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Precision Measurement of the Σ^0 Hyperon Mass*

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The BNL E766 Collaboration

presented by

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I would like to begin by thanking the organizers of this conference for inviting me to present this paper. It is very exciting to be here and see all of the students and young researchers in Mexico who are interested in careers in High Energy Physics.

The research [1] that is described in this paper is part of a program to study strong interaction mechanisms in proton proton collisions. The program consists of two experiments: Brookhaven E766 in which we studied the reactions $pp \to p+$ all charged particles with 27.5 GeV/c incident protons and Fermilab E690 in which we studied the reactions $pp \to p+$ all charged particles with 800 GeV/c incident protons. In these experiments, we employed state-of-the-art data acquisition systems and acquired large samples of data: at Brookhaven we amassed 300 million high multiplicity events and at Fermilab, 5.5 billion events. This program is rich in physics topics and has resulted in 9 Ph.D. theses granted to date, three of which were students from Mexico.

The physics topics studied with these data samples include the polarization of Λ^0's, hyperon production mechanisms, light meson spectroscopy, correlations between like-sign pions, final state Coulomb interactions, precision mass measurements, and charm production. We expect many other topics to be studied and invite you, if you are interested, to join our collaboration.

The subject of this paper is the precision measurement of the invariant mass of

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an elementary particle. One might ask why anyone should care if the Σ^0 mass is measured more accurately. There are several answers. The first and most important is that one of the major goals of experimental physics is the improvement of our knowledge of the fundamental properties of nature. If a precision measurement does that, "no further justification is needed" [2]. In addition, this particular measurement also provides essential input to theories of constituent interactions [3] and improves our understanding of the baryon octet and decuplet mass relationships [4]. But an even stronger argument is that the previous measurements of this quantity are not very good.

In Table 1, we present the previous results of experiments measuring the Σ^0 mass. As one can see from an examination of this table, even the most accurate of the previous experiments had only a very small number of events (208). The newest of these previous measurements was performed more than 20 years ago. In addition, none of these measurements were direct measurements of the Σ^0 mass – that is, the experiments were unable to measure all of the decay products of the Σ^0 so that the mass could be determined by a direct kinematic calculation.

The measurement of the Σ^0 mass in this paper uses the main decay of the Σ^0:

$$\Sigma^0 \rightarrow \Lambda^0 + \gamma \tag{1}$$

$$\Lambda^0 \rightarrow p + \pi^- \tag{2}$$

$$\gamma \rightarrow e^+ + e^-. \tag{3}$$

Naively, one might believe that the measurement of the invariant mass is easy. The steps are (1) find events in which there are Λ^0's and γ's; (2) measure the momenta of all particles; (3) calculate the invariant mass of the Λ^0 and γ; (4) fit the mass distribution to a signal plus background and (5) publish the results. None of the steps is either easy or quick.

In order to collect the large samples of data described above, we designed, constructed, and used a large spectrometer system shown in Figure 1. The proton beam interacted in a twelve inch long liquid hydrogen target. Charged particles produced in a pp interaction were detected and measured by a set of six multi-plane mini-drift chambers (A through F). The chambers were located inside the aperture of a large analyzing magnet. Particle identification was provided by a multi-element Cherenkov counter and two scintillation counter hodoscopes for time-of-flight. Further information about the spectrometer, the triggers used, and the details of the sophisticated computer algorithms developed to reconstruct the massive number of events can be found elsewhere [5]. In Figure 2, we present one view of the reconstruction of an event which is a candidate for a Σ^0 decay. The event is characterized by the existence of a two particle vertex (possibly the Λ^0 decay) clearly separated from the multi-particle vertex (the pp interaction point) and a two particle pair with a very small opening angle between the two particles. We shall return to a discussion of the selection process later in this paper.

A precision measurement requires that all of the small details are done correctly. Before describing the specific steps leading to the Σ^0 mass determination, I would like to give a flavor of the kinds of details we worried about.

