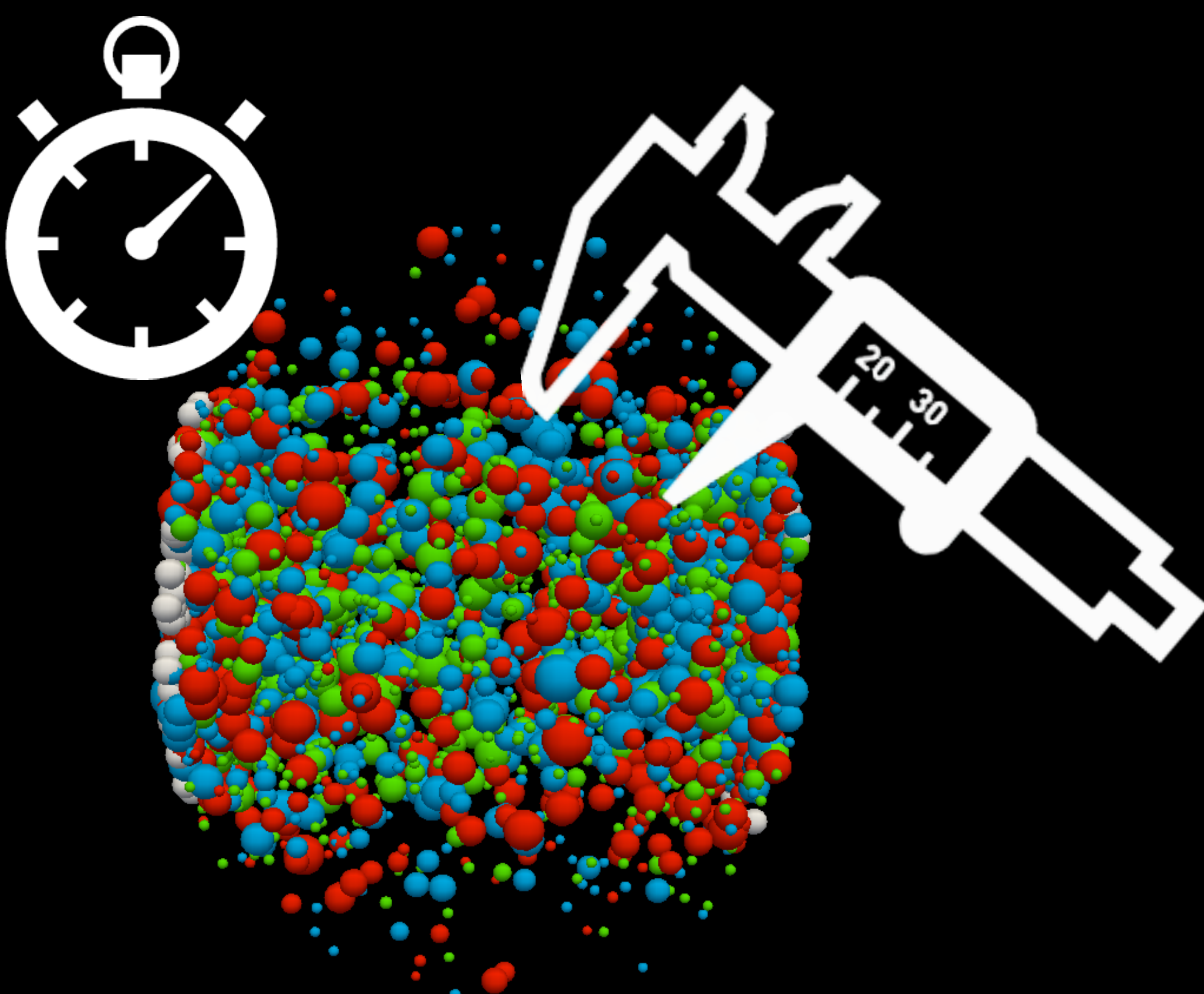
Measurements of Azimuthal Angle Dependence of HBT radii with respect to event plane in $\sqrt{s_{NN}}$ = 2.76 TeV Pb-Pb collisions at LHC-ALIE



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2017.October.23

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High Energy Nuclear Physics Group

Outline

✓ **Introduction**

- Quark Gluon Plasma
- HBT interferometory

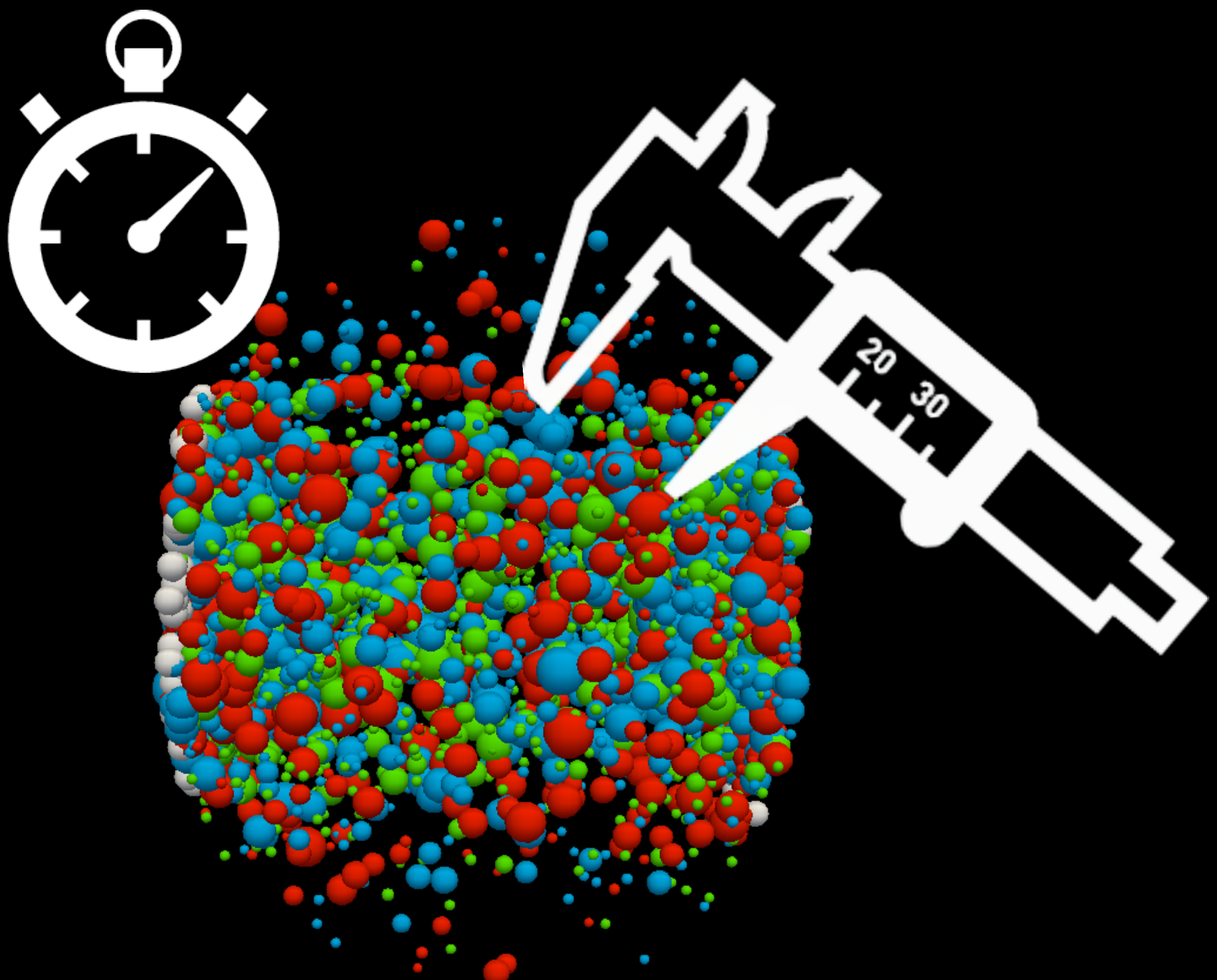
✓ **Experiment & Analysis**

- ALICE
- Analysis methods

✓ **Result & Discussions**

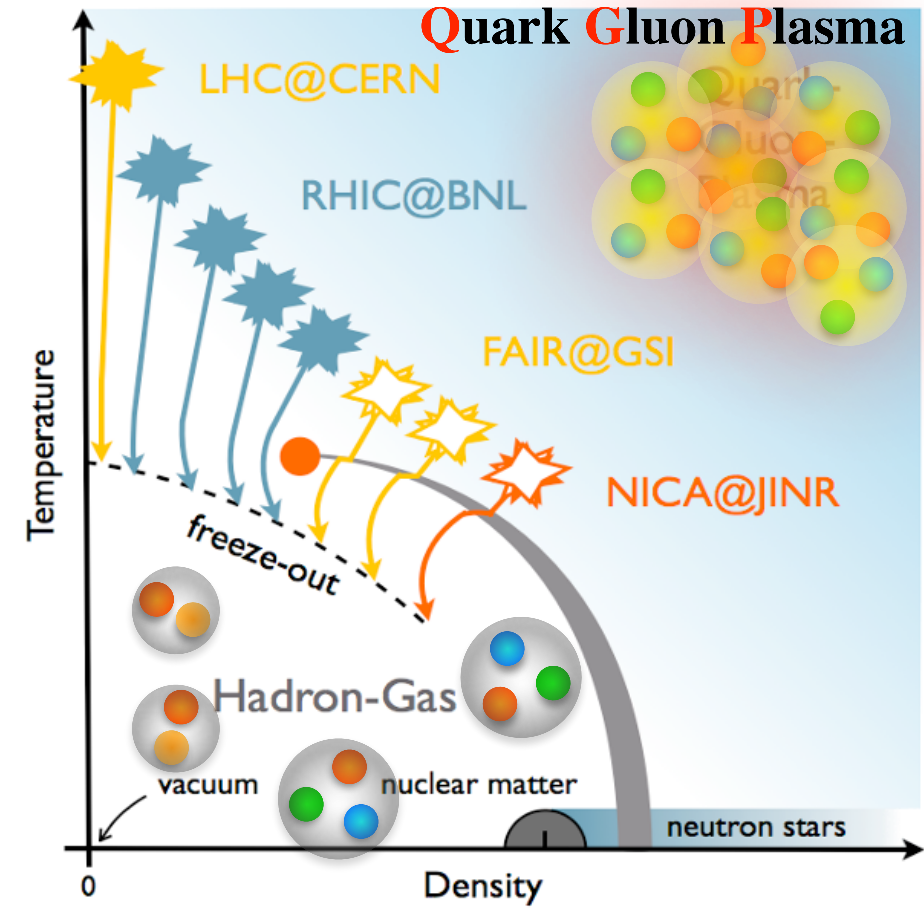
- Azimuthal angle dependence of HBT radii w.r.t. E.P.
- Blast wave fit
- Correlation between flow and HBT with ESE
- Comparison with 3+1D hydrodynamic calculation

Introduction

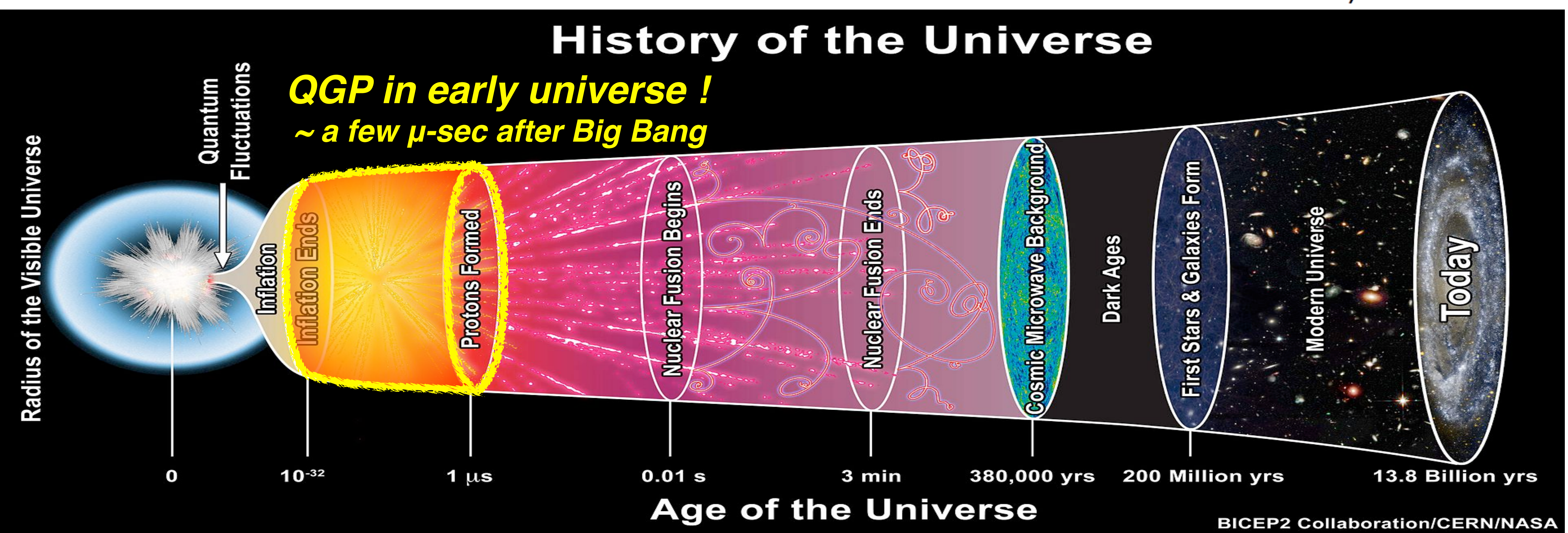


Quark Gluon Plasma (QGP)

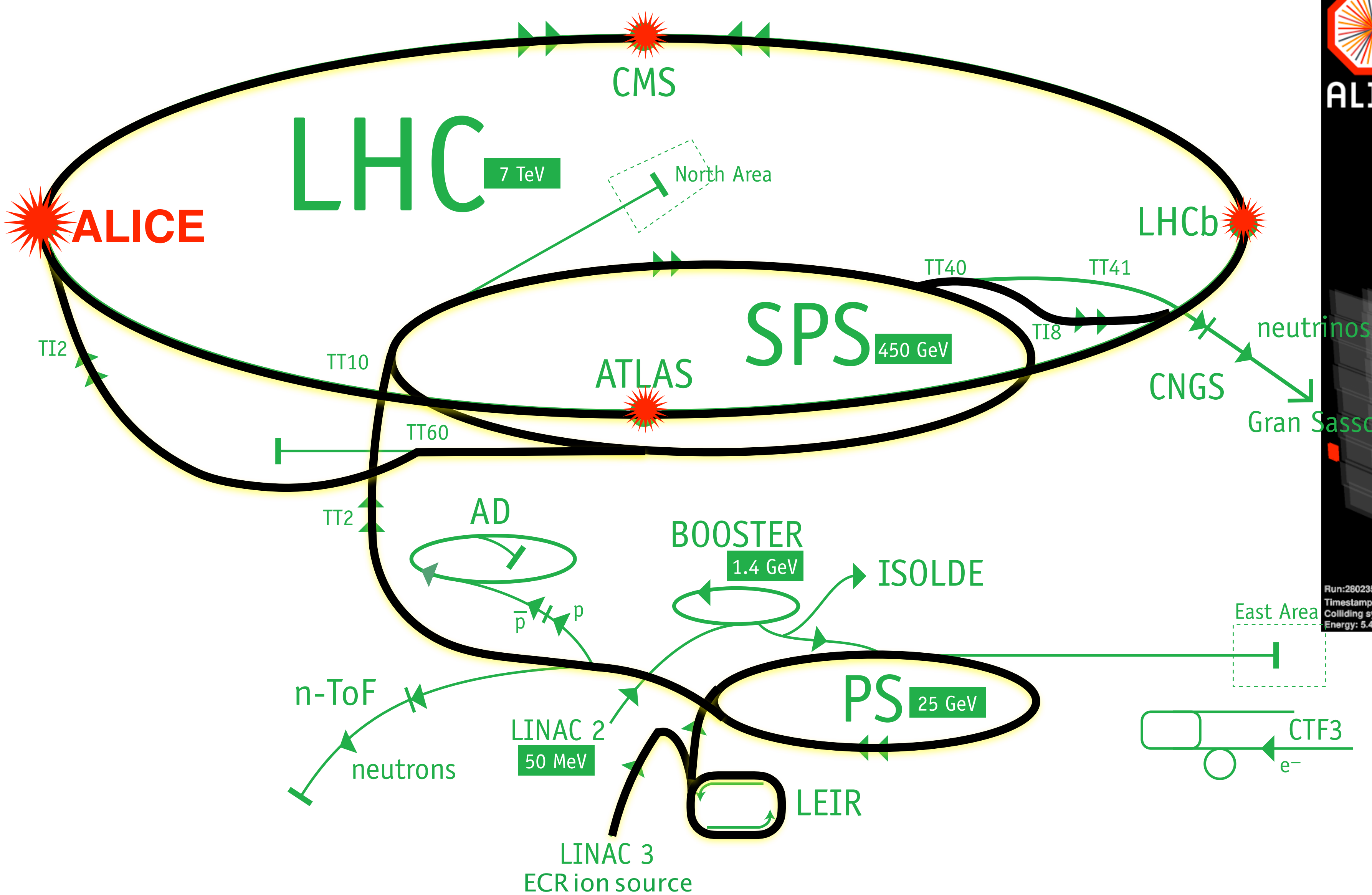
- ✓ Extremely high temperature and density
  - ✓ quarks and gluons are deconfined from hadron
- ✓ QGP exists in early universe and neutron star
- ✓ Latice QCD calculation predicts phase transition
  - ✓ $T_c \sim 170$ MeV
  - ✓ $\varepsilon_c \sim 1$ GeV/fm^3

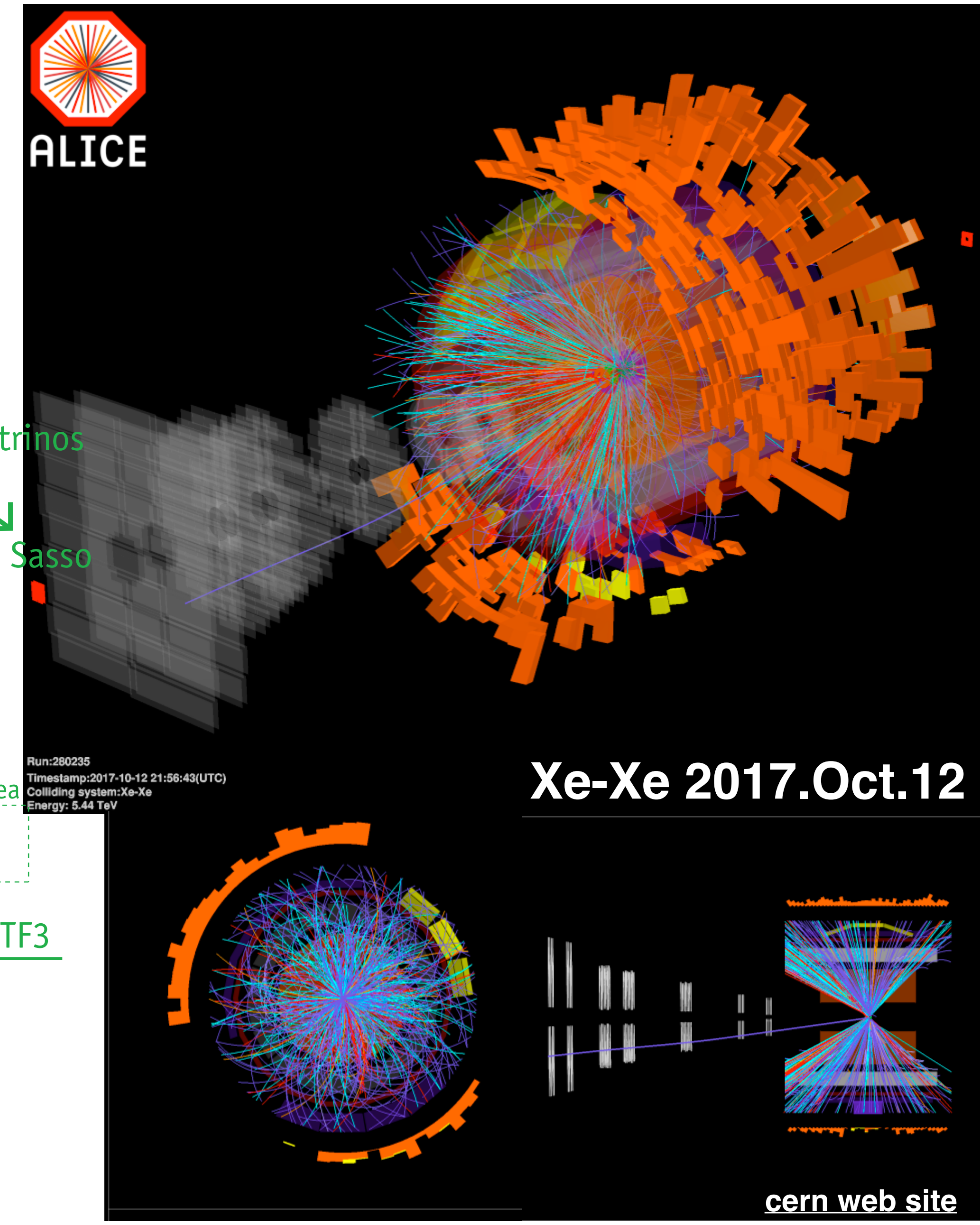


Important to understand History of the universe !



Heavy ion collision at LHC

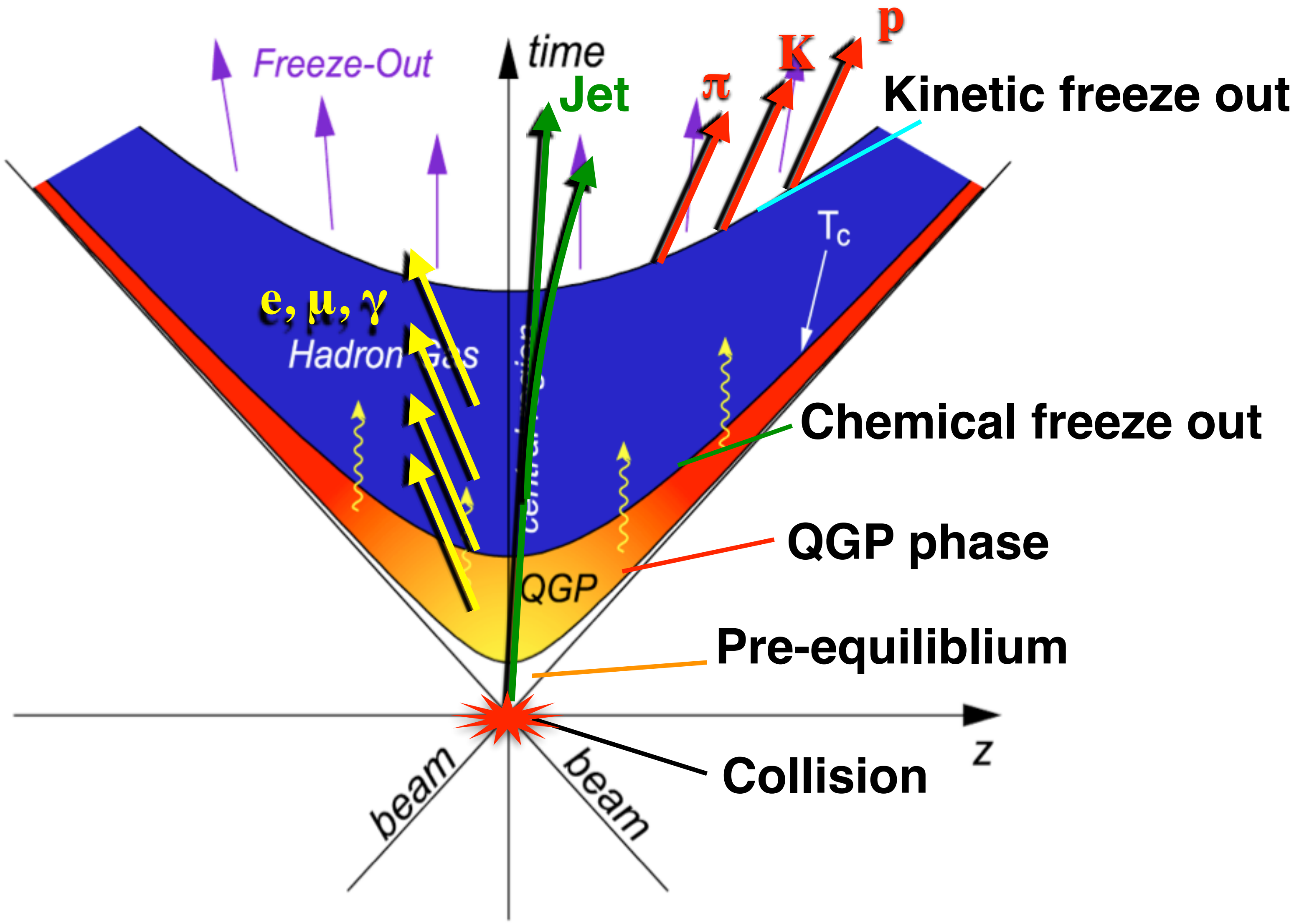




Species	Collision energy
Pb-Pb	2.76, 5.02 TeV
p-Pb	5.02, 8.16 TeV
Xe-Xe	5.44 TeV
p-p	0.9, 2.76, 5.02, 7, 13 TeV

- ✓ **Highest energy collision (energy dep.)**
- ✓ **E-loss in QGP with hard probes**
- ✓ **Detailed study of bulk property**
- ✓ **QGP in small system**

Space time evolution



- ✓ Jet, Heavy quark
  - Energy loss in QGP
- ✓ Photon and leptons
  - Direct information of QGP
- ✓ low p_T hadrons (π, K, p)
  - Spatial and temporal information of bulk
  - Spectra and Azimuthal anisotropy -> T_{kin}, ρ and η/s

✓ To quantify the properties of QGP, namely dynamically expanding source, a precise understanding of spatial and temporal evolution is required

✓ Freeze out time, emission duration, system size

➡ HBT is a unique tool to measure the size and lifetime of the source

HBT interferometry

- ✓ **Hanbury Brown & Twiss (Femtoscopy, Bose Einstein correlations)**
- ✓ **Measure the source size with correlation between two identical particles**

$$\Psi_{12}(p_1, p_2) = \frac{1}{\sqrt{2}}\left(e^{ip_1(x_1-r_1)}e^{ip_2(x_2-r_2)} \pm e^{ip_1(x_1-r_2)}e^{ip_2(x_2-r_1)}\right)$$

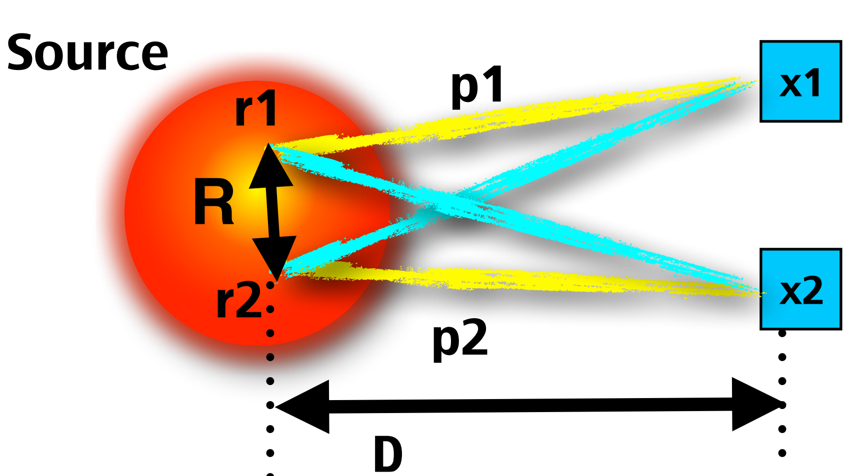
- ✓ ***Boson +***
- ✓ ***Fermion -***

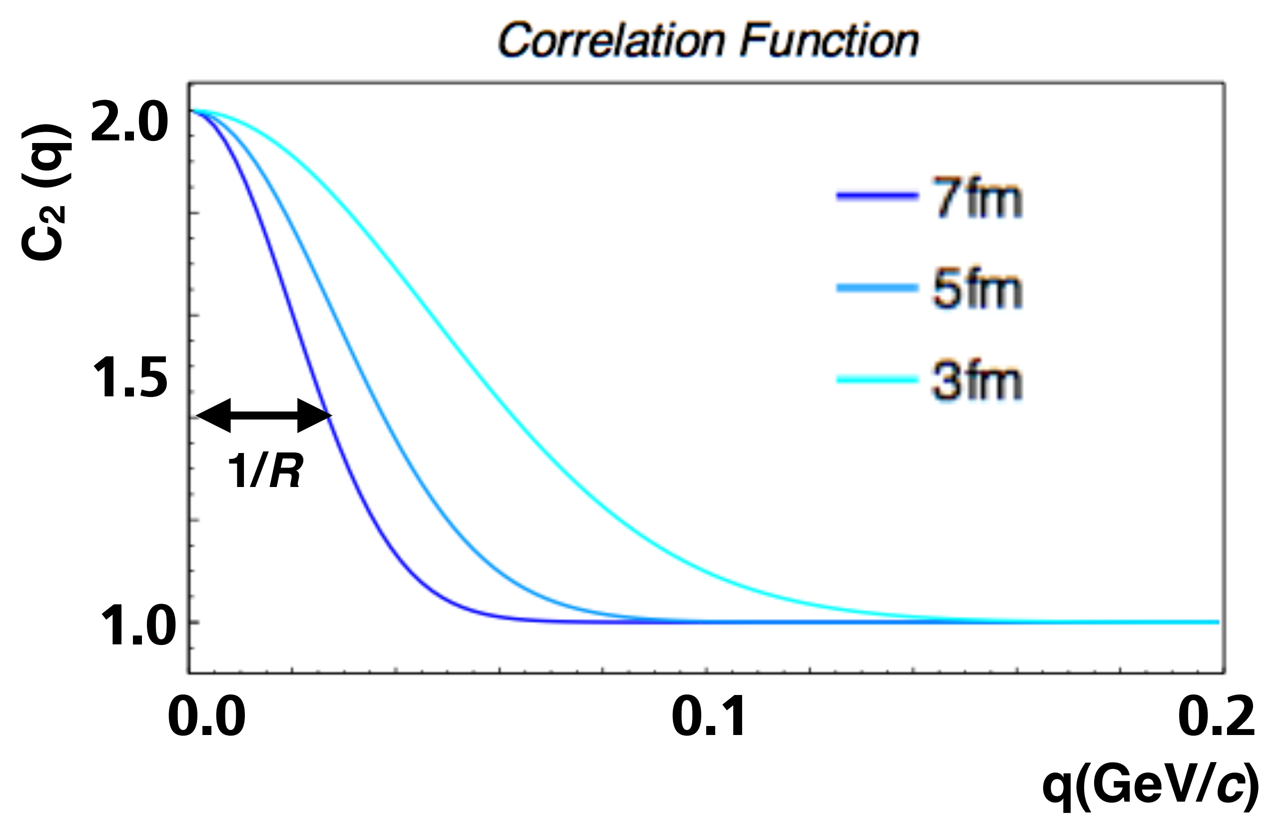
$$C_2 = \frac{P(p_1, p_2)}{P(p_1)\,P(p_2)} \approx 1 + |\tilde{\rho}(q)|^2 = 1 + \exp\left(-R^2 q^2\right)$$

✓ $q = p_1 - p_2$

- ✓ **Source distribution ρ is assumed to be gaussian**

$$\rho(r) \equiv \exp\left(-\frac{r^2}{2R^2}\right)$$





3D HBT analysis

■ For more detailed spatial information, correlation function is expanded to 3-dimension

Bartsch-Pratt parametrization

$$C_2 = 1 + \lambda G$$

$$G = \exp\left(-R_x^2 q_x^2 - R_y^2 q_y^2 - R_z^2 q_z^2 - \Delta\tau q_0^2\right)$$

$$\approx \exp\left(-R_{side}^2 q_{side}^2 - \left(R_{out}'^2 + \beta_T \Delta\tau^2\right) q_{out}^2 - R_{long}^2 q_{long}^2\right)$$

LCMS (Longitudinal Co-Moving System)

✓ $p_{z1} + p_{z2} = 0$

✓ $k_T = \frac{1}{2}\left(\overrightarrow{p_{T1}} + \overrightarrow{p_{T2}}\right)$

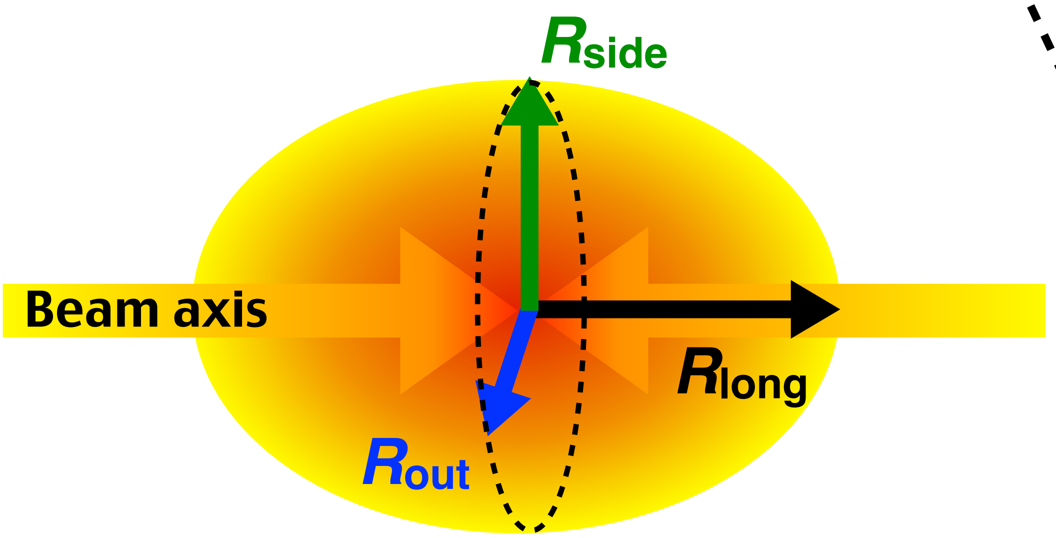
$$G = \exp\left(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2 - 2R_{os}^2 q_{out} q_{side} - 2R_{sl}^2 q_{side} q_{long} - 2R_{ol}^2 q_{out} q_{long}\right)$$

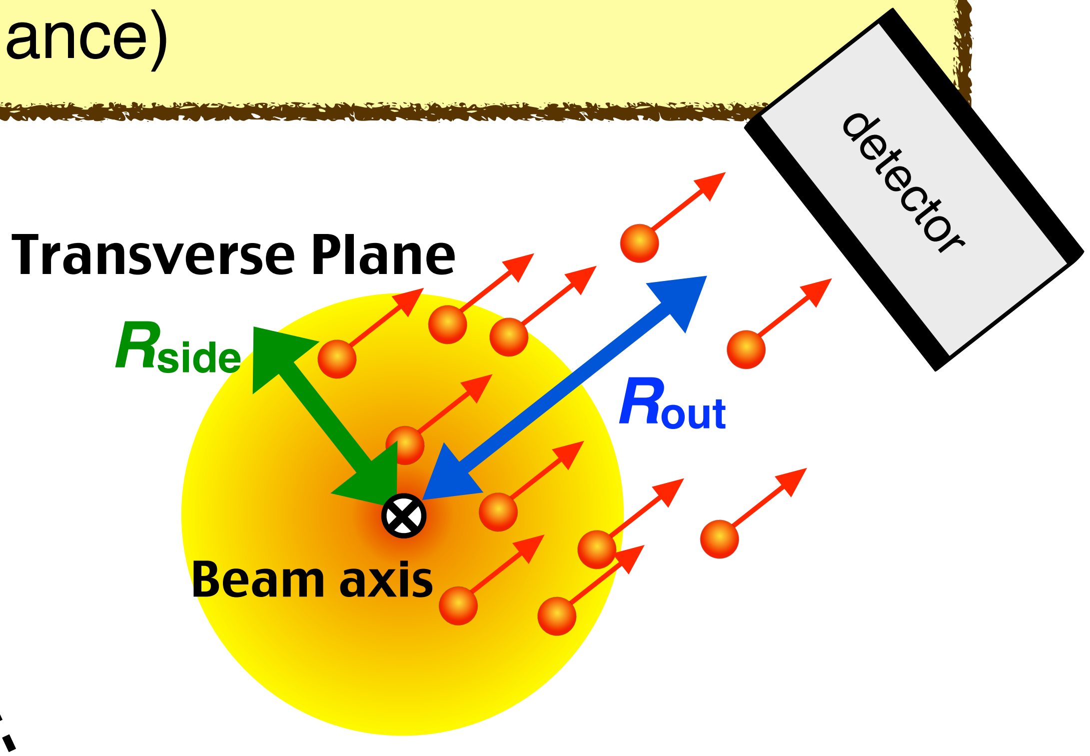
R_{long} : source size along the longitudinal direction (beam direction)

R_{out} : source along the pair transverse momentum + emission duration

R_{side} : source size along the perpendicular to Rout

λ : chaoticity = (in coherence) – (resonance)

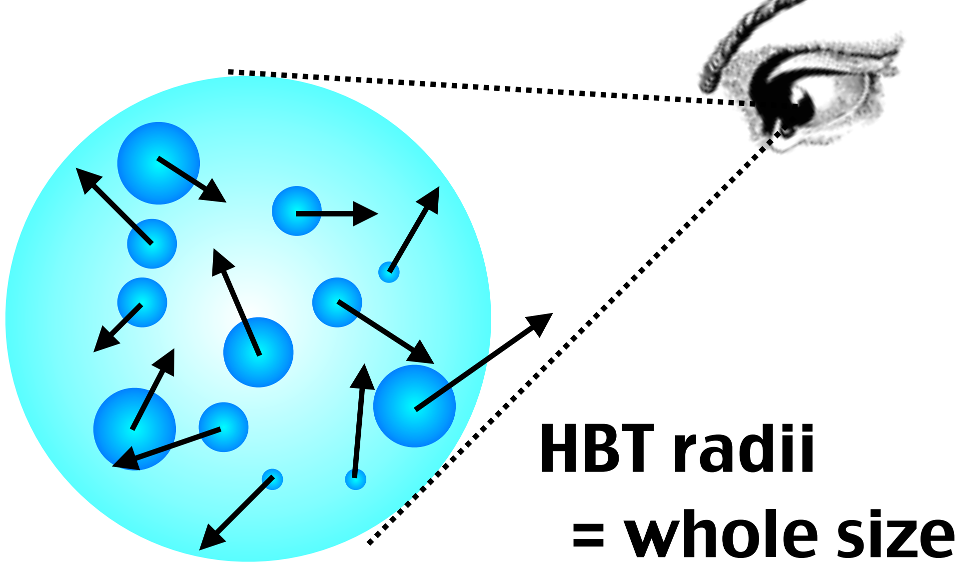




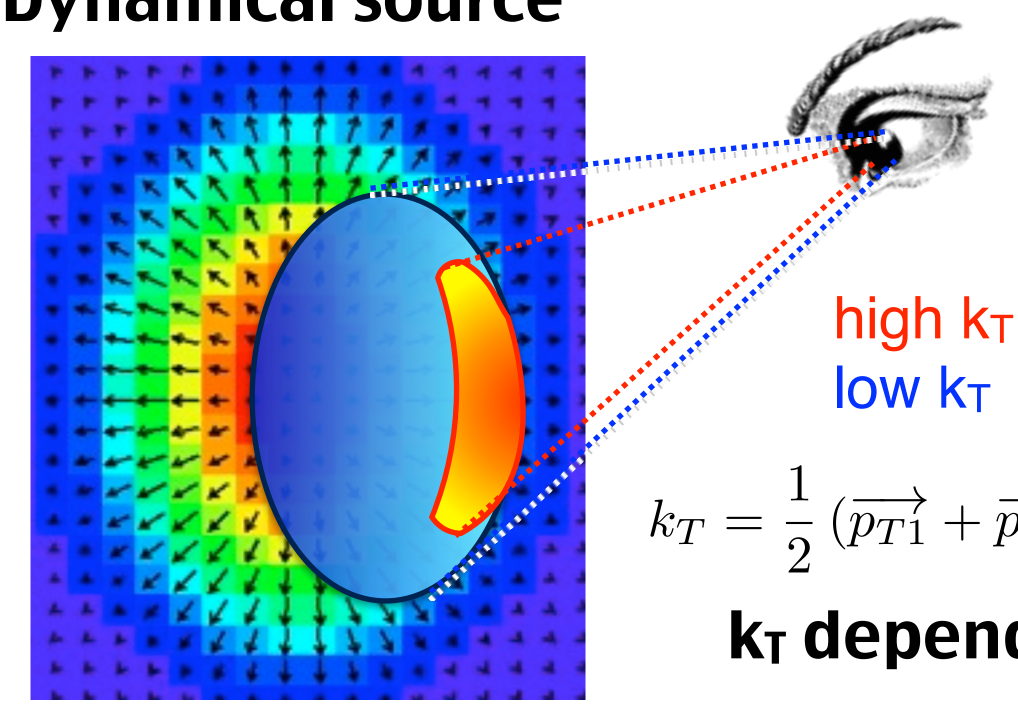
What HBT radii represents?

