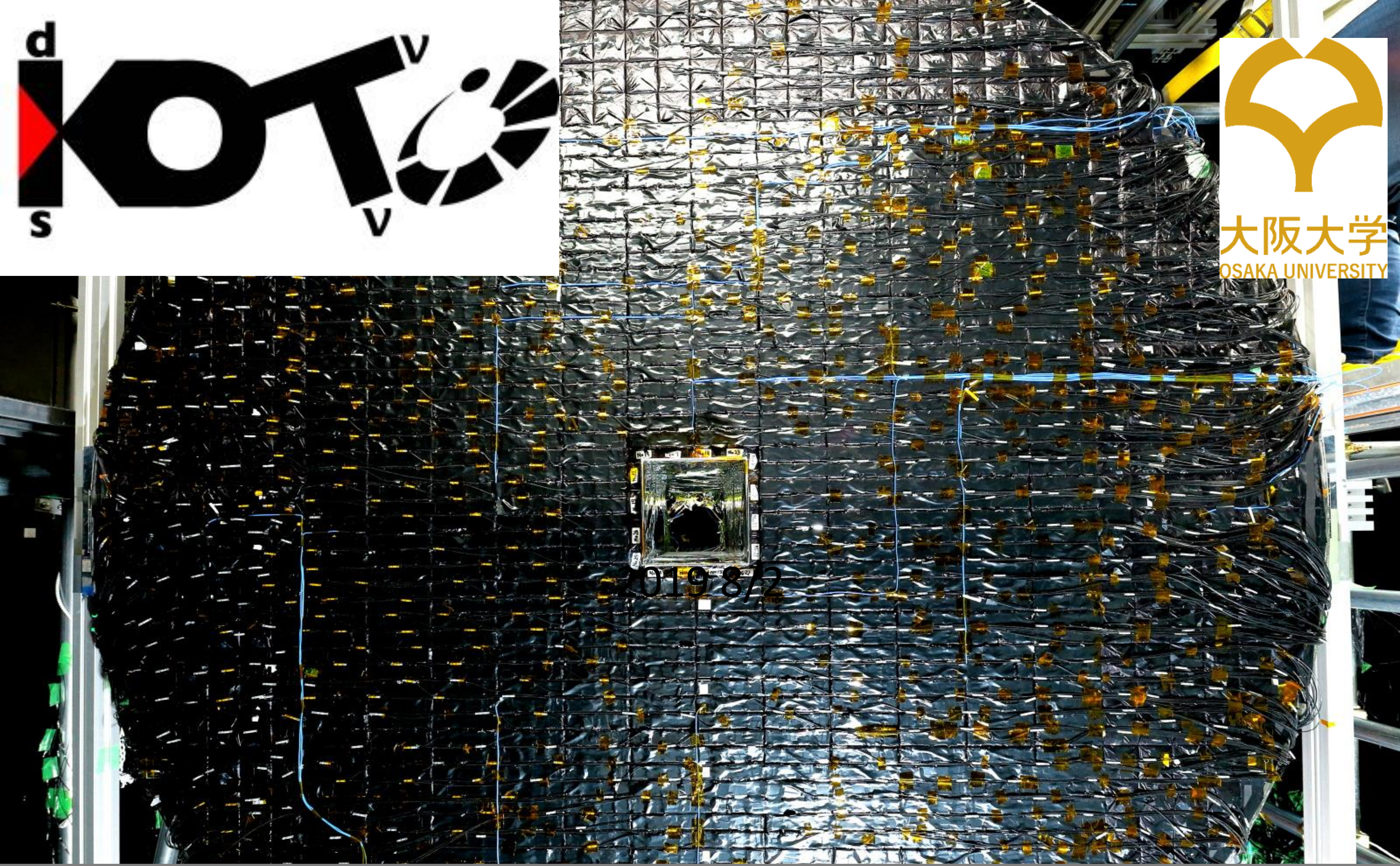


Search for $K_L \to \pi^0\gamma$ decay in the KOTO experiment

Nobuhiro Shimizu Sep. 9th

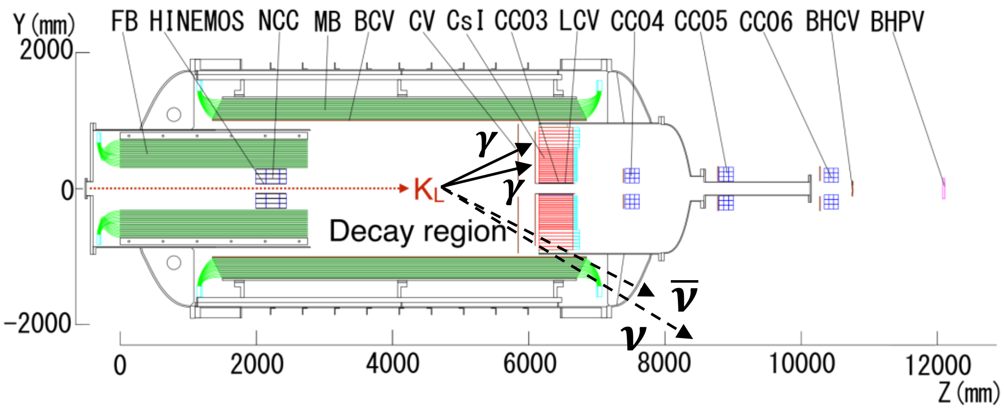
$K_L \to \pi^0\gamma$ decay?

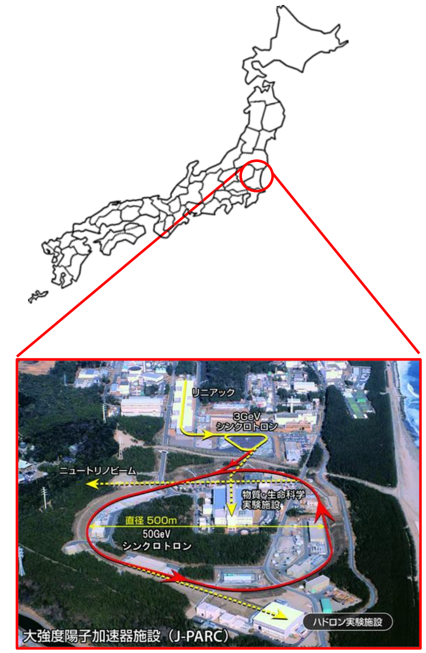
- No measurements up to now
  - ✔ $s \to d\gamma$ transition, forbidden by FCNC
  - ✔ Violates CP
  - neither for $K_S \to \pi^0\gamma$
    - Nice prove of New Physics??
  - violates an angular conservation
    - K and π = spin zeros: the spin of γ must be "compensated" by an orbital angular momentum, but back-to-back configuration cannot produce L_z (along the decay axis).
    - IF v > "speed of light", it's allowed. (see PRD **59** 116008)

<u>Oppositely to say,</u>

<u>good test of the Lorentz invariance in the realm of short distances</u>

The KOTO experiment



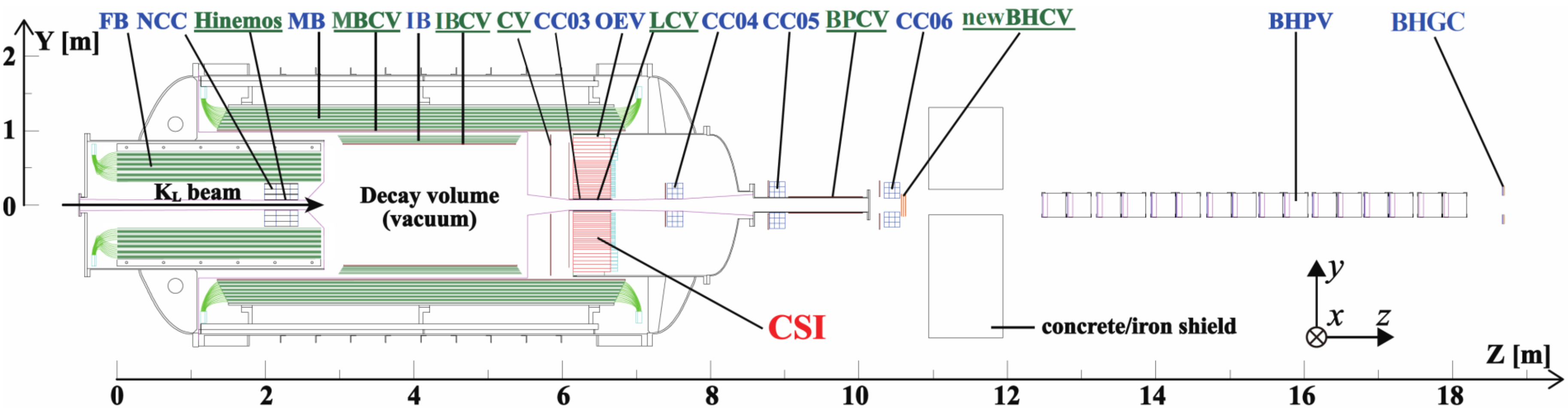


- **New Physics search via $\boldsymbol{K_L \to \pi^0 \nu \bar{\nu}}$**
  - $\mathcal{B}_{\mathrm{SM}}(K_L \to \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$ JHEP 1511 033 (2015)
  - "key" ＝ *not to miss any photons*