First, we had to align the coordinate system in which we measured the magnetic field of the spectrometer analyzing magnet with the coordinate system of the drift chambers in which the trajectories of the particles were measured. Careful surveying does most of the job, but a precise tuning of the relationship between the two coordinate systems is necessary. We accomplished this by using a sample of 60,000 K_s^0 decays from the subset of our data which were exclusive events. An exclusive event is one in which all of the final state particles have been measured and identified. There is no ambiguity about the identification of the K_s^0's in this sample. The K_s^0 invariant mass distribution was examined as a function of small changes in the relative positions of the two coordinate systems to establish the best relative alignment.

Second, we had to correct for time dependent variations of the magnetic field. The invariant masses in this experiment are calculated from the momenta of the decay particles determined from the curvature of those particles in the magnetic field. This determination depends directly on the value of the magnetic field in the spectrometer which in turn is proportional to the current in the coils of the magnet. Since the regulation of that current is only 0.1%, it was necessary to use the following technique. Due to the speed of our data acquisition system, we recorded sufficient events every six minutes to yield approximately 5000 K_s^0 decays. With these events, we were able to measure the "K_s^0 mass" as a function of time and correct for the time dependent variations of the magnetic field.

We had to ensure that the fitting routines did not depend on the step size used to calculate the momenta. Also for K_s^0 and Λ^0 decays, we selected only those events in which the two decay particles bend towards each other as they pass through the magnetic field. The invariant mass in such an event is less sensitive to measurement errors than events in which the two decay particles bend away from each other. (We leave the proof of this as an exercise for the reader.)

Finally, we had to determine the absolute value of the magnetic field. We chose to do this by adjusting the field so that the invariant mass of the exclusive K_s^0 sample coincided with the current world average value of the K_s^0 mass ($497.672 MeV/c^2$). Figure 3 shows the invariant mass distribution for that sample. We note that the standard deviation of the K_s^0 mass distribution is only $1.28 MeV/c^2$.

Using this calibration of the magnetic field, we were able to measure and publish the most precise measurement of the lambda and anti-lambda hyperon masses [6]. The excellent mass resolution of the spectrometer (the standard deviation of the Λ^0 mass distribution is $0.5 MeV/c^2$) insures that the selection of Λ^0's for the measurement of the Σ^0 mass measurement has a very small background.

The selection of γ candidates deserves some discussion. γ candidates were identified by a pair of oppositely charged particles with a small opening angle between the two particles. The selection of real e^+e^- pairs from this subset proceeded as follows.

We define the parameter q_T, the perpendicular momentum between the two particles as

$$q_T = 2\frac{|\vec{p}^{+} \times \vec{p}^{-}|}{|\vec{p}^{+} + \vec{p}^{-}|} \tag{4}$$

To determine the actual conversion point of the γ , we moved the location of the vertex of the pair until q_T^2 was minimized. In Figure 4, we show the distribution of q_T^2 for all candidates and the cut used to select the final γ candidates.

The details of the event selection are shown in Table 2, starting from total data sample of 300,000,000 events which yield 3,327 Σ^0 candidates within $\pm 6.9 MeV/c^2$ of the current world average value of $1192.55 MeV/c^2$. It is important to note that we excluded any event that could be a candidate for the decay $\Sigma^0 \to \Lambda^0 e^+ e^-$.

In order to determine the value if the mass, it is necessary to know the shape of the invariant mass distribution which depends on the details of both the uncertainties introduced in the measurement process and in the energy loss mechanisms affecting the decay particles. We chose to determine this shape by using a hybrid Monte Carlo technique [7]. In this technique, all of the parameters of the events are taken directly from the real data except those that describe the parameters of direct concern to the measurement. Thus, we began by taking events with real Σ^0's. We kept all of the information in the detector (wire hits. etc.) except those from the decay particles of the Σ^0 (the p, π^-, e^+ and e^-). Knowing the momentum vector of the Σ^0, we used standard Monte Carlo techniques to generate the decay of the Σ^0. Each "real" event was used as the seed to generate many such Monte Carlo events. We included all physical processes such as the Moliere description of multiple Coulomb scattering, energy loss by ionization and energy loss by bremsstrahlung. The particles were then propagated thorough the spectrometer. The resulting event was analyzed by the same program which had analyzed the original data sample.

