



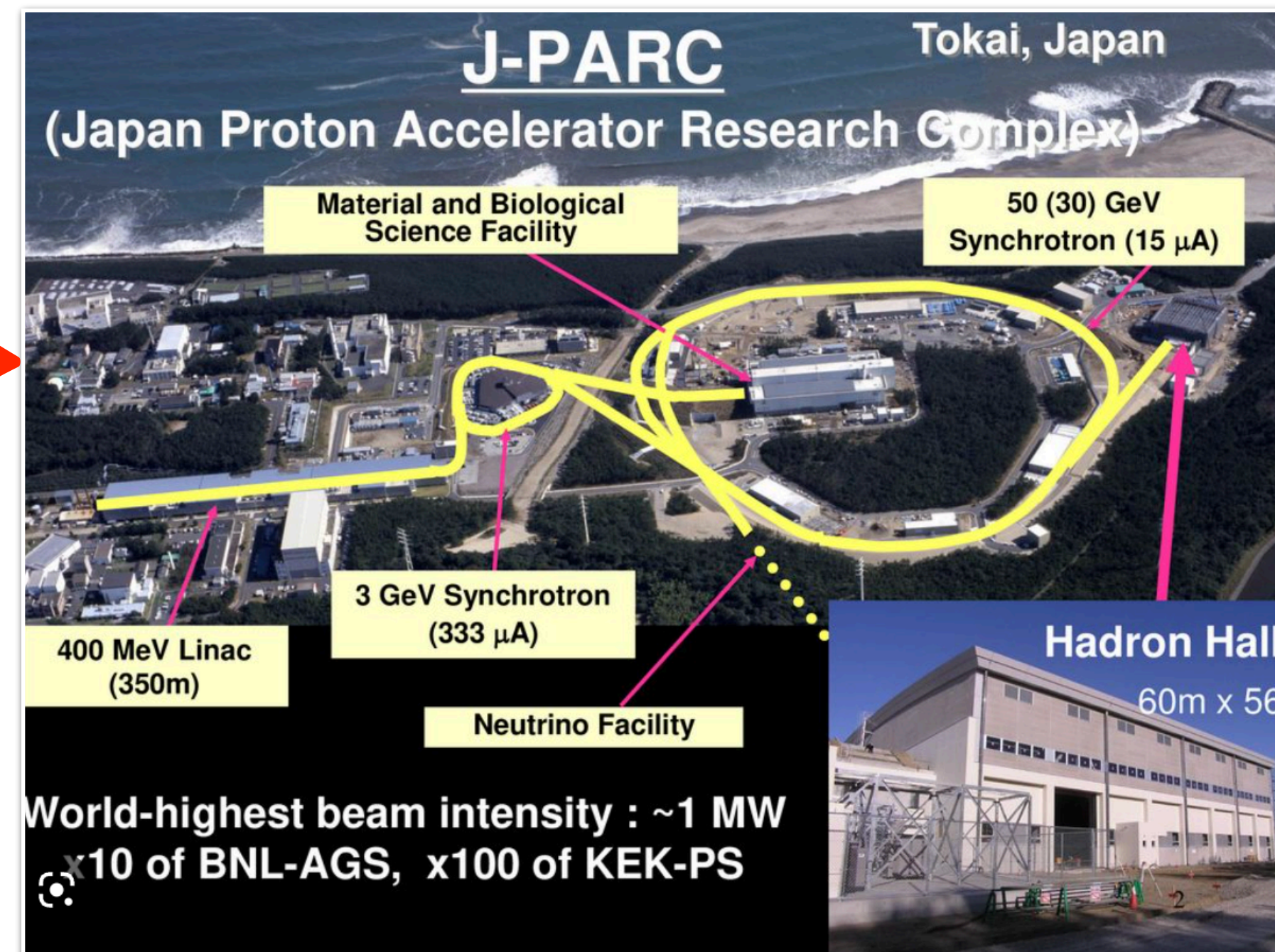
Status and Prospects of the J-PARC KOTO Experiment

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KOTO Experiment

- ~40 members from a dozen institutes
- Location: Hadron hall, J-PARC, Japan



Japan

- KEK
- Osaka Univ
- NDA
- Yamagata Univ

US

- Univ. of Chicago

Taiwan

- National Taiwan Univ
- National Changhua University of Education
- National Kaohsiung Normal Univ

Korea

- Jeonbuk National Univ
- Korea Univ
- Pusan Univ

The Golden $K_L \rightarrow \pi^0 \nu \bar{\nu}$ Decay

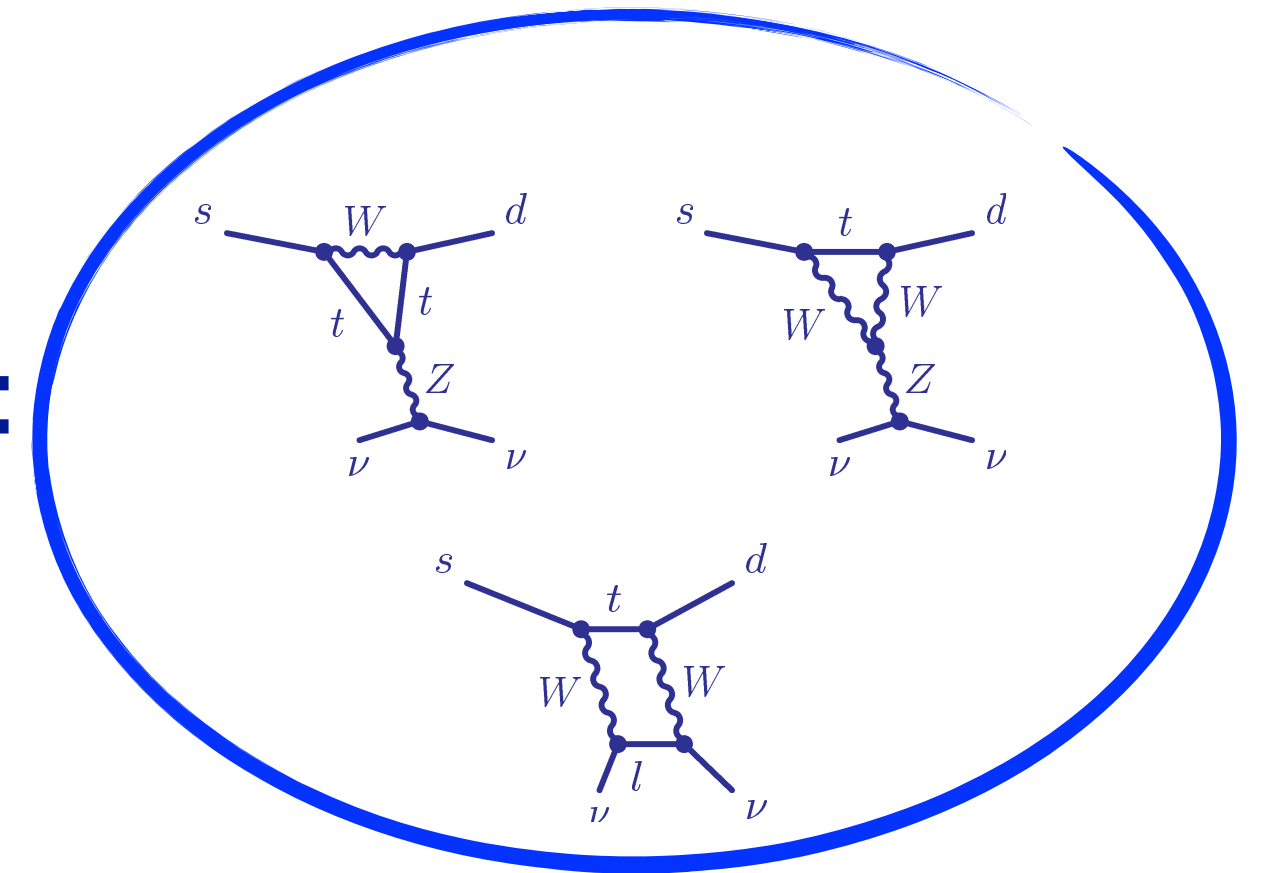
The primary goal of KOTO:

- Probing new physics by measuring $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$.
- New physics discoveries if $BR^{EXP} \neq BR^{SM}$

The $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay:

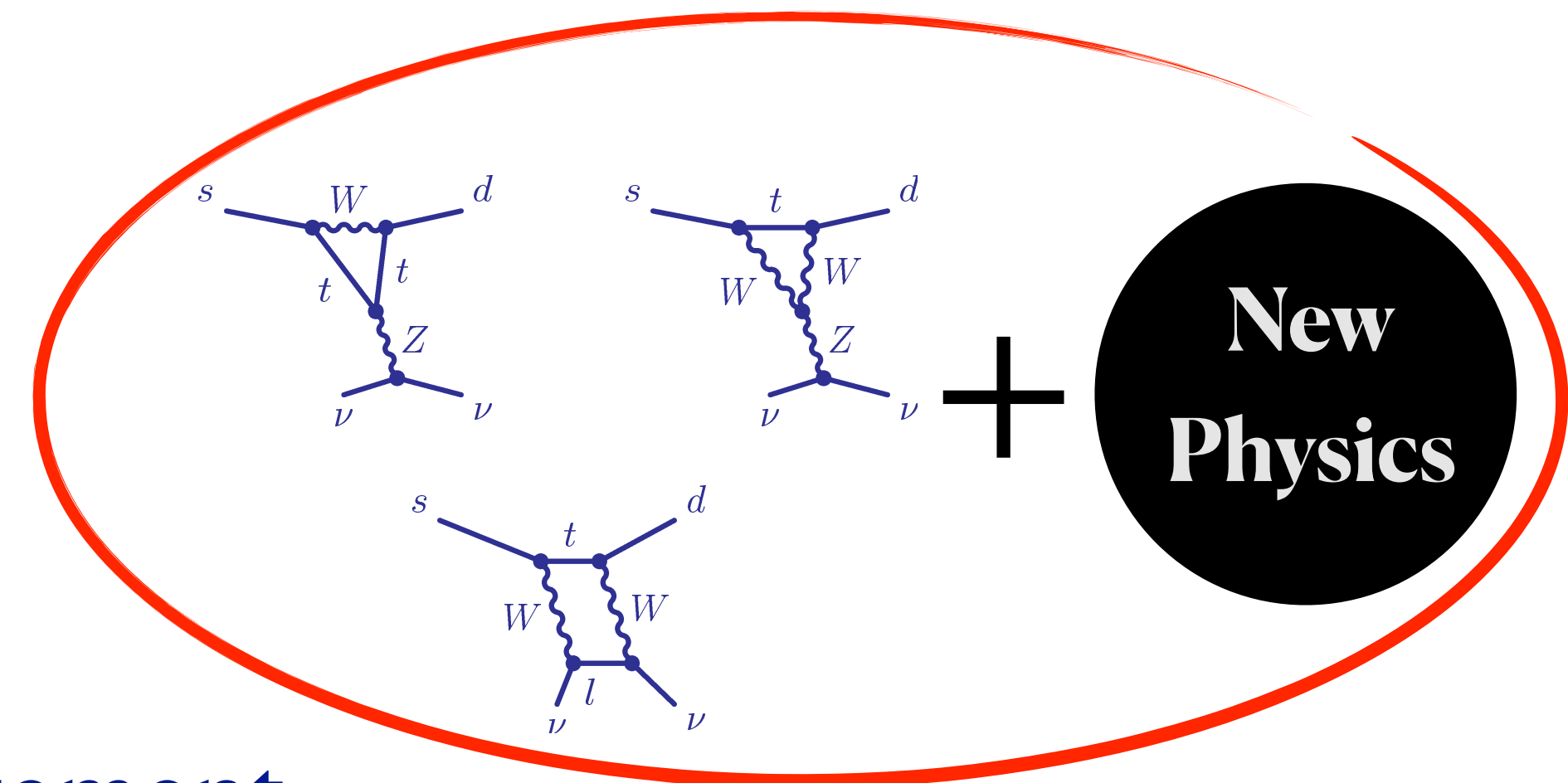
- Direct CP-violating process.
- $BR^{SM}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = 3 \times 10^{-11}$
 - Less than 2% theoretical uncertainty.
- Sensitive to new physics, but challenging for measurement.

$$BR^{SM} =$$

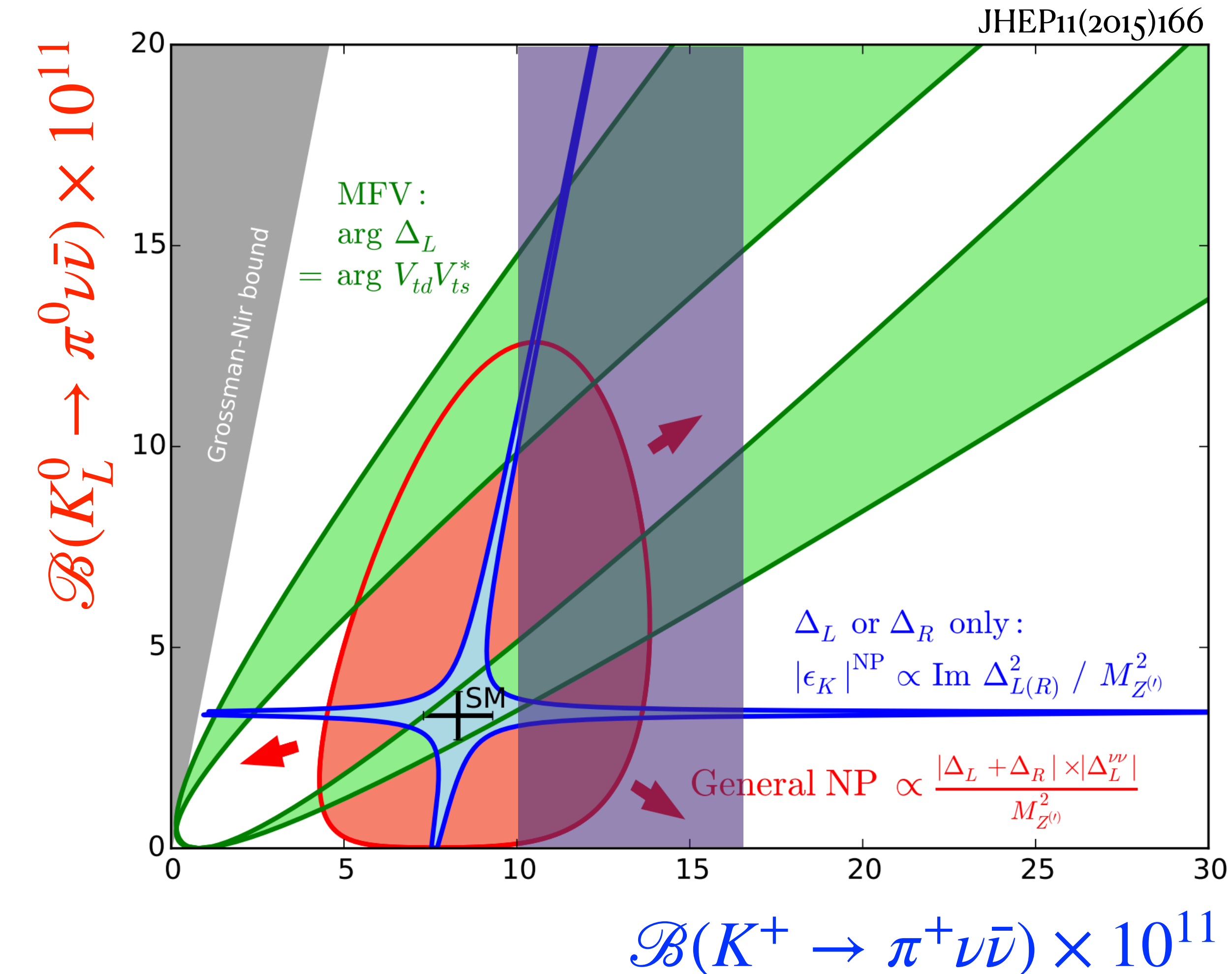


Sign of
New Physics $\neq$

$$BR^{EXP} \stackrel{?}{=}$$



$K \rightarrow \pi \nu \bar{\nu}$ and New Physics



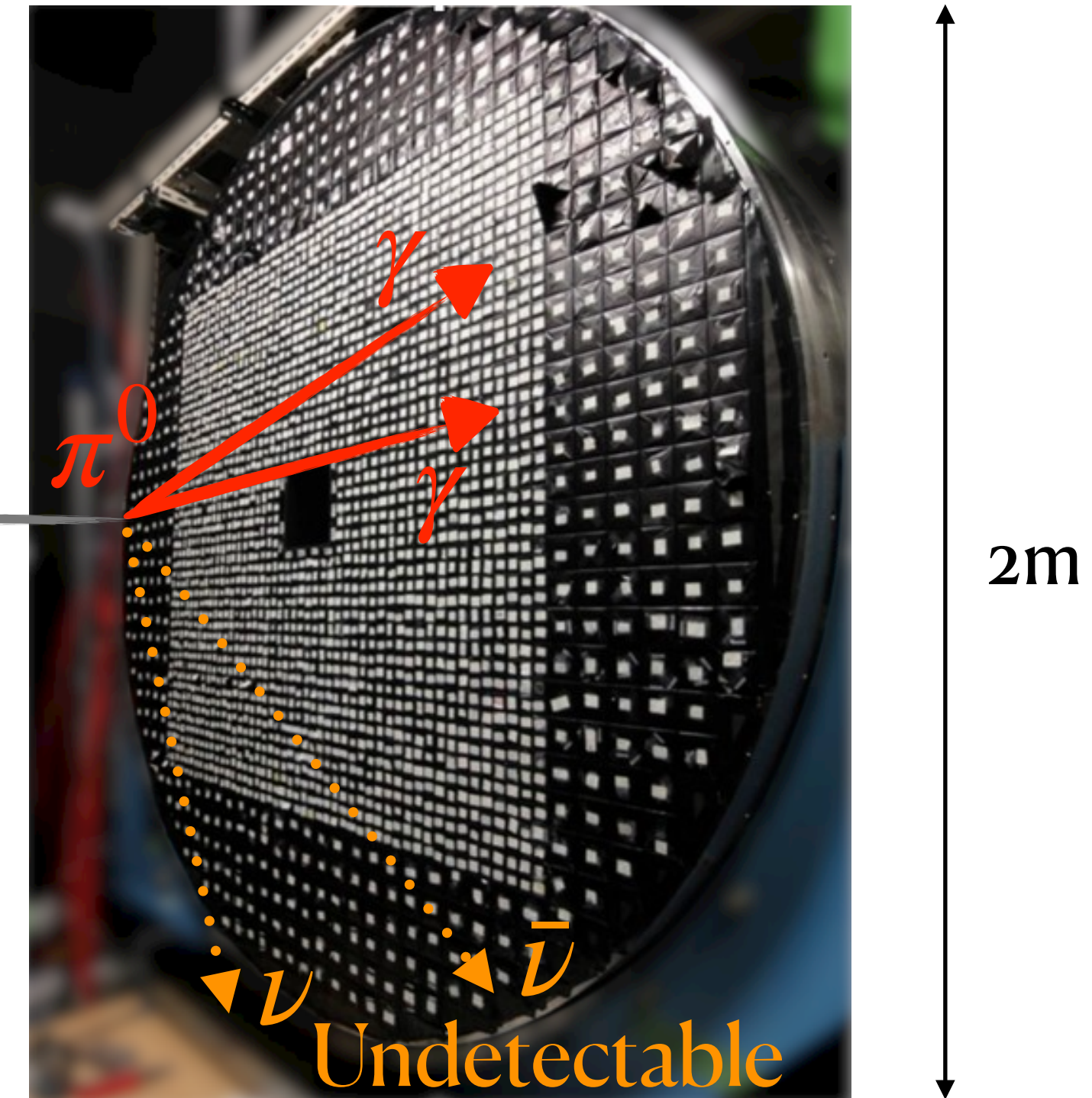
- CKM-like flavor structure – MFV
- New flavor and CP-violating interactions with dominant LH or RH couplings
- None of the above constraints
 - Randall-Sundrum
- NA62: $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11}$
 - [JHEP 02 (2025) 191]
 - Covers $\mathcal{B}^{\text{SM}}$ with 1.7σ

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

Signal Signatures:

- 2γ + “nothing” in the final state
- High transverse momentum (P_T) of π^0
- due to the missing momentum taken by $\nu \bar{\nu}$

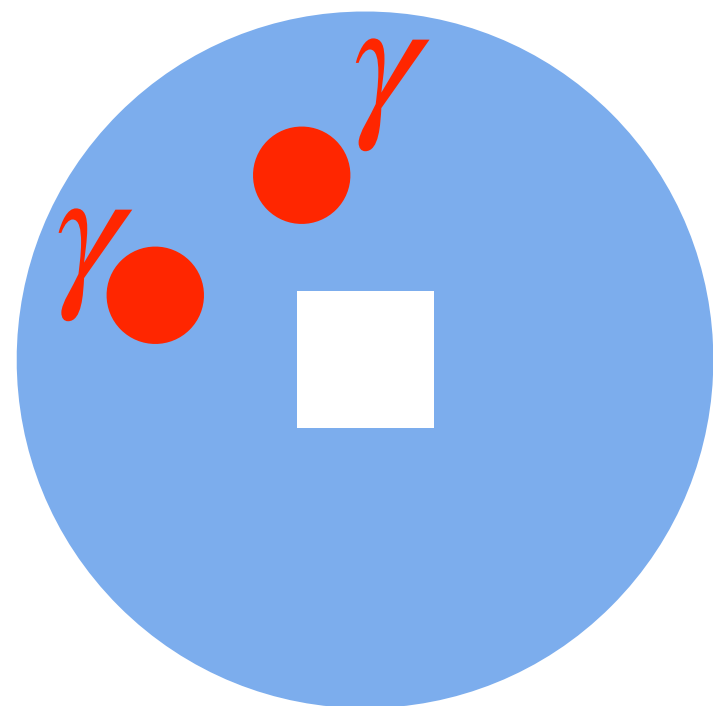
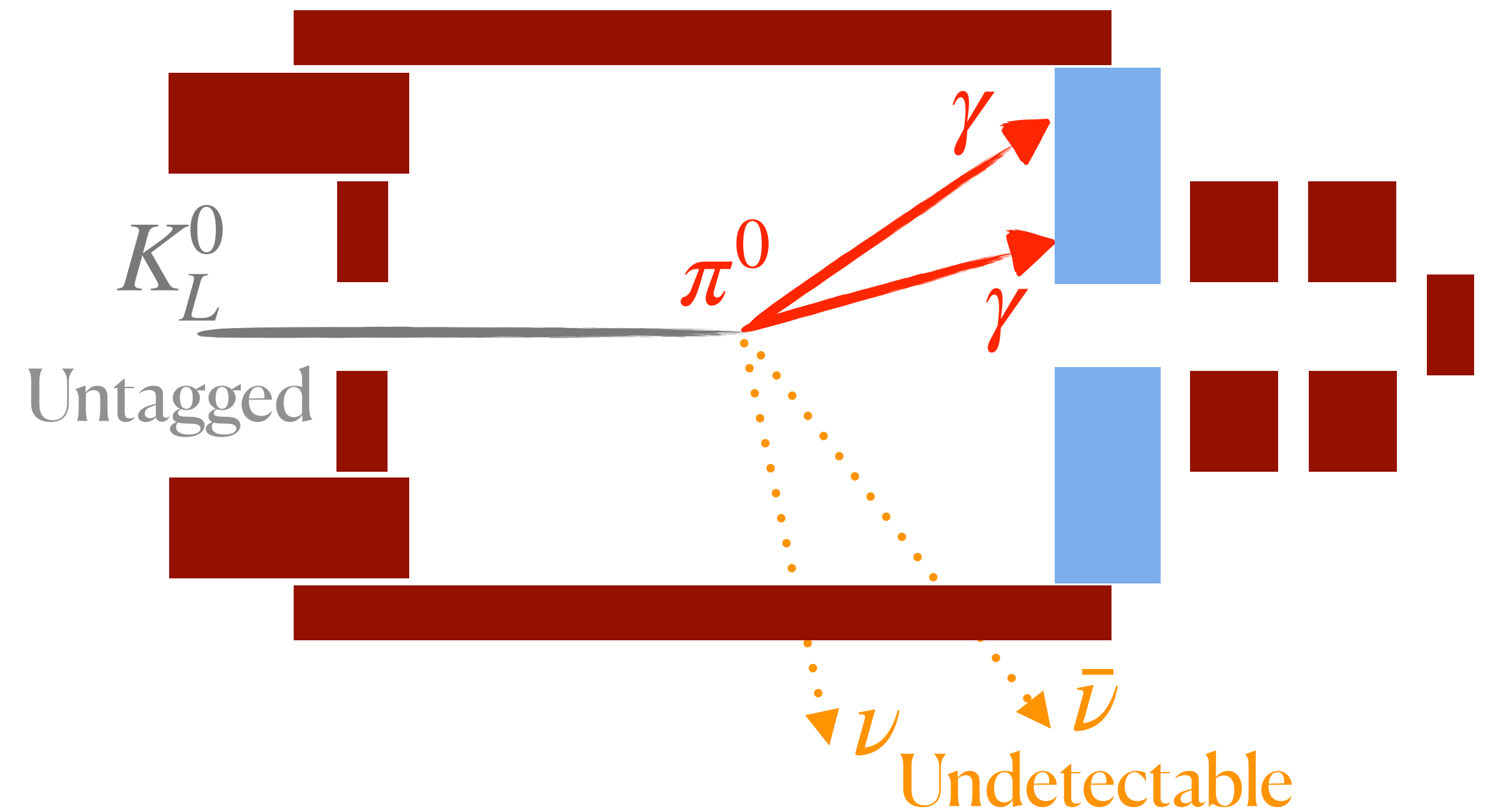
Untagged K_L^0



