Azimuthally differential pion femtoscopy in Pb-Pb collisions at 2.76 TeV with ALICE at the LHC

Quark Matter 2014
Darmstadt, Germany

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for the ALICE Collaboration

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DARMSTADT 2014

Outline

- Physics motivation
- Femtoscopy
- Results
- Comparison to models
- Summary

Femtoscopic Measurements

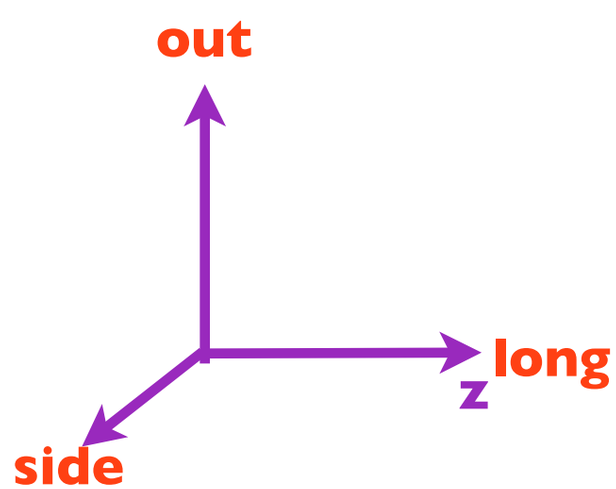
The space-time distribution of emission points for particles of a given momentum.

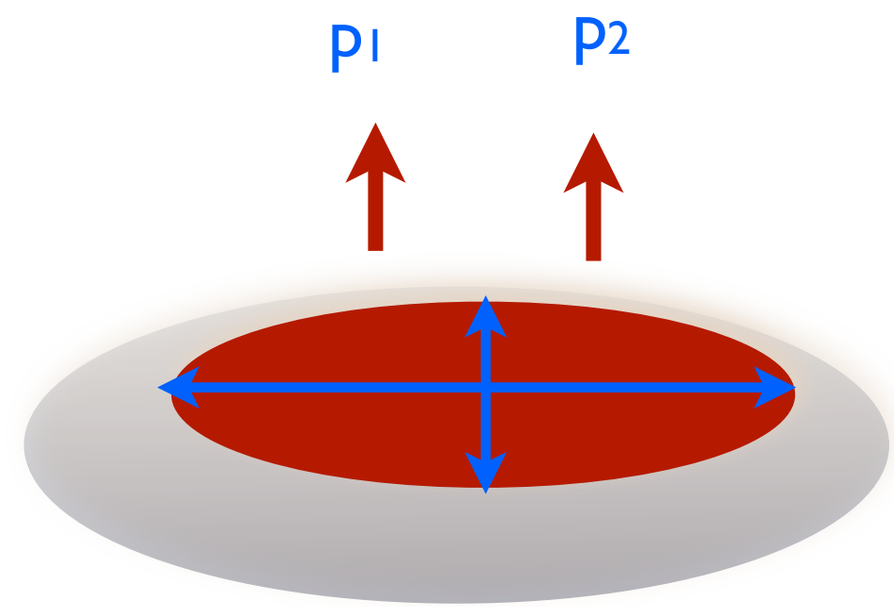
Longitudinally CoMoving System (LCMS) frame: $p_{1,z} = -p_{2,z}$

"Out" -> pair momentum direction

"Long" -> beam direction

"Side" -> perpendicular to "out" and "long"





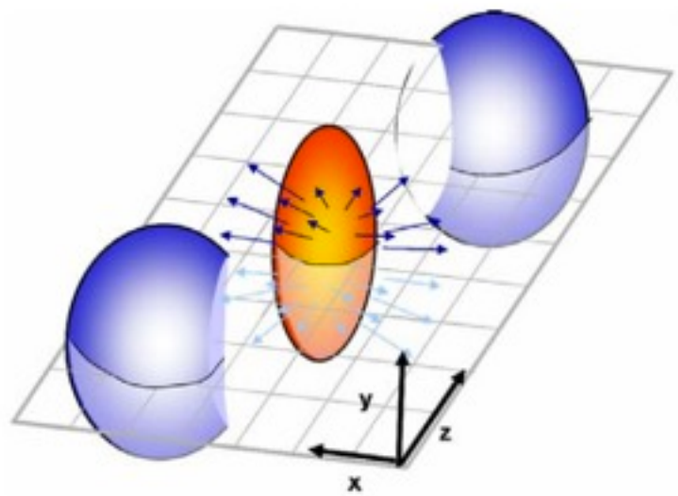
"out-side-long" reference frame (Bertsch-Pratt)

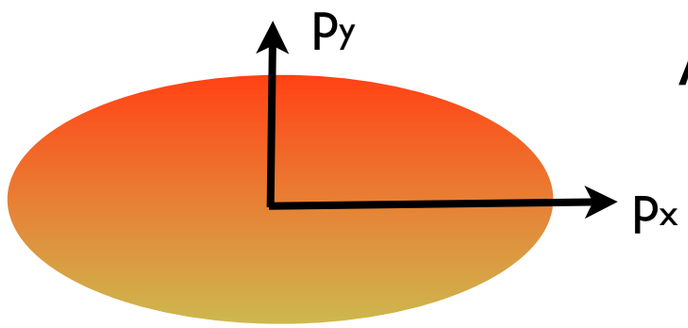
side -> geometrical size

out -> geometrical size + emission duration

long -> total evolution time

Motivation





P. Kolb and U. Heinz, Nucl. Phys. A **715**, 653 (2003).

In non-central collisions, greater transverse pressure in the reaction plane than perpendicular:

- stronger in-plane expansion measured as elliptic flow,
- in-plane expansion diminishes the out-of-plane spatial anisotropy.

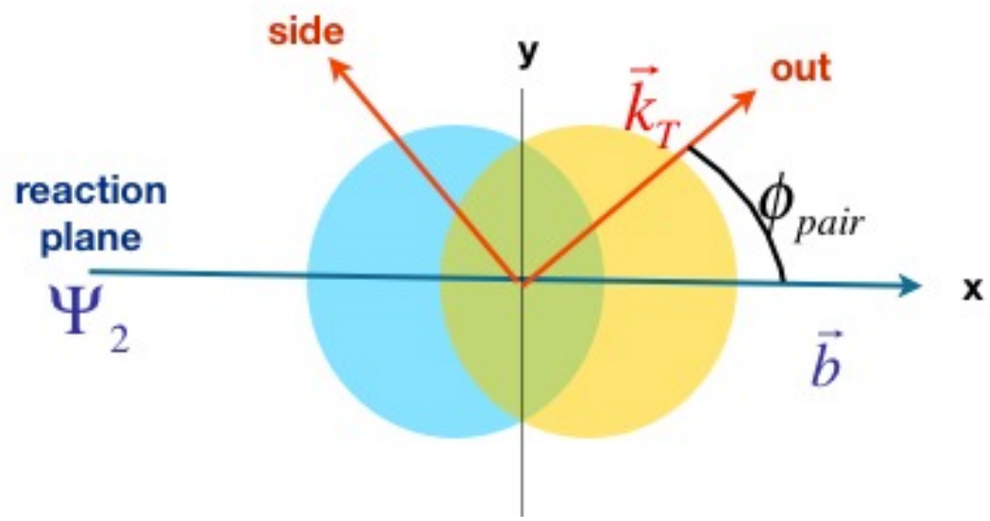
Azimuthally differential pion femtoscopy:

- HYDRO predicts that while the system is out-of-plane extended, rescattering may make the final source in-plane,
- freeze-out source shape is complementary to v_2 measurements for a complete consistency check of transverse evolution in HYDRO models,
- measurements of the freeze-out source shape will provide information on the system's evolution.

Femtoscopy

$$\vec{k}_T = \left(\vec{p}_1 + \vec{p}_2\right)/2$$

n : harmonic number



$$C(\boldsymbol{q}) = \frac{S(\boldsymbol{q})}{B(\boldsymbol{q})}, \quad \boldsymbol{q} = \boldsymbol{p_1} - \boldsymbol{p_2}$$

$S(\boldsymbol{q})$: distribution of pair mometum difference of particles from the same event

$B(\boldsymbol{q})$: distribution of pair mometum difference of particles from different (i.e. mixed) events

$$C(\boldsymbol{q}) = N\left[(1-\lambda) + \lambda K(\boldsymbol{q})\left(1 + G(\boldsymbol{q})\right)\right]$$

Correlation functions are fit by Bowler-Sinyukov formula

$$G(\boldsymbol{q}) = exp-\left(R_o^2 q_o^2 + R_s^2 q_s^2 + R_l^2 q_l^2 + 2R_{os}^2 q_o q_s + R_s^2 q_s q_l + R_{ol}^2 q_o q_l\right)$$

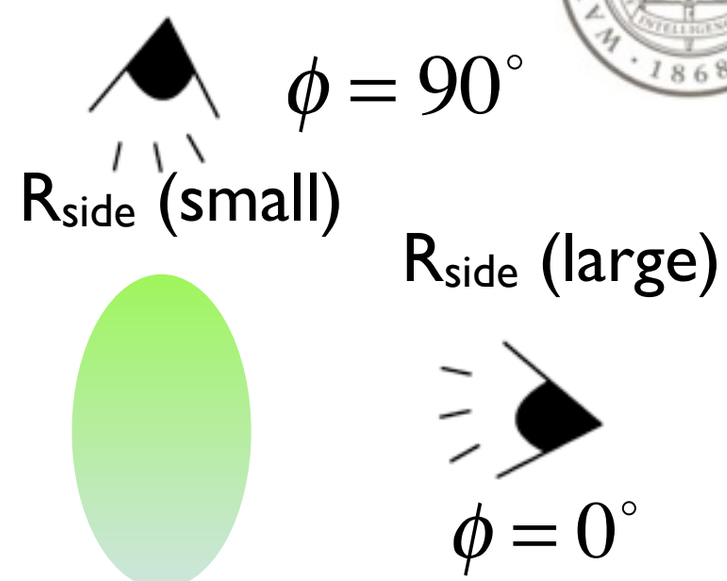
$$R_\mu^2 = R_0^2 + R_{\mu,n}^2 \cos\left[n\left(\phi_{pair} - \Psi_n\right)\right] \quad (\mu = s,\ o,\ l)$$

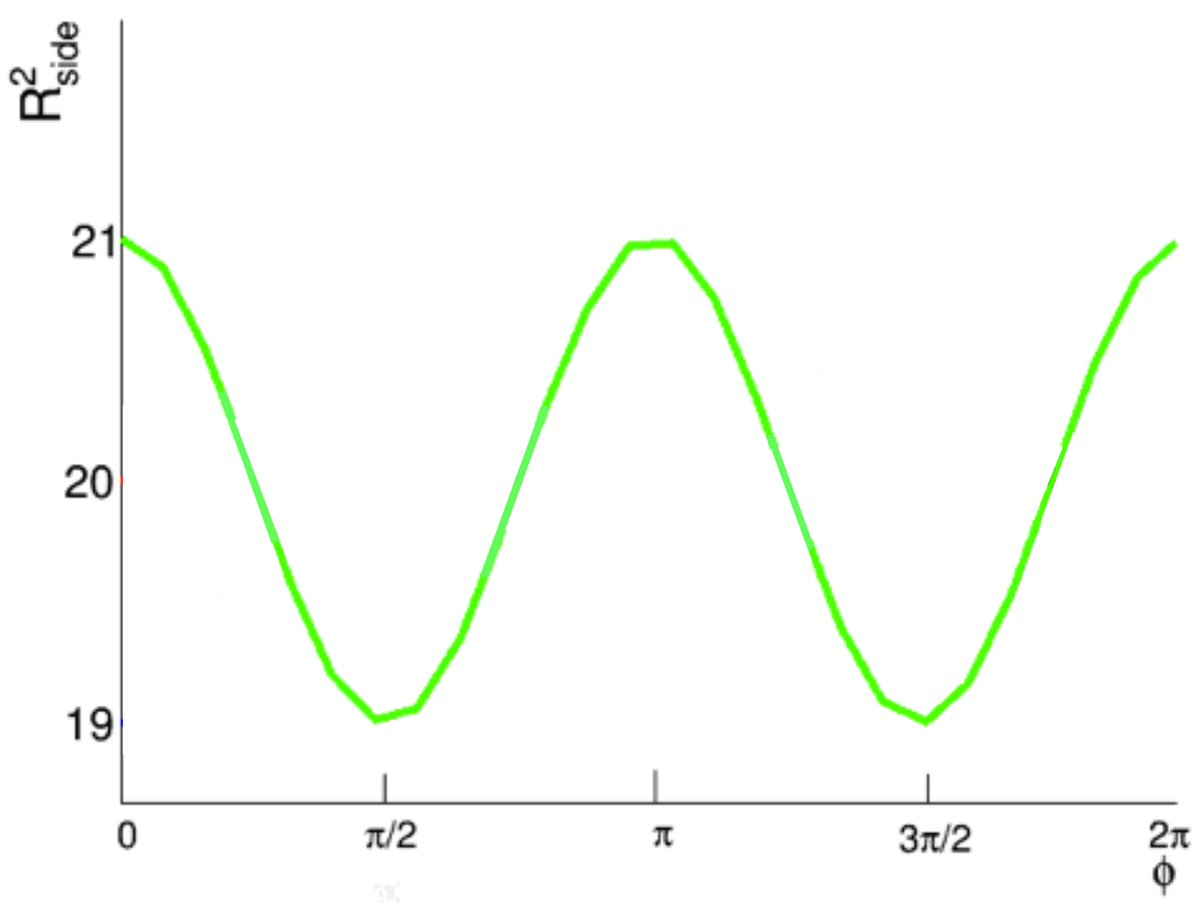
$$R_\mu^2 = R_0^2 + 2R_{\mu,n}^2 \sin\left[n\left(\phi_{pair} - \Psi_n\right)\right] \quad (\mu = os,\ sl,\ ol)$$

- separate $C(q)$ created for each ϕ_{pair} bin,
- fit each $C(q)$ to obtain the radii,
- we show the evolution of the R_i with ϕ_{pair}.

