Azimuthal angle dependence of HBT radii with respect to the Event Plane in Au+Au collisions at PHENIX

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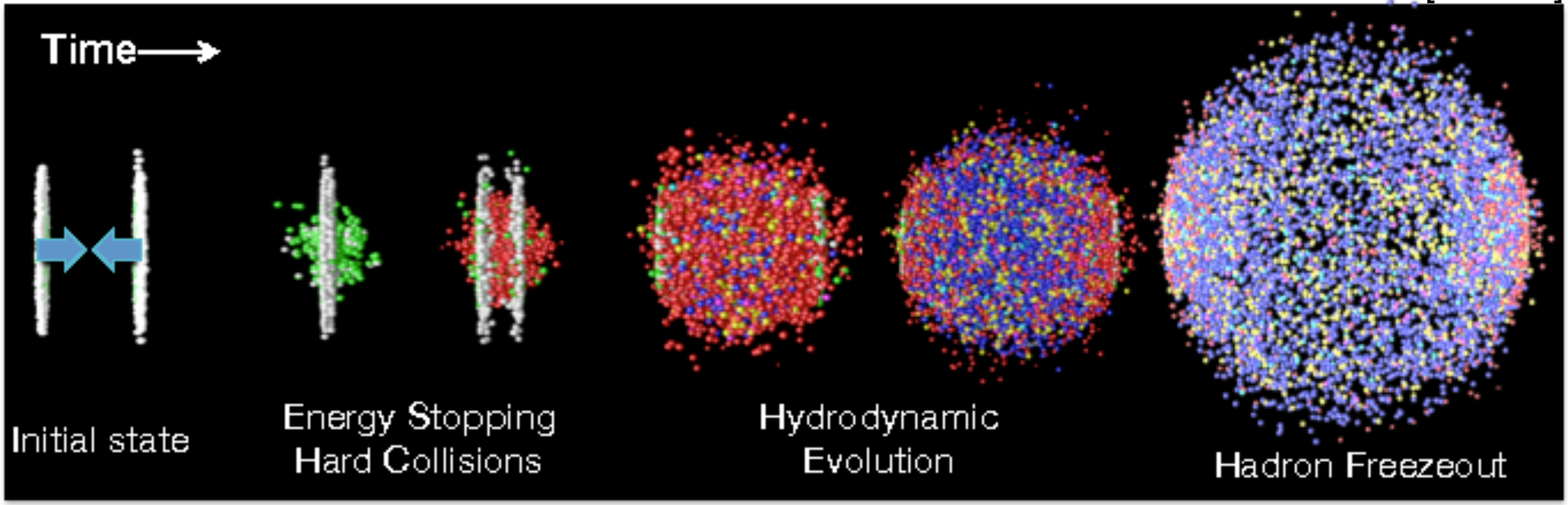
WWND2014 @Galveston, USA

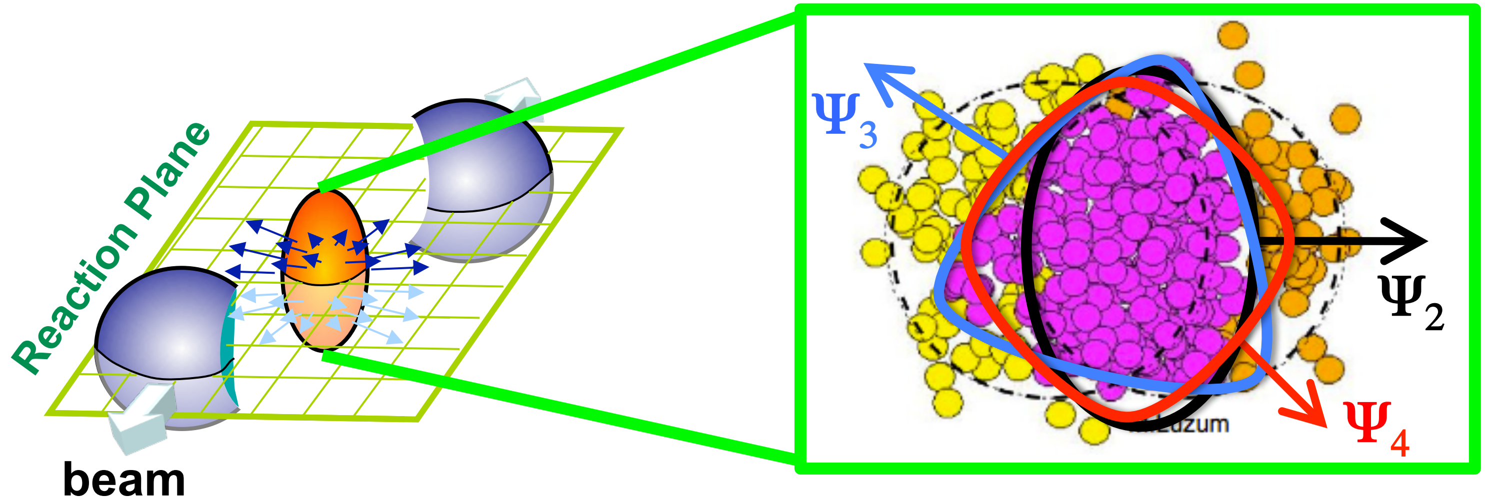
Space-Time evolution in HI collisions

arXiv:1201.4264 [nucl-ex]



- **Final emitting particles carry information on the properties of the QGP and its space-time evolution**
- **Space-time picture of the system evolution is emerging from recent studies at RHIC and the LHC**

Momentum anisotropy at final state



- **Initial source eccentricity with fluctuations leads to momentum anisotropy at final state, known as higher harmonic flow v_n**

✧Sensitive to η/s (PRL107.252301)

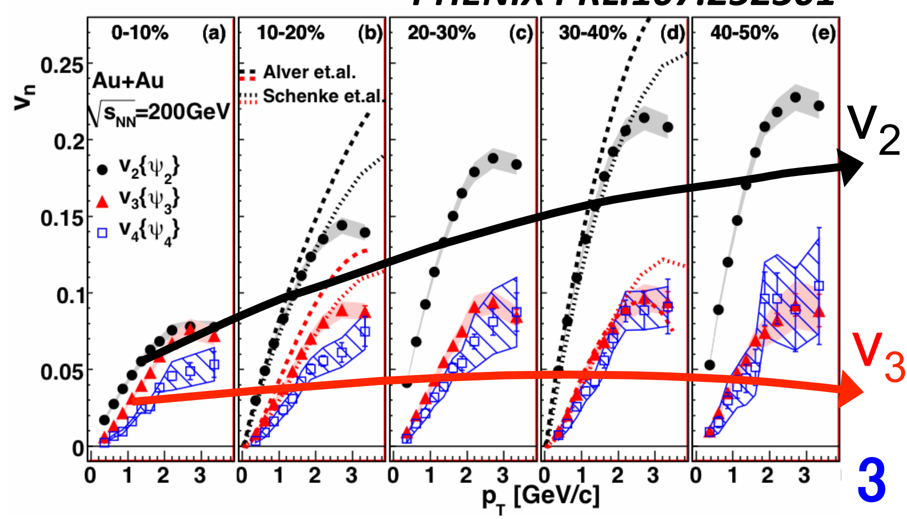
$$\frac{dN}{d\phi} \propto 1 + 2\Sigma v_n \cos[n(\phi - \Psi_n)]$$

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

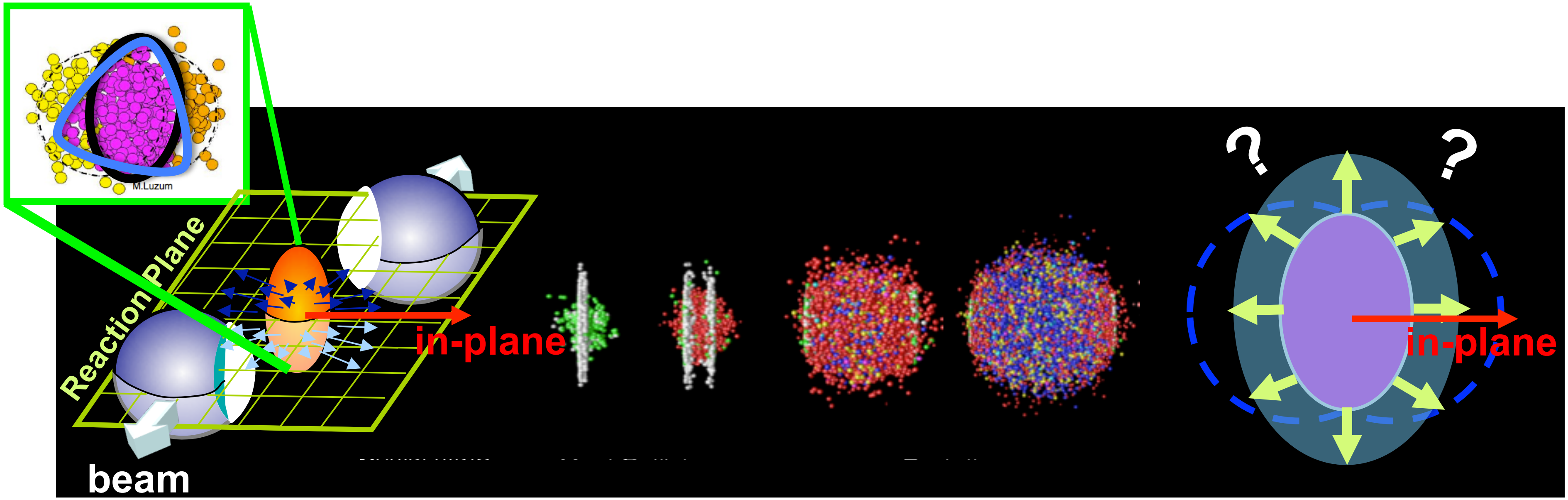
Ψ_n : higher harmonic event plane

φ : azimuthal angle of emitted particles

PHENIX PRL.107.252301



Spatial anisotropy at final state



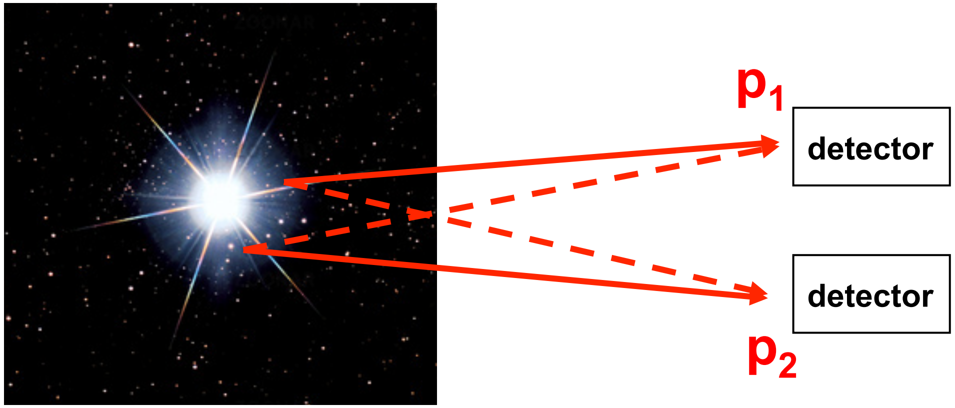
- **What is the final source shape?**
  - ✧ Spatial-extent at final state depends on the magnitude of initial eccentricity with fluctuation, the strength of flow, expansion time, and viscosity
  - ✧ Does the initial fluctuation also remain at final state?
- **HBT interferometry relative to different event plane could probe them.**

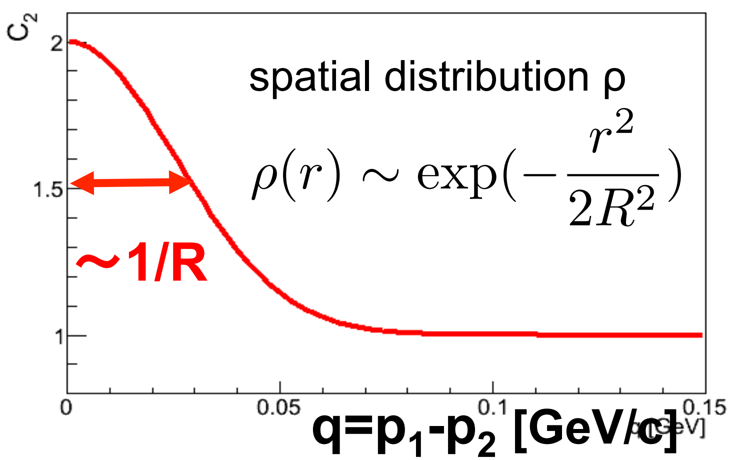
HBT Interferometry

- **1956, H. Brown and R. Twiss, measured angular diameter of Sirius**
- **1960, Goldhaber *et al*., correlation among identical pions in $p+\bar{p}$**
- **By quantum interference between two identical particles**

