THE OHIO STATE UNIVERSITY

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# Azimuthally sensitive femtoscopy with RHIC Beam Energy Scan II data from STAR

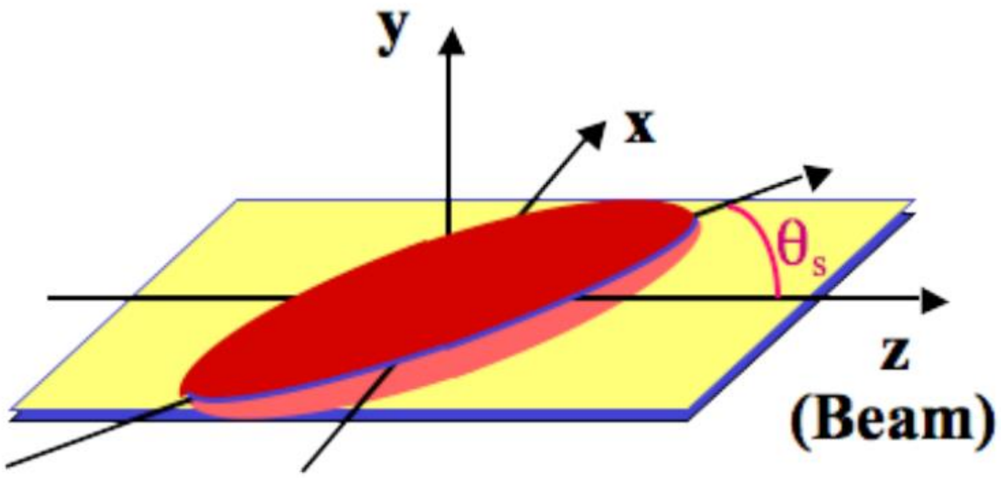
Yevheniia Khyzhniak (for the STAR Collaboration)

The $39^{th}$ Winter Workshop on Nuclear Dynamics

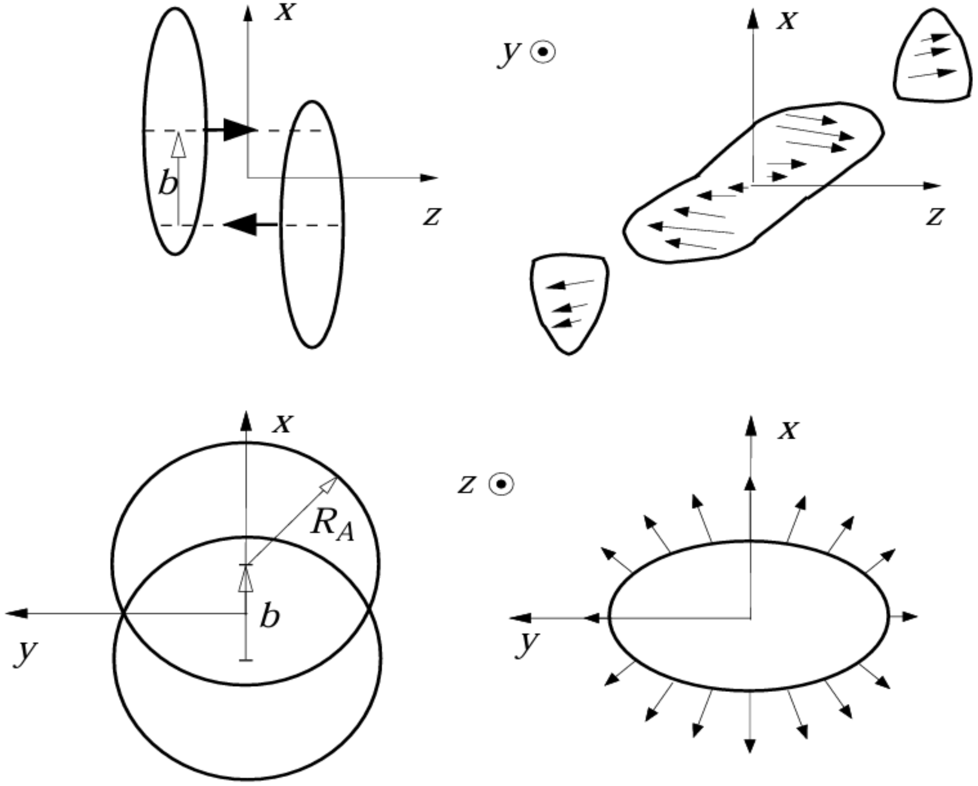
STAR

# 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

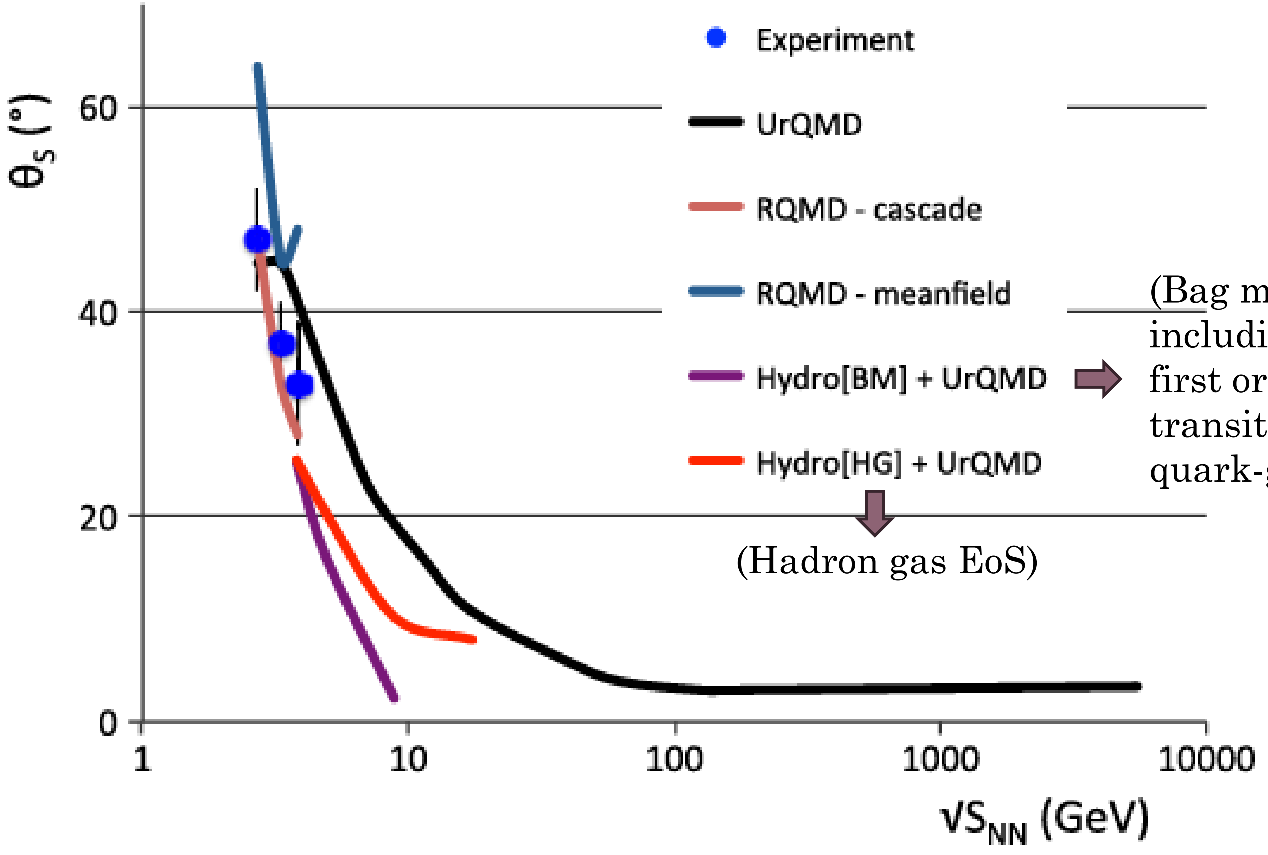



*New J.Phys.* 13 (2011) 065006




*Phys.Rev.Lett.* 94 (2005) 102301

# Motivation

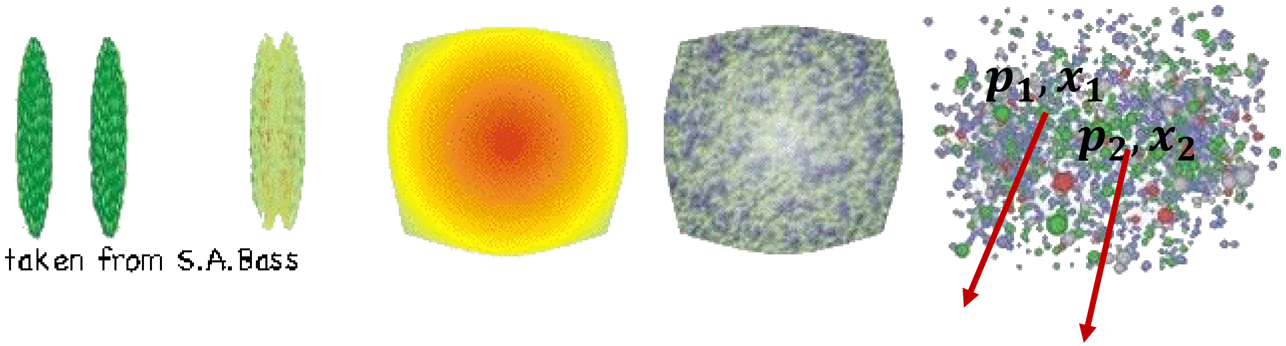



(Bag model EoS including a strong first order phase transition to the quark-gluon plasma)

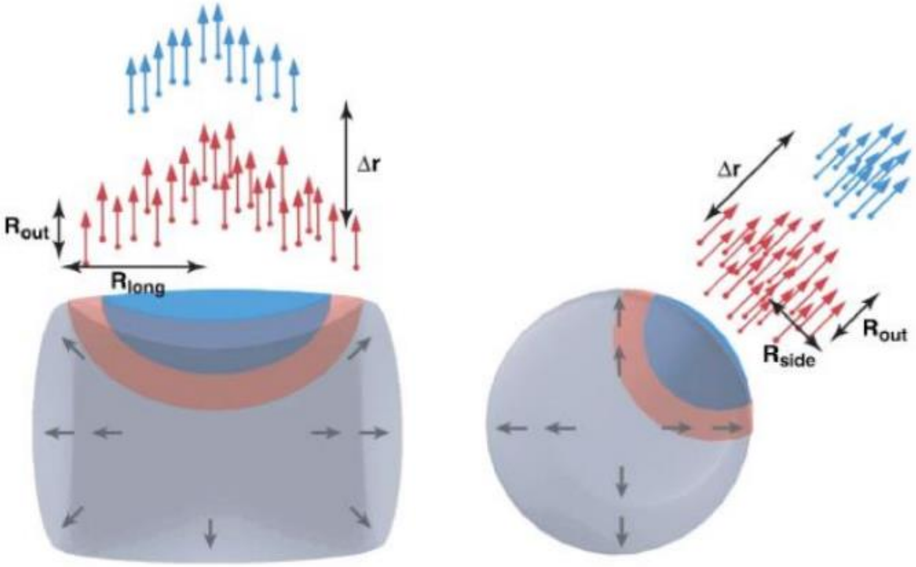
*New J.Phys.* 13 (2011) 065006

- 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




- Femtoscopy measures so-called regions of homogeneity (phase space region of outgoing particles with similar velocity vector)
- We can probe different homogeneity regions by varying pairs' transverse momenta




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

- Size: ~$10^{-15}$ m (~ 1 fm), time: ~ $10^{-23}$ s
  - impossible to measure directly
- Momentum (p) is accessible in experiment

Kinetic freeze-out

↓

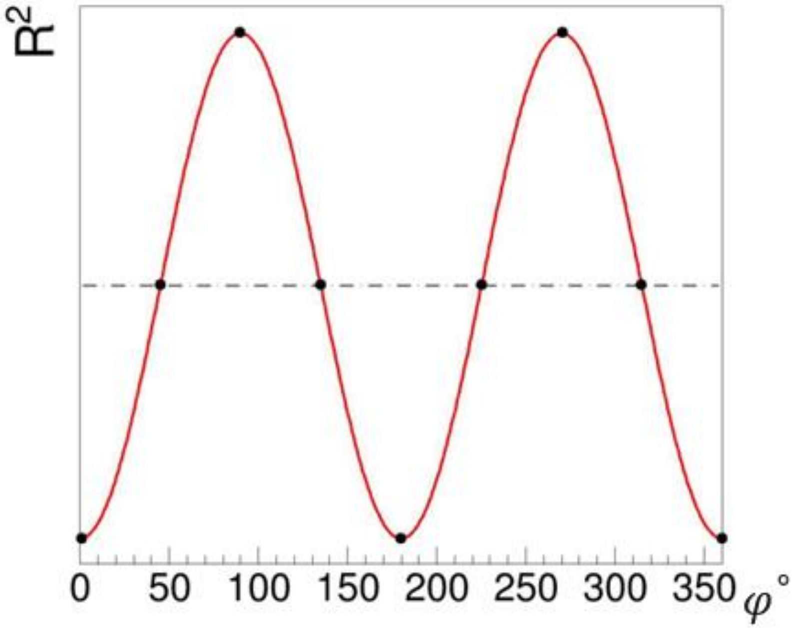
Femtoscopy

- Femtoscopy allows one to explore:
  - ➢Size of the emission source
  - ➢Lifetime of source
  - ➢Emission duration
  - ➢System dynamics
  - ➢Source shape
  - ➢Orientation

# Procedure: step 1

Created medium

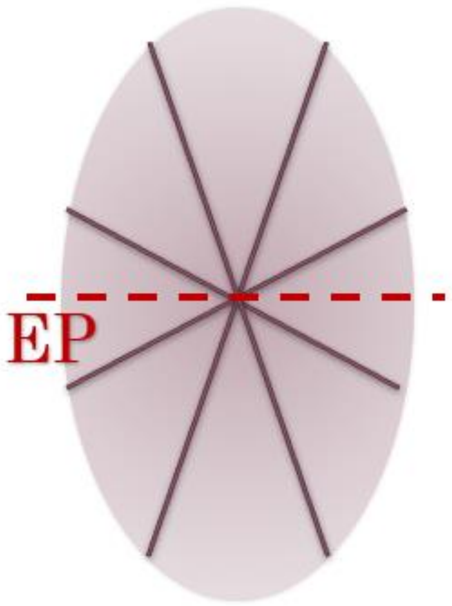
Radii response




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

# Procedure: step 1

Created medium

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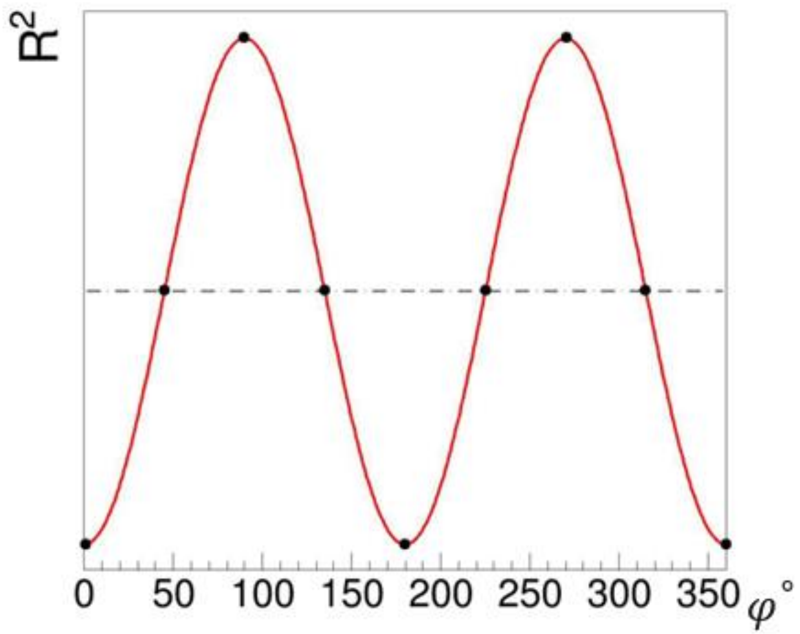


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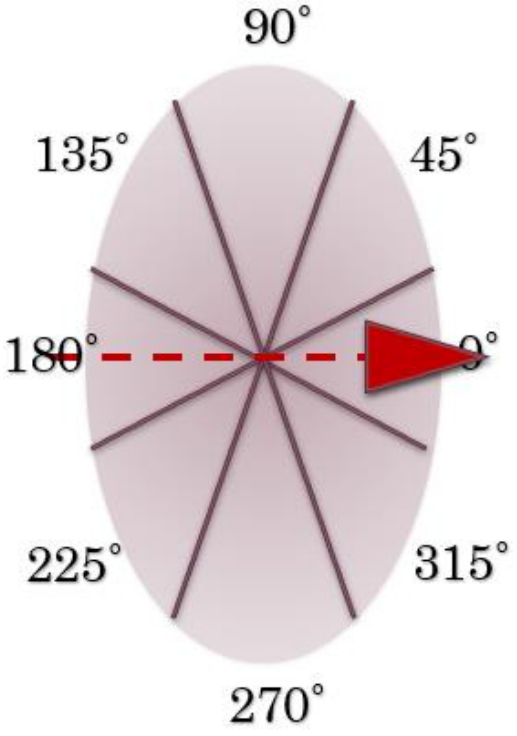


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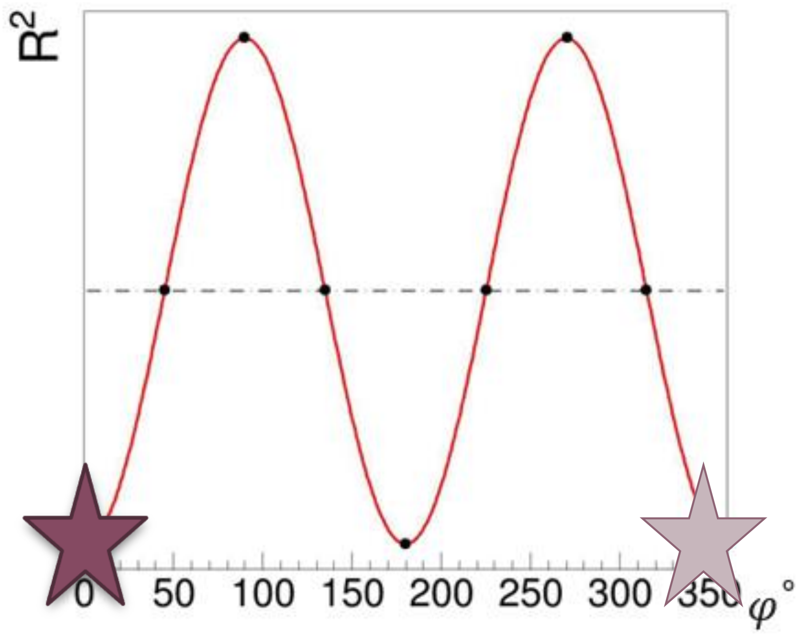


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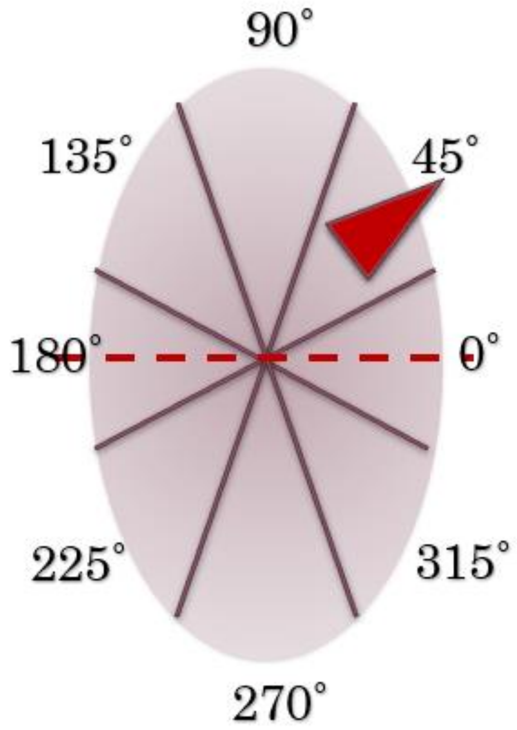


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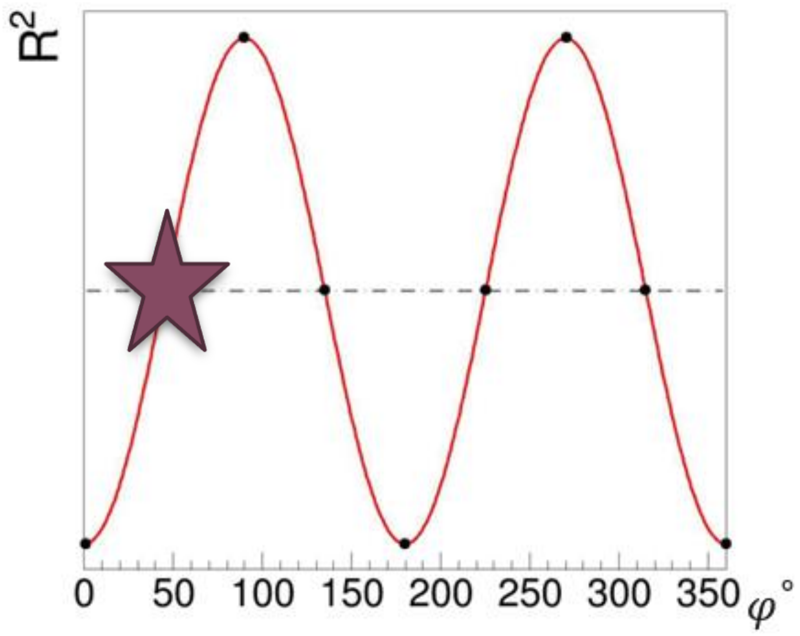


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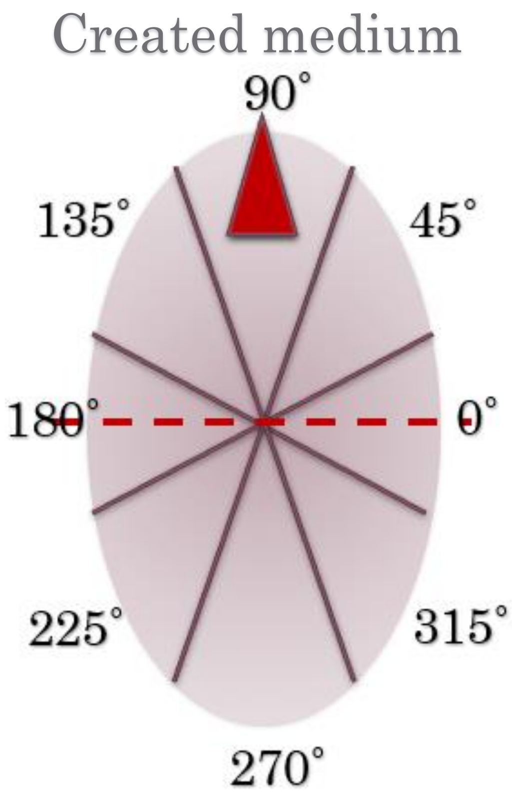


