On flow and correlations in central and non-central heavy ion collisions

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QCD and Gauge Theory Dynamics in the RHIC Era

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

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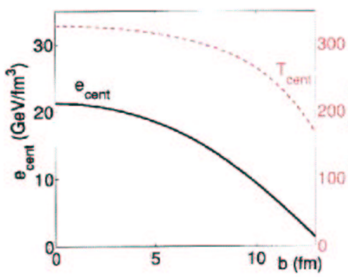
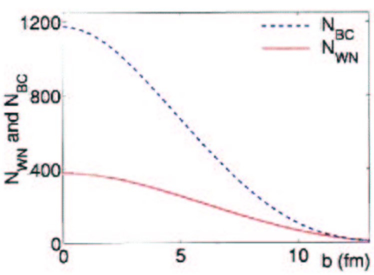
Systematic studies of non-central collisions

offer:
- variation of energy content and central energy
- different system sizes
- broken azimuthal symmetry → a wealth of new observables

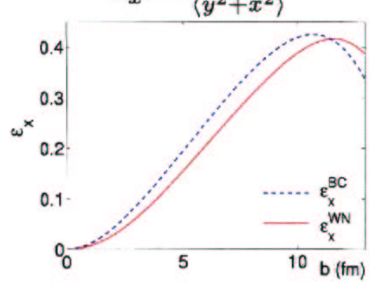
central temperature and energy density



number of participants and binary collisions



spatial anisotropy $\epsilon_x = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$



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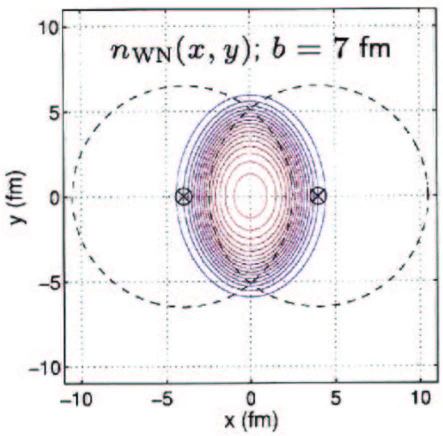
Transverse geometry of non-central collisions



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.

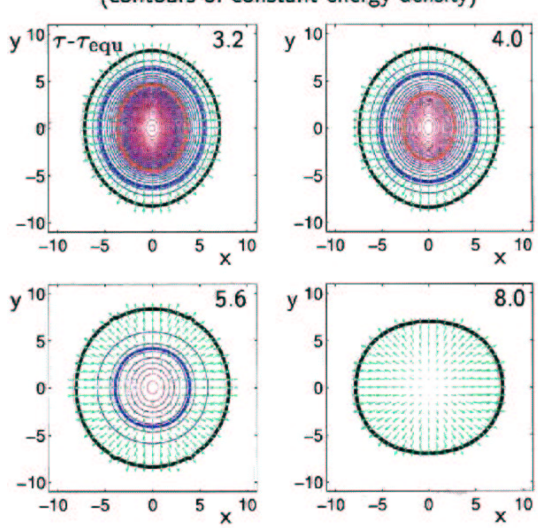
Self quenching effect, generated by *early* pressure, insensitive to later stages.

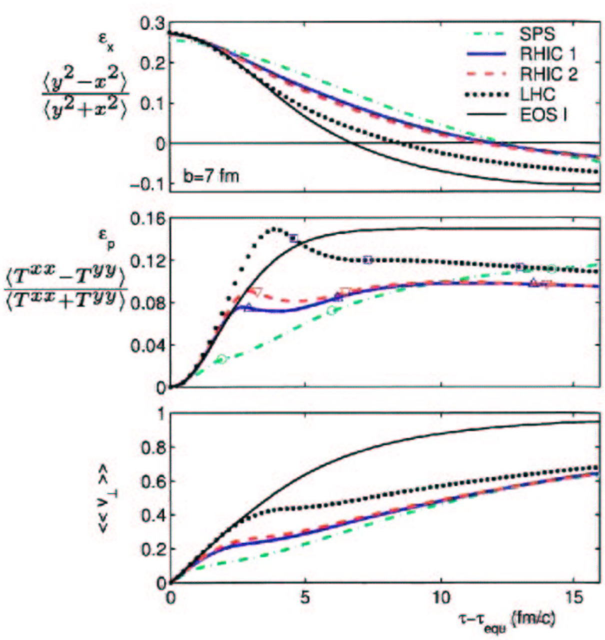
$$\frac{dN}{p_T\, dp_T dy d\varphi}(p_T, \varphi; b) = \frac{dN}{2\pi p_T dp_T dy}(1 + 2\, v_2(p_T; b)\, \cos(2\varphi) + \dots)$$

What signals can we expect in coordinate space?

