Status of $K_L \to \pi^0 \nu \bar{\nu}$ Study at J-PARC KOTO Experiment

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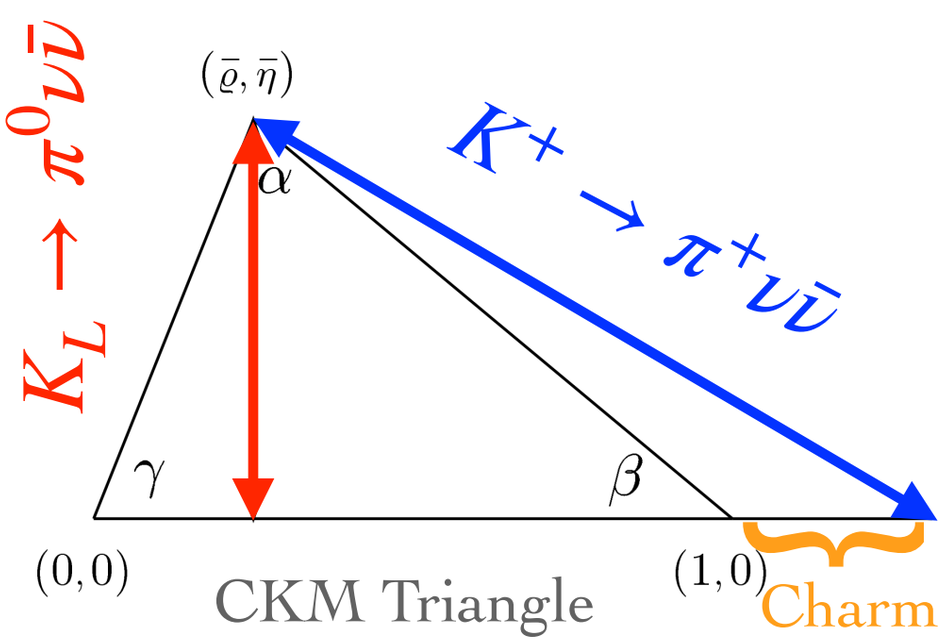
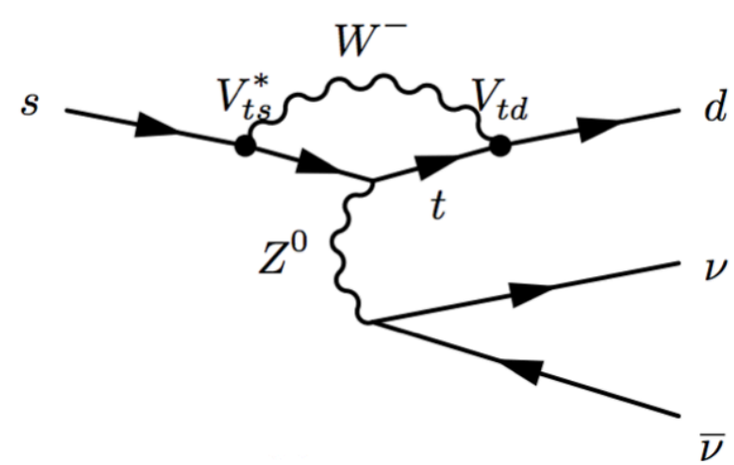
$K_L \to \pi^0 \nu\bar{\nu}$ in SM

- Direct CP violating process, $BR(K_L \to \pi^0 \nu\bar{\nu})_{SM} \propto \eta^2$
- Clean with a few % uncertainty, dominated by top quark mass.
- Ultra-rare:
  - $BR(K_L \to \pi^0 \nu\bar{\nu})_{SM} = (3.4 \pm 0.6) \times 10^{-11}$ [Buras et al, JHEP 1511]
  - Sensitive to new physics, but experimentally challenging!