- ✓ **HBT radii are extracted with two particle correlation**
- ✓ **For static source, HBT raii = Geometrical source size**
- ✓ **HBT radii = Length of homogeity region in dynamical source**

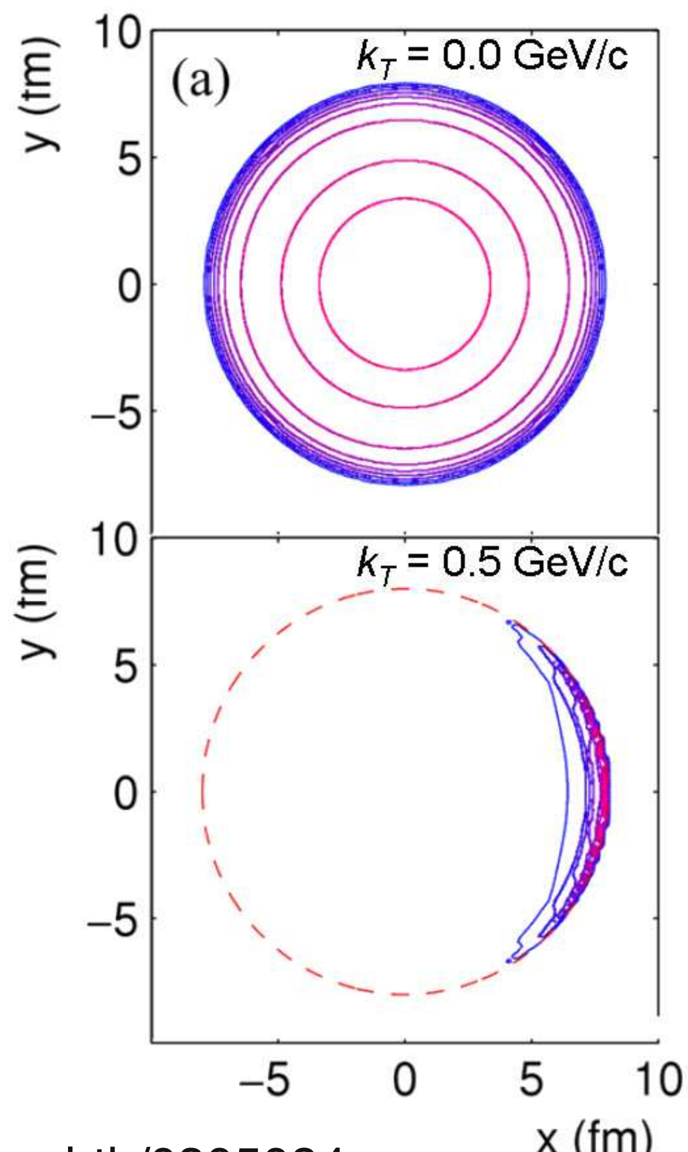
chaotic source



Dynamical source



$$k_T = \frac{1}{2}\left(\overrightarrow{p_{T1}} + \overrightarrow{p_{T2}}\right)$$



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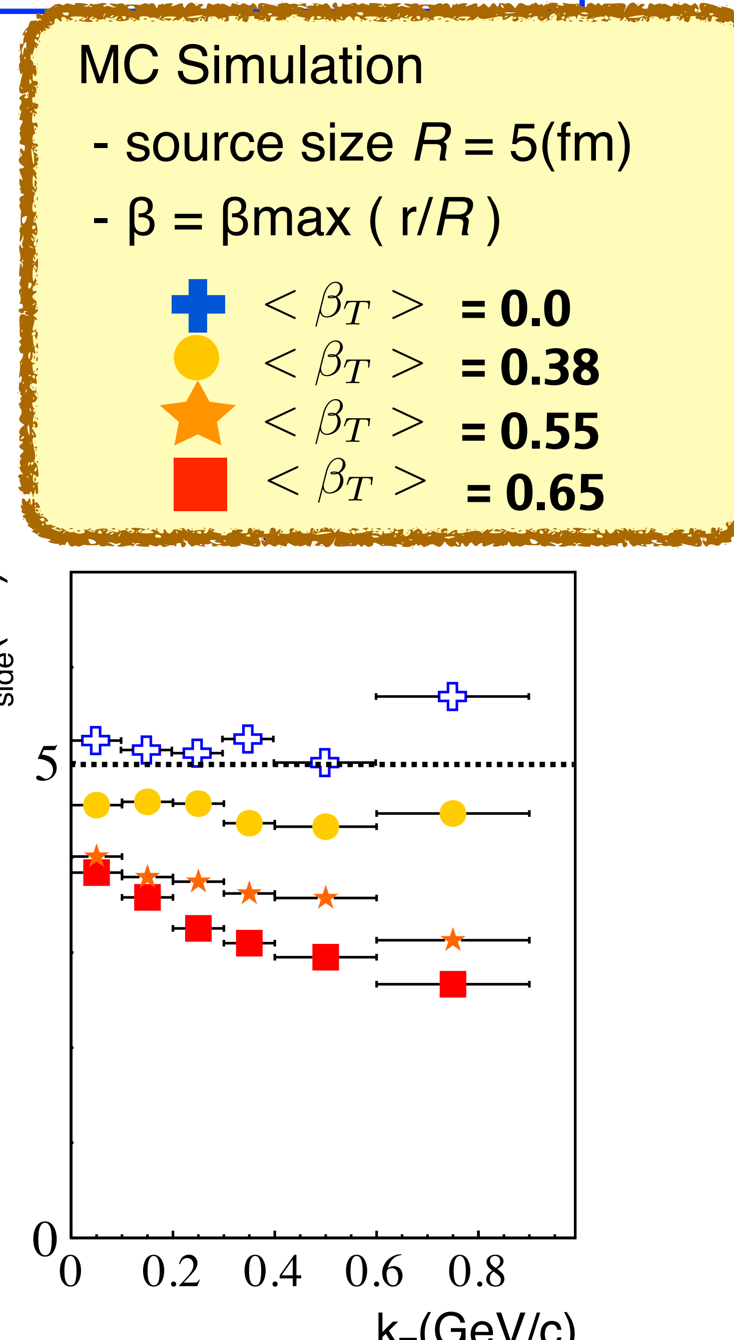
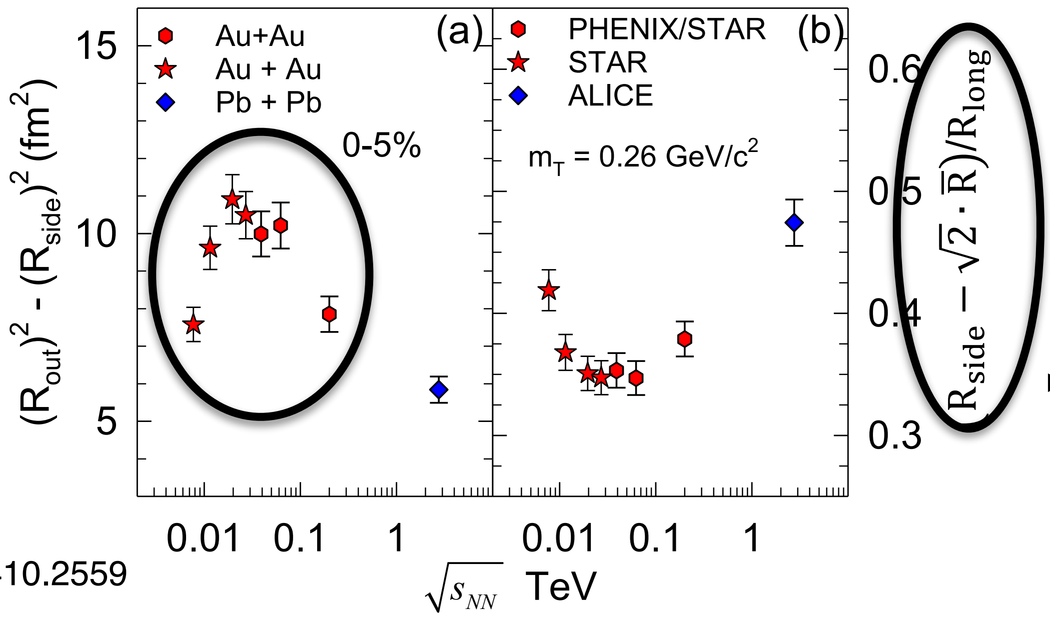


k_T dependence is important for study space time evolution !!

Recent results of HBT analysis

✓ Search of critical end point

- $(R_{out})^2$ - $(R_{side})^2$ is sensitive to emission duration
- Non monotonic behaviour can be found in 10 GeV

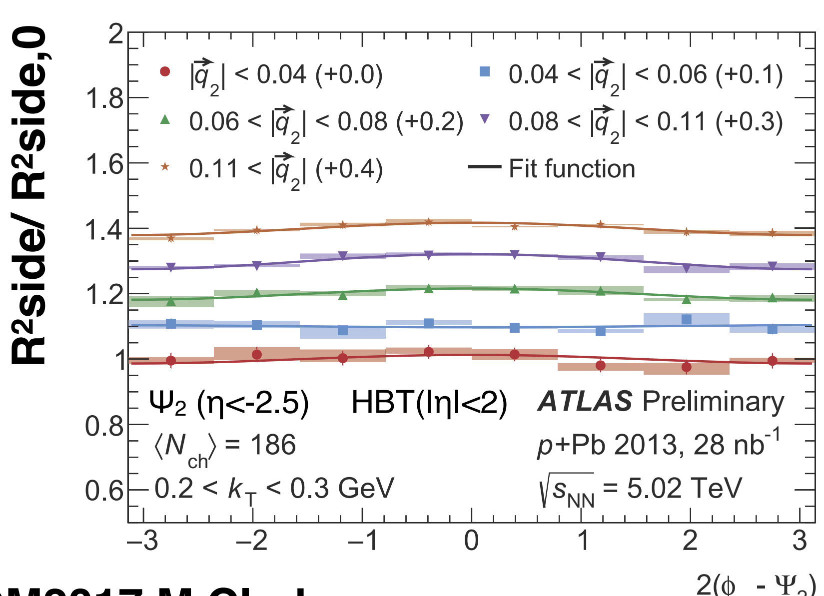


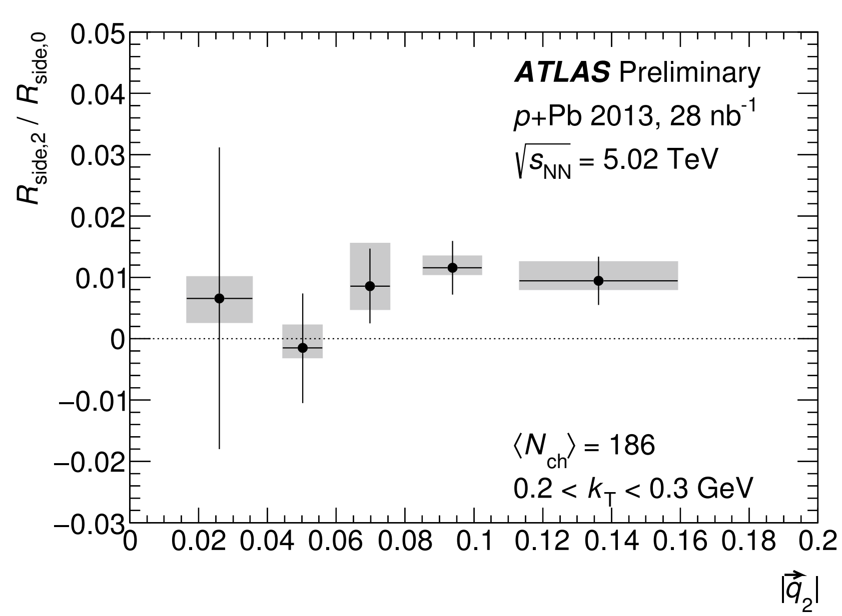
- Expansion velocity

A.Adare et al. arxiv:1410.2559

✓ Freeze out source shape in p-Pb collisions

- Finite oscillation in R_{side} and same sign but much smaller than Hydro calculation





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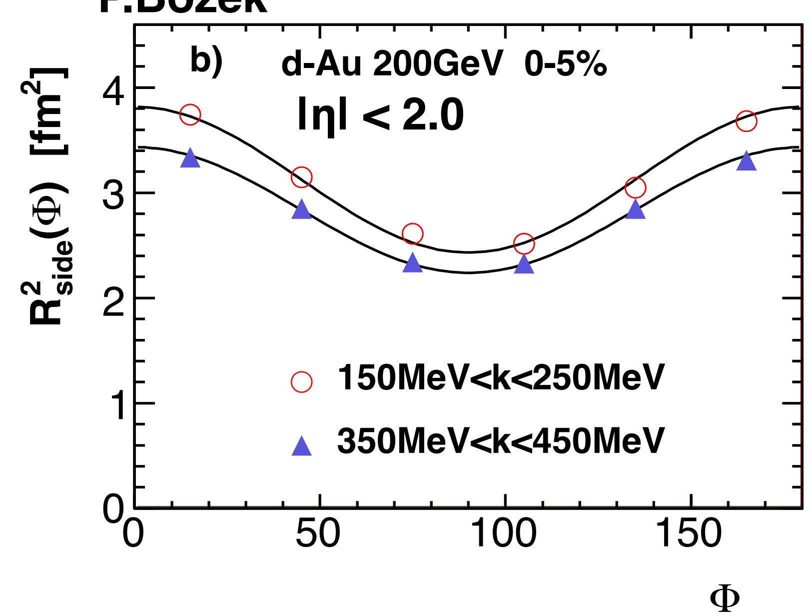
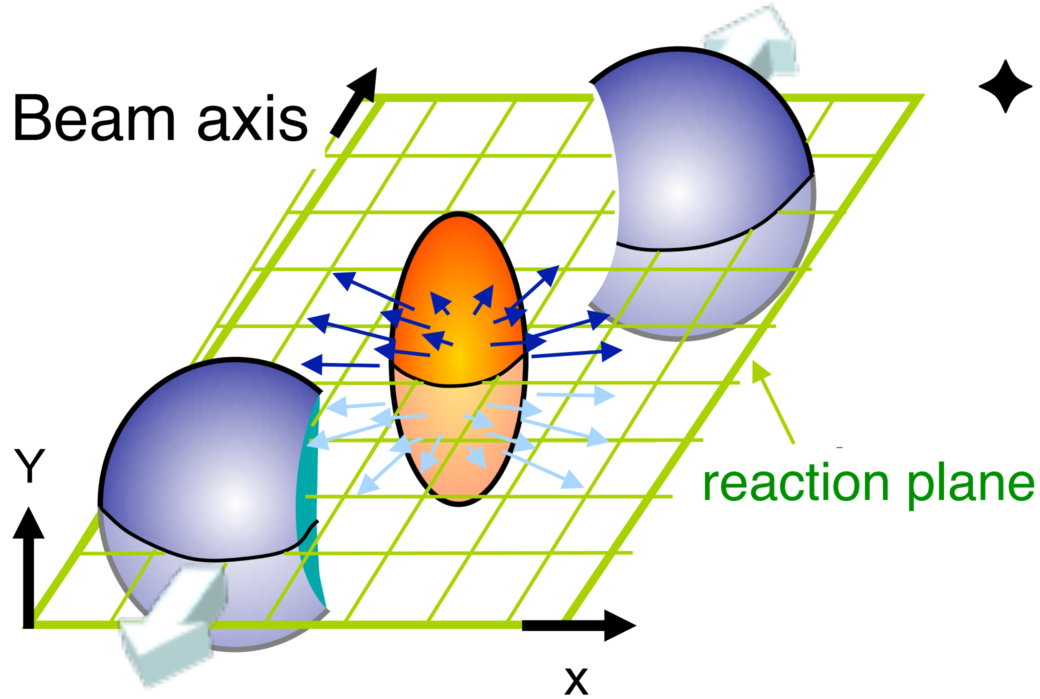
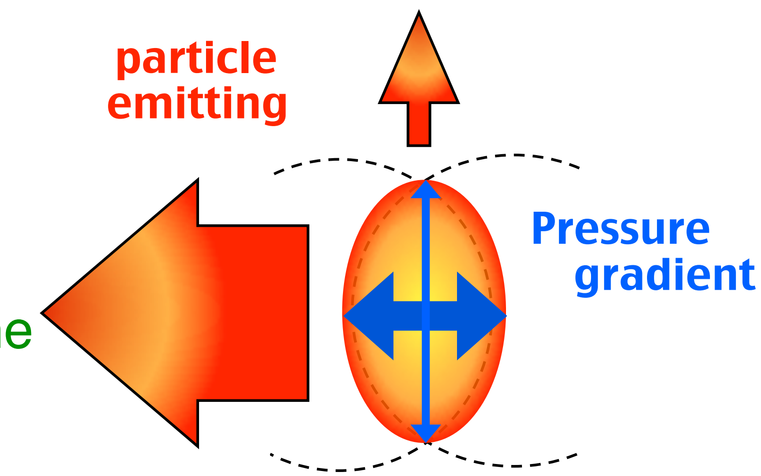


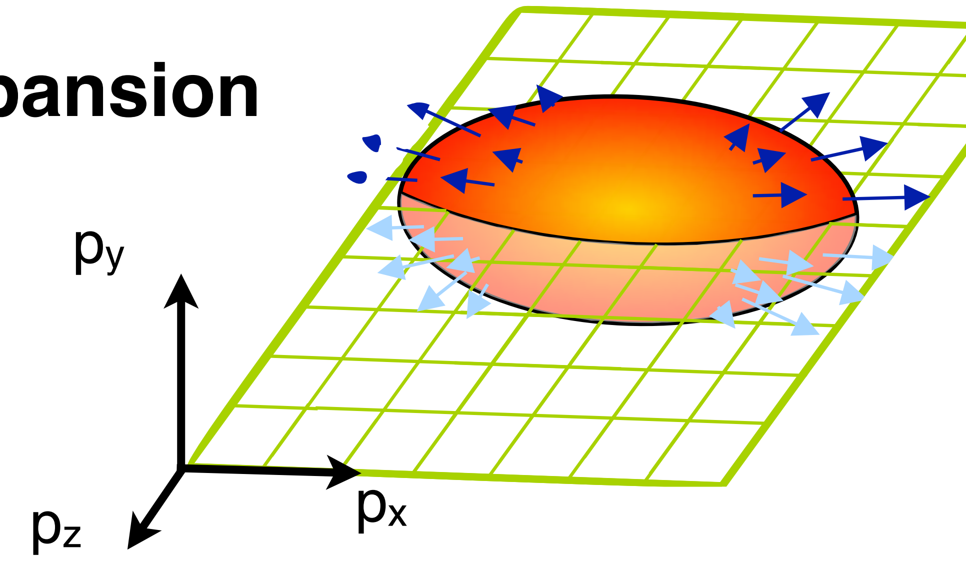
QM2017 M.Clark

Azimuthal anisotropy



✦ **Hydrodynamical expansion**

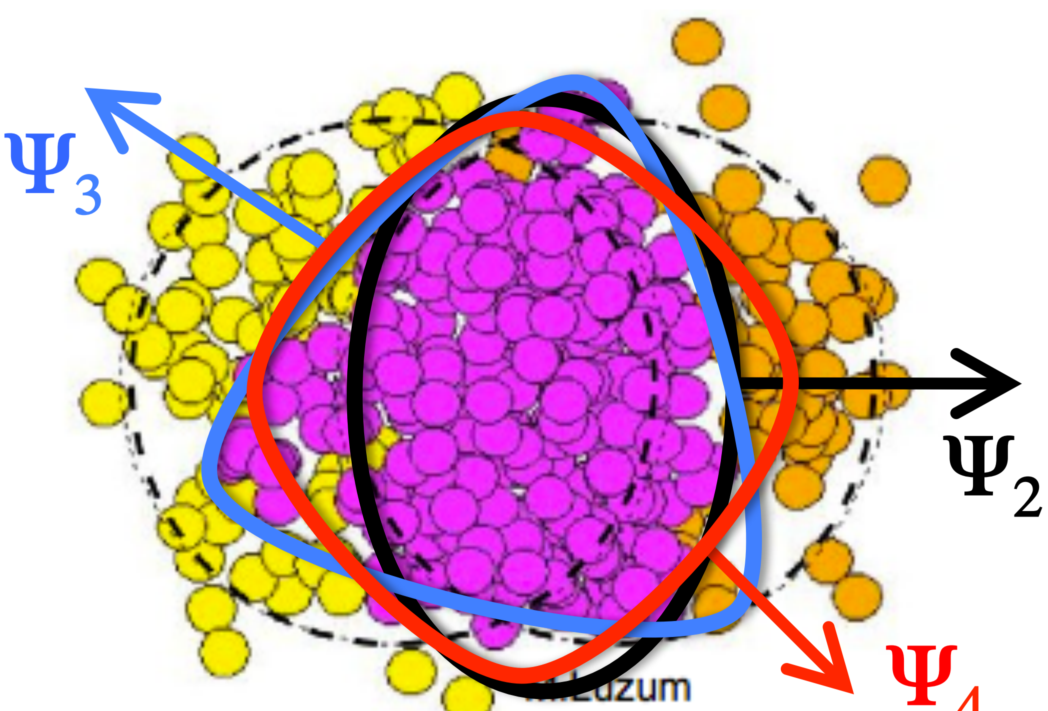


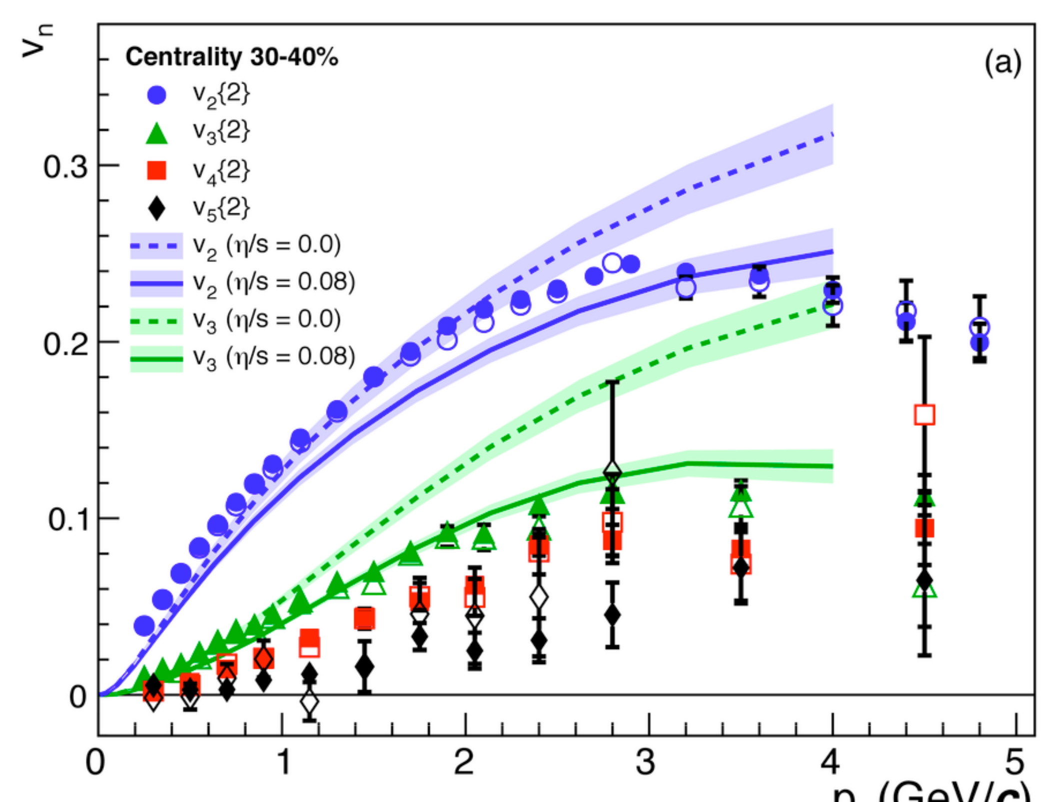


✦ **Initial elliptic shape converted to momentum anisotropy**

✦ **Finite number of nucleons makes higher order anisotropy**

✦ **Sensitive to viscosity and initial condition**

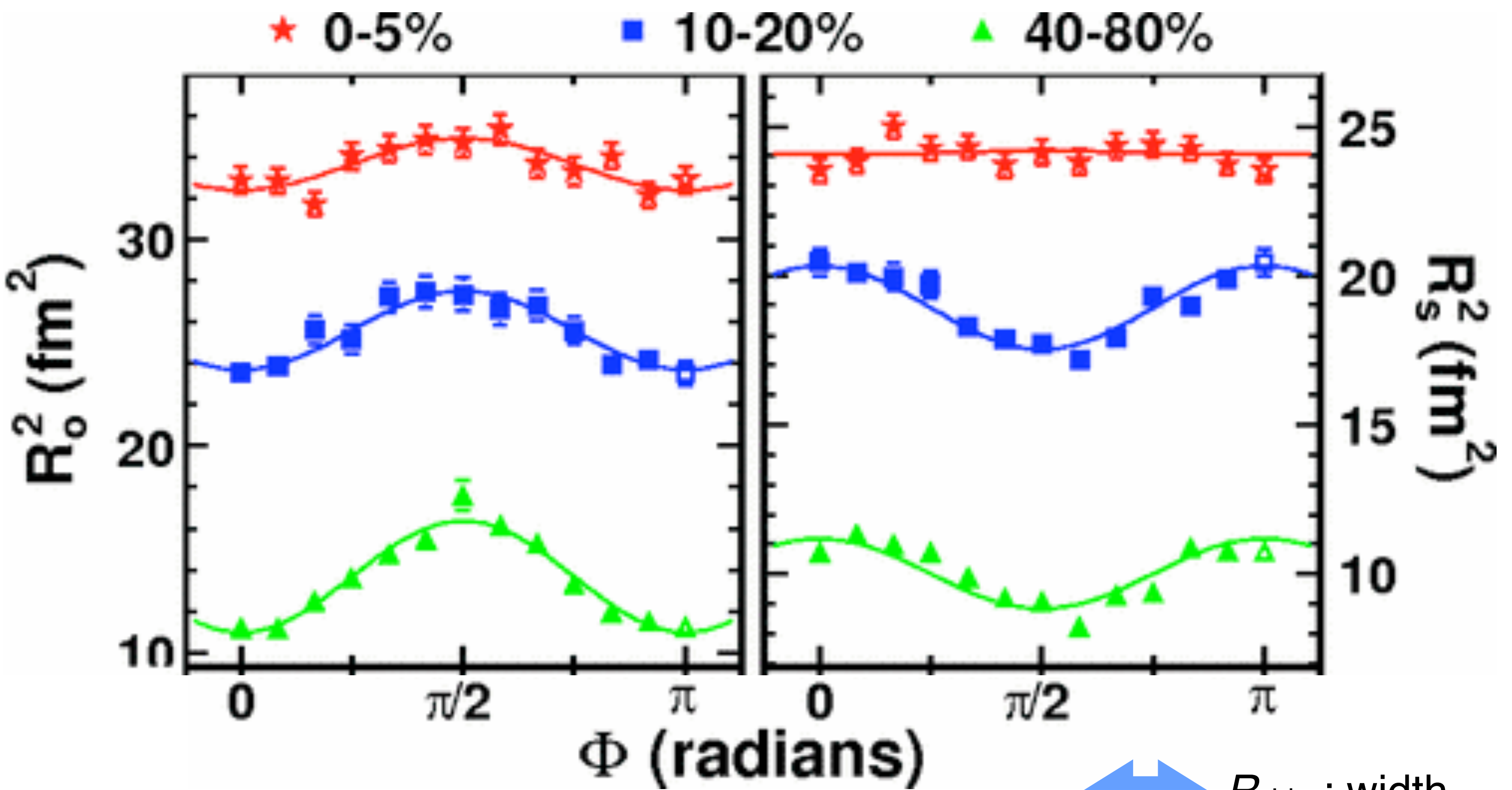


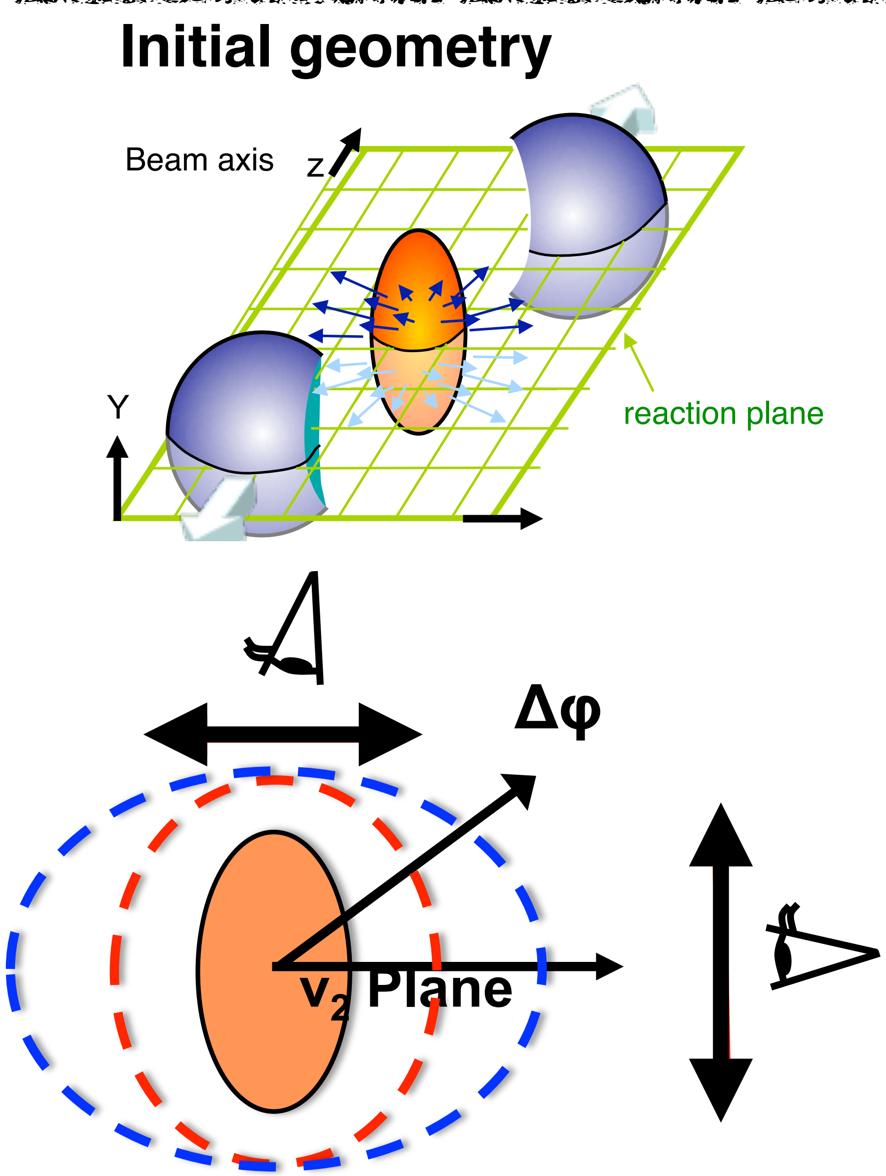


Azimuthally sensitive HBT w.r.t. Ψ_2

☑ **Powerful probe for freeze out source shape**

- **J. Adams et al., Phys. Rev. Lett. 93, 012301**





R_{side} : width

R_{out} : depth + emission duration

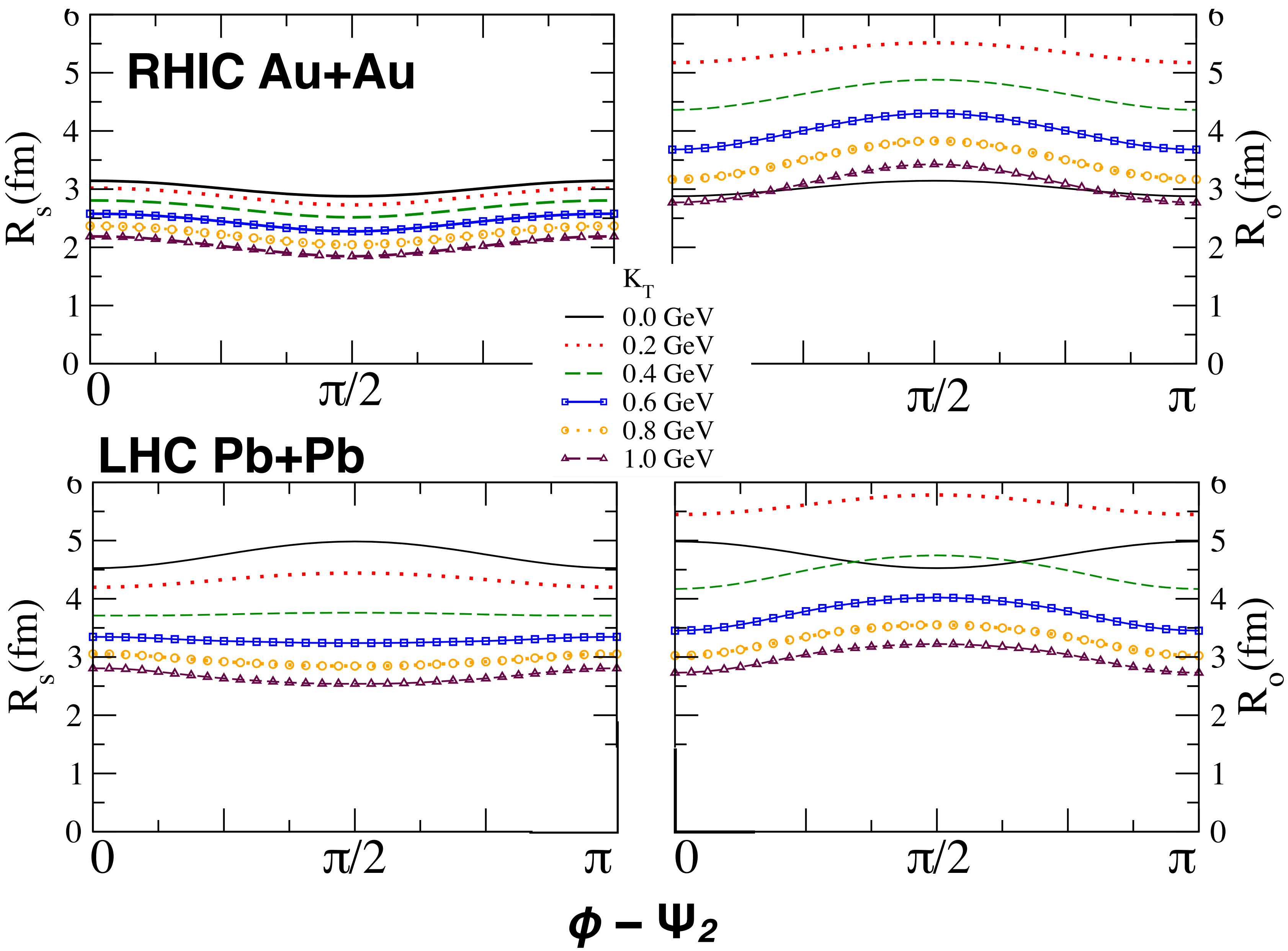
✦ Ψ_2 out-plane extended

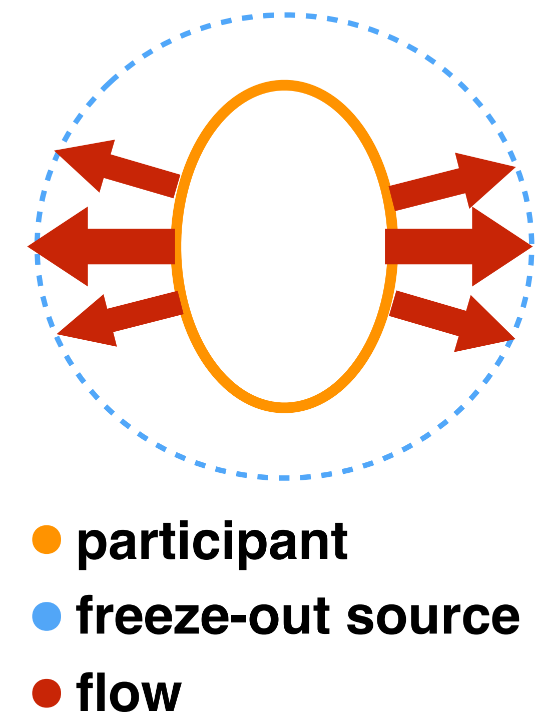
✦ Ψ_2 in-plane extended

☑ **Relation between initial and final source eccentricity allows us to study how the system evolves until the freeze-out, which likely depends on the flow velocity profile, the system lifetime and η/s**

Final source eccentricity @ LHC energy

- Hydro model predicts R_{side} and R_{out} oscillate in phase at low k_T
  - ✓ Larger collective flow deforms final source shape
  - ✓ Extract parameters of bulk property(shape, evolution time and velocity)

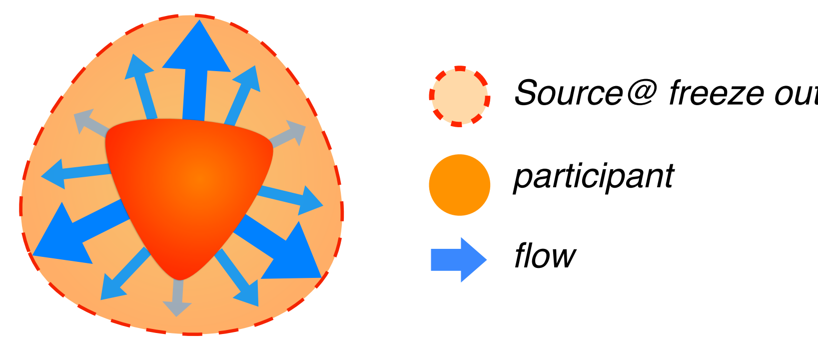




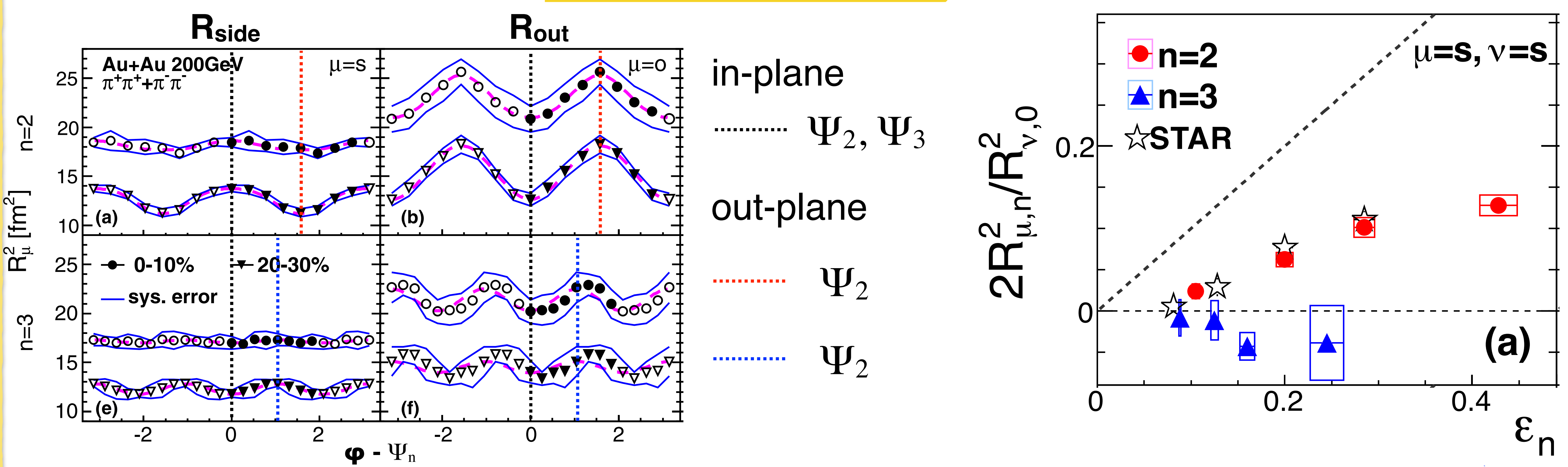
- HBT w.r.t. Ψ_2 with ideal hydro-simulation (b=7)
- J. Phys G: Nucl Part. Phys. 34 (2007) 2249-2254

Final source triangular shape and HBT w.r.t. Ψ_2

- **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**
  - ✓ **Negative or Zero oscillation in sideward**

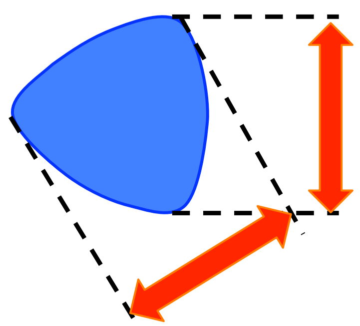


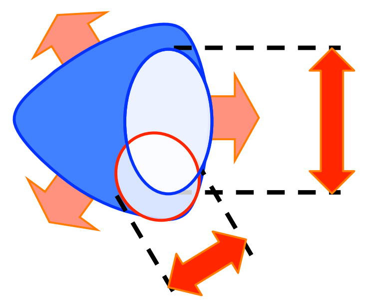
Au+Au 200GeV @ PHENIX

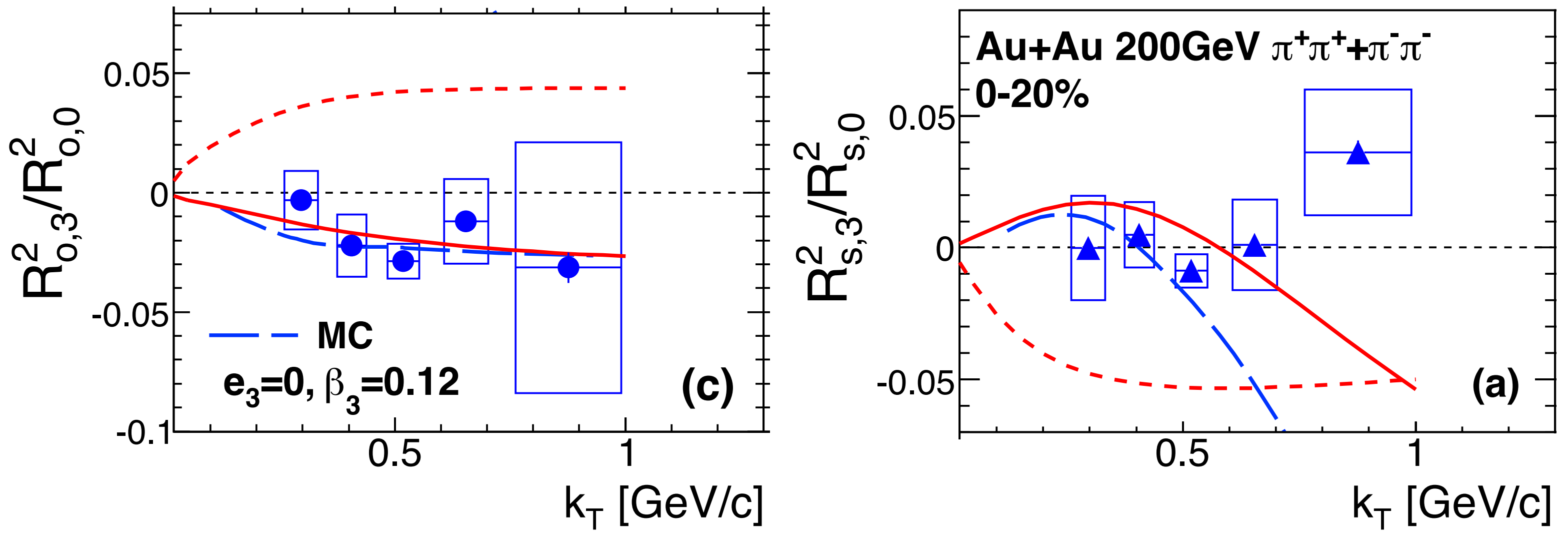


Final source triangular shape and HBT w.r.t. Ψ_3

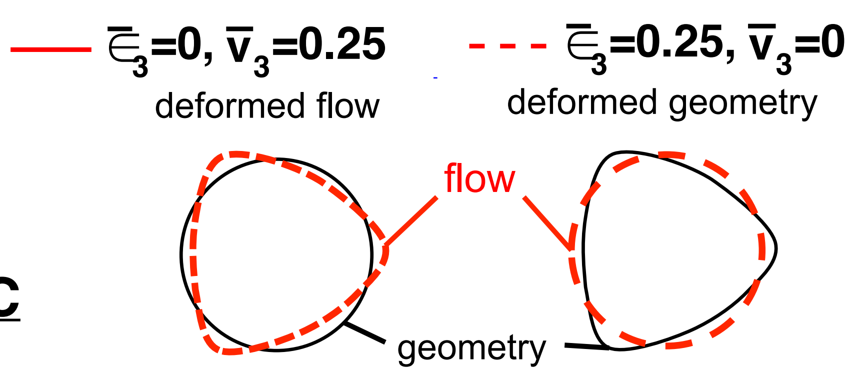
- **Triangularity cannot be directly obtained from HBT w.r.t. Ψ_3**
  - ➡ **Both triangular flow and geometrical triangularity make 3rd order oscillation of HBT radii**







- **HBT w.r.t. Ψ_3 in Au+Au 200GeV collisions**
  - A. Adare et al., PRL112.222301
  - MC simulation of two extreme case
  - HBT oscillation could be explained by "deformed flow" at RHIC



PRC88,044914

➡ Any hint of sign change of ε_3 under larger collective flow at LHC ??

