Anisotropic flow and HBT from hydrodynamics

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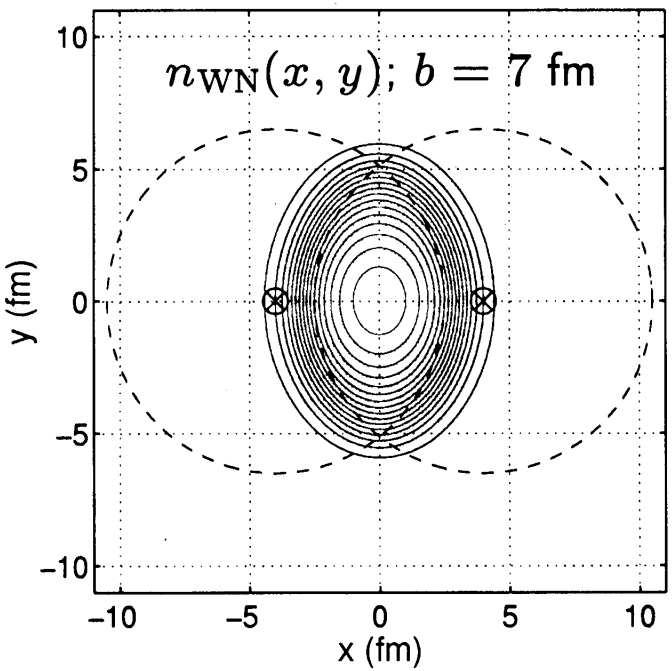
Workshop on Two-particle Interferometry and Elliptic Flow at RHIC
Brookhaven National Laboratory, June 14-15, 2002

Objective:
With the initial spatial anisotropy as a tool, what can we learn about the dynamical evolution and the geometry of heavy ion collisions?

Transverse geometry of non-central collisions



Anisotropic distribution of matter in the overlap region leads to anisotropies in the observed final particle spectra (momentum space).

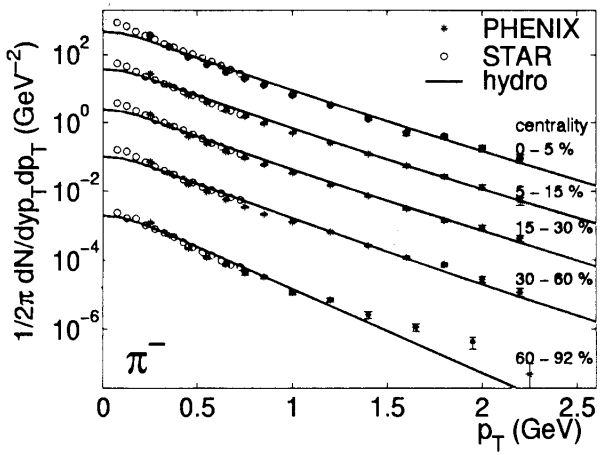
Strong rescattering is a prerequisite for large signals.

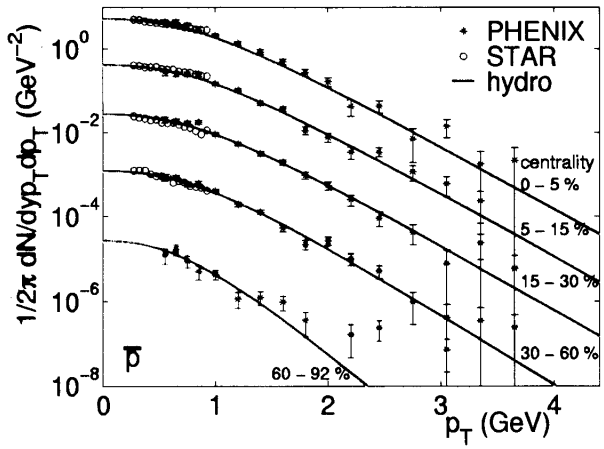
Self quenching effect, generated by *early* pressure, insensitive to later stages.

$$\frac{dN}{p_{\rm T}\, dp_{\rm T} dy d\varphi}(p_{\rm T}, \varphi; b) = \frac{dN}{2\pi p_{\rm T} dp_{\rm T} dy}(1 + 2\, v_2(p_{\rm T}; b)\, \cos(2\varphi) + \ldots)$$

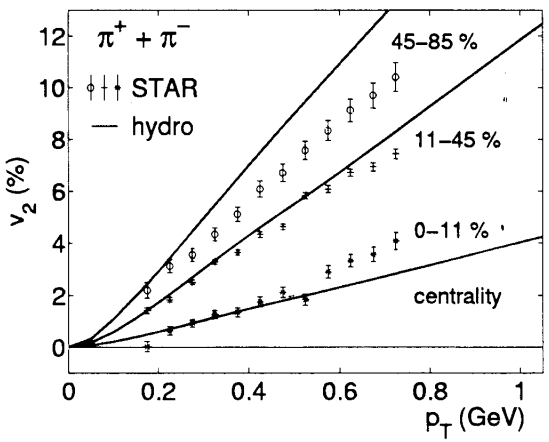
What signals can we expect in coordinate space?

