The freeze-out state at RHIC

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Collective flow and QGP properties
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1 What kind of conclusions do we seek?

- heavy ion collisions: study collective behaviour of strongly interacting matter
- HBT interferometry: measure the final state (freeze-out) of the fireball

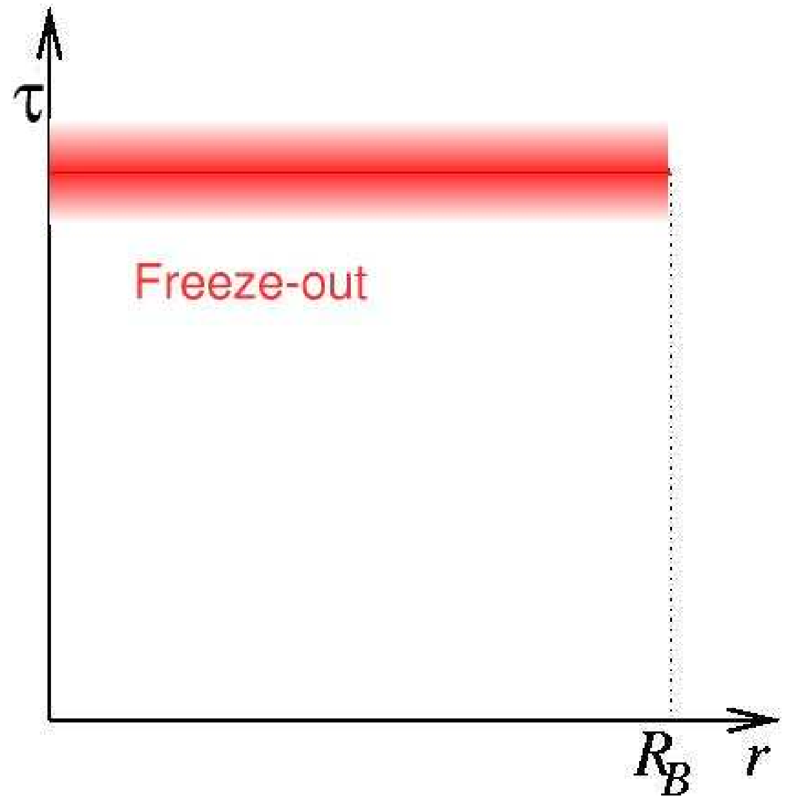
$\Rightarrow$ final state for hydro/transport/cascade ... simulation

- conclusions from HBT (& spectra):
  - large transverse size $\Rightarrow$ transverse expansion
  - limits on timing of the emission
  - freeze-out temperature and transverse flow
- temperature and transverse flow:
  - linked together in observation
    - $\rightarrow T$ and $\langle v_t \rangle$ correlated in determination of spectra and HBT
  - linked together in physics
    - $\rightarrow$ freeze-out is given by competition between scattering rate (temperature) and the expansion rate ($\langle v_t \rangle$)

2 The blast-wave model

The assumptions:

- π, N, K decouple all at the same time and very quickly in a given moment
- uniform radial distribution
- at freeze-out boost-invariant longitudinal expansion
- transverse expansion



The emission function

- probability to emit a particle with momentum p from space-time point x

(legend: parameters are red, space-time coordinates are blue, momentum coordinates are green)

$$
\begin{aligned}
S(x,p)d^4x \quad = \quad & \frac{1}{(2\pi)^3} m_\perp \cosh(y-\eta) \left[\exp\left(\frac{p_\mu u^\mu - \mu}{T} \right) - 1 \right]^{-1} \theta(R_B - r) \\
& \frac{d\tau}{\sqrt{2\pi\Delta\tau^2}} \exp\left(- \frac{(\tau-\tau_0)^2}{2\Delta\tau^2} \right) \tau \, d\eta \, r \, dr \, d\varphi
\end{aligned}
$$

$$
\begin{aligned}
u^\mu \quad &= \quad (\cosh\eta_t \, \cosh\eta, \, \sinh\eta_t \, \cos\varphi, \, \sinh\eta_t \, \sin\varphi, \, \cosh\eta_t \, \sinh\eta) \\
\eta_t \quad &= \quad \sqrt{2}\eta_f \frac{r^\alpha}{R_B}
\end{aligned}
$$

- T controls the coupling of the momentum to the flow

3 Fits to (low-momentum) p_t spectra

- fit π, K, p spectra from PHENIX

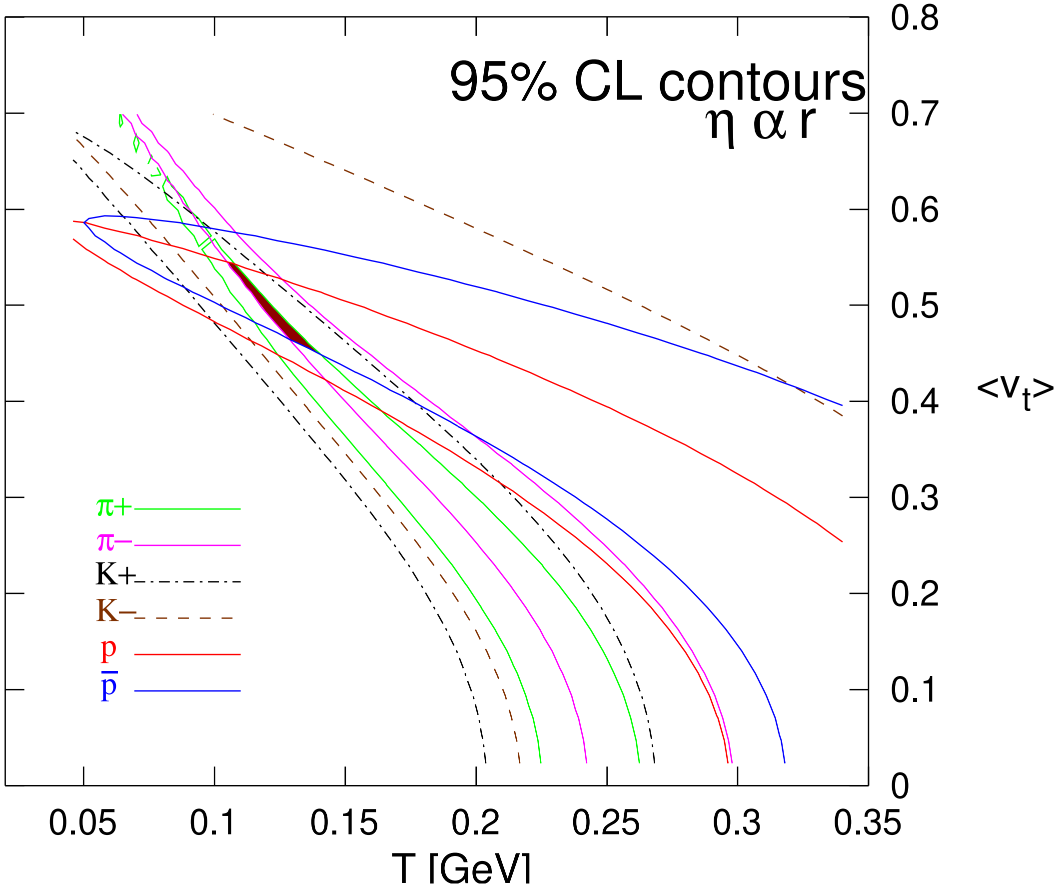
- fit each spectrum individually:
  - if the model is OK, results will agree
  - if results don't agree, the model is wrong

