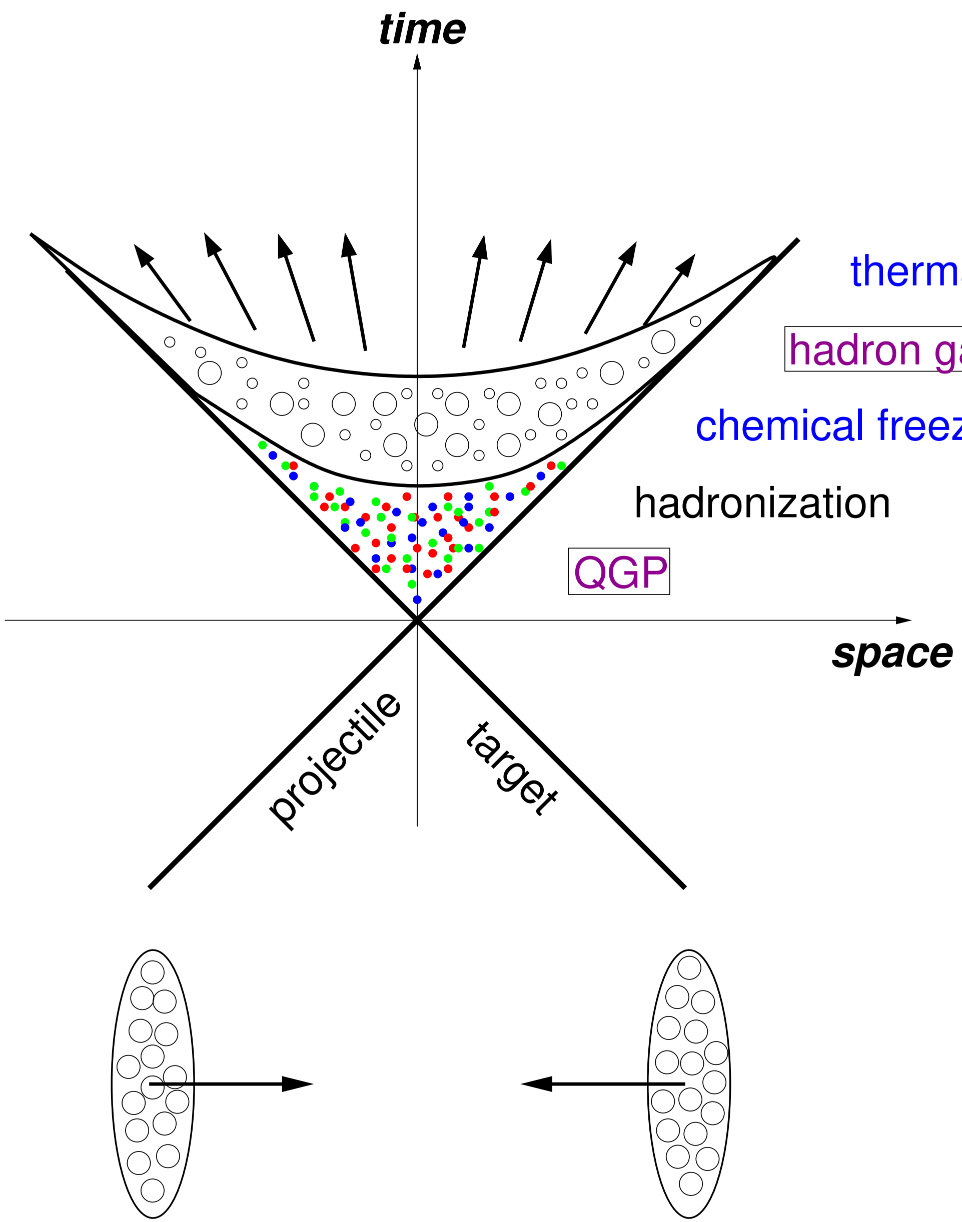
HBT at SPS
and universal pion freeze-out

Harald Appelshäuser
GSI Darmstadt
for the CERES collaboration

- **Introduction**
- **Results from pion-HBT interferometry at SPS**
- **Universal pion freeze-out**

CERES, Nucl. Phys. A714 (2003) 124
CERES, Phys. Rev. Lett. 90 (2003) 022301

Space-time evolution of A+A collisions

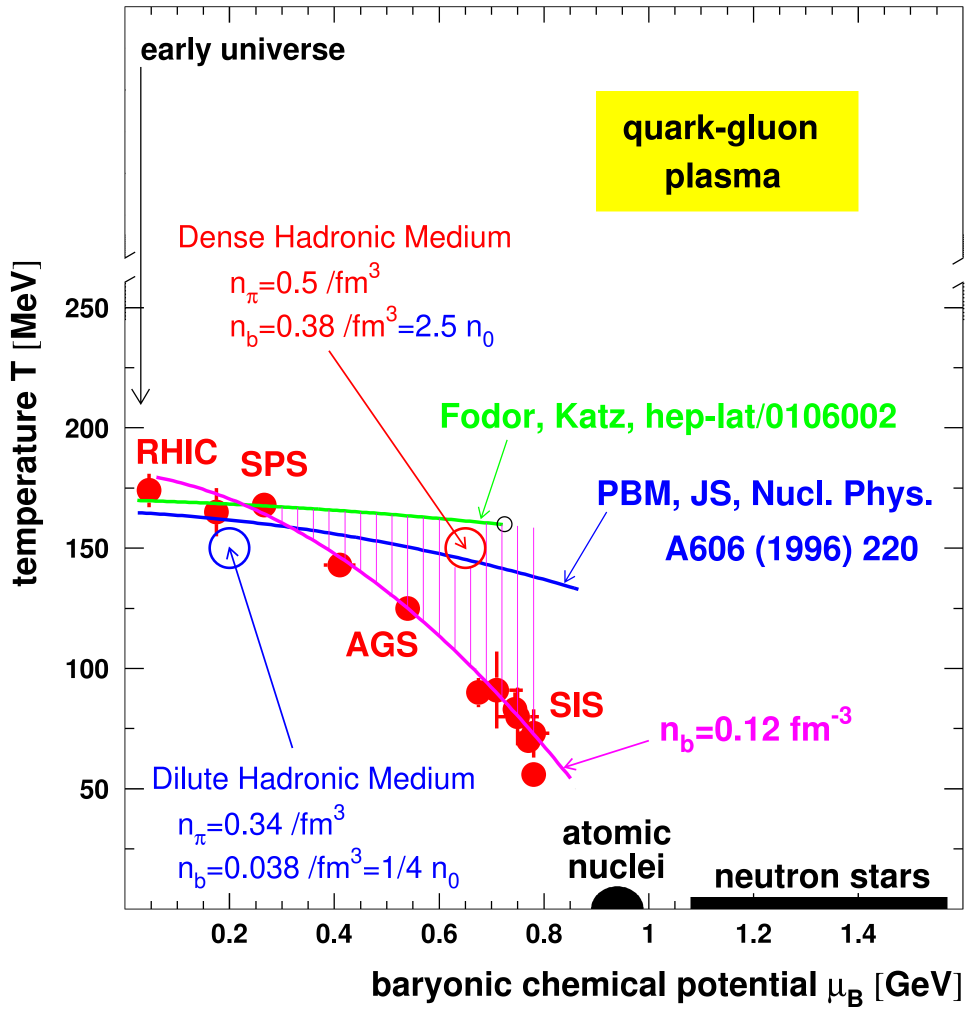


- chemical freeze-out:
  end of all inelastic processes
  hadron yields are frozen

- thermal freeze-out:
  end of all elastic processes
  momenta of hadrons are frozen

- size, lifetime, velocity fields etc.?

Phase diagram of nuclear matter and chemical freeze-out



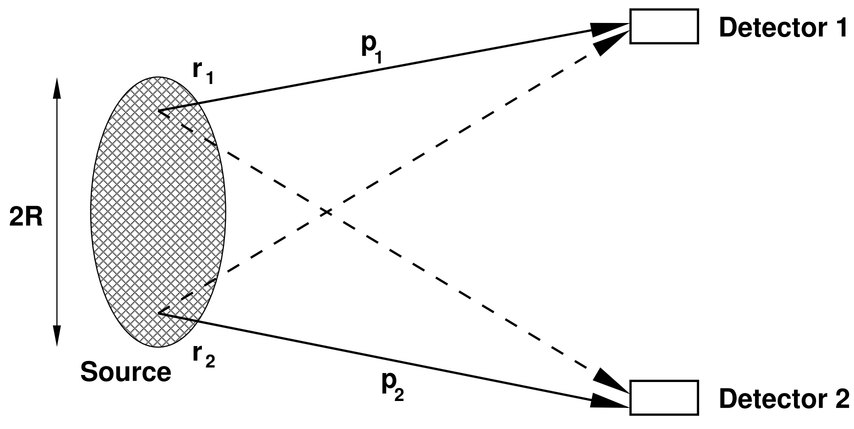
P. Braun-Munzinger, J. Stachel, J.Phys.G28 (2002) 1971

- Measured particle yields are compatible with a statistical population
  $\rightarrow$ Equilibrium, T, μ_B