Expectation of Radii Behavior

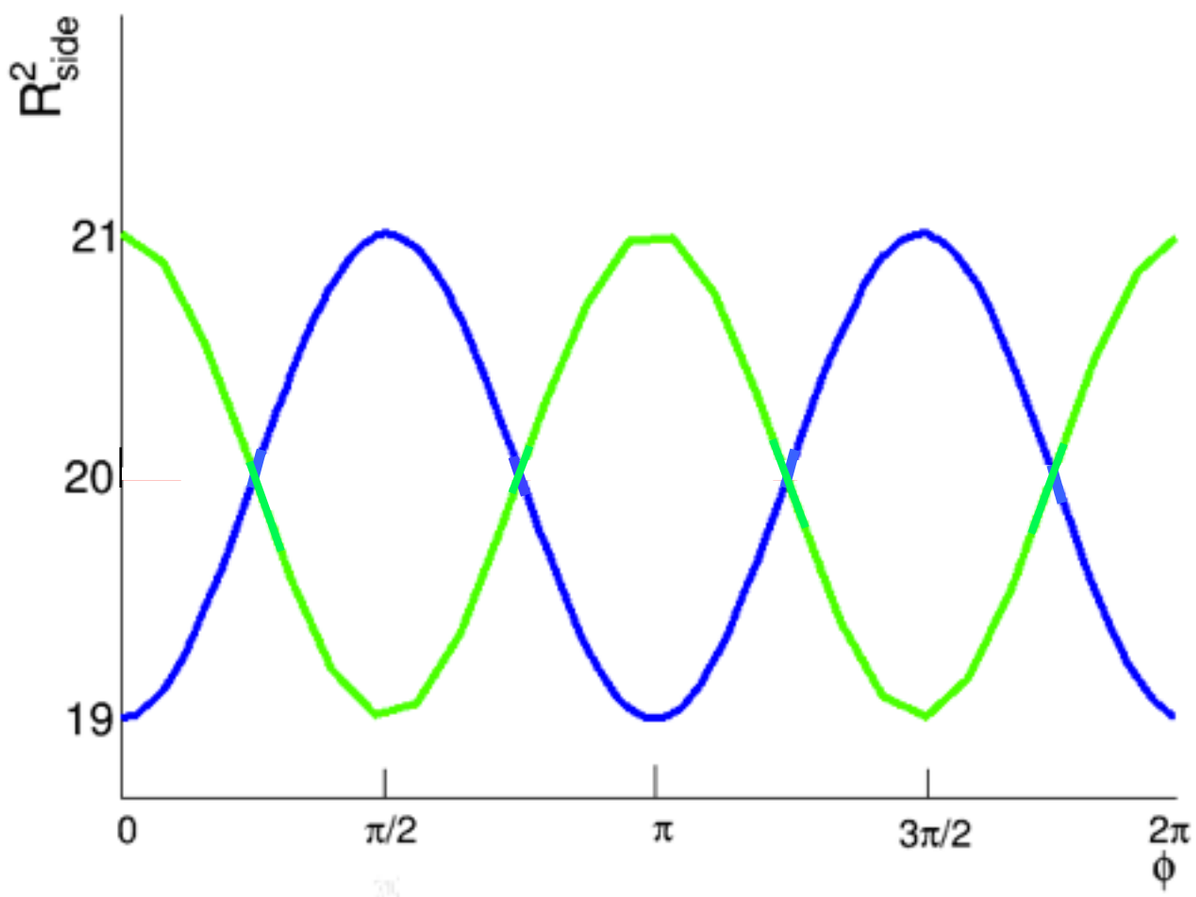
- for out-of-plane-extended source:

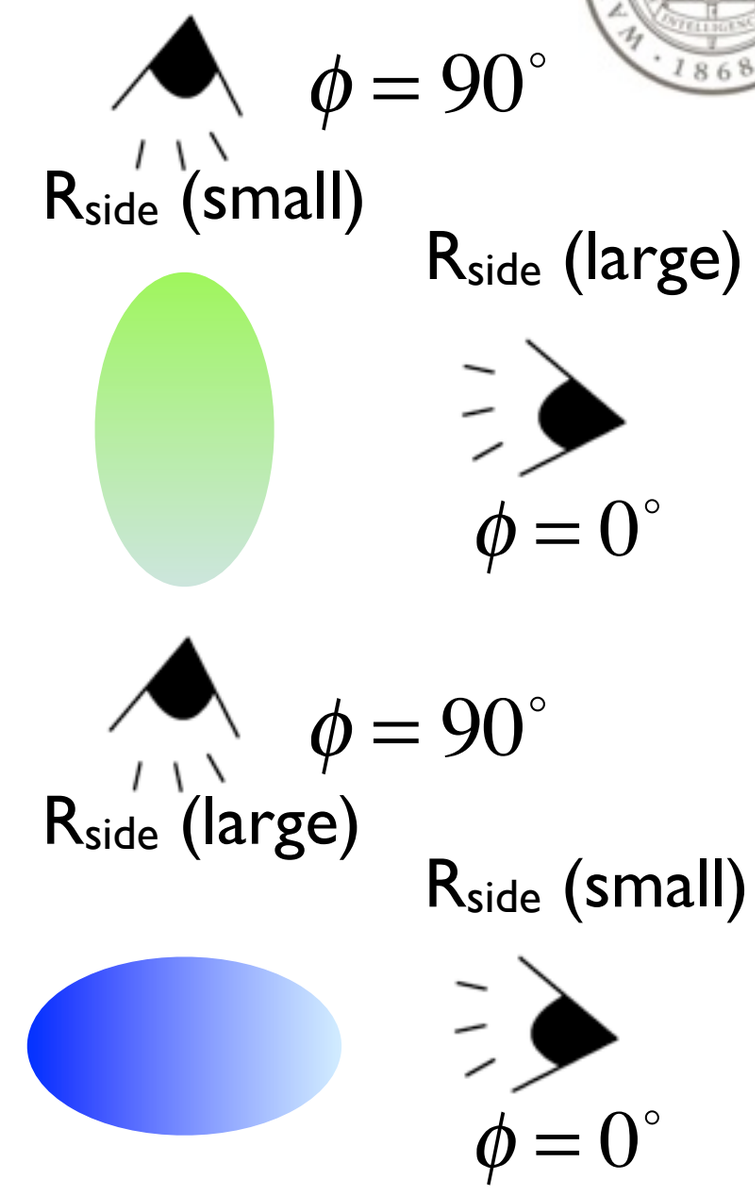




Expectation of Radii Behavior

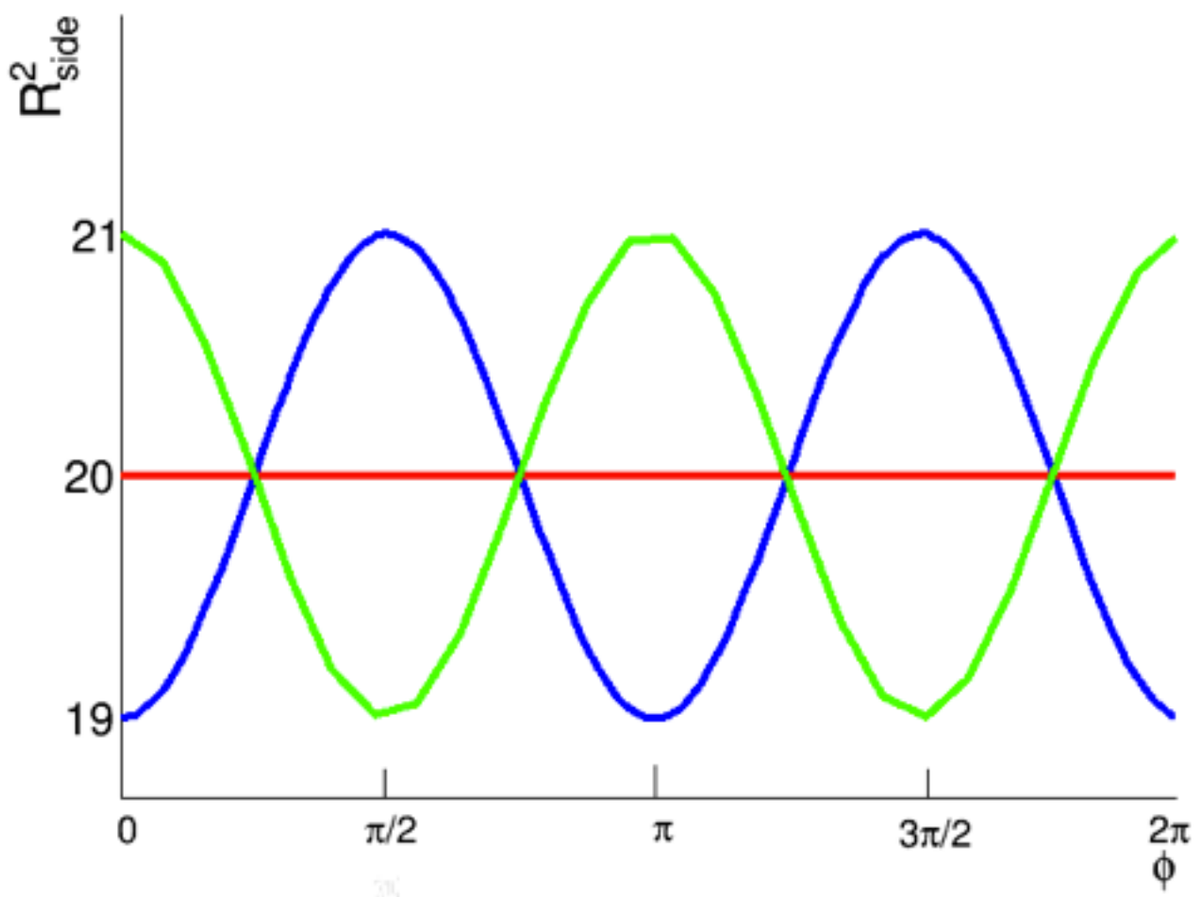
- for out-of-plane-extended source:
- for in-plane-extended source:

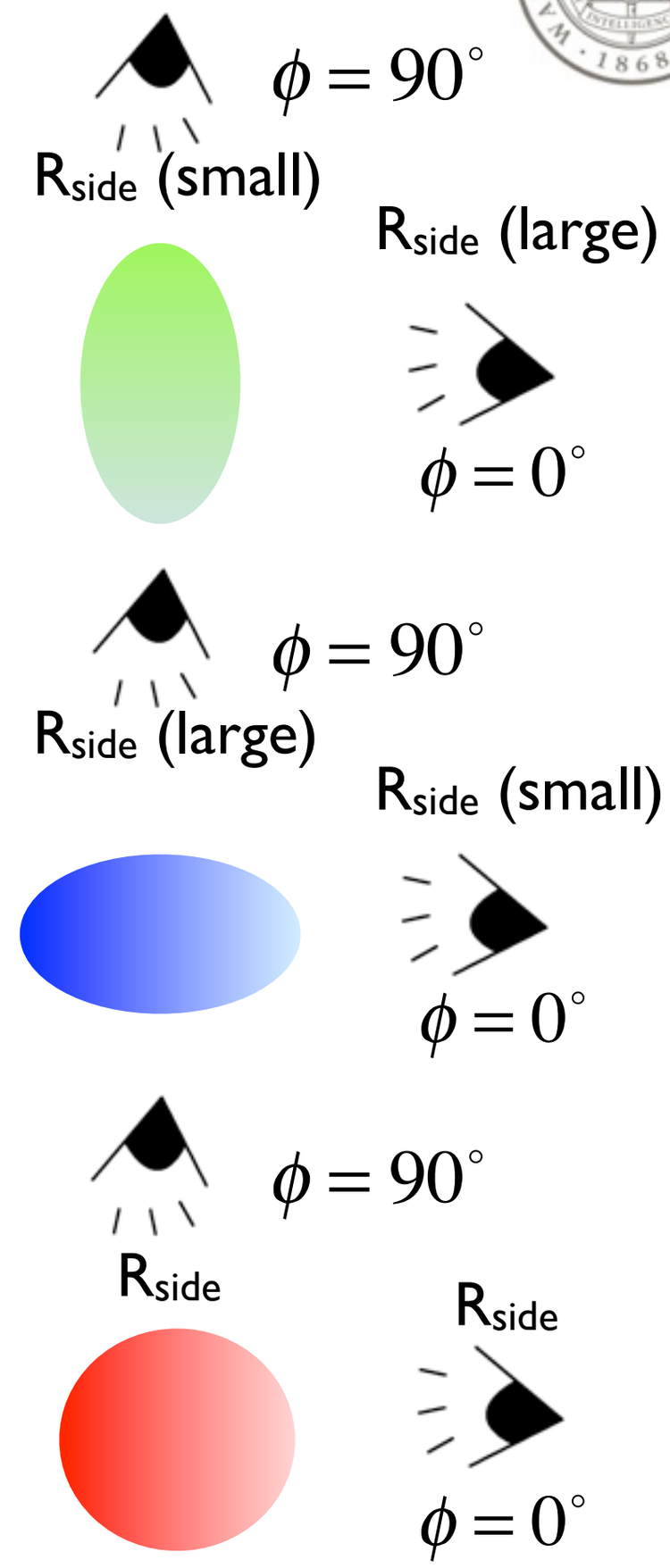




Expectation of Radii Behavior

- for out-of-plane-extended source:
- for in-plane-extended source:
- for spherical source:





RHIC vs. LHC Predictions

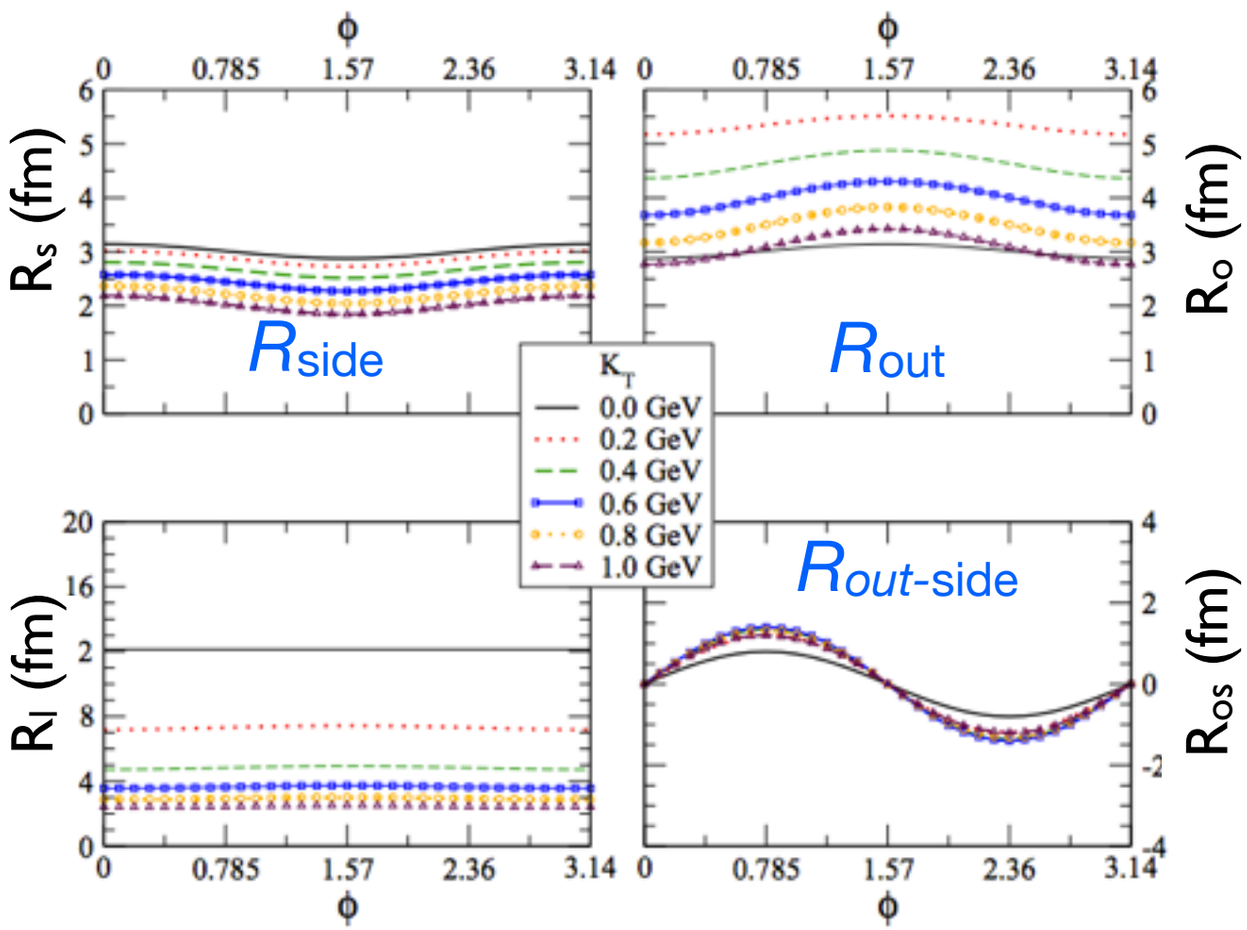
radii oscillations:

E. Frodermann, Rupa Chatterjee, and Ulrich Heinz
J. Phys. G: Nucl Part. Phys. **34** (2007) 2249-2254.

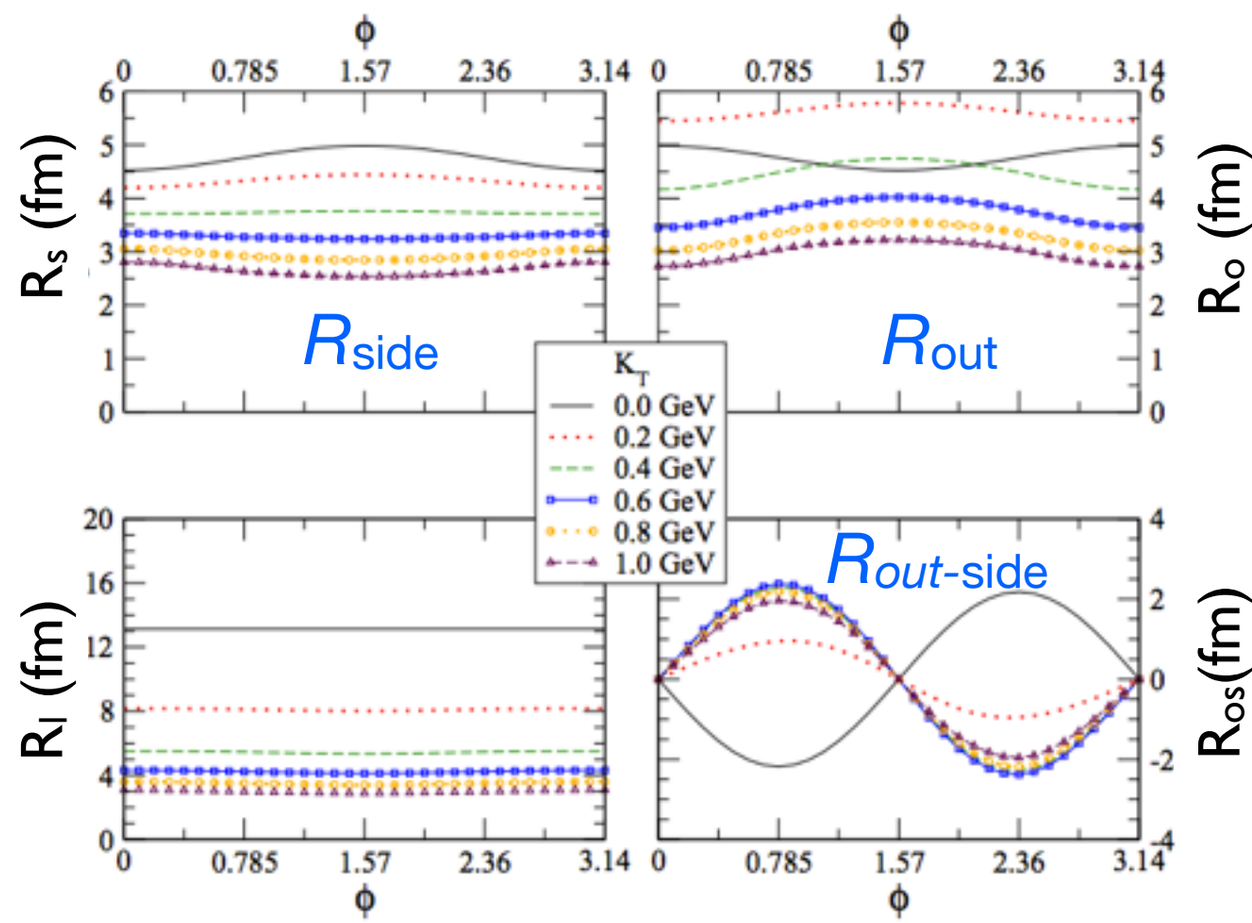
AZHYDRO model predicts:

- change in k_T scaling from RHIC -> LHC for R_{side} and $R_{out\text{-}side}$ as k_T increases,
- R_{side} and R_{out} oscillate out-of-phase at RHIC, and at LHC $k_T > 0.6$ GeV,
- Measured oscillations are time average of source eccentricity.

RHIC



LHC



RHIC vs. LHC Predictions

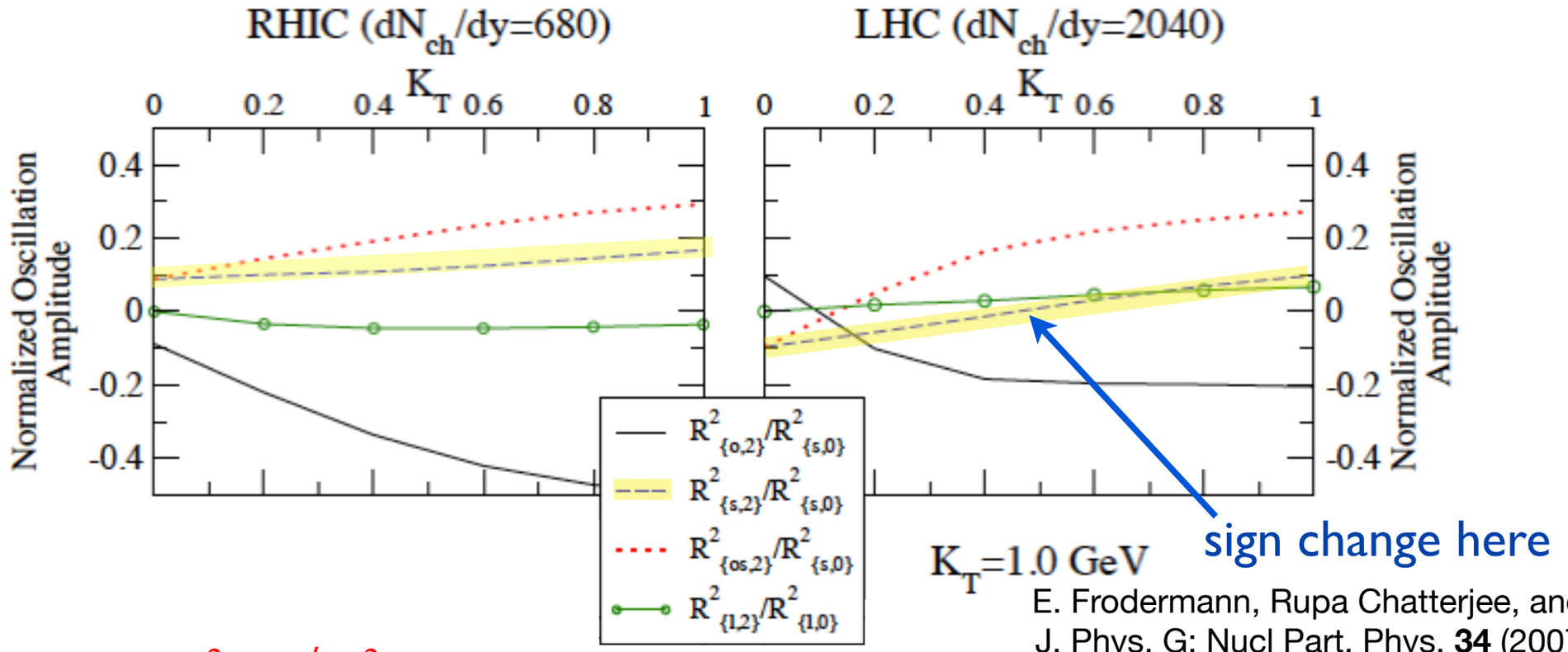
Adam Kisiel et al.
Phys. Rev. C **79**, 014902 (2009).

average radii:

THERMINATOR@5.5TeV predicts larger average radii RHIC -> LHC,
due to the growth of the overall system at freeze-out.

relative oscillation amplitudes:

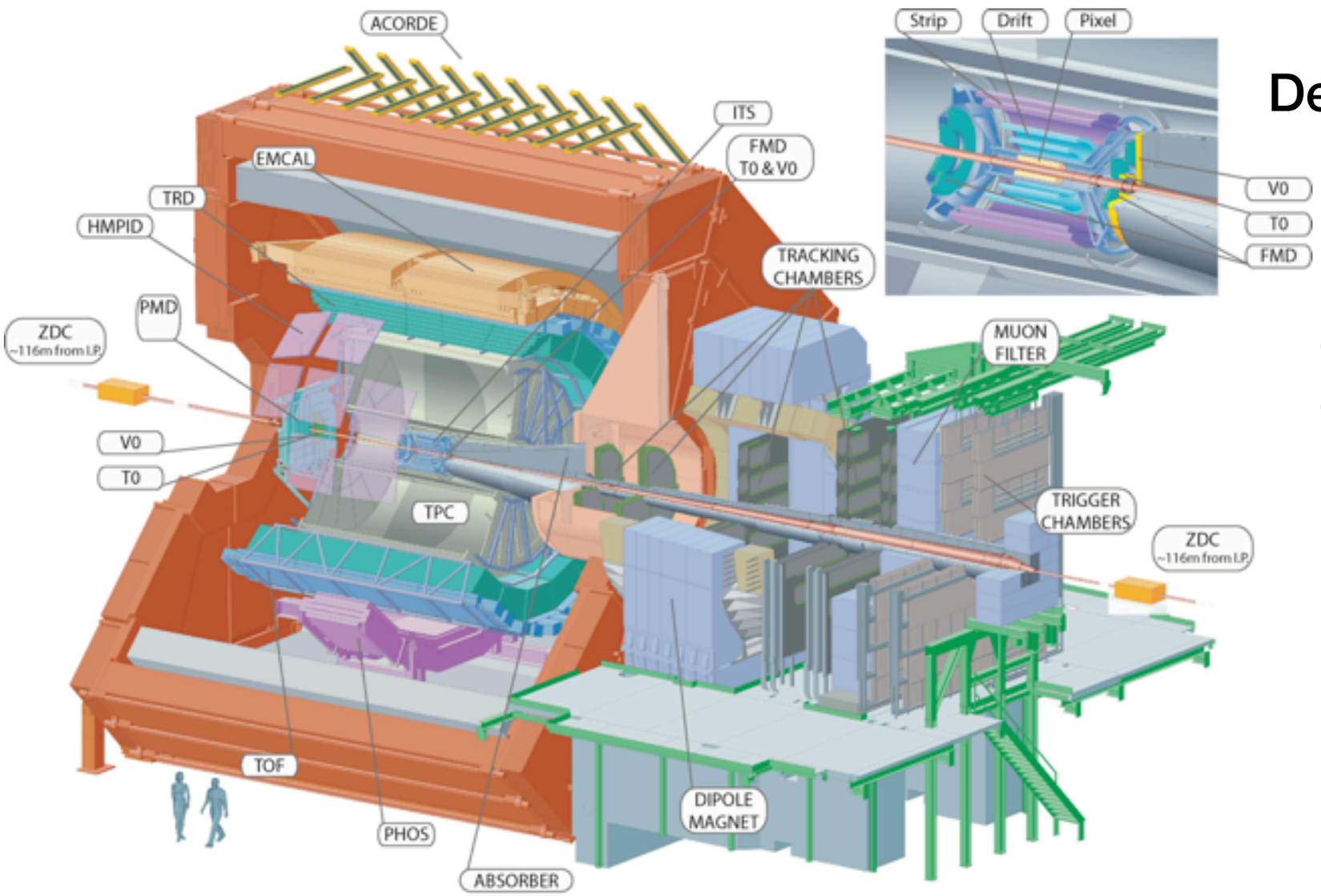
THERMINATOR@5.5TeV predicts a smaller $R^2_{side,2}/R^2_{side,0}$ RHIC -> LHC,
measured oscillations are time average of source eccentricity,
LHC evolution ends out-of-plane extended, but average is still in-plane extended.



E. Frodermann, Rupa Chatterjee, and Ulrich Heinz
J. Phys. G: Nucl Part. Phys. **34** (2007) 2249-2254.

AZHYDRO predicts $R^2_{side,2}/R^2_{side,0}$ changes sign RHIC -> LHC,
source: out-of-plane -> in-plane extended.

ALICE Experiment



Detectors used in this analysis:

Tracking and Particle Identification:

Time Projection Chamber (TPC), Time of Flight (TOF)

Vertexing and Tracking:

Inner Tracking System (ITS)

Trigger and centrality:

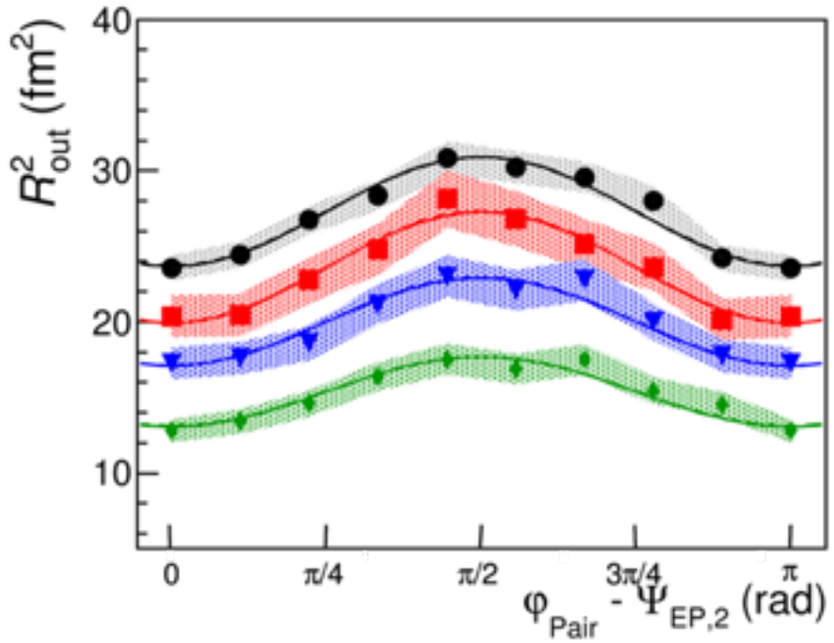
VZERO

Event Plane:

TPC

Radii vs. azimuthal angle

- k_T scaling: radii increase with decreasing k_T.



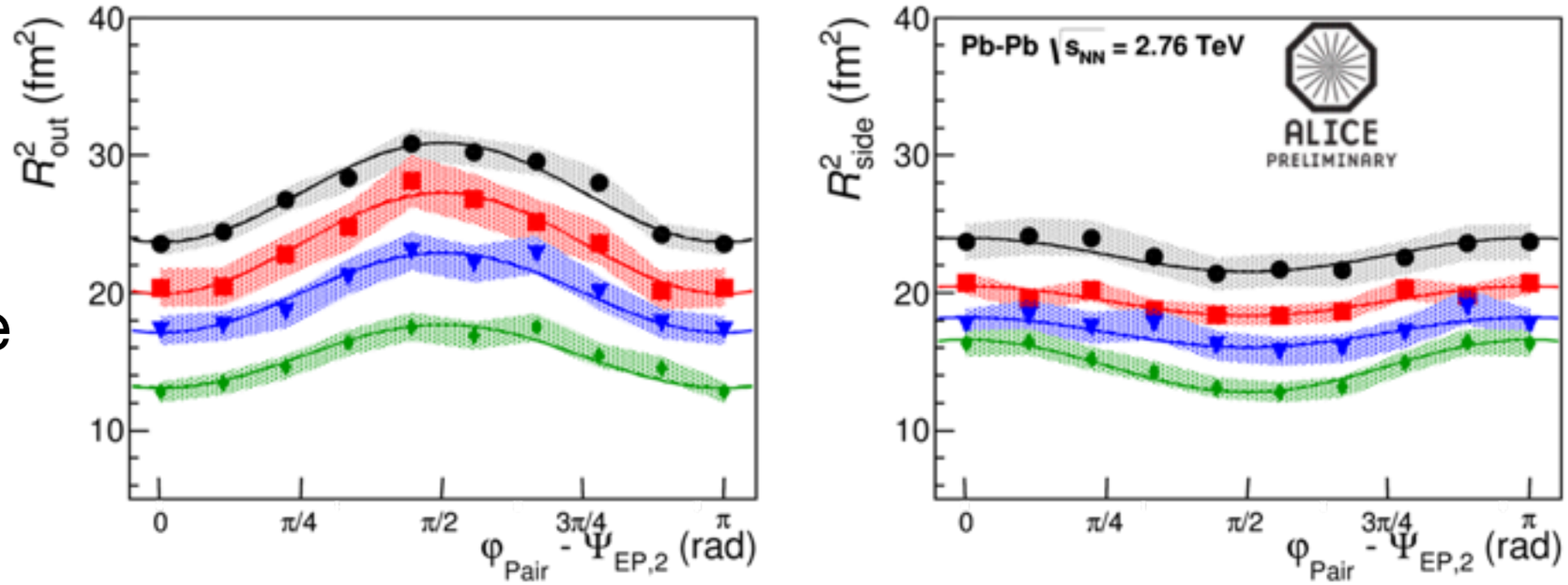
Fits:

$$R_\mu^2 = R_0^2 + 2R_{\mu,n}^2 \cos\left[n\left(\phi_{pair} - \Psi_n\right)\right] \quad (\mu = s,o,l)$$

$$R_\mu^2 = R_0^2 + 2R_{\mu,n}^2 \sin\left[n\left(\phi_{pair} - \Psi_n\right)\right] \quad (\mu = os,sl,ol)$$

Radii vs. azimuthal angle

- k_T scaling: radii increase with decreasing k_T.
- R_{out} and R_{side} oscillate out-of-phase.



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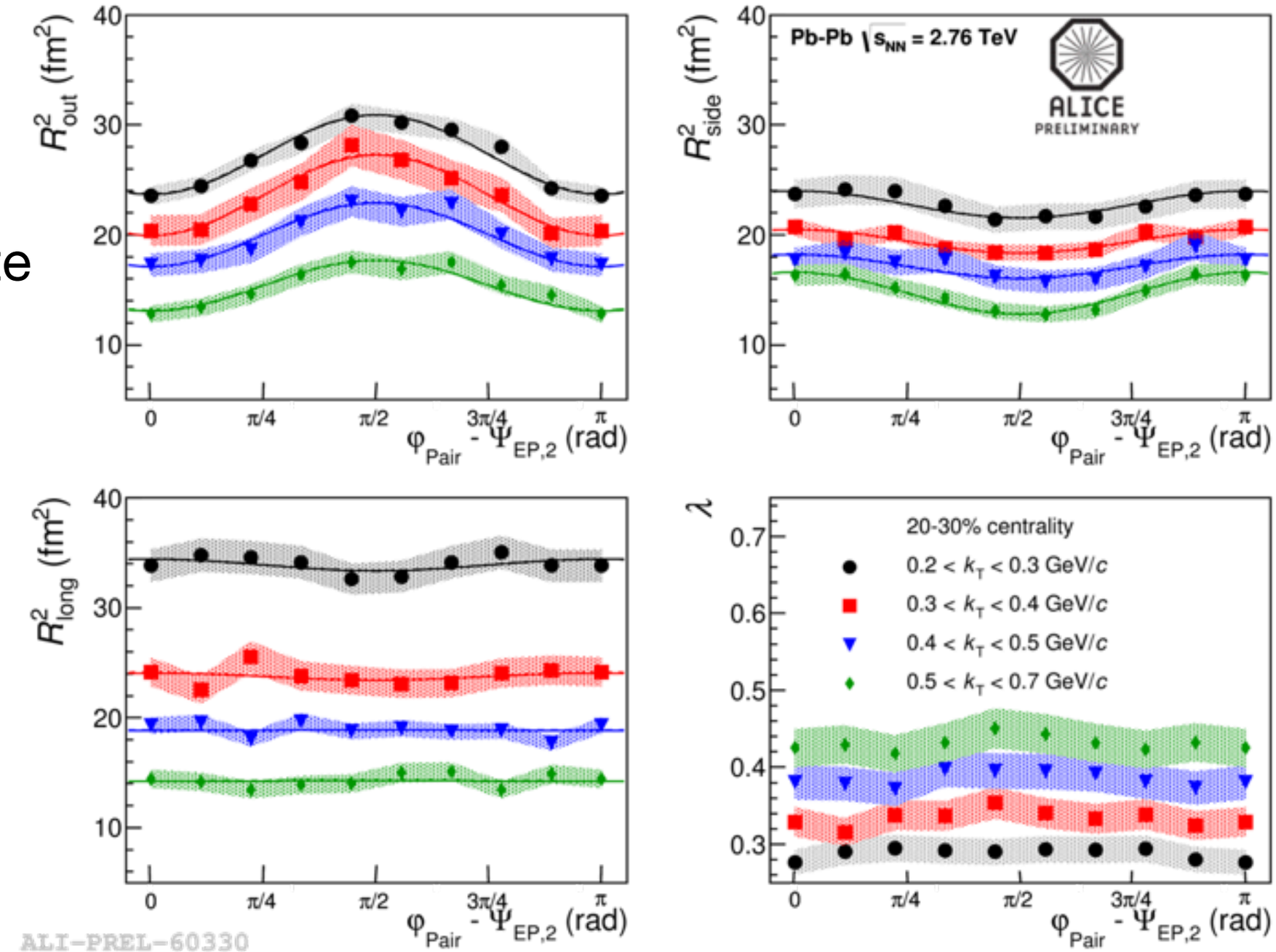
Radii vs. azimuthal angle

- k_T scaling: radii increase with decreasing k_T.
- R_{out} and R_{side} oscillate out-of-phase.
- R_{long} has no oscillation.
- R_{out} and R_{side} k_T scaling is similar to the AZHYDRO prediction at RHIC.