- then fit the model to HBT radii and see if the results are compatible

- fit only the shapes of the spectra (not the normalization): no sensitivity to R_B, $\Delta\tau$, and τ_0

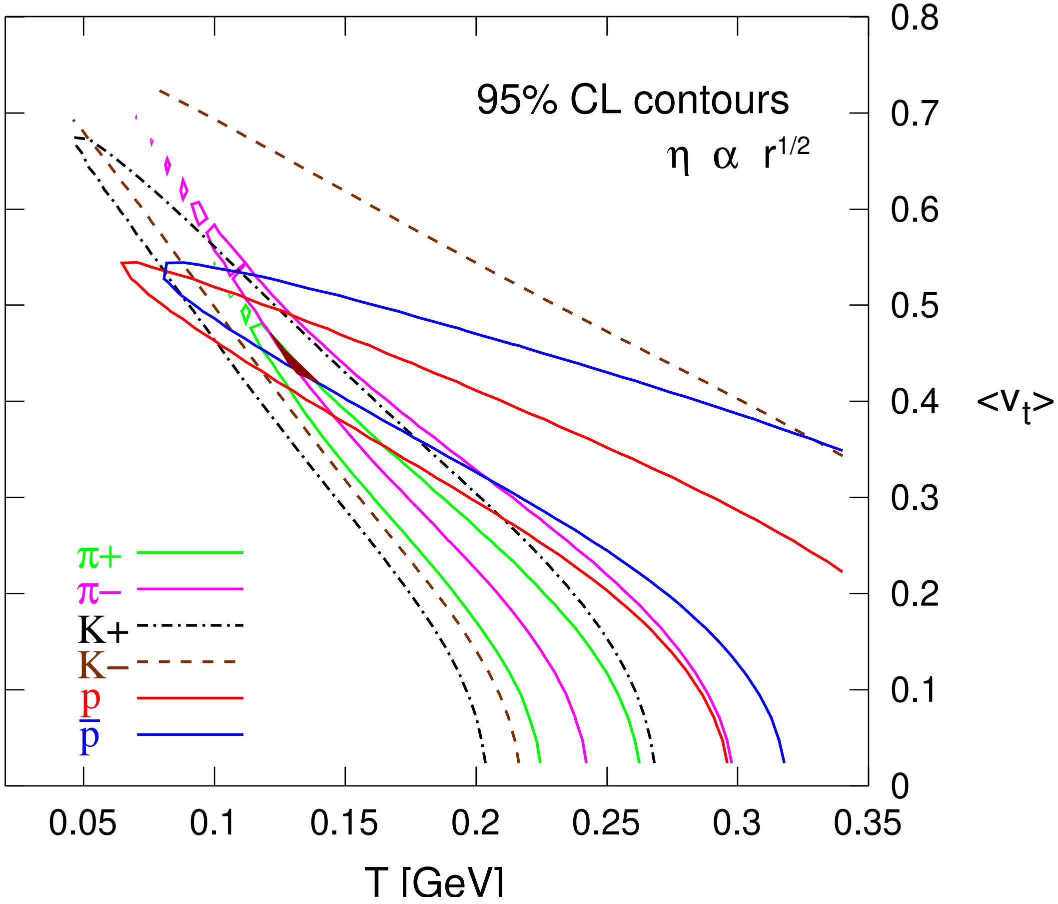
$\Rightarrow$ scan the $(T, \langle v_t \rangle)$ plane and fit the normalization
  - influence of flow profile: test three choices of α
  - influence of chemical potential: fit with and without μ

Fits to spectra with $\alpha = 1$ and $\mu = 0$



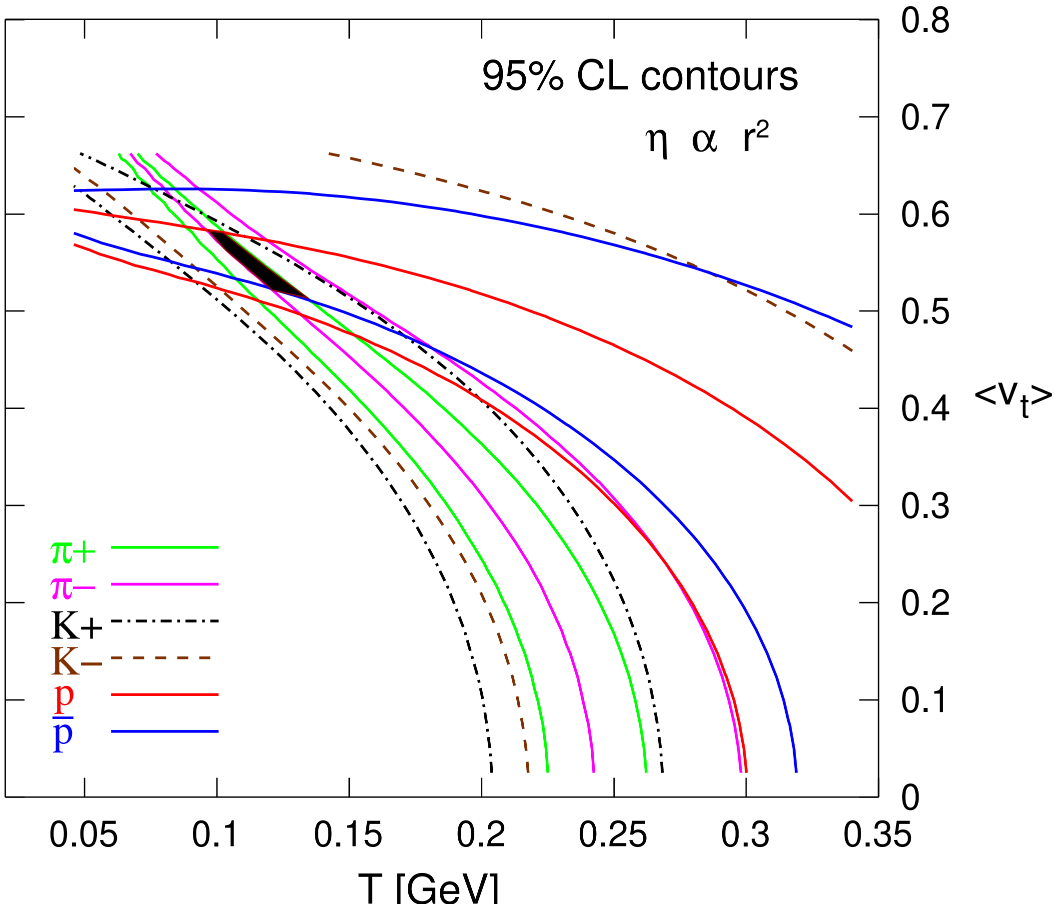
- resonances included according to temperature and $\mu = 0$
- no overlap at 1σ level!
- $T \approx 105 - 140\text{MeV}$ $\langle v_t \rangle \approx 0.45 - 0.54$

Fits to spectra with $\alpha = 1/2$ and $\mu = 0$



- resonances included according to temperature and $\mu = 0$
- no overlap at 1σ level!
- $T \approx 125 - 140$ MeV
  $\langle v_t \rangle \approx 0.42 - 0.47$

