Two-Pion Intensity Interferometry in Collisions of Au+Au @ 1.23A GeV

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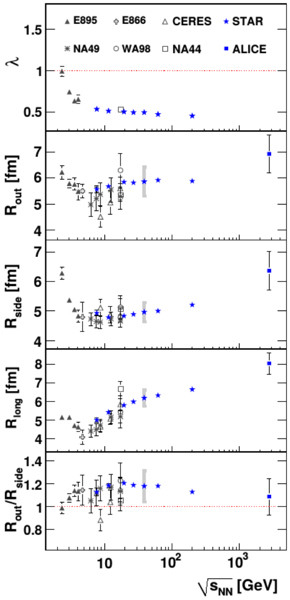
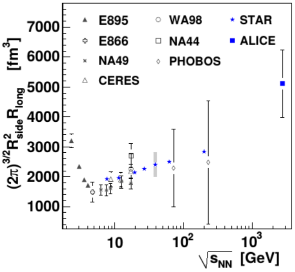
Motivation



STAR Phys. Rev. C 92, 014904 (2015)

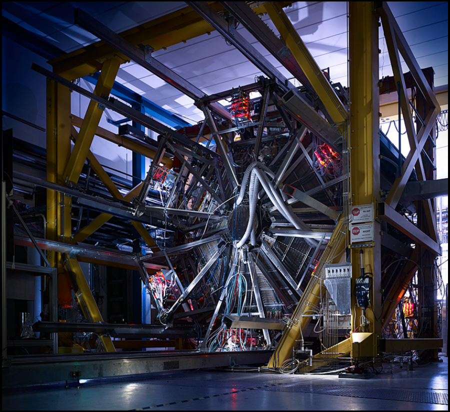


Outline:

- HADES $\pi^-\pi^-$ / $\pi^+\pi^+$ HBT radii, centrality dependent
- excitation functions ($\sqrt{s_{\mathrm{NN}}}$) (most central 0-10%)
- source size extraction (most central 0-10%)

HADES@SIS18

High Acceptance Di-Electron Spectrometer
at Heavy Ion Synchrotron SIS18 at GSI(Darmstadt, GER)



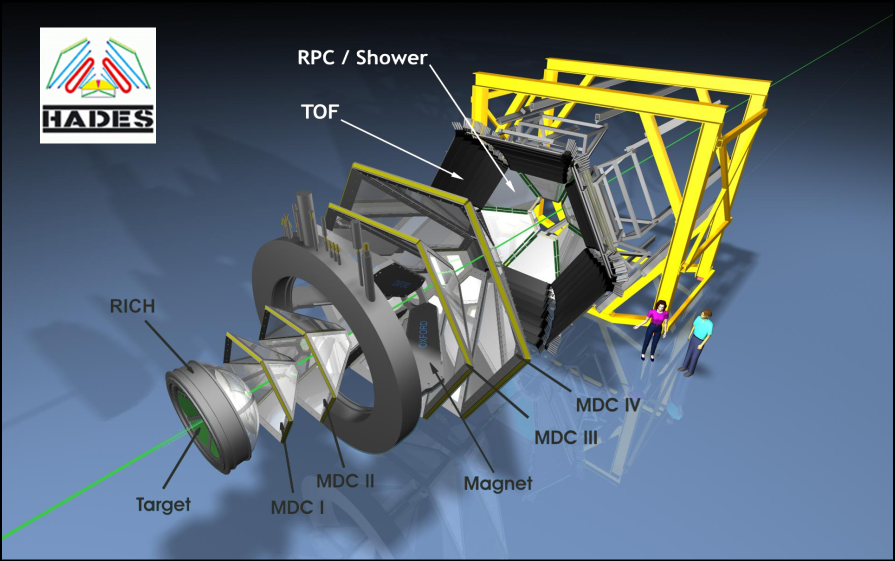
- fixed-target experiment, $16 < \theta < 88$ degrees
- Au(1.23A GeV)+Au run in April 2012

→ $\sqrt{s_{NN}} = 2.4\,\mathrm{GeV}$

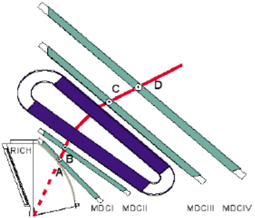
- 557 beam hours with $(1.2 - 1.5) \times 10^6$ ions/s
- target interaction probability 2.0%
- online trigger on multiplicity (centrality)

→ 2.1×10^9 events

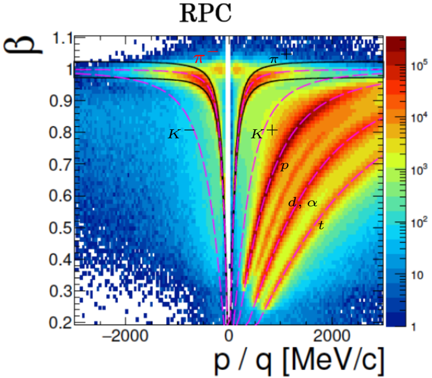
Experimental setup

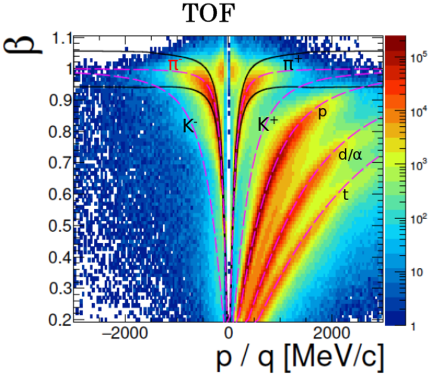


Particle Identification



- p/q via Runge-Kutta-procedure in known $\vec{B}$ field
- $\beta = \frac{s}{tc}$
  $(\; t = t_{TOF/RPC} - t_{START} \;)$





