Strange particle production by Σ^-, π^- and neutrons in WA89

The WA89 Collaboration

presented by

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- Introduction
- Apparatus
- New $\Xi(1690)$ decay channel
- Leading particle effect
- V^0V^0 correlations
- p_T distributions for hyperons and K^0_S
- Non-observation of U(3100)
- Summary

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The WA89 Collaboration

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Introduction

Main physics goals of WA89:

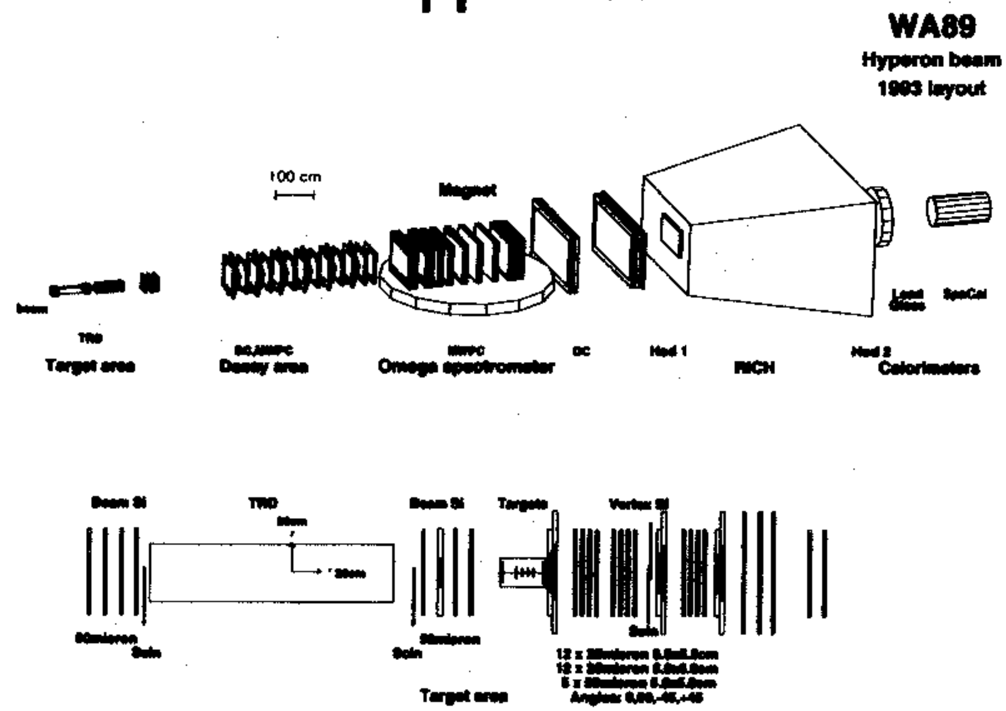
- Production and properties of charmed baryons: Λ_c, Σ_c, Ξ_c, Ω_c
- Search for exotic states: U(3100), Hexaquark H
- Production of hyperons and hyperon resonances: Λ, Σ, Ξ
- Hyperon polarization ($\rightarrow$ talk of V. J. Smith)

The most important feature of WA89 is the strange quark in the incoming hyperon. This should be seen in the x_F distribution of the outgoing particles.

Two ways to study the production mechanism:

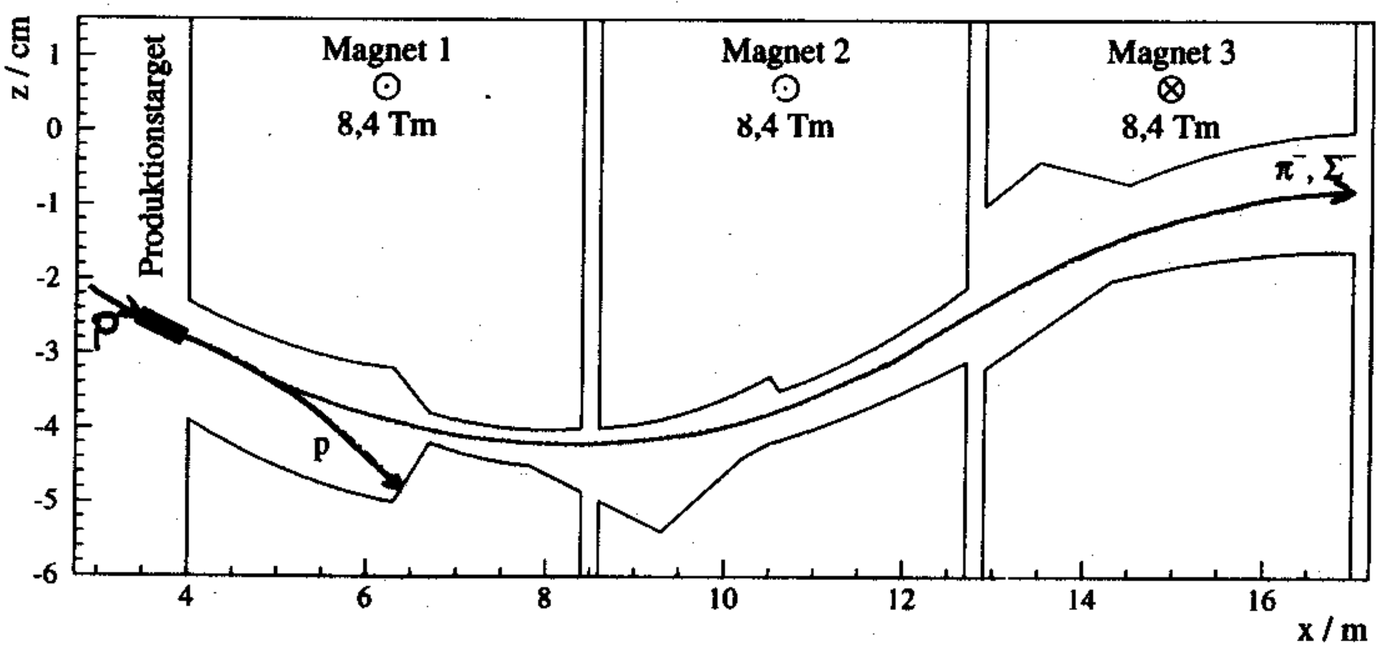
1. asymmetries (e. g. charm asymmetries)
2. production cross sections and x_F distributions for different particles

Apparatus



Setup of the WA89 experiment in the 1993 beam time.
The lower part shows an expanded view of the target area.

Beam Channel for SPS H1/Y1 Beam



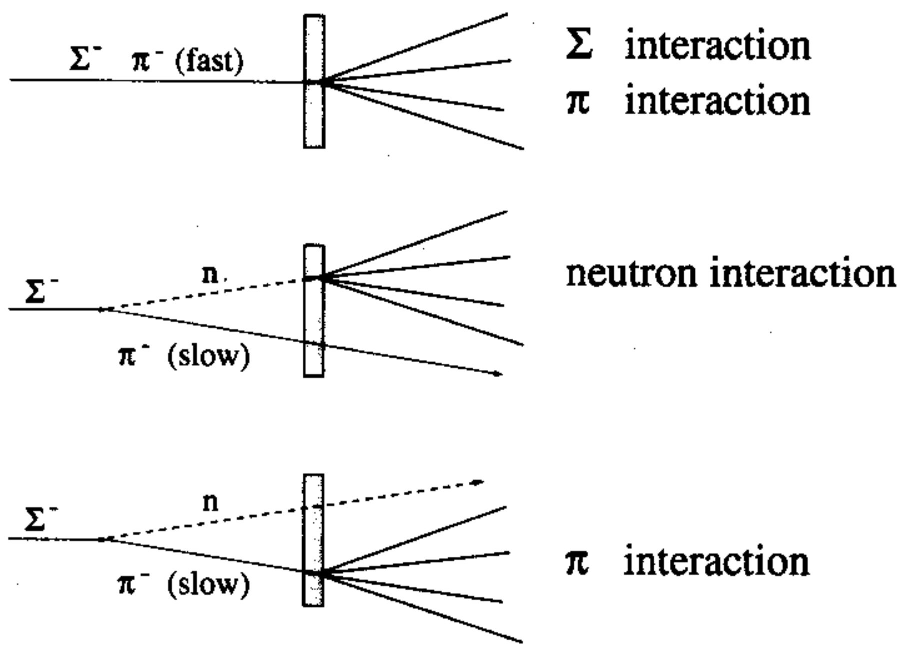
Hyperon Beam

Beam: Σ^- or π^- at 345 GeV/c with about 10% momentum spread.

