Status of KOTO Experiment: The Search for $K_L \to \pi^0 \nu \bar{\nu}$

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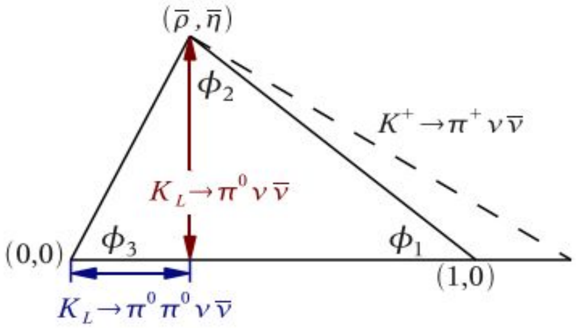
Worldwide Collaboration

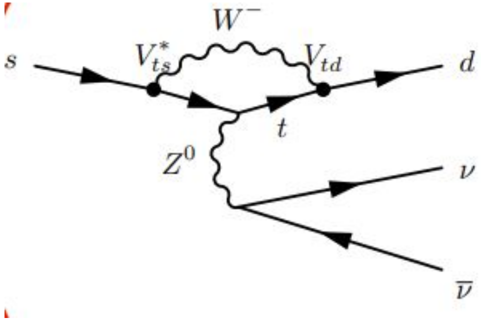
Chicago
NTU
Osaka
KEK
NDA
Saga
Yamagata
Jeonbuk
Jeju
Korea
Arizona St.
Michigan

The Golden Mode: $K_L \to \pi^0 \nu \bar{\nu}$

- Direct CP violating ⇒ $BR\left(K_L \to \pi^0 \nu \bar{\nu}\right) \propto \eta^2$
- Ultra-rare decay with very small theoretical uncertainties ~2%
  - $BR\left(K_L \to \pi^0 \nu \bar{\nu}\right)_{SM} = 2.94 \pm 0.15 \times 10^{-11}$
  - Dominating Uncertainties: ϵ_K *and* β
- Small theoretical uncertainty ⇒ sensitive to new physics!



arXiv:2109.11032v6



Sensitive to New Physics

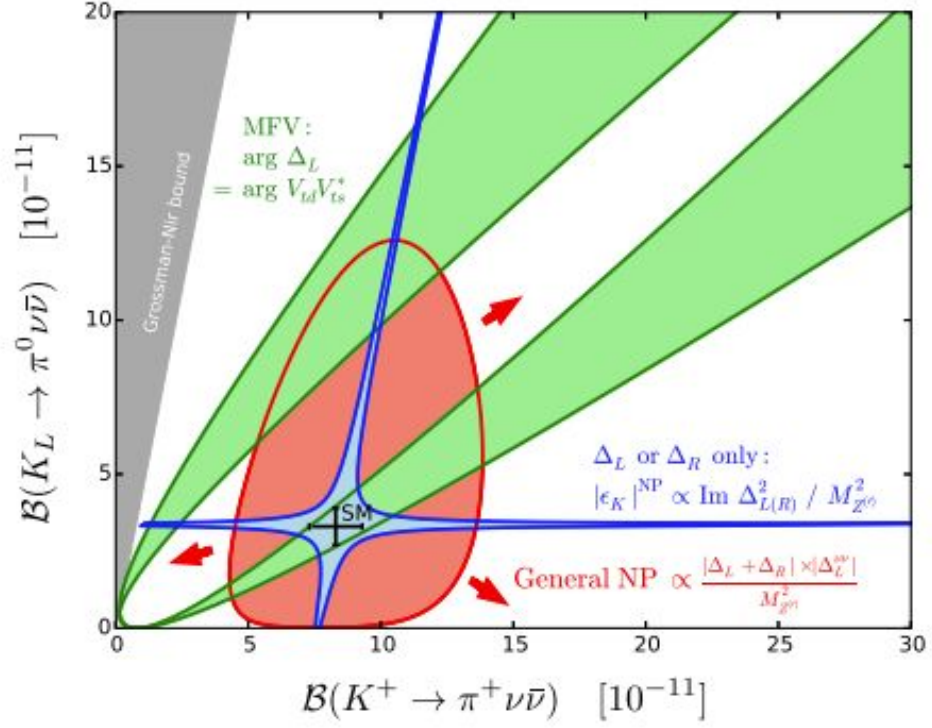
Relationship between Branching Ratios

⇕

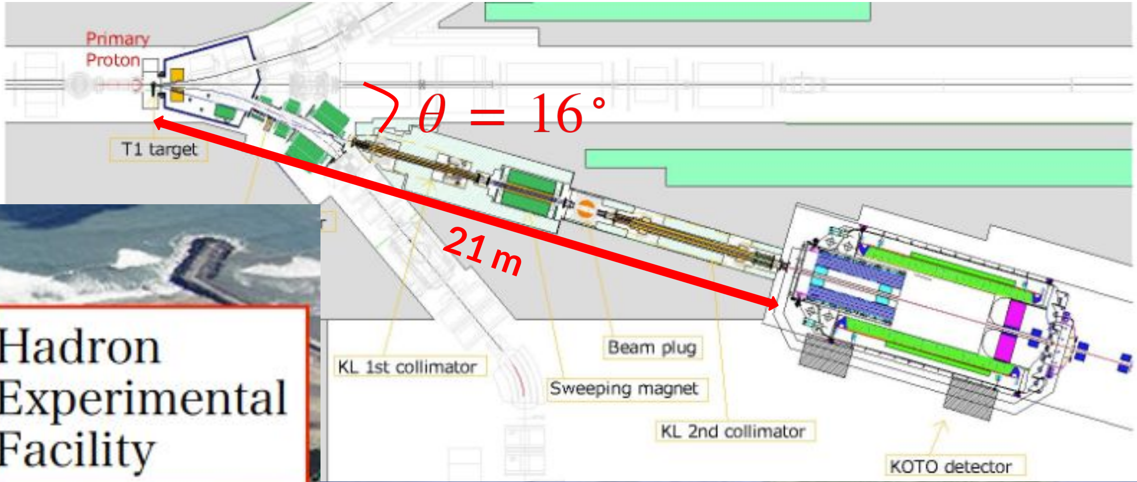
Flavour Symmetries

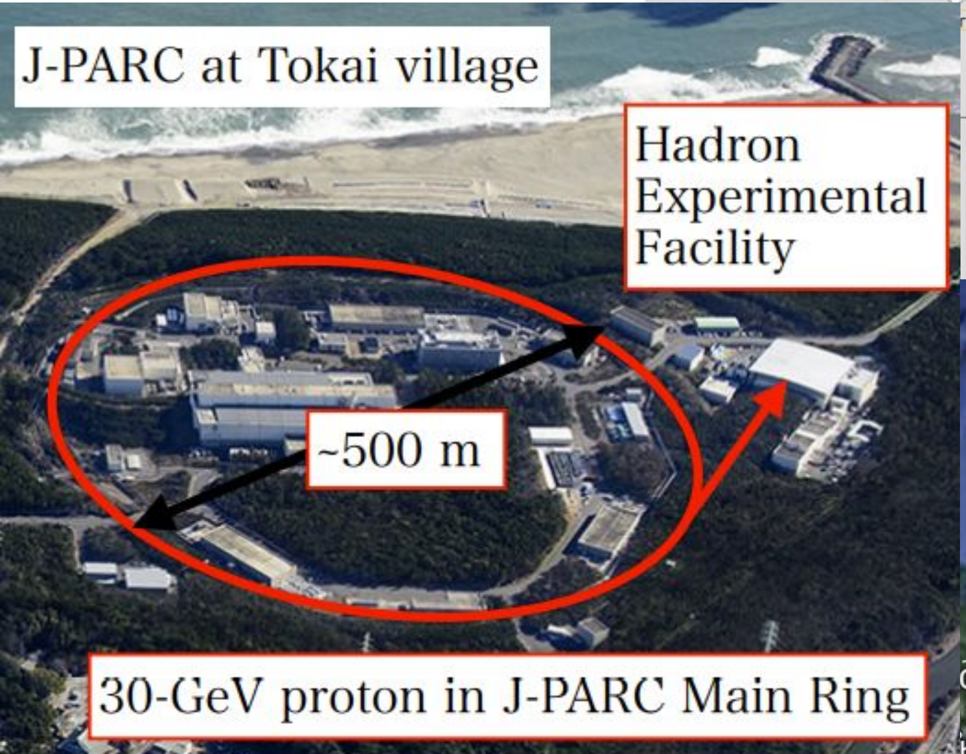
- Grossman-Nir bound
  - Model independent constraint
  - Isospin symmetry: $\Delta I = {}^{1}/_{2}$
  - $BR\left(K_L \to \pi^0 \nu\bar{\nu}\right) \leq 4.3 \times BR\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$
- CKM-like structure: Only LH or RH
- LH and RH coupling is dominant + satisfies CMFV.
- General NP