- At SPS and RHIC freeze-out points coincide with QCD phase boundary
  $\rightarrow$ Statistical hadronization at
  $T = 160 - 170$ MeV

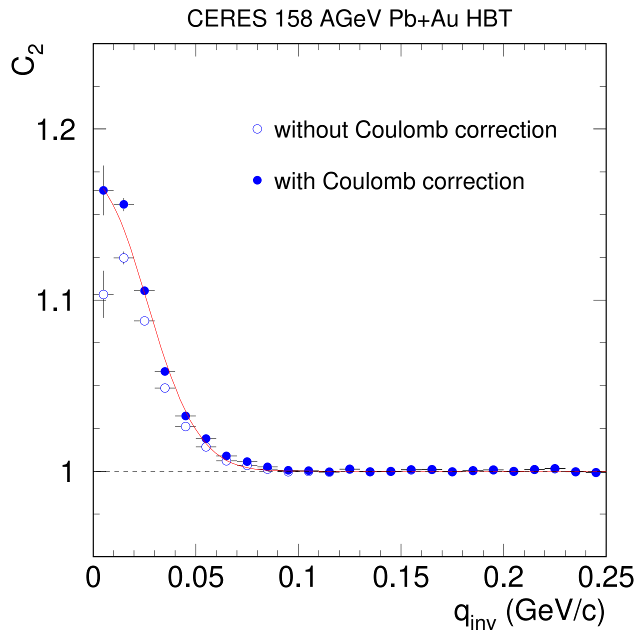
HBT-Interferometry

Bose-Einstein statistics of identical bosons leads to short range correlations in momentum space



$$C_2(\vec{p}_1, \vec{p}_2) = \frac{P_2(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1) \cdot P_1(\vec{p}_2)}$$

$$= 1 + \chi(\vec{p}_1 - \vec{p}_2)$$

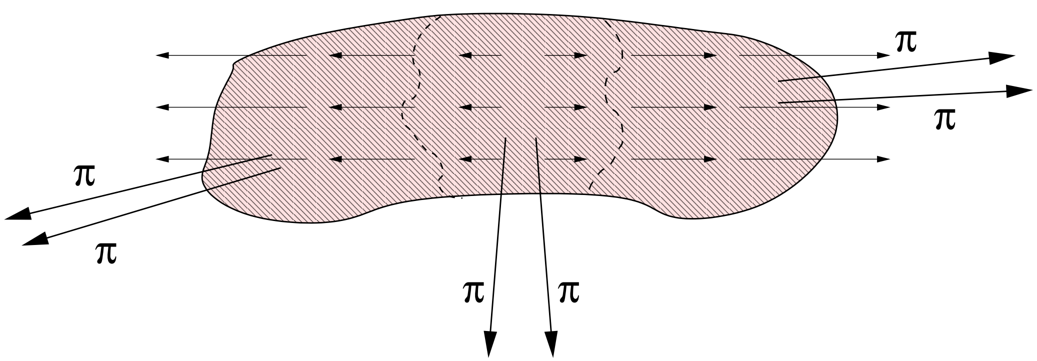


First application with photons: size of stars
(R. Hanbury-Brown, R.Q. Twiss, 1956)

In heavy ion reactions: pions, kaons, . . .

$$\Delta r = \frac{\hbar c}{\Delta p} = \frac{197\ \mathrm{MeV}/c}{\Delta p}\ \mathrm{fm}$$

HBT in expanding systems



Space-momentum correlations:

Pions with similar momenta (small q) are preferentially emitted from close-by regions

$\longrightarrow$ length of homogeneity:

$$\Delta v_{\mathrm{coll}} \approx \sqrt{\frac{T_f}{m_t}}, \quad m_t = \sqrt{m_\pi^2 + k_t^2}$$

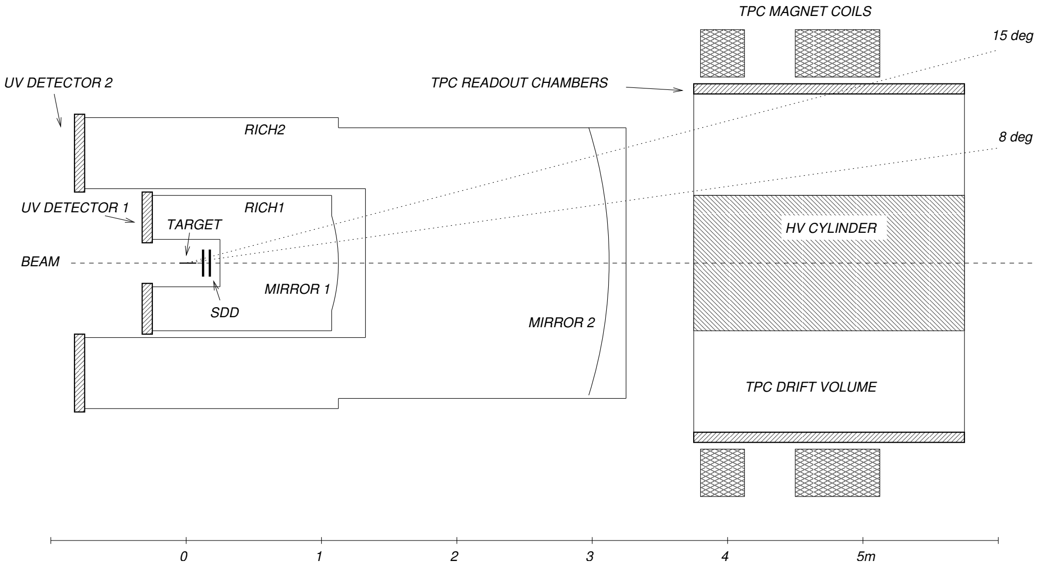
$\longrightarrow$ thermal vs. geometrical length scale,

$$R_{\mathrm{HBT}} = min(R_{\mathrm{geo}}, R_{\mathrm{therm}})$$

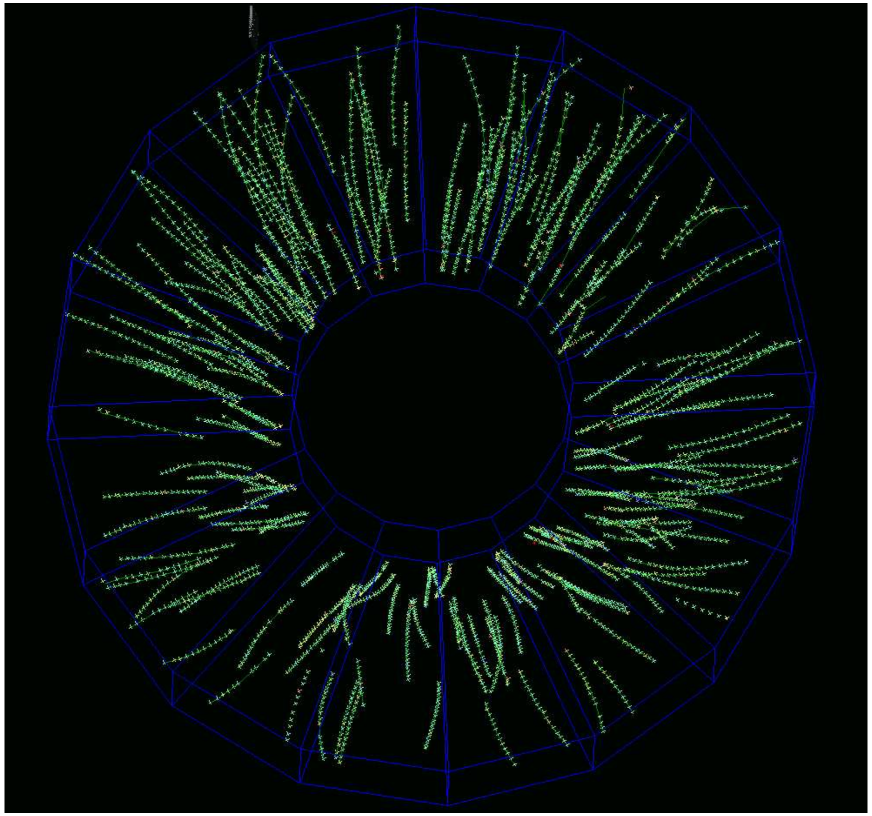
$\longrightarrow$ HBT radii depend on m_t

$\Longrightarrow$ Differential HBT-analysis as function of m_t contains information about the expansion behaviour of the source