Composition of beam:

beam particle	contamination	
Σ^-	Σ^-	61.9 %
	π^-_{fast}	12.3 %
	π^-_{slow}	22.9 %
	K^-	2.1 %
	Ξ^-	0.8 %
n	Σ^- decays	6.8 %
π^-	Σ^-, K^-, Ξ^-	2.5 %

Σ^-, n and π^- Interactions



Identification of beam particle:

- Σ^-/π^- discrimination by TRD
- Neutron identification by interaction topology

  The following topological criteria were applied:

  1. Minimal distance of approach from track to interaction vertex (DAP) has to be smaller than 100 µm:

  $$\text{DAP (Vtx} - \text{Track)} \leq 100\,\mu\text{m}$$

  2. Vertex position must be inside target within 3σ accuracy for each coordinate:

  $$d(\text{Vtx} - \text{Target}) \leq 3\sigma$$

  For Σ^-/π^- interaction:

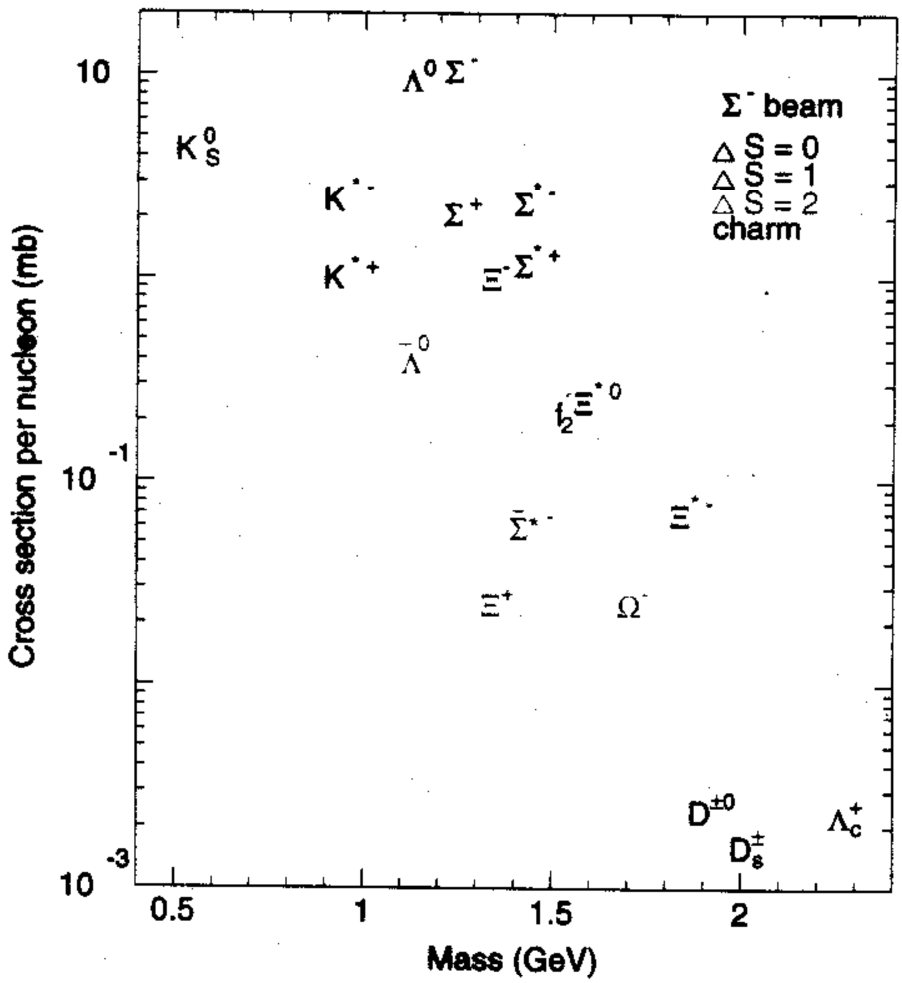
  1. $\text{DAP}(\text{Vtx} - \Sigma^- \text{ track}) \leq 6\sigma$

  For neutron interaction:

  1. $\text{DAP}(\text{Vtx} - \pi^- \text{ track}) > 6\sigma$
  2. $p(\pi^-) \leq 140\,\text{GeV}/c$

Particle	beam	Copper [mb]	Carbon [mb]	nucleon [mb]
Ξ^-	Σ^-	16.72 ± 0.21	5.4 ± 0.07	1.00 ± 0.04
	neutron	10.3 ± 0.4	2.3 ± 0.1	0.25 ± 0.03
	π^-	4.1 ± 0.2	0.9 ± 0.05	0.086 ± 0.012
Ξ^0_{1530}		4.3 ± 0.9	1.3 ± 0.26	0.22 ± 0.04
Ξ^0_{1690}				0.0056 ± 0.0002
Ξ^-_{1820}				0.021 ± 0.005
Ξ^-_{1960}				0.012 ± 0.003
$\overline{\Xi}^+$		0.64 ± 0.01	0.18 ± 0.01	0.025 ± 0.001
		1.4 ± 0.3	0.3 ± 0.1	0.020 ± 0.006
		1.4 ± 0.2	0.5 ± 0.2	0.09 ± 0.01
Ω^-		0.80 ± 0.01	0.21 ± 0.01	0.025 ± 0.01
Σ^-		123.8 ± 3.22	46.16 ± 1.12	10.52 ± 0.01
Σ^+		39.78 ± 1.9	12.25 ± 0.68	2.09 ± 0.7
Σ^-_{1385}		27.01 ± 0.43	10.20 ± 0.15	2.37 ± 0.01
		25.1 ± 1.8	8.3 ± 0.5	1.57 ± 0.01
		5.3 ± 0.5	1.8 ± 0.1	0.36 ± 0.01
Σ^+_{1385}		14.45 ± 0.26	5.29 ± 0.09	1.17 ± 0.01
		9.2 ± 1.1	2.69 ± 0.3	0.42 ± 0.01
		3.9 ± 0.4	1.0 ± 0.1	0.13 ± 0.01
$\overline{\Sigma}^-_{1385}$		1.49 ± 0.12	0.42 ± 0.03	0.06 ± 0.01
Σ^-_{1660}		23.02 ± 0.35	8.89 ± 0.13	2.14 ± 0.01
Σ^+_{1660}		11.32 ± 0.2	4.04 ± 0.07	2.1 ± 0.01
Λ^0		109.97 ± 4.12	41.26 ± 1.51	9.49 ± 0.01
		55.56 ± 2.49	18.14 ± 0.78	3.39 ± 0.01
		25.52 ± 0.89	8.29 ± 0.29	1.54 ± 0.04
K^0		66.52 ± 3.70	22.25 ± 1.2	4.31 ± 0.01
		52.14 ± 3.24	16.61 ± 1.01	2.99 ± 0.01
		58.99 ± 1.6	19.09 ± 0.55	3.52 ± 0.08
$\overline{\Lambda}^0$		6.99 ± 0.47	2.21 ± 0.15	0.39 ± 0.01
		7.65 ± 0.58	2.39 ± 0.19	0.42 ± 0.01
		12.55 ± 0.7	3.89 ± 0.20	0.67 ± 0.03
K^-_{890}		34.7 ± 0.8	12.0 ± 0.3	2.45 ± 0.8
		$13.15 \pm 2.$	$5.7 \pm 1.$	1.6 ± 0.3
		24.9 ± 1.4	8.4 ± 0.5	1.64 ± 0.4
K^+_{890}		11.7 ± 0.6	4.4 ± 0.2	1.0 ± 0.1
		15.5 ± 2.2	$4. \pm 0.5$	0.7 ± 0.2
		12.2 ± 0.9	4.8 ± 0.4	1.3 ± 0.2

Production Cross Sections



Overview of production cross sections for different particles in Σ^- interactions

New Decay Channel $\Xi^0(1690) \to \Xi^-\pi^+$

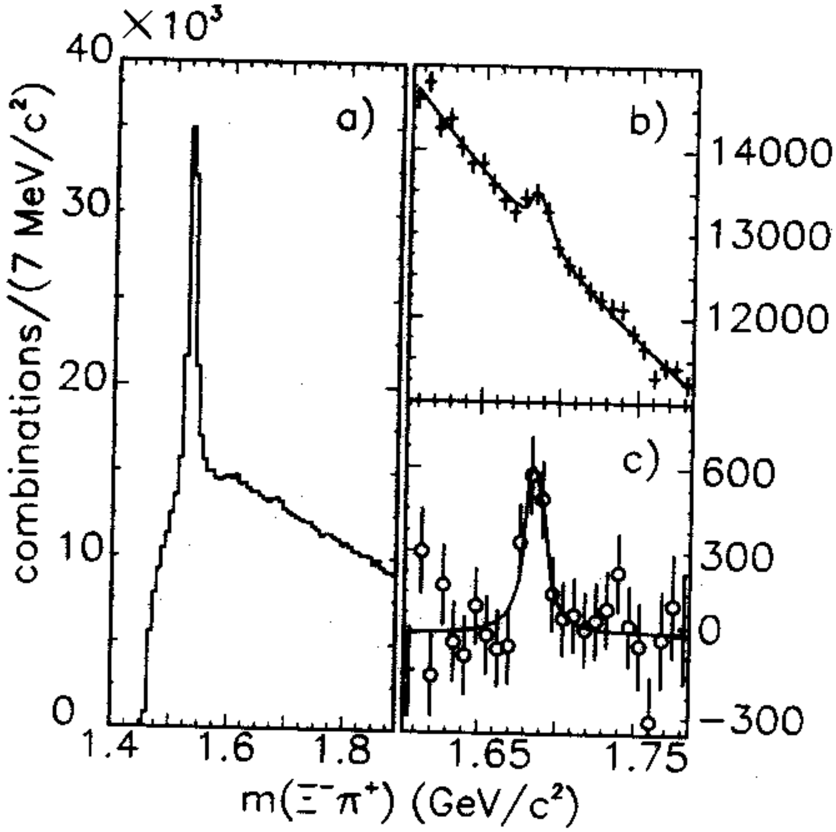
Ξ^* resonances (PDG 1998)

Table 1. The status of the Ξ resonances. Only those with an overall status of *** or **** are included in the Baryon Summary Table.

Particle	$L_{2I \cdot 2J}$	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
$\Xi(1318)$	P_{11}	****					Decays weakly
$\Xi(1530)$	P_{13}	****	****				
$\Xi(1620)$		*	*				
$\Xi(1690)$		***	new	***	**		
$\Xi(1820)$	D_{13}	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$	1	***		**	***		
$\Xi(2120)$		*		*			
$\Xi(2250)$		**					3-body decays
$\Xi(2370)$	1	**					3-body decays
$\Xi(2500)$		*		*	*		3-body decays

****	Existence is certain, and properties are at least fairly well explored.
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

The $\Xi^0_{1690} \to \Xi^- \pi^+$ decay mode.



