The Search for $K_L \to 2\pi^0 X$, $X \to 2\gamma$ in KOTO

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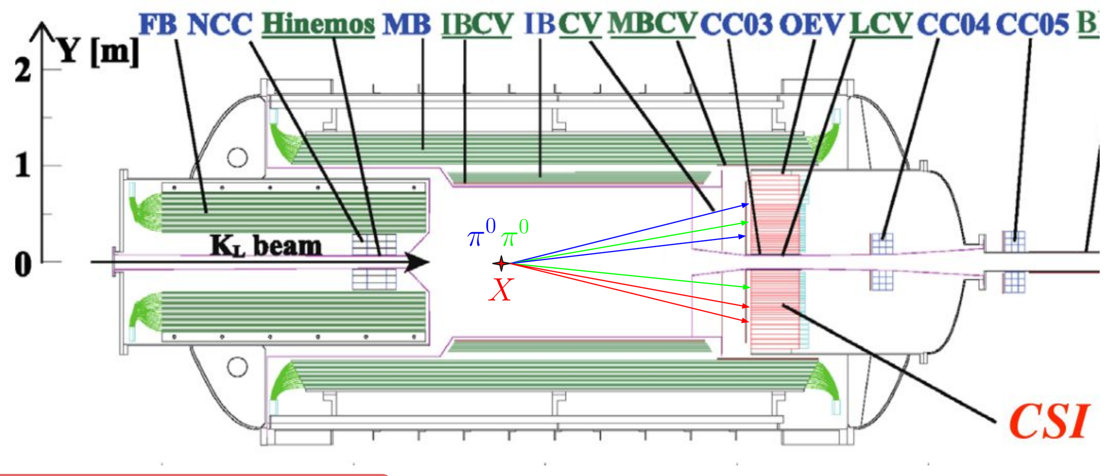
Abstract

The KOTO experiment at J-PARC searches for the rare decay, $K_L \to \pi^0 \nu\bar{\nu}$. This search requires a high intensity K_L beam which sets KOTO in a unique position to probe sub-GeV quark coupling to dark matter. One avenue to study this is the mode $K_L \to 2\pi^0 X$, where $X \to 2\gamma$. This mode was studied in the E391a experiment at KEK in the X mass region 194.3-219.3 MeV, with the best upper limit on the branching ratio set with an X mass of 214.3 MeV at $< 2.4 \times 10^{-7}$ [1]. In KOTO, with an improved calorimeter and kaon flux, the single event sensitivity is improved by more than an order of magnitude in that mass range. In addition, the scope of the study is broadened to include the first search for $K_L \to 2\pi^0 X$ with X mass in the range 155-190 MeV. I will present an update of the analysis on this mode using data collected in 2018.

Introduction

Motivation

Dark matter models in the sub-GeV range are gaining theoretical popularity, and there are many models which posit that such dark matter may couple strongly with quarks and still match observational limits on relic density [2]. Despite this, there is still a significant observational gap in the MeV range that KOTO is sensitive to. These low mass models have limitations on allowable final states which allow for KOTO to search for a specific decay signature. In this analysis, we focus on testing models where $X \to 2\gamma$.



Measurement Principal

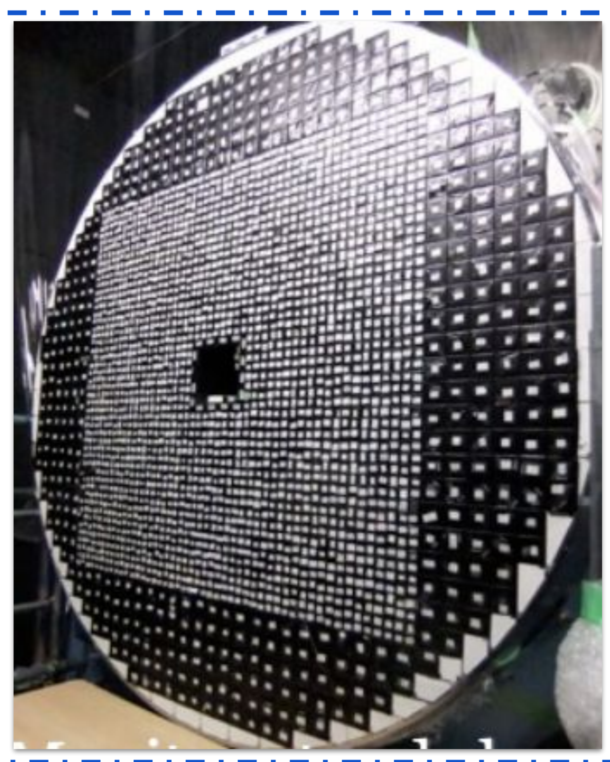
In the decay $K_L \to 2\pi^0 X$, where $X \to 2\gamma$, there are 6 final state photons. Each of the pions and the X particle will decay promptly into two photons, and the signal is six observed electromagnetic clusters in the CsI calorimeter, and nothing elsewhere.

