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Tilted source of particle emission in heavy-ion collisions

Yevheniia Khyzhniak

WPCF 2024 - 17th Workshop on Particle Correlations and Femtoscopy

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Nuclear Theory

[Submitted on 19 Oct 2024]

Pair momentum dependence of tilted source in heavy ion collisions

Yevheniia Khyzhniak, Michael Annan Lisa

In non-central heavy-ion collisions, the particle-emitting source can be tilted away from the beam direction, an effect that becomes particularly significant at collision energies of a few GeV and lower. This phenomenon, manifest itself in many observables such as directed flow, polarization, and vorticity, is therefore important to investigate. In this paper, we study the consistency between the tilt extracted directly from the freeze-out distribution of pions and the tilt parameter obtained using the azimuthally sensitive femtoscopy (asHBT) method. Using the UrQMD model, we demonstrate a strong dependence of the tilt parameter extracted with asHBT on the momentum of the particle pair. Considering the experimental challenges in accessing low particle momenta - where the tilt parameter extracted with asHBT closely matches the tilt of the freeze-out distribution of pions - we propose an exponential extrapolation method to obtain the tilt of the entire freeze-out distribution. This approach aims to enhance the accuracy of experimental measurements of tilt in non-central heavy-ion collisions.

Comments: 9 pages, 10 figures

Subjects: **Nuclear Theory (nucl-th)**; High Energy Physics - Phenomenology (hep-ph); Nuclear Experiment (nucl-ex)

Cite as: arXiv:2410.15134 **[nucl-th]**

(or arXiv:2410.15134v1 **[nucl-th]** for this version)

https://doi.org/10.48550/arXiv.2410.15134

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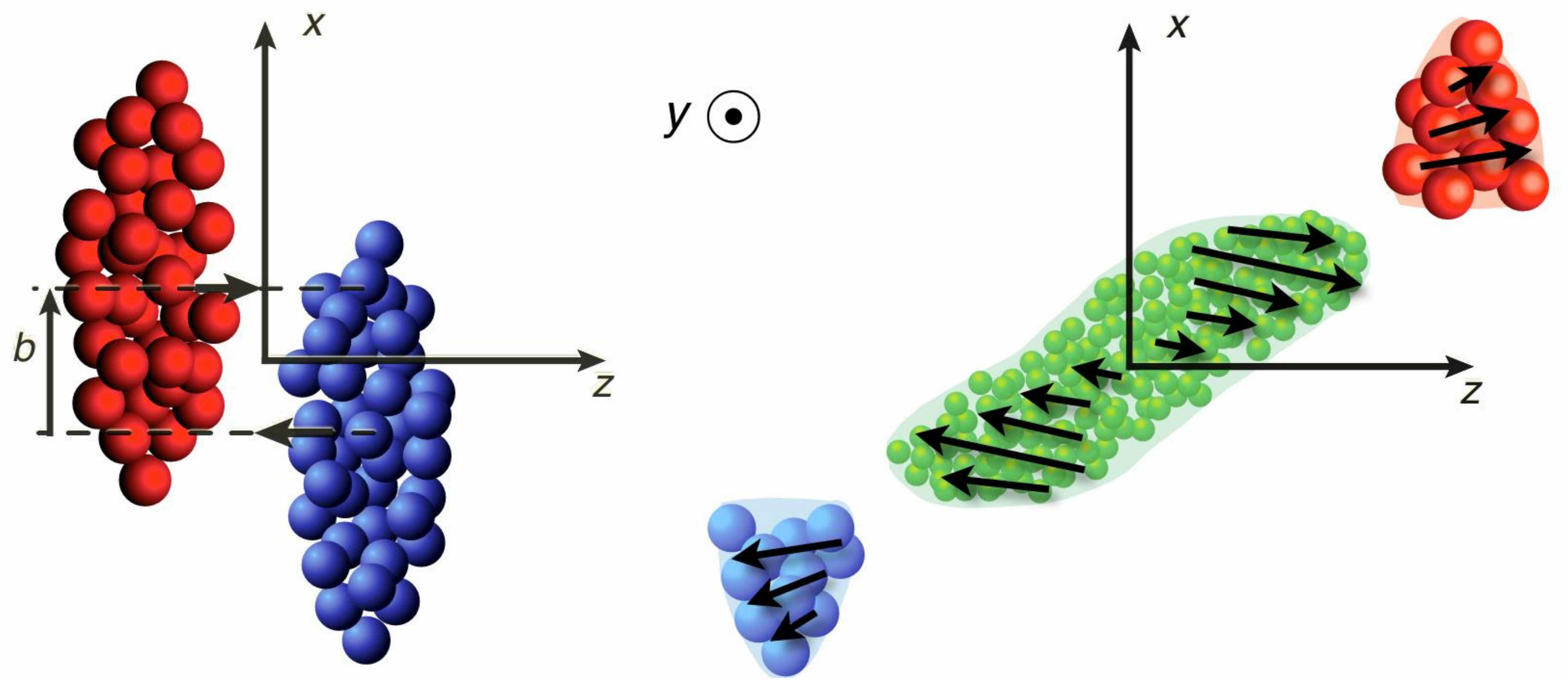
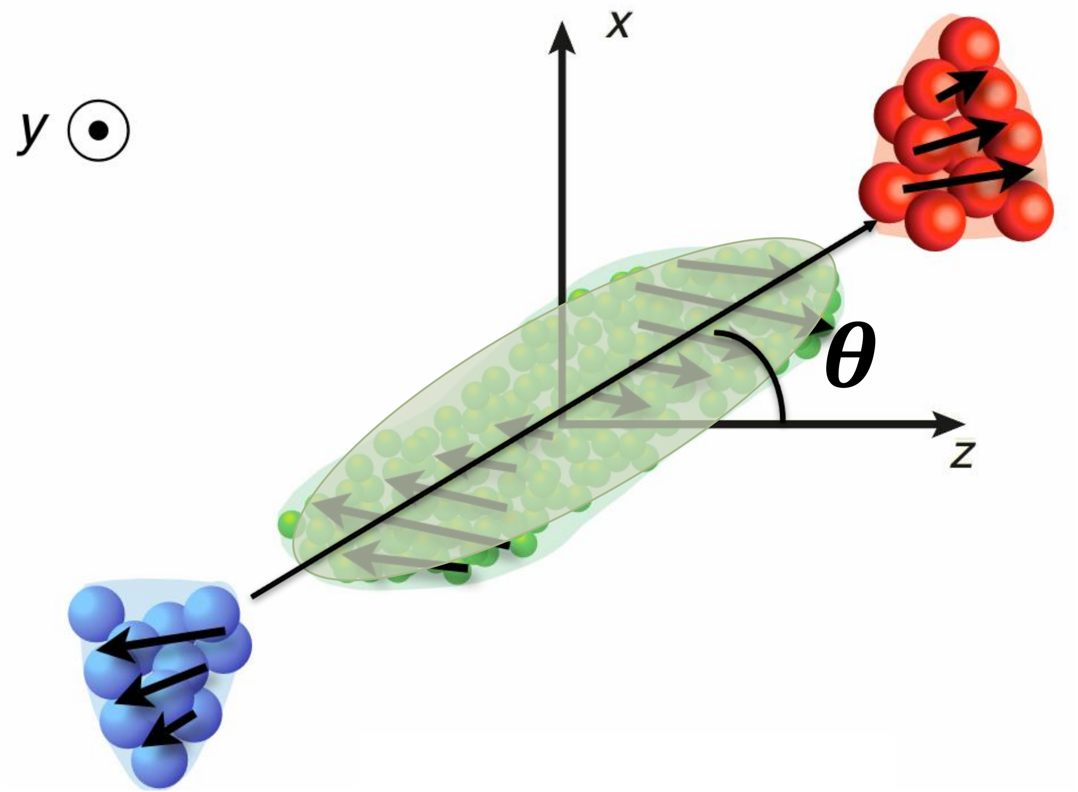
Tilted emission source



arXiv:2410.15134

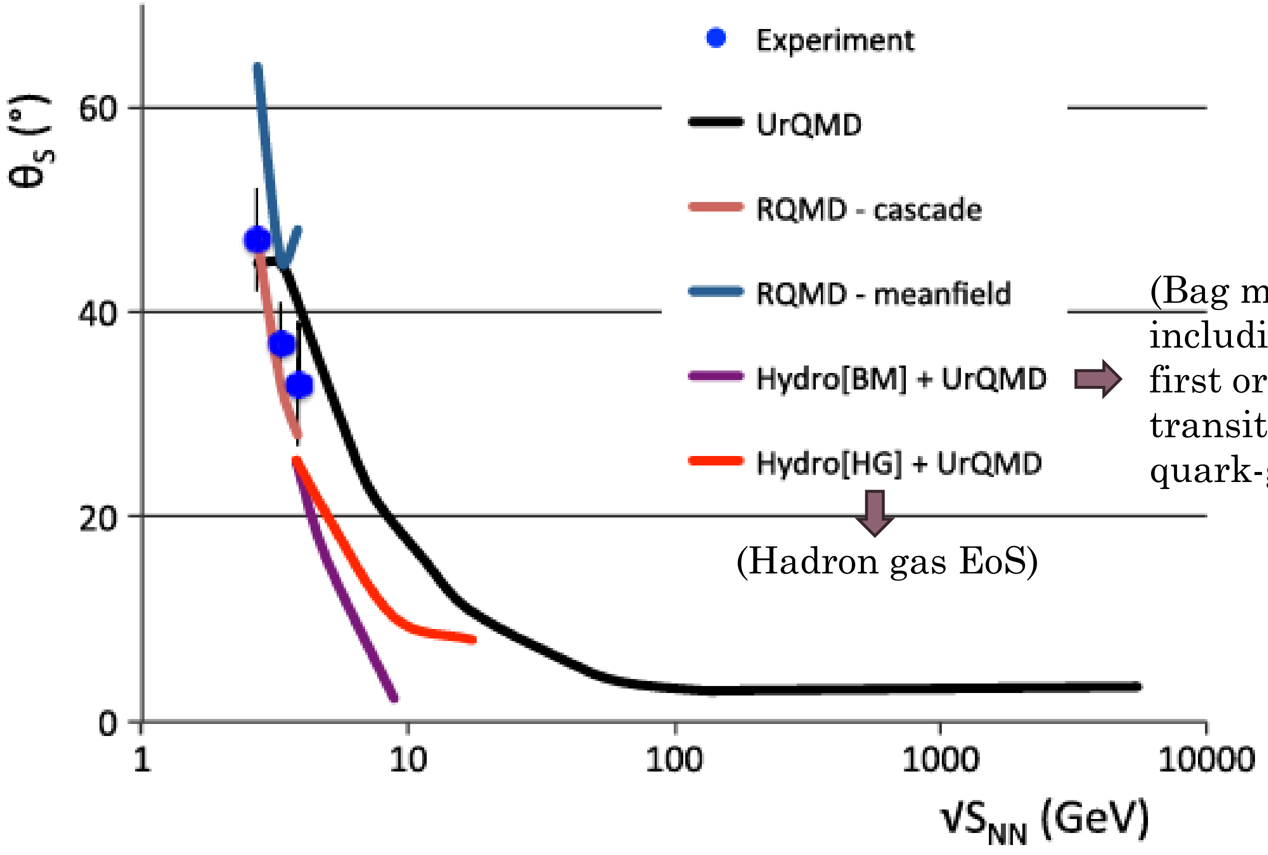
Tilted emission source

- The 3D initial geometry of a non-central heavy-ion collision breaks the forward-backward symmetry by a "tilt" of the fireball with respect to the reaction plane



arXiv:2410.15134

Motivation



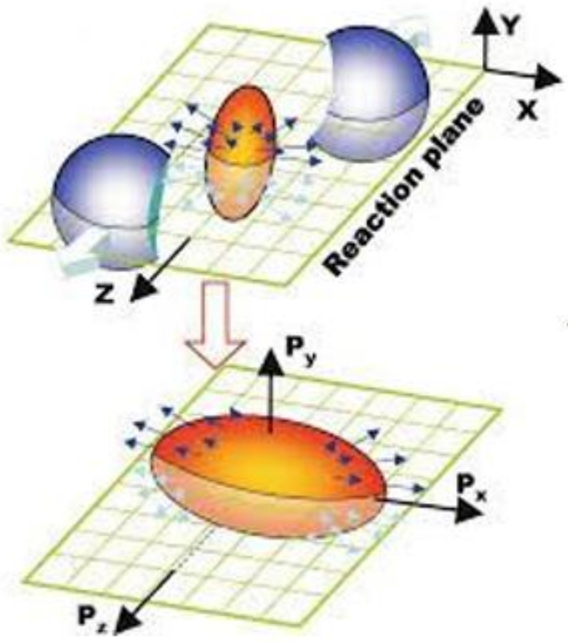
(Bag model EoS including a strong first order phase transition to the quark-gluon plasma)

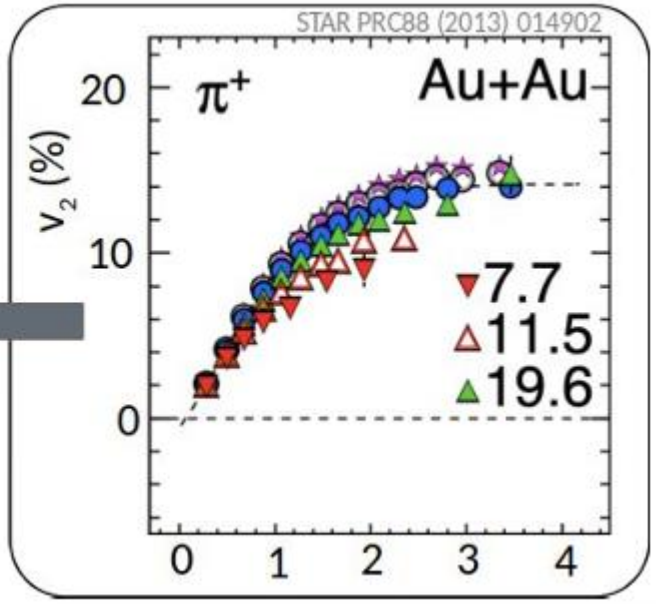
New J.Phys. 13 (2011) 065006

- The tilt is strikingly large at low energies and drops with energy, consistent with the expectation that collisions become increasingly boost invariant (at least near mid-rapidity) with increasing energy
  - ➢ Boost-invariant models incapable of capturing physics of participant zone with large spatial tilt

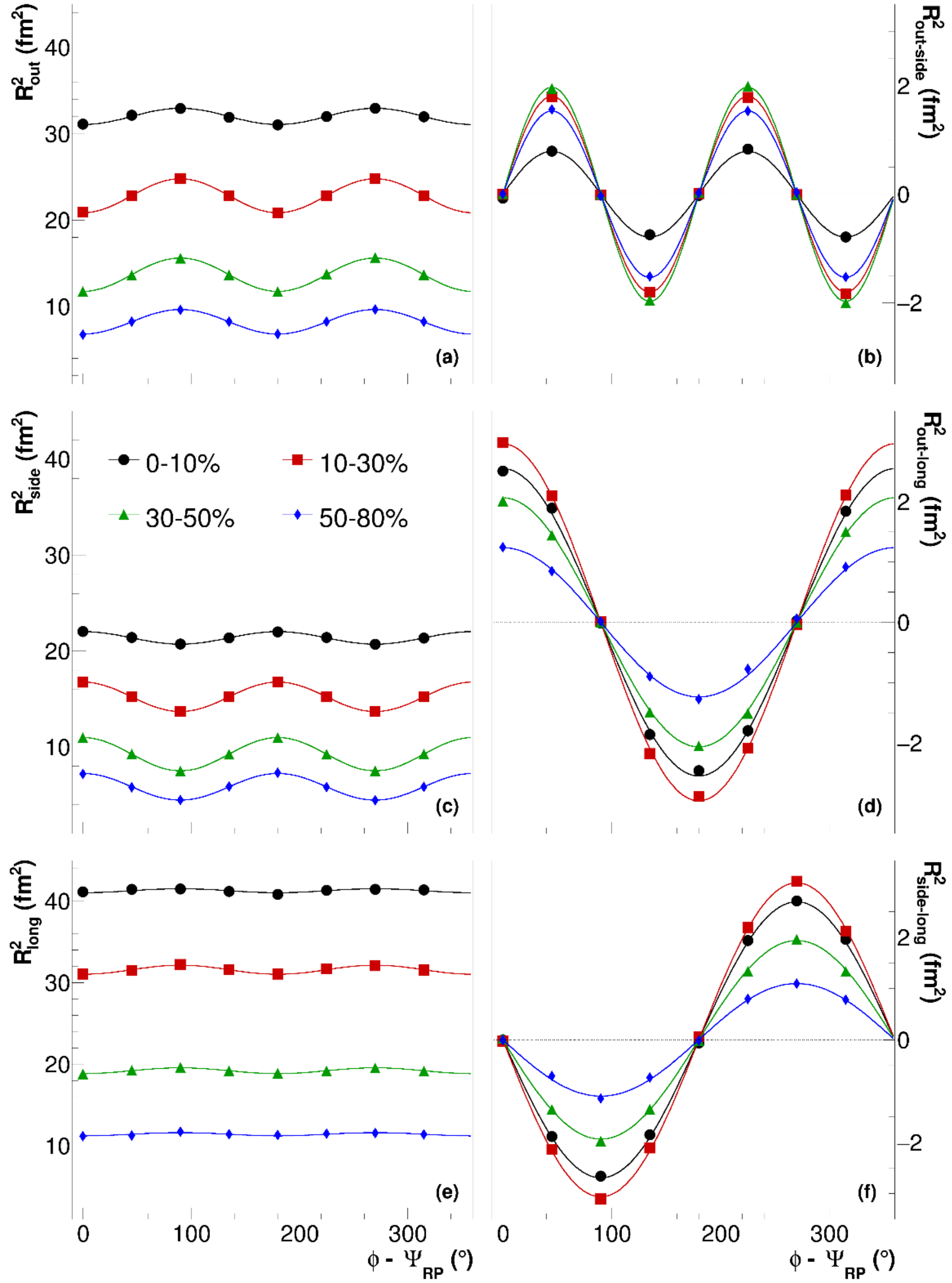
- EoS strongly influences the dynamics of an expanding system
  - ➢ Check EoS

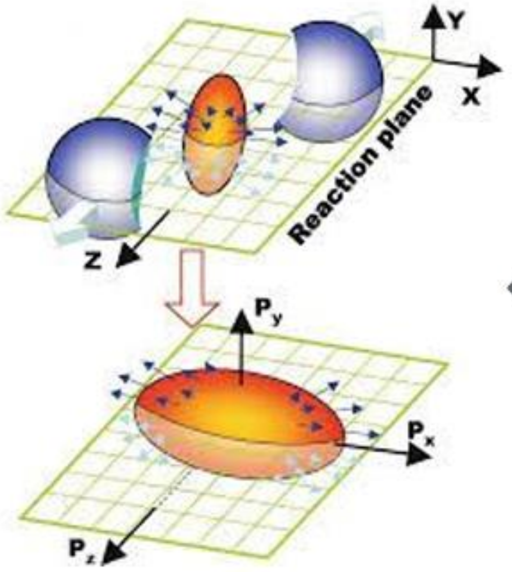
Femtoscopy and elliptic flow

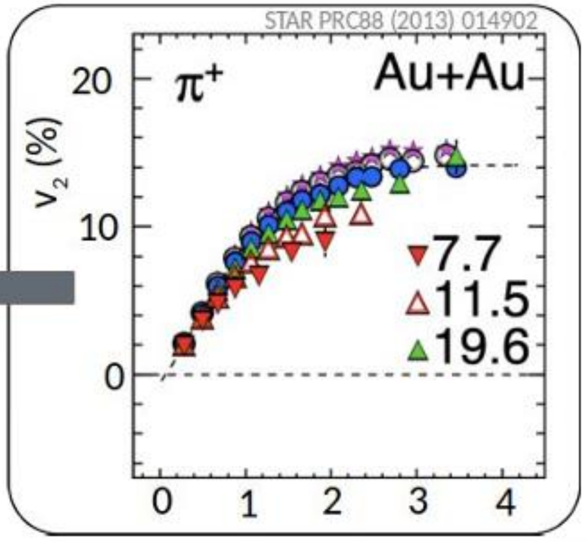




- In momentum space emission source extended in-plane

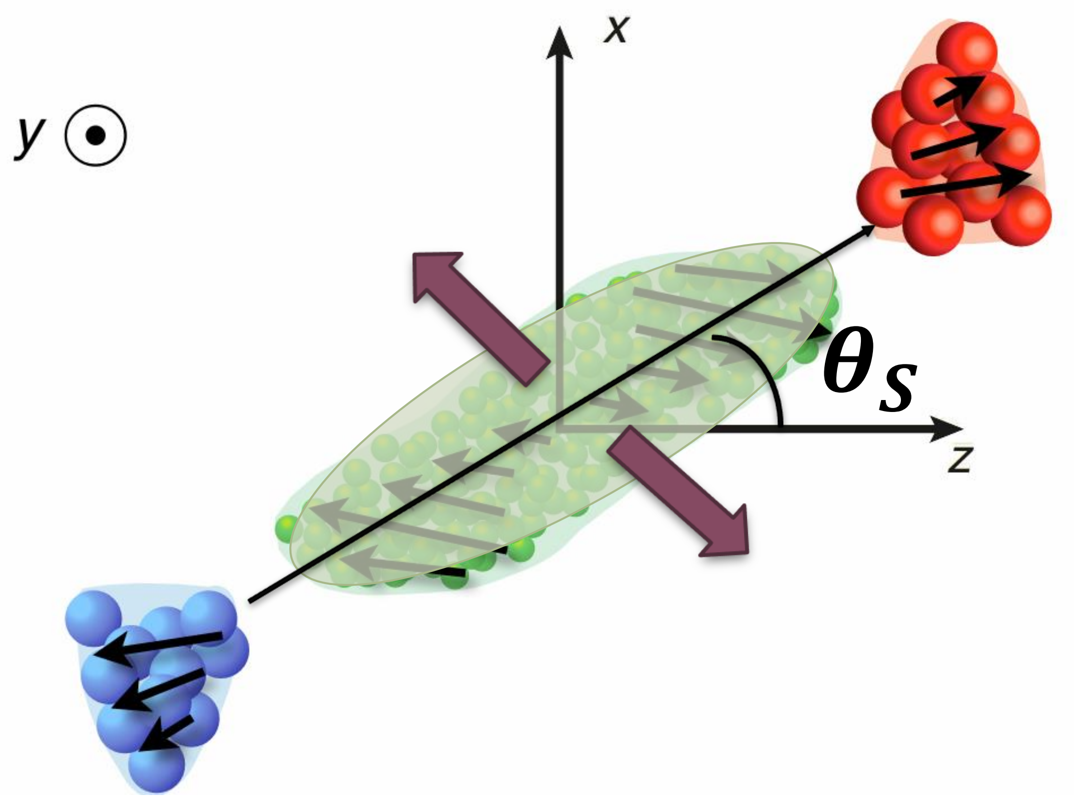




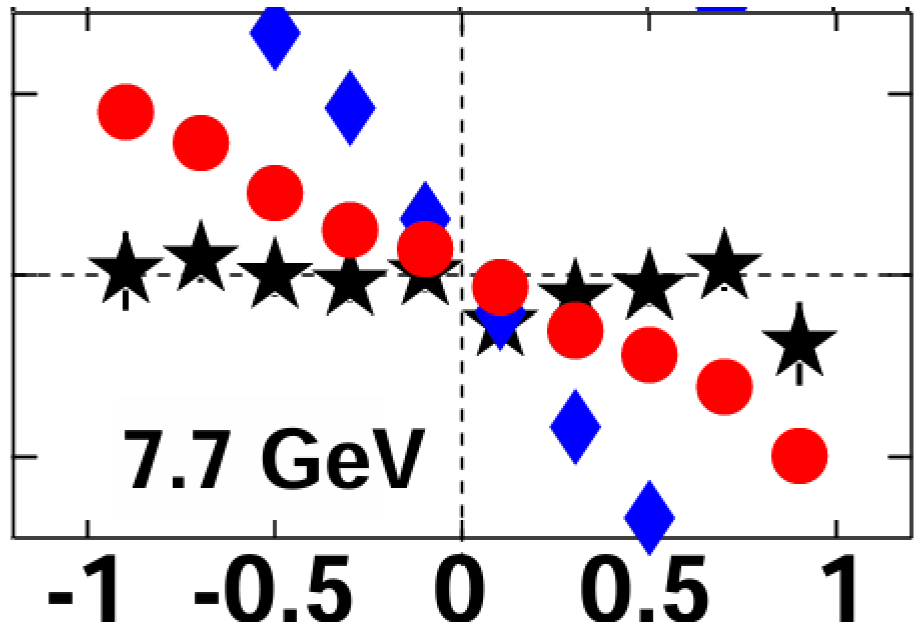


- In momentum space emission source extended in-plane
- Femtoscopy shows out-of-plane extension in the coordinate space -> stronger in-plane pressure gradients -> leading to positive v_2

Femtoscopy and directed flow



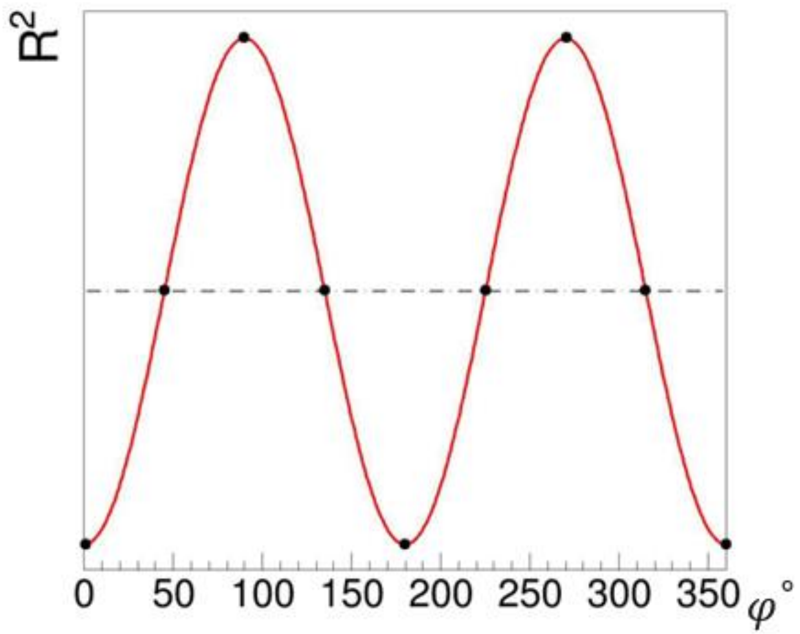
- Same reasoning for v_1 existence = stronger pressure gradients along shorter axis of the tilted source?