Signal:	1400 ± 300
Mass M:	$1686 \pm 4\,\mathrm{MeV}/c^2$
Width Γ:	$10 \pm 6\,\mathrm{MeV}/c^2$
$\sigma \cdot$ B.R.:	$6.8 \pm 0.2\,\mu\mathrm{b}/\mathrm{nucleon}$

Eur. Phys. J. C 5 (1998) 621

Interpretation of Ξ^* state at 1690 MeV/c^2

- Non relativistic quark potential model:
  Prediction of $\Xi(1/2^+)$ state around 1690 MeV/c^2, with dominating $\Xi\pi$ decay.
  K. T. Chao, N. Isgur and G. Karl, Phys. Rev. D *23* (1981) 155

- Relativistic version of this model:
  First excited state $\Xi(1/2^+)$ is pushed to about 1800 MeV/c^2.
  No state left to be identified with the observed $\Xi(1690)$.
  S. Capstick and N. Isgur, Phys. Rev. D *34* (1986) 2809

- Chiral boson exchange interaction model:
  $\Xi(1/2^+)$ is expected close to 1800 MeV/c^2.
  L. Ya. Glozman and D. O. Riska, Phys. Rep. *268* (1996) 263

Leading Particle Effect

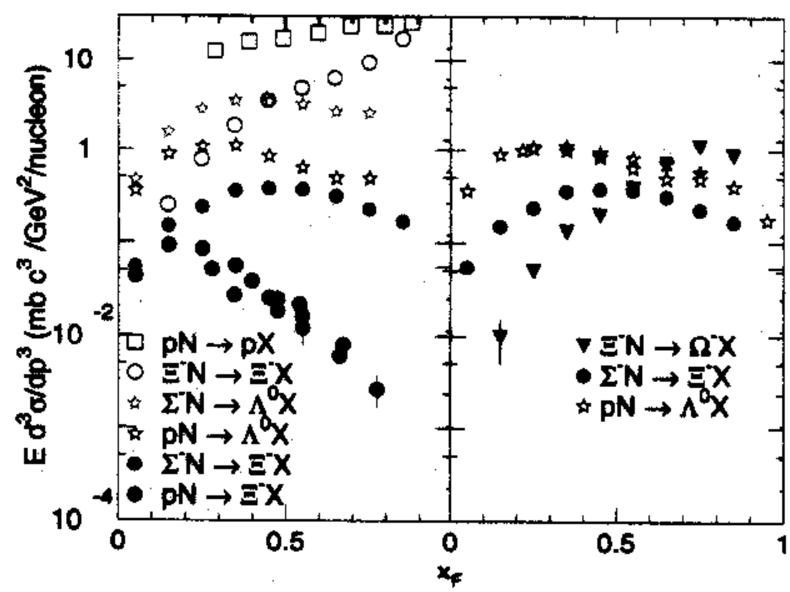
Produced particles sharing one or more quarks with the projectile have a "harder" x_F distribution.

- s quark leading: common s quark in projectile and ejectile
- non-s leading

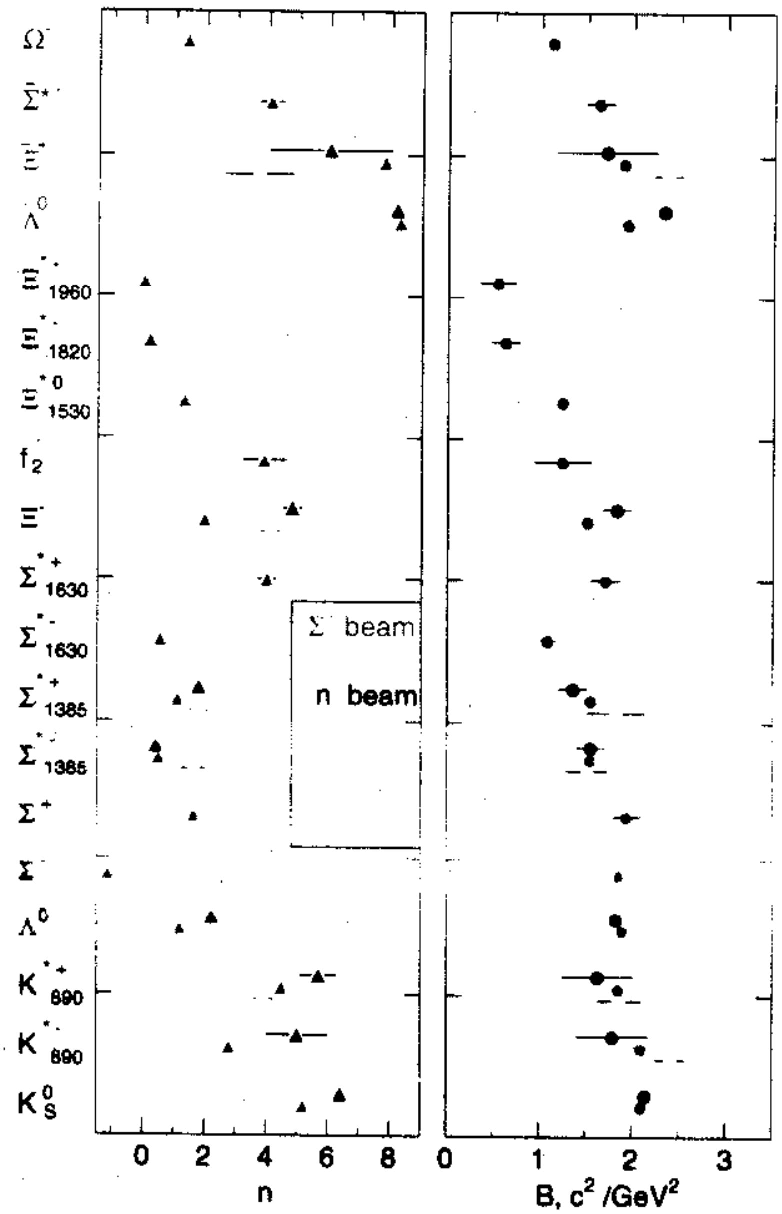
Parametrization of cross section:

$$\frac{d^2\sigma}{dp_t^2 dx_F} = C(1 - x_F)^n \cdot \exp(-Bp_t^2)$$

World data on x_F distributions showing the leading effect:

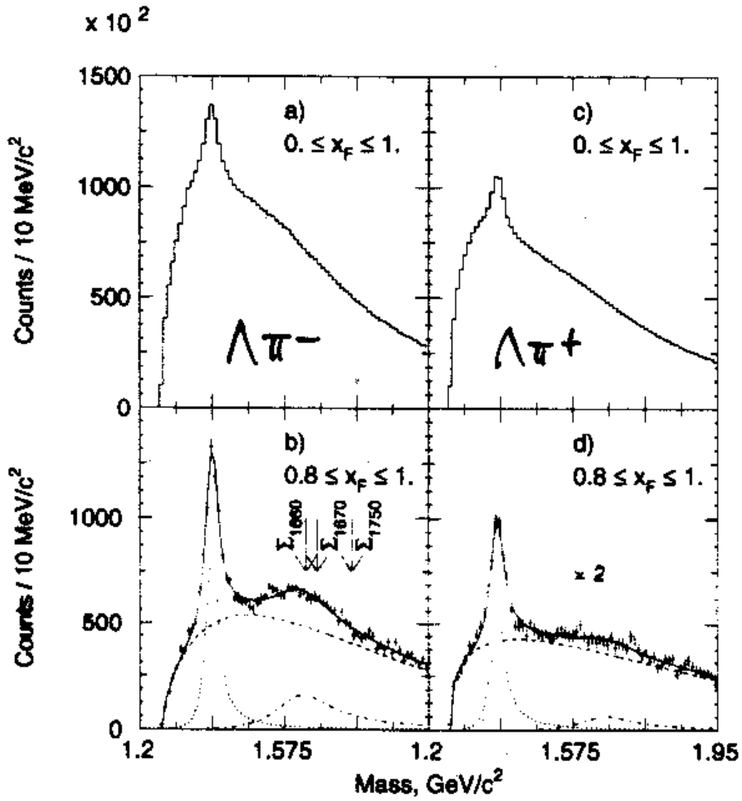


Values for n and B for particles produced by Σ^-, n, and π^- interactions in WA89