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

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





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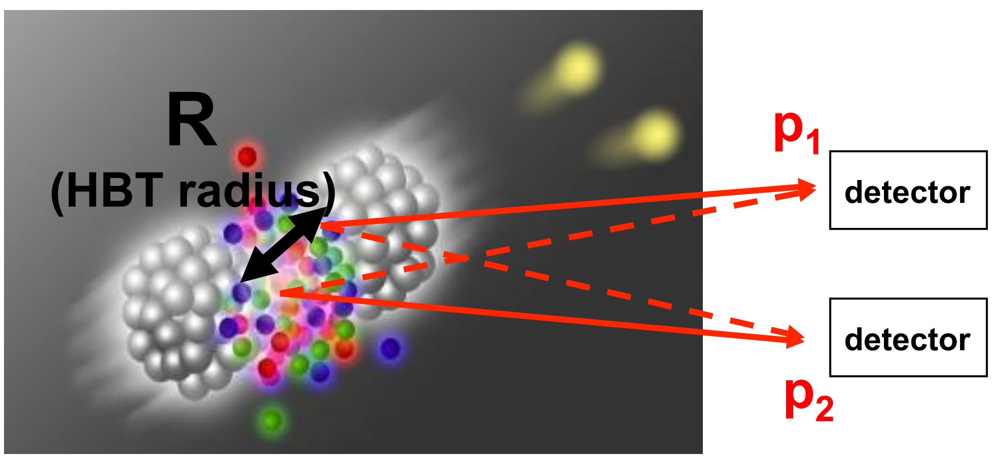
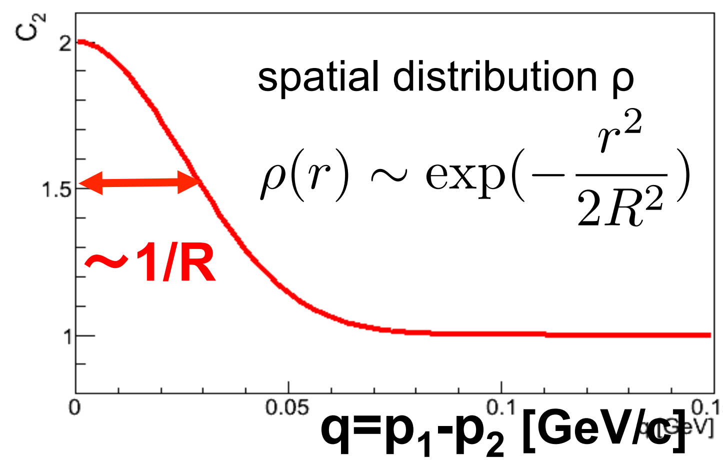
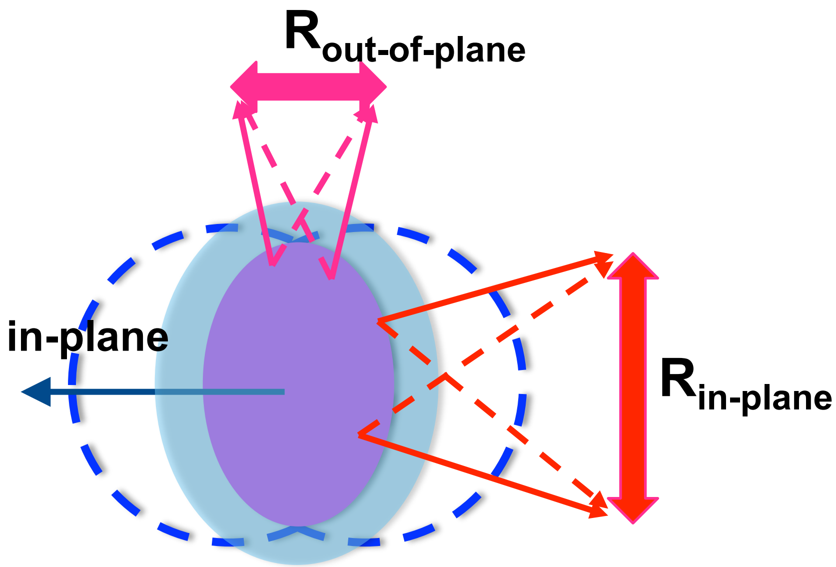




Azimuthal sensitive HBT w.r.t 2^{nd}-order event plane



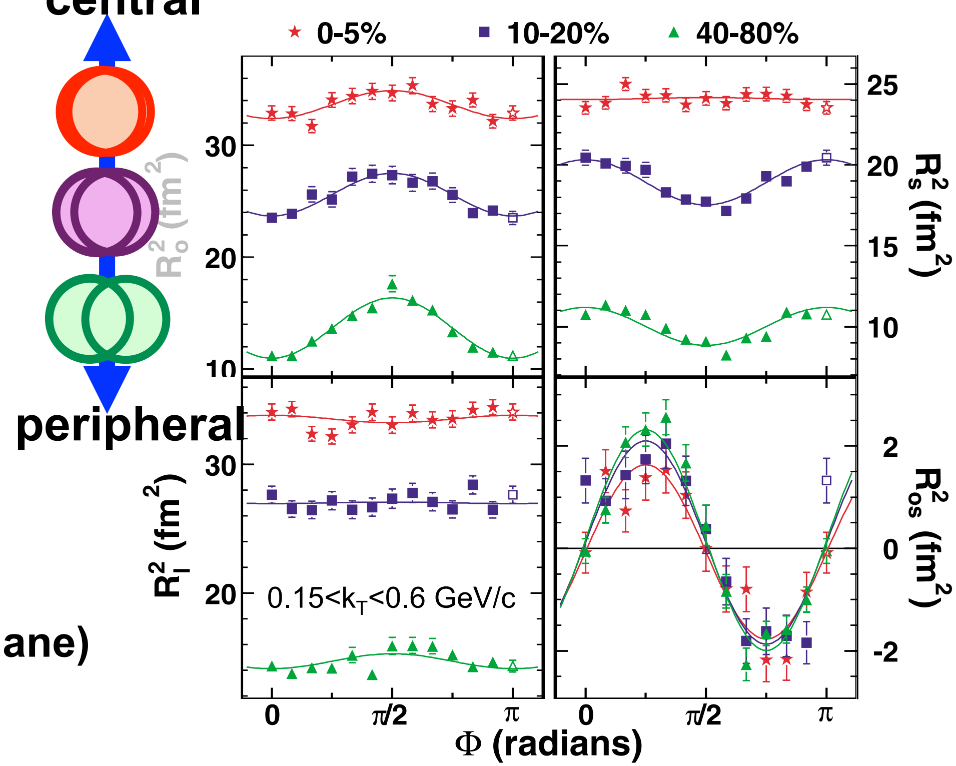
Reaction plane ≈ 2^{nd}-order event plane(v_2 plane)

PRC70, 044907 (2004), Blast-wave model

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

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

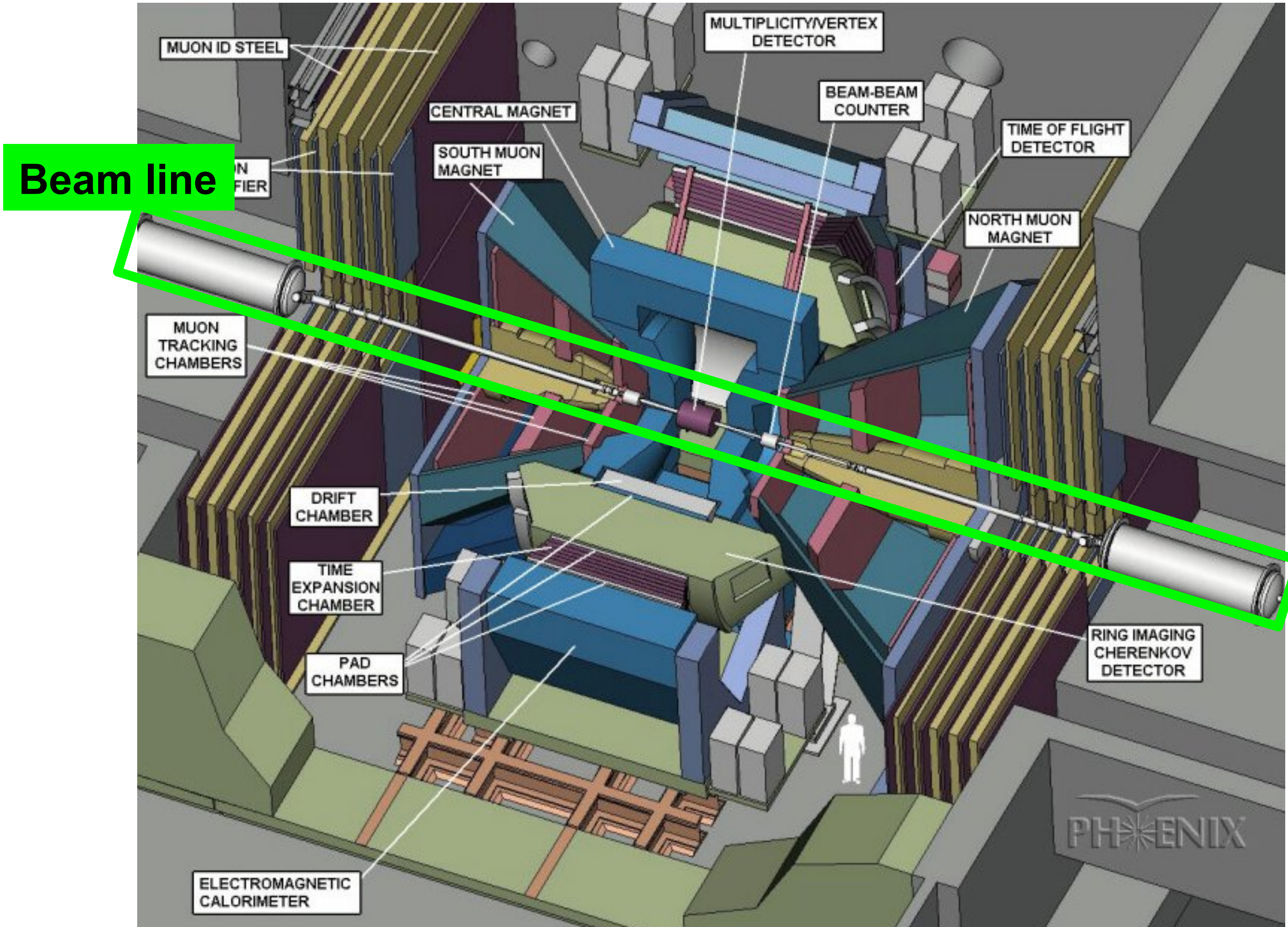
STAR, PRL93, 012301



- **$R_{s,2}$ is sensitive to final eccentricity**
  - ✧Oscillation indicates elliptical shape extended to out-of-plane direction.