☑ **Detailed analysis is necessary for understanding final source triangularity**

✦ k_T dependence of Azimuthally differential femtoscopy w.r.t. Ψ_3

➡ **High multiplicity and good E.P. resolution in ALICE Pb-Pb collisions !**

✦ **Direct measurement of correlation between geometrical and flow information**

Event shape engineering (ESE)

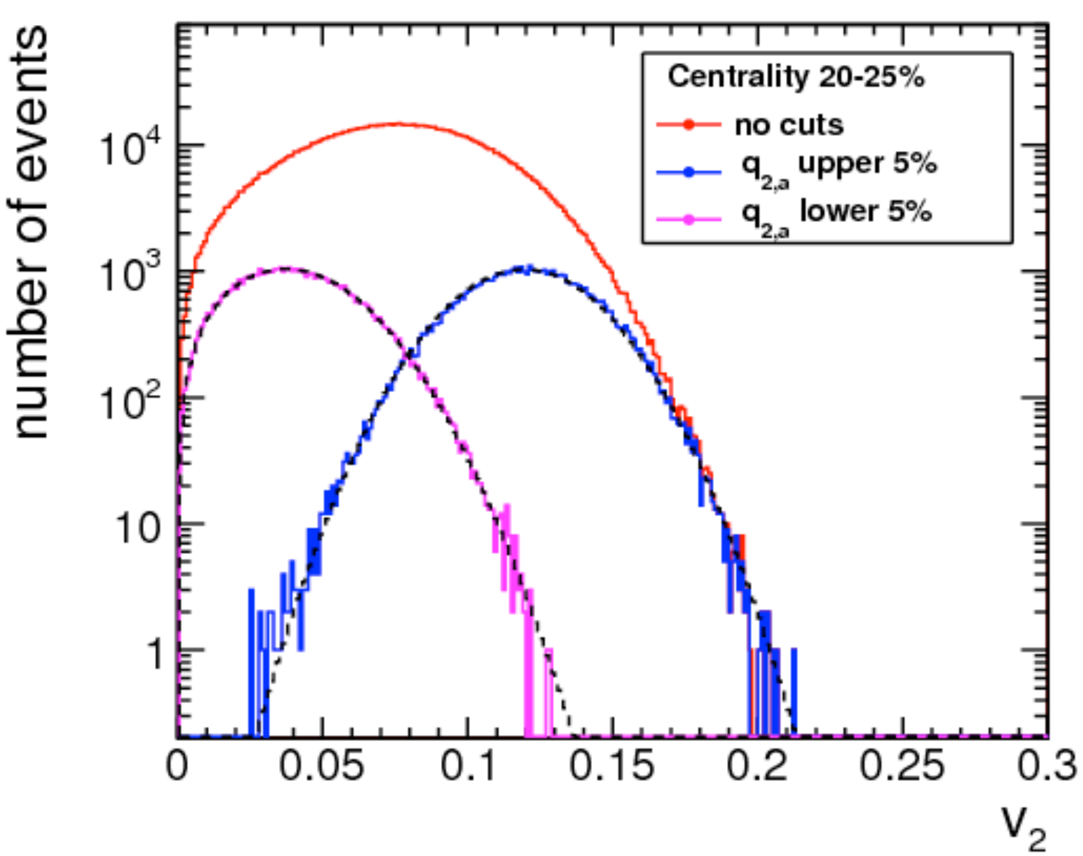
Event by event flow amplitude selection

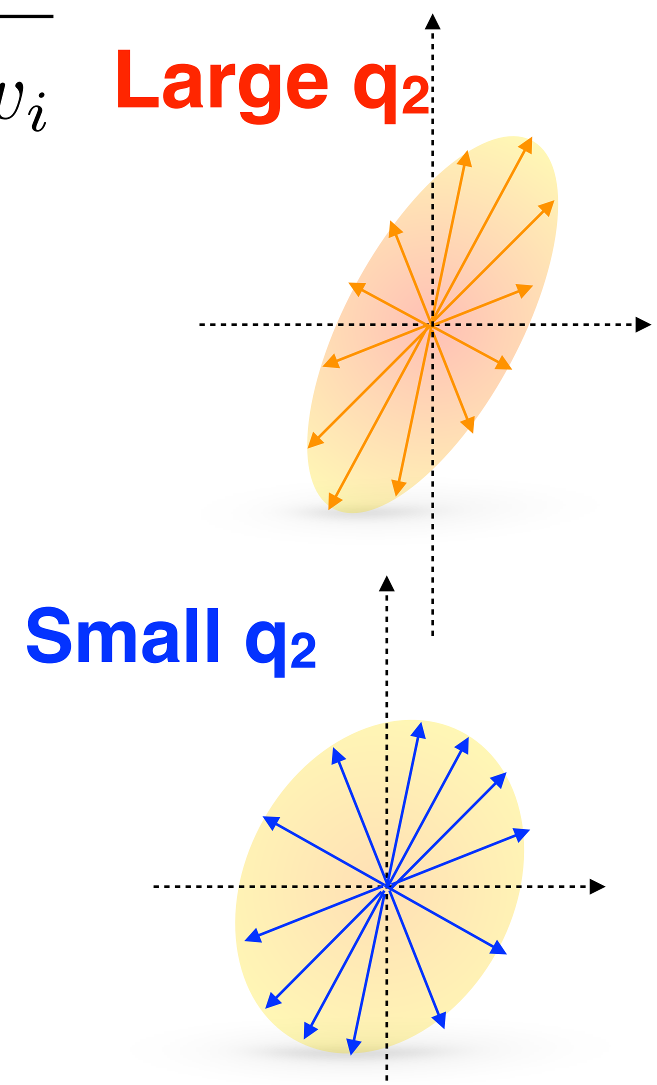
- J. Schukraft, A.Timmins and S. A. Voloshin, Phys. Lett. B719, 394-398 (2013)
- Event by event v_2(v_3) fluctuation is selected with flow vector q_2 (q_3)
  - ✓ Possibly control the initial eccentricity

$$Q_{2,x} = \sum w_i \cos(2\phi)$$

$$Q_{2,y} = \sum w_i \sin(2\phi)$$

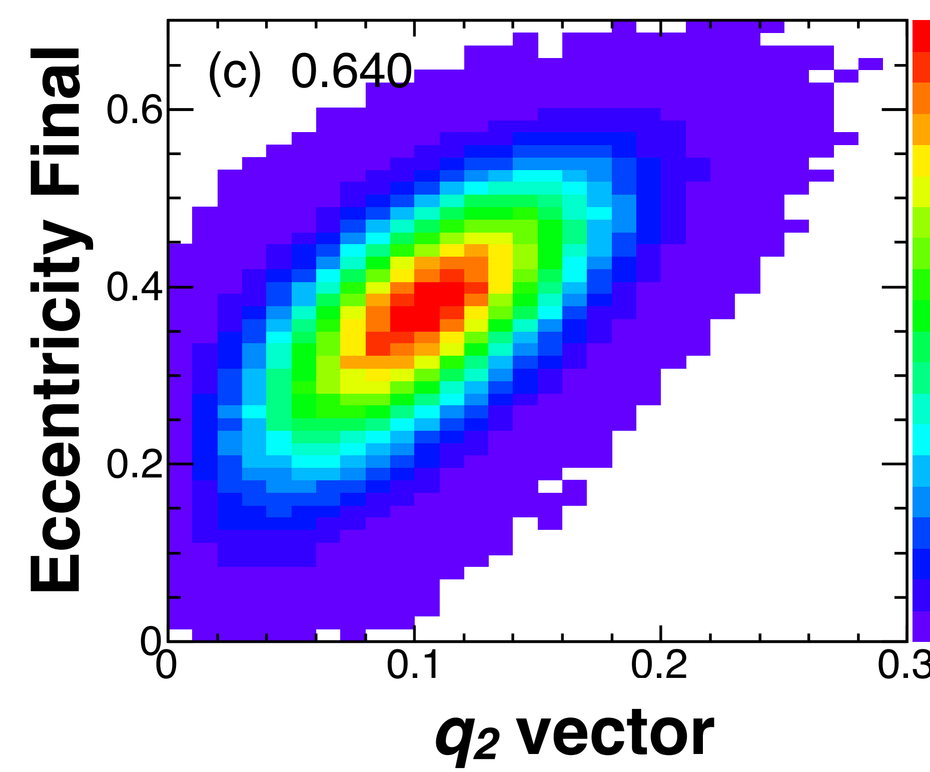
$$q_2 = \sqrt{Q_{2,x}^2 + Q_{2,y}^2} / \sqrt{\sum w_i}$$





Correlation between q_2 and $\varepsilon_2^{initial}$

- J.Jia et al., arXiv:1430.6077
- AMPT simulation



Motivation

- Extract space time extend of Quark Gluon Plasma with Azimuthally sensitive HBT and Event Shape Engineering in 2.76TeV Pb-Pb collisions
  - ✦ Elliptic shape
    - ‣ Measurements of azimuthally sensitive HBT w.r.t. Ψ_2 in LHC energy
      - ‣ centrality and k_T dependence
    - ‣ Correlation between Initial and final source eccentricity with ESE
    - ‣ Extract freeze out parameters with Blast wave fit
  - ✦ Triangular shape
    - ‣ Measurements of azimuthally sensitive HBT w.r.t. Ψ_3
      - ‣ centrality and k_T dependence
    - ‣ Measurement of correlation between v_3 and HBT oscillation w.r.t. Ψ_3

My activity

Master

- DCAL construction
- EMCAL SRU work @cern
- DCAL commissioning
- Shift taking @ PHENIX
- HBT w.r.t. Ψ_2 and Ψ_3

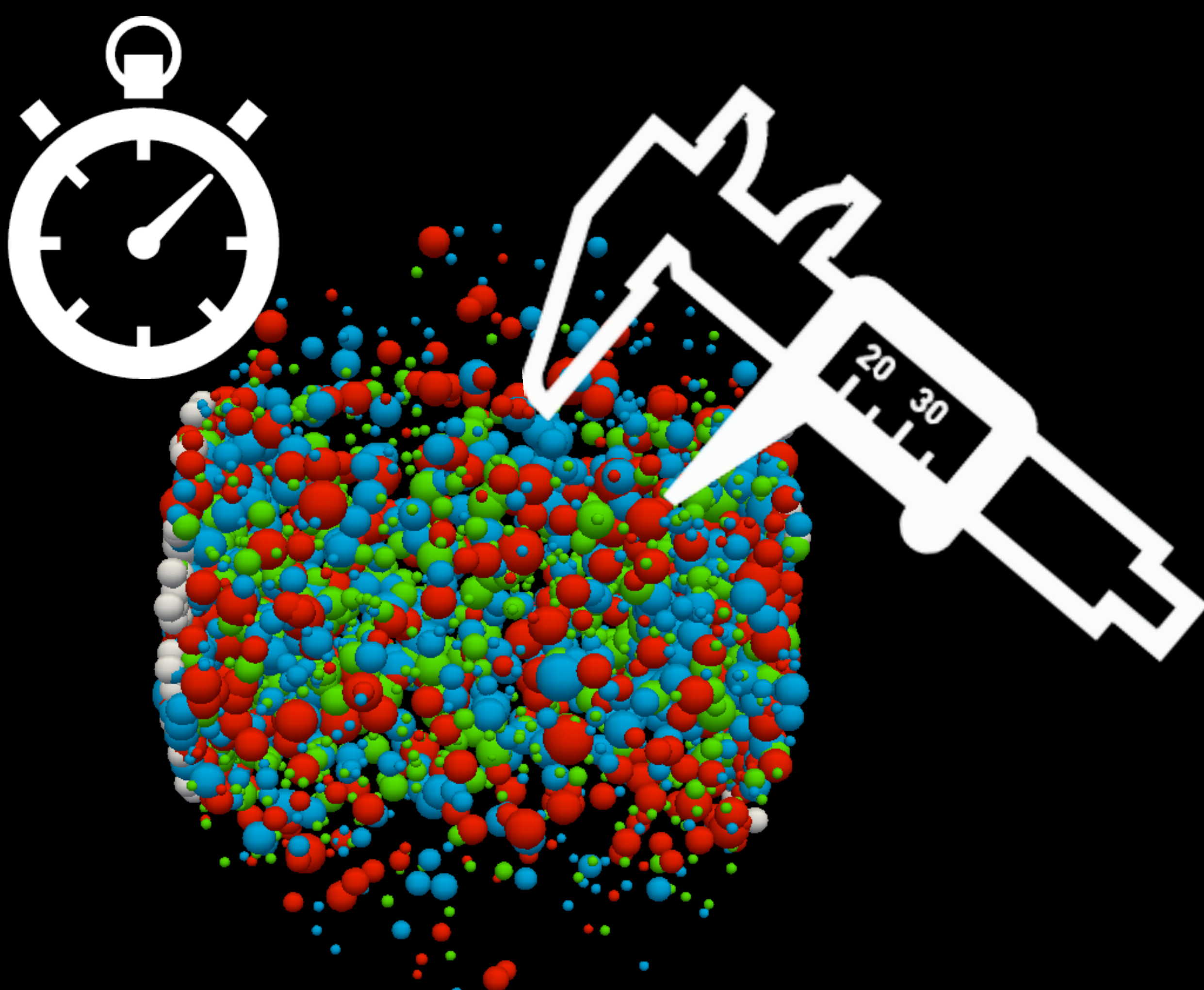
- KEK summer challenge M1->D4
- Development of radon detector ->D4

Doctor

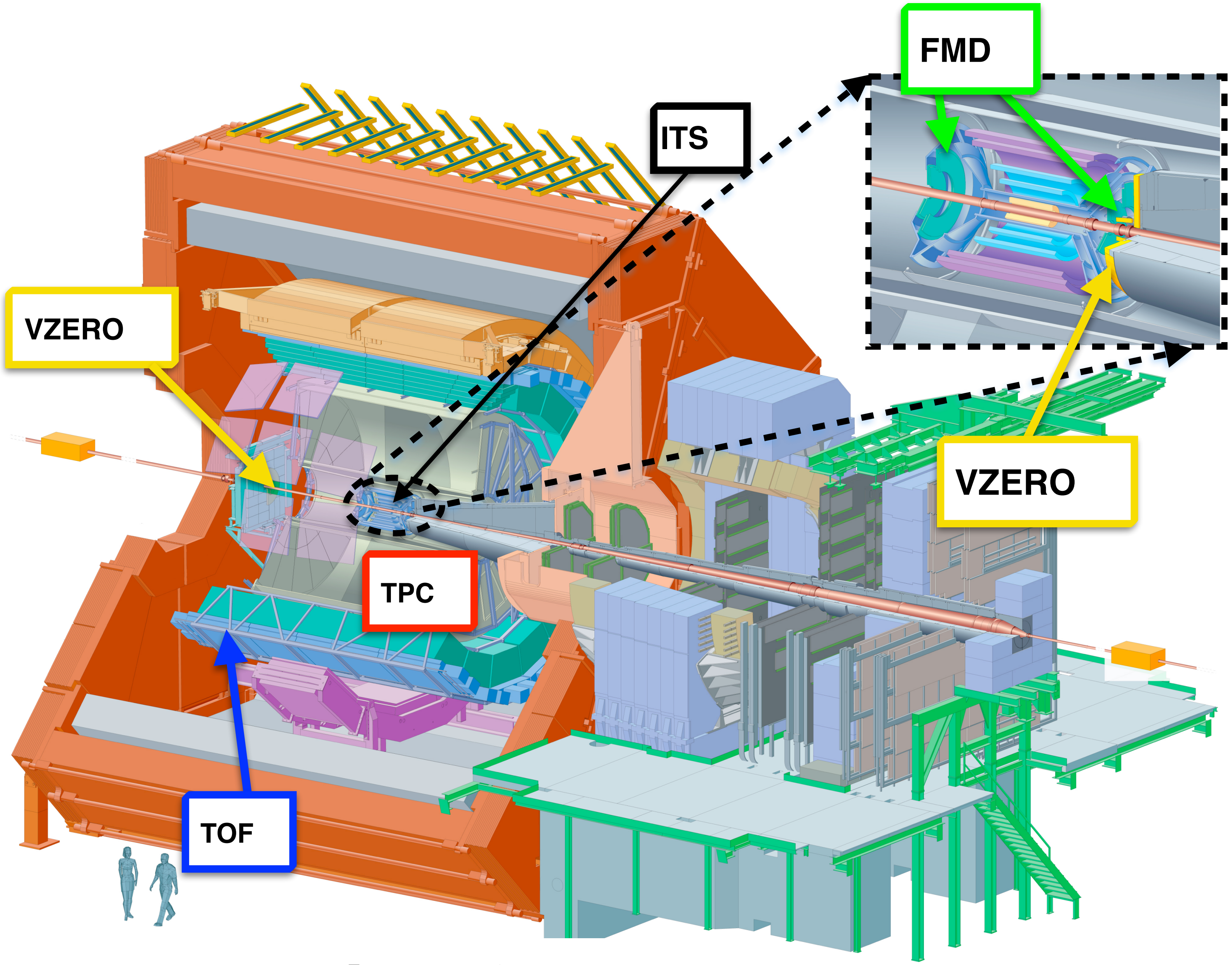
- Talk
  JPS fall 2016
- Poster
  QM2016
- Talk
  WPCF2017

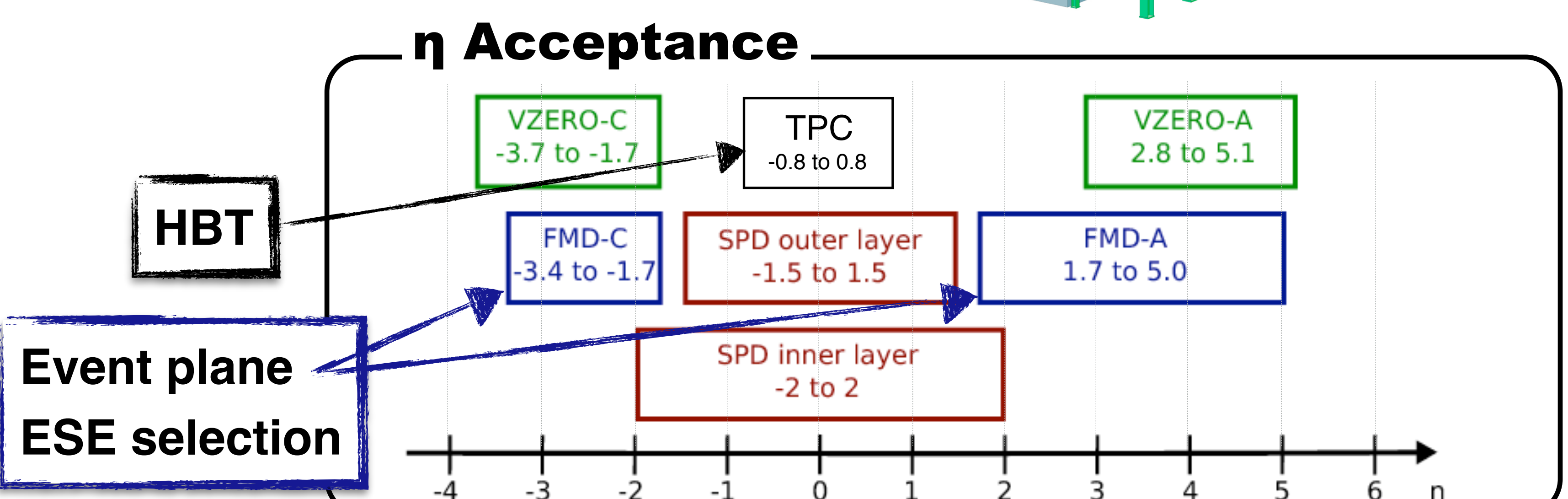
- Shift taking @ CERN
- HBT w.r.t. Jet axis
- HBT relative to Ψ_2 and Ψ_3 with ESE

Experiment & Analysis



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
- ✓ $|\eta_{track}| < 0.8$

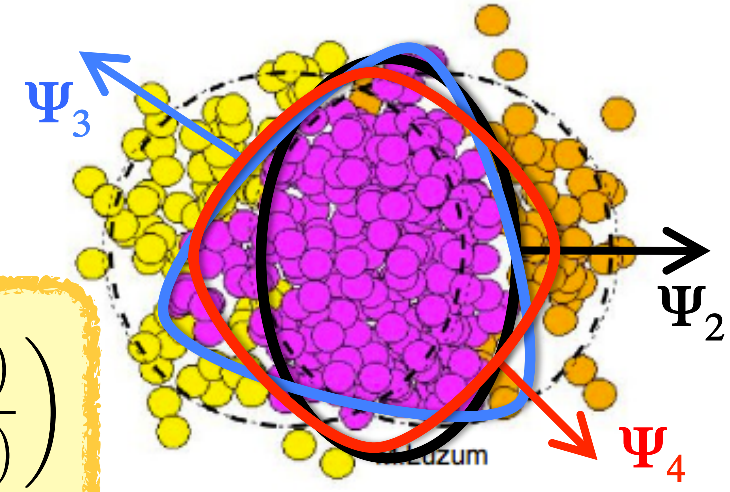
TOF
- ✓ PID
- ✓ $|\eta_{track}| < 0.8$

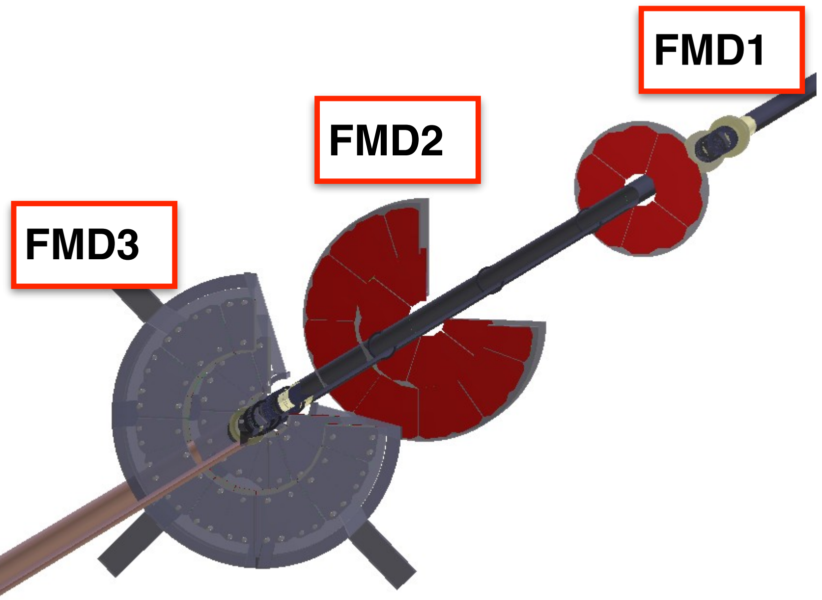
FMD
- ✓ Event plane
- ✓ FMD_A : $1.7 < \eta < 5.0$
- ✓ FMD_C : $-3.4 < \eta < -1.7$

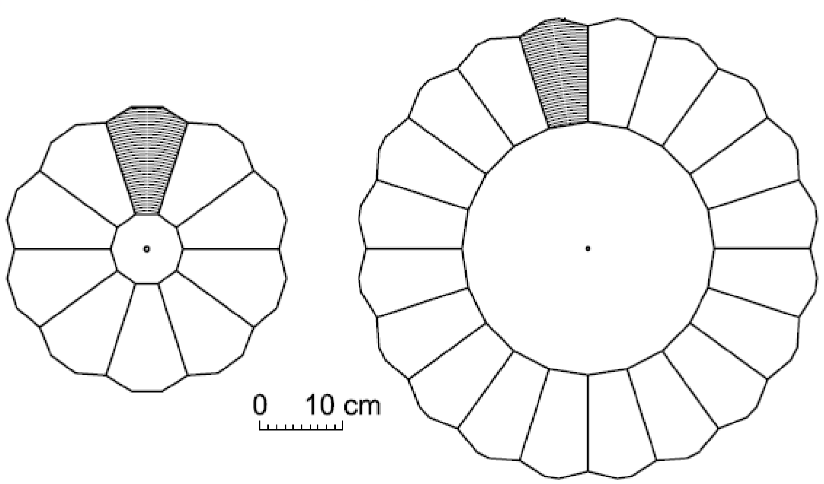
Event Plane determination

- **The FMD Detector**
- **Silicon strip detector**
- **2 type rings : inner and outer**
  - **inner : 20 sectors**
  - **outer : 40 sectors**

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

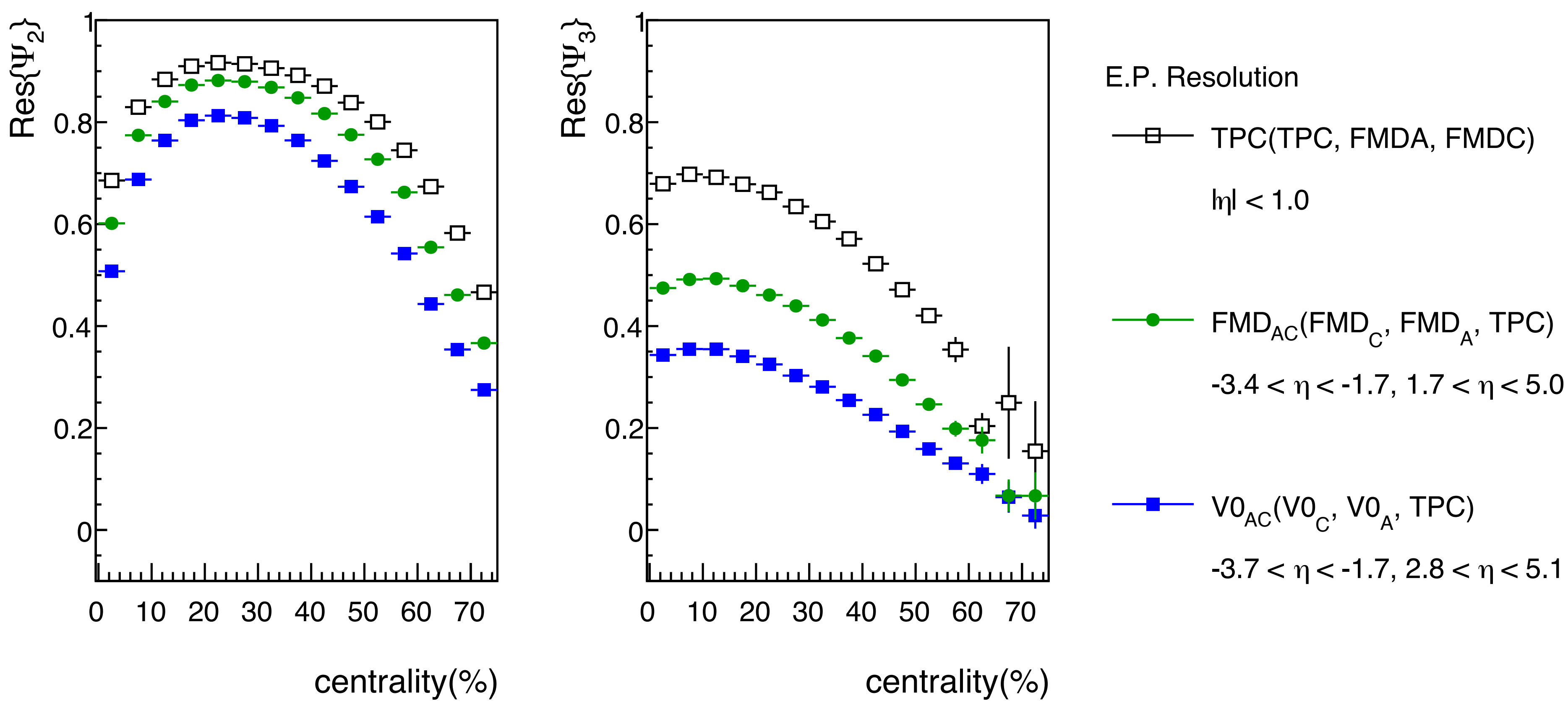






- **E.P. resolution with 3 sub method**

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

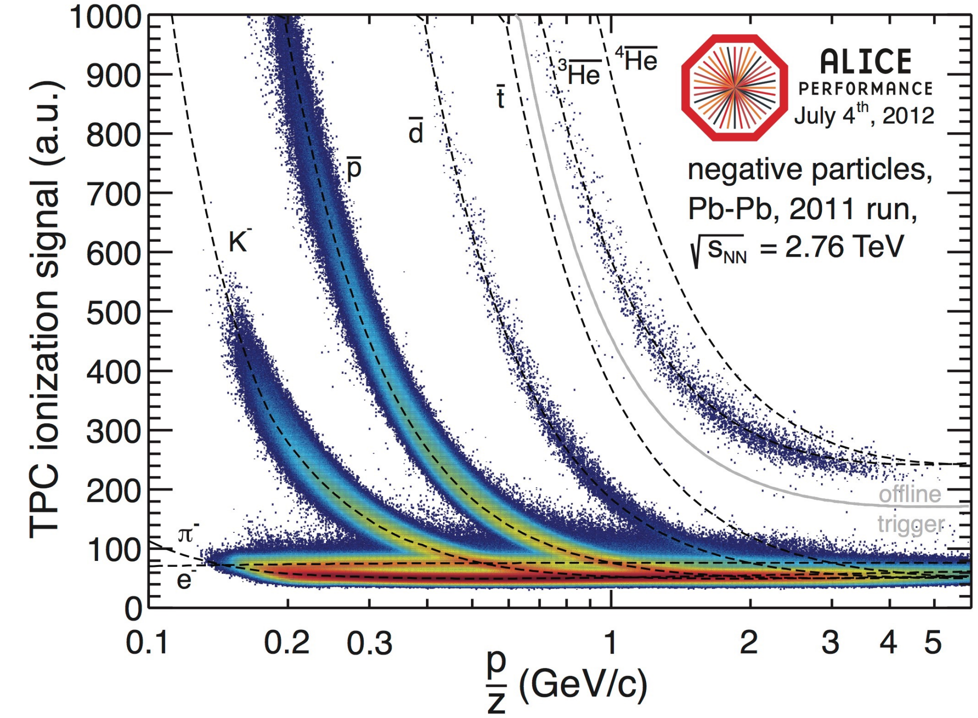


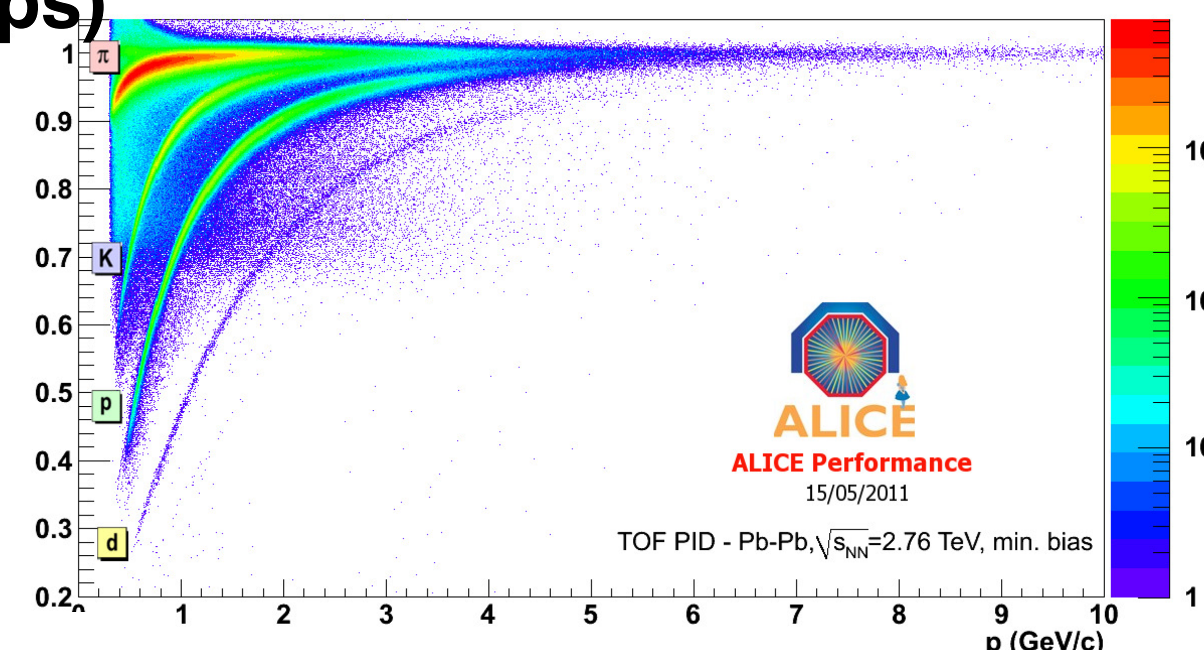
This excellent resolution allows us precise measurement of higher order E.P.

PID

- **Charged hadron identification**
  - **charged pions are identified with TPC+TOF**
  - **TPC**
    - **Energy loss (dE/dx)**
    - **dE/dx resolution ~ 6.8% in dNdy = 8000**
  - **TOF**
    - **Time of flight, mass**
    - **Performance evaluated σTOF = 60 (ps)**

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

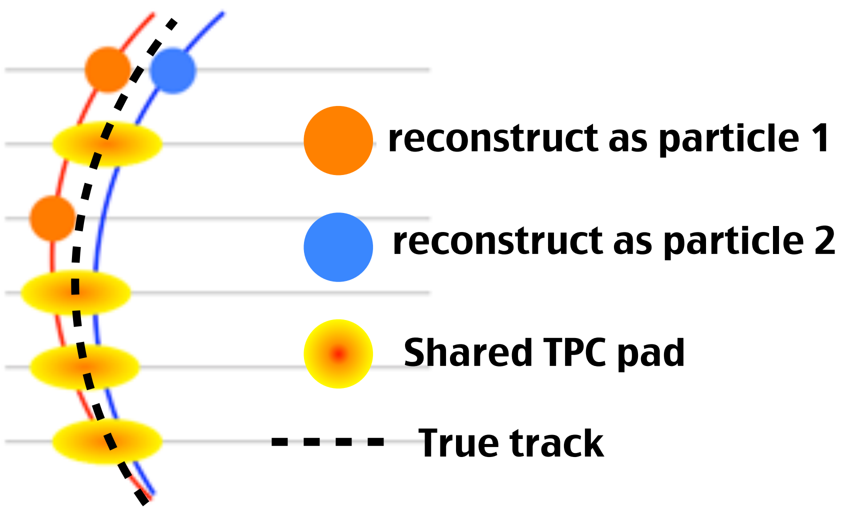


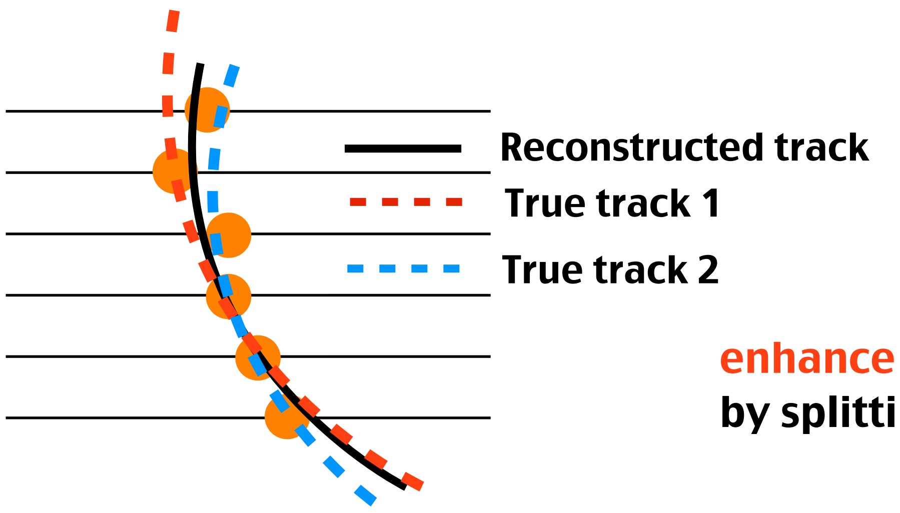


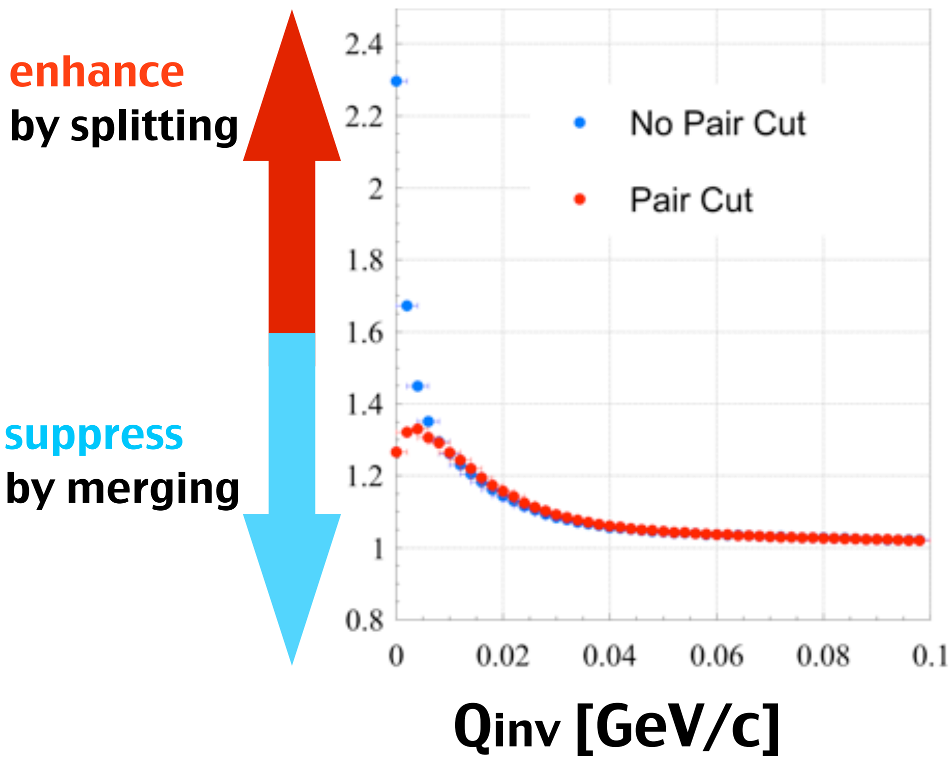
- **TPC & TOF combined PID**
  - **0 < p < 0.65 [GeV/c]**
    - TOF ✗ → 0.0 < p[GeV/c] < 0.50 : |σTPC| < 3.0; 0.5 ≤ p[GeV/c] < 0.65 : |σTPC| < 2.0
    - TOF ○ |σTOF| < 3.0, |σTPC| < 3.0
  - **0.65 ≤ p[GeV/c] < 1.5 : |σTOF| < 3.0, |σTPC| < 5.0**
  - **1.5 ≤ p[GeV/c] < 2.0 : |σTOF| < 2.0, |σTPC| < 5.0**

Two track resolution

- Due to the high multiplicity event
  - Track splitting
    - A track is falsely reconstructted as two tracks that are spatially close
  - Track merging
    - Two tracks that are spatially close are falsely reconstructed as one
    - These effect modify measured correlation function







✓Applied pair cut

- Fraction of shared TPC cluster < 5%
- Angular distance in $\Delta\phi^*$, $\Delta\eta$

Final state interaction and resonance

- **Like-sign pairs that is spatially close are repulsive with Coulomb**
  - **Correlation function is suppressed for low *q* pairs**
  - **Coulomb weight is calculated with Coulomb wave function**

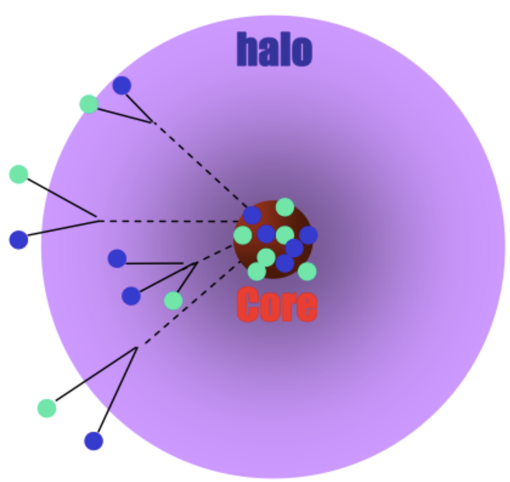
$$\left[-\frac{\hbar^2\nabla^2}{2\mu}+\frac{Z_1Z_2e^2}{r}\right]=E\Psi_c(r)$$

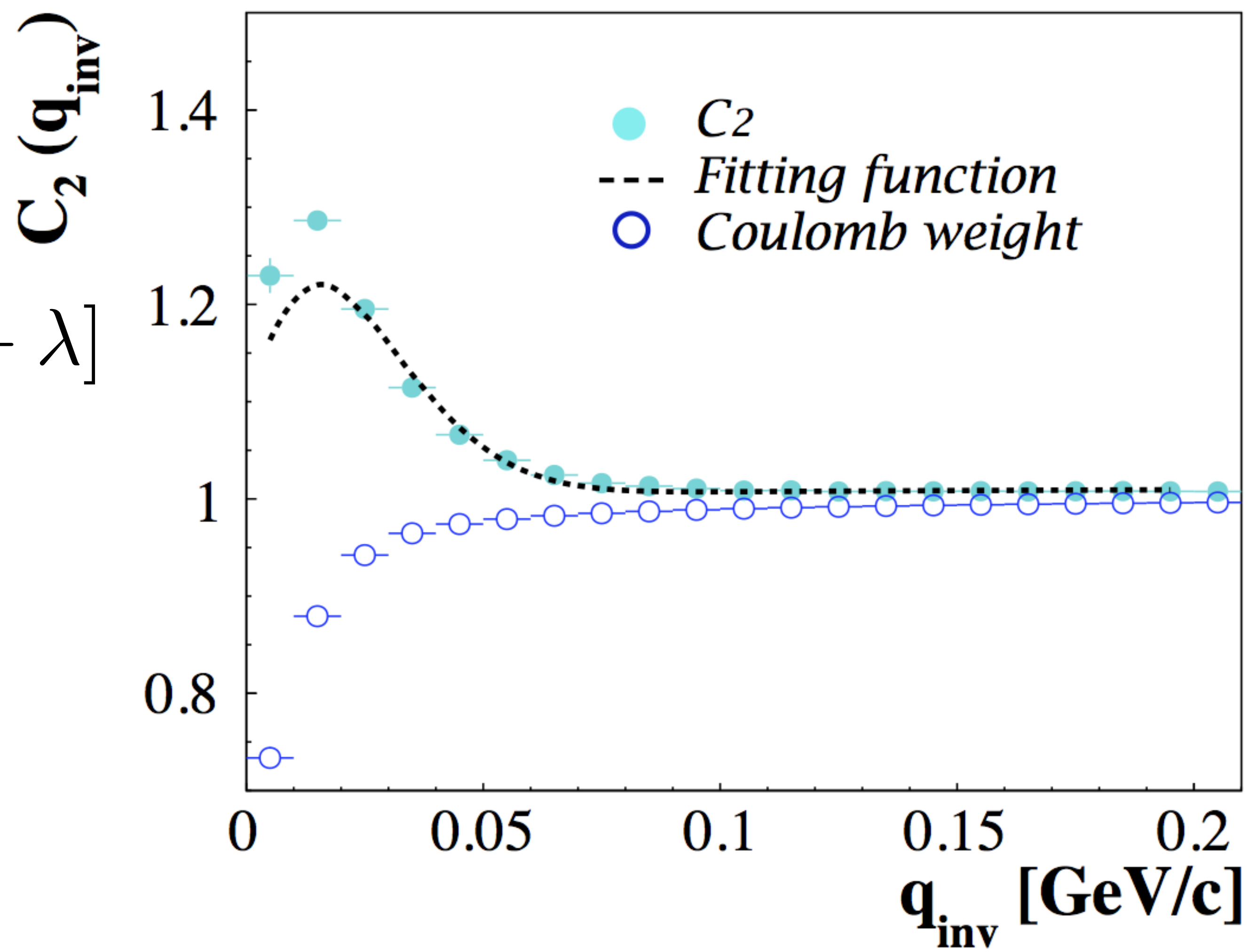
- **Resonance decay**
  - **λ in C_2 is sensitive to purity**
  - **Core-halo model**

