Strangeness production in antiproton-nucleus annihilation*

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Outline

- Motivation
- The Giessen Boltzmann-Uehling-Uhlenbeck transport model: relativistic mean field, collision terms.
- Strange particle production
- Fragment and hyperfragment production
- Summary and outlook

Based on works:

A.L., T. Gaitanos, and U. Mosel,
PRC 85, 024614 (2012)

T. Gaitanos, A.L., H. Lenske, and U. Mosel,
NPA 881, 240 (2012)

Motivation

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

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

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

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

ASTERIX@LEAR (J. Riedlberger et al., 1989): Λ from $\bar{p}$(at rest) d,^{14}N

MPS@BNL (S. Ahmad et al., 1997):

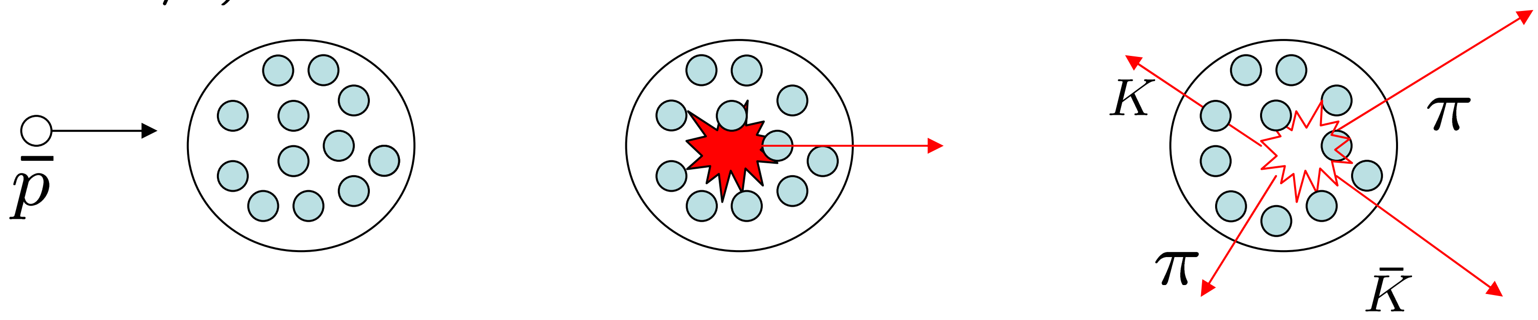
K_S^0, Λ, $\bar{\Lambda}$ from $\bar{p}$(5-9 GeV/c)^{12}C, ^{64}Cu, ^{208}Pb

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

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

***Exotic scenario (J. Rafelski, 1988)*: propagating annihilation fireball with baryon number B > 0 due to absorption of nucleons**

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



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

-Strangeness production in a QGP should be enhanced.

Obelix @ LEAR: Phase transition to the QGP ?

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

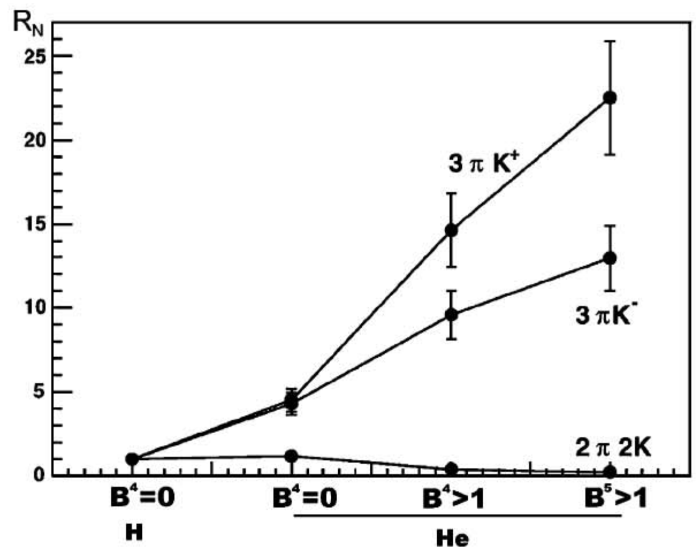
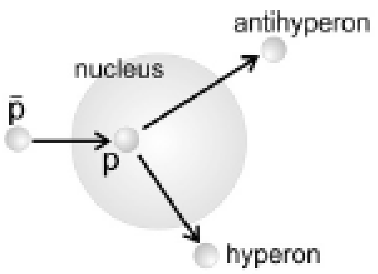


Fig. 1. Charged kaon production for the reactions without neutral mesons with 4 charged mesons (4 prongs) and with 4 charged mesons plus a fast proton (5 prongs): $3\pi K^{+}(p)$, $3\pi K^{-}(p)$ and $2\pi 2K(p)$. R_N = ratio in percentage between He and H yields; the reference value in hydrogen concerns 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 ^{4}He involving at least two nucleons is enhanced by a factor of 22.

PANDA@ FAIR: **Antihyperon potential determination**



Event-by-event correlations between transverse momentum asymmetries of the hyperon and antyhyperon are sensitive to the antyhyperon potential.

J. Pochodzalla, PLB 669, 306 (2008)

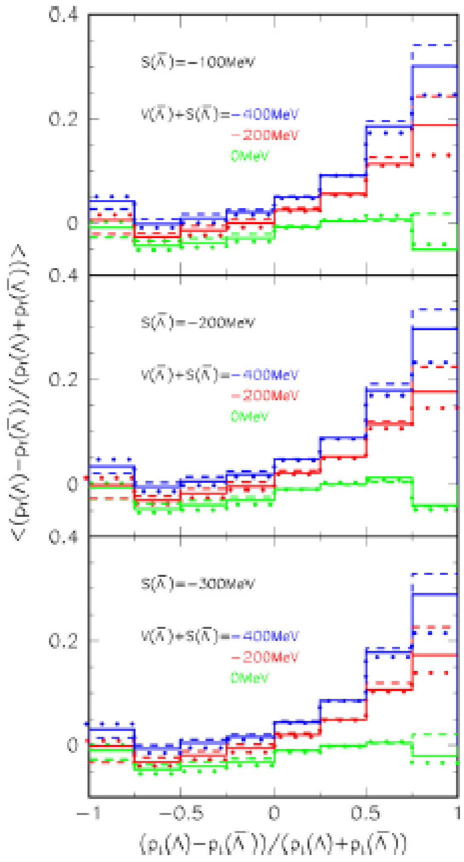


Fig. 3. Average transverse momentum asymmetry as a function of the longitudinal momentum asymmetry for different parameter pairs of the scaler and vector $\bar{\Lambda}$ potentials. In each panel calculations with 3 different Fermi momenta of 180 MeV/c (dashed lines), 220 MeV/c (solid lines), and 260 MeV/c (dotted lines) are overlaid.

GiBUU model

The Giessen Boltzmann-Uehling-Uhlenbeck model:

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

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

The set of coupled relativistic kinetic equations (D. Vasak et al., 1987; H.-Th. Elze et al., 1987; B. Blaettel et al., 1993) for different hadrons ($j = N,\ \bar{N},\ \Delta,\ \bar{\Delta},\ \pi\ldots$) :

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

$$\mu = 0, 1, 2, 3, \qquad k = 1, 2, 3, \qquad x \equiv (t, \mathbf{r}) \ .$$

collision integral

$f_j(x, \mathbf{p}^*)$ - distribution function in kinetic phase space $(\mathbf{r}, \mathbf{p}^*)$,

$m_j^\star = m_N + S_j$ - effective mass, $S_j = g_{\sigma j}\sigma$ - scalar field,

$p^{\star\mu} = p^\mu - V_j^\mu$ - kinetic four-momentum,

$p^{\star\mu} p_\mu^\star = (m_j^\star)^2$ - mass shell condition,

$F_j^{\mu\nu} = \partial^\mu V_j^\nu - \partial^\nu V_j^\mu$ - field tensor,

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

Test particle representation:

$$f_j(x, \mathrm{p}^\star) = \frac{(2\pi)^3}{g_j n} \sum_{i=1}^{nN_j} \delta(\mathbf{r} - \mathbf{r_i}(t))\delta(\mathrm{p}^\star - \mathrm{p}_\mathrm{i}^\star(t)) \ ,$$

N_j - number of physical particles of the type j ,
$n \simeq 1000$ - number of test particles per physical particle.
Hamiltonian-like equations of motion for the centroids $\mathbf{r}_i$ and $\mathbf{p}_i$
between two-body collisions:

$$\dot{\mathbf{r}}_i = \frac{\mathbf{p}_i^\star}{p_i^{\star 0}} \ ,$$

$$\dot{p}_i^{\star k} = \frac{p_{i\mu}^\star}{p_i^{\star 0}} F^{k\mu} + \frac{m_j^\star}{p_i^{\star 0}} \partial_x^k m_j^\star$$

For the calculation of mean fields:

$\delta(\mathbf{r} - \mathbf{r}_i) \to \frac{1}{(2\pi)^{3/2} L^3} \exp\{-(\mathbf{r} - \mathbf{r}_i)^2 / 2L^2\},$
$L \simeq 0.5$ fm

Meson field equations (mean field approximation):

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

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

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

$$\partial_\nu \partial^\nu A^\mu = 4\pi \sum_j e\, j^\mu_{Qj} \ ,$$

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 $N_1 N_2 \rightarrow N_3 N_4$:

relative velocity of N_1 and N_2

$$I_N = \int \frac{g_2 d^3 p_2^\star}{(2\pi)^3} \int d\sigma^\star_{12\to34}\, v^\star_{12}\, (f_3 f_4 \bar{f}_1 \bar{f}_2 - f_1 f_2 \bar{f}_3 \bar{f}_4)\ ,$$

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

(in-medium) differential cross section

Collision channels:

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 ($p_{\mathrm{lab}} > 1.9$ 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:

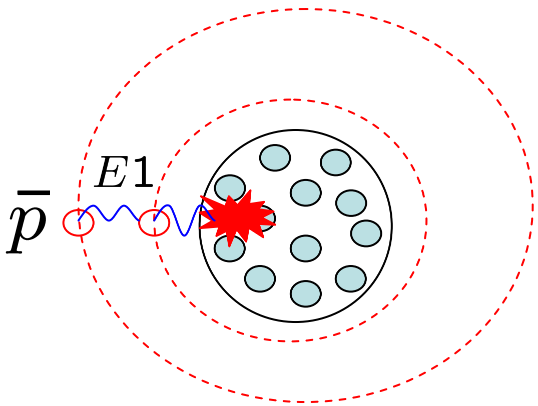
$\pi N \leftrightarrow R$, $\pi N \to K\bar{K}N$, $\pi(\eta,\rho,\omega)N \to YK$, $\bar{K}N \leftrightarrow Y^*$, $\bar{K}N \to \bar{K}N$, $\bar{K}N \leftrightarrow Y\pi$,
$\bar{K}N \leftrightarrow Y^*\pi$, $\bar{K}N \to \Xi K$.
For $\sqrt{s} > 2.2$ GeV : PYTHIA simulation of MB collisions.

