

**First observation and branching fraction and
decay parameter measurements of the weak
radiative decay $\Xi^0 \rightarrow \Lambda e^+ e^-$**

NA48 collaboration

J.R. Batley, G.E. Kalmus¹, C. Lazzeroni, D.J. Munday,
M. Patel, M.W. Slater, S.A. Wotton

*Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, U.K.*²

R. Arcidiacono³, G. Bocquet, A. Ceccucci, D. Cundy⁴,
N. Doble⁵, V. Falaleev, L. Gatignon, A. Gonidec, P. Grafström,
W. Kubischta, I. Mikulec⁶, A. Norton, B. Panzer-Steindel,
P. Rubin^{7,*}, H. Wahl⁸

CERN, CH-1211 Genève 23, Switzerland

E. Goudzovski⁵, P. Hristov⁹, V. Kekelidze, L. Litov,
D. Madigozhin, N. Molokanova, Yu. Potrebenikov, S. Stoynev,
A. Zinchenko

Joint Institute for Nuclear Research, Dubna, Russian Federation

E. Monnier¹⁰, E. Swallow, R. Winston¹¹,

*The Enrico Fermi Institute, The University of Chicago, Chicago, IL 60126,
U.S.A.*

R. Sacco¹², A. Walker

*Department of Physics and Astronomy, University of Edinburgh, JCMB King's
Buildings, Mayfield Road, Edinburgh, EH9 3JZ, U.K.*

W. Baldini, P. Dalpiaz, P.L. Frabetti¹³, A. Gianoli, M. Martini,
F. Petrucci, M. Savrié, M. Scarpa

*Dipartimento di Fisica dell'Università e Sezione dell'INFN di Ferrara, I-44100
Ferrara, Italy*

A. Bizzeti¹⁴, M. Calvetti, G. Collazuol⁵, E. Iacopini, M. Lenti,
G. Ruggiero⁹ M. Veltri¹⁵

*Dipartimento di Fisica dell'Università e Sezione dell'INFN di Firenze,
I-50125 Firenze, Italy*

M. Behler, K. Eppard, M. Eppard⁹, A. Hirstius⁹,
K. Kleinknecht, U. Koch, P. Marouelli, L. Masetti¹⁶,
U. Moosbrugger, C. Morales Morales, A. Peters⁹, R. Wanke,
A. Winhart

Institut für Physik, Universität Mainz, D-55099 Mainz, Germany¹⁷

A. Dabrowski, T. Fonseca Martin⁹, M. Velasco

*Department of Physics and Astronomy, Northwestern University, Evanston, IL
60208-3112, U.S.A.*

G. Anzivino, P. Cenci, E. Imbergamo, G. Lamanna⁵,
P. Lubrano, A. Michetti, A. Nappi, M. Pepe, M.C. Petrucci
M. Piccini⁹ M. Valdata

*Dipartimento di Fisica dell'Università e Sezione dell'INFN di Perugia,
I-06100 Perugia, Italy*

C. Cerri, F. Costantini, R. Fantechi, L. Fiorini¹⁸, S. Giudici,
I. Mannelli, G. Pierazzini, M. Sozzi

*Dipartimento di Fisica, Scuola Normale Superiore e Sezione dell'INFN di Pisa,
I-56100 Pisa, Italy*

C. Cheshkov, J.B. Cheze, M. De Beer, P. Debu, G. Gouge,
G. Marel, E. Mazzucato, B. Peyaud, B. Vallage

DSM/DAPNIA - CEA Saclay, F-91191 Gif-sur-Yvette, France

M. Holder, A. Maier⁹, M. Ziolkowski

Fachbereich Physik, Universität Siegen, D-57068 Siegen, Germany¹⁹

C. Biino, N. Cartiglia, M. Clemencic, S. Goy Lopez,
F. Marchetto, E. Menichetti, N. Pastrone

*Dipartimento di Fisica Sperimentale dell'Università e Sezione dell'INFN di
Torino, I-10125 Torino, Italy*

W. Wislicki

*Soltan Institute for Nuclear Studies, Laboratory for High Energy Physics,
PL-00-681 Warsaw, Poland²⁰*

H. Dibon, M. Jeitler, M. Markytan, G. Neuhofer, L. Widhalm

*Österreichische Akademie der Wissenschaften, Institut für Hochenergiephysik,
A-1050 Wien, Austria²¹*

Submitted to Physics Letters B

Abstract

The weak radiative decay $\Xi^0 \rightarrow \Lambda e^+ e^-$ has been detected for the first time. We find 412 candidates in the signal region, with an estimated background of 15 ± 5 events. We determine the branching fraction $\mathcal{B}(\Xi^0 \rightarrow \Lambda e^+ e^-) = [7.6 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \pm 0.2(\text{norm})] \times 10^{-6}$, consistent with an internal bremsstrahlung process, and the decay asymmetry parameter $\alpha_{\Xi\Lambda ee} = -0.8 \pm 0.2$, consistent with that of $\Xi^0 \rightarrow \Lambda\gamma$. The charge conjugate reaction $\bar{\Xi}^0 \rightarrow \bar{\Lambda} e^+ e^-$ has also been observed.

1 Introduction

Since the discovery of hyperons, their (weak) radiative decays have held particular interest [1,2]. Still, the precise nature of the decays themselves remains an open question [3,4].

* Corresponding author. *Email address:* prubin@gmu.edu

¹ Present address: Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, U.K.

² Funded by the U.K. Particle Physics and Astronomy Research Council.

³ Present address: Massachusetts Institute of Technology, Cambridge, MA 02139-4307, U.S.A.

⁴ Present address: Istituto di Cosmogeofisica del CNR di Torino, I-10133 Torino, Italy

⁵ Present address: Dipartimento di Fisica, Scuola Normale Superiore e Sezione dell'INFN di Pisa, I-56100 Pisa, Italy

⁶ On leave from Österreichische Akademie der Wissenschaften, Institut für Hochenergiephysik, A-1050 Wien, Austria

⁷ On leave from University of Richmond, Richmond, VA, 23173, USA; supported in part by the US NSF under award #0140230. Present address: Department of Physics and Astronomy, George Mason University, Fairfax, VA 22030A, USA.