Conditions

Centrality condition

- 4 multiplicity classes

Single particle conditions

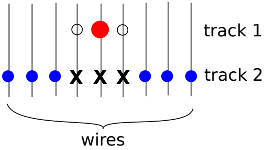
- PID via p/q vs. β

Two particle conditions

- data-driven close-track pair cut

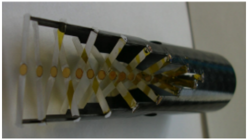
$\rightarrow$ not same TOF/RPC cell

$\rightarrow$ not same MDC wire



Event mixing conditions

- same multiplicity:
  $|mult_i - mult_j| < 10$
- same reaction plane:
  $|\phi_i - \phi_j| < 30°$
- same target slice:
  $|VerZ_i - VerZ_j| < 1.8$ mm



- all other conditions:
  as for true yield!

experimental C-function:

$$C(q) = N \frac{\sum Y_{12}(q)}{\sum Y_{12,mix}(q)}$$

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1-dim / 3-dim fit function

- including FSI → Coulomb (strong int. neglected)
- assuming Gaussian source distribution $S(r) = \frac{\lambda}{(2\sqrt{\pi}R)^3} exp(-\frac{r^2}{4R^2})$

Sinyukov-Bowler formula: **[Y. Sinyukov et al. Phys. Lett. B 432, 248 (1998)]**

$$C(q_{\text{inv}}) = C_0[(1-\lambda) + \lambda \cdot K_{\text{Coul}}(q_{\text{inv}}, R_{\text{inv}}) \cdot \underline{(1 + e^{-(2q_{\text{inv}} R_{\text{inv}})^2})]}$$

Bose-Einstein(BE) part

$\lambda < 1 \rightarrow$ incoherence + contamination

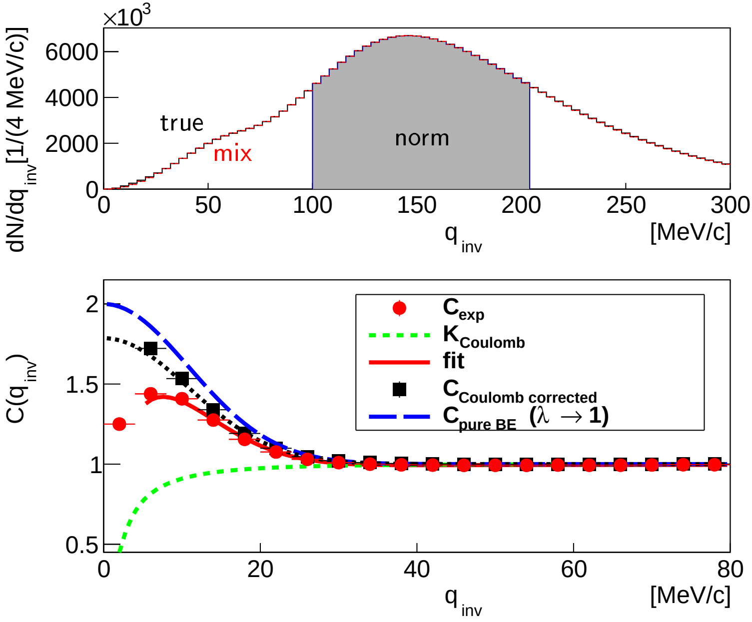
Bertsch-Pratt parametrisation: $\vec{q} \rightarrow (q_{\text{o}}, q_{\text{s}}, q_{\text{l}})$
Integration over azimuth. ang. $\phi \Rightarrow \; R_{\text{os}}, R_{\text{sl}} \rightarrow 0$
boost into longitudinal co-moving system (LCMS), $p_{1z} = -p_{2z}$

$$C(\vec{q}) = C_0[(1-\lambda) + \lambda \cdot K_{\text{Coul}}(\hat{q}, R_{\text{inv}}) \cdot \underline{(1 + e^{-(2q_{\text{o}} R_{\text{o}})^2 - (2q_{\text{s}} R_{\text{s}})^2 - (2q_{\text{l}} R_{\text{l}})^2})]}$$

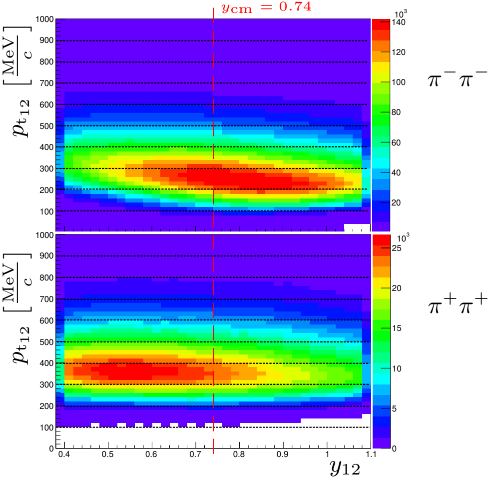
Bose-Einstein(BE) part

$\hat{q} = \langle q_{\text{inv}} \rangle (q_o, q_s, q_l, \hat{p}_{t_{12}})$
Gaussian momentum resolution correction → increase of $R_j \sim 2\%$

Example 1-dim C-fct.



