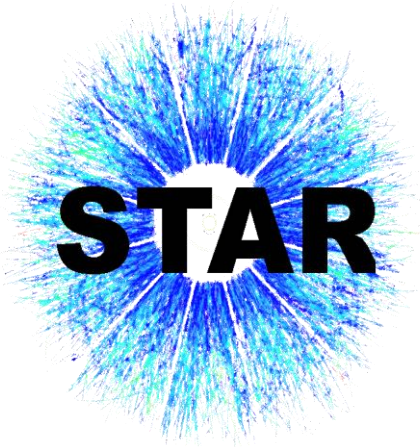
THE OHIO STATE UNIVERSITY

Supported in part by U.S. DEPARTMENT OF ENERGY | Office of Science

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

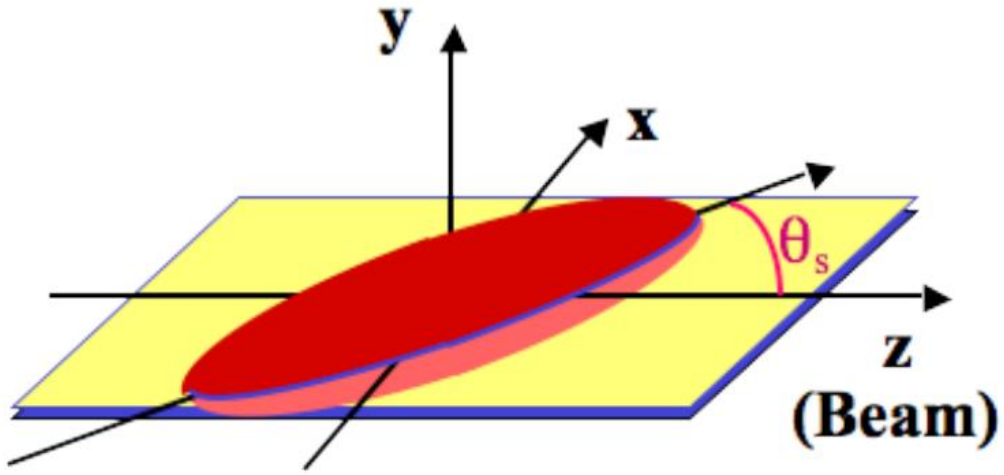
Yevheniia Khyzhniak (for the STAR Collaboration)

The 39^{th} Winter Workshop on Nuclear Dynamics

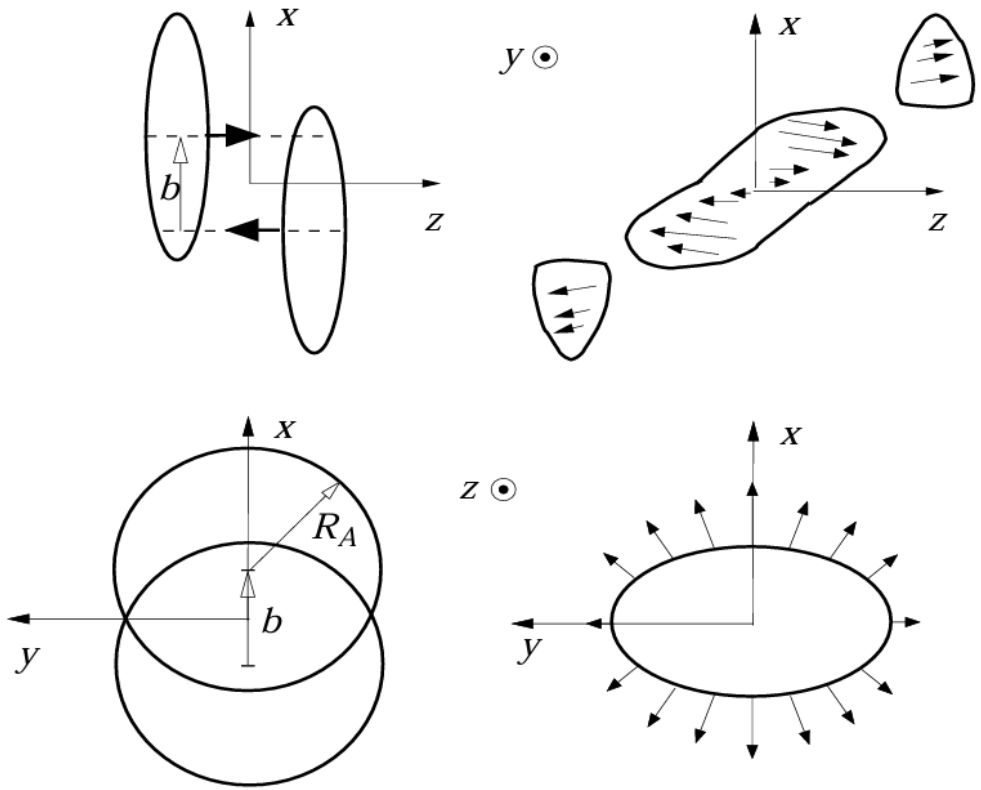


Tilted emission source

- 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

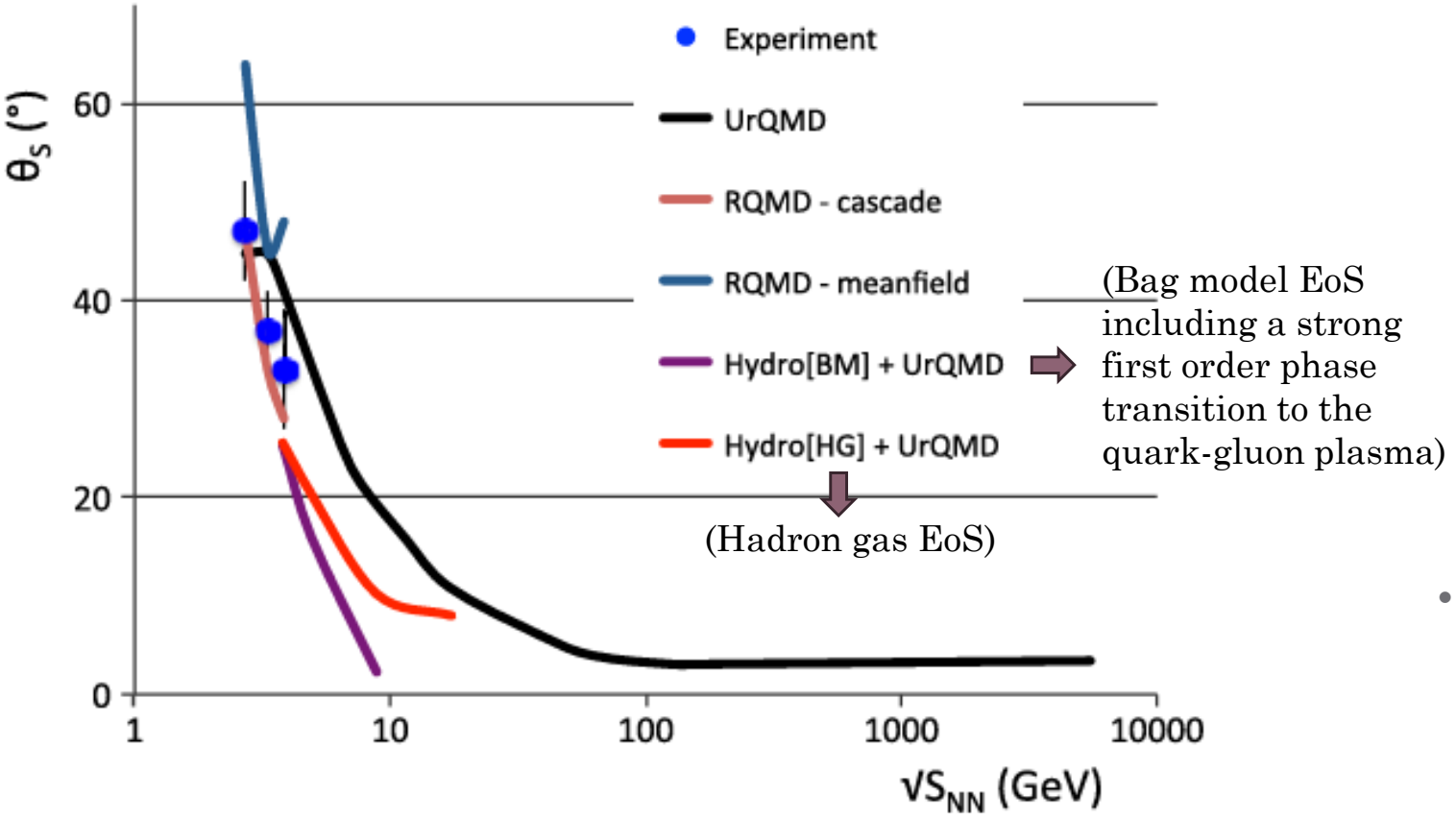


New J.Phys. 13 (2011) 065006



Phys.Rev.Lett. 94 (2005) 102301

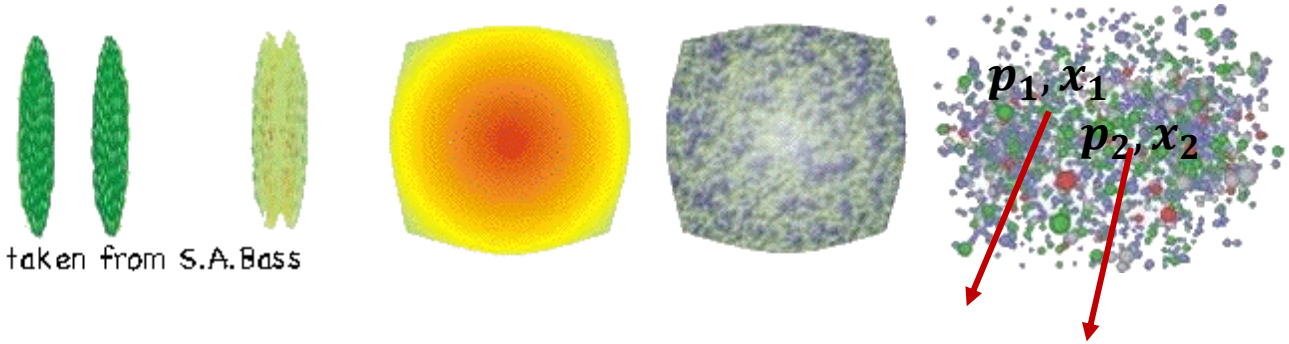
Motivation



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



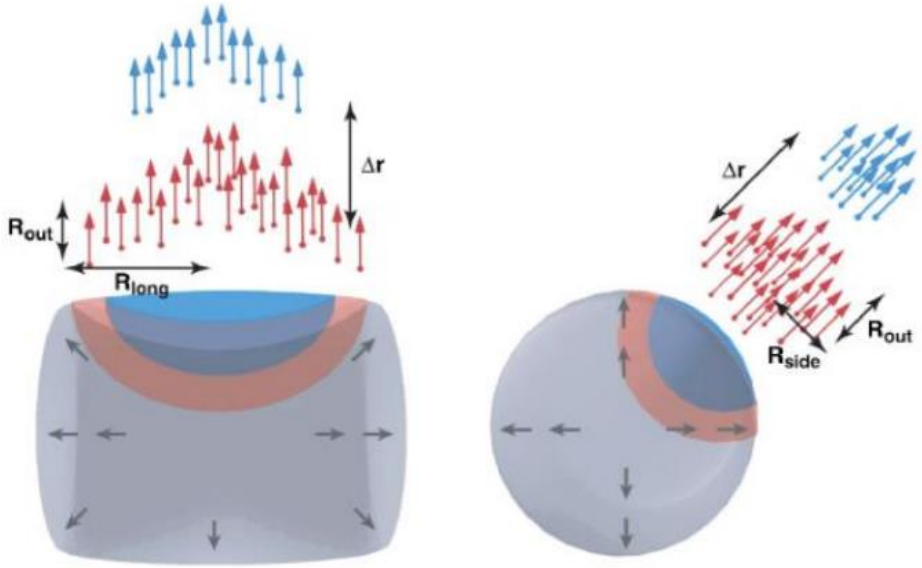
- Femtoscopy measures so-called regions of homogeneity (phase space region of outgoing particles with similar velocity vector)
- We can probe different homogeneity regions by varying pairs' transverse momenta

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

Kinetic freeze-out

↓

Femtoscopy



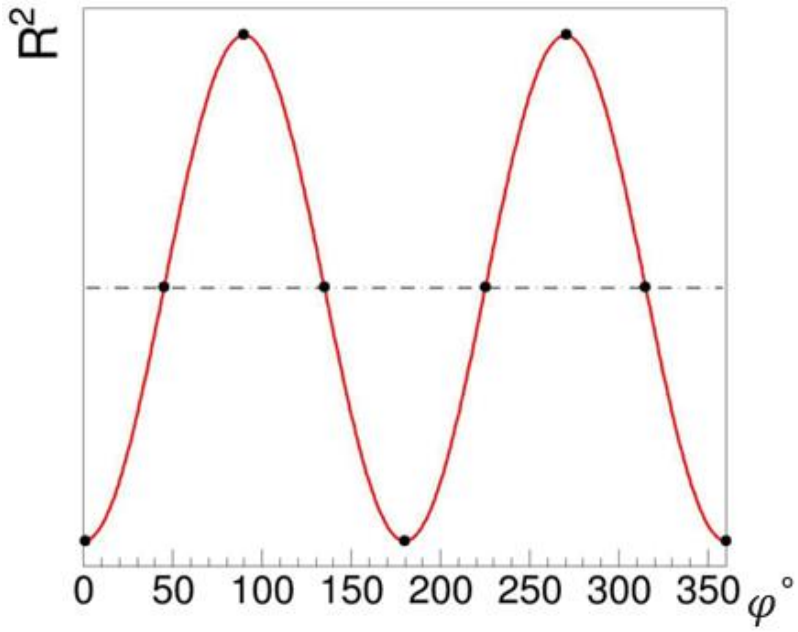
Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

- 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

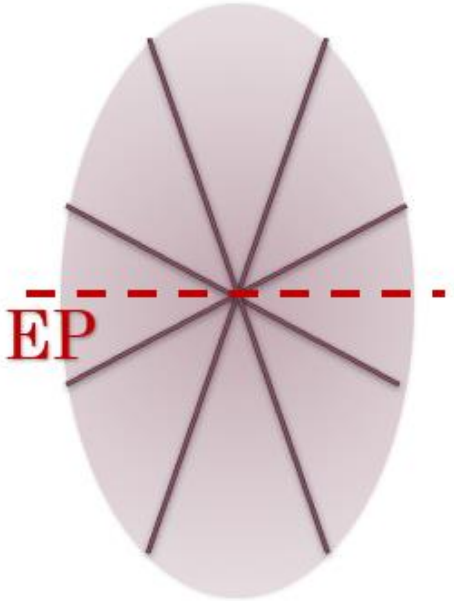
Radii response



- 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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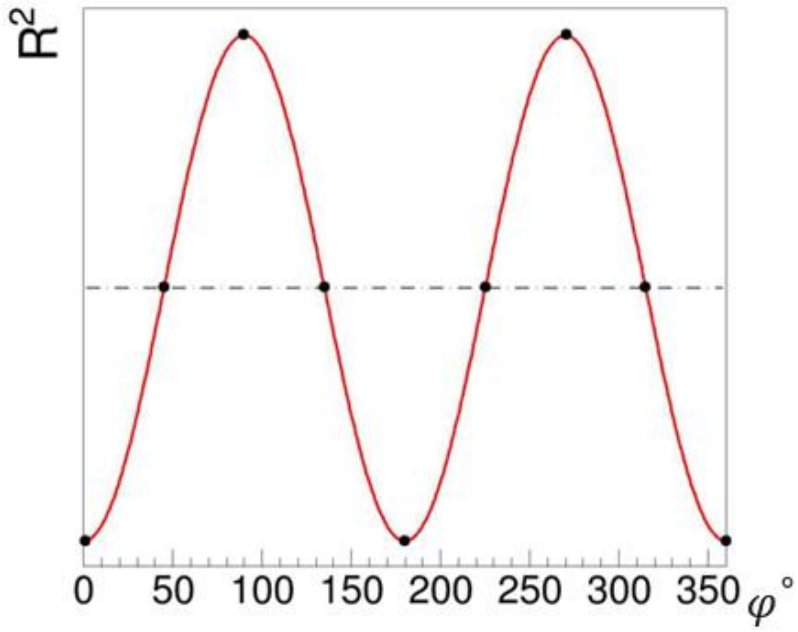

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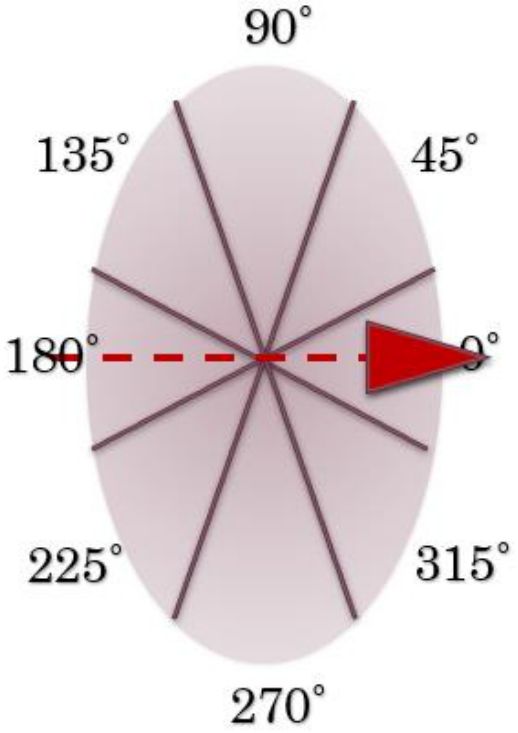

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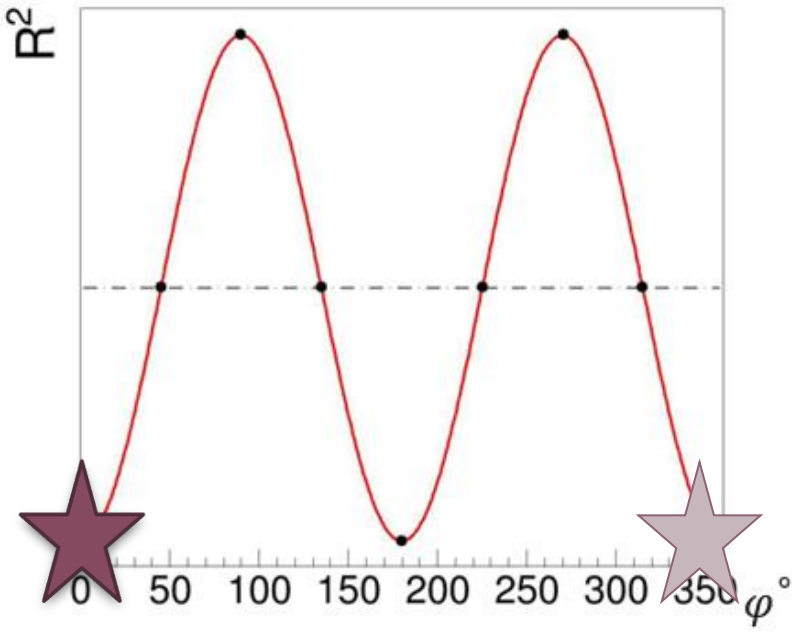

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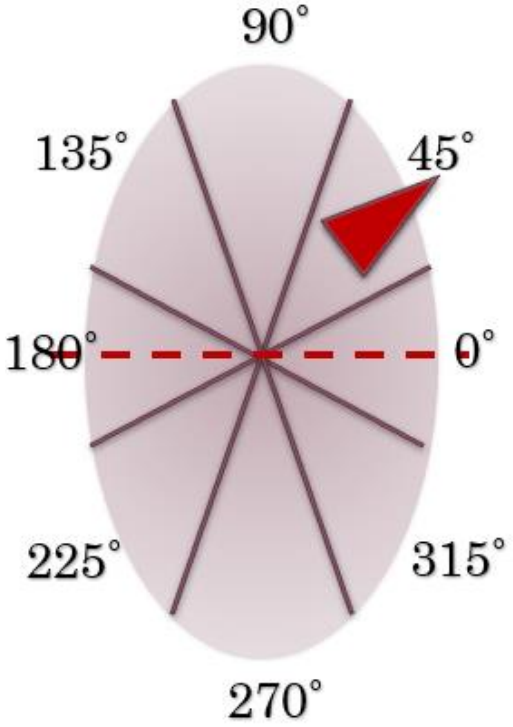

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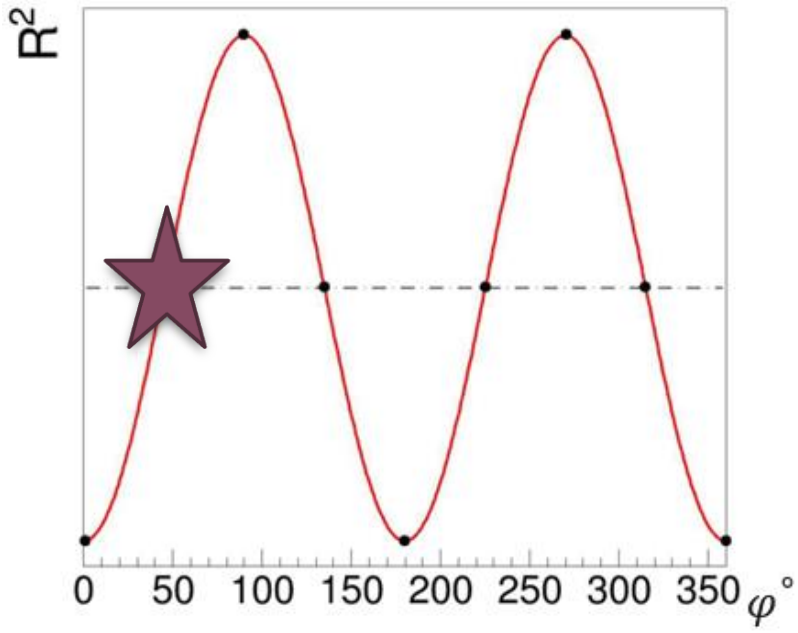

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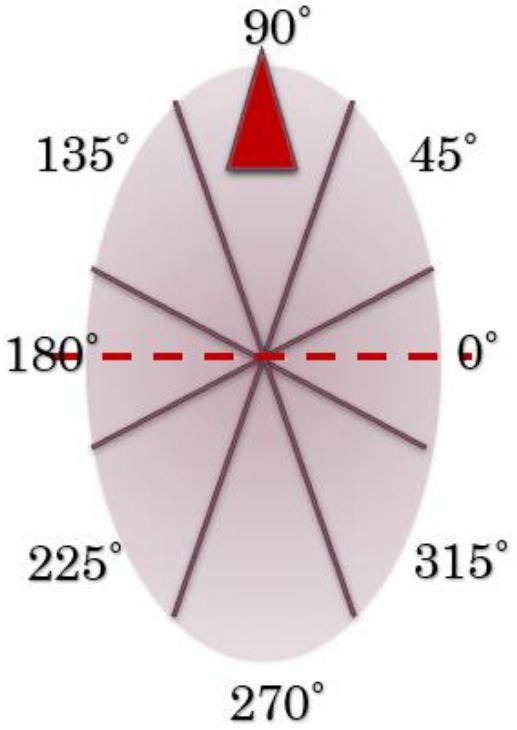

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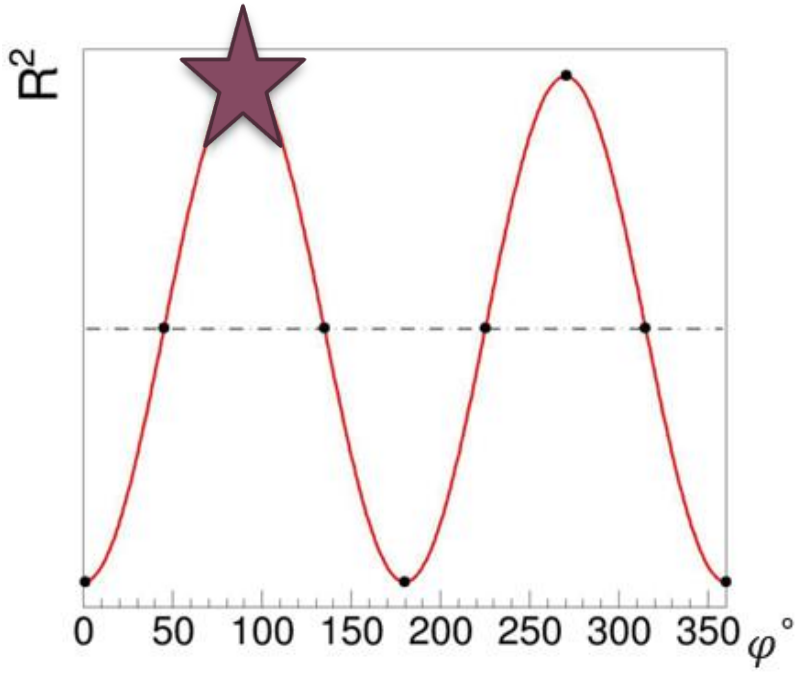

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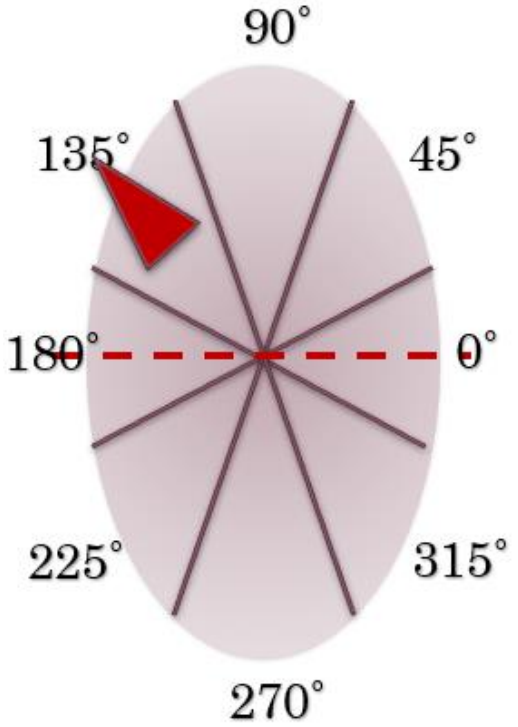