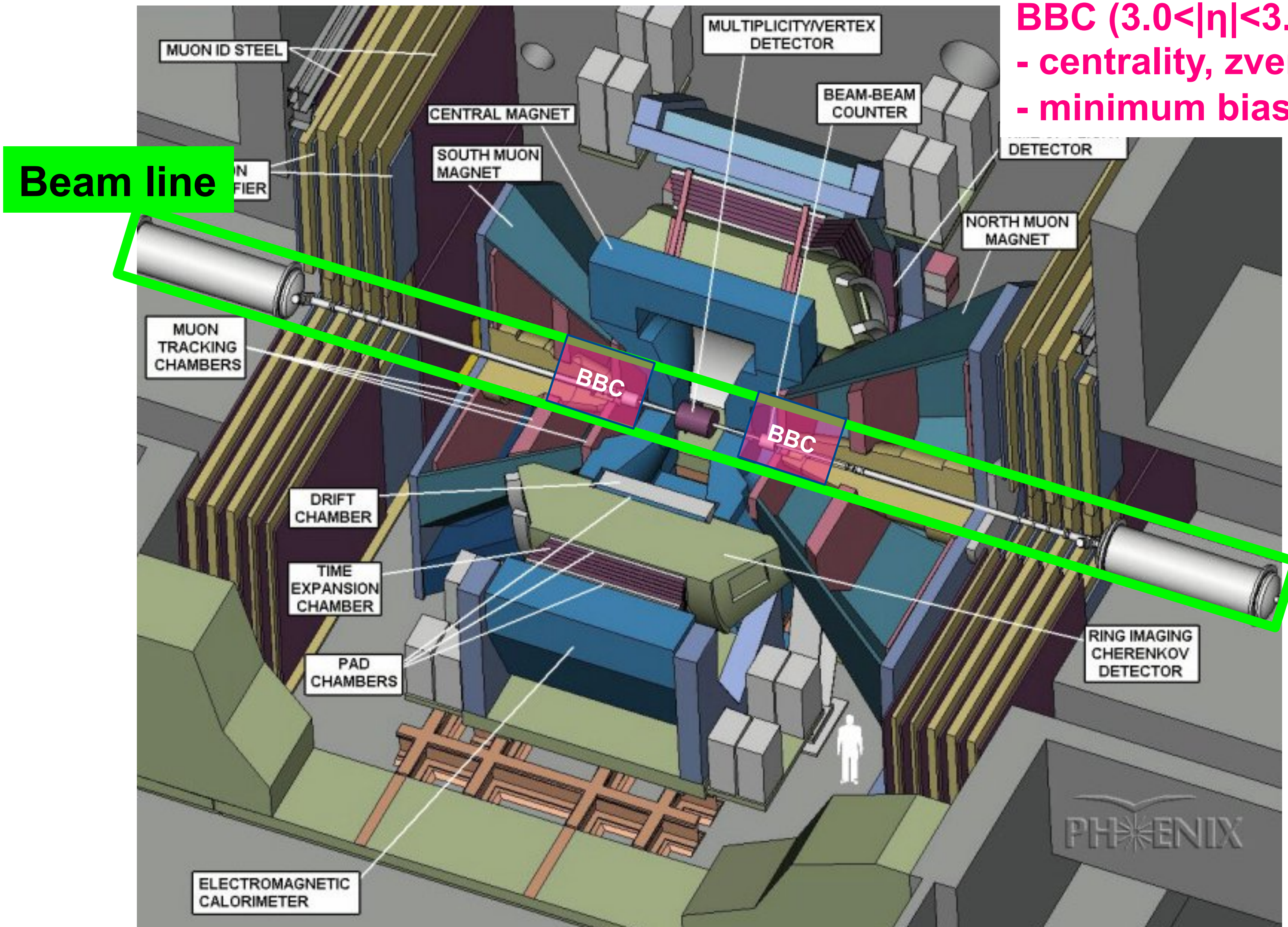
Results of HBT w.r.t 2^{nd}- and 3^{rd}-order event planes are presented today!

PHENIX Experiment

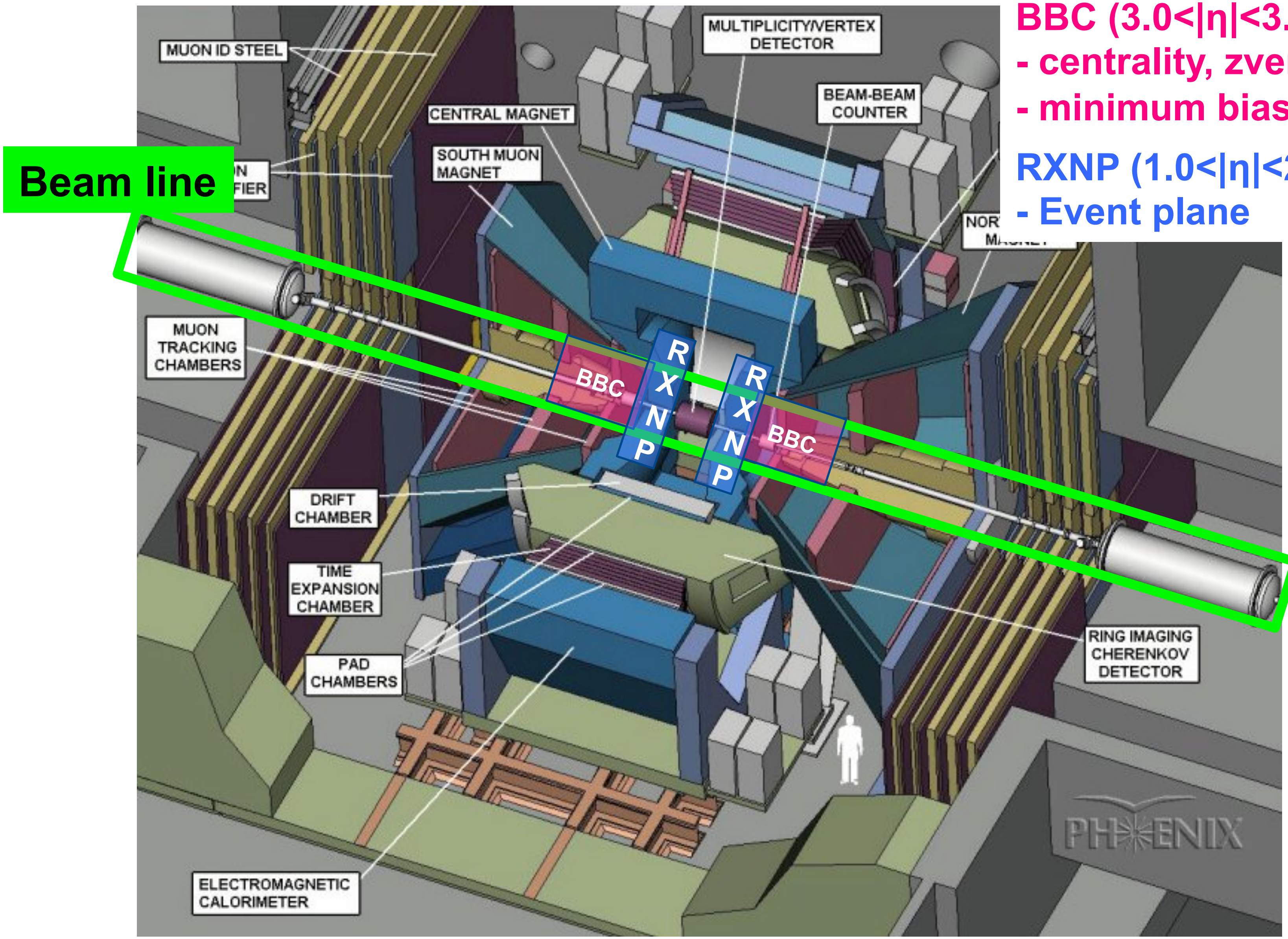


PHENIX Experiment

BBC (3.0<|η|<3.9)
- centrality, zvertex
- minimum bias trigger



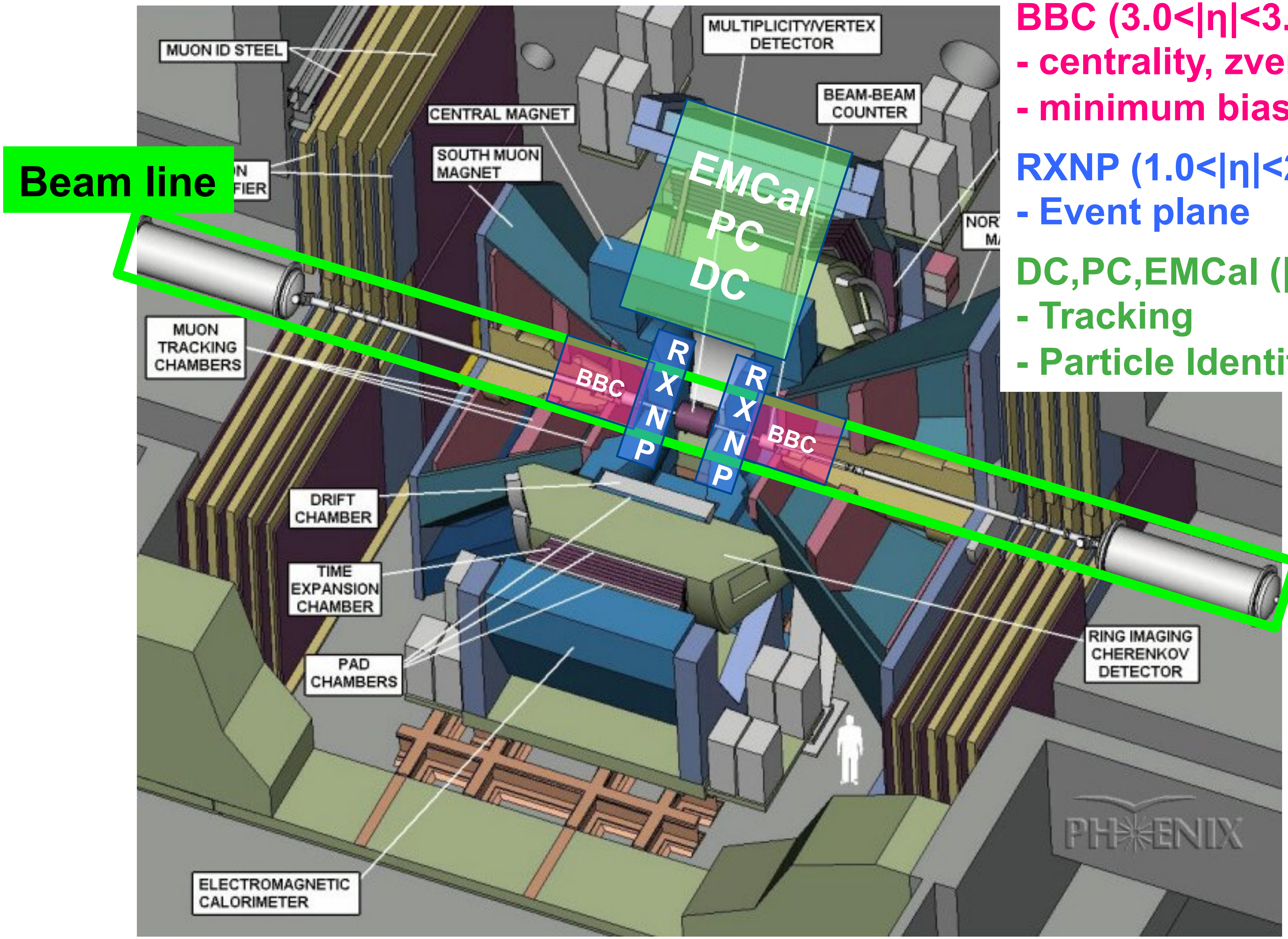
PHENIX Experiment



BBC (3.0<|η|<3.9)
- **centrality, zvertex**
- **minimum bias trigger**

RXNP (1.0<|η|<2.8)
- **Event plane**

PHENIX Experiment

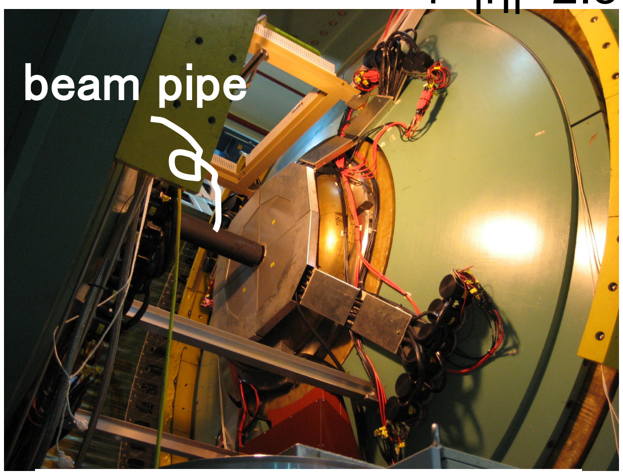


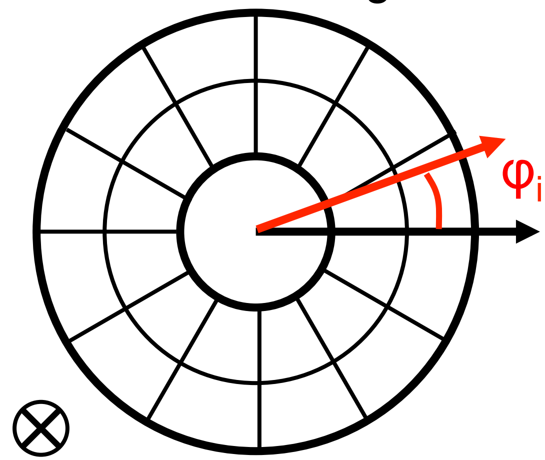
BBC ($3.0<|\eta|<3.9$)
- **centrality, zvertex**
- **minimum bias trigger**