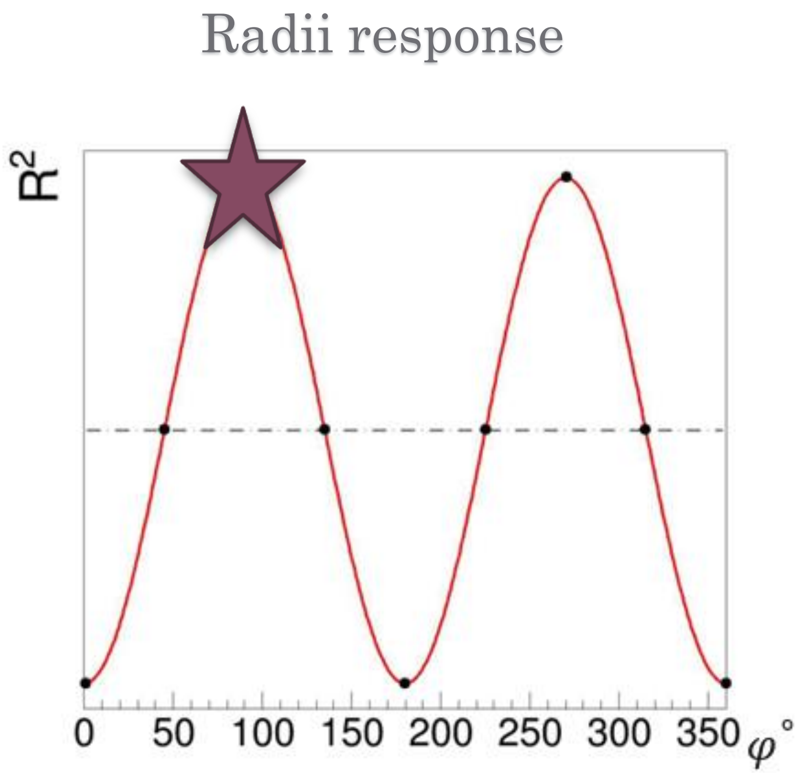


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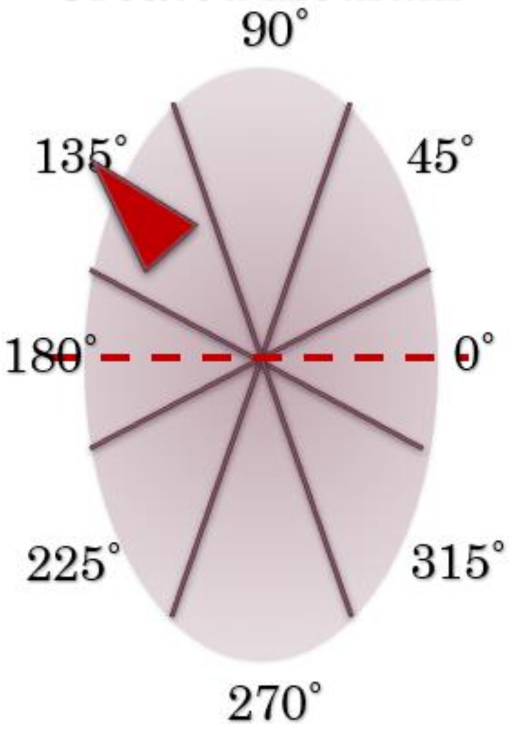


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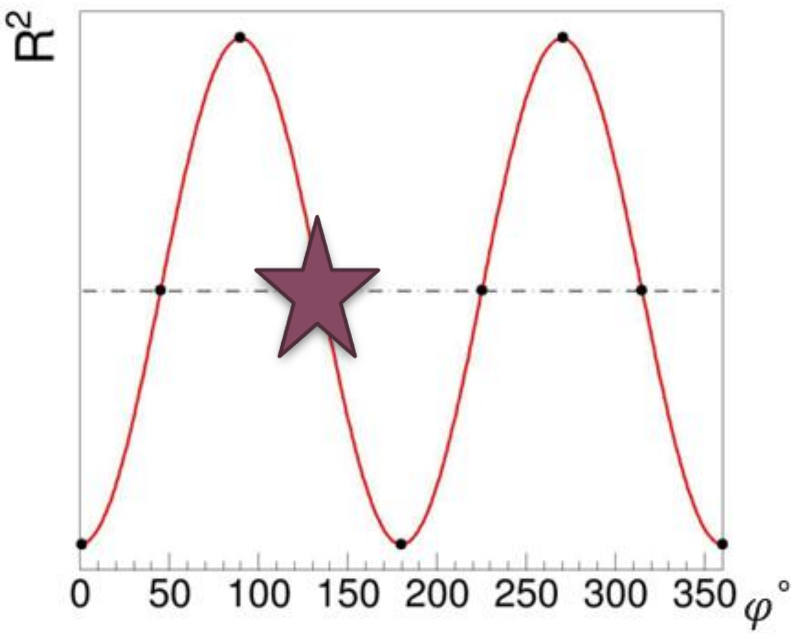


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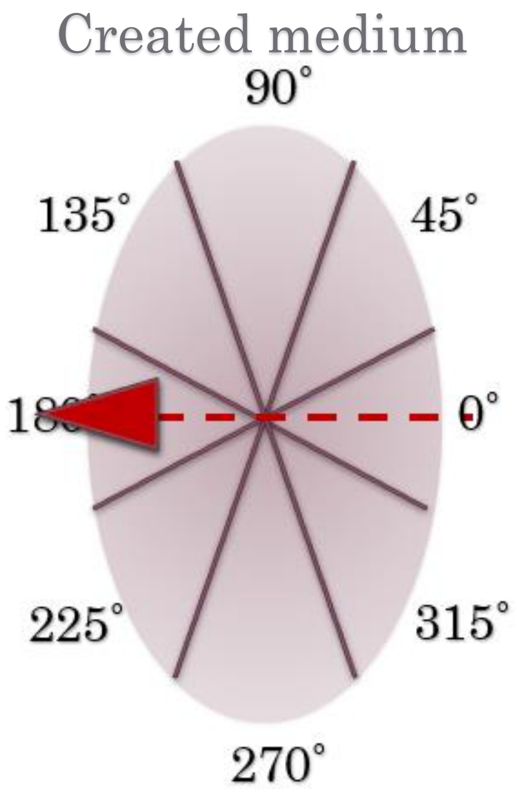


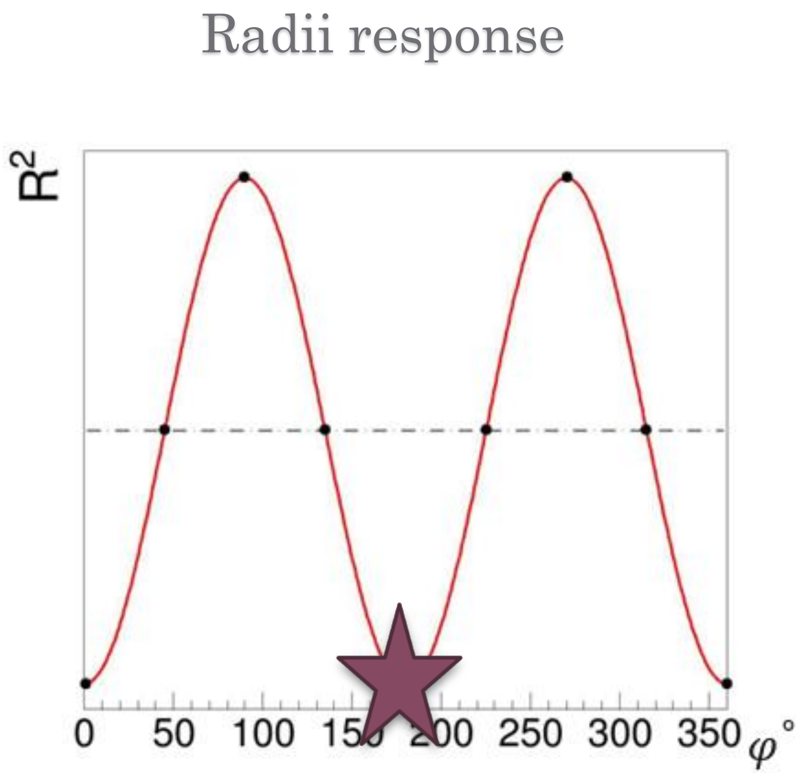


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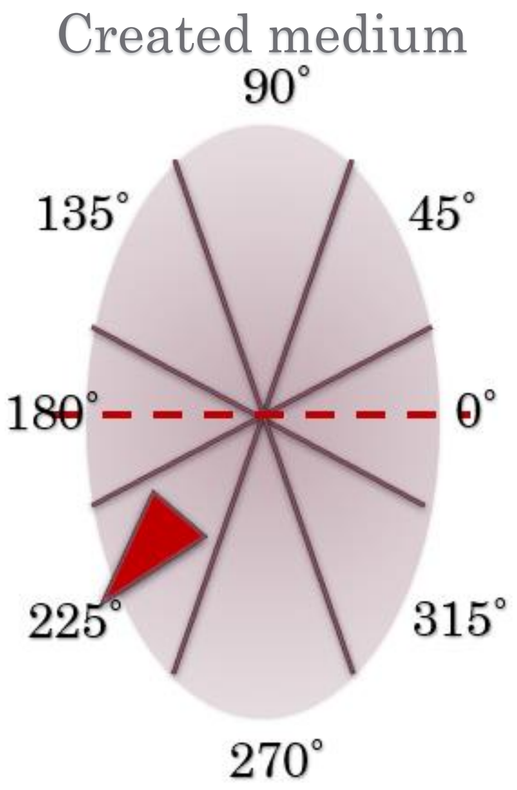


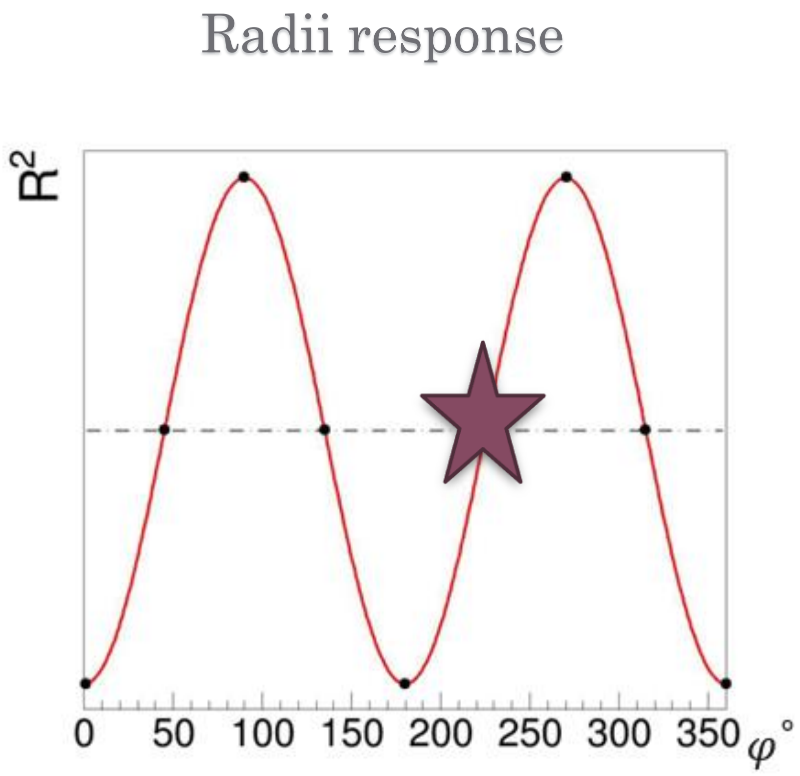


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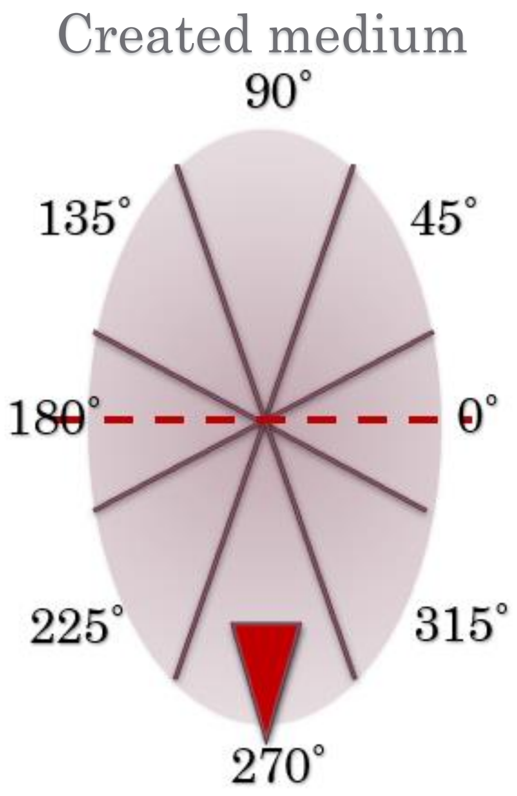


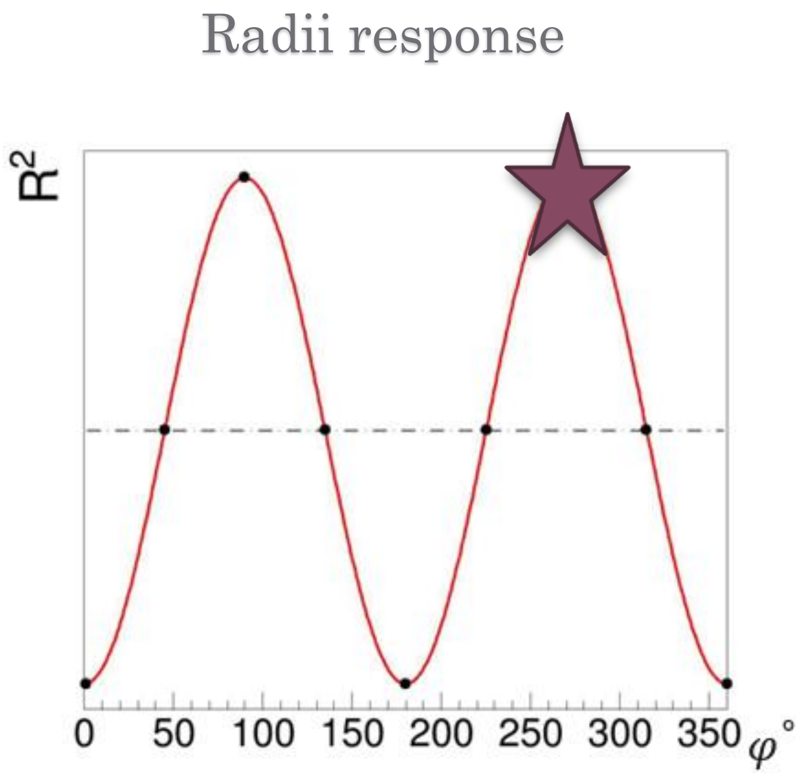


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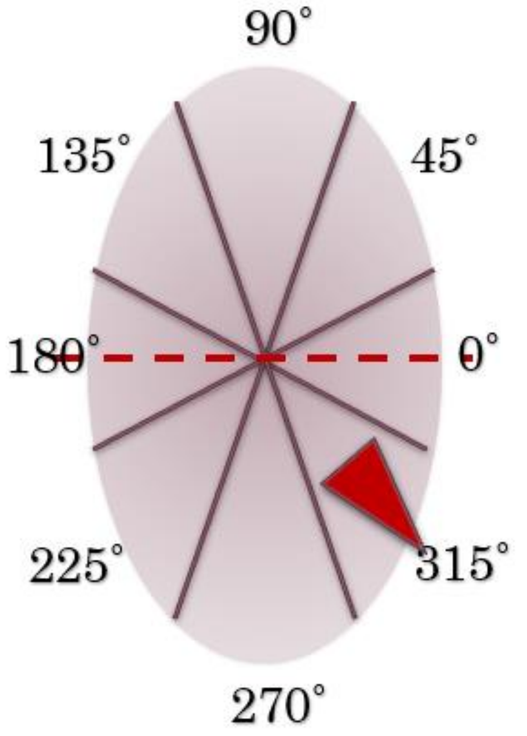
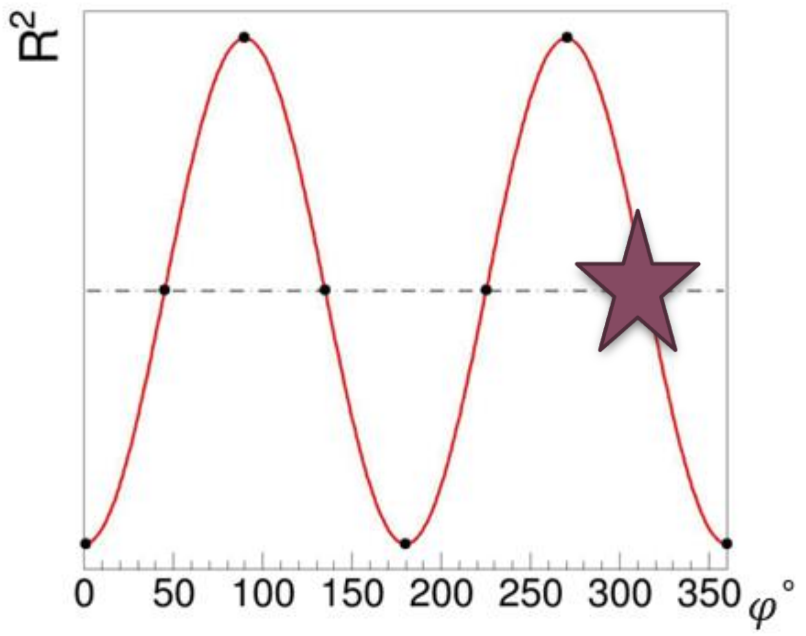
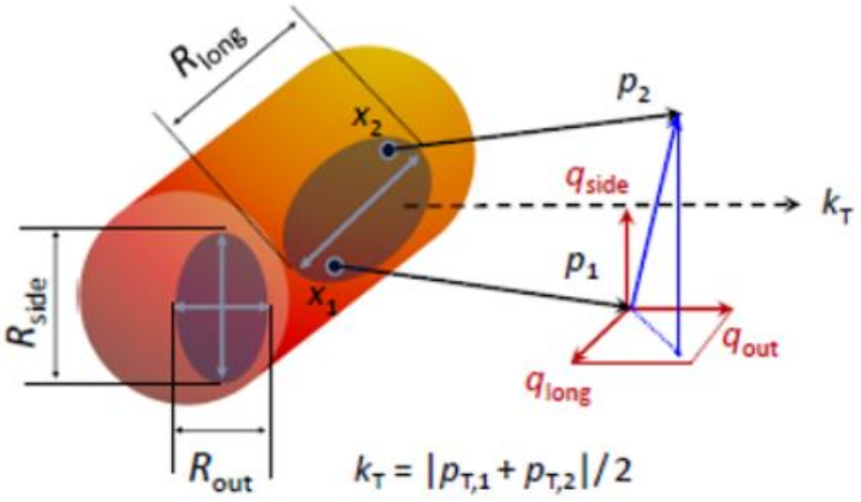



Radii response




- 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

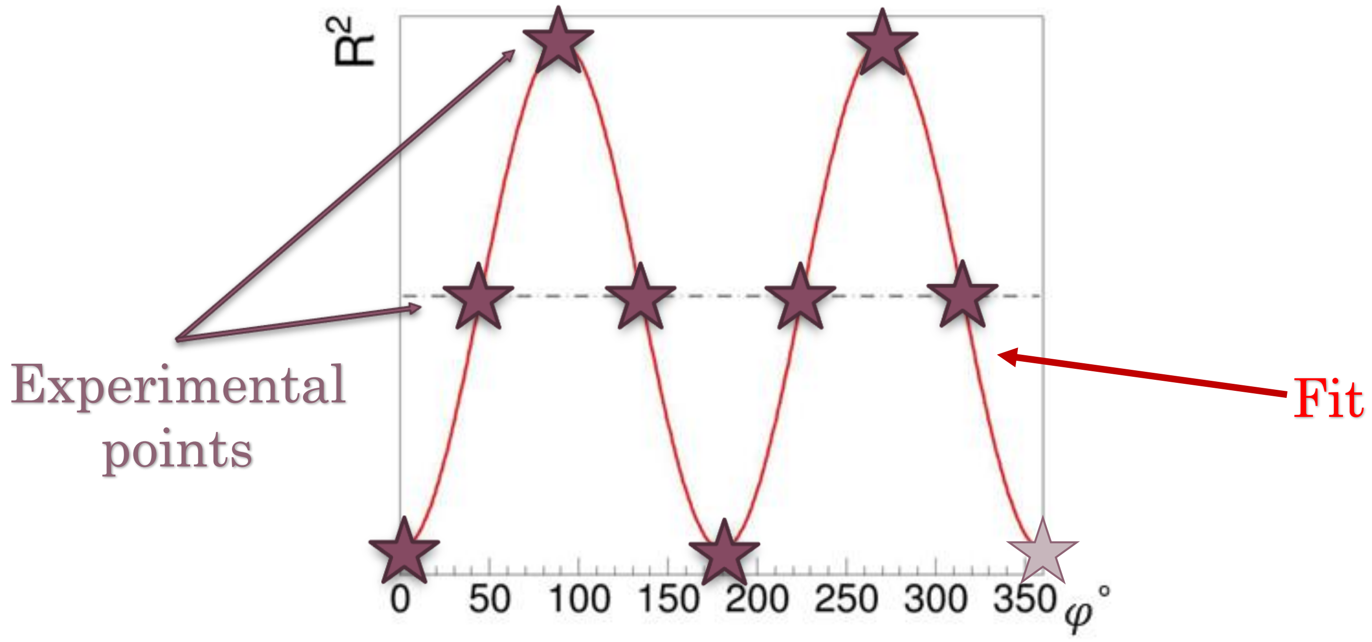
$\lambda$ – correlation strength parameter

$K(q)$ - 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




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

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

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

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

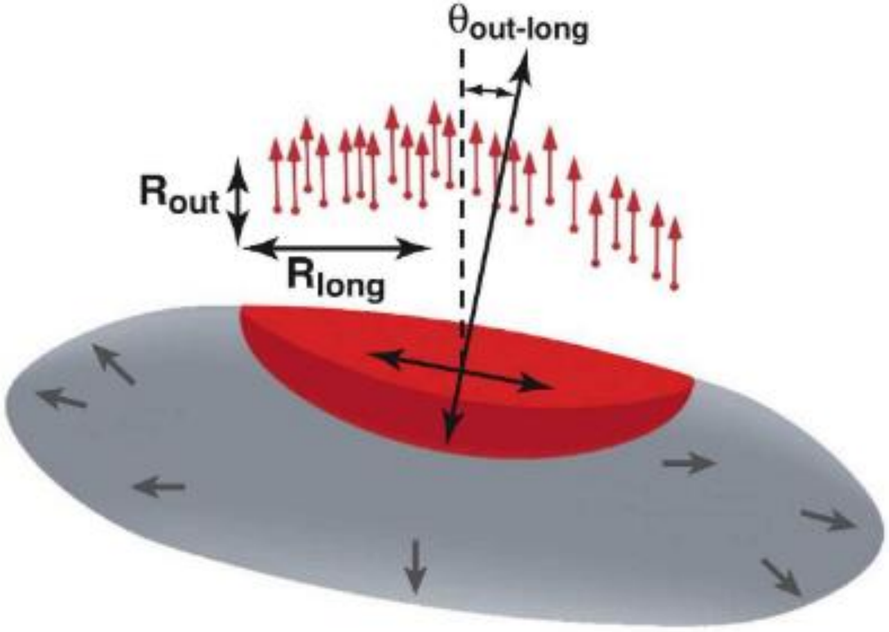
$$R_{ol}^2 = R_{ol,0}^2 + 2 \sum_{n=1,3,5\ldots} R_{ol,n}^2 \cos(n\Phi)$$

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

*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

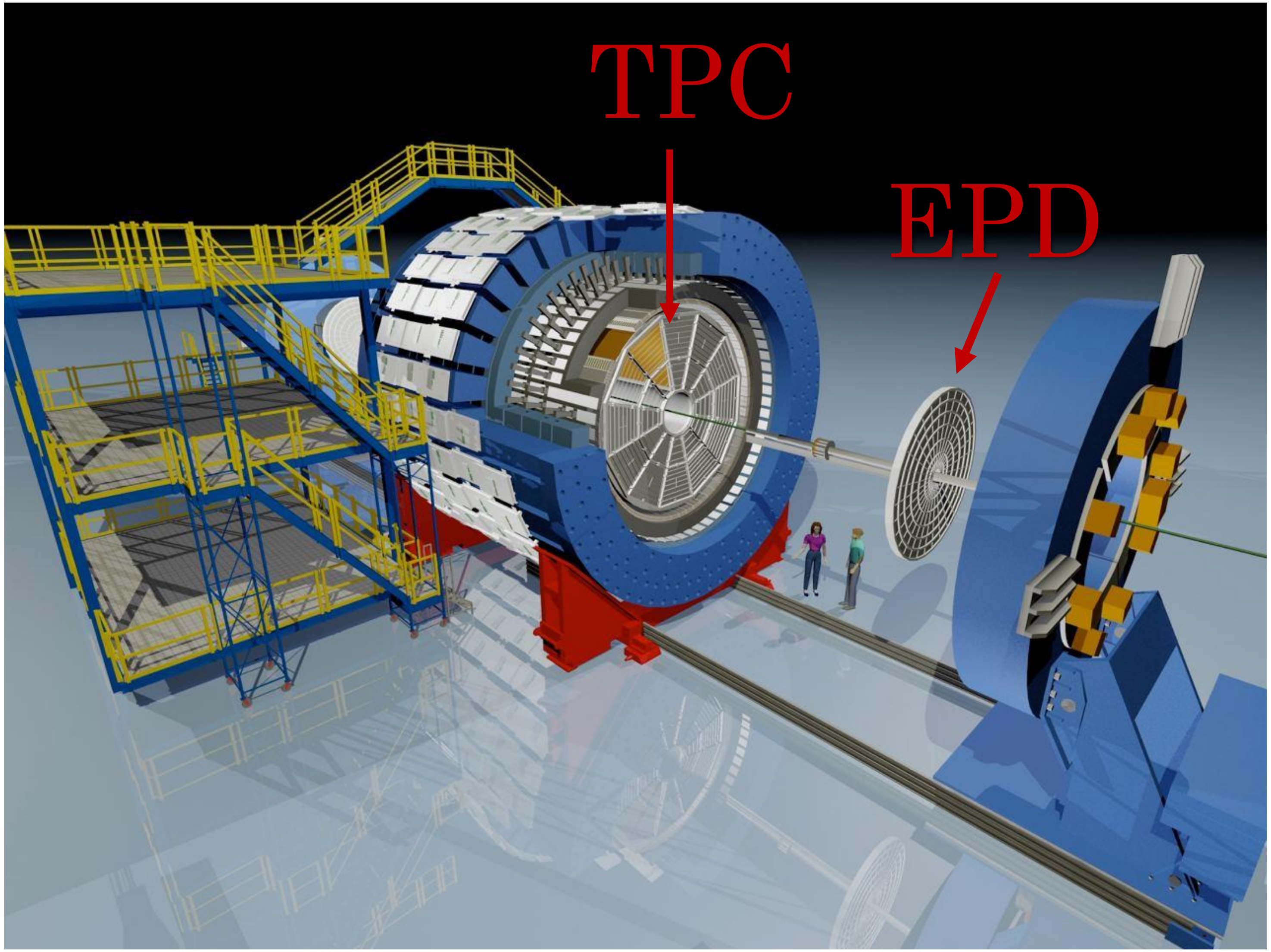
$$\theta_{sl} = \frac{1}{2} tan^{-1}\left(\frac{-4R_{sl,1}^2}{R_{l,0}^2 - R_{s,0}^2 + 2R_{s,2}^2}\right)$$