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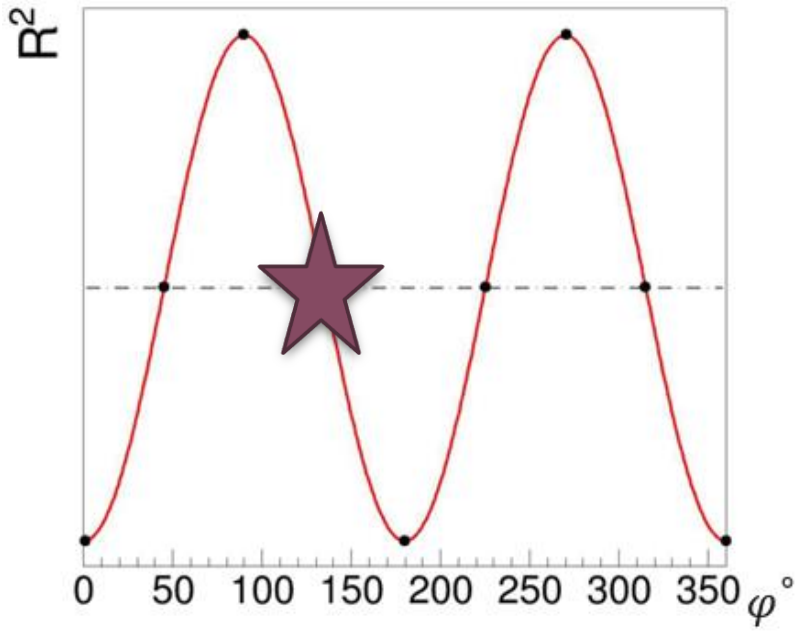

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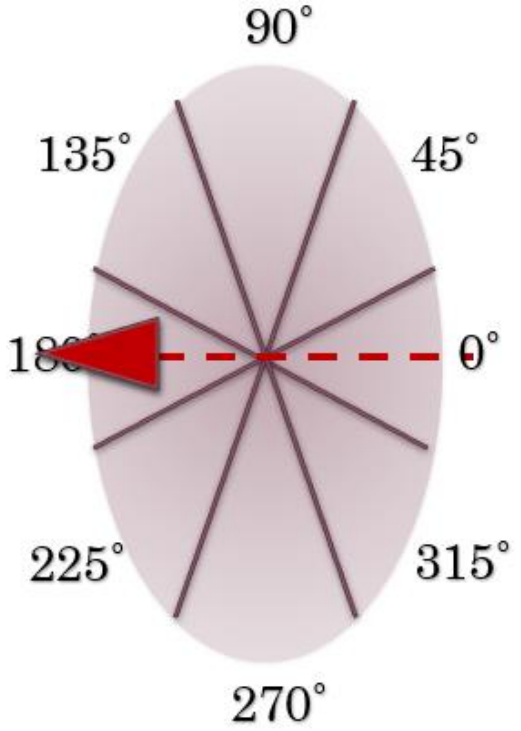

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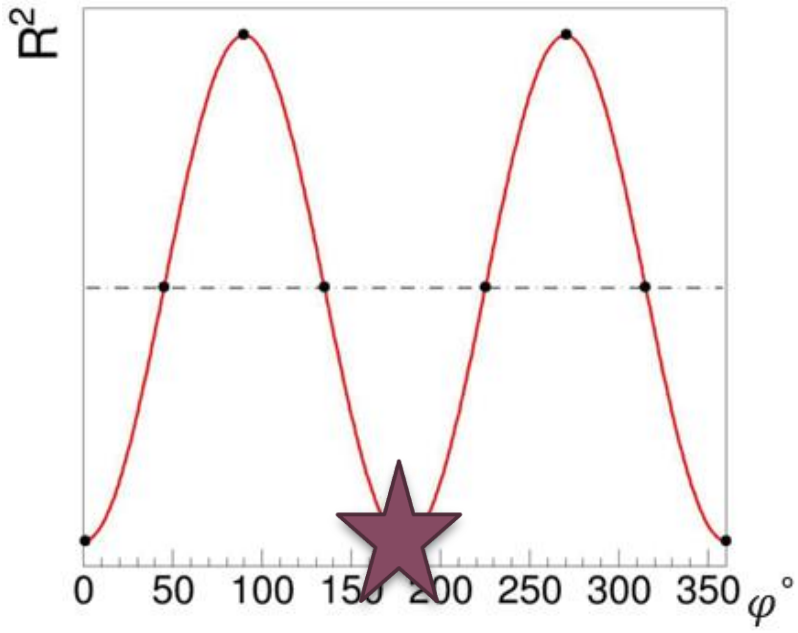

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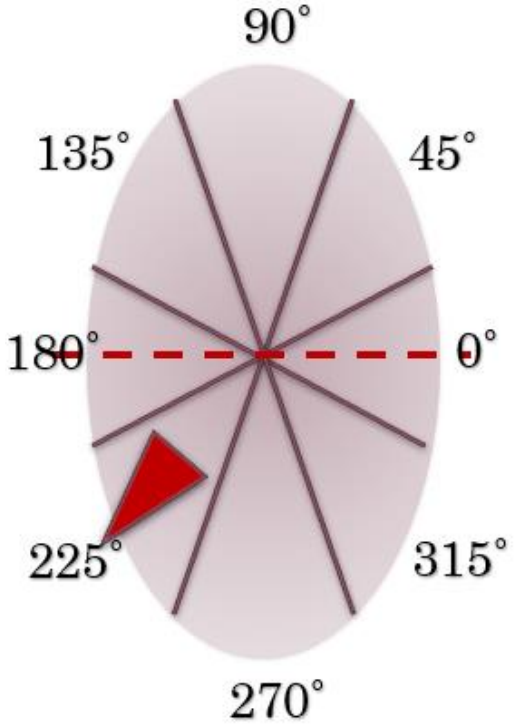

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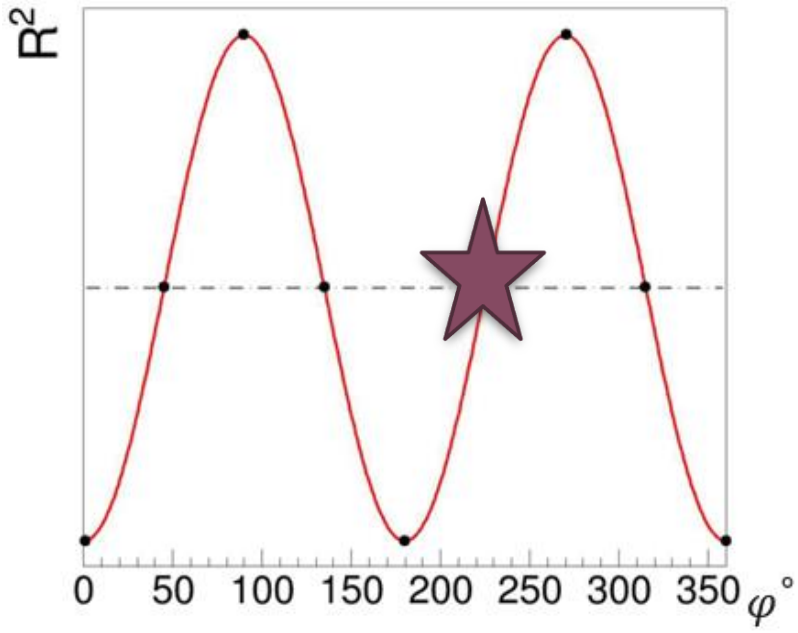

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Procedure: step 1

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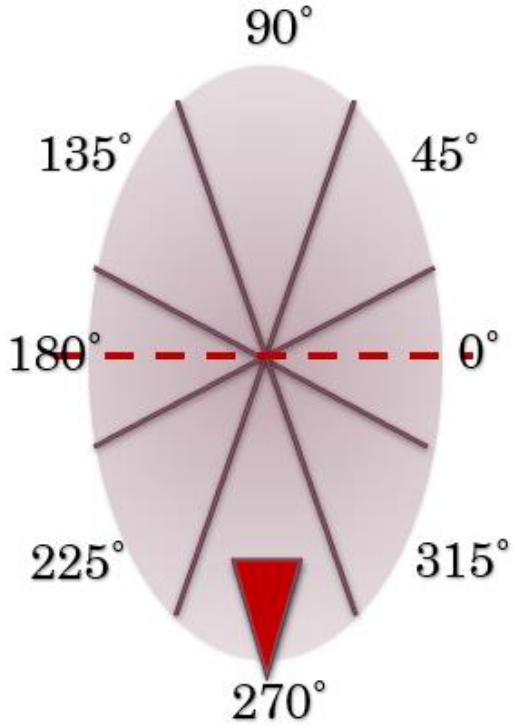

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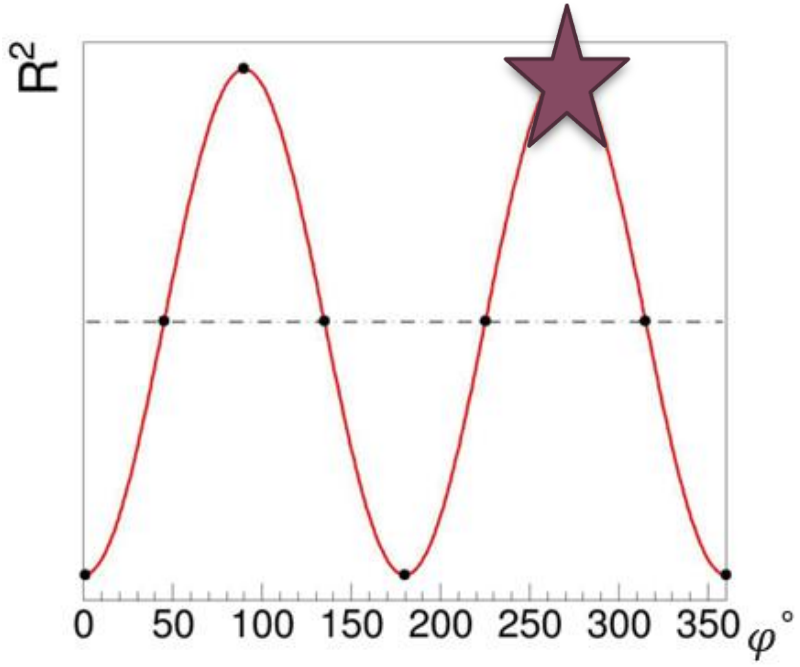

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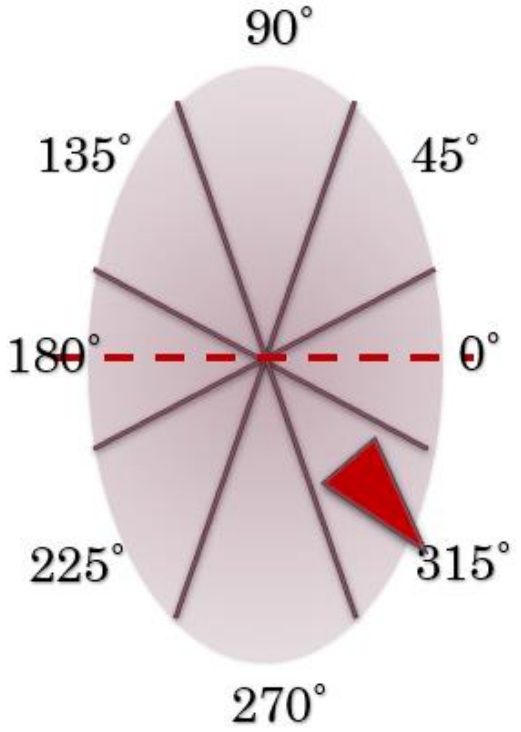
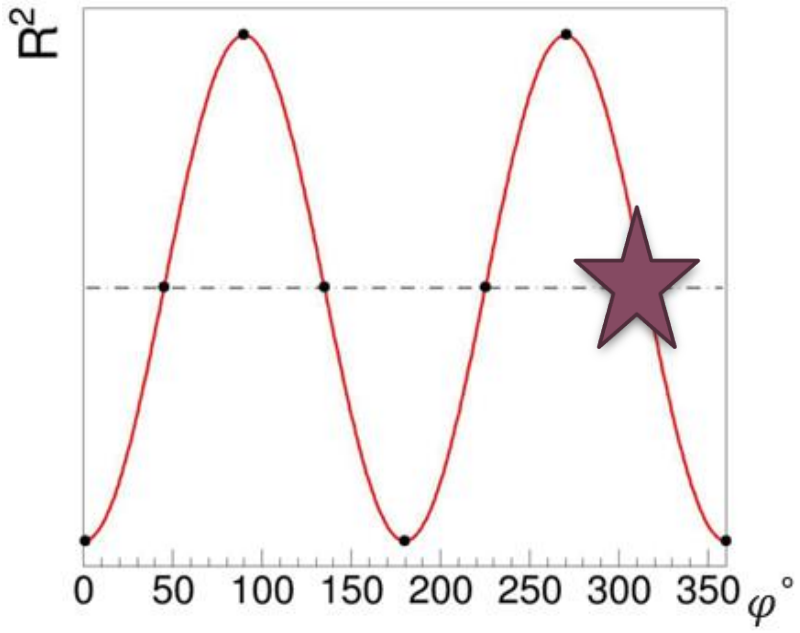
Procedure: step 1

Created medium

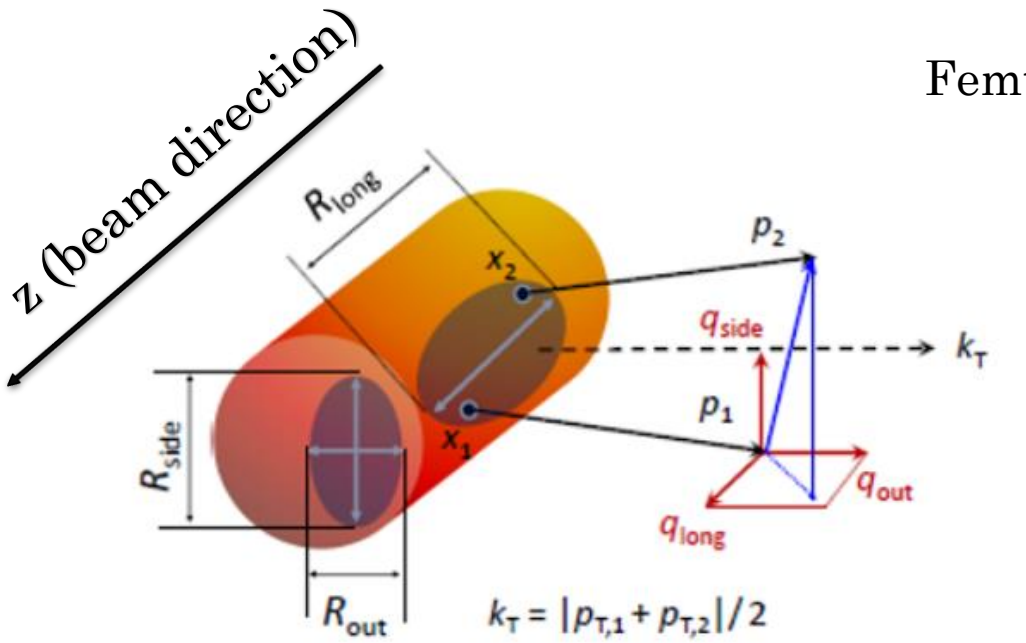


Radii response



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

Procedure: step 2



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

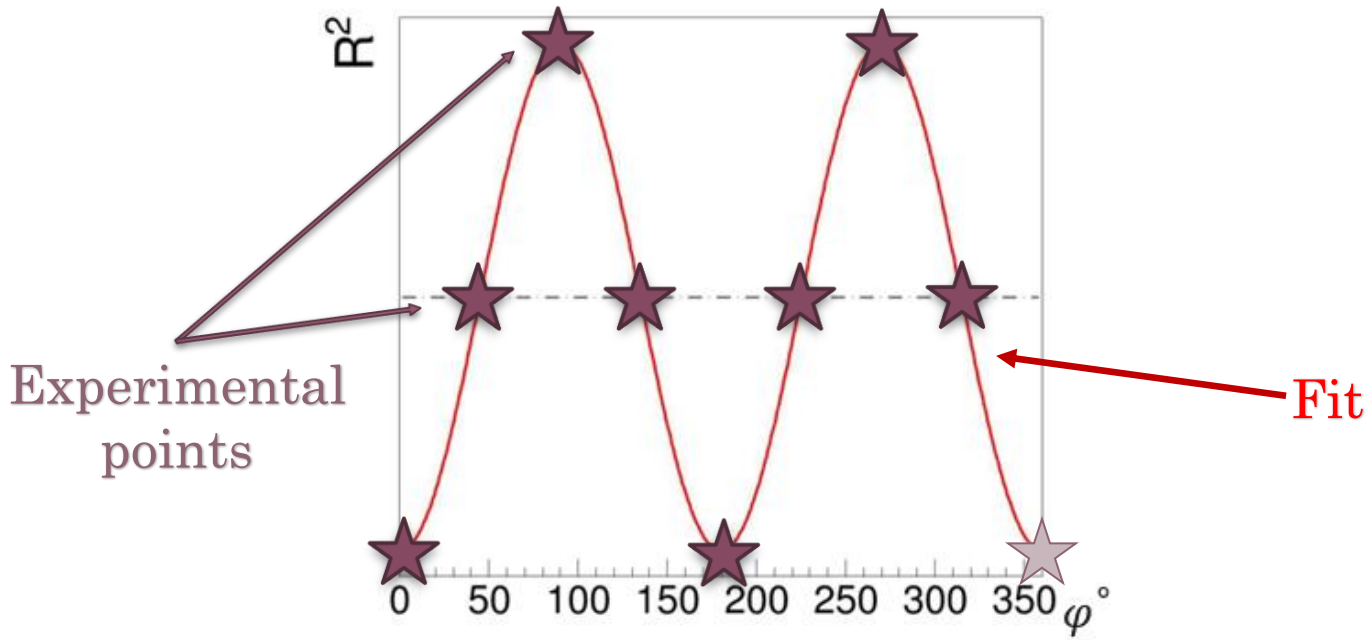
$$C(q) = N[(1-\lambda) + \lambda K(q)(1 + e^{-\sum_{i,j=o,s,l} q_i q_j R_{ij}^2})]$$

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



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

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

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

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

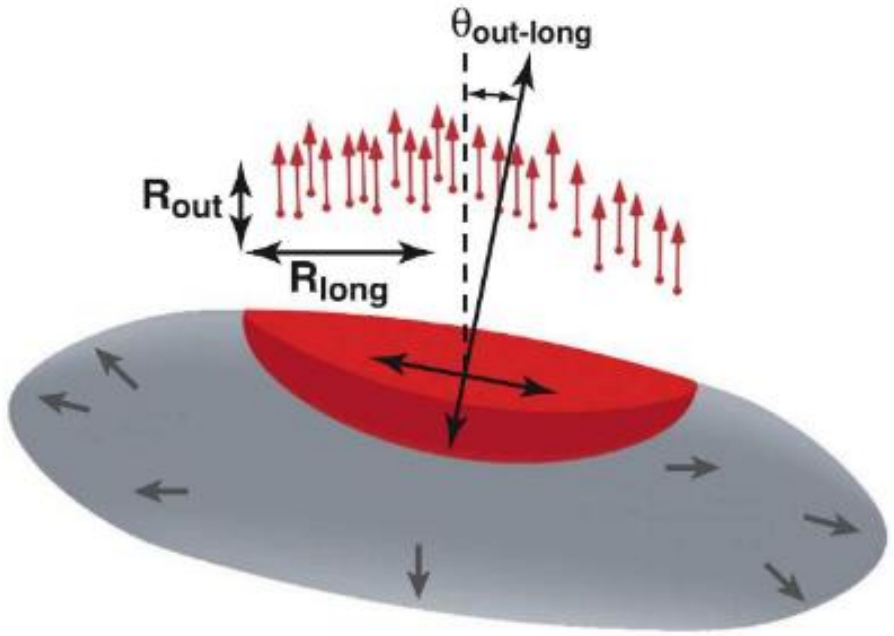
$$R_{ol}^2 = R_{ol,0}^2 + 2\sum_{n=1,3,5\ldots} R_{ol,n}^2\cos(n\Phi)$$

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

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



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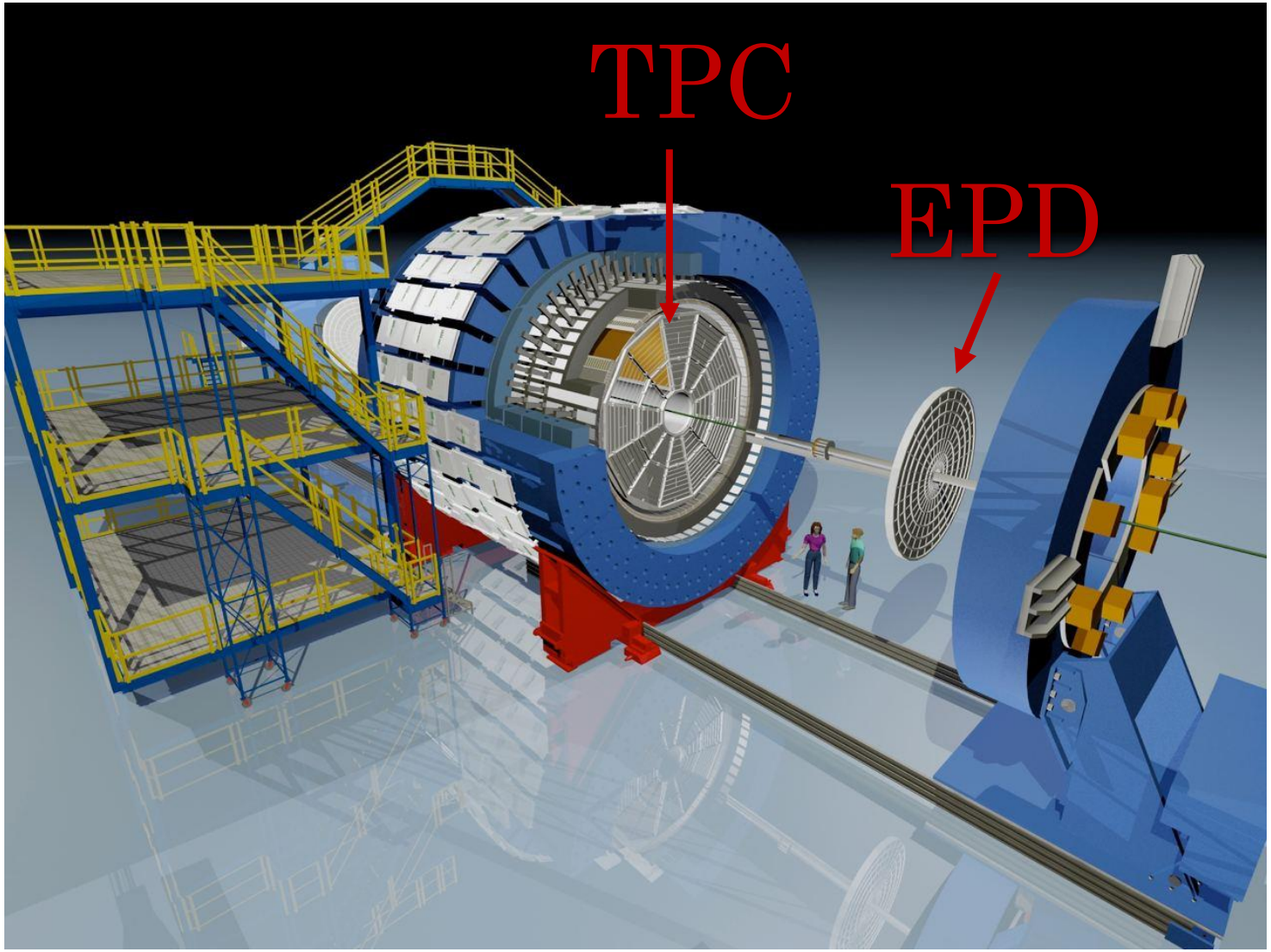
$$\theta_{sl} = \frac{1}{2} tan^{-1}\left(\frac{-4R_{sl,1}^2}{R_{l,0}^2 - R_{s,0}^2 + 2R_{s,2}^2}\right)$$

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

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

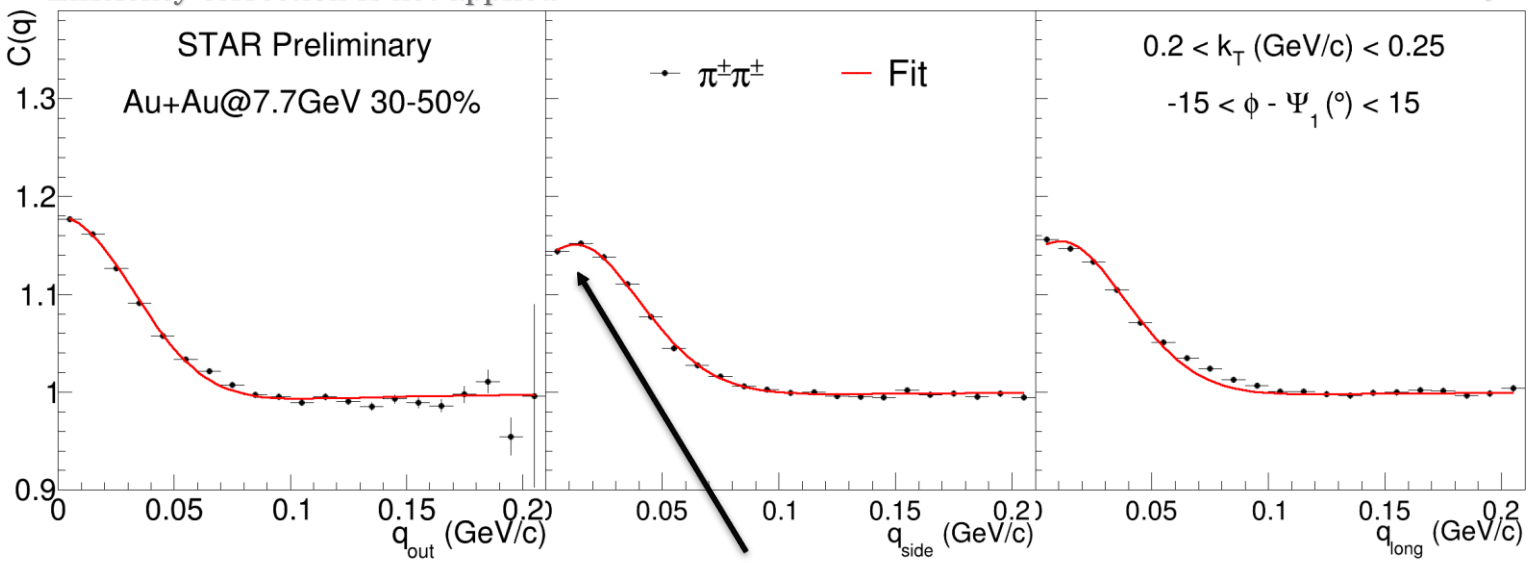


- Time Projection Chamber (TPC) + iTPC (BES-II upgrade)
  - Momentum and pion identification
- Event Plane Detector (EPD)
  - Part of the BES-II upgrade
  - Reconstruction of the first-order event plane (proxy for reaction plane)
- Energies of interest (BES-II):
  - Au+Au@7.7 GeV
  - Au+Au@14.5 GeV
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

