Dark Matter Searches at KOTO

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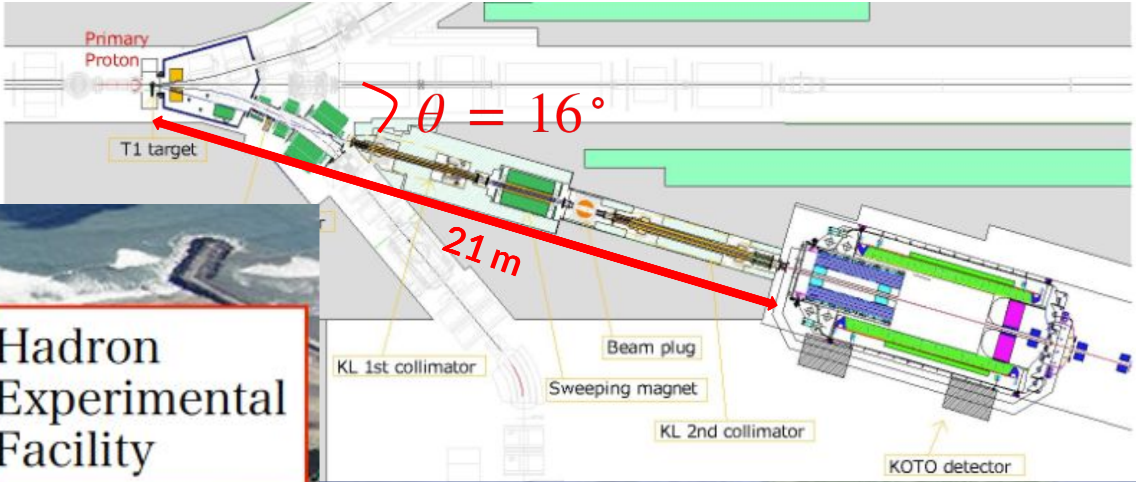
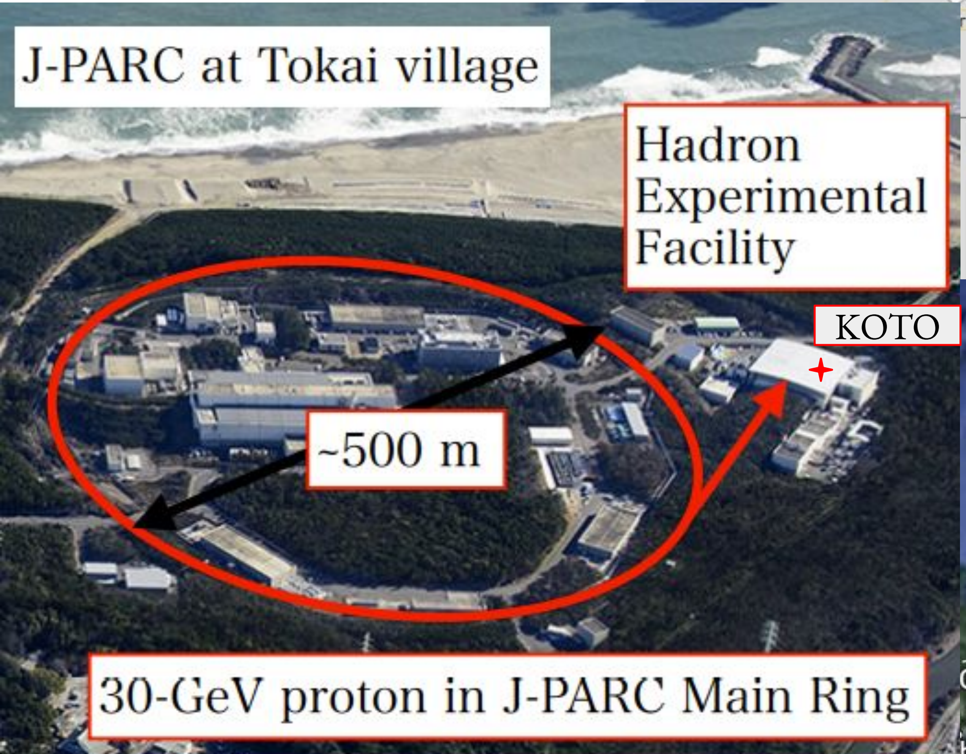
KOTO at J-PARC

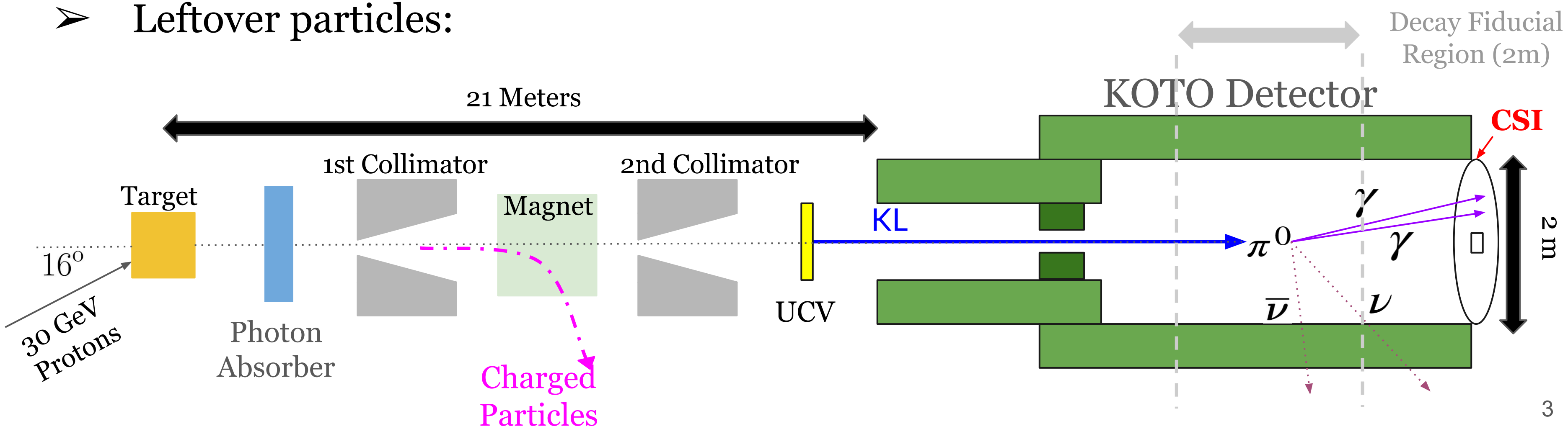




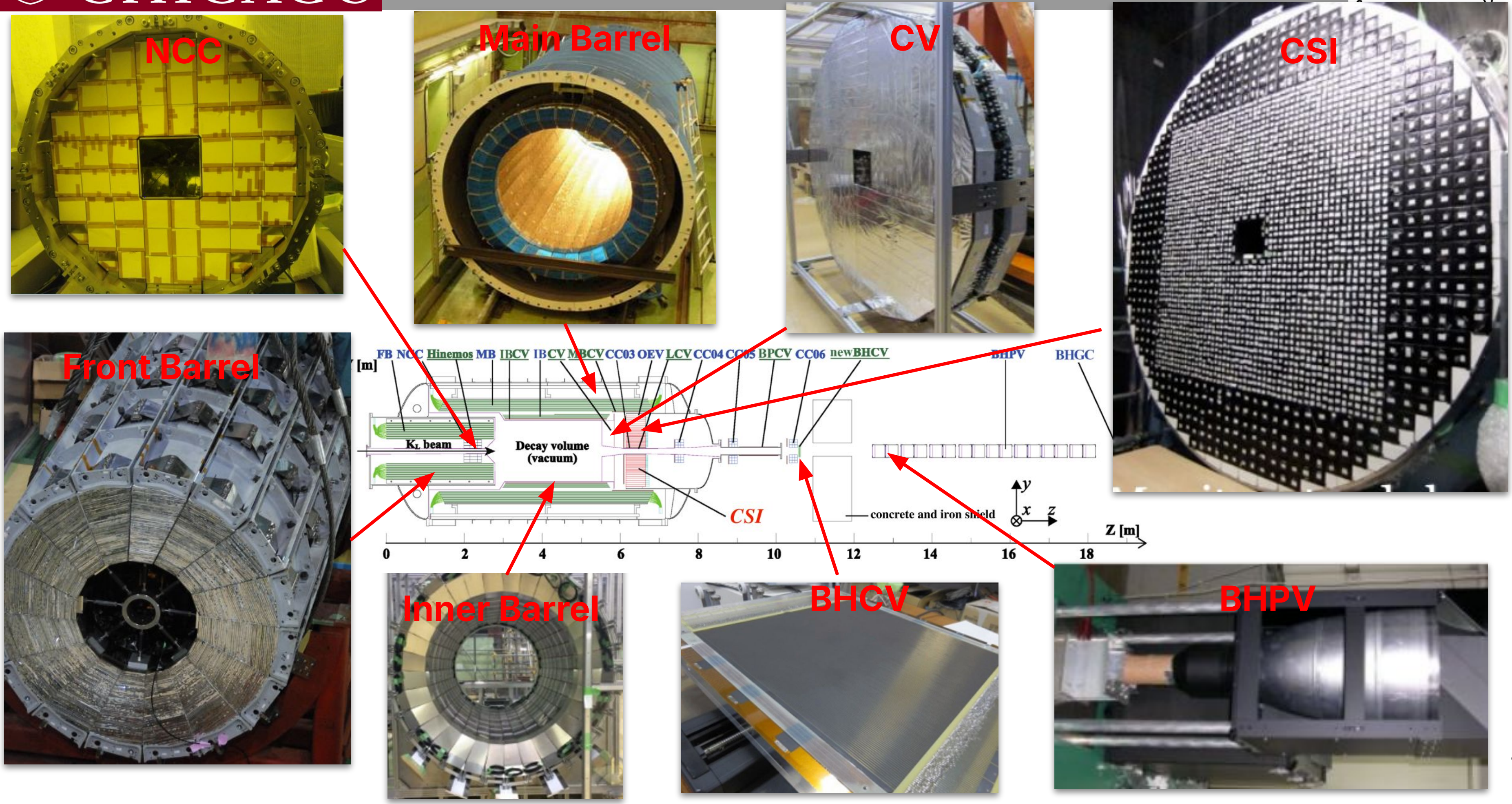
References: Iwai, E., et al. (2015). Performance study of a prototype pure CsI calorimeter for the KOTO experiment. *Nuclear Instruments and Methods in Physics Research.*, *786*, 135–14

The KOTO Beamline

- 21 Meter Beamline ⇒ Only long lived particles.
- Sweeping magnet ⇒ No charged particles. $\mathbf{K_L, n, \gamma}$
- Leftover particles:
- 2 Collimators to tightly control beam spread.
- Small $\mathbf{K_L}$ transverse momentum.



The KOTO Detector



Novel Physics Searches?

Access to high intensity beam ✔

High performance detectors ✔

Sub-GeV energy levels ✔

⇒ KOTO is in a prime position to study mid-energy NP!