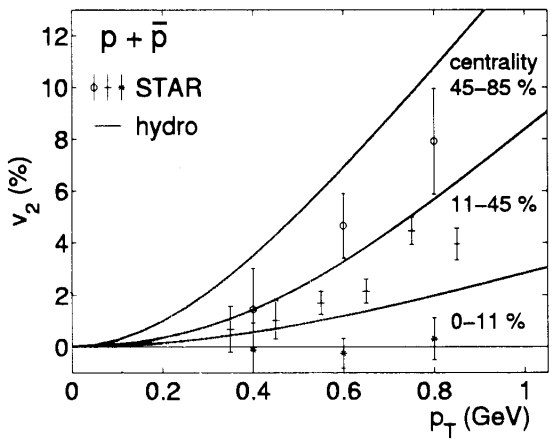
Over 99% of the emitted particles follow hydro systematics

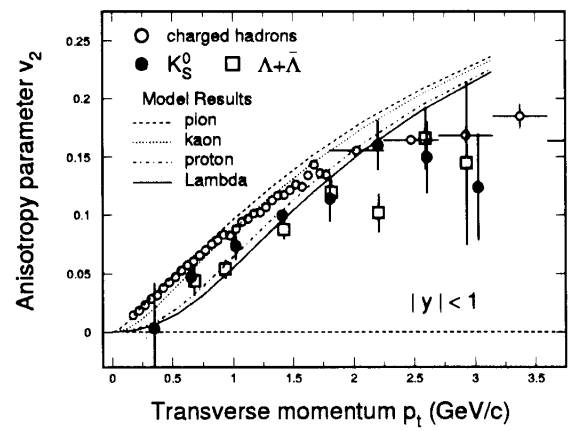




Momentum, mass and centrality dependence of particle spectra and elliptic flow

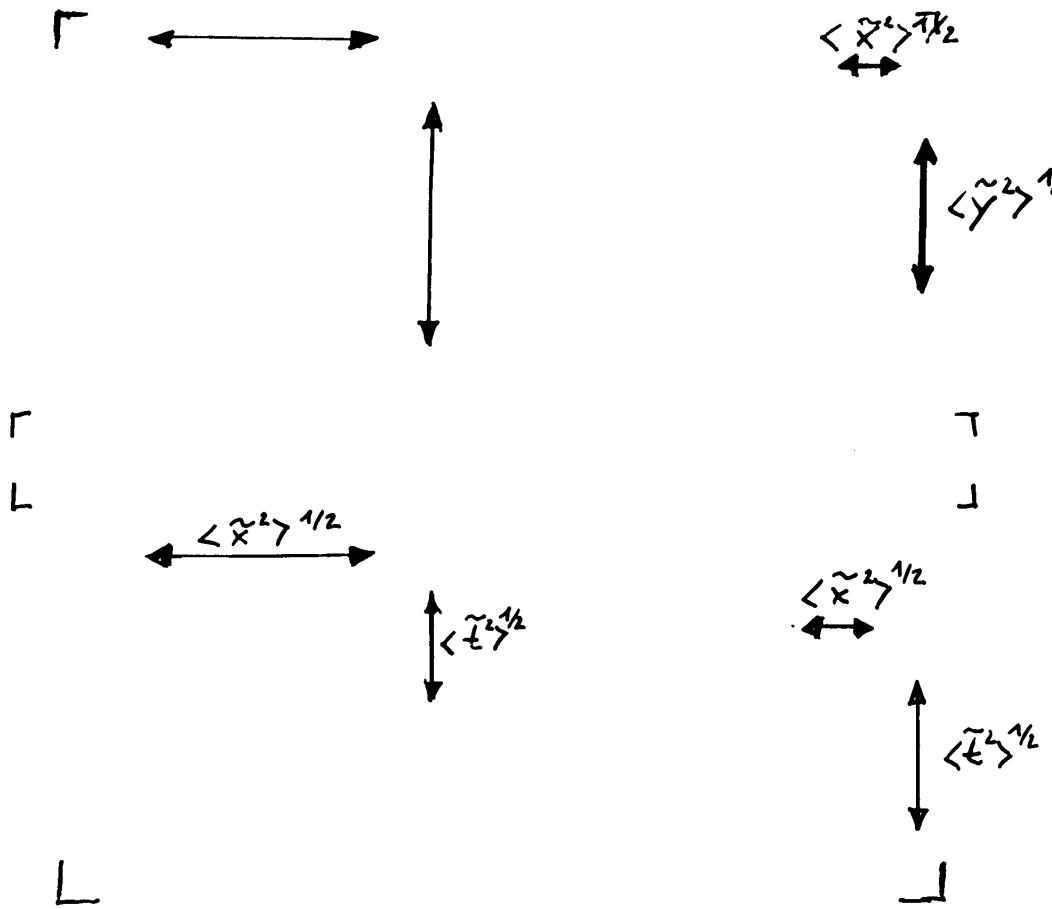






STAR, nucl-ex/0111004, PRL 87 (2001) 182301, hep-ex/0205072, PHENIX, nucl-ex/0112006

This slide is an overlay for the next slide.

