Final source eccentricity measured by HBT interferometry with the event shape selection

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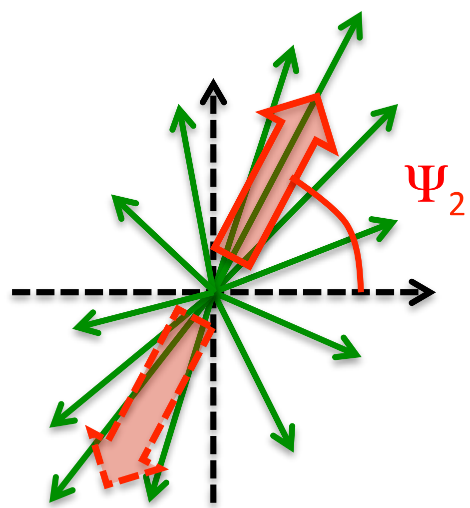
Contents

- Event shape engineering with HBT at the PHENIX experiment
- Event twist selection with HBT with AMPT model

Event shape engineering

- Event shape engineering (ESE)
  - J. Schukraft et al., arXiv:1208.4563
  - Selecting e-b-e v_2 by the magnitude of flow vector

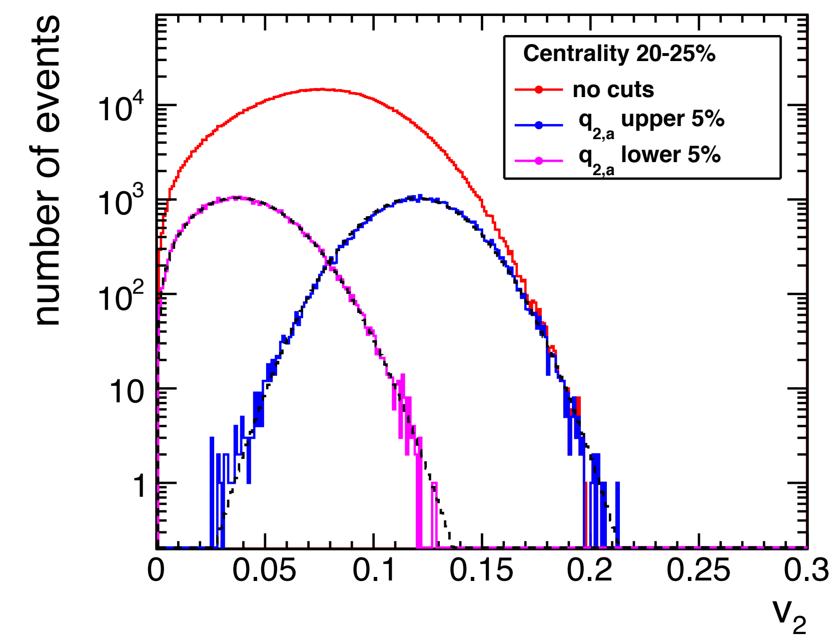
$$Q_{2,x} = \Sigma w_i \cos(2\phi)$$
$$Q_{2,y} = \Sigma w_i \sin(2\phi)$$
$$Q_2 = \sqrt{Q_{2,x}^2 + Q_{2,y}^2}/\sqrt{M}$$
$$\Psi_2 = \tan^{-1}(\frac{Q_{2,y}}{Q_{2,x}})$$



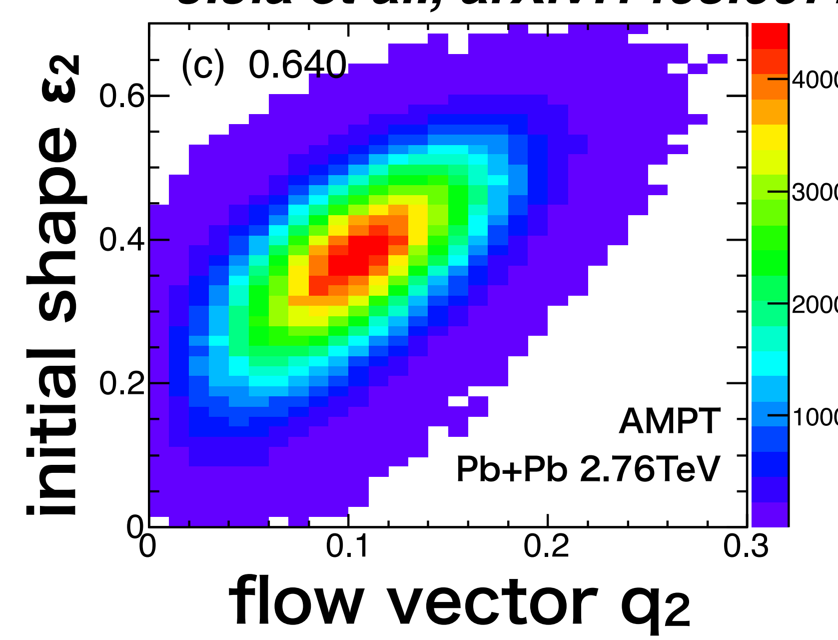
  - **Possibly control the initial geometry**

- More accurate connection between initial and final source eccentricity ?
  - Azimuthally sensitive HBT w.r.t Ψ_2

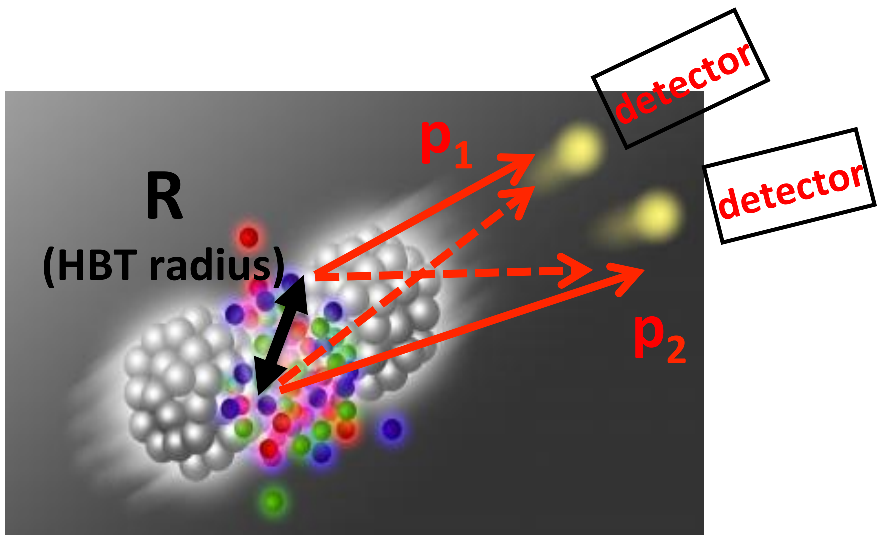
J.Schukraft et al., arXiv:1208.4563

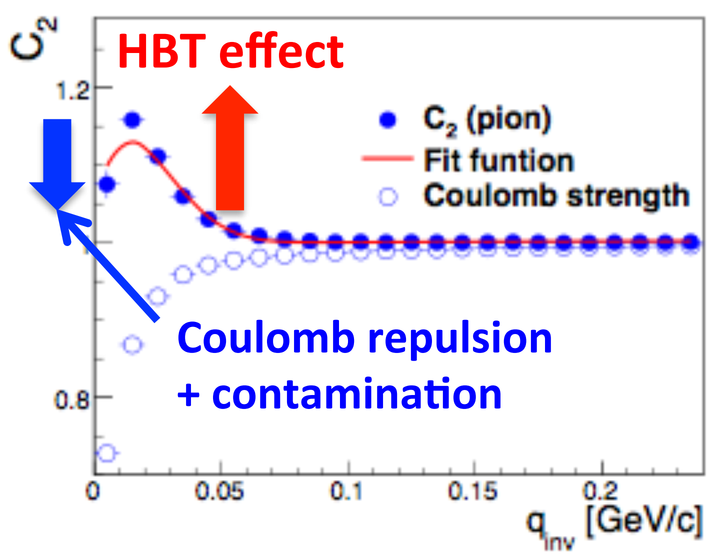


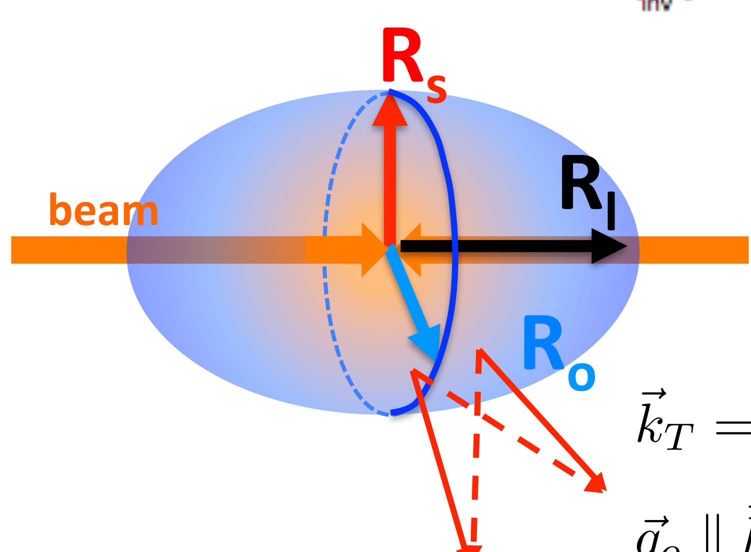
J.Jia et al., arXiv:1403.6077



Hanbury Brown and Twiss interferometry







- Hanbury Brown and Twiss effect (1950s)
  - Quantum interference b/w two identical particles
  - Due to (a)symmetrization of the wave function of identical bosons(fermions)

$$q = p_1 - p_2$$

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

- Experimentally correlation function

$$C_2 = \frac{N_{real}(q)}{N_{mixed}(q)}$$

N_{real}: real pairs in the same event

N_{mixed}: pairs made by event mixing

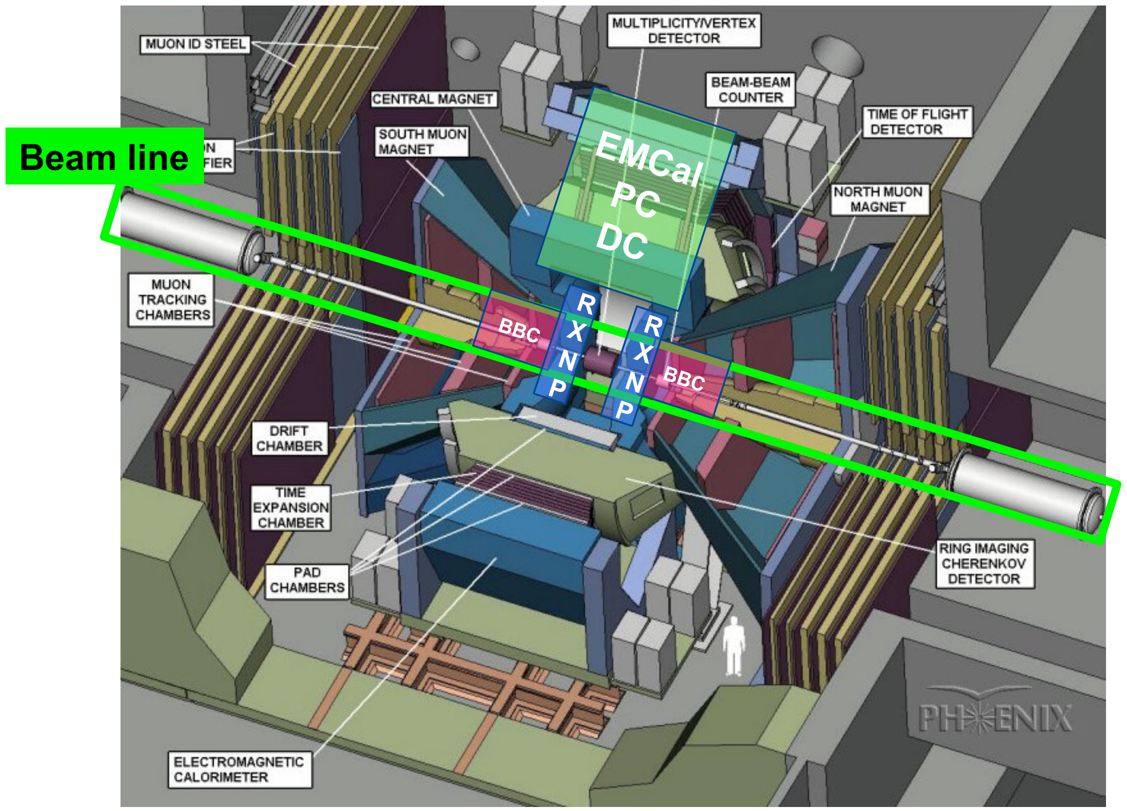
  - Enhancement at low q by HBT effect
  - including final state interaction (Coulomb, strong)
  - Bertsch-Pratt parameterization w/ core-halo picture

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

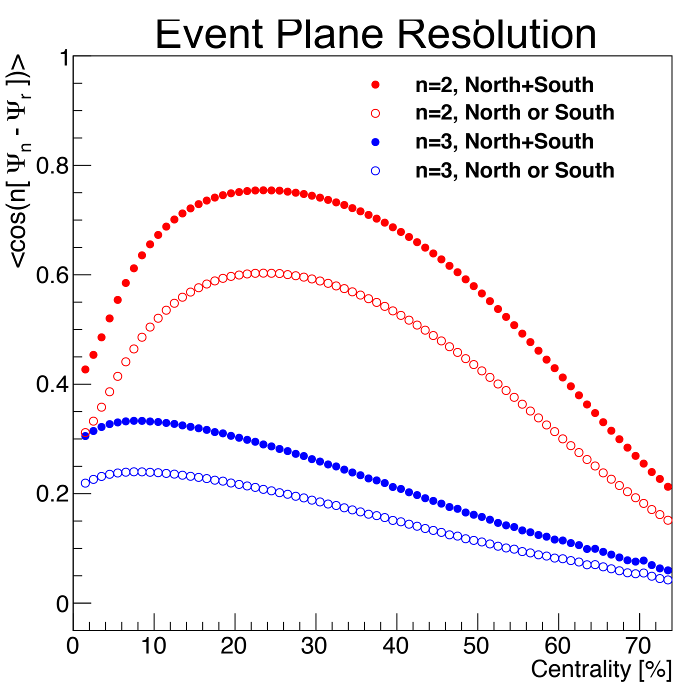
$$\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2}) \quad G = \exp(-R_s^2 q_s^2 - R_o^2 q_o^2 - R_l^2 q_l^2 - 2R_{os}^2 q_s q_o)$$