Time evolution of non-central collisions (here $b = 7$ fm)

system with ideal equation of state
(contours of constant energy density)





Relativistic Hydrodynamics:

Conservation of energy, momentum and baryon number

$$\partial_\mu T^{\mu\nu} = 0$$
$$\partial_\mu j^\mu = 0$$

with energy momentum tensor:

$$T^{\mu\nu}(x) = (e(x) + p(x))\, u^\mu(x) u^\nu(x) - g^{\mu\nu} p(x)$$

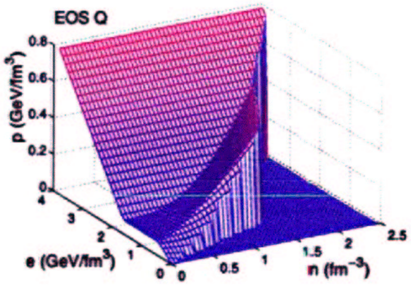
and baryon current:

$$j^\mu(x) = n(x)\, u^\mu(x)$$

Equation of state:

- EOS I: ultrarelativistic ideal gas, $p = \frac{1}{3} e$
- EOS H: massive, interacting gas of hadrons, $p \sim 0.15\, e$
- EOS Q: Maxwell construction between EOS I and EOS H
  critical temperature $T_{\text{crit}} = 164$ MeV

$\Rightarrow$ bag constant $B^{1/4} = 0.23$ GeV
latent heat $\Delta e = 1.15$ GeV/fm^3



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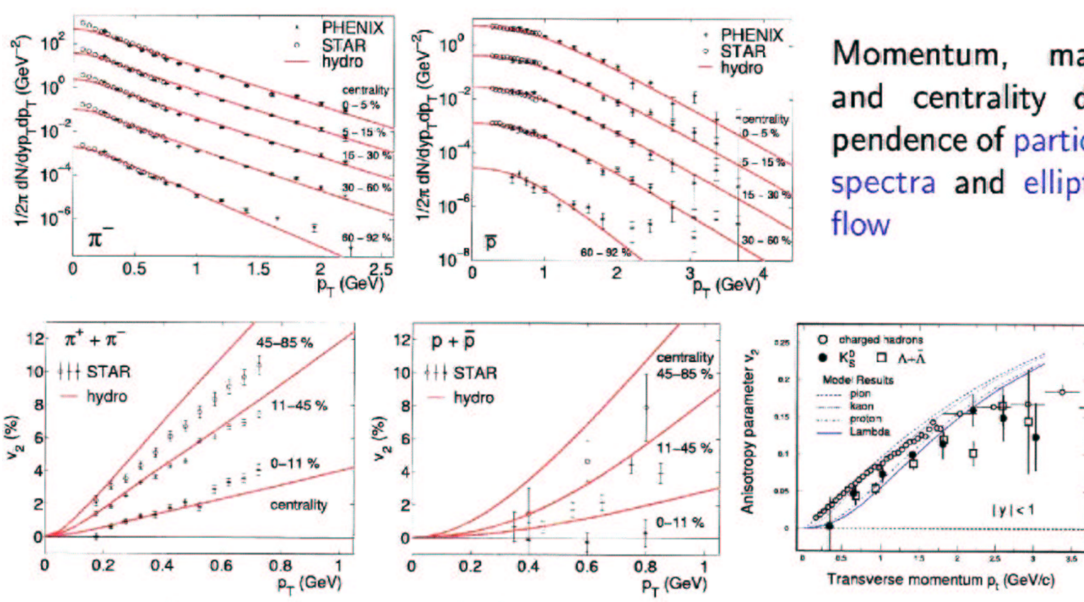
Over 99% of the emitted particles follow hydro systematics

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

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Single particle spectra and elliptic flow imply:

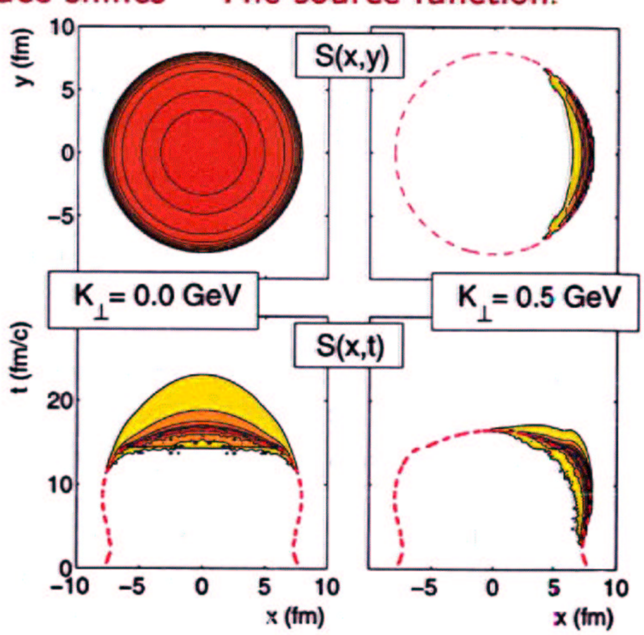
- Large transverse flow before decoupling, $\langle v_\perp \rangle \sim 0.5\, c$.
- Rapid thermalization which transforms the initial spatial anisotropy into momentum anisotropy. Here $\tau_0 = 0.6$ fm/c with $e_0 = 24.6$ GeV/fm^3, $T_0 = 340$ MeV and $s_0 = 95.0$ fm^{-3}.
- This collective behavior applies for the most abundant hadrons with transverse momenta smaller than about 2.5 - 3 GeV. This is more than 99% of the produced hadrons.
- Only if the system gets too small and too dilute (impact parameters larger than about 7 fm) the prerequisites for a hydrodynamic treatment are no longer fulfilled.

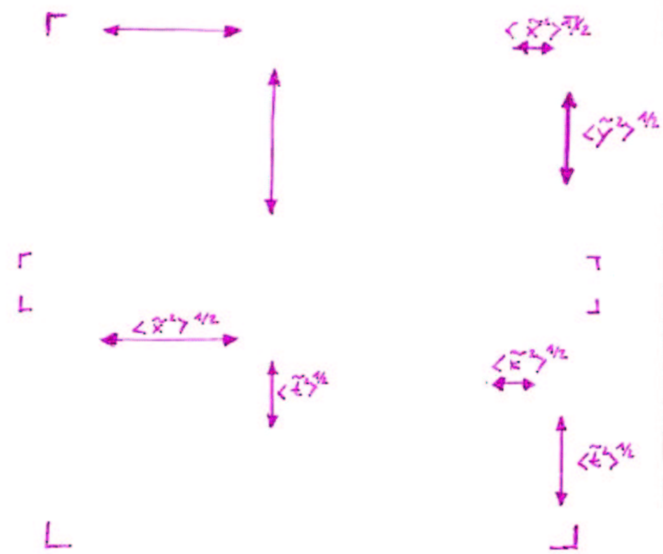
How the freeze-out surface shines – The source function:

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

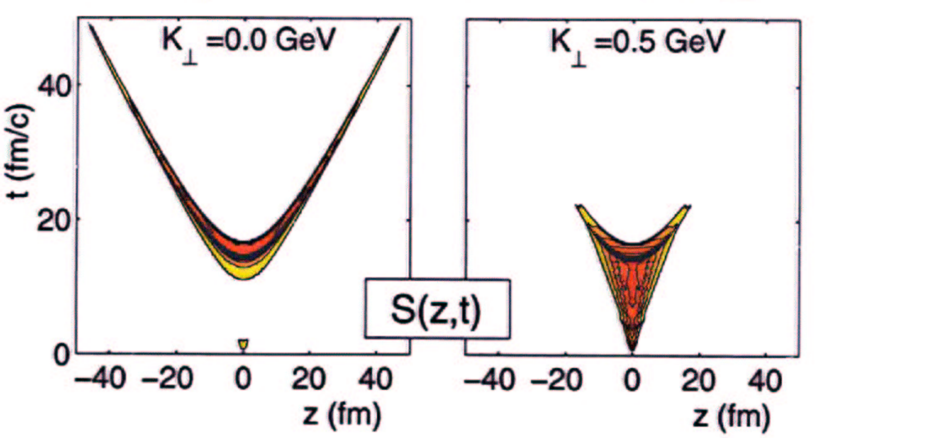
Particle spectra:
$E\, d^3N/dp^3 = \int d^4x\, S(x,p)$

