Status of the KOTO Experiment

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Japan

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

US

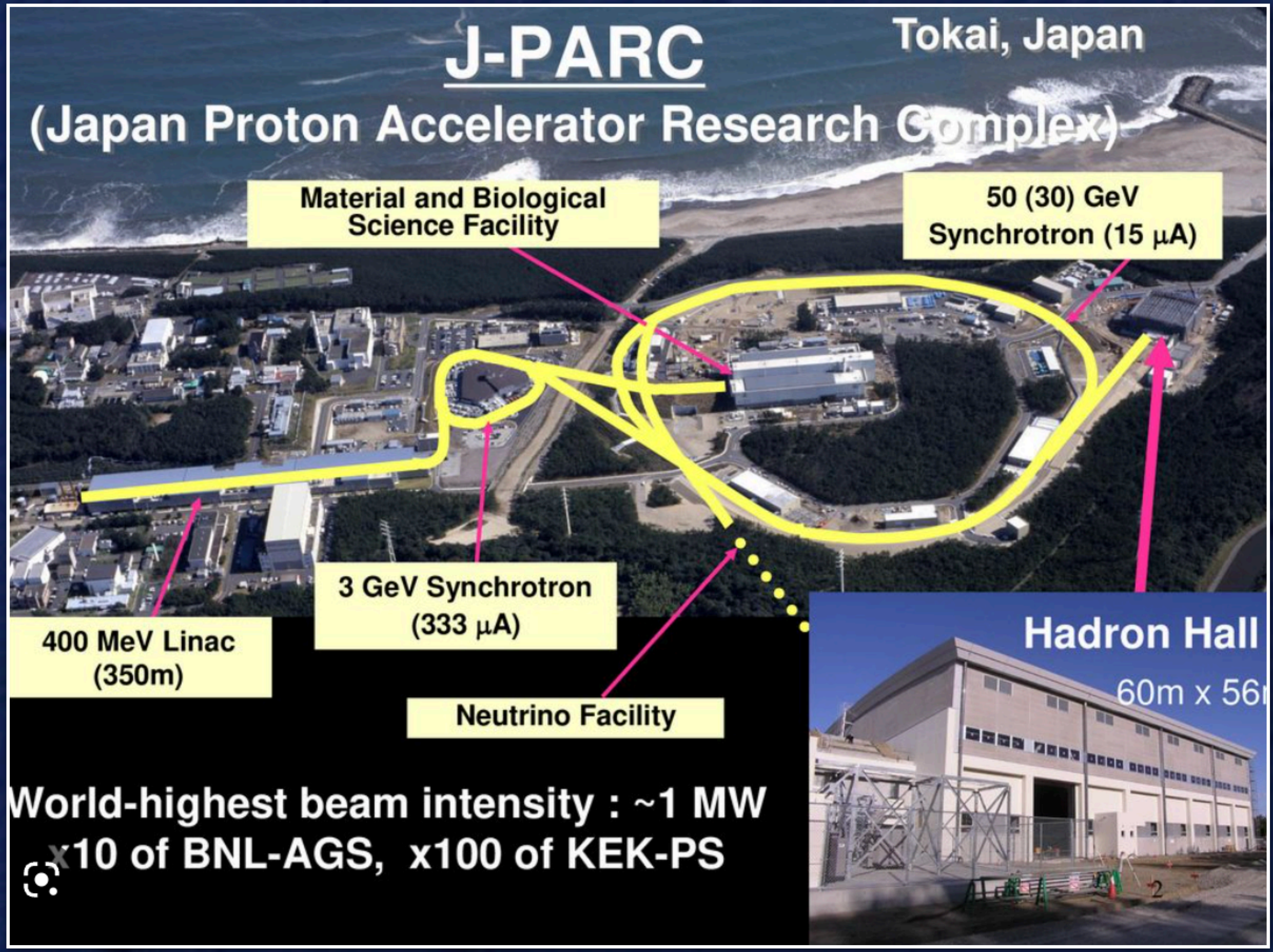
- Univ. of Chicago, Univ. of Michigan

Taiwan

- National Taiwan Univ.

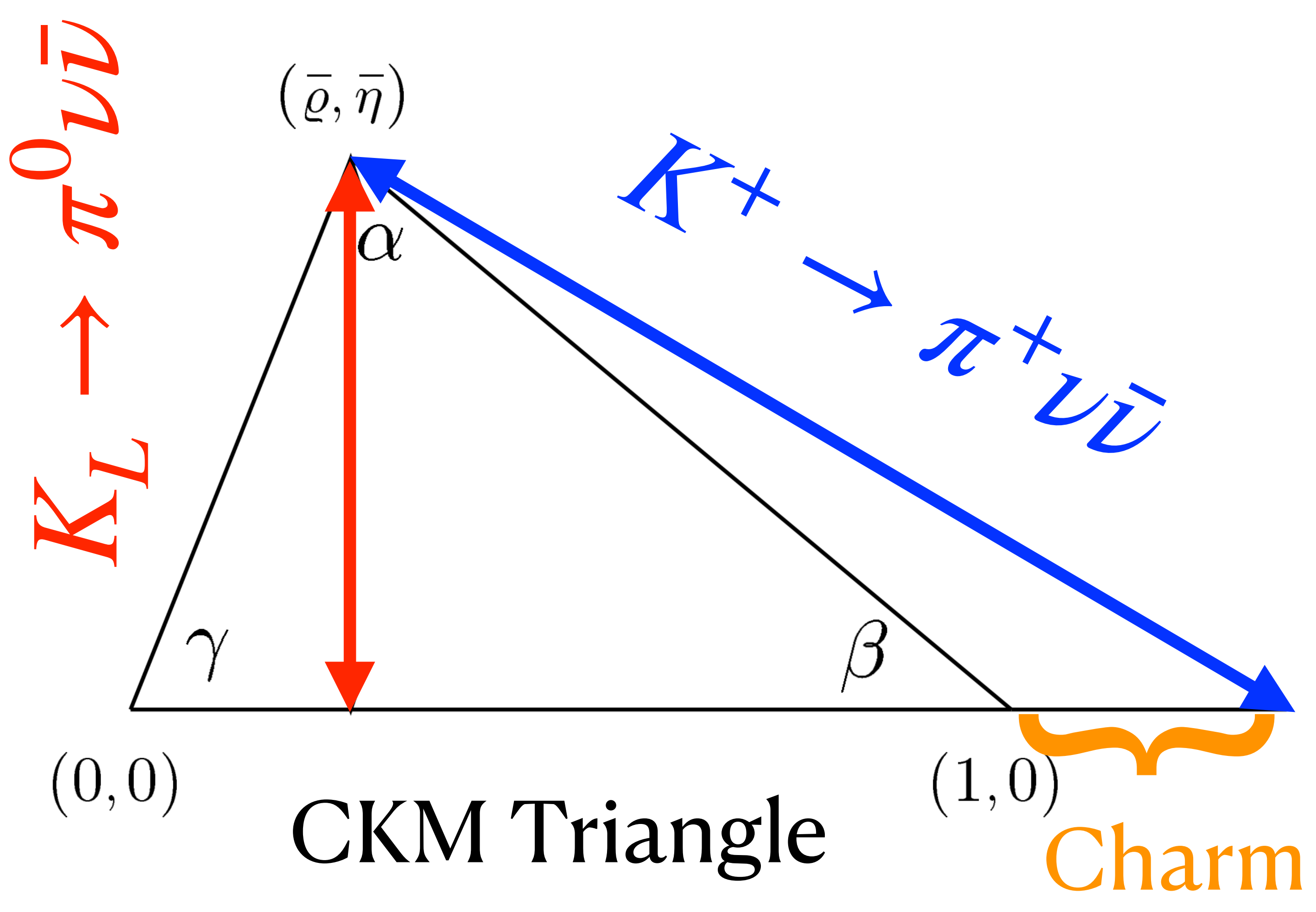
Korea

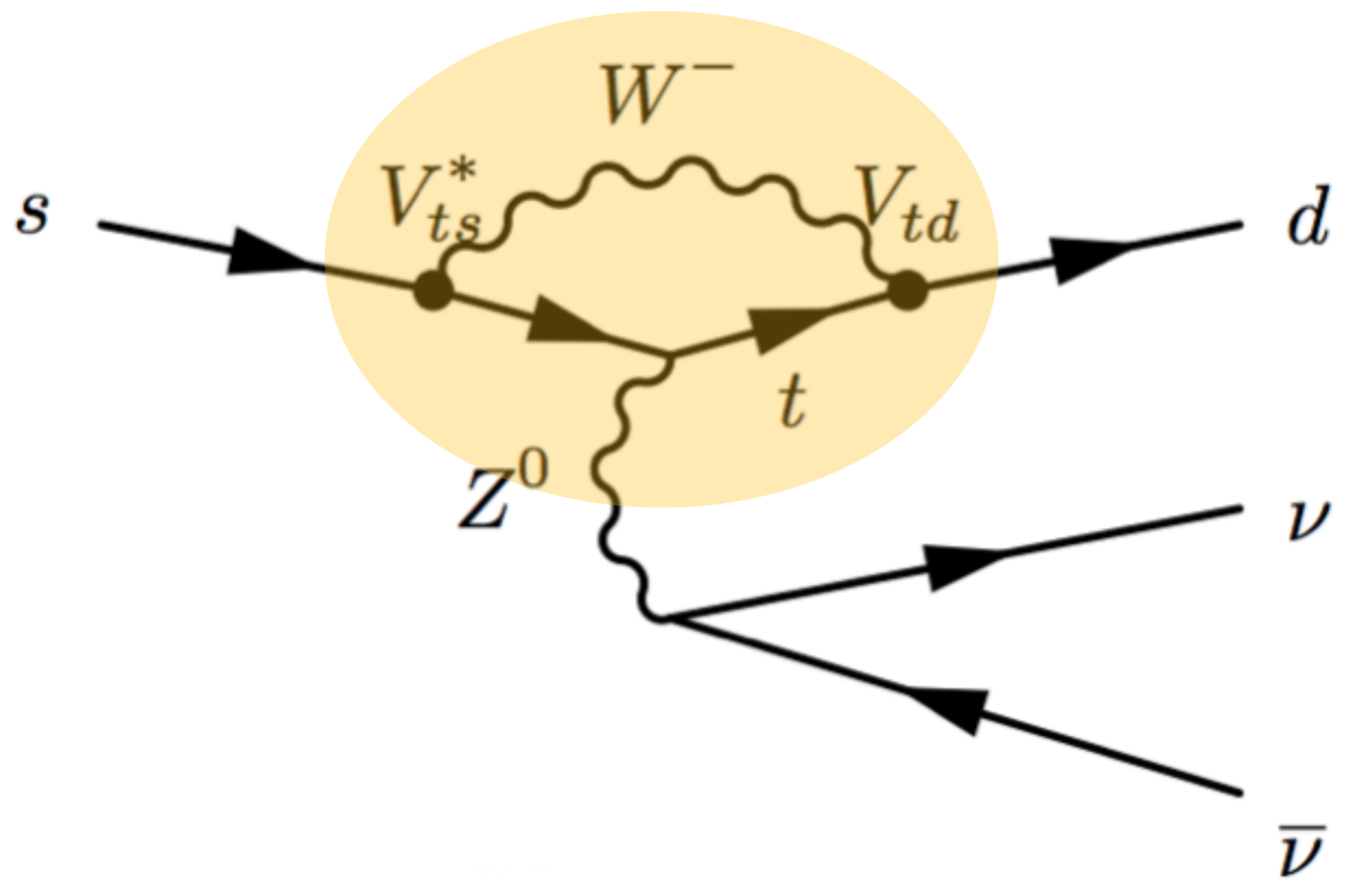
- Jeonbuk National Univ, Jeju National Univ, Korea Univ.



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

- Direct CP-violating process, $BR(K_L \to \pi^0 \nu \bar{\nu})_{SM} \propto \eta^2$
- Ultra-rare:
  - $BR(K_L \to \pi^0 \nu \bar{\nu})_{SM} = 3 \times 10^{-11}$ [Buras et al, JHEP 1511]
    - with only 2% uncertainties, dominated by top quark mass.
  - Sensitive to new physics, but experimentally challenging!