JHEP 1511 (2015) 033

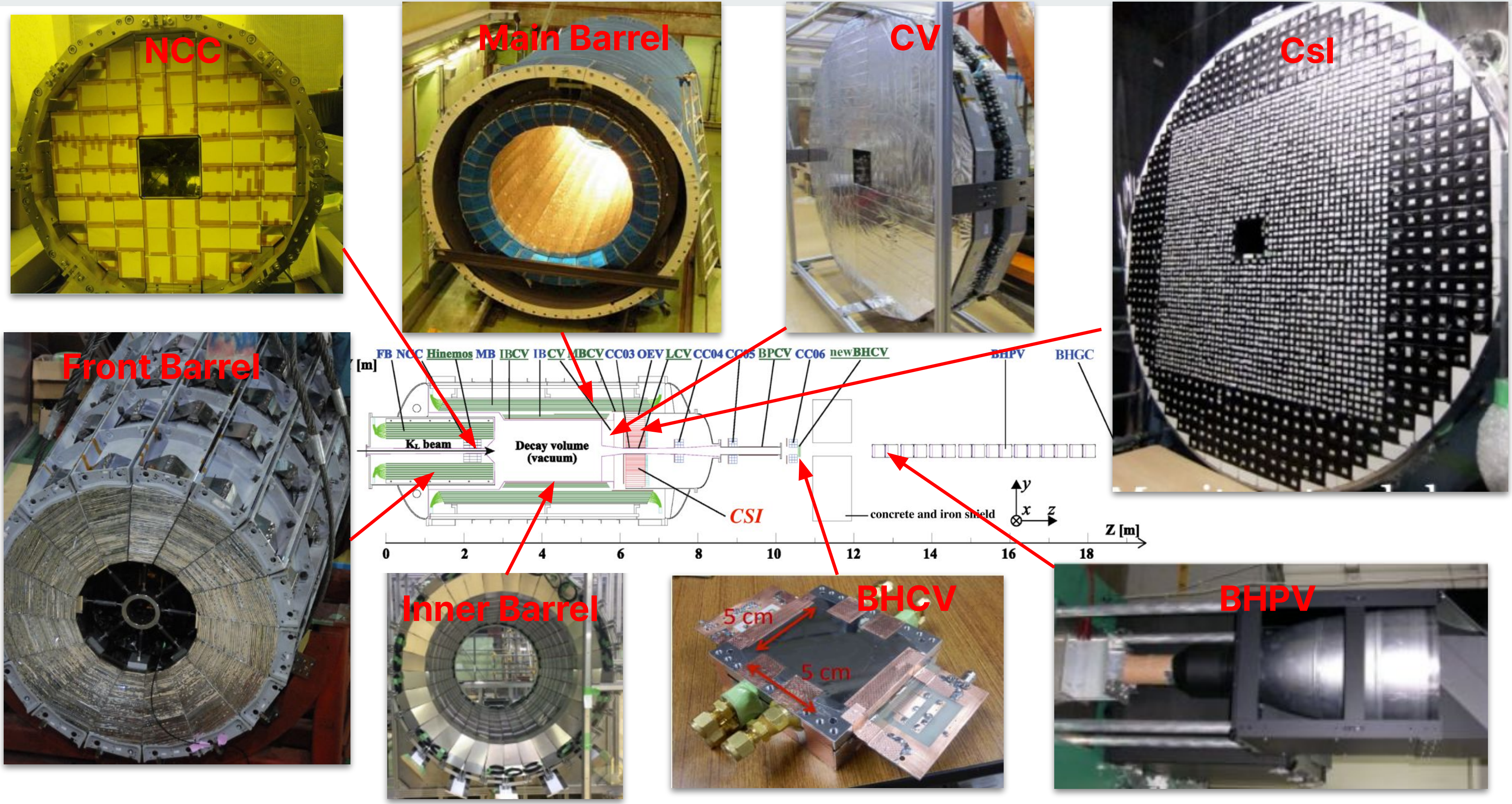


J-PARC Beamline





The KOTO Detector

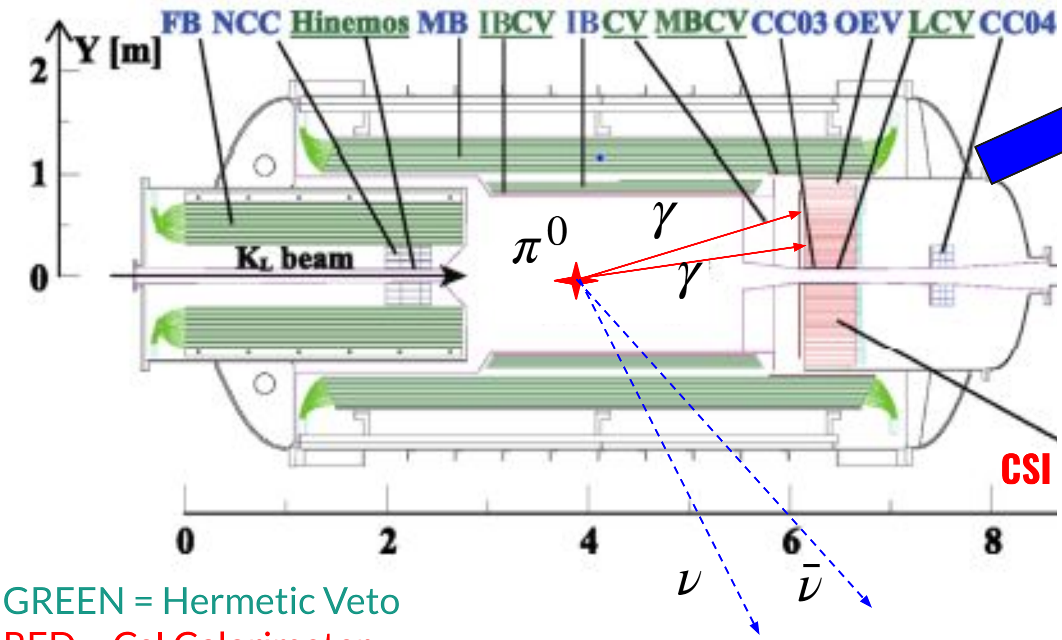


Measurement of $K_L \rightarrow \pi^0 \nu \bar{\nu}$

No tagging

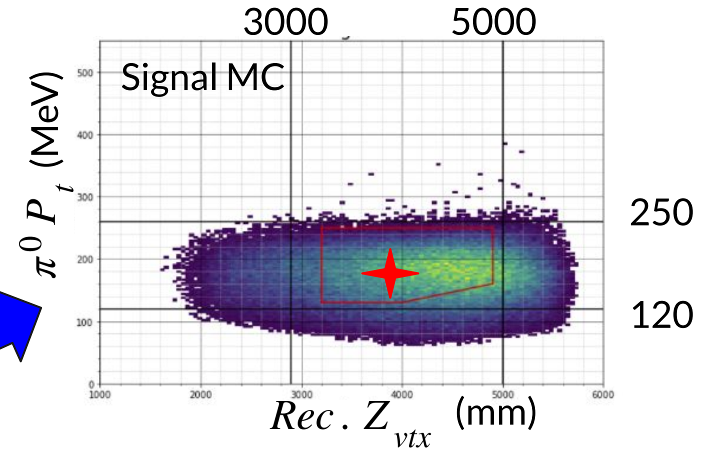
$\pi^0 \rightarrow \gamma\gamma$

Escapes undetected



GREEN = Hermetic Veto

RED = CsI Calorimeter



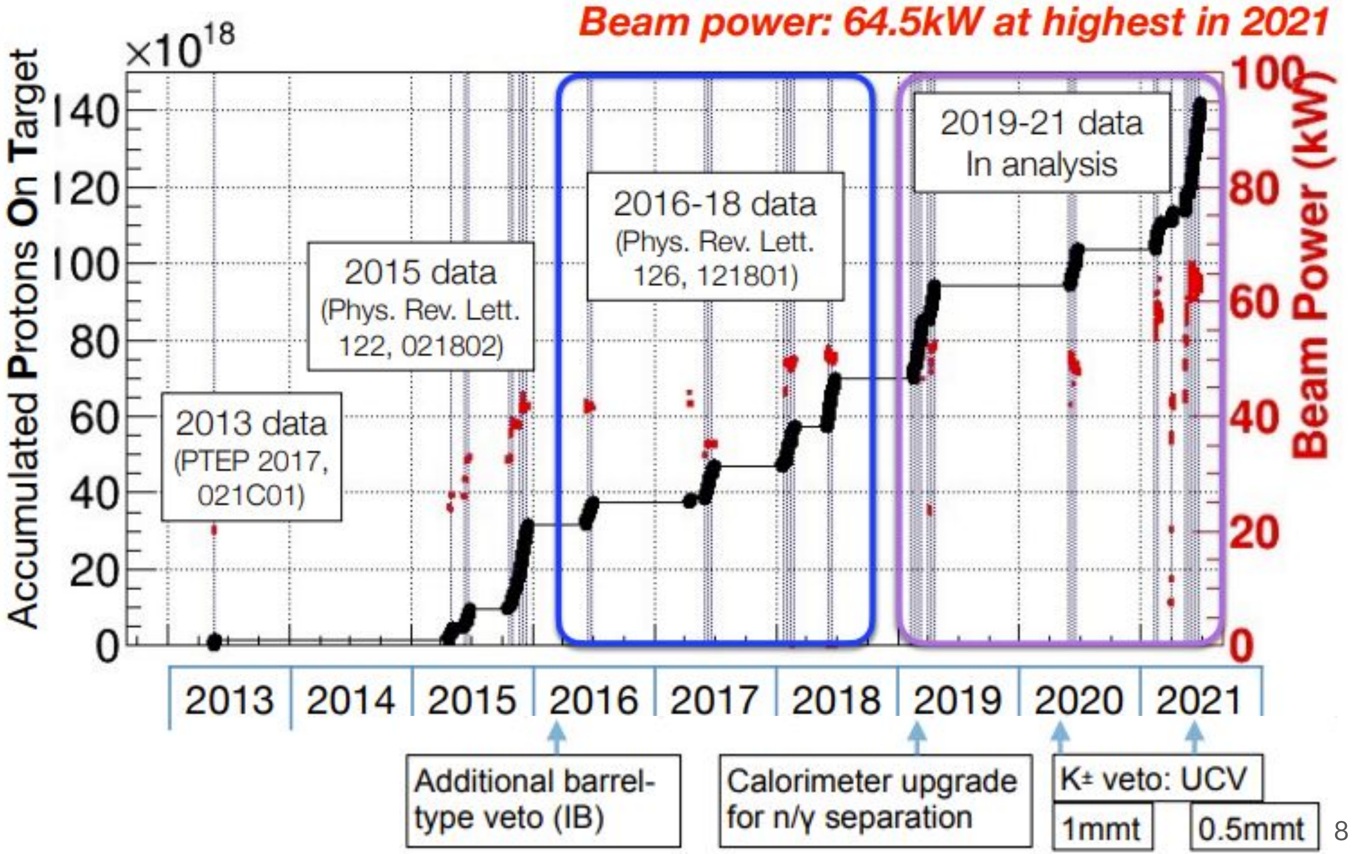
Signal

- 2 photons from π^0 hit the CSI
- High transverse momentum
- Reconstruct decay position assuming π^0 mass

$$(M_{\pi^0})^2 = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos(\theta))$$

Run History

- 2019-2021 Data:
  - $\sim 70\times 10^{18}$ POT
  - Average Beam Power ⇒ 60kW
- 2016-2018 Data:
  - $\sim 35\times 10^{18}$ POT
  - Average Beam Power < 50 kW



Recent Results: 2015

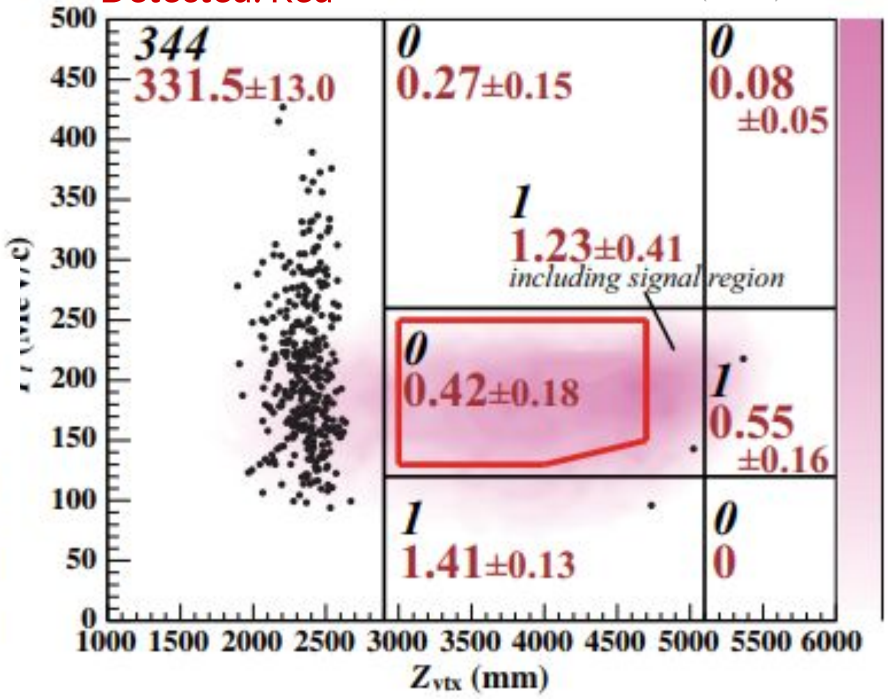
- 0.42 predicted BG events ⇒ observed none.
- Single Event Sensitivity ⇒ 1.30×10^{-9}