Fits to spectra with $\alpha = 2$ and $\mu = 0$

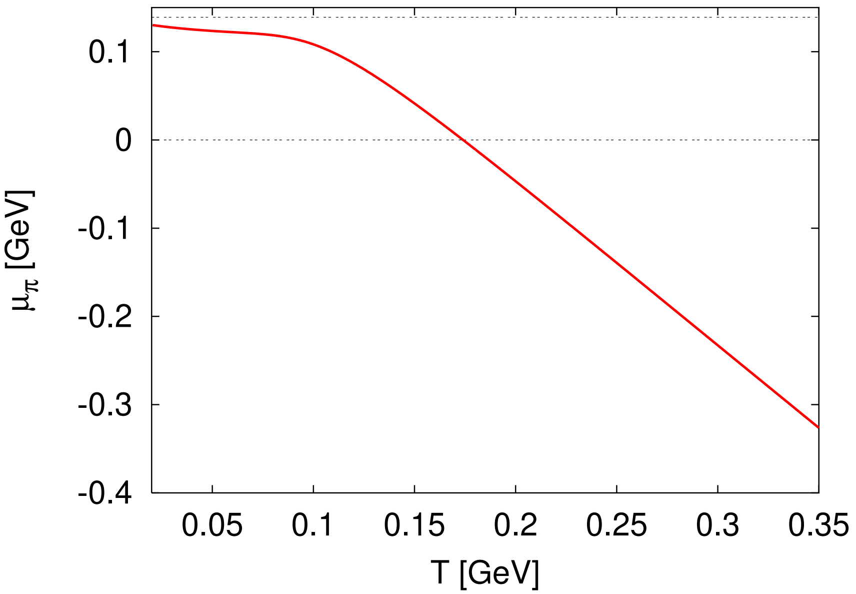


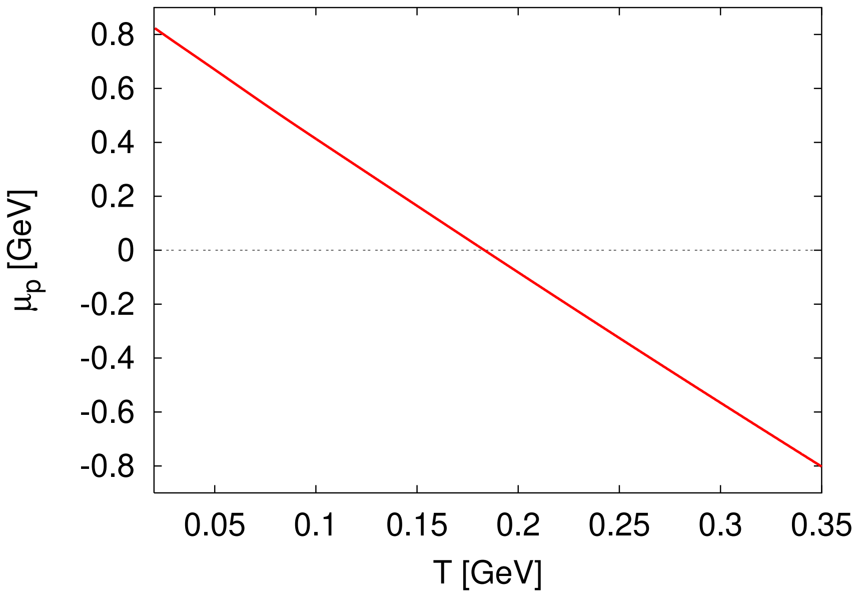
- resonances included according to temperature and $\mu = 0$
- no overlap at 1σ level!
- $T \approx 95 - 135$ MeV
  $\langle v_t \rangle \approx 0.51 - 0.58$

Chemical potential

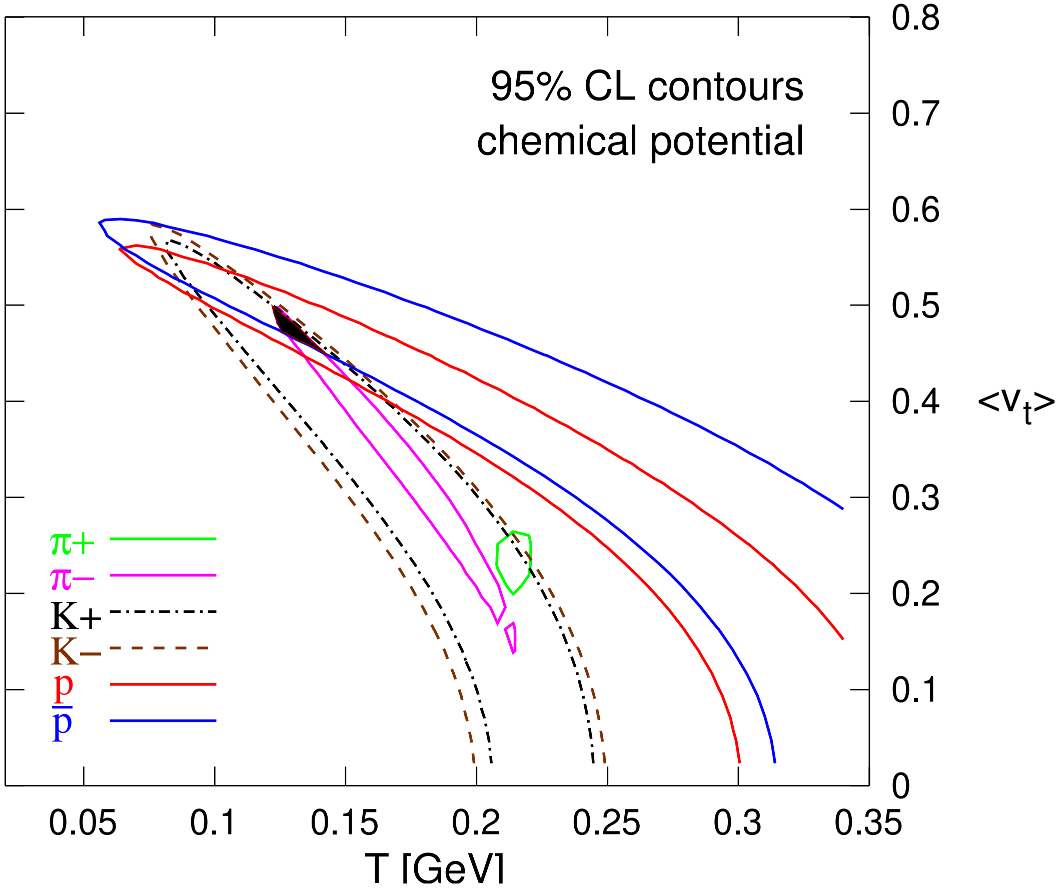
- system cools down: loss of chemical equilibrium
- assume:
  - conservation of entropy
  - conservation of effective particle numbers

  strong inelastic reactions fast enough to keep equillibrium, but weak interactions too slow



