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New Results on Ξ^0 Hyperon Decays

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1 Introduction

Hyperons have been among the first non-stable elementary particles discovered and are known for more than 50 years now. In spite of this, the physics interest in hyperons is by far not yet exhausted, several important aspects are still under intense investigation. At first, as hyperons only differ by one or two strange-quarks from proton and neutron, they are ideal playgrounds to study $SU(3)_f$ symmetry breaking. Secondly, studying their decays offers unique opportunities to understand baryon structure and decay mechanisms. Last, but not least, by comparing hyperon decays to neutron decay, it is possible to measure the CKM matrix parameter $|V_{us}|$ in a complementary way with respect to kaon decays.

However, despite of their interest, most previous measurements date back to the 1960's and 70's, in particular those on the neutral Ξ^0 hyperon. Only recently new measurements have been performed, with much increased statistics and leading to a series of new results.

The two main new experiments on Ξ^0 decays are the KTeV experiment at Fermilab and NA48/1 at the CERN SPS. Both experiments were designed to measure neutral kaon decays and profit from the fact, that the Ξ^0 lifetime and decay length are of the same order as those of the K_S^0 meson. Most of the new results are coming from NA48/1. This experiment was performed in the year 2002 to measure specifically rare K_S^0 and neutral hyperon decays. During the data taking period, in total more than 2 billion of Ξ^0 decays took place in the fiducial detector volume, providing enough statistics to precisely measure also very rare Ξ^0 decays.

2 Measurement of the Ξ^0 Lifetime

The Ξ^0 lifetime, i.e. its total decay rate, is a key parameter for interpreting other measurements on Ξ^0 decays. In particular for the determination of the CKM matrix element $|V_{us}|$, as reported in the following section, the Ξ^0 lifetime is a direct input parameter. However, the precision on the Ξ^0 lifetime is very poor. The current world average $\tau_{\Xi^0} = (2.90 \pm 0.03) \times 10^{-10}$ s [1] has less than 3% accuracy, and the last measurement dates back to 1977.

For a new, much more precise measurement the NA48/1 Collaboration has used $\Xi^0 \to \Lambda\pi^0$ decays taken with a minimum bias trigger. In total about 260 000 decays have been selected with completely negligible background. The energy spectrum of the selected events is shown in Fig. 1 (left). To be insensitive to the small residual differences between data and simulation in the spectrum, the lifetime distributions are split Ted into 10 separate bins of energy, indicated by vertical lines in Fig. 1. The fit region is shown in Fig. 1 (right). To avoid effects from the vertex resolution differences between data and simulation at the beginning of the decay region, the fit region is well separated from the final collimator. This requirement rejects about half of the statistics, leaving 133 293 events to enter the fit. The fit to the lifetime is performed using the least-squares method, with the normalisations in each energy bin left as free parameters.

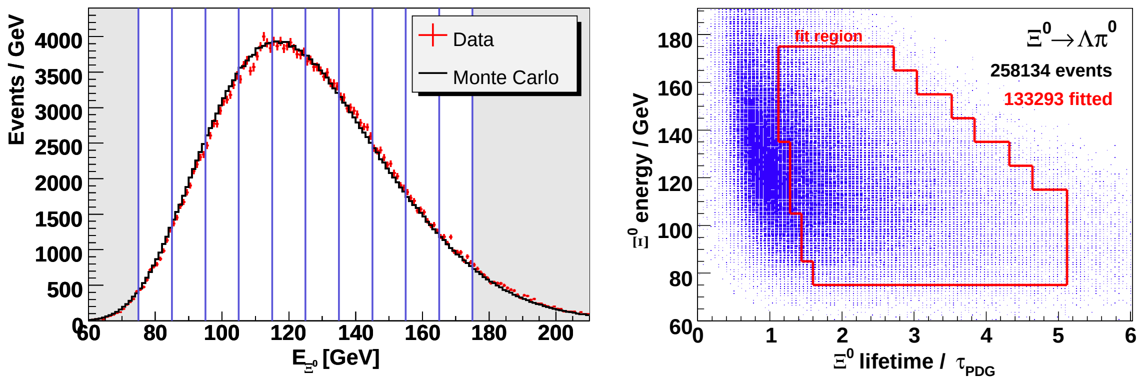

Figure 1: Left: Energy spectrum of $\Xi^0 \to \Lambda\pi^0$ data and Monte Carlo events used in the lifetime fit. Right: Energy versus proper lifetime of the selected events. Indicated is the region used in the fit.