CsI Calorimeter

KOTO's calorimeter is made of nearly 3000 individually read out CsI crystals in a fish-eye geometry. With an energy (GeV) resolution given by,

$$\frac{\sigma_E}{E}[\%] = \frac{1.26}{\sqrt{E}} \oplus \frac{0.13}{E} \oplus 0.76$$

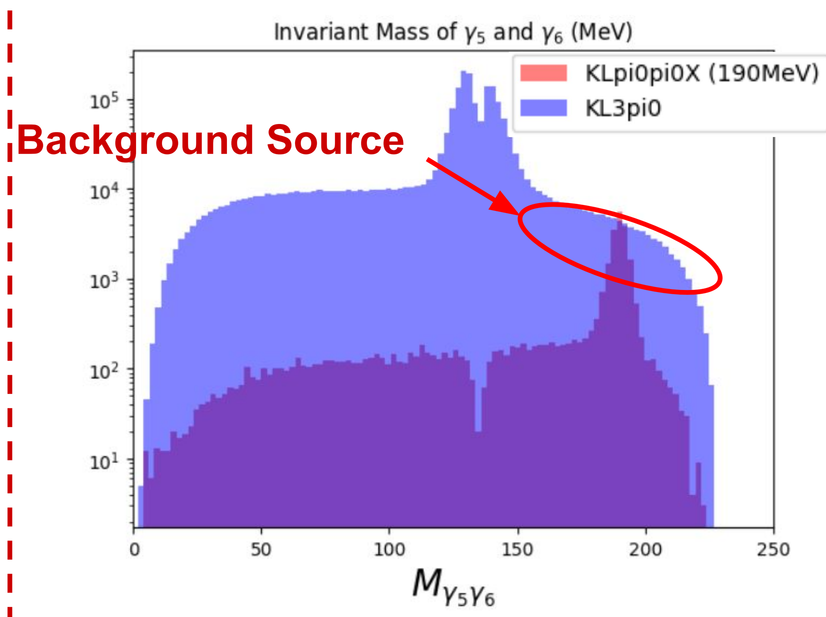
[3] It is the best at-scale photon calorimeter in the world. This makes it ideal for the sensitive measurements required for this analysis.



Event Reconstruction

Invariant Mass

The most important aspect of this analysis is the invariant mass of the two photons from the "X" particle. To calculate the invariant mass, we must first reconstruct the decay location of the K_L from the measured gamma energies and positions. The dominant background comes from $K_L \to 3\pi^0$ where the invariant mass is mis-measured as can be seen below.