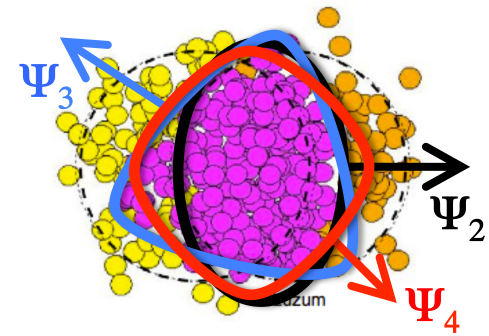
RXNP ($1.0<|\eta|<2.8$)
- **Event plane**

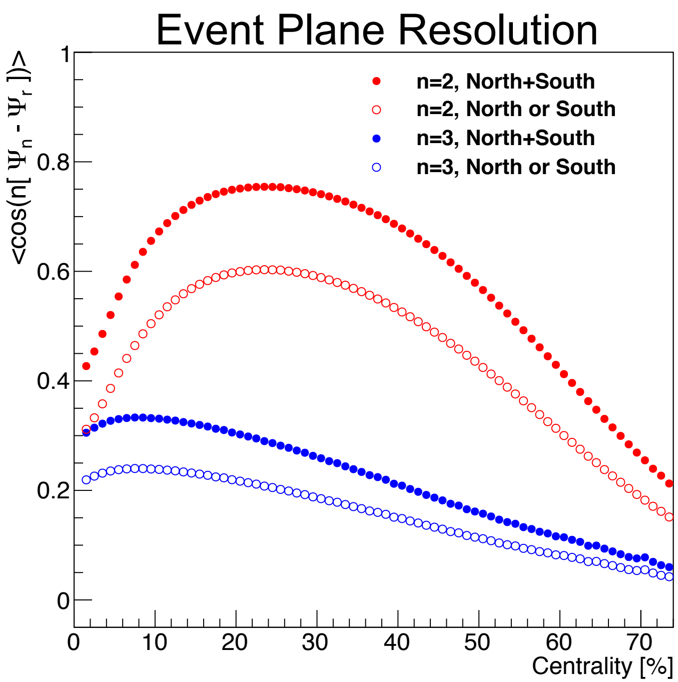
DC,PC,EMCal ($|\eta|<0.35$)
- **Tracking**
- **Particle Identification**

Event Plane Determination









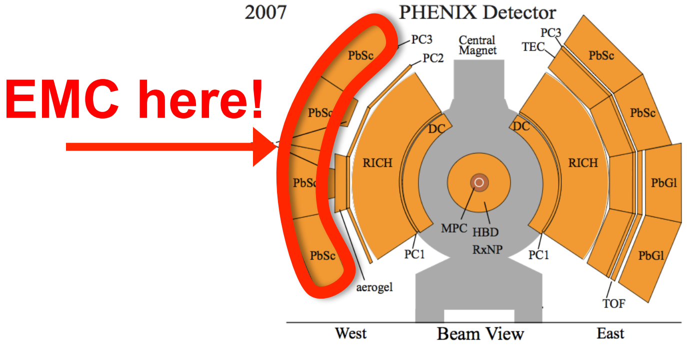
- **Determined by anisotropic flow itself using Reaction Plane Detector**

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

- **EP resolutions <cos[n(Ψ_n-Ψ_{real})]>**

✧Res{Ψ_2} ~ 0.75, Res{Ψ_3} ~ 0.34

Particle IDentification

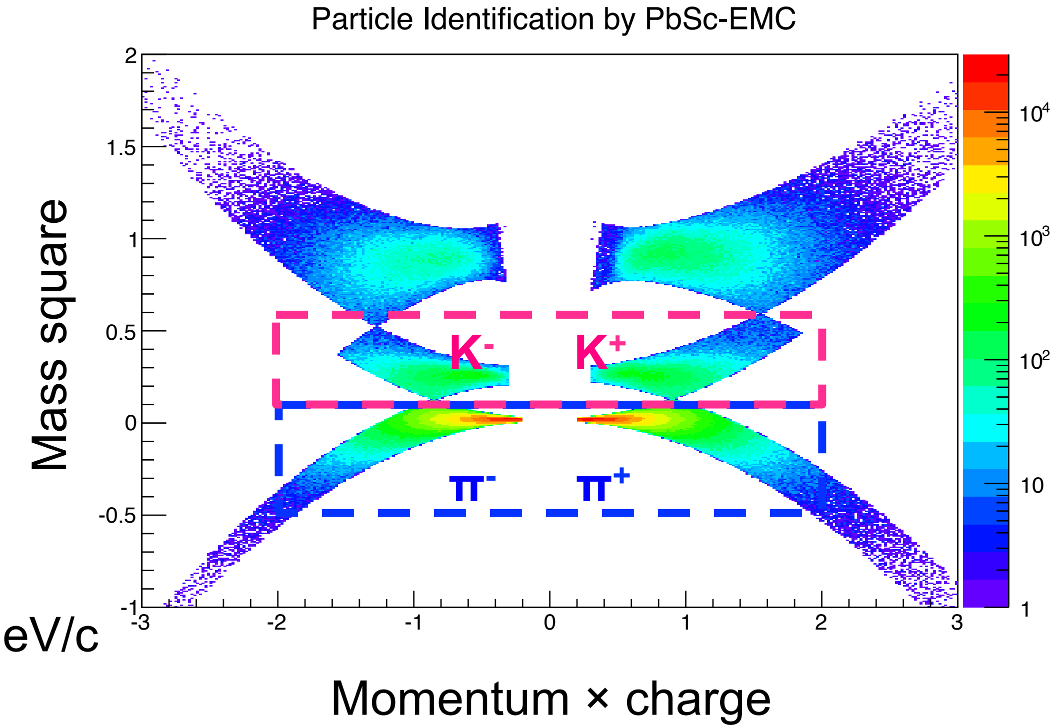


- **EMC-PbSc is used.**
  - ✧ timing resolution ~ 600 ps
- **Time-Of-Flight method**

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

p: momentum L: flight path length
t: time of flight

- **Charged π within 2σ**
  - ✧π/K separation up to ~1 GeV/c

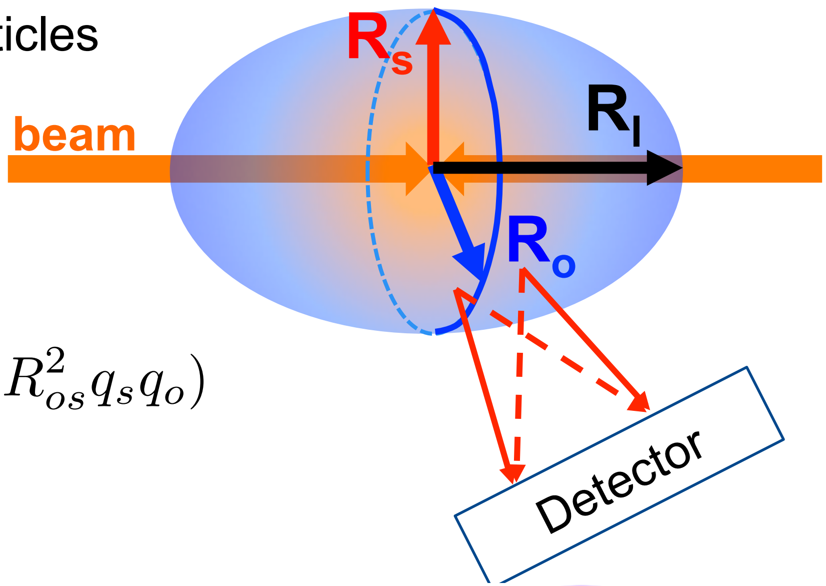


3D-HBT Analysis

- **Core-Halo picture with "Out-Side-Long" frame**
  - ✧Longitudinal center of mass system ($p_{z1}=p_{z2}$)
  - ✧taking into account long lived decay particles

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

$$\vec{q}_o \parallel \vec{k}_T, \quad \vec{q}_s \perp \vec{k}_T$$

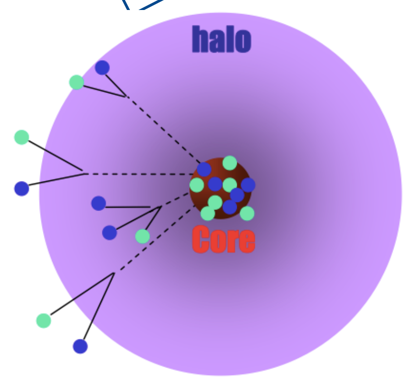


$$C_2 = C_2^{core} + C_2^{halo}$$

$$= [\lambda(1+G)F_{coul}] + [1-\lambda]$$

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

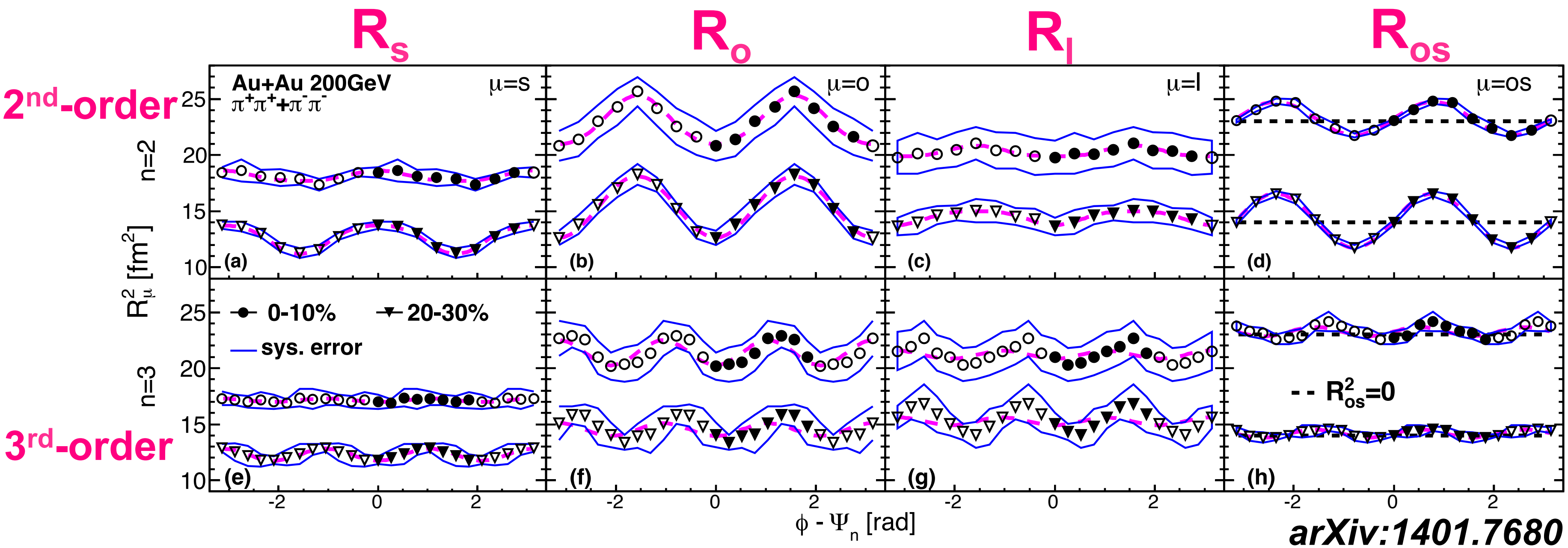
F_{coul}: Coulomb correction factor
λ : fraction of pairs in the core



R_l = Longitudinal Gaussian source size
R_s = Transverse Gaussian source size
R_o = Transverse Gaussian source size + Δ τ
R_{os}= Cross term b/w side– and outward drections