    Hermetic Veto counters surrounding the decay volume

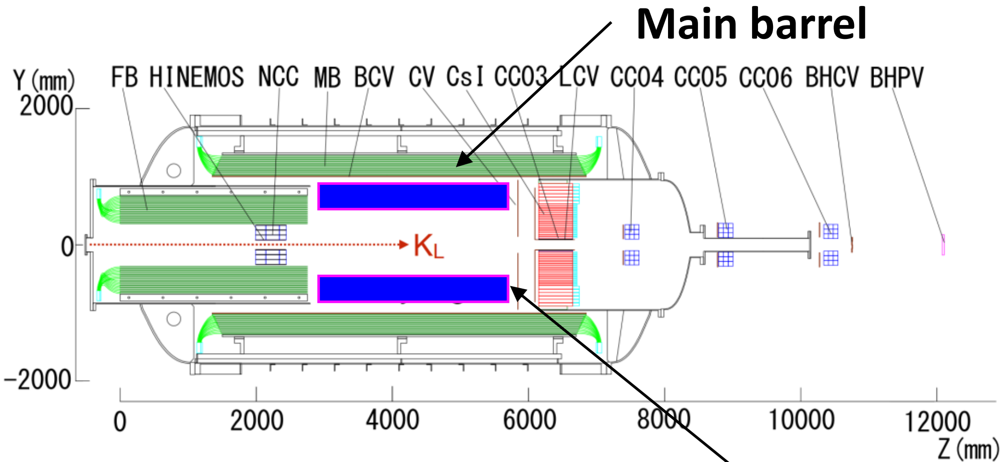
→ **High intensity K_L beam & low inefficiency**
KOTO detector is ideal tool to search for $K_L \to \pi^0 \gamma$

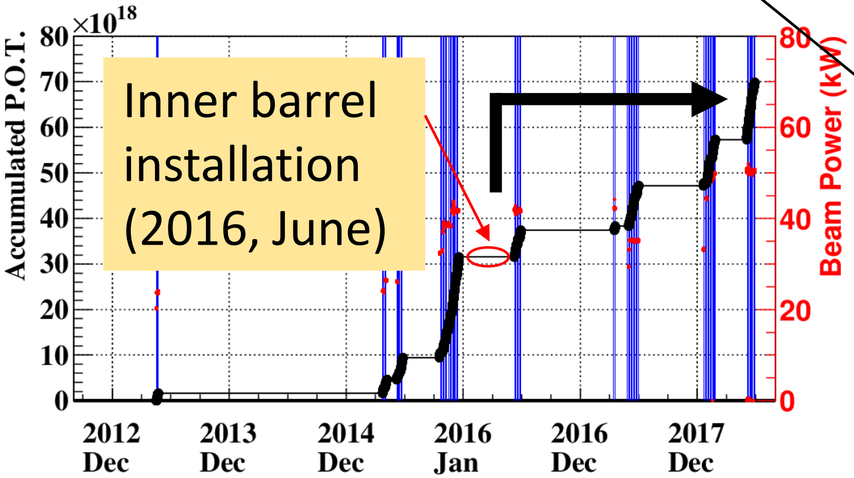
KOTO detector

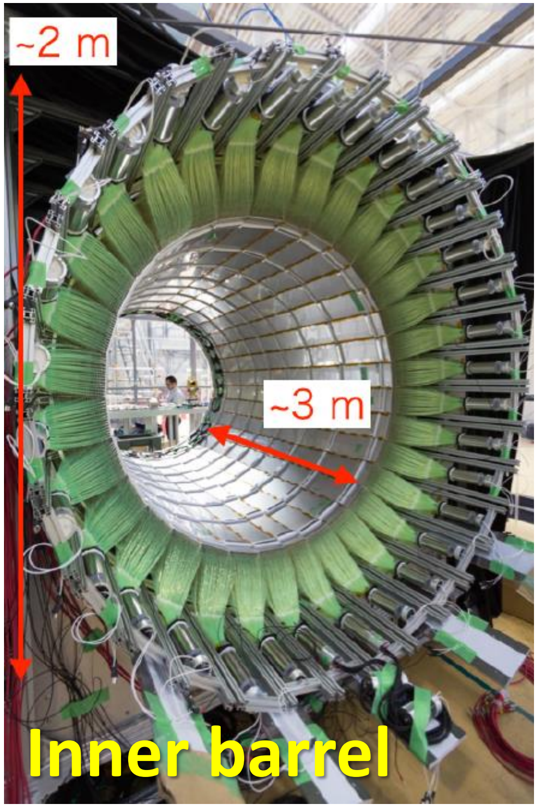


- **Measure energy and position of photons by undoped CsI calorimeter**
- **Decay volume: surrounded by 18 types of veto detectors.**
- **Two barrel counters to veto photons: main barrel (MB) and inner barrel (IB)**
- **Charged veto in front of CsI**

Data taking





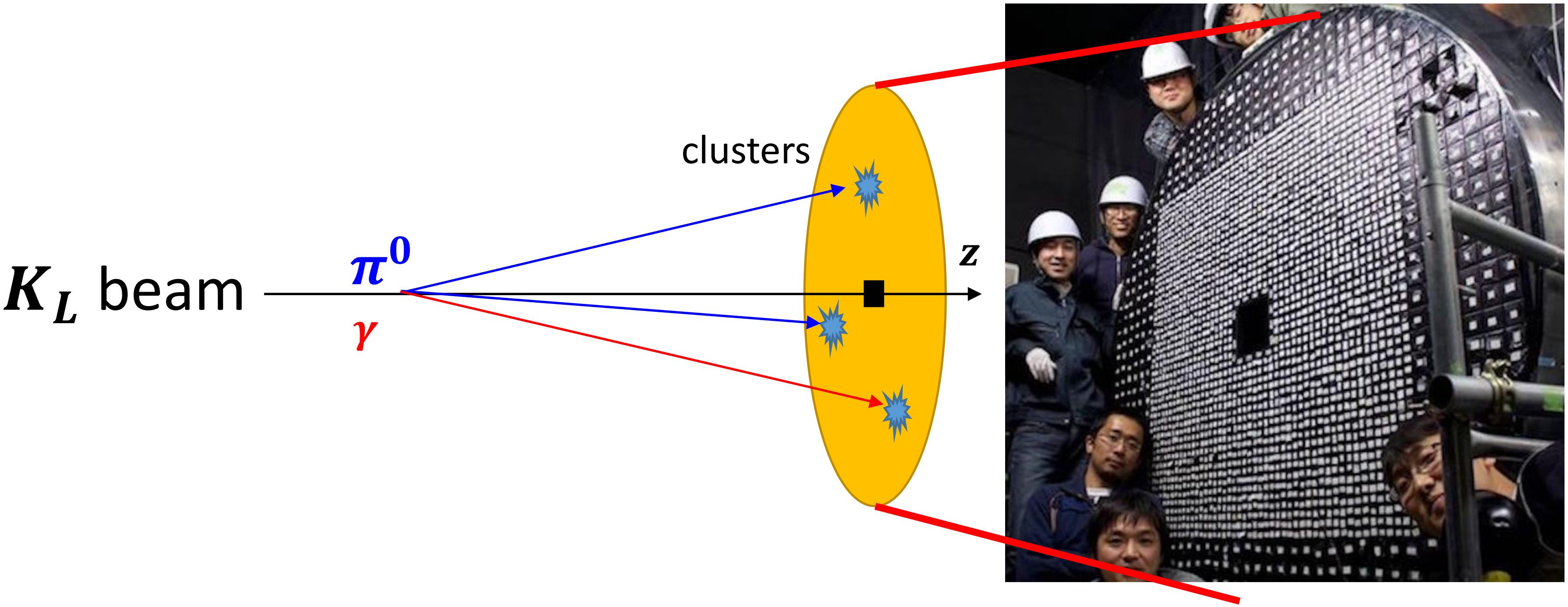


- Data taken during **2016 – 2018**: $\sim 19 \times 10^{18}$ Protons On Target (POT)
- Trigger: 3-cluster w/ energy deposit at CsI calorimeter

→ Data corresponding to $\mathbf{2.9 \times 10^{18}}$ POT was analyzed.

