Institut für Theoretische Physik I

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Dynamical compression of the ^{16}O nucleus by a moving antiproton

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DPG meeting, Bonn, 16.03.2010

Motivation

Antiproton-nucleus collisions give unique information about antimatter-matter interaction and possible in-medium modifications of the annihilation process.

The properties of an antiproton in nuclear medium can be characterized by its optical potential:
real part is governed by long-range interactions (mean field),
imaginary part – by short-range interactions ($\bar{p}N$ collisions).

Theory predicts a very strong attractive real part

$$\mathrm{Re}(V_{\mathrm{opt}}) \simeq -700\ \mathrm{MeV}$$

(G-parity transformation of nucleon mean field potentials,
H.P. Duerr and E. Teller, 1956; N. Auerbach et al, 1986)

Predictions for imaginary part range from

$$\mathrm{Im}(V_{\mathrm{opt}}) \simeq -100\ \mathrm{MeV}$$

as follows from a simple tρ-approximation to

$$\mathrm{Im}(V_{\mathrm{opt}}) \simeq -1500\ \mathrm{MeV}$$

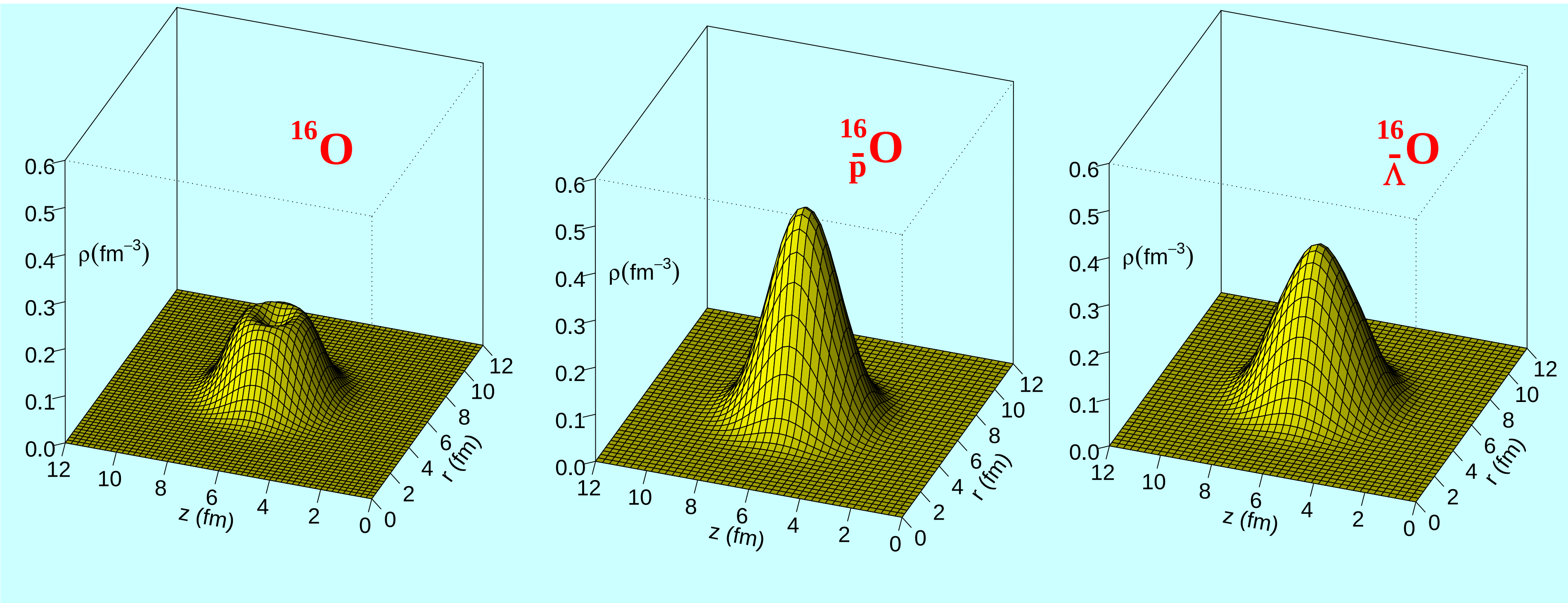
if the many-body annihilation channels are taken into account
(E. Hernández and E. Oset, 1986)

Phenomenology: $\mathrm{Re}(V_{\mathrm{opt}}) \simeq \mathrm{Im}(V_{\mathrm{opt}}) \simeq -(100 \div 200)\ \mathrm{MeV}$

(S. Teis, W. Cassing, T. Maruyama, and U. Mosel, 1993;
E. Friedman, A. Gal, and J. Mares, 2005;
A.L., I.A. Pshenichnov, I.N. Mishustin, and W. Greiner, 2009)

Static calculations of $\bar{p}$ - induced compression

G-parity potential



$BE\,(^{16}\mathrm{O}) = 130\ \mathrm{MeV}$ $BE\,(^{16}_{\bar{p}}\mathrm{O}) = 1051\ \mathrm{MeV}$ $BE\,(^{16}_{\bar{\Lambda}}\mathrm{O}) = 565\ \mathrm{MeV}$

NL3 NL3 NLZ

T. Buervenich, I.N. Mishustin, L.M. Satarov, J.A. Maruhn, H. Stoecker and W. Greiner, PLB 542, 261 (2002).

Similar results for nuclear compression by an antiproton at rest have been obtained within the GiBUU calculations (A.L., I.N. Mishustin, L.M. Satarov, W. Greiner, PRC 78, 014604 (2008))

Signals from antiproton annihilation
in a compressed nuclear system:
-enhanced kinetic energies of produced nucleons,
-softer mesonic invariant mass spectra,
-radial flow of the nuclear fragments,
-strangeness enhancement due to possible deconfinement
(A.L. et al., 2008, I.N. Mishustin et al., 2005)