RESULTS

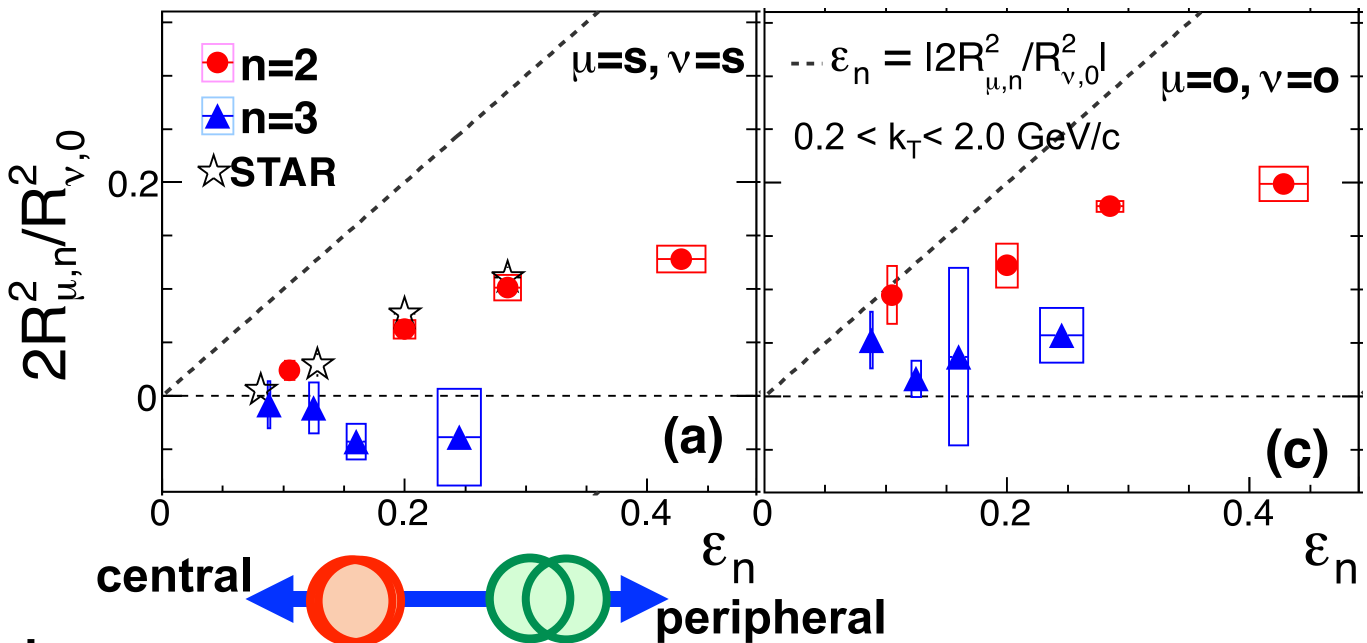
HBT radii w.r.t 2nd- and 3rd-order event planes



arXiv:1401.7680

- **Oscillation w.r.t Ψ_2 could be intuitively explained by out-of-plane extended elliptical source**
  - ✧Opposite sign of R_s and R_o
- **For Ψ_3, weak but finite oscillations can be seen, especially in R_o**
  - ✧Same sign of R_s and R_o in 20-30% centrality
- **R_o oscillation > R_s oscillation for both orders**

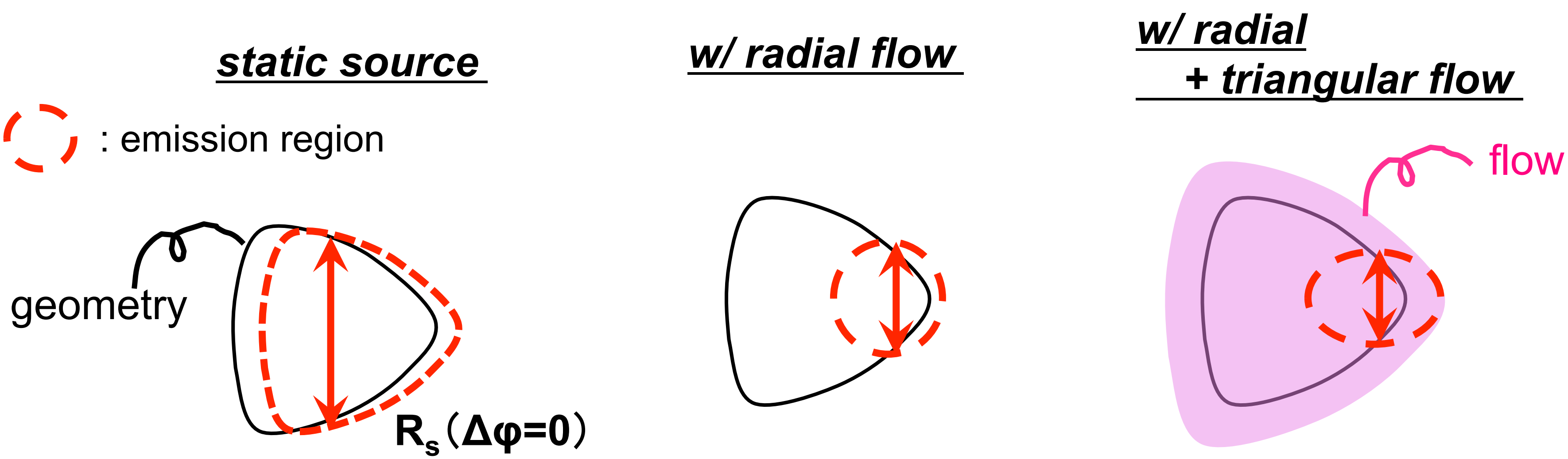
Initial ε_n vs oscillation amplitudes



- **2^{nd}-order**
  - ✧$2R_{s,2}^2/R_{s,0}^2$ ~ final source eccentricity under the BW model, and consistent with STAR result
  - ✧$\varepsilon_{final} \approx \varepsilon_{inital}/2$, source eccentricity is reduced, but still retain initial shape extended out-of-plane
- **3^{rd}-order**
  - ✧Weaker oscillation and no significant centrality(ε_n) dependence
  - ✧$R_{s,3}^2 \leq 0$ and $R_{o,3}^2 \geq 0$ are seen in all centralities.
- **Does this result indicate non spatial triangularity at final state?**

Triangular deformation can be observed via HBT?

- **HBT radii w.r.t Ψ_3 don't almost show oscillation in a static source, but it appears in a expanding source. (S. Voloshin, J. Phys. G38, 124097)**
- **Initial triangularity is weaker than initial eccentricity (Glauber MC)**
  - ✧ Effect of triangular flow may be dominant for the emission region



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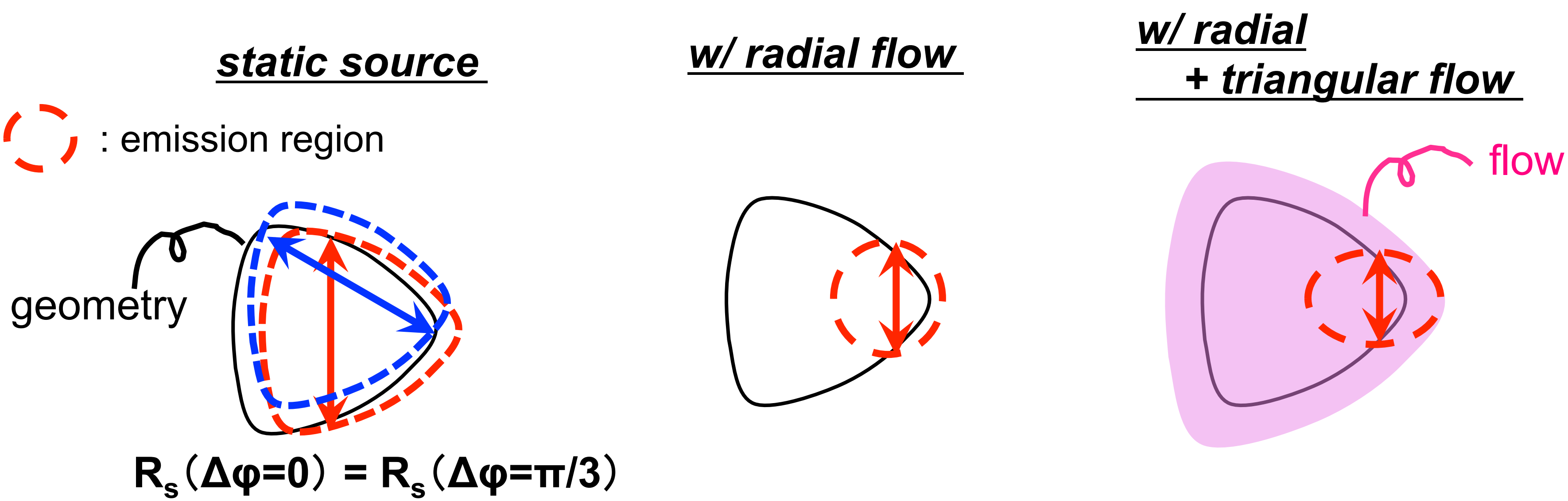

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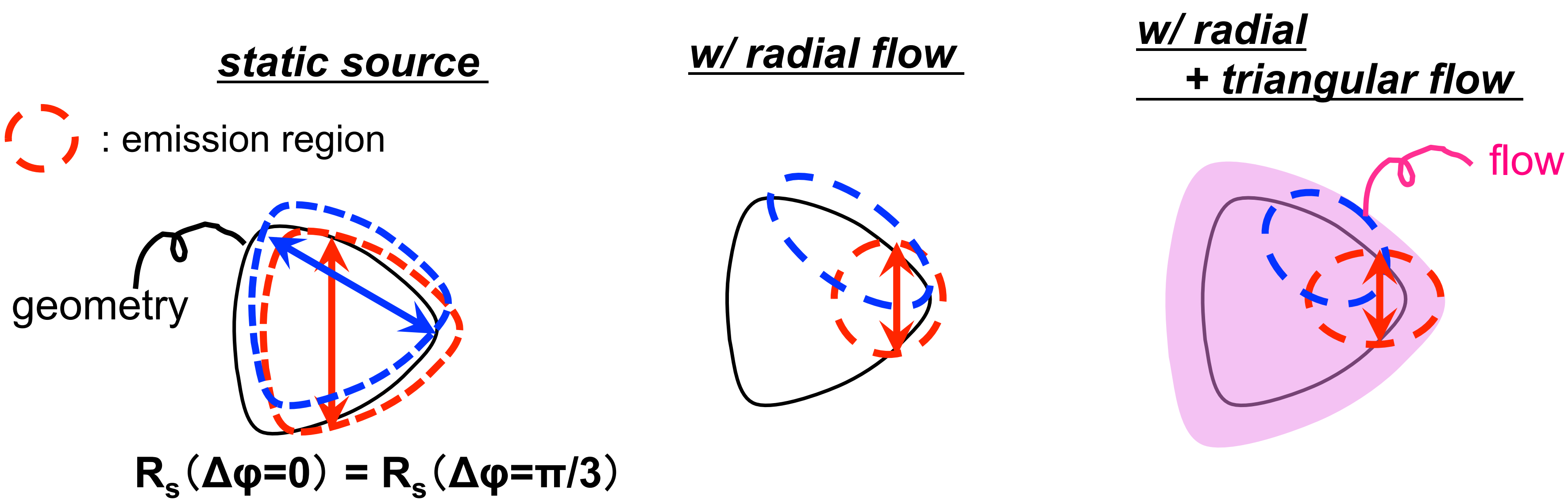
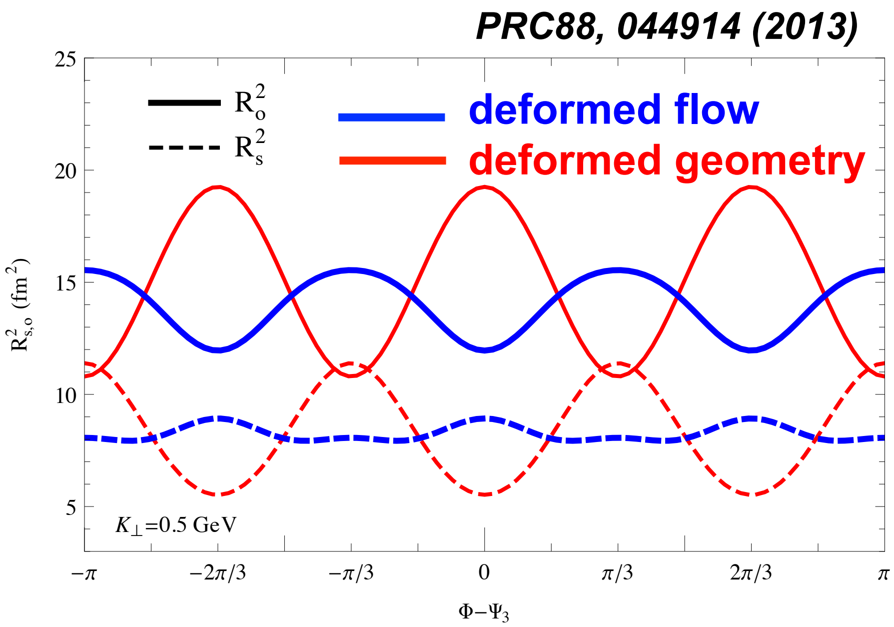


- **HBT w.r.t Ψ_3 (also Ψ_2) results from combination of spatial and flow anisotropy**
  - ✧Need to disentangle both contributions!!