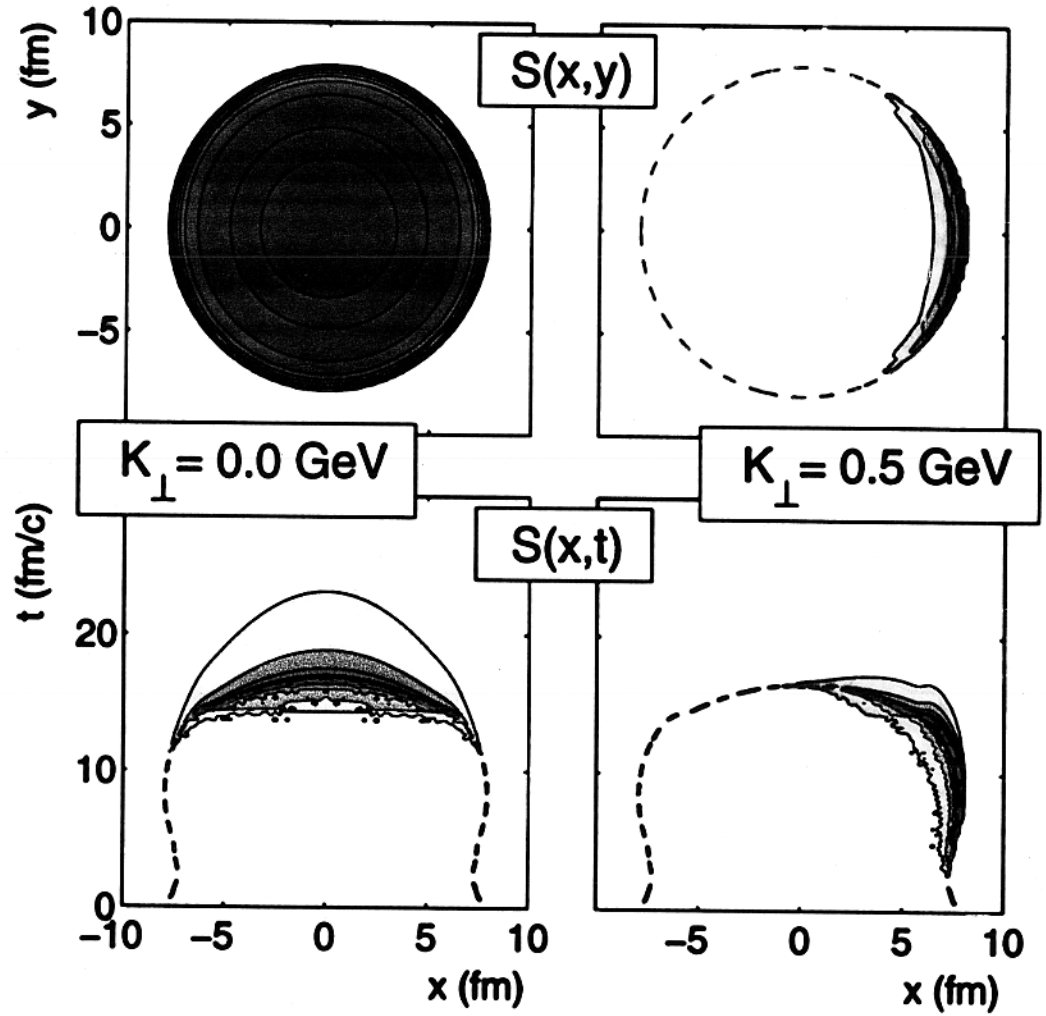


How the freeze-out surface shines – The source function:

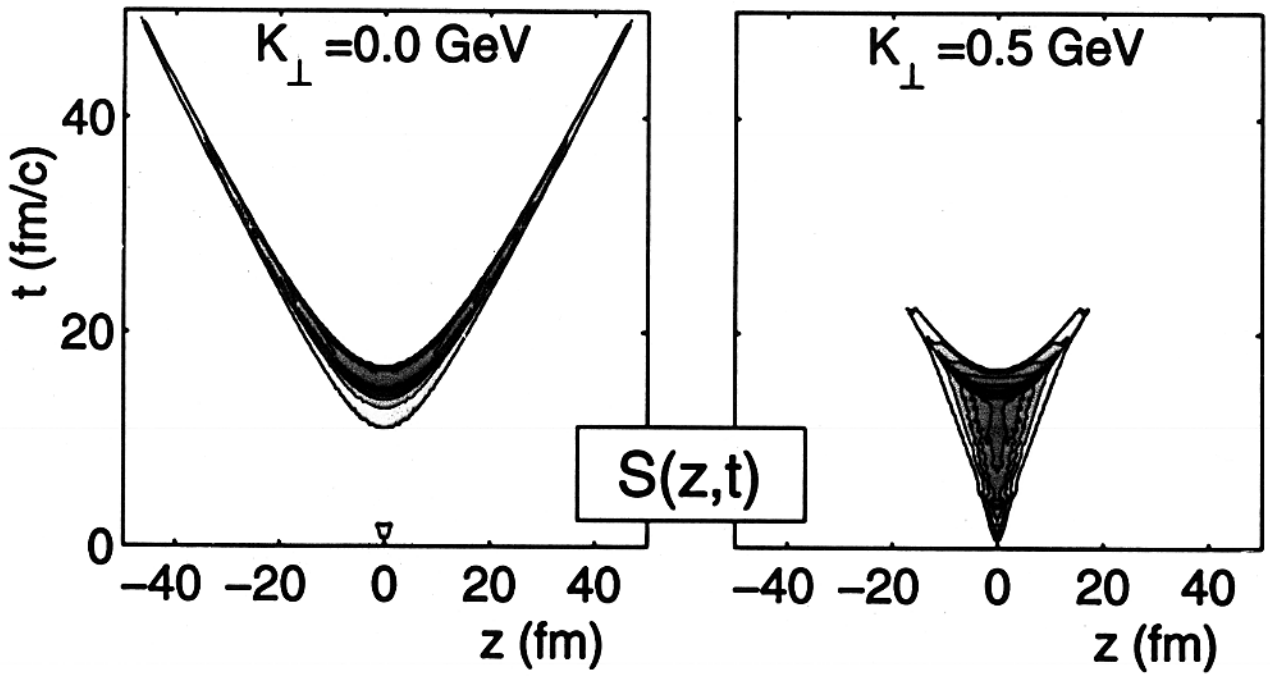
$$S(x,y,\eta,\tau;\,K) = \frac{2s+1}{(2\pi)^3}\times$$
$$\int_\Sigma \frac{K^\mu d^3\sigma_\mu(x')\delta^4(x-x')}{\exp\{\beta(x')[K\cdot u(x')-\mu_\alpha(x')]\}\pm 1}$$

Particle spectra:
$$E\,d^3N/dp^3 = \int d^4x\, S(x,p)$$

Integrate the source function over two coordinates to study density plots of the emission.