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

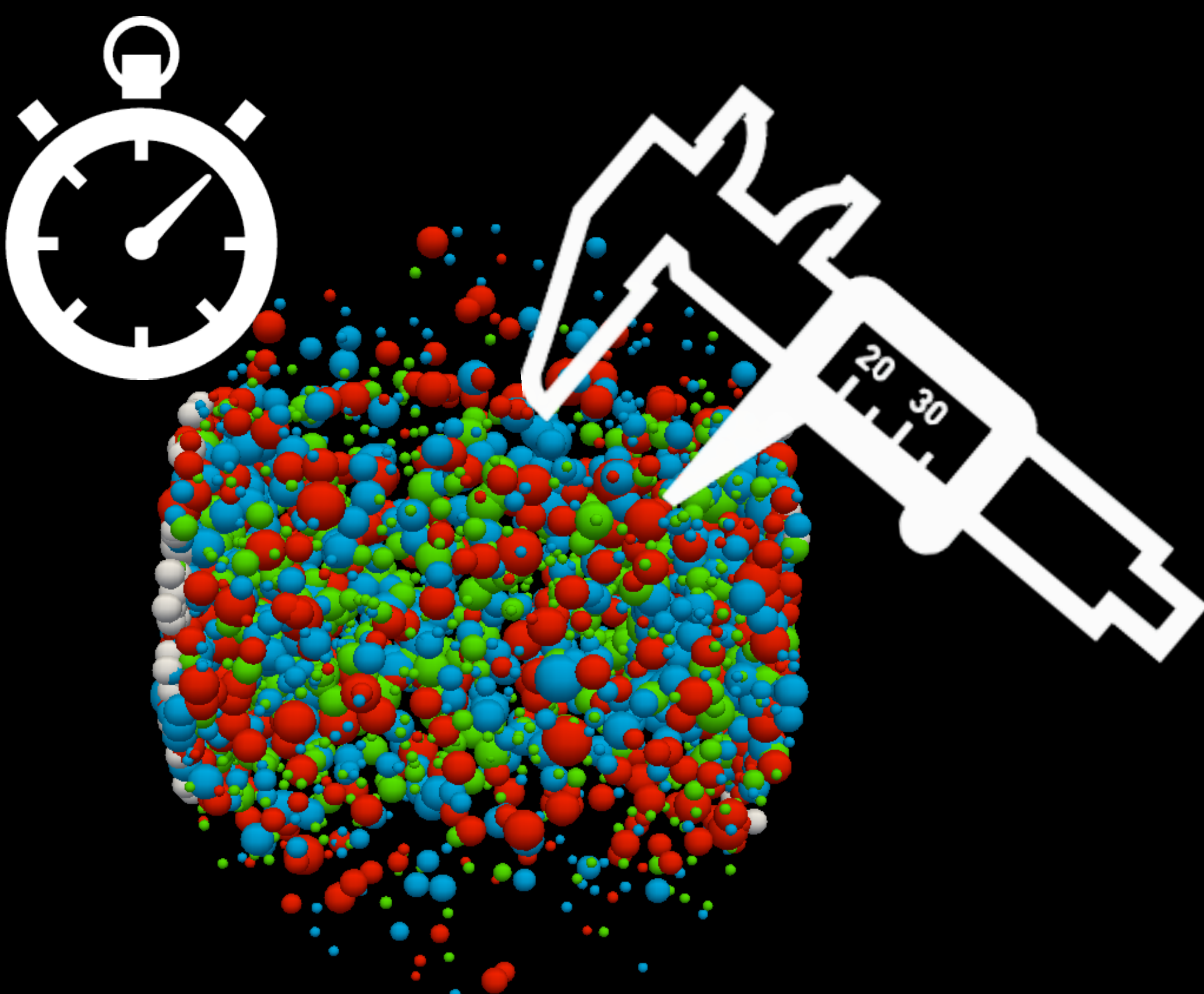
✓ ***G : HBT interferometry***

✓ ***F_{coul} : Coulomb interadtion***

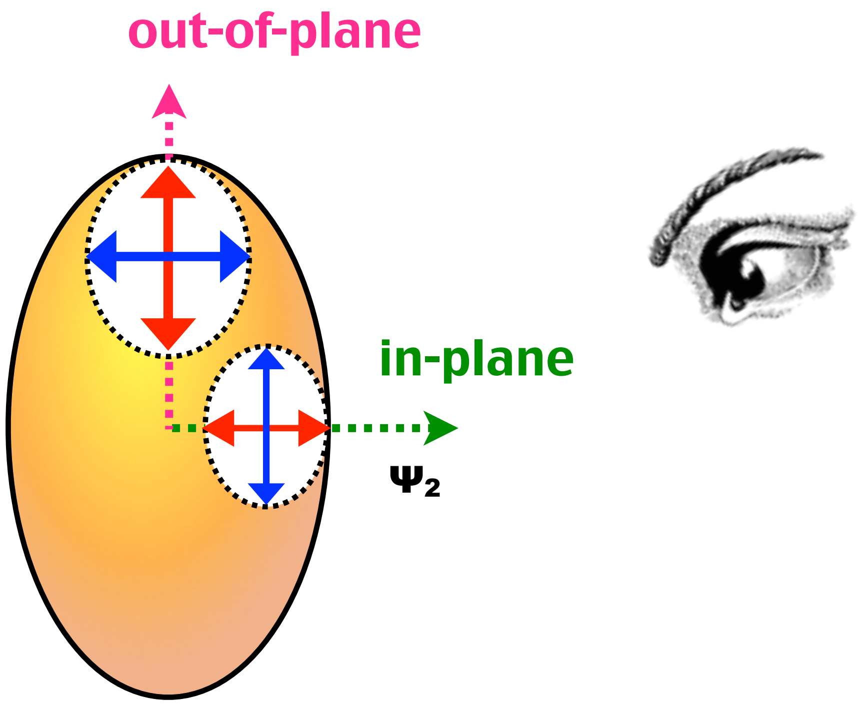




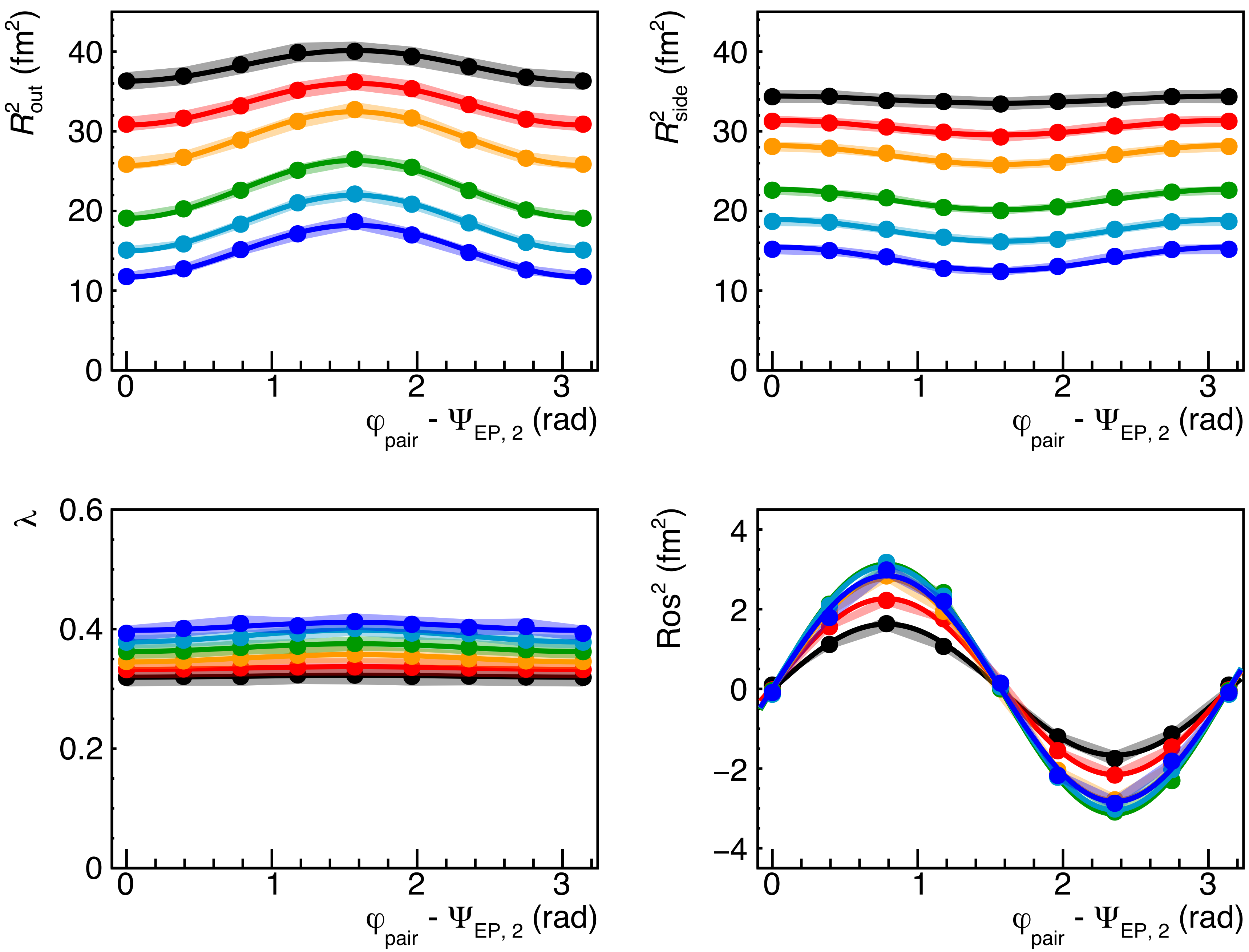
Result & Discussion

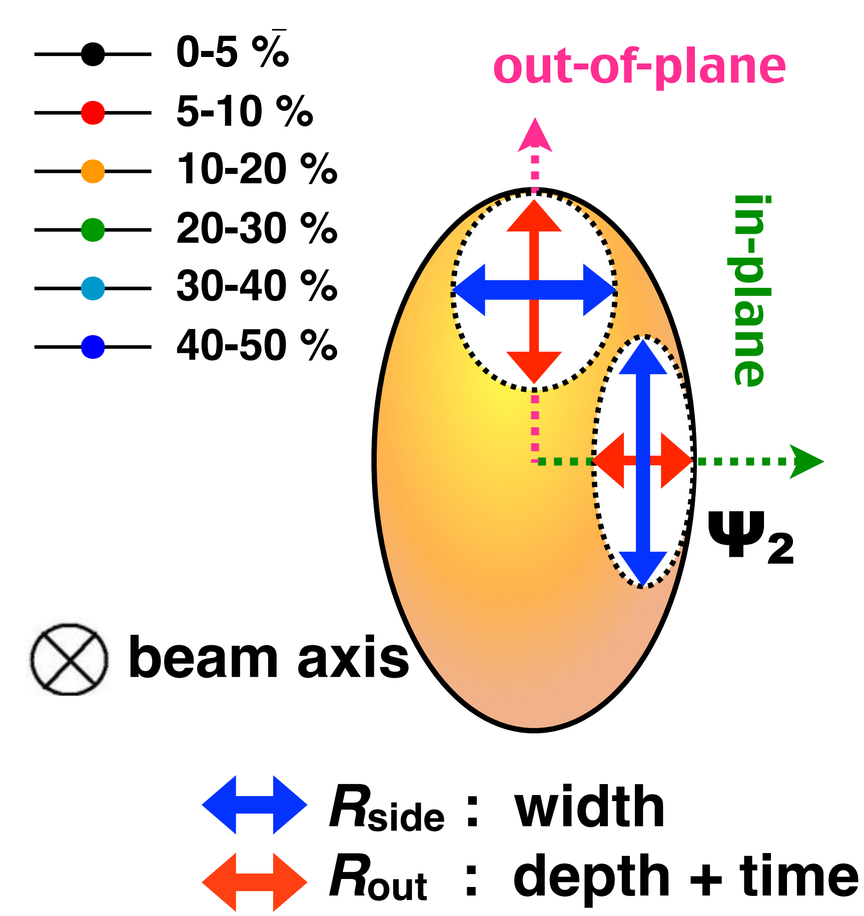


Second harmonics



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

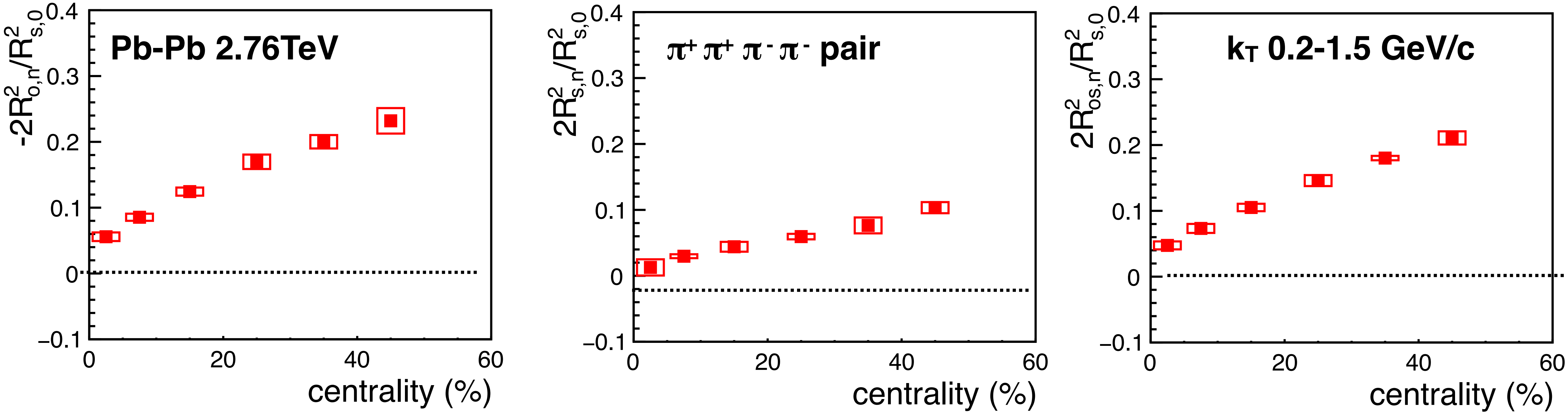




- Fit function $R^2_{2,0} + 2\,R^2_{2,2}\cos(2(\phi_{pair} - \Psi_2))$
- $R^2_{2,0}$: Average HBT radii, $R^2_{2,2}$: Oscillation amplitude

- **Explicit oscillation can be seen in R_{out}, R_{side} R_{os}**
- **R_{out} has larger oscillation than $R_{side.}$ sensitivity to duration time !**

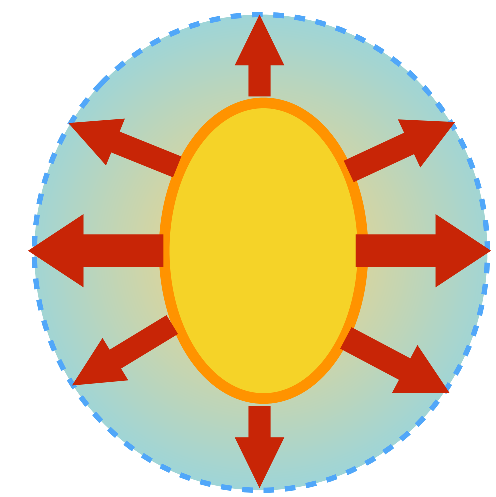
Relative amplitude of HBT radii (2nd harmonics)



Final source Eccentricity

$$\varepsilon_{final} = 2\frac{R_{side,2}}{R_{side,0}} = 2\frac{R_{out,2}}{R_{side,0}} = 2\frac{R_{os,2}}{R_{side,0}}$$

- **ε_{final} is extracted via HBT oscillation ($k_T \rightarrow 0$)**
- **F.Retiere and M.A.Lisa, PRC70.044907**

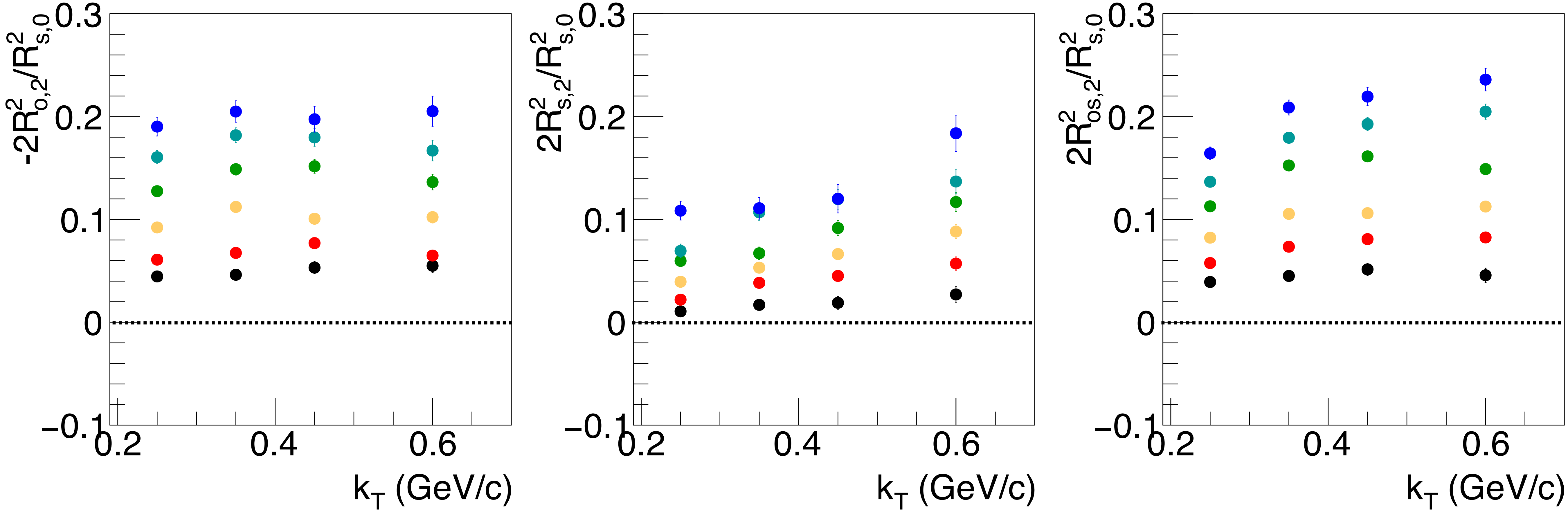


- participant
- freeze-out source
- flow

- **ocillation of *R_{out} and R_{side}, R_{os} becomes larger from central to peripheral***
- **$R^2{}_{out,2} / R^2{}_{side,0}$, $R^2{}_{os,2} / R^2{}_{side,0}$ is more sensitive to flow**
- **Geometrical information can be extracted with $2R^2{}_{side,2} / R^2{}_{side,0}$**
- **even in most central collision , $2R^2{}_{side,2} / R^2{}_{side,0} > 0$**

➡Initial out-plane elongated elliptic shape still remains at freeze-out time

k_T dependence of final source eccentricity



- 6 centrality class
  - 0 - 5 %
  - 5 - 10%
  - 10-20%
  - 20-30%
  - 30-40%
  - 40-50%

- $R^2_{out,2}$ / $R^2_{side,0}$ does not have significant k_T dependence
- $R^2_{side,2}$ / $R^2_{side,0}$ increase with increasing k_T
- $R^2_{side,2}$ / $R^2_{side,0}$ in smallest k_T has positive value
  - Inconsistent to hydro prediction
- $R^2_{os,2}$ / $R^2_{side,0}$ becomes larger from low k_T to high k_T (significant in peripheral)

Blast wave fit for Spectra, v_2 and HBT radii

- Analytical parametrisation for "Bulk property" based on the hydrodynamical model
- Extended to Azimuthally sensitive HBT interferometry (Phys. Rev. C 70 044907)
- Fitting spectra, v_2 and HBT **simultaneously**

✓ Longitudinal direction

- boost invariant longitudinal flow

★ Transverse momentum space

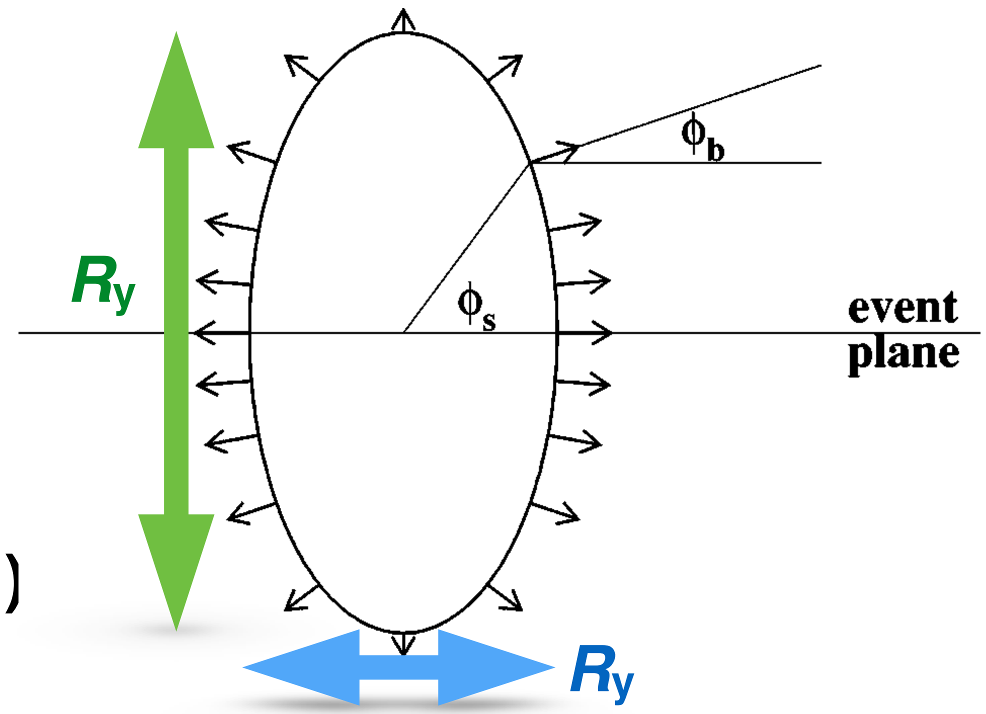
- Kinetic freeze out temperature T_f
- Transverse rapidity $\rho(r,\phi_s) = \tilde{r}\,(\rho_0 + \rho_2 \cos(2\phi_p))$

★ Coordinate space

- Transverse extents R_x, R_y

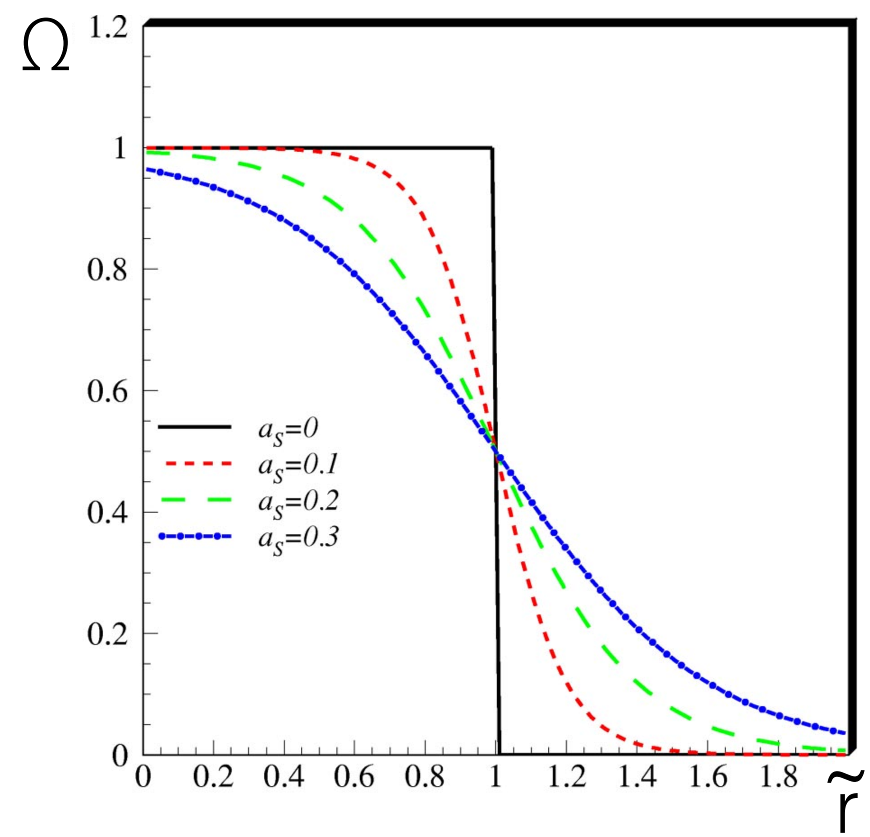
★ Freeze out time

- evolution duration τ_0
- Emission duration $\Delta\tau$

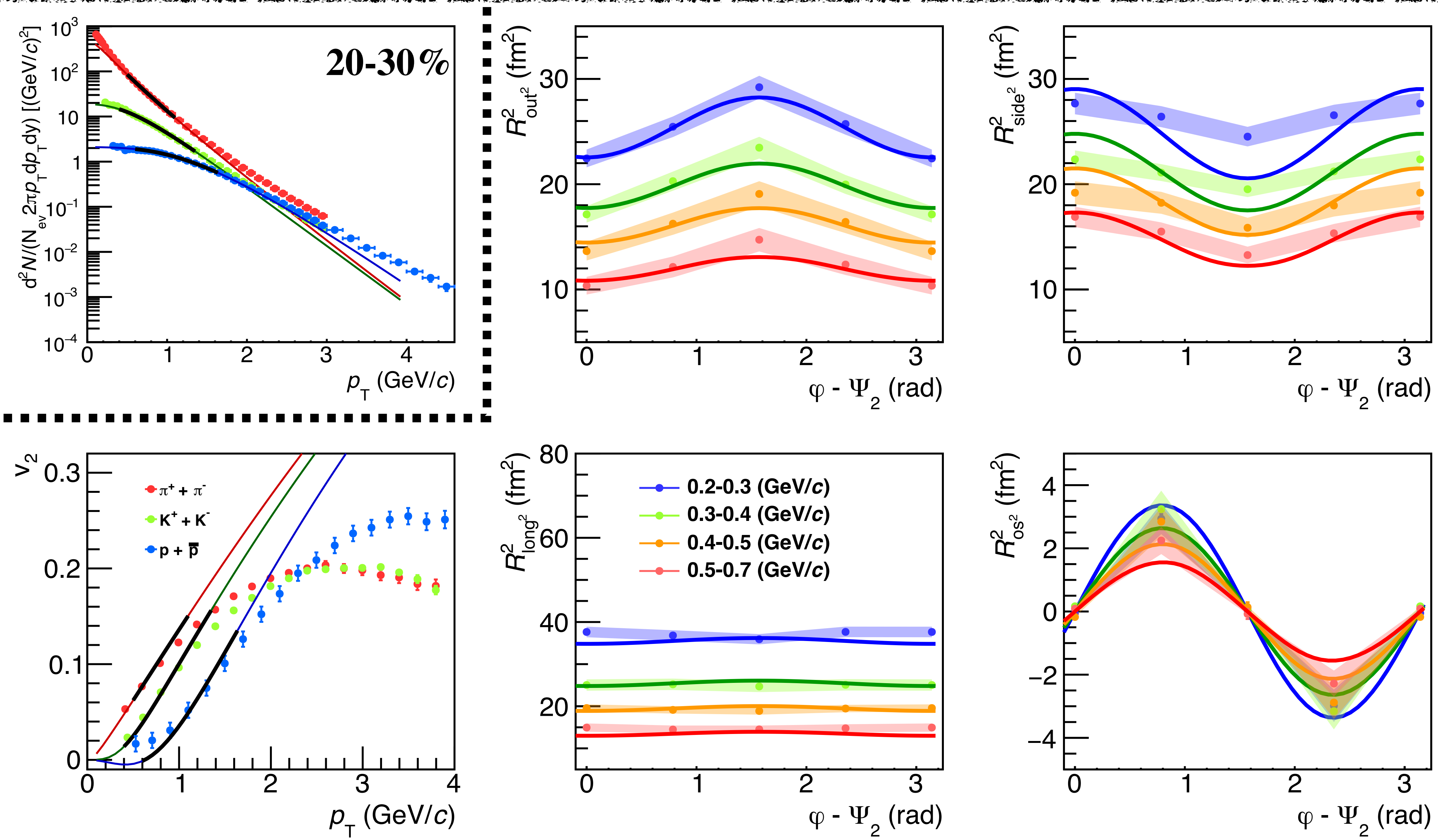


$$\Omega(r,\phi_s) = \frac{1}{1+e^{(\tilde{r}-1)/a_s}}$$

$$\tilde{r}(r,\phi_s) \equiv \sqrt{\frac{(r\cos(\phi_s))^2}{R_x^2} + \frac{(r\sin(\phi_s))^2}{R_y^2}}$$



Blast wave fit for Spectra, v_2 and HBT radii



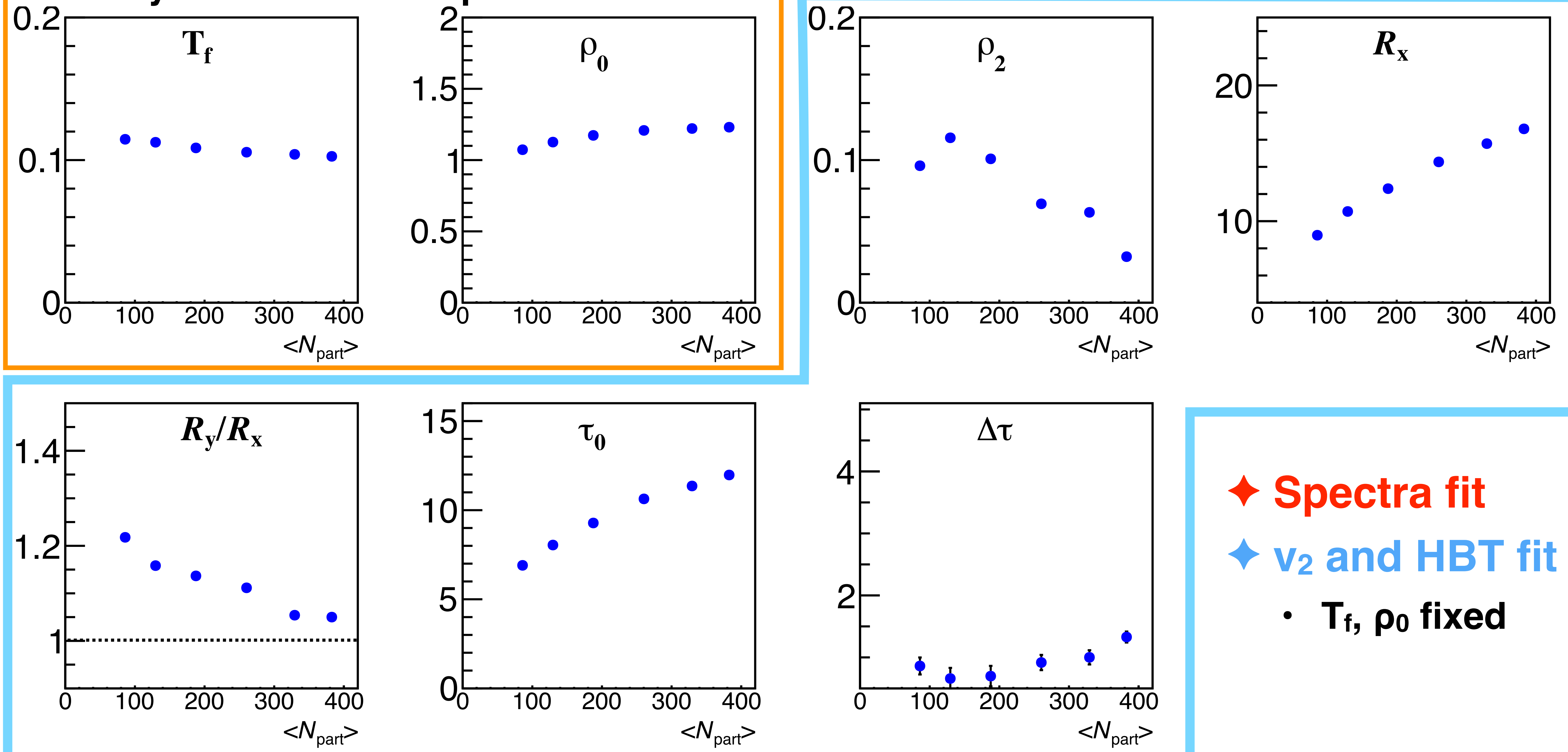
- **T_f, ρ_0** is determined with π, K, p spectra (independent of v_2 and HBT)
- **ρ_2, R_x, R_y/R_x, τ0, Δτ** are determined with v_2 and HBT fit
- Low p_T spectra and v_2 fitting is well done, but more work is necessary for HBT

✤ **π, K, p Spectra (Phys.Rev.C 88, 044910 [2013])**

✤ **PID v2 (JHEP 1609 (2016) 164)**

Extracted Blast Wave parameters

✓ Fully consistent with published result



✦ Spectra fit

✦ v_2 and HBT fit

- T_f, ρ_0 fixed

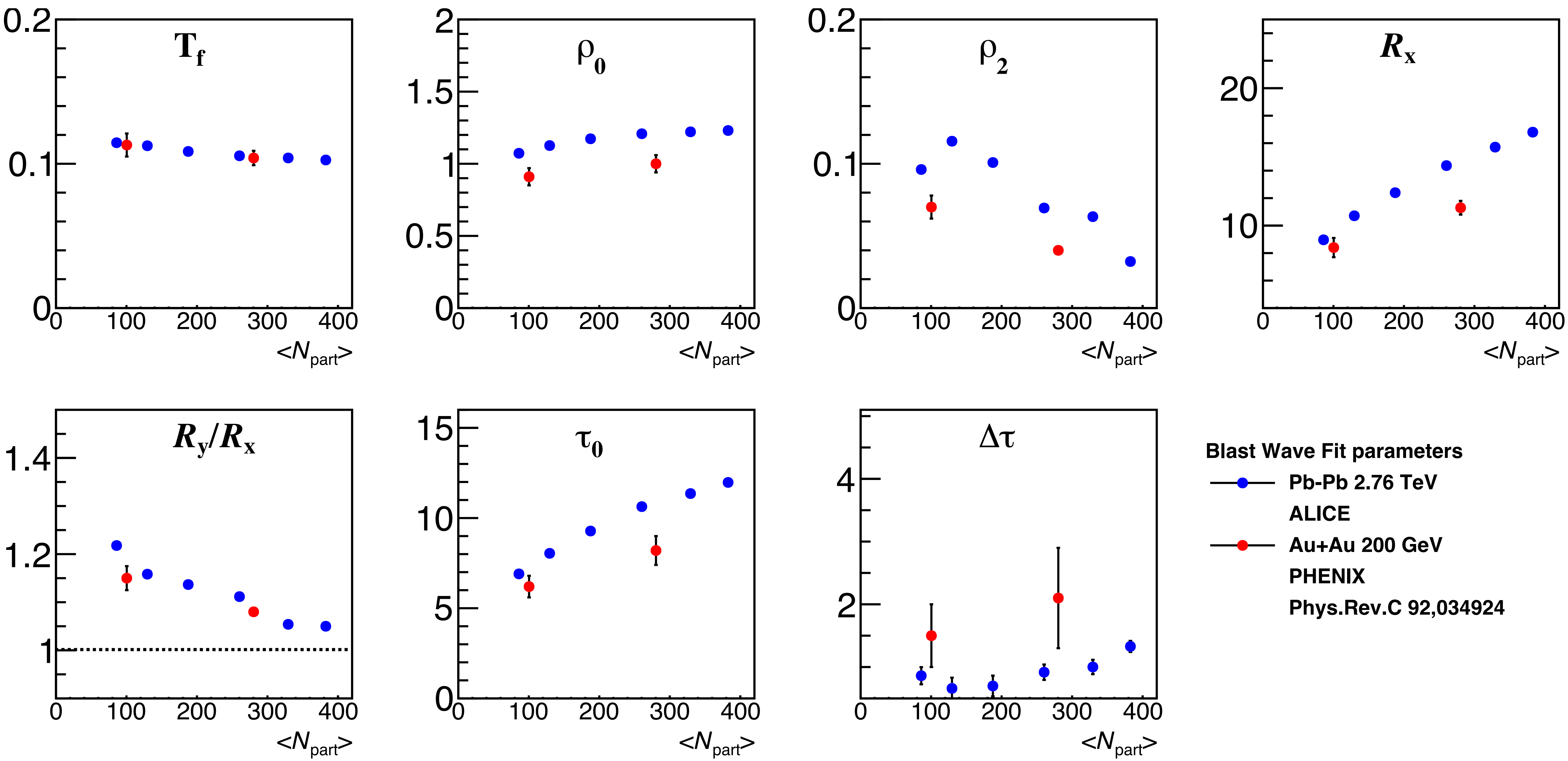
✦ Source size(R_x) and freeze out time (τ_0) increases as a function of $\langle N_{part} \rangle$

✦ Emission duration slightly increase with increasing $\langle N_{part} \rangle$

✦ Final source eccentricity decrease from peripheral to central

✓Out-plane elongated elliptic shape can be found even in most central events

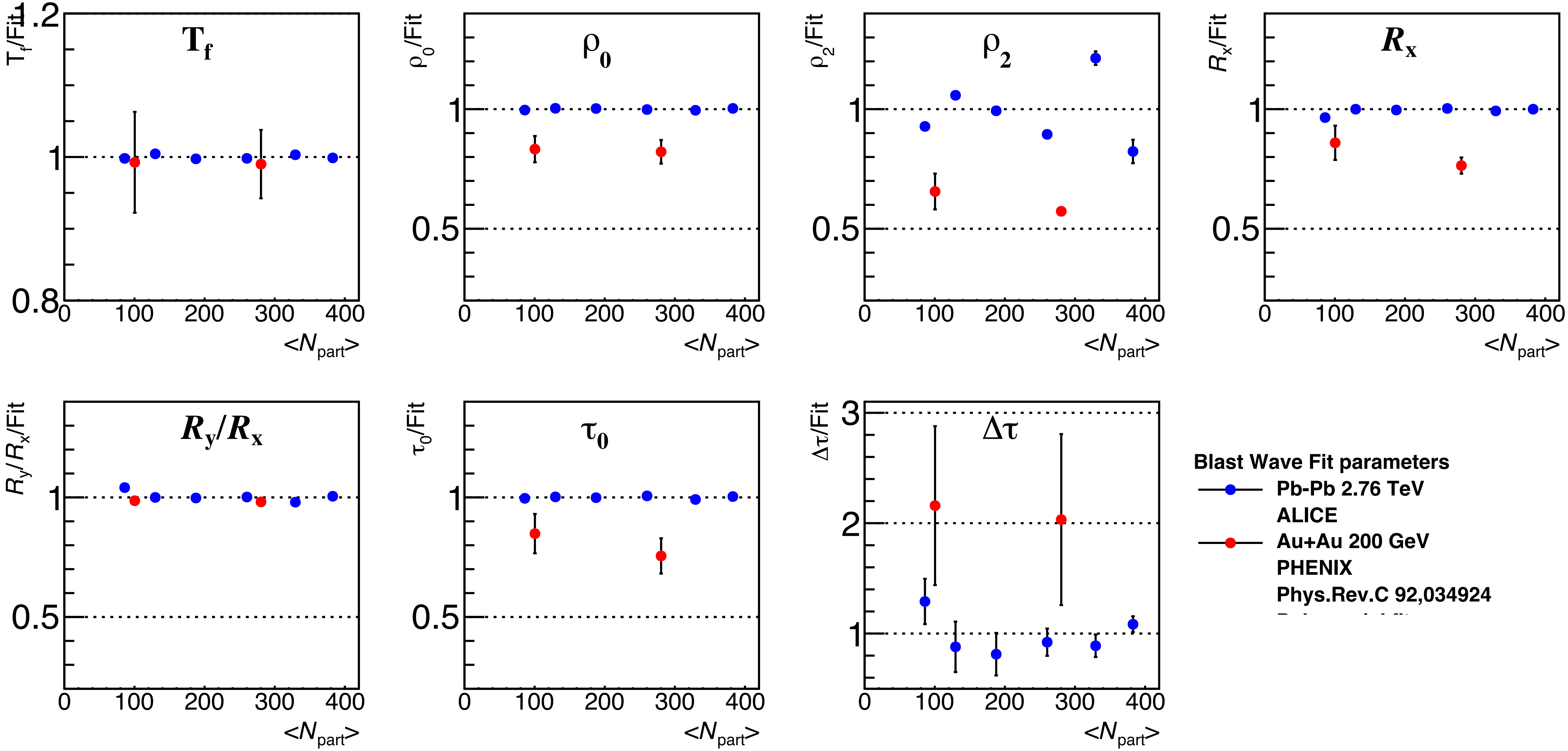
Blast Wave parameters (comparison with PHENIX)



- ✦ **Freeze out temperature(T_f) and eccentricity(R_y/R_x) : ALICE ~ PHENIX**
- ✦ **Flow velocity (ρ_0 and ρ_2) and evolution time : ALICE > PHENIX**
- ✦ **Emission duration : PHENIX > ALICE**

Blast Wave parameters (collision energy dependence)

✦ **ALICE data point is fitted with Polynomial**

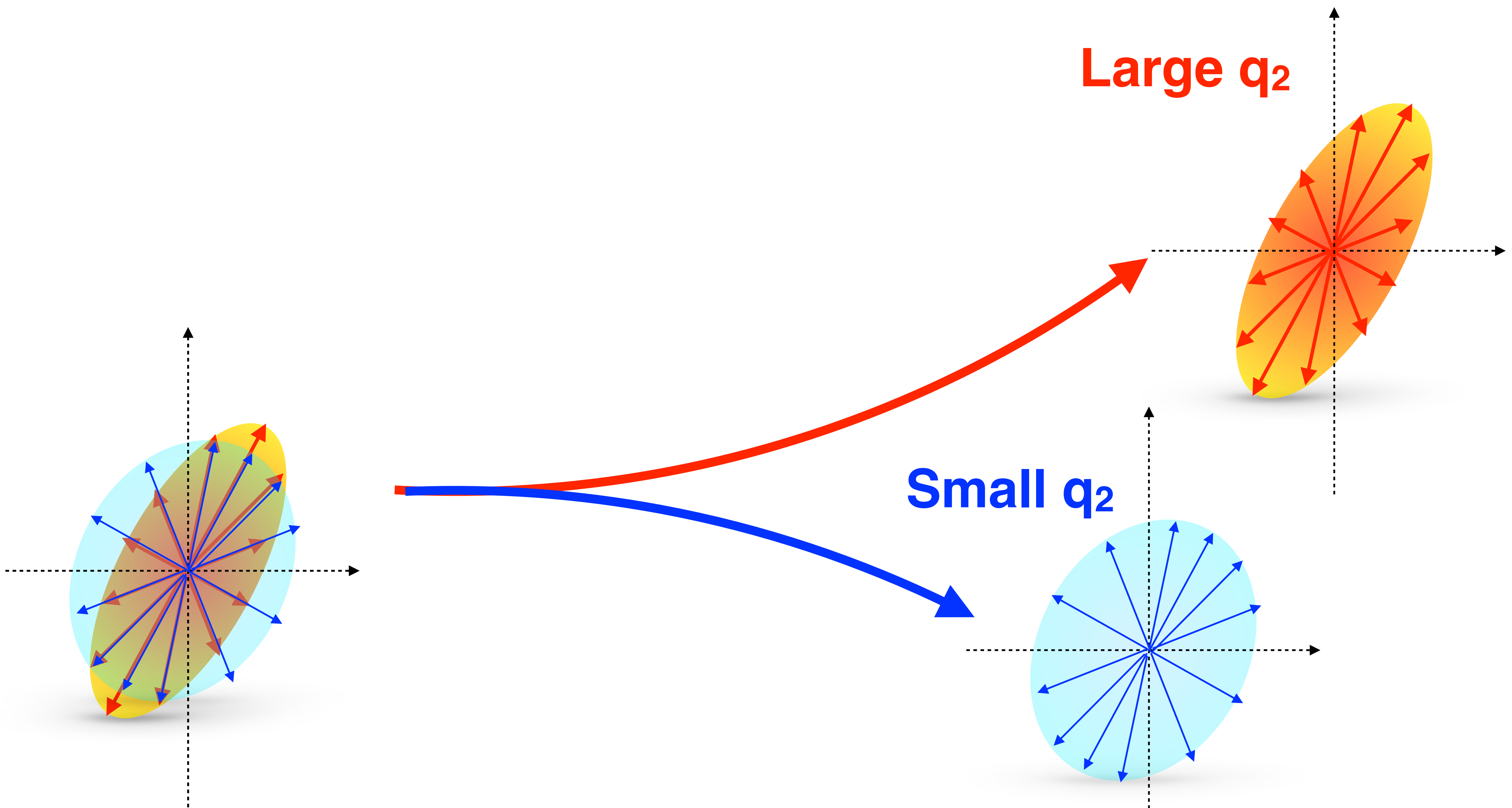


✦ **ρ_0 and τ_0 in ALICE are 10-20% larger than that in PHENIX**

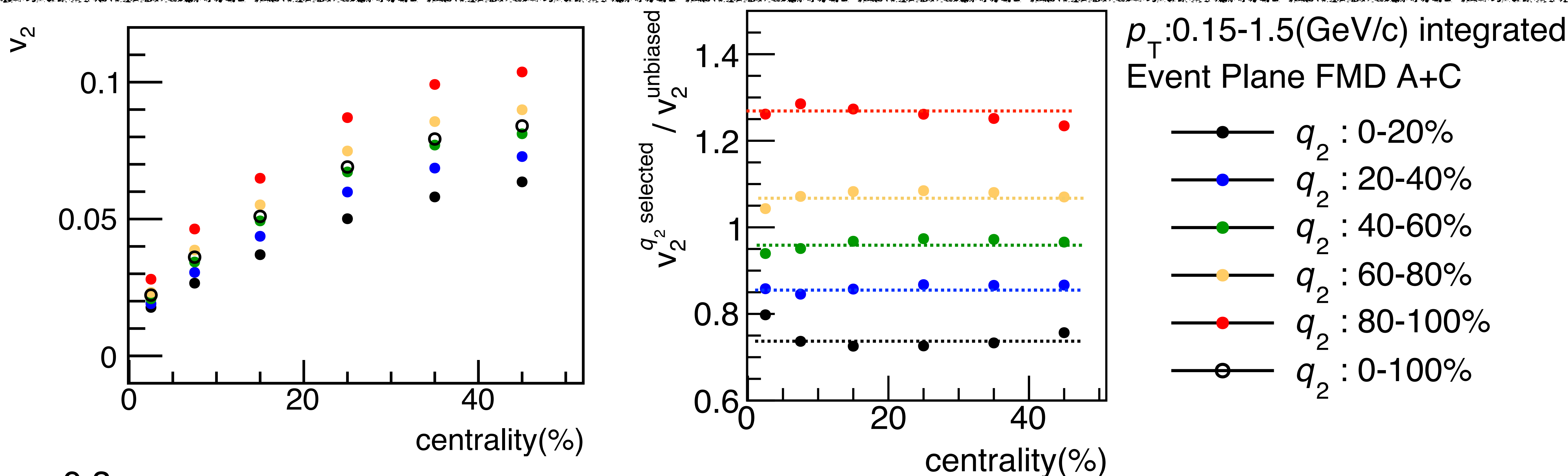
✦ **2nd order anisotropy in velocity field ρ_2 in ALICE is over 30% larger than PHENIX**