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





Particle production and boost-invariance

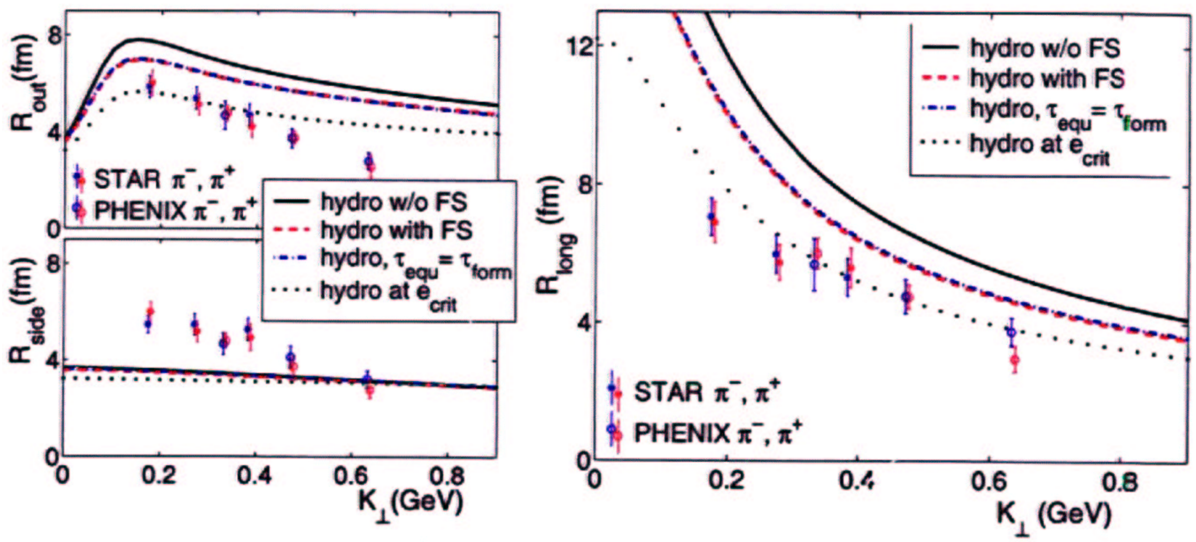


Particle emission from regions of non-zero z happens at late times as a consequence of boost invariance. The longitudinal flow gradient is then small ($\sim t^{-1}$) and fluidcells over a large variance of $\langle z^2 \rangle$ contribute to the particle spectrum at mid-rapidity. For the same reason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

HBT radii from hydrodynamics and experiment

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

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



Ideas towards a resolution of the problem:
(BNL workshop June 14-15,2002 and recent publications)

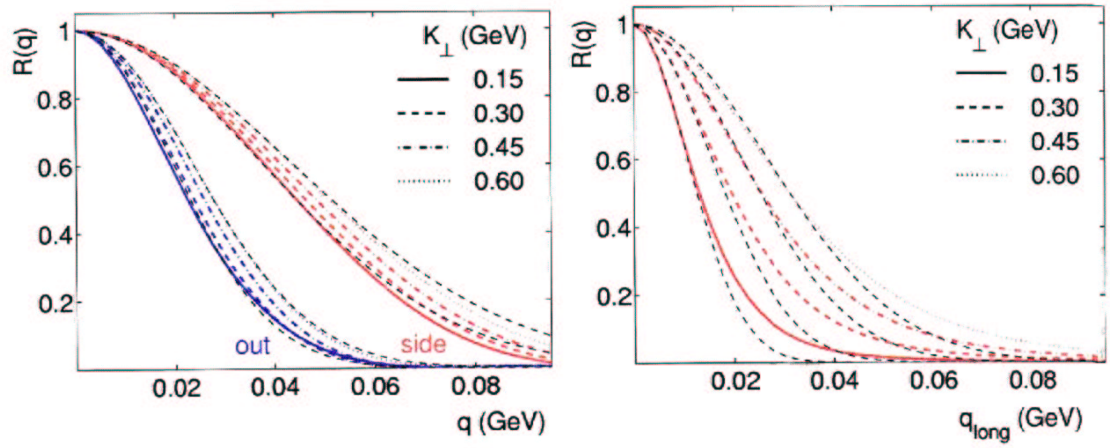
- Effects in the hadronic stage
  - medium modifications of mesons S. Soff
  - chemical non-equilibrium dynamics T. Hirano, D. Teaney
  - viscous flow of hadrons D. Teaney, A. Dumitru
- Modified expansion dynamics
  - non-boost-invariance of the source, $v_z = \alpha z/t$ D. Rischke
  - pre-equilibrium dynamics P. Kolb, U. Heinz, E. Shuryak
  - viscosity effects and reduced longitudinal pressure U. Heinz, S. Wong
- Non-gaussian homogeneity regions
  - from the microsopic point of view Z.W. Lin
  - from the macrosopic point of view P. Kolb
- 'Not all is so bad'
  - hadronic rescattering model T. Humanic
  - parameter fits, inflationary model T. Csörgö, A. Ster
  - $\Delta\tau = 0.1$ fm/c at $\tau = 6.8$ fm/c with $T = 196$ MeV and $\langle u \rangle = 0.9\,c$

