HBT measurement with respect to event plane in Pb-Pb at 2.76TeV collisions from ALICE

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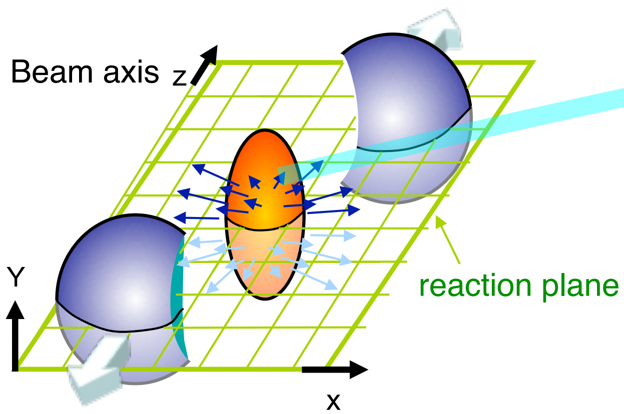
Naoto Tanaka for the ALICE collaboration
University of Tsukuba

JPS meeting @ University of Miyazaki

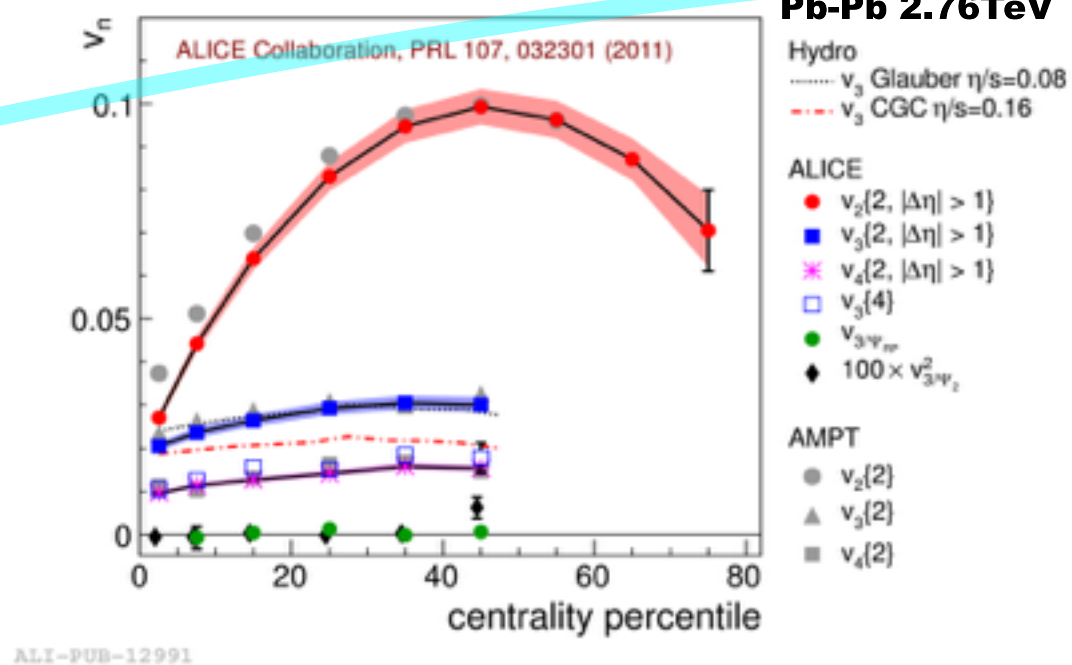
筑波大学
University of Tsukuba

Space time evolution and azimuthal anisotropy

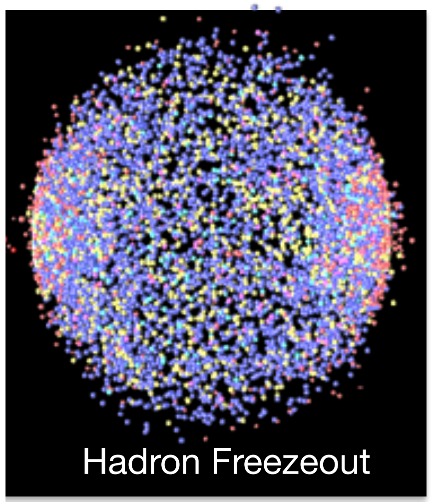
Initial geometry



Azimuthal anisotropy



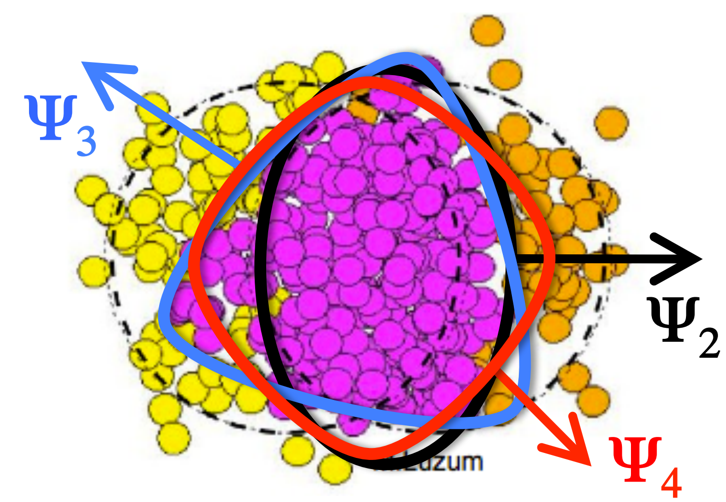
Source shape @ freezeout



✦A powerful probe of hydrodynamic evolution

✦ **Azimuthal anisotropy** $v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$

✦ **Event plane** $\Psi_n = \frac{1}{n} \tan^{-1} \left(\frac{\sum w_i \sin(n\phi_i)}{\sum w_i \cos(n\phi_i)} \right)$



■Source shape @ freeze out

✓ A lot of parameters contributes to the final source shape

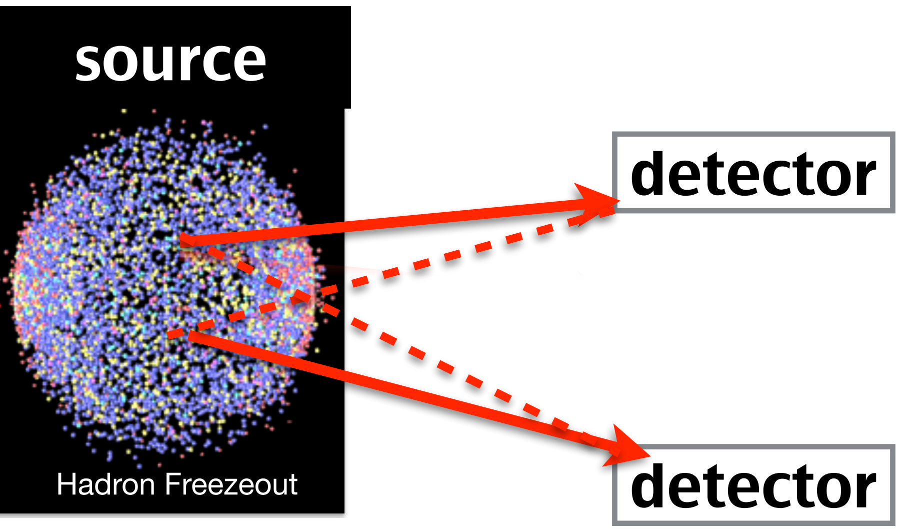
- **Initial eccentricity, collective flow, evolution time and viscosity**

✦ **To quantify the properties of QGP, a precise understanding of spatial and temporal evolution is required**