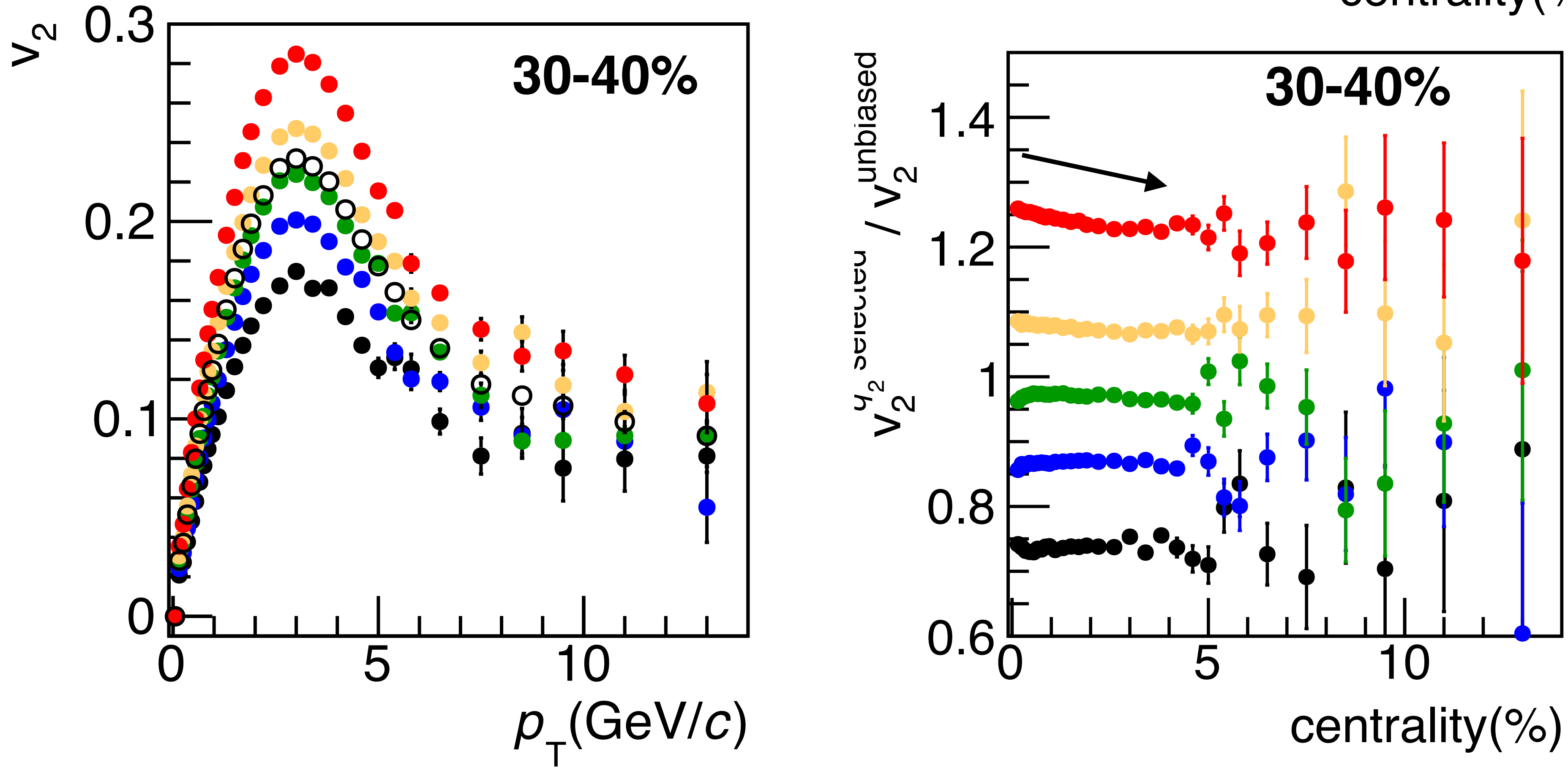
✦ **Emission duration in ALICE is at least 20% smaller than PHENIX**

HBT w.r.t. Ψ_2 + ESE
v_2 cut (initial ε_2 selection)



v_2 for each 20% Event shape q_2 selection

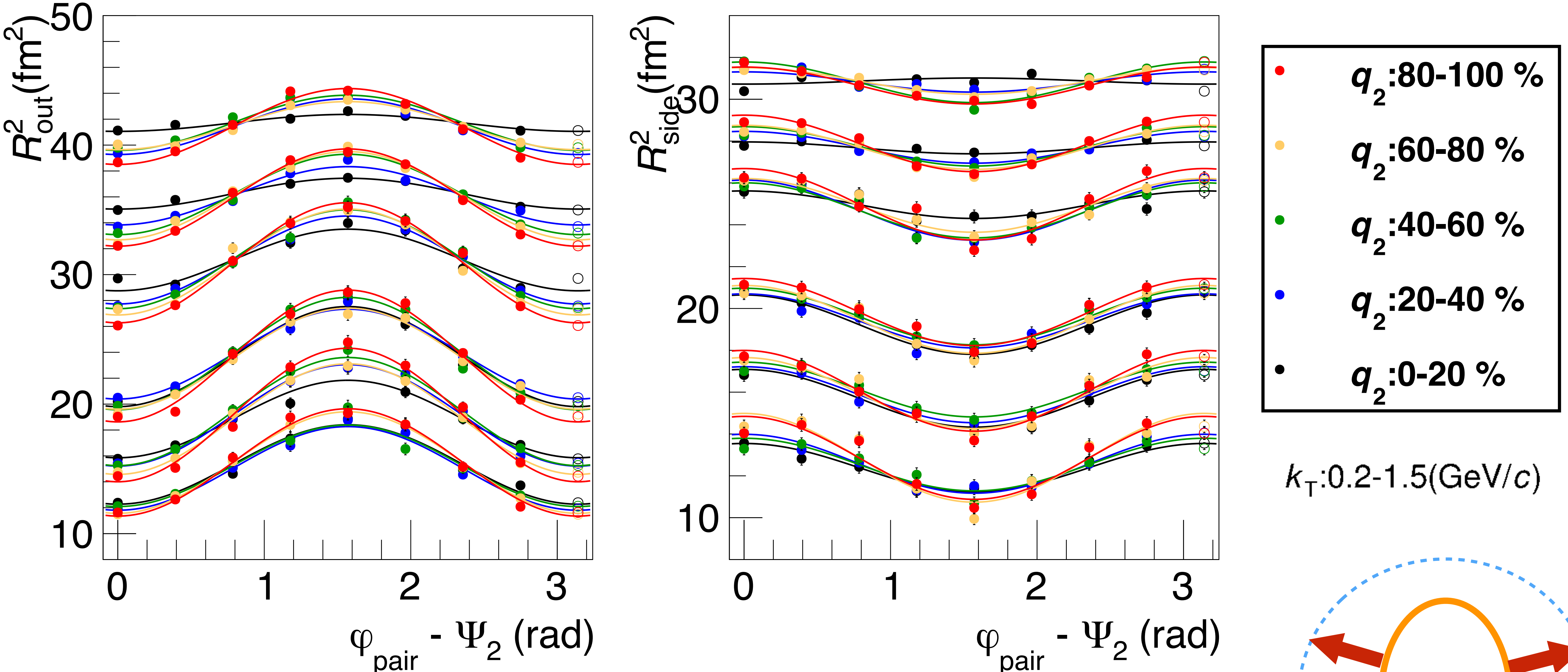


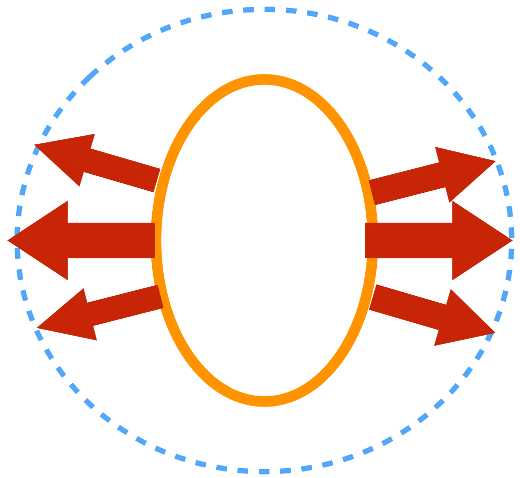


- **Small p_T dependence**

- **Event by event v2 amplitude can be selected**

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

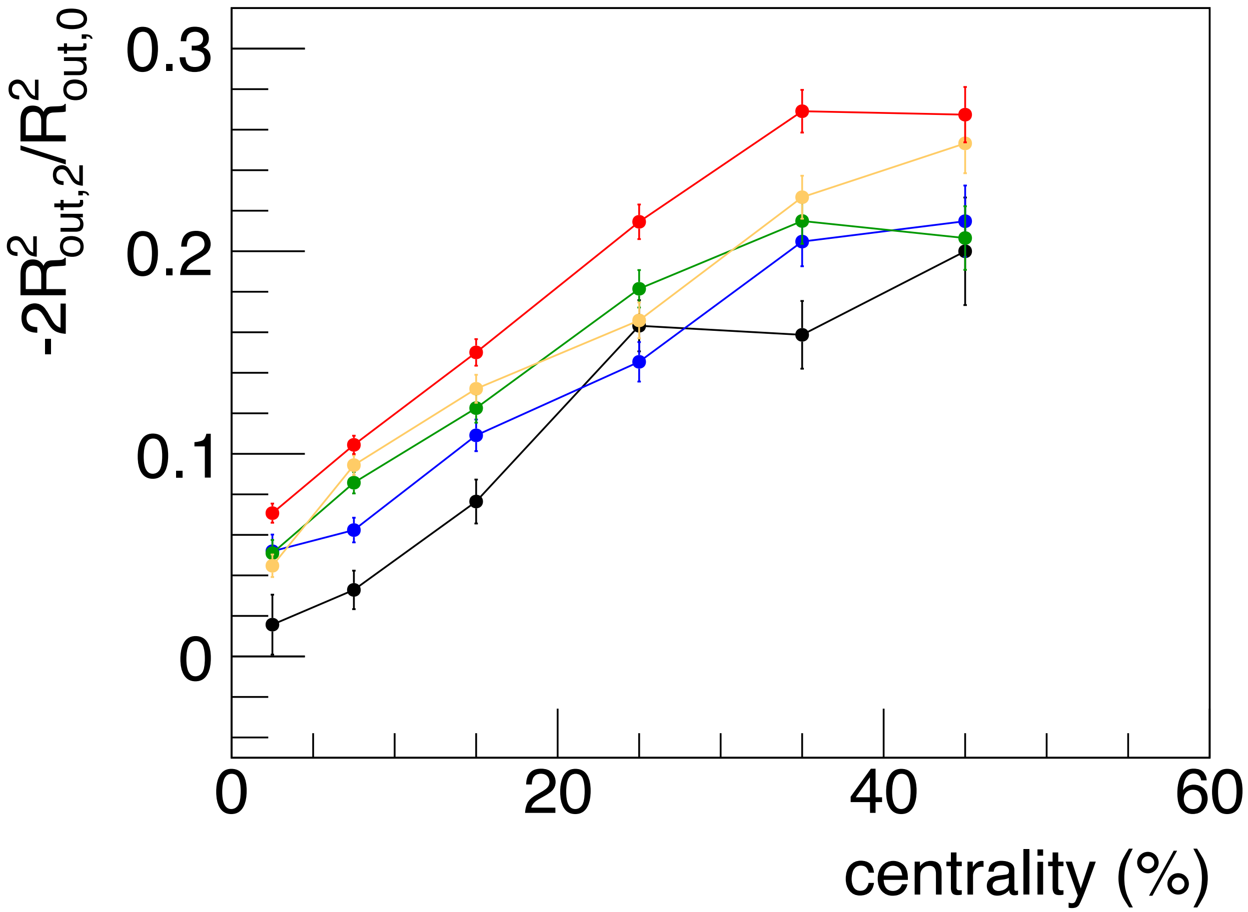


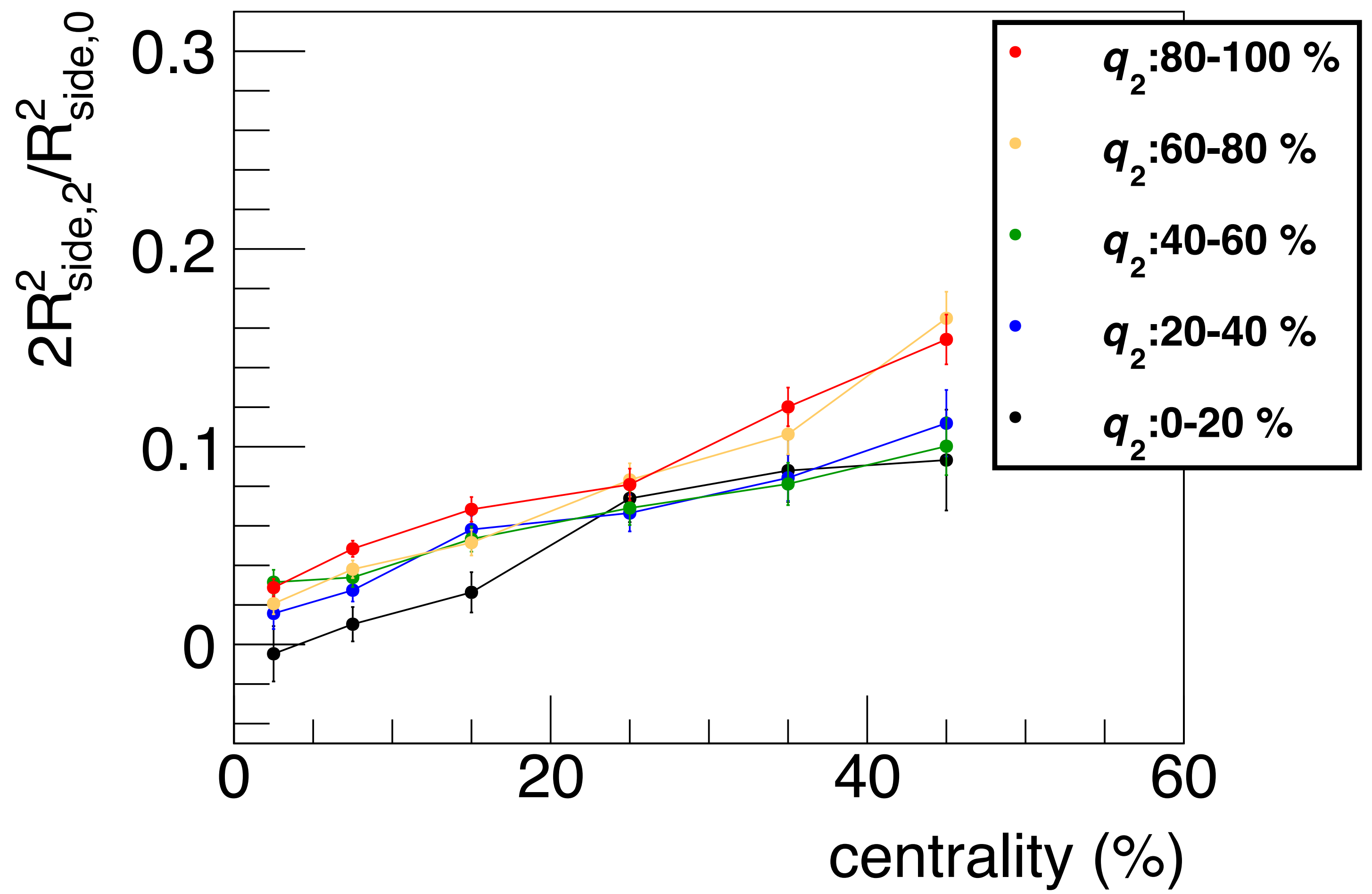


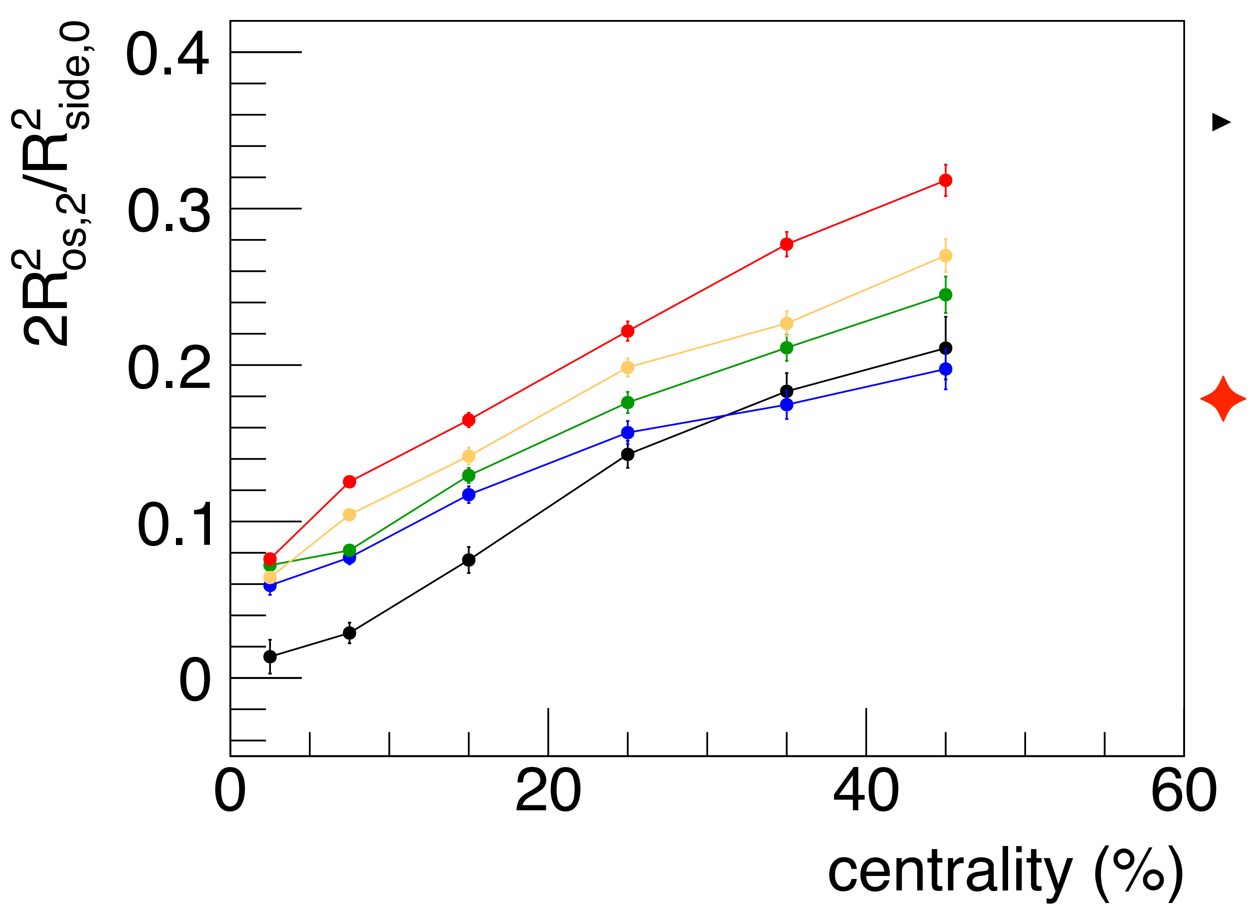
- 20% q_2 selection enhanced(suppressed) oscillation of R_{out} and R_{side}
  - Strong correlation between v_2 and ε_2 final
- For smallest q_2 selection(0-20%)
  - R_{side} has positive sign oscillation (similar to HBT w.r.t. Ψ_3)
  - Initial elliptic shape was reversed or vanished with flow
    - ✓ In-plane extended elliptic shape (or eccentricity was vanished)

- participant
- freeze-out source
- flow

Relative amplitude of HBT radii (2nd harmonics)







- **ε2(final) increases with increasing *q_2***
  - ➡ **Correlation between Initial and final ε2**
  - ✓ **Different elliptic shape in a fixed system size**
- ✦ ***R_{out} and R_{os}* is more sensitive to flow(v_2)**
  - ➡ **R_{side} is a good probe for final eccentricity**
  - ➡ **ε_2^{final} might be reversed in most central and top q_2**

What can be extracted with this ESE(q_2) analysis ?

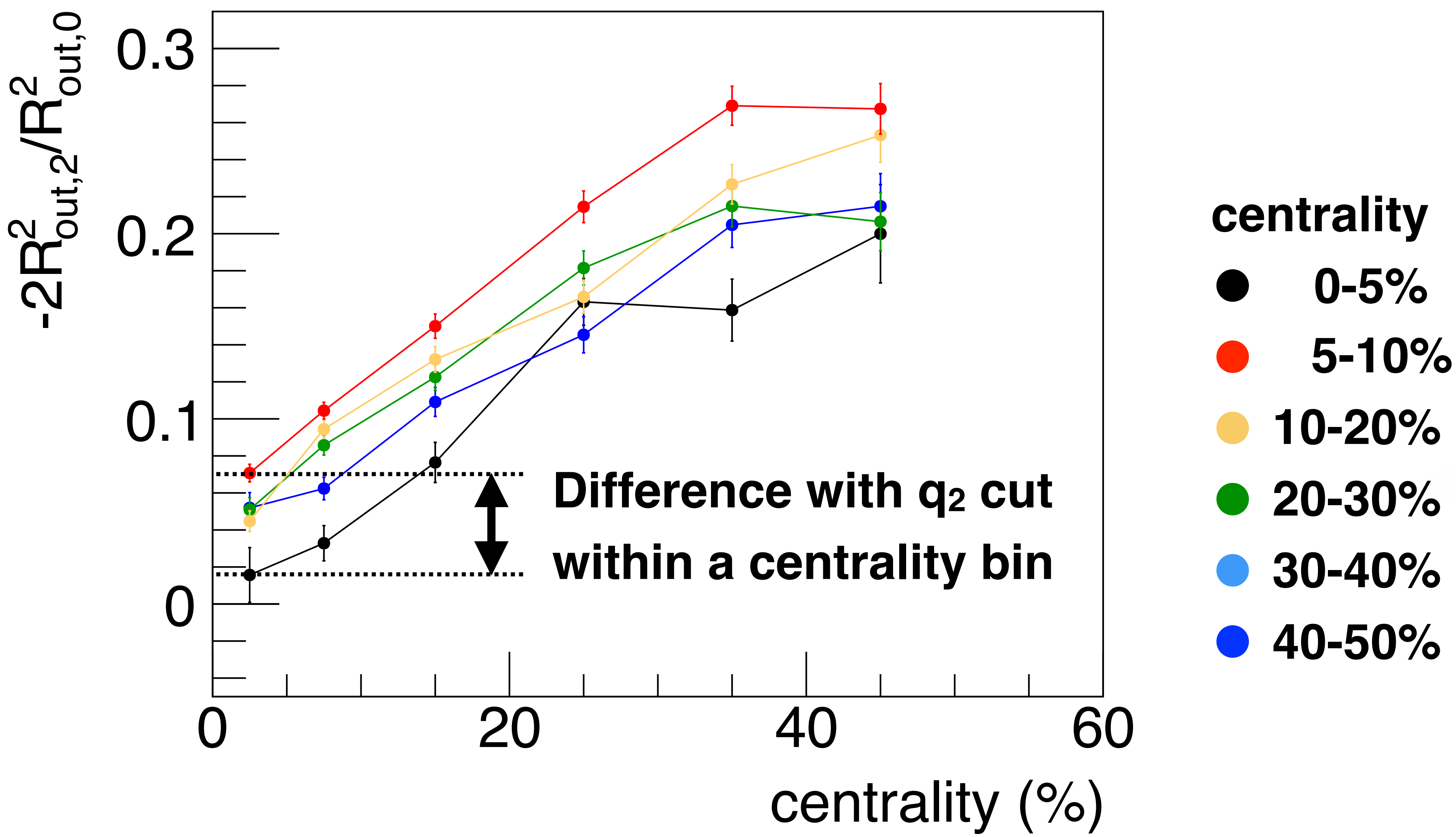
✦In order to extract "Initial ε2 v.s. final ε2", Initial ε2 is necessary !

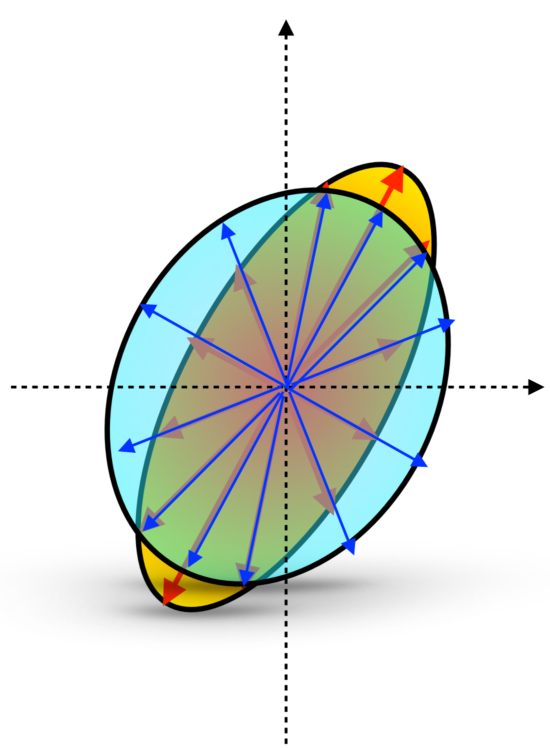
➡ **Basically initial ε_2 is calculated with Glauber "in a certain centrality"**

➡ **Difference of initial ε2 with ESE can not be reflected with this method …**

- ✦ $v_2 \propto \varepsilon_2 * f(dN/d\eta)$

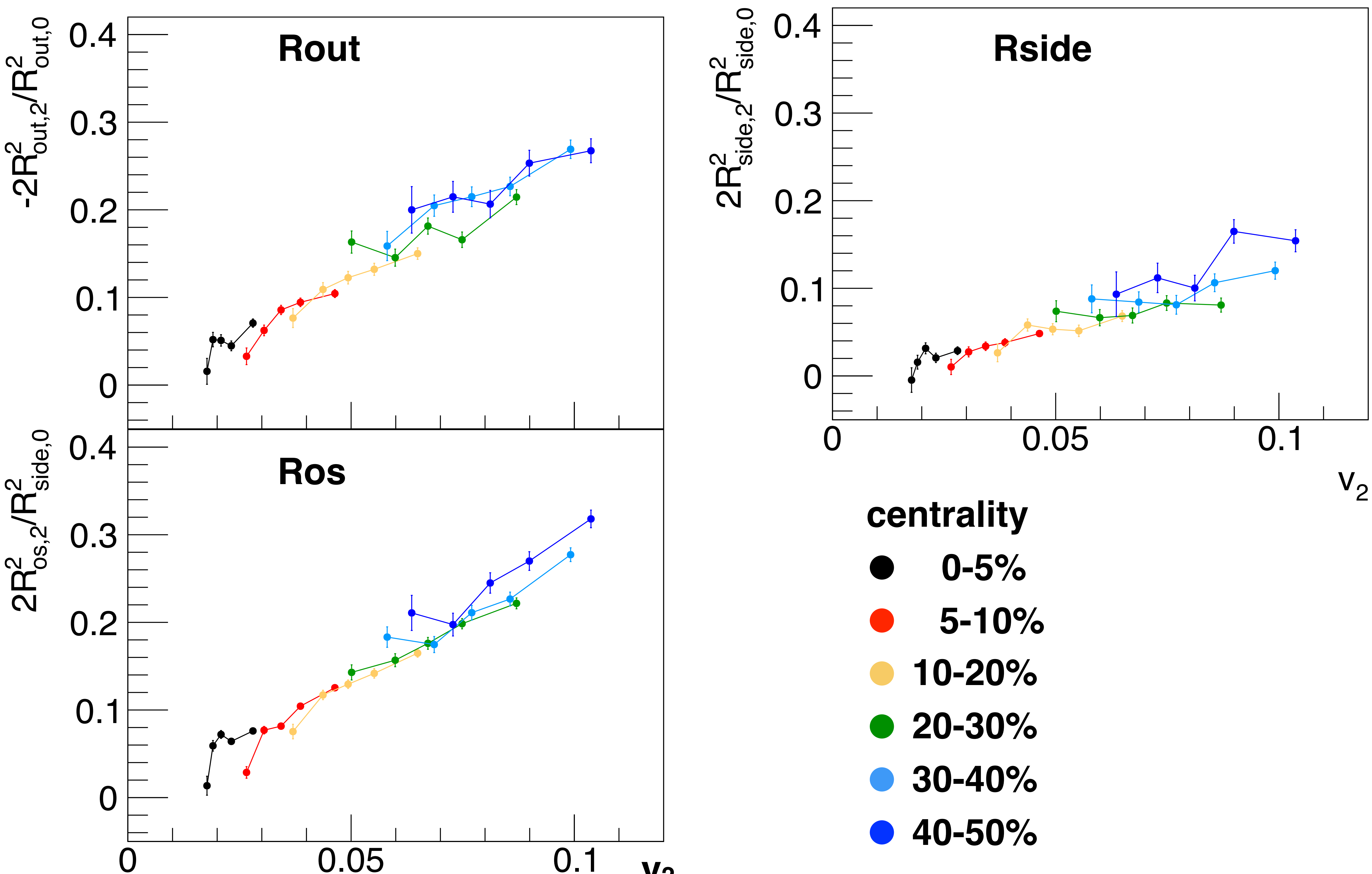
✦ **Correlation between "v2" and final eccentricity is better than centrality**



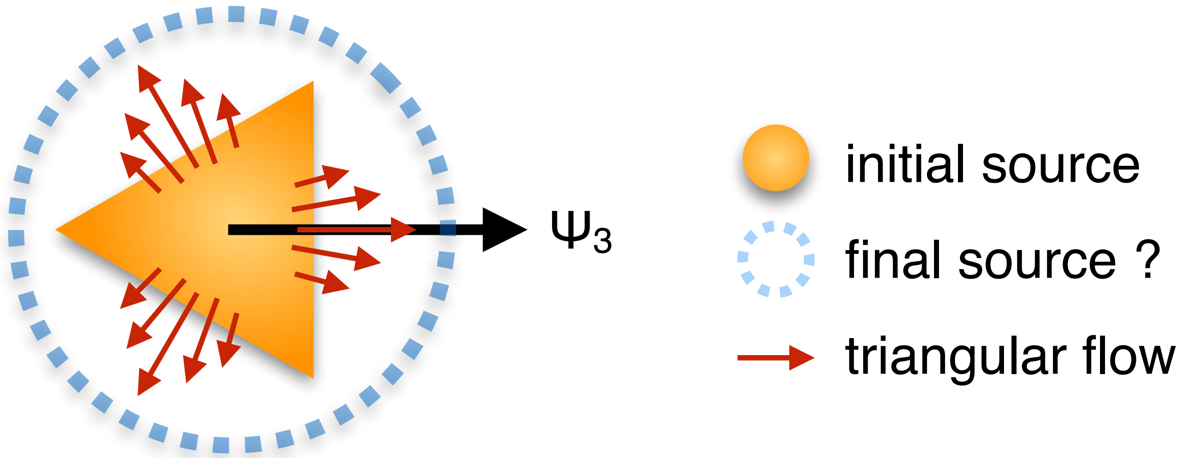


Final source eccentricity as a function of v_2

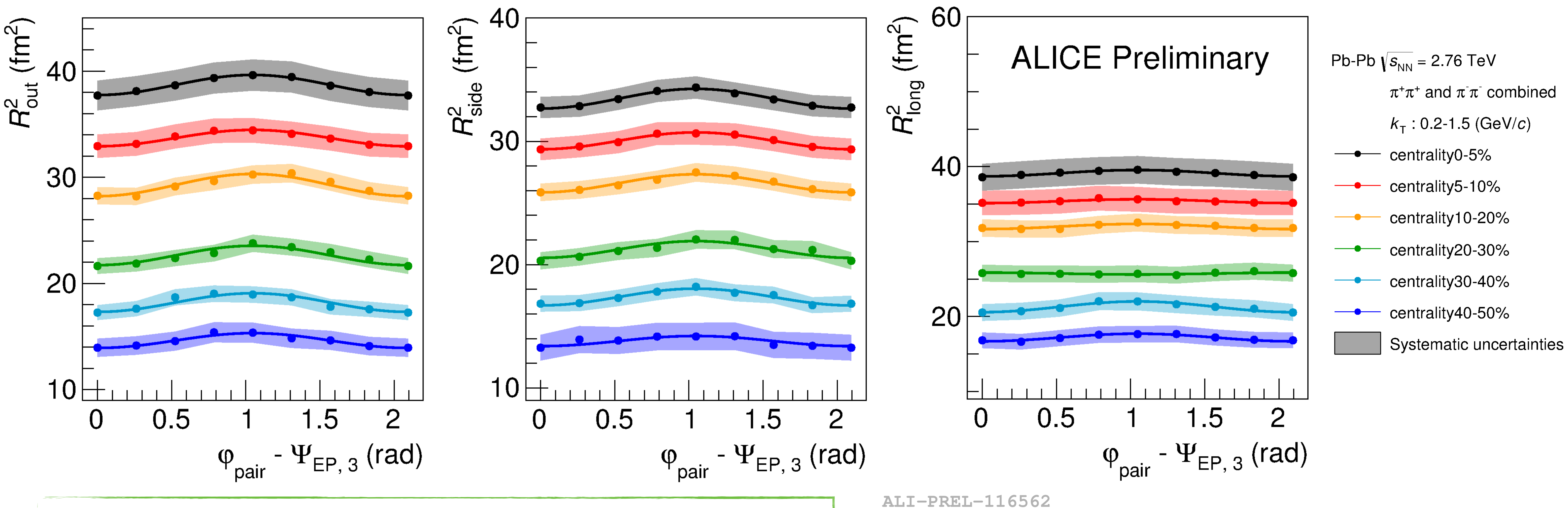
- ✓ All ε_2 with different q_2 selection are scaled with v_2
- ✓ Final source eccentricity is determined with v_2



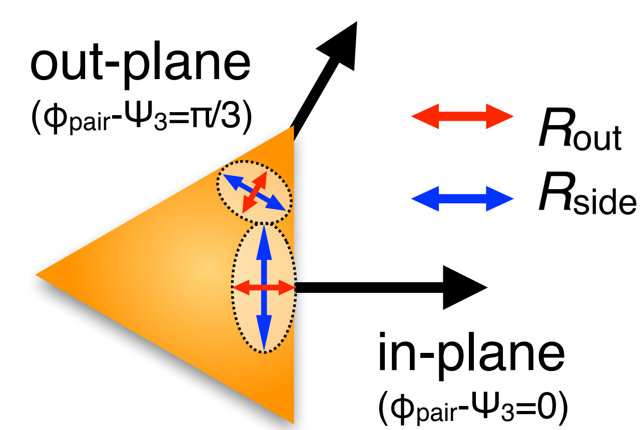
Third harmonics



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

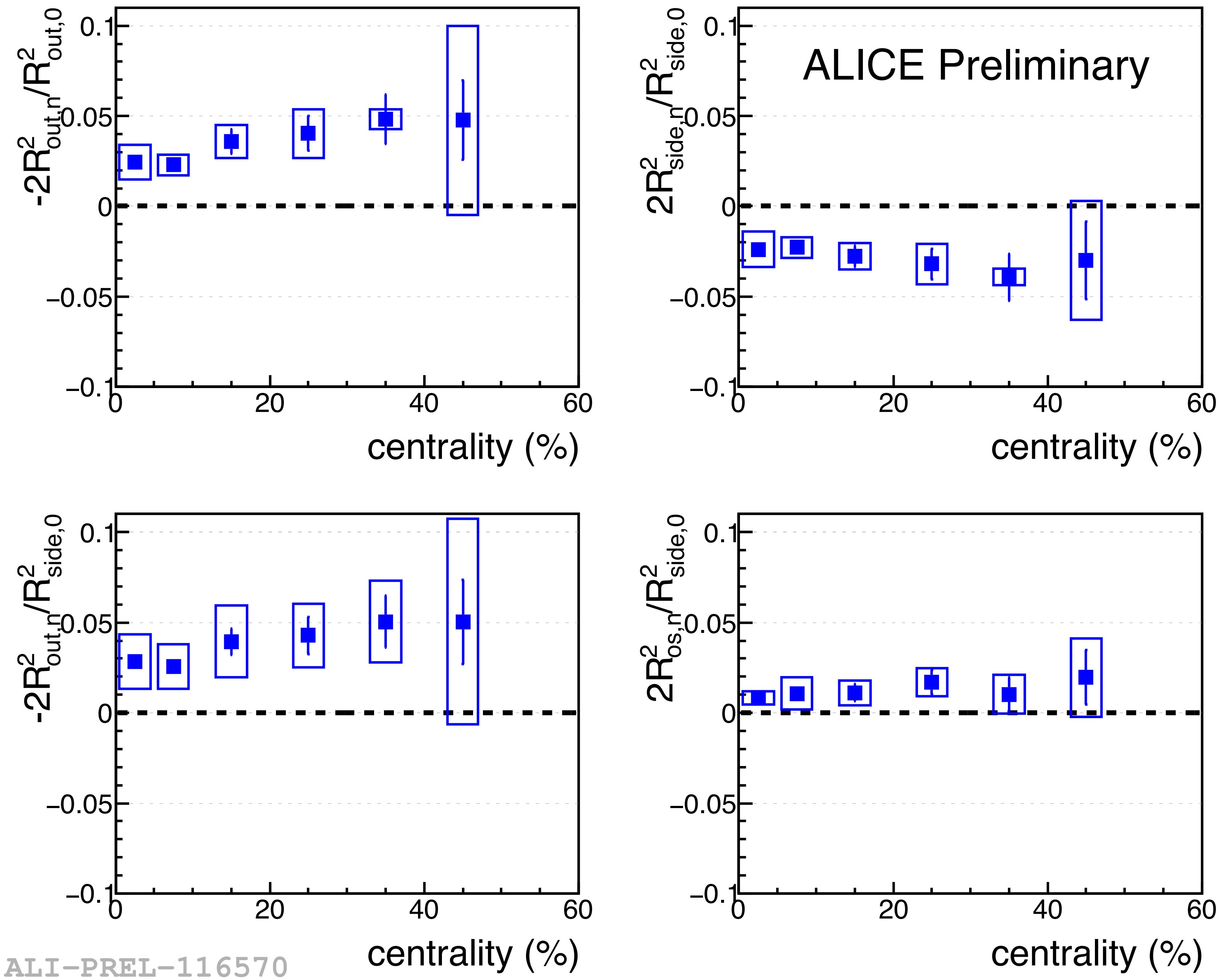


- Fit function
- $R^2_{\mu,0} + 2 R^2_{\mu,3} \cos(3(\phi_{pair} - \Psi_3))$
  - $R^2_{\mu,0}$: Average HBT radii, $R^2_{\mu,3}$: Oscillation amplitude



- **No significant oscillation can be seen in R_{long}**
- **Oscillations w.r.t. Ψ_3 are observed in R_{out} and R_{side}**
- **R_{out} and R_{side} oscillations have same sign**
  - ➡ **Consistent to PHENIX result in Au+Au 200GeV collisions (PRL112.222301)**
- **Oscillation amplitude of R_{out} and R_{side} is almost same**
  - ➡ **Different from PHENIX result due to larger collective flow?**

3rd harmonic oscillation of HBT radii



Pb-Pb 2.76 TeV

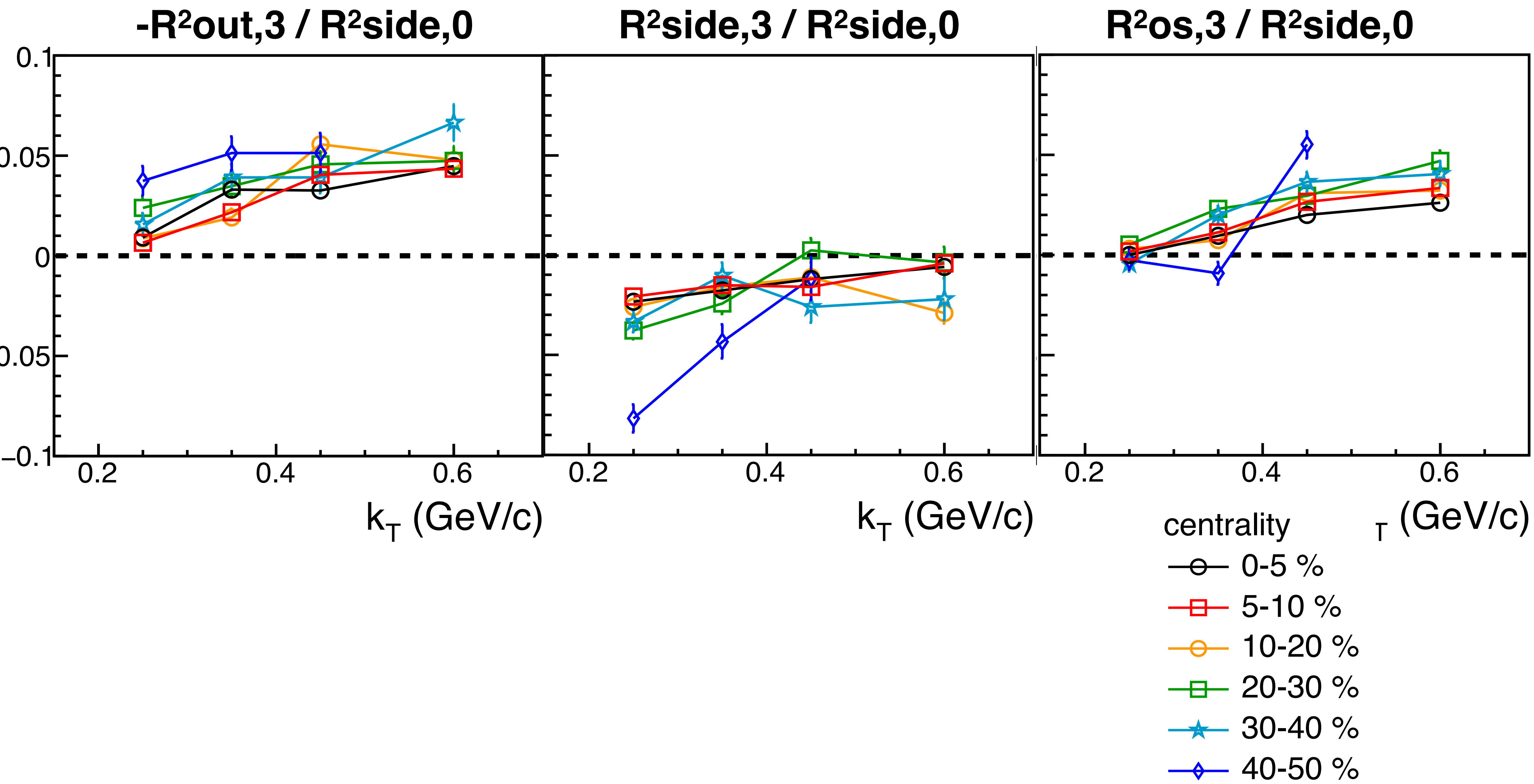
$\pi^+\pi^+ + \pi^-\pi^-$

$0.2 < k_T < 1.5$

E.P. with FMD A+C

- ✓ **3rd harmonic oscillation can be found in all centrality except for R_{long}**
- ✓ **R_{out} and R_{side} oscillation grows from central to peripheral**
- ✓ **R_{os} is always positive (triangular flow)**

