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DIFFRACTIVE PRODUCTION OF THE CHARMED BARYON Λ_c^+ AT THE CERN ISR

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Abstract

In a sample of diffractive events of high multiplicity a sharp five standard deviation signal is observed at $M = 2255$ MeV/c^2 in the $K^-p\pi^+$ mass distribution and , although with less statistical strength, at the same mass in the $\Lambda^o\pi^+\pi^+\pi^-$ channel. These signals are identified as being due to the decay of the charmed baryon Λ_c^+ which is produced with a cross-section times branching ratio $\sigma_c.B$ in the range 0.7 - 1.8 μb for the $K^-\pi^+p$ decay and 0.3 - 0.7 μb for the $\Lambda^o\pi^+\pi^+\pi^-$ system.

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We report here production of the charmed baryon $\Lambda_c^+(2255)$ in pp interactions in the CERN ISR at $\sqrt{s}$ = 63 GeV. The charmed baryon is produced diffractively and decays to $K^- p\pi^+$. This is the first observation of charmed baryon production in strong interactions; it is also the first observation of the decay mode $\Lambda_c^+ \to K^- p\pi^+$.

The experimental setup of Fig. 1 was used to detect the single diffraction dissociation process:

$$p + p \to X + p$$

and to study the decay of the excited baryon X. A large acceptance multiparticle detector in Arm 1, S1, intercepted decay products of X within 40° of beam 1. A precision spectrometer in Arm 2, S2, detected the quasi-elastic proton recoiling against X at 10 - 21 mrad from beam 2.

The Arm 1 detector consisted of two magnetic spectrometers covering the angular intervals $14^\circ - 40^\circ$ and $1^\circ - 6^\circ$ with respect to the beam 1 direction. For the outer spectrometer, $S1_a$, magnetic analysis was provided by a toroidal air-cored magnet, called the Lampshade Magnet or LSM, having an $\int B.d\ell$ of roughly 1.6 kG-m over most of its angular range. The 12 coils of the magnet are symmetrically distributed in azimuth. Ten of the intervals between them are occupied by gas Cerenkov counters containing CO_2 at atmospheric pressure. The primary purpose of these counters was electron identification. Their pion threshold was 5 GeV/c. Particle trajectories were measured with drift chambers; their design and performance is detailed in Ref. 1.

The inner arm 1 spectrometer, $S1_b$, consisted of two identical septum magnets with $\int Bd\ell$ = 12.9 kG-m placed above and below the beam pipe. Particle trajectories were recorded with proportional wire chambers having a 2 mm pitch. This spectrometer has been described in a previous communication[2)].

Cerenkov counters in the inner arm 1 spectrometer, $S1_b$, provided $\pi/K/p$ discrimination. Each septum magnet contained a 4-element gas Cerenkov counter filled with freon at atmospheric pressure.

The arm 2 spectrometer, S2, is made of one small acceptance magnet having a large $\int Bd\ell$ of 29.7 kG-m sandwiched between 1 mm pitch proportional chambers.

The characteristics of all three spectrometers are summarized in Table I.

The aim of this experiment was to look for evidence of the decay of an excited baryon $X \to \Lambda_c^+ + D + n\pi$, where X was produced in the single diffraction dissociation process $p + p \to p + X$. The requirement of single diffractive dissociation was imposed with the high precision forward spectrometer in Arm 2. Only positive particles of momentum exceeding 11 GeV could traverse this spectrometer and associated trigger counters. In this momentum interval pion contamination is negligible. To further purify the single diffractive trigger a veto counter consisting of lead fronted scintillator covered the angular range $23 < \theta_{beam2} < 100$ mr, imposing a rapidity gap $\Delta Y \simeq 1.5$ units between the proton and other particles. On the Arm 1 side we required hits in at least 3 distinct trigger counters in each of $S1_a$ and $S1_b$. This multiplicity condition of at least six particles was imposed to strongly favour a mass above the charmed particle production threshold (4.2 GeV/c^2) for the excited system X decaying in Arm 1. On the average this multiplicity of six or more corresponds to a mass $M \sim 7 - 8$ GeV/c^2 for system X[3]. In fact we expect a higher threshold because the apparatus does not cover all the possible angular range.

The results reported here are based on 9.4×10^6 events[4] recorded in 270 hours of ISR running at c.m. energy of 63 GeV and average luminosity 0.8×10^{31} cm^{-2} sec^{-1}.The integrated luminosity (corrected for dead time) was 0.78×10^{37} cm^{-2}. After data processing there remained a total of 1.16×10^6 events fulfilling the following demands for track reconstruction:

(i) 1 positive particle with momentum > 11 GeV/c in spectrometer S2,

(ii) ≥ 2 tracks through spectrometer $S1_a$,

(iii) ≥ 2 tracks through spectrometer $S1_b$.