⁸ Present address: Dipartimento di Fisica dell'Università e Sezione dell'INFN di Ferrara, I-44100 Ferrara, Italy

⁹ Present address: CERN, CH-1211 Genève 23, Switzerland

¹⁰ Present address: Centre de Physique des Particules de Marseille, IN2P3-CNRS, Université de la Méditerranée, Marseille, France.

¹¹ Also at University of California, Merced, U.S.A.

¹² Present address: Department of Physics, Queen Mary University, London, E1 4NS, U.K.

¹³ Present address: Joint Institute for Nuclear Research, Dubna, 141980, Russian Federation

¹⁴ Dipartimento di Fisica dell'Università di Modena e Reggio Emilia, I-41100 Modena, Italy

¹⁵ Istituto di Fisica dell'Università di Urbino, I-61029 Urbino, Italy

¹⁶ Present address: Physikalisches Institut, Universität Bonn, 53113 Bonn, Germany

¹⁷ Funded by the German Federal Minister for Research and Technology (BMBF) under contract 7MZ18P(4)-TP2

¹⁸ Present address: Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, U.K.

¹⁹ Funded by the German Federal Minister for Research and Technology (BMBF) under contract 056SI74

²⁰ Supported by the Committee for Scientific Research grants 5P03B10120, SPUB-M/CERN/P03/DZ210/2000 and SPB/CERN/P03/DZ146/2002

²¹ Funded by the Austrian Ministry for Traffic and Research under the contract GZ 616.360/2-IV GZ 616.363/2-VIII, and by the Fonds für Wissenschaft und Forschung FWF Nr. P08929-PHY

5 Reliable techniques to predict branching ratios remain elusive. Furthermore,
6 because SU(3) symmetry is broken only weakly in this regime, weak radiative
7 decays should approximately conserve parity [5]. Consequently, the asymme-
8 tries of decay angular distributions should be small. However, results from
9 experiments indicate a relatively large (negative) asymmetry in every mode
10 investigated [6]. A number of models have been proposed to explain this appar-
11 ent discrepancy [7]. Experimental results tend to favor pole models or models
12 based on chiral perturbation theory, which correctly find the sign of the asym-
13 metry. Recently, a resolution of at least part of the puzzle has been offered [8].

14 When the NA48 Collaboration undertook investigations with a high-intensity
15 K_S^0 beam in 2002, trigger strategies for identifying radiative hyperon decays
16 were included from the outset. The production over the full course of the run
17 of more than 3×10^9 neutral cascades, $\Xi^0(1315)$, offered NA48 unmatched
18 sensitivity for the study of such decays.¹

19 This Letter details the measurement with these data of the weak radiative hy-
20 peron decay $\Xi^0 \rightarrow \Lambda e^+ e^-$. This is the first measurement of this decay channel.
21 If one assumes an inner bremsstrahlung-like mechanism producing the $e^+ e^-$
22 pairs, the expected rate for this process may be estimated naively assuming
23 the (virtual) photon converts internally (Dalitz decay) or by using the ma-
24 chinery of QED as carried out in rate predictions for $\Sigma^0 \rightarrow \Lambda e^+ e^-$ [1,2]. The
25 results give a range from about 1/182 to 1/160 of the rate of $\Xi^0 \rightarrow \Lambda \gamma$, or
26 $(6.4 - 7.3) \times 10^{-6}$. Such a process should exhibit a decay asymmetry like that
27 in $\Xi^0 \rightarrow \Lambda \gamma$.

28 **2 Data**

29 *2.1 Beam line*

30 The NA48 beam line was designed to produce and transport both K_L^0 and K_S^0
31 beams simultaneously [9]. For the 2002 run, in order to increase dramatically
32 the intensity of the K_S^0 beam, the K_L^0 target was removed and the K_L^0 beamline
33 blocked, the proton flux on the K_S^0 target was greatly increased, and a 24 mm
34 platinum absorber was placed after the Be target to reduce the photon flux
35 in the neutral beam. An additional sweeping magnet was installed across the
36 5.2-meter long collimator, which, tilted at 4.2 mrad relative to the incoming
37 proton beam, selected a beam of long-lived neutral particles (γ , n , K^0 , Λ , and
38 Ξ^0). In each 4.8 s spill, occurring every 16.2 s, $\sim 5 \times 10^{10}$ protons impinged

¹ The $\bar{\Xi}^0$ production rate was about 1/11 that of Ξ^0 . This Letter presents numerical results for the Ξ^0 only.

39 on the target. Approximately $2 \times 10^4 \Xi^0$ s, with momenta between 60 and 220
40 GeV/ c , decayed in the fiducial volume downstream of the collimator each spill.

41 2.2 Detector

42 The detector for the 2002 run was identical to that used for NA48's measure-
43 ment of direct CP-violation [9], except that the tagging counter immediately
44 after the last collimator was removed.

45 2.2.1 Decay volume

46 The neutral beam exited the final collimation into an evacuated tank, approx-
47 imately 90 m in length, terminated by a Kevlar window 0.3% of a radiation
48 length thick. The detector was arrayed immediately downstream of this win-
49 dow.

50 2.2.2 Charged particle tracking

51 A magnetic spectrometer followed the decay volume. It consisted of four
52 drift chambers, two before and two after an analyzing magnet which pro-
53 vided a transverse momentum kick of 265 MeV/ c in the horizontal plane. The
54 chambers were identical, each with two planes of sense wires in four views
55 (x , y , u , v). All the chambers were fully instrumented except the third, which
56 had only its x - and y -views instrumented. Track-time resolution was about 1.4
57 ns. Space-point resolution was approximately 150 μm in each projection, and
58 the momentum resolution (with p in GeV/ c) was:

$$59 \quad \frac{\sigma_p}{p} = 0.48\% \oplus 0.015\% \times p.$$

60 The resulting $m_{\pi^+\pi^-}$ resolution in $K_S^0 \rightarrow \pi^+\pi^-$ decays was 3 MeV/ c^2 .

61 2.2.3 Electromagnetic calorimetry

62 A liquid krypton calorimeter (LKr) detected and measured the energy and
63 position of electromagnetic showers. Its active region was divided transversely
64 into approximately 2 cm \times 2 cm cells, and its depth was 27 radiation lengths.
65 Its single-shower time resolution was less than 300 ps; its transverse position
66 resolution was better than 1.3 mm for a single photon of energy greater than

67 20 GeV; and its energy resolution [10] was

$$68 \quad \frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\%,$$

69 where E is in GeV. The resulting $m_{\gamma\gamma}$ resolution in $\pi^0 \rightarrow \gamma\gamma$ decays was
70 approximately 1 MeV/ c^2 .