Procedure: step 1

Created medium

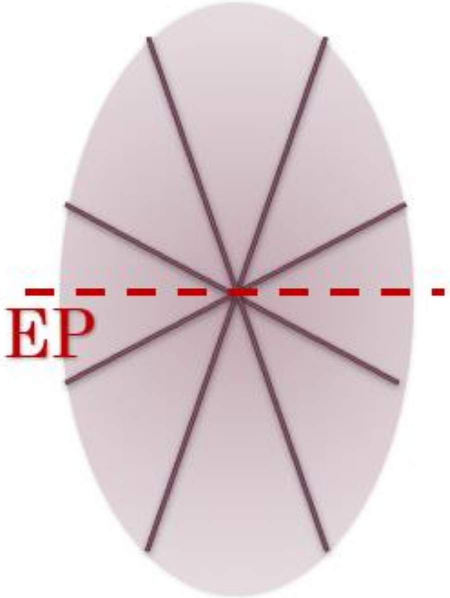
Radii response



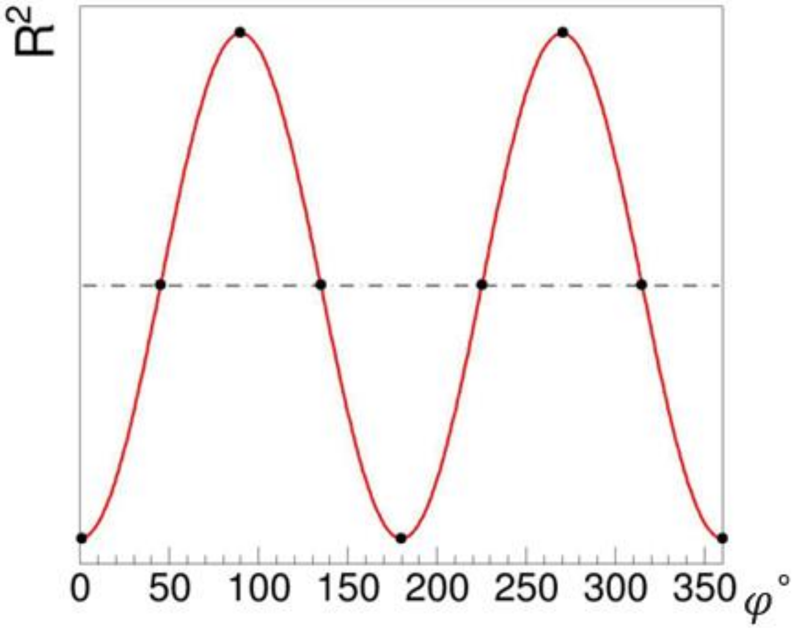
- Construct correlation functions for different ranges of azimuthal angles of the particle pair with respect to the event plane

Procedure: step 1

Created medium



Radii response



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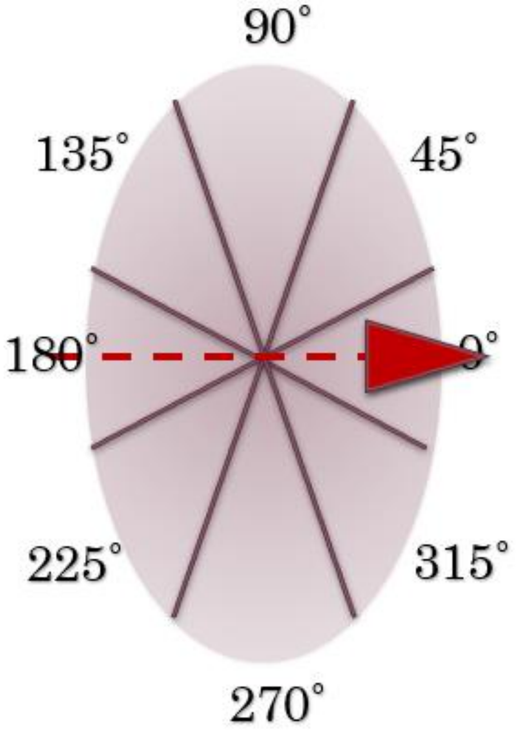
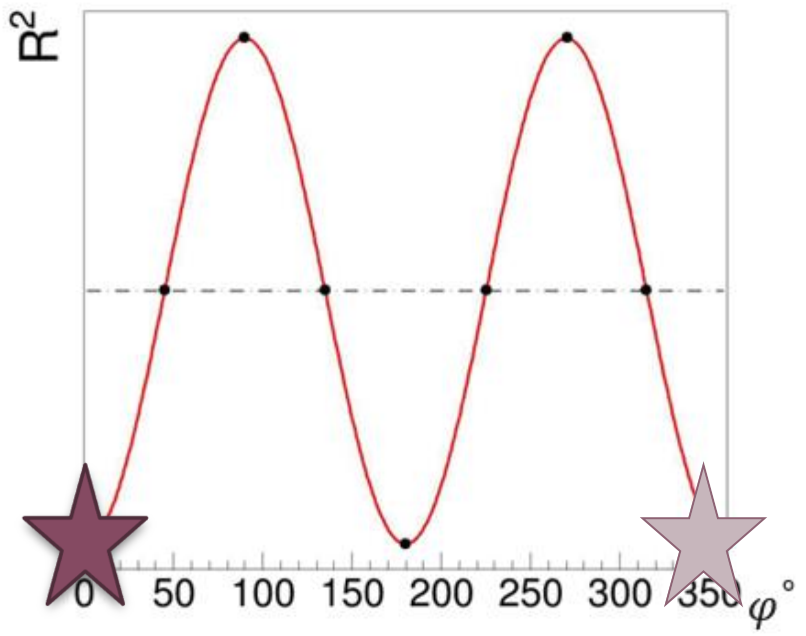


Radii response



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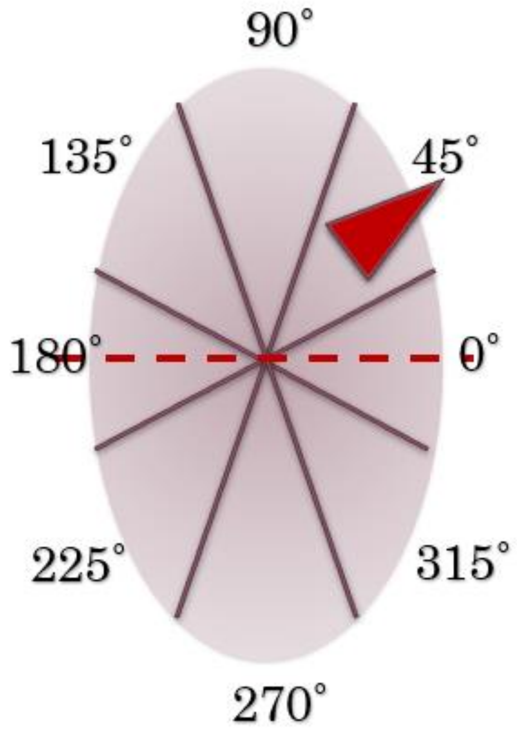
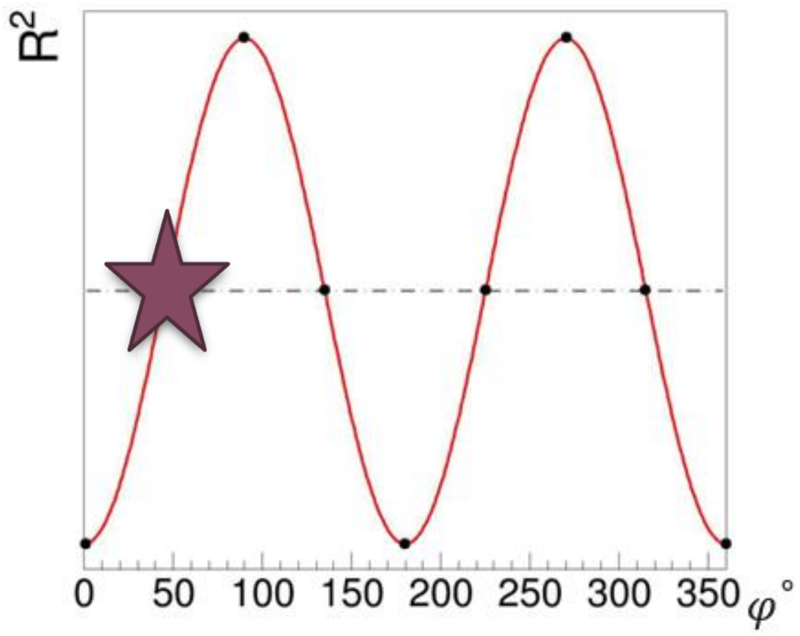


Radii response



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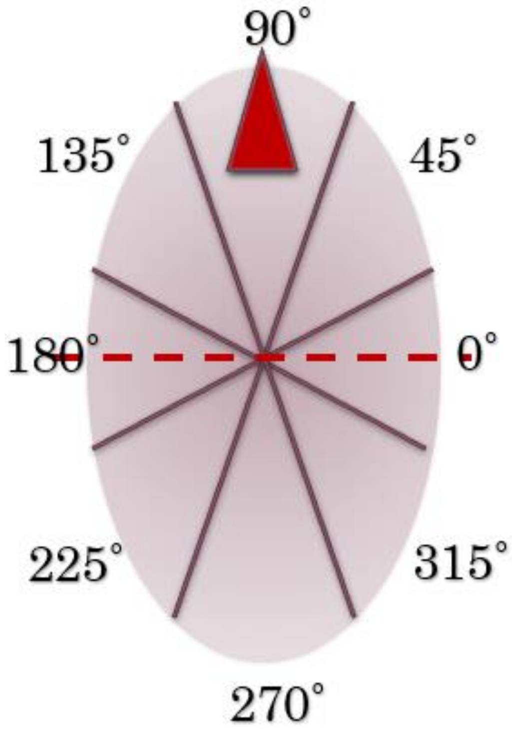
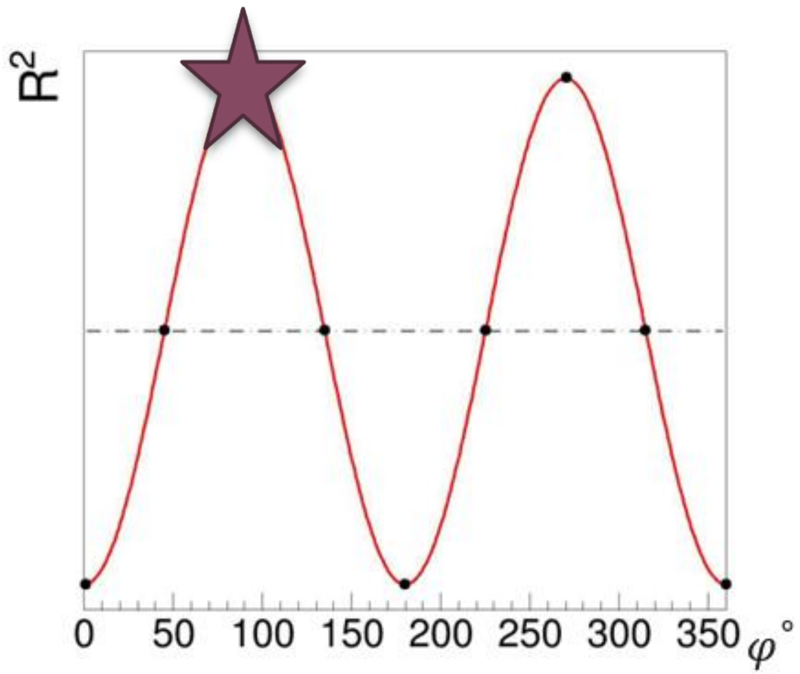


Radii response



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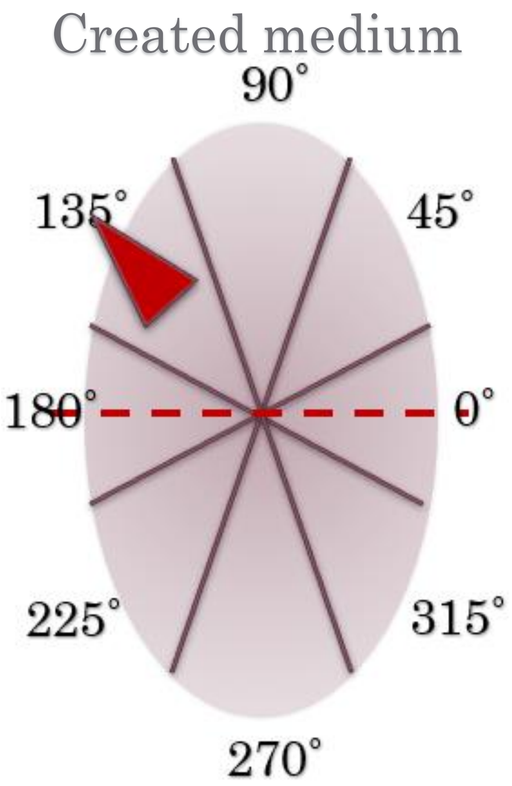
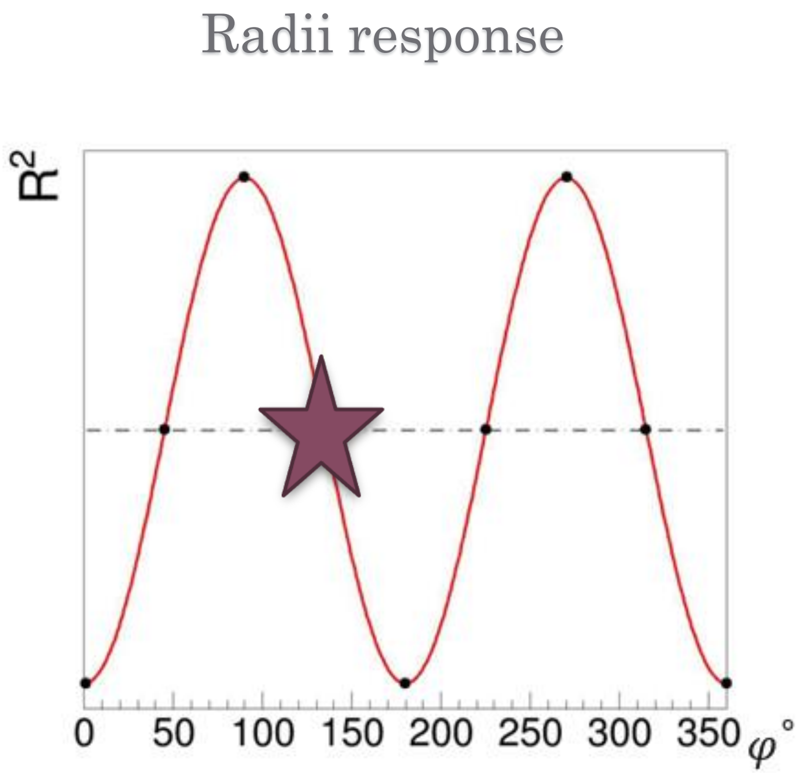
Procedure: step 1





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Procedure: step 1

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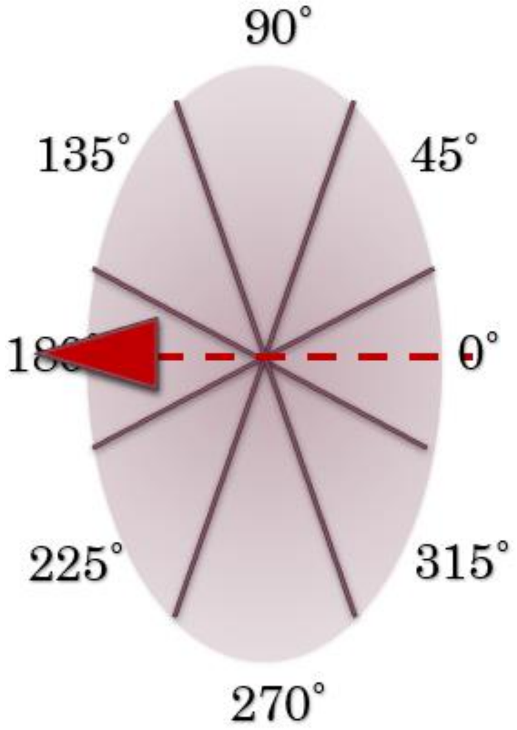
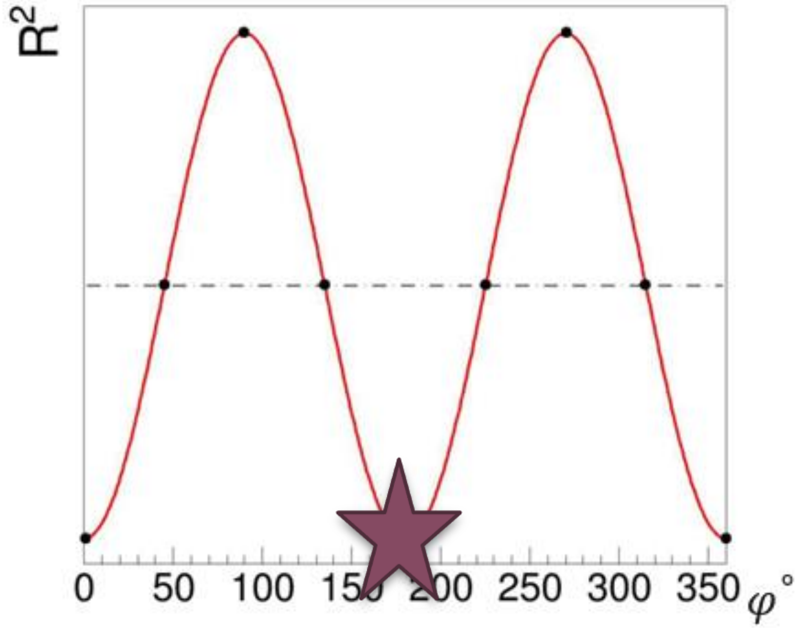


Radii response



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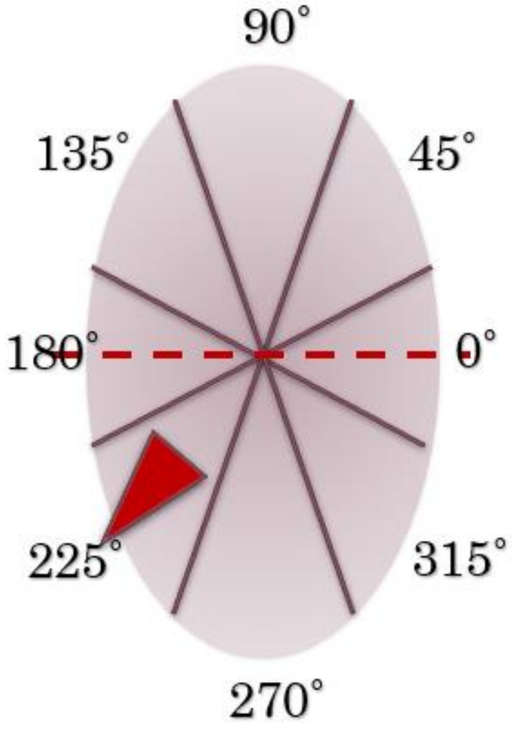
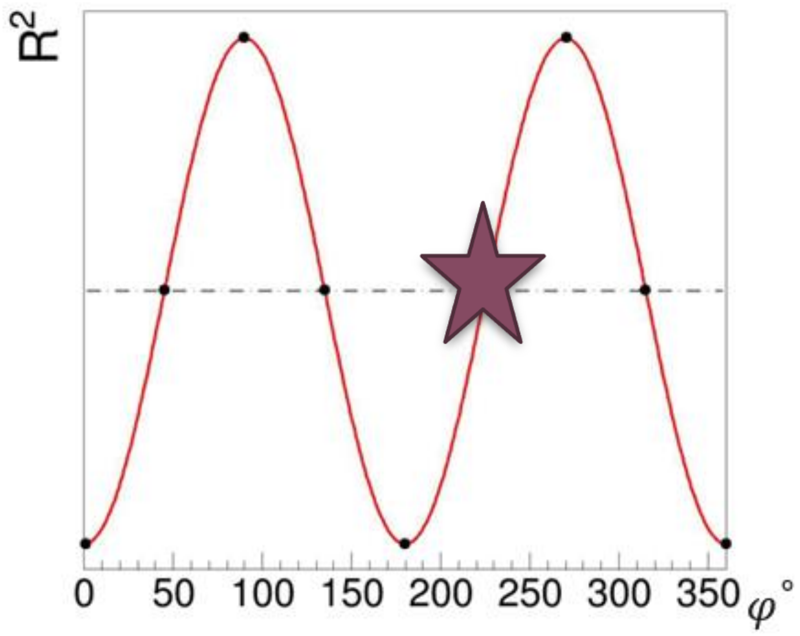


Radii response



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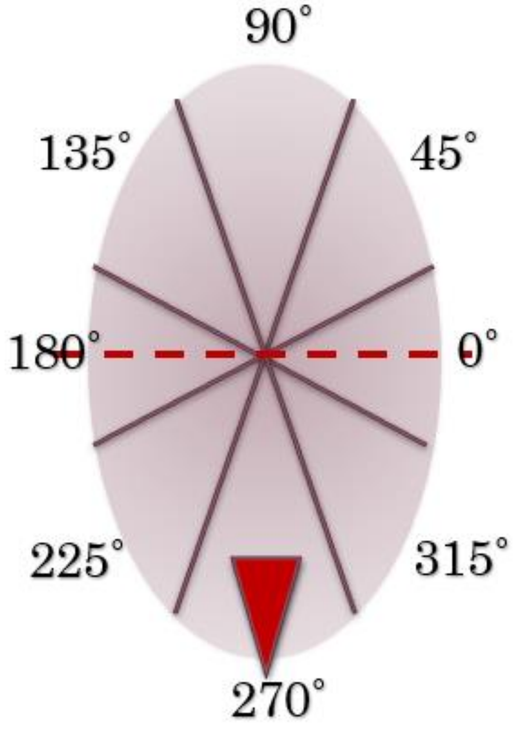
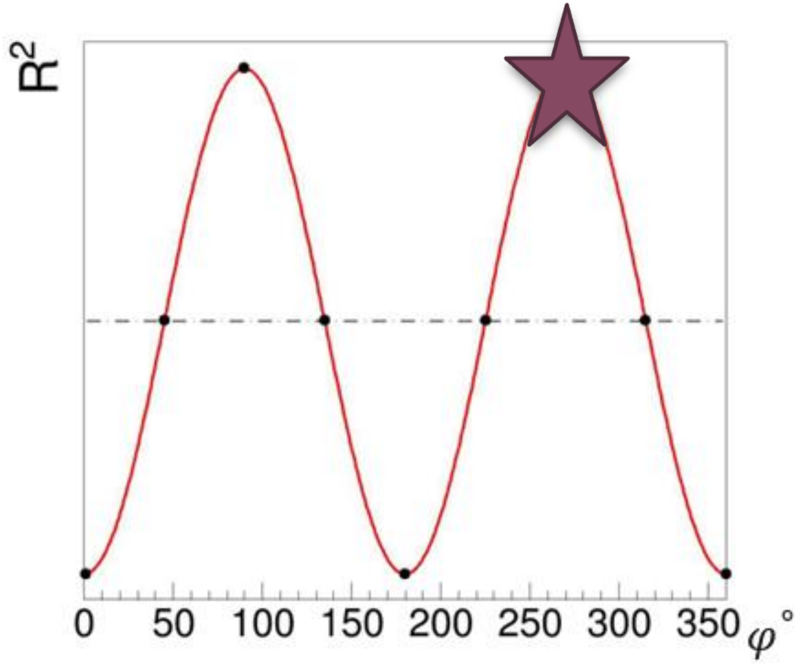