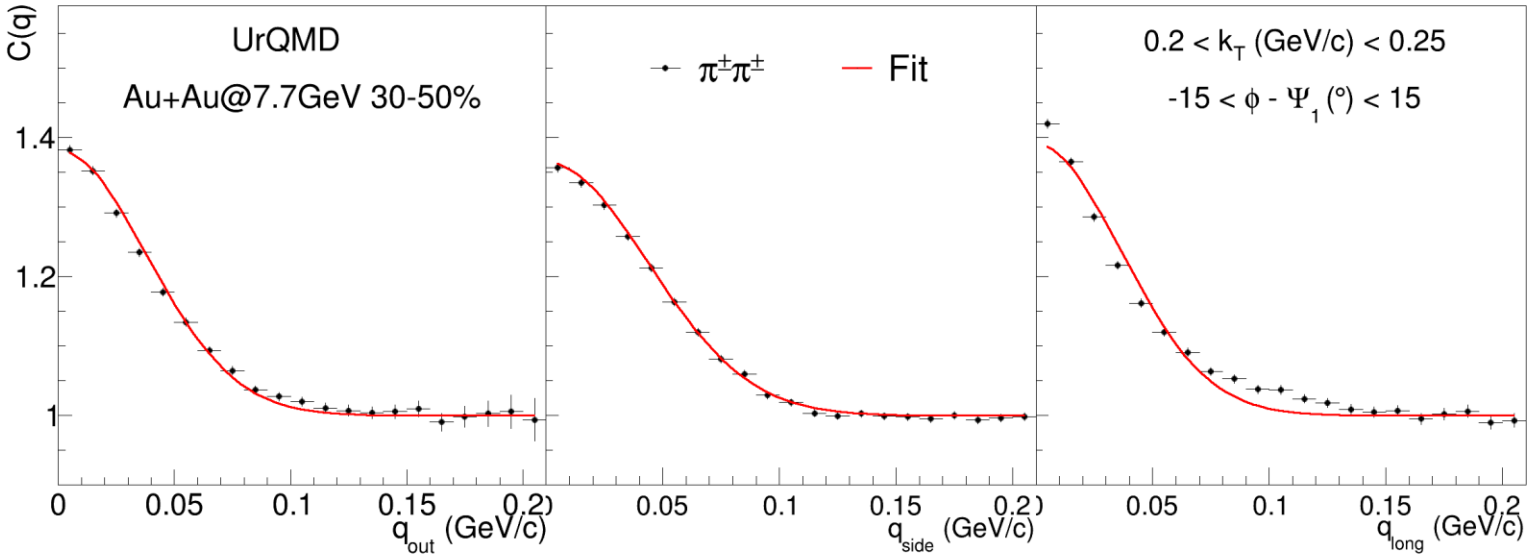
One-dimensional projection of correlation function

Efficiency correction is not applied

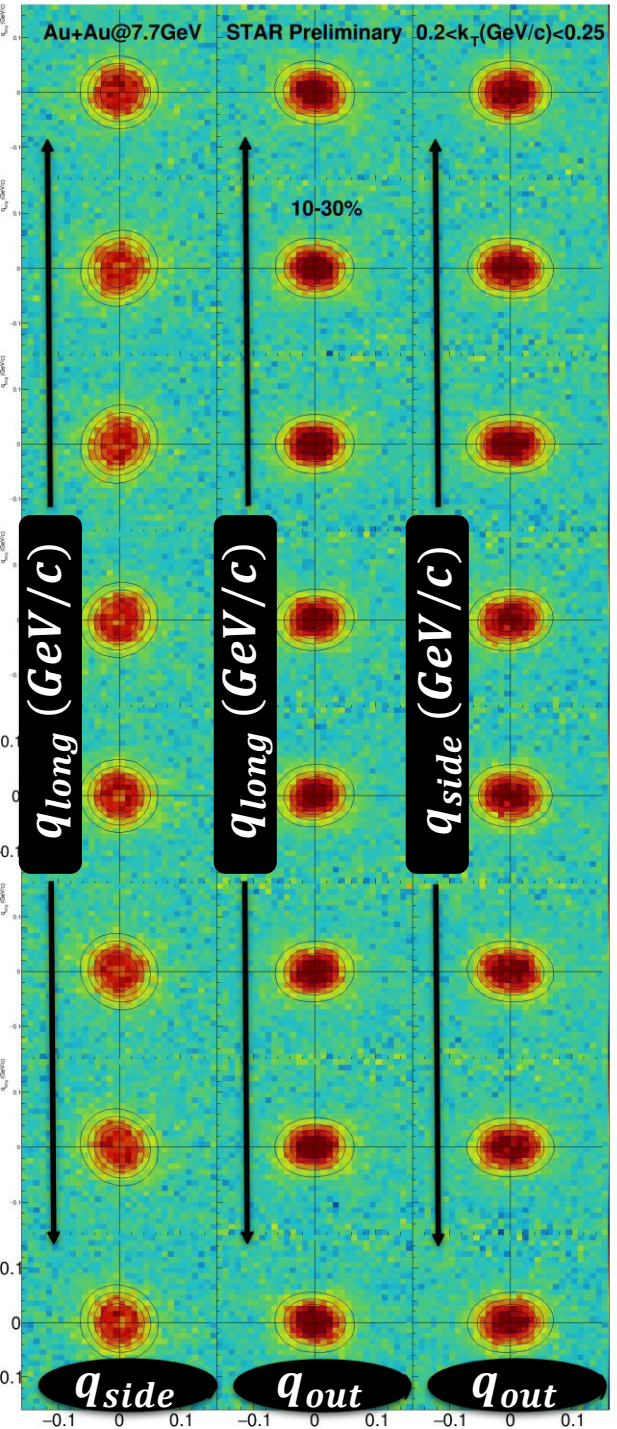
Statistical uncertainties only



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

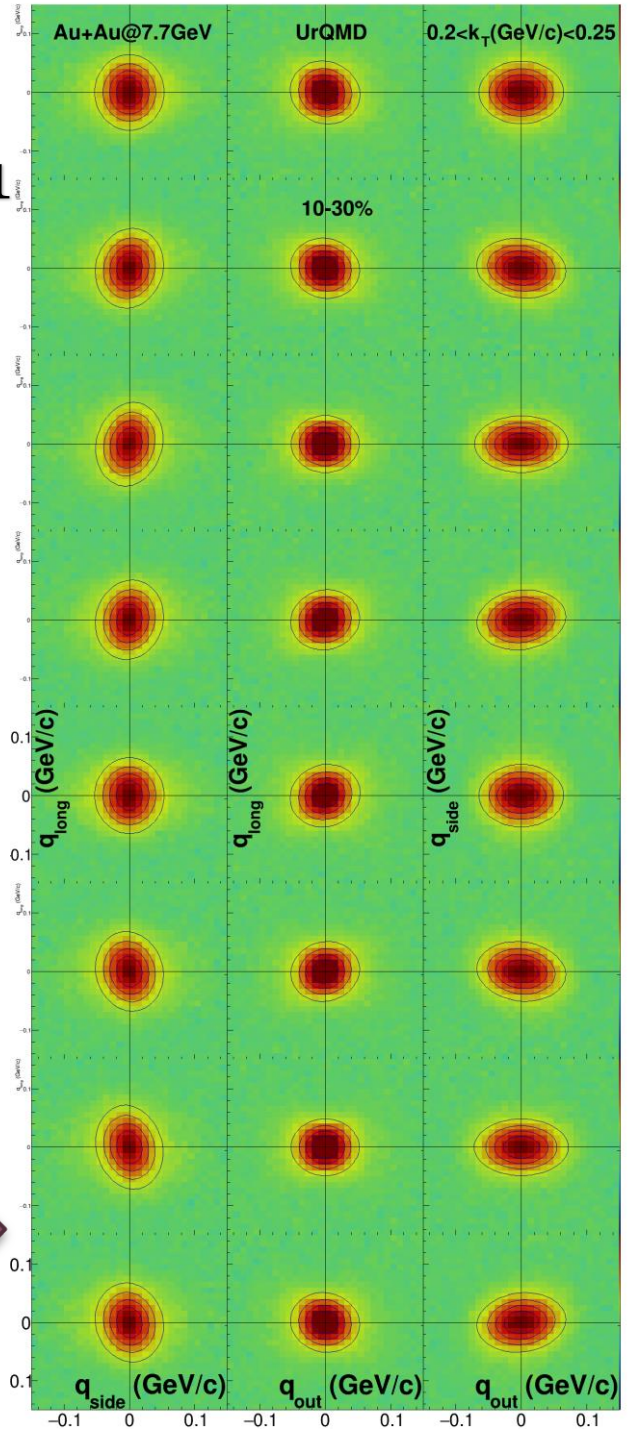


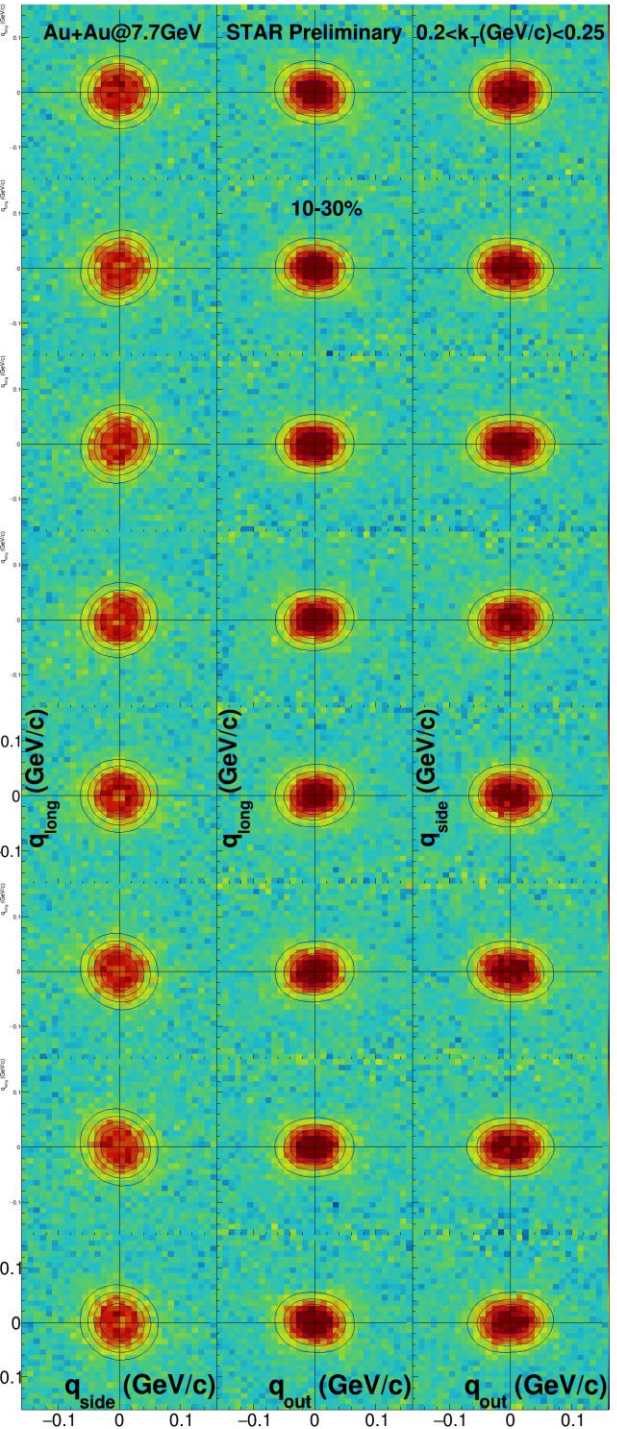
← Data

Vary $\varphi - \Psi_1$ ↓

Two-dimensional projections of correlation functions

UrQMD →




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)
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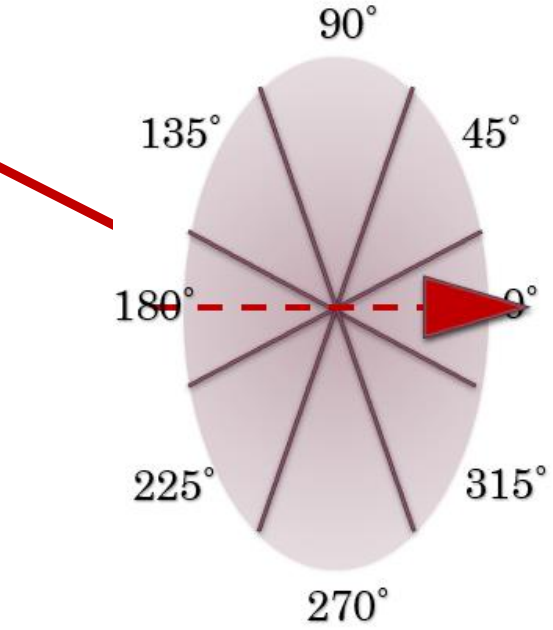
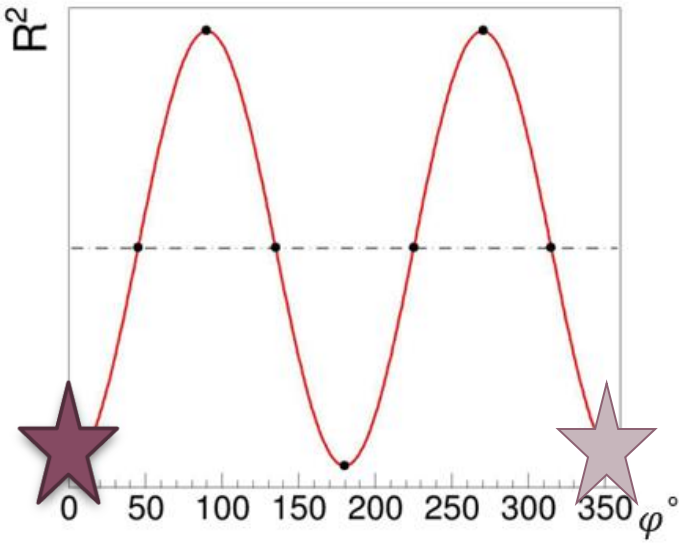