Relative amplitude of HBT radii w.r.t. Ψ_3 k_T dependence



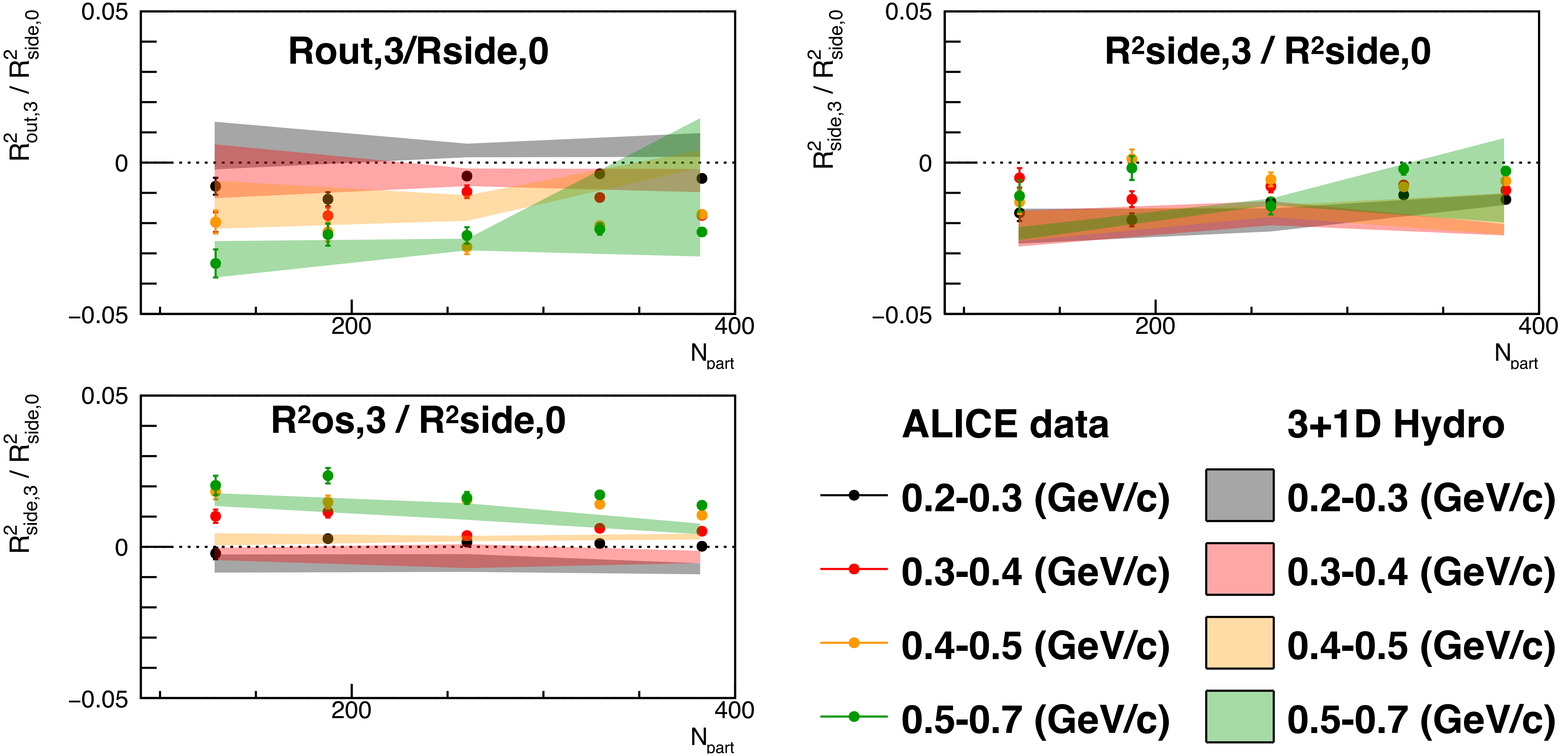
✓ **Relative amplitude of *Rout* becomes larger with increasing k_T**

✓ **Rside oscillation decreases from low k_T to high k_T**

✓ **Ros shows explicit kT dependence and Ros oscillation is 0 at k_T=0**

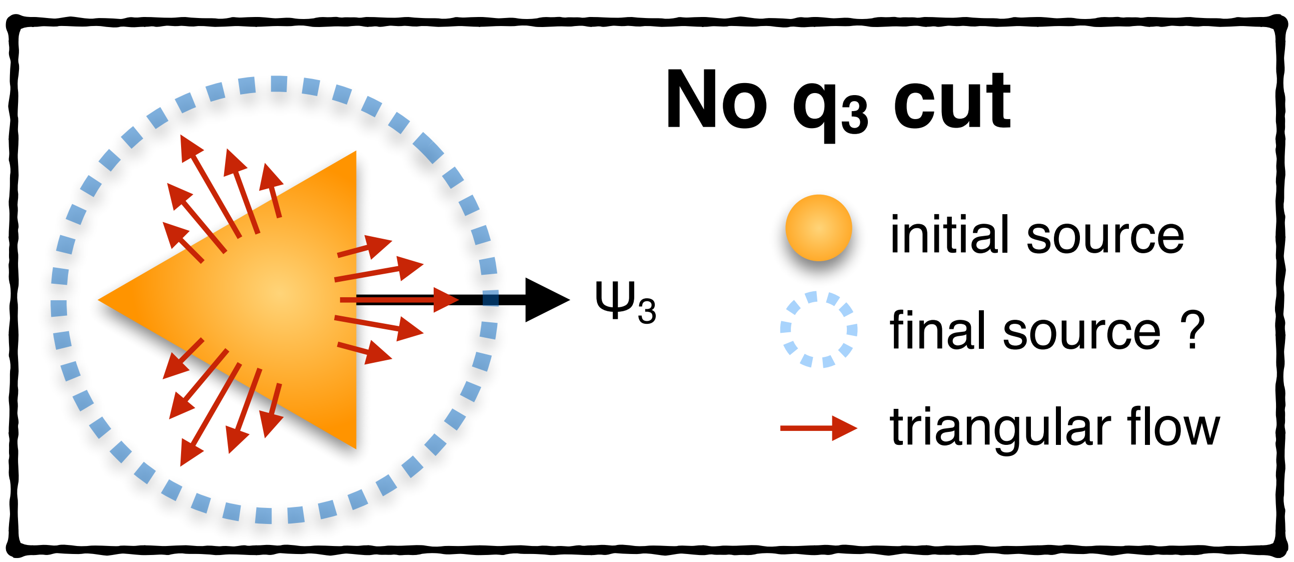
3rd harmonic oscillation amplitude of HBT radii

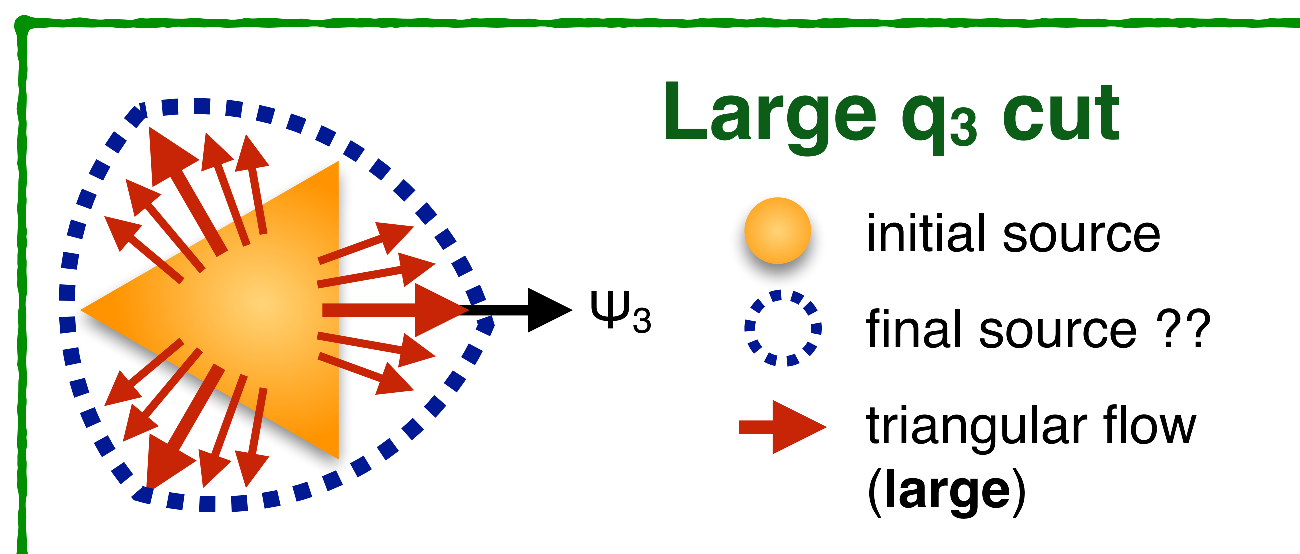
(P. Bozek, J. Phys. G**38**, 124097)



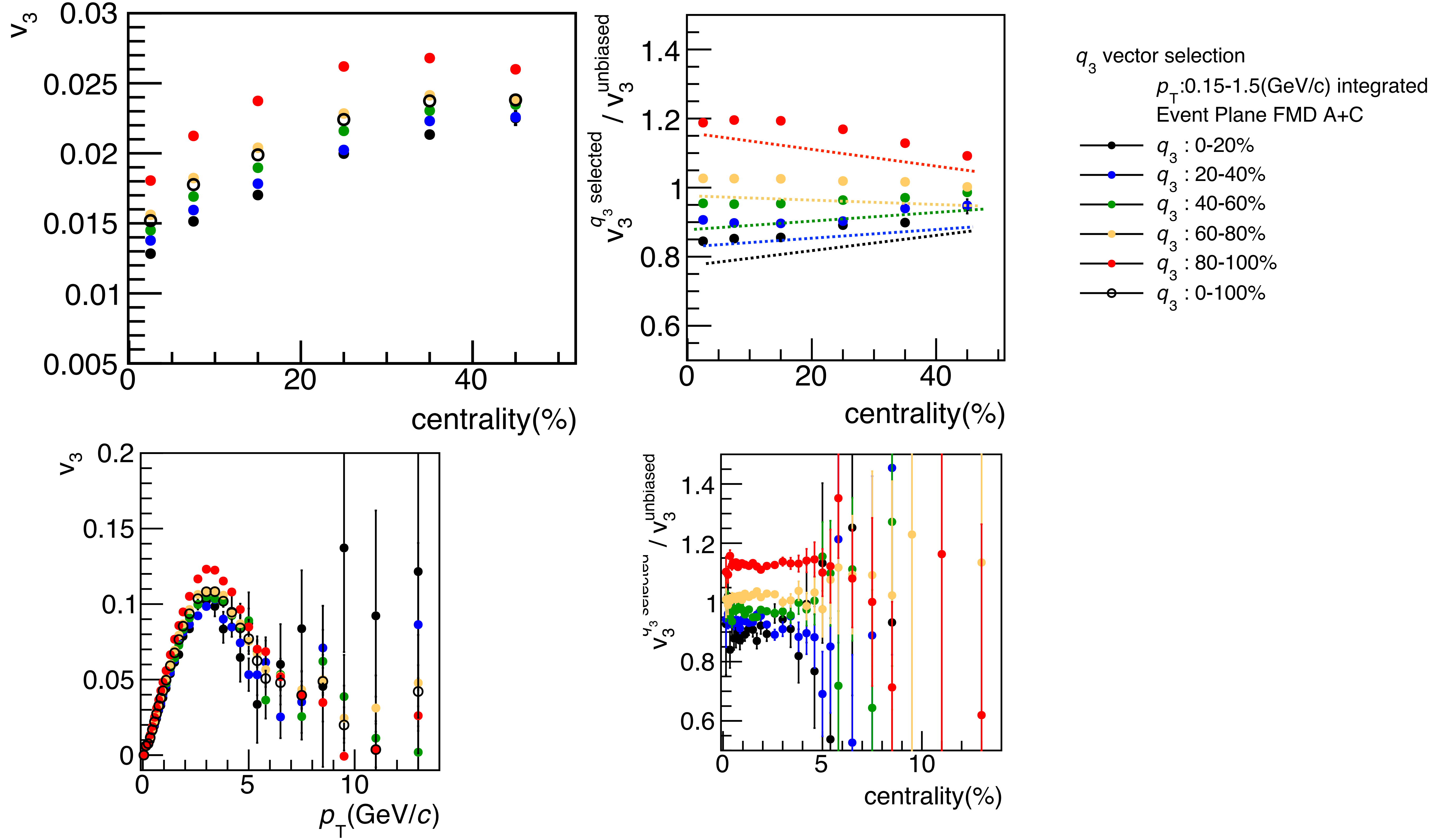
- ✦ ***Npart*** **dependence in Hydro calc. and Data are qualitative consistent**
- ✦ ***R*** $^2_{out}$ **oscillation is consistent in hight** k_T **(Hydro calc. at low** p_T **is opposite sign)**
- ✦ ***R*** $^2_{side}$ **oscillation is consistent in low** k_T **(Hydro calc. can't reproduce** k_T **dependence)**
- ✦ **Low** k_T **of** ***Ros*** **oscillation with Hydro calc is underestimate**

HBT w.r.t. Ψ_3 + ESE
v_3 cut



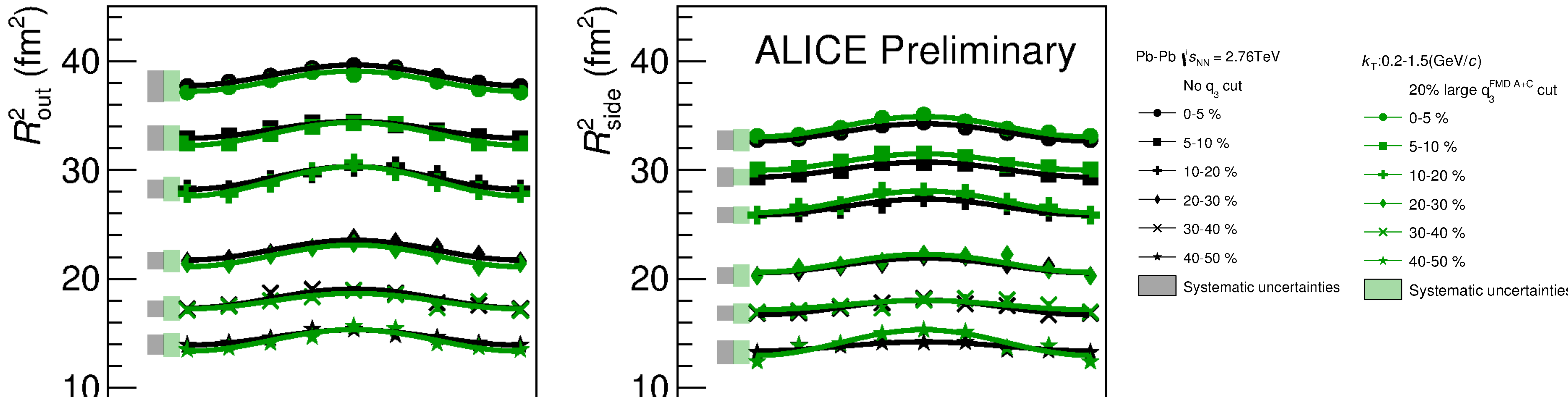


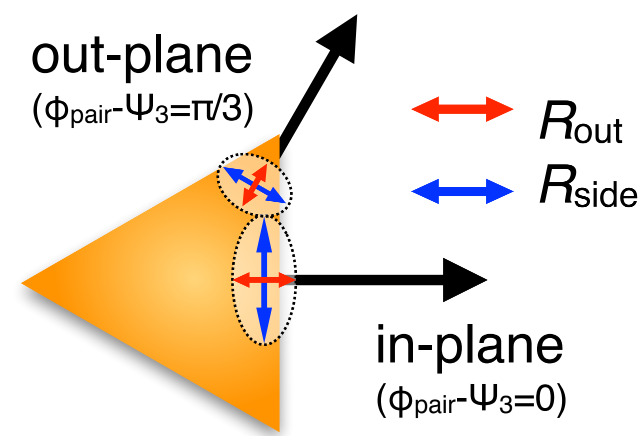
v_3 (centrality dependence) with 20% step q_3 selection



- v_3 explicitly changes with q_3 selection (enhancement depends on q_3 selectivity)
- v_3 modification is largest in central and becomes smaller from central to peripheral

Azimuthal HBT w.r.t. Ψ_3 with ESE



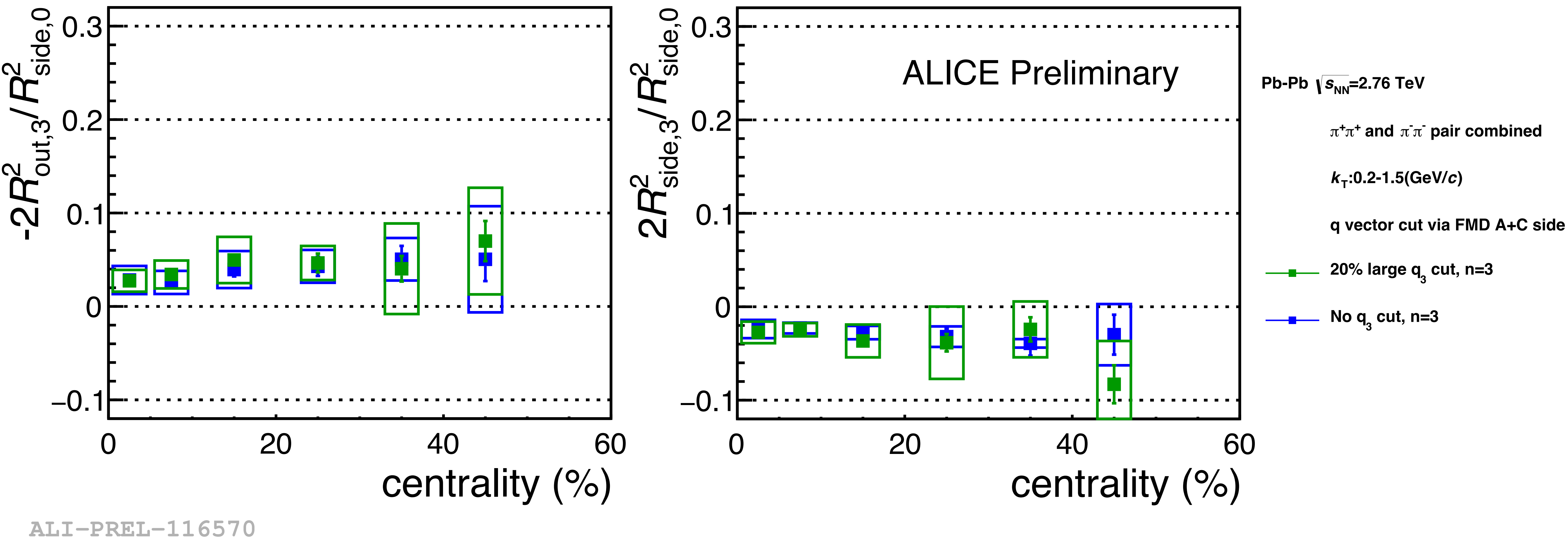


- $R^2_{\mu,0} + 2 R^2_{\mu,3} \cos(3(\phi_{pair} - \Psi_3))$
  - $R^2_{\mu,0}$: Average HBT radii, $R^2_{\mu,3}$: Oscillation amplitude

- **20% largest q_3 vector selection is applied at ($-3.4 < \eta < -1.7$, $1.7 < \eta < 5.0$)**
- **No significant effect on the R_{out} oscillation can be observed by large q_3 selection**
- **R_{side} oscillation is slightly changed by large q_3 cut**

Relative amplitude of HBT radii (3rd harmonics)

☑ R_{out} and R_{side}



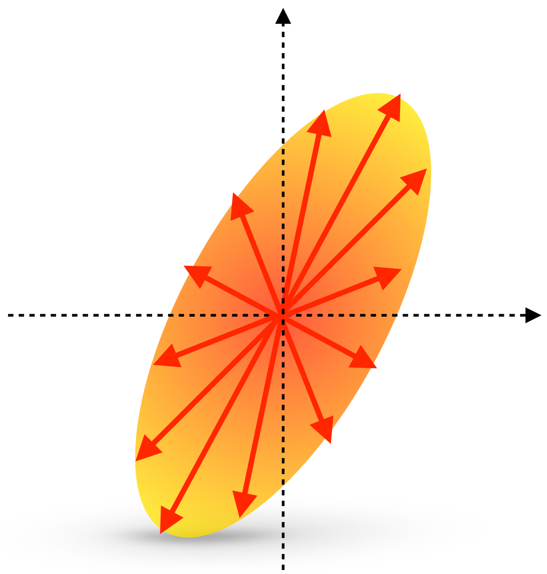
- **No significant change has been observed in relative amplitude ($R^2_{out,3}/R^2_{side,0}$ and $R^2_{side,3}/R^2_{side,0}$), though v3 is enhanced ~ 15%**
  - **Triangular flow is not dominant source of 3rd-order HBT oscillation ?**
  - **Large $v_3(q_3)$ event selection ≠ large triangular flow event selection ?**
  - **q_3 selectivity is too small ?**

➡ **Model comparison is necessary**

Summary for HBT w.r.t. Ψ_2

- Centrality & k_T dependence of HBT relative to Ψ_2
  - Out-plane extended elliptic shape can be seen in all centrality
  - Blast wave fit says T_f and ε2(v.s. N_{part}) is consistent to Au+Au 200GeV and ρ0, ρ2, τ0 is much larger than 200GeV. Δτ is ALICE < PHENIX

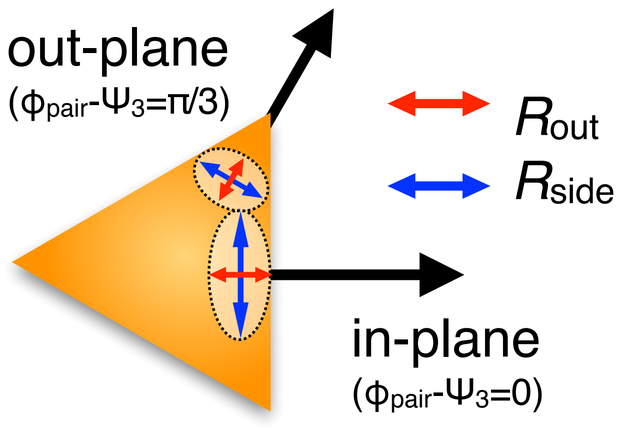
- HBT w.r.t. Ψ_2 with q2 selection
  - Final source eccentricity is strongly modified with v2 cut(initial ε2 cut)
  - In-plane extended elliptic shape could be seen in smallest q2 event
  - Difference of final source eccentricity with q2 cut is scaled with v2
    - ✓ Blast wave fit will tell some more qualitative difference (ε2 or time)



Summary for HBT w.r.t. Ψ_3

- Centrality & k_T dependence of HBT relative to Ψ_2
  - Non zero oscillation can be found in Rout, Rside and Ros
  - Small but finite kT dependence was found in Rout, Rside, Ros
  - Hydrodynamical model is qualitatively consistent to data

- HBT w.r.t. Ψ3 with q3 selection
  - Final source eccentricity is not modified with v3 cut



Outlook

- **kT dependence of Azimuthally sensitive HBT relative to Ψ_2 and Ψ_3 with ESE q_2 and q_3 respectively**
- **Blast wave fit for HBT relative to Ψ_3 and Ψ_2 with q_2**

Event plane resolution

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

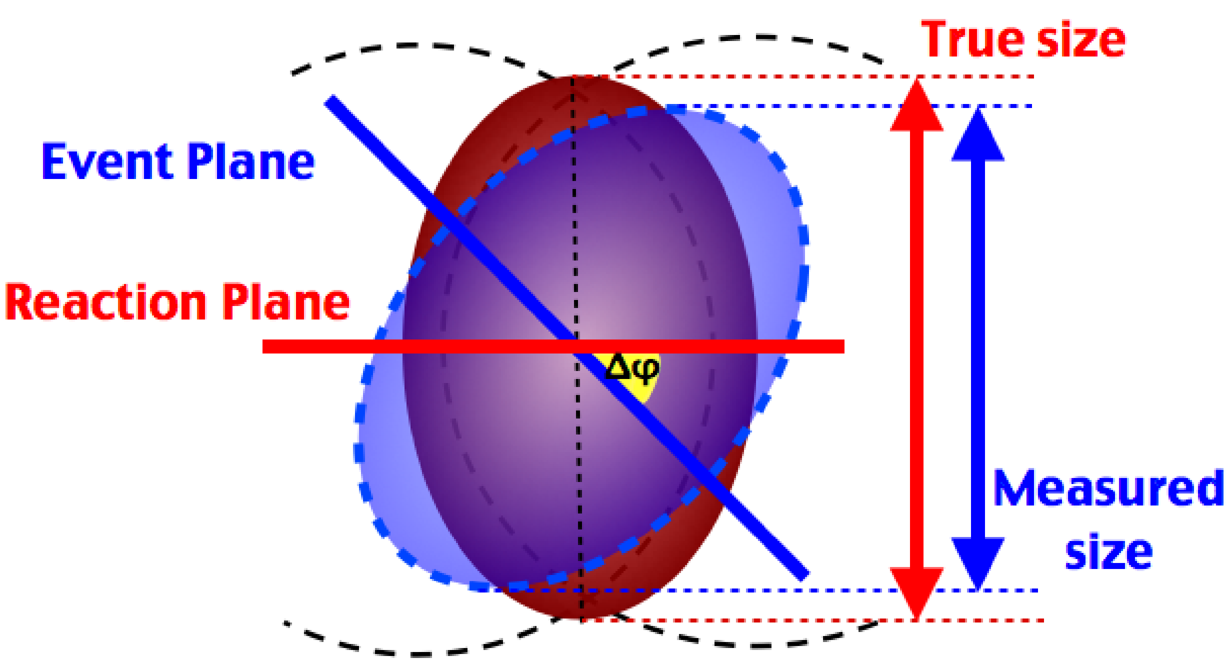
$$N\left(q,\phi_j\right) = N_{exp}\left(q,\phi_j\right) + 2\sum_{n=1}^{n_{bins}} \xi_{n,m}(\Delta)\left[N_{c,n}^{exp}(q)\cos(n\phi_j) + N_{s,n}^{exp}(q)\sin(n\phi_j)\right]$$

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

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

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

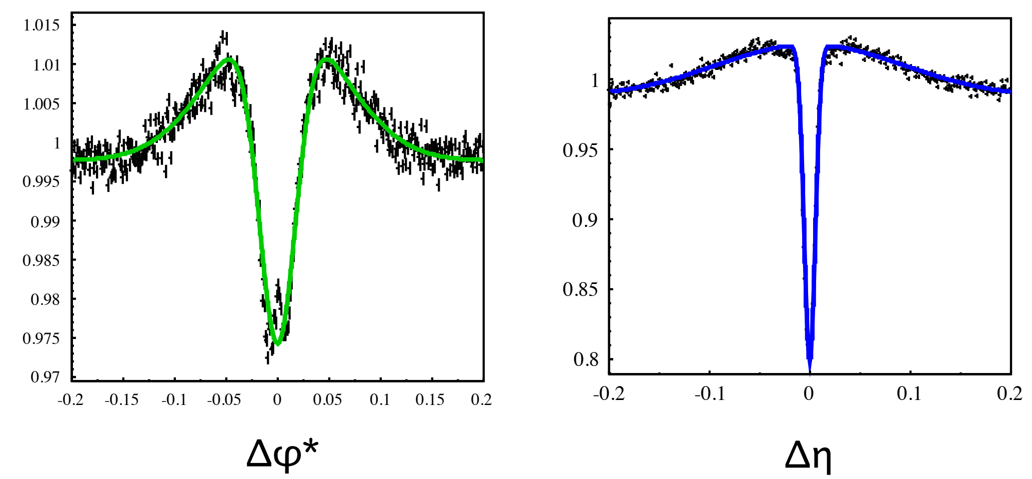
➡ event plane resolution

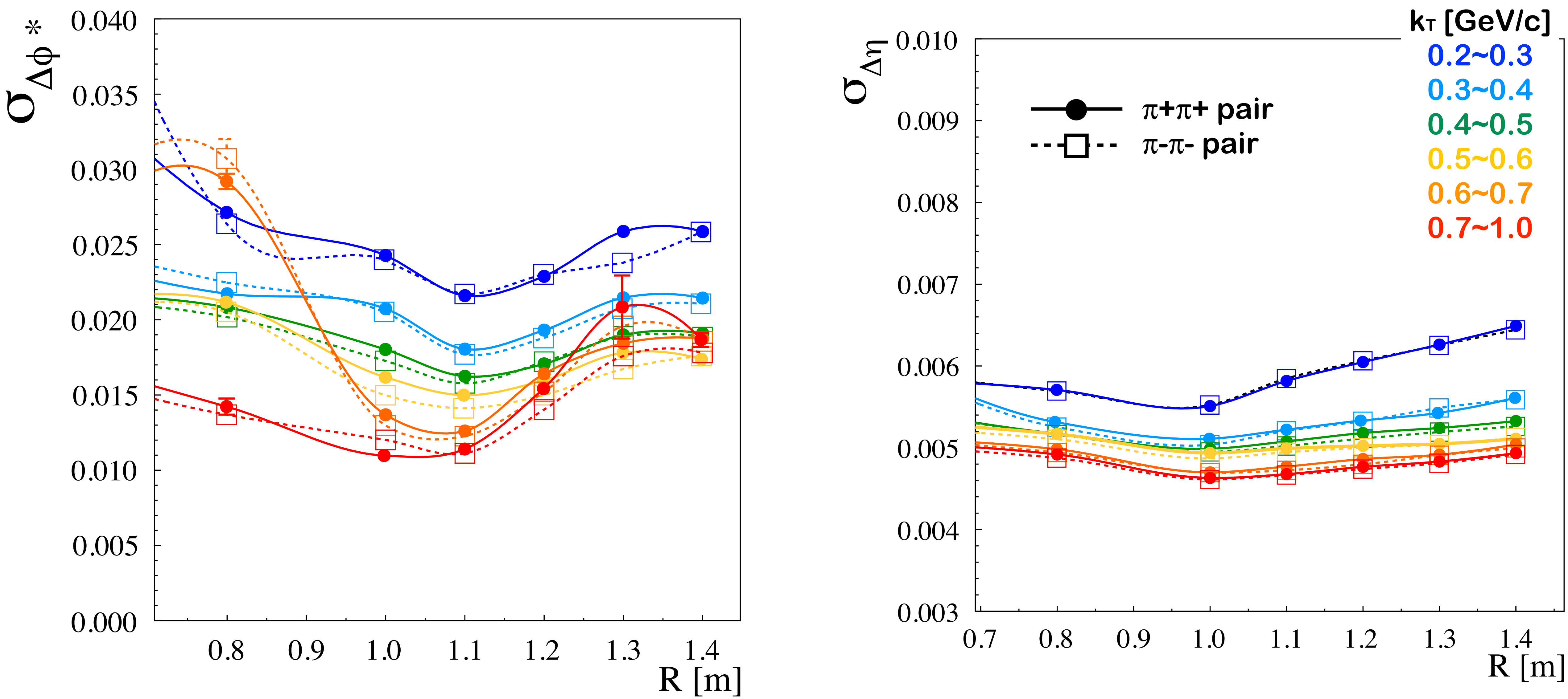


- **correction for q-distribution with EP resolution**

Angular distance in Δφ*Δη

- **Optimized Pair cut**
  - Δφ*, Δη cut @ R = 1.1 [m]
    - 3σ of gaussian cut
    - |Δφ*| < 0.066 && |Δη| < 0.018

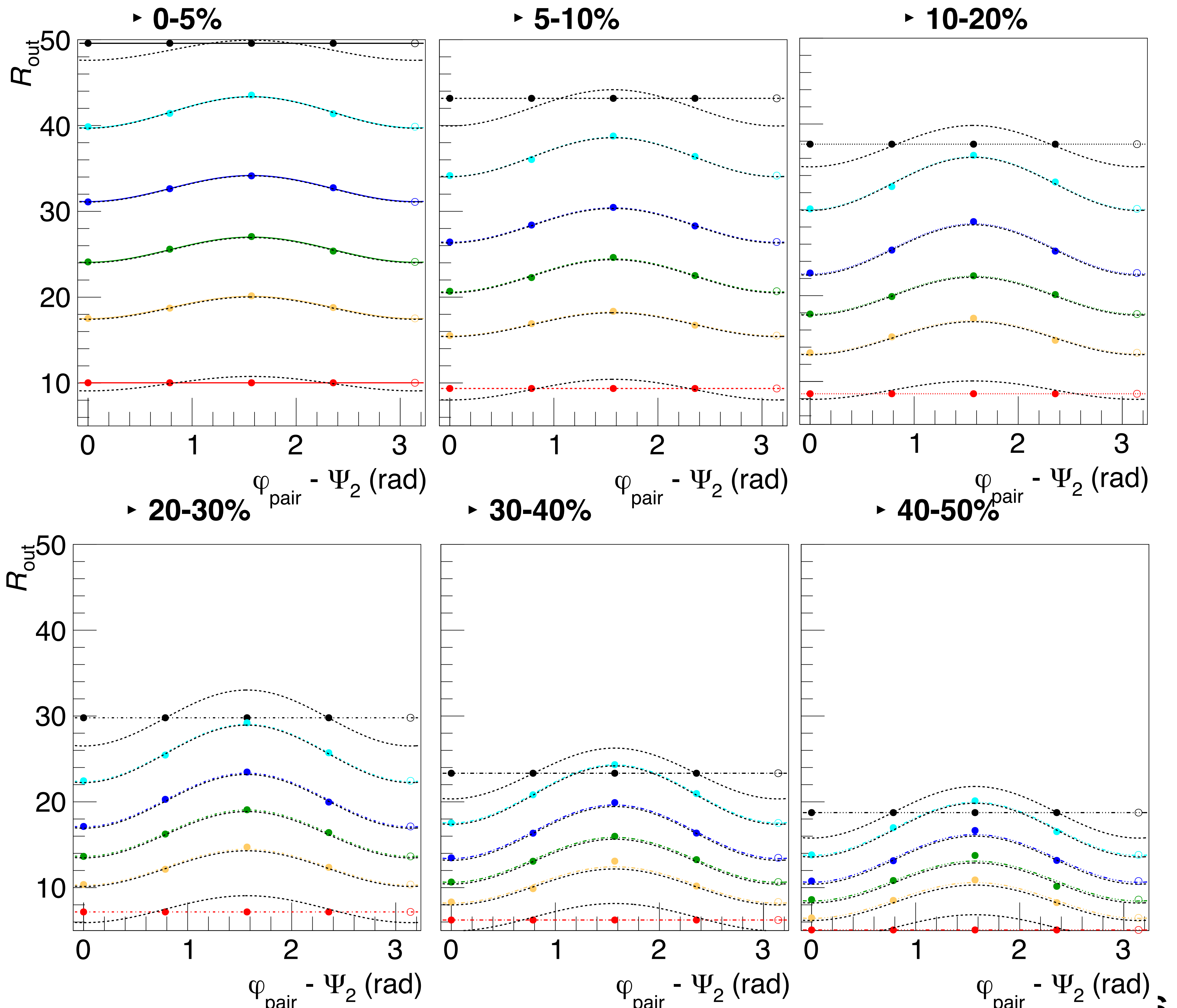




kT dependence of HBT radii w.r.t. Ψ2

★Fitting for pT spectra

- 6 centrality class
- 6 kT class
  - ● 0-0.2GeV/c
  - ● 0.2-0.3GeV/c
  - ● 0.3-0.4GeV/c
  - ● 0.4-0.5GeV/c
  - ● 0.5-0.7GeV/c
  - ● 0.7-1.5GeV/c



HBT for experimental approach

How to calculate correlation function C₂ in experiment

$$C_2 = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} = \frac{Q_{Real}}{Q_{Mix}}$$

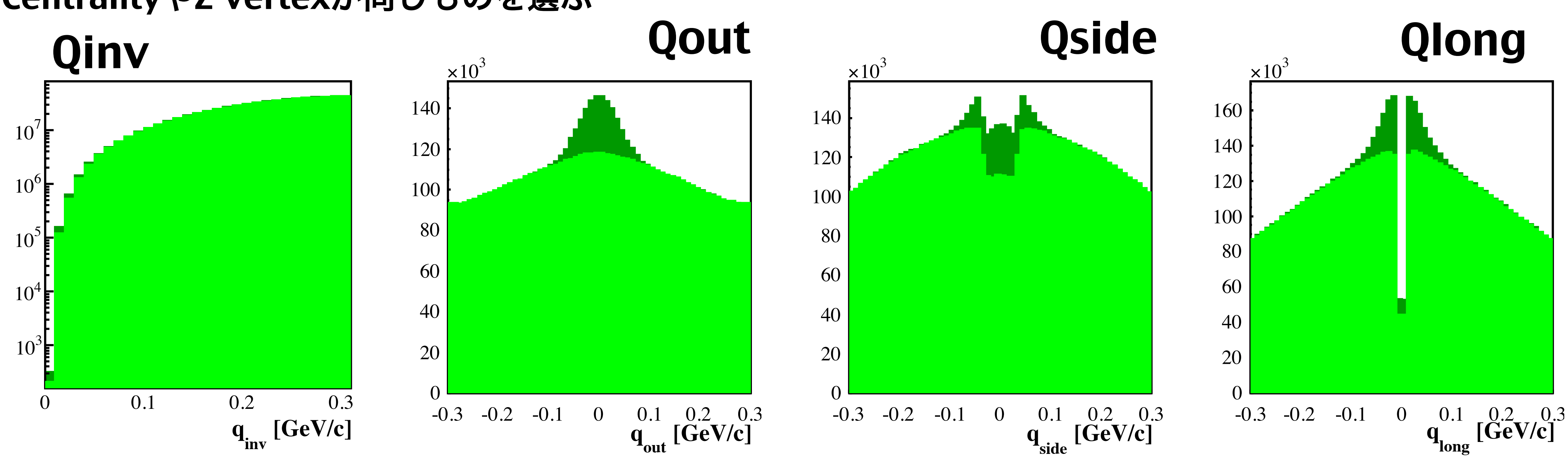
- Q_{Real} : pair in same event (HBT effect)
- Q_{Mix} : pair in different event (no HBT effect)
- C2 : Correlation function

- 補正とカット
  - Pair cut
  - Coulomb interaction

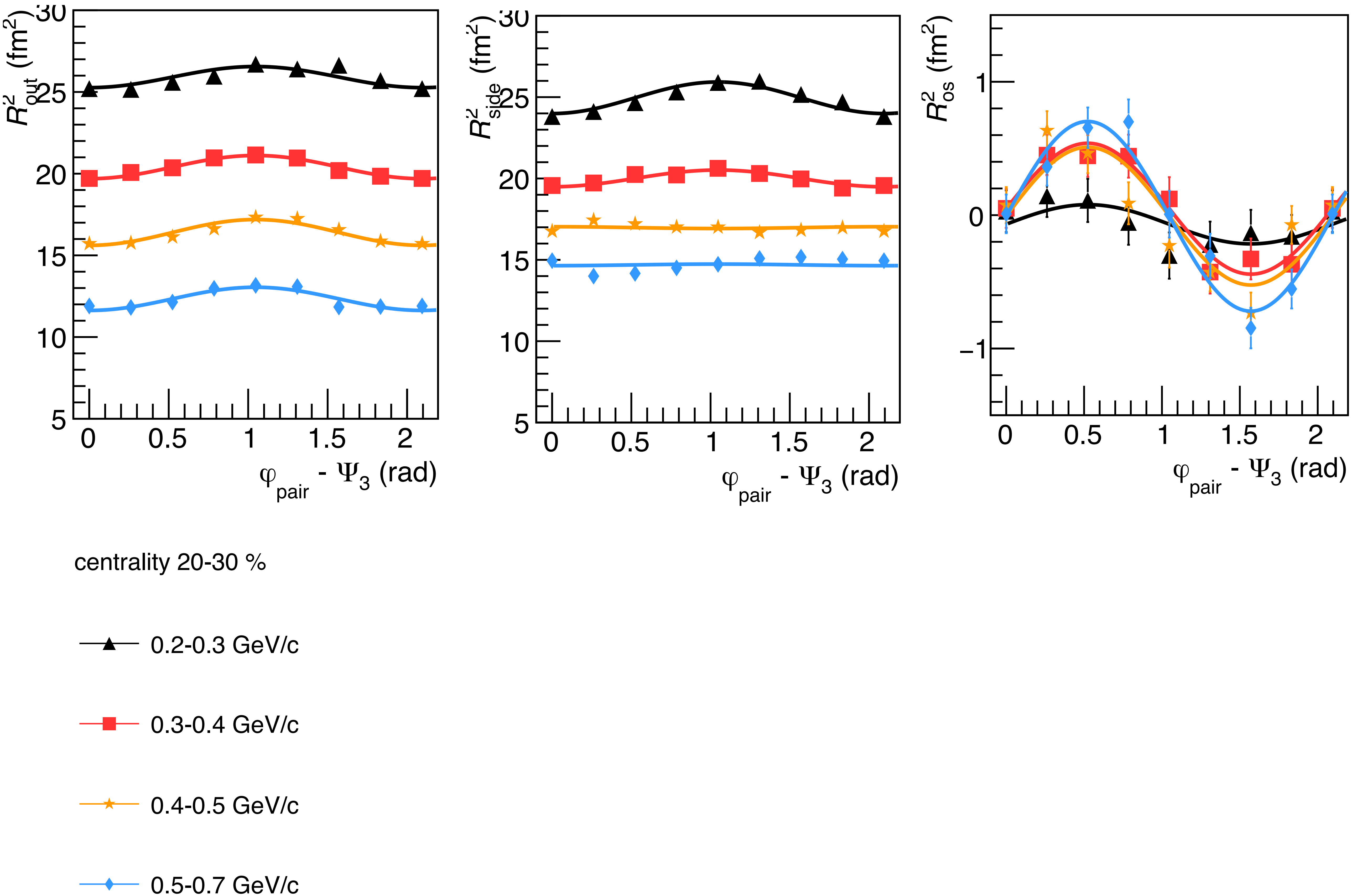
- Event Mixing
  - Real eventとMix eventを同じ特徴を持ったeventから選ぶことにより、アクセプタンスの効果、検出効率の効果をキャンセルできる

→測定したい物理的相関のみを観測することができる

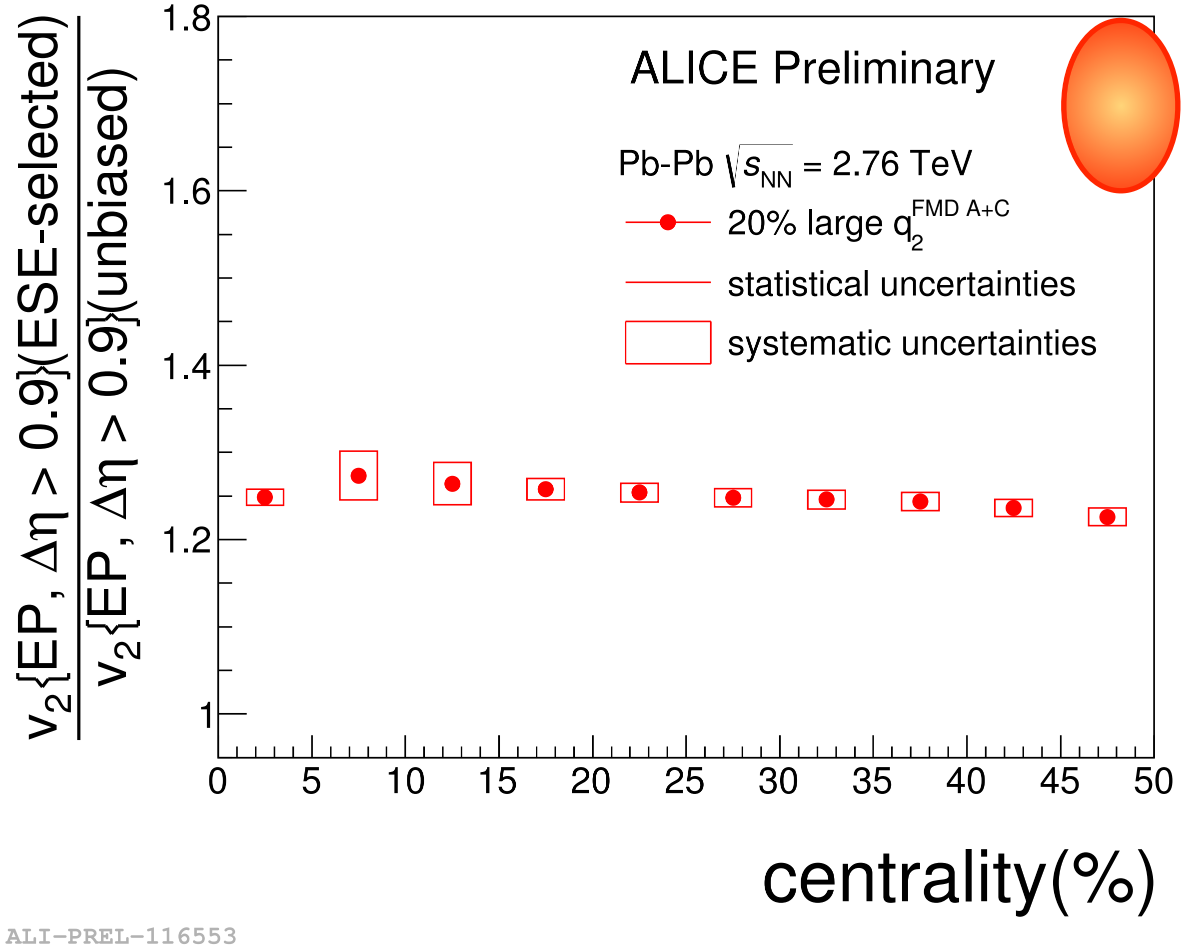
- そのためにはeventのcharacterizeが重要！
  - CentralityやZ-vertexが同じものを選ぶ