The fit result, integrated over the separate energy bins, is shown in Fig 2. The NA48/1 collaboration obtains as preliminary result

$$\tau_{\Xi^0} = (3.082 \pm 0.013_{\text{stat}} \pm 0.012_{\text{syst}}) \cdot 10^{-10}\,\text{s}, \tag{1}$$

with the systematics being dominated by uncertainties of the detector acceptance, the nominal Ξ^0 mass, and the Ξ^0 polarisation. The result is about 2 standard deviations above the current world average and five times more precise.

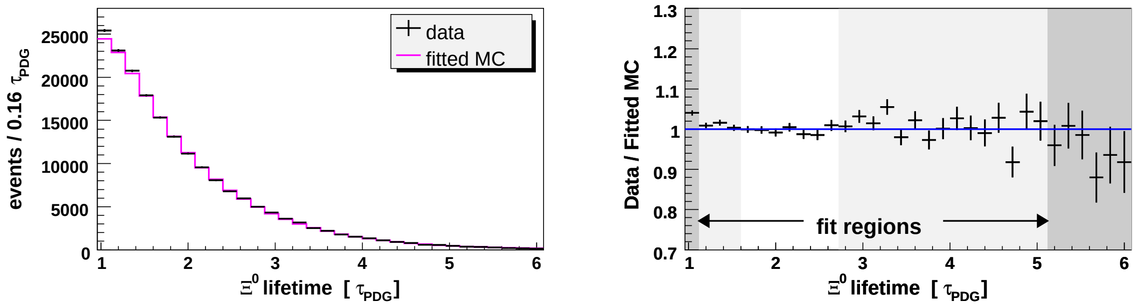

Figure 2: Fit of the Ξ^0 lifetime. Left: Comparison of data and fitted Monte Carlo simulation as function of the current PDG lifetime $\tau_{\mathrm{PDG}} = 2.90 \times 10^{-10}$ s [1]. Right: Fit residuals. The white (light grey) regions indicate the regions where the fit has been performed for all (some) energy bins.

3 Measurement of the Ξ^0 Beta Decay and Determination of $|V_{us}|$

The Ξ^0 beta decay $\Xi^0 \to \Sigma^+ e^- \overline{\nu}$ is similar to the neutron beta decay with the down-quarks exchanged by strange-quarks. The decay therefore is well suited for a measurement of the CKM parameter $|V_{us}|$ complementary to the usual determination from kaon semileptonic decays. A previous measurement has been published by the KTeV Collaboration, based on 176 events [2]. An additional preliminary KTeV result, based on 626 events, has been presented on conferences [3].

With much larger statistics, NA48/1 has now performed a precise measurement of the Ξ^0 beta decay. Since Ξ^0 semileptonic decays are the only source of Σ^+ in the neutral beam, it is sufficient to select $\Sigma^+ \to p\pi^0$ events and require an additional electron. The invariant $p\pi^0$ mass distribution of the accepted events is shown in Fig. 3, yielding 6316 $\Xi^0 \to \Sigma^+ e^- \overline{\nu}$ candidates with an estimated background contamination of about 3% mainly from in-time accidental overlaps.

Normalising to the abundant decay $\Xi^0 \to \Lambda\pi^0$, NA48/1 obtains [6]

$$\mathrm{Br}(\Xi^0 \to \Sigma^+ e^- \overline{\nu}) = (2.51 \pm 0.03_{\mathrm{stat}} \pm 0.09_{\mathrm{syst}}) \times 10^{-4} \tag{2}$$

The systematic uncertainty is dominated by the statistical uncertainty of the determination of the trigger efficiency ($\pm 2.2\%$). Further contributions are the limited knowledge of the decay form factors g_1 and f_2 ($\pm 1.6\%$), the detector acceptance, the Ξ^0 polarisation, and the normalisation ($\pm 1.0\%$ each).