GiBUU model

The Giessen Boltzmann-Uehling-Uhlenbeck model:

http://gibuu.physik.uni-giessen.de/GiBUU

Relativistic kinetic equations (D. Vasak et al., 1987; H.-Th. Elze et al.,1987; B. Blaettel et al., 1993):

$$(p_0^\star)^{-1}[p_\mu^\star \partial_x^\mu + (p_\mu^\star F_j^{k\mu} + m_j^\star(\partial_x^k m_j^\star))\partial_k^{p^\star}] f_j(x,\mathbf{p}^\star) = I_j[\{f\}]$$

$$j = N,\ \bar{N},\ \Delta,\ \bar{\Delta},\ \pi\ldots$$

$V_j^\mu = g_{\omega j}\omega^\mu + g_{\rho j}\tau^3\rho^{3\mu} + \frac{e}{2}(B_j + \tau^3)A^\mu$ - vector field,

$m_j^\star = m_j + g_{\sigma j}\sigma$ - effective mass, $F_j^{\mu\nu} = \partial^\mu V_j^\nu - \partial^\nu V_j^\mu$ -field tensor,

$p^{\star\mu} = p^\mu - V_j^\mu$ - kinetic four-momentum, $p^{\star\mu}p_\mu^\star = m_j^{\star\,2}$ - mass shell condition

Relativistic mean field (RMF) acting on baryons and antibaryons:
non-linear Walecka parameterization NL3 (G.A. Lalazissis et al.,1997).
Antibaryon-meson coupling constants (I.N. Mishustin et al, 2005):

$g_{\omega\bar{B}} = -\xi g_{\omega N}, \quad g_{\rho\bar{B}} = \xi g_{\rho N}, \quad g_{\sigma\bar{B}} = \xi g_{\sigma N},$ $0 < \xi \leq 1$ – scaling factor.

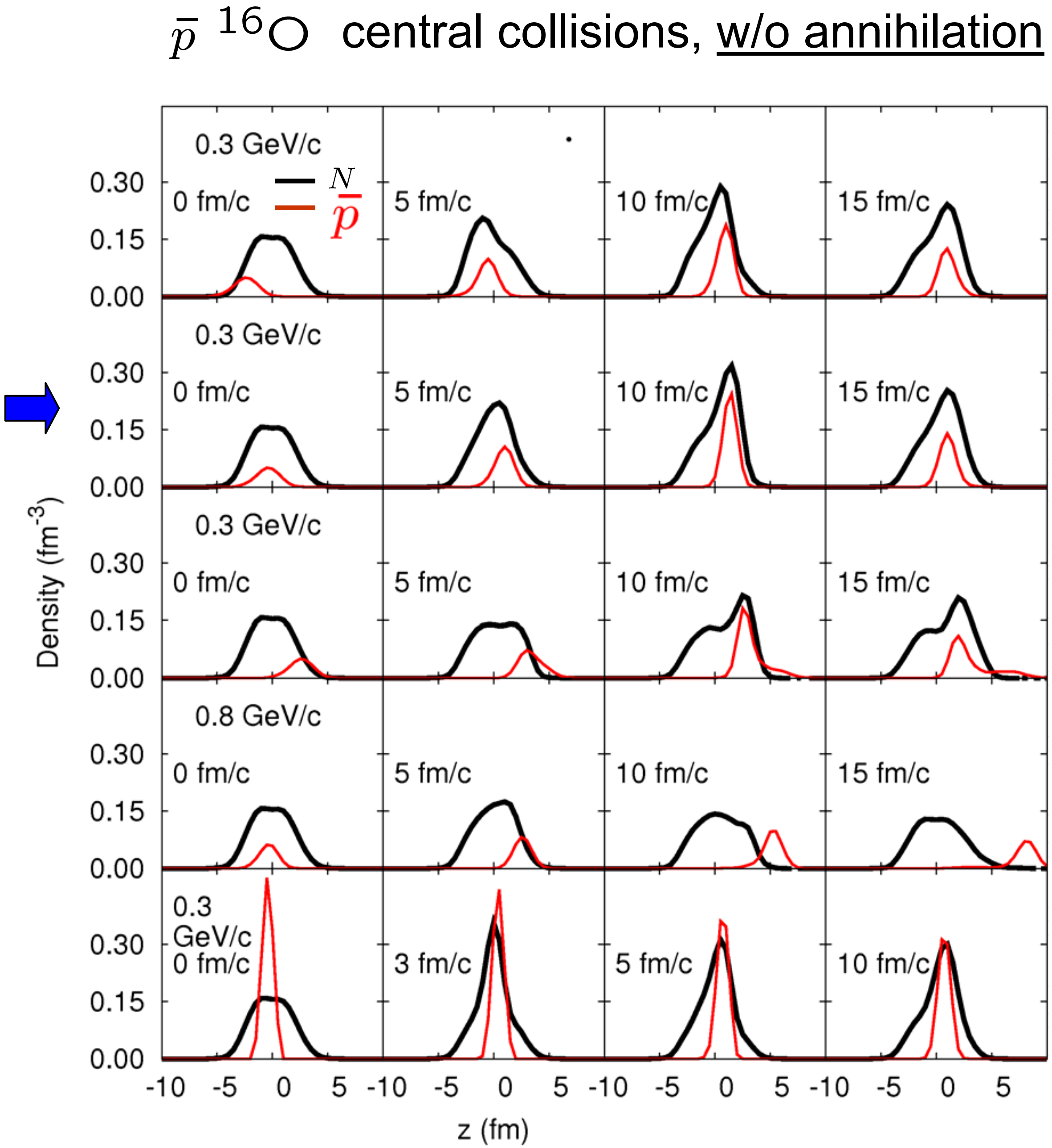
G-parity transformed nuclear potential: ξ=1, $\mathrm{Re}(V_{\mathrm{opt}}) \simeq -660$ MeV.