Particle production and boost-invariance

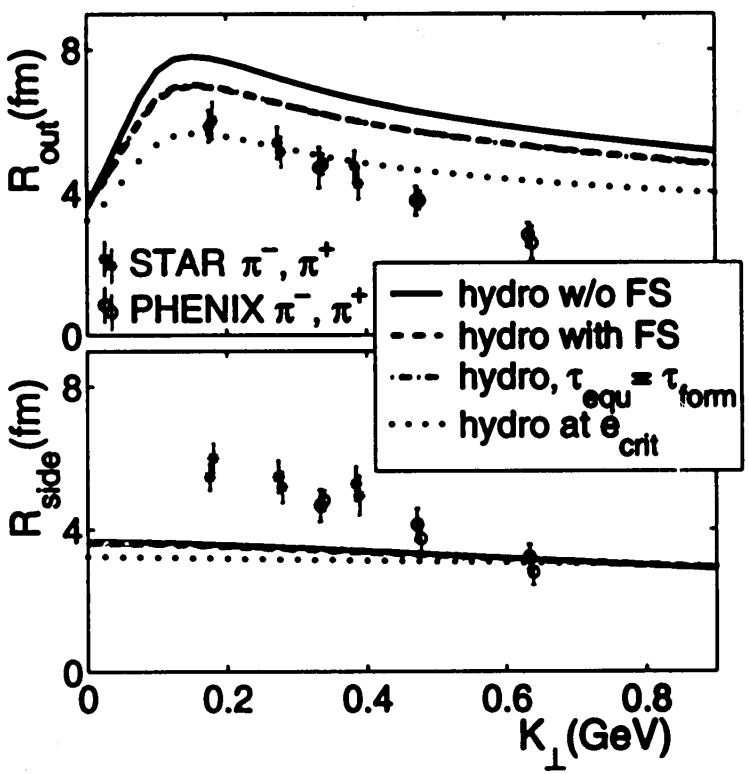


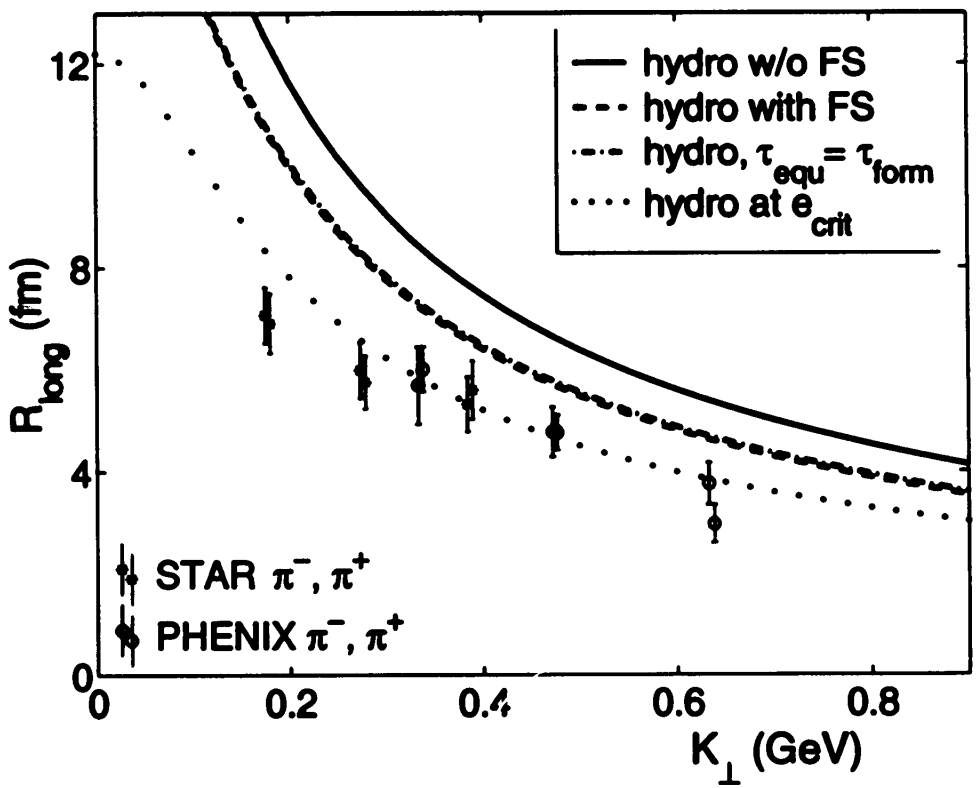
Particle emission from regions of non-zero z happens at late times as a consequence of boost invariance. The longitudinal flow gradient is then small ($\sim t^{-1}$) and fluidcells over a large variance of $\langle z^2 \rangle$ contribute to the particle spectrum at mid-rapidity. For the same reason $\sqrt{\langle t^2 \rangle - \langle t \rangle^2}$ turns out large as well.

HBT radii from hydrodynamics and experiment

STAR collaboration, PRL 87 (2001) 082301; PHENIX collaboration, nucl-ex/0104020

$$R_{\rm out} = \langle\, (\tilde{x} - \beta_\perp \tilde{t})^2 \,\rangle^{1/2}; \qquad R_{\rm side} = \langle\, \tilde{y}^2 \,\rangle^{1/2}; \qquad R_{\rm long} = \langle\, \tilde{z}^2 \,\rangle^{1/2}.$$