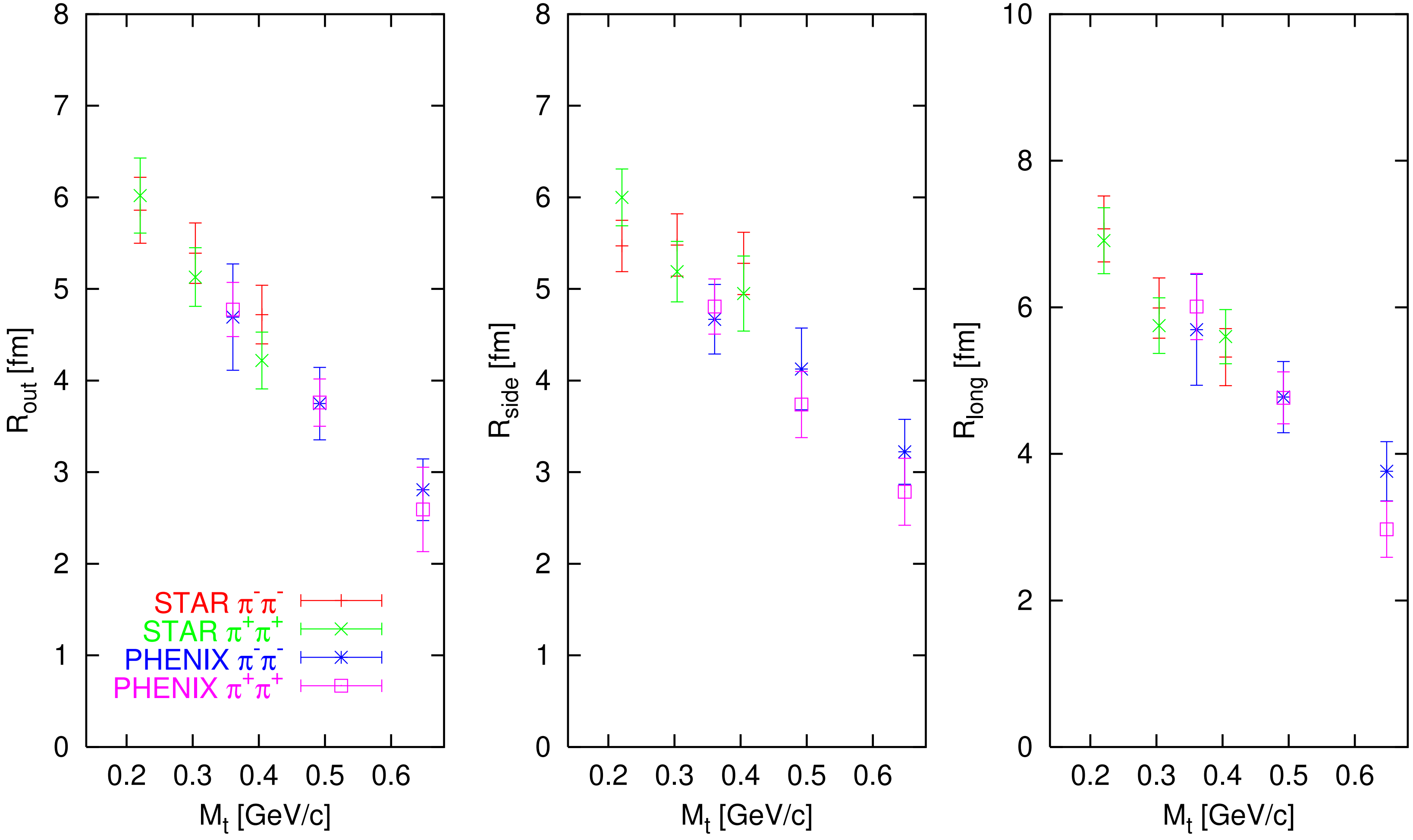


Fits to spectra with $\alpha = 1$ and chemical potential



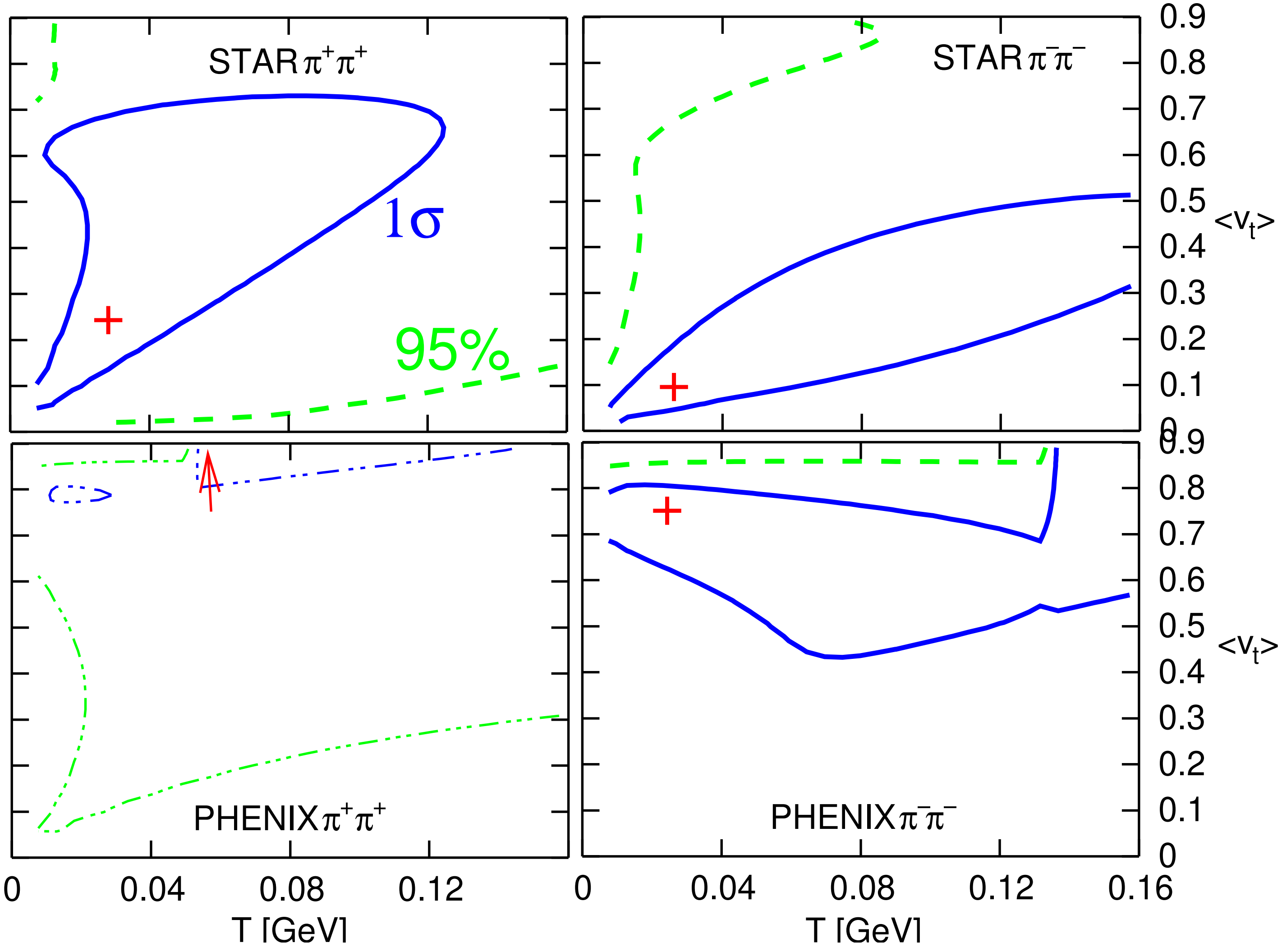
- resonances included according to temperature and the chemical potential
- no overlap at 1σ level!
- $T \approx 120 - 140$ MeV
  $\langle v_t \rangle \approx 0.45 - 0.5$