Σ^* signals

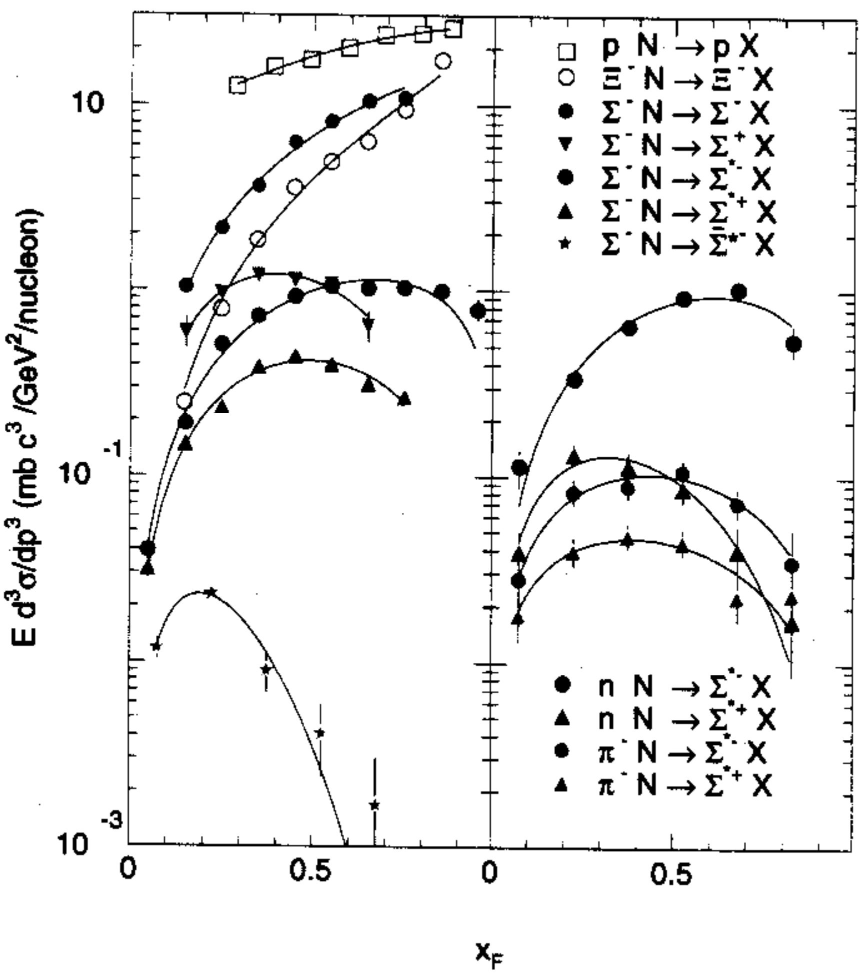
Invariant mass distribution for $\Lambda\pi^{\pm}$ in different x_F regions.



- $\Sigma(1385)^{\pm} \to \Lambda\pi^{\pm}$
- $\Sigma(1660)^{\pm} \to \Lambda\pi^{\pm}$

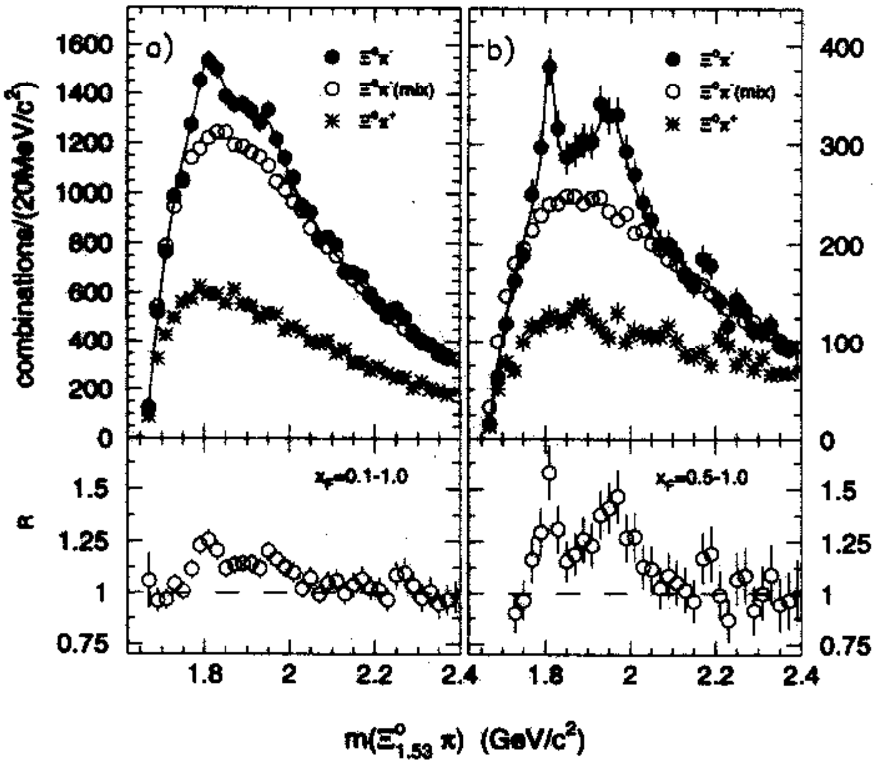
Background shown was determined by "event mixing" method.

x_F distributions measured in WA89.
($pN \rightarrow pX$ and $\Xi^- N \rightarrow \Xi^- X$ are shown for comparison.)



We observe a strong leading effect if an s quark is shared with the beam particle.

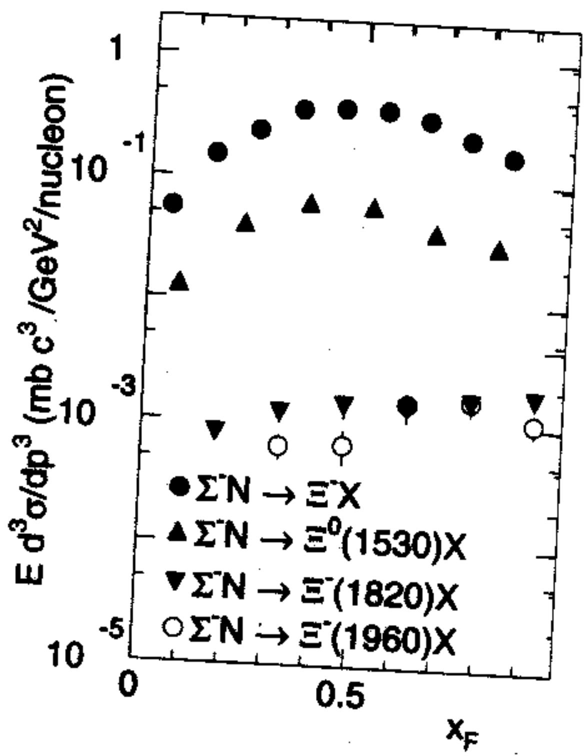
Ξ^* signals



$\Xi(1530)^0\pi^-$ ($\rightarrow \Xi^-\pi^+\pi^-$) invariant mass

Signals for $\Xi^-(1820)$ and $\Xi^-(1960)$ are clearly seen.
Open circles: background shape from event mixing.
Stars: background shape from "wrong sign" combinations.
Below: ratio of the observed spectra to the background from event mixing.

Production of Ξ^- and Ξ^* resonances: Ξ^0, Ξ^0_{1530}, Ξ^-_{1820}, Ξ^-_{1960}



For the higher exited states, the x_F differential cross section is flatter (and p_T^2 distribution is wider).

Eur. Phys. J. C *8* (1999) 593

V^0V^0 correlations

Study correlations between x_F distibutions for two Λ in same event.

If we mark one Λ as the faster one, we always see a trivial effect due to sorting:

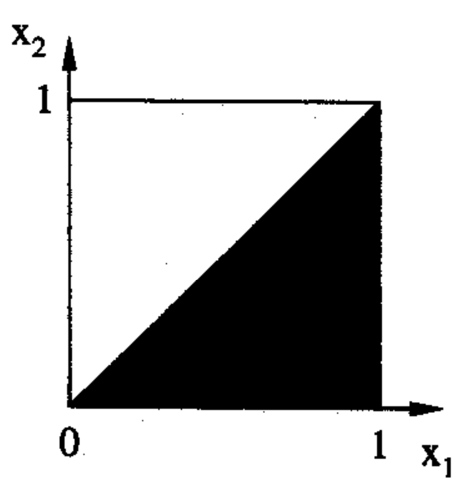
- Start with two particles with same x_F distribution $P(x) = A(1-x)^n$ for $0 < x < 1$.

  (Normalization $A = 1/(n+1)$)

  Combined distribution

$$P(x_1, x_2) = A^2(1-x_1)^n(1-x_2)^n$$

- Select particles 1 and 2 with $x_1 \leq x_2$.



- Integrate:

$$
\begin{aligned}
P_1(x_1) &= 2\int_0^{x_1} P(x_1,x_2)\,dx_2 \\
&= 2A^2(1-x_1)^n \int_0^{x_1} (1-x_2)^n\,dx_2 \\
&= 2A\left[(1-x_1)^n - (1-x_1)^{2n+1}\right]
\end{aligned}
$$

$$
\begin{aligned}
P_2(x_2) &= 2\int_{x_2}^{1} P(x_1,x_2)\,dx_1 \\
&= 2A^2(1-x_2)^n \int_{x_2}^{1} (1-x_1)^n\,dx_1 \\
&= 2A(1-x_2)^{2n+1}
\end{aligned}
$$

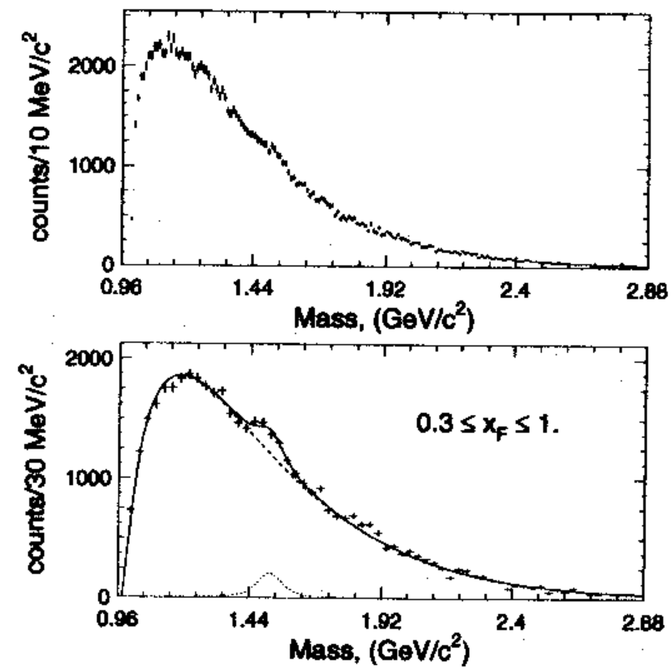
- For $x > 0$ and n not too small, $(1-x)^{2n+1} \ll (1-x)^n$, and we obtain as result:

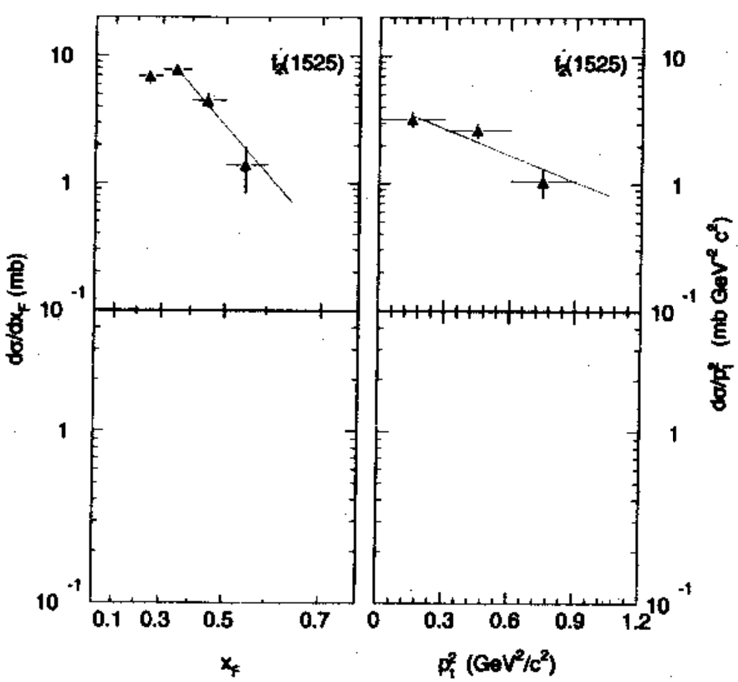
$$P_1(x) \propto (1-x)^n$$

and

$$P_2(x) \propto (1-x)^{2n+1}\,.$$

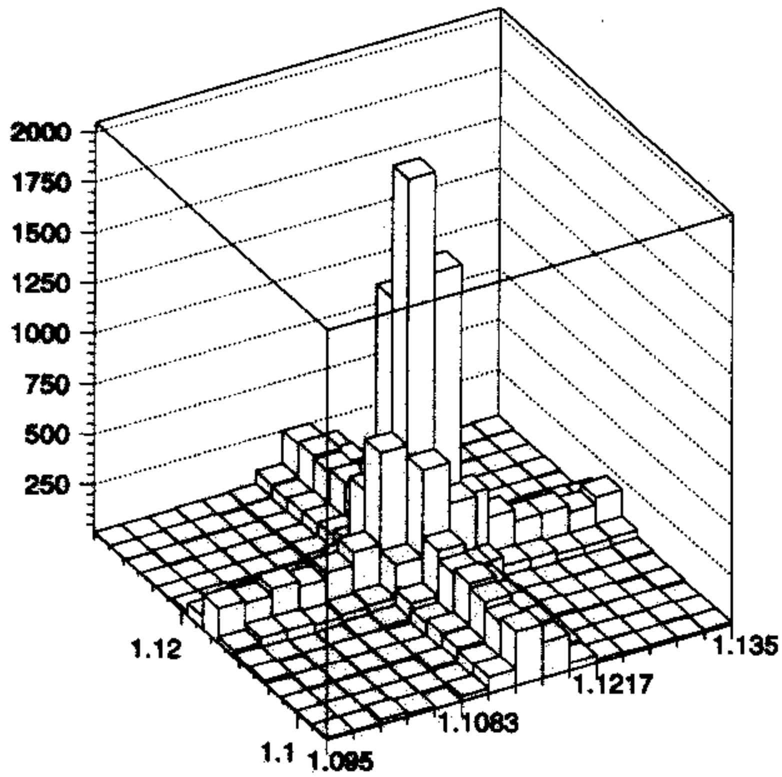
Invariant mass and x_F distribution of $K_s^0 K_s^0$ combinations