The single track reconstruction efficiency for spectrometers $S1_a$, $S1_b$ and S2 are 70%, 70% and 72%.

To search for production of baryons decaying in the channel $K^- p \pi^+$ events were selected which met the following criteria:

(1) a proton and a K^--meson in spectrometer $S1_b$, as identified by the absence of a pulse in the Cerenkov cell which they traversed. This condition distinguishes between pions and

heavier particles; the distinction can be made from pion threshold to 11 GeV/c for kaons and to 20 GeV/c for protons and antiprotons. To remove pion background the minimum momentum for kaons and protons was set at 4.5 GeV/c. The K^- and proton identification capability is verified by the K^-p invariant mass plot (Fig. 2a) in which a clear signal of $\Lambda(1520)$ is evident.

(2) at least one additional positive particle in either $S1_a$ or $S1_b$. For this particle the Cerenkov pulse-height information in whichever spectrometer it traversed had to be consistent with π^+ identification. Besides achieving the discrimination against heavier particles in $S1_b$, as mentioned earlier, this requirement removes electron background in both $S1_a$ and $S1_b$.

(3) the three-particle $K^-p\pi^+$ system must form a "good vertex" with the recoiling proton in Arm 2. A good vertex is defined as one in which the minimum root-mean-square distance of the four tracks from their mutual point of closest approach is less than 12 mm.

Figure 3a shows the distribution in invariant mass $M(K^-p\pi^+)$ for events satisfying criteria (1) through (3). A peak is seen in the 20 MeV/c^2 bin centred at 2260 MeV. The number of events in the mass range 2250 - 2270 MeV is 446 compared to an expected background of 348, calculated by fitting a polynominal background through the events on either side of the peak. The peak is thus 5.3 standard deviations above background. Since S = -1 baryon states in the same mass range have natural widths $\Gamma \geq 100$ MeV one is led to identify this structure with the charmed baryon $\Lambda_c^+(2255)$, previously observed in weak[5)] and EM[6)] interactions. As a check on this hypothesis we plot in Fig. 3b the invariant mass of $K^-p\pi^-$ systems selected in identical fashion to $K^-p\pi^+$. No structure is seen at 2260 GeV as expected if the peak in Fig. 3a is due to a charmed baryon; for strange baryon states (Y) on the other hand existence of Y^+ implies also the existence of Y^-.

The insert in Fig. 3a shows the invariant mass $M(K^-p\pi^+)$ for those events contained entirely in spectrometers $S1_b$ and S2. The statistical significance of this sub-set of data is slightly over three standard deviations. Mass scale systematic errors can be checked more easily in $S1_b$ than in $S1_a$ through the use of $S2/S1_b$ elastic data and abundant Λ^o and K^o signals in $S1_b$. This sample provides an estimate of the Λ_c invariant mass $M(\Lambda_c^+)$ = 2255 ± 2 MeV, with a possible systematic error of ∿ 3 MeV.

In the same sample of 1.1×10^6 events we also searched for the decay of the charmed baryon into $\Lambda\pi^+\pi^+\pi^-$ [5]. The $p\pi^-$ mass spectrum (Fig. 2b) for particles in the forward spectrometer S_{1b} shows a clear Λ signal, whose width is consistent with the expected mass resolution (FWHM = 9 MeV). Events with mass within 7 MeV/c^2 of the Λ^o mass were retained for further analysis. It was required that the tracks other than those from the Λ decay form a single vertex, as described before, to which the Λ momentum vector points. To reduce the background we applied the following cuts, suggested by a rather general diffractive model[6]: i) momentum of the proton in Arm 2 $\geq$ 28 GeV/c, ii) 2 pions in S_{1b} with momenta less than 4 GeV/c, iii) 1 pion in S_{1a}. The $\Lambda\pi^+\pi^+\pi^-$ and $\Lambda\pi^+\pi^-\pi^-$ mass spectra thus obtained are shown in Fig. 4a and 4b, binned in 30 MeV/c^2 intervals. Fig. 4a shows a signal in the mass range 2.24 - 2.27 GeV/c^2. Such an enhancement persists independent of the cuts chosen with a statistical significance greater than 99%.

We now calculate the production cross-section for the $K^-p\pi^+$ final state. The trigger condition was:

$T_2.T_1 \equiv$ (particle through S2).($\geq$ 6 particles in S1)

where the subscripts 1(2) denote arm 1(2) and the V2 veto is included in the definition of T2. The trigger requirement T_2 alone selects single diffraction dissociation events $pp \to pX$; the additional requirement T_1 introduces a mass threshold M' for the system X.

We estimate from the peak in Fig.3a the cross-section for charmed baryon production in single diffraction dissociation for diffractive masses M in the range $M'^2/s < M^2/s < 0.2$. It is first necessary to determine the mass threshold M' and the corresponding cross-section for the mass range $M'^2 < M^2 < 794$ $(\mathrm{GeV}/c^2)^2$.