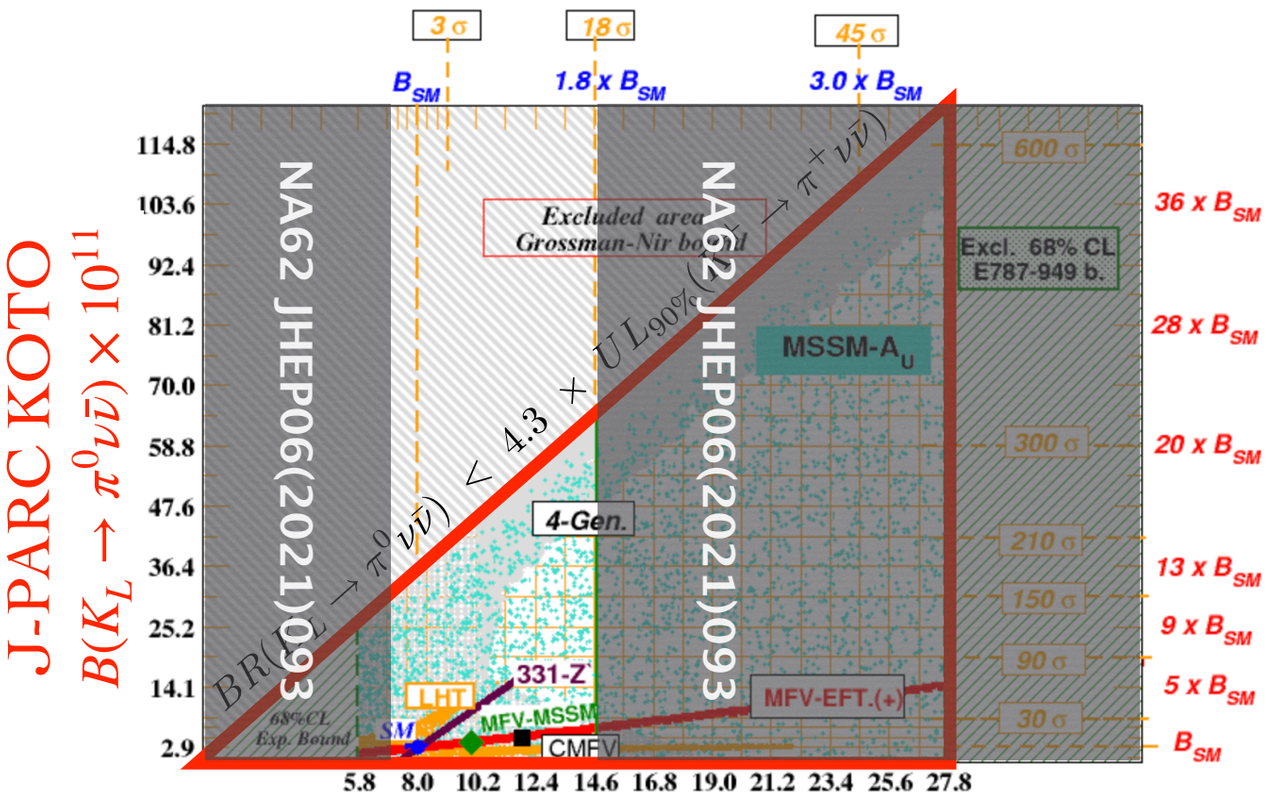


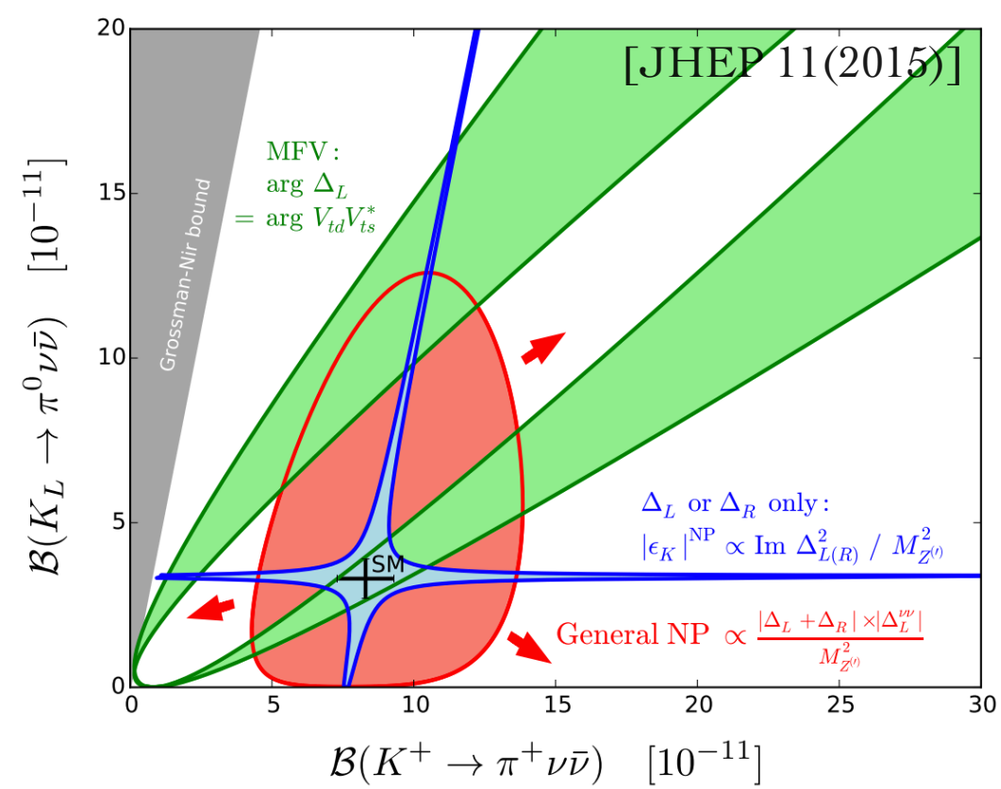


+ **New Physics?**

$K \to \pi\nu\bar{\nu}$ & New Physics

- $BR(K_L \to \pi^0\nu\bar{\nu}) < 4.3 \times BR(K^+ \to \pi^+\nu\bar{\nu})$ (Grossman-Nir bound) [Phys.Lett.B398.163]
  - Grossman-Nir bound: $BR(K_L \to \pi^0\nu\bar{\nu}) < 6.2 \times 10^{-10}$ (NA62) [JHEP06.093]
  - Experimental limit: $BR(K_L \to \pi^0\nu\bar{\nu}) < 3.0 \times 10^{-9}$ (KOTO) [PRL.122.021802]
- New physics could contribute to BR(K^+) & BR(K^0) differently. [JHEP 11(2015)]





Japan

- KEK, Kyoto Univ, NDA, Osaka Univ, Saga Univ, Yamagata Univ.

US

- Univ. of Chicago, Univ. of Michigan

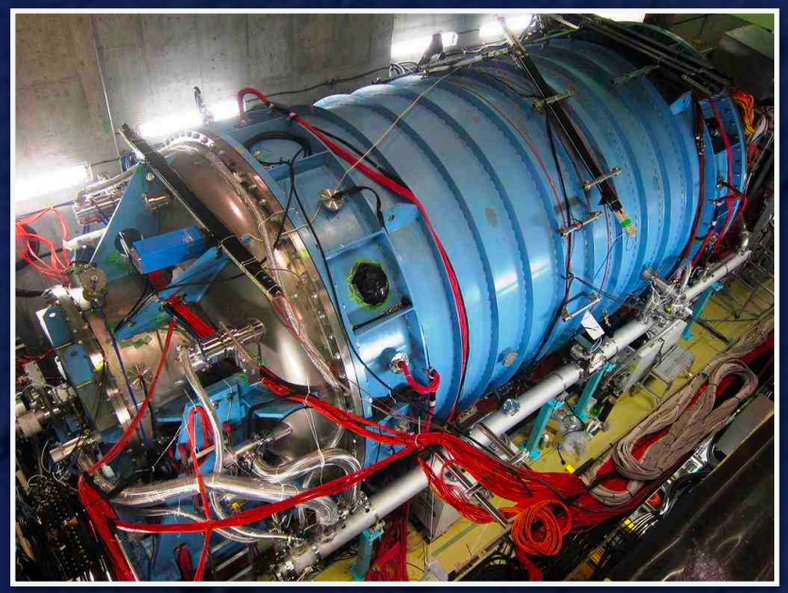
Taiwan

- National Taiwan Univ.

Korea

- Jeonbuk National Univ, Jeju National Univ, Korea Univ.

J-PARC



KOTO

Detection of $K_L \to \pi^0 \nu\bar{\nu}$

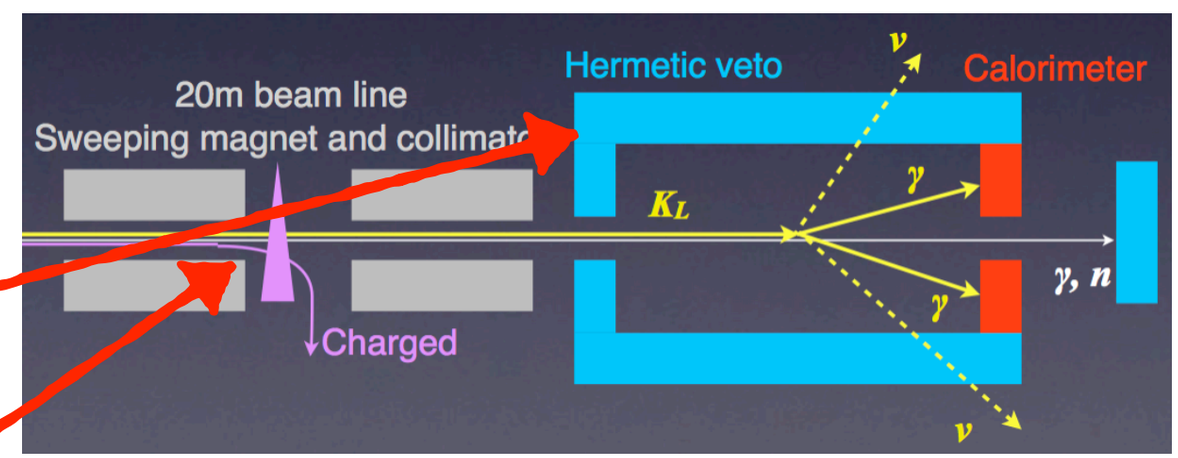
K_L untagged $\rightarrow$ π^0 $\nu\bar{\nu}$ undetectable

$\downarrow$

$\gamma\gamma$ measured by CsI

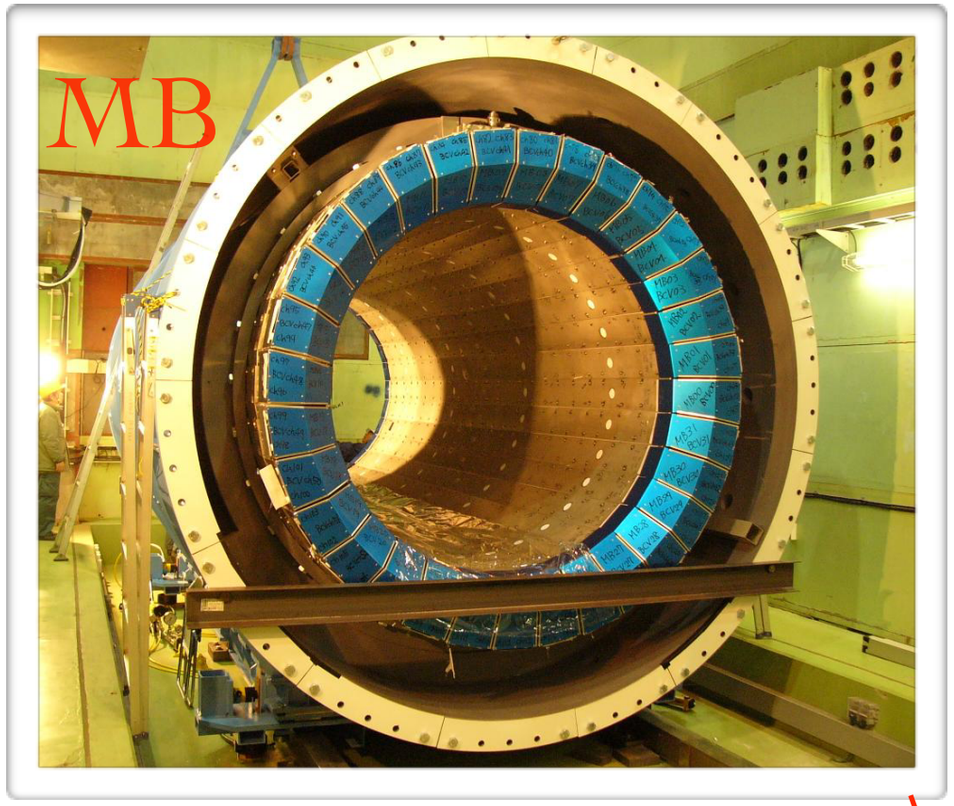
Signal Signatures:

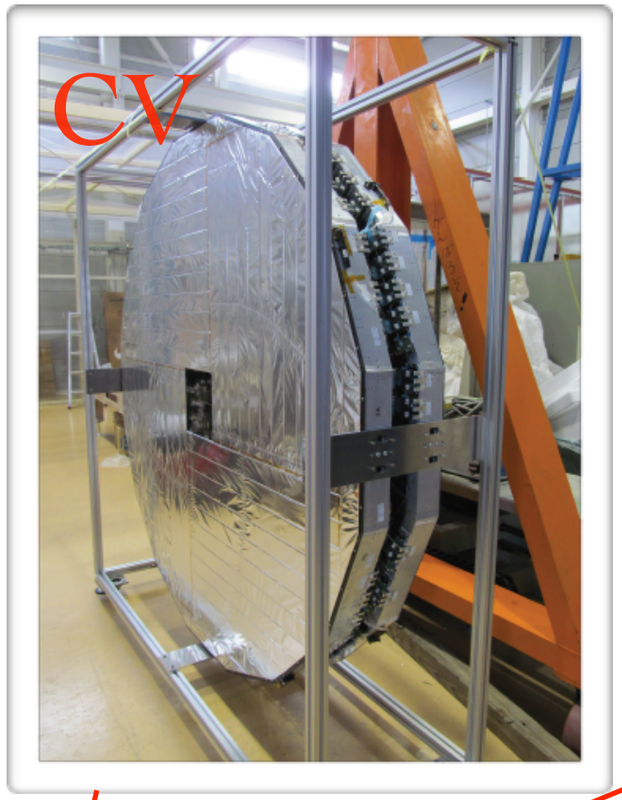
- 2γ + nothing else
- large π^0 Pt (missing momentum taken by $\nu\bar{\nu}$)



Hermetic veto

Narrow beam


MB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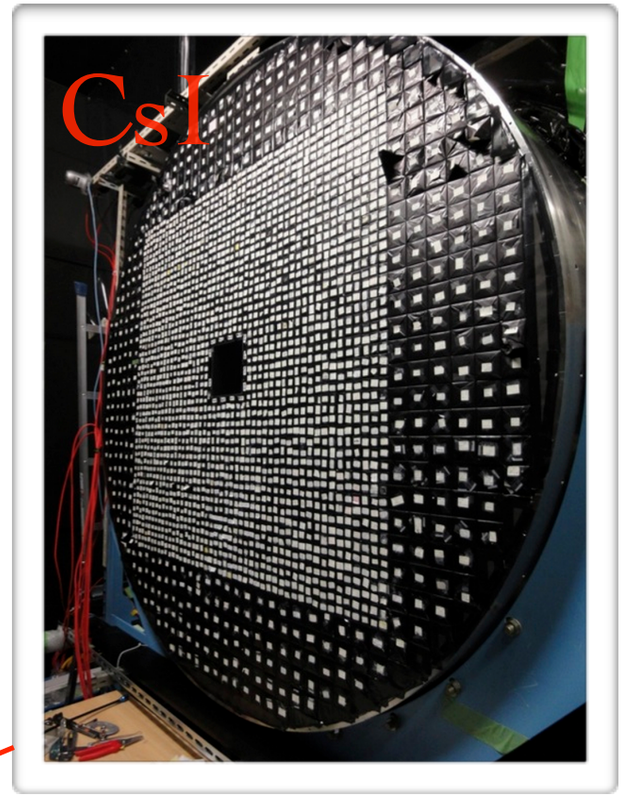
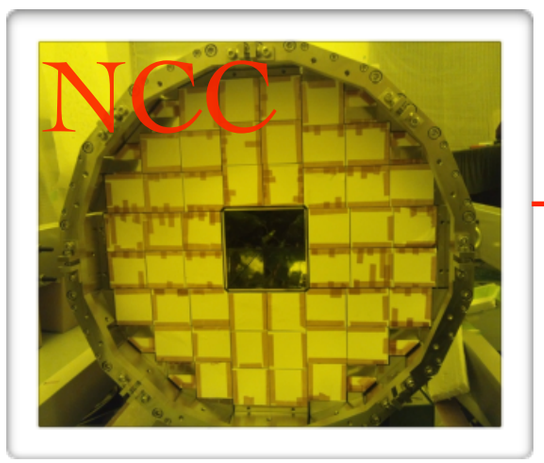
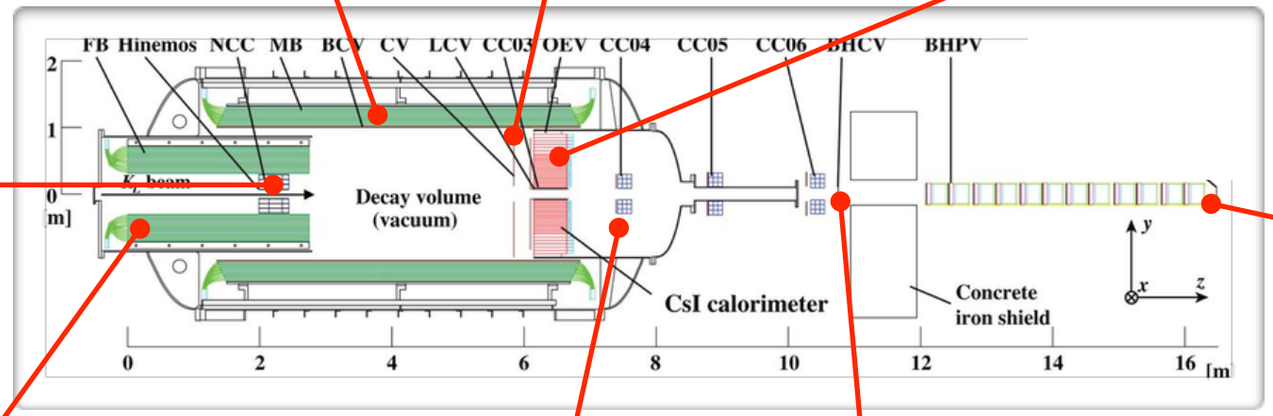
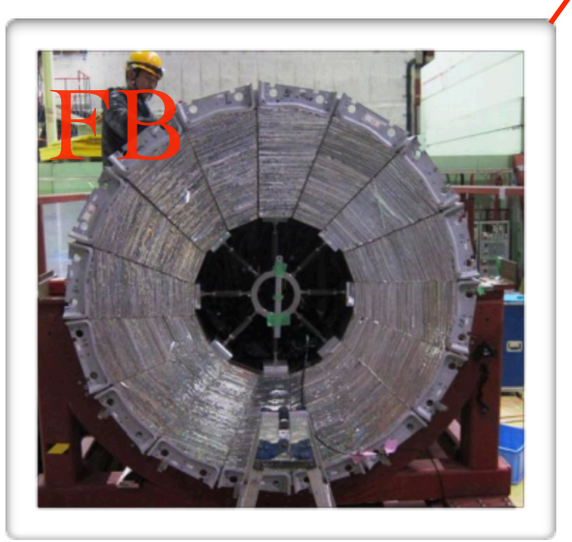
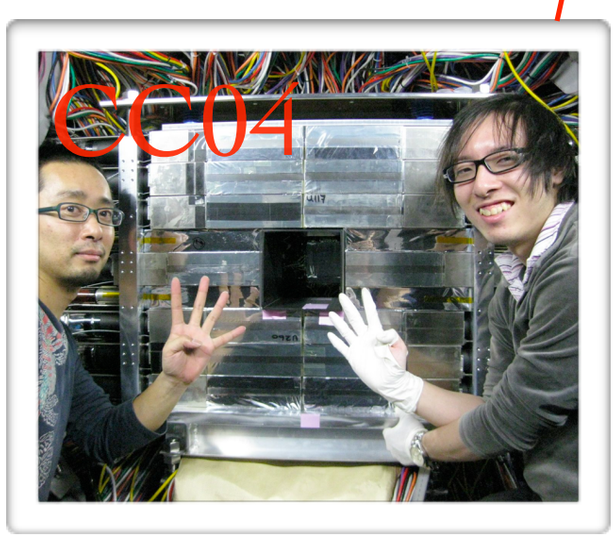

