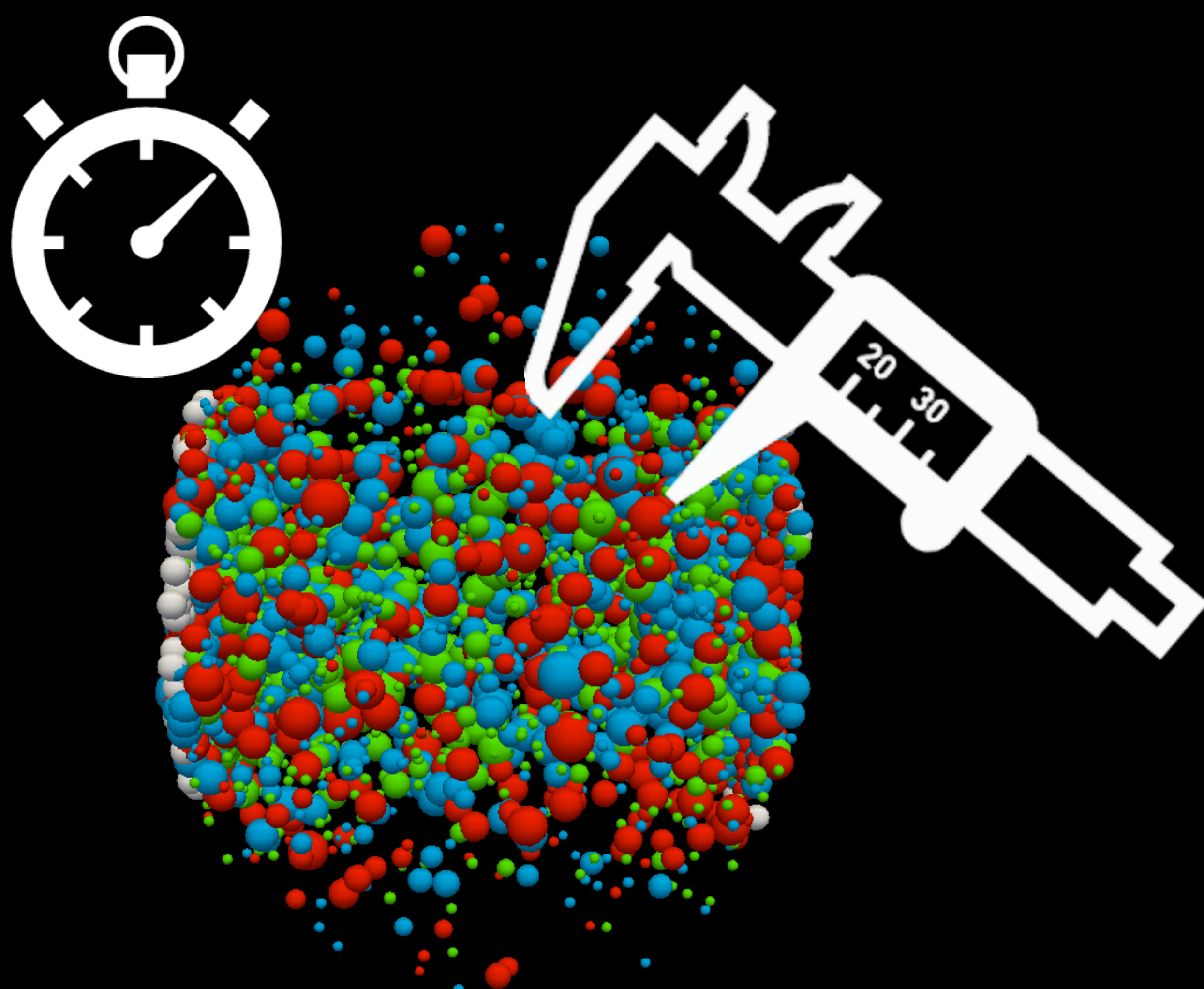
Measurements of Azimuthal Angle Dependence of HBT radii with respect to the event plane in $\sqrt{s_{NN}}$ = 2.76 TeV Pb-Pb collisions at LHC-ALICE



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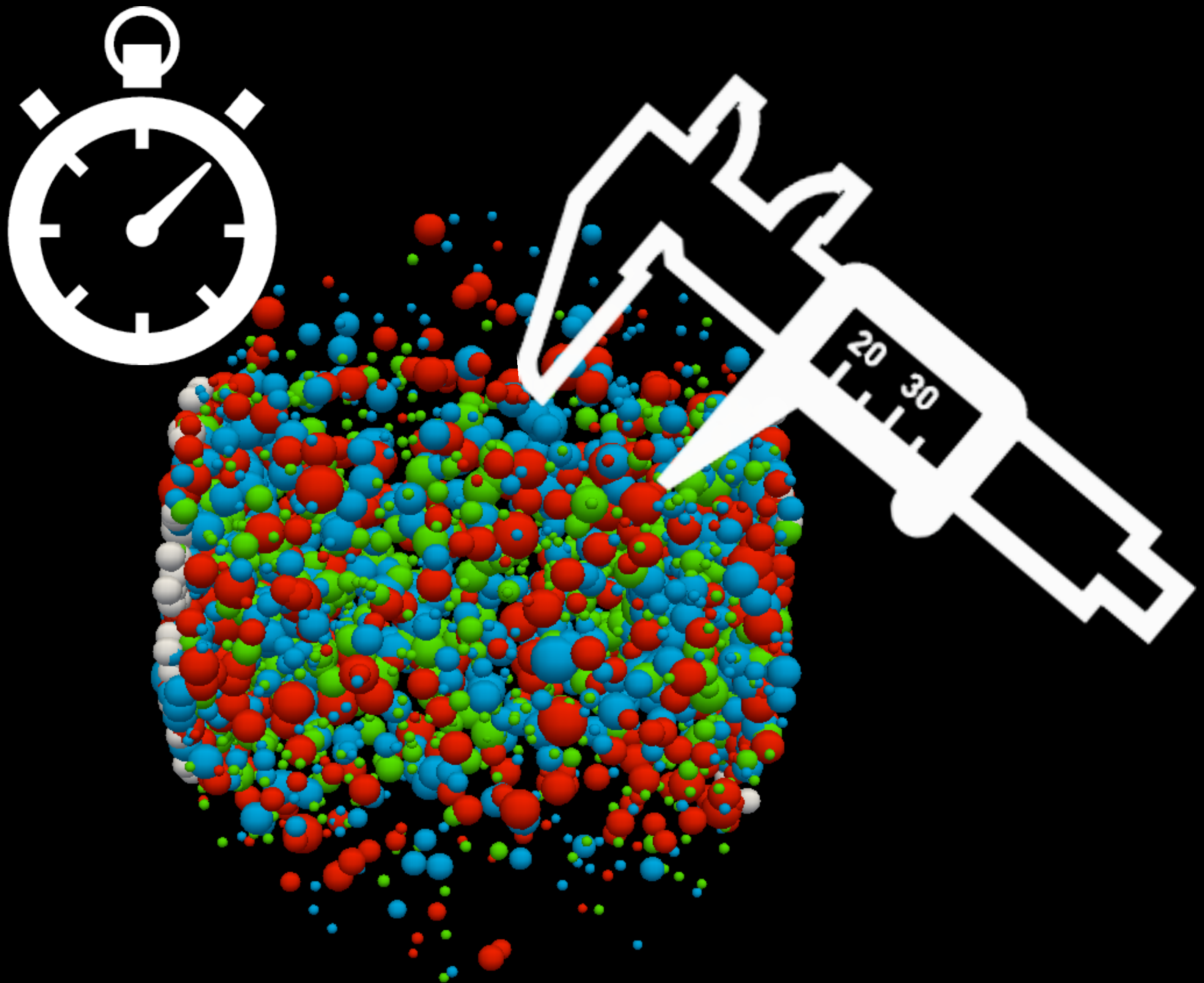
Outline

- ✓ **Introduction**
  - Quark Gluon Plasma
  - HBT interferometry
- ✓ **Experiment & Analysis**
  - ALICE
  - Analysis methods
- ✓ **Result & Discussions**
  - Azimuthal angle dependence of HBT radii w.r.t. Ψ_2
  - Azimuthal anisotropy (v_2 and v_3) with ESE cut
  - Azimuthal angle dependence of HBT radii w.r.t. Ψ_2 + q_2 cut
  - Interpretation with Blast-wave fit
  - Azimuthal angle dependence of HBT radii w.r.t. Ψ_3
  - Azimuthal angle dependence of HBT radii w.r.t. Ψ_3 + q_3 cut

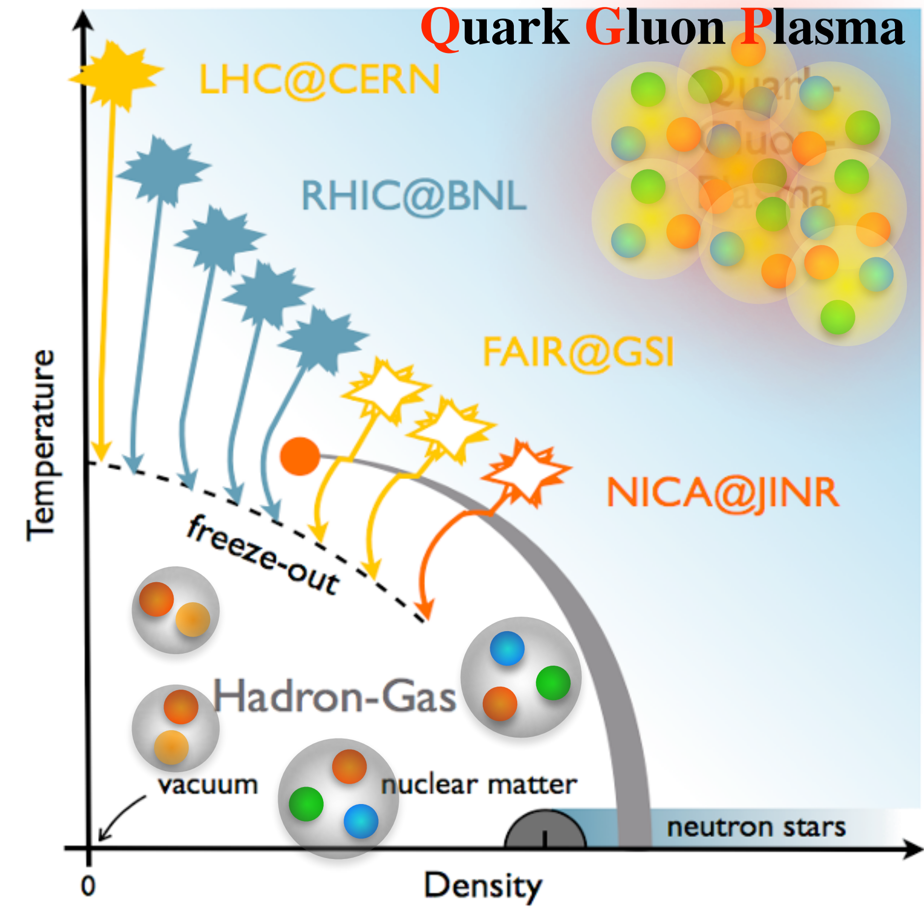
Introduction

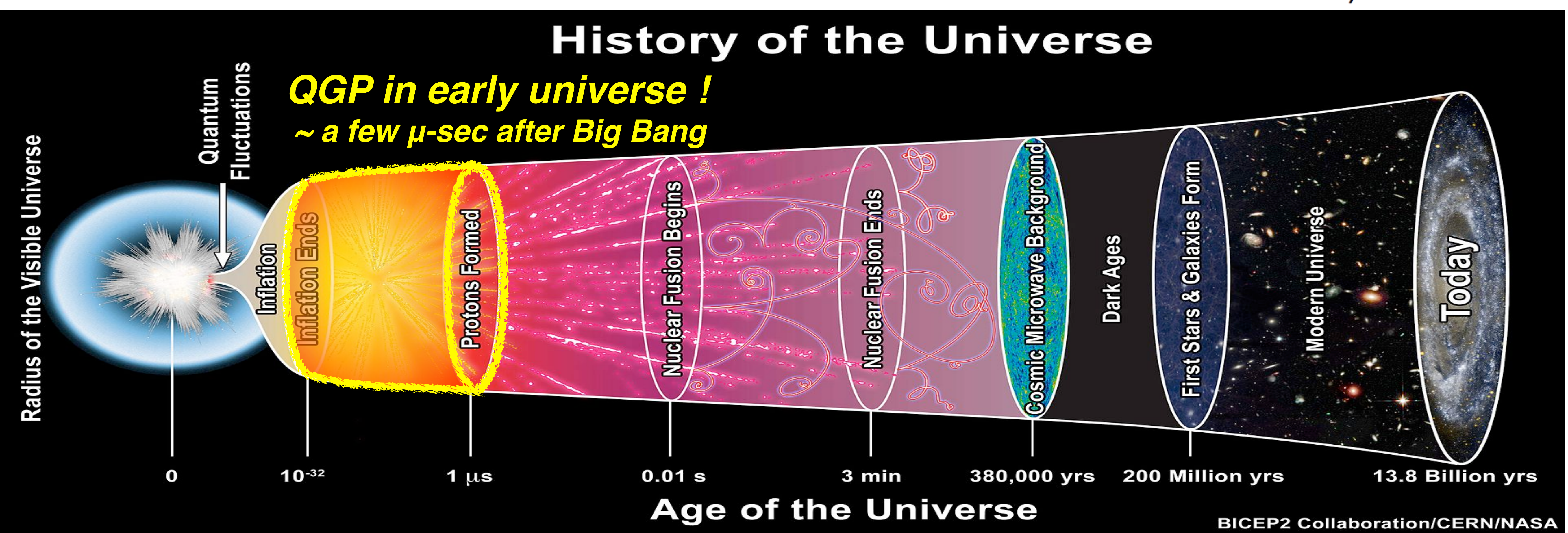


Quark Gluon Plasma (QGP)

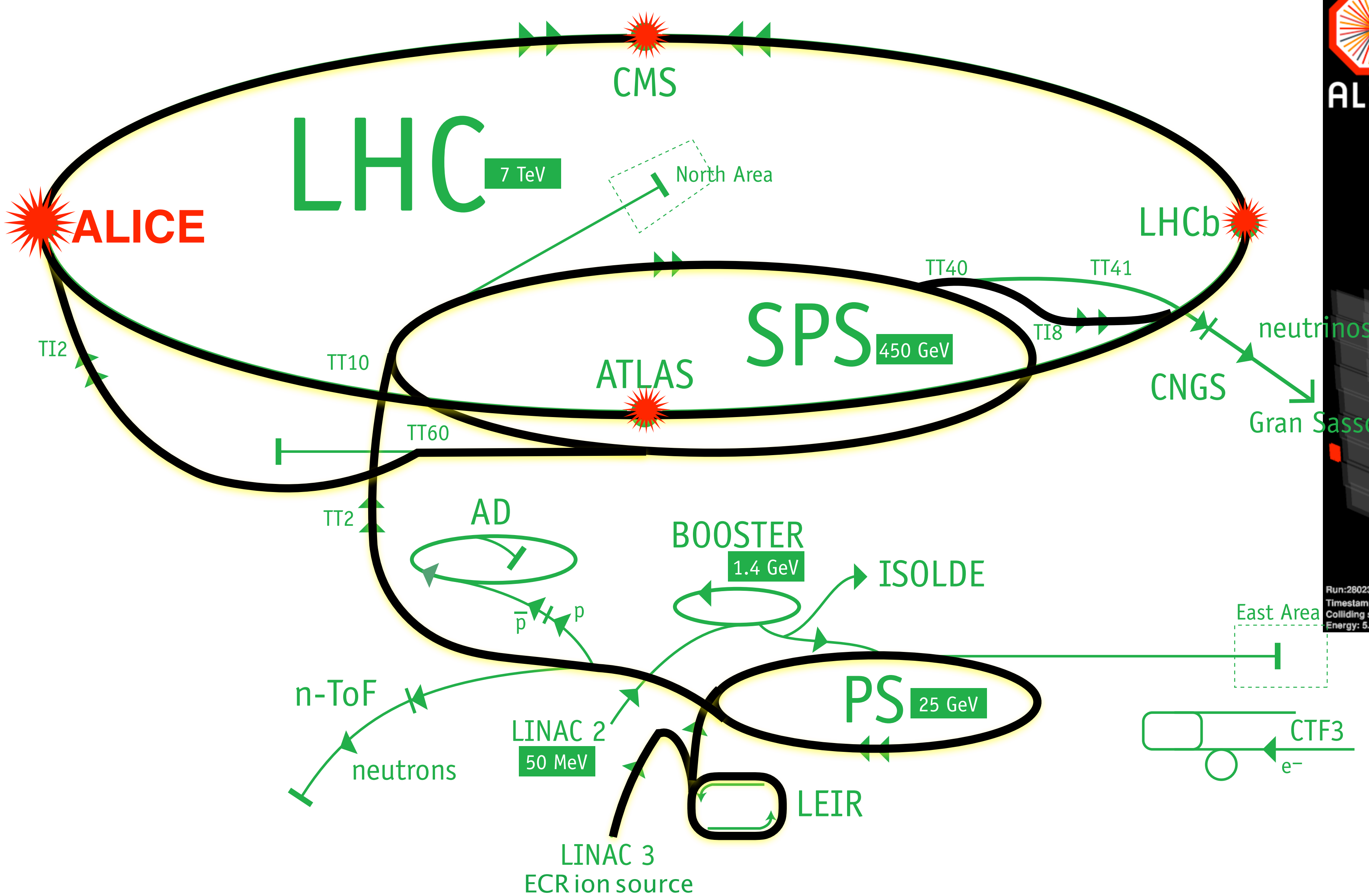
- ✓ Extremely high temperature and density
  - ✓ quarks and gluons are deconfined from hadron
- ✓ Latice QCD calculation predicts phase transition
  - ✓ $T_c \sim 170$ MeV
  - ✓ $\varepsilon_c \sim 1$ GeV/fm^3
- ✓ QGP exists in early universe and neutron star

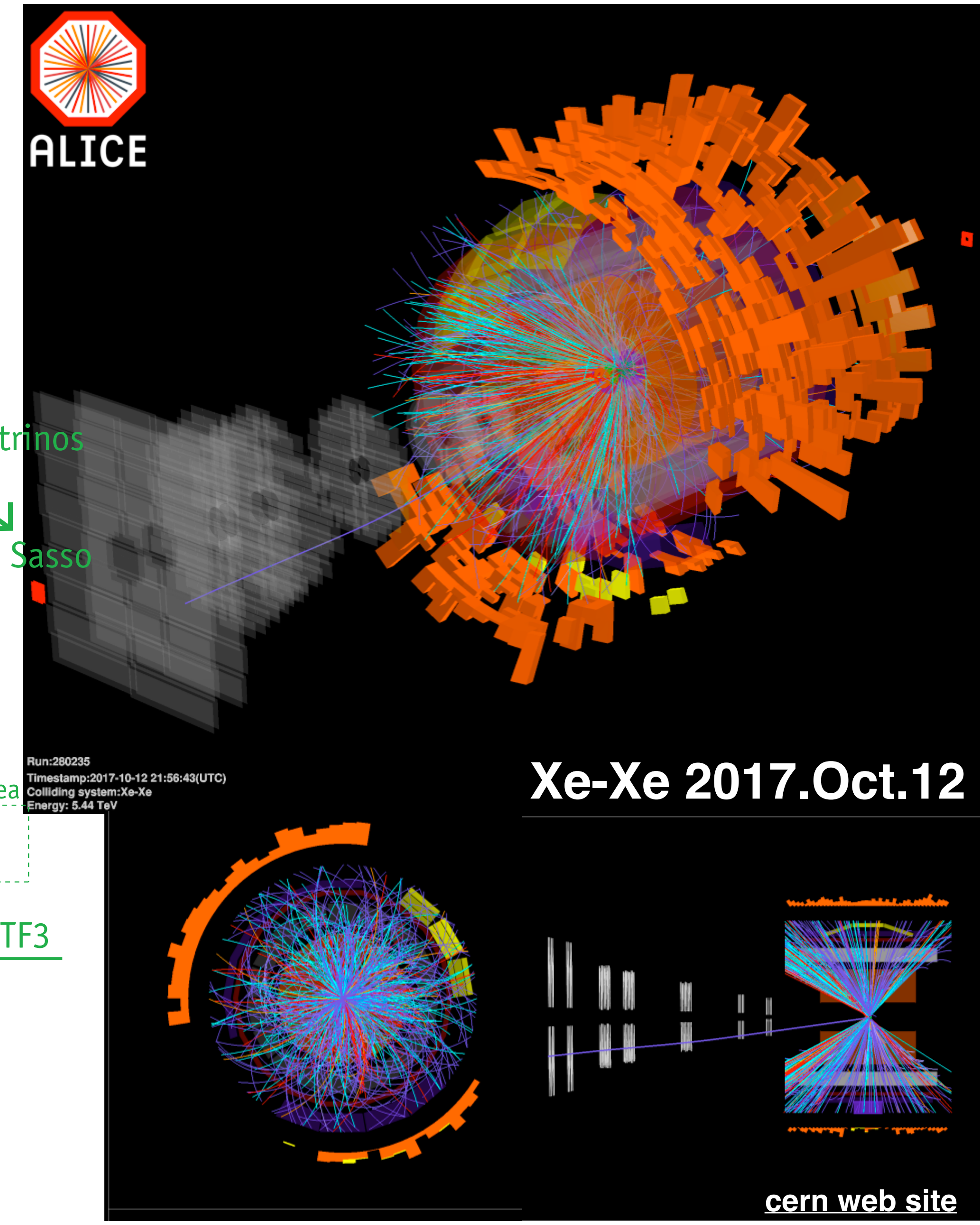
Important to understand History of the universe !





Heavy ion collision at LHC

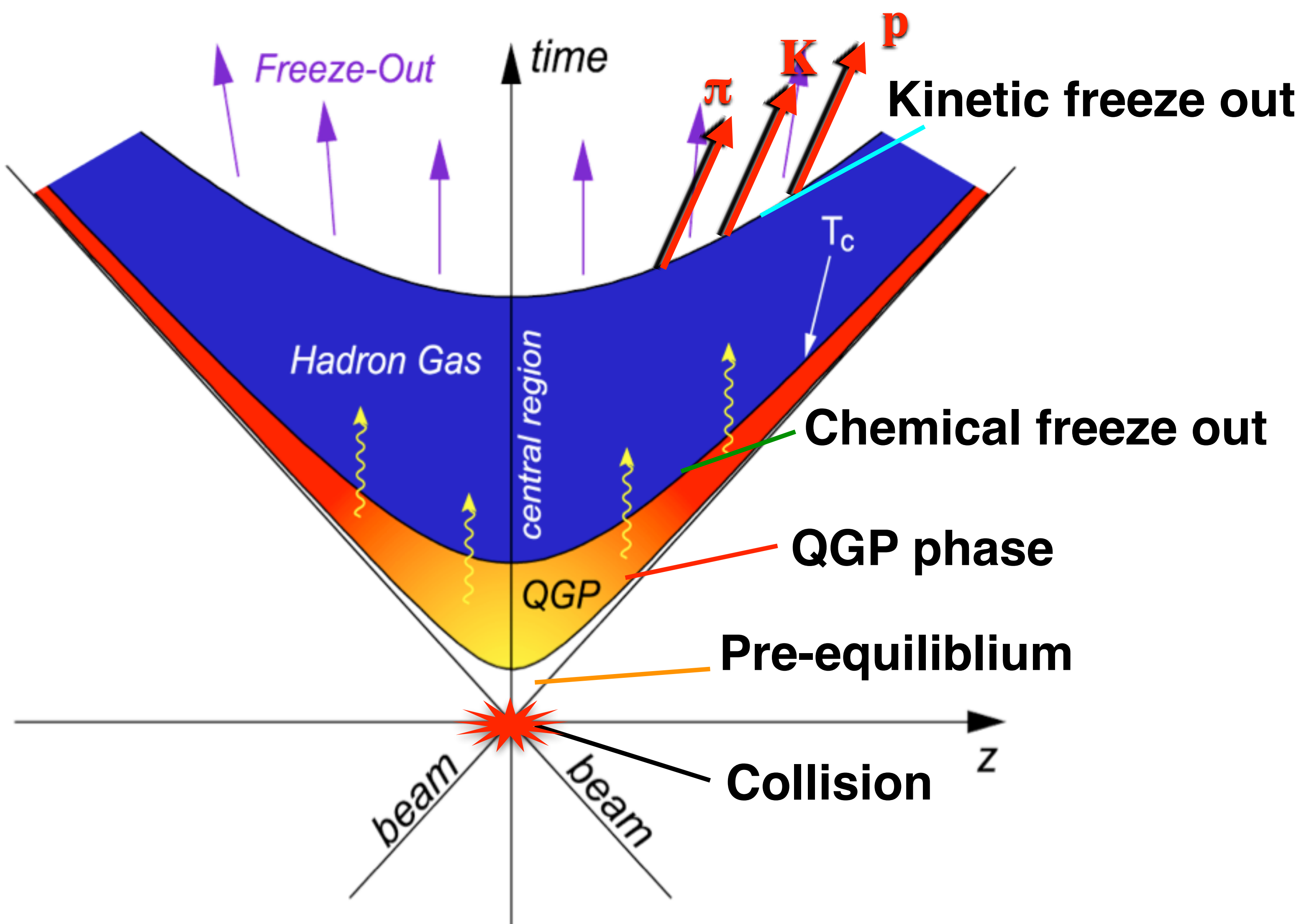




Species	Collision energy
Pb-Pb	2.76, 5.02 TeV
p-Pb	5.02, 8.16 TeV
Xe-Xe	5.44 TeV
p-p	0.9, 2.76, 5.02, 7, 13 TeV

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

Space time evolution



✓ To quantify the properties of QGP, 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**

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

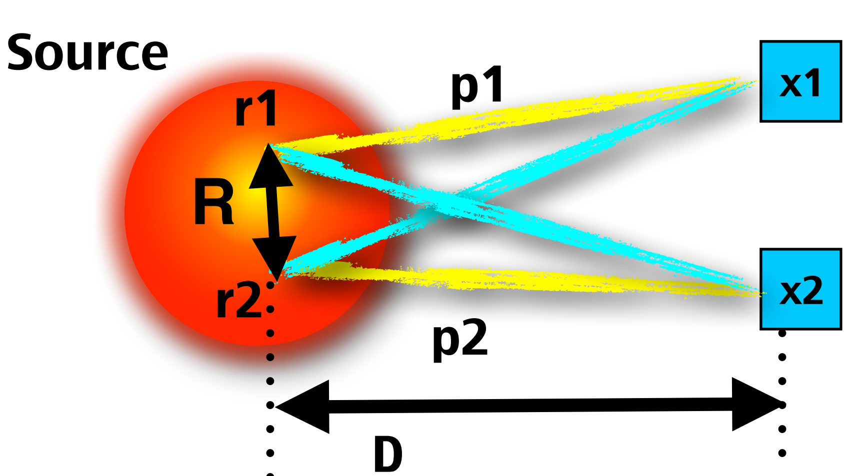
- ✓ ***Boson +***
- ✓ ***Fermion -***

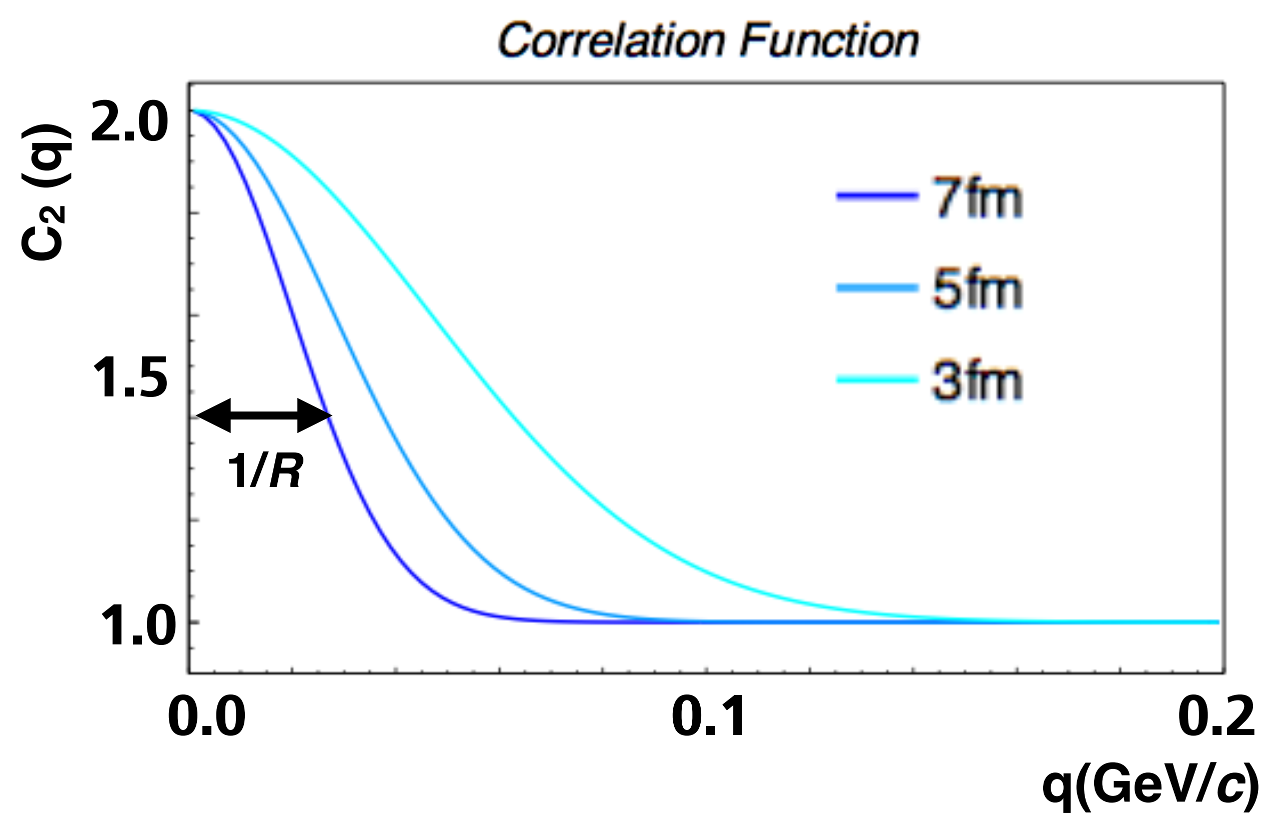
$$C_2 = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \approx 1 + |\tilde{\rho}(q)|^2 = 1 + \exp\left(-R^2 q^2\right)$$

✓ ***$q = p_1 - p_2$***

✓ **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

$$C_2 = 1 + \lambda G$$

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

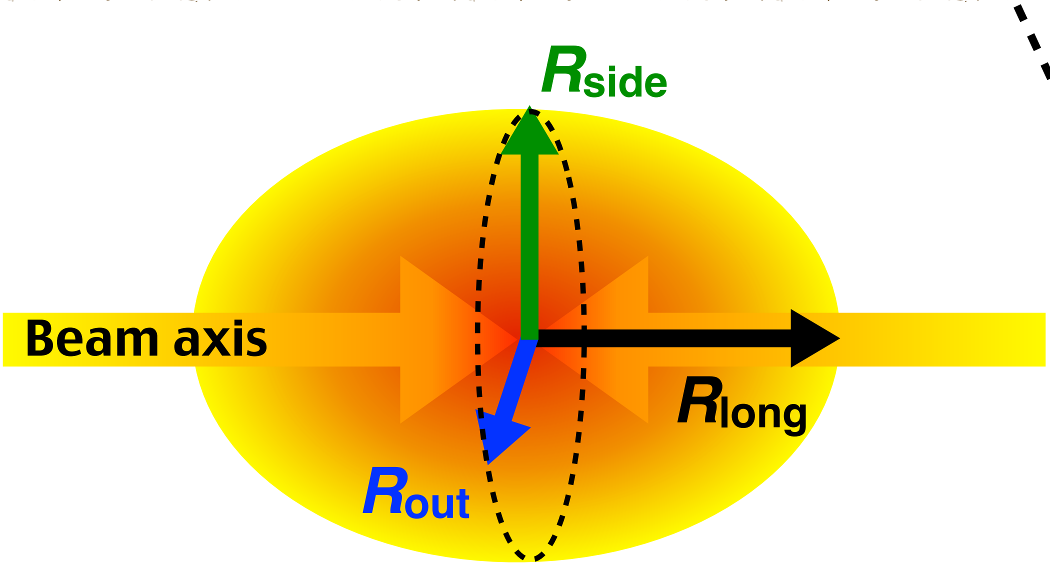
$$\approx \exp\left(-R_{side}^2 q_{side}^2 - \left(R'^2_{out} + \beta_T \Delta\tau^2\right) q_{out}^2 - R_{long}^2 q_{long}^2\right)$$

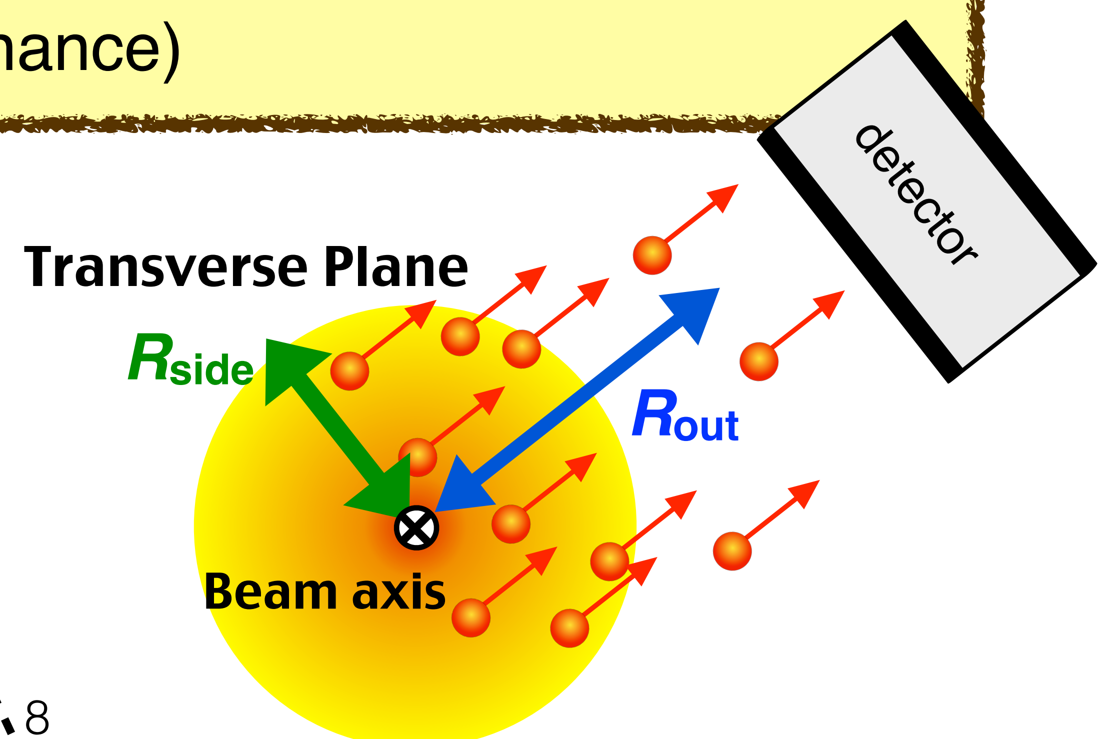
LCMS (Longitudinal Co-Moving System)

✓ $p_{z1} + p_{z2} = 0$

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

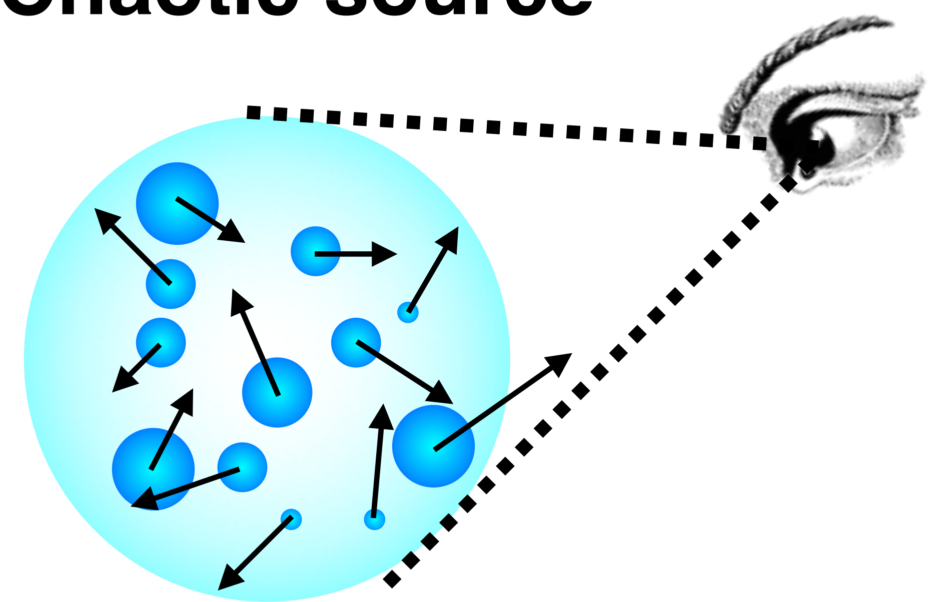
- R_{long} : source size along the longitudinal direction (beam direction)
- R_{out} : source along the pair transverse momentum + emission duration
- R_{side} : source size along the perpendicular to Rout
- λ : chaoticity＝ (in coherence) – (resonance)





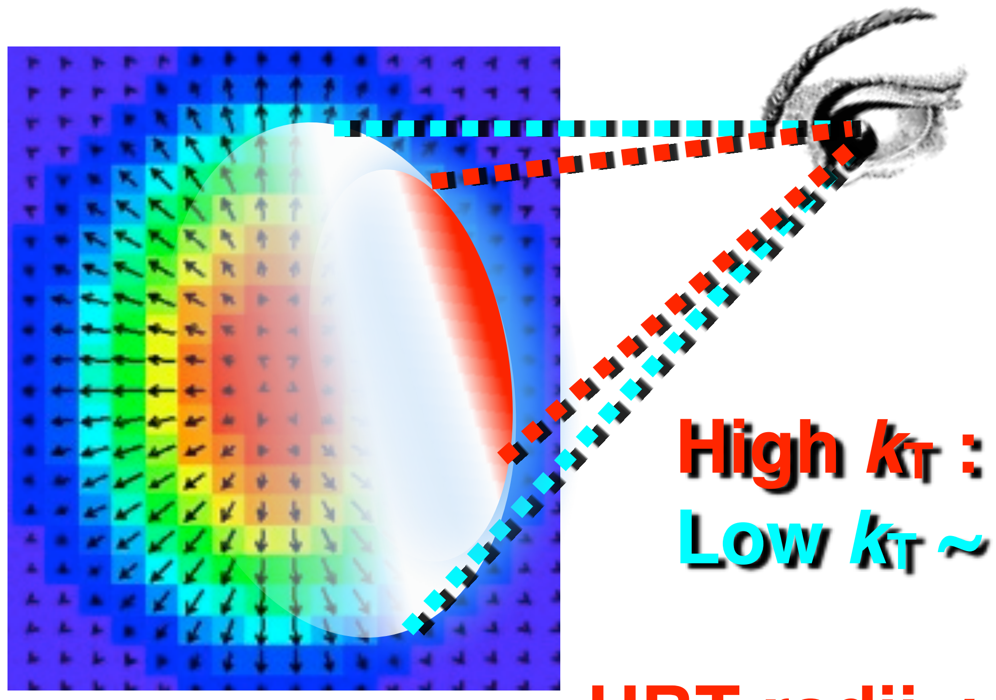
HBT radii = geometrical source size ??

Chaotic source



HBT radii = whole size

Dynamical source



High k_T : surface

Low k_T ~ whole size

HBT radii ≠ whole size

✦ For static source, HBT radii = Geometrical source size

✦ For dynamical source, HBT radii = "Length of homogeneity region"

✓ HBT radii depends on Pair transverse momentum : k_T

$$k_{\mathrm{T}} = \frac{\overrightarrow{p_{\mathrm{T1}}} + \overrightarrow{p_{\mathrm{T2}}}}{2}$$

k_T dependence of HBT radii is important to understand system evolution

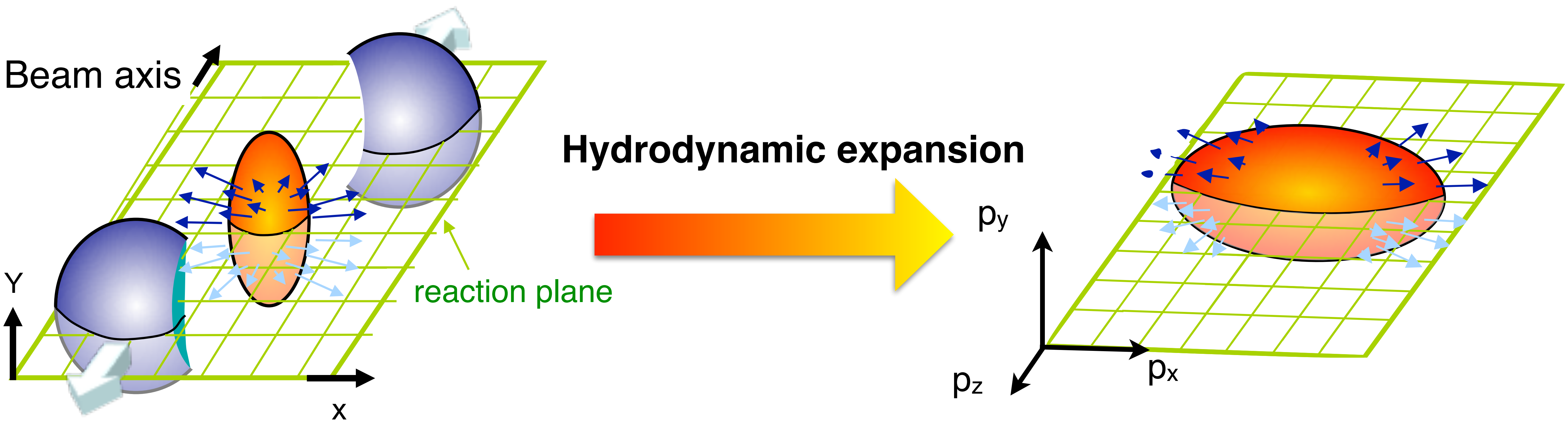
Azimuthal anisotropy

✦ **Initial state**

‣ **Geometrical coordinate**

✦ **Freeze-out**

‣ **Momentum coordinate**



$$\varepsilon_2 = \frac{\langle r^2 \cos\left(2\left(\phi - \Psi_{\mathrm{RP}}\right)\right)\rangle}{\langle r^2 \rangle}$$

$$v_2 = \langle \cos\left(2\left(\phi - \Psi_{\mathrm{RP}}\right)\right)\rangle$$

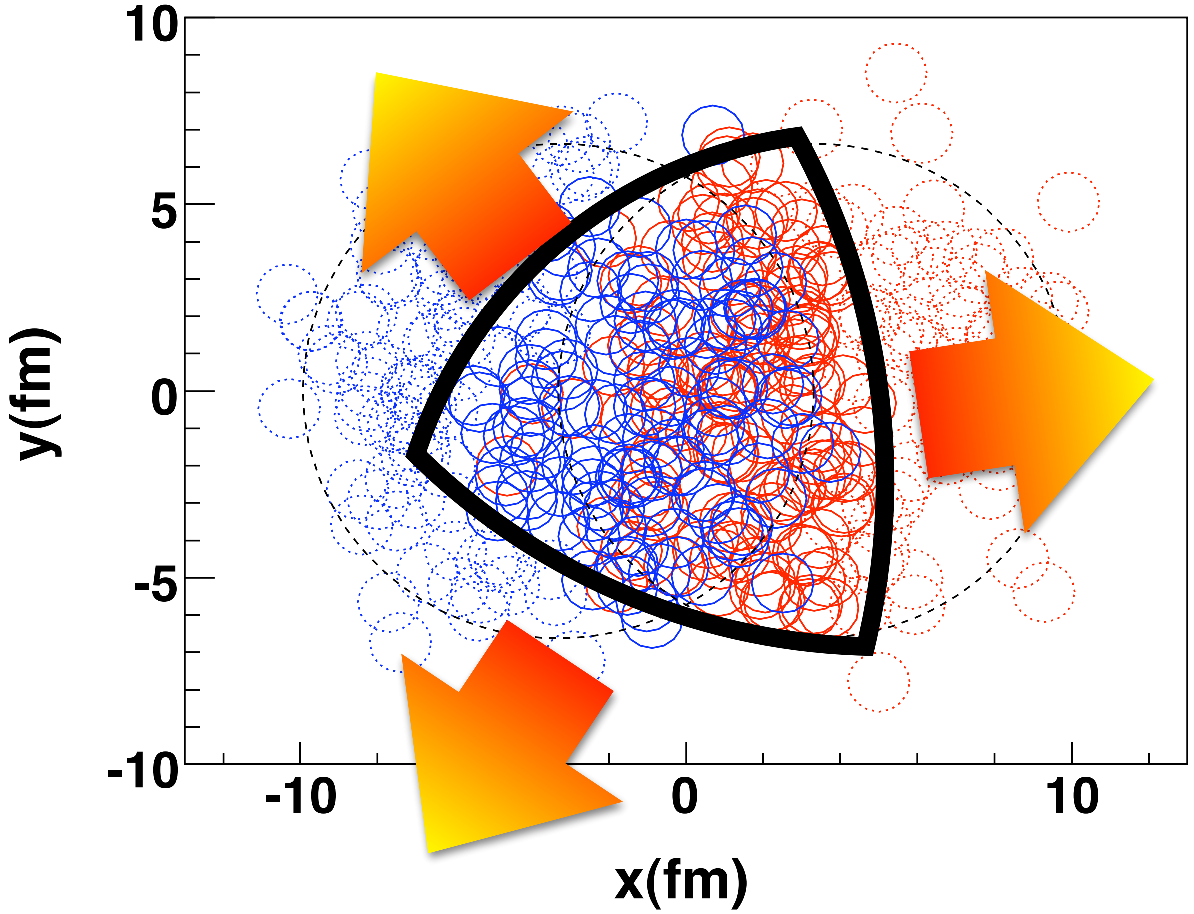
✦ **Initial geometry ε_2 makes anisotropic pressure gradient**

✦ **Hydrodynamic expansion convert ε_2 to v_2**

✓ **Sensitive to viscosity and initial geometry**

3^{rd}-order azimuthal anisotropy

- ✦ **Initial geometry**
  - ‣ **MC Glauber simulation** (arXiv:1408.2549)