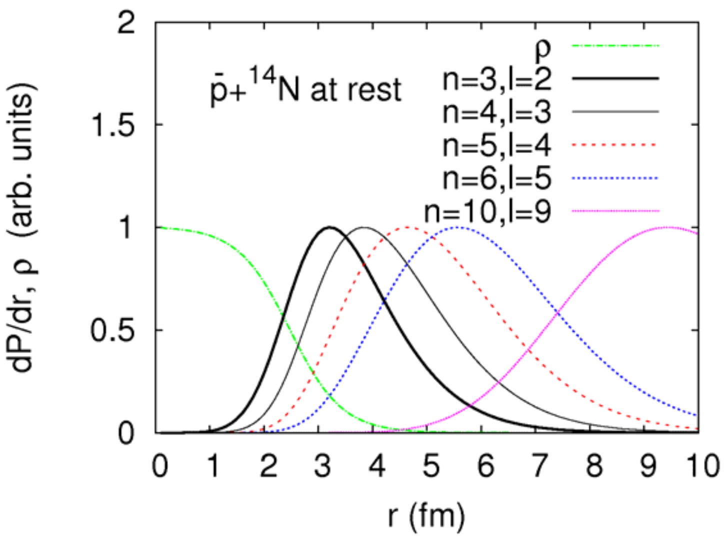
Baryon-baryon collisions:

$BB \to BB$ (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.

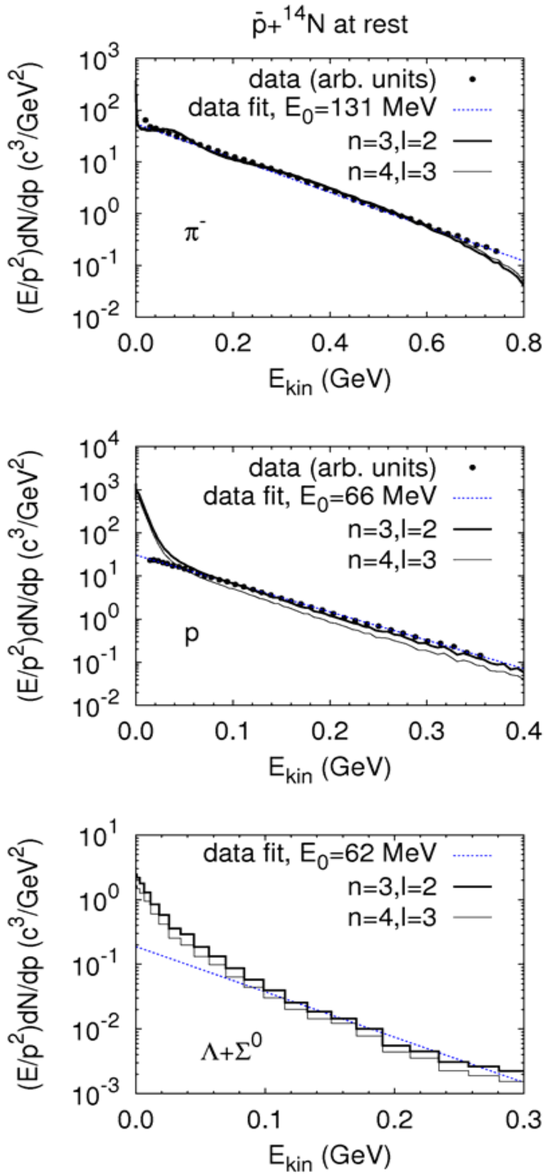
Strange particle production

Annihilation at rest:





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



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

PRC 85, 024614 (2012)

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

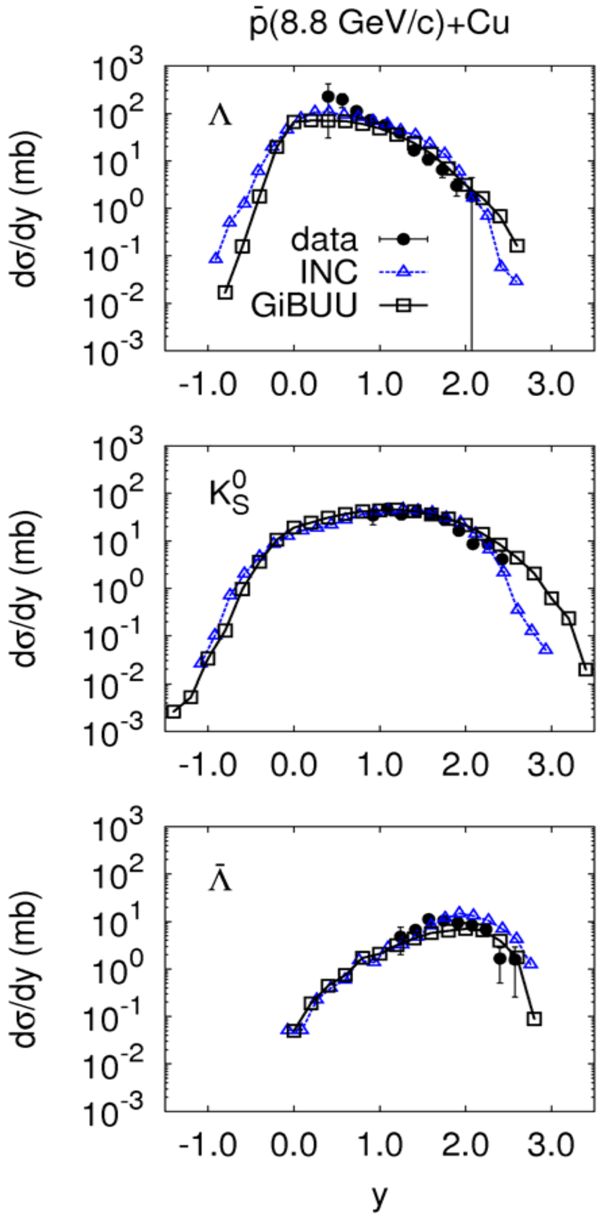
Annihilation in-flight:

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



PRC 85, 024614 (2012)

Systematics:

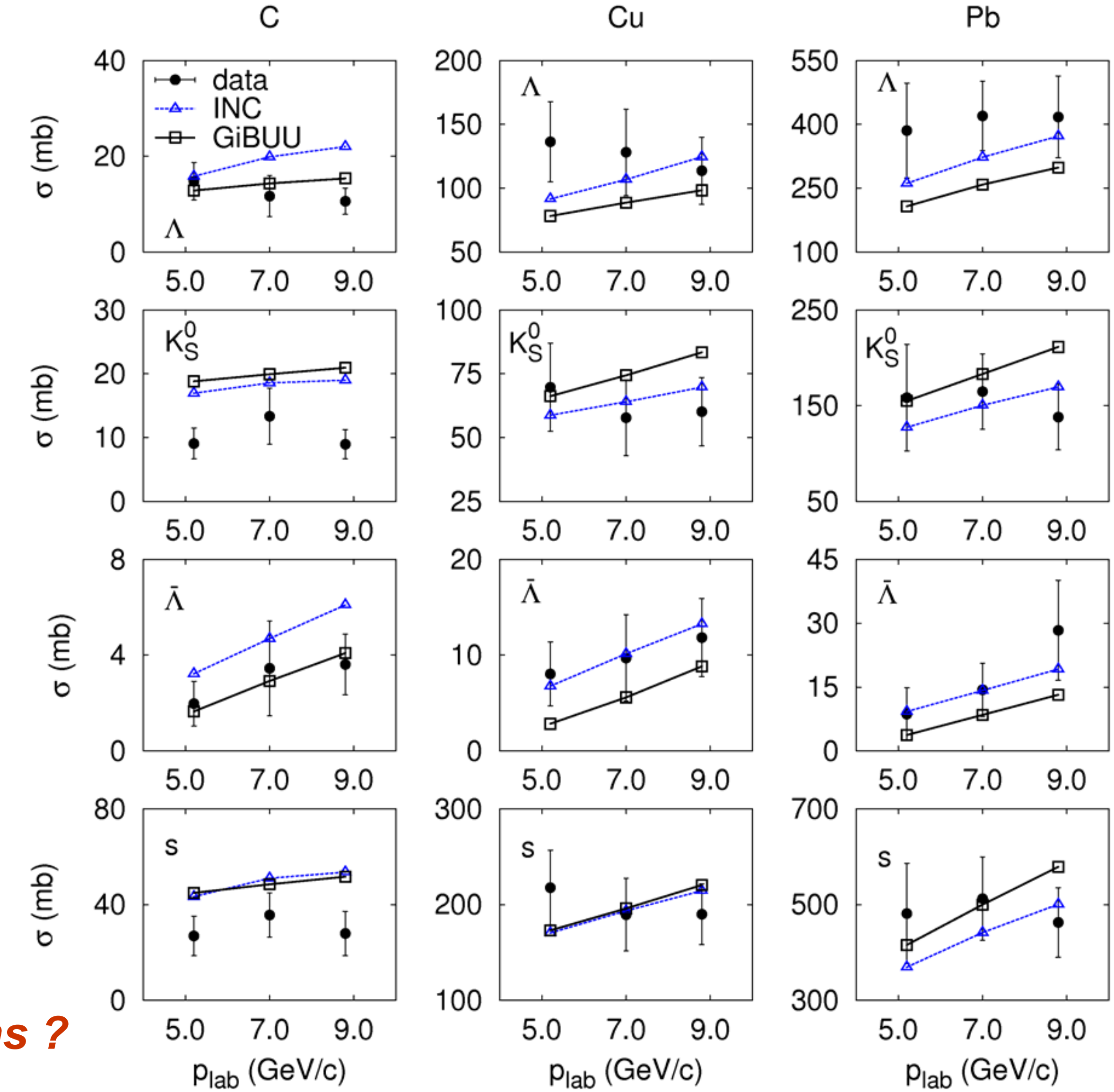
Data and INC calculations: S. Ahmad et al. (MPS@BNL), 1997.

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

→ not enough $\bar{K}$ absorption:

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

In-medium effects or inaccuracies in elementary cross sections ?