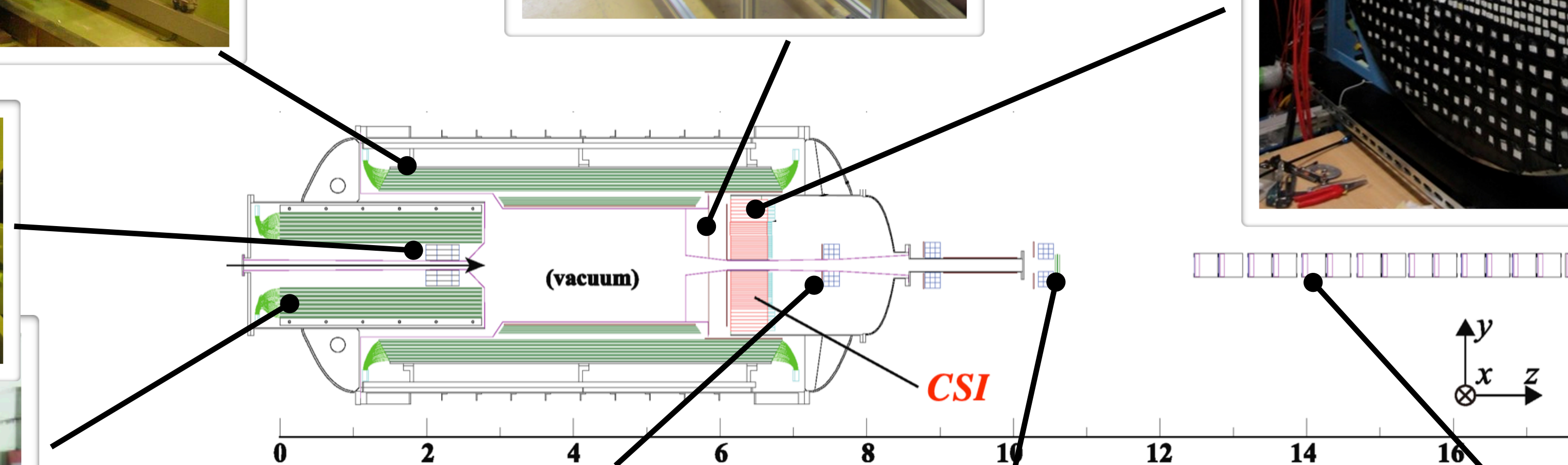
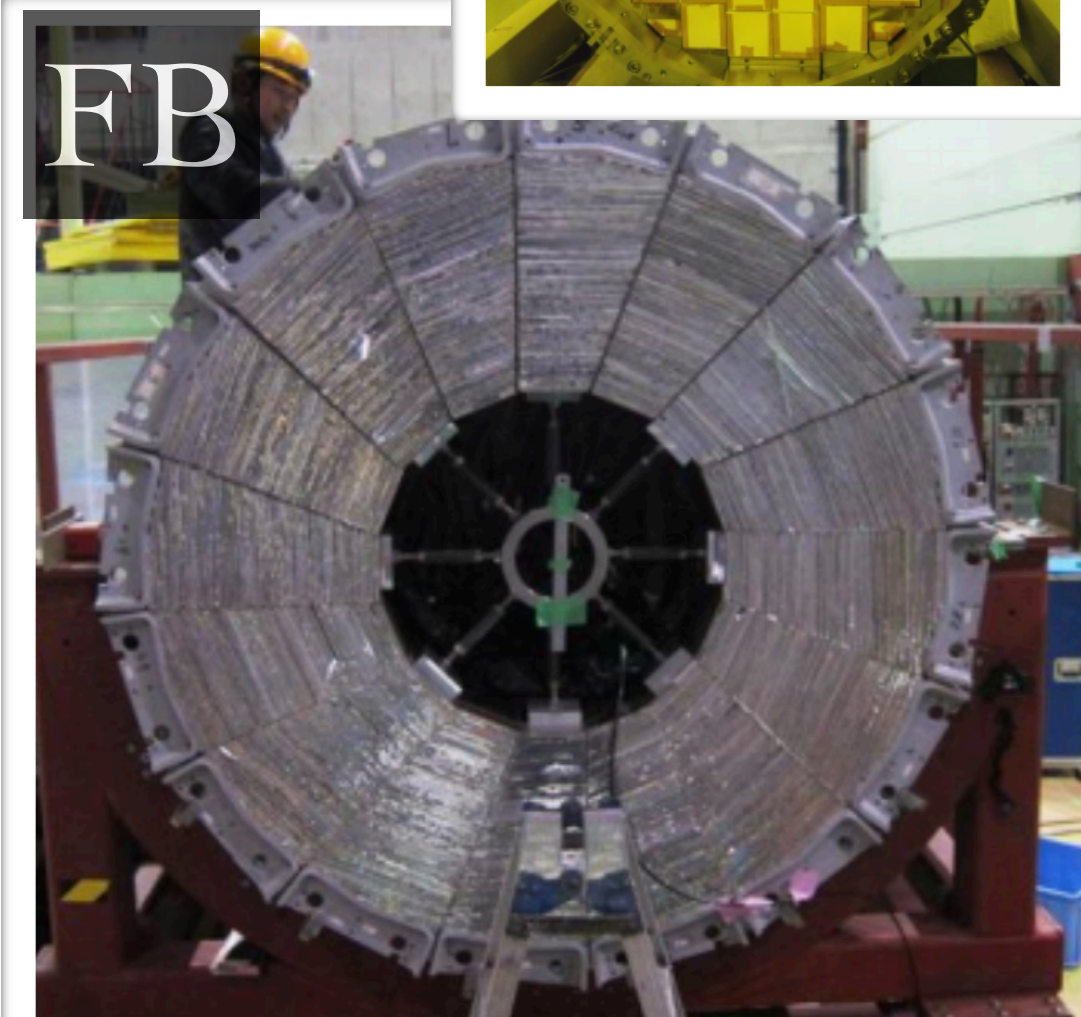
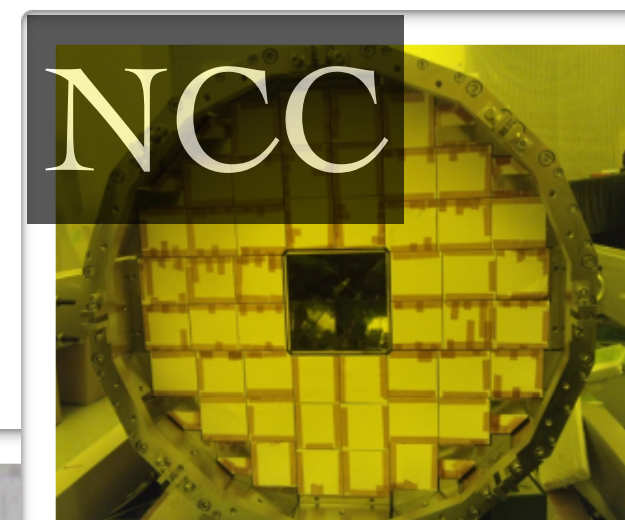
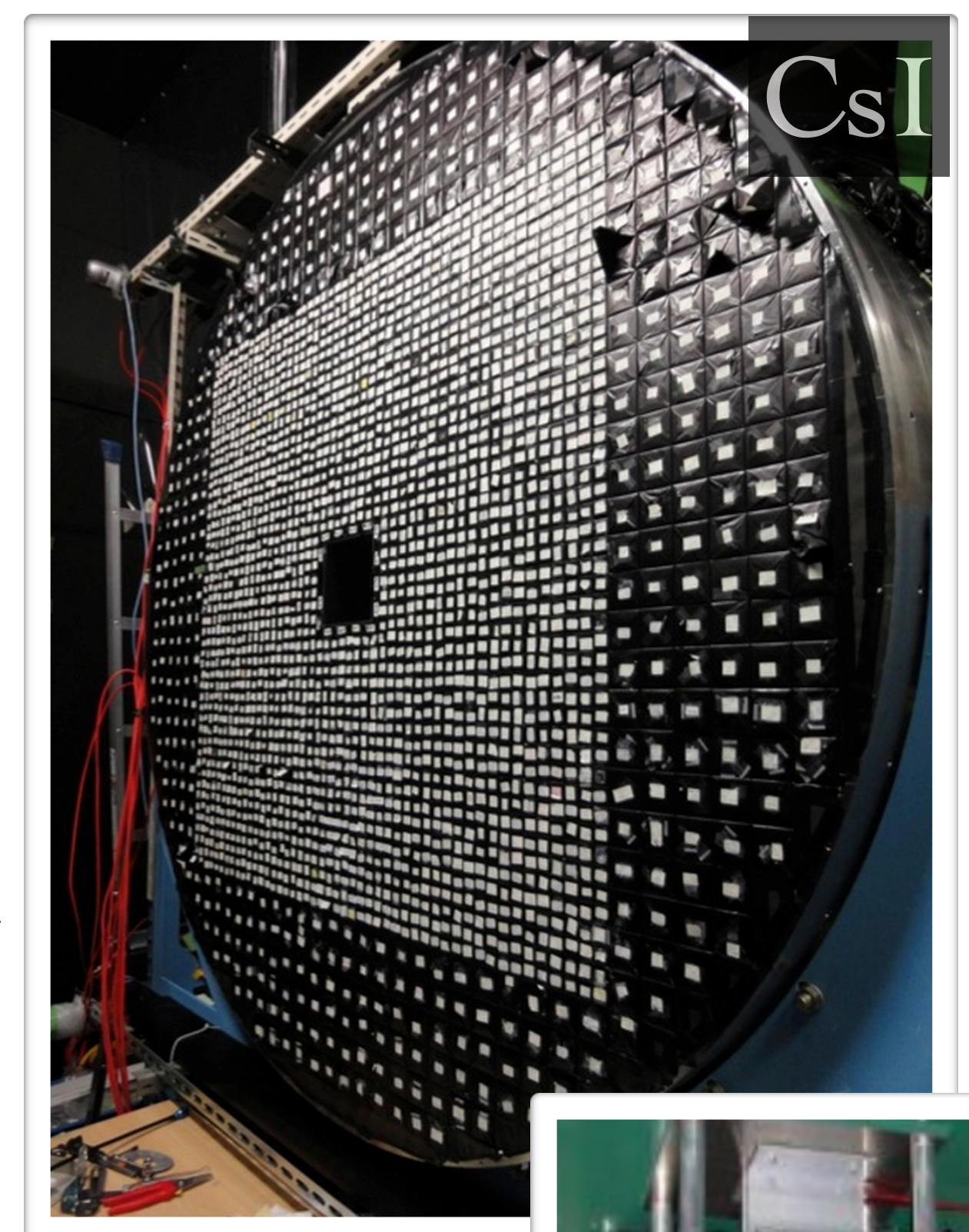
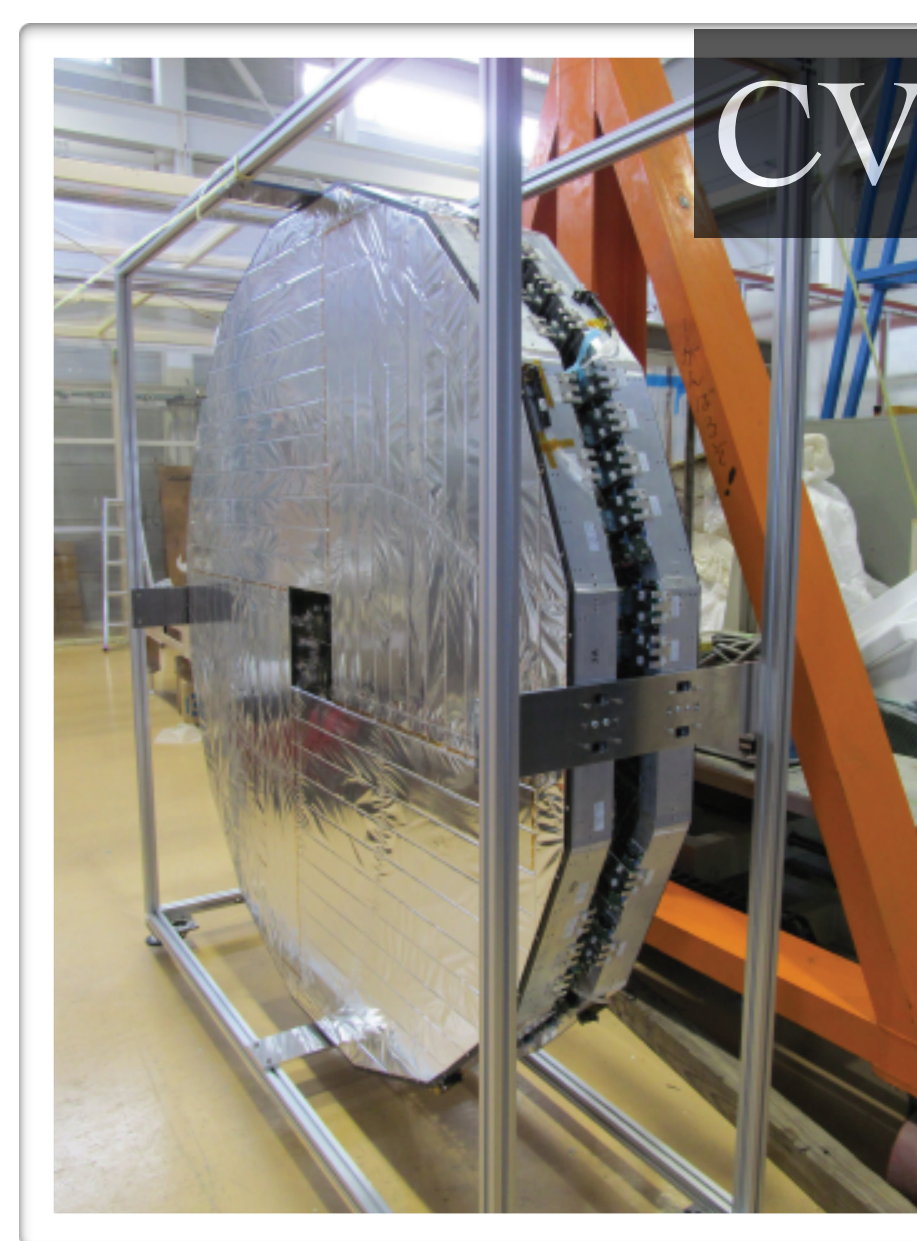
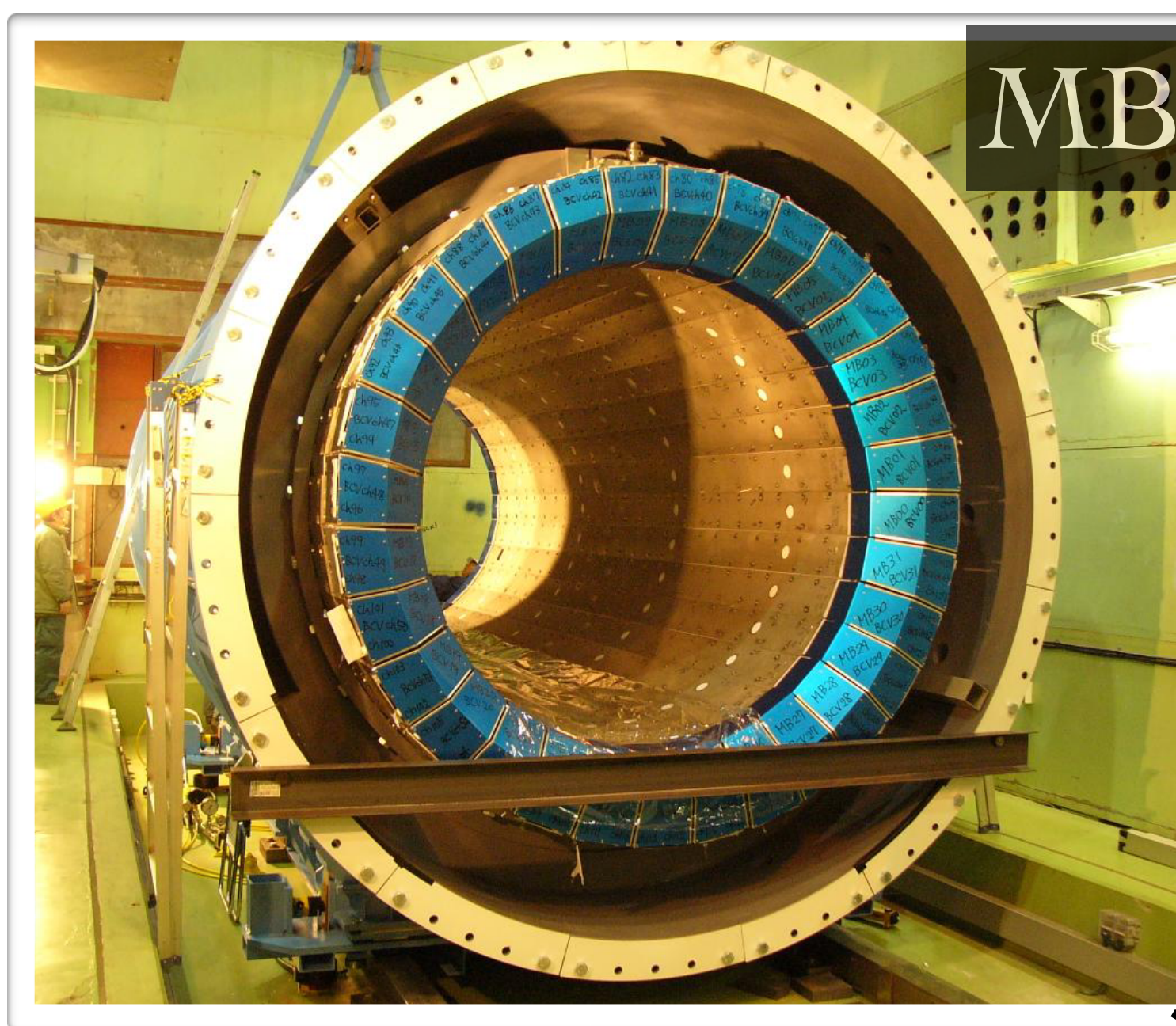
Measure 2γ 's energy and position
using CsI (Cesium Iodide) calorimeter

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

- Signal Signatures:
 - 2γ + “nothing” in the final state
- Hermetic veto system
 - to ensure “nothing” other than 2γ

