Status and prospect of K_L rare decay program at J-PARC, KOTO and KOTO II

Keita Ono (The University of Osaka)
on behalf of KOTO collaboration

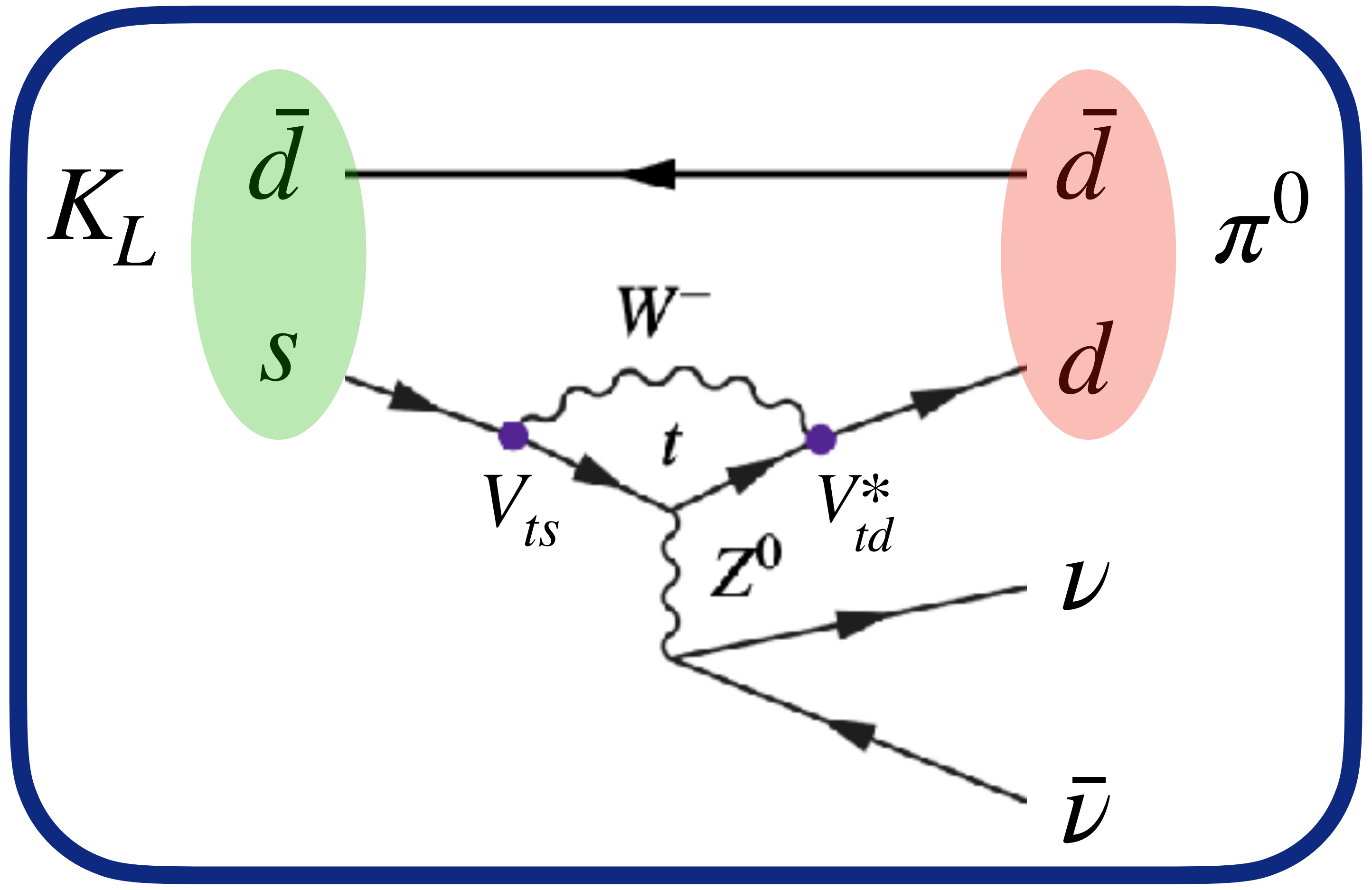
15th-22nd March, 2026
Moriond 2026

K_L rare decay : $K_L \to \pi^0 \nu \bar{\nu}$

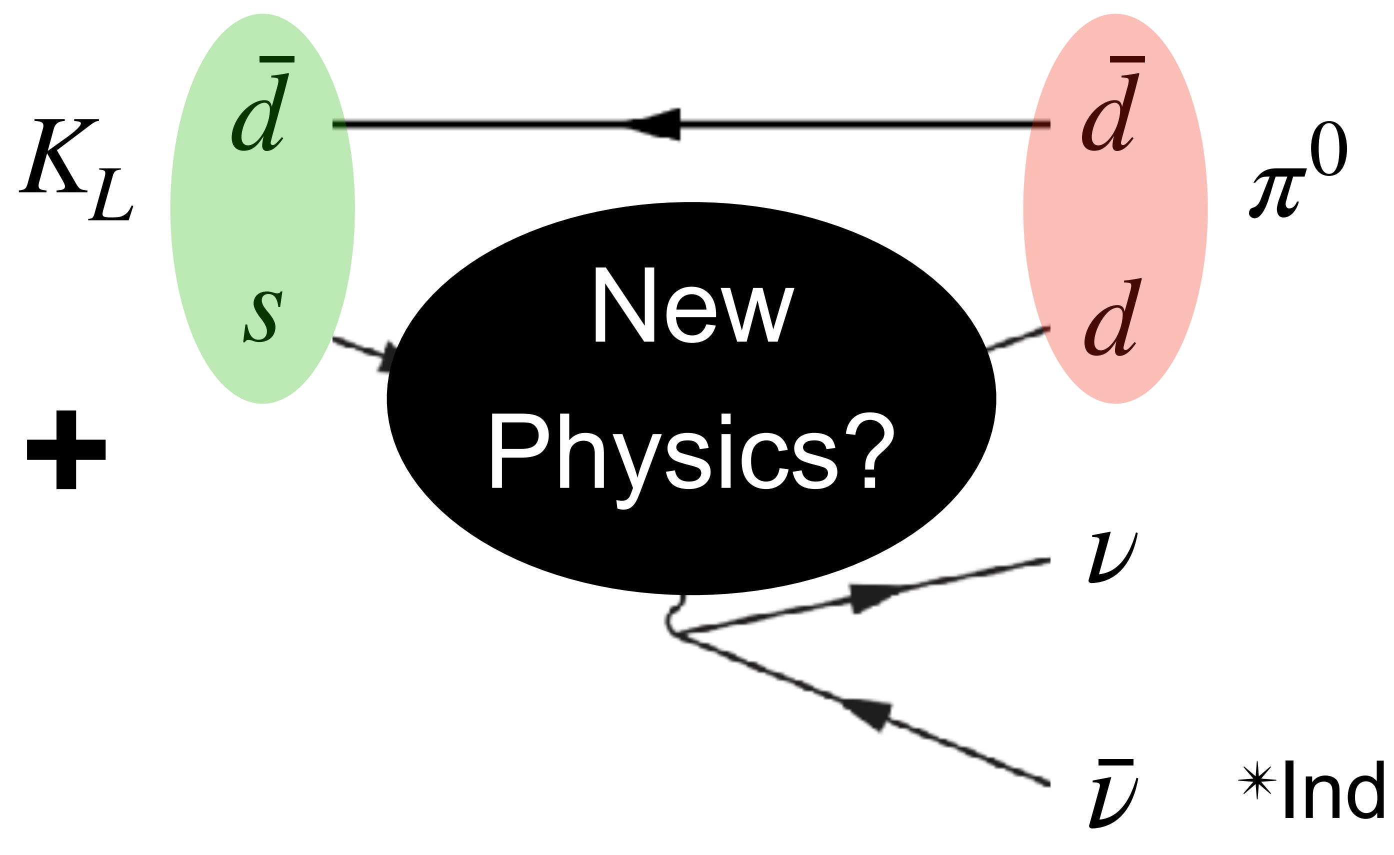
$K_L \to \pi^0 \nu \bar{\nu}$ in the Standard Model

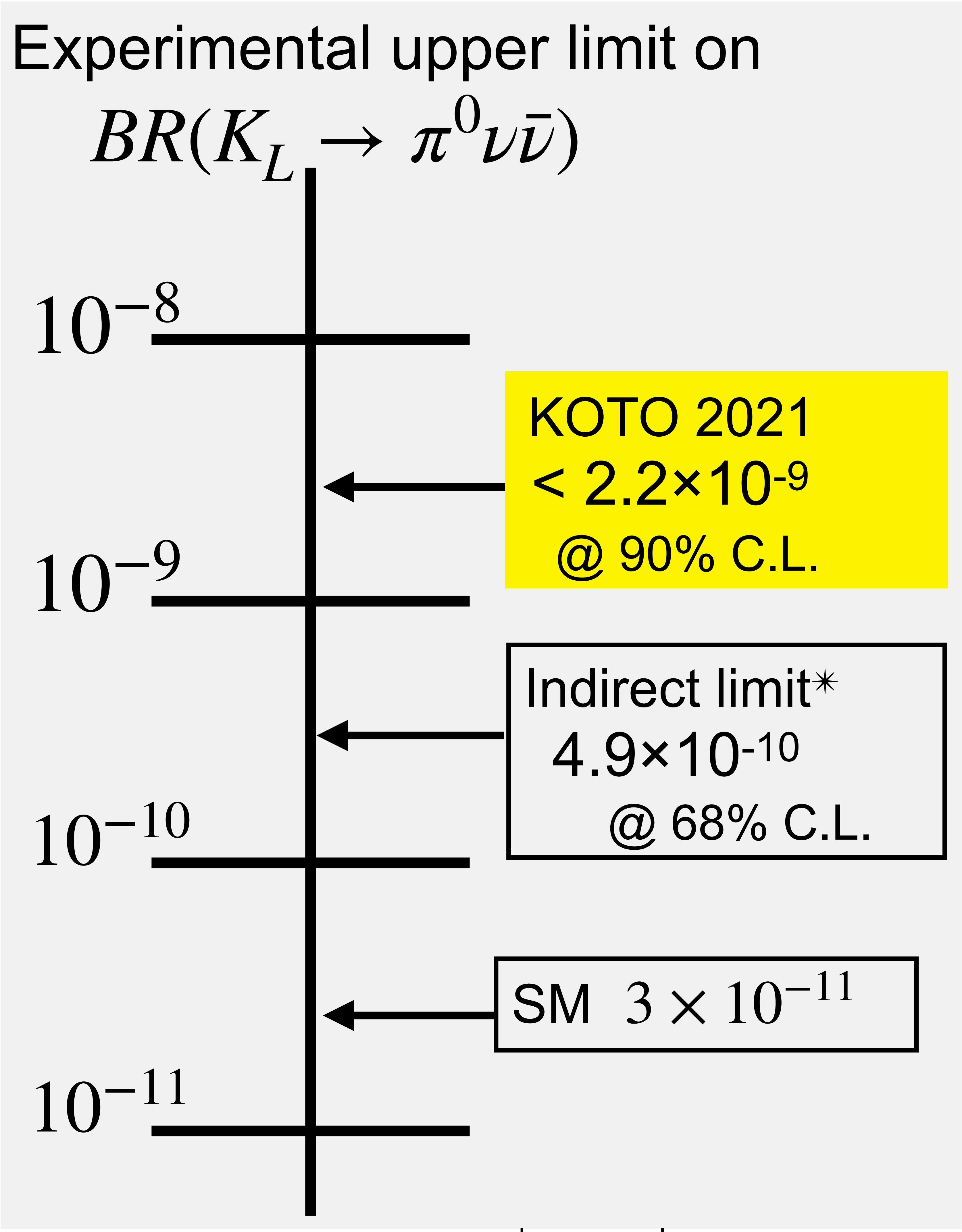
- Direct CP violation process
- Suppressed in SM: $BR_{\mathrm{SM}} = 3 \times 10^{-11}$
- Theoretically clean (<2%)

➡ ***Good probe to search for new physics***



+

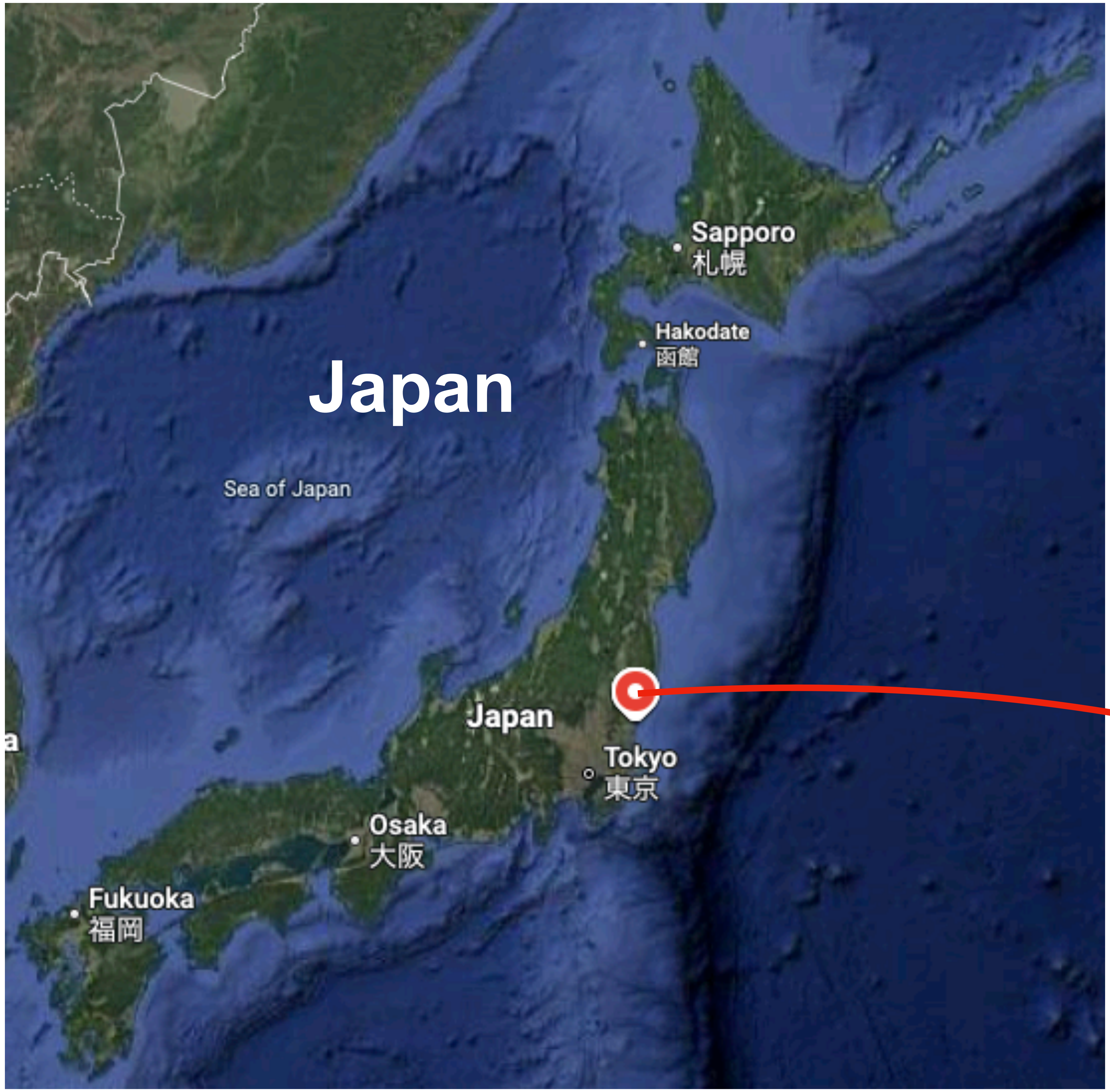




*Indirect limit from relation to $BR(K^+ \to \pi^+ \nu \bar{\nu})$
Calc'd from NA62 results (2016-2024) with 1σ region
LaThuile2026 : https://agenda.infn.it/event/48984/contributions/286360/attachments/146881/223788/Fiorenza_LaThuile2026.pdf

J-PARC KOTO experiment

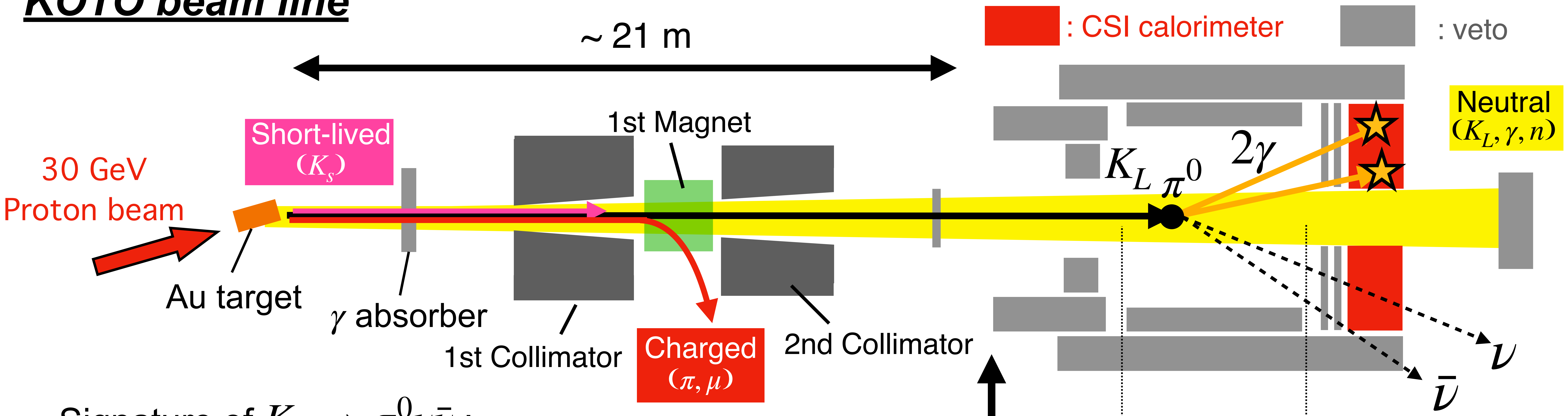
Search for $K_L \to \pi^0 \nu \bar{\nu}$ at J-PARC



Photo@Collaboration meeting on Dec. 2025

Experimental method

KOTO beam line



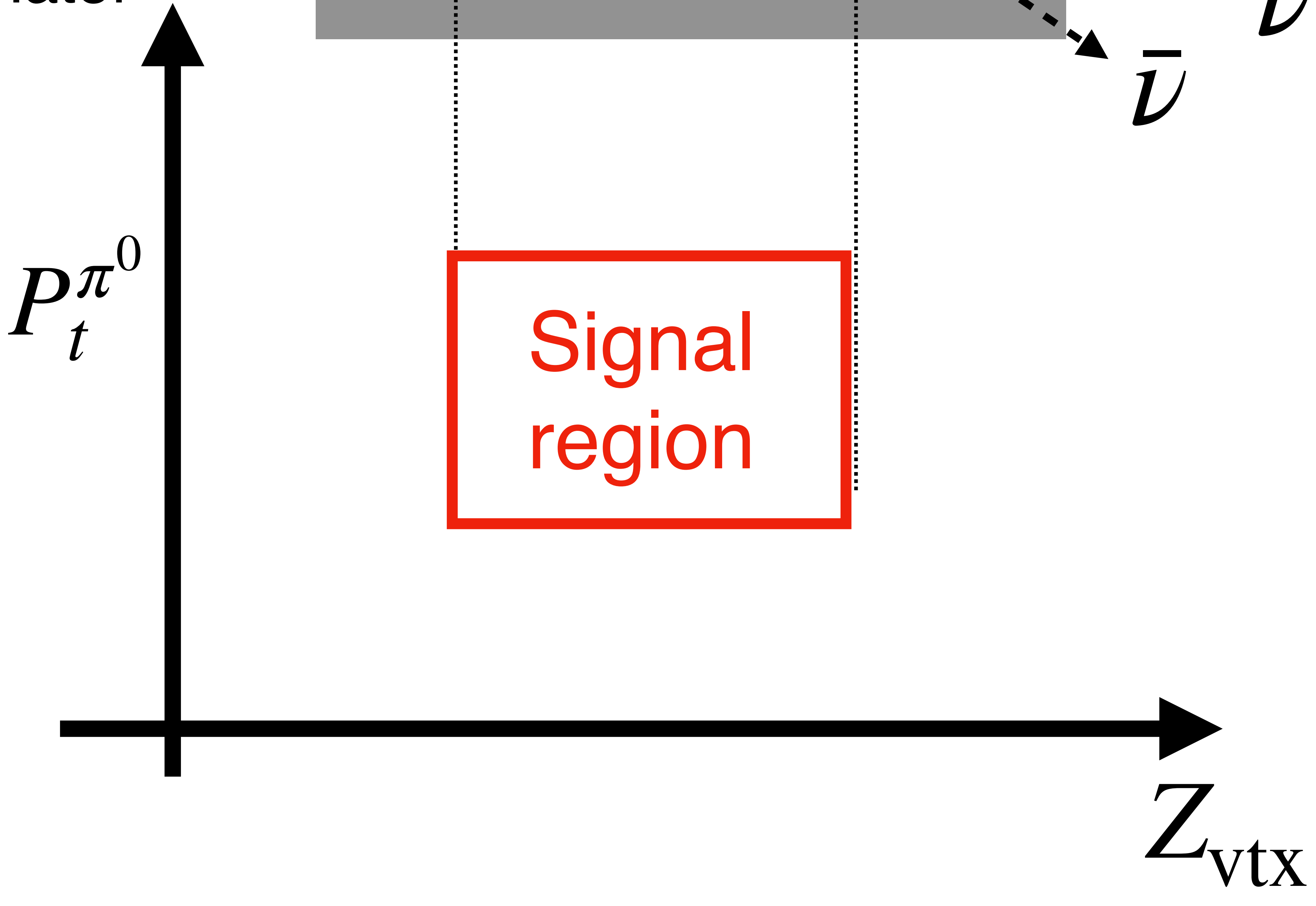
- Signature of $K_L \to \pi^0 \nu \bar{\nu}$:

  ($\pi^0 \to$) 2γ + Nothing else

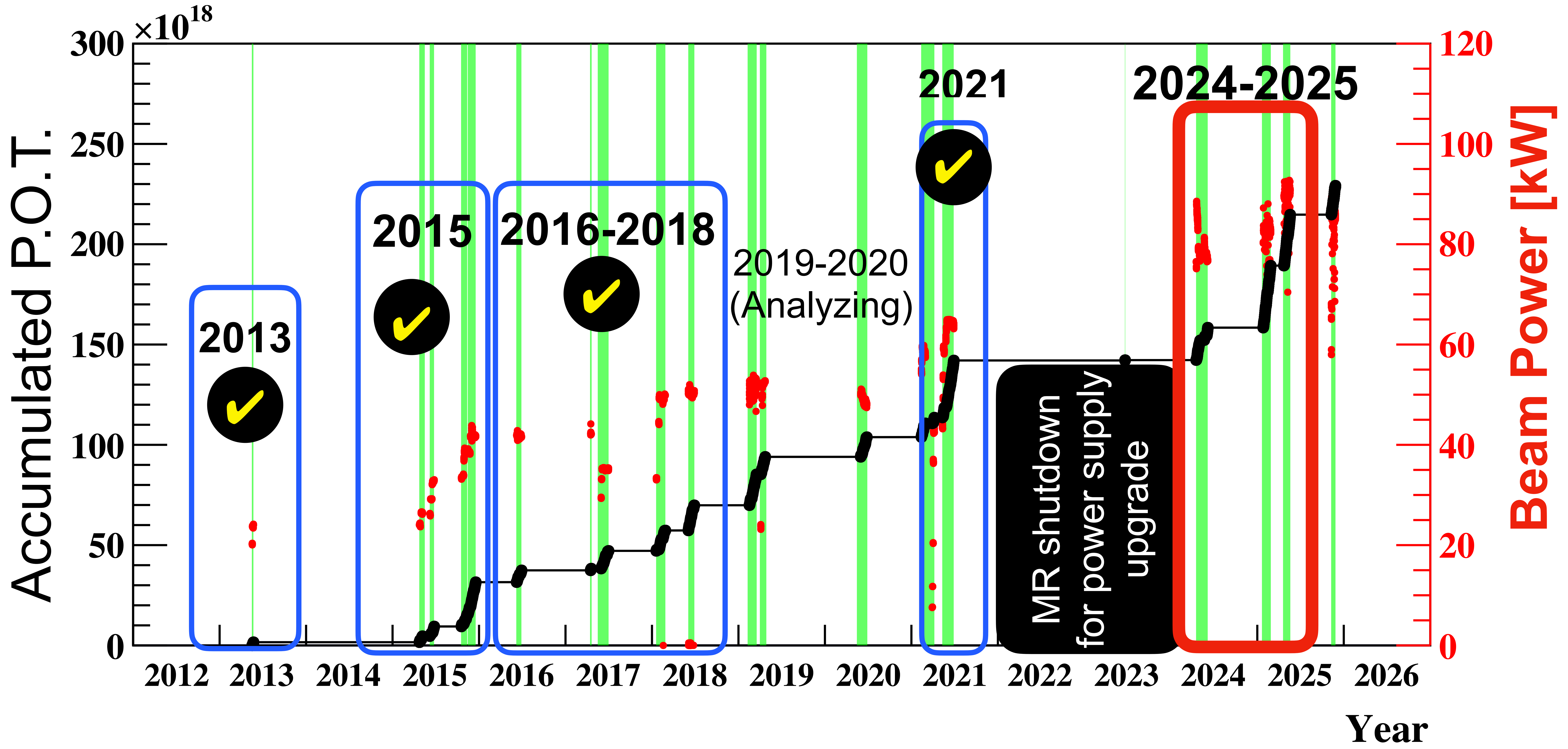
  CSI calorimeter Hermetic Veto

- Reconstruct decay position (Z_{vtx}) assuming π⁰ mass

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



History of data taking



- Beam power gradually increased : 64kW(2021) → 80kW (2024) → 92kW (2025)

