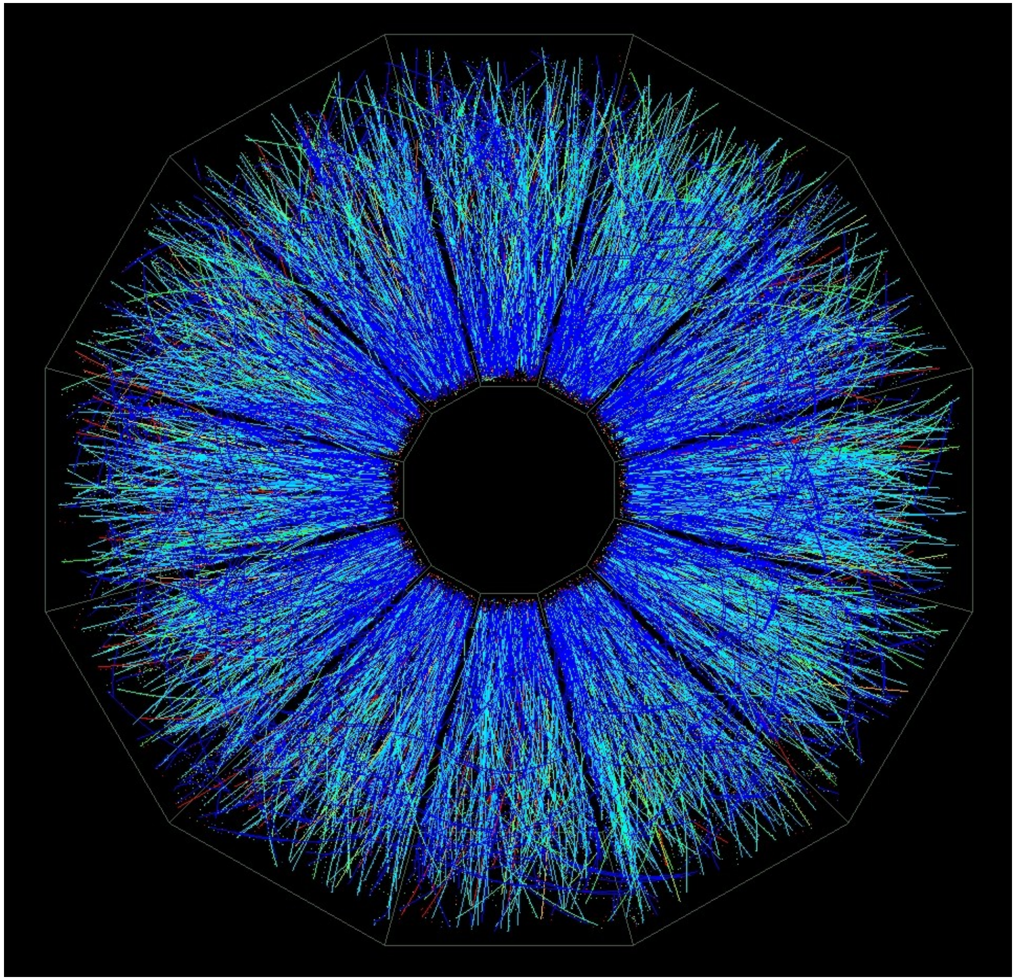
Obtaining space-time picture of the freeze-out process - femtoscopy at STAR

Adam Kisiel,
Warsaw University of Technology

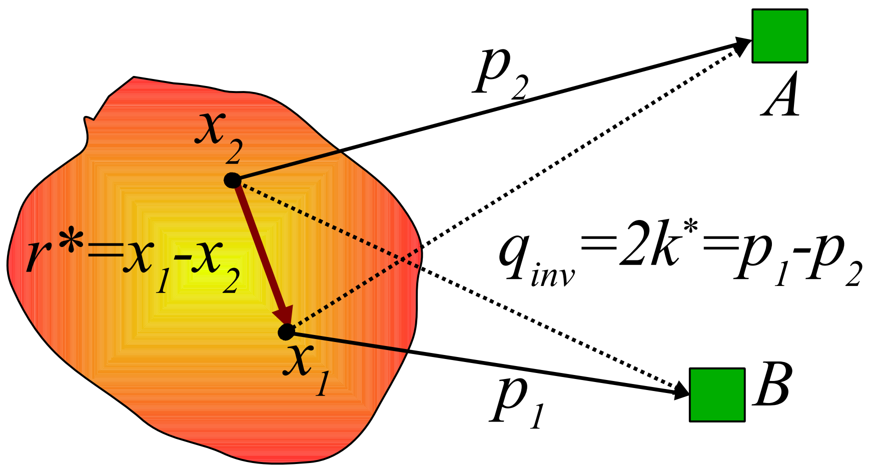
for the
STAR Collaboration

The STAR Experiment



- 52 institutions from 12 countries
- ~550 physicists
- Large acceptance TPC detector: $-1<y<1$ and 2π in azimuthal angle
- Pions, kaons and protons identified via dE/dx for p_T $0.12 - 1.2\ GeV/c$
- $V0$'s identified by their decay topology

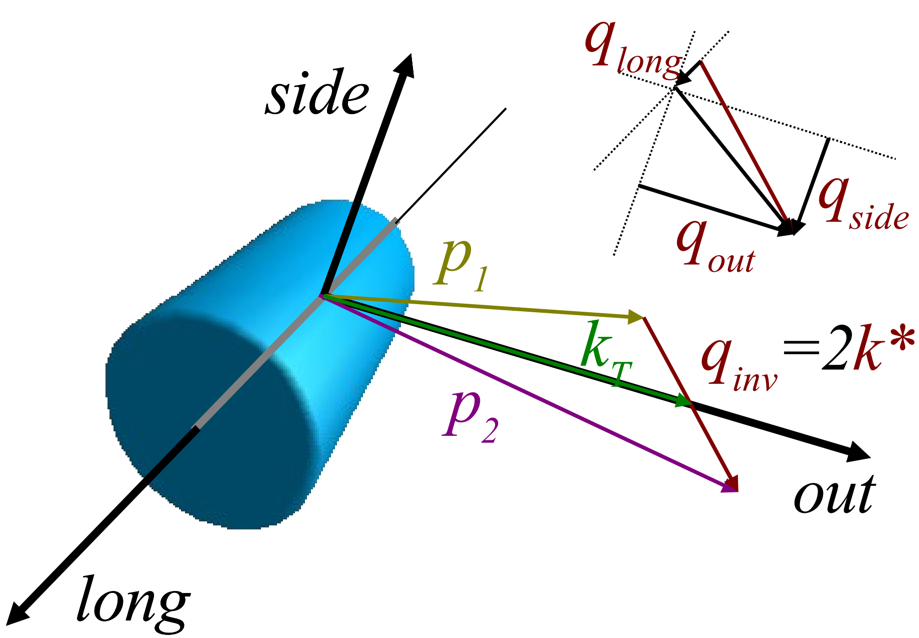
HBT definitions



- Due to pair wave function symmetrization we are more likely to see small relative momentum q:

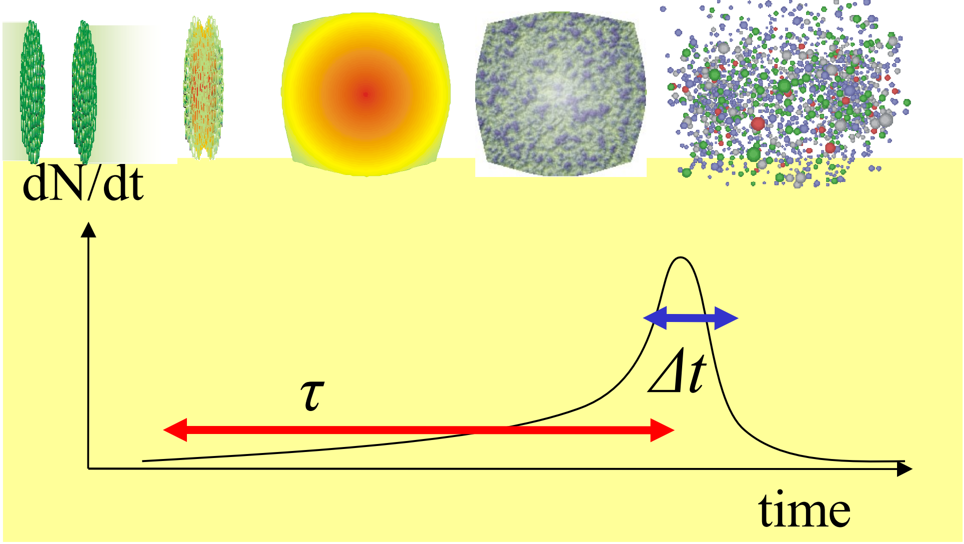
$$\left|\Psi\left(\boldsymbol{r}^{*},\boldsymbol{k}^{*}\right)\right|^{2}=1+\cos\left(\boldsymbol{q}_{inv}\cdot\boldsymbol{r}^{*}\right)$$

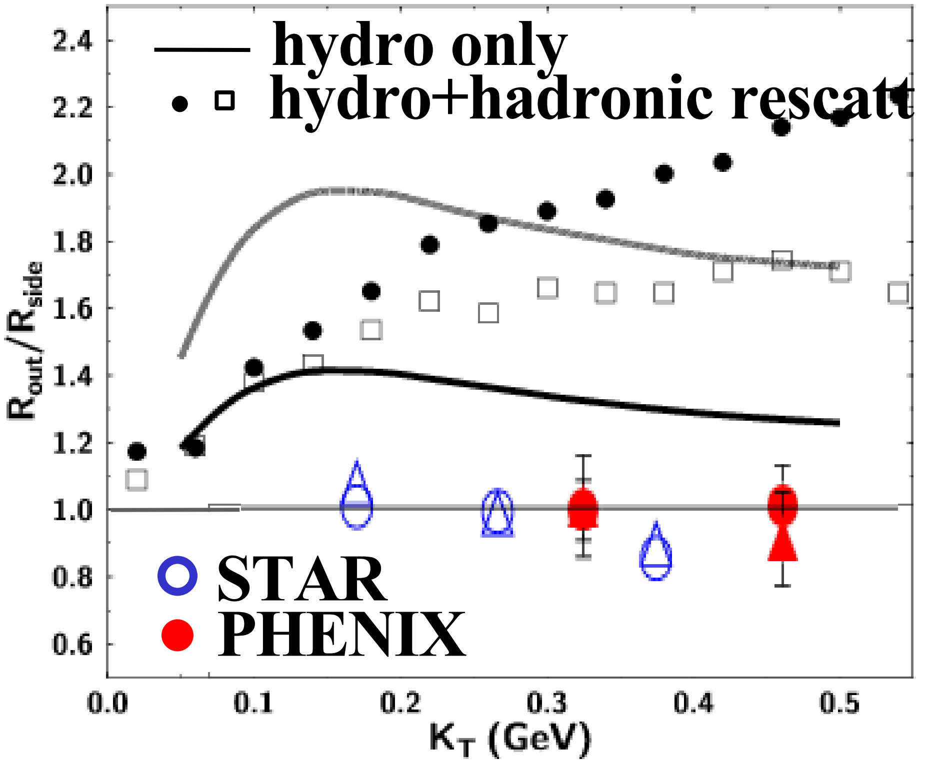
- The increase depends on the "size" of the source: $var(r^*)$
- x_1 and x_2 are emission points – position of "last scattering" or resonance decay
- The directions "out", "side" and "long" are defined with respect to the pair average transverse momentum k_T and the beam direction

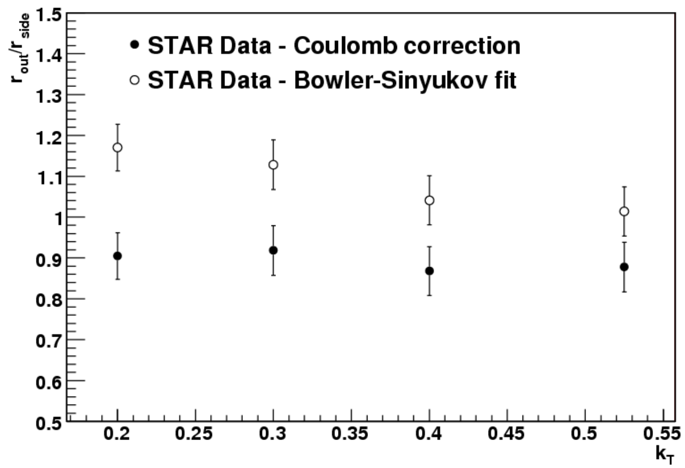


What are we sensitive to?

- HBT is the only available measure of the source space-time characteristics
- We can measure sizes in 3 directions
- HBT is also sensitive to two timescales of the collision evolution:
  - Evolution duration: τ
  - Freeze-out duration: Δt

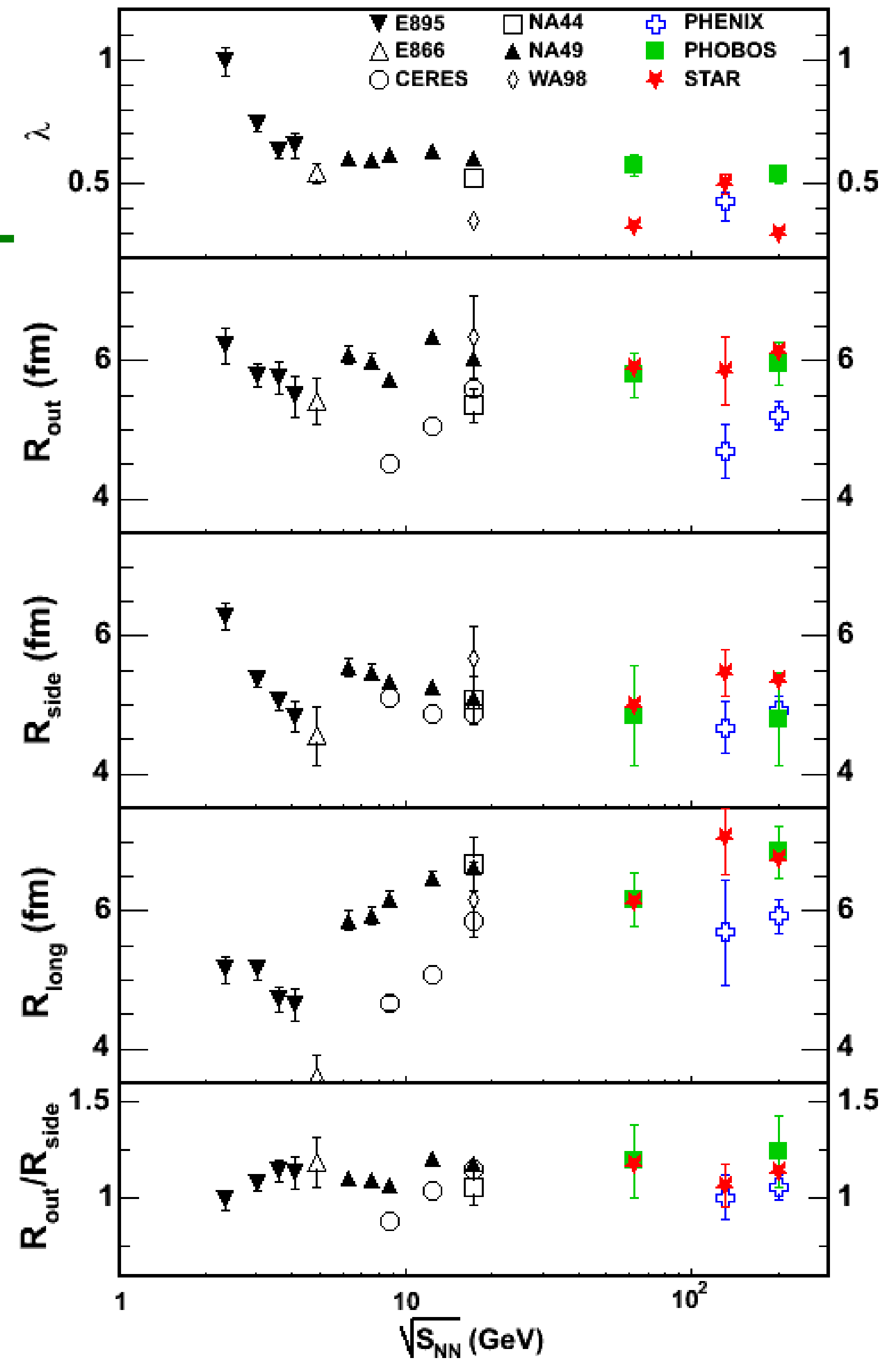






HBT excitation function

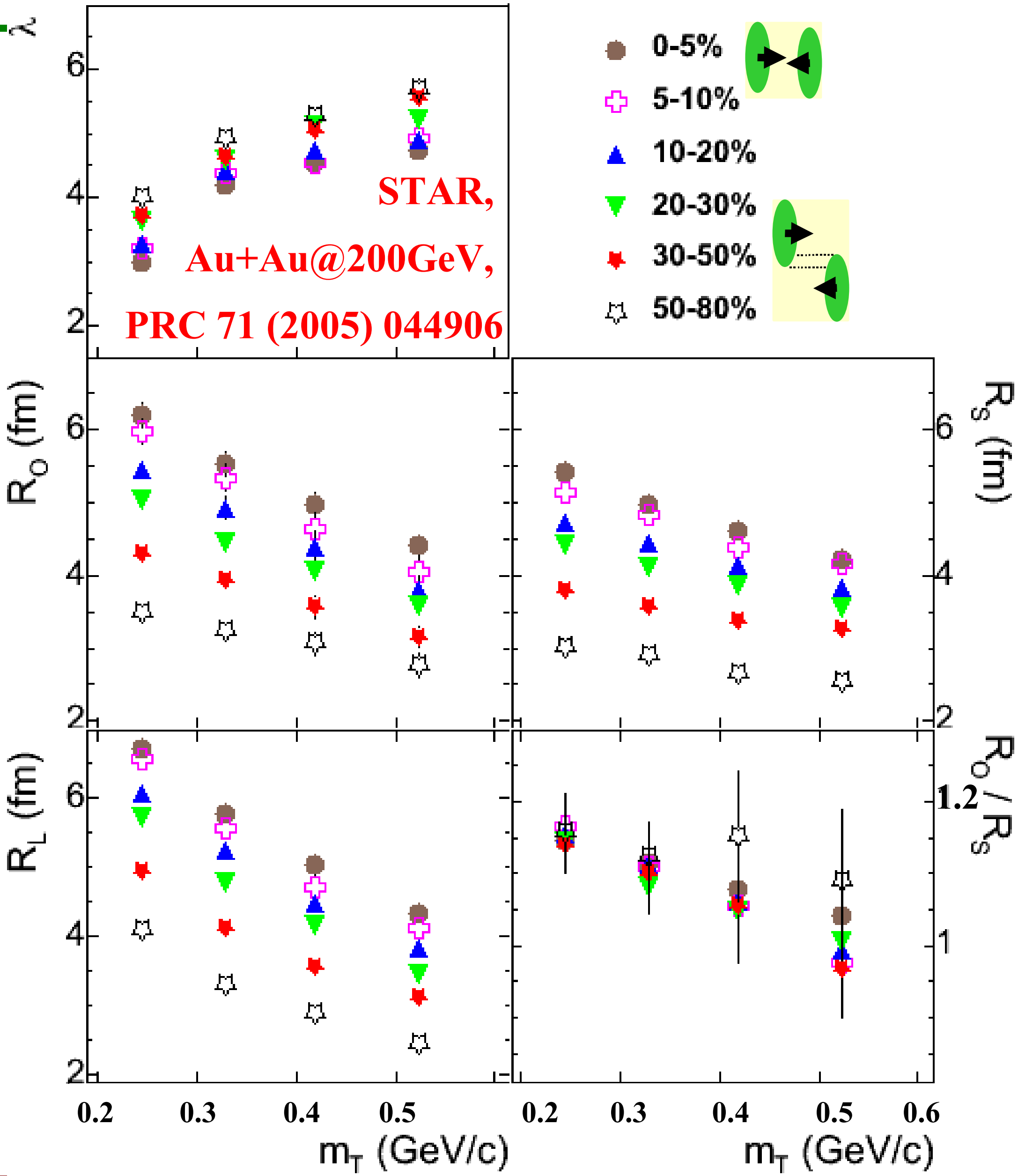
- No dramatic change in radii with energy of the collision observed in the RHIC energy range
  - Not consistent with "large-lifetime" scenario expected in the 1st order phase transition
  - How is it possible that 10x increase of energy does not change the size?