- $BR\left(K_L \to \pi^0 \nu \bar{\nu}\right) < 3.0 \times 10^{-9}$ (90% CL)

TABLE III. Summary of background estimation.

Source		No. events
K_L decay	$K_L \to \pi^+\pi^-\pi^0$	0.05 ± 0.02
	$K_L \to 2\pi^0$	0.02 ± 0.02
	Other K_L decays	0.03 ± 0.01
Neutron induced	Hadron cluster	0.24 ± 0.17
	Upstream π^0	0.04 ± 0.03
	CV η	0.04 ± 0.02
Total		0.42 ± 0.18

Observed: Black
Detected: Red

PRL 122, 021802 (2019)



Recent Results: 2016-2018

- 1.22 predicted BG events ⇒ observed 3.
- Single Event Sensitivity ⇒ 7.2×10^{-10}
- $BR\left(K_L \to \pi^0 \nu \bar{\nu}\right) < 4.9\times 10^{-9}$ (90% CL)

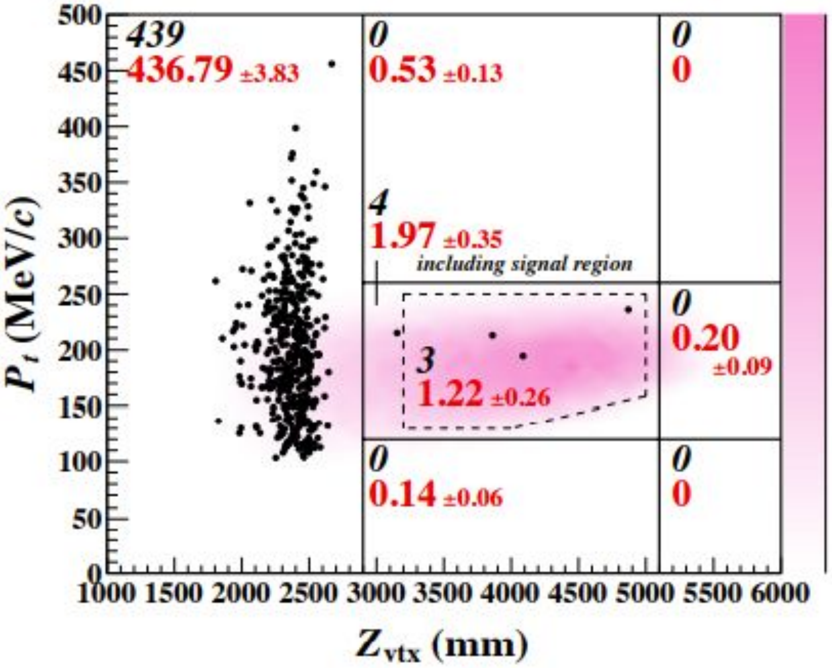
Studied after opening blinded region

Source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25[a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
Total		1.22 ± 0.26

[a]Background sources studied after looking inside the blind region.

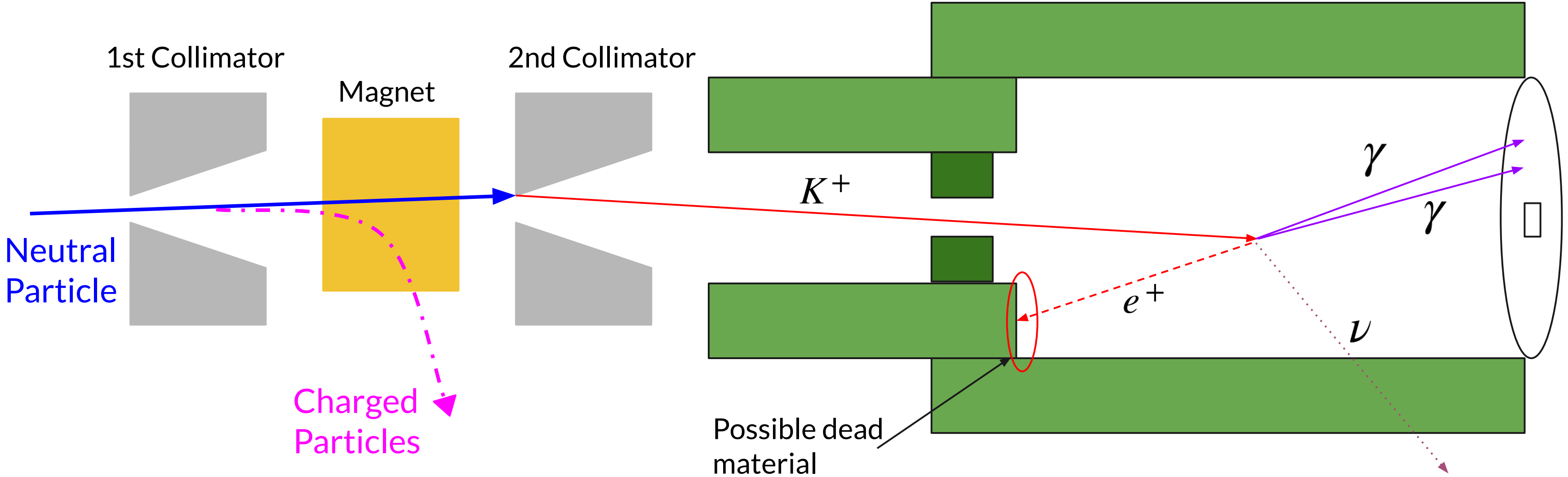
Observed: Black
Detected: Red

PRL 126, 121801 (2021)