PRC 85, 024614 (2012)

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

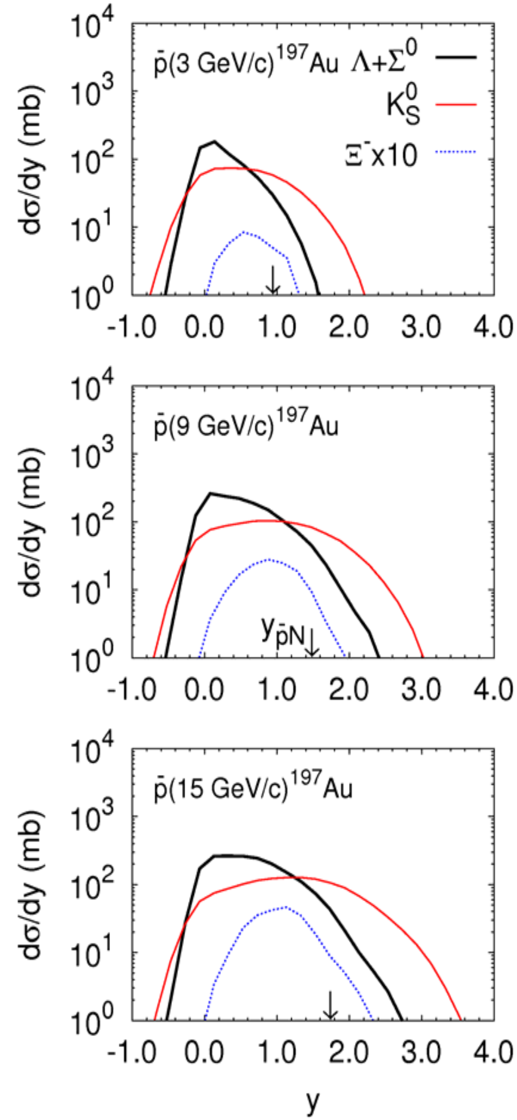
Rapidity spectra of strange particles.

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

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

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



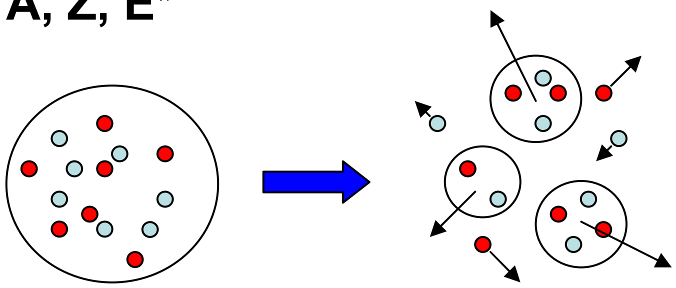
PRC 85, 024614 (2012)

Fragment and hyperfragment production

Statistical multifragmentation model (SMM)

(J. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin, K. Sneppen, 1995)

Equilibrated source:
A, Z, E*



-p

-n

$$W_{\text{partition}} \propto \exp(S_{\text{partition}})$$

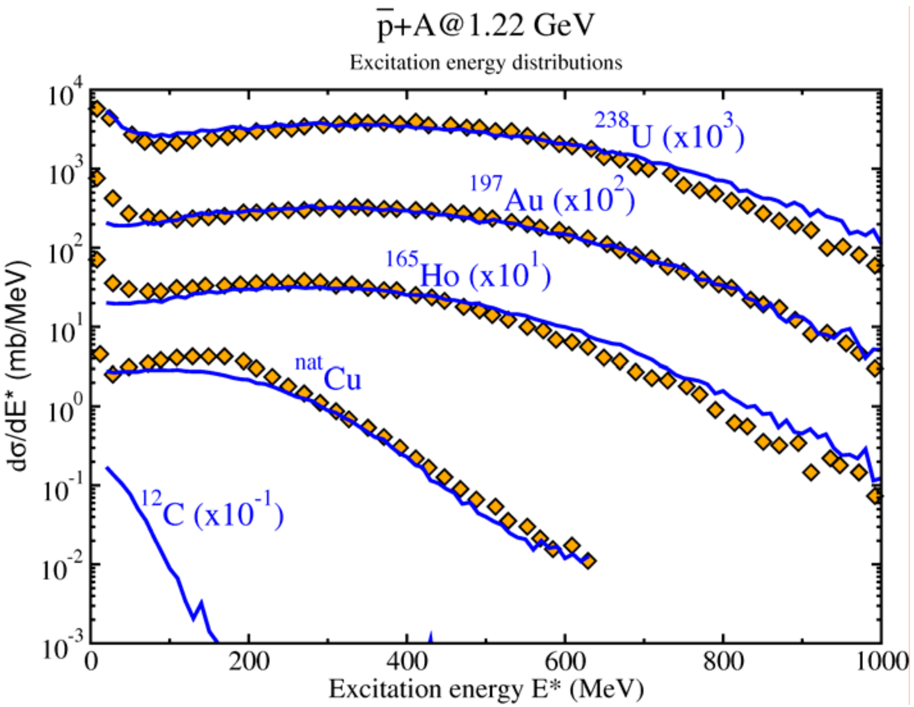
probability   entropy

Hybrid GiBUU+SMM

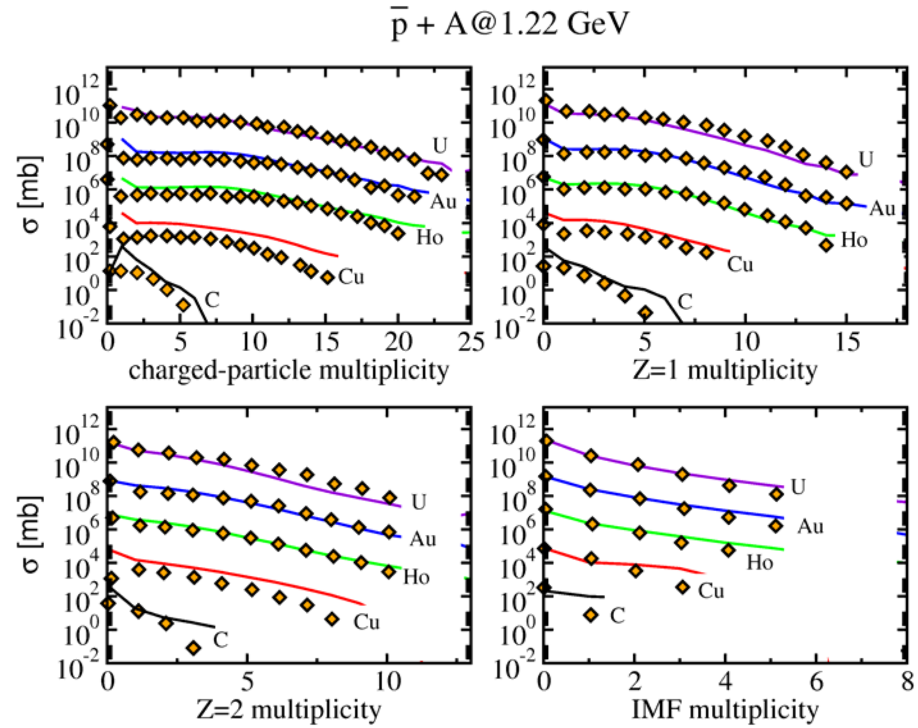
- **Non-Equilibrium dynamics within BUU until source(s) approaches stable configuration and local equilibration at $t=t_f$**
- **Determination of A, Z and E* of a source at time $t=t_f$**
- **Apply SMM**

Fragment production

Source excitation energy distributions:



Fragment multiplicity distributions:



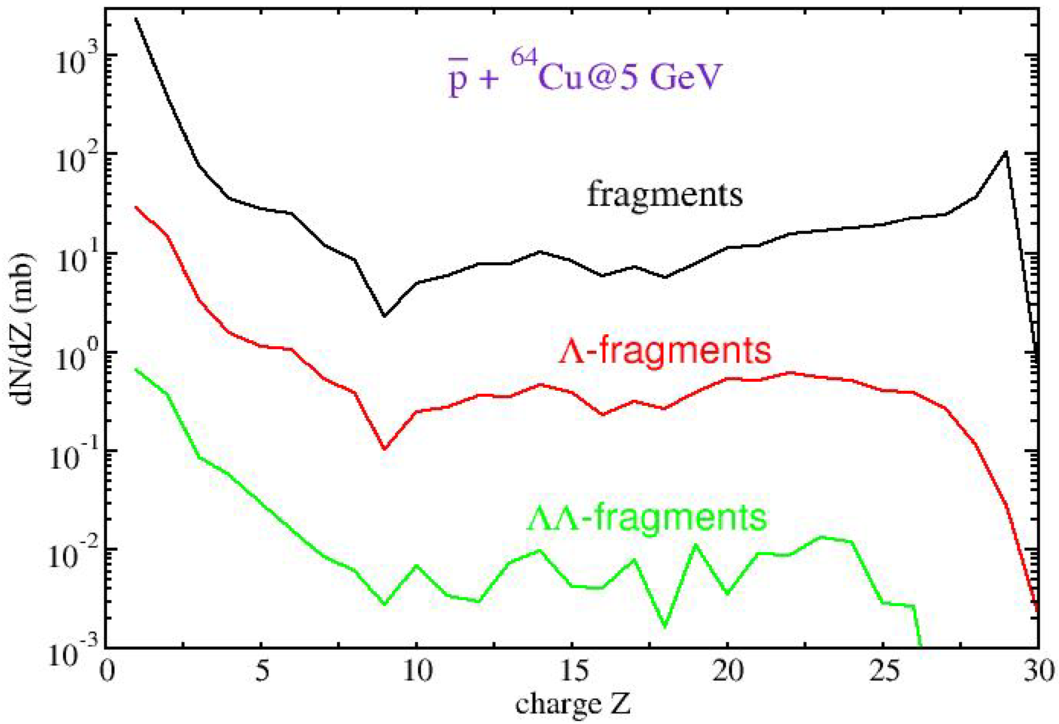
Data (LEAR): B. Lott et al, PRC 63, 034616 (2001)

GiBUU+SMM calculations: T. Gaitanos, A.L., H. Lenske and U. Mosel, NPA 881, 240 (2012)

Hyperfragment production

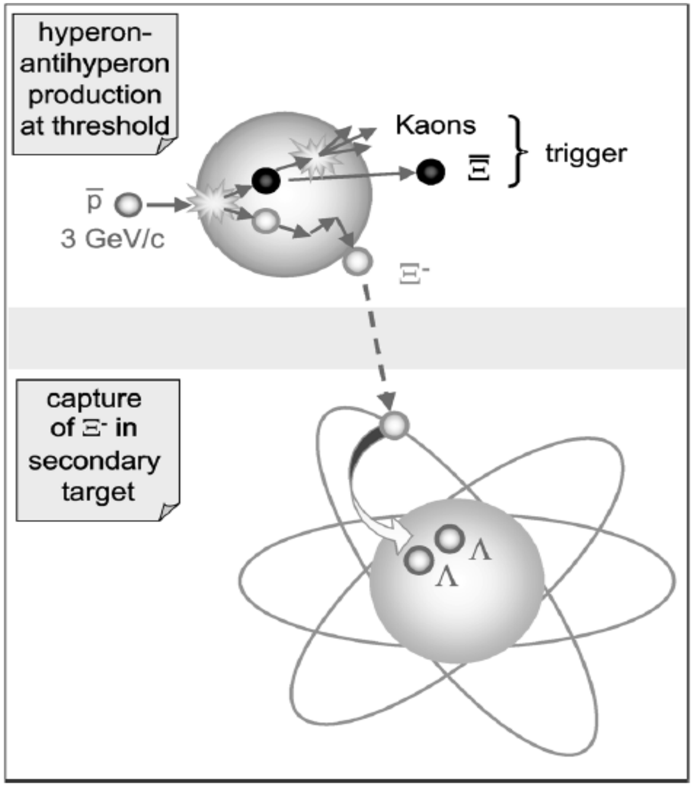
Hybrid GiBUU+SMM calculation: usual fragments – by SMM, hyperfragments – by Λ-fragment coalescence in momentum space.