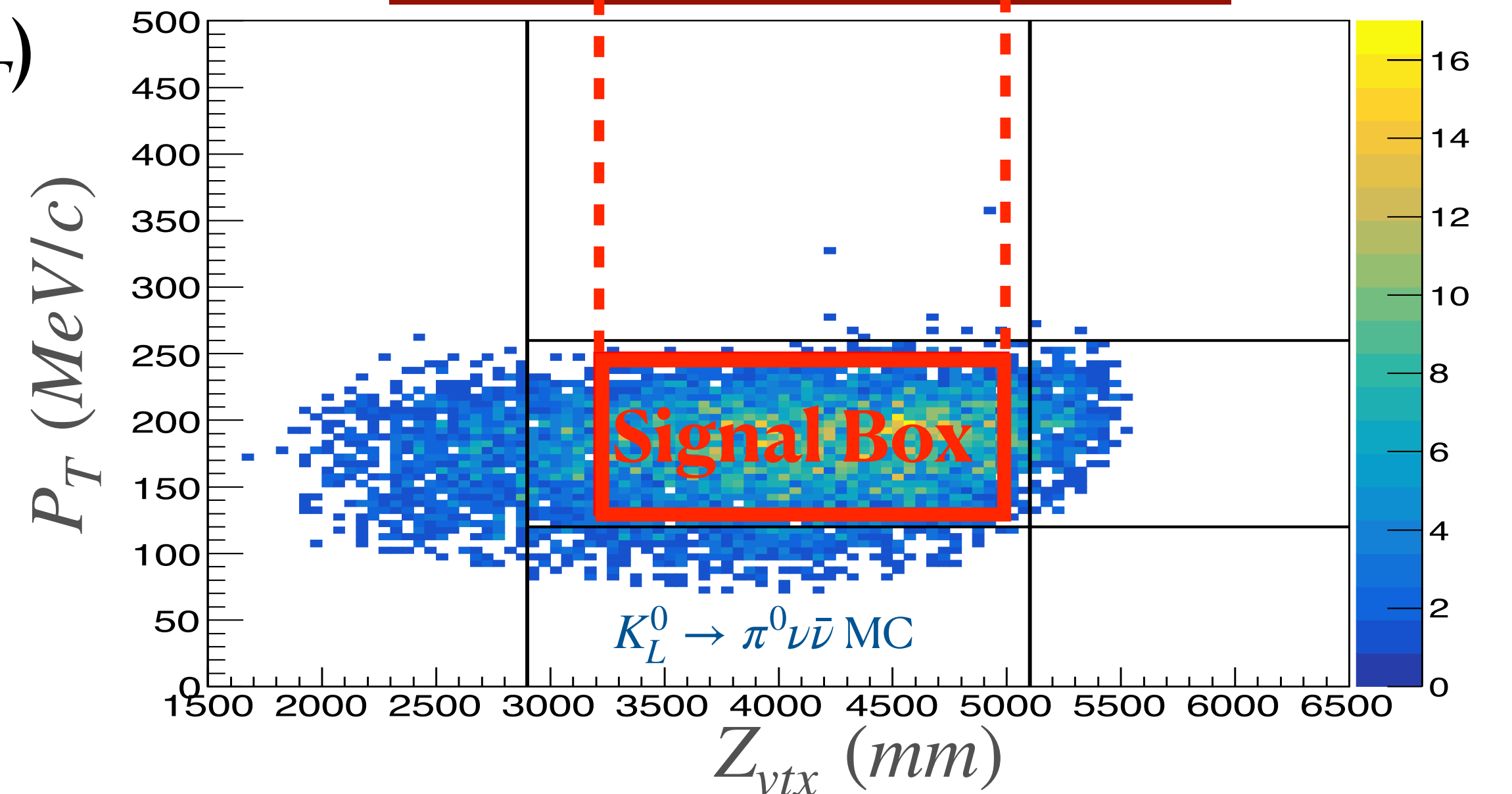
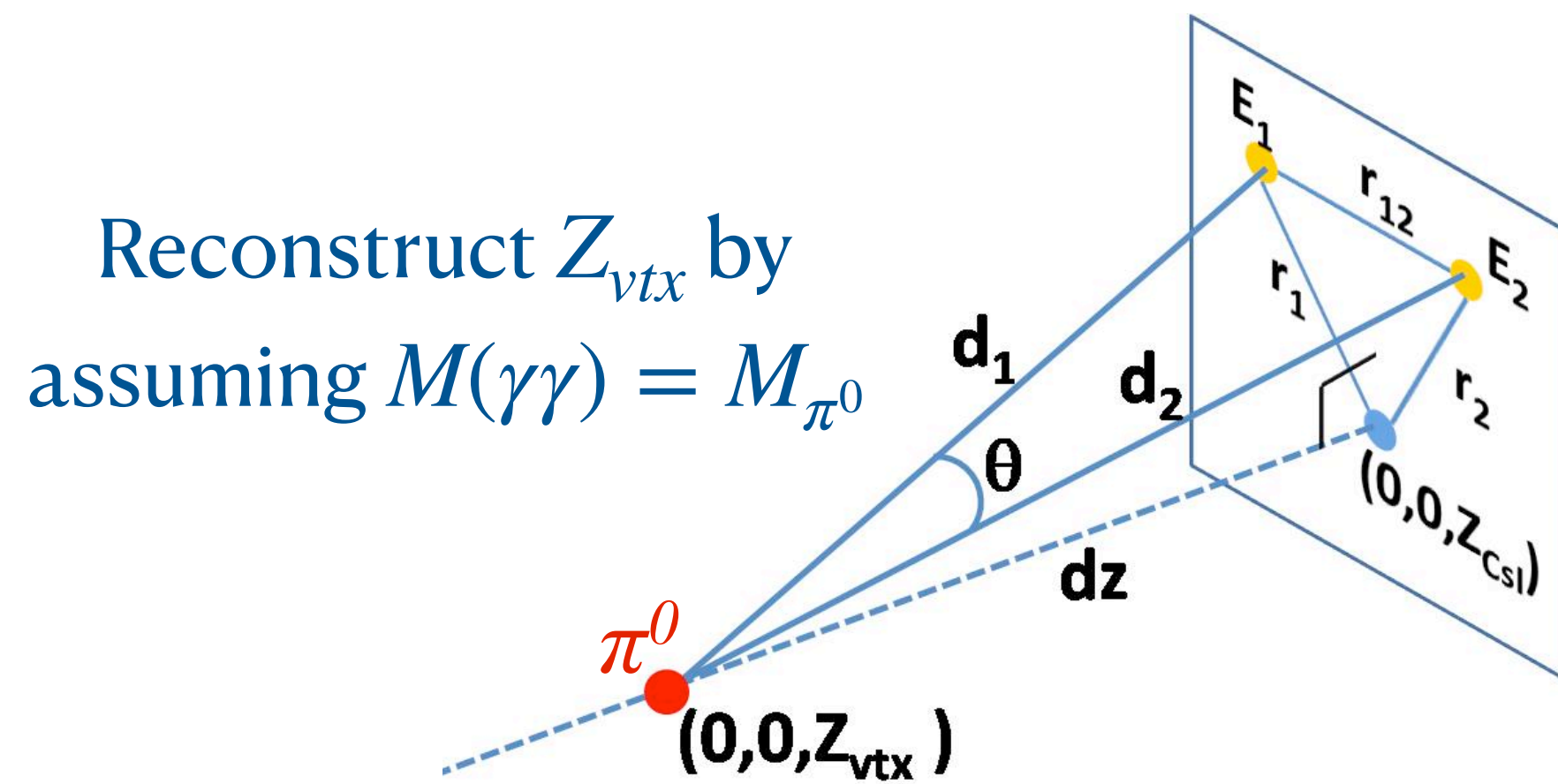
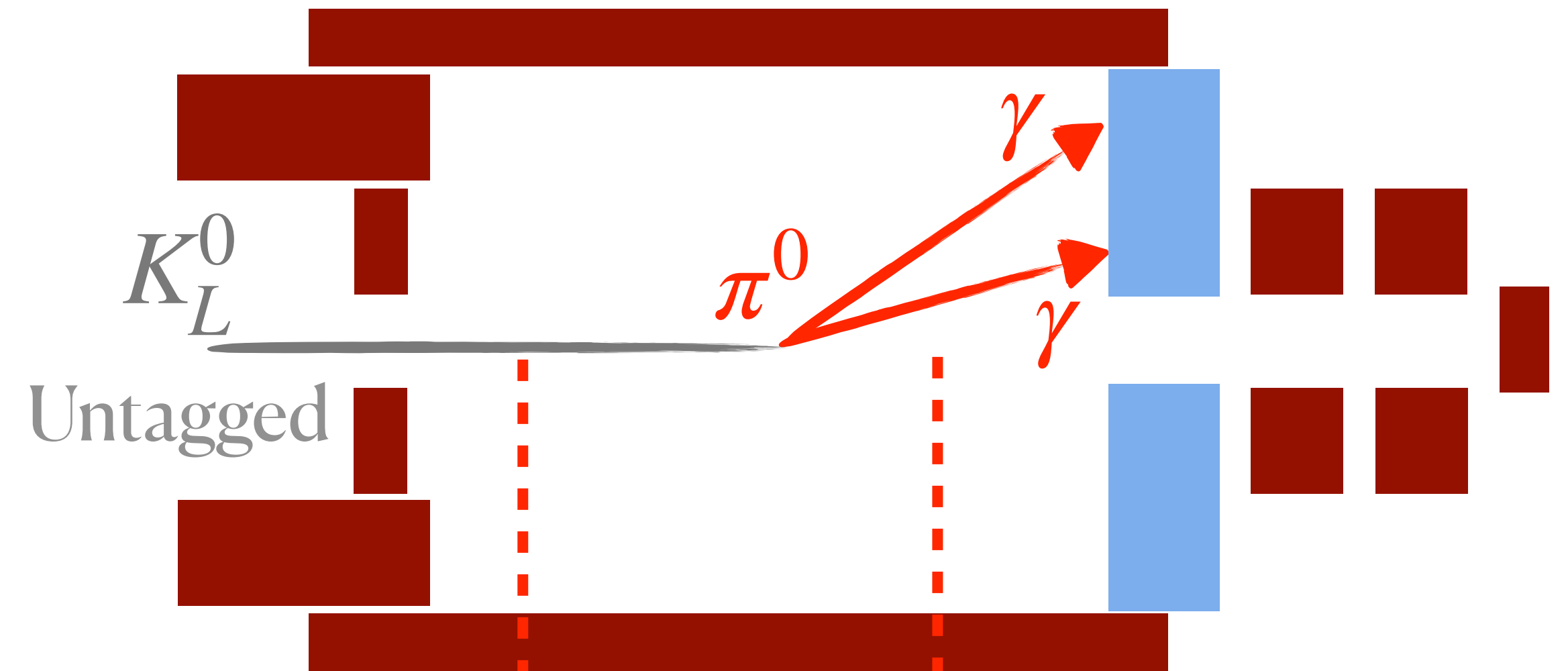


& No hits in any veto detector ()



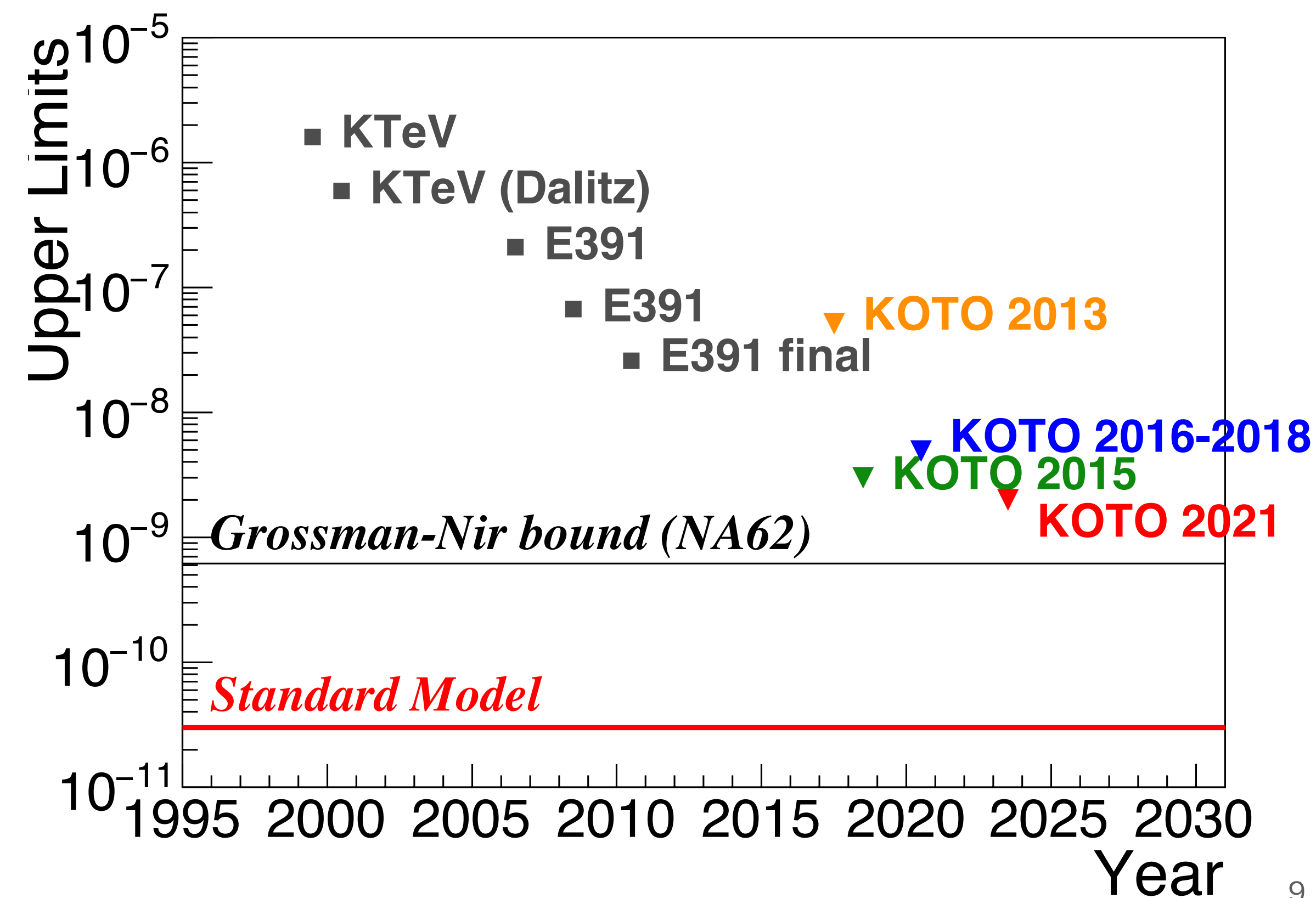
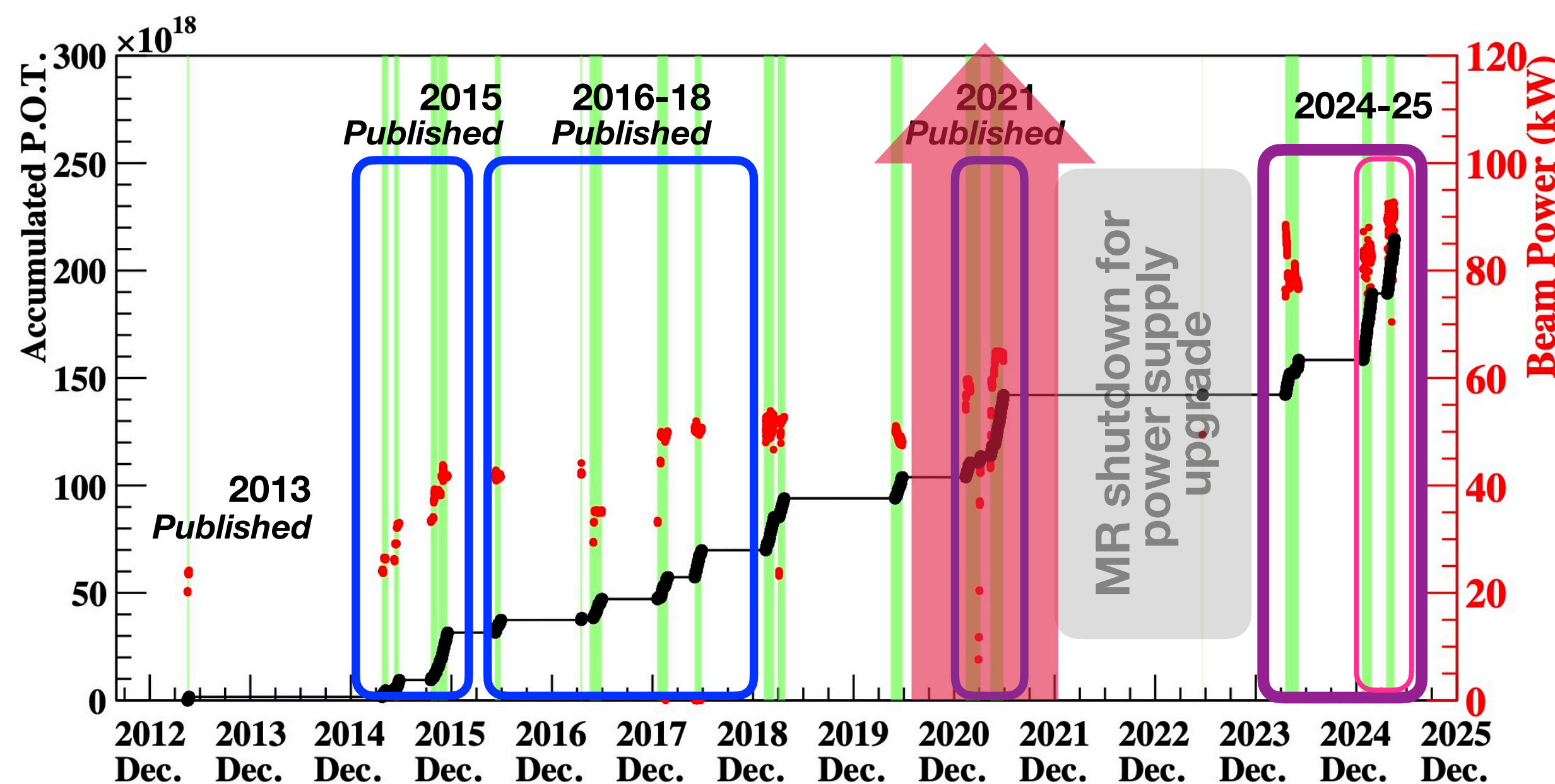
Reconstruction of $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

- Signal Signatures:
 - 2γ + “nothing” in the final state
- Signal box is defined by:
 - π^0 vertex (Z_{vtx}) within detector
 - High π^0 transverse momentum (P_T)



Run Histories and Results

- Five data-taking periods have been conducted since 2013, with four already published.
- The latest results with 2021 data [PRL.134.081802]
 - $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9}$ (90% C.L.)
 - (The current world-best upper limit!)

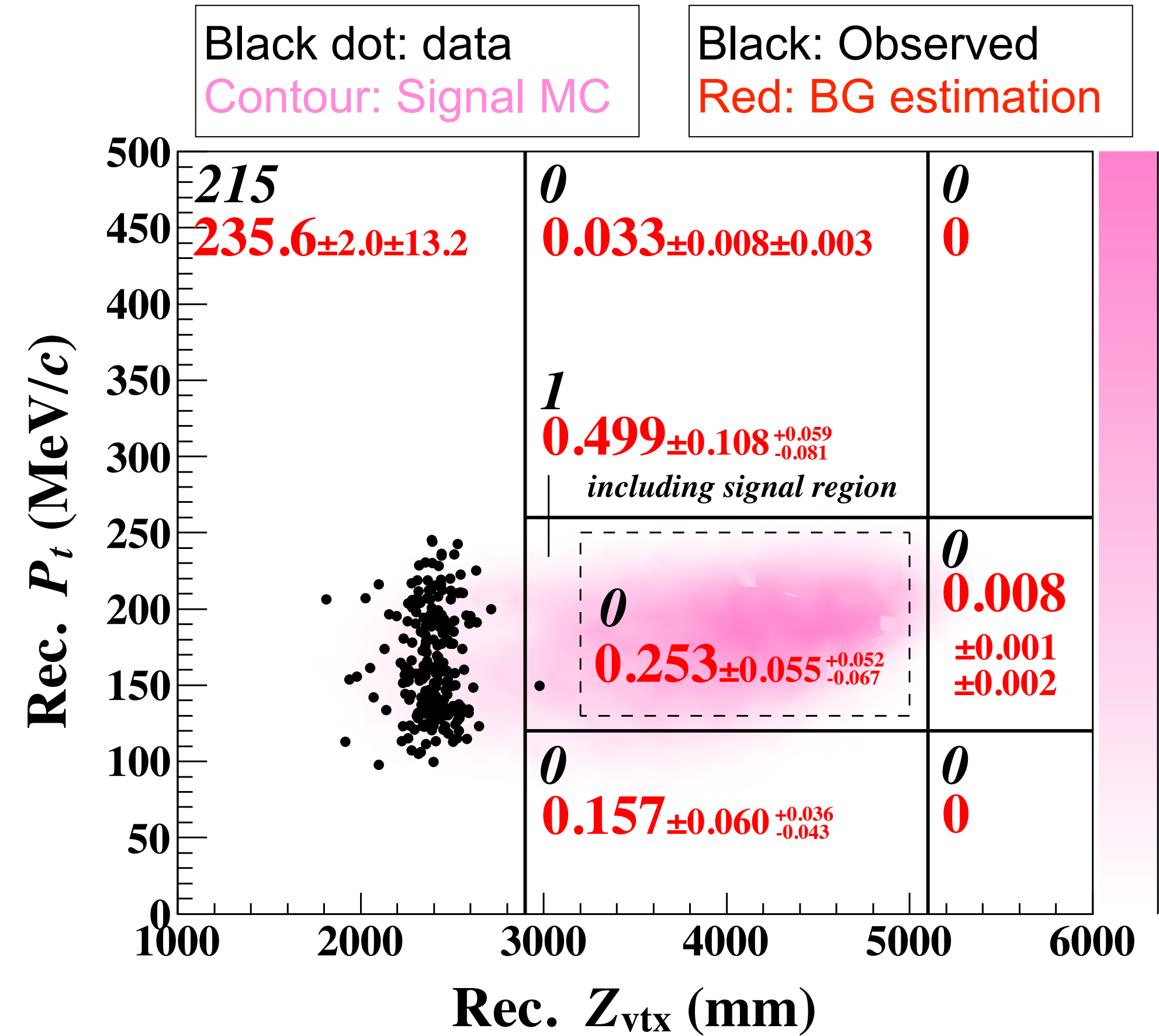


Run Histories and Results

List of the backgrounds (2021 data)

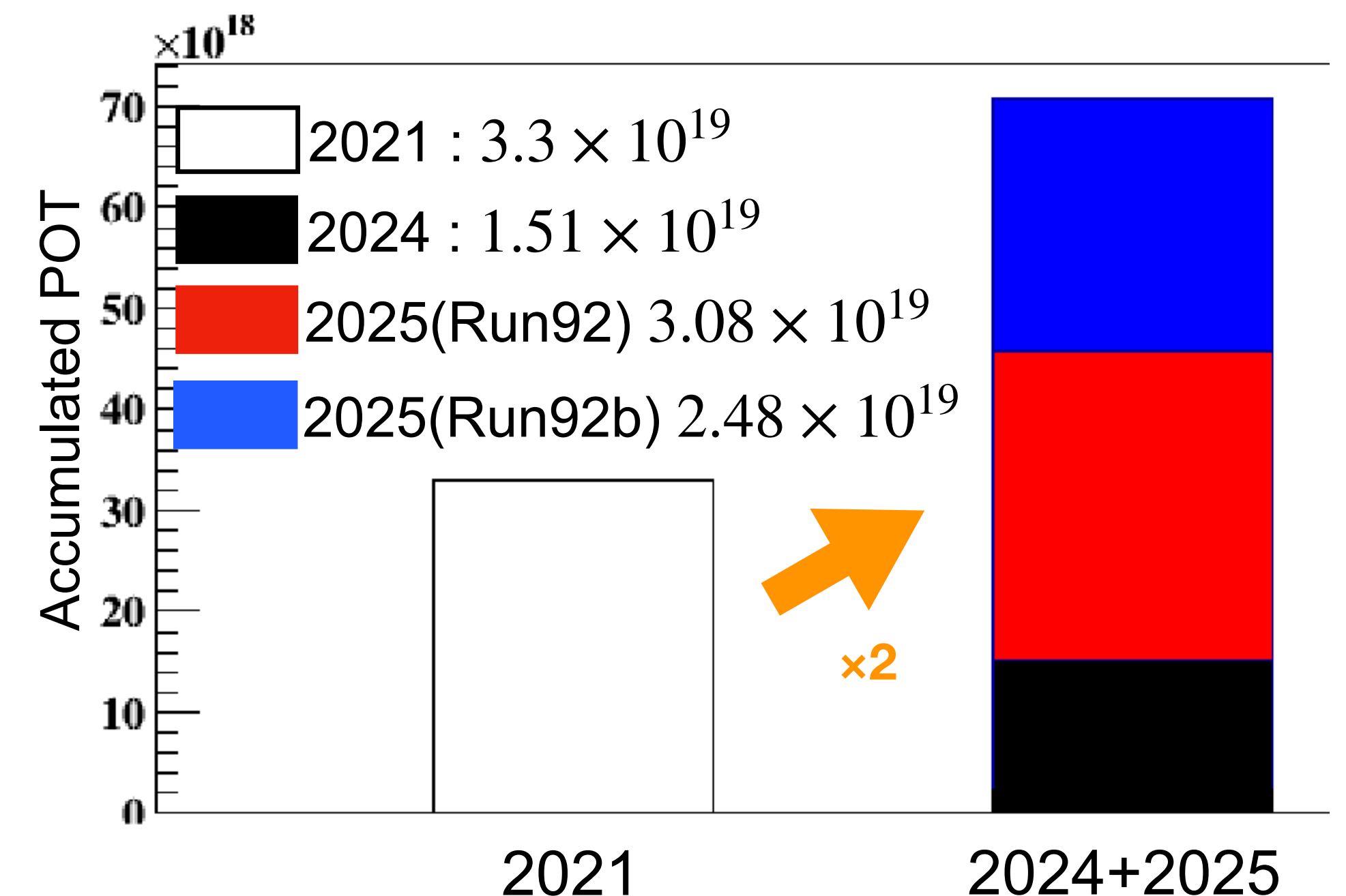
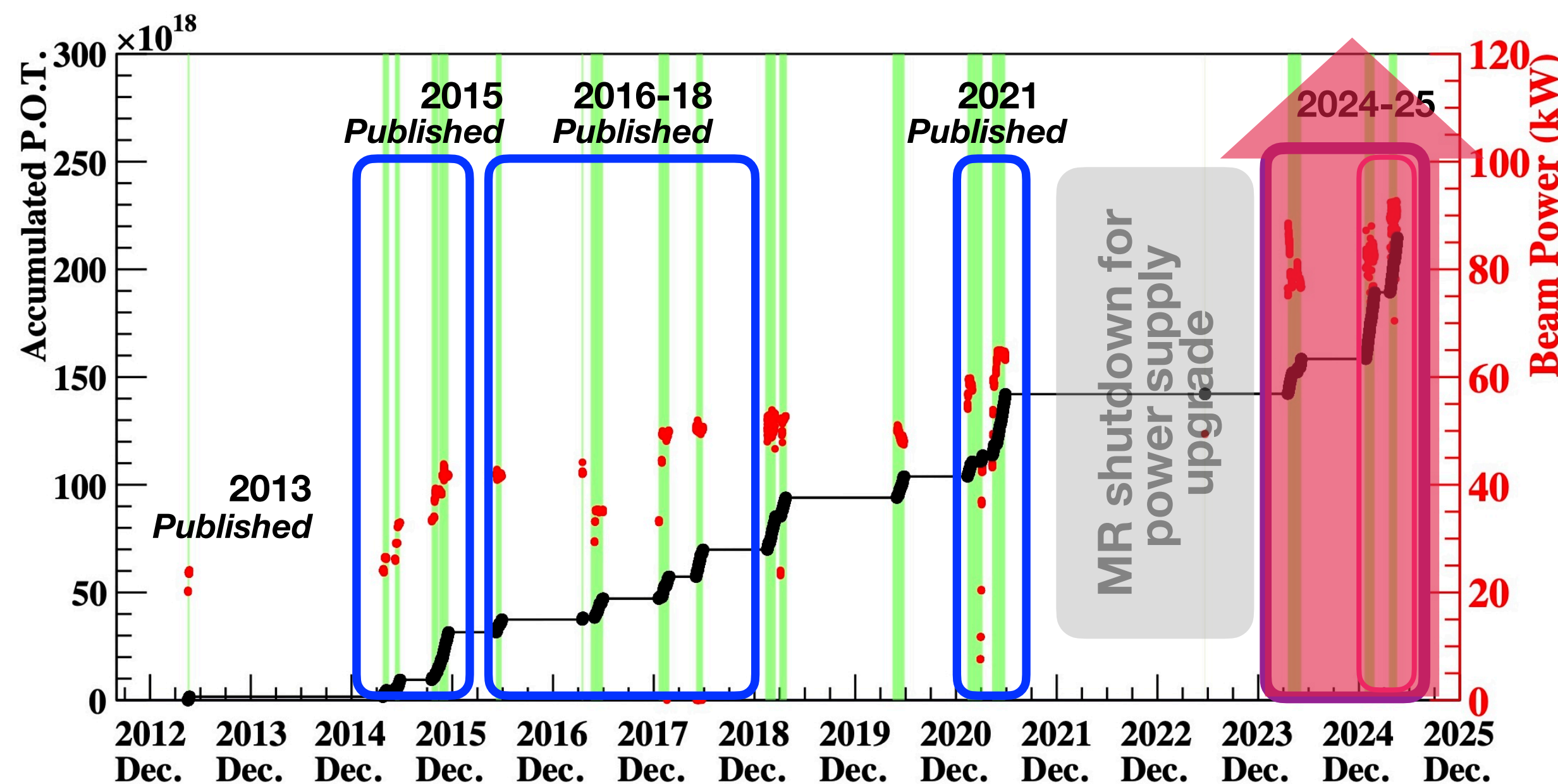
BG Source	BG Prediction
Upstream π^0	$0.060 \pm 0.046(\text{stat}) \pm 0.007(\text{sys})$
$K_L \rightarrow 2\pi^0$	$0.059 \pm (0.022)_{\text{stat}} (+0.050)_{\text{sys}}$
K^+	$0.042 \pm (0.014)_{\text{stat}} (+0.004)_{\text{sys}}$
Neutron BG	$0.024 \pm 0.004(\text{stat}) \pm 0.006(\text{sys})$
Scattered $K_L \rightarrow 2\gamma$	$0.022 \pm 0.005(\text{stat}) \pm 0.004(\text{sys})$
Halo $K_L \rightarrow 2\gamma$	$0.018 \pm 0.007(\text{stat}) \pm 0.004(\text{sys})$
η production in CV	$0.023 \pm 0.010(\text{stat}) \pm 0.005(\text{sys})$
Total	$0.253 \pm 0.055(\text{stat}) (+0.052)_{\text{sys}}$