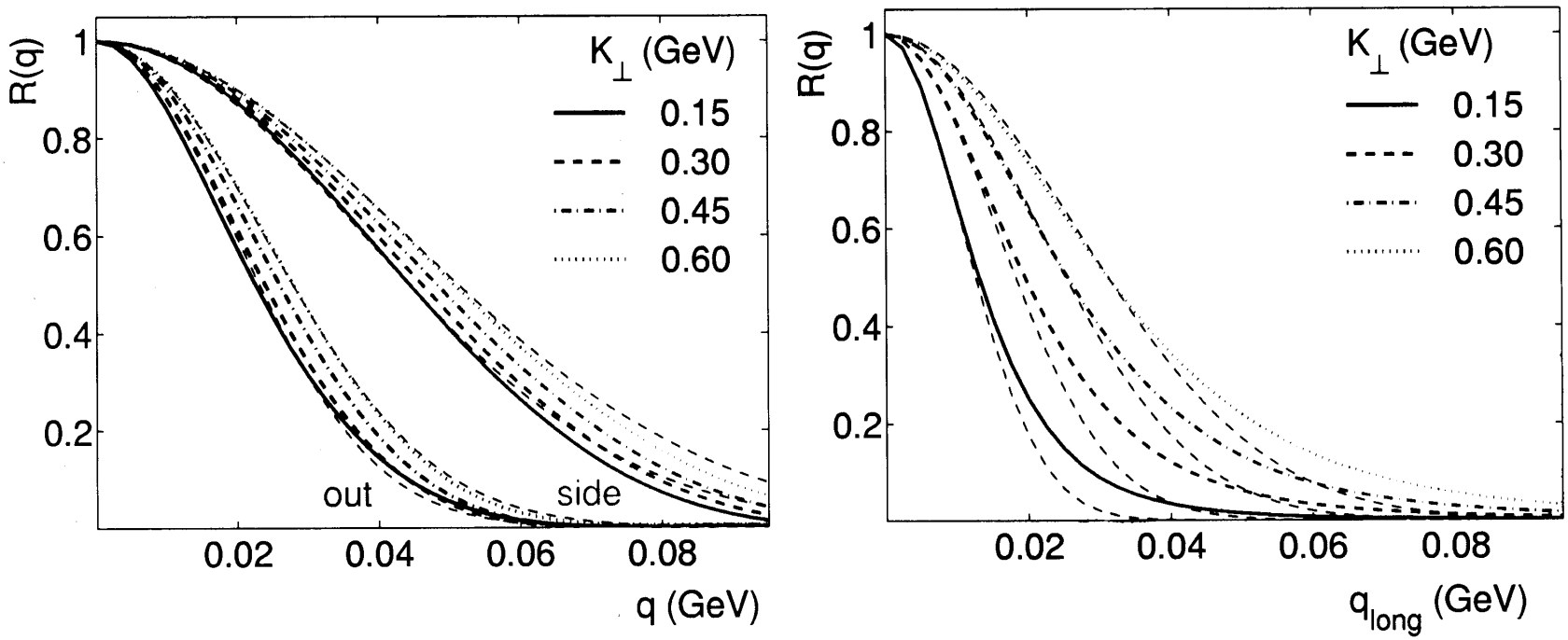


The Correlator – traditional representation

STAR collab., Phys. Rev. Lett. 87 (2001) 082301, PHENIX collab., Phys. Rev. Lett. 88 (2002) 192302

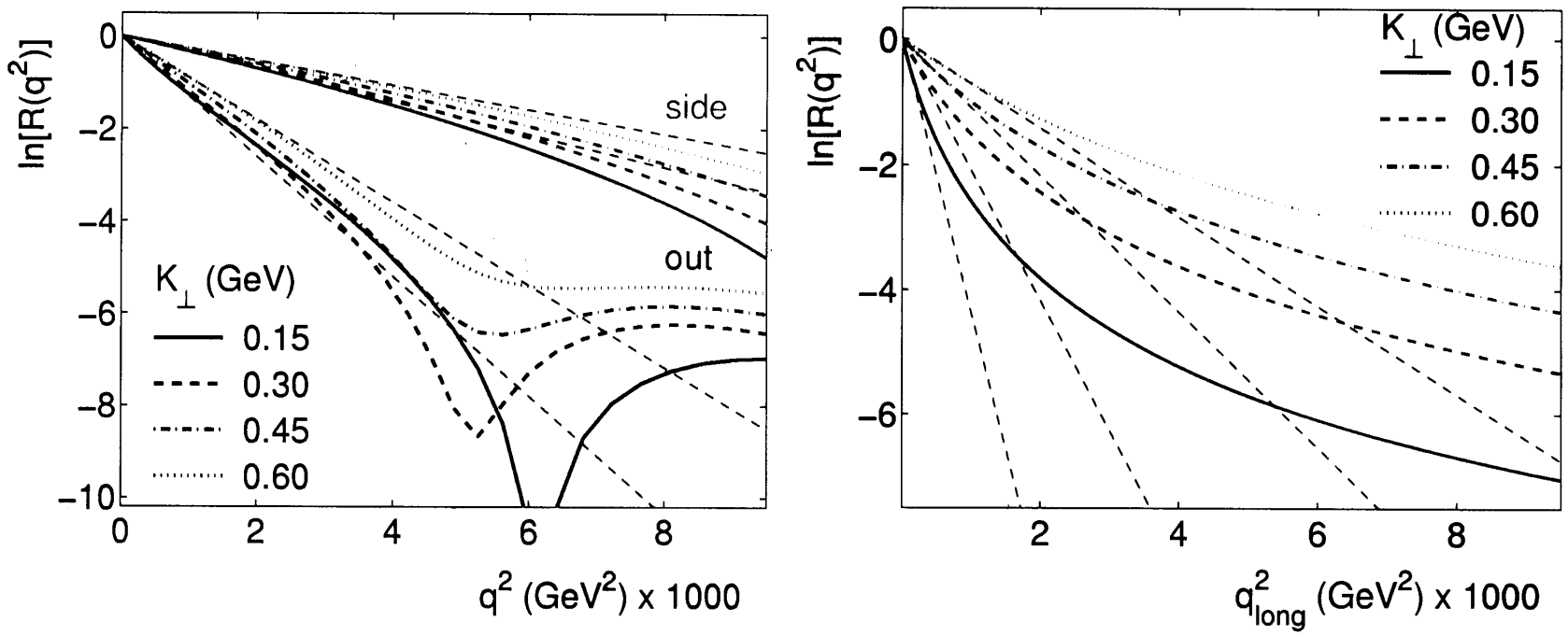
$$R(q,\,K) = C(q,\,K) - 1 = \frac{\int_\Sigma K^\mu d^3\sigma_\mu(x) K^\nu d^3\sigma_\nu(y) f(x,K) f(y,K) e^{iq\cdot(x-y)}}{\int_\Sigma p_a^\mu d^3\sigma_\mu(x) \times \int_\Sigma p_b^\mu d^3\sigma_\mu(x)}$$

experimentally fitted by Gaussian: $R(q) \propto e^{-q_{\rm out}^2 R_{\rm out}^2 - q_{\rm side}^2 R_{\rm side}^2 - q_{\rm long}^2 R_{\rm long}^2}$



The Correlator – seen logarithmically (versus q^2)

Gaussians turn into straight lines with slope $-R^2_{\mathrm{out/side/long}}$



The extracted radii parameters, in particular the long. radius, are extremely sensitive on the fitting region, due to non-Gaussian features of the correlator.

