Prospects for measuring $BR(K_L^0 \to \pi^0 \nu\bar{\nu})$ at CERN's SPS

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Abstract. The results of preliminary feasibility studies of a measurement of $BR(K_L^0 \to \pi^0 \nu\bar{\nu})$ with high-energy kaons from the SPS are presented.

1. Introduction

The unitarity of the CKM matrix implies that the sum of complex products of matched pairs of elements in two rows or columns is zero:

$$\sum_k V_{ik} V_{jk}^* = 0 \tag{1}$$

This relation can be visualized as the so-called "unitarity triangle." Over-constraining this triangle via measurement of its sides and angles is an example of precision tests of the Standard Model and of searches for physics beyond that model.

A program of second-order weak (flavor-changing neutral current) kaon decay branching ratio measurements can make such a precision test. By GIM suppression, the internal quark lines of these processes is dominated by the top quark, with, in some cases, a smaller contribution from charm. The short-distance part of $BR(K_L^0 \to \mu^+\mu^-)$ gives a measure of the base of the triangle, with an uncertainty due to the charm contribution. $BR(K^+ \to \pi^+\nu\bar{\nu})$ measures the long leg of the triangle, also subject to charm uncertainties. $BR(K_L^0 \to \pi^0\nu\bar{\nu})$ (and the short-distance part of $BR(K_L^0 \to \pi^0\ell^+\ell^-)$ gives the height of the triangle, free of charm uncertainties.

The $K \to \pi\nu\bar{\nu}$ modes are particularly clean theoretically in the Standard Model, because there are no long-distance contributions from intermediate photons and contributions from hadronic elements are measured by Ke3 rates. Their Standard Model (SM) branching ratios are therefore predicted to within 20% [1]:

$$\begin{aligned} BR(K^+ \to \pi^+\nu\bar{\nu}) &= (8.4 \pm 1.0) \times 10^{-11} \\ BR(K_L^0 \to \pi^0\nu\bar{\nu}) &= (3.4 \pm 0.6) \times 10^{-8} \end{aligned}$$

Most of this uncertainty is parametric; the intrinsic theoretical uncertainty is at the level of a frew percent.

Ten percent measurements, then, can probe for new physics [see Figure 1]. The experimental status of these modes is now [2]:

$$
\begin{aligned}
BR(K^+ \to \pi^+ \nu\bar{\nu}) &= 1.73^{+1.15}_{-1.05} \times 10^{-11} \text{ [BNL E787 and E949]} \\
BR(K^0_L \to \pi^0 \nu\bar{\nu}) &< 2.6 \times 10^{-8} \text{ (90\%) [J-PARC E391a]}
\end{aligned}
$$

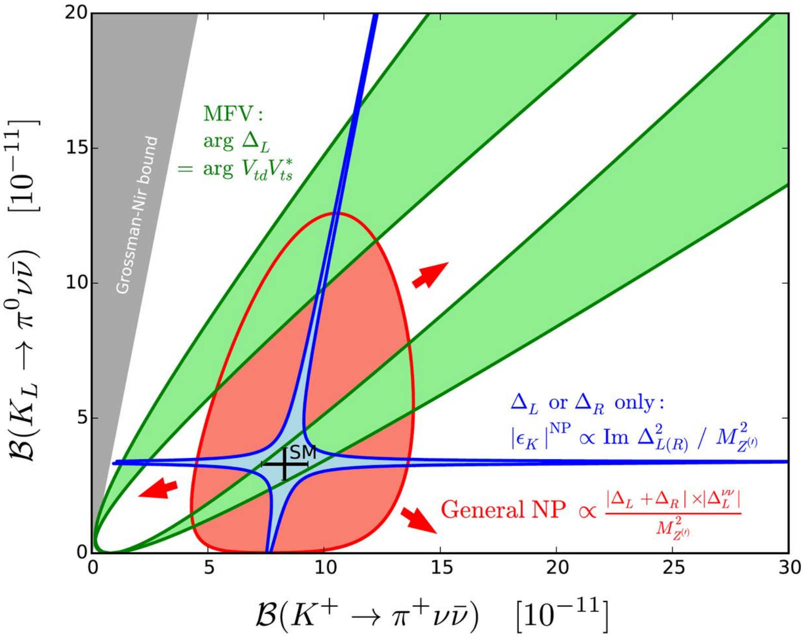

Figure 1. Sensitivity to new physics [1].