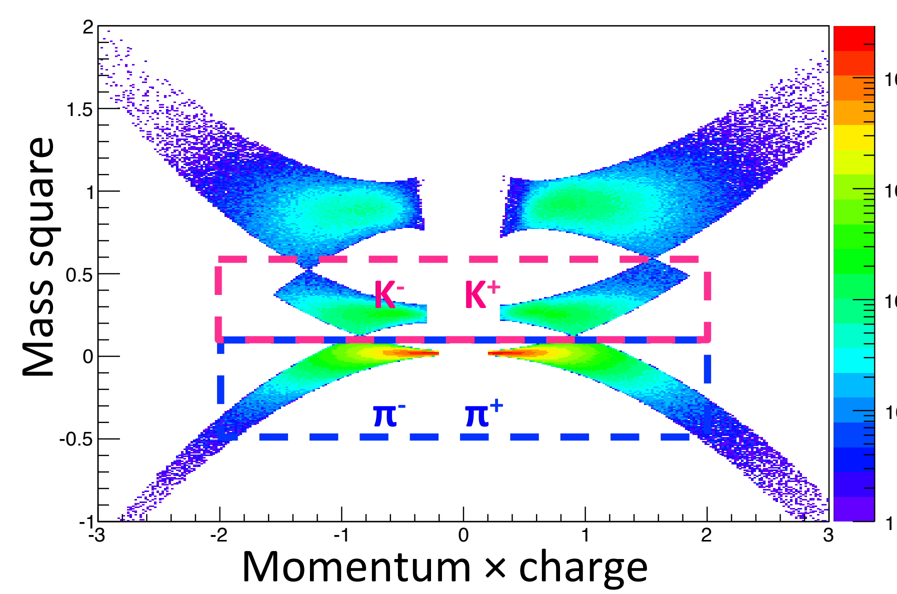
$$\vec{q}_o \parallel \vec{k}_T, \quad \vec{q}_s \perp \vec{k}_T$$

PHENIX experiment



- Centrality, zvertex
  - Beam Beam Counter (3<|η|<3.9)
- Event plane & flow vector determination
  - Reaction Plane Detectors (RxNP) (1<|η|<2.8)
  - Res(Ψ_2)~75%
- Tracking
  - Drift Chamber + Pad Chambers (|η|<0.35)
- Charged pion identification
  - Electromagnetic calorimeter (EMCal) (|η|<0.35)
  - using time-of-flight at EMCal



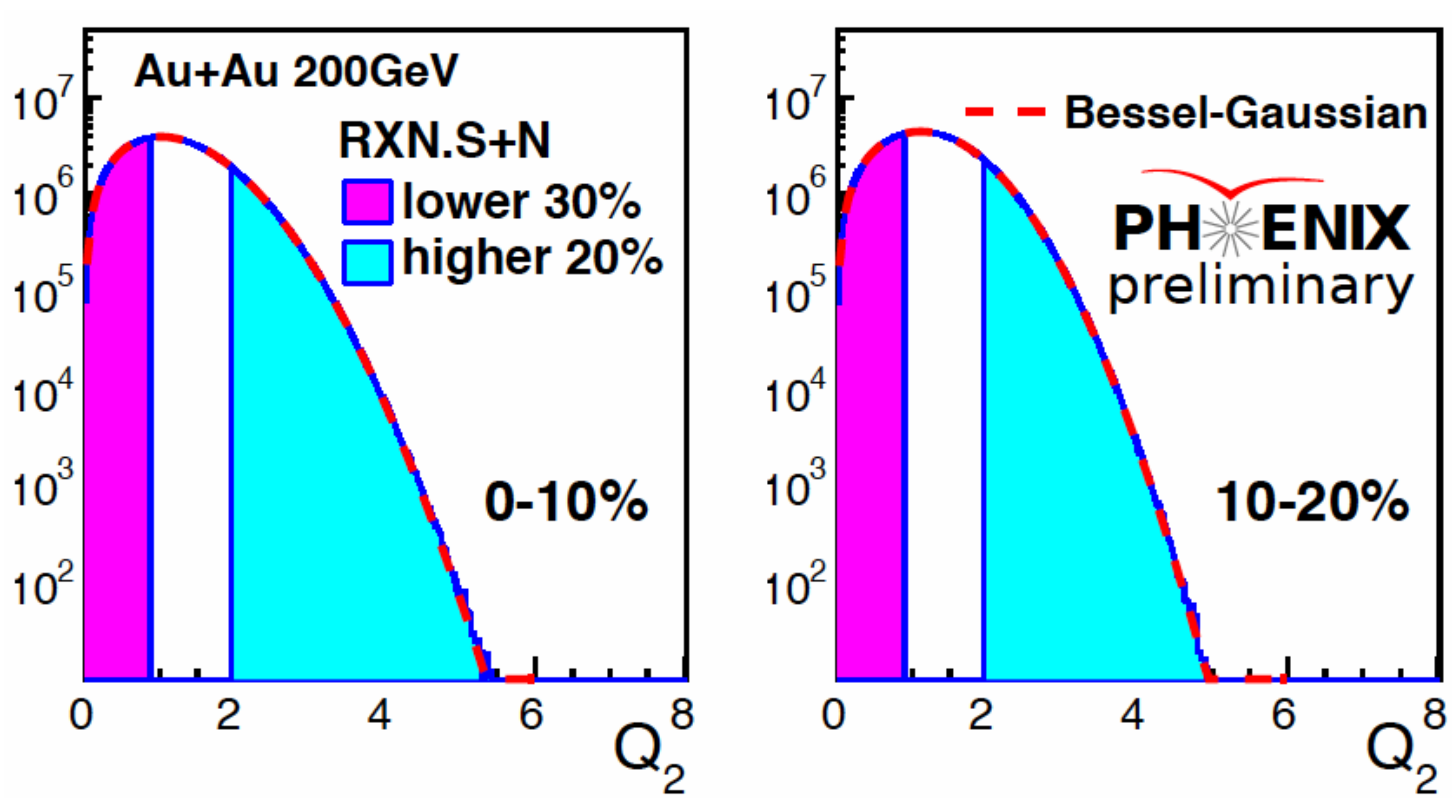


How to apply the ESE

1. Q_2 distribution measured by RxNP
2. Fitted with the Bessel-Gaussian function

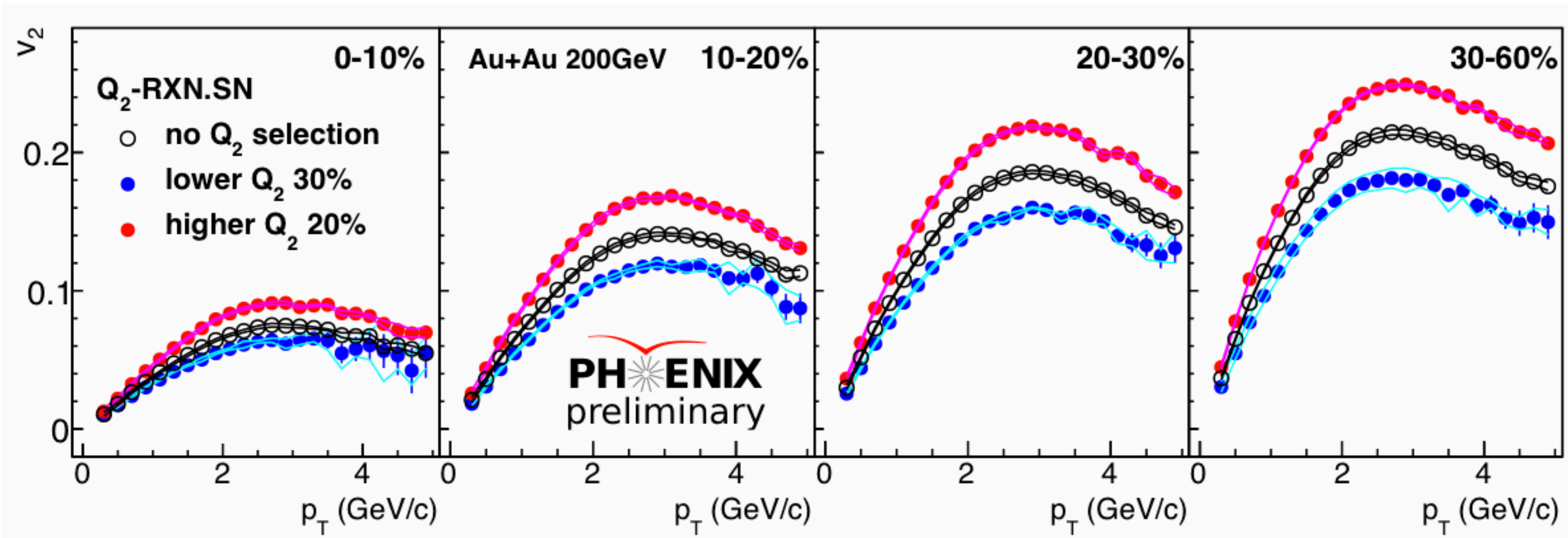
$$f_{BesselGaus} = \frac{x}{\sigma} I_0(\frac{x_0 x}{\sigma^2}) \exp(-\frac{(x_0^2 + x^2)}{2\sigma^2})$$

3. Select higher or lower Q_2 events



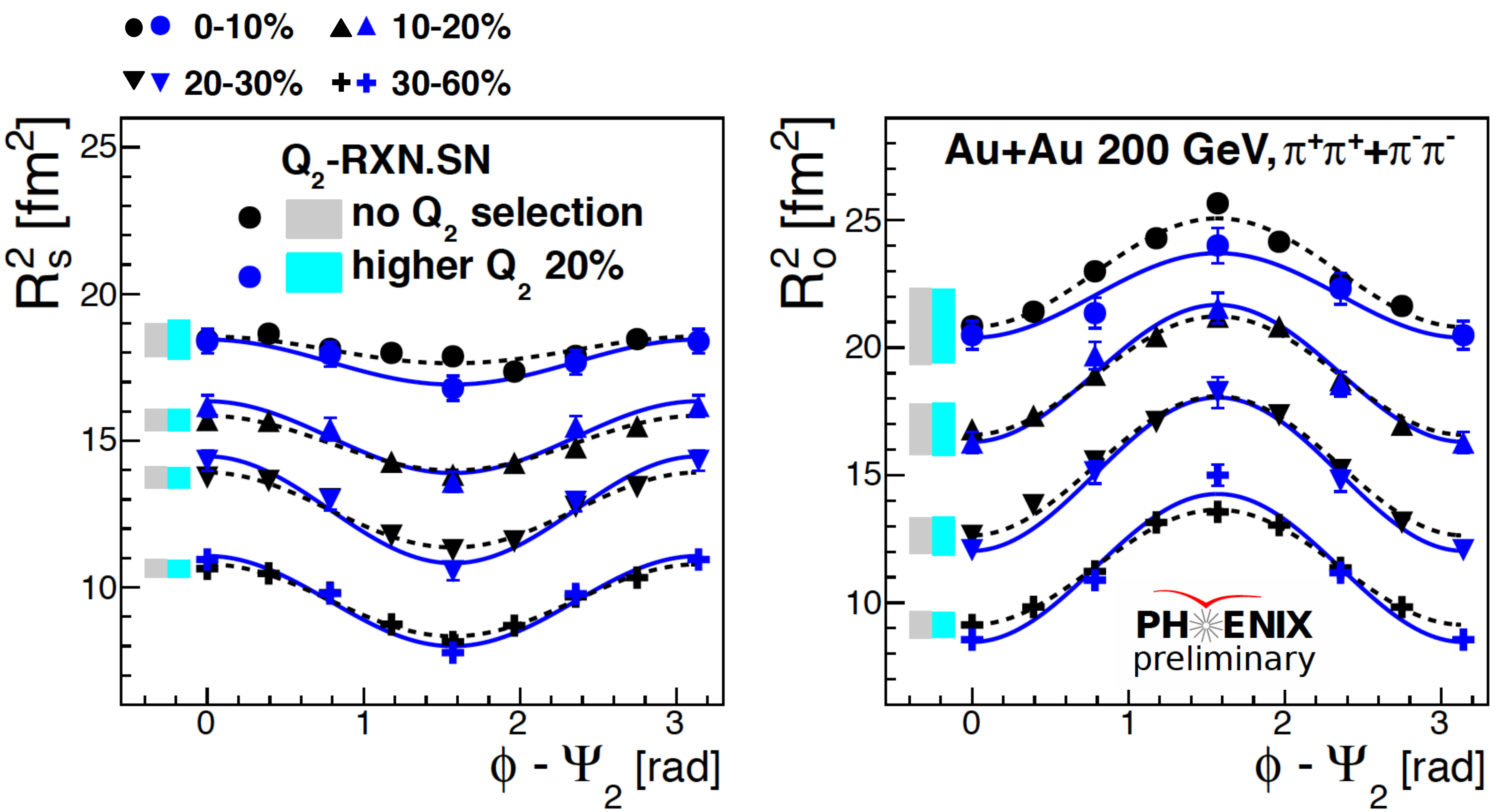
Resolutions of event planes were estimated by 3-sub method using RxNP(1<| η |<2.8) and BBC(3<| η |<3.9) applying Q_2 selection.