Charge distributions



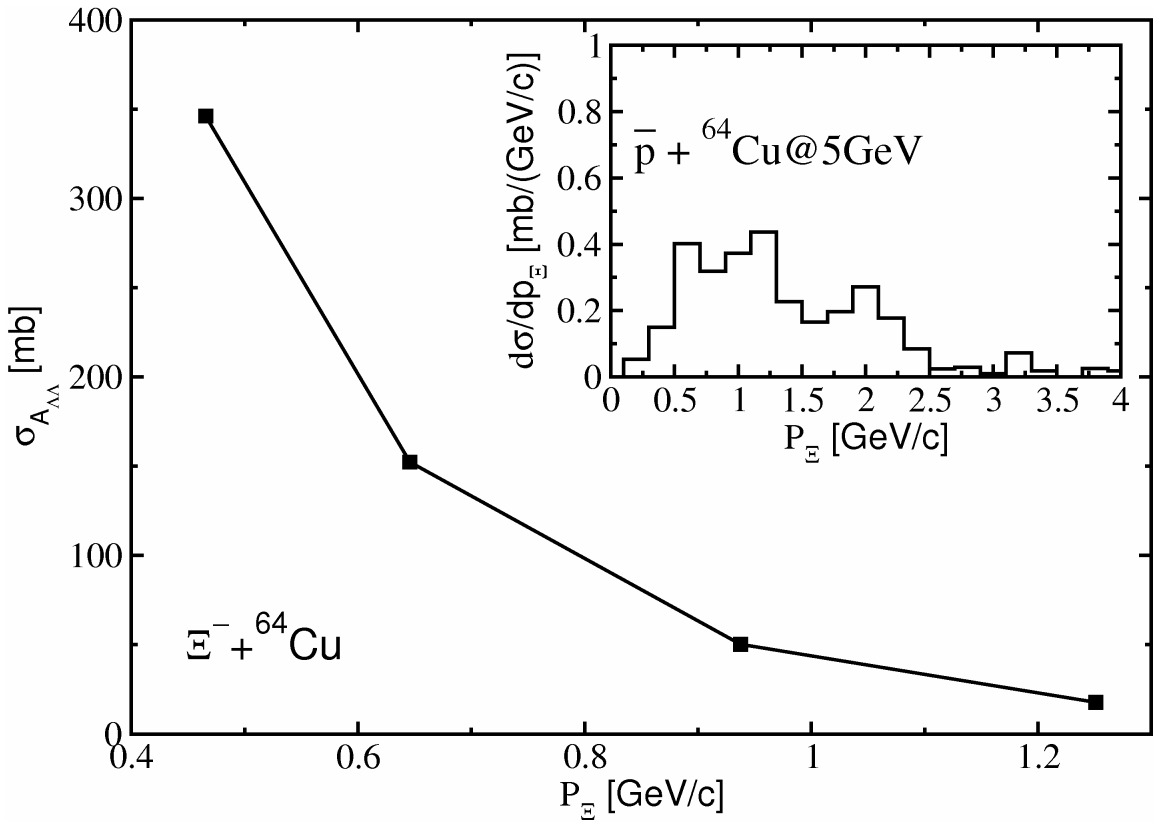
GiBUU+SMM calculations: T. Gaitanos et al, NPA 881, 240 (2012)

PANDA@ FAIR: **Double Λ hypernucleus production**



J. Pochodzalla, NPA 754, 430 (2005)

ΛΛ hyperfragment production with a secondary target (PANDA):



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

GiBUU+SMM calculations: T. Gaitanos et al, NPA 881, 240 (2012)

Summary

— GiBUU works rather well. However: tendency to underestimate Λ-yields and overestimate K_S-yields. The data on charged strange $\Sigma^{\pm},\ K^{\pm}$ particle production cross sections needed.

— Peak positions of Λ and Ξ^- rapidity spectra strongly differ in pure hadronic transport: test 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 transport models to antiproton-nucleus interactions:

— J/ψ production and propagation (work in progress)

— antibaryon potentials study, strongly bound antiproton-nucleus states

— annihilation at rest: signatures of QGP formation in Obelix data

A quantum appraoch: talk by ***Stefanie Lourenco***
on Monday, B4, 16:50 on meson production in $\bar{N}\,N$
annihilation on nuclei

Thank you for your attention !

Backup

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

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

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

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

Probability:

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

$I_1, ..., I_n$ – 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

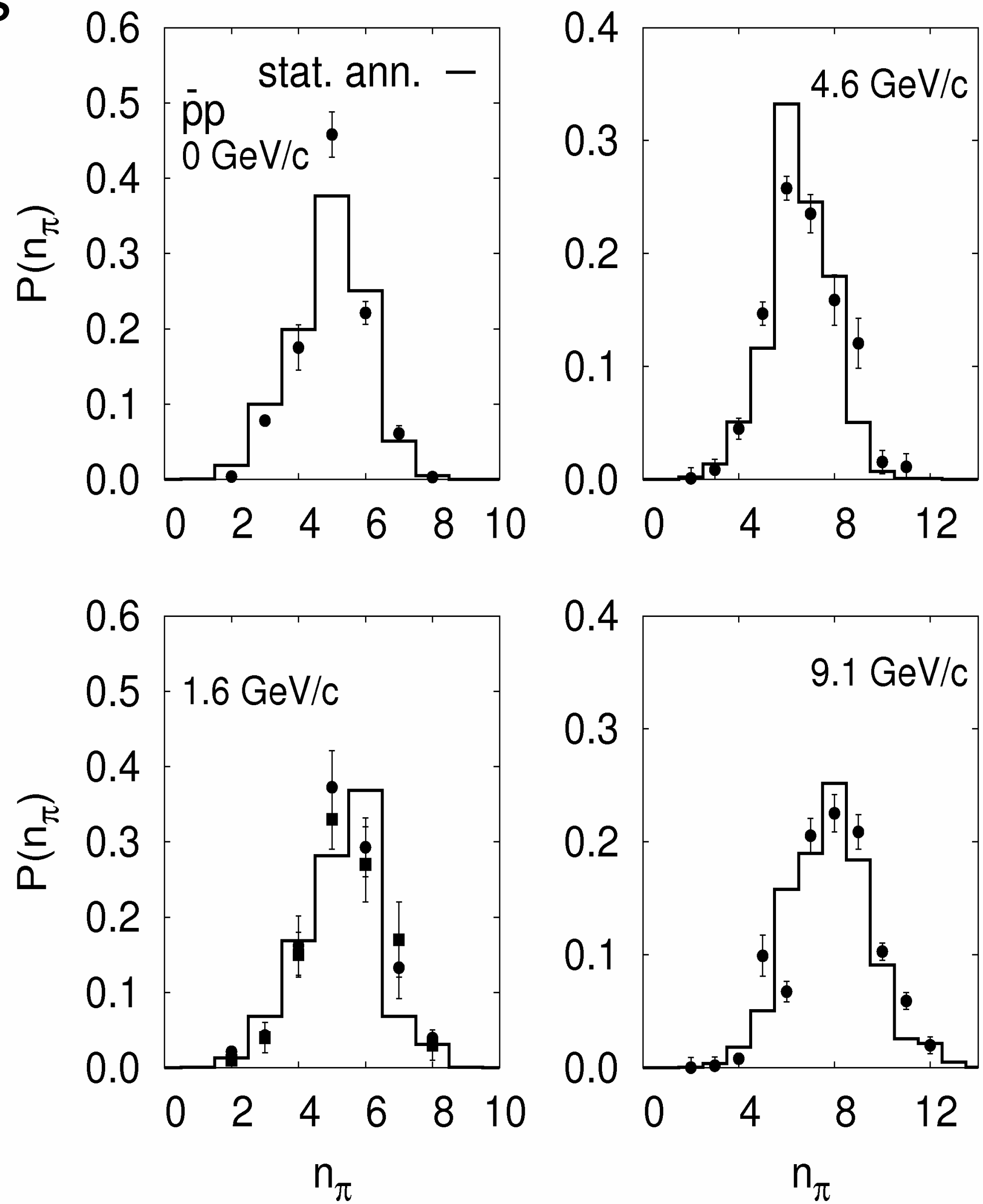
s_n — spin factor, m_N — nucleon mass

$\mathcal{M}_n(\sqrt{s})$ --- 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: $\bar{p}p \longrightarrow \bar{p}p$

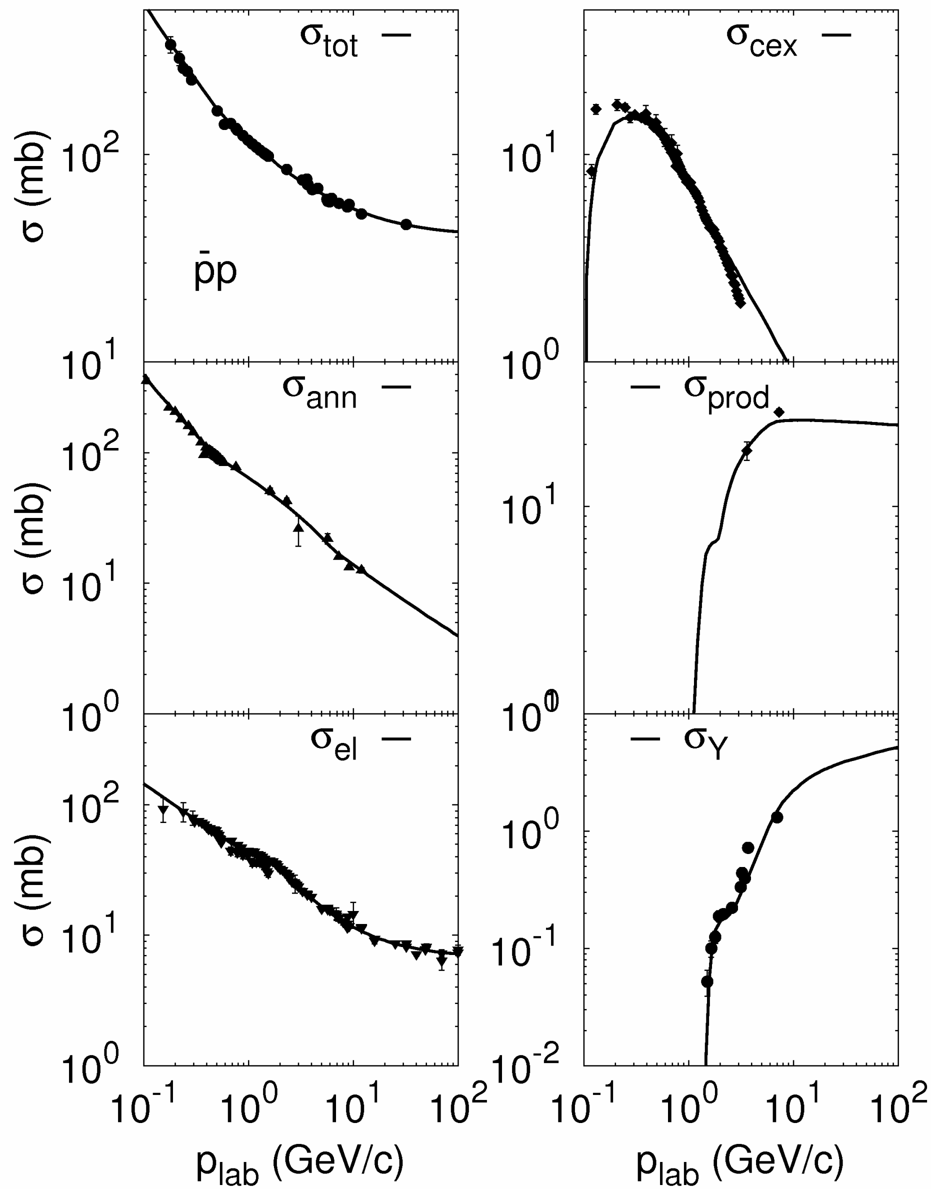
Charge exchange:
$\bar{p}p \longrightarrow \bar{n}n$