4 Fits to HBT radii



HBT radii from Au+Au at RHIC 130 at midrapidity

χ^2 contours from fitting the available sets of HBT radii individually



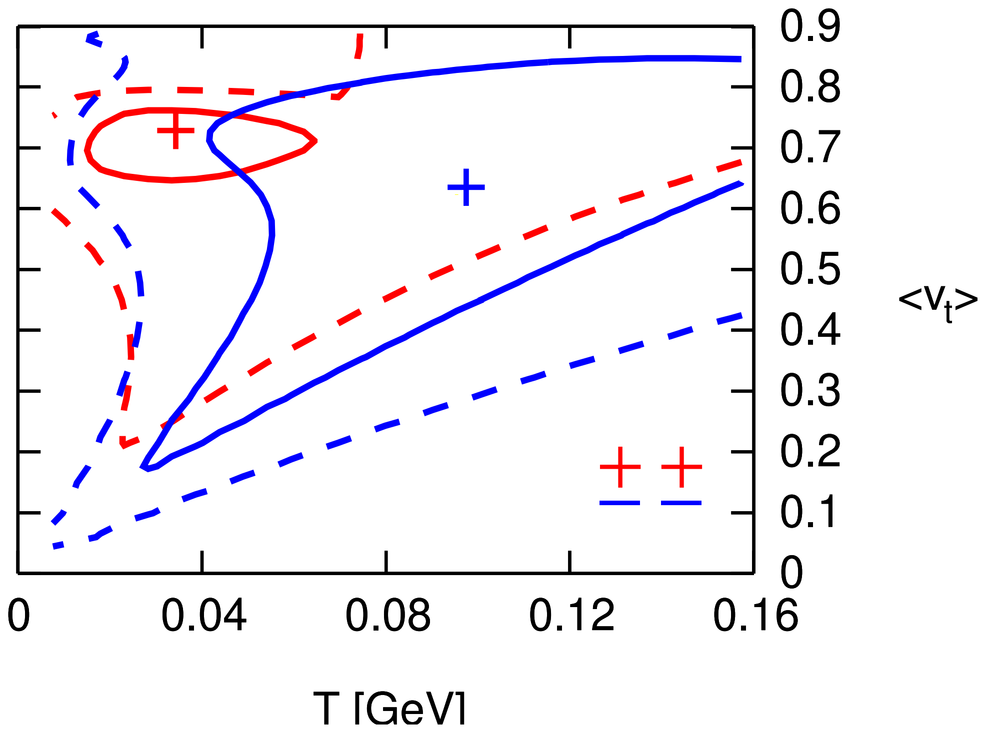
Conclusions from fits to HBT radii at RHIC 130

- PHENIX data push towards strong transverse flow

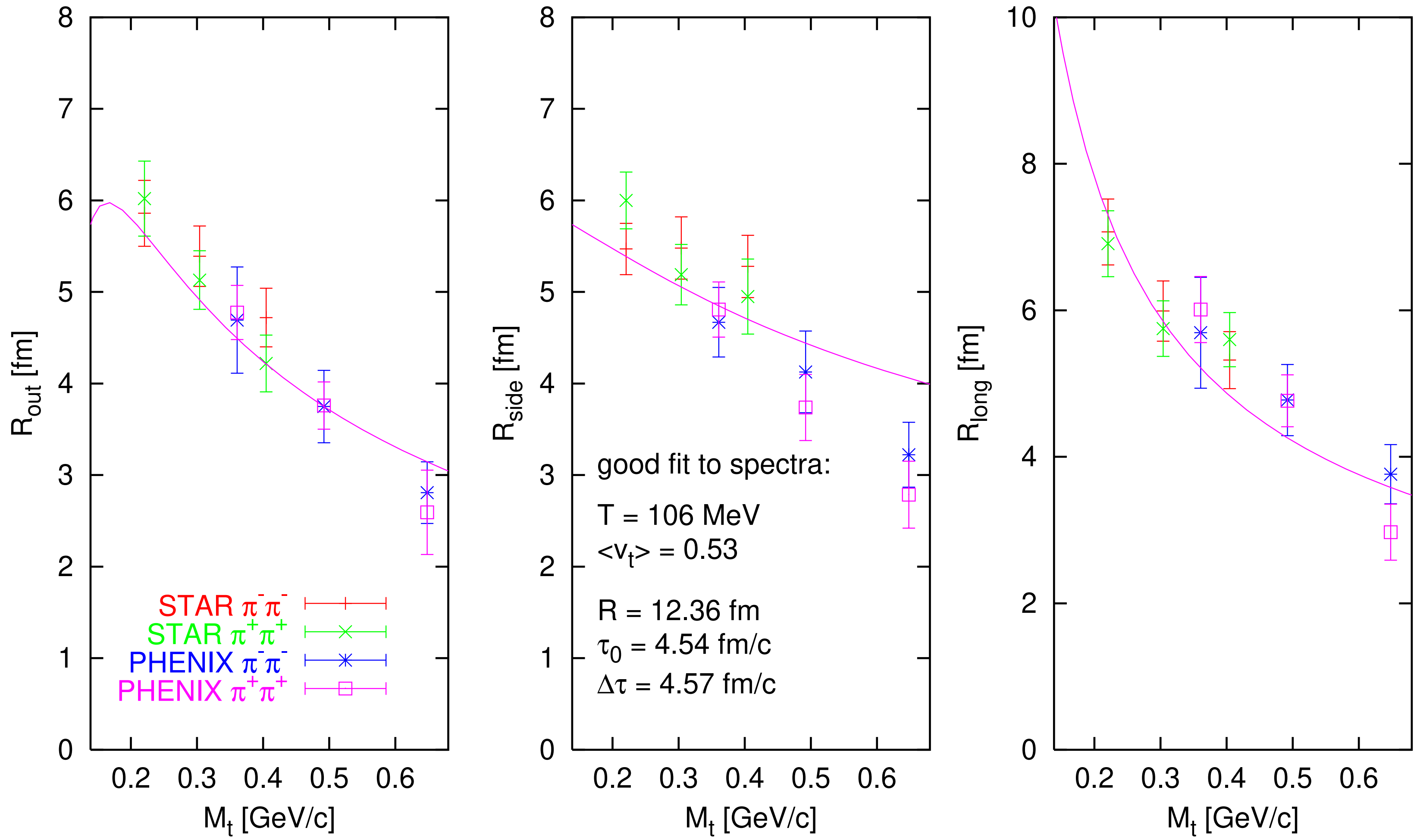
- weak-expansion-low-temperature region excluded: only tiny overlap with 95% CL from spectra!