  Shorter repetition cycle
  5.2 s → 4.2 s

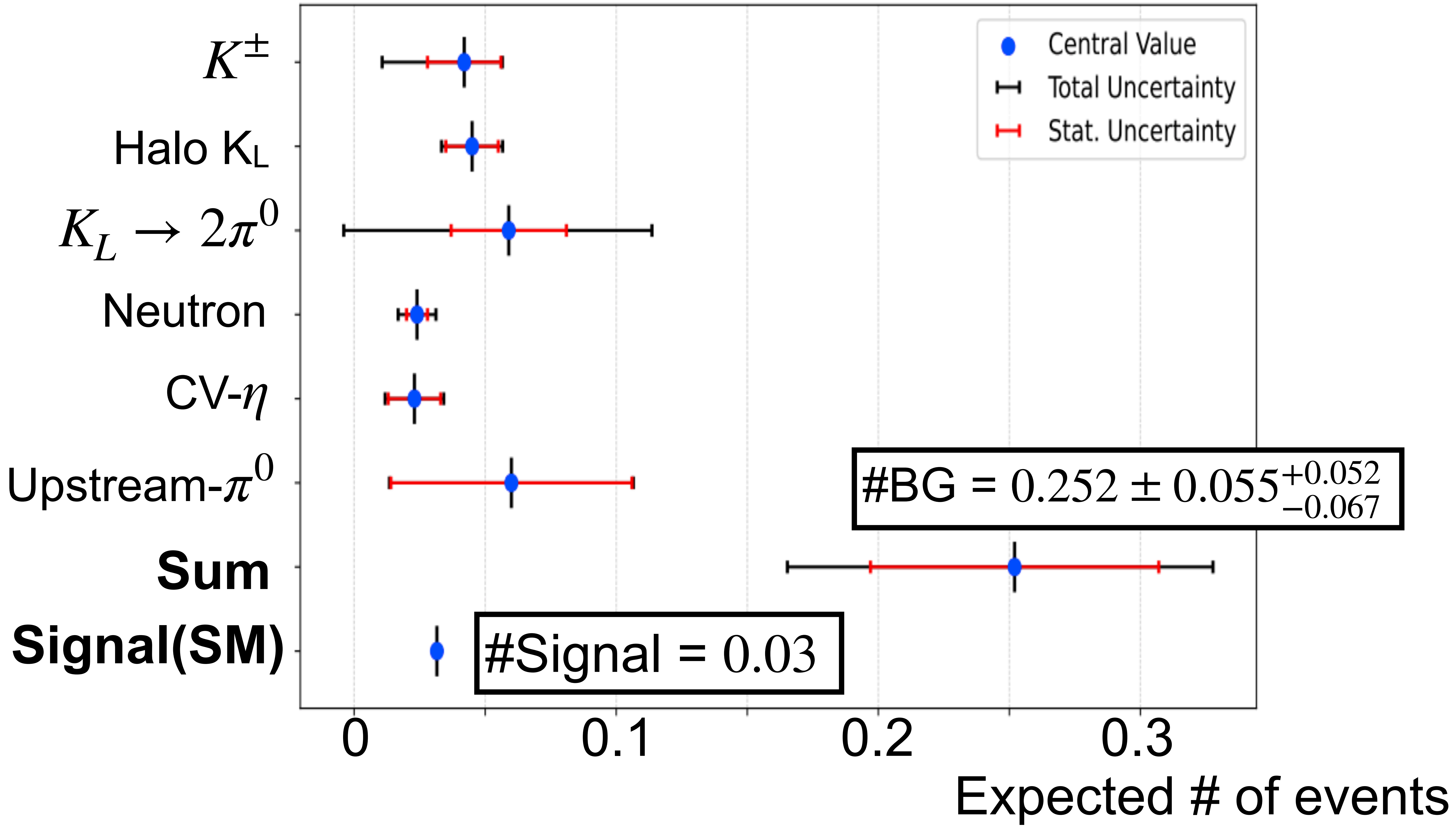
- We have collected approximately twice the statistics compared to the 2021 data in 2024, 2025

Overview of 2021 data analysis

Single Event Sensitivity (SES) : Branching ratio for which the expected number of observed events is 1

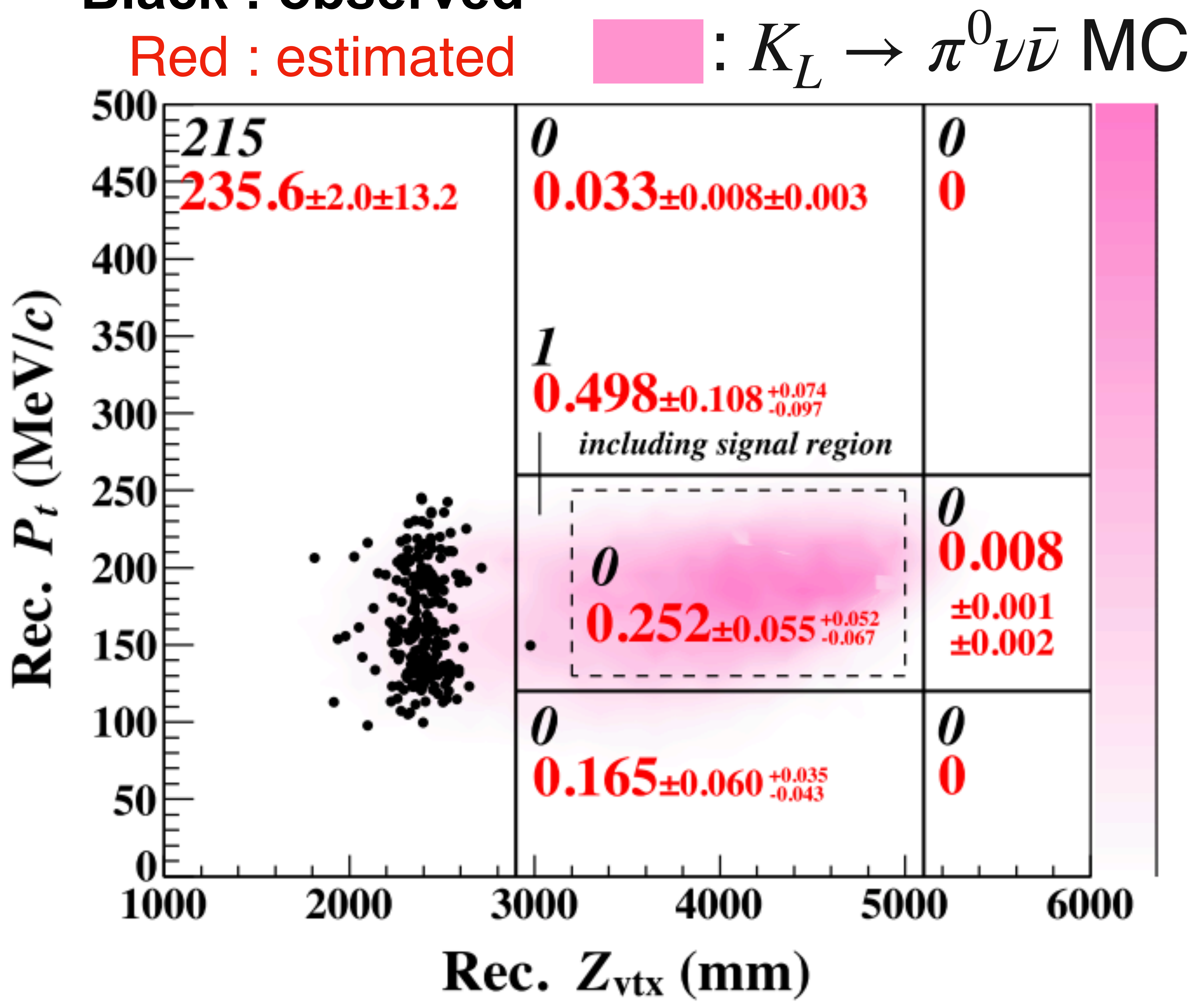
$$\mathrm{SES}_{2021} = (9.33 \pm 0.06_{\mathrm{stat}} \pm 0.84_{\mathrm{sys}}) \times 10^{-10}$$

Summary of expected events inside signal region



Black : observed

Red : estimated



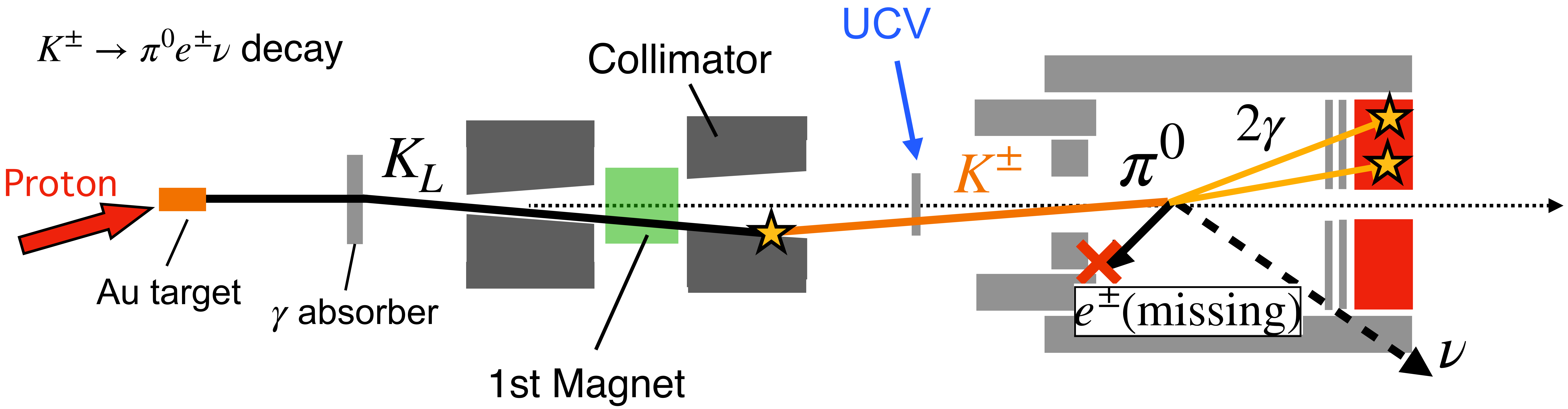
- No observed events inside signal region

$$\mathscr{B}(K_L \to \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9} \text{ (90\% C.L.)}$$

Phys. Rev. Lett. 134, 081802 (2025)

Upgrade after 2021 : Detector (1)

Upgraded **U**pstream **C**harged **V**eto(**UCV**) to further reduce the $K^{\pm}$ background



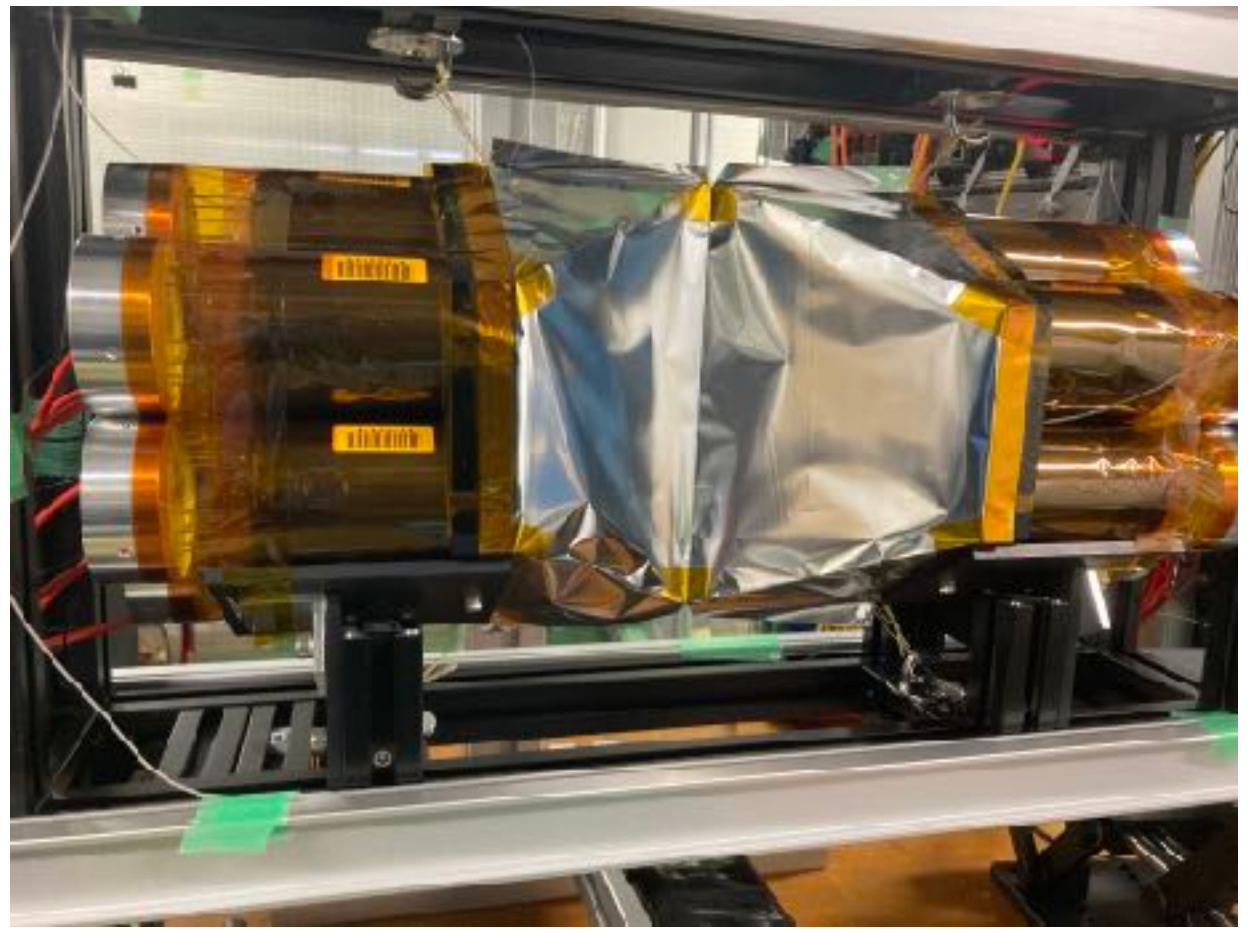
Key feature

- Sensitive to charged particles to detect $K^{\pm}$ in the beam
- Insensitive to the scattering of neutral particles (K_L, neutron)

Upgrade after 2021 : Detector (2)

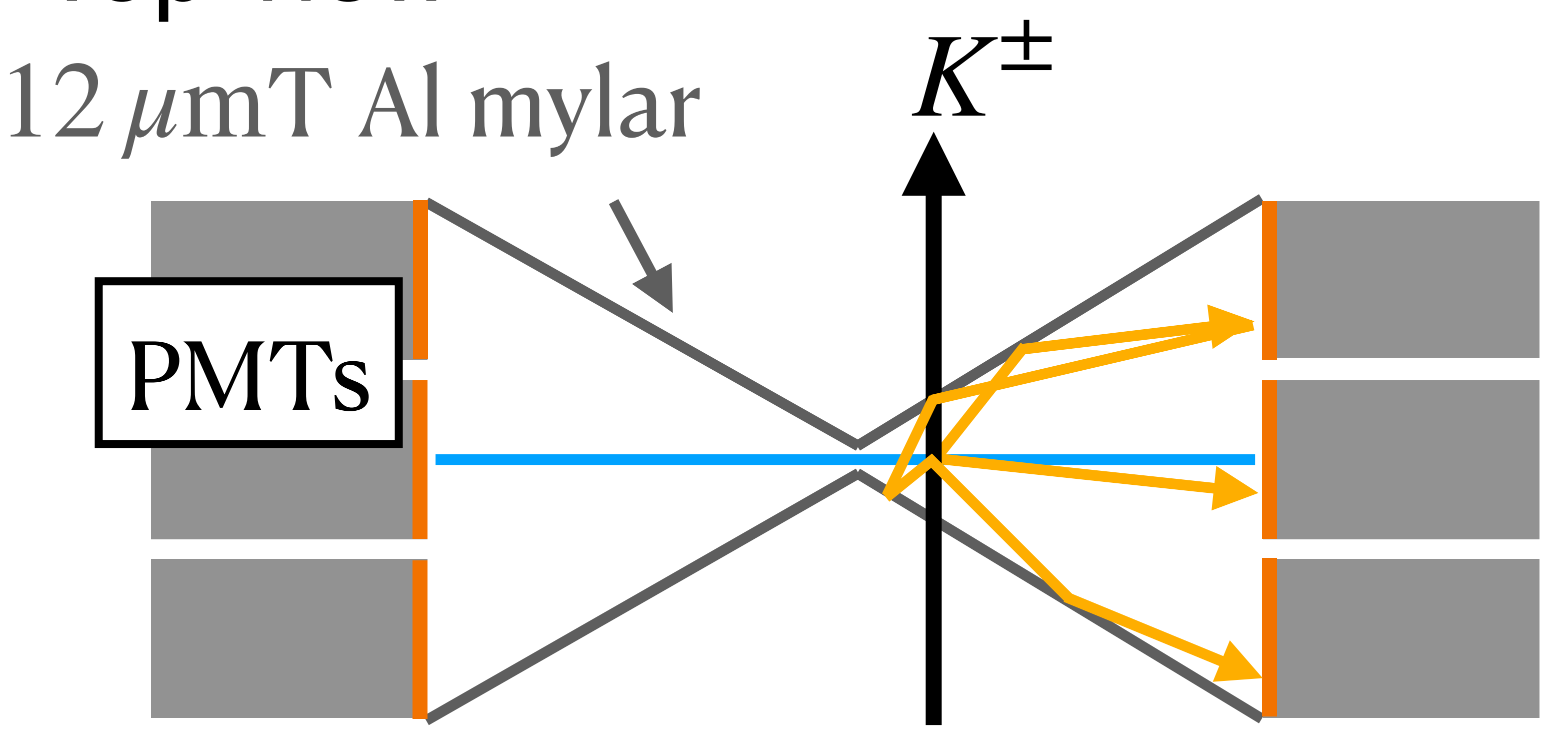
Upgraded **U**pstream **C**harged **V**eto(**UCV**) to further reduce the $K^{\pm}$ background

Photo



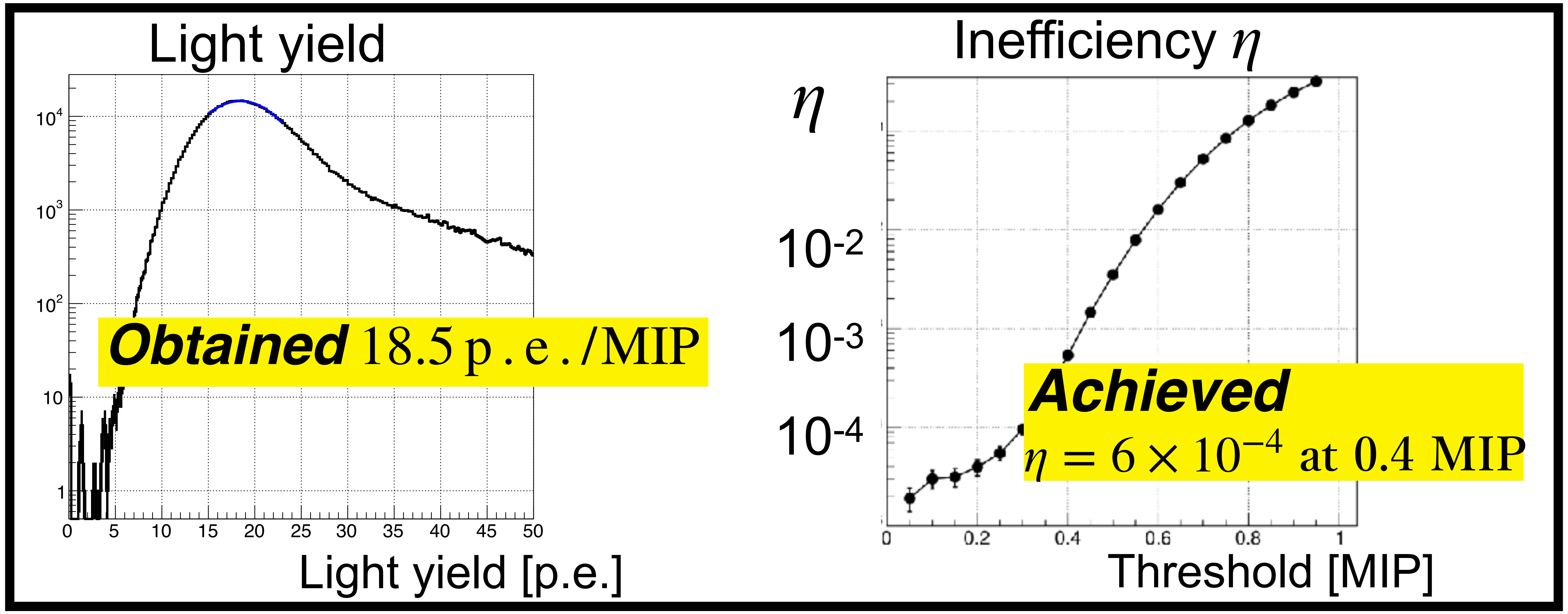
	UCV (2021)		New UCV (2023-)
Material :	0.5mmT scintillating fibers	Thinner →	**0.2mmT scintillator film**
Inefficiency :	7.8%	More sensitive →	**0.06%**