In addition to the Ξ^0 decay, 555 $\overline{\Xi^0} \to \overline{\Sigma^+} e^+ \nu$ candidates were selected with a background of about 136 events, yielding a branching fraction of $\mathrm{Br}(\overline{\Xi^0} \to \overline{\Sigma^+} e^+ \nu) = (2.55 \pm 0.14_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}}) \times 10^{-4}$ in perfect agreement with the one obtained from the Ξ^0 decay.

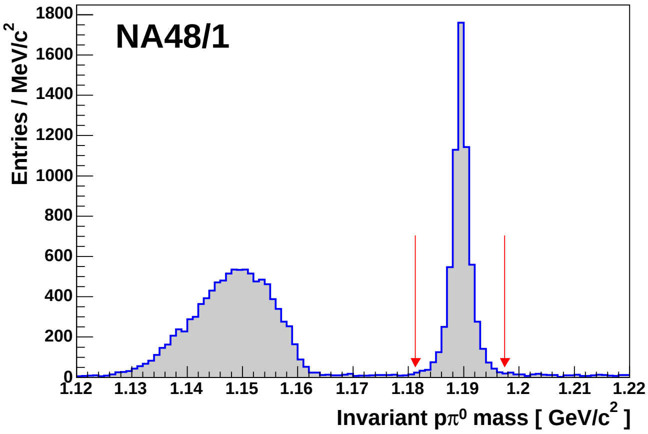

Figure 3: Invariant $p\pi^0$ mass distribution from NA48/1 $\Xi^0 \to \Sigma^+ e^- \overline{\nu}$ decays.

Using the combined result $\mathrm{Br}(\Xi^0 \to \Sigma^+ e^- \overline{\nu}) = (2.51 \pm 0.09) \times 10^{-4}$ and the new preliminary value for the Ξ^0 lifetime, the partial decay width is $\Gamma(\Xi^0 \to \Sigma^+ e^- \overline{\nu}) = (8.14 \pm 0.29) \times 10^5\ \mathrm{s}^{-1}$, from which the CKM matrix element $|V_{us}|$ can be determined. The semileptonic decay rate is given by [4]

$$\begin{aligned} \Gamma &= G_F^2\, |V_{us}|^2\, \frac{\Delta m^5}{60\pi^3}\, (1 + \delta_{\mathrm{rad}}) \\ &\quad \times \left[\left(1 - \frac{3}{2}\,\beta\right) \left(|f_1|^2 + |g_1|^2\right) + \frac{6}{7}\,\beta^2 \left(|f_1|^2 + 2|g_1|^2 + \mathrm{Re}(f_1 f_2^\star) + \frac{2}{3}\,|f_2^2| \right) + \delta_{q^2} \right], \end{aligned}$$

with $\Delta m = m_{\Xi^0} - m_{\Sigma^+}$ [1], $\beta = \Delta m / m_{\Xi^0}$, the radiative corrections δ_{rad}, and $\delta_{q^2}(f_1, g_1)$ taking into transfer momentum dependence of f_1 and g_1 [4]. The form factor ratios g_1/f_1 and f_2/f_1 have been measured by the KTeV Collaboration [5]. Neglecting $SU(3)$ breaking corrections for f_1, a value of

$$|V_{us}| = 0.203 \pm 0.004_{\mathrm{exp}}\ {}^{+0.022}_{-0.027}\ {}_{\text{form factors}} \tag{3}$$

is found, in good agreement with the value of 0.226 ± 0.002 obtained from kaon decays [1], but still large uncertainties from the form factor measurement.

4 First Measurements of the Decay $\Xi^0 \to \Sigma^+ \mu \nu_\mu$

Because of the small available phase space, the semimuonic Ξ^0 decay is highly suppressed with respect to its semielectronic counterpart. The first observation of the decay was done by the KTeV Collaboration in 2005 [7]. They observe 8 signal candidates over negligible background (Fig. 4 (left)) from which they obtain a branching fraction of $\mathrm{Br}(\Xi^0 \to \Sigma^+\mu^-\overline{\nu}) = (4.7^{+2.0}_{-1.4} \pm 0.8) \times 10^{-6}$.

More recently, the NA48/1 Collaboration reported a preliminary measurement, based on 99 signal candidates including about 30 background events (Fig. 4 (right)), leading to a value of $\mathrm{Br}(\Xi^0 \to \Sigma^+\mu^-\overline{\nu}) = (2.2 \pm 0.3 \pm 0.2) \times 10^{-6}$.