- No event inside the signal region.
- The BG level is under control.



Run Histories and Results

- 2024-25 Data:
 - Stable data-taking at 92 kW beam power following the MR upgrade.
 - A factor of 2 more data than in 2021 had been collected.
 - Analysis in progress.



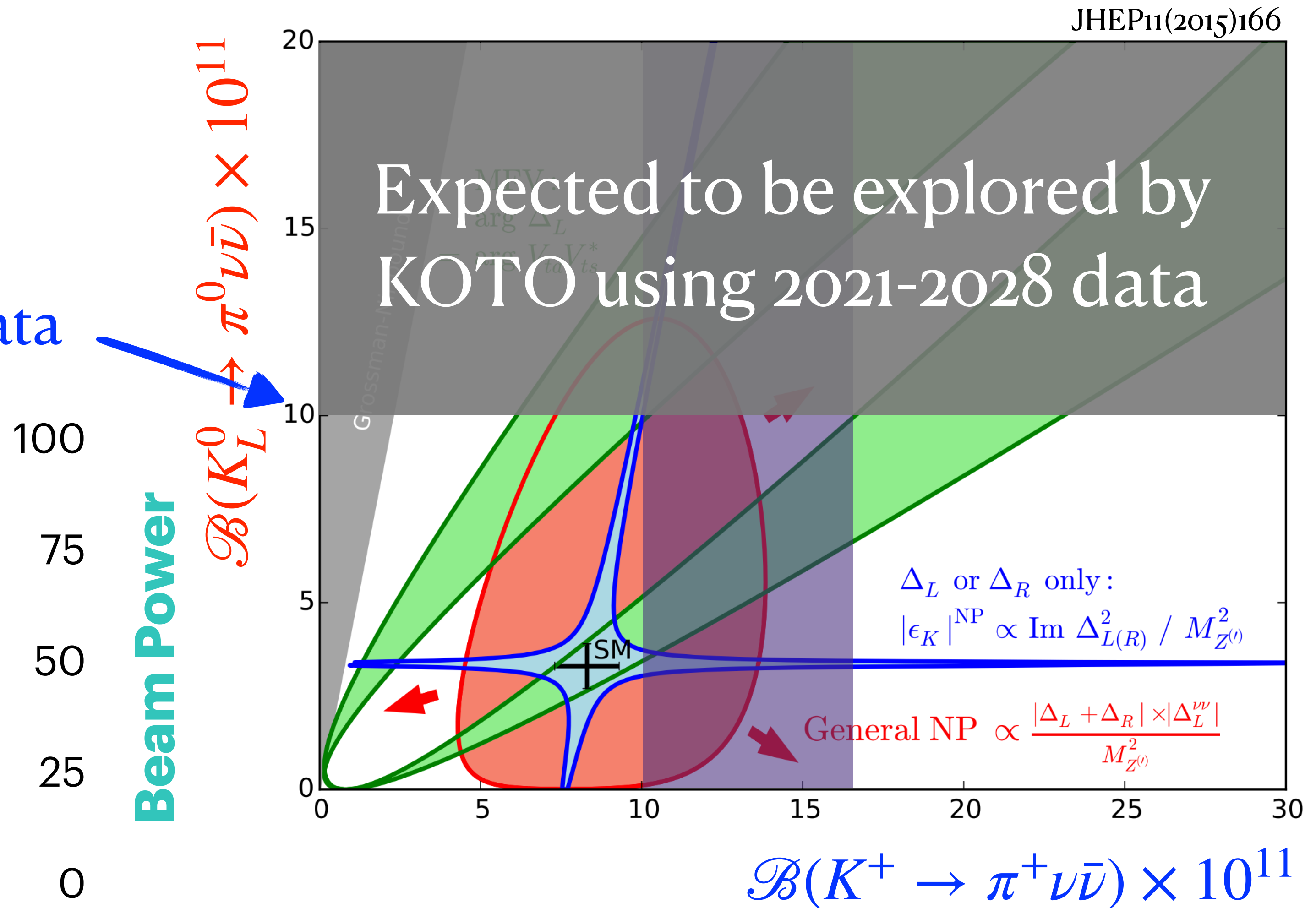
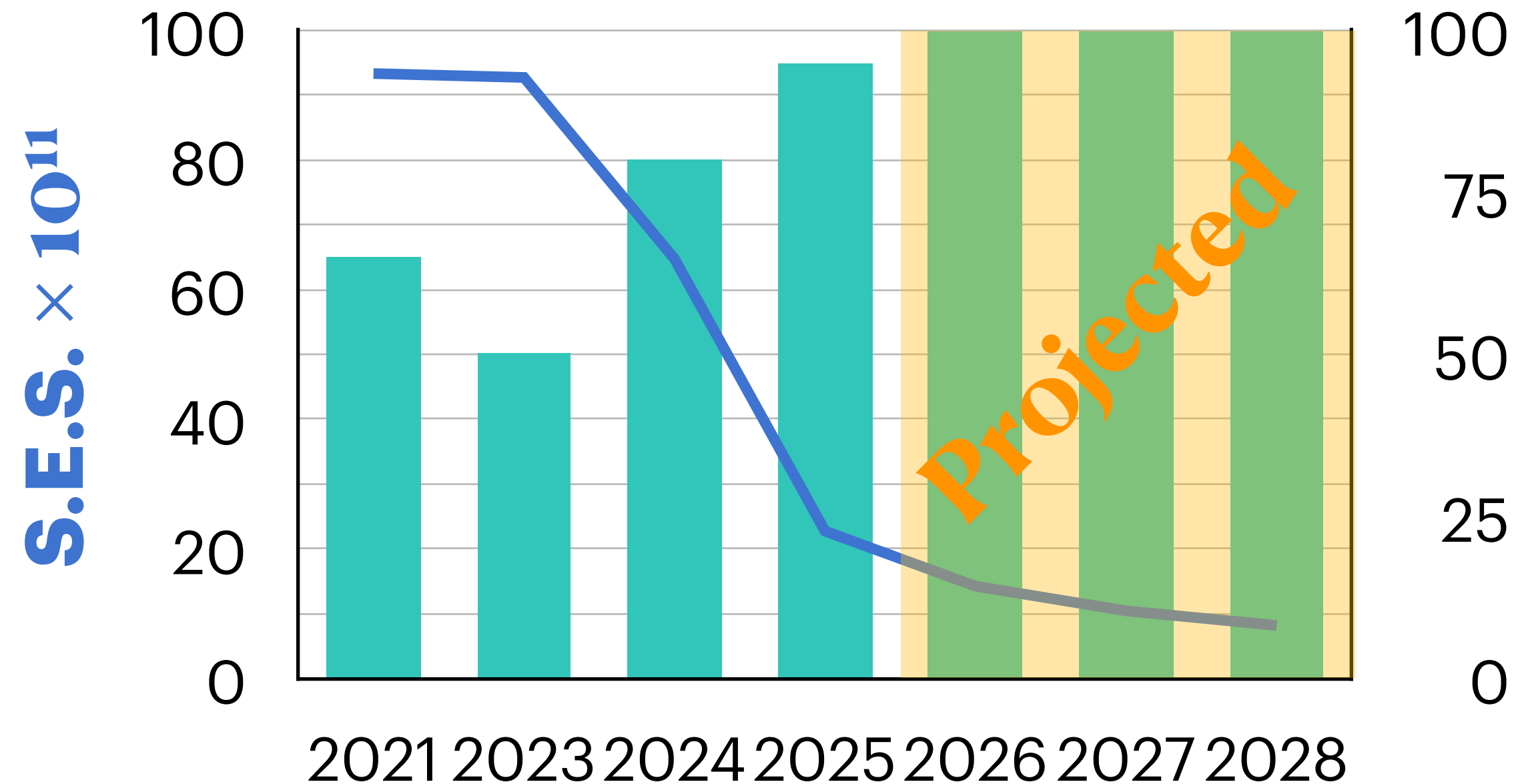
Prospects of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ Search

• KOTO

- Current Upper Limit (2021 data):

- $\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9}$

- S.E.S. $\sim 10^{-10}$ with 2021-2028 data



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

- **KOTO**

- Current Upper Limit (2021 data):

- $\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9}$

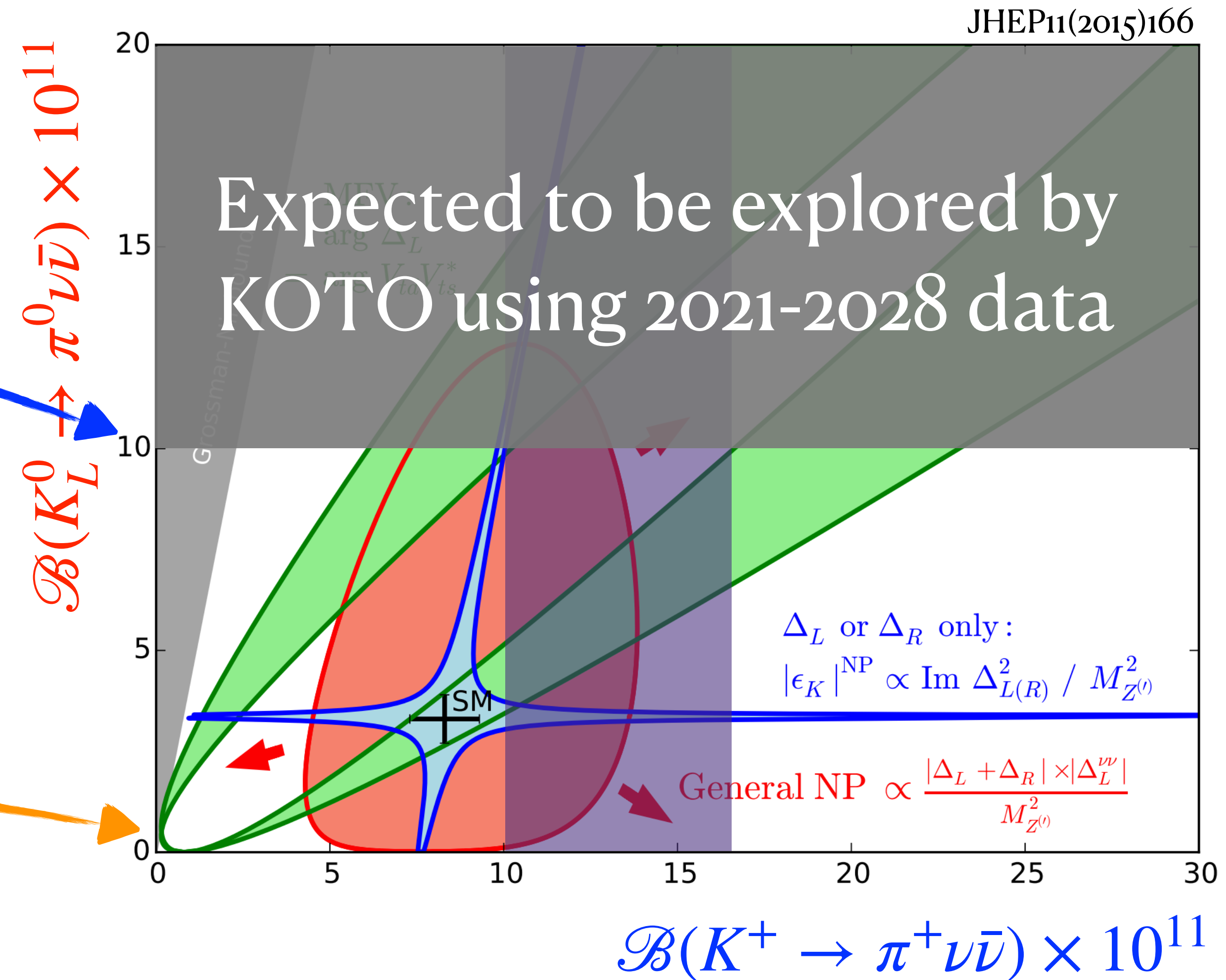
- S.E.S. $\sim 10^{-10}$ with 2021-2028 data

- **KOTO II**

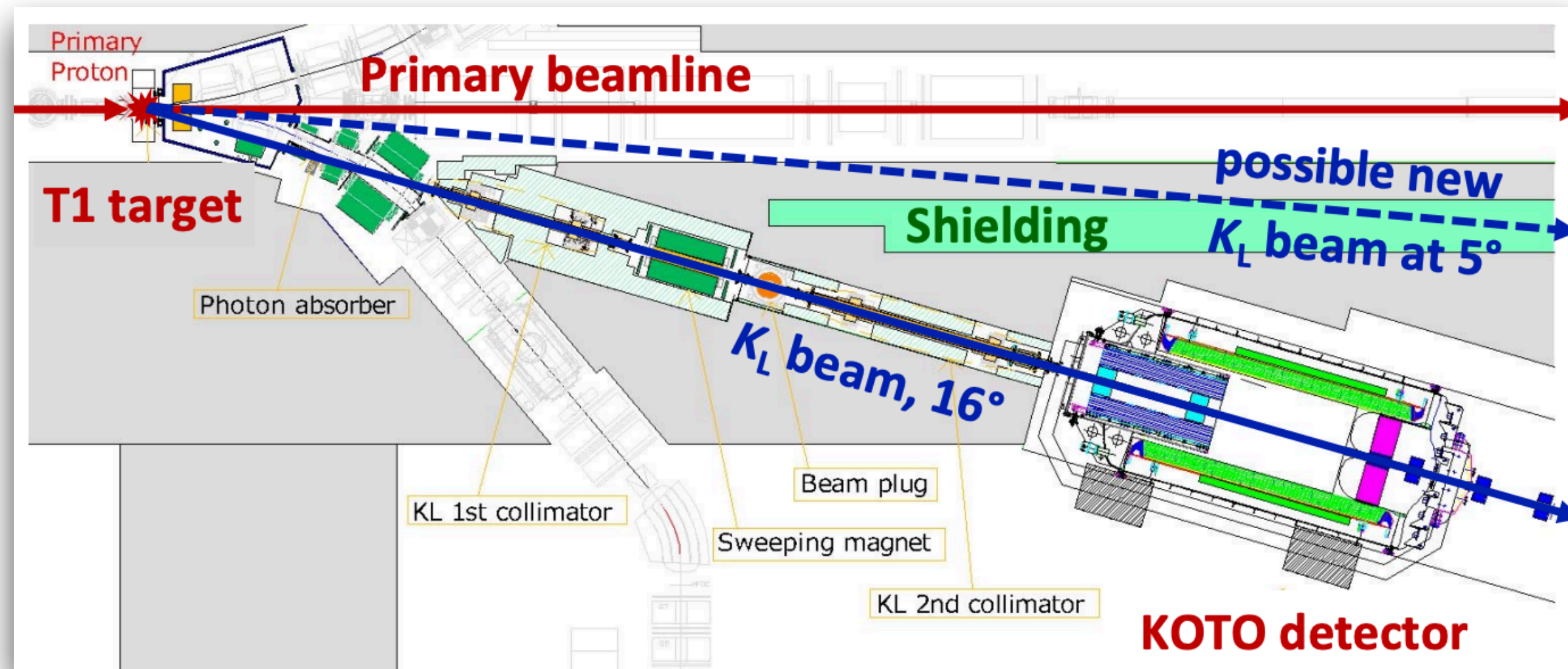
- Newly proposed Kaon project @J-PARC

- Targets to reach S.E.S. $< 10^{-12}$

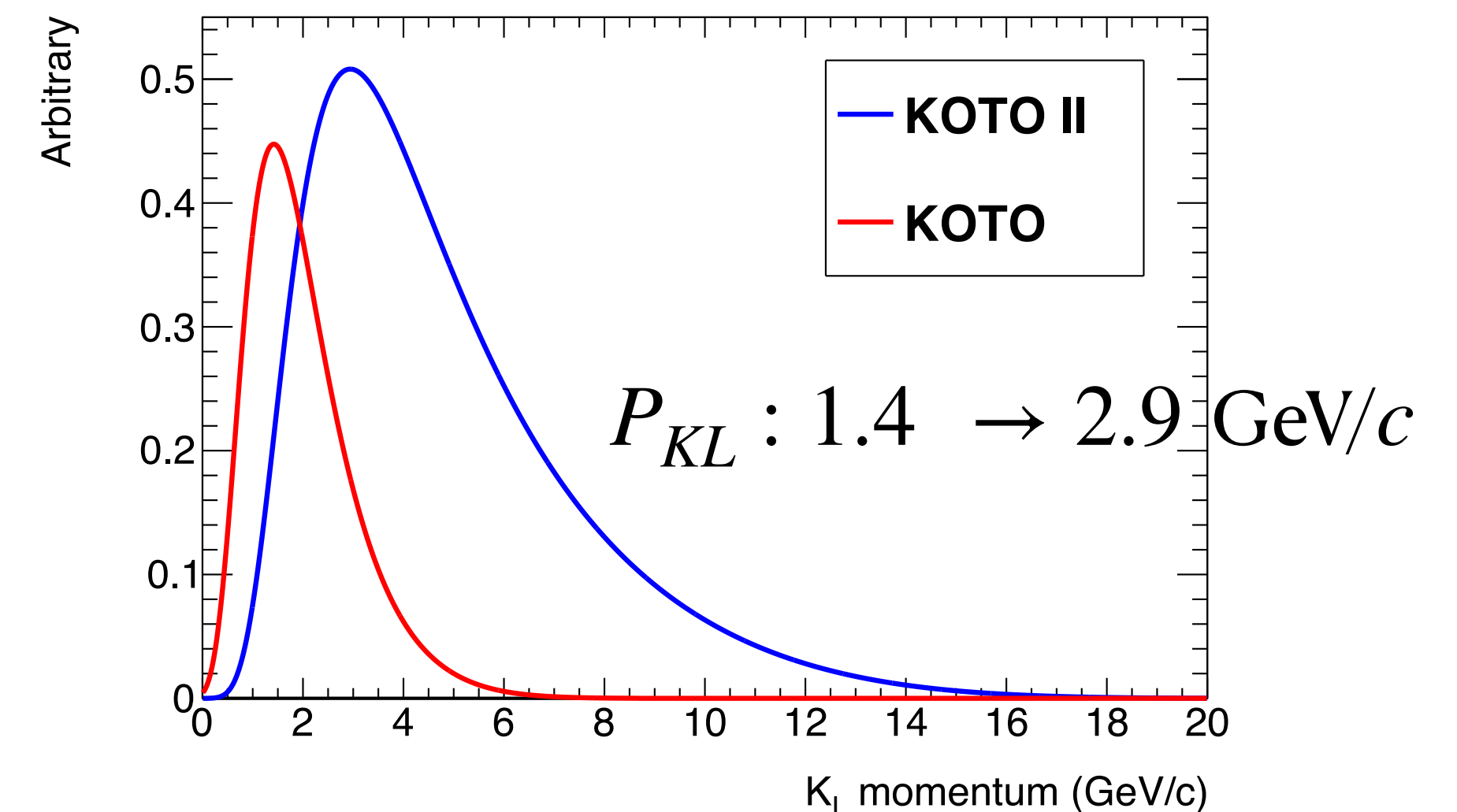
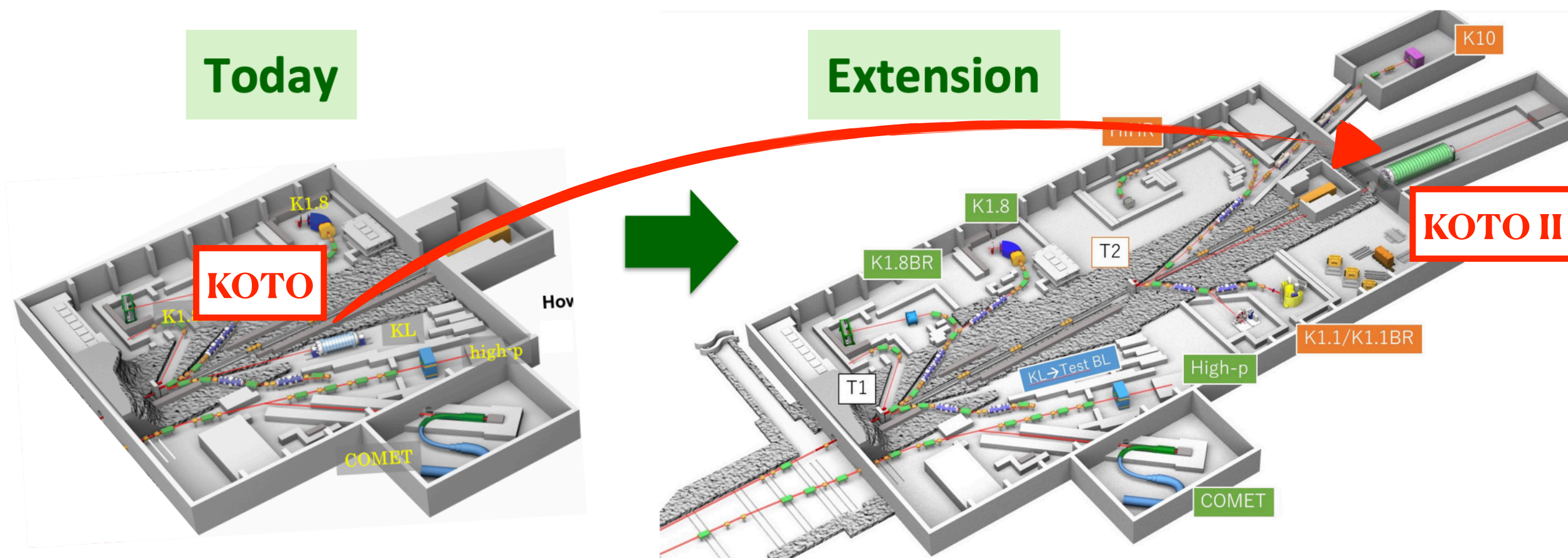
- (within 5 years of data collection)