Using a sample of data taken with the trigger T_2 alone (except that the V2 veto is temporarely removed), together with the measured ISR luminosity, we obtained $d^2\sigma/dM^2dt$ for the reaction $pp \rightarrow pX$. For this cross-section determination the geometrical acceptance of the Arm 2 spectrometer was obtained with a Monte Carlo calculation using the invariant cross-section $s/\pi . d^2\sigma/dtdM^2$ measured at $23 < \sqrt{s} < 38$ GeV.[8] We find a total cross-section of 8.8 ± 1.8 mb for $M^2/s < 0.2$ which is consistent within 20% with extrapolations of previous lower energy measurements to $\sqrt{s} = 63$ GeV.[8] We also verified that the observed M^2 and t dependence agreed with the results of Ref. 7. Fig. 5a shows the M^2 dependence when the V2 veto is included.

The mass threshold M' was then obtained from a comparison of the rates $(dN/dM^2)_{T_2}$ and $(dN/dM^2)_{T_1 . T_2}$ for the triggers T_2 and $T_1 . T_2$ respectively.
The ratio $(dN/dM^2)_{T_1 . T_2}/(dN/dM^2)_{T_2}$ showed a distinct threshold at M' of 10 GeV/c^2 and was essentially constant at higher masses, as shown in Fig. 5b. Combining this information with $d\sigma/dM^2$ measured with the T_2 trigger we determine that the cross-section for production of diffractive masses in the range 10 - 28 GeV/c^2 is 2.8 ± 0.6 mb. The triggering cross-section, that is the rate in the range 10 - 28 GeV/c^2 divided by the luminosity, is 0.62 μb so that the efficiency, ε_T, for triggering on $pp \rightarrow pX$ with the mass of X in the range 10 - 28 GeV/c^2 is determined to be $(0.22 \pm 0.04) \times 10^{-3}$.

The cross-section σ_c for charmed baryon production in this experiment is then given by:

$$\sigma_c . B = \frac{N_c}{\varepsilon_T \varepsilon_{RC} \overline{\varepsilon_1(x,p_T)}} \cdot \frac{1}{\int L dt}$$

where :

B is the branching ratio for $\Lambda_c^+ \rightarrow K^- p \pi^+$

N_c, the number of charmed baryons observed in the range $M^2/s < 0.2$, $0.3 < x < 0.8$, and $0 < p_T < 1$ GeV = 79

ε_T, the detector triggering efficiency = 0.22×10^{-3}

ε_{RC}, the combined track reconstruction and Cerenkov efficiencies = 0.20.

$\overline{\varepsilon_1(x,p_T)}$, the probability (averaged over x, p_T of Λ_c^+) that in a triggering event the Λ_c^+ decay products K^-, p, π^+ are detected in S1 = 0.20.[9]

The resulting estimate for σ_c.B is 1.2 ± 0.3 μb for $\Lambda_c^+ \rightarrow K^- p\pi^+$, where the error is purely statistical. After including the uncertainty in the estimate of the overall efficiency, we find that σ_c.B lies in the range 0.7 - 1.8 μb.

We obtain the partial cross-section σ.B for $\Lambda_c^+ \rightarrow \Lambda^0\pi^+\pi^+\pi^-$ production in a similar way, except that in calculating the acceptance we use the diffractive model described in Ref. 7. We find that σ.B is in the range 0.3 - 0.7 μb.

These results are in excellent agreement with theoretical predictions of diffractive production[10)] and the estimated branching ratios[11)] for charmed baryons. We also note that there is no inherent conflict with recent studies of prompt neutrino production at very forward angles. In these experiments cross-sections for inclusive charm production in the range σ = 40 - 200 μb were inferred assuming central production[12)]. It appears that the prompt neutrino signal in the CERN beam dump experiments is compatible with diffractive charm production with a cross-section times branching ratio of the magnitude reported here; it is not necessary to invoke large central cross-sections.

Acknowledgements

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References

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2) L. Baksay et al., Nucl. Instr. and Meth. 133, 219 (1976).

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C. Baltay et al., submitted to Phys. Rev. Lett.

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7) The diffractive model used is based on inelastic diffractive data obtained at the CERN ISR (Ref. 8) for the reaction $pp \to pX$, where X is an excited state of mass M. Charmed particles are assumed to be produced in association, i.e. $X \to \bar{D} + \Lambda_c^+ + n\pi$. The Λ_c^+ longitudinal momentum dependence is modeled after strange Λ^o production but is limited to a maximum value $x = p_{\Lambda_c}/p_X = (M - M_o)/M$. The transverse distribution is assumed to follow an e^{-bE_T} law (the results are quite insensitive to the value of b).

8) M.G. Albrow et al., Nucl. Phys. B108, 1 (1976).