Charged hadron v_2 with ESE



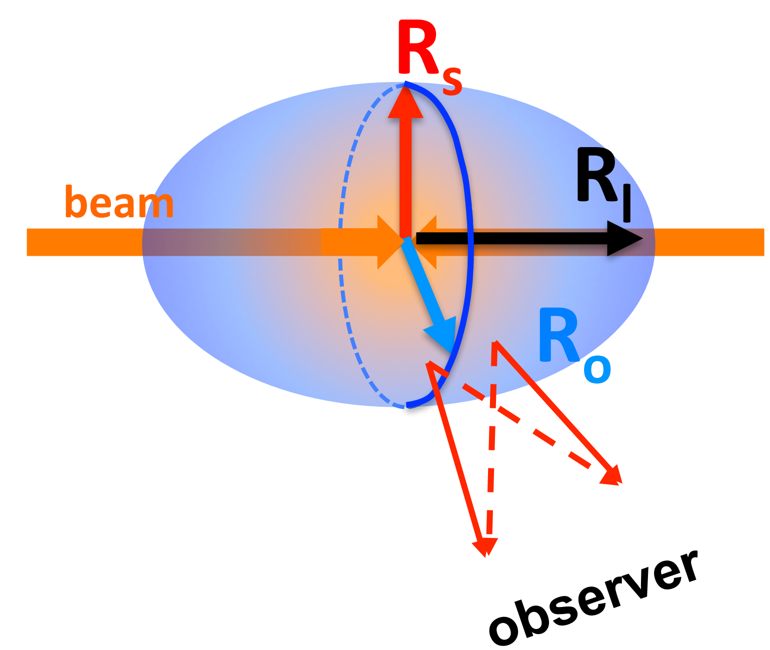
- Test of the event shape engineering for v_2 in Au+Au 200GeV collisions
  - v_2 measured at mid-rapidity ($|\eta|<0.35$)
  - Q_2 and EP determined at $1<|\eta|<2.8$
- Confirmed that higher(lower) Q_2 selects larger(smaller) v_2

HBT radii w.r.t Ψ_2 with ESE



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

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

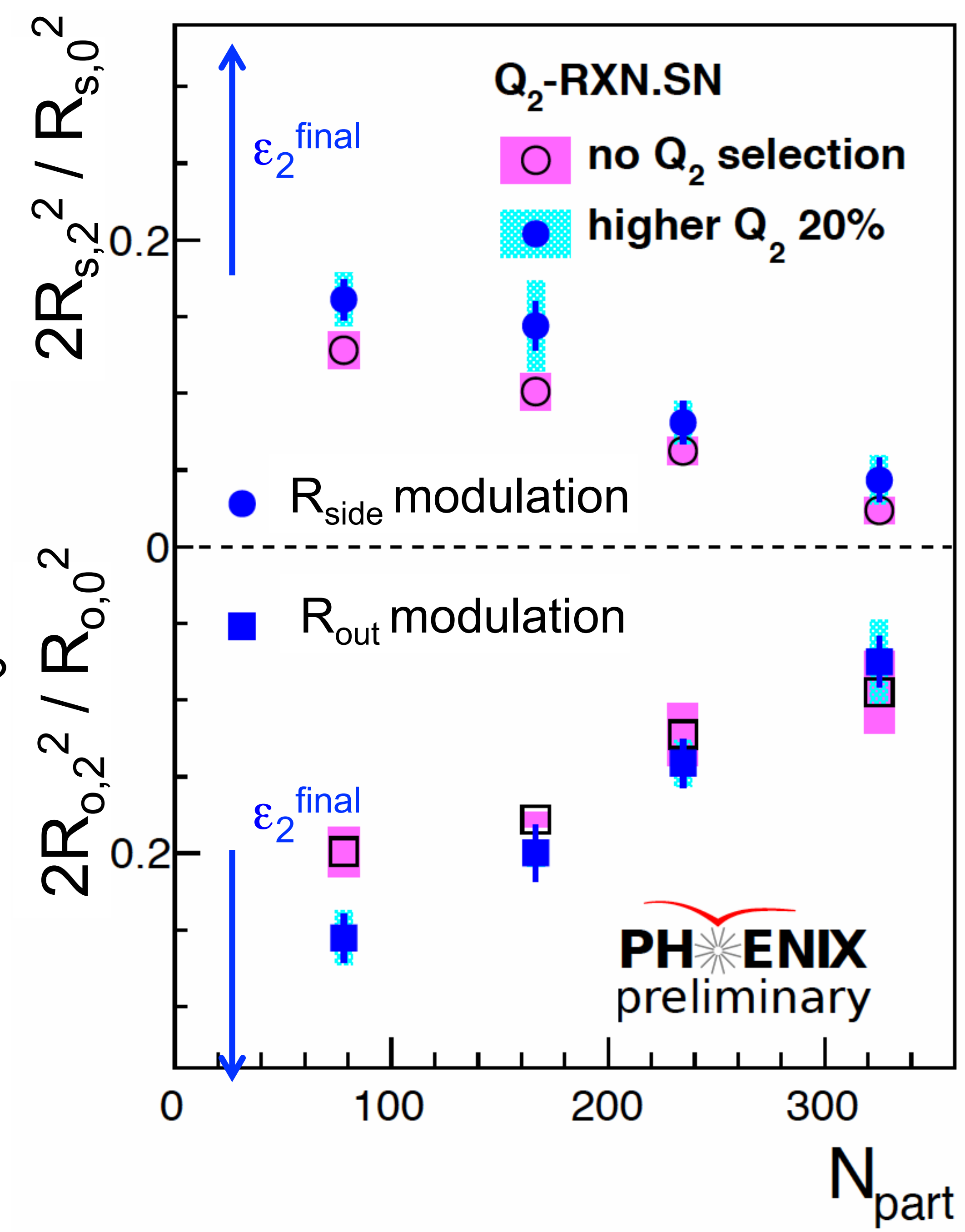


$$R_\mu^2 = R_{\mu,0}^2 + 2R_{\mu,2}^2 \cos(2\Delta\phi)$$

- Applying the ESE to azimuthal HBT
  - charged $\pi\pi$-correlation measured at mid-rapidity ($|\eta|<0.35$)
  - Q_2 and EP determined at $1<|\eta|<2.8$
- Oscillations of R_s and R_o become larger when selecting higher Q_2 except R_o in 0-10%

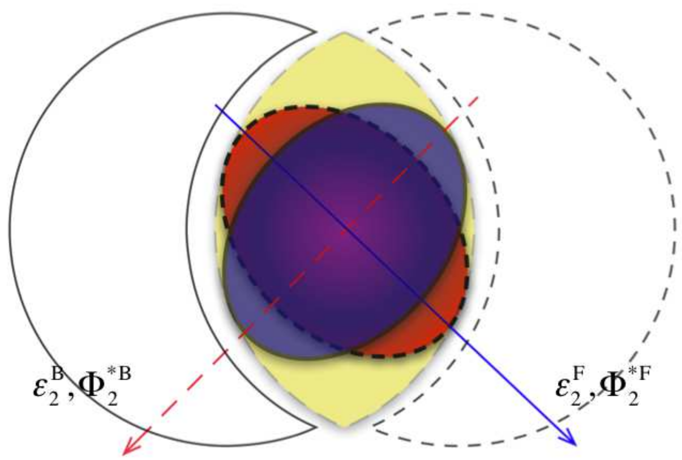
Freeze-out eccentricity vs N_{part} with ESE

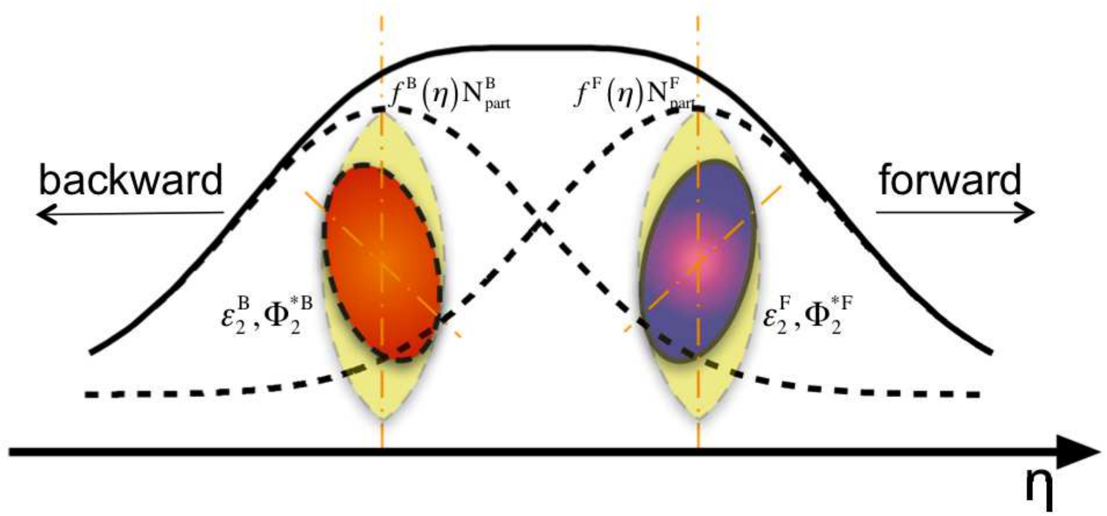
- $\varepsilon_{final} \sim 2R_{s,2}^2/R_{s,0}^2$
  - F. Retiere and M. A. Lisa, PRC70.044907
  - at the limit of $k_T=0$
- Higher Q_2 selection increases the measured ε_{final}
  - Selected more elliptical source at freeze-out?
  - might be originated from ε_{init}
  - Or just v_2 effect?



Event twist selection with HBT with AMPT model

Twisted source?

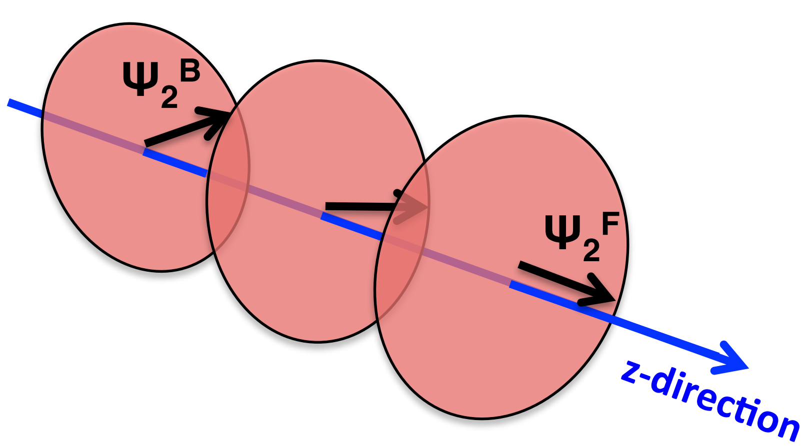




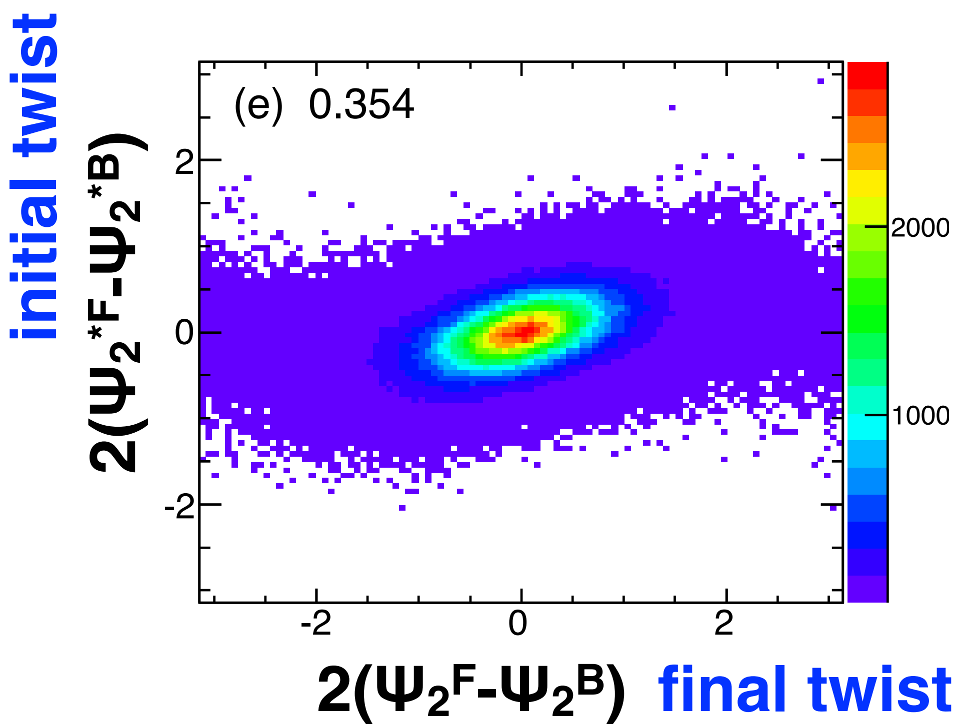
arXiv:1403.6077

$$N_{part}^B \neq N_{part}^F$$
$$\varepsilon_n^B \neq \varepsilon_n^F$$
$$\Psi_{part,n}^B \neq \Psi_{part,n}^F$$

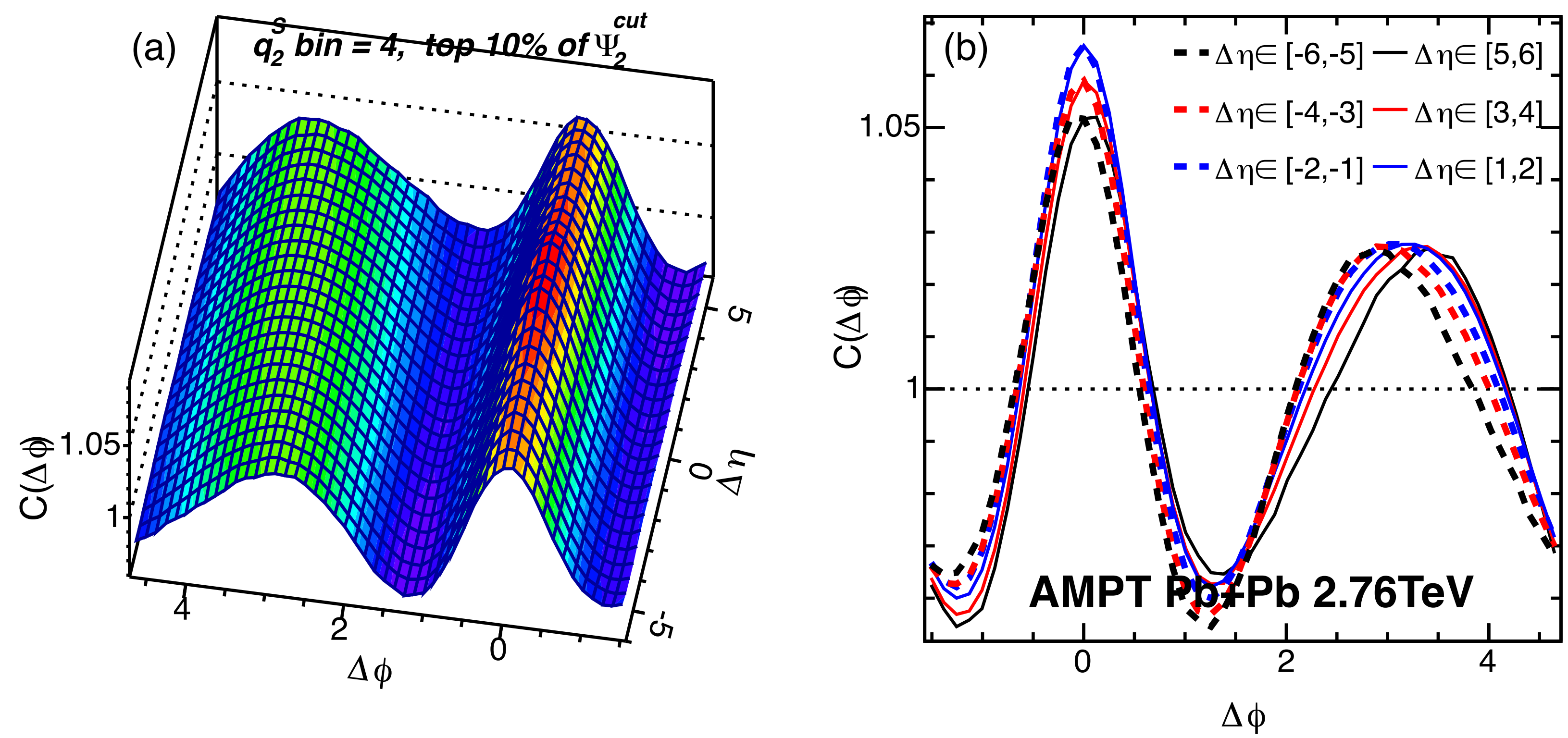
- Twisted fireball due the density fluctuation of wounded nucleons going to forward and backward directions
  - P. Bozek et al., PRC83.034911
  - J. Jia et al., arXiv:1403.6077
- Also known as "event plane decorrelation"
  - K. Xiao et al., PRC87.011901
  - decorrelation increases with increasing η-gap
- v_n may be underestimated, which means overestimating η/s