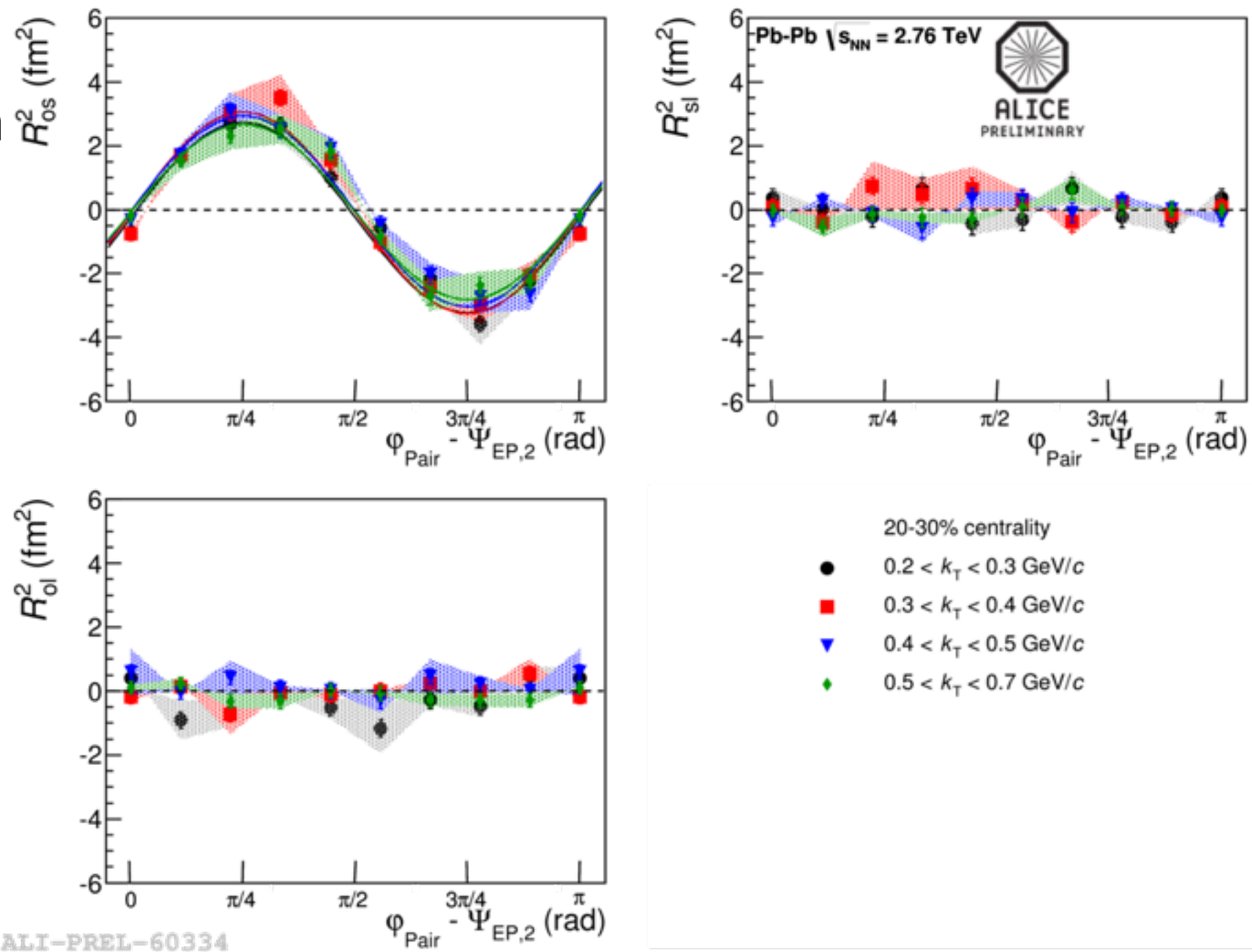
Fits:

$$R_\mu^2 = R_0^2 + 2R_{\mu,n}^2 \cos\left[n\left(\phi_{pair} - \Psi_n\right)\right] \quad (\mu = s,o,l)$$

$$R_\mu^2 = R_0^2 + 2R_{\mu,n}^2 \sin\left[n\left(\phi_{pair} - \Psi_n\right)\right] \quad (\mu = os,sl,ol)$$

Radii vs. azimuthal angle

- $R_{\text{out-side}}$ has very weak dependence on k_T.
- R_{sl} and R_{ol} are consistent with zero as expected from symmetry reasons. An important cross-check of the method and the data.
- $R_{\text{out-side}}$ k_T scaling similar to AZHYDRO



Fits:

$$R_\mu^2 = R_0^2 + 2R_{\mu,n}^2 \cos\left[n\left(\phi_{pair} - \Psi_n\right)\right] \quad (\mu = s,o,l)$$

$$R_\mu^2 = R_0^2 + 2R_{\mu,n}^2 \sin\left[n\left(\phi_{pair} - \Psi_n\right)\right] \quad (\mu = os,sl,ol)$$

Azimuthal dependence of pion radii: LHC vs. RHIC

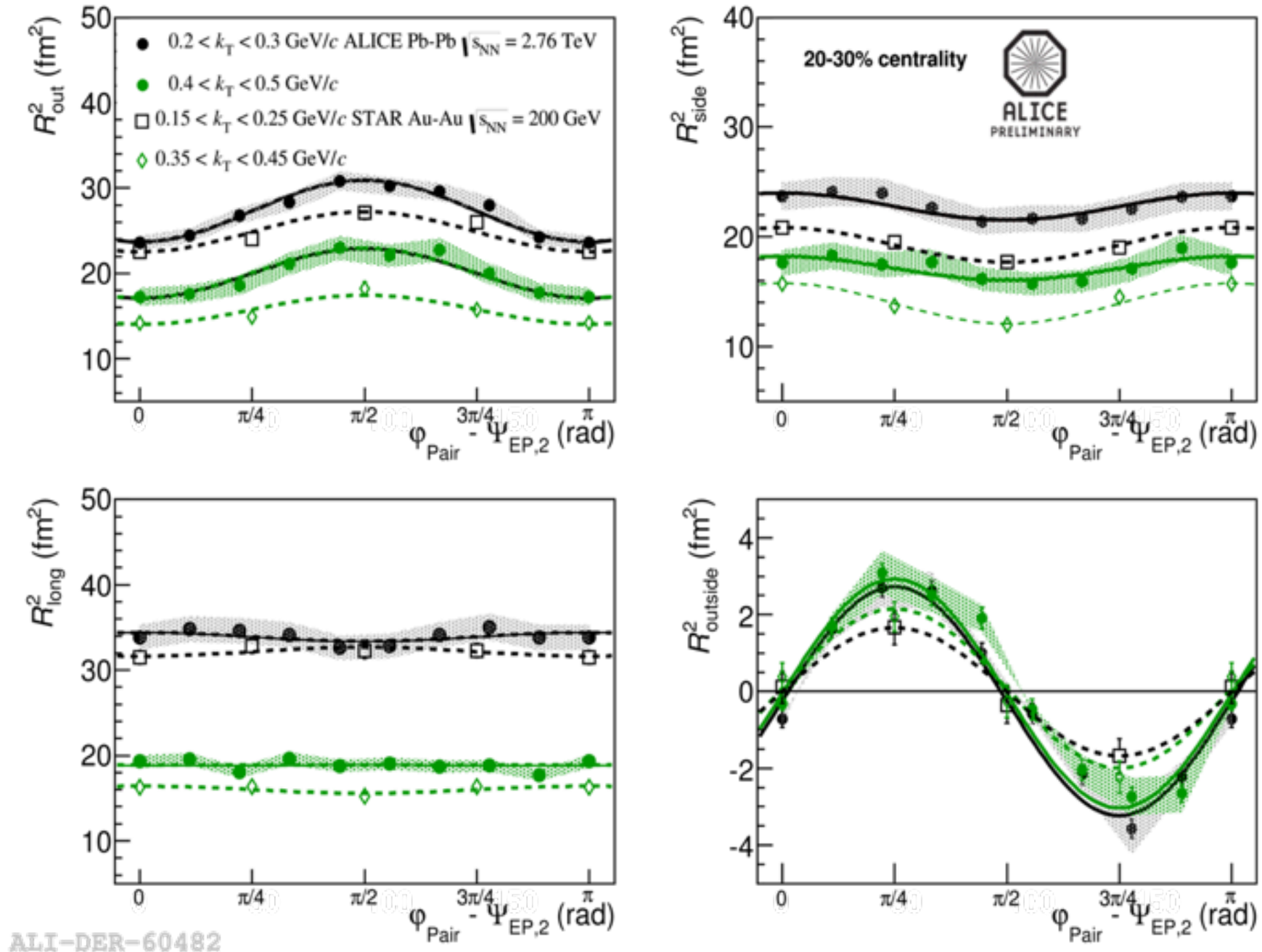
ALICE Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

- ● $0.2 < k_T < 0.3$ GeV/c
- ● $0.4 < k_T < 0.5$ GeV/c

STAR Au-Au $\sqrt{s_{NN}} = 200$ GeV

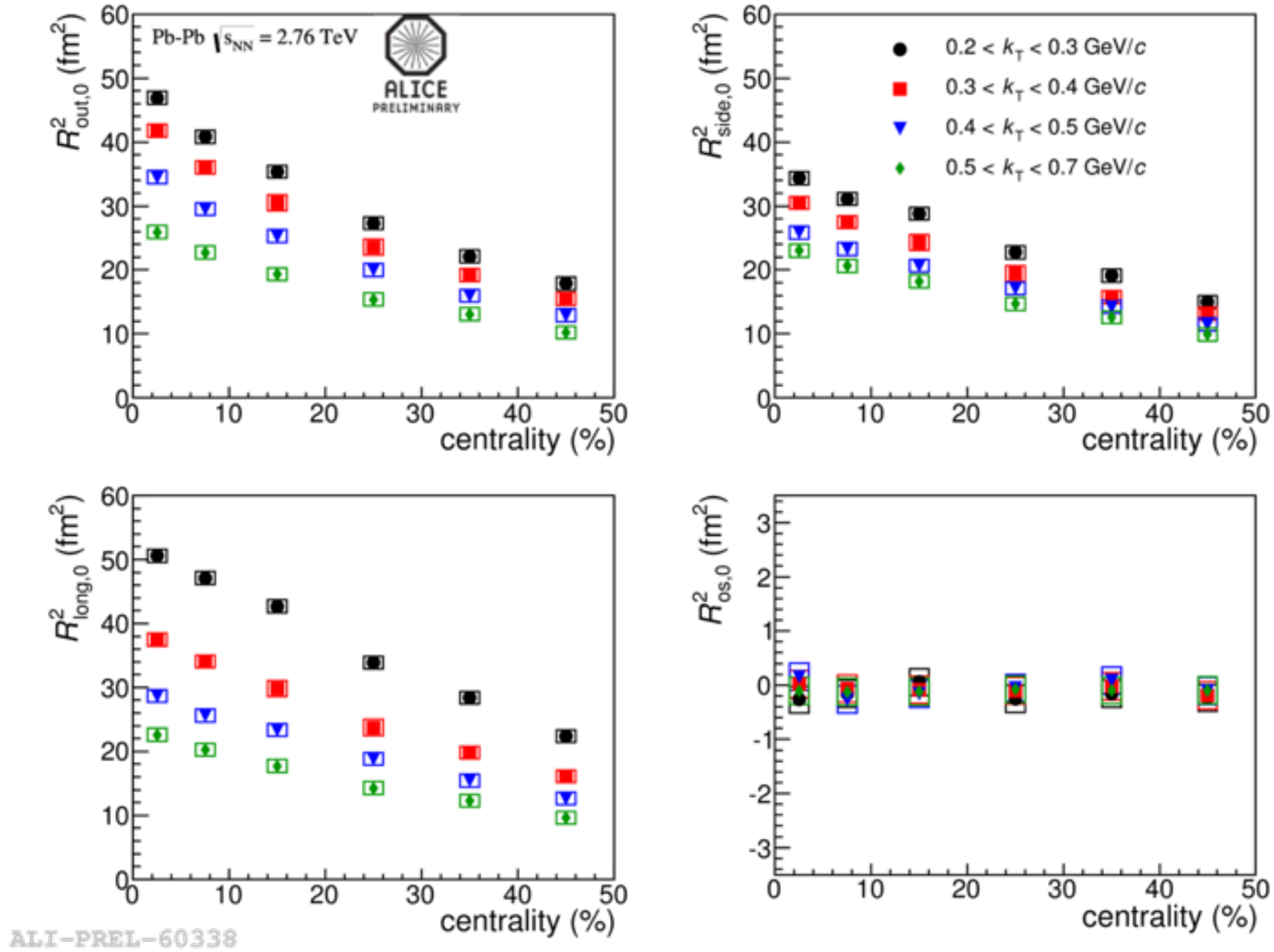
- □ $0.15 < k_T < 0.25$ GeV/c
- ◇ $0.35 < k_T < 0.45$ GeV/c

- ALICE and STAR have the same behavior of radii oscillation.
- No change of oscillation sign is observed for R_{side}
- R_{side} has weaker oscillation in ALICE.
- ALICE agrees with predictions for R_{side} oscillation decreasing RHIC -> LHC.