The Correlator – traditional representation

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

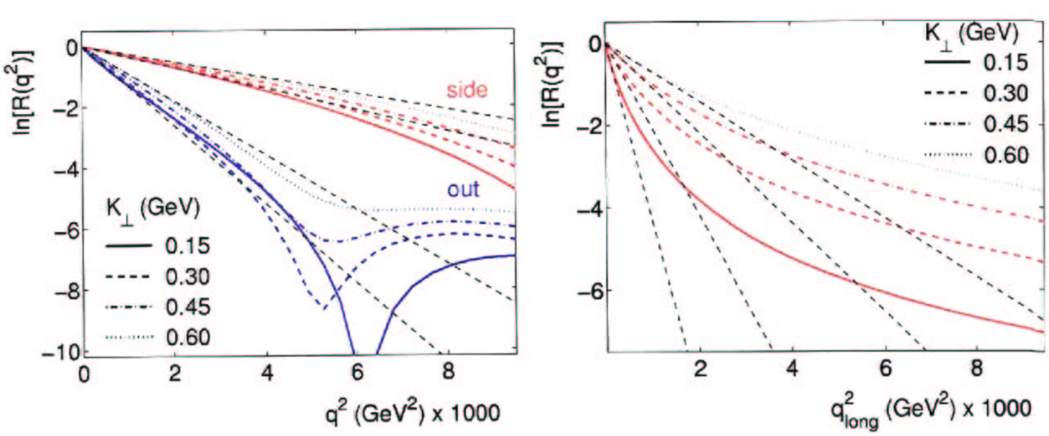
$$R(q,\,K) = C(q,\,K) - 1 = \frac{\int_\Sigma K^\mu d^3\sigma_\mu(x) K^\nu d^3\sigma_\nu(y) f(x,K) f(y,K) e^{iq\cdot(x-y)}}{\int_\Sigma p_a^\mu d^3\sigma_\mu(x) \times \int_\Sigma p_b^\mu d^3\sigma_\mu(x)}$$

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)

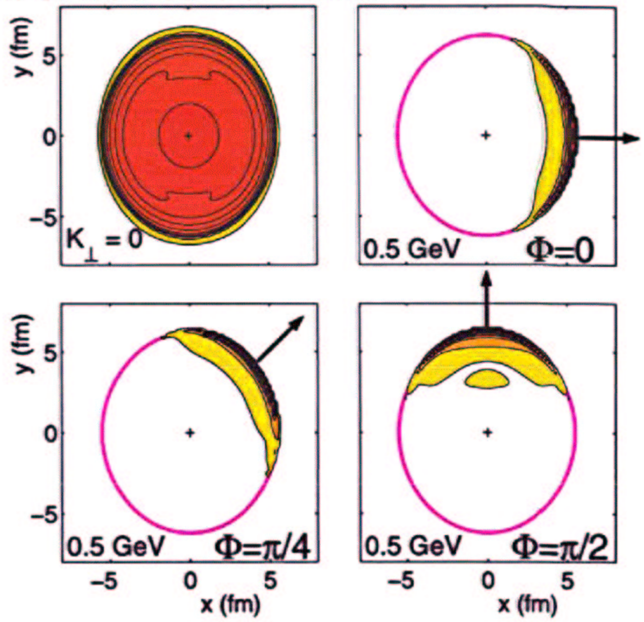
Gaussians turn into straight lines with slope $-R^2_{\rm out/side/long}$