71 *2.2.4 Scintillators*

72 The sensitive region of the electromagnetic calorimeter primarily constrained
73 the fiducial volume of the experiment. Seven rings of scintillation counters
74 bounded, in projection, the edges of this acceptance region, and the last two
75 rings acted as trigger vetoes of extraneous activity.

76 A scintillator hodoscope, comprised of segmented horizontal and vertical strips
77 arranged in four quadrants and located between the downstream end of the
78 spectrometer and the upstream face of the calorimeter served as a zeroth-level
79 charged-track trigger. Beyond the electromagnetic calorimeter stood an iron-
80 scintillator sandwich hadron calorimeter and three layers of muon counters,
81 each shielded by an iron wall.

82 *2.2.5 Trigger and readout*

83 The entire detector array was sampled every 25 ns. An event trigger initiated
84 a readout of information within a 200 ns window around the trigger time. In
85 this way, time sidebands allowed investigations of accidental activity.

86 The experiment employed a multi-level trigger designed to maximize flexibility
87 while minimizing pile-up, dead-time losses, and the collection of uninteresting
88 events. To be included in the present analysis, events passed the lowest level
89 hardware trigger if a horizontal-vertical coincidence occurred in at least one
90 quadrant of the scintillator hodoscope, there were no in-time hits in the veto
91 rings, at least three views in the first drift chamber registered more than two
92 hits (as required in the case of more than one track), and either the energy
93 in the electromagnetic calorimeter exceeded 15 GeV or the total energy in
94 the electromagnetic and hadron calorimeters exceeded 30 GeV. The next level
95 trigger required more than one track to have passed through the spectrome-
96 ter forming one or more good vertices². The highest level trigger, an offline
97 software cull, passed events containing a good Λ candidate and at least one

² A good vertex is defined, in this context, as the occurrence of two tracks passing within 5 cm of one another between the target and the first drift chamber

98 high-energy cluster in the calorimeter not associated with either of the tracks
99 forming the Λ .

100 A downsampled sample of minimum bias events was collected concurrently
101 with the physics data. Complete trigger information was available for these
102 events, so trigger efficiencies could be measured. The relative fraction of events
103 containing all signal final state particles that passed the required triggers
104 was $\epsilon_{\text{trig}}^{\text{sig}} = (96.5 \pm 0.2)\%$, while the relative fraction of normalization events
105 ($\Xi^0 \rightarrow \Lambda\pi^0, \pi^0 \rightarrow e^+e^-\gamma$) was $\epsilon_{\text{trig}}^{\text{norm}} = (97.1 \pm 0.2)\%$. This channel was chosen
106 for normalization due to its relative abundance, the similarity of its final state
107 to that of the signal channel, and its selection via the same trigger tree as the
108 signal channel.

109 *2.3 Event selection criteria*

110 Selection criteria were chosen to identify with high efficiency events containing
111 one lambda, one electron, and one positron, all in time. An additional photon
112 was required for the normalization channel.

113 From events passing all trigger levels, those containing exactly four charged
114 tracks, two of each charge sign, that passed well within the fiducial volumes
115 of the first and fourth drift chambers were kept for further analysis.

116 Signal event simulation showed that 99% of final state pions, electrons, and
117 positrons had momenta of less than 30 GeV/c. A track with momentum greater
118 than 3 GeV/c and associated shower energy within 5% of this momentum was
119 identified as an electron or positron, depending on charge. A (positive) track
120 whose momentum was greater than 30 GeV/c and either had no associated
121 electromagnetic shower or the shower energy to momentum ratio was less than
122 0.8 was identified as a proton. If no such track was found, or if there were not
123 both an electron and a positron identified, the event was abandoned. If the
124 final track had a momentum greater than 4 GeV/c, but not more than 1/3.7
125 that of the proton track, it was identified as a pion. Otherwise, the event was
126 abandoned.

127 The tracks associated with the proton and pion had to be separated by at least
128 5 cm in the first drift chamber and their detection times had to be within 2 ns.
129 If not, the event was abandoned. The distance-of-closest-approach (doca) of
130 the two tracks when projected back towards the target was required to be less
131 than 2.2 cm, and the longitudinal position of this doca had to lie between 4
132 and 40 meters down stream of the target for the event to be further considered.
133 The momentum vectors of the two tracks were projected, with respect to a
134 reference frame centered on the beam axis, from their positions in the first
135 drift chamber onto the face of the LKr. These projections were weighted by

136 the relativistic energies of the particles associated with the respective tracks,
137 added vectorially, and then normalized to the energy sum of the two particles.
138 The result, a quantity called the center of gravity (COG), had to be greater
139 than 8 cm to ensure that a parent of the two tracks was unlikely to have been
140 directly produced in the target. The COG of a directly produced particle
141 should be small.

142 The invariant mass of surviving proton and pion candidate pairs was calcu-
143 lated. If the result differed from the nominal mass of the Λ by more than 3
144 MeV/c^2 (approximately 3σ), the event was abandoned.

145 The electron and positron tracks had to have times within 2 ns and a spatial
146 separation in the first drift chamber of at least 2.5 cm. The latter require-
147 ment rejects conversions in the Kevlar window. Any unassociated shower in
148 the calorimeter with energy above 1.5 GeV disqualified the event as a signal
149 candidate.

150 A shower of between 3 and 120 GeV in the electromagnetic calorimeter was
151 considered a photon candidate for the normalization channel if it was unasso-
152 ciated with any track, centered within the fiducial volume of the detector at
153 least 5 cm from a dead cell, and isolated from any other shower.