Radii response



- Construct correlation functions for different ranges of azimuthal angles of the particle pair with respect to the event plane

Procedure: step 1

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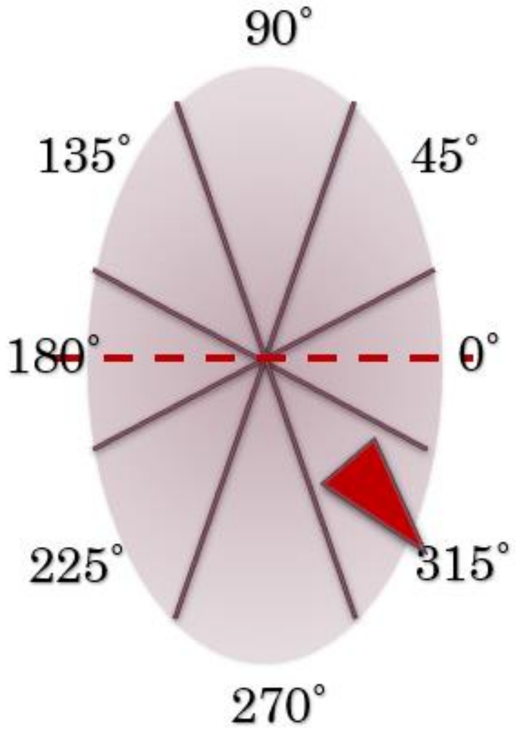
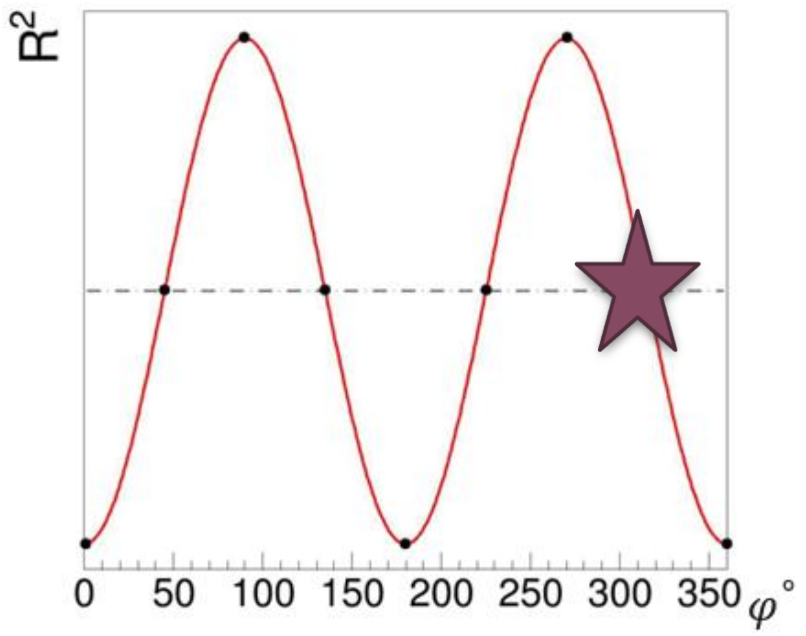
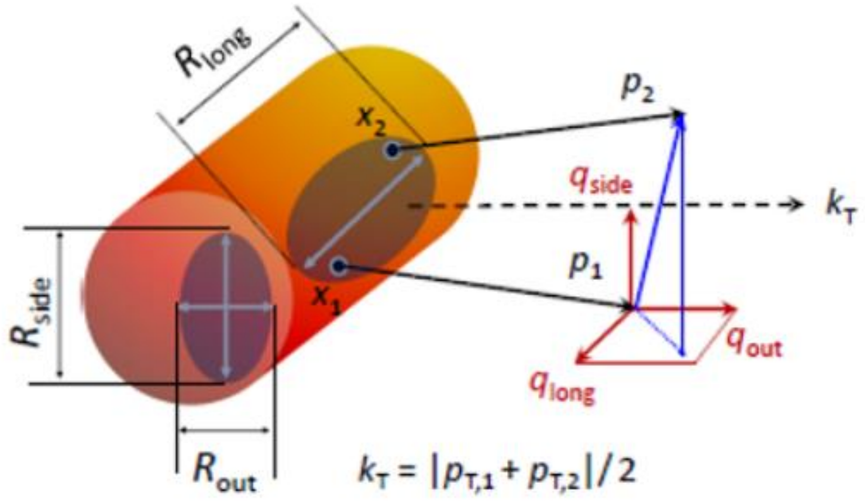


Radii response



- Construct correlation functions for different ranges of azimuthal angles of the particle pair with respect to the event plane

Procedure: step 2



Femtoscopic parameters are extracted by fitting correlation function with Bowler-Sinyukov procedure

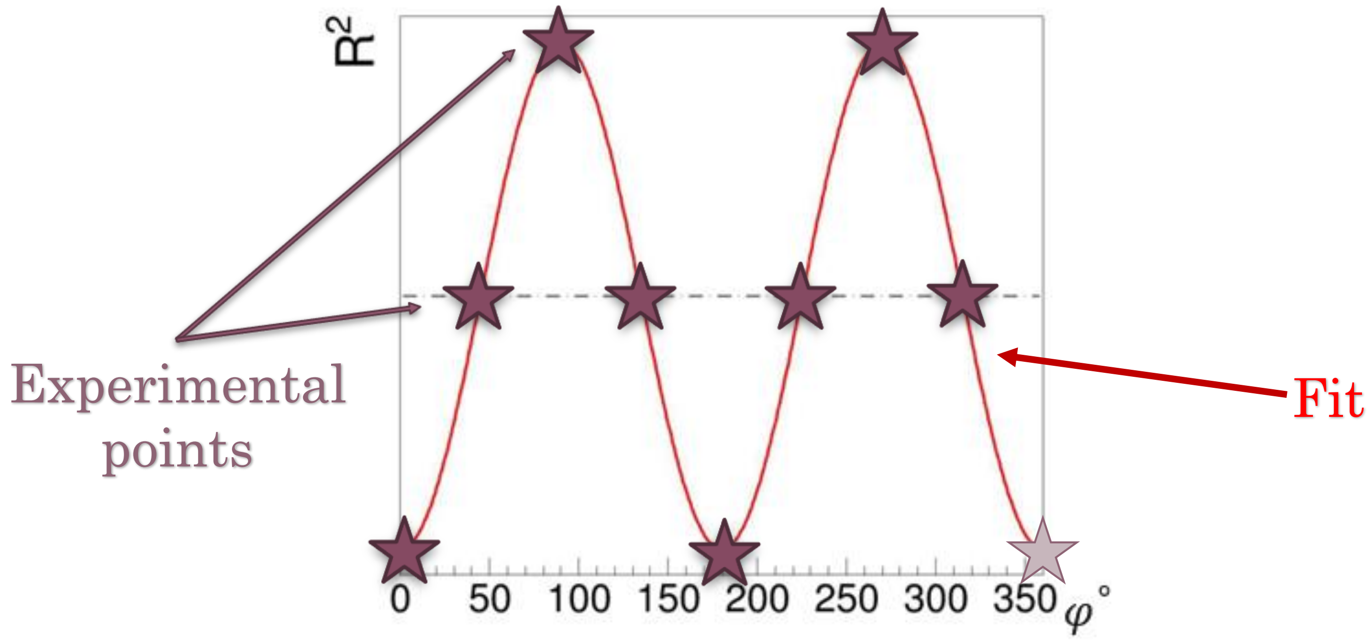
$$C(q) = N[(1-\lambda) + \lambda K(q)(1 + e^{-\sum_{i,j=o,s,l} q_i q_j R_{ij}^2})]$$

Phys. Lett. B 270 (1991) 69
Phys. Lett. B 432 (1998) 248

N – normalization factor
λ – correlation strength parameter
$K(q)$ - is a squared like-sign pion pair Coulomb wave-function integrated over a spherical Gaussian source
R_{ij} - femtoscopic radii

- Fit correlation functions in different azimuthal angles with respect to the event plane and extract source parameters for each case

Procedure: step 3



$$R_o^2 = R_{o,0}^2 + 2\sum_{n=2,4,6\ldots} R_{o,n}^2\cos(n\Phi)$$

$$R_s^2 = R_{s,0}^2 + 2\sum_{n=2,4,6\ldots} R_{s,n}^2\cos(n\Phi)$$

$$R_l^2 = R_{l,0}^2 + 2\sum_{n=2,4,6\ldots} R_{l,n}^2\cos(n\Phi)$$

$$R_{os}^2 = R_{os,0}^2 + 2\sum_{n=2,4,6\ldots} R_{os,n}^2\sin(n\Phi)$$

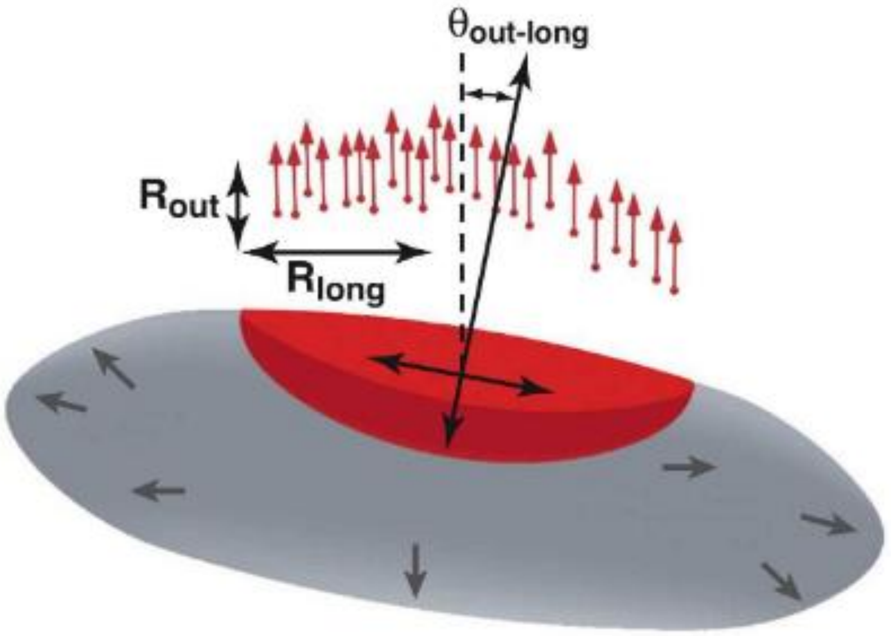
$$R_{ol}^2 = R_{ol,0}^2 + 2\sum_{n=1,3,5\ldots} R_{ol,n}^2\cos(n\Phi)$$

$$R_{sl}^2 = R_{sl,0}^2 + 2\sum_{n=1,3,5\ldots} R_{sl,n}^2\sin(n\Phi)$$

Phys.Lett.B 496 (2000) 1-8
Phys.Lett.B 489 (2000) 287-292
Phys.Rev.C 66 (2002) 044903
Phys.Rev.C 84 (2011) 014908
Phys.Rev.C 89 (2014) 1, 014903

- Construct azimuthal angle dependence of the extracted parameters (R_{ij}) and fit these oscillations

Procedure: step 4



Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

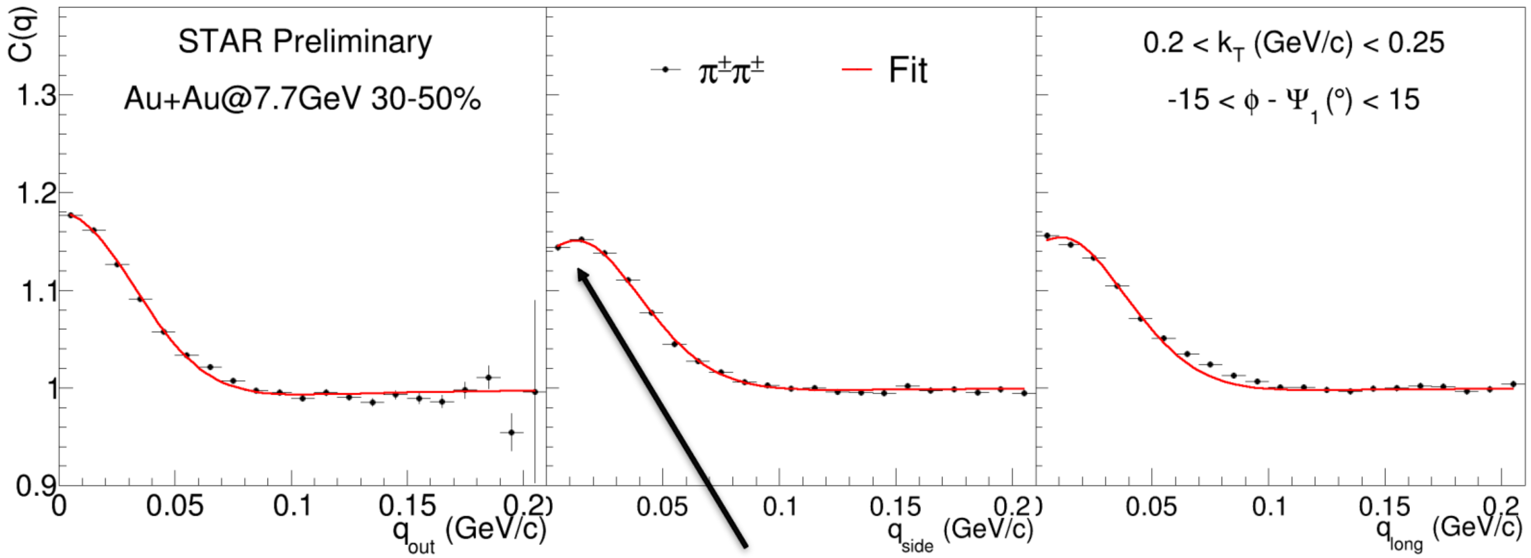
$$\theta_{sl} = \frac{1}{2} tan^{-1}\left(\frac{-4R_{sl,1}^2}{R_{l,0}^2 - R_{s,0}^2 + 2R_{s,2}^2}\right)$$
$$\theta_{ol} = \frac{1}{2} tan^{-1}\left(\frac{4R_{ol,1}^2}{R_{l,0}^2 - R_{s,0}^2 + 2R_{s,2}^2}\right)$$

Phys.Lett.B 489 (2000) 287-292
Phys.Rev.C 66 (2002) 044903
Phys.Rev.C 84 (2011) 014908

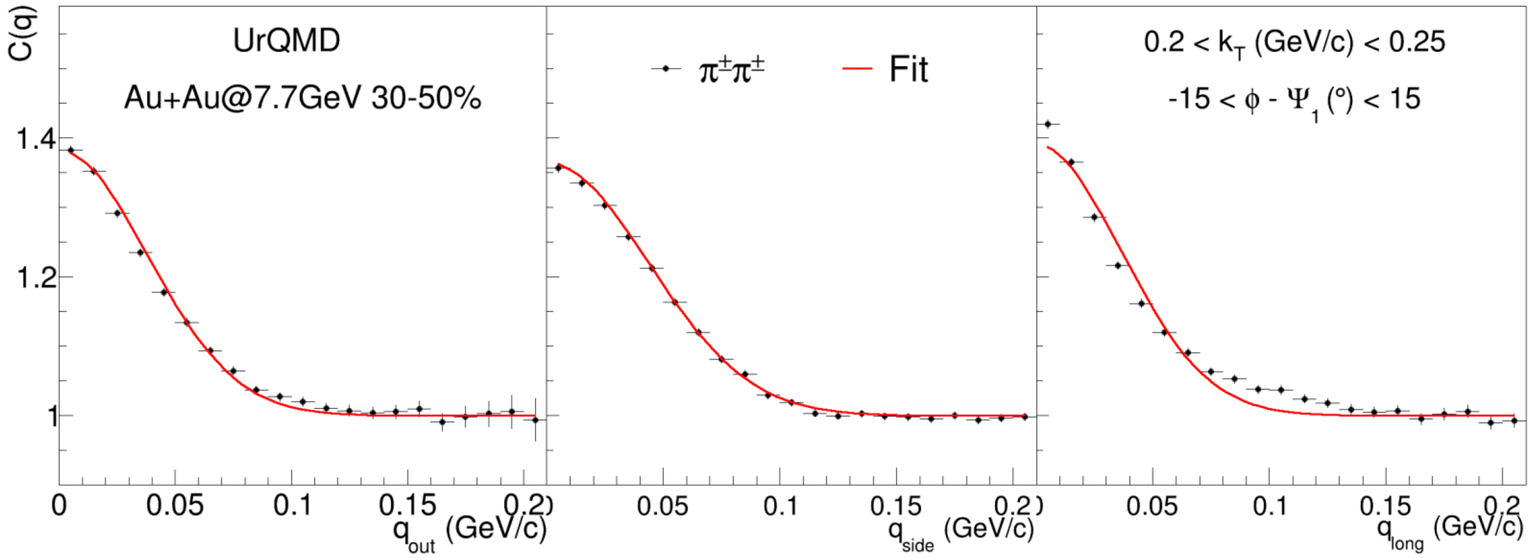
- Tilt calculation from extracted fit parameters

One-dimensional projection of correlation function

Statistical uncertainties only

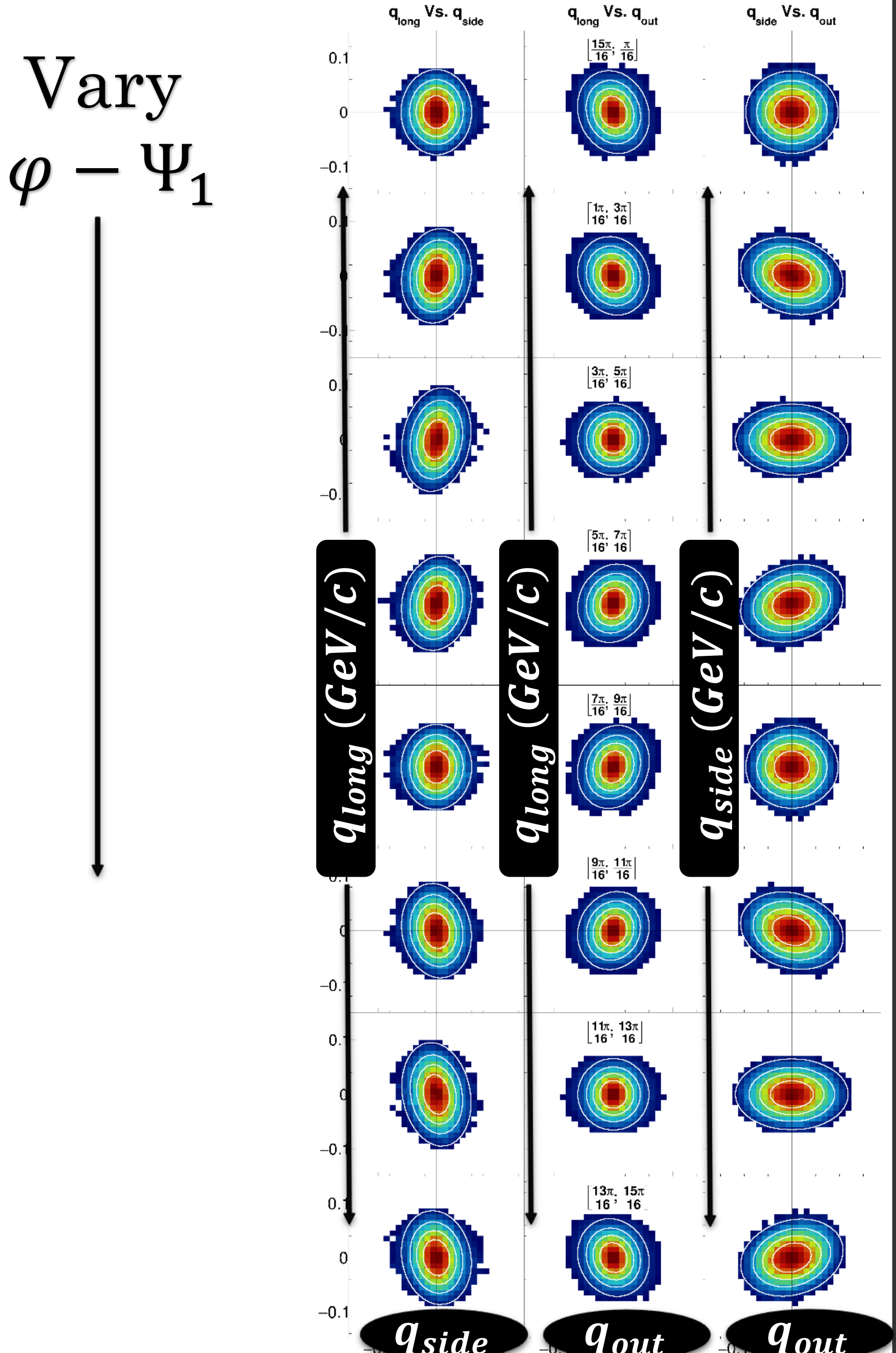


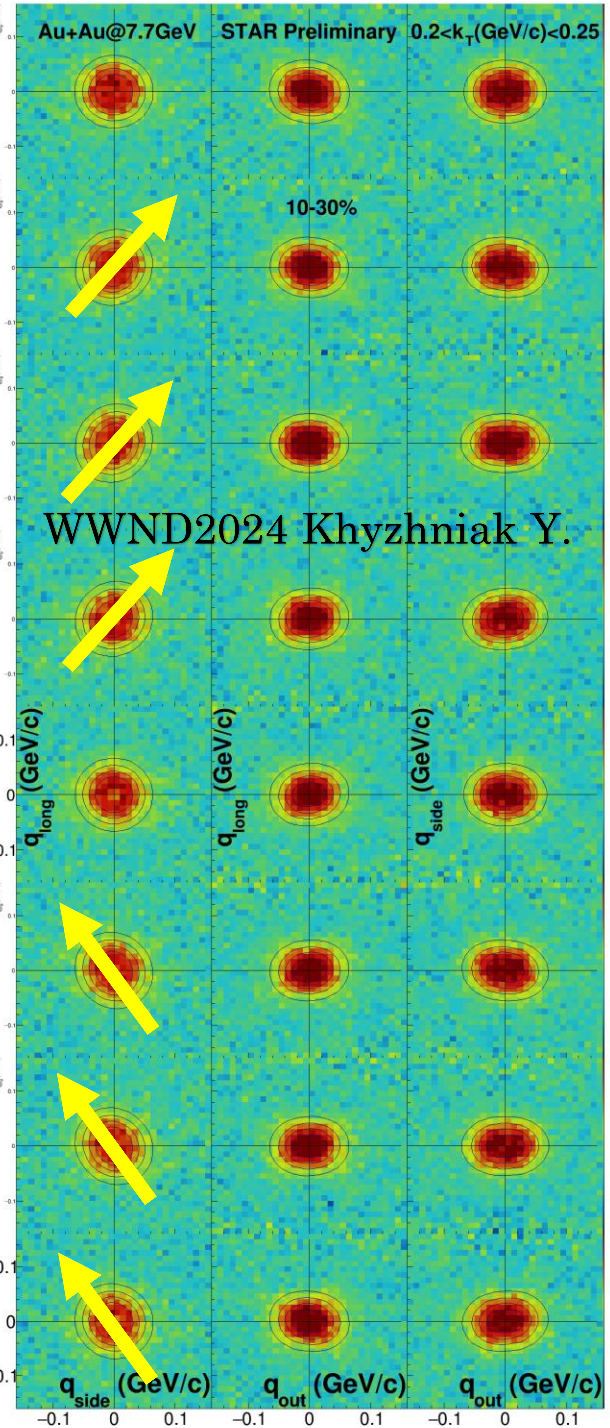
There is a slight suppression due to the Coulomb repulsion of like-sign pion pairs



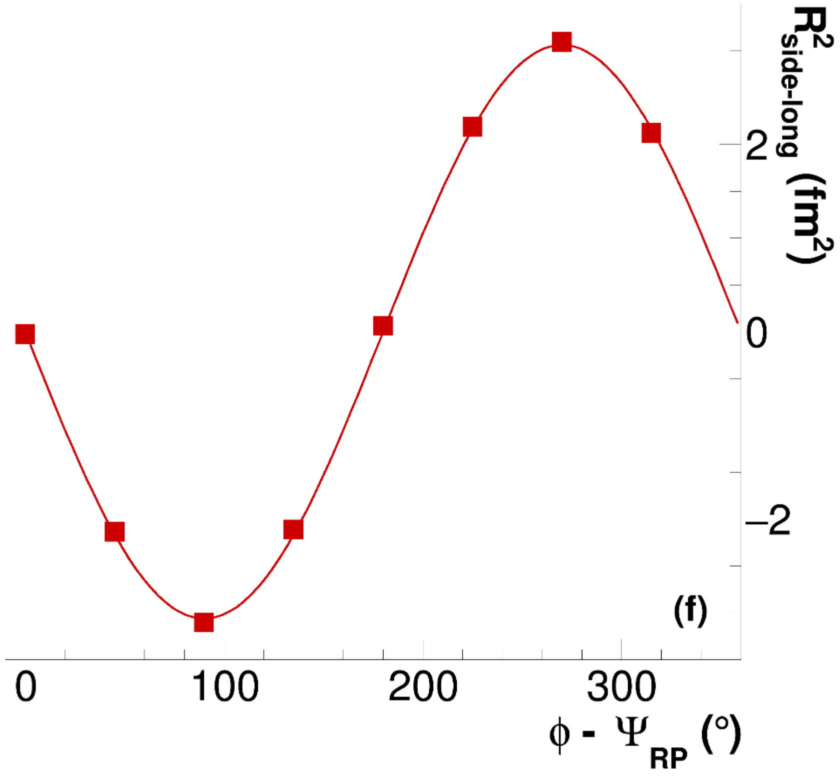
- Fit describes correlation functions reasonably well in both experiment and UrQMD
- A slight deviation from the Gaussian shape in the longitudinal direction can be attributed to a “halo” emission from resonance