CERES at CERN-SPS - TPC-event display



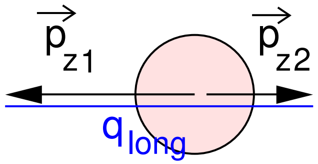
Pb+Au 158 AGeV



Bertsch-Pratt parametrization

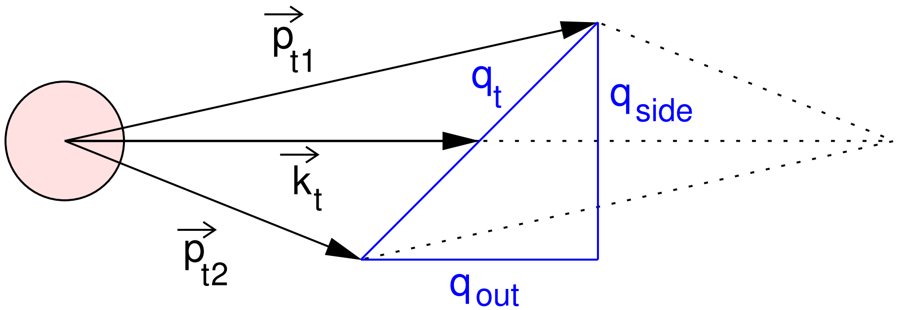
$$\vec{p}_{\pi 1} - \vec{p}_{\pi 2} = \vec{q} = (q_{\rm long}, q_{\rm side}, q_{\rm out}) \rightarrow R_{\rm long}, R_{\rm side}, R_{\rm out}$$

longitudinal:



$$q_{\rm long} = \vec{p}_{z1} - \vec{p}_{z2}$$

transverse:



$$\vec{k}_t = \frac{1}{2}(\vec{p}_{t1} + \vec{p}_{t2})$$

$$q_t = \vec{p}_{t1} - \vec{p}_{t2}$$

$$q_{\rm side} \perp \vec{k}_t \,, \quad q_{\rm out} \parallel \vec{k}_t$$

$\rightarrow$ $R_{\rm long}$: longitudinal expansion und lifetime τ_f

$\rightarrow$ $R_{\rm side}$: transverse size, radial expansion

$\rightarrow$ $R_{\rm out}$: as $R_{\rm side}$, but also duration of emission $\Delta\tau$ from $R_{\rm out}/R_{\rm side}$

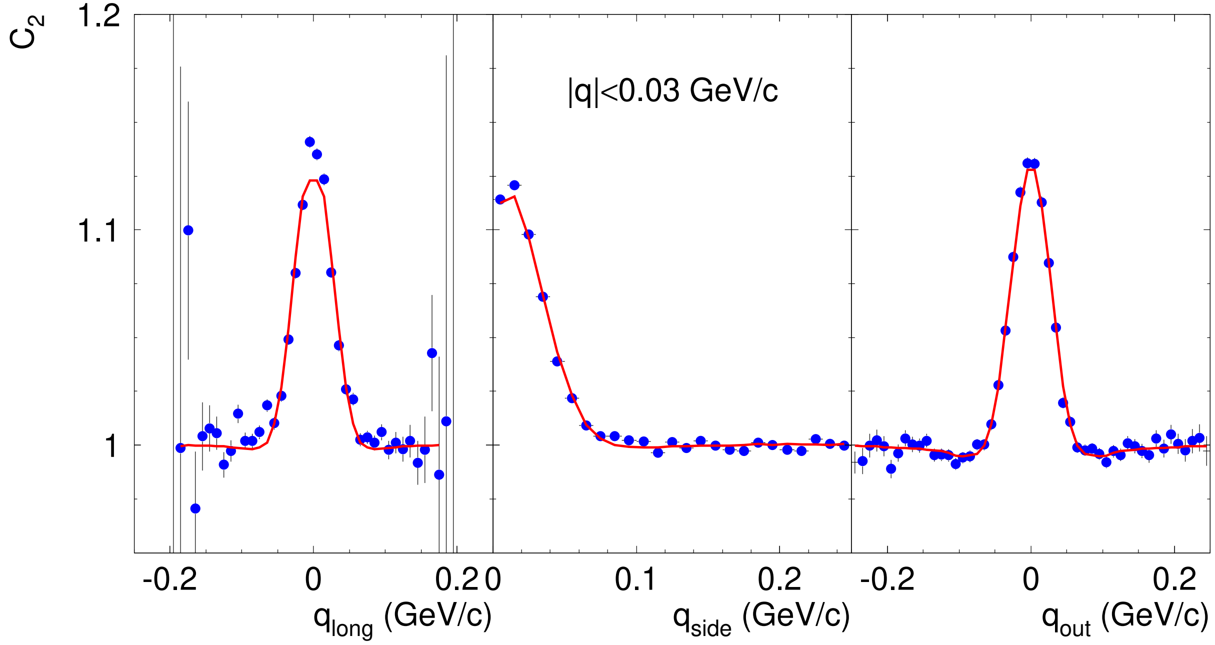
Analysis of correlation function

$$C_2(\vec{q}) = A_2(\vec{q})/B_2(\vec{q}) = 1 + \lambda^{'} \left((1+G) \cdot F^{\star} - 1\right)$$

$$G = \exp(-R_{\mathrm{long}}^2 q_{\mathrm{long}}^2 - R_{\mathrm{side}}^2 q_{\mathrm{side}}^2 - R_{\mathrm{out}}^2 q_{\mathrm{out}}^2 - 2R_{\mathrm{out,long}}^2 q_{\mathrm{out}} q_{\mathrm{long}})$$

$$F^{\star} = w(k_t) \cdot (F_{\mathrm{coul}}(q_{\mathrm{inv}}) - 1) + 1$$ Coulomb repulsion

CERES 158A GeV Pb+Au, *Nucl. Phys. A714 (2003) 124*



$\Rightarrow R_{\mathrm{long}}, R_{\mathrm{side}}, R_{\mathrm{out}}$

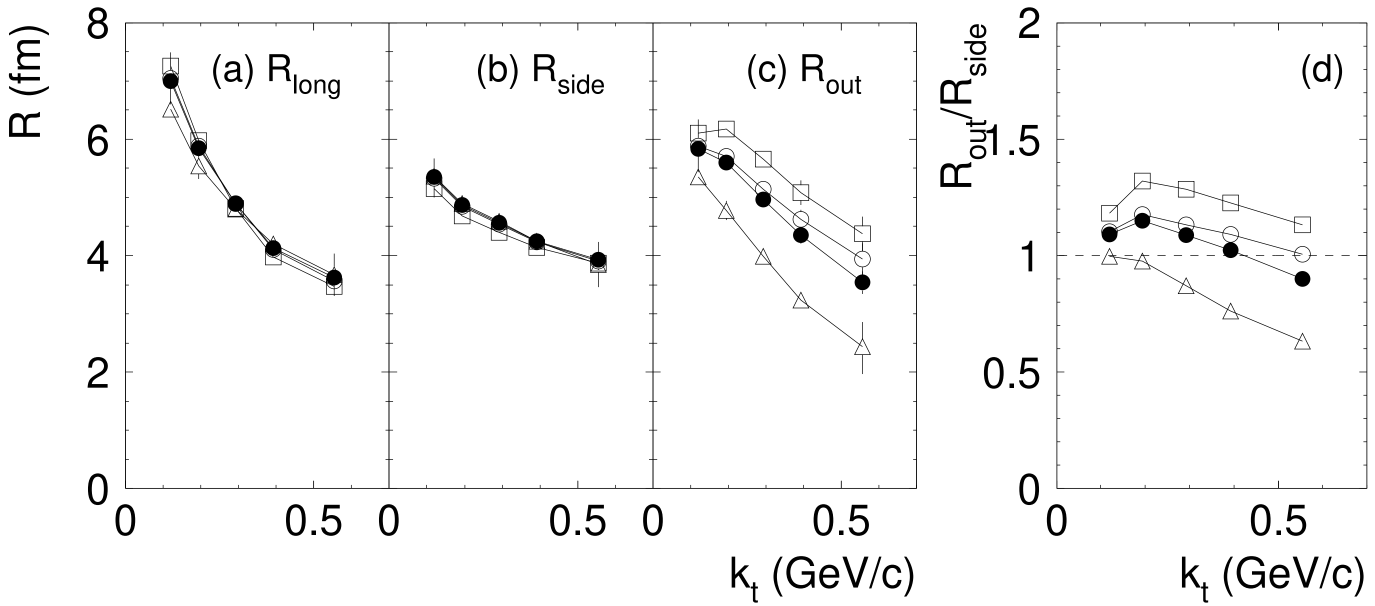
Sensitivity to Coulomb correction

$$C_2(\vec{q}) = A_2(\vec{q})/B_2(\vec{q}) = 1 + \lambda' \left((1+G)\cdot F^{\star} - 1\right)$$

$$G = \exp(-R^2_{\rm long}q^2_{\rm long} - R^2_{\rm side}q^2_{\rm side} - R^2_{\rm out}q^2_{\rm out} - 2R^2_{\rm out,long}q_{\rm out}q_{\rm long})$$