Phase space binning, Centrality

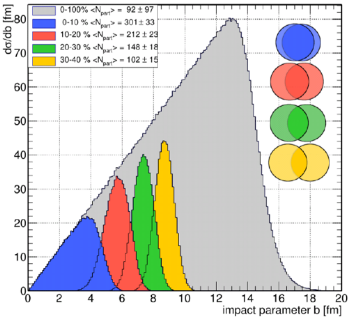


$q_{inv} < 50\text{MeV}/c$

$p_{t_{12}} = |\vec{p}_{t,1} + \vec{p}_{t,2}|$, y_{12}: pair rapidity

$|y_{12} - y_{cm}| < 0.35$

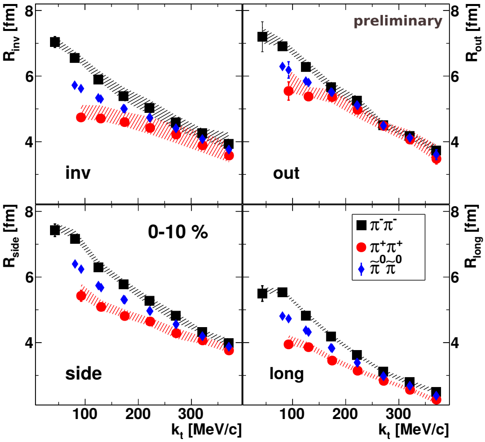
centr. determ. with GlauberMC



centr. (%)	$\langle b \rangle$ [fm]	$\langle A_{part} \rangle$
0-10	3.1	303
10-20	5.5	213
20-30	7.2	150
30-40	8.8	103

HADES Eur.Phys.J. A54 (2018)

Accounting for 'central' Coulomb potential



G. Baym, Acta Phys. Polon. B 29, 1839 (1998)

$$e(\mathbf{p}_\mathrm{f}) = e(\mathbf{p}_\mathrm{i}) \pm V_\mathrm{eff}(\mathbf{p}_\mathrm{f}(\mathbf{r}_\mathrm{i}))$$

$\mathbf{p}_\mathrm{i}$ ($\mathbf{p}_\mathrm{f}$) initial (final) momentum, e total energy, $\mathbf{r}_\mathrm{i}$ inital pion pos. in central Coul. pot. V_eff

$$\frac{R_{\pi^\pm\pi^\pm}}{R_{\pi^0\pi^0}} \approx \frac{q_\mathrm{i}}{q_\mathrm{f}} = \frac{|\mathbf{p}_\mathrm{i}|}{|\mathbf{p}_\mathrm{f}|}$$

$$= \sqrt{1 \mp 2\frac{V_\mathrm{eff}}{|\mathbf{p}_\mathrm{f}|}\sqrt{1+\frac{m_\pi^2}{\mathbf{p}_\mathrm{f}^2}} + \frac{V_\mathrm{eff}^2}{\mathbf{p}_\mathrm{f}^2}}$$

q_i (q_f) initial (final) rel. momentum

$V_\mathrm{eff}/k_\mathrm{t} \ll 1 \rightarrow$

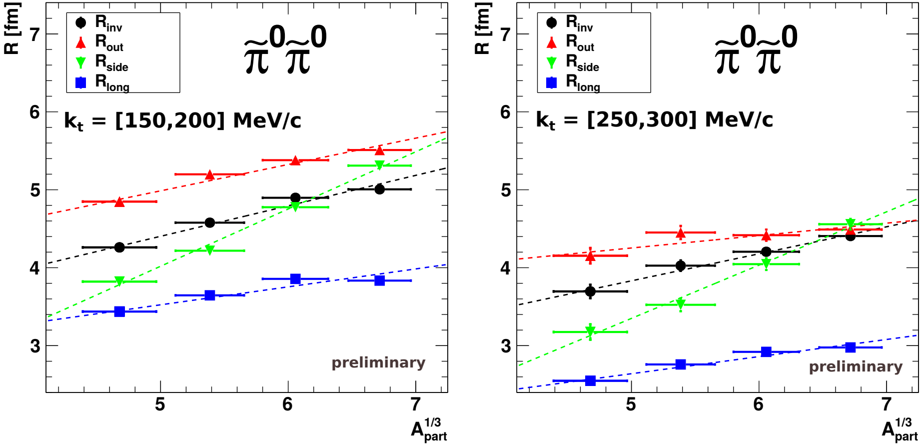
$$R^2_{\tilde{\pi}^0\tilde{\pi}^0} = \frac{1}{2}\left(R^2_{\pi^+\pi^+} + R^2_{\pi^-\pi^-}\right)$$

constructed $\tilde{\pi}^0\tilde{\pi}^0$ radii derived from cubic spline interpol. of experim. $\pi^-\pi^-$ & $\pi^+\pi^+$ data

indications for charge-sign differences reported previously:
E866 **R. A. Soltz, M. Baker, J. H. Lee, Nucl. Phys. A 661, 439c (1999)**
E877 **D. Miskowiec et al., Nucl. Phys. A590, 473c (1995)**
opposite effect (!):
NA44 **I.G. Bearden et al., Nucl. Phys. A638, 103c (1998)**

First time observation of substantial difference!