The invariant mass distribution resulting from this hybrid Monte Carlo technique was then fit to the invariant mass distribution from the data. The fit determined the values of the Σ^0 invariant mass, the number of events, and included a linear background. The results of the fit are shown in Figure 5.

Before quoting our result it is necessary to note that we had to consider possible systematic errors in addition to the statistical uncertainty. This measurement depends on the value of both the Λ^0 hyperon mass and the K_s^0 meson mass. The contribution to the Σ^0 mass systematic uncertainty from the uncertainties in these two masses are 0.006 and $0.0077 MeV/c^2$ respectively. The systematic uncertainty from the hybrid Monte Carlo technique is less than $0.0005 MeV/c^2$ and our uncertainty (at the 5% level) in the amount of material in the spectrometer contributes at most $0.01 MeV/c^2$ to the Σ^0 mass systematic uncertainty.

Adding the systematic errors in quadrature we find for our results on the Σ^0 mass and the $\Sigma^0 - \Lambda^0$ mass difference to be:

$$M_{\Sigma^0} = 1192.65 \pm 0.020 \pm 0.014 MeV/c^2 \tag{5}$$

and:

$$M_{\Sigma^0} - M_{\Lambda^0} = 76.966 \pm 0.020 \pm 0.013 MeV/c^2. \qquad (6)$$

Let me close by noting that this is a significant result. Our uncertainty in the Σ^0 mass is more than 7 times smaller than the best previous result and was based on 16 times the statistics. Likewise, the $\Sigma^0 - \Lambda^0$ mass difference is more than 14 times more accurate than the previous best result. Finally, we note that this measurement is the first direct measurement of the Σ^0 mass. Based on these observations, we felt it imperative to redo the world averages which are presented in Table 2.

We look forward to other interesting results coming from our data sample and encourage any of you who wish to work in this experiment to contact the members of our collaboration.

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TABLE 1. Previous Results on Σ^0 Mass

value (MeV/c^2)	# events	technique
1191.83 $\pm$ 0.55	109	heavy liquid bubble chamber [8]
1192.41 $\pm$ 0.14	208	H2 bubble chamber [9]
1192.25 $\pm$ 0.23	18	H2 bubble chamber [10]
1190.3 + 1.2 -2.0	8	LH2 bubble chamber [11]
1184.7 $\pm$ 3.6	3	propane bubble chamber [12]

TABLE 2. New World Averages (MeV/c^2)

Σ^-	1197.451 $\pm$ 0.031	$\Sigma^- - \Lambda^0$	*81.694 $\pm$ 0.066*
Σ^0	*1192.65 $\pm$ 0.025*	$\Sigma^0 - \Lambda^0$	*76.96 $\pm$ 0.03*
Σ^+	1189.37 $\pm$ 0.06	$\Sigma^- - \Sigma^0$	4.86 $\pm$ 0.07
Λ^0	1115.683 $\pm$ 0.006	$\Sigma^- - \Sigma^+$	8.10 $\pm$ 0.11