Top view

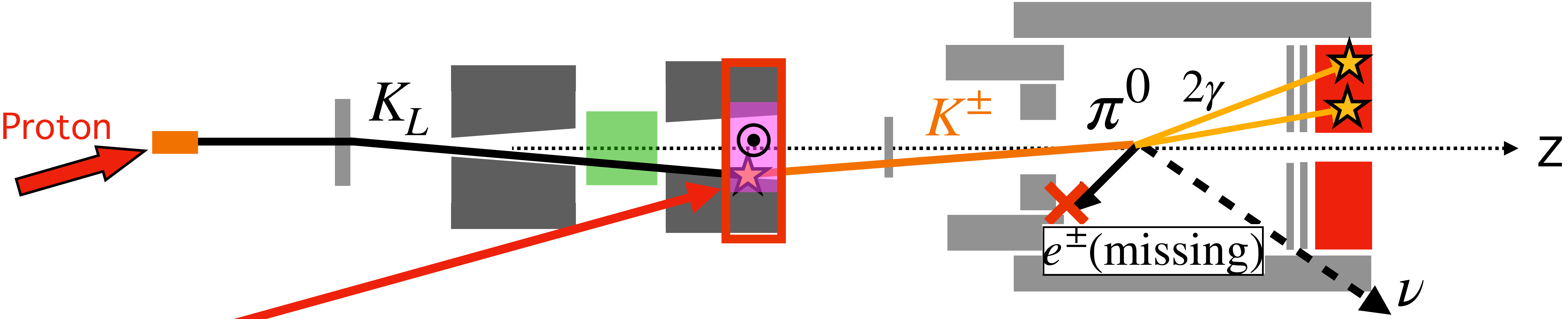


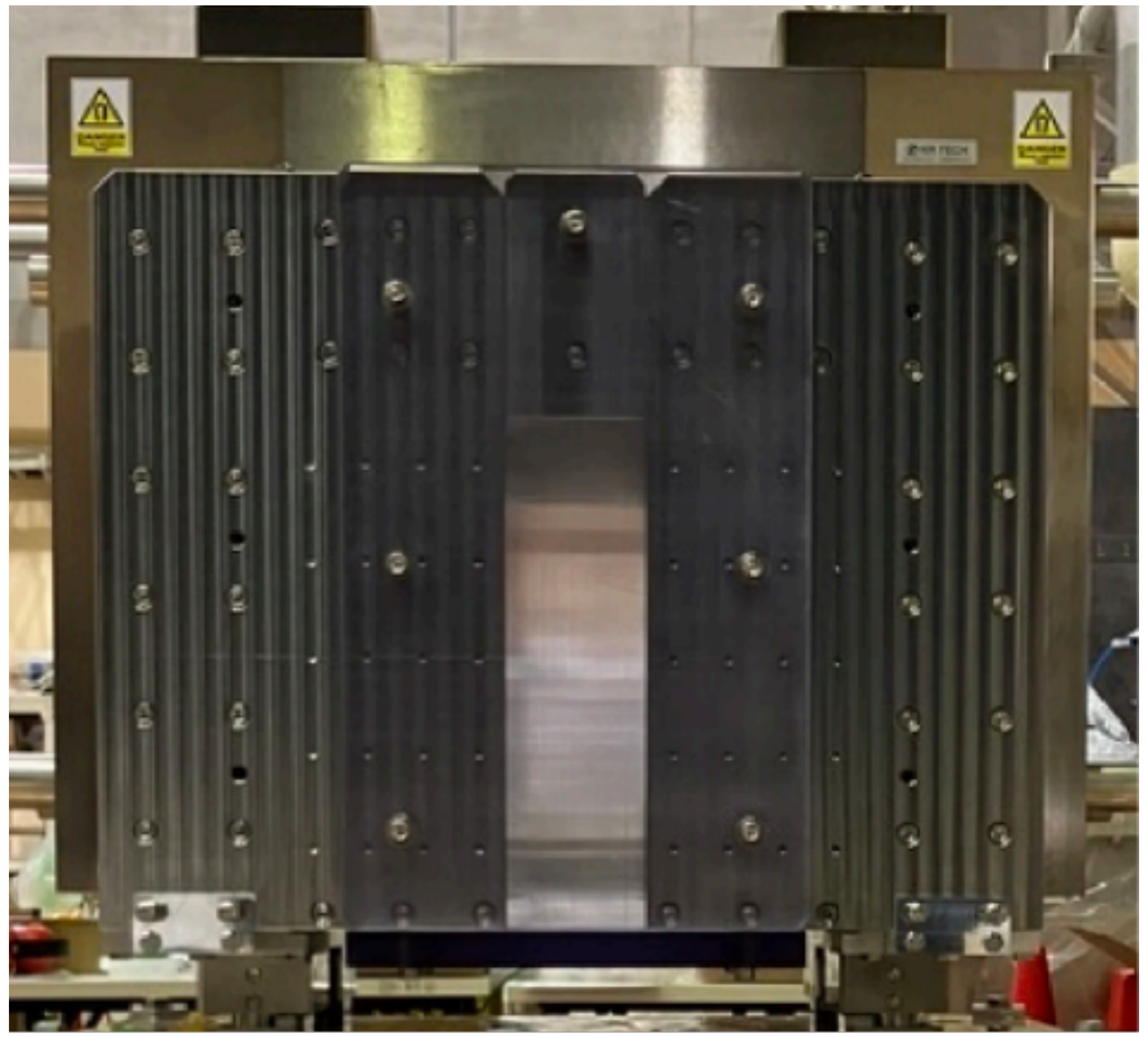
Collect the scintillation light escaping from the scintillator

Performance



Upgrade after 2021 : Magnet





Installed permanent magnet in the beam line

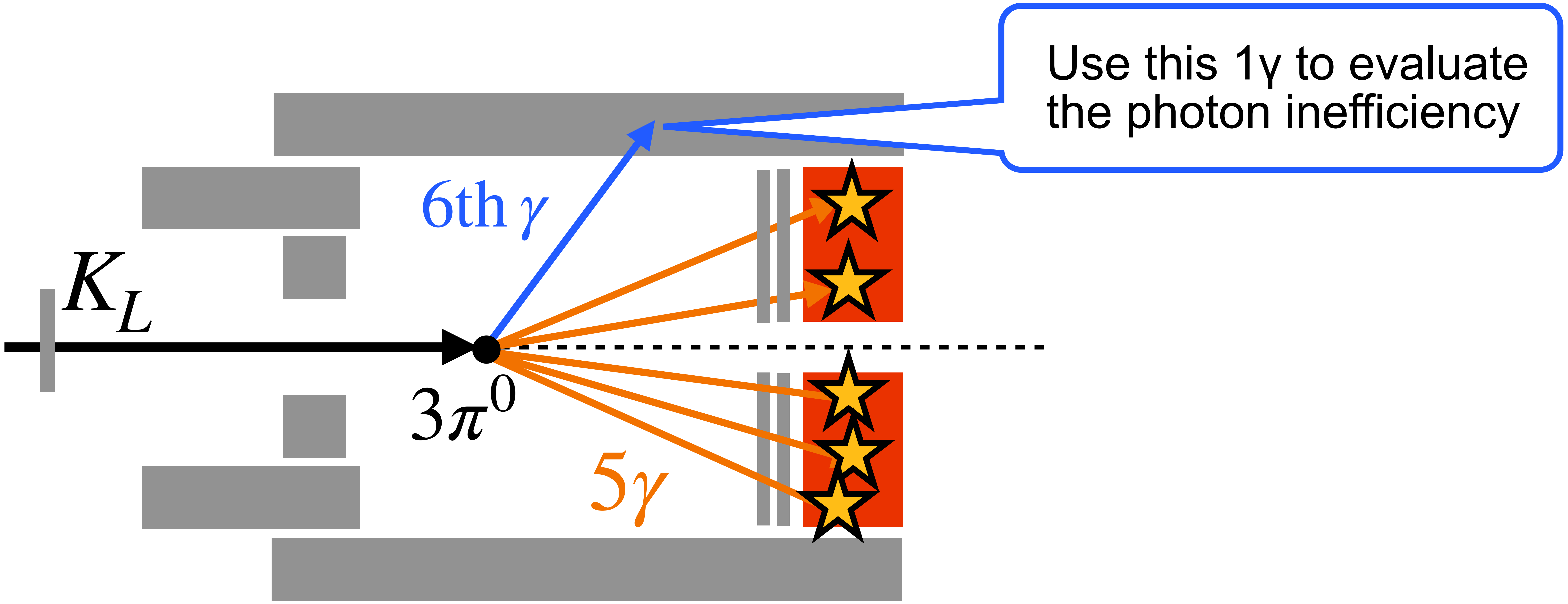
- Permanent magnet
- B (~ 0.9 T) × 0.5 m in average
- Reduction of $K^{\pm}$ flux is expected to be 1/10

With UCV and magnet, $K^{\pm}$ BG is expected to be negligible

Upgrade after 2021 : DAQ system

- Upgraded DAQ system in 2021-2023 to have more DAQ rate capability
  - Add new triggers to collect data for
    - By-product physics (e.g. : $K_L \to \pi^0 ee$)
    - ***Data-driven evaluation for photon inefficiency (5γ data) to reduce the systematic uncertainty of*** $K_L \to 2\pi^0$ ***BG***

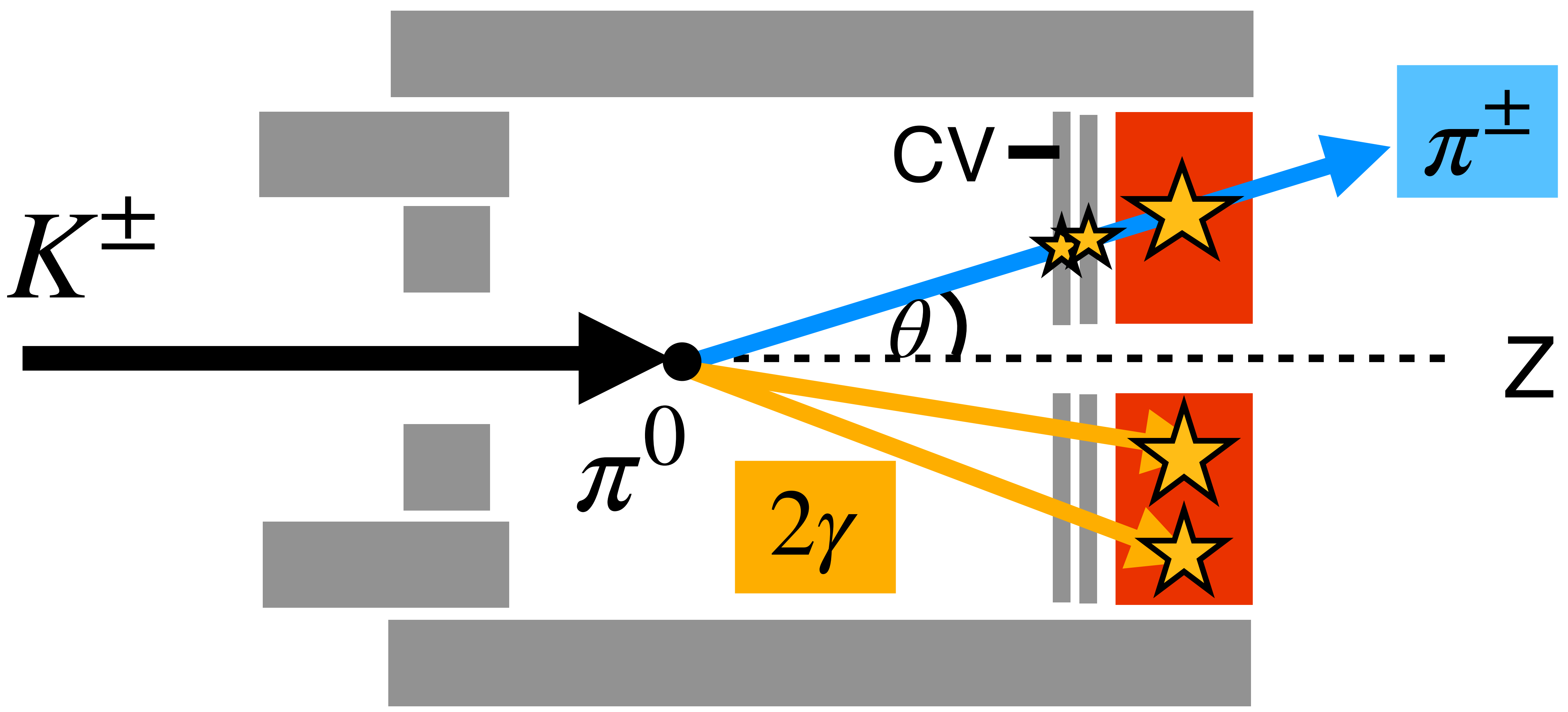
5γ data : 5 clusters in CSI calorimeter + loose veto

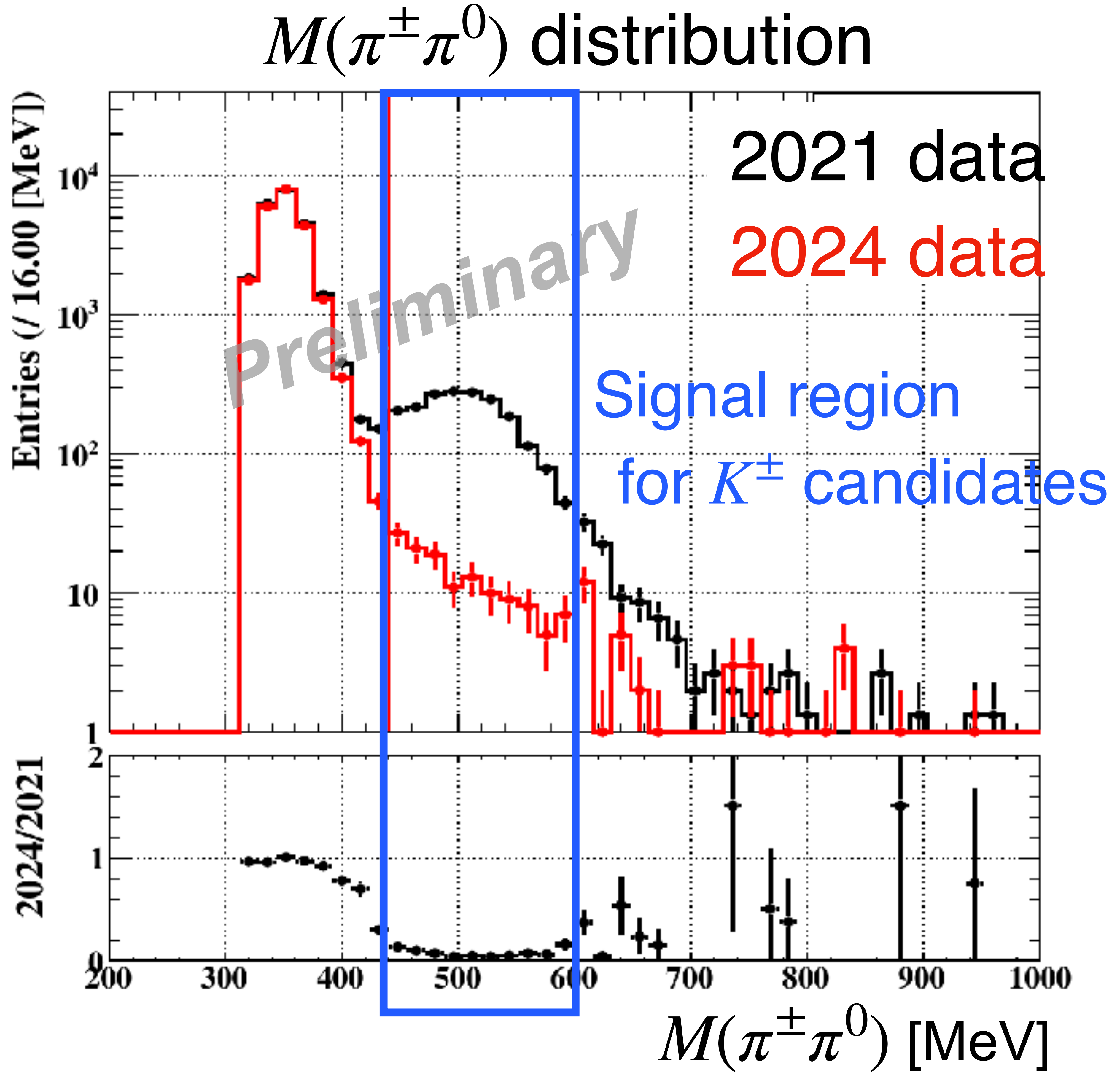


Status of 2024-2025 analysis

Reduction of $K^{\pm}$ flux

$K^{\pm}$ flux was evaluated using control sample simultaneously taken with physics data in 2024





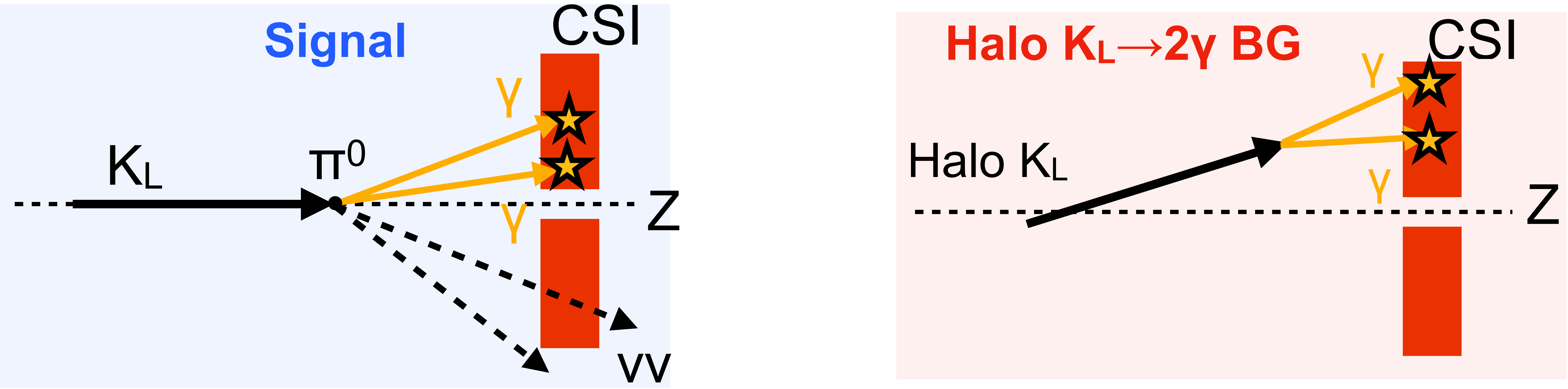
1. Reconstruct π^0 from 2γ's energies and positions → Get Z_{vtx}, $P_T(\pi^0)$
2. Calculate $\pi^{\pm}$ direction θ from Z_{vtx} + hit position on CSI calorimeter
3. Calculate $\pi^{\pm}$ momentum ($P(\pi^{\pm})$) with the assumption of $P_T(\pi^{\pm}) = P_T(\pi^0)$
4. Reconstruct the mass $M(\pi^{\pm}\pi^0) = \sqrt{(p_{\gamma 1} + p_{\gamma 2} + p_{\pi^+})^2}$

K^+ flux was reduced by a factor of > 15 thanks to magnet(Preliminary)

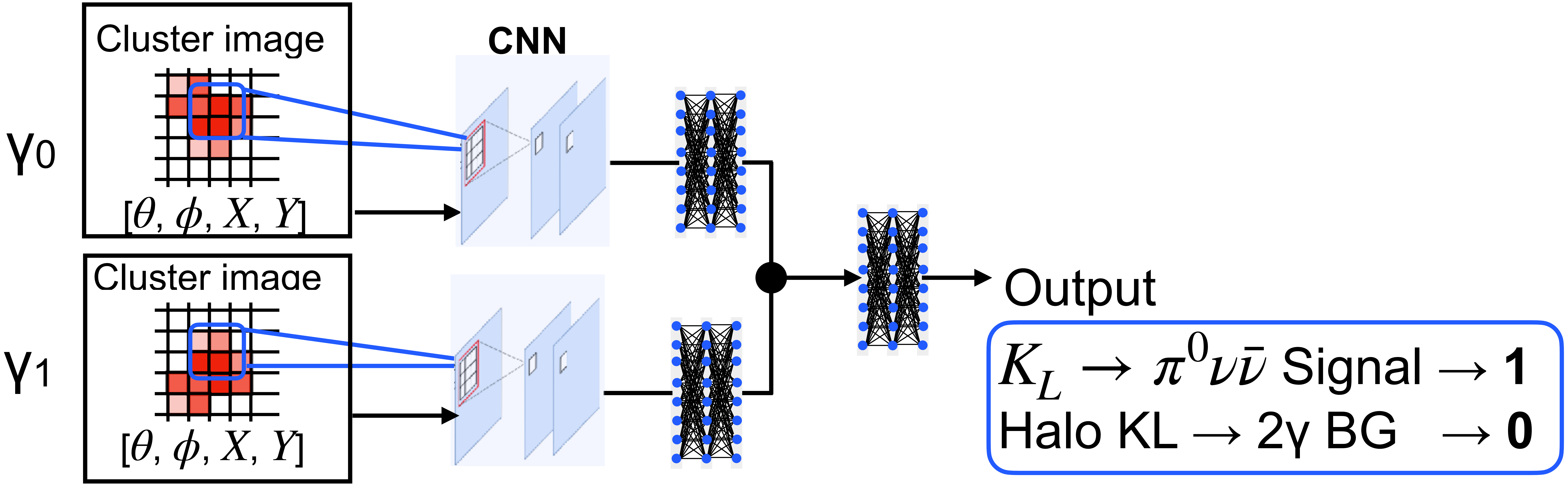
With magnet and new UCV, $K^{\pm}$ BG would be negligible

New event classifier against Halo $K_L \to 2\gamma$ BG (1)

Develop new event selection to further reduce Halo $K_L \to 2\gamma$ BG

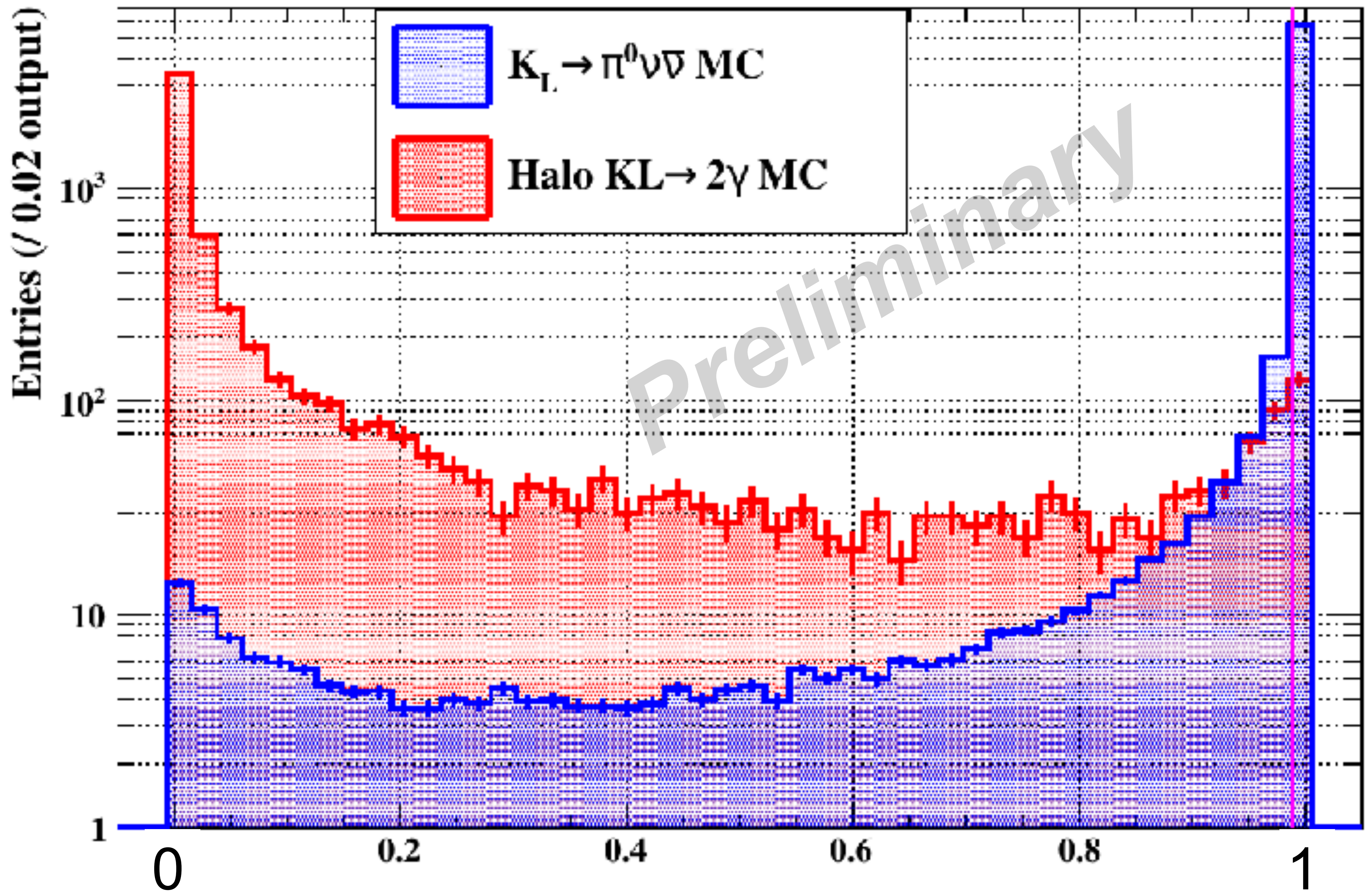


- Used **C**onvolutional **N**eural **N**et(CNN) to extract the feature from the cluster image