$R(\sqrt{S_{NN}}, m_T, b, N_{part}, A, B, PID)$

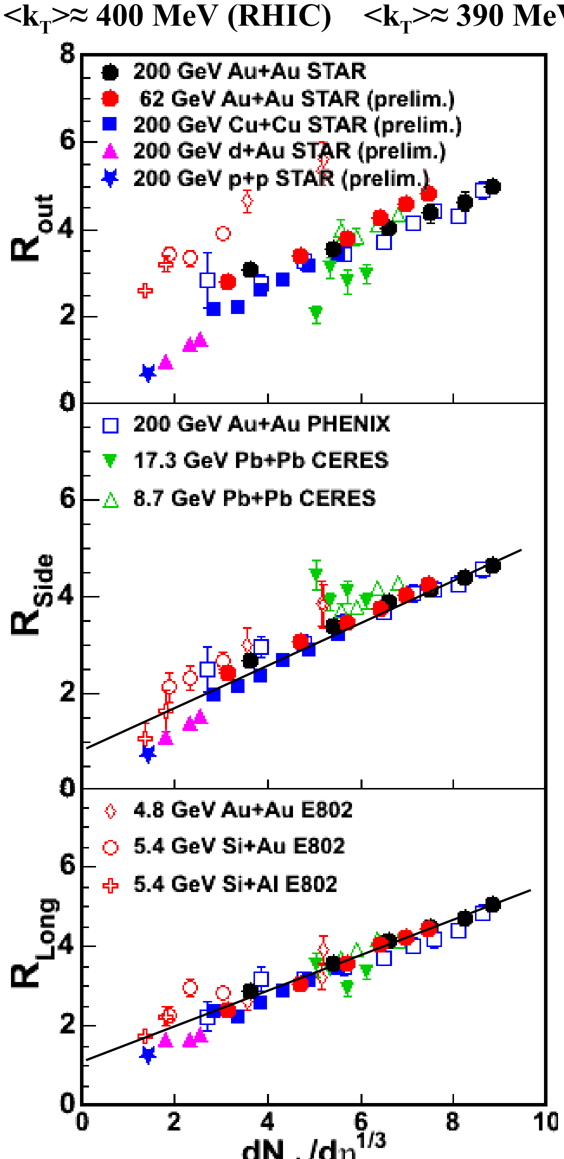
Centrality and m_T dependence

- Radii increase with centrality as expected from the initial size
- Radii decrease with transverse mass
  - Naturally explained by hydro models with radial and longitudinal flow
  - Other possibility – emission from "earlier and hotter" stages of the collision
  - Contribution from long-lived resonances must have some impact, but how big?



„Universal” scaling ?

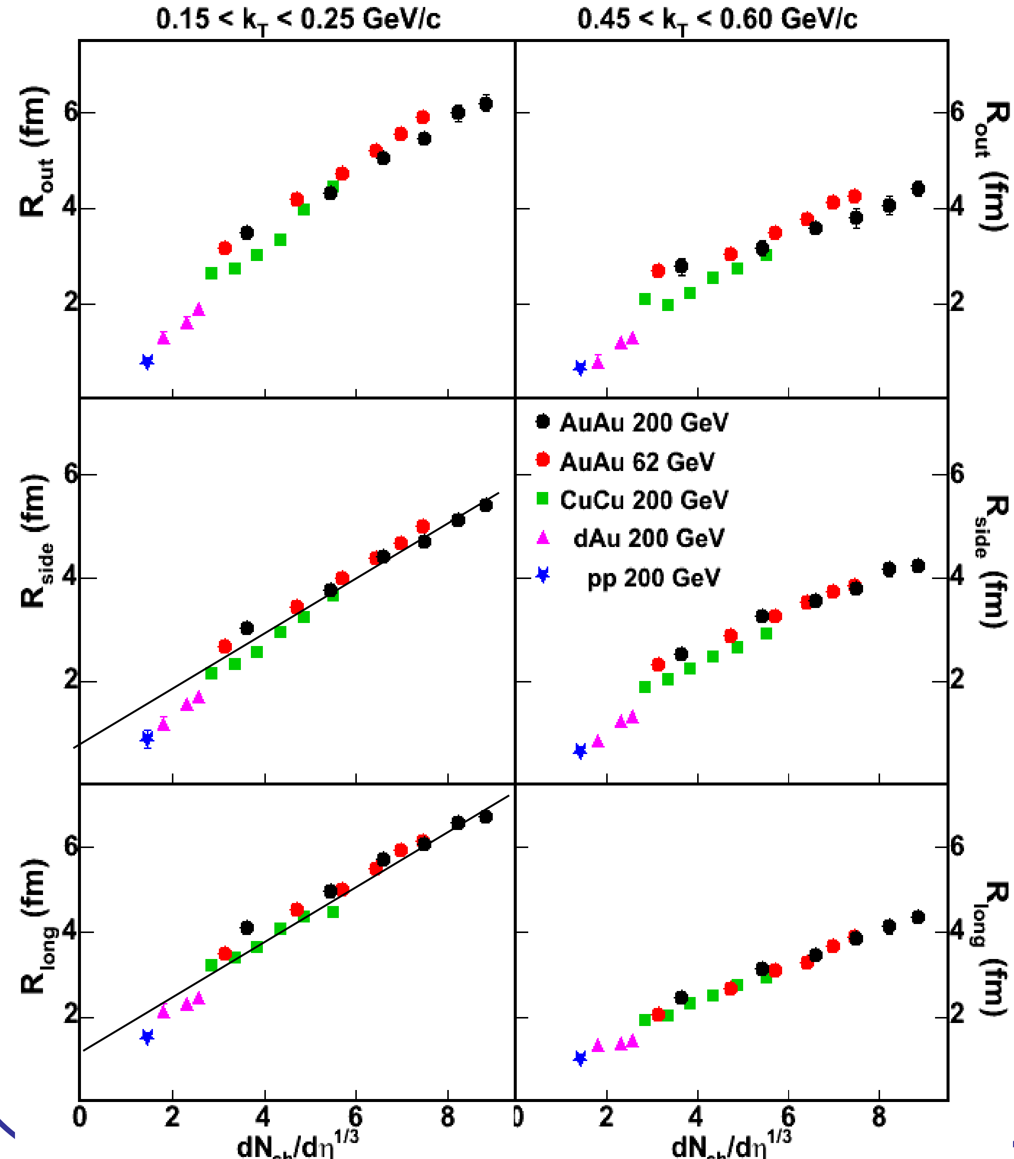
RHIC/AGS/SPS



Lisa, Pratt, Soltz, Wiedemann, nucl-ex/0505014, Annu. Rev. Nucl. Part. Sci. (2005) 55:357-402

STAR DATA

(pp,dAu,CuCu,AuAu@62GeV - prelim.)

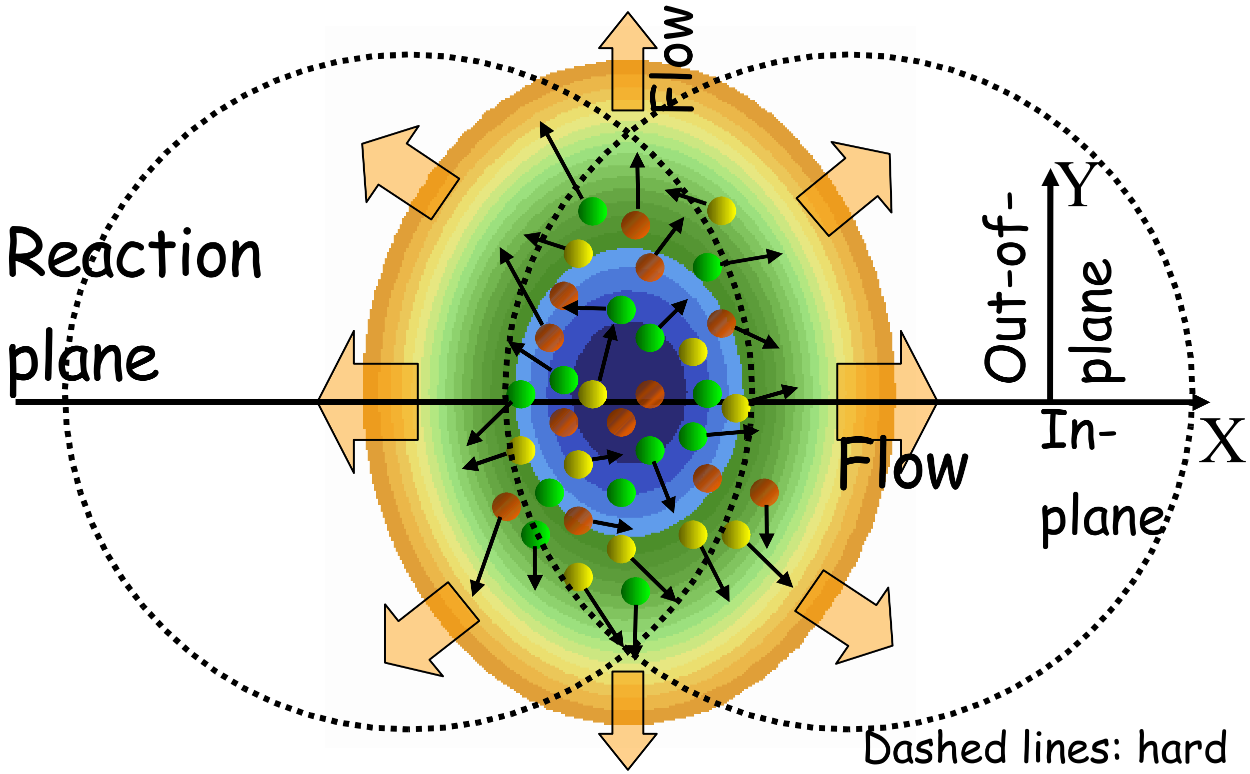


Forget A,B,√s, N_{part}...
dN/dη determines HBT radii, at all m_T (!!!!)

observed scaling
$R_i = C_i \cdot (dN/d\eta)^{1/3} + D_i$, i=o,s,l

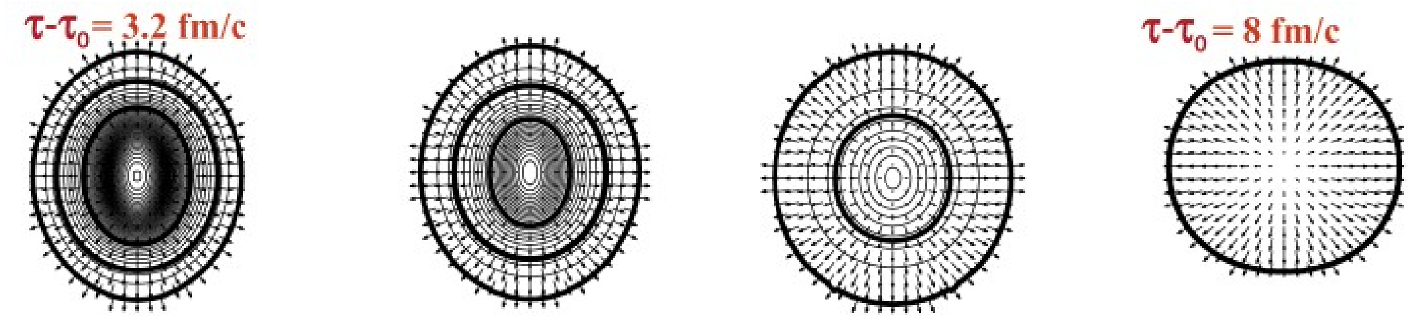
HBT and azimuthal asymmetry

- Initial size should be reflected in the final one
- But hydrodynamics predicts a transition from out-of-plane extended to in-plane extended source with time
- An independent handle on emission duration



Dashed lines: hard sphere radii of nuclei

Hydrodynamic evolution:

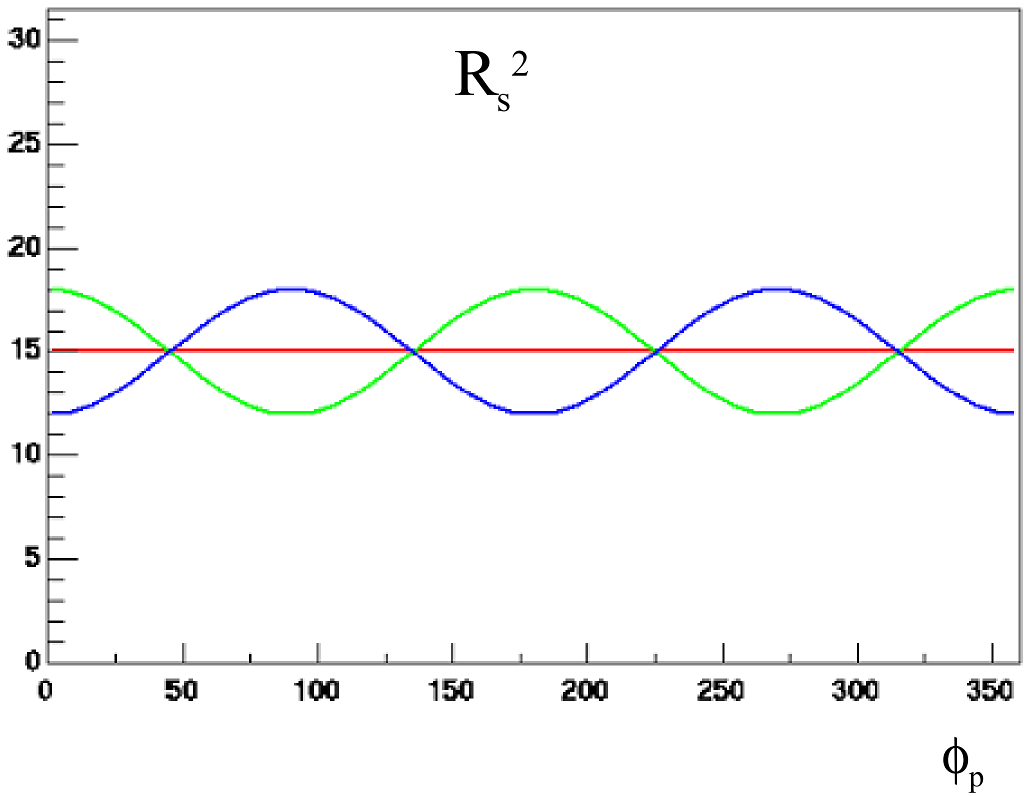


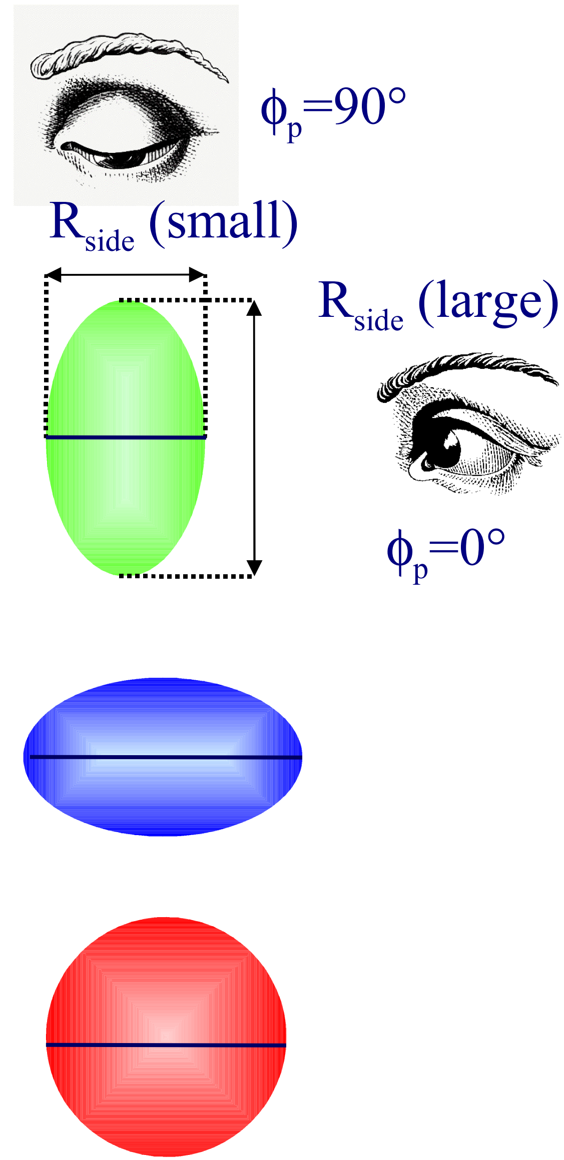
Kolb&Heinz

Azimuthally sensitive HBT

- For out-of-plane extended source we expect:
  - Large R_{side} at 0°
  - Small R_{side} at 90°