Event twist selection



J.Jia et al., arXiv:1402.6680

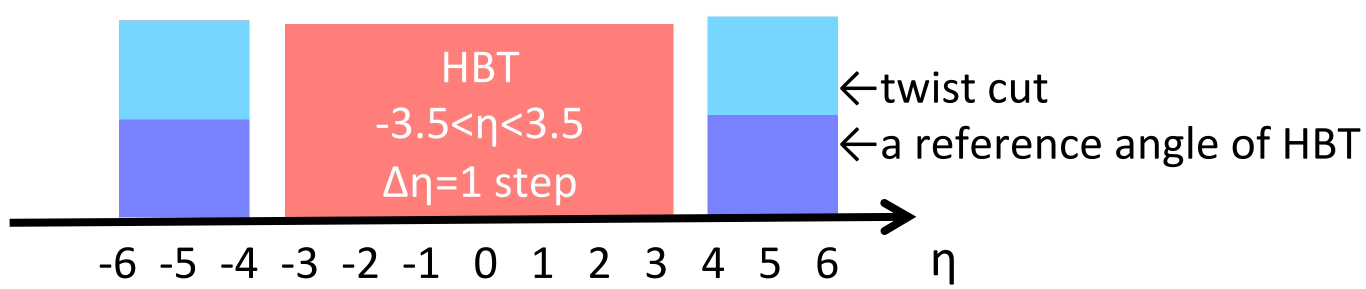


$$C(\Delta\phi, \Delta\eta) \propto 1 + 2\Sigma v_n^a v_n^b \cos(n\Delta\phi - n\Delta\phi_n^{rot})$$

- Twist effect on anisotropic flow&2PC studied with AMPT
  - Requiring finite difference b/w forward and backward EPs ($\Psi_2{}^B$-$\Psi_2{}^F$)
- Twist effect appears as a phase shift in Δϕ-Δη correlation
  - initial twist survives as a final state flow in momentum space
- **How about in spatial coordinate space?**

HBT study in AMPT

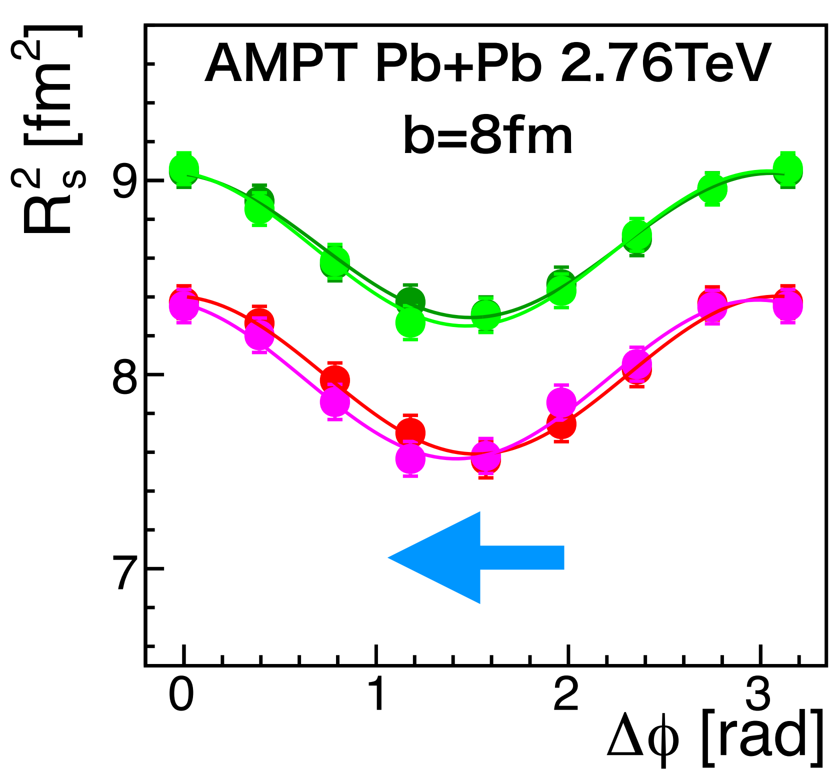
- AMPT model
  - ver.2.25 (string melting)
  - Pb+Pb 2.76 TeV collisions, b=8fm
  - initial fluctuation based on Glauber model and final state interaction via transport model
- EP determination at $4<|\eta|<6$

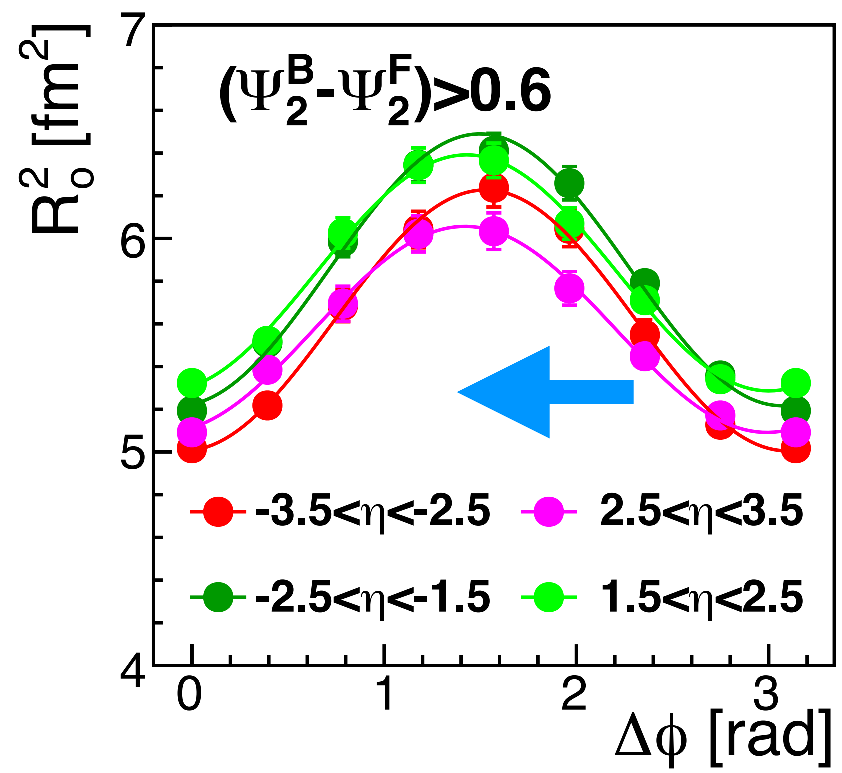


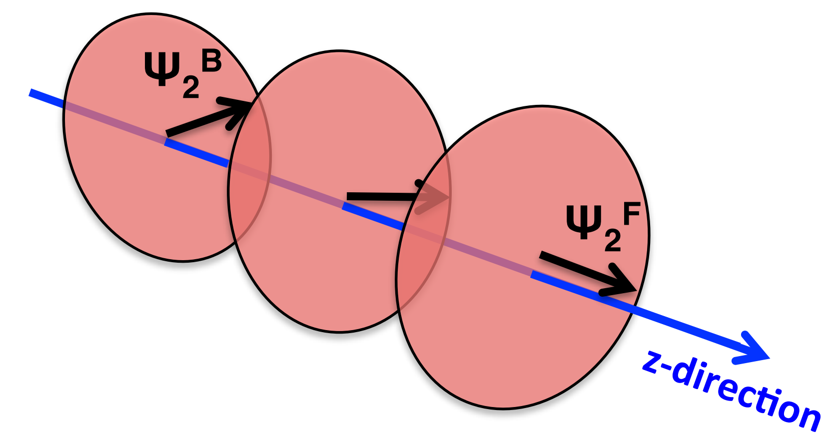
- HBT analysis
  - Add HBT correlation between two pion pairs
    - $(1+\cos(\Delta r \Delta q))$ was weighted when making q-distribution of real pairs
  - Allowing to take $\pi+\pi-$ pairs to increase statistics
    - confirmed a good agreement between $\pi^+\pi^+$ and $\pi^-\pi^-$
  - No EP resolution correction
  - Bertsch-Pratt parameterization

$$C_2 = 1 + \exp(-R_s^2 q_s^2 - R_o^2 q_o^2 - R_l^2 q_l^2 - 2R_{os}^2 q_o q_s - 2R_{ol}^2 q_o q_l - 2R_{sl}^2 q_s q_l)$$

HBT radii w.r.t backward Ψ_2



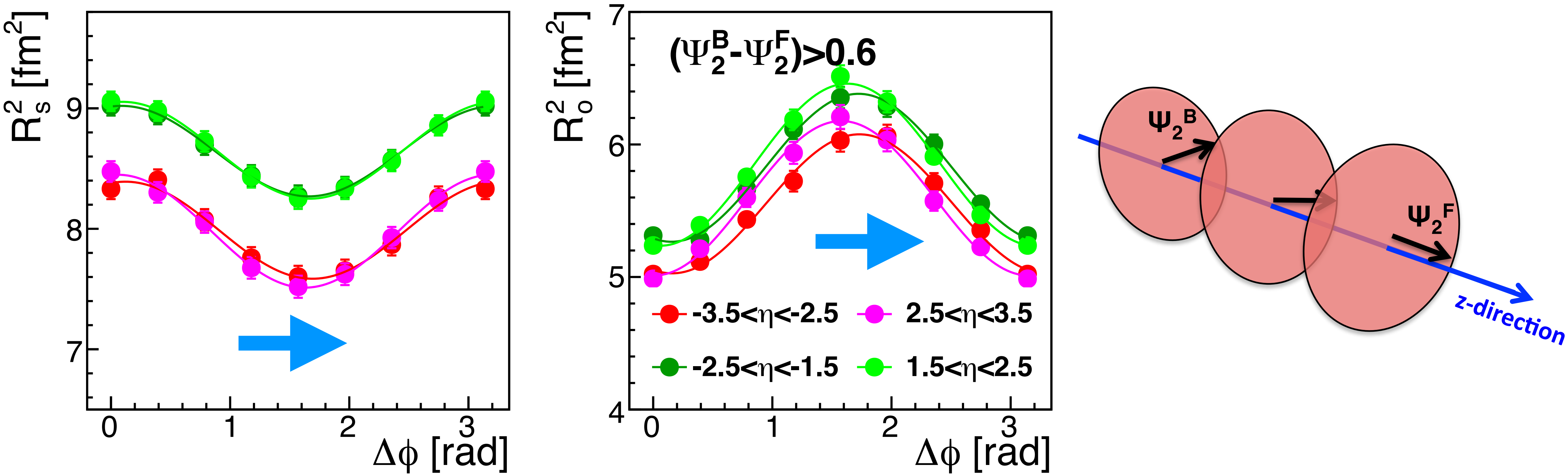




- Selected events with $(\Psi_2{}^B-\Psi_2{}^F)>0.6$
- Phase shift can be seen, and data are fitted with cosine(sine) function including a phase shift parameter α

$$R_\mu^2 = R_{\mu,0}^2 + 2R_{\mu,2}^2 \cos(2\Delta\phi + \alpha)$$

HBT radii w.r.t forward Ψ_2

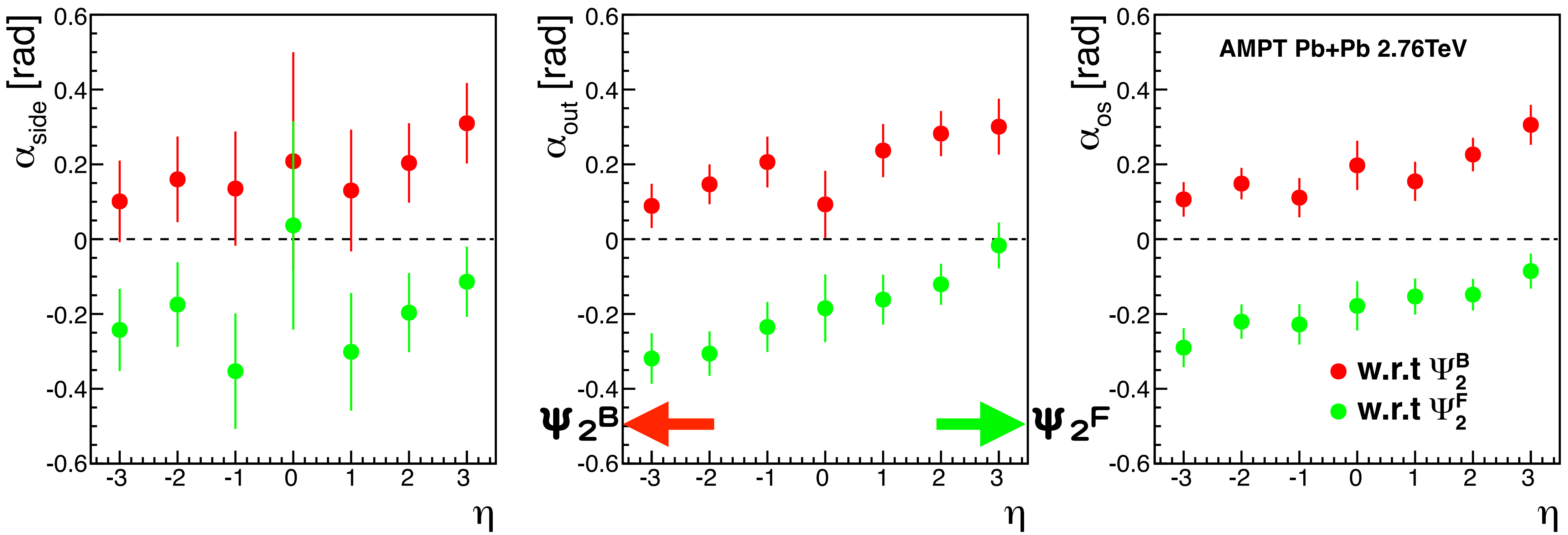


- Selected events with $(\Psi_2{}^B-\Psi_2{}^F)>0.6$
- Phase shift can be seen, and data are fitted with cosine(sine) function including a phase shift parameter α

$$R_\mu^2 = R_{\mu,0}^2 + 2R_{\mu,2}^2 \cos(2\Delta\phi + \alpha)$$

η-dependence of phase shift

$$R_\mu^2 = R_{\mu,0}^2 + 2R_{\mu,2}^2 \cos(2\Delta\phi + \alpha)$$
$$R_{os}^2 = 2R_{os,2}^2 \sin(2\Delta\phi + \alpha)$$