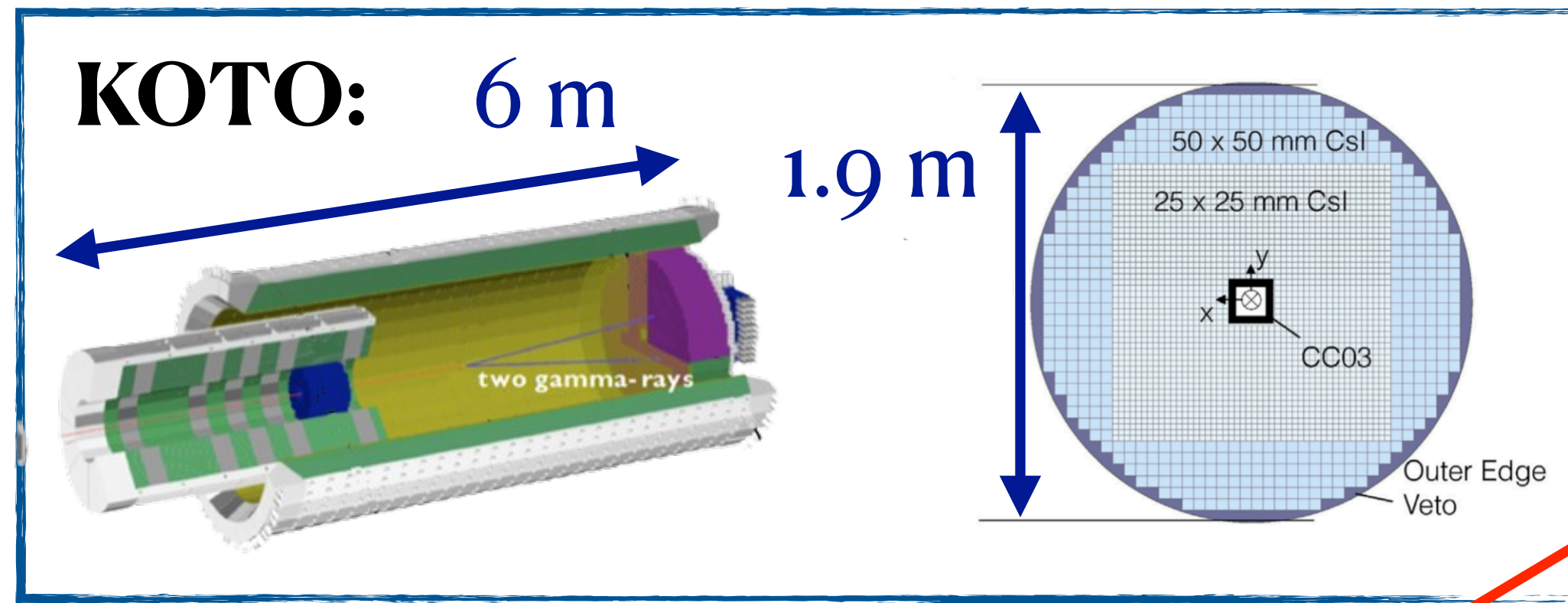
New Beamline for KOTO II



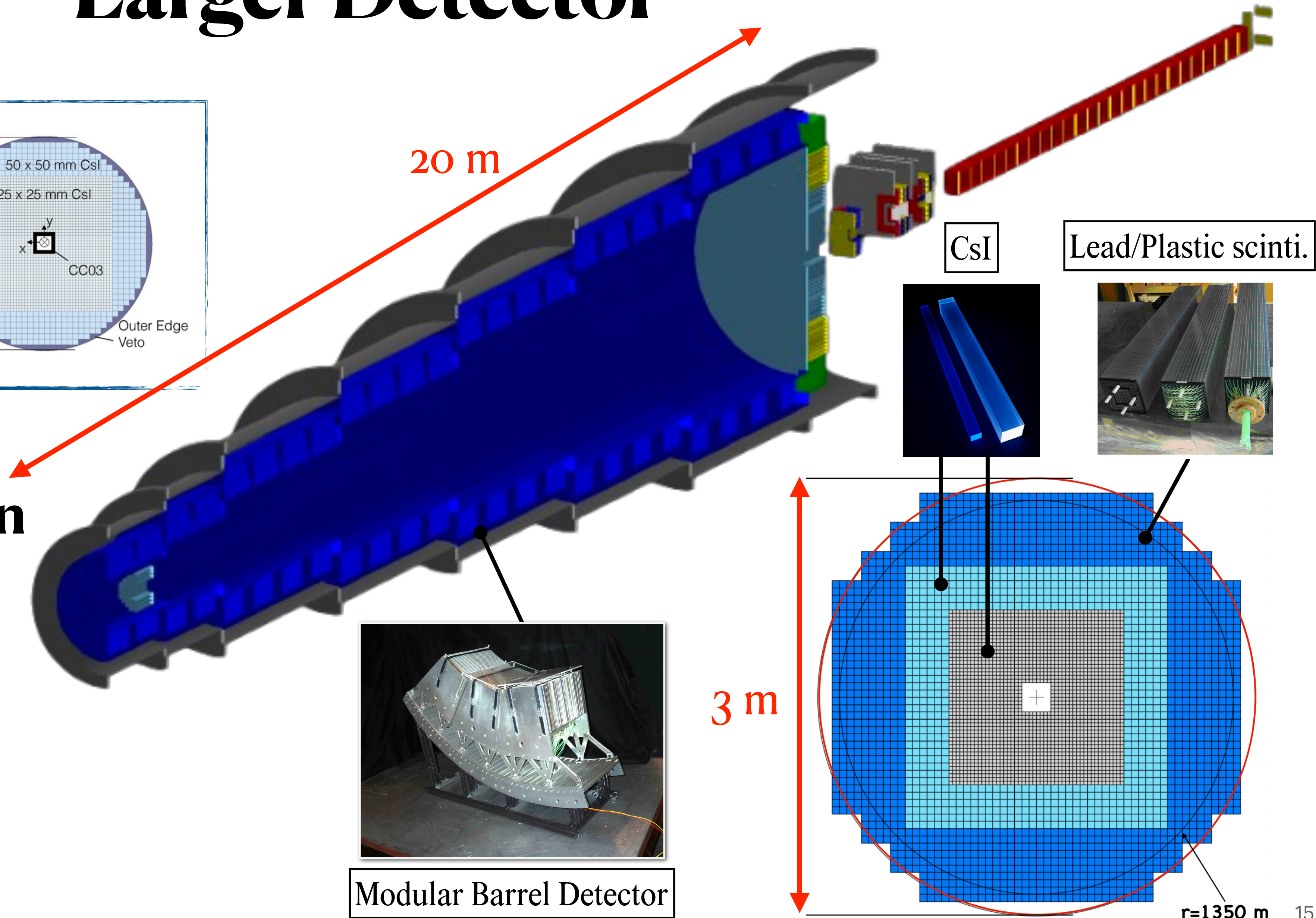
- Extraction angle from 16° to 5° :
- $5 \times K_L^0$ production on target
- $2 \times K_L^0$ momentum
- Peak $P_{KL} : 1.4 \rightarrow 2.9 \text{ GeV}/c$
- Better detection efficiency



Larger Detector



- Longer decay region
 - 2 m $\rightarrow$ 12 m
- Larger calorimeter
 - $\varnothing$ 2 m $\rightarrow$ 3m



$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ Signal Yield

- Overall **$\times 58$** improvement in the signal yield.
- In **five years** of data-collection with **100 kW beam power**
 - Single Event Sensitivity: 8.5×10^{-13}
 - **$35 K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ events**, assuming $\mathcal{B}^{SM}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$
 - With 40 background events.

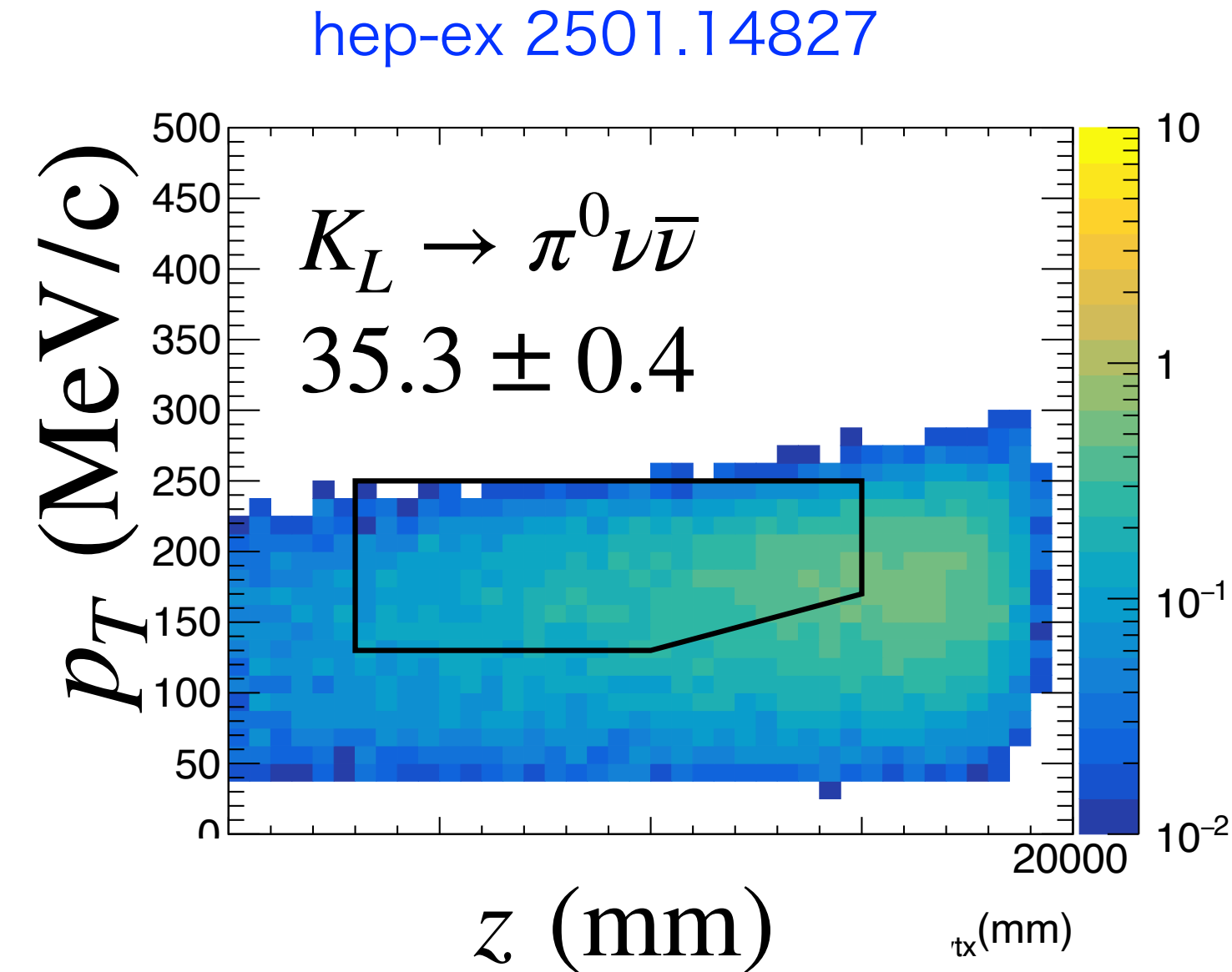


Table 6: Comparison of the signal acceptance with KOTO II and KOTO

- **5.6σ** observation
- $\Delta \mathcal{B} / \mathcal{B} = 25 \%$

	KOTO II	KOTO	Improvement factor
Number of K_L /POT	$\times 2.6$		2.6
P_{decay}	9.9%	3.3%	3.0
A_{geom}	24%	26%	0.9
A_{cut}	26%	11%	2.4
1-accidental loss	61%	29%	2.1
1-backsplash loss	91%	56%	1.6
Total			58

Project Progress of KOTO II

- The KOTO II proposal has been submitted: [hep-ex 2501.14827](#)
- Scientific approval from J-PARC was granted (Stage-1 status).
- Aims to obtain Stage-2 approval for operation starting from 2030s.
- A draft schedule after the completion of the beamline:

Year	Main object
1	Beam line survey
2	Construction of the rest of the detector
3-6	Phase I: Physics run for mainly $K_L \rightarrow \pi^0 \nu \bar{\nu}$
7	Single event sensitivity will reach 8.5×10^{-13} for the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ search
8	Detector upgrade
9-12	Phase II: Physics run mainly for $K_L \rightarrow \pi^0 \ell^+ \ell^-$ with an optimized setup
13	End of Phase II

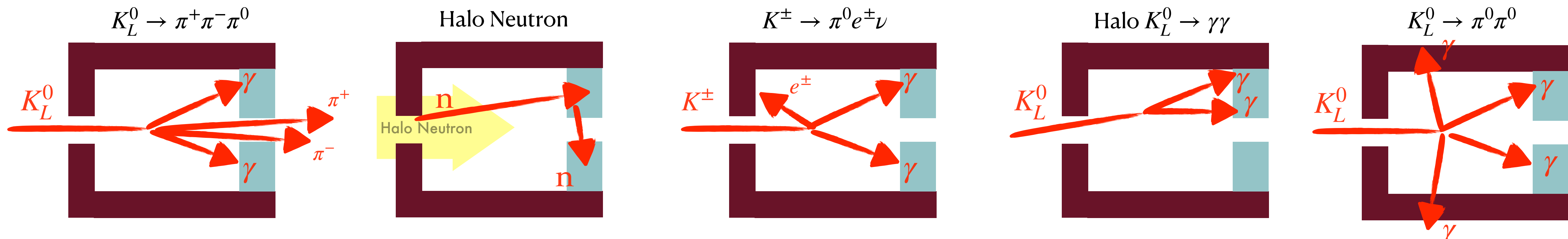
- We currently have **82** members from **11** countries — you're **Welcome to Join Us!**

Summary

- KOTO has updated the upper limit for $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ at 2.2×10^{-9} (2021 data).
 - KOTO will continue data collection and improve the sensitivity by an order of magnitude in 3-4 years.
- KOTO II is a next-generation kaon experiment starting in the 2030s at J-PARC.
 - Aims to measure $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ with the S.E.S. below 10^{-12} .
 - Welcome to JOIN us if you're interested.

Backup

New Elements in the 2021 Analysis



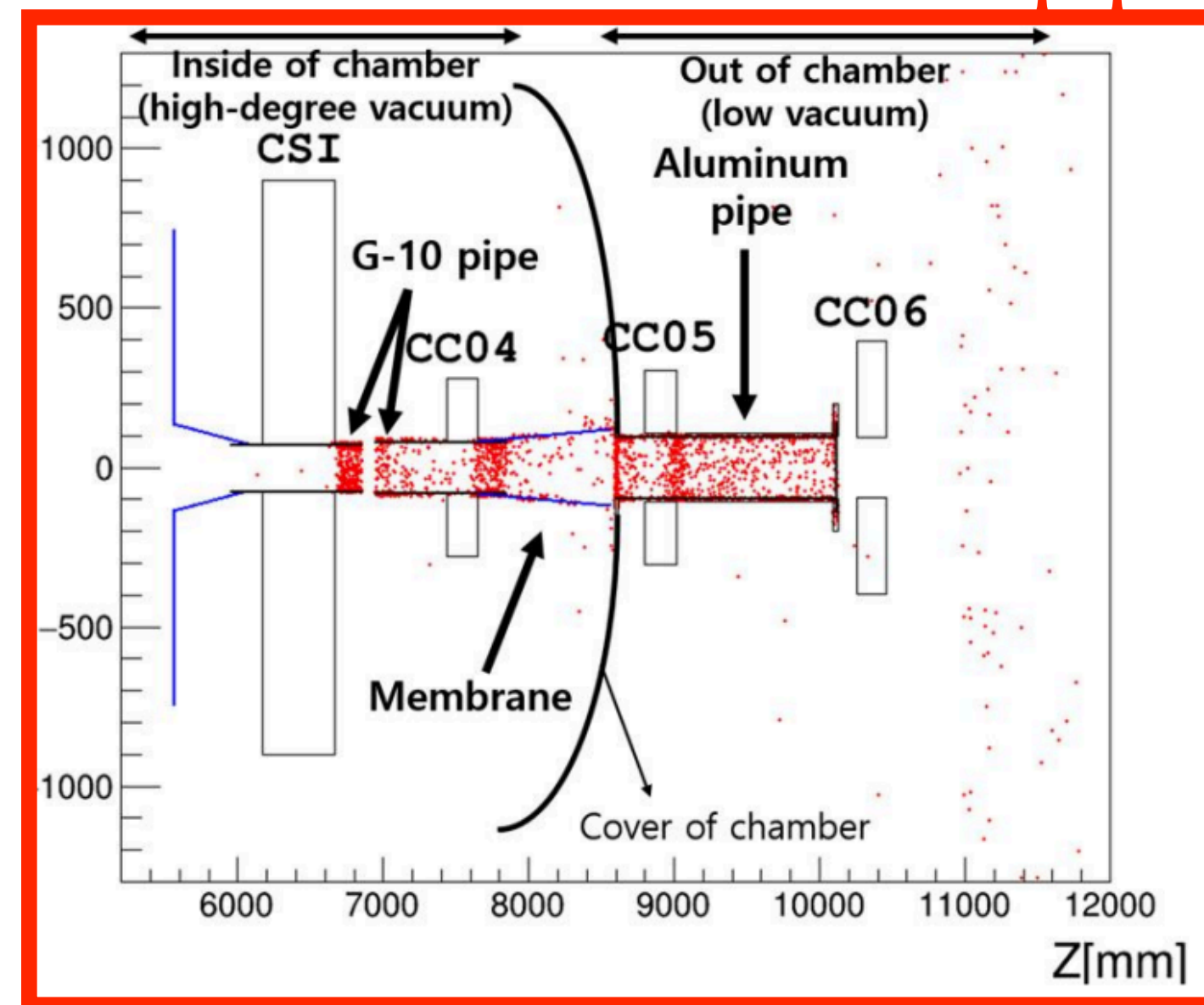
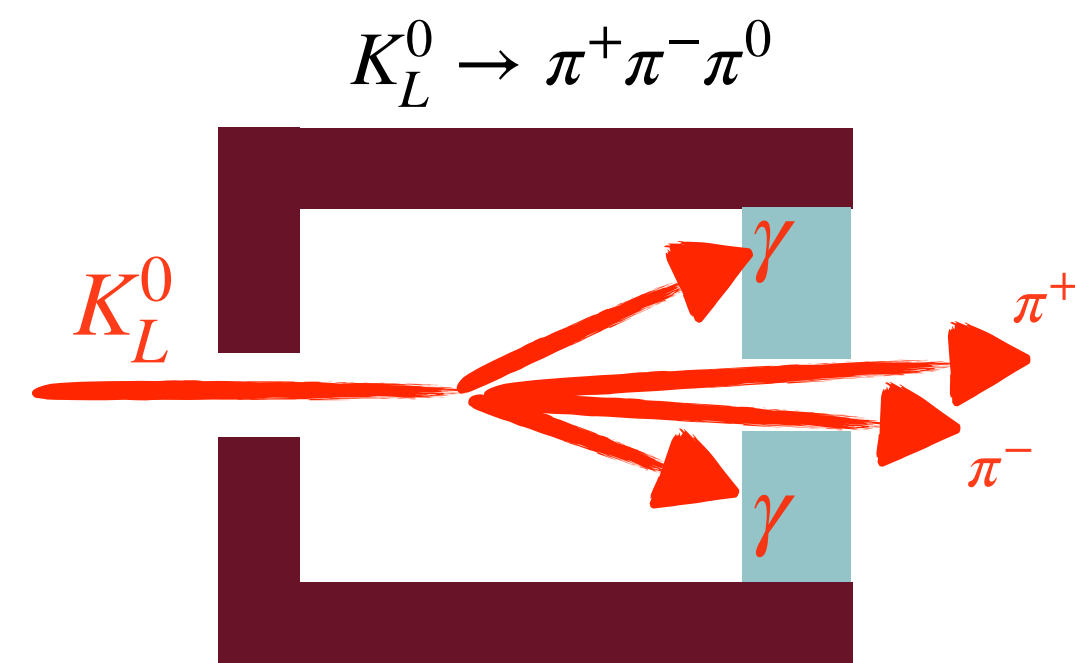
	# Protons On Target ($\times 10^{18}$)	Downstream Charged Veto	Calorimeter Upgrade	Upstream Charged Veto	New Cut for Halo $K_L \rightarrow \gamma\gamma$	New Cut for $K_L \rightarrow \pi^0 \pi^0$
2015	22					
2016-2018	30					
2019	18	✓	✓		✓	✓
2020	7	✓	✓	Prototype	✓	✓
2021	32	✓	✓	✓	✓	✓