} 2nd-order oscillation





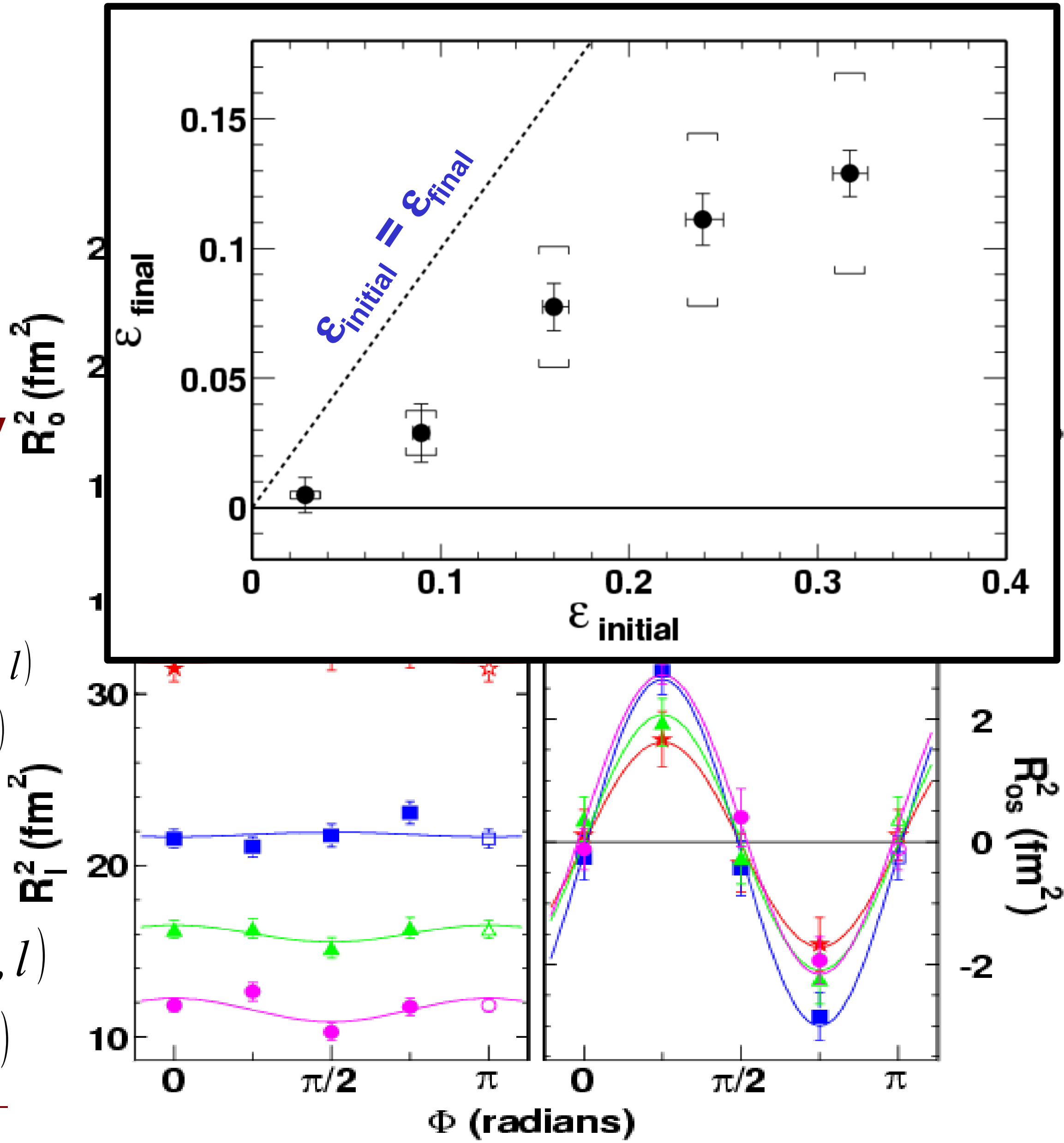
asHBT at 200 GeV in STAR – R(Φ) vs k_T

- Clear oscillations indicating out-of-plane extended source observed at all k_T – the source lives fairly short
- Comparing to initial anisotropy from Glauber we see smaller anisotropy, as expected

$$R^2_\mu(k_T) = \begin{cases} R^2_{\mu,0}(k_T) + 2\sum R^2_{\mu,n}(k_T)\cos(n\varphi) & (\mu = o, s, l) \\ R^2_{\mu,n}(k_T)\cdot \sin(n\varphi) & (\mu = os) \end{cases}$$

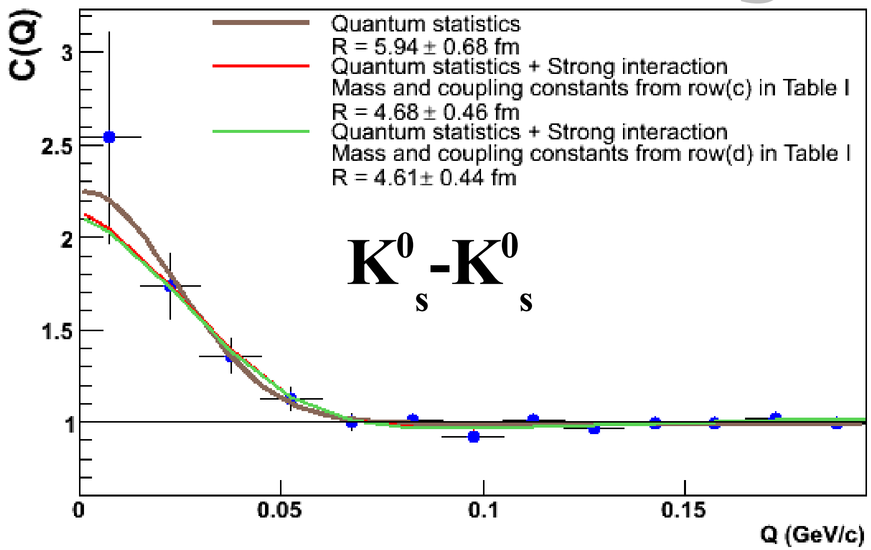
Lines: Fourier expansion of the allowed oscillations

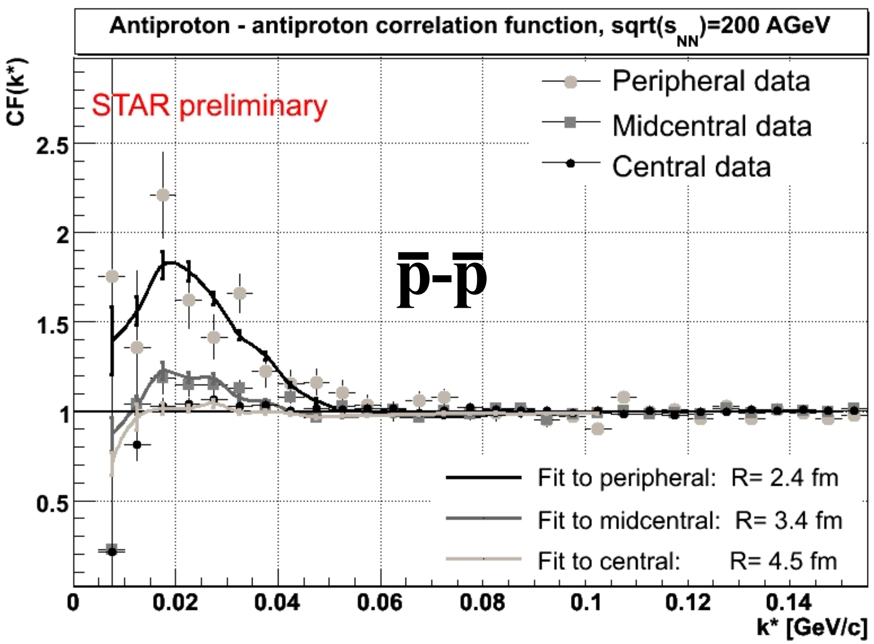
$$R^2_{\mu,n}(k_T) = \begin{cases} \langle R^2_\mu(k_T,\varphi)\cdot\cos(n\varphi)\rangle & (\mu = o, s, l) \\ \langle R^2_\mu(k_T,\varphi)\cdot\sin(n\varphi)\rangle & (\mu = os) \end{cases}$$

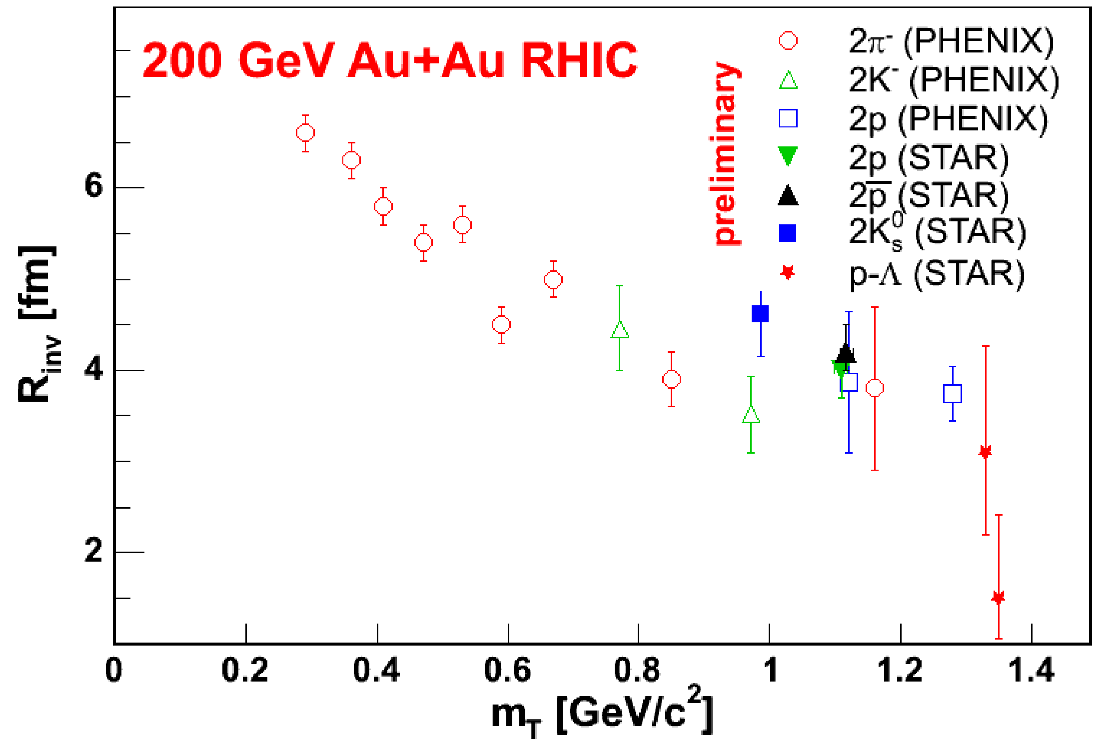


Phys. Rev. Lett. **93** (2004) 012301

Moving beyond Pion HBT

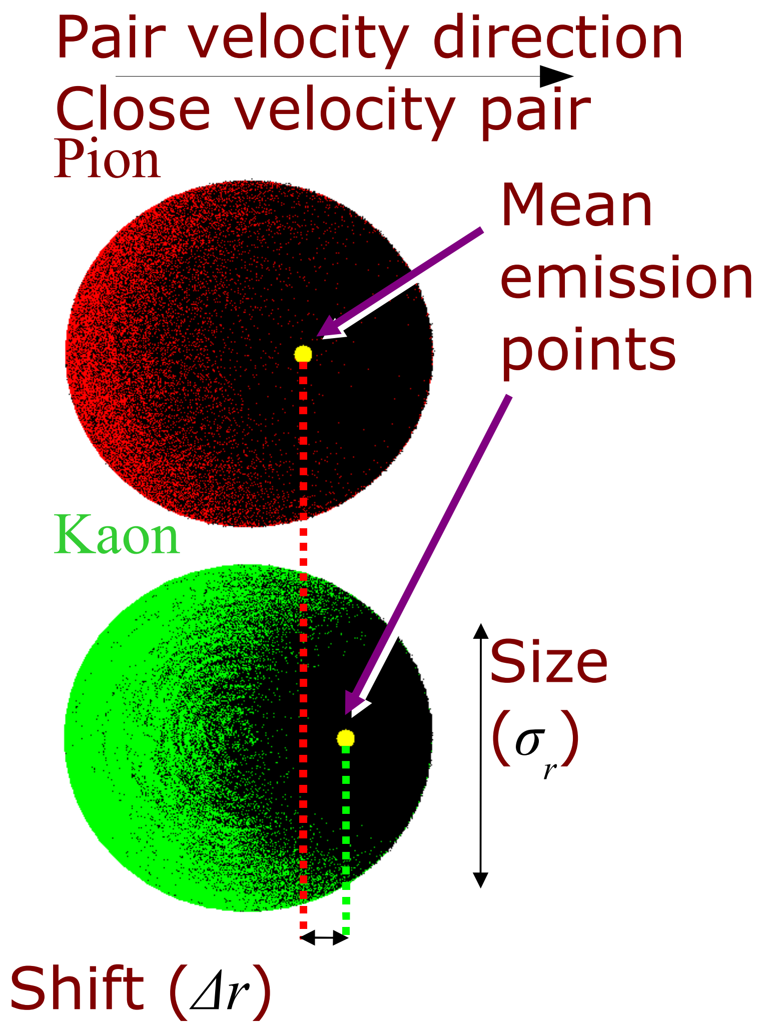






- Radii for all systems follow the m_T scaling predicted by hydro calculations, coming from collective flow

Femtoscopy is not only HBT

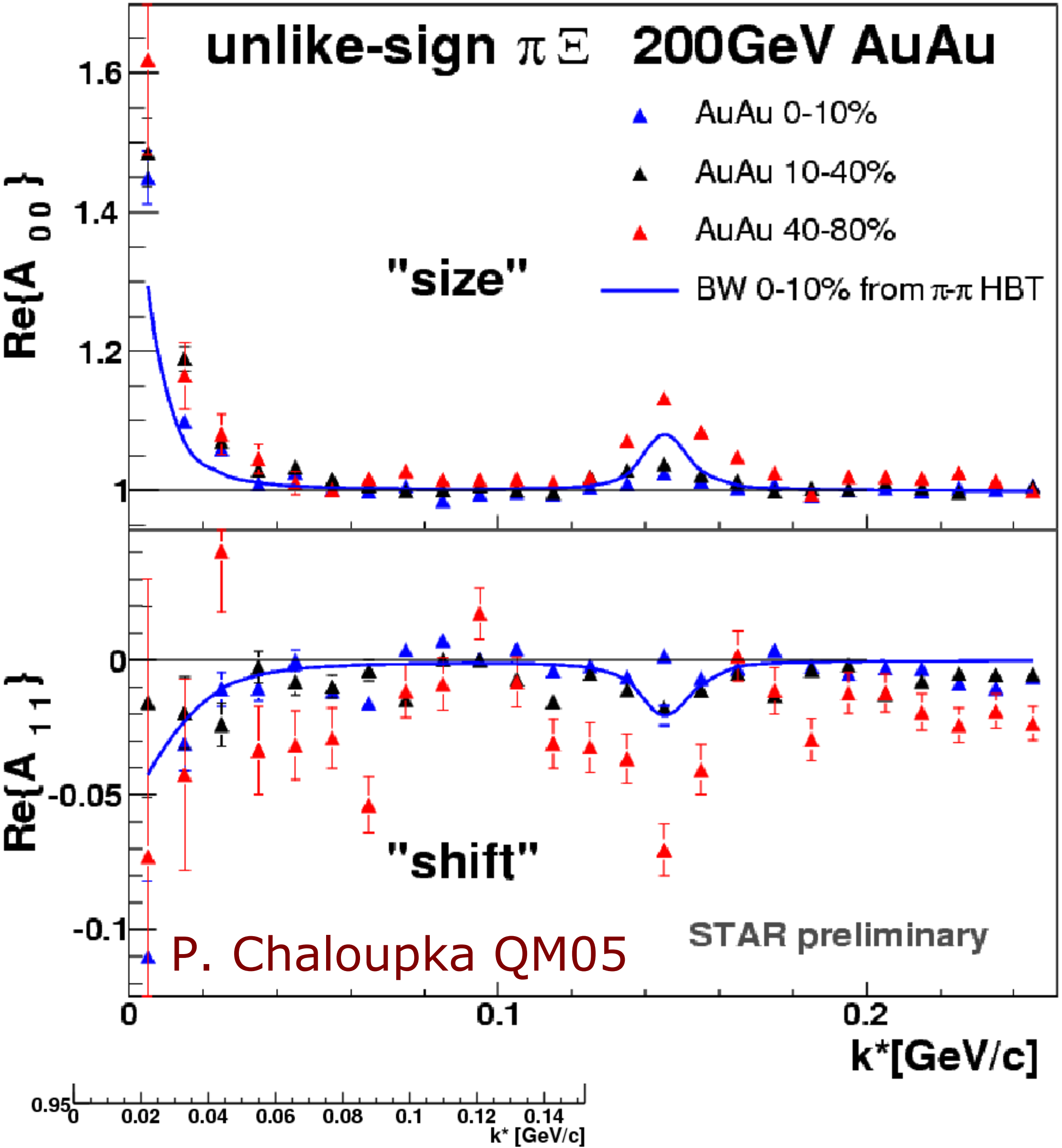


R.Lednicky et al.Phys.Lett. B373 (1996) 30.
S.Voloshin, R.Lednicky, S. Panitkin, N.Xu, Phys.Rev.Lett.**79**(1997)30

- Hydrodynamic calculations with radial flow predict two effects:
  - Size decreases with particle m_T (length of homogeneity)
  - Mean emission point is shifted from the center (along the pair velocity to the edge of the source) with m_T
- Non-identical particle femtoscopy correlates particles with different m_T and is sensitive to this shift
- This is the only direct measurement of radial flow (understood as an x-p correlation)

Pion-Kaon emission asymmetry

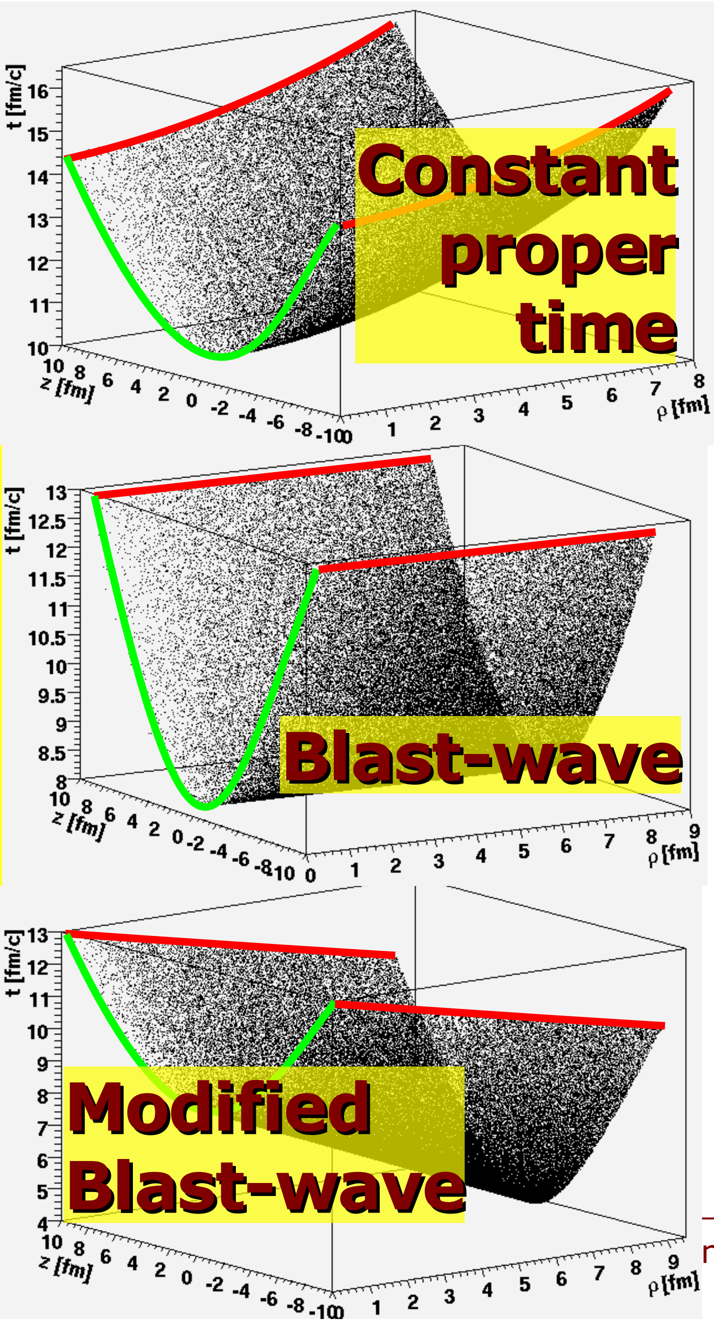
- Emission asymmetry C_+/C_- is observed for all pion-kaon pairs, consistent with the hydro radial flow scenario
  - This invalidates the "emission from earlier and hotter source" explanation of m_T dependence of pion HBT
- Similar effect is observed for pion-proton, kaon-proton and pion-Xi correlations