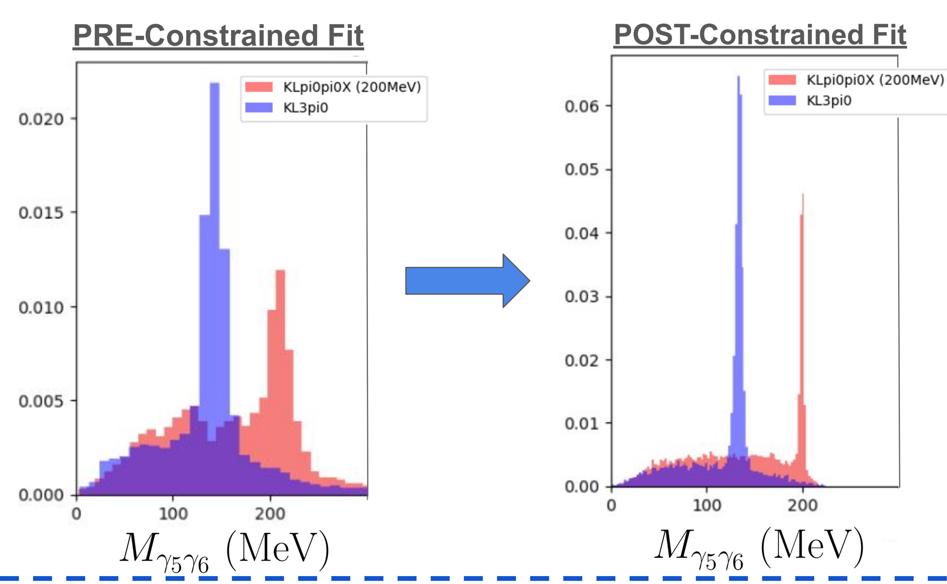


Constrained Fit

$$H_1 = \left(\sum_i E_i\right)^2 - \left(\sum_i p_i\right)^2 - M_{KL}^2 = 0$$
$$H_2 = E(\gamma_1, \gamma_2)^2 - p(\gamma_1, \gamma_2)^2 - M_\pi^2 = 0$$
$$H_3 = E(\gamma_3, \gamma_4)^2 - p(\gamma_3, \gamma_4)^2 - M_\pi^2 = 0$$
$$H_4 = \frac{L_{CSI}}{COE_x} - \frac{v_z}{v_x} = 0$$
$$H_5 = \frac{L_{CSI}}{COE_y} - \frac{v_z}{v_y} = 0$$

The first constraint is from the K_L mass constraint, while the H_2 and H_3 constraints require two photon pairs to have the invariant mass of a pion. The last two constraints require the reconstructed position of the K_L to be between the center of energy and the K_L generated position.

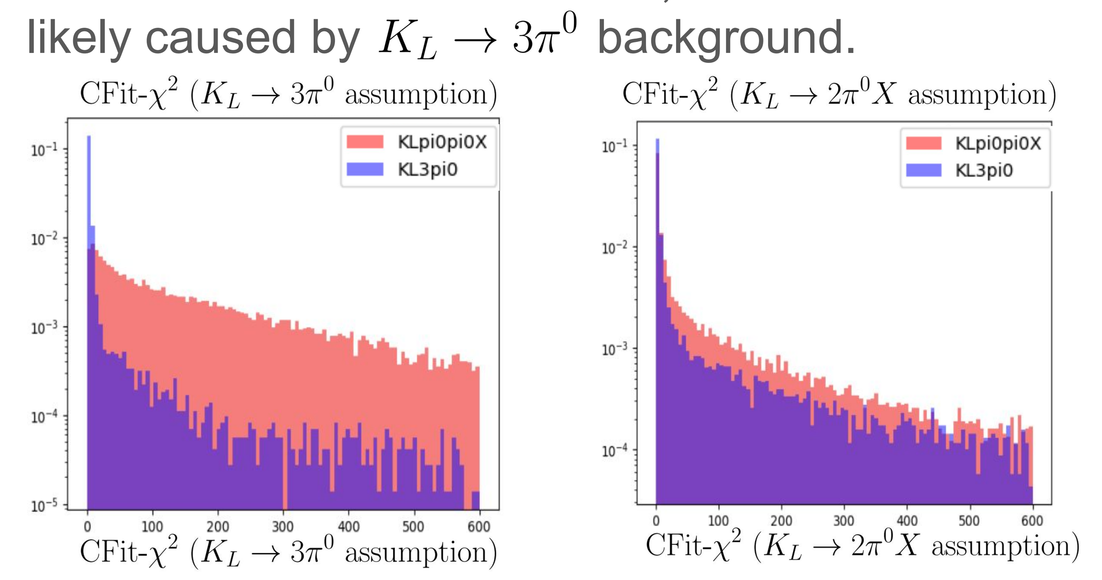
We can obtain a much narrower invariant mass peak by taking advantage of our constraints. This improves signal sensitivity and background rejection significantly.



CFit-χ^2

$$\chi^2 = \sum_i \frac{\left(x_{i,fit} - x_{i,meas}\right)^2}{\sigma_x^2} + \frac{\left(y_{i,fit} - y_{i,meas}\right)^2}{\sigma_y^2} + \frac{\left(E_{i,fit} - E_{i,meas}\right)^2}{\sigma_E^2}$$