90°
135°
45°
180°
0°
225°
315°
270°


R²
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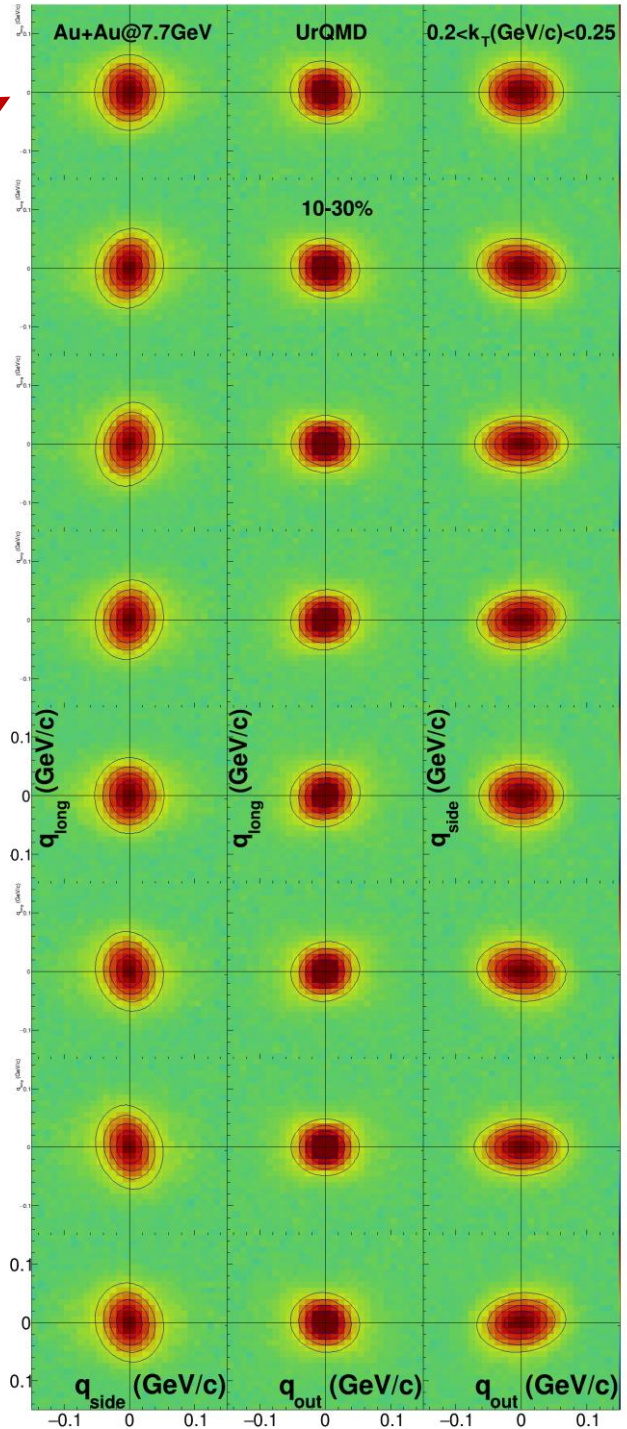
φ°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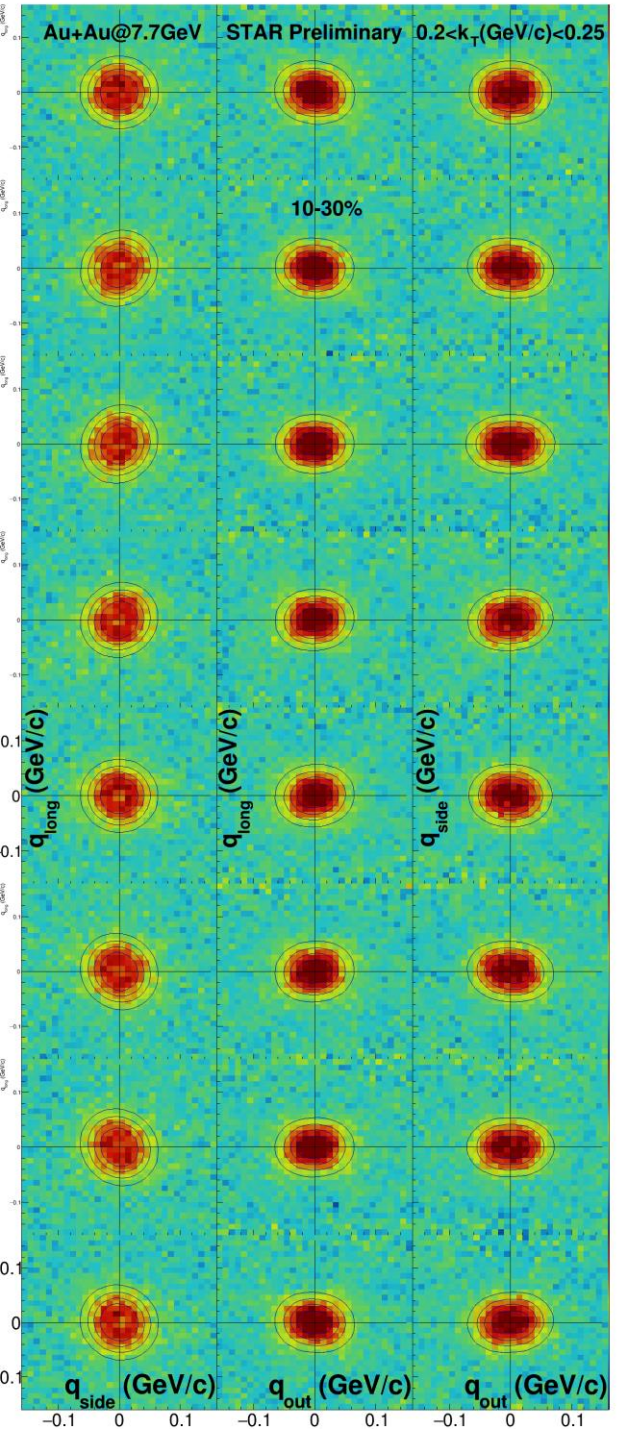
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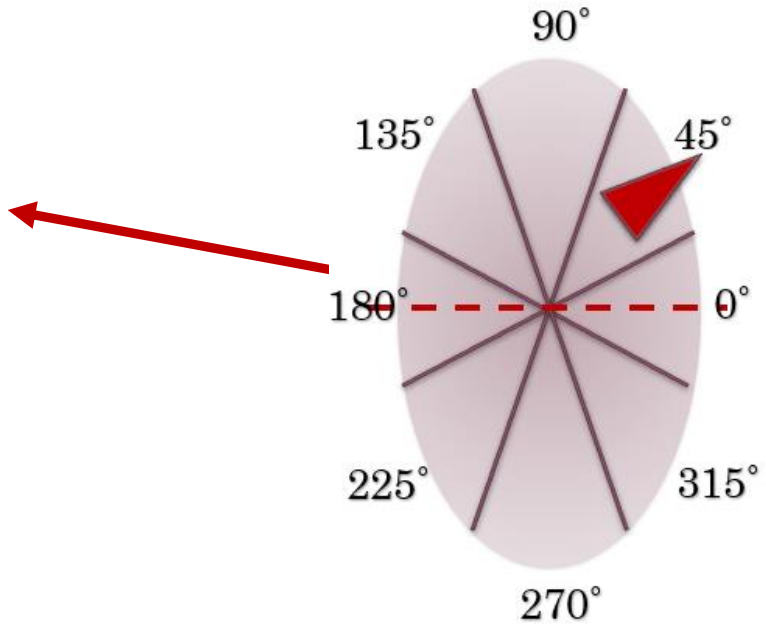
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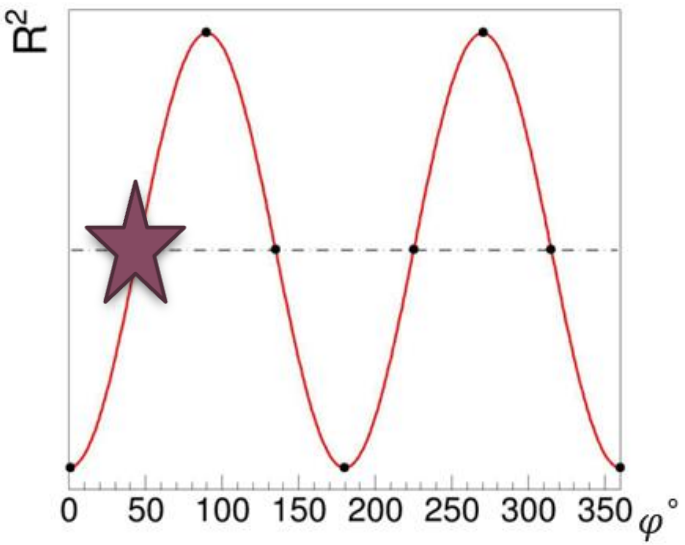
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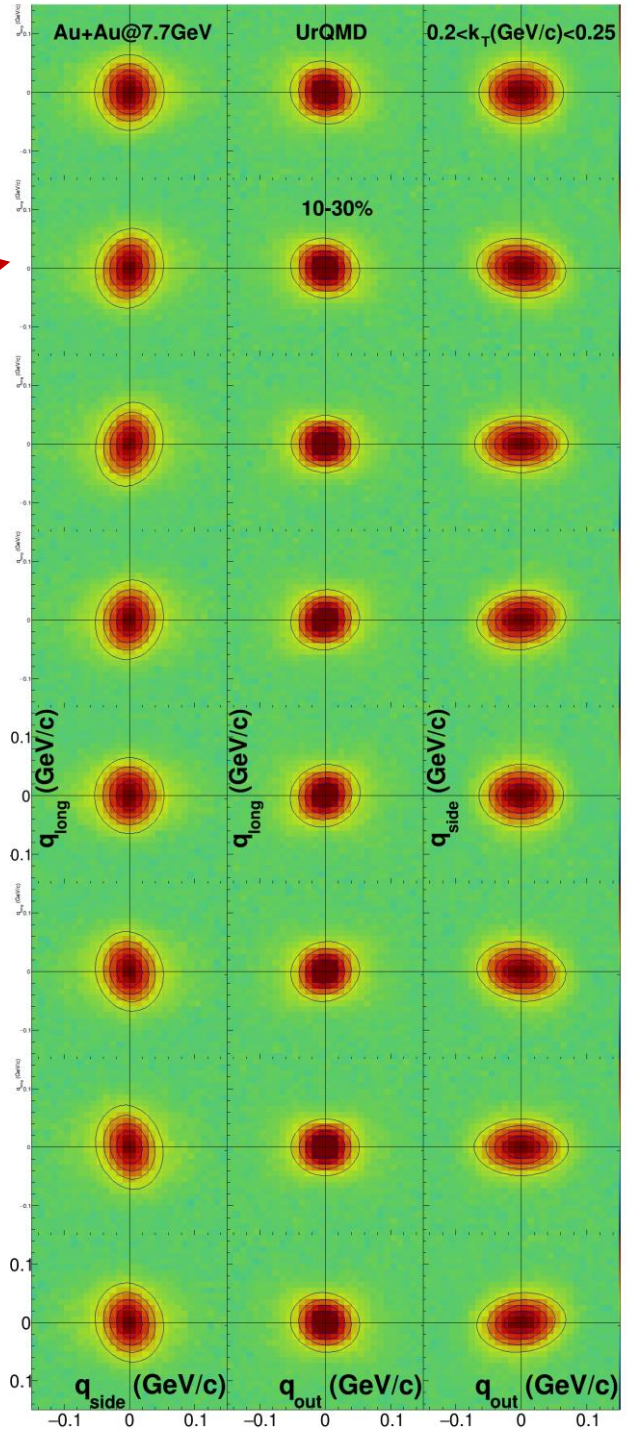
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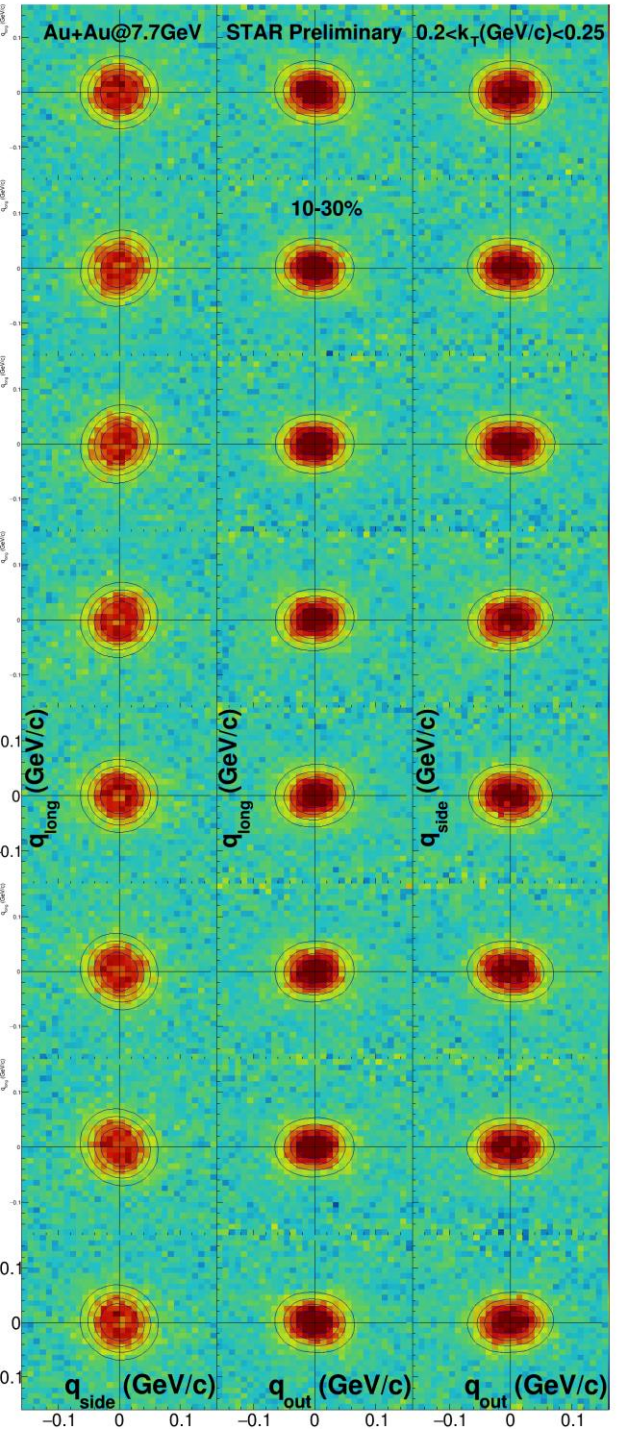
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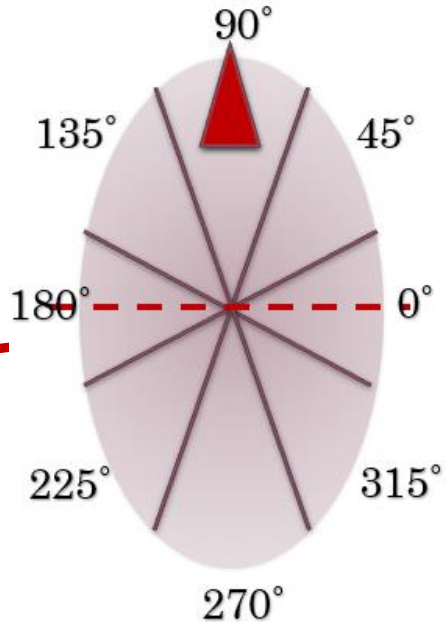
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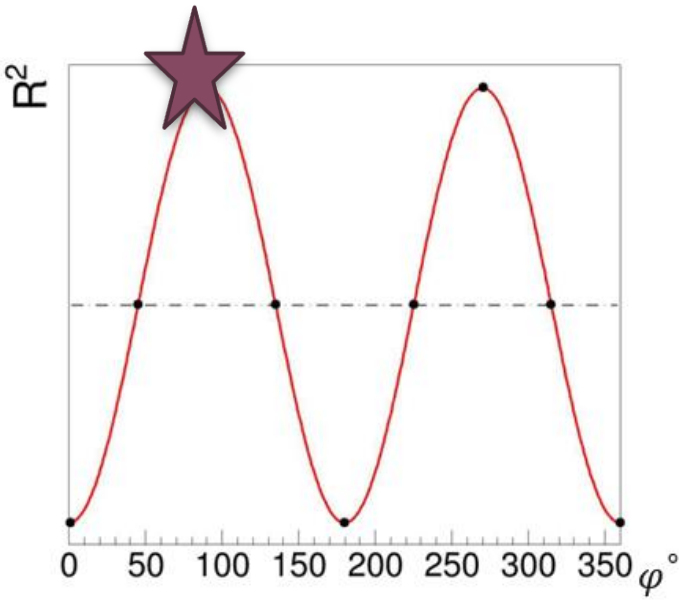
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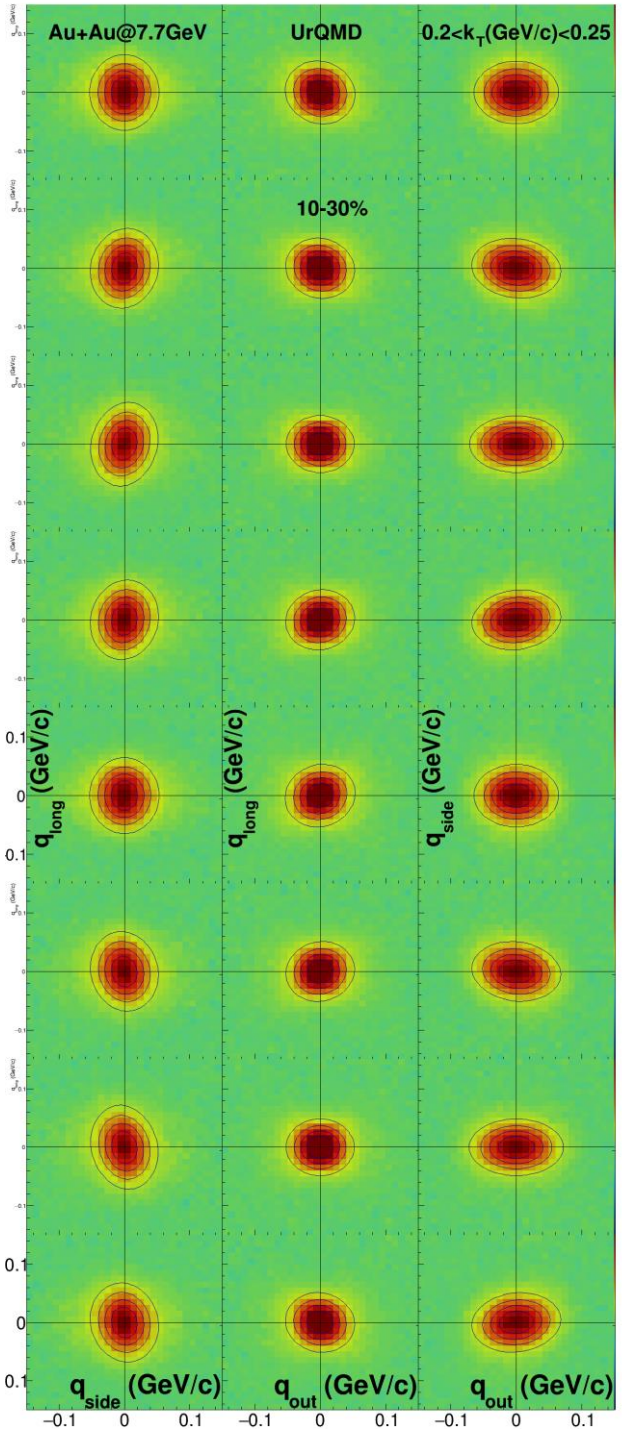
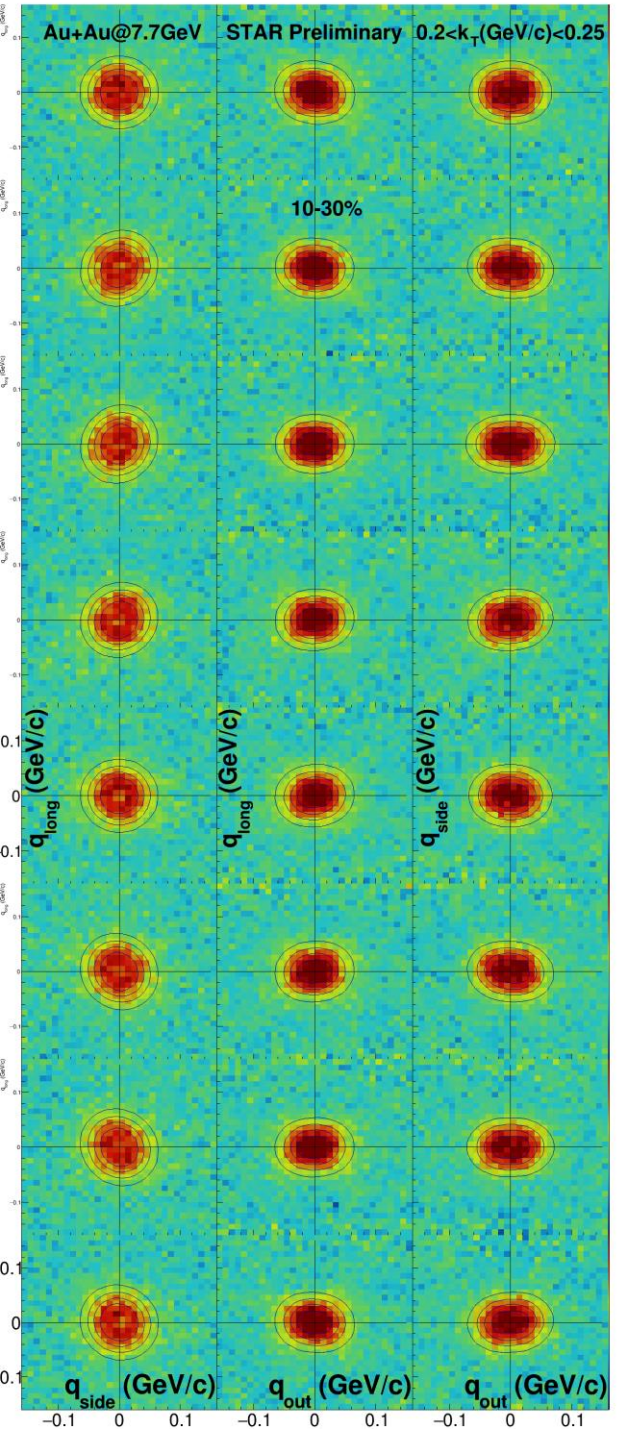
350
φ°


Au+Au@7.7GeV
UrQMD
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)