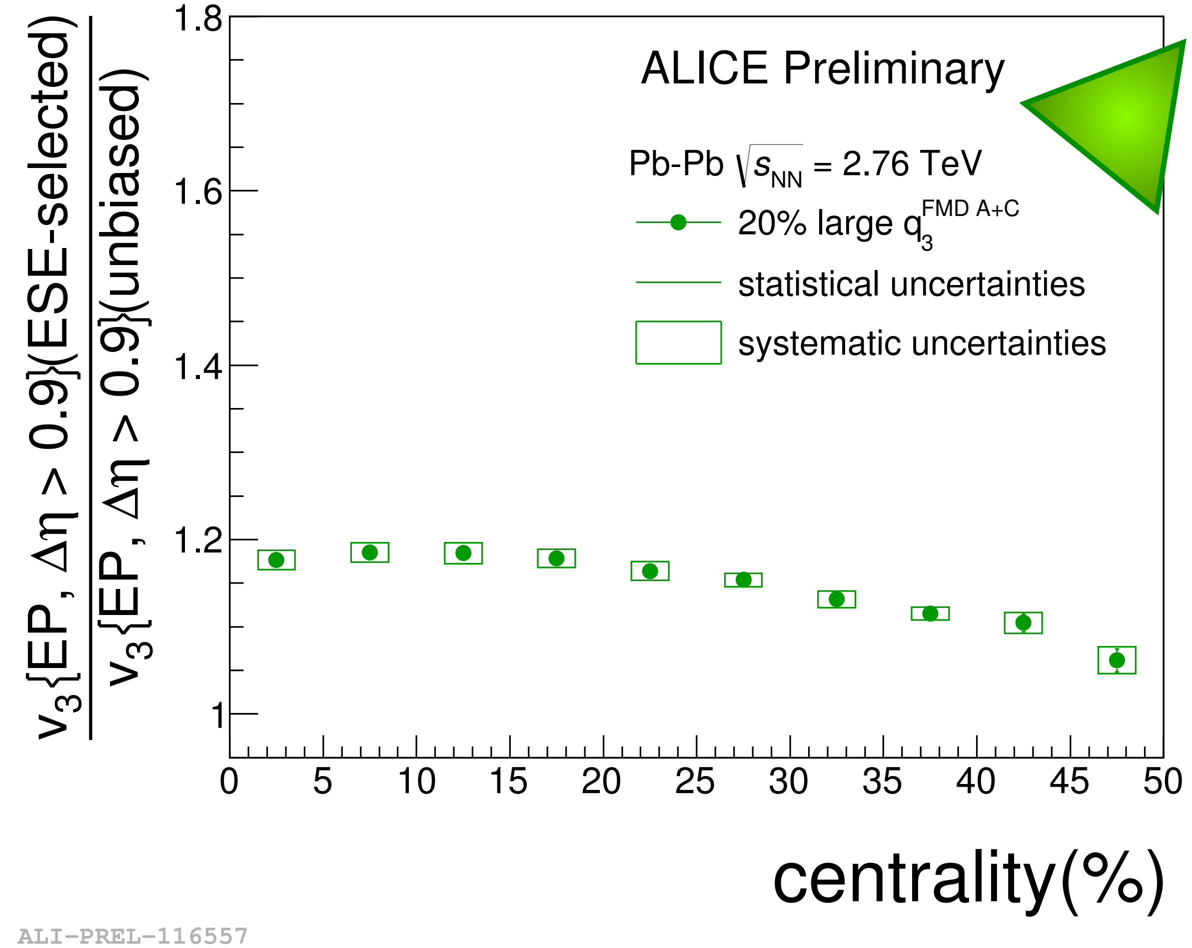


k_T dependence of Rout, Rside, Ros



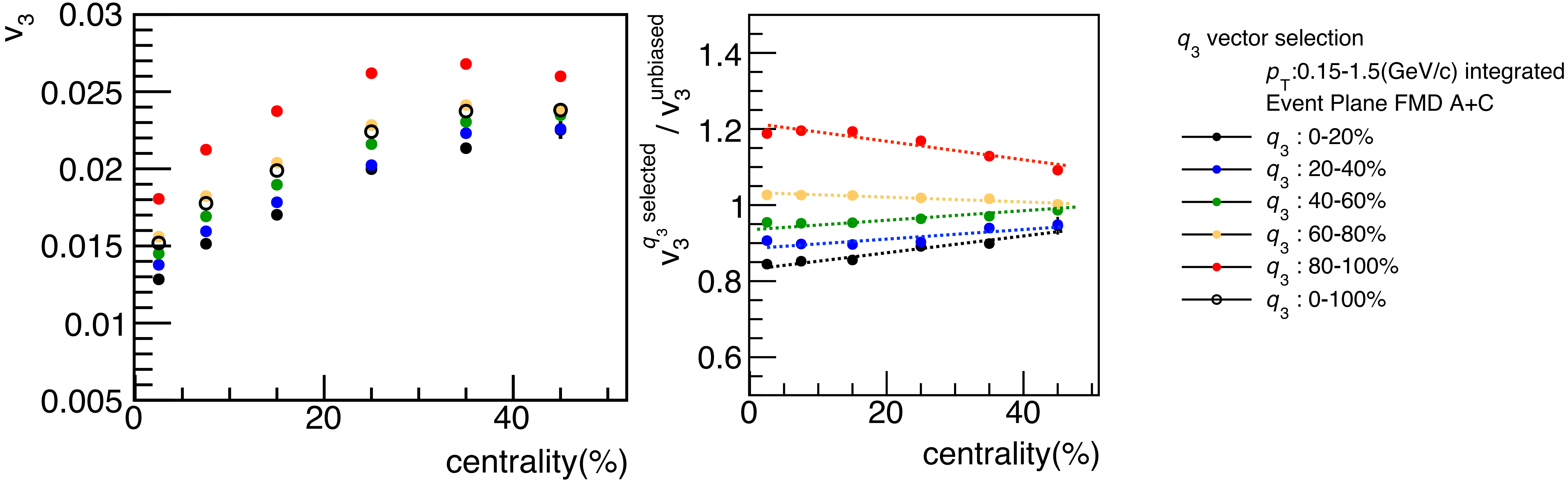
Charged hadron v_2 and v_3 ratio with ESE cut





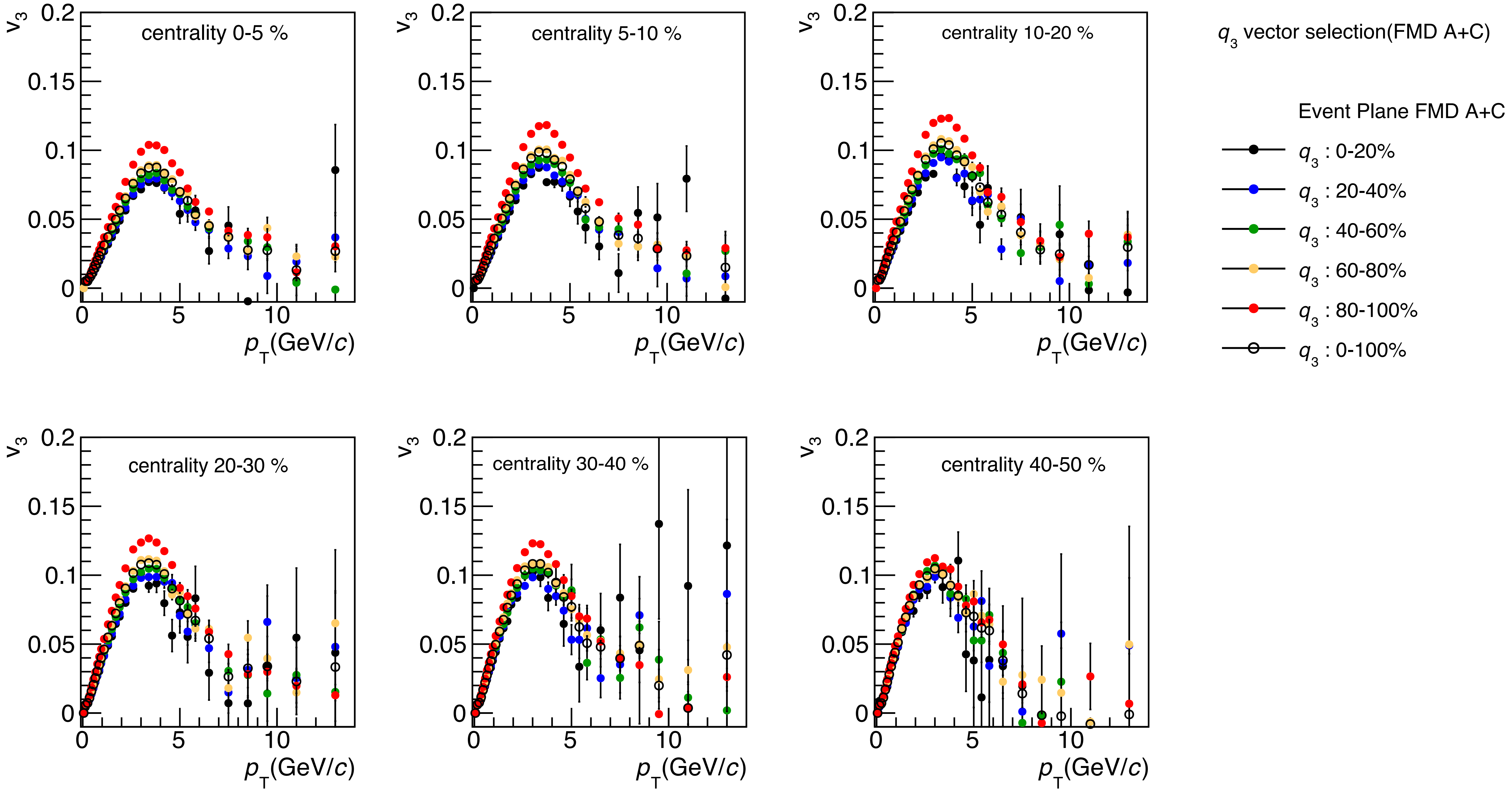
- **v_n is measured with Event plane method**
- **Top 20% largest q_2, q_3 vector selection is applied**
- **v_2 is enhanced by 25% with large q_2 selection**
- **v_3 grows by 15% with large q_3 selection**

v_3 (centrality dependence) with 20% step q_3 selection



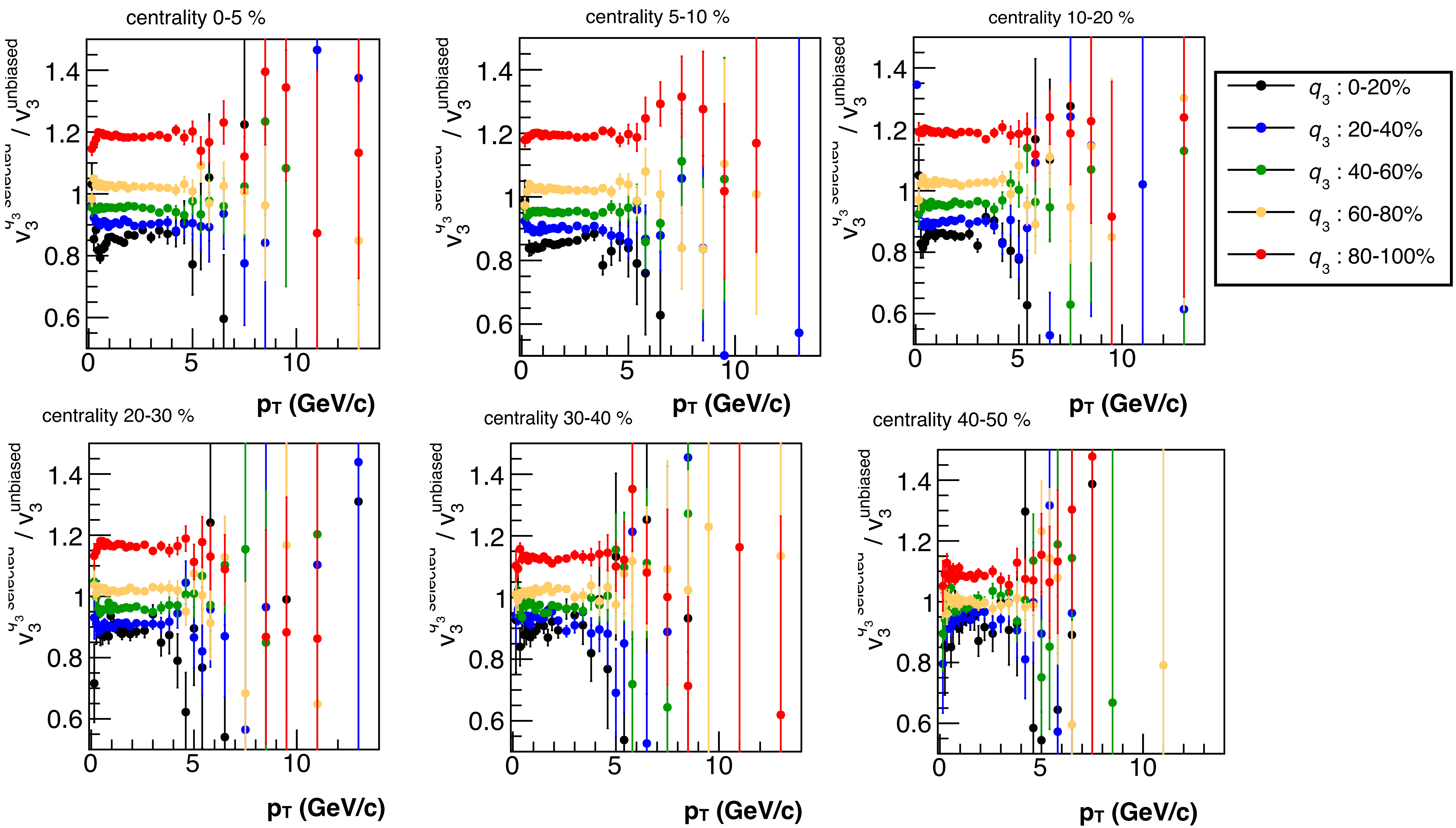
- **20% step q_3 (v3) event selection**
  - ***v_3 explicitly changes with q_3 selection (enhancement depends on q3 selectivity)***
    - ***q3 80-100% -> +10 ~ +20%***
    - ***q3 60-80% -> +3%***
    - ***q3 40-60% -> -5%***
    - ***q3 20-40% -> -10%***
    - ***q3 0-20% -> -15 ~ -5%***
  - **v3 modification is largest in central and becomes smaller from central to peripheral**

v_3 (p_T dependence) with 20% step q_3 selection



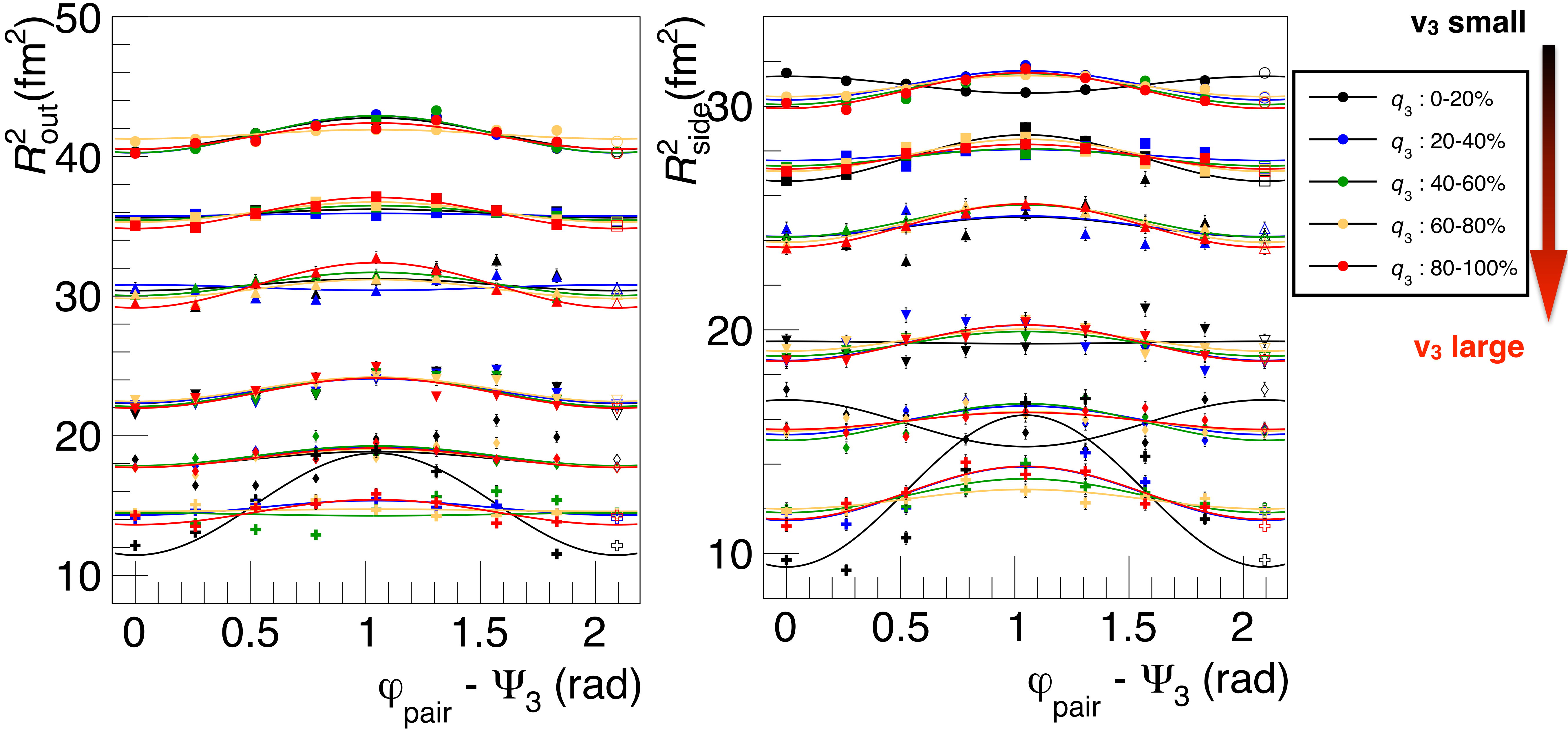
- **20% step q_3 (v_3) event selection**
    - ***v_3 slightly changes with q_3 selection in p_T 0.15-14 (GeV/c)***
    - ***Modification is largest in central collisions***

Ratio of v_3 with q_3 selection / v_3 unbiased



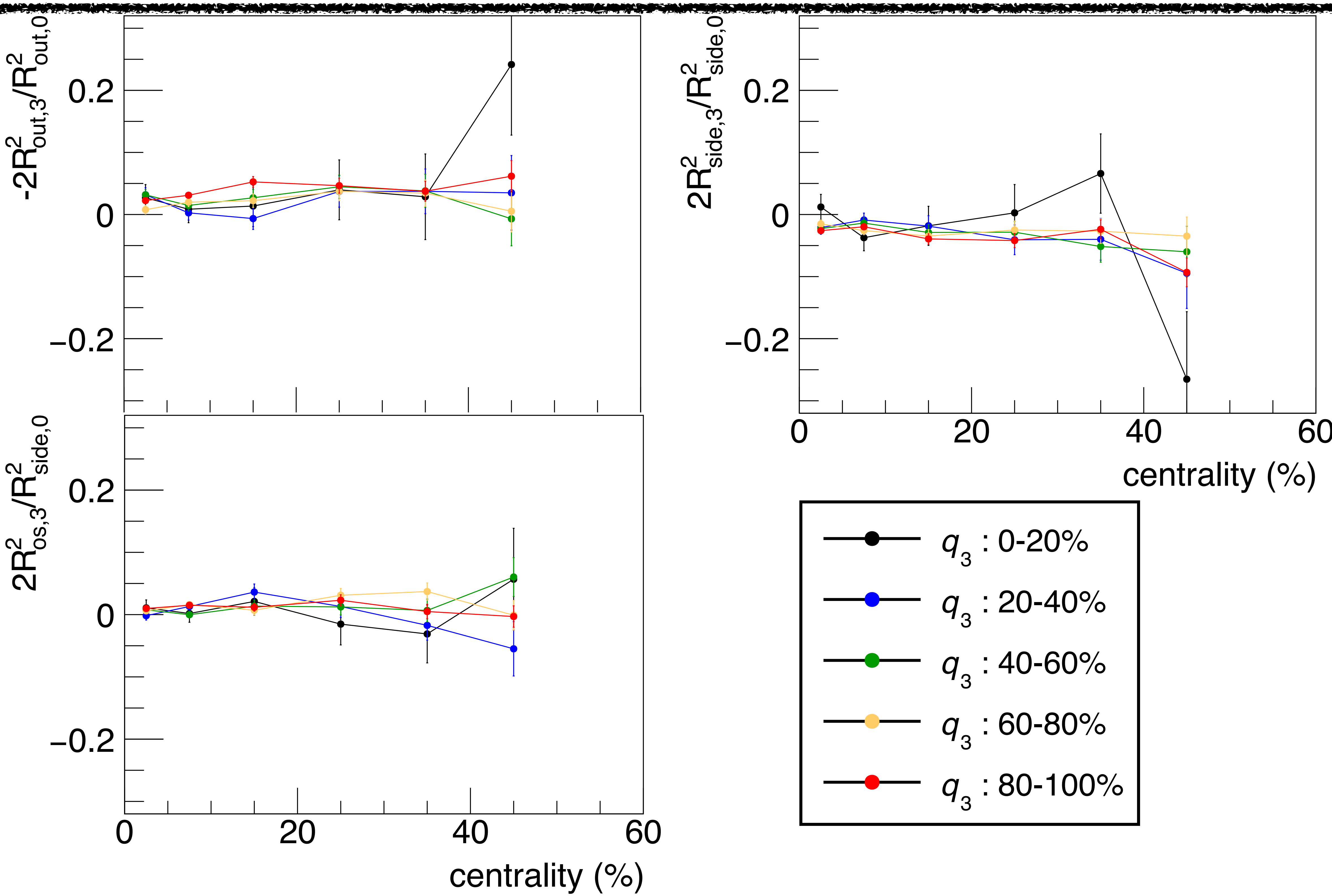
- **No explicit p_T dependence can be found for the ratio of *v_3 (p_T dependence)***
- ***The slope which can be found in v2 was not found in v3***

R_{out} R_{side} w.r.t. Ψ_3 with ESE(q_3 20% step)



- Enhancement(suppression) w/ q3 cut is much smaller than that w/ q2
  - *Weak correlation between v3 and e3 final??*
- Fit is not good in centrality 20-50% ?
- For smallest q2 selection(0-20%)
  - *R_{side} has negative sign oscillation (similar to HBT w.r.t. Ψ2)*

Relative amplitude of HBT radii (3rd harmonics)



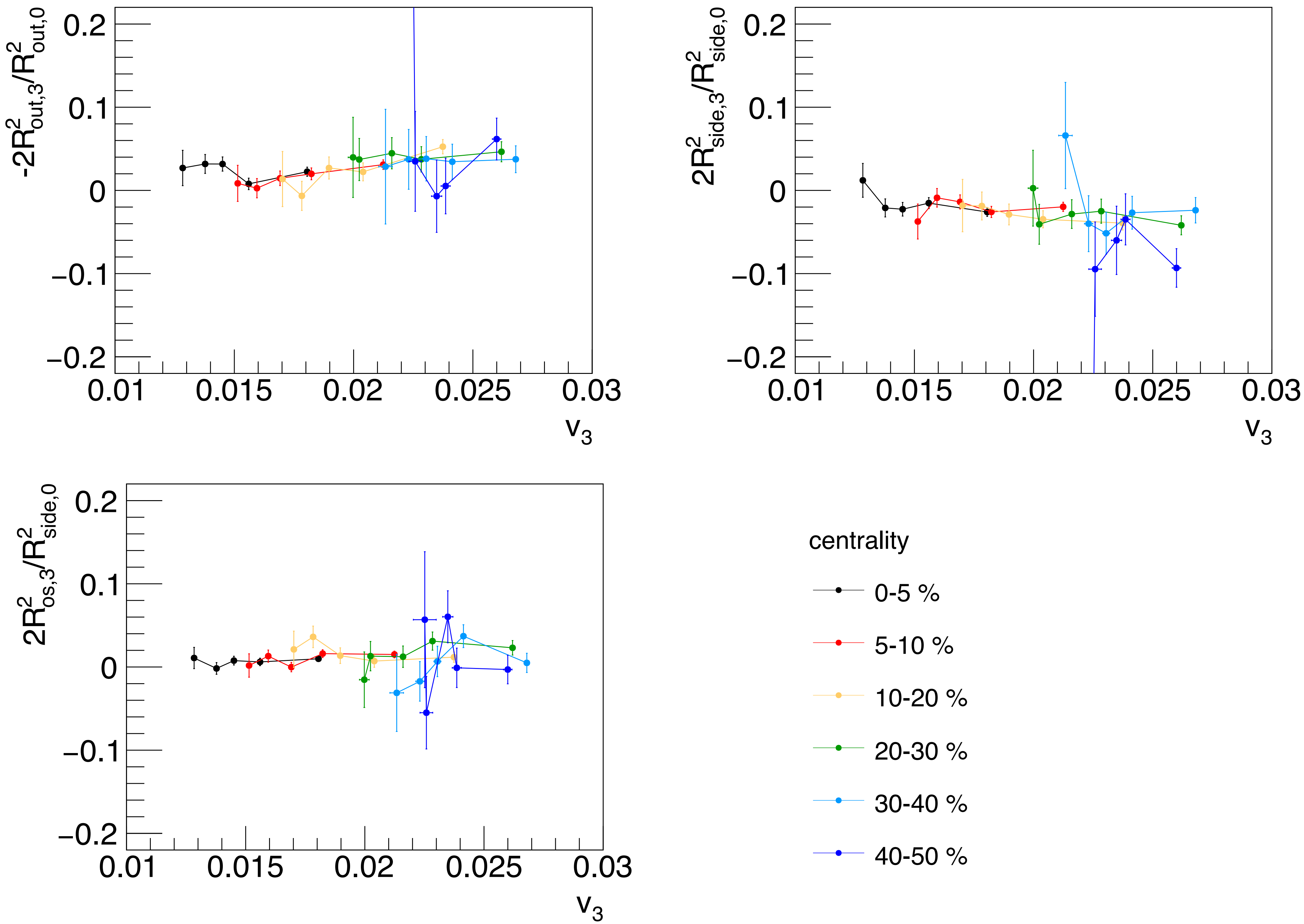
✦**In centrality 0-5, 20-40% collisions, No explicit modification on R_{out} can be found**

✓**Though the ratio of v_3 (q_3 selected / unbiased) is largest in centrality 0-5%**

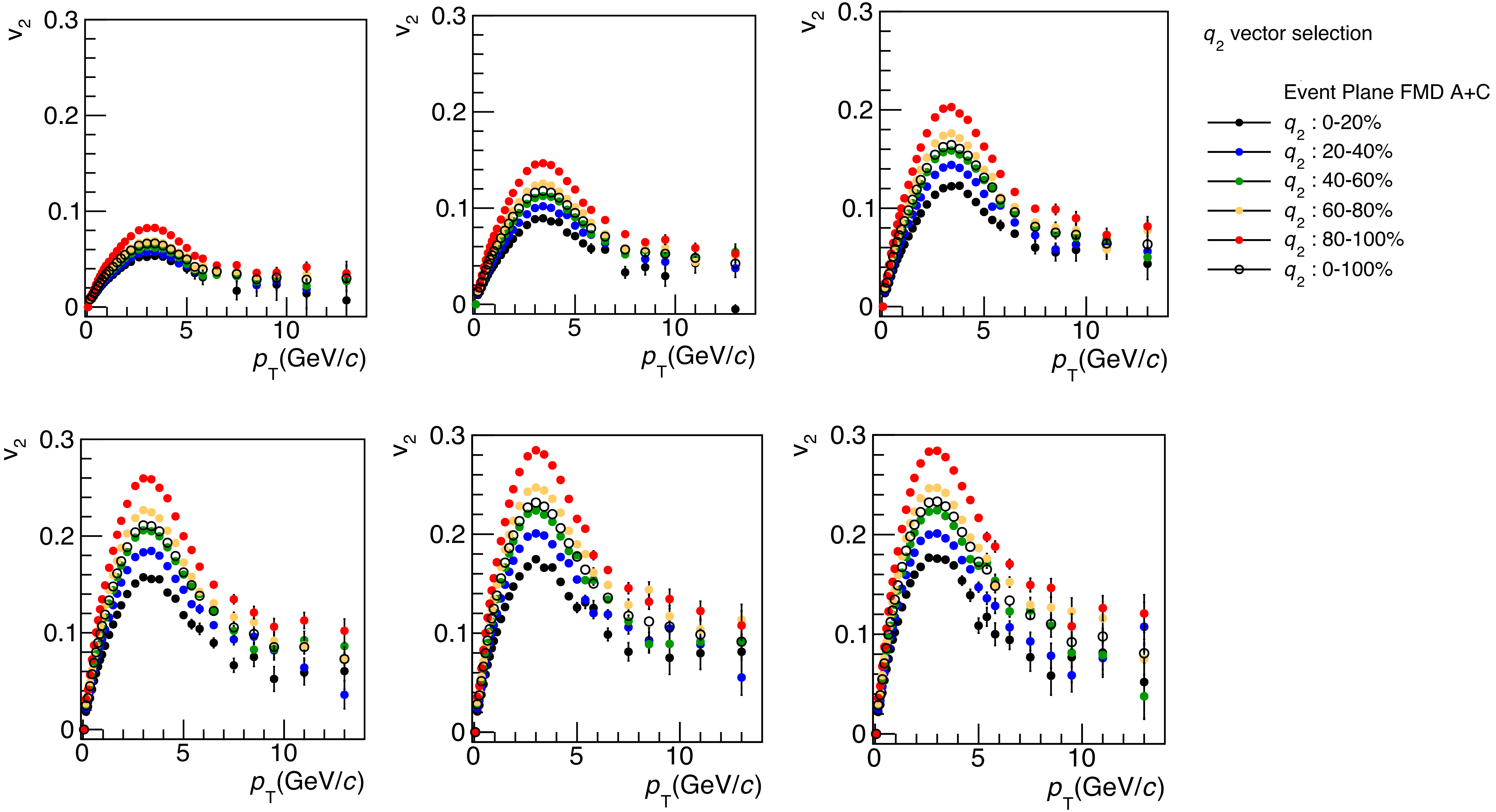
✦**R_{side} slightly changed with q3 selection, q3 0-20% could have positive value**

v_3 v.s. Relative amplitude of HBT radii w.r.t. Ψ_3

- ***R*$_{out}$ and *R*$_{side}$ ratio**
  - **Modification of q3 in 5-20% seems to be scaled with v3**

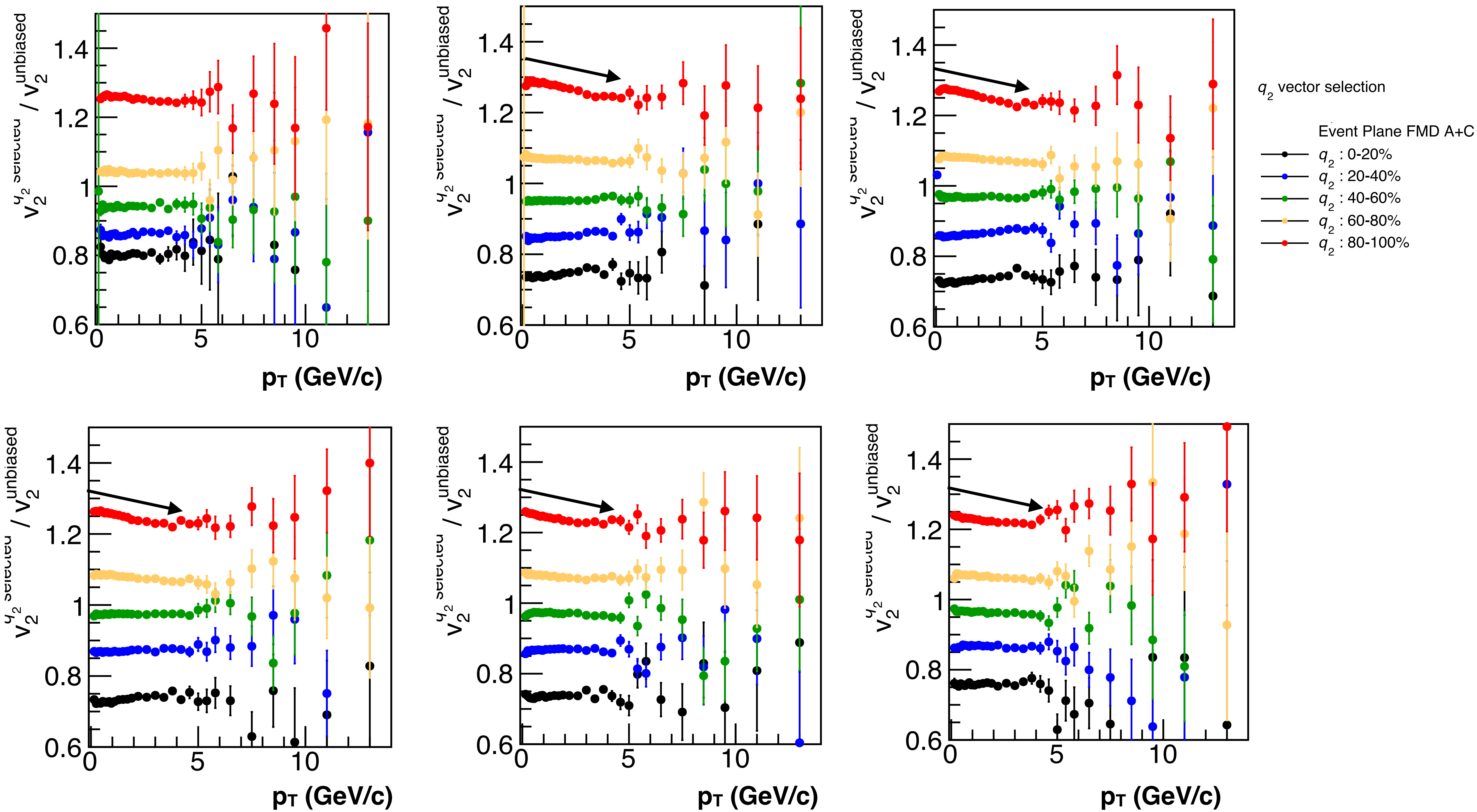


v_2 (p_T dependence) for each 20% q_2 selection



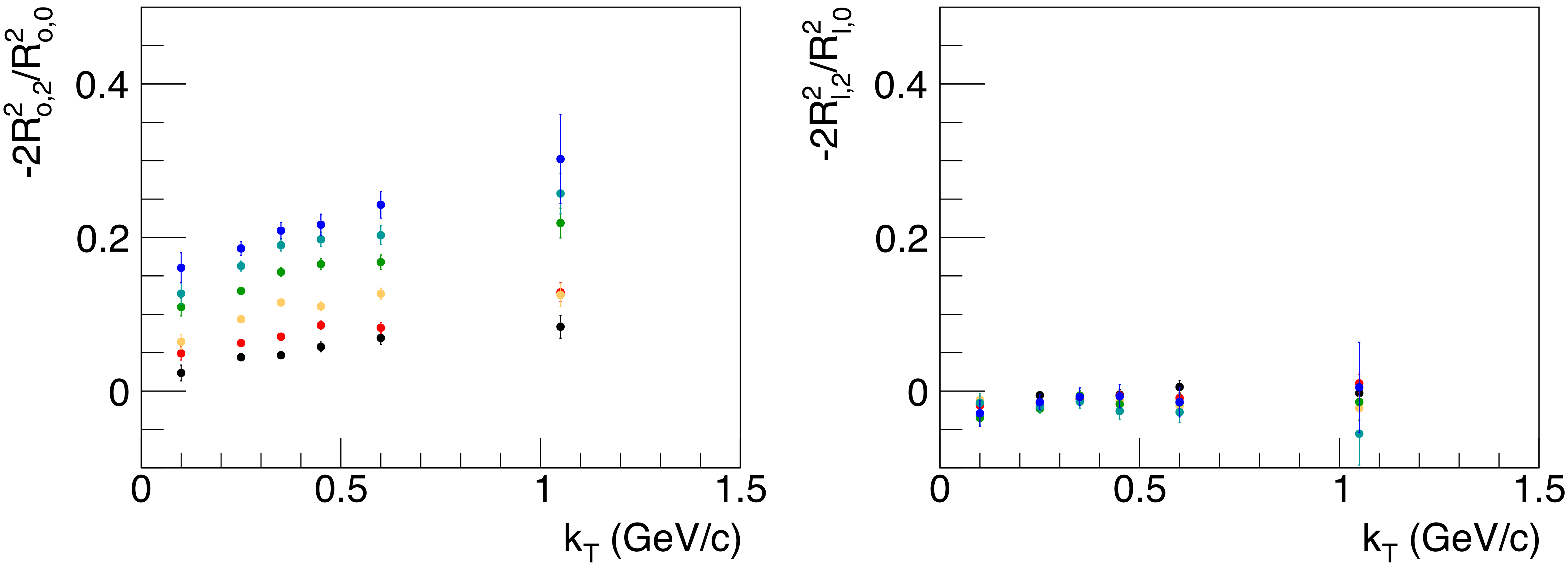
- **20% step q_2 (v_2) event selection**
  - **In pT 0.15-14 GeV/c, *v_2 explicitly changes with q_2 selection***

Ratio of v_2 with q_2 selection / v_2 unbiased



- **No explicit p_T dependence can be found for the ratio of *v_2 (p_T dependence)***
  - ***But small p_T dependence in q_2 80-100% cut could be found ??***

Relative amplitude of HBT radii



- **6 centrality class**
  - **0 - 5 %**
  - **5 - 10%**
  - **10-20%**
  - **20-30%**
  - **30-40%**
  - **40-50%**

Blast wave fit for π, K, p Spectra

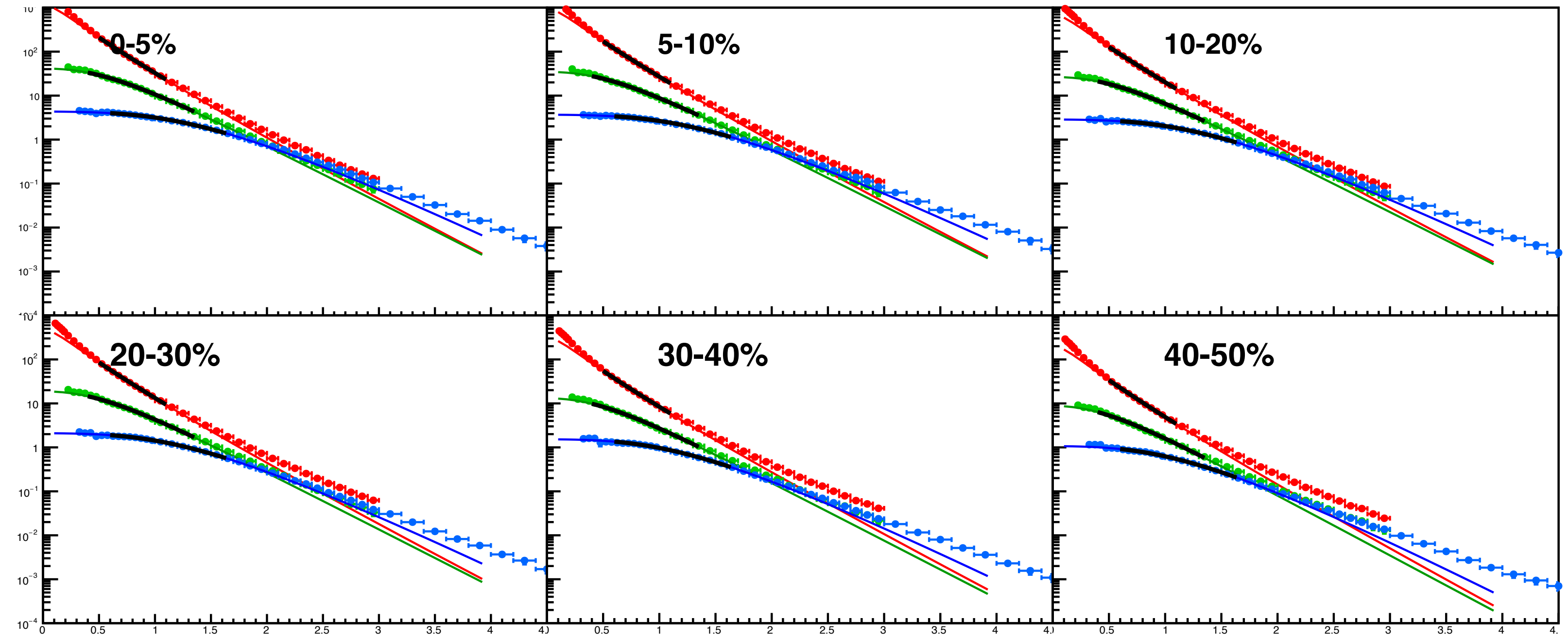
★Fitting for pT spectra

- positive and negative particle
- π, K, p
- 6 particles pT spectra (simultaneous)
  - pion
  - Kaon
  - proton

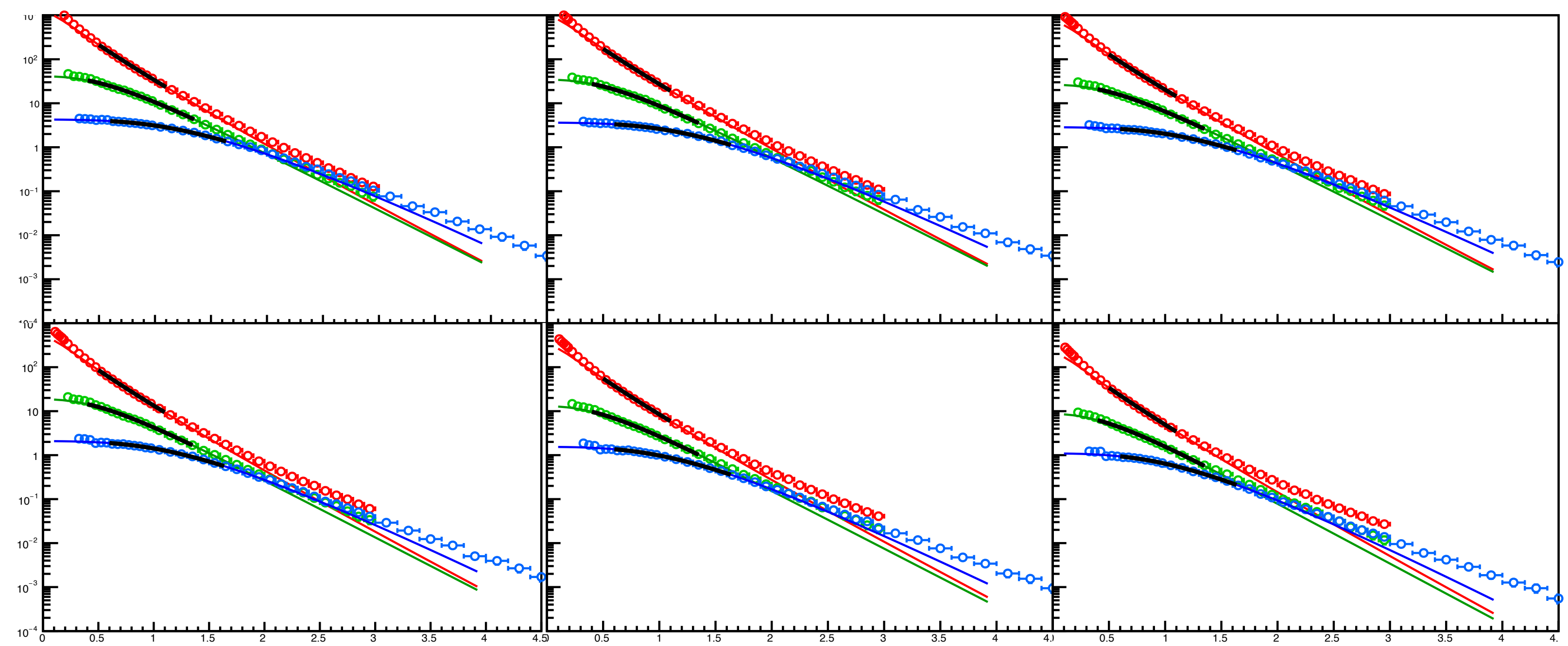
★ 2 Parameters

- **Tf** : Kinetic freeze out temperature
- **ρ0** : Transverse rapidity
- **ρ2** : 2nd order modulation
- **τ0** : Freeze out time
- **Δτ** : Emission duration

