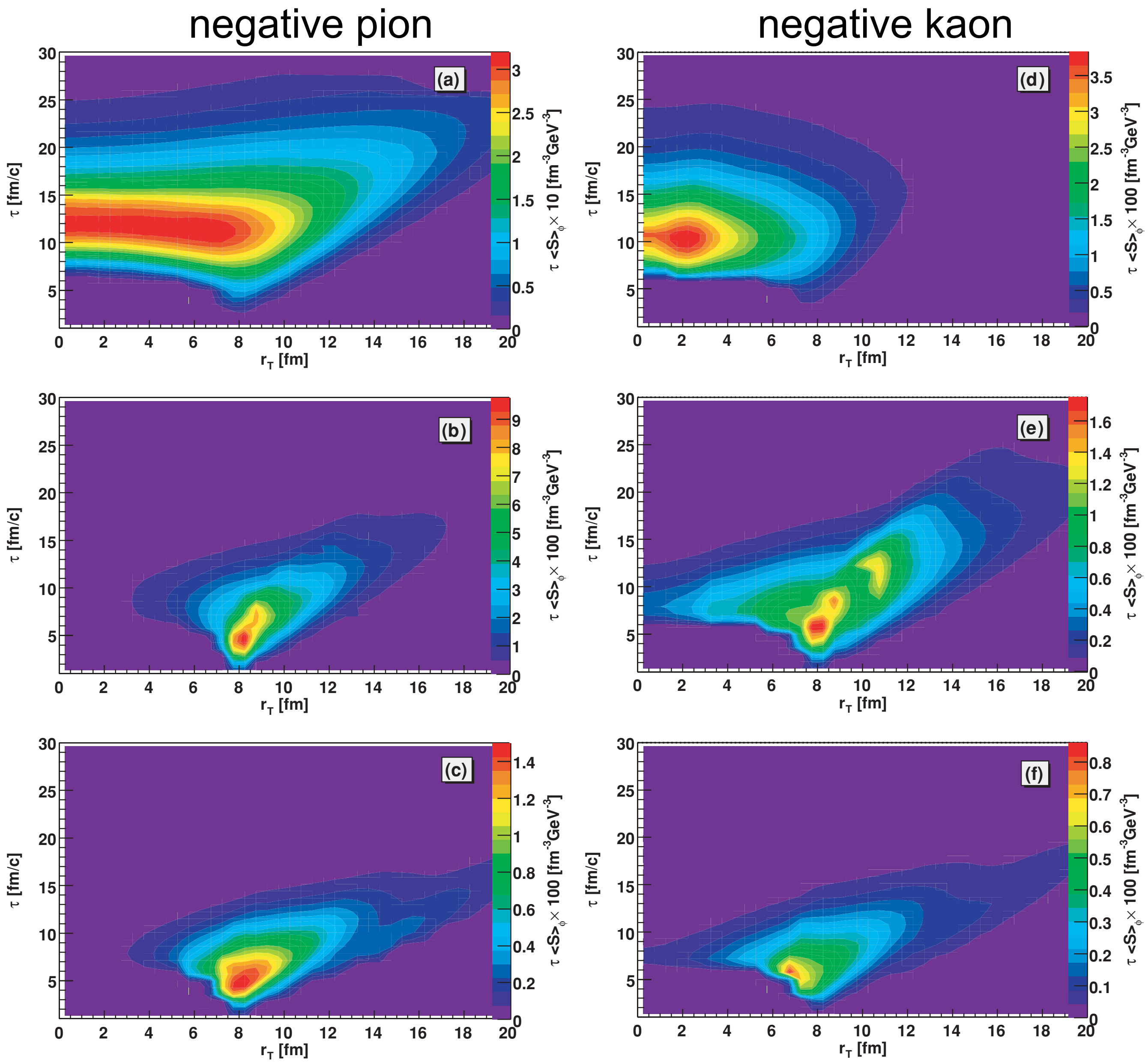
K. Morita, S. Muroya, Prog. Theor. Phys. 111, 93 (2004)





Opacity leads to a small decrease of R_o at low k_T and a small increase of R_s at low k_T.

Emission function from HKM model

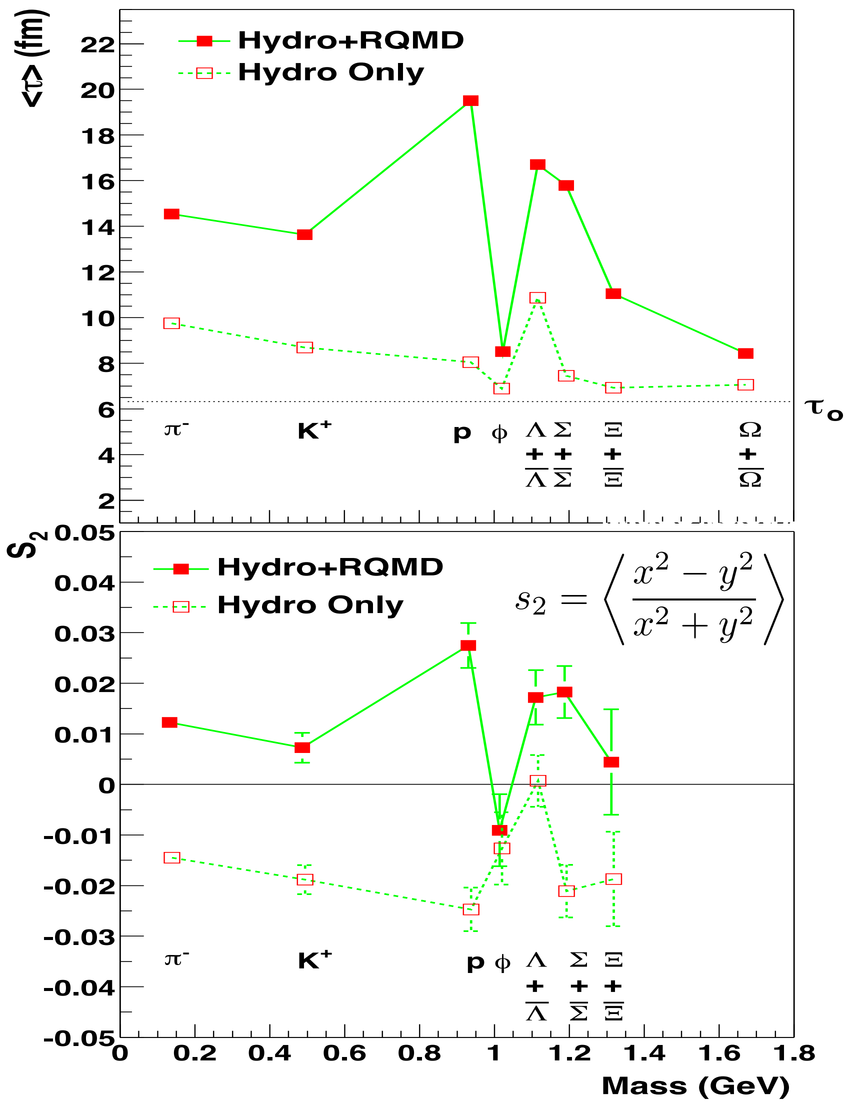


p_T=0.2GeV/c

m_T=0.86GeV/c

p_T=1.2GeV/c

Hydro+RQMD



Hydro only (including resonance decay)
vs
Hydro + hadronic rescattering