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

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

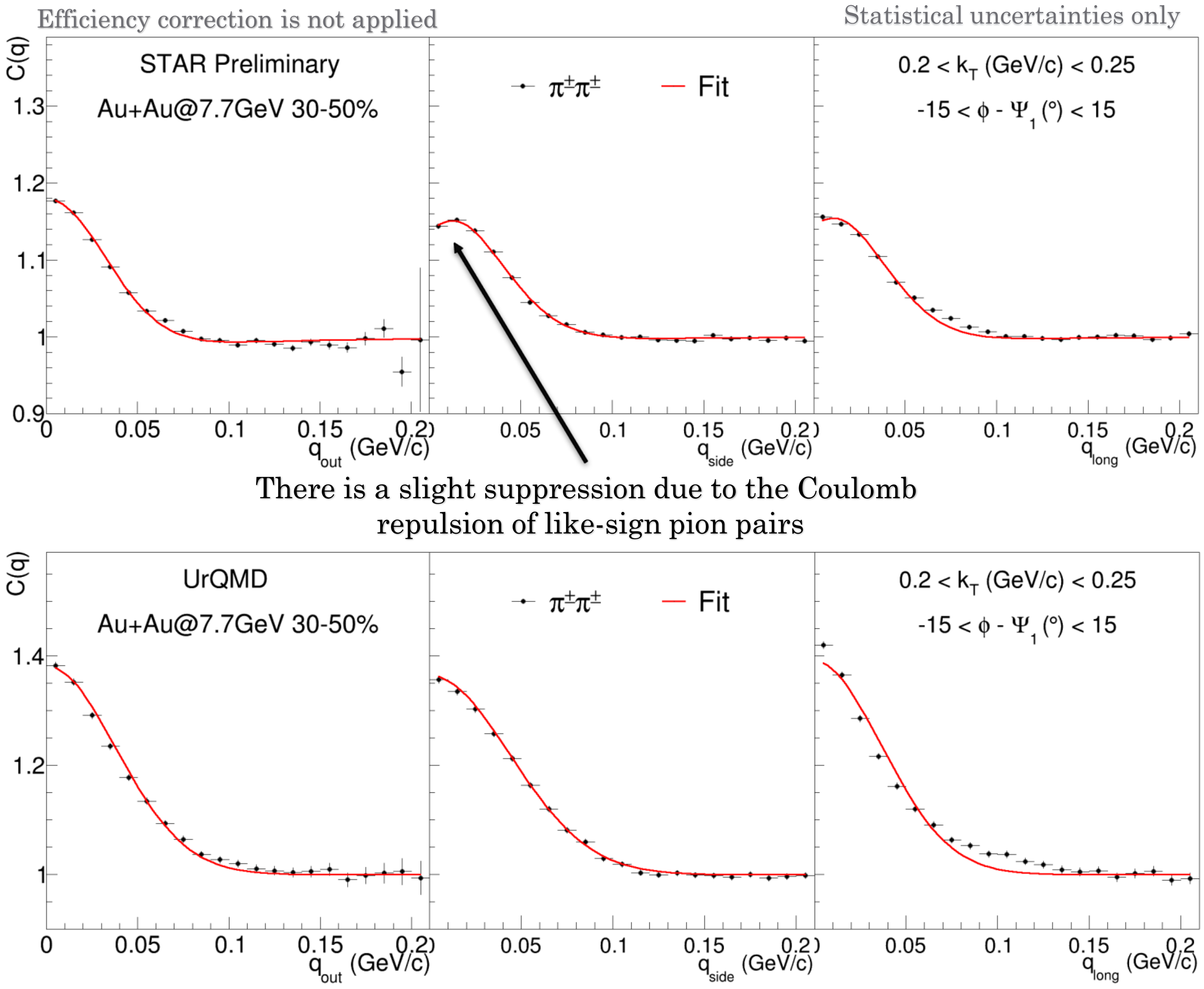
- Tilt calculation from extracted fit parameters

# The STAR experiment

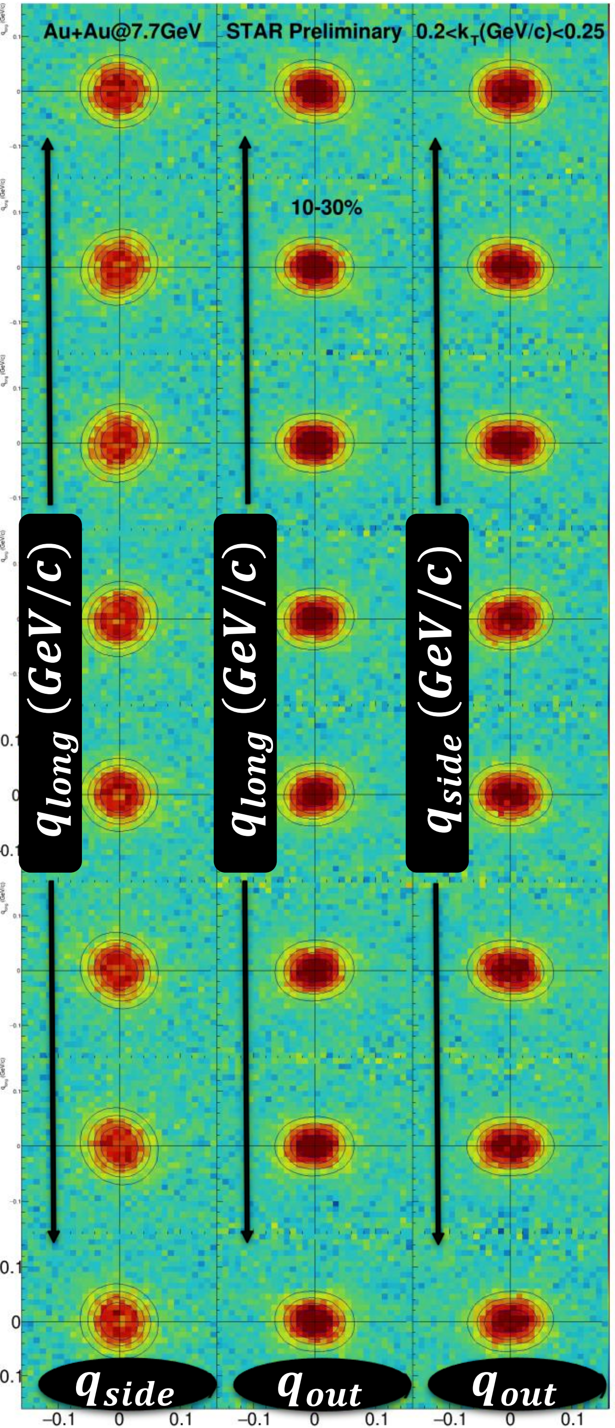



- Time Projection Chamber (TPC) + iTPC (BES-II upgrade)
  - Momentum and pion identification
- Event Plane Detector (EPD)
  - Part of the BES-II upgrade
  - Reconstruction of the first-order event plane (proxy for reaction plane)
- Energies of interest (BES-II):
  - Au+Au@7.7 GeV
  - Au+Au@14.5 GeV
  - Au+Au@27 GeV

# One-dimensional projection of correlation function

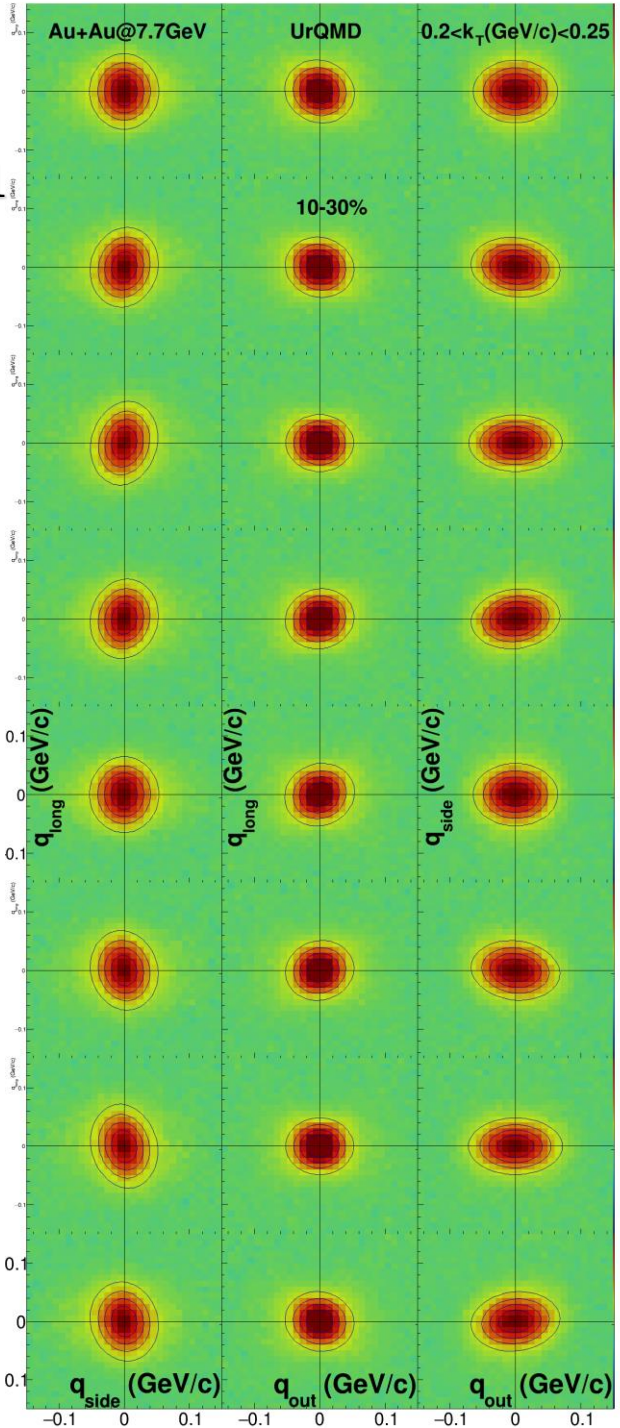


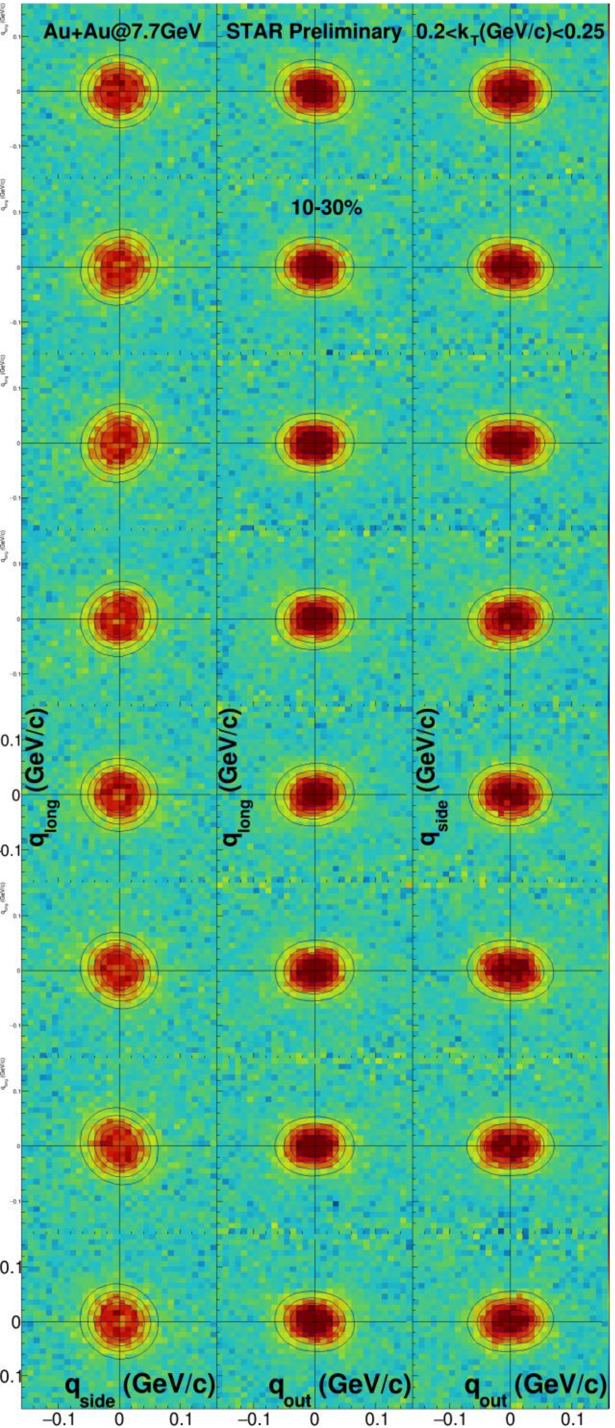

- Fit describes correlation functions reasonably well in both experiment and UrQMD
- A slight deviation from the Gaussian shape in the longitudinal direction can be attributed to a “halo” emission from resonance

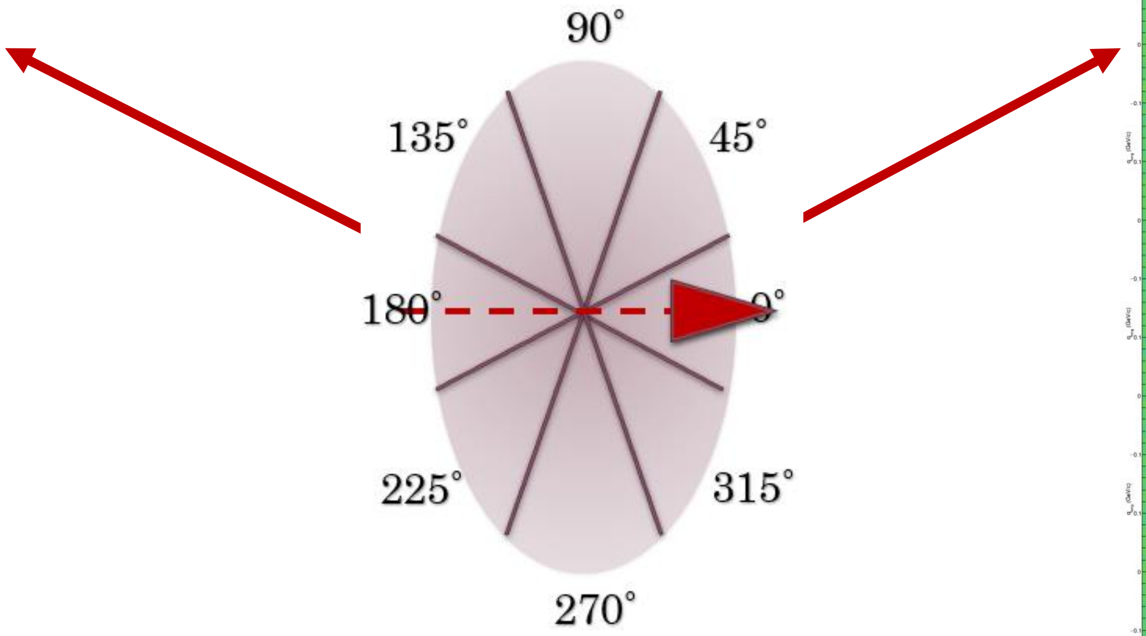



Vary
$\varphi - \Psi_1$

# Two-dimensional projections of correlation functions




Au+Au@7.7GeV
STAR Preliminary
0.2<k_T(GeV/c)<0.25
10-30%
q_long (GeV/c)
q_long (GeV/c)
q_side (GeV/c)
q_side (GeV/c)
q_out (GeV/c)
q_out (GeV/c)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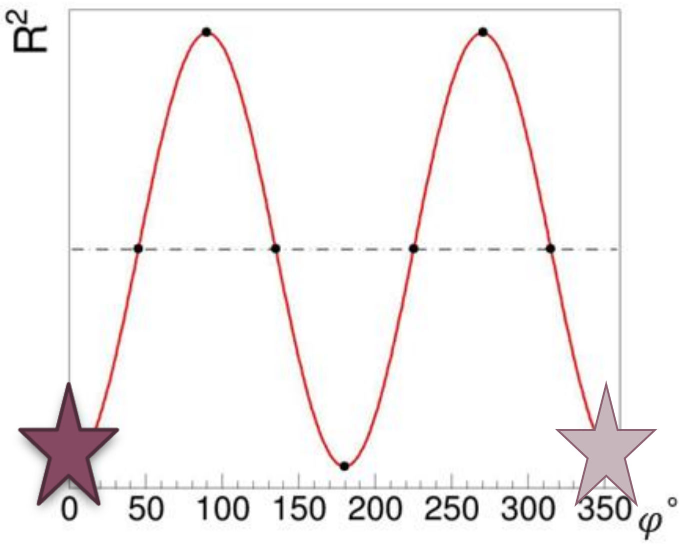
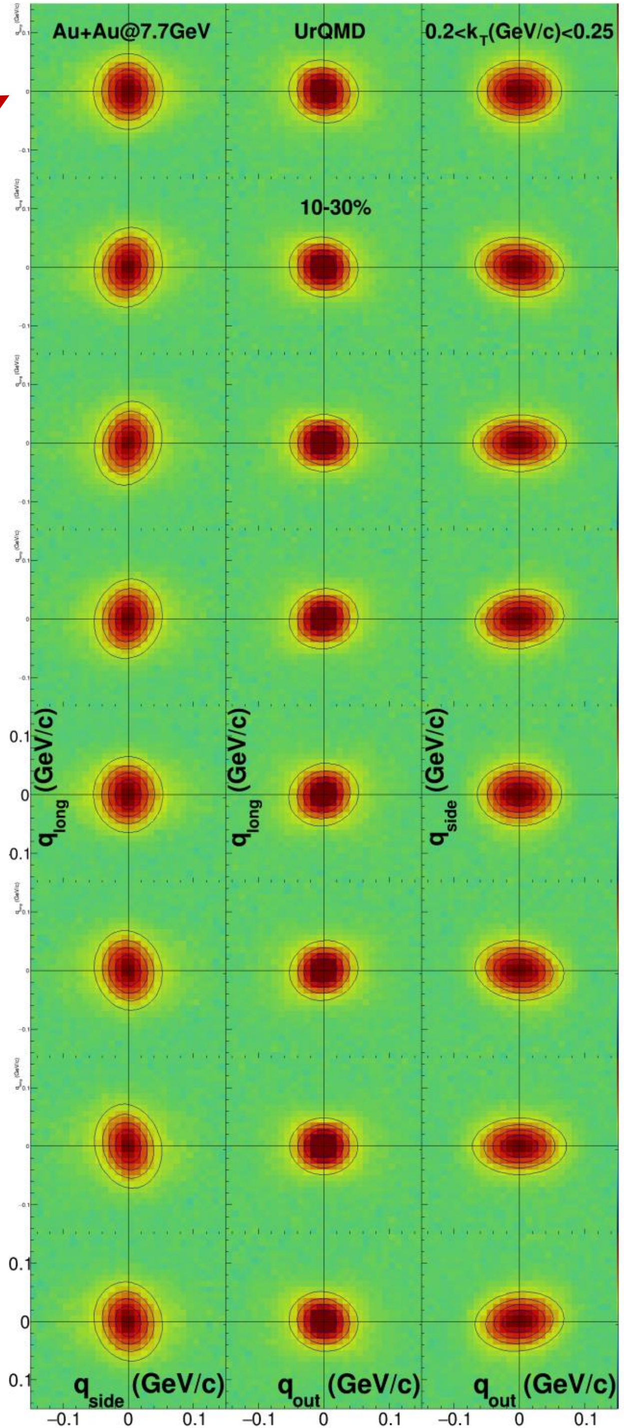

