Strange particles production in antiproton-nucleus collisions

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Experiments on strangeness production in $\bar{p}$-induced reactions:

BNL (G.T. Condo et al, 1984): Λ in $\bar{p}$(0-450 MeV/c)^{12}C,^{48}Ti,^{181}Ta,^{208}Pb

LEAR (F. Balestra et al, 1987): K_S^0, Λ in $\bar{p}$(607 MeV/c)^{20}Ne

KEK (K. Miyano et al, 1988): K_S^0, Λ, $\bar{\Lambda}$ in $\bar{p}$(4 GeV/c)^{181}Ta

LEAR (A. Panzarasa et al, 2005, G. Bendiscioli et al, 2009):

$K^{\pm}$ in $\bar{p}$(at rest)$p, d,^{3}$He,^{4}He

-Large energy deposition ~2m$_N$ in a small volume of nuclear matter.
QGP might be formed if more than one nucleon participate in annihilation.

-Strangeness production in a QGP should be enhanced.

- **Large ratio** $\Lambda/K_S^0 = 2-3$ **both for light (^{20}Ne) and heavy (^{181}Ta) targets.**

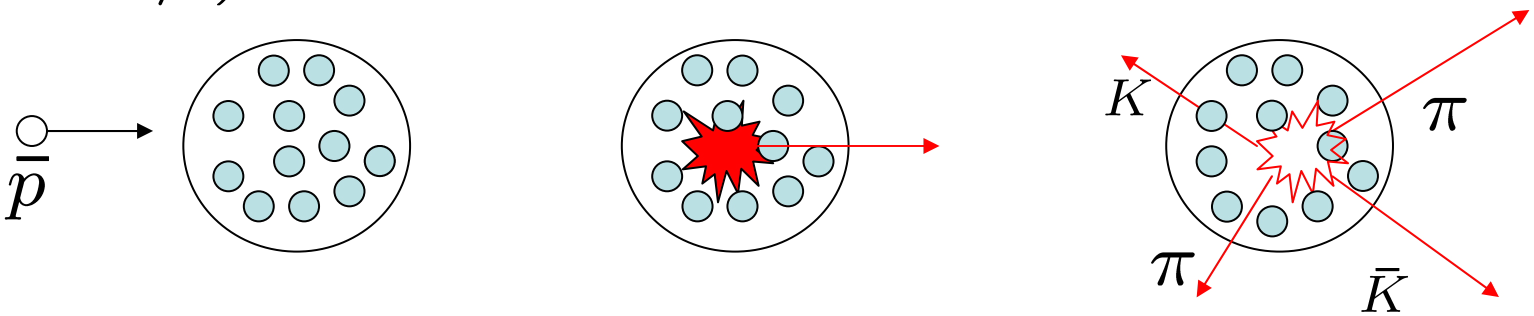
- **Λ rapidity spectrum is peaked close to y=0 in lab. frame even for energetic collisions** $\bar{p}(4\ \mathrm{GeV/c})^{181}\mathrm{Ta}$.

- **Enhanced strangeness production for B>0 annihilations at rest.**

Exotic mechanisms or conventional hadronic picture ?

-Propagating annihilation fireball with baryon number B > 0 due to absorption of nucleons, supercooled QGP (J. Rafelski, 1988).

$\bar{p}(4\ \mathrm{GeV/c})^{181}\mathrm{Ta}$



Our purposes:

— Transport model analysis of existing data on strangeness production in $\bar{p}A$ collisions.
— Calculation of Ξ –hyperon (S=-2) production at p_{lab}=3-15 GeV/c (PANDA@FAIR).

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):

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

$$j = N,\ \bar{N},\ \Delta,\ \bar{\Delta},\ Y,\ \bar{Y},\ \pi,\ K,\ \bar{K}...$$

$S_j = g_{\sigma j}\sigma,\ V_j^\mu = g_{\omega j}\omega^\mu + g_{\rho j}\tau^3\rho^{3\mu} + q_j A^\mu$ - 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):

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

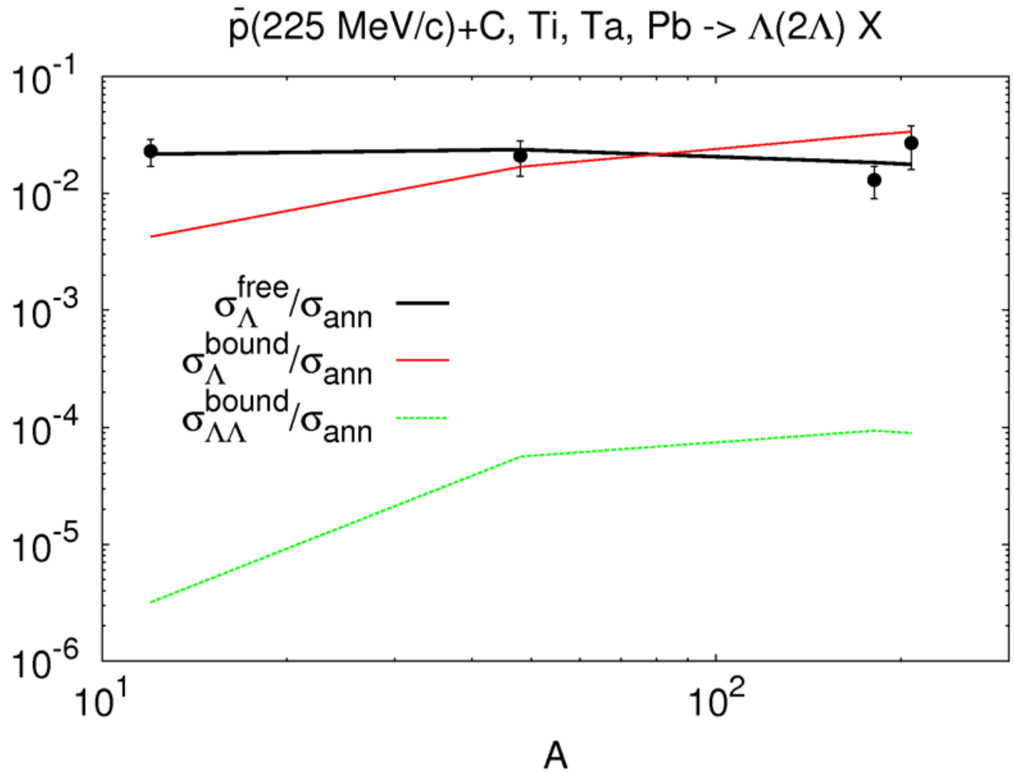
G-parity transformed nuclear potential: ξ=1, $\mathrm{Re}(V_{\mathrm{opt}}) \simeq -660$ MeV.