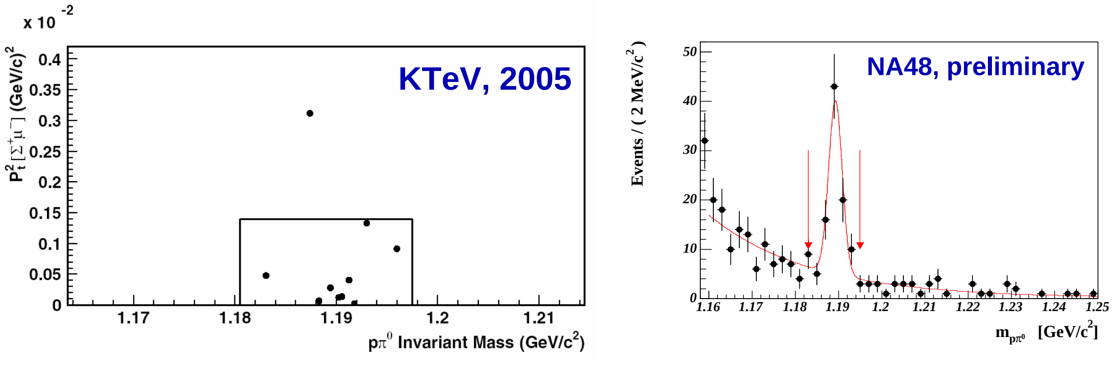

Figure 4: Invariant $p\pi^0$ mass distributions of $\Xi^0 \to \Sigma^+\mu^-\overline{\nu}$ decays measured by KTeV (left) and NA48/1 (right).

5 Weak Radiative Ξ^0 Decays

Up to this day, weak radiative hyperon decays as $\Xi^0 \to \Lambda\gamma$ and $\Xi^0 \to \Sigma^0\gamma$ are still barely understood. Several competing theoretical models exist, which give very different predictions. An excellent experimental parameter to distinguish between models is the decay asymmetry α of these decays. It is defined as

$$\frac{dN}{d\cos\Theta} = N_0(1 + \alpha\,\cos\Theta), \tag{4}$$

where Θ is the direction of the daughter baryon with respect to the polarisation of the mother in the mother rest frame. For e.g. $\Xi^0 \to \Lambda\gamma$, the decay asymmetry can then be measured by looking at the angle between the incoming Ξ^0 and the outgoing proton from the subsequent $\Lambda \to p\pi^-$ decay in the Λ rest frame (see Fig. 5) Using this method, the measurement is independent of the unknown initial Ξ^0 polarisation.

The NA48/1 experiment has selected 48314 $\Xi^0 \to \Lambda\gamma$ and 13068 $\Xi^0 \to \Sigma^0\gamma$ candidates (Fig. 6). The background contributions are 0.8% for $\Xi^0 \to \Lambda\gamma$ and about 3% for $\Xi^0 \to \Sigma^0\gamma$, respectively.

Using these data, fits to the decay asymmetries have been performed. In case of $\Xi^0 \to \Sigma^0\gamma$, where we have the subsequent decay $\Sigma^0 \to \Lambda\gamma$, the product $\cos\Theta_{\Xi\to\Sigma\gamma}$ ·

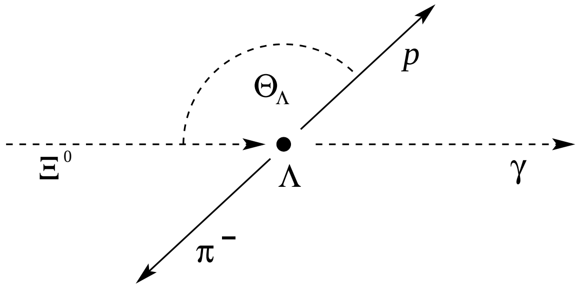

Figure 5: Definition of the angle Θ between the proton and the incoming Ξ^0 in the Lambda rest frame.