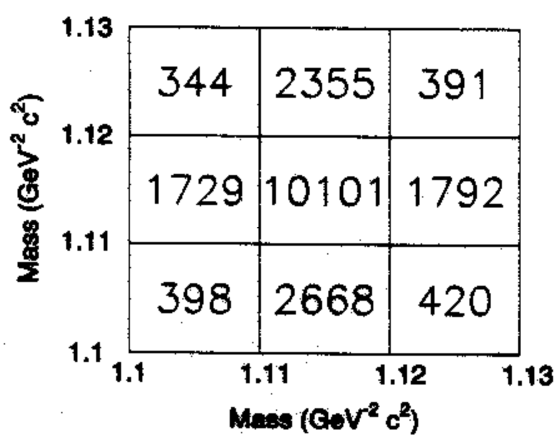


We identify the bump at 1520 MeV/c^2 with $f_2'(1525) \rightarrow K_S^0 K_S^0$

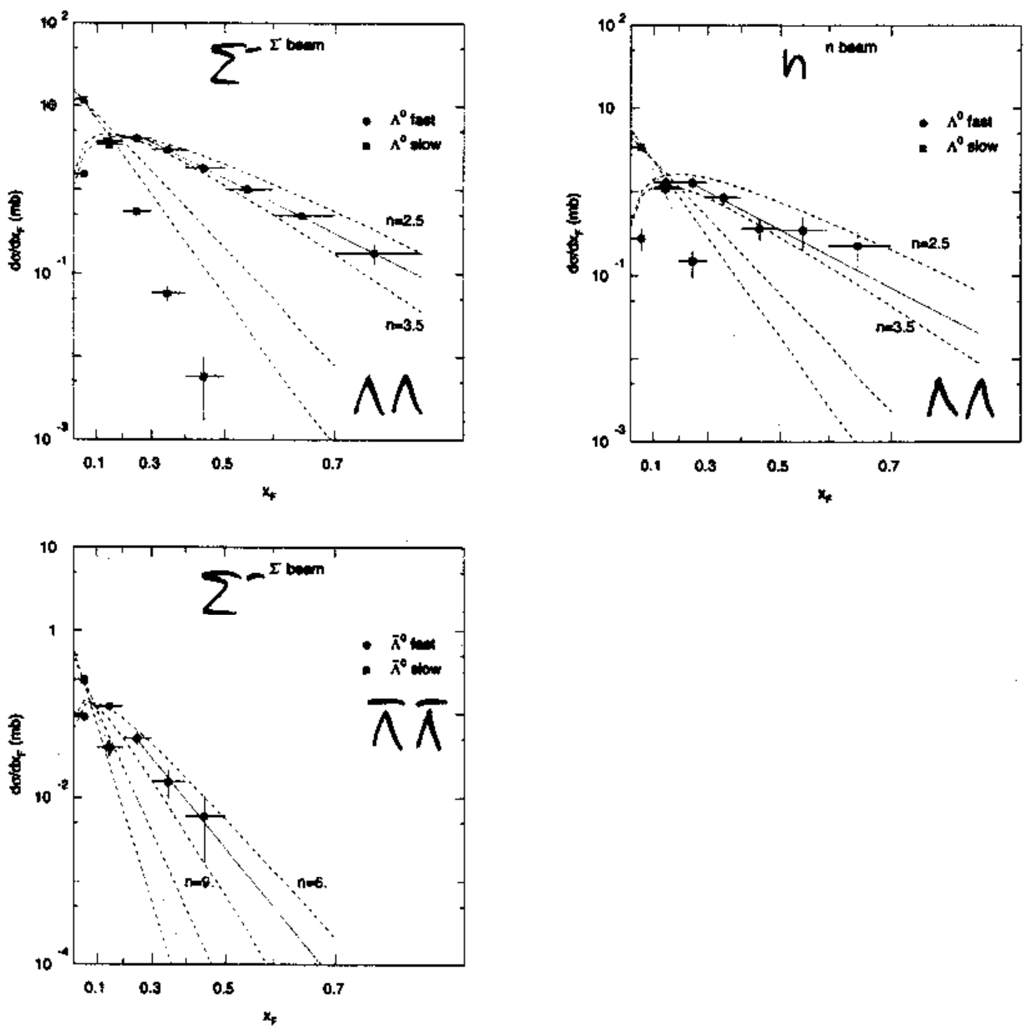
Invariant mass of $\Lambda\Lambda$



3×3 bin plot for background estimation



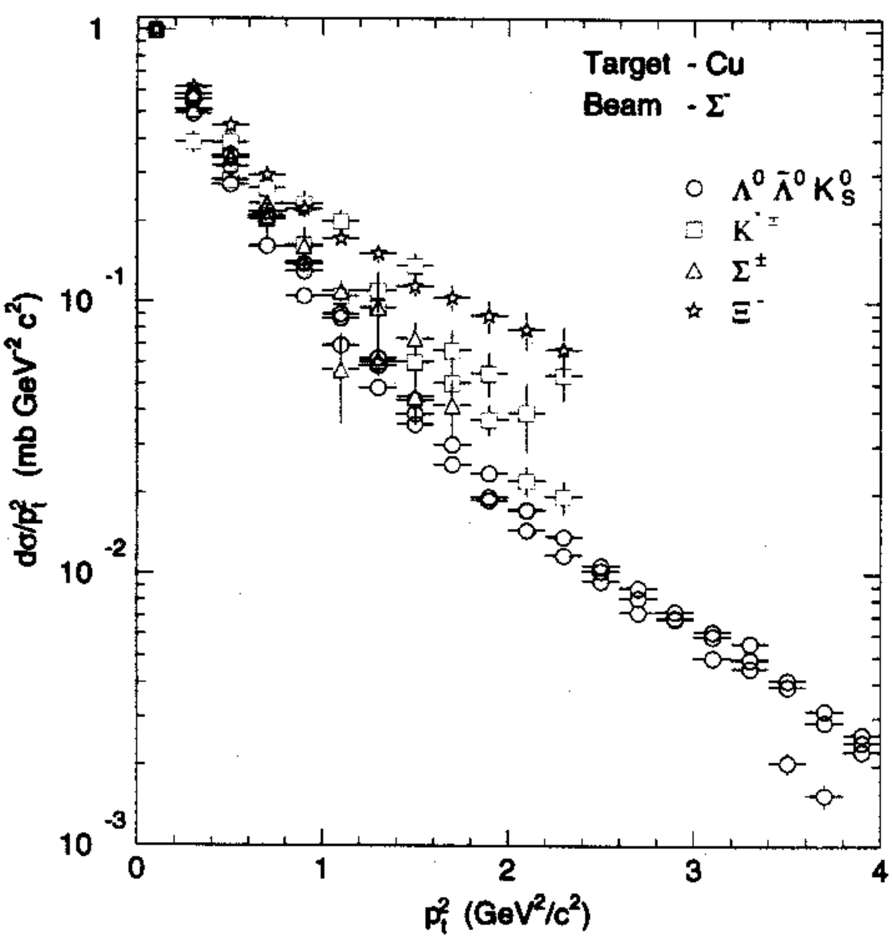
Differential cross sections for inclusive V^0V^0 pair production



- For $\overline{\Lambda\Lambda}$, no correlations are visible, i.e. x_F distributions are consistent with "sorting effect".

- For $\Lambda\Lambda$, deviations are visible, due to 2 leading quarks for Σ^- (sdd) and neutron (udd) beam.

p_T Distributions for Inclusive Y and K Production by Σ^-



Measured p_T distributions for hyperons and kaons (values are normalized to 1 for $p_T^2 = 0$)

p_T^2 distributions for Ξ^- and $K(892)^{\pm}$ are harder than for V^0 and $\Sigma^{\pm}$.

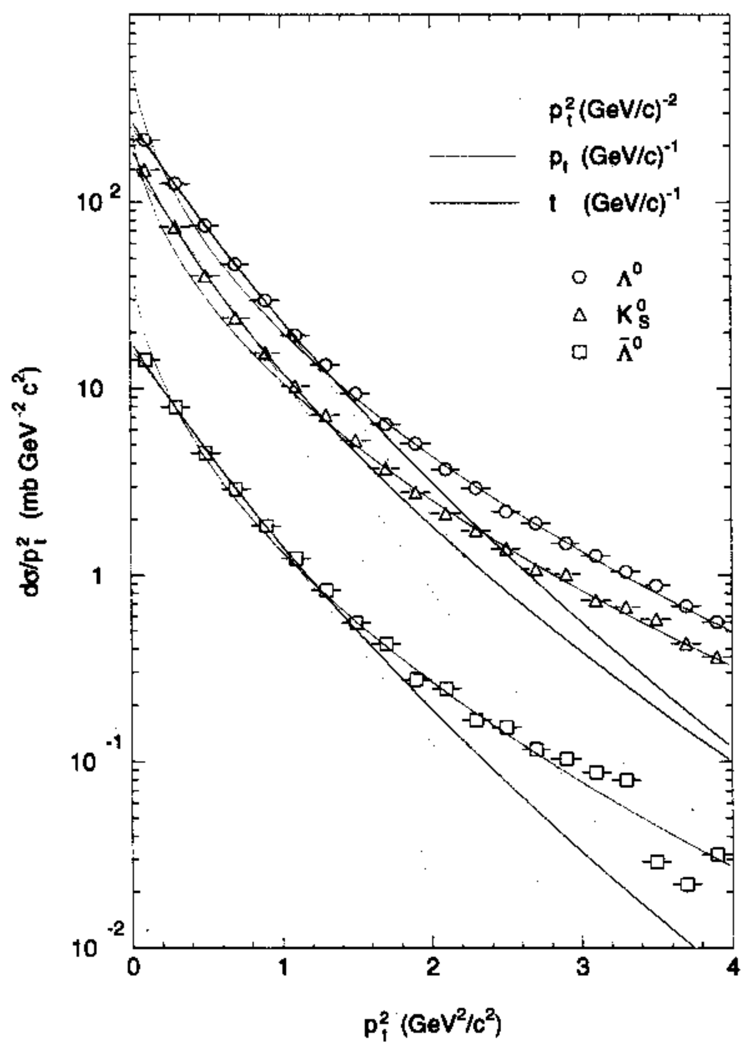
The p_T dependency of the cross section can be parametrized in 3 different ways:

- $d\sigma/dp_T^2 \propto \exp(-Bp_T^2)$:
  Gaussian behaviour.

- $d\sigma/dp_T^2 \propto m_T^{3/2} \exp(-m_T/kT)$:
  "thermal distribution".

- $d\sigma/dp_T^2 \propto \exp(-bp_T)$:
  non-Gaussian tails at high p_T.

p_T^2 distributions for V^0 particles produced by Σ^-

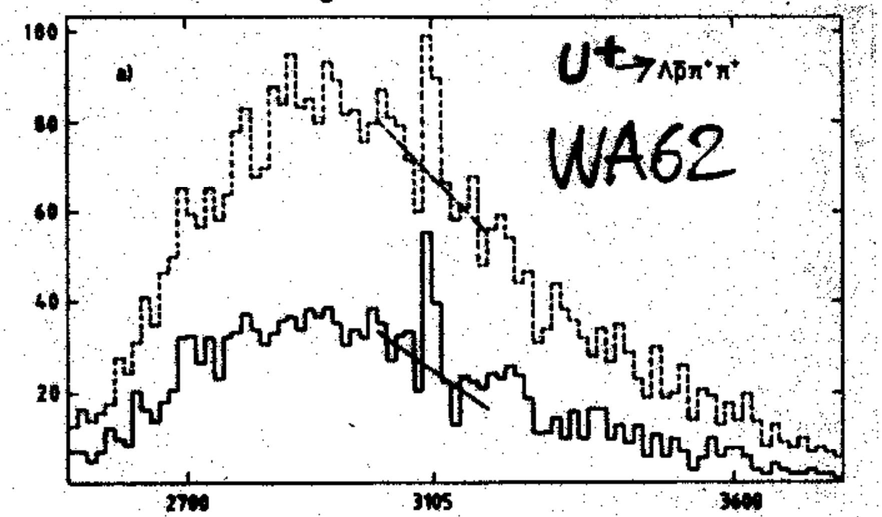


The fitted curves indicate a strong (non-gaussian, non-thermal) enhancement at large transverse momenta.

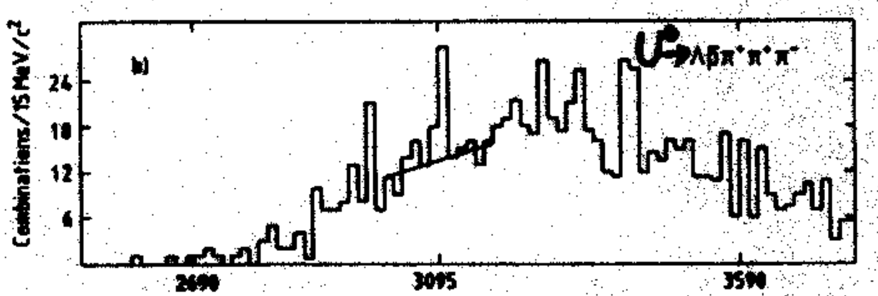
1. Experimental evidence

- **WA62**: Hyperon beam experiment at CERN-SPS
  135 GeV $\Sigma^- + Be$
  → Observed signal for charmed baryon decay
  $$\Xi_c^+ \rightarrow \Lambda K^- \pi^+ \pi^+$$
  Checked particle identification $K^- \leftrightarrow \bar{p}$ (thresh. $\check{C}$)
  → Peaks in spectra $\Lambda \bar{p}$ + pions
  $m = 3100\ MeV/c^2$, $\Gamma < 30\ MeV$

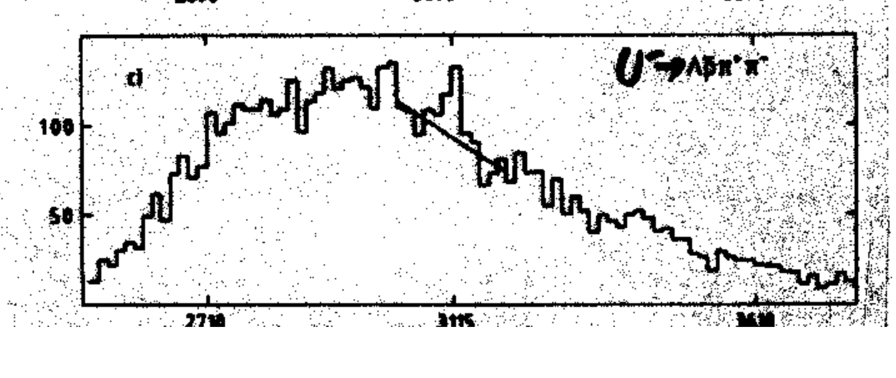
$U^+ \rightarrow \Lambda \bar{p} \pi^+ \pi^+$
$S/B = 45/50$
$\sigma \cdot B = 4.8 \pm 1.4 \pm 0.8\ \mu b/Be$
for $x_F > 0.6$