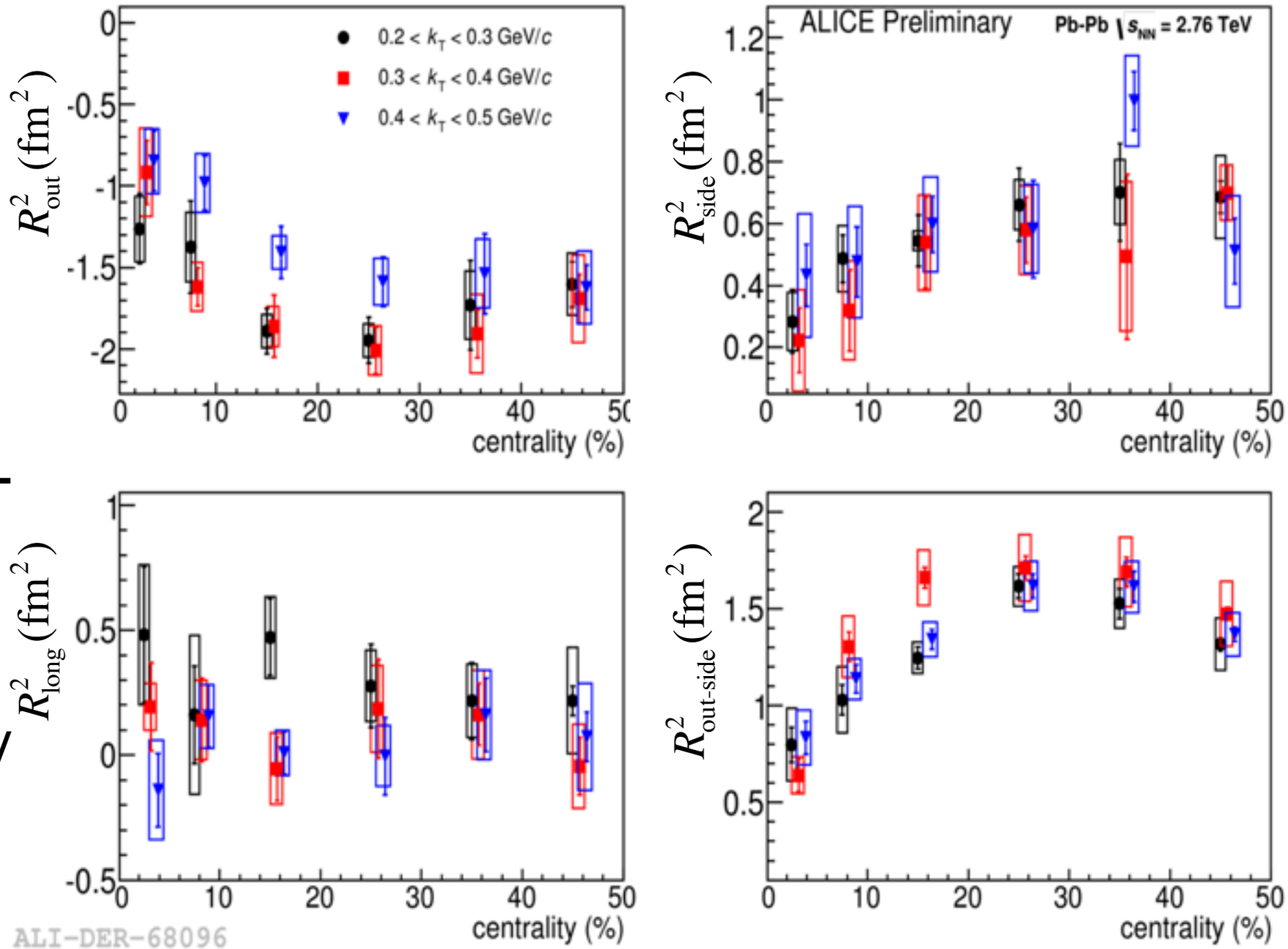
Average radii as a function of centrality

- R_{out}, R_{side}, and R_{long} increase with more central bins.
- The fall of radii with k_T is due to collective radial flow.
- Growth of size with multiplicity also naturally expected.
- $R_{out\text{-}side}$ remains zero for all centralities due to symmetry.



Oscillation amplitudes, $R^2_{i,2}$ vs. centrality

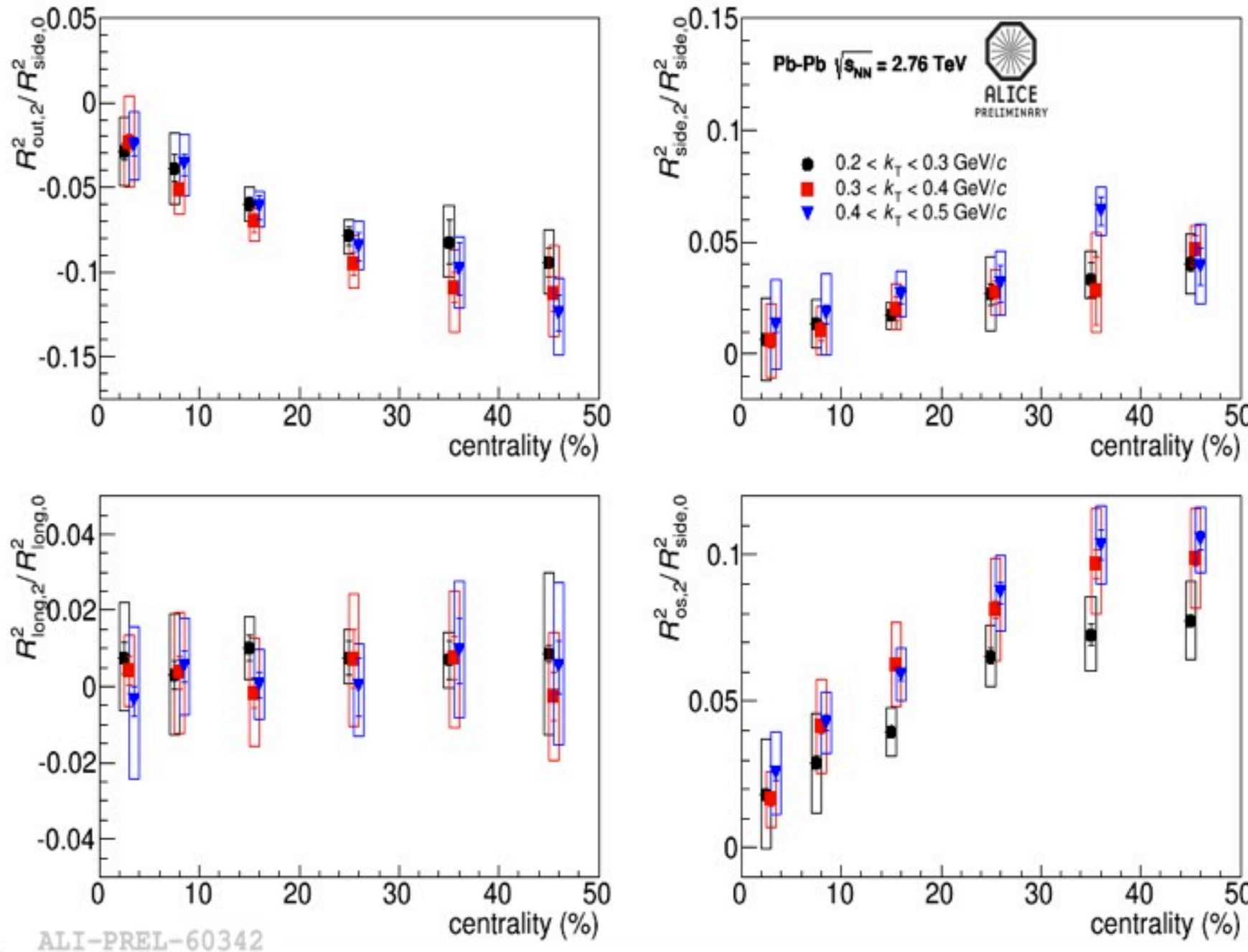
- Weak k_T dependence except for R_{out}.
- Almost zero R_{long} except probably the lowest k_T bin.
- Oscillations consistent with out-of-plane extended source.
- Source eccentricity evolves with centrality in a way similar to v_2



Relative oscillation amplitudes vs. centrality

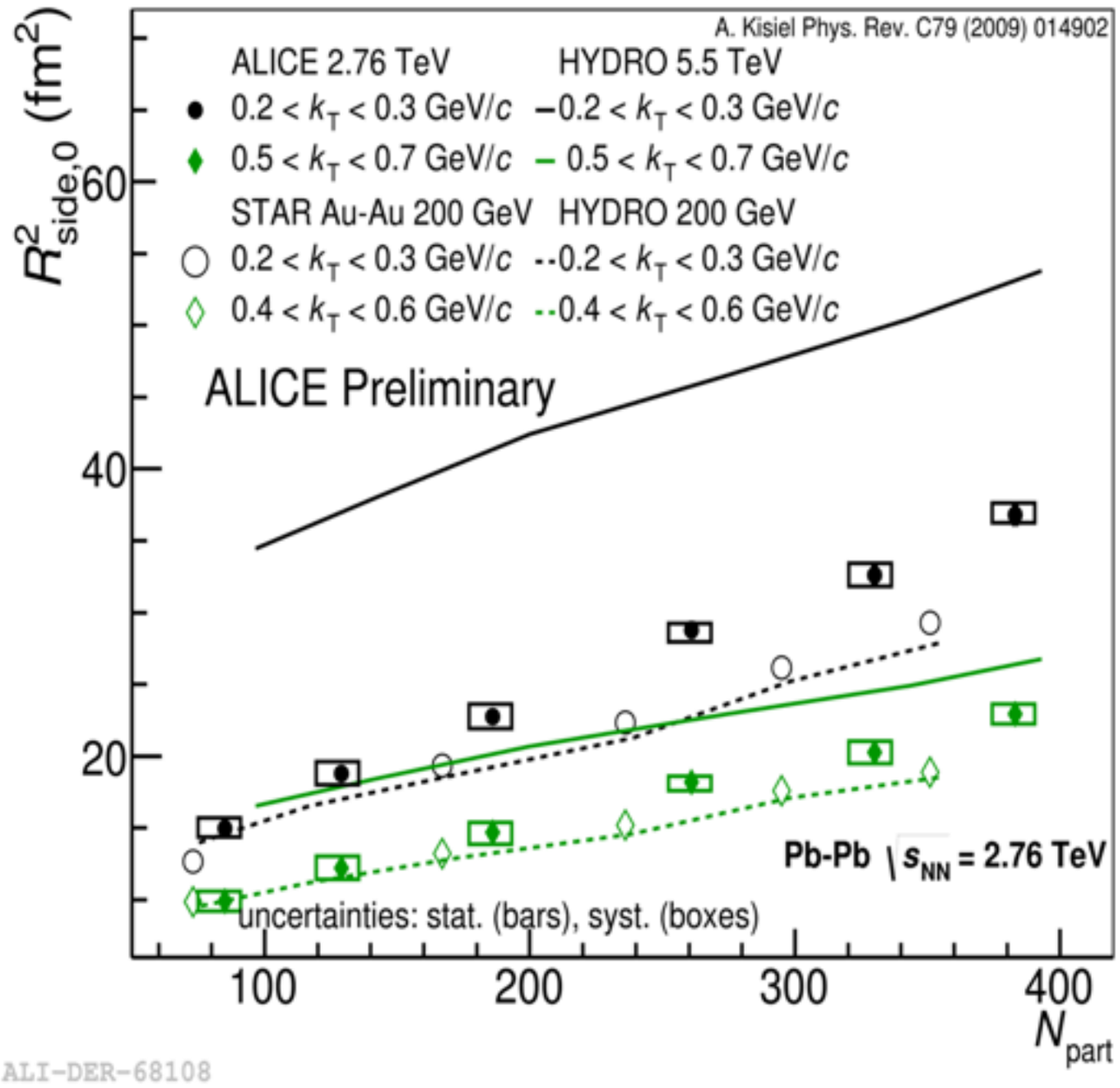
As the collisions become more peripheral:

- The magnitude of the relative amplitudes of R_{out}, R_{side}, and $R_{out\text{-}side}$ increase.
- Source becomes more out-of-plane extended with centrality.
- Can be a consequence of larger initial state anisotropy and/or shorter evolution duration.