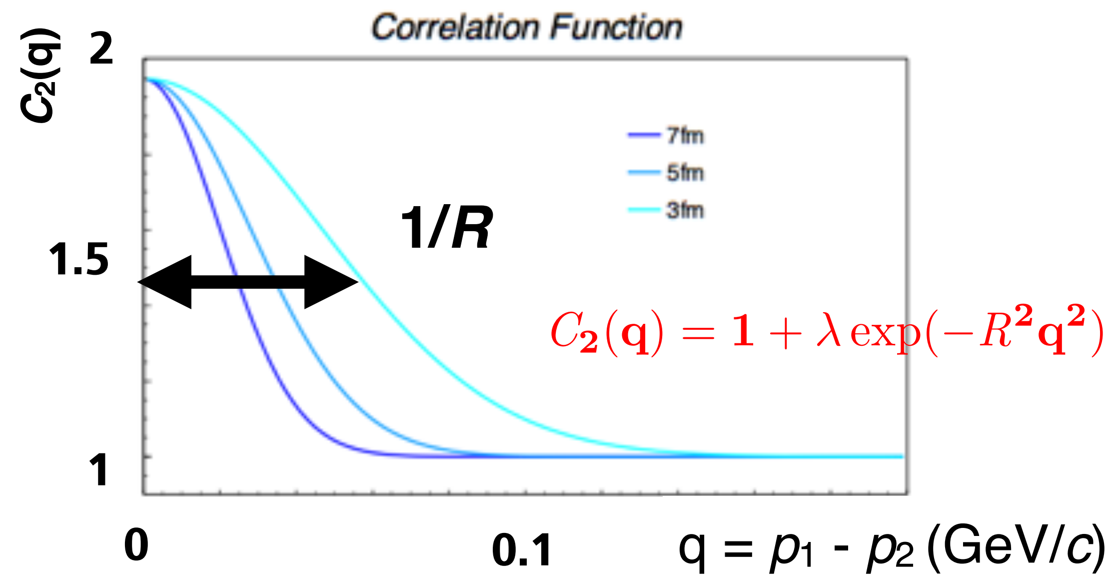
HBT

Method to measure the source size with two identical particles

- Quantum interference between two identical particles
- **Unique tool** to measure source size at kinetic freeze out
- Geometrical source size ≠ HBT radii = "**Length of homogeneity**"



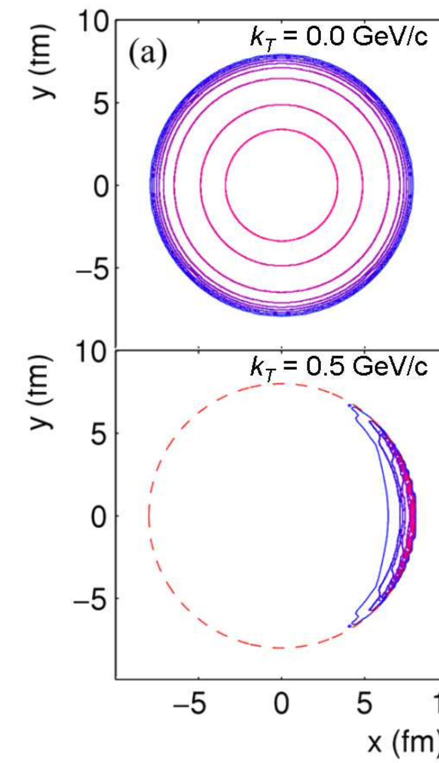
$$C_2(p_1,p_2) \equiv \frac{P\ (p_1,p_2)}{P(p_1)P(p_2)}$$



$$C_2(\mathbf{q}) = 1 + \lambda \exp(-R^2\mathbf{q}^2)$$

★ k_T dependence

$$\overrightarrow{k_T} = \frac{(\overrightarrow{p_{T1}} + \overrightarrow{p_{T2}})}{2}$$



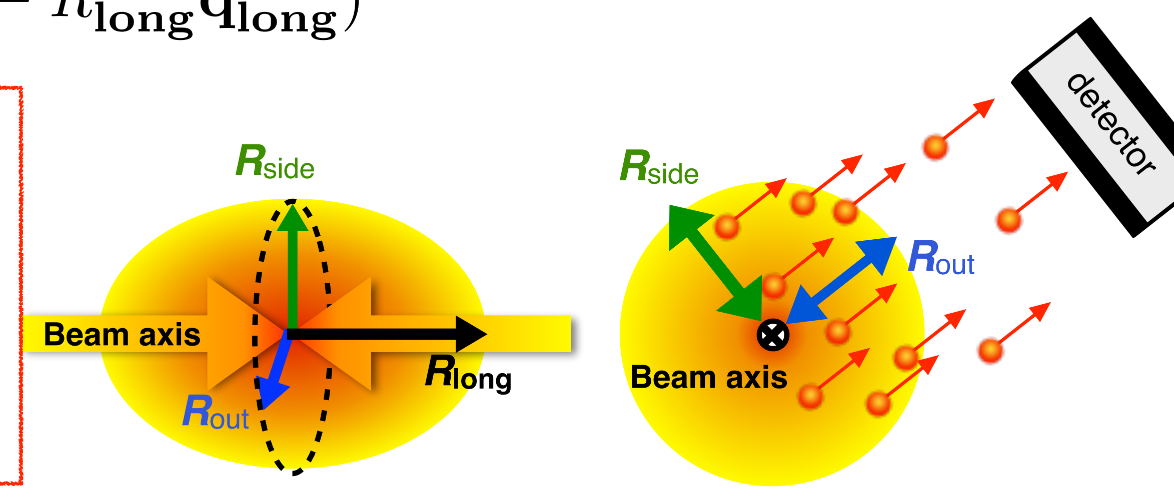
nucl-th/0305084

3D HBT analysis

Bertsch Pratt parametrization

$$C_2(\mathbf{q}_{\mathbf{out}}, \mathbf{q}_{\mathbf{side}}, \mathbf{q}_{\mathbf{long}}) = \mathbf{1} + \lambda(-R^2_{\mathbf{out}}\mathbf{q}^2_{\mathbf{out}} - R^2_{\mathbf{side}}\mathbf{q}^2_{\mathbf{side}} - R^2_{\mathbf{long}}\mathbf{q}^2_{\mathbf{long}})$$

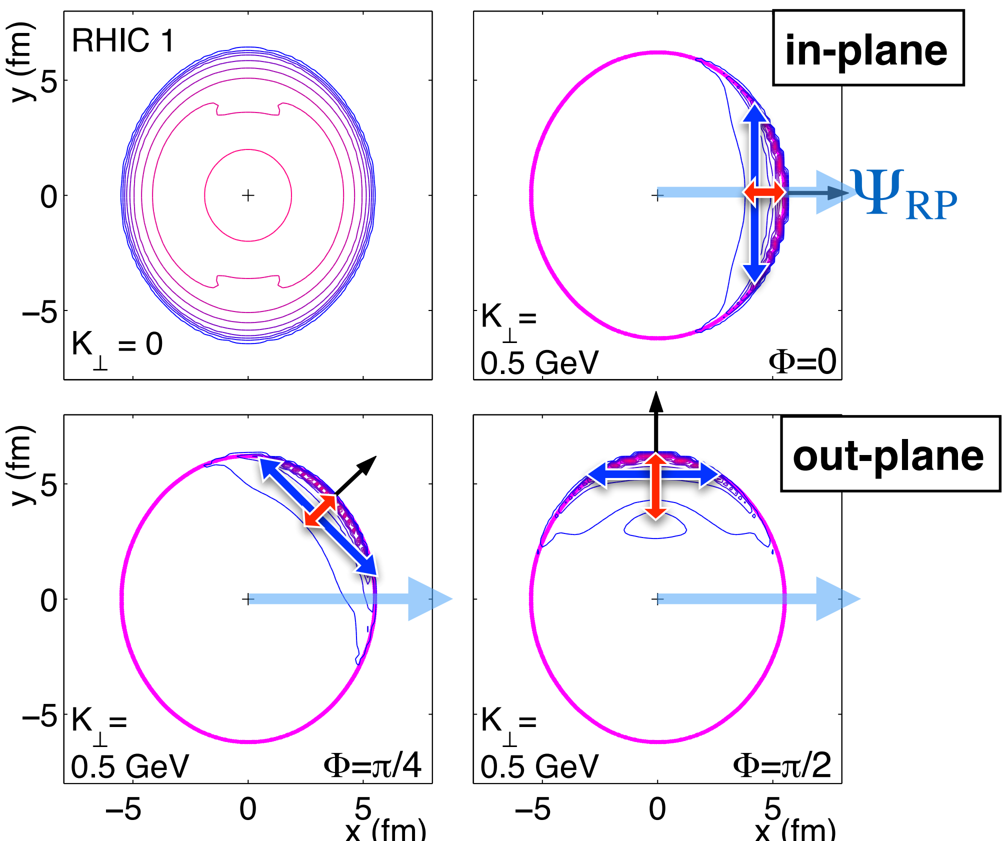
R_{long} : source size along the longitudinal direction (beam direction)
R_{out} : source along the pair transverse momentum + emission duration
R_{side} : source size along the perpendicular to Rout
λ : chaoticity = (in coherence) – (resonance) – (Background)