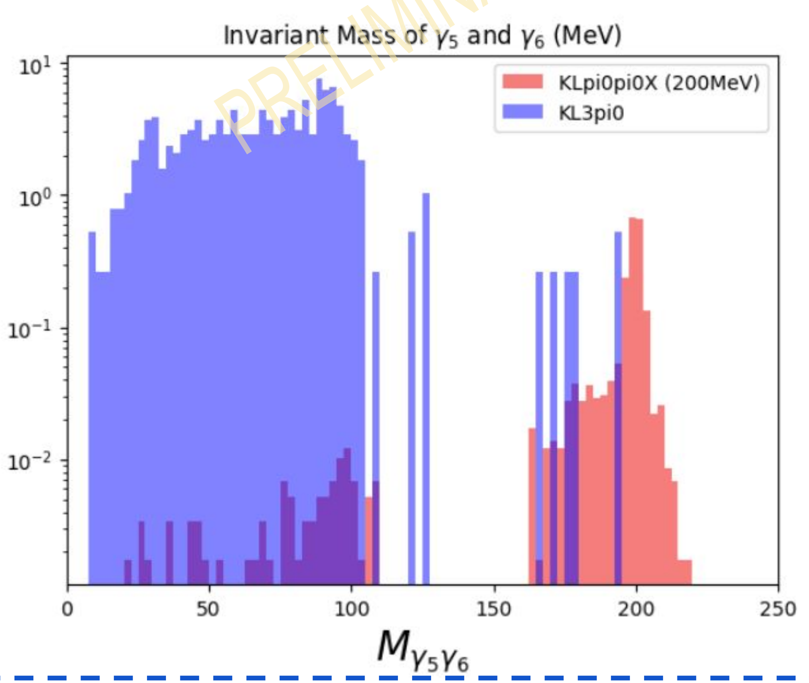
We know well the energy and position resolutions of the KOTO calorimeter. This allows us to extract a χ^2 value from the constrained fit. By minimizing this χ^2, we can pick the best combinations of photons which satisfy the constraints, making it a powerful tool to quantify the quality of an event's reconstruction. With this technique, we can also find a constrained fit χ^2 value under the assumption where a third pion mass constraint is added. If this χ^2 value is small, then we know it is likely caused by $K_L \to 3\pi^0$ background.



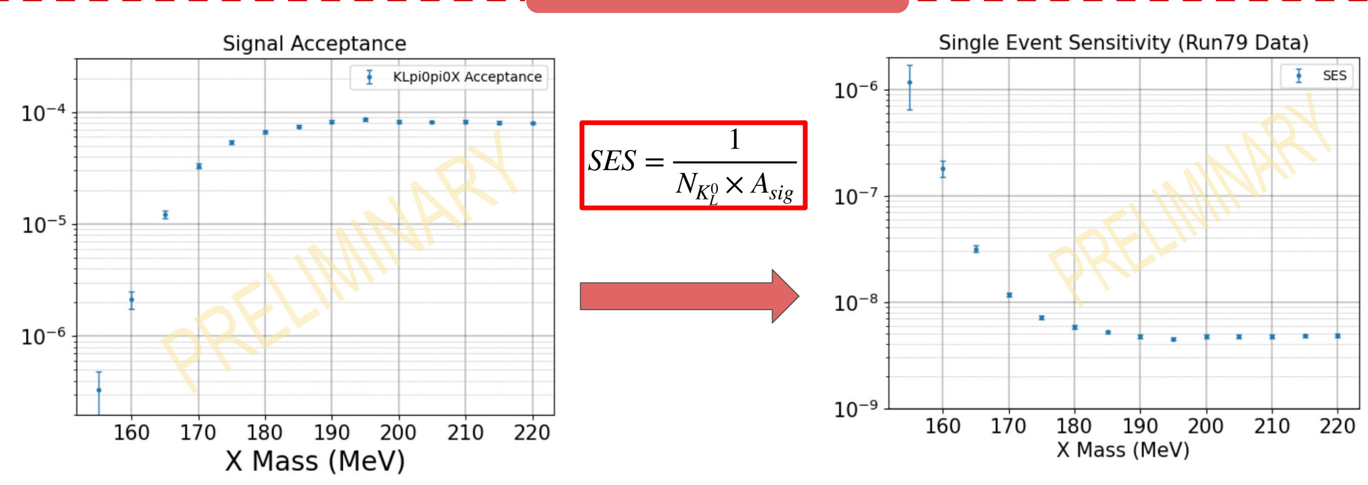
Current Analysis

Monte Carlo

After optimizing CFit-χ^2 cut values, we can observe the effect on $K_L \to 3\pi^0$ background in the high mass region. We observe 6 events in monte carlo $K_L \to 3\pi^0$ simulation, corresponding to an expected background level of ~ 0.6 events in the entire high mass region for 2018 data.