Two-dimensional projections of correlation functions

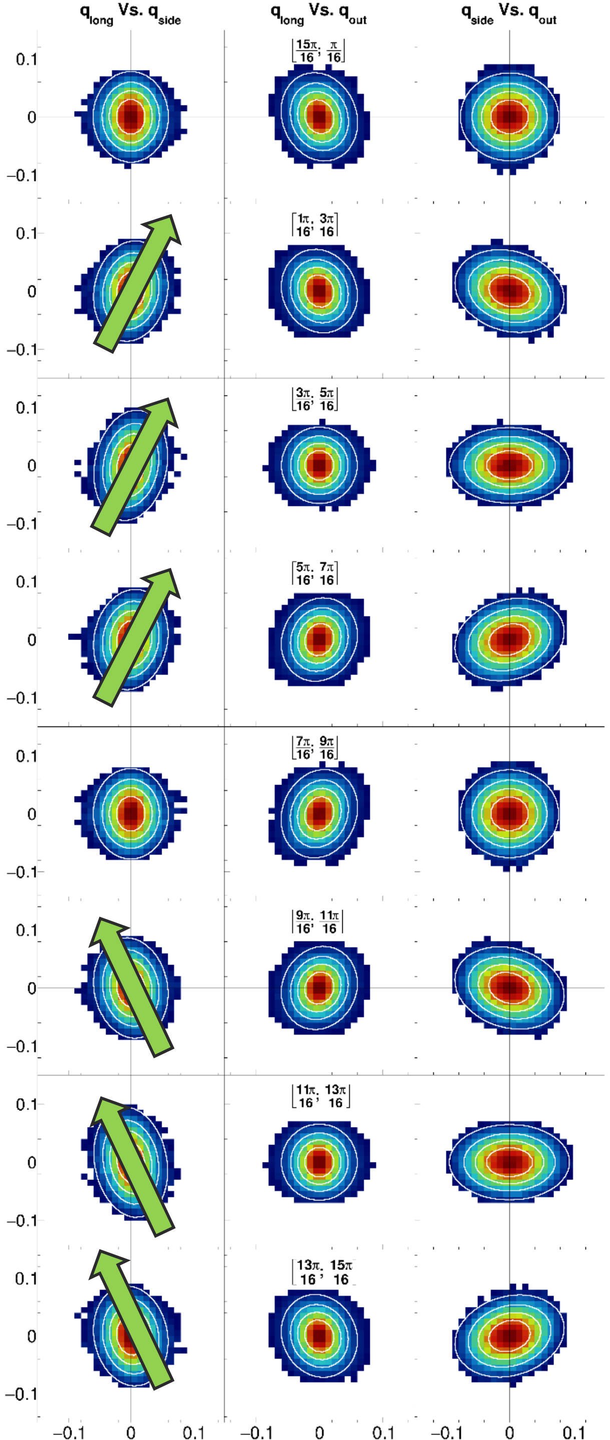


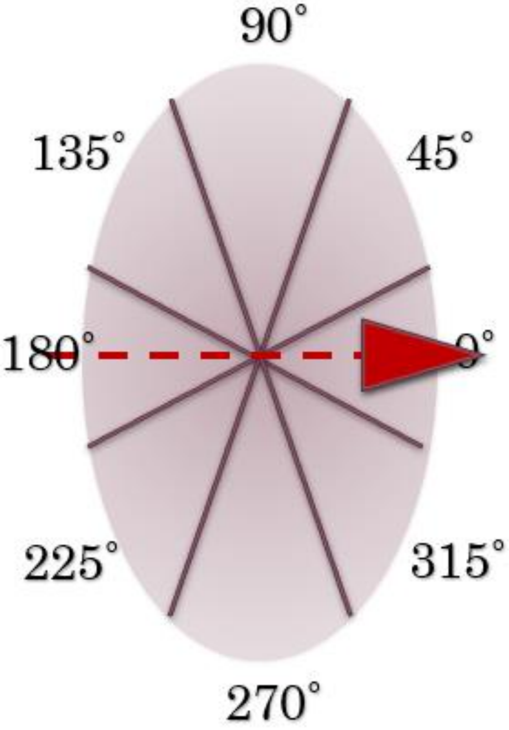


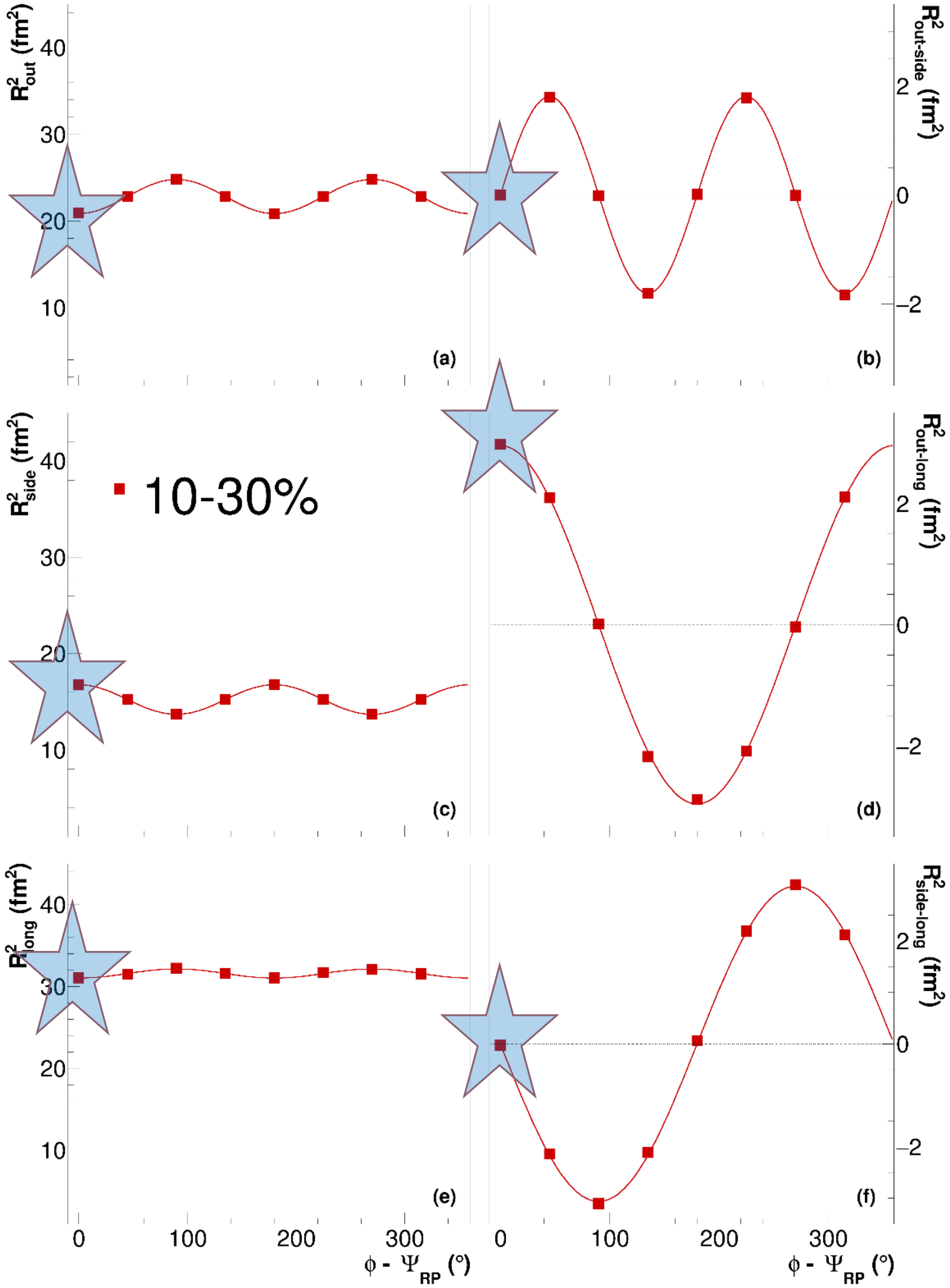
- $R_{out}, R_{side}, R_{long}$ inversely ~ width of the CF in the out, side, long directions

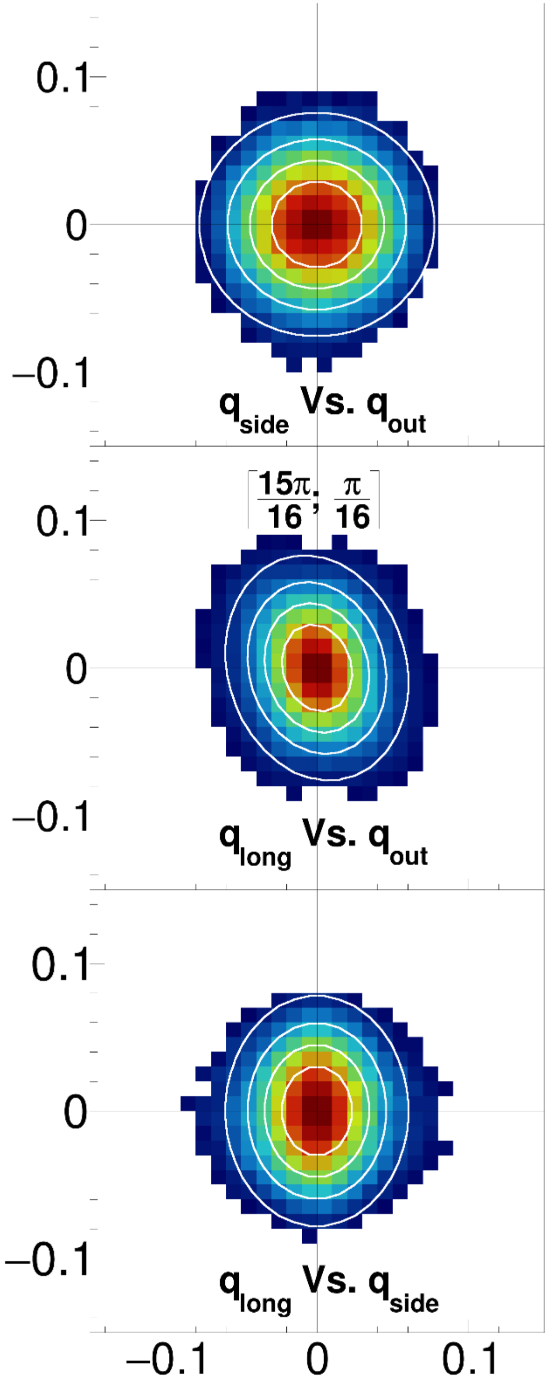


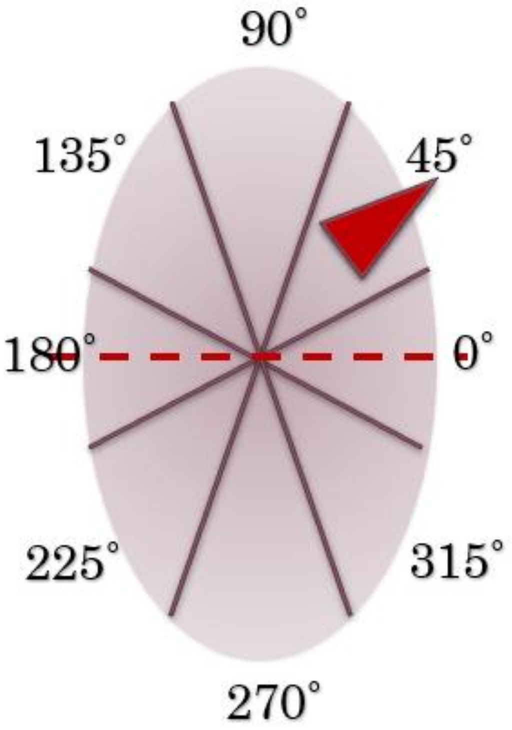
- "Cross-term" radii are reflected in the "tilt" of the CF
  - Example: $R^2_{side-long}$ shows up as a tilt of the CF in $\{q_{side}, q_{long}\}$ projection




90°
135°
45°
180°
0°
225°
315°
270°


R^2_{out} (fm^2)
$R^2_{out\text{-}side}$ (fm^2)
R^2_{side} (fm^2)
$R^2_{out\text{-}long}$ (fm^2)
R^2_{long} (fm^2)
$R^2_{side\text{-}long}$ (fm^2)
10-30%
(a)
(b)
(c)
(d)
(e)
(f)
$\phi - \Psi_{RP}$ (°)
$\phi - \Psi_{RP}$ (°)


q_{side} Vs. q_{out}
$\left[\frac{15\pi}{16}, \frac{\pi}{16}\right]$
q_{long} Vs. q_{out}
q_{long} Vs. q_{side}


90°
135°
45°
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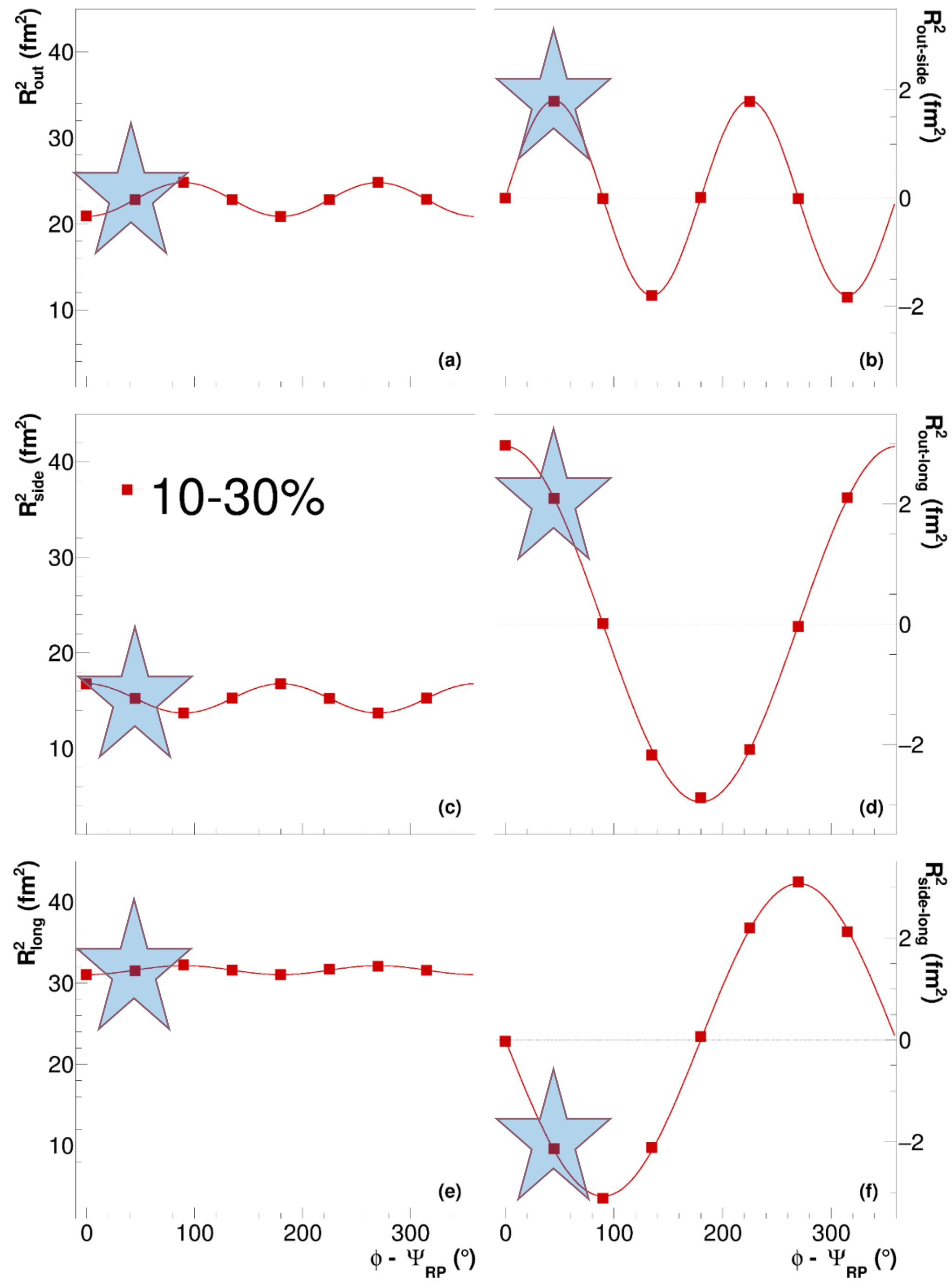
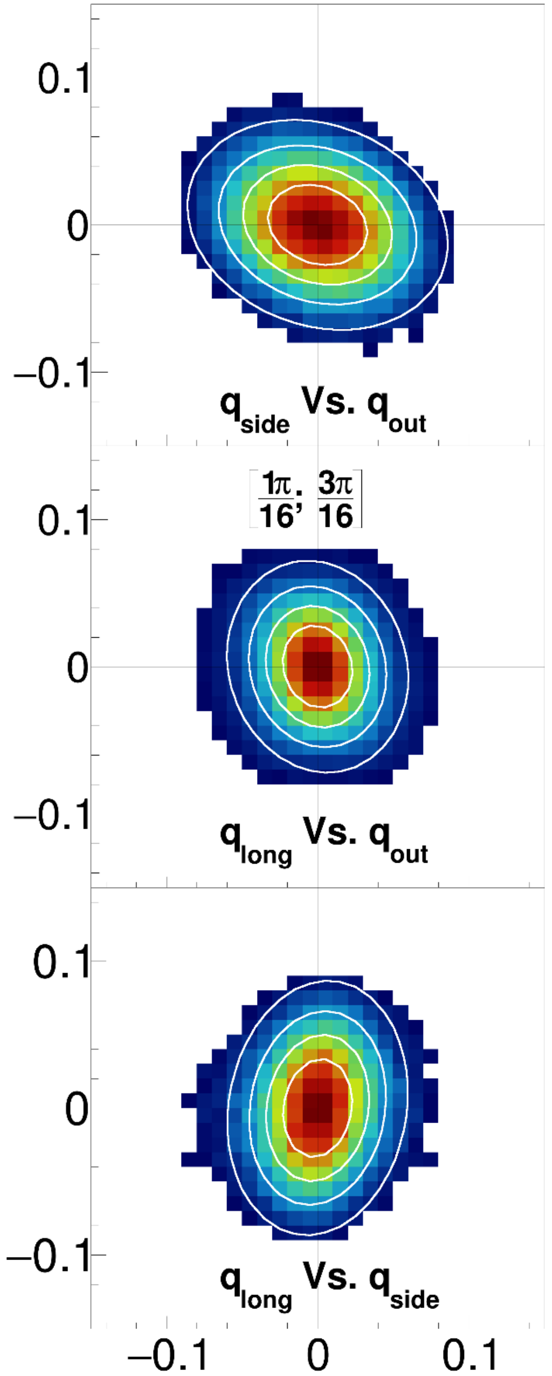
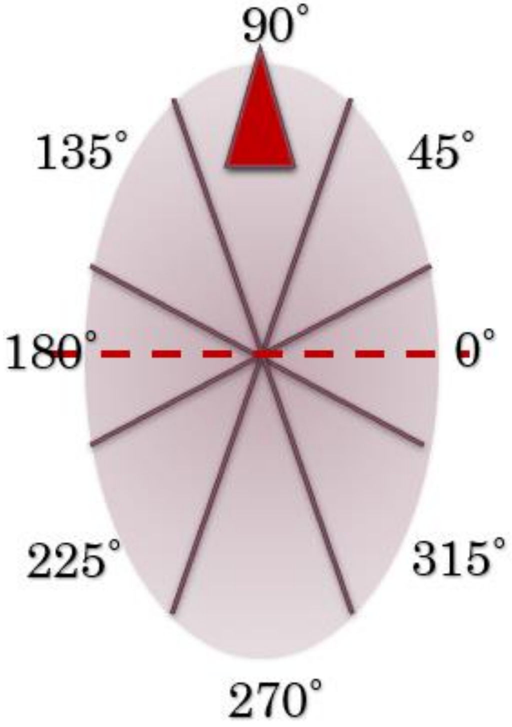
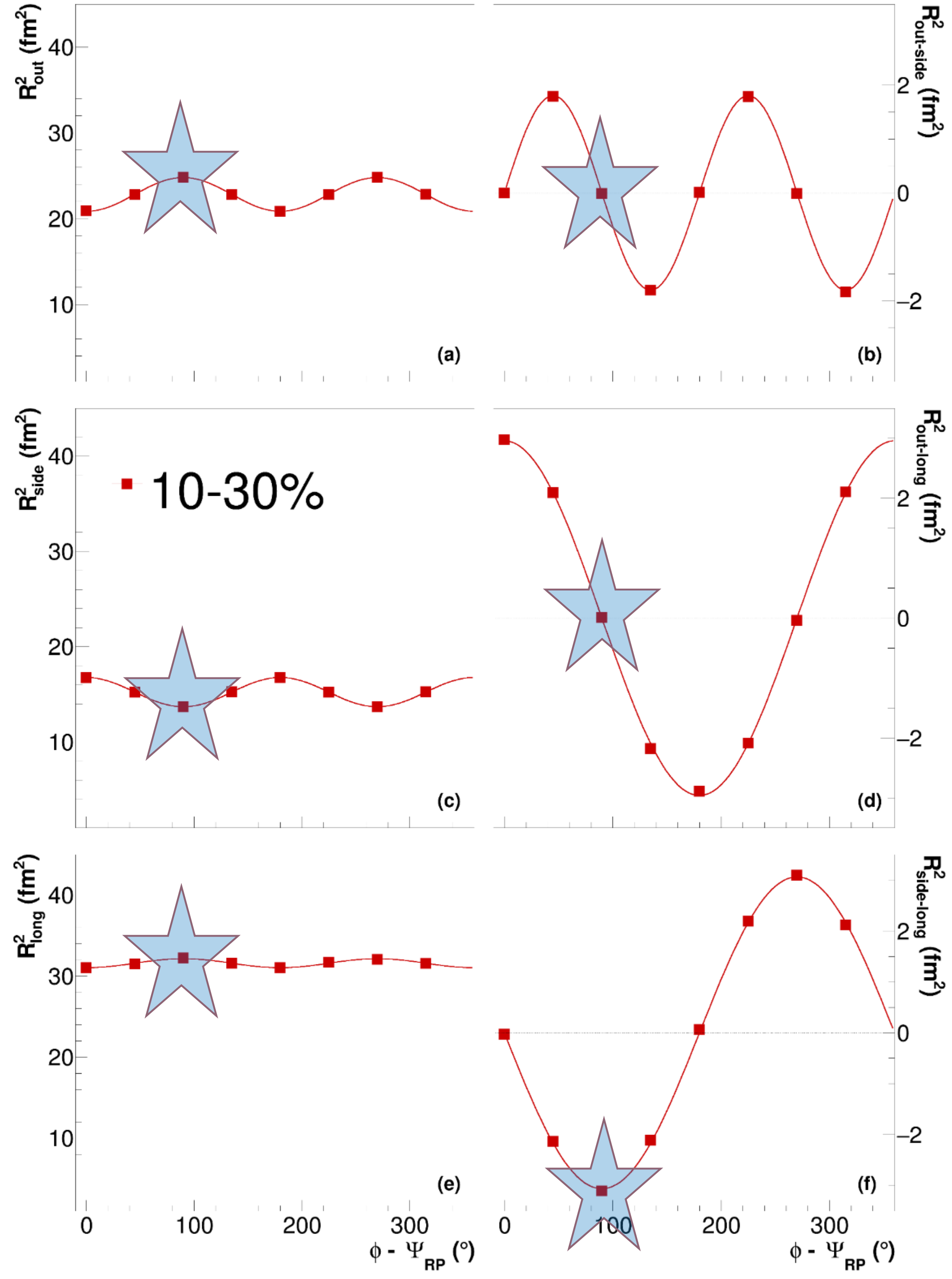
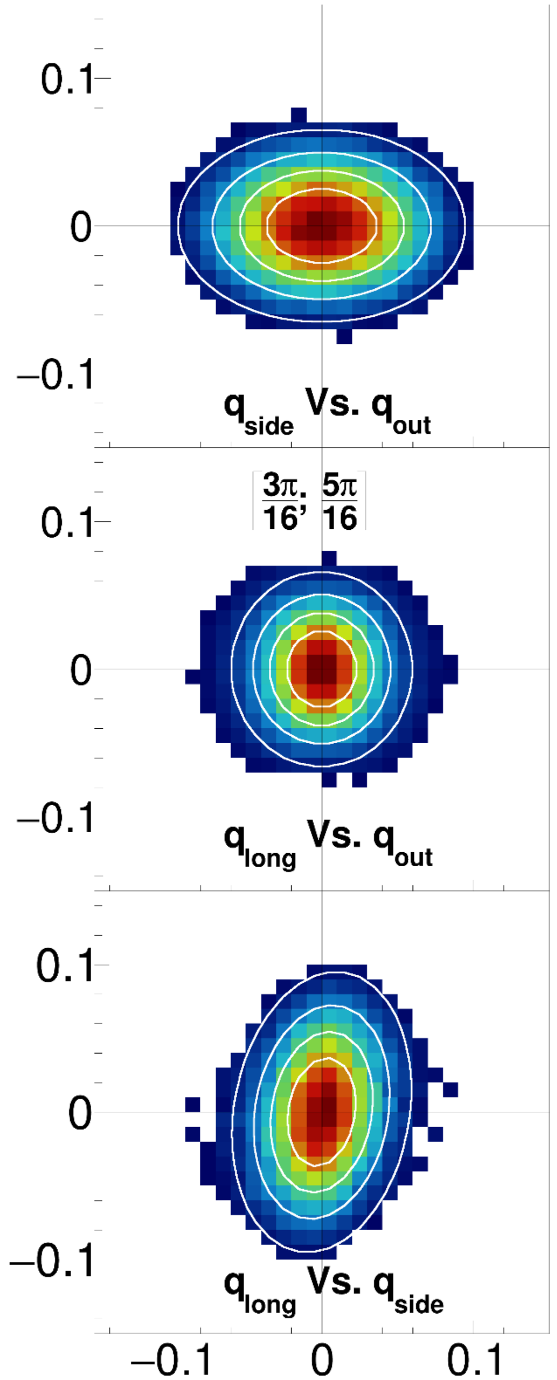
225°
315°
270°