154 Finally, for both signal and normalization channels, the event COG, which
155 ideally would be 0 (see above), had to be equal to or less than 6 cm.

156 A signal (normalization) region was defined as 2σ either side of the nominal
157 $\Lambda e^+e^-(\gamma)$ invariant mass, where $\sigma_m = 1 \text{ MeV}/c^2$. For the Λ , the $p\pi$ invariant
158 mass was used. Selection from the entire data set according to these criteria re-
159 sulted in 412 signal candidates and 29522 normalization events reconstructed.

160 **3 Acceptance and reconstruction efficiency**

161 The product of geometrical acceptance (A) and selection criteria efficiency (ϵ)
162 was determined with a Monte Carlo simulation. Nearly 10^5 signal-like events
163 were generated according to a two-body model of a Λ and a virtual photon.
164 The model included the decay parameter $\alpha = -0.78$, found for the decay
165 $\Xi^0 \rightarrow \Lambda\gamma$ [11], and a $1/m_{ee}^2$ energy distribution for the converting photon, as
166 would be the case for inner conversion. In this way, the model was intended
167 to represent inner bremsstrahlung production. Generated events were stepped
168 through a GEANT simulation of the NA48 detector and analyzed as real data,
169 with the result: $(A \times \epsilon)_{\text{sig}} = (2.69 \pm 0.05)\%$. For the normalization channel,
170 about 160×10^6 events (about $7\times$ the measured flux) were generated with
171 the latest PDG values for the decay parameters incorporated [6]. The result

172 of the detector simulation and reconstruction was $(A \times \epsilon)_{\text{norm}} = (0.1251 \pm$
 173 $0.0003)\%$. Radiative corrections, using PHOTOS [12], were included, as was
 174 a Ξ^0 polarization of -10% for signal generation.³

175 4 Background

176 Two sources of background were identified: physics and accidentally in-time
 177 combinations.

178 4.1 Physics backgrounds

179 4.1.1 $\Xi^0 \rightarrow \Lambda\pi^0$

180 The Ξ^0 decays predominantly to $\Lambda\pi^0$. If the π^0 Dalitz-decays, and the photon
 181 goes undetected, the final state is that of the signal. Similarly, if the π^0 decays
 182 via the double-Dalitz mechanism, and an electron and a positron go unde-
 183 tected, the final state is again that of the signal. Finally, the $\pi^0 \rightarrow e^+e^-$ decay
 184 results in an irreducible background, but its rate is very small. Simulations
 185 of each of these channels at about seven times the flux lead to estimates of
 186 4.6 ± 0.8 , 0.1 ± 0.1 , and 1.2 ± 0.4 events, respectively, infiltrating the signal
 187 region.

188 4.1.2 Kaon decays

189 The flux of neutral kaons was an order of magnitude larger than that of the
 190 Ξ^0 . The decay $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ has a branching fraction of 4.7×10^{-5} . If
 191 one of the pions met the requirements of a proton in this analysis, and the
 192 resulting $m_{p\pi} \approx m_\Lambda$, then this process would mimic the signal. Simulation with
 193 twice the flux of such events demonstrated that an explicit mass cut $|m_{\pi\pi ee} -$
 194 $m_{K_S^0}| > 0.015 \text{ GeV}/c^2$ eliminated essentially any trace of this background with
 195 negligible impact on signal-finding efficiency. The decay chain $K_L^0 \rightarrow \pi^+\pi^-\pi^0,$
 196 $\pi^0 \rightarrow e^+e^-\gamma$, has a product branching ratio of about 1.5×10^{-3} . The K_L^0
 197 lifetime and their typical momentum of $80 \text{ GeV}/c$ mean that about 4% of them
 198 decay in the experiment's decay volume. For these to become a background to
 199 the Λee signal, a pion would have to be mistaken as a proton and the invariant
 200 mass of it combined with that of the other pion would have to be close to that
 201 of the Λ . In addition, the photon would have to go undetected. Because of
 202 this last condition, an explicit kaon mass cut would be ineffective in reducing

³ This polarization value is consistent with that reported by other experiments [13] and with indications from an ongoing study of the NA48 beam.

203 the background. On the other hand, the efficiency for this chain appearing in
 204 the signal region is correspondingly reduced and the COG is smeared out. We
 205 estimate on the basis of Monte Carlo simulation that 2 ± 2 such events will
 206 populate the signal region.

207 4.2 *Accidentally in-time combinations*

208 We estimated the contamination by accidental coincidences four ways:

- 209 (1) Running the same analysis on the data, but requiring that the final-state
 210 leptons have the same charge.
- 211 (2) Requiring that at least one track or shower be between 10 and 20 ns
 212 out-of-time and scaling appropriately.
- 213 (3) Taking events with $m_{p\pi}$ values between 7 and 10 standard deviations
 214 from the central value (m_Λ) and computing $m_{\Lambda ee}$.
- 215 (4) Defining two “side-band” regions, one along each axis in COG-versus-
 216 $m_{\Lambda ee}$ space [see, in Figure 1, the hatched rectangles at high COG and
 217 high mass; each region has the same “area” as the signal region, the open
 218 rectangle in the figure].

219 These approaches, which are not independent, yielded between 1 and 9 events
 220 in the signal region; we take the number to be 7 ± 5 events.

221 In conclusion, combining the physics backgrounds with those attributed to
 222 accidentals and combinatorics, the estimated number of background events in
 223 the signal region is 15 ± 5 [see Table 1 for a summary of the background
 224 estimation].

Table 1
Sources of expected background events.

Source	Estimate
$\Xi^0 \rightarrow \Lambda\pi^0, \pi^0 \rightarrow e^+e^-\gamma$	4.6 ± 0.8
$\Xi^0 \rightarrow \Lambda\pi^0, \pi^0 \rightarrow e^+e^-e^+e^-$	0.1 ± 0.1
$\Xi^0 \rightarrow \Lambda\pi^0, \pi^0 \rightarrow e^+e^-$	1.2 ± 0.4
Kaon Decays	2 ± 2
Accidentals & Combinatorics	7 ± 5
TOTAL	15 ± 5

225 The background contamination of the normalization sample was estimated
 226 from the tails of the $m_{ee\gamma}$ spectrum, which peaks sharply at m_{π^0} . Including
 227 a linear extrapolation under the mass peak, the number was estimated to be
 228 428 ± 258 .