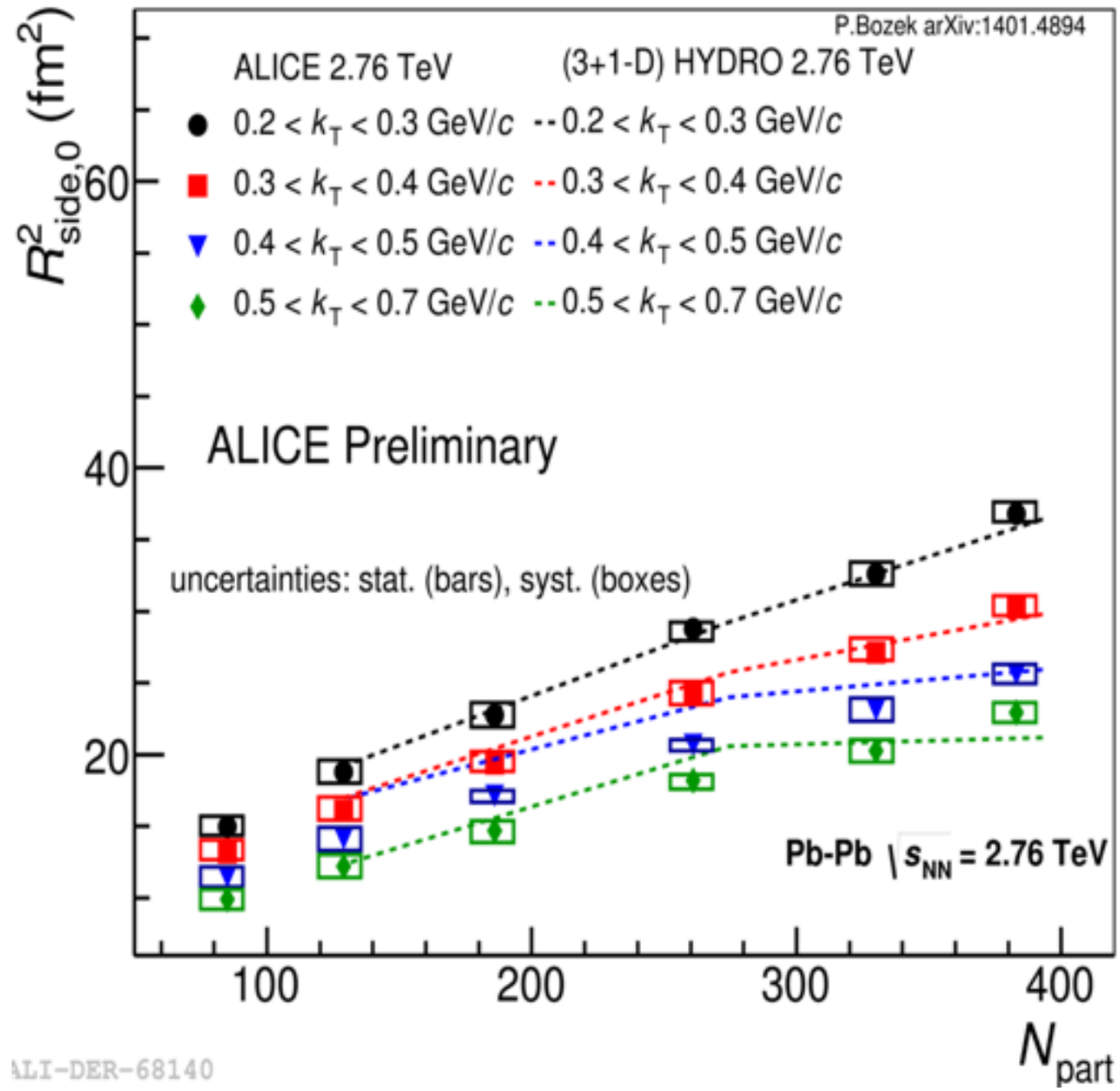


HYDRO Model Comparison $R^2_{side,0}$

THERMINATOR@5.5TeV



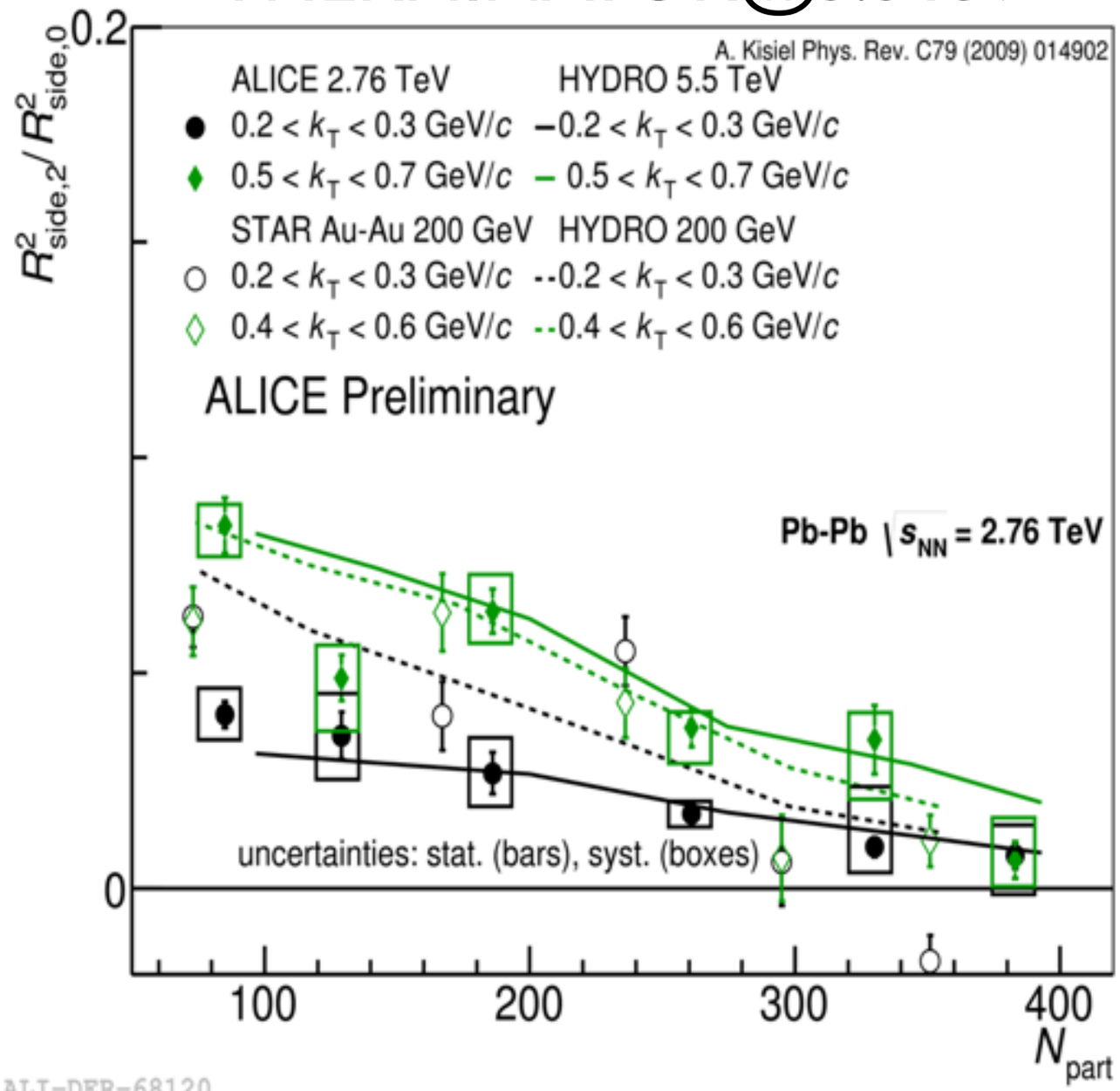
Bozek 3D HYDRO



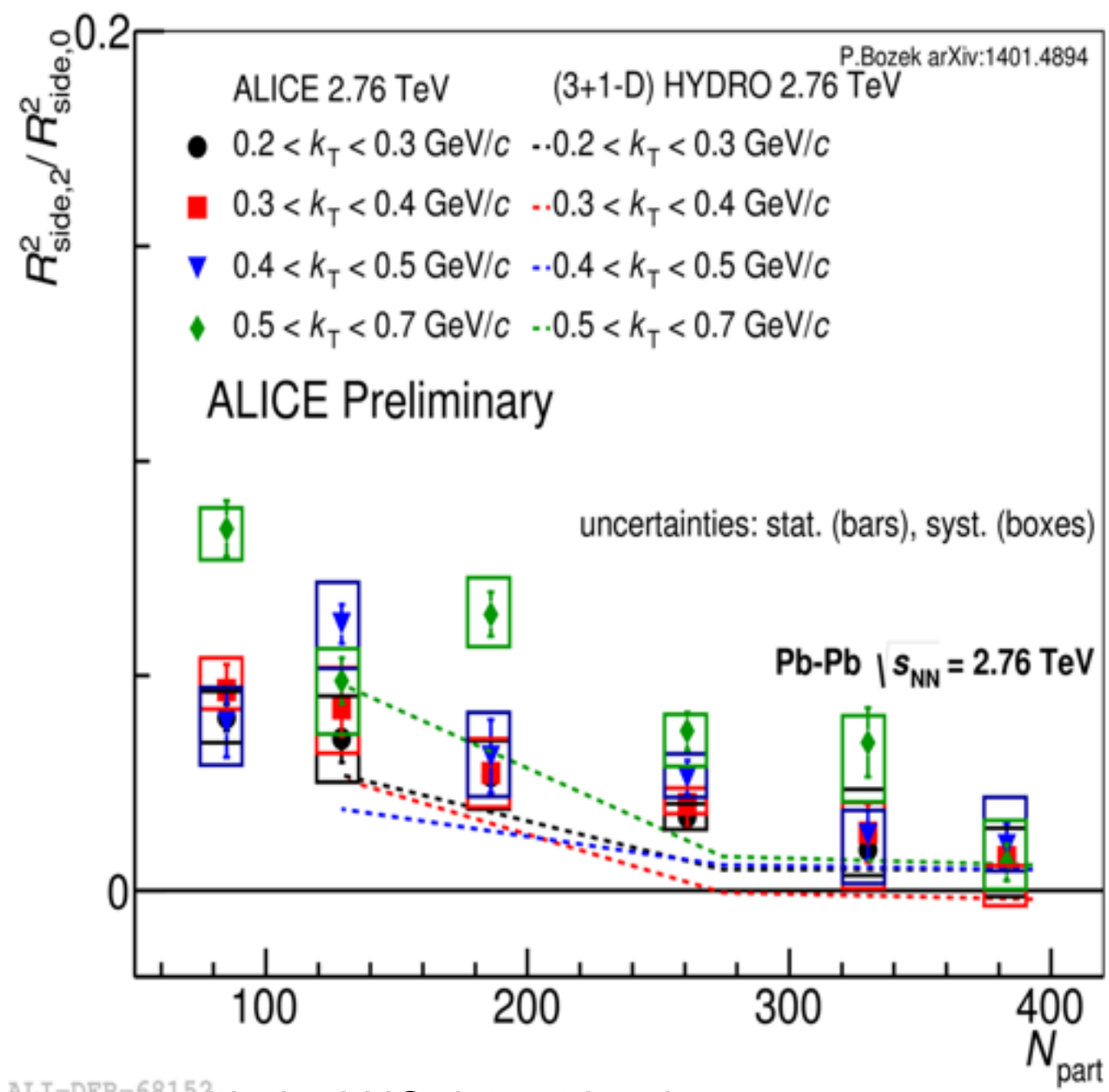
- THERMINATOR@5.5TeV model reproduces RHIC data at 200 GeV,
- Bozek 3D HYDRO model is in qualitative agreement with the LHC data.

HYDRO Model Comparison $\frac{R^2_{side,2}}{R^2_{side,0}}$

THERMINATOR@5.5TeV



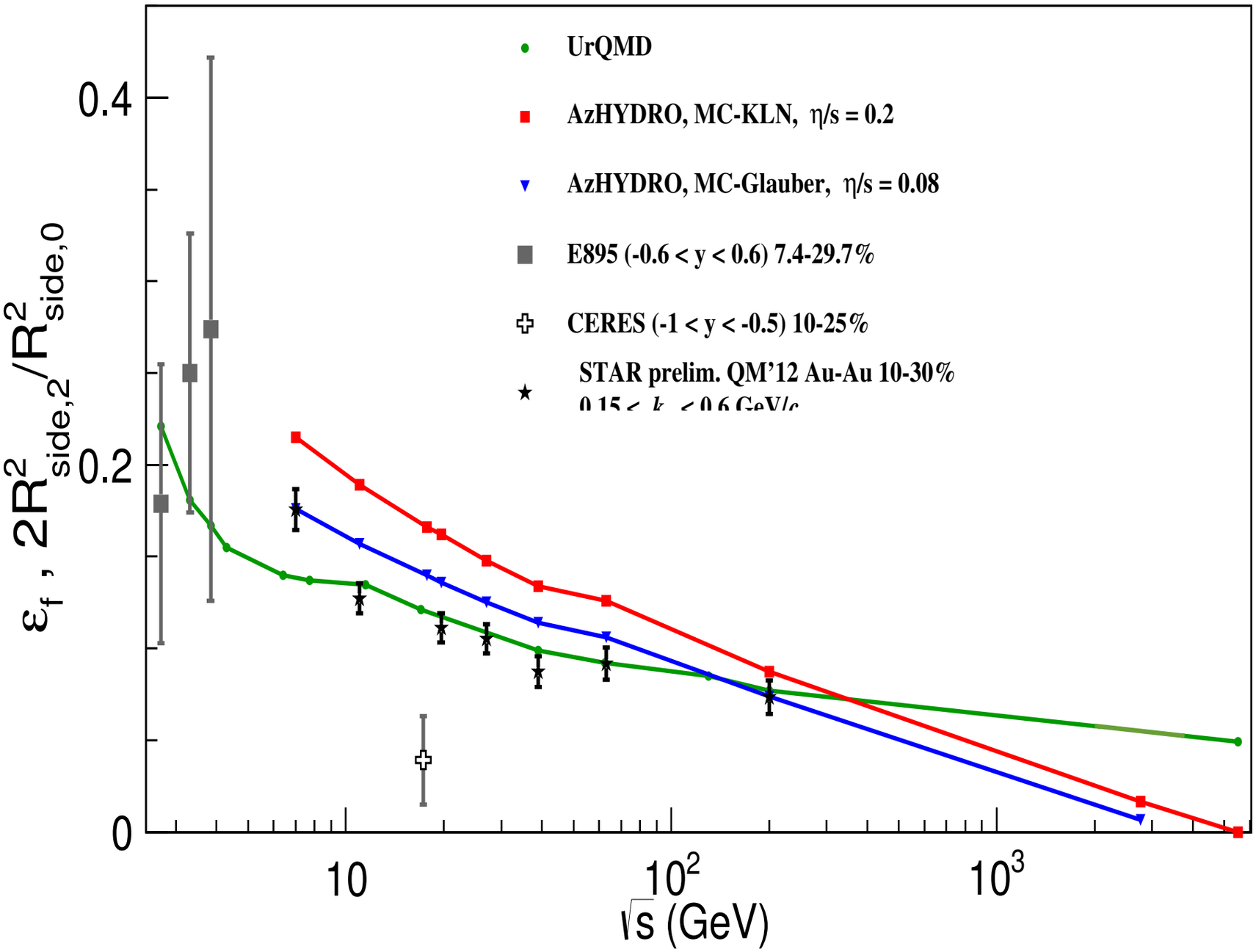
Bozek 3D HYDRO



- THERMINATOR@5.5TeV in qualitative agreement with the LHC data at low k_T, and agrees with predictions of lower relative R_{side} oscillation amplitude.
- Bozek 3D HYDRO has correct sign, lower amplitude.