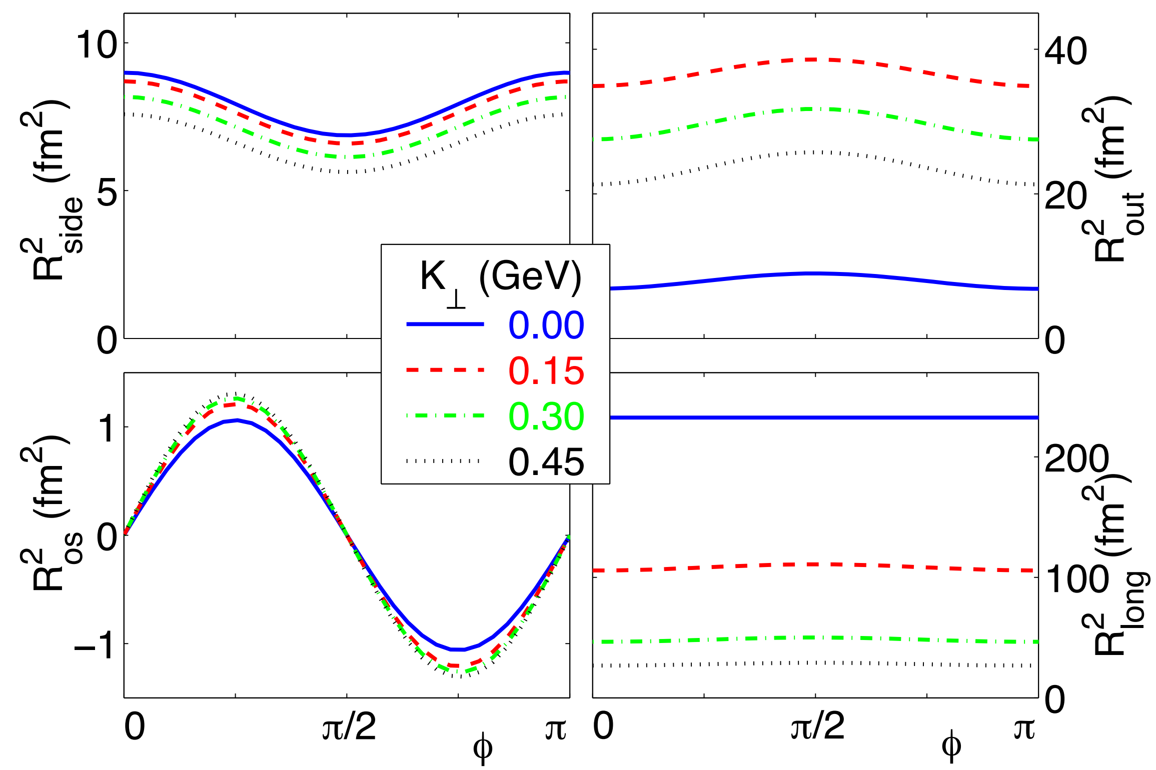
Azimuthally sensitive HBT with respect to Ψ_2

- **Dividing the pair angle relative to the Ψ_2 in azimuthal plane**
- Differential azimuthal angle HBT measurements explores **spatial deformation of the source**
- Hydrodynamical model shows **oscillation** in azimuthal angle dependence of HBT radii (**out-of-plane extended source shape**)

Hydrodynamic model
Au+Au 130GeV



Azimuthal angle dependence of HBT radii



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R_{side} : width
R_{out} : depth + time

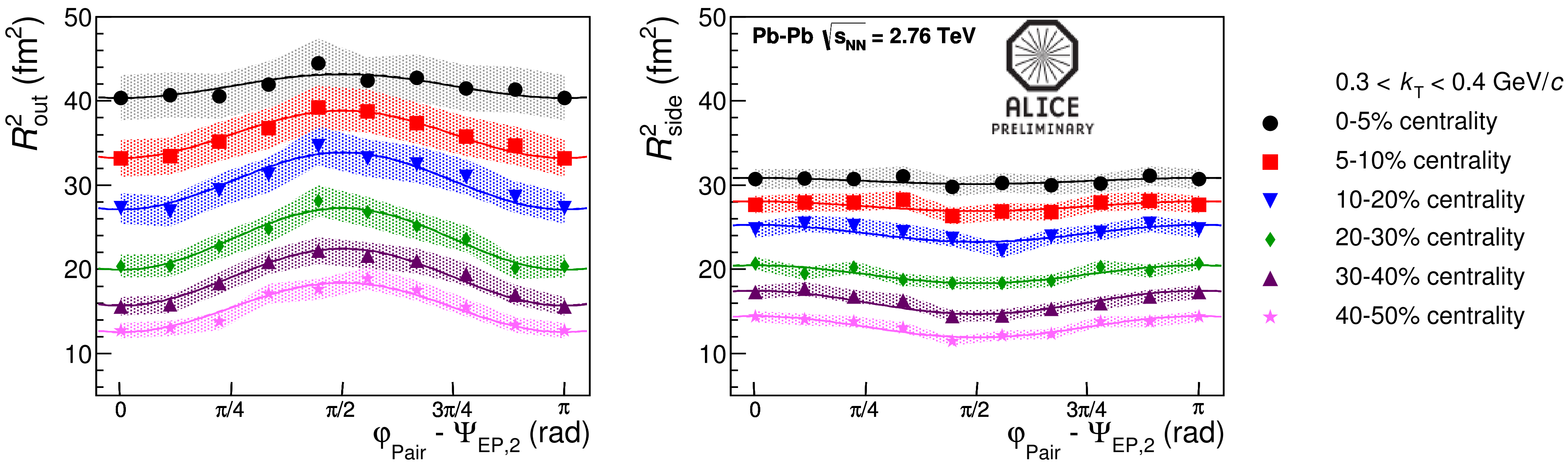
Azimuthally sensitive HBT gives us more detailed information of space-time evolution

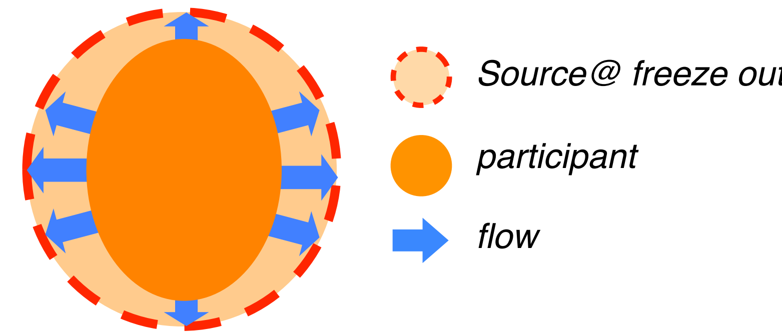
Azimuthal angle dependence of HBT w.r.t. Ψ_2

- R_{out} has explicit oscillation and R_{side} has weak oscillation
- R_{out} and R_{side} oscillate out-of-phase

➡ Initial elliptic shape still remains at freeze out (out-of-plane extended source)

✓ Fit function
- $R^2_{\mu,0} + 2R^2_{\mu,n}\cos(n(\phi_{pair} - \Psi_n))$
  - $R^2_{\mu,0}$: Average HBT radii
  - $R^2_{\mu,n}$: n_{th} order Oscillation





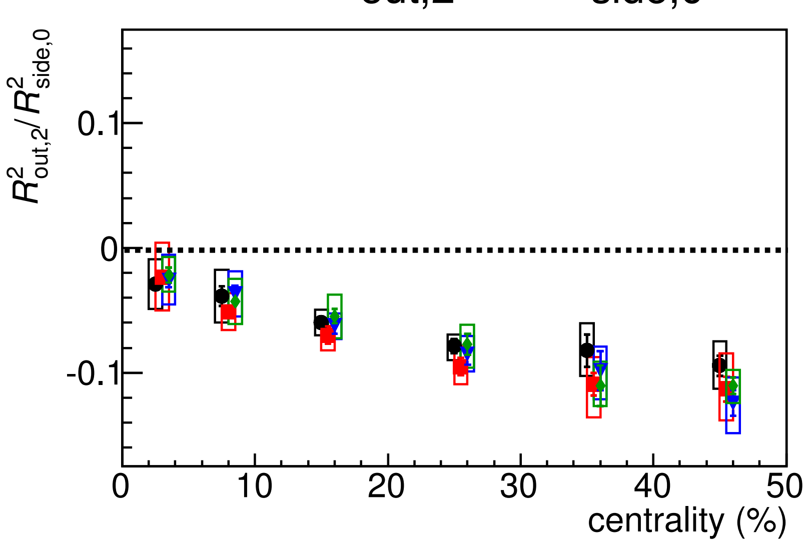
✦ R_{side} : width
✦ R_{out} : depth + time