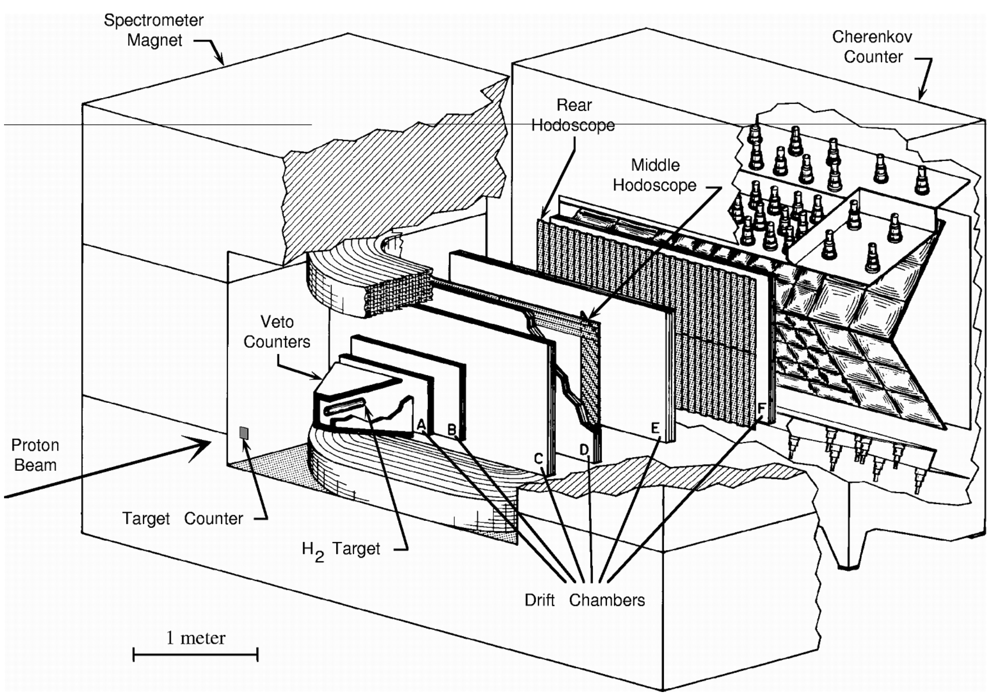

FIGURE 1. The BNL E766/FNAL E690 Multiparticle Spectrometer.