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
$\tilde{S}(x, y; K_\perp) = \int dt dz S(x^\mu; K_\perp)$



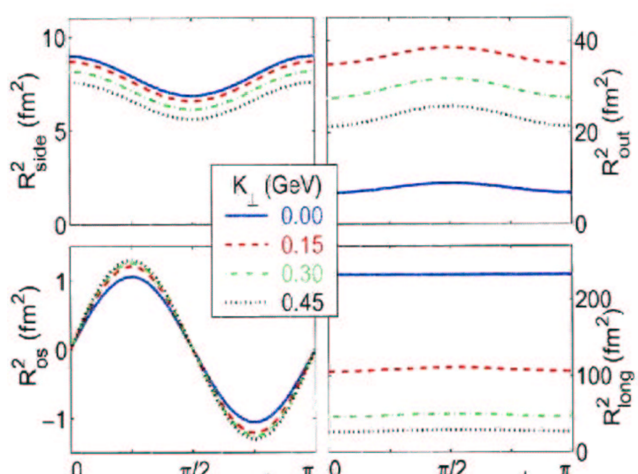
Geometrical as well as dynamical effects determine oscillations of HBT-radii with azimuthal angle.

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

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

Azimuthally sensitive HBT-radii

spatial correlation tensor $S_{\mu\nu} = \langle \tilde{x}_\mu \tilde{x}_\nu \rangle$ with $\tilde{x}_\nu = x_\nu - \langle x_\nu \rangle$ rotated to out-side frame



$$R^2_{\rm side}(\Phi) = S_{xx}\sin^2\Phi + S_{yy}\cos^2\Phi - S_{xy}\sin 2\Phi$$

$$R^2_{\rm out}(\Phi) = S_{xx}\cos^2\Phi - S_{yy}\sin^2\Phi + S_{xy}\cos 2\Phi + \beta_\perp^2 S_{tt} - 2\beta_\perp(S_{tx}\cos\Phi + S_{ty}\sin\Phi)$$

$$R^2_{\rm os}(\Phi) = \tfrac{1}{2}(S_{yy} - S_{xx})\sin 2\Phi + S_{xy}\cos 2\Phi + \beta_\perp(S_{tx}\sin\Phi - S_{ty}\cos\Phi)$$

$$R^2_{\rm long}(\Phi) = S_{zz}$$

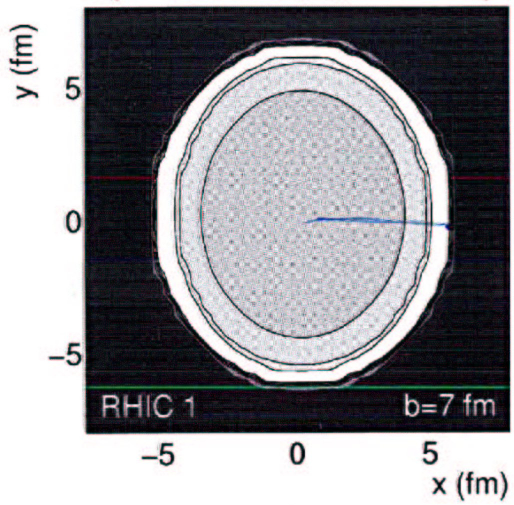
→ U. A. Wiedemann Phys. Rev. C 57 (1998) 266

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:

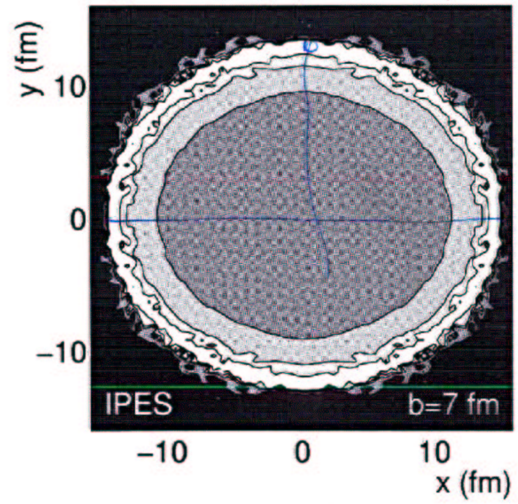
$T_0 = 340$ MeV, $\tau_0 = 0.6$ fm/c



total source still out of plane !