Reconstruction

Reconstruction of $K_L \rightarrow \pi^0\gamma$



1. Find events which have exactly 3 clusters
2. Reconstruct a π^0 : $m_{\pi^0}^2 = 2E_1E_2(1-\cos\theta_{\gamma\gamma}) \rightarrow z_{vtx}^{\pi^0}$
3. Reconstruct a K_L: $m_{K_L}^2 = (p_{\gamma_1}+p_{\gamma_2}+p_{\gamma_3})^2 \rightarrow z_{vtx}^{K_L}$

   Two types of vertex position, which should be close.
4. Define $\Delta z_{vtx} = z_{vtx}^{\pi^0} - z_{vtx}^{K_L}$ to suppress various BGs

Event selection

Event selections

1. **Online trigger (veto and cluster counting)**
2. **Requirement of $N_{cls} == 3$ offline**
3. **Vetoes**

4. **Cluster shape discrimination (CSD)**

5. **Kinetic cuts**
   - ✓ $\Delta z_{vtx} = z_{vtx}^{\pi^0} - z_{vtx}^{K_L}$
   - ✓ E_{γ}^{min}

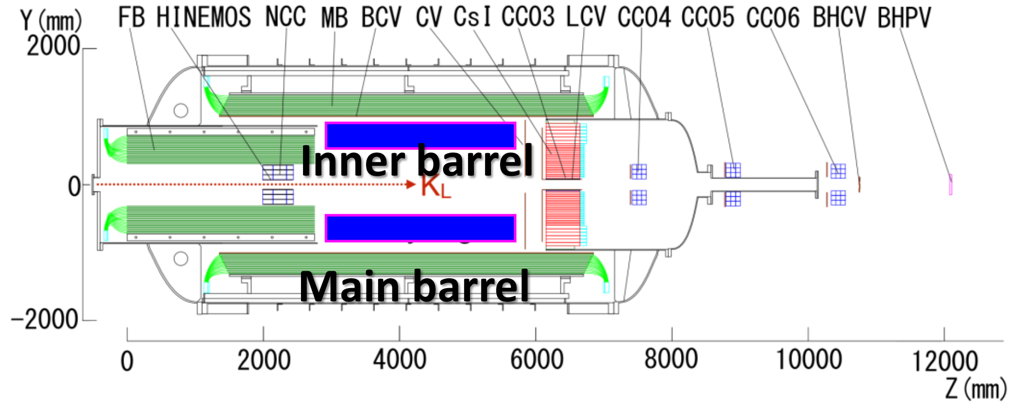
6. **Signal box**
   1. $(z_{vtx}^{\pi^0}, M_{\pi^0\gamma})$

Possible background sources

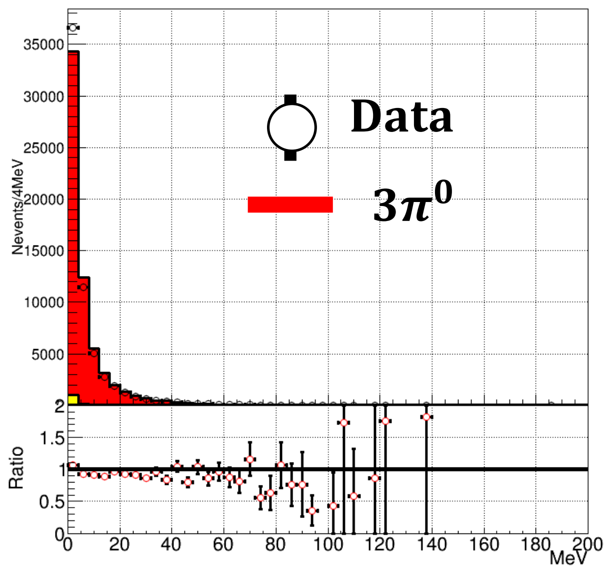
Large

- $K_L \to 2\pi^0$ $\cancel{\gamma}\ \gamma\ \gamma\ \gamma$ 1
  1. a photon missed by some way
  2. two photons fuse $\gamma\ \gamma\ \gamma\ \gamma$
- $K_L \to 3\pi^0$ $\gamma\ \gamma\ \gamma\ \cancel{\gamma}\ \gamma\ \gamma$ <1
  mechanisms similar to $2\pi^0$
- Neutron induced BG
  π^0 produced from *n* and a single acc. cluster <0.01
- $K_L \to 2\gamma$
  combines with neutrons $\gamma\ \gamma\ n$ <0.01
- $K_L \to \pi^+\pi^-\pi^0$
  combines with neutrons $\gamma\ \gamma\ n\ \cancel{\pi}^+\ \cancel{\pi}^-$ <0.01
- $K_L \to \ell\pi\nu\ (\ell = e \text{ or } \mu)$ <0.001
  e.g., $e^+e^-_{\text{detector}} \to 2\gamma$ and π^- missed by CV

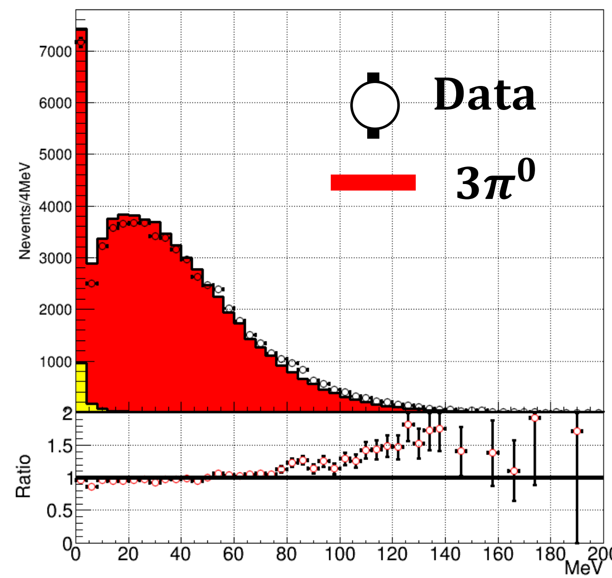
Veto counters



Main barrel veto energy

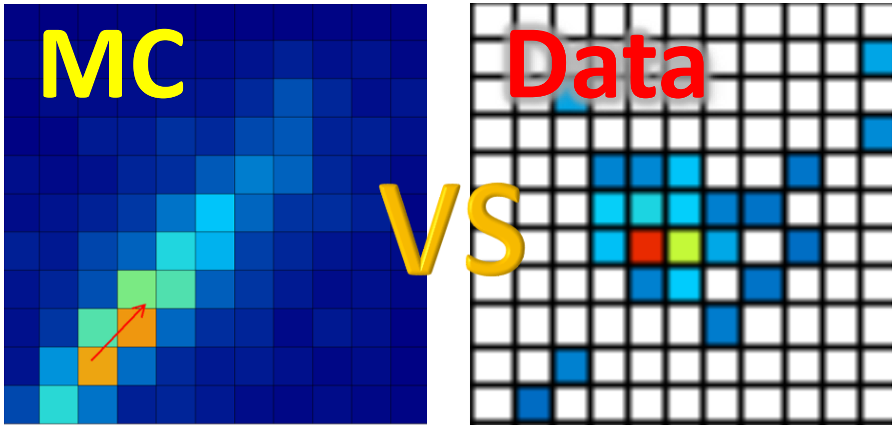


Inner barrel veto energy



Two barrel veto counters play crucial roles to suppress $K_L \rightarrow 2\pi^0$ and $K_L \rightarrow 3\pi^0$ decay modes.