CsI


NCC


FB
Hinemos
NCC
MB
BCV
CV
LCV
CC03
OEV
CC04
CC05
CC06
BHCV
BHPV
K_L beam
Decay volume
(vacuum)
CsI calorimeter
Concrete
iron shield
y
x
z
0
2
4
6
8
10
12
14
16
[m]


FB

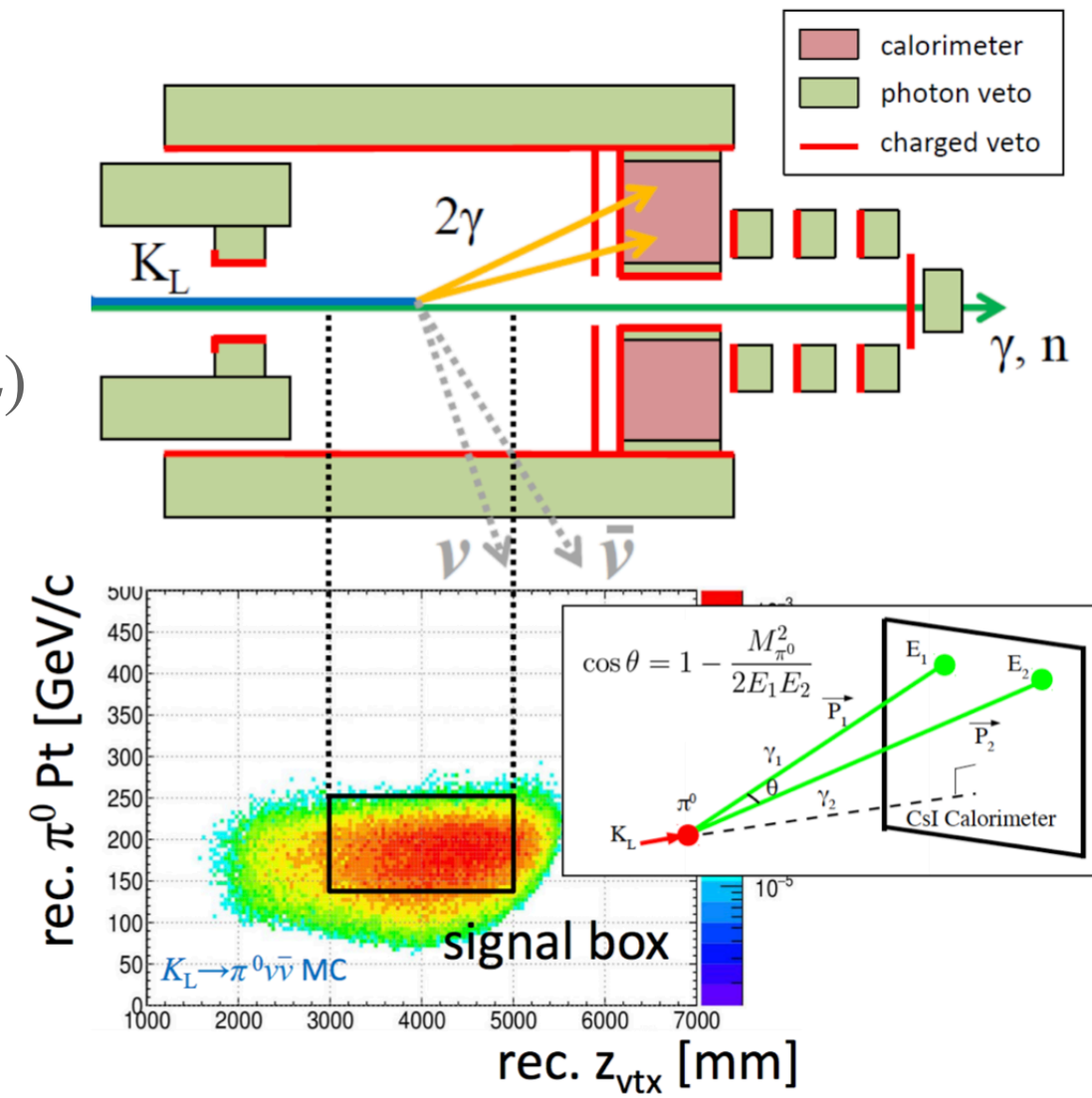

CC04

BHCV

BHPV

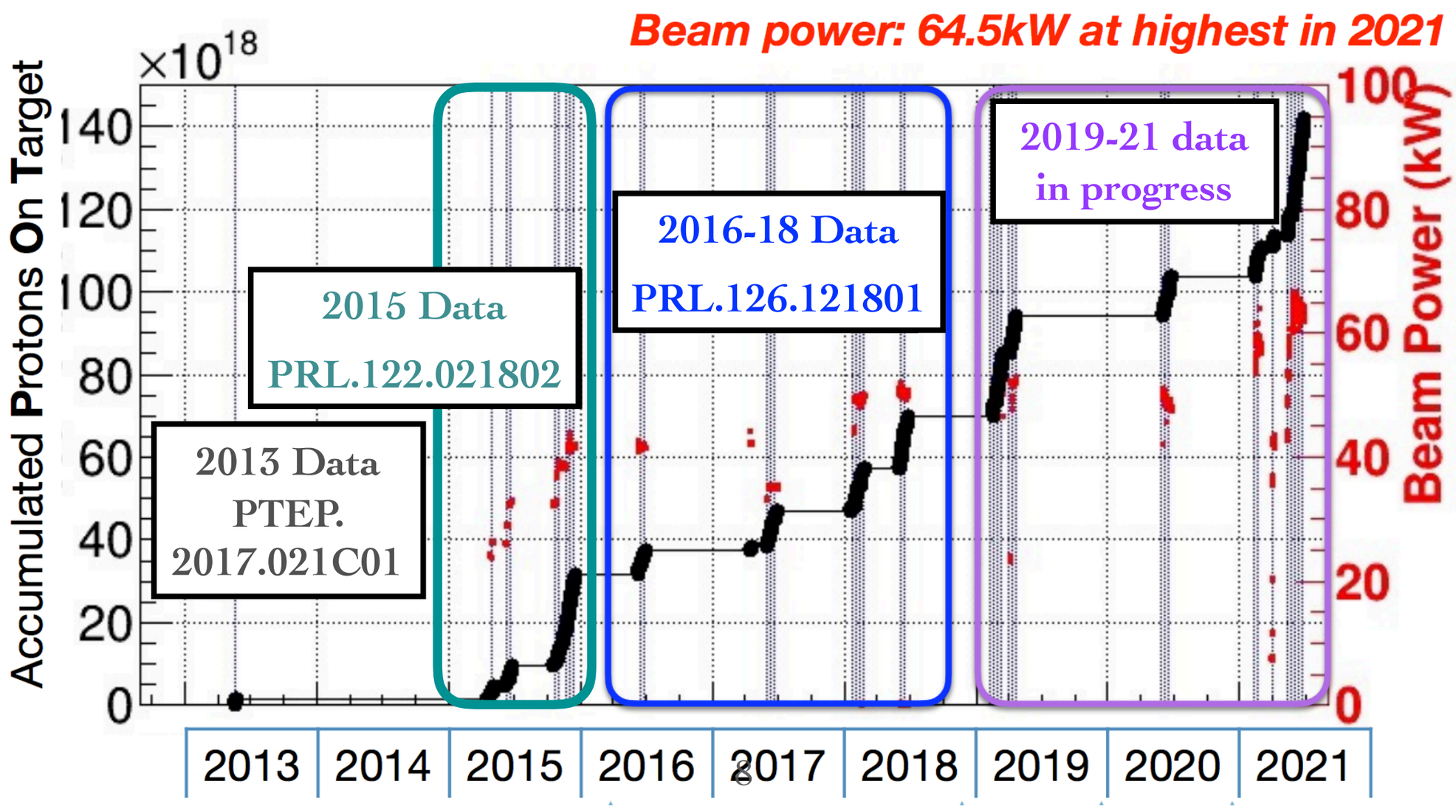
Reconstruction of $K_L \to \pi^0 \nu \bar{\nu}$

- Reconstruct decay vertex (Z_{vtx}) by assuming $M(\gamma\gamma) = M_{\pi^0}$
- Calculate transverse momentum (P_T) of π^0 by using Z_{vtx}
- Signal Region:
  - Large π^0 P_T
  - Z_{vtx} within fiducial region