Au+Au@7.7GeV
STAR Preliminary
0.2<k_T(GeV/c)<0.25
10-30%
q_long (GeV/c)
q_long (GeV/c)
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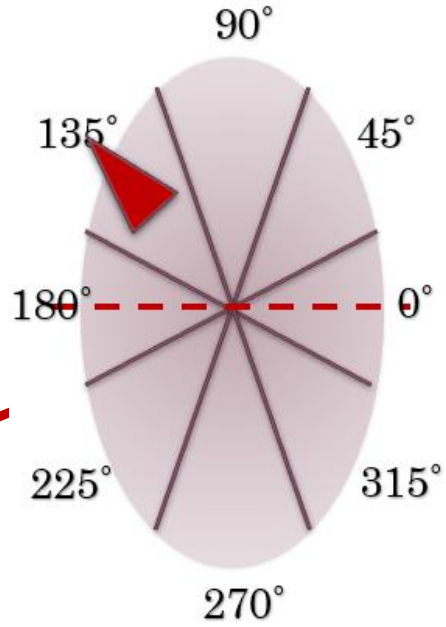
q_side (GeV/c)
q_out (GeV/c)
q_out (GeV/c)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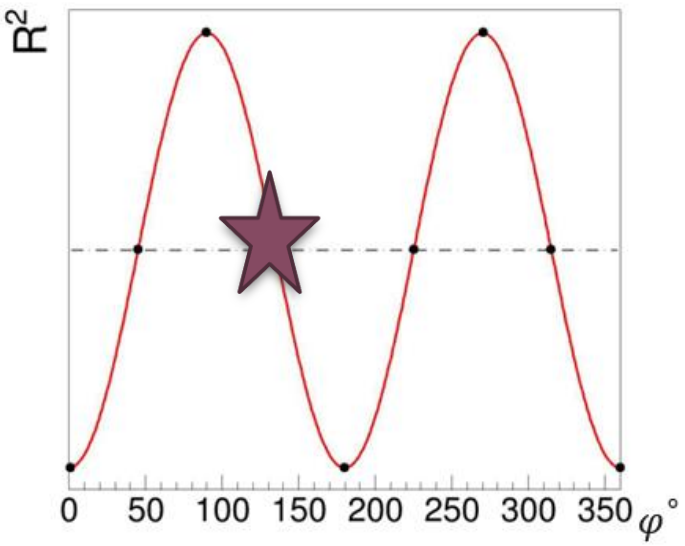
R²
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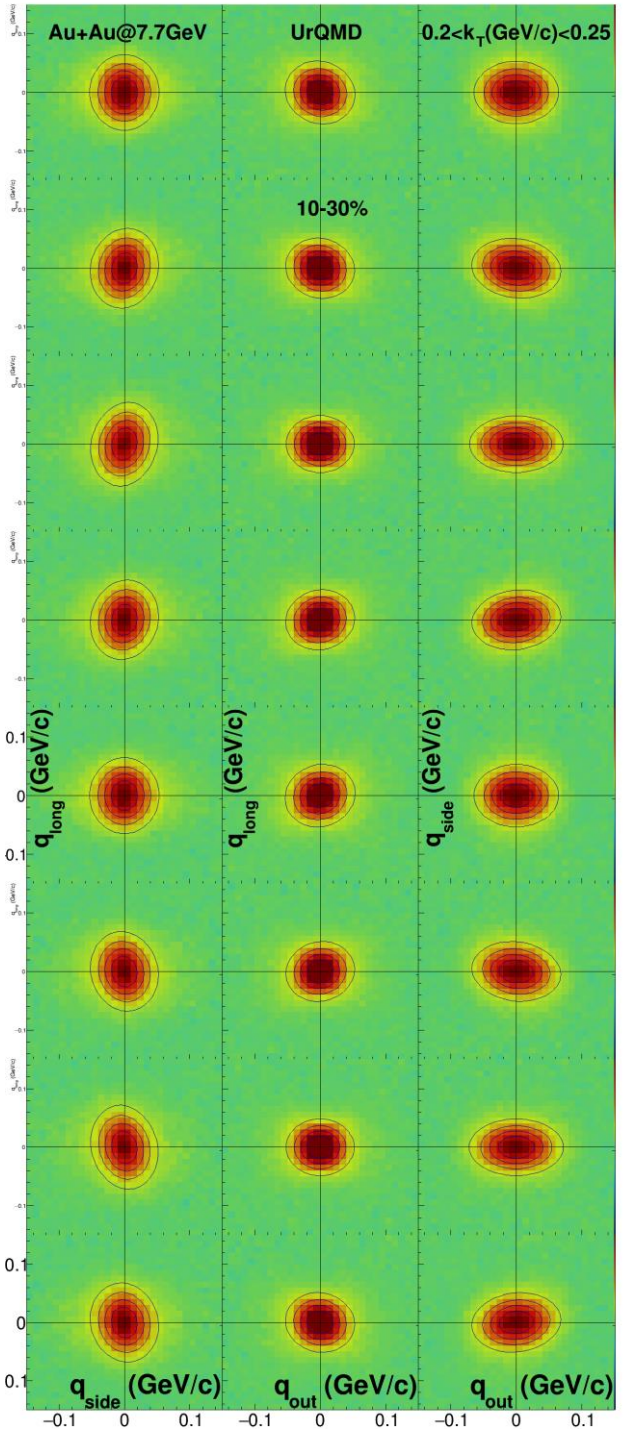
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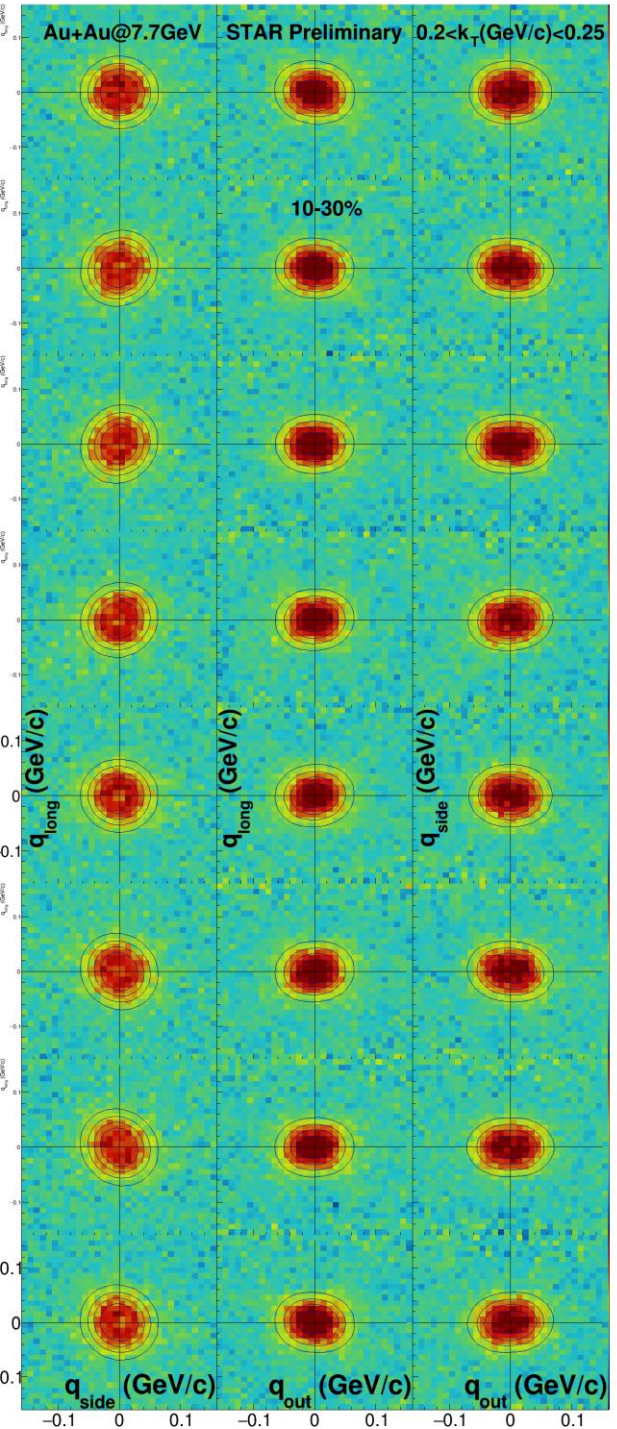
q_out (GeV/c)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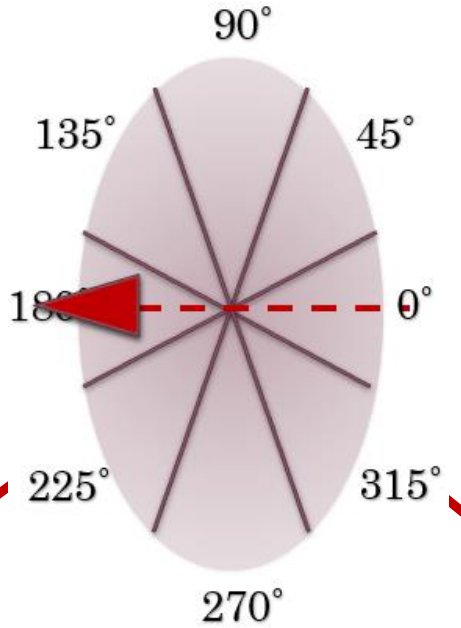
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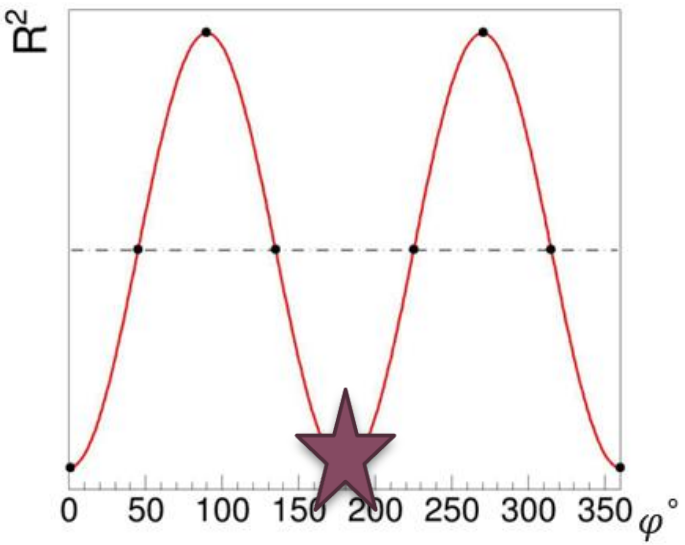
R²
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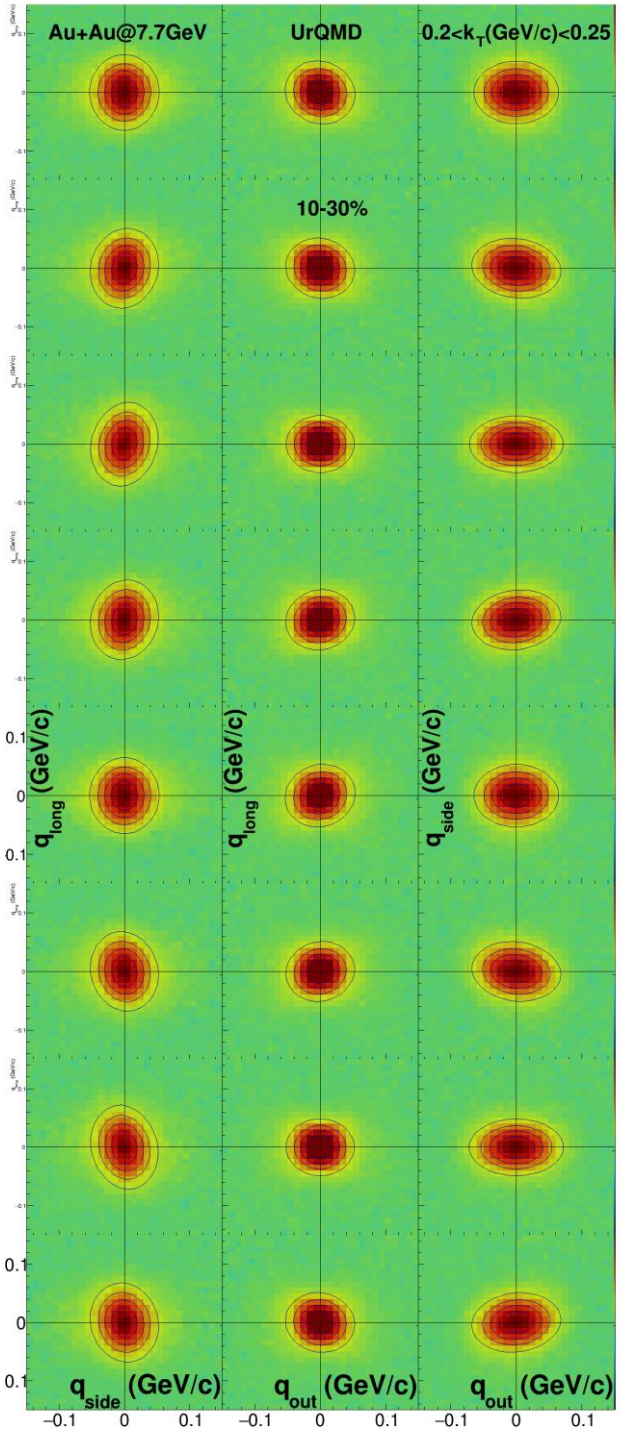
φ°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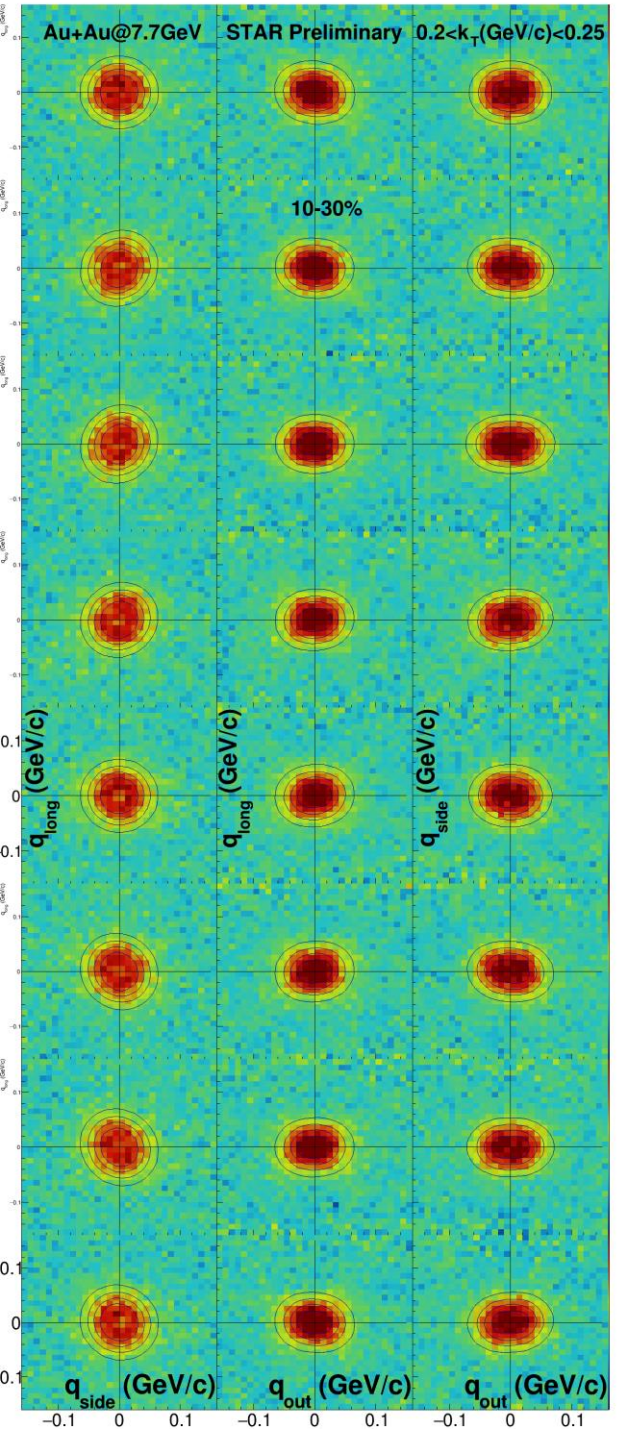
q_out (GeV/c)
q_out (GeV/c)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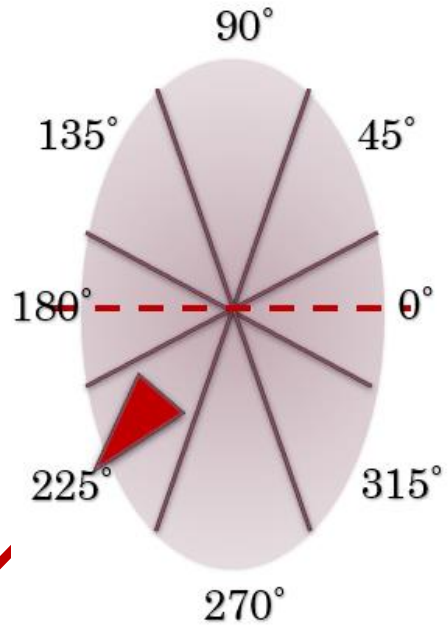
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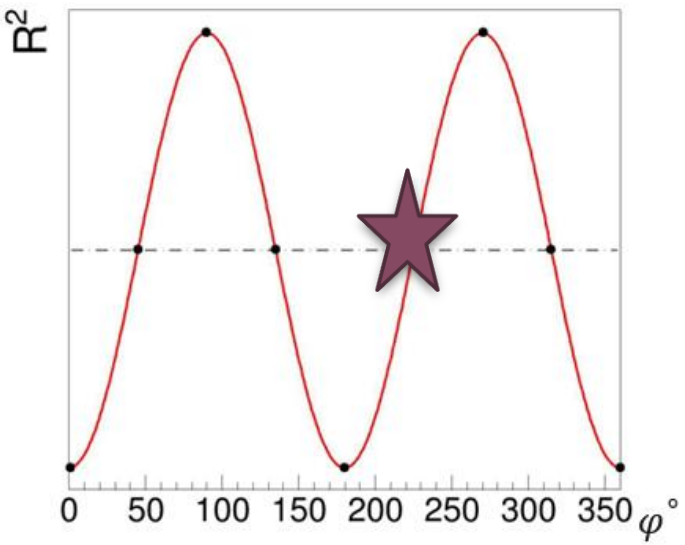
R²
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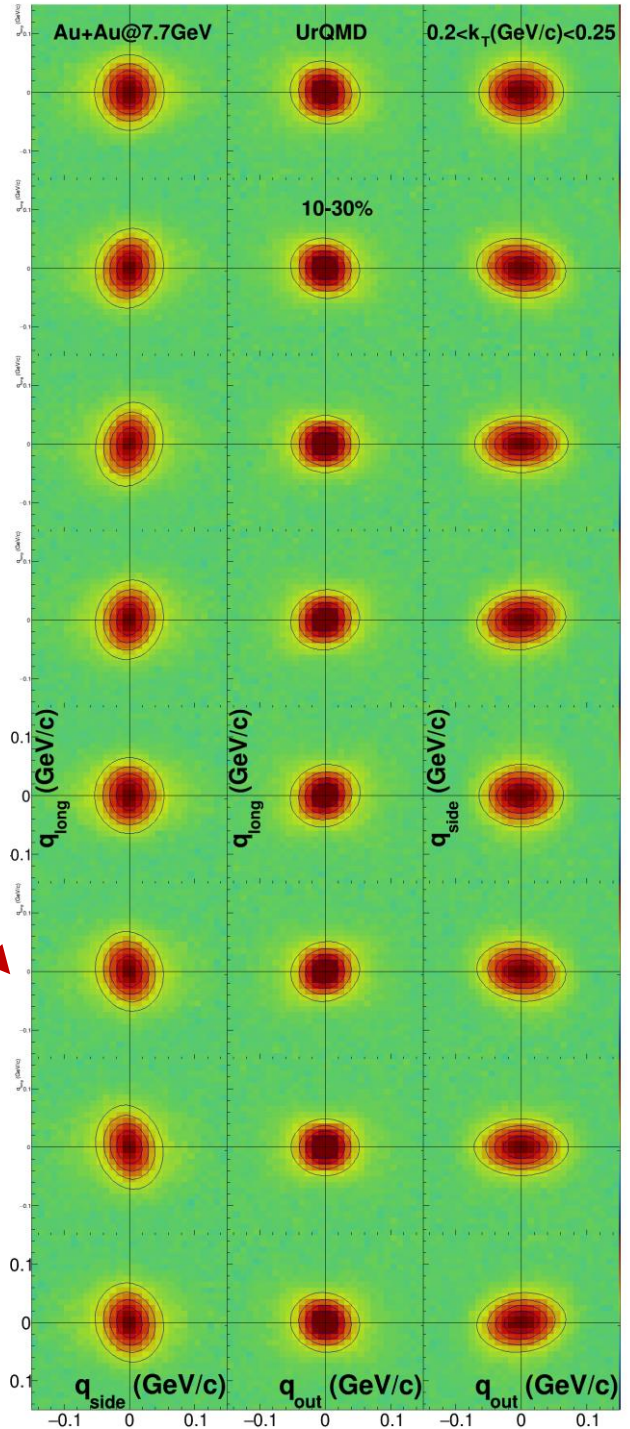
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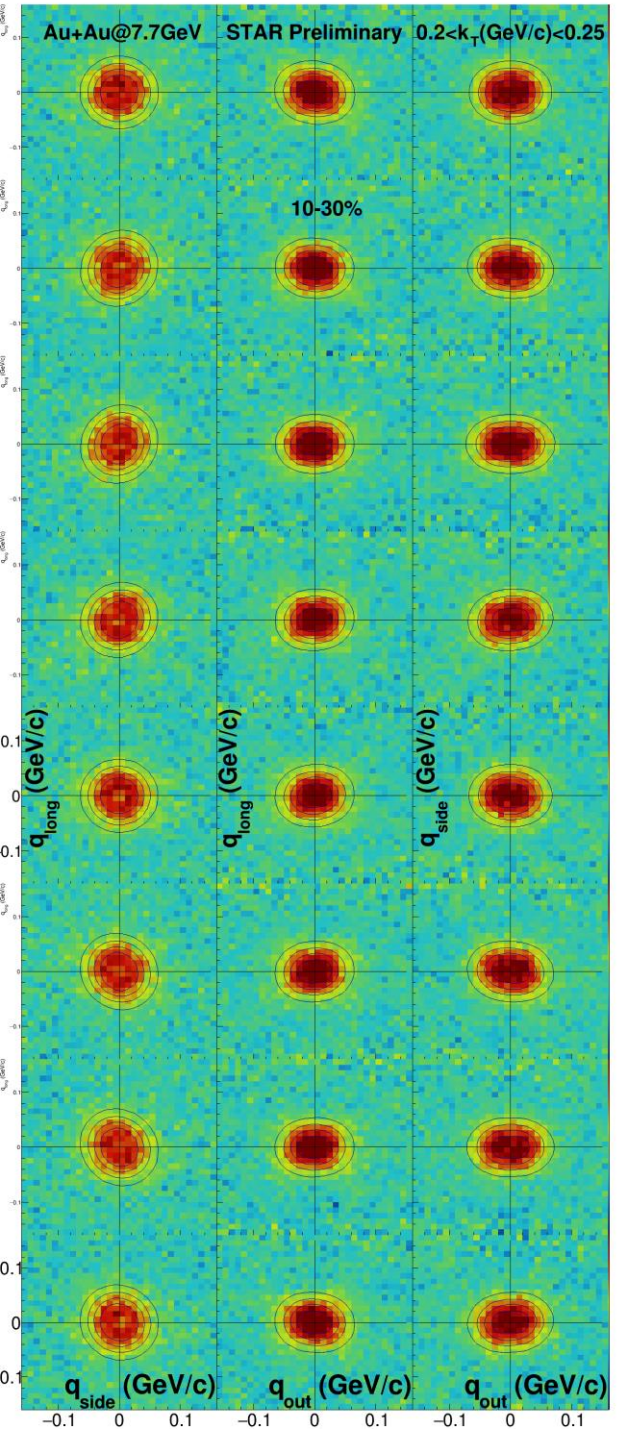
q_side (GeV/c)
q_out (GeV/c)
q_out (GeV/c)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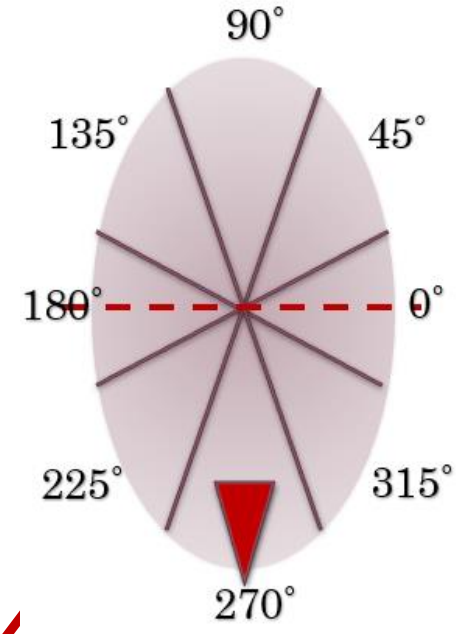
q_side (GeV/c)
q_out (GeV/c)
q_out (GeV/c)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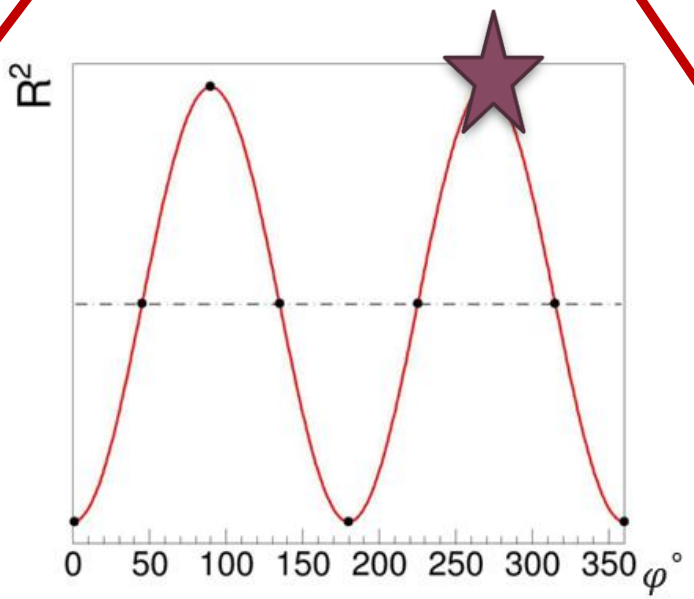
R²
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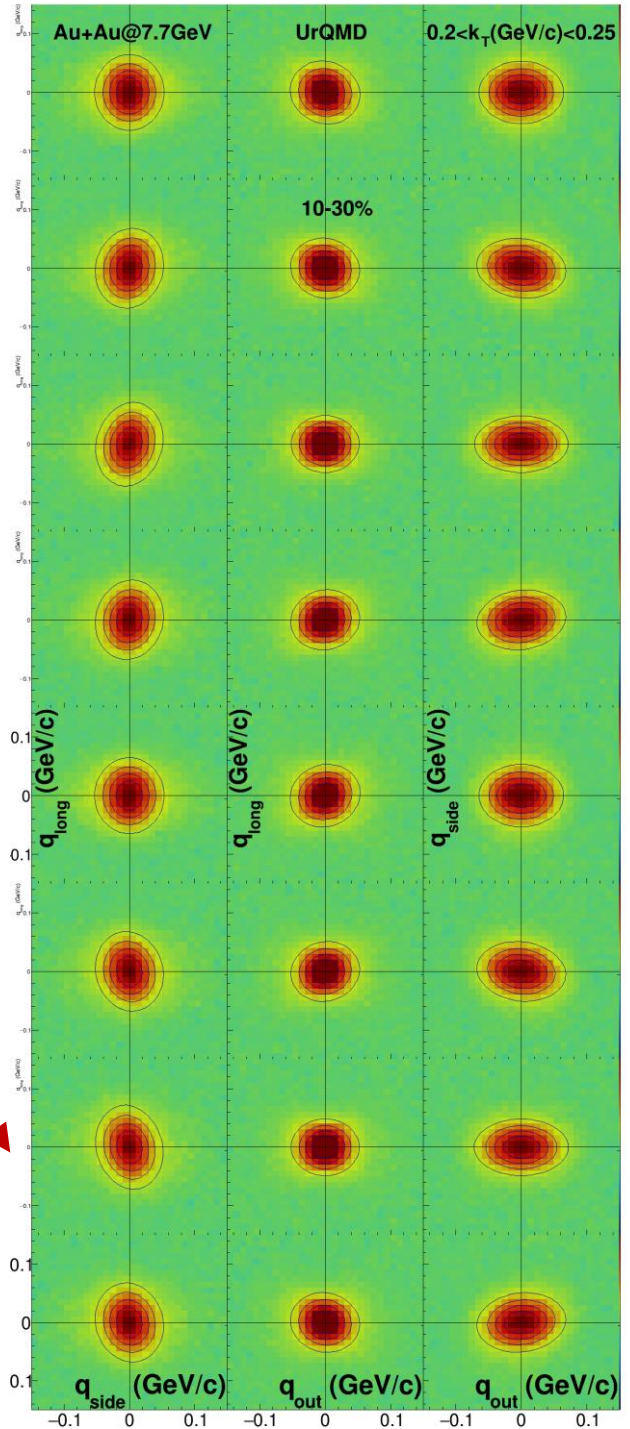
Au+Au@7.7GeV
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0.2<k_T(GeV/c)<0.25
10-30%
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q_side (GeV/c)
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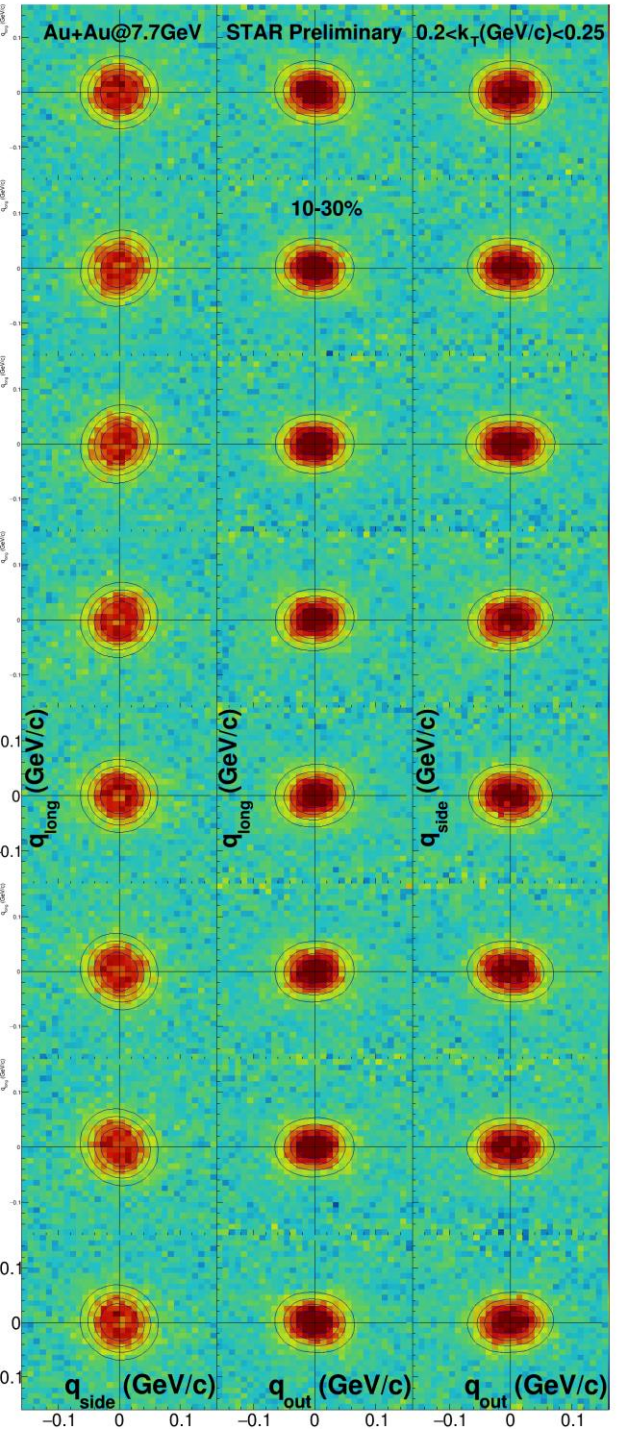
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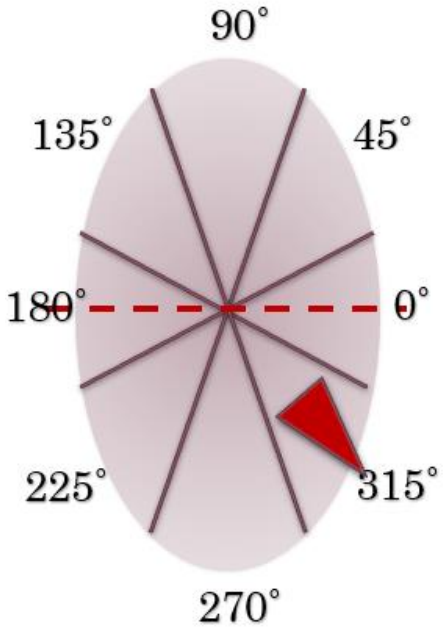
q_side (GeV/c)
q_out (GeV/c)
q_out (GeV/c)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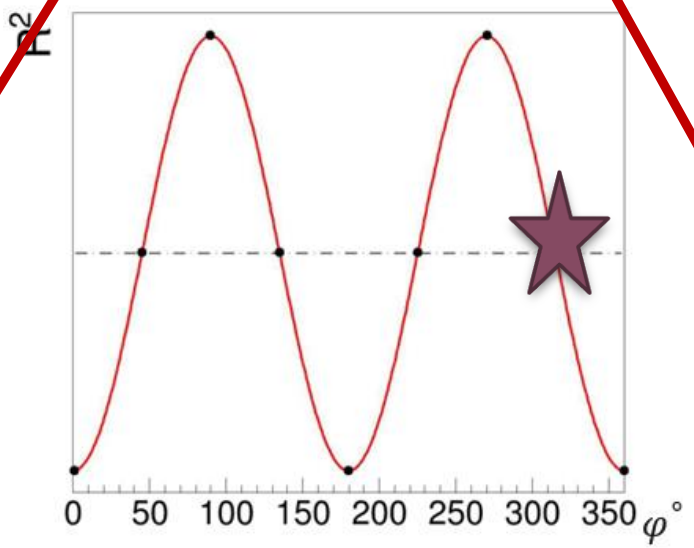
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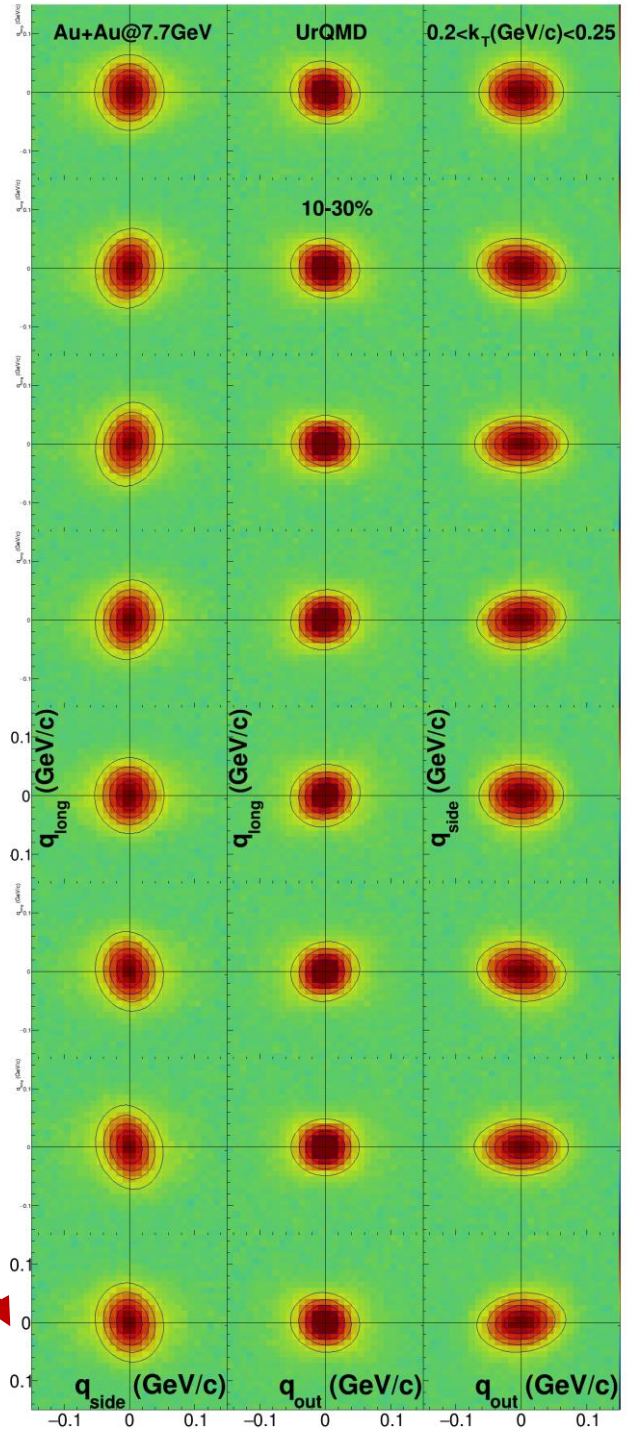
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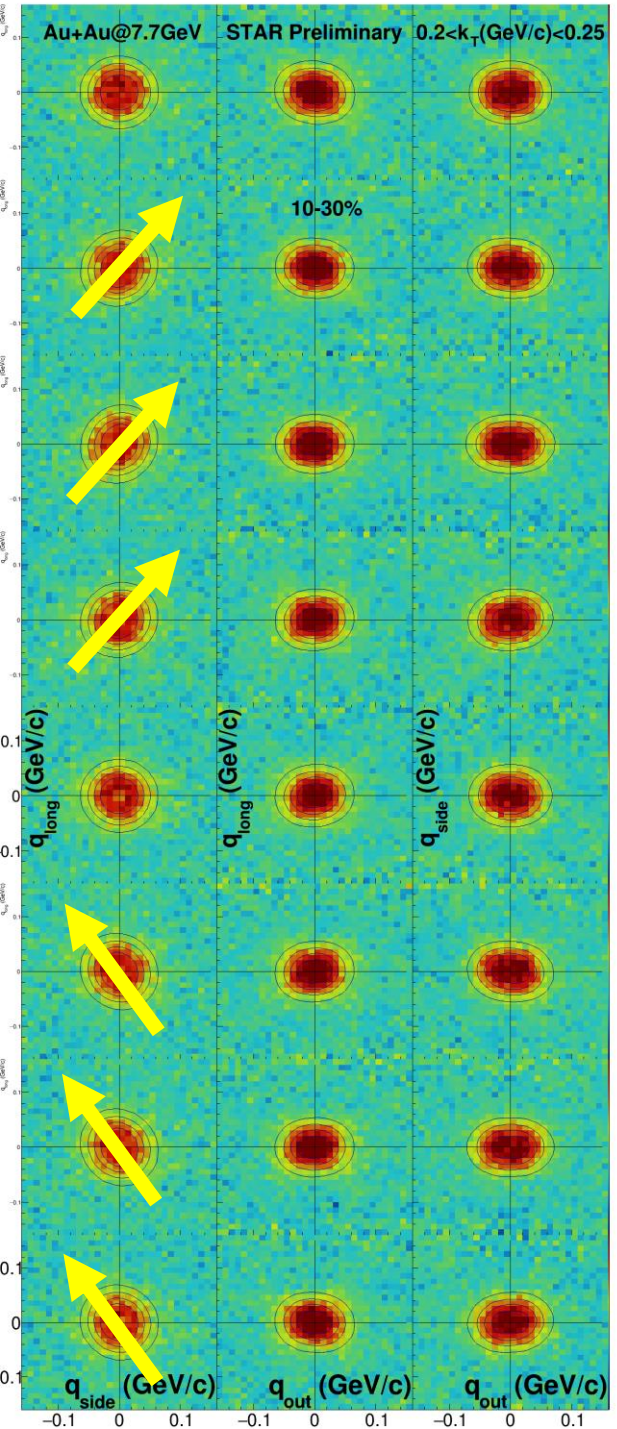
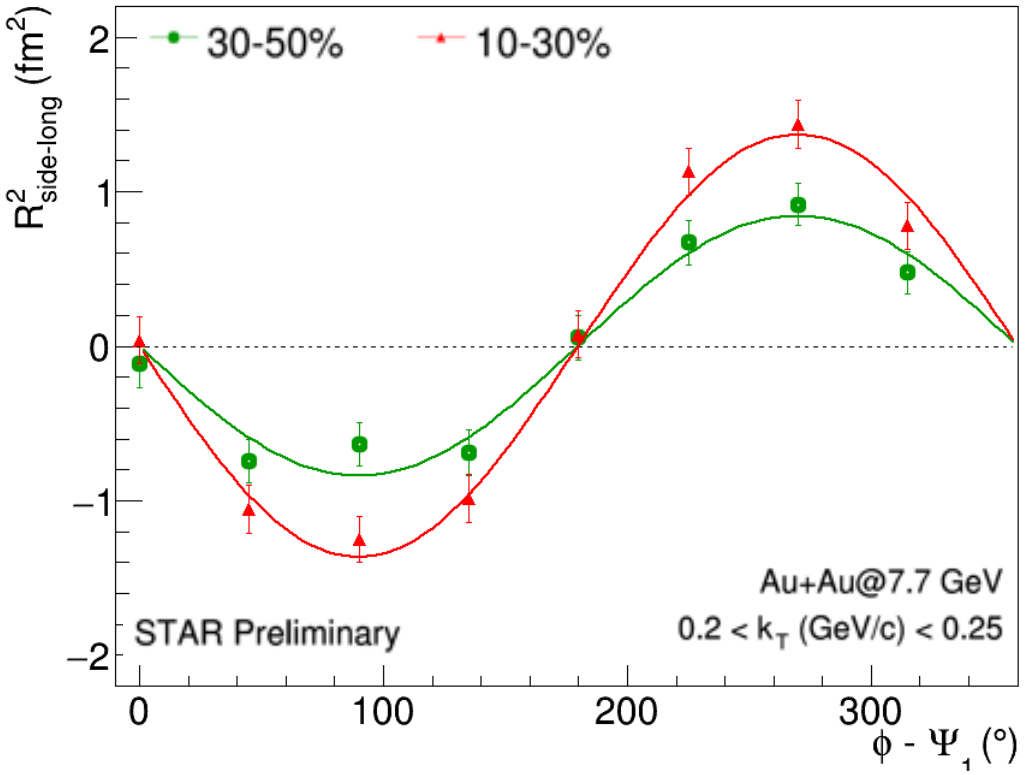
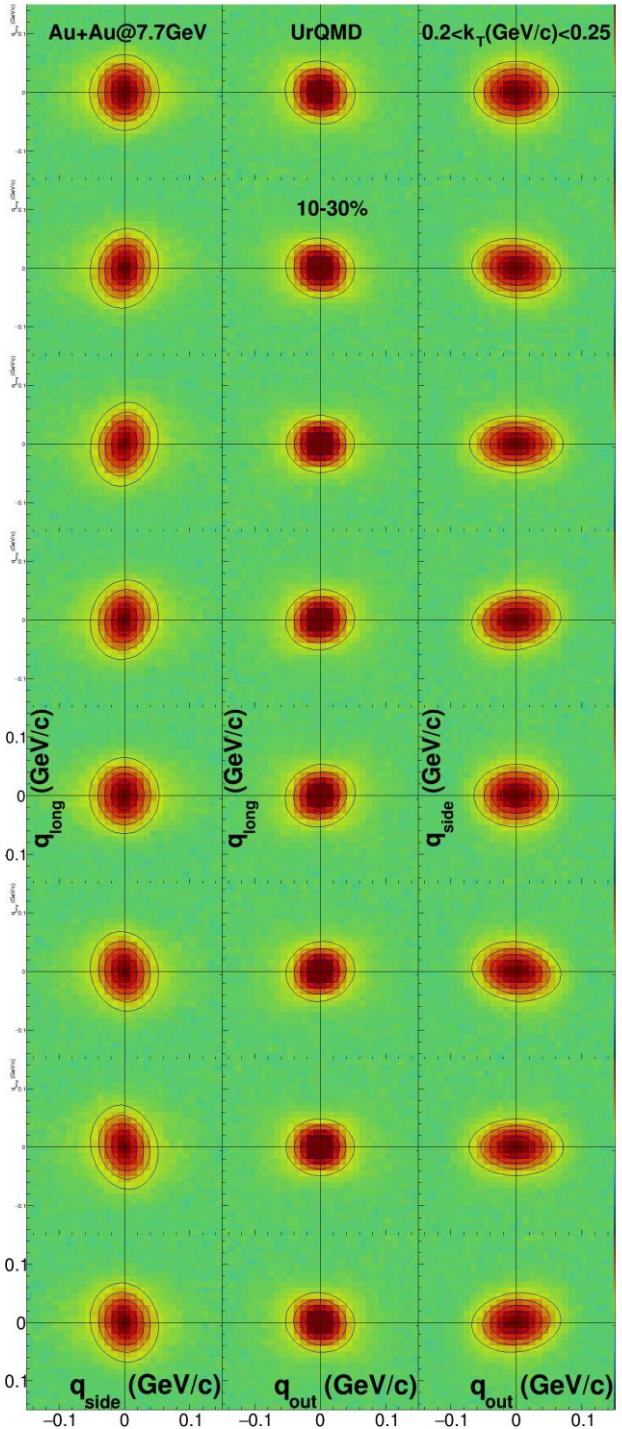