Today's focus

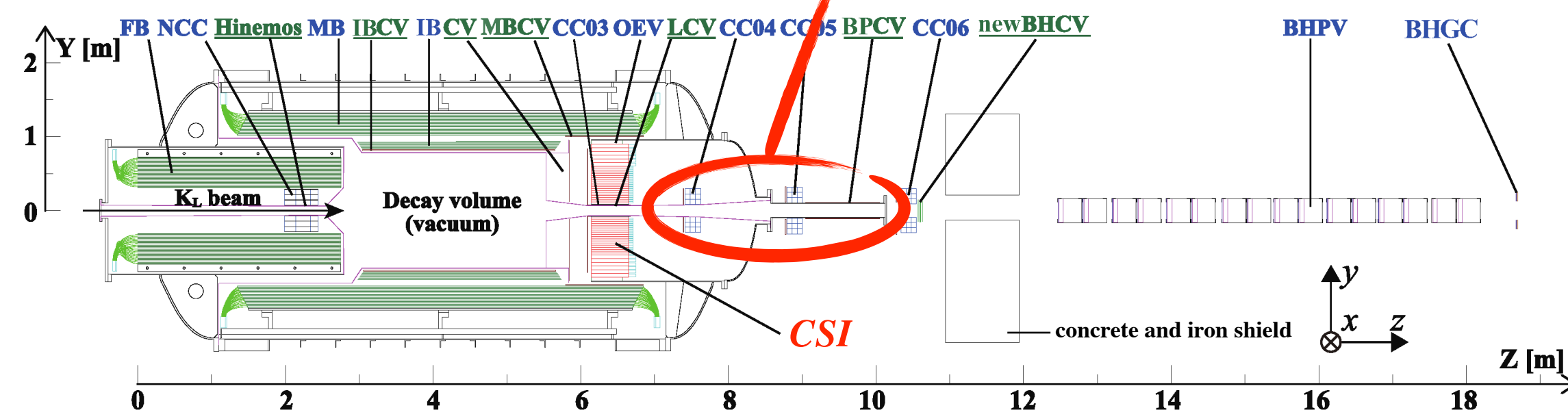
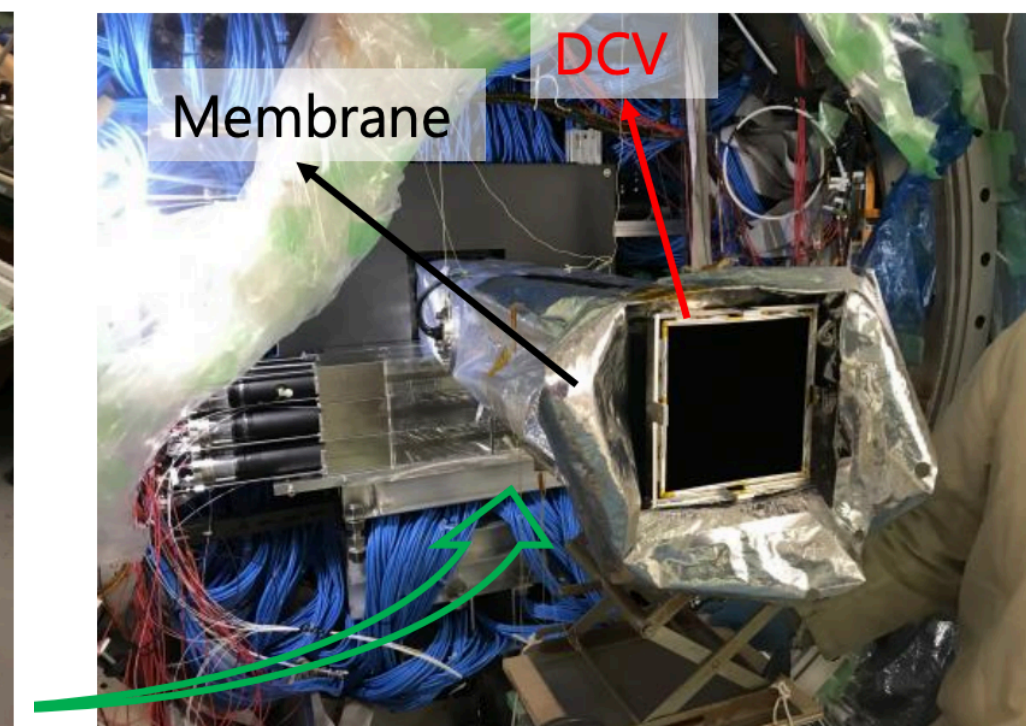
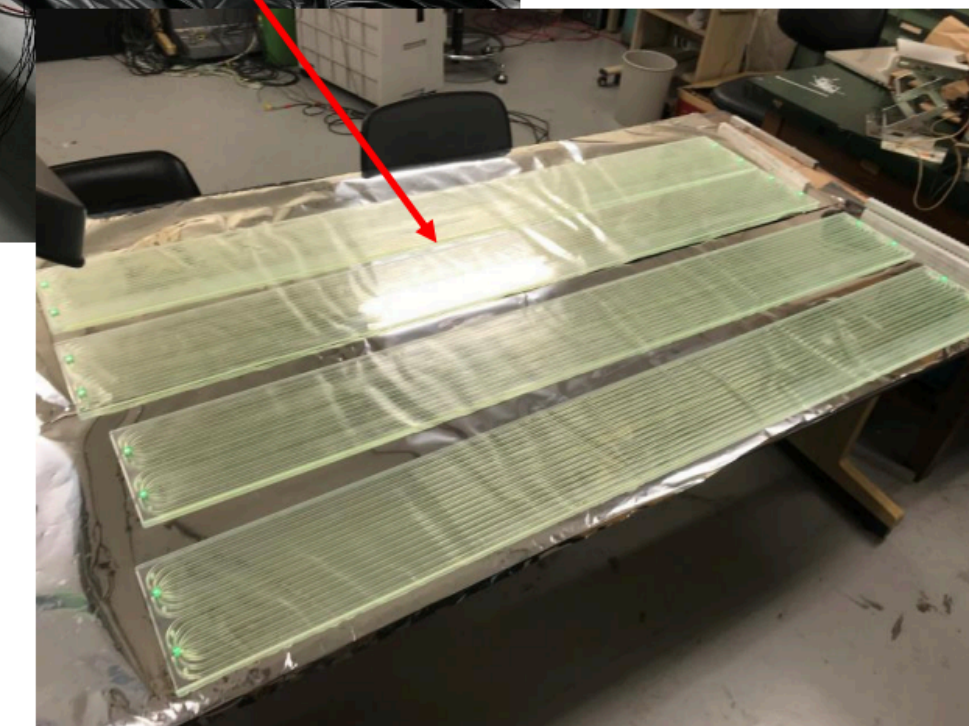
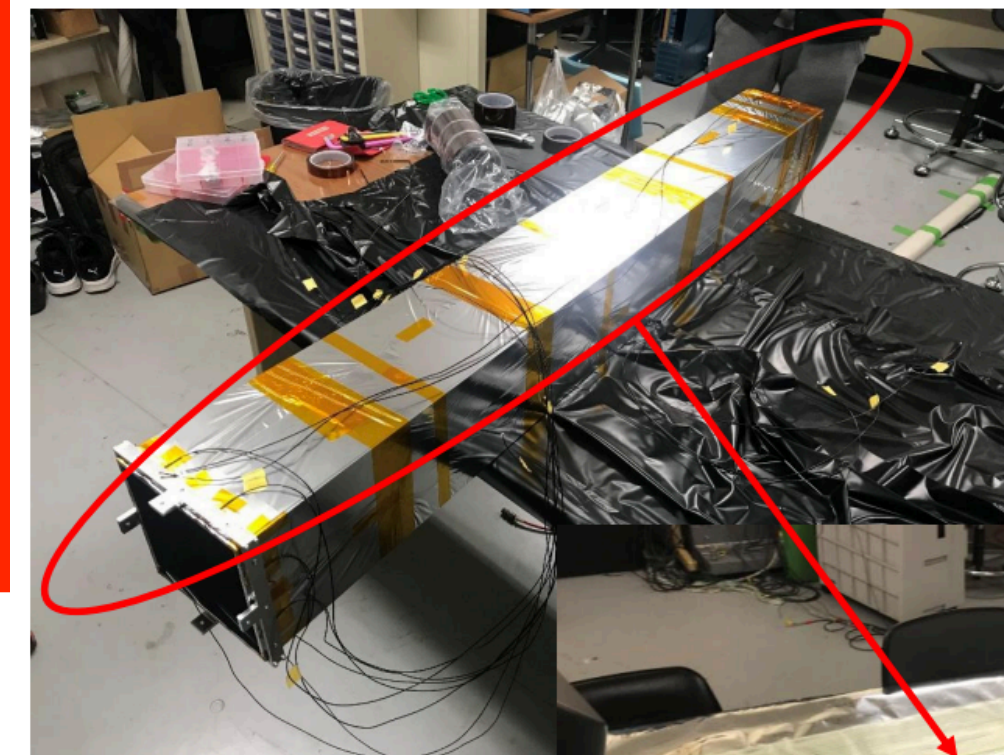
$K_L \rightarrow \pi^0 \pi^+ \pi^-$ Background

Downstream Charged Veto (since 2019)

Hit position of $\pi^\pm$
in the downstream beam pipe

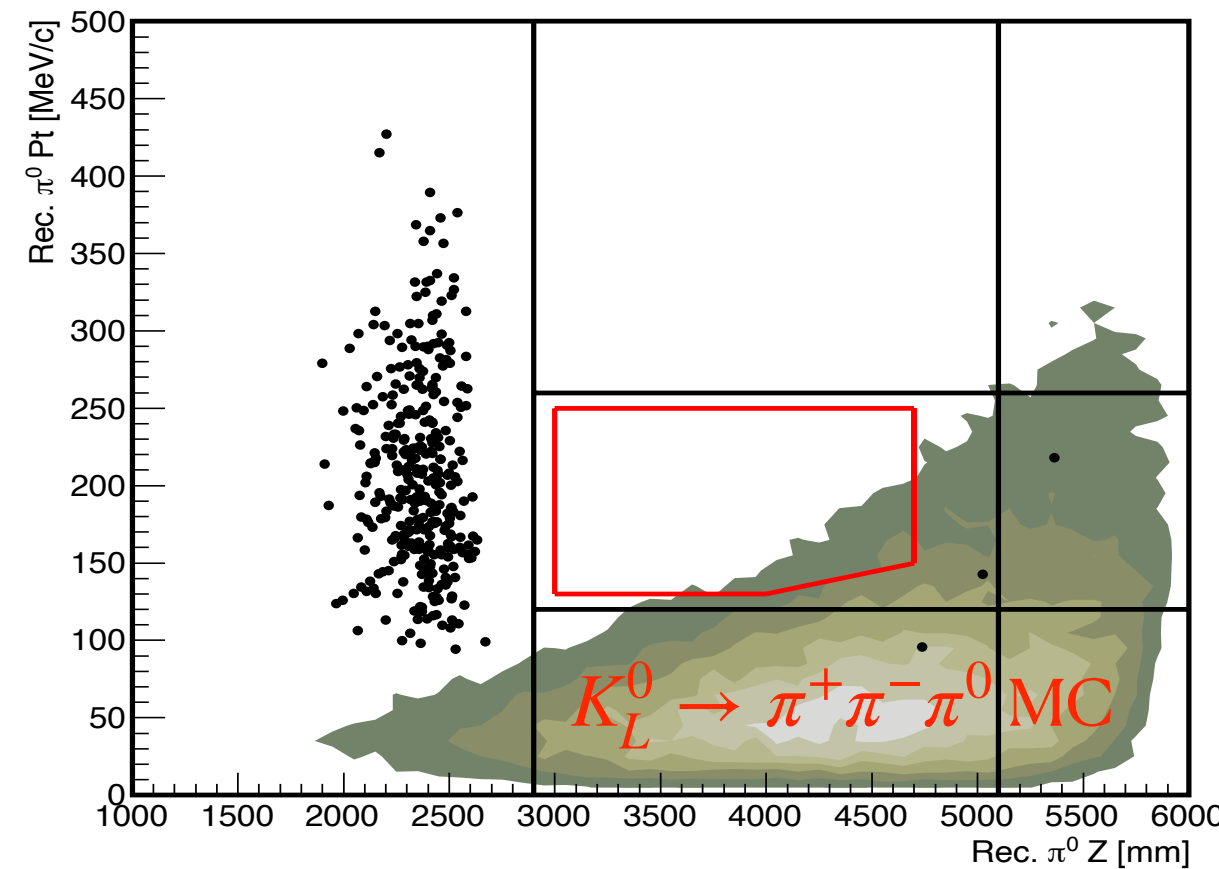


New Downstream Charged Veto (DCV) inside the vacuum beam pipe to provide a better detection coverage.

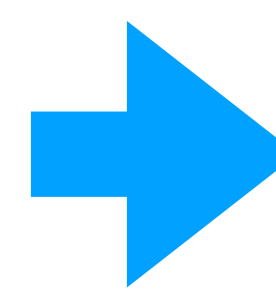
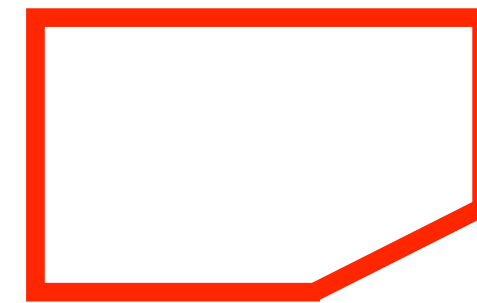


$K_L \rightarrow \pi^0 \pi^+ \pi^-$ Background

Downstream Charged Veto (since 2019)



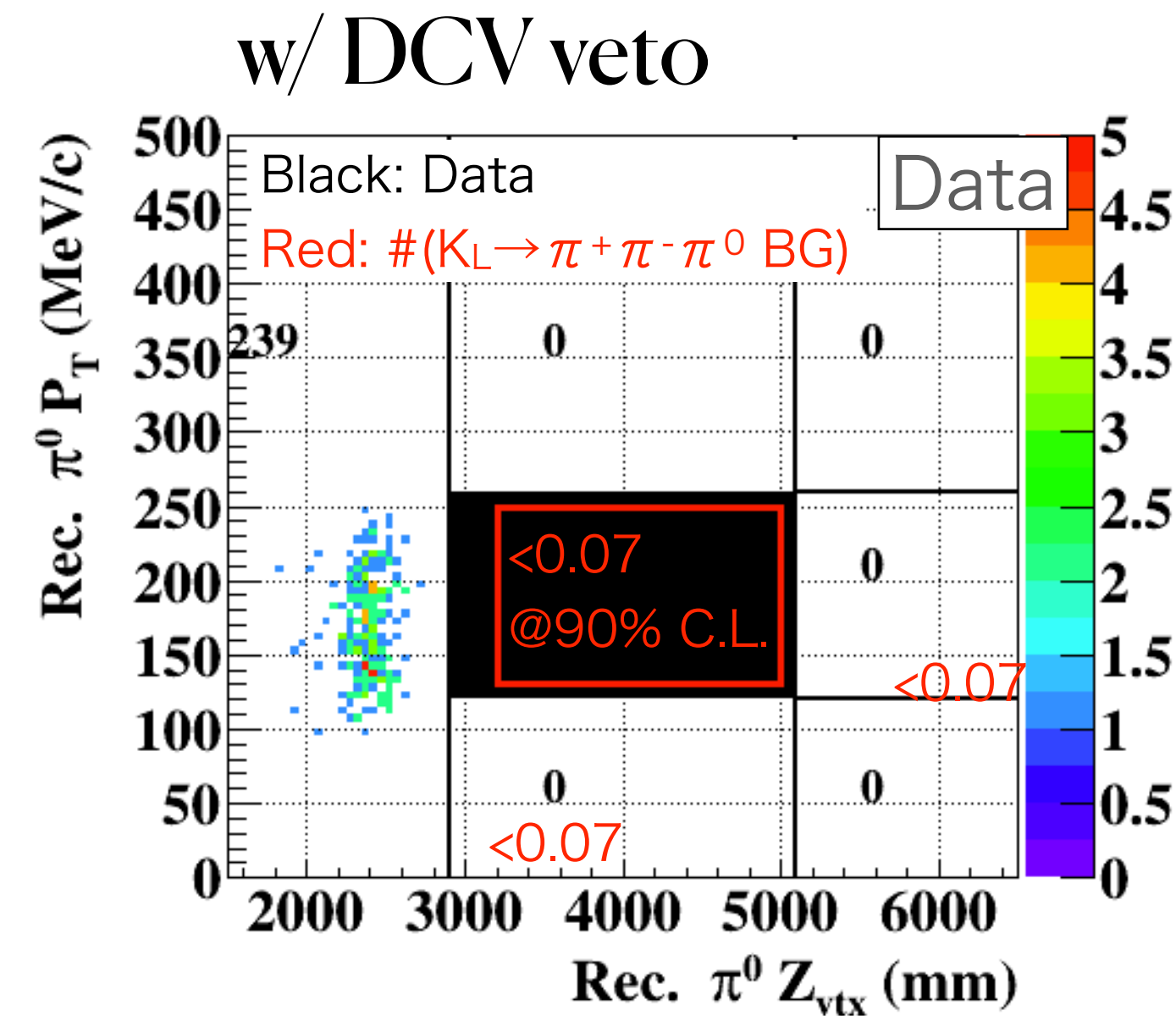
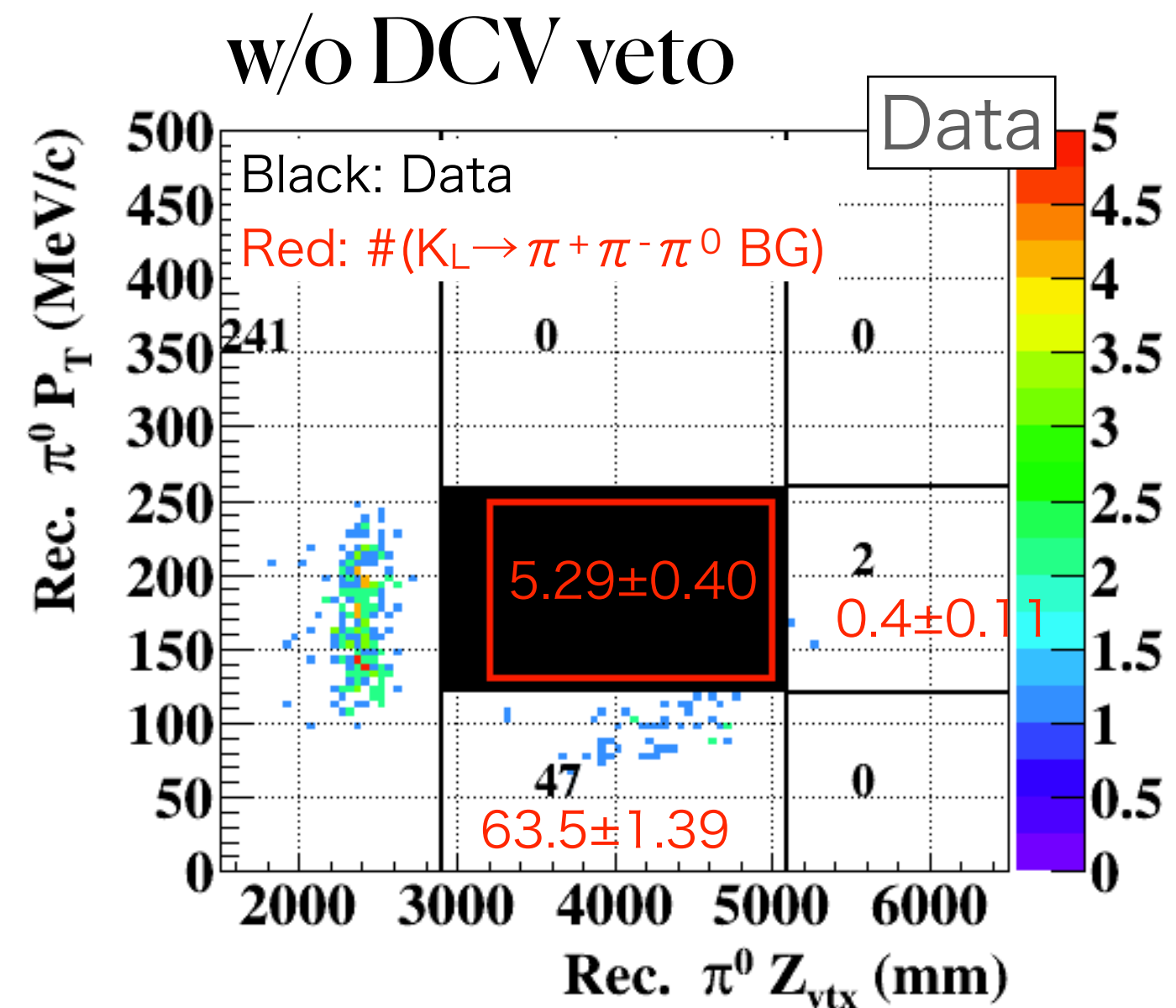
2016-2018 Signal Box