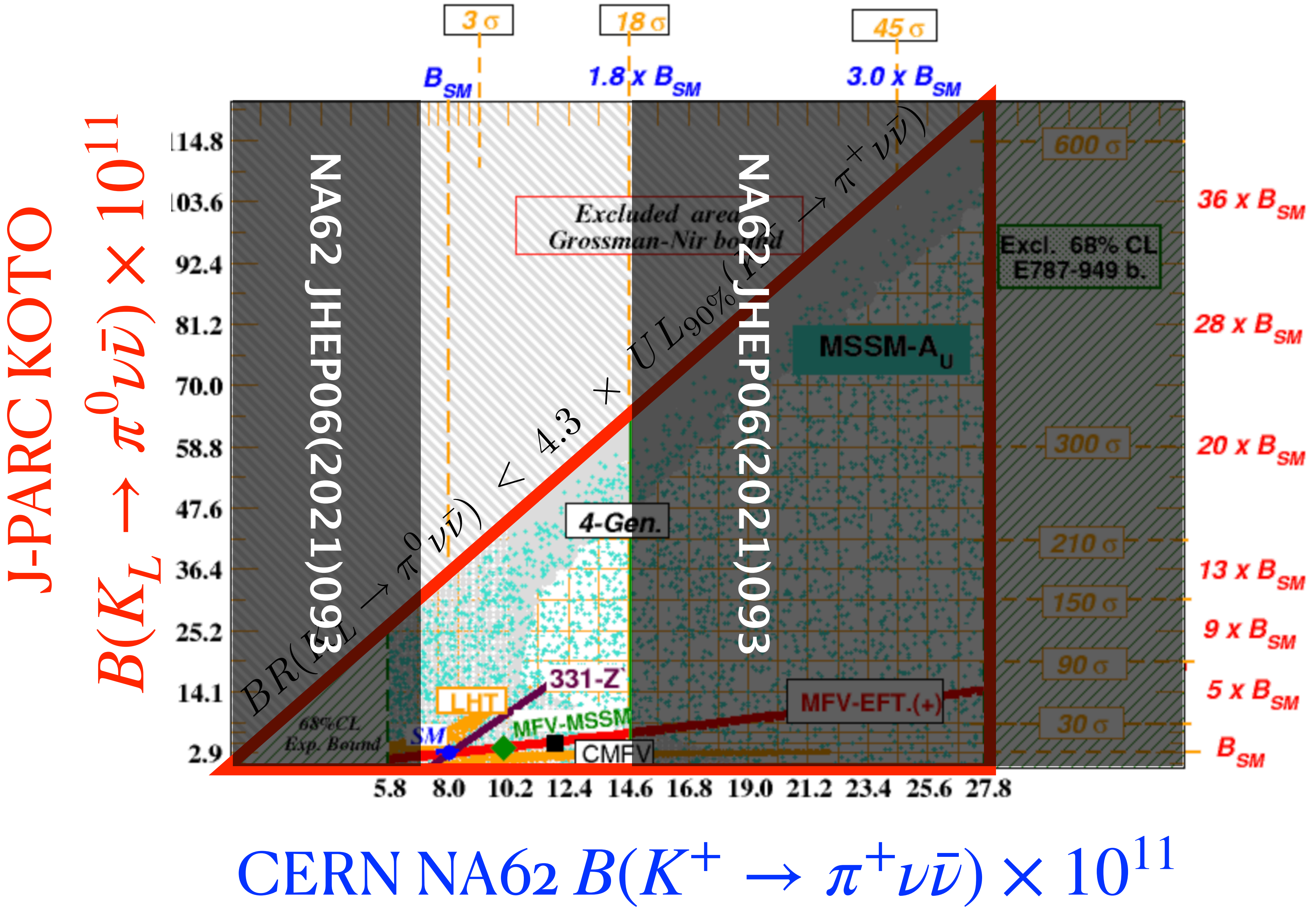


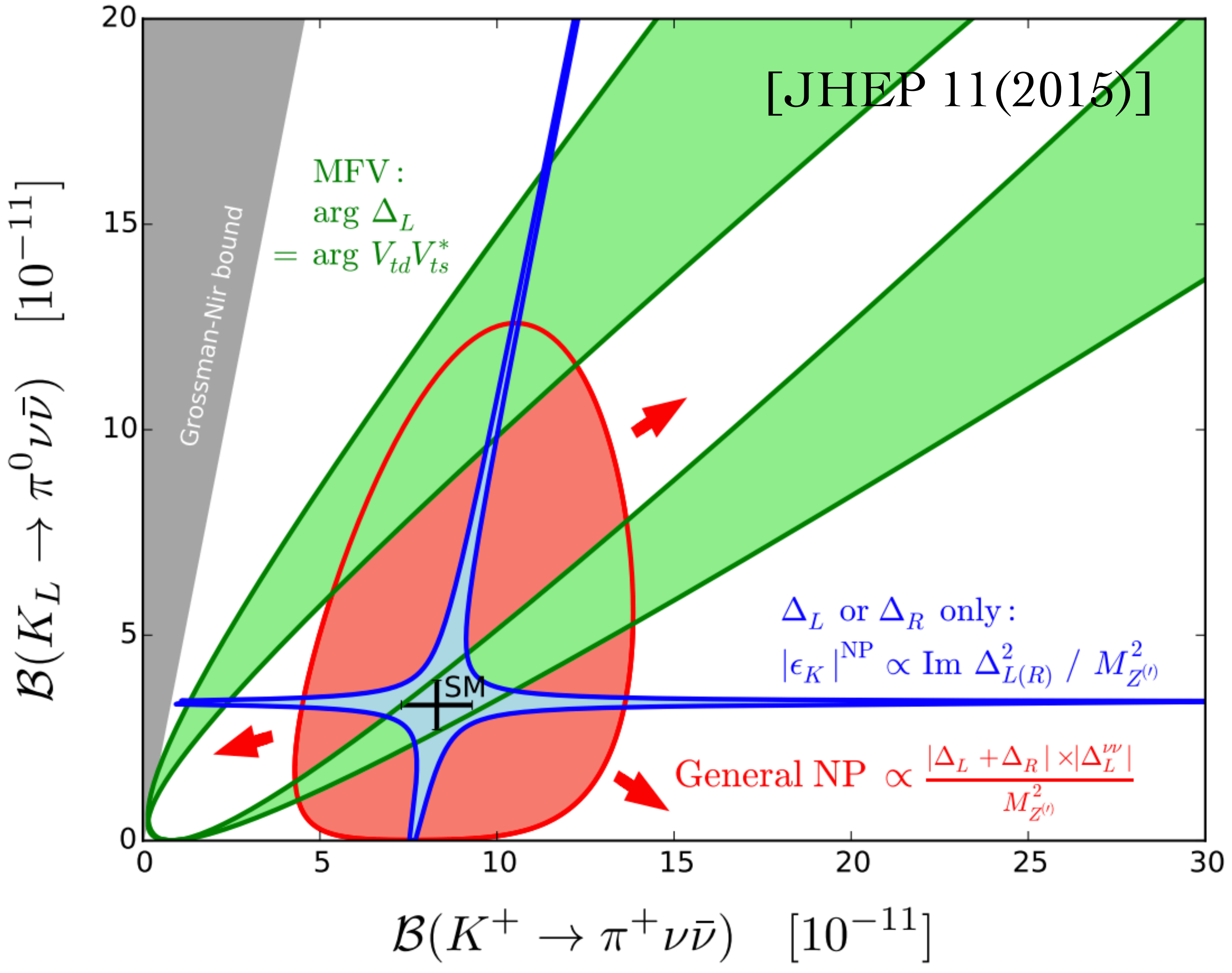


+ New Physics?

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

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





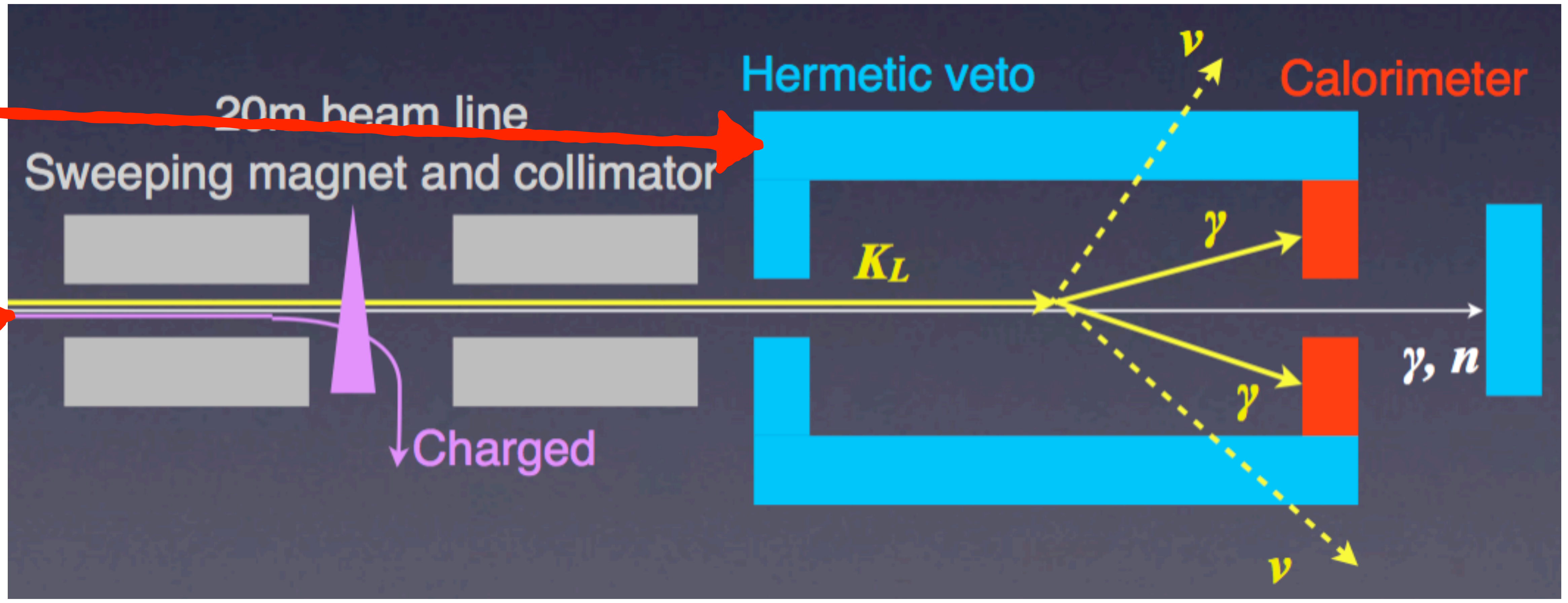
Detection of $K_L \to \pi^0 \nu \bar{\nu}$

Signal Signatures:

- 2γ in the final state
  - Measured by CsI calorimeter
- Nothing else
  - Hermetic veto system
- Large π^0 P_T (missing P taken by $\nu\bar{\nu}$)
  - Narrow beam

K_L (untagged) $\to$ π^0 $\nu\bar{\nu}$ (undetectable)

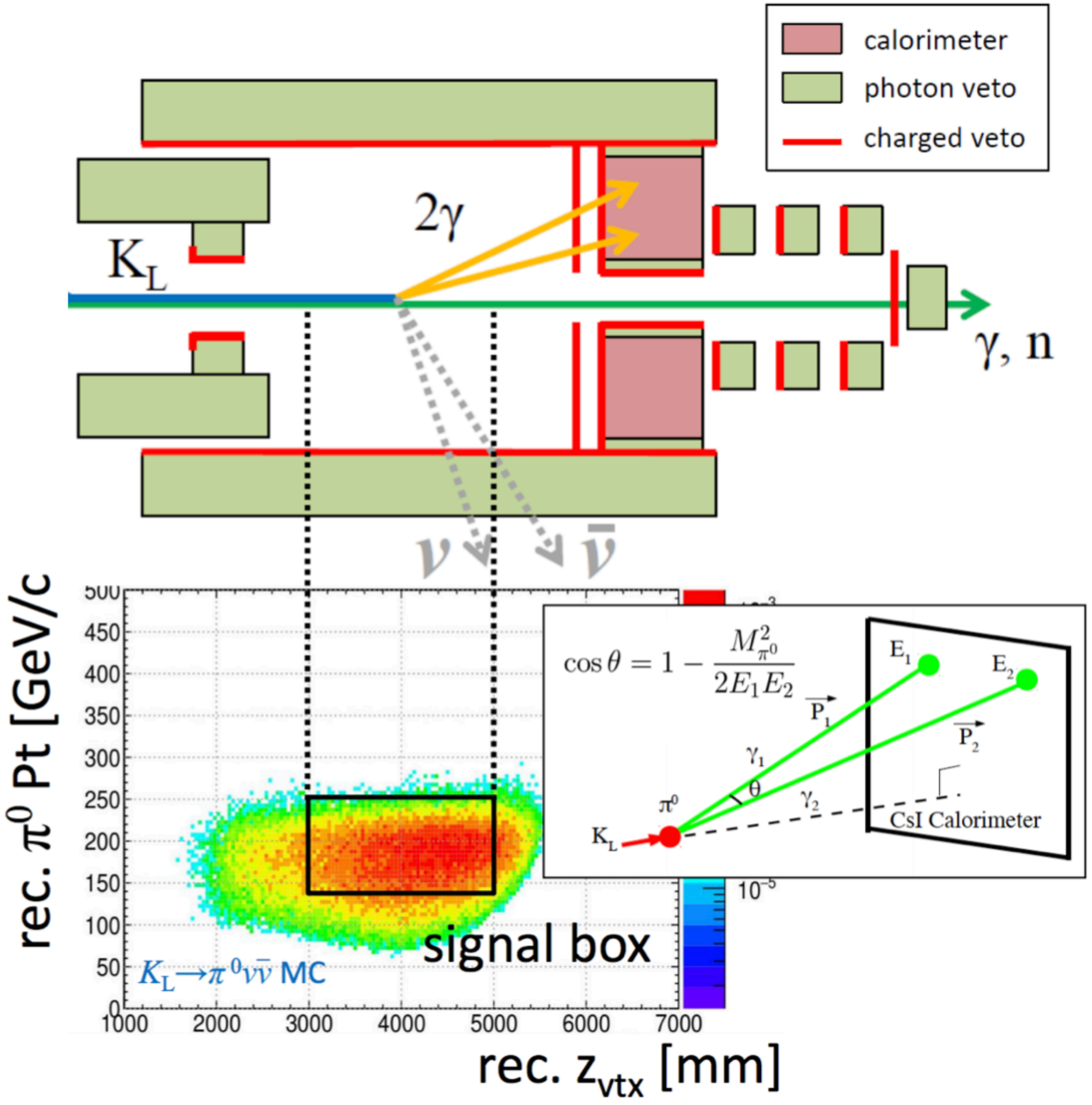
$\pi^0 \downarrow$ $\gamma\gamma$ measured by CsI



MB
CV
CsI
NCC
FB
CC04
BHCV
BHPV
FB NCC Hinemos MB IBCV IB CV MBCV CC03 OEV LCV CC04 CC05 BPCV CC06 newBHCV
Y [m]
2
1
0
K$_L$ beam
Decay volume
(vacuum)
CSI
concrete and iron shield
y
x
z
0
2
4
6
8
10
12
14
16

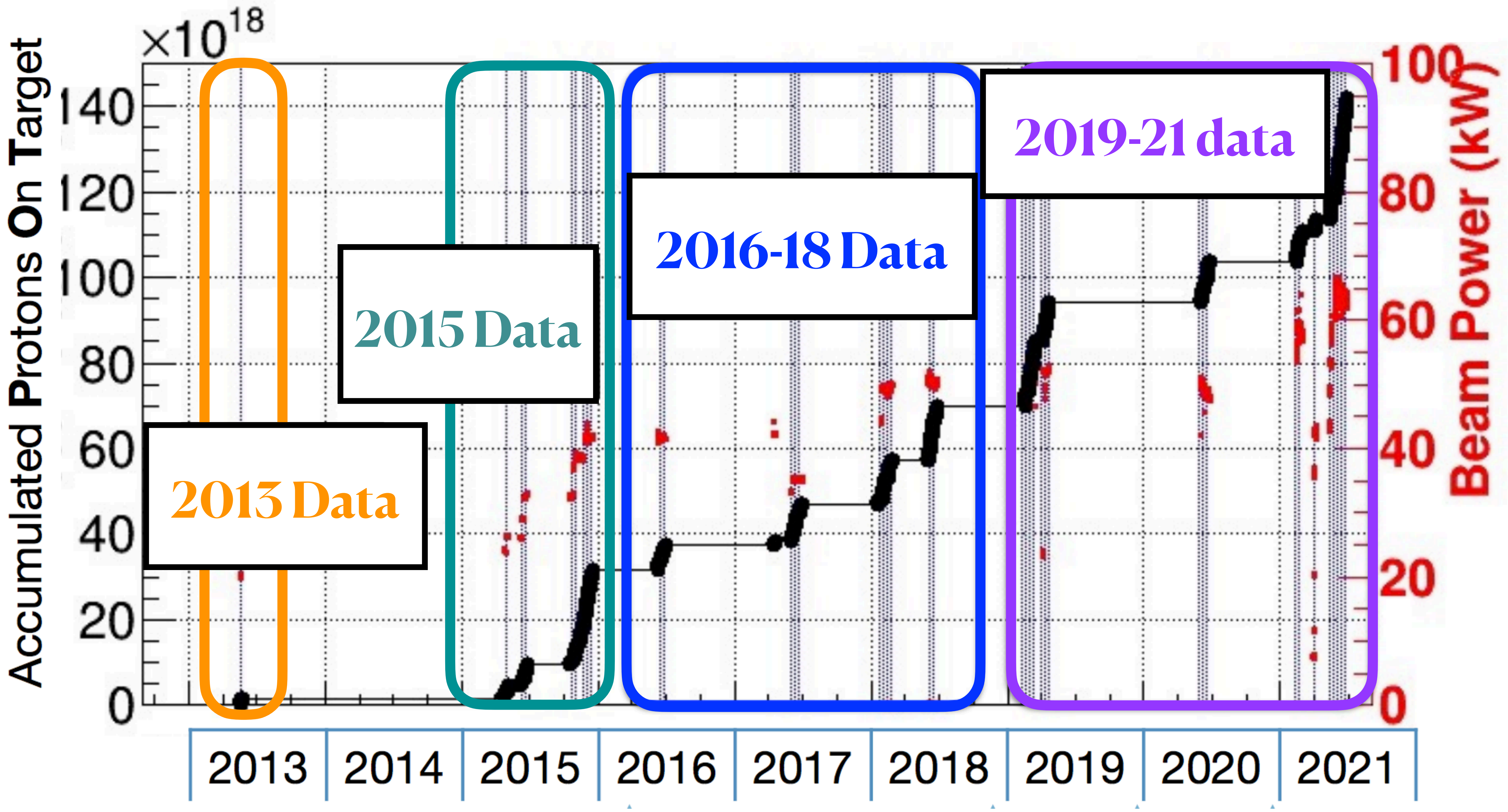
Reconstruction of $K_L \to \pi^0 \nu\bar{\nu}$