CERN's NA62 experiment (see the contribution by Perrin-Terrin in this volume) is now collecting data to measure the charged mode to nearly 10%. The neutral mode limit was set by J-PARC's E391a experiment and matched by KOTO at the same facility. KOTO intends to reach SM sensitivity by around 2019, and then to upgrade both detector and beamline so as to collect ∼ 10 events per year.

2. An experiment at the SPS?

With higher energy kaons (than at J-PARC), photon vetoing–essential considering that the primary background comes from $K^0_L \to \pi^0\pi^0$–is easier, because the typical energy is greater, and polar angle coverage need only extend to 100 mr. On the other hand, a larger veto volume would be required.

2.1. Beam

The primary slow-extraction proton beam at the SPS is $p_0 = 400$ GeV/c. The beam would impinge on a 400 mm-long Beryllium target ($0.94\lambda_{\mathrm{int}}$) at an angle of 2.4 mrad. This angle optimizes the K^0_L to neutron and photon flux ratios. The conical angular acceptance of the secondary beam, which contains about 2.8×10^{-5} K^0_L per proton, would be collimated at 0.3 mrad [see Figure 2]. Peaking at around 35 GeV/c, the K^0_L spectrum would have a mean momentum of about 97 GeV/c.

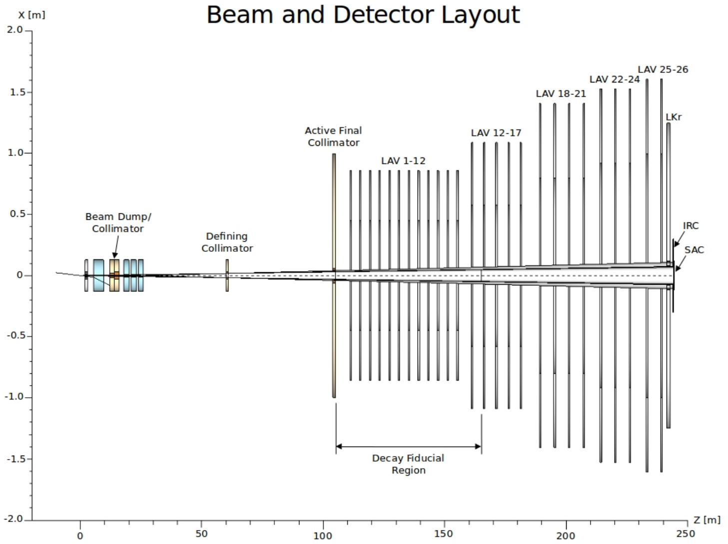

Figure 2. Secondary beam line and neutral detector layout.

For the studies reported here, a primary beam intensity of 2×10^{13} protons per pulse, delivered over a spill length of 4.8 s every 16.8 s (effective spill length: 3 s), was assumed. Also assumed was a 200 days/year data-taking period that is active 50% of the time. No doubt, the present beamline cavern and experimental areas would require extensive upgrades to handle the necessary rates.

2.2. Detector model

A baseline assumption of the feasibility studies reported here has been that the NA48 liquid Krypton calorimeter (LKr) remains the primary photon detector. The LKr has a photon inefficiency of 9×10^{-6} for $E_\gamma > 10$ GeV. Clusters are resolvable to a separation of about 6 cm, and the time resolution is $\sigma_t = 2.5\ \mathrm{ns}/\sqrt{E}$ (GeV), which may require improvement.

High-efficiency photon vetoes would be arrayed along an 140 m-long vacuum volume in such a way as to cover out to a polar angle of 100 mrad from the beamline [see Figure 3].

