Institut für Theoretische Physik I

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Strangeness production in antiproton-nucleus collisions*

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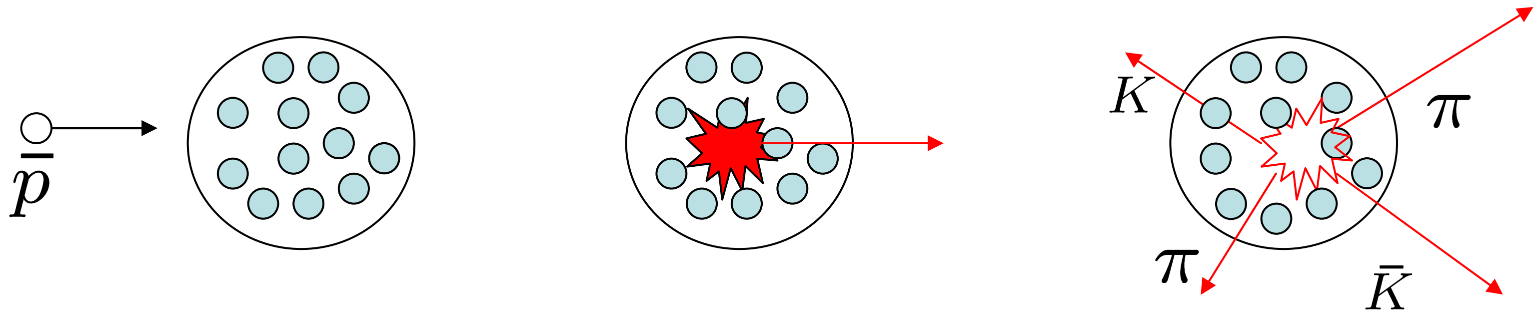
Antiproton annihilation inside a nucleus:



-Large energy deposition ~2m_N in a small volume of nuclear matter. QGP might be formed if more than one nucleon participate in annihilation. (J. Rafelski, 1988).

-Strangeness production in a QGP should be enhanced.

-Test for the interactions of secondary produced particles in a nucleus $\bar{\Lambda}, \bar{K}, \phi, J/\Psi, D, \bar{D}$ (PANDA Physics Book, arXiv:0903.3905).

-Source of Ξ^--hyperons for ΛΛ-hypernucleus production on a secondary target (J. Pochodzalla, 2005).

Our purposes:

— Transport GiBUU model analysis of experimental data on strangeness production in $\bar{p}A$ collisions and in annihilation at rest.

— Calculation of Ξ –hyperon (S=-2) production at p_{lab}=3-15 GeV/c.

— Ξ^- interaction with a secondary nucleus.
ΛΛ-hypernuclei production.
(talk by ***Theodoros Gaitanos*** on Monday, HK 10.8).

A.L., T. Gaitanos, U. Mosel, PRC 85, 024614 (2012);
T. Gaitanos, A.L., H. Lenske, U. Mosel, arXiv:1111.5748, NPA in press

GiBUU model

The Giessen Boltzmann-Uehling-Uhlenbeck model:

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

O. Buss et al, Phys. Rept. 512, 1 (2012)

talk by *Janus Weil* on Monday, HK 7.1

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

collision term

$$(p_0^\star)^{-1}[p_\mu^\star \partial_x^\mu + (p_\mu^\star F_i^{k\mu} + m_i^\star(\partial_x^k m_i^\star))\partial_k^{p^\star}] f_i(x,\mathbf{p}^\star) = I_i[\{f\}]$$

mean –field gradients

$$i = N,\ \bar{N},\ \Delta,\ \bar{\Delta},\ Y,\ \bar{Y},\ \pi,\ K,\ \bar{K}\ldots$$

$N_1N_2 \to N_3N_4$:

relative velocity of N_1 and N_2

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

(in-medium) differential cross section

Pauli blocking factors: $\bar{f}_i = 1 - f_i$

Antibaryon-baryon collisions:

$\bar{B}B \to$ mesons — statistical annihilation model (I.A. Pshenichnov et al., 1992);

$\bar{B}B \to \bar{B}B$ (EL and CEX), $\bar{N}N \leftrightarrow \bar{N}\Delta(\bar{\Delta}N)$, $\bar{N}N \to \bar{\Lambda}\Lambda$, $\bar{N}(\Delta)N(\Delta) \to \bar{\Lambda}\Sigma(\bar{\Sigma}\Lambda)$, $\bar{N}(\Delta)N(\Delta) \to \bar{\Xi}\Xi$.

For $\sqrt{s} > 2.4$ GeV ($p_{\rm lab} > 1.9$ GeV/c for $\bar{N}N$) : FRITIOF simulation of inelastic production $\bar{B}_1 B_2 \to \bar{B}_3 B_4 +$ mesons.

Meson-baryon collisions:

$\pi N \leftrightarrow R$, $\pi N \to K\bar{K}N$, $\pi(\eta,\rho,\omega)N \to YK$, $\bar{K}N \leftrightarrow Y^*$, $\bar{K}N \to \bar{K}N$, $\bar{K}N \leftrightarrow Y\pi$, $\bar{K}N \leftrightarrow Y^*\pi$, $\bar{K}N \to \Xi K$.

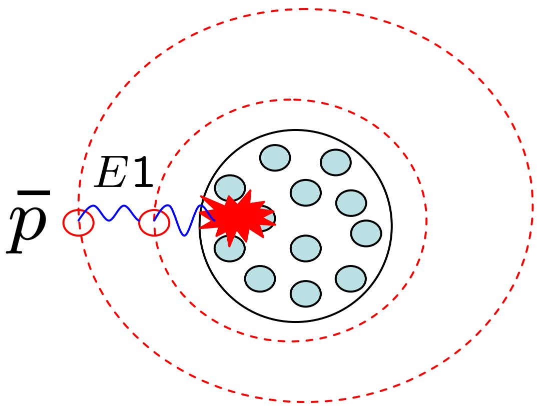
For $\sqrt{s} > 2.2$ GeV : PYTHIA simulation of MB collisions.