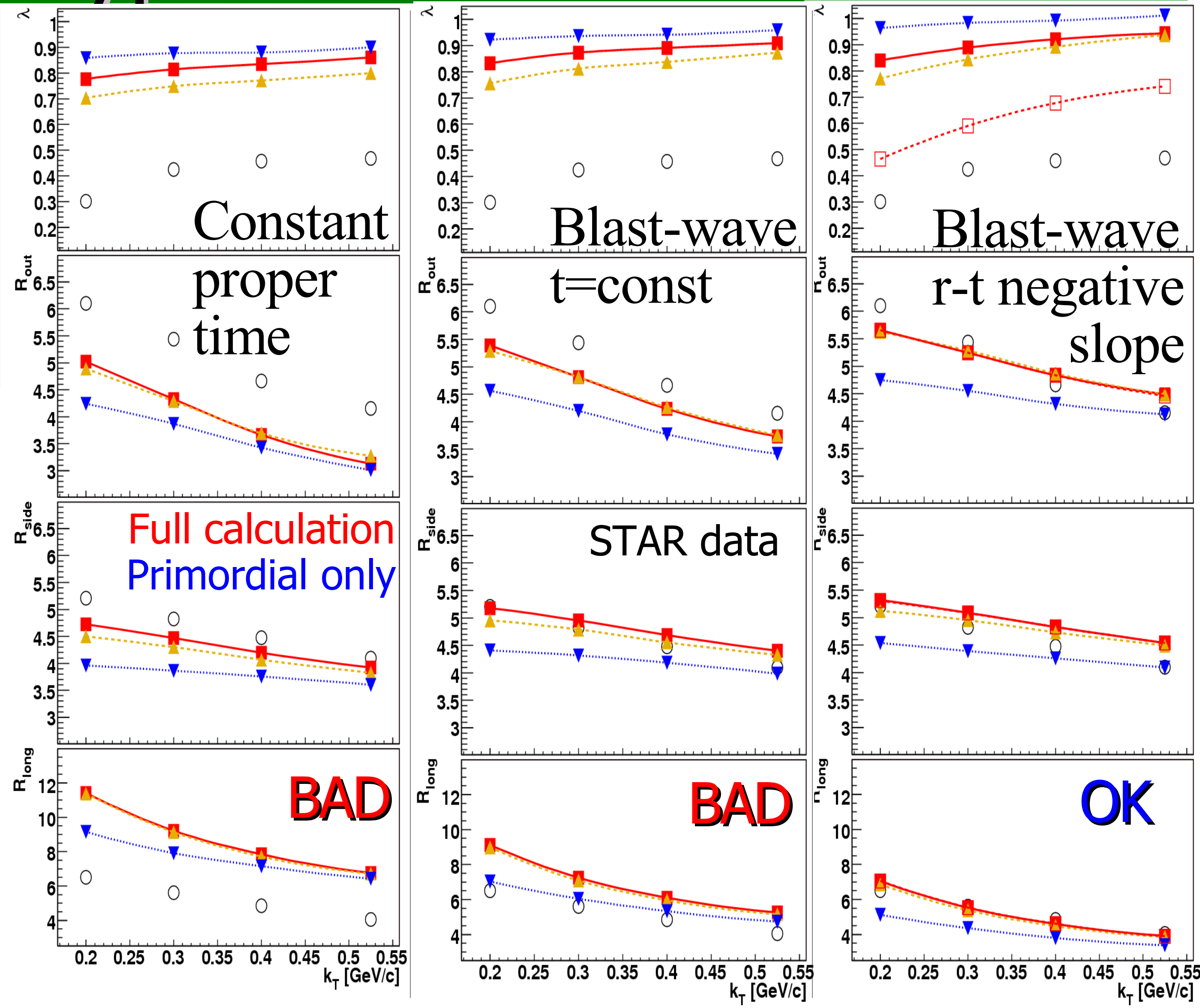


Interpreting the results

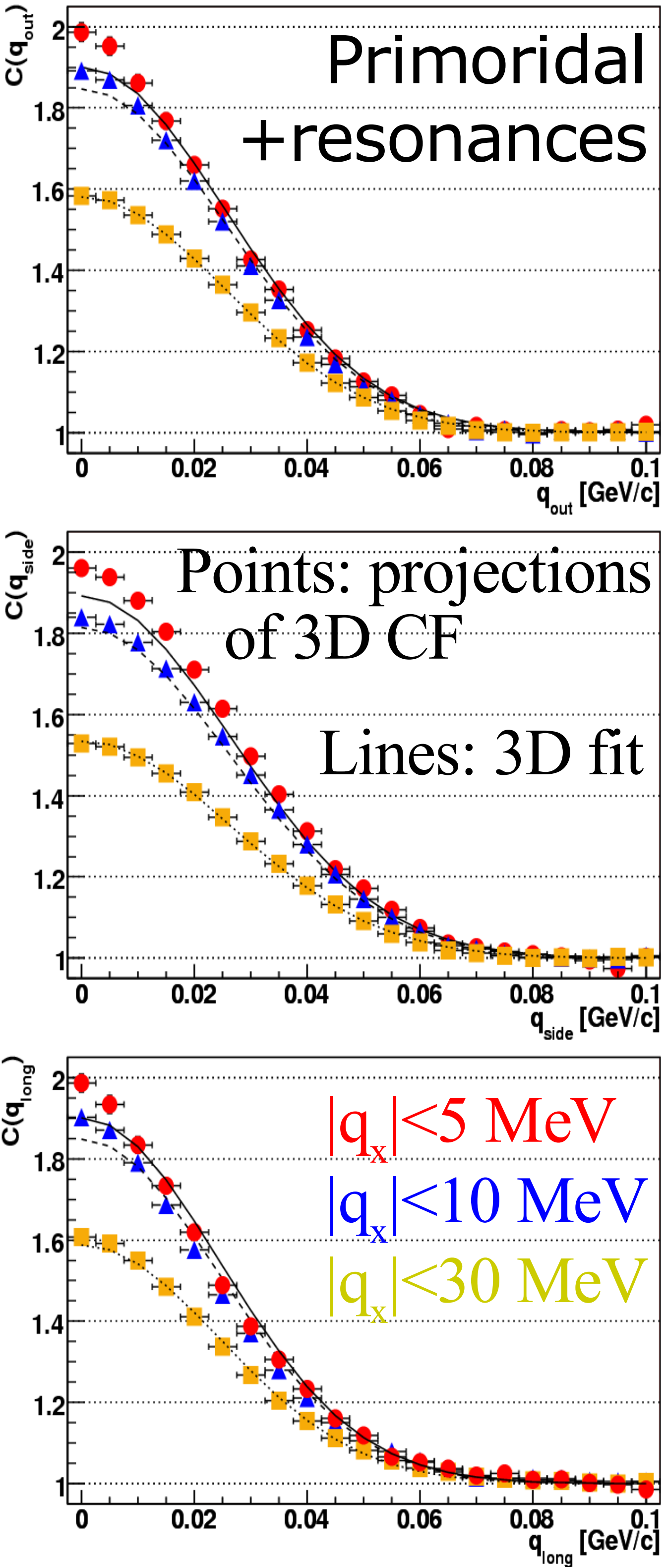
- Can we say something about the emission region – the freeze-out hypersurface?
- Does the hadronic rescattering/resonance decay influence the observed HBT and if so, how?
- Can we explain the observed intercept parameter lambda?
- How good is the gaussian approximation of the source?
- How do we compare theoretical predictions to the observed HBT radii?
- How can we get more information from the correlation function, beyond the simple HBT radii?

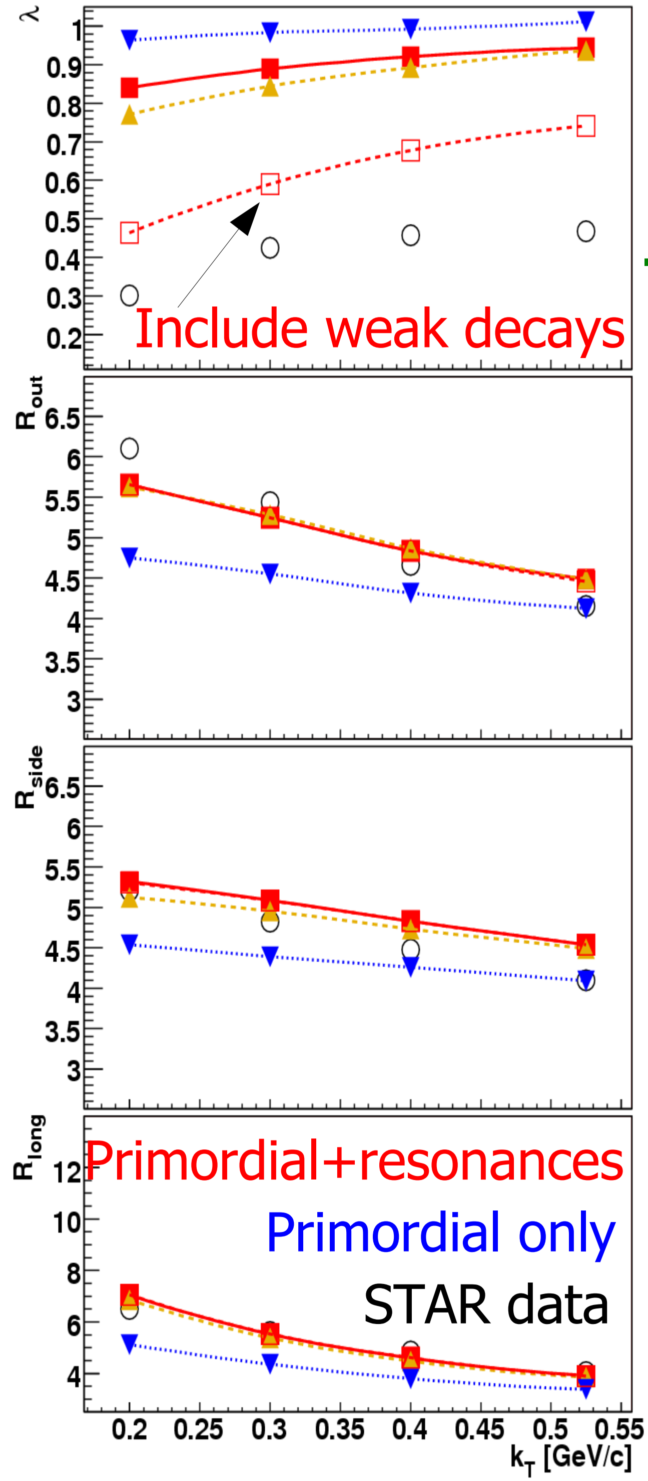
Importance of the freeze-out hypersurface





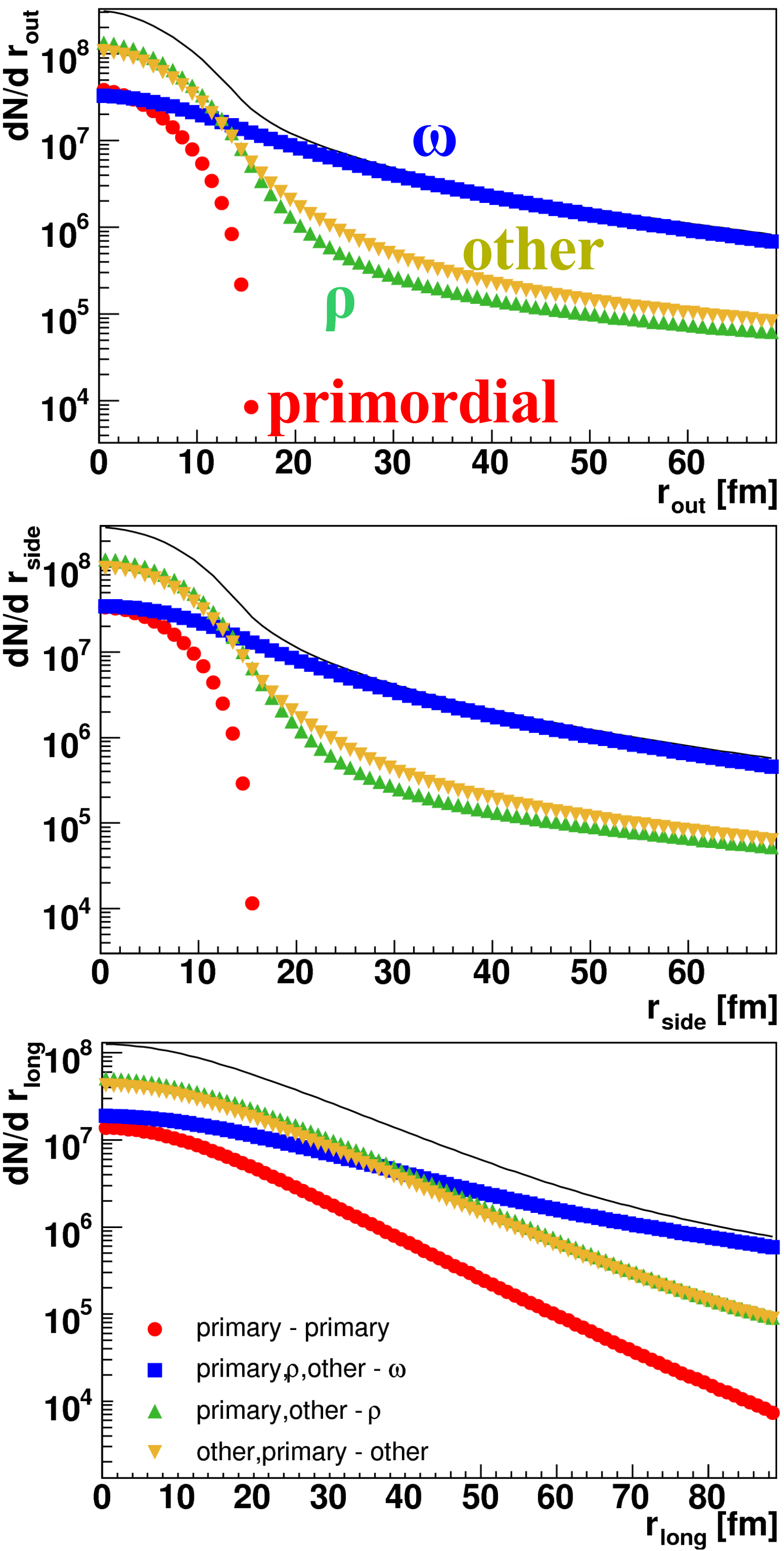
nucl-th/0602039, AK, W.Broniowski, W.Florkowski et al., accepted for PRC





Resonance contribution

- Resonances increase the observed radii
  - Essential for quantitative comparisons
  - m_T dependence cannot be explained by resonances alone
- Correlation function is not gaussian in all directions – effect of non-gaussian contribution of resonances (only?)



Separation distributions

- Resonances have significant influence on the separation distributions – they produce long tails and enlarge the source
- The shape of the source is significantly non-gaussian
- The effect in the long direction is mixed with the influence of longitudinal expansion – see also: E.Frodermann, U.Heinz, M.Lisa, "Fitted HBT radii versus space-time variances in flow-dominated models", nucl-th/0602023, PRC 73 (2006) 044908
- Variances are not always a good theoretical measure of HBT radii

Summary

- STAR has measured a set of pion HBT results over a broad range of: collision system, collision energy, pair momentum and centrality providing a rich systematic study of space-time at freeze-out
  - No dramatic change in radii with collision energy is observed – no signature of first order phase transition
  - m_T and centrality dependence of HBT radii is observed, consistent with expectations from hydro
  - R_{out}/R_{side} ratio close to 1.0 indicates a short emission duration
  - Scaling of HBT radii with $dN/d\eta$ is observed for all k_T
  - Azimuthally sensitive HBT points to short evolution duration ($\sim 10\ fm/c$)
- Non-identical correlations provide new and unique information on the emission asymmetries for particles with different m_T, confirming radial flow - a first direct measurement of x-p correlations

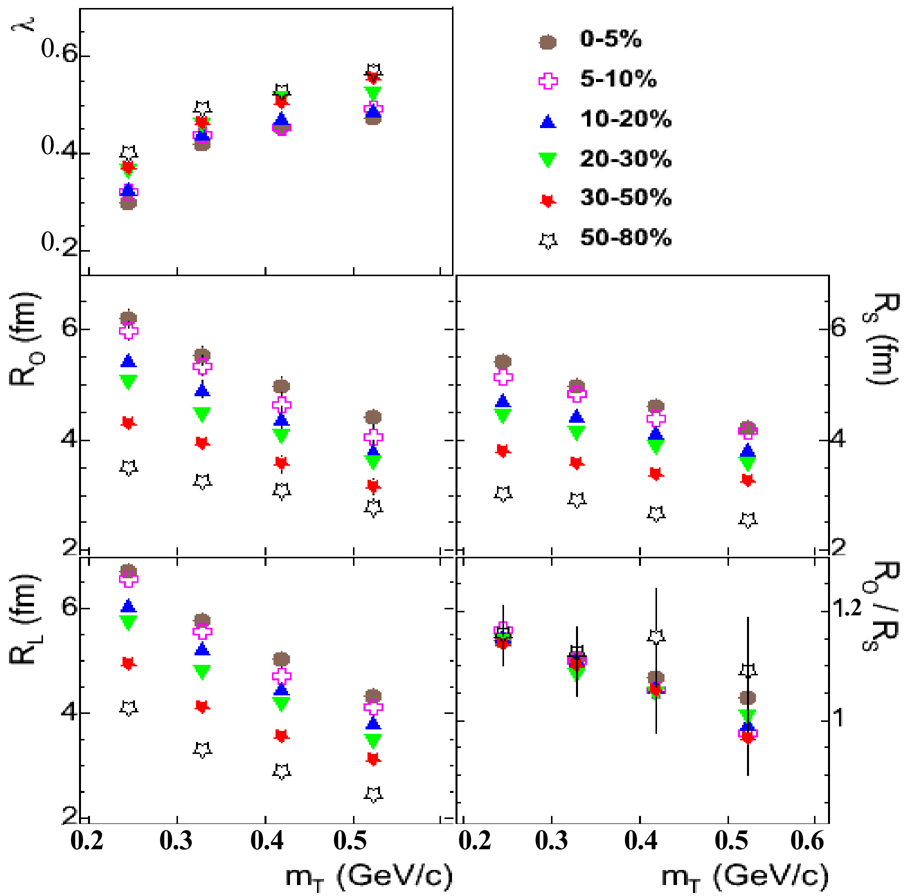
Outlook

- Femtoscopy results are shown to be sensitive to the freeze-out hypersurface – may be used as guidance for models
- Resonances play an important role in the determination of radii, but also influence the shape of the correlation function
- Shape analysis of the correlation function is required to obtain information beyond simple sizes, providing more detailed constraints for the models
  - Spherical harmonics decomposition enables the study of the (a-)symmetries of the correlation function
  - Source imaging can provide information on long-range behavior of the source function

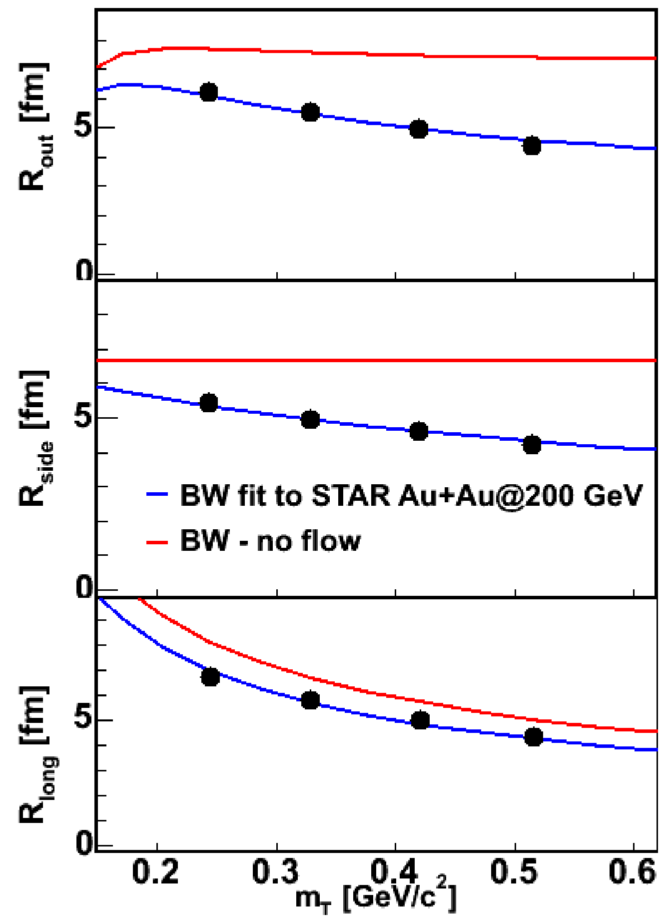
- Extra slides...