Cluster shape discrimination (CSD)



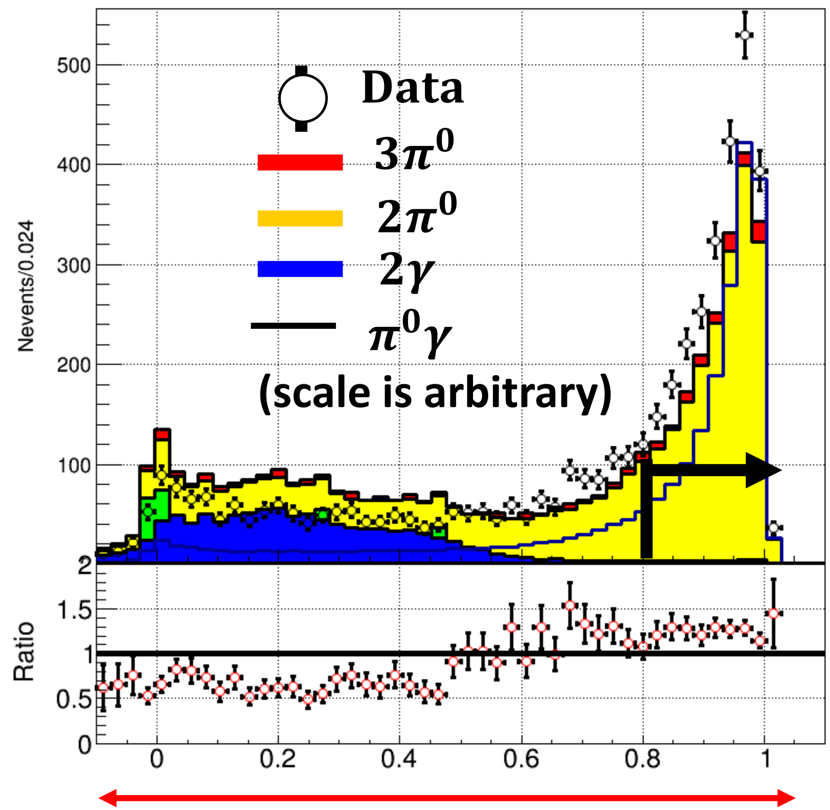
Energy deposition of photon cluster

Using neural network, the shower shape development in the CsI calorimeter is evaluated.

→ Separate **clean photon clusters** from those of **BG**

① neutron cluster
② fused cluster

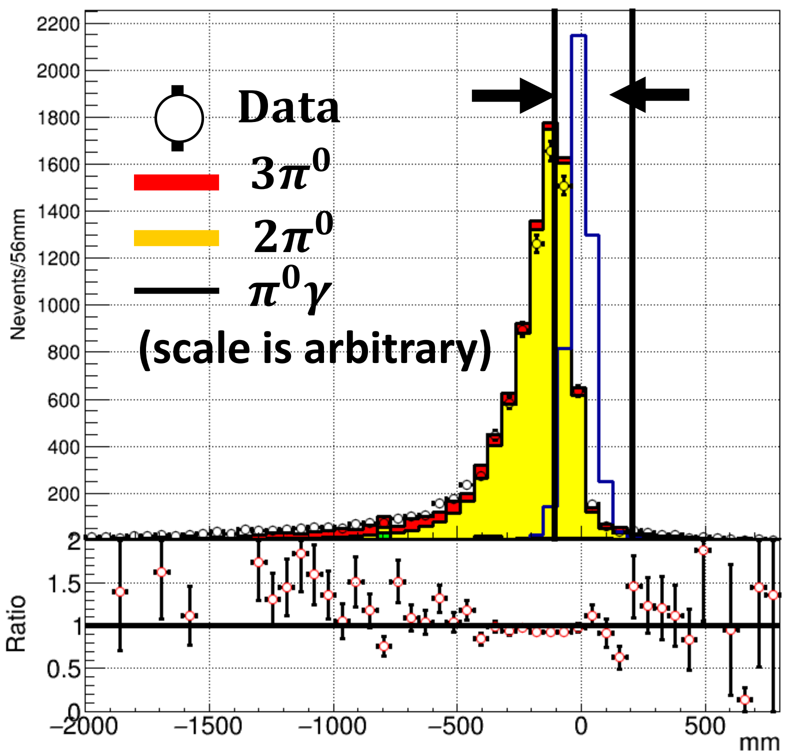
minimum CSD (the smallest one out of 3)

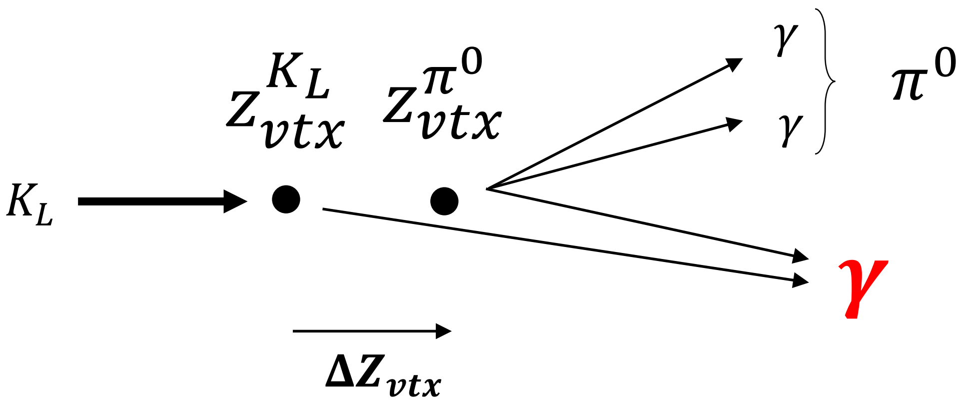


not γ like γ like

Δz_{vtx} distribution

Under vetoes, CSD





In the signal case $\boldsymbol{\Delta Z_{vtx} \sim 0}$

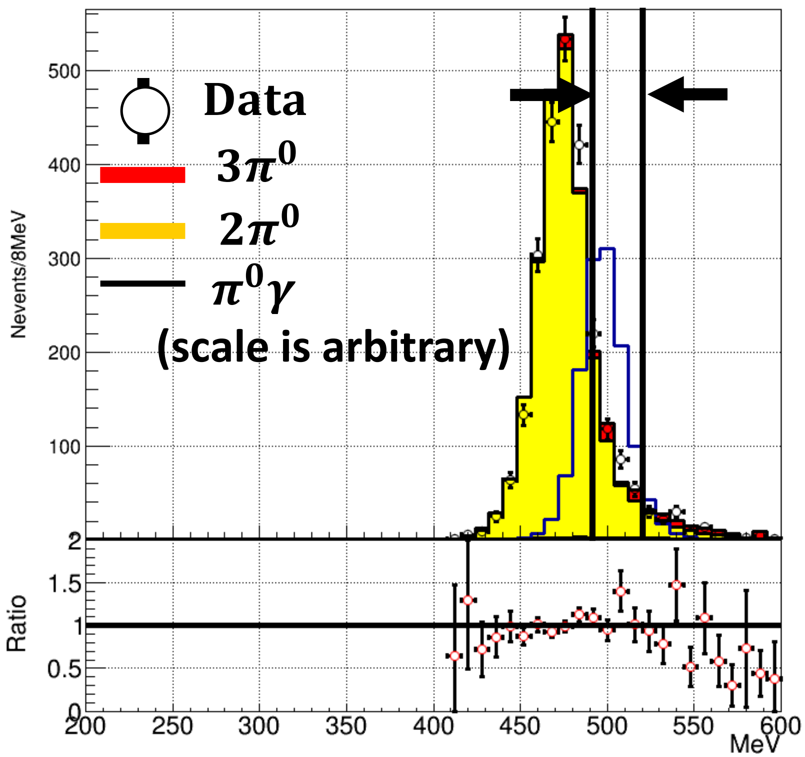
$$\mathbf{-100} < \boldsymbol{\Delta z_{vtx}}/\mathrm{mm} < \mathbf{200}$$

One of the important cut to reduce $2\pi^0$ decay

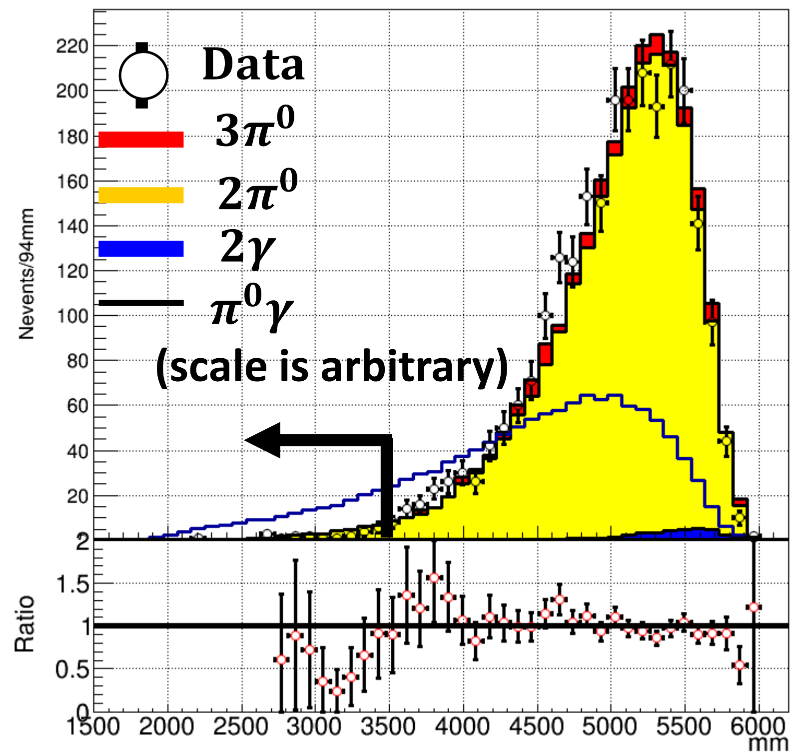
$M_{\pi^0\gamma}$ and $z_{vtx}^{\pi^0}$ distributions