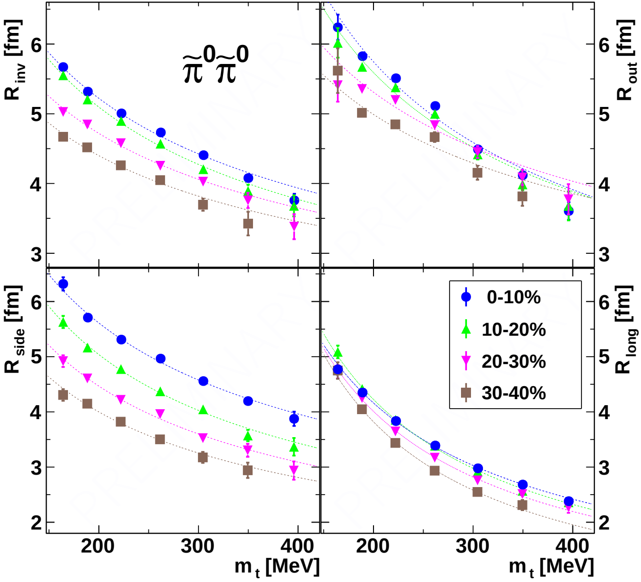
Dependence on centrality (exemplary)



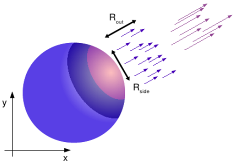
$A_{\rm part}$: number of nucleons in overlap region

freeze-out vol. $V_{\rm fo} \sim A_{\rm part} \rightarrow R_i \sim A_{\rm part}^{1/3}$

Dependence on m_t and centrality



$$m_t = \sqrt{k_t^2 + m_\pi^2}$$
$$k_t = p_{t_{12}}/2$$

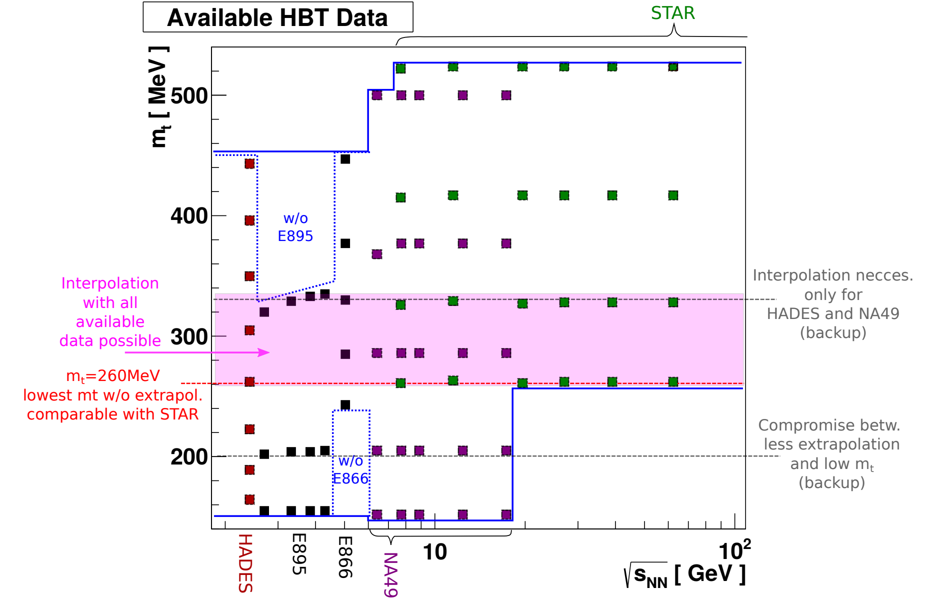


Dipl.Th. S. Schuchmann

$$R_j = R_j^0 \left(\frac{m_t}{m_\pi}\right)^\alpha$$

0-10%	R^0 [fm]	α
inv	6.03(3)	-0.40(1)
out	6.96(8)	-0.54(2)
side	6.70(9)	-0.49(2)
long	5.50(6)	-0.78(2)

Excitation function, map of avaible data points



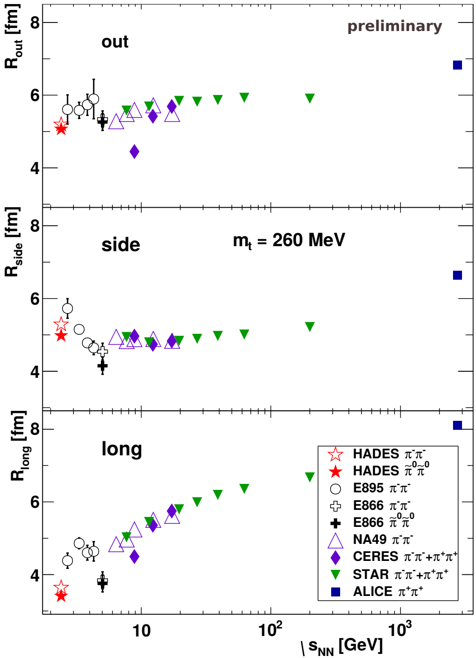
Excitation function

Au+Au, Au+Pb and Pb+Pb

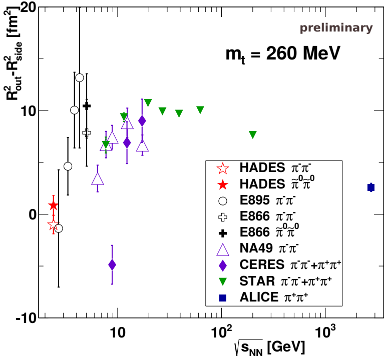
linear + spline3 interpolation for
$m_{\mathrm{t}} = 260\,\mathrm{MeV}/c$