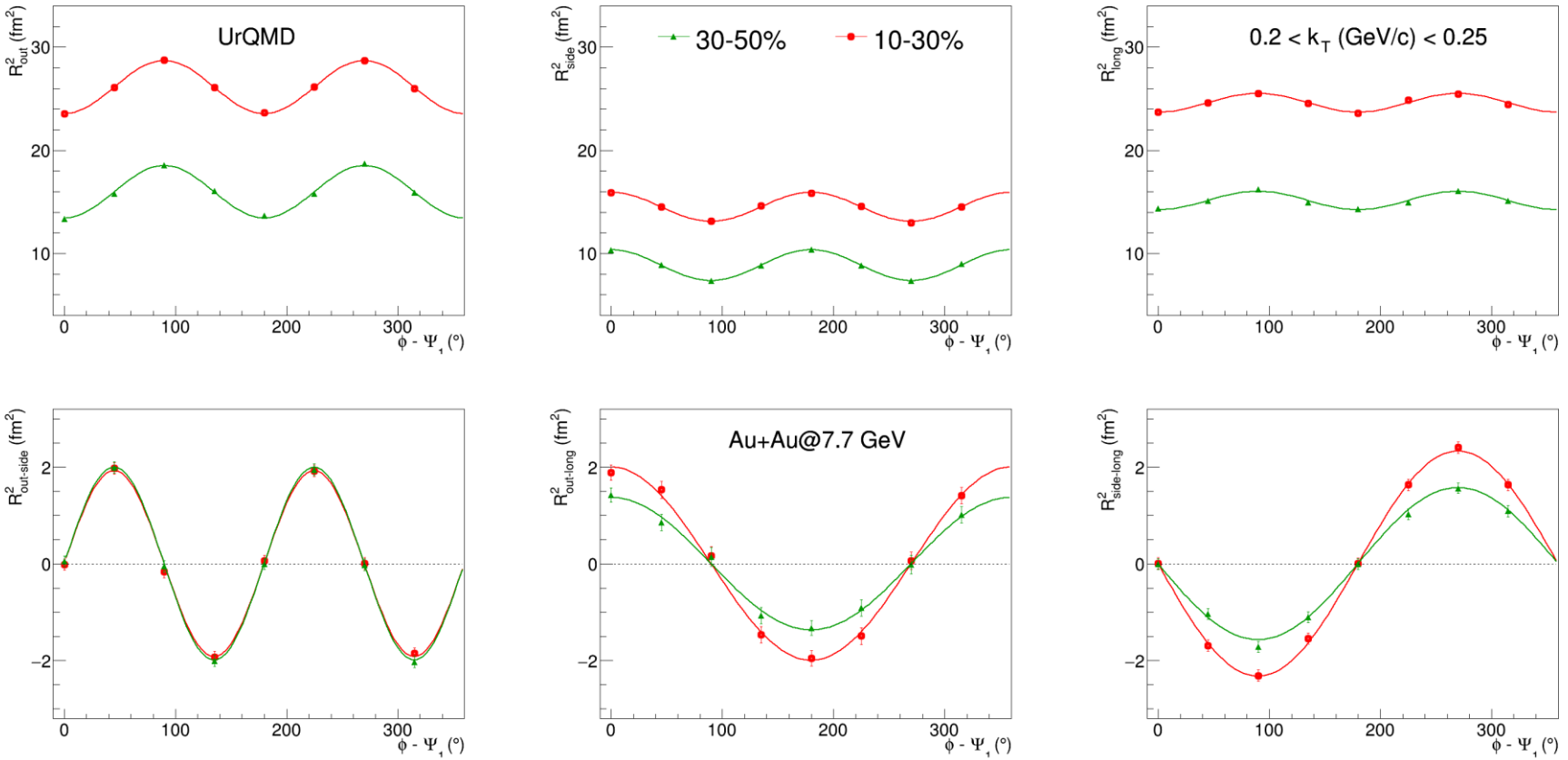
- $R_{out}, R_{side}, R_{long}$ inversely ~ width of the CF in the out, side, long directions

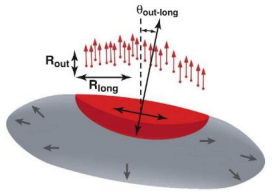


- "Cross-term" radii are reflected in the "tilt" of the CF
  - Example: $R^2_{side-long}$ shows up as a tilt of the CF in $\{q_{side}, q_{long}\}$ projection



Radii oscillations example in UrQMD

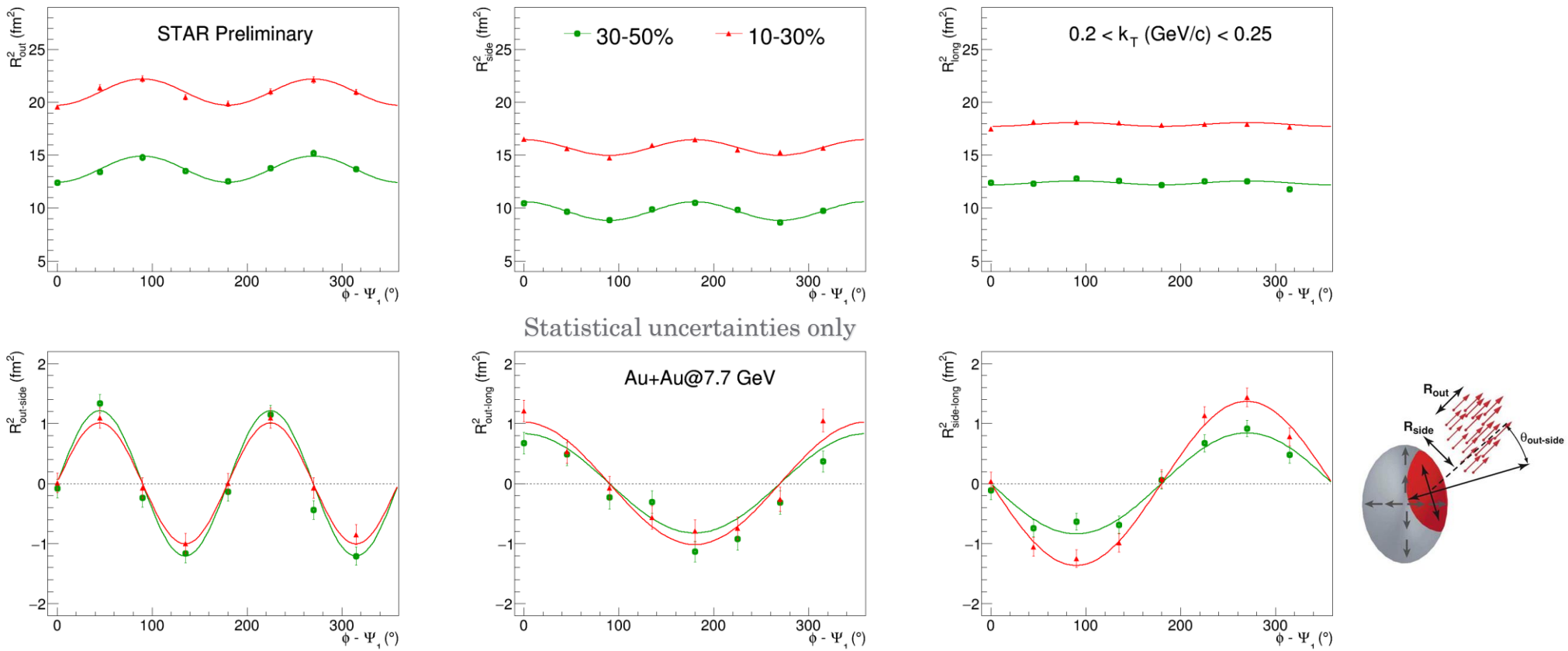




Ann.Rev.Nucl.Part. Sci. 55 (2005) 357-402

- 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

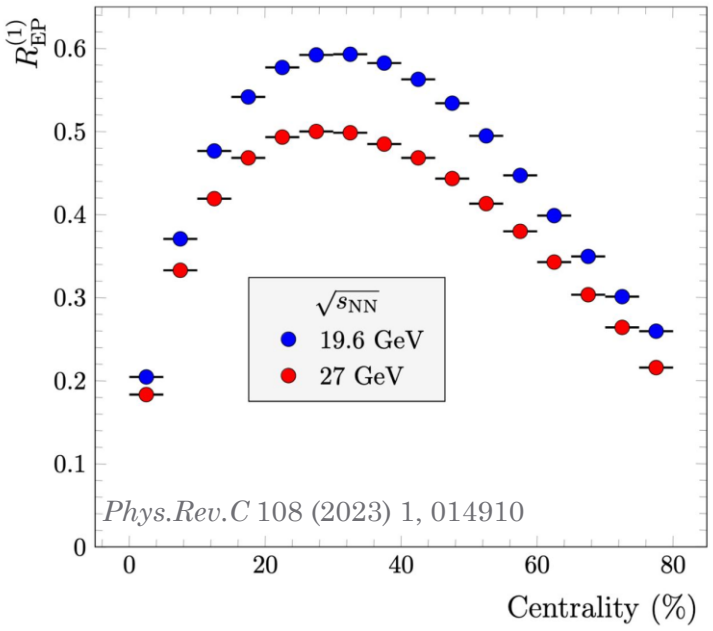


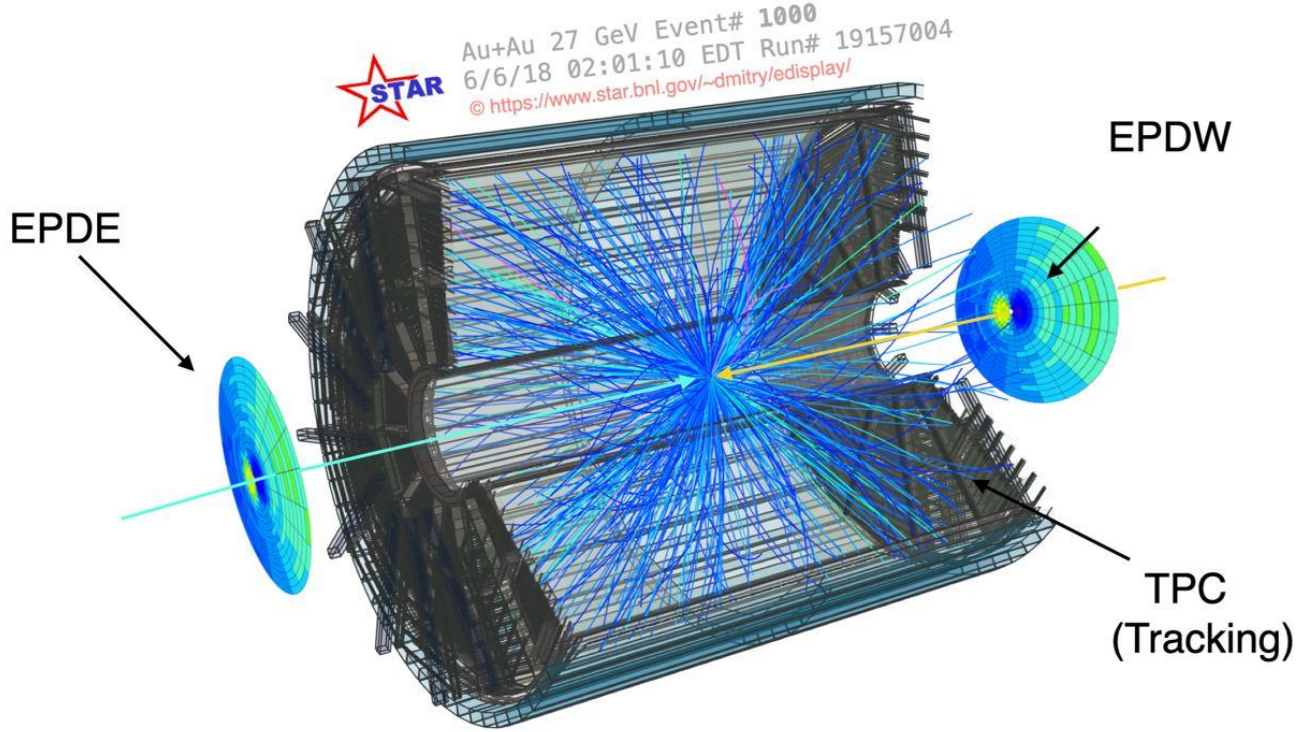
Statistical uncertainties only

- 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

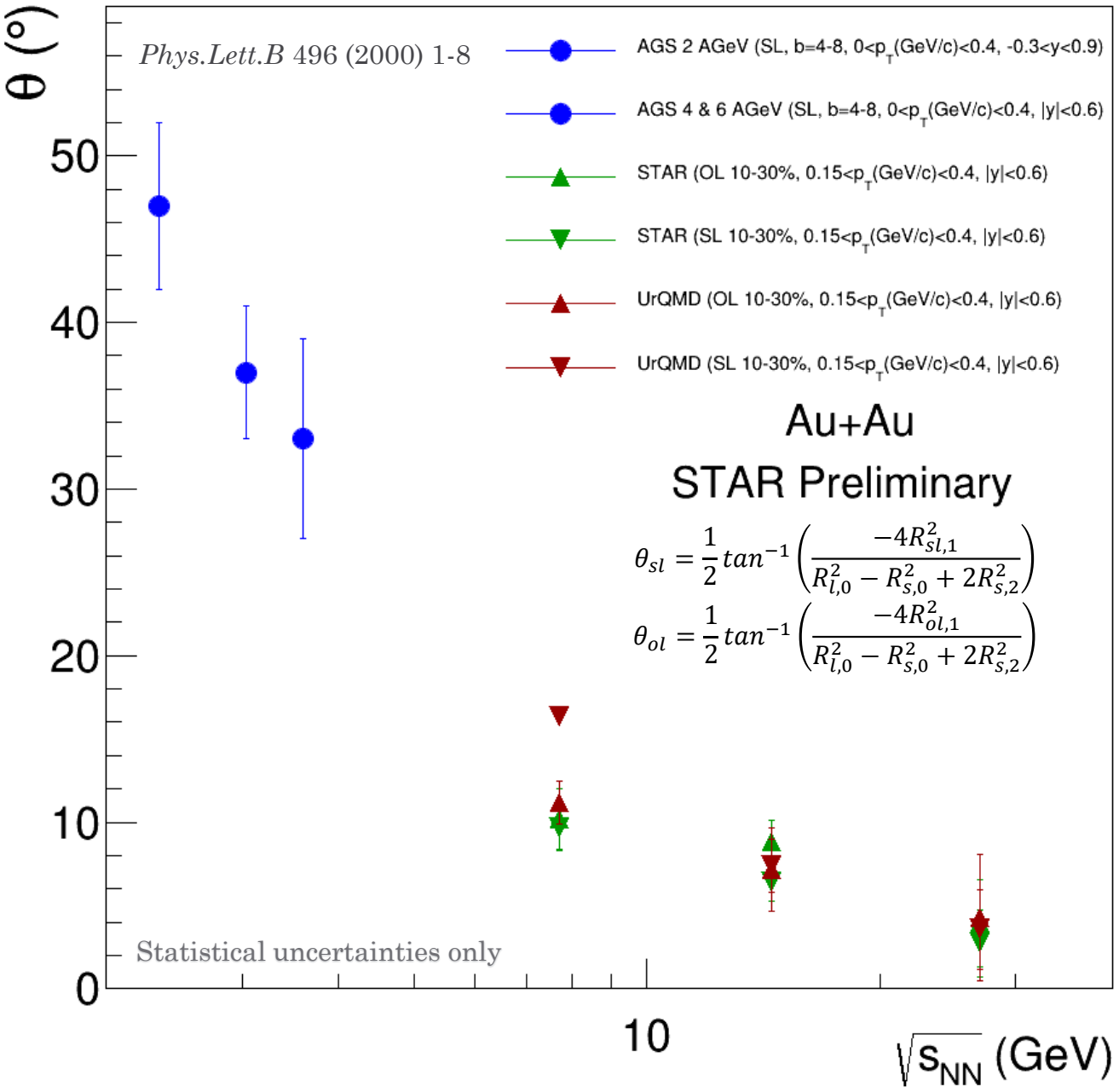




Correction of magnitudes

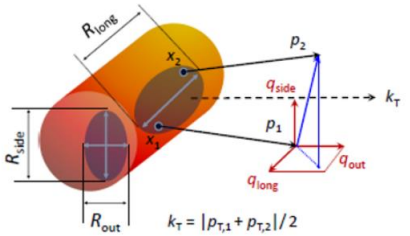
$$R_{\mu,n}^{2true} = \frac{R_{\mu,n}^{2obs}}{\langle \cos(n(\Psi_n - \Psi_{RP})) \rangle}$$

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

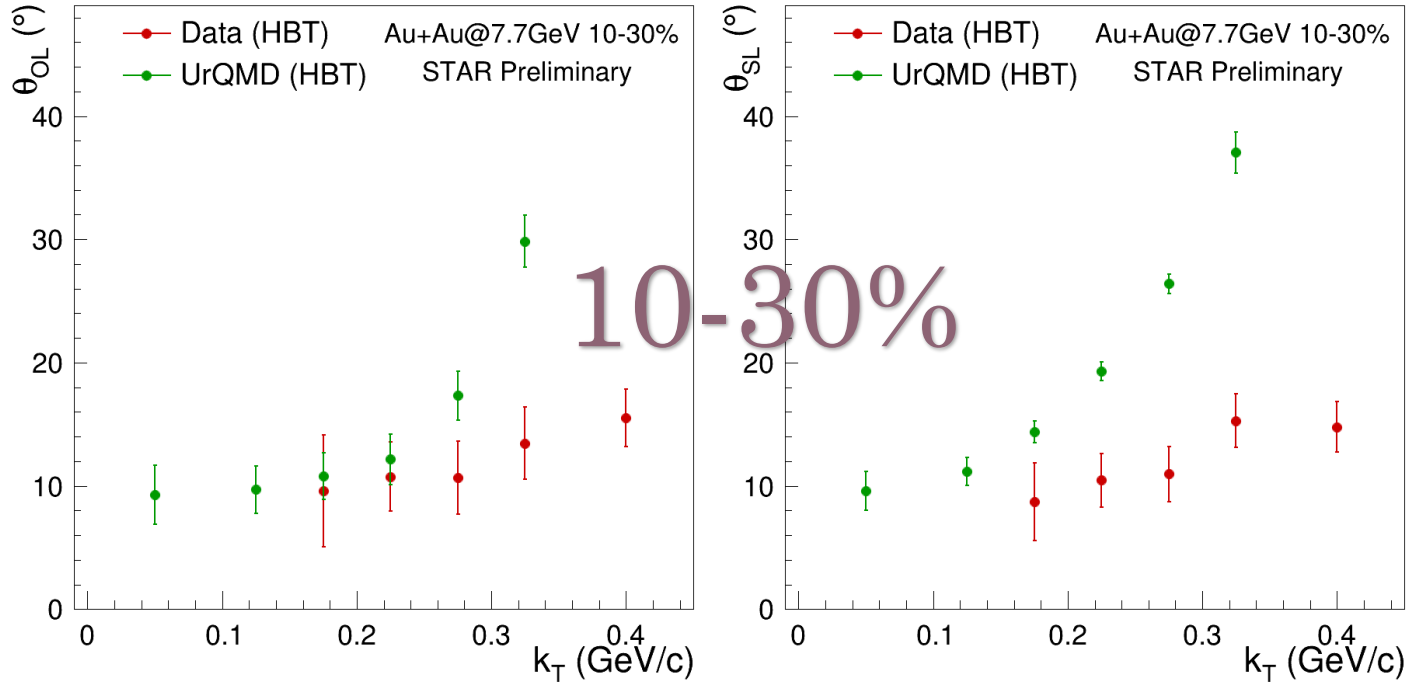


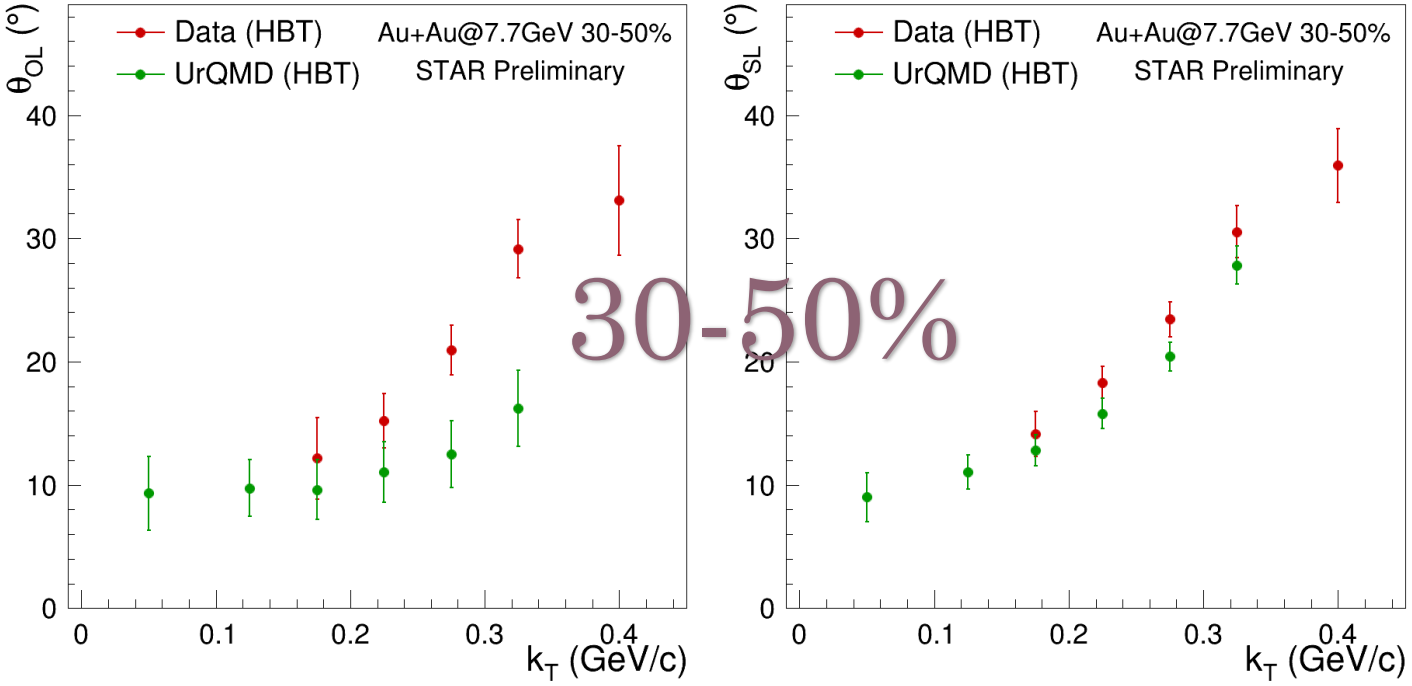
Energy dependence of the tilt

- 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 θ_{SL} and θ_{OL} tilts



Statistical uncertainties only

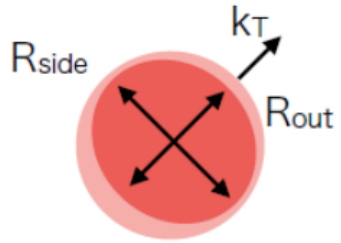




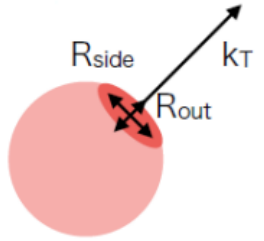
k_T dependence of the tilt in the experiment and UrQMD