★Positive



★Negative



★ Fit function for spectra

$$\frac{dN}{p_T dp_T} = 2(2\pi)^{3/2}\,\tau_0 \Delta\tau m_T \int_0^{2\pi} d\phi_s \int_0^{\infty} r dr\, \Omega(r,\phi_s)\, I_0(\alpha) K_1(\beta)$$

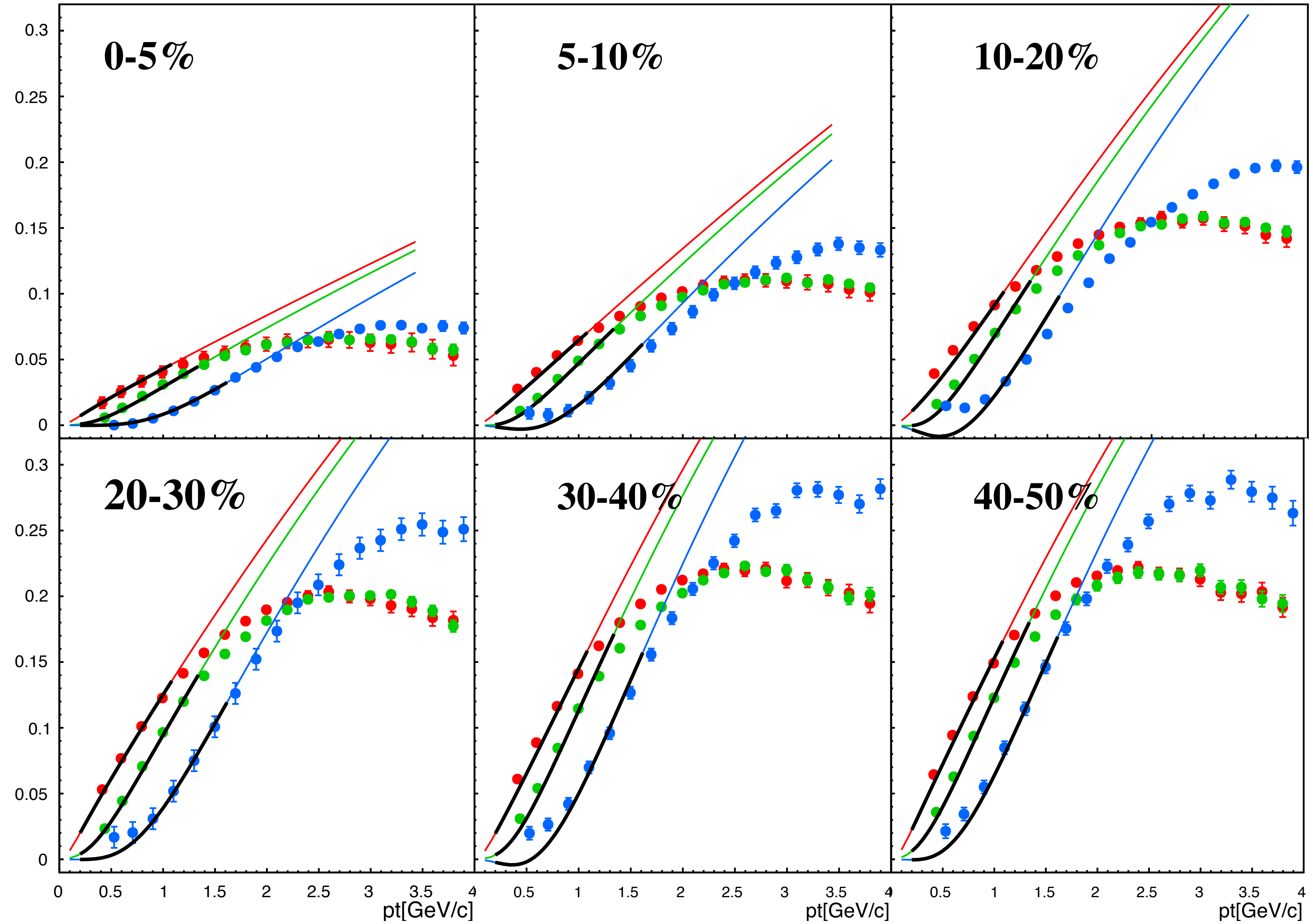
Blast wave fit for PID v_2

★ **Fitting for pT dependence of π, K, p v2**

- pion
- Kaon
- proton

★**4 Parameters**

- **Tf** : Kinetic freeze out temperature
- **ρ0** : Transverse rapidity
- **ρ2** : 2nd order modulation
- **Rx, Ry** : Transverse size



★**Fit function for v2**

$$v_2(p_T, m) = \frac{\int_0^{2\pi} d\phi_p \int_0^{\infty} rdr\, \Omega(r,\phi_s) K_1(\beta)\cos(2\phi_b) I_2(\alpha)}{\int_0^{2\pi} d\phi_s \int_0^{\infty} rdr\, \Omega(r,\phi_s)\, I_0(\alpha) K_1(\beta)}.$$

Blast wave fit for HBT radii

HBT radii relative to Ψ_2

★ 7 Parameters

- **Tf** : Kinetic freeze out temperature
- **ρ0** : Transverse rapidity
- **ρ2** : 2nd order modulation in transverse flow
- **Rx, Ry** : Transverse size of the source
- **τ0** : Freeze out time
- **Δτ** : Emission duration

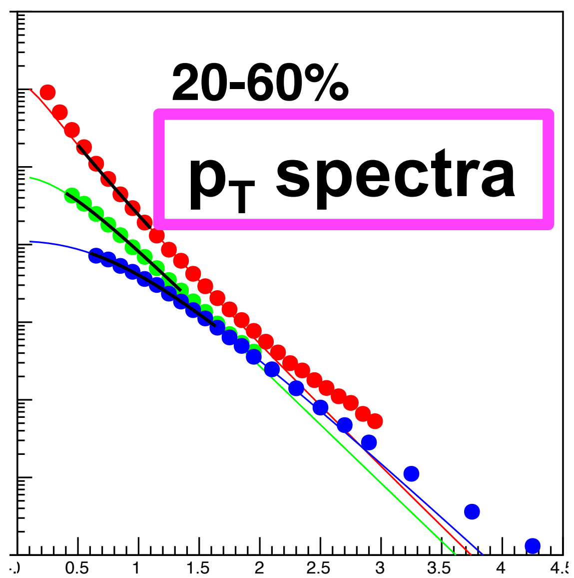
$$\langle f(x)\rangle = \frac{\int d^4x f(x) S(x,K)}{\int d^4x S(x,K)},$$
$$\tilde{x}^\mu = x^\mu - \langle x^\mu \rangle,$$

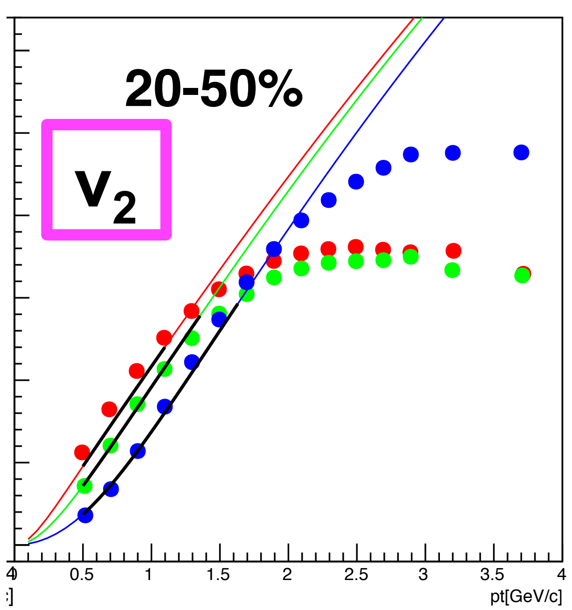
★ Fit function for HBT

$$\begin{aligned}
R_s^2 &= \frac{1}{2}(\langle\tilde{x}^2\rangle + \langle\tilde{y}^2\rangle) - \frac{1}{2}(\langle\tilde{x}^2\rangle - \langle\tilde{y}^2\rangle)\cos(2\phi_p) - \langle\tilde{x}\tilde{y}\rangle\sin(2\phi_p),\\
R_o^2 &= \frac{1}{2}(\langle\tilde{x}^2\rangle + \langle\tilde{y}^2\rangle) + \frac{1}{2}(\langle\tilde{x}^2\rangle - \langle\tilde{y}^2\rangle)\cos(2\phi_p) + \langle\tilde{x}\tilde{y}\rangle\sin(2\phi_p),\\
&\quad -2\beta_T(\langle\tilde{t}\tilde{x}\rangle\cos\phi_p + \langle\tilde{t}\tilde{y}\rangle\sin\phi_p) + \beta_T^2\langle\tilde{t}^2\rangle,\\
R_{os}^2 &= \langle\tilde{x}\tilde{y}\rangle\cos(2\phi_p) - \frac{1}{2}(\langle\tilde{x}^2\rangle - \langle\tilde{y}^2\rangle)\sin(2\phi_p) + \beta_T(\langle\tilde{t}\tilde{x}\rangle\sin\phi_p - \langle\tilde{t}\tilde{y}\rangle\cos\phi_p),\\
R_l^2 &= \langle\tilde{z}^2\rangle - 2\beta_l\langle\tilde{t}\tilde{z}\rangle + \beta_l^2\langle\tilde{t}^2\rangle,\\
&= \langle\tilde{z}^2\rangle,
\end{aligned}$$

Fit by Blast wave model

- **Transverse momentum distribution (p_T spectra) and v_2 are used to reduce parameter.**



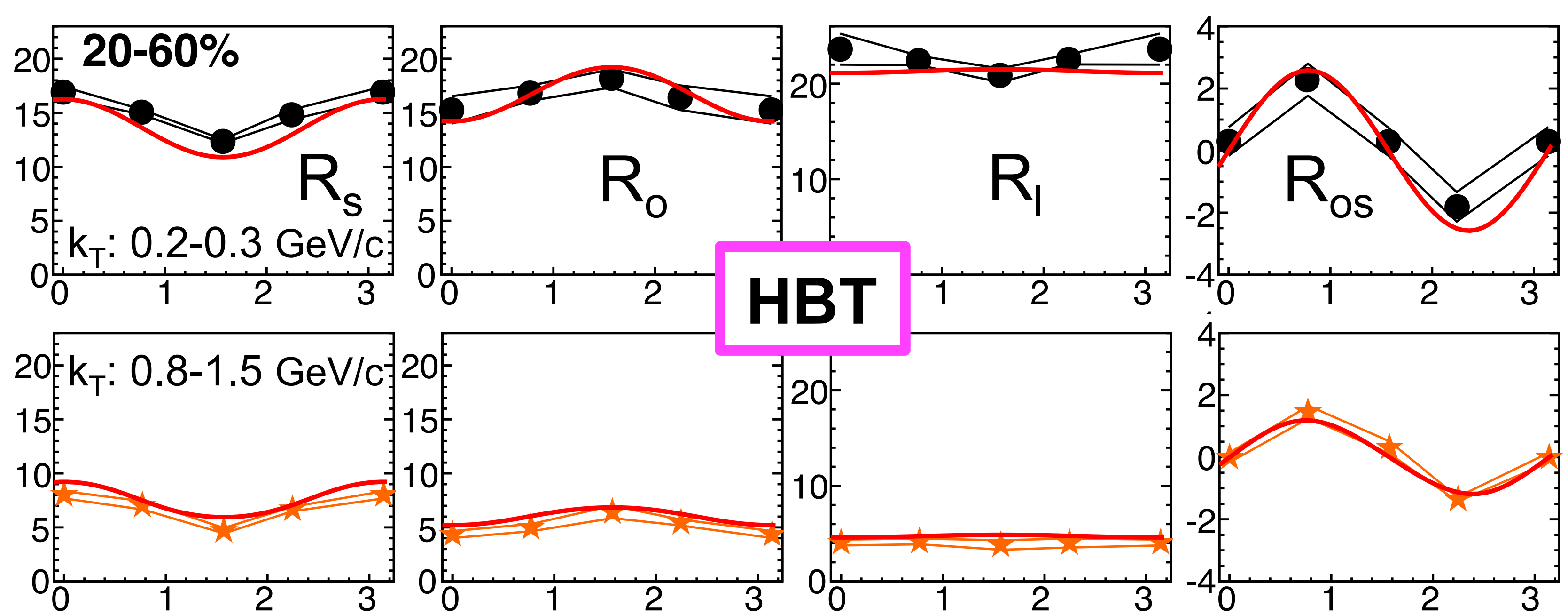


1. Fit p_T spectra to obtain T_f and ρ_0

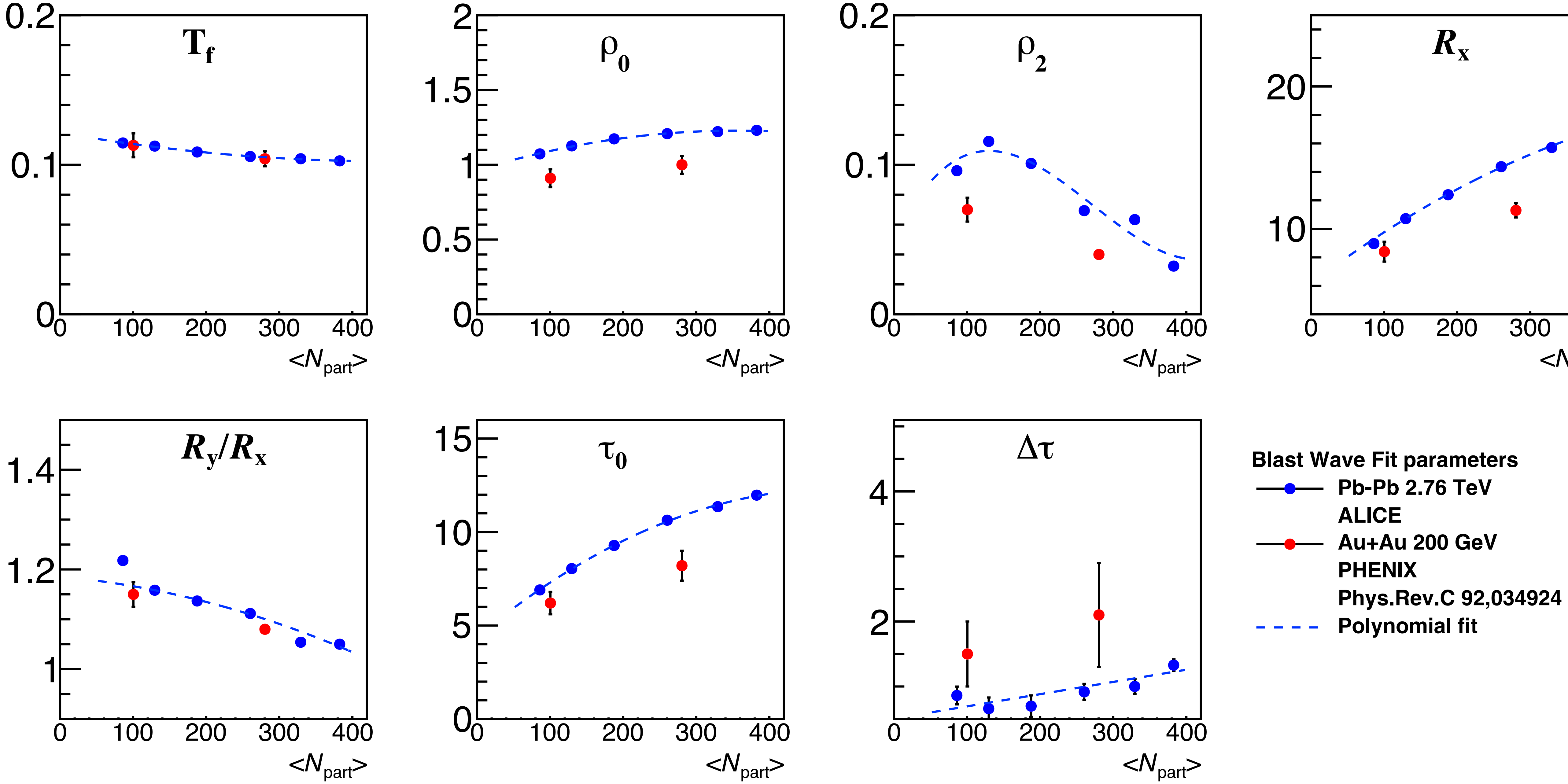
- spectra data from PHENIX (PRC69,034909(2004))

2. Fit v_2 and HBT radii for all k_T simultaneously

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

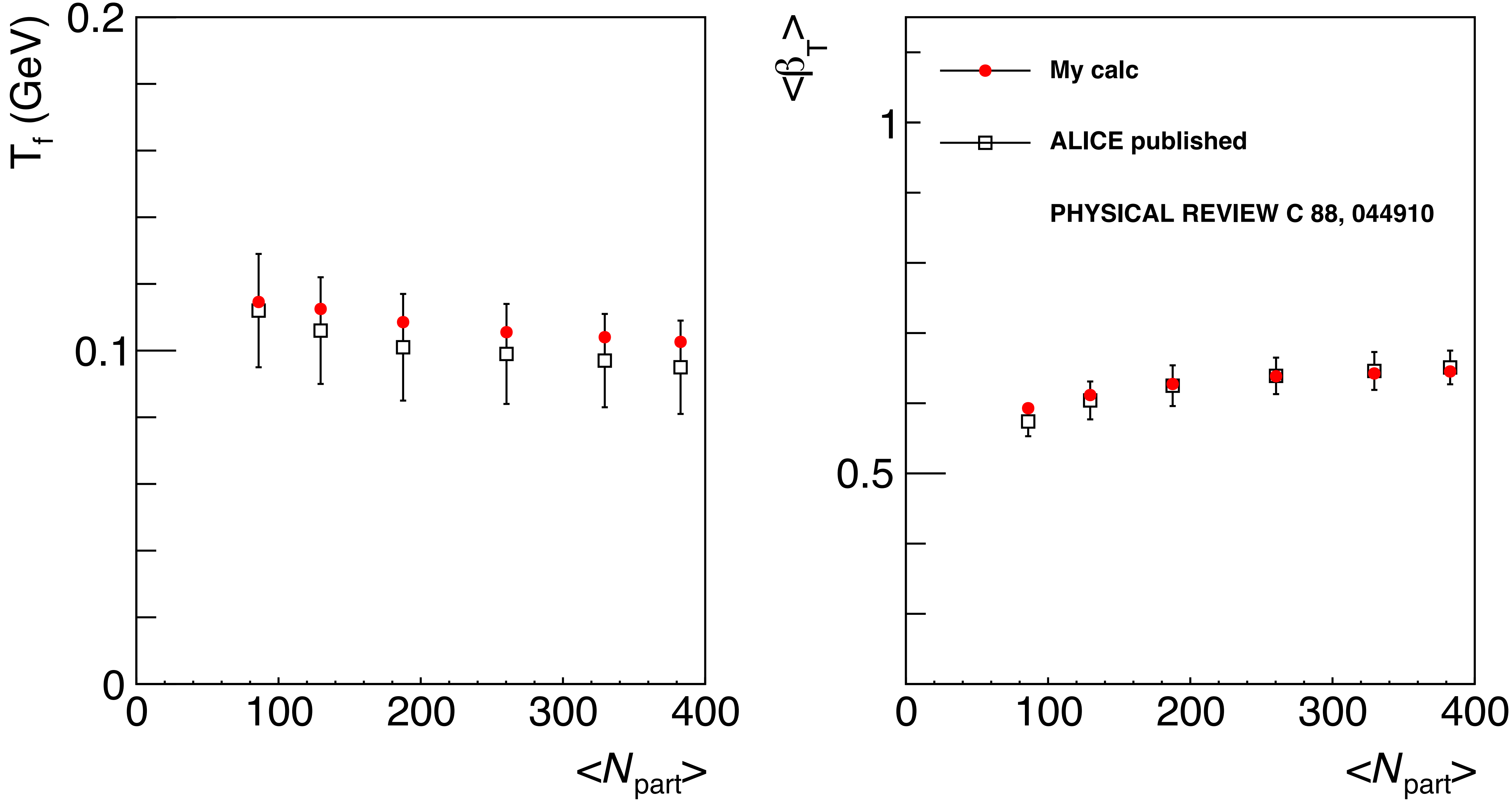


Blast Wave parameters (comparison with PHENIX)



- ✦ Tf, ρ0, Rx, Ry/Rx, τ0, Δτ are fitted with Polynomial2
- ✦ ρ2 is fitted with Polynomial3

Blast Wave parameters (comparison with ALICE published)

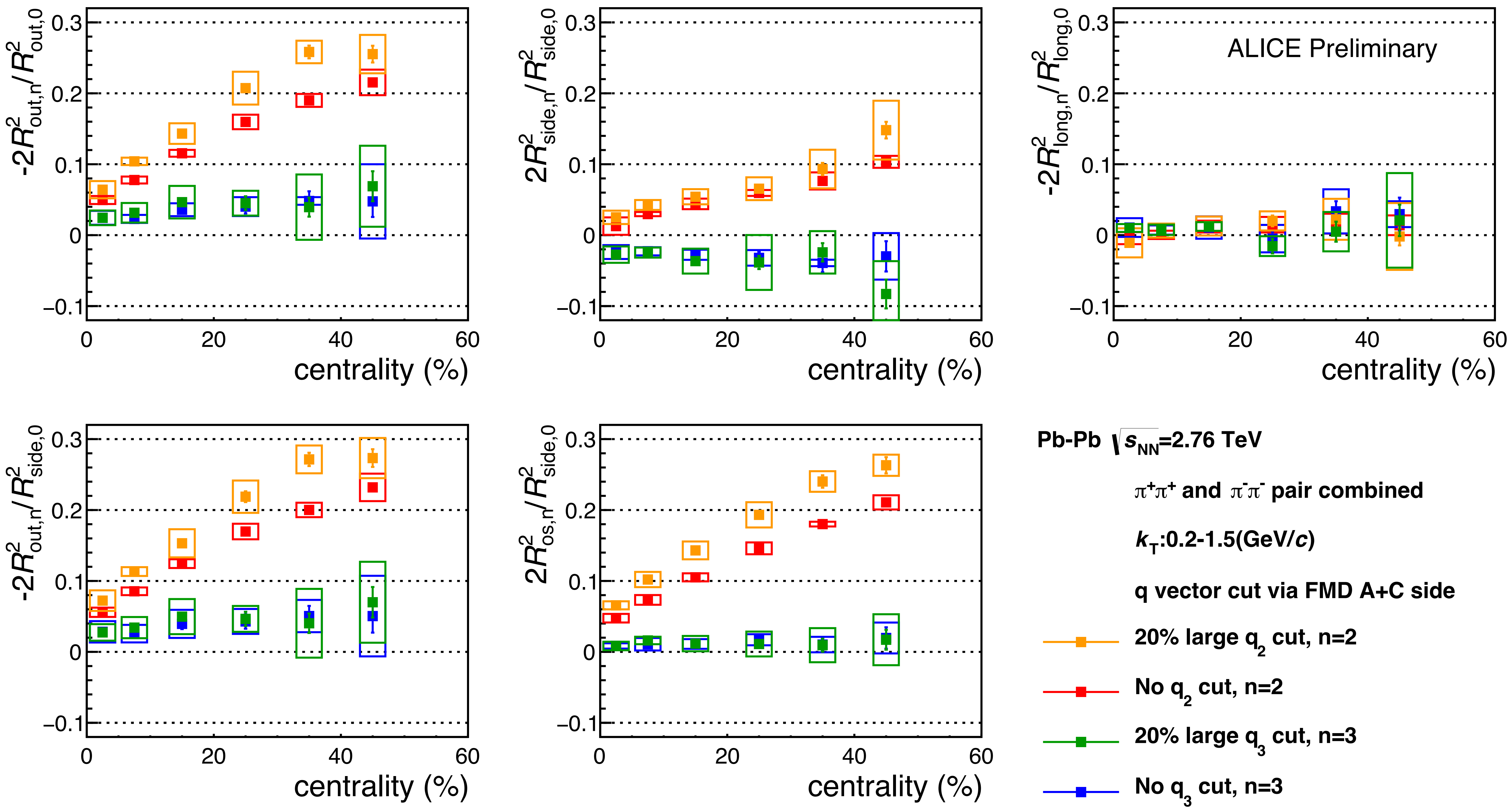


✦ **Fully consistent within the systematic uncertainties**

$$\langle \beta_T \rangle = \int_0^{2\pi} d\phi \int_0^1 dr \tanh\left(\left(\rho_0 + \rho_2 \cos\left(2\phi\right)\right) r^n\right) r \left(1 + 2s_2 \cos\left(2\phi\right)\right)$$

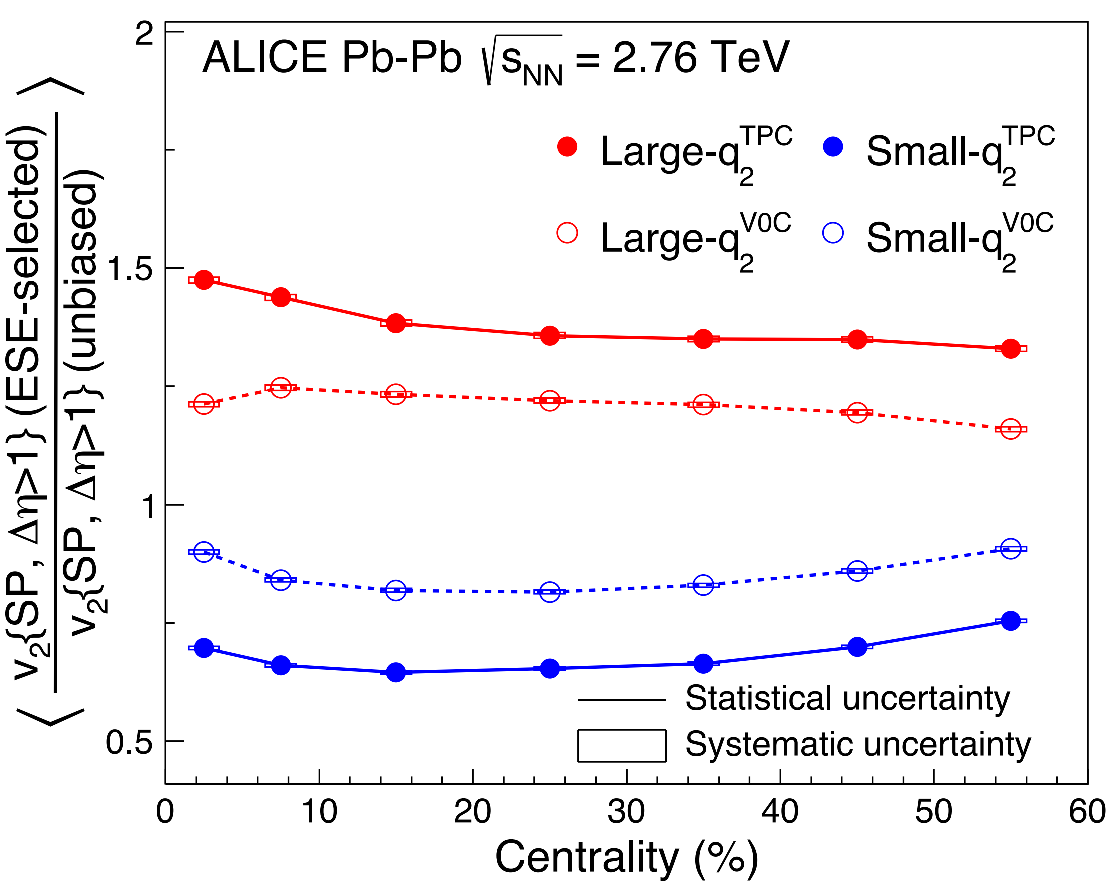
$$s_2 = \frac{1}{2}\frac{\left(R_y/R_x\right)^2 - 1}{\left(R_y/R_x\right)^2 + 1}$$

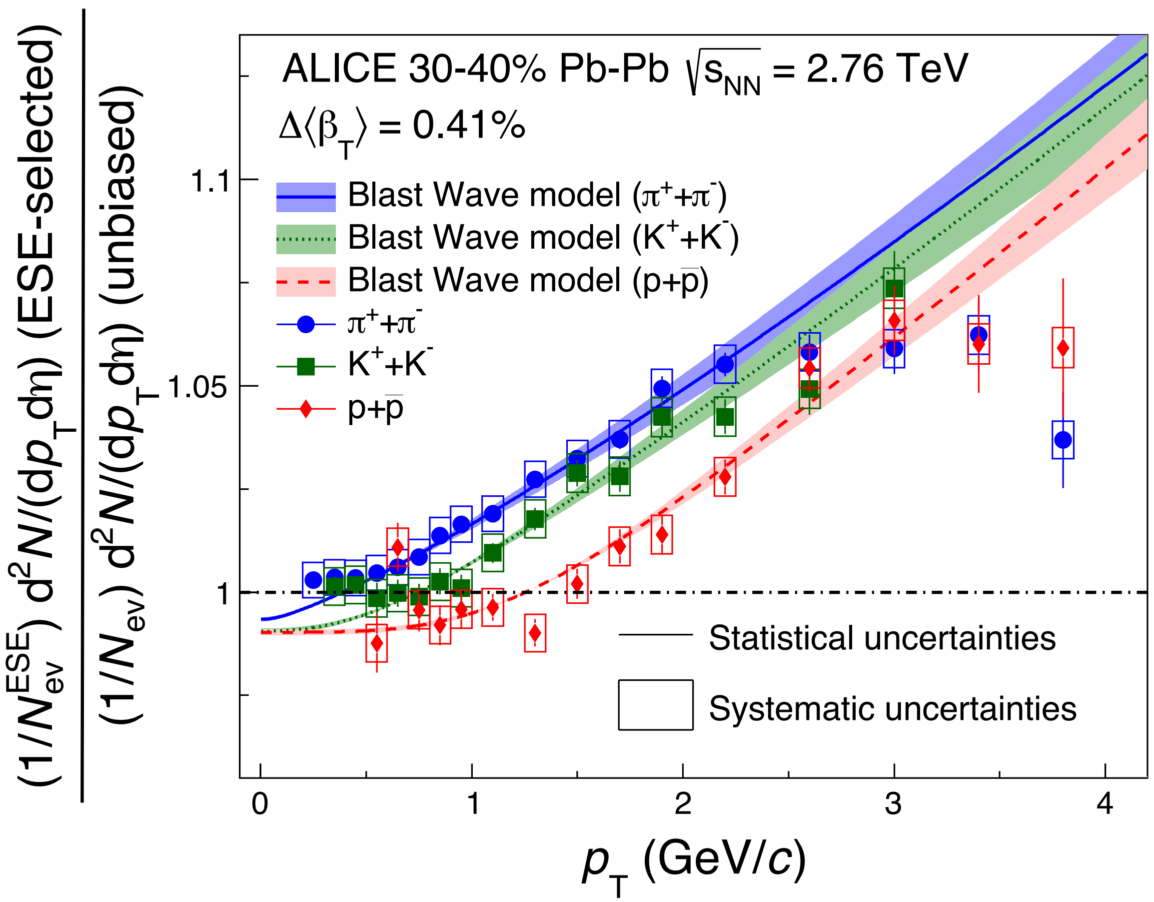
HBT relative to Ψ_n with ESE(q_n cut)



Spectra + Event shape engineering

✦ **Positive correlation between <v_2> and <p_T>**





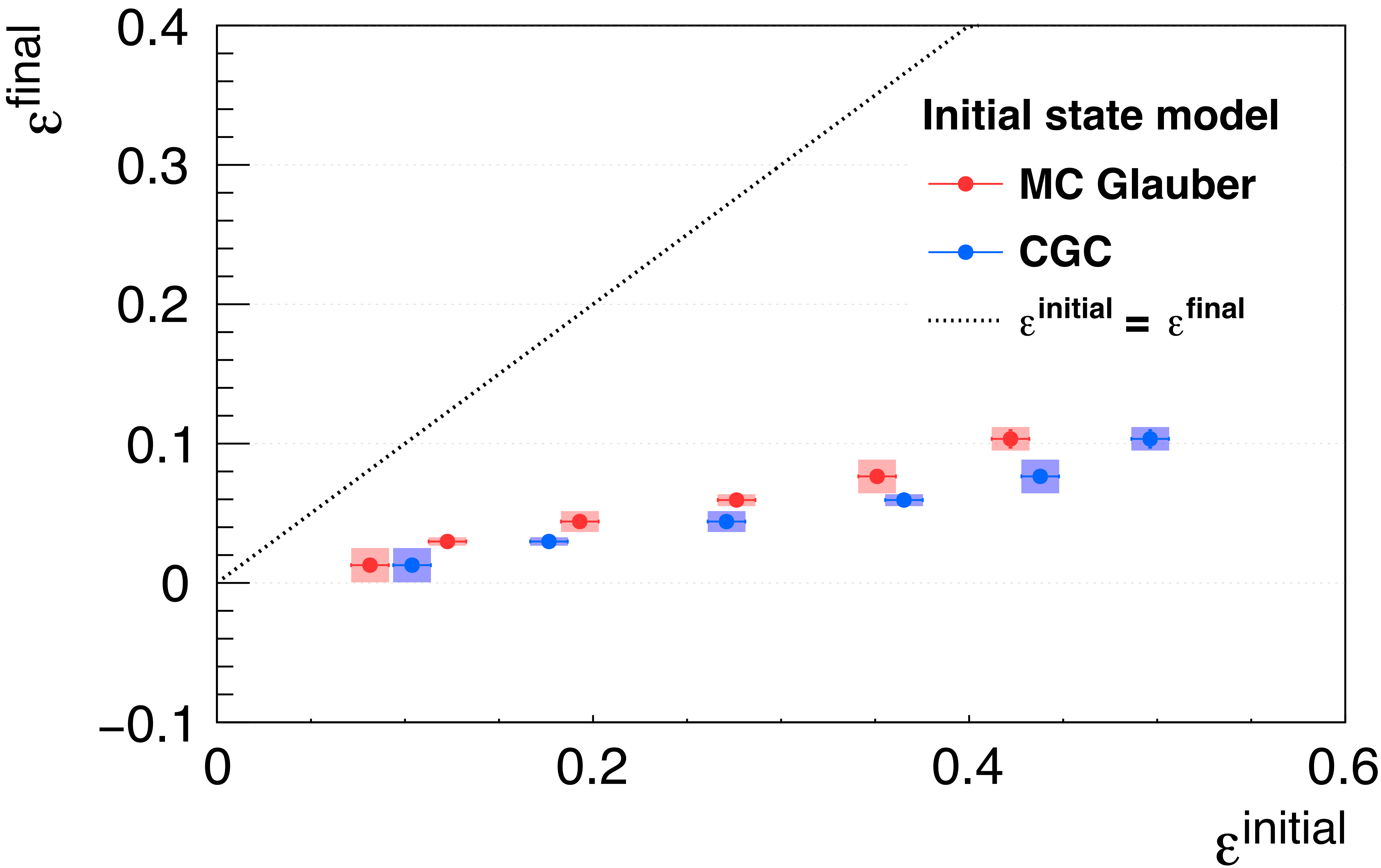
✦ **v_2 ratio with q_2 large(small) cut**
- ✓ **large q_2^{TPC} top10% (bottom10%)**
- ✓ **large q_2^{VZERO} top10%(bottom10%)**

✦ **Ratio of p_T distribution of π, K, p**

✦ **q_2^{TPC} top 10% cut (Iηl < 0.4)**

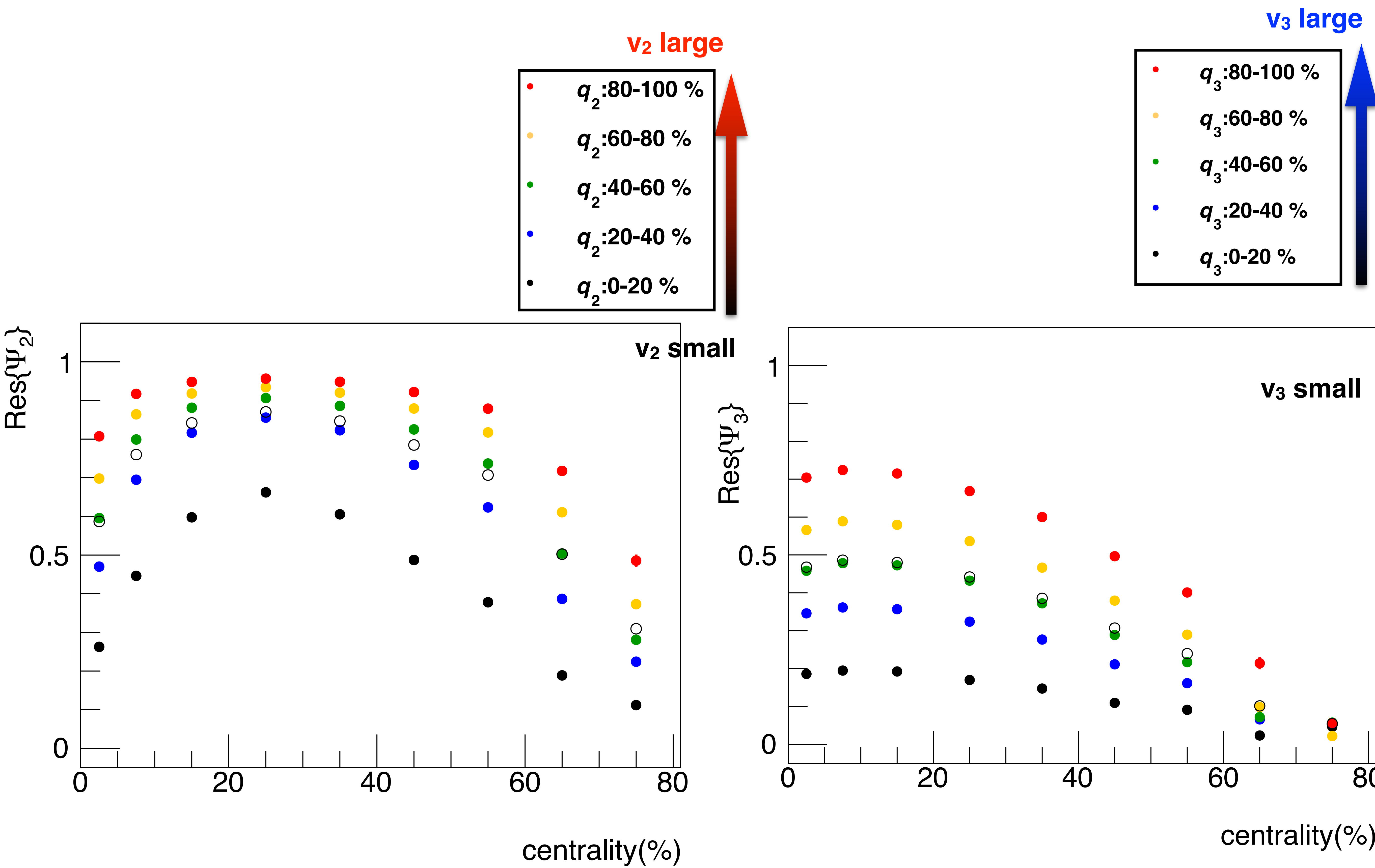
✦ **Blast wave model comparison**
- ✓ **Δ<β_T> = +0.41%**

Initial v.s. final source eccentricity



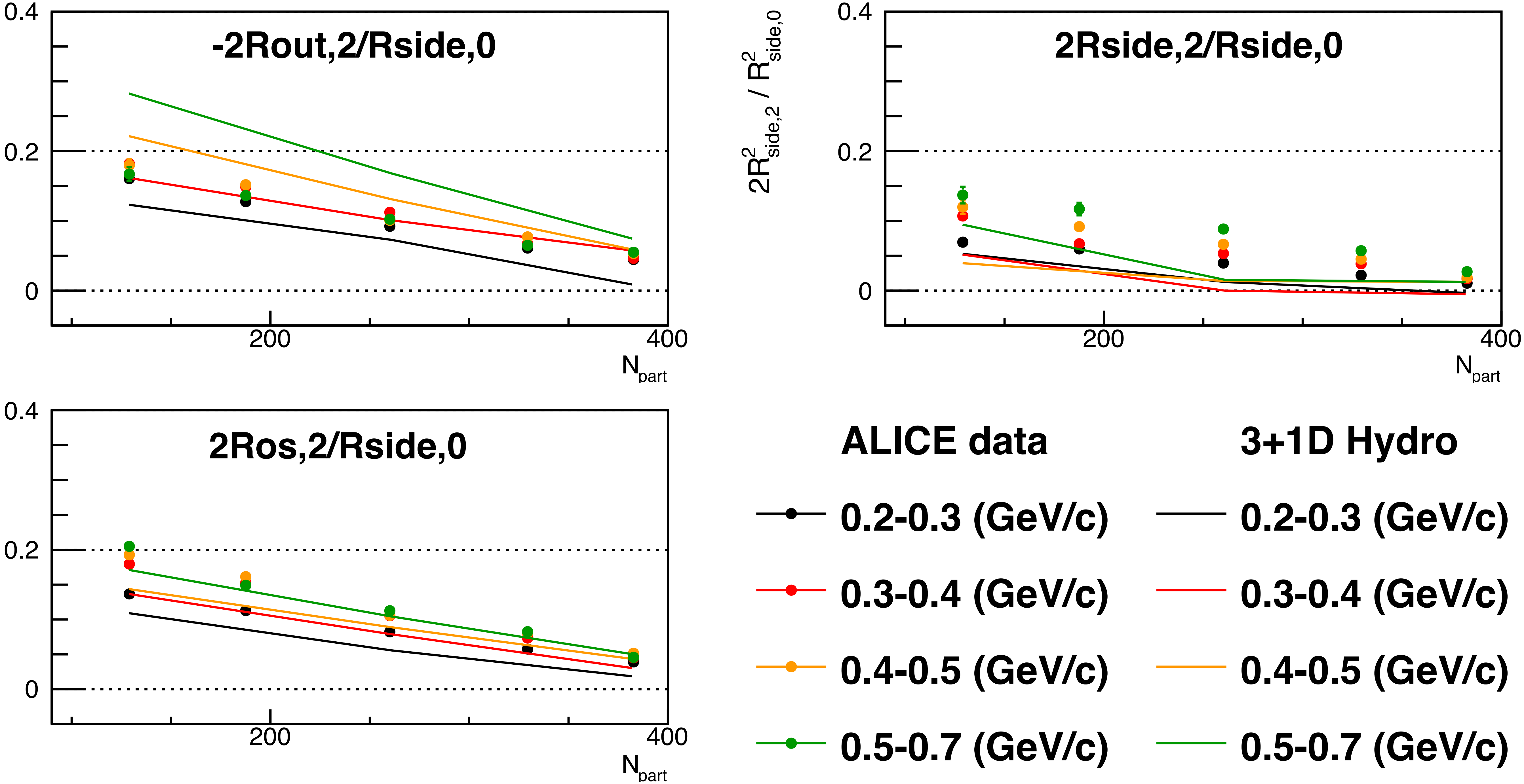
- k_T : 0.2-1.5 GeV/c
- Final source eccentricity is strongly diluted with collective flow

E.P. resolution with qn cut



2nd harmonic oscillation amplitude of HBT radii

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



- ✦ **Hydro calculation cannot reproduce $R^2_{out,2} / R^2_{side,0}$ small k_T dependence**
  - ✦ **N_{part} dependence of $R^2_{out,2} / R^2_{side,0}$ is very similar though**
- ✦ **$R^2_{out,2} / R^2_{side,0}$ in lowest k_T is consistent but not in high k_T (under estimate)**
- ✦ **$R^2_{os,2} / R^2_{side,0}$ is well reproduced**