Annihilation:
$\bar{p}p \rightarrow$ mesons

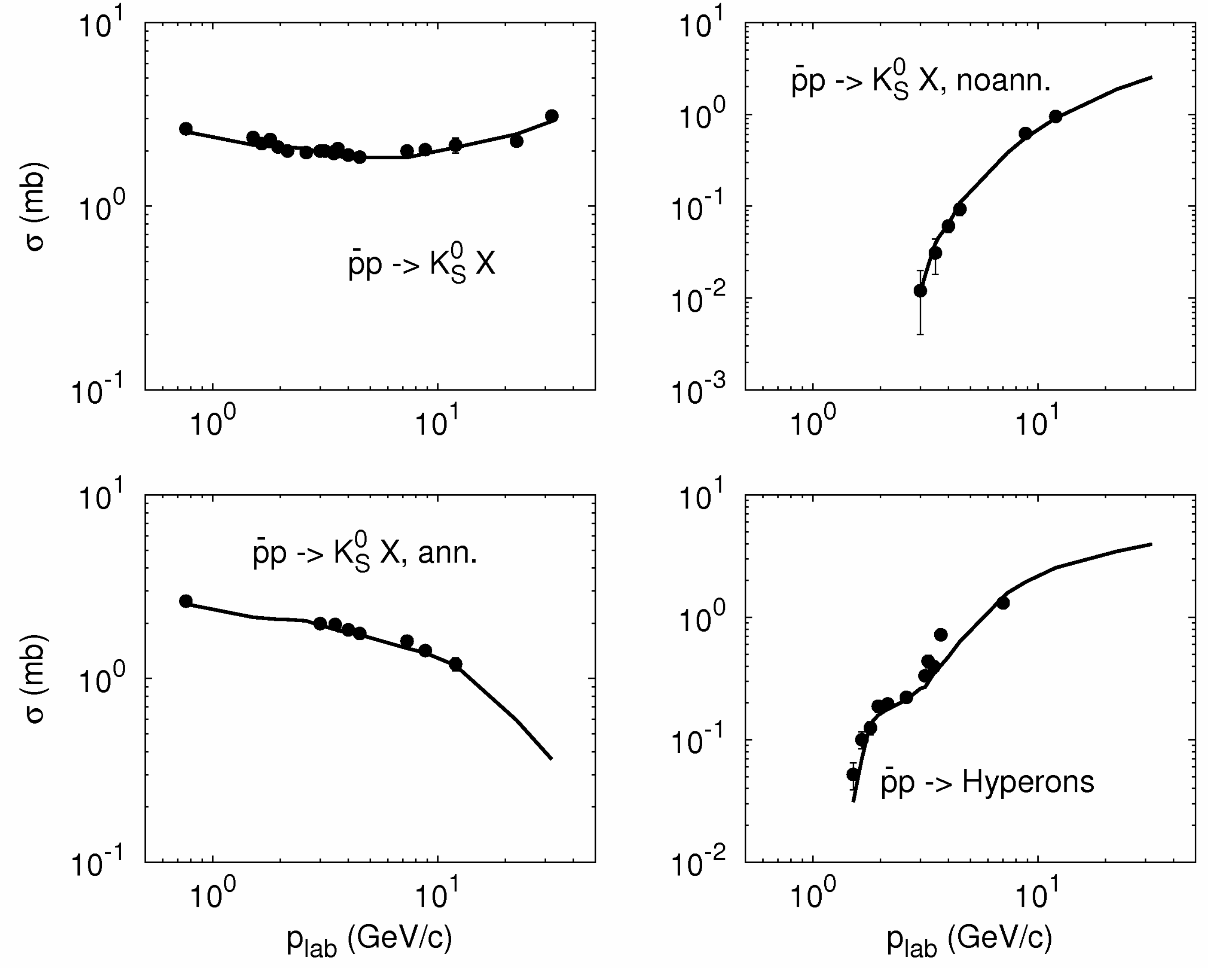
Production:
$\bar{p}p \rightarrow \bar{N}N +$ mesons

Hyperon production:

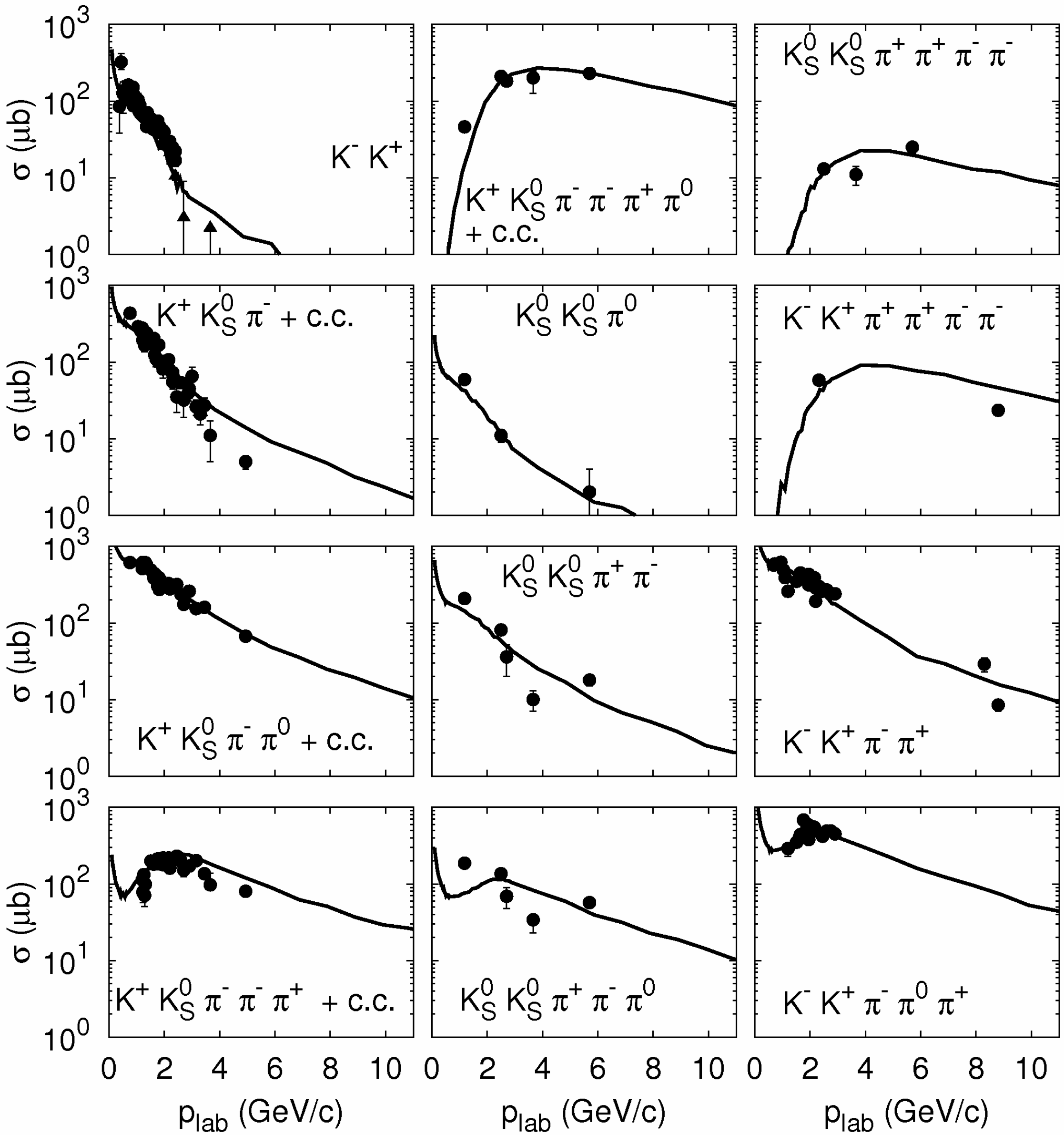
$$\begin{aligned}\bar{p}p \quad \rightarrow \quad & Y\bar{Y} + \text{mesons},\\ & YK\bar{N} + \text{mesons},\\ & N\bar{K}\bar{Y} + \text{mesons}.\end{aligned}$$