- Phase shifts become larger with going far from η of a reference EP (-6<η<-4 or 4<η<6)
- Source at freeze-out might be also twisted as well as EP angles
  - It may include the effect from twisted flow
- This twist effect could be measured experimentally

Summary

- Event shape engineering at PHENIX
  - Azimuthal HBT measurement with the event shape engineering have been performed in Au+Au 200GeV collisions
  - Higher Q_2 selection enhances the measured ε_{final} as well as v_2
  - More accurate relation between initial and final eccentricity
  - Applicable for detailed study like a path-length dependence in 2PC?

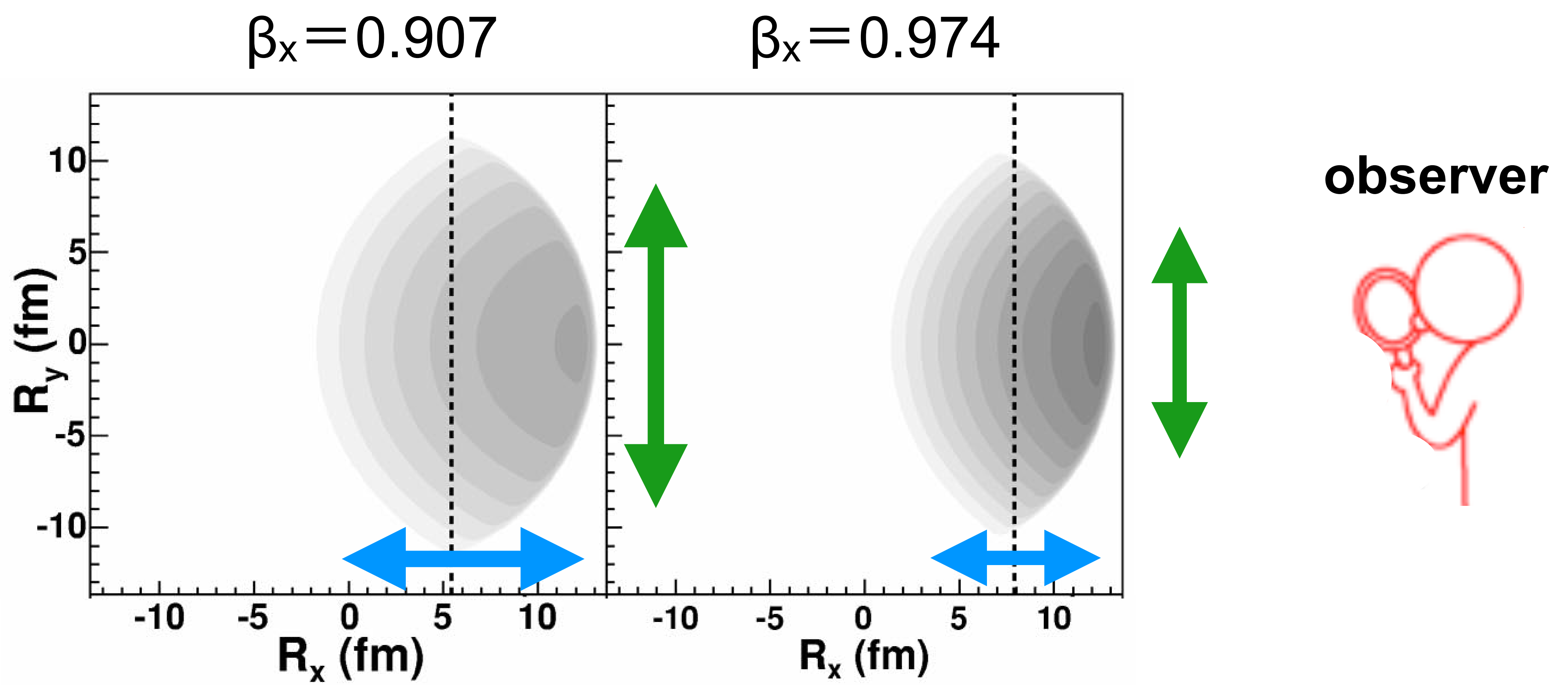
- Event twist selection with AMPT model
  - A possible twisted source have been studied via HBT measurement with AMPT Pb+Pb 2.76TeV collisions
  - Phase shifts of HBT oscillations are seen as a function of η, possibly indicating the twisted source at final state
  - This effect might be measured in RHIC and the LHC, especially in ATLAS or CMS

- These technique might be useful for Cu+Au and U+U

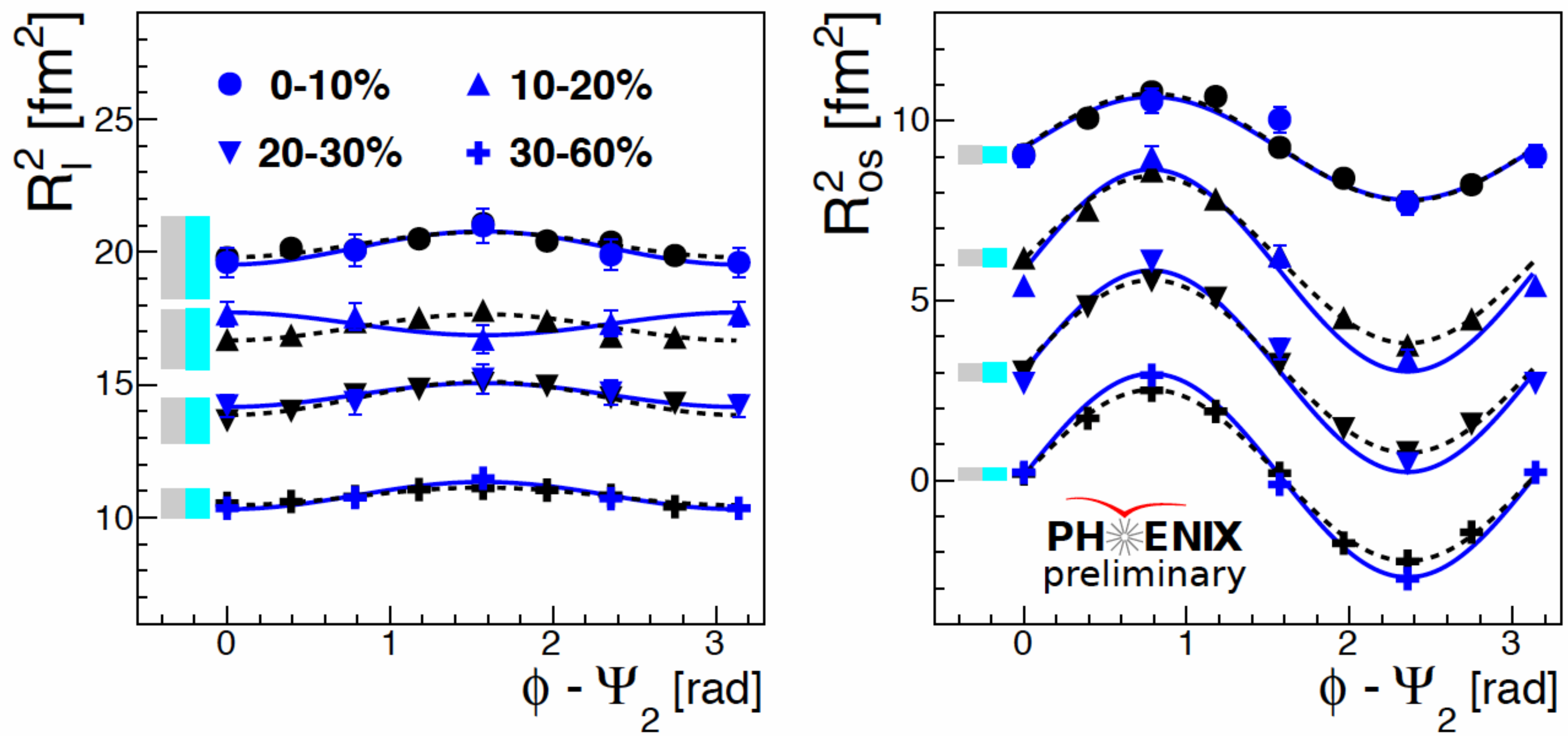
Thank you for your attention

Space-momentum correlation

- Emission points of pions in the Blast-wave model (PRC70, 044907)
- HBT radii = "length of homogeneity"
    - known as k_T dependence of HBT radii by radial flow

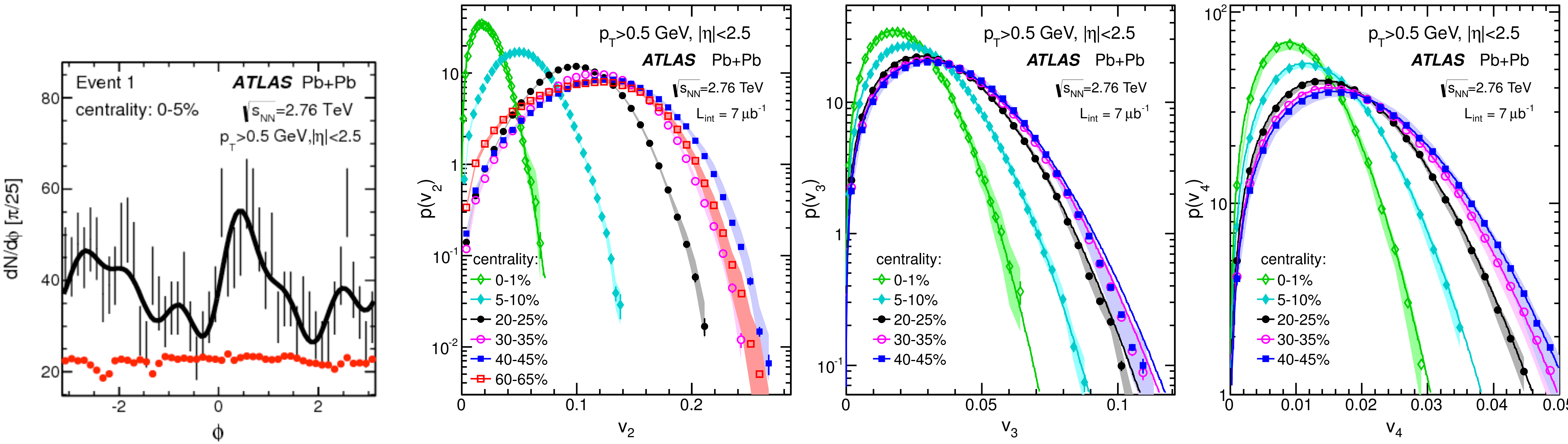


HBT radii w.r.t Ψ_2 with ESE (R_l and R_{os})

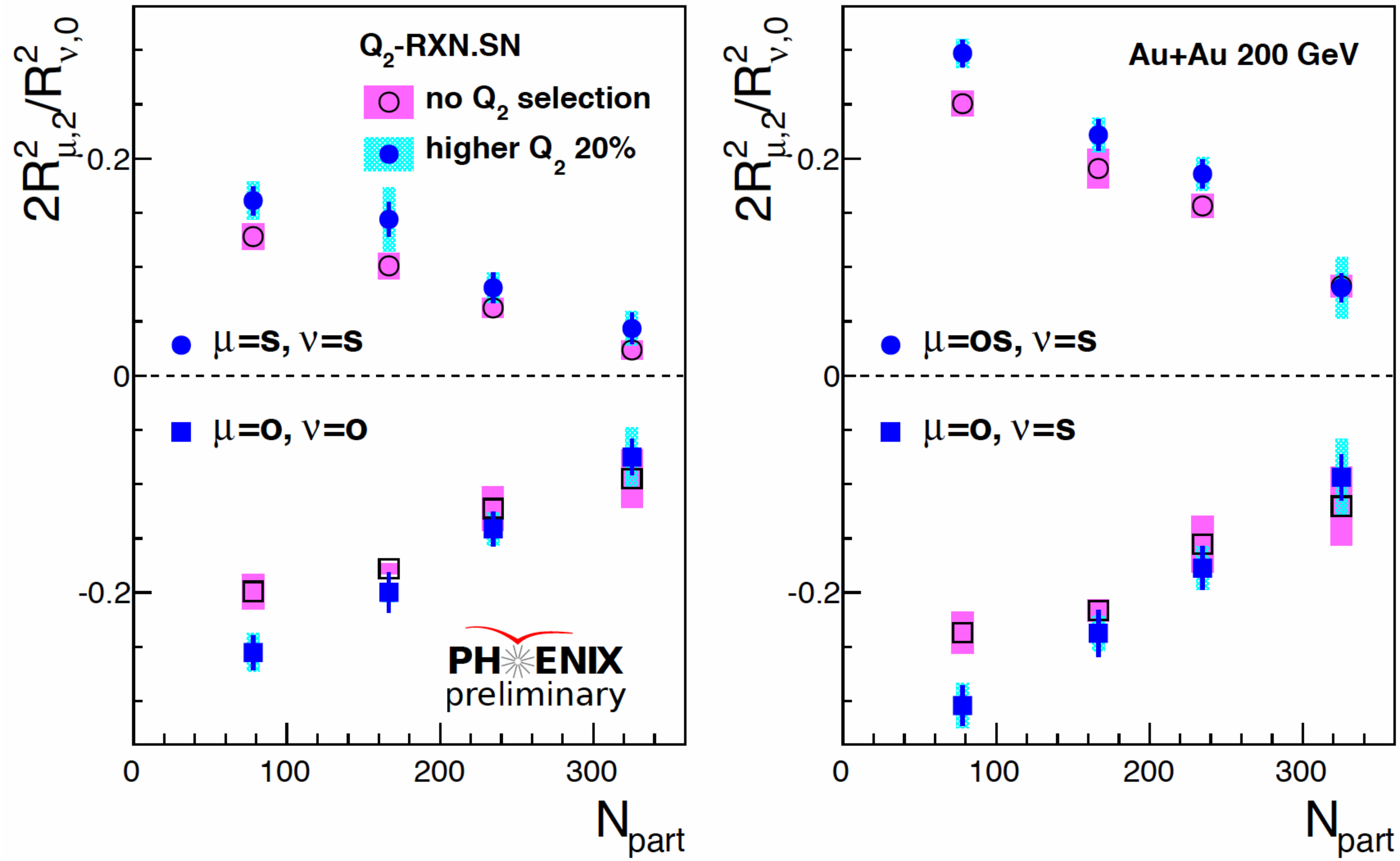


- Oscillation of R_l doesn't change, while R_{os} increases when selecting higher Q_2 events as well as R_s and R_o