$U^0 \rightarrow \Lambda \bar{p} \pi^+ \pi^+ \pi^-$
$S/B = 19/28$
$\sigma \cdot B = 1.2 \pm 0.7 \pm 0.2\ \mu b/Be$

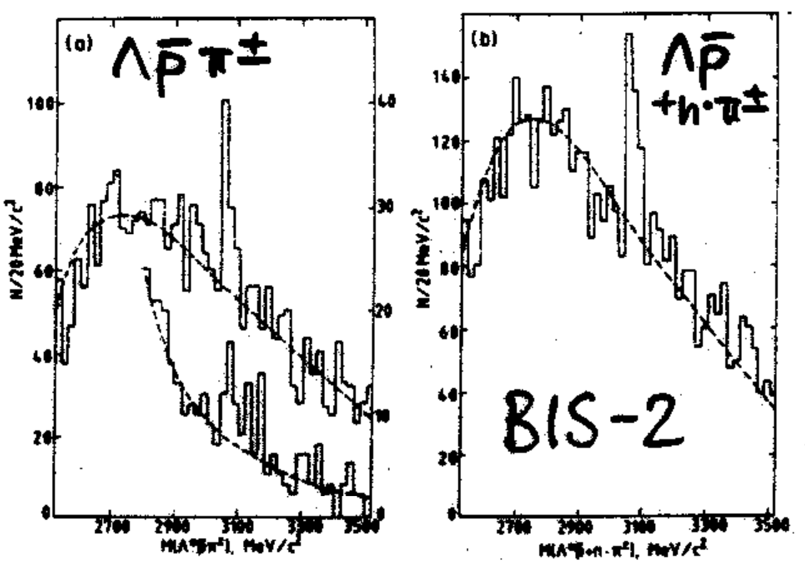


$U^- \rightarrow \Lambda \bar{p} \pi^+ \pi^-$
$S/B = 62/187$
$\sigma \cdot B = 3.0 \pm 1.7 \pm 0.5\ \mu b/Be$



- **BIS-2**, Serpukhov

  40 GeV $n + A$



→ Observed peaks in

$$\left.\begin{array}{l} U^{+} \to \Lambda \bar{p} \pi^{+} \pi^{+} \\ U^{0} \to \Lambda \bar{p} \pi^{+} \\ U^{-} \to \Lambda \bar{p} \pi^{+} \pi^{-} \\ U^{--} \to \Lambda \bar{p} \pi^{-} \end{array}\right\} \quad \frac{S}{B} = \frac{242}{667} \quad \text{c.c.: } \frac{S}{B} = \frac{210}{921}$$

$m = 3060\ \mathrm{MeV}/c^2$

$\sigma \cdot B = 1\,\mu b/N$ for $x_F > 0.2$

- **E771**, Brookhaven

  8 GeV $\bar{p} + p$

Looked for $\bar{\Lambda} p$ + pion states → no signal

$\sigma \cdot B < 23\,nb$, $\bar{U}^{0} \to \bar{\Lambda} p \pi^{-}$

$17\,nb$, $\bar{U}^{+} \to \bar{\Lambda} p \pi^{+} \pi^{-}$

$12\,nb$, $\bar{U}^{++} \to \bar{\Lambda} p \pi^{+}$

2. "Theory"

Interpretation of observed peaks
(if they should be real signals):

- Strong decay of $q\bar{q}$ meson?

  No: $U^+ \rightarrow \Lambda \bar{p} \pi^+ \pi^+$ $Q=+1$, $S=-1$ "exotic"

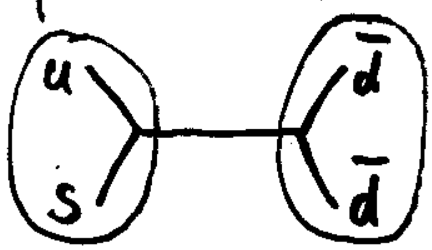
- Weak decay? $c \rightarrow u s \bar{d}$

  $D^*(3100)^+ \xrightarrow{\text{weak}} \Lambda \bar{p} \pi^+ \pi^+$?

  $(c\bar{d})$ $(uds)(\bar{u}\bar{u}\bar{d})(u\bar{d})(u\bar{d})$

  No: $D^* \xrightarrow{\text{strong}} D +$ pions → no baryons

- "Diquonium" $(us\,\bar{d}\bar{d})$



Bound state of diquark and anti-diquark

Several theoretical models:

— "true" diquonia: colour anti-triplet $\bar{3}$ $\Gamma_{B\bar{B}} \approx 100$ Me

— "mock" diquonia: colour sextet 6 $\Gamma_{MM} > \Gamma_{B\bar{B}}$

Try to save the model:

- angular momentum barrier $(L=4, L=5)$?
- decay cascade with pion radiation ?
- mock–true mixing ?

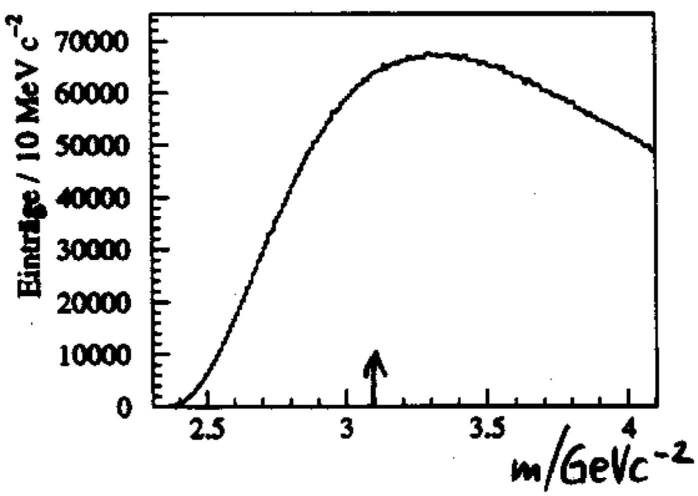
4. Search for $U \to \Lambda\bar{p}$ + pions

Data from 1993 beam time:
$200 \cdot 10^6$ events reconstructed.

- Preselection ("filter") of $\Lambda\bar{p}$ events
  - $\Lambda \to p\pi^-$ within 2.5σ of exp. mass resolution
  - $\bar{p}$ momentum > 45 GeV/c + RICH ID
    <u>or</u> momentum > 120 GeV/c

  $\to$ Reduction to $1.9 \cdot 10^6$ events ($\approx$ 4 Gbyte)

$\Lambda\bar{p}\pi^+\pi^+$
mass spectrum
after $\Lambda\bar{p}$ selection



- Further cuts:
  - Λ: daughter tracks p, π^- both begin in same detector group.
  - $\bar{p}$: harder cut on RICH identification
  - π: reject low momentum tracks ($p < 5$ GeV/c) and clearly identified $K^\pm, p, \bar{p}$
  - rough vertex cuts

- Looked for channels:

  $\Lambda \bar{p}$ + up to four charged pions

  e.g. $U^+ \to \Lambda \bar{p} \pi^+ \pi^+$
  $U^0 \to \Lambda \bar{p} \pi^+$
  $U^0 \to \Lambda \bar{p} \pi^+ \pi^+ \pi^-$
  $U^- \to \Lambda \bar{p} \pi^-$

