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Bose–Einstein correlations and pion laser in strong interaction processes

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Outline

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Why study BEC

Analysis of correlations provides unique information about various stages of space-time evolution of multiparticle production.

- Bose–Einstein correlations (BEC) is defined as correlations between two identical bosons with low relative momentum; BEC effect corresponds to an enhancement in two identical boson correlation function (CF) when the two particles are near in momentum space.

- BEC leads also to Bose–Einstein condensates responsible for laser, superfluids and superconductors. Thus boson (pion) laser can be created if the phase-space density of these bosons will be large enough.

- Dependence of BEC on collision energy helps, in particular, to search for the novel effects in multiparticle production processes.

Parameterization of BEC effect

In 3D case almost all experimental data for strong interactions are obtained for Gauss parameterization and Pratt–Bertsch coordinate system:

$$C_2(q,k) \propto 1+\Omega(q,k), \quad \Omega(q,k) = \lambda \exp(-\sum\nolimits_{i=\mathrm{s,o,l}} q_i^2 \mathrm{R}_i^2).$$

Here R_i are space-time extents (BEC radii) of particle source along 3 axis: “long” – along the beam axis, “out” – along the transverse momentum of pair, and “side” – perpendicular to those two.

The geometric mean 3D BEC radius and source volume are calculated with R_i

$$\mathrm{R}_\mathrm{m}^3 = \prod\nolimits_{i=\mathrm{s,o,l}} \mathrm{R}_i, \quad \mathrm{V}=(2\pi)^{3/2}\mathrm{R}_\mathrm{s}^2\mathrm{R}_\mathrm{l}.$$

Energy dependence of BEC radii is fitted by function

$$f_i(\varepsilon) = a_1^i[1+a_2^i \ln^{a_3^i} \varepsilon],$$

i = s,o,l; $\varepsilon \equiv s/s_0$, $s_0 = 1$ GeV^2.
V.O. arXiv: 1312.4269 [nucl-ex], Adv. HEP 2015, 790646 (2015).

Space density of charged particles

The particle density is defined as follows:

$$n_{ch} = N_{ch} / \mathrm{V},$$

where N_{ch} is the total charged particle multiplicity, V – estimation for BEC volume.

The critical value for n_{ch} can be calculated with help of the equation above and transition to the critical total multiplicity:

$$N_{ch}^{c} = \eta^{-1}[(\Delta \mathrm{R_m})^2 + \sqrt{(9T^3 \mathrm{R_m} / 2\Delta^2)^2 + 0.25}]^{3/2}.$$

This relation is suggested for critical multiplicity for 3D case based on the model for 1D thermal Gaussian distribution [*S. Pratt, PLB 310, 159 (1993)*]. Here $\Delta = 0.25$ GeV is the momentum spread, $\eta = 0.25$ is the fraction of the pions to be emitted from a Gaussian source, $T \approx T_{ch}$ is the source temperature supposed equal to the parameter value at chemical freeze-out.

Taking into account the similarity of thermodynamic properties of matter created in p+p / A+A collisions the same analytic energy dependence of T_{ch} [*J. Cleymans et al., PRC 73, 034905 (2006)*] is suggested for various strong interaction processes.

Parameterization for N_{ch}

The following functions are used for p+p collisions:
a) hybrid function [*E.K.G. Sarkisyan et al. PRD 93, 054046 (2016)*]

$$1.60-0.03\ln\varepsilon+0.18\ln^2\varepsilon+0.03\varepsilon^{0.29};$$

b) 3NLO pQCD function for which numerical values of coefficients can be found elsewhere [*I.M. Dremin, J.W. Gary. PR 301, 349 (2001)*]

$$\frac{K_{LHPD}}{r_0}y^{-a_1c^2}\exp\left(2c\sqrt{y}+\frac{c}{\sqrt{y}}\left[r_1+2a_2c^2+\frac{\beta_1}{\beta_0^2}(\ln 2y+2)\right]+\frac{c^2}{y}\left[a_3c^2+\frac{r_1^2}{2}+r_2-\right.\right.$$
$$\left.\left.-\frac{a_1\beta_1}{\beta_0^2}(\ln 2y+1)\right]\right)+n_0,\quad y\equiv\ln\left(\frac{K_0\sqrt{\varepsilon}}{2\Lambda_{QCD}}\right).$$