Under vetoes, CSD, Δz_{vtx} cuts

$M_{\pi^0\gamma}$



$z_{vtx}^{\pi^0}$



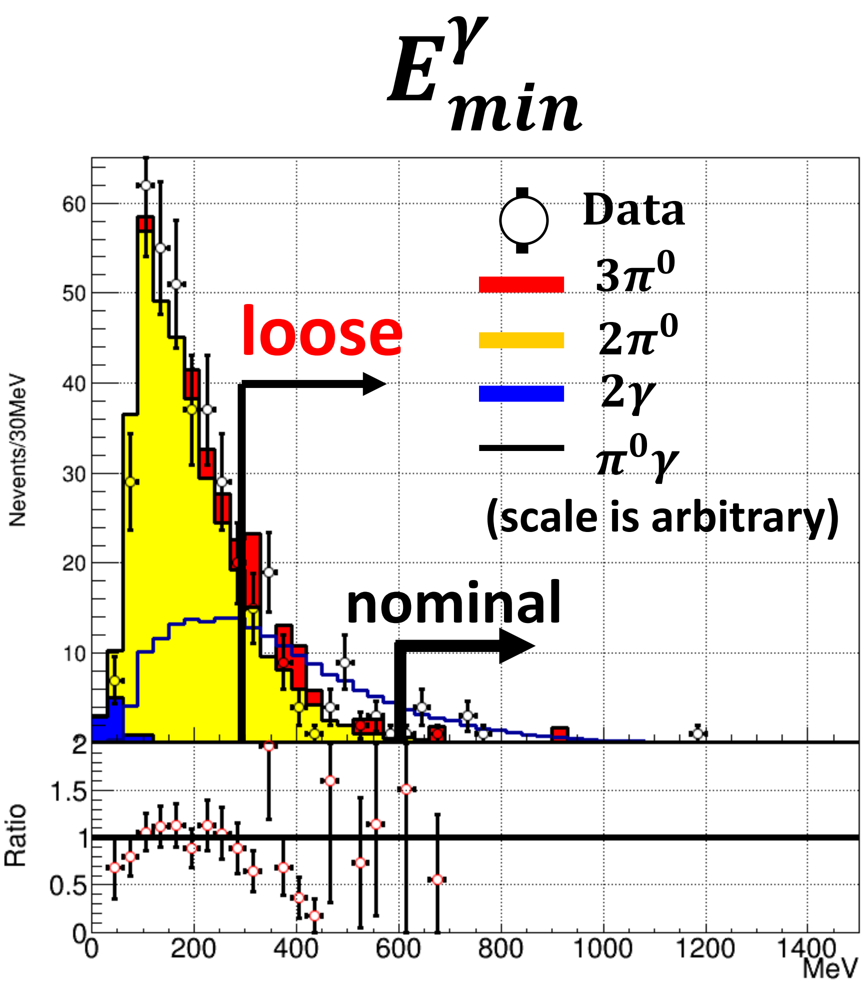
These variables are used for defining the signal box.

$$\mathbf{490} < M_{\pi^0\gamma}/\mathrm{MeV} < \mathbf{520},\ \mathbf{1500} < z_{vtx}^{\pi^0}/\mathrm{mm} < \mathbf{3500}$$

E^{γ}_{min} distribution

Under vetoes, CSD, M_{K_L}, Δz_{vtx} cuts

E^{γ}_{min}: minimum photon energy



Under M_{K_L} cut, E^{γ}_{min} is useful variable to remove $2\pi^0$.

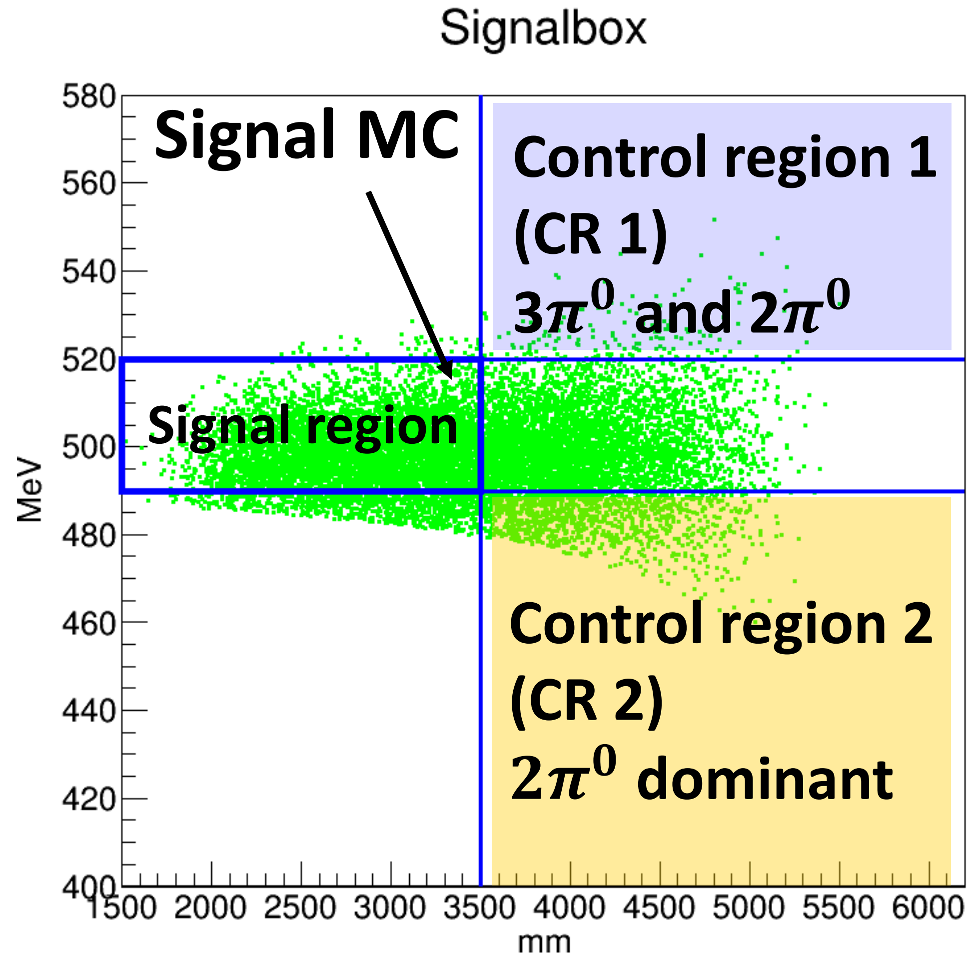
To measure $2\pi^0$ and $3\pi^0$ a loose E^{γ}_{min} cut is also used.

Signal box

Under the condition of

1. ***vetoes,***
2. ***CSD,***
3. $\boldsymbol{\Delta z_{vtx}}$***,***
4. $\boldsymbol{E^{\gamma}_{min}}$ ***cuts***

Signal box, defined in the 2D plane: $\boldsymbol{(z^{\pi^0}_{vtx}, M_{\pi^0\gamma})}$



- ✓ $\mathcal{B}(K_L \to \pi^0\gamma)$ is obtained as a ratio towards $\mathcal{B}(K_L \to 2\pi^0)$
- ✓ CR2 is used to normalize statistics/estimate $\boldsymbol{2\pi^0}$ BG
- ✓ Signal region (SR) is blinded before determining the selection critaria to avoid human bias.

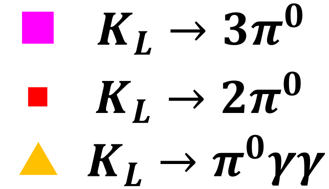
Summary of the event selection

Uncertainties are statistical only.