  $\Sigma^*(1385) \bar{p}$ + pions

  $\Sigma^\pm \bar{p}$ + pions

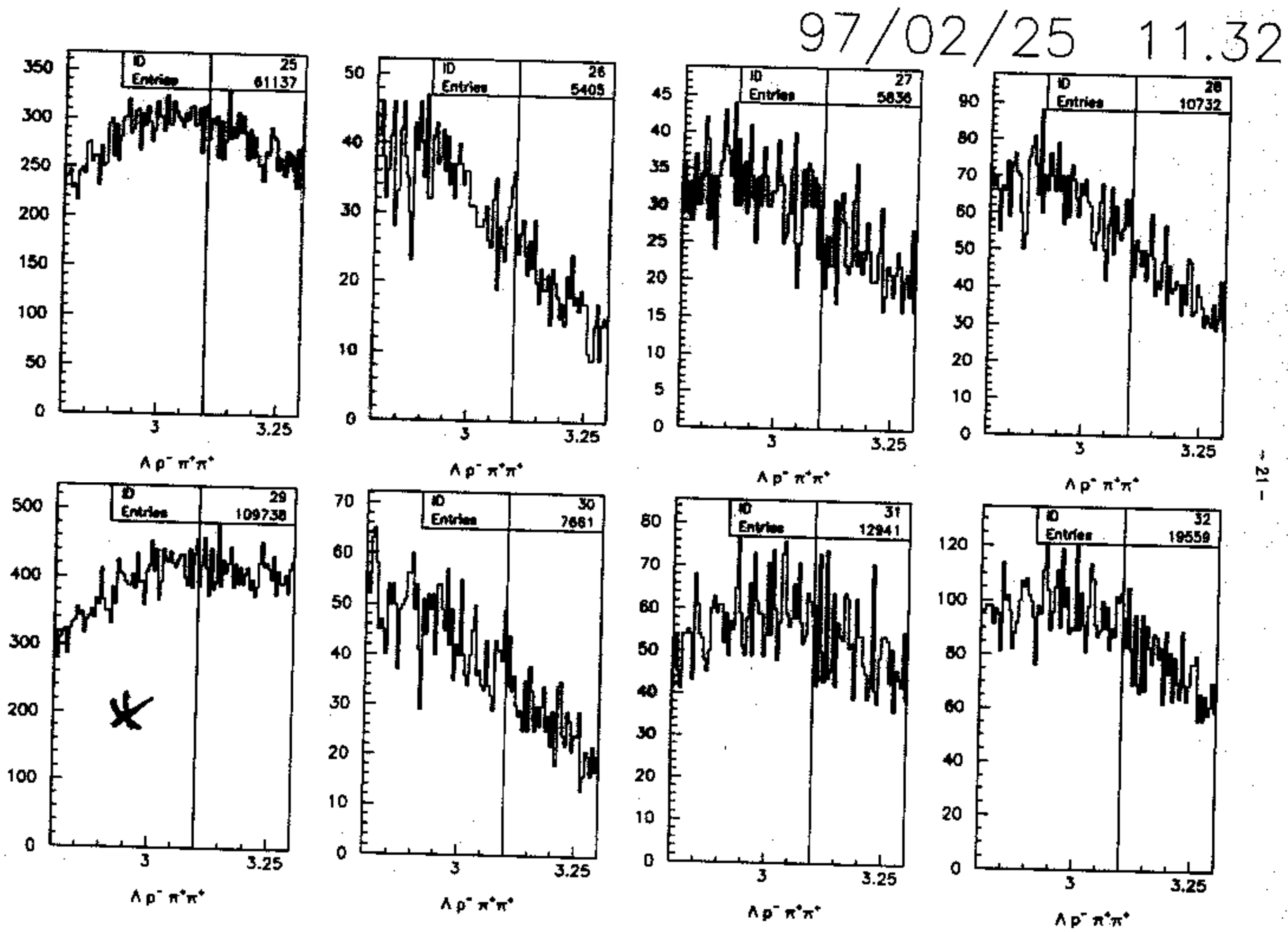
  $\bar{\Lambda} p$ + pions

- Wide variation of cuts
  - vertex
  - particle identification
  - phase space cuts
  - substates
  - Λ kinematical correction

→ No significant signal seen!

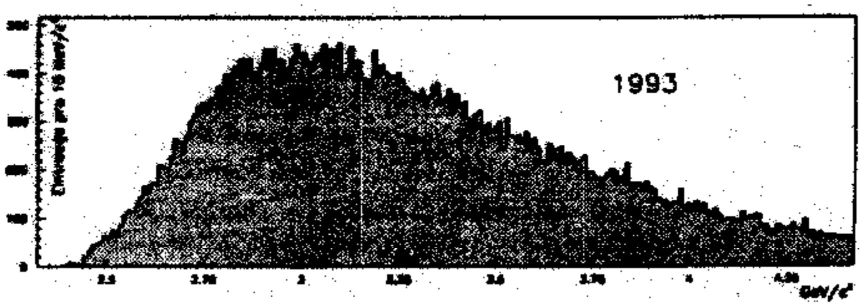
<u>Significant</u>: $\geq 4\sigma$ statistical significance,
seen with similar cuts
in more than one beam time.

1994 data


97/02/25 11.32
ID 25 Entries 61137
ID 26 Entries 5405
ID 27 Entries 5836
ID 28 Entries 10732
ID 29 Entries 109738
ID 30 Entries 7661
ID 31 Entries 12941
ID 32 Entries 19559
$\Lambda p^- \pi^+ \pi^+$

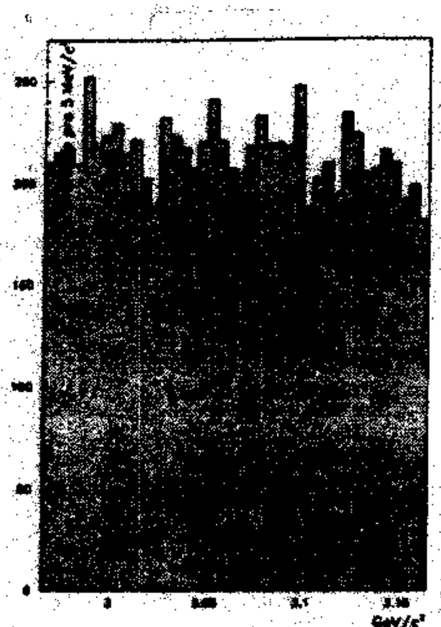
5. Upper limit for $\sigma \cdot B$ for $U^+ \to \Lambda \bar{p} \pi^+ \pi^+$

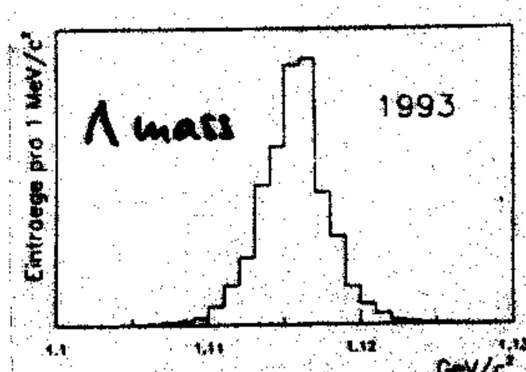
Use 1993 data set:

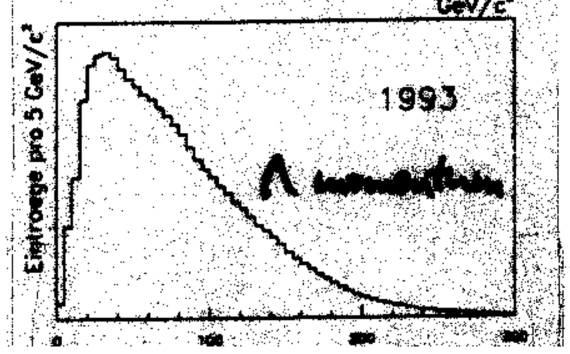


- **Cuts:**

Λ mass within 2.5σ
$\bar{p}$ momentum > 45 GeV/c
$\bar{p}$ RICH ID
π^+ momenta > 5 GeV/c
π^+: K, p cand. excluded (RICH)
main vertex in target





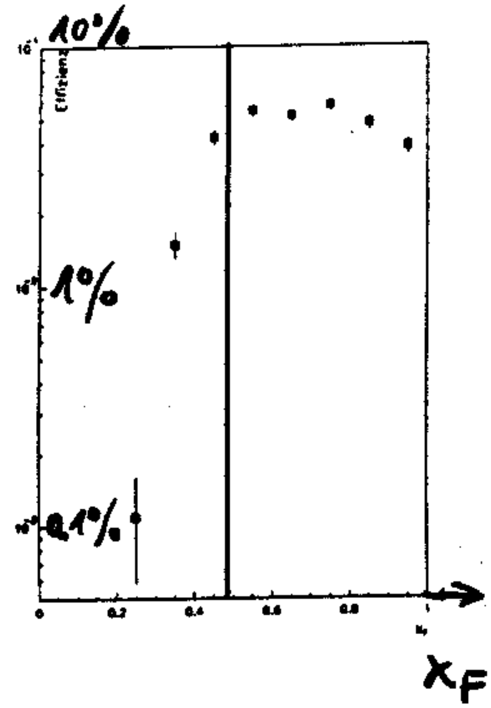


- Experimental acceptance and efficiency

Monte Carlo simulation of $U^+ \to \Lambda \bar{p} \pi^+ \pi^+$
Detector simulation with OMGEANT3.

→ Acceptance dependent on Feynman x_F
(with all cuts included)

~constant for $x_F > 0.5$
≈ 6%
cut on x_F keeps
≈ 60% of events



<u>Luminosity</u>

Integrated over 1993 data used for this analysis:

$$\int L\,dt = 4600\ \mu b^{-1} \quad \text{(per nucleon)}$$

assuming $\sigma \sim A^{2/3}$ (C, Cu targets)

Limit based on 1993 data

→ $\sigma \cdot B < 0.15\ \mu b$ / nucleon $x_F > 0.5$
90% C.L.

channel $U^+ \to \Lambda \bar{p} \pi^+ \pi^+$, $\Gamma \leq 20$ MeV

Expect similar limits for other channels.

6. Conclusion

- Compare with other experiments:
  - WA62: 135 GeV $\Sigma^- + Be$

    $\sigma \cdot B = 4.8 \pm 1.4 \pm 0.8\ \mu b/Be$, $x_F > 0.6$

    $\rightarrow$ $2.3\ \mu b/\text{nucleon}$ assuming $A^{2/3}$
  - BIS-2: 40 GeV $n + A$

    $\sigma \cdot B \approx 1\ \mu b/\text{nucleon}$, $x_F > 0.2$
  - WA89: 330 GeV $\Sigma^- + C/Cu$

    $\sigma \cdot B < 0.18\ \mu b/\text{nucleon}$, $x_F > 0.5$

- $\rightarrow$ At least one order of magnitude smaller cross section seen as in WA62.

  $\rightarrow$ Might still be compatible with BIS-2. ?

  $\rightarrow$ No signal for U(3100) seen in WA89.

- Hyperon beam is an ideal instrument to study hyperon production.
- Tagged s quark allows to study the influence of the projectile structure. (leading effect!)
- Leading is not only a function of flavor, but also depends on internal hadron structure.
- $\Lambda\Lambda$ correlation indicates that our picture of the leading effect (2 different Λs) is correct.
- Observed p_T distributions have non-thermal component.
- Upper limit for $U(3100)$

After 50 years of hyperon physics there are still many open questions concerning resonances, decays, and branching ratios.