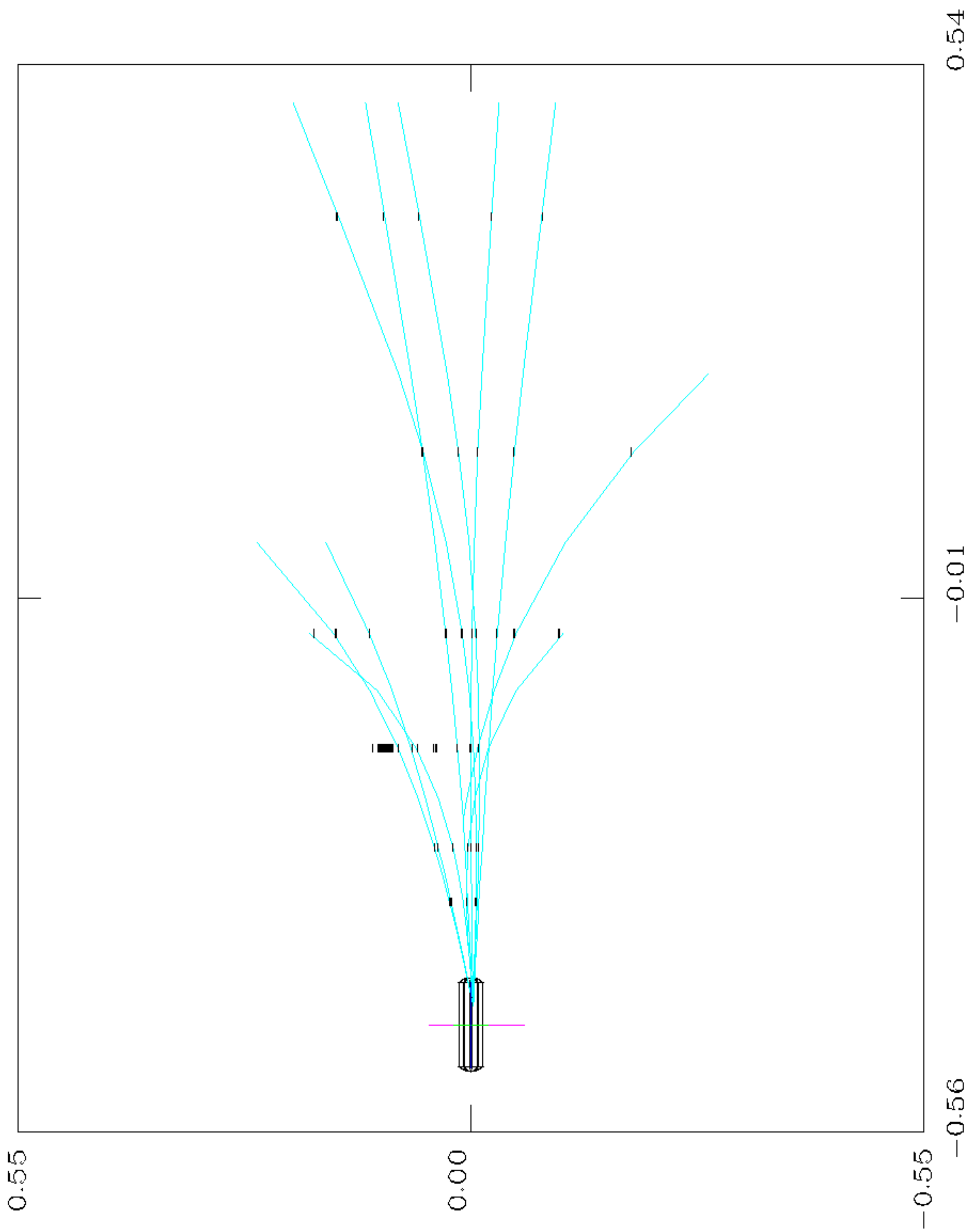

FIGURE 2. One view of a $\Sigma^0 \rightarrow \Lambda^0 + \gamma$ candidate event.