Gaussian toy model



- **Gaussian source including 3rd-order modulation for flow and geometry**
  - ✧ $\bar{\epsilon}_3$: triangular spatial deformation
  - ✧ $\bar{v}_3$: triangular flow deformation

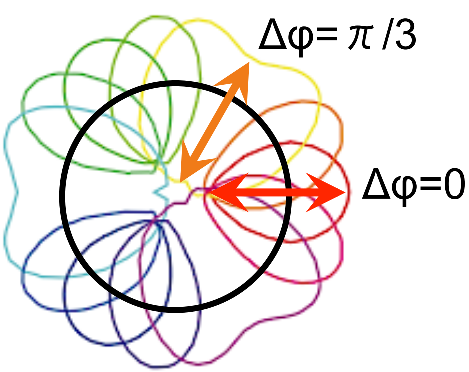
Emission function(S) and transverse flow rapidity η_t :

$$\tilde{S}(x,K) \propto \exp[-\frac{r^2}{2R^2}(1+2\bar{\epsilon}_3\cos[3(\phi-\bar{\psi}_3)])]$$

$$\eta_t = \eta_f \frac{r}{R}(1+2\bar{v}_3\cos[3(\phi-\bar{\psi}_3)])$$

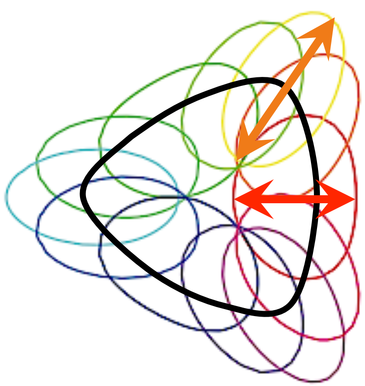
deformed flow

$\bar{\epsilon}_3 = 0, \bar{v}_3 \neq 0$



deformed geometry

$\bar{\epsilon}_3 \neq 0, \bar{v}_3 = 0$

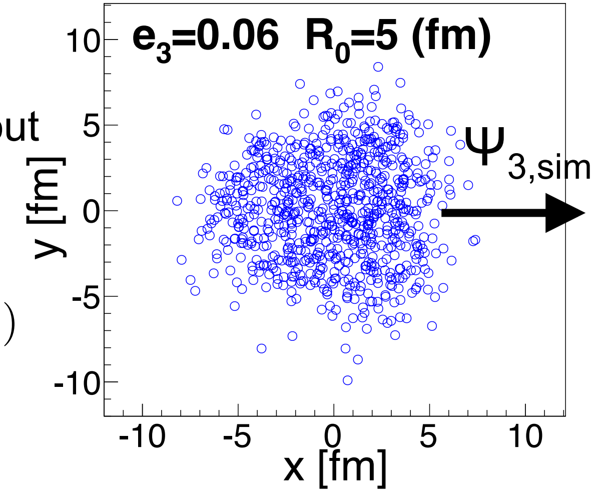


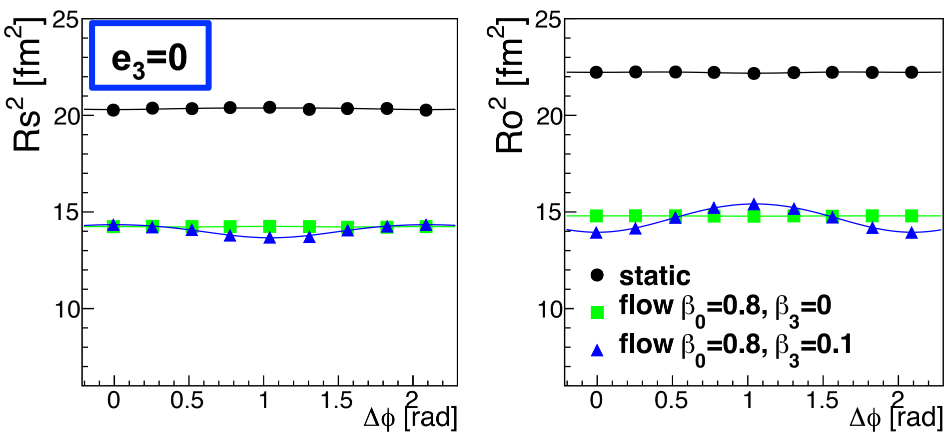
- **Two extreme case was tested**
  - ✧ Spherical source with triangular flow(+radial flow)
  - ✧ Triangularly deformed source with radial flow
- **"Deformed flow" shows qualitative agreement with data**

Monte-Carlo simulation

- **Similar to Blast-wave model but Monte-Carlo approach**
  - ✧thermal motion + transverse boost (PRC70.044907)
  - ✧introduced spatial anisotropy and triangular flow at freeze-out
- **Setup**
  - ✧Woods-saxon particle distribution:
    $\Omega = 1/(1+\exp[(r-R)/a]),\ \ R = R_0(1-2e_3\cos[3(\phi-\Phi)])$
  - ✧transverse flow: $\beta_T = \beta_0(1+2\beta_3\cos[3(\phi-\Psi)])$
  - ✧HBT correlation: $1+\cos(\Delta x\cdot\Delta p)$
  - ✧parameters like T_f(temperature), β_0, R_0 were tuned by spectra and mean HBT radii

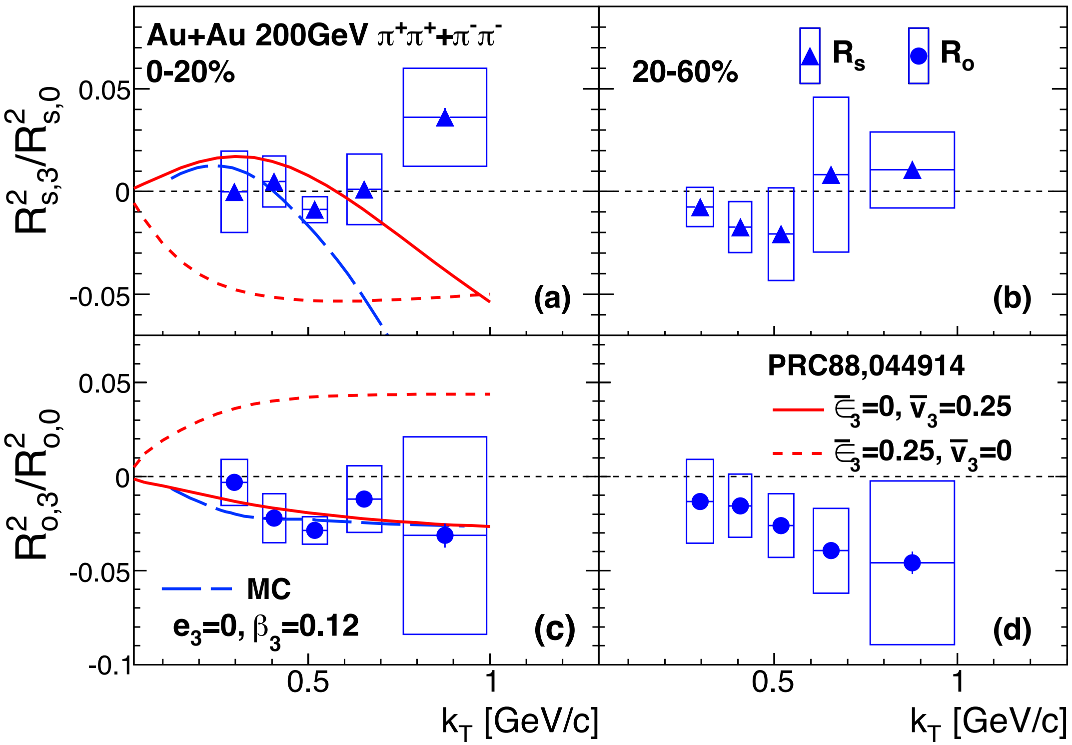
※Assuming the spatial and momentum dist. at freeze-out



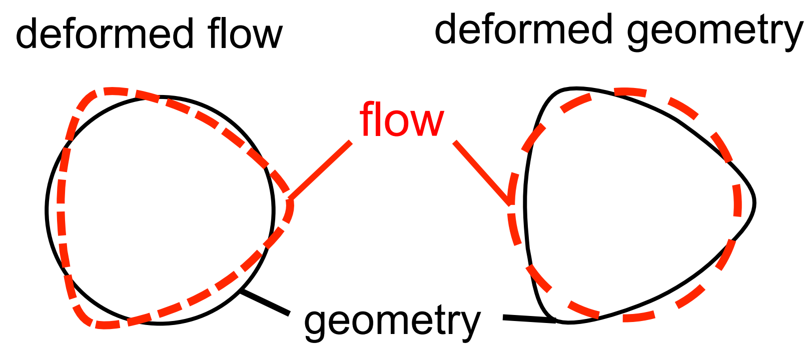


- **Oscillations of R_s^2 and R_o^2 are controlled by e_3 and β_3**

k_T dependence of 3rd-order oscillation amplitude

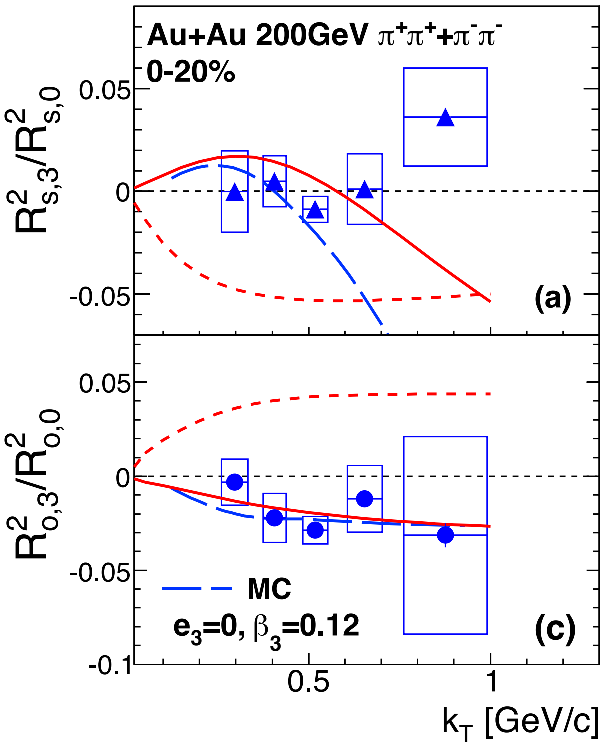


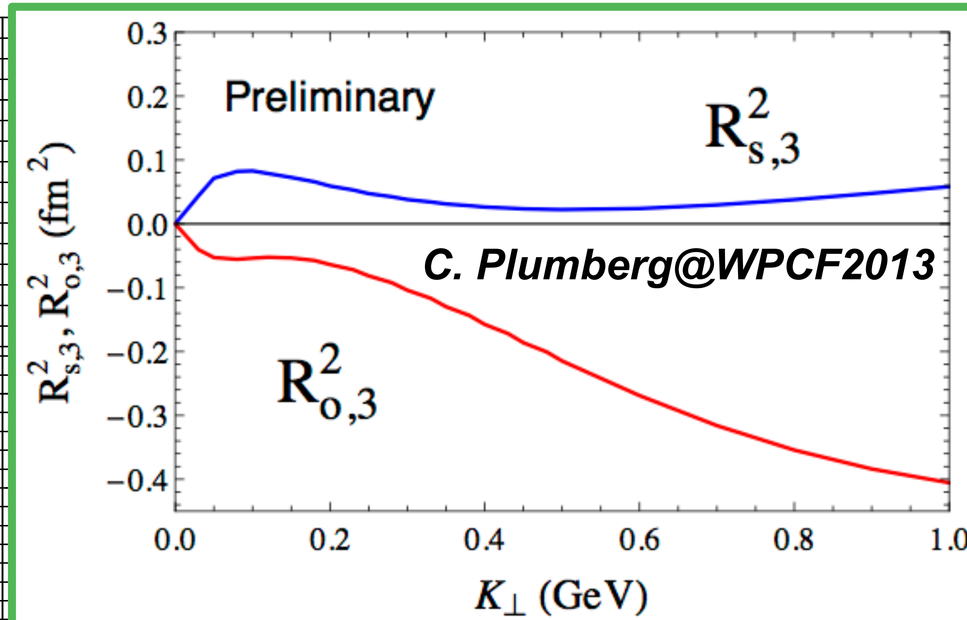
- **MC simulation qualitatively agrees with Gaussian toy model**



- **$R_{o,3}^2$ seems to be explained by "deformed flow" in both centralities.**
  - ✧Note that model curves are scaled by 0.3 for the comparison with the data
- **$R_{s,3}^2$ seems to show a slight opposite trend to "deformed flow".**
  - ✧Zero~negative value at low m_T, and goes up to positive value at higher m_T

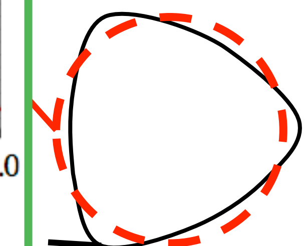
k_T dependence of 3^{rd}-order oscillation amplitude





alitatively
sian toy model

formed geometry



Behavior of $R_{s,3}{}^2$ at higher k_T may be reproduced by a full hydrodynamic calculation.