Just need to look…

The Search for $K_L \to \pi^0\pi^0 X$ and $K_L \to 2\pi^0\gamma\gamma$ in the KOTO Experiment

(Based on data taken in 2021)

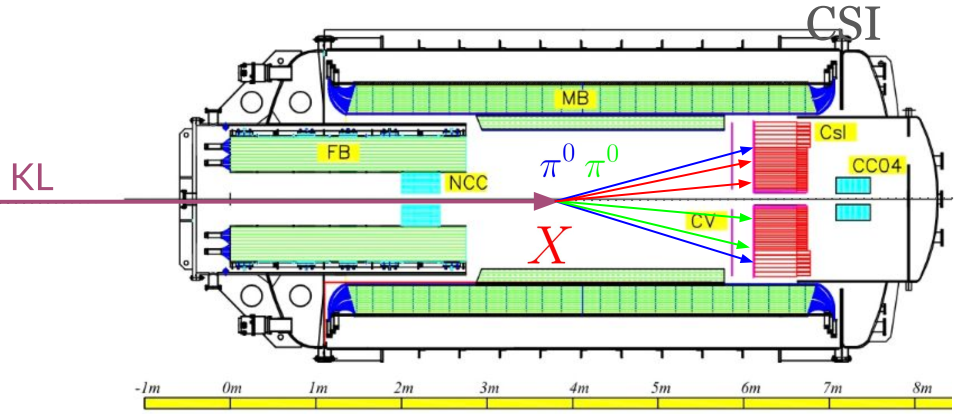
References: [1] Phys. Rev. D **98**, 116009 (2018)
[2] Nuclear Physics B396 (1993) 53—80
[3] arXiv:2507.01947v1 [hep-ph] 2 Jul 2025

Multi-Purpose Analysis

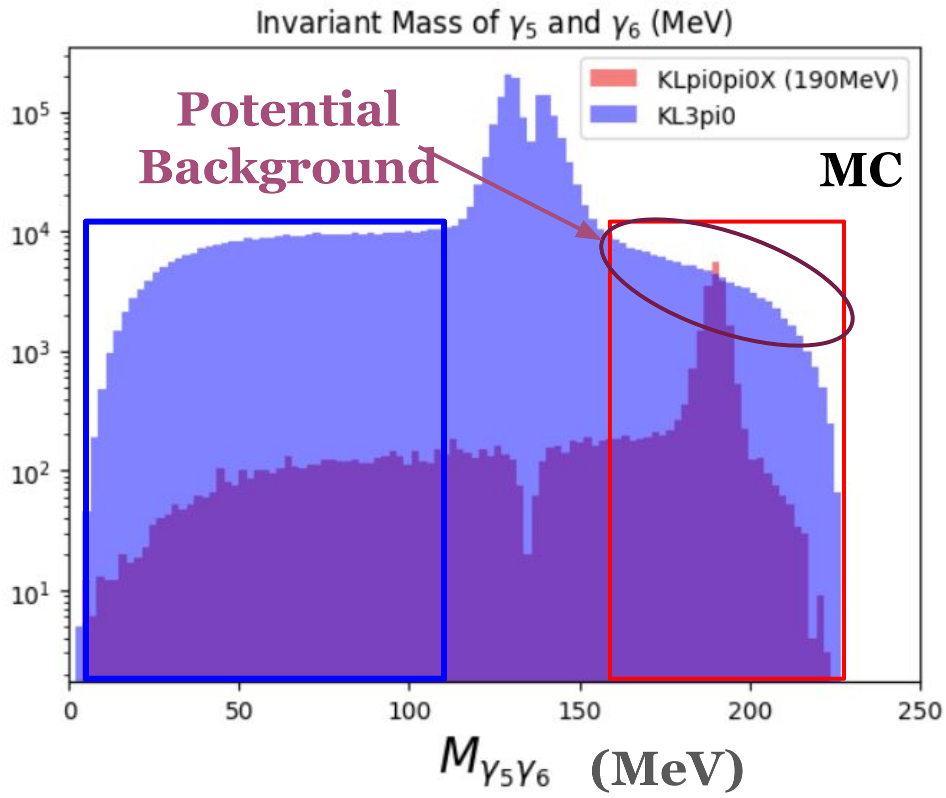
- ➢ Study sub-GeV quark coupling to dark matter, through modes with photons in the final state [1] [3]
- ➢ A test of ChPT via the mode $K_L \to 2\pi^0\gamma\gamma$ [2] (BR ~O(-8))
- ➢ Study energy mismeasurement in $K_L \to 3\pi^0$ decays.

Assumption:
X decays promptly to 2 photons

Main Question:
How to determine X is not a pion from $K_L \to 3\pi^0$ decays



Analysis Strategy



- Signal Region:

- Control Region

Blind Box strategy ⇒ Cannot observe data within the signal region during the analysis.

Study $M_X \in [160, 220]$ MeV

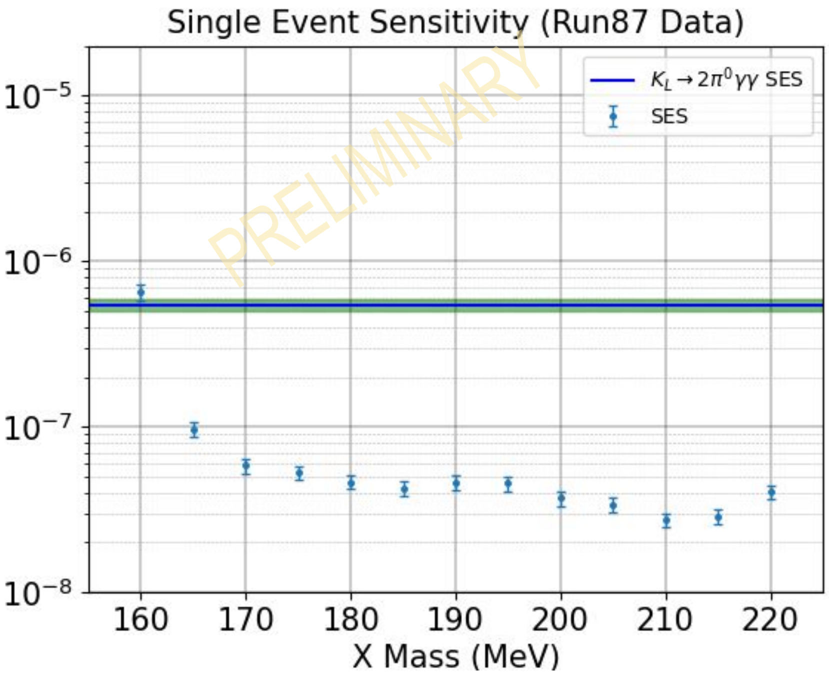
Single Event Sensitivity (SES)

- SES ⇒ The central value of the branching ratio if one signal event is observed.

$$\mathrm{SES} = \frac{1}{A_{sig} \cdot N_{K_L}}$$

- The number of kaons in data is determined through $\boldsymbol{K_L \to 3\pi^0}$ decays.

$$Y = (4.27 \pm 0.03_{stat} \pm 0.31_{sys}) \times 10^{12}$$



Each X mass has optimized selection criteria in order to obtain the best SES.

Open the Blinded Regions…

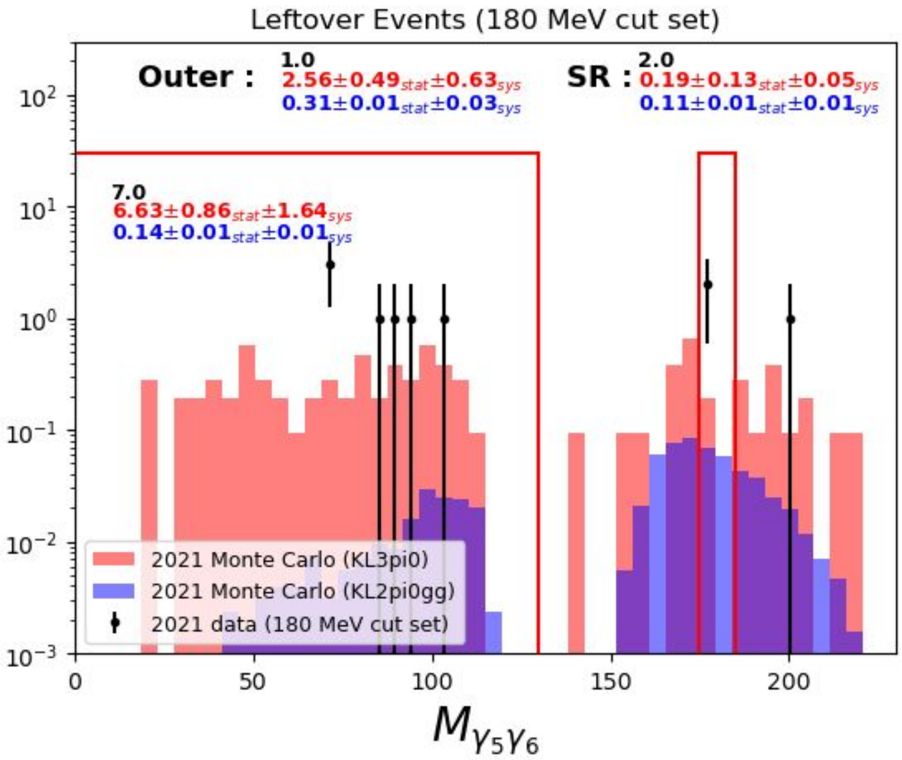
Outer: Outside signal region (high mass)
SR: Signal region

Red : $K_L \to 3\pi^0$ background

Blue: $K_L \to 2\pi^0\gamma\gamma$ expectation

Black: Number observed in data.

Two events observed in the signal region with an invariant mass within 2 MeV of each other.



Summary of Results

Three unique events observed in the different analyses.

Feldman-Cousins limits were determined accounting for the uncertainty in the background levels.

Results are not uncorrelated…

Analysis	N_{obs}	Result @95% C.L. ($\times 10^{-7}$)
$M_X = 160$	0	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 18.6$
$M_X = 165$	0	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 2.37$
$M_X = 170$	0	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 1.17$
$M_X = 175$	1	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 2.02$
$M_X = 180$	2	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 3.04$
$M_X = 185$	0	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 1.18$
$M_X = 190$	0	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 1.24$
$M_X = 195$	0	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 1.25$
$M_X = 200$	0	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 0.988$
$M_X = 205$	0	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 0.902$
$M_X = 210$	1	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 1.3$
$M_X = 215$	0	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 0.845$
$M_X = 220$	0	$BR(K_L \to \pi^0\pi^0 X, X \to \gamma\gamma) < 1.12$
$K_L \to \pi^0\pi^0\gamma\gamma$	0	$BR(K_L \to \pi^0\pi^0\gamma\gamma) < 11.2$

PRELIMINARY

Interpretation of Results

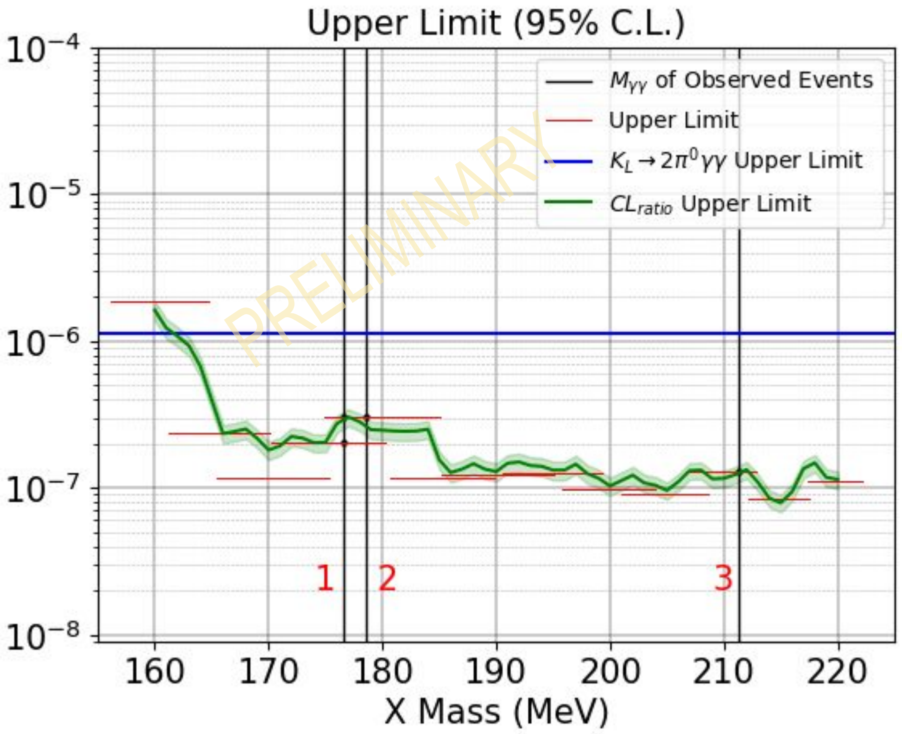
Low Background ⇒ Push further with new data

- Account for the correlation between nearby results.

- Take the ratio of weighted probabilities under s + b and b only assumptions.

$$CL_{ratio} = \frac{P_w(n_{s+b} \leq n_{obs}|s+b)}{P_w(n_b \leq n_{obs}|b)}$$

- The upper limit is the branching ratio such that $CL_{ratio} = 5\%$



The Search for $K_L \to XX,\ X \to 2\gamma$ in the KOTO Experiment

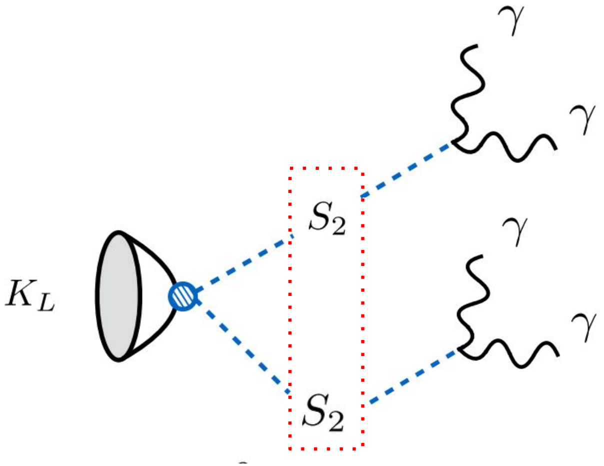
(Based on data taken in June 2018)

Dark Pair Production in Meson Decays

- $s \to d$ quark transition may result in the production of a "dark pair" (pion imposter). [4]
- Unique! May happen in K_L decays, but not in $K^{\pm}$.
- KOTO is in a good position to search for such decays, such as when $X \to 2\gamma$.