$$F^{\star} = w(k_t)\cdot(F_{\rm coul}(q_{\rm inv}) - 1) + 1$$ Coulomb repulsion

CERES 158A GeV Pb+Au, *Nucl. Phys. A714 (2003) 124*



Boxes: no Coulomb

Triangles: full Coulomb

Open circles: $w(k_t) = 1$

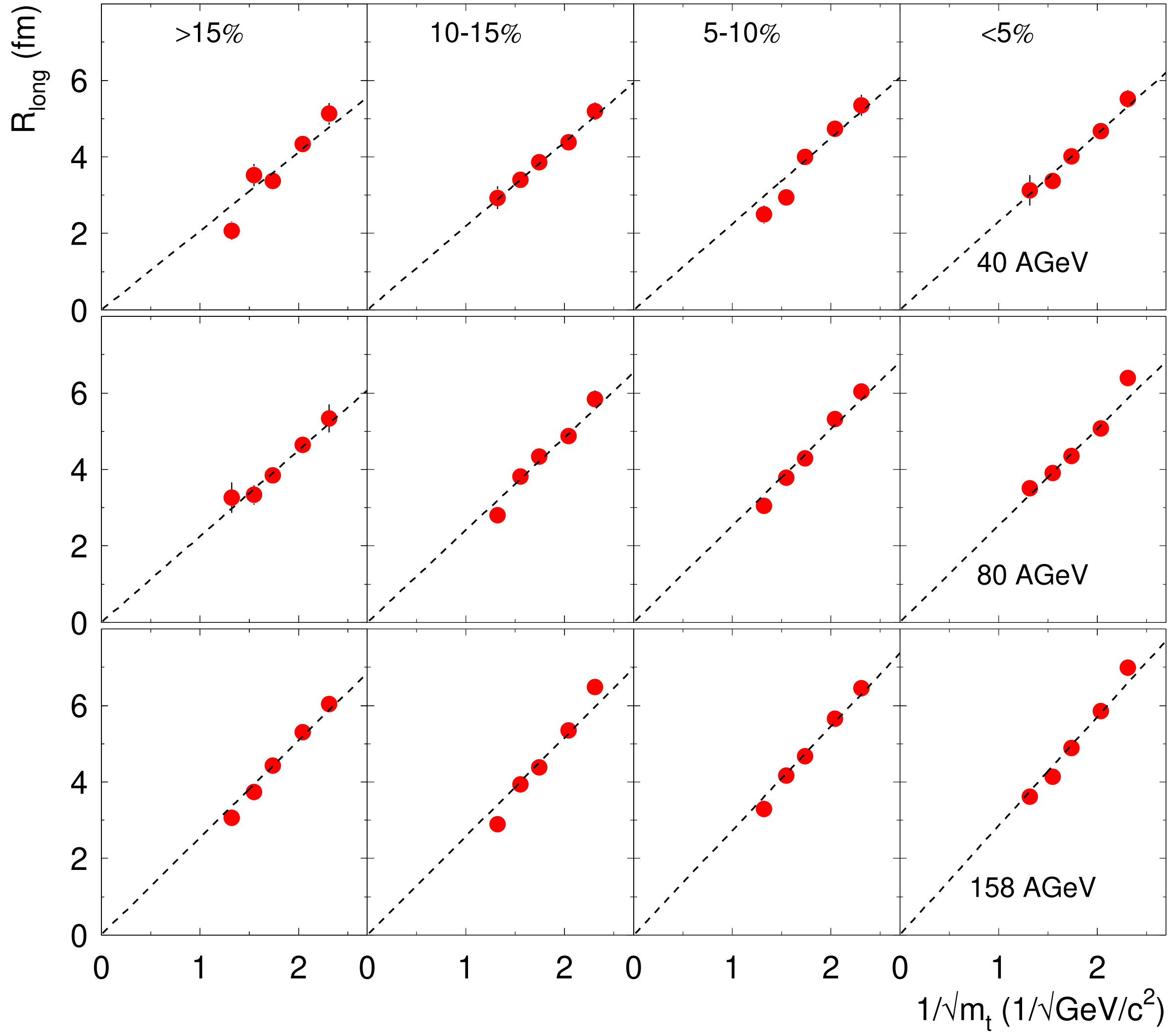
Full circles: final result

$\Rightarrow$

Strong sensitivity of $R_{\rm out}/R_{\rm side}$ to the treatment of Coulomb repulsion!

$R_{\rm long}$ - longitudinal expansion and lifetime

CERES Pb+Au, *Nucl. Phys. A714 (2003) 124*



Hubble-Expansion:

$$R_{\rm long} = \tau_f \cdot \sqrt{\frac{T_f}{m_t}}$$ (Y. Sinyukov)

lifetime

$\approx$ thermal velocity

$$m_t = (m_\pi^2 + k_t^2)^{\frac{1}{2}}$$

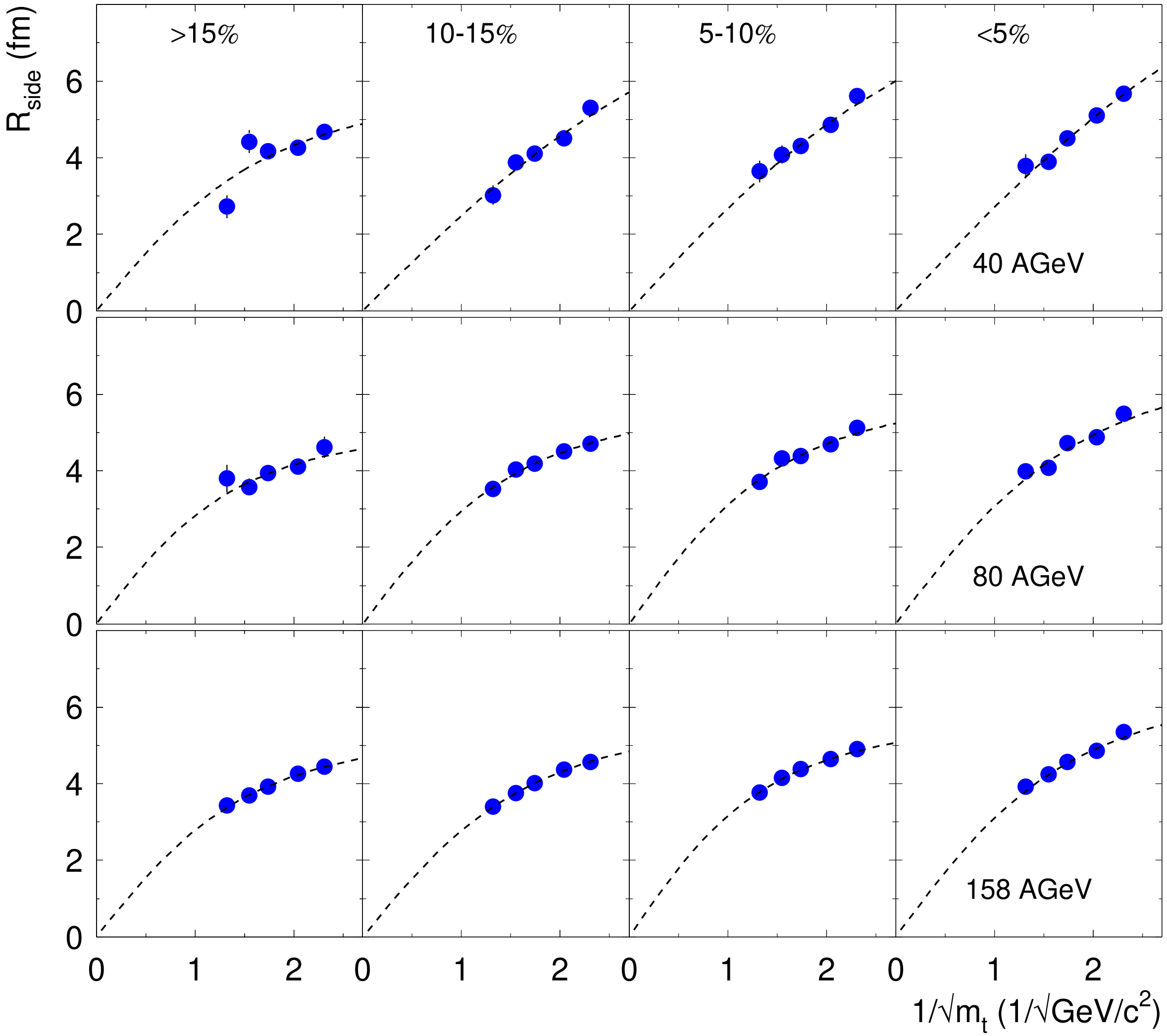
At 158 AGeV:

$$\boxed{\tau_f \approx 7 - 8 \text{ fm/c}}$$

for $T_f = 160 - 120$ MeV

$R_{\rm side}$ - transverse expansion and geometry

CERES Pb+Au, *Nucl. Phys. A714 (2003) 124*



U. Heinz, B. Tomasik, U. Wiedemann:

$$R_{\rm side} = \frac{R_{\rm geo}}{(1+\eta_f^2 \frac{m_t}{T_f})^{\frac{1}{2}}}$$