- Final source eccentricity is obtained by relative amplitude from Blast Wave model

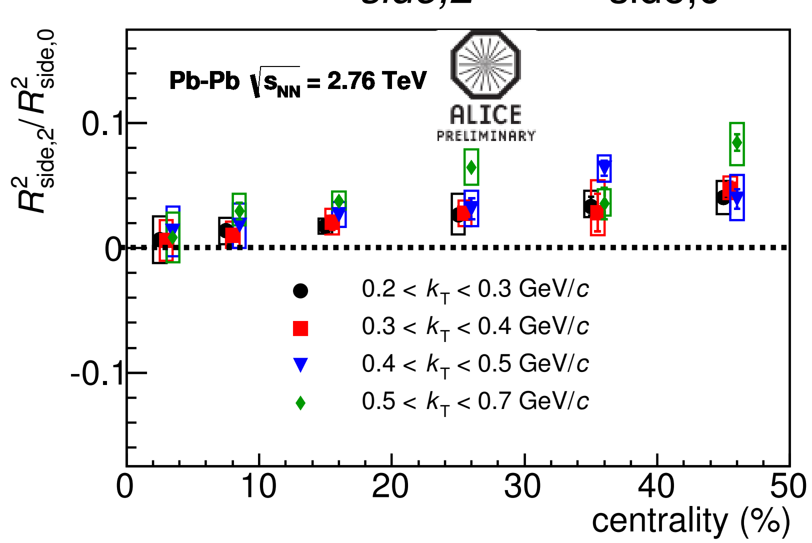
(Phys. Rev. C **70**, 044907)

- The magnitude of R_{out} R_{side} relative amplitude decreases from central to peripheral collisions

$R^2_{out,2} / R^2_{side,0}$



$R^2_{side,2} / R^2_{side,0}$



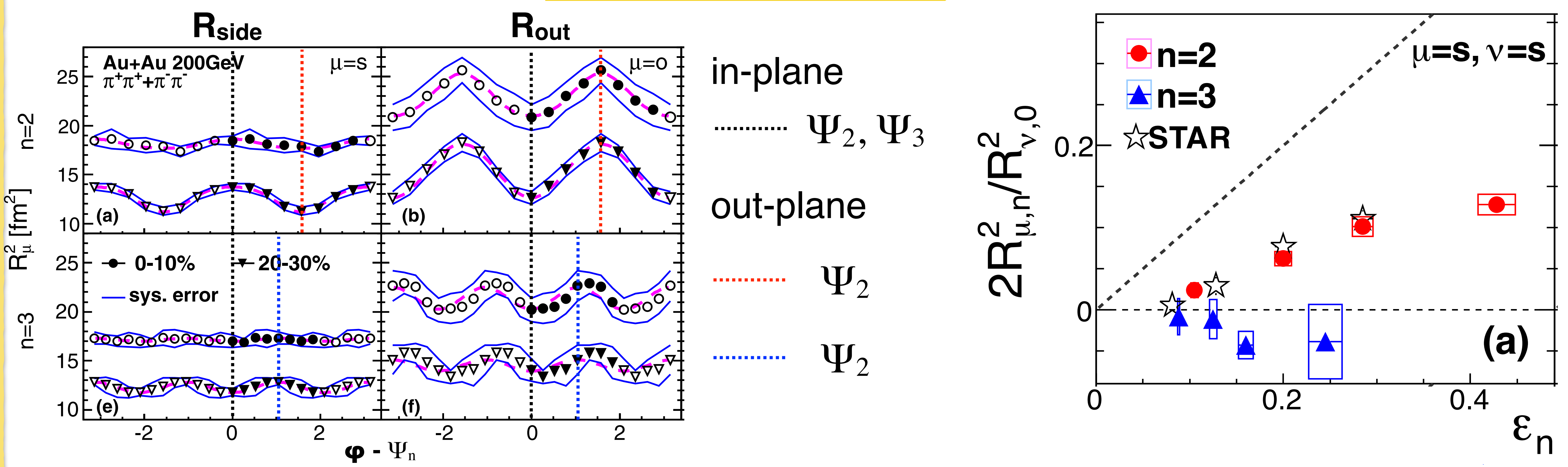
✓ Final source eccentricity
- $\varepsilon_{final} = 2\,R^2_{side,2} / R^2_{side,0}$

★ **Contributing factors to ε_{final}**
- initial geometry
- collective flow
- freeze out time

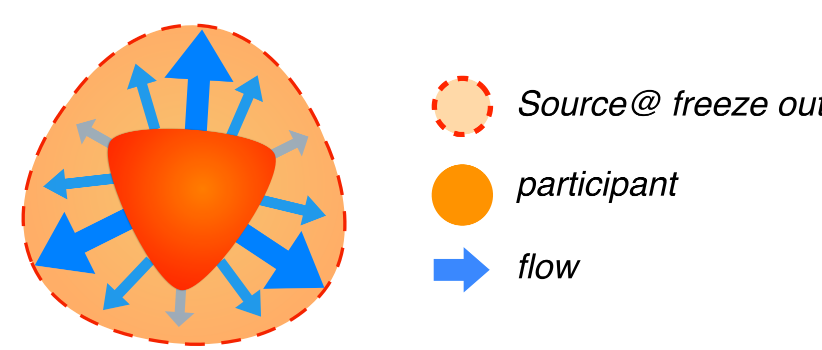
Triangular deformation via HBT

- **AMPT and Blast wave model** (S.Voloshin, J. Phys. G**38**, 124097)
  - ✓ HBT w.r.t. Ψ_3 shows finite oscillation in expanding source, but almost no oscillation in static source
- **HBT w.r.t. Ψ3 measured @ PHENIX Au+Au 200GeV** (Phys.Rev.Lett. **112** 222301)
  - ✓ Same oscillation sign of R_{out} and R_{side} → Relative amplitude **negative value**