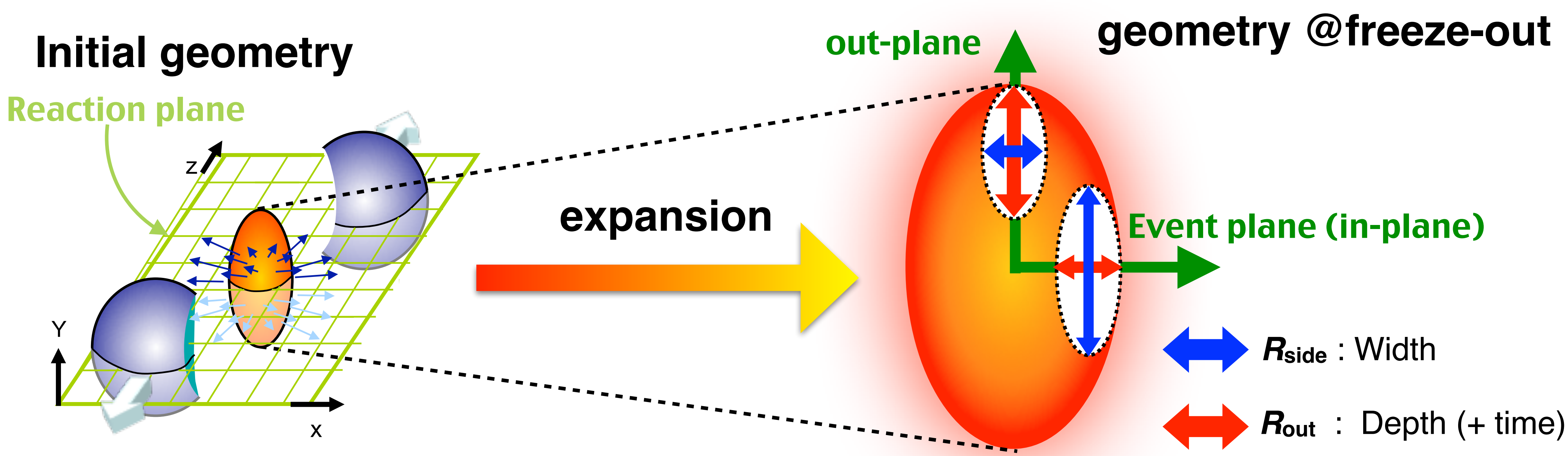


$$\frac{\mathrm{dN}}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2) + 2v_3 \cos 3(\phi - \Psi_3)$$

- ✦ **Initial participant shape ≠ smooth elliptic shape**
- ✦ **Finite number of nucleons makes 3^{rd}-order anisotropy**
- ✦ **Initial triangular shape is converted to v_3**
  - ✦ **Initial geometry and viscosity are more sensitive to v_3 than v_2**

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

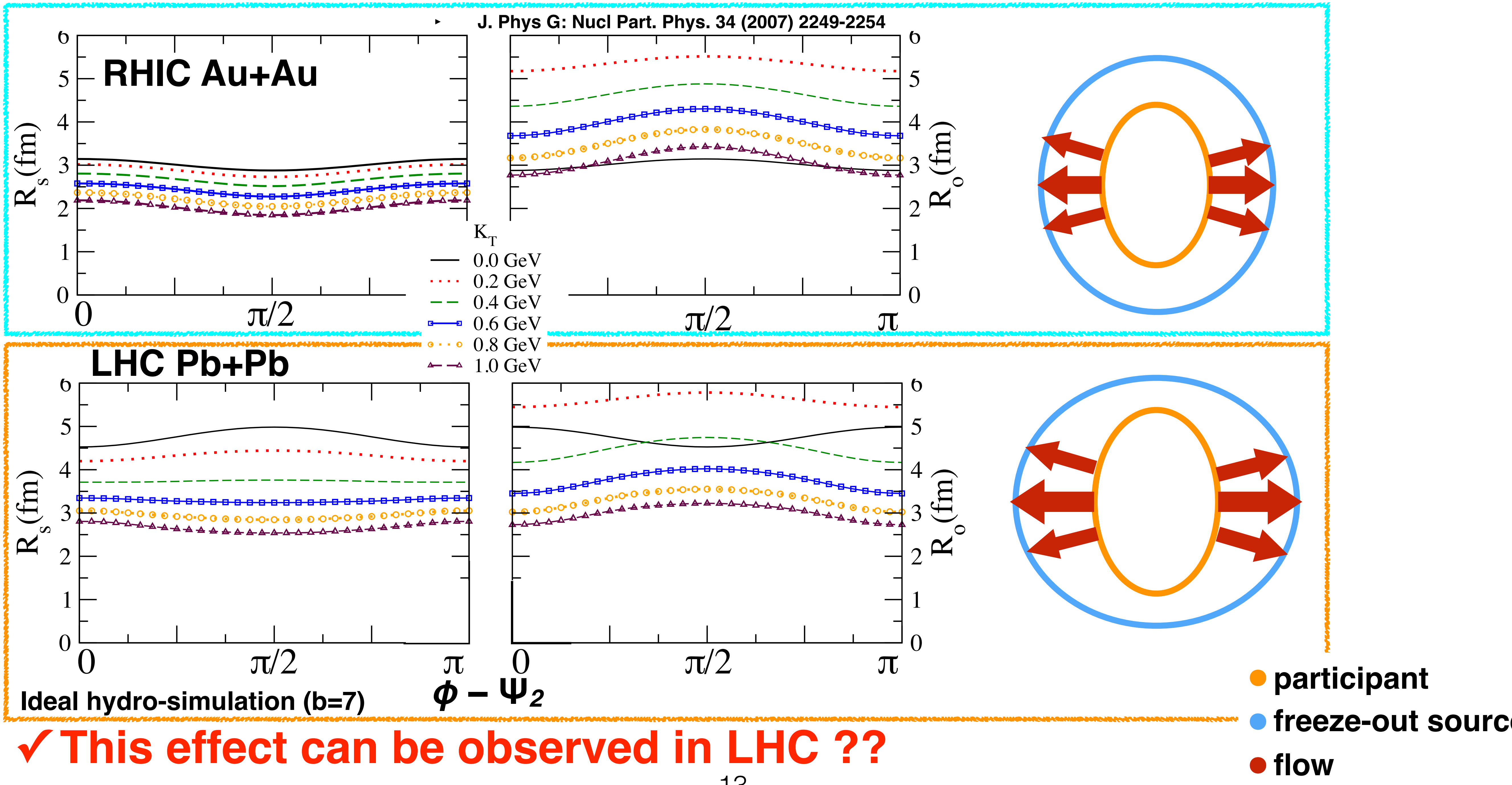
- Azimuthal angle dependence of 3D HBT radii gives us the **source shape** at freeze-out
- Event plane Ψ_2 ~ reaction plane (determined with azimuthal anisotropy)
- Relation between initial and final source shape will constrain the freeze-out parameter
  - ➡ **flow velocity profile, system life time and viscosity**



- Spherical source
  - R_{side} (in-plane) = R_{side} (out-plane)
- Out-plane elongated elliptic source
  - R_{side} (in-plane) $>$ R_{side} (out-plane) & R_{out} (in-plane) $<$ R_{out} (out-plane)
- In-plane elongated elliptic source
  - R_{side} (in-plane) $<$ R_{side} (out-plane) & R_{out} (in-plane) $>$ R_{out} (out-plane)

Final source eccentricity @ LHC energy

- **Hydro model predicts R_{side} and R_{out} oscillate in phase at lower k_T**
  - ✓ At RHIC energy, out-plane elongated elliptic shape still remains at freeze-out
  - ✓ Initial elliptic shape will be vanished or even reversed in LHC

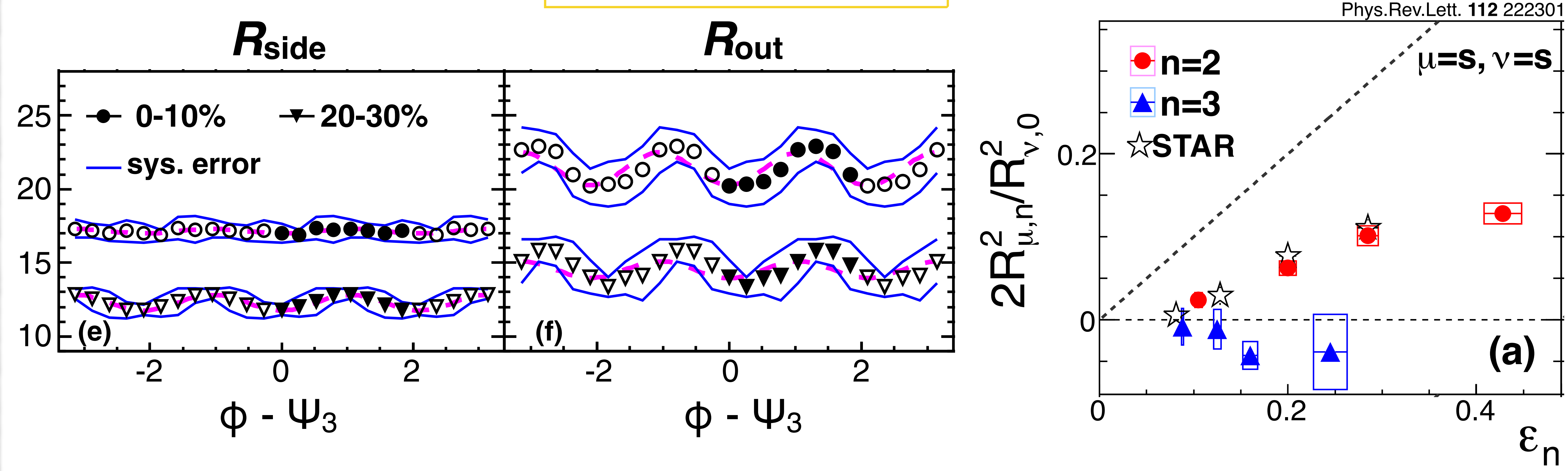


✓ **This effect can be observed in LHC ??**

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

- **Model suggests HBT w.r.t. Ψ_3 shows finite oscillation in expanding source**
  - ✓ S.Voloshin, J. Phys. G**38**, 124097
- **First measurement of HBT w.r.t. Ψ_3 was measured @ PHENIX Au+Au 200GeV**
  - ✓ **<u>Negative or zero oscillation</u> was observed in R_{side}**

Au+Au 200GeV @ PHENIX



☑ **In order to constrain the freeze-out parameters, to determine the oscillation sign and centrality dependence is indispensable !!**

- ✓ **Precise measurement @LHC is expected**

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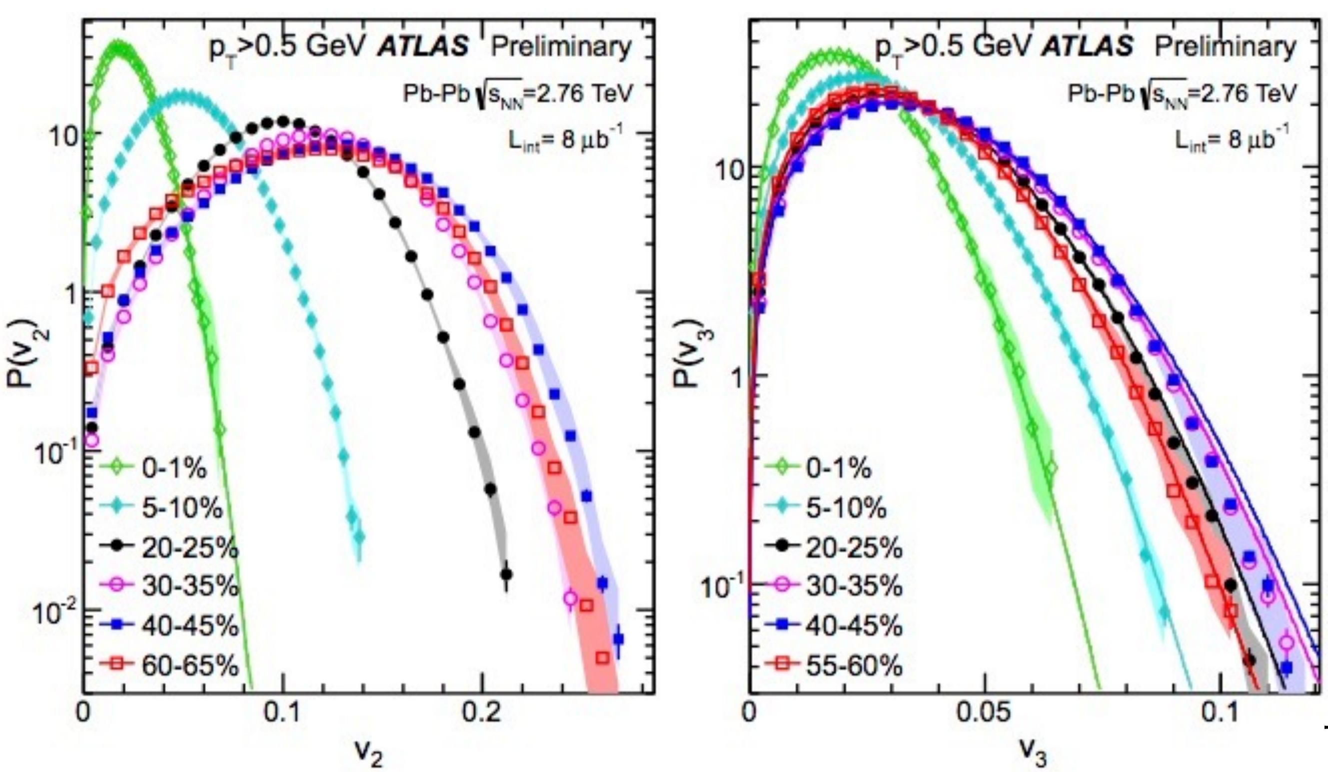
Event shape engineering (ESE)

Event by event flow amplitude selection
J. Schukraft et al., Phys. Lett. B719, 394-398 (2013)

- v_2 and v_3 largely fluctuate within a fixed centrality
- Event by event $v_2(v_3)$ fluctuation is selected with flow vector q_2 (q_3)
  - ✓ Possibly control the initial eccentricity

★ q-verctor is defined by $q_n = \sqrt{Q_{n,x}^2 + Q_{n,y}^2}$ $\left(\begin{array}{l} Q_{n,x} = \sum w_i \cos(n\phi) / \sum w_i \\ Q_{n,y} = \sum w_i \sin(n\phi) / \sum w_i \end{array} \right)$

- Centrality is not best probe for initial geometry!! (system size also changes)
- By applying ESE technique to other observables, separation of volume effect and geometrical effect can be allowed



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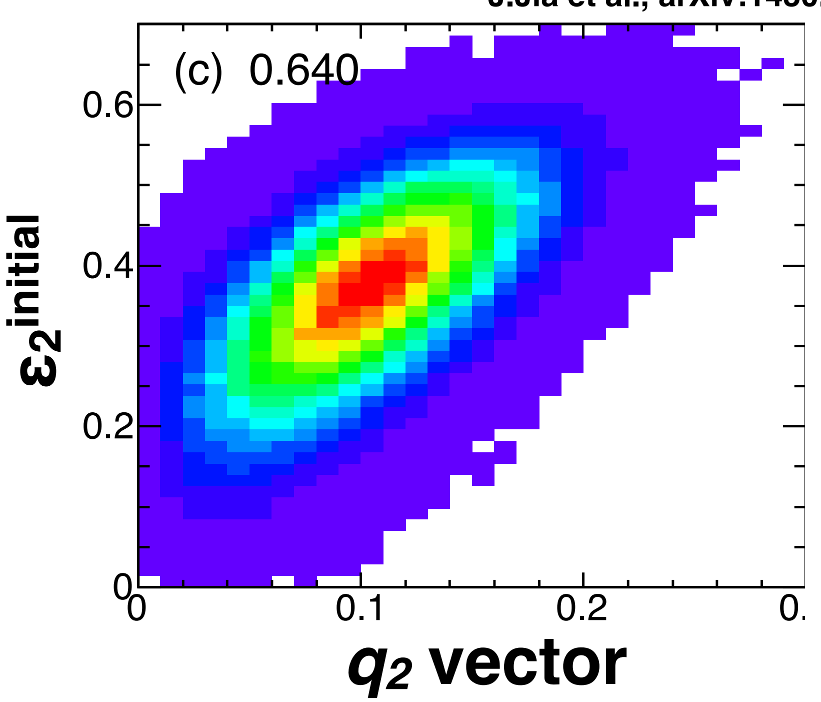
J.Phys.Conf.Ser. 446 (2013) 012024

Explicit correlation between q_2 and $\varepsilon_2^{initial}$

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



Motivation

- Study the space time evolution of QGP 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
    - Relation 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 in LHC energy
    - Relation between v_3 (initial triangular shape) and HBT oscillation with ESE (q_3) selection

My activity

Master

- DCAL construction
- EMCAL SRU work @cern
- DCAL commissioning
- Shift taking @ PHENIX

- Development of read out module with FPGA and Flash ADC
- KEK summer challenge M1->D4
- Development of radon detector ->D4

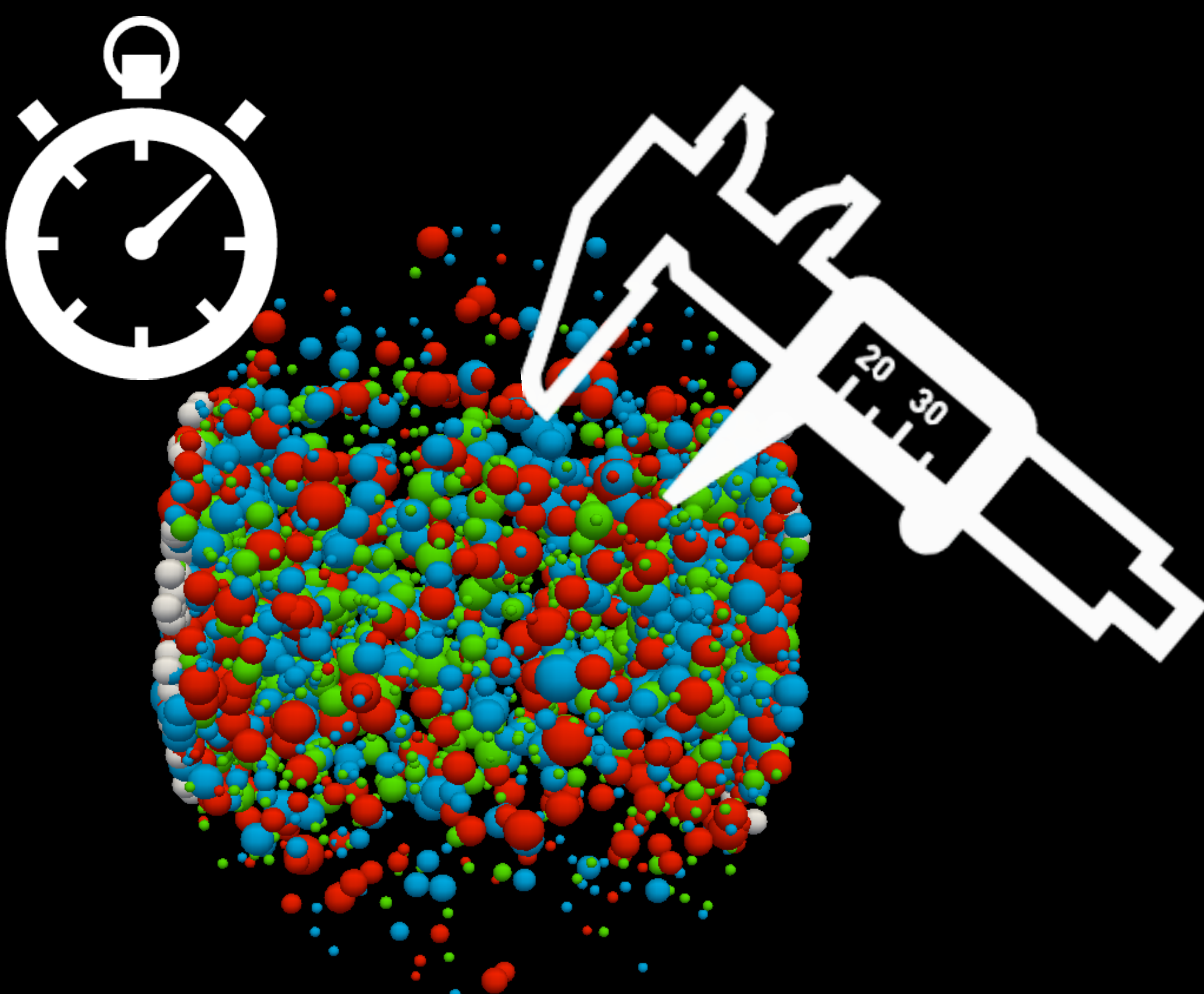
- Azimuthal angle dependence of HBT radii w.r.t. Ψ_2 and Ψ_3

Doctor

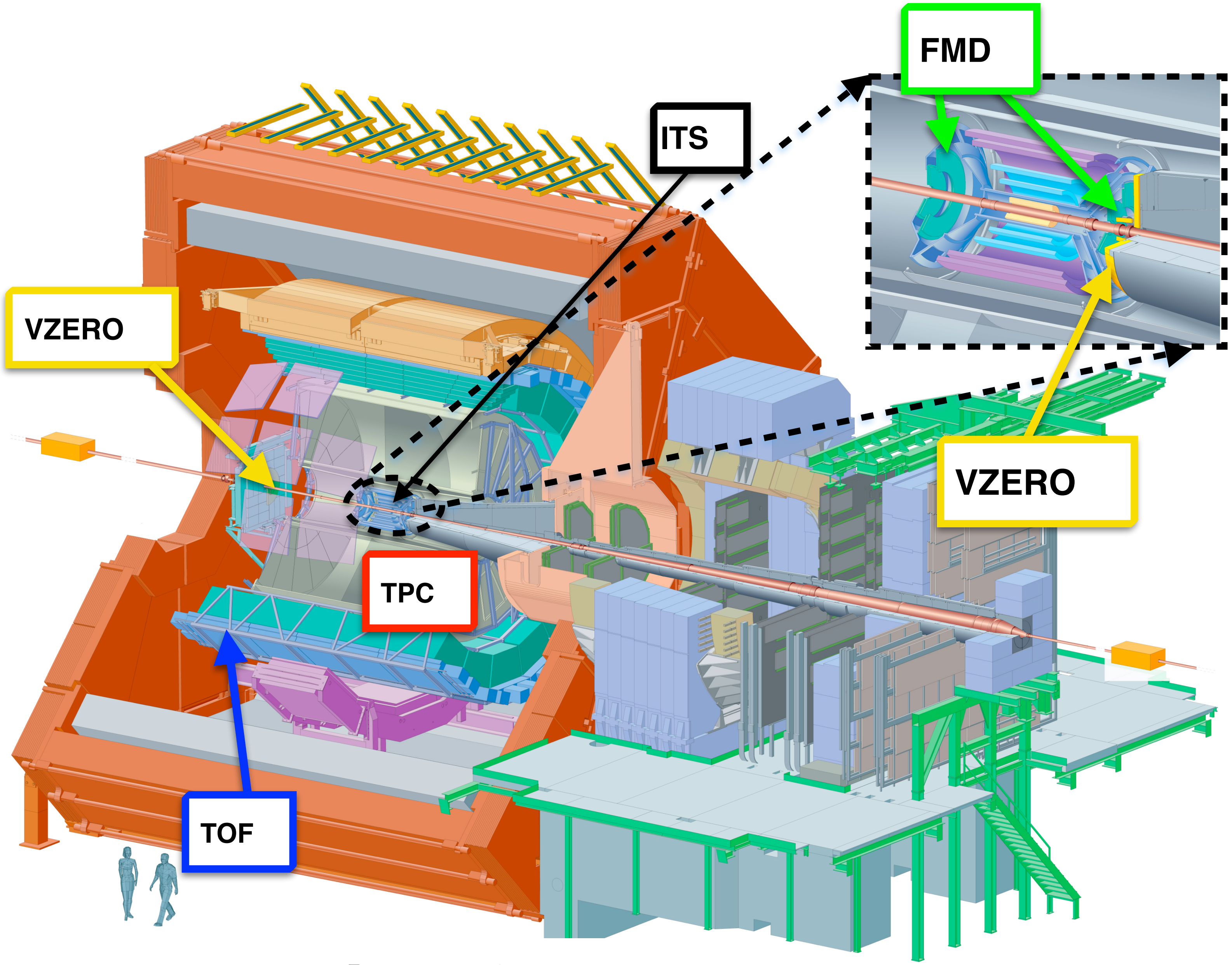
‣ Talk JPS fall 2016	‣ Poster QM2016	‣ Talk WPCF2017

- Shift taking @ ALICE
- 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
- ✓ $|\eta_{track}| < 0.8$

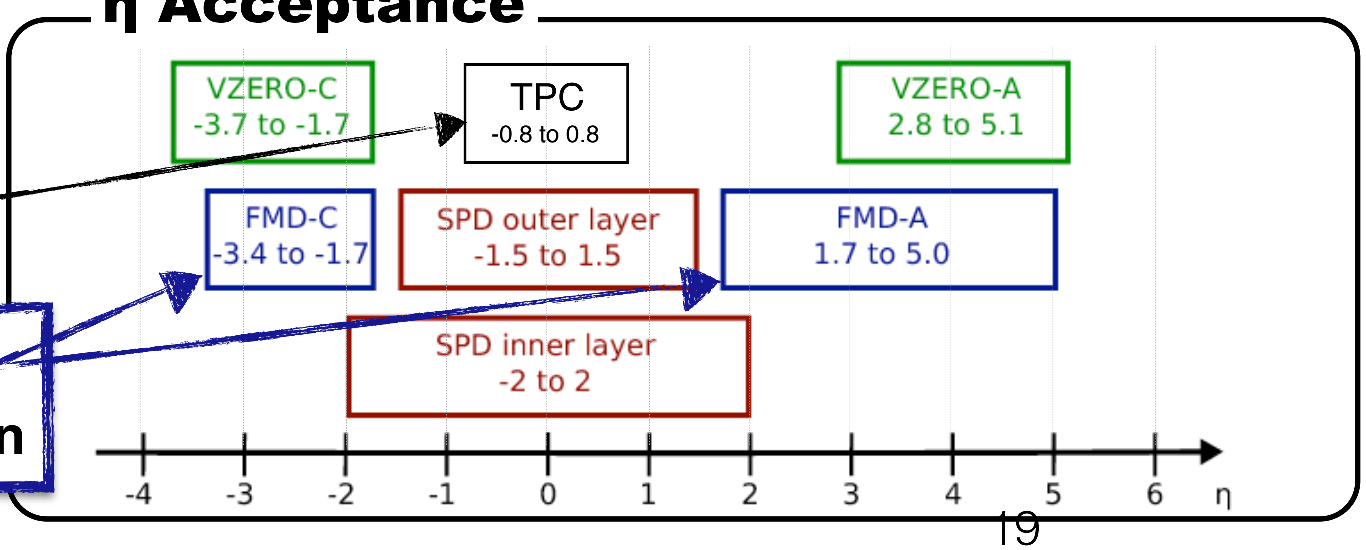
TOF
- ✓ PID
- ✓ $|\eta_{track}| < 0.8$

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

η Acceptance

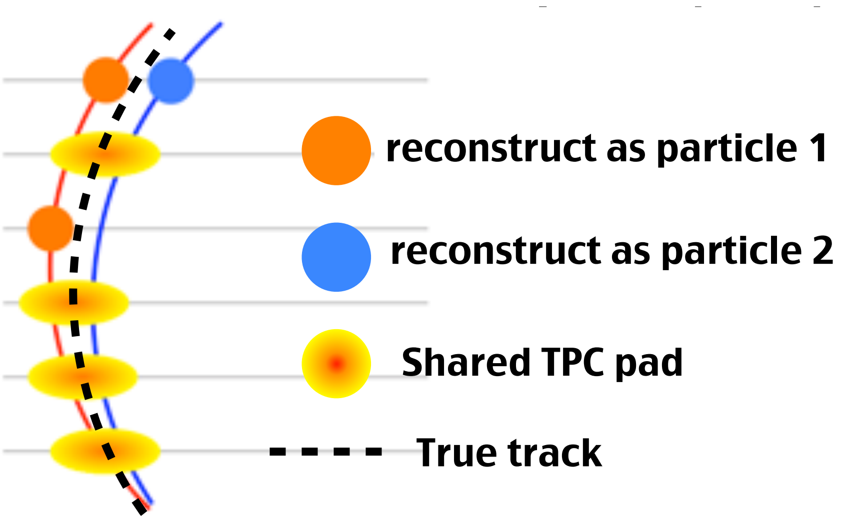
HBT

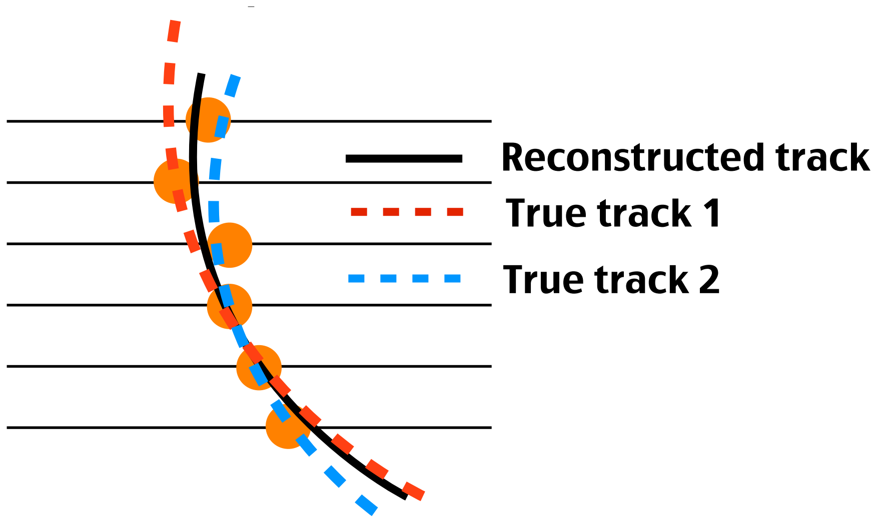
Event plane
ESE selection



Two track resolution

- Due to the high multiplicity event
  - Track splitting
    - A track is falsely reconstructed 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 $\Delta\phi^*$, $\Delta\eta$

HBT for experimental approach

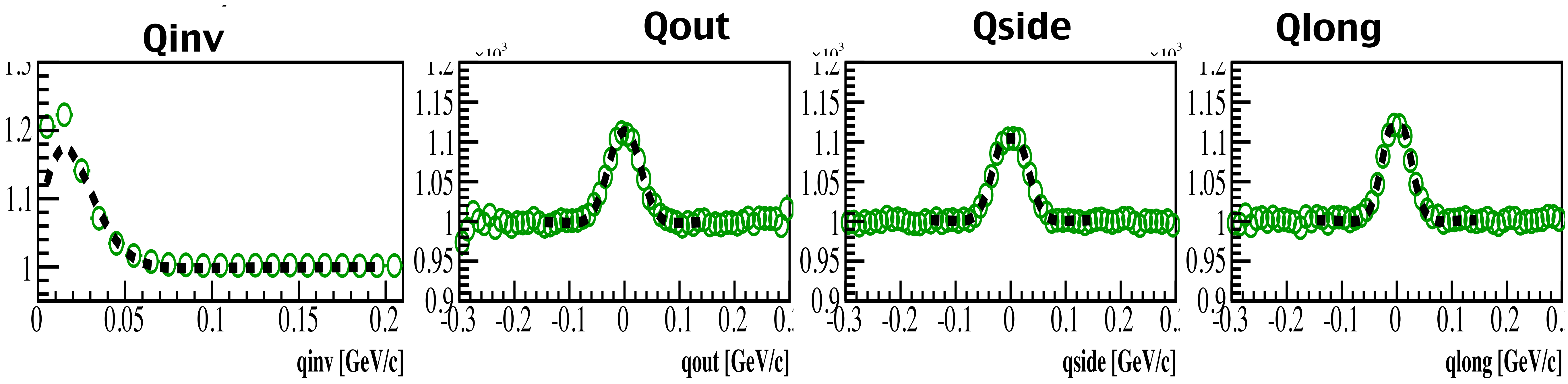
How to calculate correlation function C_2 in experiment

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

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

✓ **Event Mixing**

- Both real pairs and mixed pairs has detector efficiency
- HBT correlation is included only in real pairs
- C_2 has HBT correlation without acceptance effect and detector efficiency



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**

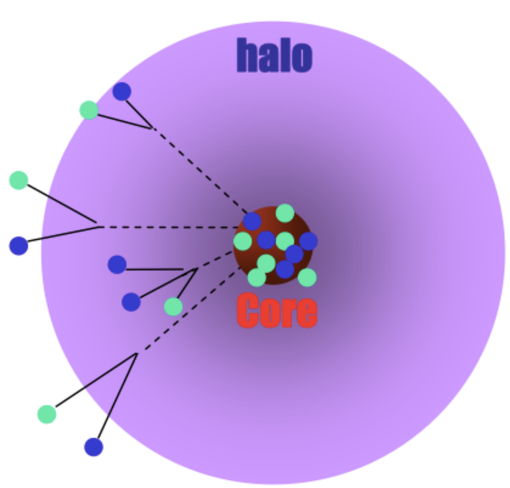
$$\left[-\frac{\hbar^2\nabla^2}{2\mu}+\frac{Z_1Z_2e^2}{r}\right]=E\Psi_c(r)$$

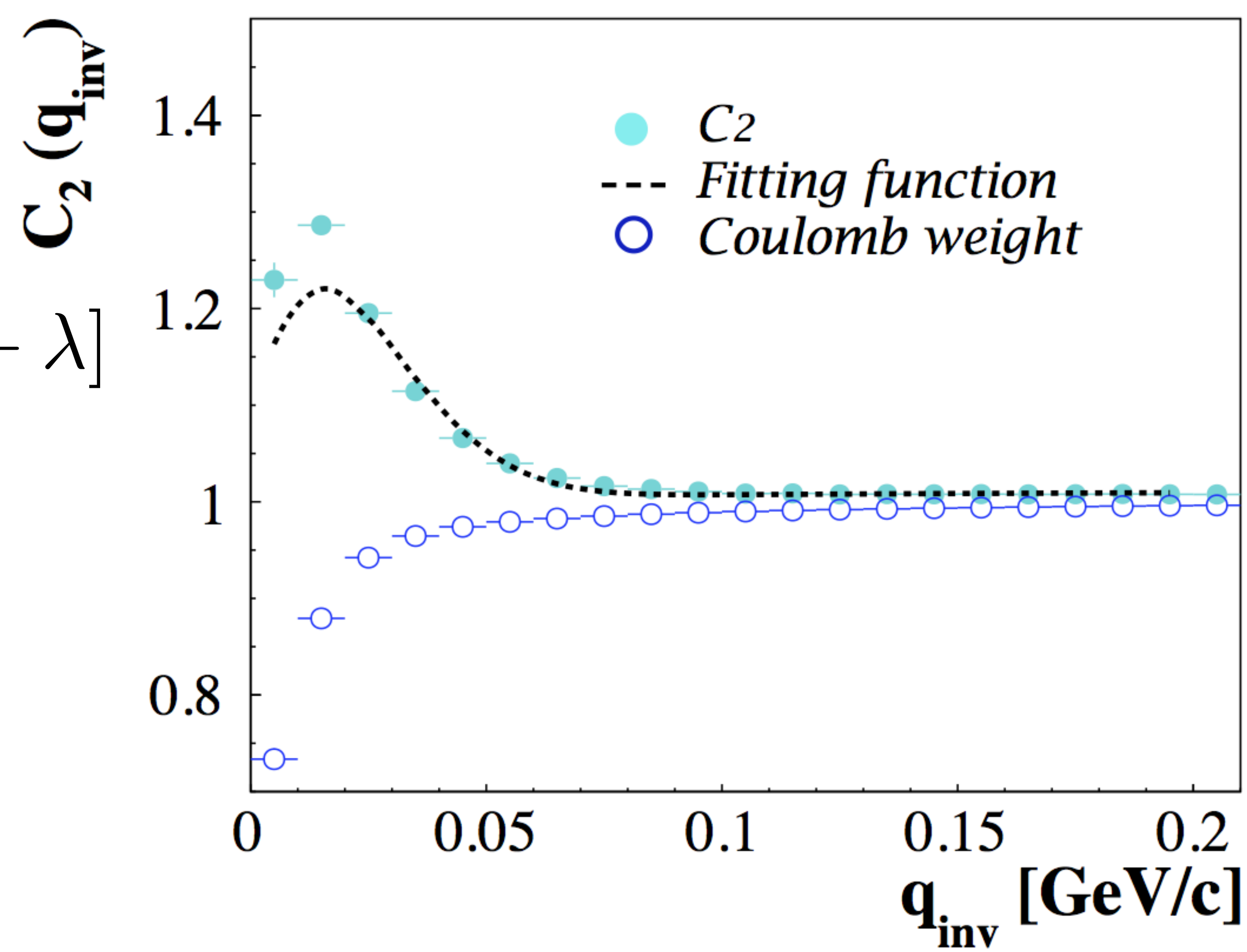
- **Resonance decay**
  - **λ in C_2 is sensitive to purity**
  - **Core-halo model**

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

✓ ***G : HBT interferometry***

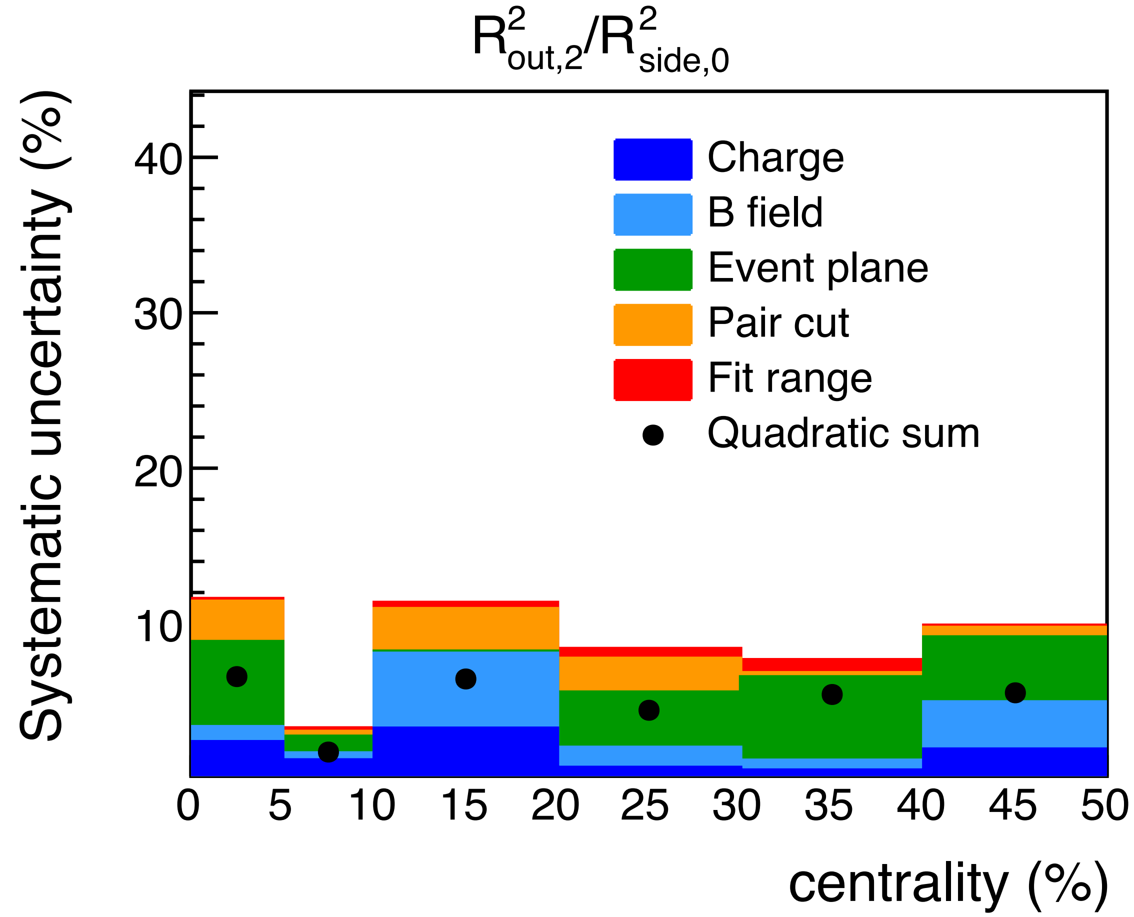
✓ ***F_{coul} : Coulomb interadtion***



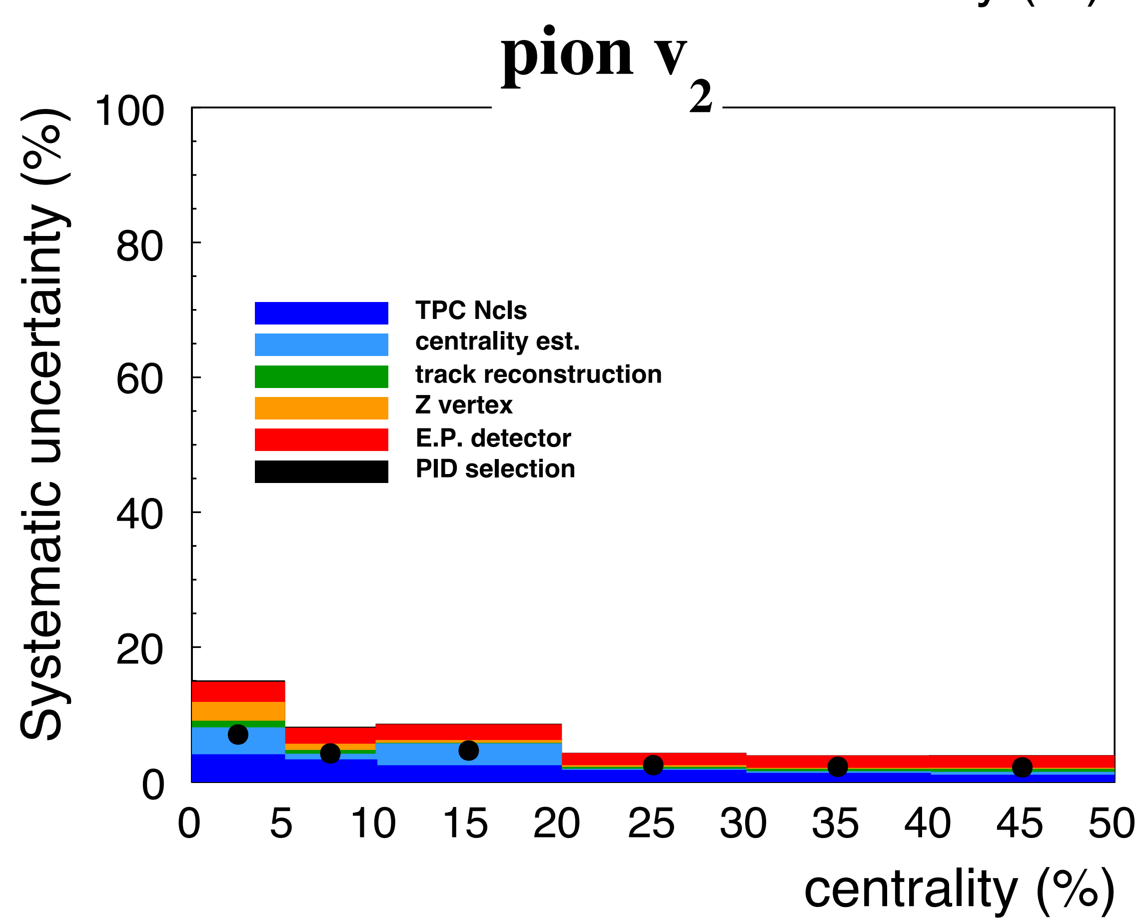


Systematic uncertainties

- HBT analysis
  - ✓ charge ($\pi^+\pi^+$ pair and $\pi^-\pi^-$ pair)
  - ✓ B field (positive and negative)
  - ✓ Event plane (VZERO detector)
  - ✓ Pair cut (tight cut 3.5σ)
  - ✓ Fit range (140, 130 MeV/*c*)



- Flow analysis
  - ✓ TPC # of clusters (50, 90)
  - ✓ Centrality estimator (ITS 2nd layer)
  - ✓ Z-vertex (5, 10cm)
  - ✓ Event Plane
    - ✓ FMDA, FMDC, V0A, V0C, V0AC, TPC(-1<η<-0.5) and TPC(0.5<η<1.0)
  - ✓ PID probability (75, 90%)