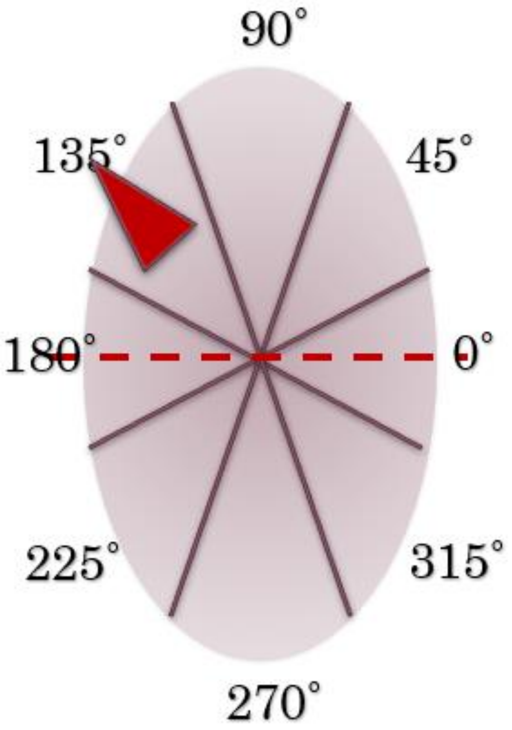

R²out (fm²)
R²out-side (fm²)
R²side (fm²)
R²out-long (fm²)
R²long (fm²)
R²side-long (fm²)
10-30%
(a)
(b)
(c)
(d)
(e)
(f)
φ - ΨRP (°)
0
100
200
300
10
20
30
40
2
0
−2


qside Vs. qout
qlong Vs. qout
qlong Vs. qside
[1π/16, 3π/16]
0.1
0
−0.1


90°
135°
45°
180°
0°
225°
315°
270°


R^2_{out} (fm^2)
$R^2_{out\text{-}side}$ (fm^2)
R^2_{side} (fm^2)
$R^2_{out\text{-}long}$ (fm^2)
R^2_{long} (fm^2)
$R^2_{side\text{-}long}$ (fm^2)
10-30%
(a)
(b)
(c)
(d)
(e)
(f)
$\phi - \Psi_{RP}$ (°)
$\phi - \Psi_{RP}$ (°)


q_{side} Vs. q_{out}
$\frac{3\pi}{16}, \frac{5\pi}{16}$
q_{long} Vs. q_{out}
q_{long} Vs. q_{side}


90°
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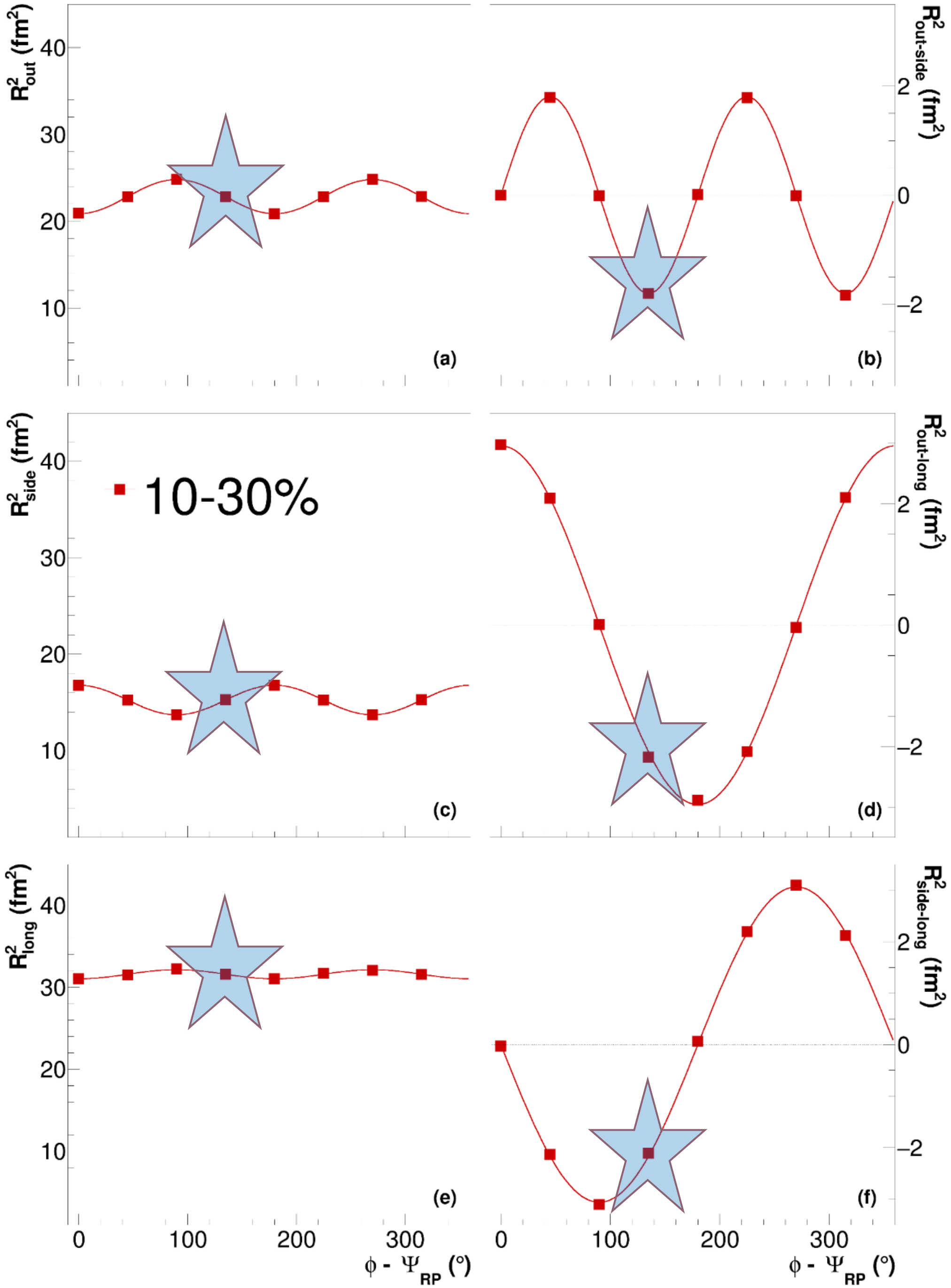
225°
315°
270°


R^2_{out} (fm^2)
$R^2_{out\text{-}side}$ (fm^2)
R^2_{side} (fm^2)
$R^2_{out\text{-}long}$ (fm^2)
R^2_{long} (fm^2)
$R^2_{side\text{-}long}$ (fm^2)
10-30%
(a)
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(c)
(d)
(e)
(f)
$\phi - \Psi_{RP}$ (°)
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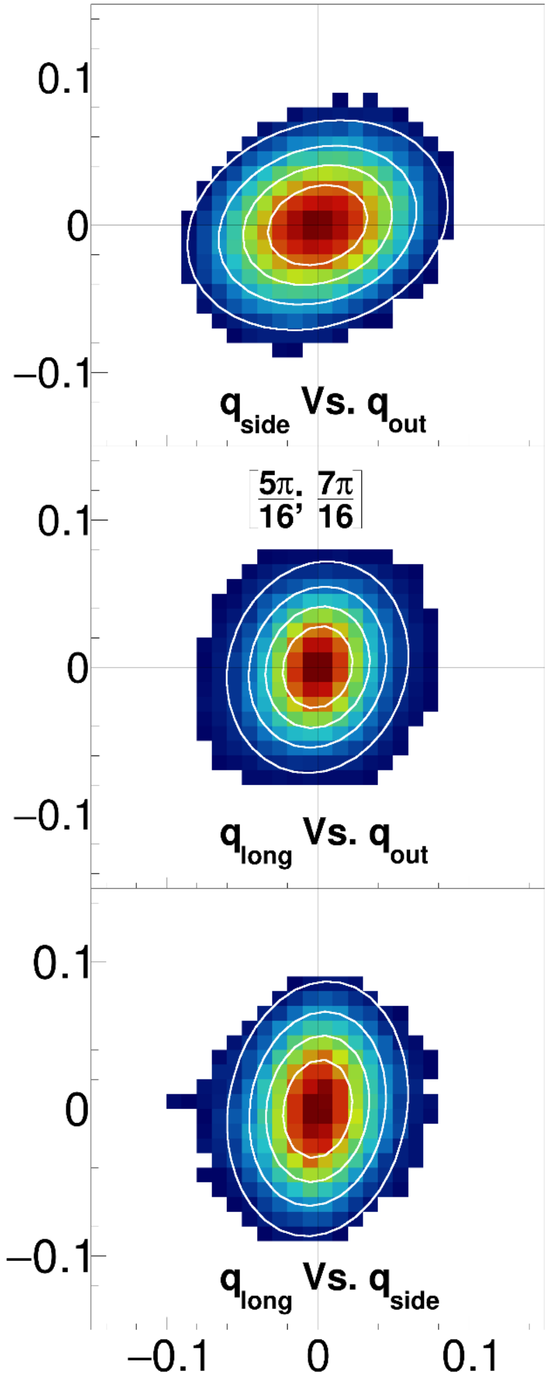
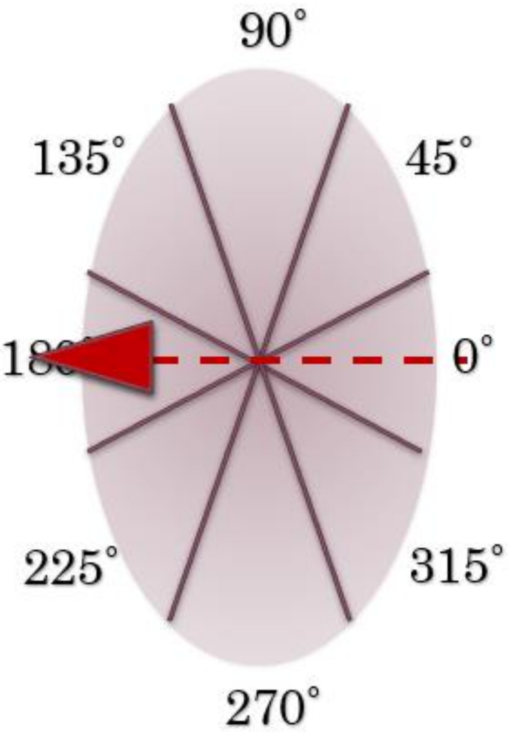
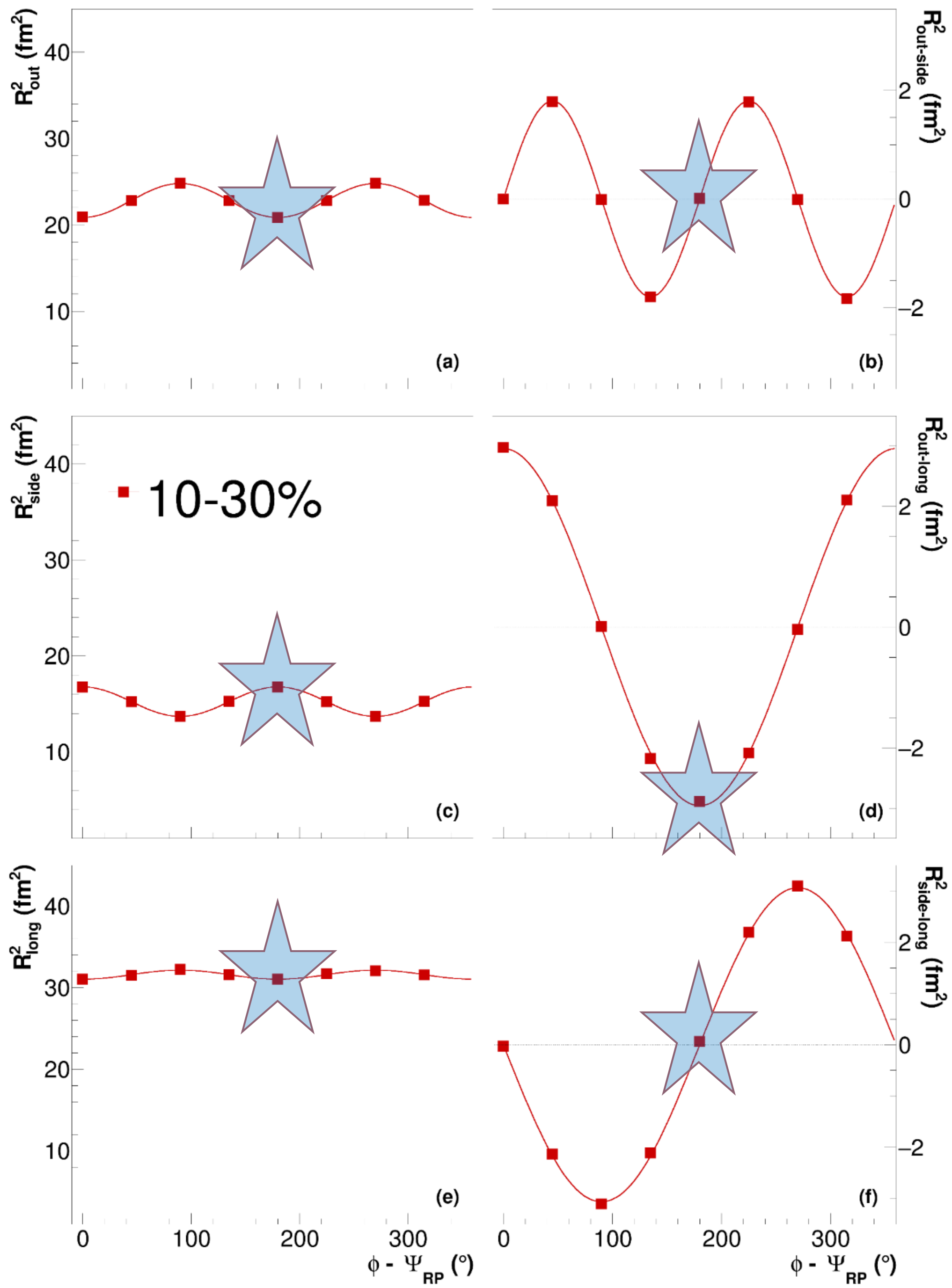
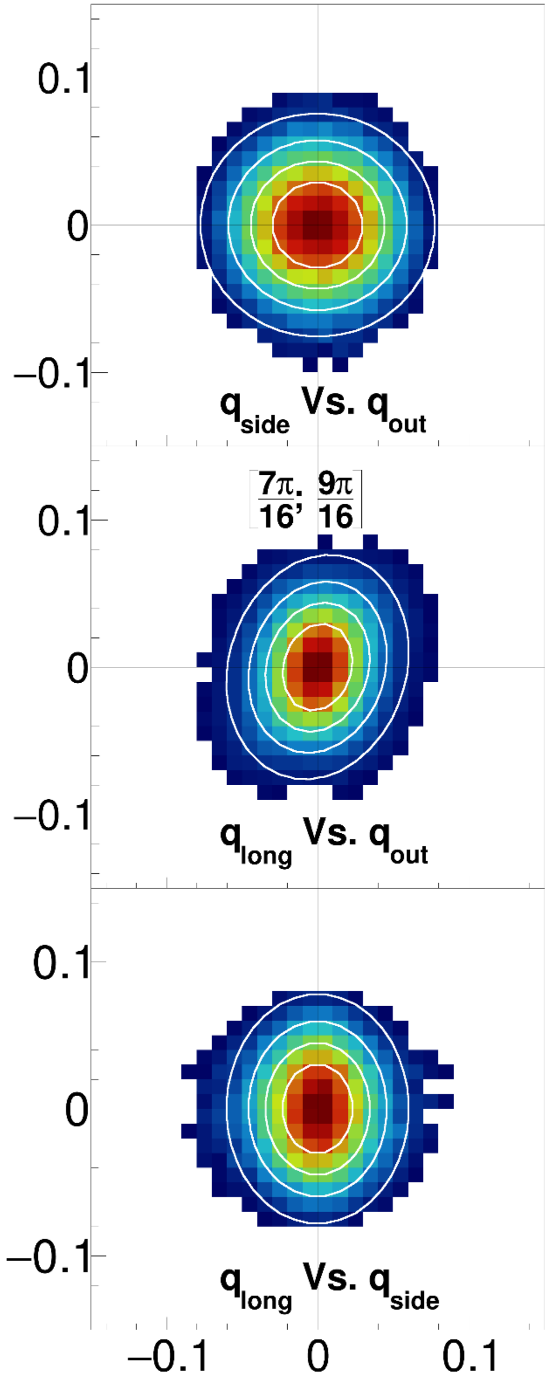
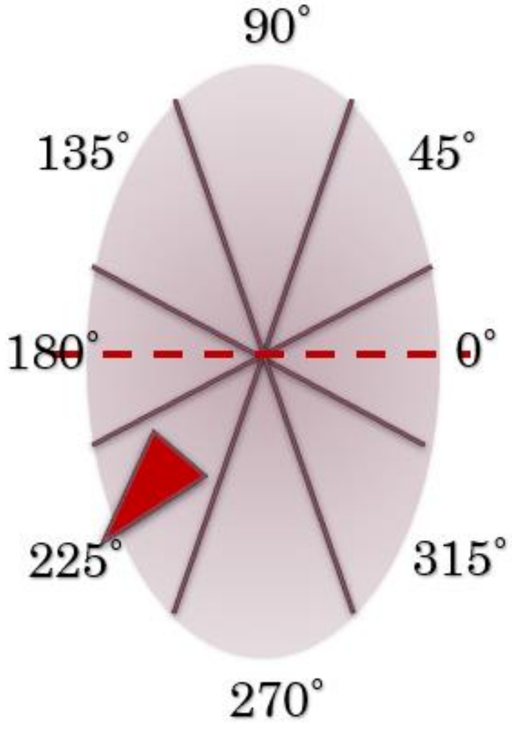

q_{side} Vs. q_{out}
$\left[\frac{5\pi}{16}, \frac{7\pi}{16}\right]$
q_{long} Vs. q_{out}
q_{long} Vs. q_{side}


90°
135°
45°
180°
0°
225°
315°
270°


R^2_{out} (fm^2)
$R^2_{out\text{-}side}$ (fm^2)
R^2_{side} (fm^2)
$R^2_{out\text{-}long}$ (fm^2)
R^2_{long} (fm^2)
$R^2_{side\text{-}long}$ (fm^2)
10-30%
(a)
(b)
(c)
(d)
(e)
(f)
$\phi - \Psi_{RP}$ (°)
$\phi - \Psi_{RP}$ (°)


q_{side} Vs. q_{out}
$\left[\frac{7\pi}{16}, \frac{9\pi}{16}\right]$
q_{long} Vs. q_{out}
q_{long} Vs. q_{side}


90°
135°
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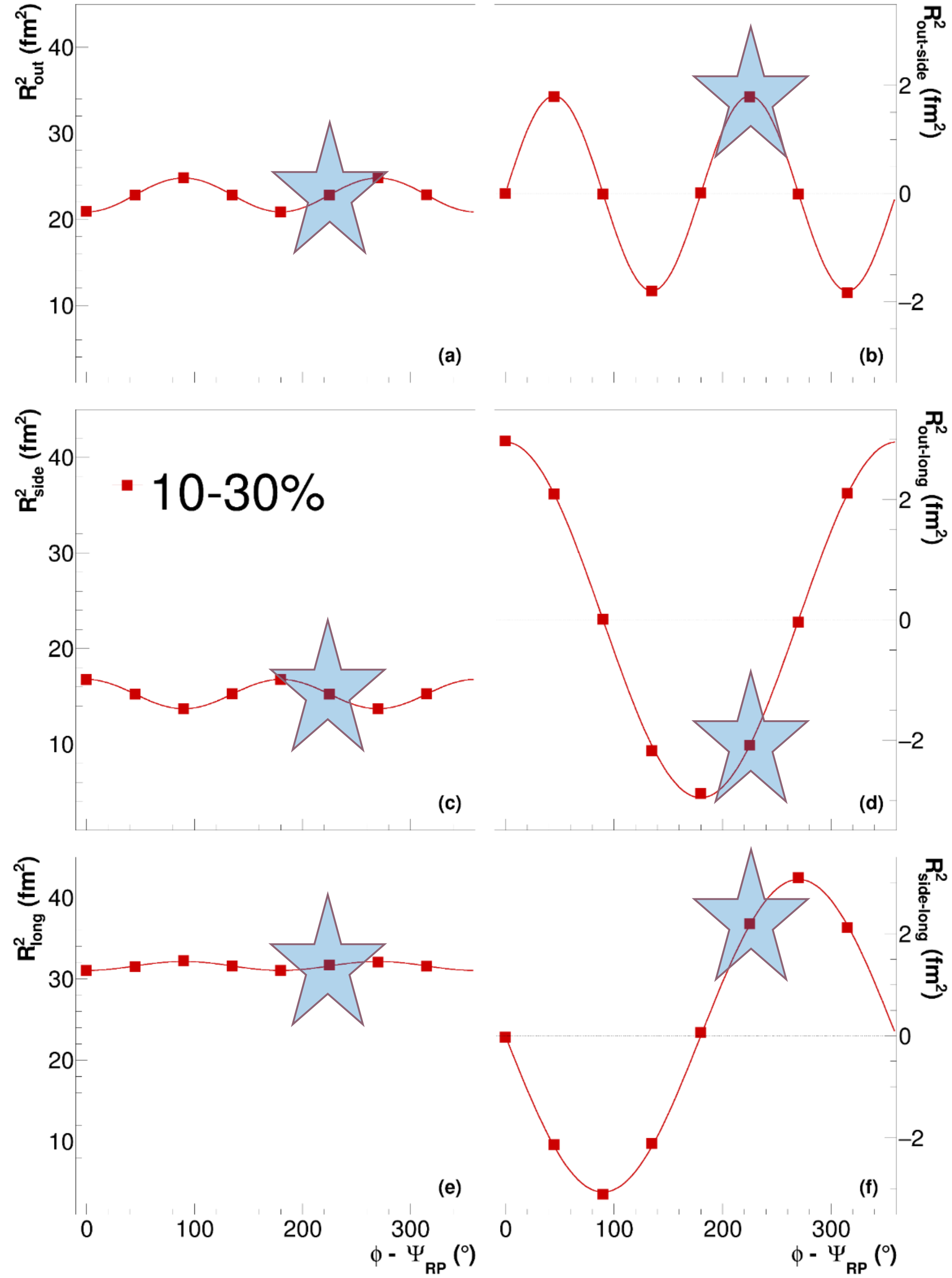
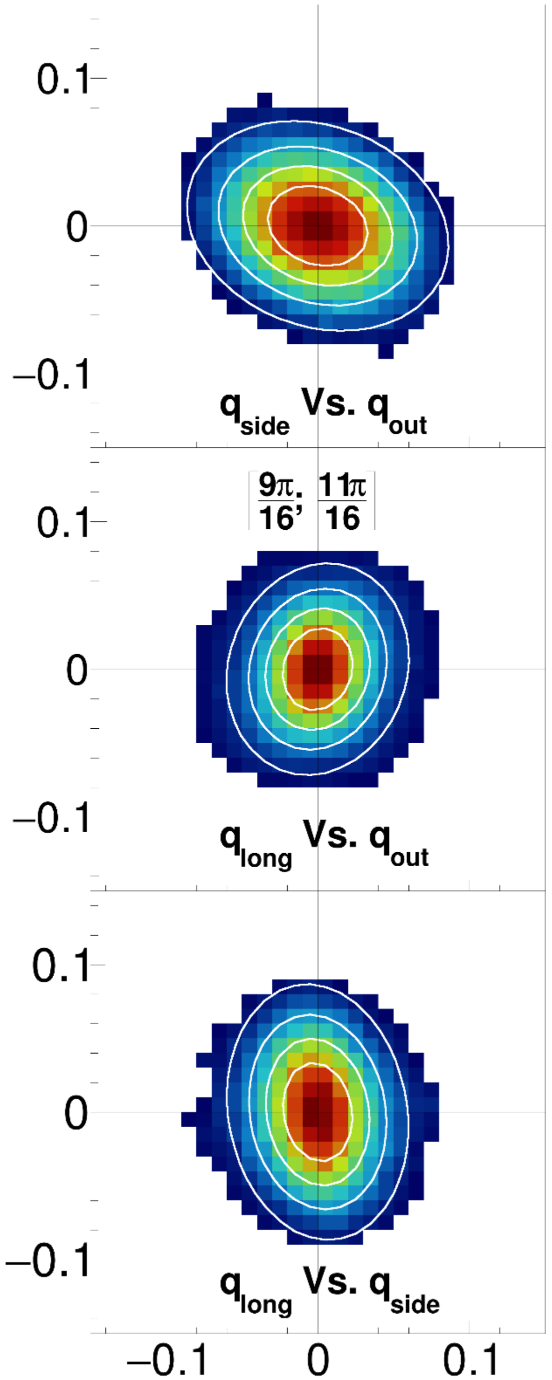
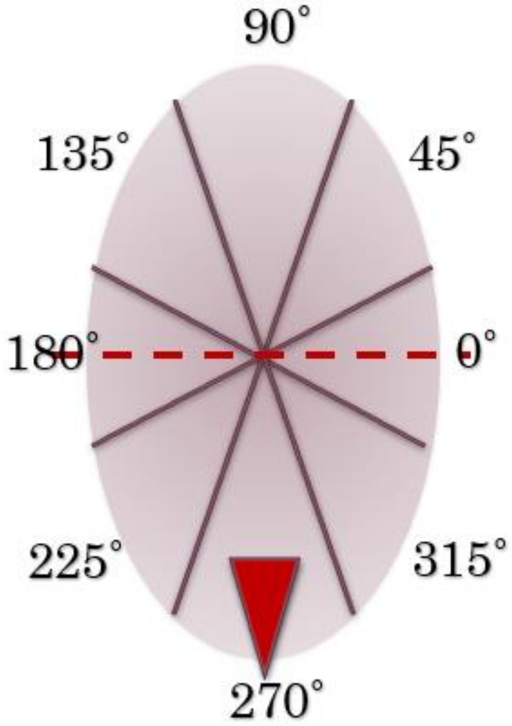