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

Λ production from

$\bar{p}(0-450\ \mathrm{MeV}/c)^{12}\mathrm{C}$, $^{48}\mathrm{Ti}$, $^{181}\mathrm{Ta}$ and $^{208}\mathrm{Pb}$

Data (BNL): G.T. Condo et al, PRC 29, 1531 (1984)



Good agreement with data on the yields of free Λ's.
Single (double) Λ hypernucleus formation probability reaches ~3% (0.01%) for ^{208}Pb.

More detailed study of the hypernuclei production: previous talk by T. Gaitanos

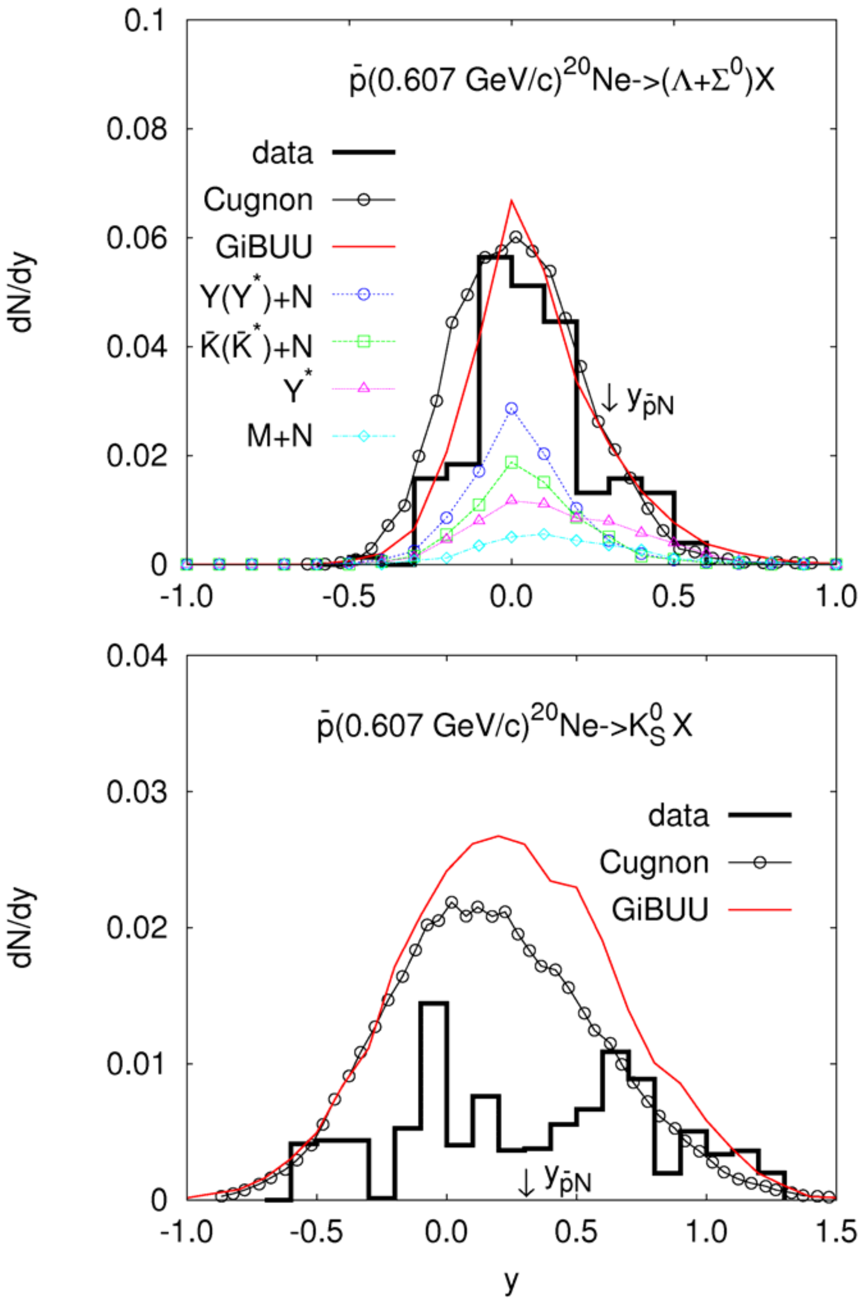
Rapidity distributions of Λ and K_S^0 from $\bar{p}(607\ MeV/c)^{20}$Ne.

Data (LEAR): F. Balestra et al., PLB 194, 192 (1987).

Comparison of the GiBUU and cascade calculations by J. Cugnon et al., PRC 41, 1701 (1990).

Hyperons are mostly produced in $\bar{K}(\bar{K}^*)N$ collisions. Hyperon rescattering with flavour/charge exchange very important (e.g. $\Sigma^+ n \to \Lambda p$).

Good agreement of with data on Λ production. The yield of K_S^0 is overestimated.



Rapidity distributions of Λ and K_S^0 from $\bar{p}(4\ GeV/c)^{181}$Ta with partial contributions from different reaction channels