Among the most daunting challenge facing such an experiment is small-angle photon detection in an environment of extremely high beam neutron and photon fluxes. An intermediate ring calorimeter (IRC) should be capable of detecting photons from downstream decays that pass through the LKr bore. While an absorber after the target can modulate photons in the neutral beam, the large number of neutrons in the neutral beam, however, creates an extremely difficult environment for vetoing photons from kaon decays that head down the beam pipe. Studies with a tungsten-crystal absorber in a small-angle calorimeter (SAC) are ongoing. Because coherent effects of the lattice can enhance pair production, such a crystal can be made very thin and consequently more transparent to neutrons. very thin

It will also be necessary to veto charged decays, in particular $Ke3$, since, in a neutrals detector like that shown in Figure 2, $(BR \times \epsilon)_{Ke3} = 3 \times 10^{-5}$, while $(BR \times \epsilon)_{\pi^0 \nu\bar{\nu}} = 8 \times 10^{-14}$. Thin detectors upstream of the LKr and an hadronic calorimeter downstream can reduce this background to less than 1 event per running year. Similarly for photons from kaon decays far upstream of the vacuum decay region: active collimation should be able to reduce $K_L^0 \to \pi^0\pi^0$ background to 10% or less of the total contamination from this mode.

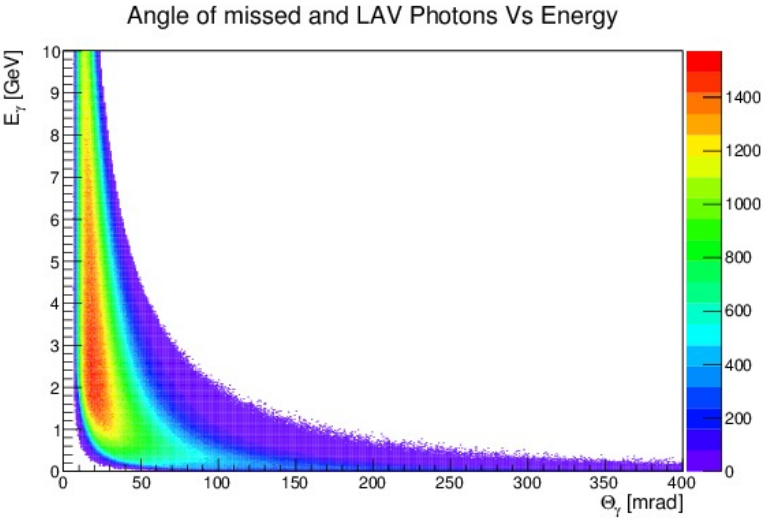

Figure 3. E vs θ of otherwise undetected photons.

2.3. Sensitivity Studies

Two simulation packages were employed to study signal acceptance and background contamination. The first was a fast Monte Carlo algorithm with hard-coded geometry, straight-line particle propagation, and parameterized detector efficiencies. The second was Geant4-based. The two were cross-checked for consistency.

Signal identification was based on four primary selection criteria:

(i) Exactly two LKr clusters consistent with two photon interactions;

(ii) Assuming the two clusters are from the $\pi^0 \to 2\gamma$ transition, the π^0 (and therefore K_L^0) decay point is in the fiducial volume of the vacuum region;

(iii) Both clusters exceed a minimum distance from the beamline at the face of the LKr; and

(iv) The transverse momentum of the two photons is significantly different from zero.

Table 1. Summary of results from a signal study and a $K_L^0 \to \pi^0\pi^0$ background study.

Analysis stage	$\pi^0\nu\bar{\nu}$		$\pi^0\pi^0$	
Generated	956.3 M (100 kyr)		1,215 G (5 yr)	
		Even	Odd	Fused
2γ on LKr	19 M	12 M	104 M	3 M
$105\text{m} < z_{\text{rec}} < 155$ m	6 M	81 k	3 M	607 k
$r_{\text{min}} > 35$ cm	2.5 M	23 k	764 k	29 k
$p_\perp > 0.12$ GeV	2 M	43	12	30
All cuts, 1 yr	19		17	

Representative results for the signal can be seen in Figure 4 and Table 1. The effect of these cuts on the primary ($K_L^0 \to \pi^0\pi^0$) background can be seen in Figure 5 and also Table 1.