→ Use phenomenological couplings: ξ=0.22, $\mathrm{Re}(V_{\mathrm{opt}}) \simeq -150$ MeV.

Dynamical compression of a nucleus by an antiproton in-flight

A.L., I.N. Mishustin, L.M. Satarov, W. Greiner,
arXiv:0912.1794

Stronger compression for initially slower and closer to the nuclear centre antiproton.



Maximum nucleon density and survival probability of $\bar{p}$

$$P_{\mathrm{surv}} = \exp\{-\int_0^t dt' \, \Gamma_{\mathrm{ann}}(t')\}$$

$$\Gamma_{\mathrm{ann}} = \rho_N \langle v_{\bar{p}N} \sigma_{\mathrm{ann}} \rangle$$

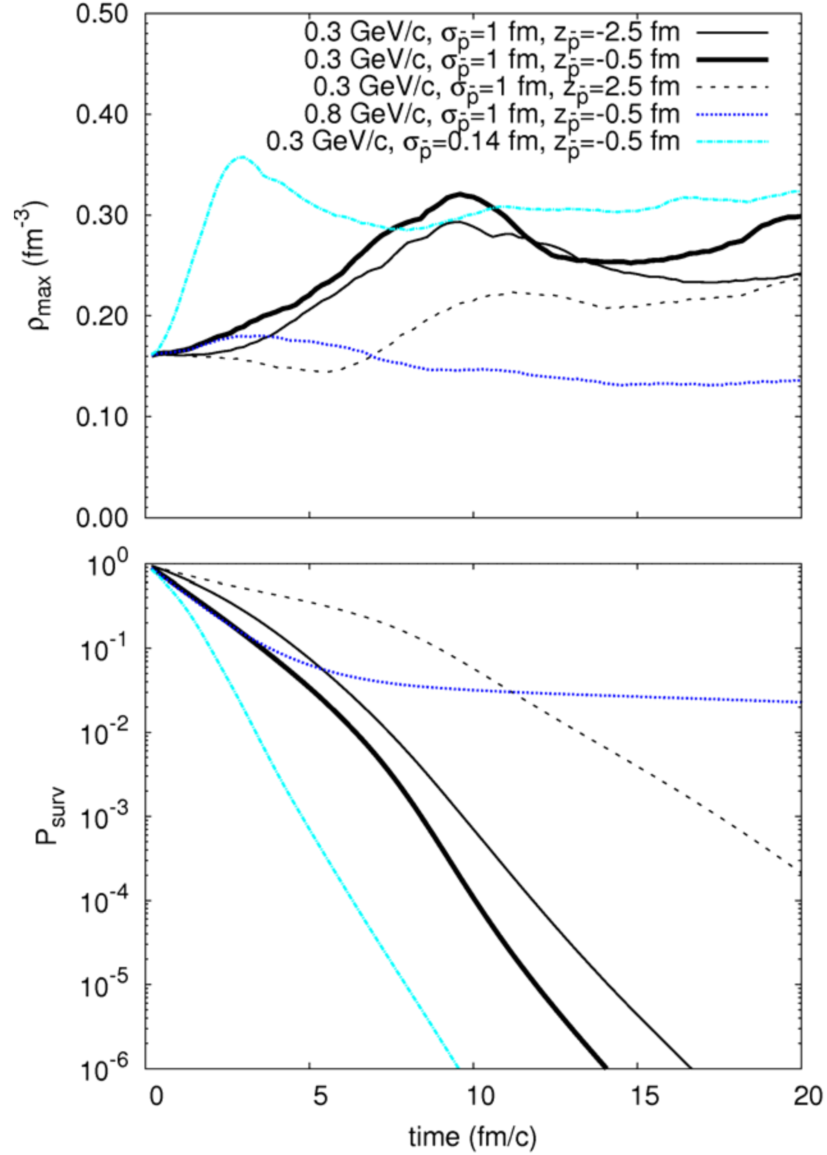
The probability of annihilation in a compressed state:

$$P_{\mathrm{compr}}(\rho_c) = P_{\mathrm{surv}}(t_1) - P_{\mathrm{surv}}(t_2)$$

$$t_1 < t_2, \quad \rho_{\max}(t_1) = \rho_{\max}(t_2) = \rho_c$$

$$\Rightarrow \quad P_{\mathrm{compr}}(2\rho_0) \sim 10^{-3}$$

$\bar{p}\ {}^{16}\mathrm{O}$



-Events with nuclear compression are very rare: in the most events the antiproton annihilates at the nuclear periphery.

-At high beam momenta the antiproton must be slowed down by inelastic collisions with nucleons in order to induce compression.

A hybrid calculation:

1. Determine coordinates $\vec{r}$ and momentum $\vec{p}$ of an antiproton at the annihilation point from a standard GiBUU.

2. Initialize $\overline{p}$ at $(\vec{r};\vec{p})$ and run GiBUU w/o annihilation.

3. Compute $P_{\mathrm{compr}}(\rho_c)$ - the probability of annihilation in a compressed state $(\rho_{\mathrm{max}} > \rho_c)$.