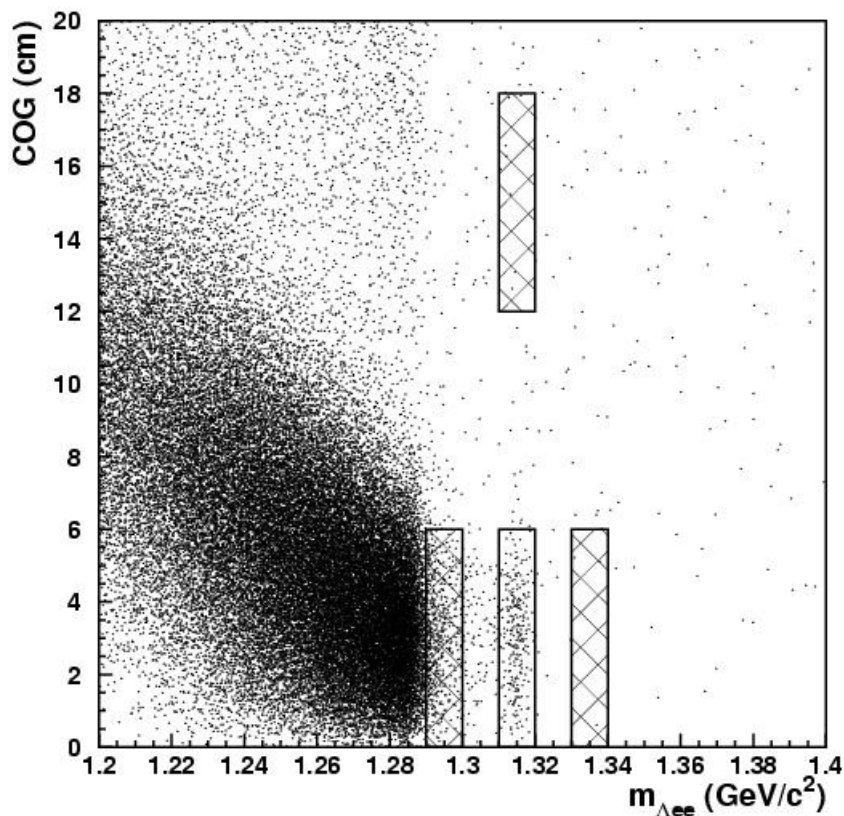


Fig. 1. COG versus $m_{\Lambda ee}$ after all other selection criteria were imposed. The three hatched boxes are side-band regions. The signal region is the open box at low COG around m_{Ξ^0} . The side-band regions at high mass-low COG and high COG were used to estimate accidental and combinatoric backgrounds in the signal region. All three side-band regions were used in the subtraction of background under the decay-angle distribution (see text).

229 5 Ξ^0 Flux

230 The total number of Ξ^0 produced during the run was estimated by fully re-
 231 constructing $\Xi^0 \rightarrow \Lambda\pi^0$, $\pi^0 \rightarrow e^+e^-\gamma$ events without a longitudinal vertex
 232 position cut and using the equation

$$233 \quad \Phi_{\Xi^0} = \frac{N_{norm} - N_{norm \ bkgd}}{(A \times \epsilon)_{norm} \epsilon_{trig}^{norm} \mathcal{B}(\Xi^0 \rightarrow \Lambda\pi^0) \mathcal{B}(\Lambda \rightarrow p\pi^-) \mathcal{B}(\pi^0 \rightarrow e^+e^-\gamma)} \quad (1)$$

234 From the entire data set, 29522 such events were reconstructed. After back-
 235 ground subtraction, this gives an integrated flux of

$$236 \quad \Phi_{\Xi^0} = (3.15 \pm 0.03 \pm 0.08) \times 10^9.$$

237 The first uncertainty is due to statistics, and the second is from branching
 238 fraction uncertainties, primarily that on $\mathcal{B}(\pi^0 \rightarrow e^+e^-\gamma)$.

Table 2

Quantities that entered into Ξ^0 flux calculations.

No. of events in signal region	29552
Estimated no. of background events	428 ± 258
$(A \times \epsilon)_{\text{norm}}$	$(0.1251 \pm 0.0003)\%$
$\epsilon_{\text{trig}}^{\text{norm}}$	$(97.1 \pm 0.2)\%$
$\mathcal{B}(\Xi^0 \rightarrow \Lambda\pi^0)$	0.9952 ± 0.0003
$\mathcal{B}(\Lambda \rightarrow p\pi^-)$	0.639 ± 0.005
$\mathcal{B}(\pi^0 \rightarrow e^+e^-\gamma)$	0.01198 ± 0.00032

239 6 Results

240 At the end of the analysis, 412 events were found in the signal region [see
 241 Figure 2].

242 6.1 m_{ee} spectrum

243 The associated m_{ee} distribution is consistent with a $1/m_{ee}^2$ shape [see Fig-
 244 ure 3], and we consider only this model (presumably inner bremsstrahlung) in
 245 determining of the branching fraction, including systematic uncertainties.

246 6.2 Branching fraction

247 Given the background estimate, efficiencies, and flux discussed above, and
 248 the PDG $\Lambda \rightarrow p\pi^-$ branching ratio [see Table 3], the branching ratio for
 249 $\Xi^0 \rightarrow \Lambda e^+e^-$ is determined to be

$$250 \quad \mathcal{B}(\Xi^0 \rightarrow \Lambda e^+e^-) = (7.6 \pm 0.4) \times 10^{-6}$$

251 where the uncertainty here is statistical only.

252 Anti-cascades also were reconstructed, from $\bar{\Lambda}e^+e^-$ [see Figure 4]. The signal
 253 region contains 24 events. Since the anti-cascade has kinematics, backgrounds,
 254 and flux that differ from those of the cascade, we undertake no further analysis
 255 of this channel here.