9) A Monte Carlo calculation was made to evaluate $\varepsilon_1(x,p_T)$. The calculation was made for the x,p_T range $0.3 < x < 0.8$ and $0 < p_T < 1$ GeV/c, since $K^-p\pi^+$ systems in the mass range around 2.26 GeV/c^2 are produced predominantly with these values. In the Monte Carlo calculation we assumed phase space kinematics for $\Lambda_c^+ \to K^-p\pi^+$, and an x, p_T distribution for Λ_c^+ similar to that of the background at the same mass.

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TABLE I. SPECTROMETER CHARACTERISTICS

	$S1_a$	$S1_b$	S2
Magnet construction $\int B.d\ell$	Air core toroid $\sim$ 1.6 kG - m	Two dipole septums 12.9 kG - m	One dipole septum 29.7 kG - m
Detector	Drift Chambers	MWPC's, 2 mm pitch	MWPC's, 1 mm pitch
Acceptance	$14^\circ < \theta < 40^\circ$ $\Delta\phi \simeq .8 \times 2\pi$	$1.1^\circ < \theta < 5.4^\circ$ $\Delta\phi \simeq .5 \times 2\pi$	10 mrad $< \theta <$ 21 mrad $\Delta\phi \simeq .14 \times 2\pi$
Cerenkov	CO_2 Used for electrons (π threshold 5 GeV/c)	Freon 114 ($C_2Cl_2F_4$) π/K/p threshold = 2.7/9.9/18.8 GeV/c	None

Figure captions

1) Spectrometers $S1_a$ and $S1_b$ in Arm 1 and spectrometer S2 in Arm 2 of intersection 6 at the CERN ISR. Heavy lines indicate trigger counters.

2a) Invariant mass plot for K^-p, showing a $\Lambda(1520)$ peak; 5 MeV/c^2 bins.

2b) Invariant mass plot for πp, showing a $\Lambda^o(1115)$ peak; 2 MeV/c^2 bins.

3a) Invariant mass plot for $K^-p\pi^+$ in 20 MeV/c^2 bins showing a five standard deviation peak above a polynominal background as described in the text; the insert shows a subset of events for which all three particles traverse spectrometer $S1_b$ plotted in 10 MeV/c^2 bins.

3b) Invariant mass plot for $K^-p\pi^-$ in 20 MeV/c^2 bins.

4a) Invariant mass plot for $\Lambda^o\pi^+\pi^+\pi^-$ in 30 MeV/c^2 bins, with a 12 parameter polynominal background (dashed line)

4b) Invariant mass plot for $\Lambda^o\pi^+\pi^-\pi^-$, same binning.

5a) Invariant mass squared of the diffractively produced system X for the trigger T2 alone.

5b) The ratio $(dN/dM^2)_{T_1 \cdot T_2}/(dN/dM^2)_{T_2}$ as described in the text.