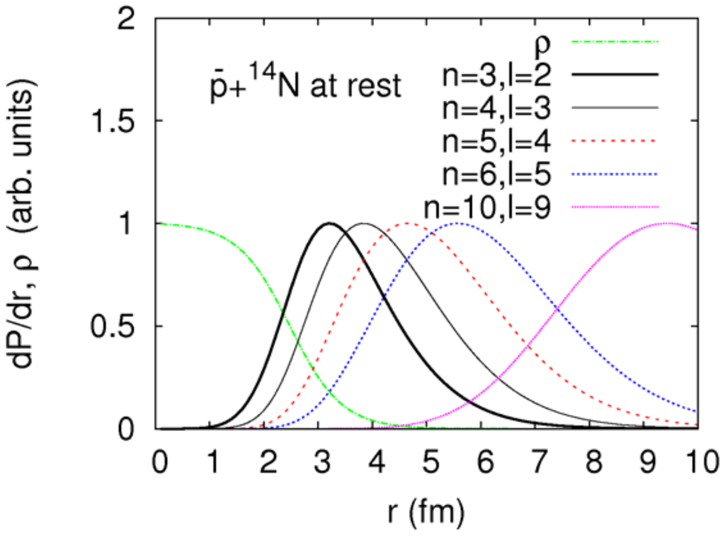
Baryon-baryon collisions:

$BB \to BB$ (EL and CEX), $NN \leftrightarrow NN\pi$, $NN \leftrightarrow \Delta\Delta$, $NN \leftrightarrow NR$, $N(\Delta,N^*)N(\Delta,N^*) \to N(\Delta)YK$, $YN \to YN$, $\Xi N \to \Lambda\Lambda$, $\Xi N \to \Lambda\Sigma$, $\Xi N \to \Xi N$.

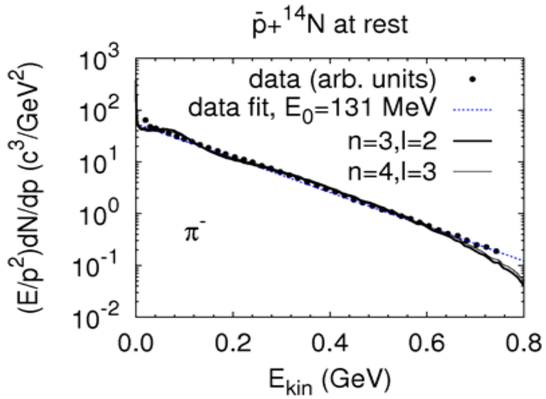
For $\sqrt{s} > 2.4$ GeV : PYTHIA simulation of inelastic production $B_1 B_2 \to B_3 B_4 +$ mesons.

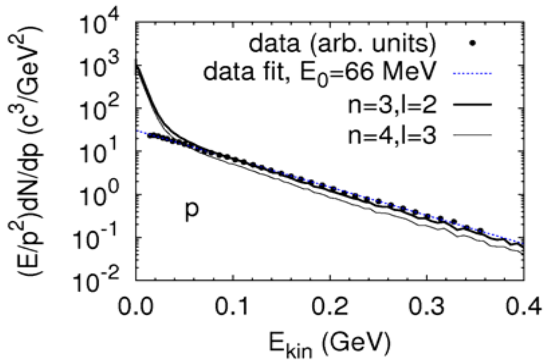
Annihilation at rest:

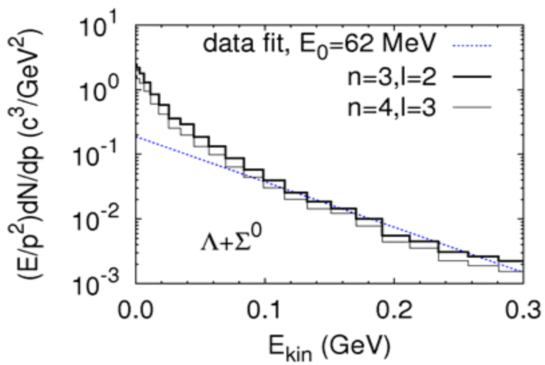




$$dP = C|R_{nl}|^2\rho(r)r^2dr$$







Data: J. Riedlberger et al. (ASTERIX@LEAR), 1989

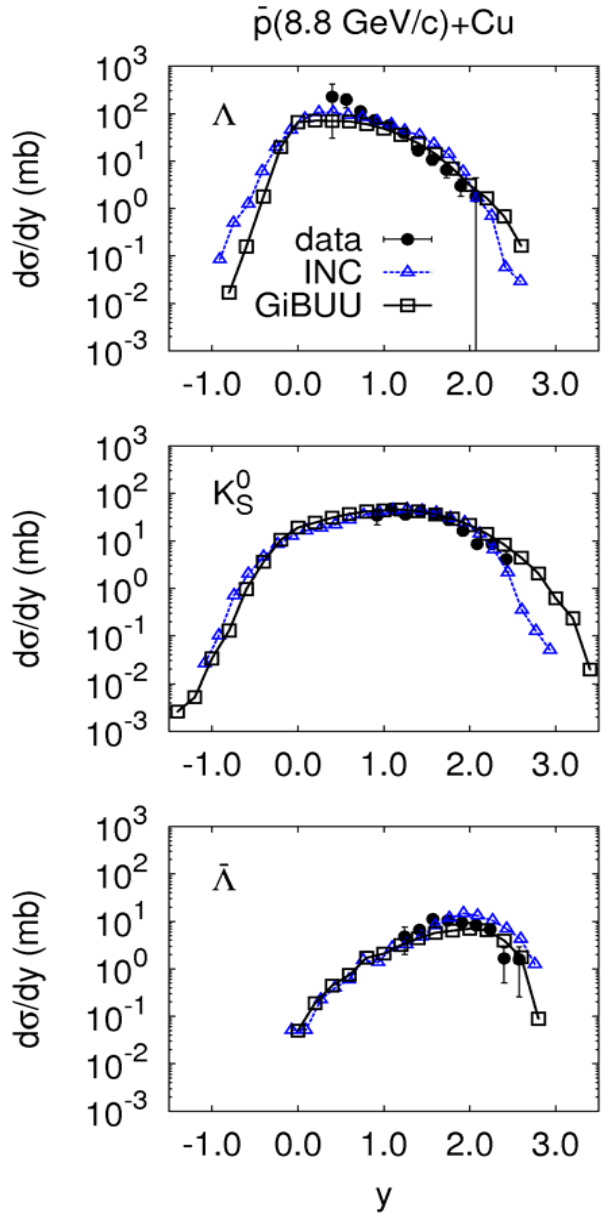
Data fit: $E\frac{dN}{p^2dp} = A\exp(-E_{\mathrm{kin}}/E_0)$

Annihilation in-flight:

Data and INC calculations:
S. Ahmad et al. (MPS@BNL), 1997.