Parameterizations for A+A collisions:
c) hybrid function [*E.K.G. Sarkisyan et al. PRD 93, 054046 (2016)*]

$$k(-0.577+0.394\ln\varepsilon+0.213\ln^2\varepsilon+0.005\varepsilon^{0.55});$$

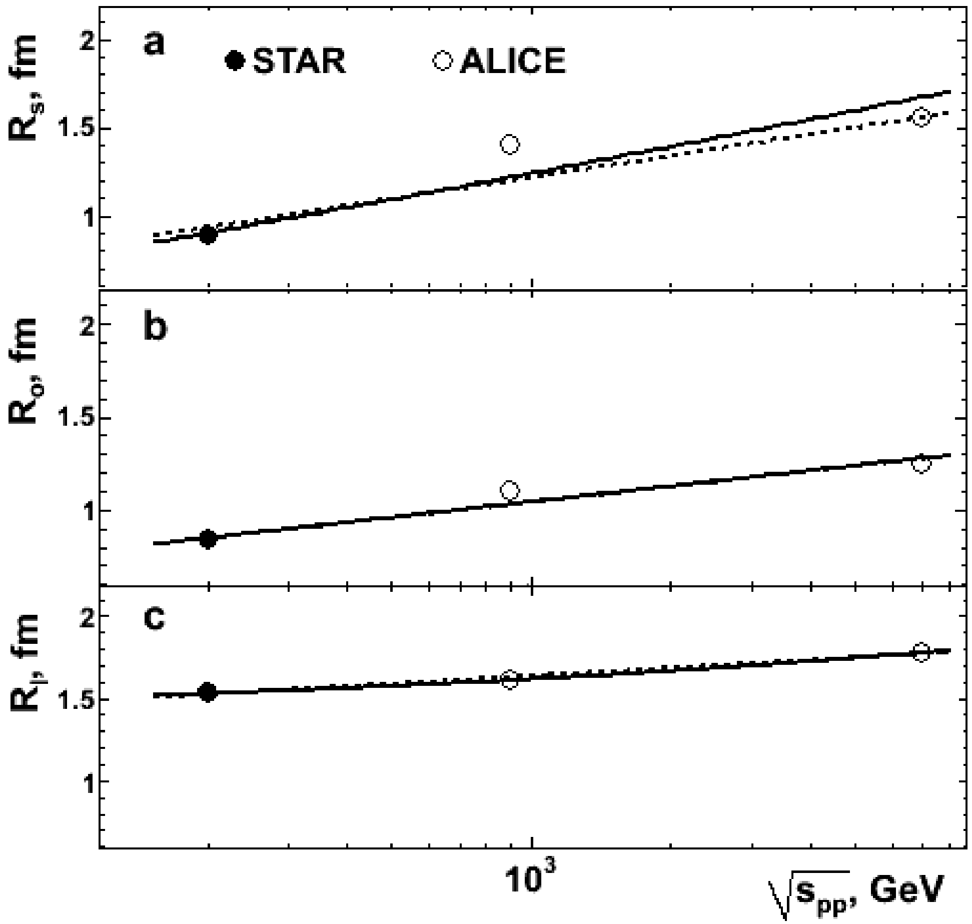
d) hybrid function [*E. Abbas et al. PLB 726, 610 (2013)*]

$$k(0.512\varepsilon^{0.15}\ln\varepsilon+1.962),$$

where $k\equiv\langle N_{part}/2\rangle=382.1$ for central Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV.

p+p: BEC radii vs collision energy

Fig. 1. Energy dependence of the BEC radii. Errors for points are statistical only. Fits by f_i are shown by solid lines, dashed lines present the results for f_i with $a_3 = 1.0$.



- Fits (at fixed a_3) agree with experimental BEC reasonably.