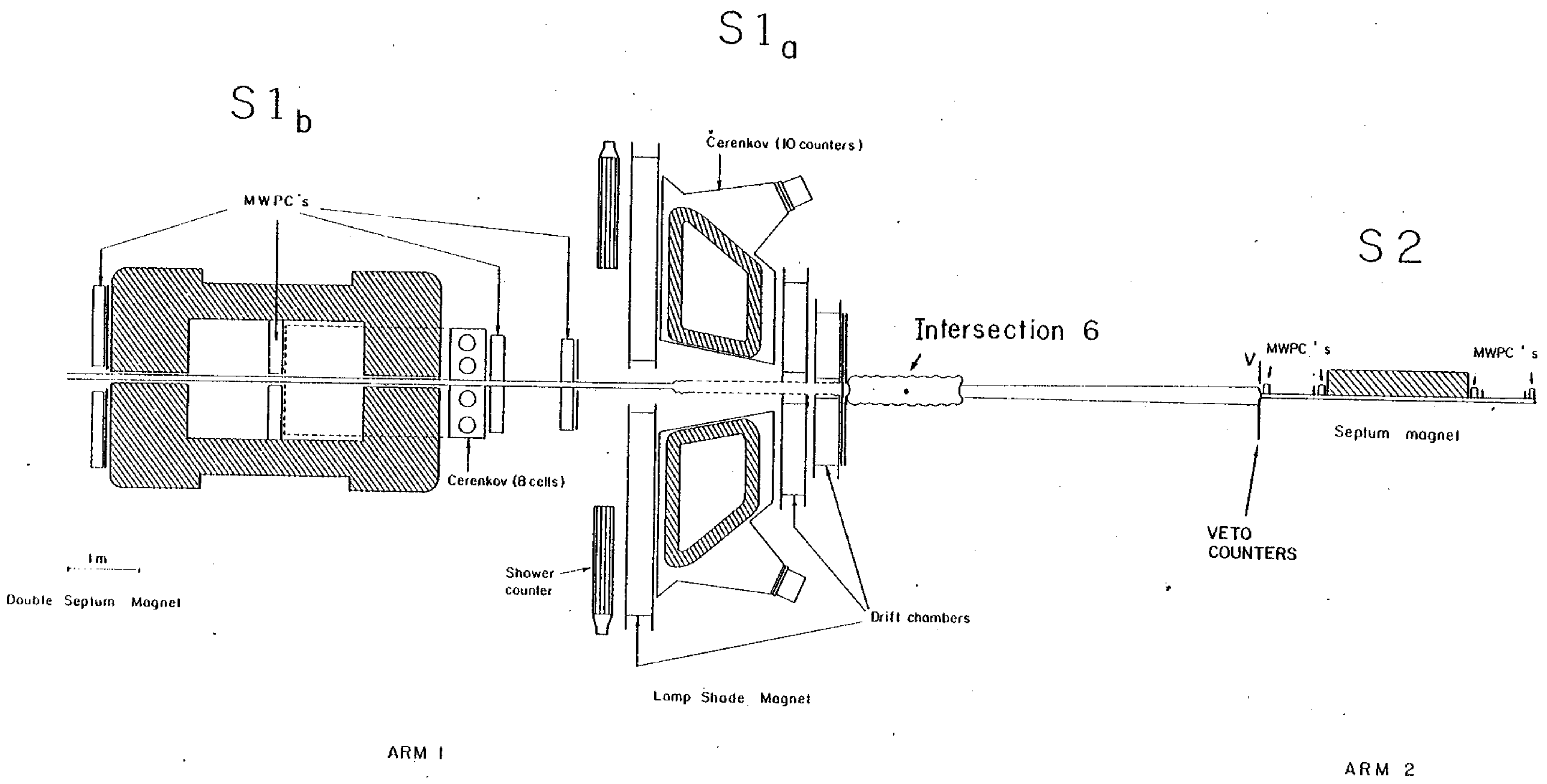
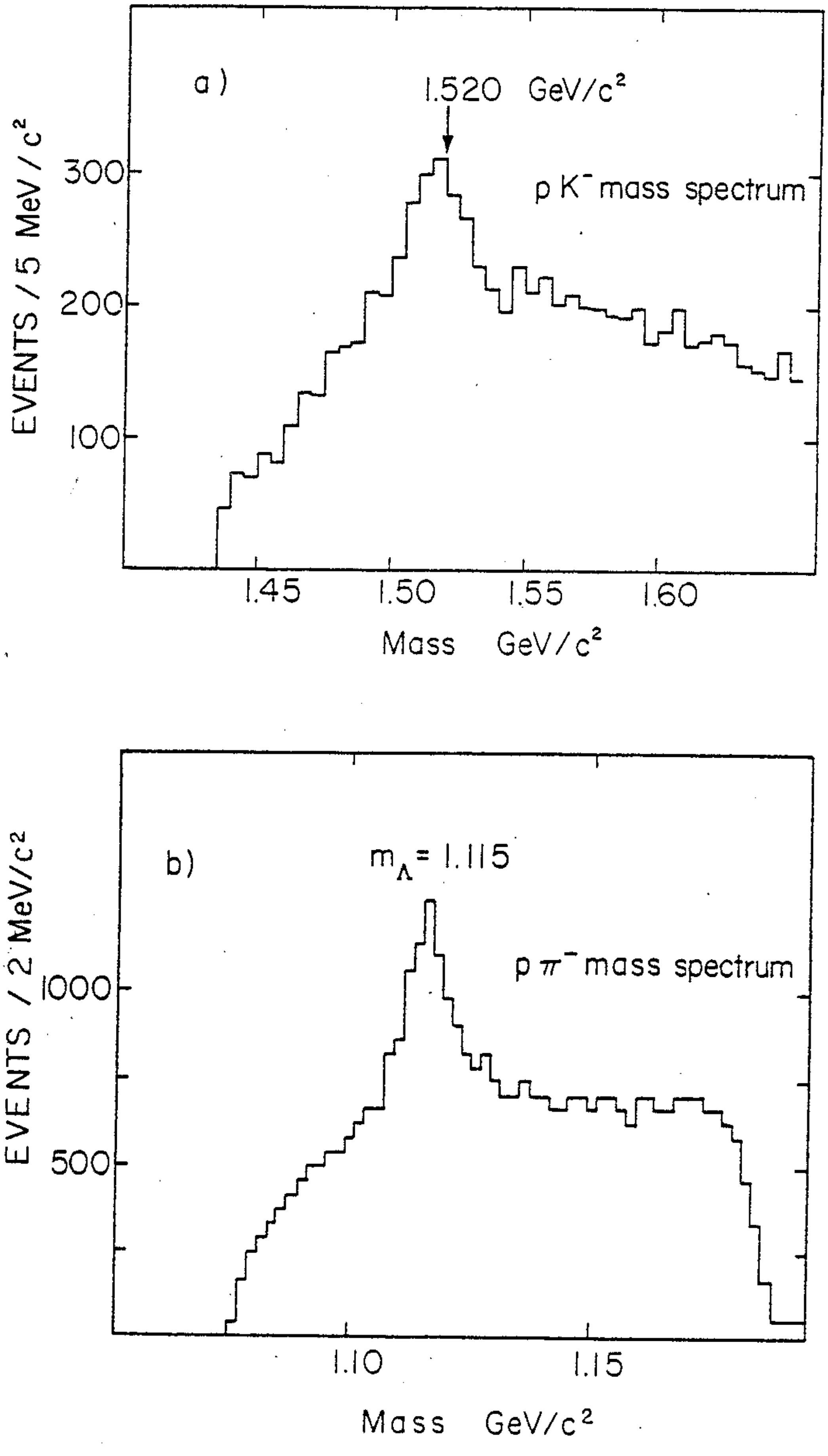