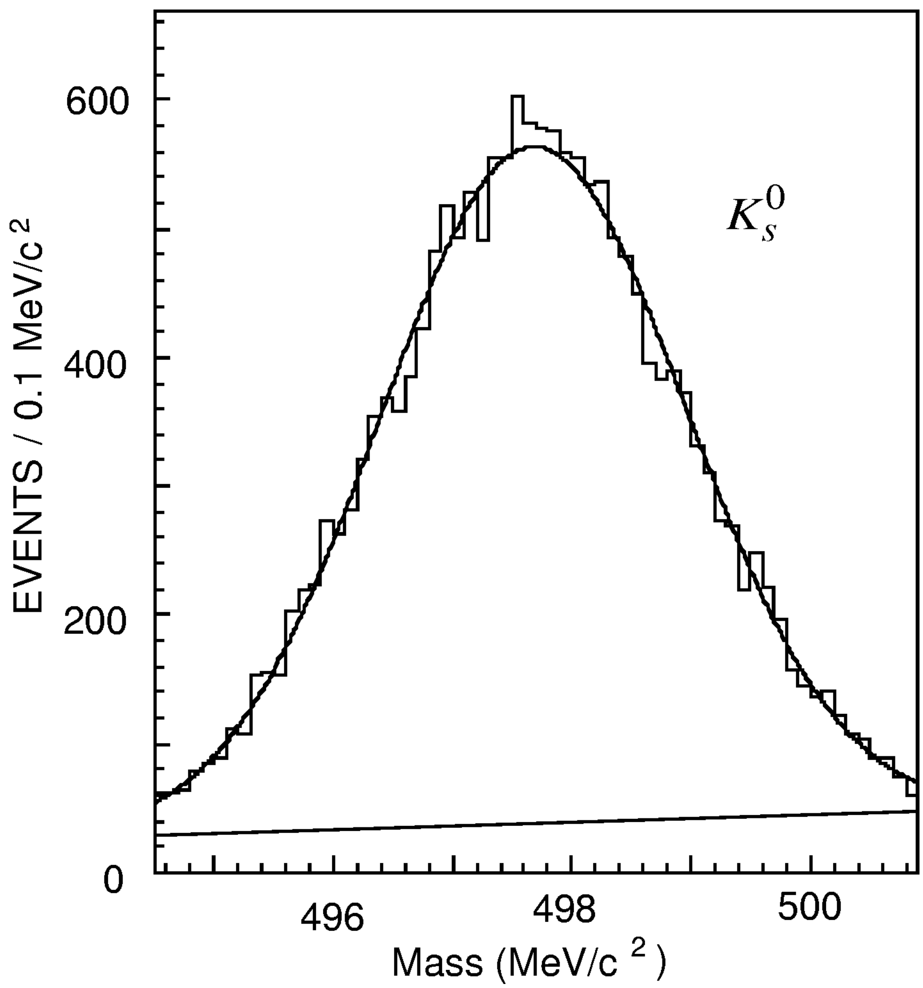

FIGURE 3. Invariant mass for the K_S^0 events fit to a Gaussian and a linear background shown explicitly. The standard deviation is $1.28 MeV/c^2$.

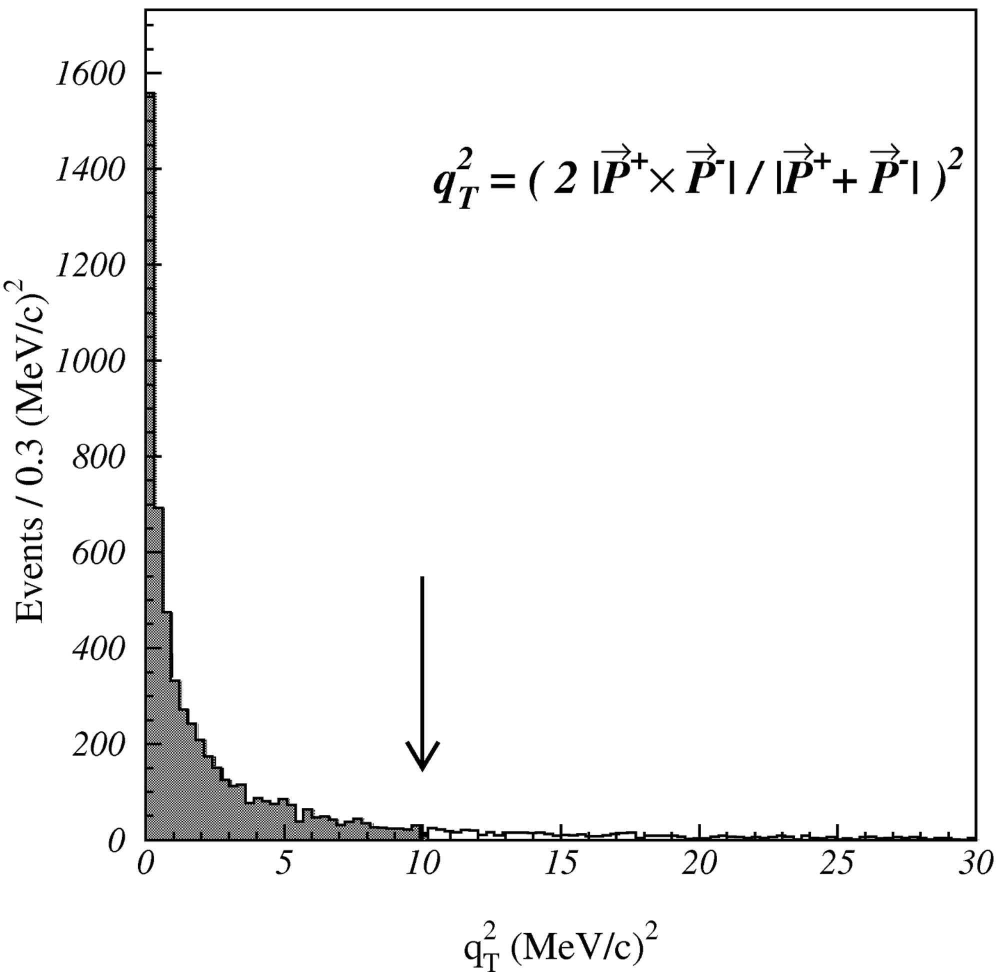

FIGURE 4. q_T^2 distribution of candidate e^+e^- pairs from the γ conversion of $\Sigma^0 \to \Lambda^0 + \gamma$ events. The arrow shows the location of the cut used.

