Search for $\mathrm{K_L^0} \to \pi^0\pi^0\mu^+\mu^-$ with KTeV Data

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This presentation reports on the first experimental search for the decay $\mathrm{K_L^0} \to \pi^0\pi^0\ \mu^+\mu^-$ based on data collected by the KTeV experiment. Although this decay mode is possible within the standard model, its rate is phase space suppressed. The HyperCP experiment has recently observed 3 $\Sigma^+ \to p\ \mu^+\mu^-$events within a narrow di-muon mass range, suggesting that the process may occur via a new neutral state: $\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-$with $m(X^0) = 214.3\,\mathrm{MeV}$. The X^0 would create an s- to d- quark transition at a rate that would cause $\mathrm{K_L^0} \to \pi\pi X^0, X^0 \to \mu^+\mu^-$ to occur at rates considerably over the standard model expectation. Our preliminary results significantly constrain this possibility.

1. Introduction

1.1. The HyperCP Result

Early in 2005, the HyperCP collaboration reported [1] an unusual result in their search for the decay $\Sigma^+ \to p\mu^+\mu^-$. They found 3 events, corresponding to a branching ratio of $[8.6\,^{+\,6.6}_{-\,5.4}(stat) \pm 5.5(syst)] \times 10^{-8}$ for this mode. That value is consistent both with the expectations of the time [2] and the results of revisiting the calculation of the branching ratio following the publication of the HyperCP result [3]. What was surprising is that all 3 events appeared with the same reconstructed $m(\mu^+\mu^-)$ to within the rather narrow resolution ($\approx 0.5\,\mathrm{MeV}$) of the HyperCP detector. The probability of such a result occuring randomly as a result of only standard model processes is less than 1%. Naturally, the HyperCP collaboration speculated that there might be a contribution from a new intermediate state with a mass of $214.3 \pm 0.5\,\mathrm{MeV}$. Were that to be the case, the acceptance of the HyperCP detector would be different than in the $\Sigma^+ \to p\mu^+\mu^-$ case, and the 3 events would correspond to $\mathrm{Br}(\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-) = [3.1\,^{+\,2.4}_{-\,1.9}(stat) \pm 1.5(syst)] \times 10^{-8}$. Expressed as a partial width, 3.1×10^{-8} corresponds to $2.5 \times 10^{-19}\,\mathrm{MeV}$.

1.2. Response to the HyperCP Result

The HyperCP result produced a flurry of excitement. One early suggestion [4] was that they had observed an sgoldstino; this interpretation suggests that $\mathrm{Br}(X^0 \to \gamma\gamma)$ might be much greater than $\mathrm{Br}(X^0 \to \gamma\gamma)$; in response, the E391 collaboration looked for [5] (and did not find) $\mathrm{K_L^0} \to \pi\pi X^0, X^0 \to \gamma\gamma$, setting an upper limit of 2.4×10^{-7} at the 90% C.L.

Another suggestion [6] was that HyperCP had observed the $CP-$odd a Higgs boson of the next-to-minimal supersymmetric extention to the standard model (NMSSM). In the NMSSM, existing search techniques will not reveal the Higgs boson, and indeed searches for the standard model Higgs have already ruled out the most likely range of possible masses. The minimal supersymmetric extention to the standard model is also under some pressure in terms of theoretically possible *vs.* experimentally allowed masses for Higgs bosons, and that situation also would be resolved by the NMSSM. This combination of motivations lead the CLEO [7], D0 [8] and BaBar [9] collaborations to search for the a with particular attention to the $m(a) = 214.3\,\mathrm{MeV}$ case. The searches all returned null results, and the CLEO paper discusses implications of this for the NMSSM model.

Last year, Chen *et al.* suggested [10] that the HyperCP result could be the result of a spin-1 gauge boson of the $U(1)'$ gauge model. Of particular significance for what follows, they found that such a model does not enhance the rate of $K \to \pi\mu^+\mu^-$. This scenario was further investigated in references [11, 12].

Apart from explanations in the contexts of specific models, considerable understanding can be gained from model-independent analyses. If X^0 is indeed a new neutral flavor changing current that creates an s- to d- quark transition, it should appear in kaon decays. The KTeV limit [13] of $\mathrm{Br}(\mathrm{K_L^0} \to \pi^0\mu^+\mu^-) < 3.8 \times 10^{-10}$ corresponds to a partial width of $4.9 \times 10^{-24}\,\mathrm{MeV}$, more than 4 orders of magnitude below the corresponding partial width in the HyperCP result. The existing [14] world average $\mathrm{Br}(\mathrm{K_L^0} \to \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}$ corresponds to a partial width of $8.8 \times 10^{-21}\,\mathrm{MeV}$, and the result that we present here, $\mathrm{Br}(\mathrm{K_L^0} \to \pi^0\pi^0\mu^+\mu^-) < 8.63 \times 10^{-11}$ corresponds to a partial width of $1.1 \times 10^{-24}\,\mathrm{MeV}$. Plainly, these should provide tight constraints and indeed, more detailed analyses than these simple comparisons of partial widths are revealing.