S1b
S1a
S2
MWPC's
Čerenkov (10 counters)
Intersection 6
V
MWPC's
MWPC's
Septum magnet
Cerenkov (8 cells)
VETO COUNTERS
1m
Double Septum Magnet
Shower counter
Drift chambers
Lamp Shade Magnet
ARM I
ARM 2

Fig. 1



a)
1.520 GeV/c²
p K⁻ mass spectrum
EVENTS / 5 MeV/c²
300
200
100
1.45
1.50
1.55
1.60
Mass GeV/c²
b)
m_Λ = 1.115
p π⁻ mass spectrum
EVENTS / 2 MeV/c²
1000
500
1.10
1.15
Mass GeV/c²

Fig. 2

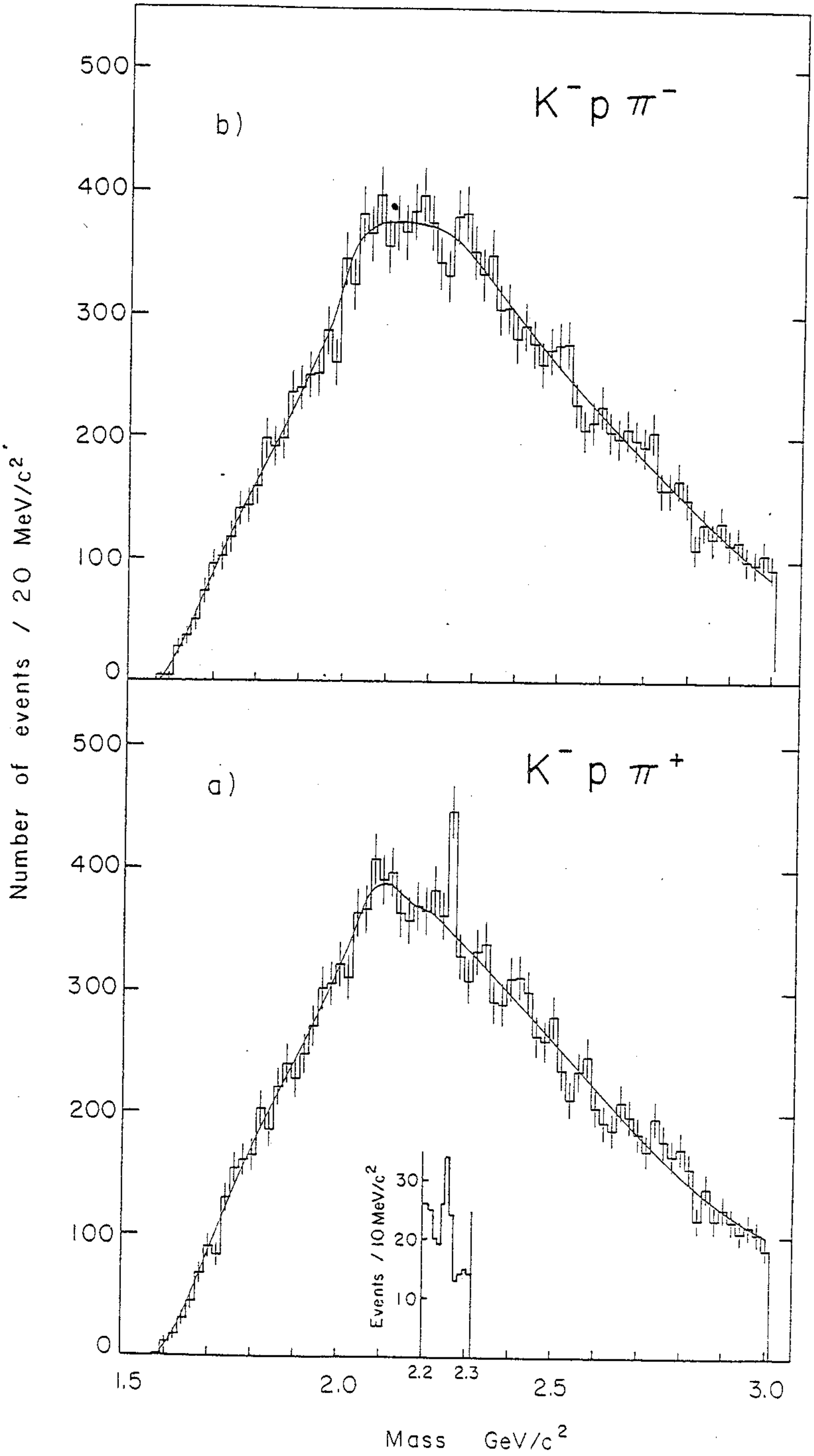

K⁻p π⁻
b)
K⁻p π⁺
a)
Number of events / 20 MeV/c²
Events / 10 MeV/c²
Mass GeV/c²
0
100
200
300
400
500
10
20
30
1.5
2.0
2.2
2.3
2.5
3.0