R^2_{out} (fm^2)
$R^2_{out-side}$ (fm^2)
R^2_{side} (fm^2)
$R^2_{out-long}$ (fm^2)
R^2_{long} (fm^2)
$R^2_{side-long}$ (fm^2)
10-30%
(a)
(b)
(c)
(d)
(e)
(f)
$\phi - \Psi_{RP}$ (°)
$\phi - \Psi_{RP}$ (°)


q_{side} Vs. q_{out}
$\left[\frac{9\pi}{16}, \frac{11\pi}{16}\right]$
q_{long} Vs. q_{out}
q_{long} Vs. q_{side}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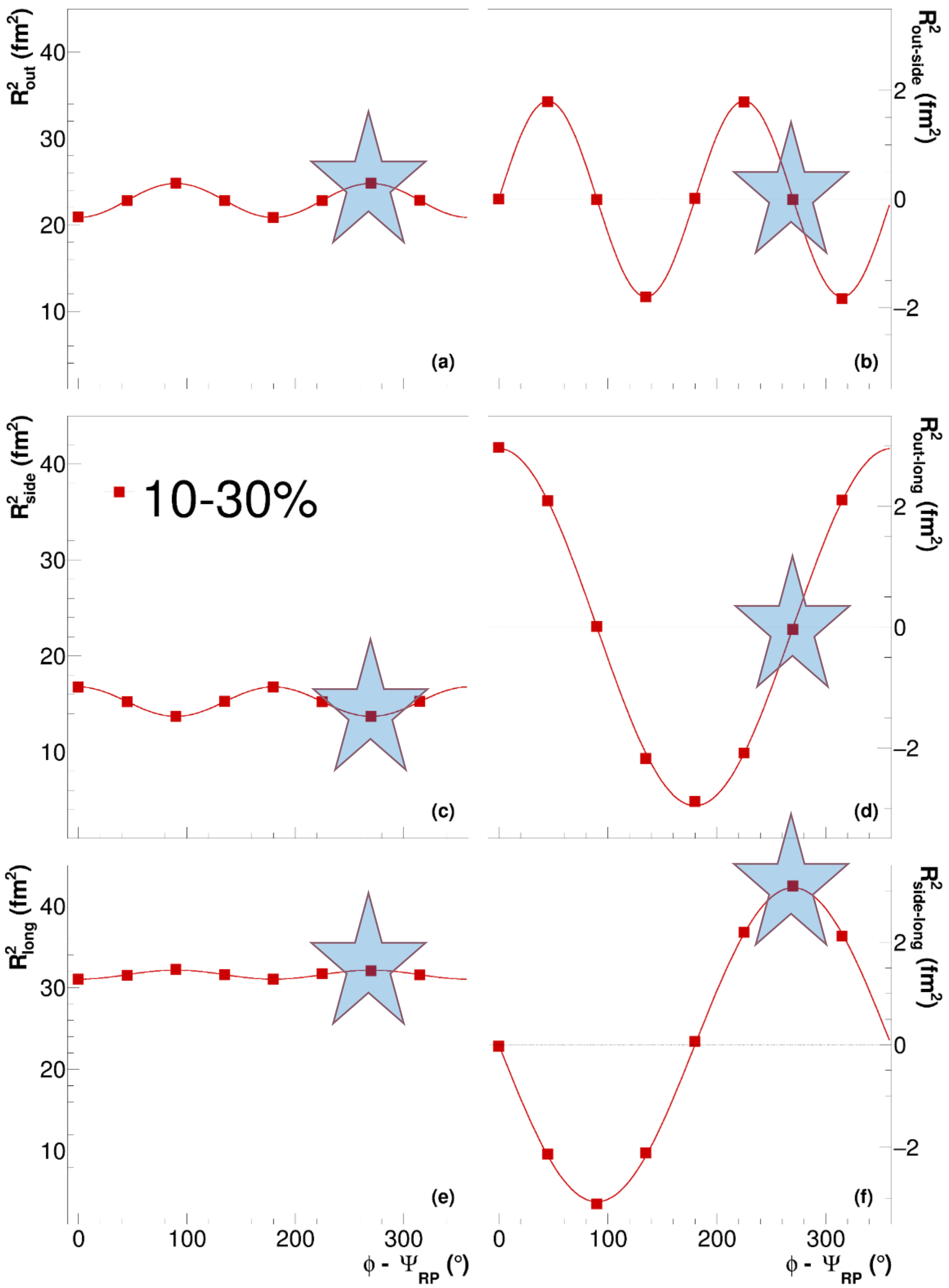
R^2_{out} (fm^2)
$R^2_{out\text{-}side}$ (fm^2)
R^2_{side} (fm^2)
$R^2_{out\text{-}long}$ (fm^2)
R^2_{long} (fm^2)
$R^2_{side\text{-}long}$ (fm^2)
10-30%
(a)
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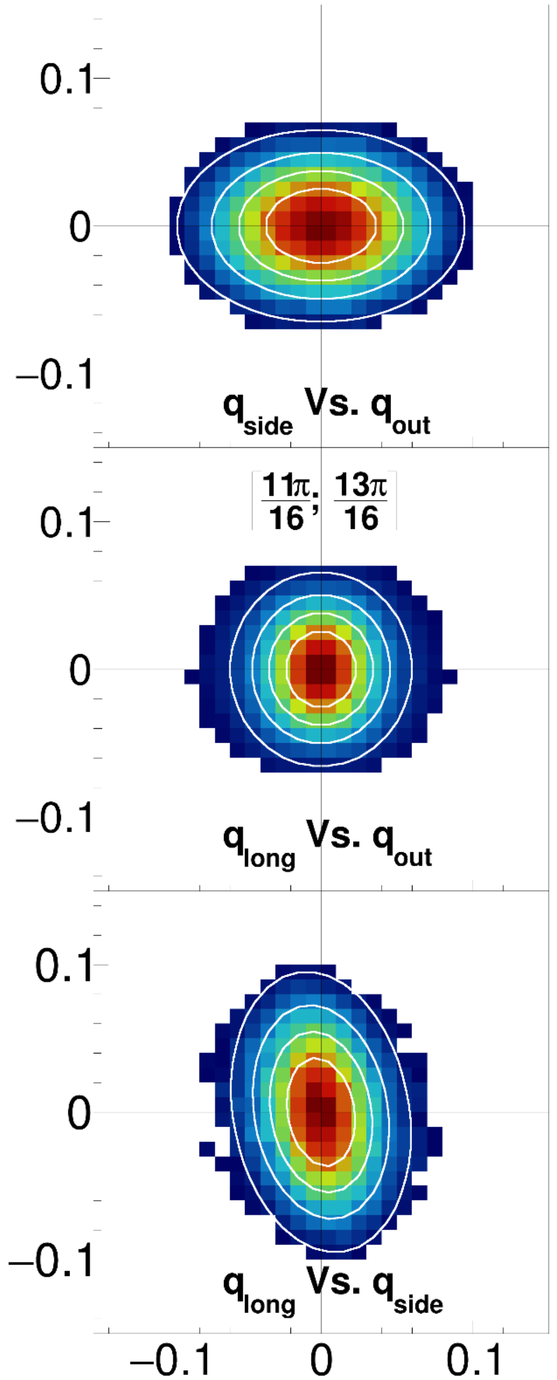
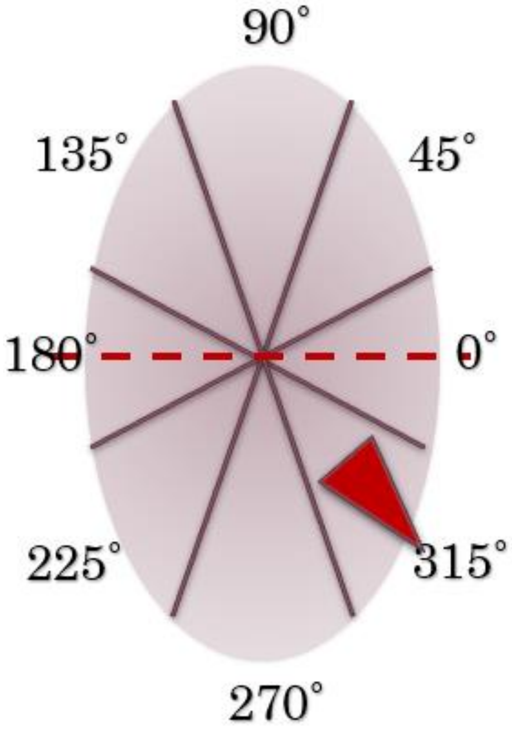
(f)
$\phi - \Psi_{RP}$ (°)
$\phi - \Psi_{RP}$ (°)


q_{side} Vs. q_{out}
$\left|\frac{11\pi}{16}, \frac{13\pi}{16}\right|$
q_{long} Vs. q_{out}
q_{long} Vs. q_{side}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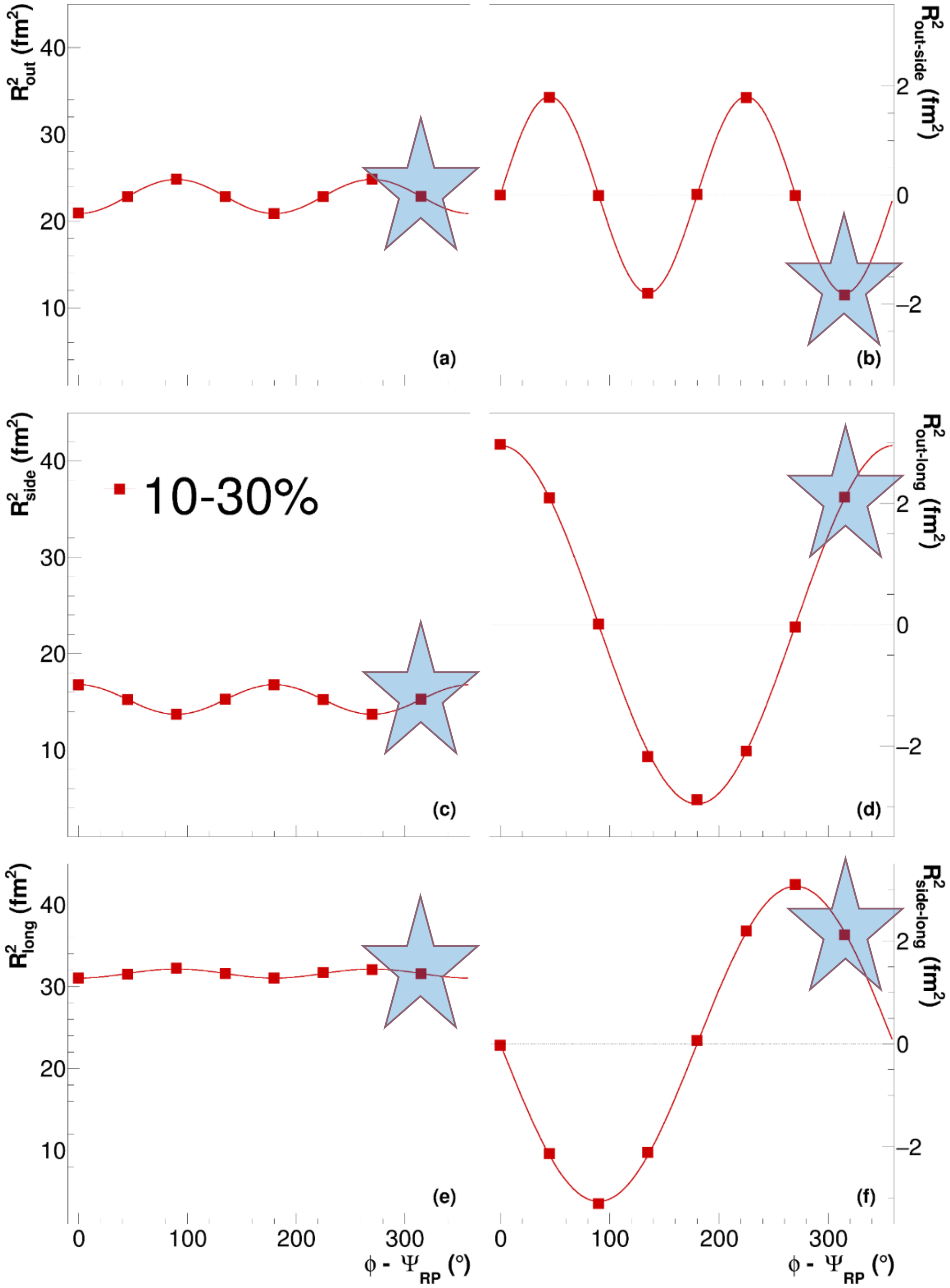
R^2_{out} (fm^2)
$R^2_{out\text{-}side}$ (fm^2)
R^2_{side} (fm^2)
$R^2_{out\text{-}long}$ (fm^2)
R^2_{long} (fm^2)
$R^2_{side\text{-}long}$ (fm^2)
10-30%
(a)
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(f)
$\phi - \Psi_{RP}$ (°)
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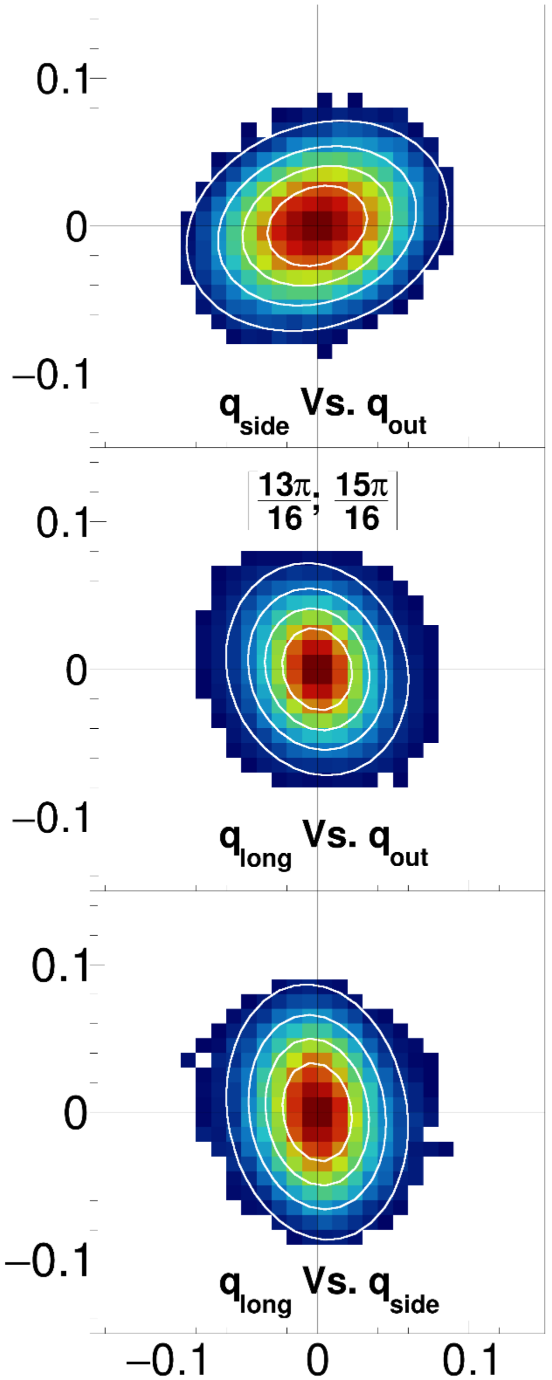
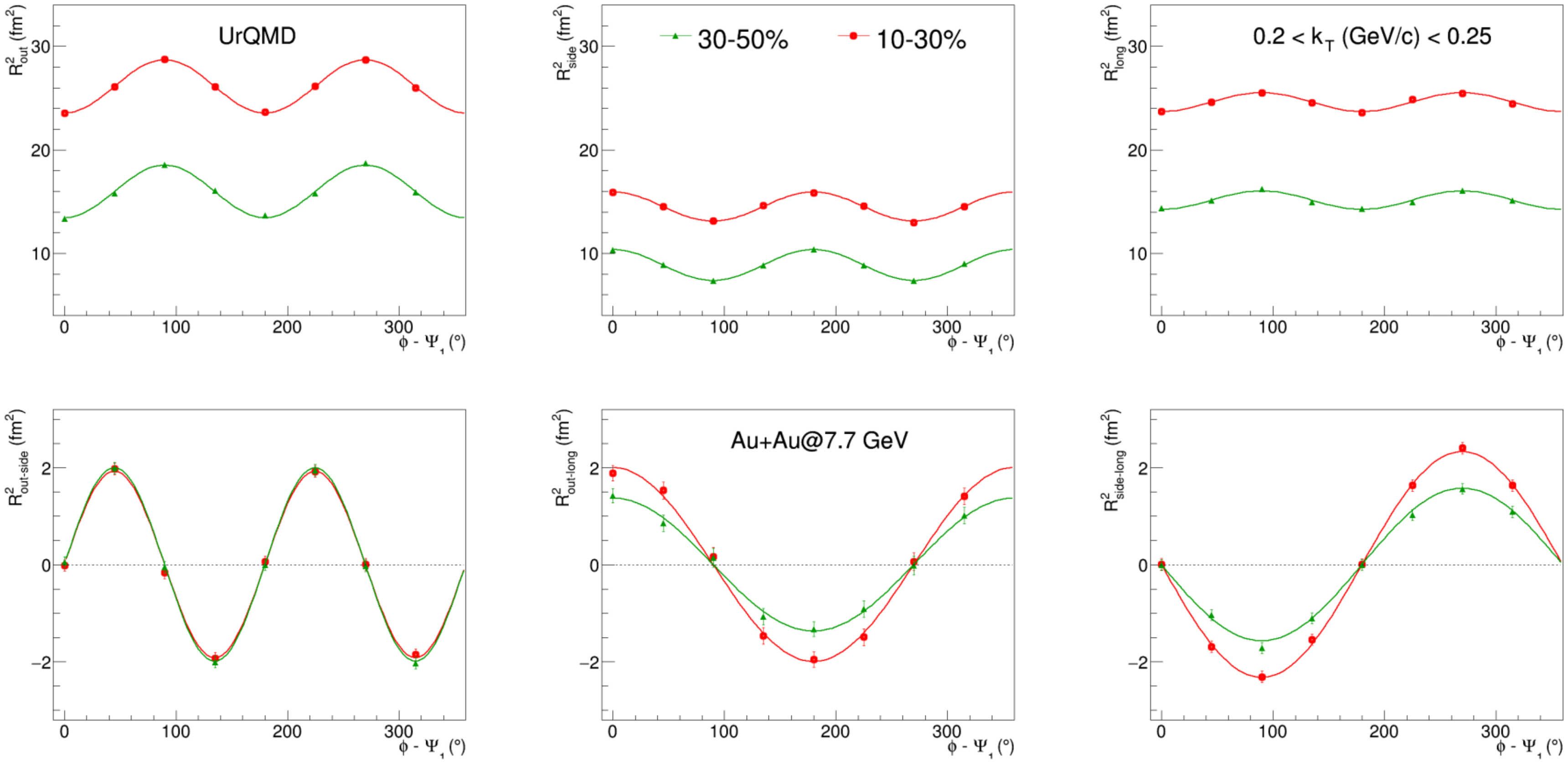
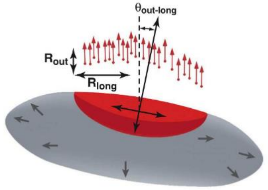

q_{side} Vs. q_{out}
$\left[\frac{13\pi}{16}, \frac{15\pi}{16}\right]$
q_{long} Vs. q_{out}
q_{long} Vs. q_{side}