INC model: D. Strottman & W. Gibbs, 1984; W. Gibbs & J. Kruk, 1990

$$\sigma_{K_S^0} = \frac{1}{2}(\sigma_{K^0} + \sigma_{\bar{K}^0})$$



$\bar{K}, \bar{K}^* + N \sim 60\%$,
$\pi, \eta, \rho, \omega + N \sim 30\%$ of $Y(Y^*)$ production rate

Systematics:

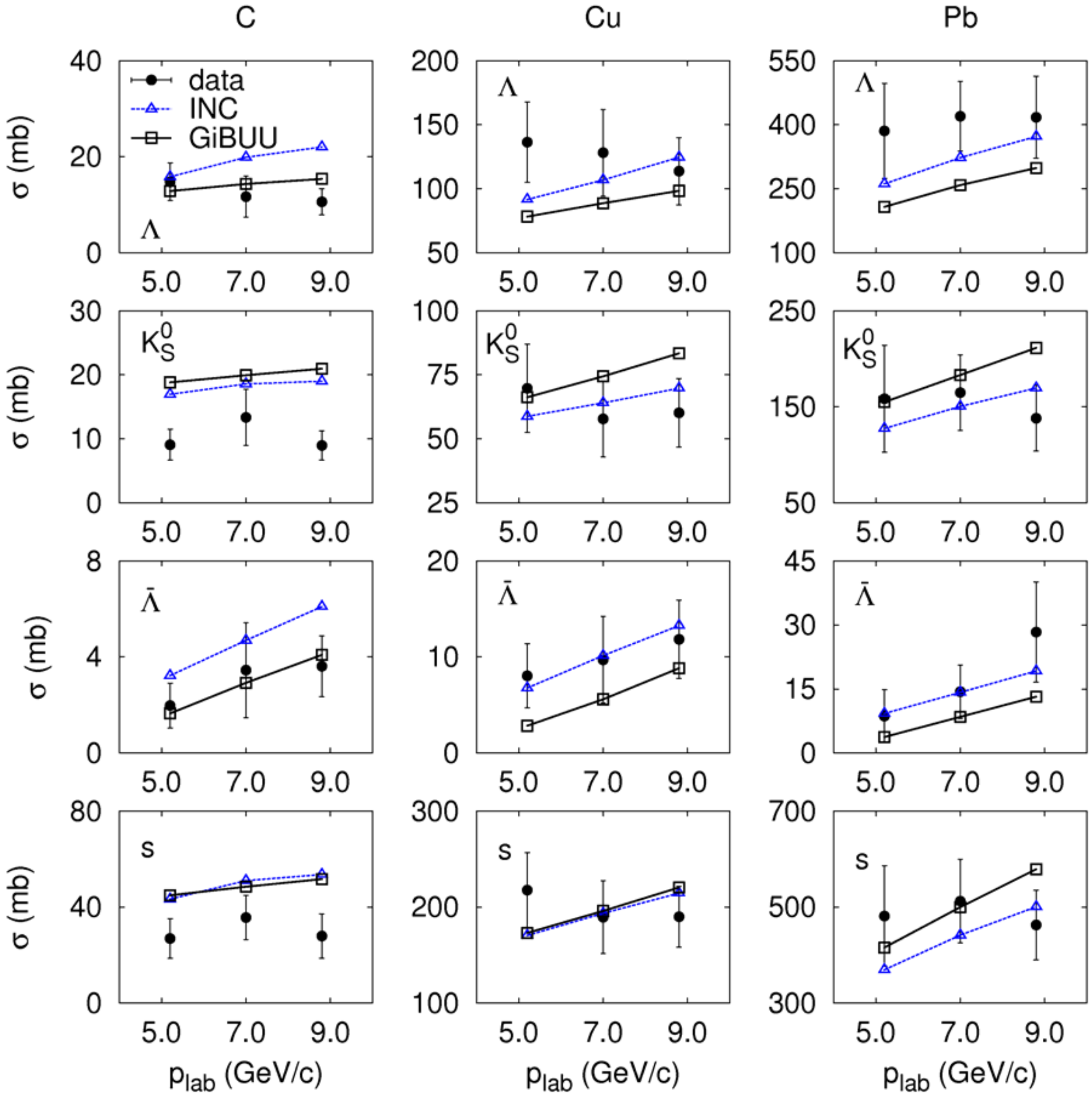
Data and INC calculations: S. Ahmad et al. (MPS@BNL), 1997.

INC model: D. Strottman & W. Gibbs, 1984; W. Gibbs & J. Kruk, 1990

→ not enough $\bar{K}$ absorption:

$$\bar{K}N \rightarrow YX$$

In-medium effects or inaccuracies in elementary cross sections ?



$$\sigma_s = \frac{1}{2}(4\sigma_{K^0_S} + \sigma_\Lambda + \sigma_{\Sigma^0} + \sigma_{\bar{\Lambda}} + \sigma_{\bar{\Sigma}^0})$$

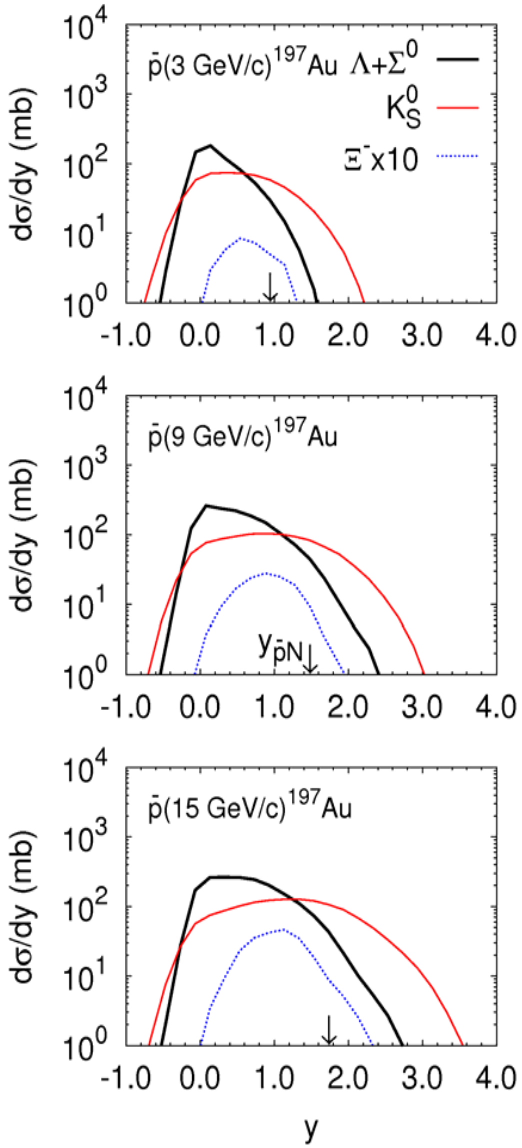
Ξ^- production:

Λ spectra always peak at y≈0 due to exothermic reactions $\bar{K}N \to Y\pi$ with slow $\bar{K}$