$B \equiv N,\ \Delta,\ N^*...$

– nonstrange baryons,

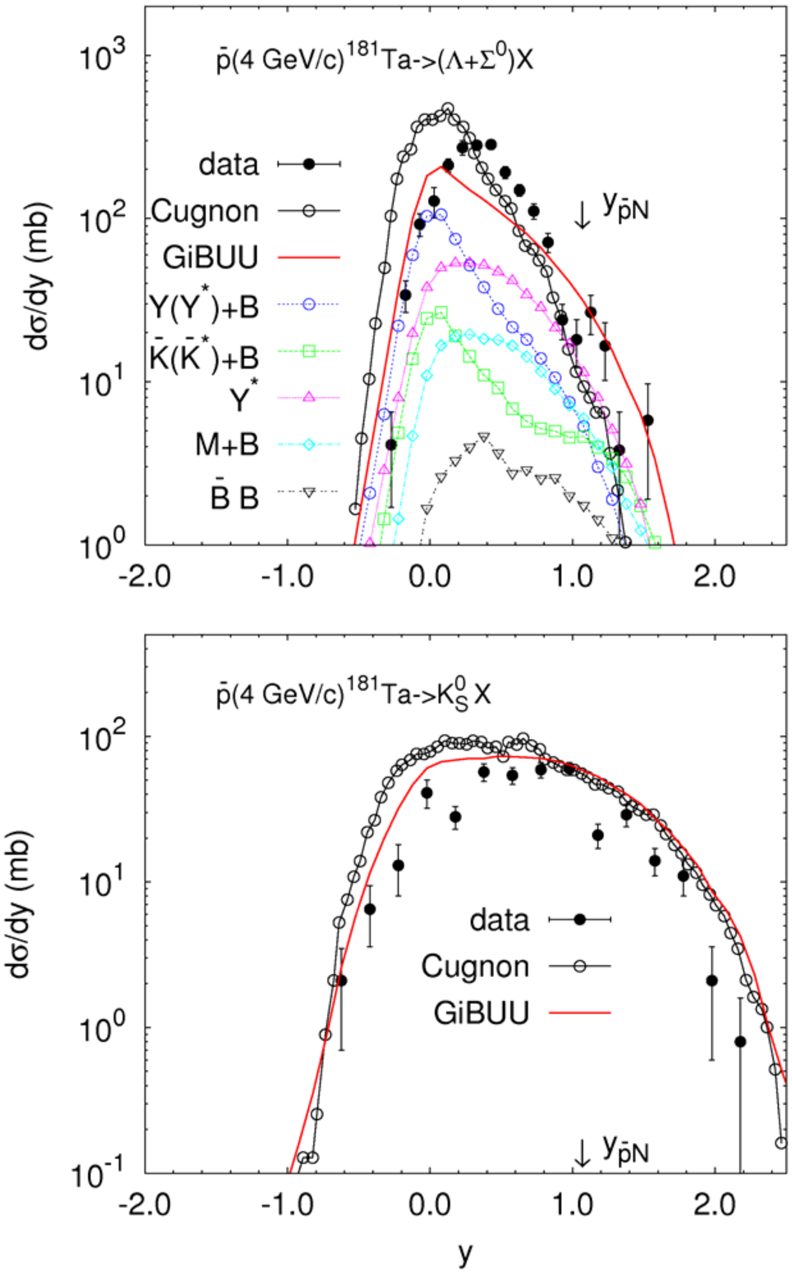
$M \equiv \pi,\ \eta,\ \rho,\ \sigma,\ \omega,\ \eta'$

– nonstrange mesons

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

~70-80% of the Y(Y*) production rate is due to antikaon absorption

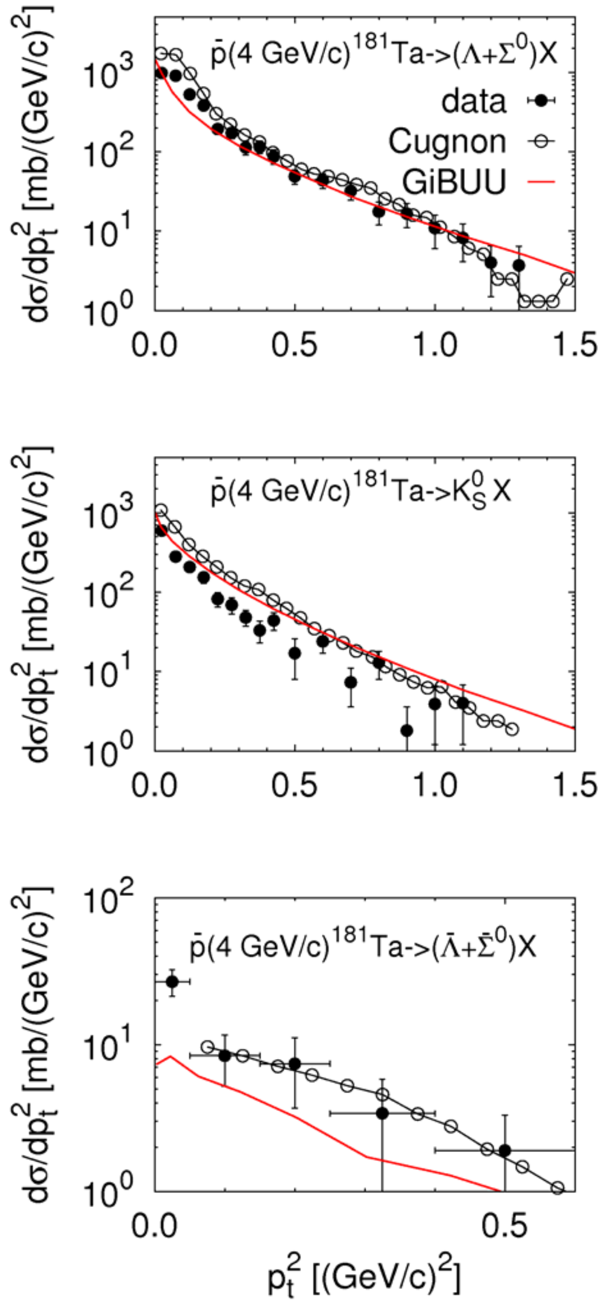
$$\bar{K}B \to YX,\ \ \bar{K}B \to Y^*,\ \ \bar{K}B \to Y^*\pi$$



Transverse momentum distributions of Λ, K_S, and $\bar{\Lambda}$ from $\bar{p}(4\ GeV/c)^{181}$Ta

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

Comparison of the GiBUU and cascade calculations by J. Cugnon et al., PRC 41, 1701 (1990).



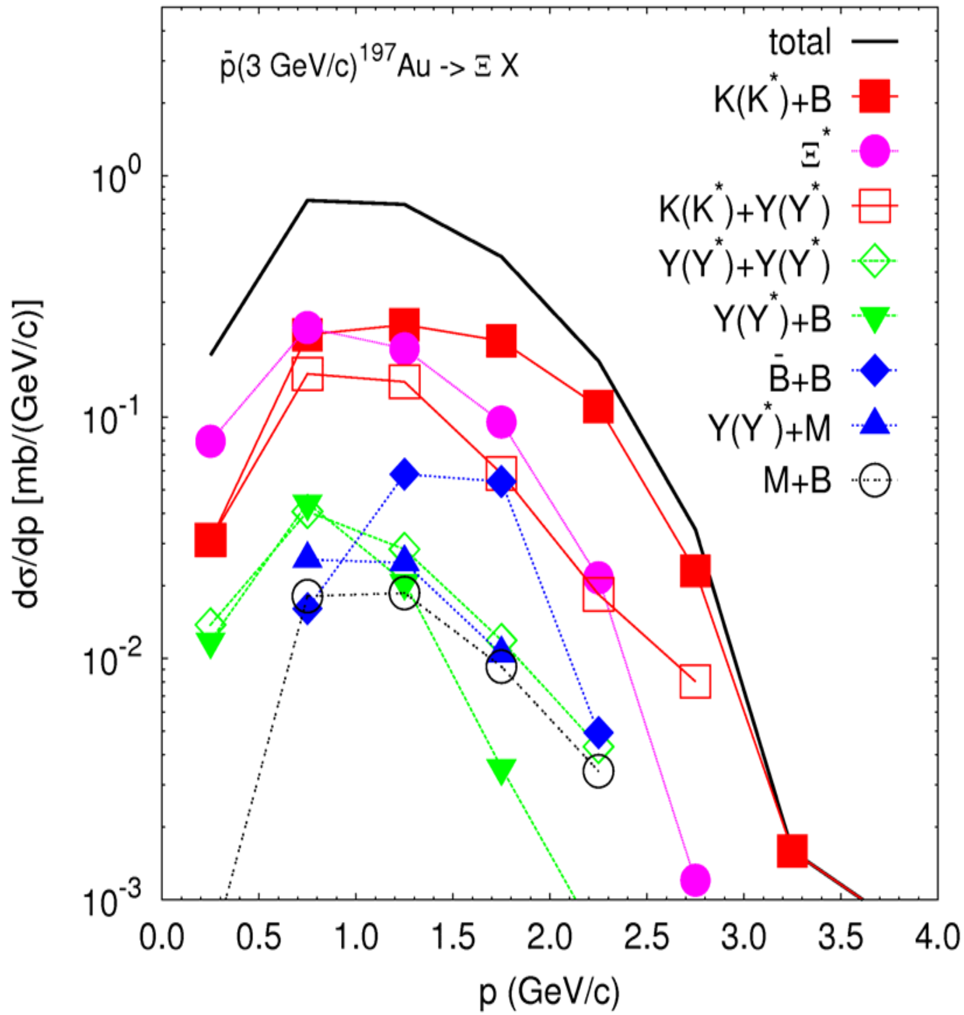
Spectral shapes well described.
K_S yield overestimated by both models.
$\bar{\Lambda}$ yield underestimated by GiBUU.