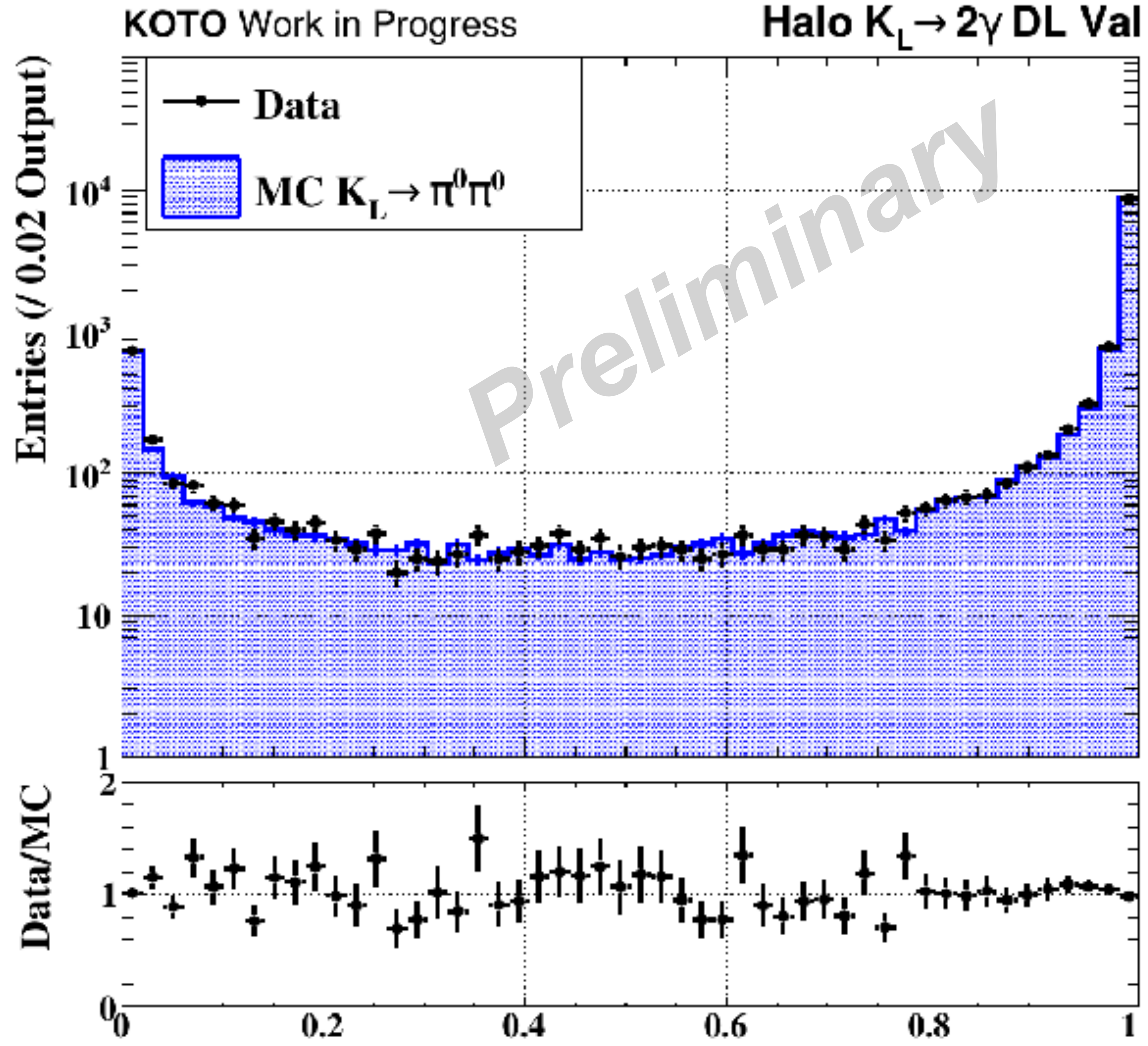


New deep neural network classifier (2)

Distribution of Deep learning output



Reproducibility check using $K_L \rightarrow 2\pi^0$ sample



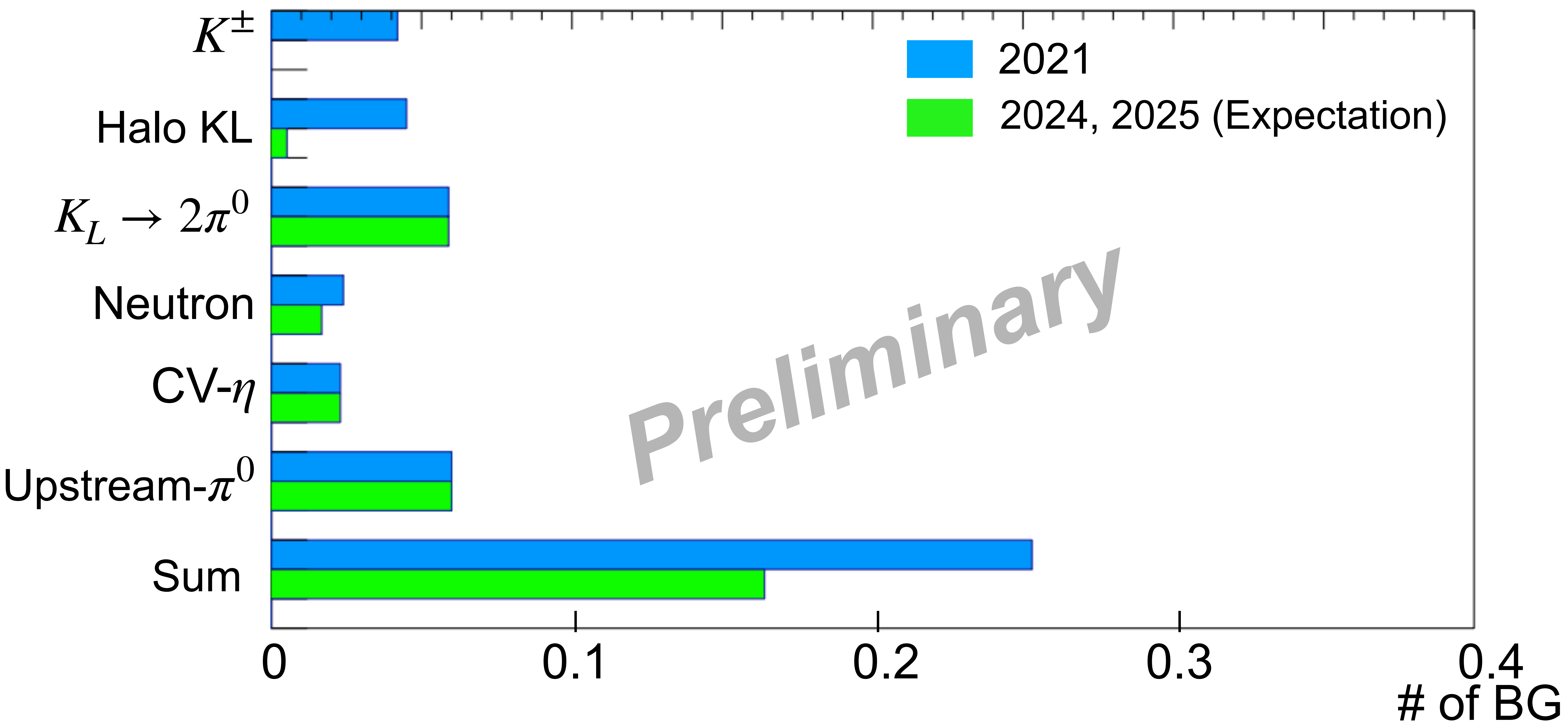
- ***Halo $K_L \rightarrow 2\gamma$ BG can be reduced to be ~2% with 95% signal efficiency***
  →× 6 higher rejection power than that in the previous cuts

- The reproducibility of the MC simulation was tested using $K_L \rightarrow 2\pi^0$ sample
  → **Good agreement between Data and MC**

Expected improvement from 2021 data analysis

Expected improvement of BG from 2021 data analysis

- Assume the same sensitivity of 2021 data analysis



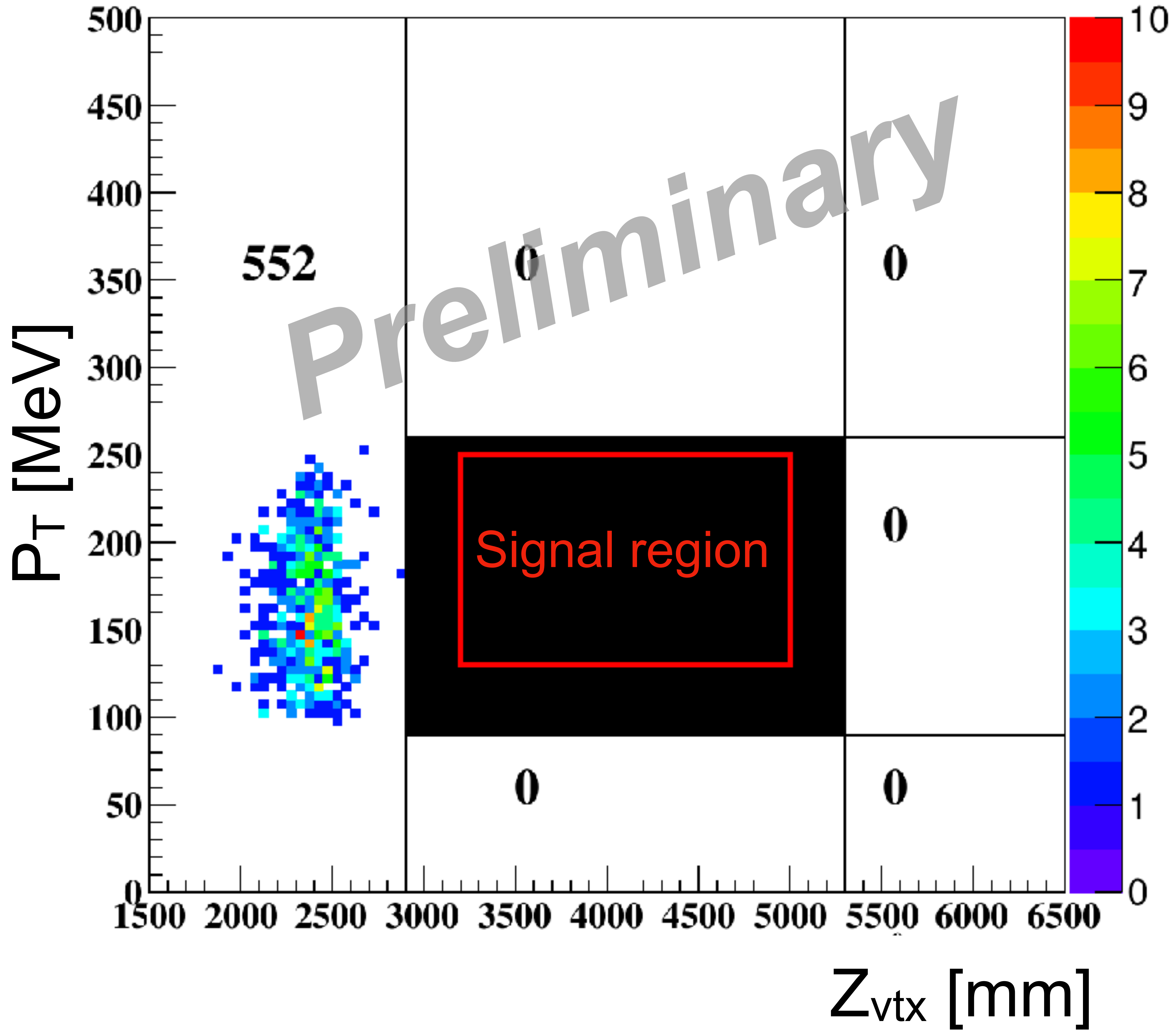
- ***# of BG would be reduced by 35 %***
- ***More accurate estimation of $K_L \to 2\pi^0$ BG would be achieved with the precise measurement of veto inefficiency using 5γ data***

Status of 2024-2025 data analysis

- We have collected approximately twice the statistics compared to the 2021 data
- No events were found outside the blind region except for the upstream events

  →**No surprise so far**
- We enlarged the blind region to consider the possibility to extend the signal region (to lower P_T and larger Z)
- Will estimate sensitivity and background soon
- Considering the combined analysis from 2021 data

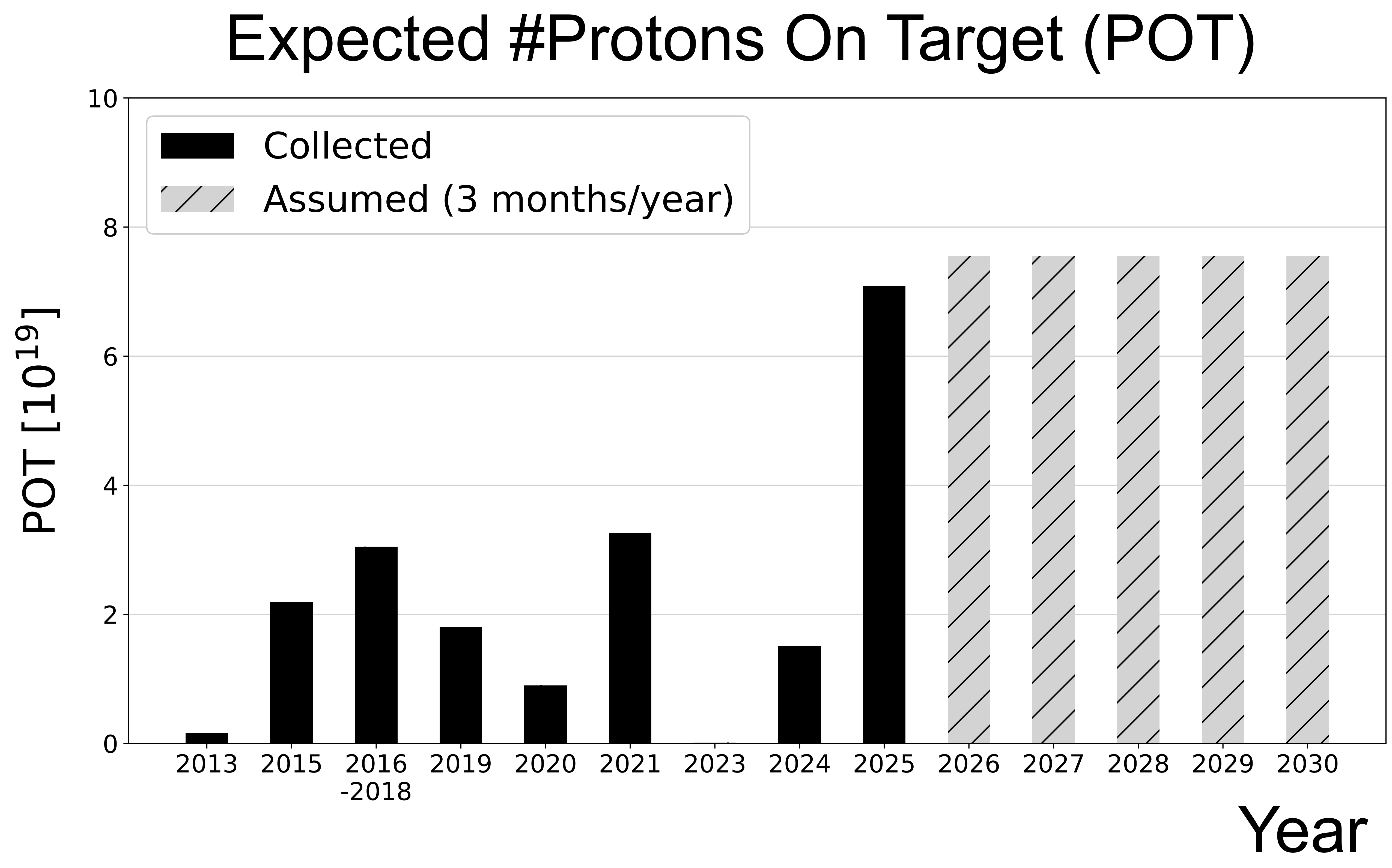
P_T vs Z_{vtx} plot under almost same cut as 2021 data analysis

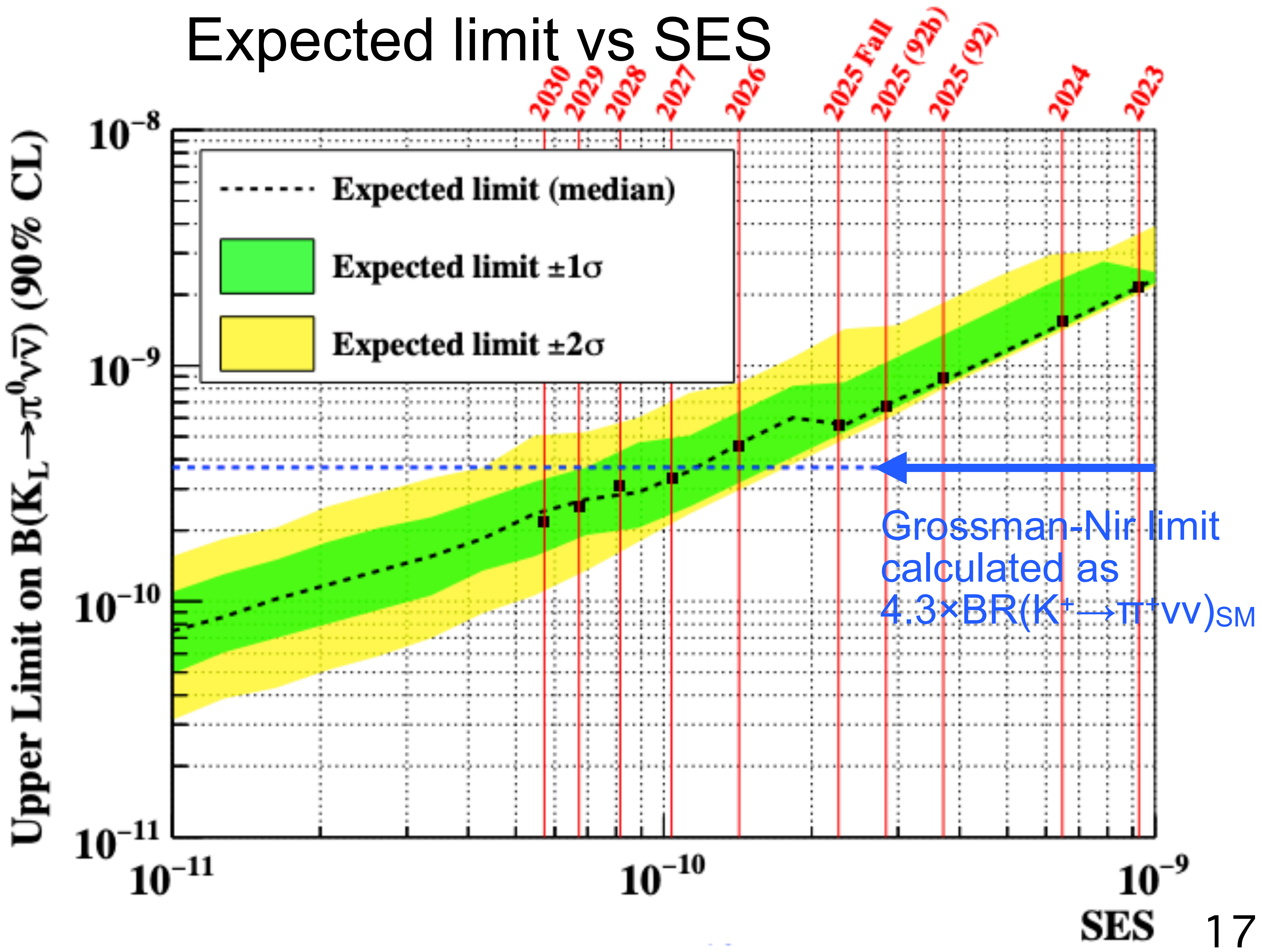


Prospect of KOTO

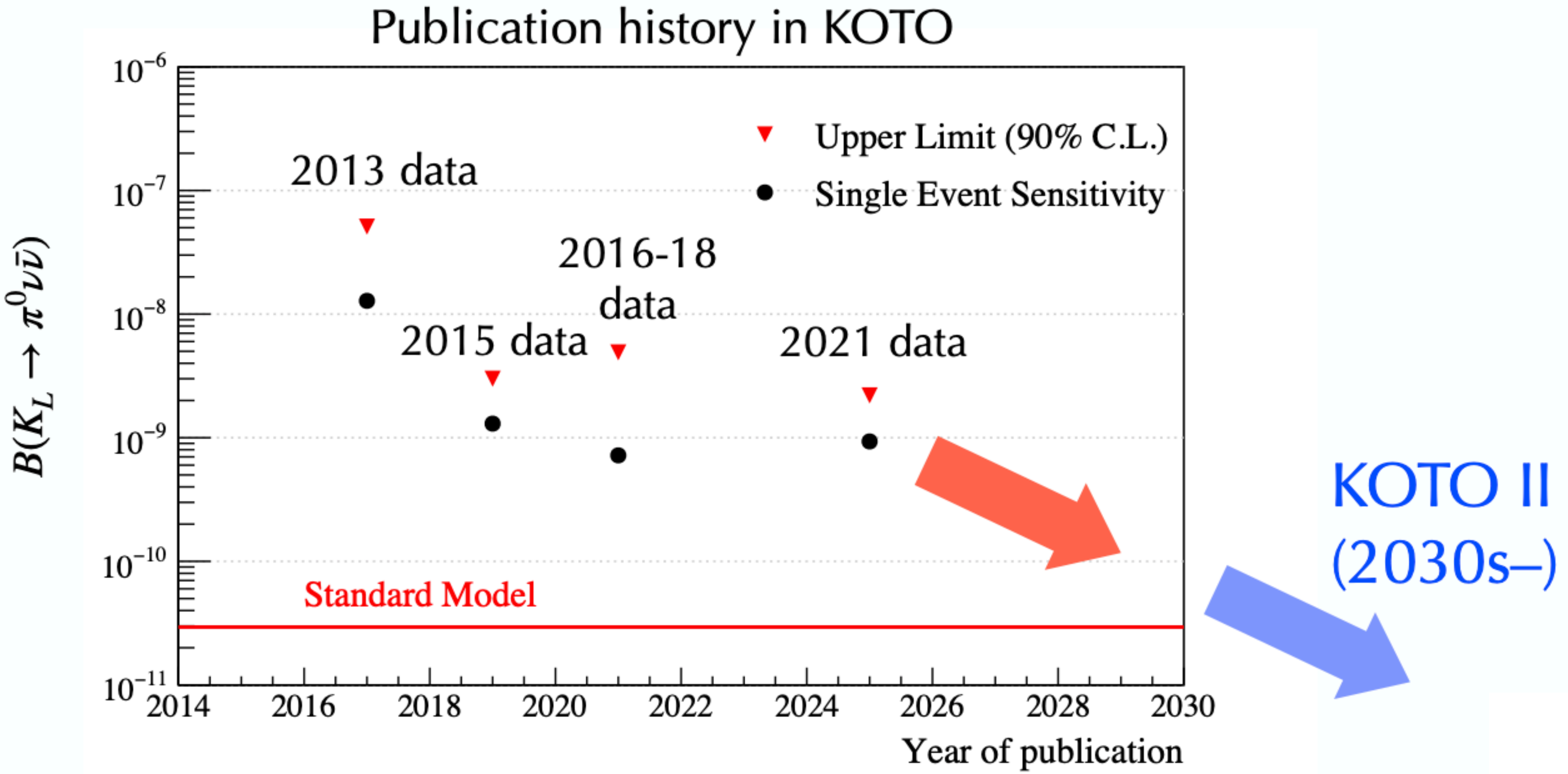
With the following assumptions, we aim to reach SES < 10^{-10} in 3-4 years

- Beam power will reach 100kW in 2026-
- Beam Run time : 20 days/month × 3 months/year
- 70% efficiency for physics data taking





Next Step : KOTO II



KOTO II @ J-PARC

KOTO II : Next generation of kaon experiment at J-PARC

Photo@KOTO II workshop in Mainz, Germany 2025

J-PARC KOTO II (E107)

KOTO II collaboration has been formed

- 10 countries
- 76 members from 26 institutions
  + 11 observers as of March 2026

- **Aiming to measure the branching ratio of $K_L \to \pi^0 \nu \bar{\nu}$ decay** (to study $K_L \to \pi^0 l^+ l^-$ also)
  - ~35 Signal events / ~40 BG events with 3×10^7 s running time
  - >5σ discovery of SM events
  - $\Delta\mathscr{B}/\mathscr{B} = 25\,\%$

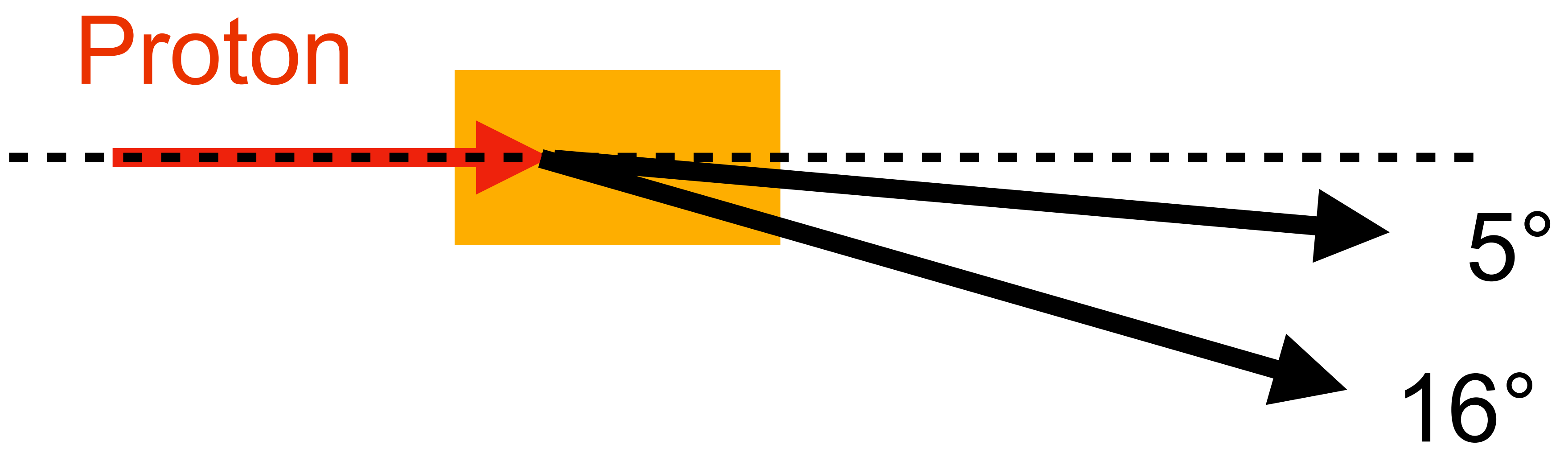
The proposal (arXiv:2501.14827) was submitted and was scientifically approved (Stage 1 status)