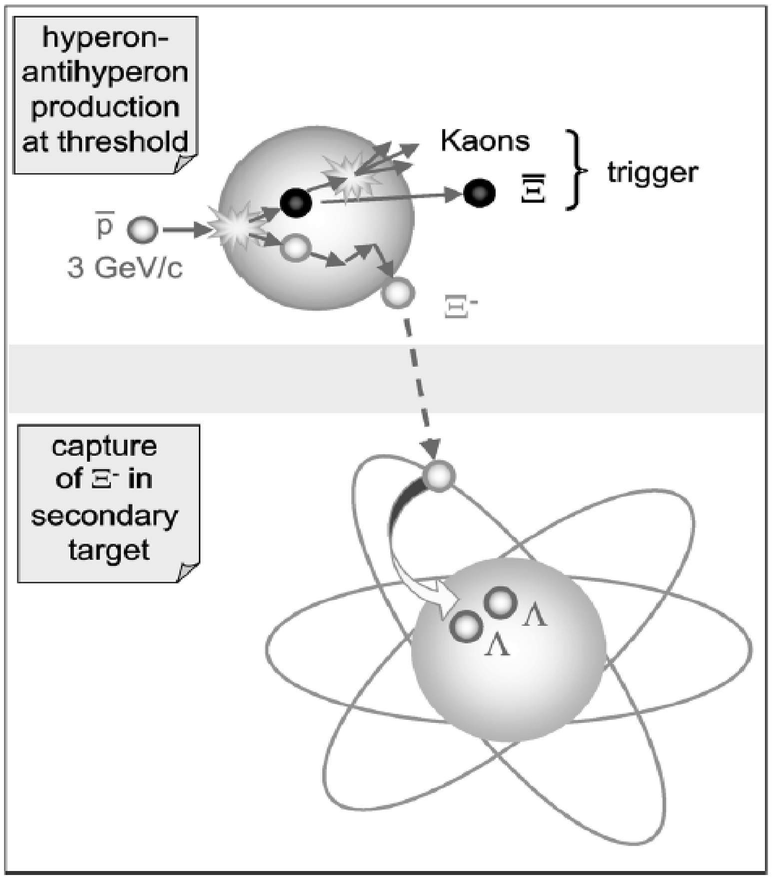
Spectra for Ξ^- are shifted to forward rapidities due to endothermic reactions $\bar{K}N \to \Xi K$

$(p_{\mathrm{lab}}^{\mathrm{thr}} = 1.048\ \mathrm{GeV/c},\ y_{\bar{K}N}^{\mathrm{thr}} = 0.55)$

In the QGP fireball scenario (J. Rafelski, 1988) the rapidity spectra of all strange particles would be peaked at the same rapidity.

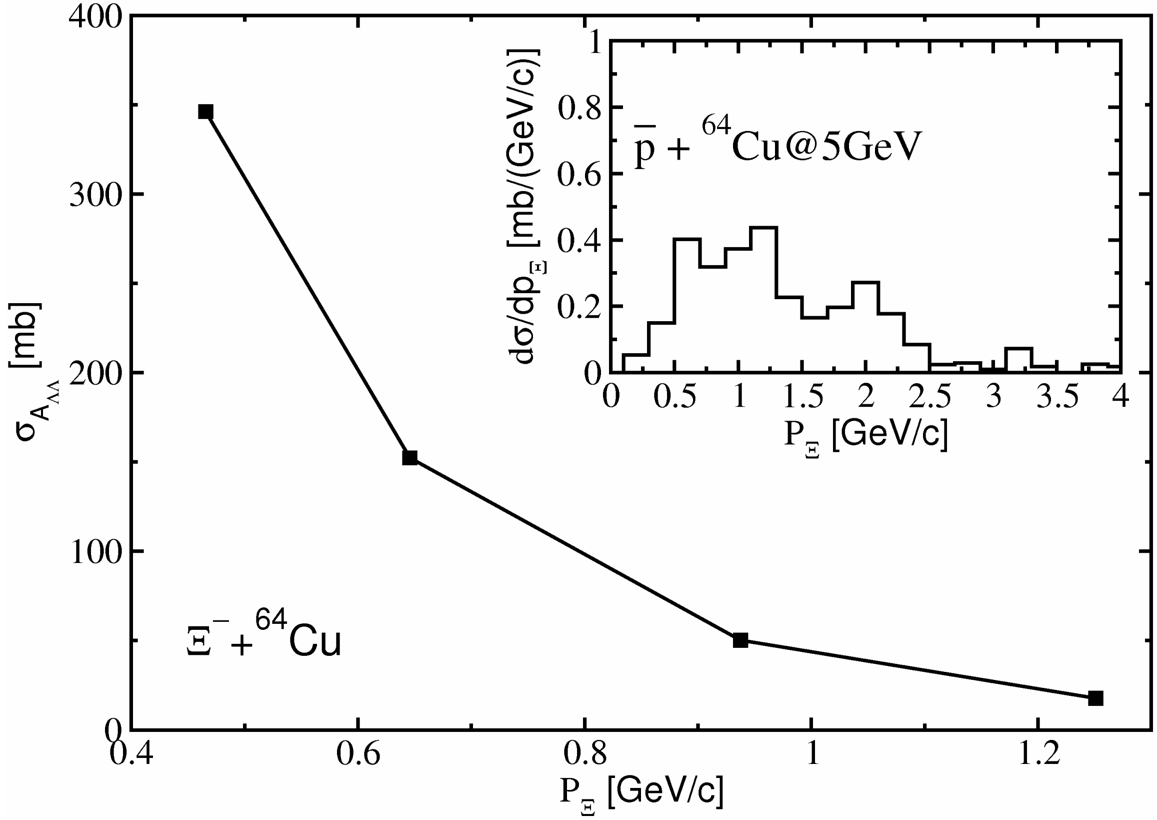


ΛΛ-hypernucleus production at PANDA@FAIR
(J. Pochodzalla, 2005).



Double Λ production at PANDA: Ξ^- interaction with a secondary target

(talk by T. Gaitanos on Monday and **arXiv:1111.5748**)



Low-momentum (< 0.5 GeV/c) Ξ^-'s are the best suited for double Λ production.

Conclusions:

— Tendency to underestimate Λ-yields and overestimate K_S-yields in GiBUU and INC. $\bar{K}N \to Y\pi$ channel needs improvements (work in progress). The data on charged strange particle production cross sections $\Sigma^{\pm}$, $K^{\pm}$ are desirable.

— Peak positions of Λ and Ξ^- rapidity spectra strongly differ in pure hadronic transport: challenge for a QGP scenario.

— Big cross section of double Λ hypernuclei production by in-flight interaction of slow Ξ^- with a secondary target.

Outlook:

Several new interesting applications of GiBUU model to antiproton-nucleus interactions:

— J/ψ production and propagation (PANDA Physics Book, arXiv:0903.3905).

— antibaryon potentials study, strongly bound antiproton-nucleus states (talk by Yue Ma on Monday, HK 8.7)

— annihilation at rest: signatures of QGP formation in Obelix data (G. Bendiscioli et al., 2009).

Thank you for your attention !