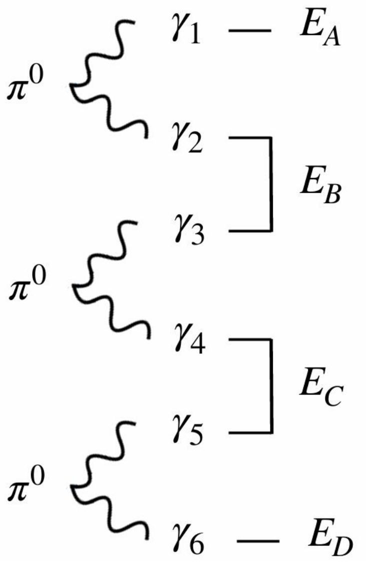
Challenging Backgrounds

1. $K_L \to 2\pi^0$ (mispairing).
2. $K_L \to 3\pi^0$ (double fusion)



π^0 IMPOSTOR

Background Analysis: Double Fusion



$$E_{\gamma_1} = E_A$$

$$E_{\gamma_2} + E_{\gamma_3} = E_B$$

$$E_{\gamma_4} + E_{\gamma_5} = E_C$$

$$E_{\gamma_6} = E_D$$

$$2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{\gamma_1\gamma_2}) = 2E_{\gamma_5}E_{\gamma_6}(1-\cos\theta_{\gamma_5\gamma_6})$$

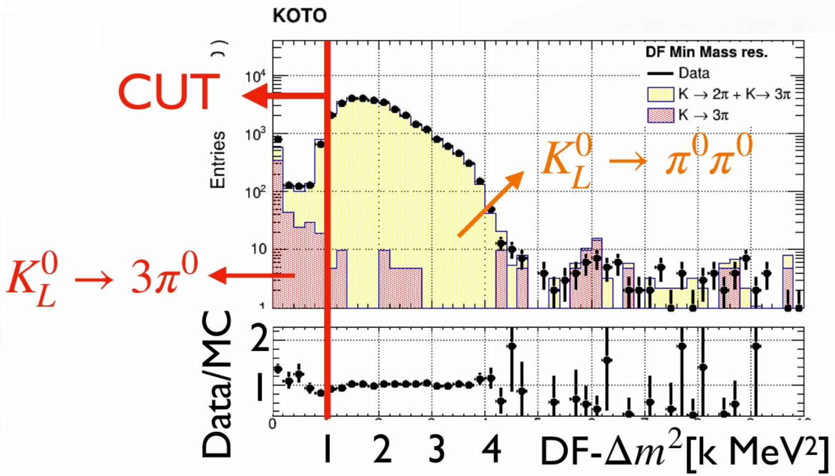
$$2E_{\gamma_3}E_{\gamma_4}(1-\cos\theta_{\gamma_3\gamma_4}) = M_{\pi^0}$$

$M_{\gamma_1\gamma_2}$

$M_{\gamma_5\gamma_6}$

6 constraints ⇒ 6 unknowns ⇒ solve

$$\text{DF-}\Delta m^2 = (M_{\gamma_1\gamma_2} - M_{\pi^0})^2 + (M_{\gamma_5\gamma_6} - M_{\pi^0})^2$$



$K_L \to 2\pi^0$

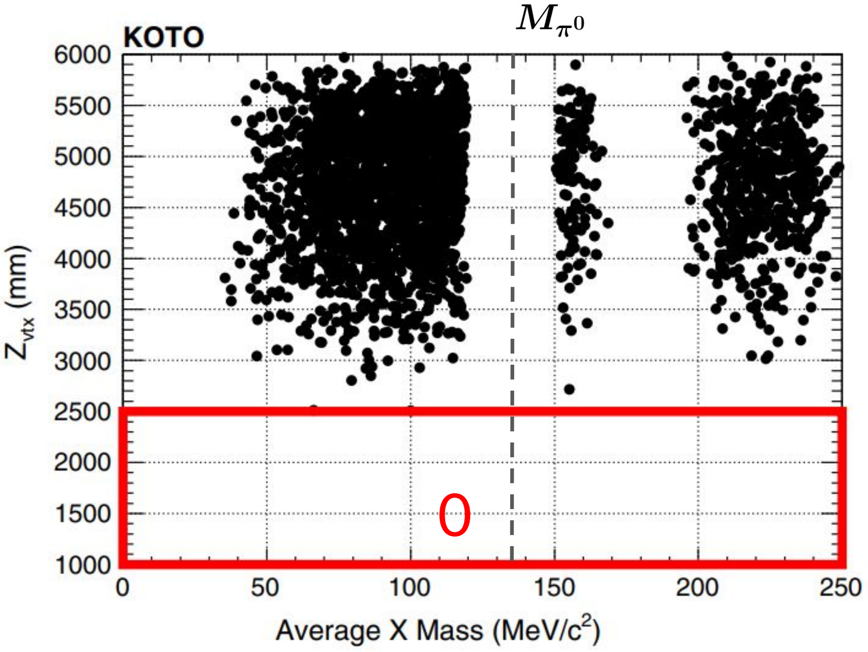
- Loop over six possible photon pairs and select the one that is closest to M_{π^0}.
  - If it is within $M_{\pi^0} \pm 15$ MeV, this event is rejected.

Nearly all $K_L \to 2\pi^0$ background are rejected this way.

Open Box Result

Low Background ⇒ Push further with new data

Source	Estimated Value
$K_L \to 2\pi^0$	0.61 ± 0.61
$K_L \to 3\pi^0$	< 0.62 (90% C.L.)



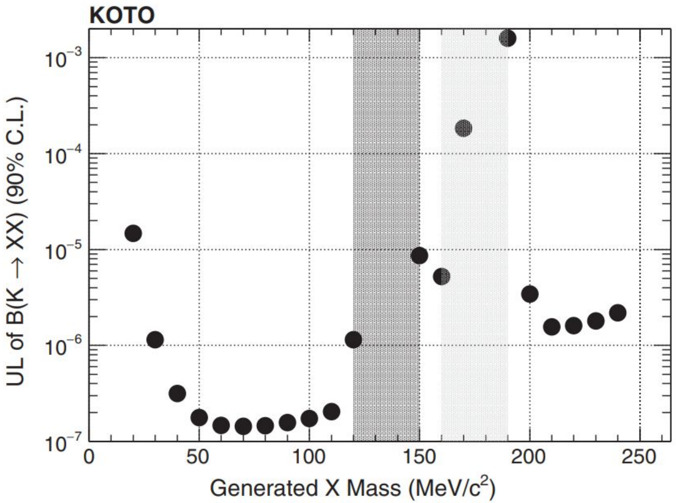


FIG. 6. Upper limit (UL) of $\mathcal{B}(K_L^0 \to XX)$ for different M_X at the 90% C.L. The dark (light) gray region indicates the exclusion by the cuts against the $K_L^0 \to \pi^0\pi^0$ background (the ΔM_{DF}^2 cut).

The Search for $K_L \to \gamma\overline{\gamma}$ in the KOTO Experiment

(Based on a special run taken in 2021)

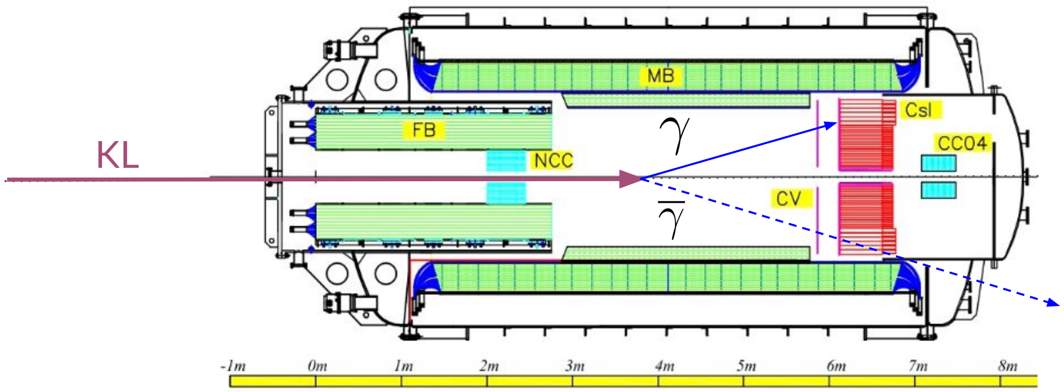
References: [6] M. Fabbrichesi, et al., The Physics of the Dark Photon: A Primer, SIP (2021)
[7] J.-Y. Su, et al., Kaon decays shedding light on massless dark photons, The European 99 Physical Journal C 80 (2020)

The Massless Dark Photon

- Does not couple to normal matter ⇒ cannot be directly detected [6]
- Theoretical calculations predict the possibility of dark photons in neutral kaon decays with BR ~ O(-3) [7]
- One photon in the CSI ⇒ nothing hits the veto

Challenging Backgrounds

1. Neutron induced single cluster (accidental hit).
2. $K_L \to \gamma\gamma$ with one missing photon (veto inefficiency).



Analysis Strategy

Blind Box strategy used to avoid human bias ⇒ Cluster Energy vs. HitXY : blinded (signal) region B (A)

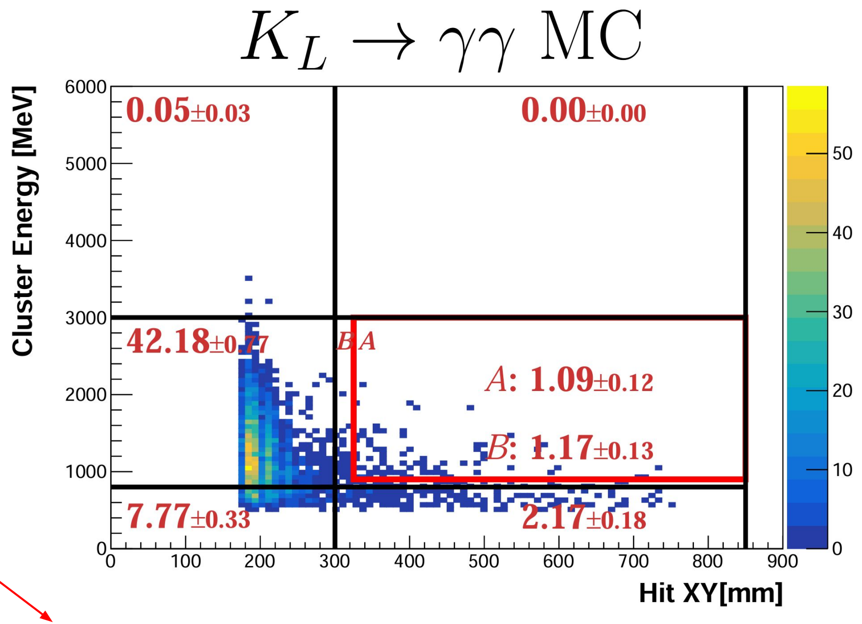
Neutron Induced Bkg Reduction

1. Deep Learning Cluster Shape Discriminator (CSDDL)
2. CsI Dual End Readout using MPPC's (deltaT)
3. Pulse Shape Discriminator using Fourier Transform (FPSD)

Type	Source	Background Level
K_L^0 decay	$K_L^0 \to 2\gamma$	$1.09 \pm 0.12_{stat.} \pm 0.05_{syst.}$
	$K_L^0 \to 3\pi^0$	< 0.18 (90% C.L.)
	$K_L^0 \to 2\pi^0$	< 0.51 (90% C.L.)
	$K_L^0 \to \pi^\pm e^\mp \nu_e$	< 0.27 (90% C.L.)
	$K_L^0 \to \pi^\pm \mu^\mp \nu_\mu$	< 0.25 (90% C.L.)
	$K_L^0 \to \pi^+\pi^-\pi^0$	< 0.17 (90% C.L.)
Neutron		$11.57 \pm 4.42_{stat.} \pm 2.13_{syst.}$
Total (exclude sources without central value)		$12.66 \pm 4.42_{stat.} \pm 2.13_{syst.}$