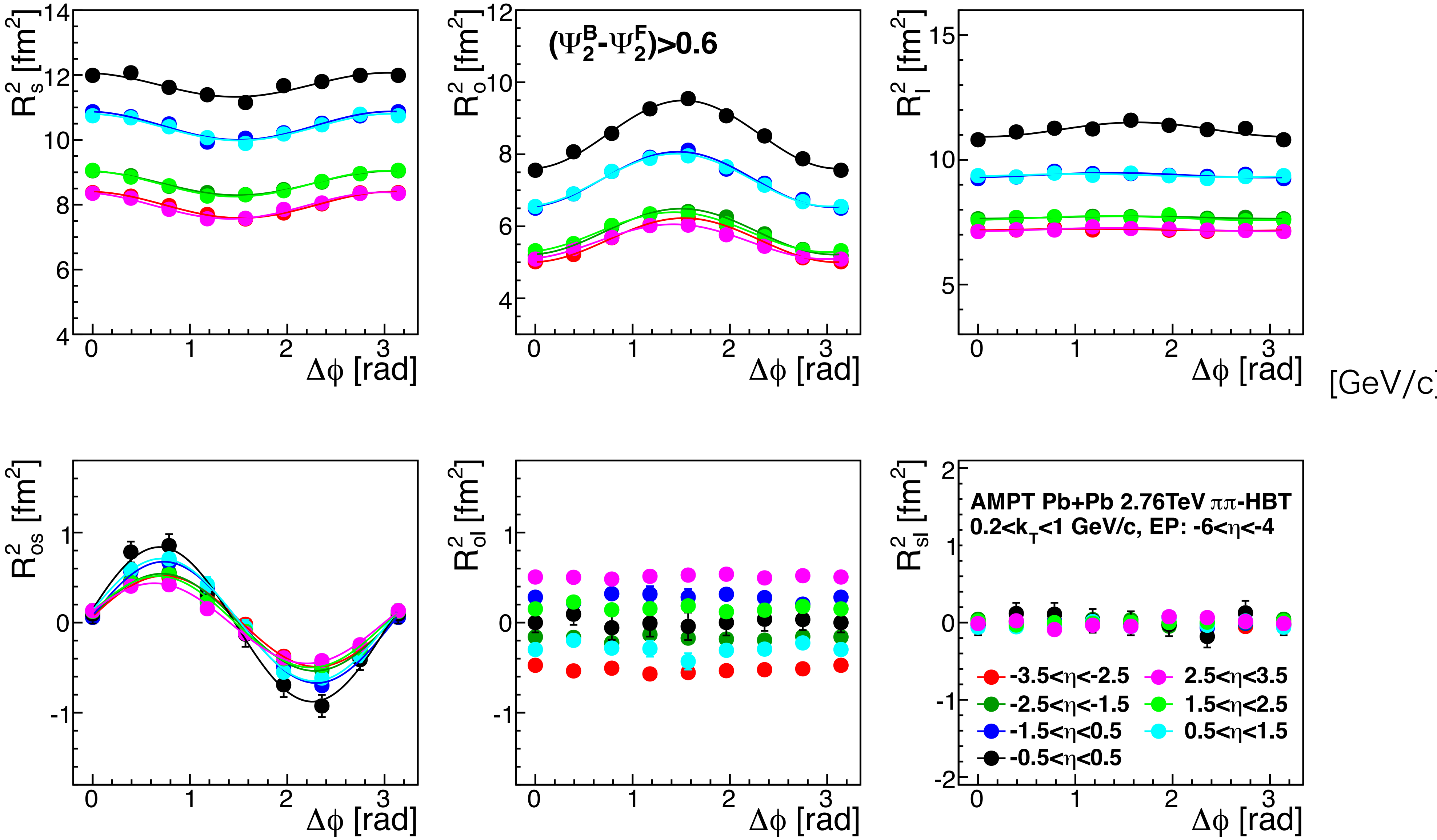
Event-by-event v_n at ATLAS



Oscillation amplitudes as a function of N_{part} with ESE

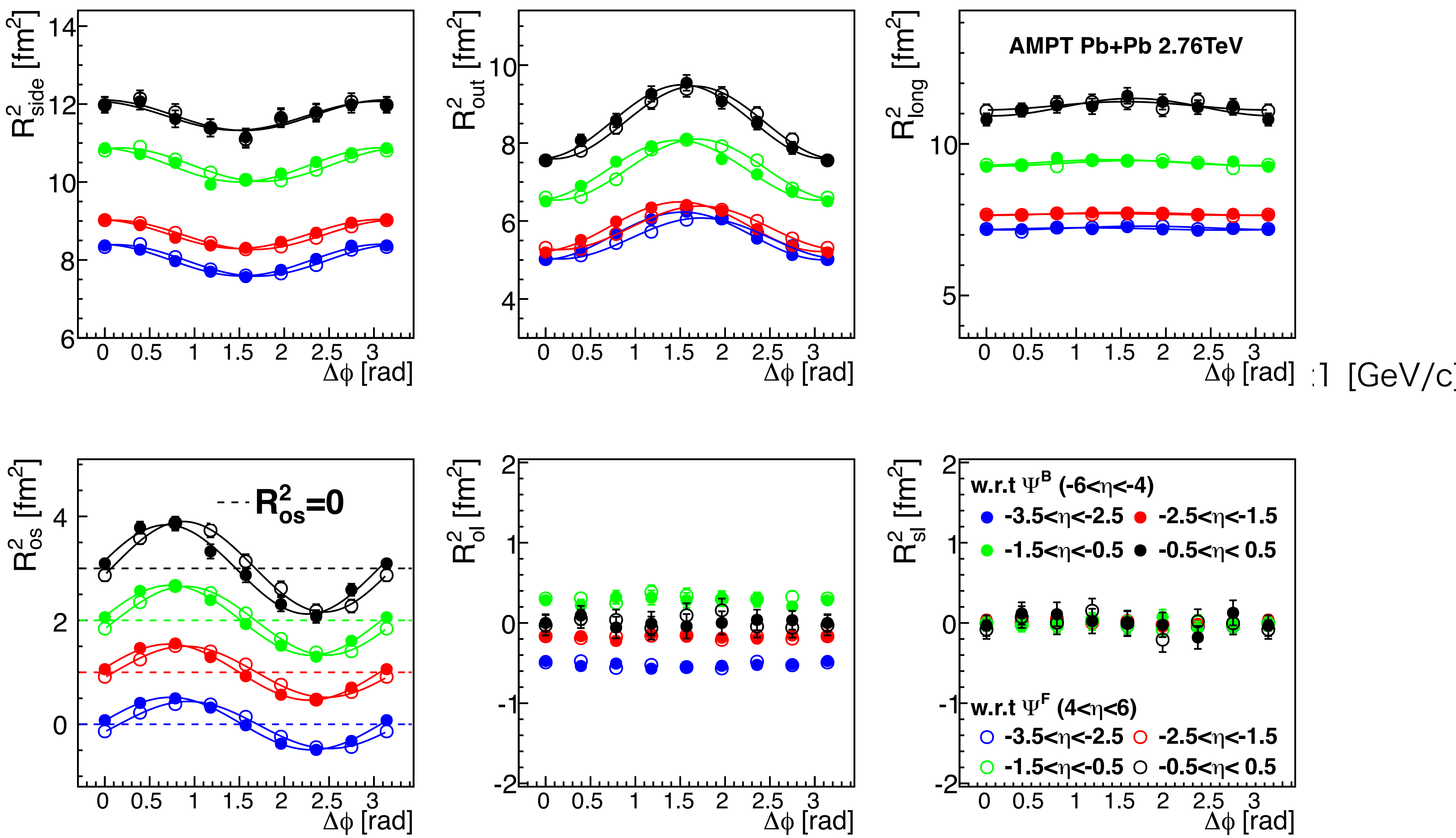


HBT radii w.r.t Ψ_2^B



- Selected events with $(\Psi_2^B-\Psi_2^F)>0.6$
- Phase shift can be seen, and become larger with going far from η of EP for a reference angle ($-6<\eta<-4$)

HBT radii w.r.t $\Psi_2^{B(F)}$ (η<0)

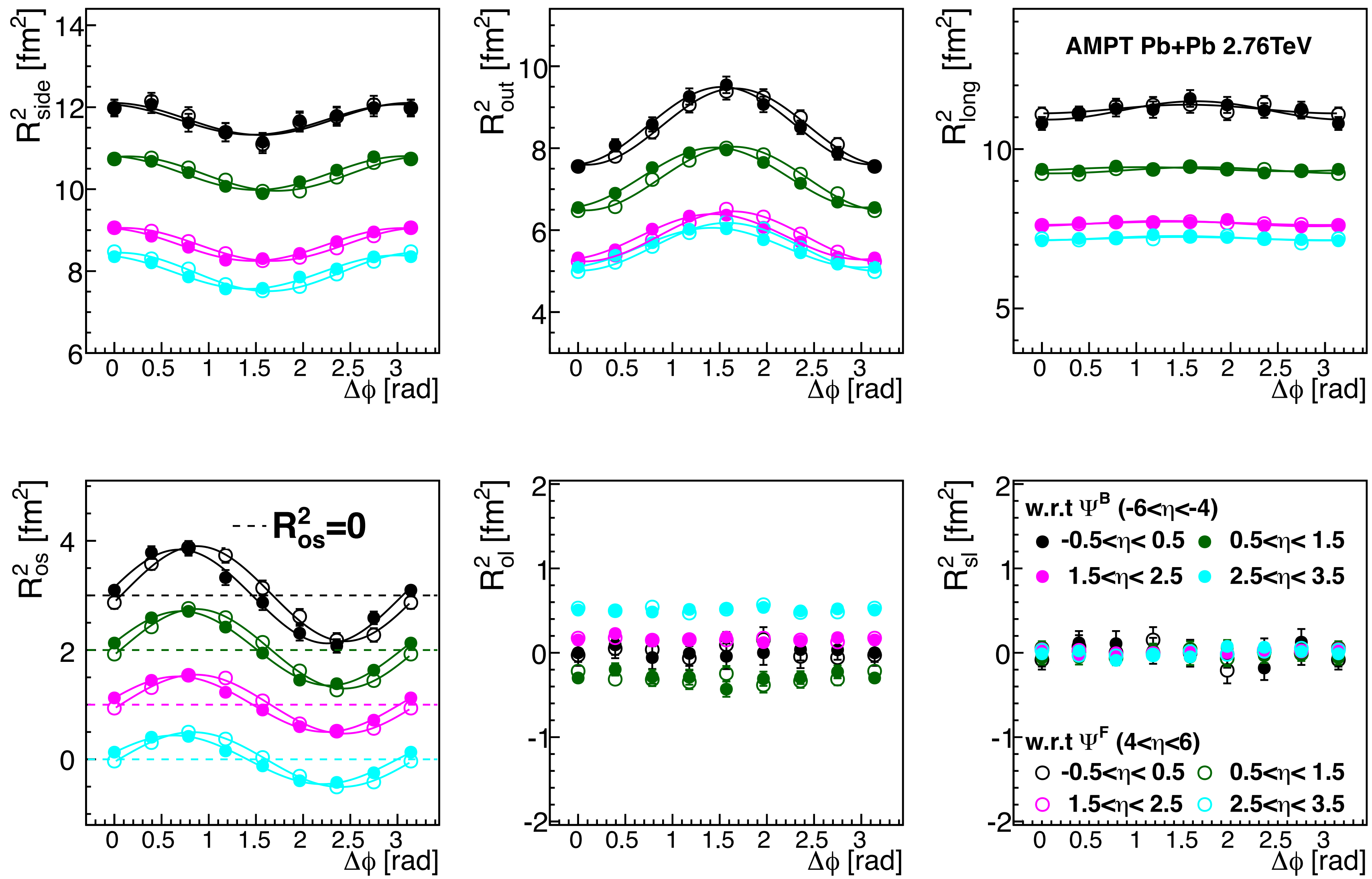


$$R_\mu^2 = R_{\mu,0}^2 + 2R_{\mu,2}^2 \cos(2\Delta\phi + \alpha)$$

$$R_{os}^2 = 2R_{os,2}^2 \sin(2\Delta\phi + \alpha)$$

- Selected events with (Ψ_2^B-Ψ_2^F)>0.6
- Phase difference between Ψ_2^B and Ψ_2^F can be seen in R_s, R_o, and R_{os}

HBT radii w.r.t $\Psi_2^{B(F)}$ (η>0)



<1 [GeV/c]