Fig. 3

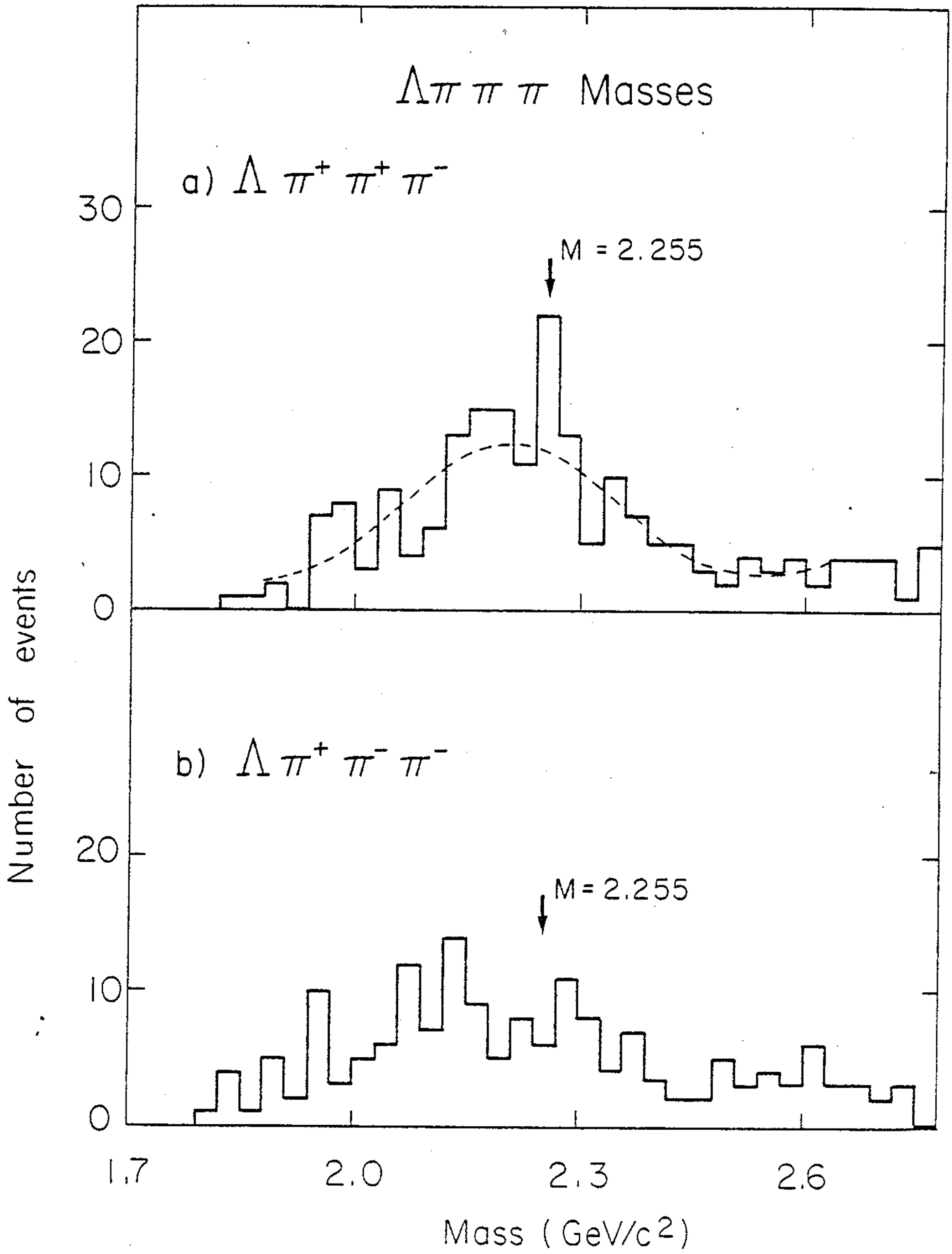
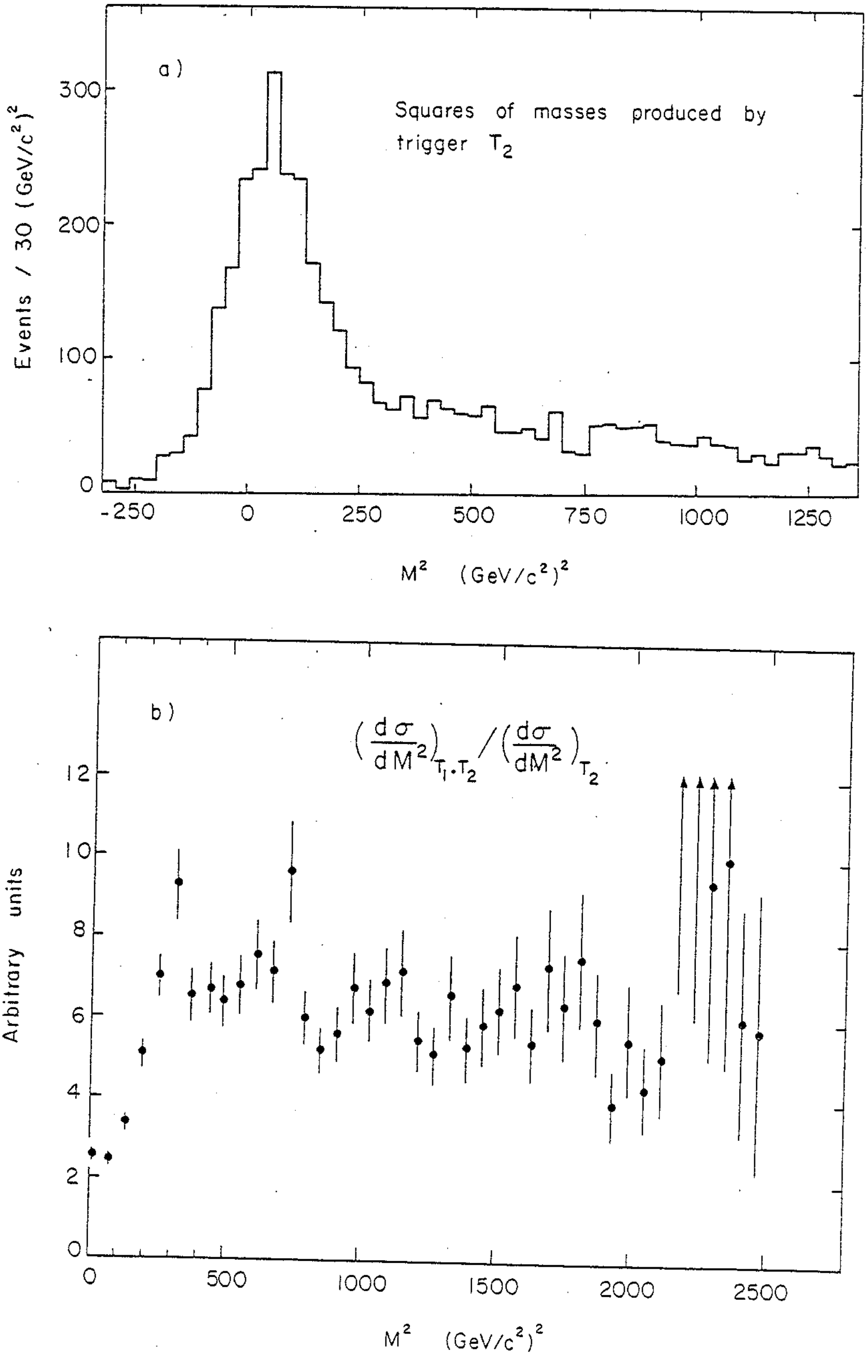

$\Lambda\pi\pi\pi$ Masses
a) $\Lambda\pi^+\pi^+\pi^-$
M = 2.255
b) $\Lambda\pi^+\pi^-\pi^-$
M = 2.255
30
20
10
0
20
10
0
Number of events
1.7
2.0
2.3
2.6
Mass (GeV/c²)

Fig. 4



a)
Squares of masses produced by trigger T_2
Events / 30 $(GeV/c^2)^2$
M^2 $(GeV/c^2)^2$
b)
$\left(\frac{d\sigma}{dM^2}\right)_{T_1 \cdot T_2} / \left(\frac{d\sigma}{dM^2}\right)_{T_2}$
Arbitrary units
M^2 $(GeV/c^2)^2$

Fig.5