- improvements with chemical potential, other flow profiles, etc to be checked

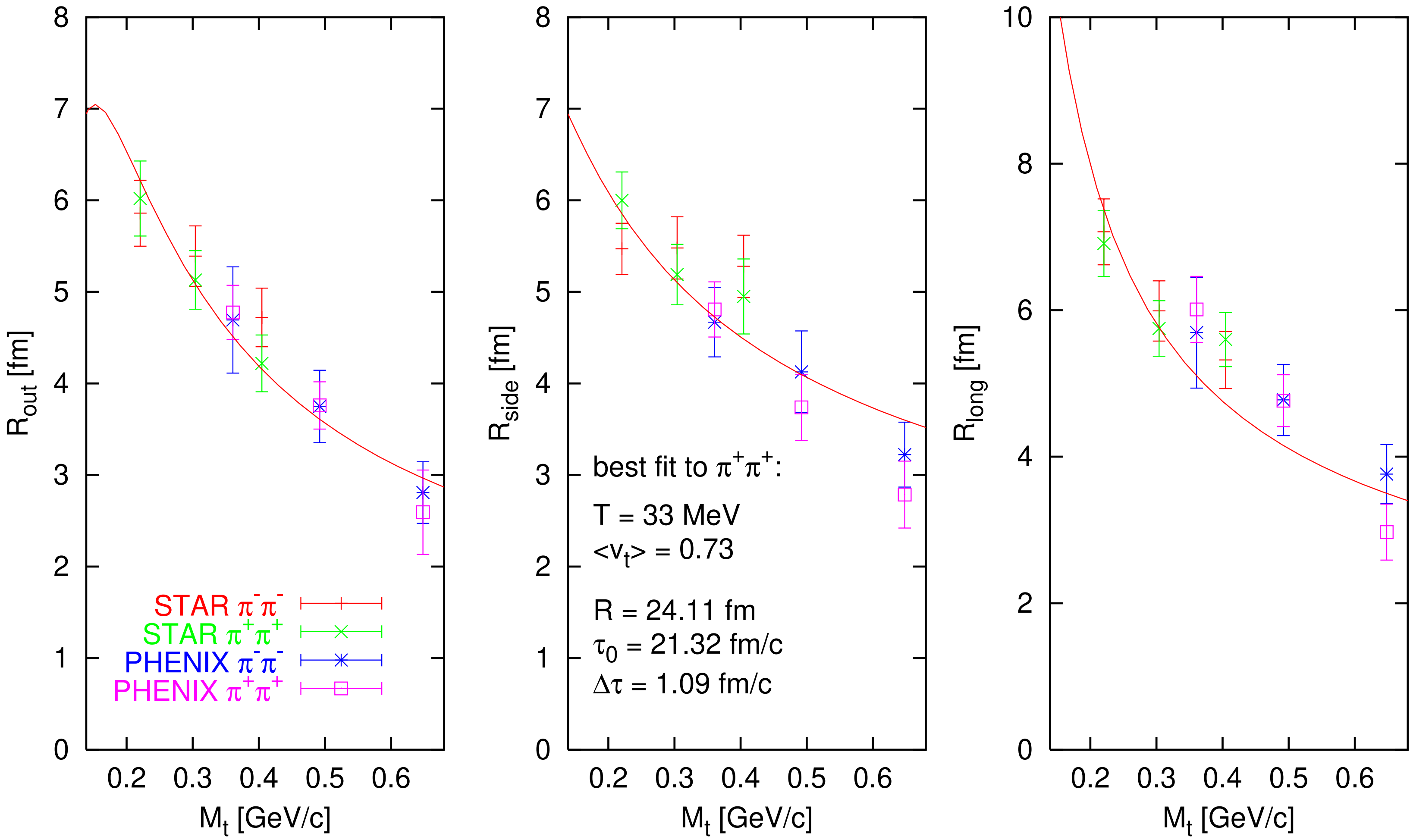
1σ and 95% CL contours from fits to $\pi^+\pi^+$ and $\pi^-\pi^-$ HBT radii from STAR and PHENIX



Model that fits HBT and spectra from RHIC 130



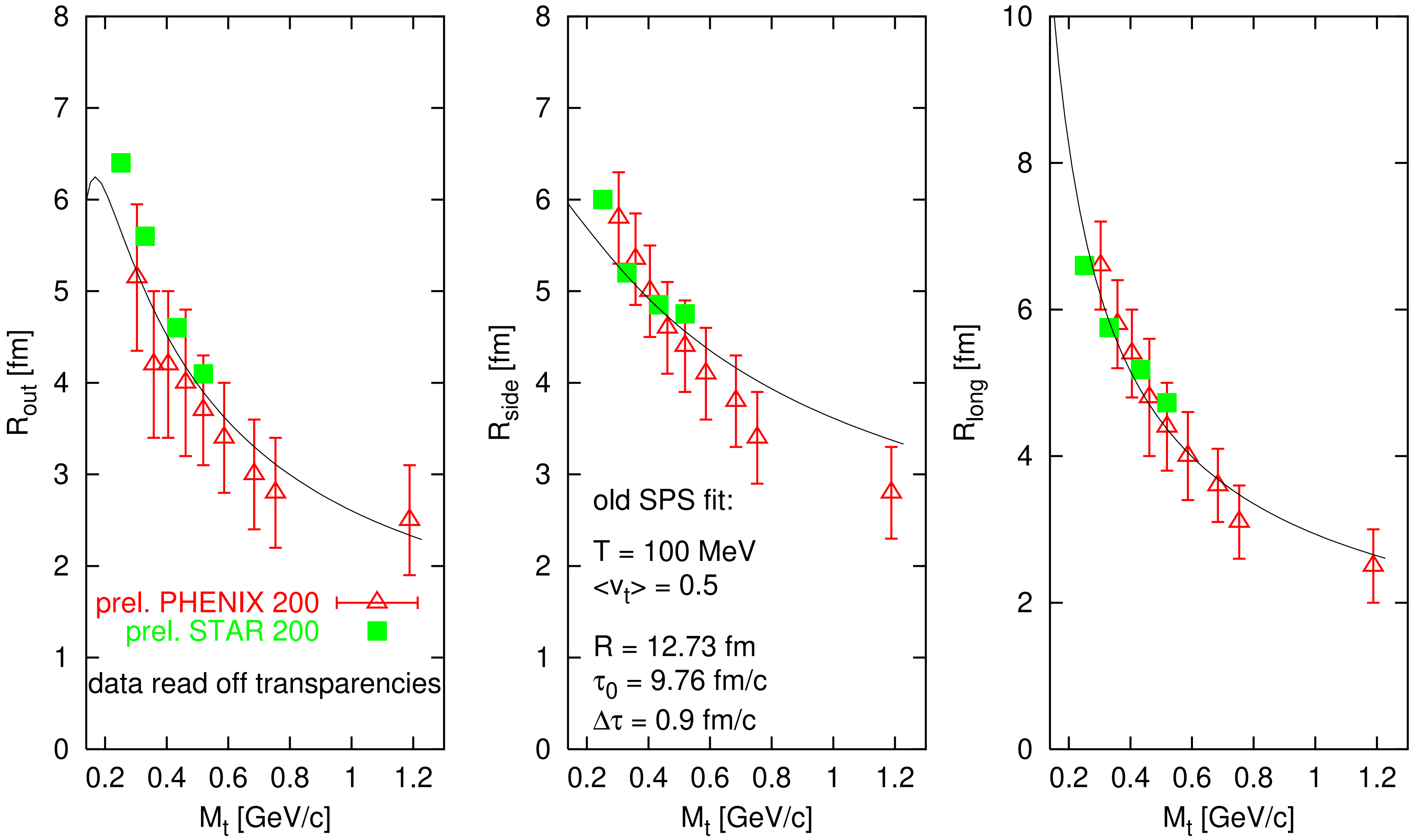
Best model to fit $\pi^+\pi^+$ HBT radii from RHIC 130