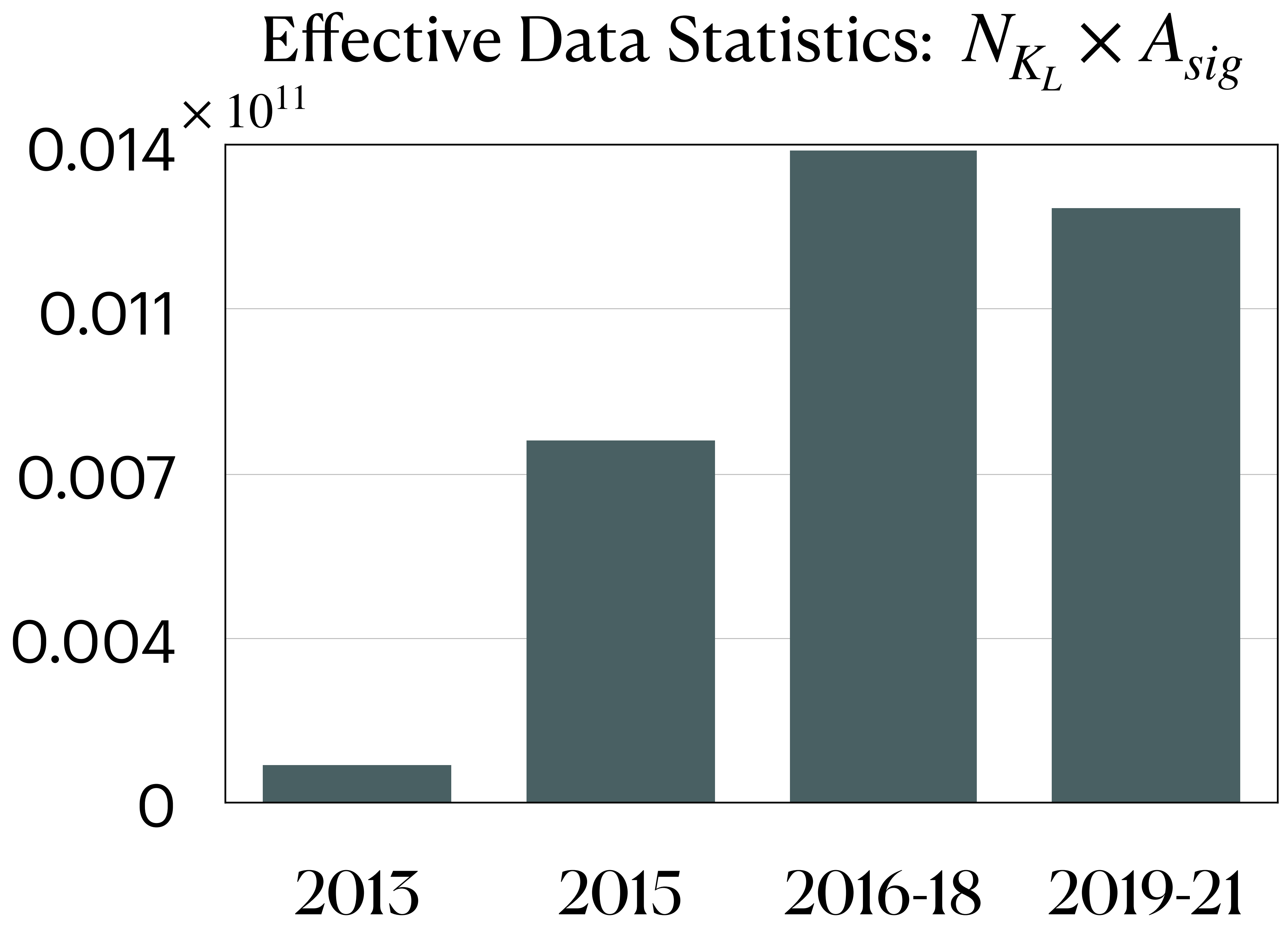
- Reconstruct decay vertex (Z_{vtx}) by assuming $M(\gamma\gamma) = M_{\pi^0}$
- Calculate P_T of π^0 by using Z_{vtx}
- Signal Region:
  - Z_{vtx} within the fiducial decay region
  - Large π^0 P_T



Run History and Results

- 2013 data: 100h run, interrupted by radiation accident. [PTEP.2017.021C01]
- 2015 data: set the current best limit on $B(K_L \to \pi^0 \nu \bar{\nu})$. [PRL.122.021802]
- 2016-2018 data: recent results with new background sources. [PRL.126.121801]
- 2019-2021: analysis in progress.

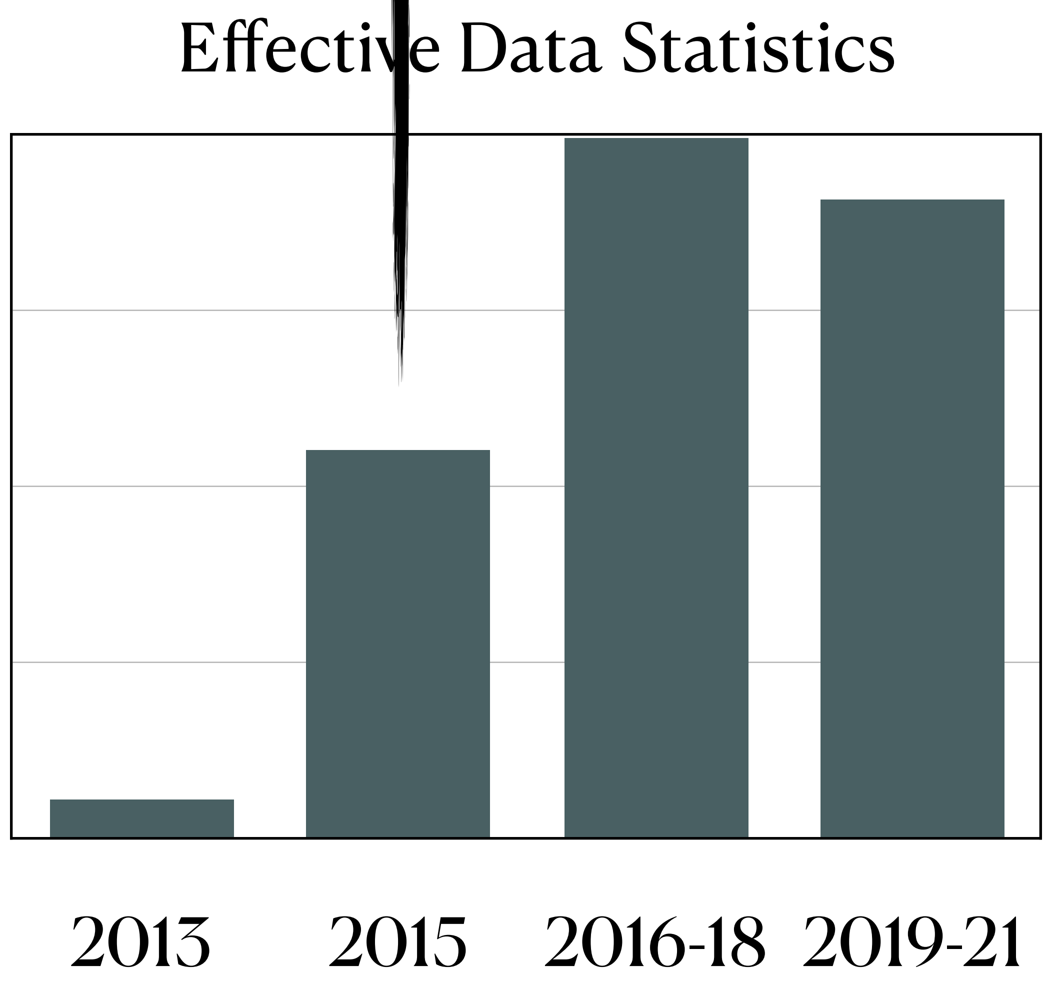




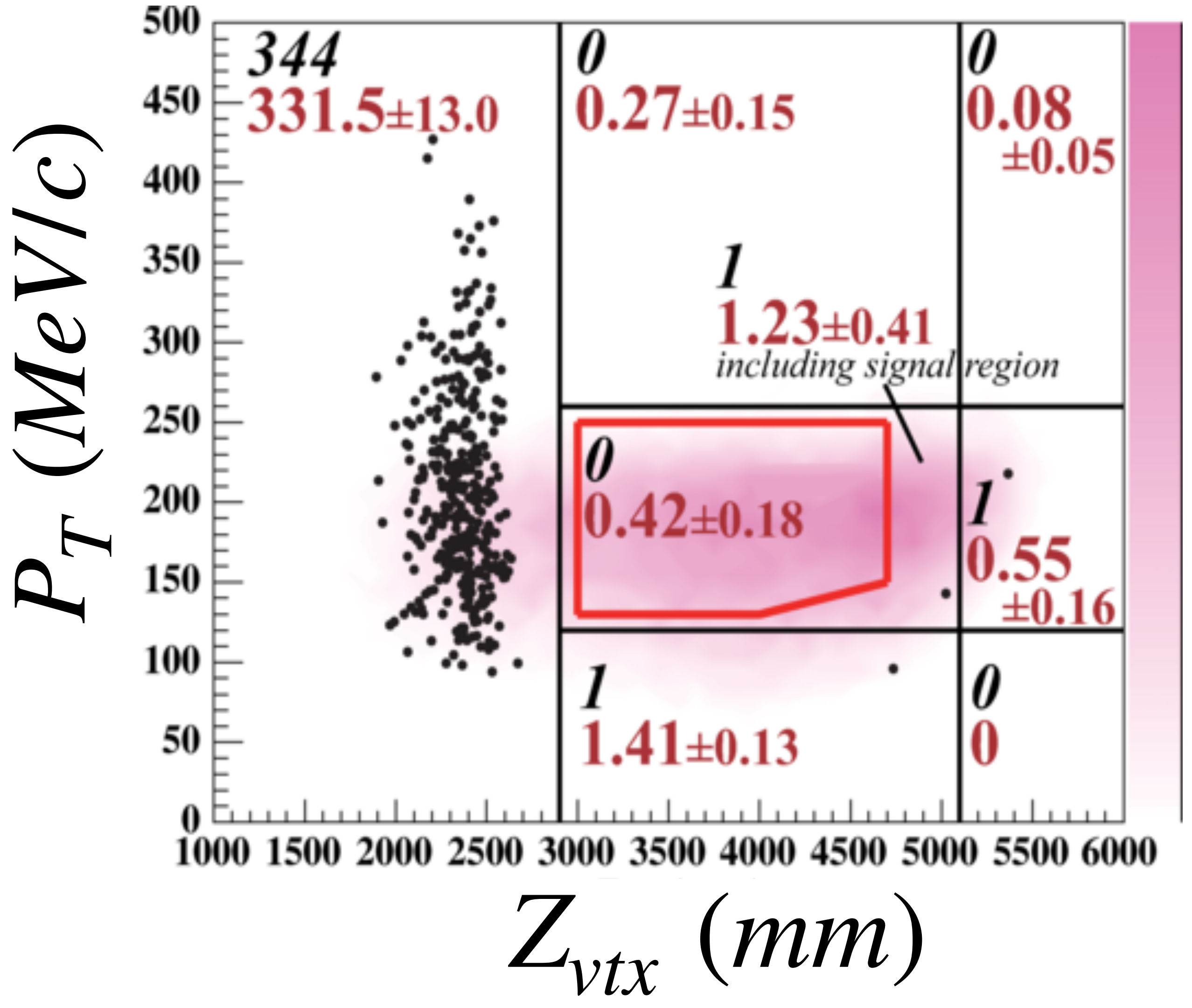
Recent Results

- 2015 data [PRL.122.021802]:
  - No event was 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 $90\,\%$ $C.L.$
    - The world's best limit.

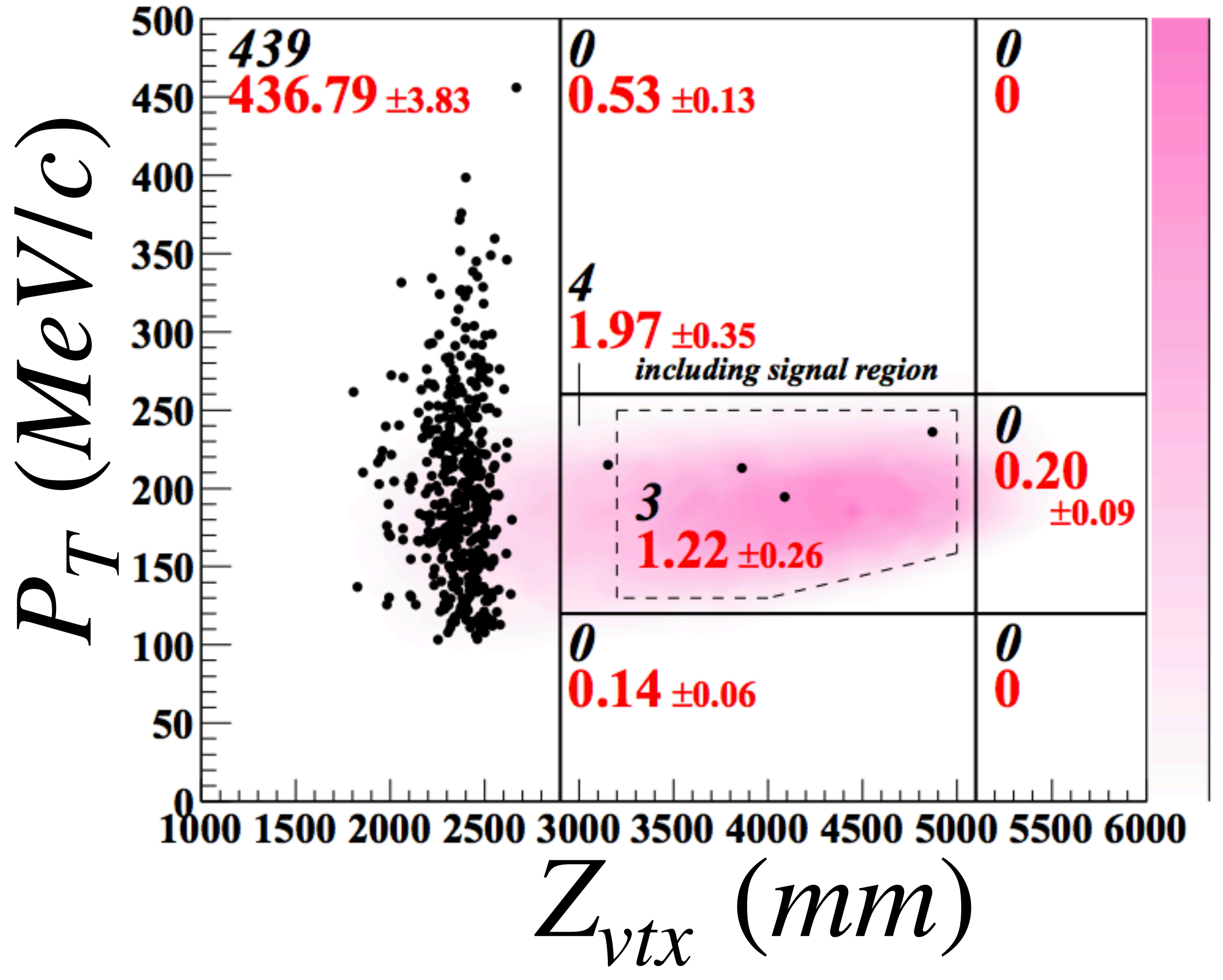
- 2016-2018 data [PRL.126.121801]:
  - $S.E.S. = 7.20 \times 10^{-10}$
  - Observed 3 events with 1.22 predicted BG.
    - 1.22 BG events included newly found BGs.
  - $BR(K_L \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ at $90\,\%$ $C.L.$