PRELIMINARY

Table 1: Background Level predicted for each source inside the signal region



Largest Bkg Source

Result

1 cluster trigger (two hour special run)
$\Rightarrow 1.29 \times 10^{10}\ K_L^0$

Achieved,

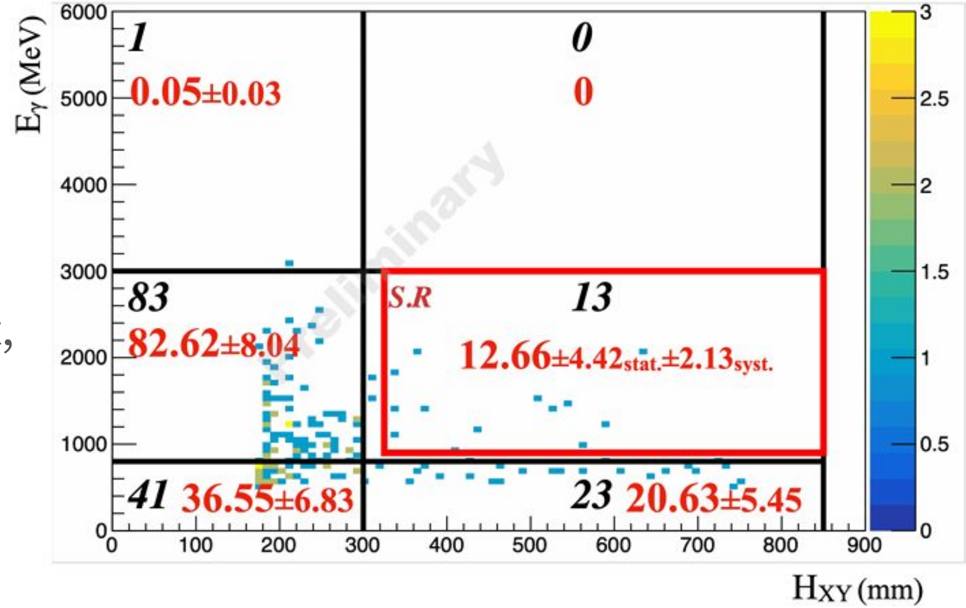
$$SES = \frac{1}{A_{sig} \times N(K_L^0)} = (2.91 \pm 0.05) \times 10^{-8}$$

Using FC, KOTO set the upper limit at,

$$\mathcal{BR}(K_L^0 \to \gamma\bar{\gamma}) < 3.47 \times 10^{-7}$$

PRELIMINARY

Black ⇒ Number Observed
Red ⇒ Number Expected (Bkg)



Conclusion

- The analysis of the novel decay mode $\boldsymbol{K_L \to 2\pi^0\gamma\gamma}$ was performed on 2021 data, a first search which sets an upper limit on the branching ratio (95% C.L.),

$$\mathrm{BR}(\boldsymbol{K_L \to \pi^0\pi^0}\gamma\gamma) < \mathbf{1.12 \times 10^{-6}}$$

PRELIMINARY

- The secondary analysis of $K_L \to \pi^0\pi^0 X, X \to \gamma\gamma$ was also performed, with two events with an invariant mass near 177 MeV observed in the signal region.

- No signal was observed in the mass range of 40–110 MeV and 210–240 MeV.
$\Rightarrow \mathrm{BR}(\boldsymbol{K_L \to XX}) < \mathbf{(1\text{-}4) \times 10^{-7}}$ and $\mathrm{BR}(\boldsymbol{K_L \to XX}) < \mathbf{(1\text{-}2) \times 10^{-6}}$ (90% C.L.)

- An upper limit on the branching ratio of $K_L \to \gamma\bar{\gamma}$ at 90% C.L. was set at,

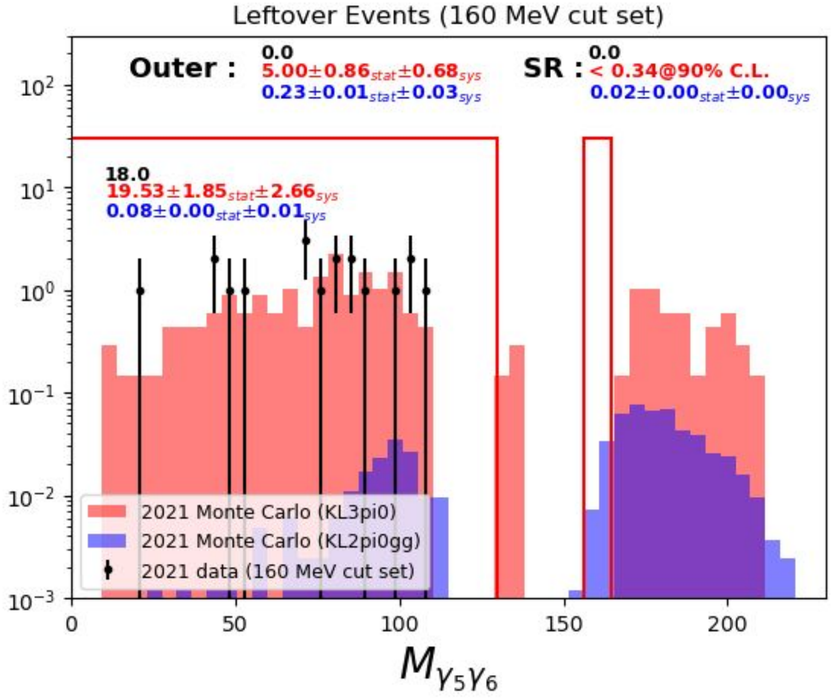
$$\mathcal{BR}(K_L^0 \to \gamma\bar{\gamma}) < 3.47 \times 10^{-7}$$

PRELIMINARY

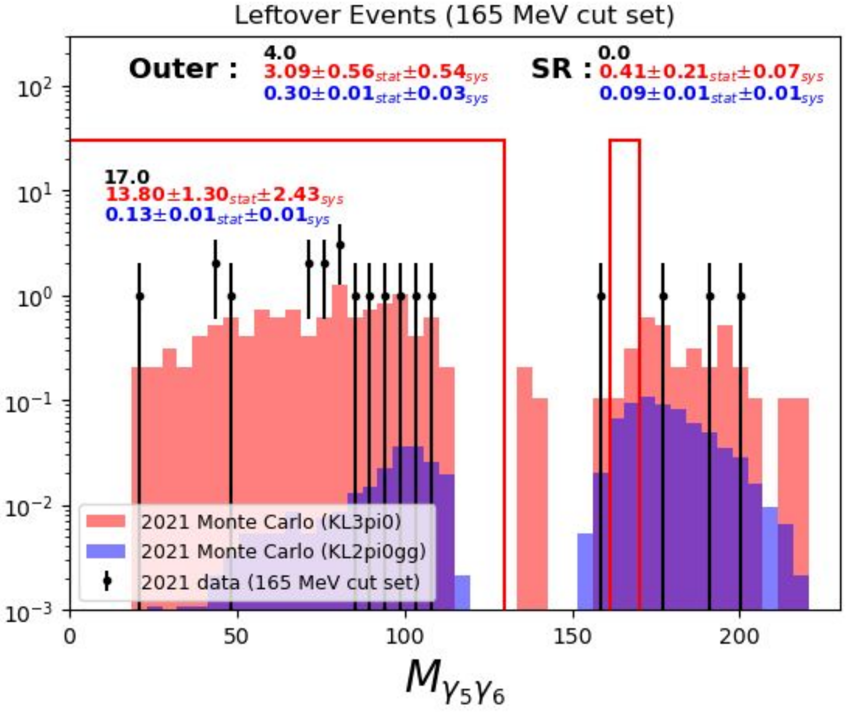
Backup

Plots for all open box results shown in following slides

160-165 MeV

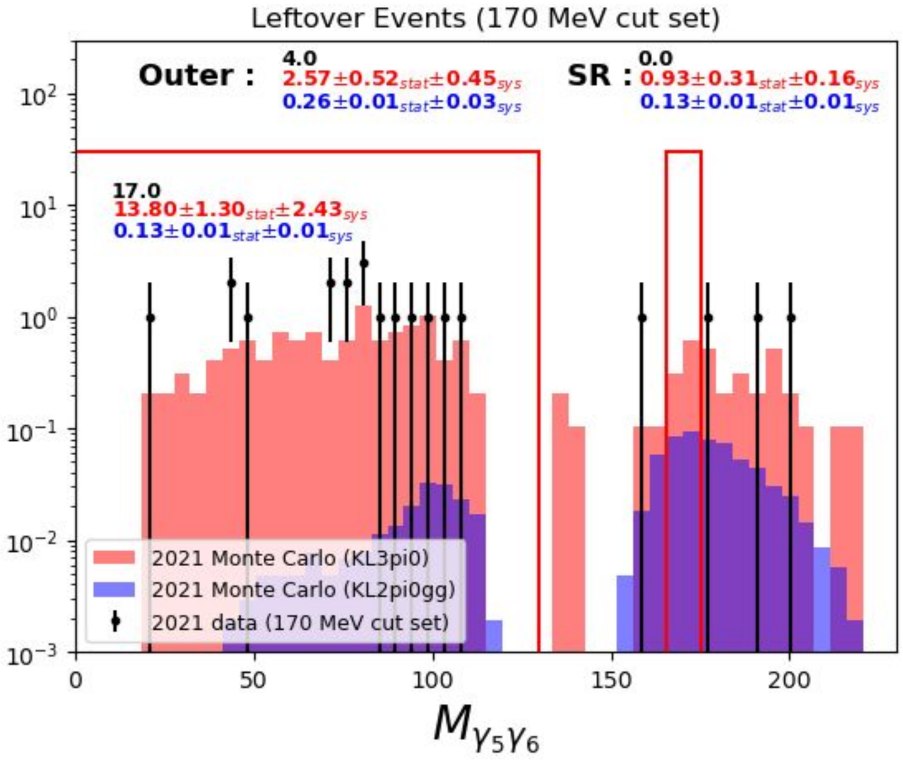


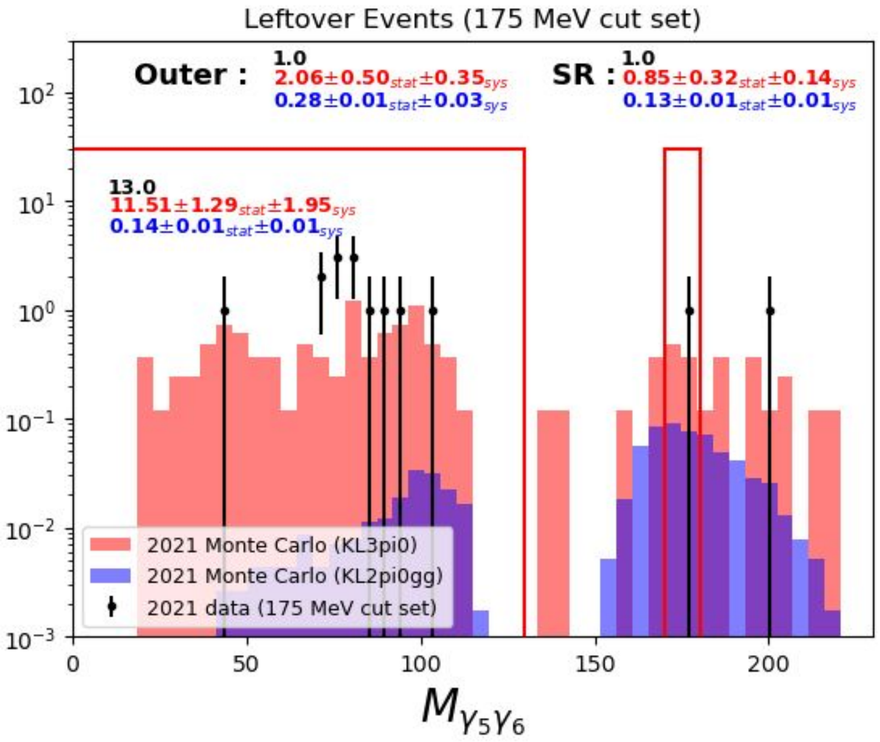
Leftover Events (160 MeV cut set)
Outer :
0.0
5.00±0.86stat±0.68sys
0.23±0.01stat±0.03sys
SR :
0.0
< 0.34@90% C.L.
0.02±0.00stat±0.00sys
18.0
19.53±1.85stat±2.66sys
0.08±0.00stat±0.01sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (160 MeV cut set)
$M_{\gamma_5\gamma_6}$