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



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

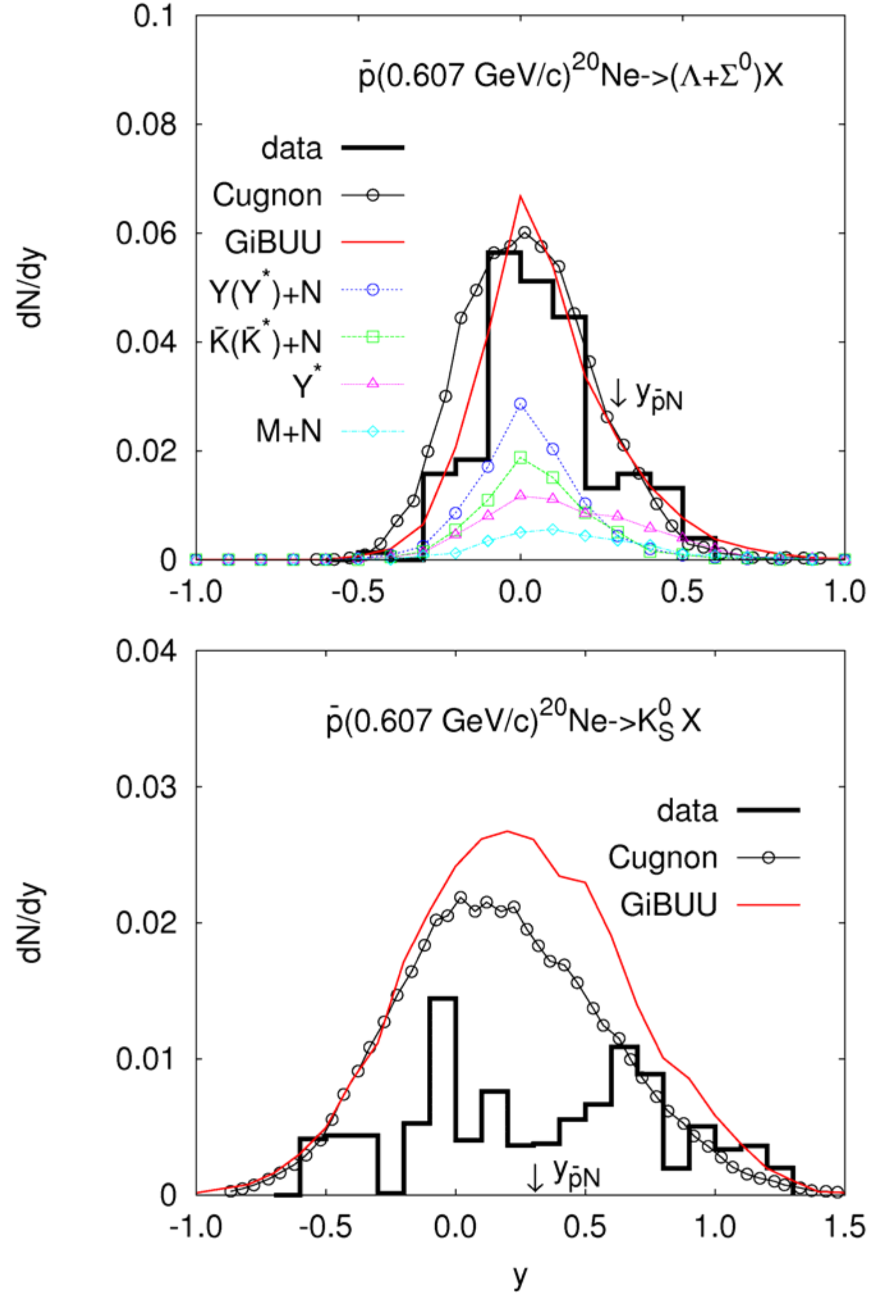


Rapidity distributions of Λ and K_S^0 from $\bar{p}(607\ MeV/c)^{20}$Ne.

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

Intranuclear Cascade (INC) Model calculations from 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. $\Sigma^+ n \to \Lambda p$).***



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,

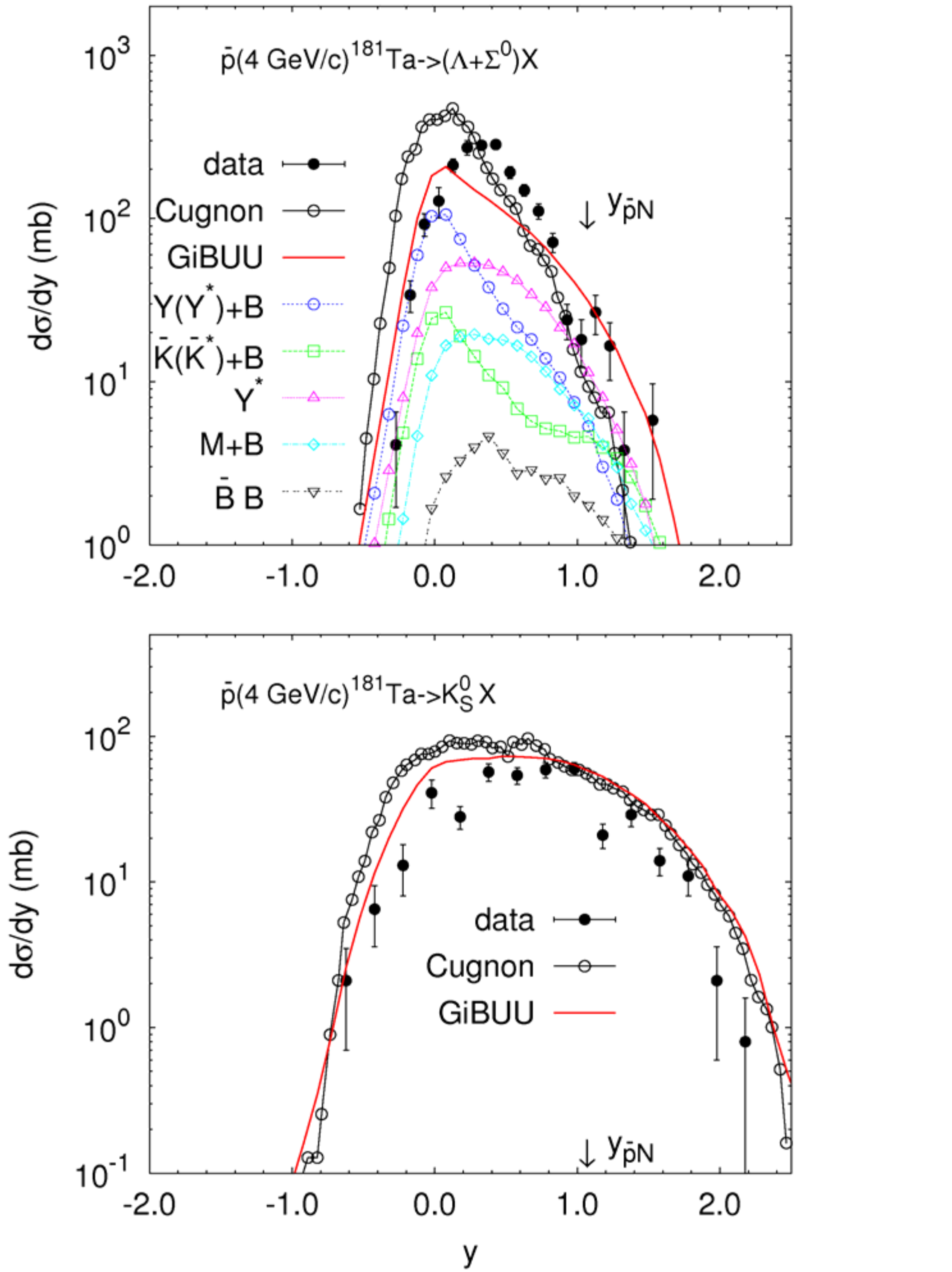
$M \equiv \pi,\ \eta,\ \rho,\ \sigma,\ \omega,\ \eta'$

– nonstrange mesons

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

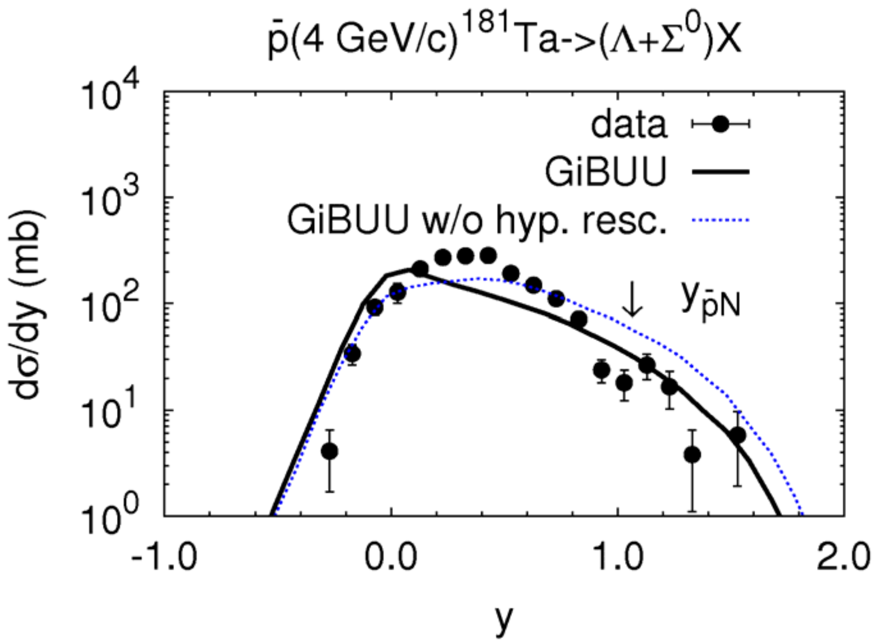
~70-80% of the Y(Y*) production rate is due to antikaon absorption

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



Hyperon rapidity distribution:

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

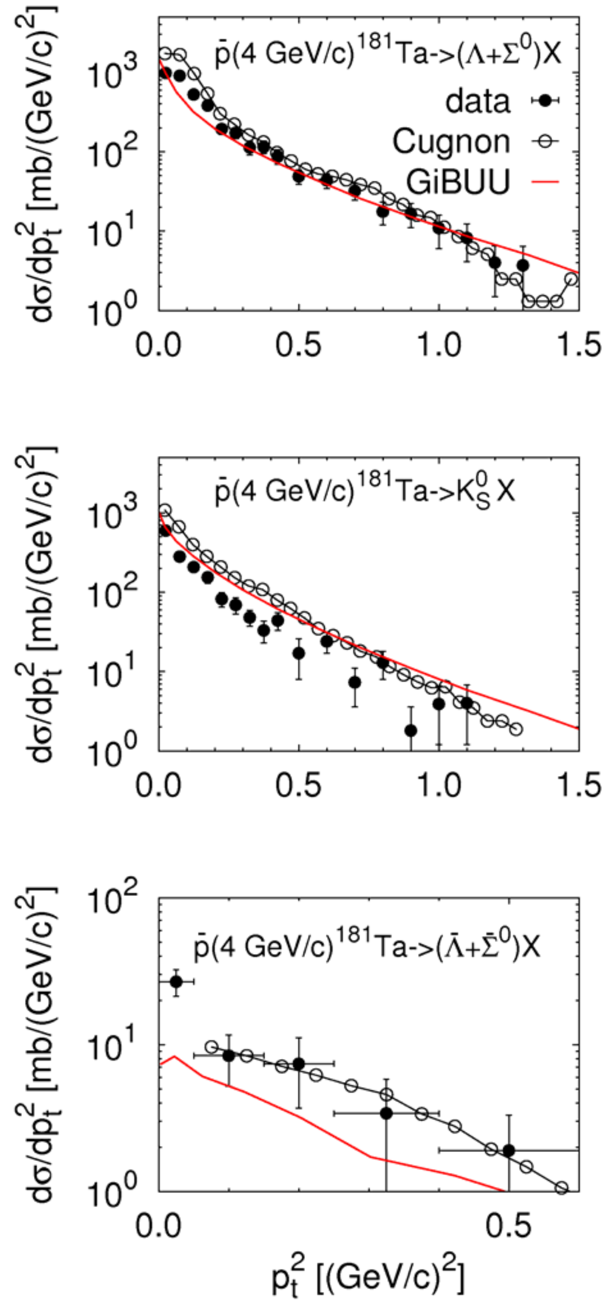


→ ***Sensitivity to the hyperon-nucleon scattering cross sections***

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).