He *et al.* in 2005 concluded [15] that as a consequence of the known $K^+ \to \pi^+\mu^+\mu^-$ rate, the X^0 could not be a scalar or vector particle. If the HyperCP result is the result of a new pseudoscalar, they predict (among other results) that $\mathrm{Br}(\mathrm{K_L^0} \to \pi^0\pi^0 X^0, X^0 \to \mu^+\mu^-) = (8.3\,^{+\,7.5}_{-\,6.6}) \times 10^{-9}$. If the HyperCP result is the result of a new axial vector, He *et al.* predict this product branching ratio would be $(1.0\,^{+\,0.9}_{-\,0.8}) \times 10^{-10}$. Deshpande *et al.* [16] considered spin 0 bosons and also came to the conclusion that pseudoscalar couplings have to dominate. Their prediction for the pseudoscalar case branching ratio is 8.02×10^{-9}, consistent with that of He *et al.*. Geng *et al.* [17] came to basically the same conclusions although (as they describe in detail) there were some differences between their calculations and the two proceeding ones. Chen *et al.* [18] discussed what the pseudoscalar and axial vector scenarios would imply for b and τ decays. We also cite here [19] the work of Oh and Tandean, which became available after this conference.

Tensor couplings evidently can not contribute [20] to decays of the type studied by HyperCP.

1.3. Search for $\mathrm{K^0_L} \to \pi^0\pi^0\mu^+\mu^-$ at KTeV

With the KTeV detector, one could search for either $\mathrm{K^0_L} \to \pi^+\pi^-\mu^+\mu^-$ or $\mathrm{K^0_L} \to \pi^0\pi^0\mu^+\mu^-$; in fact, the neutral mode is the better choice. The difference in rest masses between the $\mathrm{K^0_L}$ and the final states is quite small, and the 4.6 MeV difference between the mass of the charged and neutral pion creates a factor of 10 difference in available phase space. This is the primary cause of the difference in predicted rates for the charged-pion *vs.* neutral-pion modes in reference [15]. Secondly, although the geometric acceptance of the KTeV detector decreases as a rule with the number of particles in the final state, the excellent energy resolution of the CsI electromagnetic calorimeter makes π^0 detection relatively easy.

The KTeV detector has been described in detail elsewhere [21]. We will here discuss the performance of two elements of it which are crucial for this analysis. The electromagnetic calorimeter was made of pure CsI, and was 27 radiation lengths deep. For photons over 10 GeV, the energy resolution was better than 1%. With electrons we obtained a positional resolution of about 1 mm. In a fixed target $\mathrm{K^0_L}$ experiment, where the decay point varies from event to event, the mass resolution of a π^0 depends on the precision of the decay point, which in turn depends on the $\mathrm{K^0_L}$ decay mode. That said, resolutions as low as 2 MeV in $m(\pi^0)$ have been obtained. The muon system was constructed of 5.1 m of steel, which is about 31 hadronic interaction lengths. For muons of 10 GeV or more, the efficiency was over 98%. The probability for a $\pi^\pm$ to punch through the muon system and appear as a muon was about $(1.69 + 0.17P[\mathrm{GeV}]) \times 10^{-3}$. In the rare-decay configuration, 733×10^9 $\mathrm{K^0_L}$ decays occured in the decay volume during 2 separate data taking periods begining in 1996 and 1999, respectively.

The number of $\mathrm{K^0_L}$ decays in the sample is measured by counting $\mathrm{K^0_L} \to 3\pi^0$ decays, where one of the 3 π^0s decays to $e^+e^-\gamma$. Our results are normalized to this well-understood mode, and our reported branching ratio limits are the result of multiplying our measurement by the branching ratios for this normalization mode. The normalization mode is selected to be as similar in detection signature to the signal mode as is possible in order to cancel systematic uncertainties.

2. Analysis Procedure

The definitive description of the analysis is the thesis of David Phillips [22]. The interested reader should also examine Dave's contribution to the proceedings of the KAON09 conference [23].

Signal candidates are required to have 4 clusters of energy in the CsI calorimeter which are not associated with tracks. Two tracks of opposite charge assignment with matching hits in the muon system and momentum over 7 GeV are required, and the calorimeter clusters created by the muon candidates must have less than 1 GeV of energy. The 4 photons and 2 muons must have a sum of momenta perpendicular to the $\mathrm{K^0_L}$ line of flight less than $\sqrt{0.00013}$ GeV; this helps assure that all of the products of a single decay have been reconstructed. The kinematic requirement $m(\mu^+\mu^-)$ is applied, and the reconstructed $m(\pi^0)$ values have to be within 9 MeV of the accepted value. The reconstructed mass of all of the decay products for signal candidates must lie within the range 495 - 501 MeV.