Improvement from KOTO to KOTO II

More K_L

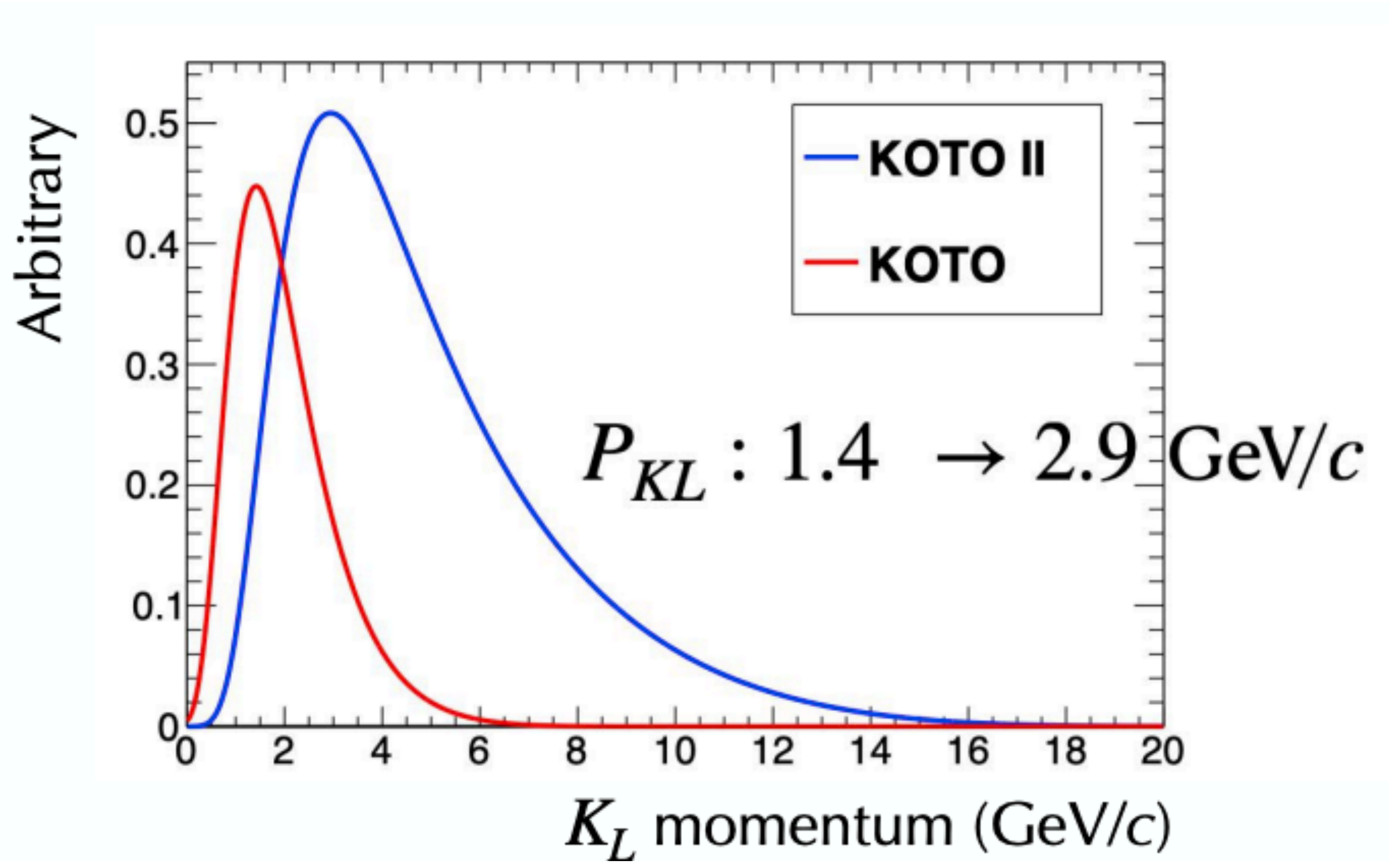
- Extraction angle : 16° → 5°

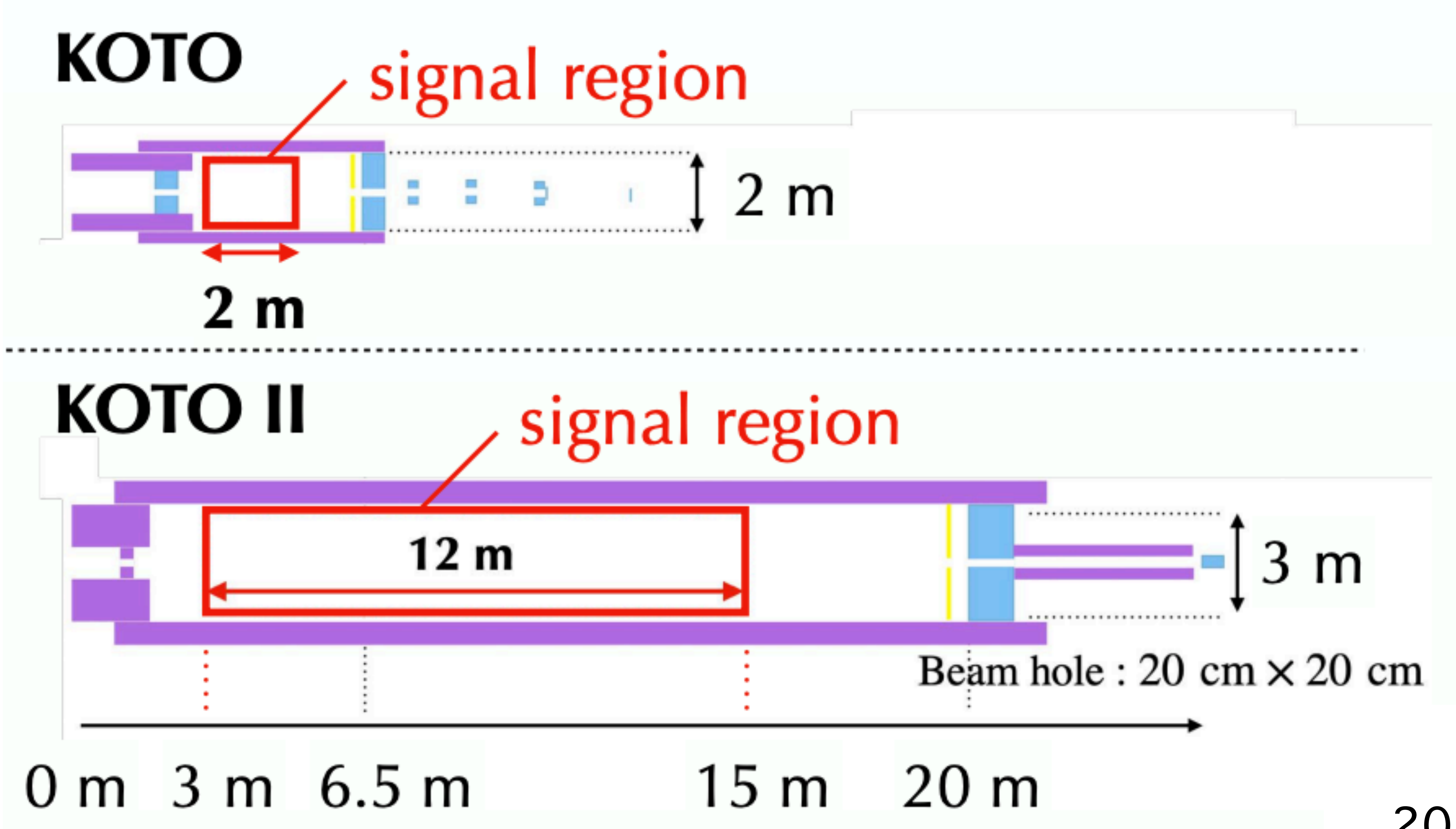
→ **× 2.6 flux + harder spectrum**



More signal acceptance

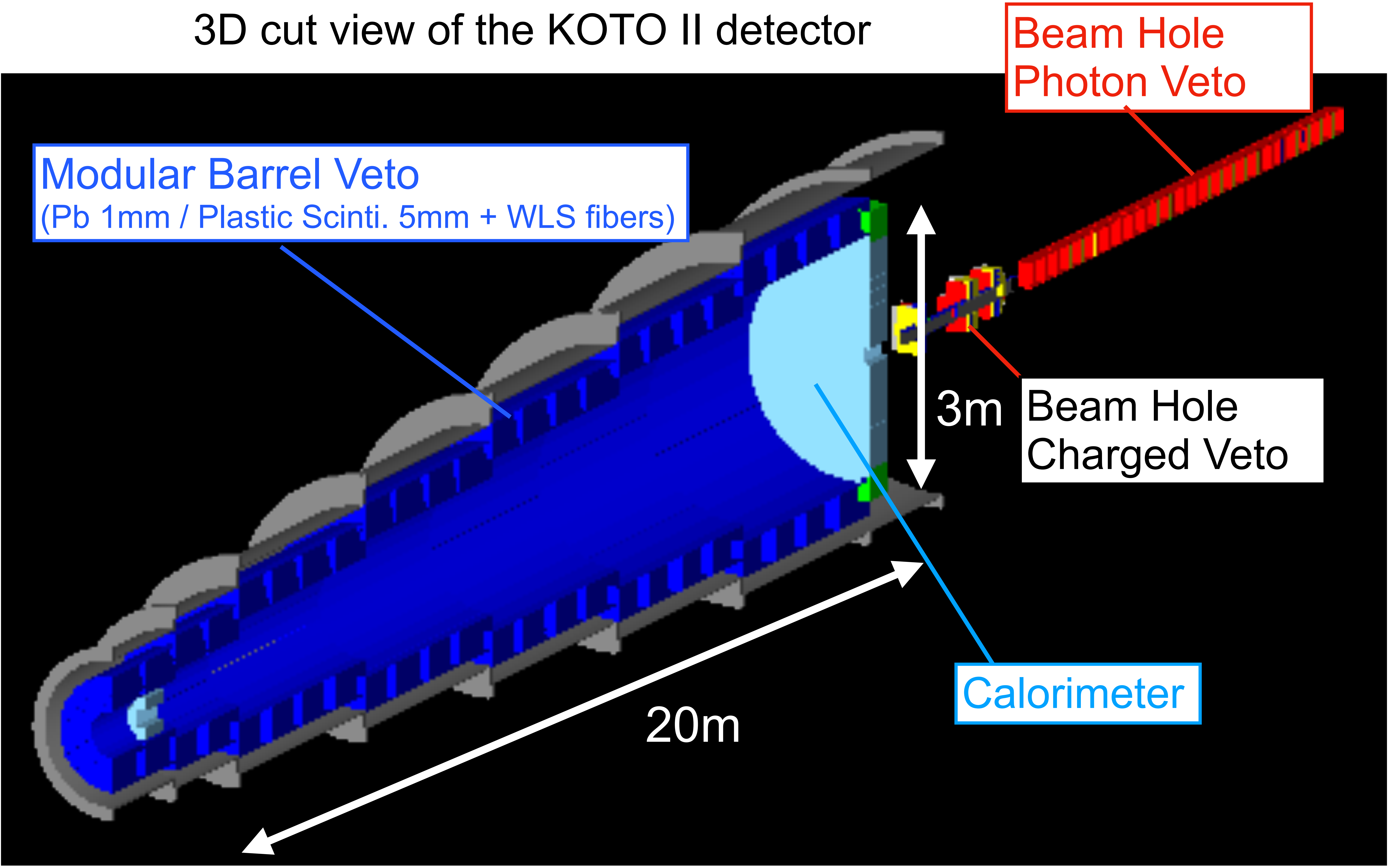
- Larger decay volume (signal region) : 2 m → 12 m
- Larger calorimeter : 2 m → 3 m

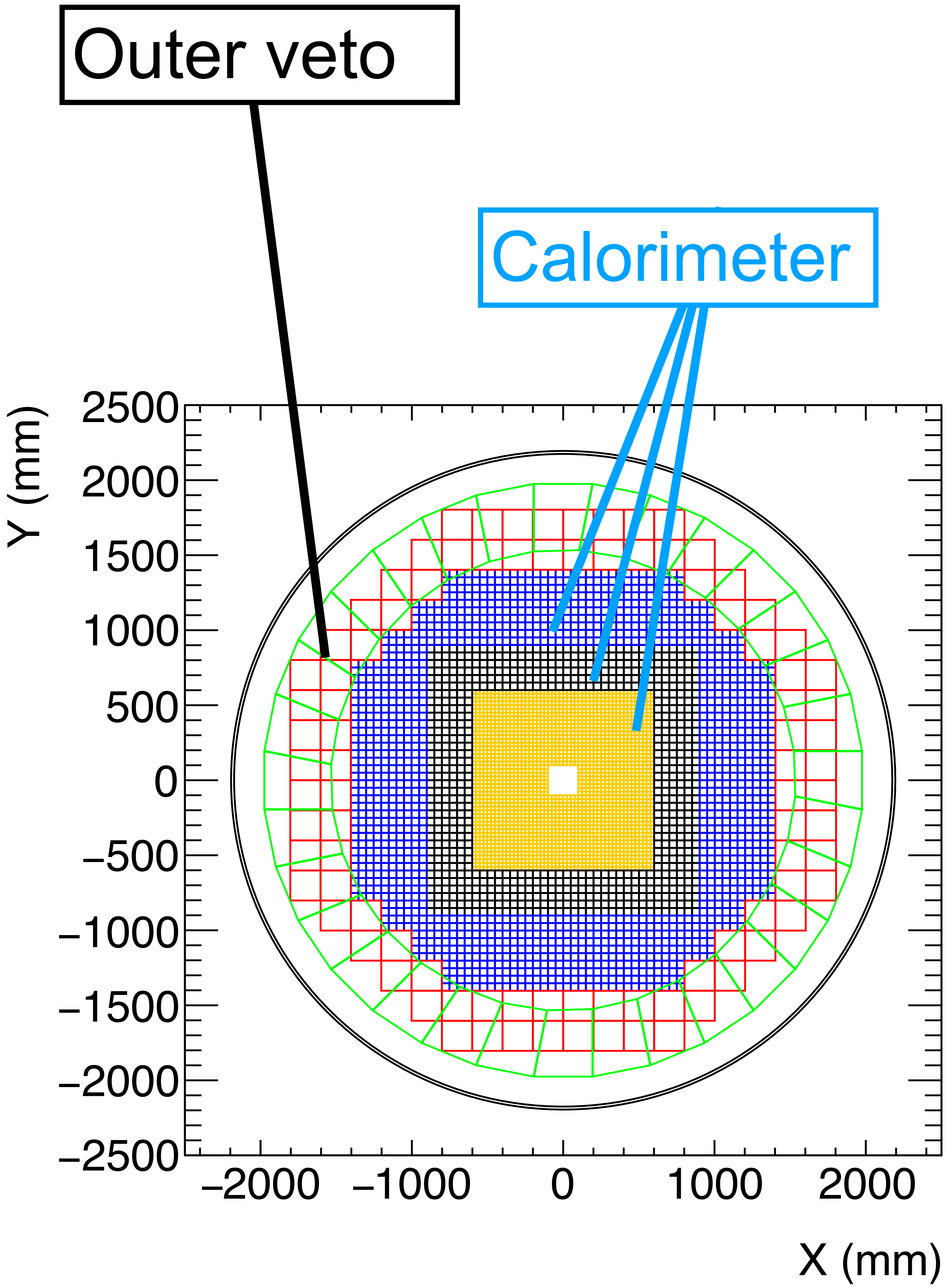




KOTO II detector (Base design)

3D cut view of the KOTO II detector





It is just a base design and there are many rooms to improve and contribute.
Please join us if you are interested in!

Summary

KOTO

- 2024-2025 data analysis is ongoing (×~2 statistics of 2021 data)
- With the hardware upgrade and analysis improvement, # of BG would be further reduced by 35%
- KOTO will reach SES below 10^{-10} in 3-4 years

KOTO II

- Experimental project has been scientifically approved and the KOTO II collaboration has been formed.
- Aim to discover $K_L \to \pi^0 \nu \bar{\nu}$ with > 5σ and measure $\mathscr{B}(K_L \to \pi^0 \nu \bar{\nu})$ with 25% precision

Roadmap	2025	2030	2035	2040
KOTO	Data taking (SES < 10^{-10}) →			
KOTO II		Construction →	Data taking →	

Backup

KOTO

By product physics at KOTO

1γ $K_L \to \gamma\bar{\gamma}$: Dark photon search — *T. Wu, Talk @ ICHEP2024*

- SES=2.9×10^{-8} (2 hours run), expected N$_{BG}$=12.7, observed 13 => BR<3.5×10^{-7} (90% CL) ***Preliminary***

2γ $K_L \to \pi^0 X$ (X: invisible)

- Simple byproduct of $K_L \to \pi^0 \nu\bar{\nu}$ analysis

3γ $K_L \to \pi^0 \gamma$: Violating Lorentz invariance — *N. Shimizu et al, PRD102, 051103 (2020)*

- (2016-18 data) SES=7.1×10^{-8}, estimated N$_{BG}$=0.34
  - No events observed, BR<1.7×10^{-7} (90% CL)

4γ $K_L \to \pi^0\pi^0\nu\bar{\nu}$ and $K_L \to \pi^0\pi^0 X$ (X: invisible) … taken in 2018; now revisited by a student in Taiwan G

4γ $K_L \to XX, X \to 2\gamma$ — *C. Lin et al, PRL130, 111801 (2023)*

- (2018 data) N$_{BG}$=0.61, No events observed.
- BR<(1-4)×10^{-7} (M$_X$: 40-110MeV/c^2), BR<(1-2)×10^{-6} (M$_X$: 210-240MeV/c^2)

6γ $K_L \to \pi^0\pi^0 X, X \to 2\gamma$ and $K_L \to \pi^0\pi^0\gamma\gamma$ ***Preliminary*** — **Talk by J. Redeker**

- (2021 data) BR<(0.8-3)×10^{-7} (Mx=170-220MeV/c^2), BR($K_L \to \pi^0\pi^0\gamma\gamma$)<11.2×10^{-7}

6EM $K_L \to \pi^0 4e$ — *X. Li, Talk @ ICHEP2024*

- (2018 data) No events observed, BR<4.1×10^{-7} (90% CL) ***Preliminary***

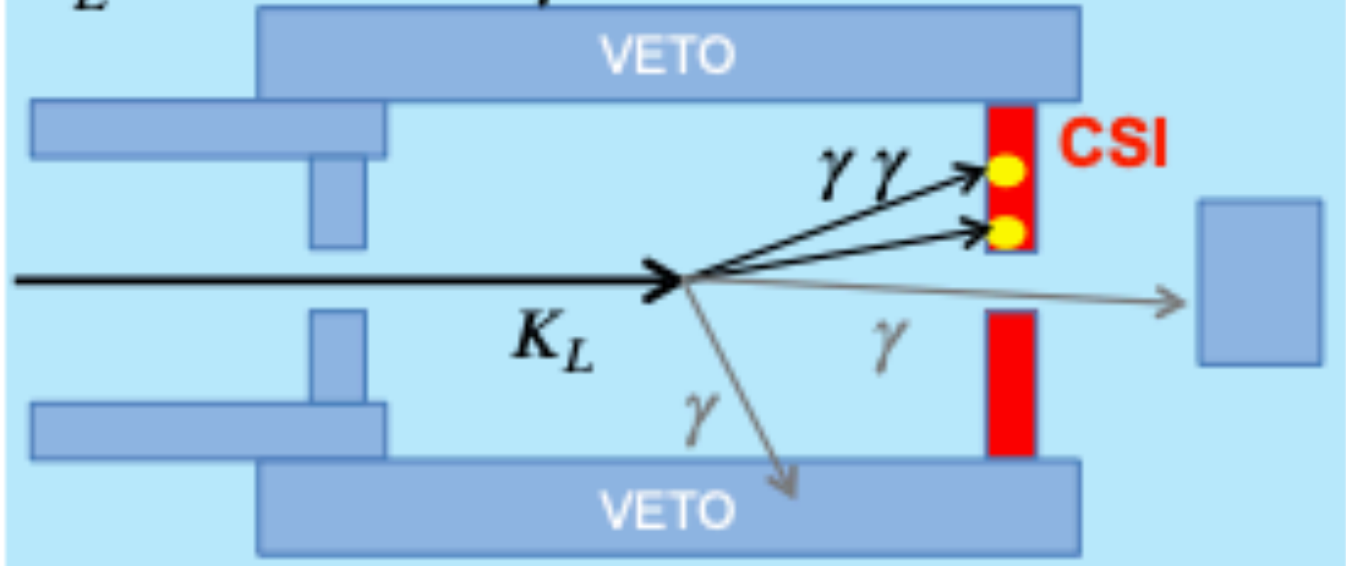
4EM $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0 X, X \to e^+e^-$ … trial data taking in 2024/2025 runs — **Poster by Y. T. Su**

EM: γ or e$^+$/e$^-$

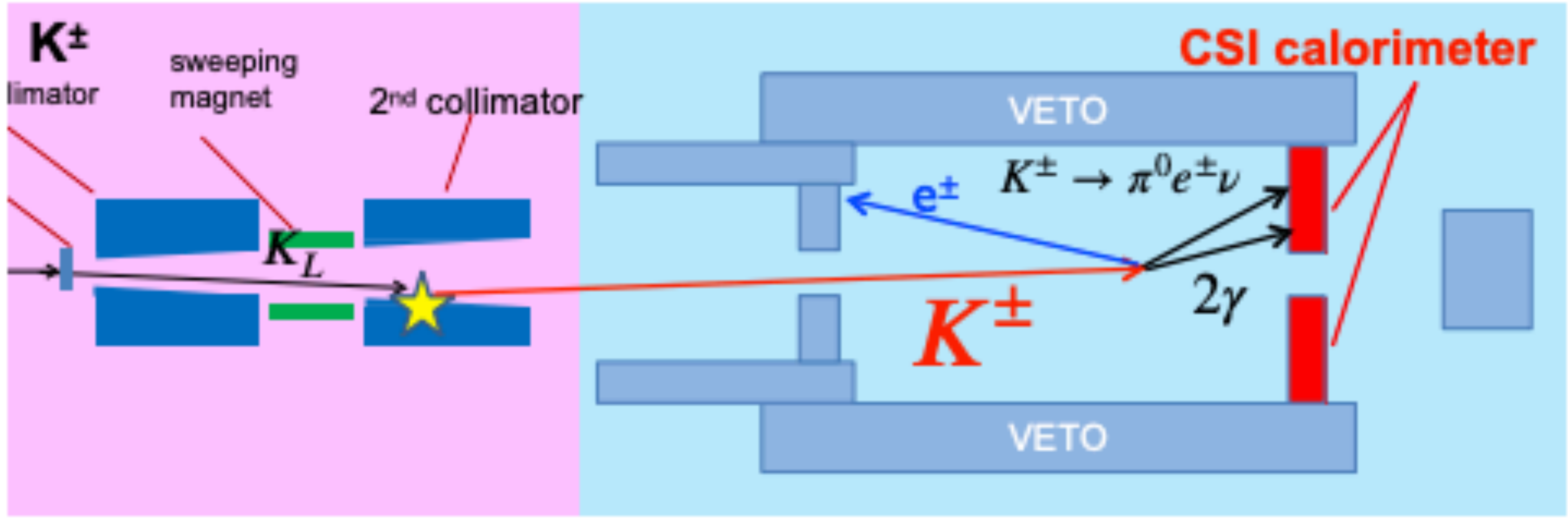
3EM $K_L \to \gamma X, X \to e^+e^-$ … trial data accumulation in 2025 run