- 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

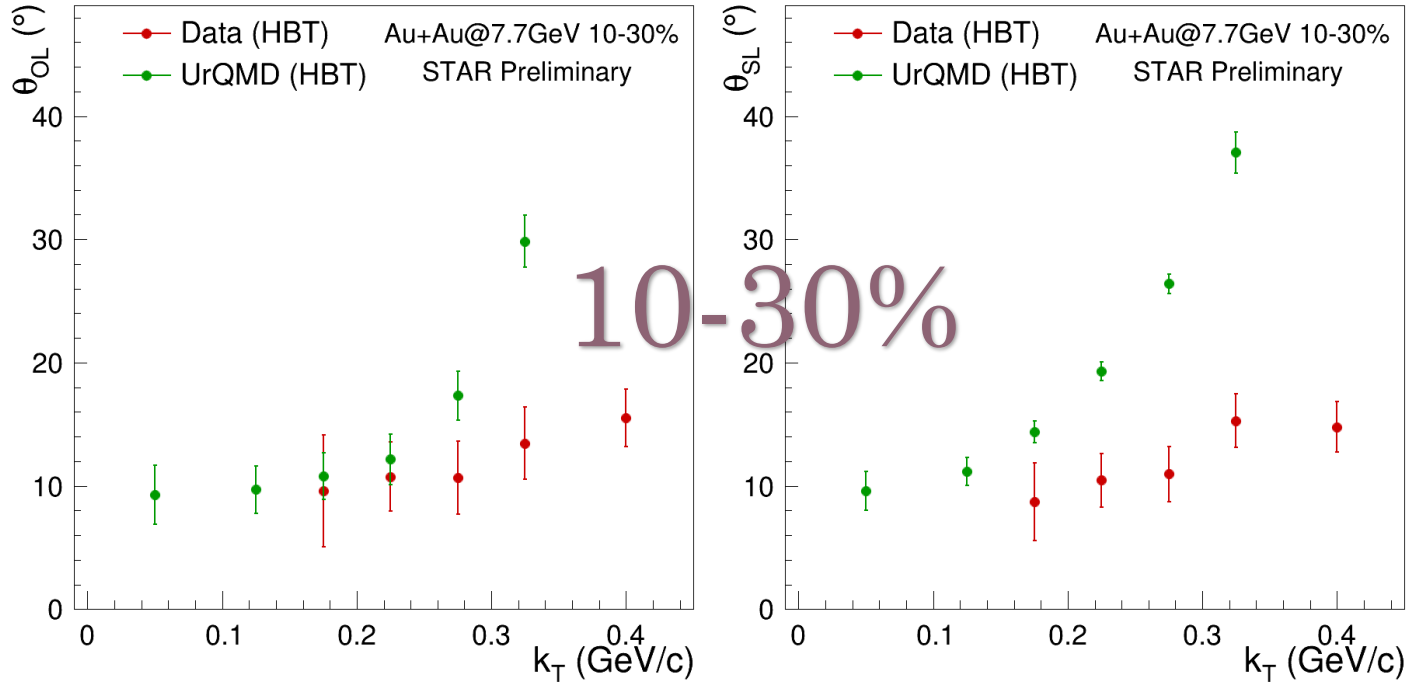
Low kT



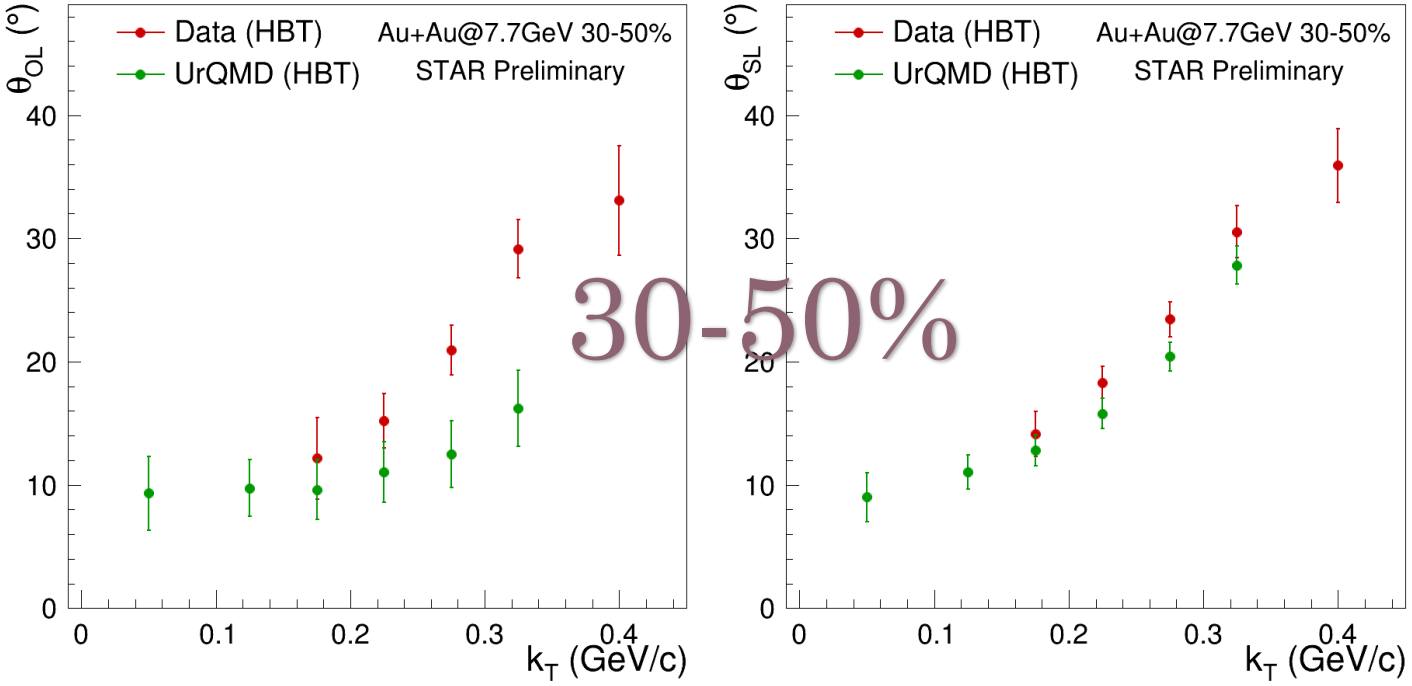
High kT



Statistical uncertainties only



10-30%

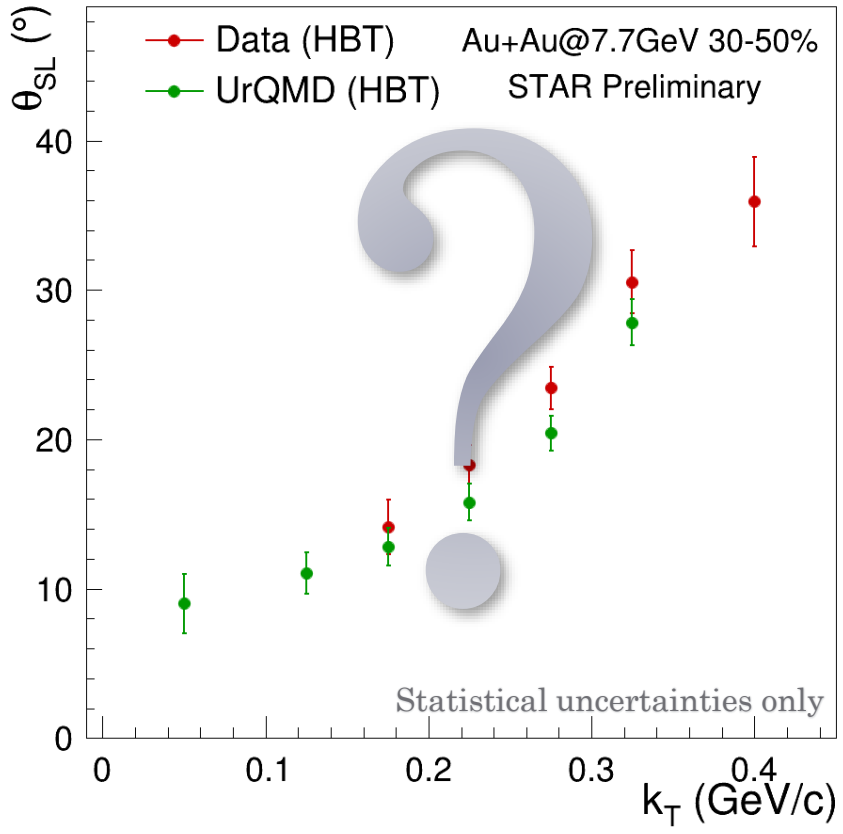


30-50%

k_T dependence of the tilt in the experiment and UrQMD

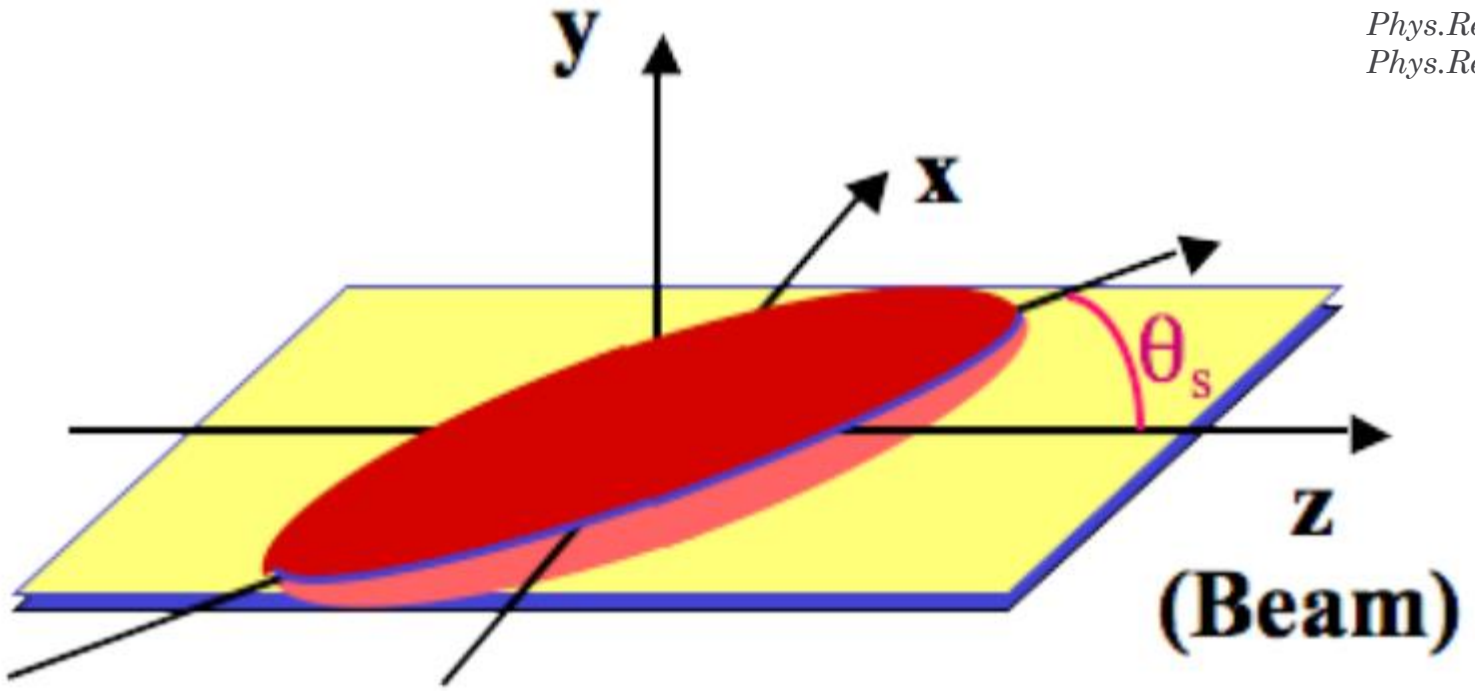
- Discrepancy between "out-long" and "side-long" tilt in UrQMD might be attributed to model limitations to describe system evolution
  - "side" radius reflects the spatial extent of the pion-emitting source, while "out" combines both spatial extent and the emission duration of the fireball
- Better agreement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

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



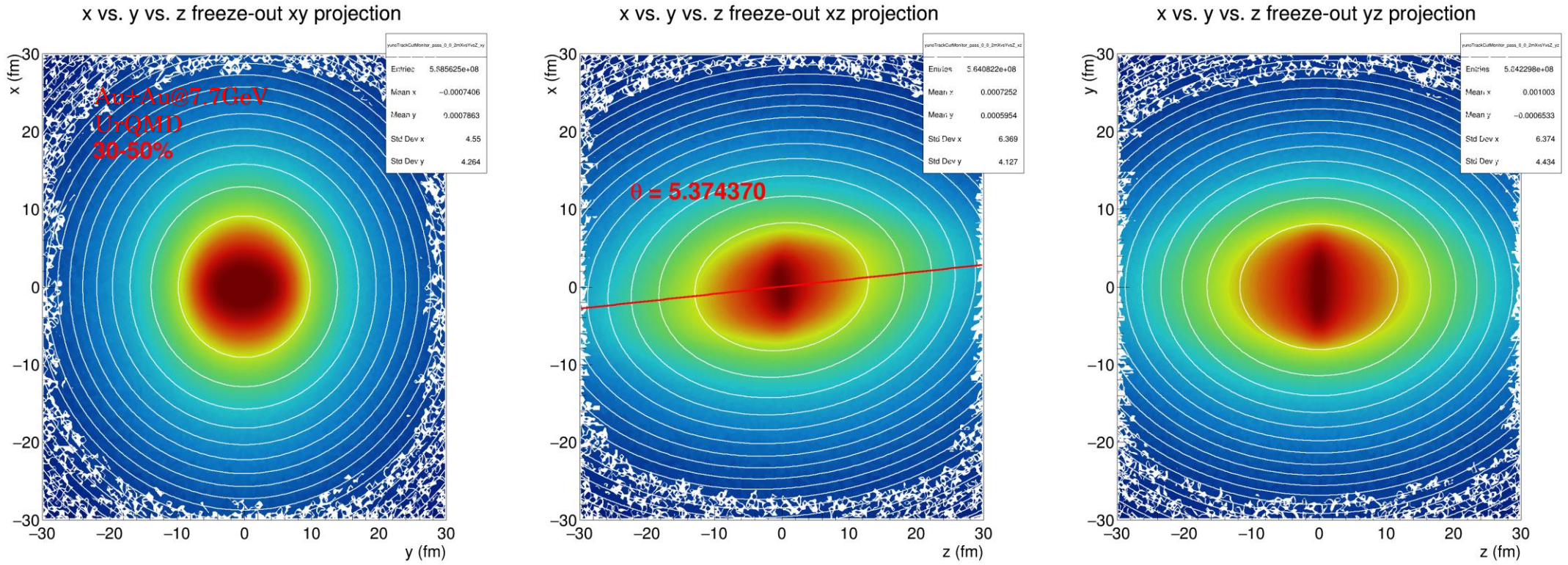
The simplistic model with unique spatial tilt

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



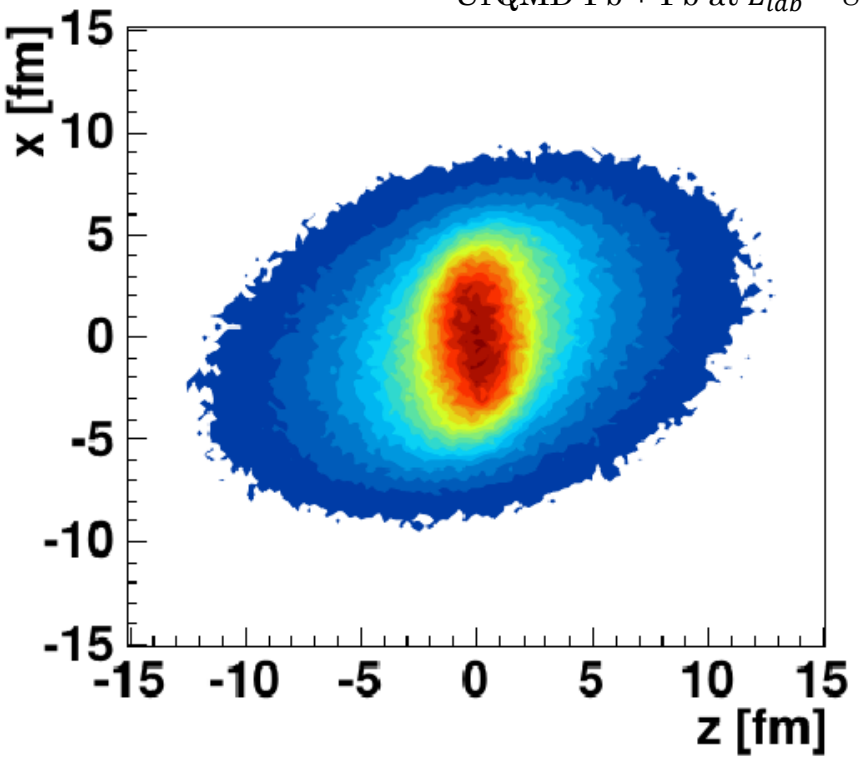
$$f(x,y,z) \sim \exp\left(-\frac{(x\cos\theta_S - z\sin\theta_S)^2}{2\sigma_{x'}^2} - \frac{y^2}{2\sigma_y^2} - \frac{(x\sin\theta_S + z\cos\theta_S)^2}{2\sigma_{z'}^2}\right)$$

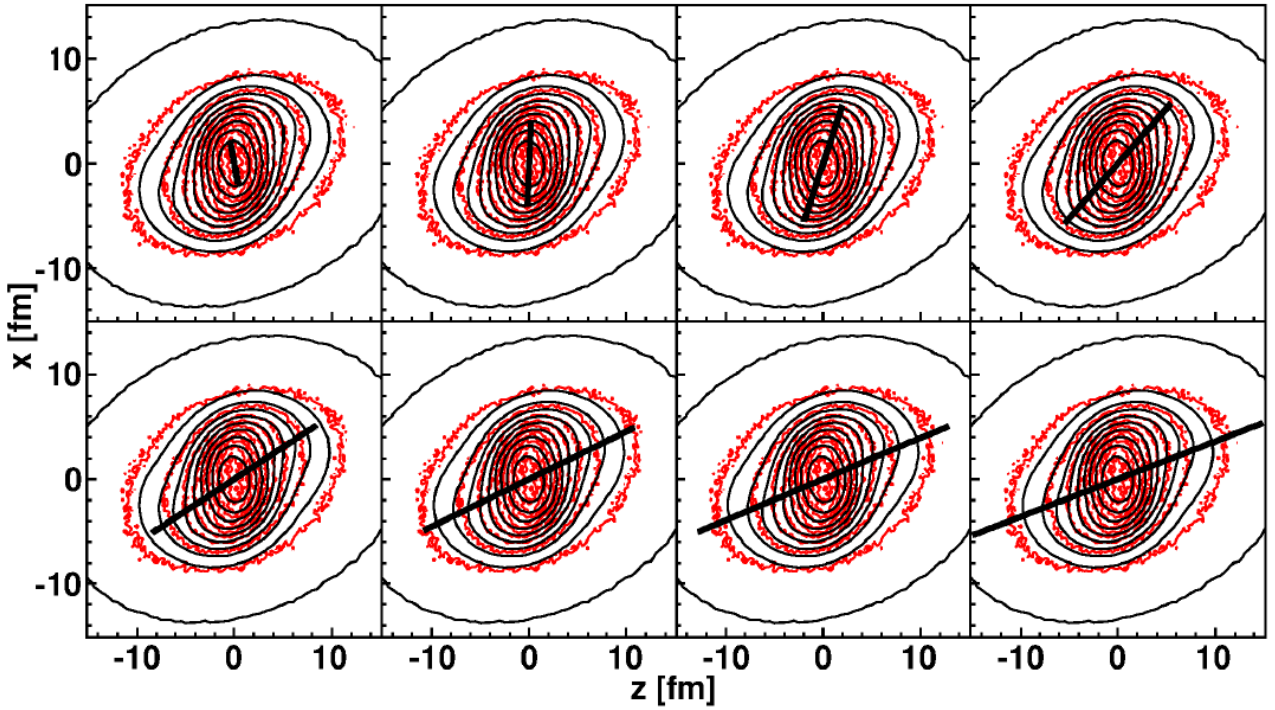
- Realistic picture is more complicated than just tilted ellipsoid

Complicated structure of the freeze-out distribution

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

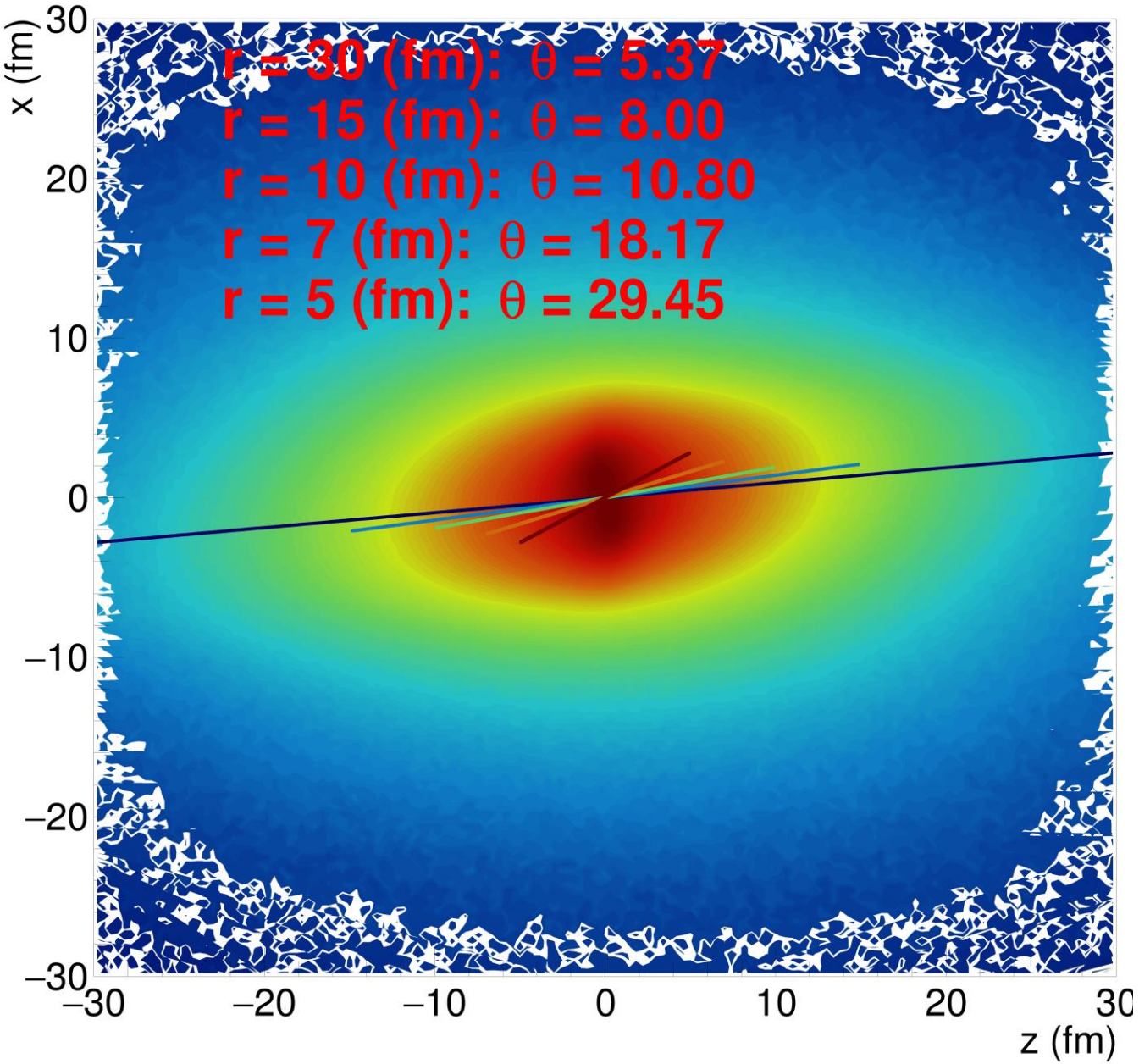
UrQMD Pb + Pb at E_{lab} = 8 GeV, b = 3.4–6.8 fm, $|y| < 0.5$, and $p_{\perp} < 0.4$ GeV