2015 Data

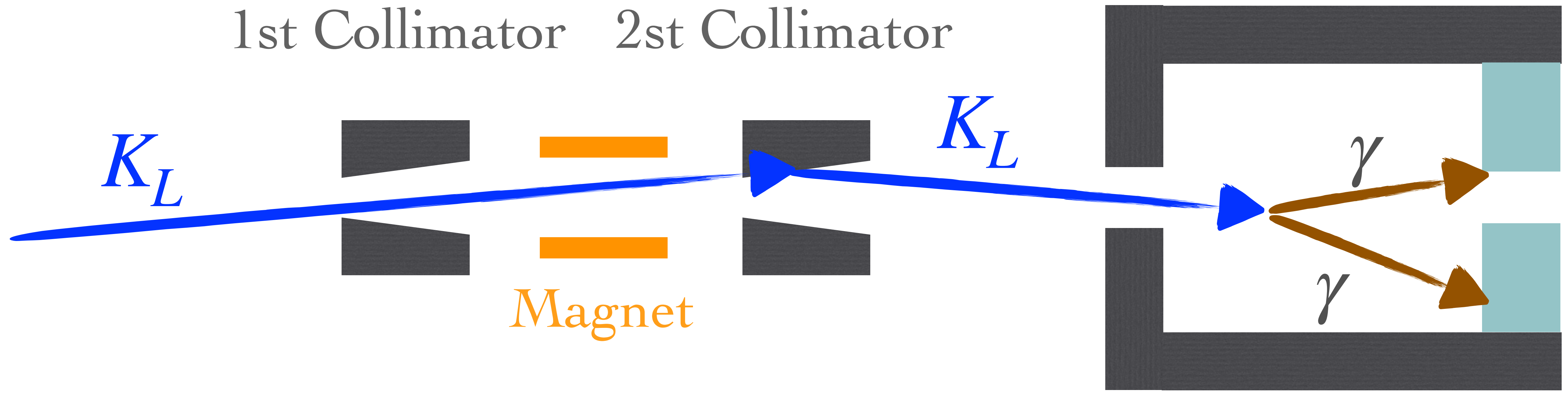


2016-2018 Data

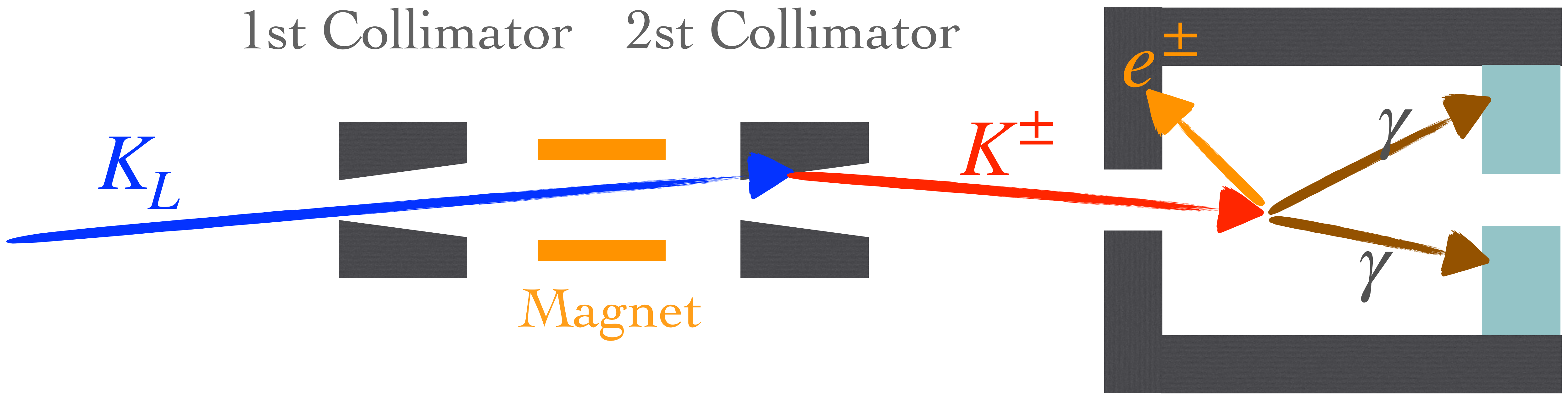


New BG Sources

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



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



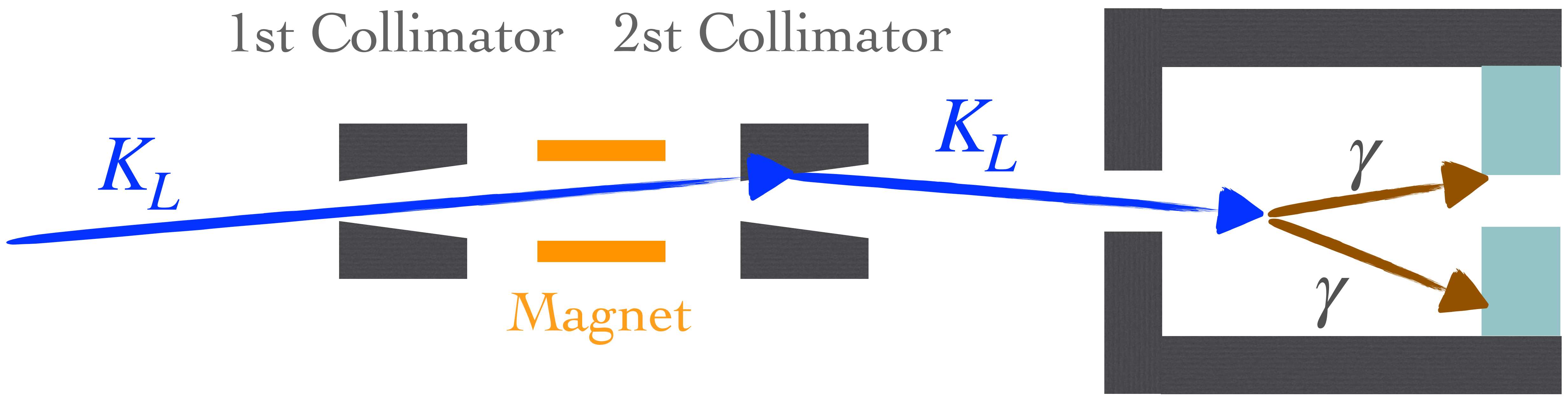
BG Table of 2016-2018 data

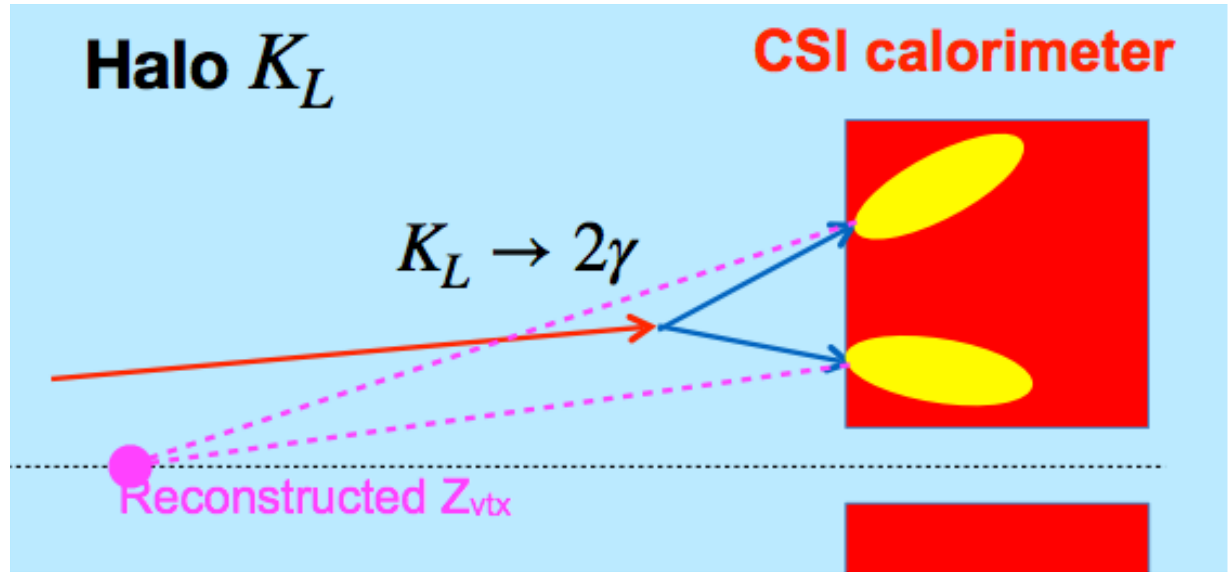
source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07 [a]
	Other K_L decays	0.005 ± 0.005
$K^{\pm}$		0.87 ± 0.25 [a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
total		1.22 ± 0.26

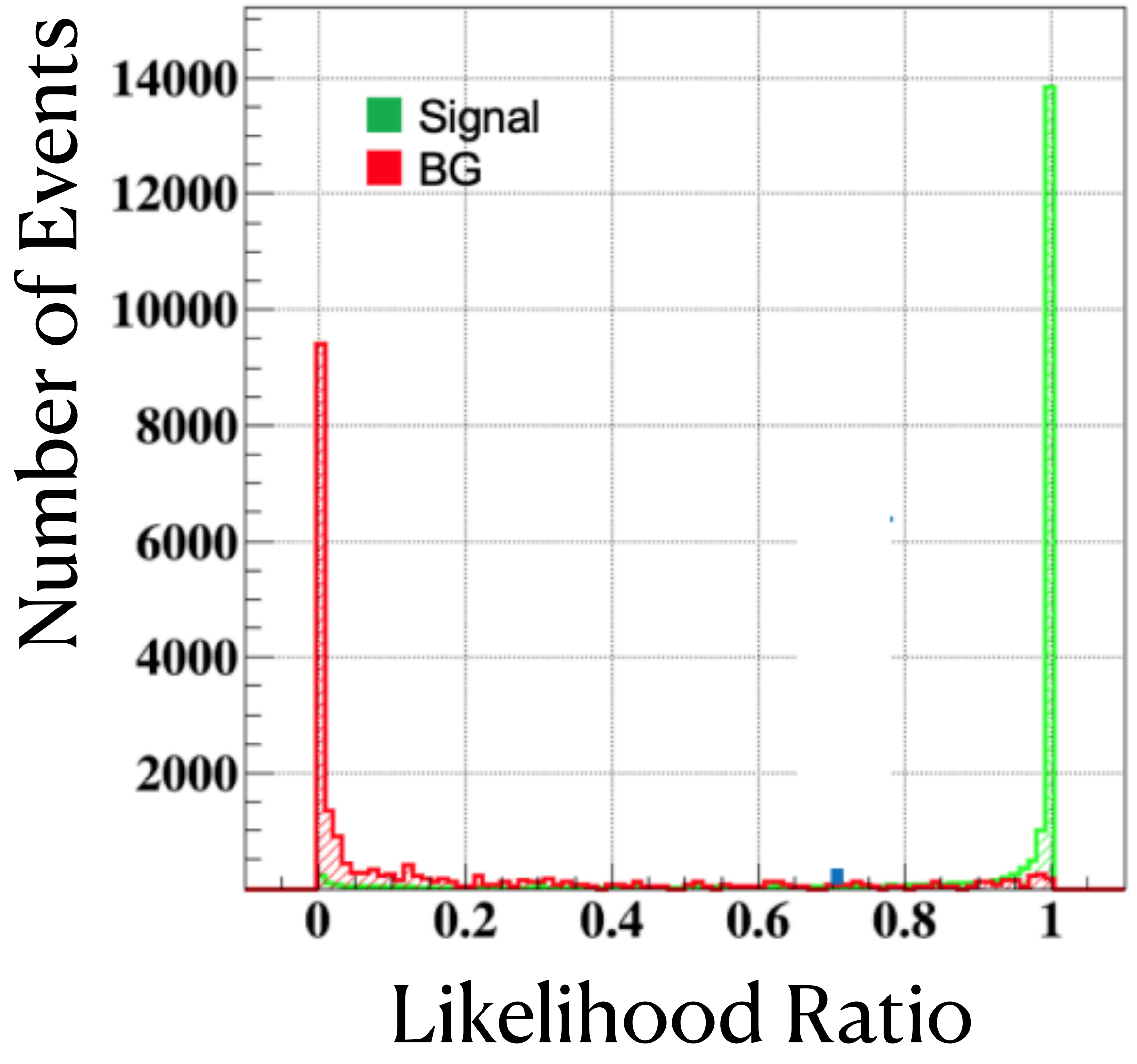
[a] Background sources studied after looking inside the blind region.

Beam Halo K_L BG

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





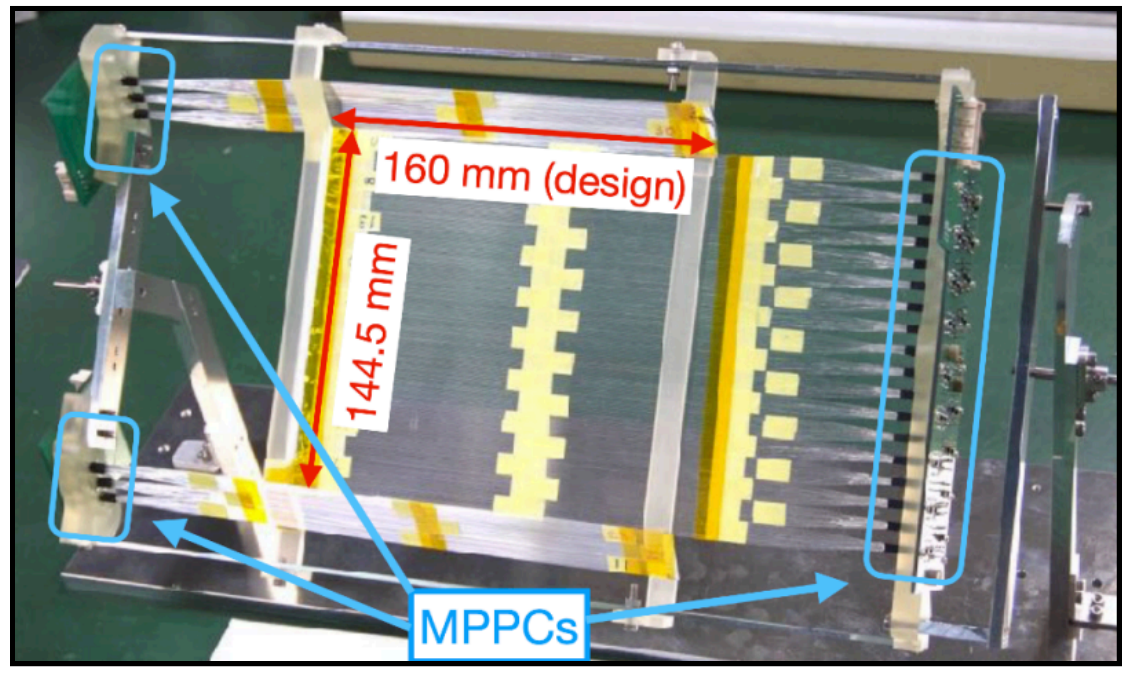


- A new cut based on the cluster shape and γ angle suppressed the halo K_L by a factor of 16. (Not applied to the 2016-2018 analysis)
- BG level ~0.4 events at $BR_{EXP}(K_L \to \pi^0 \nu \bar{\nu}) \sim O(10^{-11})$.