- Values of a_3 are close to the 1.0 for transverse radii $R_{s,o}$

- Inclusion of total errors allows us to get statistically acceptable fit qualities for all BEC radii.

p+p: R_m and V at freeze-out

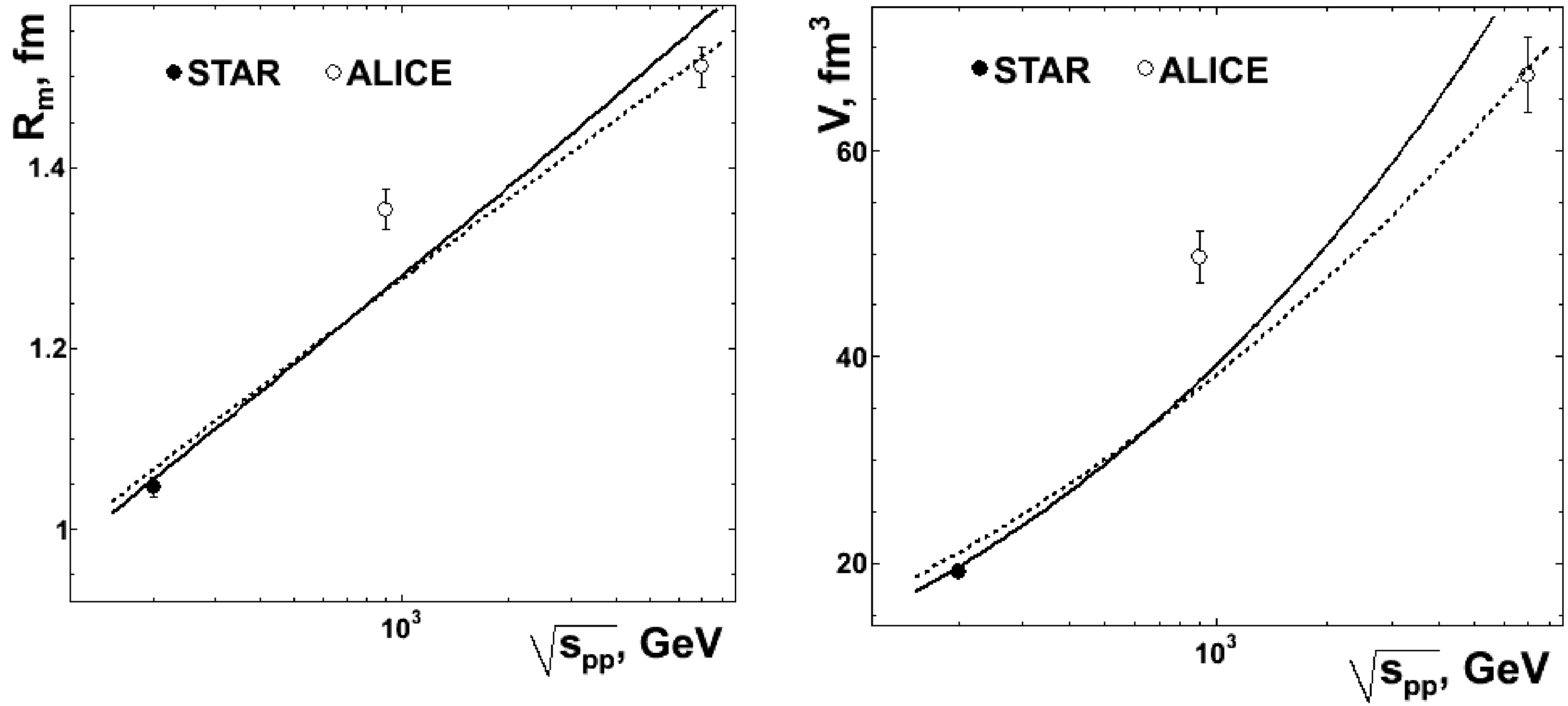
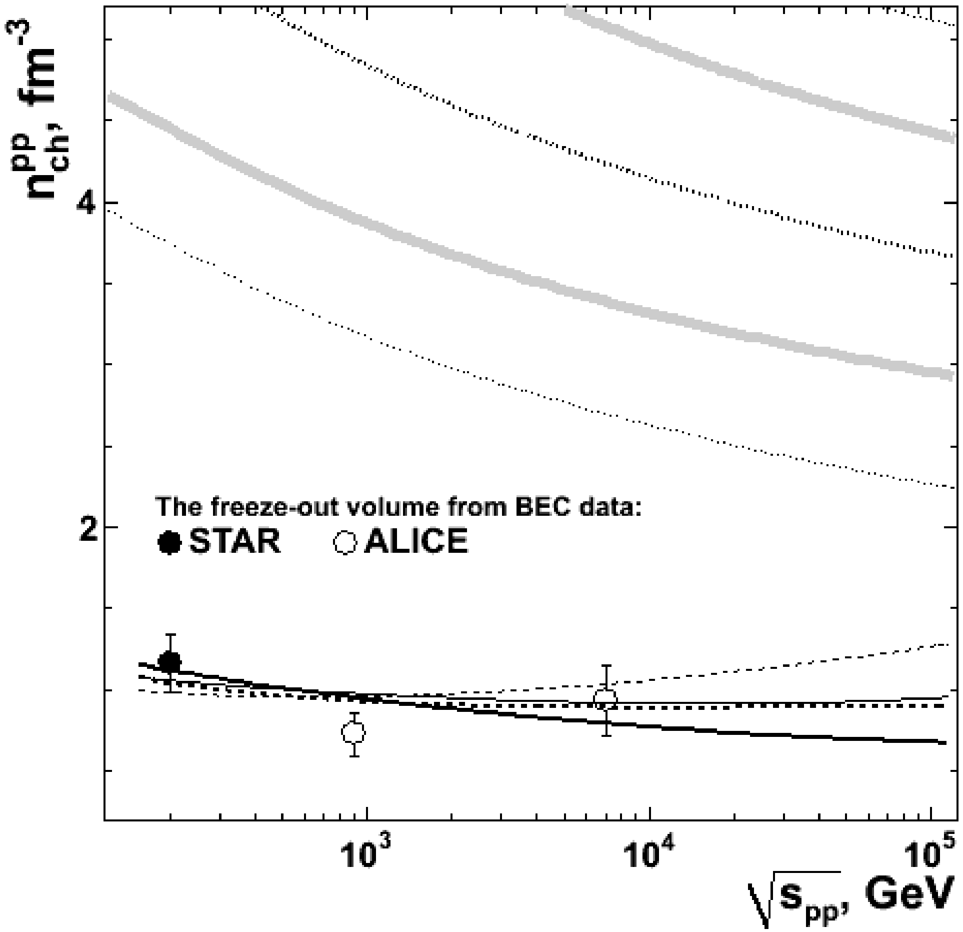