R²
0 50 100 150 200 250 300 350
φ °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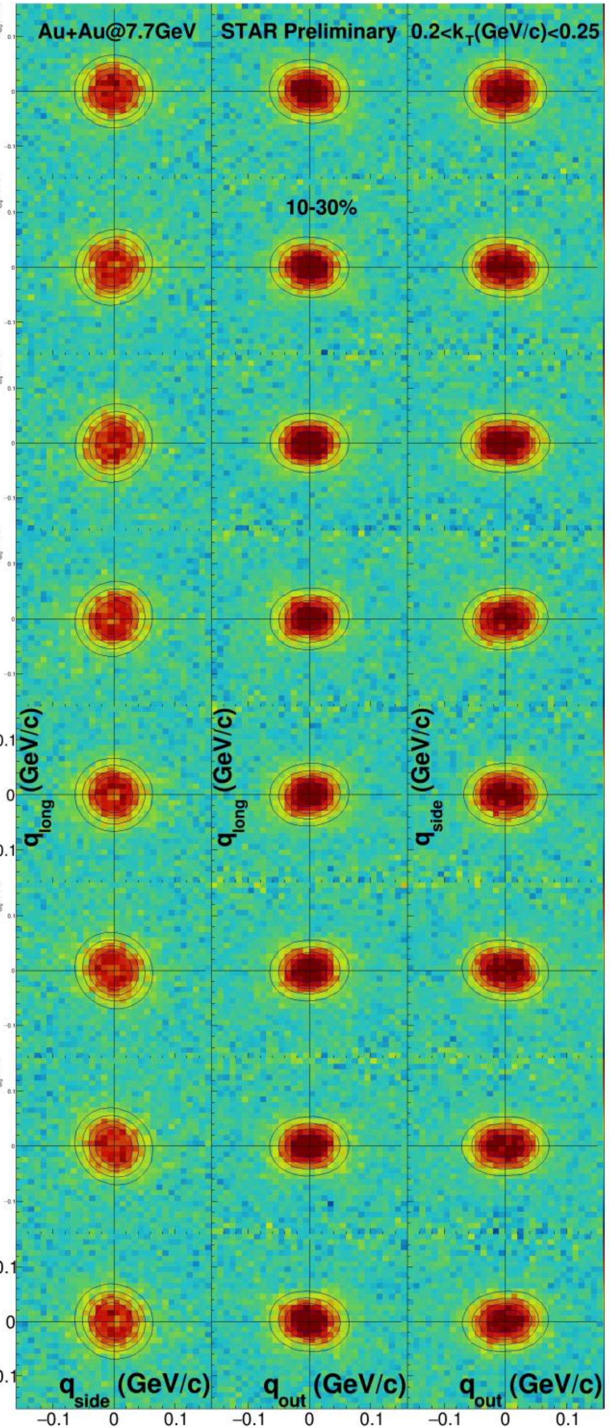
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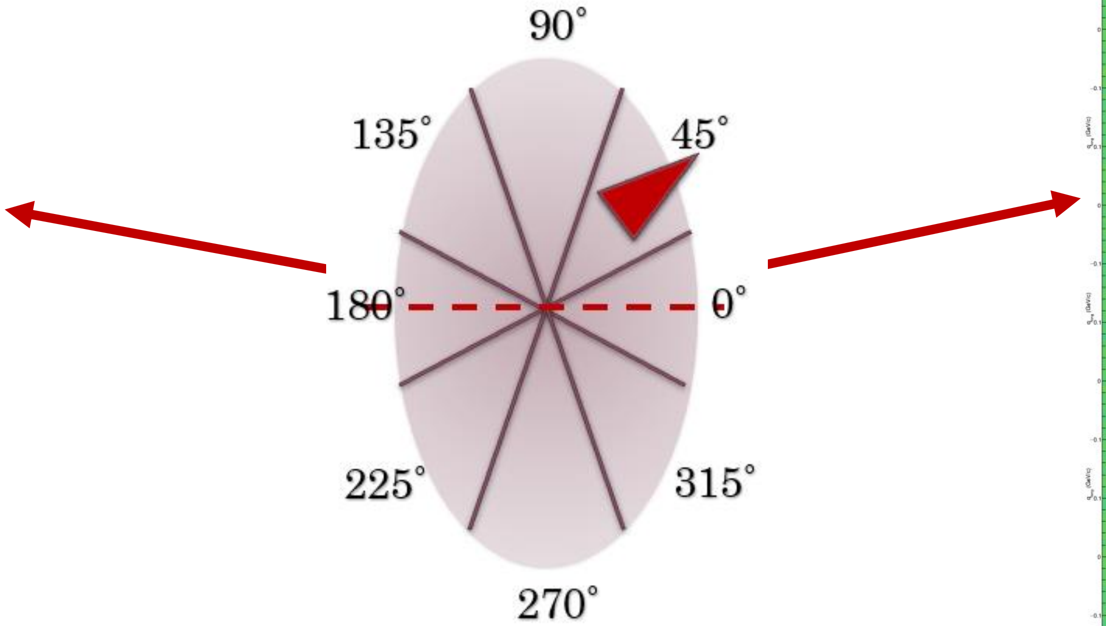
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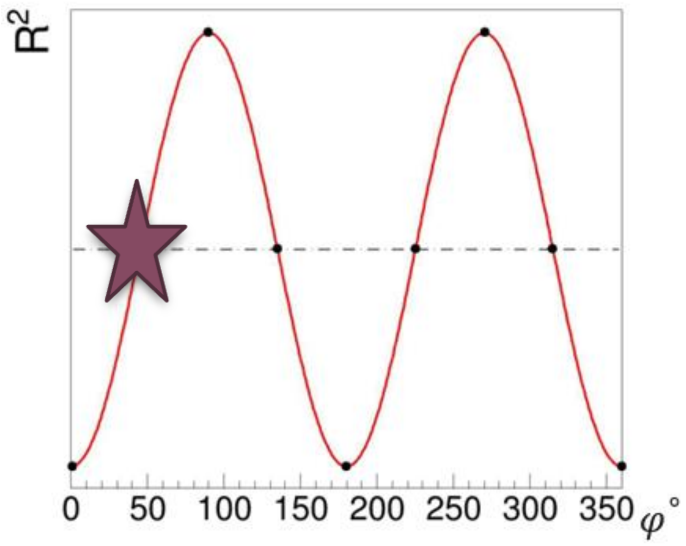
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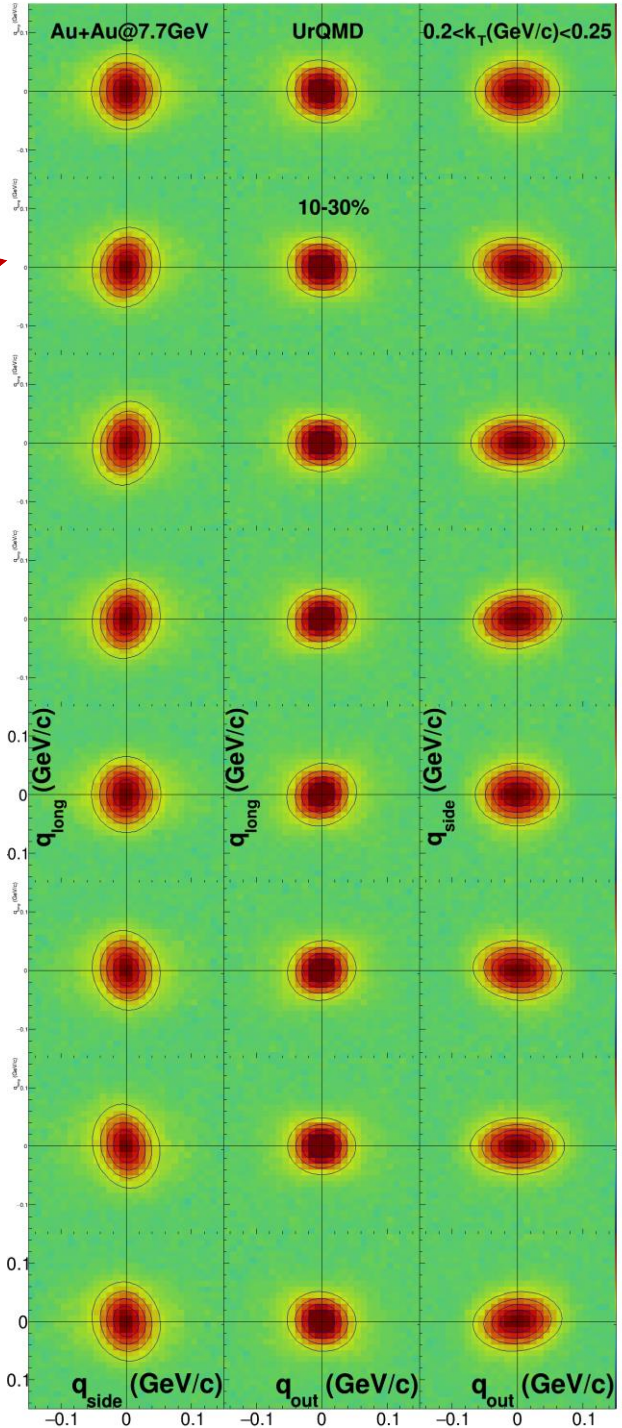
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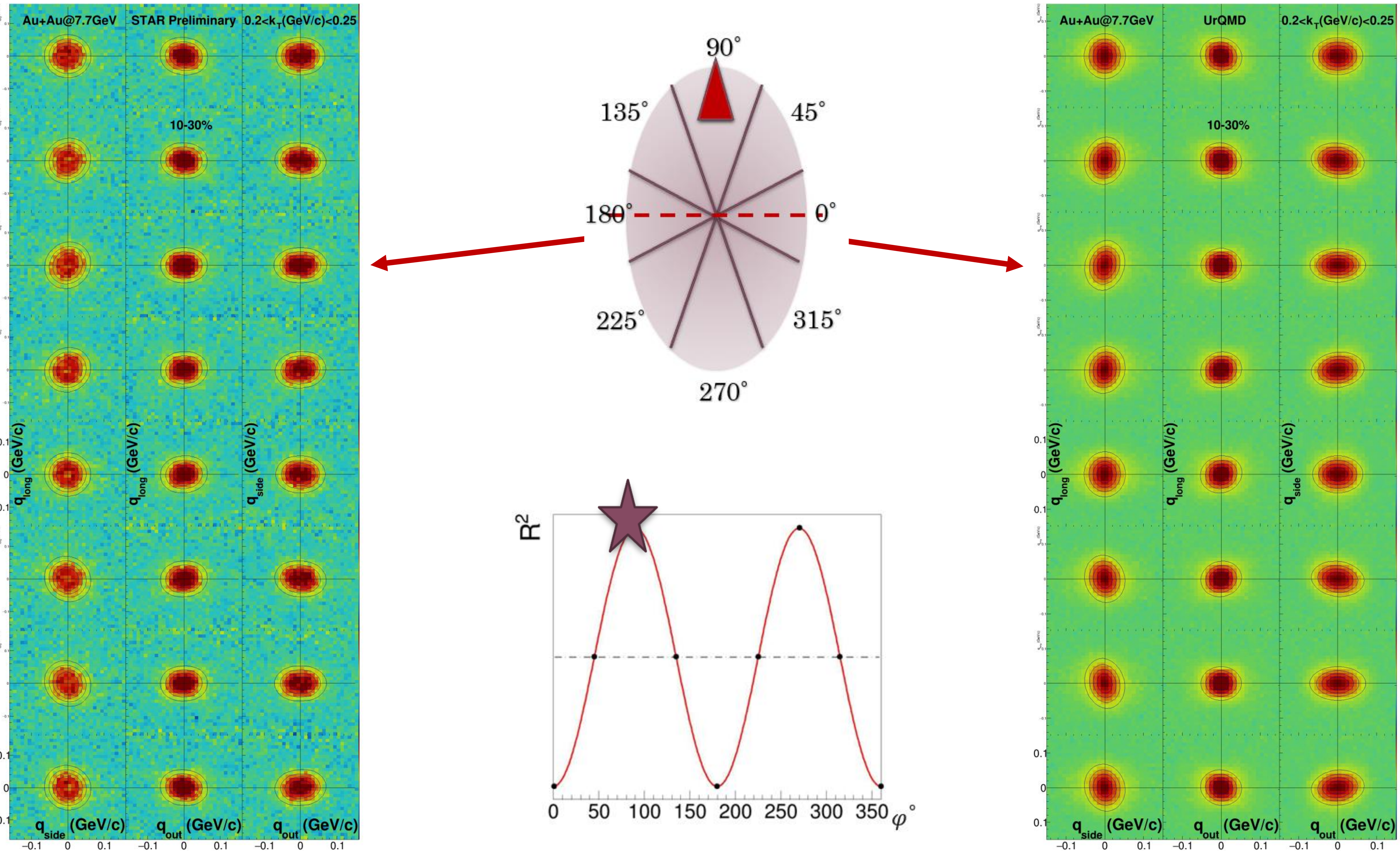
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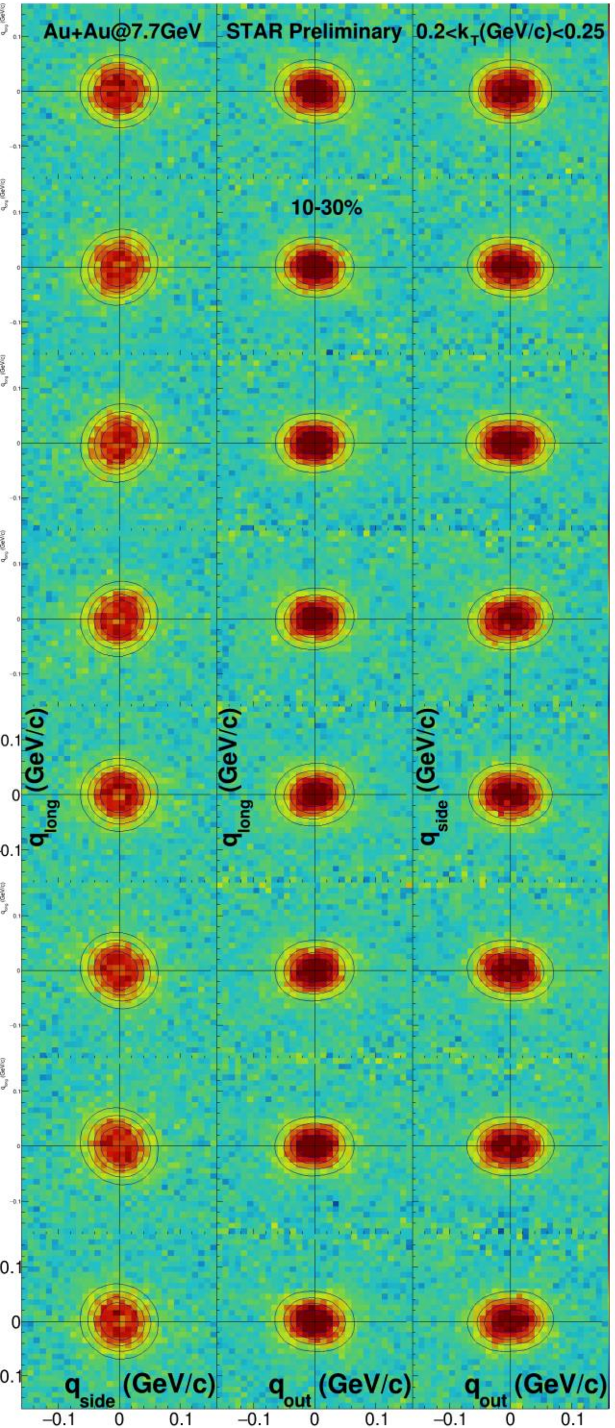
UrQMD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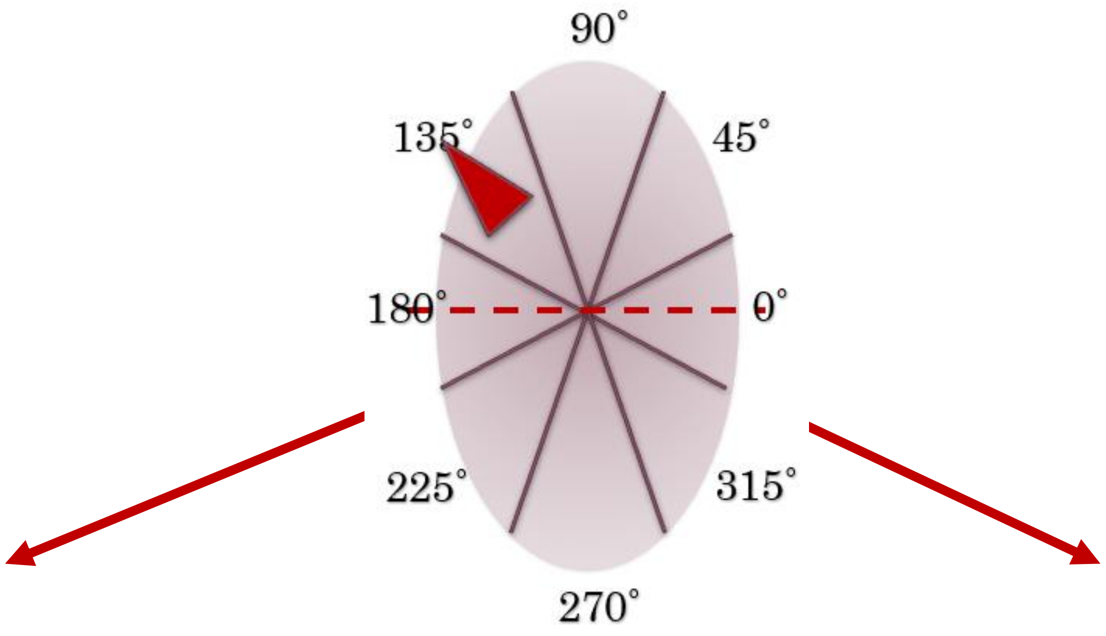
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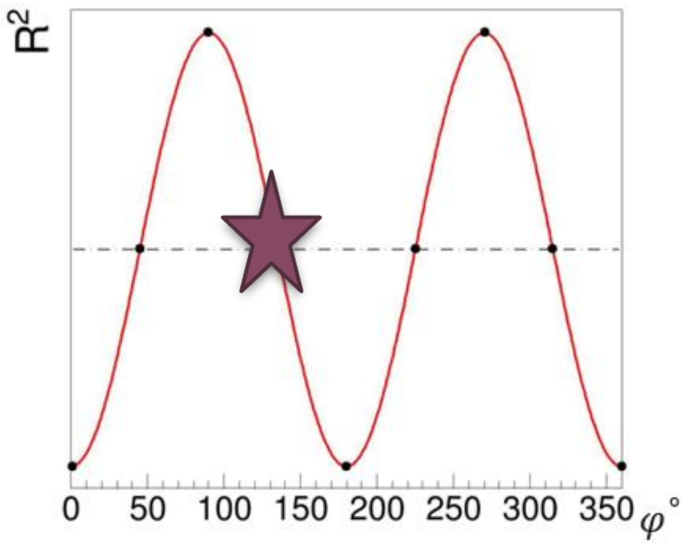
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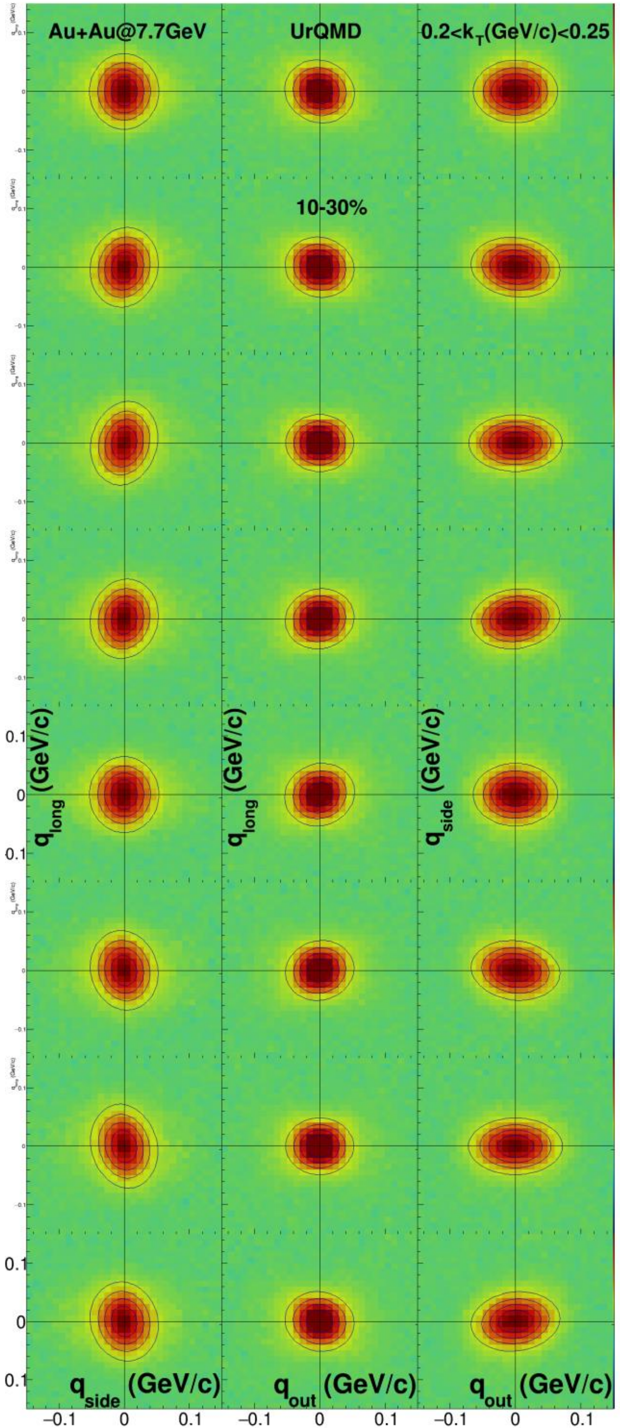
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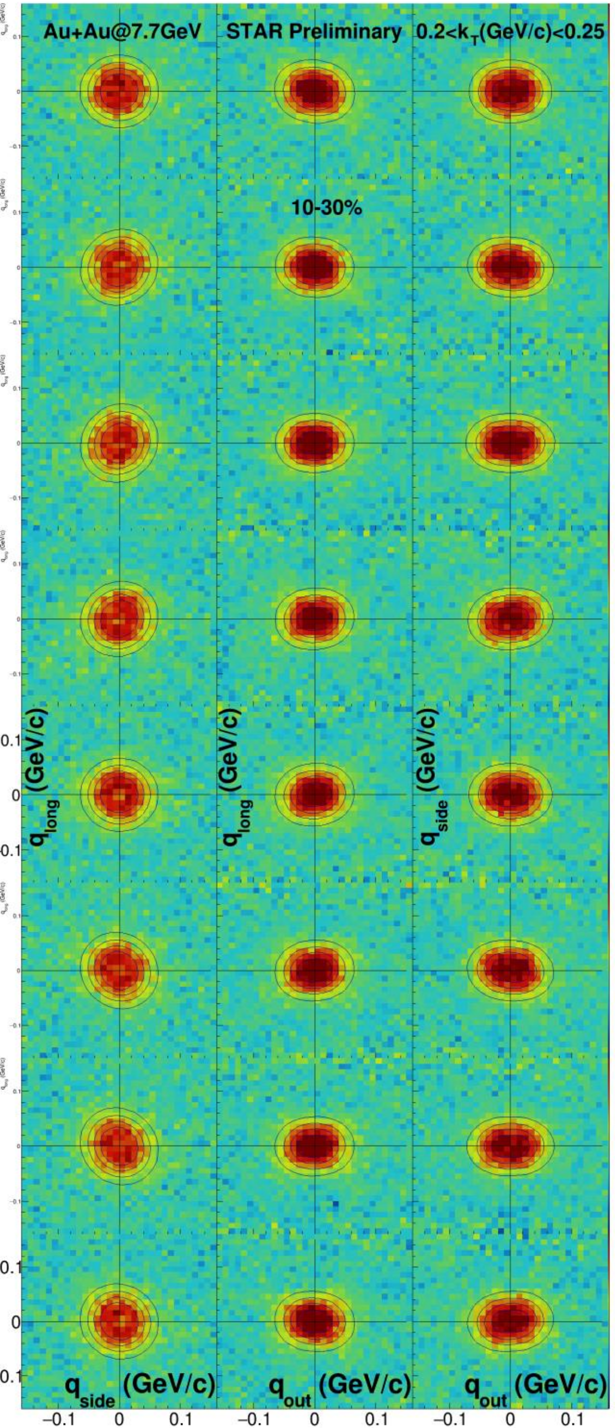
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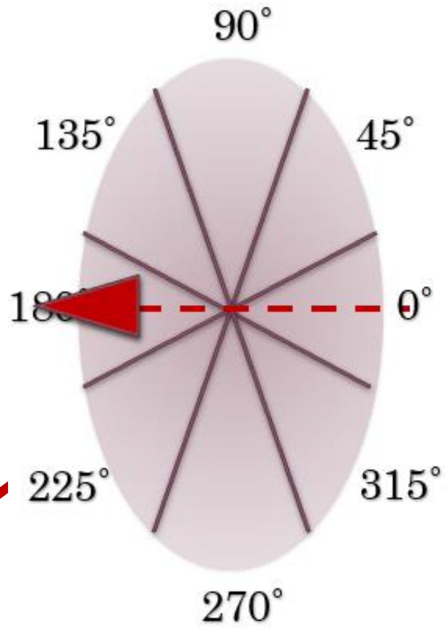
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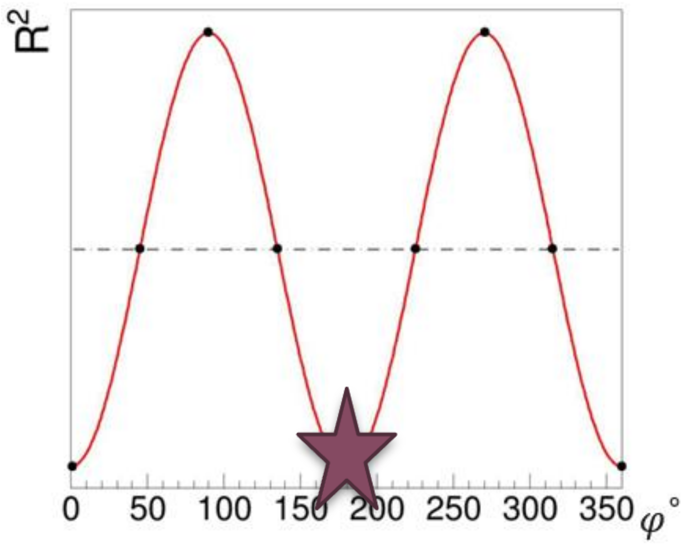
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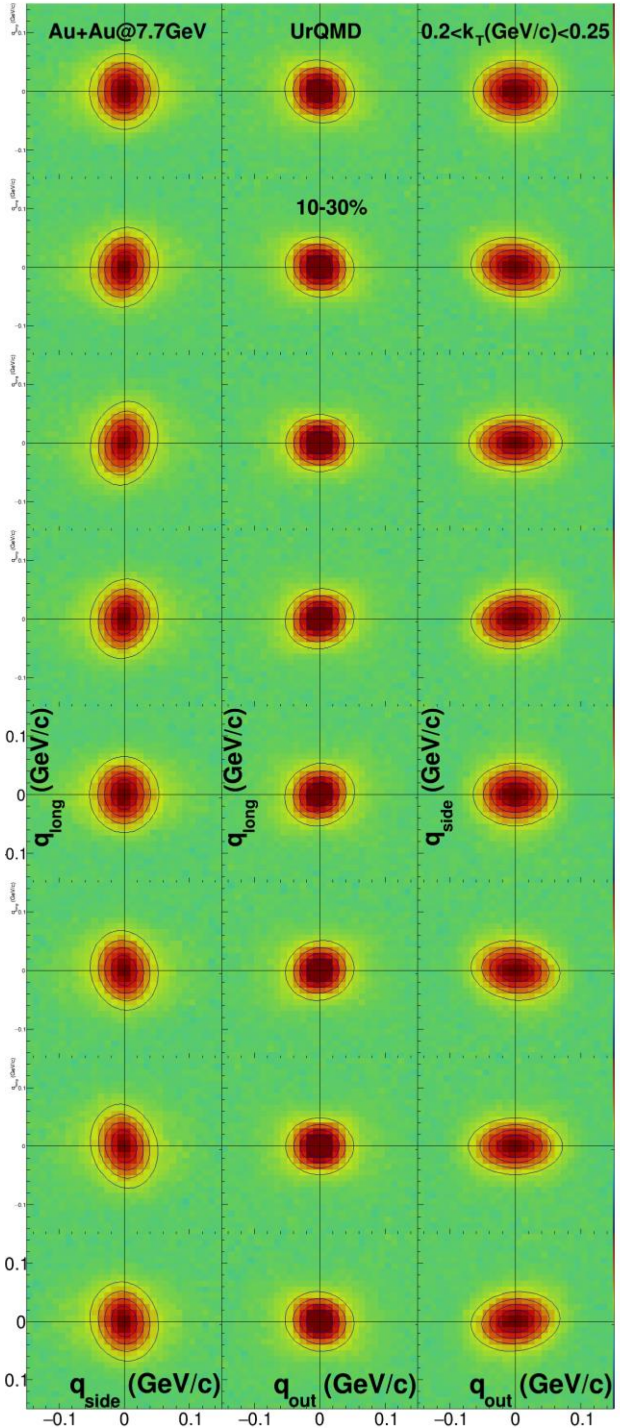
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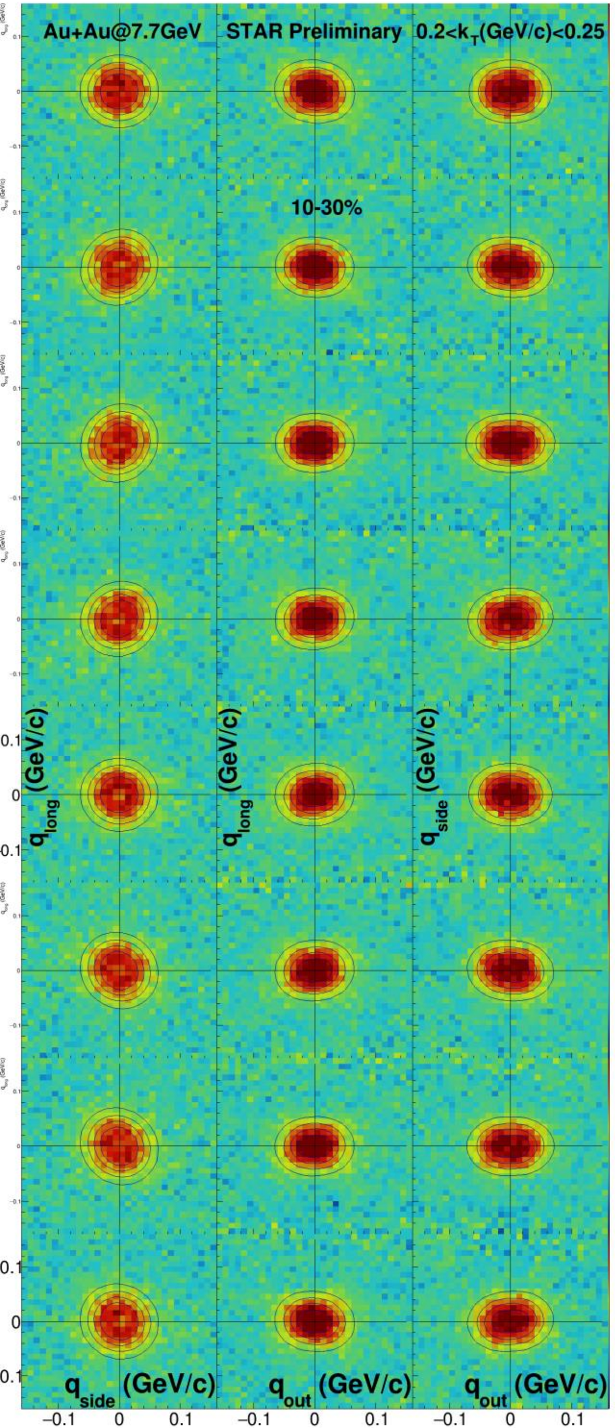
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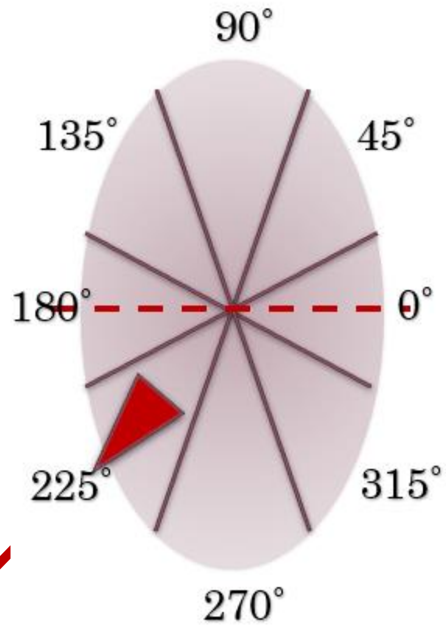
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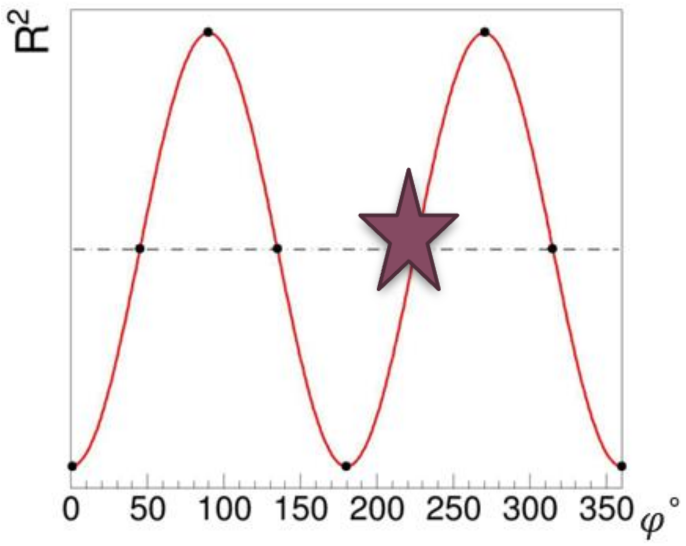
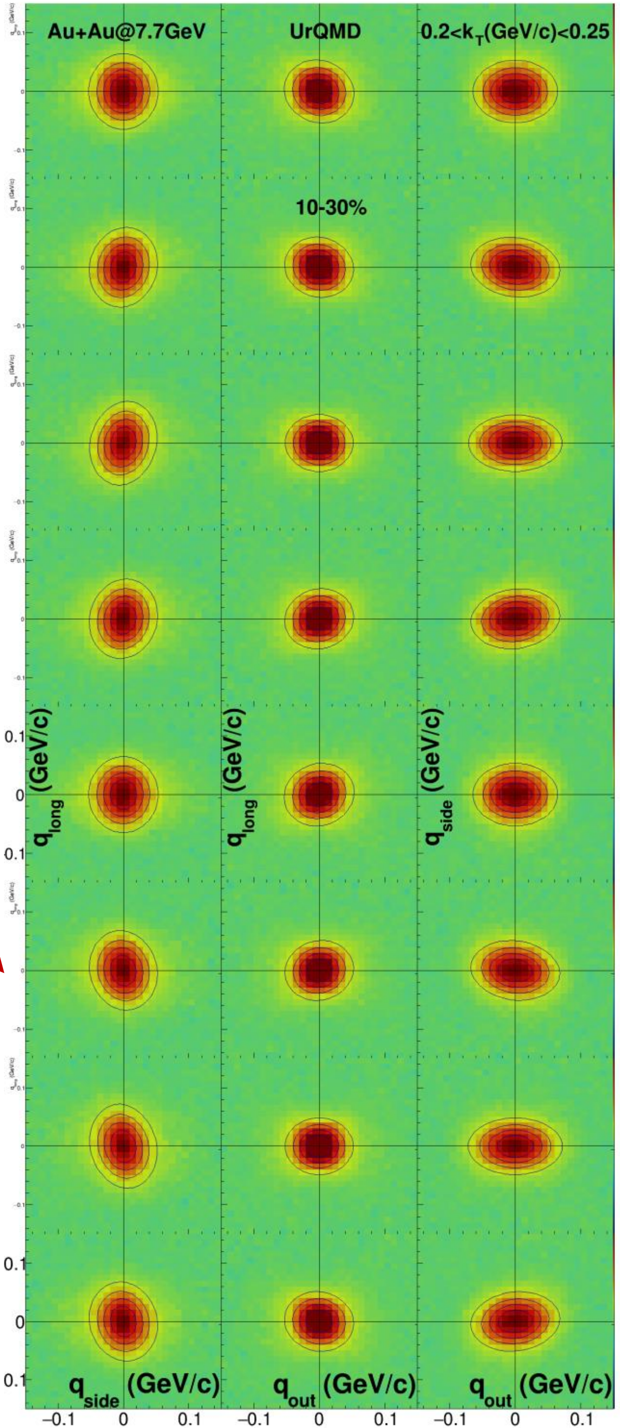
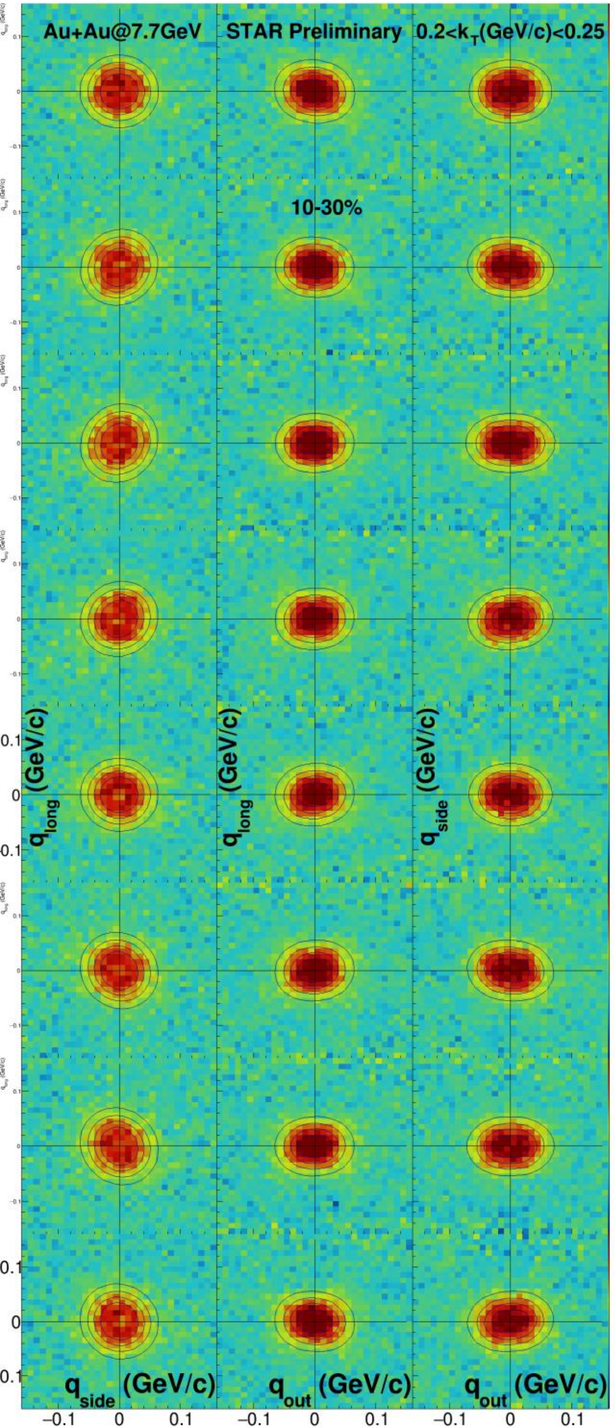
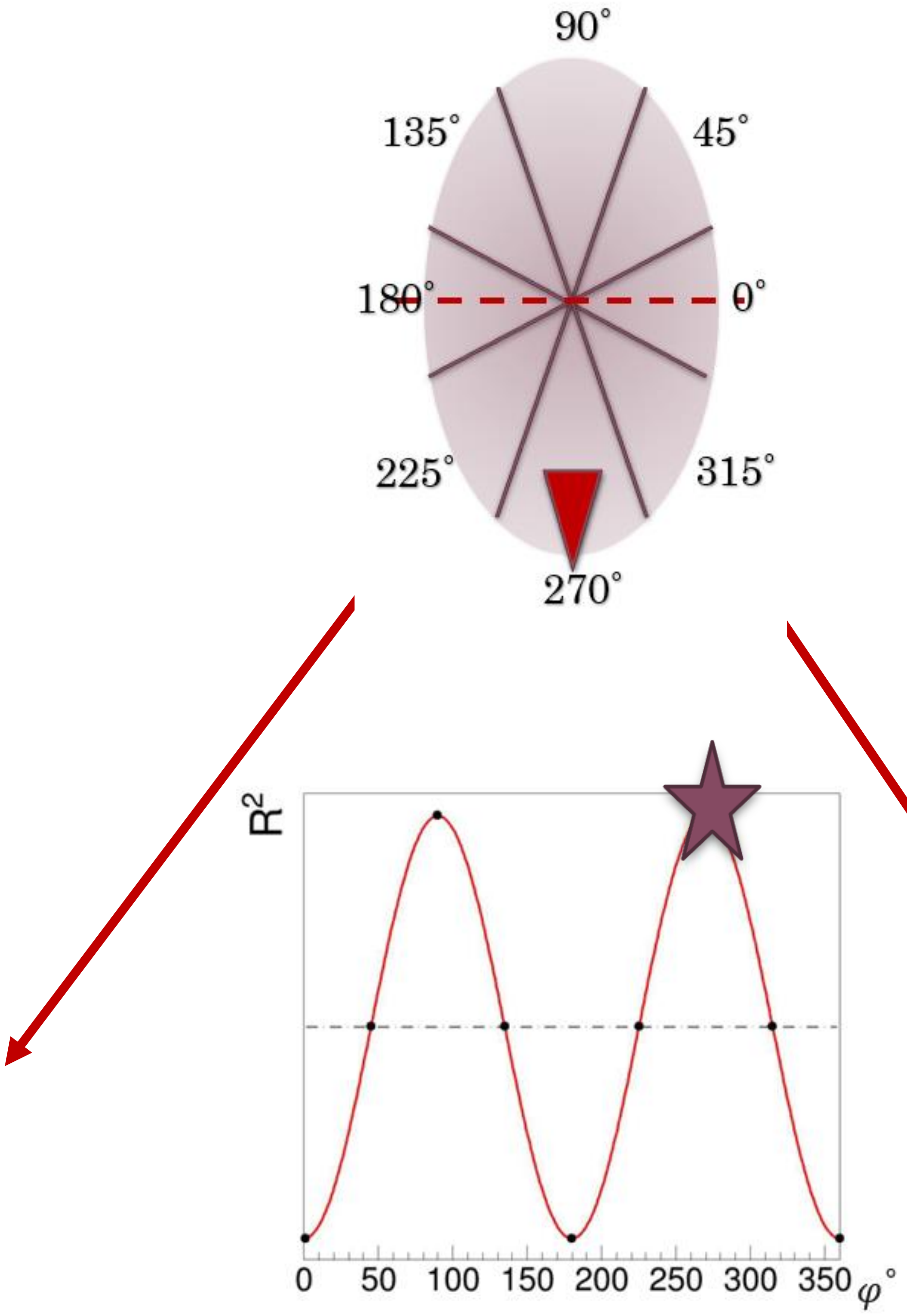
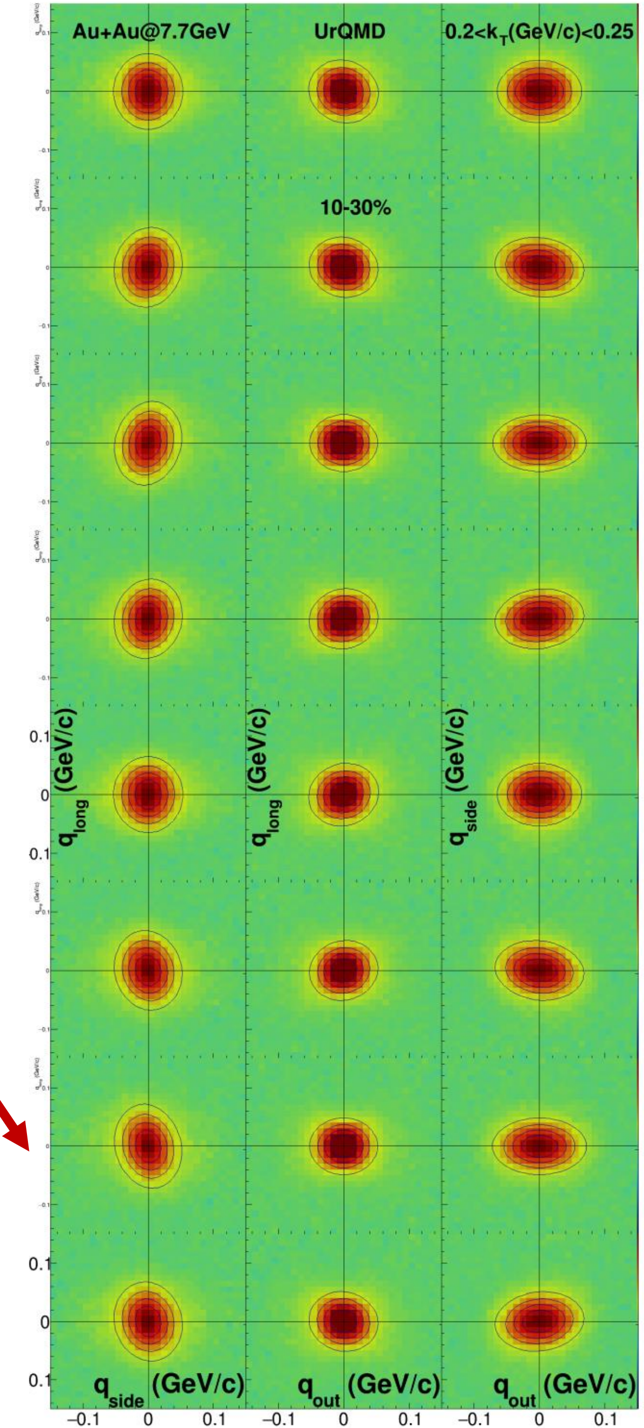
315°
270°