BG mechanism

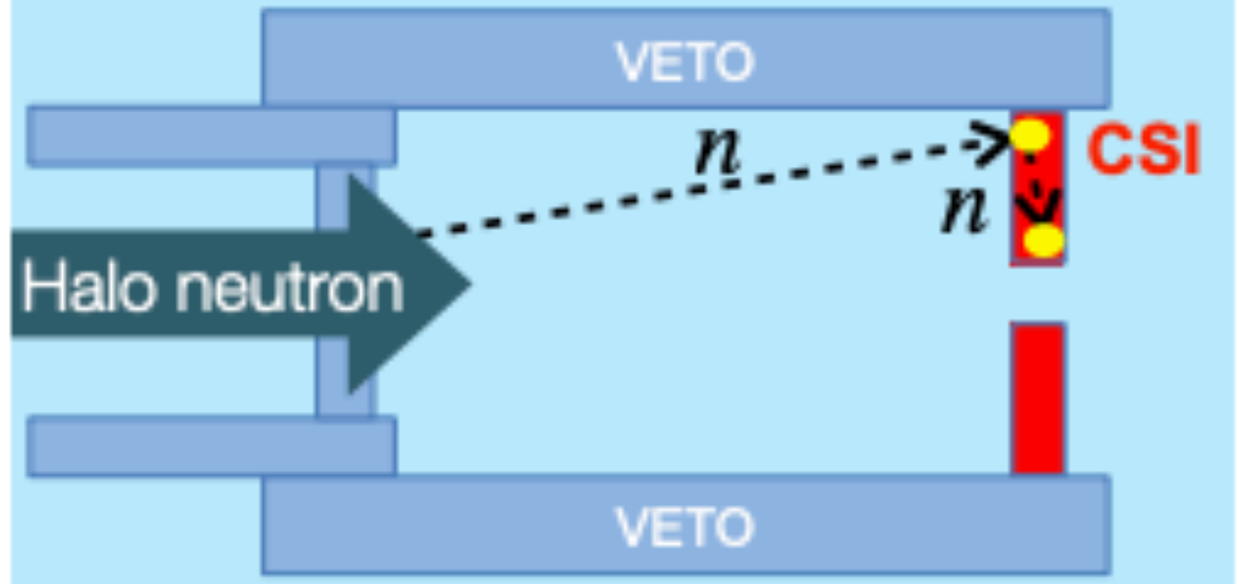
$K_L \to \pi^0\pi^0 \to 4\gamma$



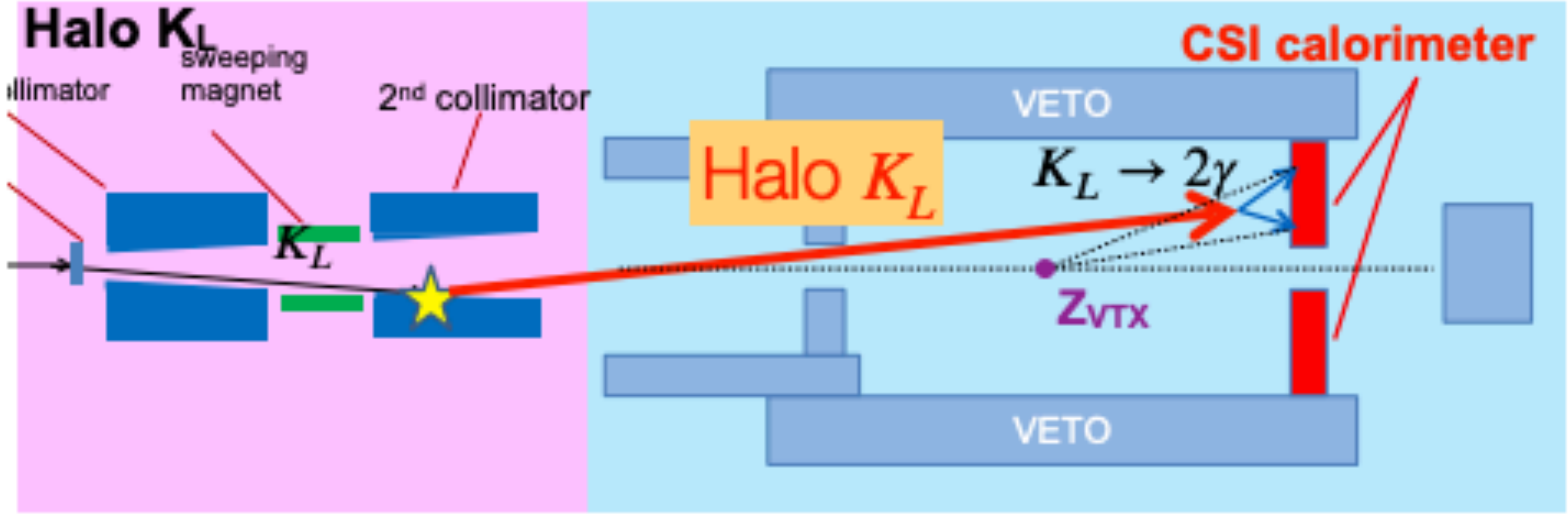
2 of 4γ hit CSI and
2 are lost due to detection inefficiency



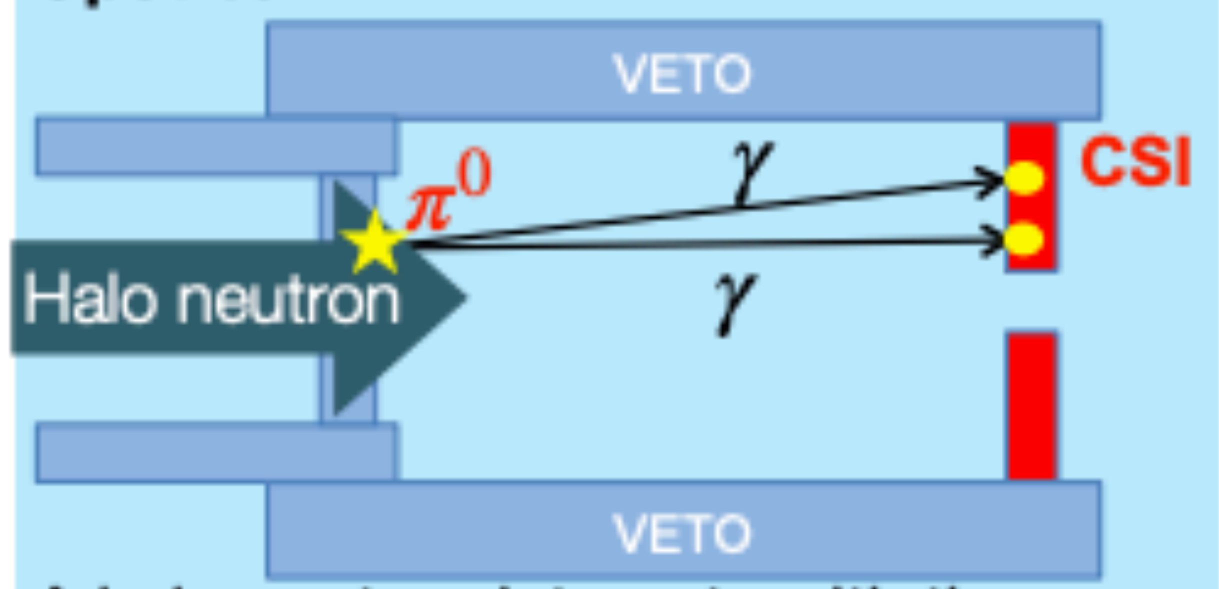
Hadron cluster



A halo neutron directly hit the calorimeter
and makes 2 clusters

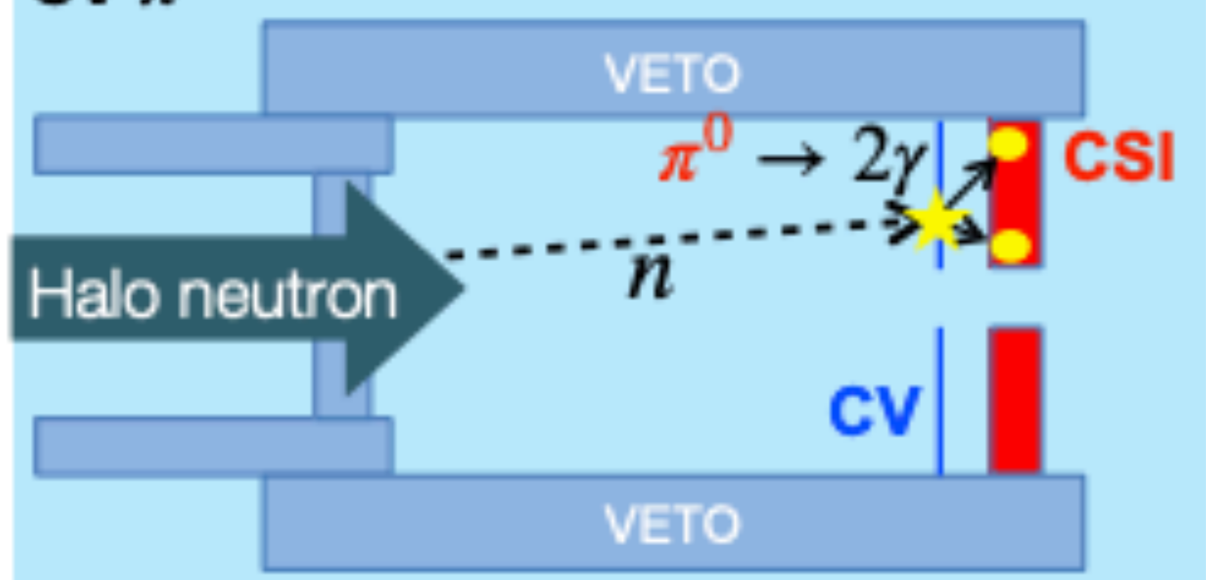


Upstream π^0



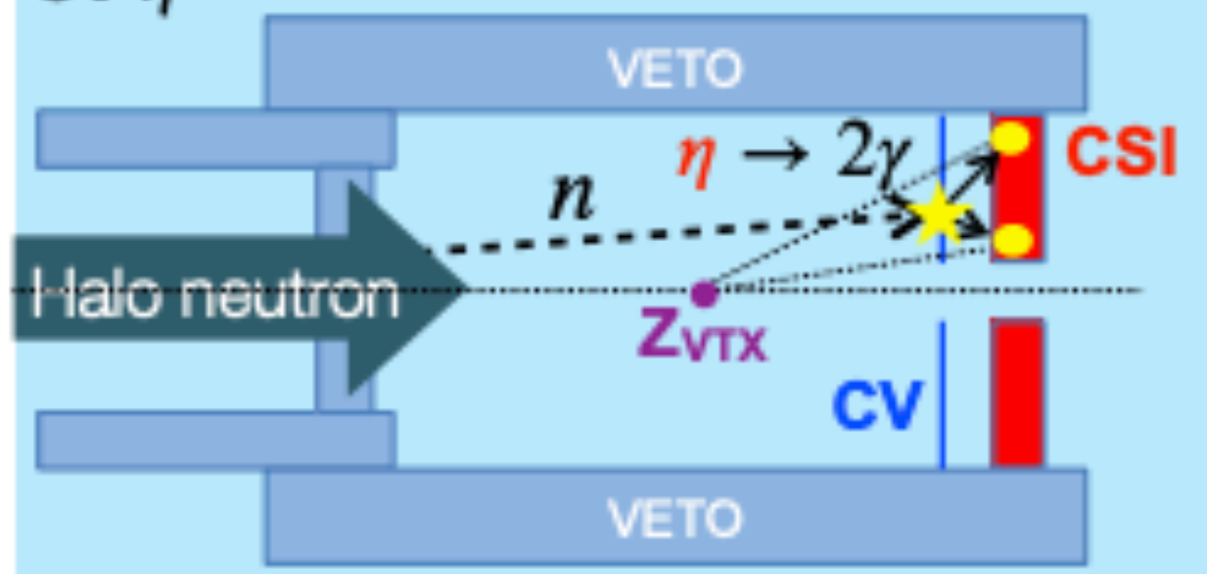
A halo neutron interacts with the
upstream detector and produces π^0