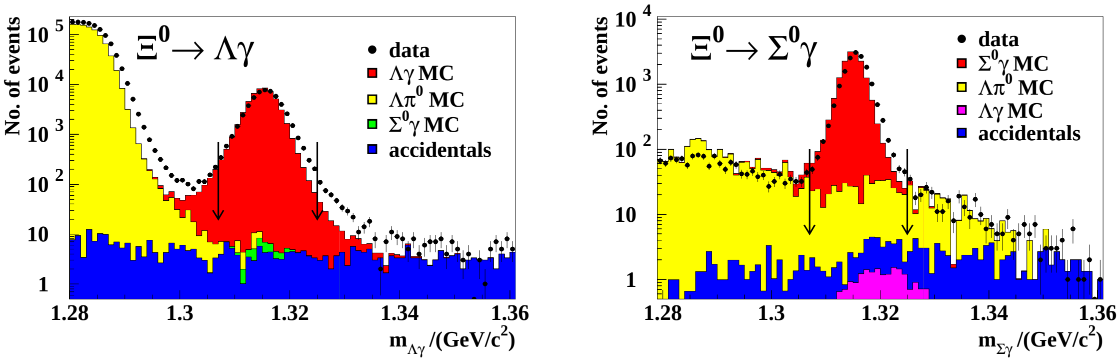

Figure 6: $\Xi^0 \to \Lambda\gamma$ (left) and $\Xi^0 \to \Sigma^0\gamma$ (right) signal together with MC expectations for signal and backgrounds.

$\cos\Theta_{\Sigma\to\Lambda\gamma}$ has to be used for the fit. Both fits show the expected linear behaviour on the angular parameters (Fig. 7)

After correcting for the well-known asymmetry of $\Lambda \to p\pi^-$, values of

$$\alpha_{\Xi^0\to\Lambda\gamma} = -0.684 \pm 0.020 \pm 0.061 \quad \text{and} \tag{5}$$
$$\alpha_{\Xi^0\to\Sigma^0\gamma} = -0.682 \pm 0.031 \pm 0.065 \tag{6}$$

are obtained, where the first error is statistical and the second systematic. These values agree with previous measurements by NA48 on $\Xi^0 \to \Lambda\gamma$ [8] and KTeV on $\Xi^0 \to \Sigma^0\gamma$ [9], but are much more precise. In particular the result on $\Xi^0 \to \Lambda\gamma$ is of high theoretical interest, as it confirms the large negative value of the decay asymmetry, which is difficult to accommodate for quark and vector meson dominance models.

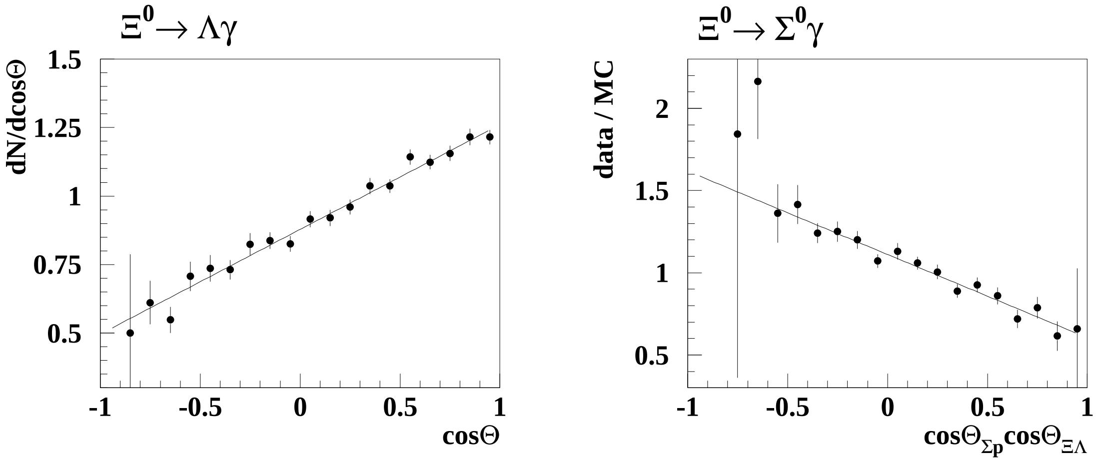

Figure 7: Fits of the decay asymmetries in $\Xi^0 \to \Lambda\gamma$ (left) and $\Xi^0 \to \Sigma^0\gamma$ (right).

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