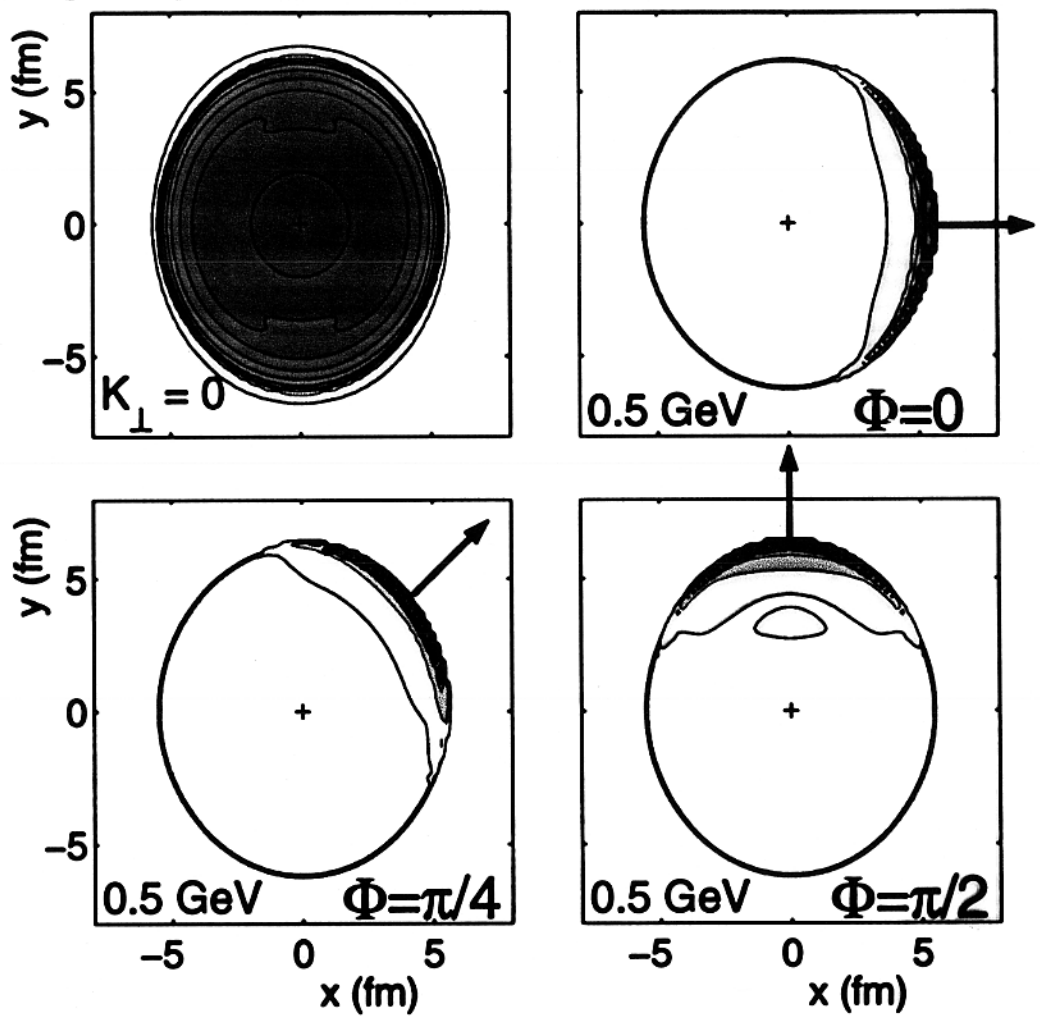
The source function of non-central collisions

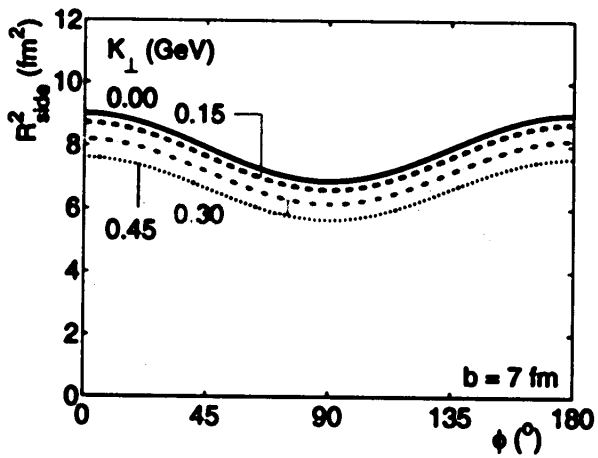
Contours of
$\tilde{S}(x, y; K_\perp) = \int dtdzS(x^\mu; K_\perp)$

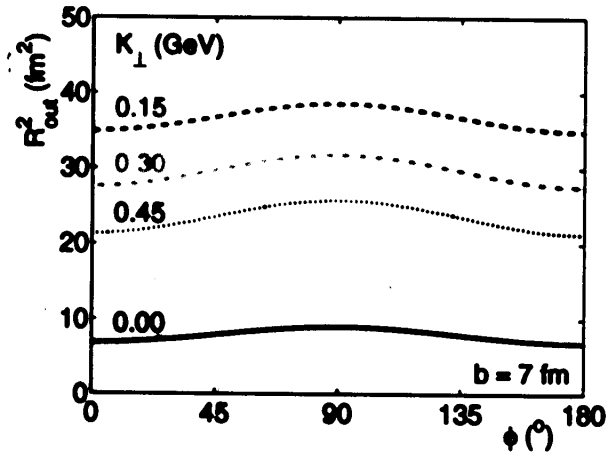
Geometrical as well as dynamical effects determine oscillations of HBT-radii with azimuthal angle.