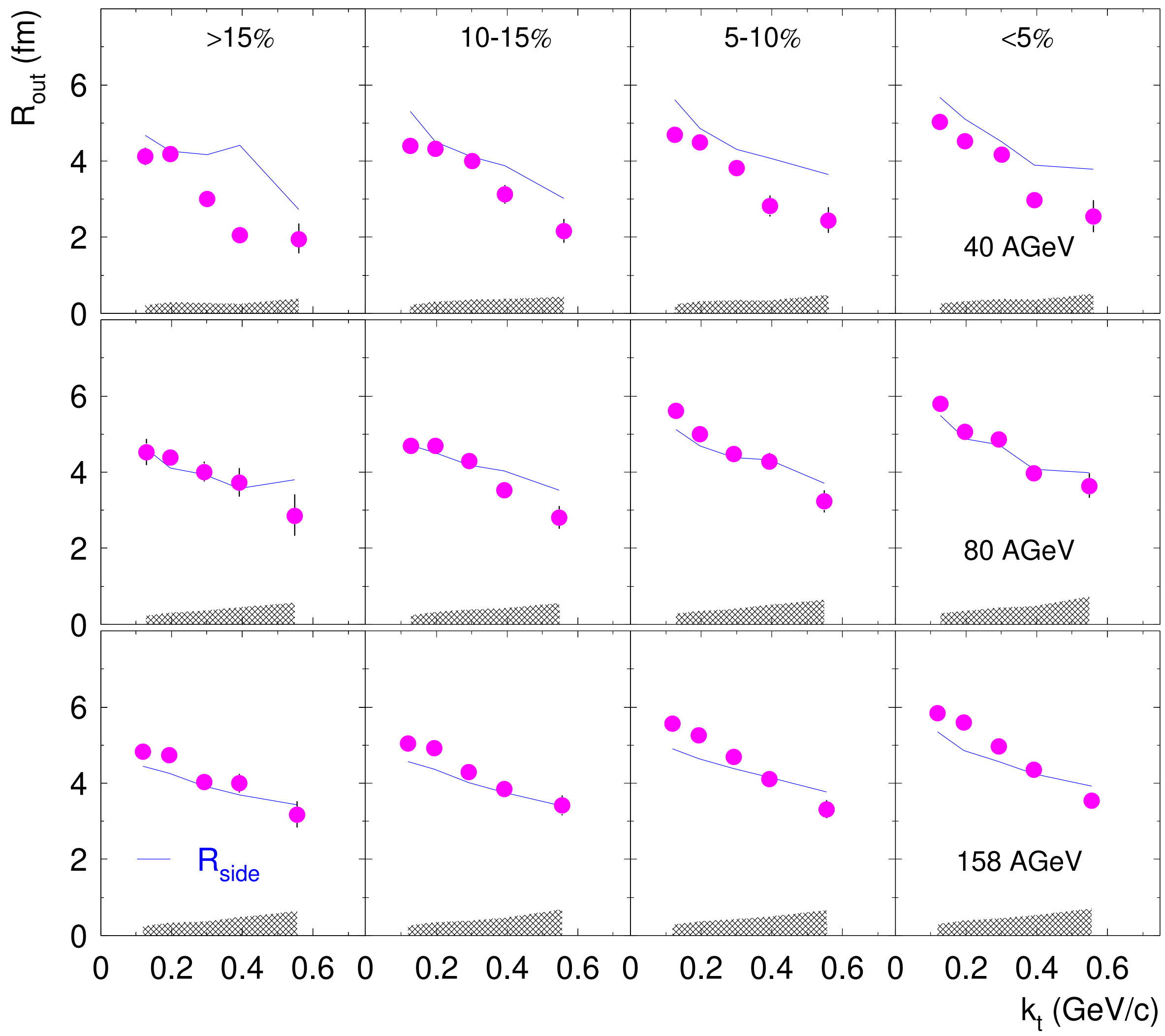
η_f^2: strength of transverse expansion

$$\boxed{< v_t >= 0.5 \text{ - } 0.6c}$$

for $T_f = 120 - 160$ MeV

$R_{\rm out}$ - emission duration

CERES Pb+Au, *Nucl. Phys. A714 (2003) 124*



duration of emission $\Delta\tau$:

$$\Delta\tau^2 = \frac{1}{\beta_t^2} \cdot (R^2_{\rm out} - R^2_{\rm side})$$

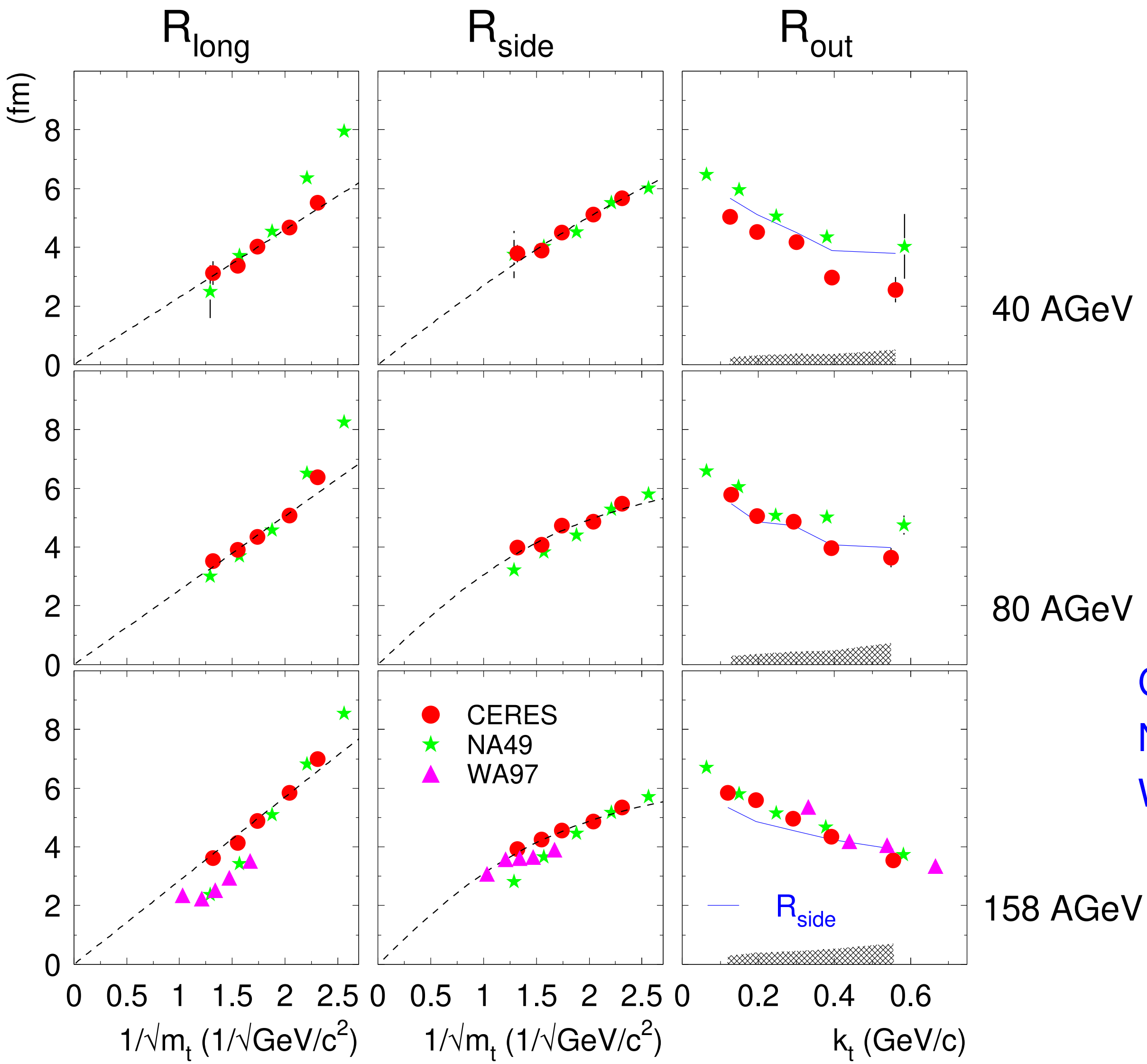
$\rightarrow$ in general: $R_{\rm out} \approx R_{\rm side}$