Radii oscillations example in UrQMD

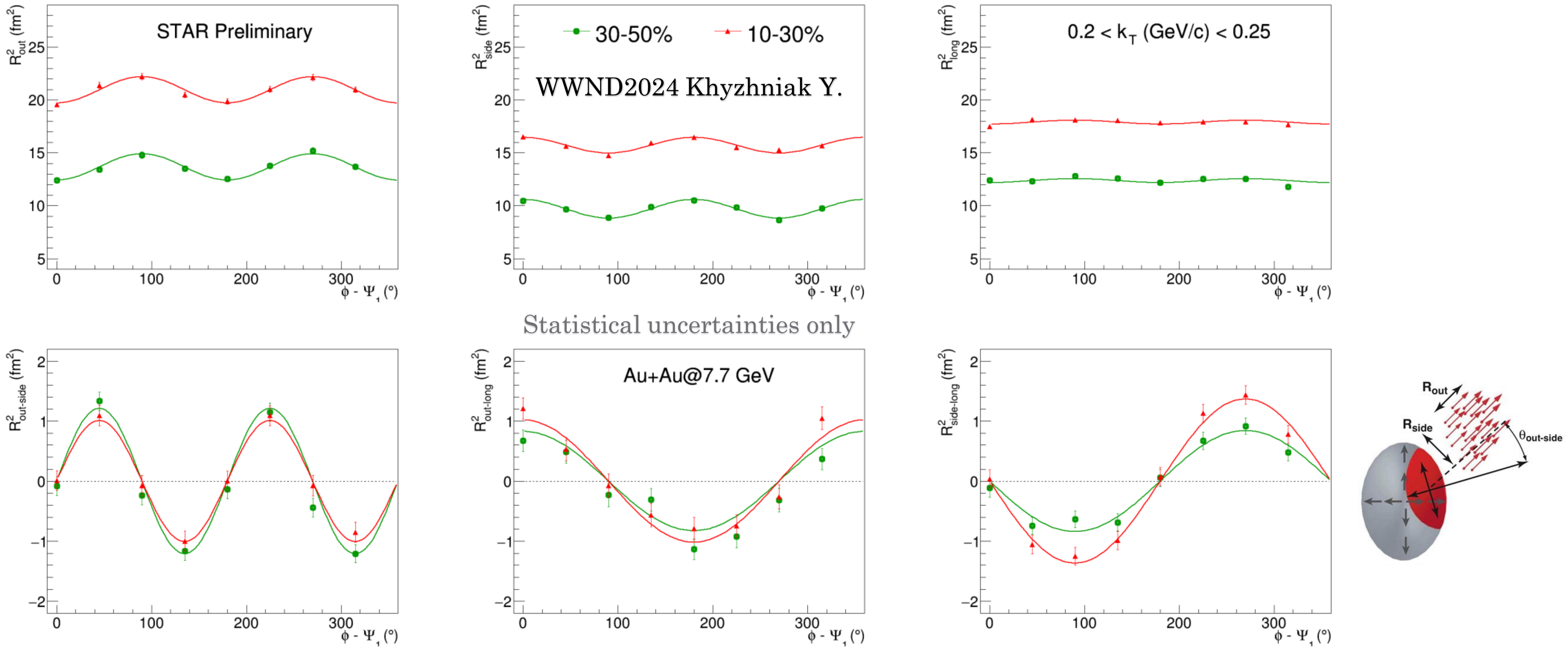




Ann.Rev.Nucl.Part. Sci. 55 (2005) 357-402

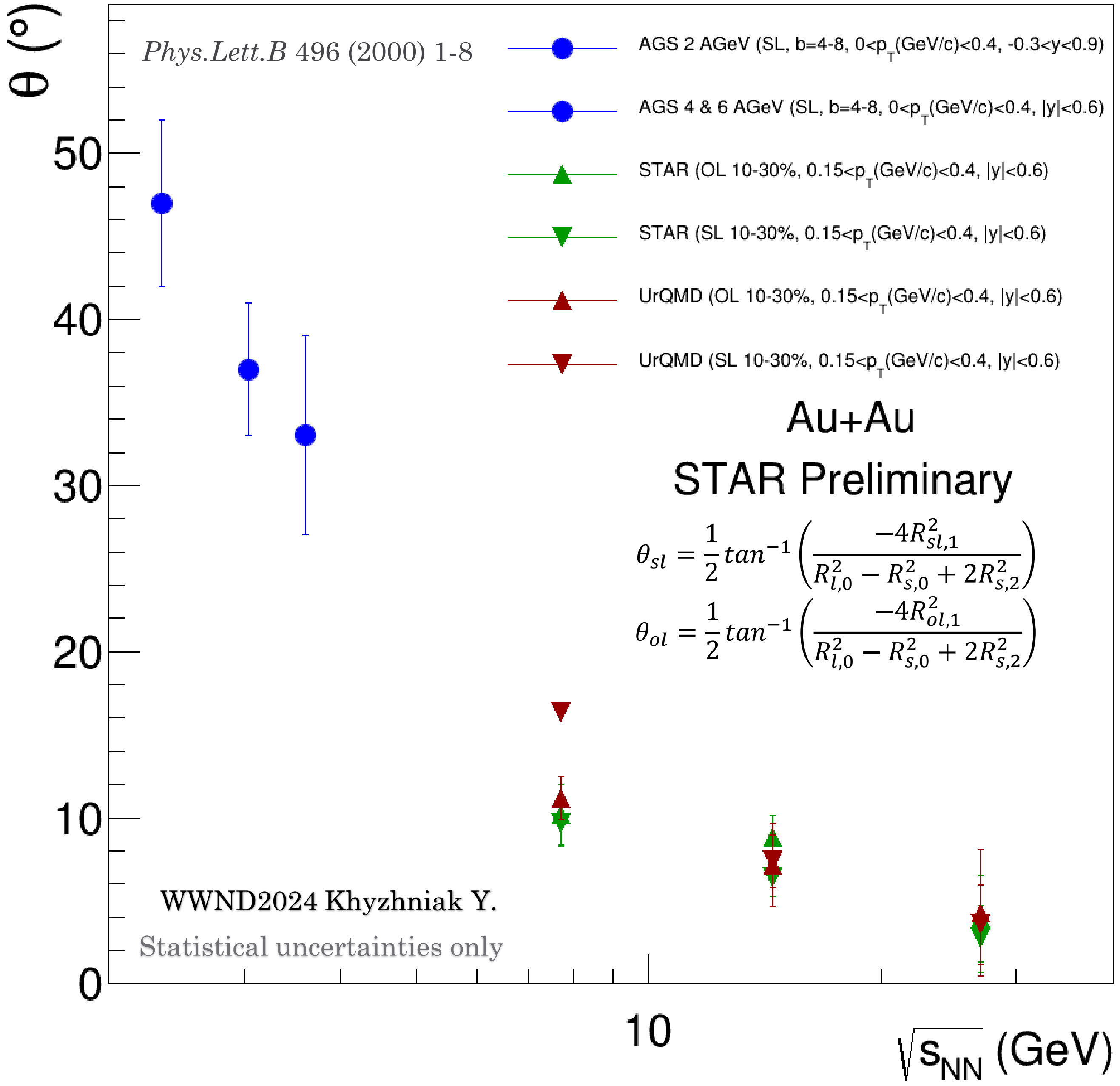
- R_o^2 and R_s^2 exhibit significant, equal and opposite oscillations in φ, reflecting an almond-shaped overlap region between the target and projectile spheres
- R_{ol}^2 and R_{sl}^2 exhibit oscillations of equal magnitude, aligning with the emission of pions from an ellipsoidal source tilted in coordinate space away from the beam axis

Radii oscillations example in experiment

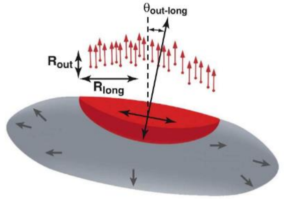


- R_o^2 and R_s^2 exhibit significant, equal and opposite oscillations in φ, reflecting an almond-shaped overlap region between the target and projectile spheres
- R_{ol}^2 and R_{sl}^2 exhibit oscillations of equal magnitude, aligning with the emission of pions from an ellipsoidal source tilted in coordinate space away from the beam axis

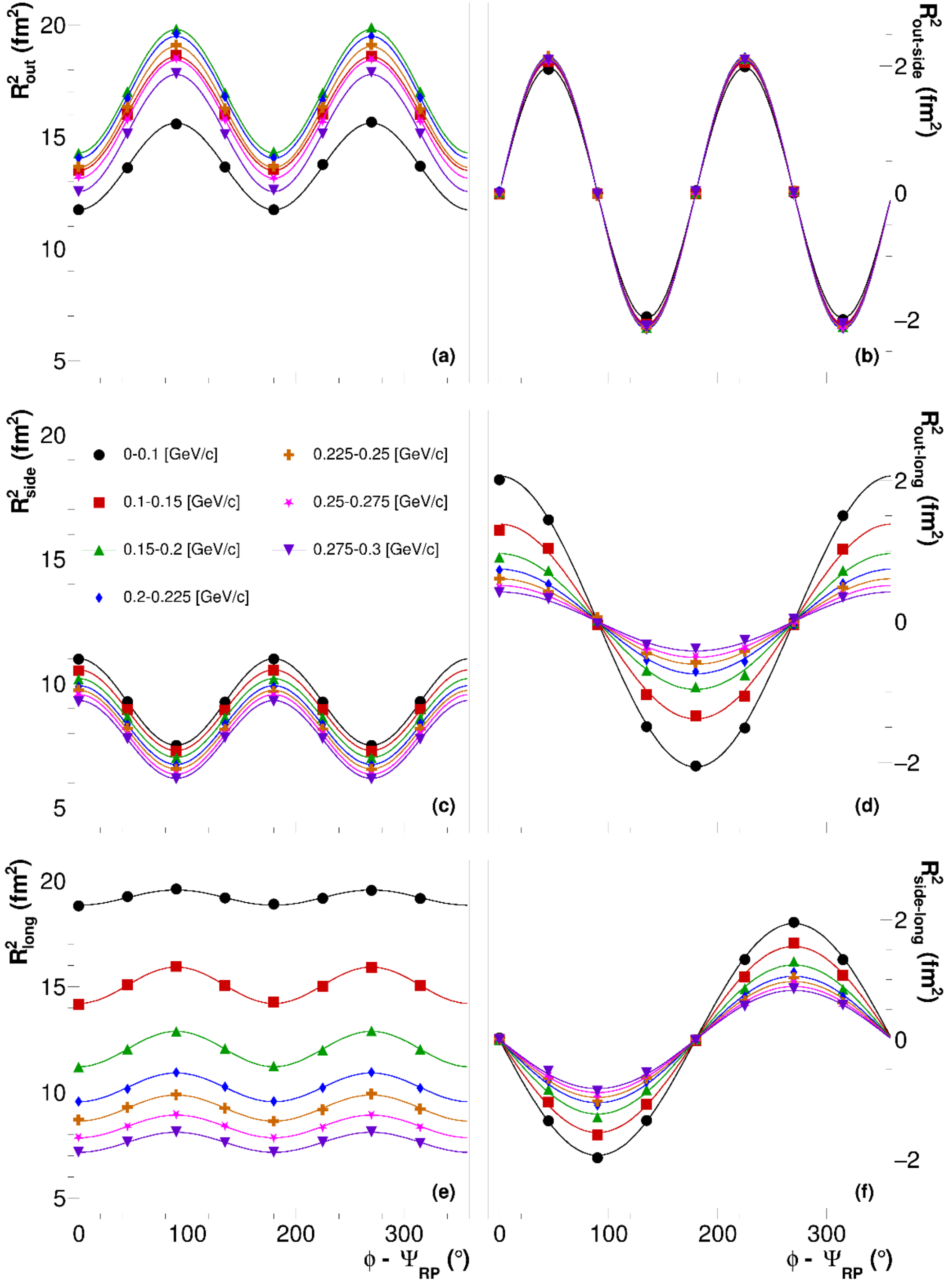
Energy dependence of the tilt



- In trend with AGS data
- Drops with energy, consistent with the expectation that collisions become increasingly boost invariant
- Good agreement with UrQMD 3.4 (“cascade” mode)
- Slight difference between θ_{SL} and θ_{OL} tilts

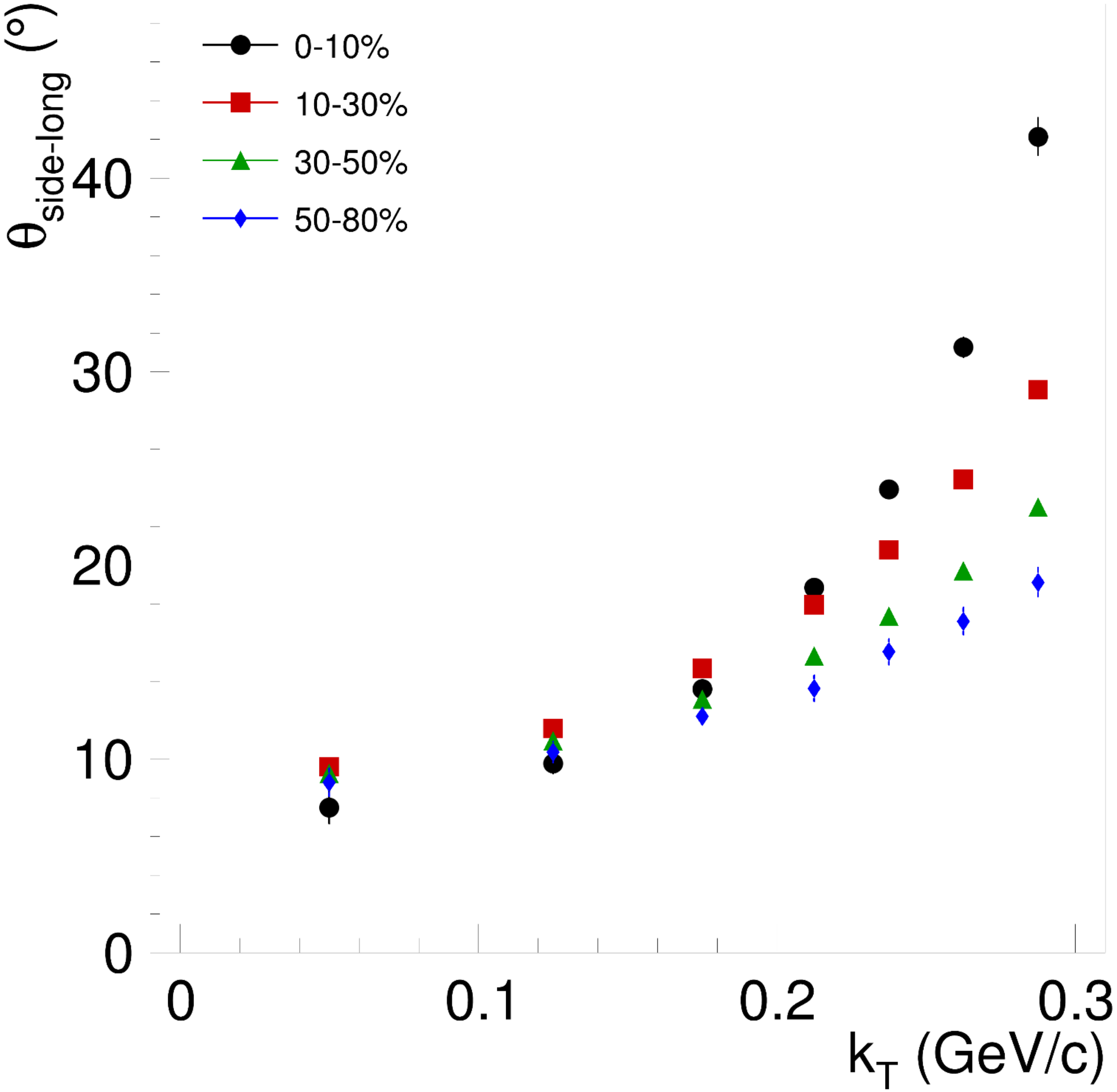


Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402



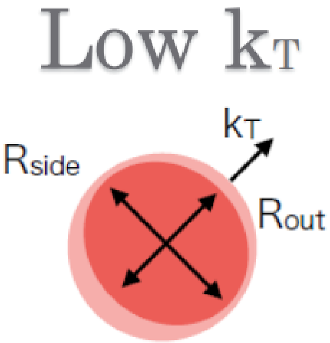
k_T dependence of the tilt

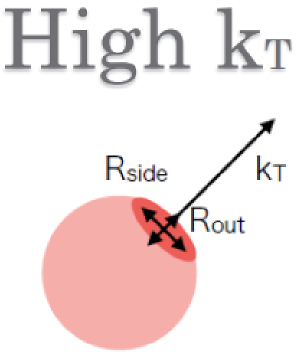
- Radii dependence on azimuthal angle for different k_T
- Suggests that there is dependence of the tilt on the k_T



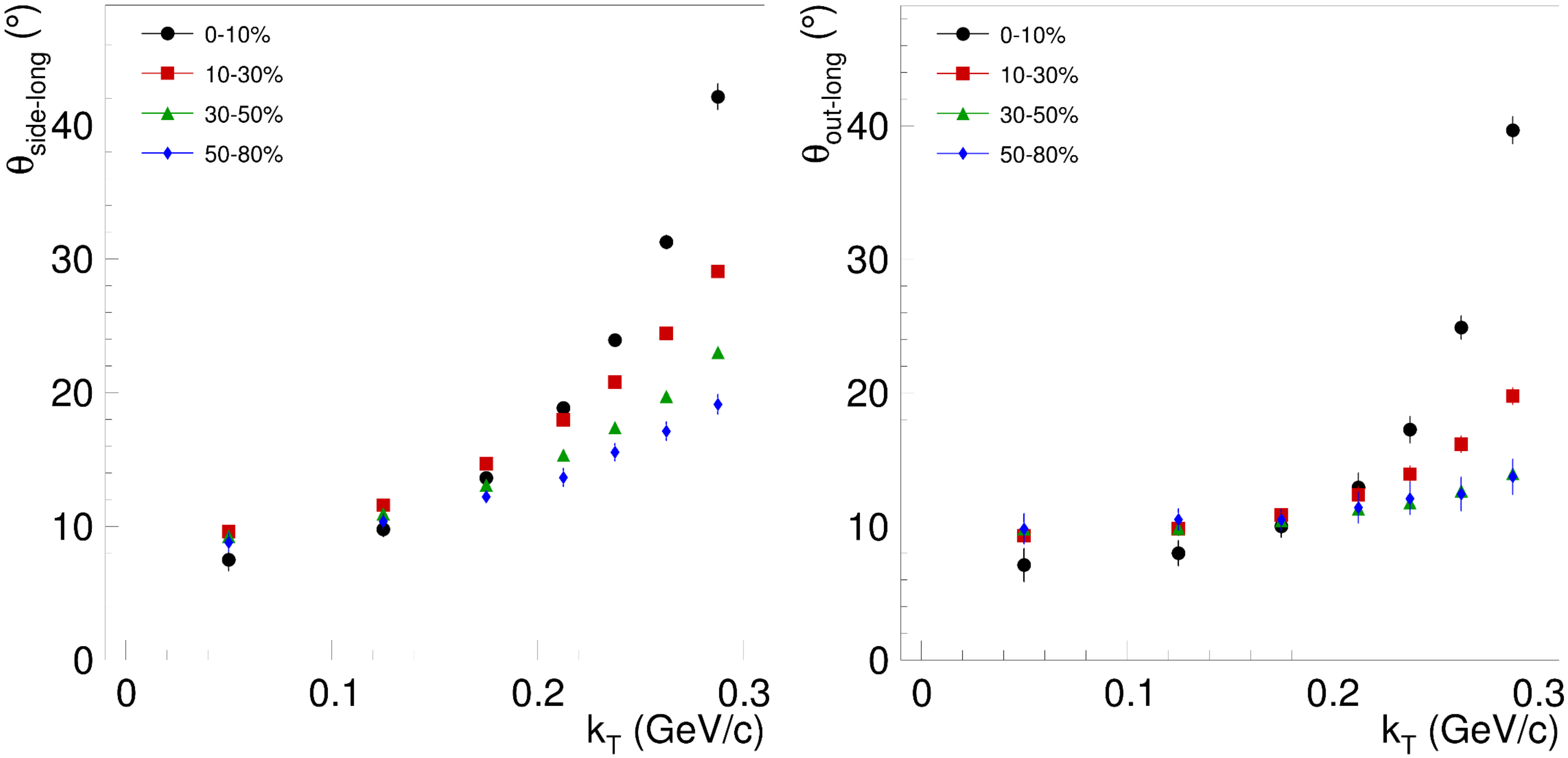
k_T dependence of the tilt

- Larger k_T pairs are emitted from smaller emission regions at earlier times with less correspondence to the size and shape of the entire fireball



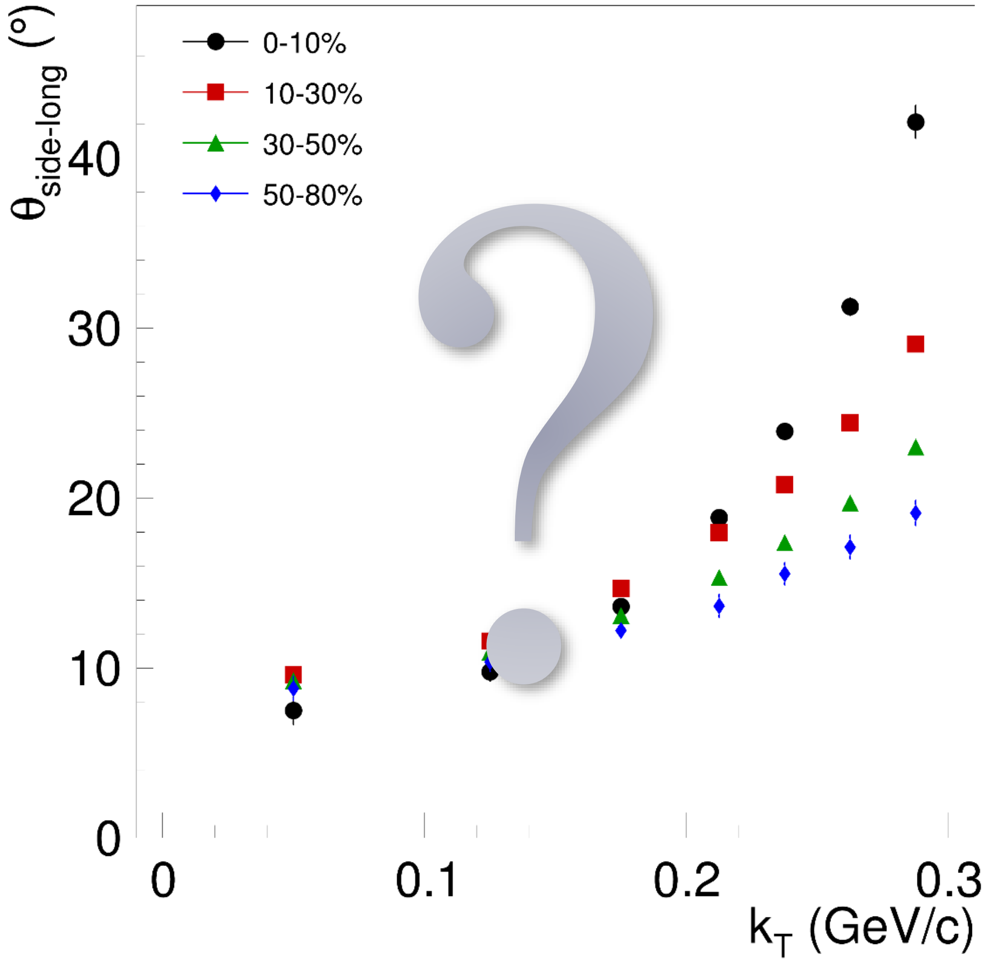


k_T dependence of the tilt in the experiment and UrQMD

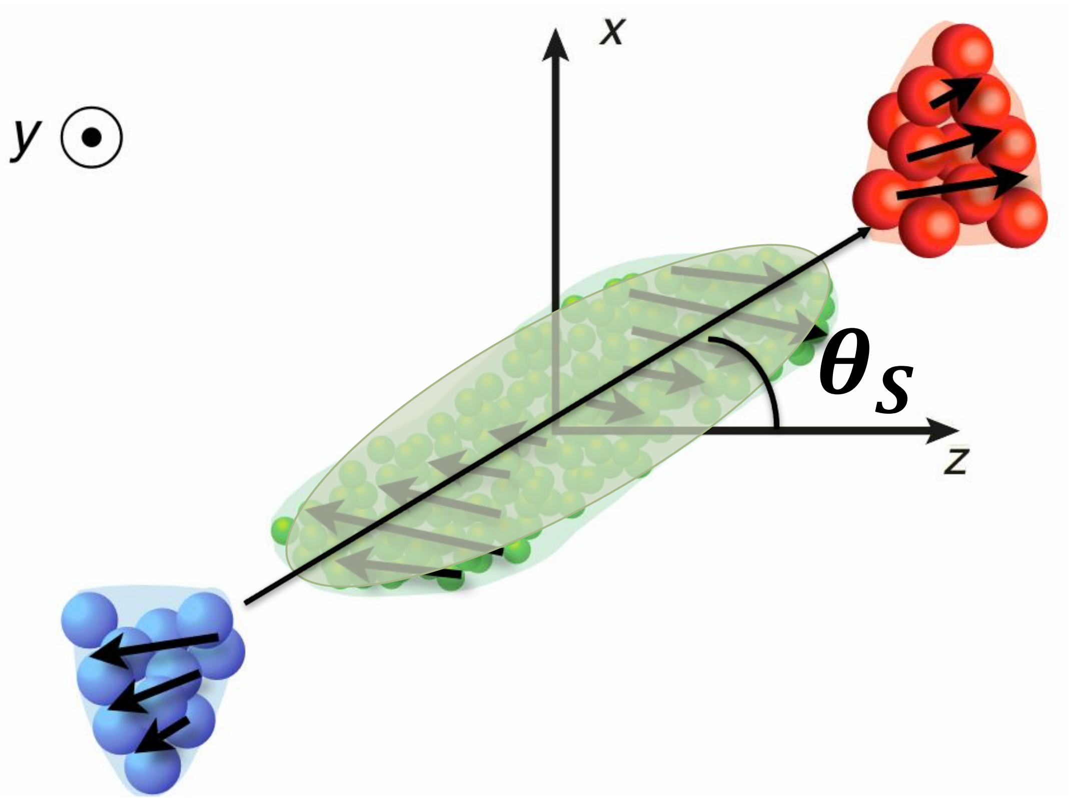


- Discrepancy between “out-long” and “side-long” tilt in UrQMD might be attributed to model limitations to describe system evolution
  - “side” radius reflects the spatial extent of the pion-emitting source, while “out” combines both spatial extent and the emission duration of the fireball

What is the correspondence of the femtoscopy tilt and tilt of the freeze-out distribution?