Run History

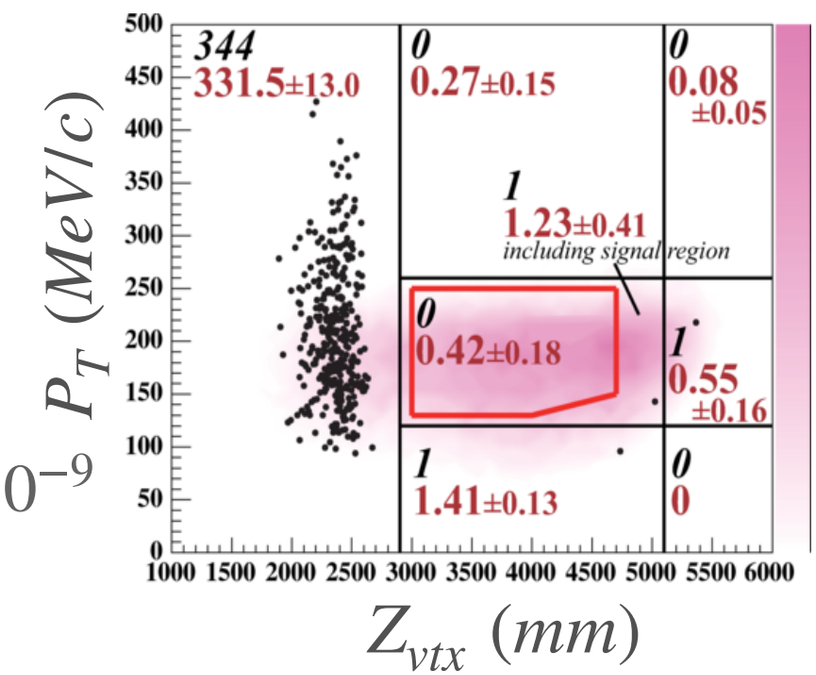
- 2015 data: set the current best limit on $B(K_L \to \pi^0 \nu\bar{\nu})$.
- 2016-2018 data: recent results with new background sources.
- 2019-2021: analysis in progress.



Recent Results

- 2015 data [PRL.122.021802]:
  - No event observed with 0.42 predicted BGs.
  - Single Event Sensitivity (S.E.S):
    - $S.E.S. = \frac{1}{(K_L\ flux) \times (Acceptance_{sig})} = 1.30 \times 10^{-9}$
- $BR(K_L \to \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9}\ at\ 90\%\ C.L.$
  - Current best limit.

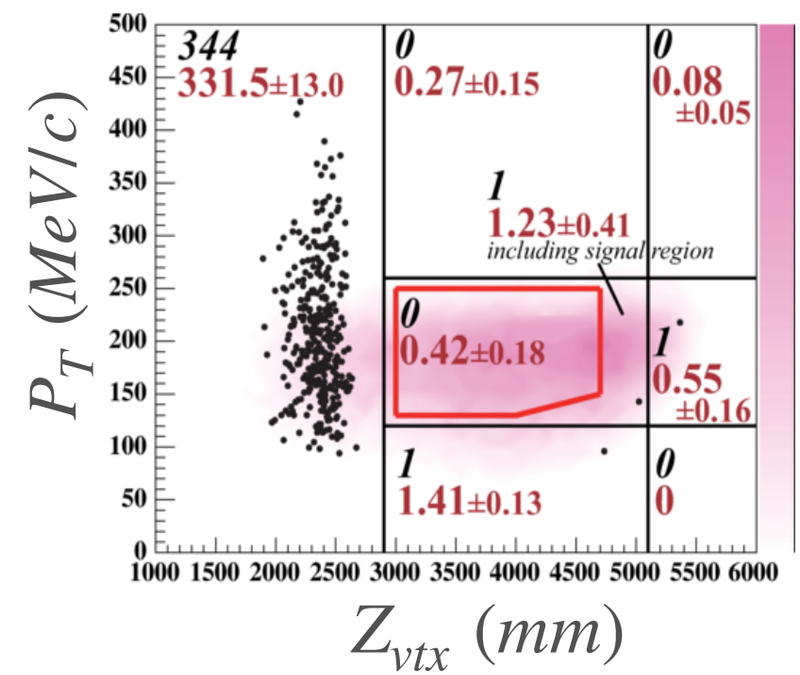
2015 Data



Recent Results

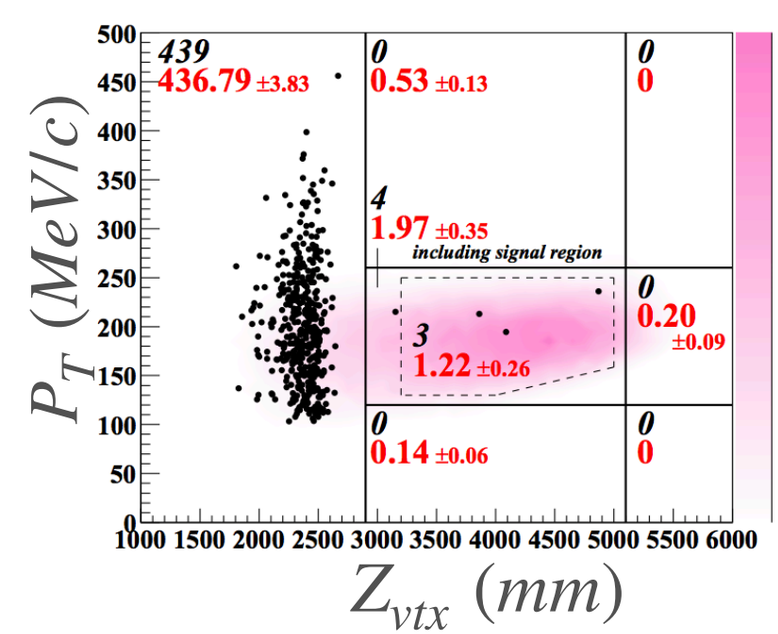
- 2015 data [PRL.122.021802]:
  - No event observed with 0.42 predicted BGs.
  - $S.E.S. = 1.30 \times 10^{-9}$
  - $BR(K_L \to \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9}$ *at* 90% $C.L.$
    - Current best limit.

2015 Data



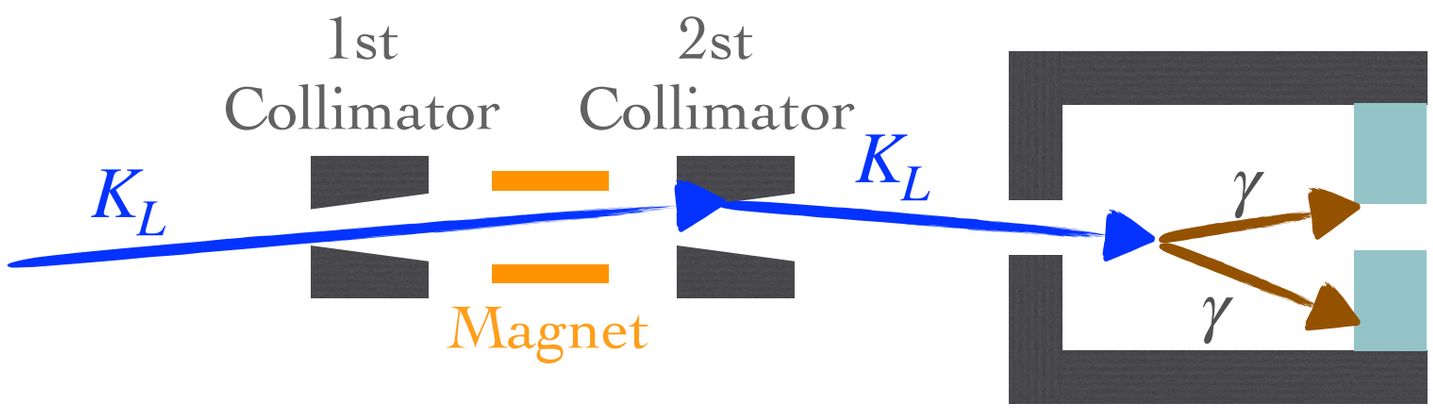
- 2016-2018 data [PRL.126.121801]:
  - $S.E.S. = 7.20 \times 10^{-10}$
  - Observed 3 events with 1.22 predicted BG.
    - 1.22 BG events included newly found BGs.
  - $BR(K_L \to \pi^0 \nu\bar{\nu}) < 4.9 \times 10^{-9}$ *at* 90% $C.L.$