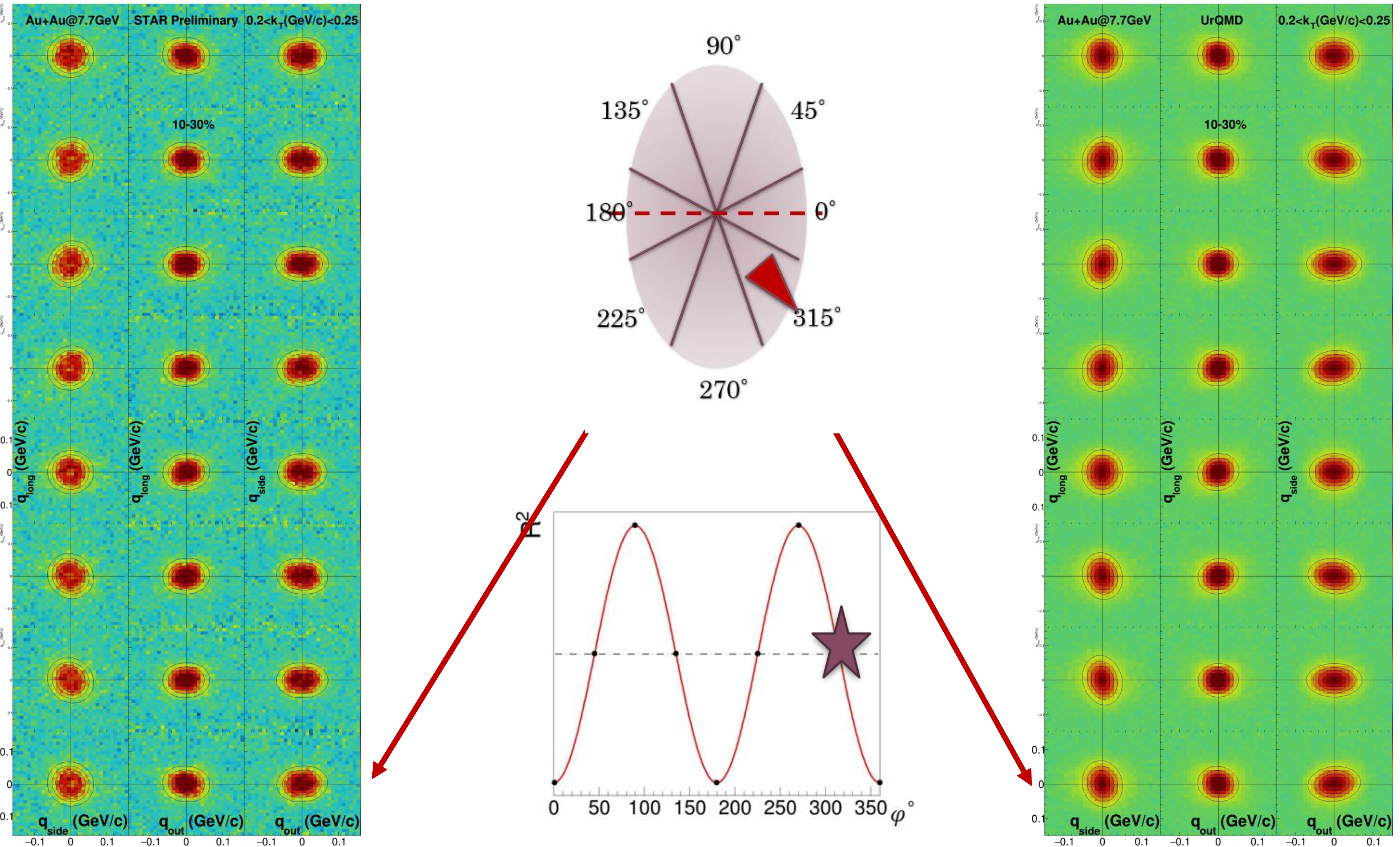

R²
0
50
100
150
200
250
300
350
φ°


Au+Au@7.7GeV
UrQMD
0.2<k_T(GeV/c)<0.25
10-30%
q_long (GeV/c)
q_side (GeV/c)
q_out (GeV/c)


Au+Au@7.7GeV
STAR Preliminary
0.2<k$_T$(GeV/c)<0.25
10-30%
q$_{long}$ (GeV/c)
q$_{side}$ (GeV/c)
q$_{out}$ (GeV/c)


90°
135°
45°
180°
0°
225°
315°
270°
R$^2$
0 50 100 150 200 250 300 350
φ°


Au+Au@7.7GeV
UrQMD
0.2<k$_T$(GeV/c)<0.25
10-30%
q$_{long}$ (GeV/c)
q$_{side}$ (GeV/c)
q$_{out}$ (GeV/c)