Contamination can arise from this mode if both photons of one π^0 shower in the LKr while those of the other fail to be detected (even); if one photon from each π^0 showers in the LKr while the other photons fail to be detected (odd); or if three photons shower in the LKR, but two interact too closely to be differentiated, while the last photon fails to be detected (fused).

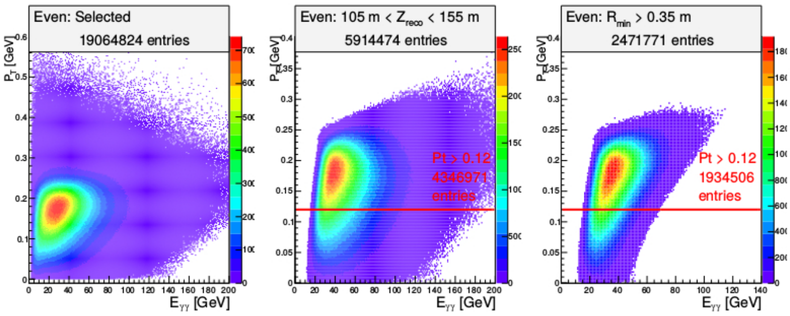

Figure 4. $p_\perp$ vs. $E_{\gamma\gamma}$ for simulated signal events with (left) both photons on the LKr, (center) vertex reconstructed within fiducial volume, and (right) $r > 35$ cm for both LKr clusters. The $p_\perp > 0.12$ GeV/c is overlain center and right. Note scale changes between plots.

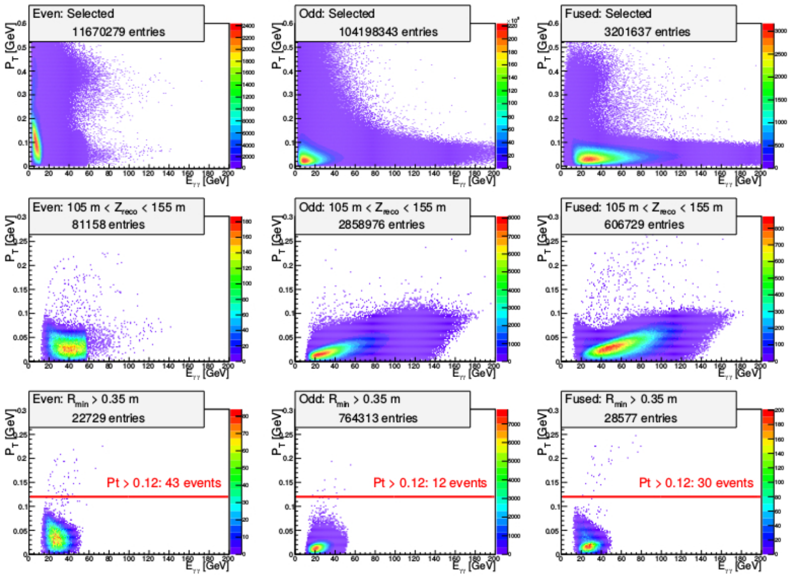

Figure 5. $p_\perp$ vs. $E_{\gamma\gamma}$ for simulated $K_L^0 \to \pi^0\pi^0$ events. From left to right, the columns are even, odd, and fused events, respectively. The first row shows events with both photons on the LKr, the second row shows events with vertex reconstructed within fiducial volume, and the third row shows events with $r > 35$ cm for both LKr clusters. The $p_\perp > 0.12$ GeV/c is overlain on the third row plots. Note that the vertical scale differs among the first-row plots.

3. Conclusion

A competitive high kaon energy measurement of $K_L^0 \to \pi^0\nu\bar{\nu}$ seems feasible. Many design challenges–primarily in background suppression and small-angle activity–remain to be worked out. Alternative detector elements, particulary for charged daughters, are being considered. A reasonable time frame for such an experiment would be LHC run 4.

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