$\bar{p}\ ^{16}O$

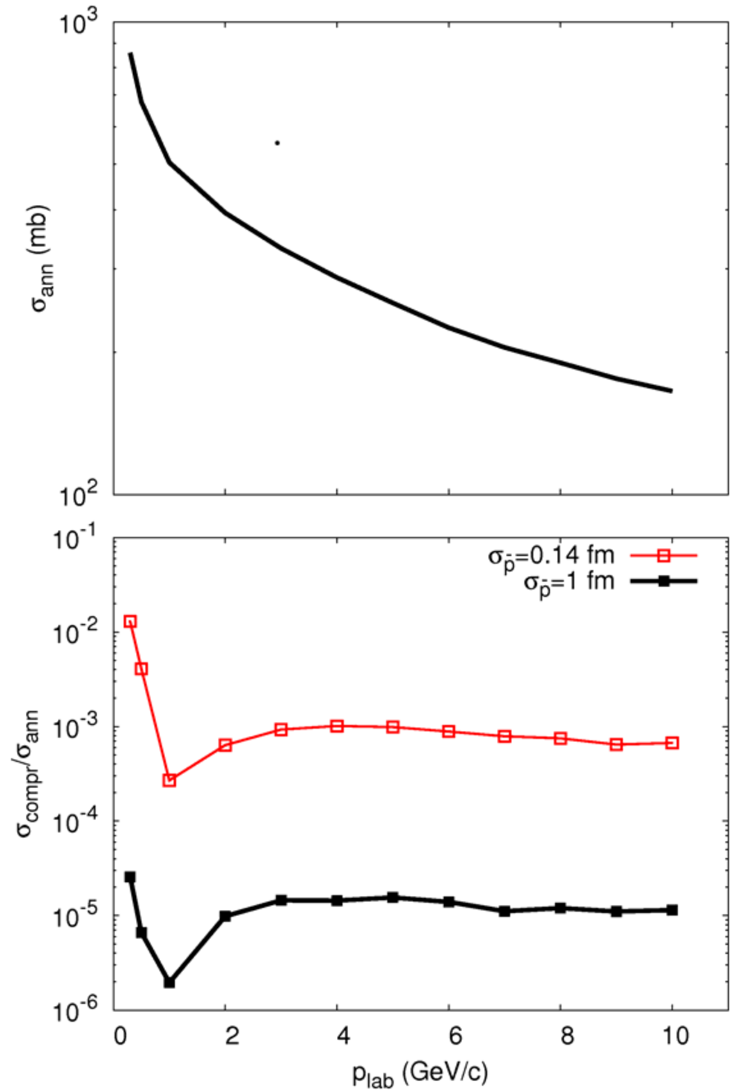
Inclusive annihilation cross section (standard GiBUU)

Cross section of $\bar{p}$ annihilation at the compressed nuclear state (hybrid calculation):

averaging over events with fixed b

$$\sigma_{\rm compr} = \int\limits_0^\infty db\, 2\pi b\, \overline{P_{\rm compr}}(\rho_c, b)$$

Relative probability of annihilation at $\rho_{max} > \rho_c = 2\rho_0$



Summary and outlook

- A slowly moving antiproton ($p \leq p_F$) gives rise to the local nuclear compression up to $\sim 2\rho_0$.

-At FAIR beam momenta 3-10 GeV/c the probability of antiproton annihilation in compressed nuclear state is $\sim 10^{-5}$.

$\Rightarrow$ Event rate: $Y=10^2 - 10^3\ s^{-1}$

Next steps:

-strangeness production in $\bar{p}p$ collisions

(with A. Goritschnig and U. Mosel)

-(double) hypernuclei production in antiproton-induced reactions

(with T. Gaitanos, H. Lenske, and U. Mosel)

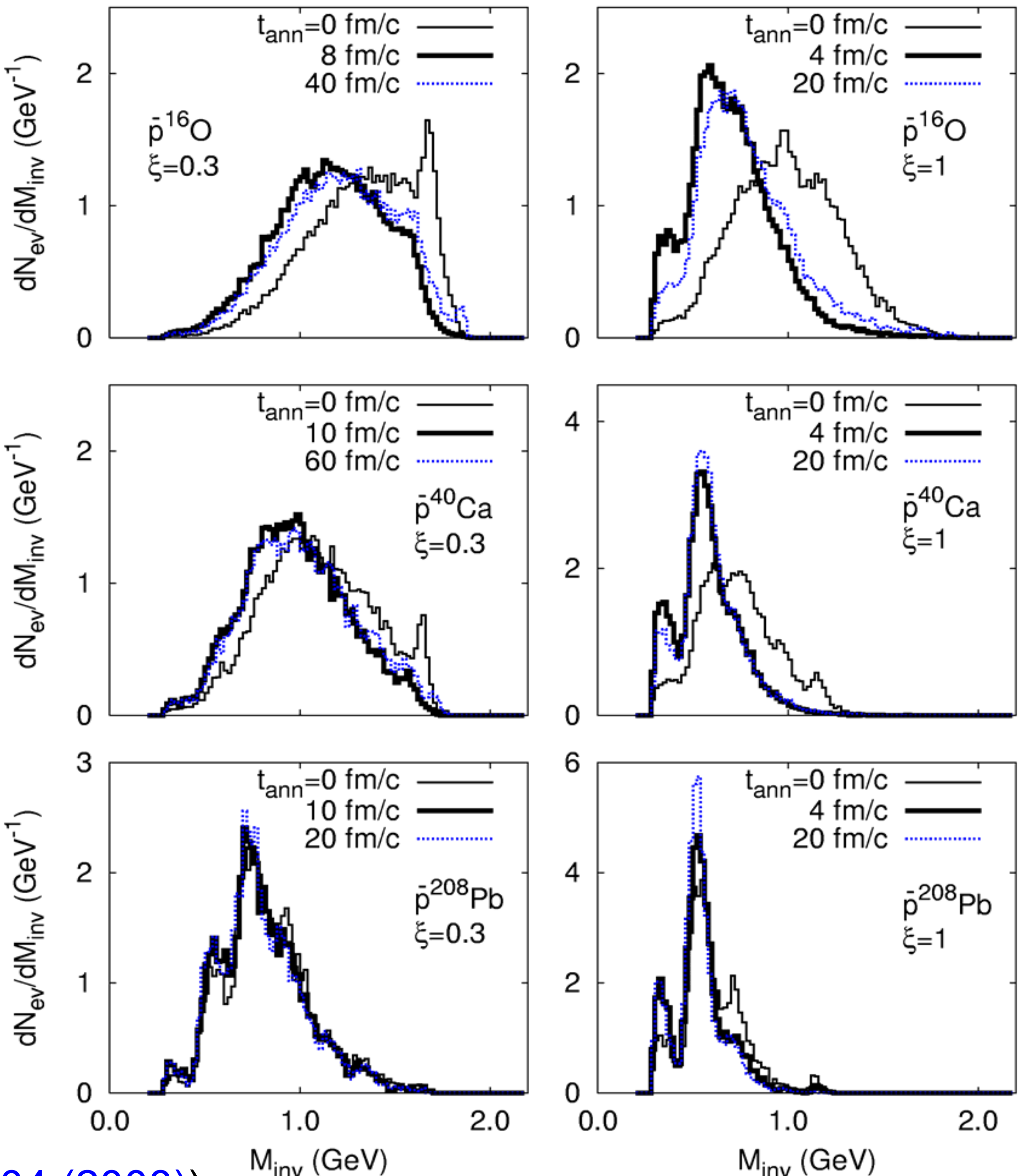
Many thanks to A. Gillitzer, U. Mosel, I.A. Pshenichnov, J. Ritman, and to the members of the GiBUU team for stimulating discussions !