Background Mechanism: $K^+ \rightarrow \pi^0 e^+ \nu$

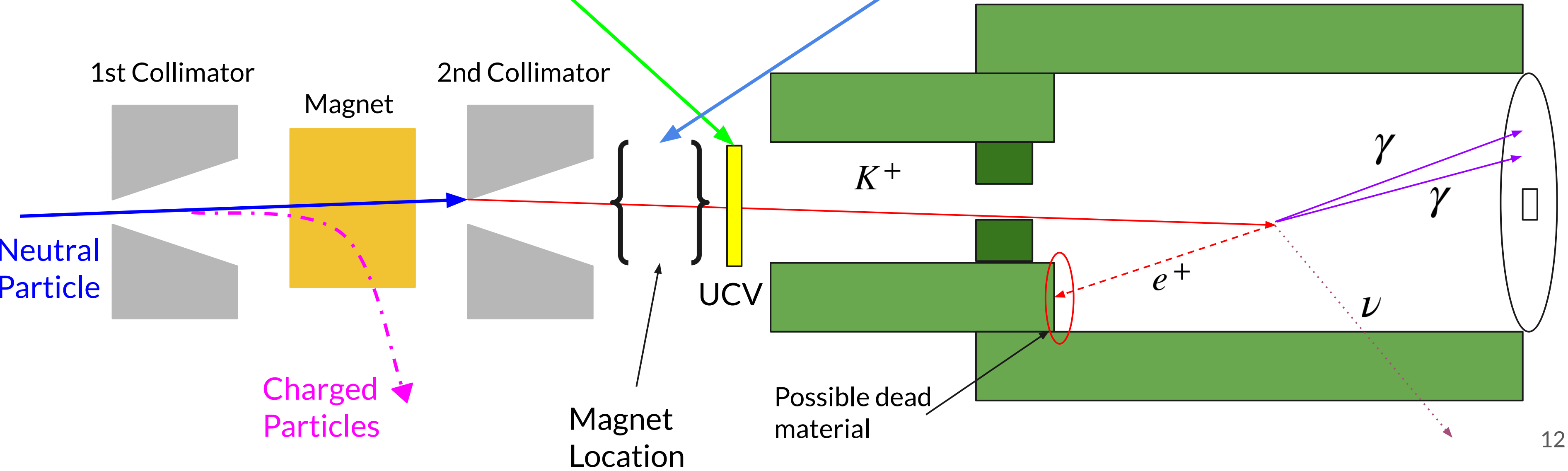
- "Signal-like" photons
  - High transverse momentum
  - Well reconstructed π^0
- Low energy e^+
  - Detector inefficiency
  - Dead material



Steps Against $K^+ \to \pi^0 e^+ \nu$

- UCV Installed in 2021
  - BG level ~ $\times\, ^1/_{13}$
- UCV Upgrade in 2022
  - Expected BG level ~ $\times\, ^1/_{100}$
- Magnet Installed (2023)
  - Expected BG level ~ $\times\, ^1/_{10}$

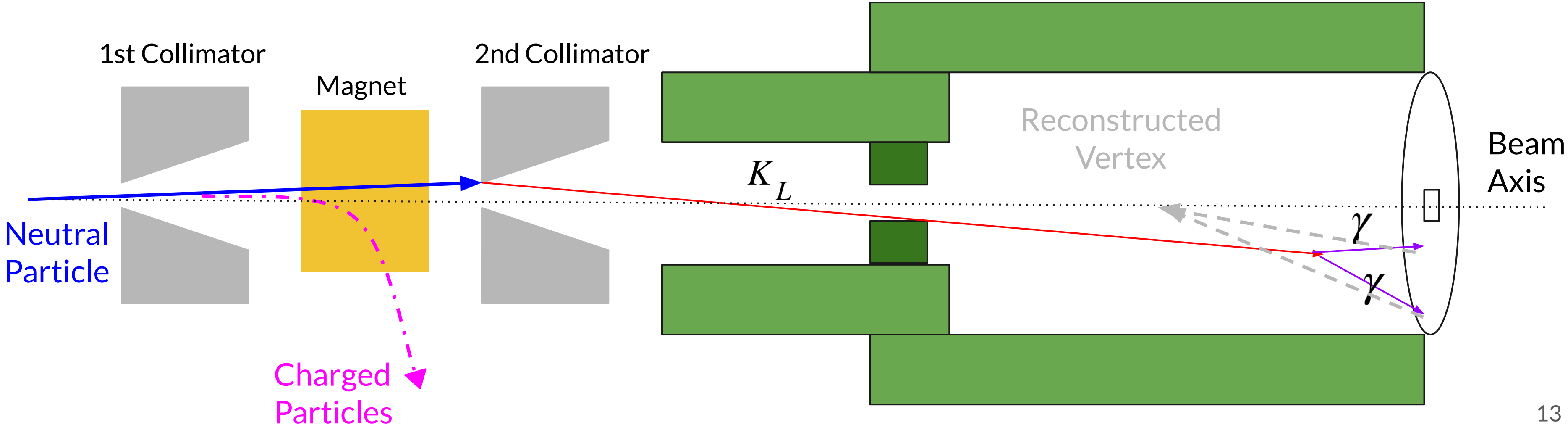
Total Expected Reduction: ~ $\times\, ^1/_{1000}$



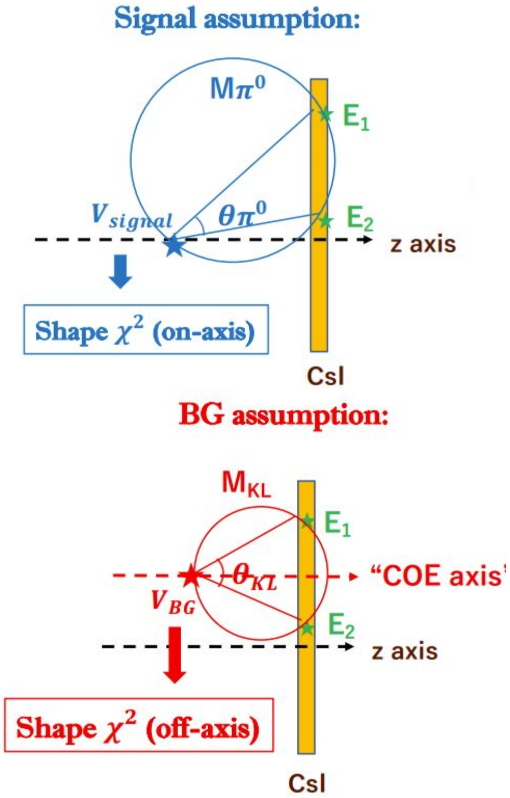
Background Mechanism: $Halo\ K_L \rightarrow \gamma\gamma$

- Enters signal region from the high off axis momentum of K_L

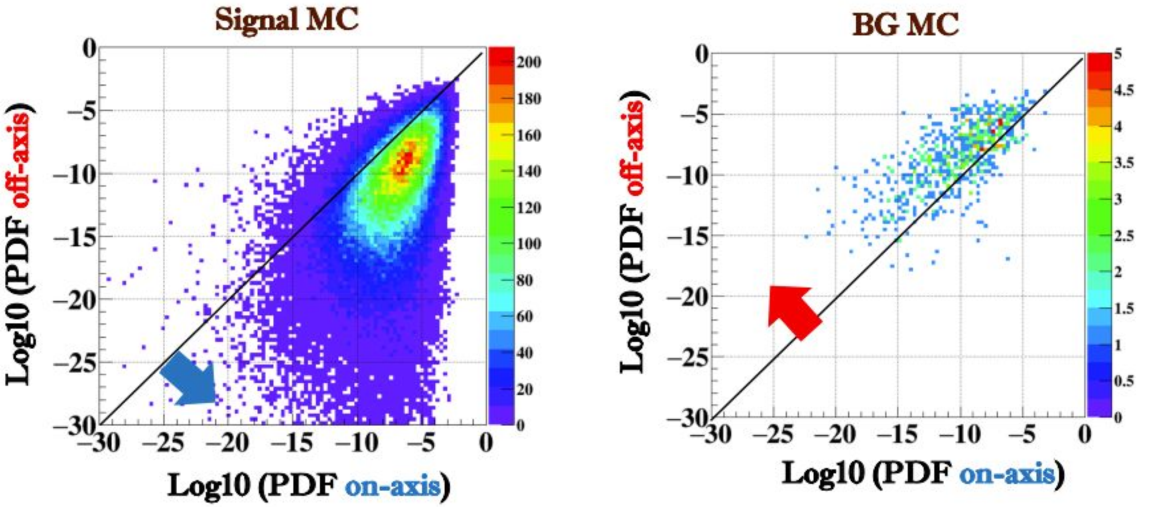
- Misreconstructed K_L upstream as a π^0
  - True decay vertex is close to CsI