Transverse mass dependence in Au+Au

STAR, Au+Au@200GeV, PRC 71 (2005) 044906



In Au+Au p_T (m_T) dependence attributed to collective expansion of the source



Calc. with Blast-Wave -
Retiere, Lisa, PRC 70 (2004) 044907

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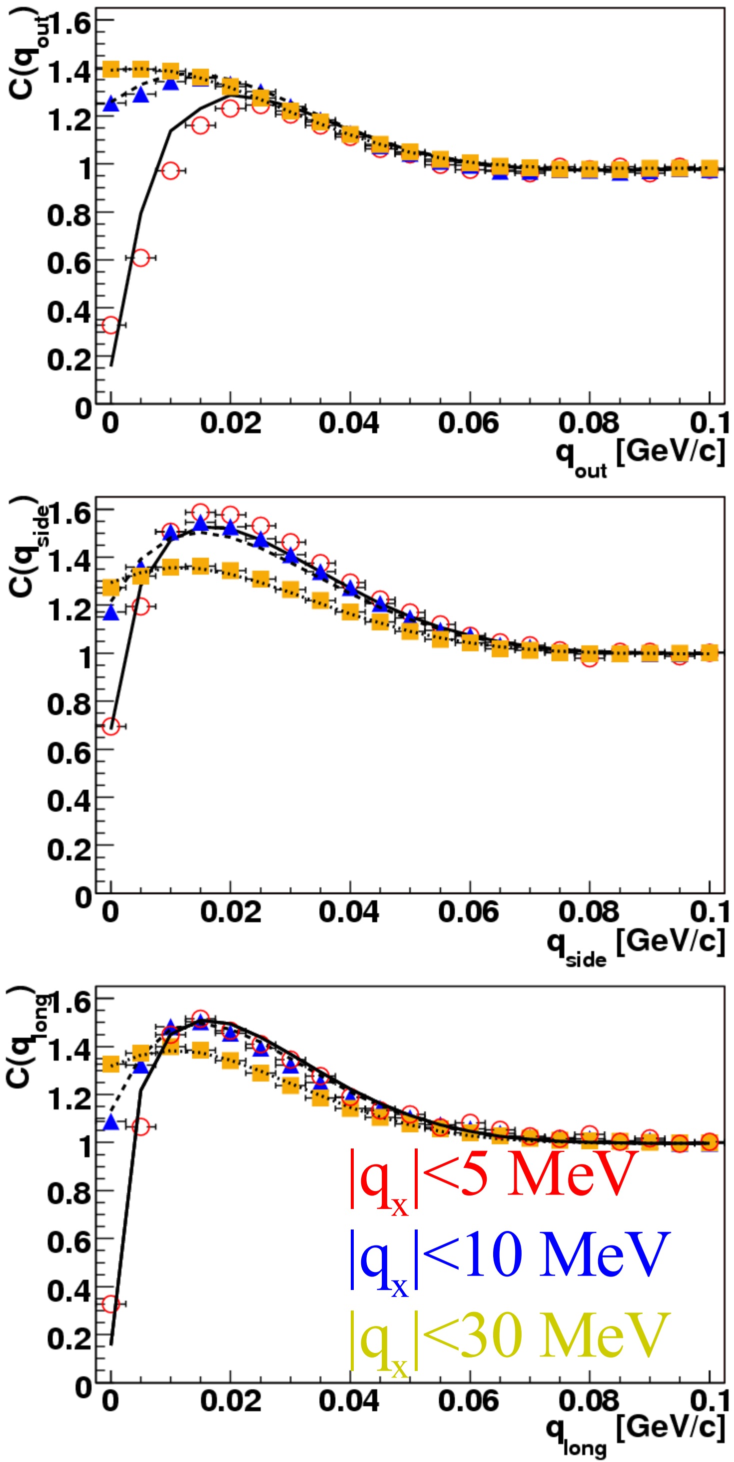
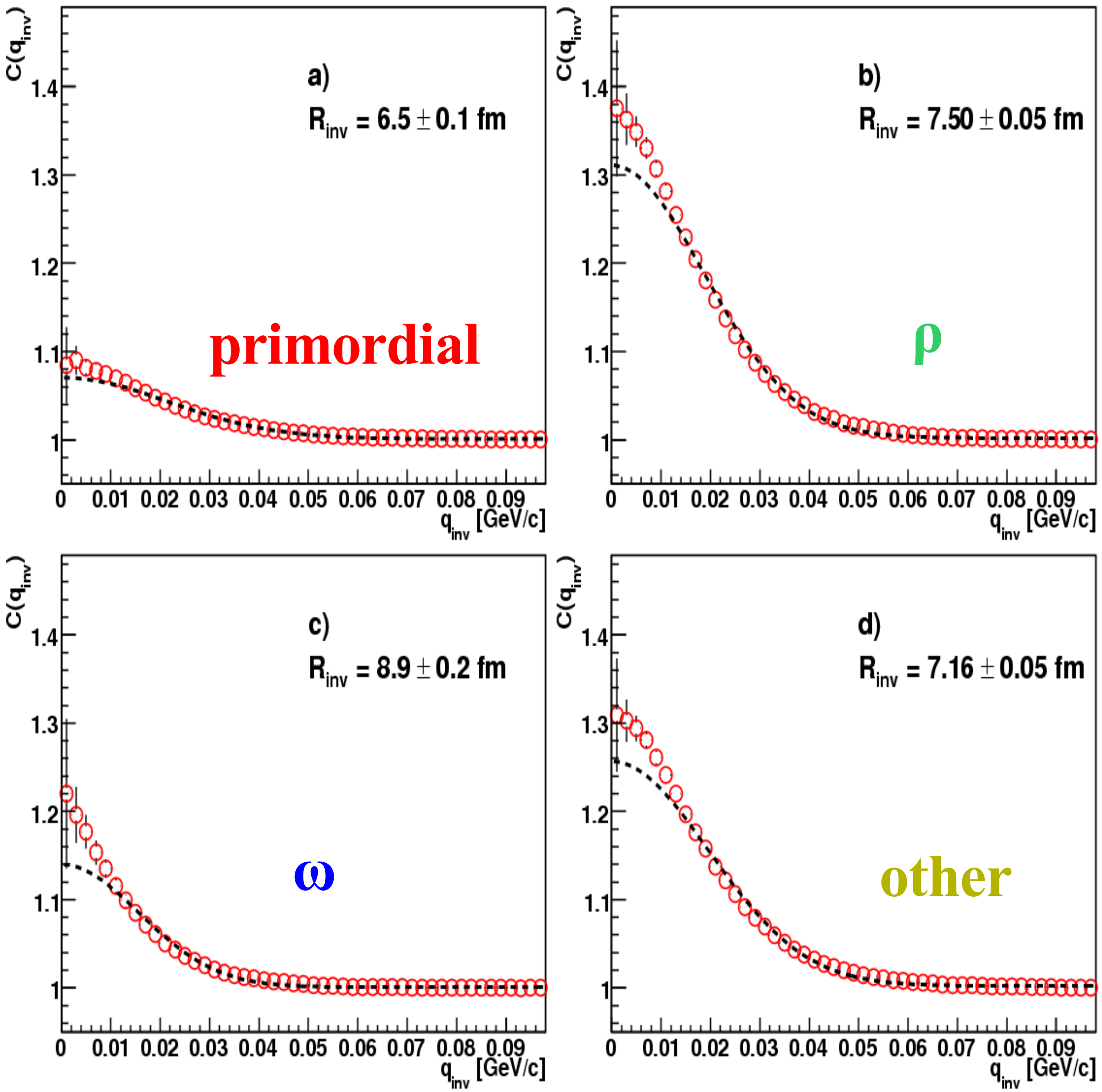
3D correlation functions with Coulomb



- The correlation function with full simulation of Coulomb effects can also be calculated
- It is fit with Bowler-Sinyukov formula. The fit is fully 3D. To plot it, we project it in the same manner as the input function.
- In this case we try to reproduce STAR data, therefore the K_{coul} for the spherical gaussian with radius 5fm in all directions was used.

Influence on the correlation function



- Functions non-gaussian, as expected
- Primordial particles give only 10% of correlation effect
- Resonances increase the size by about 1fm
- Contribution from omega sharply peaked – mostly visible in the lambda parameter

Non-identical correlations

- When dealing with non-identical correlations we have to use the full two-particle wave-function:

$$C(\bar{q}, x) = \sum_S G_S \frac{\int d^{4x} S(x, q) \left| \Psi_{\tilde{q}}^{S(+)} \right|^2}{\int d^{4x} S(x, q)}$$

where x, q are relative position, momentum. Here we cannot easily go from x and q to single particle distributions, as sizes for different particle species differ.

- In order to produce a correlation function, one must perform a full two-particle integration over the emission function, convoluted with the pair Bethe-Salpeter amplitude squared. This has the advantage of automatically including all interactions (Coulomb, strong and quantum statistics through symmetrization)

Radius extraction in data

- To fit the experimental data, an approximation is used stating that Coulomb and symmetrization of the wave function factorize, which gives "Bowler-Sinyukov" formula:

$$C(\vec{q}) = (1-\lambda) + \lambda K_{coul}(q_{inv})(1+\exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2))$$

- Here K_{coul} is the Coulomb-only wave-function integrated over some source. Usually the simplest form is used: a function integrated over 3D gaussian with the same, fixed size in all directions, which is another approximation.

- Experiments usually analyze their correlation functions in LCMS (Longitudinally Co-Moving System), which means their radii are also extracted for LCMS, while pair wave function is most easily calculated in Pair Rest Frame.

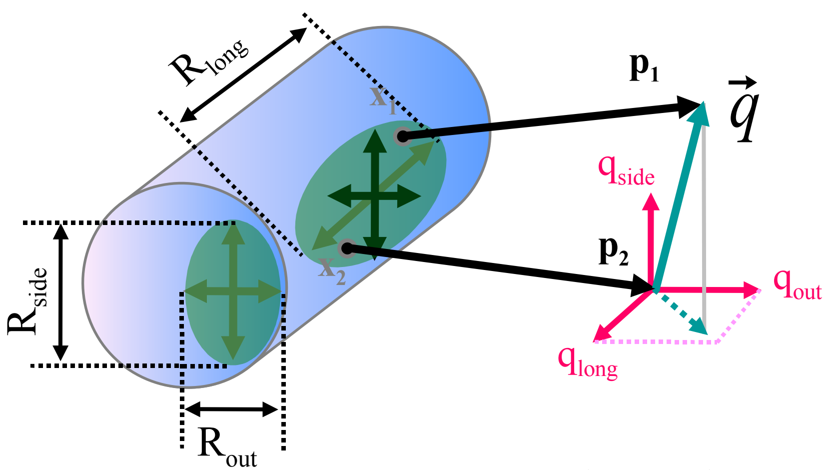
Gaussian Parameterization

$$C\left(\vec{q},\vec{k}\right)=1+\lambda(\vec{k})\,exp\left(-\sum_{i,\,j=o,s,l} R_{ij}^2(\vec{k})\,q_i q_j\right)$$

If source is approximated as

a Gaussian →
3D Cartesian Pratt-Berstch
parameterization:

λ takes non BE correlations into account (0 < λ < 1)



- for an azimuthally symmetric collision
- in the LCMS frame at midrapidity

$$C\left(\vec{q},\vec{k}\right)=1+\lambda(\vec{k})\,exp\left(-R_o^2(\vec{k})\,q_o^2-R_s^2(\vec{k})\,q_s^2-R_l^2(\vec{k})\,q_l^2\right)$$

$$\vec{q}=\vec{p}_2-\vec{p}_1$$

$$\vec{k}=\frac{1}{2}\left(\vec{p}_2+\vec{p}_1\right)$$

Final state Coulomb interaction

The Coulomb interaction between two charged particles is described by the Coulomb wave function which is calculated by solving the Schrödinger equation:

$$\left(-\frac{\nabla}{2\mu}-E+\frac{e^2}{r}\right)\psi_c(\vec{q},\vec{r})=0$$

Using ψ_c we can calculate the contribution of the Coulomb interaction to the correlation function:

$$P_c=\int d^3r\;\rho(\vec{r})|\psi_c(\vec{q},\vec{r})|^2=K_{coul}(m_\pi,R,q)$$

Assuming that the source function is a **spherical Gaussian** we calculate K_{coul}, it depends on the **mass of the particles**, the assumed **source radius** (5 fm), and the **relative momentum of the pair q**.

Coulomb interaction and fitting procedures

If one assume all particles entering the CF Coulomb interact, a possible way of "eliminating" the Coulomb interaction from the numerator (pairs from same event) is to introduce this interaction in the denominator:

$$\frac{A(q)}{B(q)\cdot K_{coul}(q)} = N\cdot(1+\lambda\cdot exp(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2))$$

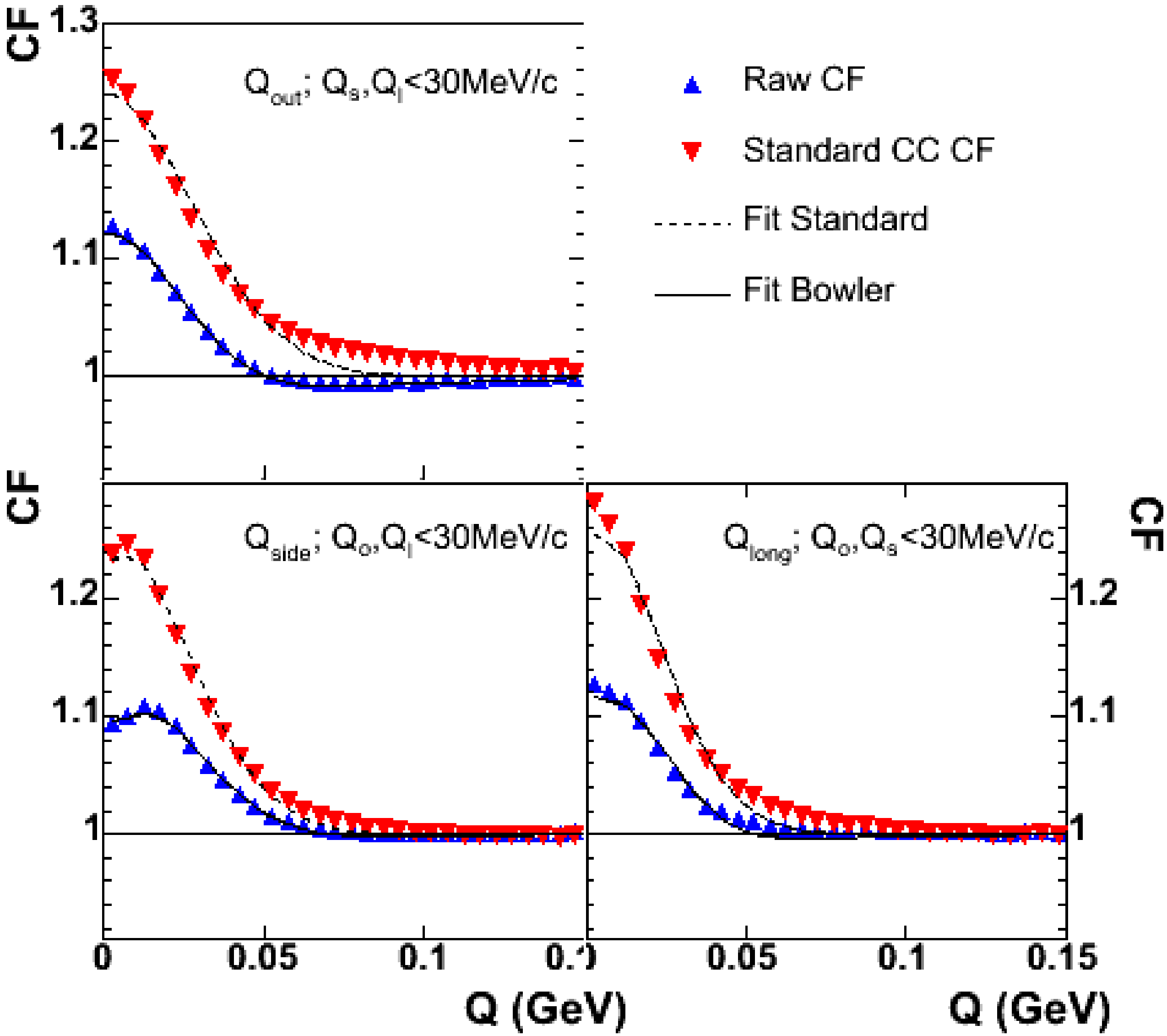
Standard procedure

However this procedure assumes all pairs are formed by primary pions and this is not necessarily true. A better approach is to fit the correlation function according to:

$$\frac{A(q)}{B(q)} = N\cdot\left\{\underbrace{(1-\lambda)}_{\text{Not interacting part}} + \underbrace{\lambda\cdot K_{coul}(q)\cdot\left[1+exp\left(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2\right)\right]}_{\text{Coulomb and Bose-Einstein interacting part}}\right\}$$