$\rightarrow$ at 158 AGeV:
short but finite emission duration

$$\boxed{\Delta\tau \approx 2 \text{ fm/c}}$$

$\rightarrow$ similar situation at RHIC

Comparison to other SPS experiments



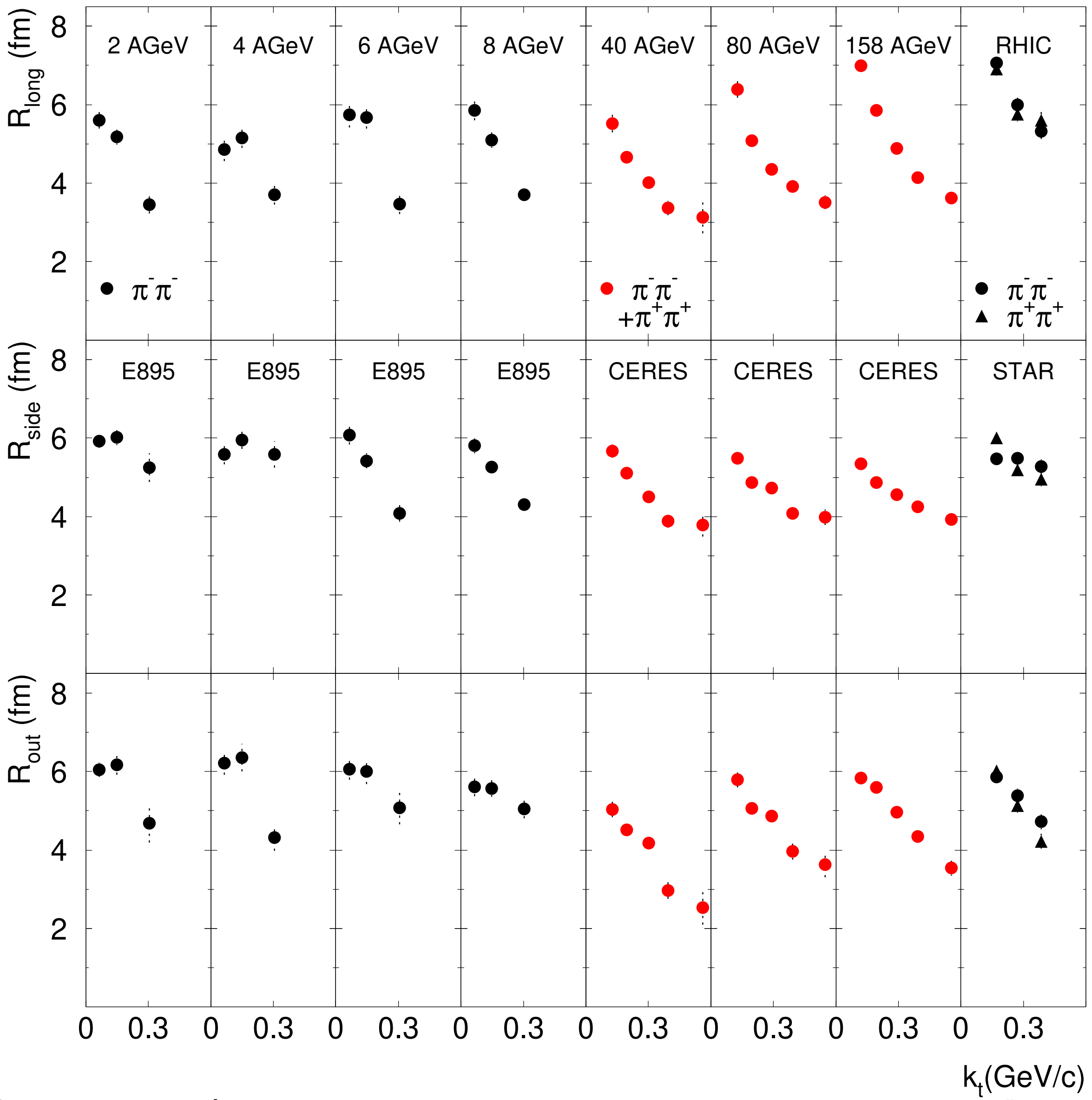
CERES central Pb-Au, *Nucl. Phys. A714 (2003)*

NA49 central Pb-Pb, *Quark Matter 2002*

WA97 central Pb-Pb, *J. Phys. G27 (2001)*

HBT Radii: AGS - SPS - RHIC

CERES *Nucl. Phys. A714 (2003) 124*



$R_{\rm long}$: (lifetime)

increase SPS $\rightarrow$ RHIC

BUT:

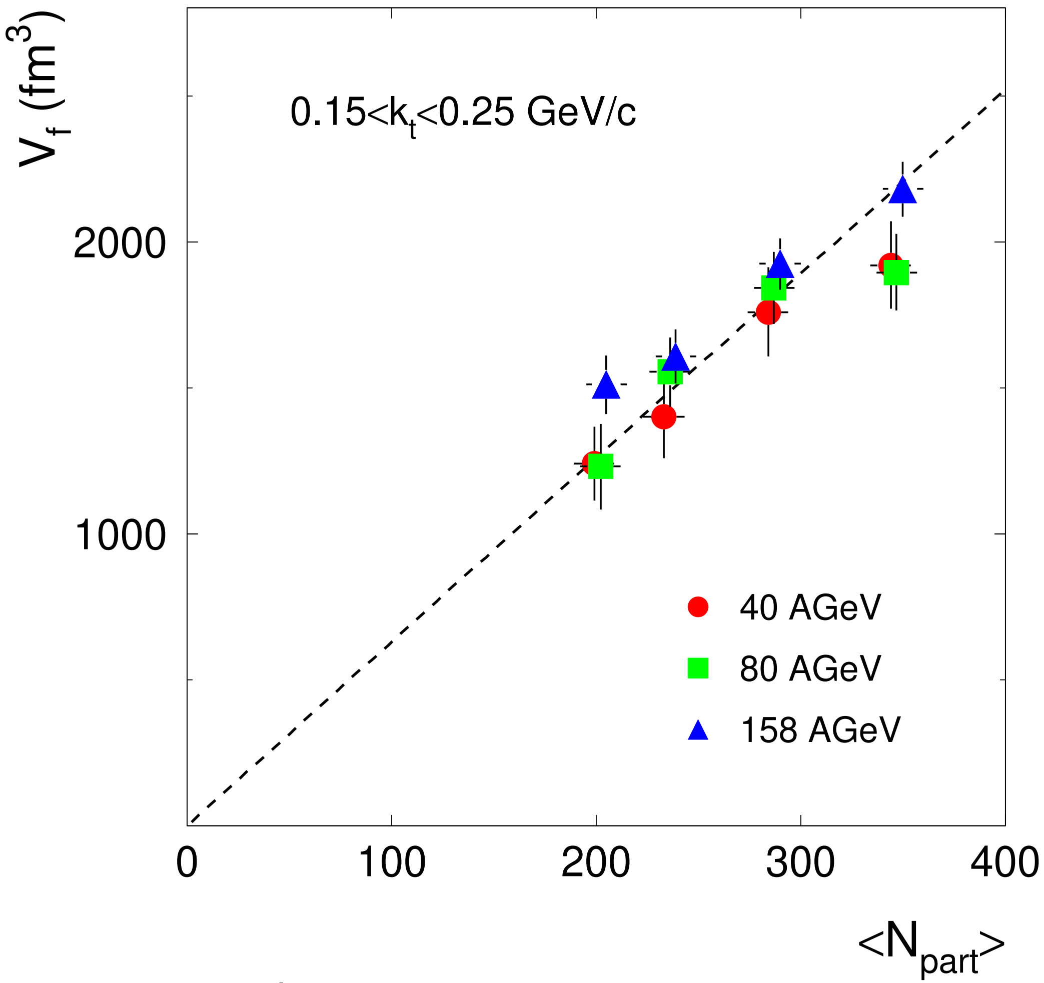
all in all weak $E_{\rm beam}$-dependence!

$\rightarrow$???

Freeze-out volume

freeze-out volume: $V_f = \sqrt{2\pi}^3 \cdot R_{\rm long} \cdot R^2_{\rm side}$

CERES *Phys. Rev. Lett.90 (2003) 022301*



centrality dependence:

$\boxed{V_f \propto < N_{\rm part} >}$

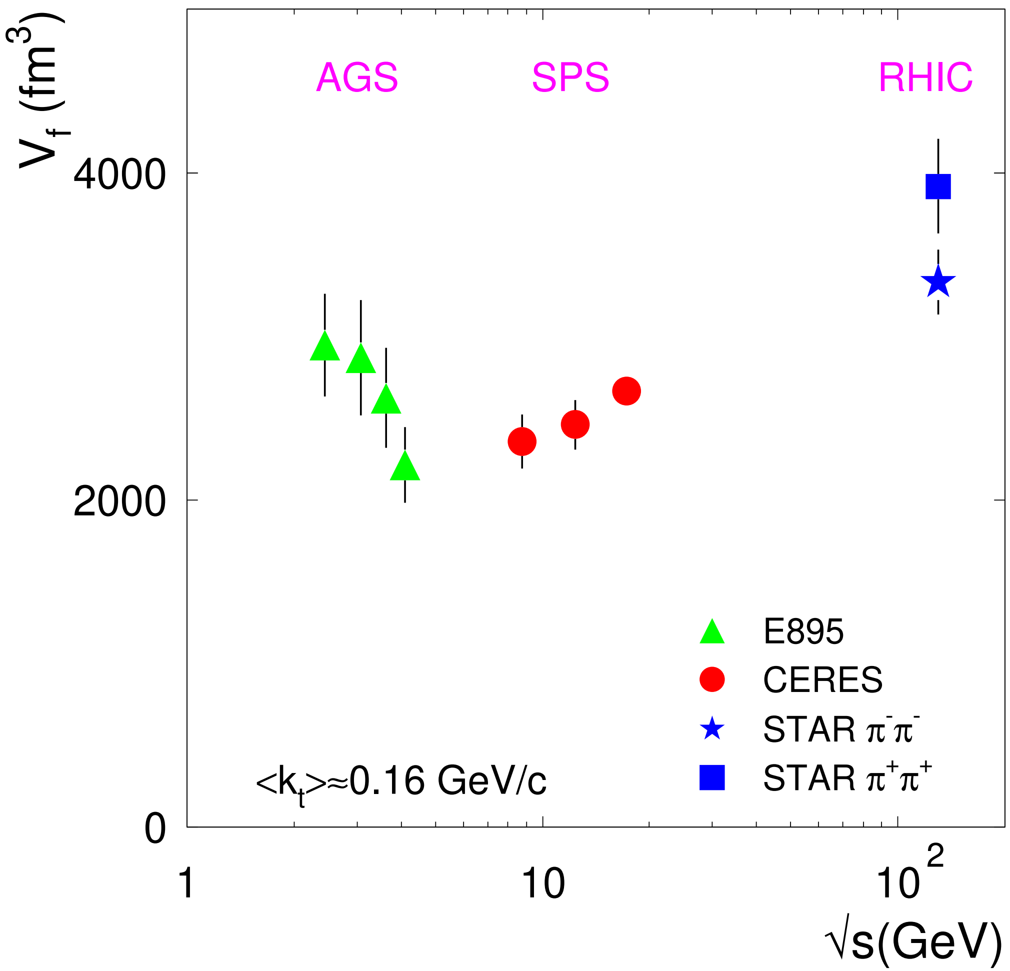
at SPS: $N_{\rm ch} \propto < N_{\rm part} >$

$\Rightarrow \rho_f = const.$

... only at fixed beam energy!