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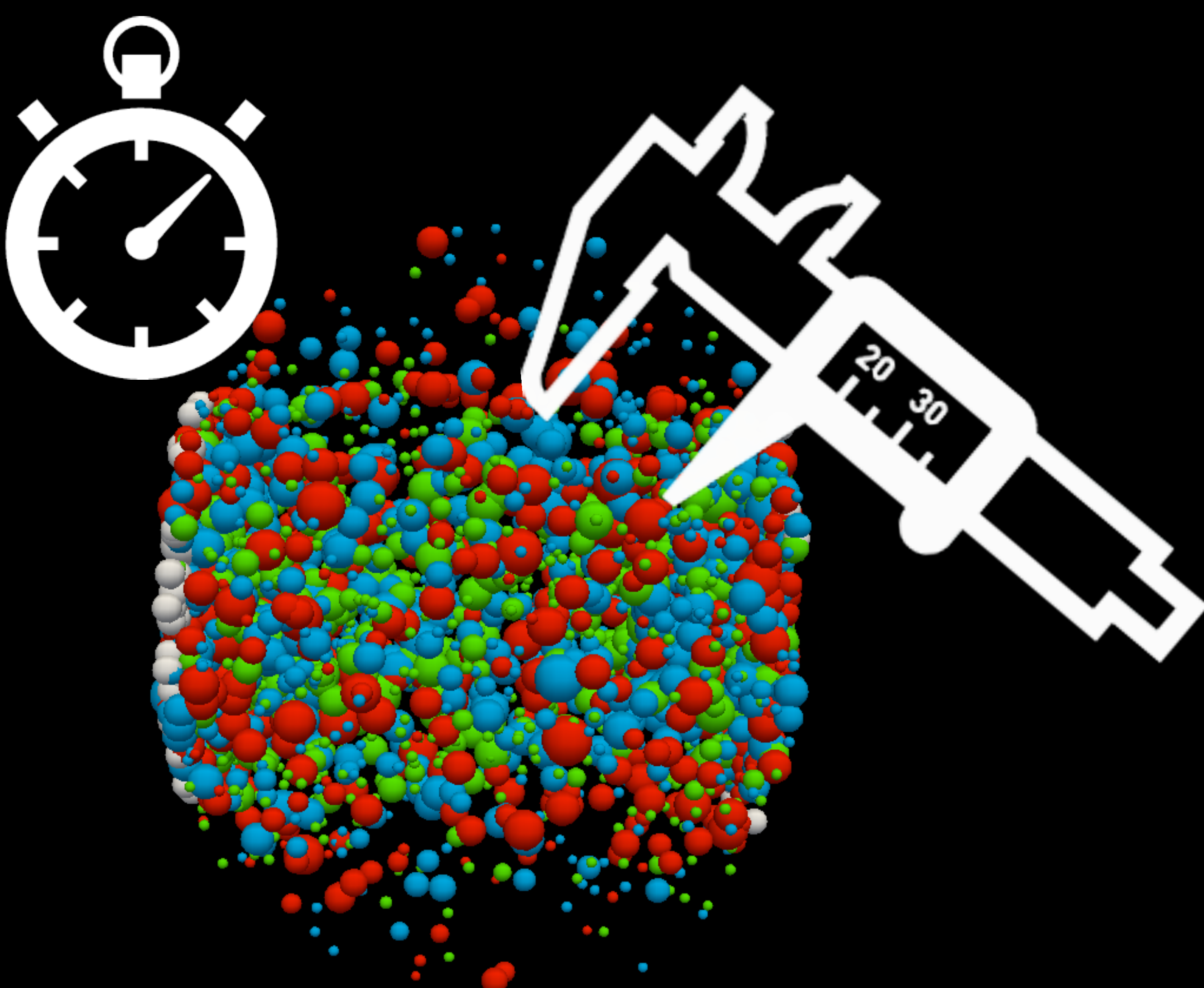
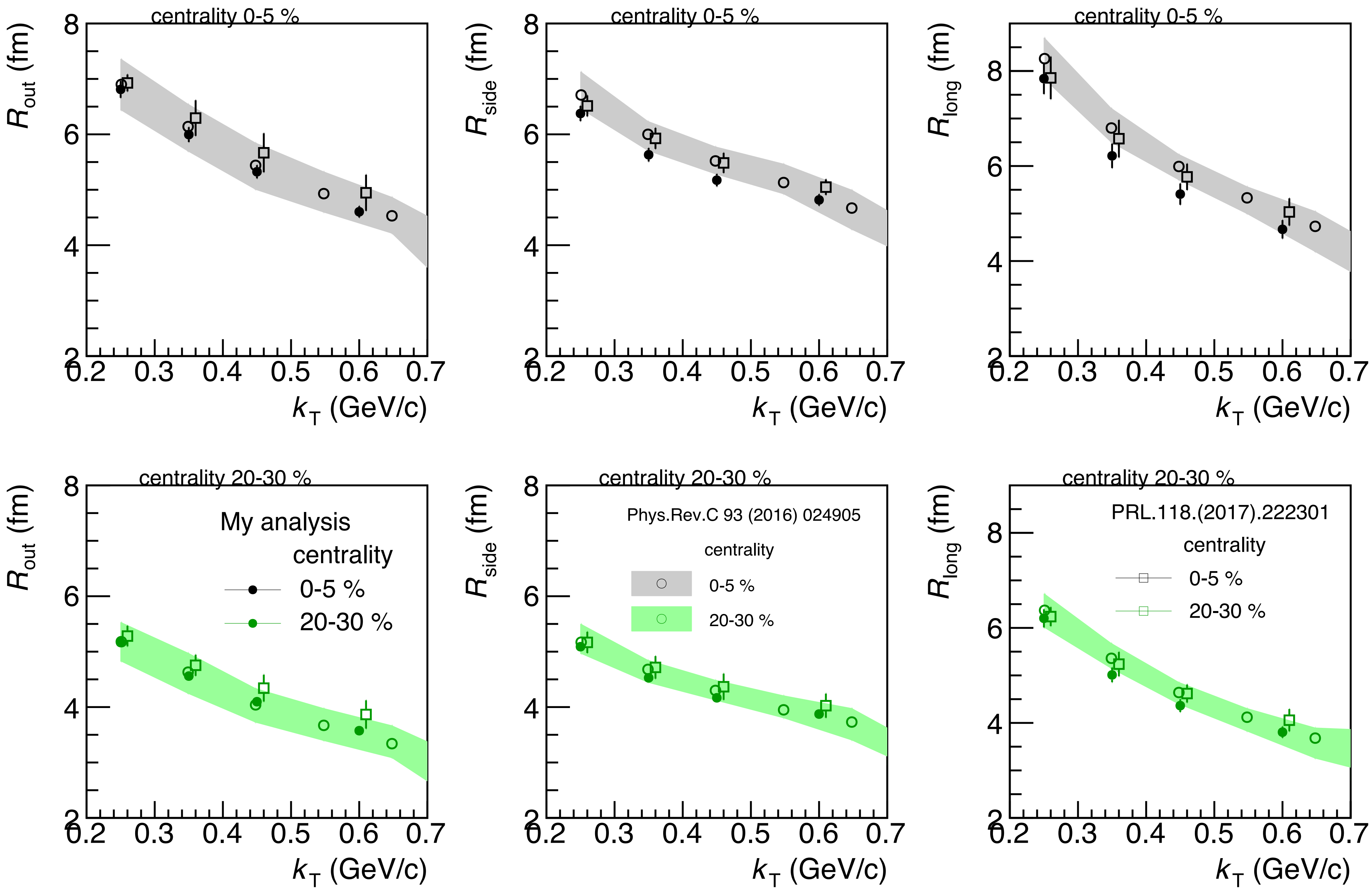
Result & Discussion

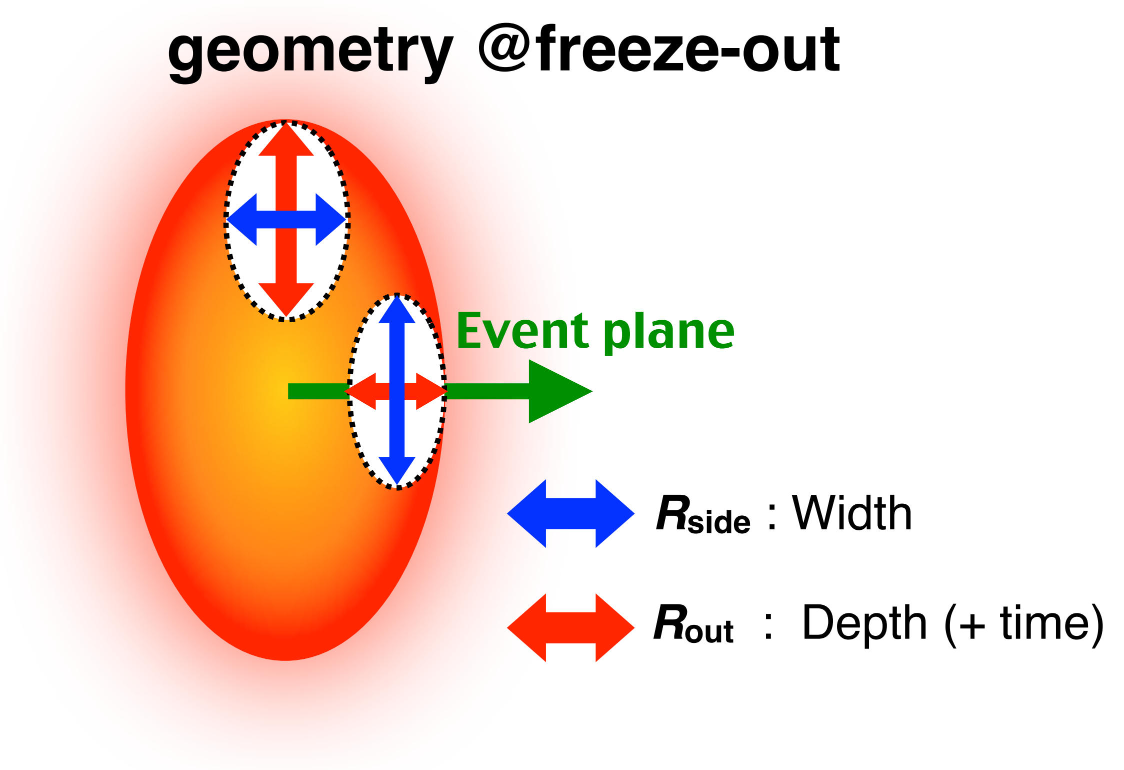


Consistency check with published results

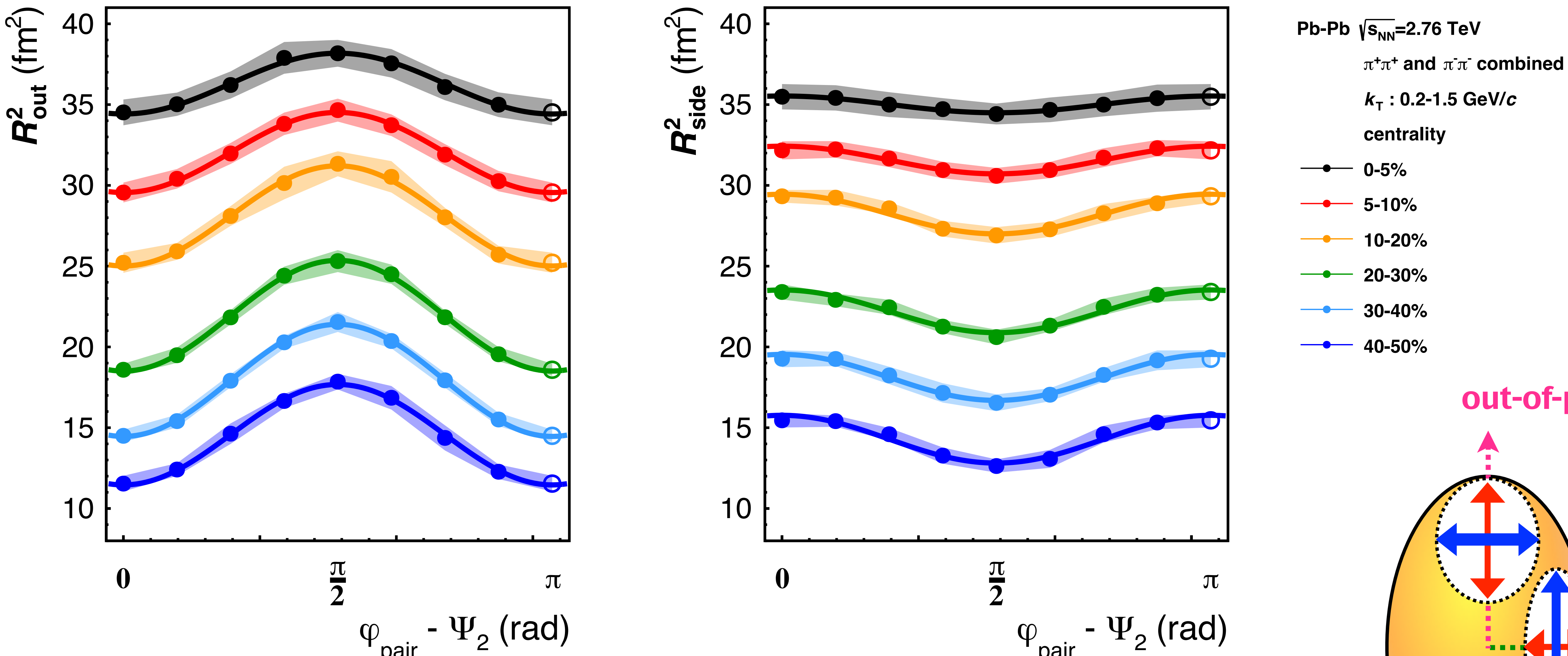


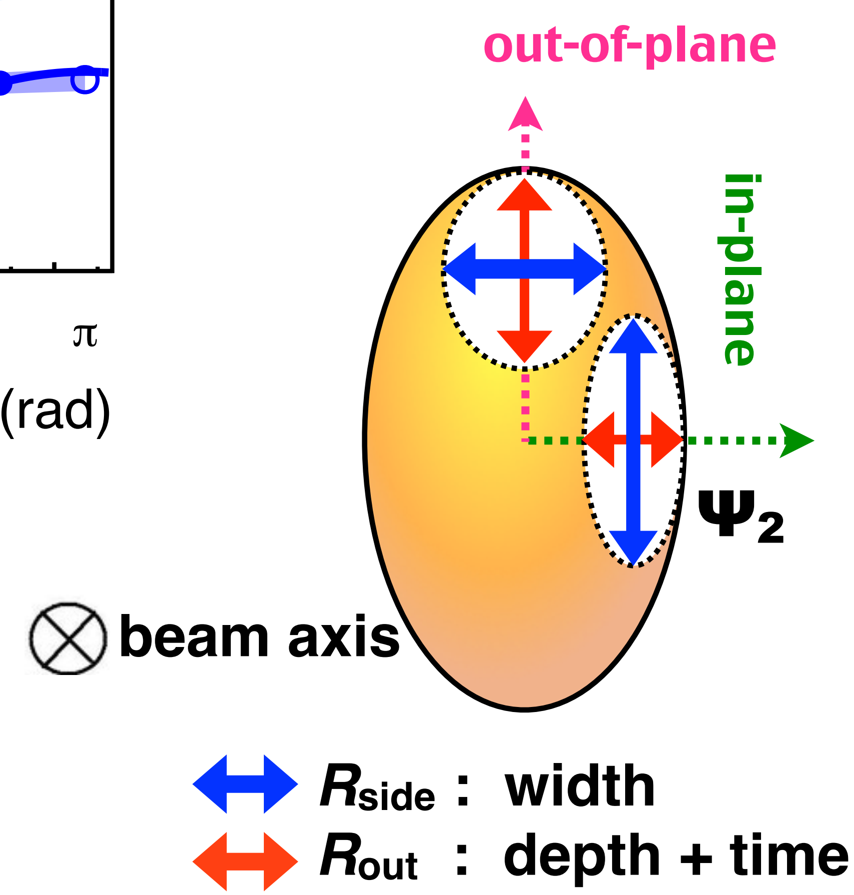
- R_{out} is fully consistent with published results
- R_{side} and R_{long} are systematically smaller than published result, but all results are consistent within systematic uncertainties

Second harmonics



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

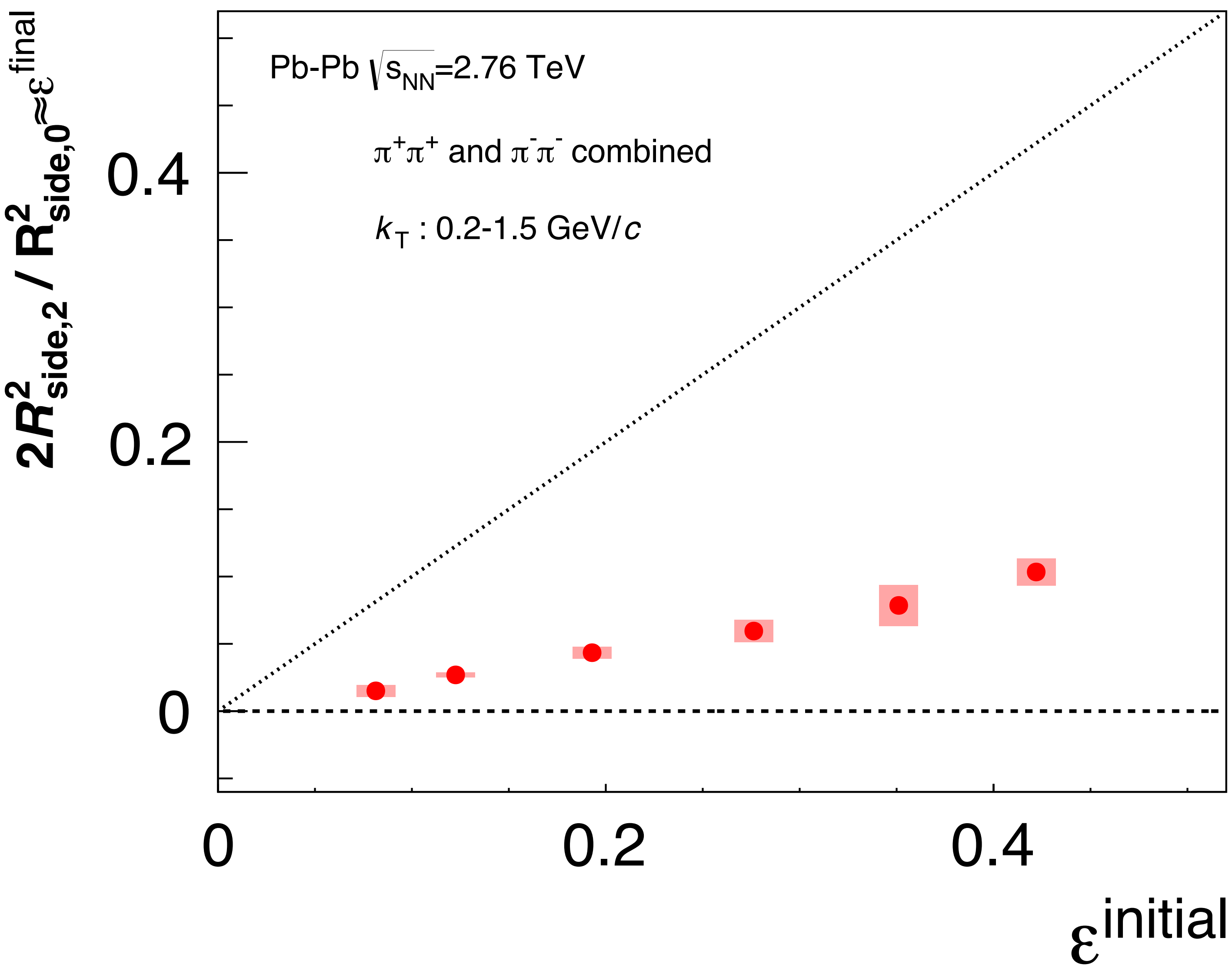




- Fit function : $R^2_{\mu,0} + 2 R^2_{\mu,2} \cos(2(\phi_{pair} - \Psi_2))$
  - $R^2_{\mu,0}$: Average HBT radii
  - $R^2_{\mu,2}$: Oscillation amplitude

- **Explicit oscillation can be seen in R_{out}, R_{side}**
- **Oscillation of R_{out} and R_{side} is out-phase**
- **R_{out} has larger oscillation than R_{side}. sensitivity to duration time !**
  - ✓ **R_{out} is sensitive to β_T ($R^2_{out} = R^{2*}_{out} + \beta_T \Delta\tau^2$)**

Initial ε_2 v.s. final ε_2

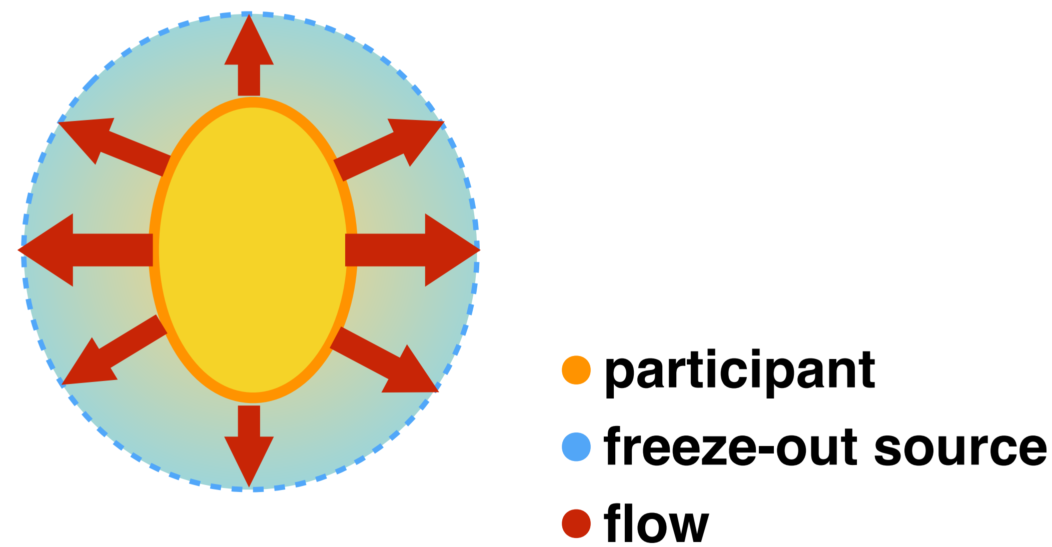


Final source Eccentricity

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

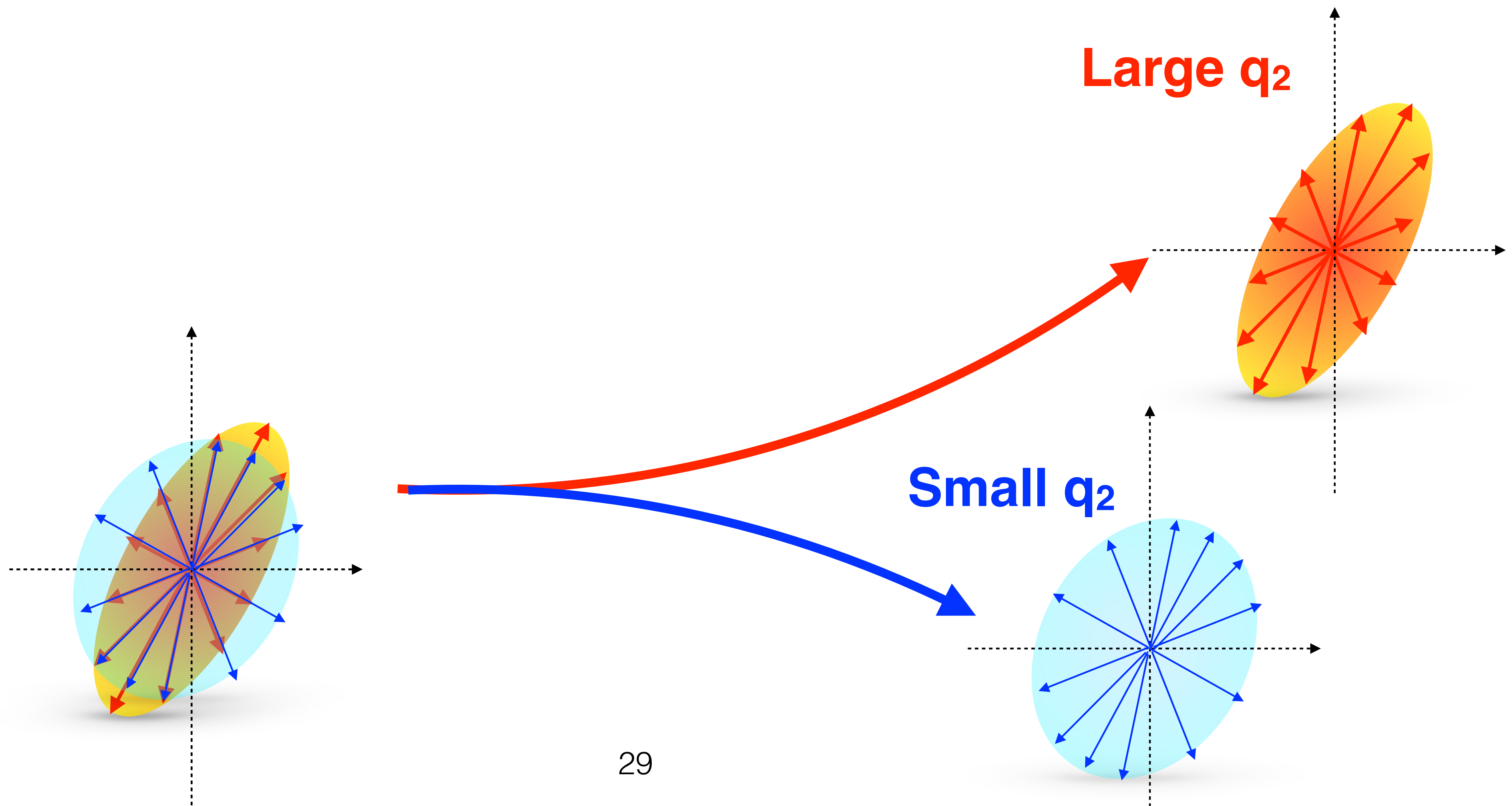
- **ε_{final} is extracted via HBT oscillation ($k_T \to 0$)**

F. Retiere and M.A.Lisa, PRC70.044907

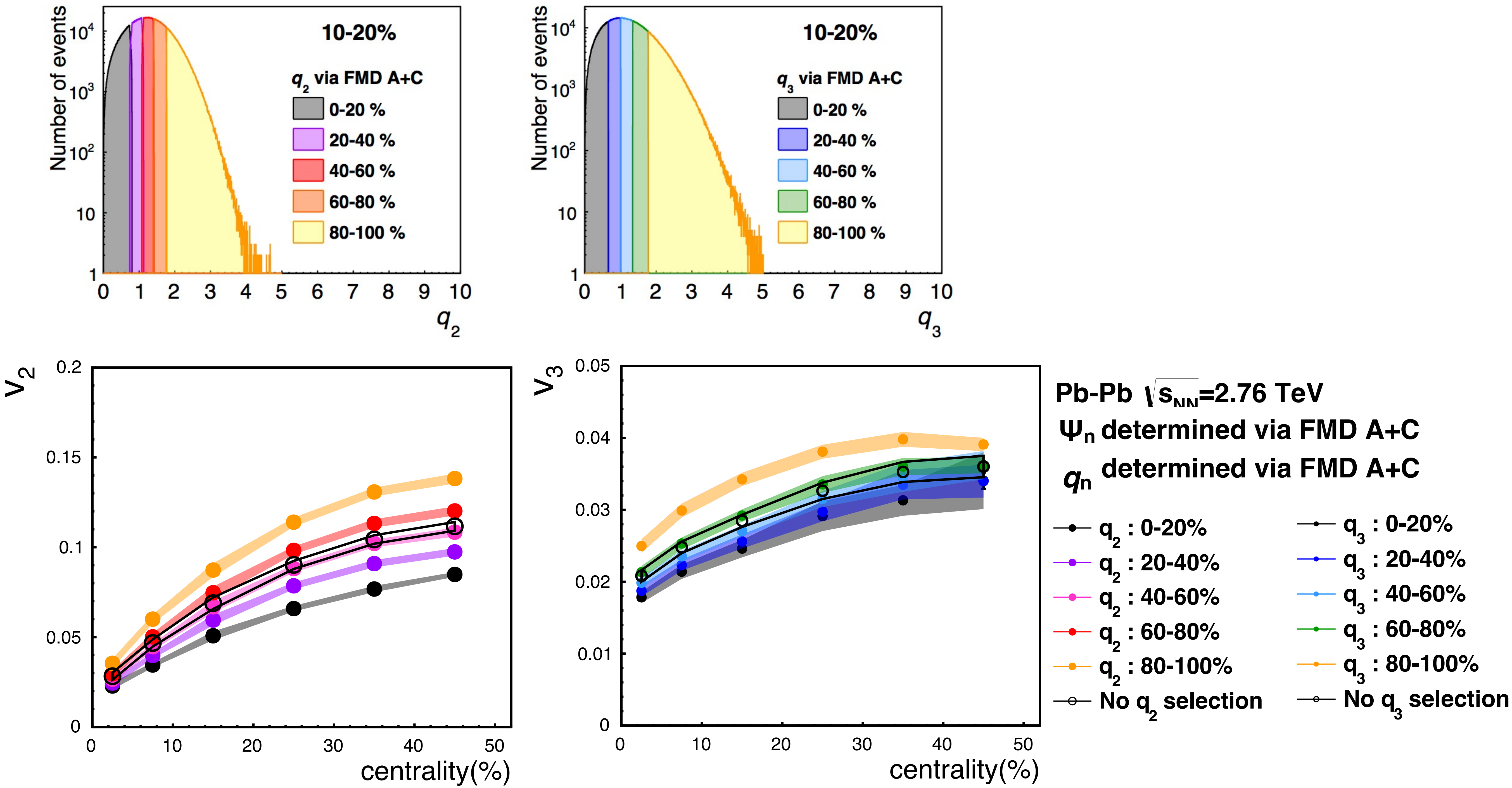


- **Initial elliptic shape has strongly diluted with radial flow and elliptic flow**
- **Final source eccentricity linearly increases with increasing $\varepsilon^2_{initial}$**
  - ➡ **Dilution effect linearly increases to $\varepsilon_2^{initial}$?**
- **Even in most central collision , $2R^2_{side,2} / R^2_{side,0} > 0$**
  - ➡ **Initial out-plane elongated elliptic shape still remains at freeze-out time**

Event Shape Engineering
v_n cut (initial ε_n selection)

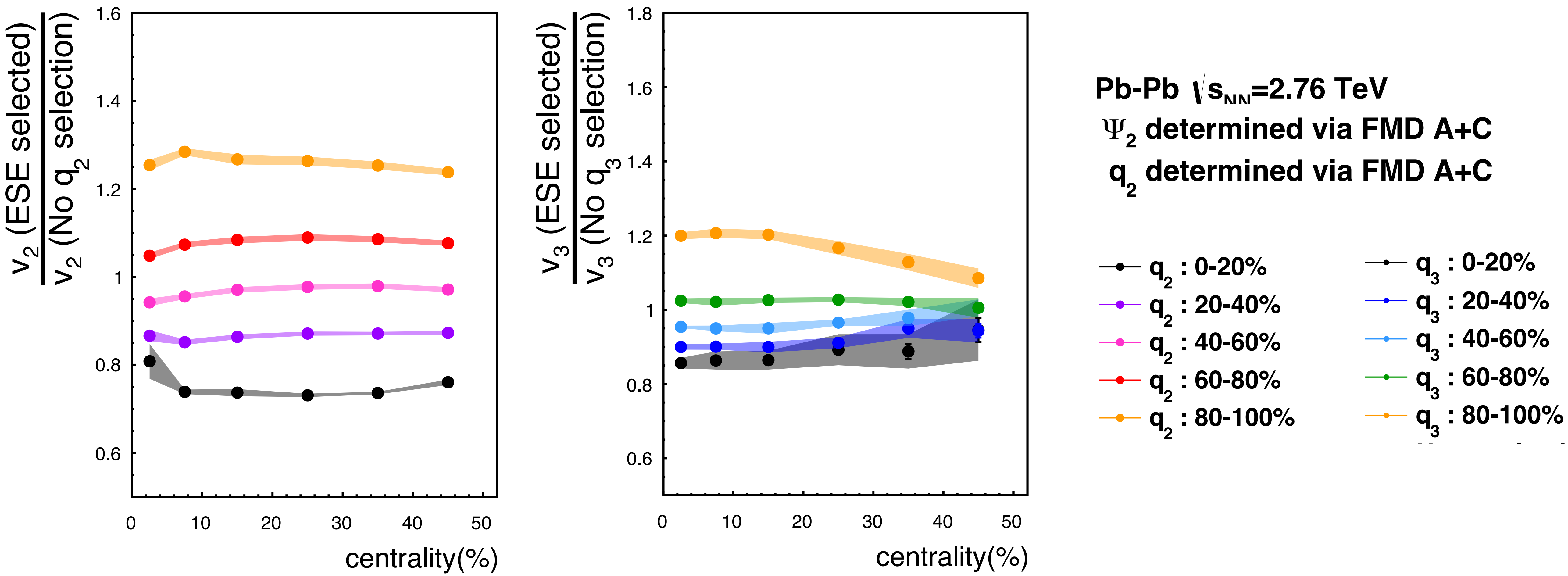


v_n for each 20% Event shape q_2, q_3 selection



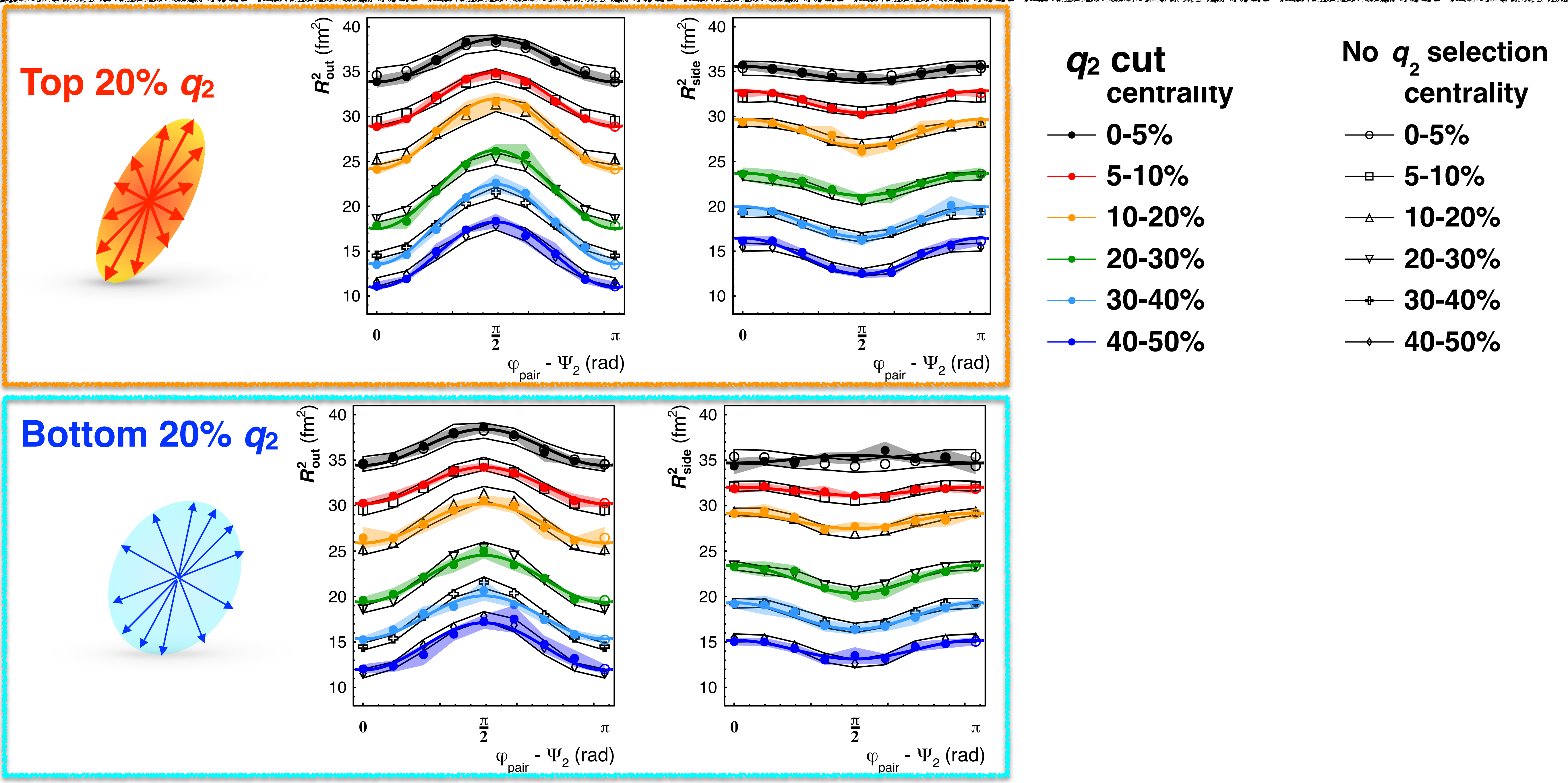
- ☐ 0-20% (80-100%) q_n selection denotes top (bottom) 20% cut
- ☐ Event by event v_2 and v_3 fluctuations can be selected with ESE cut

Ratio of v_2 and v_3 (ESE selected / No ESE cut)



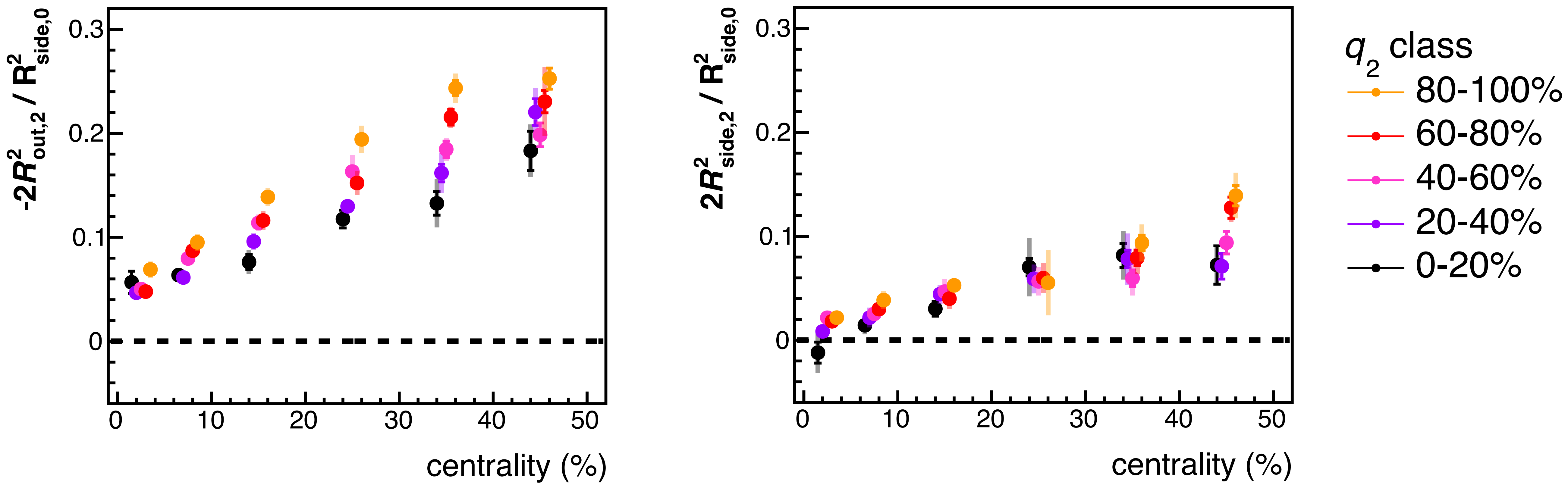
- **Both q_2 and q_3, enhancement (suppression) with ESE cut can be found**
- **Ratio of v_2 slightly depends on centrality**
- **Enhancement(suppression) effect becomes smaller from central to peripheral collisions in ratio of v_3**
- **"Selectivity " of q_2 cut is larger than that of q_3**
  - ✓ **Centrality dependence and difference of selectivity can be interpreted with Event plane resolution**

q_2 selection + azimuthal angle dependence of HBT w.r.t. Ψ_2



- 20% q_2 selection enhanced(suppressed) oscillation of R_{out} and R_{side}
  - Correlation between v_2 and ε_2 final can be found
- For smallest q_2 selection(0-20%)
  - R_{side} could have positive sign oscillation

Relative amplitude of HBT radii (2nd harmonics)



✴ All points are shifted along x-axis for visibility

- ✦ $-2R^2_{out,2}$ / $R^2_{side,0}$ increase from small q_2 to large q_2 in all centrality
- ✦ $2R^2_{side,2}$ / $R^2_{side,0}$ (~ε_2^{final}) increases with increasing q_2 in 0-20% and 40-50% collisions
- ✦ In most centrality 0-5% and smallest q_2, $2R^2_{side,2}$ / $R^2_{side,0}$ (~ε_2^{final}) shows <u>negative (or zero)</u>

➡ Elliptic shape at freeze out might be vanished or even reversed

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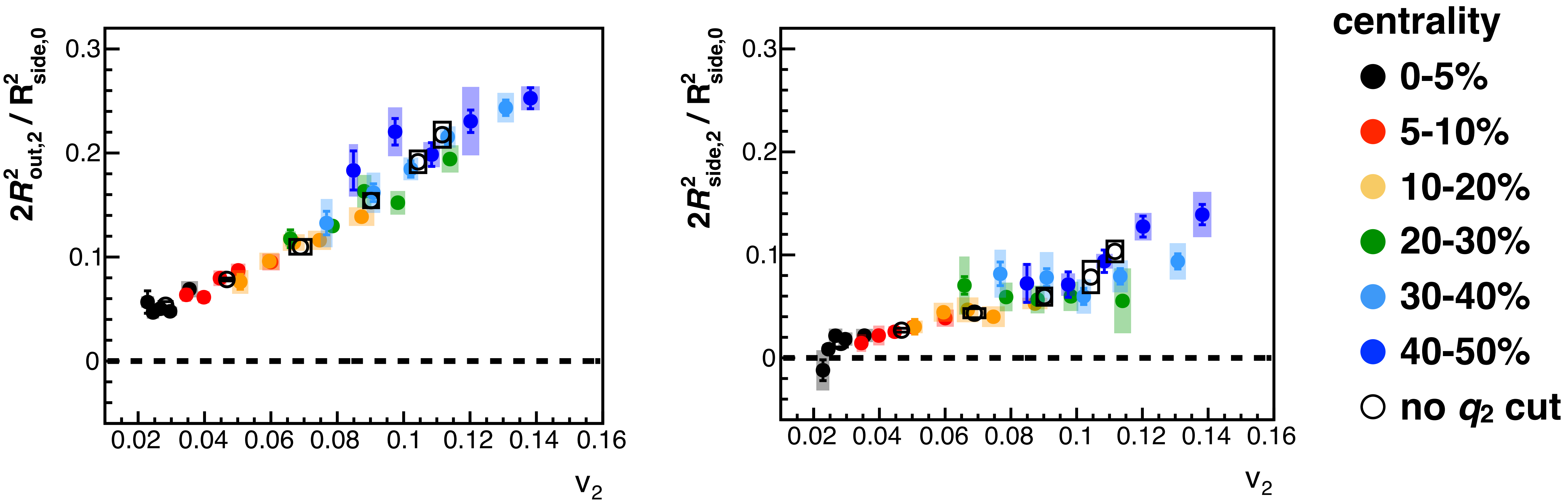
v_2 scaling to Relative amplitude of HBT radii

✓ Difference of event by event initial geometry fluctuation can not be reflected to "centrality"

✓ More sensitive probe is necessary !