Final spatial eccentricity $\varepsilon_f \approx 2\frac{R^2_{side,2}}{R^2_{side,0}}$

- **UrQMD** agrees with relative oscillation magnitude, but not with absolute values of R_{side} and its oscillation.
- Hydro with **MC-KLN** and **MC-Glauber** initial conditions:
  - overestimates final spatial eccentricity at **RHIC.**

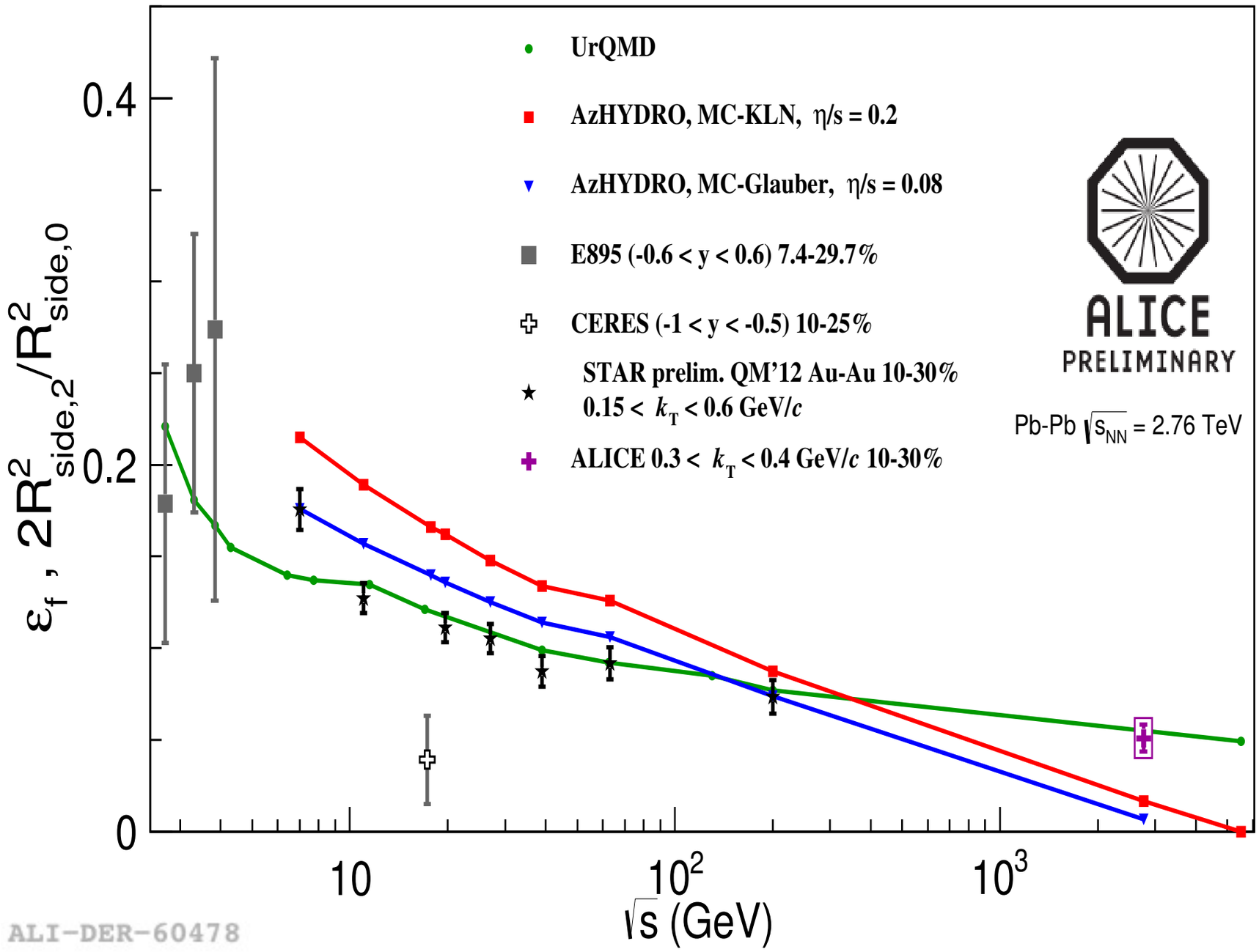


UrQMD model by M. Lisa et al. arXiv: 1104.5267
MC-Glauber, ML-KLN by U. Heinz and C. Shen arXiv: 1210.2074
STAR prelim. data QM'12 C. Anson

(2+1)-D viscous hydro w/ lattice QCD EOS
ε_i =0.26 MC-Glauber, ε_i =0.32 MC-KLN,
T_{dec}=120MeV

Final spatial eccentricity $\varepsilon_f \approx 2\frac{R^2_{side,2}}{R^2_{side,0}}$

- **UrQMD** agrees with relative oscillation magnitude, but not with absolute values of R_{side} and its oscillation.
- Hydro with **MC-KLN** and **MC-Glauber** initial conditions:
  - overestimates final spatial eccentricity at **RHIC.**
  - underestimates final spatial eccentricity at **LHC.**
- Final eccentricity is lower than at **RHIC.**



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STAR prelim. data QM'12 C. Anson

Summary

Radii oscillations vs. angle:

- R_{out} & R_{side} oscillate out-of-phase,
- compared to RHIC, at LHC we observe weaker oscillation in R_{side}.

Model Comparisons:

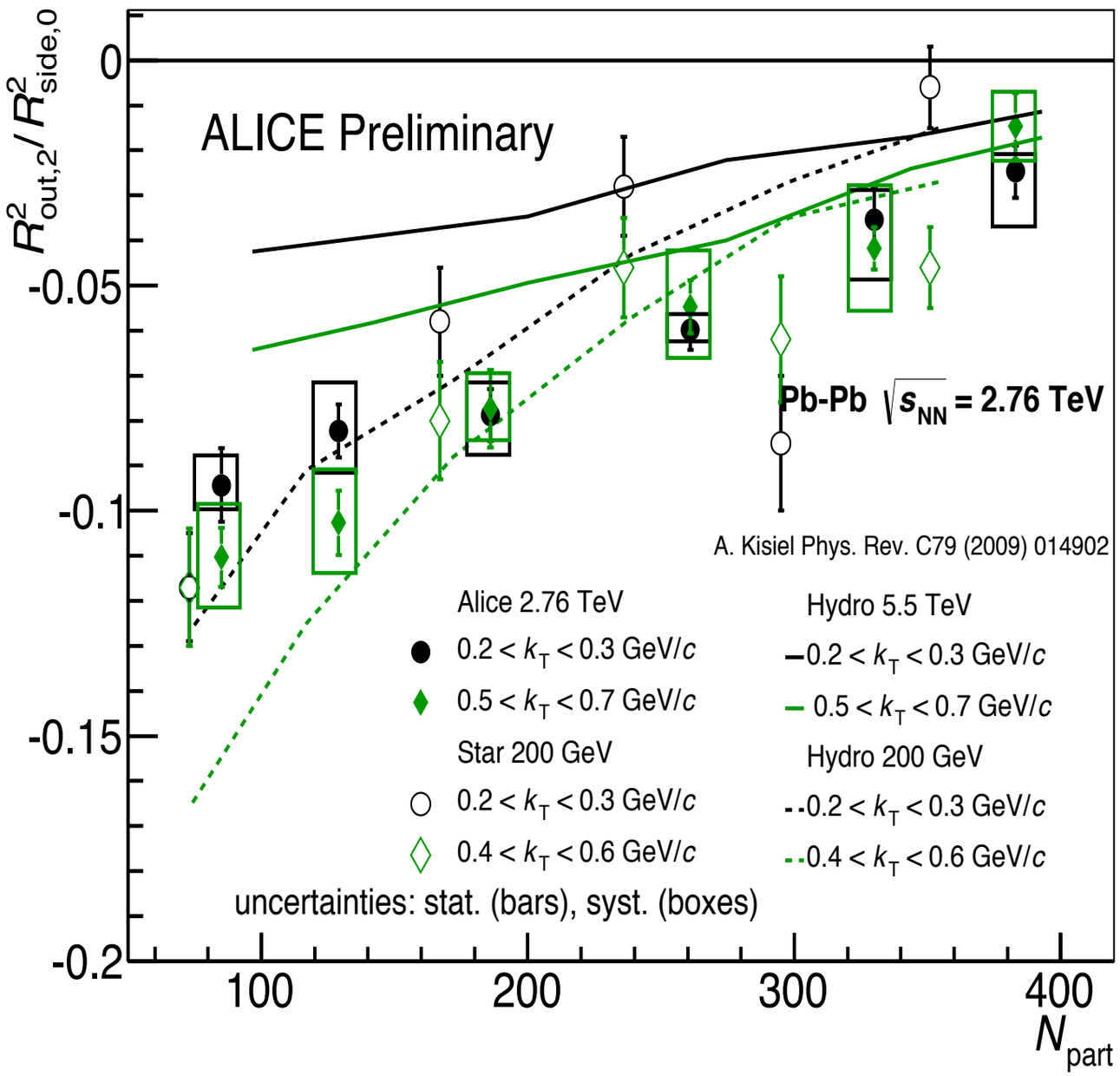
- $R^2_{side,0}$ Bozek 3D HYDRO prediction shows qualitative agreement with ALICE data.
- $R^2_{side,2} / R^2_{side,0}$ THERMINATOR@5.5TeV shows qualitative agreement with ALICE, predicts smaller oscillations at LHC.

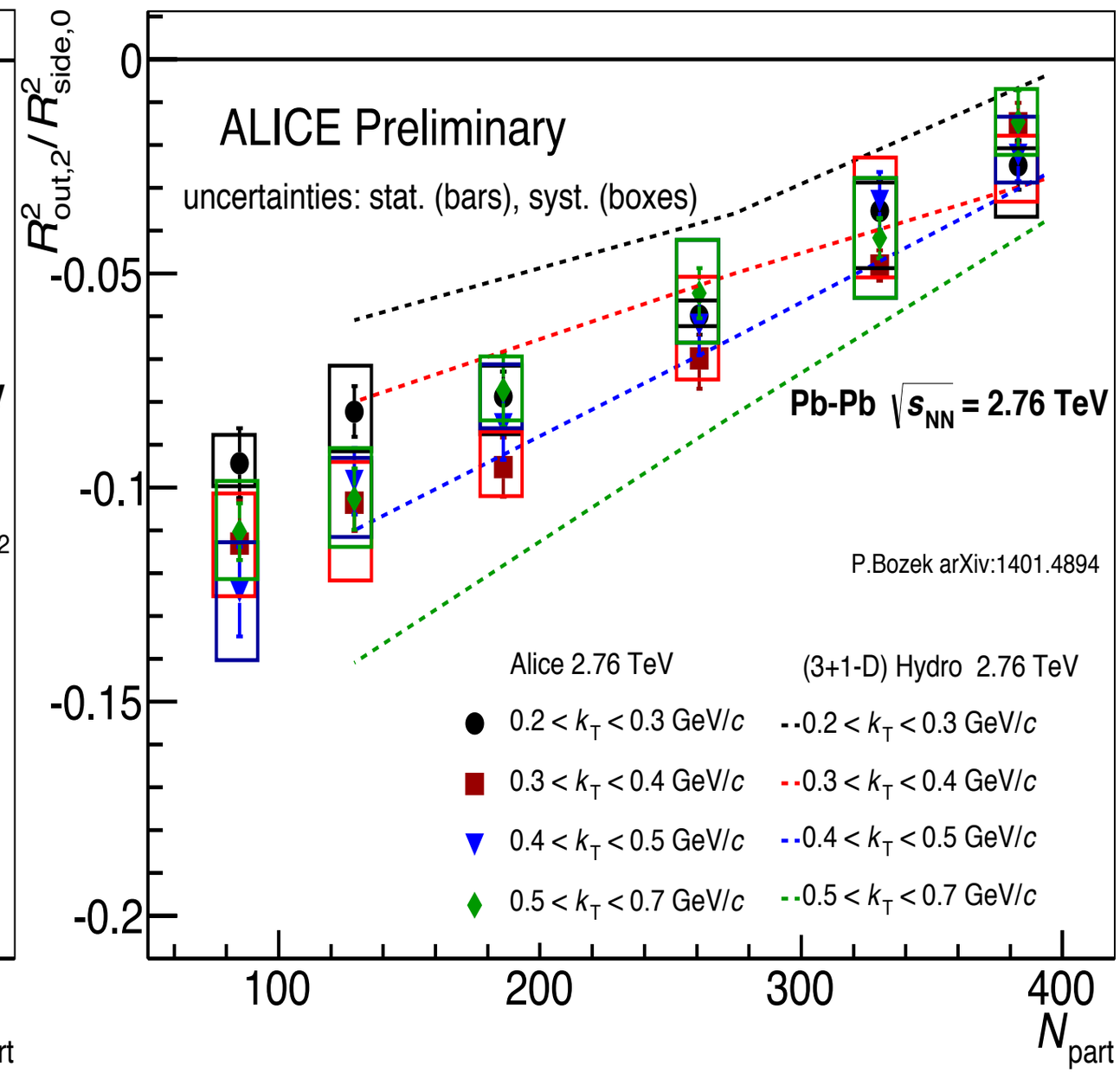
Final spatial eccentricity: $\varepsilon_f \approx 2 \frac{R^2_{side,2}}{R^2_{side,0}}$

- is in agreement with the relative oscillation magnitude of UrQMD model and is in disagreement with HYDRO predictions,
- decreases from LHC to RHIC, however remains positive, consistent with moderately longer system evolution duration.

Backup Slides

HYDRO Model Comparison





HYDRO Model Comparison