Steps Against $Halo\ K_L \to \gamma\gamma$: Likelihood Method



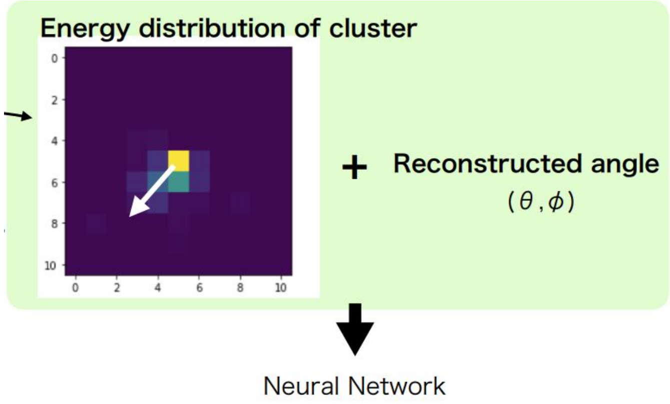
$$\text{Likelihood ratio} = \frac{\text{PDF(on-axis)}}{\text{PDF(on-axis)} + \text{PDF(off-axis)}}$$



Total BG Rejection ~ 1/25

Steps Against *Halo* $K_L \to \gamma\gamma$: Neural Networks

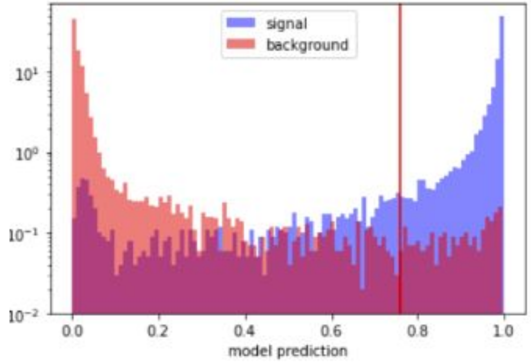
Deep Learning Convolutional Neural Network



Background Rejection: ~1/50

- Uses cluster shape information, as well as kinematic information.

Kinematic Neural Network



- ~Factor of 2 improvement
- With Likelihood method: Total Rejection: ~1/50

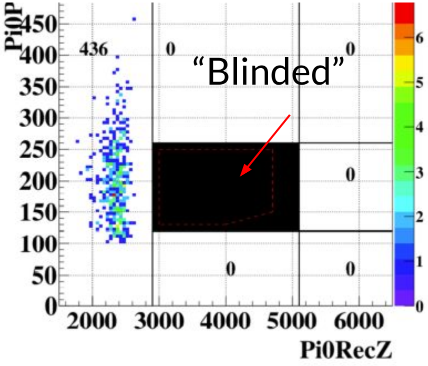
Total Expected BG Rejection ~ 1/50

2019-2021: Analysis Status

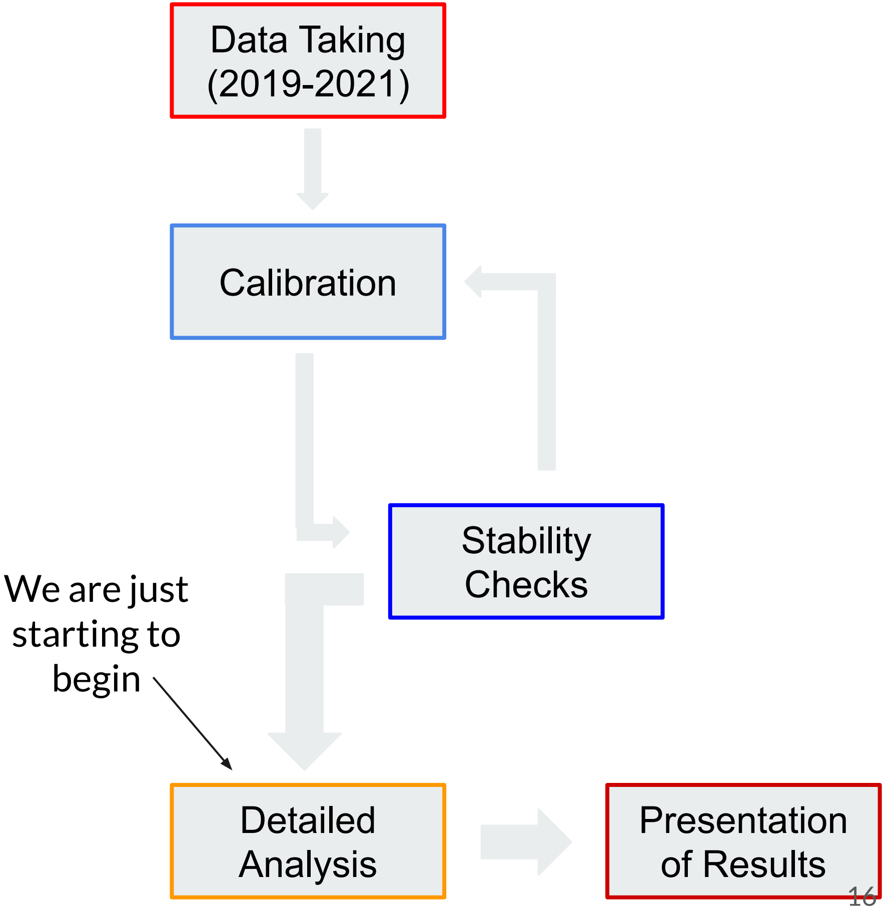
Performed a pure blinded analysis in 2016-2018 data

3 events were observed in signal region with little background estimation.

2016-2018 Pre-opening

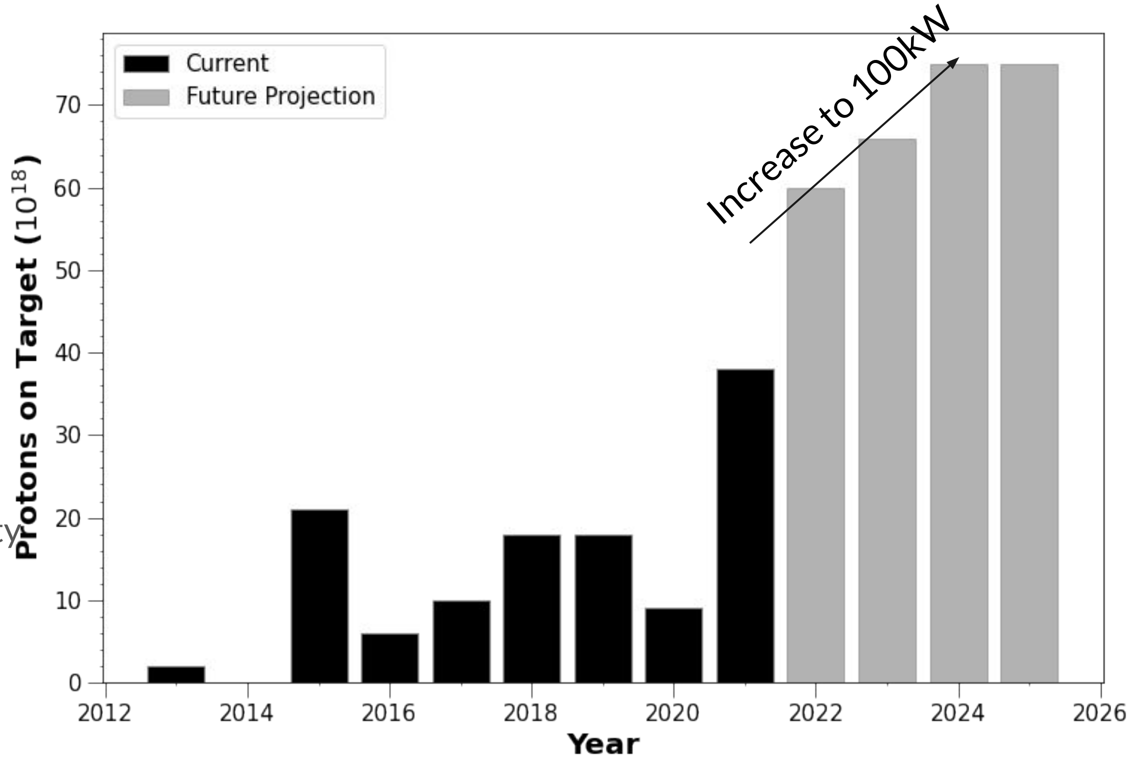


- Implement inverse cut studies for the detailed analysis of 2019-2021 data
  - Look inside the blinded region while loosening veto cuts.
  - Compare distribution in data to simulation
  - Deviation ⇒ New background source?



KOTO Prospects

- Assumptions:
  - 3 months of data taking per year
  - Steady increase of Beam Power ⇒ 100kW
- KOTO may reach a SES of O(10^-11) in 3-4 years ⇒ pushing towards SM sensitivity by 2026.