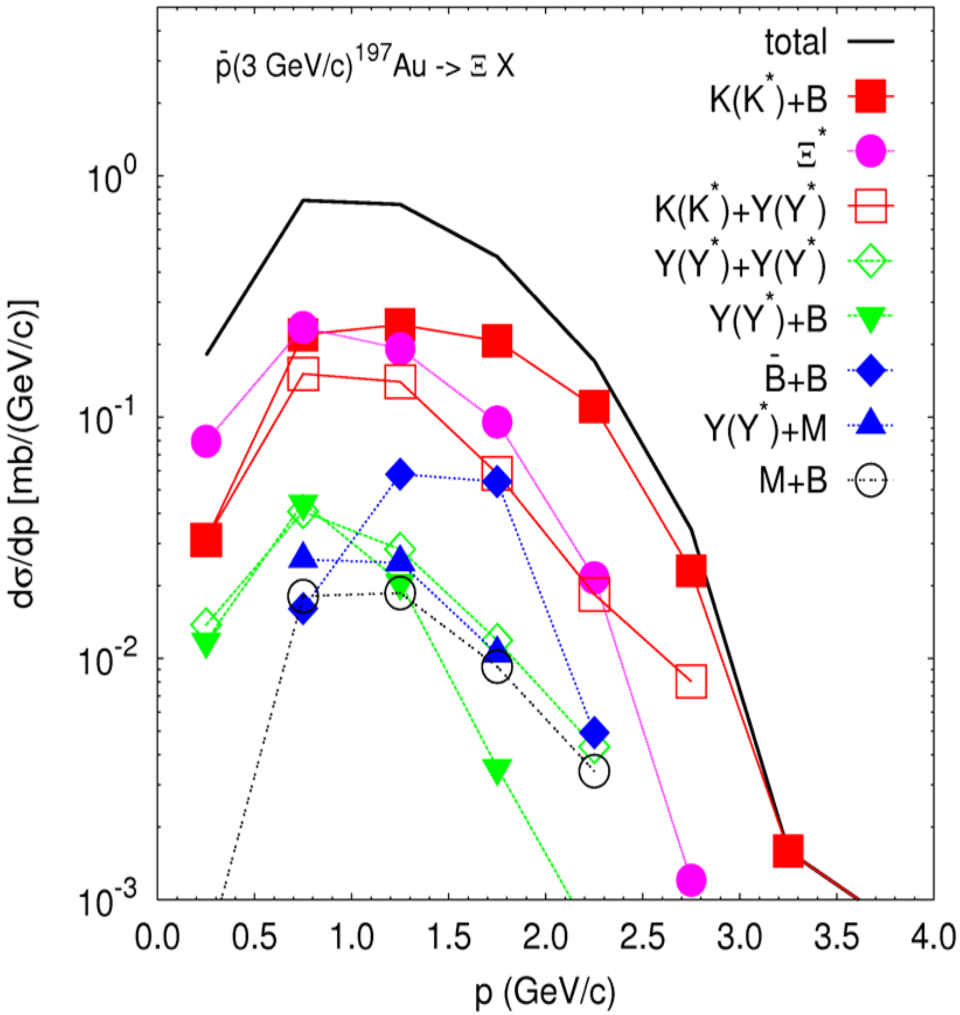
INC calculations from J. Cugnon et al., PRC 41, 1701 (1990).



Ξ inclusive momentum spectrum with partial contributions

Partial contributions to the Ξ production rate:

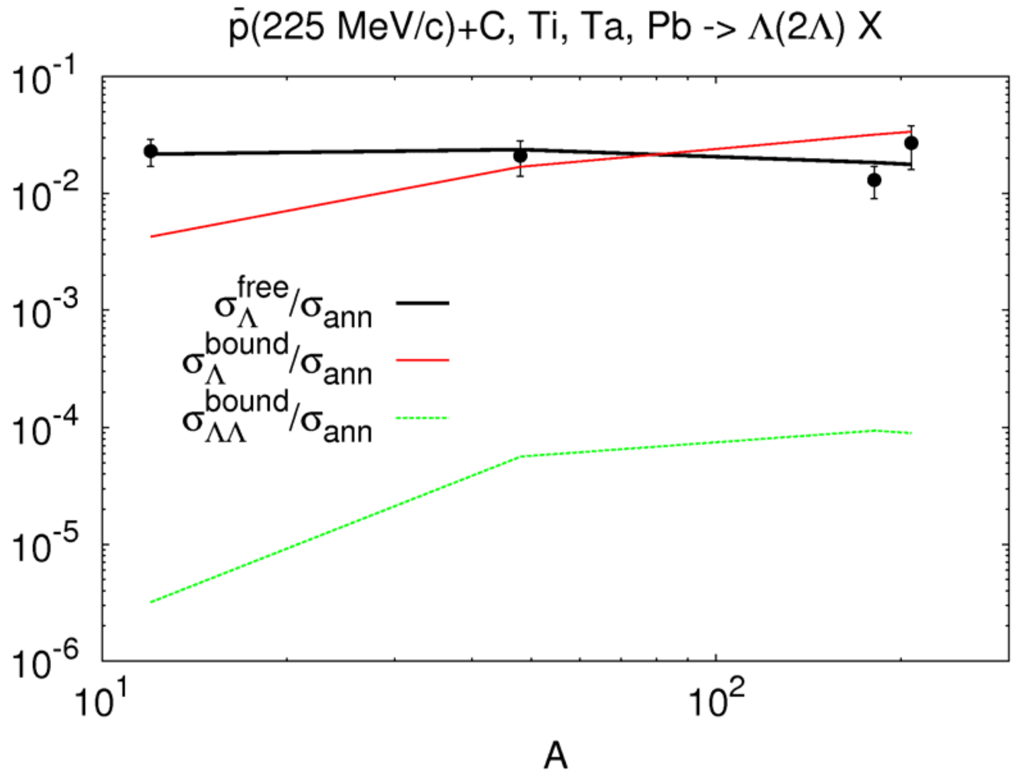
$$
\begin{aligned}
K(K^*)B \to \Xi X &\sim 35\% \\
\Xi^* \to \Xi\pi &\sim 26\% \\
K(K^*)Y(Y^*) \to \Xi X &\sim 17\% \\
\bar{B}B \to \Xi X &\sim 6\%
\end{aligned}
$$



Λ production from

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

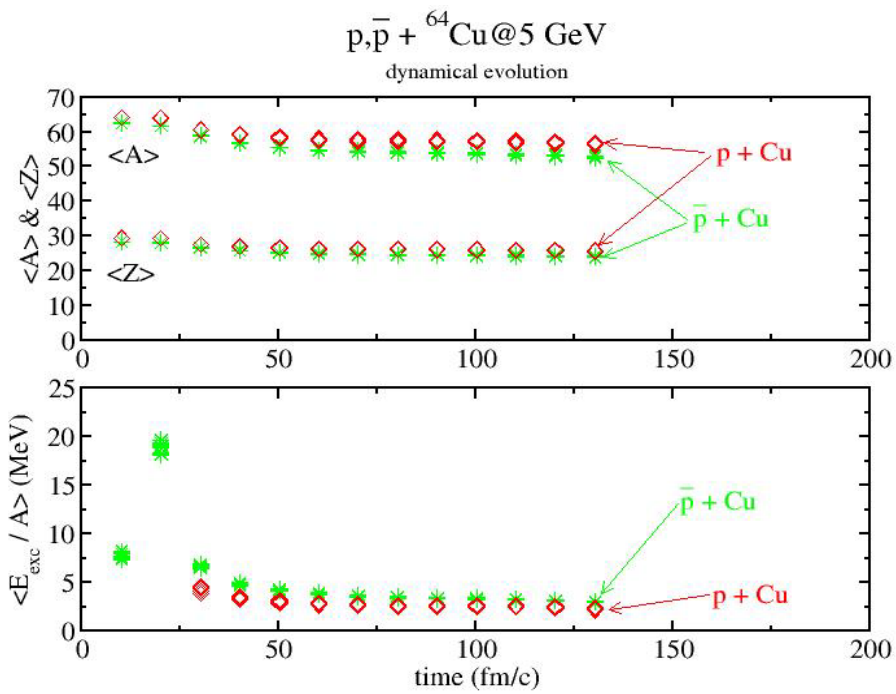
Without SMM



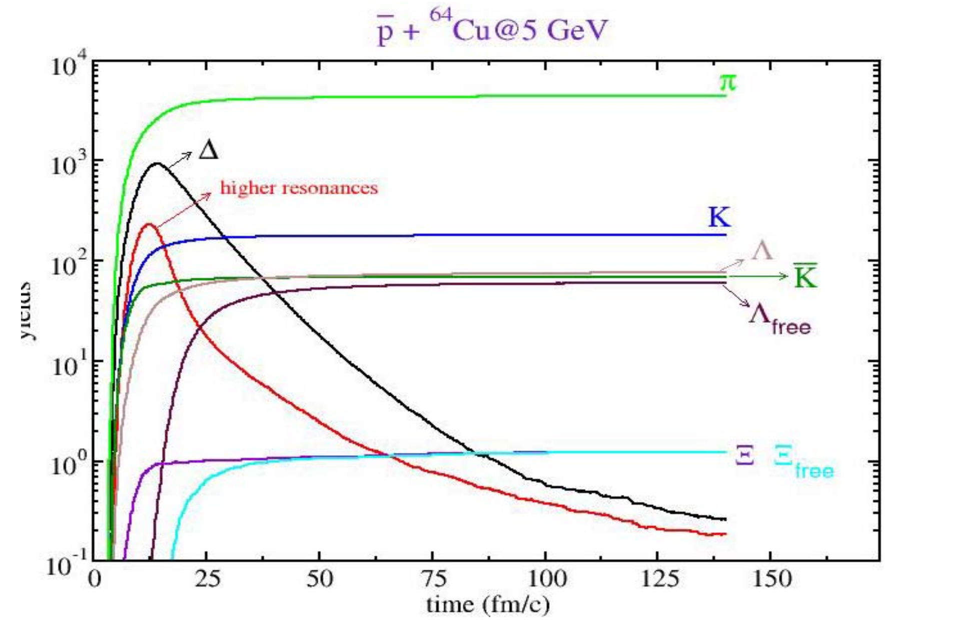
Data (BNL): G.T. Condo et al, PRC 29, 1531 (1984)