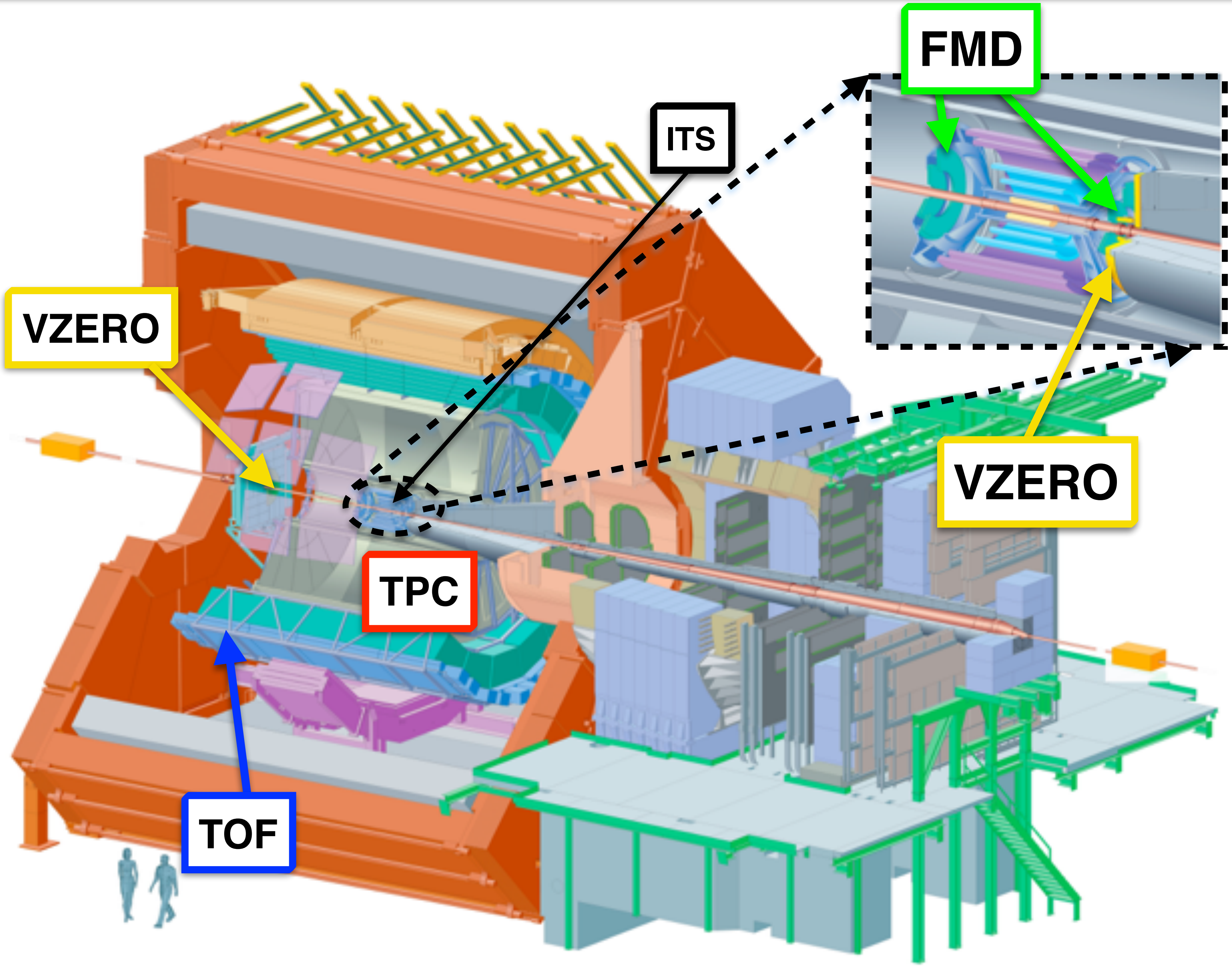
Au+Au 200GeV @ PHENIX

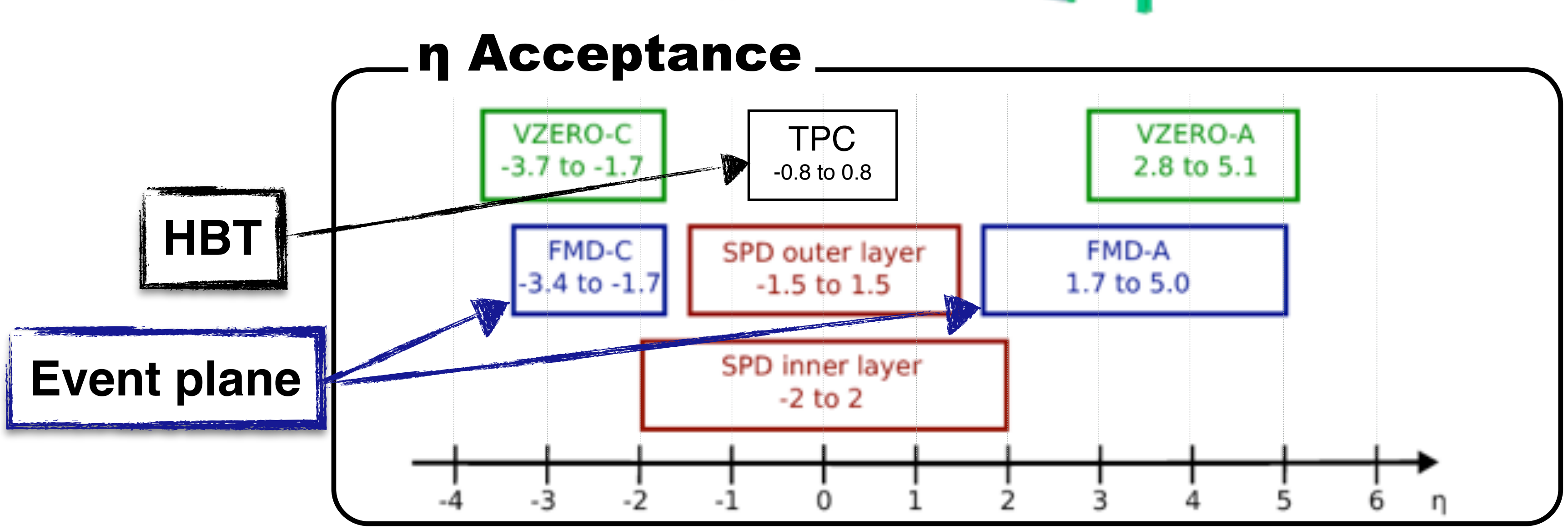


- **HBT w.r.t. Ψ_3 in LHC energy**
  - ✓ Difference between RHIC and LHC
    - **Larger radial flow & evolution duration**
    - **viscosity**
  - ✓ Hydrodynamic model (P. Bozek, J. Phys. G**38**, 124097)
    - Relative amplitude of R_{side} is negative
    - Triangular deformation is **washed-out or even reversed**



ALICE detector





In this analysis

VZERO
- ✓ Trigger & centrality
- ✓ $V0_A$: $2.8 < \eta < 5.1$
- ✓ $V0_C$: $-3.7 < \eta < -1.7$

TPC & ITS
- ✓ Tracking & PID
- ✓ Vertex
- ✓ $|\eta_{track}| < 0.8$

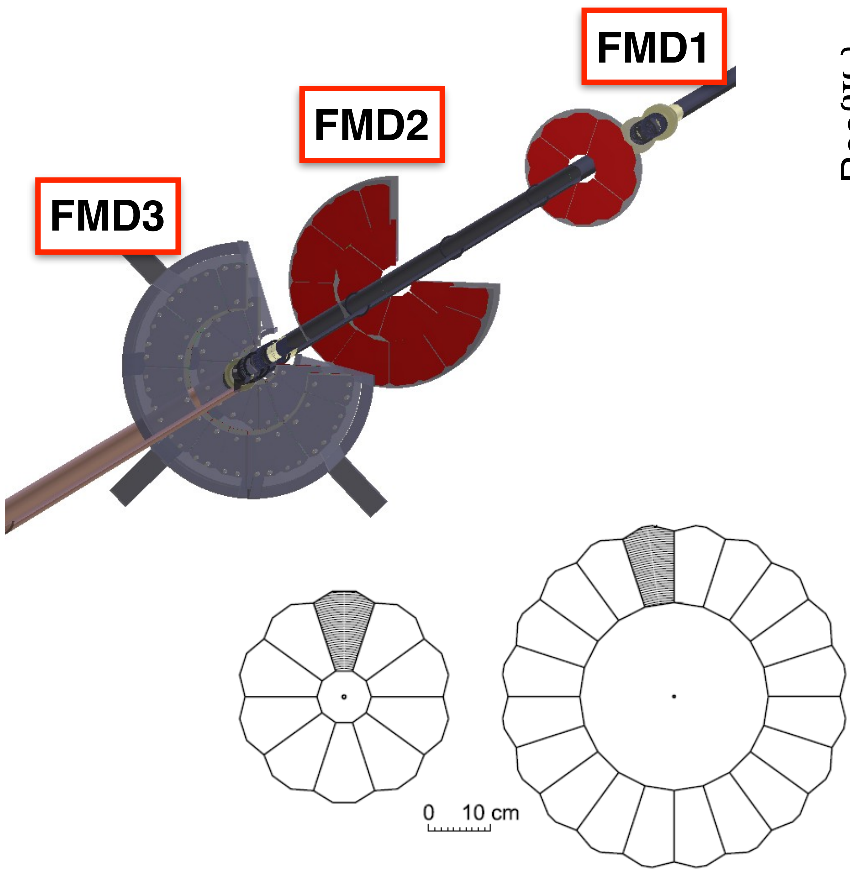
TOF
- ✓ PID
- ✓ $|\eta_{track}| < 0.8$

FMD
- ✓ Event plane
- ✓ FMD_A : $1.7 < \eta < 5.0$
- ✓ FMD_C : $-3.4 < \eta < -1.7$