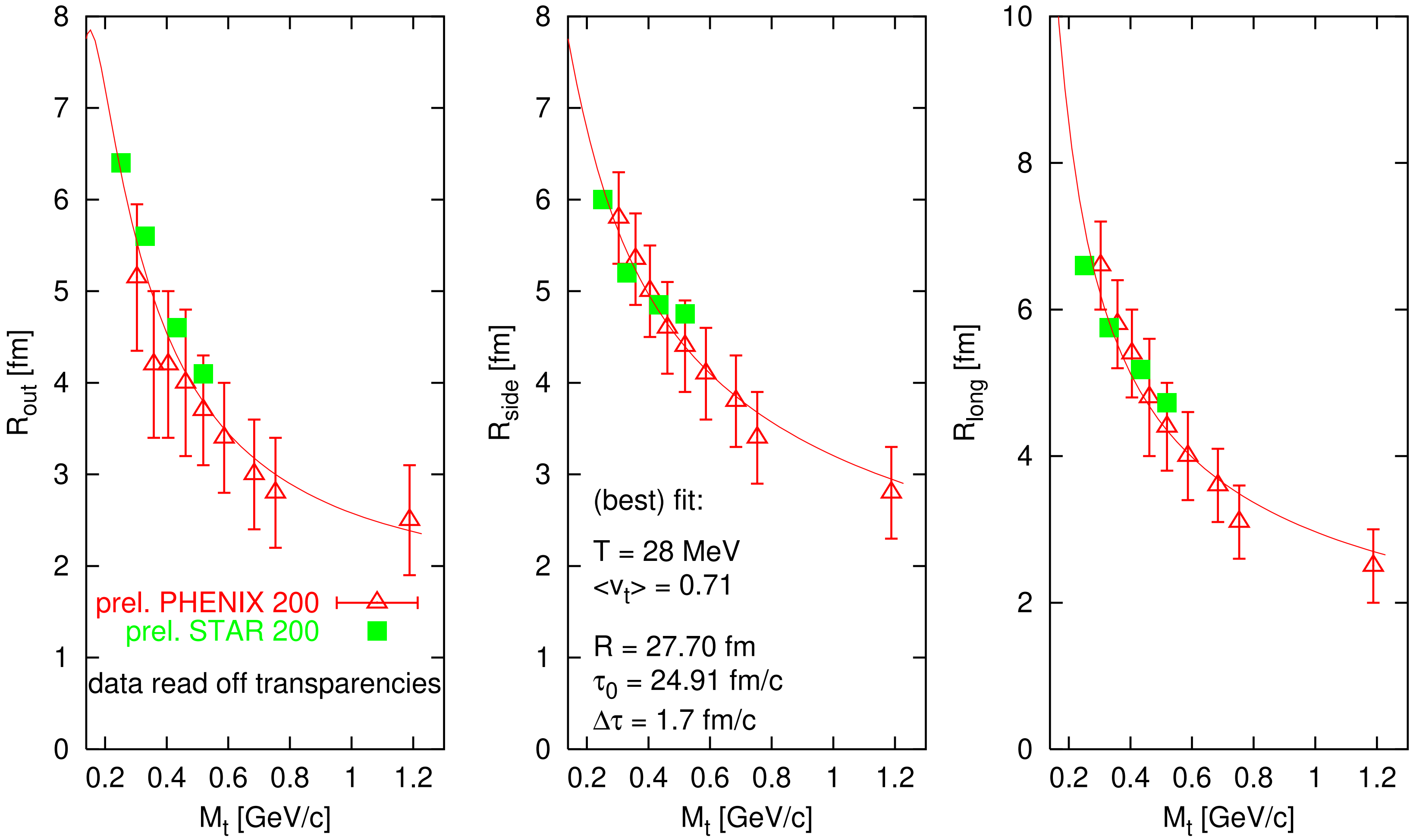
5 How about other collision systems?

- RHIC at CMS energy 200 AGeV: preliminary data (from transparencies)
- SPS at CMS energy 17 AGeV: published data from 5 collaborations
- problems with statistics $\rightarrow$ only informative

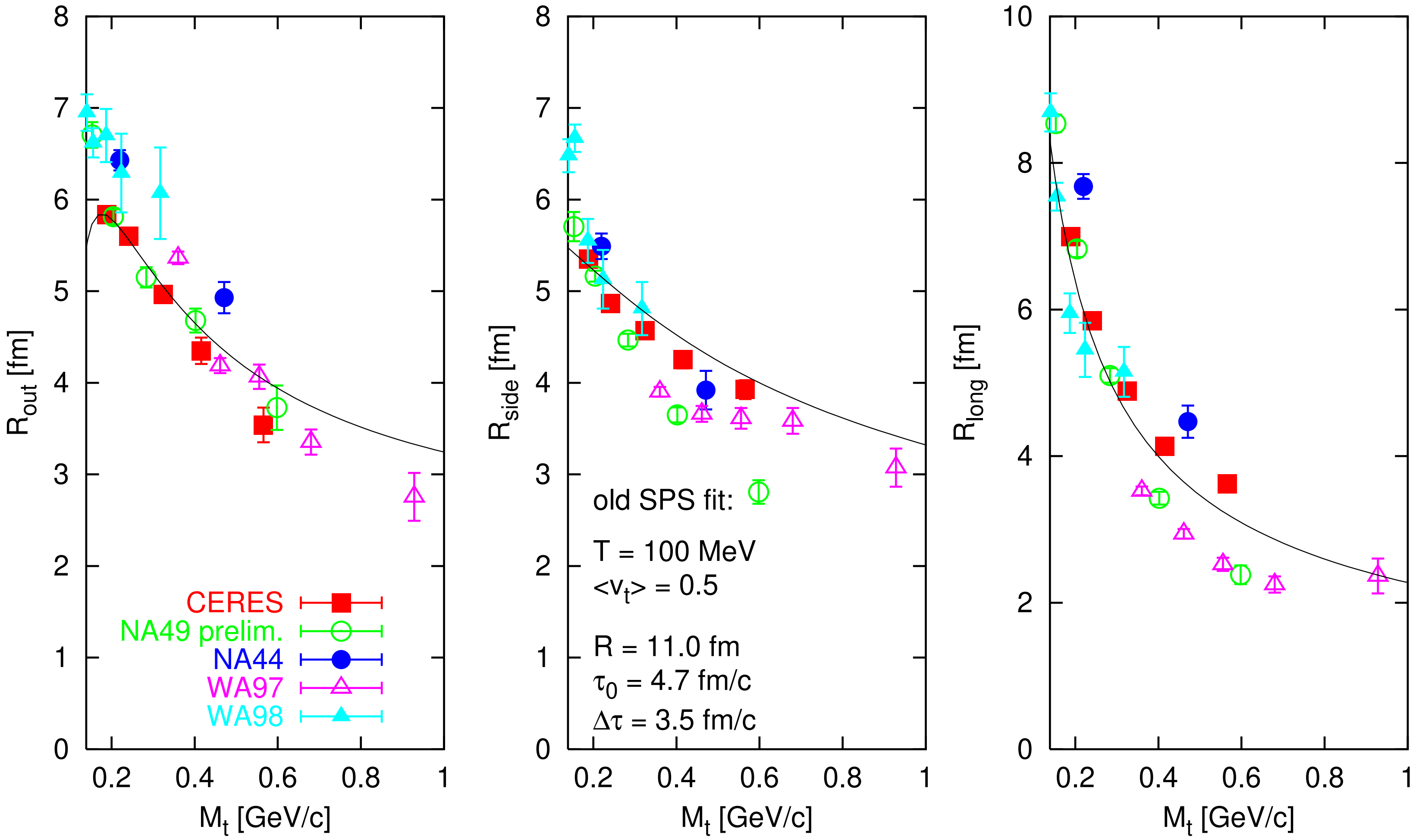
“Traditional” fit to HBT radii from RHIC 200