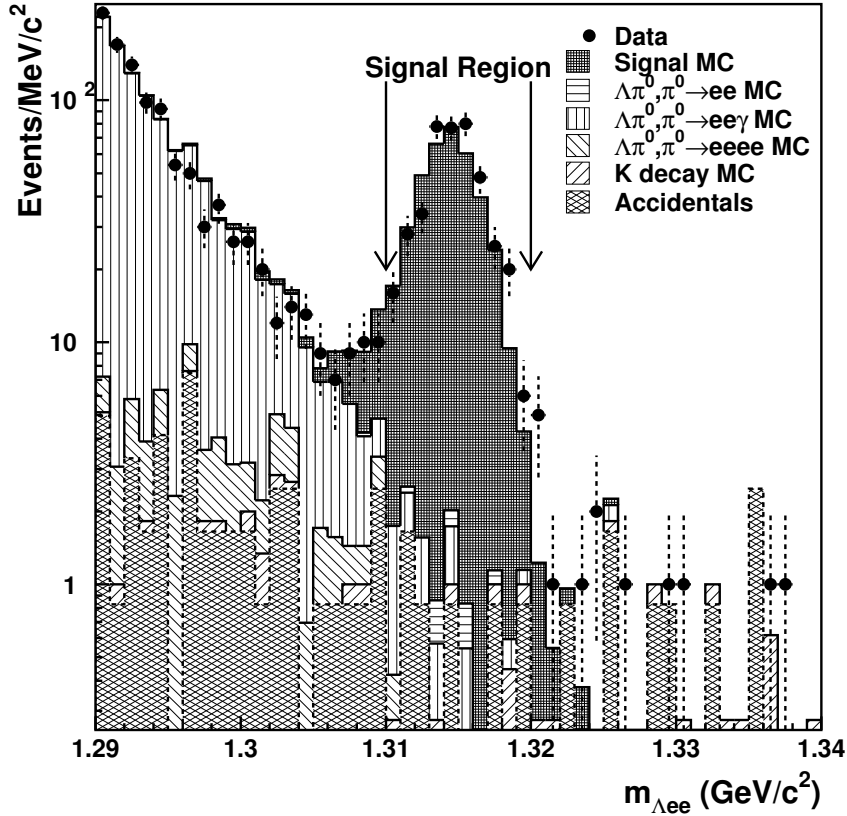


Fig. 2. $m_{\Lambda\pi^0}$ after all selection criteria. Arrows indicate signal region. Stacked in various hatchings (see legend) are the estimated sources of background.

256 6.3 Systematic uncertainties

257 Analysis selection criteria were varied when looking at the data and when
 258 determining reconstruction efficiencies. The branching fraction result was most
 259 sensitive to the treatment of the reconstructed Ξ^0 vertex and backgrounds from
 260 the $\Xi^0 \rightarrow \Lambda\pi^0$ channel in relation to m_{ee} . No cut was placed on the longitudinal
 261 position of the Ξ^0 vertex. Requirements varying the minimum longitudinal
 262 position of the vertex in 6-m intervals beginning before the target (to account

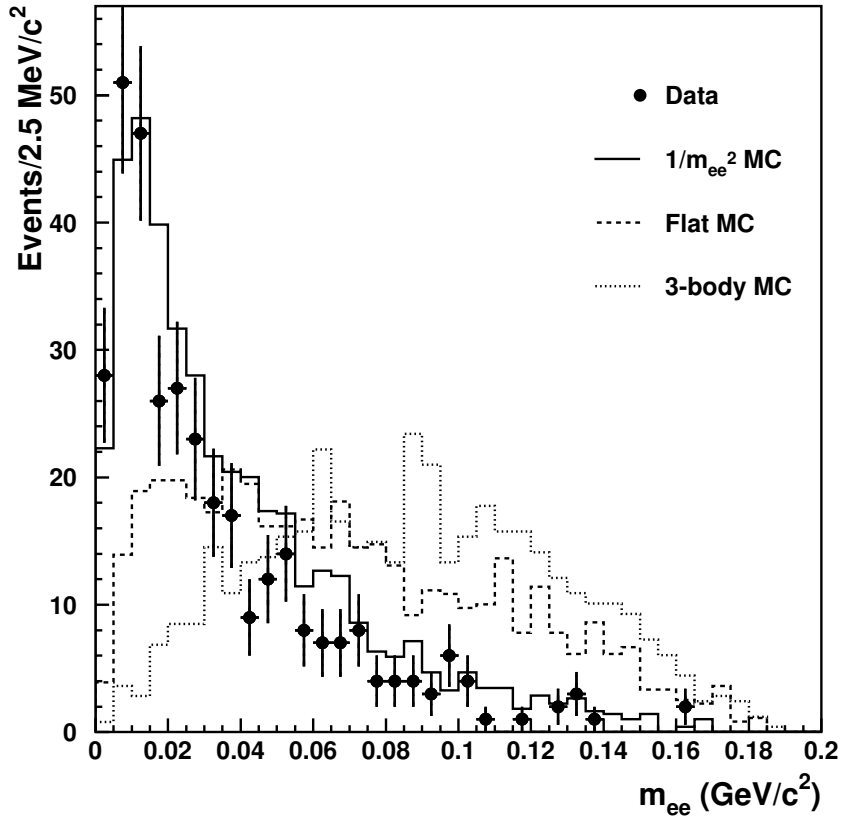


Fig. 3. Reconstructed m_{ee} spectra from data (points), $1/m_{ee}^2$ (solid line), 2-body flat (dashed line), and 3-body phase space (dotted line). The distributions from simulated data have been normalized to the integral of the experimental data. No background subtraction was made on the data.

263 for resolution effects) resulted in branching fraction changes of between 0.2%
 264 and 3%. We assign the highest variation ($\pm 3\%$) as a systematic error.

265 It was possible to eliminate nearly all physics backgrounds by excluding signal
 266 events with $0.100 \text{ GeV}/c^2 < m_{ee} < 0.135 \text{ GeV}/c^2$, which, according to signal
 267 Monte Carlo, reduces the reconstruction efficiency by 5%. Cutting this region
 268 from the final data sample, and recalculating the branching ratio, results in a

Table 3

Quantities that entered into branching fraction calculations.