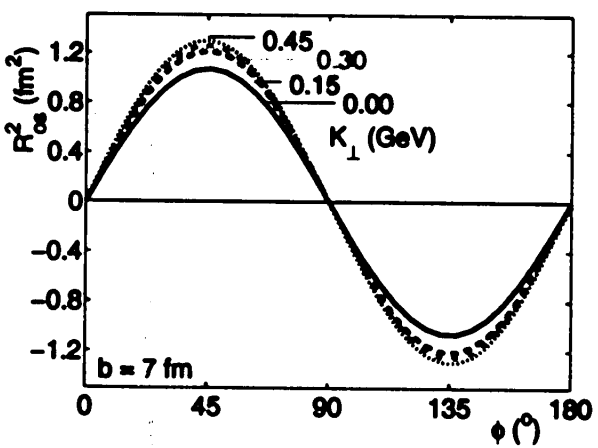
At RHIC energies, the FOHS is still deformed *out of plane* at its largest expansion.

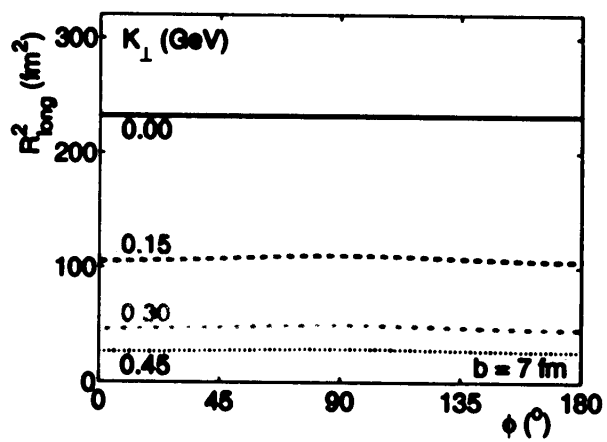
From $\phi = 0$ to $\pi/2$:
R_{side} decreases due to geometry
R_{out} increases due to anisotropic flow.











Azimuthally sensitive HBT-radii

spatial correlation tensor

$$S_{\mu\nu} = \langle \tilde{x}_\mu \tilde{x}_\nu \rangle$$

$$R^2_{\text{side}}(\Phi) = S_{11}\sin^2\Phi + S_{22}\cos^2(\Phi)$$

$$R^2_{\text{out}}(\Phi) = \beta_\perp^2 S_{00} + S_{11}\cos^2\Phi + S_{22}\sin^2(\Phi)$$

$$R^2_{\text{os}}(\Phi) = \frac{1}{2}(S_{22} - S_{11})\sin(2\Phi)$$

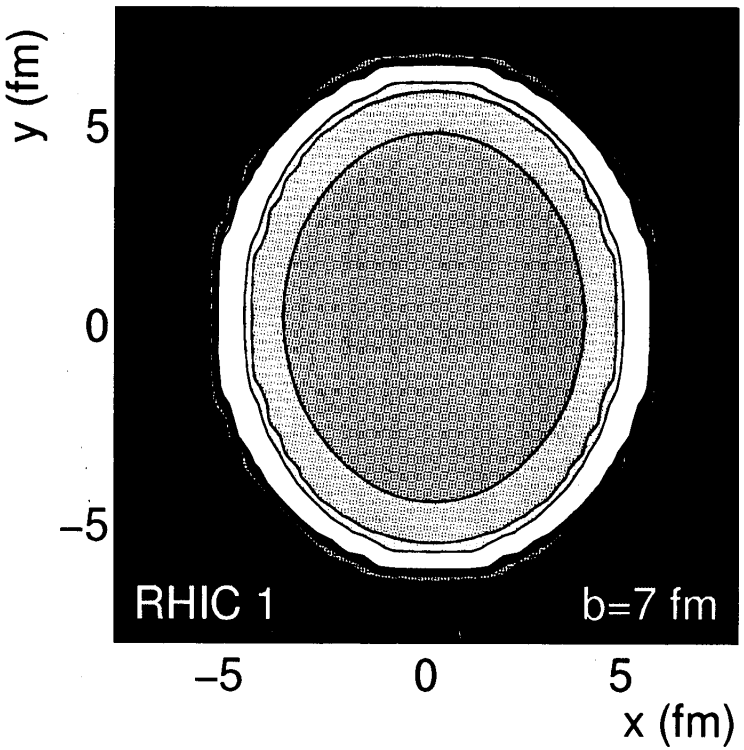
$$R^2_{\text{long}}(\Phi) = S_{33}$$

The total source (time and momentum integrated)

$$\frac{dN}{dxdydY} \sim \int d^2K_\perp \int d\tau d\eta S(x,y,\tau,\eta,K)$$

RHIC energies:

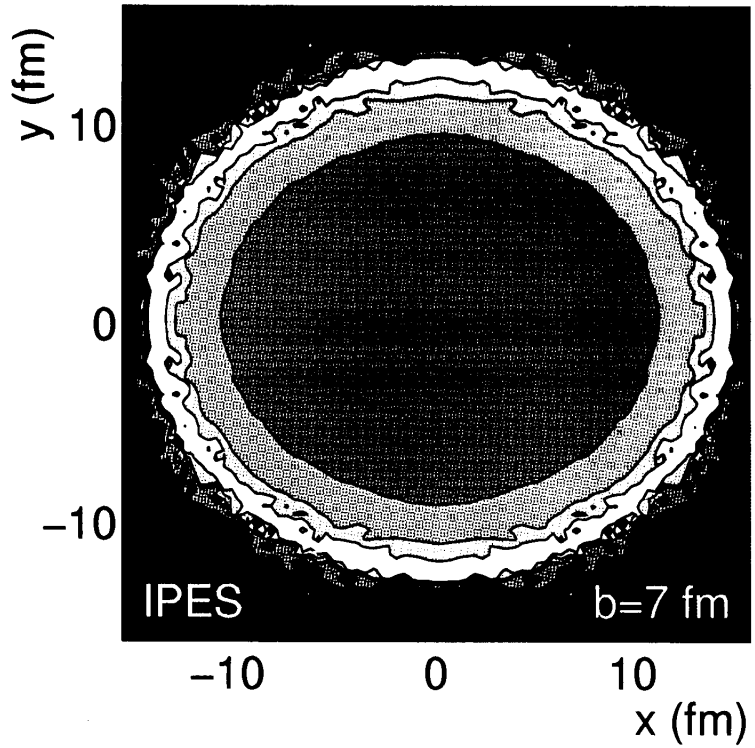
$T_0 = 340$ MeV, $\tau_0 = 0.6$ fm/c



total source still out of plane !

LHC energies:

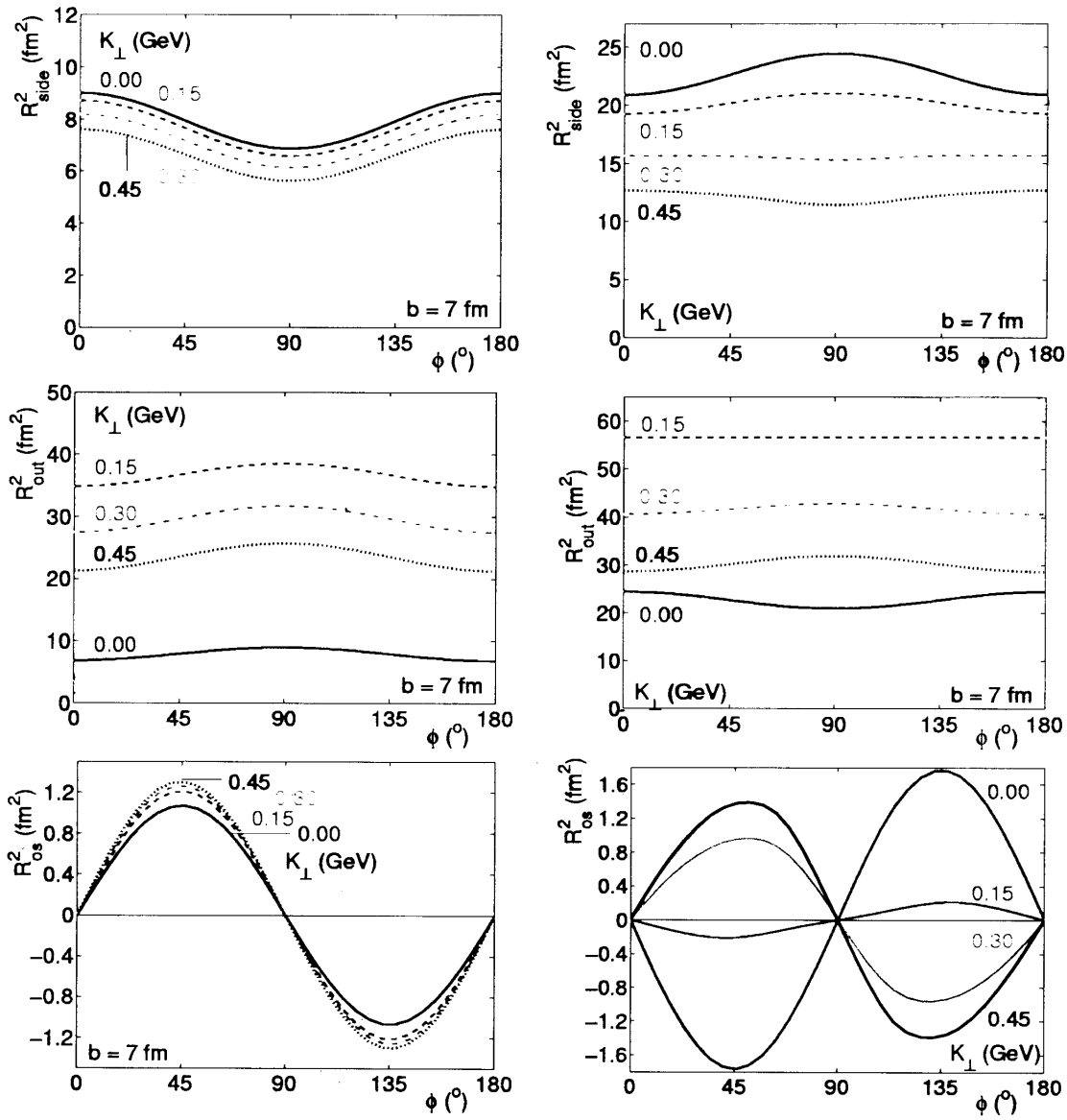
$T_0 = 2$ GeV, $\tau_0 = 0.1$ fm/c



total source in plane elongated

HBT, in-plane elongated source (IPES)

RHIC 1 IPES (LHC)



Note the change in sign of the osciallation !! Only pairs with small average momentum show the oscillation pattern expected from total fireball geometry.

Summary

- When extracting HBT parameters through Gaussian fits one has to be well aware of the influence of the fitting region on the results

- The life-time problem which originates from the observed longitudinal radii is partially resolved through rapid cooling in the hadronic stage which is out of chemical equilibrium (T. Hirano, R. Rapp, D. Teaney). Drastic changes of the initial configuration might hold further clues (Kolb, Shuryak).

- HBT studies from non-central collisions shows promising features to resolve the dynamics of the fireball geometry