Backup

$\bar{p}p$ cross sections

Elastic: $\bar{p}p \longrightarrow \bar{p}p$

Charge exchange:

$\bar{p}p \longrightarrow \bar{n}n$

Annihilation:

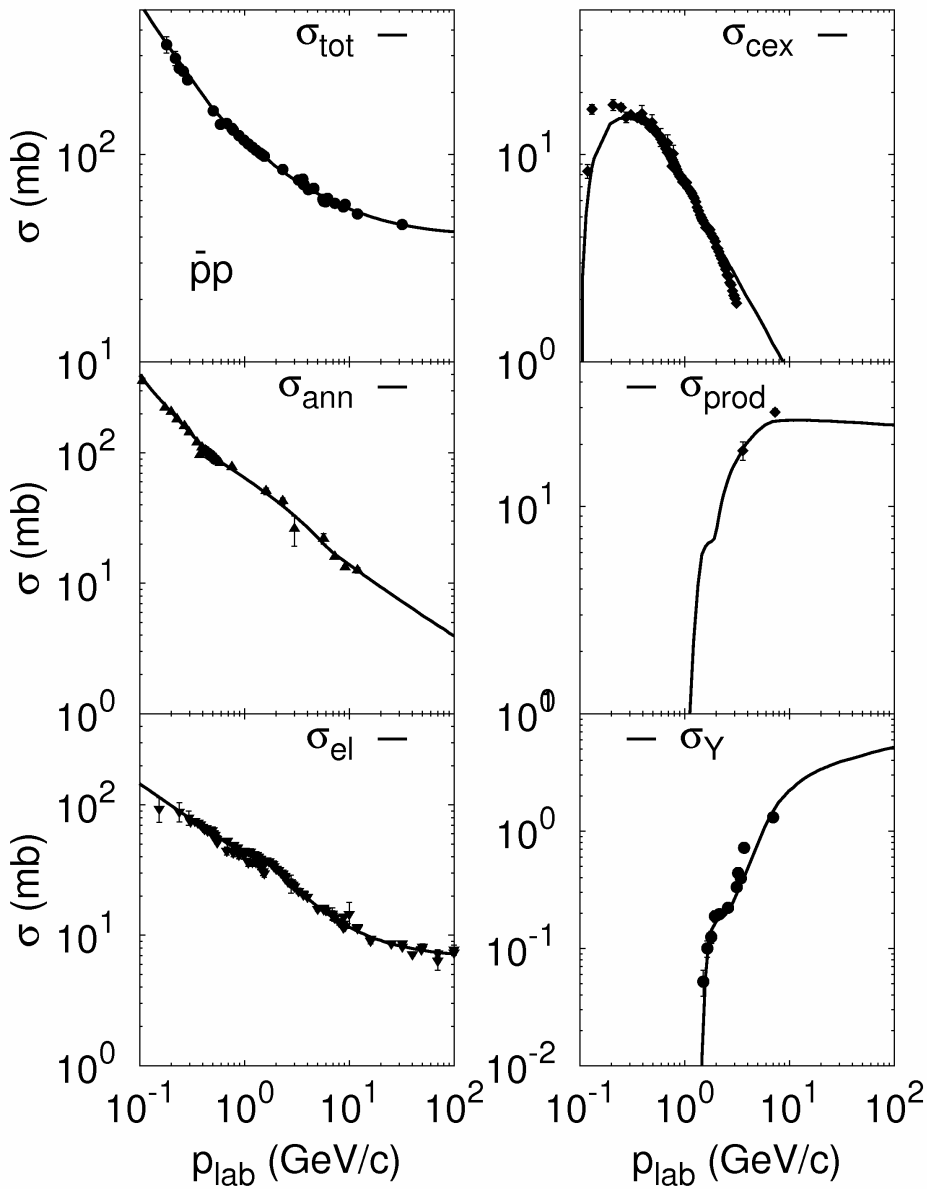
$\bar{p}p \rightarrow$ mesons

Production:

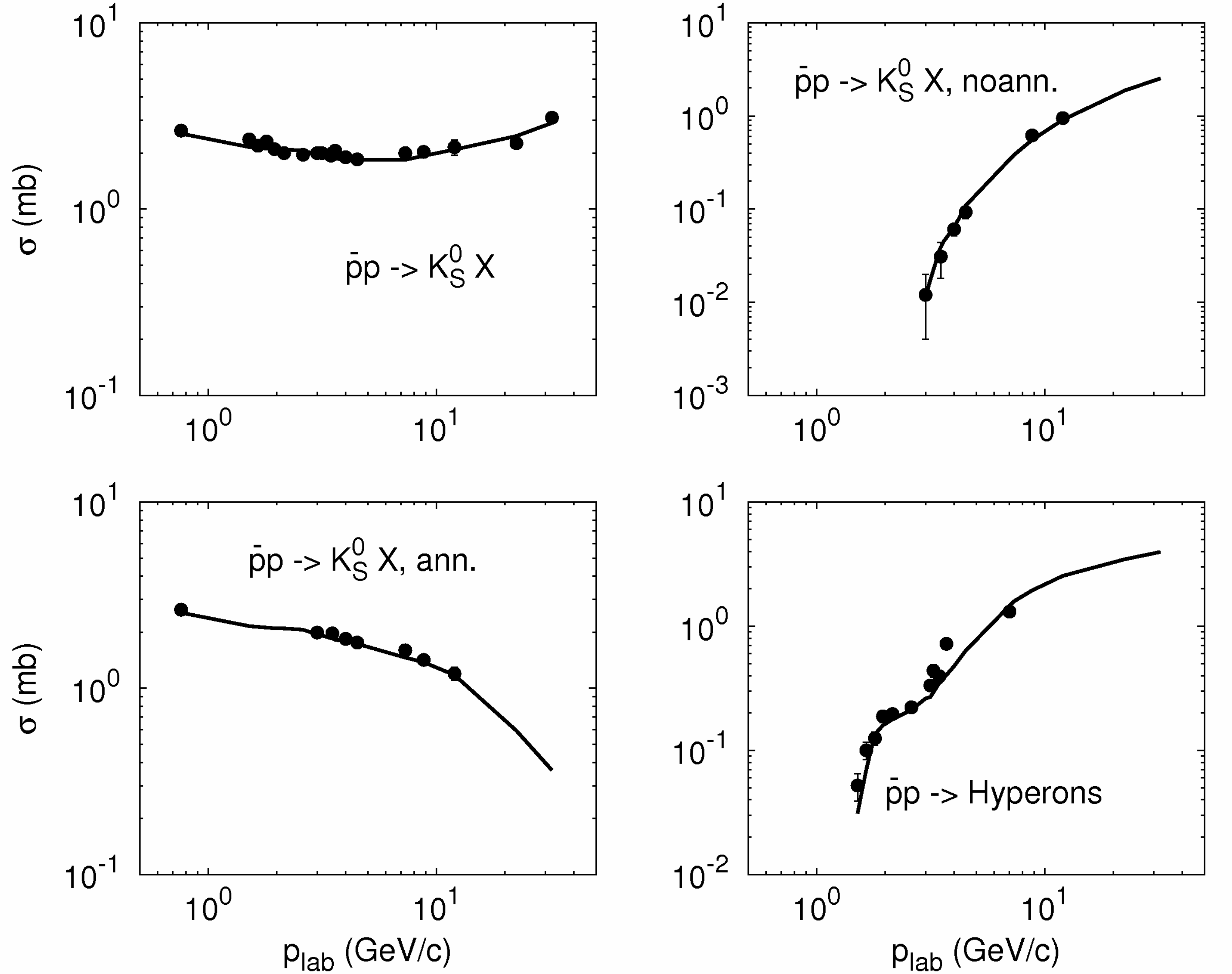
$\bar{p}p \rightarrow \bar{N}N +$ mesons