Fig. 2. Energy dependence of R_m (left) and V (right) with statistical errors for points. Smooth curves are calculated with help of fit results for BEC radii, solid lines are from fits of BEC radii by f_j and dashed lines correspond to the fits by specific case $R_i \propto \ln\varepsilon$, $i = s; o; l$.

- Expectations for $R_m(\sqrt{s_{NN}})$ and $V(\sqrt{s_{NN}})$ describe of experimental measured values at qualitative level.

p+p: density of charged particles

Fig. 3. Energy dependence of n_{ch} and critical parameter in p + p collisions. Points are calculated with help of the hybrid function (a) for N_{ch} and the experimental estimations for V. Solid lines correspond to the hybrid approximation (a) of N_{ch} and dashed lines are for 3NLO pQCD equation (b) for two approaches for V.Critical density is shown by dotted line with its statistical uncertainty levels represented by thin dotted lines. The heavy grey lines correspond to the systematic ±1 s.d. of the quantity calculated by varying of η on ±0.05.



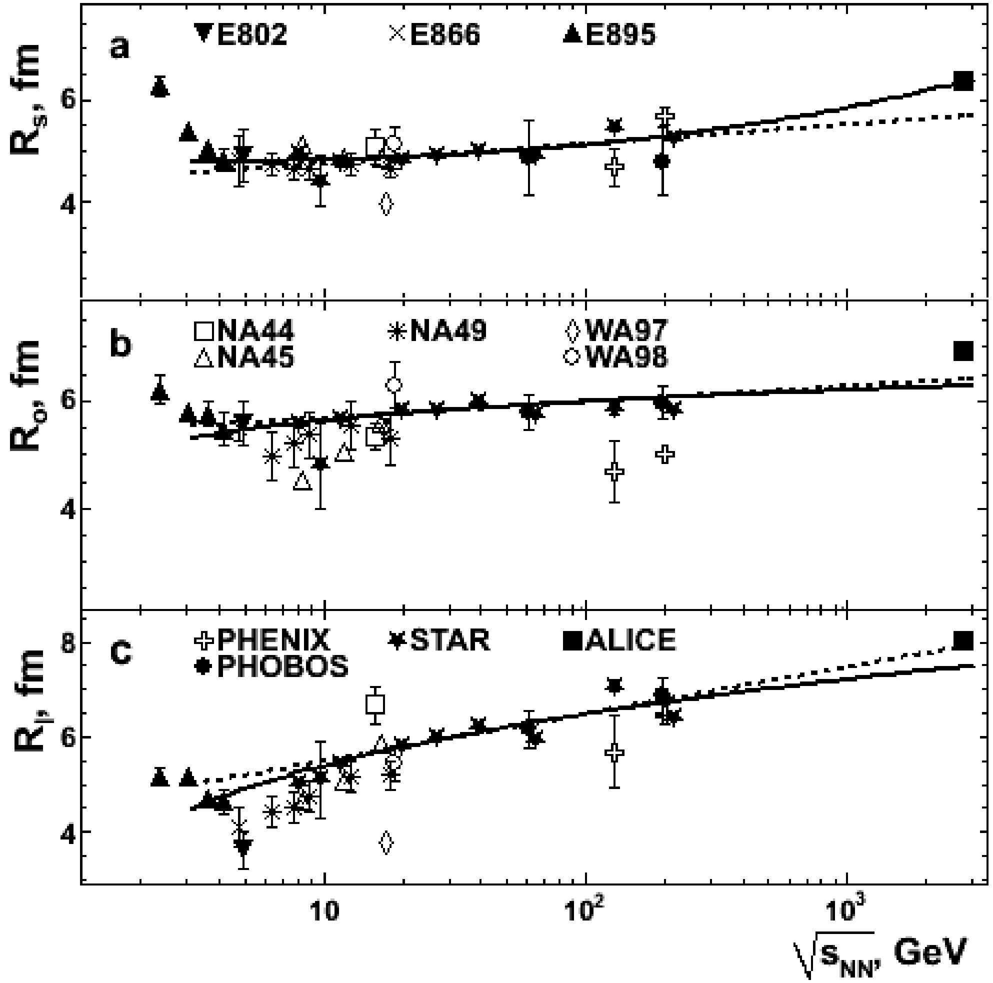
- Curve for $n_{ch}(\sqrt{s_{NN}})$ agrees rather well with experimental values.

- The n_{ch} smaller than its critical value at collision energies up to $\sqrt{s_{pp}} \approx 100$ TeV.

A+A: BEC radii vs collision energy

Fig. 4. Energy dependence of the BEC radii. Errors for points are statistical only. Fits by fi are shown by solid lines, dashed lines present the results for fi with $a_3 = 1.0$.

V.O. Adv. HEP 2015, 790646 (2015).



- Fit functions agree with experimental BEC radii reasonably at $\sqrt{s_{NN}} \geq 5$ GeV.
- Inclusion of total errors allows us to get statistically acceptable fit qualities for BEC radii (χ^2/ndf ~ ~ 1.0–2.6).