Au+Au@7.7GeV
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0.2<k_T(GeV/c)<0.25
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q_out (GeV/c)
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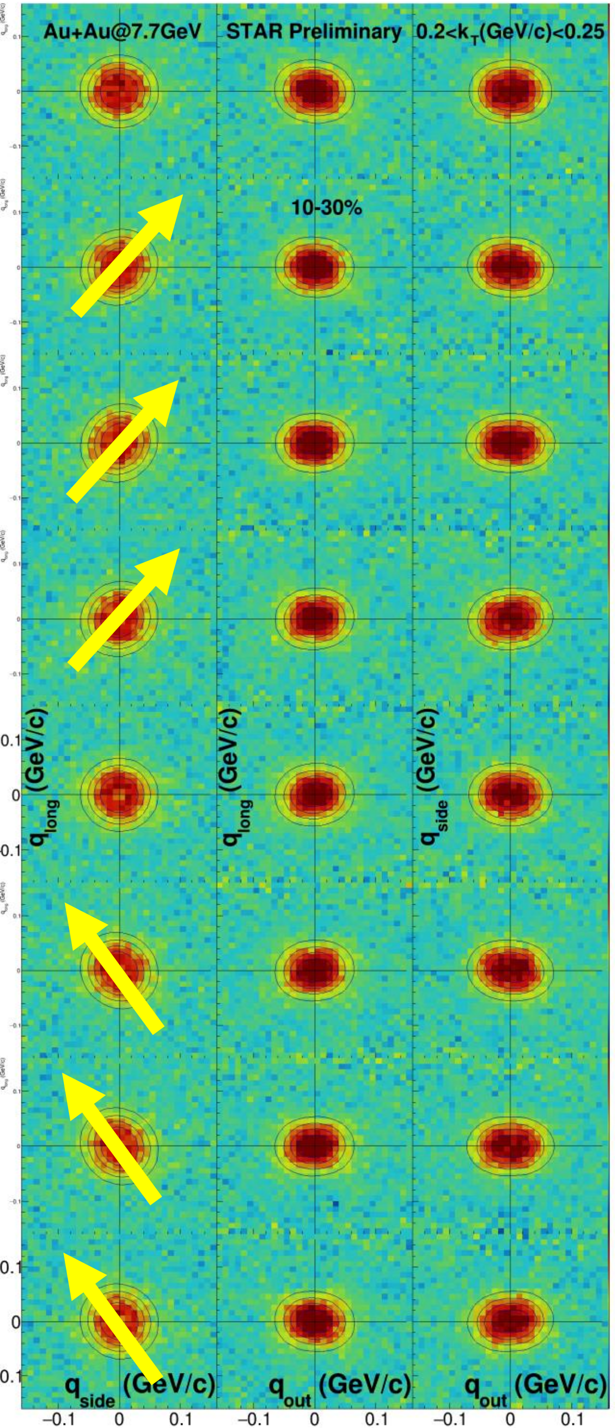
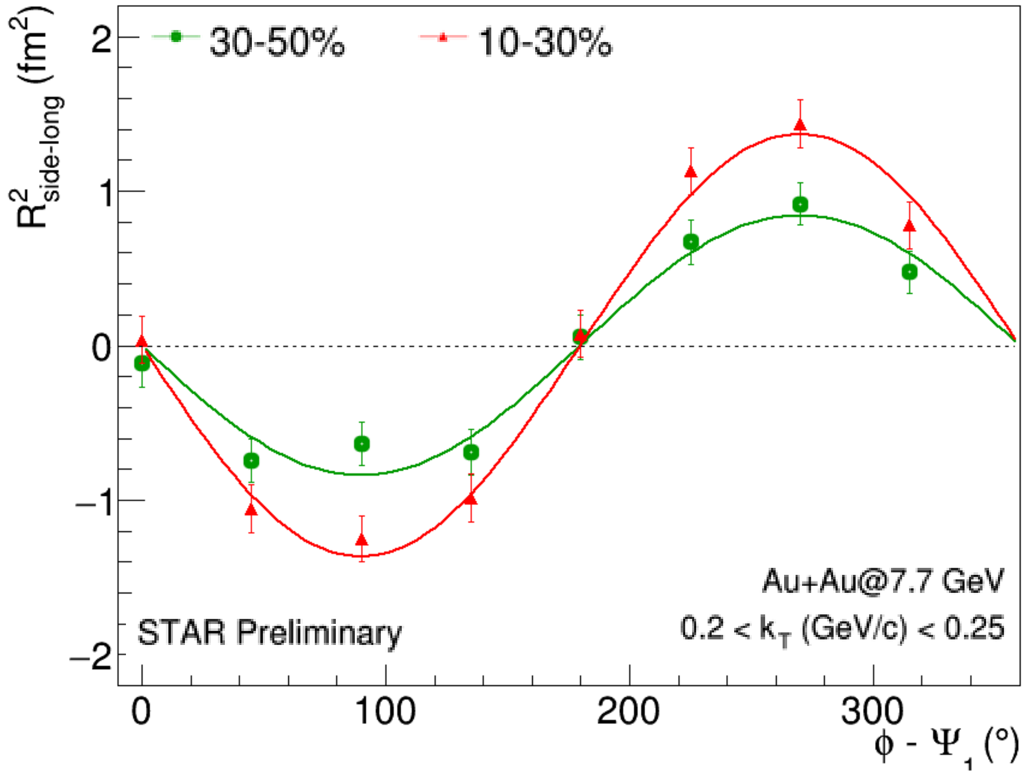
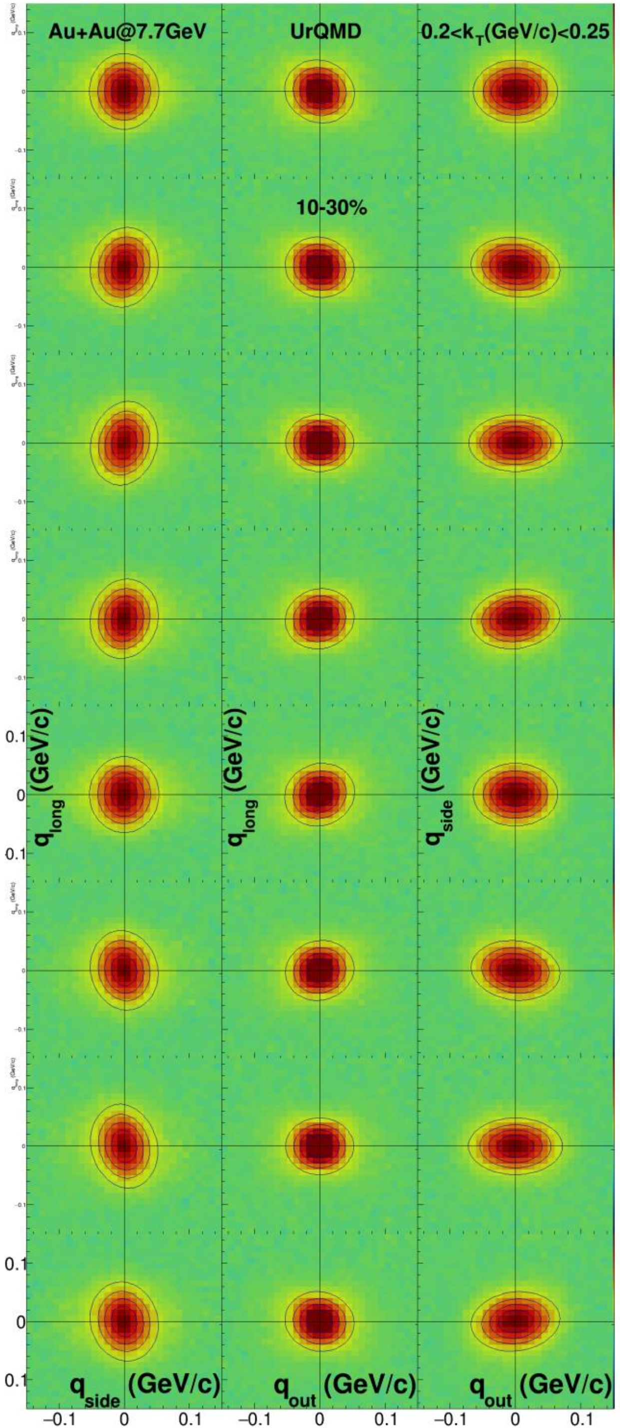
135°
45°
180°
0°
225°
315°
270°
R^2
0 50 100 150 200 250 300 350
φ°
Au+Au@7.7GeV
UrQMD
0.2<k_T(GeV/c)<0.25
10-30%
q_long (GeV/c)
q_side (GeV/c)
q_out (GeV/c)



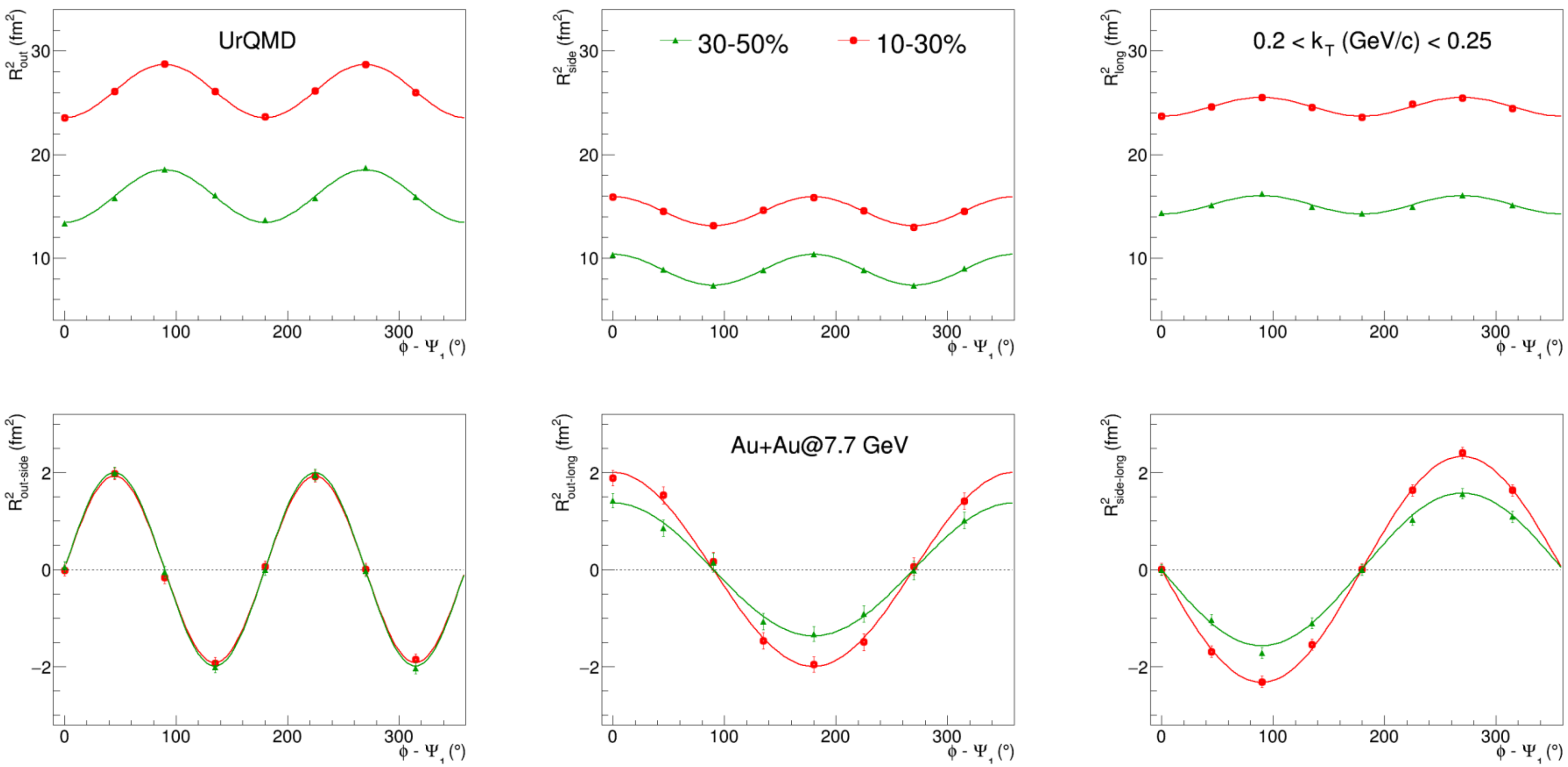

- $R_{out}, R_{side}, R_{long}$ inversely ~ width of the CF in the out, side, long directions

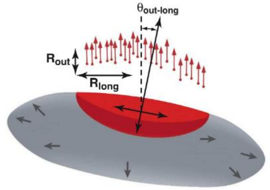



- "Cross-term" radii are reflected in the "tilt" of the CF
  - Example: $R^2_{side-long}$ shows up as a tilt of the CF in $\{q_{side}, q_{long}\}$ projection



# Radii oscillations example in UrQMD

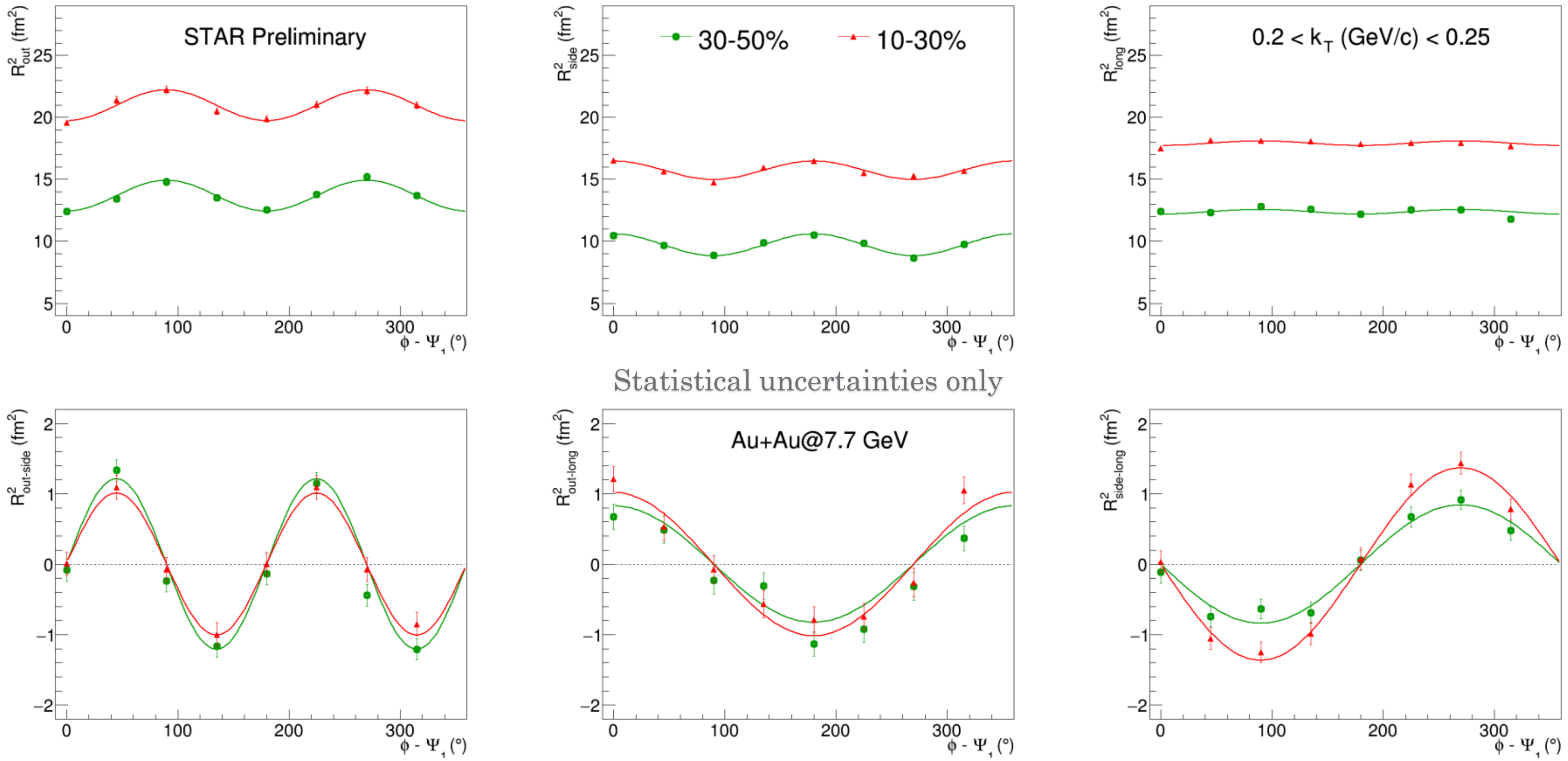


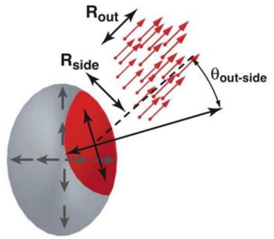




*Ann.Rev.Nucl.Part. Sci.* 55 (2005) 357-402

- $R_o^2$ 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



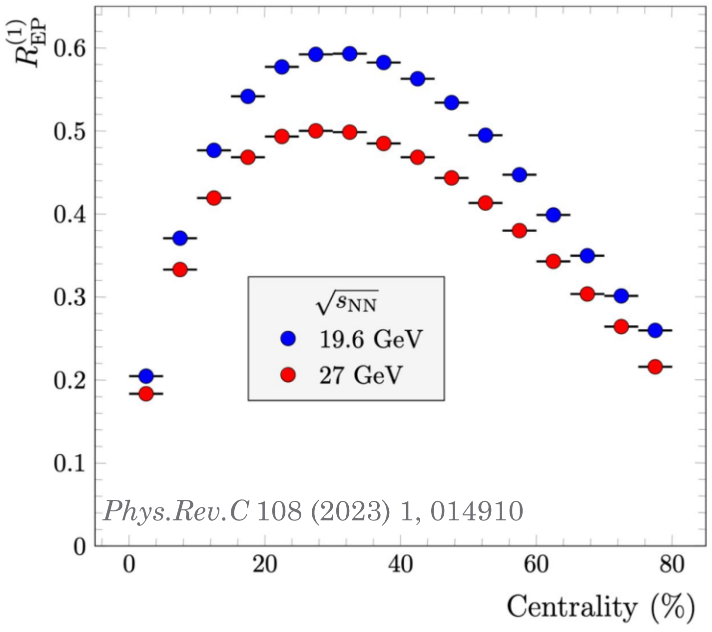



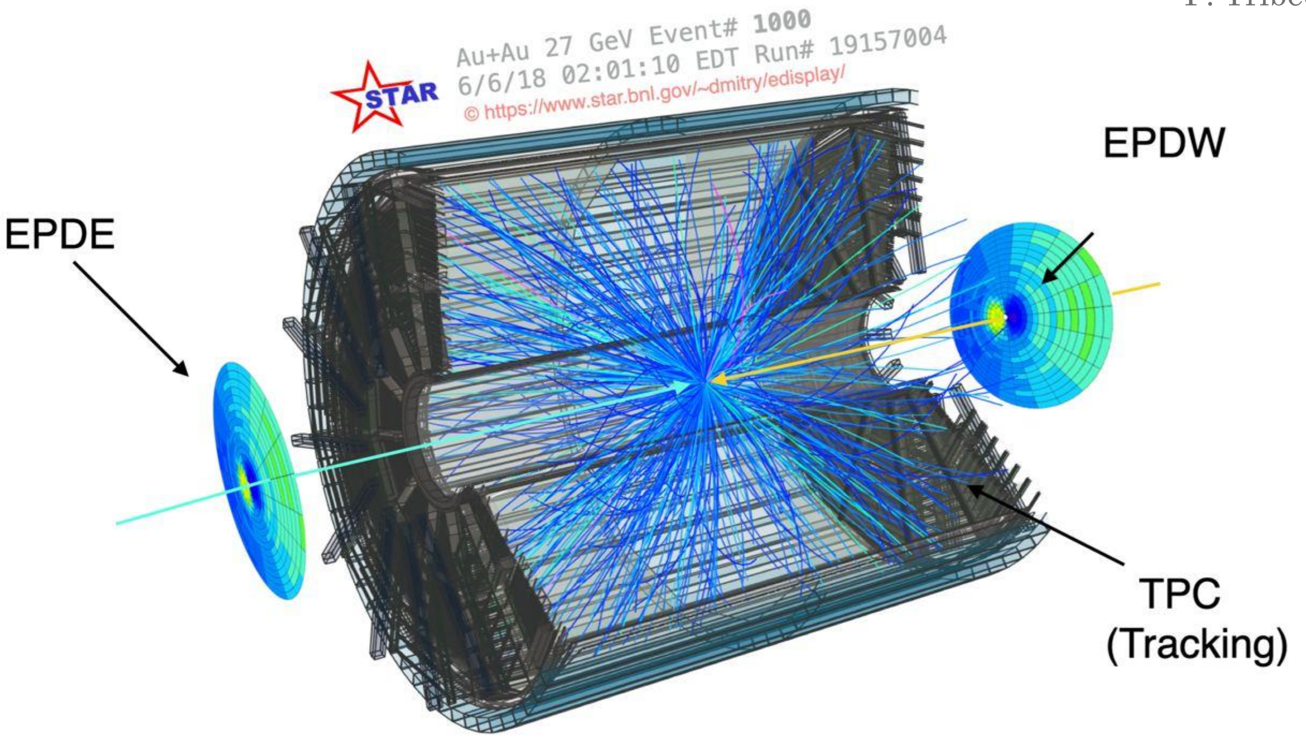

- $R_o^2$ and $R_s^2$ exhibit significant, equal and opposite oscillations in φ, reflecting an almond-shaped overlap region between the target and projectile spheres

- $R_{ol}^2$ 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

# Correction for event plane resolution

Workshop on QCD phase structure at high baryon density, CCNU, 2019
P. Tribedy

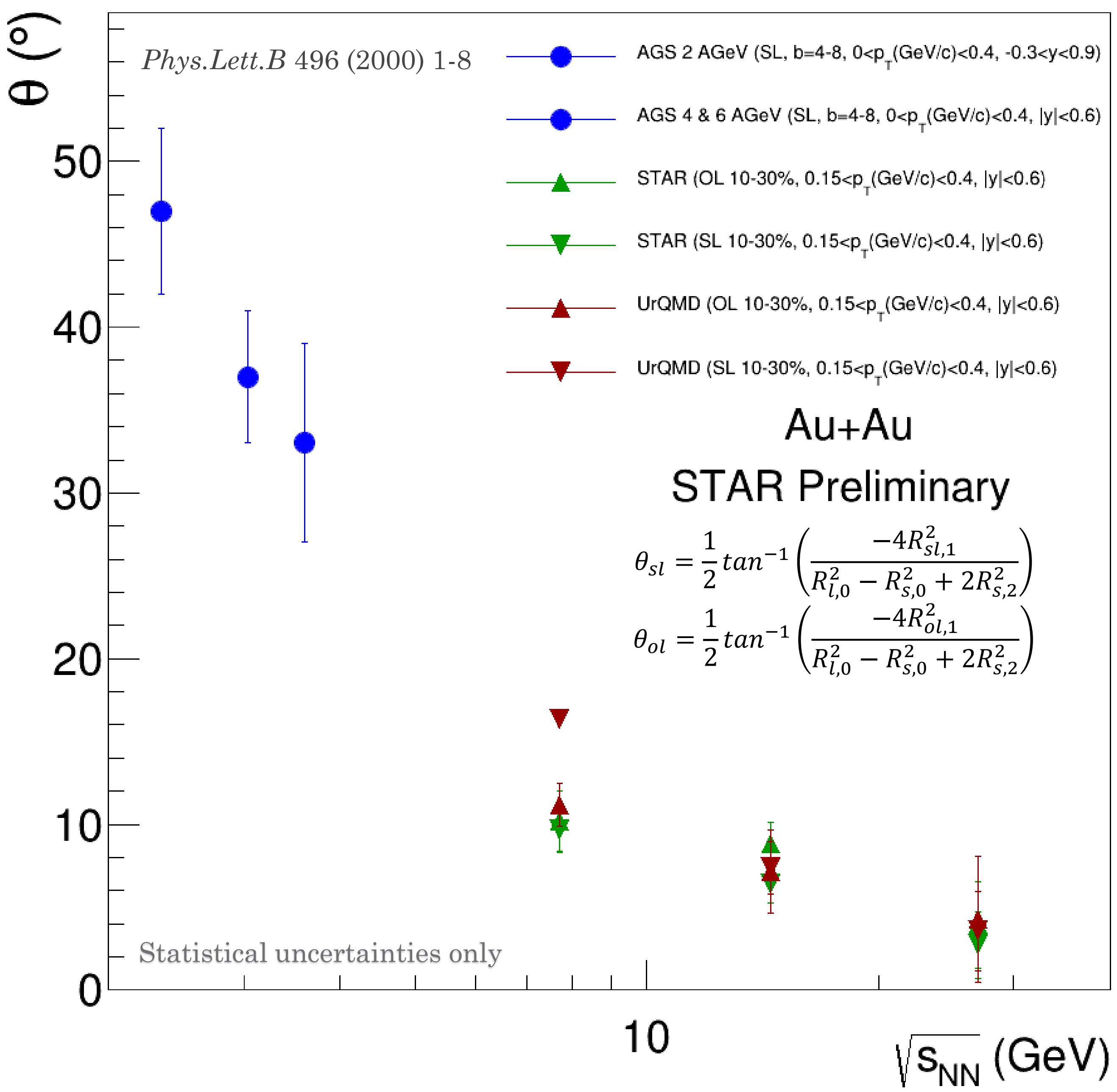



## Correction of magnitudes

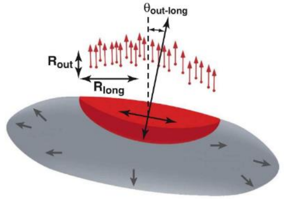
$$R_{\mu,n}^{2true} = \frac{R_{\mu,n}^{2obs}}{\langle \cos(n(\Psi_n - \Psi_{RP})) \rangle}$$

*Phys.Lett.B* 496 (2000) 1-8
*Phys.Rev.C* 92 (2015) 1, 014904
*Phys.Lett.B* 785 (2018) 320-331