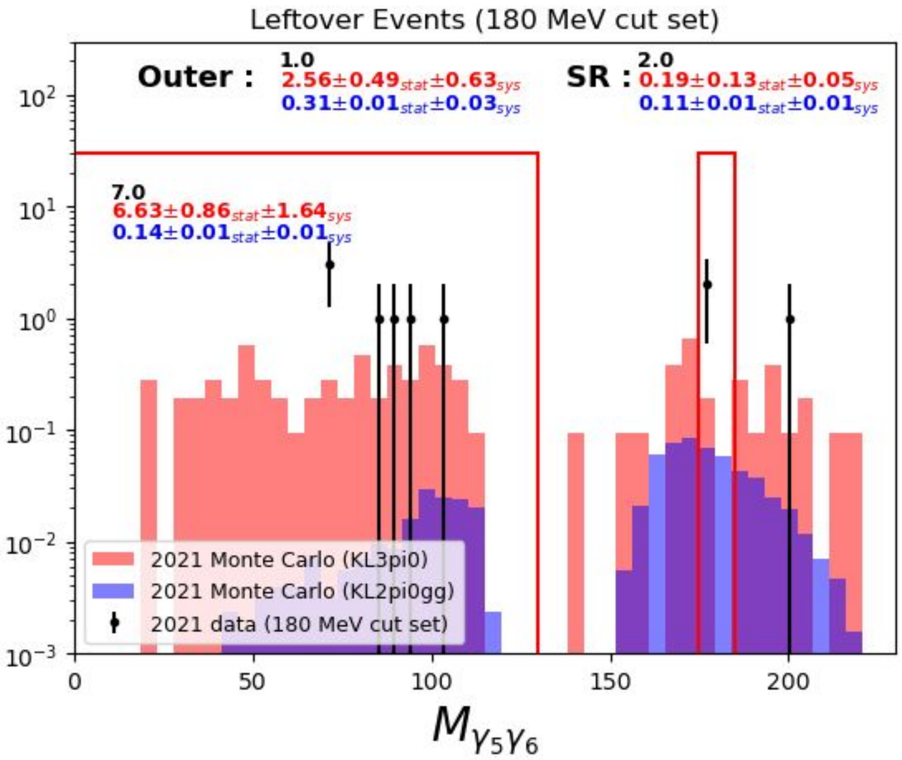
Leftover Events (165 MeV cut set)
Outer :
4.0
3.09±0.56stat±0.54sys
0.30±0.01stat±0.03sys
SR :
0.0
0.41±0.21stat±0.07sys
0.09±0.01stat±0.01sys
17.0
13.80±1.30stat±2.43sys
0.13±0.01stat±0.01sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (165 MeV cut set)
$M_{\gamma_5\gamma_6}$

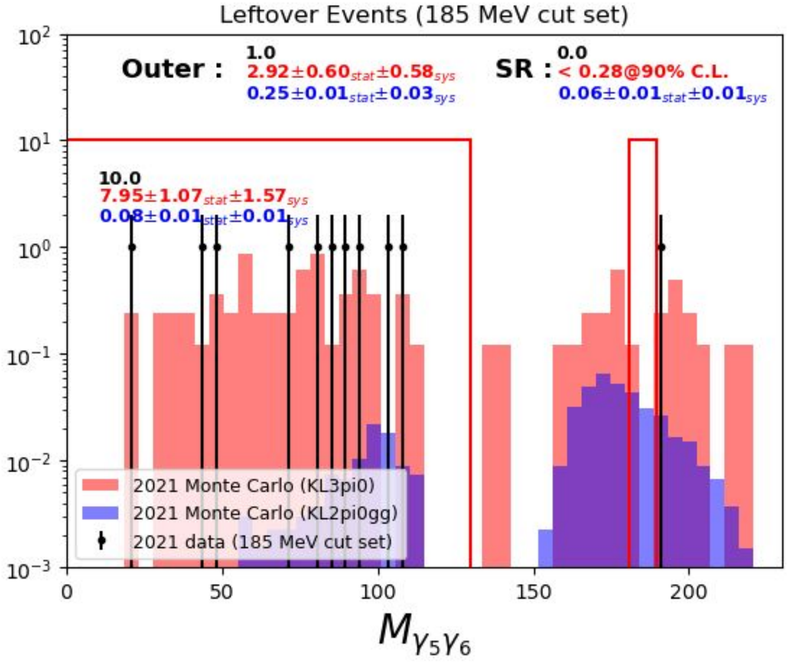
(170-175 MeV)


Leftover Events (170 MeV cut set)
Outer :
4.0
2.57±0.52stat±0.45sys
0.26±0.01stat±0.03sys
SR :
0.0
0.93±0.31stat±0.16sys
0.13±0.01stat±0.01sys
17.0
13.80±1.30stat±2.43sys
0.13±0.01stat±0.01sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (170 MeV cut set)
$M_{\gamma_5\gamma_6}$

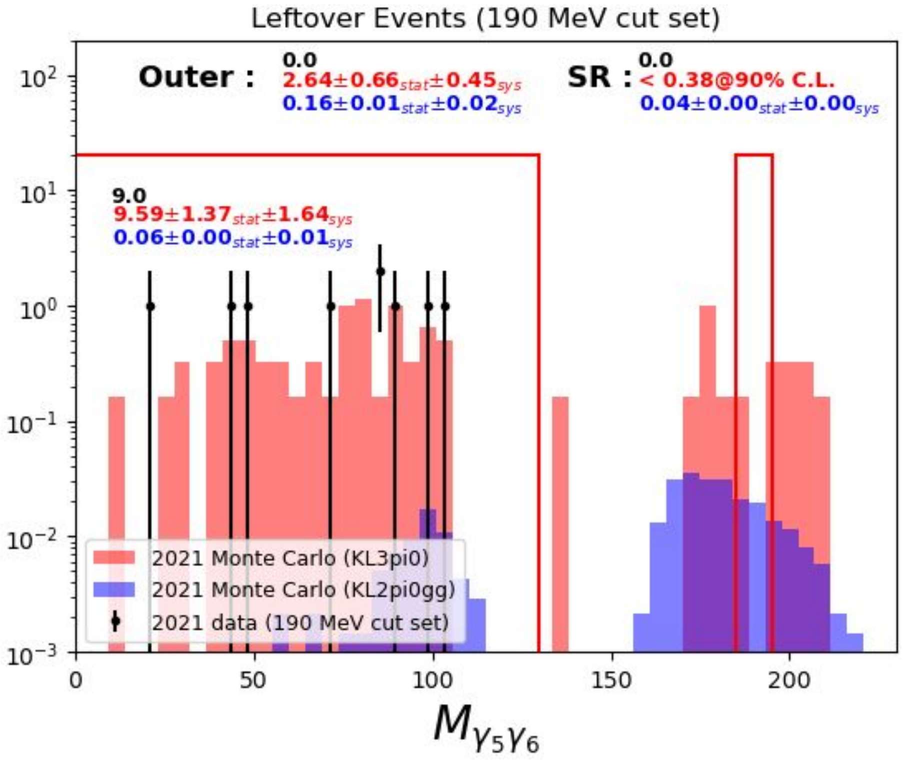

Leftover Events (175 MeV cut set)
Outer :
1.0
2.06±0.50stat±0.35sys
0.28±0.01stat±0.03sys
SR :
1.0
0.85±0.32stat±0.14sys
0.13±0.01stat±0.01sys
13.0
11.51±1.29stat±1.95sys
0.14±0.01stat±0.01sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (175 MeV cut set)
$M_{\gamma_5\gamma_6}$

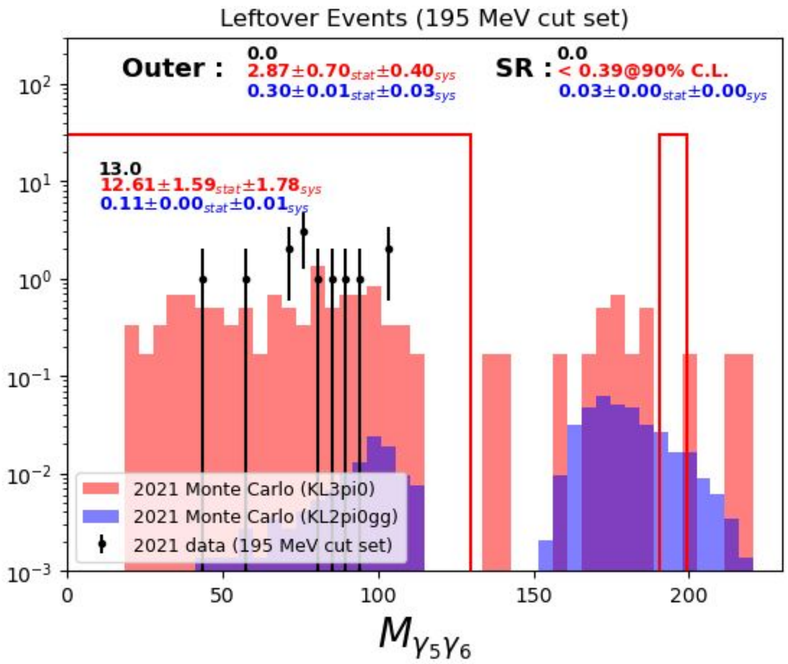
180-185


Leftover Events (180 MeV cut set)
Outer :
1.0
2.56±0.49stat±0.63sys
0.31±0.01stat±0.03sys
SR :
2.0
0.19±0.13stat±0.05sys
0.11±0.01stat±0.01sys
7.0
6.63±0.86stat±1.64sys
0.14±0.01stat±0.01sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (180 MeV cut set)
Mγ5γ6

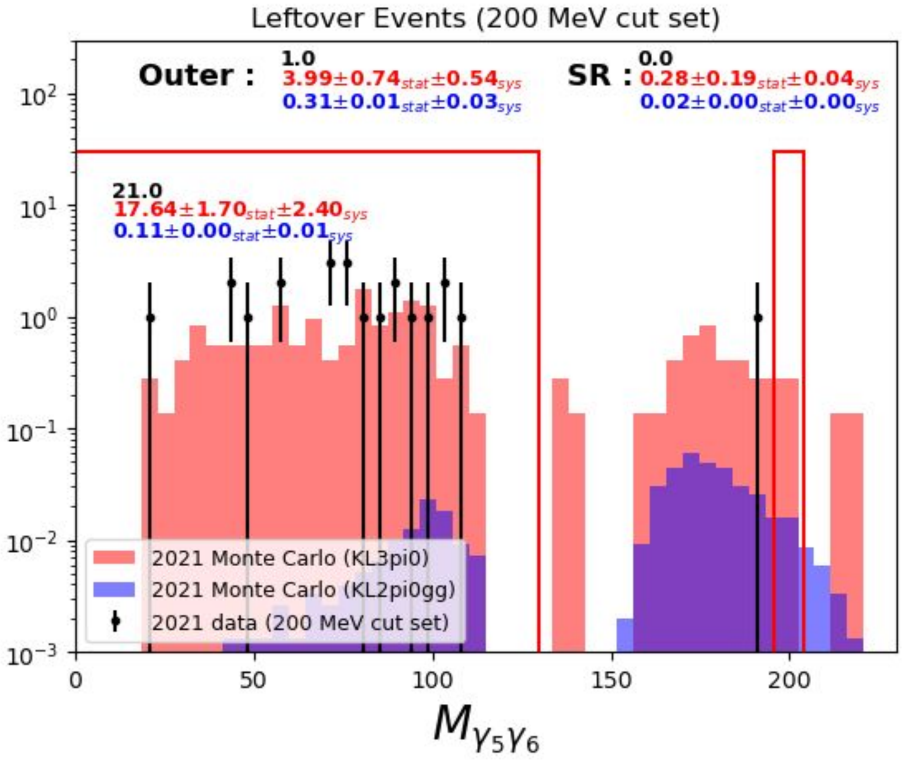

Leftover Events (185 MeV cut set)
Outer :
1.0
2.92±0.60stat±0.58sys
0.25±0.01stat±0.03sys
SR :
0.0
< 0.28@90% C.L.
0.06±0.01stat±0.01sys
10.0
7.95±1.07stat±1.57sys
0.08±0.01stat±0.01sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (185 MeV cut set)
Mγ5γ6