Summary

- 2015 Data sets the current best upper limit:

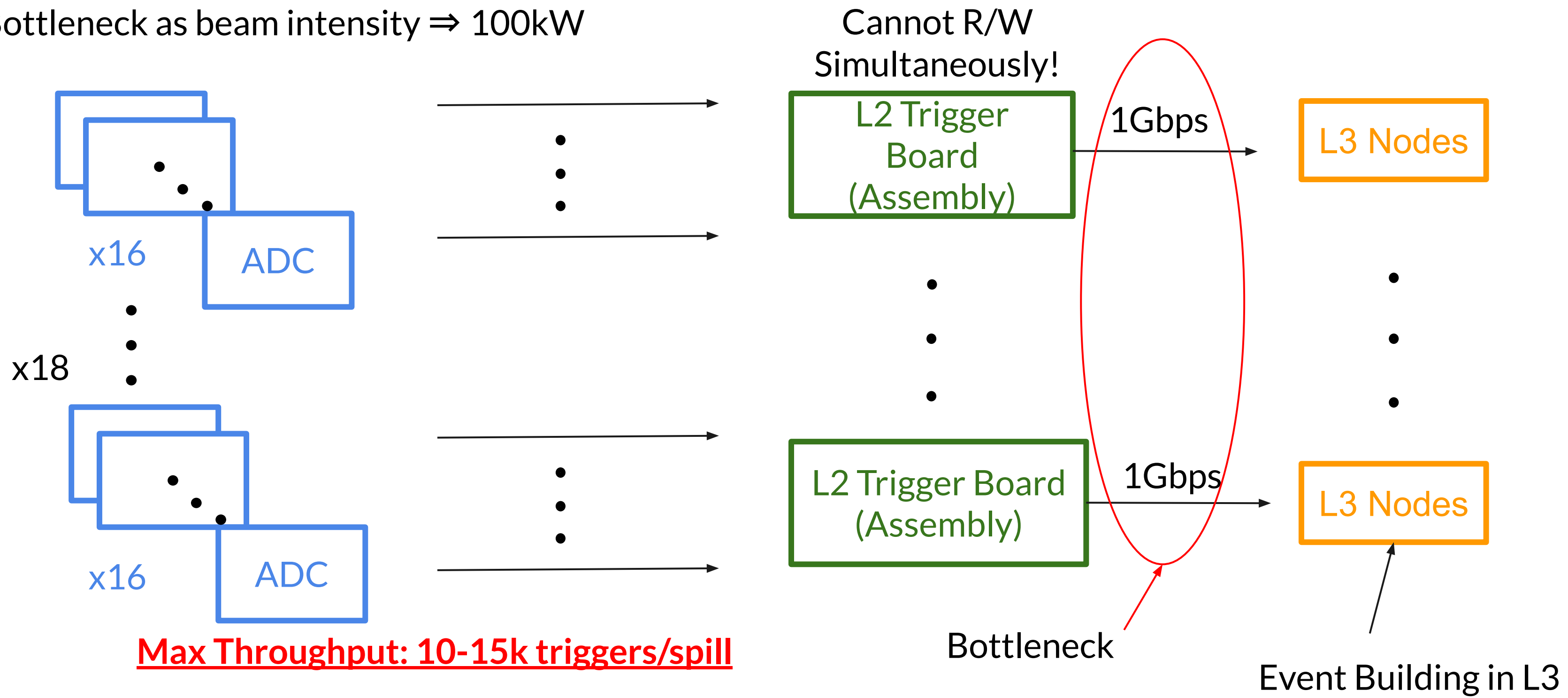
$$BR\left(K_L \to \pi^0 \nu \bar{\nu}\right) < 3.0 \times 10^{-9}\ (90\%\ CL)$$

- 2016-2018 data saw 3 events in the signal region with an expected BG of 1.22
  - $K^+ \to \pi^0 e^+ \nu$ ⇒ UCV upgrades
  - $Halo\ K_L \to \gamma\gamma$ ⇒ Analysis Techniques
- KOTO is moving forward with many important detector, DAQ, and analysis improvements.
  - UCV Upgrades
  - Level 2 and Level 3 DAQ Upgrade
  - New analysis techniques (AI, Likelihood Ratio) to discriminate background and signal.
- 2019-2021 data analysis is ongoing.

Backup

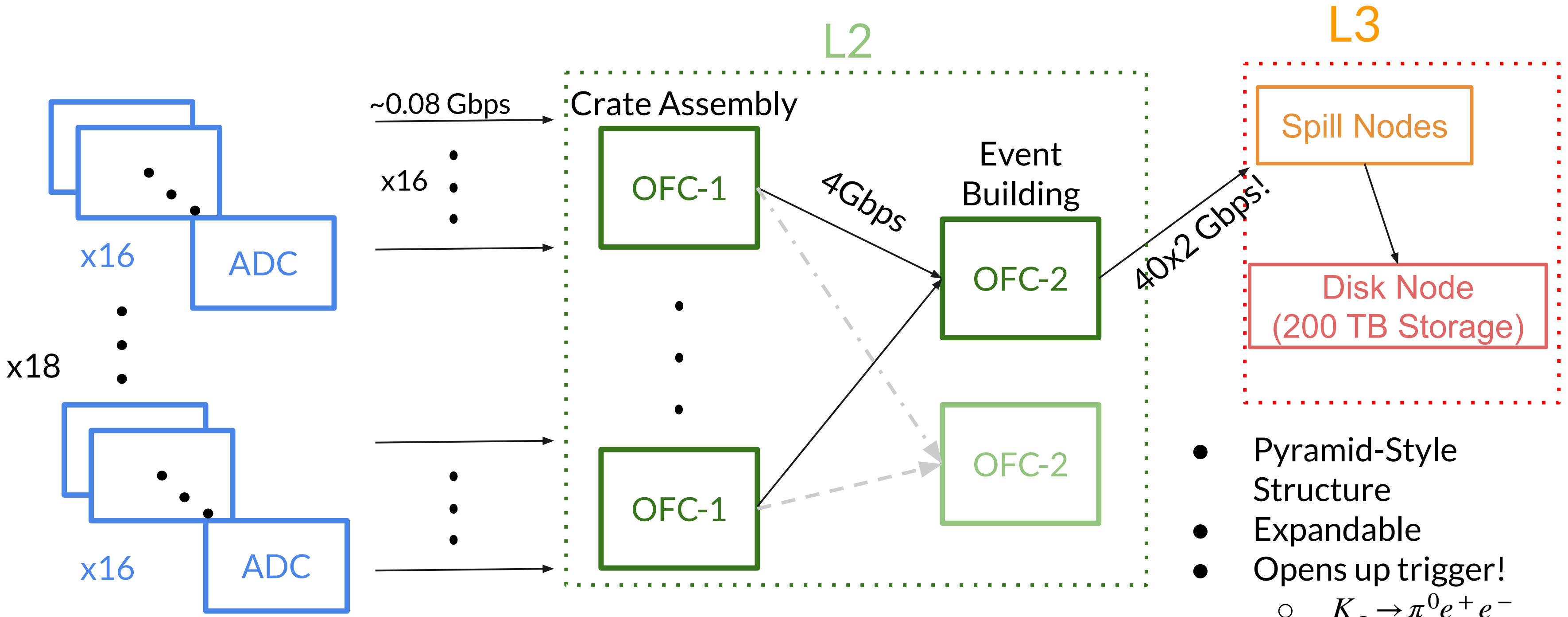
KOTO Upgrades: DAQ-The Old System

Current Trigger Rate: ~ 10k trigger/spill ⇒
Bottleneck as beam intensity ⇒ 100kW



Max Throughput: 10-15k triggers/spill

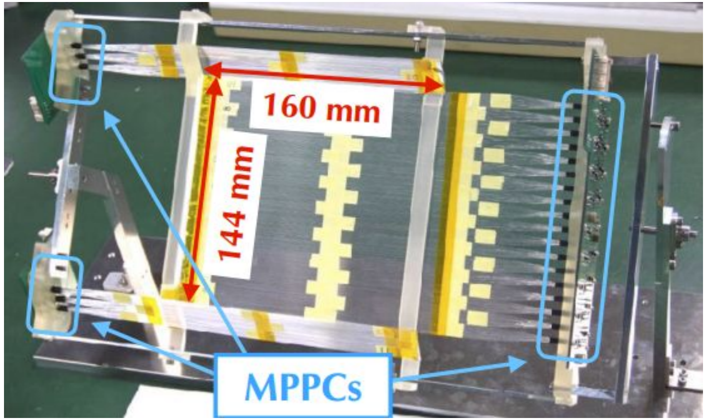
KOTO Upgrade: DAQ-The New System



- Pyramid-Style Structure
- Expandable
- Opens up trigger!
  - $K_L \rightarrow \pi^0 e^+ e^-$
  - New Physics?