No. of events in signal region	412
Estimated no. of background events	15 ± 5
$(A \times \epsilon)_{\text{sig}}$	$(2.69 \pm 0.05)\%$
$\epsilon_{\text{trig}}^{\text{sig}}$	$(96.5 \pm 0.2)\%$
Ξ^0 flux	$(3.14 \pm 0.03) \times 10^9$
$\mathcal{B}(\Lambda \rightarrow p\pi^-)$	0.639 ± 0.005

269 shift of 1.8%, which was included symmetrically as a systematic uncertainty.
 270 These, along with smaller variations in the branching fraction resulting from
 271 other modifications of the selection criteria, were added in quadrature to give
 272 a systematic uncertainty of $\pm 3.6\%$ on the branching fraction.

273 We conservatively assign a relative $\pm 1\%$ uncertainty on the determination of
 274 the background to account for correlations in methods for estimating acciden-
 275 tally in-time events.

276 The branching fraction differed by about 1% when signal and normalization
 277 modes were simulated with and without radiative corrections, and we include
 278 this difference symmetrically as a systematic uncertainty.

279 For the $A \times \epsilon$ determinations, the Ξ^0 polarization of simulated events was set
 280 to -10% . Samples of simulated data, generated with the polarization varied
 281 between 0% and -20% ($\pm 10\%$), were used to recalculate the branching frac-
 282 tion vary. The largest variation among these trials was 2.7%, and this variation
 283 is taken symmetrically as a systematic uncertainty.

284 The decay asymmetry used in generating simulated signal events was that of
 285 the process $\Xi^0 \rightarrow \Lambda\gamma$ [11]. Our measurement, discussed below, is in agreement
 286 with this value, but with a 25% uncertainty. Varying our simulation within
 287 this 25% range changed the branching fraction by at most 2.5%, and this is
 288 symmetrically assigned to systematic uncertainty.

289 The determination of the trigger efficiency and Ξ^0 flux were discussed above.
 290 The difference between trigger efficiencies for signal and normalization chan-
 291 nels is taken as an uncertainty, affecting the branching ratio by 0.6%. An
 292 alternative, less direct, calculation of the flux was statistically consistent with
 293 the one described above. The two differed by 1.9%, and we conservatively
 294 include, symmetrically, this amount as a systematic uncertainty.

295 The total systematic uncertainty on the branching fraction, recounted in Ta-
 296 ble 4, is $\pm 5.7\%$, the sum in quadrature of each of the sources described. This

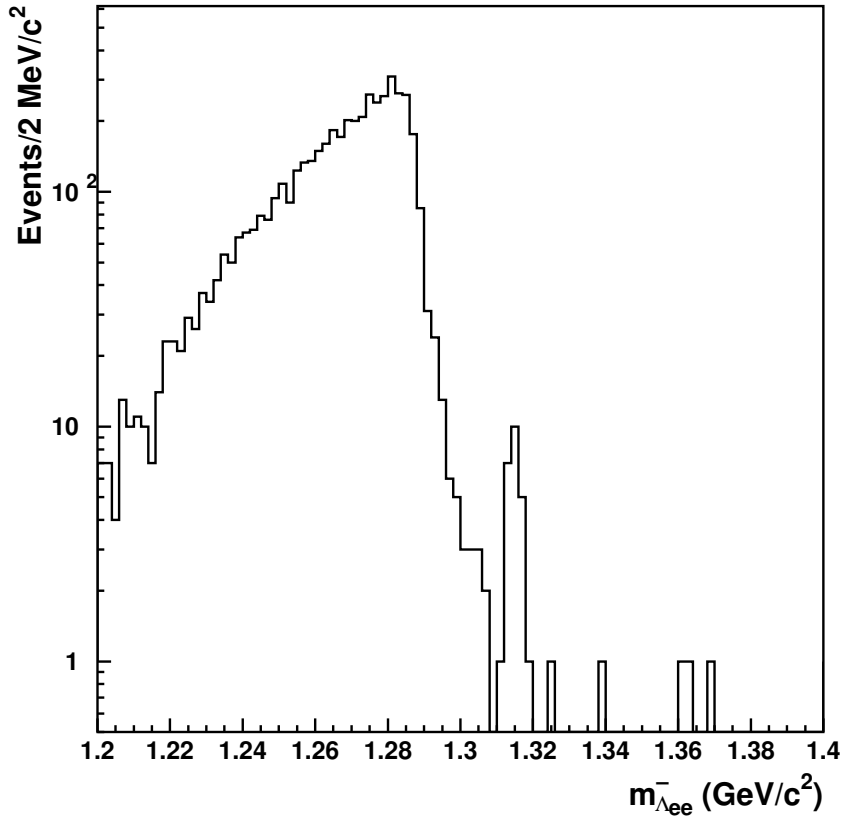


Fig. 4. The $m_{\Lambda e e}^-$ spectrum after all cuts.

297 gives a final branching fraction of:

298
$$\mathcal{B}(\Xi^0 \rightarrow \Lambda e^+ e^-) = [7.6 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \pm 0.2(\text{norm})] \times 10^{-6}.$$

Table 4
Sources of systematic uncertainty on the branching fraction.