HADES follows trend from STAR/NA49 more than trend from E895

→ **No new features visible**



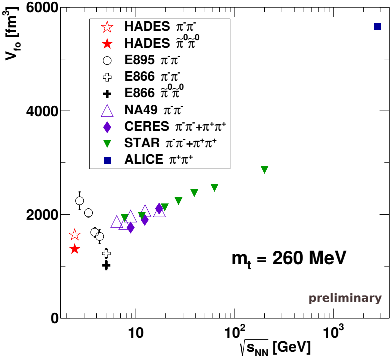
Excitation function



$R^2_{\mathrm{out}} - R^2_{\mathrm{side}} \sim \Delta\tau^2$
(freeze-out duration)

→ opaqueness ?

H. W. Barz, Phys.Rev.C 592214 (1999)



$$V_{\mathrm{freezeout(fo)}} := (2\pi)^{\frac{3}{2}} R^2_{\mathrm{side}} R_{\mathrm{long}}$$

→ necessity for remeasurement
CBM@SIS100 $\sqrt{s_{\mathrm{NN}}} = 2.7 - 5\,\mathrm{GeV}$
NICA $\sqrt{s_{\mathrm{NN}}} = 2.7 - 11\,\mathrm{GeV}$

extrapol. V_{fo} to $k_{\mathrm{t}} = 0\,\mathrm{MeV}/c$:
$V_{\mathrm{fo}} = 3900\,\mathrm{fm}^3$ $(\tilde{\pi}^0\tilde{\pi}^0, \mathrm{HADES})$

Model fit(s)

source distribution with relativistic long. flow (Bjorken scaling, finite η-distrib.):

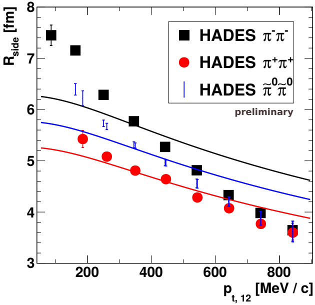
$$S(x,K) = m_t \cosh(\eta - Y) \exp\left(-\frac{K^\mu u_\mu}{T}\right) \cdot (2\pi R_G^2)^{-\frac{1}{2}} \cdot I(\tau-\tau_0, \Delta\tau) \cdot I(\rho, R_G^2) \cdot I(\eta, \Delta\eta)$$

$$I(x,\Delta x) = \frac{1}{\sqrt{2\pi\Delta x^2}} e^{-\frac{x^2}{2\Delta x^2}}$$

$$u(x^\mu) = \begin{pmatrix} \cosh\eta \cosh\eta_t \\ \frac{x}{\rho}\sinh\eta_t \\ \frac{y}{\rho}\sinh\eta_t \\ \sinh\eta\cosh\eta_t \end{pmatrix}$$

$$\rho = \sqrt{x^2+y^2}\ ,\ \tau = \sqrt{t^2-z^2}\ ,\ \eta = \frac{1}{2}\ln\left(\frac{t+z}{t-z}\right)$$

S. Chapman, P. Scotto, U. Heinz, Acta Phys. Hung., HIP 1, 1 (1995)



$$\mathbf{R_{side}^2} = \langle y^2 \rangle = \frac{\int d^4x\, y^2\, S(x,K)}{\int d^4x\, S(x,K)}$$

$$= \frac{\mathbf{R_G^2}}{\mathbf{1} + \eta_t^2 \frac{\mathbf{m_t}}{\mathbf{T}}}$$

$\eta_t = 0.4$
$T = 40$ MeV
(extreme values for large slope)

fit function not adequate!

(analog for $R_{long}^2 = \langle (z-\beta_l t)^2 \rangle - \langle (z-\beta_l t) \rangle^2$)

new: Comb. single part. spec. + HBT analysis

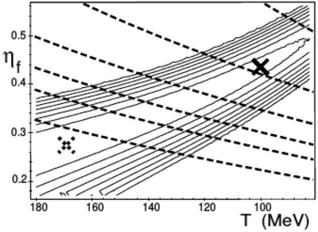
→ recipe from U. Wiedemann, U. Heinz, Phys. Rept. 319, 145 (1999)