This work was supported by the Helmholtz International Center for FAIR within the framework of the LOEWE program.

HIC for FAIR
Helmholtz International Center

Backup

Annihilation event spectra on the total invariant mass of emitted mesons.



Shift of the peak by

$\sim$ 0.5 GeV to smaller M_{inv} for light systems

due to compression.

(A.L. et al, PRC 78, 014604 (2008))

Nucleon kinetic energy spectra

Nucleons are accelerated mostly by

$$\pi N \rightarrow \Delta \rightarrow \pi N$$

processes

(M. Cahay, J. Cugnon,

P. Jasselette,

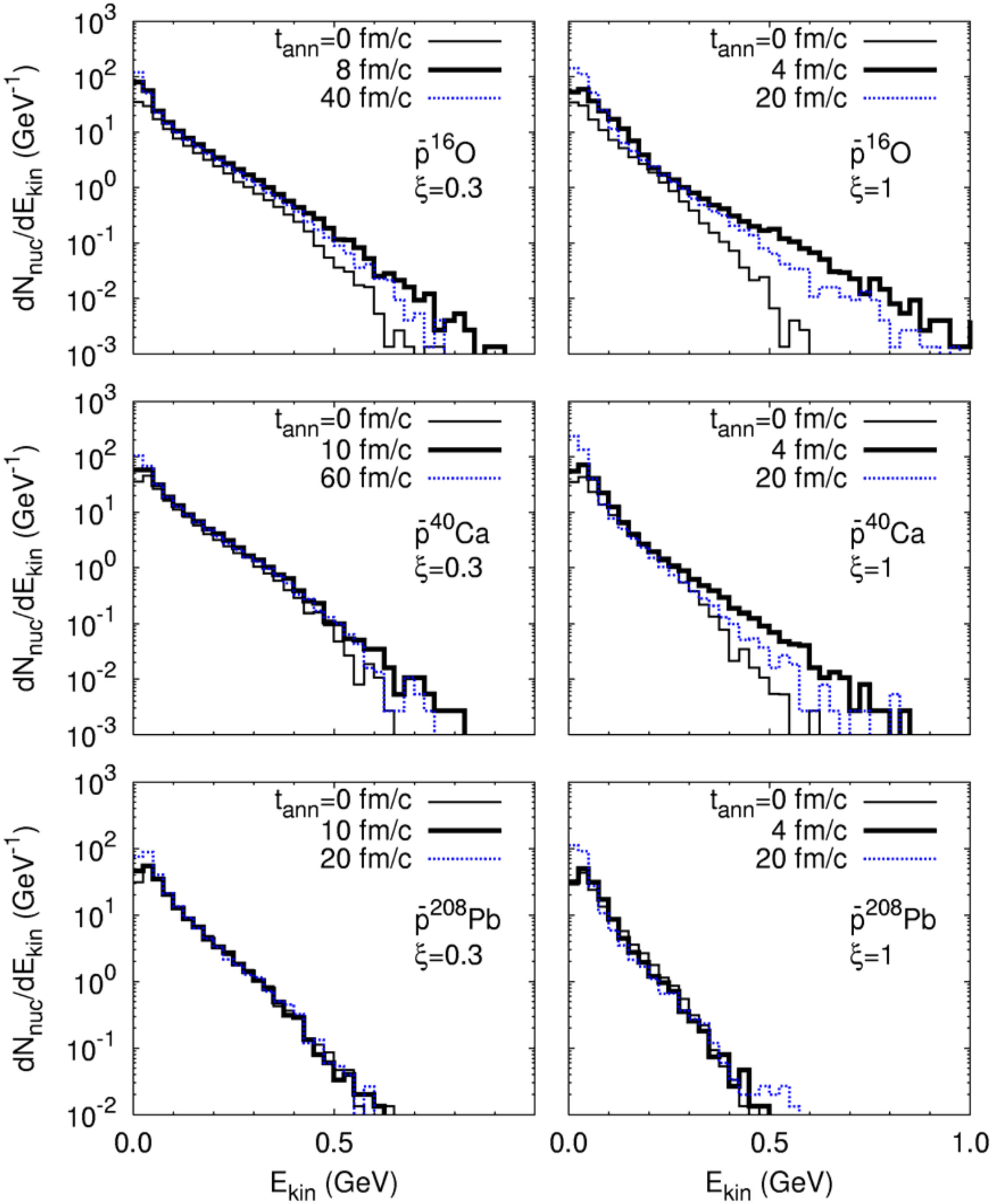
J. Vandermeulen,

PLB 115, 7 (1982))