Hyperon production:

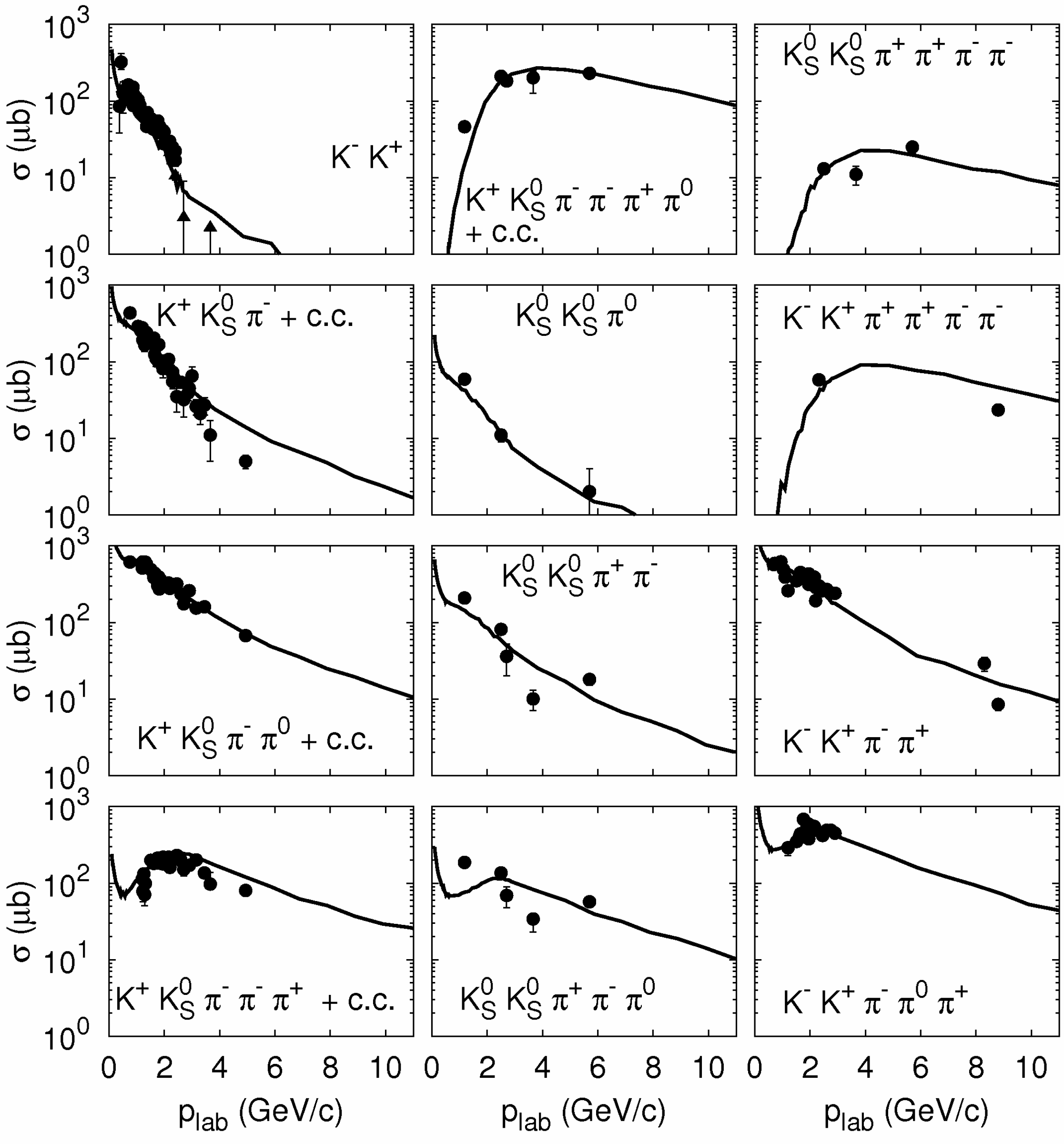
$$\begin{aligned} \bar{p}p \;\; \rightarrow \;\; & Y\bar{Y} + \text{mesons}, \\ & YK\bar{N} + \text{mesons}, \\ & N\bar{K}\bar{Y} + \text{mesons}. \end{aligned}$$



Strangeness production in $\bar{p}p$ collisions



Some exclusive $\bar{p}p$ annihilation channels to $K\bar{K}$



Relativistic kinetic equation:

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

$S_j = g_{\sigma j}\sigma,\ V_j^\mu = g_{\omega j}\omega^\mu + g_{\rho j}\tau^3\rho^{3\mu} + q_j A^\mu$ - scalar and vector fields,

$m_j^\star = m_j + S_j$ - 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):

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

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

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

Hyperon and kaon couplings – from a constituent quark model and G-parity (for antiparticles):

$$g_{\omega Y} = -g_{\omega \bar{Y}} = \frac{2}{3} g_{\omega N}, \quad g_{\sigma Y} = g_{\sigma \bar{Y}} = \frac{2}{3} g_{\sigma N},$$
$$g_{\omega \Xi} = -g_{\omega \bar{\Xi}} = \frac{1}{3} g_{\omega N}, \quad g_{\sigma \Xi} = g_{\sigma \bar{\Xi}} = \frac{1}{3} g_{\sigma N},$$
$$g_{\omega K} = -g_{\omega \bar{K}} = \frac{1}{3} g_{\omega N}, \quad g_{\sigma K} = g_{\sigma \bar{K}} = \frac{1}{3} g_{\sigma N}$$

(J. Schaffner, I.N. Mishustin, 1996; G.E. Brown, M. Rho, 1996)