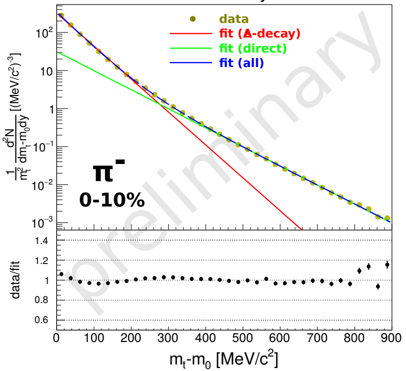
$$E\frac{dN}{d^3p} = P_1(p) = \int d^4x\, S(x,p) \;\Leftrightarrow\; C_2(\vec{q},\vec{K}) \approx 1 + \frac{|\int d^4x S(x,K) e^{iqx}|^2}{|\int d^4x S(x,K)|^2}$$

$$\Leftrightarrow\; R_i^2 = <\tilde{x}_i{}^2> = \frac{\int d^4x\, \tilde{x}_i{}^2\, S(x,K)}{\int d^4x\, S(x,K)}$$

courtesy: M. Gumberidze

motivation: determ. flow velocity η_t ↔ kin. freeze-out Temperature T_{fo}





$\rightarrow S = S^{\Delta} + S^{\text{direct}}$

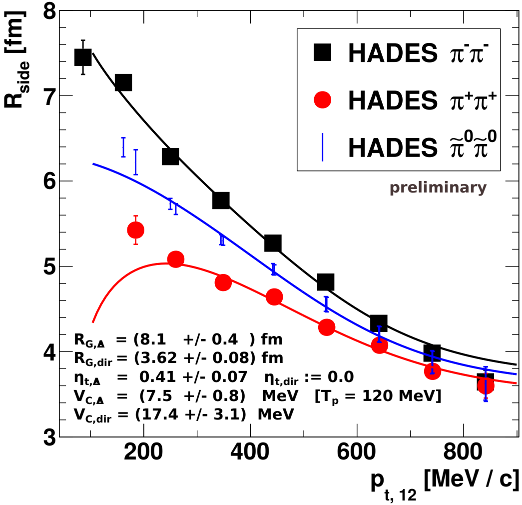
$$\Rightarrow R_i^2 = \frac{P_{1,\Delta}\cdot R_{i,\Delta}^2 + P_{1,\text{dir}}\cdot R_{i,\text{dir}}^2}{(P_{1,\Delta} + P_{1,\text{dir}})}$$

Single-part. spec. in SIS/AGS* energy regime best descr. by sum of direct + (mainly)Δ decay pions

* E895 Phys. Rev. C 68, 054905

new: Comb. single part. spec. + HBT analysis

R_{side}



$p_{\mathrm{t}_{12}} = 2k_{\mathrm{t}}$

simultanious fit to π^+ and π^-

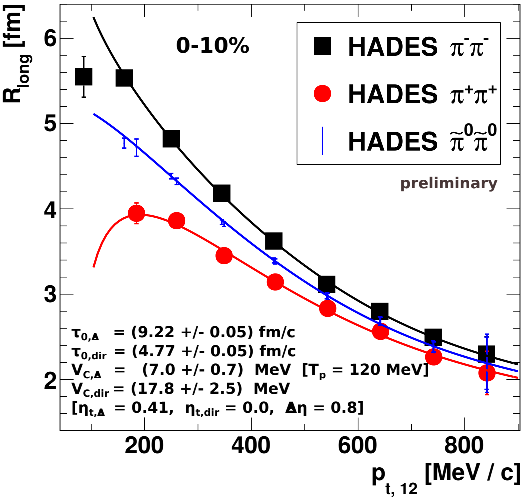
effect of 'central' Coulomb pot. a la slide 9 with $V_{\mathrm{C,dir}} = \mathrm{const.}$, $V_{\mathrm{C}}^{\mathrm{eff}} = V_{\mathrm{C},\Delta} \cdot (1 - e^{-E_{\mathrm{kin}}^{\mathrm{max}}/T_{\mathrm{p}}})$ (non-static source)

iterative adjustment of η_{t} and T together with Boltzmann like fits to single particle spectra

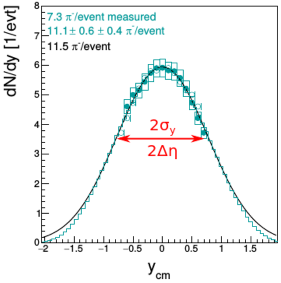
$T_\Delta = (61 \pm 5)$ MeV,
$T_{\mathrm{dir}} = (82.5 \pm 2.8)$ MeV

new: Comb. single part. spec. + HBT analysis

$$R_{\rm long} \sim \tau\sqrt{\frac{T}{m_t}} \cdot (1 + f(m_t/T, \eta_t, \Delta\eta))$$



[Diss. Heidi Schuldes]



finite rapid. distrib., $\Delta\eta \approx 0.8$

with $L_{\rm G} = \tau_0 \cdot \Delta\eta$ and
$V_{\rm fo} = (2\pi)^{\frac{3}{2}} R_{\rm G}^2 \cdot L_{\rm G}$

$\rightarrow V_{\rm fo}^{\rm dir} \approx 790\,{\rm fm}^3$
$\rightarrow V_{\rm fo}^{\Delta} \approx 7600\,{\rm fm}^3$

Summary

- investigation of $\pi^-\pi^-$ and $\pi^+\pi^+$ HBT data with substantial charge-sign diff., strongest for Au+Au compared to literature!