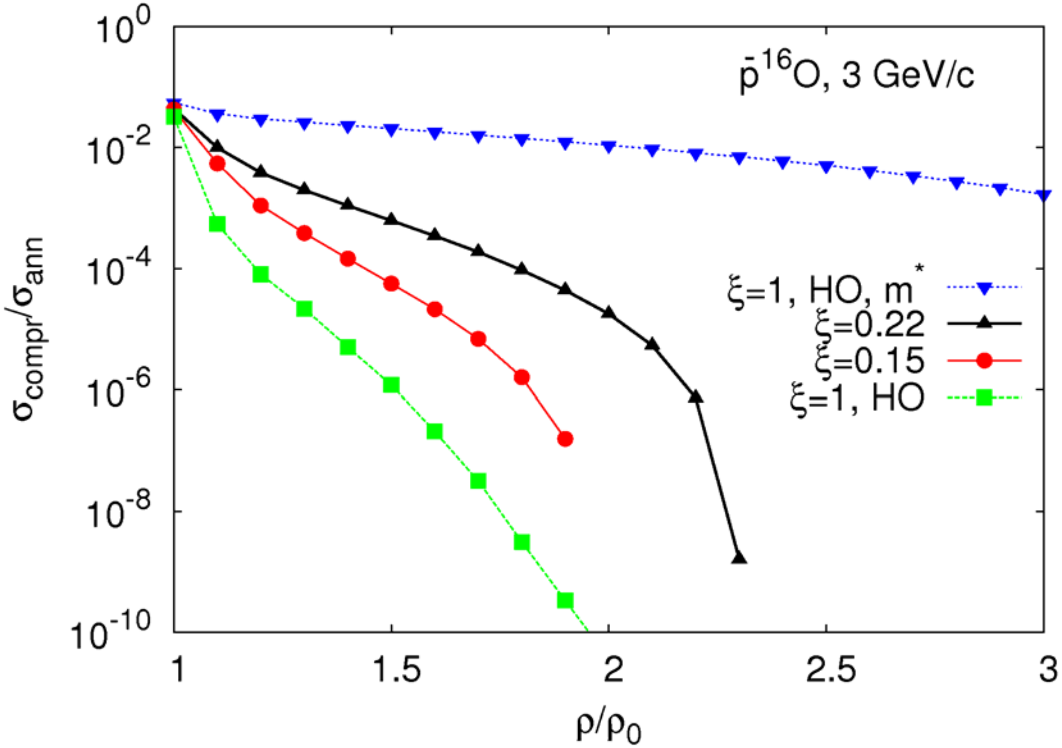
Compression enhances

the slope temperature.

Effect is stronger for lighter systems.



Sensitivity to the antiproton-meson coupling constants and to the in-medium modifications of annihilation



HO – Hernández and Oset formula for the many-body annihilation cross section:

$$\sigma_{\rm ann}^{\rm med} = \sigma_{\rm ann}\left(1 + 4.59\frac{\rho}{\rho_0} + 10.6\left(\frac{\rho}{\rho_0}\right)^2 + 12.8\left(\frac{\rho}{\rho_0}\right)^3\right)$$

Relativistic mean field (RMF) Lagrangian density:

$$\mathcal{L} = \sum_{j=N,\bar{N}} \bar{\psi}_j[\gamma(i\partial - g_{\omega j}\omega - g_{\rho j}\vec{\rho}\vec{\tau} - \frac{e}{2}(B_j + \tau^3)A) - m_N - g_{\sigma j}\sigma]\psi_j + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 - \frac{1}{4}\vec{\rho}_{\mu\nu}\vec{\rho}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^2 - \frac{1}{4}A_{\mu\nu}A^{\mu\nu} \ ,$$

$$U(\sigma) = \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4 \ ,$$

$$G_{\mu\nu} \equiv \partial_\mu G_\nu - \partial_\nu G_\mu \ , \qquad G = \omega,\ \vec{\rho},\ A \ .$$

G.A. Lalazissis et al., PRC 55, 540 (1997);
I.N. Mishustin et al., PRC 71, 035201 (2005);
A.L. et al., PRC 76, 044909 (2007).

NL3 set of parameters (G.A. Lalazissis et al.,1997):

m_N=939.0 MeV, m_σ=508.2 MeV, m_ω=782.5 MeV, m_ρ=763.0 MeV, $g_{\sigma N}$=10.2, $g_{\omega N}$=12.9, $g_{\rho N}$=4.5, g_2=-10.4 fm^{-1}, g_3=-28.9

$\Rightarrow$ K=271.8 MeV, $m_N^\star = 0.60 m_N$ at ρ_0=0.148 fm^{-3},
and good reproduction of the g.s. properties of finite nuclei.