- ✦ Empirical correlation between v_2, $\varepsilon_2^{initial}$ and energy density
- ✦ $v_2 \propto \varepsilon_2^{\mathrm{initial}} \cdot \mathrm{f}\,(d\mathrm{N}/d\eta)$



✓ **Both relative amplitudes of R_{out} and R_{side} are scaled with v_2**

✓ In a same dN/dη(centrality), correlation between v_2 and relative amplitudes of HBT radii ~ correlation between $\varepsilon_2^{initial}$ and ε_2^{final}

✓ **In centrality 20-40%, $2R^2_{side,2} / R^2_{side,0}$ (~ε_2^{final}) does not depends on $\varepsilon_2^{initial}$**

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k_T dependence of relative amplitude of HBT radii (2nd harmonics)

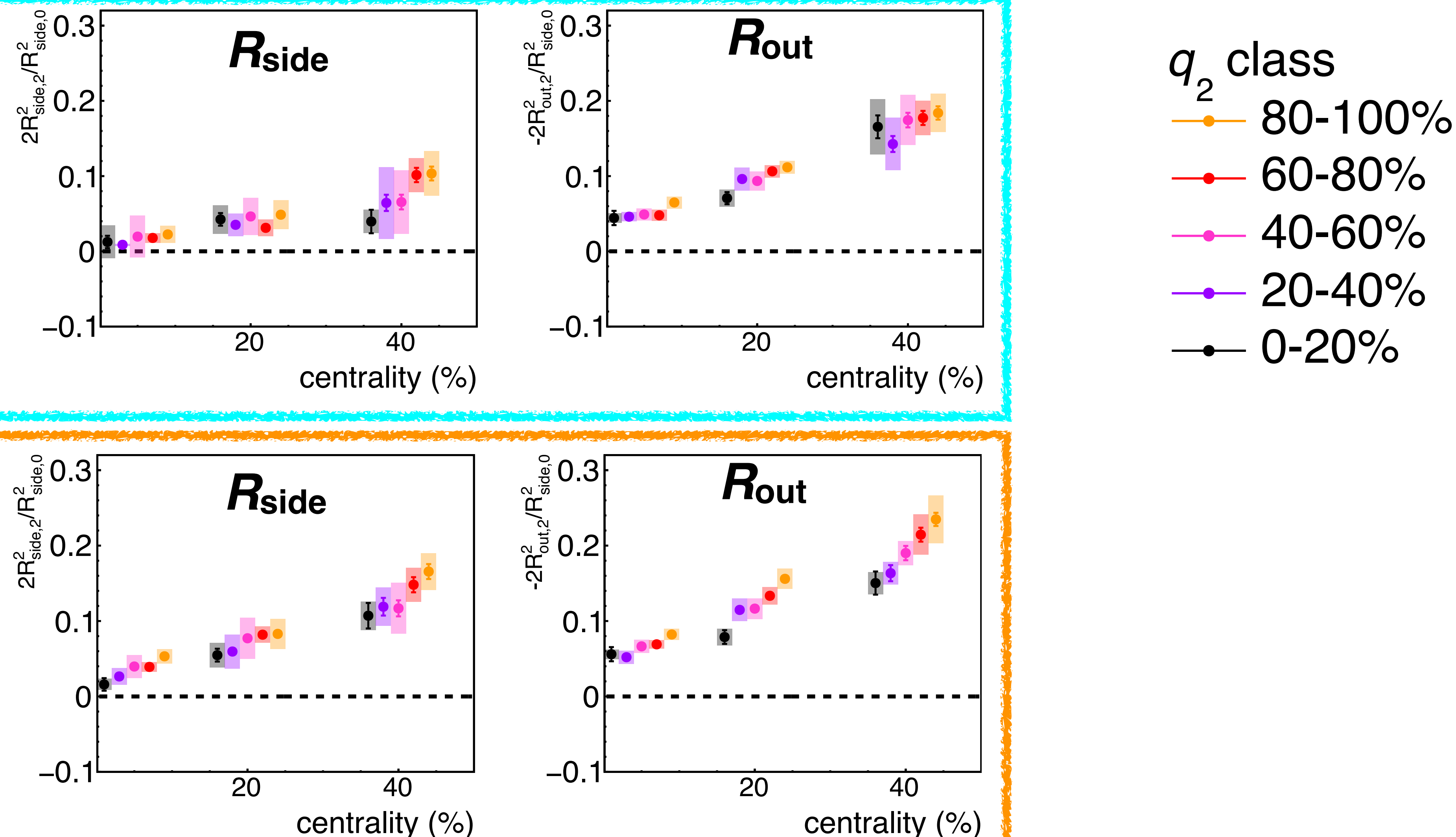
✴ All points are shifted along x-axis for visibility

low k_T

$0.2 < k_T$ (GeV/c) < 0.3

high k_T

$0.4 < k_T$ (GeV/c) < 1.5



- ✦ $-2R^2_{out,2} / R^2_{side,0}$ increase from small q_2 to large q_2 in all k_T
- ✦ Insensitivity of $2R^2_{side,2} / R^2_{side,0}$ ($\sim\varepsilon_2^{final}$) to q_2 can be found in low k_T and mid central collisions
- ✦ In mid central collisions, elliptic shape at freeze-out might not be changed by initial elliptic shape
  - ➡ correlation between initial geometry and collective flow could generate this effect

Blast-wave fit for spectra, v_2 and HBT radii

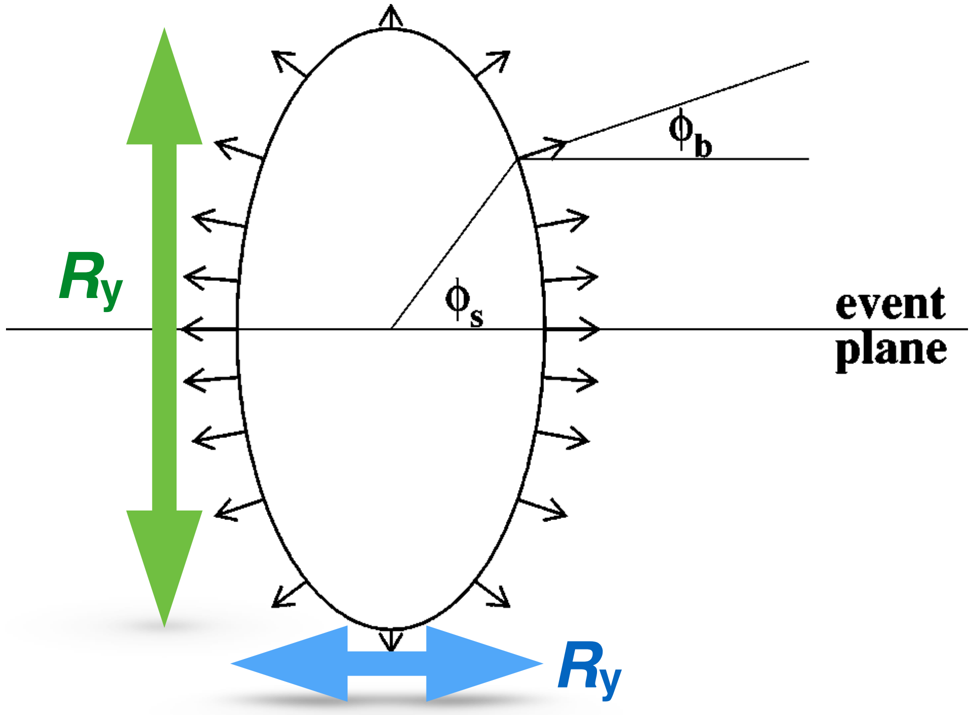
- **What makes the difference of relative amplitude of HBT radii with q_2 selection ?**
    - ✦Blast-wave model allows us to extract spatio-temporal parameters, analytically
- Blast-wave model is based on the hydrodynamical model
- Extended to Azimuthally sensitive HBT interferometry (Phys. Rev. C 70 044907)

★ **Blast-wave parameters**

- Freeze out temperature : T_f
- Flow velocity : $\rho(r,\phi_s) = r(\rho_0 + \rho_2 \cos(2\phi_b))$
- Transverse extents R_x, R_y
- System lifetime : τ_0
- Emission duration : $\Delta\tau$

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

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



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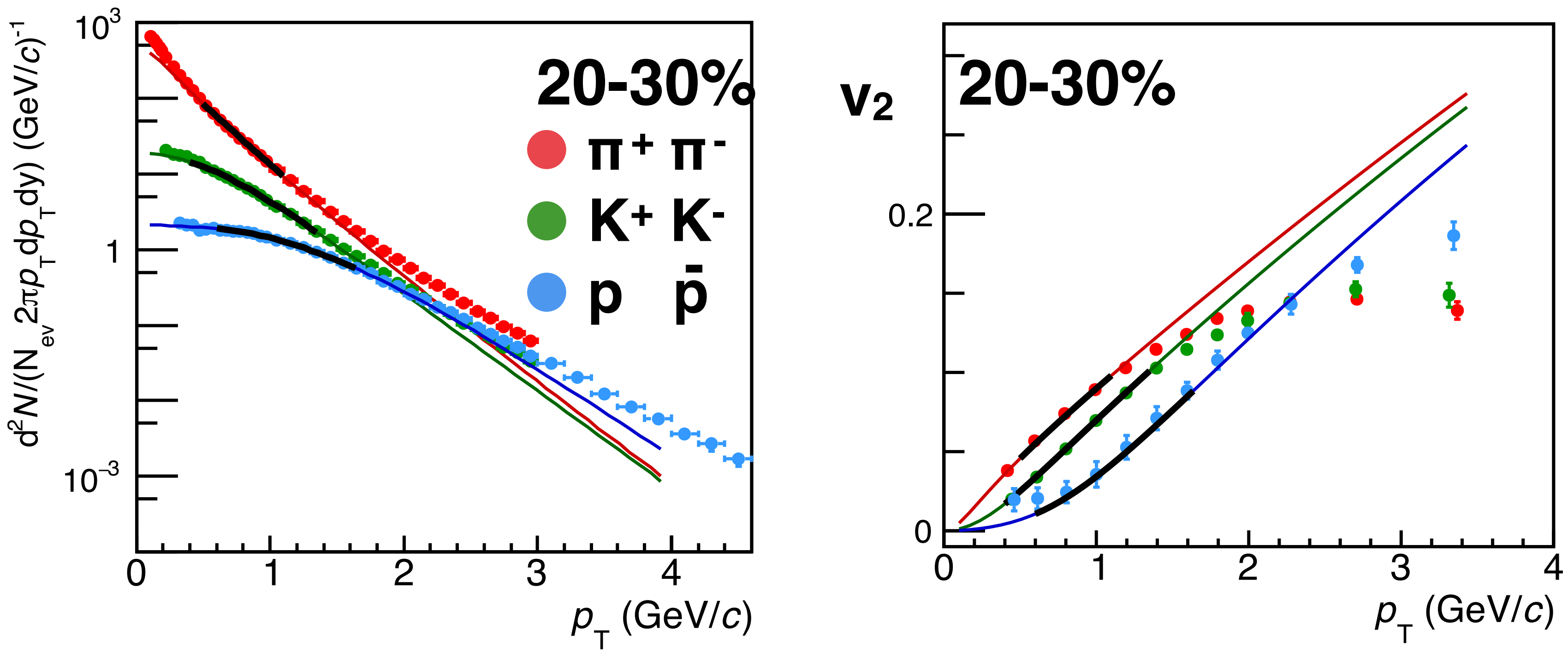
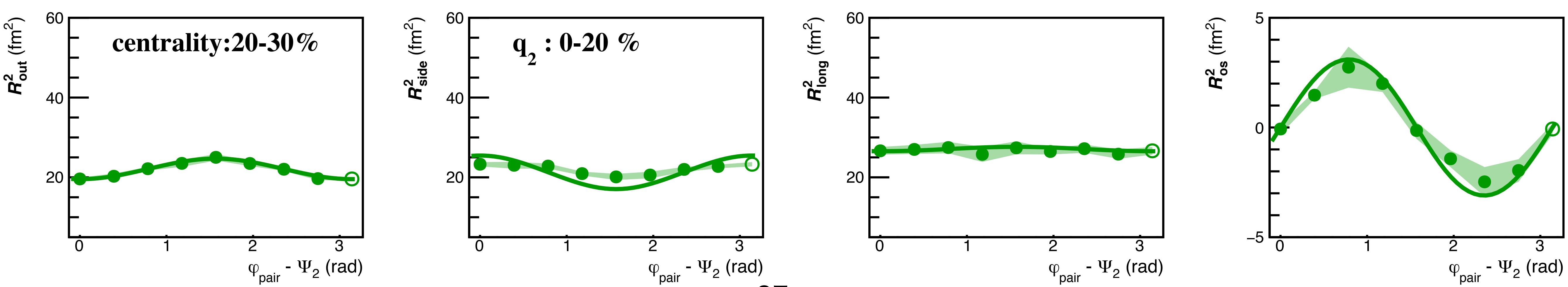
Blast wave fit for Spectra, v_2 and HBT radii

- **T_f, ρ_0** is determined with π, K, p spectra (independent of v_2 and HBT)
  - ✓ assuming that T_f and ρ_0 don't change within systematic uncertainties
- **ρ_2, R_x, R_y/R_x, τ0, Δτ** are determined with simultaneous fitting of v_2 and HBT fit



✤ spectra (Phys.Rev.C 88, 044910 [2013])



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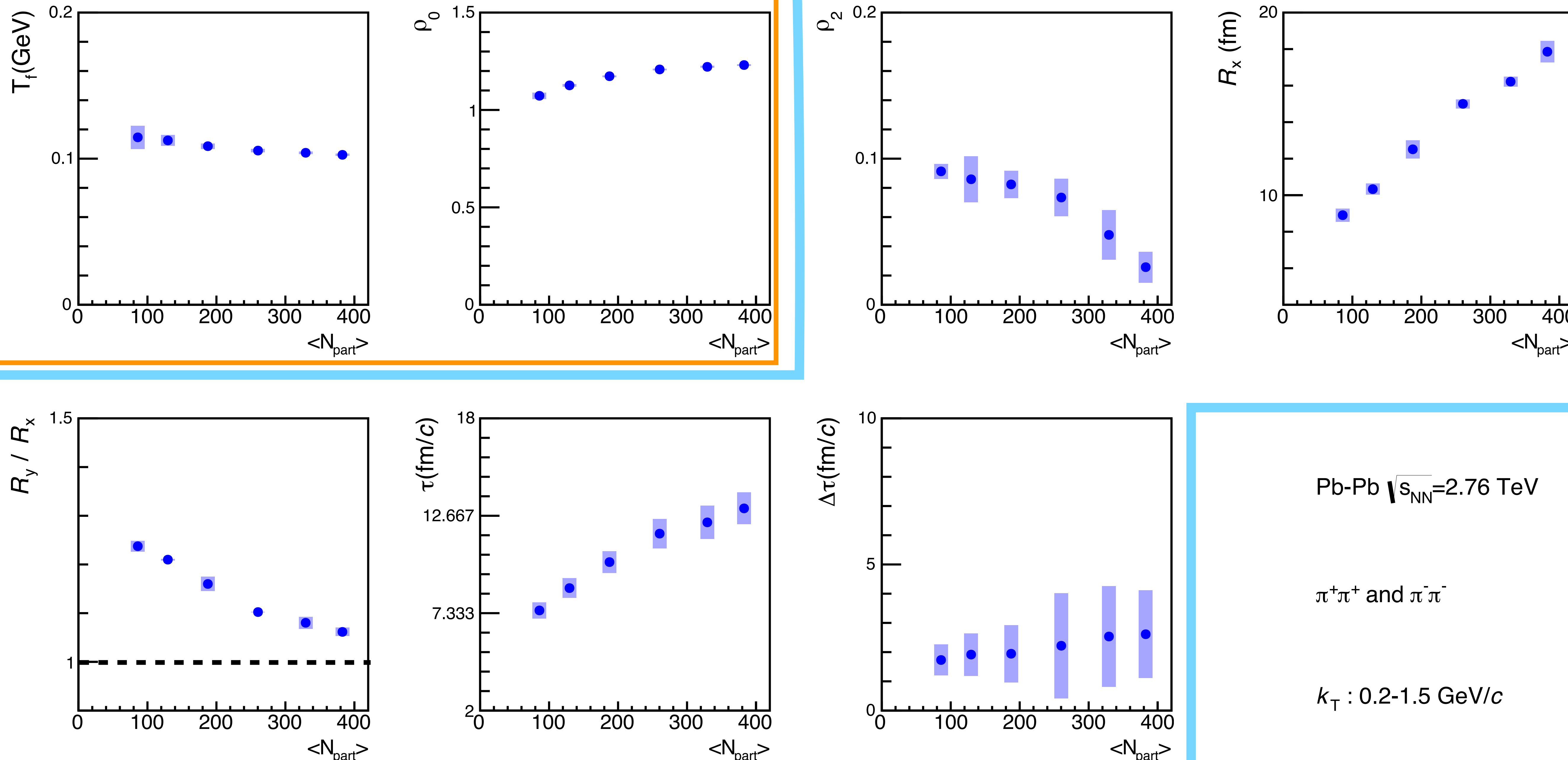
Extracted Blast Wave parameters

✓ Fully consistent with published result



✦ Source size(R_x) and freeze out time (τ_0) increases as a function of <N_{part}>

✦ Emission duration slightly increase with increasing <N_{part}>

✦ R_y/R_x, T_f and ρ_2 decrease from peripheral to central

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

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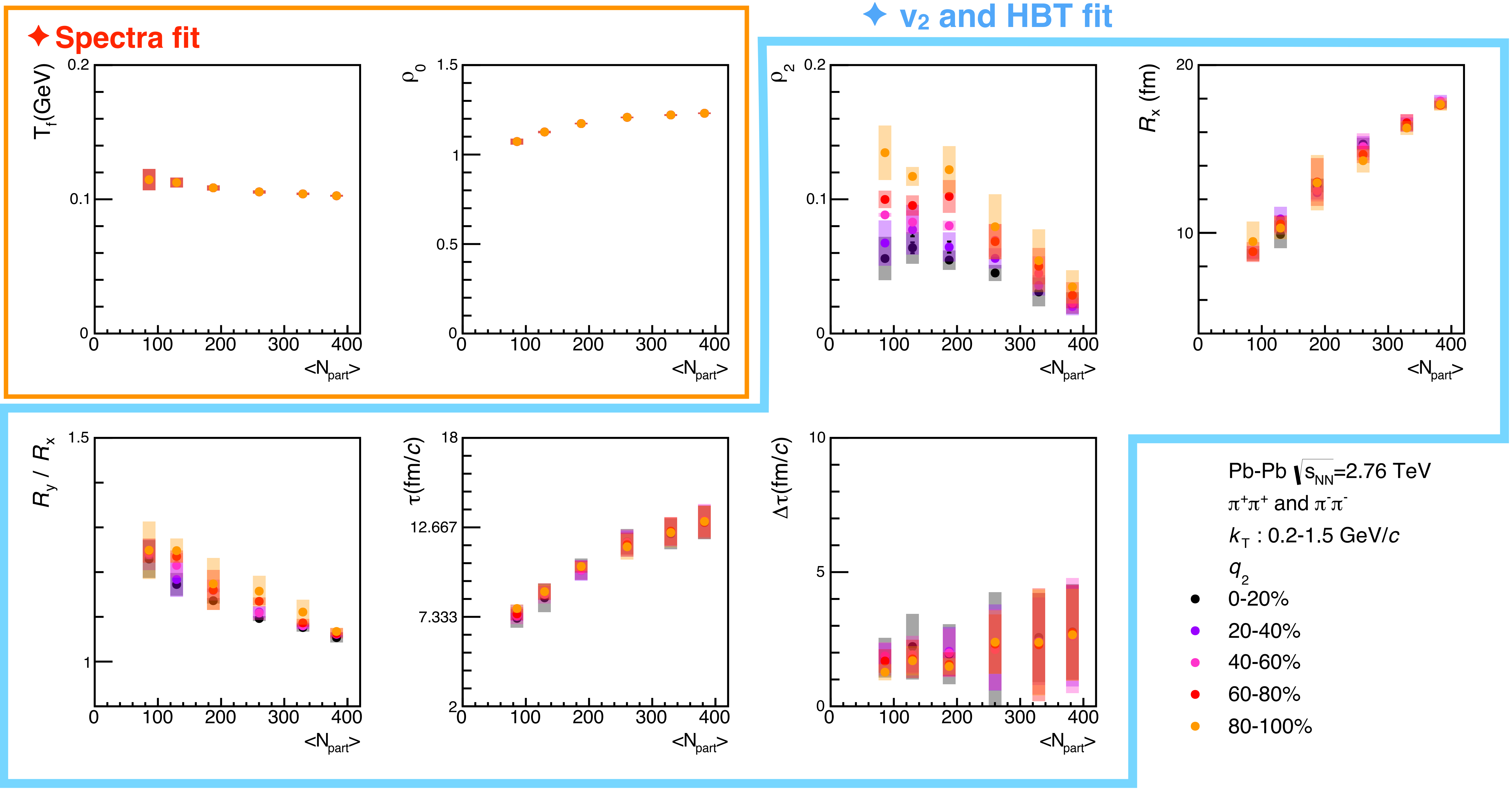
Extracted Blast Wave parameters with ESE q_2 cut



- ✦ ρ_2 significantly changes with q_2 selection
- ✦ R_y/R_x, τ slightly changes with q_2 cut, but consistent within systematic uncertainties
- ✦ No significant difference can be found in R_x, Δτ

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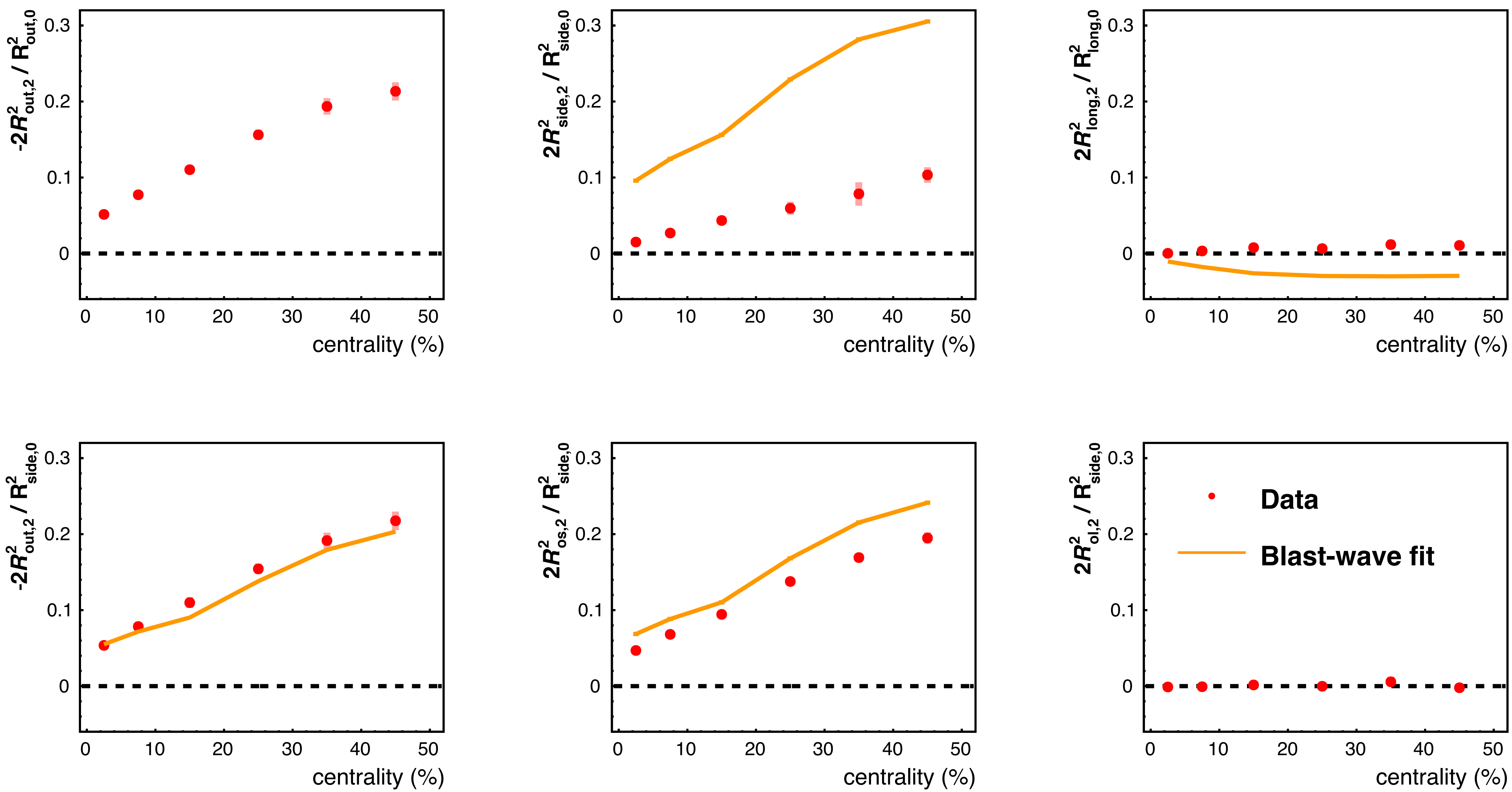
Comparison with Blast-wave model (relative amplitude)



✦ $-2R^2_{out,2} / R^2_{side,0}$ is consistent within a systematic uncertainty

✦ $2R^2_{side,2} / R^2_{side,0}$ of Blast-wave is much larger than that of Data

✦ $2R^2_{os,2} / R^2_{side,0}$ of Blast-wave is slightly larger than that of Data

★ More realistic model is necessary 40

Summary-1

- **Azimuthal angle dependence of HBT relative to 2nd order event plane**
  - **Explicit oscillation can be found in R_{out}, R_{side}**
  - **Initial elliptic shape is strongly diluted by collective flow, but out-plane elongated elliptic shape still remains at freeze-out**

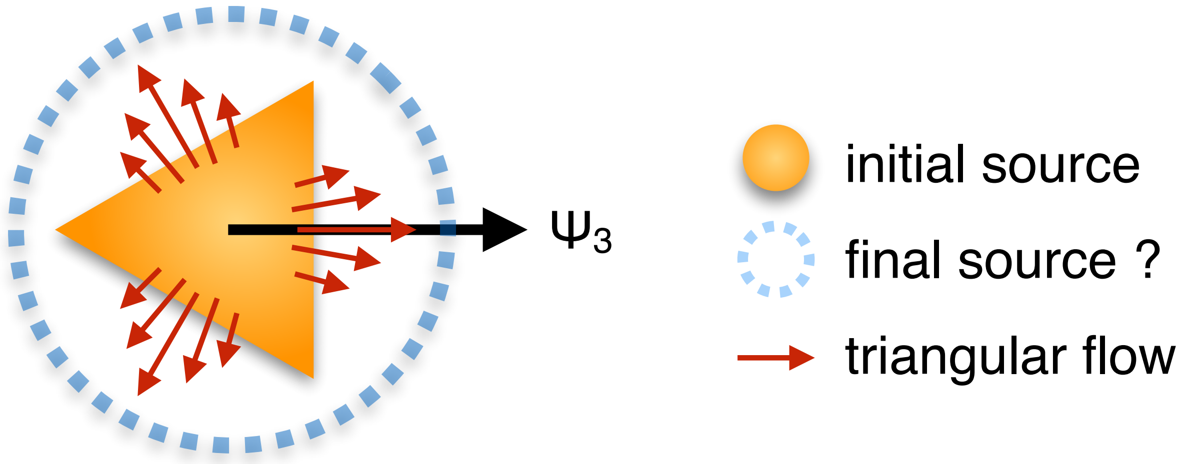
- **ESE applies to measurements of azimuthal anisotropy (v_2 and v_3)**
  - **Both v_2 and v_3 are enhanced (suppressed) with large(small) q_2 and q_3 cut**
  - **"Selectivity" of q_2 to v_2 is larger than that of q_3 to v_3**

- **ESE applies to HBT measurements w.r.t. 2nd order event plane**
  - **First measurement of q_2 selection + HBT**
  - **Relative amplitudes of R_{out}, R_{side} and R_{os} vary with q_2 selection**
  - **In most central collisions 0-5% and smallest q_2, relative amplitude of R_{side} is negative or zero**
  - **Modification with q_2 was scaled with v_2, but q_2 dependence of R_{side} could change in centrality 20-40%**

Summary-2

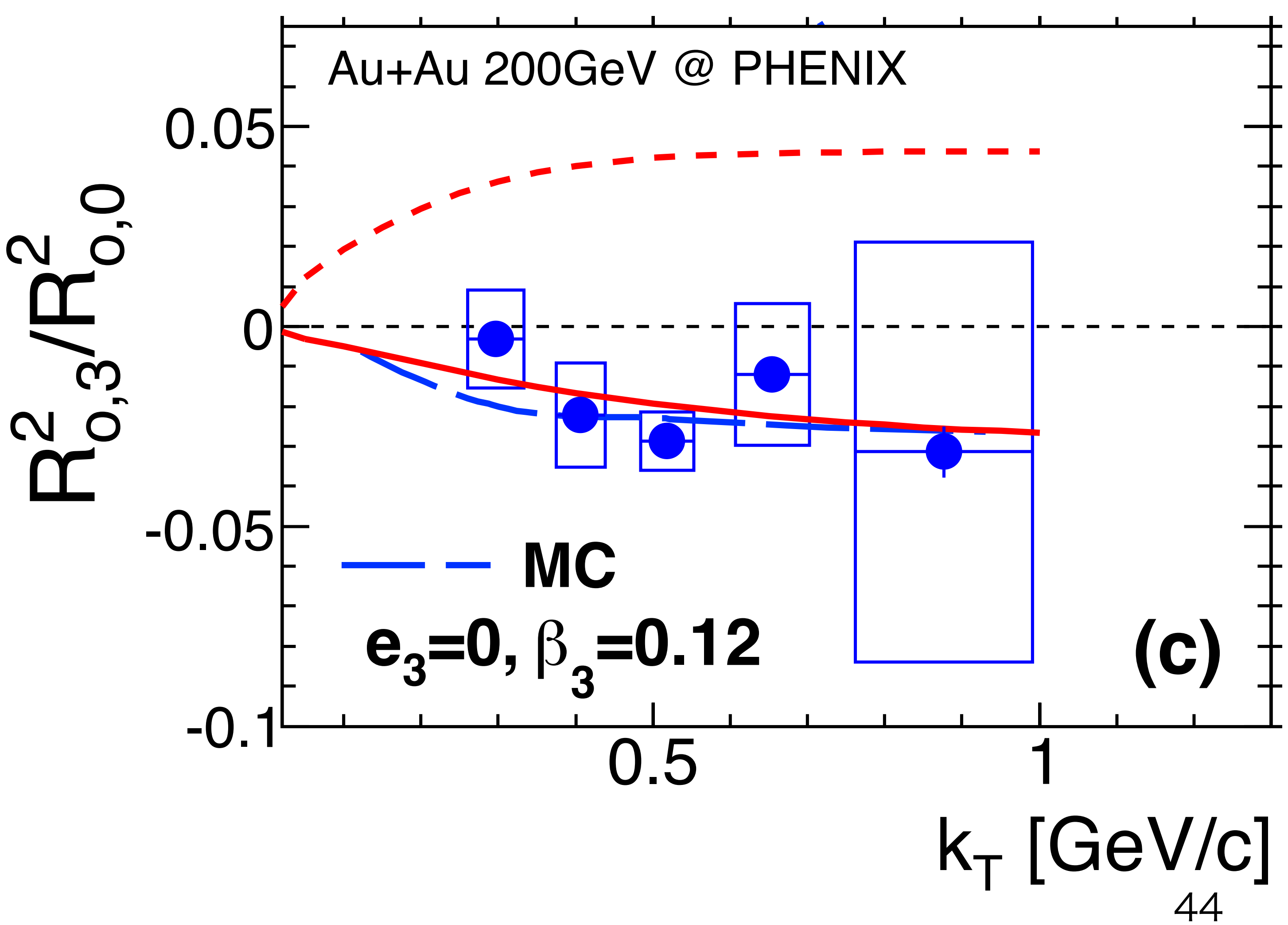
- **Interpretation with Blast-wave model**
  - **ρ_2 explicitly changes with q_2 selection**
  - **R_y/R_x, system life time slightly changes with q_2 selection, but no significant change was found within systematic uncertainties**
  - **Oscillation of R_{side} can not be reproduced with Blast-wave model**

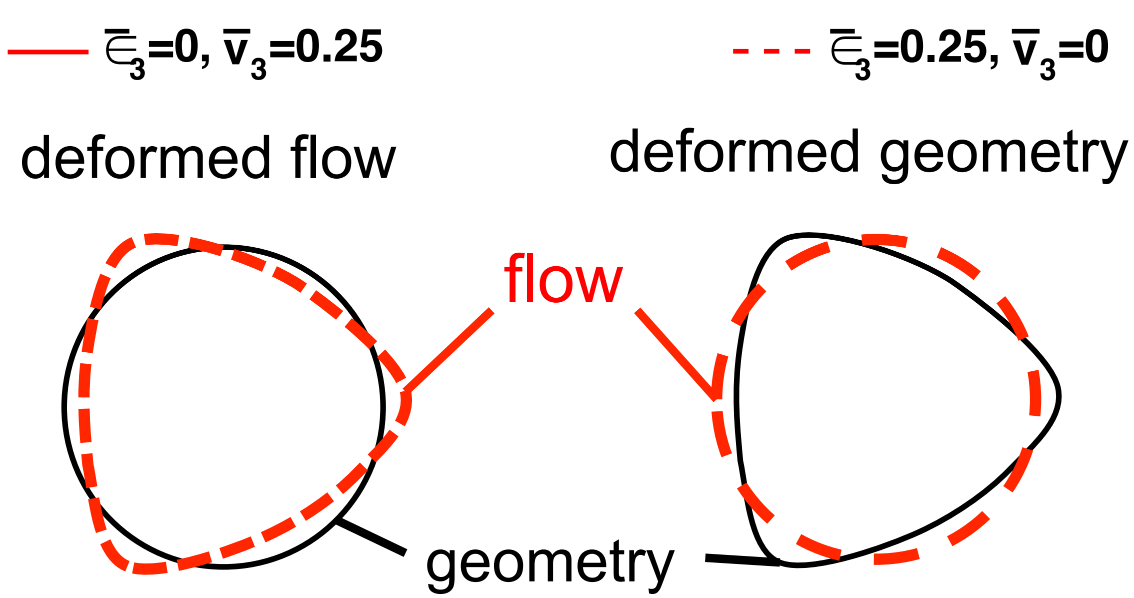
Triangular shape @ freeze-out



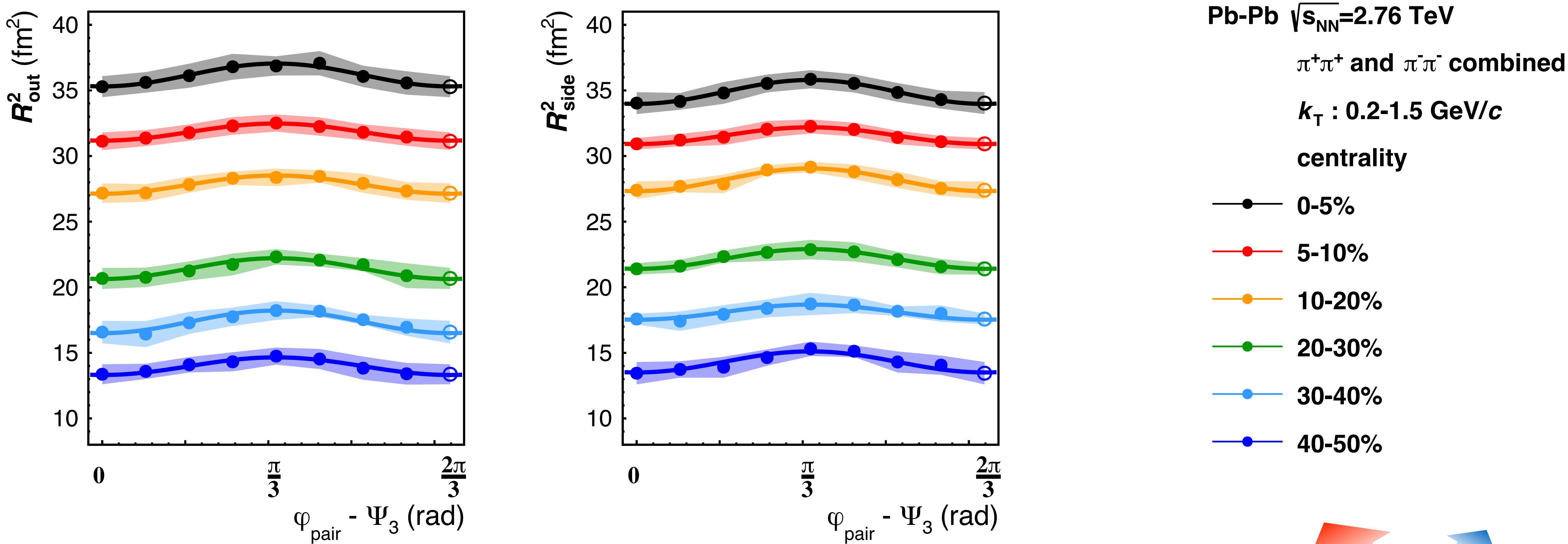
Oscillation of HBT w.r.t. Ψ_3 is flow dominant

- k_T dependence of 3rd-order oscillation at PHENIX is described by flow dominant case of Gaussian toy model
  - ➡ q_3 + Azimuthal angle dependence of HBT radii is direct measurement of relation between v_3 and oscillation of HBT radii

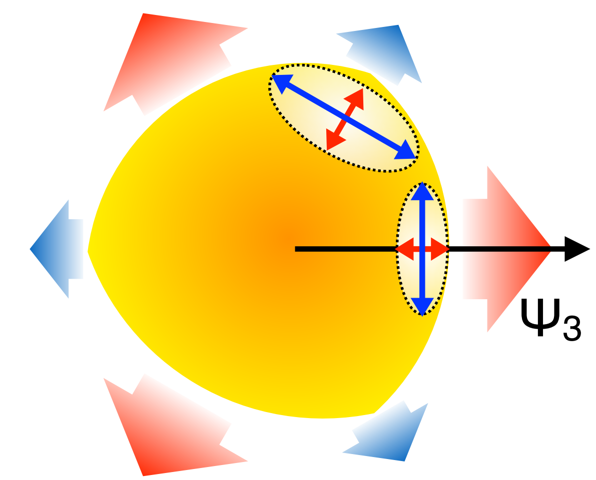




Azimuthal angle dependence of HBT radii w.r.t. Ψ_3

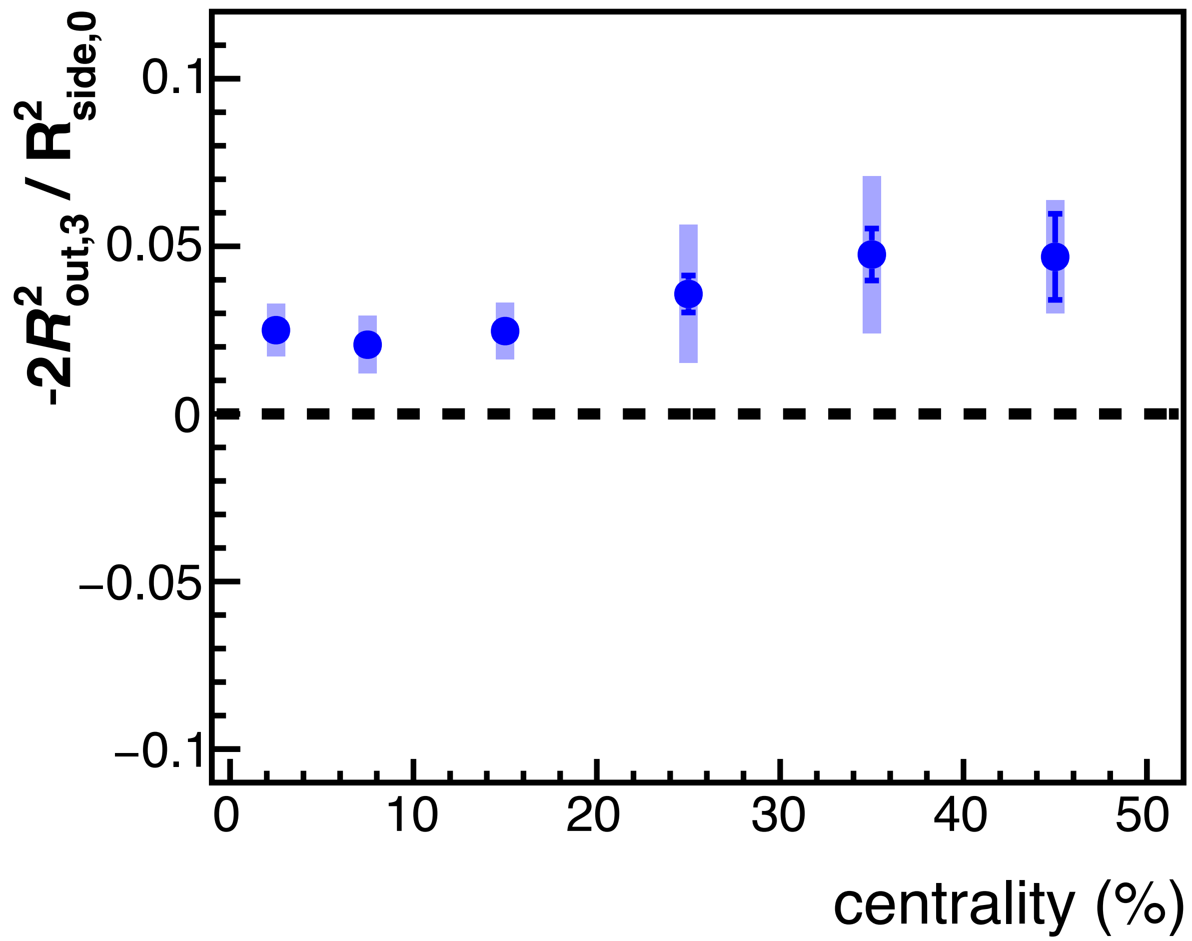


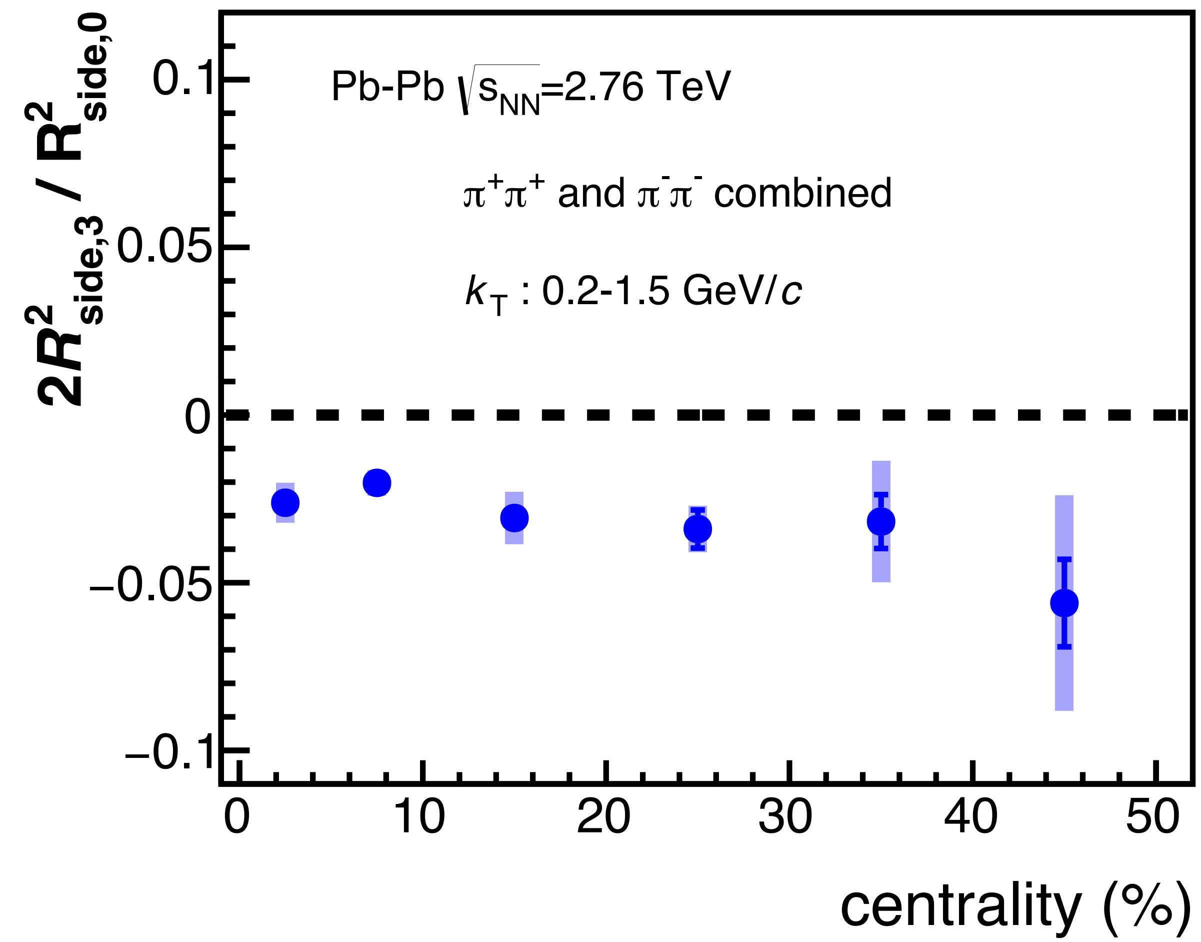
- Fit function
- $R^2_{\mu,0} + 2 R^2_{\mu,3} \cos(3(\phi_{pair} - \Psi_3))$
  - $R^2_{\mu,0}$: Average HBT radii, $R^2_{\mu,3}$: Oscillation amplitude



- **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)
  - ➡ **Similar behaviour to HBT w.r.t. Ψ_2 in most central smallest q_2**
  - ➡ **When the initial eccentricity is small, oscillation of R_{out} and R_{side} could have same sign.**

3^{rd} harmonic oscillation of HBT radii

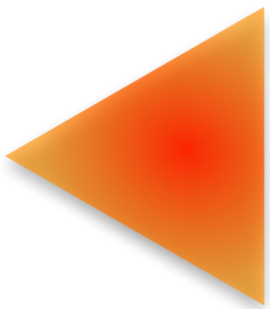


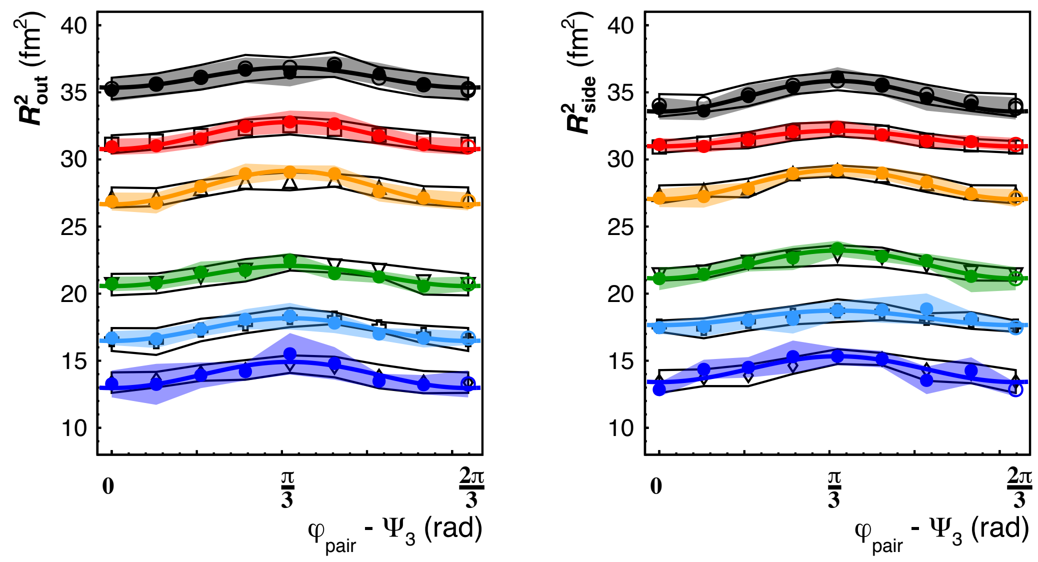


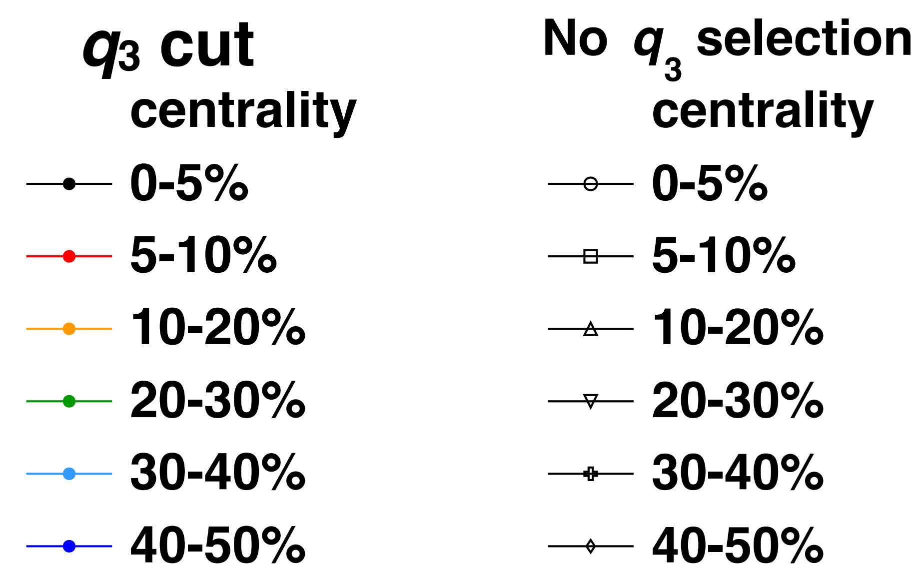
- ✓ $-2R^2_{out,3}$ / $R^2_{side,0}$ **has positive value in all centrality**
- ✓ $2R^2_{side,3}$ / $R^2_{side,0}$ **has negative value in all centrality**
- ✓ $R^2_{out,3}$ / $R^2_{side,0}$ **slightly increase with increasing centrality**
- ✓ $R^2_{side,3}$ / $R^2_{side,0}$ **slightly becomes smaller from central to peripheral**