190-195

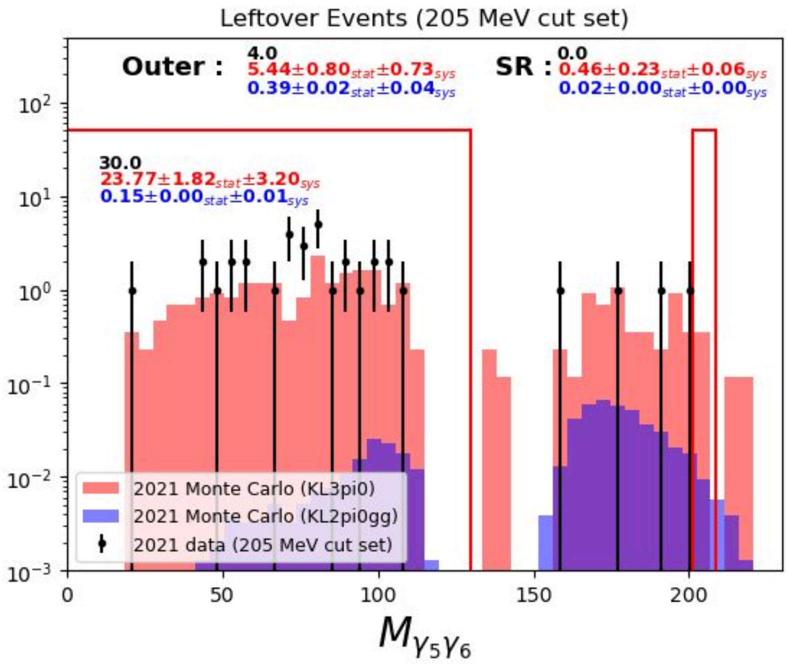

Leftover Events (190 MeV cut set)
Outer :
0.0
2.64±0.66stat±0.45sys
0.16±0.01stat±0.02sys
SR :
0.0
< 0.38@90% C.L.
0.04±0.00stat±0.00sys
9.0
9.59±1.37stat±1.64sys
0.06±0.00stat±0.01sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (190 MeV cut set)
$M_{\gamma_5\gamma_6}$


Leftover Events (195 MeV cut set)
Outer :
0.0
2.87±0.70stat±0.40sys
0.30±0.01stat±0.03sys
SR :
0.0
< 0.39@90% C.L.
0.03±0.00stat±0.00sys
13.0
12.61±1.59stat±1.78sys
0.11±0.00stat±0.01sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (195 MeV cut set)
$M_{\gamma_5\gamma_6}$

200-205

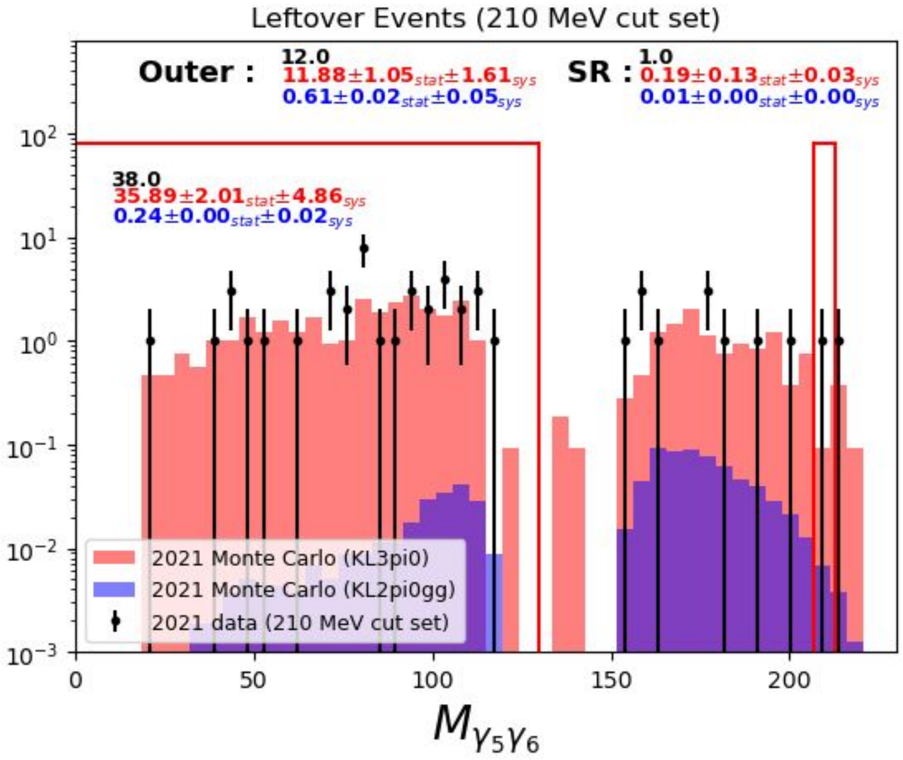


Leftover Events (200 MeV cut set)
Outer :
1.0
3.99±0.74stat±0.54sys
0.31±0.01stat±0.03sys
SR :
0.0
0.28±0.19stat±0.04sys
0.02±0.00stat±0.00sys
21.0
17.64±1.70stat±2.40sys
0.11±0.00stat±0.01sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (200 MeV cut set)
$M_{\gamma_5\gamma_6}$

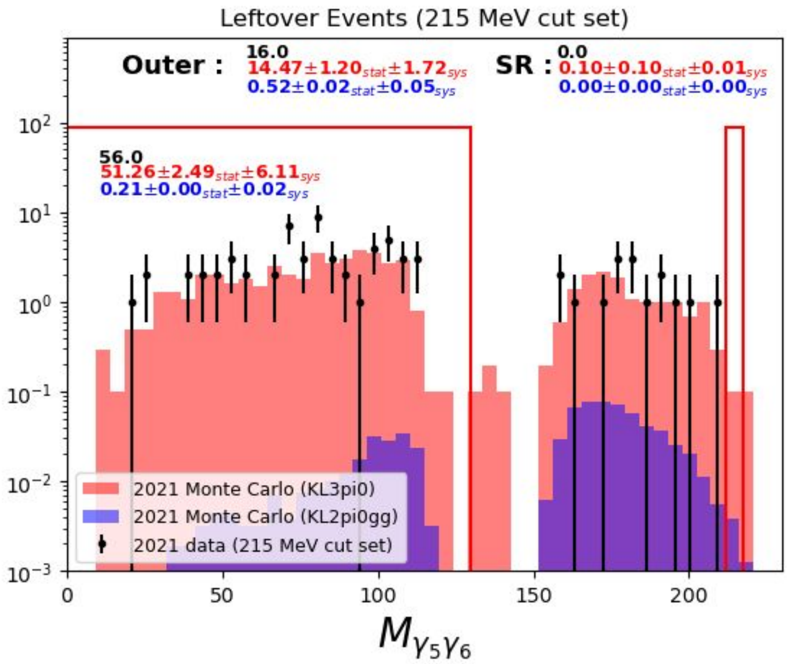


Leftover Events (205 MeV cut set)
Outer :
4.0
5.44±0.80stat±0.73sys
0.39±0.02stat±0.04sys
SR :
0.0
0.46±0.23stat±0.06sys
0.02±0.00stat±0.00sys
30.0
23.77±1.82stat±3.20sys
0.15±0.00stat±0.01sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (205 MeV cut set)
$M_{\gamma_5\gamma_6}$

210-215



Leftover Events (210 MeV cut set)
Outer :
12.0
11.88±1.05stat±1.61sys
0.61±0.02stat±0.05sys
SR :
1.0
0.19±0.13stat±0.03sys
0.01±0.00stat±0.00sys
38.0
35.89±2.01stat±4.86sys
0.24±0.00stat±0.02sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (210 MeV cut set)
$M_{\gamma_5\gamma_6}$



Leftover Events (215 MeV cut set)
Outer :
16.0
14.47±1.20stat±1.72sys
0.52±0.02stat±0.05sys
SR :
0.0
0.10±0.10stat±0.01sys
0.00±0.00stat±0.00sys
56.0
51.26±2.49stat±6.11sys
0.21±0.00stat±0.02sys
2021 Monte Carlo (KL3pi0)
2021 Monte Carlo (KL2pi0gg)
2021 data (215 MeV cut set)
$M_{\gamma_5\gamma_6}$

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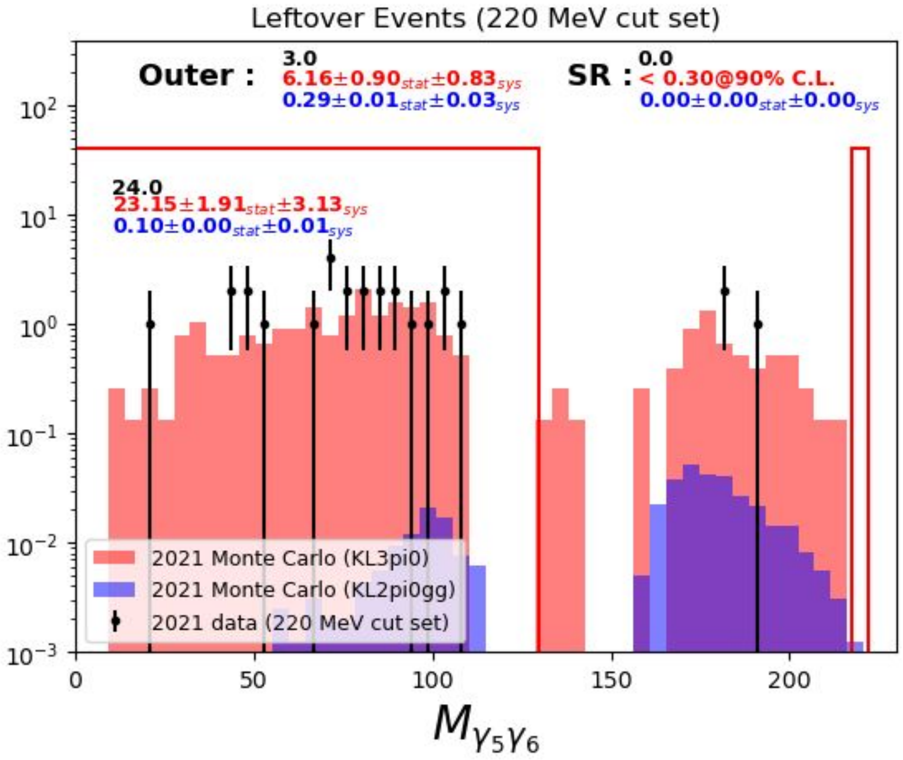
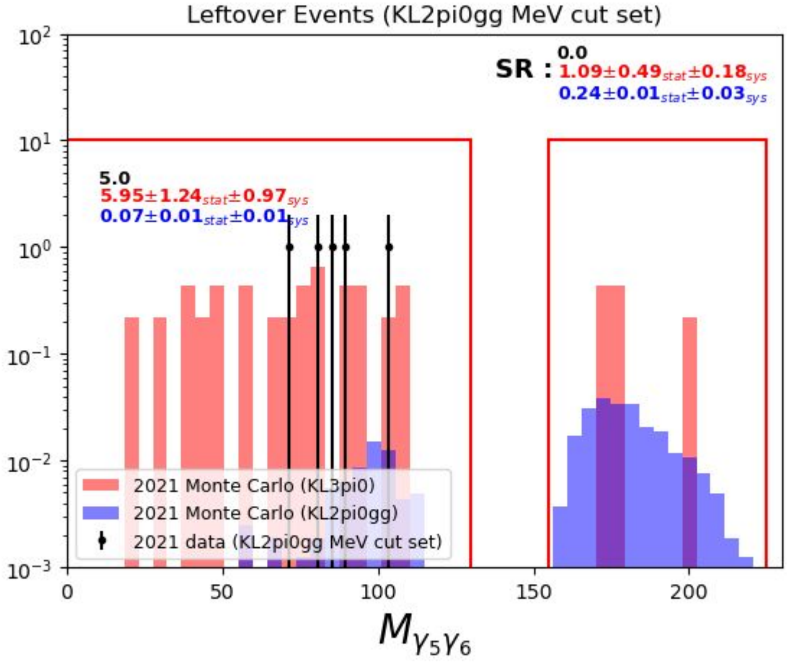
220 MeV + KL2pi0gg