Meson field equations (mean field approximation):

$$\partial_\nu \partial^\nu \sigma + \frac{\partial U(\sigma)}{\partial \sigma} = -\sum_j g_{\sigma j}\, \rho_{Sj} \ ,$$

$$(\partial_\nu \partial^\nu + m_\omega^2)\, \omega^\mu = \sum_j g_{\omega j}\, j^\mu_{Bj} \ ,$$

$$(\partial_\nu \partial^\nu + m_\rho^2)\, \rho^{3\,\mu} = \sum_j g_{\rho j}\, j^\mu_{Ij} \ ,$$

$$\partial_\nu \partial^\nu A^\mu = \sum_j e\, j^\mu_{Qj} \ ,$$

where $\rho_{Sj}(x) =< \bar{\psi}_j \psi_j >= \frac{g_j}{(2\pi)^3} \int \frac{d^3 p^\star}{p^{\star 0}} m_j^\star f_j(x, \mathbf{p}^\star) \ ,$

$$j^\mu_{Aj}(x) =< \bar{\psi}_j \gamma^\mu O_A \psi_j >= \frac{g_j}{(2\pi)^3} \int \frac{d^3 p^\star}{p^{\star 0}} p^{\star\mu} O_A f_j(x, \mathbf{p}^\star) \ ,$$

$$O_B = 1, \quad O_I = \tau^3, \quad O_Q = \frac{B_j + \tau^3}{2} \ ,$$

g_j - spin degeneracy

Technical approximation : $\partial_\nu \partial^\nu = \cancel{(\partial_t)^2} - \triangle$

Collision integral:

E.g., for $N_1N_2 \rightarrow N_3N_4$:

relative velocity of N_1 and N_2

$$I_1 = \int \frac{g_2 d^3 p_2^\star}{(2\pi)^3} \int d\sigma^\star_{12\rightarrow 34}\, v^\star_{12} \, (f_3 f_4 \bar{f}_1 \bar{f}_2 - f_1 f_2 \bar{f}_3 \bar{f}_4) \ ,$$

(in-medium) differential cross section

where $\bar{f} = 1 - f$

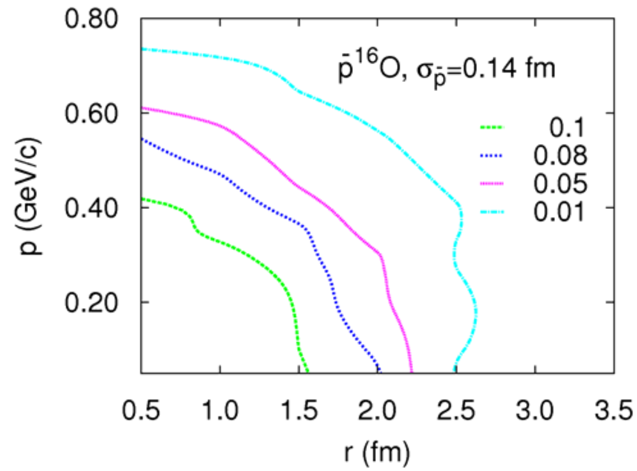
Included channels: $\bar{N}N \rightarrow \mathrm{mesons}$ -statistical annihilation model by I.A. Pshenichnov et al., 1992,

$\bar{N}N \rightarrow \bar{N}N$ also with charge exchange,

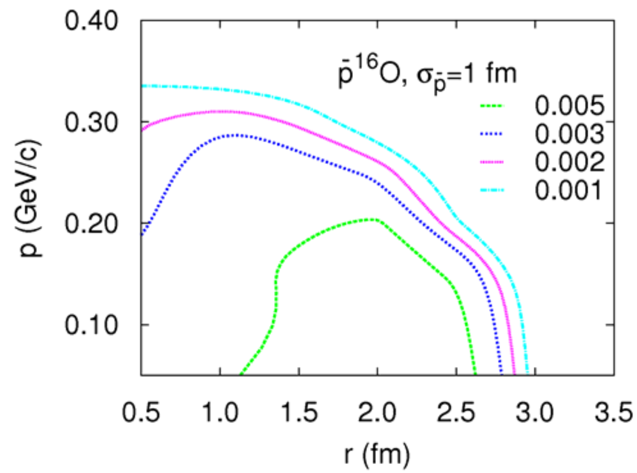
$\bar{N}N \rightarrow \bar{B}B + \mathrm{mesons}$,

$MB \rightarrow R \rightarrow MB, \ \ BB \rightarrow BB$ elastic and inelastic

Contour plots of the antiproton annihilation probability in the compressed nuclear state $P_{\mathrm{compr}}(2\rho_0)$. The probability is averaged w/r to $\cos(\theta) = \vec{r}\vec{p}/rp$, where $\vec{r}$ and $\vec{p}$ are the initial position and momentum of the antiproton, respectively.