Azimuthal HBT w.r.t. Ψ_3 with ESE

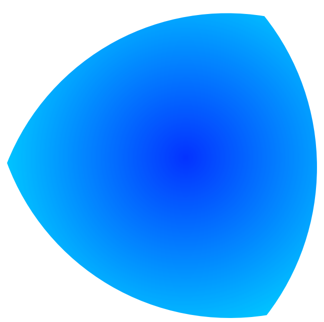
Top 20% q_3

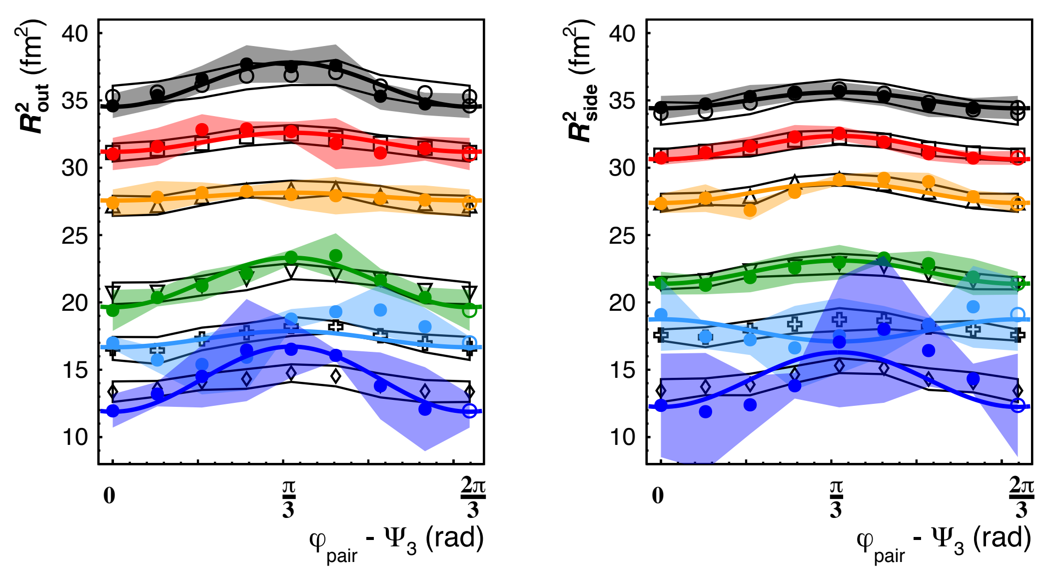






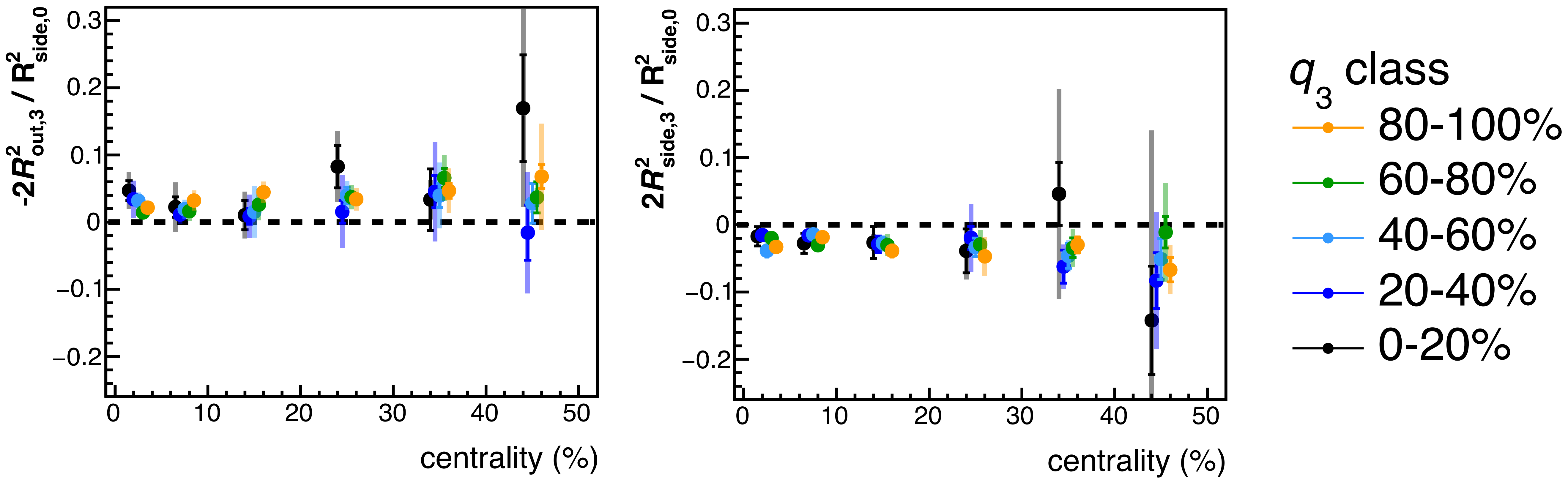
Bottom 20% q_3





- **Top(Bottom) 20% q_3 vector selection is applied to HBT w.r.t. Ψ_3**
- **No significant effect on the R_{out} oscillation can be observed by large q_3 selection, though v_3 changes with q_3 selection**

Relative amplitude of HBT radii (3rd harmonics)



- **No significant change has been observed in relative amplitudes ($R^2_{out,3}$ / $R^2_{side,0}$ and $R^2_{side,3}$ / $R^2_{side,0}$), though v_3 is enhanced ~ 15%**

  ➡ Different behaviour to HBT w.r.t. Ψ2 + q_2 selection

  - **Triangular shape at freeze-out seems to be saturated by radial flow and triangular flow**

Summary-3

- Azimuthal angle dependence of HBT relative to 3rd order event plane
  - Small but finite oscillation can be found in R_{out}, R_{side}
  - Relative amplitude of R_{out} has positive and that of R_{side} has negative value
  - Both $R^2_{out,3}$ / $R^2_{side,0}$ $R^2_{side,3}$ / $R^2_{side,0}$ has small centrality dependence

- ESE applies to HBT measurements w.r.t. 3rd order event plane
  - First measurement of q_3 selection + HBT
  - No significant change can be found in relative amplitudes of R_{out} and R_{side} with q_3 selection

Conclusion

- **Azimuthal angle dependence of HBT relative to 2nd-order event plane**
  - **Initial elliptic shape strongly diluted, but out-plane elongated elliptic shape still remains at freeze-out**
  - **Final eccentricity enhanced(suppressed) with q_2 (ε_2^{inital}) selection**
  - **q_2 dependence could be different in centrality 20-40%**

- **Azimuthal angle dependence of HBT relative to 3rd order event plane**
  - **$-2R^2_{out,3} / R^2_{side,0} > 0$ and $2R^2_{side,3} / R^2_{side,0} < 0$ in all centrality. This will constrain the freeze-out parameters**
  - **Relative amplitudes of HBT radii w.r.t. Ψ_3 did not change with q_3 selection. it might indicate freeze-out triangular shape saturates**

Back up

Event plane resolution

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

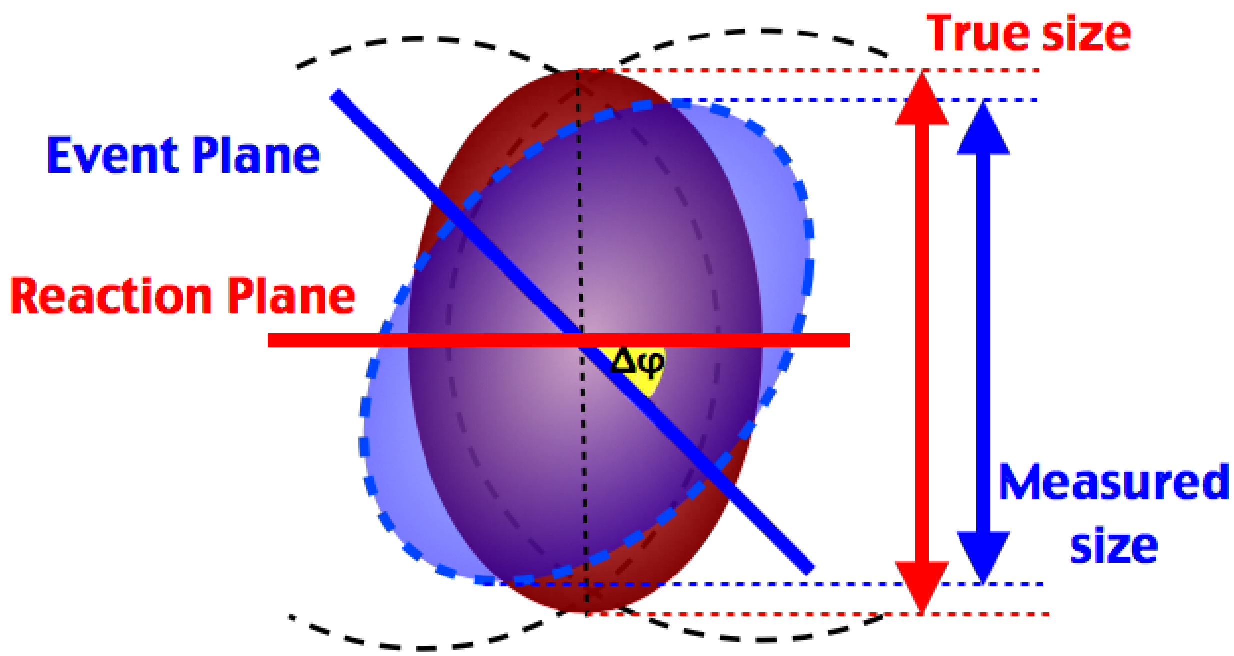
$$N\left(q,\phi_j\right) = N_{exp}\left(q,\phi_j\right) + 2\sum_{n=1}^{n_{bins}} \xi_{n,m}(\Delta)\left[N^{exp}_{c,n}(q)\cos(n\phi_j) + N^{exp}_{s,n}(q)\sin(n\phi_j)\right]$$

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

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

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

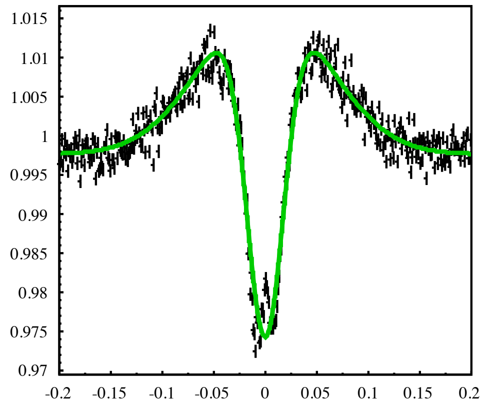
➡ **event plane resolution**

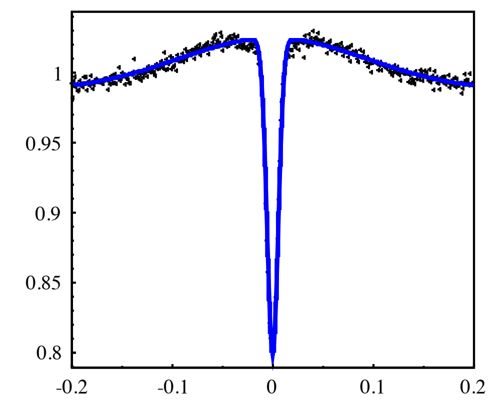


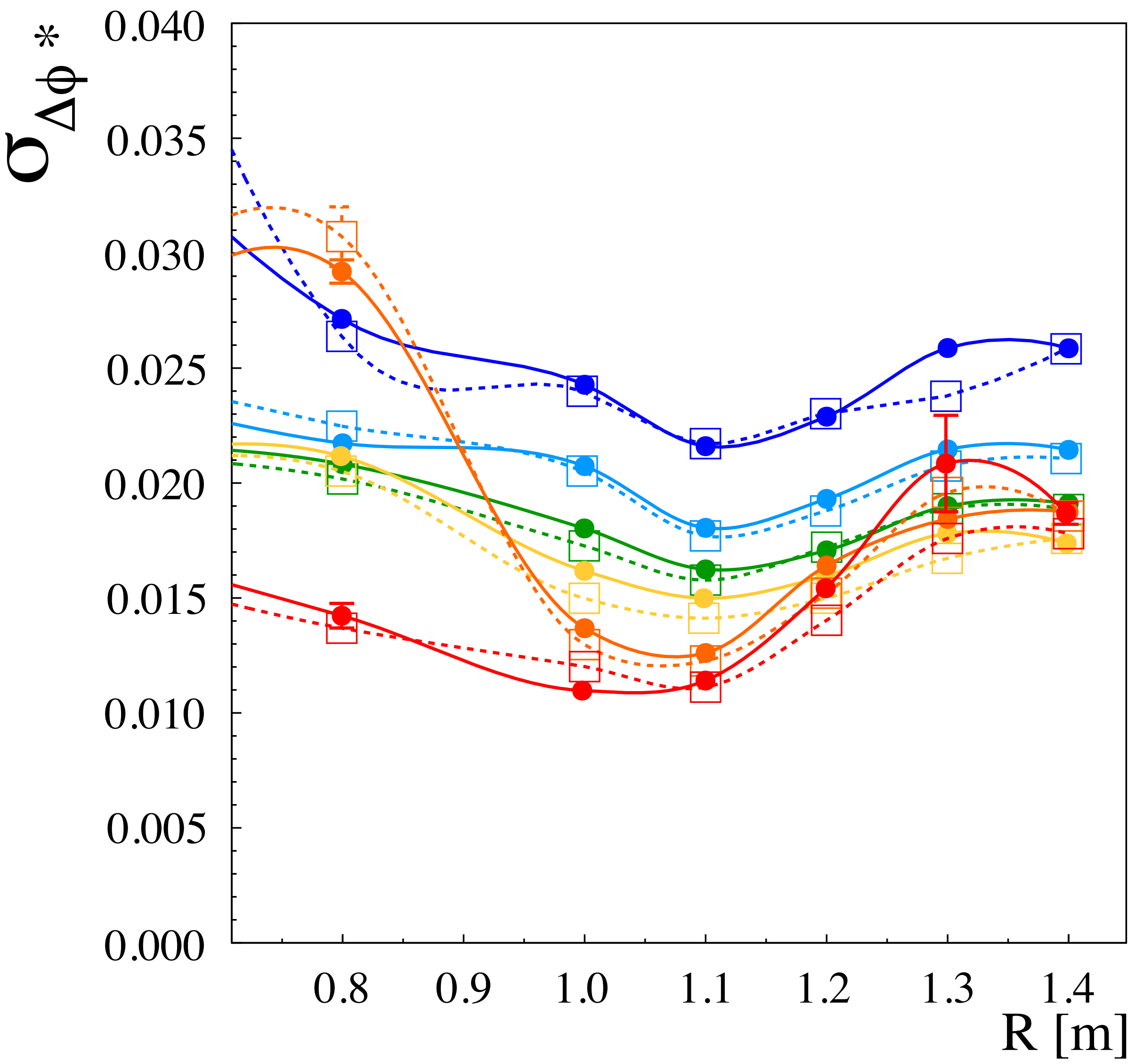
- **correction for q-distribution with EP resolution**

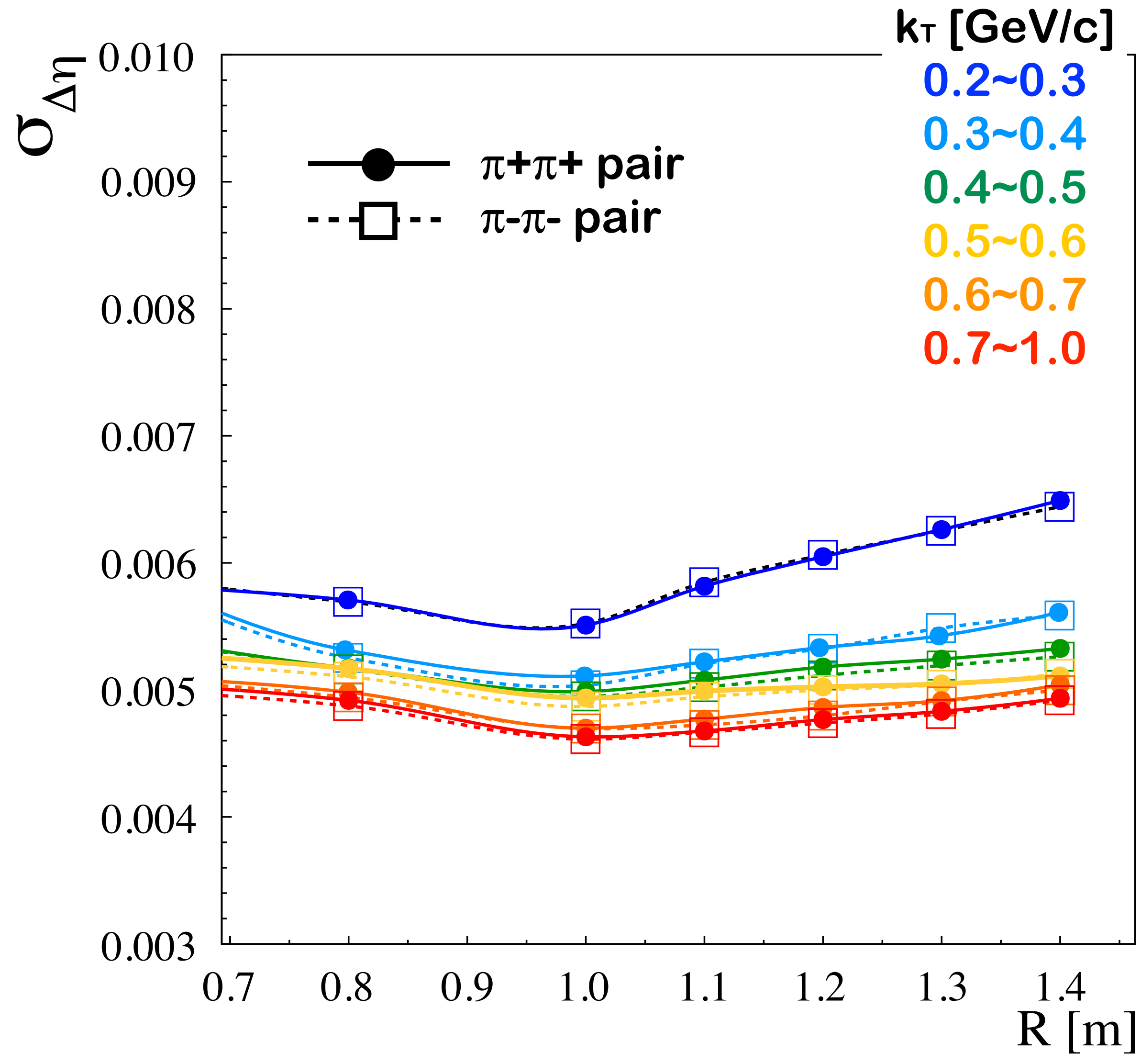
Angular distance in Δφ*Δη

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



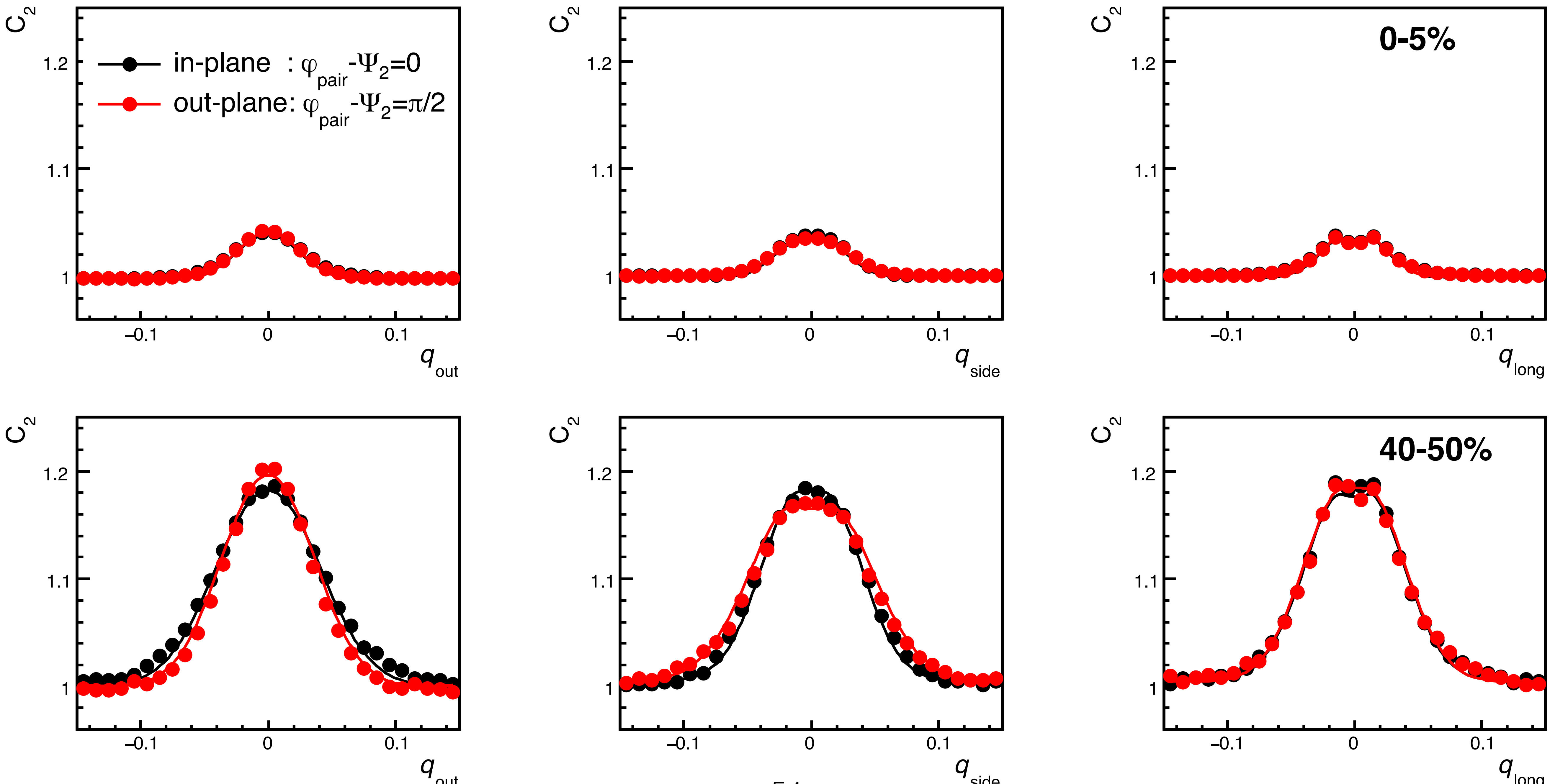






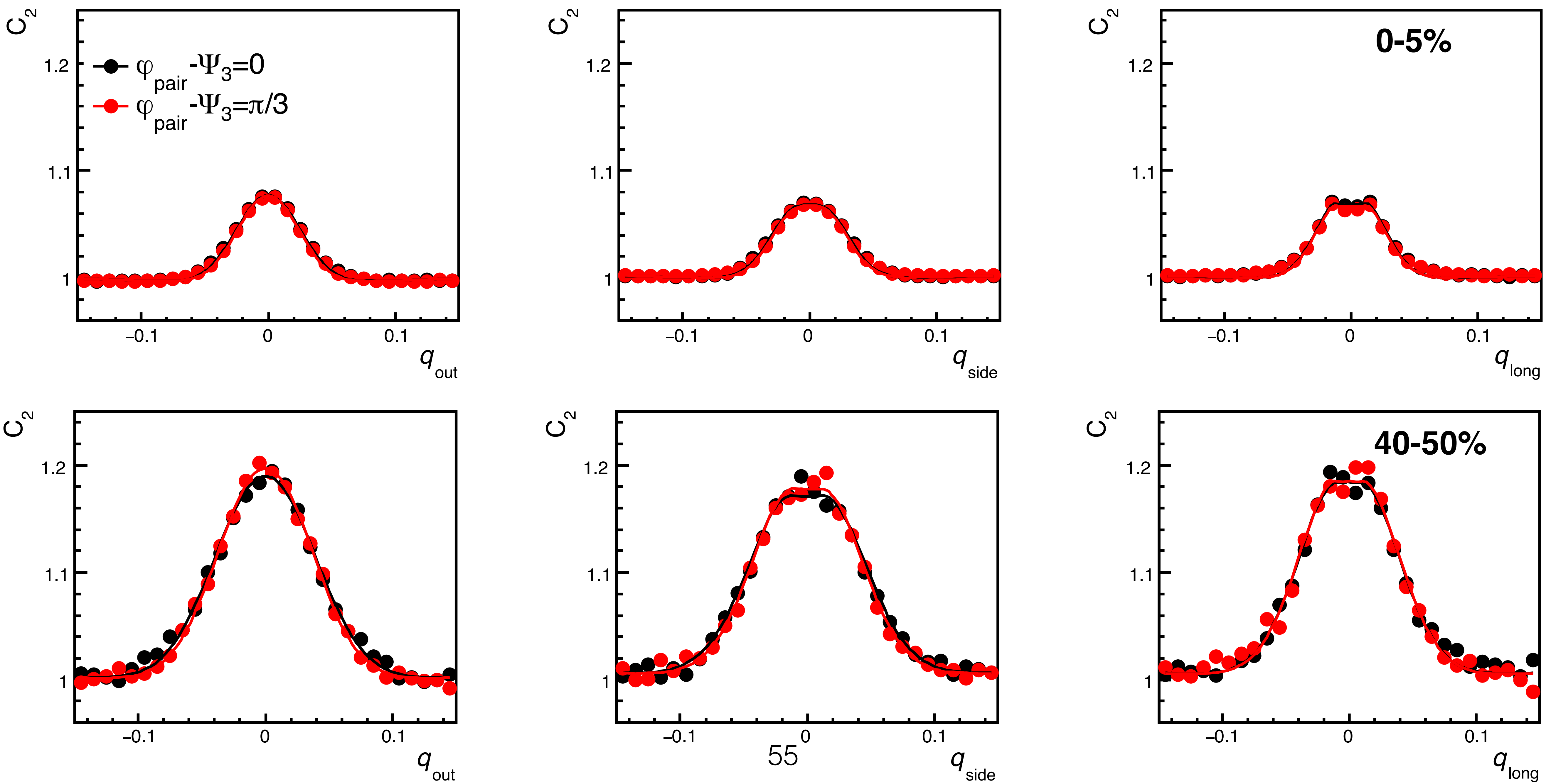
Correlation function (HBT w.r.t. Ψ_2)

- **1D projection of 3D correlation functions**
  - **Projections of the other component within 50 MeV/*c***
  - **Different HBT radii can be found in peripheral collisions (oscillation of radii)**

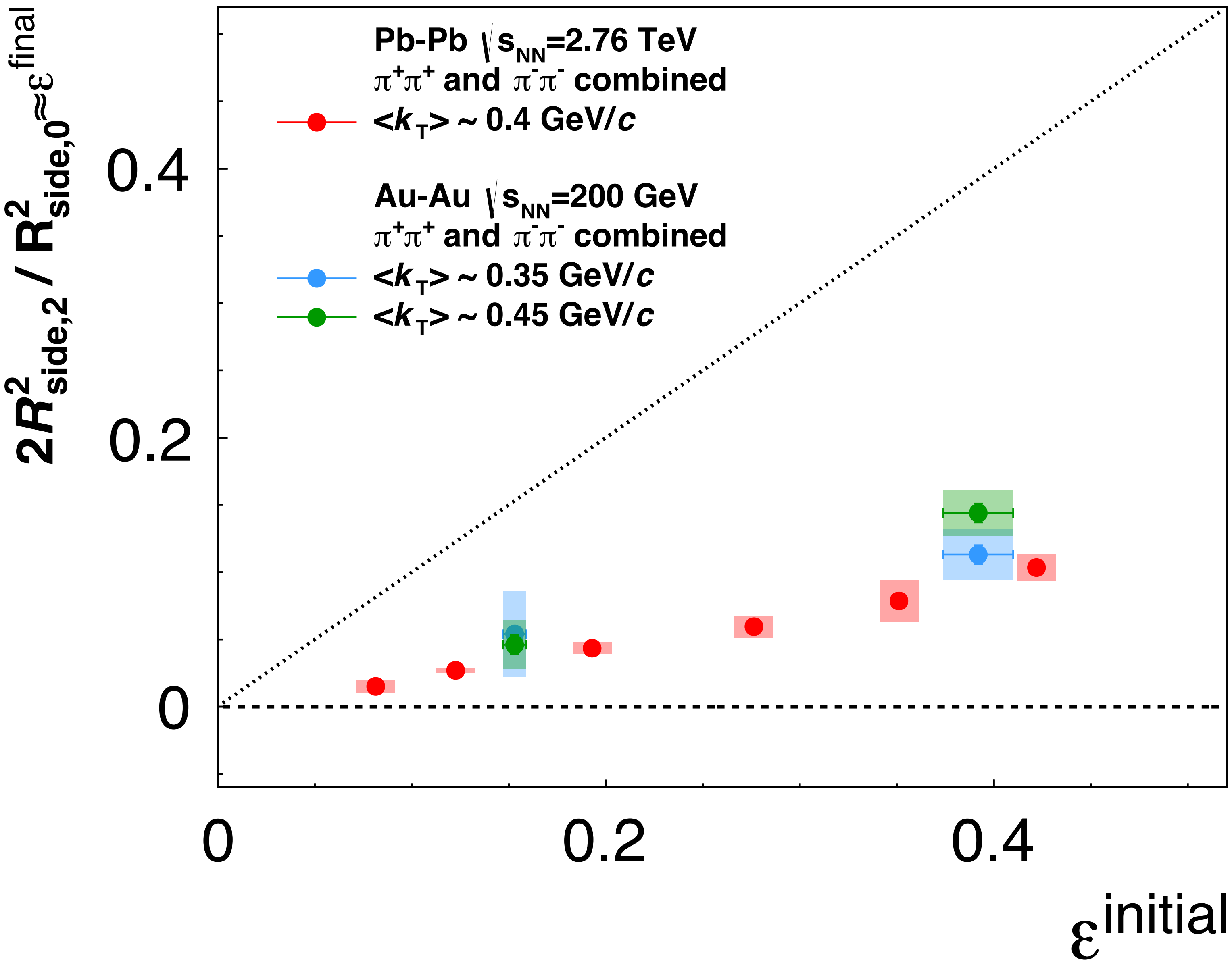


Correlation function (HBT w.r.t. Ψ_3)

- 1D projection of 3D correlation functions
  - Projections of the other component within 50 MeV/*c*
  - Different HBT radii can be found in peripheral collisions (oscillation of radii)

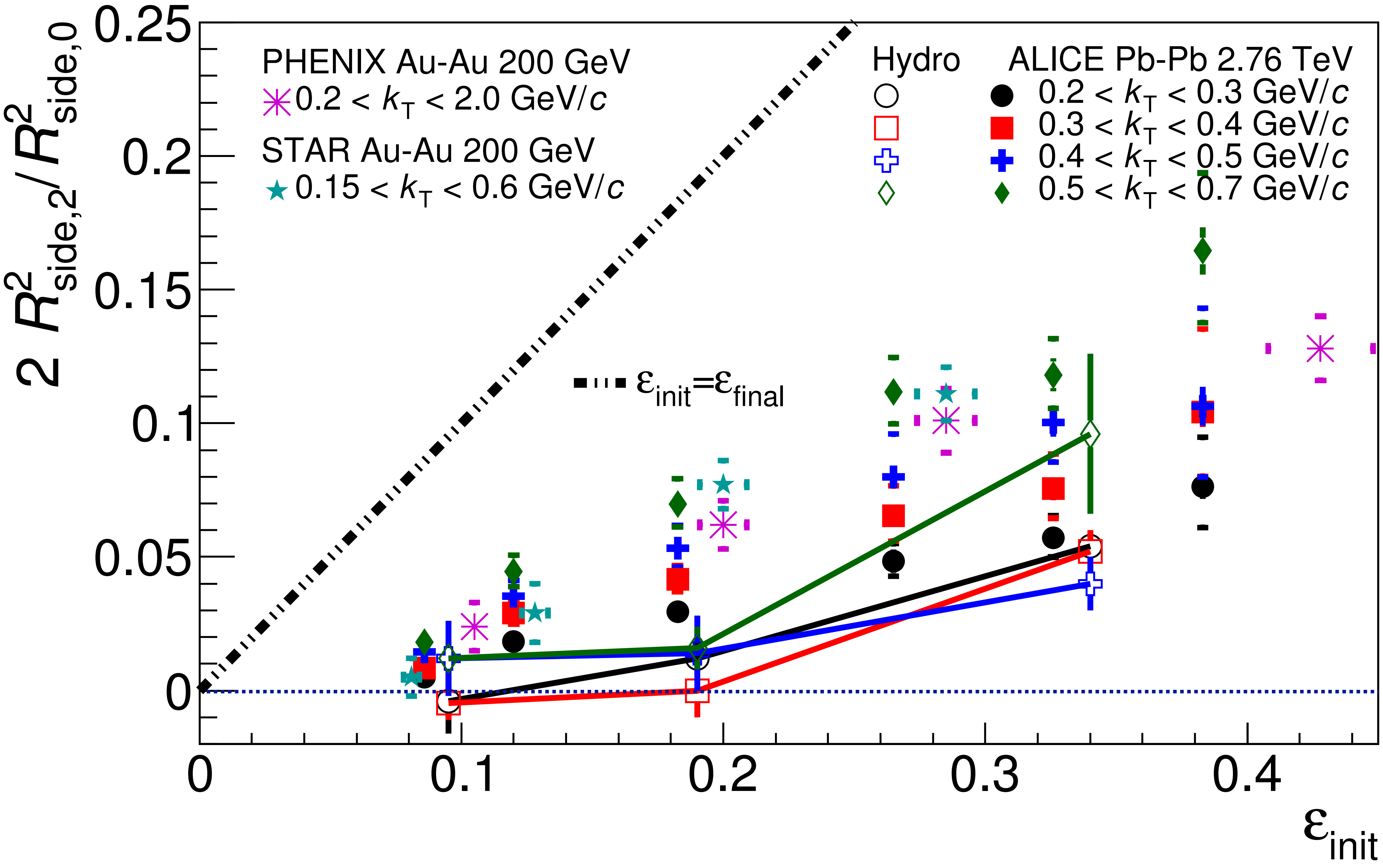


Comparison with result in Au-Au 200GeV

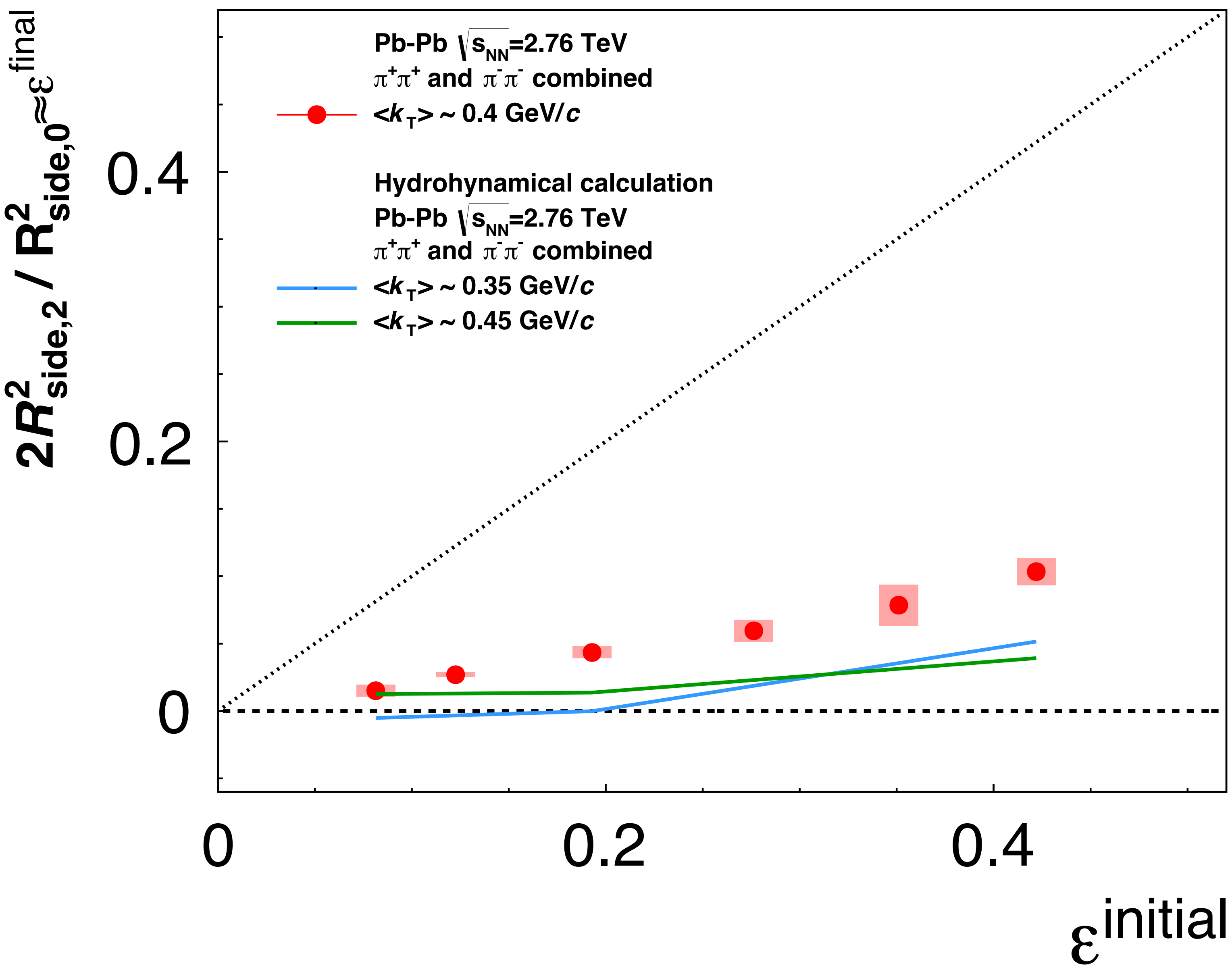


- Dilution effect at LHC is stronger than that at RHIC
  - Due to larger collective flow in LHC energy
- Difference between RHIC and LHC is remarkable at peripheral collisions

k_T dependence of ε_2^{final} in Pb-Pb 2.76 TeV



Comparison with hydrodynamical calculation

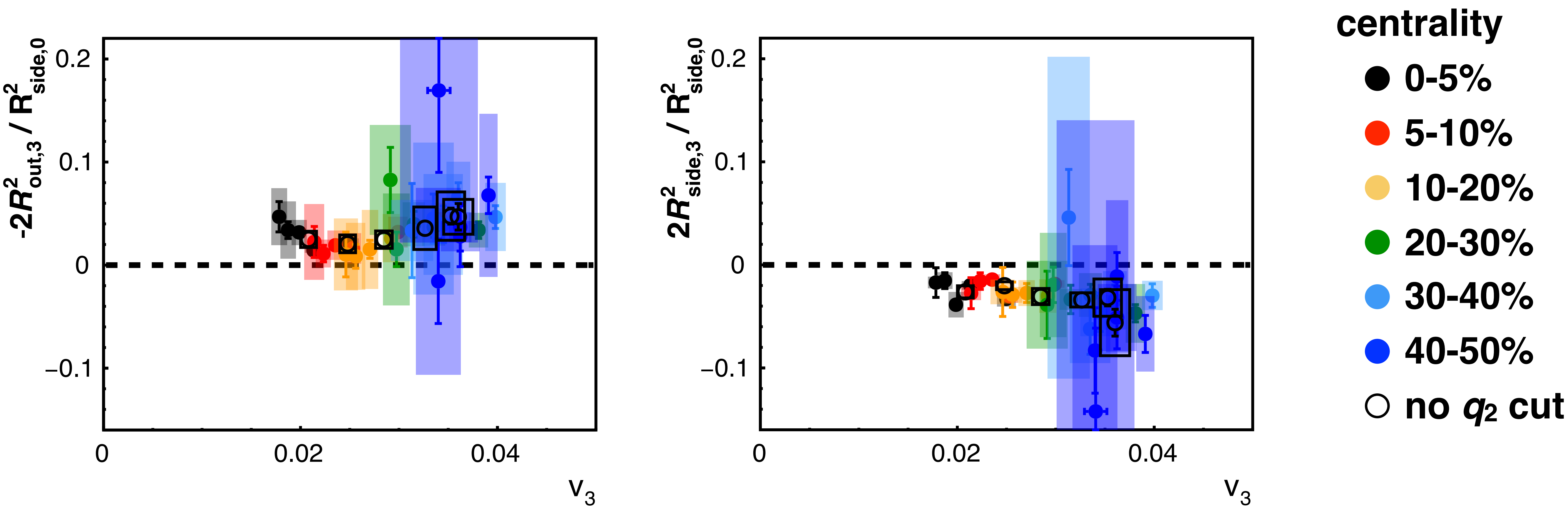


- **Hydrodynamical calculation is qualitatively consistent to data**
- **Final eccentricity at freeze-out of hydrodynamical prediction is slightly smaller than experimental result**
- **Difference between model and data is larger in peripheral than central collisions**

v_3 scaling to Relative amplitude of HBT radii

✓ Difference of event by event initial geometry fluctuation can not be reflected to "centrality"

✓ More sensitive probe is necessary !

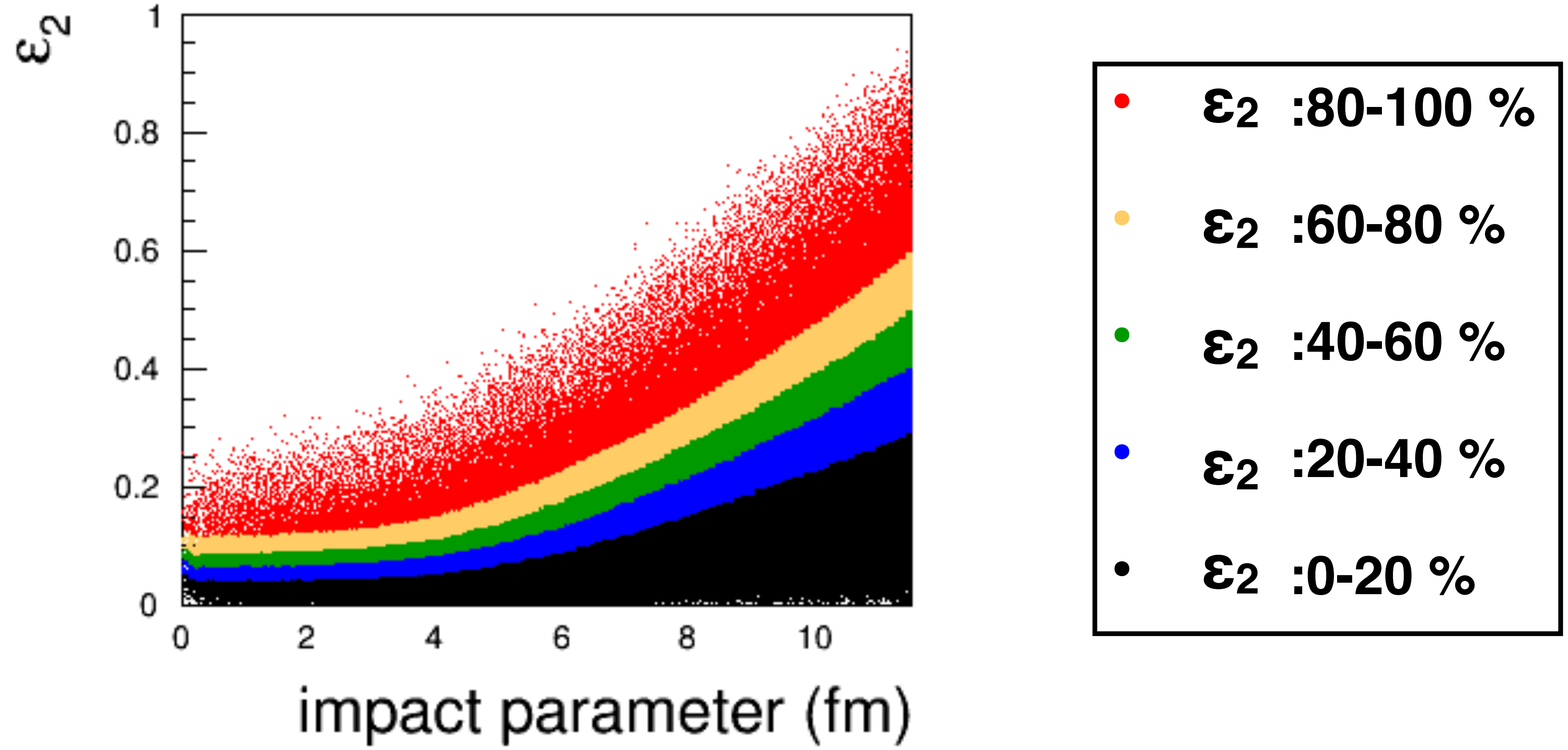


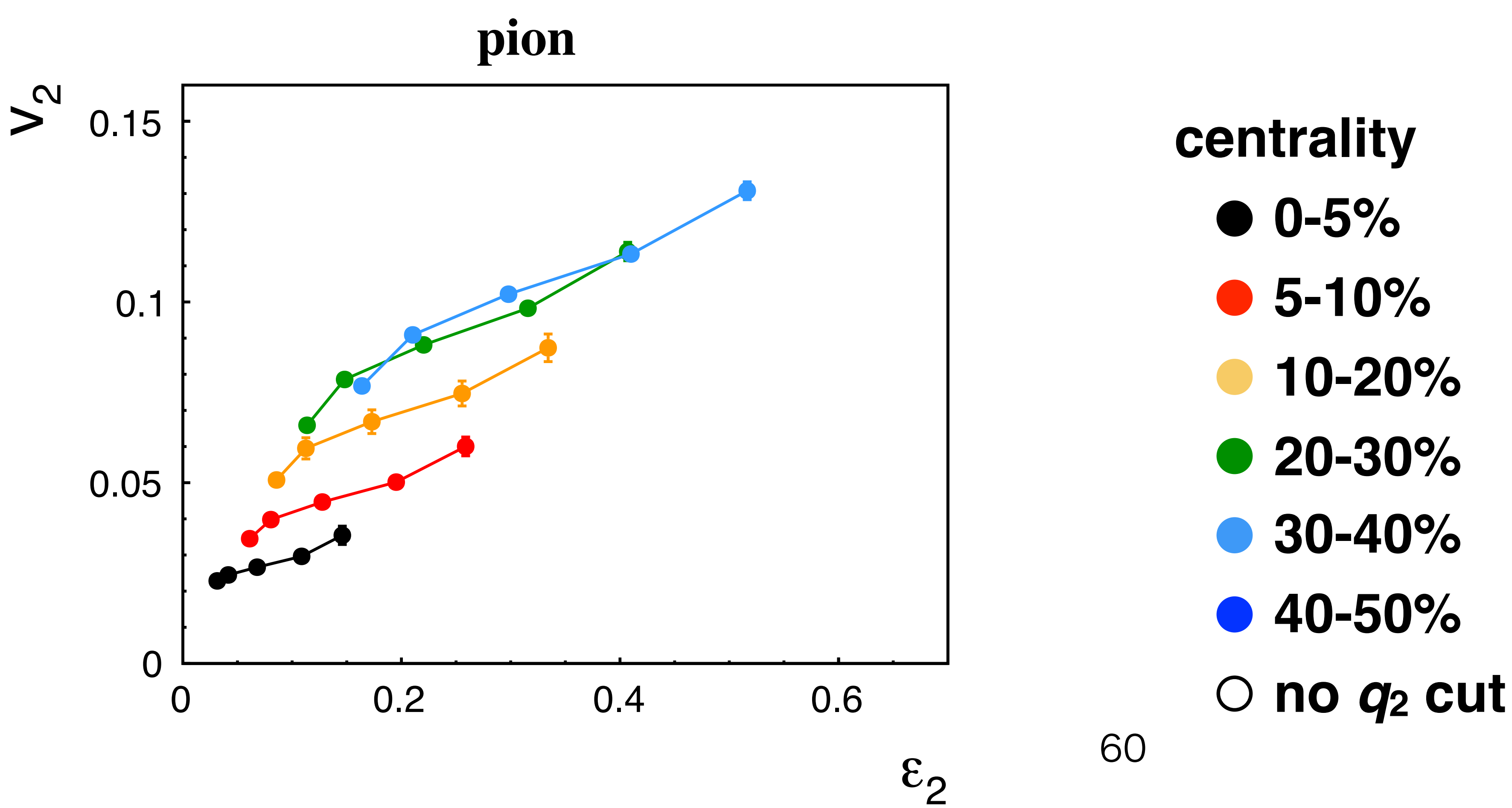
✓ Both relative amplitudes of R_{out} and R_{side} are scaled with v_3

✓ Non linear correlation between $-2R^2_{out,3} / R^2_{side,0}$ and v_3

✓ No significant correlation can be found between $-2R^2_{side,2} / R^2_{side,0}$ and v_3

Correlation between v_2 and $\varepsilon_2^{initial}$ (Glauber)