Source	Fractional Uncertainty
Detector Acceptance	3.6%
Background	1.0%
Radiative Corrections	1.0%
Polarization	2.7%
Signal Modeling	2.5%
Trigger Efficiency	0.6%
Ξ^0 Flux	1.9%
TOTAL	5.7%

299 *6.4 Asymmetry parameter*

300 The angular distribution of the proton relative to the Ξ^0 line of flight in the
301 Λ rest frame is given by [6]:

$$302 \quad \frac{dN}{d \cos \theta_{p\Xi}} = \frac{N}{2} (1 - \alpha_{\Xi\Lambda ee} \alpha_- \cos \theta_{p\Xi}). \quad (2)$$

303 The $\cos \theta_{p\Xi}$ spectrum from signal events was corrected by subtracting scaled
304 backgrounds from the side-band regions indicated in Figure 1 and by dividing,
305 bin-by-bin, the acceptance as determined from a $\Xi^0 \rightarrow \Lambda e^+ e^-$ simulation
306 where the spectrum was generated to be flat in $\cos \theta_{p\Xi}$. A two-parameter fit to
307 this corrected spectrum gives the product of asymmetry parameters $\alpha_{\Xi\Lambda ee} \alpha_-$,
308 where α_- is the asymmetry parameter for the decay $\Lambda \rightarrow p \pi^-$. This latter was
309 taken to be $\alpha_- = 0.642 \pm 0.013$ [6]. The fit (over the interval $-0.8 < \cos \theta_{p\Xi} < 1$)
310 [see Figure 5] to the data yields,

$$311 \quad \alpha_{\Xi\Lambda ee} = -0.8 \pm 0.2$$

312 This is consistent with the latest published value of $\alpha_{\Xi\Lambda\gamma} = -0.78 \pm 0.18(\text{stat}) \pm$
313 $0.06(\text{syst})$ [11].

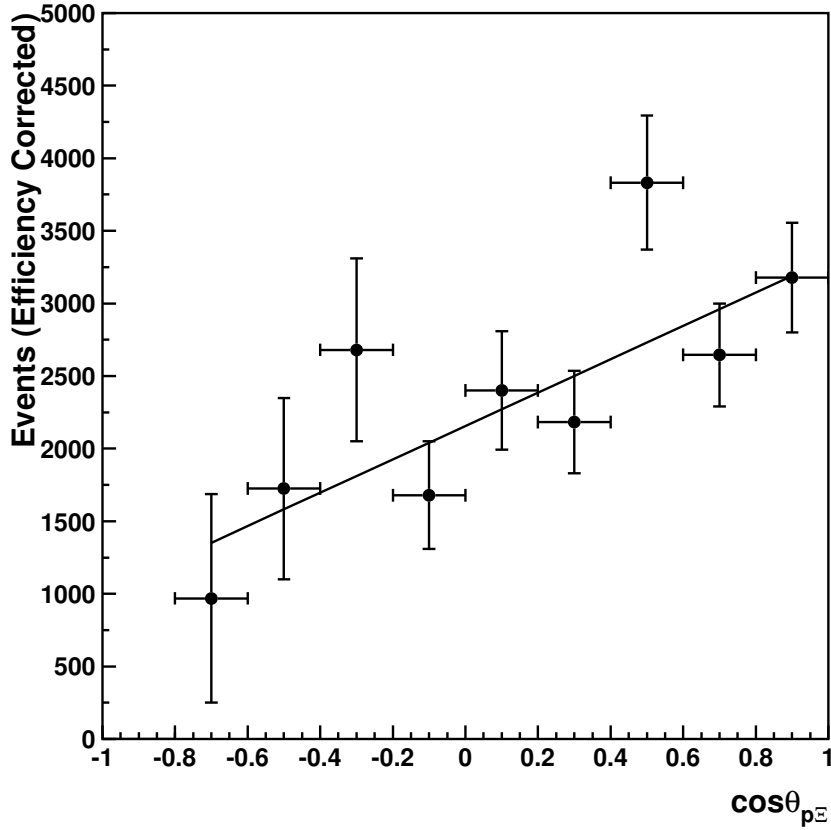


Fig. 5. Background-subtracted and acceptance-corrected $\cos \theta_{p\Xi}$ distribution. The line is the fit result.

314 7 Summary and conclusions

315 The weak radiative decay channel $\Xi^0 \rightarrow \Lambda e^+ e^-$ has been identified. Its branch-
 316 tion fraction has been determined to be

$$317 \quad \mathcal{B}(\Xi^0 \rightarrow \Lambda e^+ e^-) = [7.6 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \pm 0.2(\text{norm})] \times 10^{-6},$$

318 consistent with an inner bremsstrahlung-like production mechanism for the
319 e^+e^- pair. The consistency is further supported by the m_{ee} spectrum. The
320 decay parameter

$$321 \quad \alpha_{\Xi\Lambda ee} = -0.8 \pm 0.2,$$

322 is consistent with that measured for $\Xi^0 \rightarrow \Lambda\gamma$.

323 Twenty four events of the charge conjugate reaction $\bar{\Xi}^0 \rightarrow \bar{\Lambda}e^+e^-$ populate
324 the nominal signal region. This number is consistent with the Ξ^0 branching
325 fraction and the relative Ξ^0 and $\bar{\Xi}^0$ production rates.

326 Acknowledgments

327 It is a pleasure to thank technical personnel from participating laboratories
328 and universities, and affiliated computer centers, for their essential contribu-
329 tions to constructing the apparatus, running the experiment, and processing
330 the data.

331 References

- 332 [1] J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev. **139**, 1650 (1965).
- 333 [2] G. Feldman and T. Fulton, Nucl. Phys. B **8**, 106 (1958).
- 334 [3] J. Lach, P. Żenczykowski, Int. J. Mod. Phys. A **10**, 3817 (1995).
- 335 [4] D. A. Jensen, Nucl. Phys. B (Proc. Suppl.) **93**, 22 (2001).
- 336 [5] Y. Hara, Phys. Rev. Lett. **12**, 378 (1964).
- 337 [6] W.-M. Yao et al. (Particle Data Group), J. Phys. G **33**, 1 (2006) (URL:
338 <http://pdg.lbl.gov>)
- 339 [7] P. Żenczykowski, Phys. Rev. D **62**, 014030 (2000), and references therein.
- 340 [8] P. Żenczykowski, hep-ph/0610191.
- 341 [9] J. R. Batley, et al., Phys. Lett. B **544**, 97 (2002).
- 342 [10] NA48 Collaboration, G. Unal, in: IX International Conference on
343 Calorimetry, October 2000, Annecy, France, hep-ex/0012011.
- 344 [11] A. Lai, et al., Phys. Lett. B **584**, 251 (2004).
- 345 [12] E. Barberio and Z. Was, Comput. Phys. Commun. **79**, 291 (1994).
- 346 [13] E. Abouzaid, et al., hep-ex/0608007.