Freeze-out volume vs. beam energy (central events)

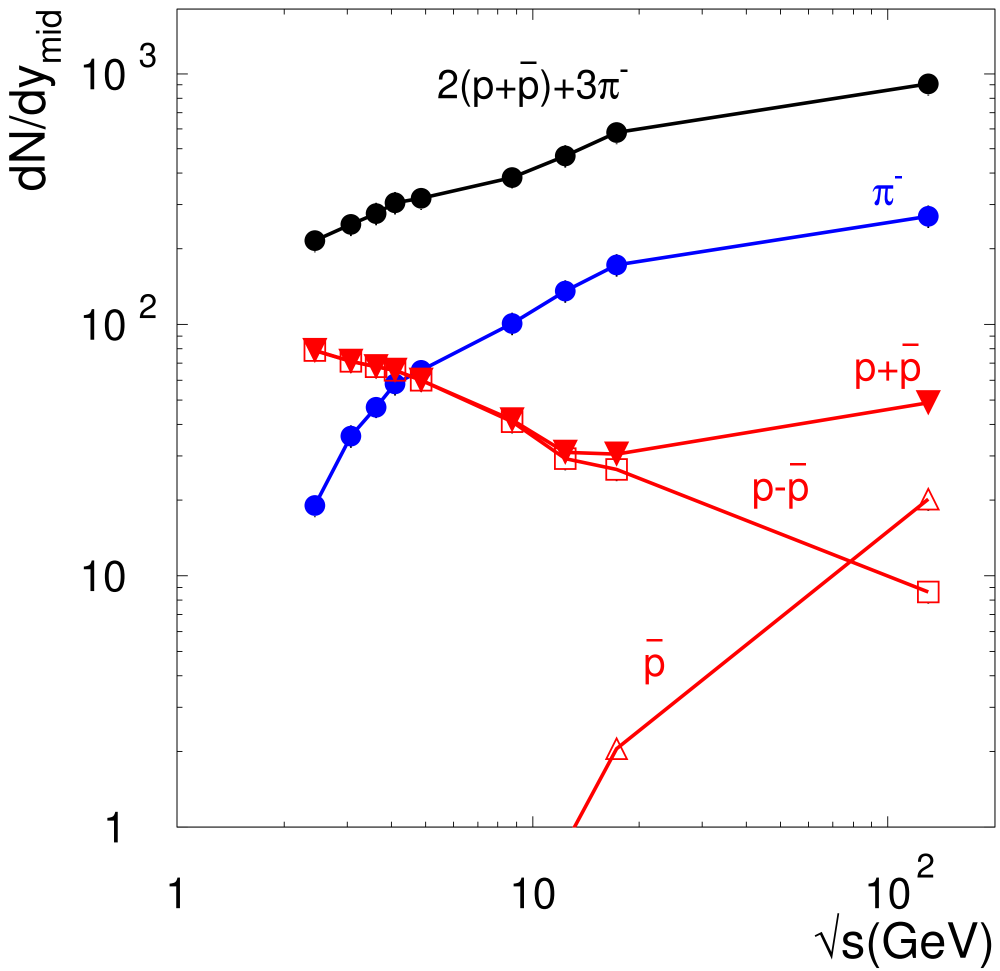
CERES *Phys. Rev. Lett.90 (2003) 022301*



- surprise: non-monotonic behaviour
- minimum between AGS and SPS

Particle multiplicity vs. beam energy

CERES *Phys. Rev. Lett.90 (2003) 022301*



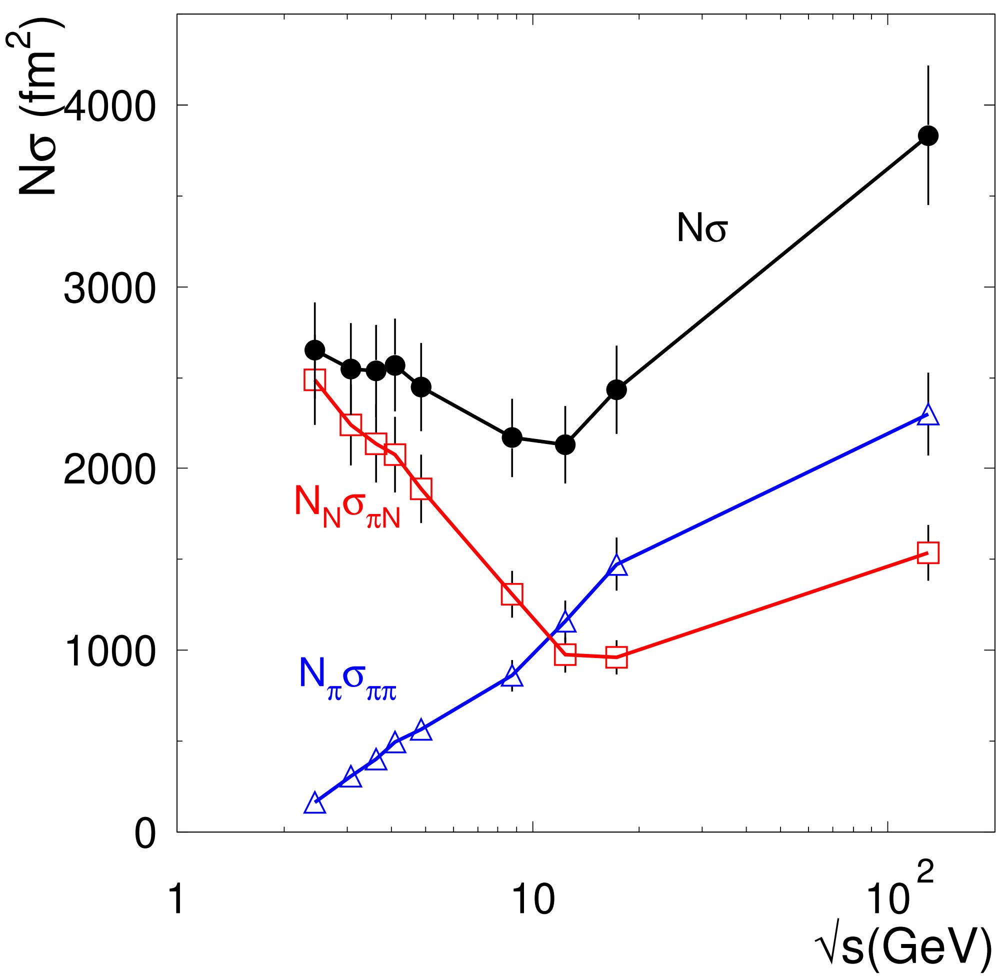
- particle number increases monotonically
  → freeze-out at constant density excluded

- chemical composition changes
- cross-sections are very different
  → try mean free path:

$$\lambda = \frac{1}{\rho \cdot \sigma}$$

Mean free path

CERES *Phys. Rev. Lett.90 (2003) 022301*



$$\lambda_f = \frac{1}{\rho_f \cdot \sigma} = \frac{V_f}{N \cdot \sigma}$$

in a composed medium:

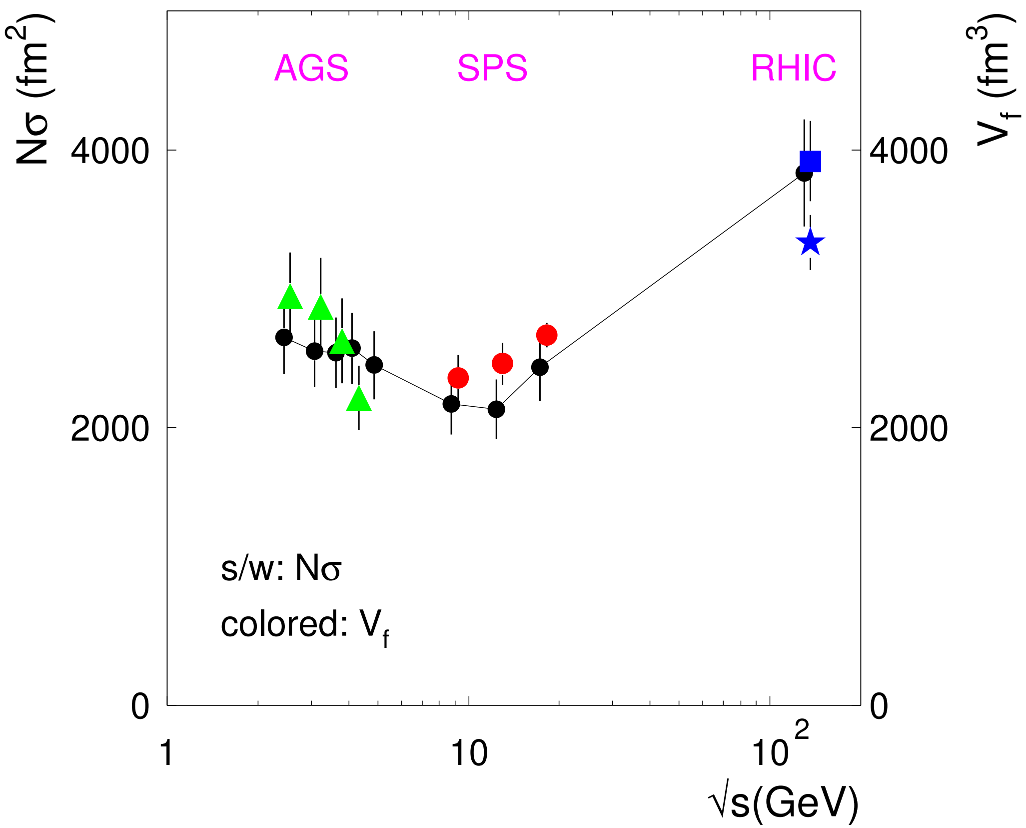
$$N \cdot \sigma = N_N \cdot \sigma_{\pi N} + N_\pi \cdot \sigma_{\pi\pi} + \ldots$$

- $N_N = 2 \cdot \sqrt{2\pi} \cdot 0.87 \cdot \mathrm{d}N_{p+\bar{p}}/\mathrm{d}y|_{y_{\mathrm{mid}}}$
- $N_\pi = 3 \cdot \sqrt{2\pi} \cdot 0.87 \cdot \mathrm{d}N_{\pi^-}/\mathrm{d}y|_{y_{\mathrm{mid}}}$
- $\sigma_{\pi N} = 72$ mb, $\sigma_{\pi\pi} = 13$ mb

→ also $N \cdot \sigma$ shows non-monotonic behaviour . . .

Universal pion freeze-out

CERES *Phys. Rev. Lett.90 (2003) 022301*



$$\lambda_f = \frac{1}{\rho_f \cdot \sigma} = \frac{V_f}{N \cdot \sigma}$$

$\Rightarrow$ universal freeze-out condition:

$$\boxed{\lambda_f \approx 1 \text{ fm}}$$

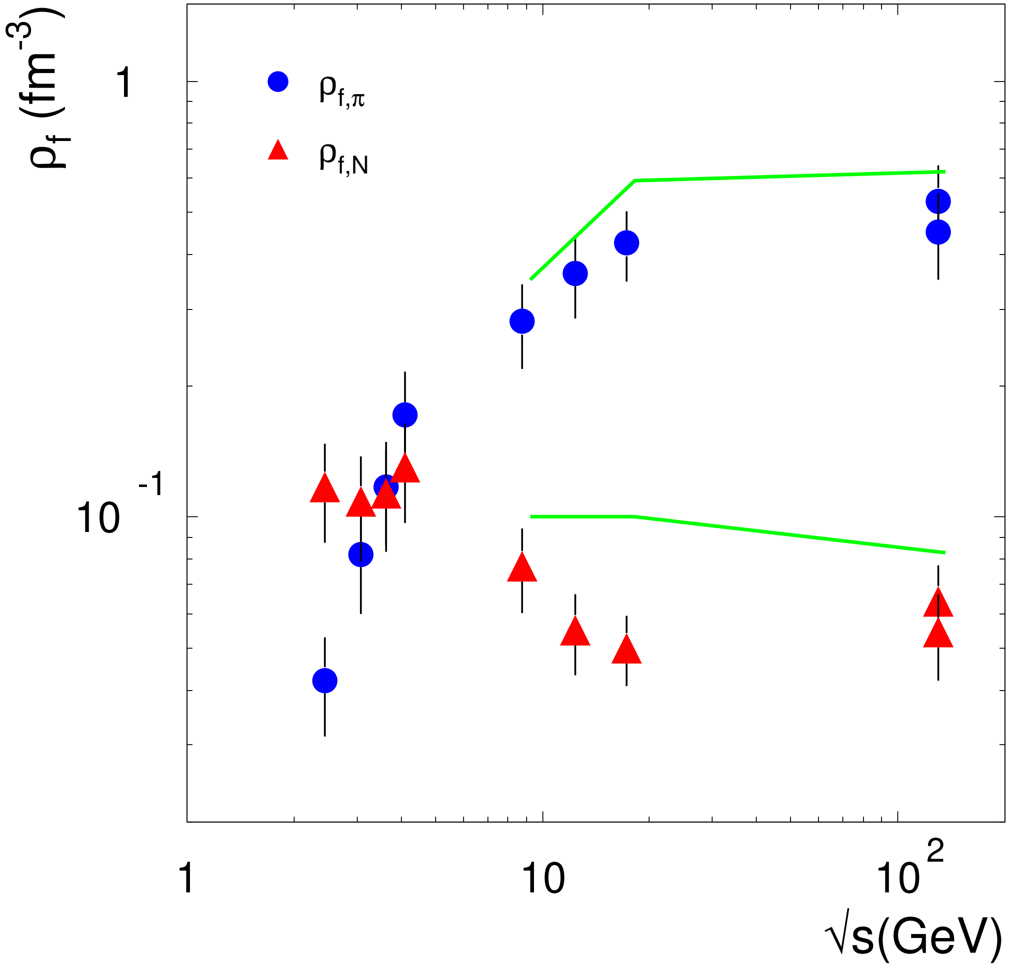
independent of beam energy and centrality!

$$\lambda_f << R_{\mathrm{HBT}} \leq R_{\mathrm{geom}}$$

$\Rightarrow$ ”local” freeze-out

Freeze-out density

CERES coll. *Phys. Rev. Lett.90 (2003) 022301*



- $\rho_{f,\pi} \approx \rho_{f,N}$ at AGS
- asymptotic densities at high beam energies
- at chemical freeze-out (from thermal model[1]) density only $\approx$ 30% higher than at thermal freeze-out (HBT)

[1]) *P. Braun-Munzinger, K. Redlich, J. Stachel*

Summary

- weak E_{beam} dependence of HBT radii explained by universal freeze-out condition $\lambda_f \approx 1$ fm $\rightarrow$ no HBT puzzle
- density decreases by only $\approx 30\%$ between chemical and thermal freeze-out
- $\Rightarrow$ volume increases by $\approx 30\%$
- $\Rightarrow$ radii increase by $\approx 10\%$
- expansion velocity $v_t \approx 0.5c$ and $R \approx 5 - 8$ fm
- $\Rightarrow$ lifetime of hadronic phase $\approx 1 - 2$ fm/c out of a total lifetime of $\tau_f \approx 7 - 8$ fm/c

$\Rightarrow$ no evidence for a long-lived hadronic phase

- explosive expansion, consistent with $R_{\mathrm{out}} \approx R_{\mathrm{side}}$, $\lambda_f \approx 1$ fm

CERES/NA45 collaboration

D. Adamová, V. Kushpil, M. Šumbera
NPI ASCR, Řež, Czech Republic

G. Agakichiev, H. Appelshäuser,
P. Braun-Munzinger, A. Castillo,
C. Garabatos, G. Hering, J. Holeczek,
A. Maas, S. Sedykh, A. Marín,
D. Miśkowiec, J. Rak, H. Sako
GSI Darmstadt, Germany

S. Damjanović, T. Dietel, L. Dietrich,
S. I. Esumi, K. Filimonov, P. Glässel,
W. Ludolphs, J. Milošević, V. Petráček,
W. Schmitz, J. Slívová, H. J. Specht,
J. Stachel, H. Tilsner, J. P. Wessels,
T. Wienold, B. Windelband, S. Yurevich
Heidelberg University, Germany

V. Belaga, K. Fomenko, Yu. Panebrattsev,
O. Petchenova, S. Shimansky, V. Yurevich
JINR Dubna, Russia

A. Cherlin, Z. Fraenkel, A. Gnaenski,
A. Milov, I. Ravinovich, I. Tserruya, W. Xie
Weizmann Institute, Rehovot, Israel

A. Drees, F. Messer
SUNY at Stony Brook, U.S.A.

B. Lenkeit, A. Pfeiffer, J. Schukraft
CERN, Geneva, Switzerland

P. Rehak
BNL, Upton, U.S.A.

J. P. Wurm
MPI, Heidelberg, Germany