2016-2018 Data

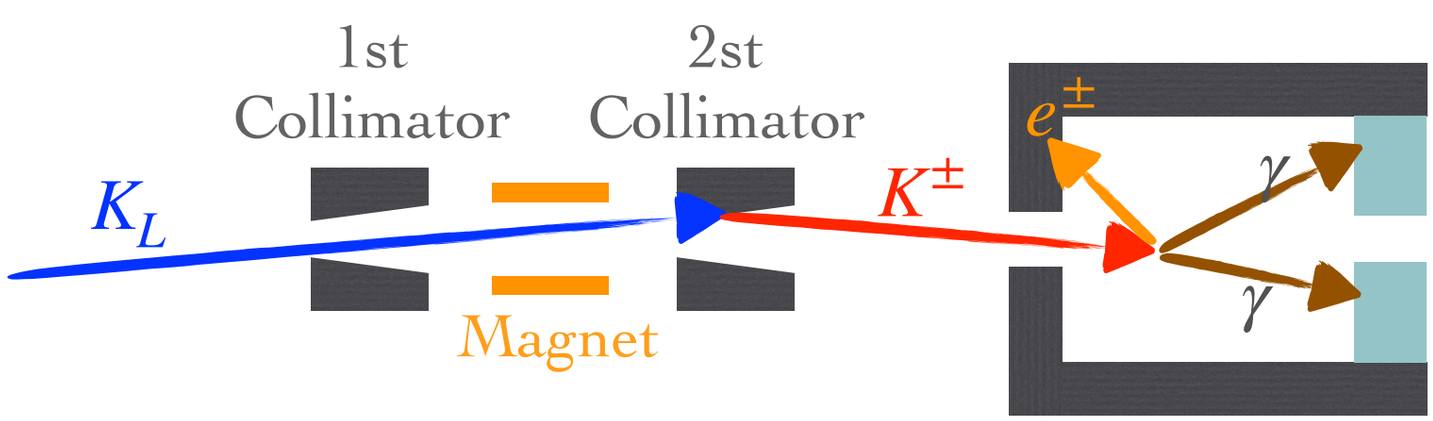


New BG Sources

Beam halo K_L BG ($K_L \to \gamma\gamma$)



$K^\pm$ BG ($K^\pm \to \pi^0 e^\pm \nu$)



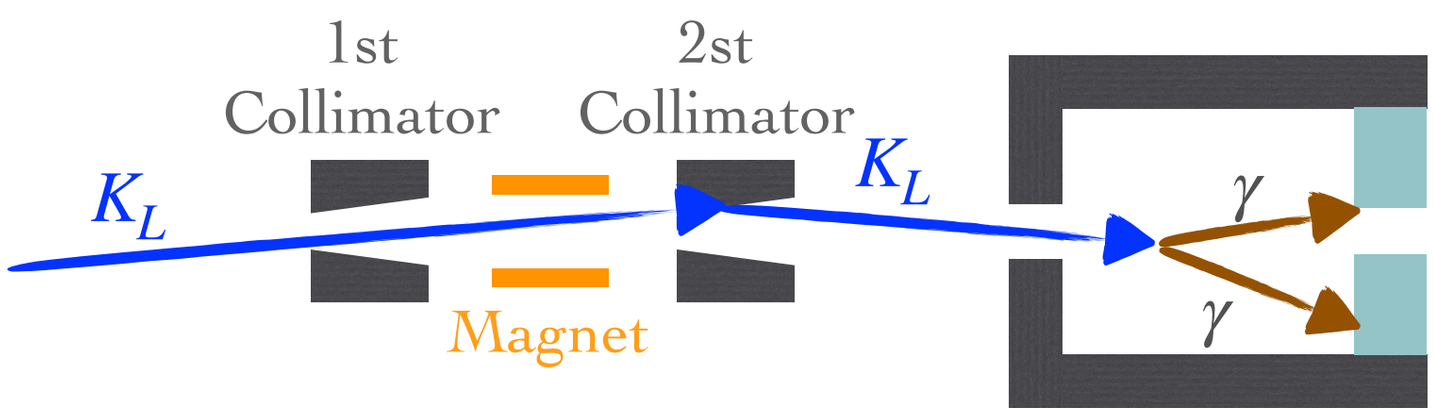
BG Table
of 2016-2018 data

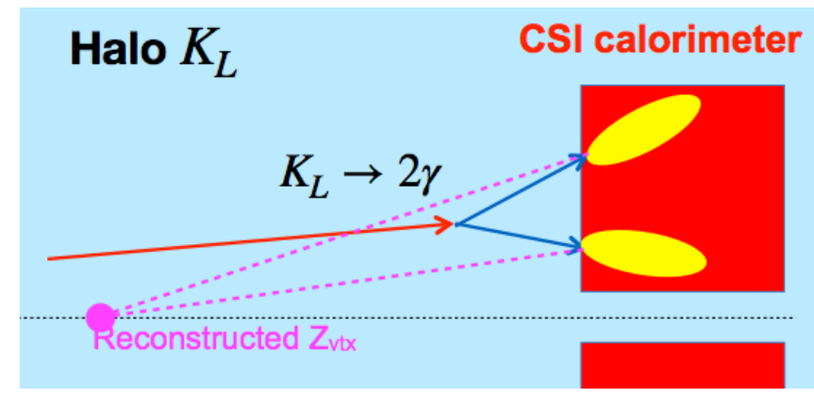
source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07 [a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25 [a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
total		1.22 ± 0.26

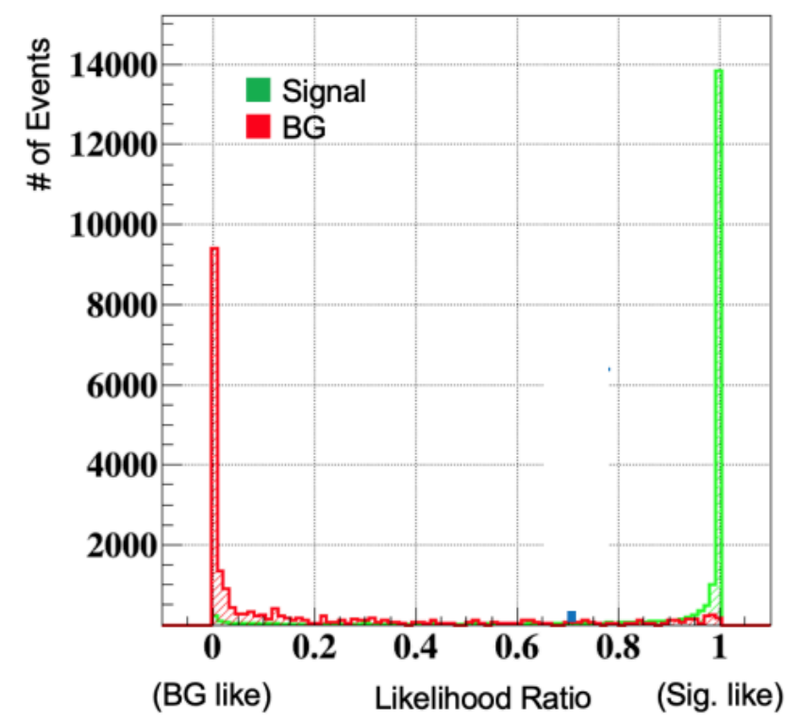
[a] Background sources studied after looking inside the blind region.