Step (after)	Signal ACC (10^{-5})	$2\pi^0$ ACC (10^{-5})	Nobs (Data)
Ncls==3 and online veto*	219	31	1150585
Shape χ^2	204	24	233568
Fiducial cut	189	22	214043
Veto	71	2.0	15732
Cluster shape	51	1.3	9483
Δz_{vtx}	49	0.41	2544
(loose) E^{γ}_{min}	(24.4) 5.0	(0.1) 0.0041	(635) 36
loose CR2		0.0888 ± 0.007	528
SR	2.11 ± 0.03	$(5.56 \pm 1.76) \times 10^{-5}$	?

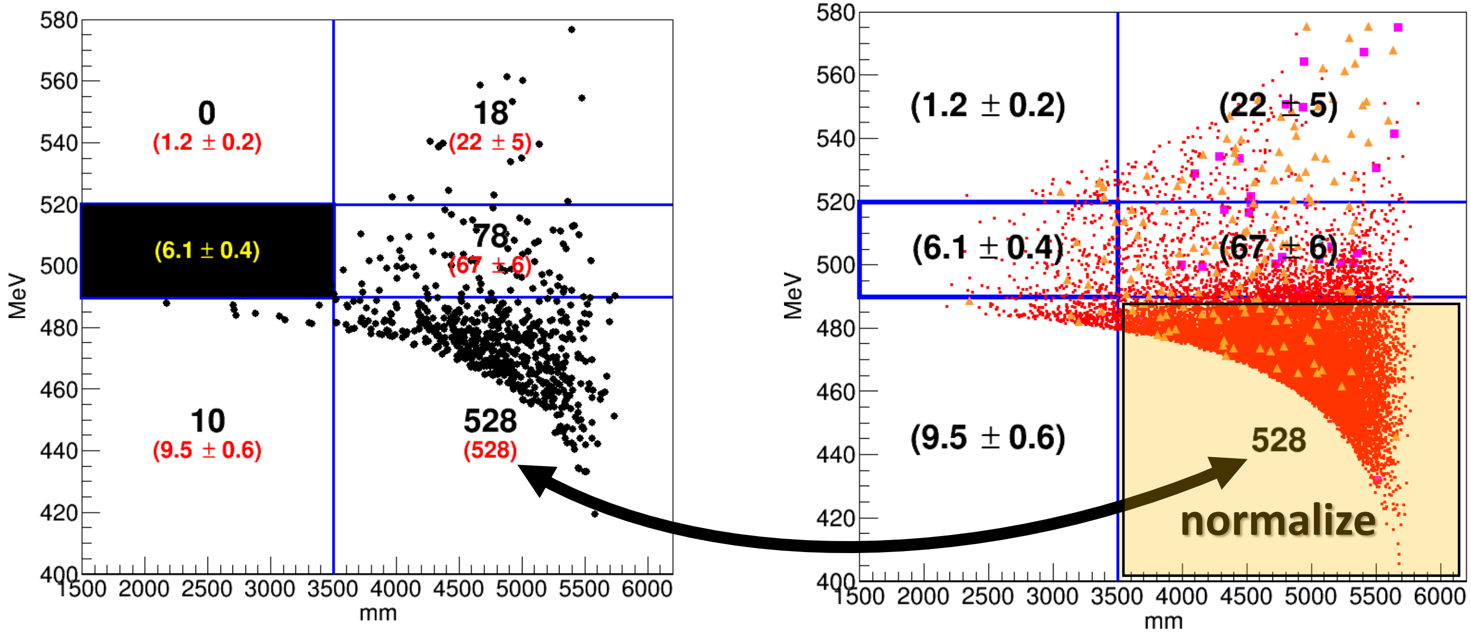
Single event sensitivity of signal: $\frac{1}{N_{K_L}\epsilon(K_L \to \pi^0\gamma)} = 6.9 \times 10^{-8}$

Z-$m_{\pi^0\gamma}$ correlation plot under loose cut

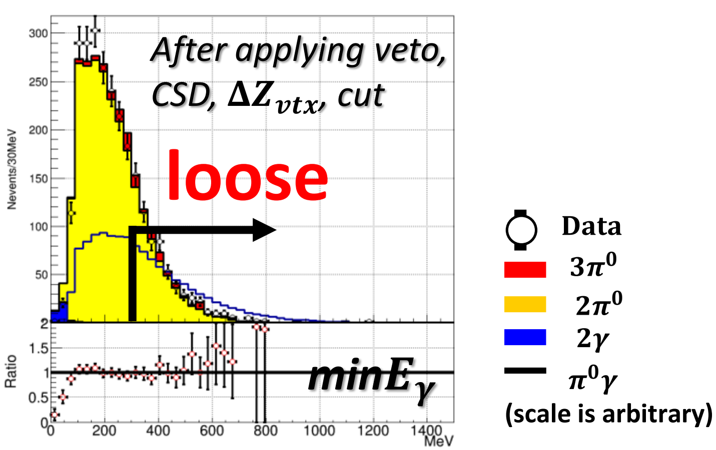


*After applying veto, CSD, ΔZ_{vtx}, **loose $minE_\gamma$** cut*

Data **MC**

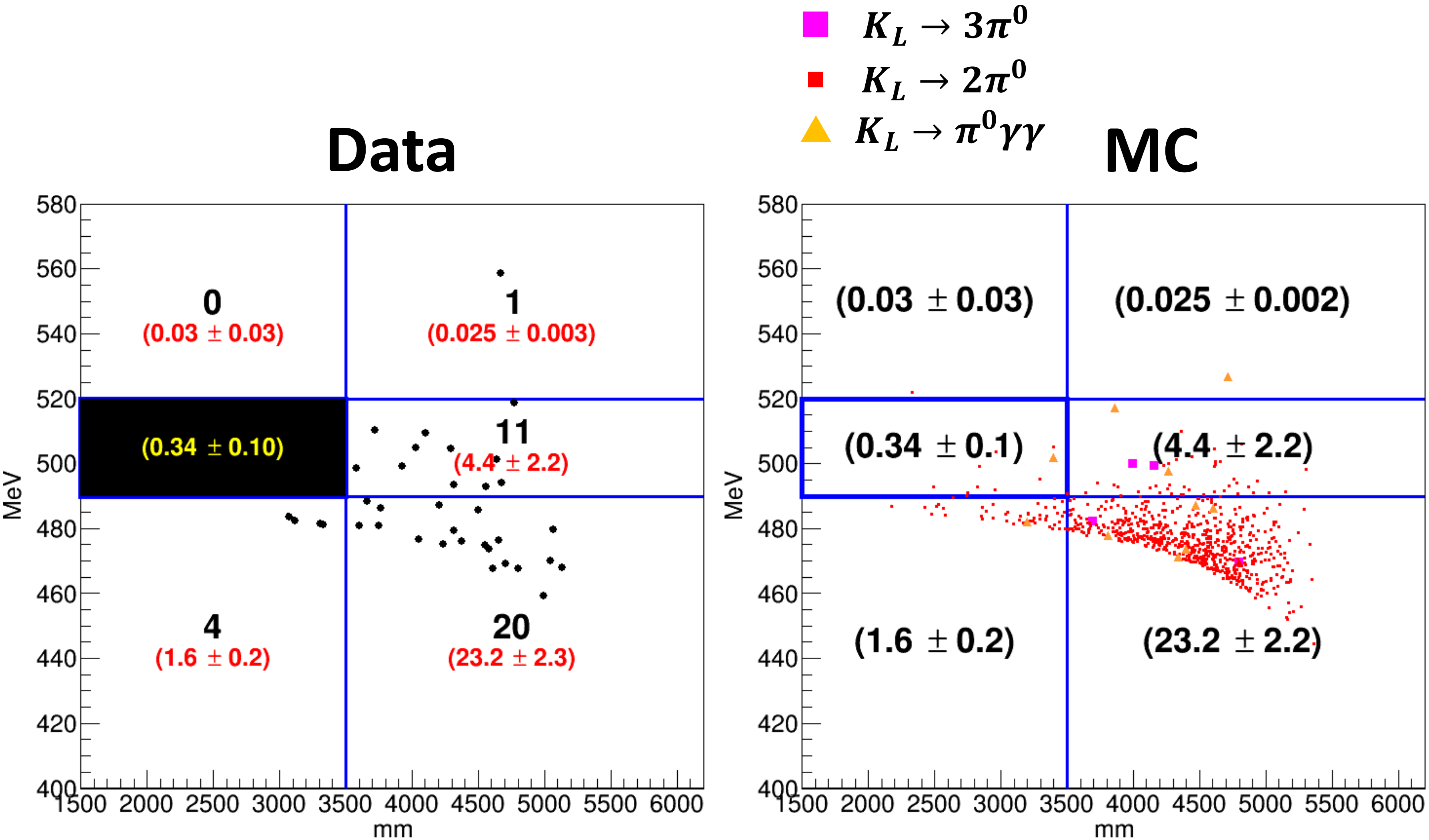


Control region 2 (CR 2)



We use CR2 region with loose $minE_\gamma$ selection to measure $K_L \to 2\pi^0$ contribution of data.