- Selected events with (Ψ_2^B-Ψ_2^F)>0.6
- Phase difference between Ψ_2^B and Ψ_2^F can be seen in R_s, R_o, and R_{os}

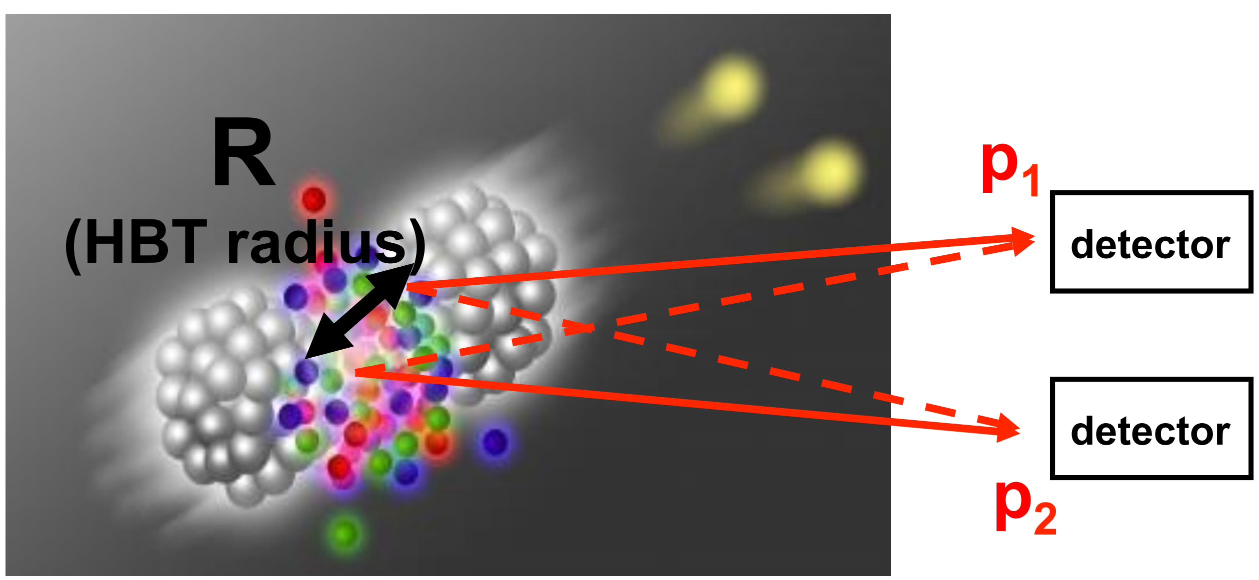
HBT Interferometry

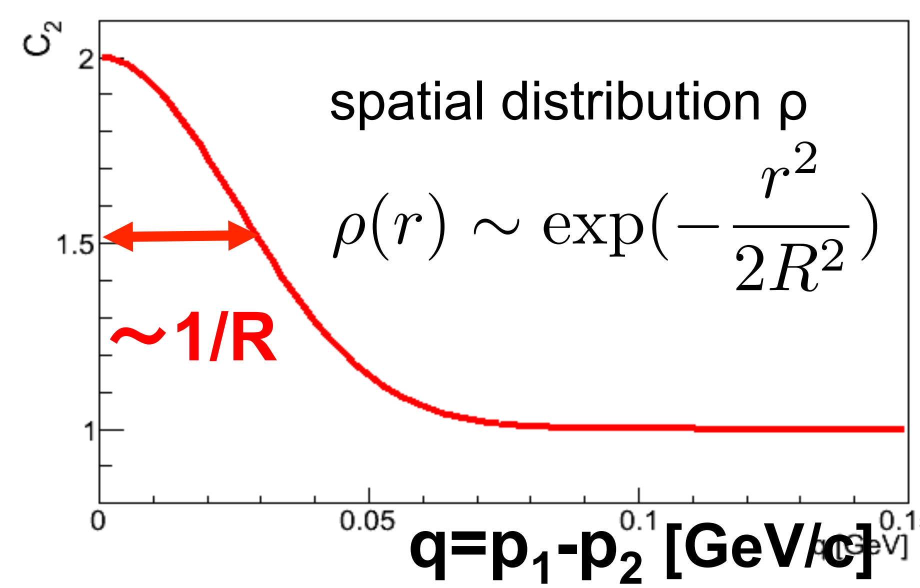
- 1956, H. Brown and R. Twiss, measured angular diameter of Sirius
- 1960, Goldhaber *et al.*, correlation among identical pions in $p+\bar{p}$
- By quantum interference between two identical particles

wave function for
2 bosons(fermions) :

$$\Psi_{12} = \frac{1}{\sqrt{2}}[\Psi(x_1,p_1)\Psi(x_2,p_2) \pm \Psi(x_2,p_1)\Psi(x_1,p_2)]$$

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





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.

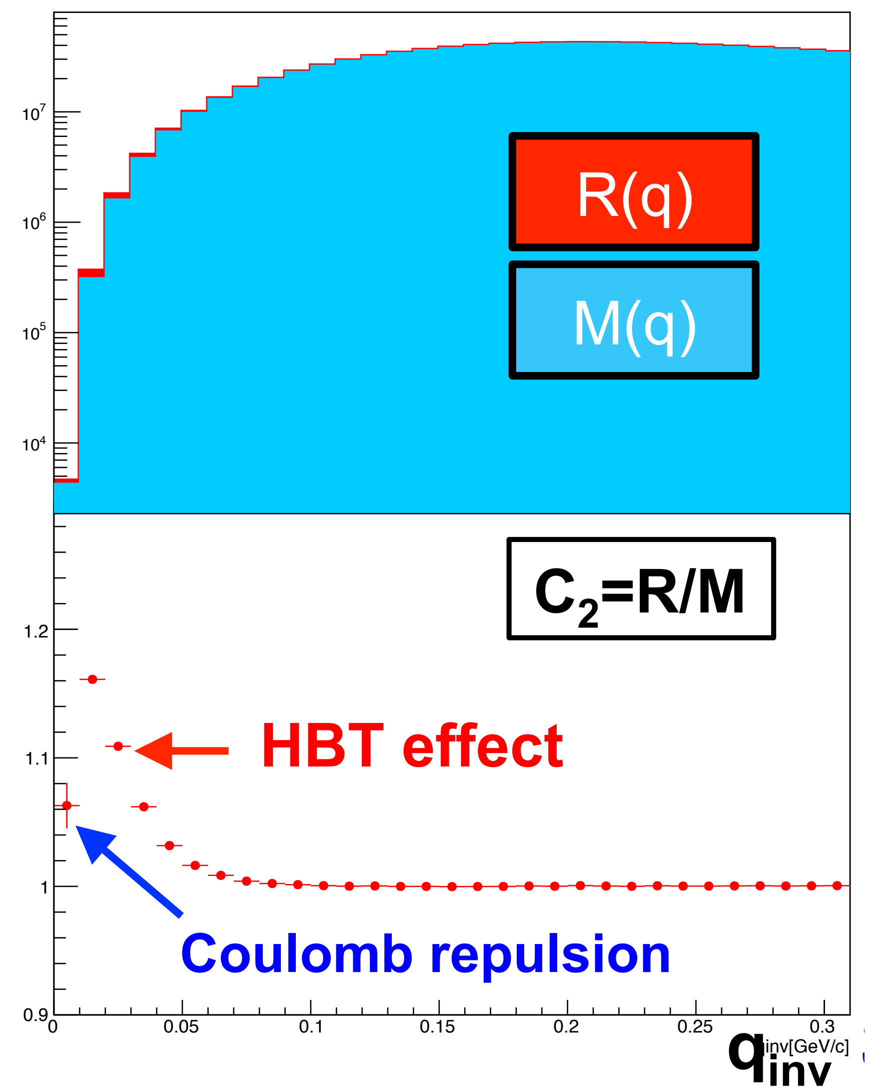
$$C_2 = \frac{R(\mathbf{q})}{M(\mathbf{q})}$$

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

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

  Mixed pairs doesn't include HBT and Coulomb effects.

relative momentum dist.

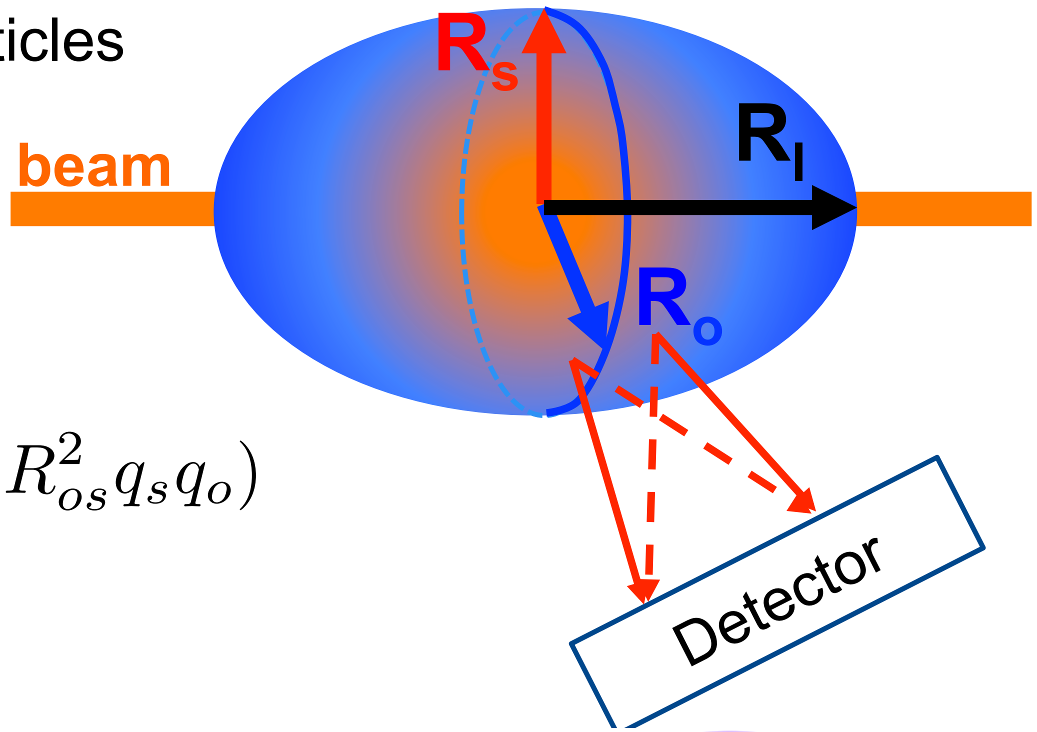


3D-HBT Analysis

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

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

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

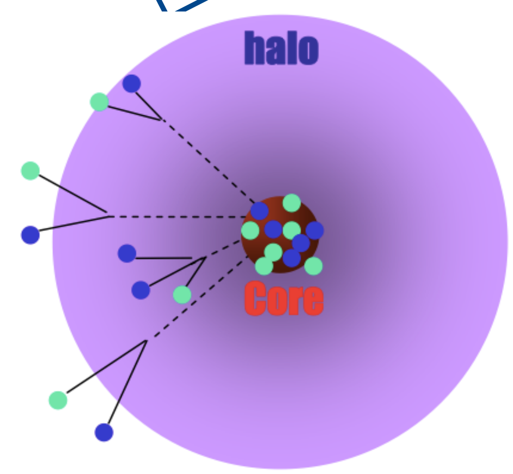


$$\begin{aligned} C_2 &= C_2^{core} + C_2^{halo} \\ &= [\lambda(1+G)F_{coul}] + [1-\lambda] \end{aligned}$$

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

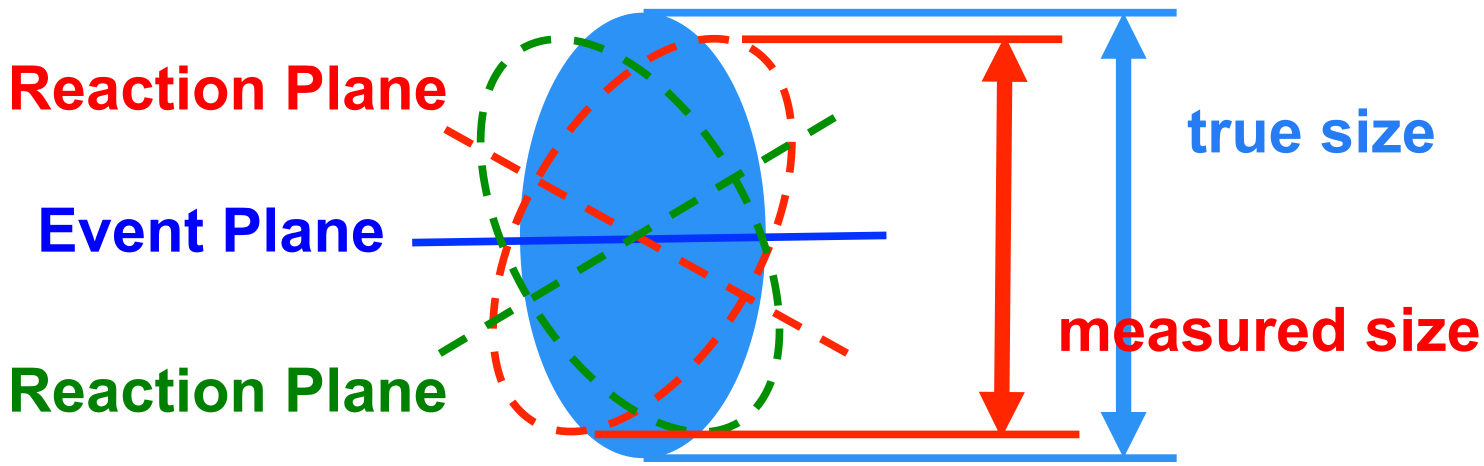
F_{coul}: Coulomb correction factor
λ : fraction of pairs in the core