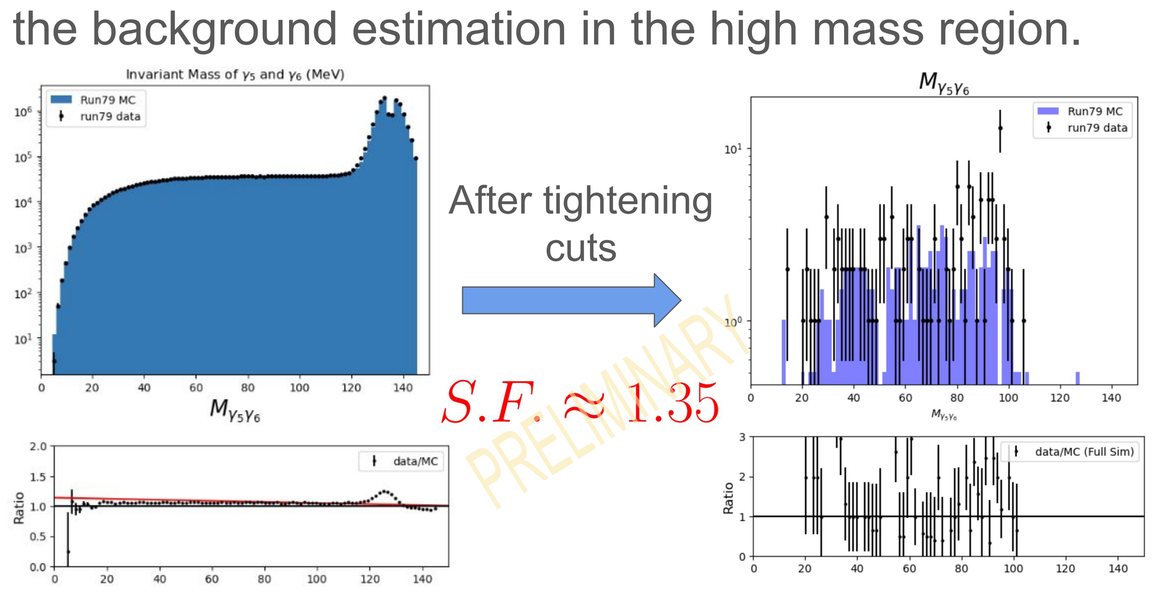
S.E.S



We can calculate the Single Event Sensitivity (S.E.S) at a given X mass from the signal acceptance calculated in the Monte Carlo simulation. The sensitivity gets significantly better farther away from the pion mass, with a maximal single event sensitivity around 4.5×10^{-9} which is more than an order of magnitude increase in sensitivity from the E391a study, while keeping expected background levels more than two orders of magnitude lower. The increase in sensitivity is from an improved K_L flux from the J-PARC accelerator, while the increase in background rejection is from the improved CsI calorimeter.

Data vs. Monte Carlo

In this analysis, we keep events in the high mass region blinded, and use the low mass region as a control region to study data vs. Monte Carlo. As we apply all cuts, there is a slight discrepancy between data and Monte Carlo. This is caused by energy mis-measurement not being well simulated in Monte Carlo, and an overestimation of background rejection. We calculate a background level scale factor to scale the background estimation in the high mass region.



Next Steps

$K_L \to 2\pi^0\gamma\gamma$

The S.E.S is near SM prediction of the branching ratio of the rare decay, $K_L \to 2\pi^0\gamma\gamma$ [4]. Analysis is ongoing to estimate the expected contribution from this mode in 2018 data.

2021 Data

We're working to finalize the treatment of the scale factor, and its effect on signal acceptance and background level. After analyzing 2018 data, we will move to analyze 2021 data which has a similar K_L flux to 2018 data. After analyzing 2021 data, we plan to publish the results as soon as possible.

Summary

Dark matter models in the sub-GeV range are gaining theoretical popularity, which sets KOTO in a unique position to probe sub-GeV quark coupling to dark matter. We study this by analyzing the mode $K_L \to 2\pi^0 X$, where $X \to 2\gamma$. The maximal single event sensitivity is 4.5×10^{-9} which is more than an order of magnitude improvement on the past analysis while reducing $K_L \to 3\pi^0$ background by more than two orders of magnitude. In addition, the scope of the study is broadened to include the first search for $K_L \to 2\pi^0 X$ with X mass in the range 155-190 MeV. We are finalizing the analysis of data taken in 2018, and plan to study data taken in 2021 promptly. This search is also sensitive to the mode $K_L \to 2\pi^0\gamma\gamma$ and we plan to make a world first measurement.

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References

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