Charged Kaon BG

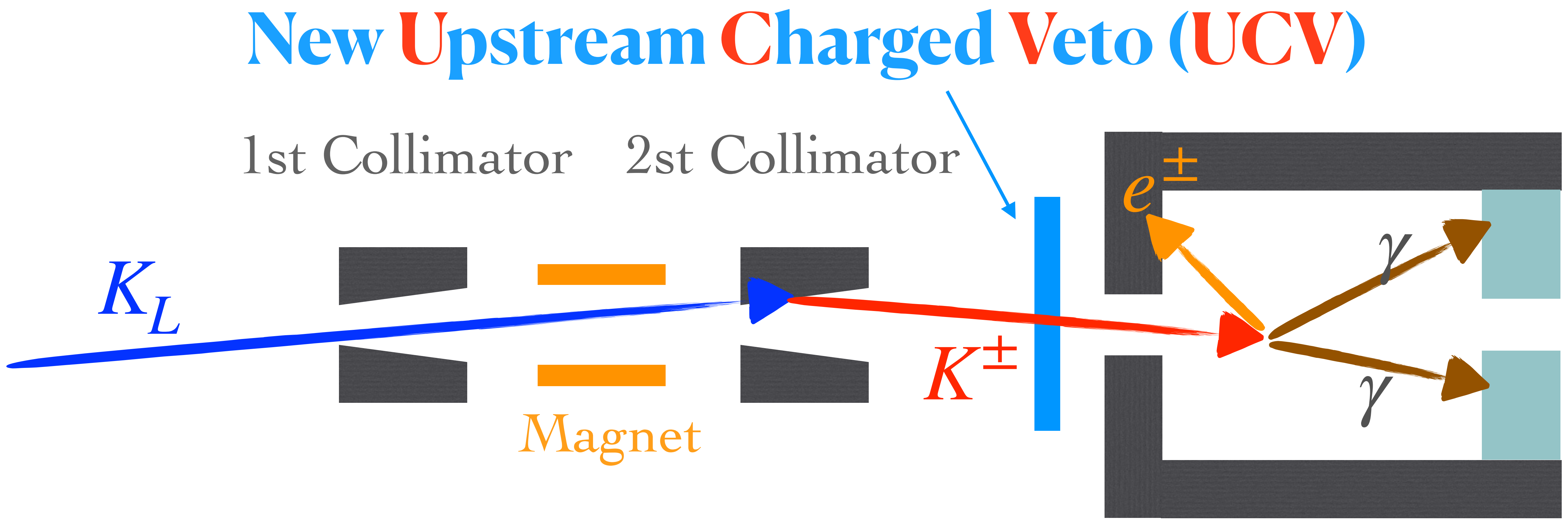
2021

- UCV was installed.
- Scintillating fiber.
- K±BG × 1/13



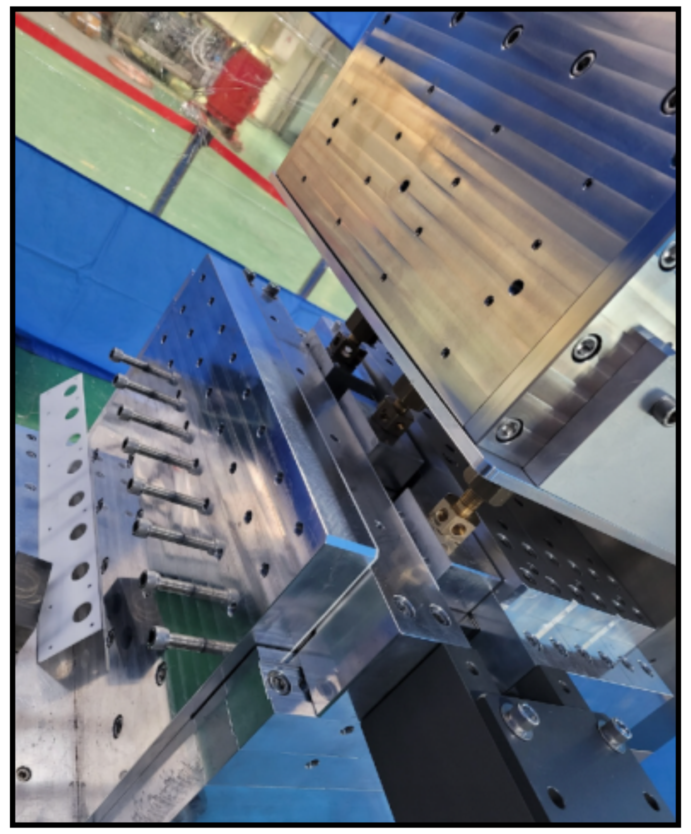
2023

- UCV will be upgraded.
- Scintillator film.
- K±BG × 1/100



2023

- Will install a magnet after 2nd collimator.
- K±BG × 1/10

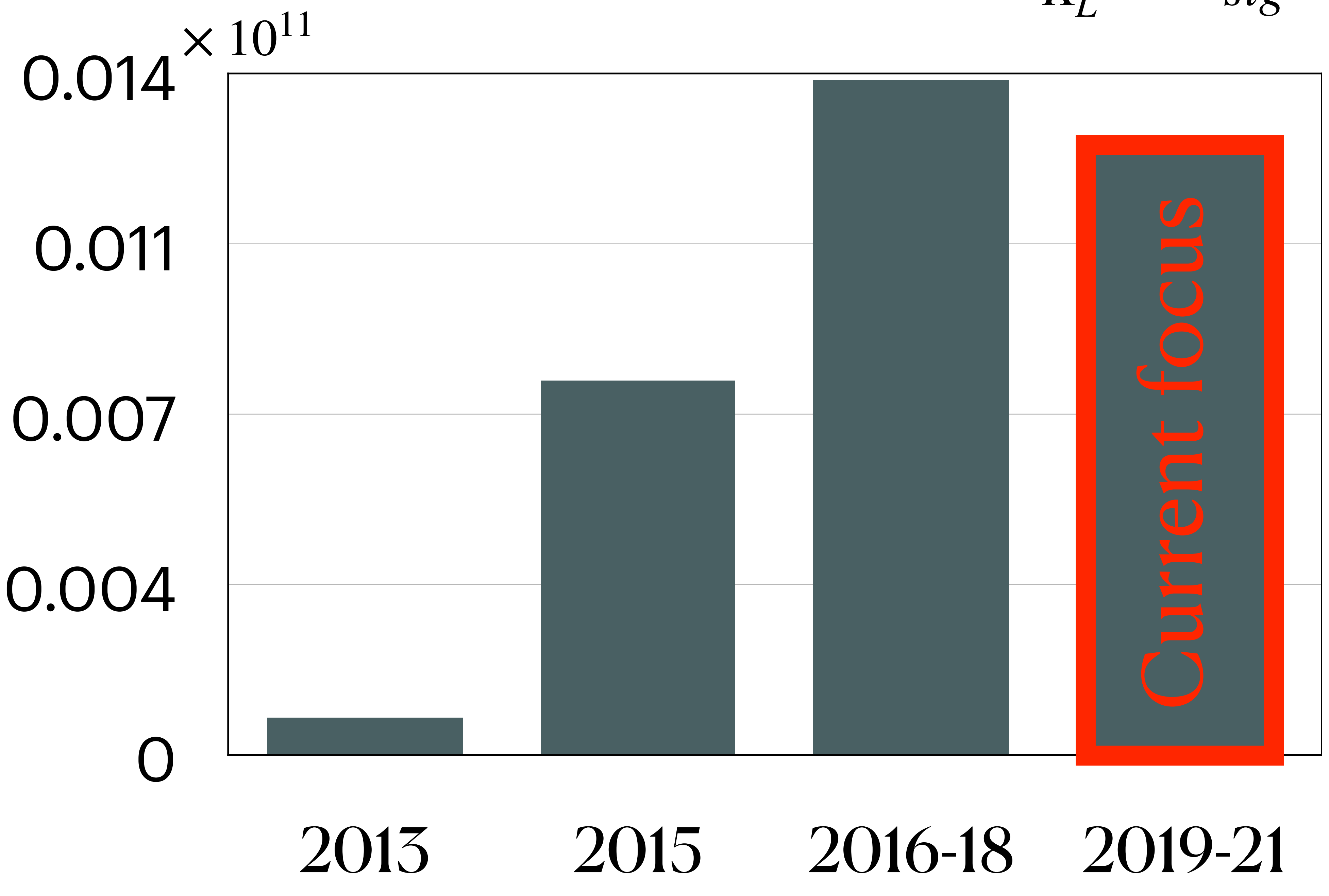


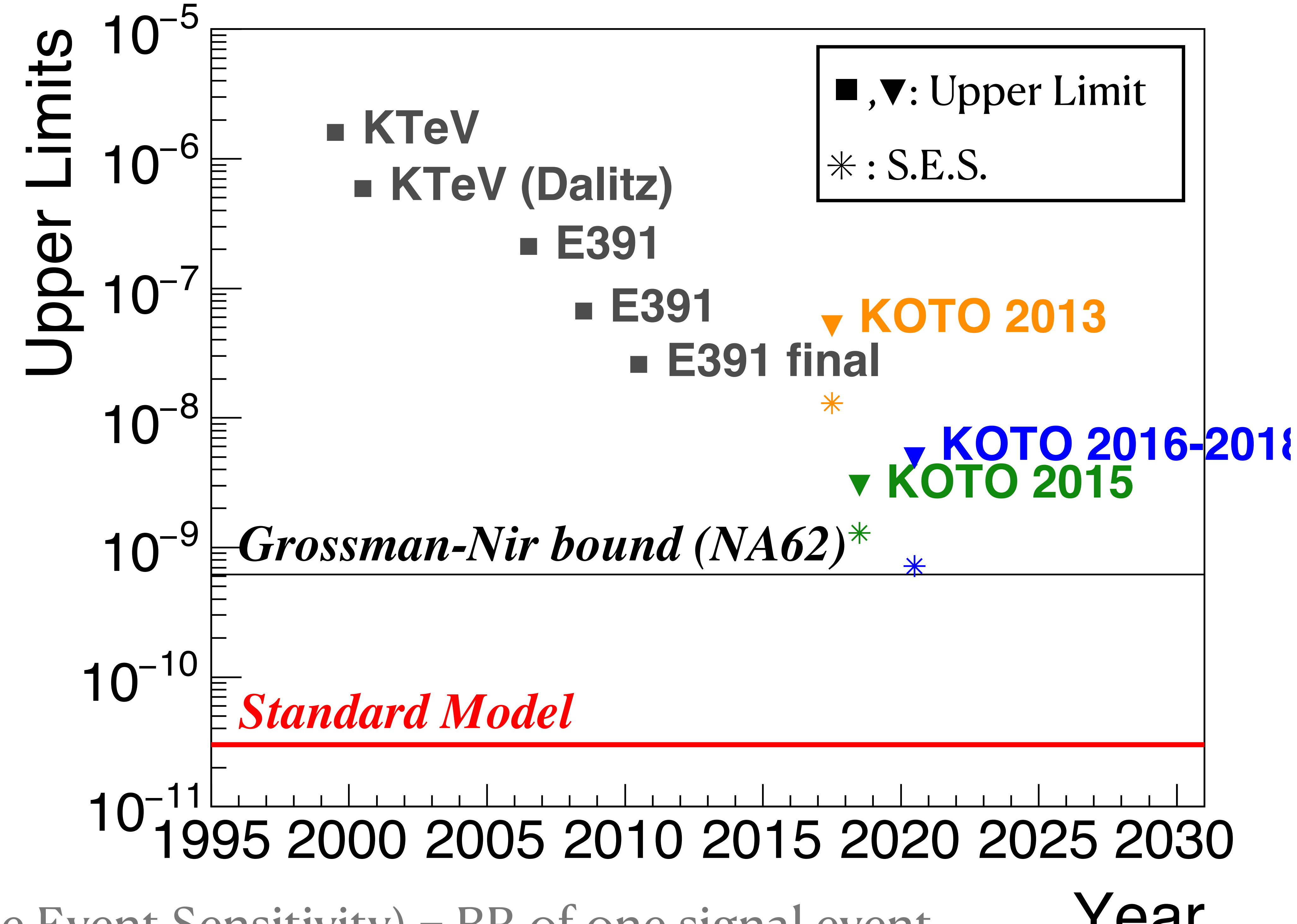
- Combined reduction ~1/1000 after 2023.
- K±BG ~0.02 events at $BR_{EXP}(K_L \to \pi^0 \nu \bar{\nu}) \sim O(10^{-11})$.

Run History and Results

- 2013 data: 100h run, interrupted by radiation accident. [PTEP.2017.021C01]
- 2015 data: set the current best limit on $B(K_L \to \pi^0 \nu \bar{\nu})$. [PRL.122.021802]
- 2016-2018 data: recent results with new background sources. [PRL.126.121801]
- 2019-2021: analysis in progress.