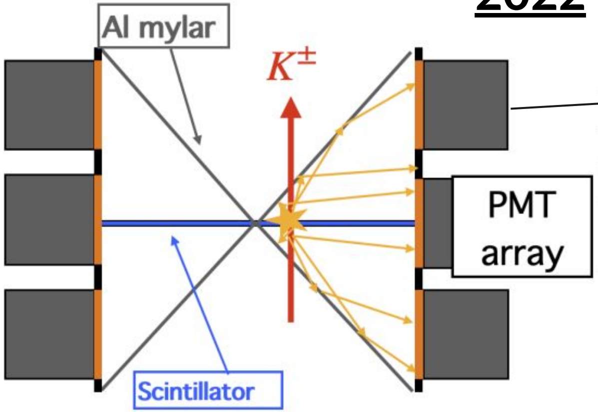
Max Throughput: 50-60k triggers/spill

Detector Upgrades: UCV

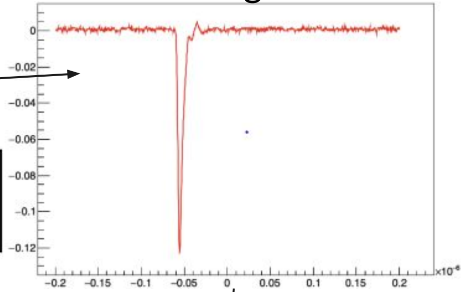


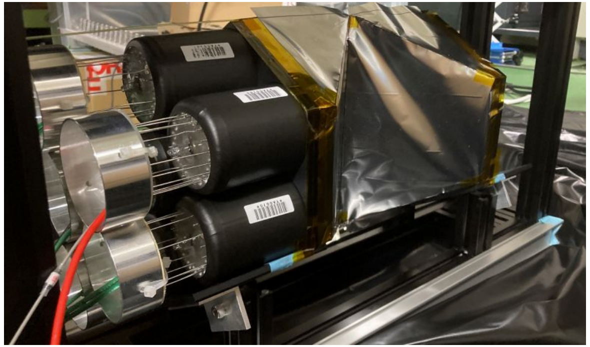
- K^+ **Reduction:** ~ 1/13
- MPPC Readout
- 0.5 mm scintillator

2022



Voltage





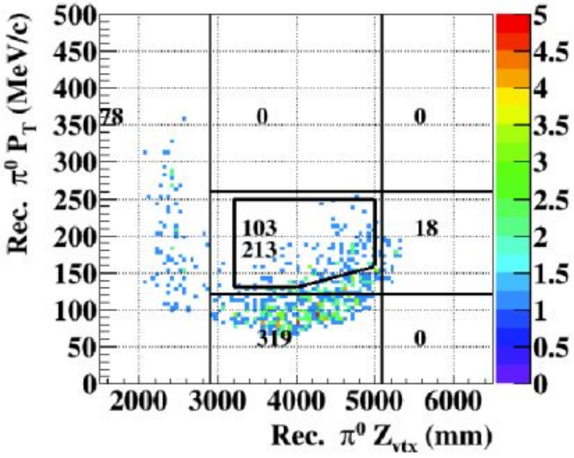
- Beamline Tests Ongoing
- MPPC⇒ PMT array
- Dual end readout
- Expected K^+ **Reduction: ~** 1/100

INVERSE CUT STUDY (RUN 87)

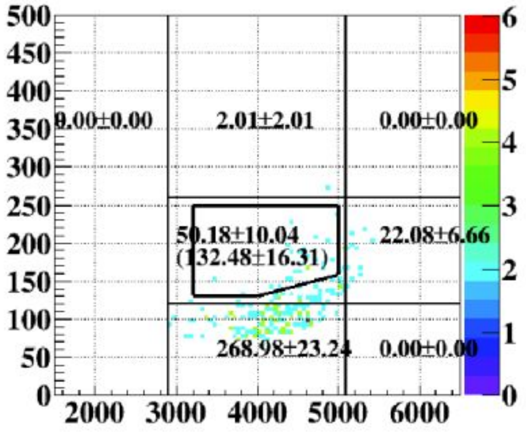
Inverse cut of CBAR and IB

(CBAR>3MeV or IB>3MeV)&& CBAR<10MeV && IB<10MeV

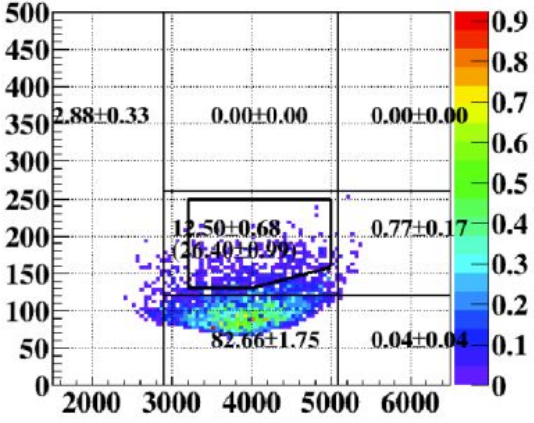
Run87



KL->3pi0 MC



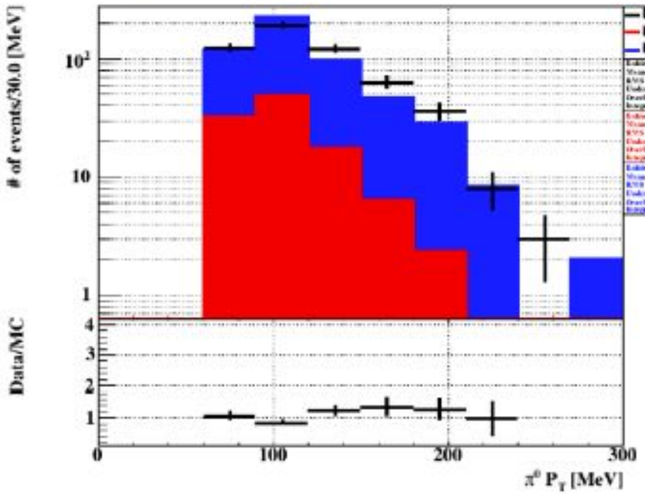
KL->2pi0 MC



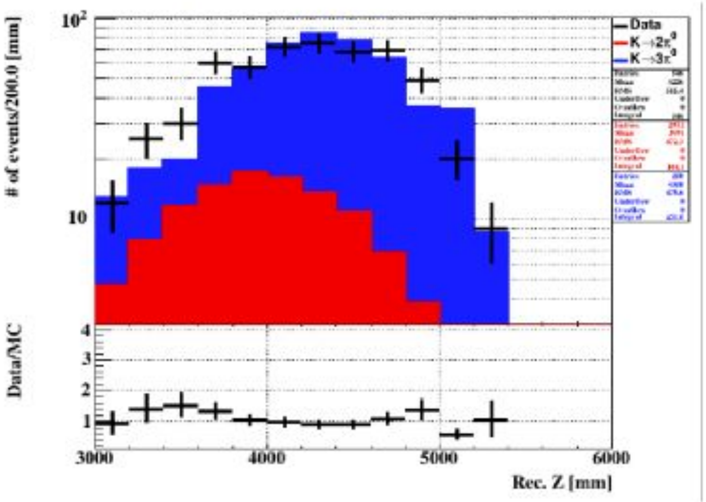
Inverse cut of CBAR and IB

(CBAR>3MeV or IB>3MeV)&& CBAR<10MeV && IB<10MeV

Pi0 Pt



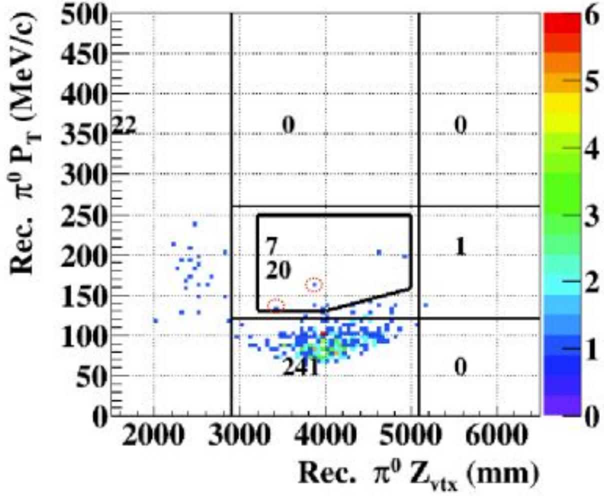
Pi0 RecZ



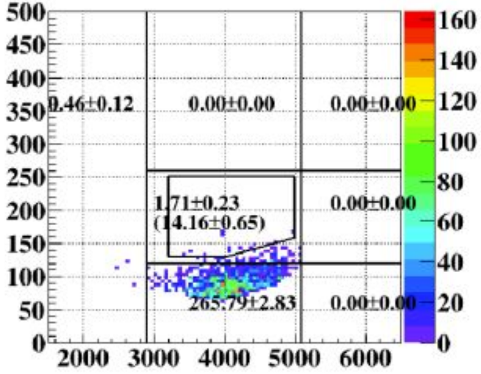
Inverse cut of newBHCV w/o BHPV veto

Requirement on the newBHCV:newBHCVModHitCount==3 && newBHCVVetoEne>884.e-6/2.