A+A: R_m and V at freeze-out

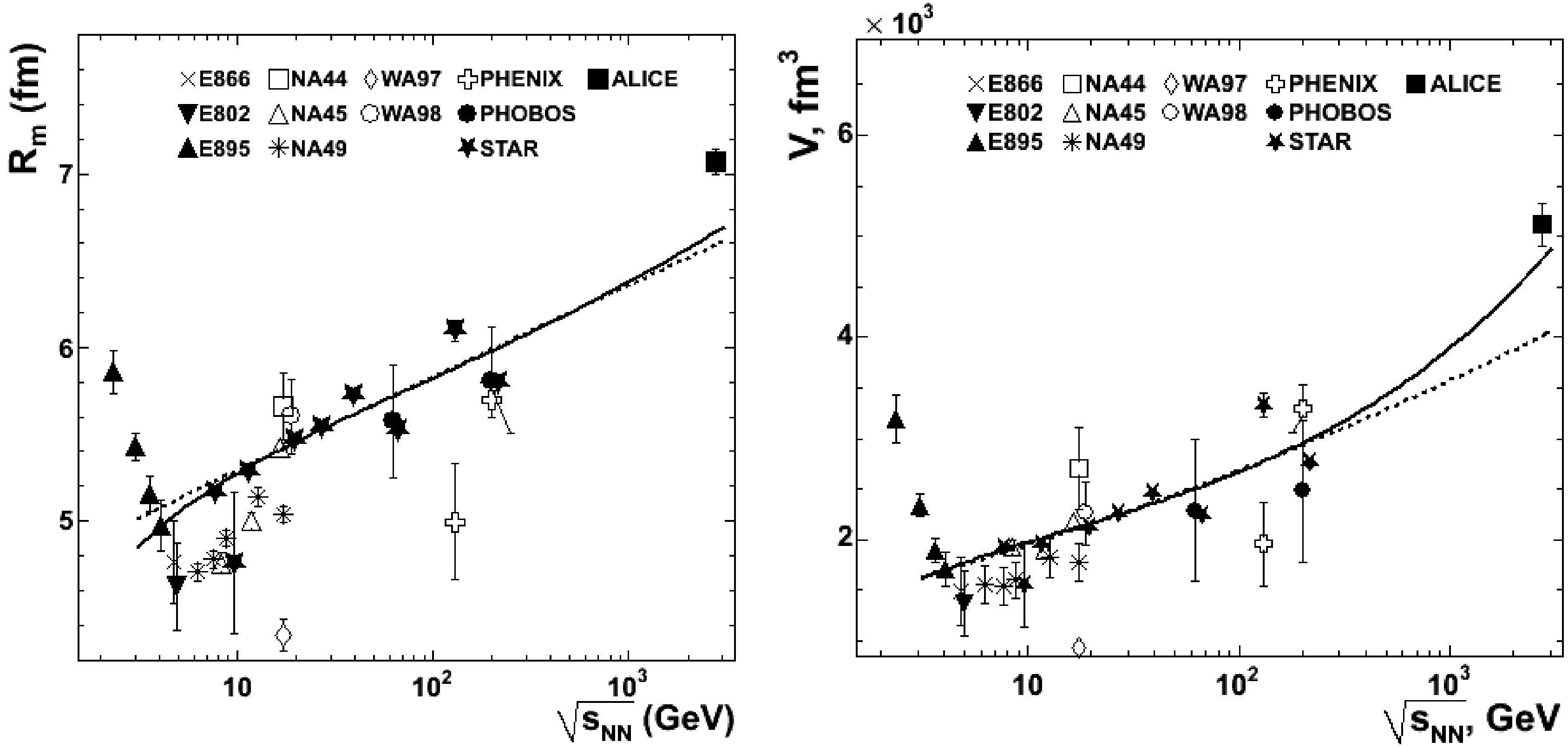
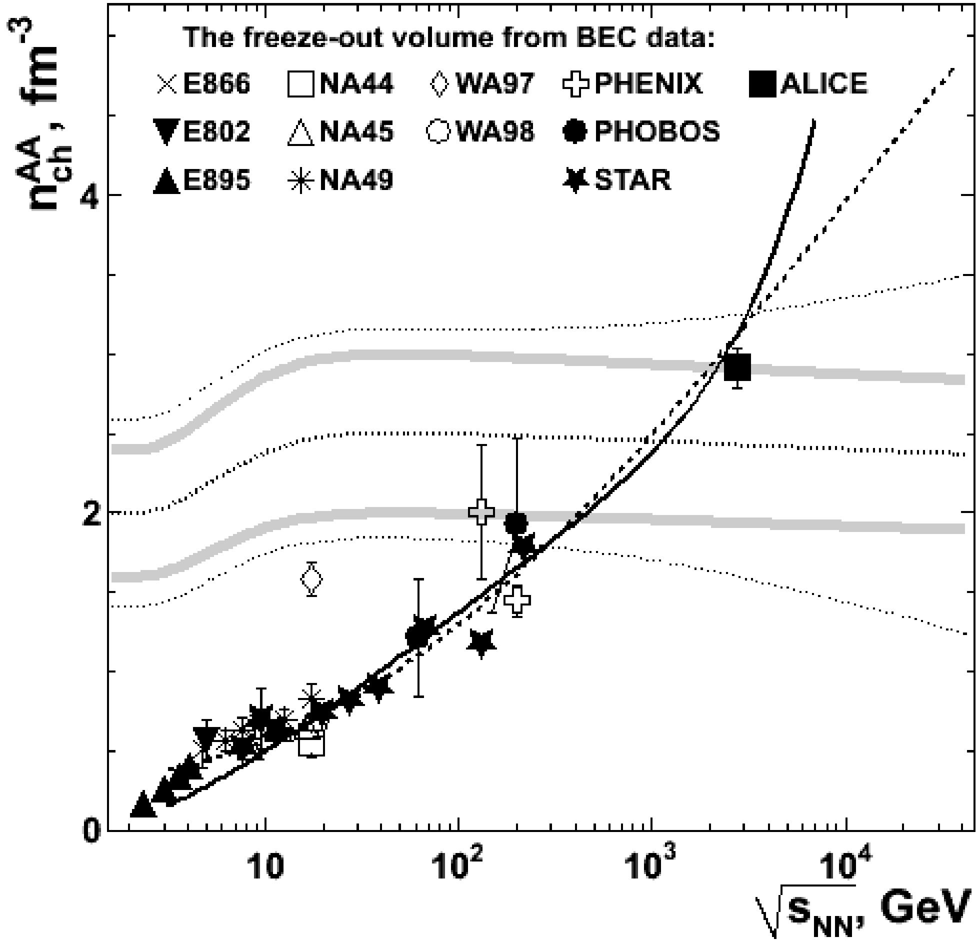