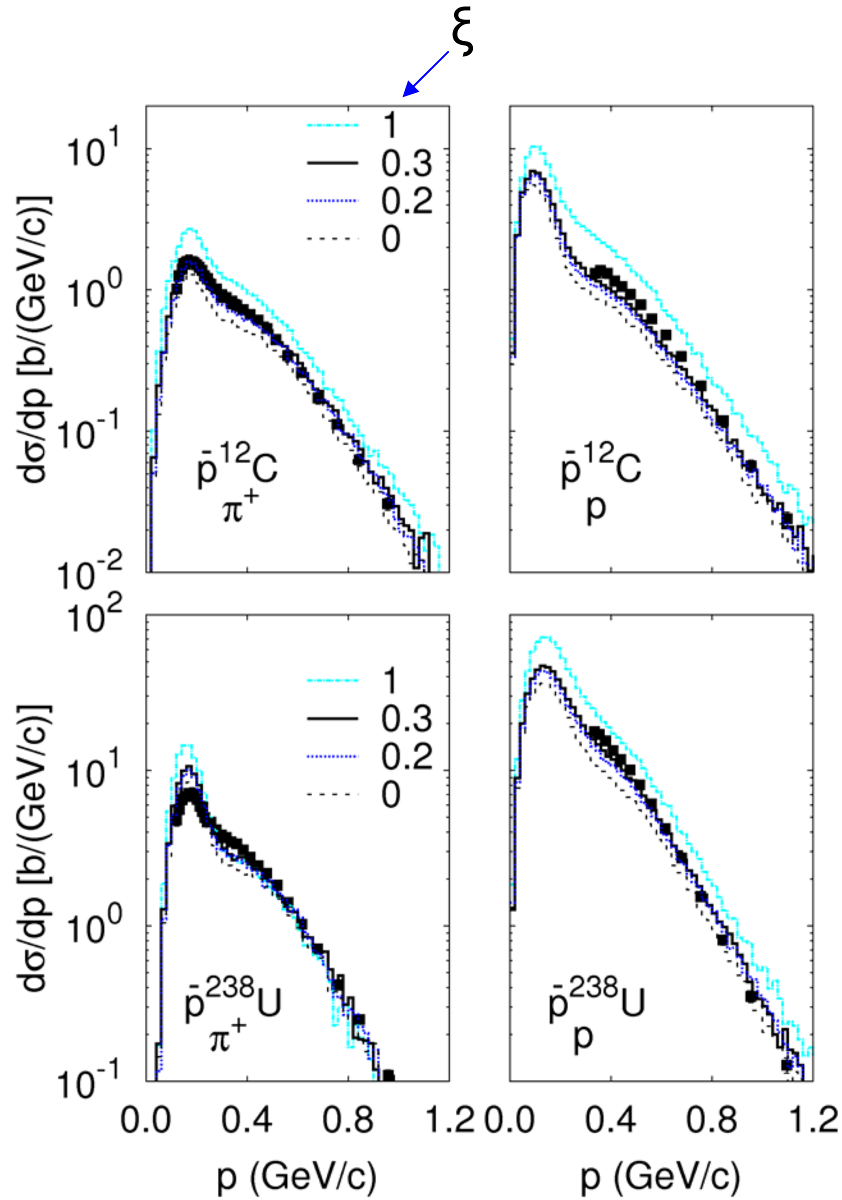
Schrödinger equivalent potentials (in MeV) at normal nuclear density:

j	N	Λ	Σ	Ξ	K	$\bar{N}$	$\bar{\Lambda}$	$\bar{\Sigma}$	$\bar{\Xi}$	$\bar{K}$
U_j	-46	-38	-39	-22	-18	-150	-449	-449	-227	-224

$$U_j = S_j + V_j^0 + \frac{S_j^2 - (V_j^0)^2}{2m_j},$$
$$S_N = -380 \text{ MeV}, \quad V_N^0 = 308 \text{ MeV}$$

Momentum spectra of protons and pions for p_{lab}=608 MeV/c.

Data (LEAR): P.L. McGaughey et al., PRL 56, 2156 (1986).

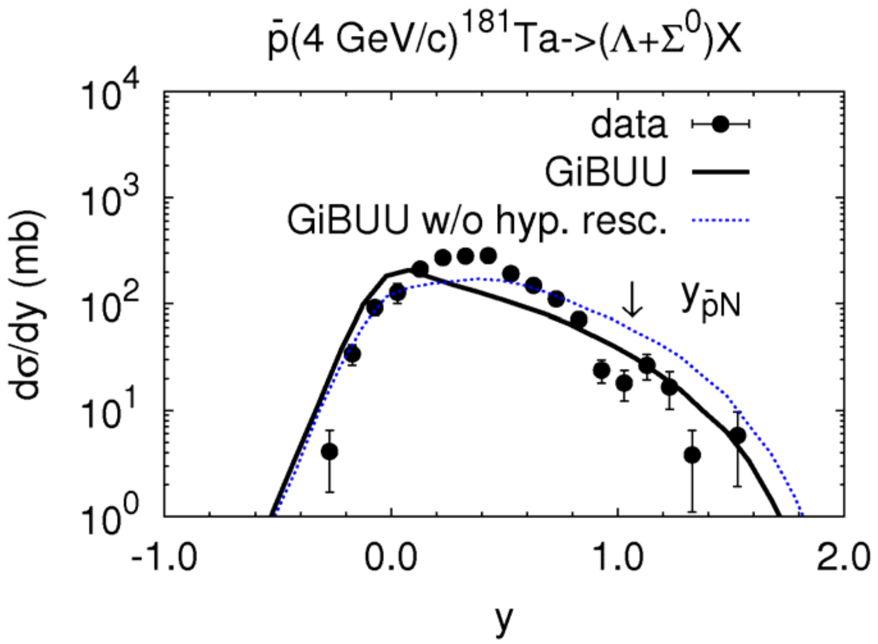


A weak sensitivity to the $\bar{p}$ mean field: best agreement for ξ≈0.3, or $Re(V_{opt})$=-(220±70) MeV

A.L., I.A. Pshenichnov, I.N. Mishustin, and W. Greiner, PRC 80, 021601 (2009)

Hyperon rapidity distribution:

Data (KEK): K. Miyano et al., PRC 38, 2788 (1988).