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

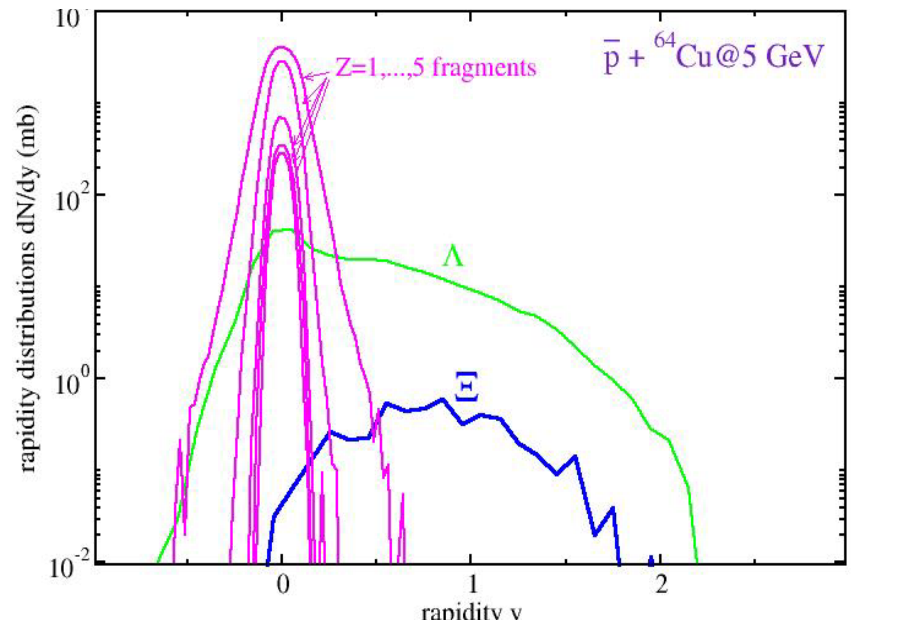
Source parameters



Particle production



Rapidity spectra



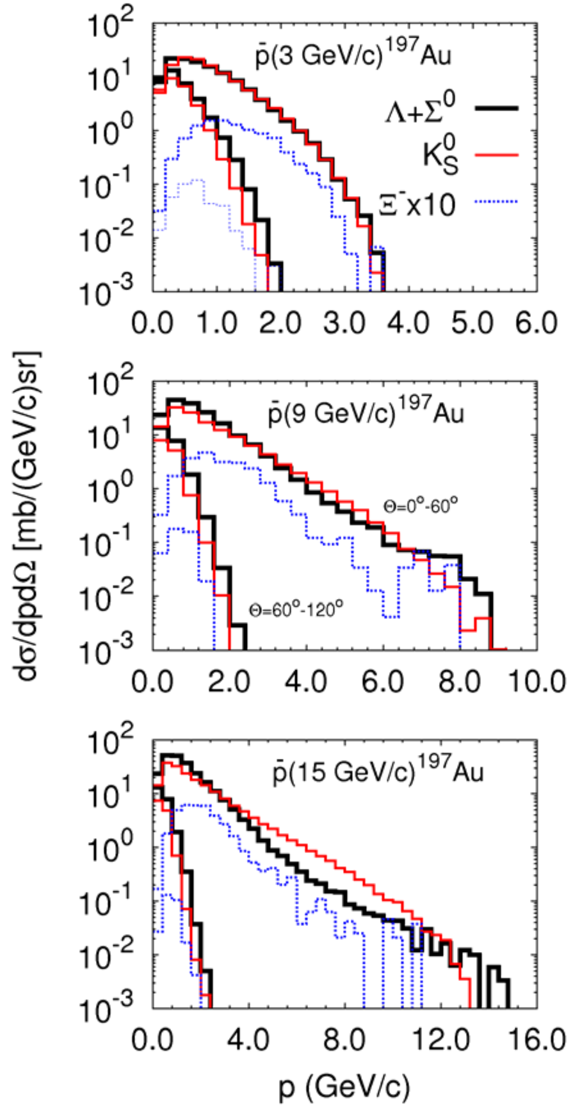
Fragment and Λ spectra overlap at y≈0. Coalescence possible.

T. Gaitanos, A.L., H. Lenske, and U. Mosel, NPA 881, 240 (2012)

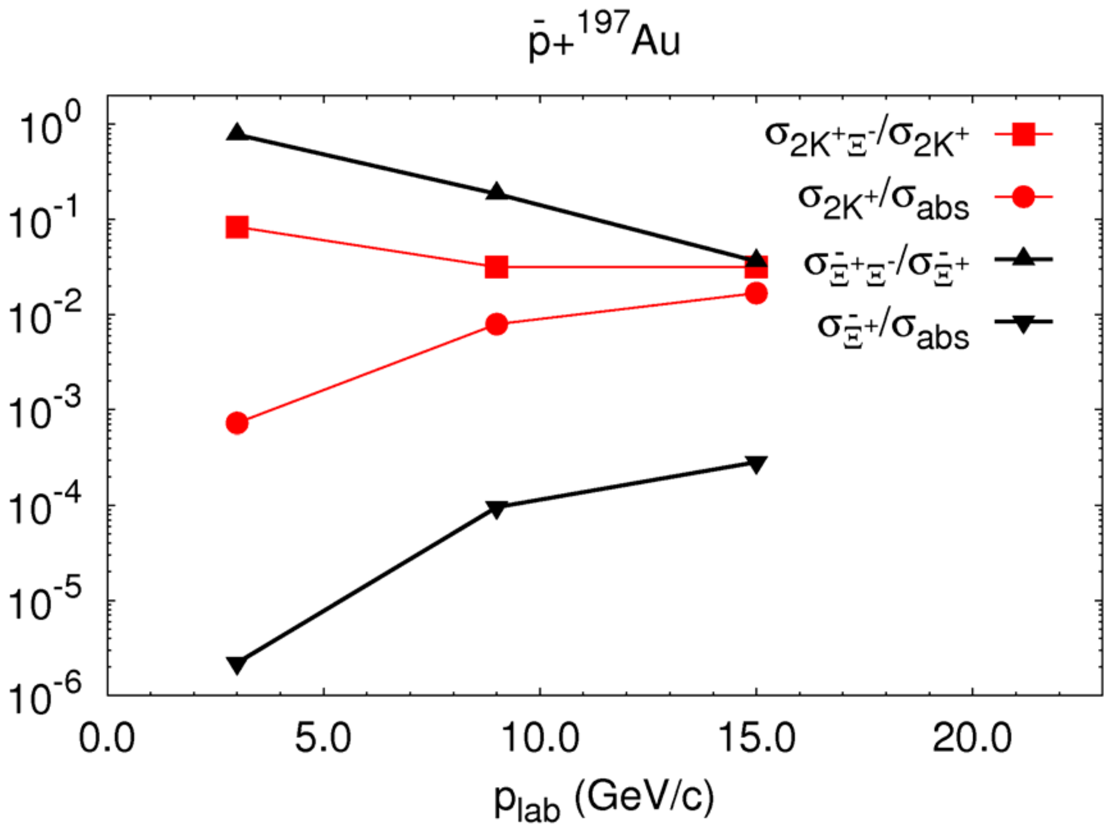
Momentum spectra of produced strange particles.

Similar behaviour at large momenta for all particles.

Ξ^- spectra are suppressed at low momenta.



Triggering Ξ^-:



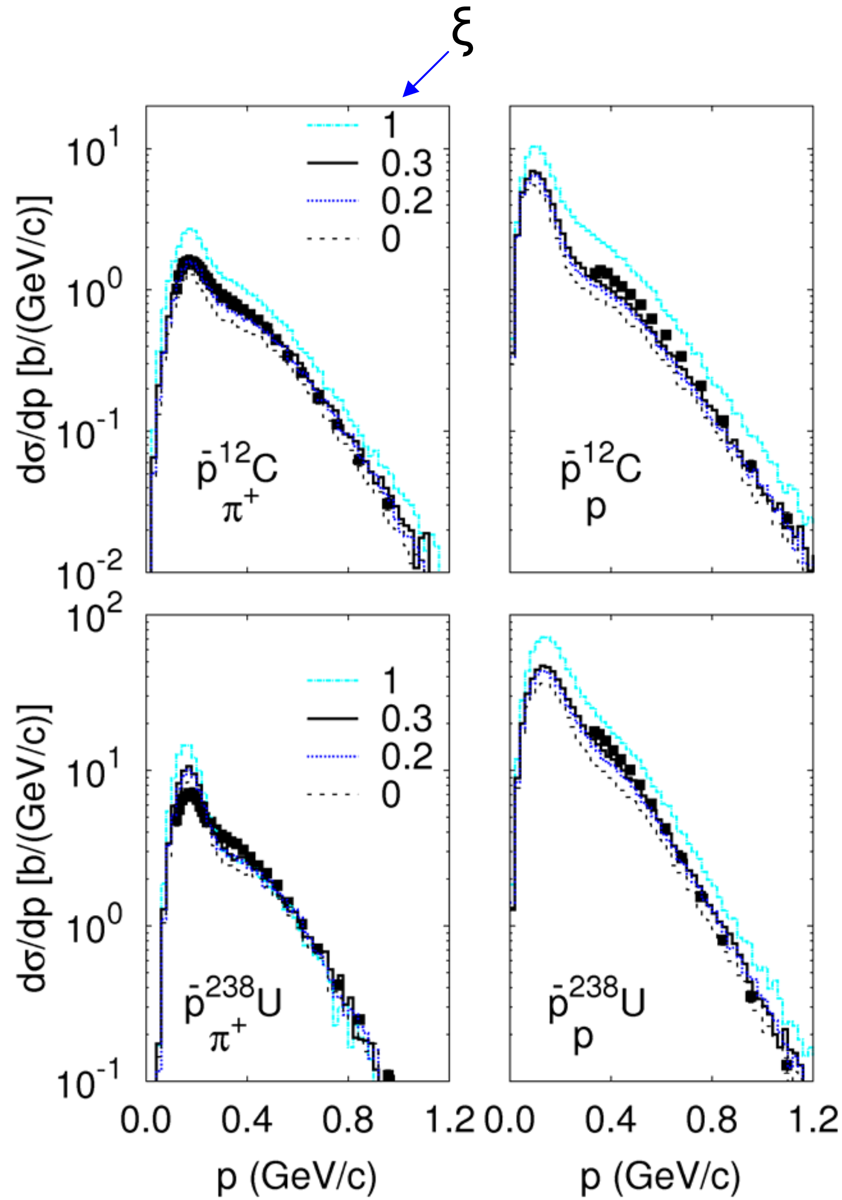
Large background due to $\pi, \eta, \rho, \omega + N \to YK$.

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

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

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)

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

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