Fig. 5. Energy dependence of R_m (left) and V (right) with statistical errors for points. Smooth curves are calculated with help of fit results for BEC radii, solid lines are from fits of BEC radii by f_j and dashed lines correspond to the fits by specific case $R_i \propto \ln\varepsilon$, $i = s; o; l$.

- Expectations for $R_m(\sqrt{s_{NN}})$ and $V(\sqrt{s_{NN}})$ describe reasonably of experimental measured values, especially for freeze-out volume.

A+A: density of charged particles

Fig. 6. Energy dependence of n_{ch} and critical quantity in A + A collisions. Points are calculated with help of the hybrid function (d) for N_{ch} and the experimental estimations for V. Solid line corresponds to the hybrid approximation (c) for N_{ch} and dashed line is for equation (d). Critical density is shown by dotted line with its statistical uncertainty levels represented by thin dotted lines. The heavy grey lines correspond to the systematic ±1 s.d. of the quantity calculated by varying of η on ±0.05.



- Curves for $n_{ch}(\sqrt{s_{NN}})$ agree well with experimental values.

- The situation is quite different with regard of *p+p*:
n_{ch} larger than its critical value with error band at $\sqrt{s_{NN}} > 5$ TeV.

Summary

1. The charged particle density and its critical value is estimated for strong interaction processes (p+p and A+A) with help of Bose–Einstein correlations at various collision energies.

2. The experimental dependence $n_{ch}(\sqrt{s_{pp}})$ is almost flat in p+p while the $n_{ch}(\sqrt{s_{NN}})$ increases with energy in A+A collisions. The charged particle density is noticeably larger in heavy ion collisions than that in $p + p$ at similar collision energies.

3. The Bose–Einstein condensation is not expected for secondary pions in p+p collisions up to $\sqrt{s_{pp}} \approx 100$ TeV. But there is possibility for Bose–Einstein condensation and novel effects, in particular, pion laser in A+A collisions at $\sqrt{s_{NN}} > 5$ TeV.

Thanks for you attention