There is a second signal box which examines the $\mu^+\mu^-$ pair for consistency with the HyperCP result; this allows us to obtain results for $\mathrm{K^0_L} \to \pi\pi X^0, X^0 \to \mu^+\mu^-$ in addition to $\mathrm{K^0_L} \to \pi^0\pi^0\mu^+\mu^-$. The second signal box is defined as $213.8 \le m(\mu\mu) \le 214.8$ MeV, $|p^2_\perp(\mu\mu) - p^2_\perp(\pi\pi)| \le 0.0007(\mathrm{GeV}^2)$. A single detected signal event would correspond to a branching ratio of 3.75×10^{-11} for $\mathrm{K^0_L} \to \pi^0\pi^0\mu^+\mu^-$ and 4.10×10^{-11} for $\mathrm{K^0_L} \to \pi\pi X^0, X^0 \to \mu^+\mu^-$.

Background events are so-called 'accidentals', where particles from a 2nd decay that occurs in the beam at the same time as the $\mathrm{K^0_L}$ decay lead to misinterpretation of the event. Accidental backgrounds are modeled in the simulation by overlaying a simulated decay with an event taken from the detector on a trigger that fires randomly. This method is quite effective when the decay has a relatively low branching ratio and for those cases, we have been able to simulate event samples many times larger than the actual dataset. None of these events pass the selection criteria. This method is less effective for modes such as $\mathrm{K^0_L} \to \pi^\pm\mu^\mp\nu$, where a sample of 4.4 billion events corresponds to only 3.2% of the data sample.

Ultimately we need to control our background levels with an understanding of the basic kinematics of our signal process and an examination of the rate at which data events appear near but not in our signal boxes. The small phase space for the decay make background rejection relatively easy through the requirement that the reconstructed mass of the 6 decay product candidates match the $\mathrm{K^0_L}$ mass. A small phase space means that in the K_L^0 frame, the 6 decay products have low momenta; but as the accidentally coincident decaying particle will not have the same lab-frame momentum as the K_L^0, the accidental decay products will have a considerable boost in the K_L^0 frame. As a result, background events will tend to be higher in reconstructed K_L^0 mass than the signal. In the end, we observe very low background rates and take the mildly conservative approach of setting the total background rate to 0.

3. Result and Discussion

The search was conducted using standard 'blind analysis' techniques, and was done separately on the data sets taken starting in 1996 and in 1999. Figure 1 shows the resulting distributions of candidate events in these two data sets. There being no events in the signal regions, we use the methodology of reference [24] to set 90% C.L. limits of

$$\mathrm{Br}(K_L^0 \to \pi^0\pi^0 X^0, X^0 \to \mu^+\mu^-) < 9.44 \times 10^{-11}$$

and

$$\mathrm{Br}(K_L^0 \to \pi^0\pi^0\mu^+\mu^-) < 8.63 \times 10^{-11}.$$

This result is some 90 times below the predictions for the pseudoscalar a hypothesis; that hypothesis no longer appears tenable. Comparison of our result with the predictions based on an axial vector a are less conclusive, particularly in light of the large uncertainties on that prediction. This hypothesis must still be considered possible.

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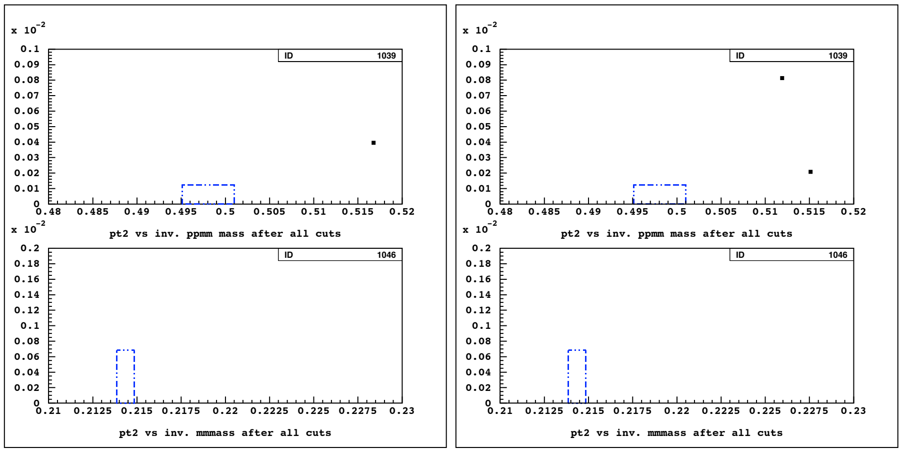

Figure 1: Left, top: p_T^2 *vs.* $M_{\mu\mu\pi\pi}$ for candidate events in the 1996 data set. Left, bottom: $|p^2_{T,\mu\mu} - p^2_{T,\pi\pi}|$ *vs.* $M_{\mu\mu}$ for candidate events in the 1996 data set. Right, top: p_T^2 *vs.* $M_{\mu\mu\pi\pi}$ for candidate events in the 1999 data set. Right, bottom: $|p^2_{T,\mu\mu} - p^2_{T,\pi\pi}|$ *vs.* $M_{\mu\mu}$ for candidate events in the 1999 data set. All plots are shown immediately after the masked signal boxes were opened, which are indicated by dotted blue boxes.