- **$R_{o,3}{}^2$ seems to be explained by "deformed flow" in both centralities.**
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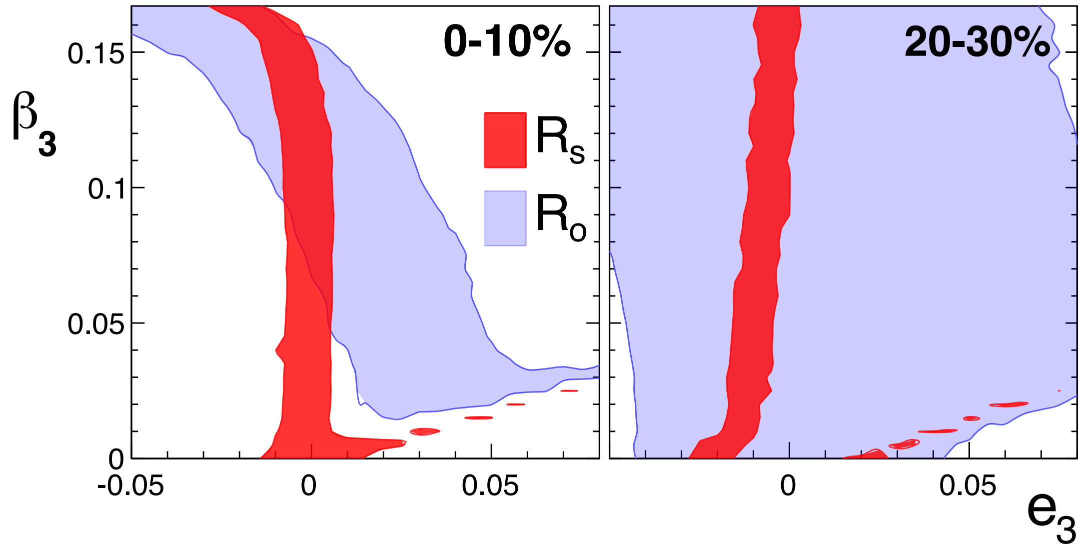
- **$R_{s,3}{}^2$ seems to show a slight opposite trend to "deformed flow".**
  - ✧Zero~negative value at low k_T, and goes up to positive value at higher k_T

Constrain spatial(e_3) and flow(β_3) anisotropy

- MC simulation are compared to data varying e_3 and β_3
- χ^2 minimization: $\chi^2 = (([R^2_{\mu,3}/R^2_{\mu,0}]^{\text{exp}} - [R^2_{\mu,3}/R^2_{\mu,0}]^{\text{sim}})/E)^2$

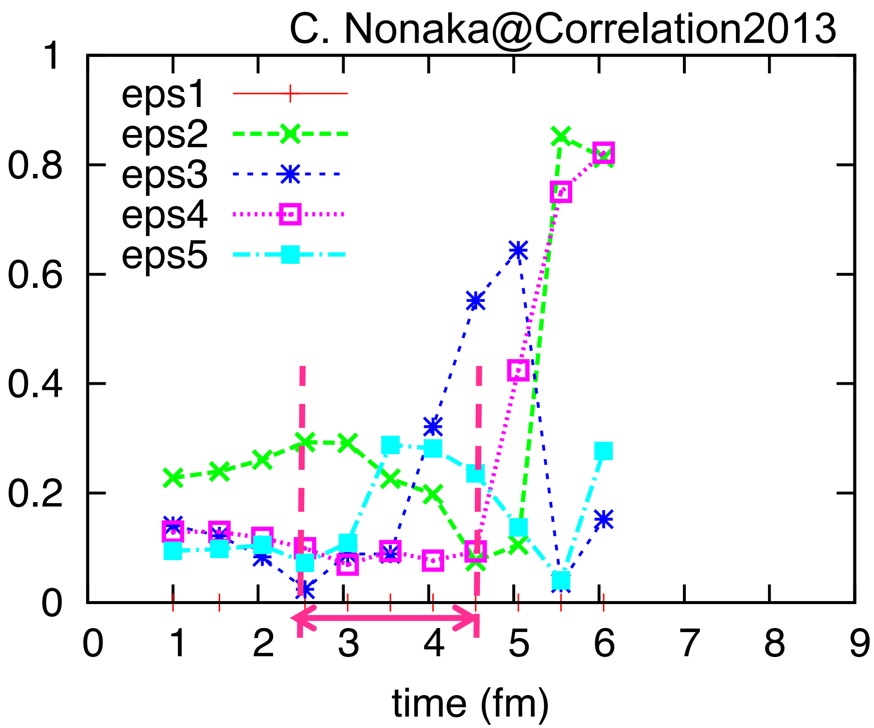
where E is experimental uncert.. Shaded areas show $\chi^2<1$.



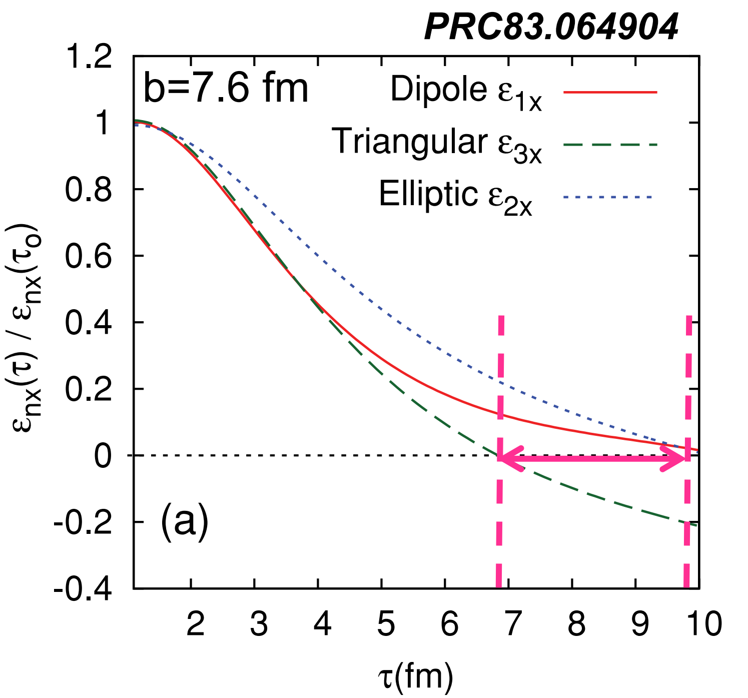
- e_3 is well constrained by $R_{s,}$ less sensitivity to β_3
- Overlap of R_s and R_o shows positive β_3 and zero e_3 in 0-10%
- R_s seems to favor negative e_3 in 20-30%
  - Triangular deformation is reversed at freeze-out?

Time evolution of spatial anisotropy

- **MC-KLN + e-b-e Hydrodynamics**
  ✧15-20%, Parameters are not tuned.



- **IC with cumulant expansion + ideal Hydrodynamics**



➢ **The time that ε_3 turns over is faster than ε_2 in the hydrodynamic models.**

➢ **Comparison with (e-b-e) full hydrodynamics may constrain the space-time picture of the system.**

Summary

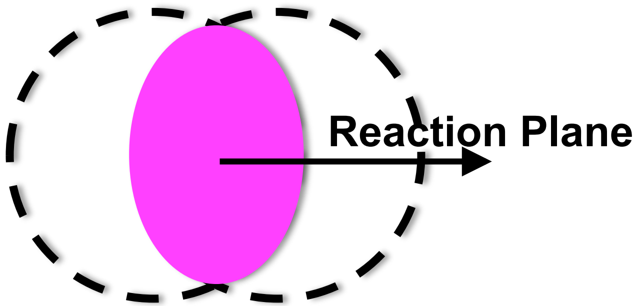
- **Azimuthal angle dependence of HBT radii w.r.t 2nd- and 3rd-order event planes was measured at PHENIX**
  - ✧Finite oscillation of R_o^2 is seen for 3rd-order event plane as well as 2nd-order.
  - ✧Gaussian toy model and MC simulation were compared with data. They suggest that R_o oscillation comes from triangular flow.
  - ✧χ^2 minimization by MC simulation shows finite β_3 and zero ~ slightly negative e_3, which may imply that initial triangular shape is significantly diluted, and possibly reversed by the medium expansion

THANK YOU!

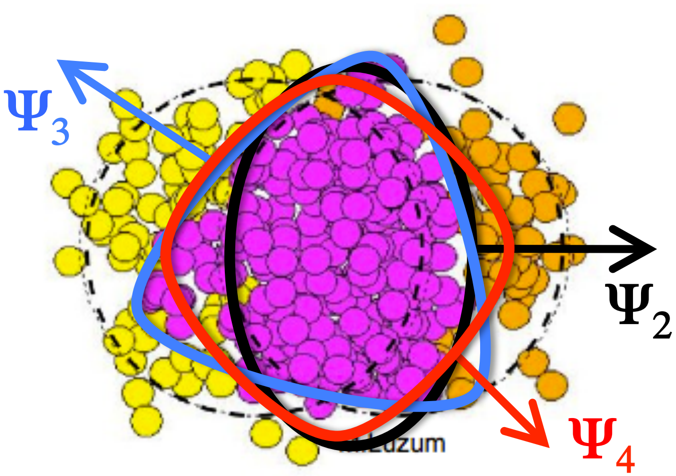
Higher Harmonic Flow and Event Plane

- **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

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.