Event plane via FMD

The FMD Detector

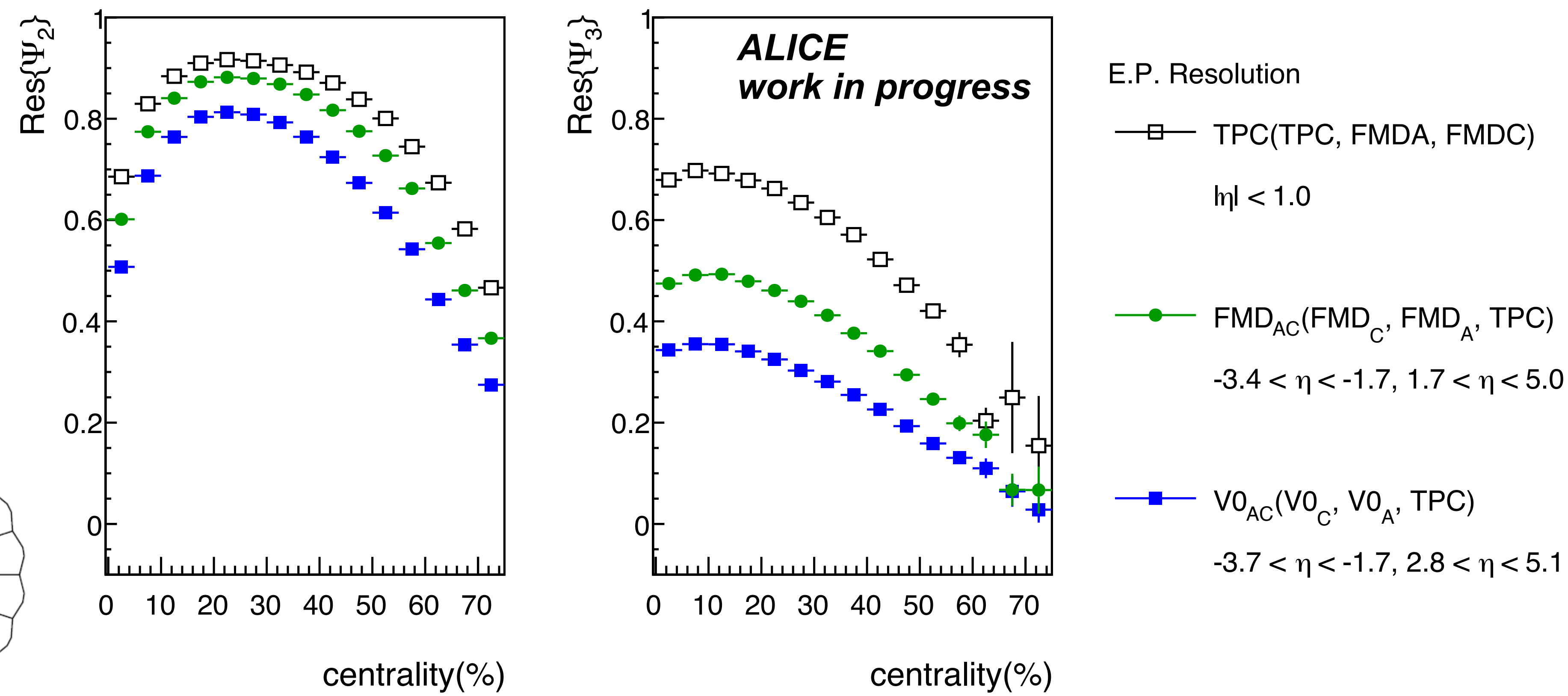
- **Silicon strip detector**
- **3 sub detector : FMD1, FMD2, FMD3**
- **2 types of rings : inner and outer**
  - **inner : 20 sectors (0 < φ < 2π)**
  - **outer : 40 sectors (0 < φ < 2π)**



Event plane resolution

- **Event plane resolution are extracted with 3 sub event method**

$$\mathrm{Res}\{\Psi_n\} = \sqrt{\frac{<\cos(n(\Psi_n^A - \Psi_n^B))><\cos(n(\Psi_n^A - \Psi_n^C))>}{<\cos(n(\Psi_n^B - \Psi_n^C))>}}$$



FMD event plane and HBT measurememt

- 3rd order harmonics, FMD resolution is approximately 15% better than V0
  - ☑ This excellent resolution allows us precise measurement of higher order event plane
- Rapidity gap between HBT measurement and E.P. is |Δη| > 0.9
  - HBT → Mid-rapidity (-0.8 < η < 0.8)
  - Event Plane → Forward rapidity (-3.4 < η < -1.7, 1.7 < η < 5.0)

Analysis method for HBT

- **2.76 TeV Pb-Pb collisions**
- **Particle Identification**
  - **Charged pions** are identified with **TPC and TOF combined PID**
- **Correlation function**

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

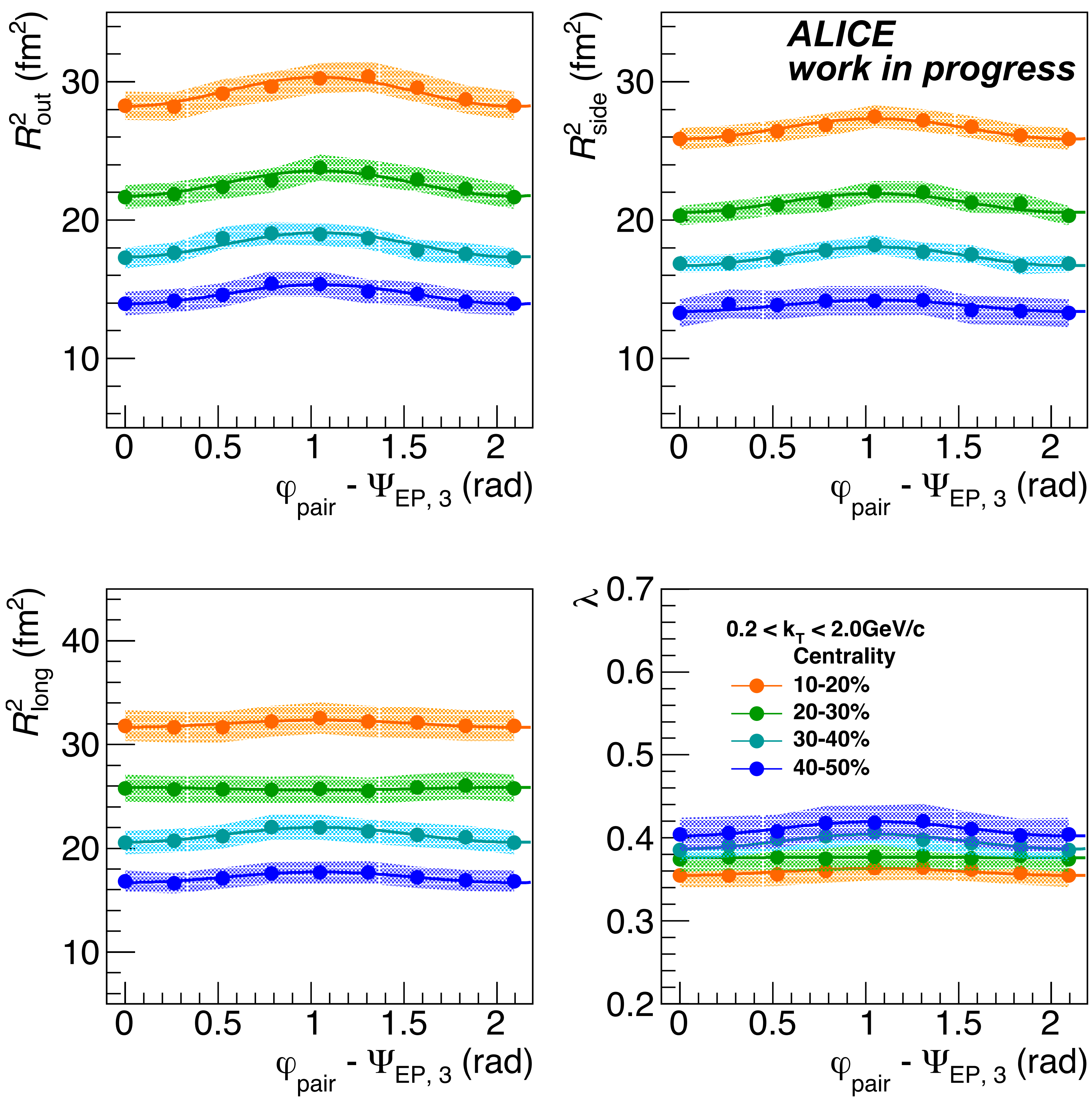
  - R(q) : real pairs
  - M(q) : mixed pairs (made by event mixing)
  - q : relative momentum
- **Event mixing class**
  - Event with similar centrality, Z-vertex and Ψ_3 angle are used
- **Fit function**

$$C_2 = N\left[(1-\lambda) + \lambda K_c \left(1 + \exp\left(G\right)\right)\right]$$

$$G = -R^2_{\mathrm{out}} q^2_{\mathrm{out}} - R^2_{\mathrm{side}} q^2_{\mathrm{side}} - R^2_{\mathrm{long}} q^2_{\mathrm{long}} - R^2_{\mathrm{os}} q_{\mathrm{out}} q_{\mathrm{side}} - R^2_{\mathrm{ol}} q_{\mathrm{out}} q_{\mathrm{long}} - R^2_{\mathrm{sl}} q_{\mathrm{side}} q_{\mathrm{long}}$$