$\rightarrow$ effect of 'central' Coulomb pot. must not be neglected at $\sqrt{s_{\rm NN}} \lesssim$ 10 GeV

- $\tilde{\pi}^0\tilde{\pi}^0$ follow systematic trends (decreasing with $p_{t_{12}}$, linear $A_{\rm part}^{\frac{1}{3}}$ scaling)

- HADES data follows smooth global trend in excitation function (RHIC, SPS), but does not agree with strong energy dependence implied by AGS data

- HBT radii AND single particle spectra give access to geom.+dynam. properties of HIC fireball in SIS energy region
  - $R_{\rm G}^{\Delta} \sim 7 - 9\,{\rm fm}\,,\ \tau_0^{\Delta} \sim 8 - 10\,{\rm fm}/c$

    radial flow velocity $\eta_{\rm t} \sim 0.4 \pm 0.1$
  - $R_{\rm G}^{\rm dir} \sim 3 - 4\,{\rm fm}\,,\ \tau_0^{\rm dir} \sim 4 - 5\,{\rm fm}/c$

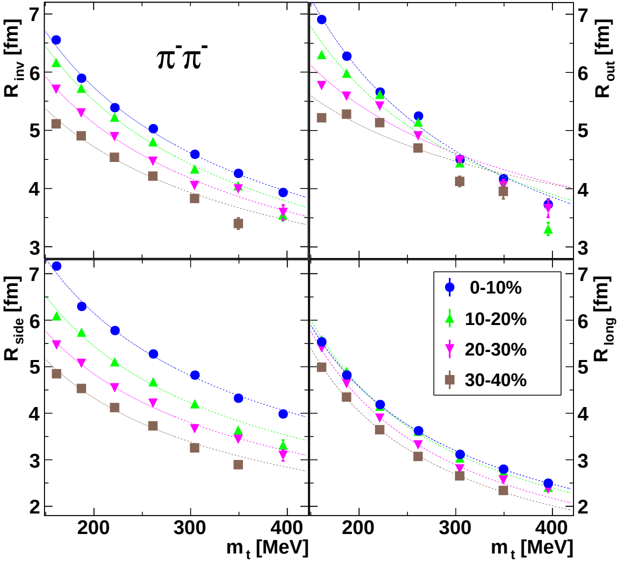
    $\rightarrow$ compare to thermo-stat. models, talk M. Lorenz

Thank you for your attention!