Beam Halo K_L BG

Beam halo K_L BG







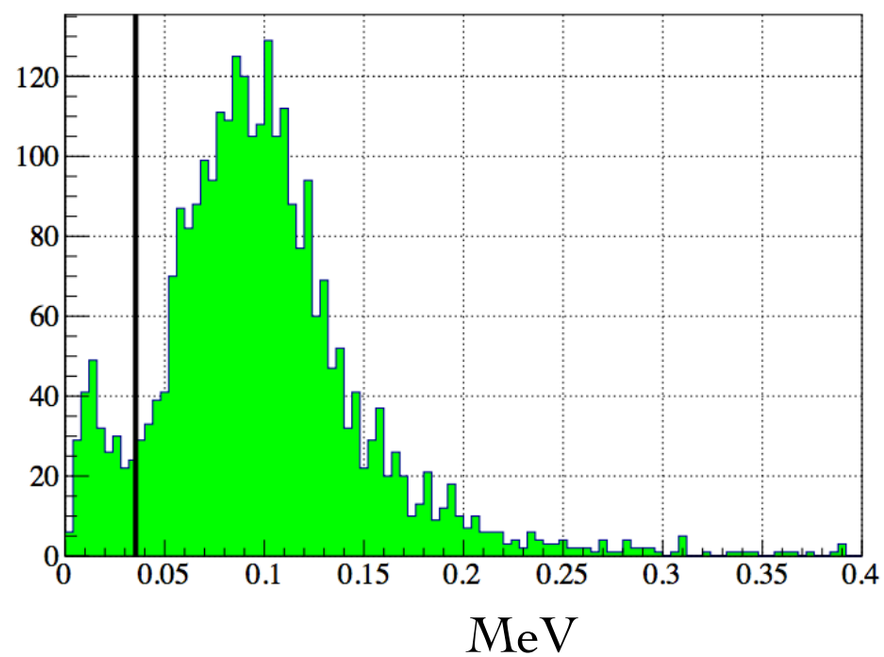
- New cut based on the cluster shape and γ angle suppressed the halo K_L by 1/16.
  (new cut isn't applied to the 2016-2018 analysis)
- BG level ~0.4 events at $BR_{EXP}(K_L \to \pi^0 \nu\bar{\nu}) \sim O(10^{-11})$.

Charged Kaon BG

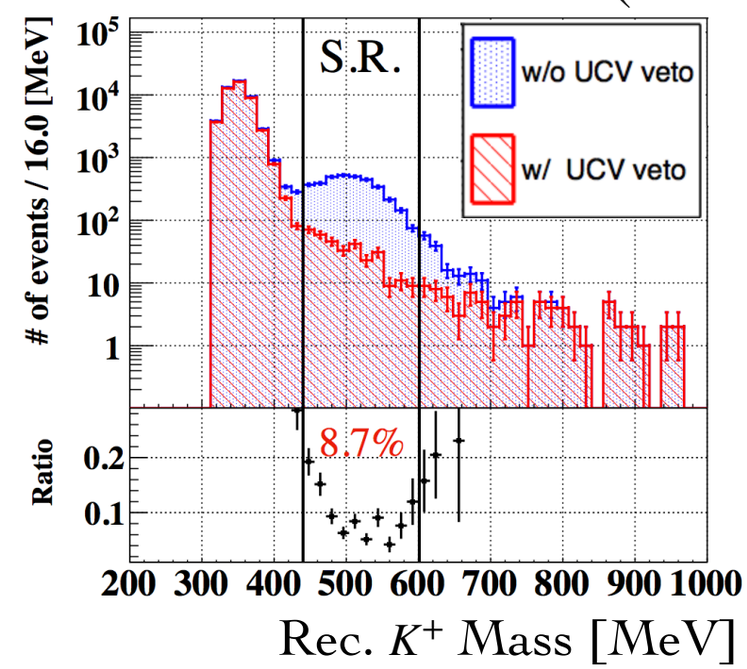
2021

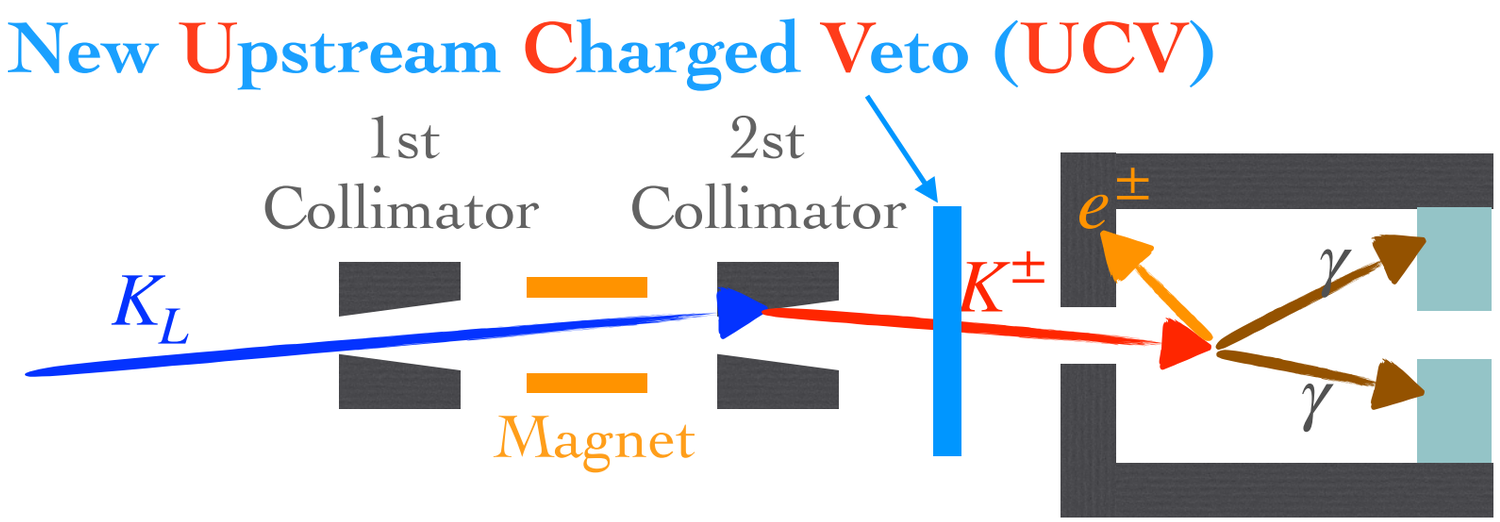
- UCV was installed
- Scintillating fiber.
- $K^{\pm}$ BG × 1/13

Deposited Energy in UCV (data)



$K^{+} \rightarrow \pi^{+}\pi^{0}$ events (data)





Charged Kaon BG

2021

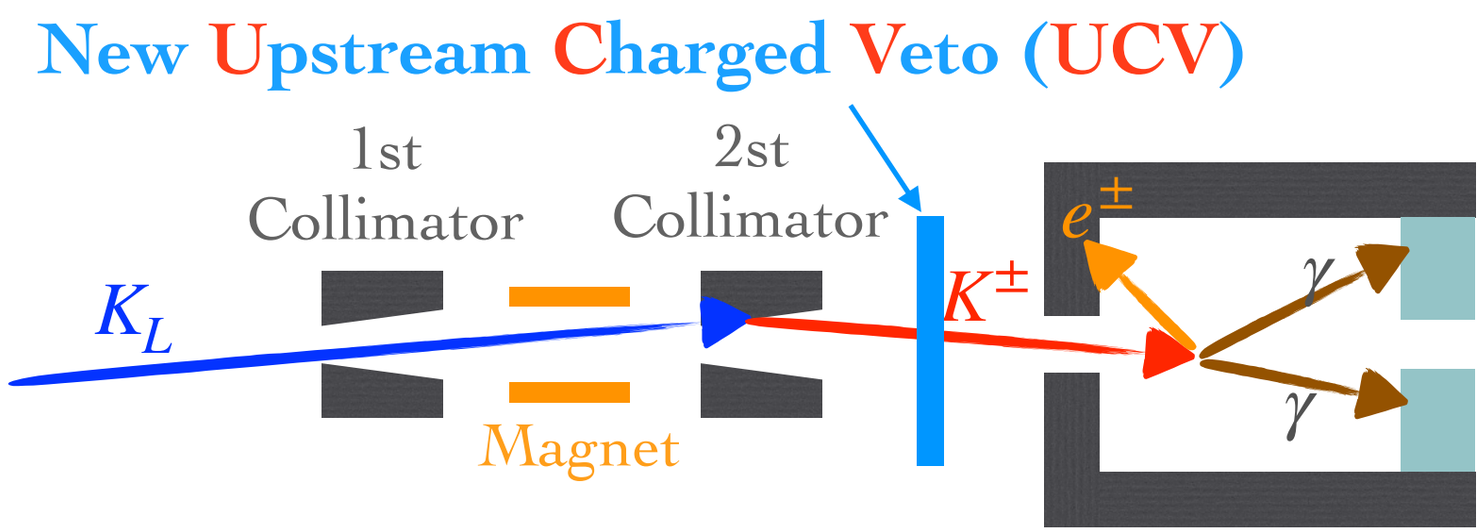
- UCV was installed.
- Scintillating fiber.
- $K^{\pm}$ BG × 1/13