Backup: Details on CL Ratio

1. For each cut condition, I evaluated the signal acceptance in mass bins with enough statistics (some cases it is low).
2, Select a test mass x_m, and determine the acceptance at that mass bin (width 1 MeV) for the two nearest analysis results.
3. Scan signal branching ratio values, and evaluate $s + b$ and b.
4. For each value of $s + b$ and b, evaluate the probability ratio for the two nearby analysis,

$$r = \frac{P(n_{s+b} \leq n_{obs}|s+b)}{P(n_b \leq n_{obs}|b)}$$

5. Calculate the gaussian weighted ratio for the two nearest analyses, where $\mathrm{Gaus}_i(x_m)$.is the amplitude of the gaussian fit mass width at the test mass (weights closest result more)

$$r_w = \frac{\sum_i \mathrm{Gaus}_i(x_m) \cdot r_i}{\sum_i \mathrm{Gaus}_i(x_m)}$$

6. Choose the r_w closest to 10%, and the corresponding branching ratio is the 90% C.L. upper limit

Backup: Cut Optimization for KL2pi0X Analysis

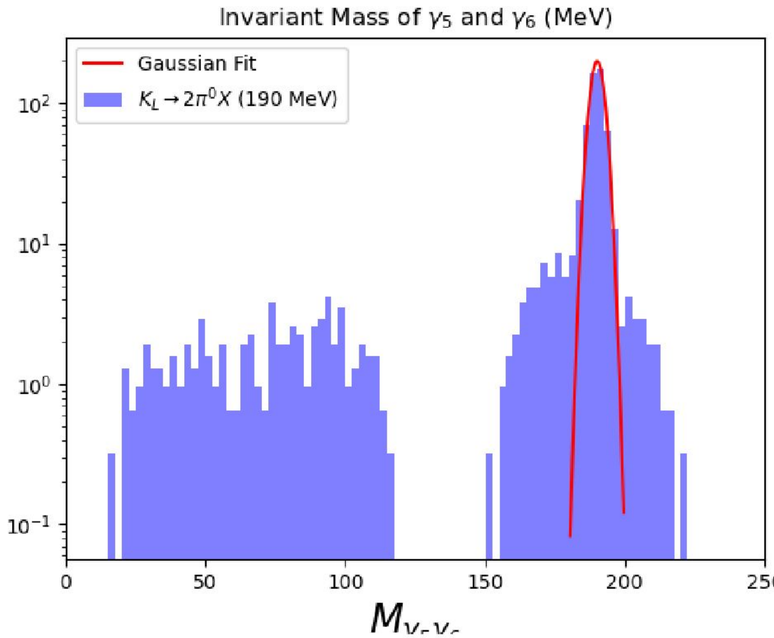
Regions of Interest

- X masses studied range from 160 - 220 MeV (5 MeV intervals)

- Regions of interest are decided based on the signal Monte Carlo mass widths

$$\mu_{peak} \pm 2\sigma$$

- Analysis of KL⇒2pi0gg ROI is above 160 MeV

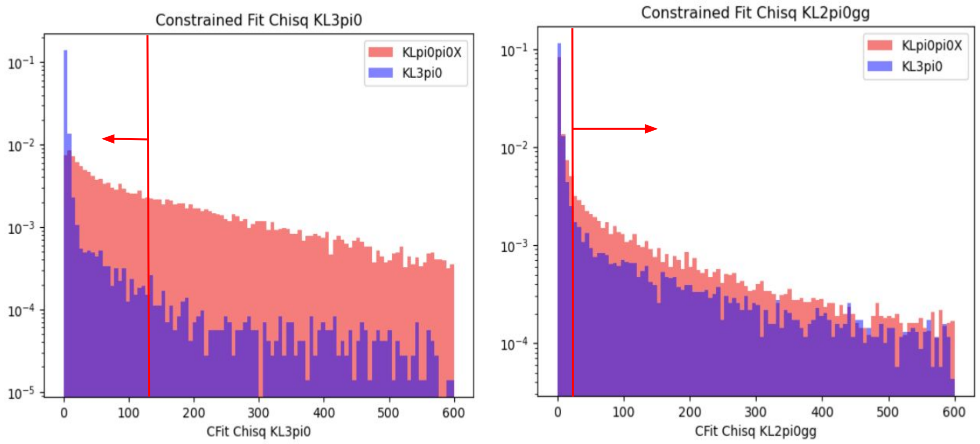


(g) Gaussian fit for X mass of 190 MeV.

Important Variables

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

1. KL⇒2pi0X Constrained Fit χ^2 :
   a. Only assume two pion mass constraints.
   b. Require this value to be *small*.
2. KL⇒3pi0 Constrained Fit χ^2 :
   a. Used an additional pion mass constraint.
   b. Require this value to be *large*.
3. MinCSDDLVal
   a. Developed for n-gamma discrimination
   b. Effective at discriminating odd cluster shapes (photo-nuclear interactions)



Example Cuts

Flexible Cut Conditions: Optimization

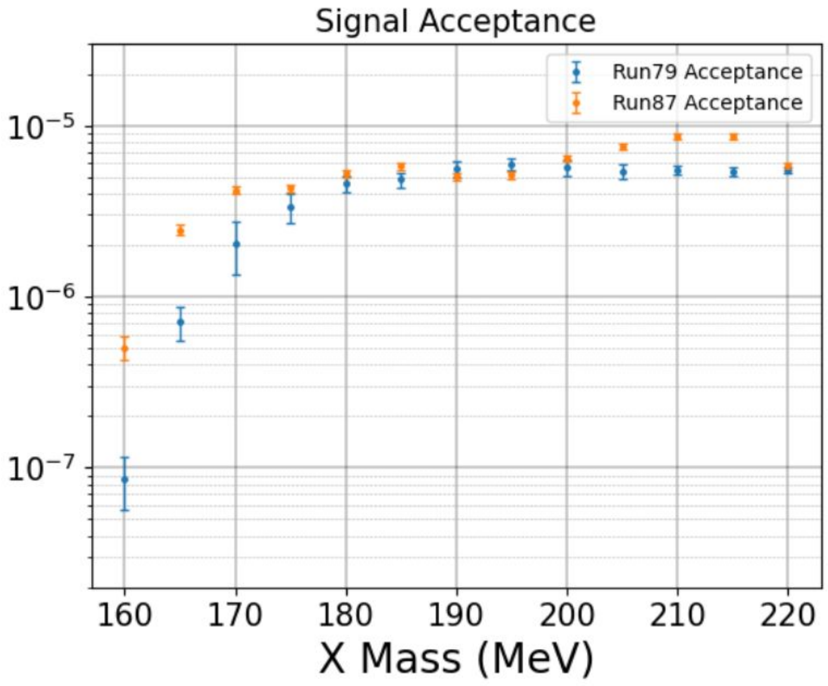
➢ Need to optimize cut conditions from the previous slide.

➢ Same cut set for all X-masses is not efficient
  - Different X mass analyses want different thresholds.

➢ FOM study for each individual X mass ⇒ Dynamic thresholds

➢ Optimize within each X mass ROI:

  - ROI ⇒ $\boldsymbol{\mu_{peak} \pm 2\sigma}$

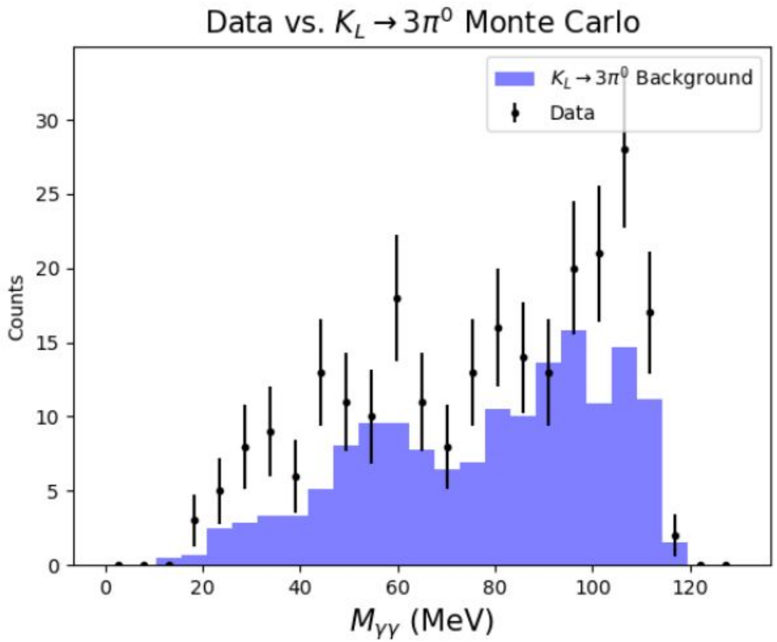


$$f_3(N_{sig}, N_{bkg}) = \sqrt{2\ln(Q)}\,, \qquad Q = e^{-N_{sig}}\left(1 + \frac{N_{sig}}{N_{bkg}}\right)^{N_{sig}+N_{bkg}}$$

Backup: Control Region Study

Low Mass Discrepancy: Background Level Scale Factor

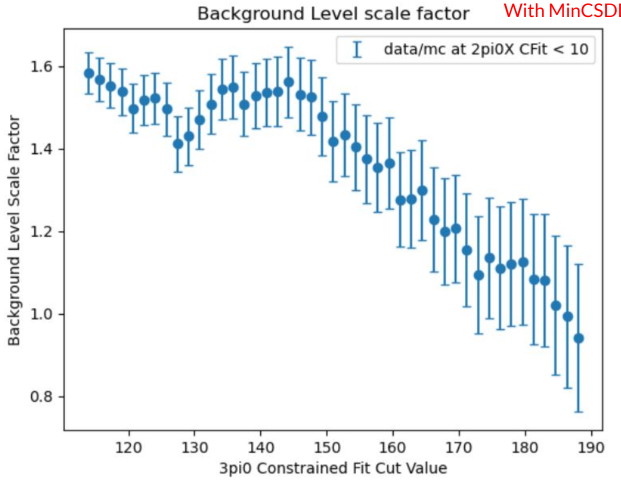
- ➢ Under loose cut conditions, a discrepancy between data and Monte Carlo emerges.
- ➢ Observed in the low mass tail of the Mgg distribution of KL⇒3pi0 data
- ➢ ⇒ Energy mis-measurement is not well understood (photo-nuclear effect???)
- ➢ Introduce a scale factor on the background level in the signal region.

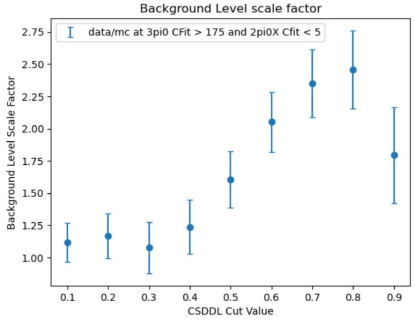


Control Region Analysis

- Study the low mass region while changing the 3pi0 constrained fit cut value.
    - Data/mc ⇒ "Background level scale factor"
- Found large correlations with csddl, for example…
- For a given cut set, the background level scale factor is evaluated considering multivariate correlations (tends to be ~2)

With MinCSDDLVal > 0.1

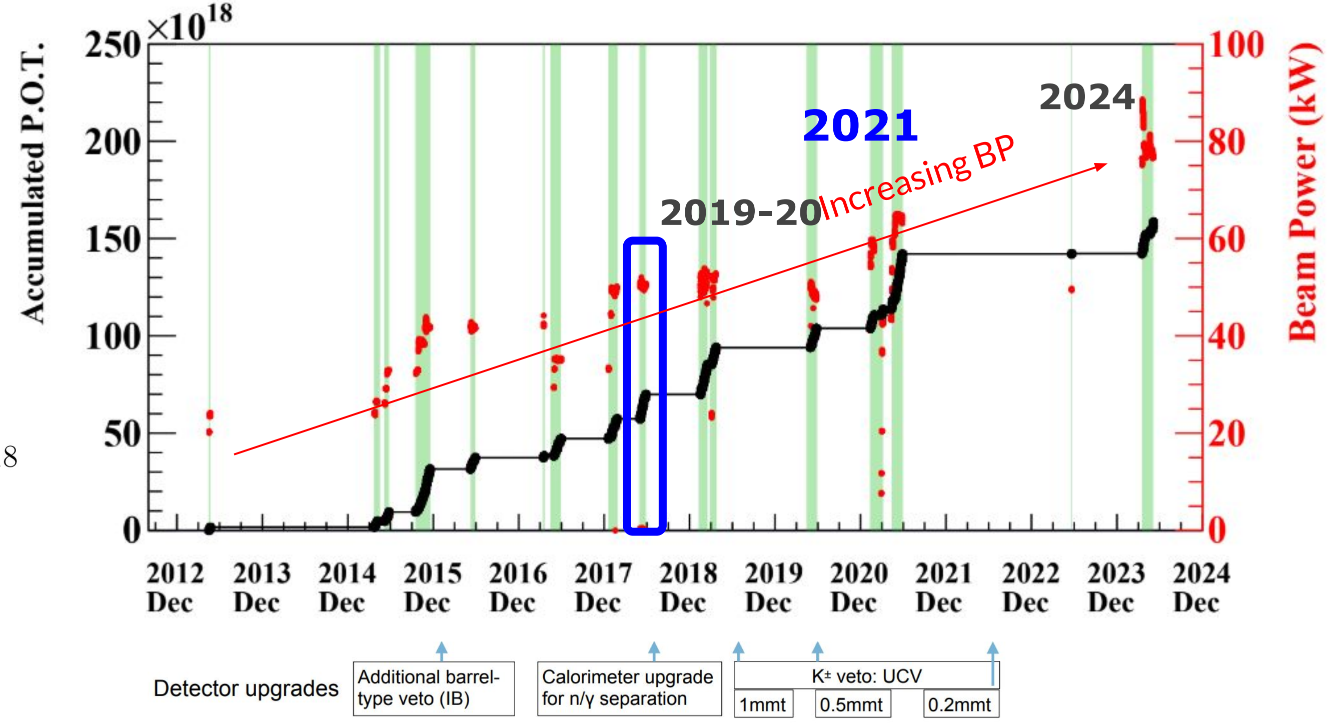




Dark Pair Backup Slides:

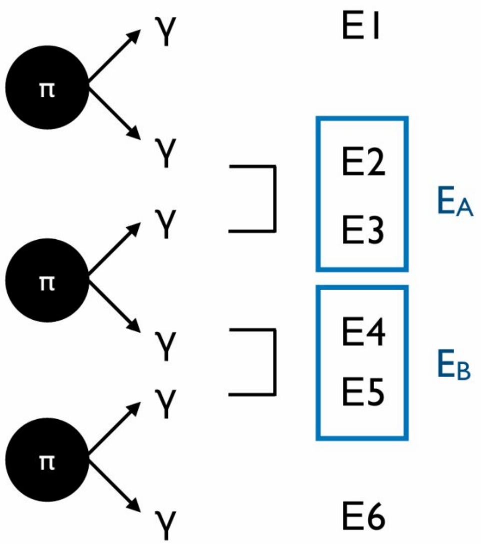
KOTO Run History

- 2021 Data:
  - Average Beam Power $\Rightarrow$ 60kW
  - In 2021 data Analysis: $\approx 40 \times 10^{18}$
- Nearly 4 times larger than June 2018 data taking.



Further Explanation of Double Fusion Rejection

**Slide taken from internal KOTO slides by Chieh Lin



Vertex is well reconstructed $\Longrightarrow$ Opening angle can be obtained.

$$2E_1(E_2+E_3)(1-\cos\theta_{12}) = 2(E_4+E_5)E_6(1-\cos\theta_{56}) = M_X^2 \qquad \text{(eq. 1)}$$

$$2E_1E_2(1-\cos\theta_{12}) = 2E_5E_6(1-\cos\theta_{56}) = M_{\pi^0}^2 \qquad \text{(eq. 2)}$$

By substituting blue box in (eq. 1), we have $\Rightarrow \dfrac{E_3}{E_2} = \dfrac{E_4}{E_5}$

Define "k" as $E_3 = kE_A$ and $E_4 = kE_B$

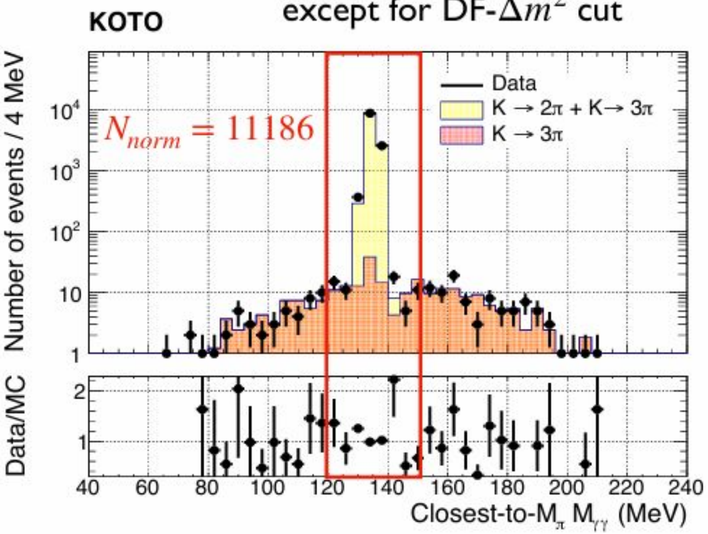
$$2E_3E_4(1-\cos\theta_{34}) = M_{\pi^0}^2 \Rightarrow k^2 = \frac{M_{\pi^0}^2}{2E_AE_B(1-\cos\theta_{34})}$$

If an event is induced by such topology, $0 < k < 1$ is expected.

$K_L^0 \to \pi^0\pi^0$ suppression and normalization

- By requiring M_X to be outside of $M_{\pi^0} \pm 15$ MeV, 99.2% of the $K_L^0 \to \pi^0\pi^0$ events can be removed.
    - Remaining event property:
      Other pairing have smaller $|m_{12} - m_{34}|$.
- Loop over six possible photon pairs and select the one that is closest to M_{π^0}.
    - If it is within $M_{\pi^0} \pm 15$ MeV, this event is rejected.
    - ~100% $K_L^0 \to \pi^0\pi^0$ background can be suppressed.
- Normalization:
    - The red box is dominated by $K_L^0 \to \pi^0\pi^0$ and used to normalize MC to data.

Impose all selection criteria except for DF-Δm^2 cut

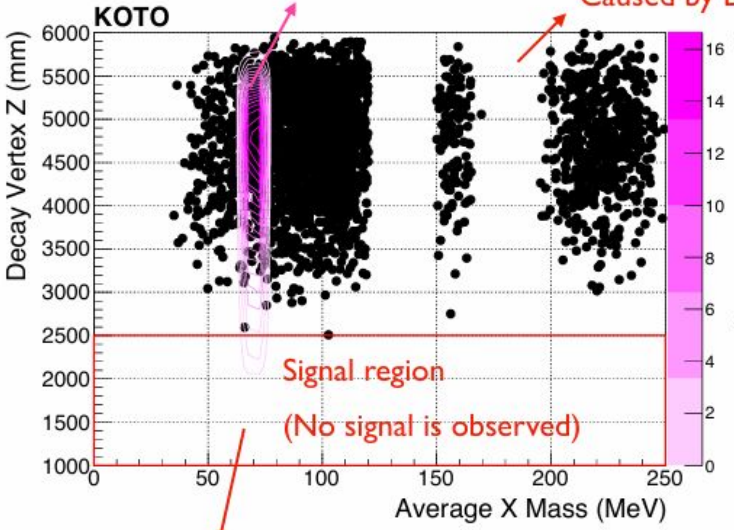


Signal region and background estimation

Signal contour of $M_X = 70$ MeV.

● Data points   Assuming BR = 10^{-6}.

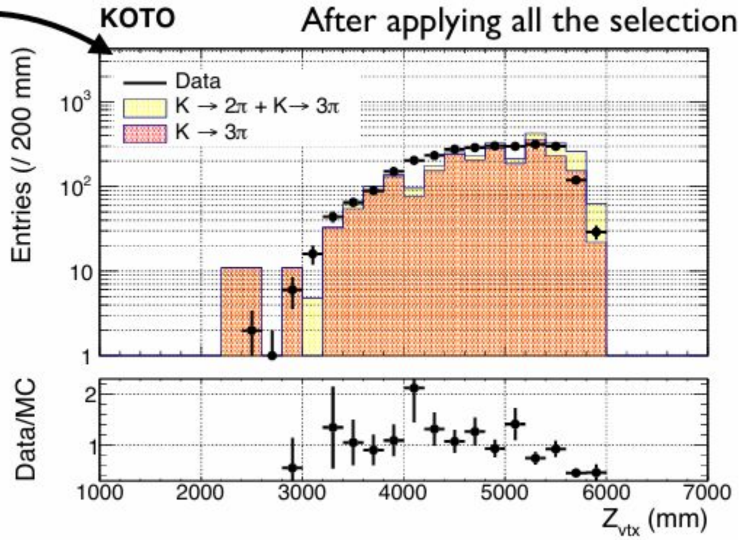
Caused by DF-Δm^2 cut



$$N(K_L^0 \to 3\pi^0) = 0.61 \pm 0.61$$

$$N(K_L^0 \to \pi^0\pi^0) < 0.62 \text{ (90\% CL)}$$

Downstream region can be predicted by $K_L^0 \to 3\pi^0$ MC.



Acceptance Distribution

Acceptance drop around 160-190 MeV caused by double fusion cut selection.

Acceptance loss near pion mass is due to KL2pi0 background

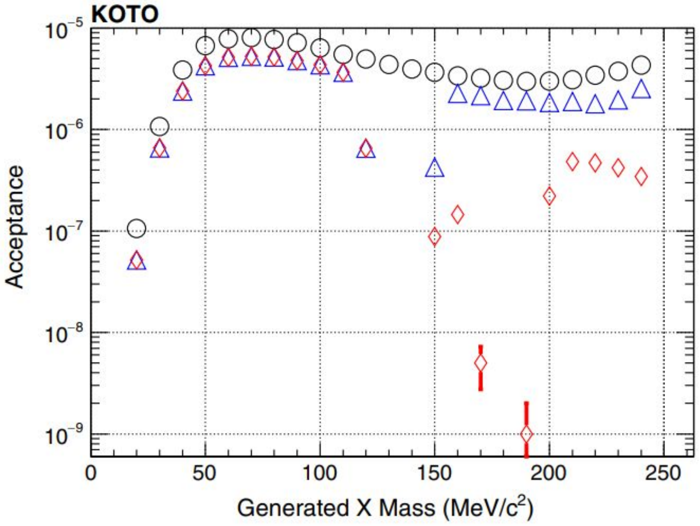
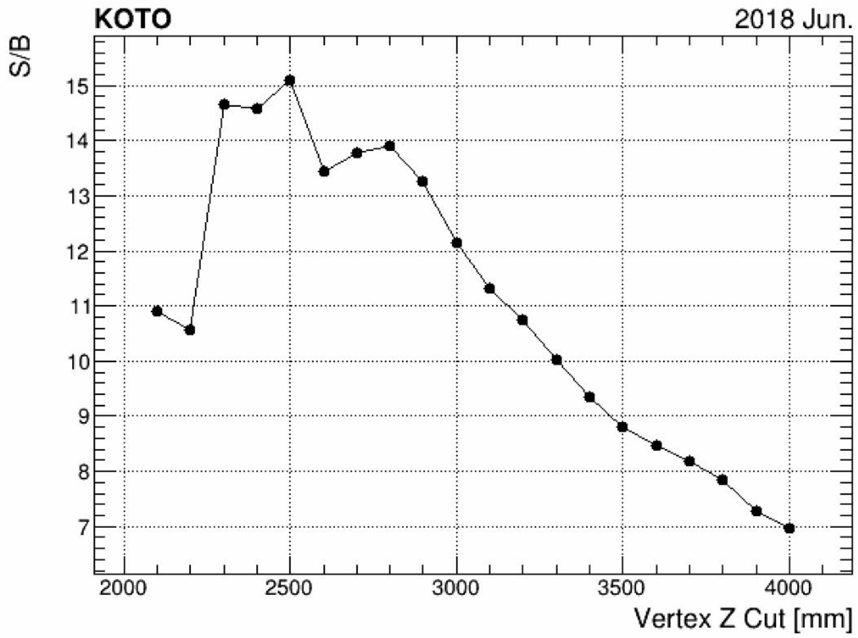


FIG. 5. Signal acceptance versus M_X. The red diamond, blue triangle, black circular markers indicate the acceptance after imposing all the cuts, all but the ΔM^2_{DF} cut, and further excluding the cuts against the $K^0_L \to \pi^0\pi^0$ background, respectively.

Vertex Z Optimization

Require upstream decay vertex position to minimize KL⇒3pi0 fusion background.

Longer ToF ⇒ further separation of hit positions.



Dark "Photon": Mass Dependence on UL

Larger mass ⇒ Lower acceptance mostly due to the high deposit energy requirement (550 MeV).