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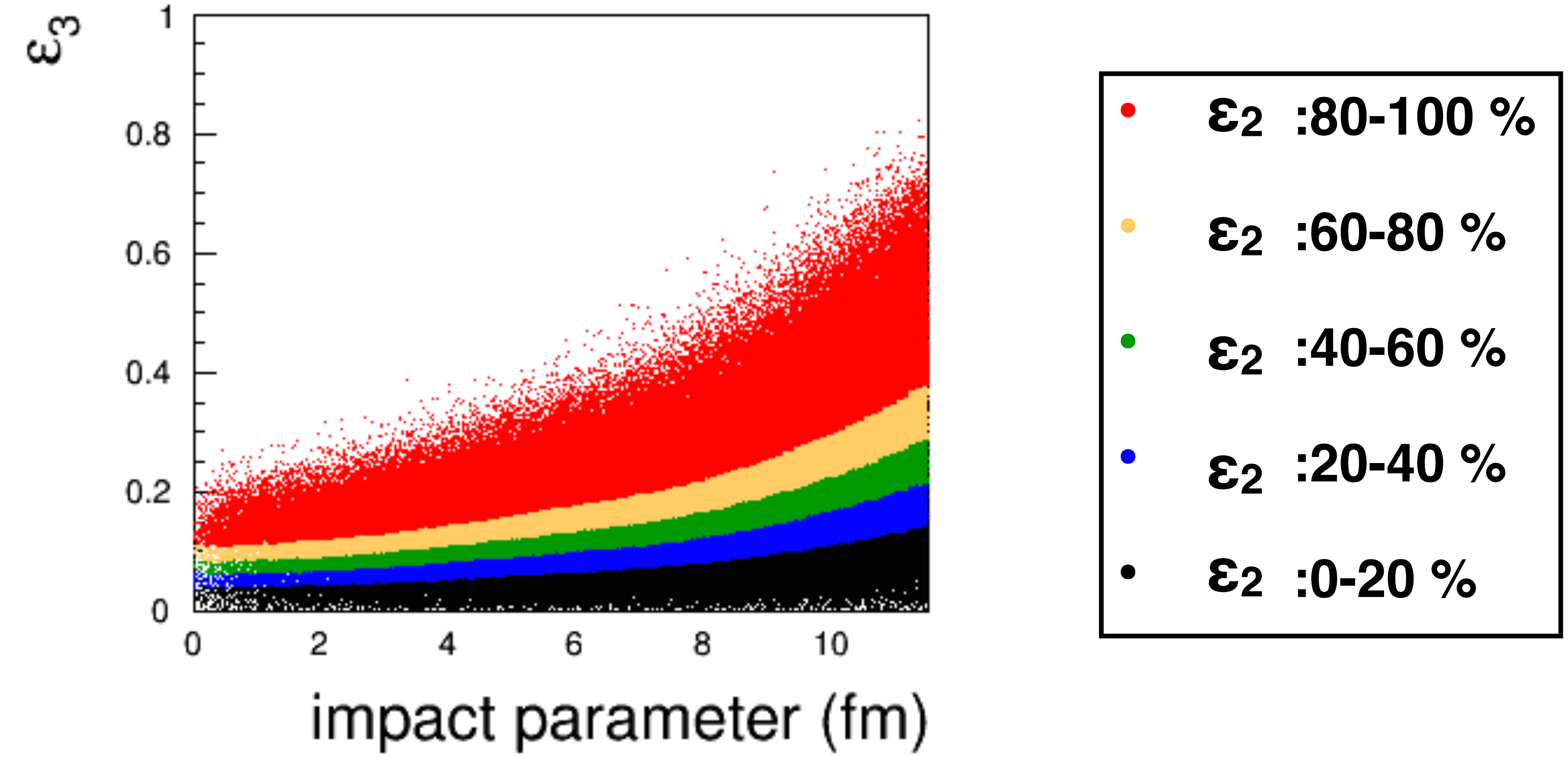
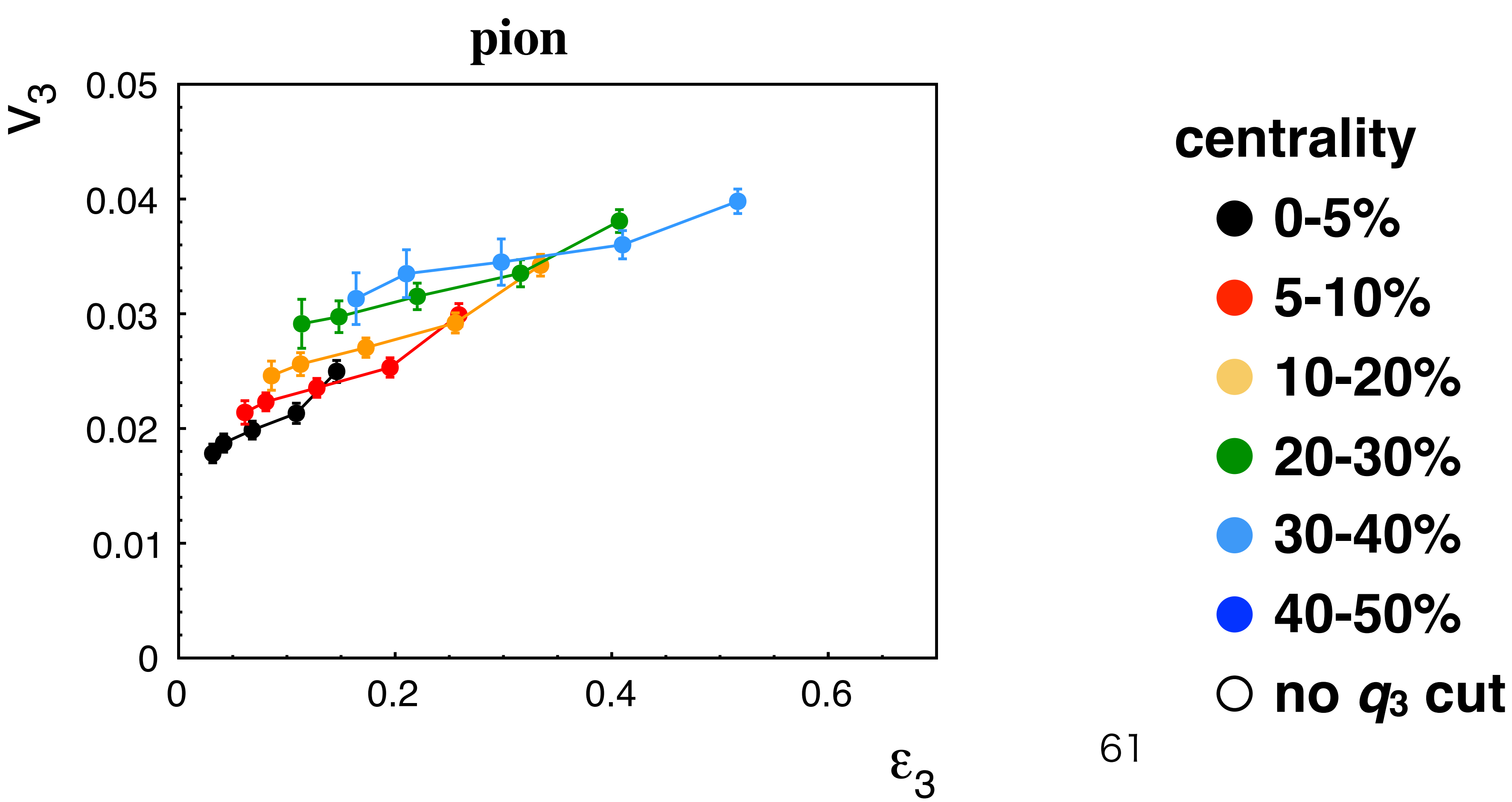
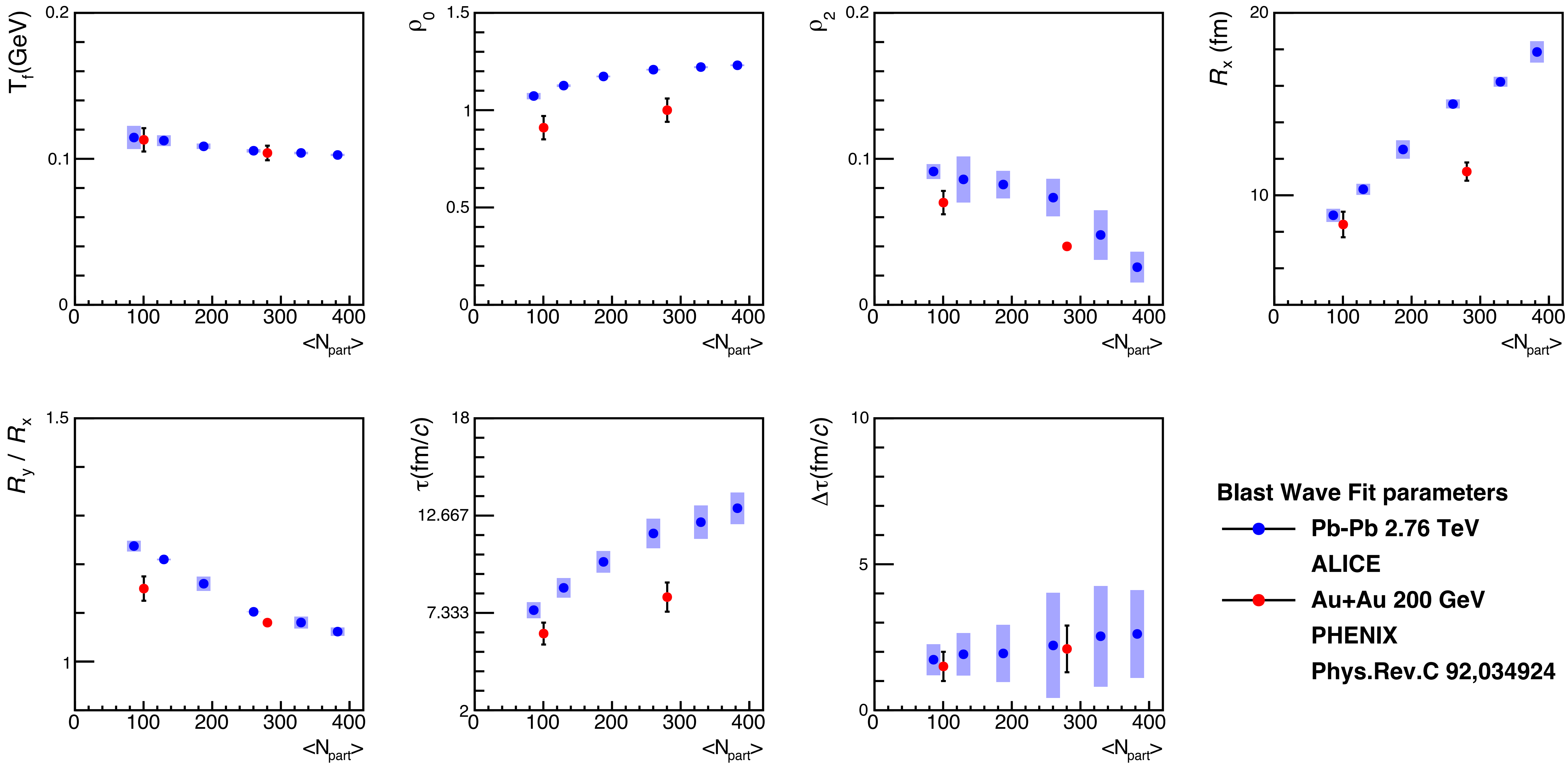
Correlation between v_3 and $\varepsilon_3^{initial}$ (Glauber)





61

Blast-wave parameters (comparison with PHENIX)



- ✦ Freeze out temperature(T_f), eccentricity(R_y/R_x), duration($\Delta\tau$) : ALICE ~ PHENIX
- ✦ Flow velocity (ρ_0 and ρ_2) and system life time : ALICE > PHENIX

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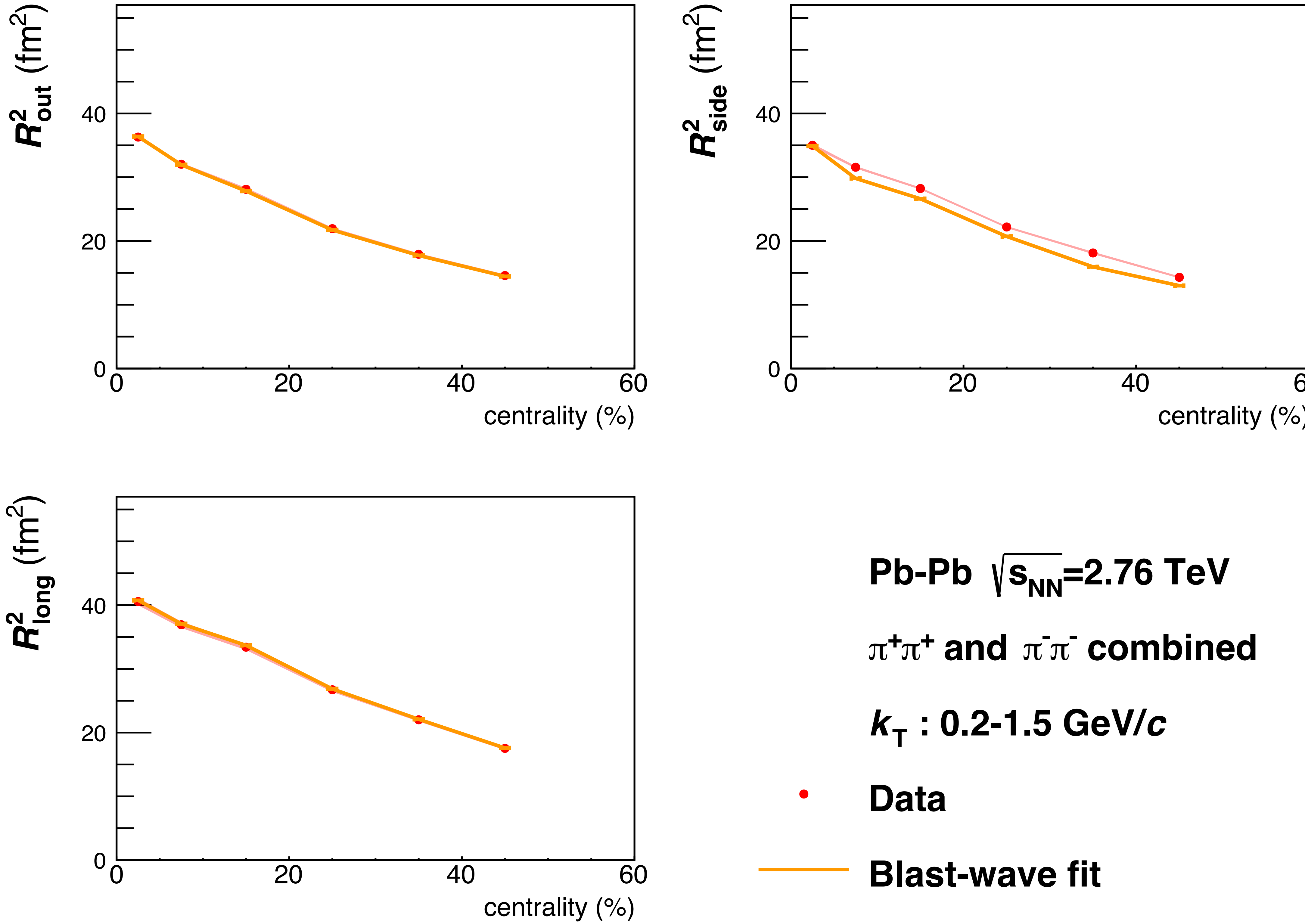
Comparison with Blast-wave model (average HBT radii)

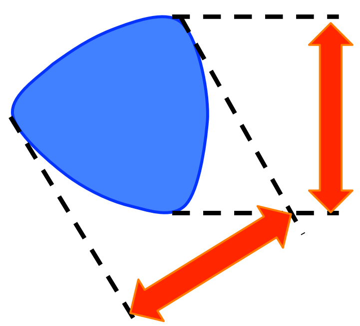


- ✦ R_{out} and R_{long} of Blast-wave fit is consistent to that of Data
- ✦ R_{side} of Blast-wave fit is slightly smaller than that of Data

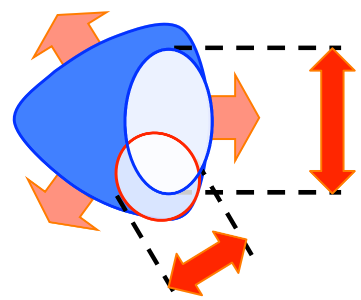
Final source triangular shape and HBT w.r.t. Ψ_3

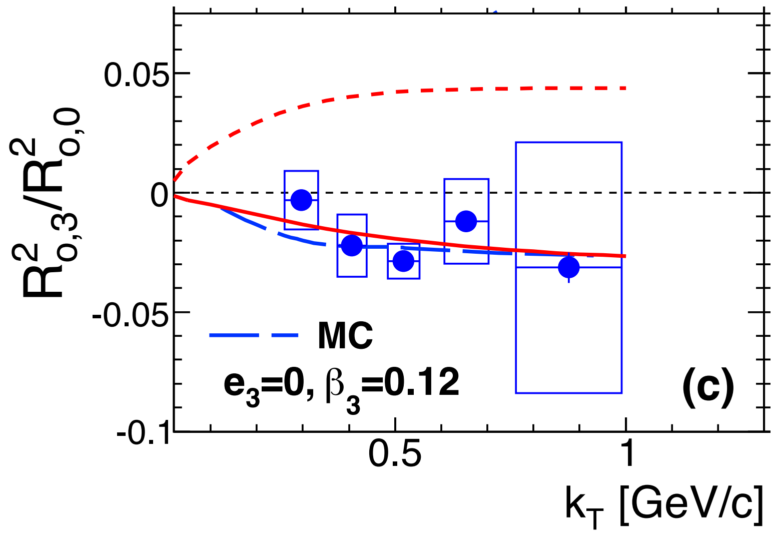
- **Triangularity cannot be directly obtained from HBT w.r.t. Ψ_3**
  - ➡ **Both triangular flow and geometrical triangularity make 3rd order oscillation of HBT radii**

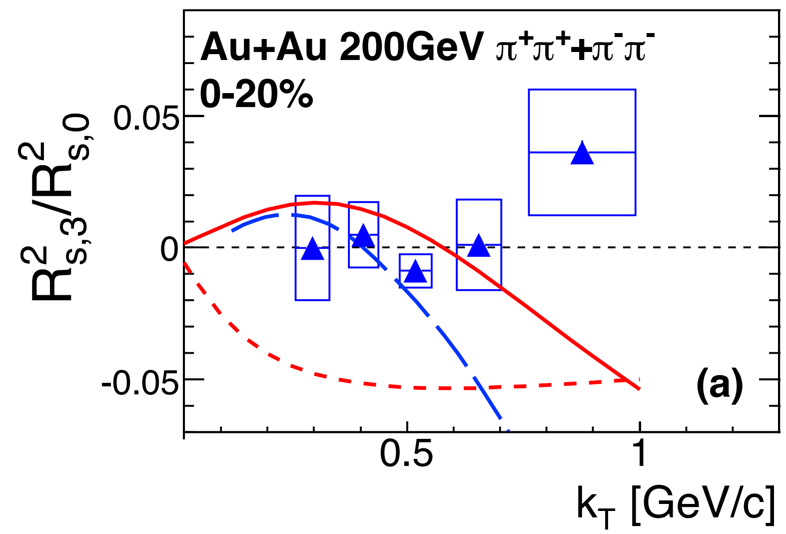
- **Static source**



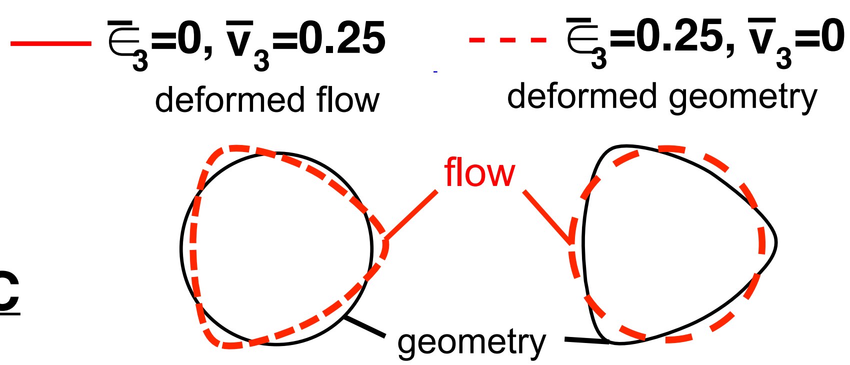
- **Dynamic source**







- **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

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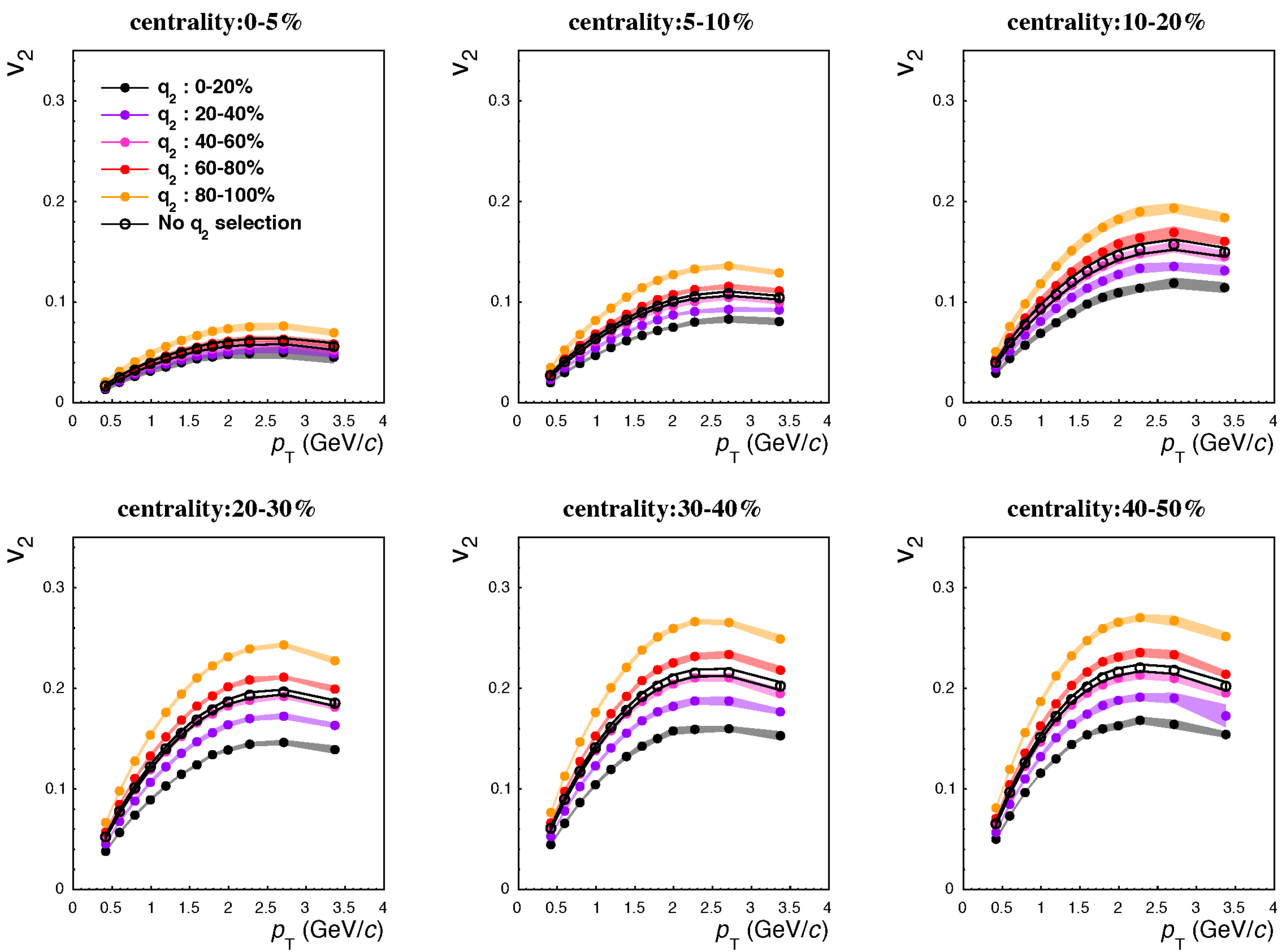
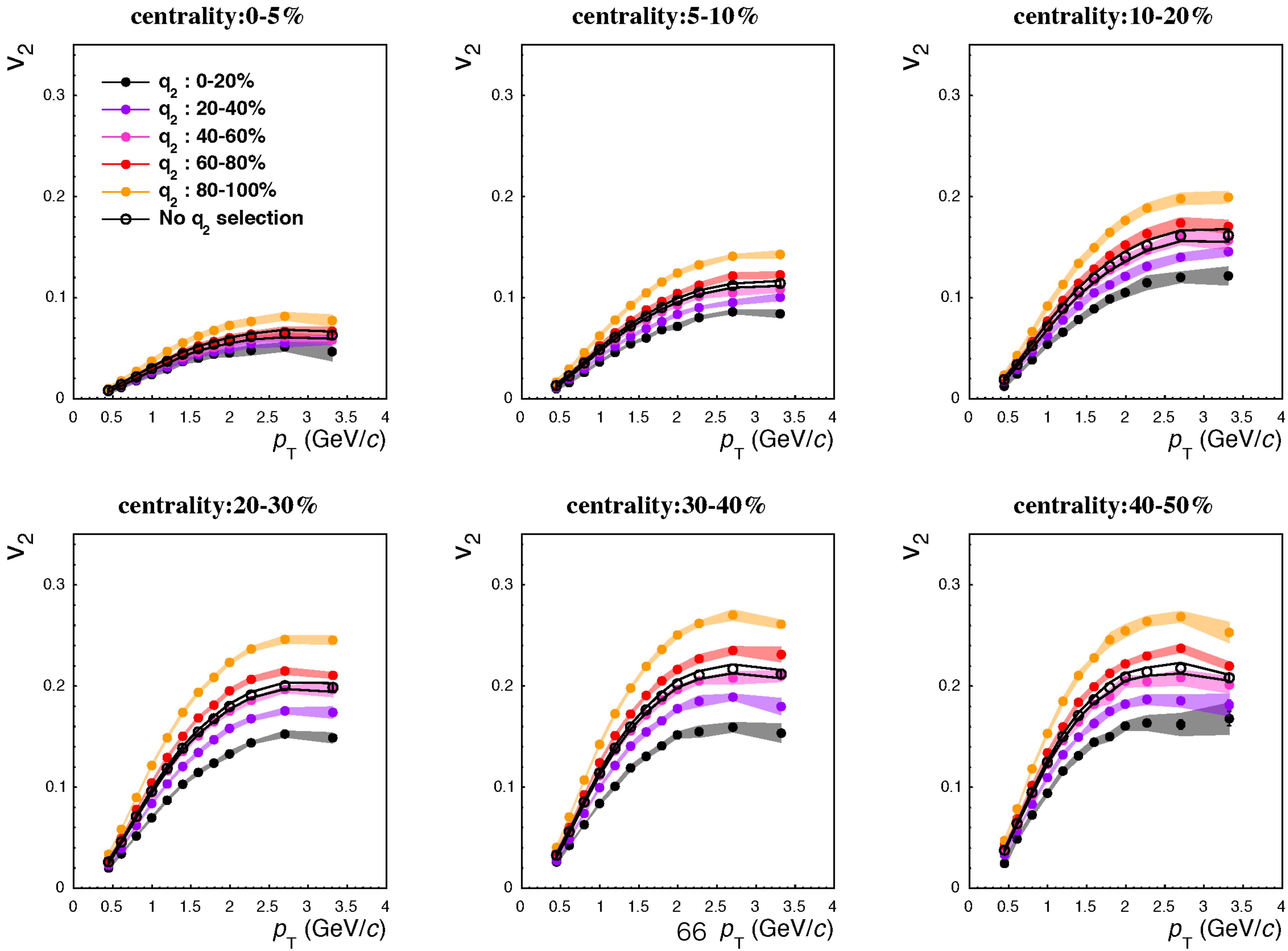
v_2 (p_T dependence) for each 20% q_2 selection (pion)

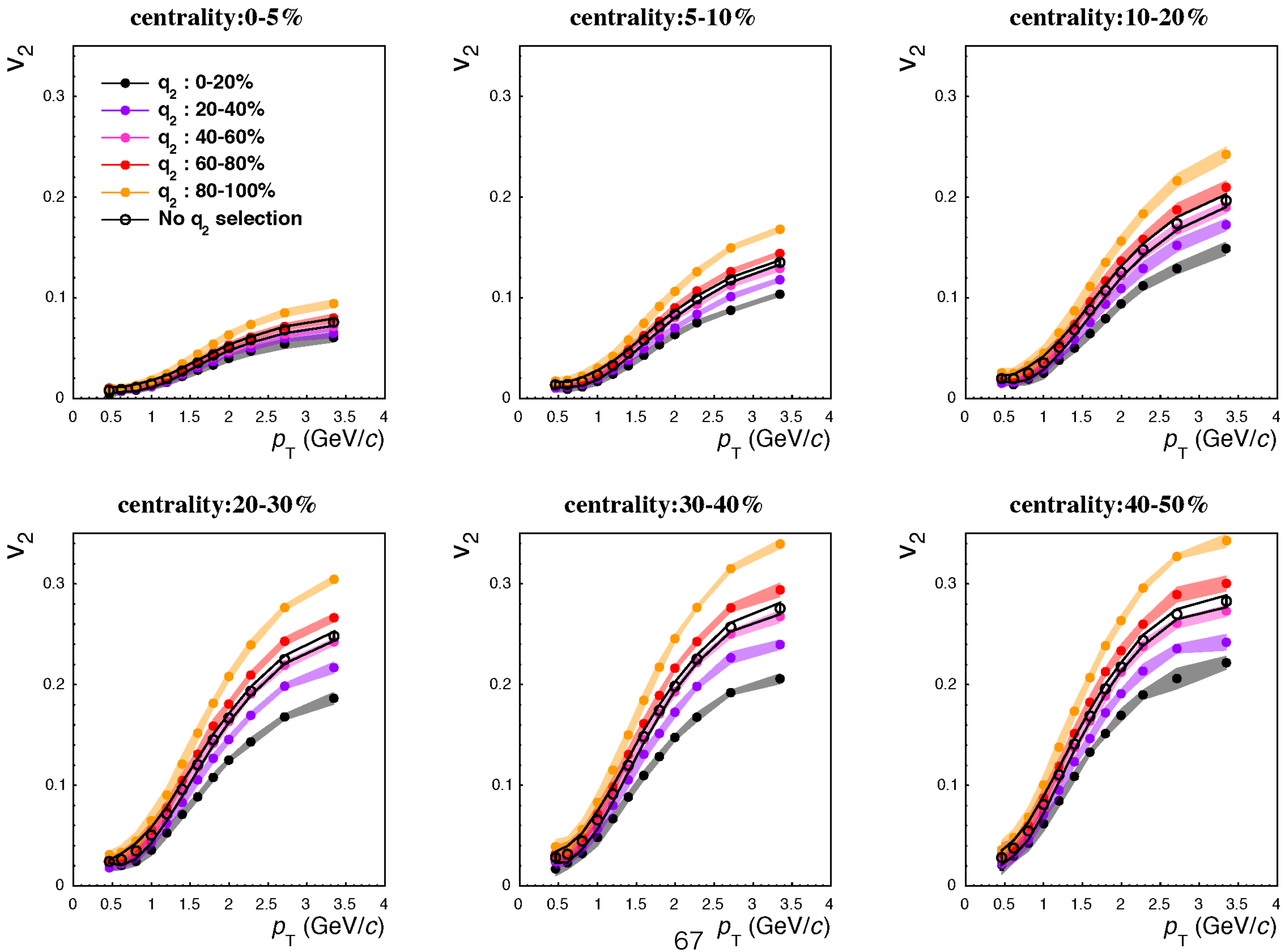


65

v_2 (p_T dependence) for each 20% q_2 selection (kaon)

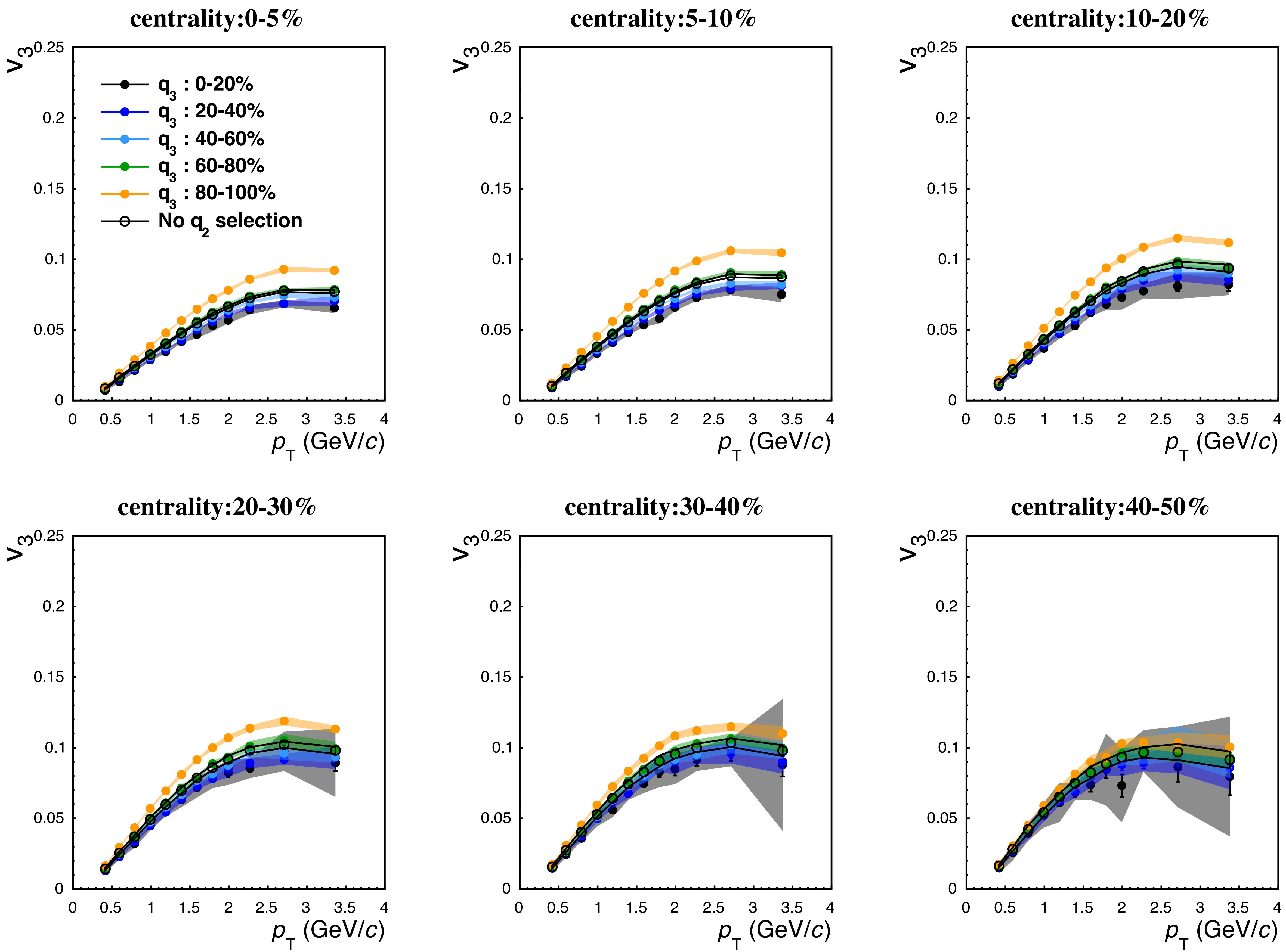


v_2 (p_T dependence) for each 20% q_2 selection (proton)



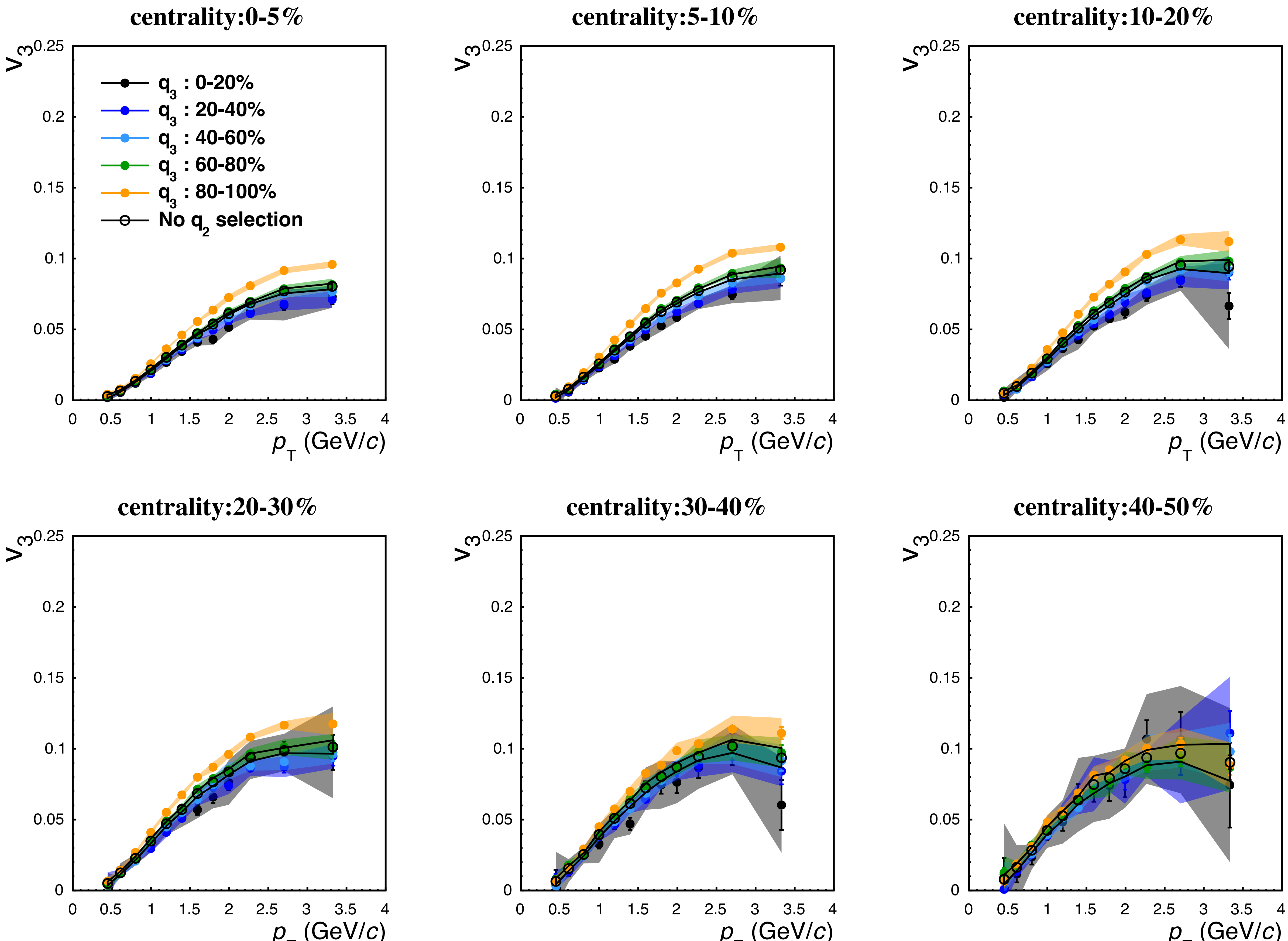
67

v_2 (p_T dependence) for each 20% q_2 selection (pion)



68

v_2 (p_T dependence) for each 20% q_2 selection (kaon)



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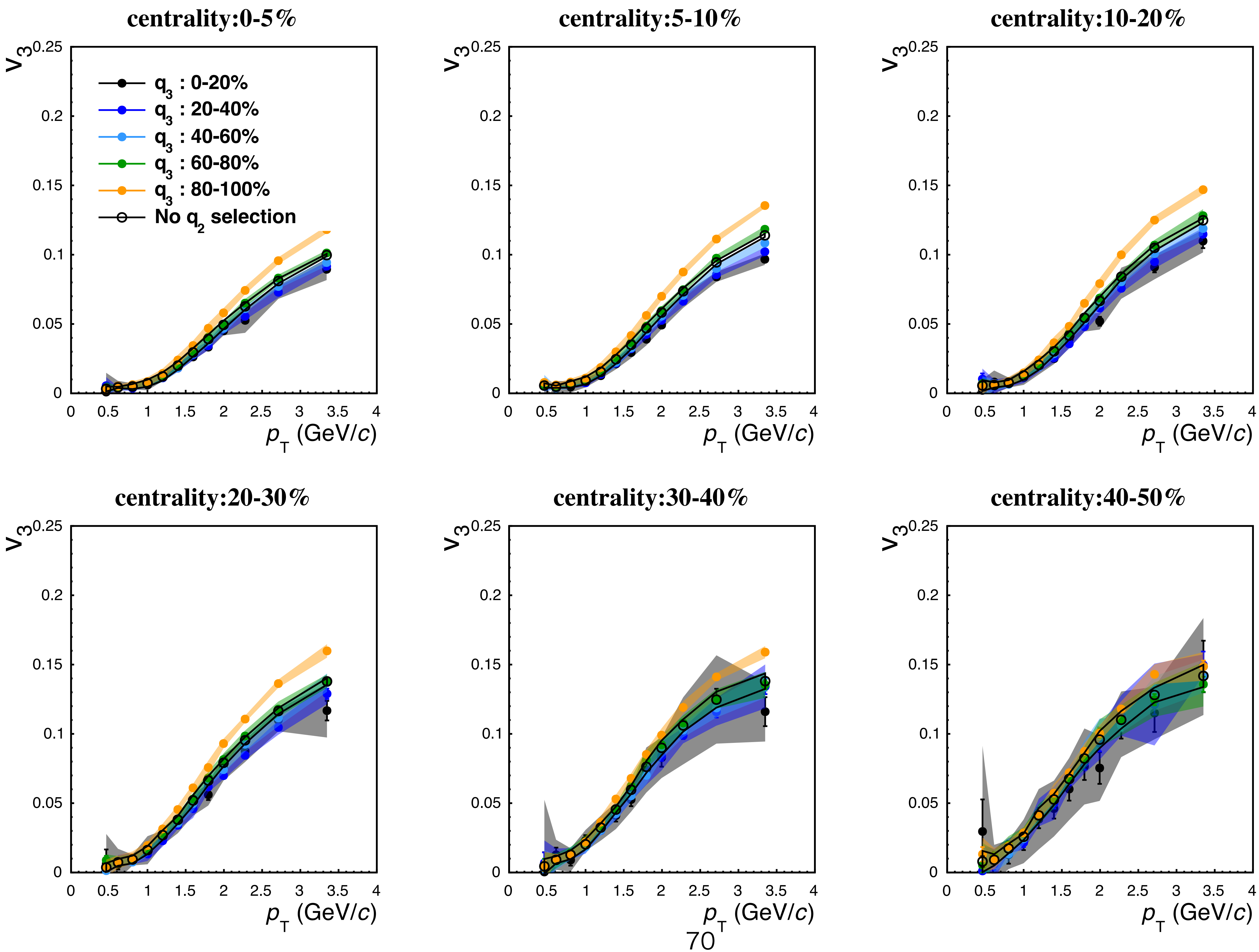
v_2 (p_T dependence) for each 20% q_2 selection (proton)