Predictions for PANDA@FAIR

Ξ inclusive momentum spectrum with partial contributions

Partial contributions to the Ξ production rate:

$$\begin{aligned} K(K^*)B \to \Xi X &\sim 35\% \\ \Xi^* \to \Xi\pi &\sim 26\% \\ K(K^*)Y(Y^*) \to \Xi X &\sim 17\% \\ \bar{B}B \to \Xi X &\sim 6\% \end{aligned}$$

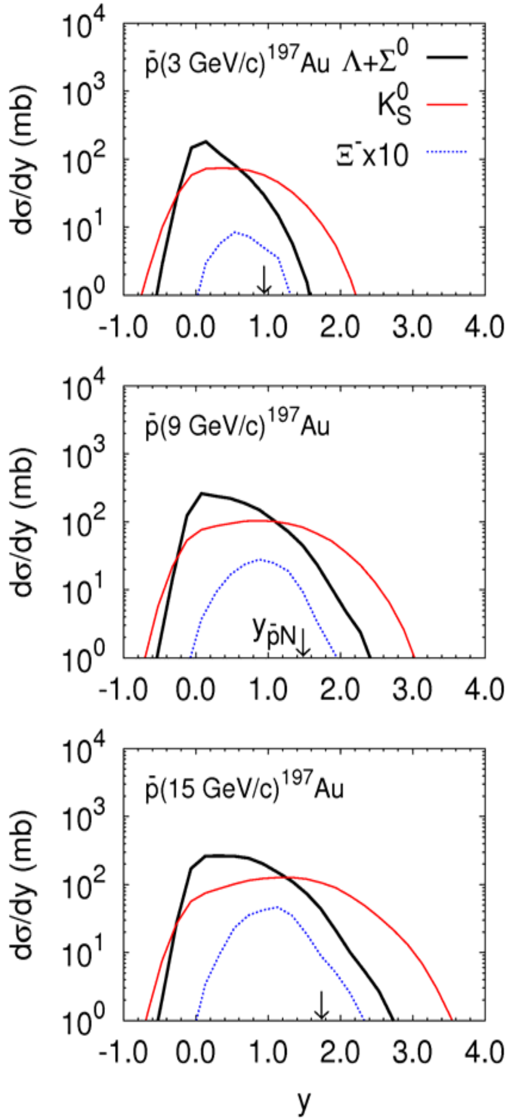


Rapidity spectra of strange particles.

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 $\bar{K}N \to \Xi K$

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



In the fireball scenario the rapidity spectra of all strange particles would be peaked at the same rapidity !

Conclusions:

— Λ-yields well described, K_S-yields overestimated. For $\bar{p}^{20}$Ne at 608 MeV/c the yield ratios are: Λ/K_S=1.0 (GiBUU), Λ/K_S=1.4 (Cugnon), Λ/K_S=2.3±0.7 (exp.). Not enough antikaon absorption by $\bar{K}N \to Y\pi$ in transport calculations.

— Total strange quark production cross sections are overestimated by transport calculations. No need in new exotic strangeness production mechanisms.

— The peak positions of the Λ and Ξ rapidity spectra strongly differ.

Backup

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.

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.

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.

Statistical annihilation model

E.S. Golubeva, A.S. Iljinov, B.V. Krippa, I.A. Pshenichnov, NPA 537, 393 (1992);
I.A. Pshenichnov, Doctoral thesis, INR, Moscow, 1998;
+ some improvements for strangeness production
in the present work

$\bar{N}N \rightarrow$ up to 6 mesons, π, η, ω, ρ, K, $\bar{K}$, $K^{\star}$, $\bar{K}^{\star}$

Probability:

$$\begin{aligned} W_n(\sqrt{s}, I_1, ..., I_n, Y_1, ..., Y_n) &= w_n(\sqrt{s}, I_1, ..., I_n, Y_1, ..., Y_n) \\ &\times a_{\pi}^{n_\pi} a_{\eta}^{n_\eta} a_{\omega}^{n_\omega} a_{\rho}^{n_\rho} a_{K}^{n_K + n_{\bar{K}}} a_{K^*}^{n_{K^*} + n_{\bar{K}^*}} , \end{aligned}$$

$I_1, ..., I_n$ – isospins of produced mesons,

$Y_1, ..., Y_n$ – hypercharges,

$a_\pi, a_\eta, ...$– SU(3) symmetry breaking constants.