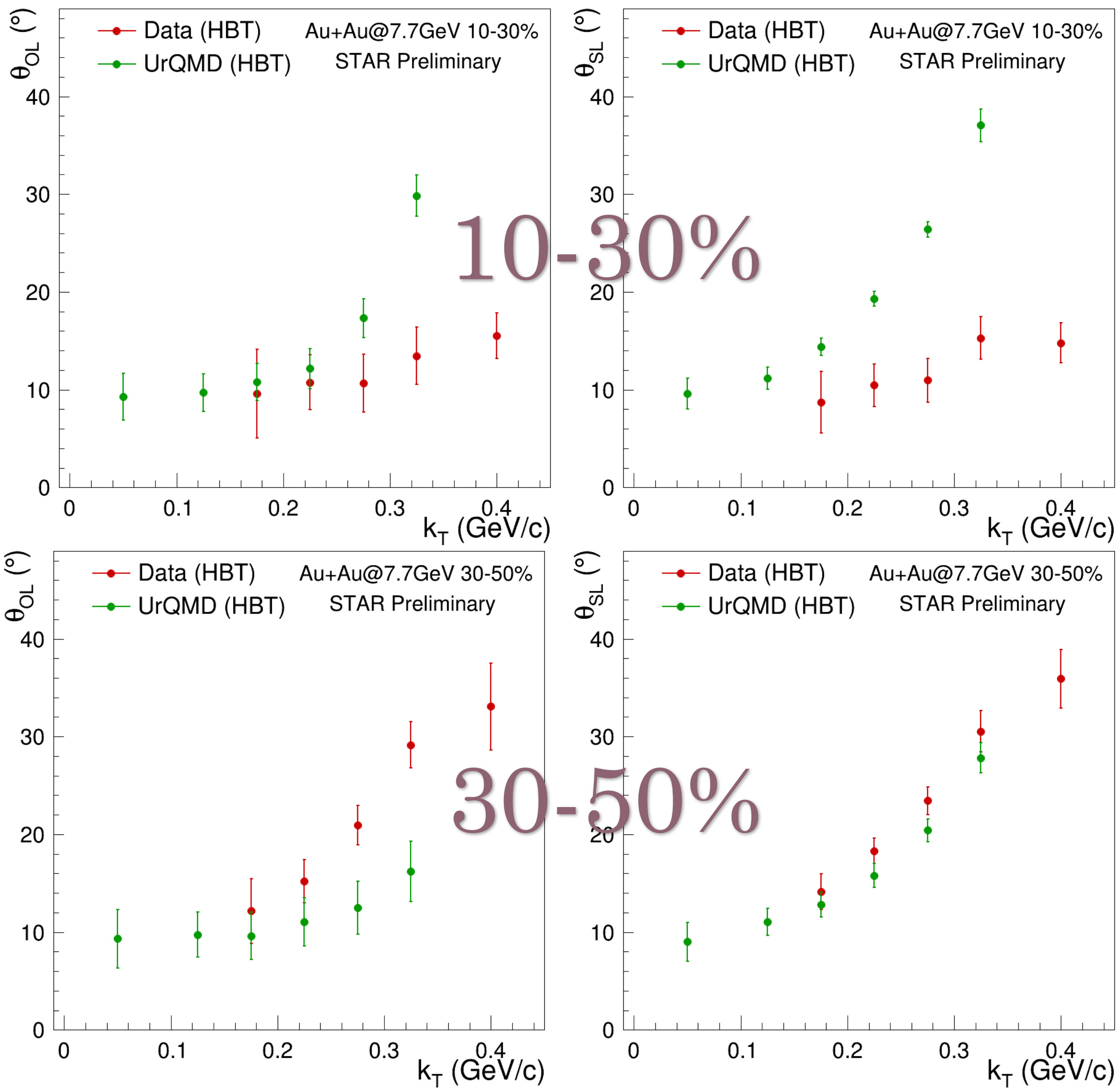

# Energy dependence of the tilt

- 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 $\theta_{SL}$ and $\theta_{OL}$ tilts



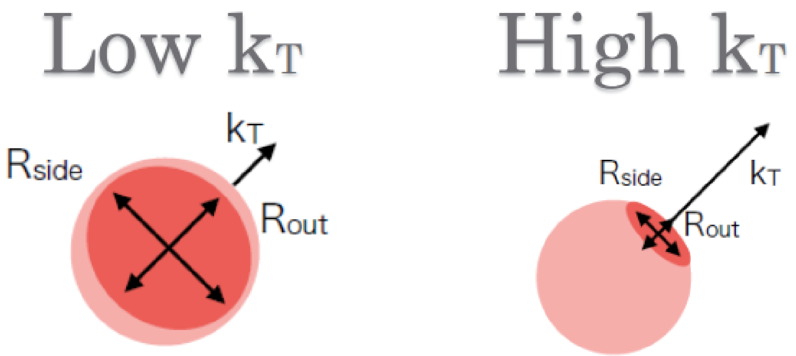

Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

Statistical uncertainties only

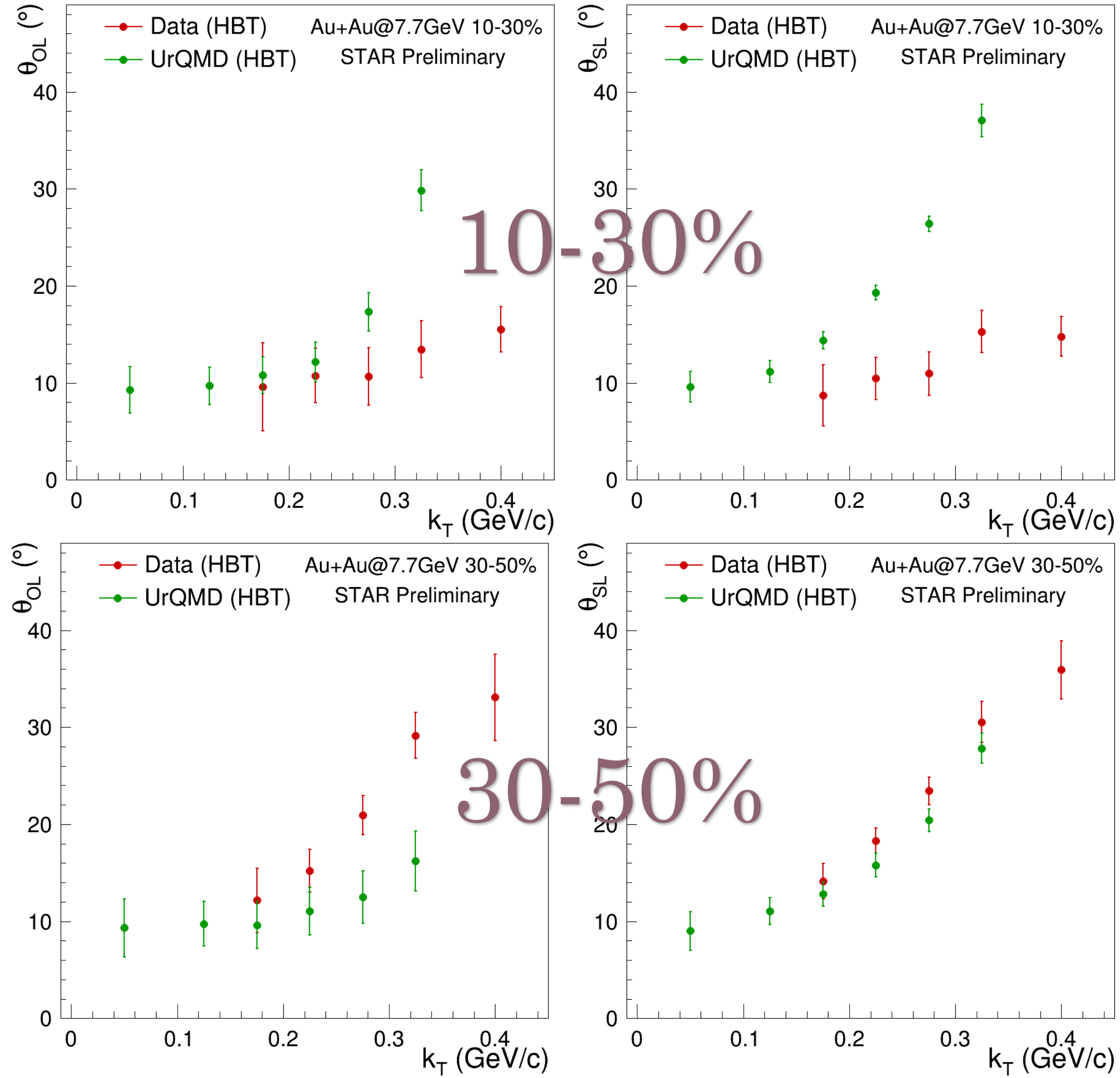



# $k_T$ dependence of the tilt in the experiment and UrQMD

- 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



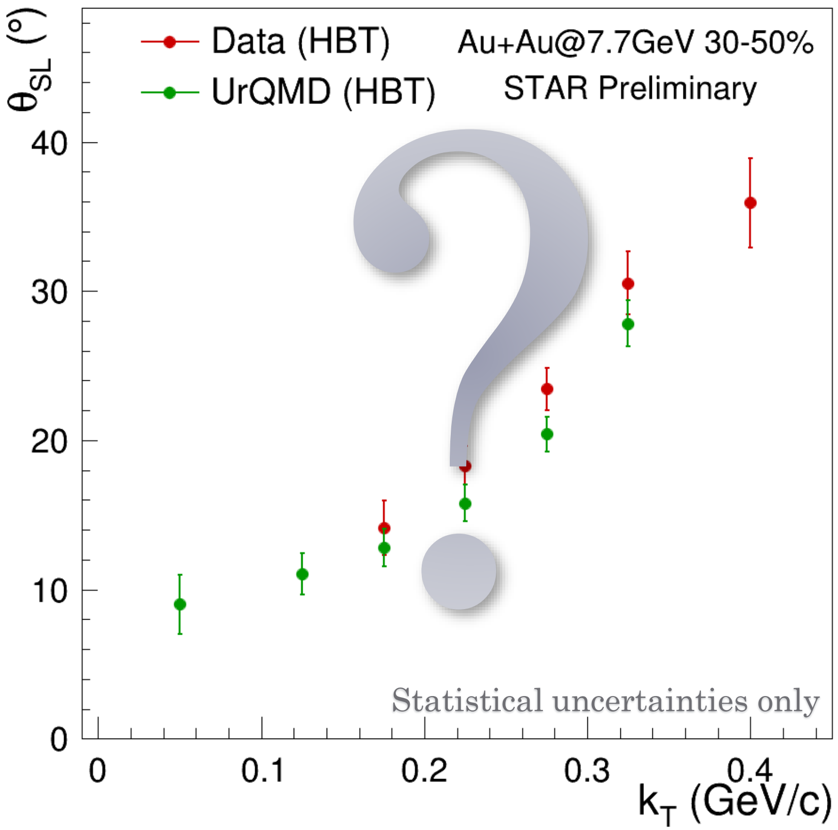
Statistical uncertainties only




# $k_T$ dependence of the tilt in the experiment and UrQMD

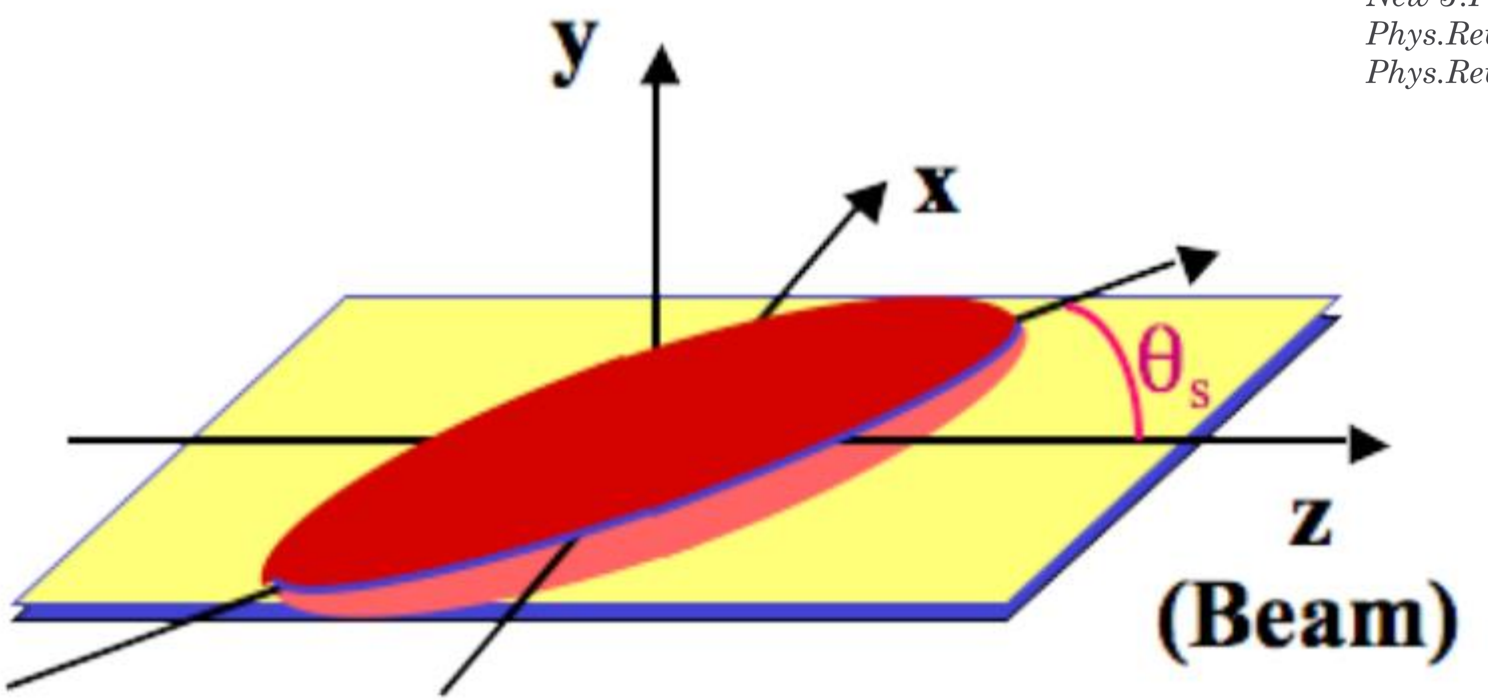
- Discrepancy between "out-long" and "side-long" tilt in UrQMD might be attributed to model limitations to describe system evolution
  - "side" radius reflects the spatial extent of the pion-emitting source, while "out" combines both spatial extent and the emission duration of the fireball
- Better agreement between experiment and UrQMD at 30-50% centrality

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



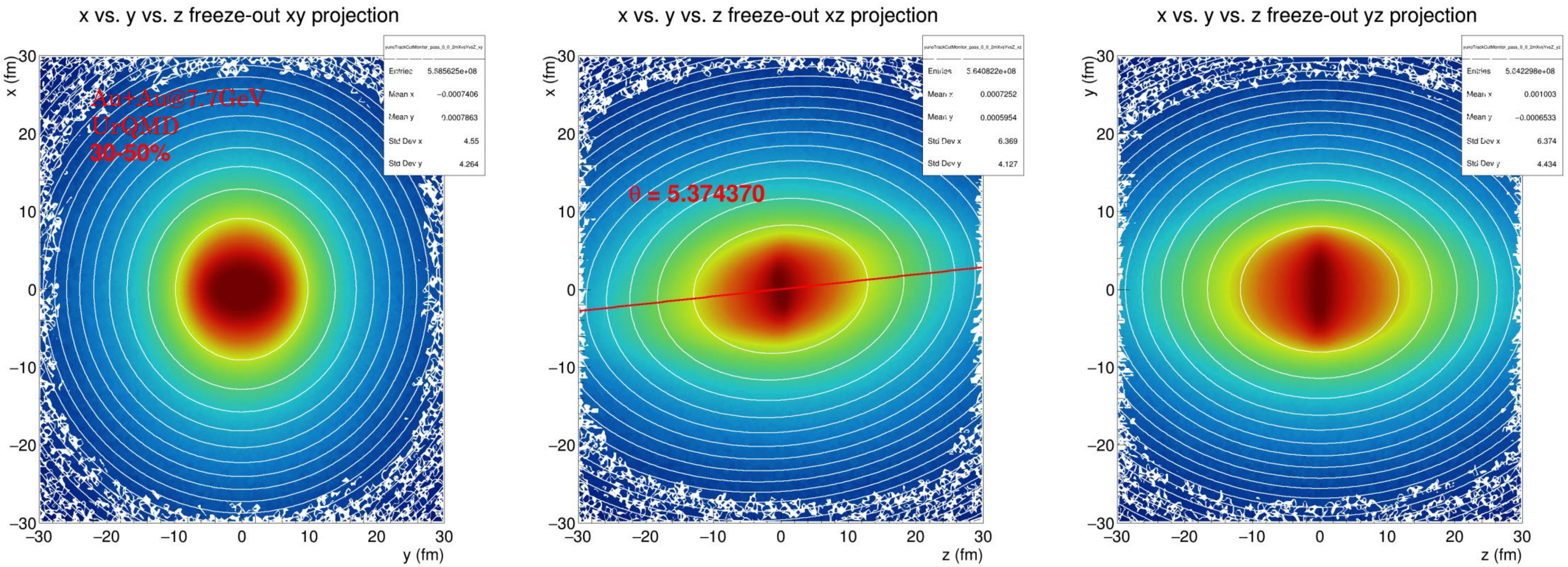
# The simplistic model with unique spatial tilt

*New J.Phys.* 13 (2011) 065006
*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



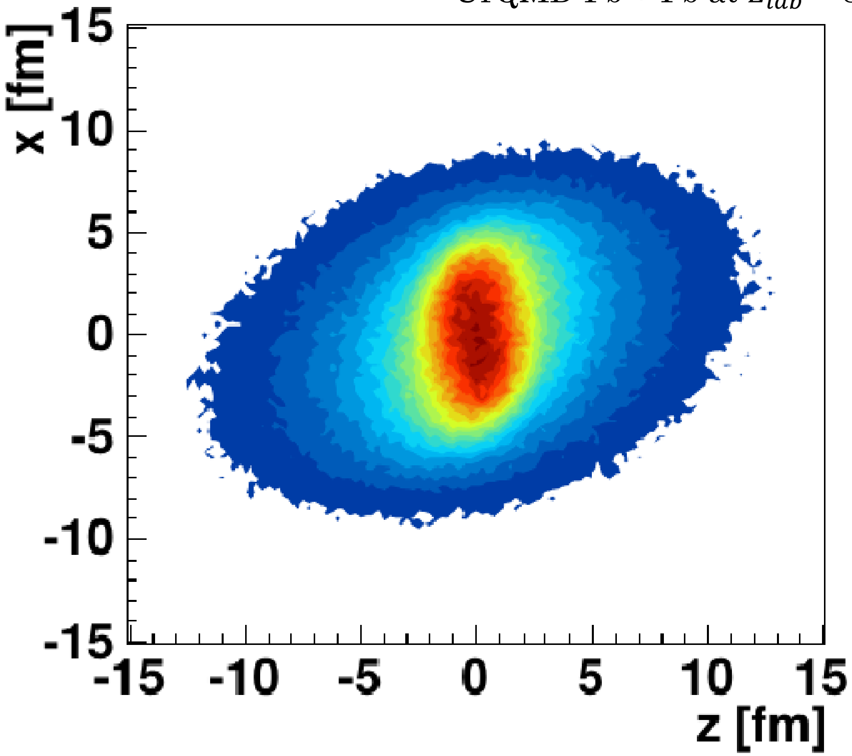

$$f(x,y,z) \sim \exp\left(-\frac{(x\cos\theta_S - z\sin\theta_S)^2}{2\sigma_{x'}^2} - \frac{y^2}{2\sigma_y^2} - \frac{(x\sin\theta_S + z\cos\theta_S)^2}{2\sigma_{z'}^2}\right)$$

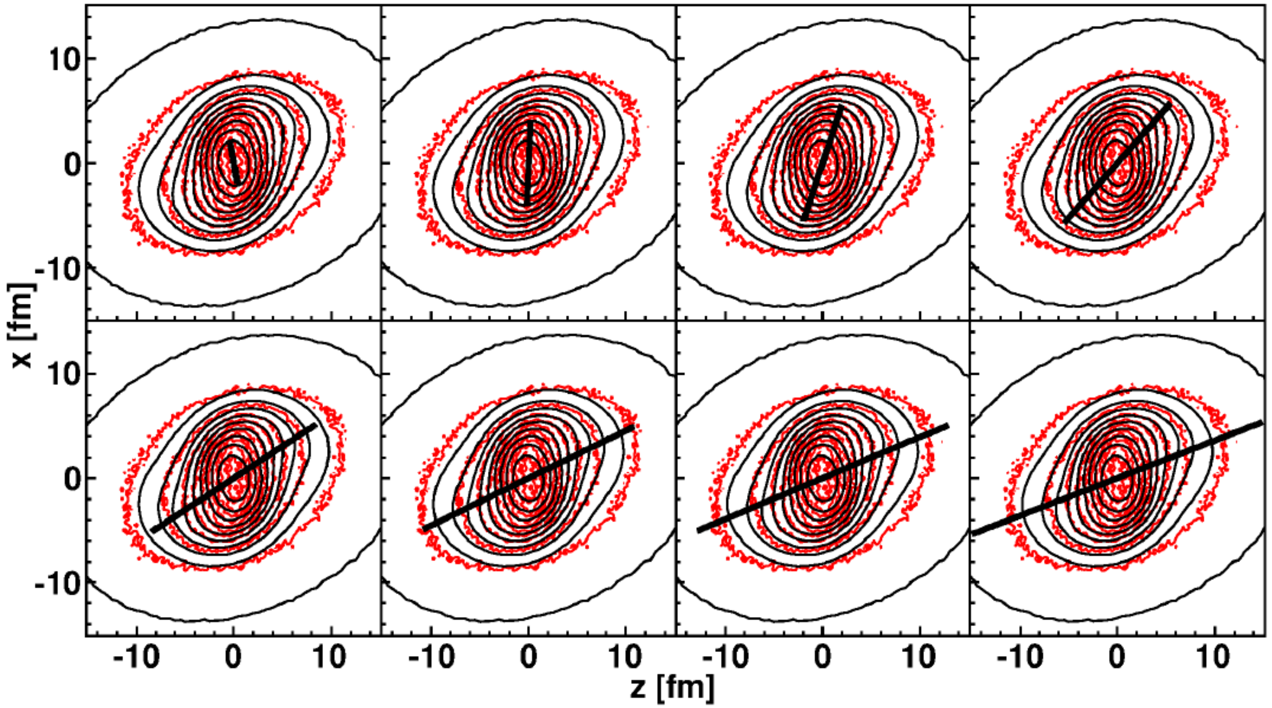
- Realistic picture is more complicated than just tilted ellipsoid

# Complicated structure of the freeze-out distribution

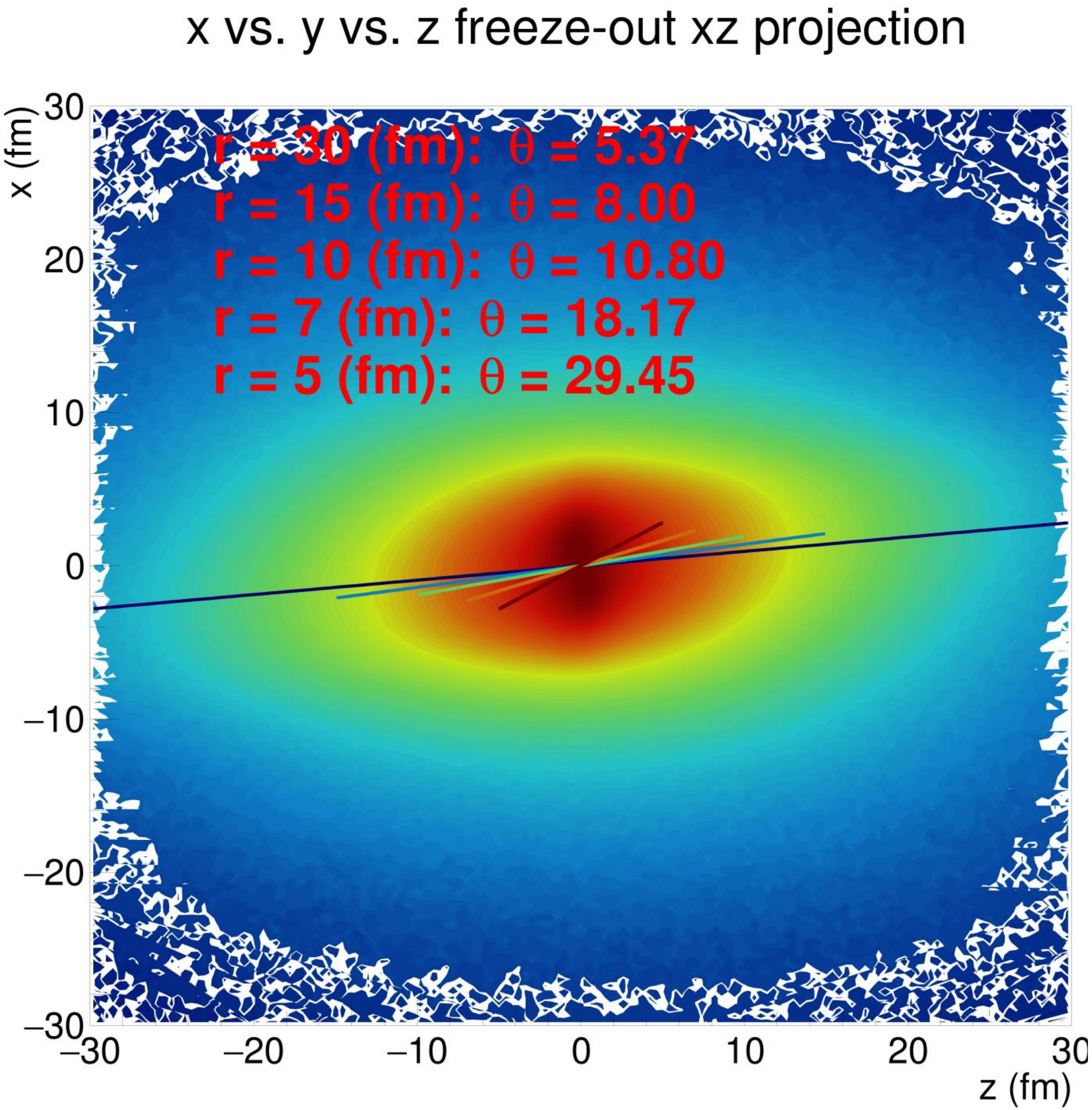
*Phys.Rev.C* 84 (2011) 014908
*Phys.Rev.C* 89 (2014) 1, 014903