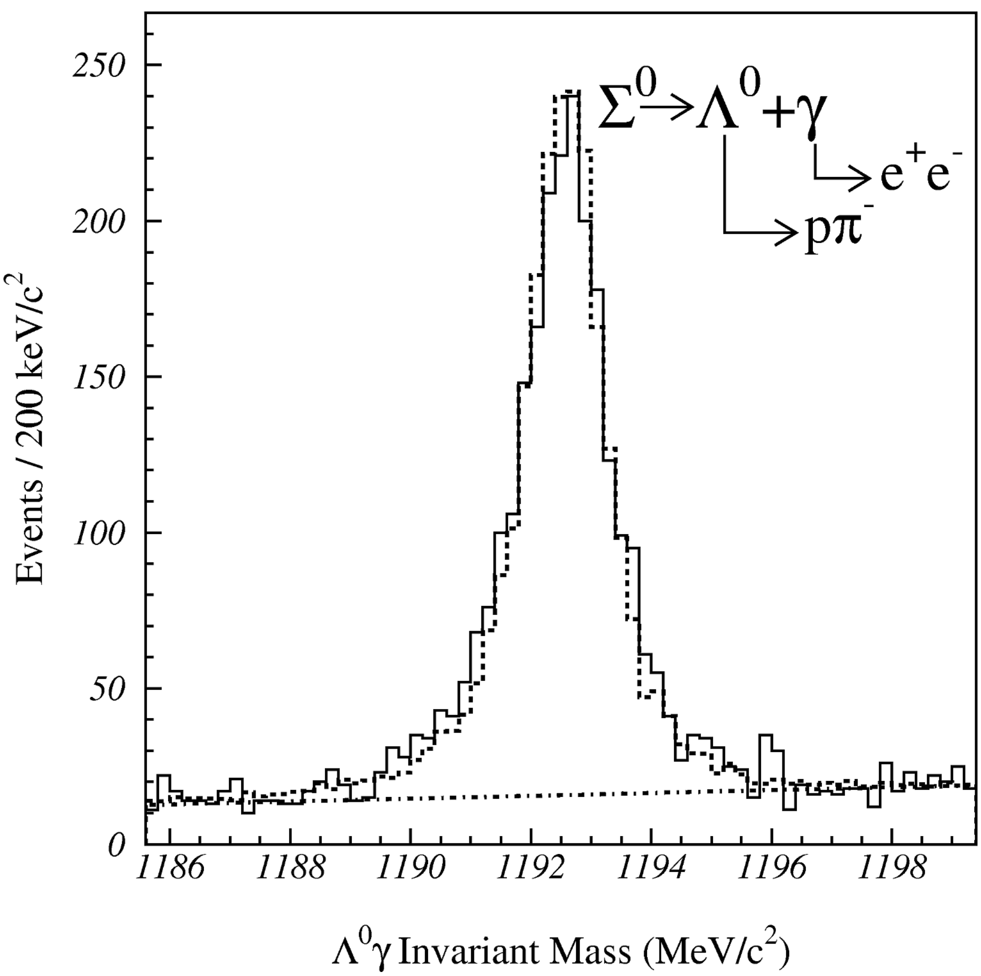

FIGURE 5. Invariant mass for $\Sigma^0 \to \Lambda^0 + \gamma$ events (solid line) fit to the Monte Carlo distribution (dashed line) added to a linear background (dot-dashed line).

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