Bowler procedure

3D Correlation Functions



STAR, Au+Au@200GeV, PRC 71 (2005) 044906

Central Events

k_T = 0.15-0.25 GeV/c

Projections of the 3D CF according to Pratt-Bertsch Parameterization

Two possible fits

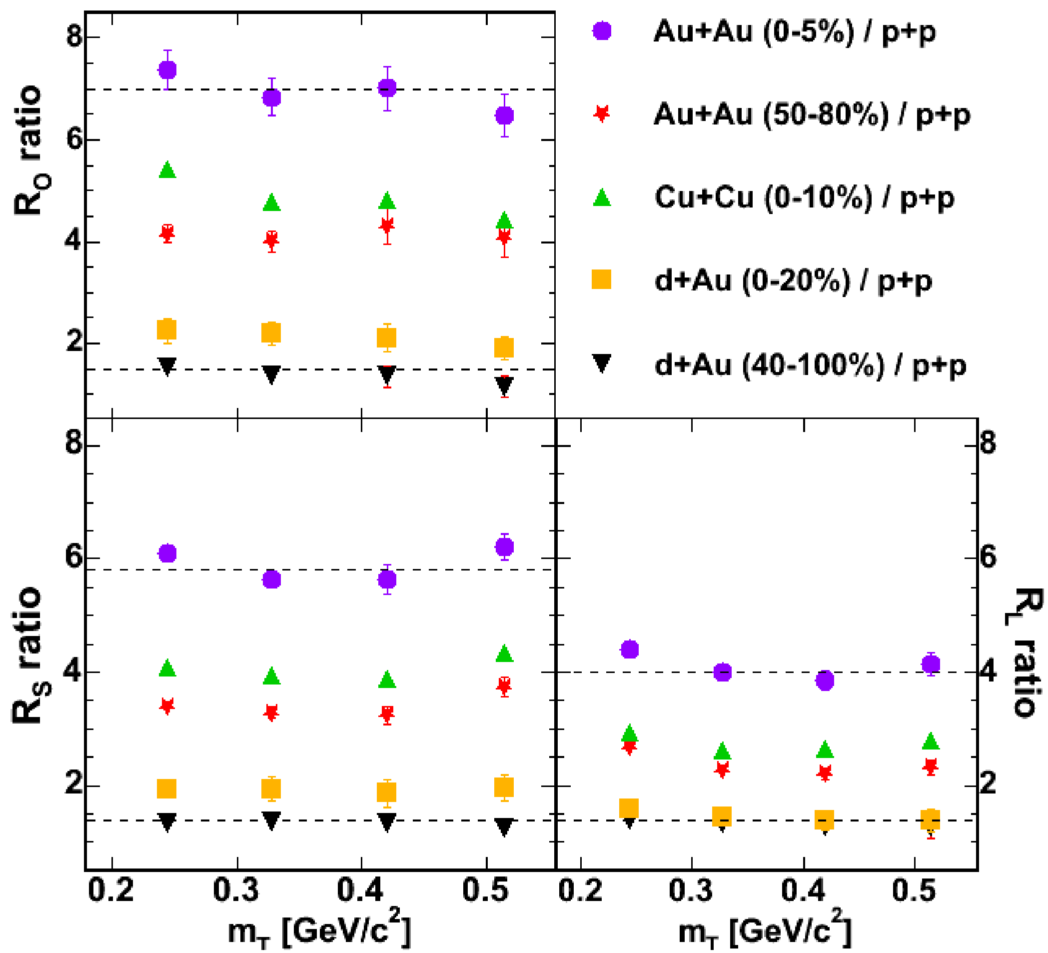
Surprising scaling

- All $p_T(m_T)$ dependences of HBT radii observed by STAR scale with pp although it's expected that different origins drive these dependences

HBT radii scale with pp

Scary coincidence or something deeper?

Ratio of (AuAu, CuCu, dAu) HBT radii by pp



pp, dAu, CuCu - STAR preliminary

Coulomb interaction

- At RHIC one usually measures HBT of charged particles, therefore one cannot neglect the Coulomb interaction. It modifies the pair wave-function:

$$\Psi(\boldsymbol{k}^*, \boldsymbol{r}^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\frac{1}{\sqrt{2}}\left[e^{-i\boldsymbol{k}^*\boldsymbol{r}^*}F(-i\eta, 1, i\xi^+) \pm (-1)^S e^{i\boldsymbol{k}^*\boldsymbol{r}^*}F(-i\eta, 1, i\xi^-)\right]$$

where $\xi^{+/-} = \boldsymbol{k}^*\boldsymbol{r}^* \pm k^* r^* \equiv \rho(1 \pm \cos(\theta^*)),\ \rho = k^* r^*,\ \eta = (k^* a)^{-1},\ a = (\mu z_1 z_2 e^2)^{-1}$ $A_c(\eta)$ is the Gamow factor, and F is the confluent hypergeometric function. The full wave-function includes strong interaction as well, but for pions we can neglect it.

- We emphasize that in the Monte-Carlo approach the correlation function with two-particle Coulomb effects can be calculated exactly

Quantitative analysis - Gaussian correlation function

- When fitting, one assumes the emission function is:

$$S(x,K) \sim \exp\left(-\frac{x_{out}^2}{2R_{out}^2} - \frac{x_{side}^2}{2R_{side}^2} - \frac{x_{long}^2}{2R_{long}^2}\right)$$

- The source is static, gaussian and single-particle
- The integration yields a well known fit formula:

$$C(\vec{q}) = 1 + \lambda \exp\left(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2\right)$$

which, when fitted to the "experimental" correlation function, provides the "HBT radii" R_{out}, R_{side}, R_{long}

- The R^2's are the variances of the single-particle gaussian space-time emission point distributions. Note that only for the gaussian distribution the combination of single-particle sources is also a gaussian

Radius extraction in data

- To fit the experimental data, an approximation is used stating that Coulomb and symmetrization of the wave function factorize, which gives "Bowler-Sinyukov" formula:

$$C(\vec{q}) = (1-\lambda) + \lambda K_{coul}(q_{inv})(1+\exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2))$$

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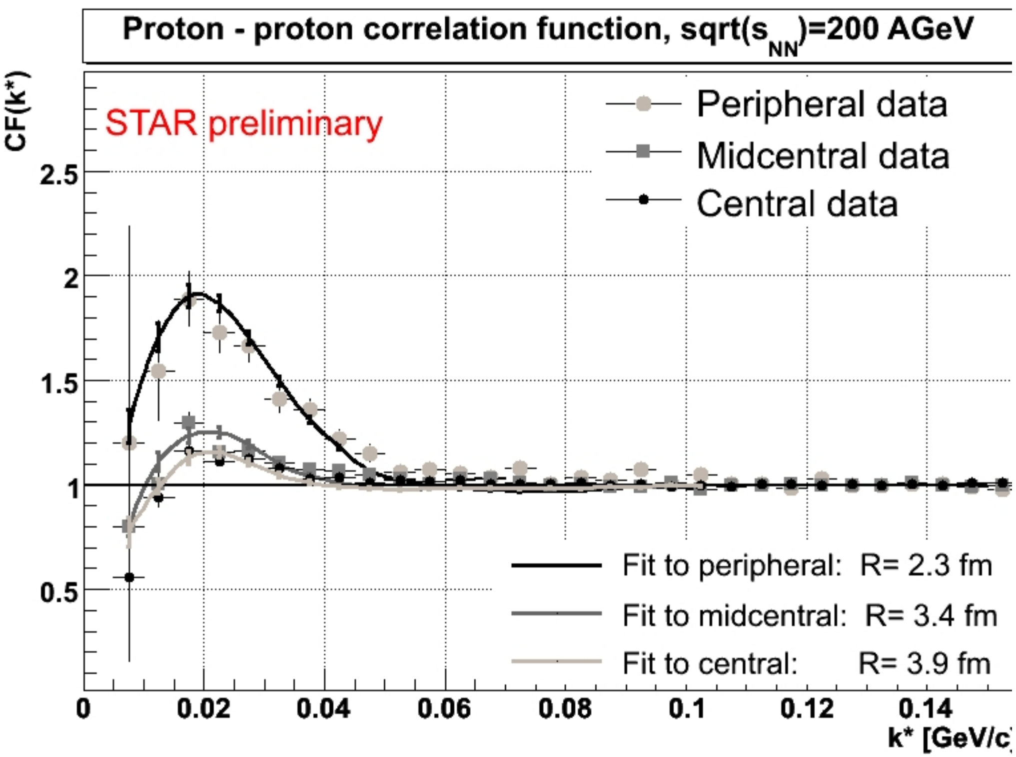
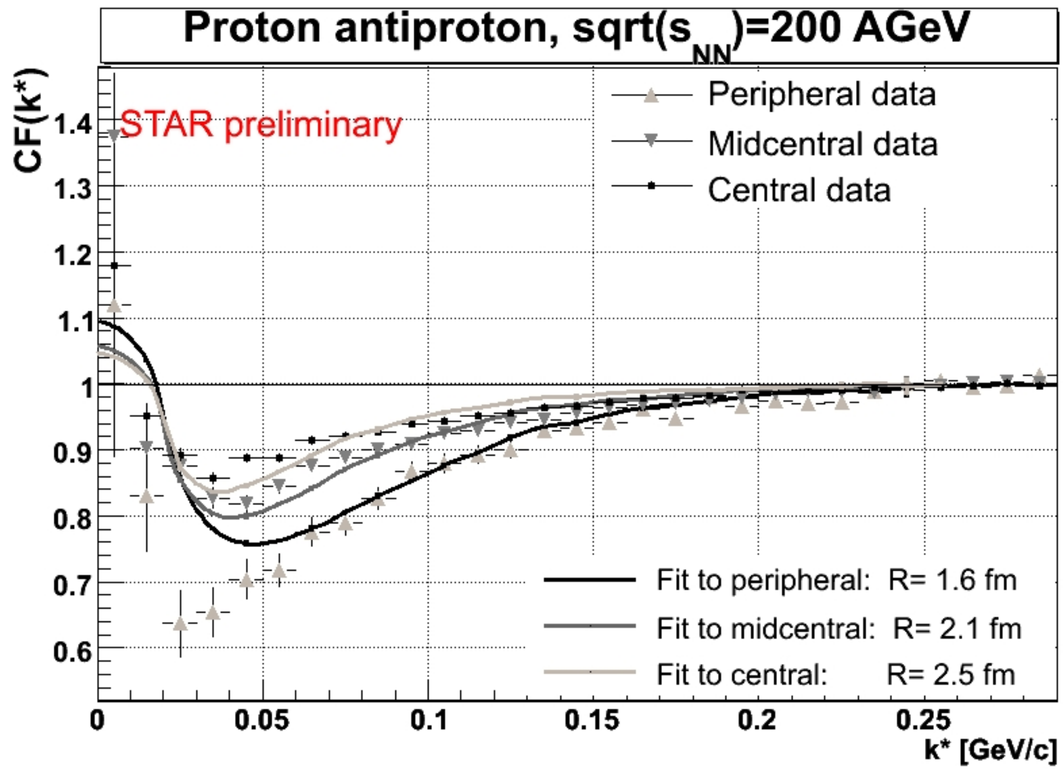
Baryon-baryon: identical and nonidentical correlations





No residual correlations, with resolution smearing

	$p-p$	$\bar{p}-\bar{p}$	$p-\bar{p}$
peripheral	$2.3^{+0.1}_{-0.1}$ *fm*	$2.4^{+0.1}_{-0.2}$ *fm*	$1.6^{+0.1}_{-0.1}$ *fm*
midcentral	$3.4^{+0.1}_{-0.1}$ *fm*	$3.5^{+0.1}_{-0.1}$ *fm*	$2.1^{+0.1}_{-0.1}$ *fm*
central	$3.9^{+0.2}_{-0.1}$ *fm*	$4.5^{+0.1}_{-0.1}$ *fm*	$2.5^{+0.1}_{-0.2}$ *fm*

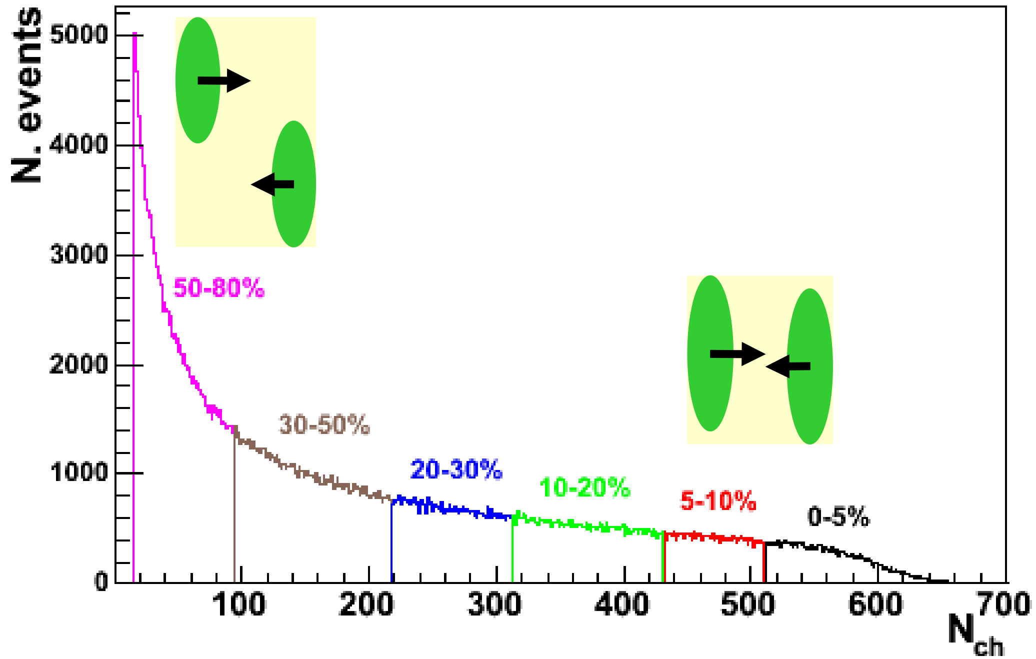
2 different sizes!

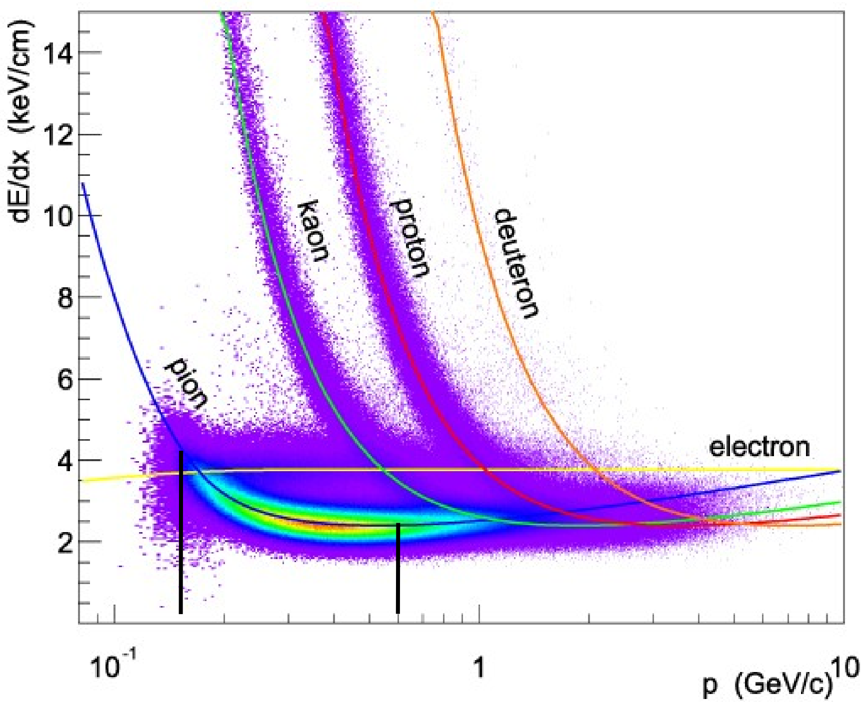
2 different sources?

Event and Particle Selection

Centrality selection based on number of charged hadrons at midrapidity

Events binned according to their centrality in 6 bins





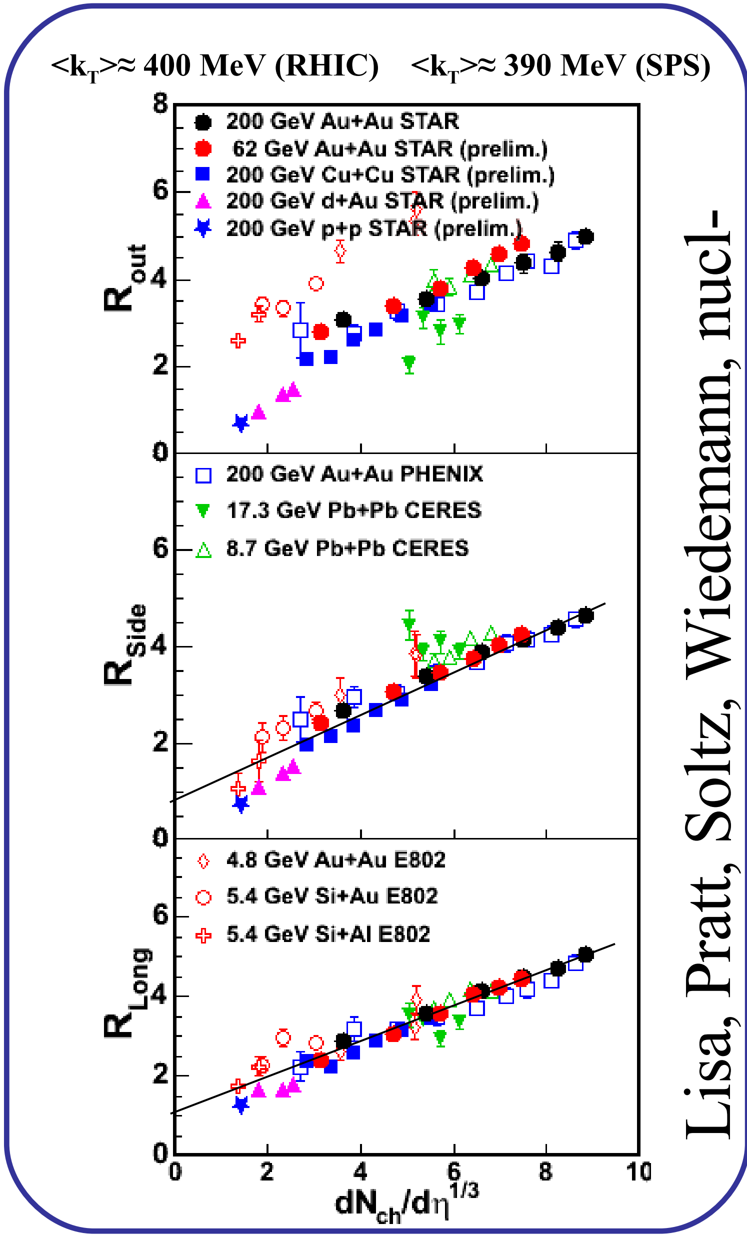
Particle identification via specific ionization (dE/dx)

-0.5 < Y < 0.5

DCA < 3 cm

Do we „universal" scaling ?