LHC energies:

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



total source in plane elongated

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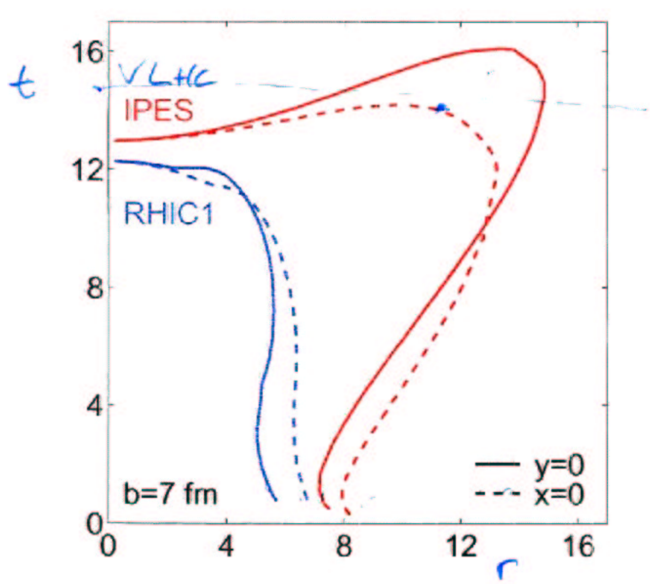
$\vec{K}_\perp \parallel \vec{e}_x$

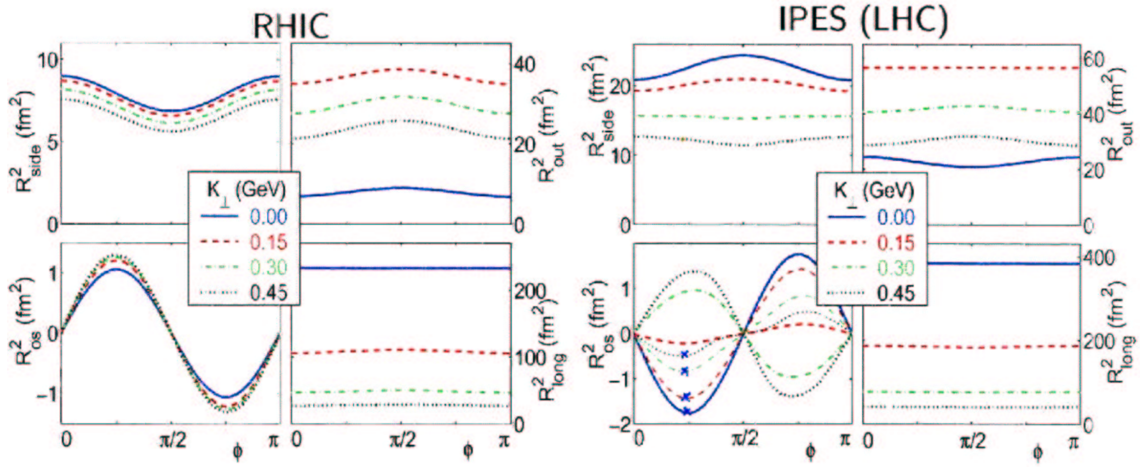
Freeze-out hypersurfaces at RHIC and LHC



For LHC / IPES note that

* the deformation is into the reaction plane for a long time
* hyperbola shapes start to form in the transverse direction
* the center freezes out earlier than a surrounding shell (and we actually see it 'crack', Teaney, Shuryak PRL 83 (99) 4951)

Oscillations at RHIC and the LHC



$$R^2_{os}(\Phi) = \tfrac{1}{2}(S_{yy} - S_{xx})\sin 2\Phi \;+\; S_{xy}\cos 2\Phi + \beta_\perp(S_{tx}\sin\Phi - S_{ty}\cos\Phi)$$

The temporal part induces a change of sign in the in plane elongated source

Summary

- The systematic investigation of the centrality dependence of various observables can be used to study excitation functions at fixed beam energy (threshold effects?)
- Anisotropic observables are a great tool to study collective effects and the global dynamics of the expansion
- An understanding for the discrepancy of the dynamical models and the geometry at freeze-out inferred from HBT measurements is emerging
- Azimuthal oscillations of the HBT radii are understood from the dynamical picture. The experimental analysis is on the way
- The new features predicted for LHC energies fall right into the kinematic region where they are experimentally accessible