Blast wave fit for π, K, p Spectra

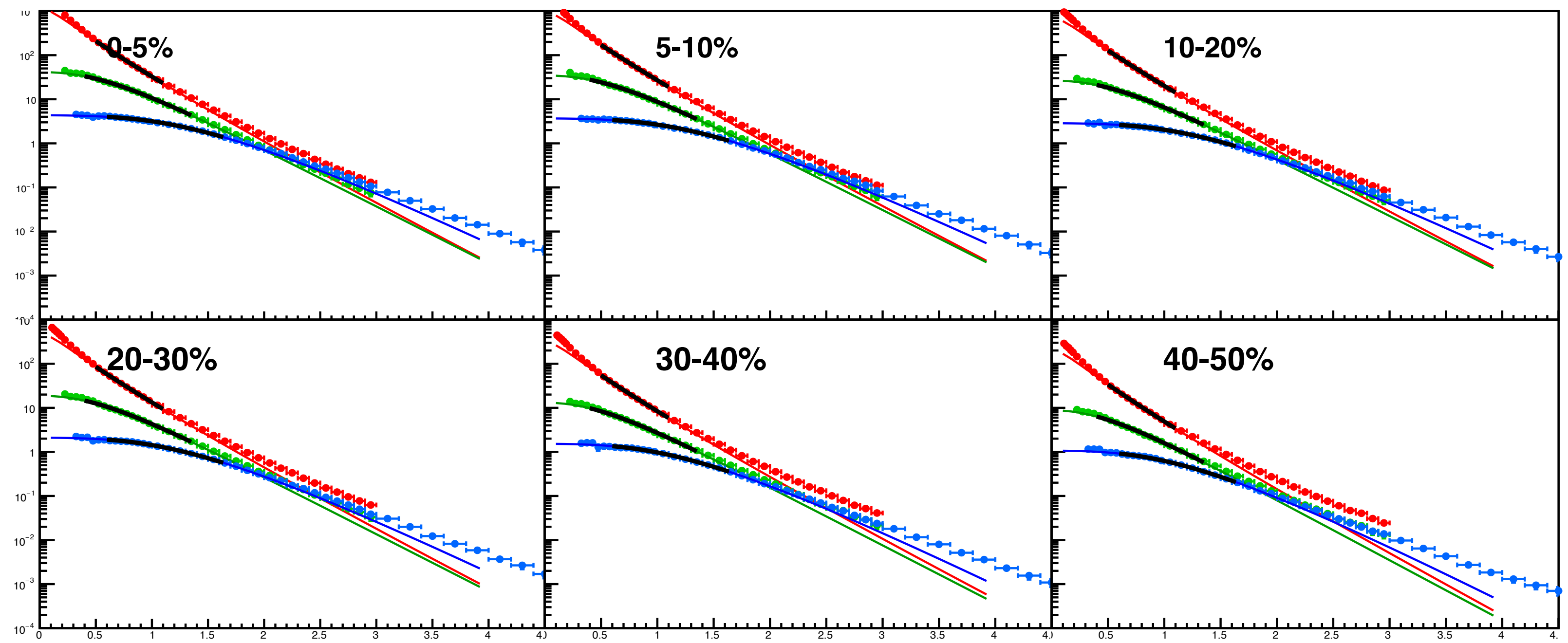
★**Fitting for pT spectra**

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

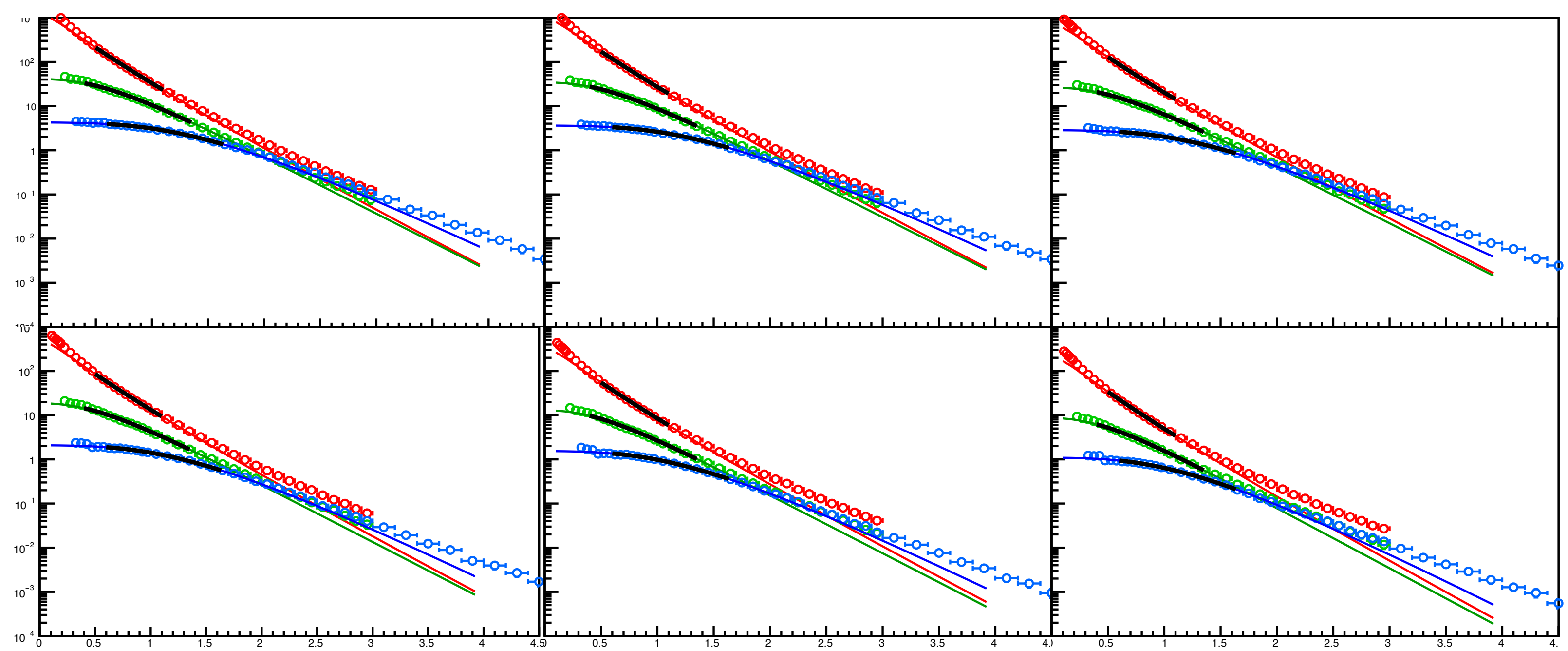
★ **2 Parameters**

- **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**

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

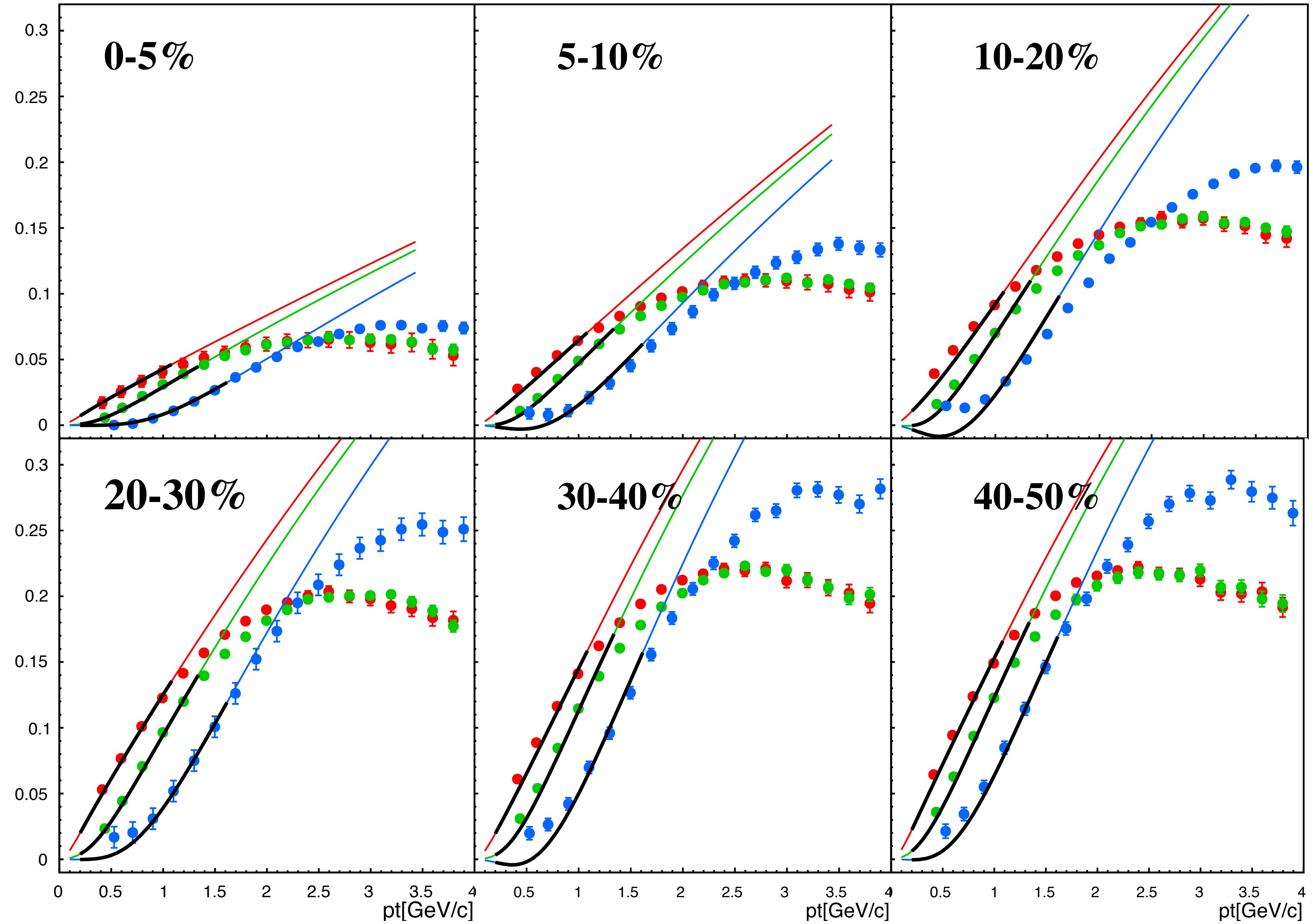
Blast wave fit for PID v_2

★ **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

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

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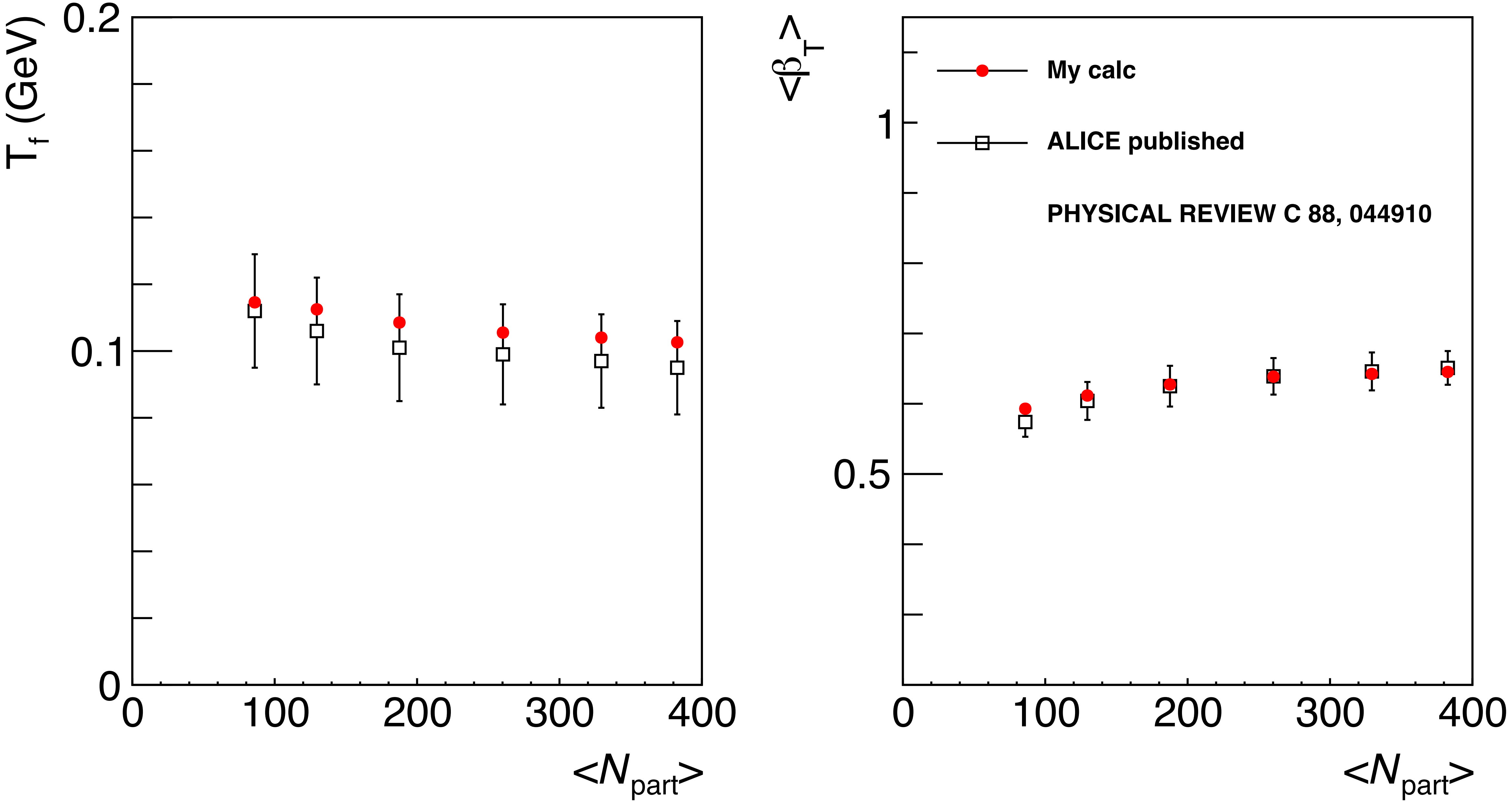
Blast Wave parameters (comparison with ALICE published)



✦ **Fully consistent within the systematic uncertainties**

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

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

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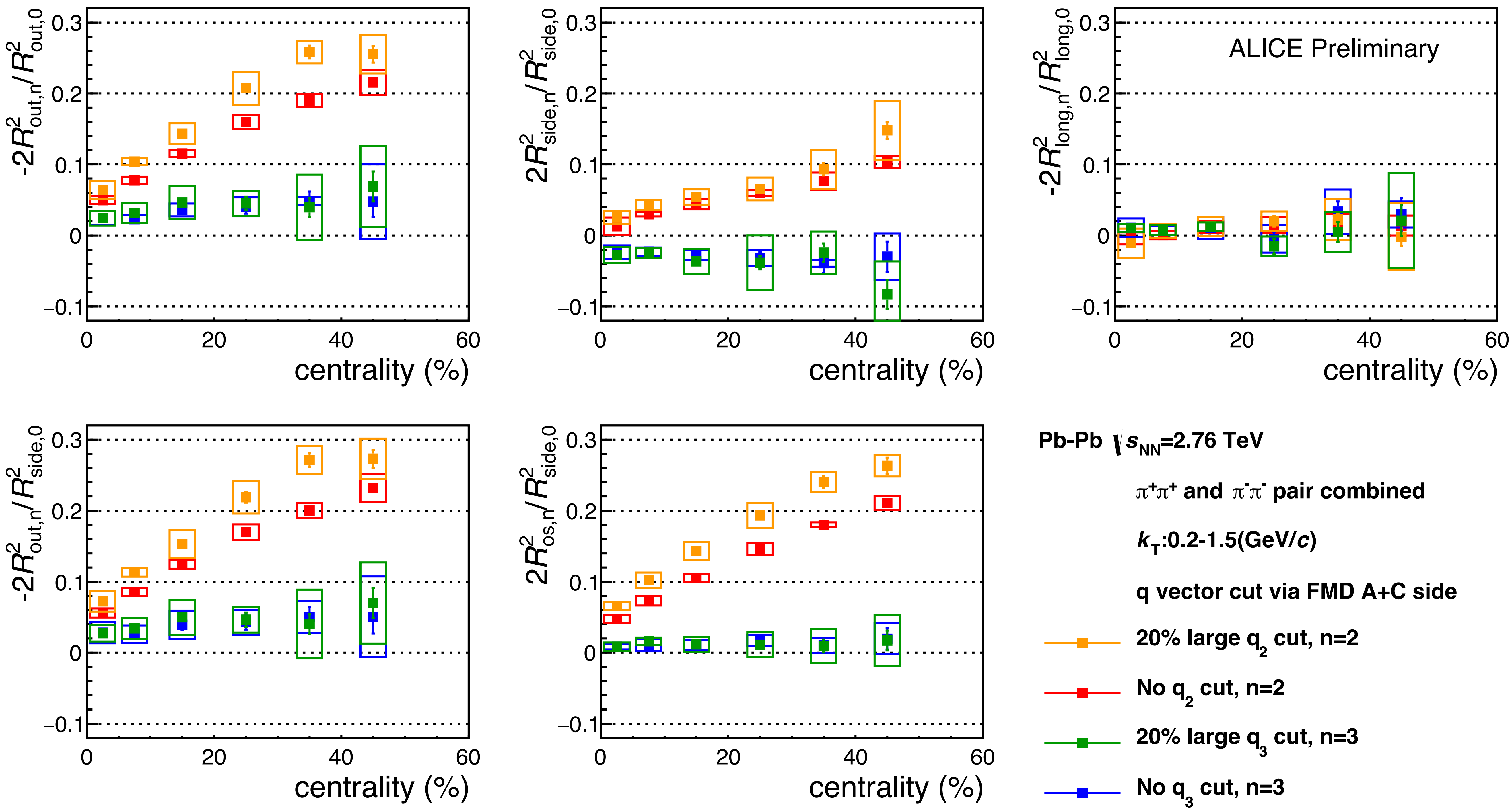
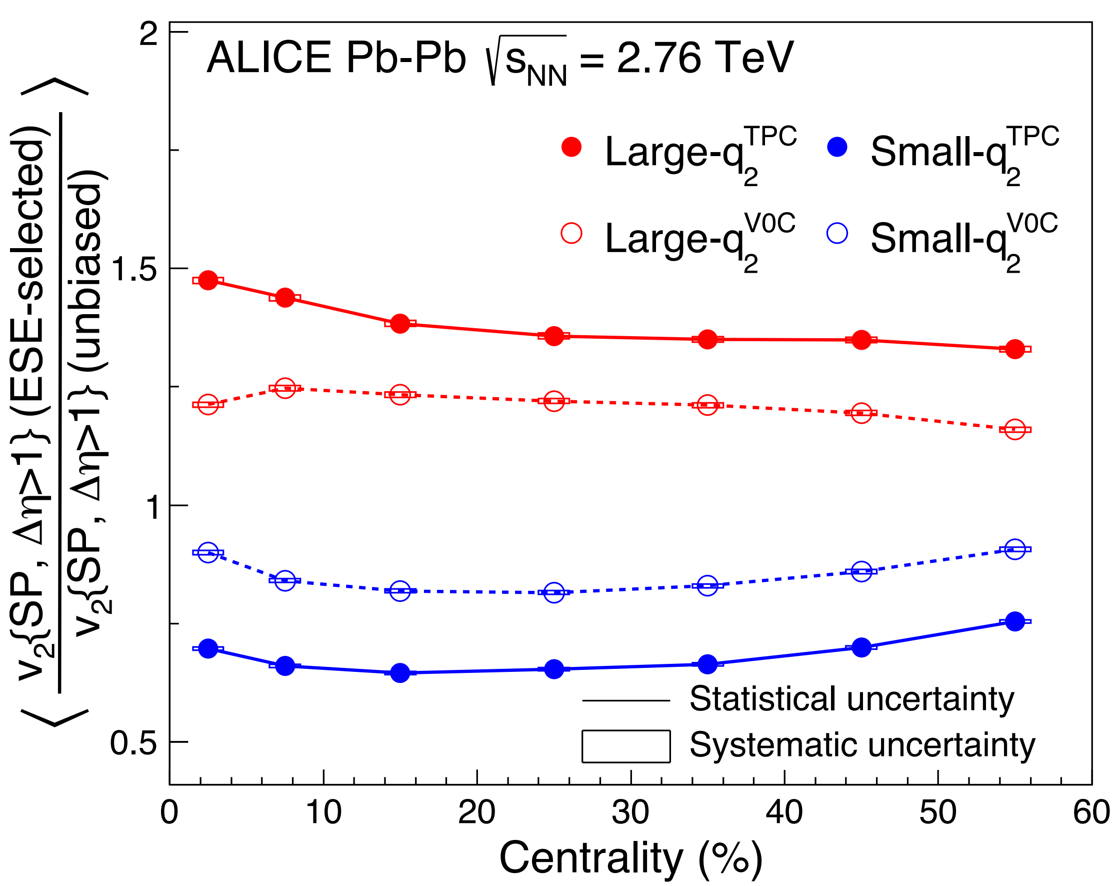
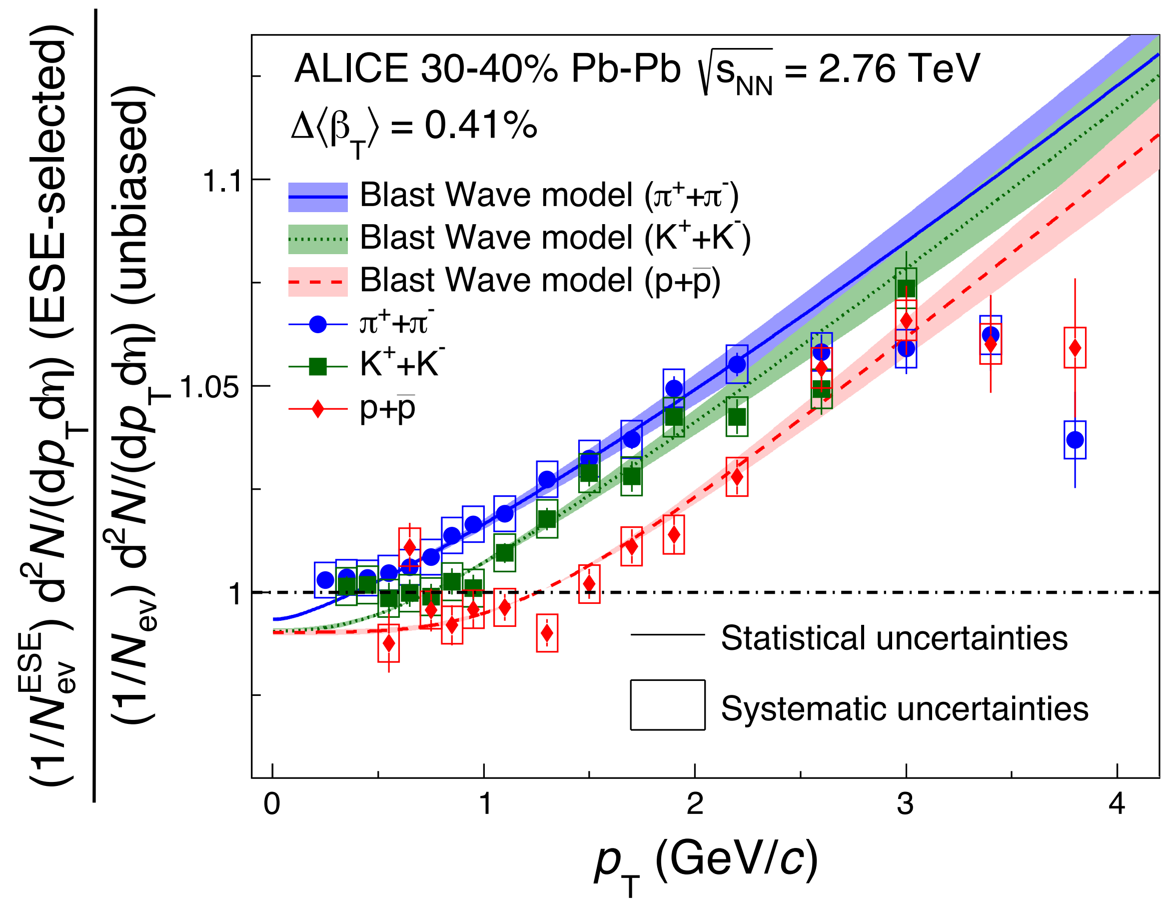
HBT relative to Ψ_n with ESE(q_n cut)



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%)**

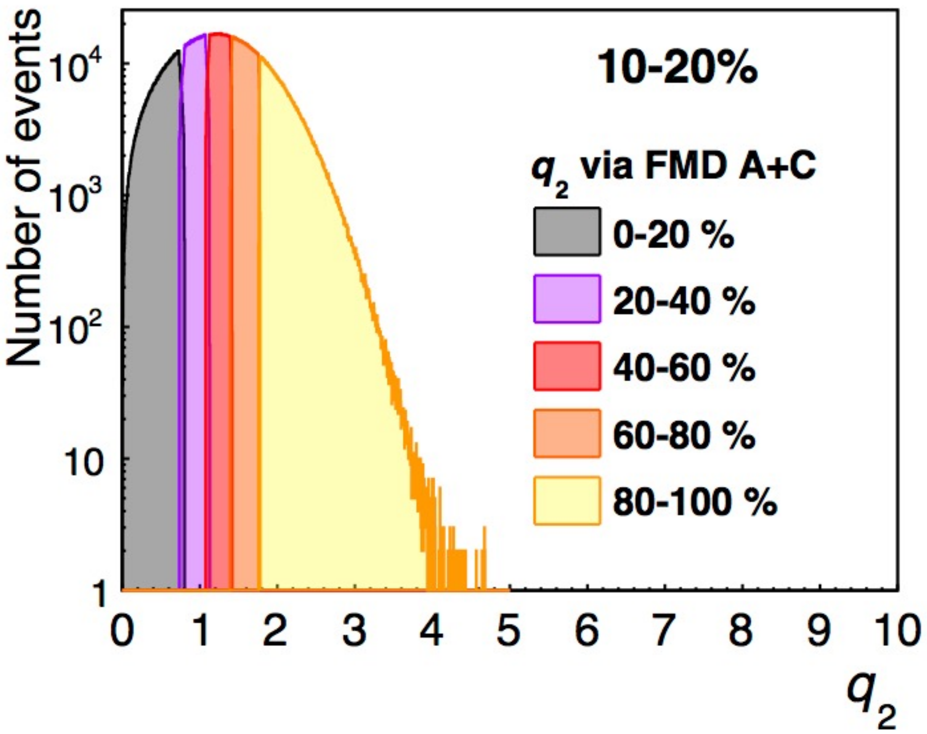
✦ **Ratio of p_T distribution of π, K, p**

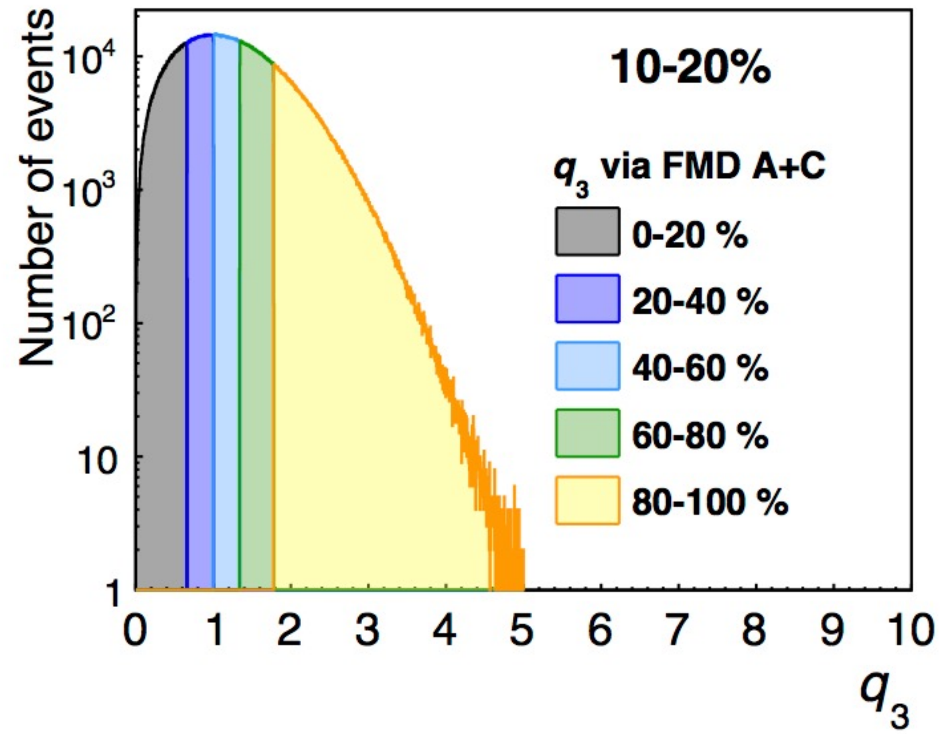
✦ **q_2^{TPC} top 10% cut (|η| < 0.4)**

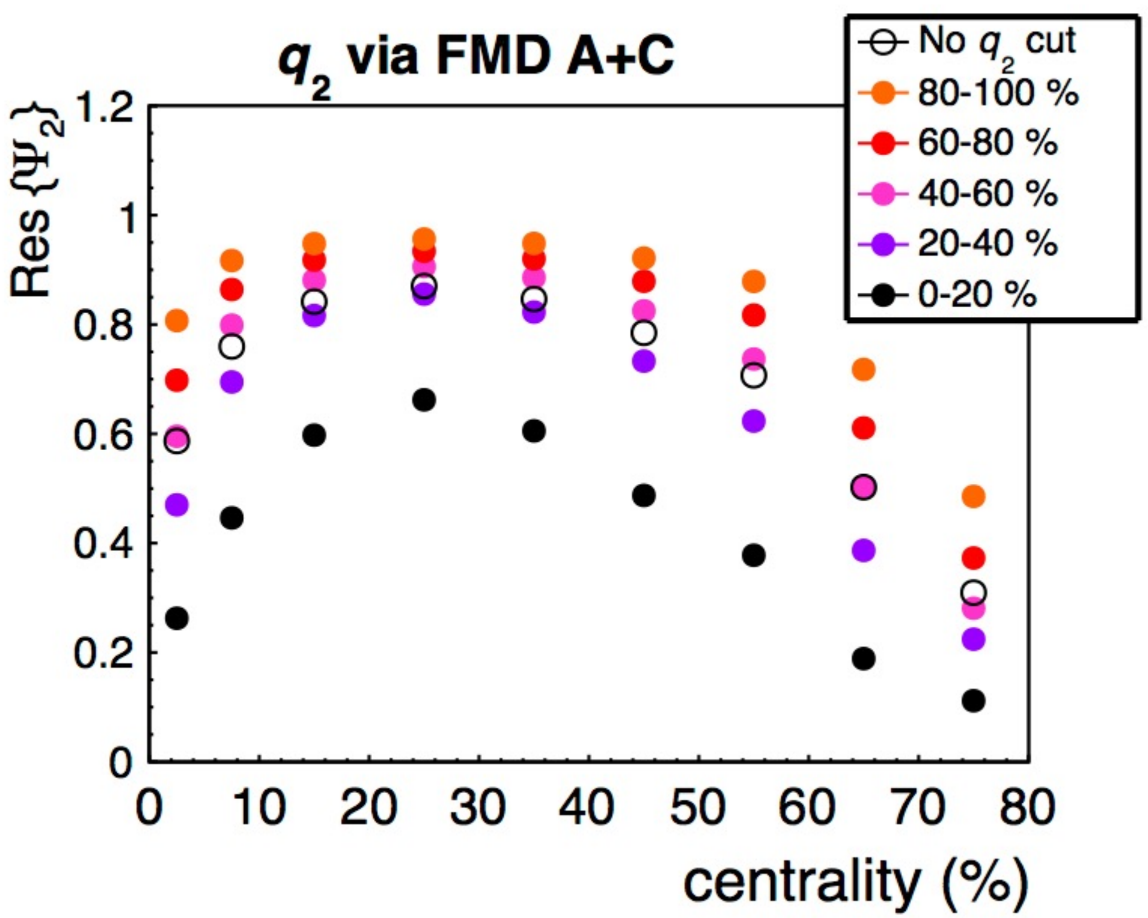
✦ **Blast wave model comparison**

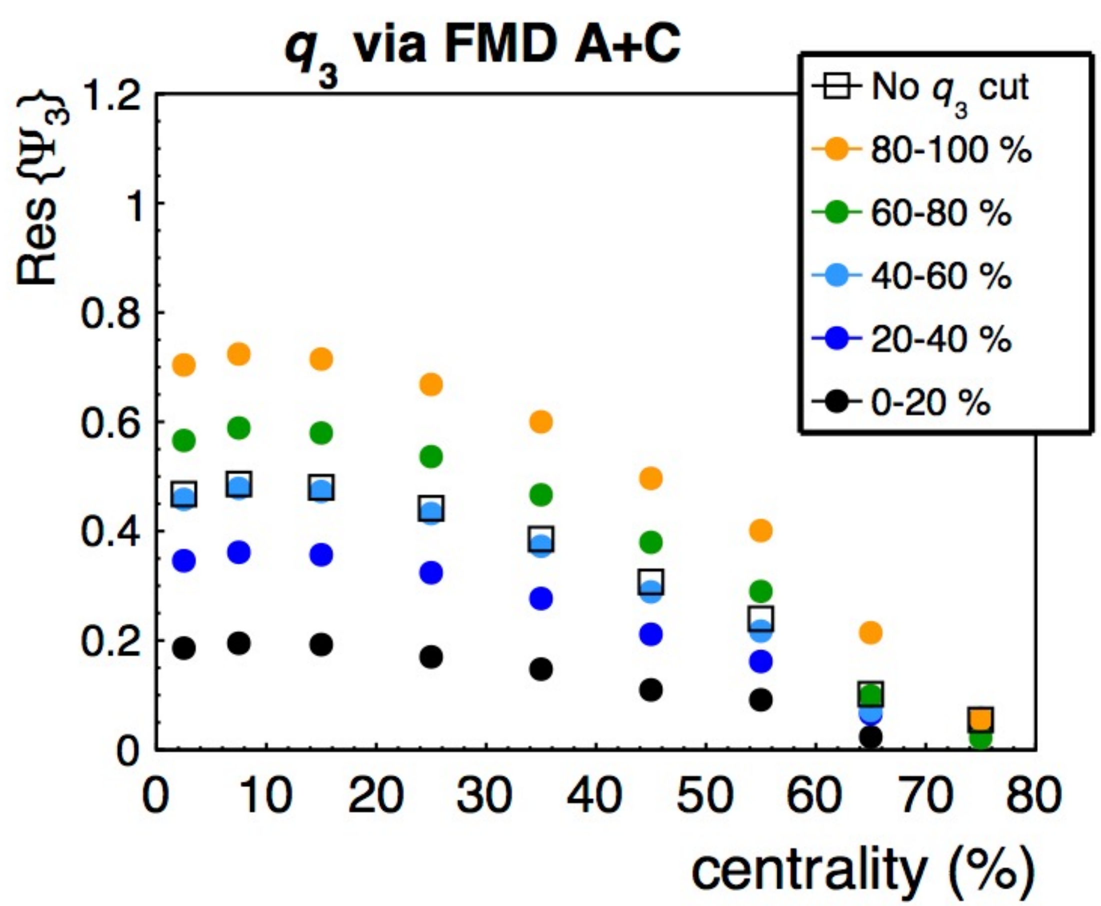
- √ **Δ<β_T> = +0.41%**

E.P. resolution with q_n cut









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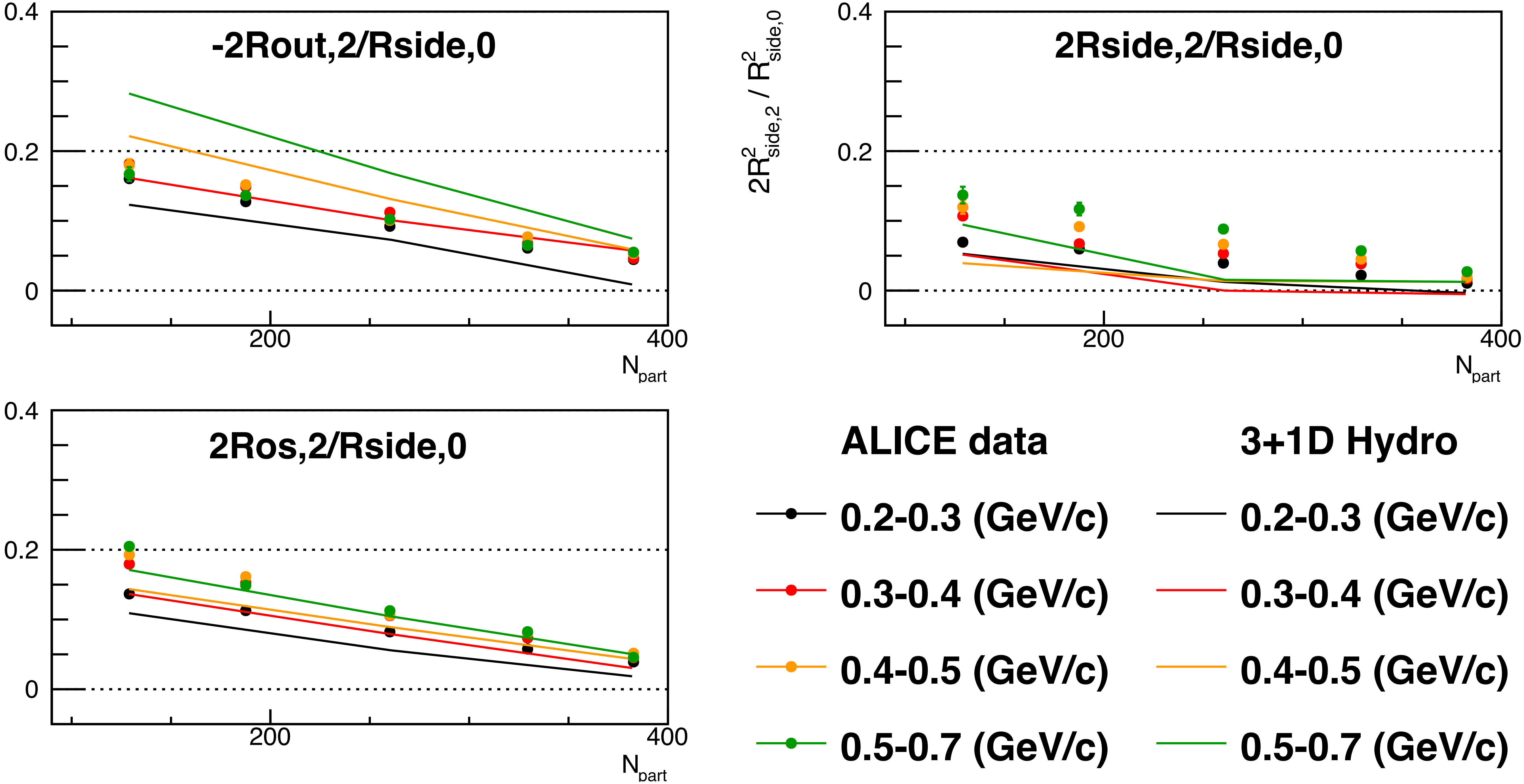
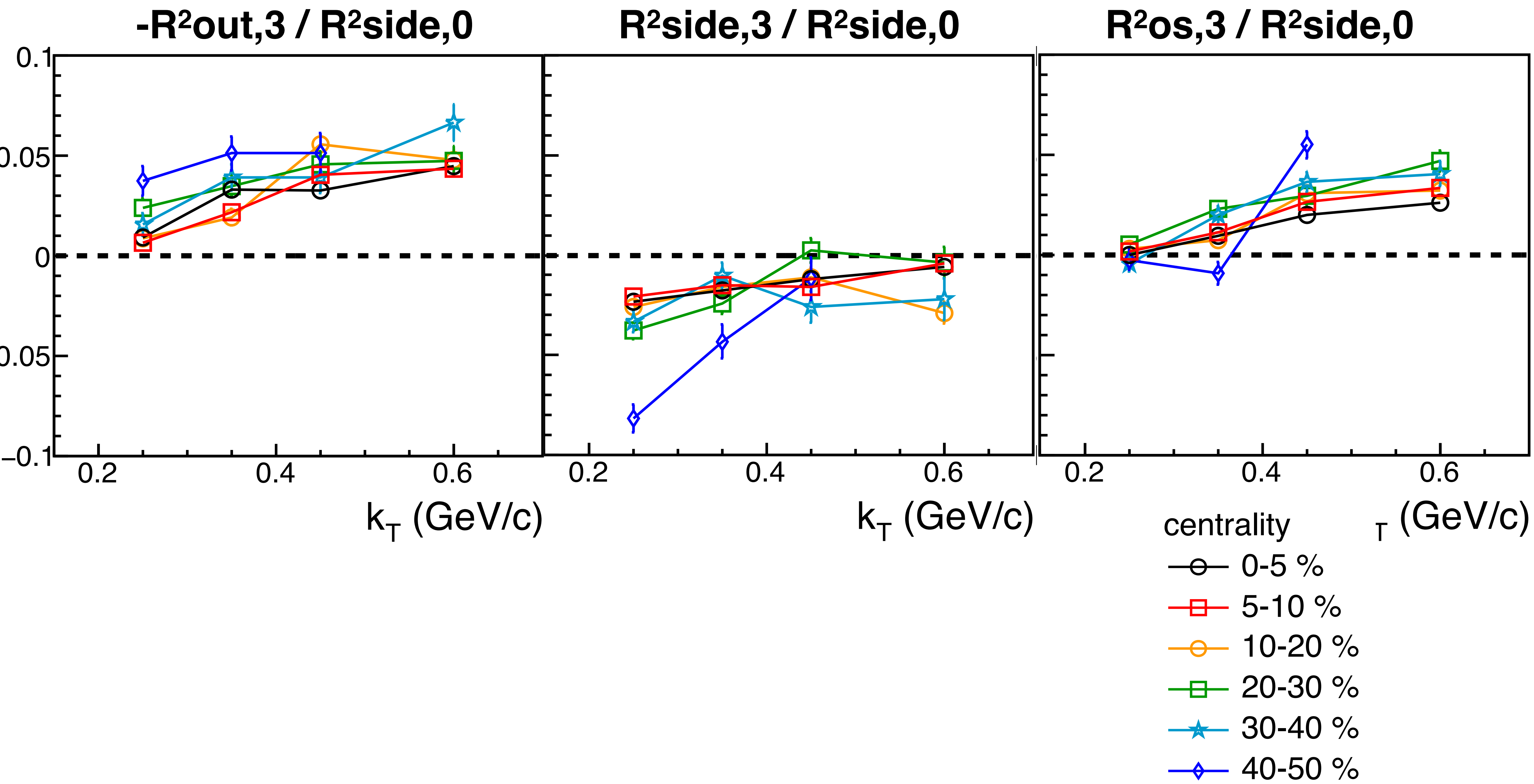
2nd harmonic oscillation amplitude of HBT radii

(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**

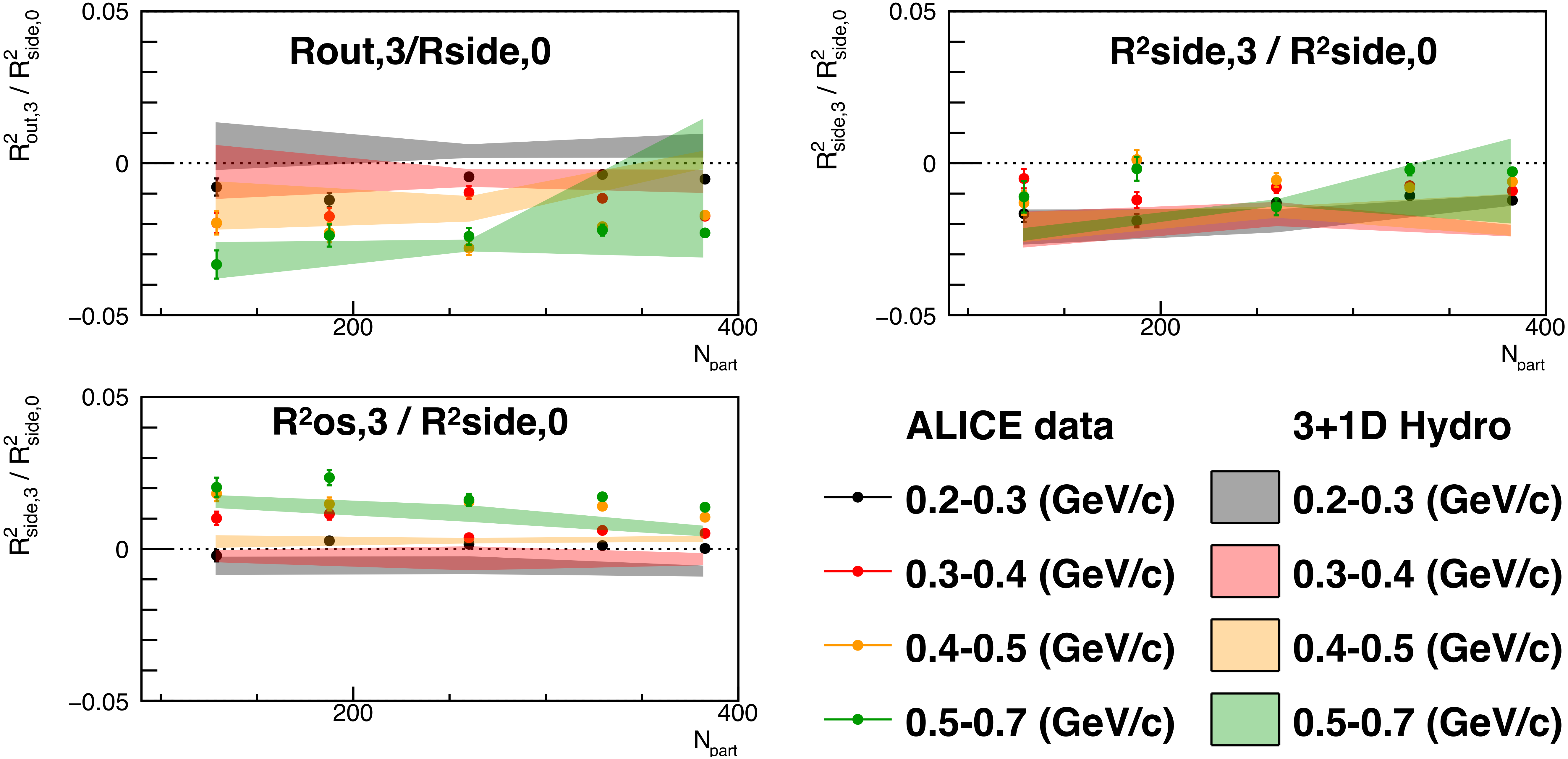
Relative amplitude of HBT radii w.r.t. Ψ_3 k_T dependence



- ✓ **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

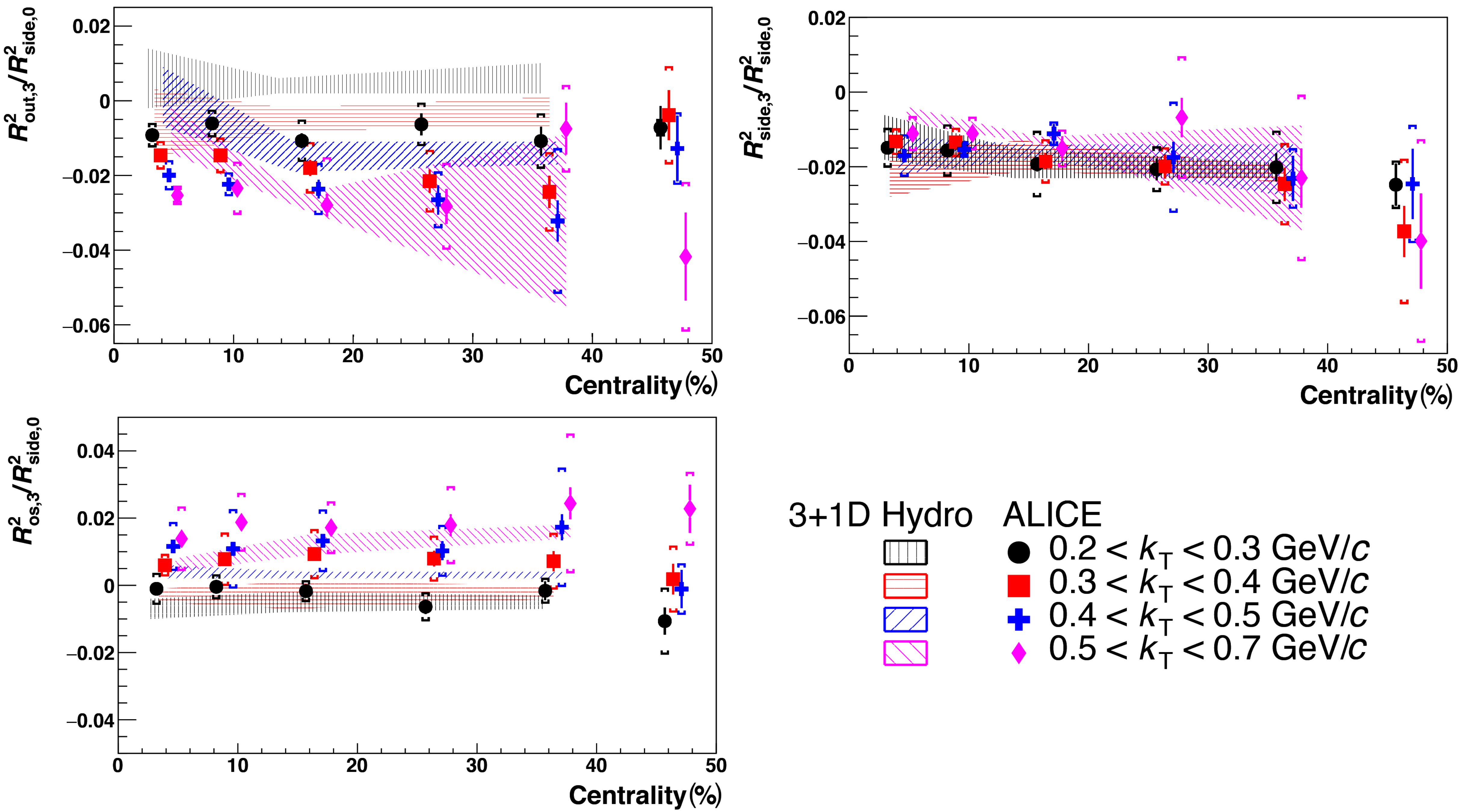
(P. Bozek, J. Phys. G**38**, 124097)