The HADES collaboration

Backup material

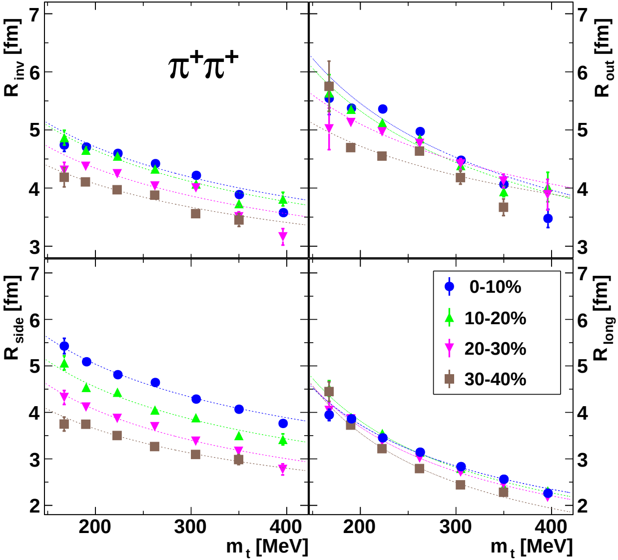
Dependence on m_t and centrality



$$m_t = \sqrt{k_t^2 + m_\pi^2}$$
$$k_t = p_{t_{12}}/2$$

$$R_j = R_j^0 \left(\frac{m_t}{m_\pi}\right)^\alpha$$

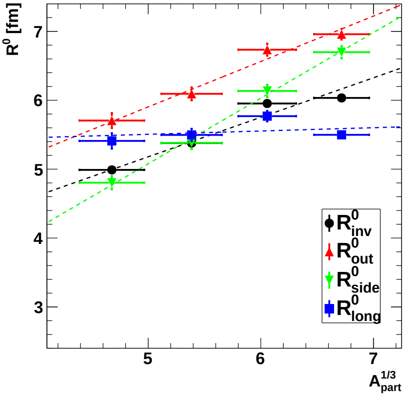
Dependence on m_t and centrality

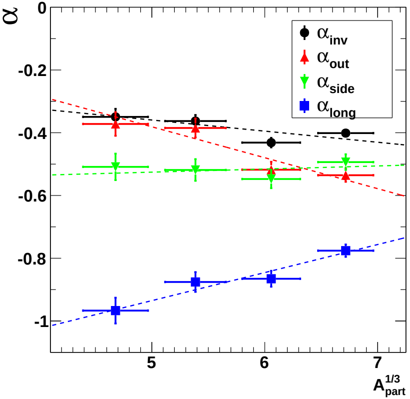


$$m_t = \sqrt{k_t^2 + m_\pi^2}$$
$$k_t = p_{t_{12}}/2$$

$$R_j = R_j^0 \left(\frac{m_t}{m_\pi}\right)^\alpha$$

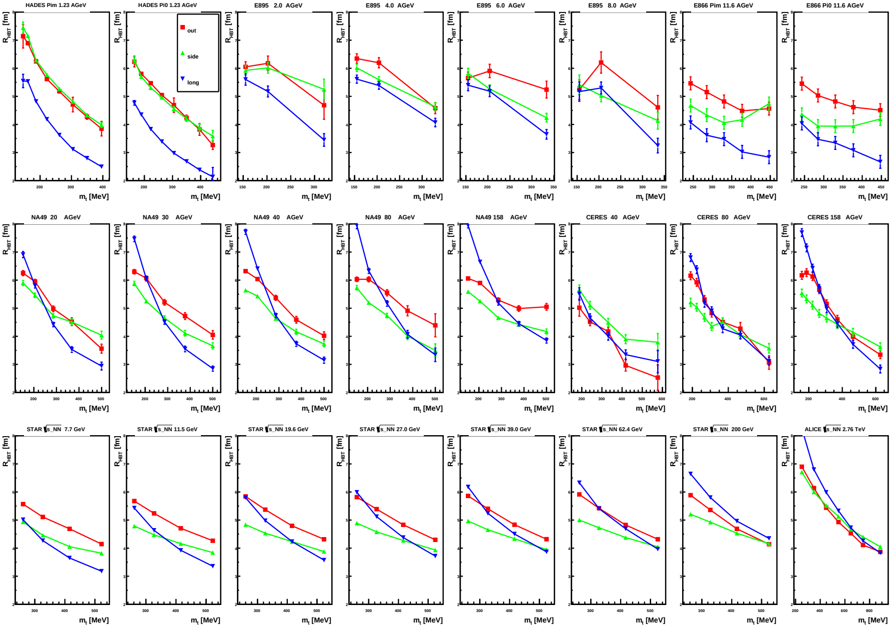
Parametrization, $\tilde{\pi}^0\tilde{\pi}^0$



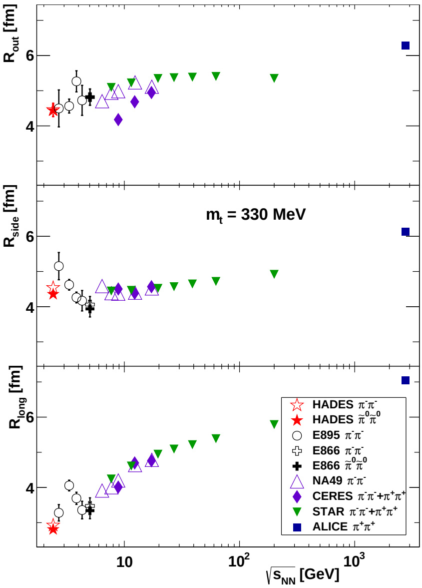


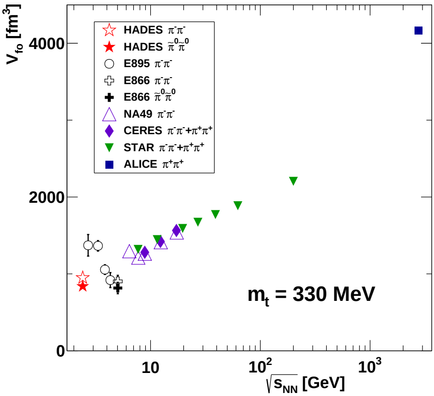
$$R_j = R_j^0 \left(\frac{m_t}{m_\pi}\right)^\alpha$$

Excitation function, m_t-dep. of world data

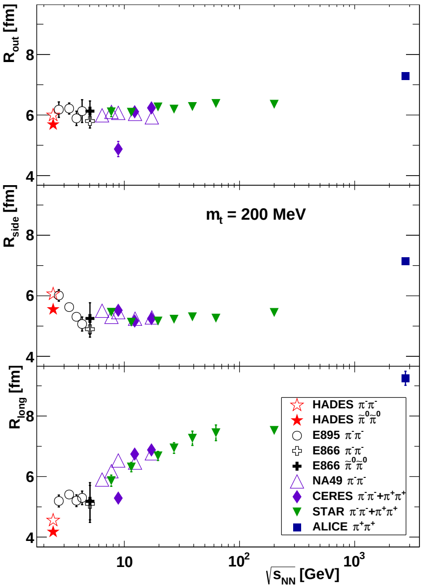


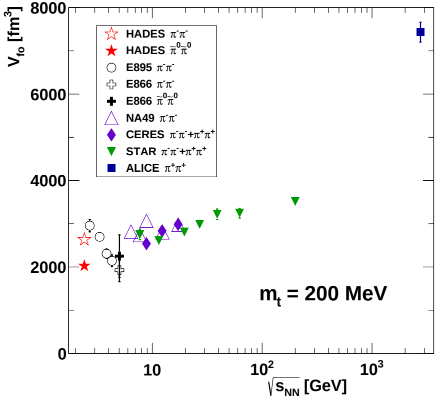
Excitation function, $m_t = 330\,\mathrm{MeV}/c$





Excitation function, $m_t = 200\,\mathrm{MeV}/c$

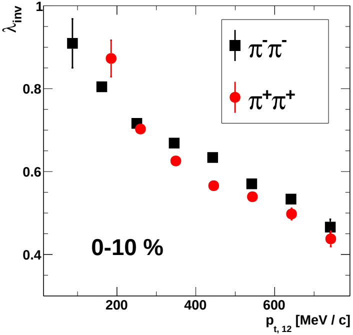




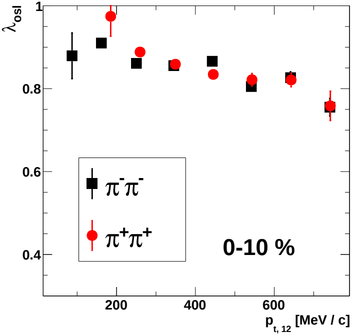
STAR/E866 data extrapolated!

λ parameters

1dim (inv)



3dim (osl)



invariant description not adequate enough for 3-dim. extended source ... ?

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