RHIC/AGS/SPS



Lisa, Pratt, Soltz, Wiedemann, nucl-ex/0505014

observed scaling

$$R_i = C_i \bullet (dN/d\eta)^{1/3} + D_i \quad , \ i=o,s,l$$

Finite intercept means that freeze-out does not occur at constant density

scaling breaks down at lower energies, when baryons constitute a significant fraction of the a-out system (Stock, Csorgo, Lisa at el.)

so far the scaling was presented only for data at mid-rapidity and *some* dependence of this scaling of rapidity may be expected (Stock, Csorgo, Csernai)

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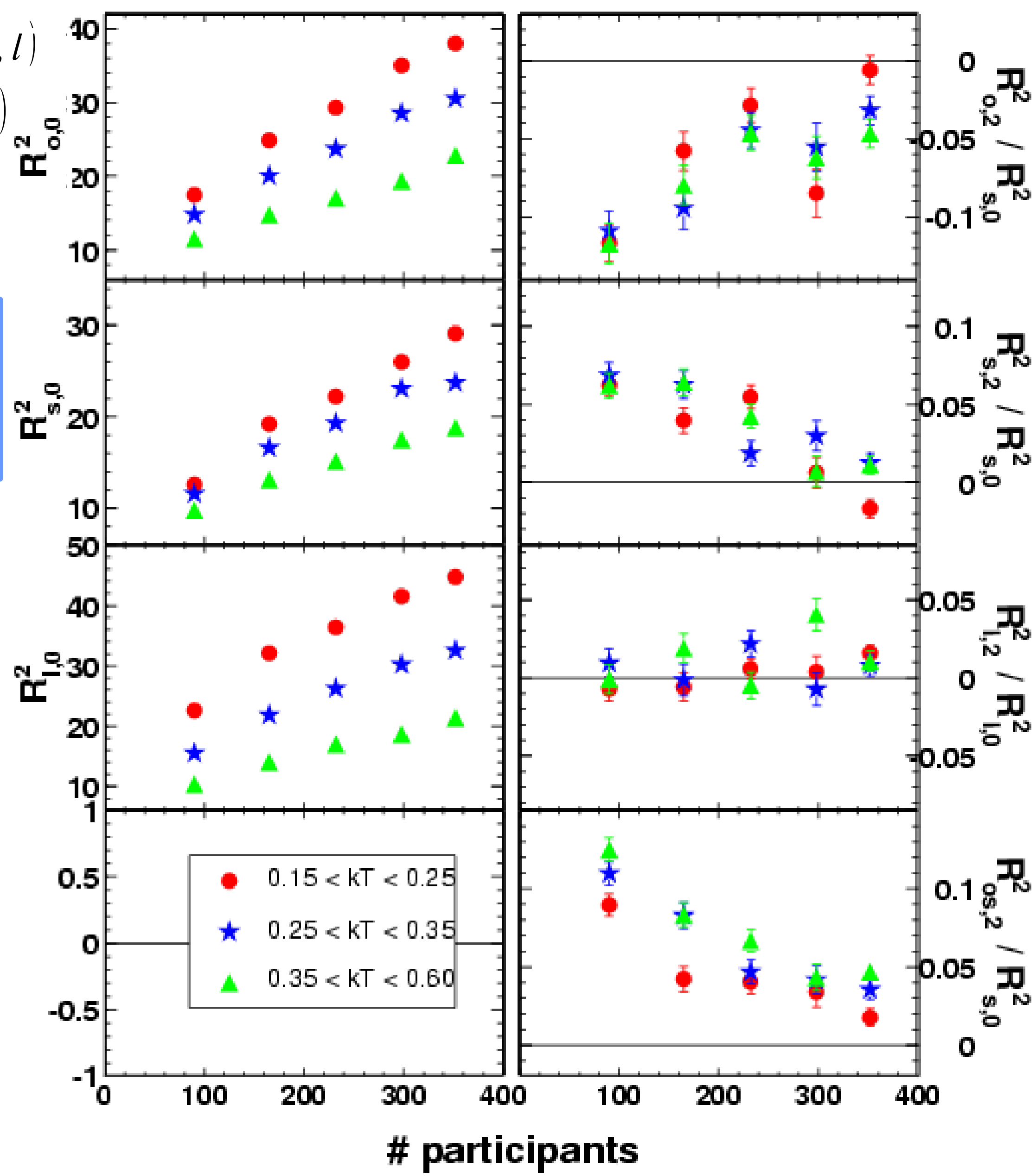
Grand Data Summary - $R^2_{\mu,n}$ vs k_T, centrality

$$R^2_{\mu}(k_T)=\begin{cases} R^2_{\mu,0}(k_T)+2\text{sum}\,R^2_{\mu,n}(k_T)\cos(n\varphi) & (\mu=o,s,l) \\ R^2_{\mu,n}(k_T)\cdot\sin(n\varphi) & (\mu=os) \end{cases}$$

$$R^2_{\mu,n}(p_T)=\begin{cases} \langle R^2_{\mu}(p_T,\varphi)\cdot\cos(n\varphi)\rangle & (\mu=o,s,l) \\ \langle R^2_{\mu}(p_T,\varphi)\cdot\sin(n\varphi)\rangle & (\mu=os) \end{cases}$$



- left: $R^2_{\mu,0}$ ≈ “traditional” radii
  - usual kT, centrality dependence
- right: $R^2_{\mu,0}$/ $R^2_{\nu,0}$
  - reasonable centrality dependence
  - BW: sensitive to FO source

What m_T scaling can tell us?

Flat ratio of Au+Au/p+p

Does it indicate that m_T dep. has the same origin in large and small system? – rather not

We cannot distinguish between different physics scenarios looking into femtoscopic signal?

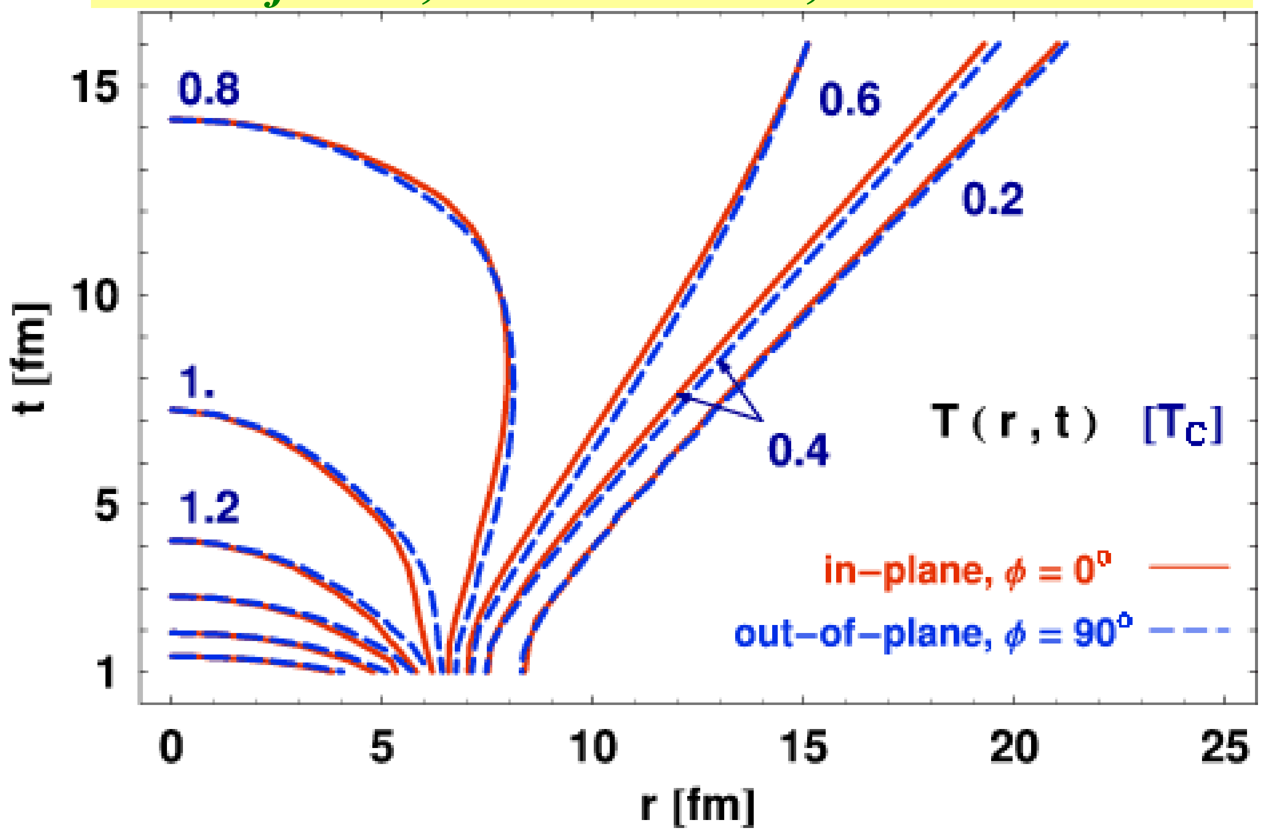
m_T dependence also seen in elementary particle collisions (OPAL, DELPHI, NA22,..)

Can we build a consistent picture indicating differences/ /simillarities between elementary particle and heavy ion 38 collisions using femtoscopy as a probing device?

The importance of freeze-out hypersurface

- The Cracow single freeze-out model implemented a particular shape of freeze-out hypersurface where $\tau = const$
- Commonly used Blast-wave models have a hypersurface defined as $t = const$
- Hydrodynamic calculations usually produ
- Generalized Blast-wave was use

M. Chojnacki, W. Florkowski, nucl-th/0603035



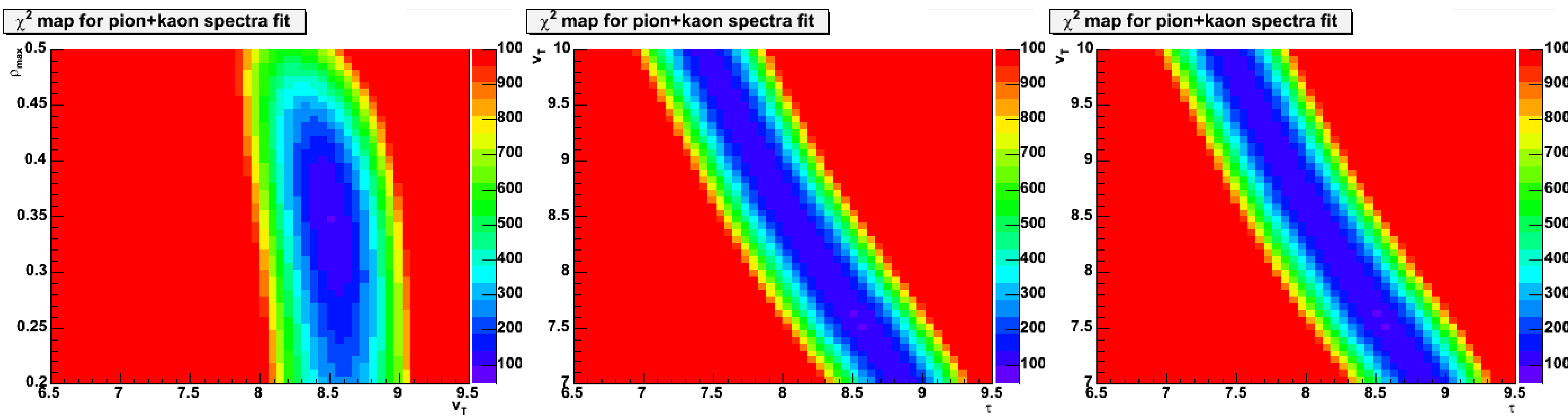
Different freezeout hypersurface – "BlastWave" with resonances

- In Therminator we have complete freedom of choice of the emission function. We use generalized "BlastWave":

$$\frac{dN}{dp_\perp d\phi_p dy d\rho d\phi_S d\alpha_\parallel} = \frac{p_T \rho}{(2\pi)^3}(\tau + a\rho)\left[m_\perp \cosh\left(\alpha_\parallel - y\right) - a p_\perp \cos\left(\phi_P - \phi_S\right)\right]$$

$$\times \left\{\exp\left[\beta m_\perp \frac{1}{\sqrt{1-v_\perp^2}}\cosh\left(\alpha_\parallel - y\right) - \beta p_\perp \frac{v_\perp}{\sqrt{1-v_\perp^2}}\cos\left(\phi_P - \phi_S\right) - \beta\mu\right] \pm 1\right\}^{-1}$$

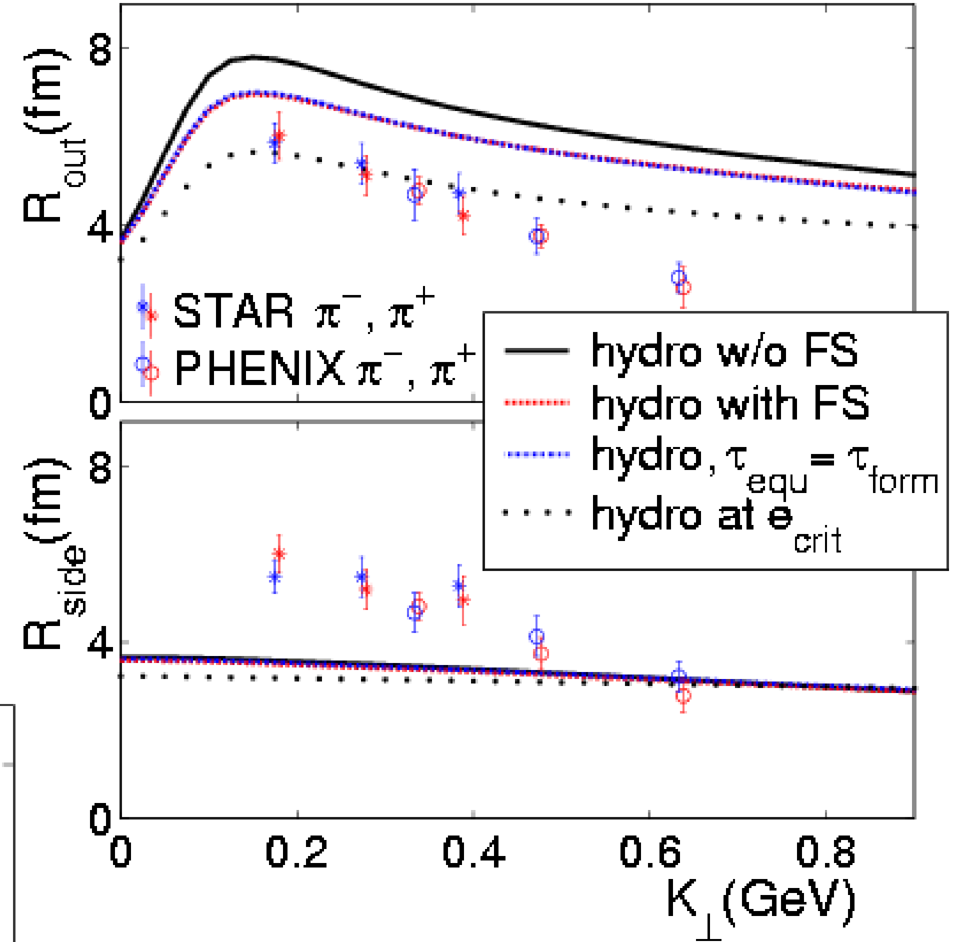
- Thermodynamical parameters (T, μ_B) stay the same. ρ_{max} and τ have the same meaning. We introduce new parameter: v_T that characterizes flow.

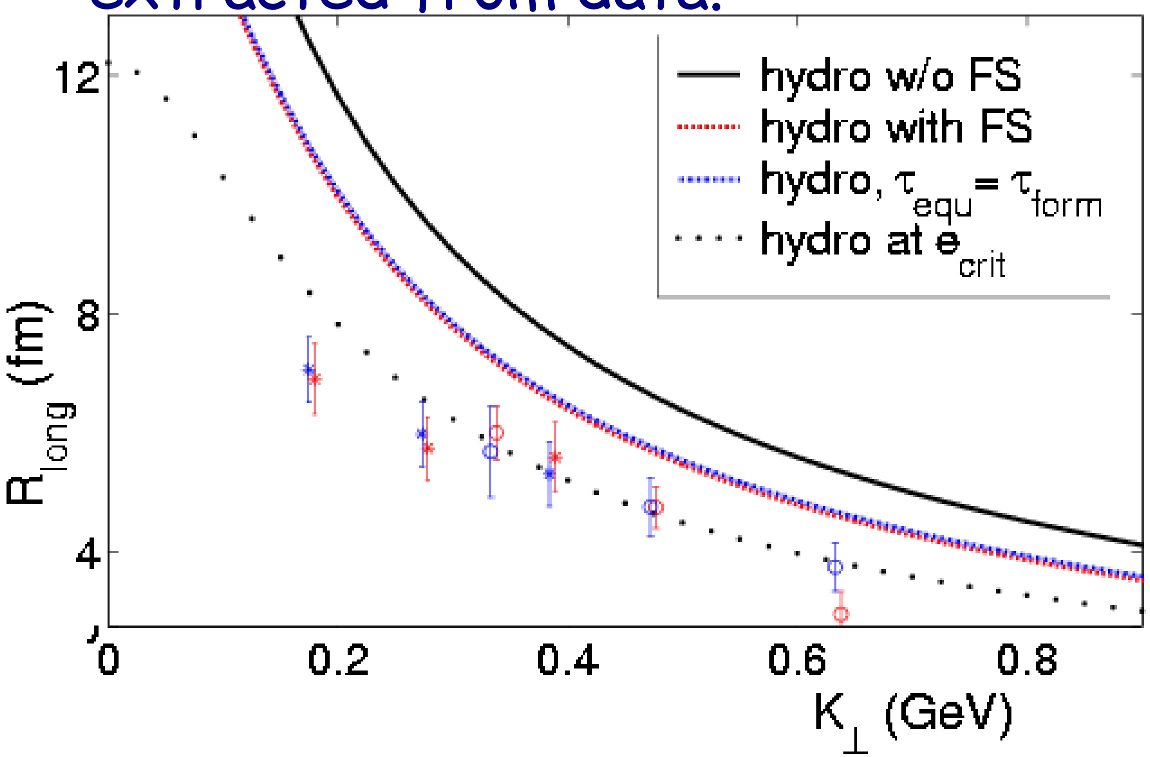


Timescales: origin of the "HBT puzzle"?

Hydrodynamic calculations that reproduce spectra and v_2 fail to reproduce HBT results.

Their timescales are larger than those extracted from data.