  - ✓ K_C is Coulomb correction factor
- **Event plane**
  - Ψ_3 is determined via FMD (1.7 < η < 5.0, -3.4 < η < -1.7)
- **Event plane resolution correction** (U.Heinz, Phys.Rev.C66, 044903(2002))
- **Momentum resolution correction**
  - Estimated with HIJING and GEANT

Azimuthal angle dependence of HBT w.r.t. Ψ_3



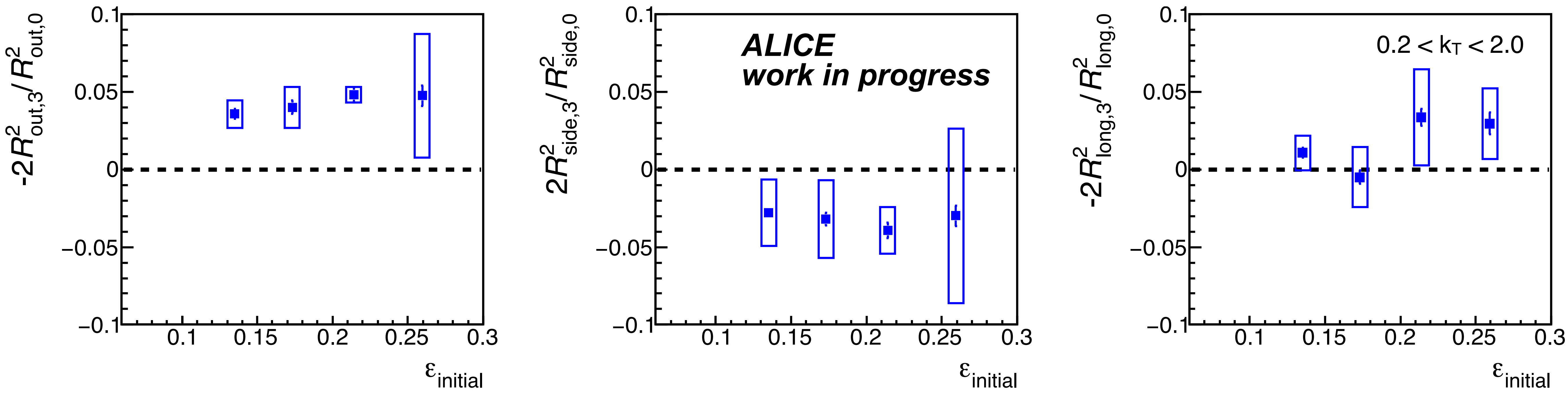
Pb-Pb 2.76TeV in ALICE
Charged pion pair
(-0.8 < η < 0.8)

Event plane is determined with FMD

- Fit function
  - $R^2_{\mu,0} + 2 R^2_{\mu,3} \cos(3(\phi_{pair} - \Psi_3))$
    - $R^2_{\mu,0}$: Average HBT radii
    - $R^2_{\mu,3}$: Oscillation amplitude

- ✦ **Average HBT radii**
  - ✓ **centrality dependence**
- ✦ **Azimuthal angle dependence**
  - ✓ **R_{out} has explicit oscillation**
  - ✓ **R_{side} has small oscillation**
  - ✦ **R_{out} and R_{side} oscillate in-phase**
    - ➡ **unlike HBT w.r.t. Ψ_2**
  - ✓ **R_{long} and λ have no oscillation**
  - ✓ **Small centrality dependence**
    - ➡ **similar to v_3**