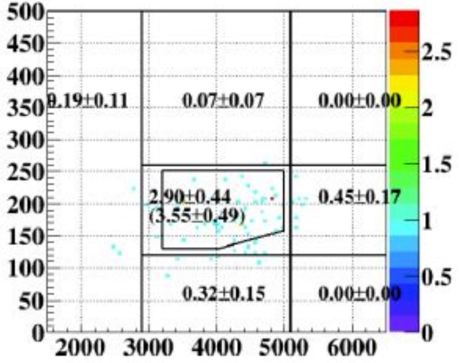
Run87 data



KL->pipipi0 MC



K+ MC



Events in red : Energy deposit on UCV

4

Future Physics Prospects

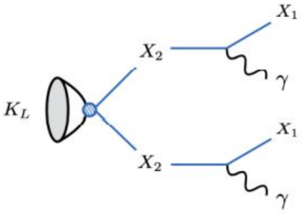
Main Author: Chieh Lin (Chicago Postdoc)

Search for the Pair Production of Dark Particles X with $K_L^0 \to XX, X \to \gamma\gamma$

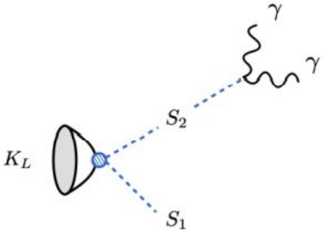
J. K. Ahn,[1] B. Beckford,[2] M. Campbell,[2] S. H. Chen,[3] J. Comfort,[4] K. Dona,[2] M. S. Farrington,[5] K. Hanai,[6] N. Hara,[6] H. Haraguchi,[6] Y. B. Hsiung,[3] M. Hutcheson,[2] T. Inagaki,[7] M. Isoe,[6] I. Kamiji,[8] T. Kato,[6] E. J. Kim,[9] J. L. Kim,[9] H. M. Kim,[9] T. K. Komatsubara,[7,10] K. Kotera,[6] S. K. Lee,[9] J. W. Lee,[6,*] G. Y. Lim,[7,10] Q. S. Lin,[5] C. Lin,[3] Y. Luo,[5] T. Mari,[6] T. Masuda,[11] T. Matsumura,[12] D. Mcfarland,[4] N. McNeal,[2] K. Miyazaki,[6] R. Murayama,[6,†] K. Nakagiri,[8,‡] H. Nanjo,[8,§] H. Nishimiya,[6] Y. Noichi,[6] T. Nomura,[7,10] T. Nunes,[6] M. Ohsugi,[6] H. Okuno,[7] J. C. Redeker,[5] J. Sanchez,[2] M. Sasaki,[13] N. Sasao,[11] T. Sato,[7] K. Sato,[6,¶] Y. Sato,[6] N. Shimizu,[6] T. Shimogawa,[14,**] T. Shinkawa,[12] S. Shinohara,[8,§] K. Shiomi,[7,10] R. Shiraishi,[6] S. Su,[2] Y. Sugiyama,[6,**] S. Suzuki,[14] Y. Tajima,[13] M. Taylor,[2] M. Tecchio,[2] M. Togawa,[6,**] T. Toyoda,[6] Y.-C. Tung,[5,††] Q. H. Vuong,[6] Y. W. Wah,[5] H. Watanabe,[7,10] T. Yamanaka,[6] H. Y. Yoshida,[13] and L. Zaidenberg[2]
(KOTO Collaboration)

The dipole portal can be examined if both have the same mass and decay to two photons (pi0 impostor).

$$K_L^0 \to X + X \to (\gamma\gamma)(\gamma\gamma)$$



B) DIPOLE PORTAL



C) π^0 IMPOSTOR

Dark Pair

<u>Main Backgrounds in signal region</u>

$\#(K_L \rightarrow 3\pi) = (0.61 \pm 0.61)$

$\#(K_L \rightarrow 2\pi) = < 0.62$ (90% C.L.)

- $K_L \rightarrow 3\pi^0$ background primarily stems from double fusion.
- $K_L \rightarrow 2\pi^0$ background stems from mis-pairing

DATA/MC comparison plot.

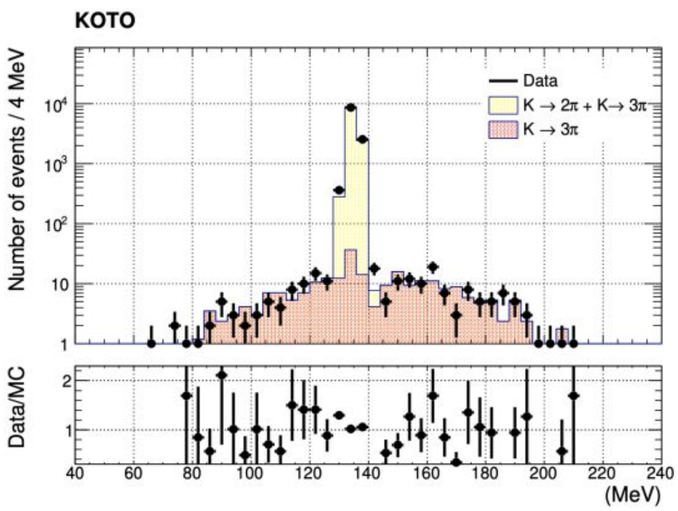
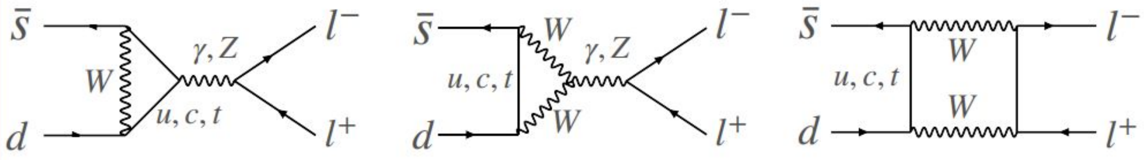


FIG. 2. Distribution of the photon pair invariant mass that is closest to the nominal π^0 mass. The circular markers and the histograms indicate the data and the MC prediction.

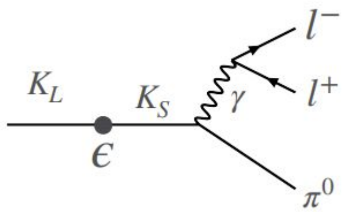
$K_L \to \pi^0 e^+ e^-$

(a) Direct CPV ranging between 3×10^{-12} [SM] - 7.8×10^{-11}[Nucl.Phys. B697, 133-206]

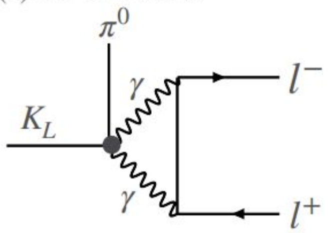


Possible enhancement from new physics effect [Nucl.Phys. B697, 133-206].

(b) Indirect CPV < 4.5×10^{-12}

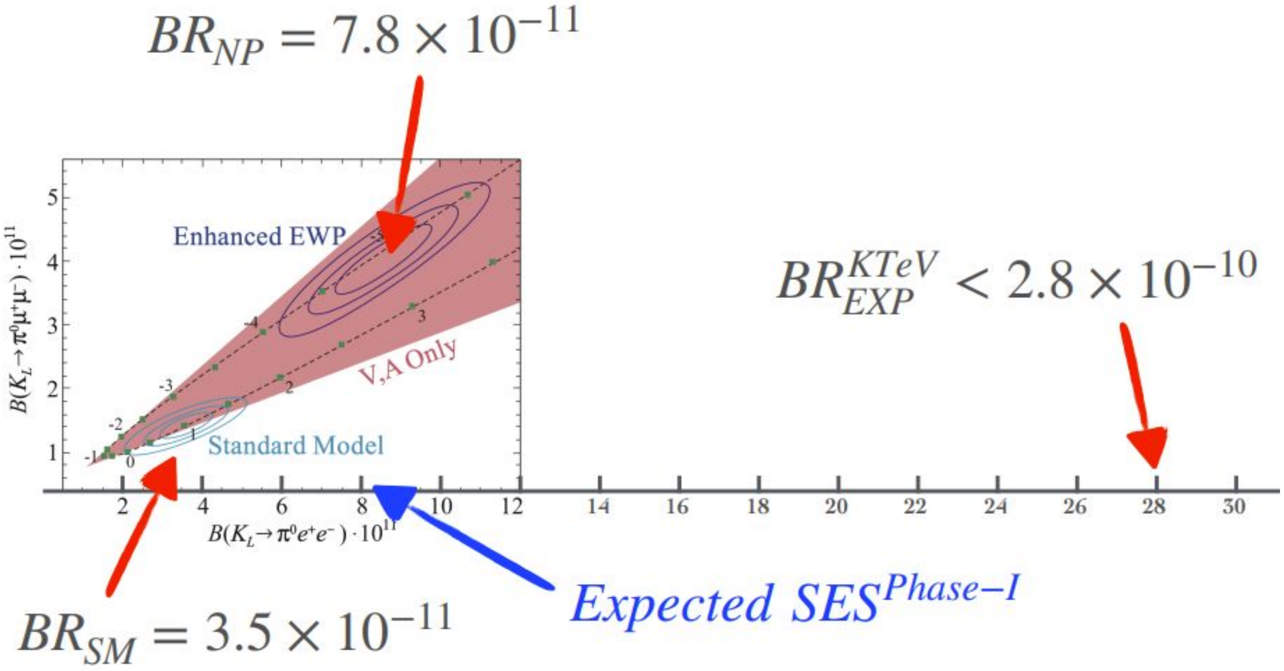


(c) CPC < 3×10^{-12}



Amplitude of (b), (c) were constrained by the experimental measurements: $\epsilon, K_S \to \pi^0 e^+ e^-$ & $K_L \to \pi^0 \gamma\gamma$

$K_L \to \pi^0 e^+ e^-$



$BR_{NP} = 7.8 \times 10^{-11}$
Enhanced EWP
Standard Model
V,A Only
$B(K_L \to \pi^0 \mu^+ \mu^-) \cdot 10^{11}$
$B(K_L \to \pi^0 e^+ e^-) \cdot 10^{11}$
$BR_{EXP}^{KTeV} < 2.8 \times 10^{-10}$
$BR_{SM} = 3.5 \times 10^{-11}$
Expected $SES^{Phase-I}$

Reconstruction

- Reconstruct pi0 decay vertex (6 pairings).
  - Assuming decay vertex (x, y) = (0.,0.)
- Require remaining two clusters with “CV tag” on.
- Reconstruct kaon mass with pion vertex.

- Requires CV in trigger.
    - ⇒ a huge increase in trigger rate.
    - Only possible with the new DAQ system.