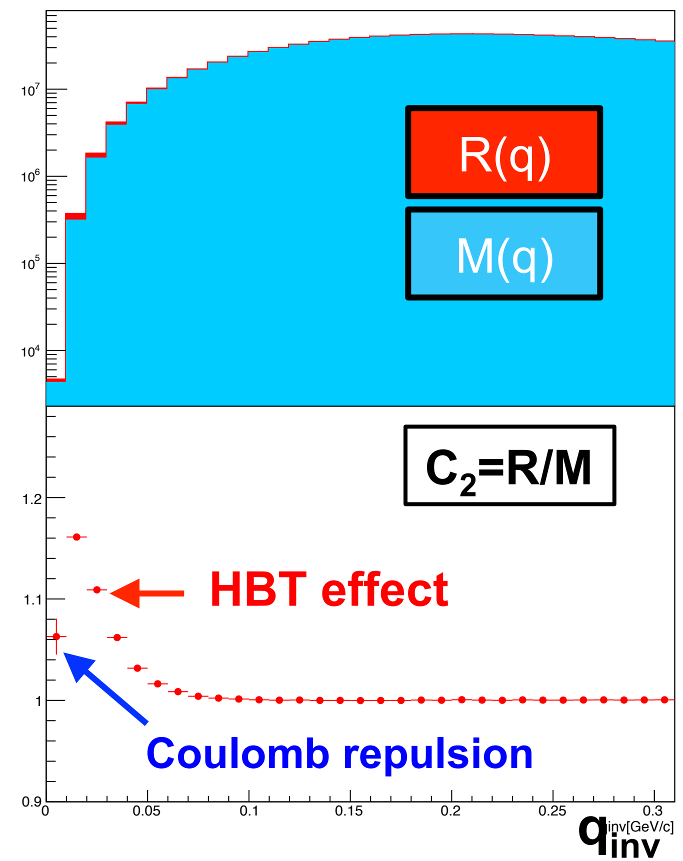
$$C_2 = \frac{R(\mathbf{q})}{M(\mathbf{q})}$$

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

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

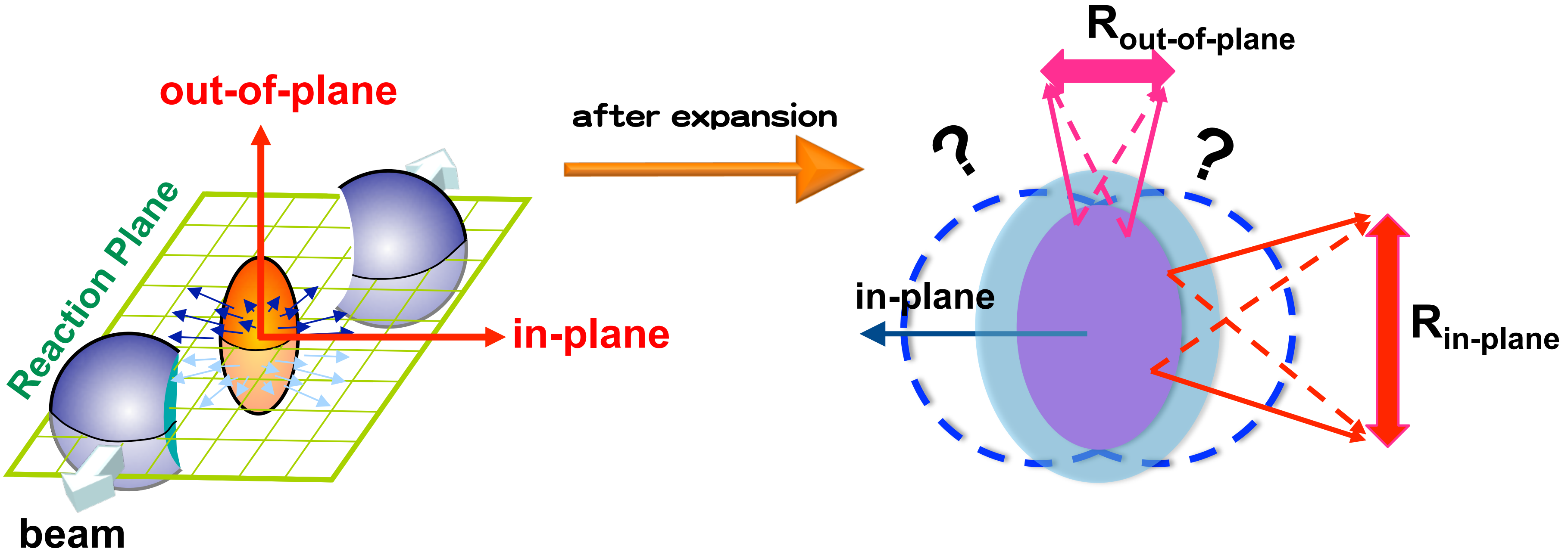
  Mixed pairs doesn't include HBT and Coulomb effects.

relative momentum dist.



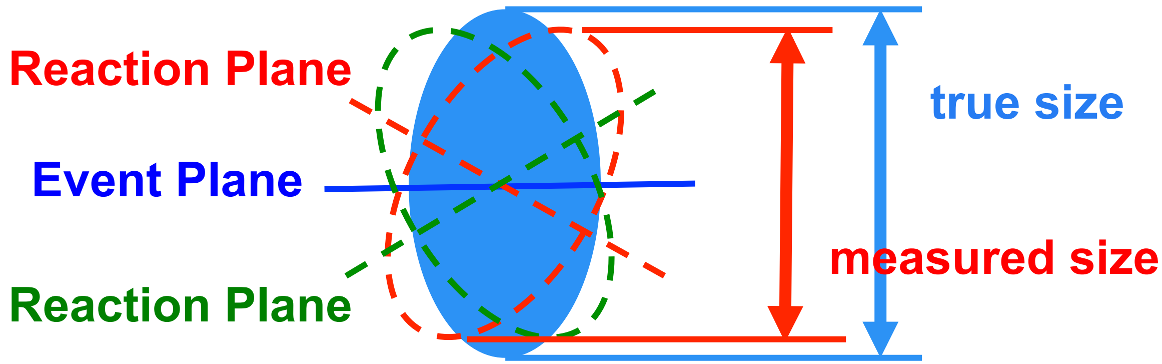
Spatial anisotropy at final state

- **Angle dependence of HBT radii relative to Reaction Plane reflects the source shape at kinetic freeze-out.**
- **Initial spatial anisotropy causes momentum anisotropy (flow anisotropy)**
  - ✧One may expect in-plane extended source at freeze-out
- **Final source eccentricity will depend on initial eccentricity, flow profile, expansion time, and viscosity etc.**



Correction of Event Plane Resolution

- Smearing effect by finite resolution of the event plane



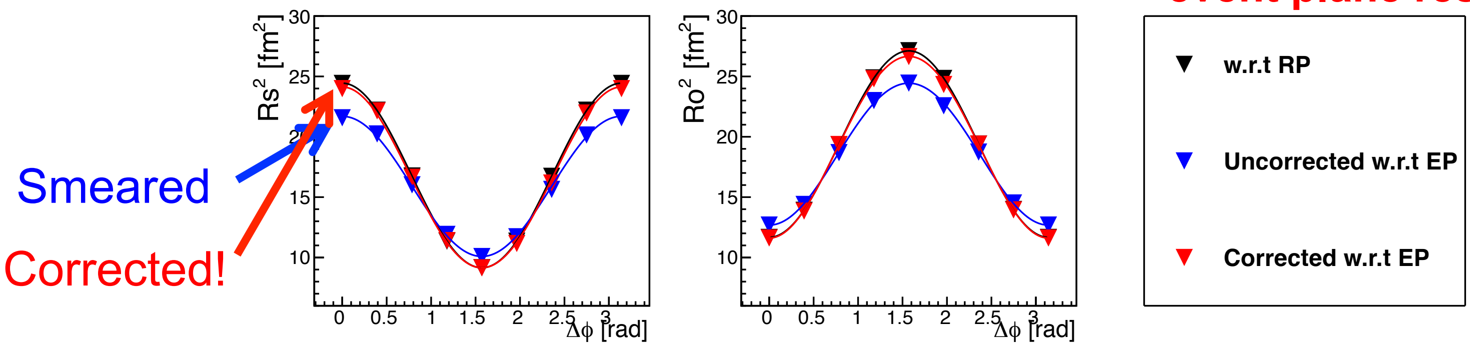
- Correction for q-distribution

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

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

event plane resolution

  - ✧PRC.66, 044903(2002)
    - ✓ model-independent correction
  - ✧Checked by MC-simulation



Centrality dependence of v_n and initial ε_n

Higher harmonic flow v_n | **Initial source anisotropy ε_n**

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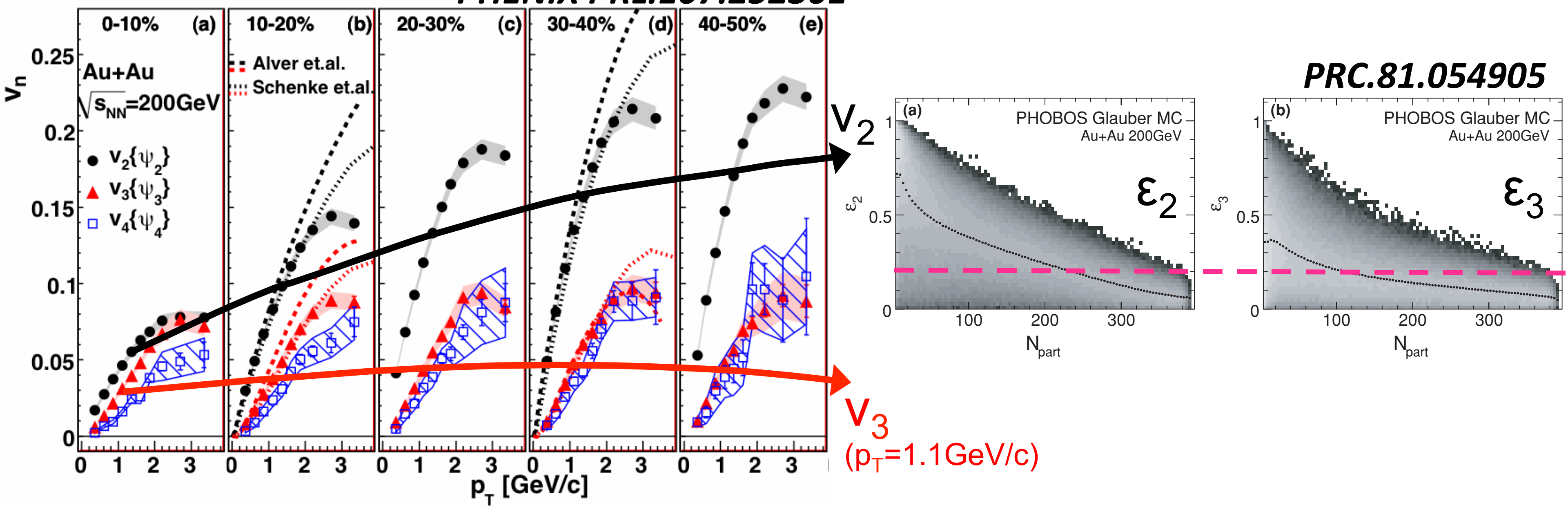
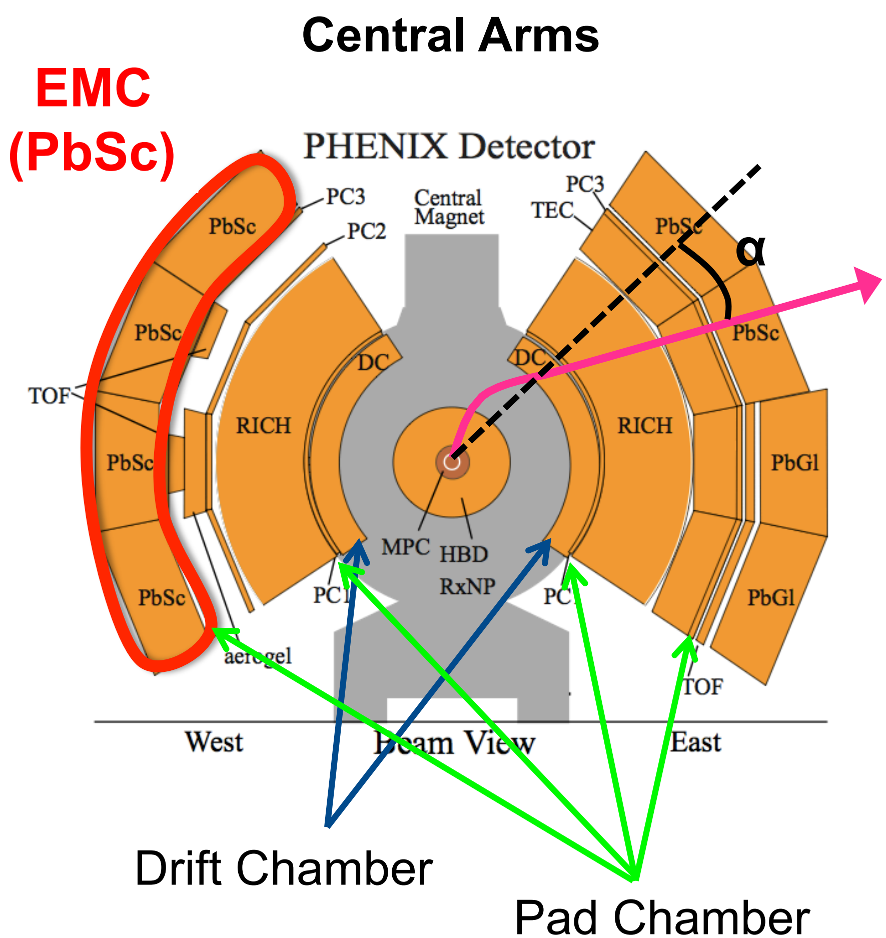


- Weak centrality dependence of v_3 unlike v_2
- Initial ε_3 has finite values and weaker centrality dependence than ε_2 in Glauber MC simulation

Triangular component in source shape exists at final state?
➡Measurement of HBT radii relative to Ψ_3

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