$$w_n(\sqrt{s}; I_1, ..., I_n; Y_1, ..., Y_n) = V_n(\sqrt{s}) s_n \mathcal{M}_n(\sqrt{s}) \prod_{i=1}^{n} 2m_i$$

$$\times \sum_{(p,q)} K^2_{(p,q)}(I, I_3, Y) \mathcal{U}_n(p, q; I_1, ..., I_n; Y_1, ..., Y_n) \ .$$

$$V_n(\sqrt{s}) = (2m_N V_0/\sqrt{s})^{n-1}$$

$V_0 \simeq 20$ GeV^{-3} — interaction volume

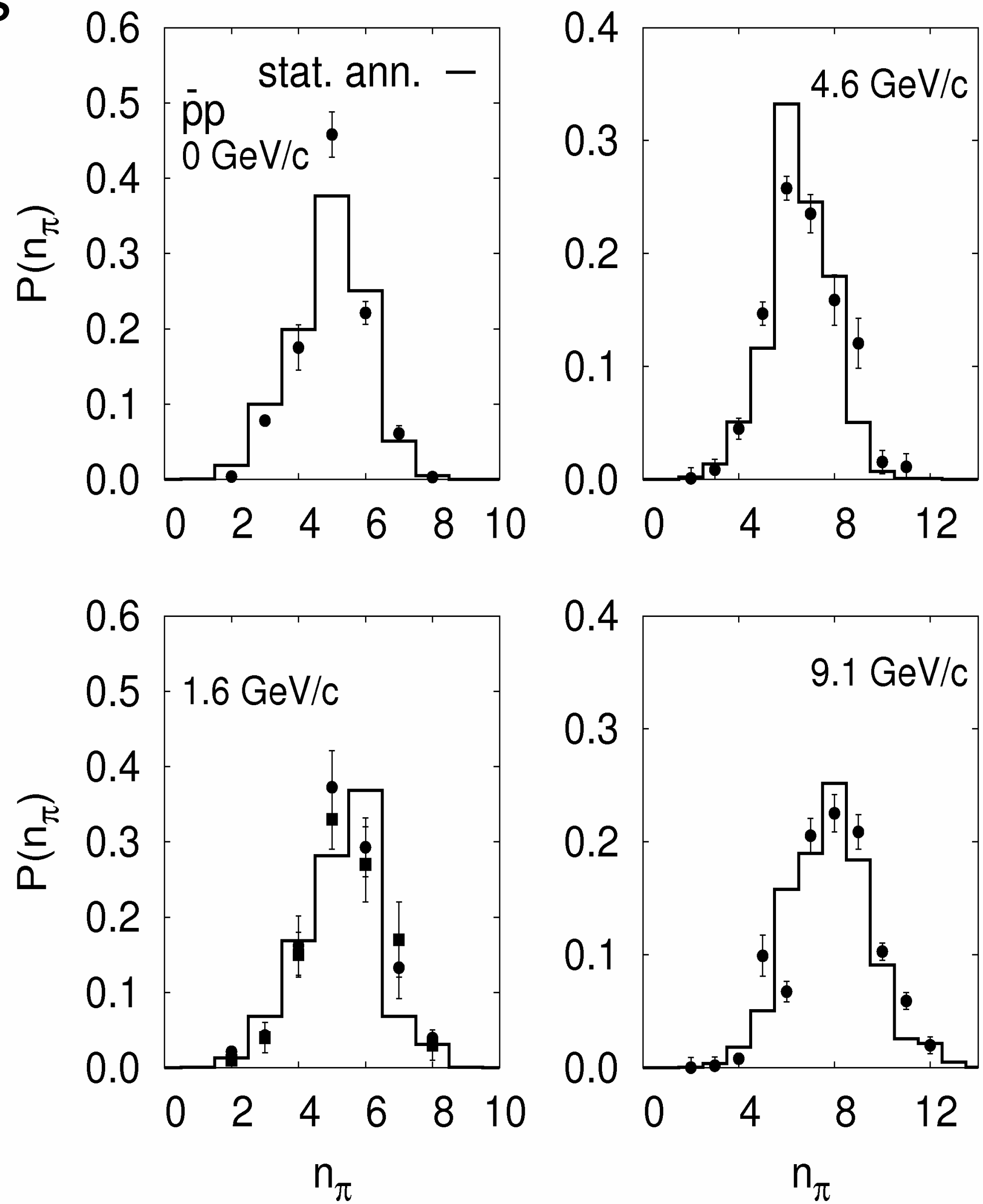
s_n — spin factor, m_N — nucleon mass

$\mathcal{M}_n(\sqrt{s})$ --- Lorentz invariant phase space volume

$K^2_{(p,q)}(I, I_3, Y)$ --- decomposition coefficients of initial state of $\bar{N}N$ system $(I = 0, 1;\ I_3 = 0,\ \pm 1;\ Y = 0)$ into a sum of irreducible representations (p,q) of the SU(3) group

$\mathcal{U}_n(p, q; I_1, \ldots, I_n; Y_1, \ldots, Y_n)$ --- isoscalar factor

Pion multiplicity distributions from $\bar{p}p$ annihilation



$\bar{p}p$ cross sections

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

Charge exchange:

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

Annihilation:

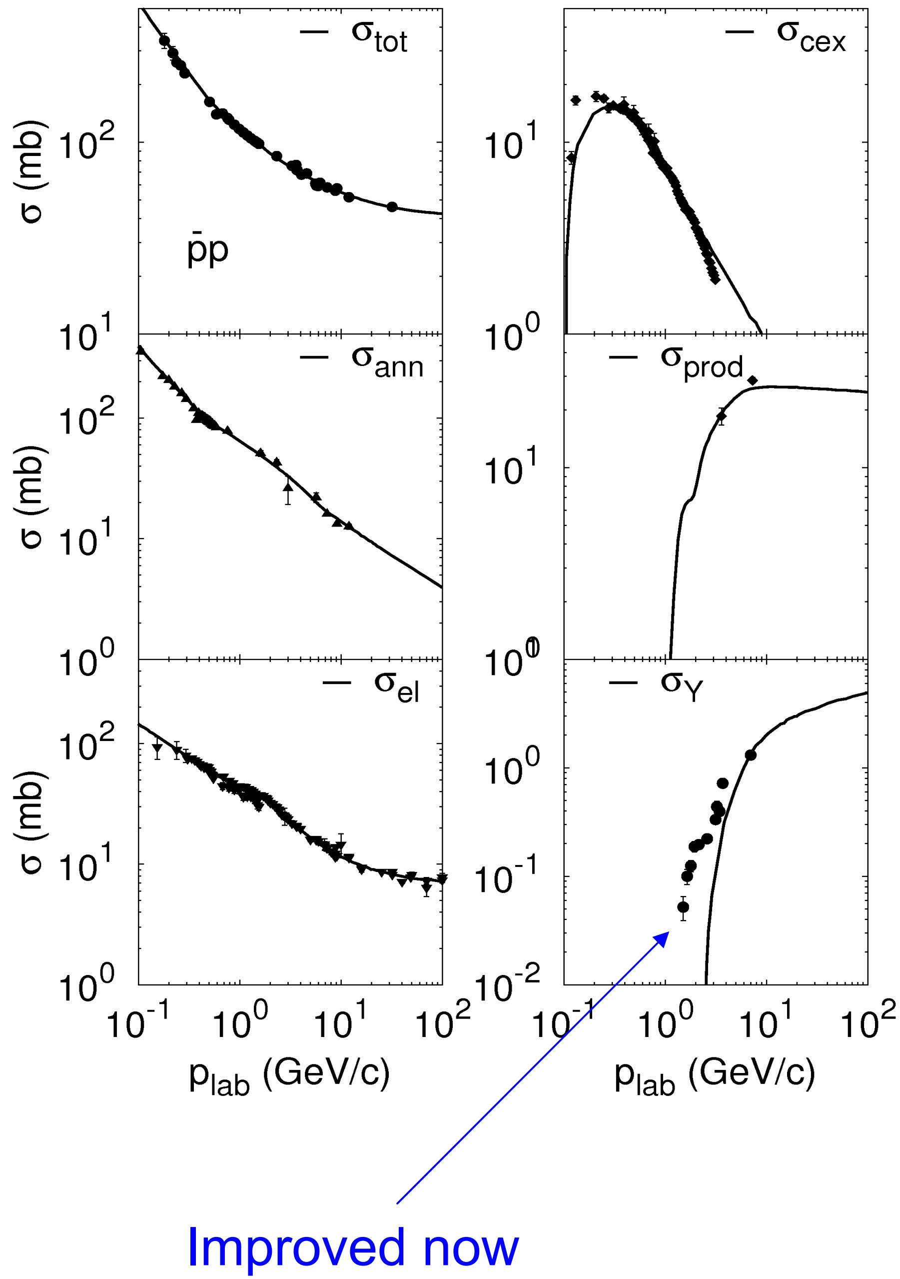
$\bar{p}p \rightarrow$ mesons

Production:

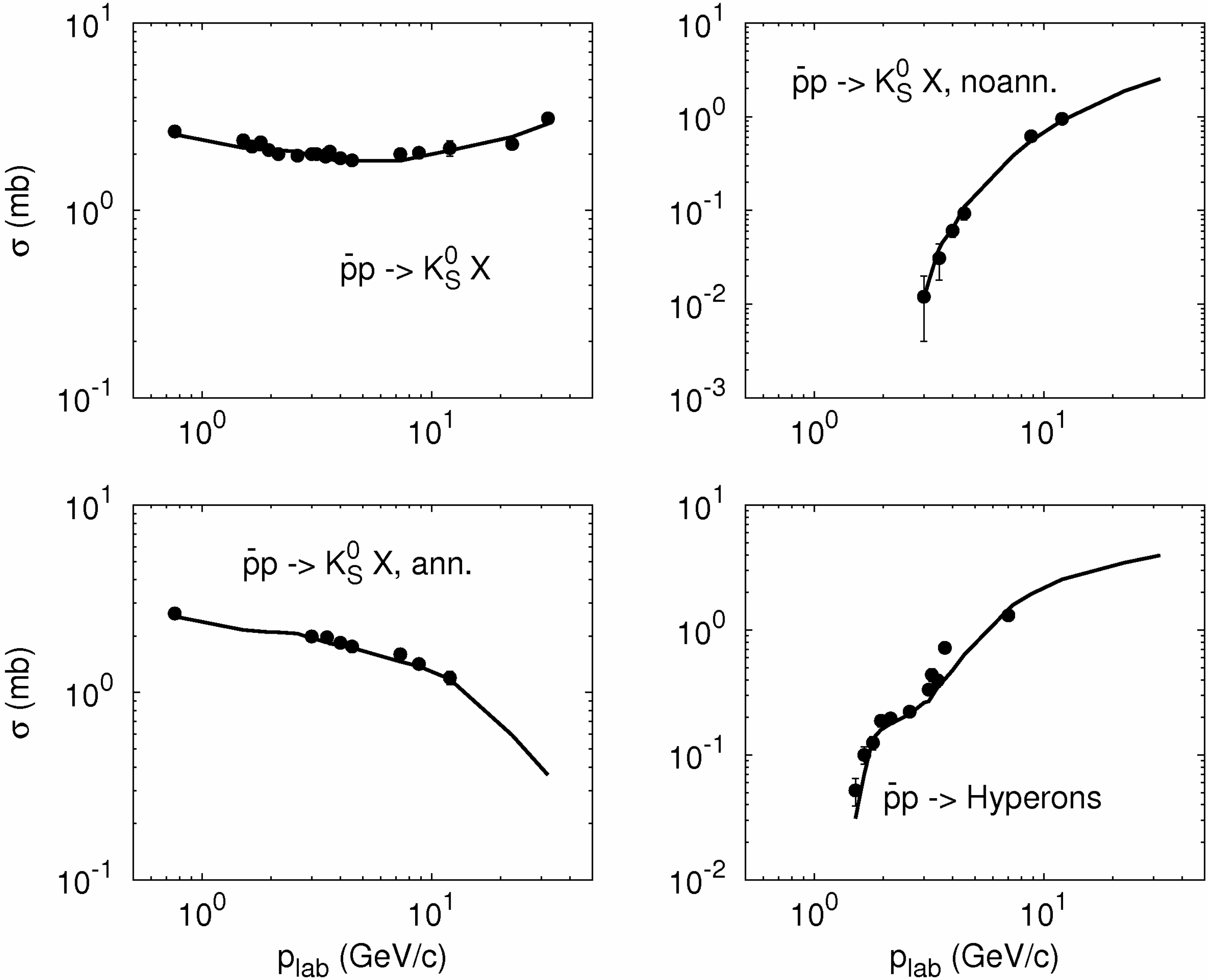
$\bar{p}p \rightarrow \bar{N}N +$ mesons

Hyperon production:

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



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



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:

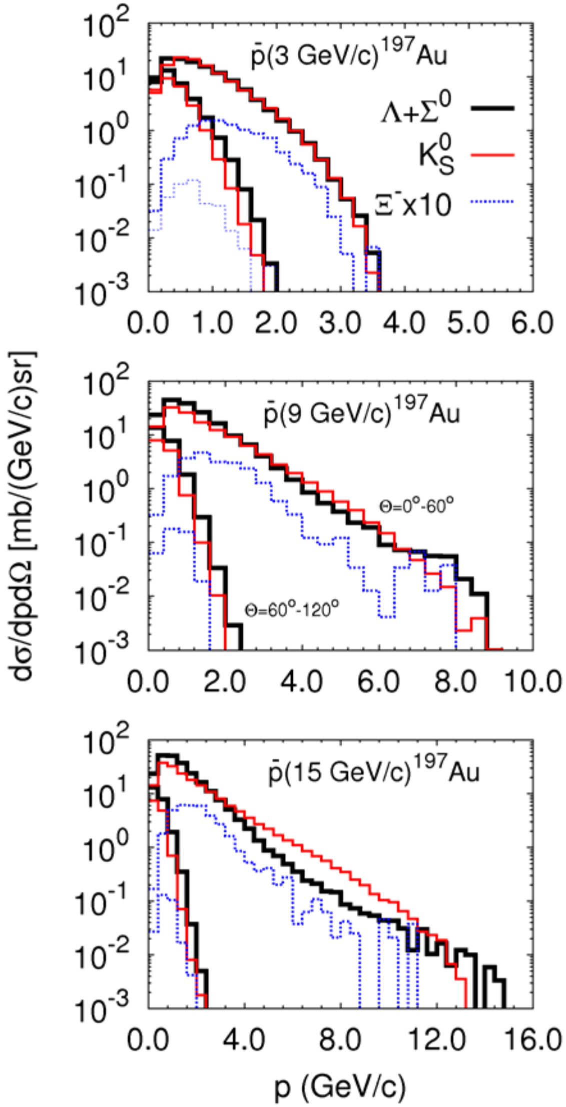
j	N	Λ	Σ	Ξ	K	$\bar{N}$	$\bar{\Lambda}$	$\bar{\Sigma}$	$\bar{\Xi}$	$\bar{K}$
U_j	-46	-38	-39	-22	-18	-150	-449	-449	-227	-224

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

Momentum spectra of produced strange particles.

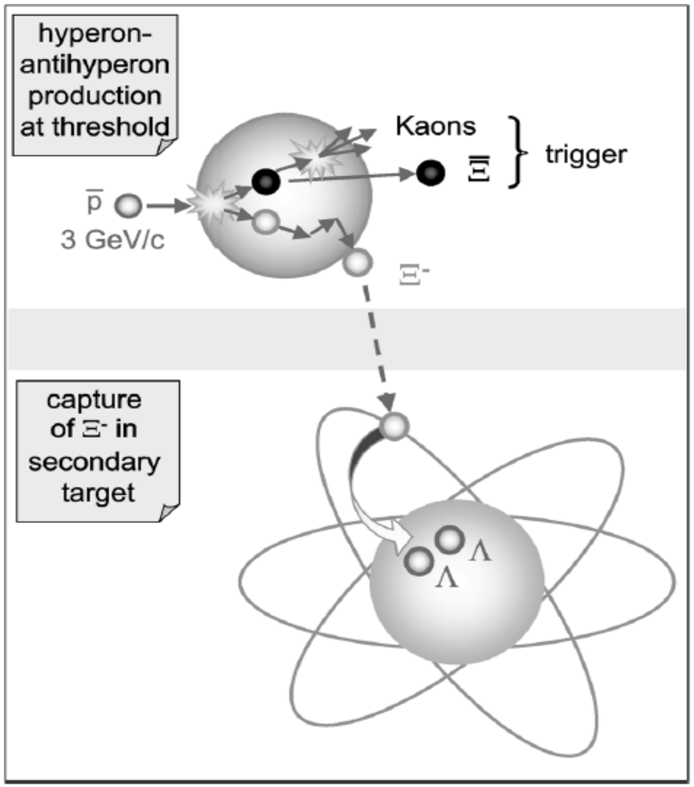
Similar behaviour at large momenta for all particles.

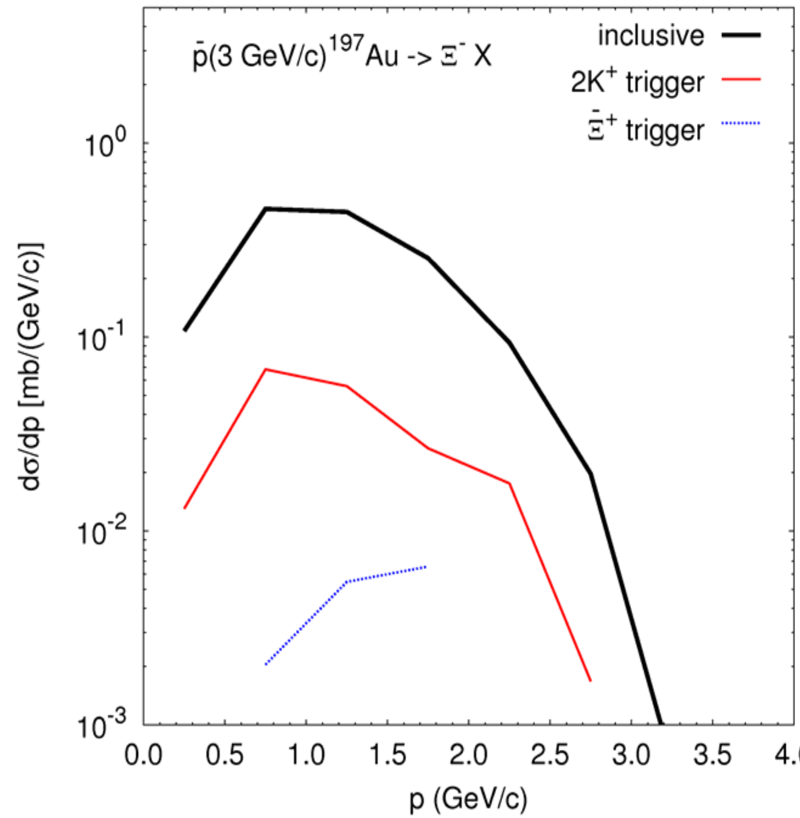
Ξ^- spectra are suppressed at low momenta.



The double Λ hypernucleus production experiment by PANDA@FAIR
(J. Pochodzalla, NPA 754, 430 (2005))