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

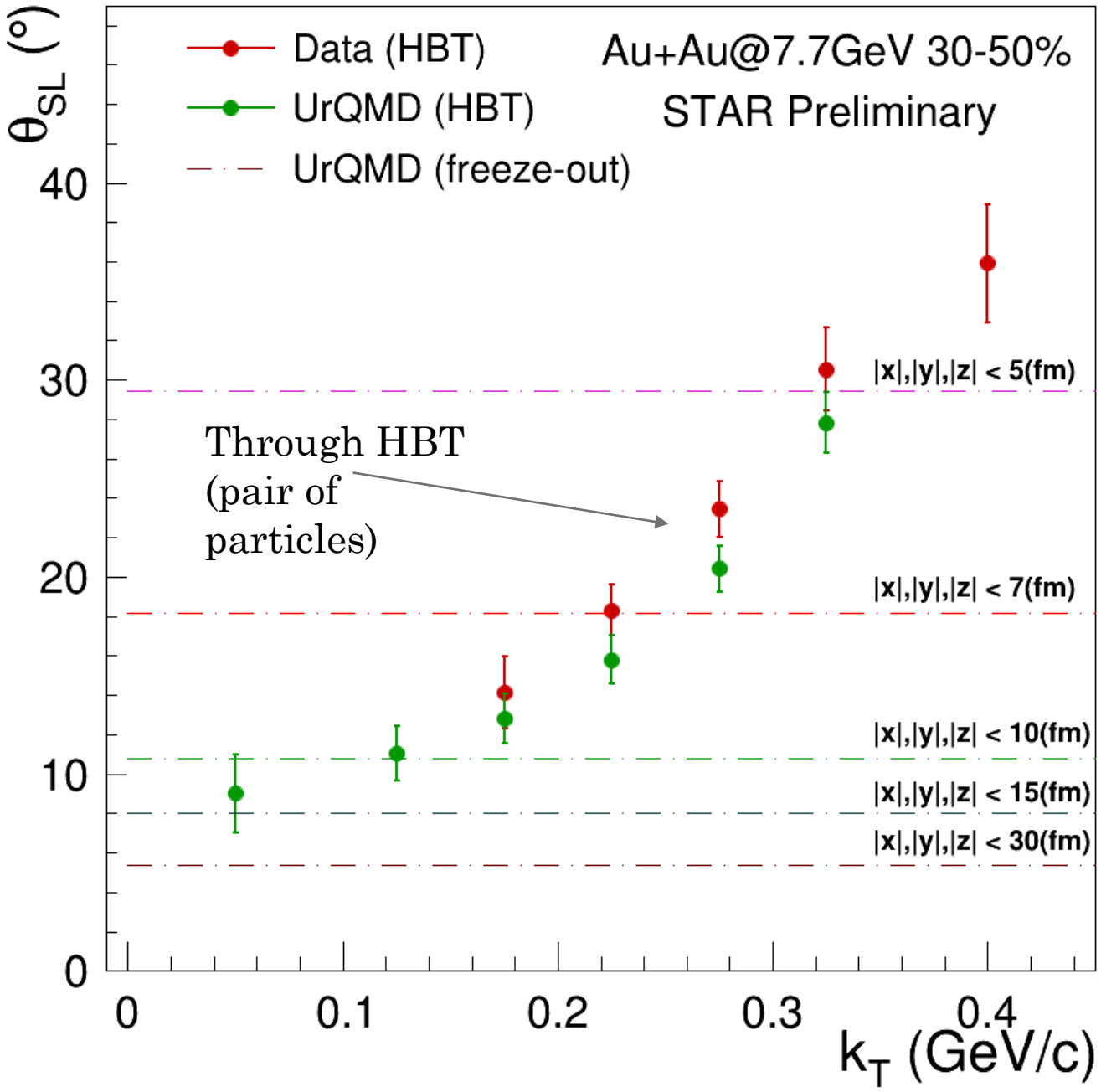
x vs. y vs. z freeze-out xz projection



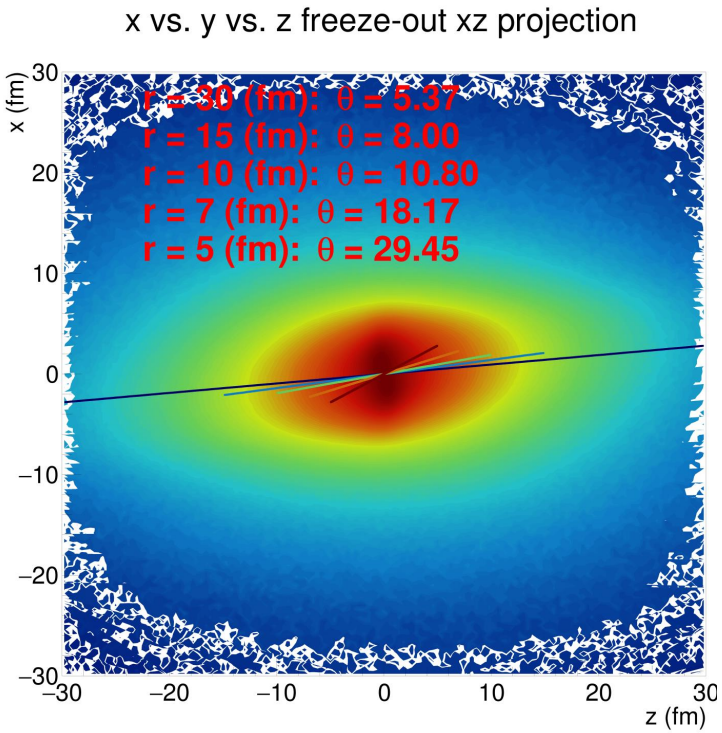
Range of freeze-out distribution fitting

- Extracted tilt strongly depends on the spatial scale

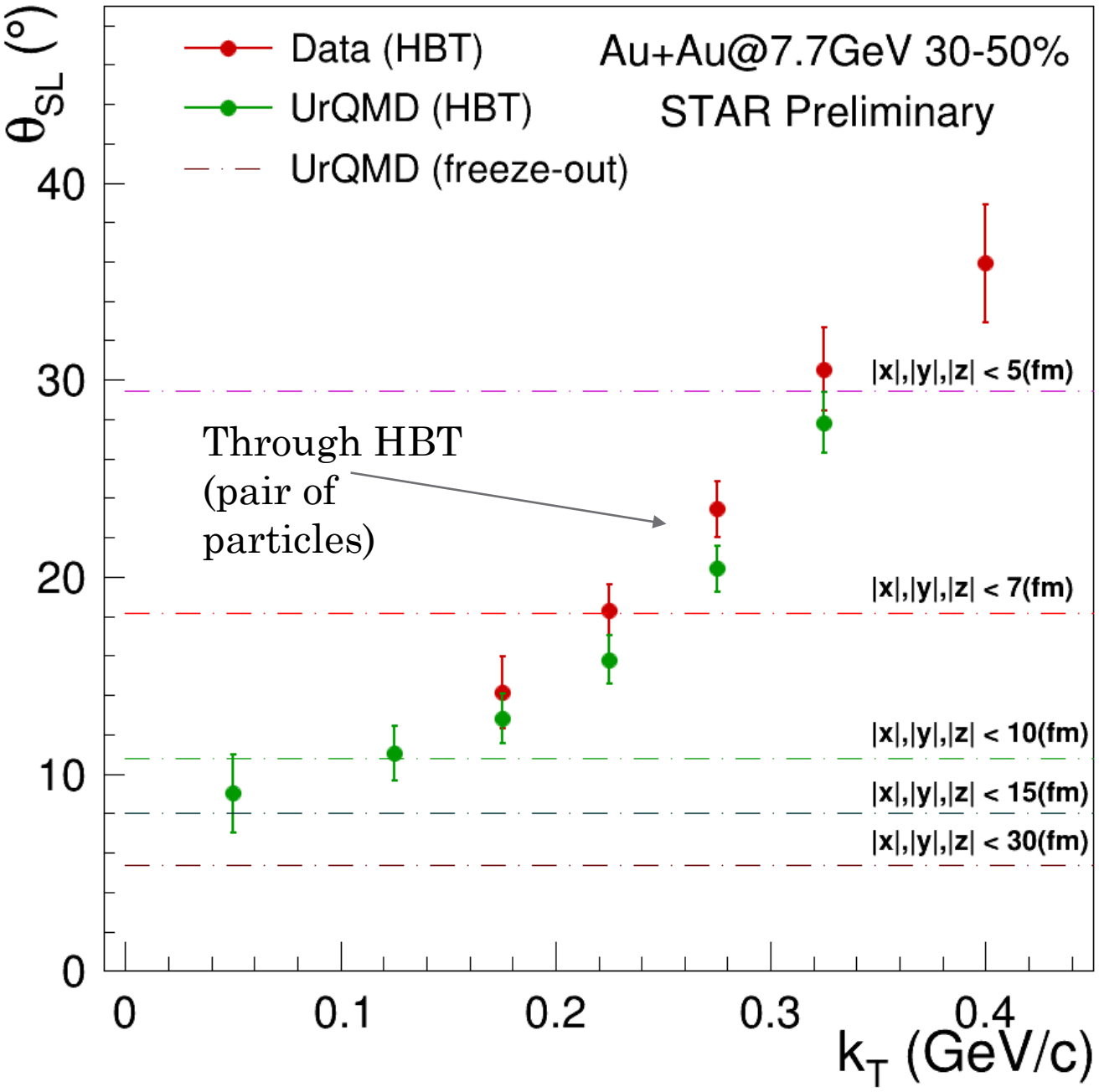
Statistical uncertainties only



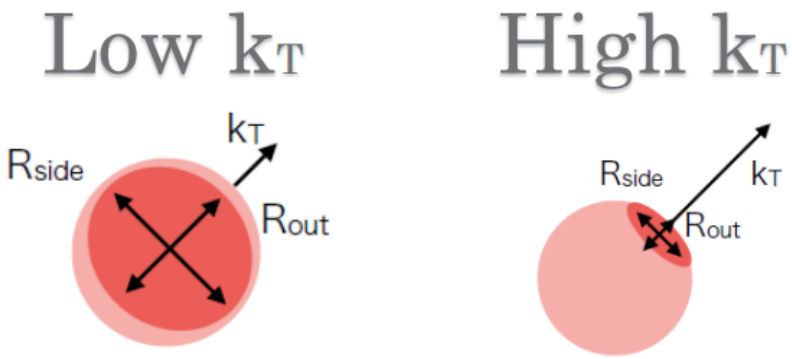
Correspondence between femtoscopy tilt and freeze-out distribution tilt



Statistical uncertainties only

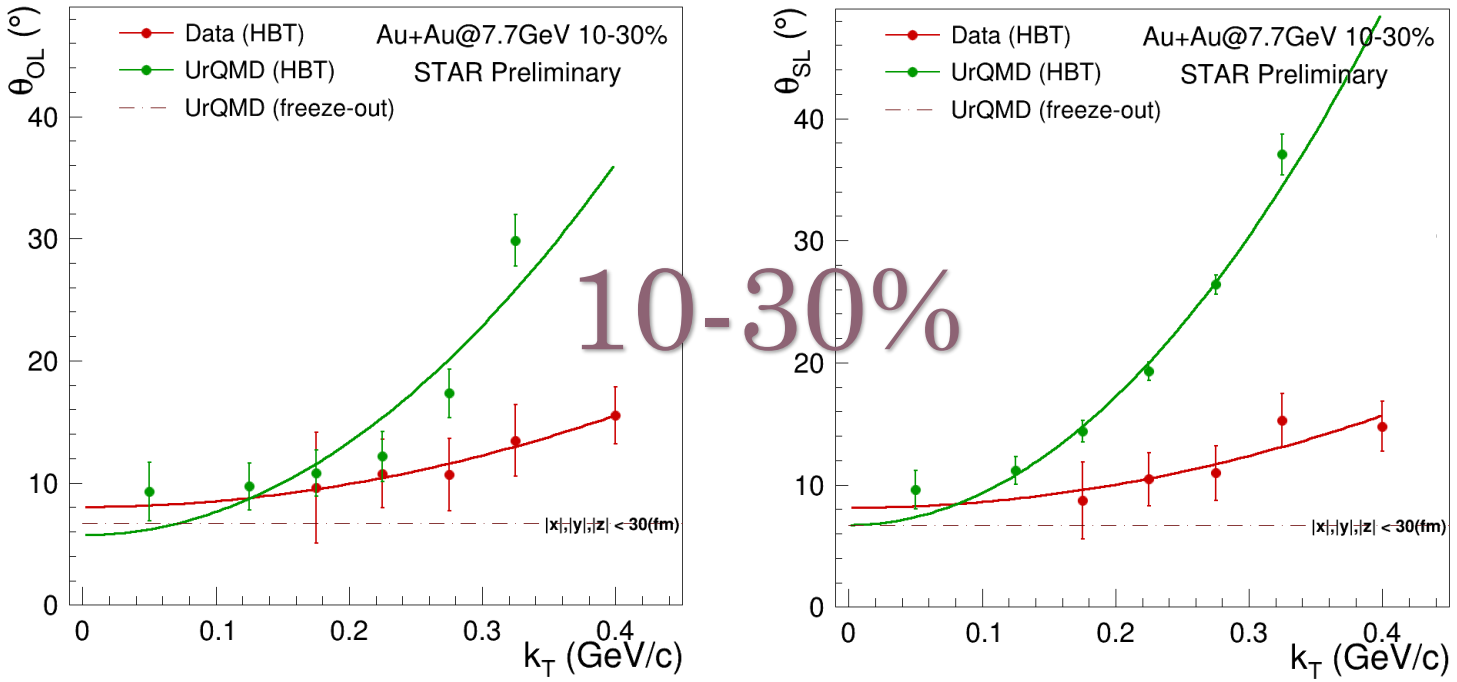


Correspondence between femtoscopy tilt and freeze-out distribution tilt

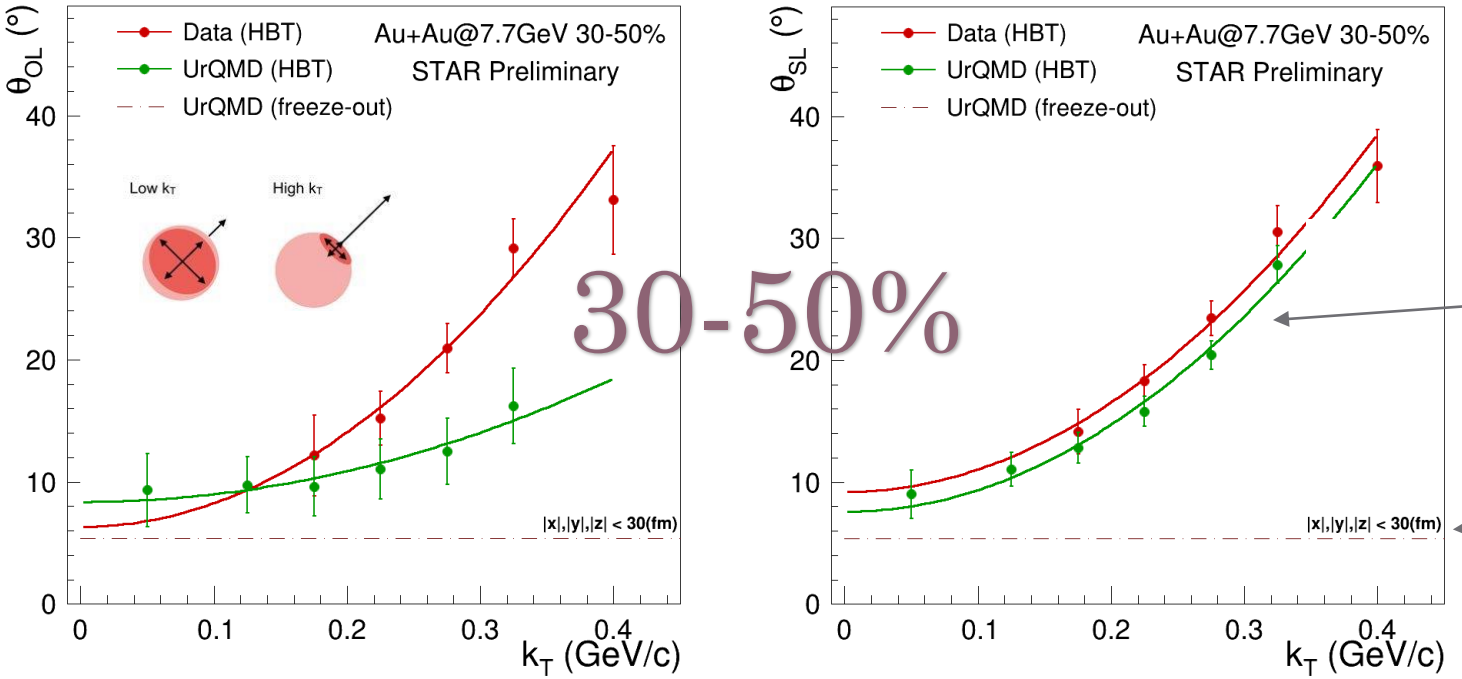


- Extrapolation to $k_T = 0$ will give the best possible comparison between tilt of homogeneity region and freeze-out distribution tilt of the "whole source"

Statistical uncertainties only



10-30%



30-50%

Tilt in the experiment and in the UrQMD

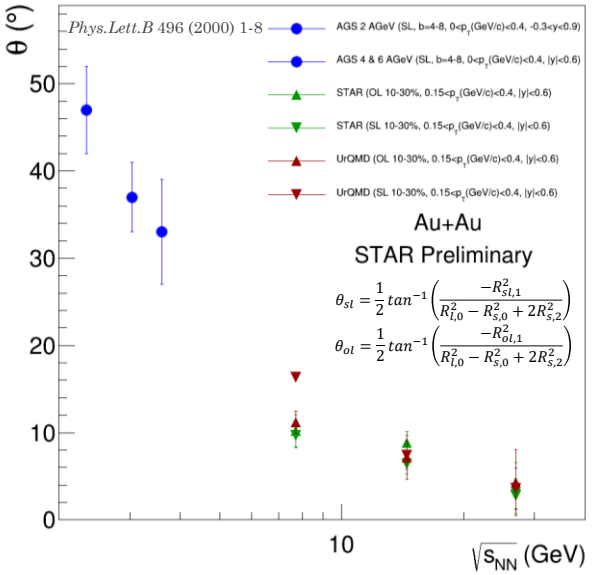
Good agreement between femtoscopy results from experiment, UrQMD and the tilt from the freeze-out distribution at low momentum

Quadratic approximation of the functional form

Through freeze-out distribution of pions

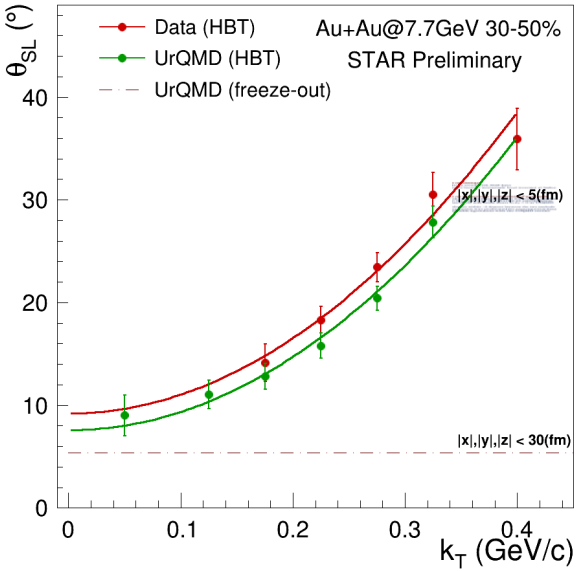
Summary

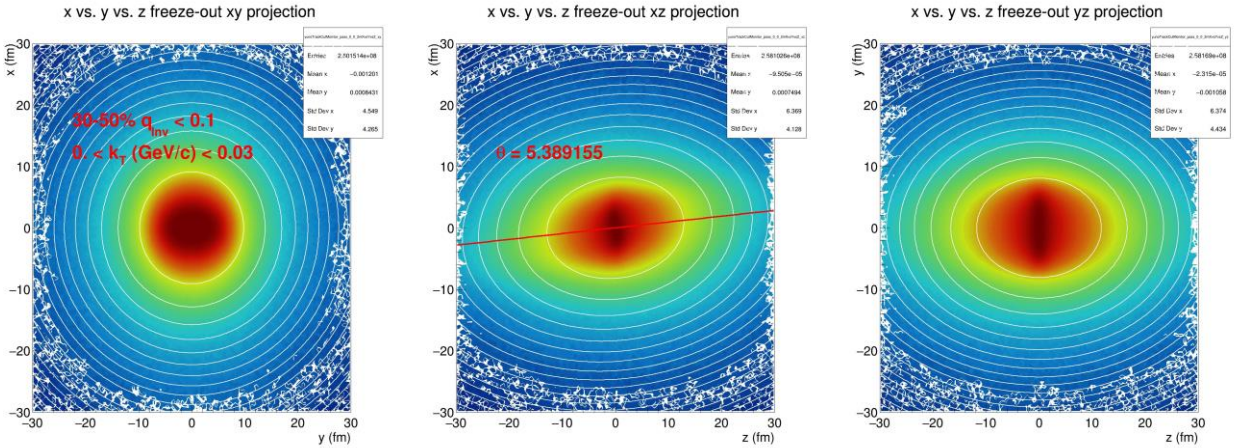
- First measurements of the spatial tilt at the RHIC energies was done
- Tilt dependence on energy
  - Obtained results in trend with AGS data
    - Collision geometry becomes increasingly boost invariant at higher energies



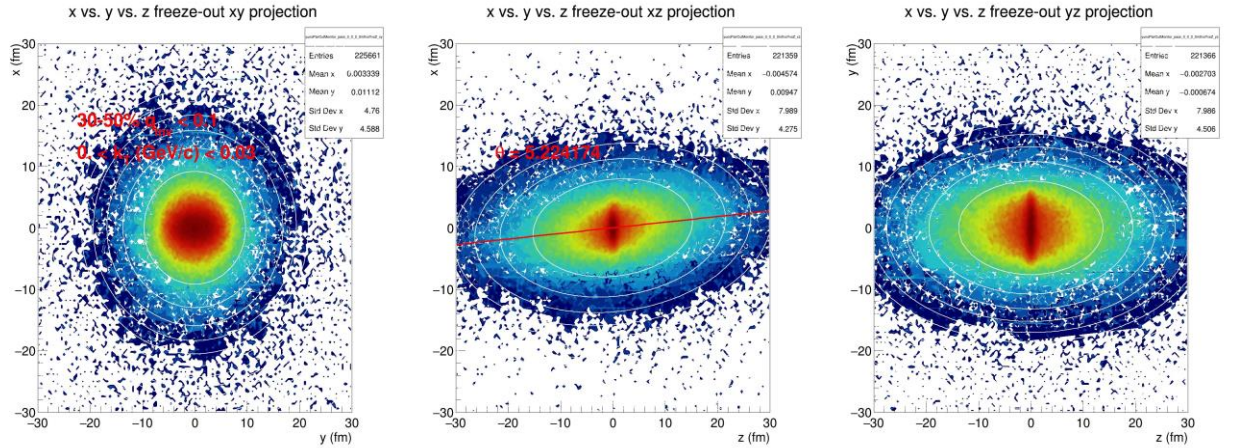
Statistical uncertainties only

- 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



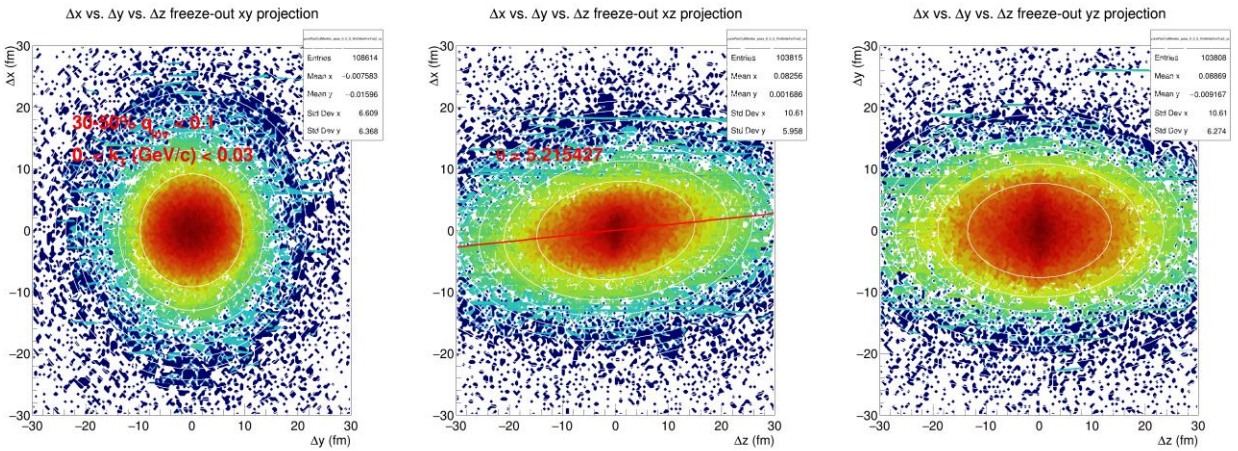


Freeze-out distribution pions



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