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



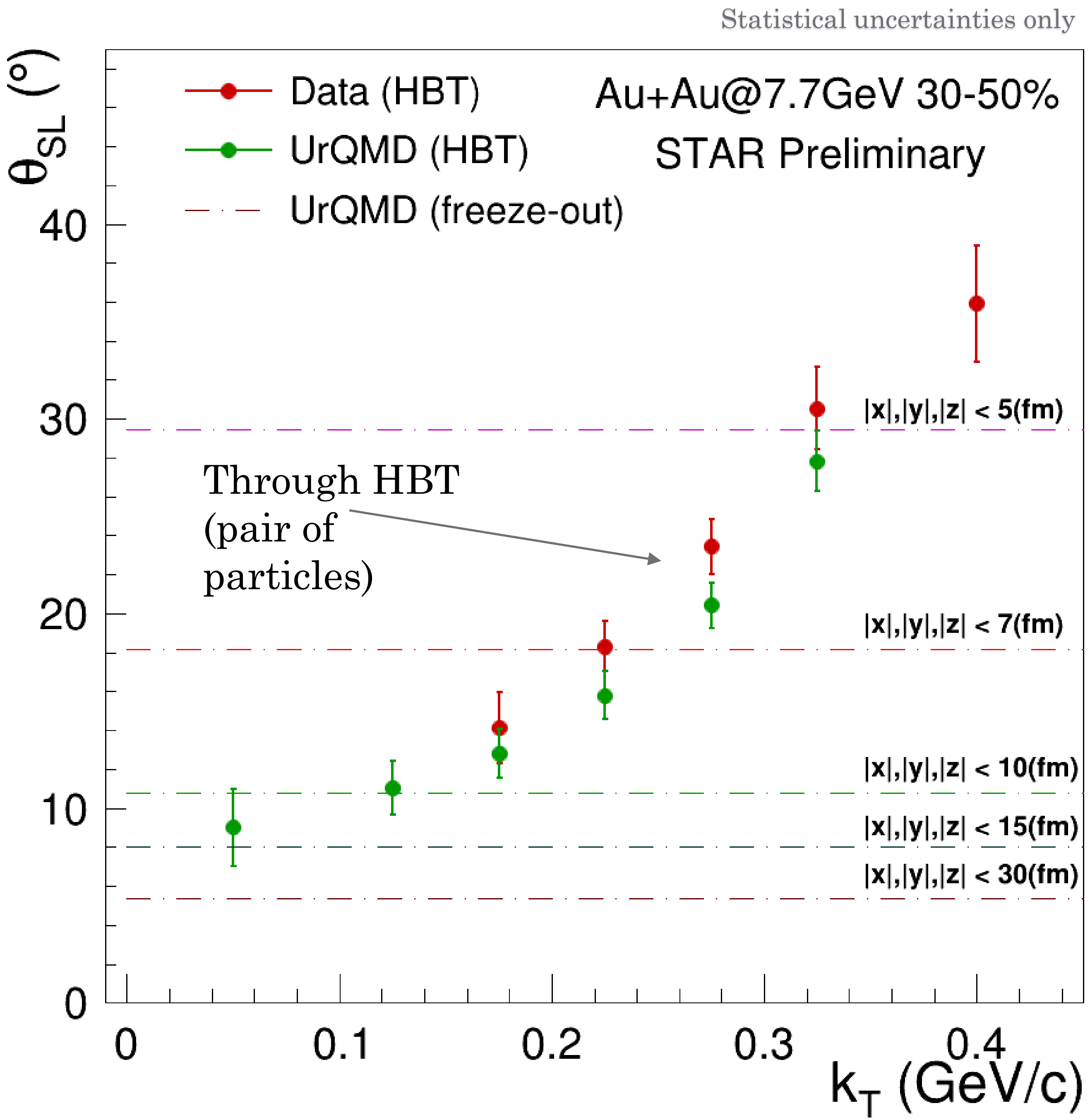

- Realistic picture reveals complex geometry and affected by non-Gaussianity of the source, collective flow…
- Extracted tilt strongly depends on the fit range in $\vec{r}\ [fm]$

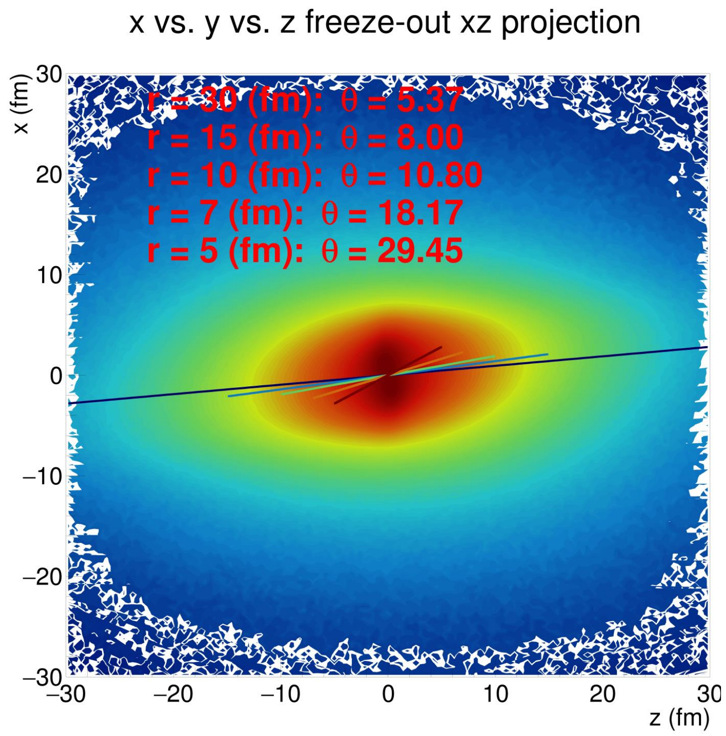


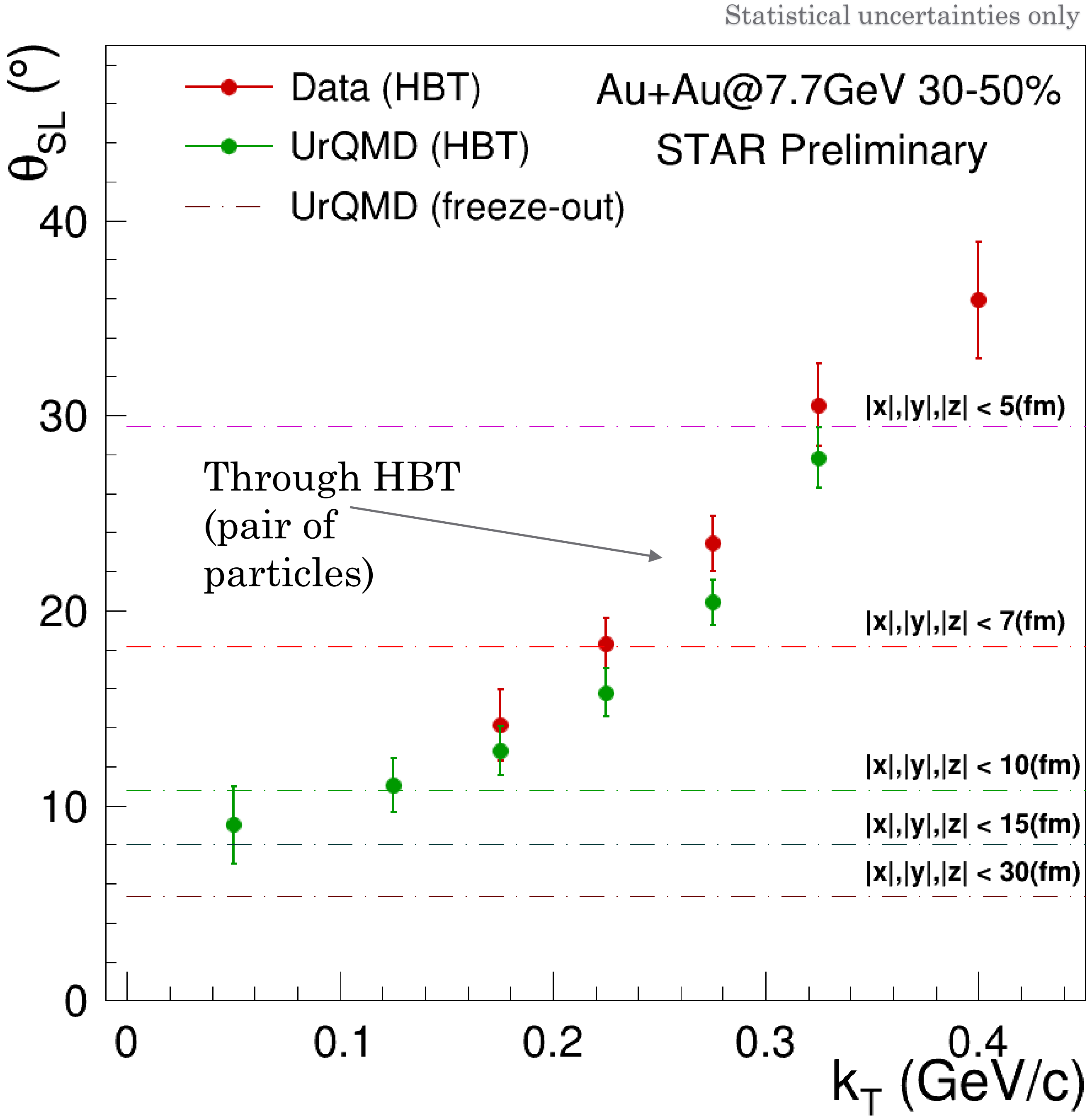

# Range of freeze-out distribution fitting

- Extracted tilt strongly depends on the spatial scale

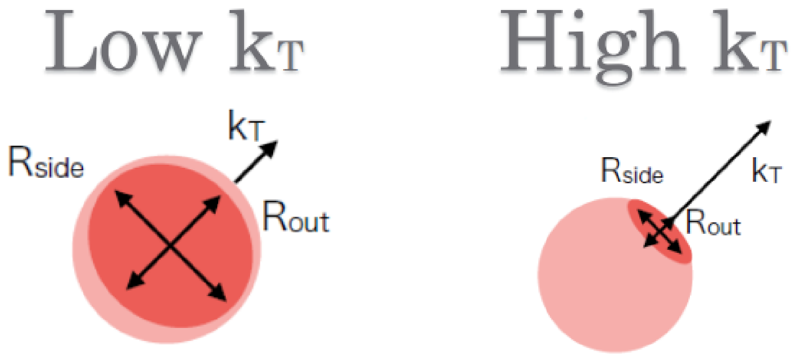
# Correspondence between femtoscopy tilt and freeze-out distribution tilt



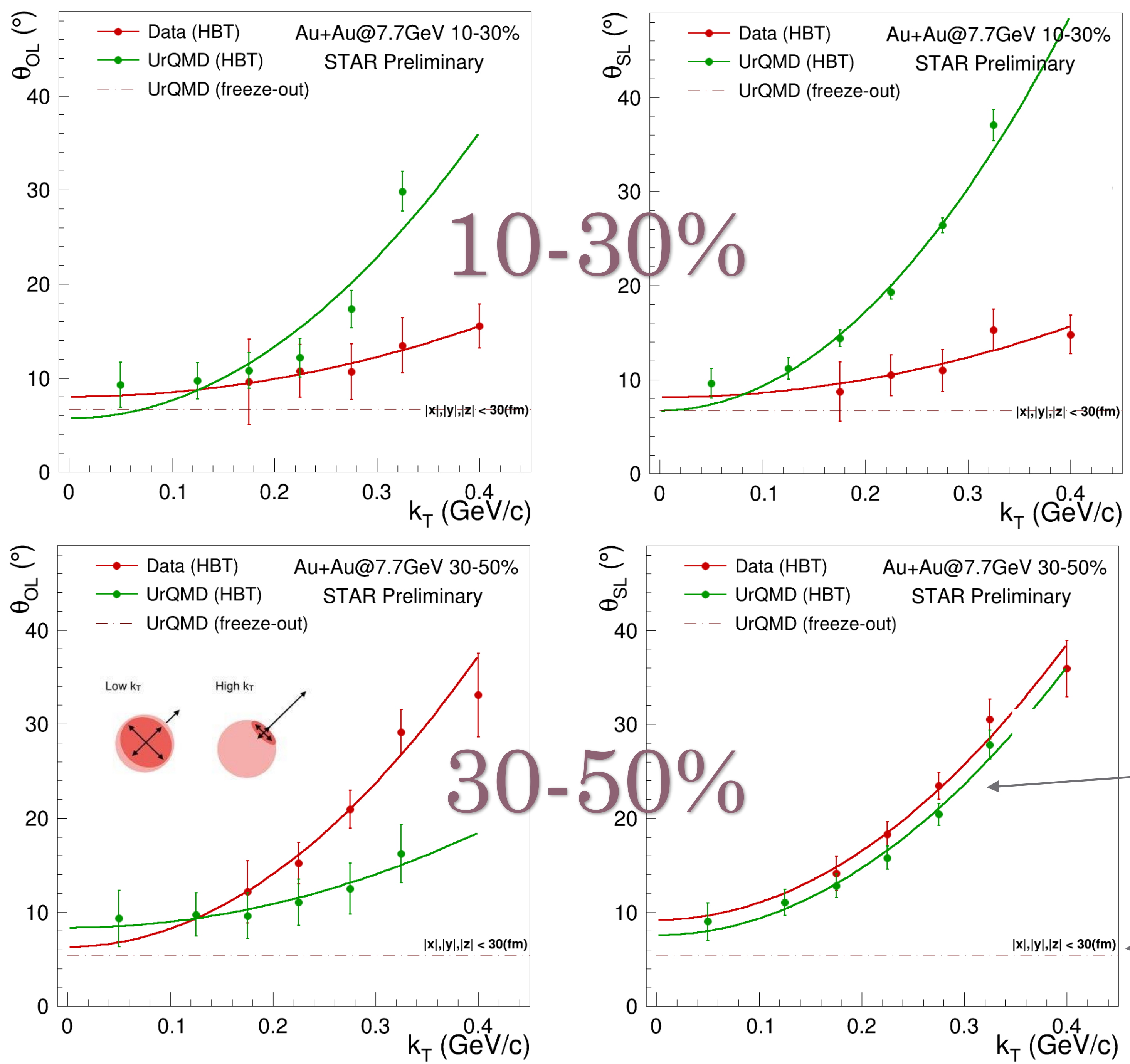



# Correspondence between femtoscopy tilt and freeze-out distribution tilt




- 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

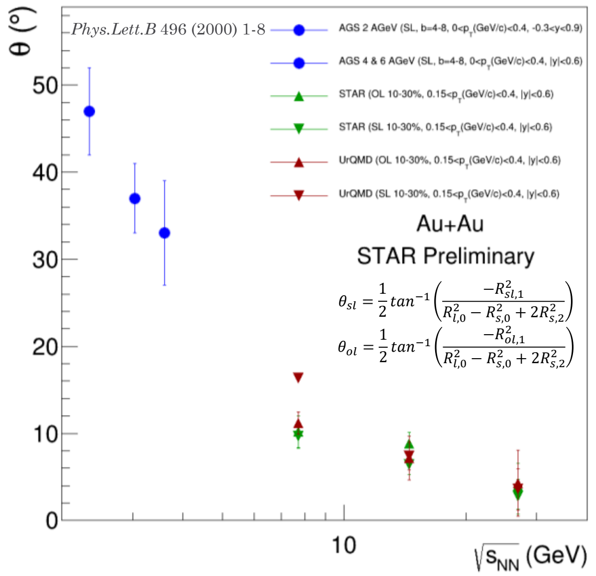
Good agreement between femtoscopy results from experiment, UrQMD and the tilt from the freeze-out distribution at low momentum

Quadratic approximation of the functional form

Through freeze-out distribution of pions

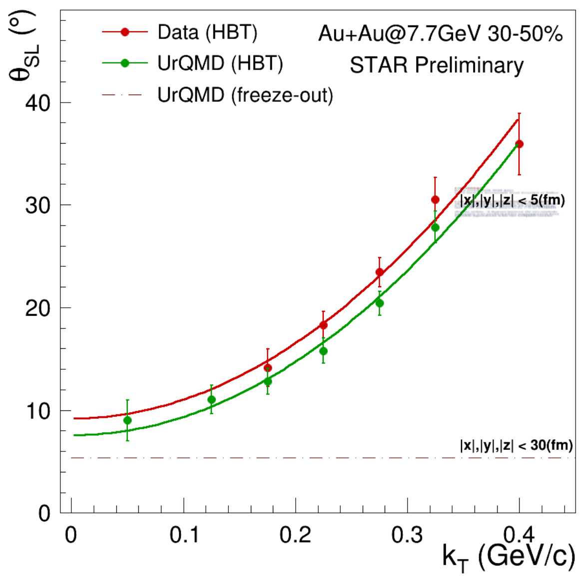
# Summary

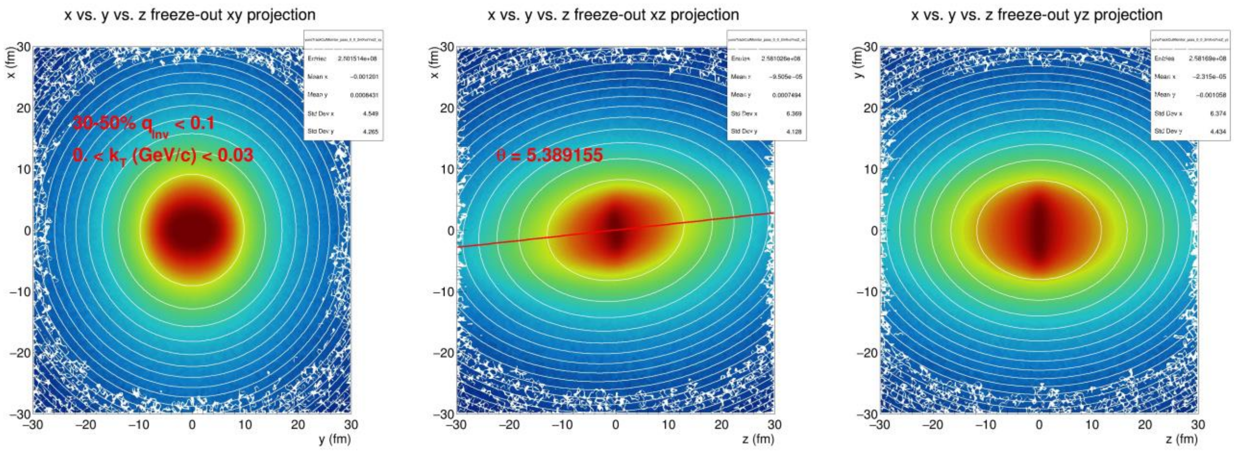
- First measurements of the spatial tilt at the RHIC energies was done
- Tilt dependence on energy
  - Obtained results in trend with AGS data
    - Collision geometry becomes increasingly boost invariant at higher energies



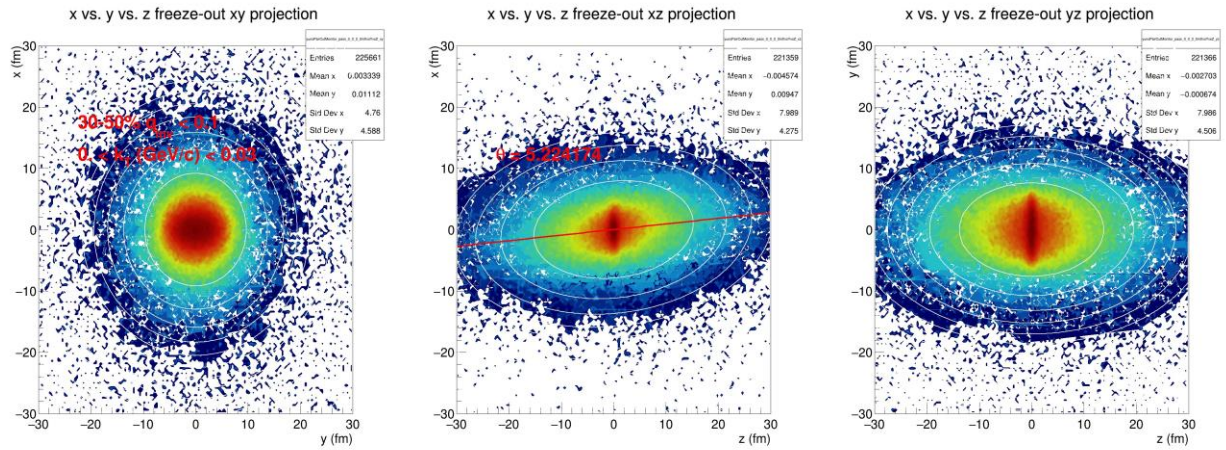

Statistical uncertainties only

- 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



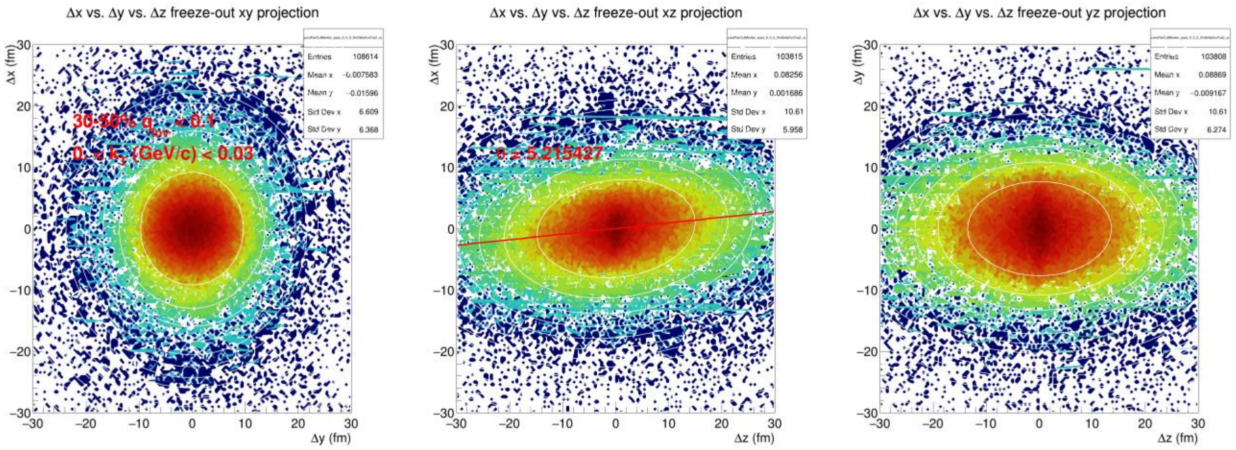



Freeze-out distribution pions




No difference for tilt

Freeze-out distribution of pairs of pions




Freeze-out distribution of pairs of pions (delta of coordinates of the pair)

Back-up slide