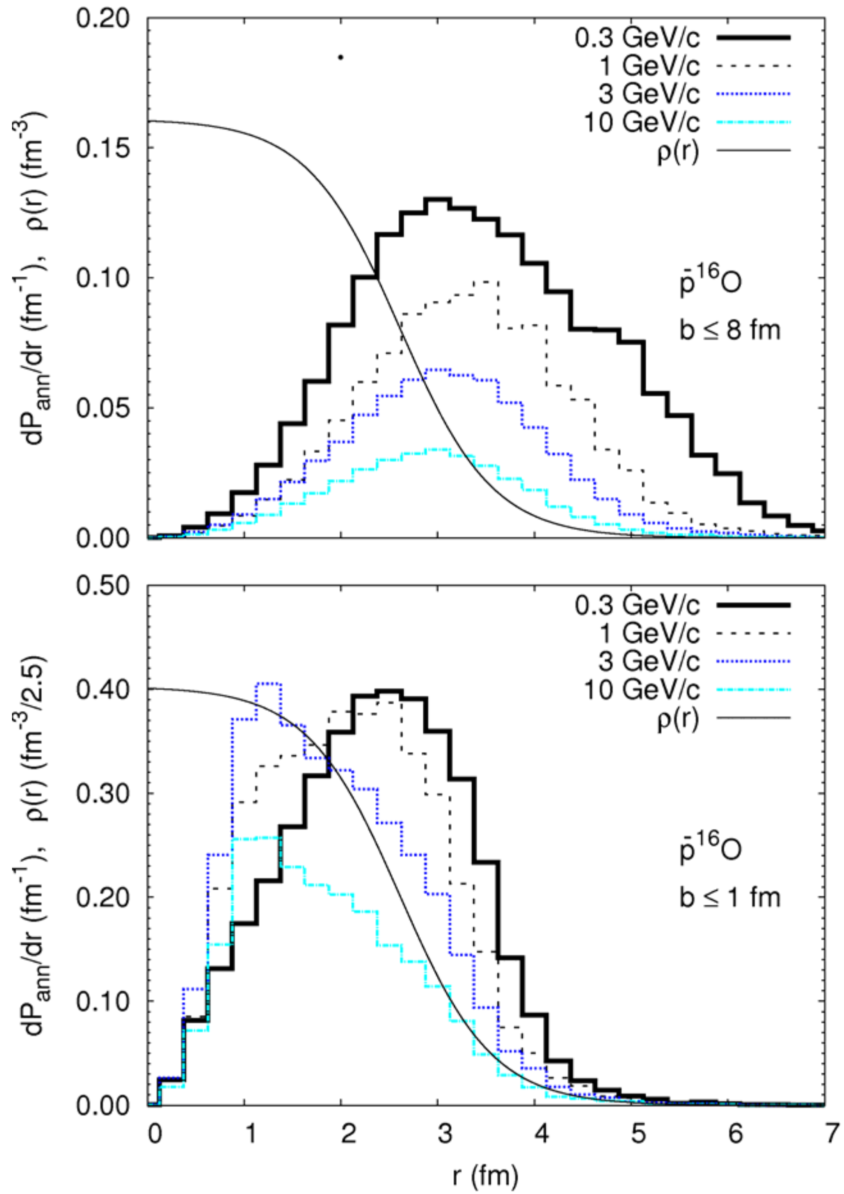
Larger compression probability for the slower and closer to the nuclear centre antiproton.



Radial distributions of the annihilation points at various beam momenta.

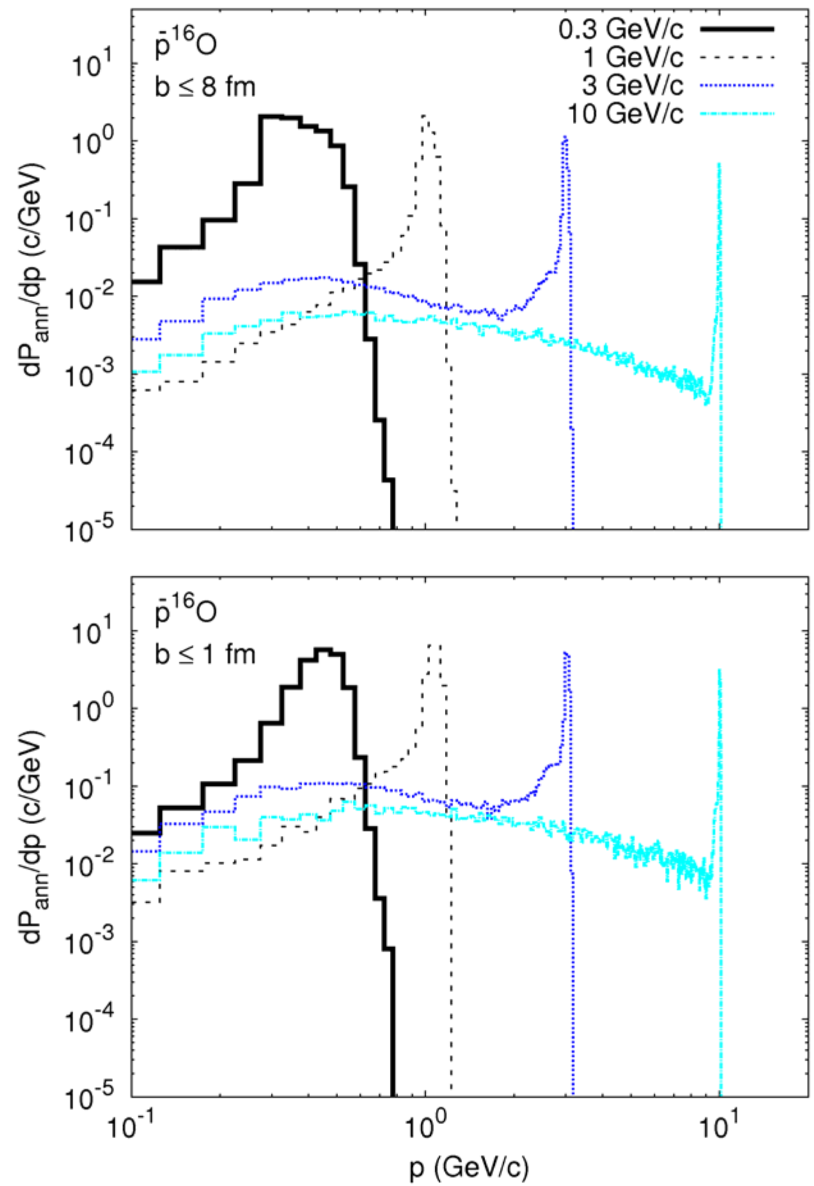
For the inclusive spectrum, the antiproton annihilates mostly at about a half-density radius, independent on the beam momentum.

For the central events, the peak of the spectrum shifts to the nuclear centre with increasing p_{lab}.



Antiproton momentum spectra at the annihilation points at different beam momenta.

At high beam momenta, only a very small fraction of antiprotons get stopped.



The trigger for selecting a stopped antiproton: a fast forward proton (The PANDA Collaboration et al., arXiv:0903.3905 (2009))

Cross section of annihilation <u>at the condition of outgoing proton with momentum > p</u> (standard GiBUU)

Relative probability of annihilation at $\rho_{max} > \rho_c = 2\rho_0$