Effective Data Statistics: $N_{K_L} \times A_{sig}$

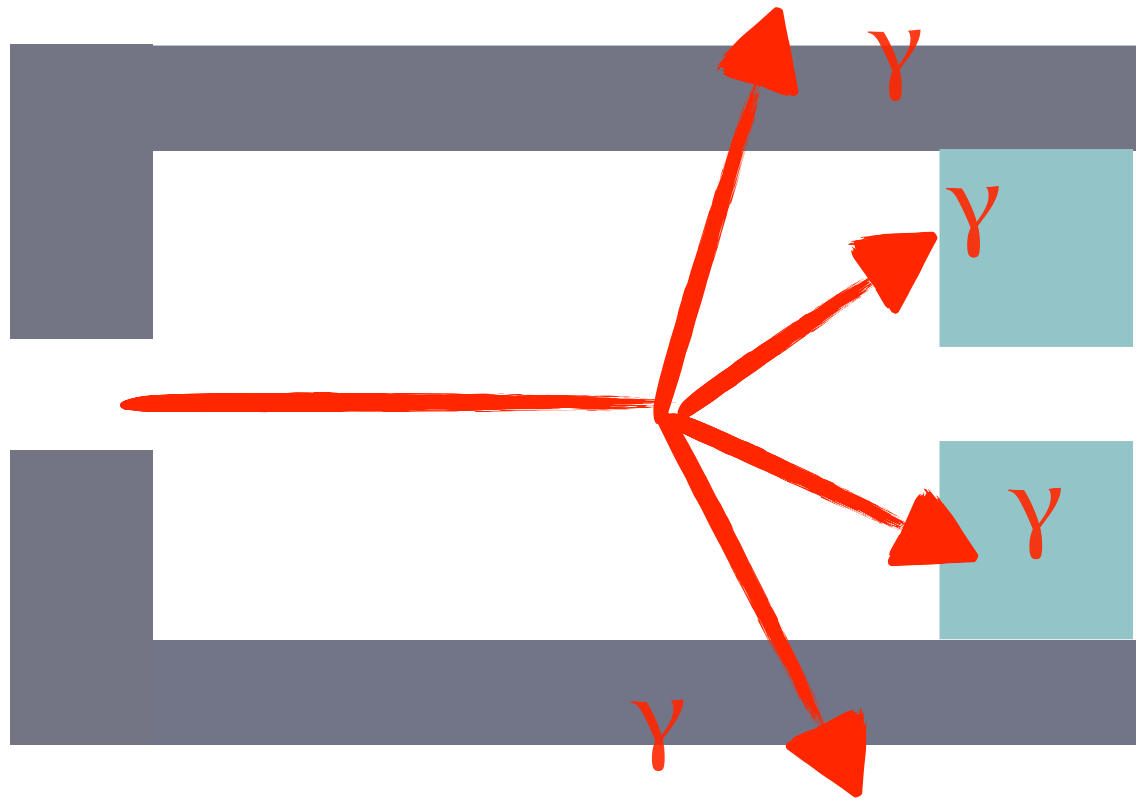


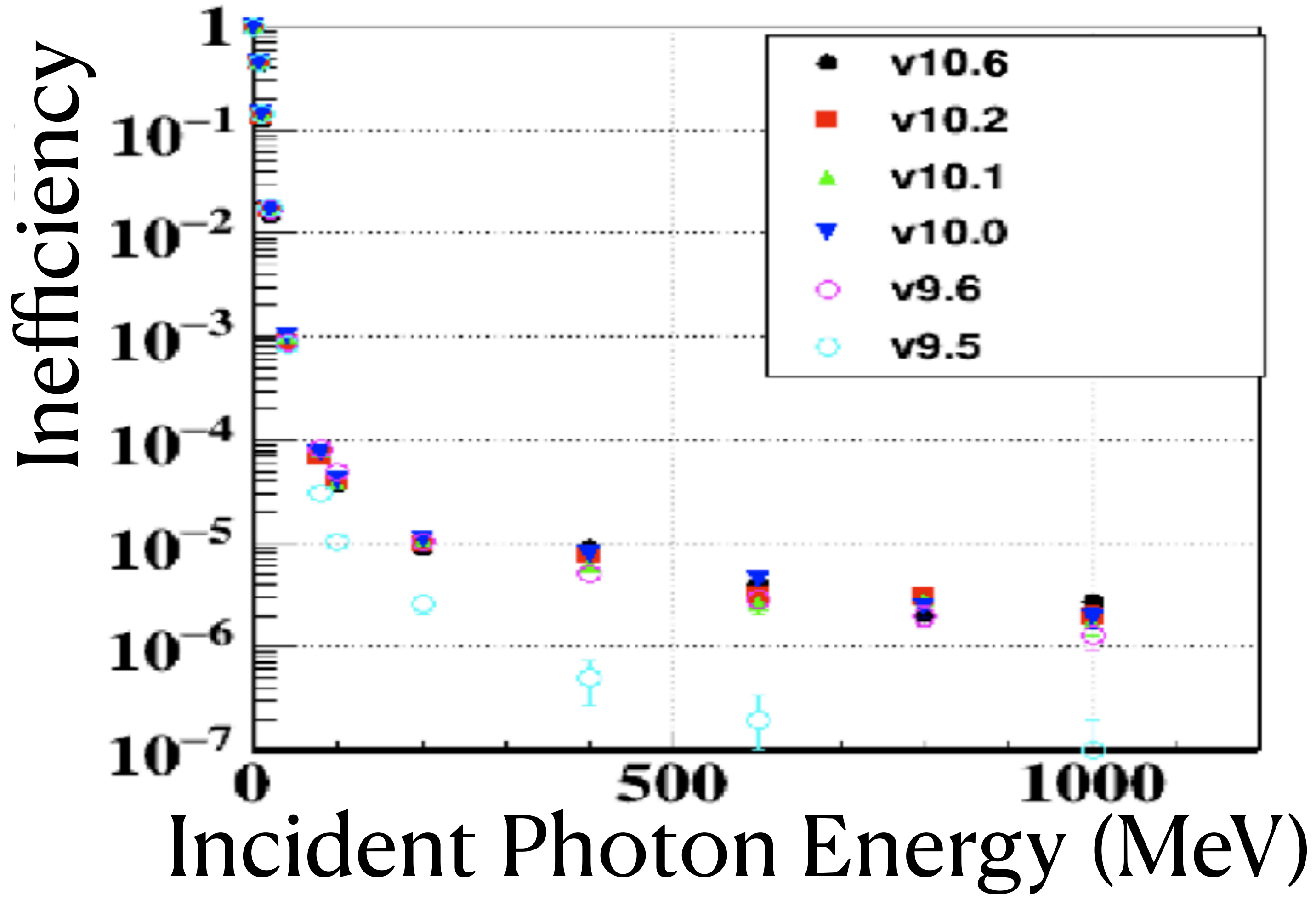


*S.E.S. (Single Event Sensitivity) = BR of one signal event

2019-21 Data Analysis (ongoing)

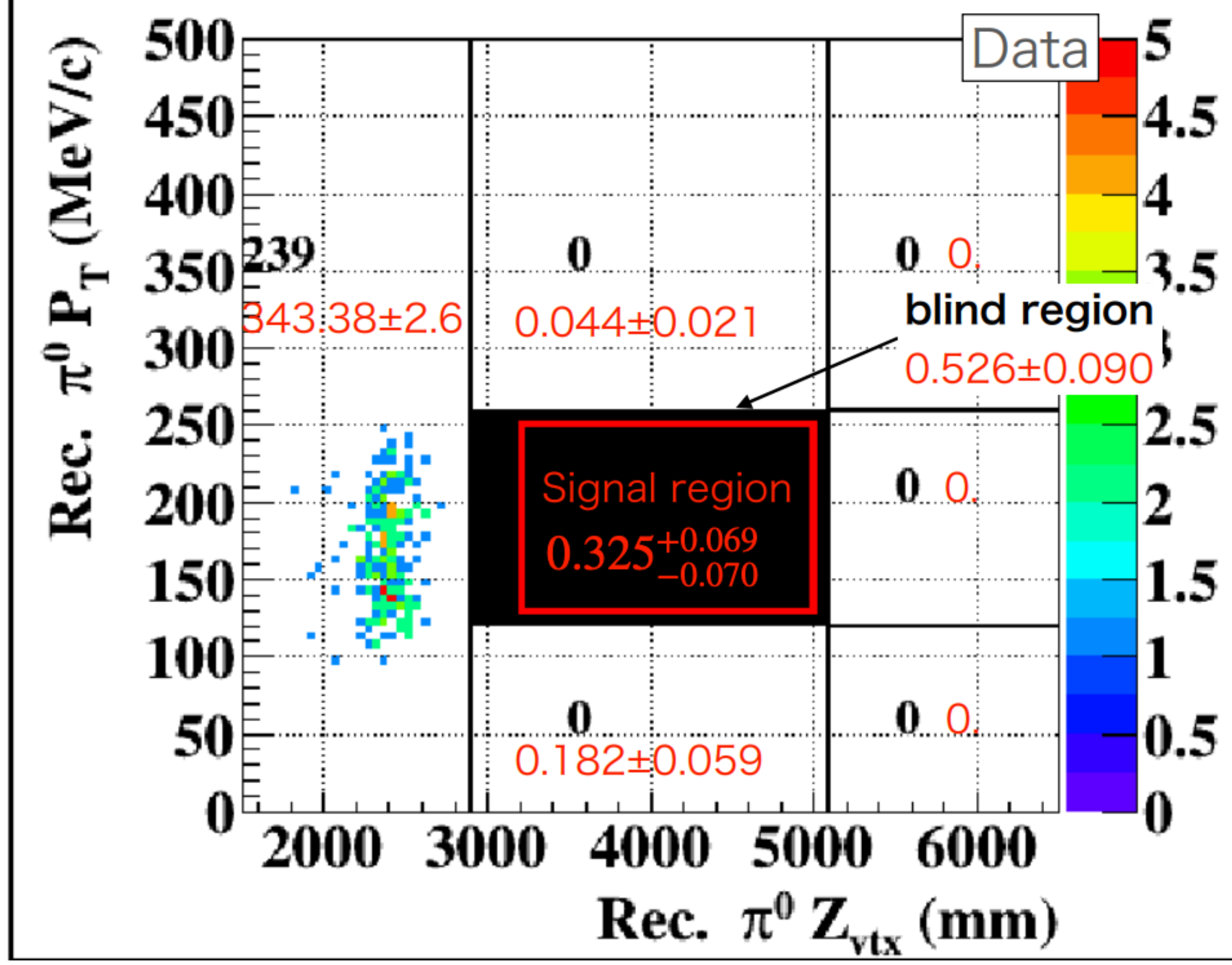
- $S.E.S. = 7.9 \times 10^{-10}$ (preliminary).
- With a new detector and analysis technique,
  - Halo K_L BG → 0.013 events
  - Charged K BG → 0.043 events
- Dominant BG: $K_L \to \pi^0\pi^0$ (0.14 events)
  - MC results depend on GEANT4 versions.
    - Will verify the MC simulation with data.





BG Estimation

c.f. 2016-2018 analysis:1.23±0.26



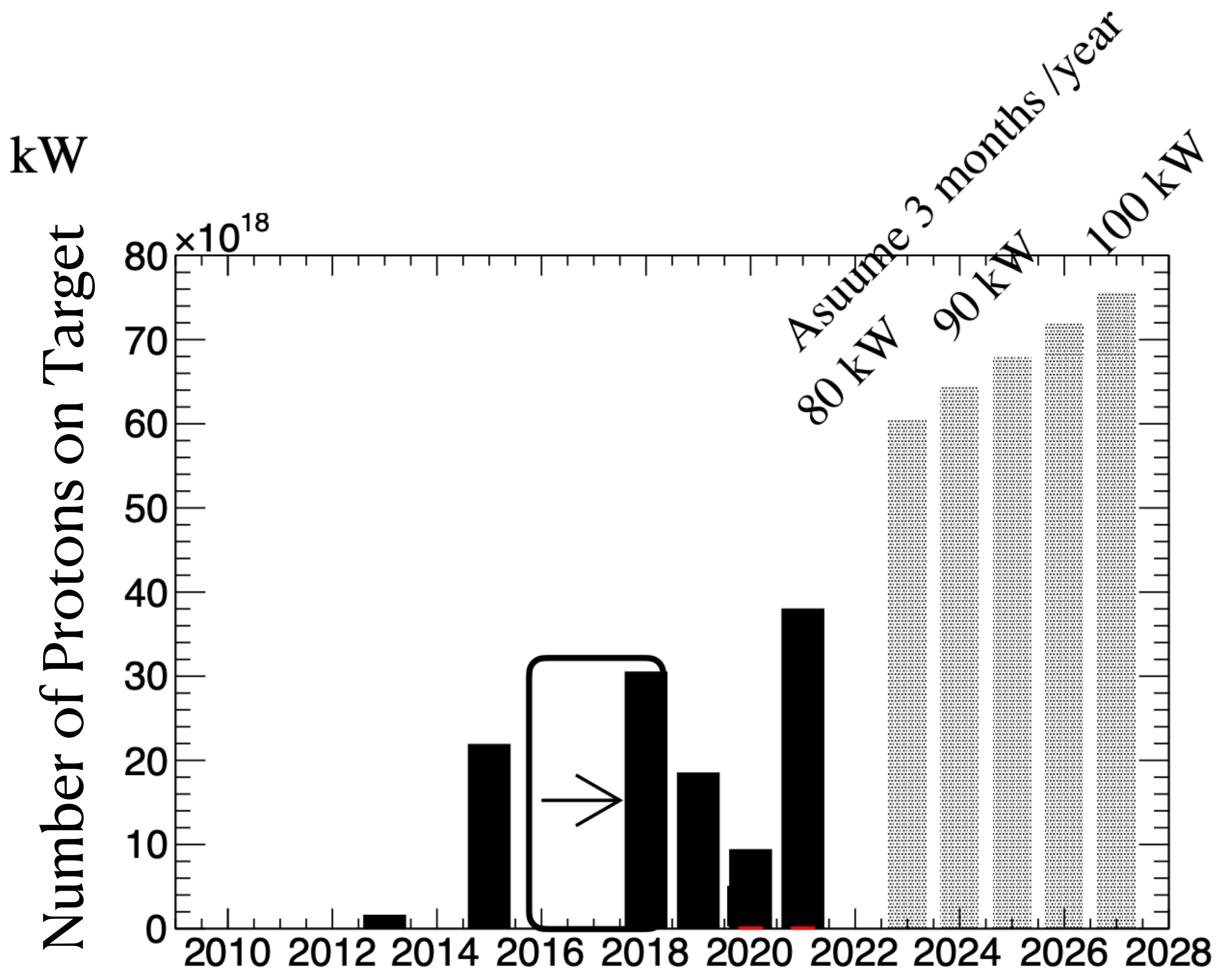
source	#BG in the signal box
$K_L \to 2\pi^0$	0.141±0.059
K^+	$0.043^{+0.016}_{-0.022}$
Hadron cluster BG	0.042±0.007
Halo $K_L \to 2\gamma$	0.013±0.006 ✓
Scattered $K_L \to 2\gamma$	0.025±0.005 ✓
η production in CV	0.023±0.010
Upstream π^0	0.02±0.02
$K_L \to 3\pi^0$	0.019±0.019
Sum	$0.325^{+0.069}_{-0.070}$

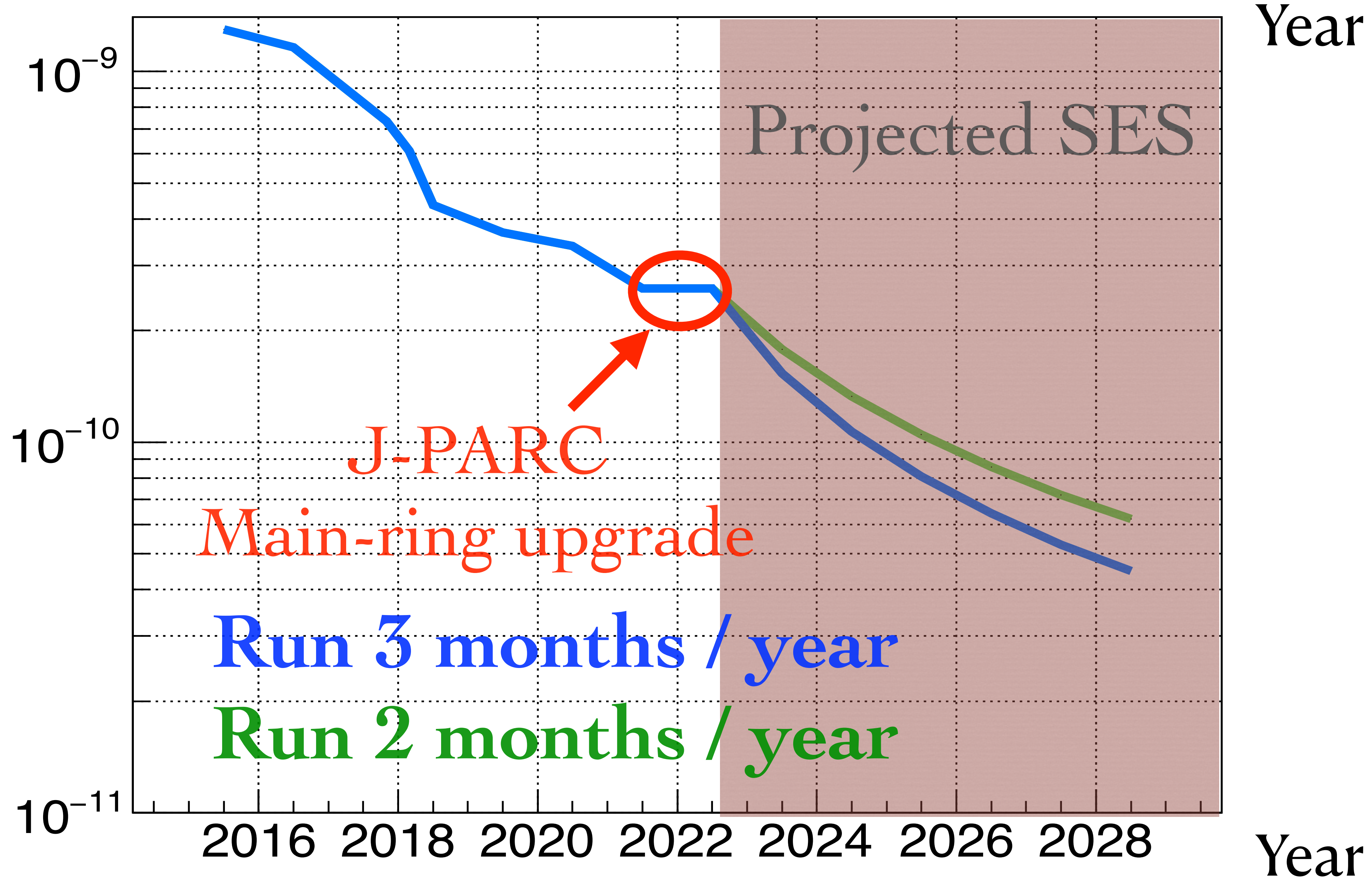
Prospects

- **2021-2022 Accelerator Shutdown**
  - Main-ring power supply upgrade.
    - Beam power 64kW → 80-100kW.