2022

- UCV will be upgraded.
- Scintillator film.
- $K^{\pm}$ BG × 1/100

2023

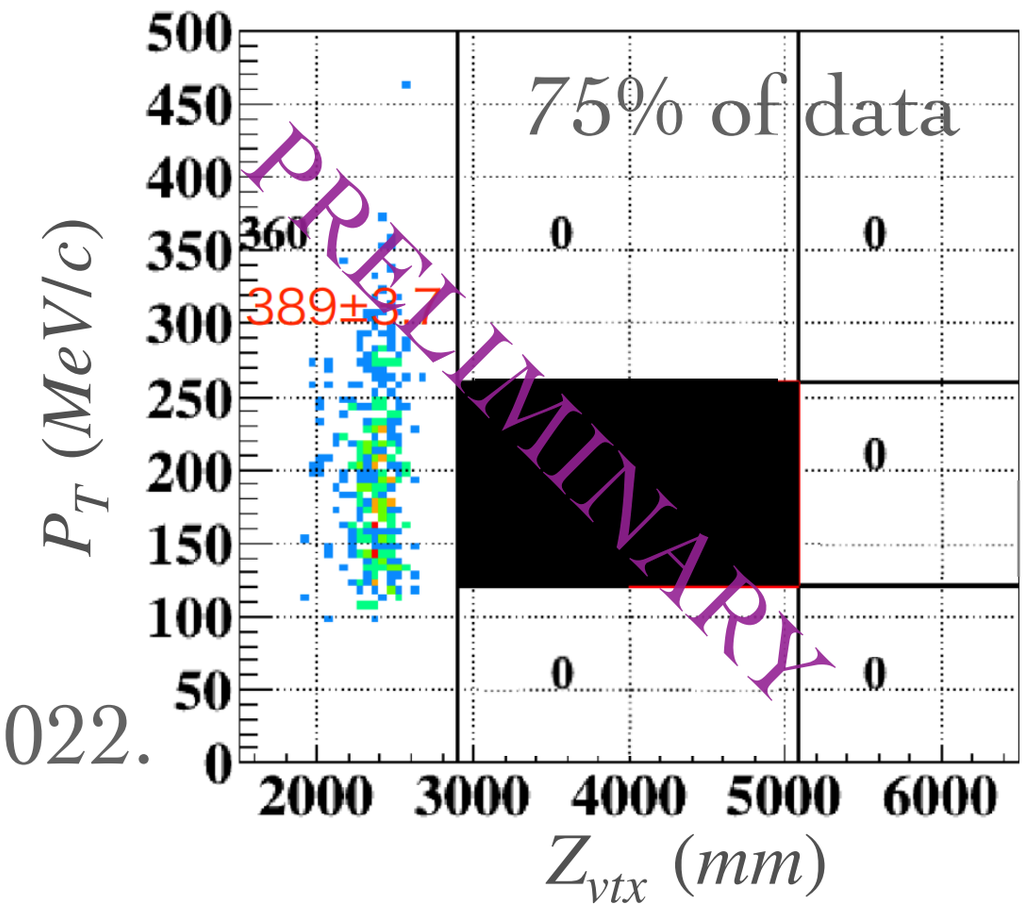
- Will install a magnet after 2nd collimator.
- $K^{\pm}$ BG × 1/10



- Combined reduction ~1/1000 after 2023.
- $K^{\pm}$ BG ~0.02 events in the SM S.E.S.

2019-2021 Data Analysis

- Analysis in progress.
  - ~75% of 2019-2021 data.
    - $S.E.S. = 1.2 \times 10^{-9}$ (preliminary).
  - Cut condition not optimized yet.
- Plan to unblind the full data in Aug. 2022.



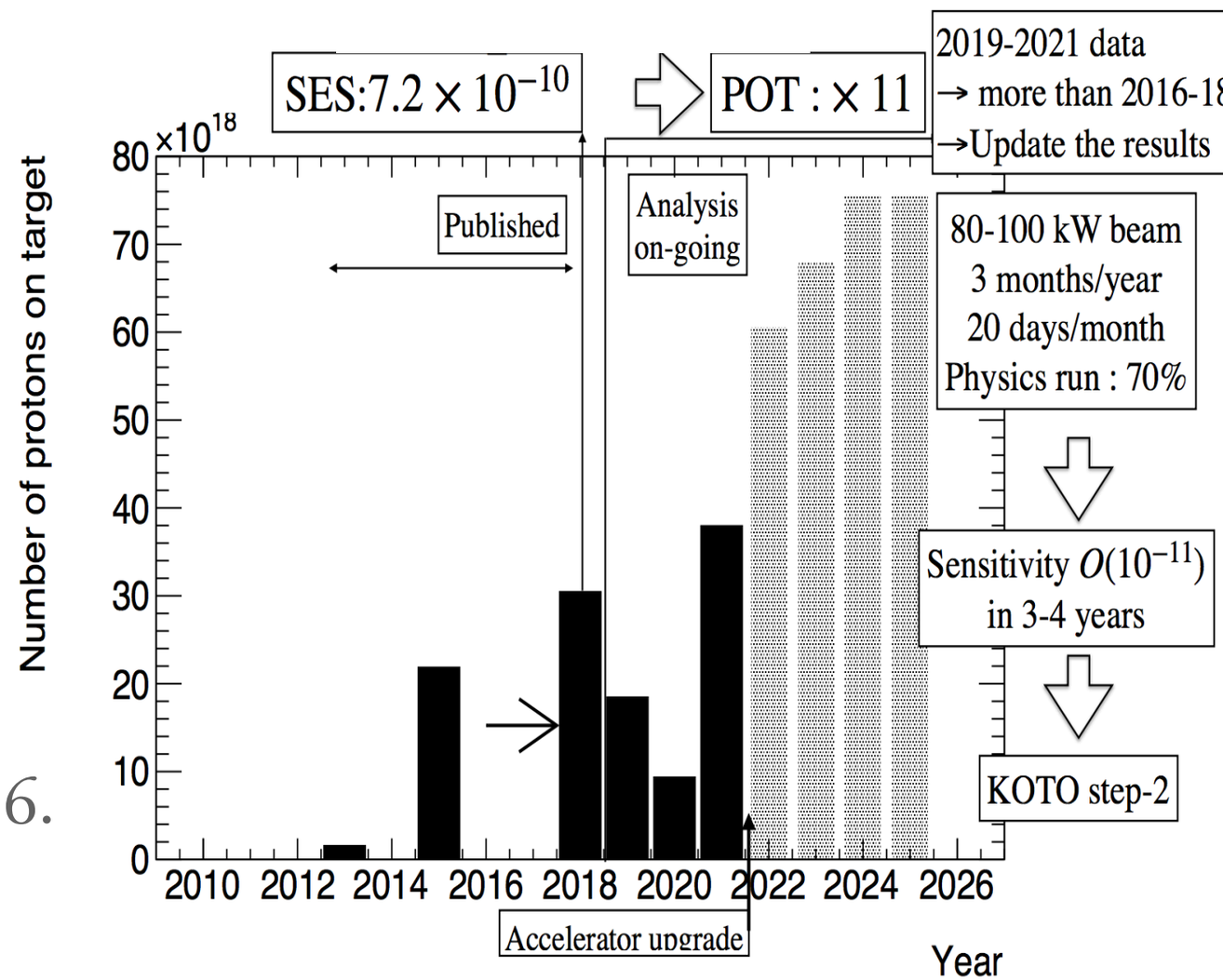
Prospects

2021-2022 Accelerator Shutdown

- Main-ring power supply upgrade.
- Beam power 64kW → 80-100kW.

2023-2025

- Expect to collect ×11 data.
- Projected S.E.S. ~O(10^{-11}) by 2026.



Summary

Analysis Status:

- 2015 data [PRL.122.021802]
  - $BR(K_L \to \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9}\ at\ 90\,\%\ C.L.$
  - The current best limit on $BR(K_L \to \pi^0 \nu\bar{\nu})$
- 2016-2018 data [PRL.126.121801]
  - $BR(K_L \to \pi^0 \nu\bar{\nu}) < 4.9 \times 10^{-9}\ at\ 90\,\%\ C.L.$
  - New background sources found.
- 2019-2021 data (analysis in progress)
  - New detector and analysis tools for suppressing new BG.

Prospects:

- KOTO expects to improve the S.E.S. to $O(10^{-11})$ by 2026.