Z-$m_{\pi^0\gamma}$ correlation plot of under tight cut



The expected number of events in the signal region is 0.34 ± 0.10

BG contribution (summary)

Sources	Expected in signal box	Comment
$K_L \to 2\pi^0$	0.32 ± 0.11	Evaluated by MC
$K_L \to 3\pi^0$	<0.5 (68% C.L)	Data driven estimation
$K_L \to 2\gamma$	<< 0.06 (68% C.L)	Evaluated by full MC
Neutron induced BG	<<0.02 (68% C.L)	Evaluated by dedicated MC
Other K_L decays	<0.02	
Sum	0.85 (<1.0 at 68% C.L.)	

Dominant background: the $K_L \to 2\pi^0$ decay due to inefficiency of the barrel veto

$K_L \to 3\pi^0$ decay can be BG due to
① production of the overlapped γ clusters (fusion)
② wrong paring of $\pi^0 \to 2\gamma$ conbinations.
Production of the sufficient amount of MC sample is difficult,
but data driven approach gives an upper limit of 0.5 at 68% C.L.

Other decays → negligible.

Systematic uncertainty of S.E.S

$$\mathcal{B}(K_L \to \pi^0\gamma) = \frac{N^{obs(SR)}}{N_{2\pi^0}^{obs(CR2)}} \cdot \frac{\epsilon_{2\pi^0}^{CR2}}{\epsilon_{\pi^0\gamma}^{SR}} \cdot \mathcal{B}(K_L \to 2\pi^0)$$

preliminary

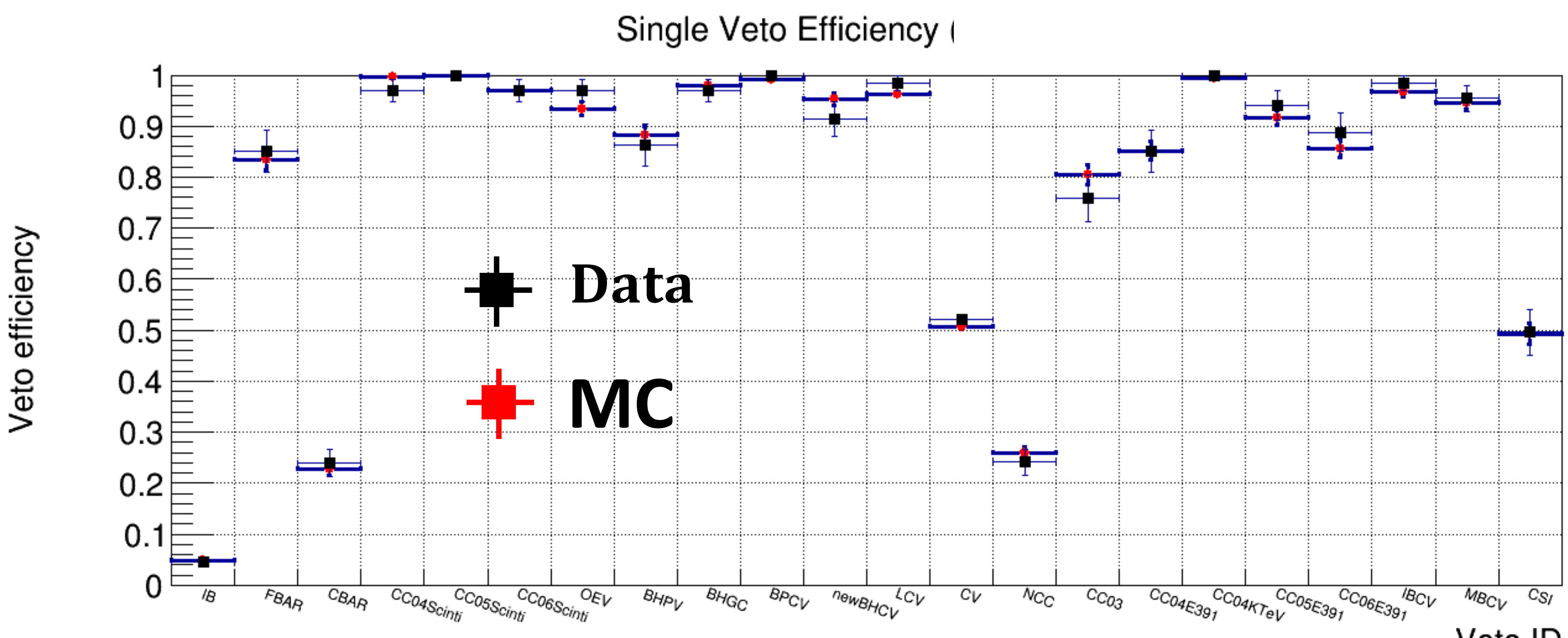
Source	σ_ϵ/ϵ (in %)	Comment
$\mathcal{B}(K_L \to 2\pi^0)$	**0.6**	From PDG
Geometry	**1.5**	Estimated by varying beam E (+1%) and position (x,y=1mm) for signal
Veto cuts	**17**	By comparing data and MC in CR2 with $\boldsymbol{\Delta Z_{vtx}}$ cut
Online veto	**6.4**	From the detector bits in the minimum bias data
Kinematic cuts	**12**	100% error of $\|1-\epsilon_{Data}^{2\pi^0}/\epsilon_{MC}^{2\pi^0}\|$
Clustering	**1.0**	Compare five and six cluster events
CSD cuts	**1.5**	Use five cluster events
Reconstruction	**0.3**	By comparing $N_{rec\ 3\pi^0}^{obs\ 6cls}$ and $N_{rec\ 2\pi^0}^{obs\ 6cls}$
Trigger	**1.8**	Difference of CDT efficiency from unity
Statistics	**4.4**	Statistics of normalization
Total	**22**	

Syst. uncertainty due to ϵ^{veto}

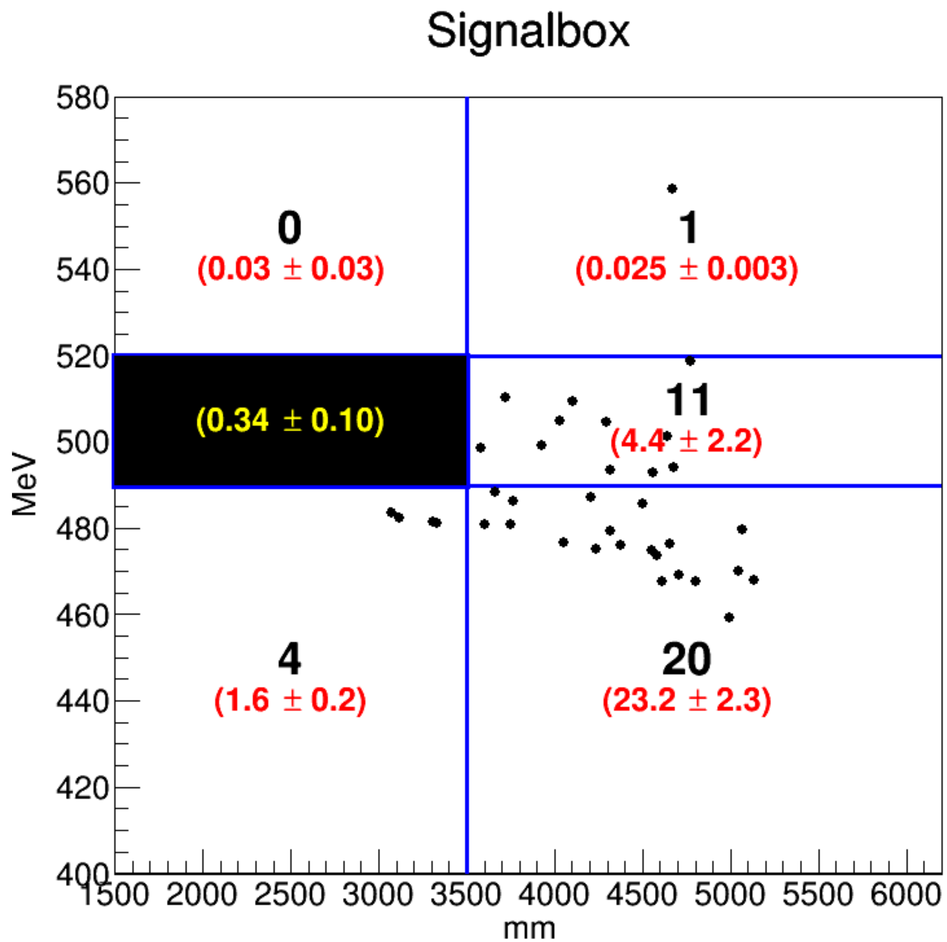
$\epsilon^{veto} = \frac{N_{all}}{N_{all\,wo/\,ith\,veto}}$ is compared between data and MC: $R = \epsilon^{DT}_{CR2}/\epsilon^{MC}_{CR2}$

$$\frac{\sigma_{\epsilon^{veto}}}{\epsilon^{veto}} = \sqrt{\sum_{i:all\ detectors} (R_i - 1)^2} = 17\%$$