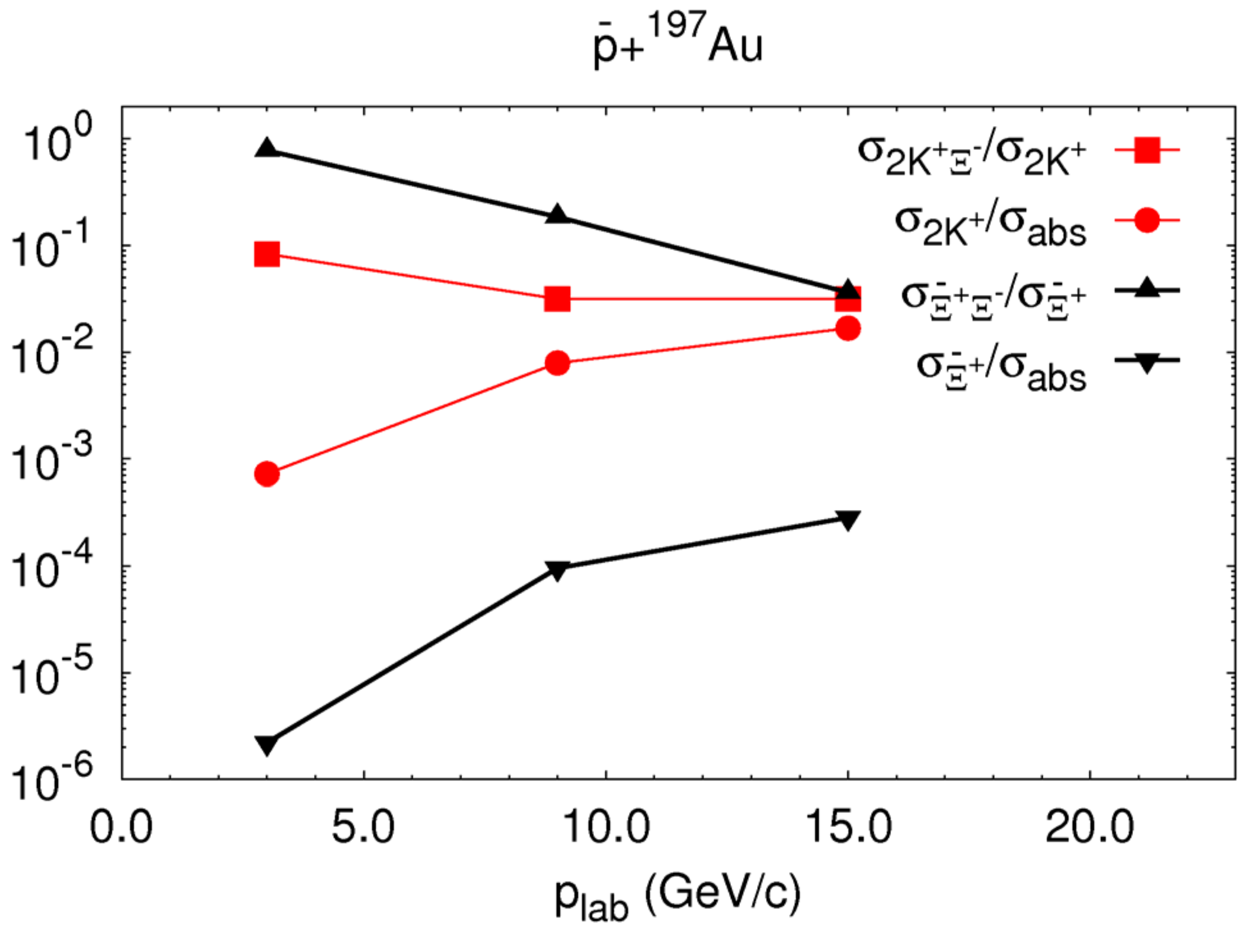
Ξ^- momentum spectrum triggered by $2K^+$ and Ξ^+





Strong reduction of the Ξ^- yield by triggering on Ξ^+, but …

…the Ξ^+ trigger is much more selective near threshold !



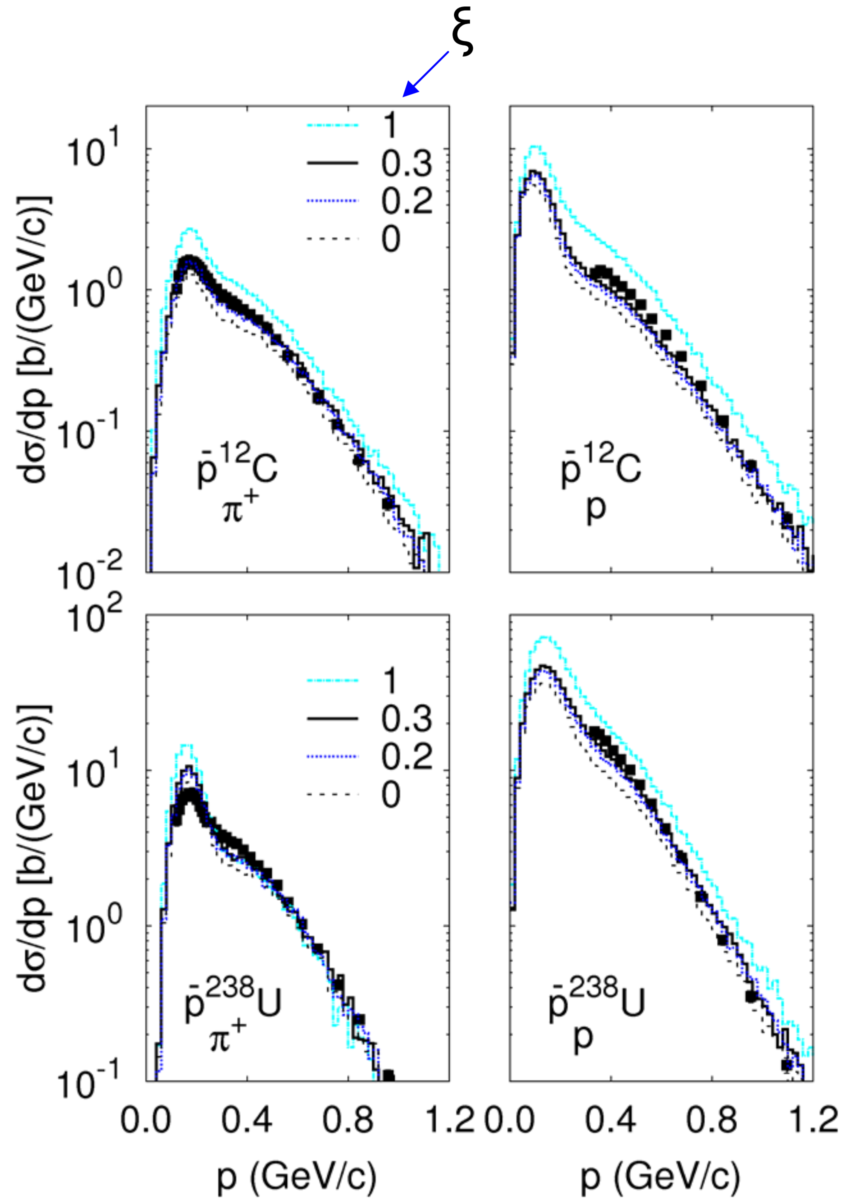
$$p_{\mathrm{lab}}^{\mathrm{thr}} = 2.6\ \mathrm{GeV/c\ for}\ \bar{p}p \to \Xi^-\Xi^+$$

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 $\xi\approx0.3$, or $Re(V_{opt})$=-(220±70) MeV



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

Rapidity spectra of protons

and pions for p_{lab}=608 MeV/c.

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