CV π^0



A halo neutron interacts with CV and
produces π^0

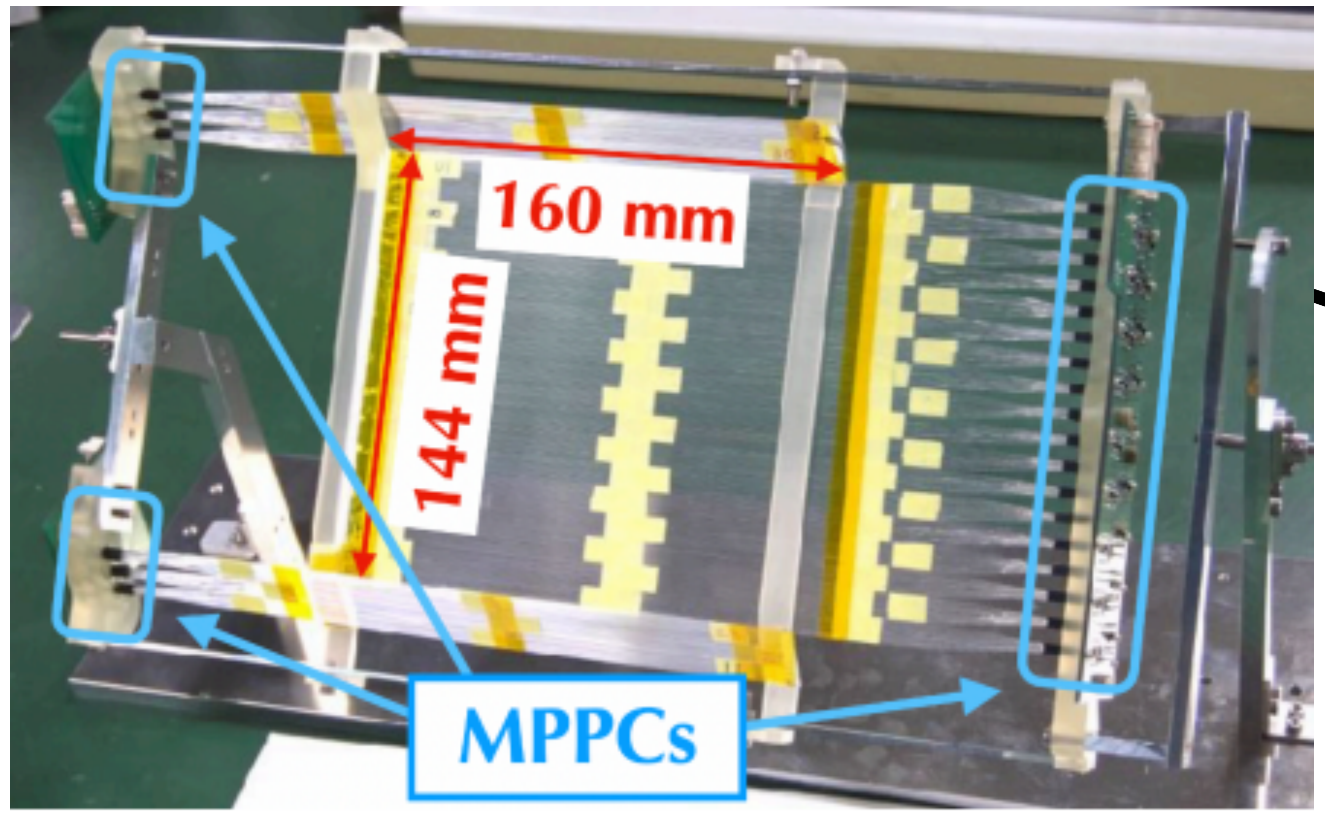
CV η

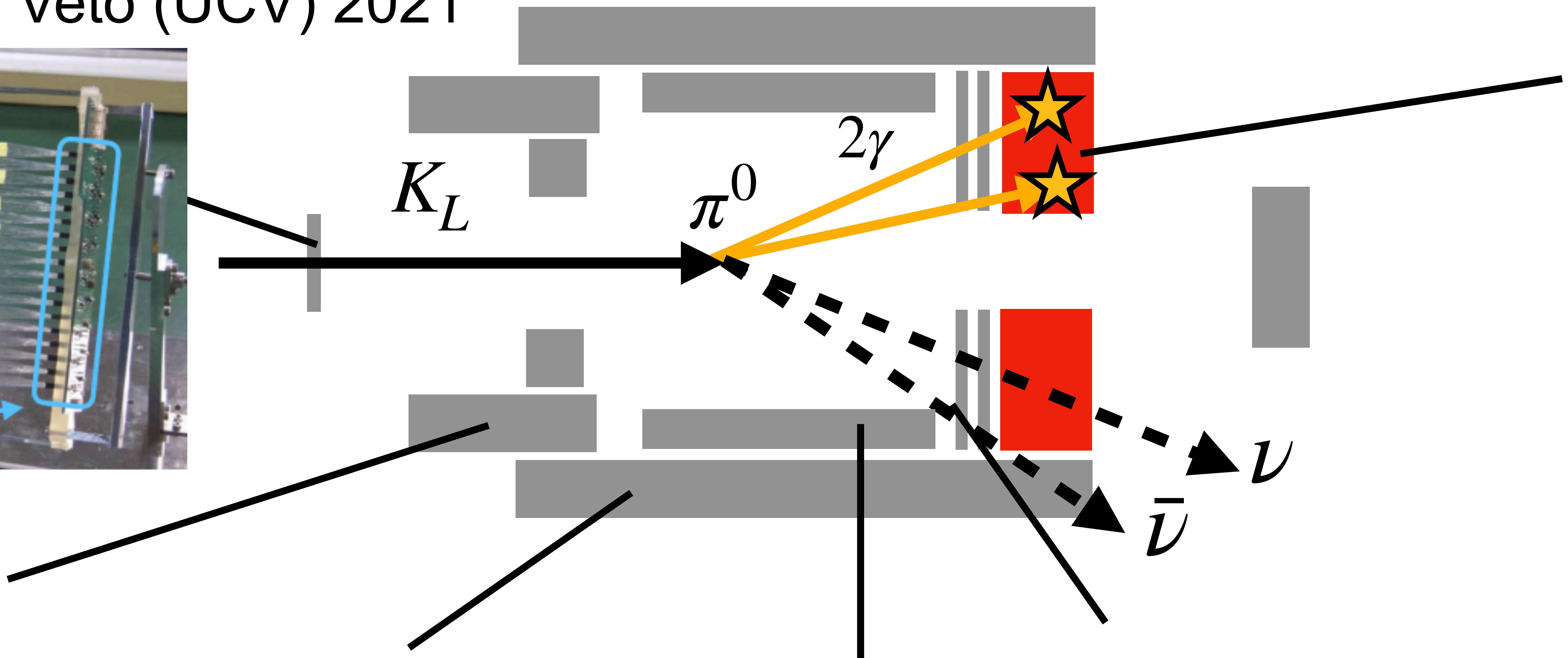


A halo neutron interacts with CV and
produces η →wrong vertex reconstruction

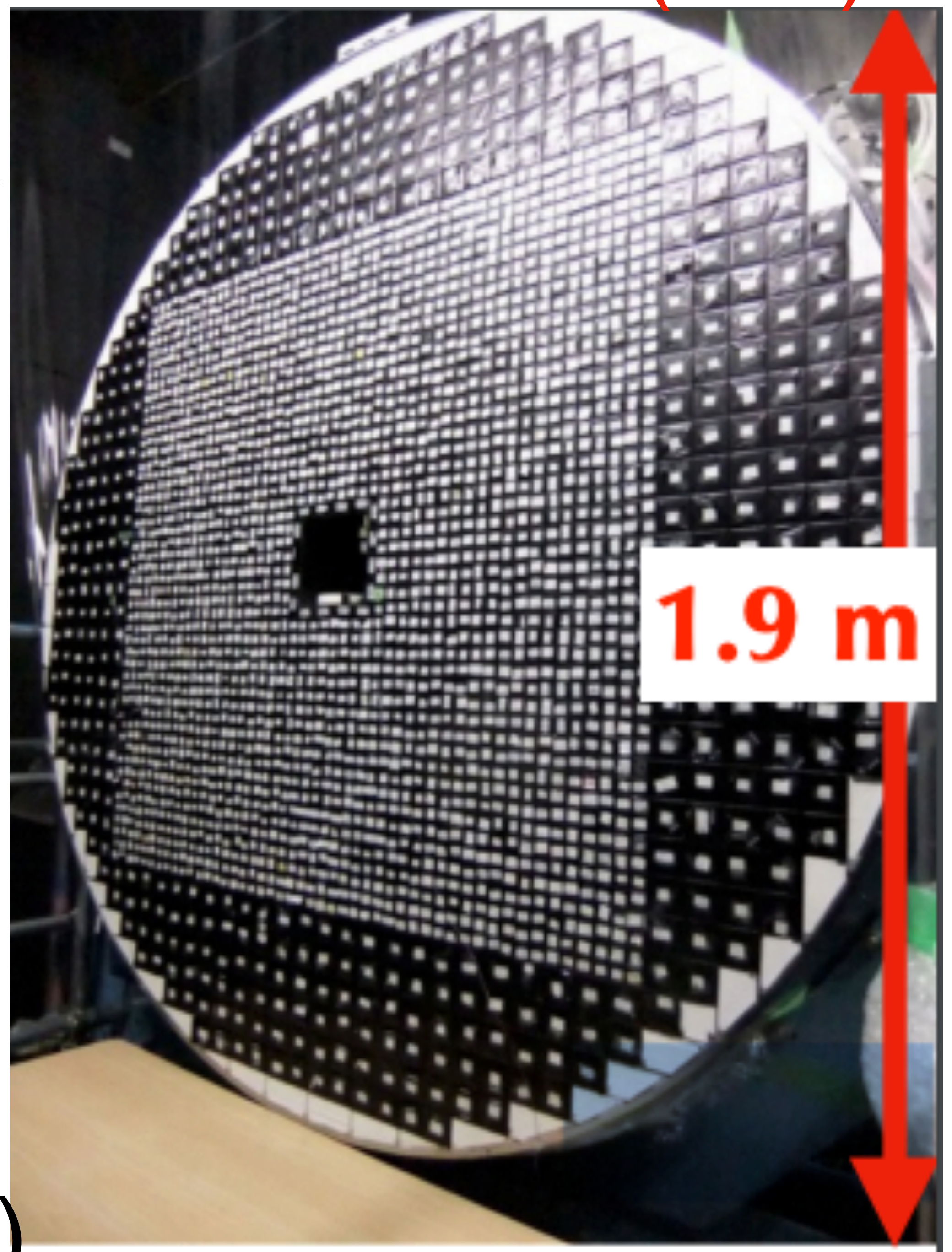
KOTO detector

Upstream Charged Veto (UCV) 2021

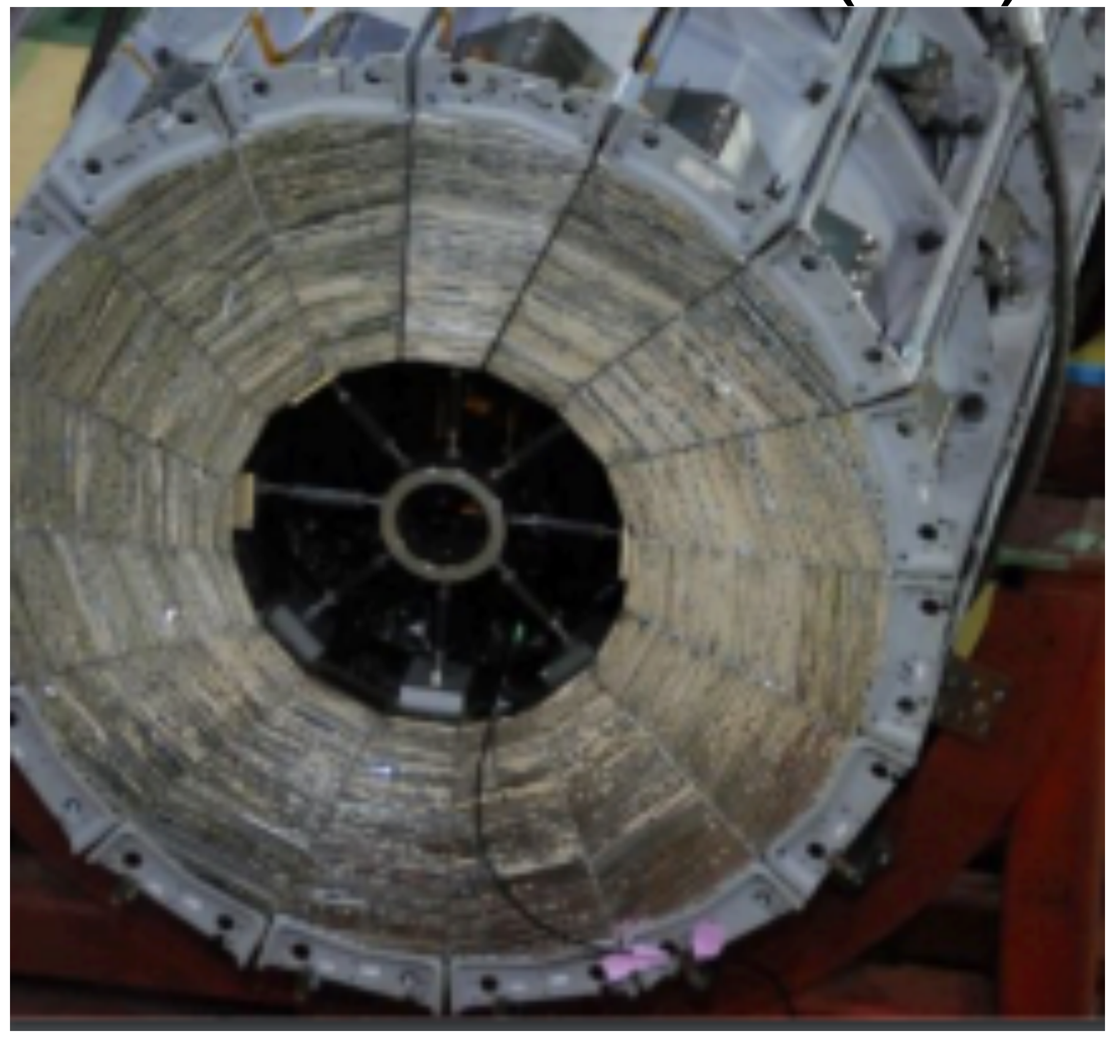




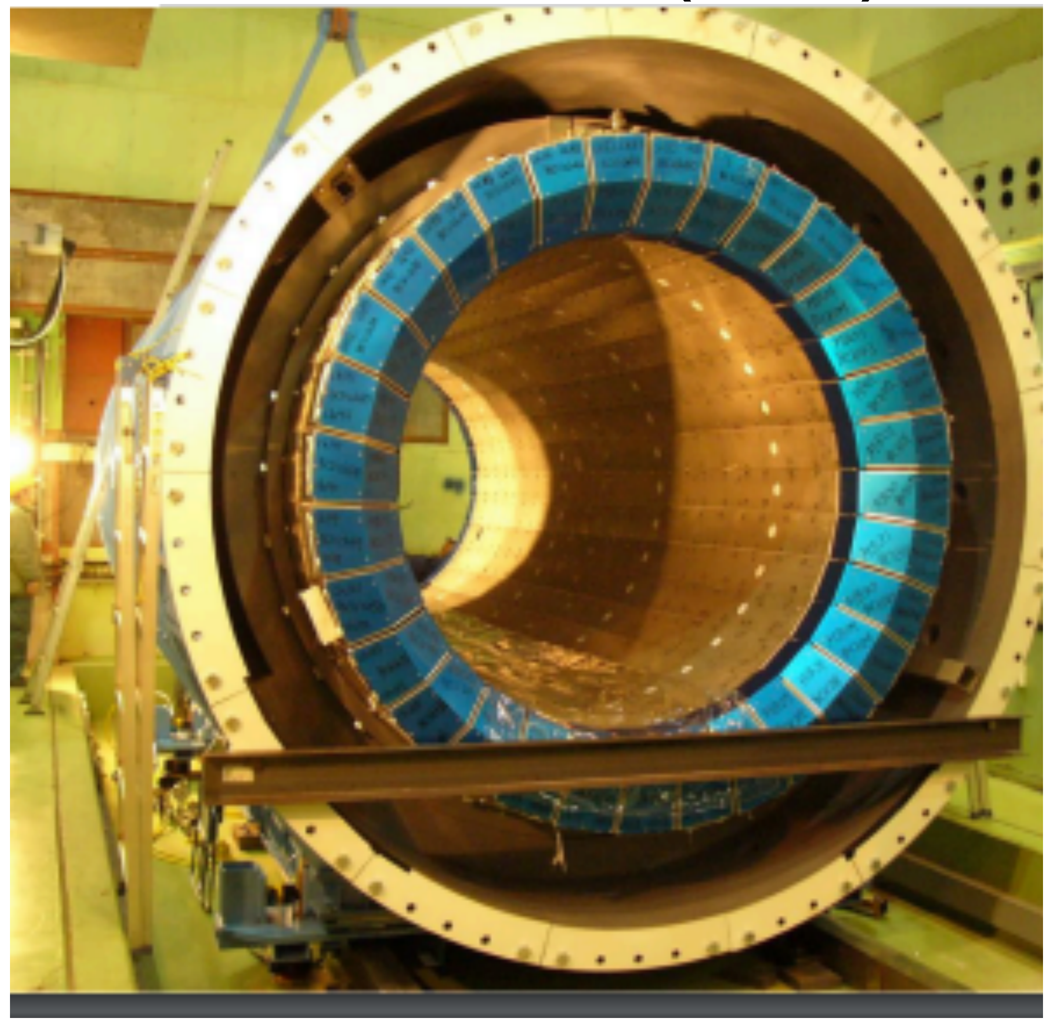
Calorimeter (CSI)



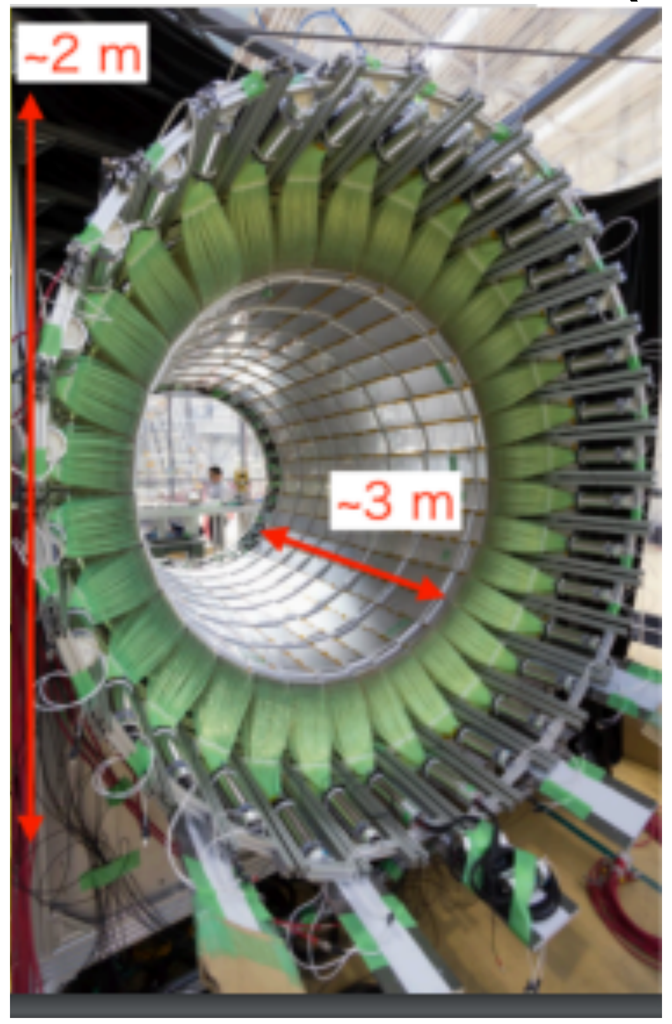
Front Barrel(FB)



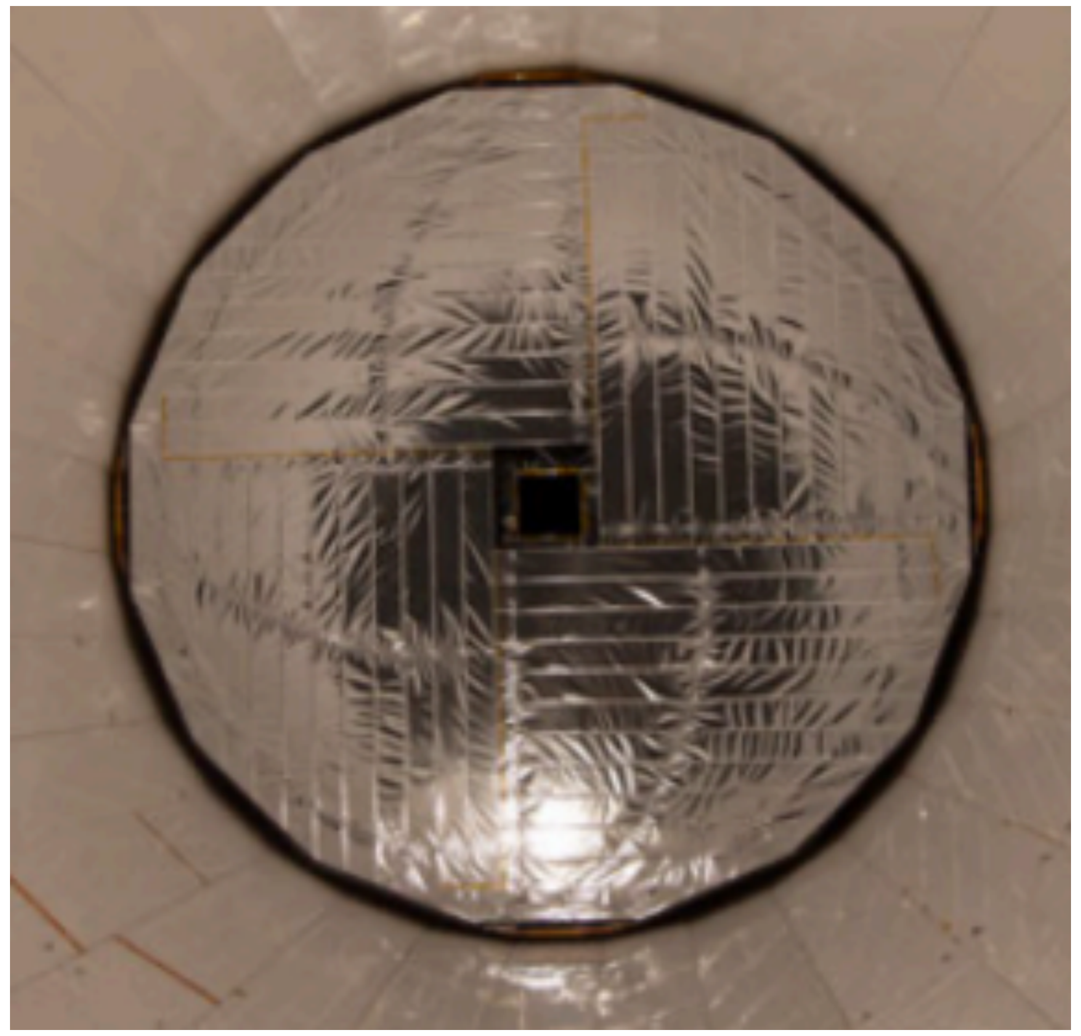
Main Barrel (MB)



Onner Barrel (IB)



Charged Veto(CV)

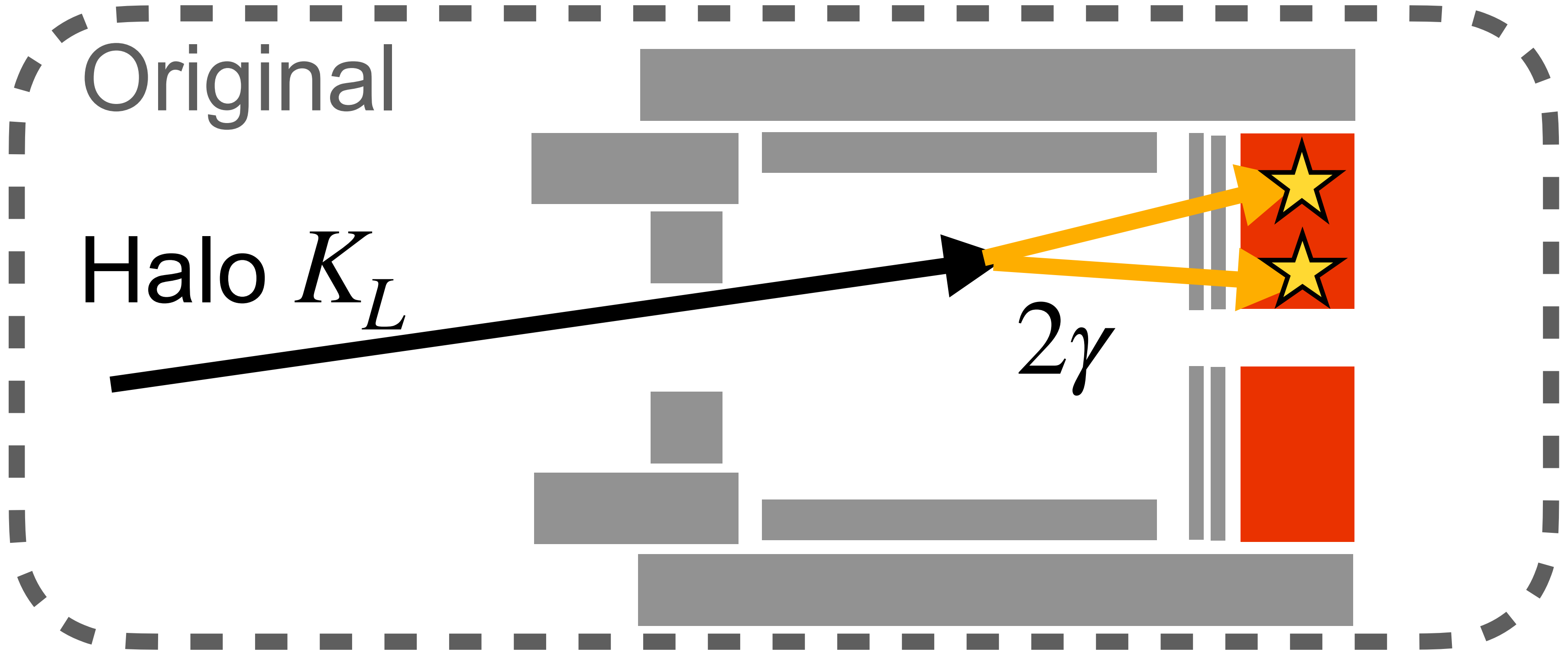


Lessons from 2021 data analysis : UCV drawback

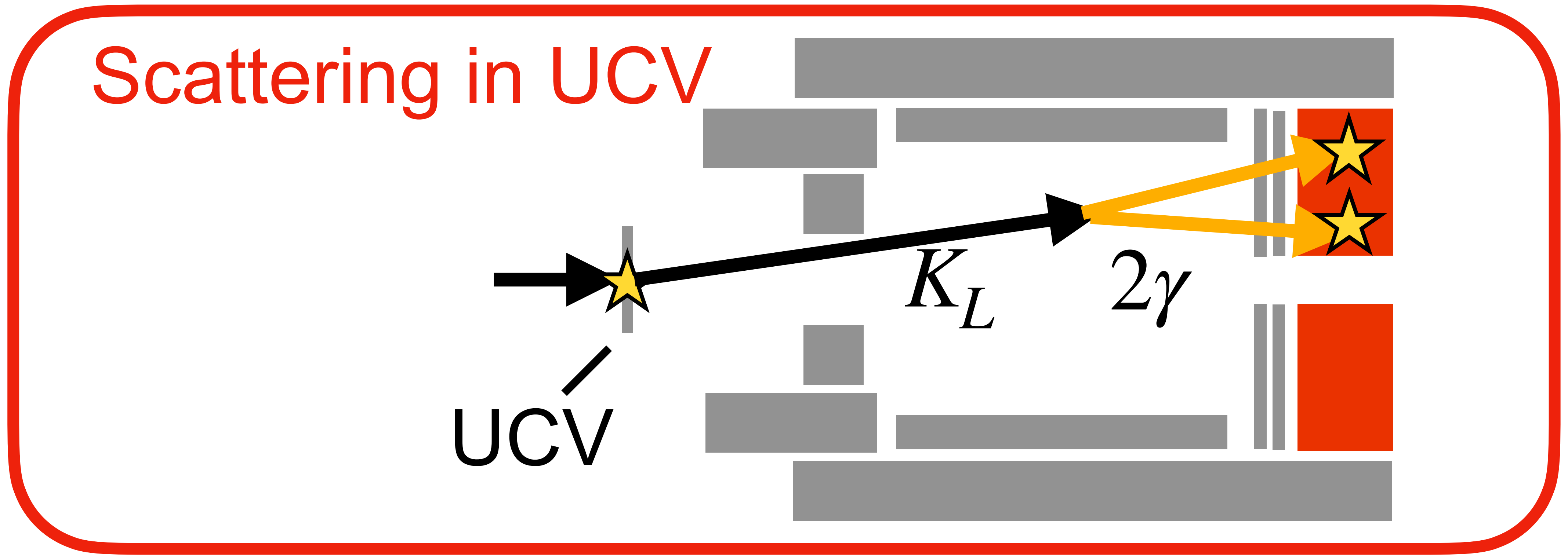
- Installed Upstream Charged Veto (UCV) to suppress $K^{\pm}$ BG in 2021
- It had several drawbacks

  - Contribution of $K^{\pm}$ BG was still as large as SM signal
  - Increased halo $K_L \to 2\gamma$ BG and Neutron BG (× 2) due to the scattering of K_L and neutron in UCV

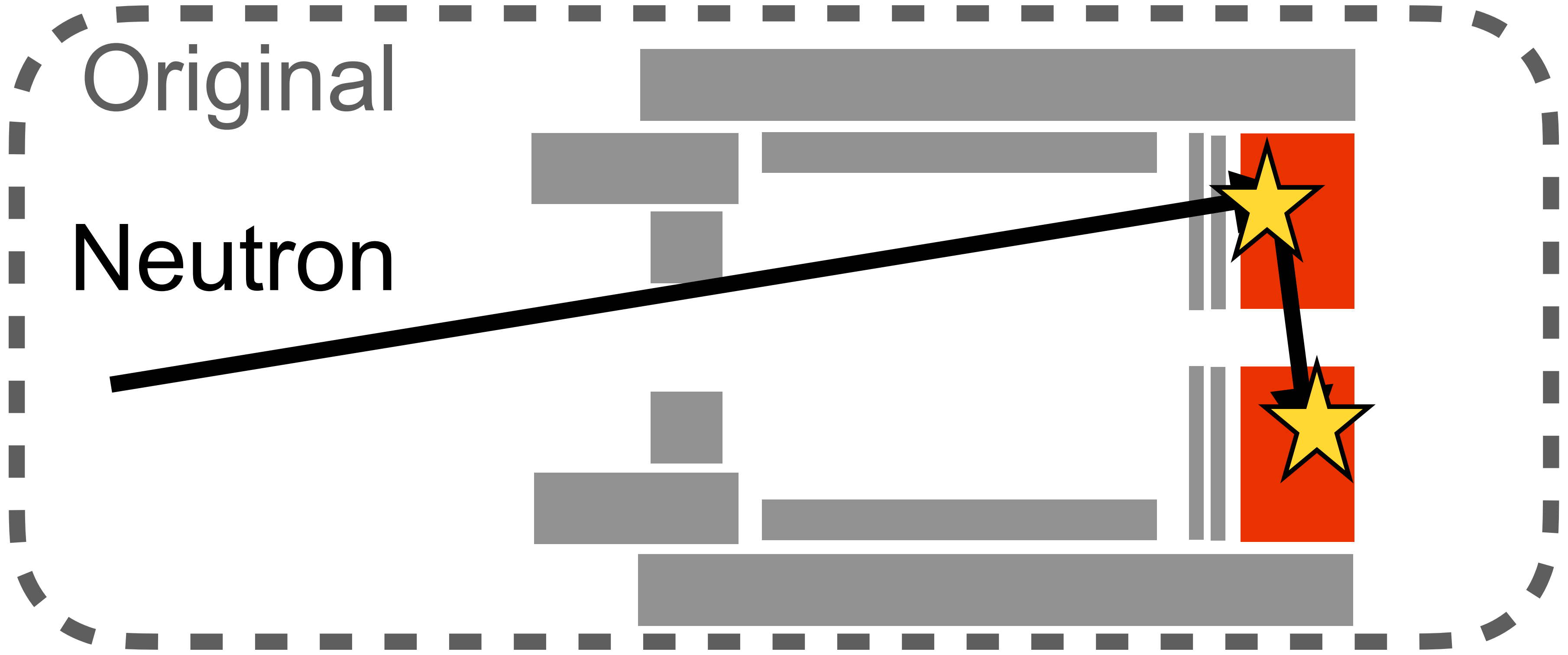
Halo $K_L \to 2\gamma$ BG



+



Neutron BG



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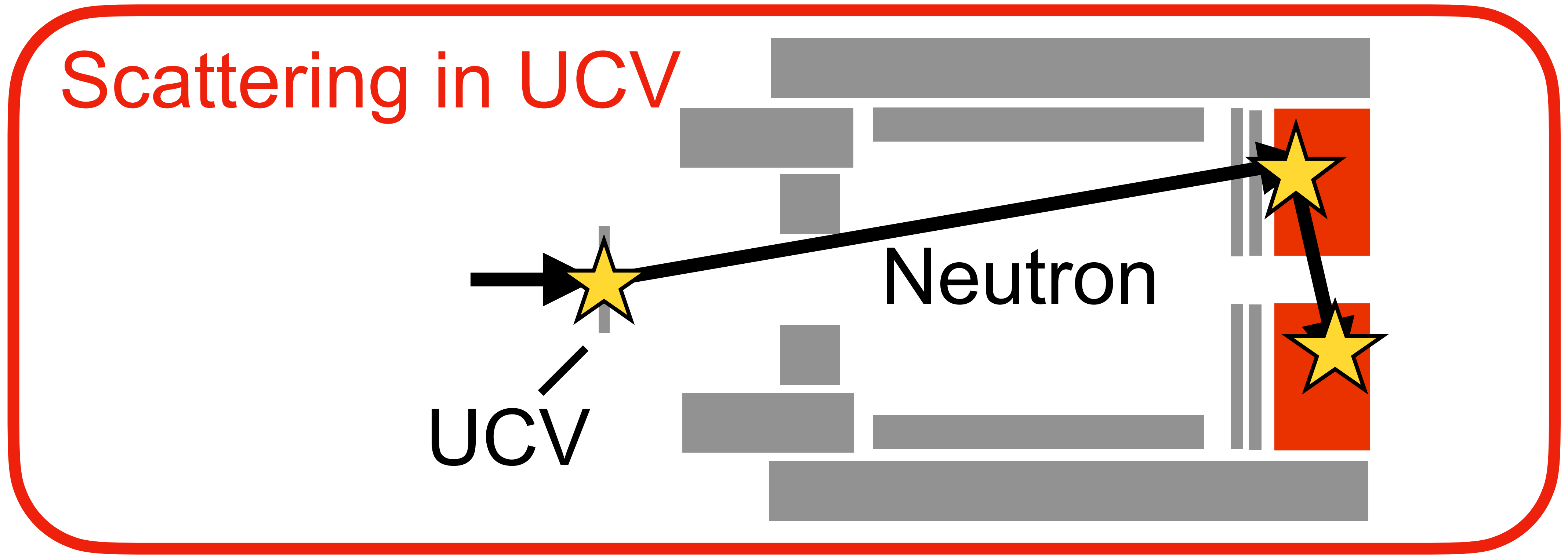
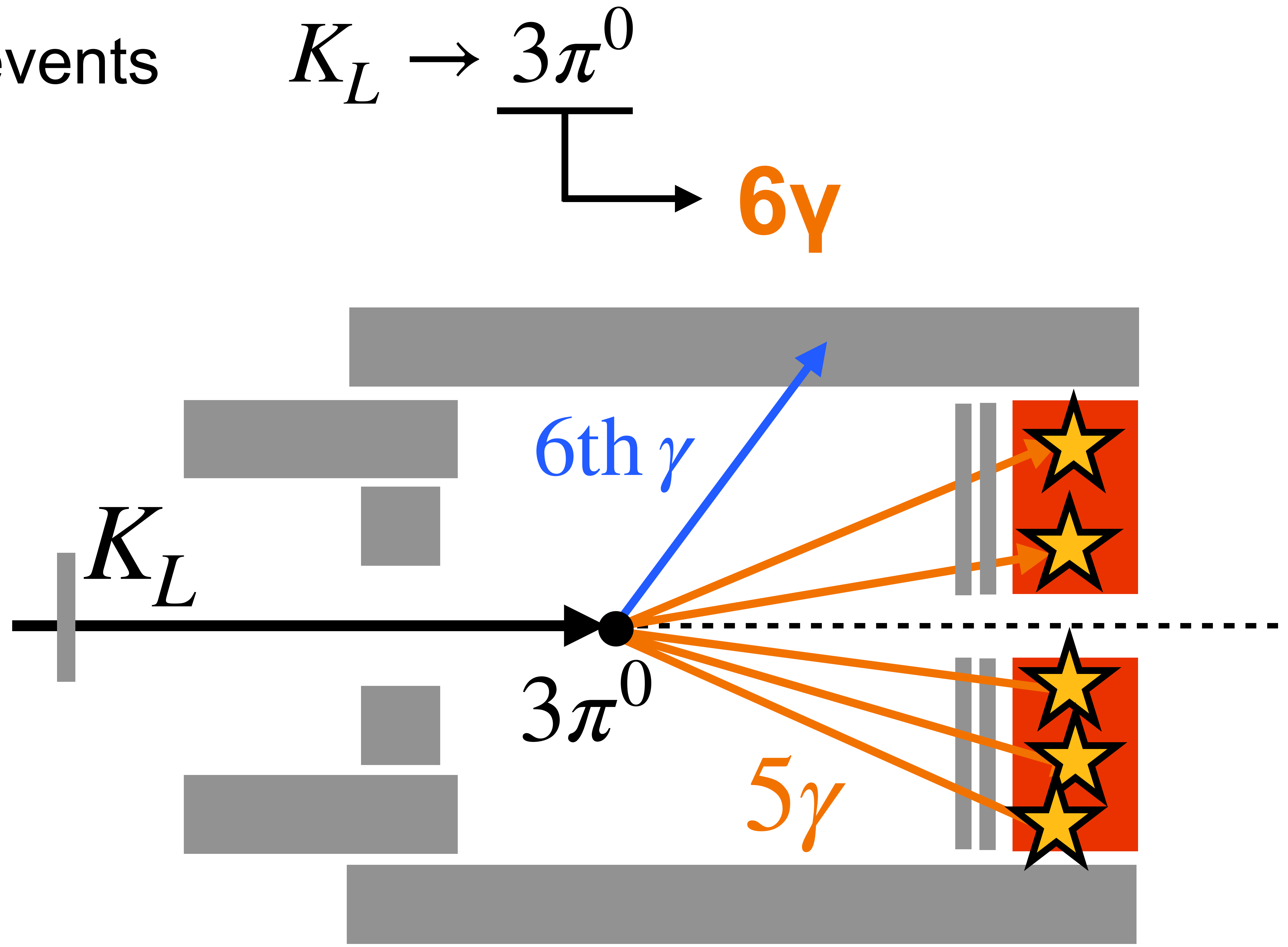