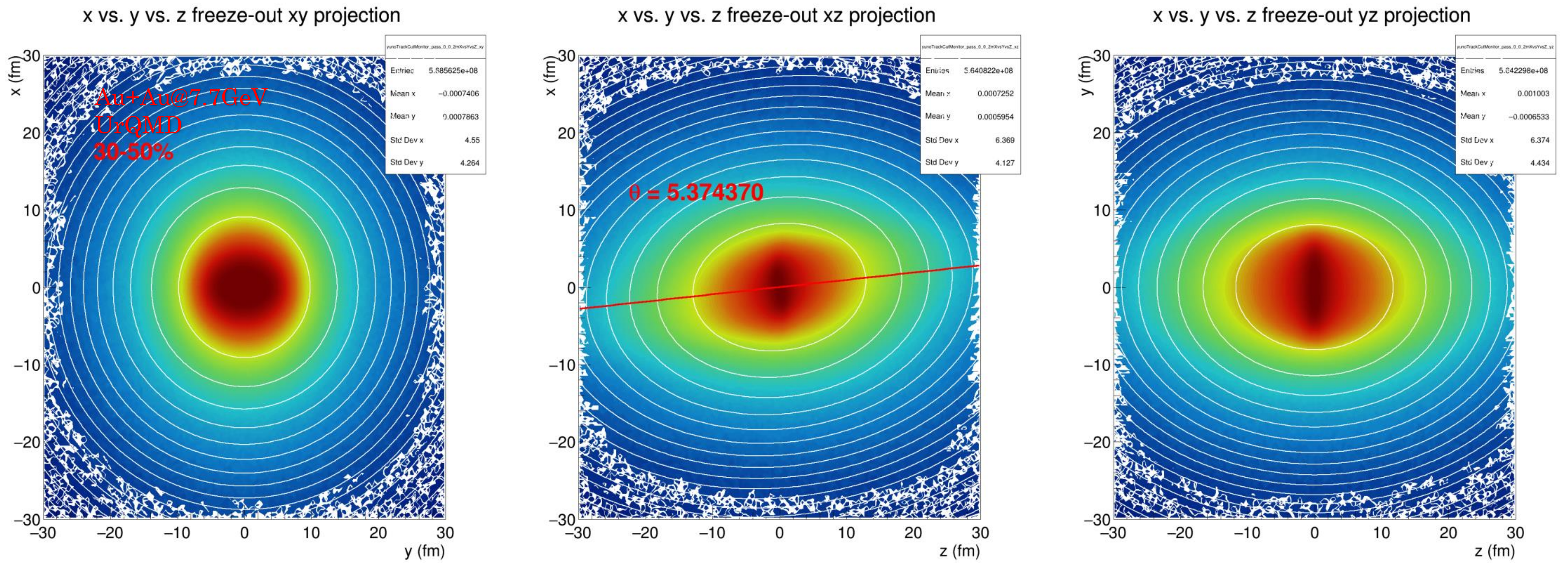
The simplistic model with unique spatial tilt



arXiv:2410.15134
Phys.Rev.C 84 (2011) 014908
Phys.Rev.C 89 (2014) 1, 014903

$$f(x,y,z) \sim \exp\left(-\frac{(x\cos\theta_S - z\sin\theta_S)^2}{2\sigma_{x'}^2} - \frac{y^2}{2\sigma_y^2} - \frac{(x\sin\theta_S + z\cos\theta_S)^2}{2\sigma_{z'}^2}\right)$$

Freeze-out coordinates in UrQMD



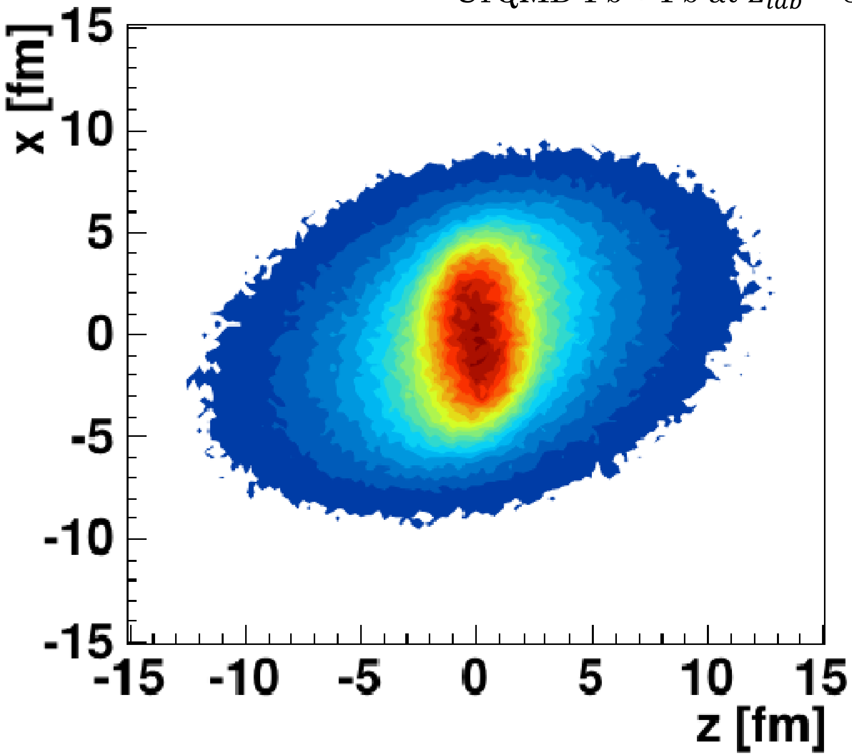
$$f(x,y,z) \sim \exp\left(-\frac{(x\cos\theta_S - z\sin\theta_S)^2}{2\sigma_{x'}^2} - \frac{y^2}{2\sigma_y^2} - \frac{(x\sin\theta_S + z\cos\theta_S)^2}{2\sigma_{z'}^2}\right)$$

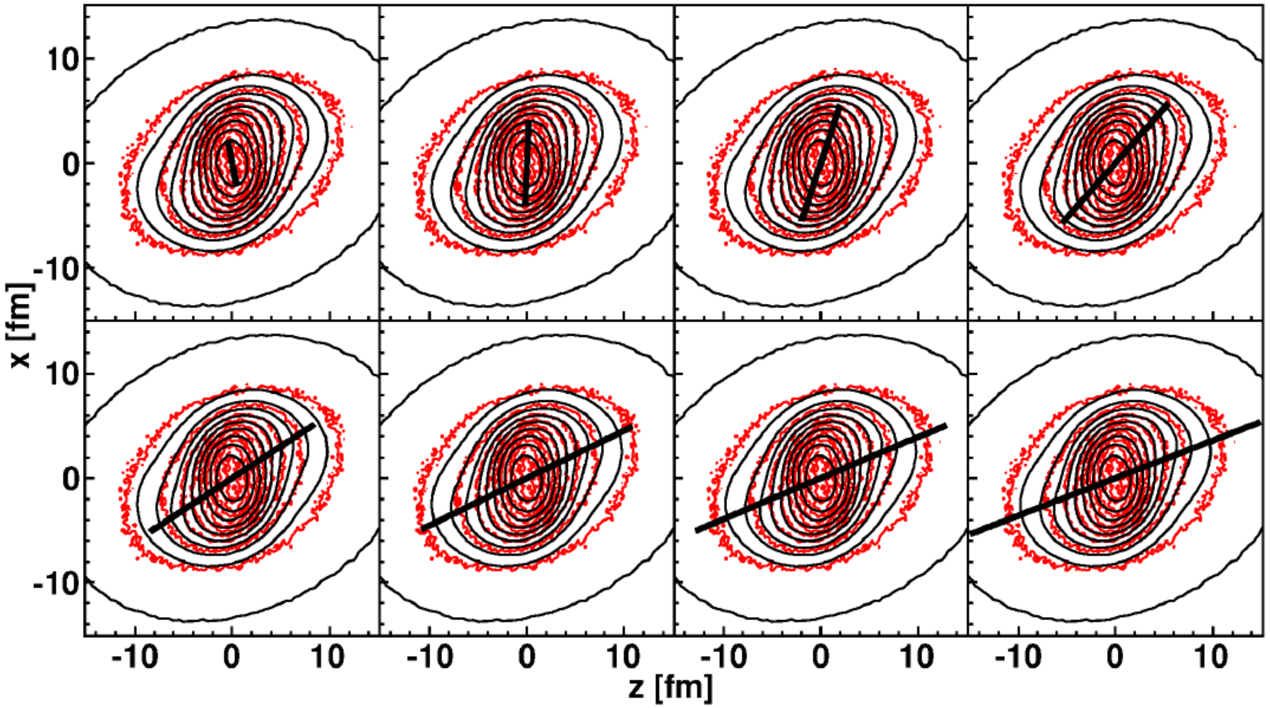
- Realistic picture is more complicated than just tilted ellipsoid

Complicated structure of the freeze-out distribution

Phys.Rev.C 84 (2011) 014908
Phys.Rev.C 89 (2014) 1, 014903

UrQMD Pb + Pb at E_{lab} = 8 GeV, b = 3.4–6.8 fm, |y| < 0.5, and $p_\perp$ < 0.4 GeV



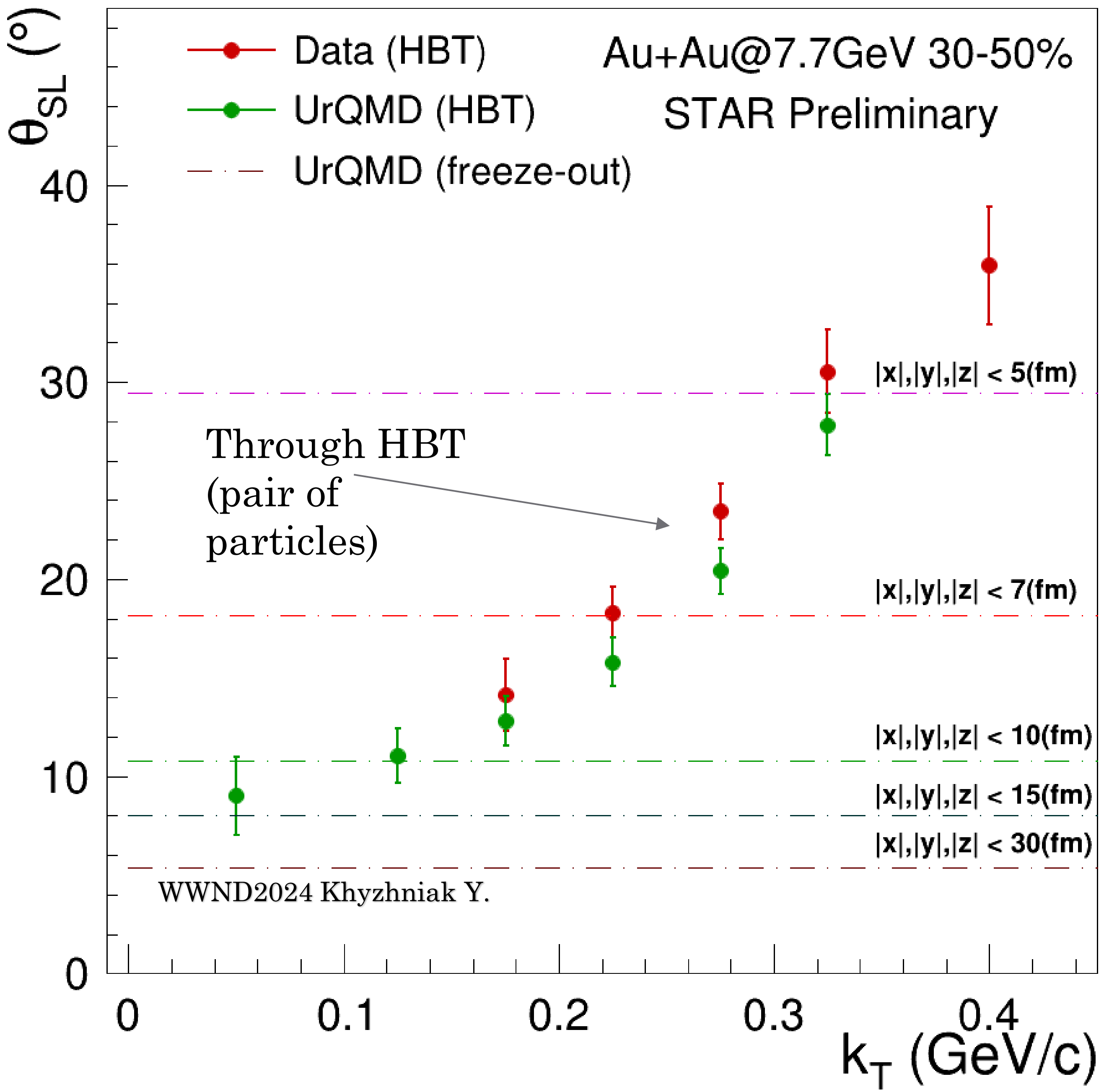


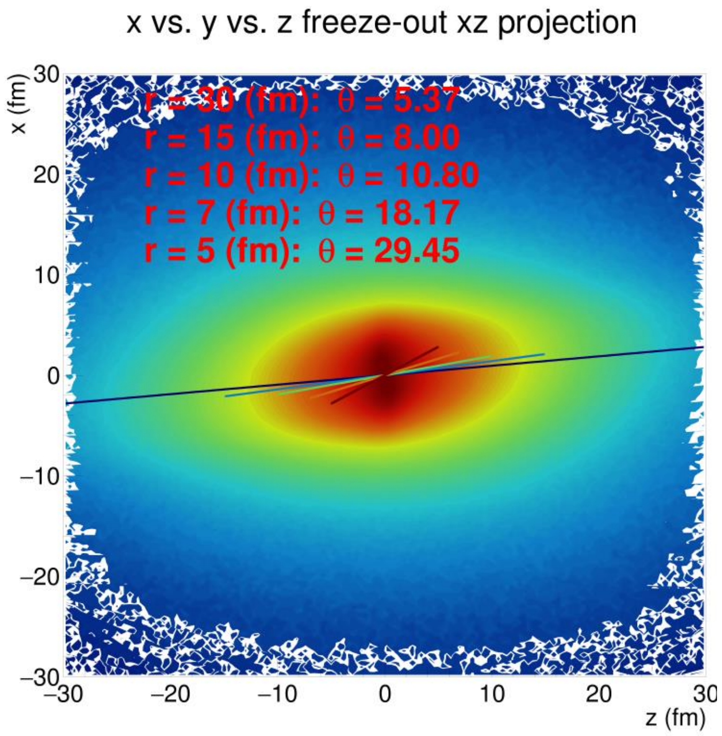
- Realistic picture reveals complex geometry and affected by non-Gaussianity of the source, collective flow…

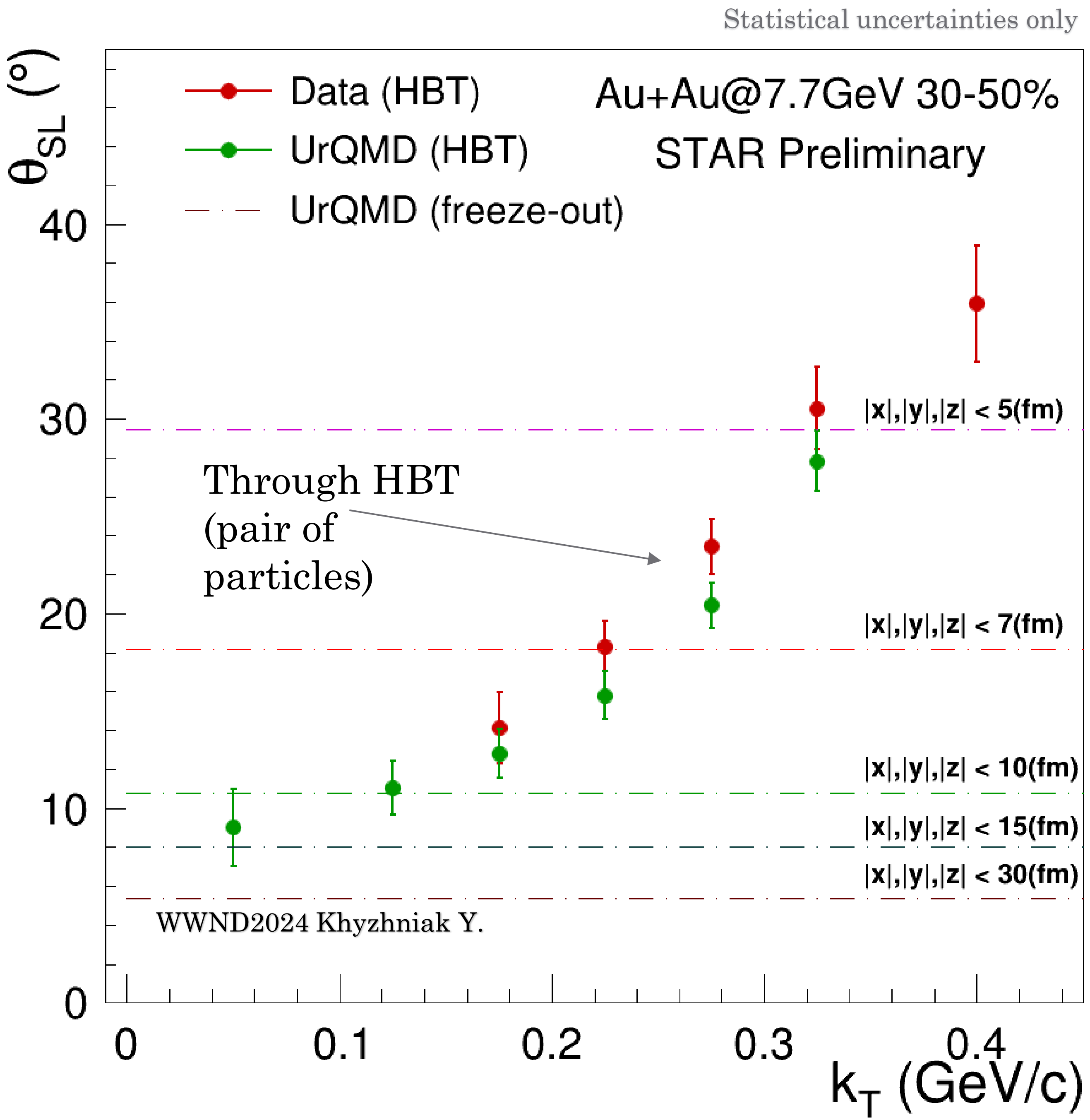
- Extracted tilt strongly depends on the fit range in $\vec{r}$ $[fm]$

Correspondence between femtoscopy tilt and freeze-out distribution tilt

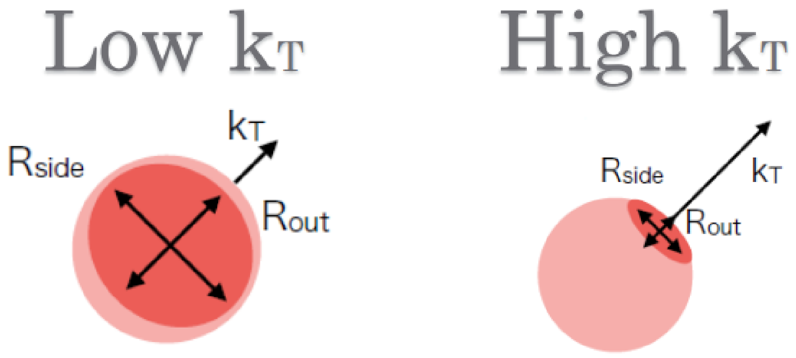
Statistical uncertainties only





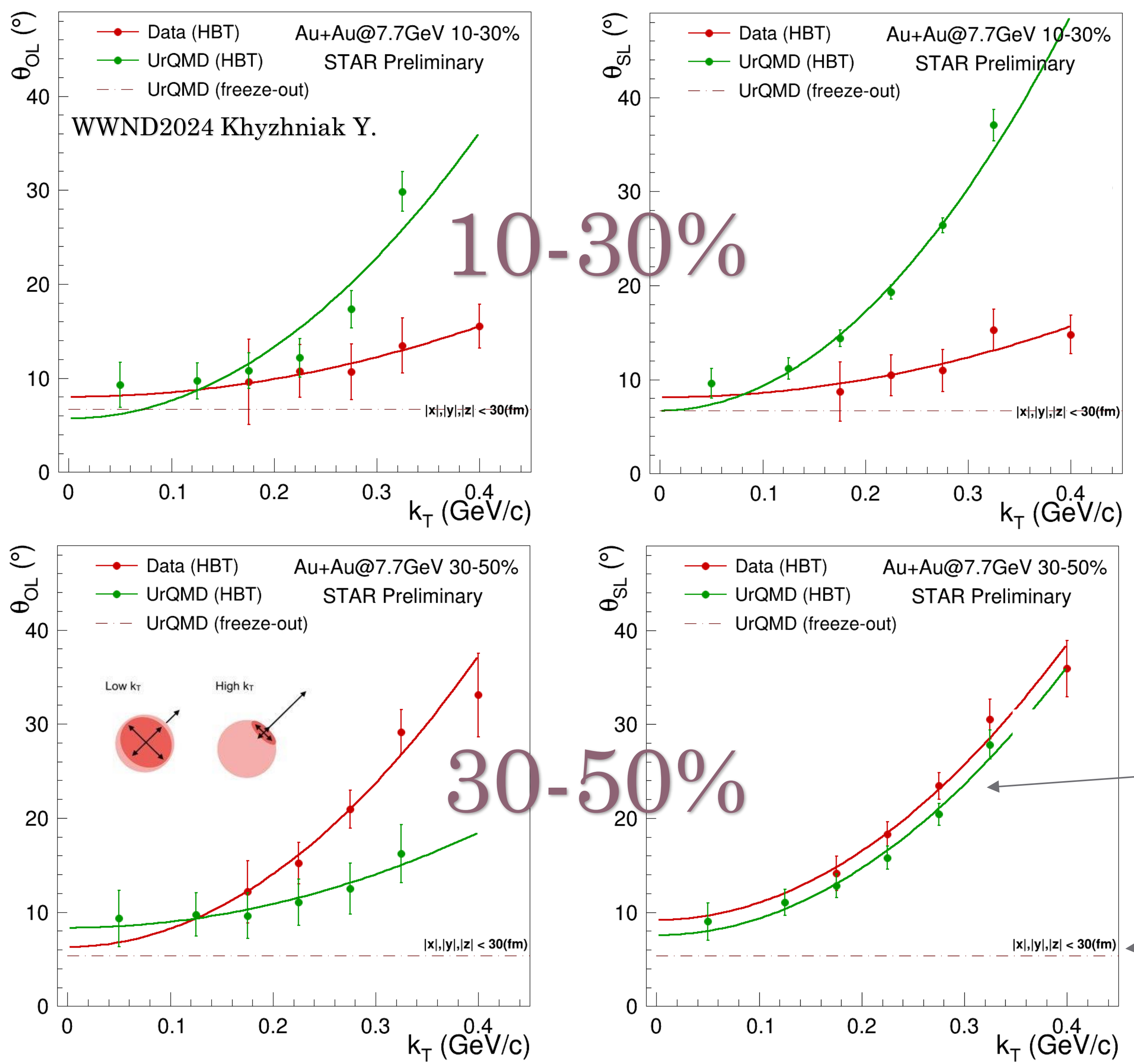


Correspondence between femtoscopy tilt and freeze-out distribution tilt



- Extrapolation to $k_T = 0$ will give the best possible comparison between tilt of homogeneity region and freeze-out distribution tilt of the "whole source"

Statistical uncertainties only



Tilt in the experiment and in the UrQMD

Good agreement between femtoscopy results from experiment, UrQMD and the tilt from the freeze-out distribution at low momentum

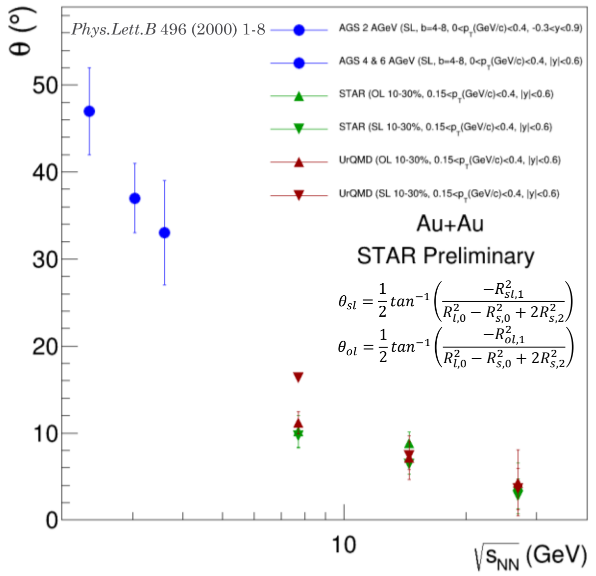
Quadratic approximation of the functional form

Through freeze-out distribution of pions

Summary

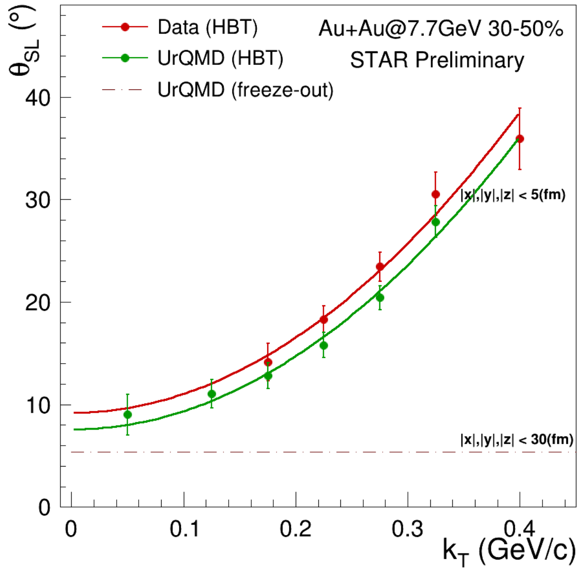
- First measurements of the spatial tilt at the RHIC using BES data are available

- Tilt dependence on energy
  - Obtained results in trend with AGS data
    - Collision geometry becomes increasingly boost invariant at higher energies



Statistical uncertainties only

- Tilt dependence on transverse momentum of pion pair
  - In order to check correspondence between femtoscopy results and direct fit to the freeze-out distribution an extrapolation of k_T dependence of tilt was made down to $k_T = 0$ in UrQMD model
    - Obtained results lies within ~2 degrees between the two methods
  - The same extrapolation was performed for experimental data and shows reasonable agreement with the UrQMD results



Thank you for the attention!

- The dependence of the tilt angle on the transverse momentum of a pair of particles itself may also be of interest. One can think about the k_T dependence of the tilted homogeneity regions in order to describe directed flow of heavier particles
- As k_T can be used as the proxy for m_T
- Havier particles have larger directed flow