- **Will resume data-taking from May, 2023**

- **By 2027, with 2-3 month run per year**
  - Expect to collect ×11 more data.
  - S.E.S. can reach below O(10^{-10}).





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 were 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. below $O(10^{-10})$ by 2027.

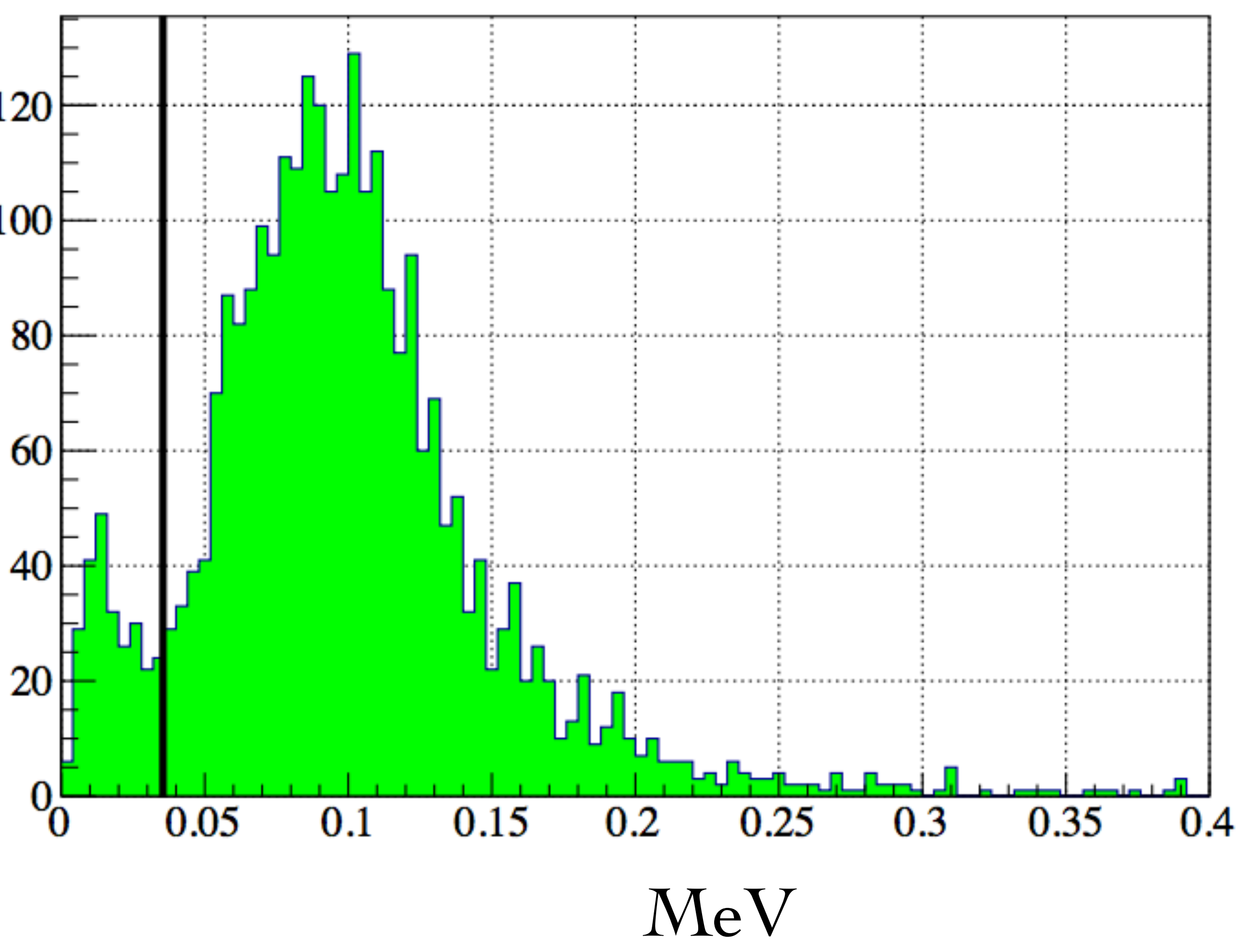
Backup slides

Charged Kaon BG

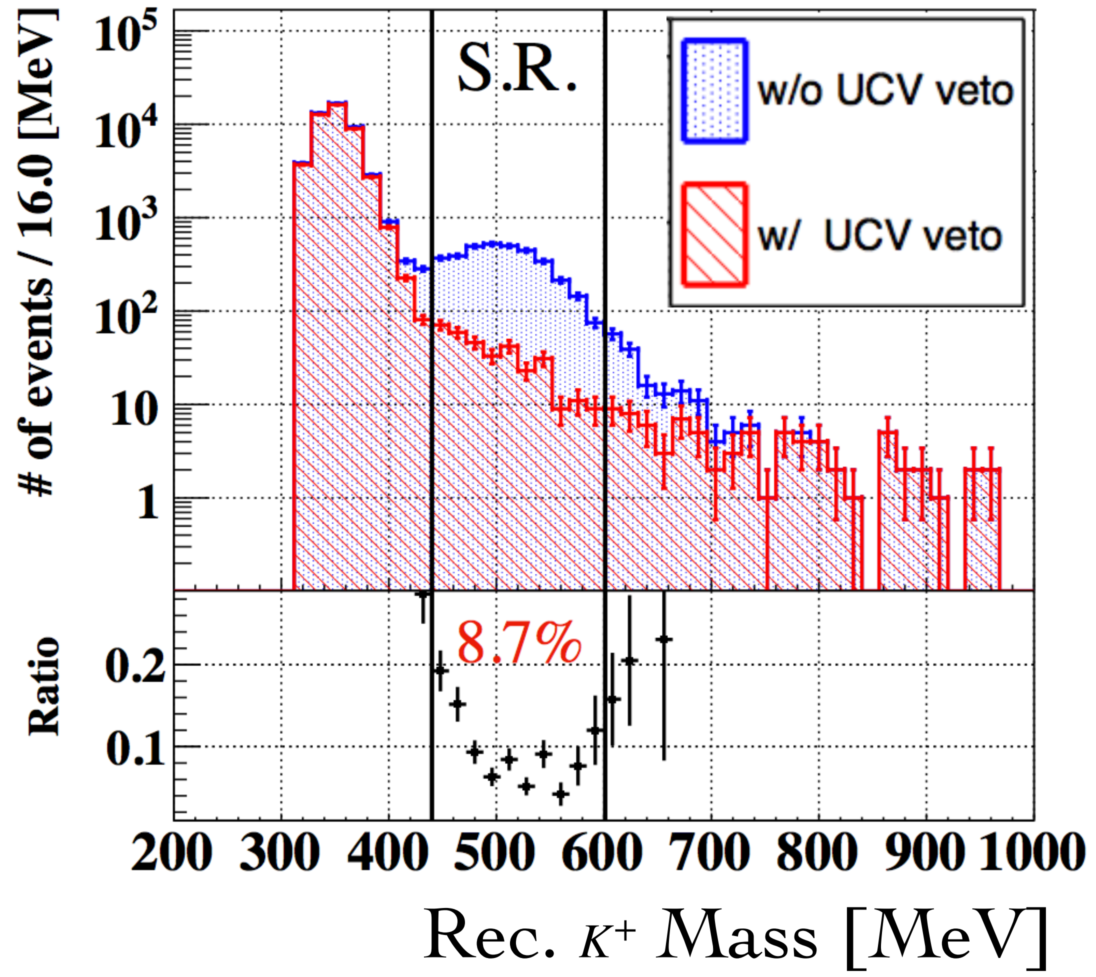
2021

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

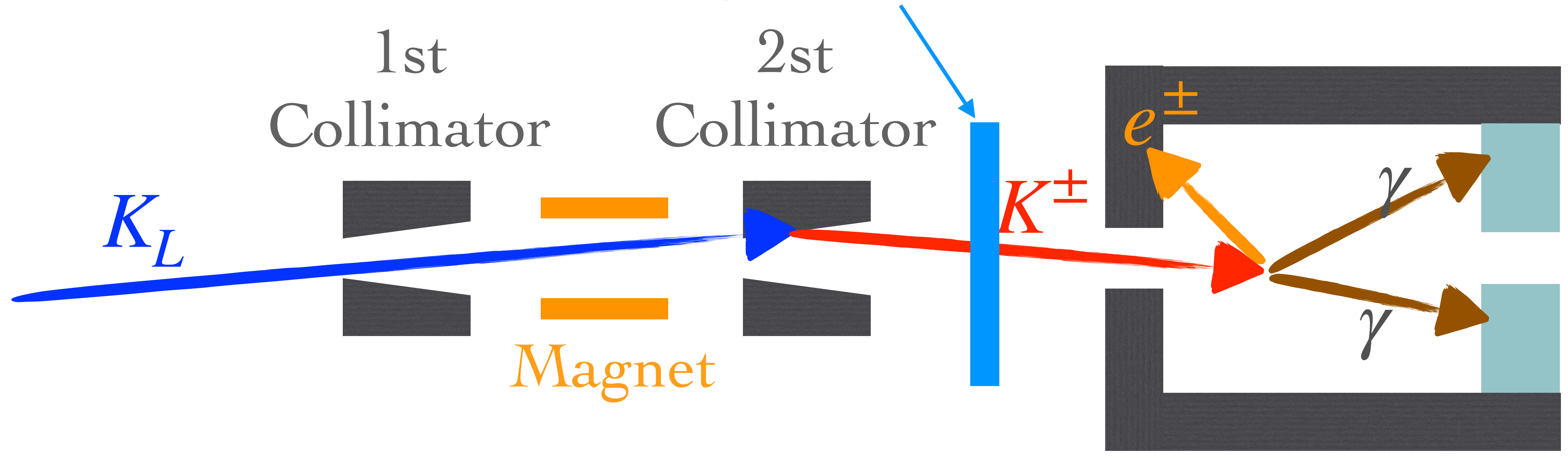
Deposited Energy in UCV (data)



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



New Upstream Charged Veto (UCV)



Background Control

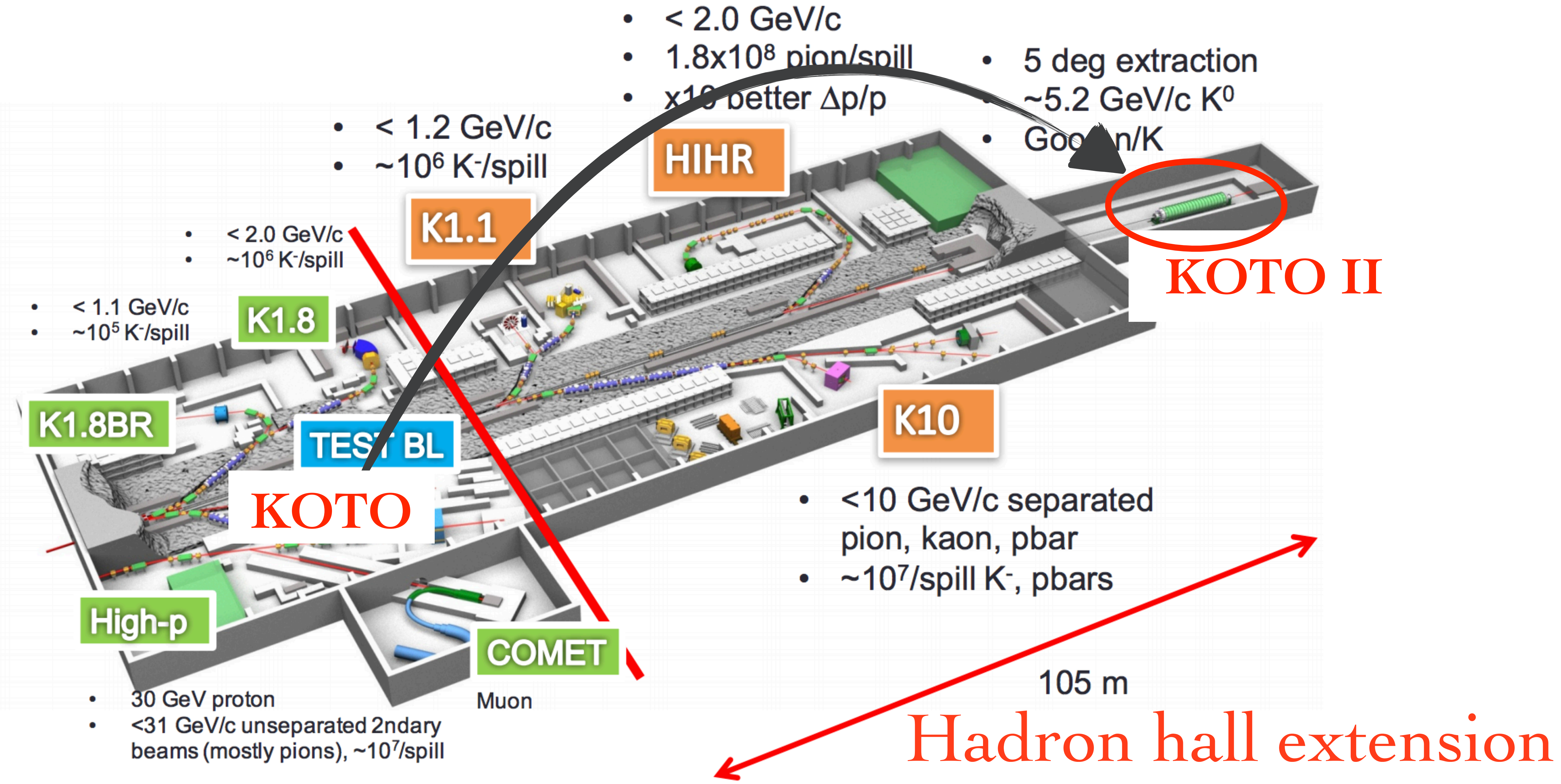
source	Study item
$K_L \to 2\pi^0$	Veto performance
K^+	K^+ flux, UCV inefficiency
Hadron cluster BG	Performance of cuts against Hadron cluster BG
Halo $K_L \to 2\gamma$	Halo K_L flux, Performance of cuts against Halo $K_L \to 2\gamma$
Scattered $K_L \to 2\gamma$	Scattered K_L flux, Performance of cuts against Halo $K_L \to 2\gamma$
η production in CV	Compare η production in the Al target with data and MC
Upstream π^0	Probability of mis-energy-measurement in the CsI calorimeter
$K_L \to 3\pi^0$	Probability of overlapped pulse