2021 Signal Box



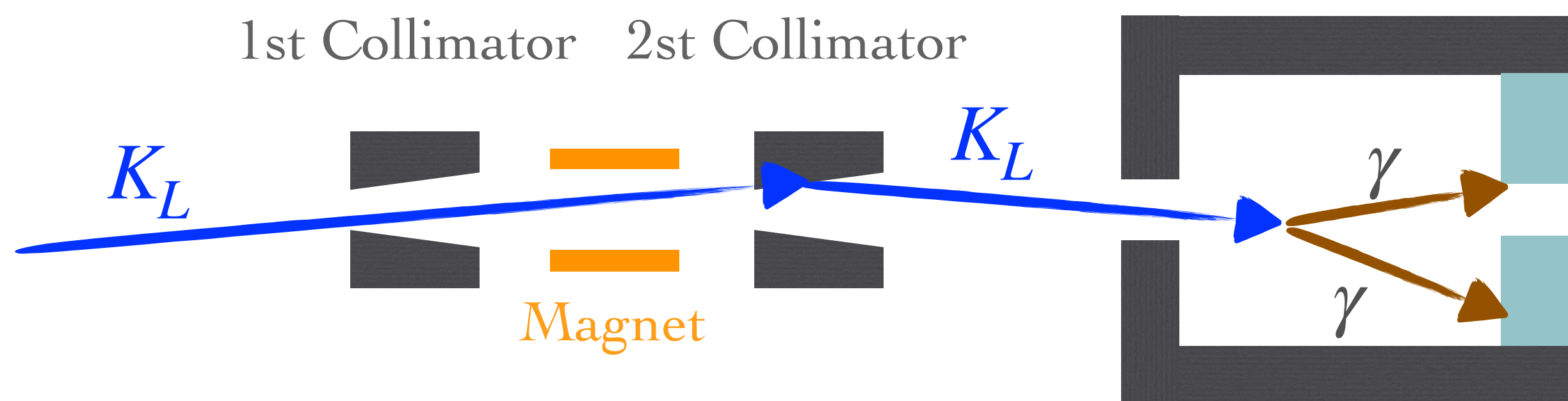
Recovered 5%
of the signal efficiency



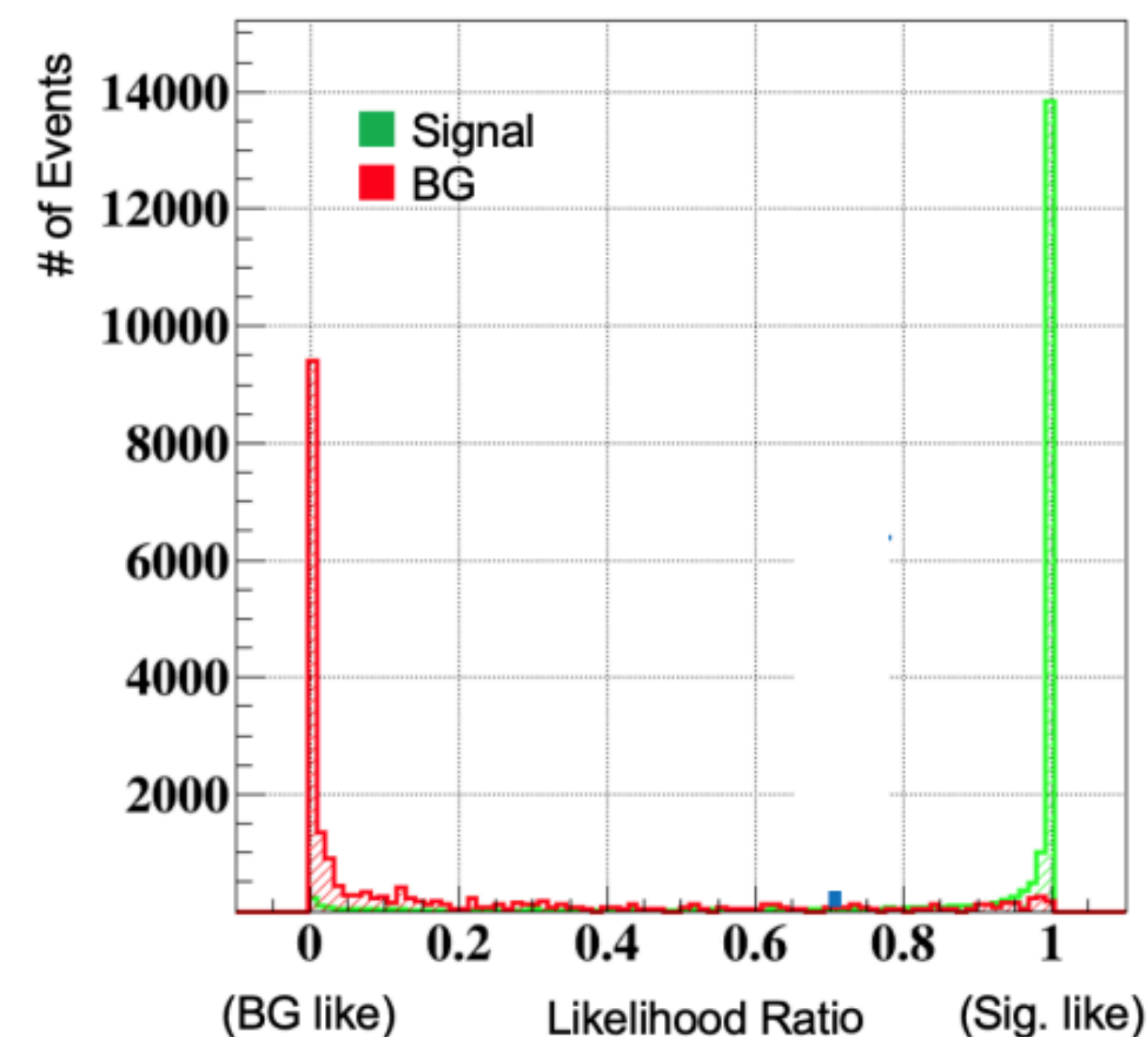
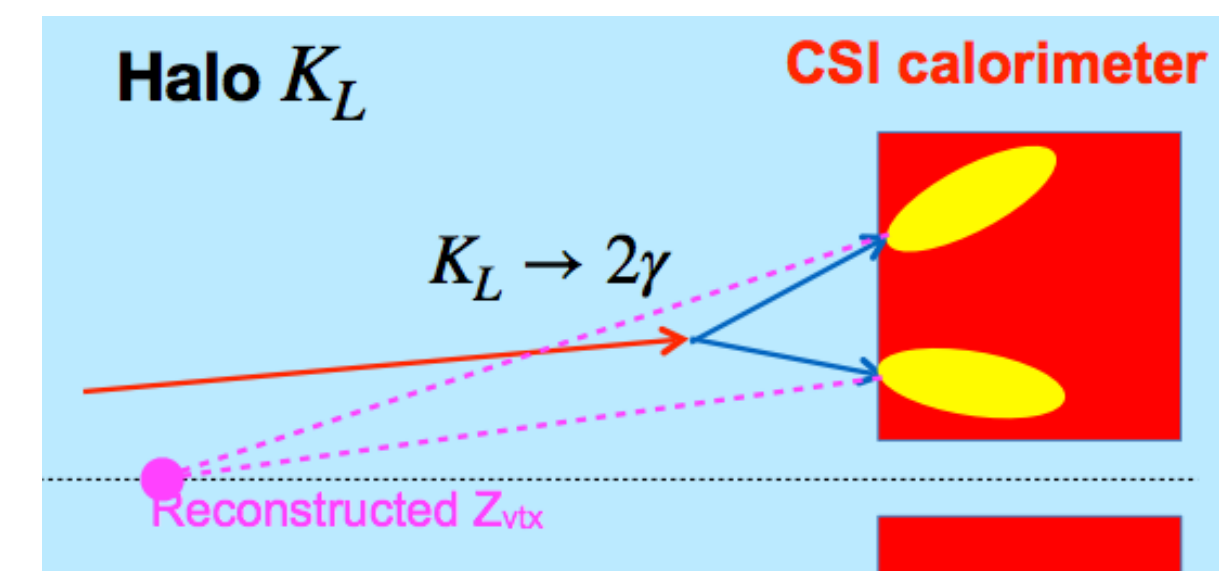
$K_L \rightarrow \pi^0 \pi^+ \pi^- \text{ BG} < 0.07$
@90% C.L.

Beam Halo K_L BG

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

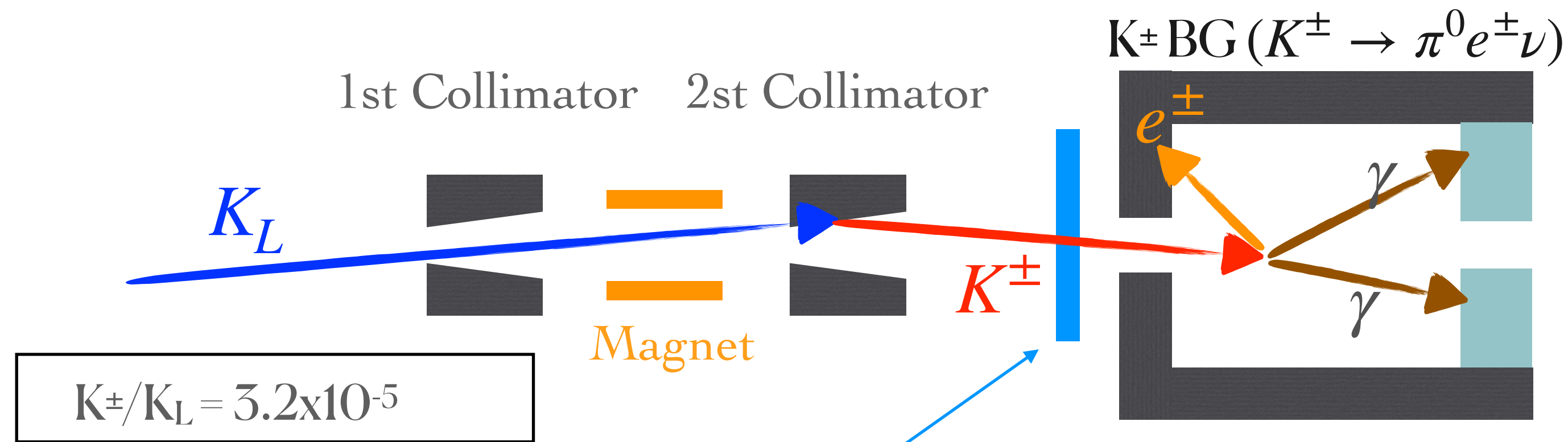


- A new cut based on the cluster shape and γ angle suppressed the halo K_L by 1/16. (Not applied to the 2016-2018 analysis)
- BG level ~ 0.4 events at $BR_{EXP}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \sim O(10^{-11})$.



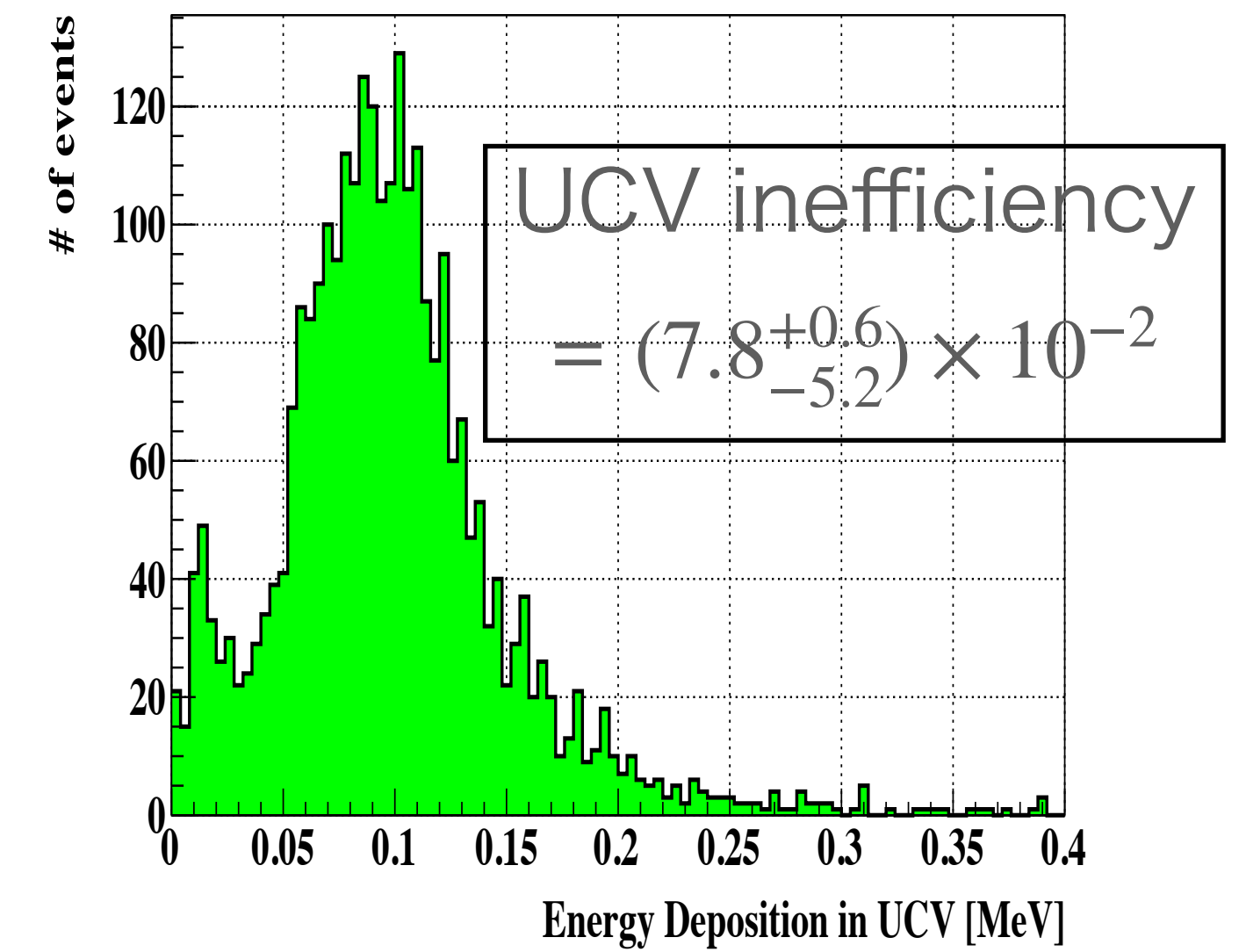
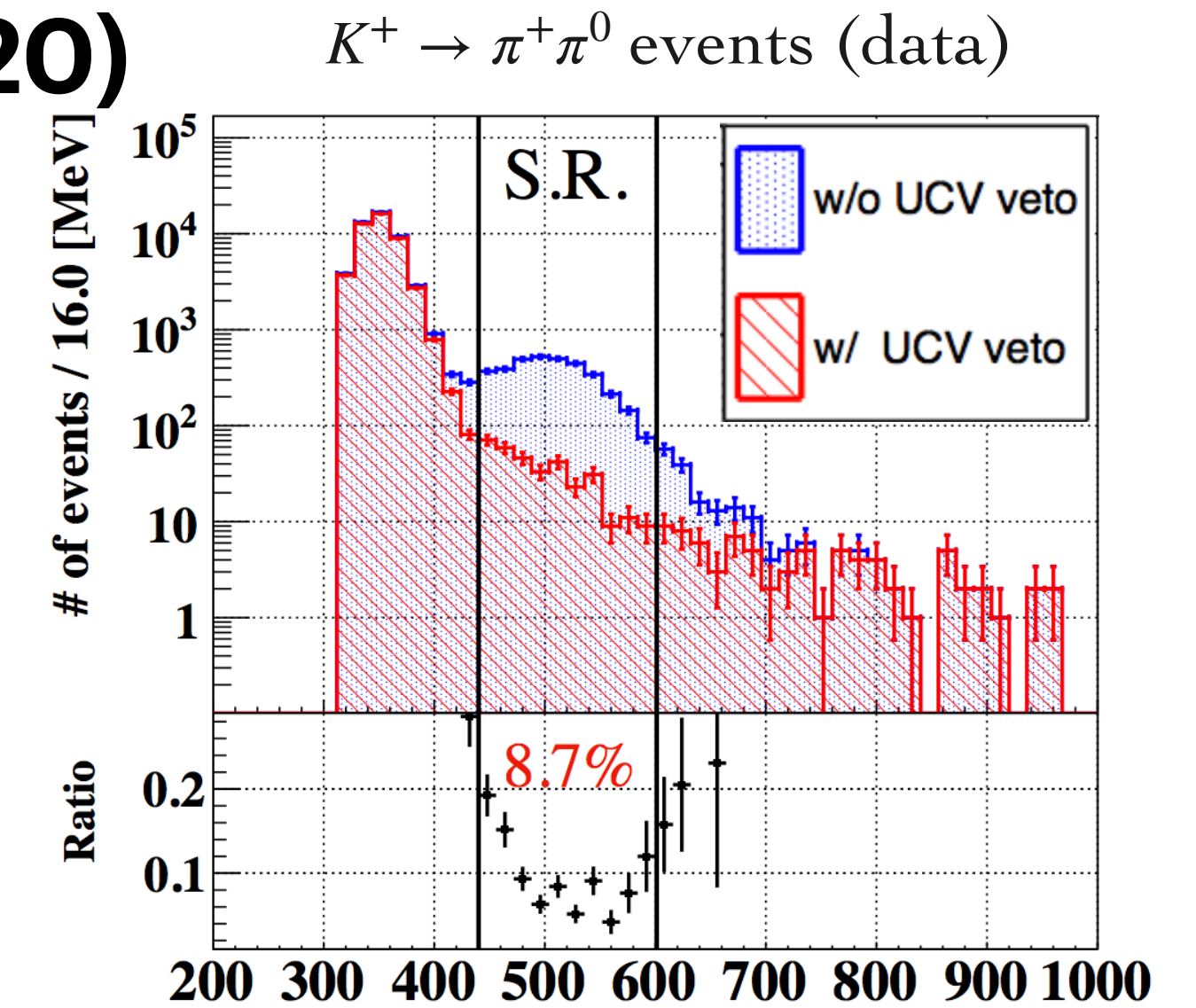
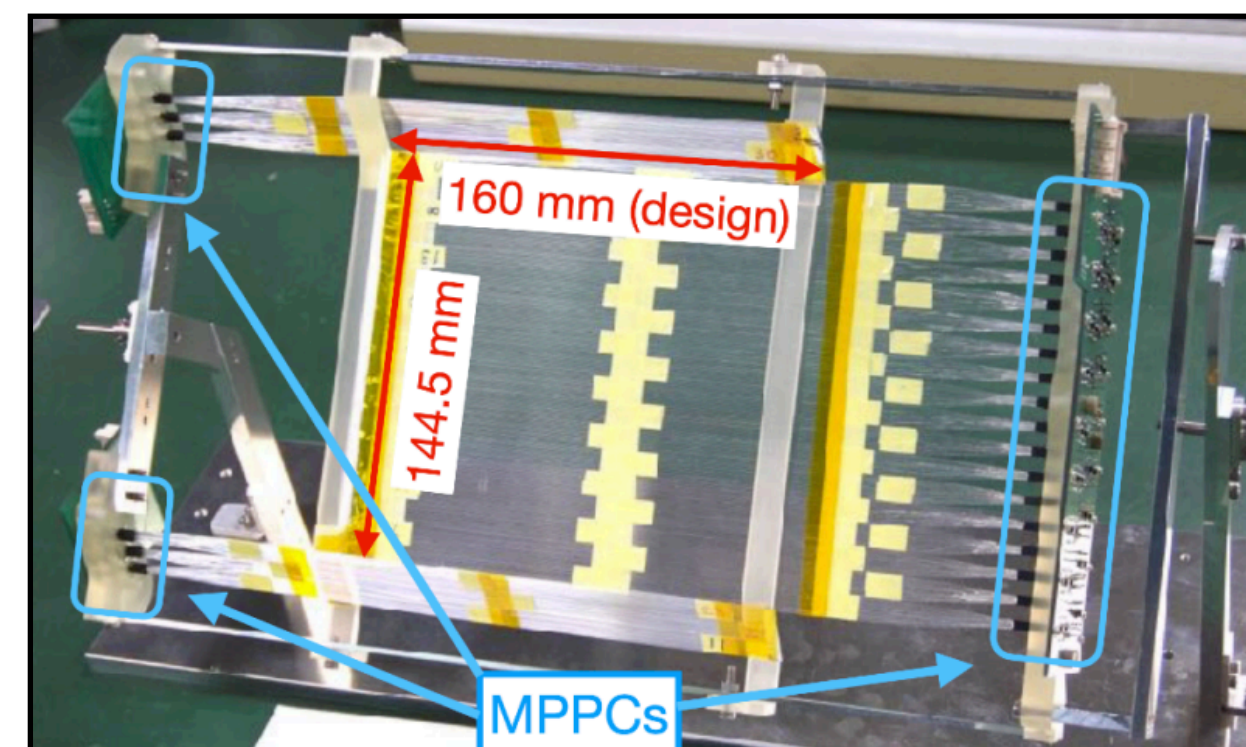
$K^\pm$ Background

Upstream Charged Veto (since 2020)



New Upstream Charged Veto (UCV)

- UCV (Scintillating fiber)
- $K^\pm \text{ BG} \times 1/13$



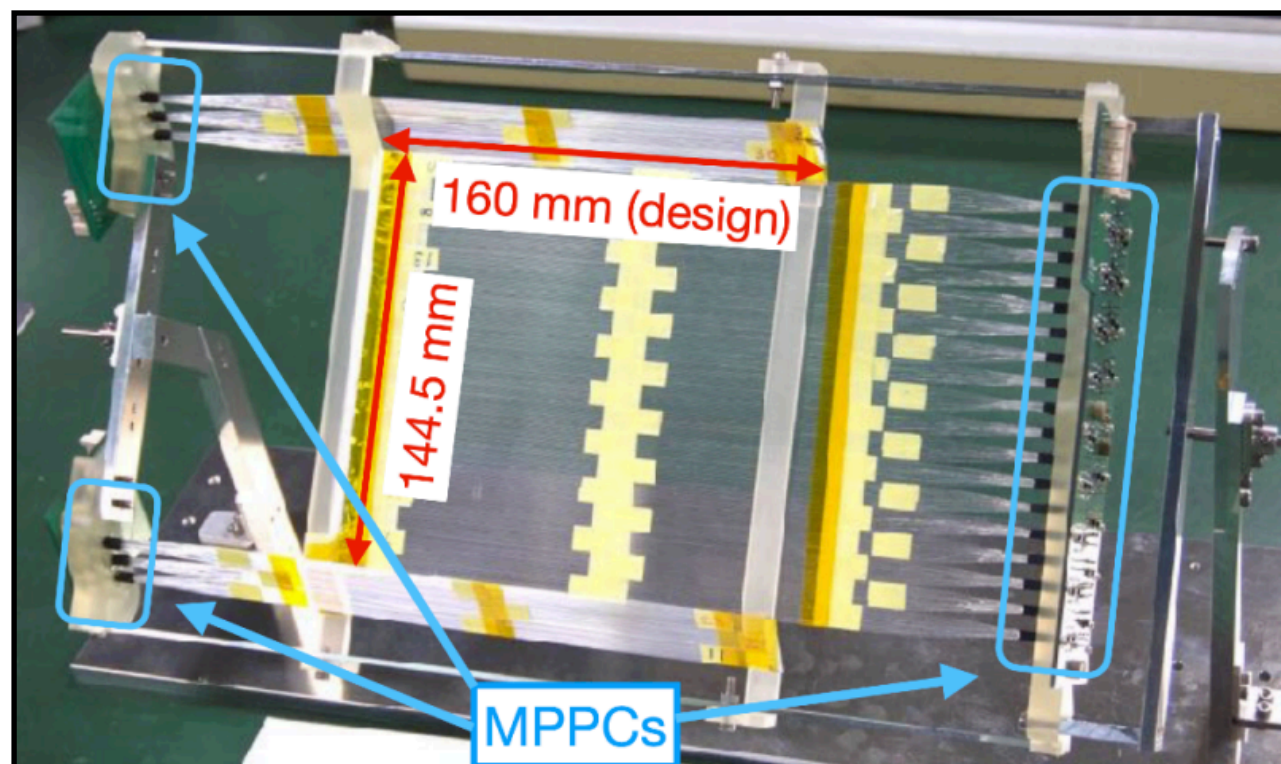
$K^\pm$ Background

Upstream Charged Veto (since 2020)