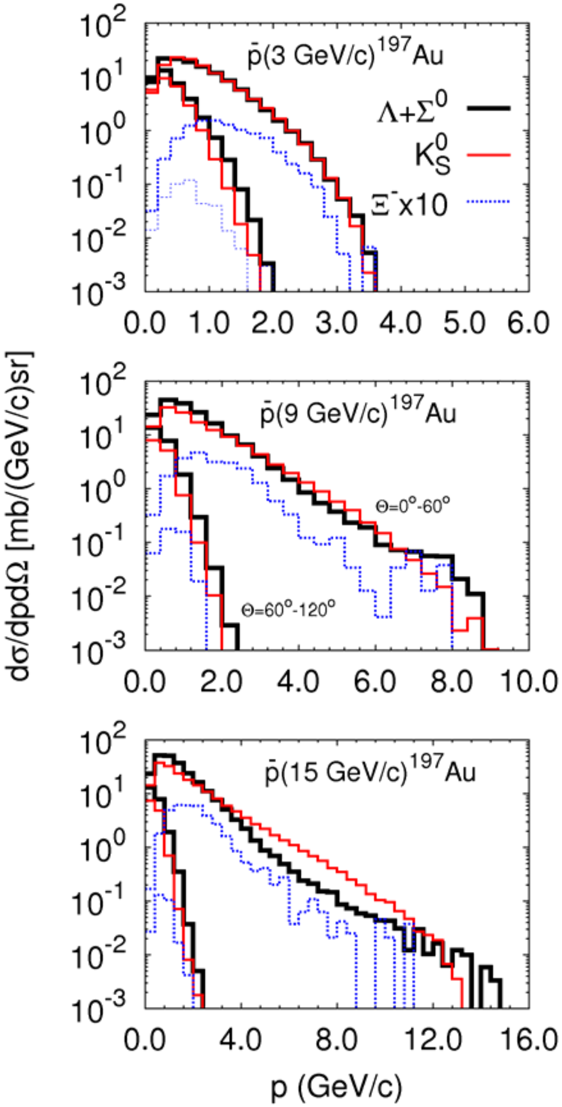


→ ***Sensitivity to the hyperon-nucleon scattering cross sections***

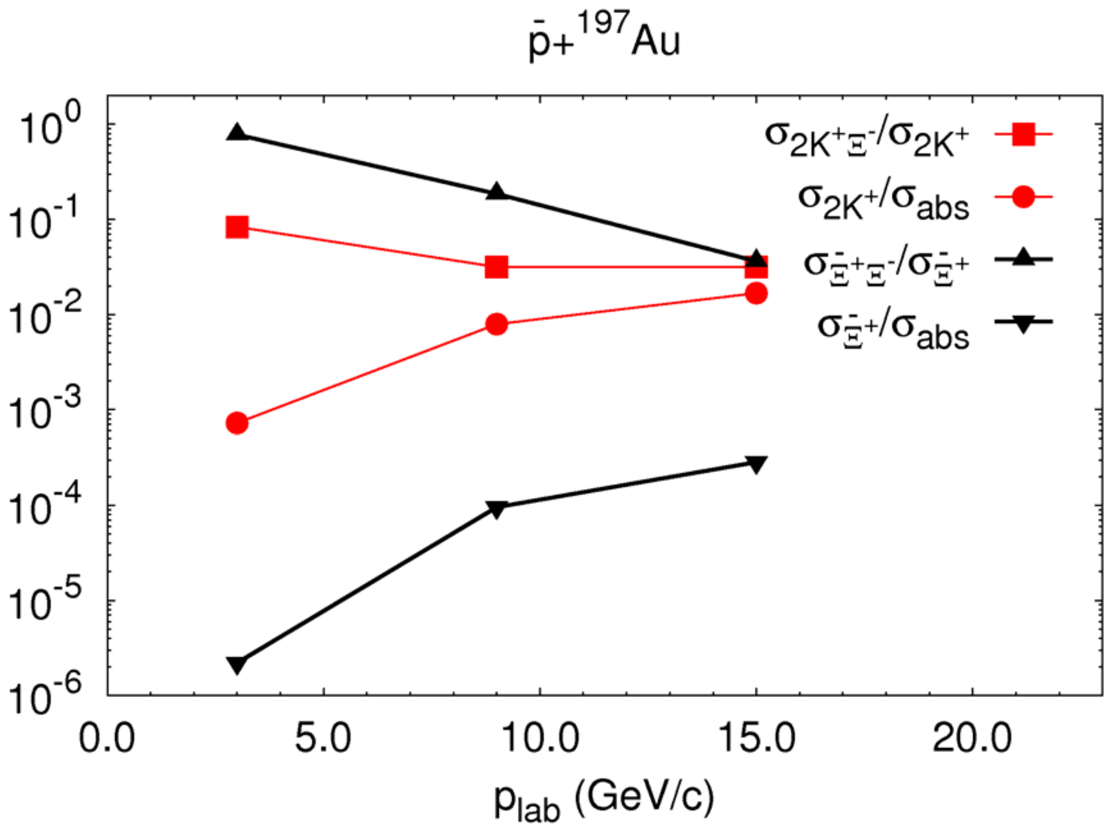
Momentum spectra of produced strange particles.

Similar behaviour at large momenta for all particles.

Ξ^- spectra are suppressed at low momenta.



Triggering Ξ^-:



Large background due to $\pi, \eta, \rho, \omega + N \to YK$.

$\bar{\Xi}^+$***-trigger is much more selective near threshold***

($p_{\rm lab}^{\rm thr} = 2.6$ GeV/c for $\bar{p}p \to \Xi^-\bar{\Xi}^+$) ***than*** $2K^+$***-trigger.***

Phase transition to the QGP ?

G. Bendiscioli et al. / Nuclear Physics A 815 (2009) 67–88 71

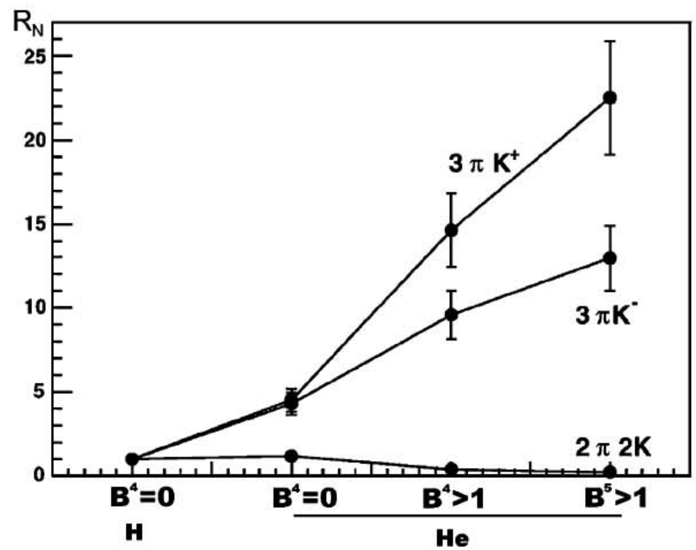


Fig. 1. Charged kaon production for the reactions without neutral mesons with 4 charged mesons (4 prongs) and with 4 charged mesons plus a fast proton (5 prongs): $3\pi K^+(p)$, $3\pi K^-(p)$ and $2\pi 2K(p)$. R_N = ratio in percentage between He and H yields; the reference value in hydrogen concerns annihilations into four pions without neutrals. The lines join values concerning reactions with different numbers of prongs (four or five) and B values. The errors are statistical plus systematic [7].

K^+ production in 5-prong annihilations on ^4He involving at least two nucleons is enhanced by a factor of 22.