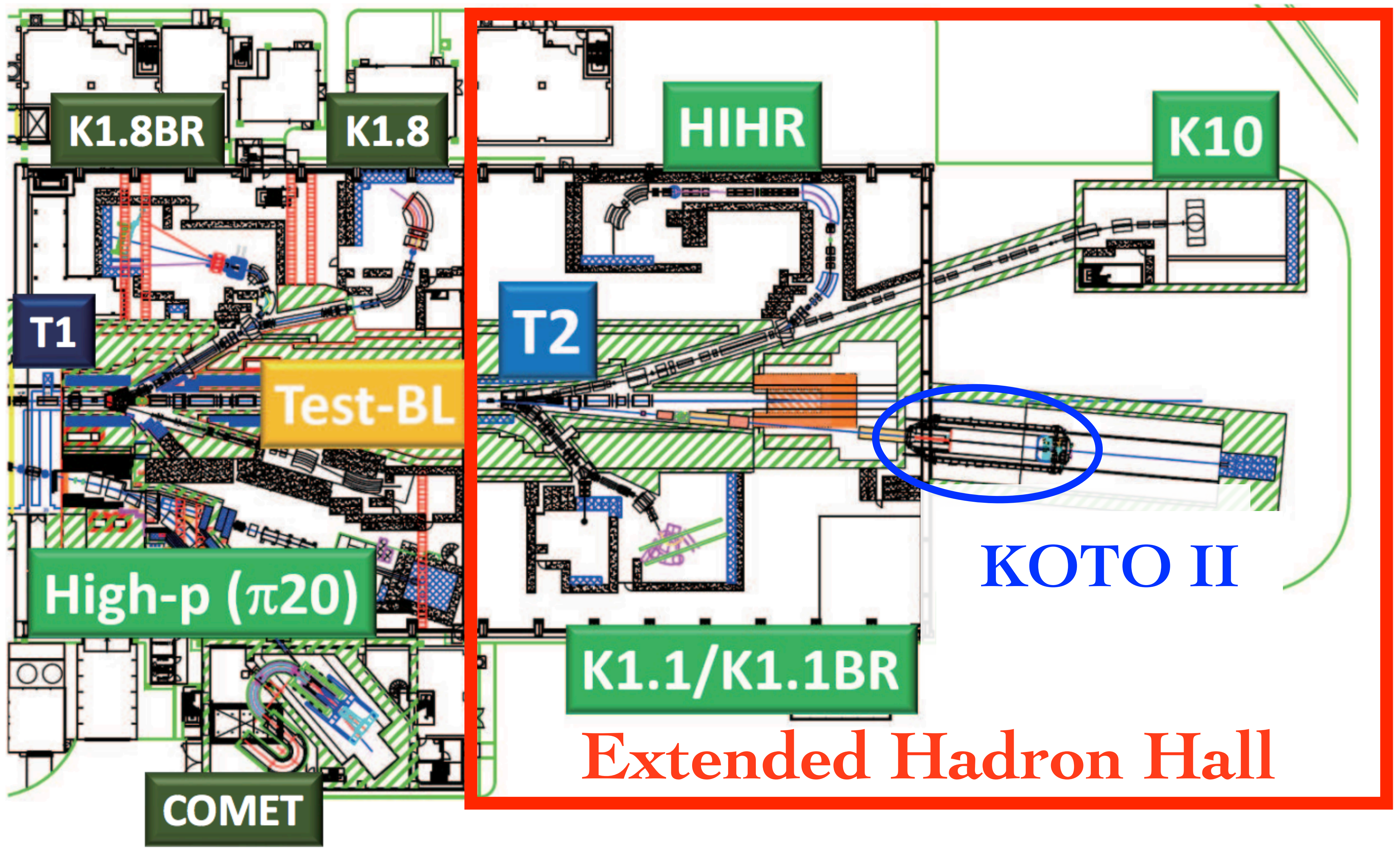
KOTO II

[arXiv:2110.04462v1]

KOTO II aims to measure $K_L \rightarrow \pi^0 \nu \bar{\nu}$ with SES of O(10^-13), based on:

- Higher J-PARC accelerator beam power (up to 100kW from 2023).
- New beamline with richer KL yields (the construction begins in 2023).
- Larger detector with better signal acceptance (currently in R&D stage).





KOTO II

[arXiv:2110.04462v1]

Expect KOTO II to start data-taking from 2029.

J-PARC Main-Ring Upgrade ⟷ | Beam Continues ⟷ | Beam Suspended ⟷

Hadron Hall Extension ⟷ | KOTO II ⟶

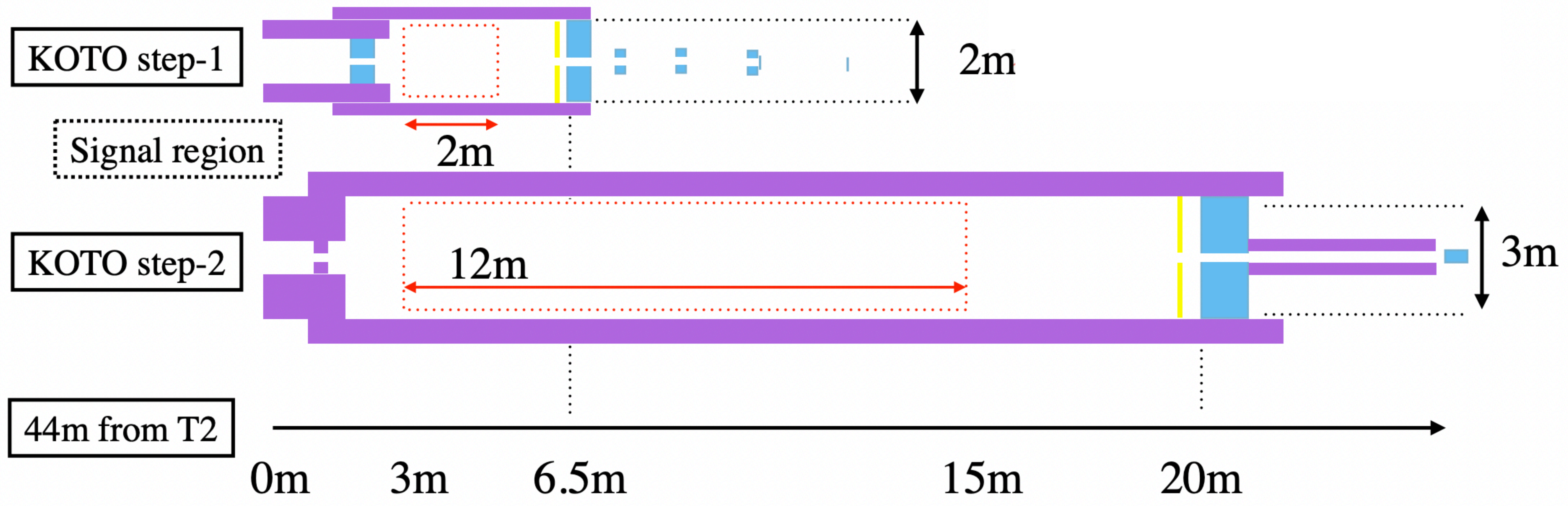
	FY2021	FY2022	FY2023	FY2024	FY2025	FY2026	FY2027	FY2028	FY2029	FY2030
MR	Upgrade of Magnet PS		*construction parallel to beam operation in the first 3 years, beam-suspension in the next 2.5 years*							
HD			*The Extension Project of the HEF (6 years)*							
		Current Programs with SX Power towards 100kW				Hall Extension			Expanded Programs with more BLs	
COMET	Construction		COMET1			COMET2 Construction				COMET2

Detector

KOTO II

[arXiv:2110.04462v1]

- Kaon beam extraction angle: 16°(KOTO) → 6° (KOTO II)
    - P_{K_L} peaks at 1.4 GeV/c (KOTO) → 3 GeV/c (KOTO II)
- Larger detector:
    - Fuduical decay region: $2m \rightarrow 12m$
    - Diameter of calorimeter: $2m \rightarrow 3m$



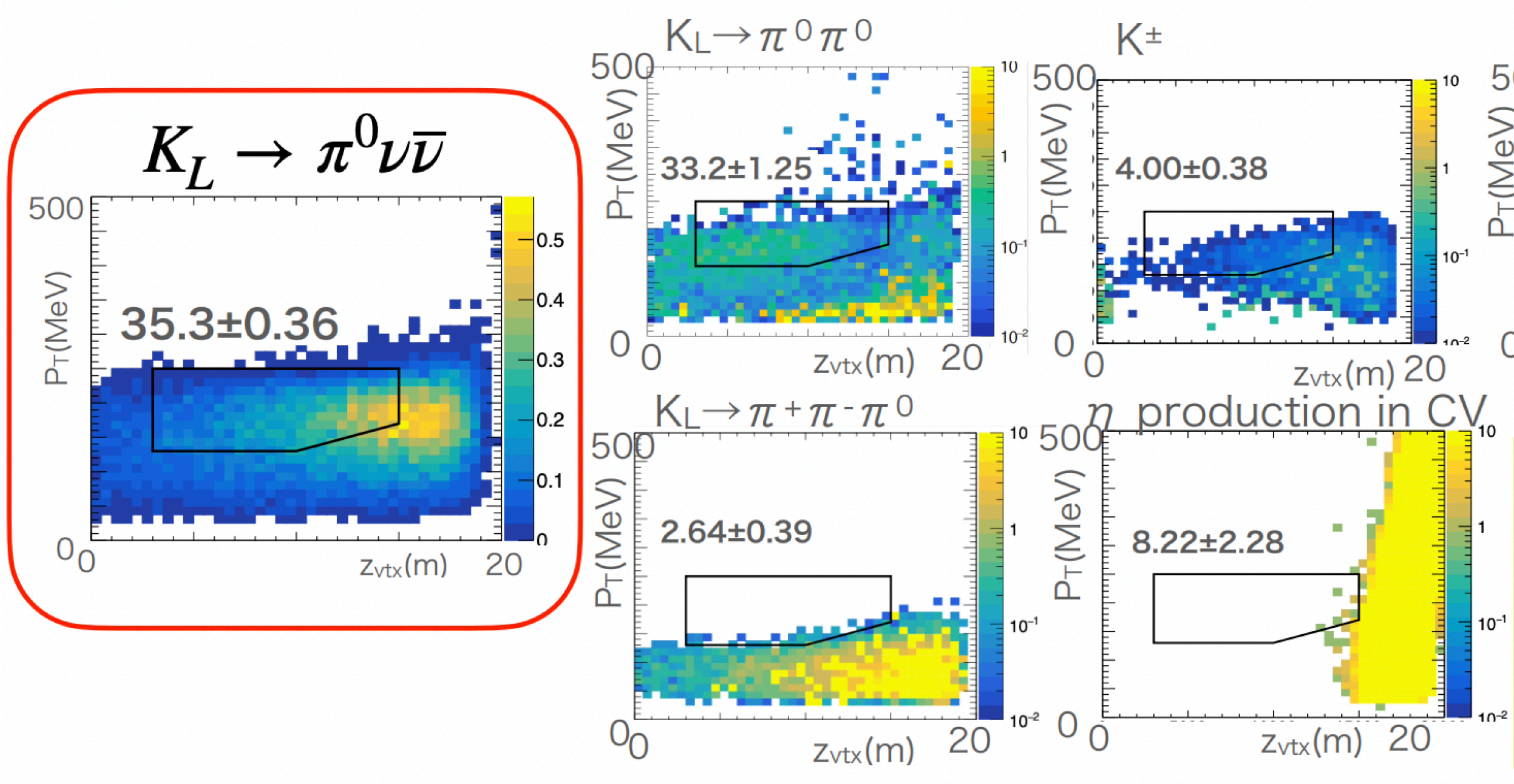
Signal & BG

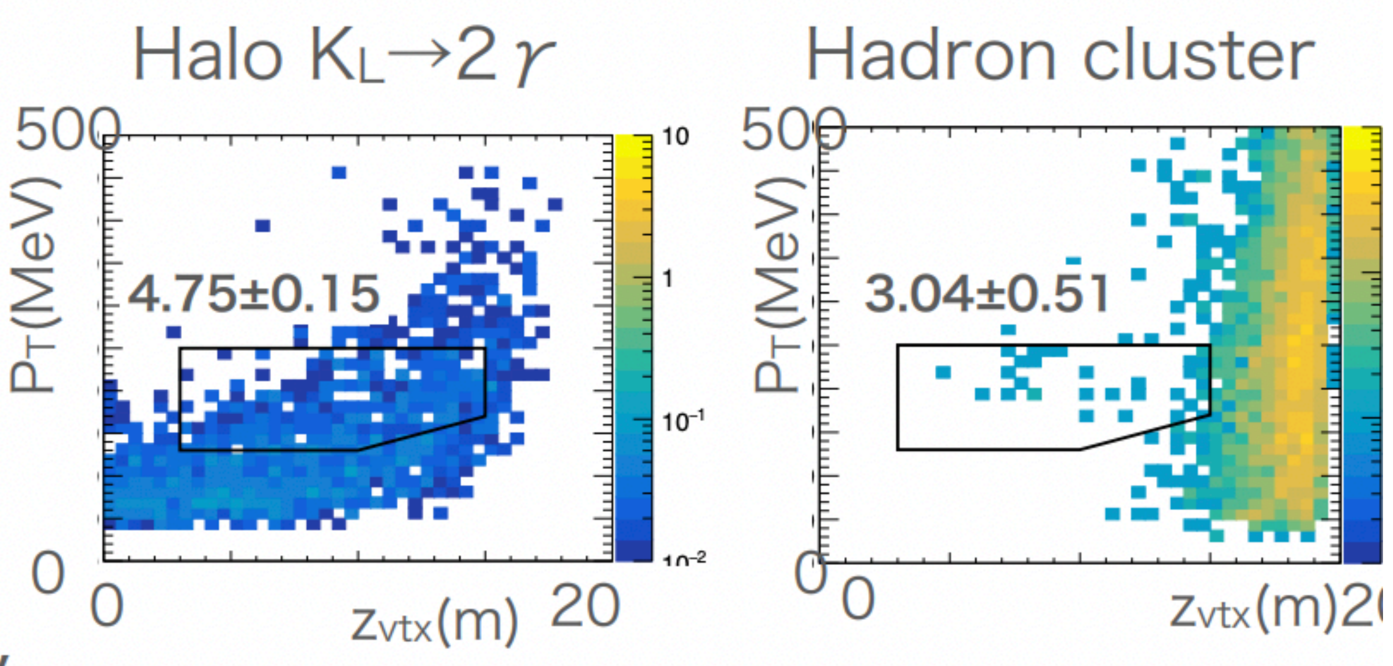
KOTO II

[arXiv:2110.04462v1]

Beam power	100 kW	(at 1-interaction-length T2 target) $(1.1 \times 10^7 K_L / 2 \times 10^{13}$ POT)
Repetition cycle	4.2 s	
Spill length	2 s	
Running time	3×10^7 s	~effectively 730 days of data-taking

Background	Number	
$K_L \to \pi^0\pi^0$	33.2	± 1.3
$K_L \to \pi^+\pi^-\pi^0$	2.5	± 0.4
$K_L \to \pi^\pm e^\mp \nu$	0.08	± 0.0006
halo $K_L \to 2\gamma$	4.8	± 0.2
$K^\pm \to \pi^0 e^\pm \nu$	4.0	± 0.4
hadron cluster	3.0	± 0.5
π^0 at upstream	0.2	± 0.1
η at downstream	8.2	± 2.3
Total	56.0	± 2.8





# of signal events : 35
# of background events : 56
S/N = 0.63
→ 4.7σ observation

KOTO II

Signal & BG

[arXiv:2110.04462v1]

- With 35 $K_L \to \pi^0 \nu \bar{\nu}$ SM events and 56 BG events,
  - S/B = 0.63, 4.7σ observation.
  - 14% precision for CKM η parameter.
  - New physics discovery at 90% C.L. for 44% deviations from SM.