- ✦ *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

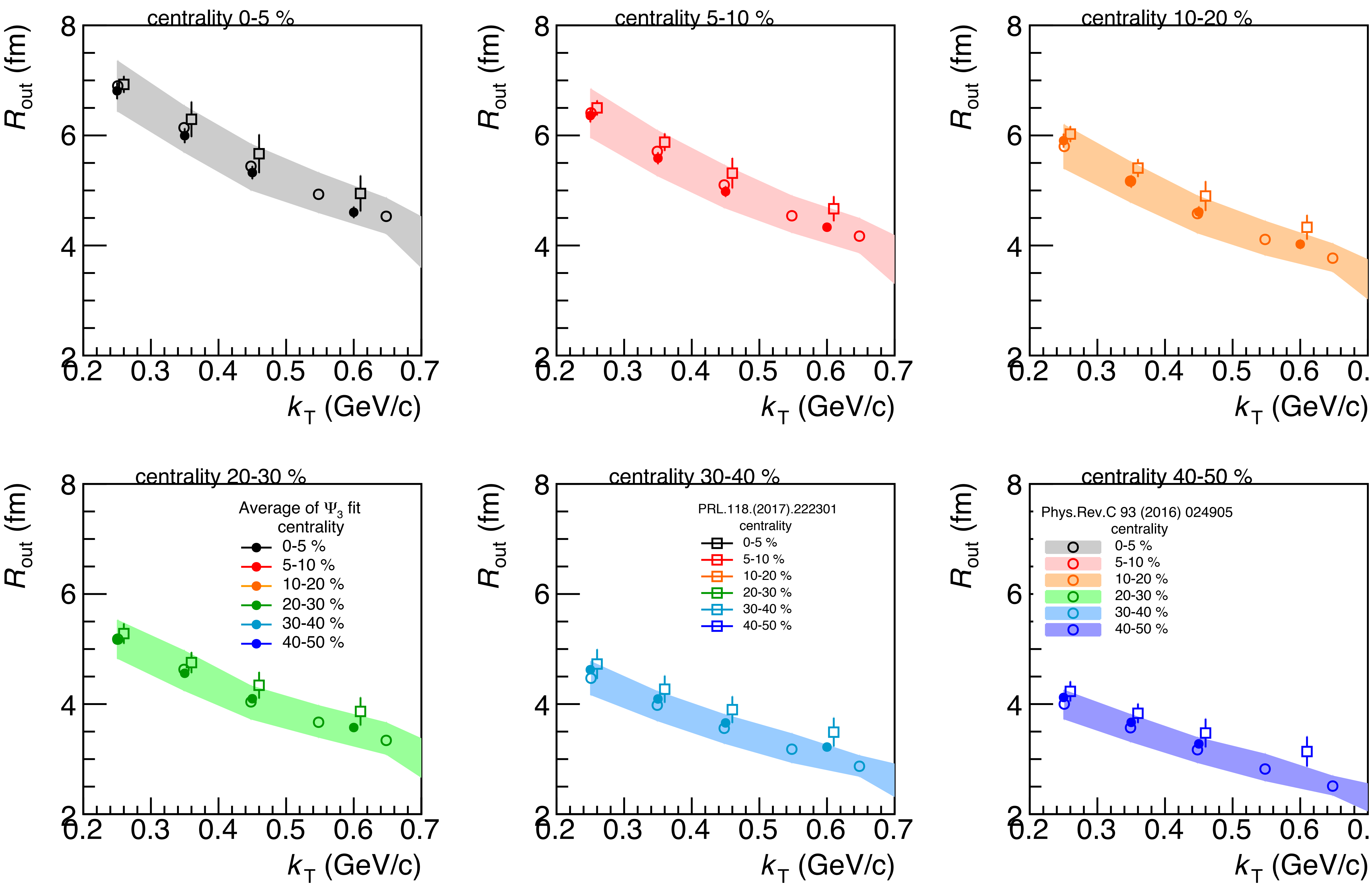
3rd harmonic oscillation amplitude of HBT radii

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

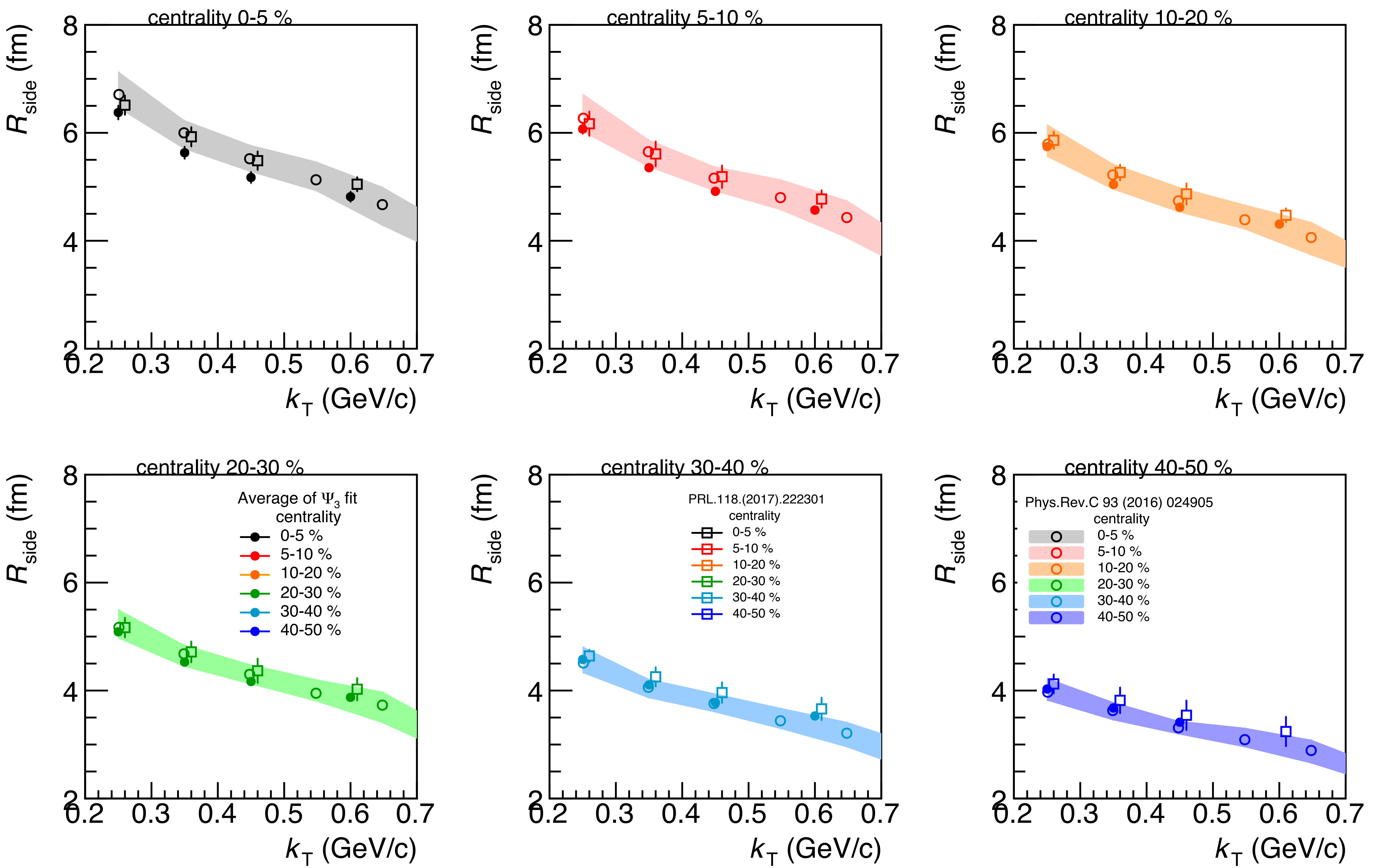


- ✦ **N_{part} dependence in Hydro calc. and Data are qualitatively consistent**
- ✦ **R^2_{out} oscillation is consistent in hight k_T (Hydro calc. at low p_T is opposite sign)**
- ✦ **R^2_{side} oscillation is consistent in low k_T**

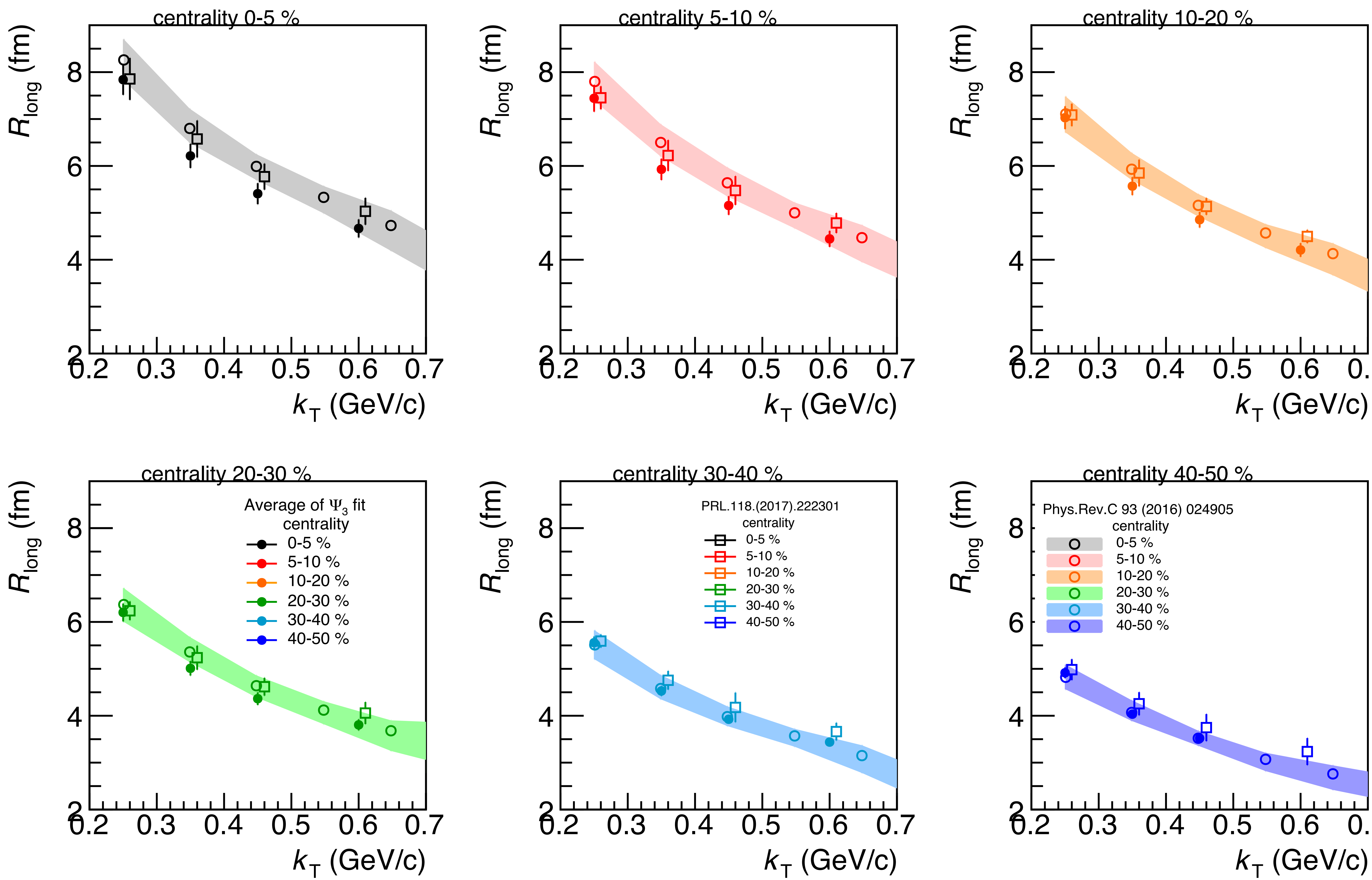
Consistency check of R_{out}



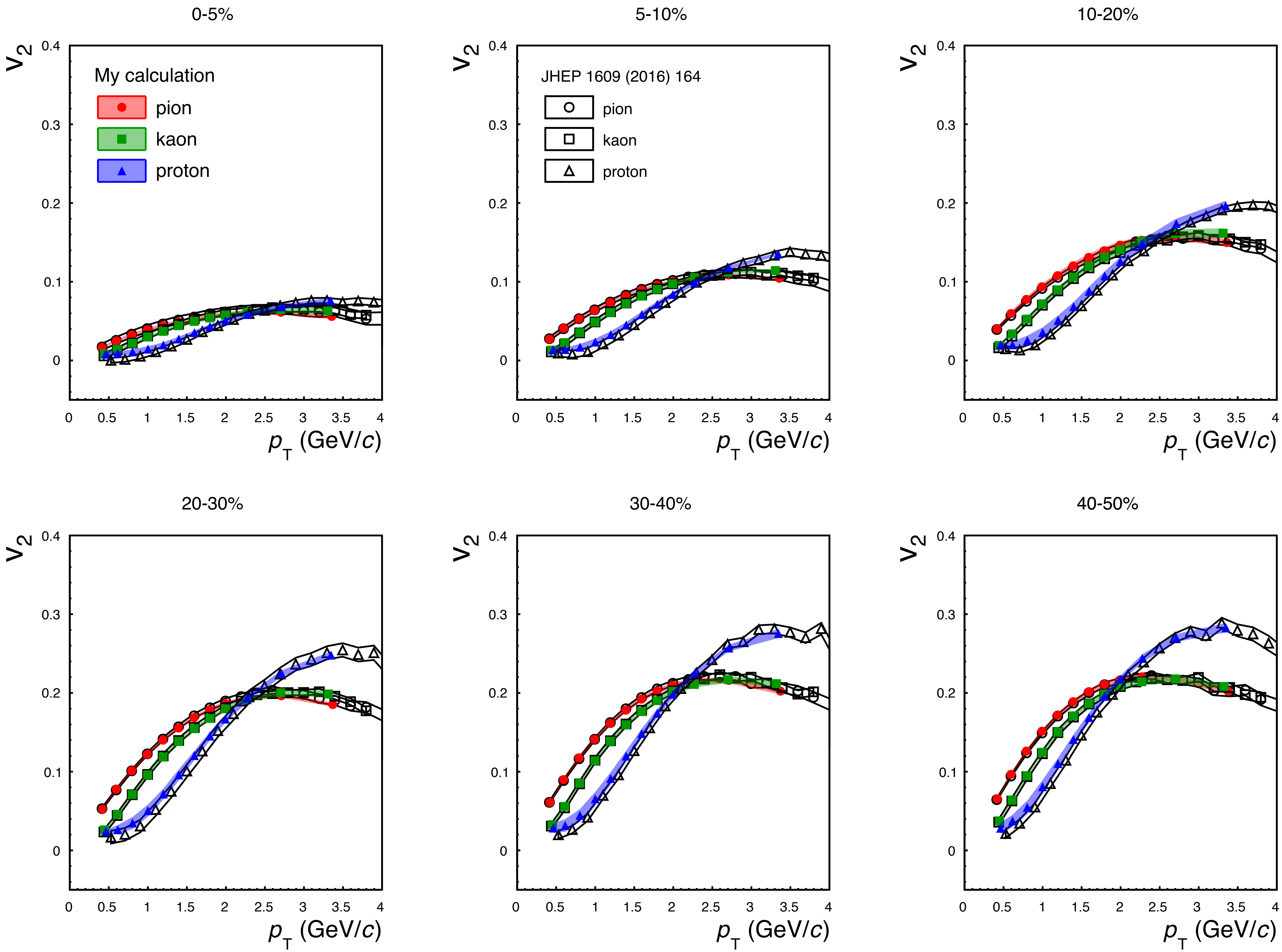
Consistency check of R_{side}



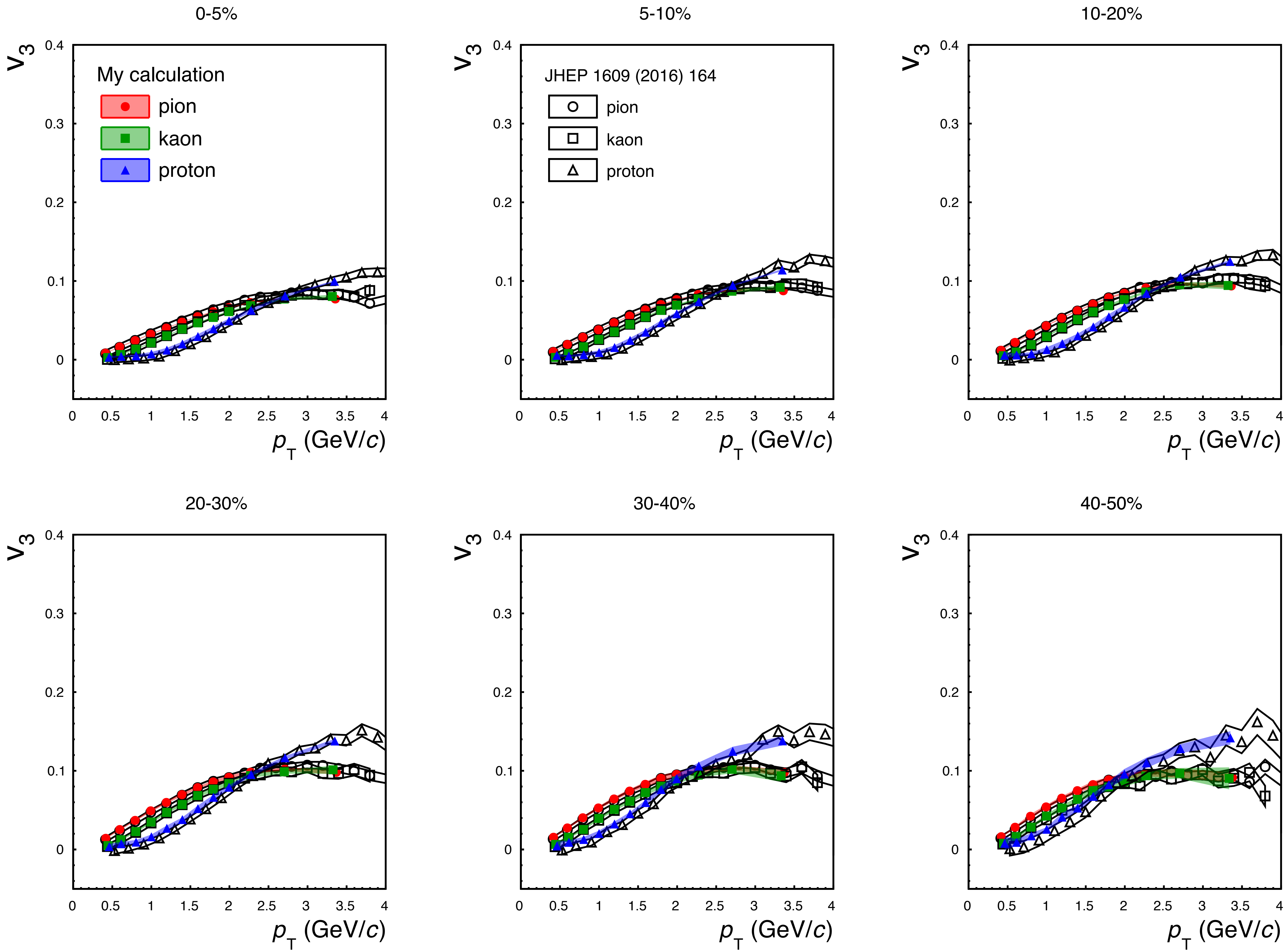
Consistency check of R_{long}



Consistency check of v_2

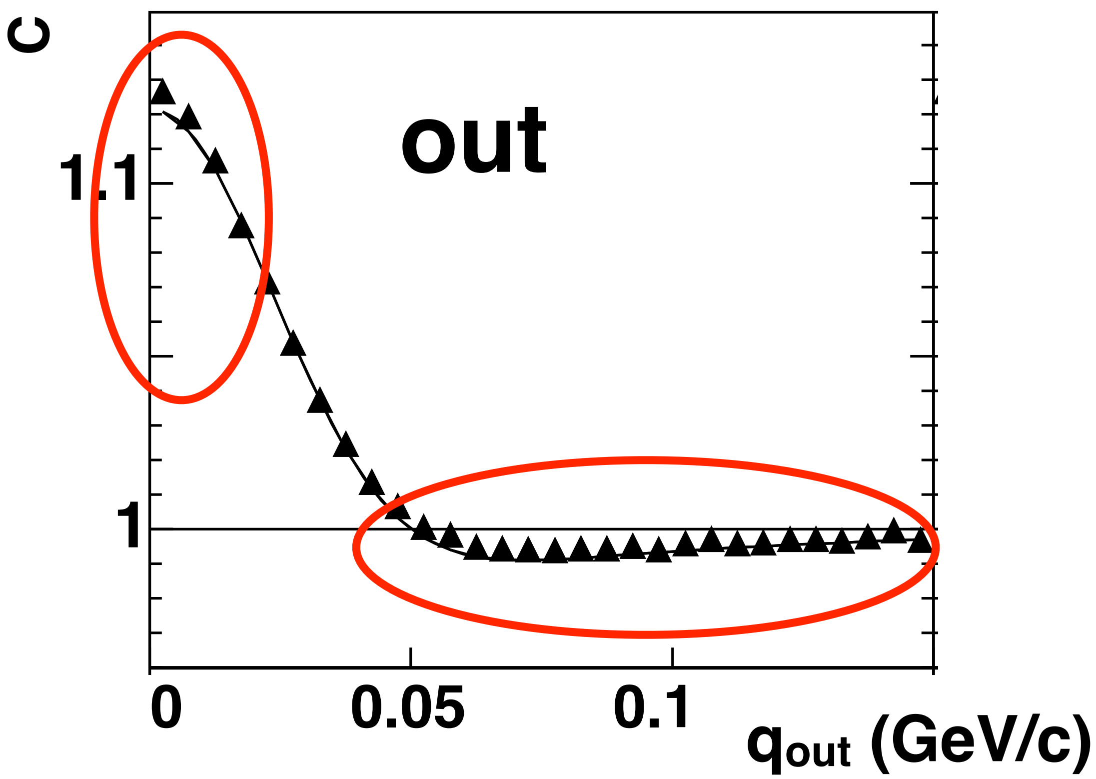


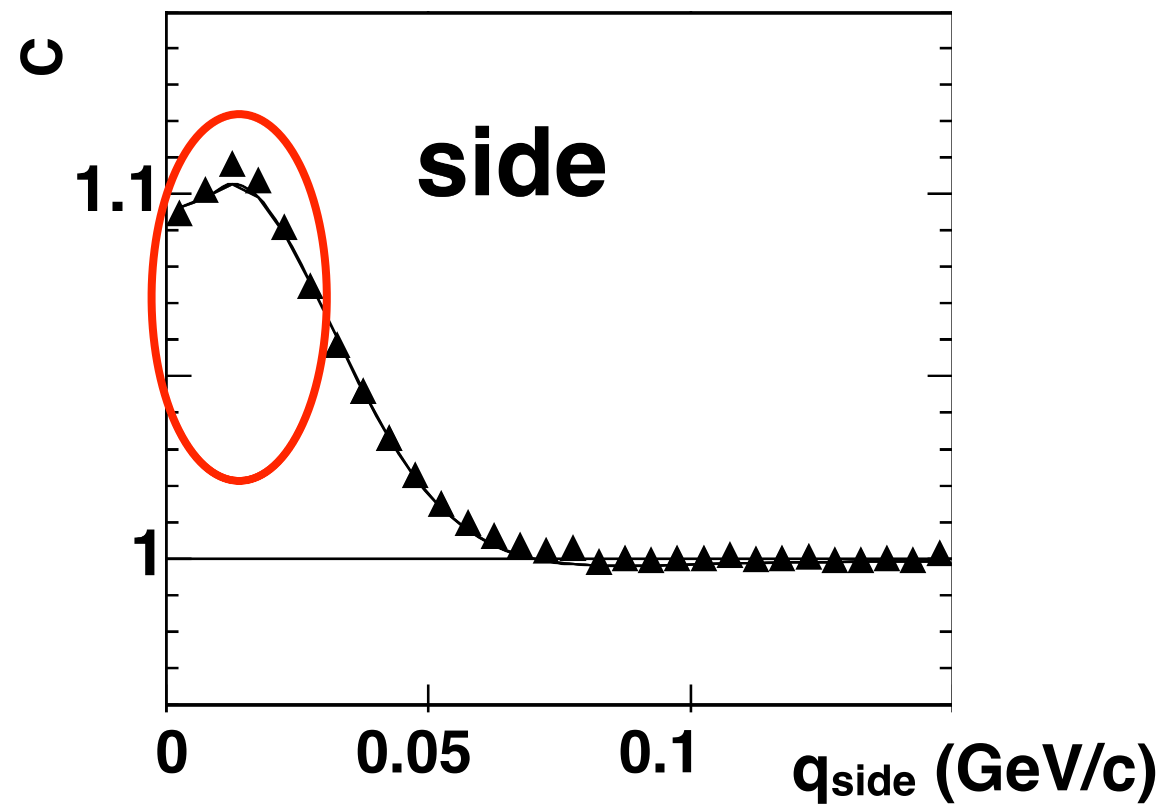
Consistency check of v_3

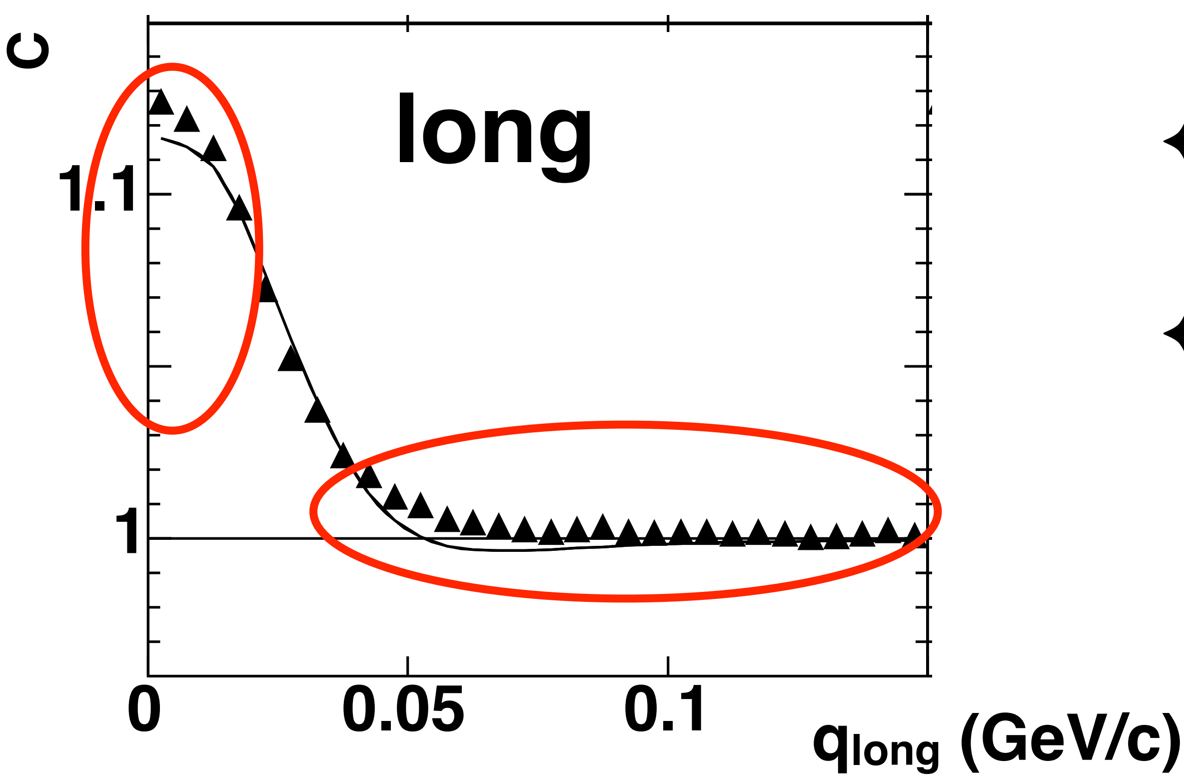


Measured correlation function is really gaussian ??

- ✦ Source distribution is assumed as “Gaussian distribution”
  - ‣ But measured correlation function is not “completely Gaussian”







- ✦ Au-Au collisions at $\sqrt{s_{NN}}$ = 200GeV
- ✦ Non gaussian features can be found in
  - ‣ small q (q < 0.02)
  - ‣ q : 0.04 - 0.15 GeV/c

✦J.Adams et al. PRC 71, 044906

Edgeworth expansion

- ✦ **Correlation function is extended to non-gauss distribution**
  - ▸ **model independent method**

$$C_2(q) = 1 + \exp\left(-q^2R^2\right) \times \left(1 + \sum_{n}^{\infty} \frac{\kappa_n}{n!\left(\sqrt{2}\right)^n} H_n\left(qR\right)\right)$$

$$H_n\left(x\right) = \left(-1\right)^n \mathrm{e}^{x^2} \frac{d^n}{dx^n} \mathrm{e}^{-x^2}$$

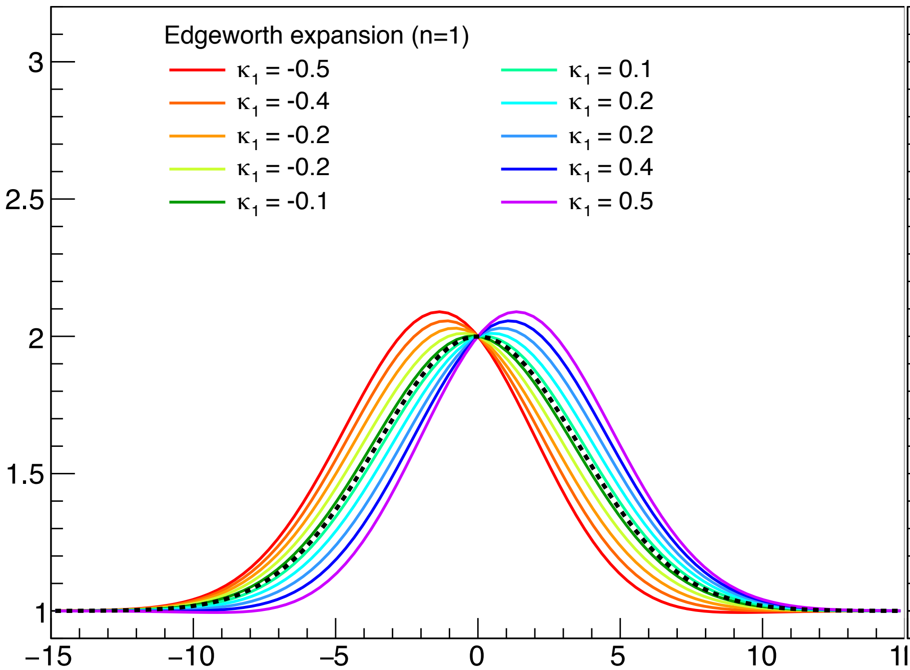
- Gauss distribution
- Non gaussian term
  - ▸ n^{th}-order Edgeworth expansion

✦**J.Adams et al. PRC 71, 044906**

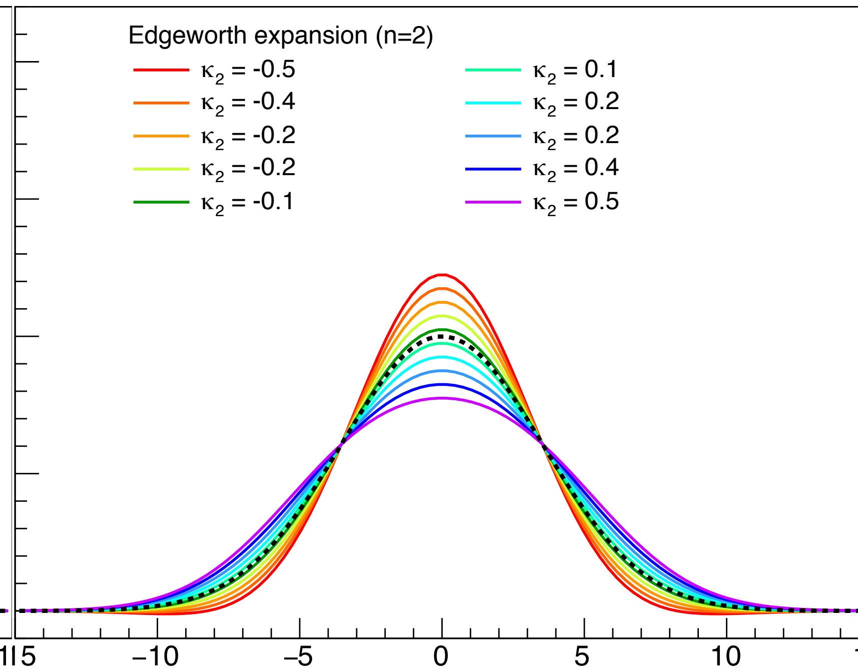
Edgeworth expansion

- ✦ **How Edgeworth expansion modified gaussian shape (1st - 6th) ??**
  - ‣ **Default gaus function is $1+\exp(-x^2/25)$** **mean:0, sigma:5, height:1**

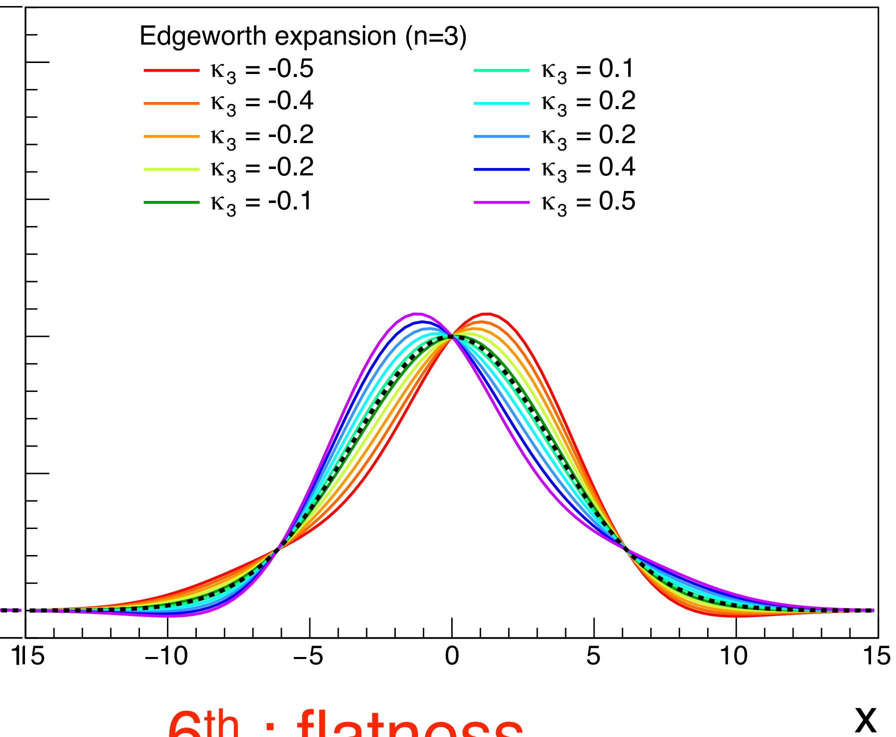
1st : mean



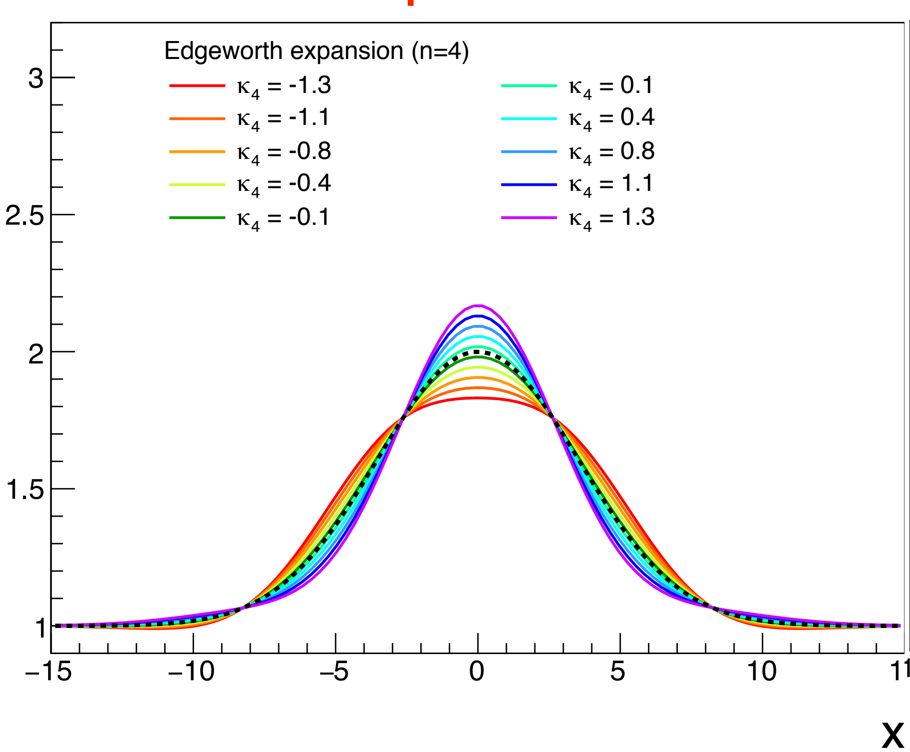
2nd : sigma



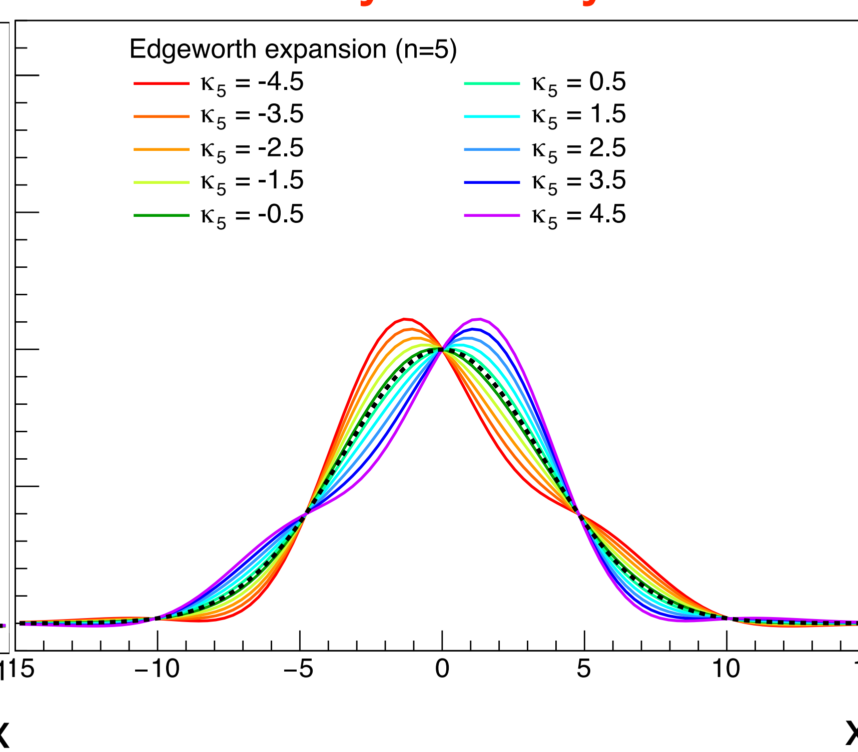
3rd : asymmetry



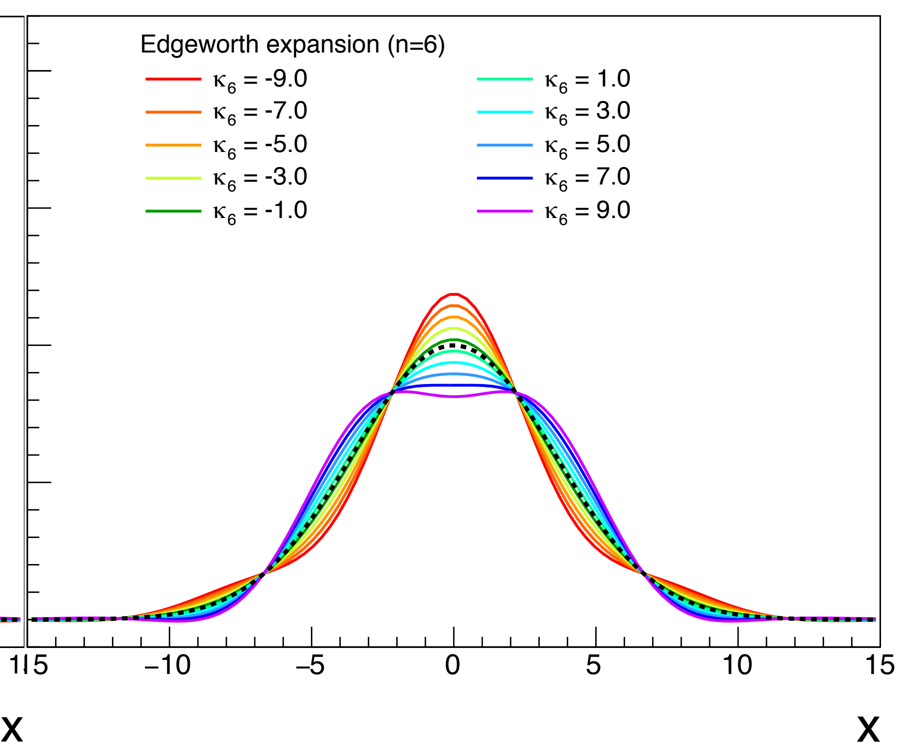
4th : sharpness



5th : asymmetry



6th : flatness



Correlation function with Edgeworth expansion

- **Correlation function with 4th and 6th Edgeworth expansion**
  - **Identical particles must be invariant under ($q_{out}, q_{side}, q_{long}$) -> ($-q_{out}, q_{side}, q_{long}$)**

$$C_2(q_{\rm out}, q_{\rm side}, q_{\rm long}) = (1-\lambda) + \lambda K_{\rm coul}\left(1 + {\rm G} \times {\rm NGF}\right)$$

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

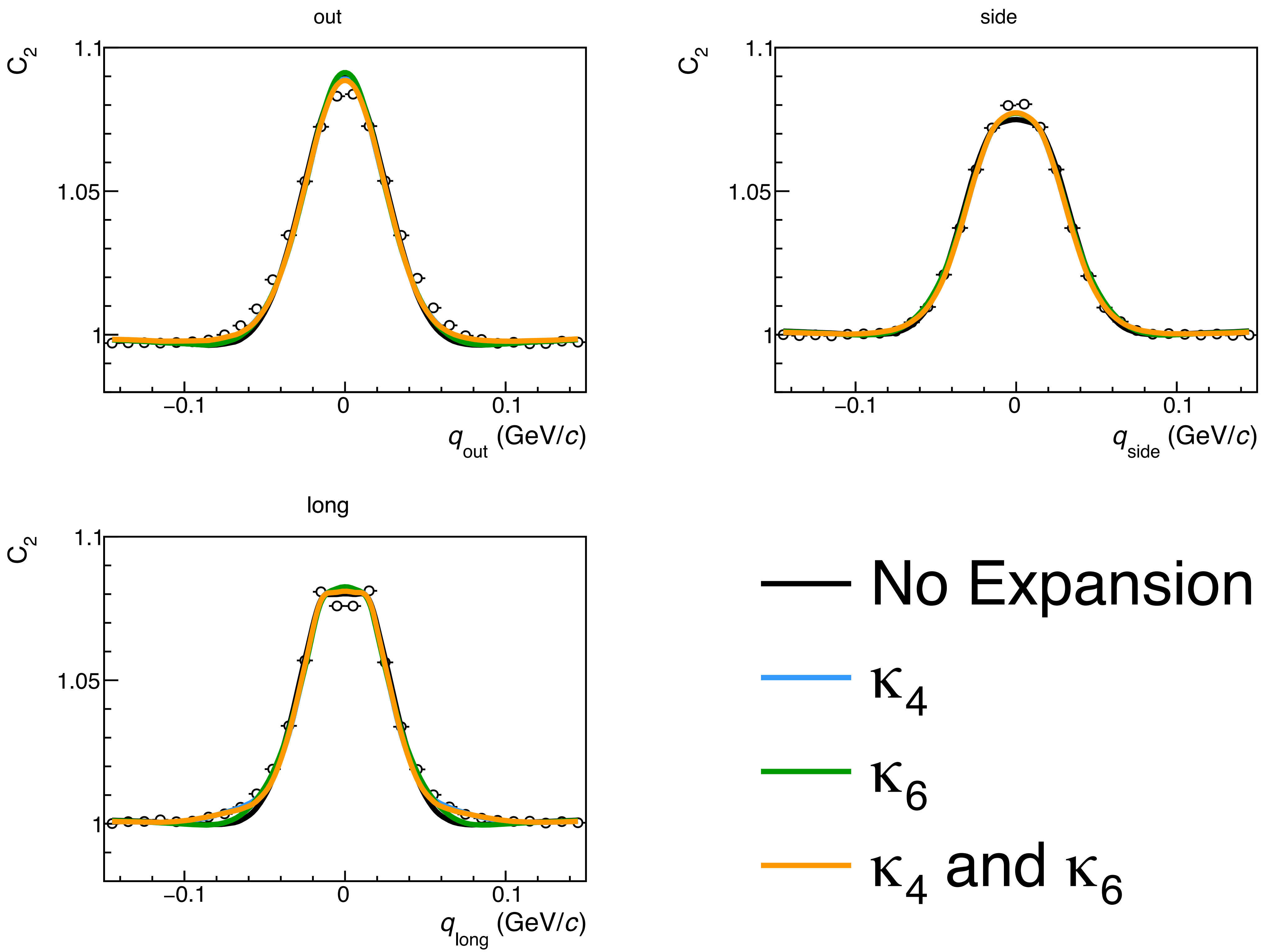
$$\begin{aligned}{\rm NGF} = &\left(1 + \sum_{n=4,6}^{\infty} \frac{\kappa_n}{n!\left(\sqrt{2}\right)^n} H_n\left(q_{out} R_{out}\right)\right)\\ &\times \left(1 + \sum_{n=4,6}^{\infty} \frac{\kappa_n}{n!\left(\sqrt{2}\right)^n} H_n\left(q_{side} R_{side}\right)\right)\\ &\times \left(1 + \sum_{n=4,6}^{\infty} \frac{\kappa_n}{n!\left(\sqrt{2}\right)^n} H_n\left(q_{long} R_{long}\right)\right)\end{aligned}$$

$$H_n(x) = (-1)^n \, {\rm e}^{x^2} \frac{d^n}{dx^n} {\rm e}^{-x^2}$$

✦J.Adams et al. PRC 71, 044906

Correlation function with Edgeworth expansion

- Correlation function with 4th and 6th Edgeworth expansion
  - Gauss (+ coulomb) distribution could not describe tail shape of out, long
  - 4th-order Edgeworth expansion is effective to non-gaussian shape of C_2



Azimuthal angle dependence of HBT radii

- **Extracted HBT radii as a function of ϕ_{pair} - Ψ_2**
  - **Edgeworth expansion makes smaller extracted HBT radii**
  - **Not only average HBT radii but also oscillation has changed in R_{out}**