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

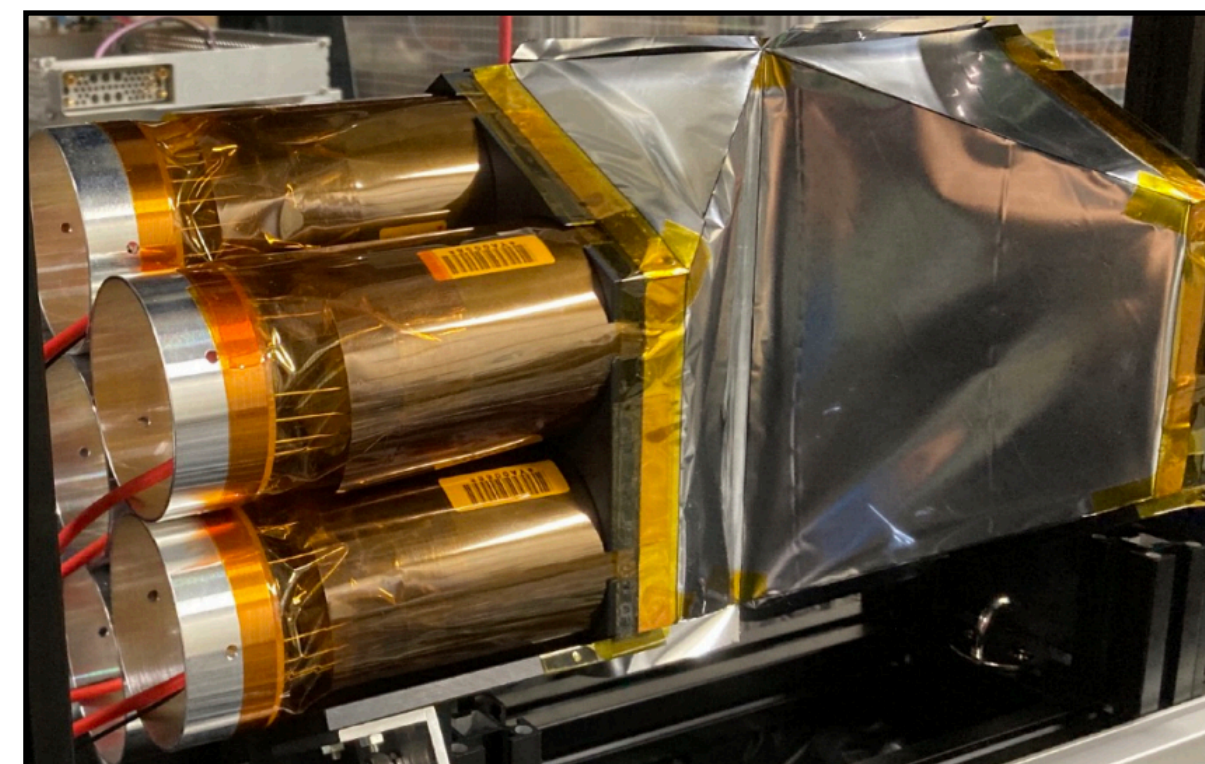
2021

- Scintillating fiber.
- $K^\pm$ BG $\times 1/13$



2023

- Scintillator film.
- $K^\pm$ BG $\times 1/100$



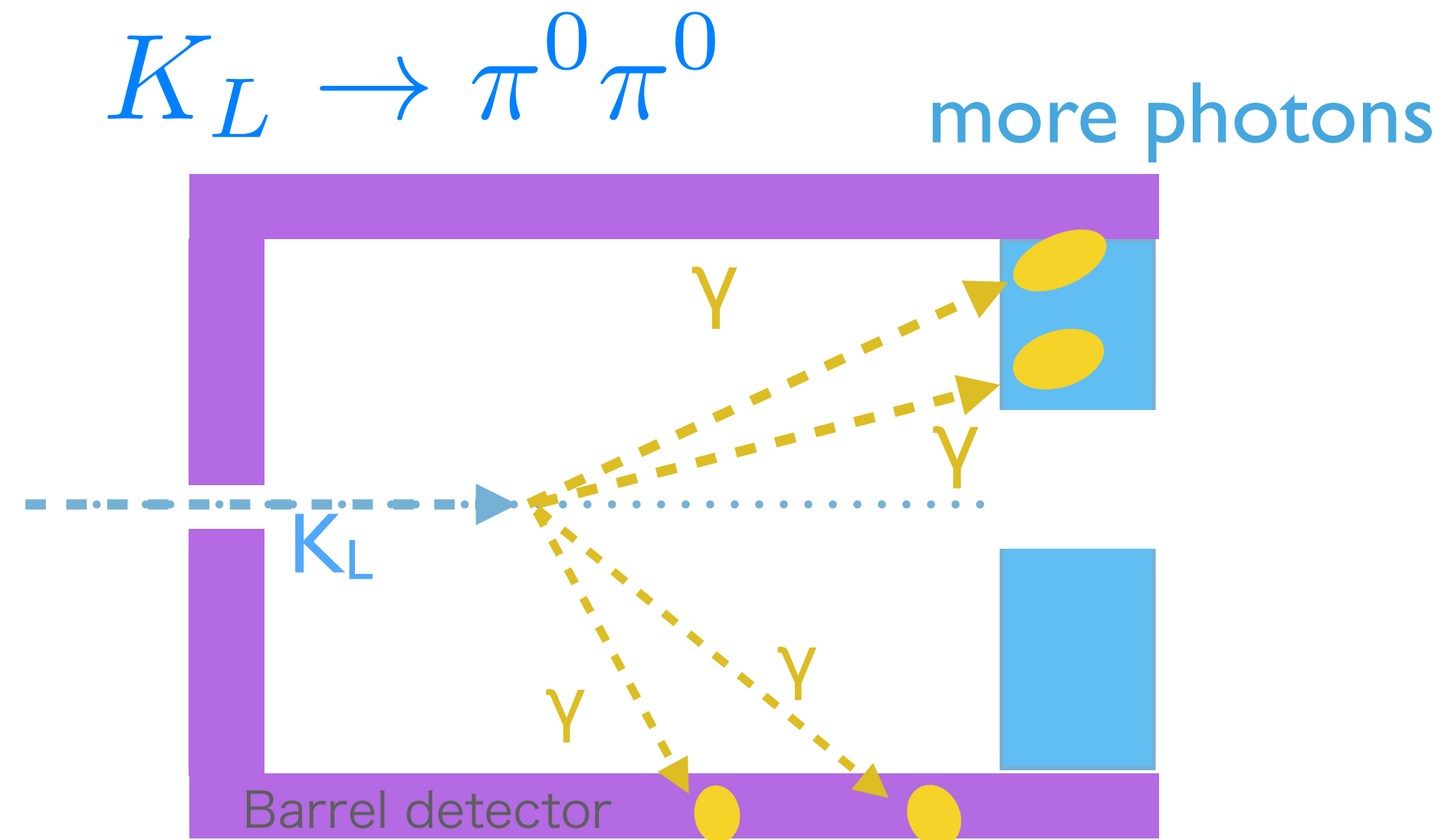
2023

- Magnet after 2_{nd} collimator.
- $K^\pm$ BG $\times 1/10$

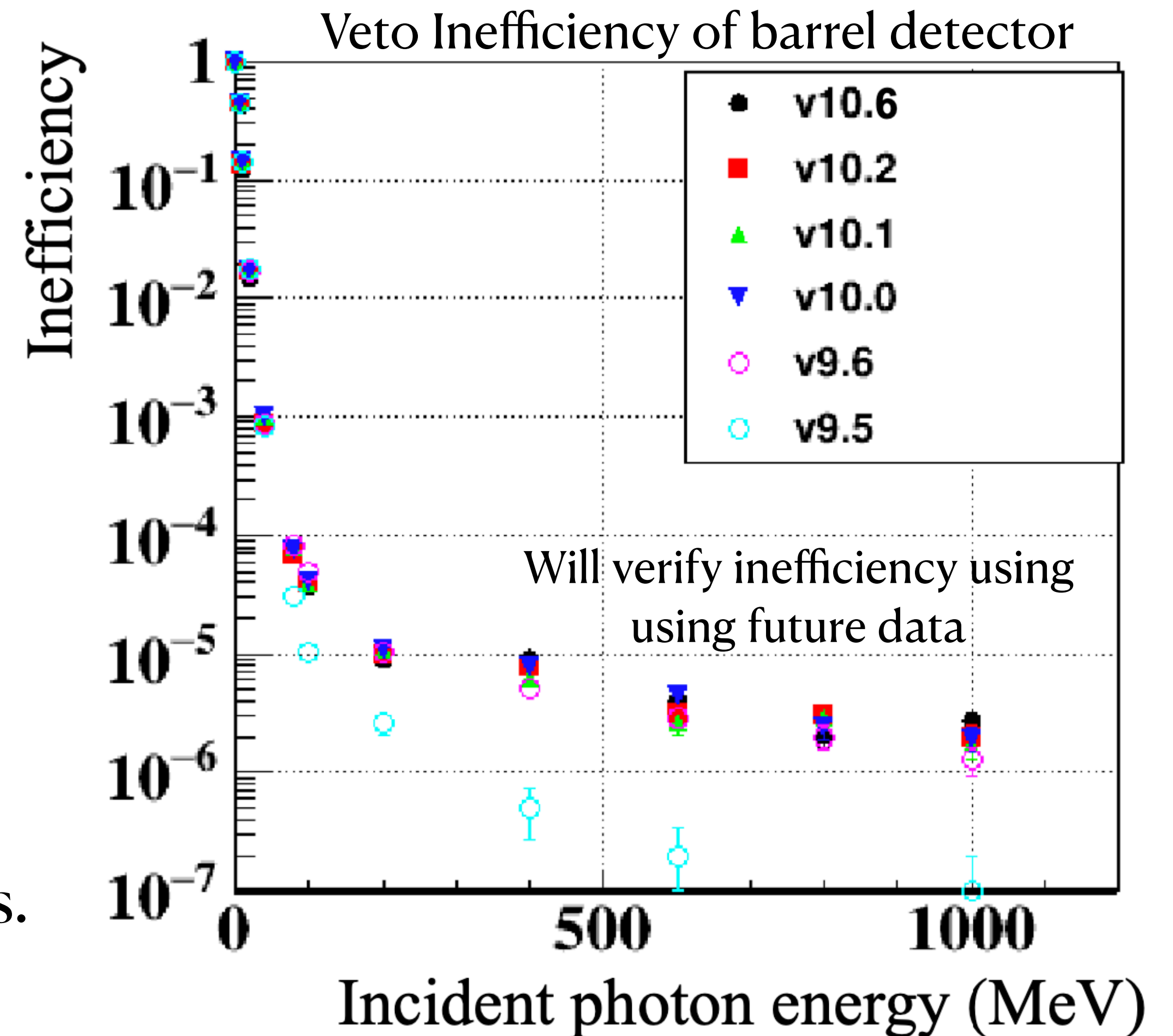


$K_L^0 \rightarrow \pi^0 \pi^0$ Background

The Ultimate Background due to Veto Inefficiency



- $K_L^0 \rightarrow \pi^0 \pi^0$ BG due to the detection inefficiency in the barrel detectors.
- But, the MC results depend on the GEANT versions.
 - Will verify the inefficiency function in the future.

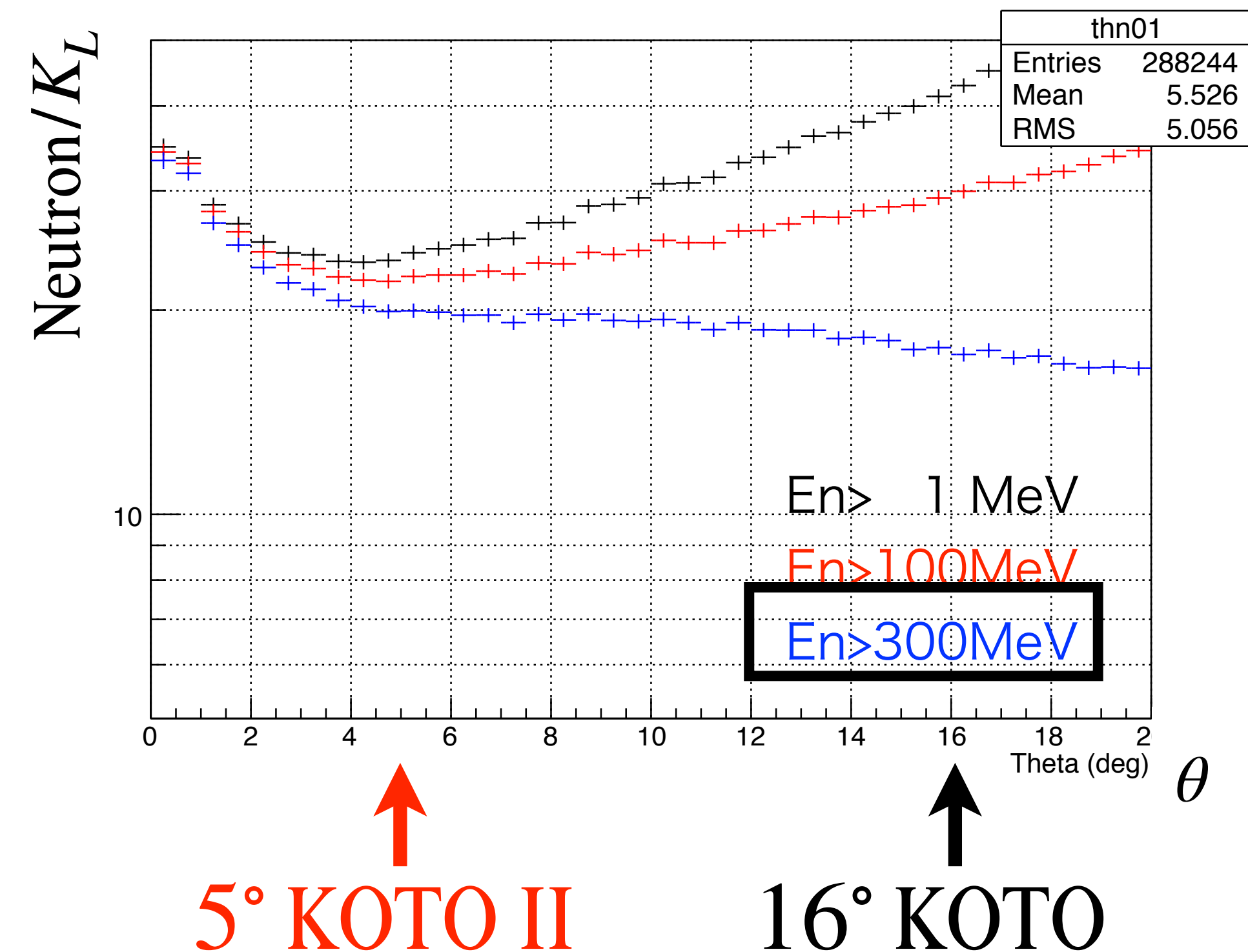
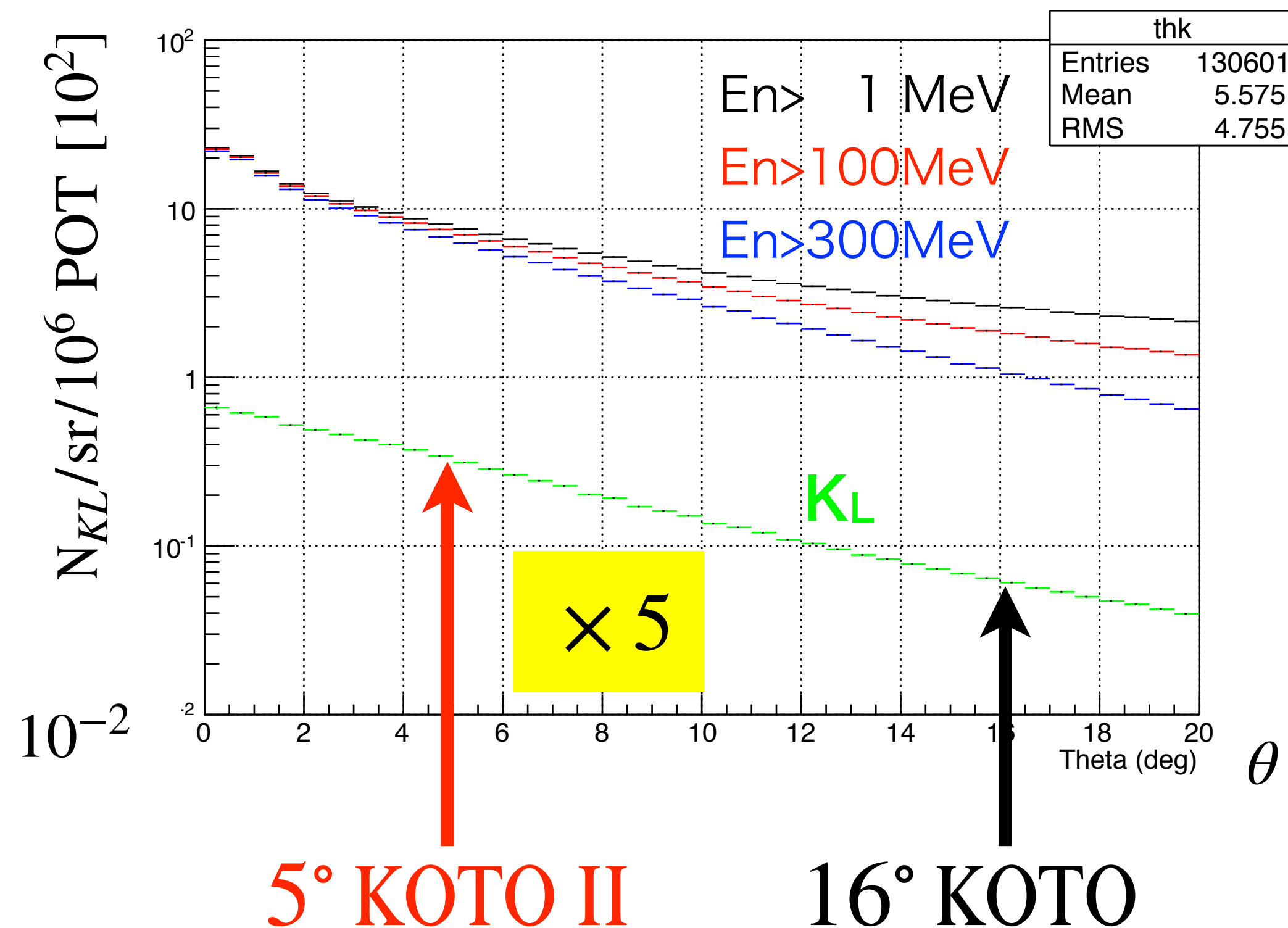


New Beamline for KOTO II

- The optimal extraction angle of 5° with
 - $5 \times K_L^0$ production on target $\rightarrow 2.6 \times K_L^0$ flux
 - A manageable increase in the Neutron/ K_L ratio.

	Production angle	Beam line	Solid angle
KOTO	16°	20 m	$7.8 \mu\text{sr}$
KOTO II	5°	43 m	$4.8 \mu\text{sr}$
Gain	$\times 5$	$\times 0.8$	$\times 0.6$

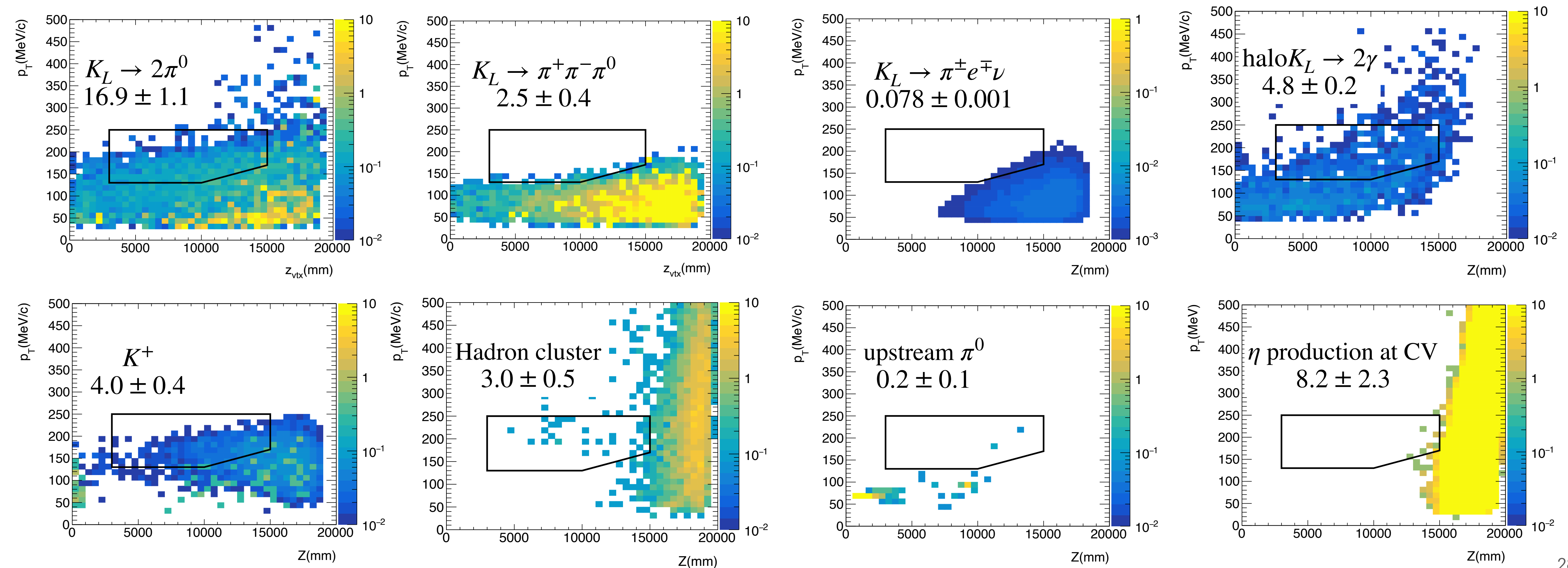
$\times \sim 2.6$
from KOTO



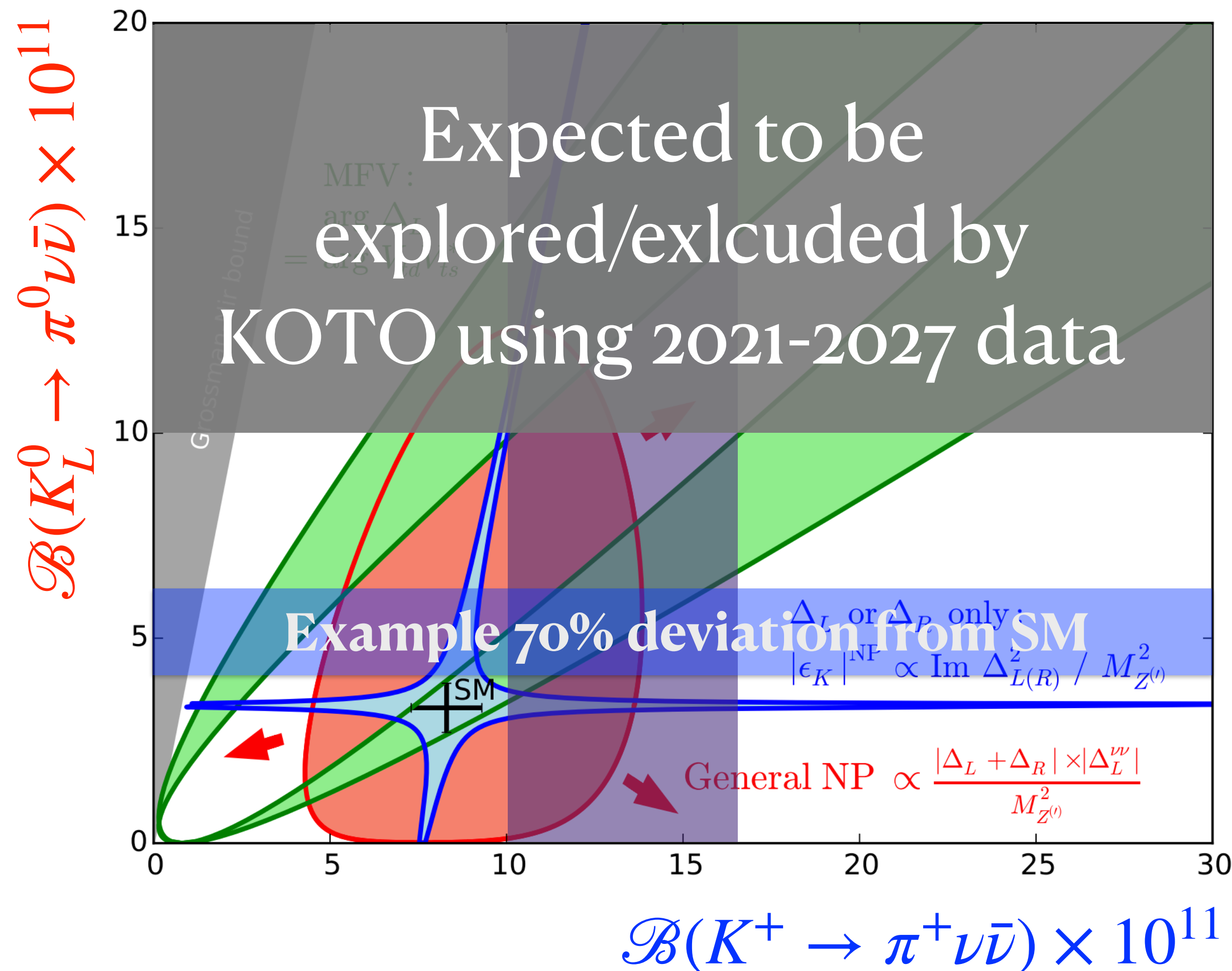
Estimated Backgrounds to $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

of signal events (SM) : 35
of background events : 40

$>5.6 \sigma$ observation
for $\mathcal{B}^{SM}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$



Physics Impacts from KOTO II



With **five years** of data-collcation:

- 35 SM signal / 40 background events
- **5.6 σ** observation
- $\Delta \mathcal{B} / \mathcal{B} = 25 \%$ for $\mathcal{B}^{\text{SM}}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$
- 90%-CL indication of NP for 40% deviation from SM
- **Potential to find NP effects!**