Inefficiency of veto detector is well understood by MC.



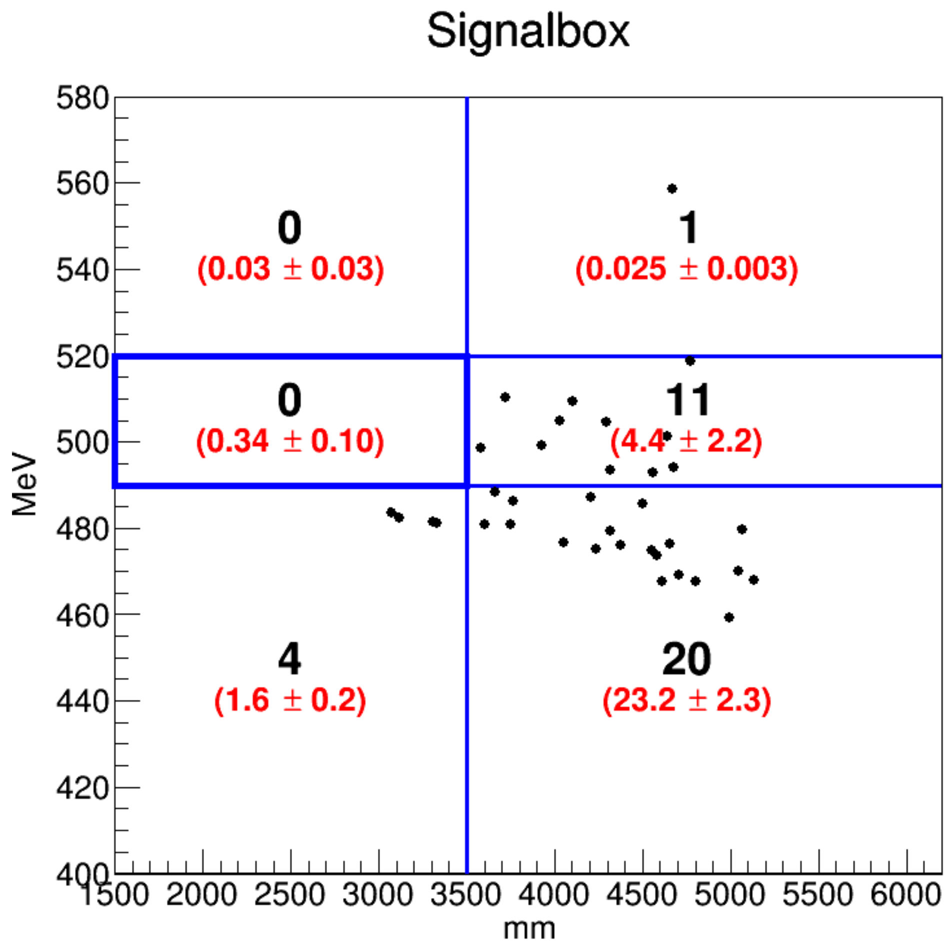
Open signal box



Single event sensitivity of signal:

$$\frac{1}{N_{K_L}\epsilon(K_L \to \pi^0\gamma)} = (6.9 \pm 0.3_{stat} \pm 1.5_{syst}) \times 10^{-8}$$

Open signal box



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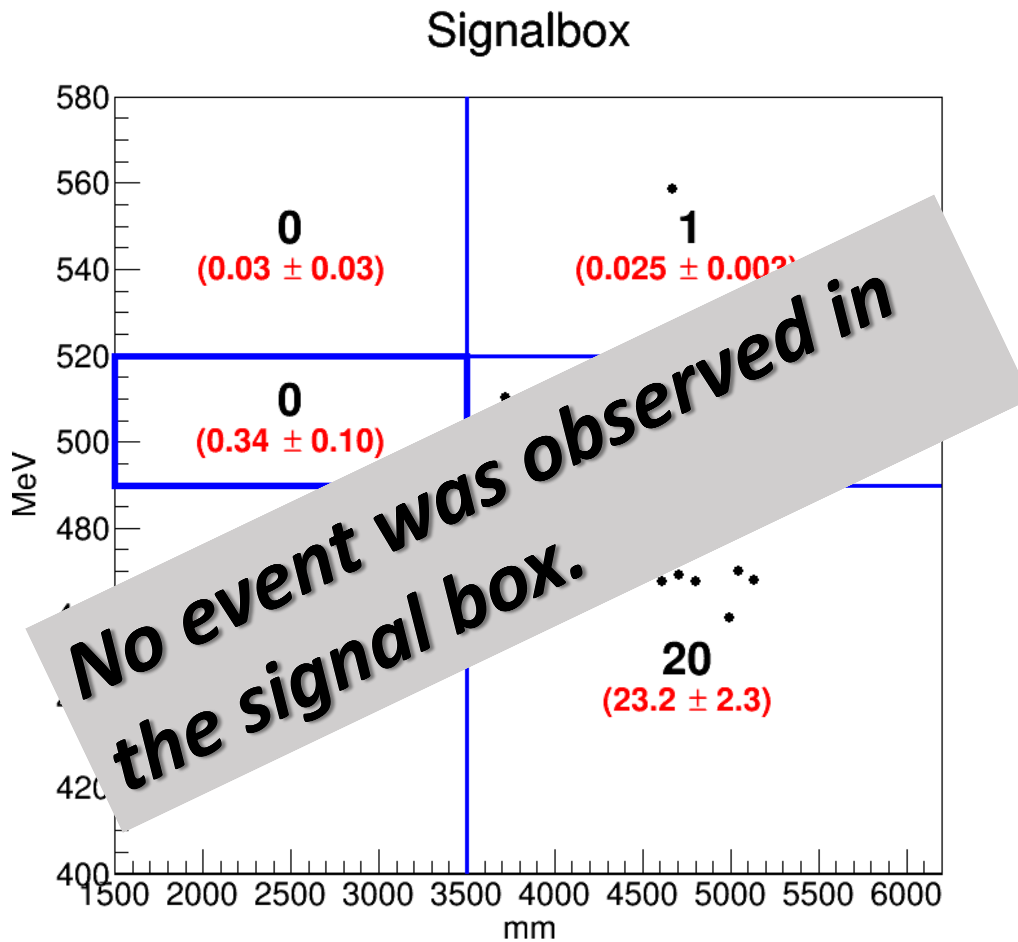

Taking into account the systematic uncertainty, the obtained upper limit is

preliminary

$$\mathcal{B}(K_L \to \pi^0\gamma) < 1.7 \times 10^{-7} \text{ at 90\% C.L.}$$

Summary

- Neither $\boldsymbol{K_L \to \pi^0\gamma}$ nor $\boldsymbol{K_S \to \pi^0\gamma}$ decay have been measured yet.

- These decays violate the Lorentz invariance and are forbidden by the SM
  - ✓ Lorentz invariance should be tested also in the high energy regime.

- Studying backgrounds, we fixed the selection criteria with S.E.S $= 6.8 \times 10^{-8}$. The expected number of background is 0.3.

- **We opened the signal box and could not find any signal candidate**.

- The upper limit of the branching fraction is obtained for the first time!

$$\mathcal{B}(K_L \to \pi^0\gamma) < 1.7 \times 10^{-7} \text{ at 90\% C.L.}$$

backup