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



Correction of Event Plane Resolution

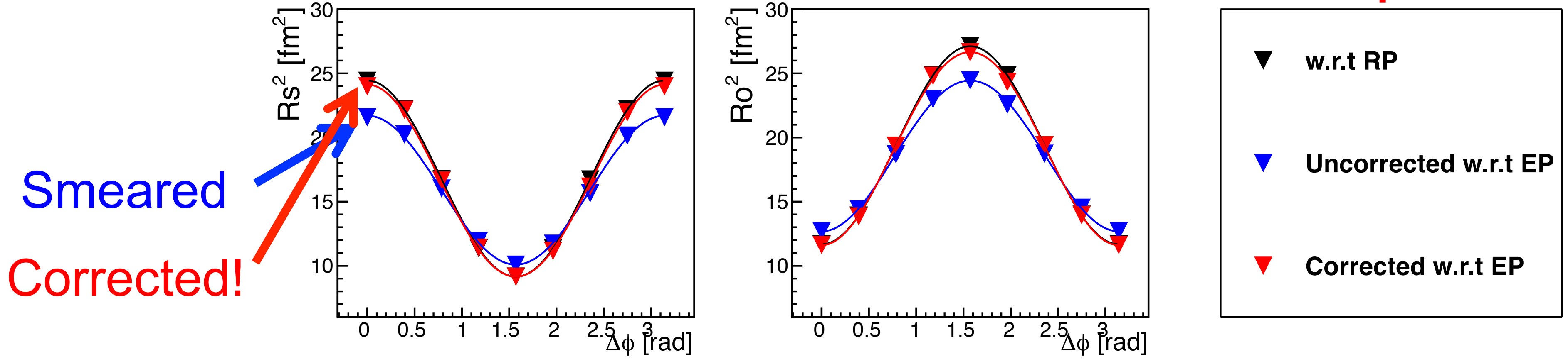
- Smearing effect by finite resolution of the event plane



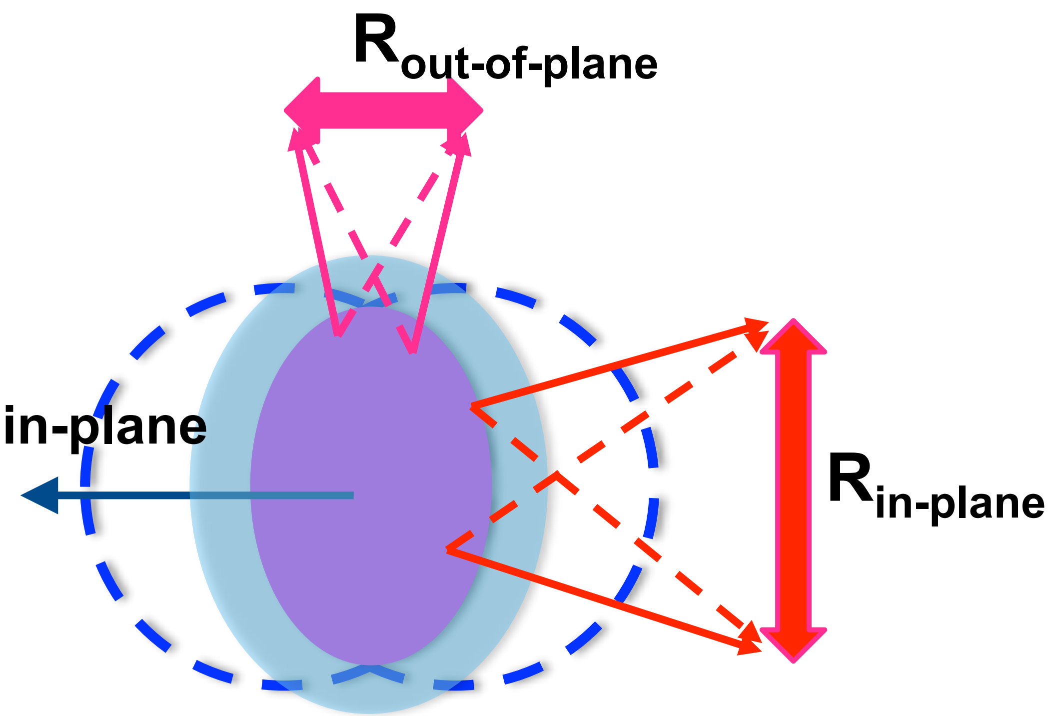
- Correction for q-distribution $A_{crr}(q,\Phi_j) = A_{uncrr}(q,\Phi_j) + 2\Sigma\zeta_{n,m}[A_c\cos(n\Phi_j) + A_s\sin(n\Phi_j)]$
  - ✧PRC.66, 044903(2002)
    - ✓ model-independent correction
  - ✧Checked by MC-simulation

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

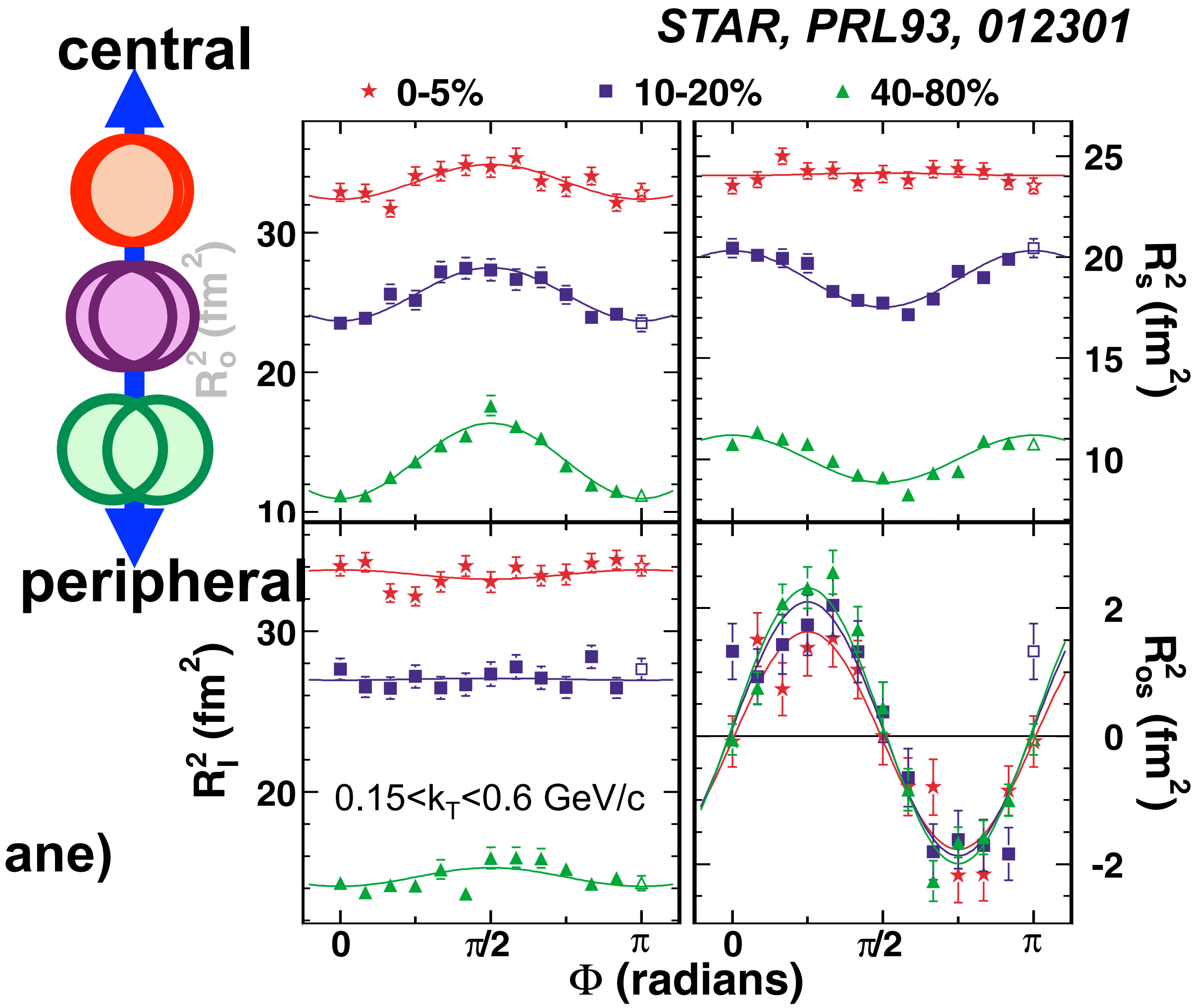
event plane resolution



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



Reaction plane ≈ 2nd-order event plane(v_2 plane)



PRC70, 044907 (2004), Blast-wave model

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

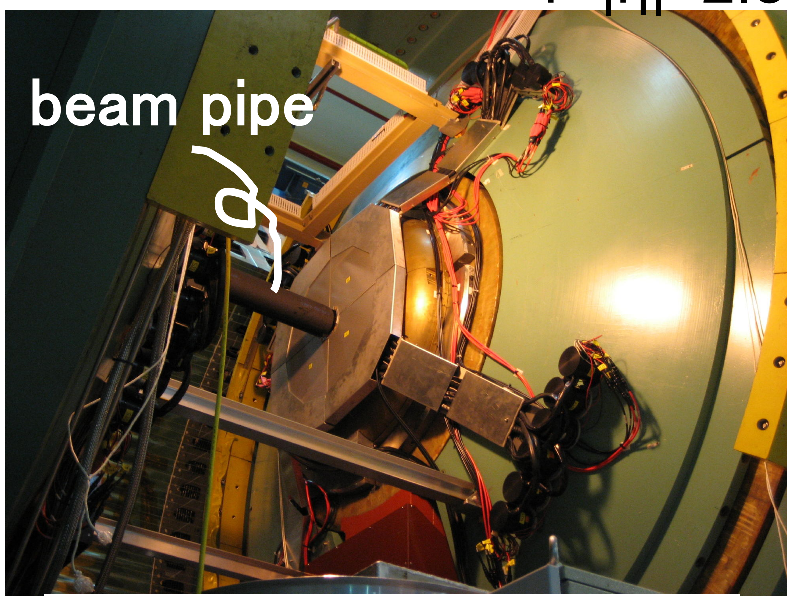
$$\varepsilon_{final} = 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

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

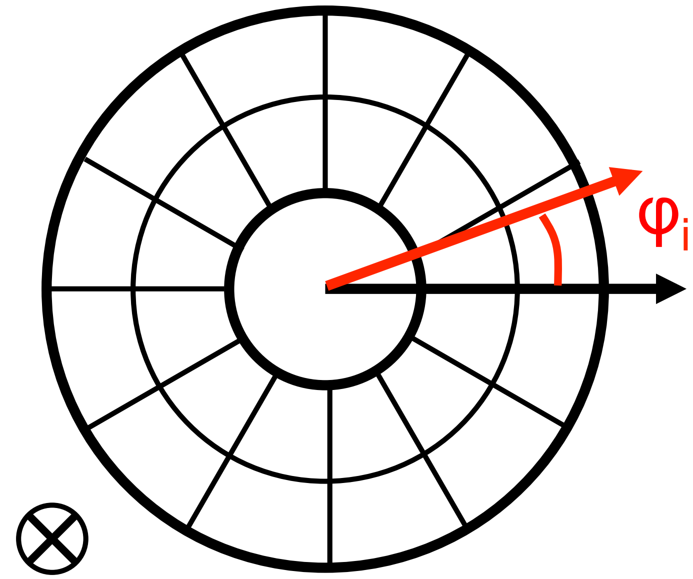
Results of HBT w.r.t 2nd- and 3rd-order event planes are presented today!

Event Plane Determination

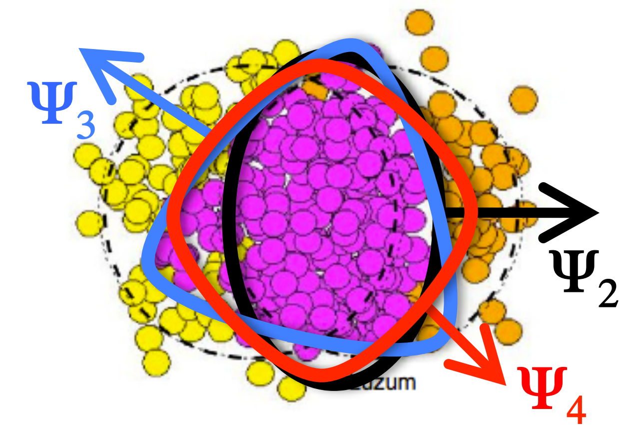
1<|η|<2.8

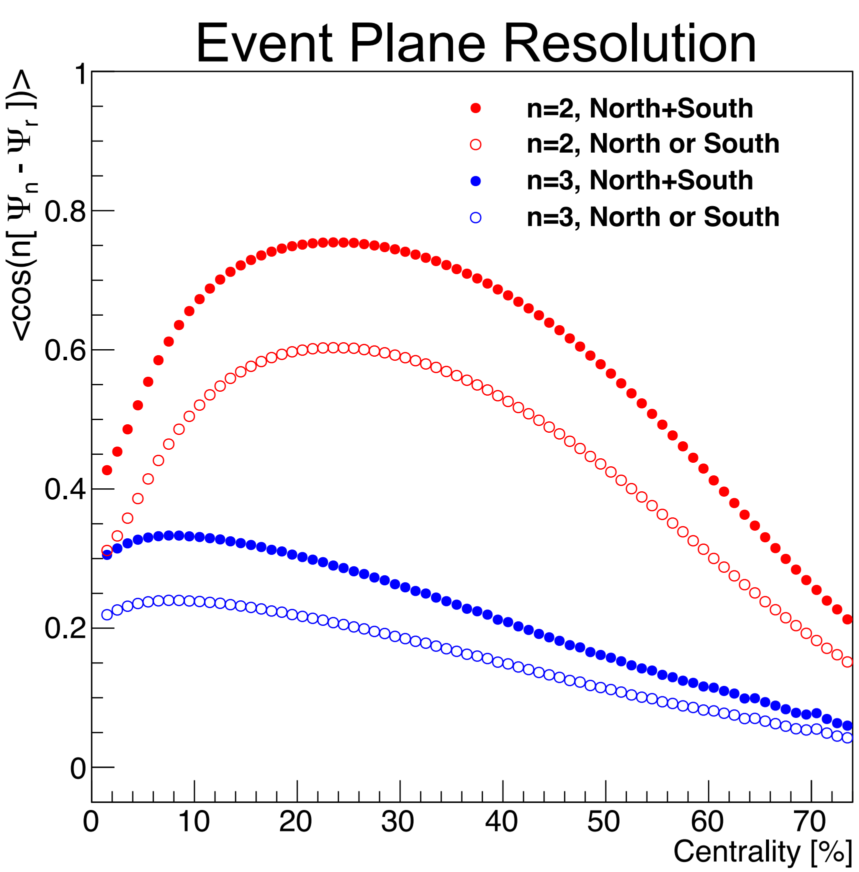


24 scintillator segments



beam axis





- **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