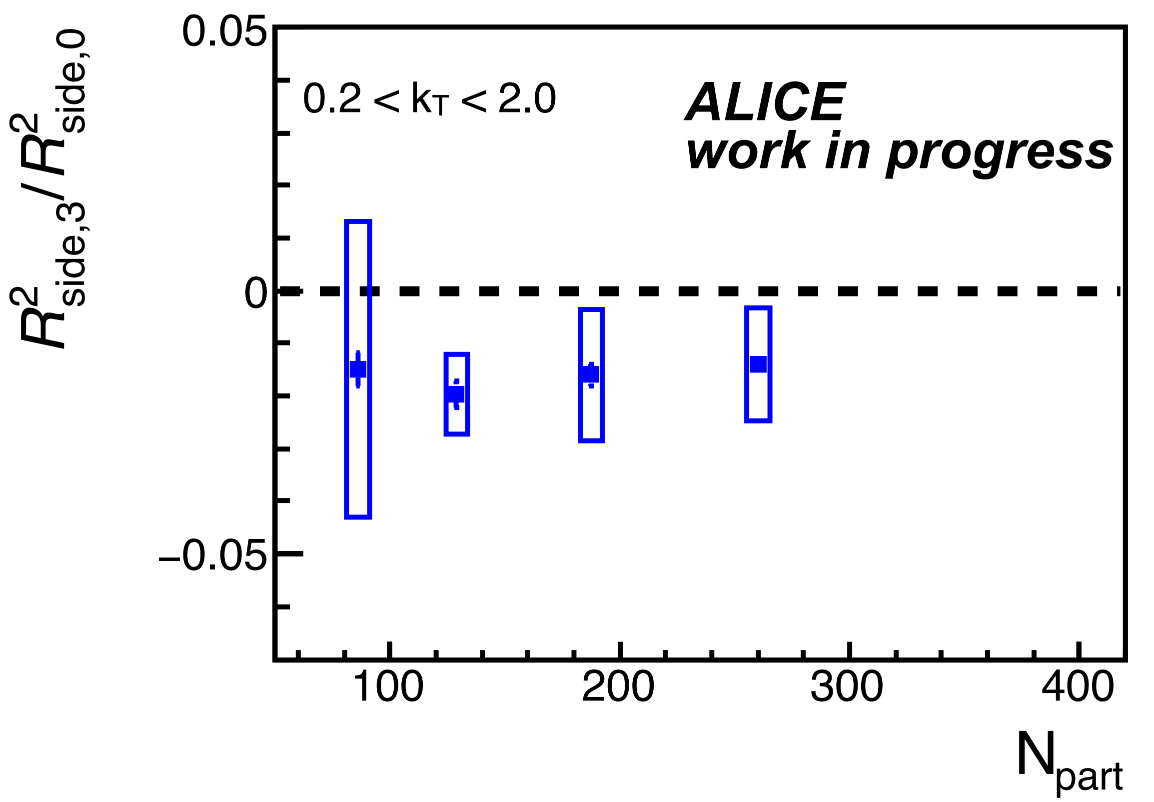
Initial ε_3 vs Relative amplitude



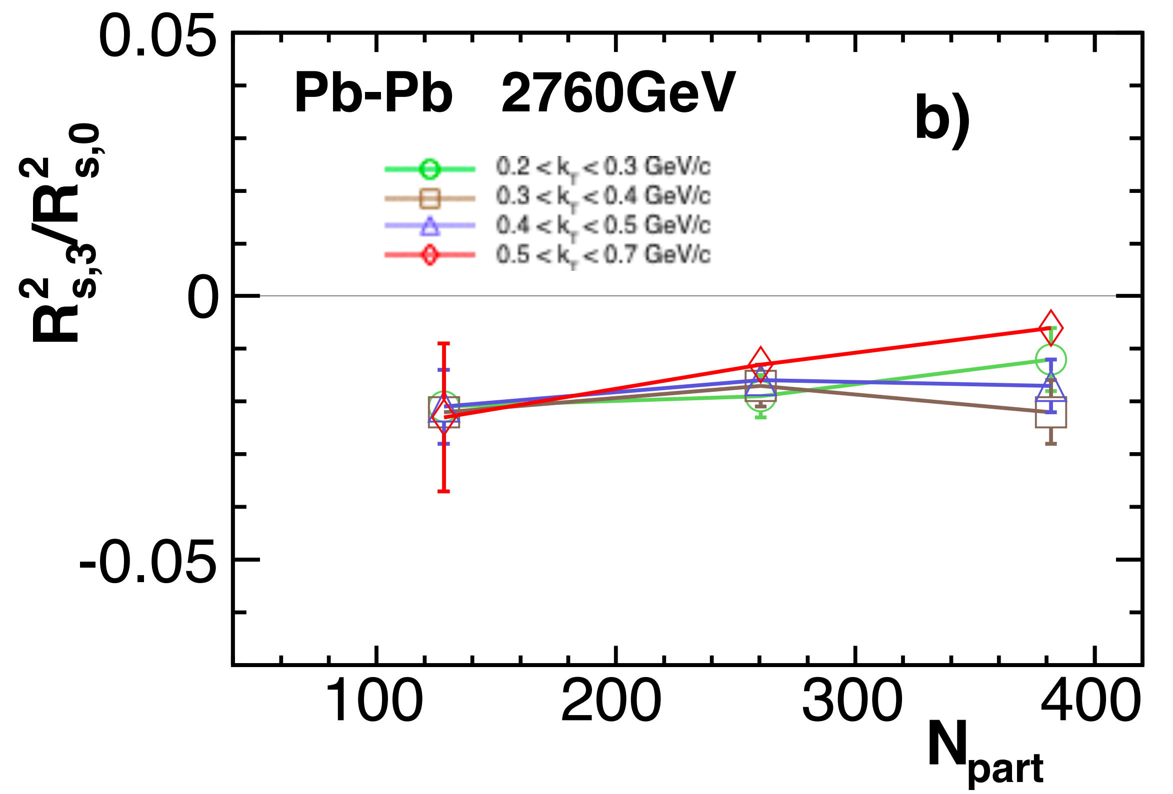
- ✦ $R^2_{out,3}$ / $R^2_{out,0}$
  - ✓ Relative amplitude of R^2_{out} is positive
  - ✓ $-2R^2_{out,3}$ / $R^2_{out,0}$ increase with increasing initial ε_3
- ✦ $R^2_{side,3}$ / $R^2_{side,0}$
  - ✓ Relative amplitude of R^2_{side} is negative ($\varepsilon_{initial} < 0.25$)
  - ✓ No centrality dependence can be seen
- ✦ $R^2_{long,3}$ / $R^2_{long,0}$
  - ✓ Relative amplitude of R^2_{long} has almost no amplitude

Hydrodynamic model comparison

ALICE Pb-Pb 2.76TeV



3+1D Hydrodynamic model



(P. Bozek, J. Phys. G**38**, 124097)

- ✦ $R^2_{side,3} / R^2_{side,0}$
  - ✓ N_{part} dependence of $R^2_{side,3} / R^2_{side,0}$ can be reproduced by 3+1D hydrodynamic model within the systematic uncertainty
  - ✓ $R^2_{out,3} / R^2_{side,0}$ and $R^2_{os,3} / R^2_{side,0}$ will be compared with hydrodynamic model
  - ✓ Need k_T dependence !!

Summary

- ✦ **Azimuthal angle dependence of HBT radii w.r.t. Ψ_3**
  - $\boldsymbol{R}_{out}$ and $\boldsymbol{R}_{side}$ oscillate in-phase
  - Explicit oscillation of $\boldsymbol{R}_{out}$ and small oscillation of $\boldsymbol{R}_{side}$ can be seen
  - $\boldsymbol{R}_{long}$ and λ have almost no oscillation
- ✦ **Relative amplitude of squared HBT radii**
  - $-2\boldsymbol{R}^2_{out,3}/\boldsymbol{R}^2_{out,0}$ is positive in centrality 10-50% and small centrality dependence
  - $2\boldsymbol{R}^2_{side,3}/\boldsymbol{R}^2_{side,0}$ is negative in centrality 10-40%
- ✦ **Hydro dynamical model comparison**
  - Bozek $\boldsymbol{R}^2_{side,3}/\boldsymbol{R}^2_{side,0}$ calculation shows good agreement within Syst. error

Outlook

- ✦ Azimuthal angle dependence of HBT w.r.t. Ψ_3 in centrality 0-10% is ongoing
- ✦ k_T dependence of HBT w.r.t. Ψ_3 for more precise understanding
- ✦ Azimuthally sensitive HBT with Event shape engineering (J. Schukraft et al., arXiv:1208.4563)
  - ✓ Selecting of event by event v_n by the magnitude of flow vector
  - ➡ Impact on final source shape by larger triangular flow (initial ε_3)

Backup

Event plane resolution correction

- **Event Plane Resolution Correction** (Phys. Rev. C66, 044903 (2002))

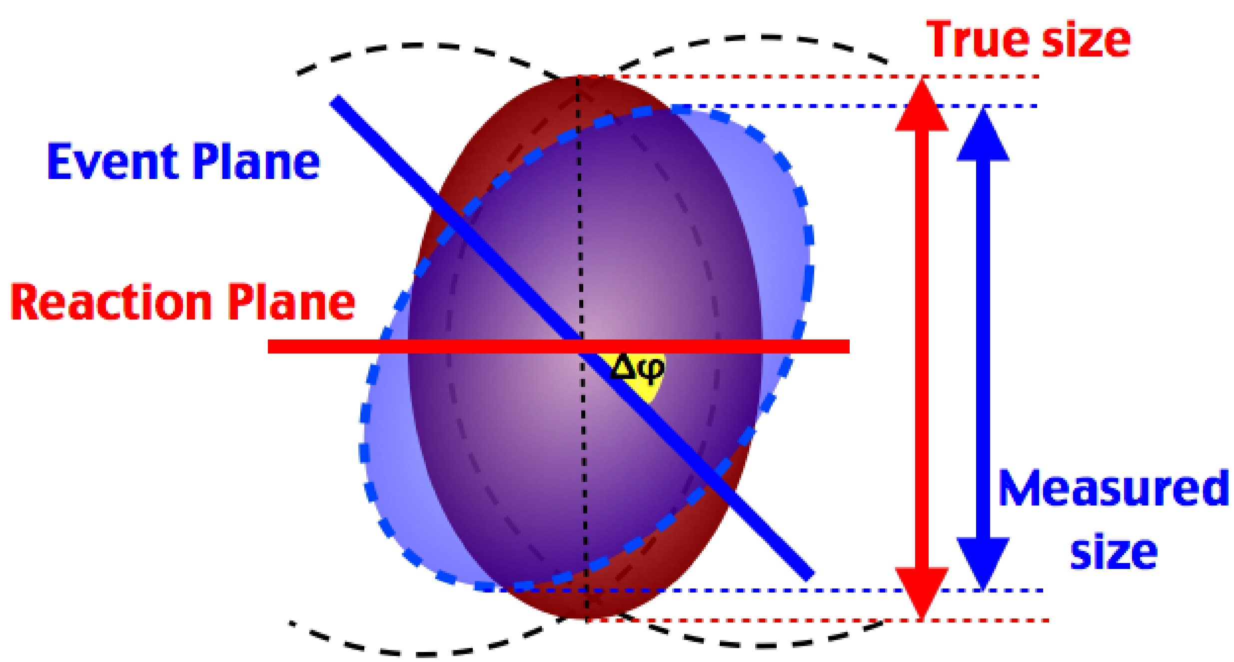
$$N\left(q,\phi_j\right) = N_{exp}\left(q,\phi_j\right) + 2\sum_{n=1}^{n_{bins}} \xi_{n,m}(\Delta)\left[N_{c,n}^{exp}(q)\cos(n\phi_j) + N_{s,n}^{exp}(q)\sin(n\phi_j)\right]$$

$$N_{c,n}^{exp}(q)\cos(n\phi_j) = \langle N_{exp}(q,\phi_j)\cos(n\phi)\rangle = \frac{1}{n_{bins}}\sum_{n=1}^{n_{bins}} N_{exp}(q,\phi_j)\cos(n\phi_j)$$

$$N_{s,n}^{exp}(q)\sin(n\phi_j) = \langle N_{exp}(q,\phi_j)\sin(n\phi)\rangle = \frac{1}{n_{bins}}\sum_{n=1}^{n_{bins}} N_{exp}(q,\phi_j)\sin(n\phi_j)$$

$$\xi_{n,m}(\Delta) = \frac{n\Delta/2}{\sin(n\Delta/2)\langle\cos\left(n\left(\Psi_n^m - \Psi_n^{true}\right)\right)\rangle}$$

➡ event plane resolution



- **correction for q-distribution with EP resolution**