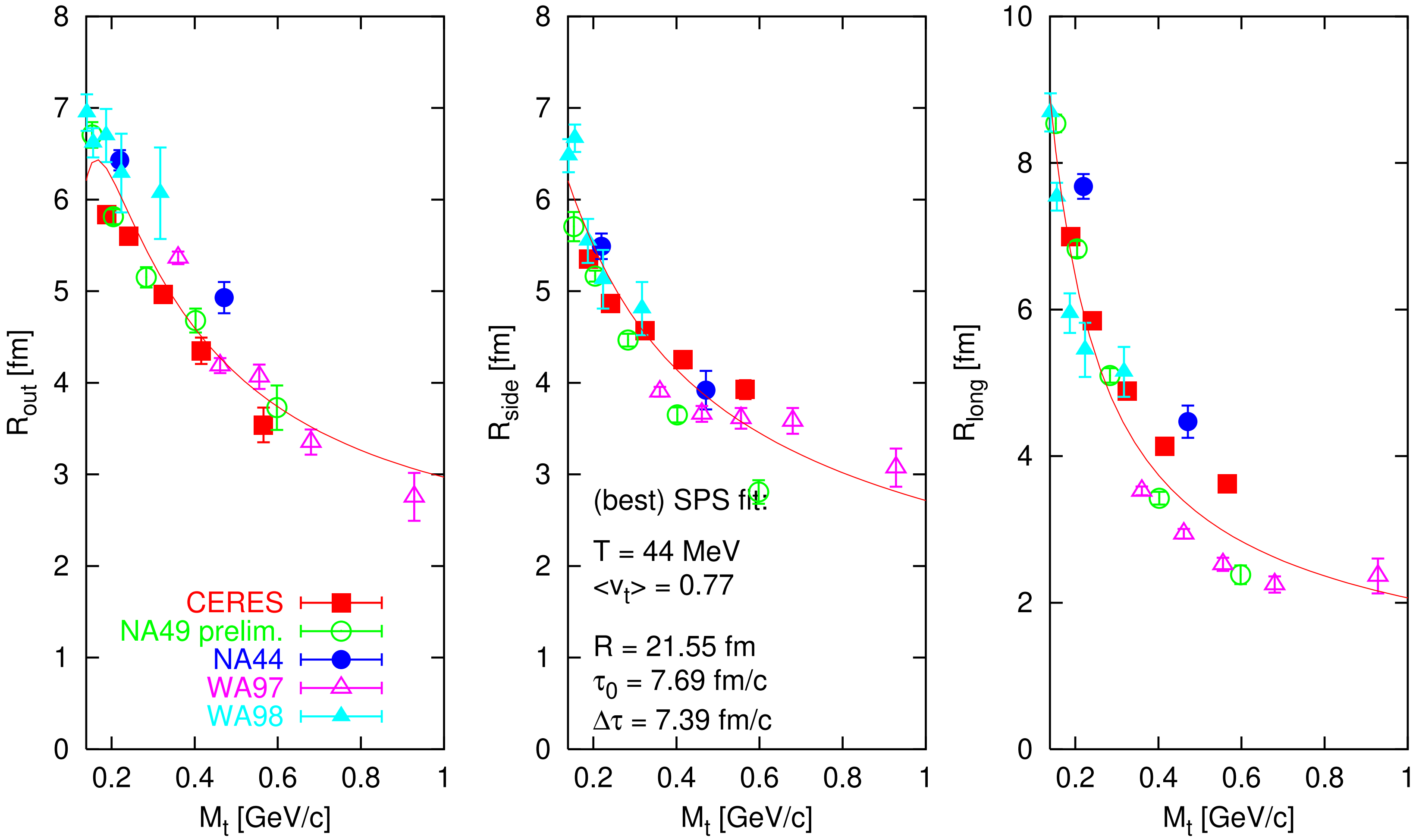
“Good” fit to HBT radii from RHIC 200



“Traditional” fit to HBT radii from SPS 160



"Good" fit to HBT radii from SPS 160



6 Conclusions from HBT

- T and $\langle v_\perp \rangle$ from fits with the blast-wave model to the spectra and HBT at RHIC agree only marginally
- best fits to HBT lead to T and $\langle v_\perp \rangle$ which are problematic to interpret

$\Rightarrow$ blast-wave model may not be a good description of the freeze-out

Continuous freeze-out

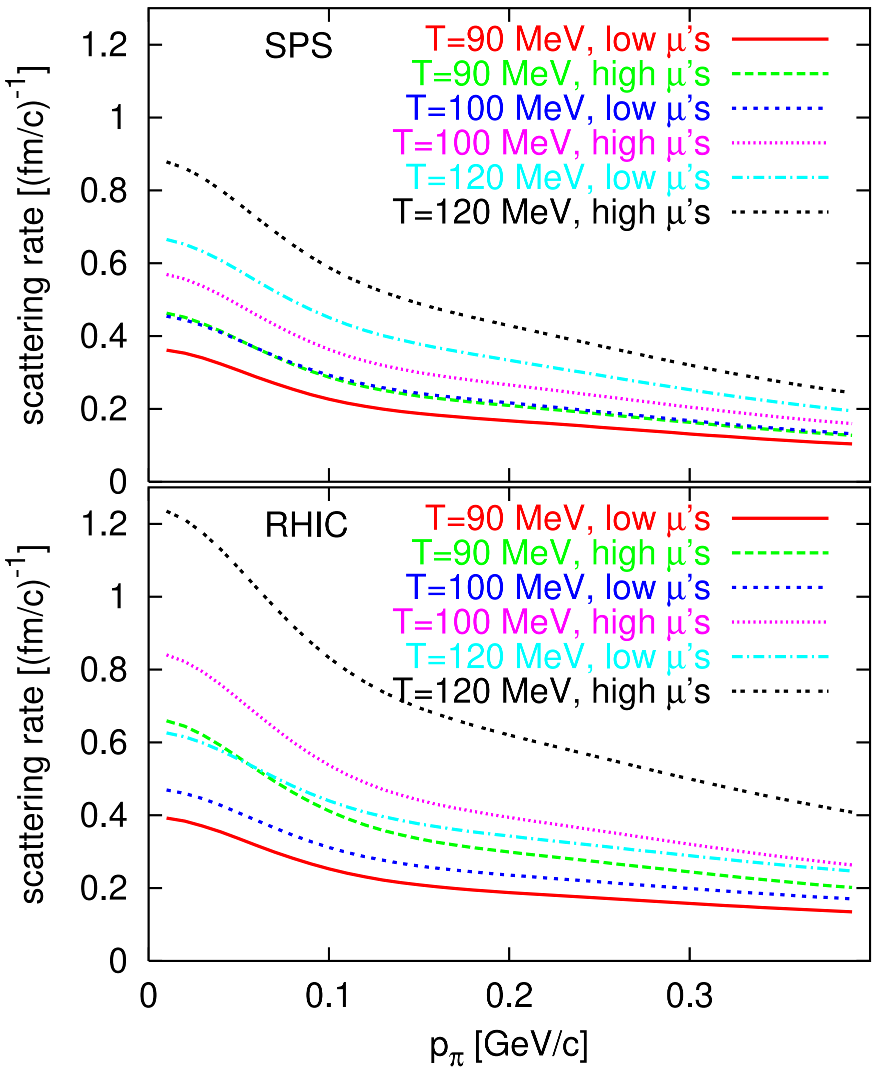
- momentum dependence of the scattering rate

$\Rightarrow$ easier decoupling for high momentum particles

$\Rightarrow$ sequential freeze-out of different momenta

- temperature dependence of the scattering rate

$\Rightarrow$ realistic escape probability at $T \approx 100\,\mathrm{MeV}$



7 Final remarks

⇒ blast-wave model may not be a good description of the freeze-out

- there are indications from cascade generators and studies of scattering rate in favour of a continuous freeze-out

- continuous emission may be another mechanism contributing to the strong $M_\perp$ dependence of HBT radii