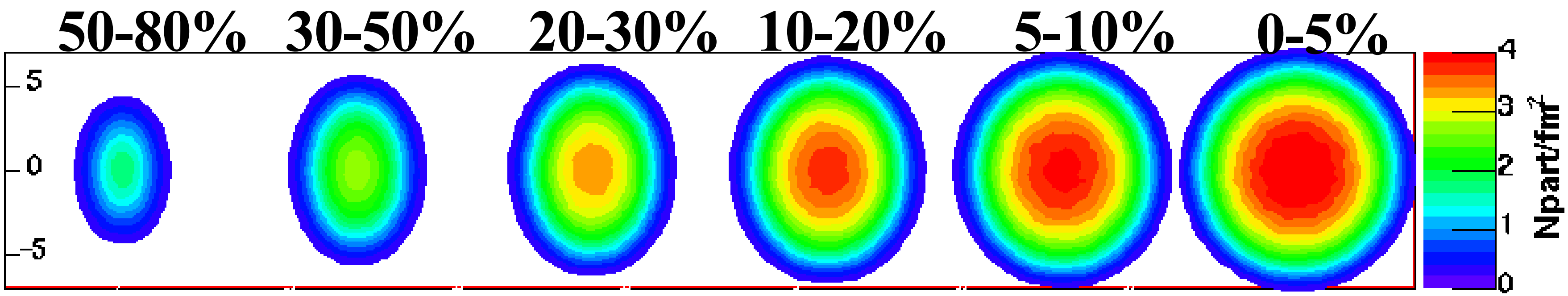


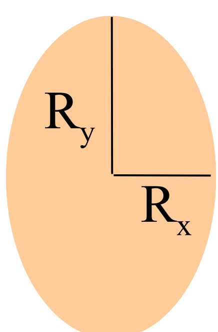


Initial source size

Monte Carlo Glauber model calculation

AuAu collisions as a superposition of many individual nn collisions.



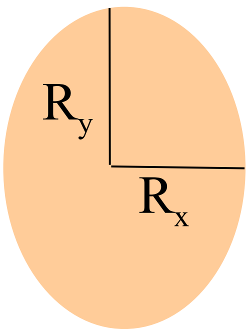


$$R_{x,in} = 2 \cdot R^{RMS}_{x,inital}$$

$$R_{y,in} = 2 \cdot R^{RMS}_{y,inital}$$

$$R_{in} = \sqrt{\frac{R^2_{x,in} + R^2_{y,in}}{2}}$$

How does the system expand?



Initial radii: Glauber model.

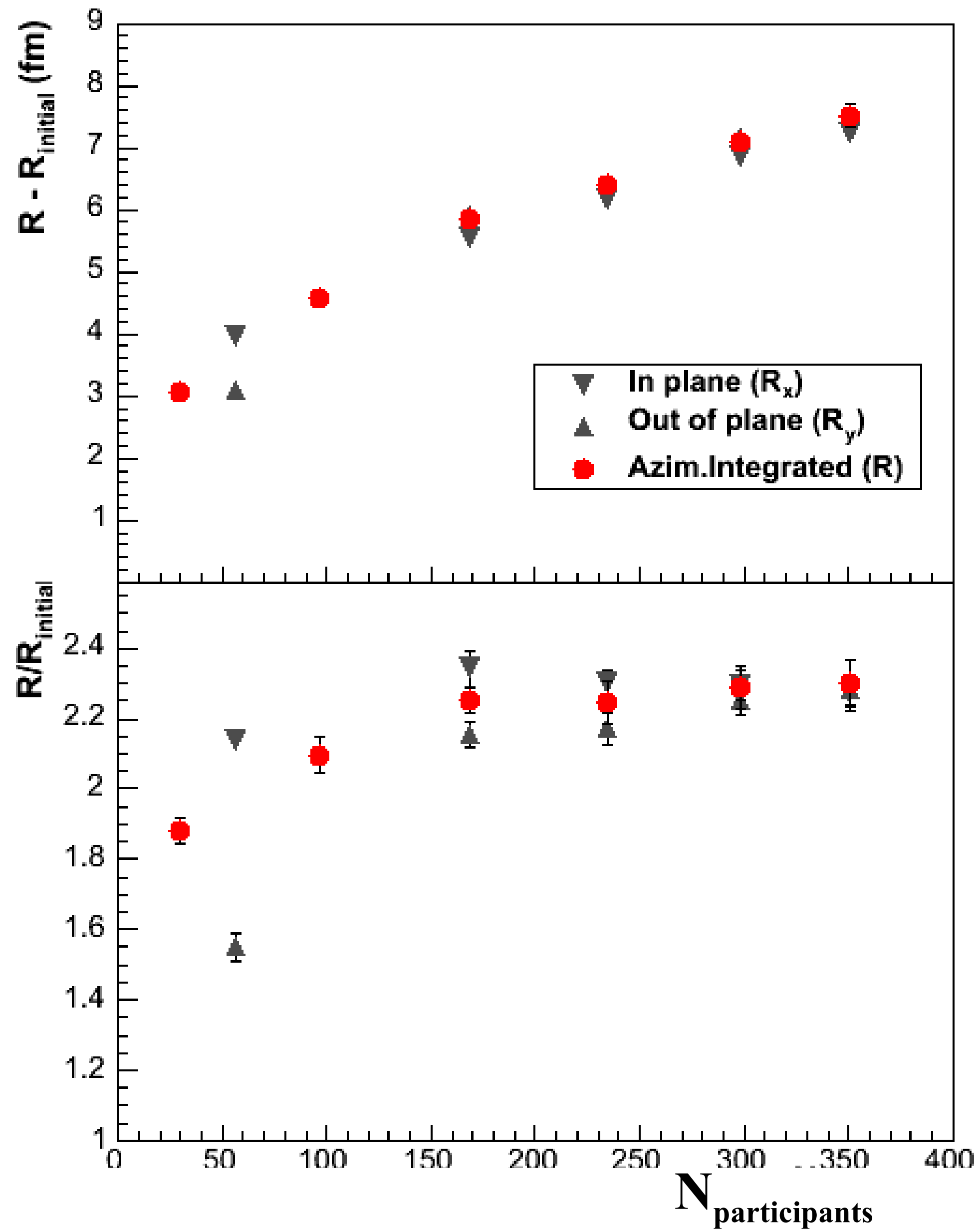
Final radii: blast wave fits to spectra, v_2 and HBT/asHBT ("hydro-like" parameterization)

Overall expansion ($R-R_{initial}$):

- increasing with centrality
- larger in-plane for most peripheral collisions

Relative expansion ($R/R_{initial}$):

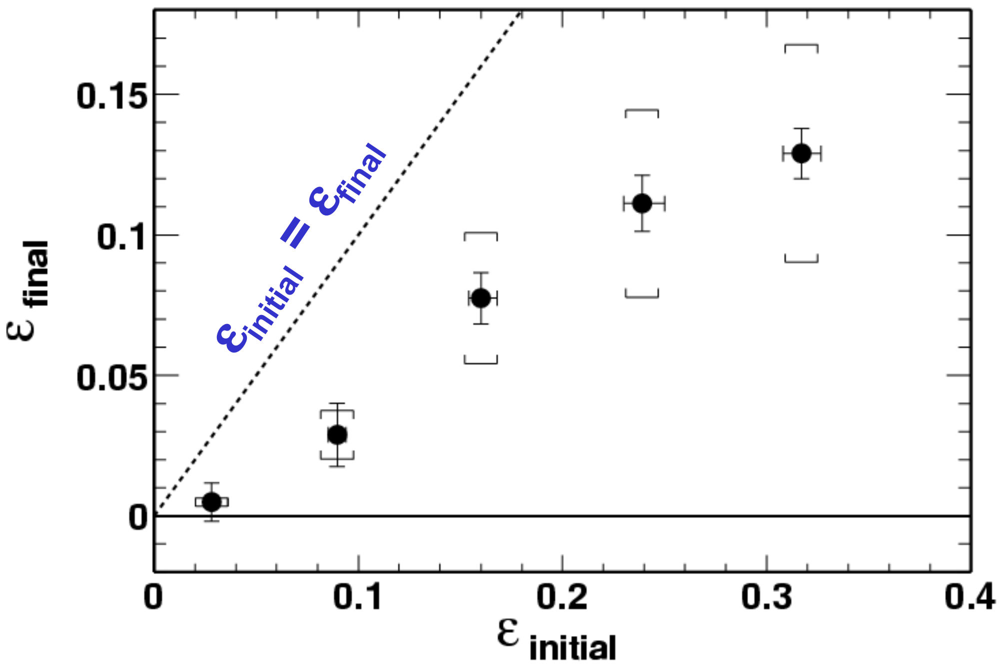
- weaker for very peripheral, almost constant for other centralities
- stronger in-plane than out-of-plane for non-central collisions



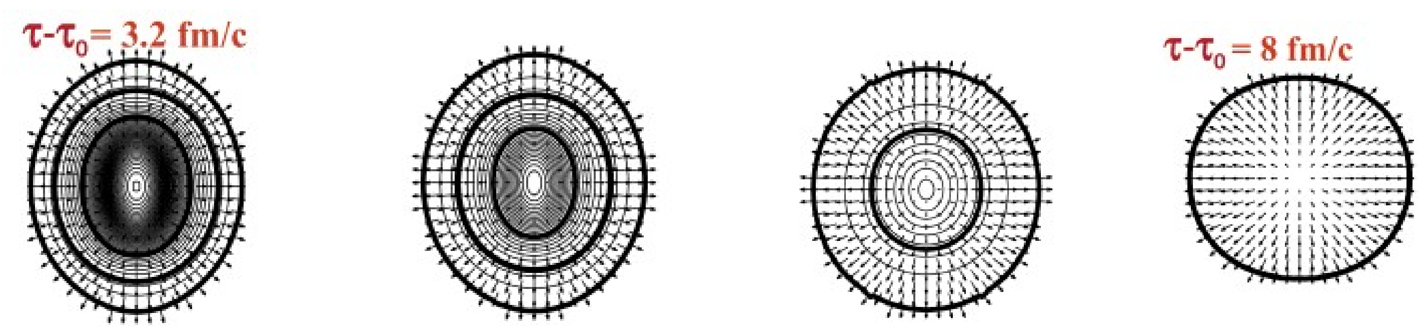
Phys. Rev. C71, 044906 (2005)

Estimate of initial vs F.O. source shape

- Out-of-plane sources at freeze-out
  - Pressure and/or expansion time was not sufficient to quench initial shape
- From v_2 we know…
  - Strong in-plane flow → significant pressure build-up in system



$$\varepsilon \equiv \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} = 2\frac{R_{s,2}^2}{R_{s,0}^2} = 2\frac{R_{os,2}^2}{R_{s,0}^2} = -2\frac{R_{o,2}^2}{R_{s,0}^2}$$



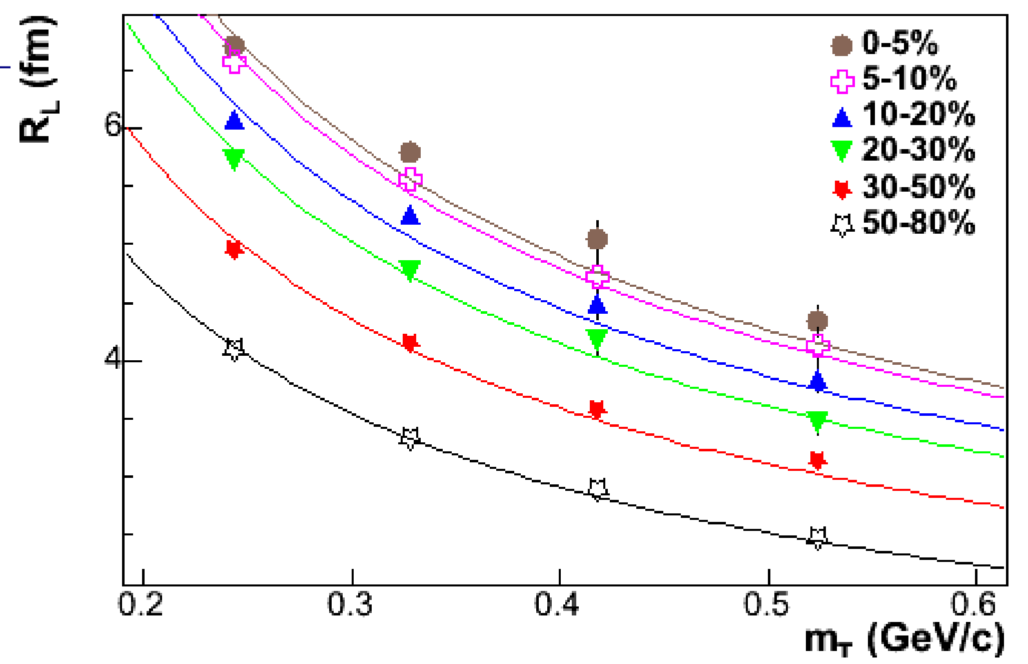
Source remains out-of-plane extended at freeze out

Evolution duration

- From BW fit
- Modified Sinyukov fit to R_L:

$$R_L(m_T) = \langle t_{fo} \rangle \sqrt{\frac{T}{m_T} \cdot \frac{K_2(m_T/T)}{K_1(m_T/T)}}$$

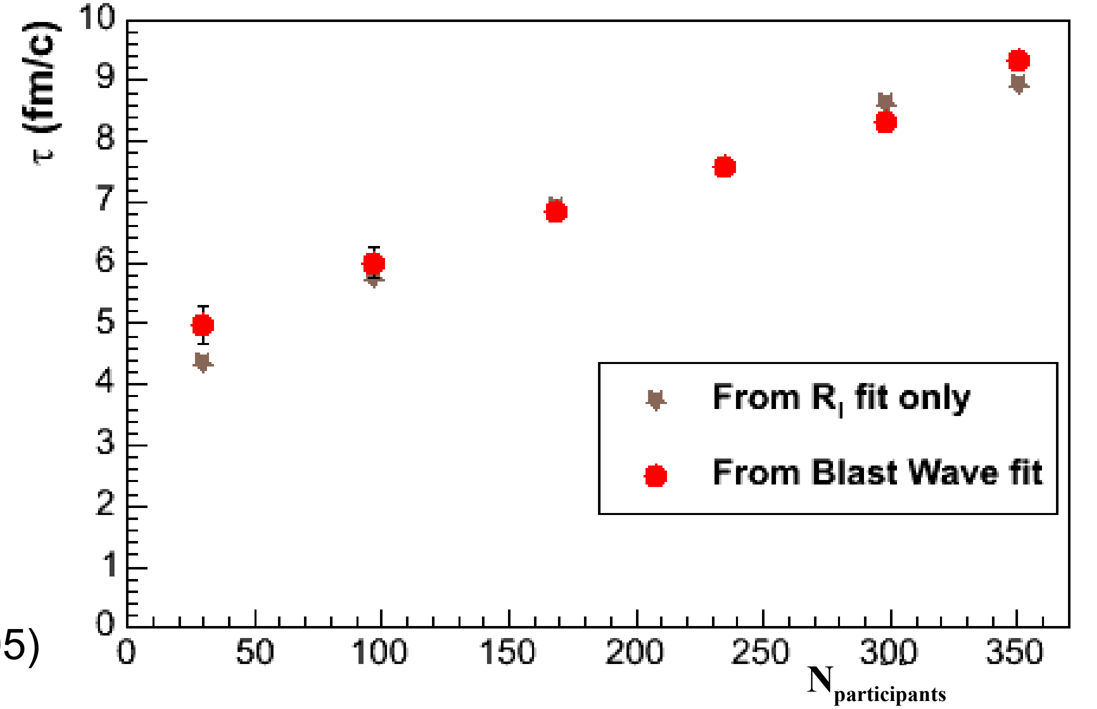
M. Herrmann and G.F. Bertsch, Phys. Rev. C51 (1995) 328



$\langle t_{fo} \rangle_{central} \approx 9$ fm/c
$\langle t_{fo} \rangle_{peripheral} \approx 5$ fm/c

Shorter than predictions by hydrodynamic models ~ 15 fm/c

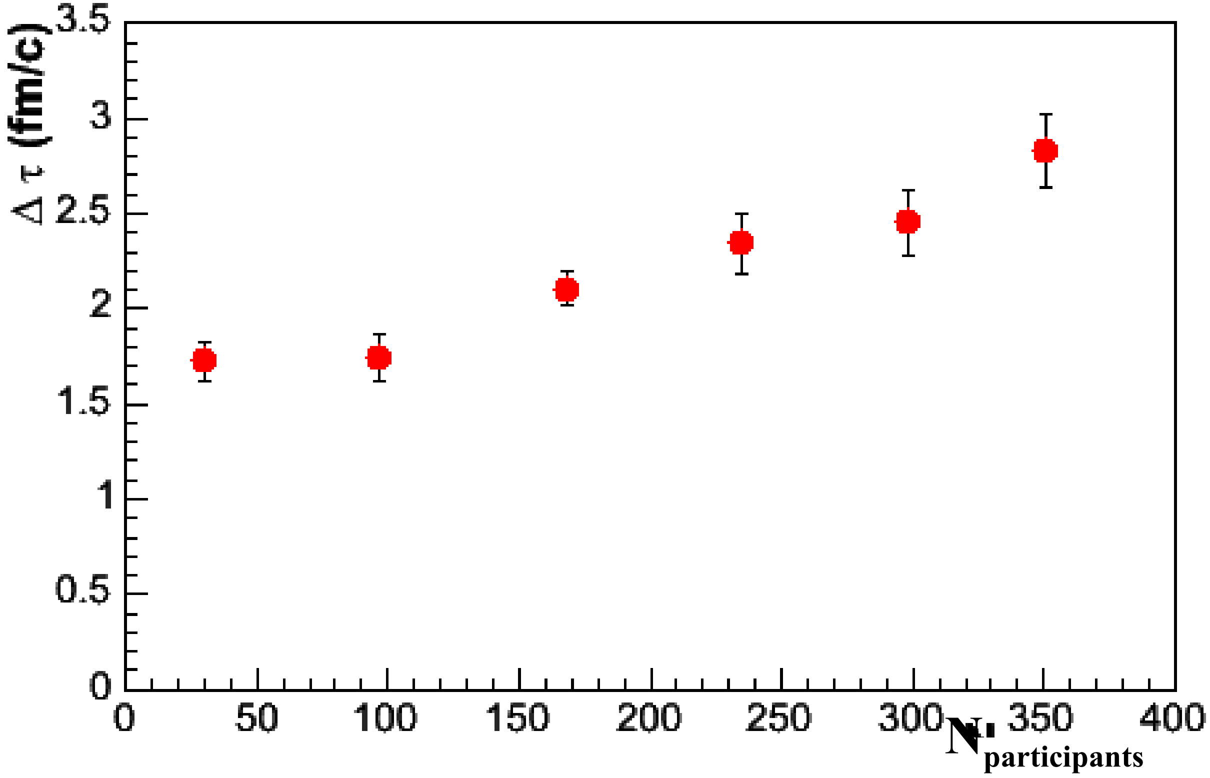
Heinz & Kolb, hep-ph/0204061



Phys. Rev. C71, 044906 (2005)

Emission duration

From BW fit to
spectra, v_2 and HBT



Very short emission time!

Conclusions – part IV

- Pressure and/or expansion time was not sufficient to quench initial shape
- Expansion is stronger for the most central collisions
- $R_o/R_s \sim 1$: short emission duration $\Delta\tau$
- $R_s(m_T)$/BW: Geometrical radius ~ 13 fm
- $R_L(m_T)$: Evolution time ~ 9 fm/c
- *A* model that describes all observables is needed to get the whole picture