Lessons from 2021 data analysis : $K_L \to 2\pi^0$ BG estimation

Introduced a data-driven photon inefficiency evaluation for $K_L \to 2\pi^0$ BG estimation

- Evaluate the inefficiency with $K_L \to 3\pi^0$ events
  - Require 5γ in CSI calorimeter
  - Reconstruct the momentum of the 6th γ by kinematic constraints
  - Check the energy deposit in veto detector

$$\text{Inefficiency} = \frac{N_{E_{dep}<\text{threshold}}}{N_{5\gamma\,\text{in CSI}}}$$



100% statistical uncertainty of inefficiency due to the limited statistics of control data

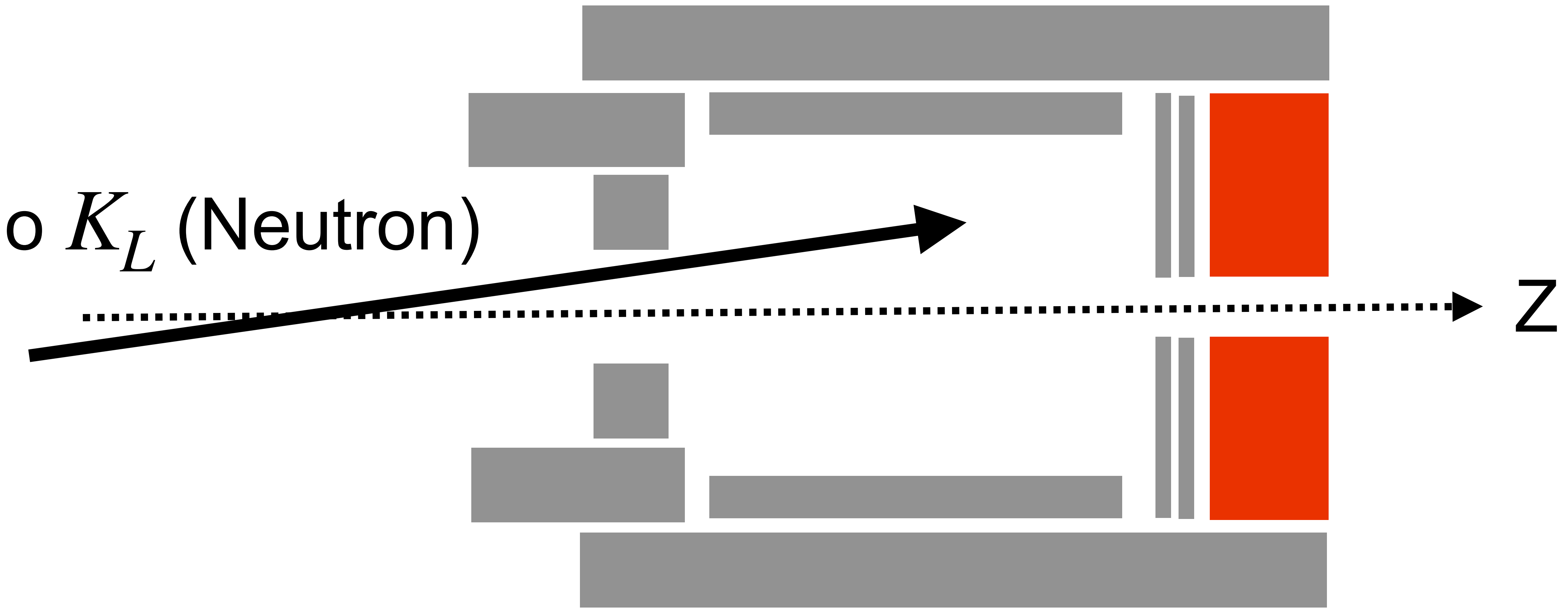
Flux change of halo KL and neutron（Expectation）

- Evaluated the change of the flux of BG source (halo KL and neutron) after our upgrade

Expectation

UCV upgrade
- Reduced material budget
  →**Flux will decrease** ☺️

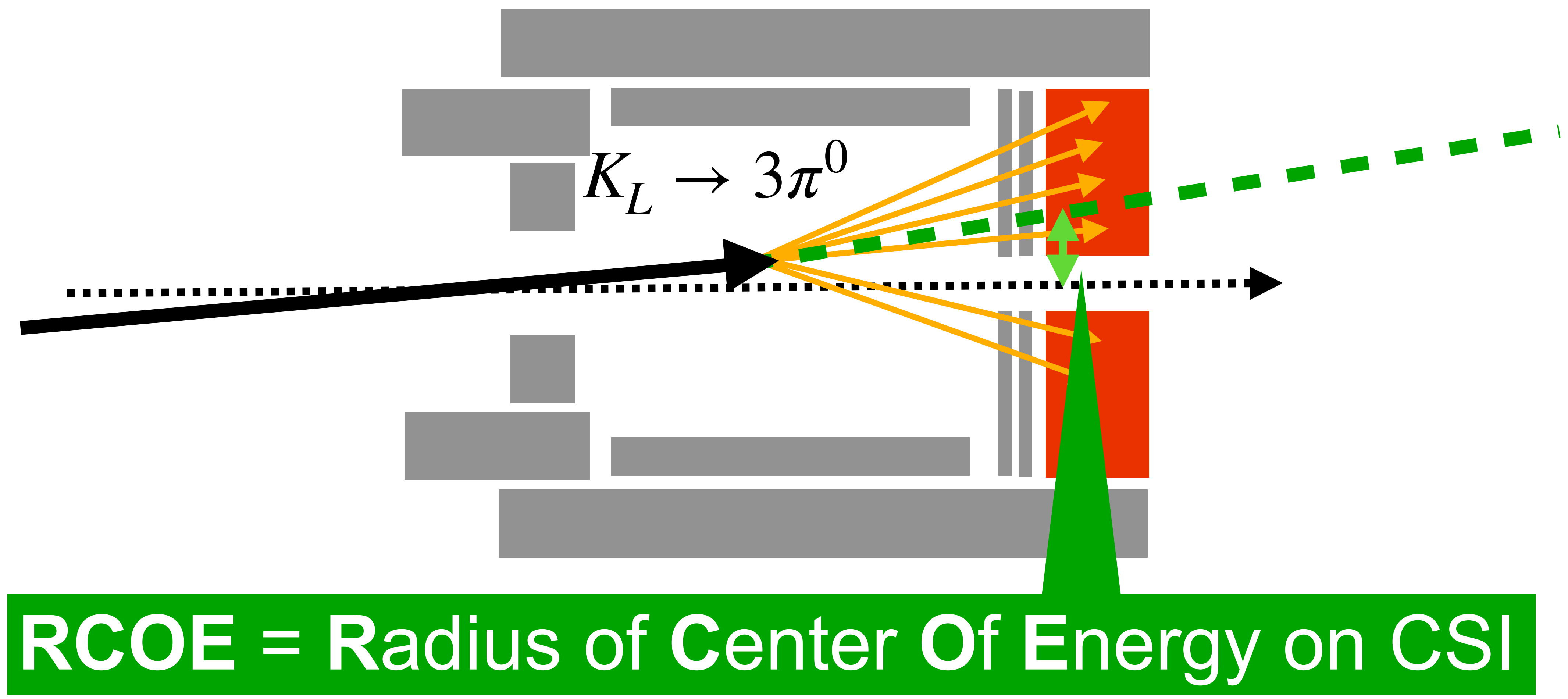
Magnet installation
- Changed the last part of collimator
  →**Flux will increase** 😭

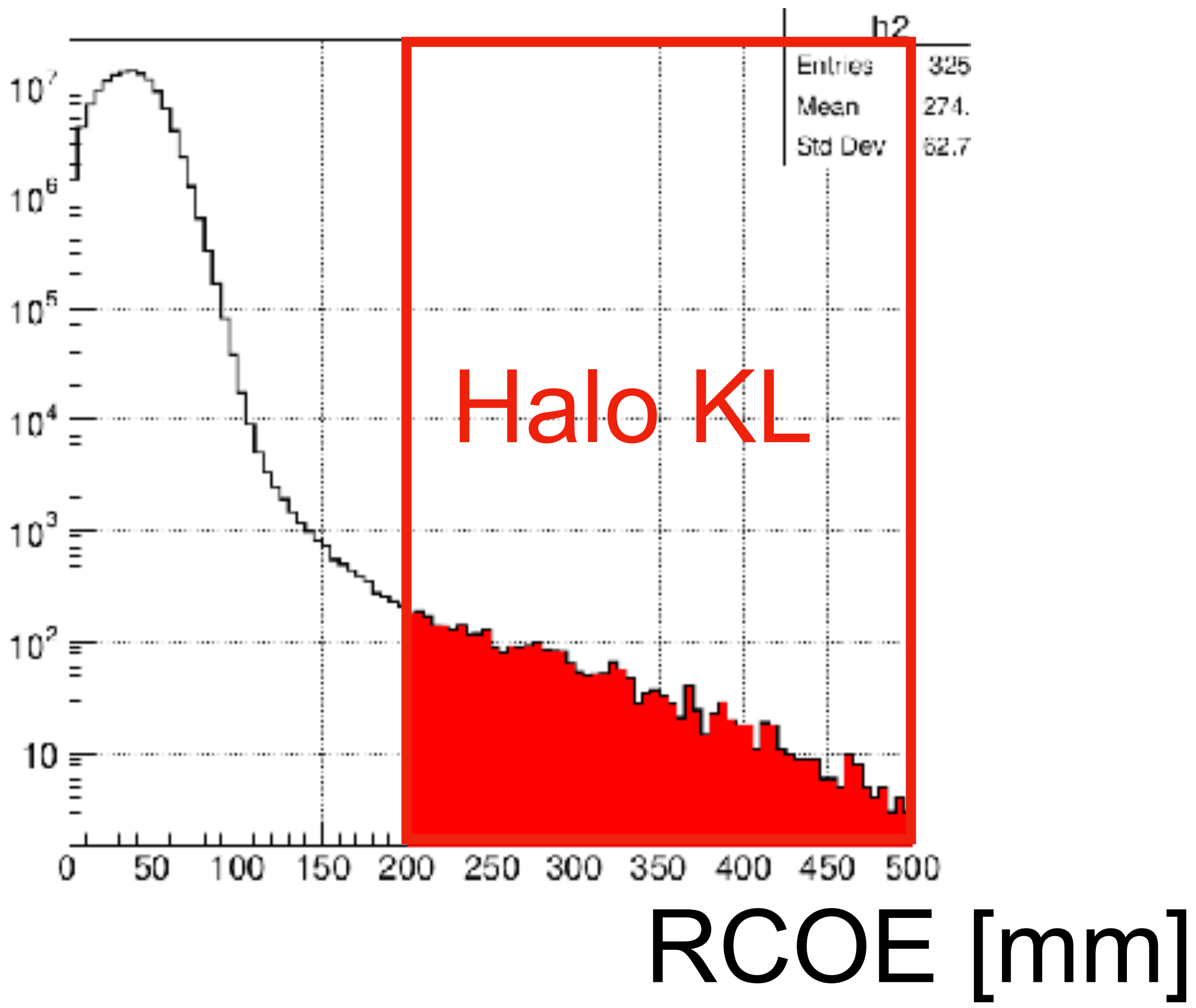


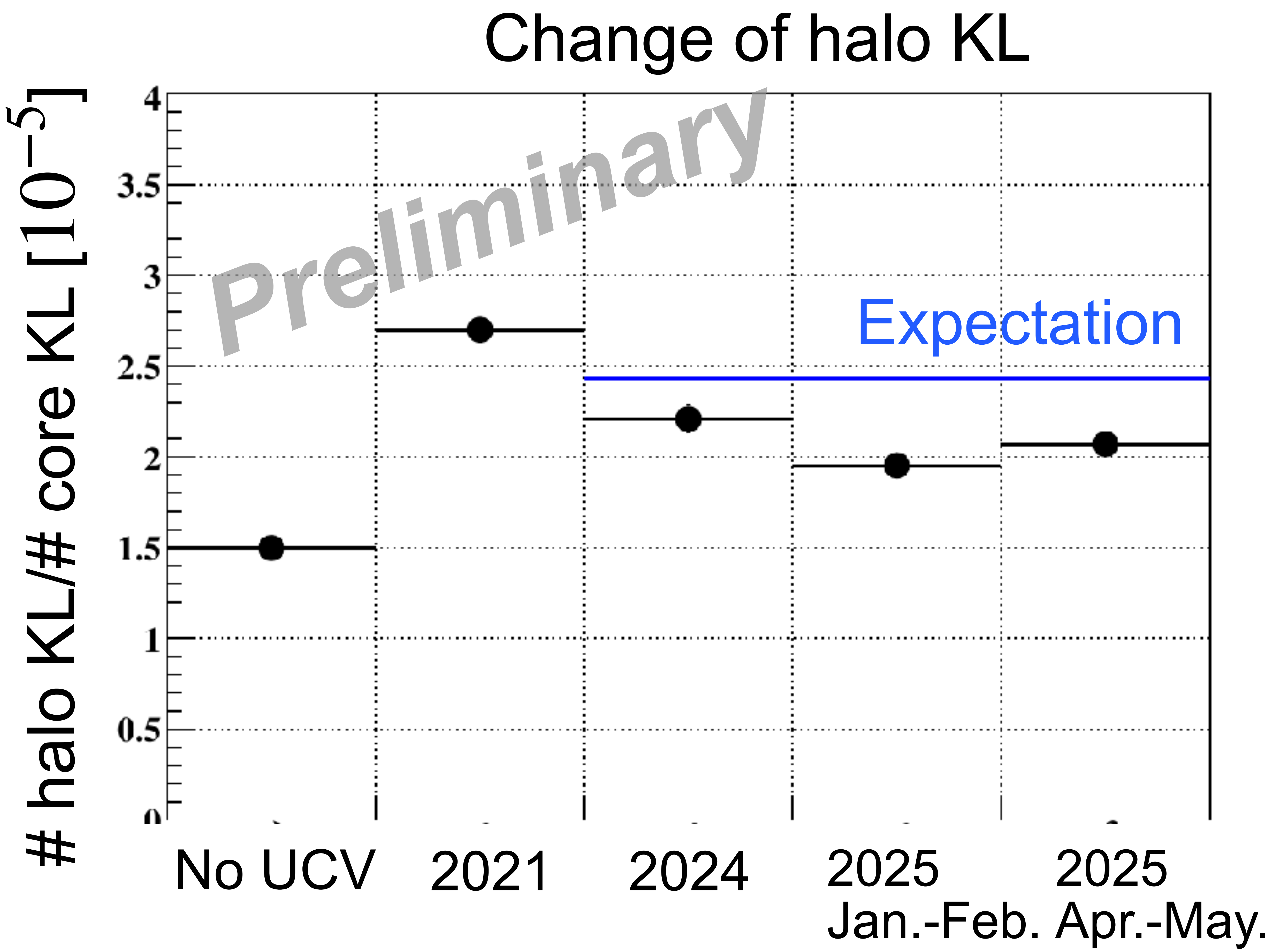
	2021	UCV upgrade		Magnet installation	**2024, 2025**
Halo KL :	1	×0.7 →	0.7	×1.2 →	**0.84 (-16%)**
Neutron :	1	×0.75 →	0.75	×1.07 →	**0.80 (-20%)**

Flux change : Halo KL

Halo KL : Evaluated by using $K_L \to 3\pi^0$ sample



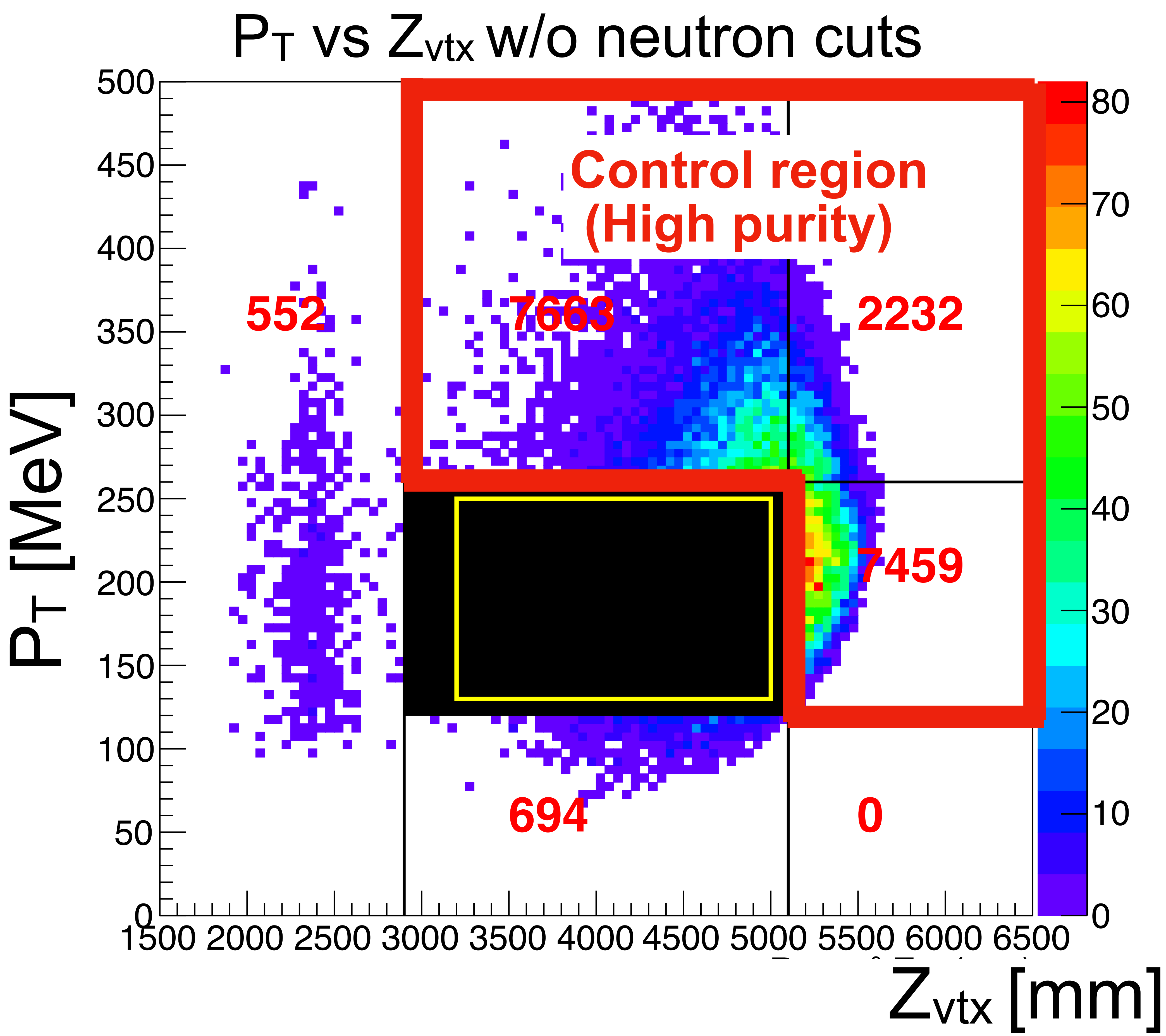


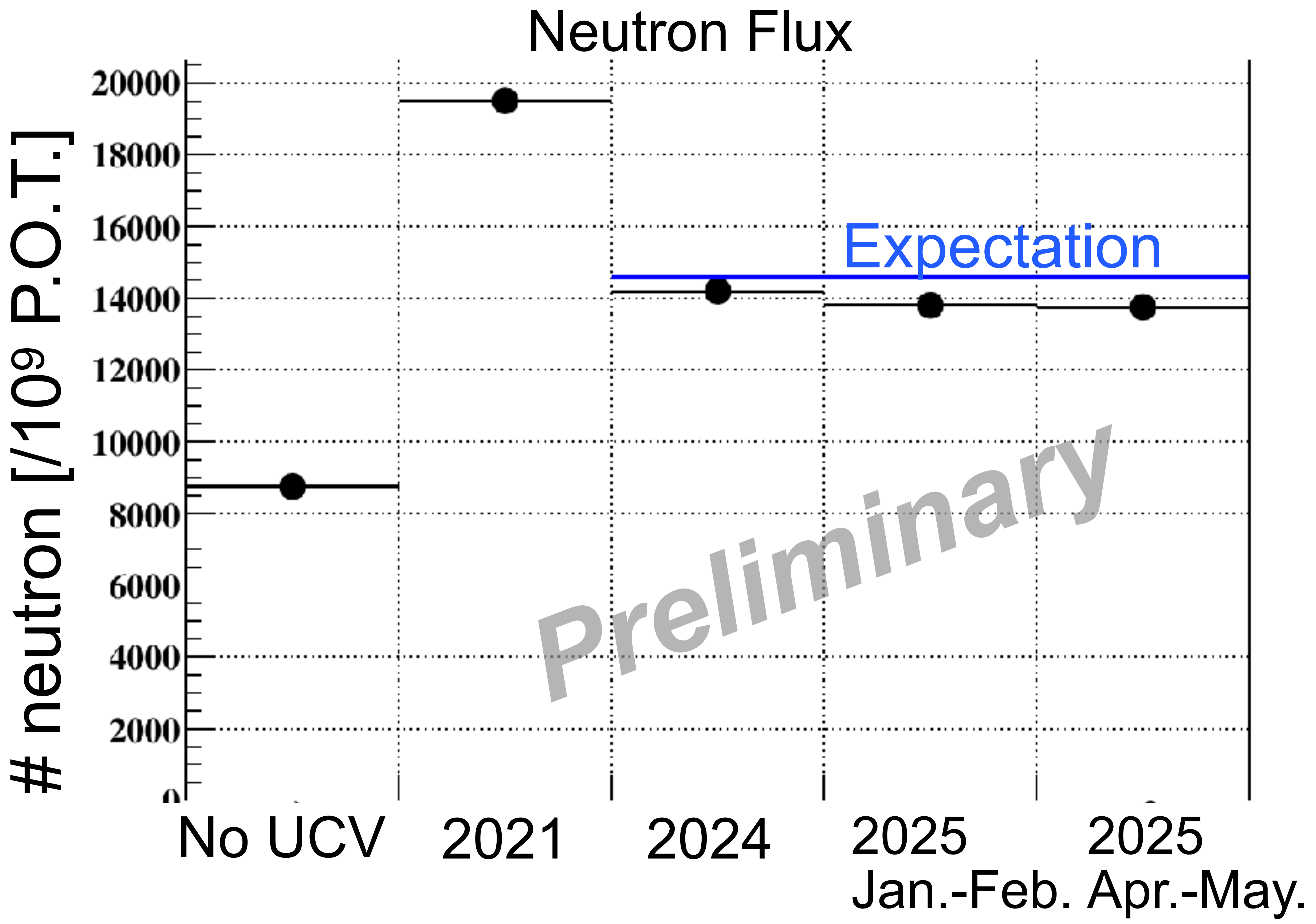


The flux of halo KL decreased by 23% due to the combined effects of both UCV and magnet

Flux change : Neutron

Neutron : Evaluated by using control region in P_T vs Z_{vtx} plane





The flux of neutron decreased by 30% due to the combined effects of both UCV and magnet

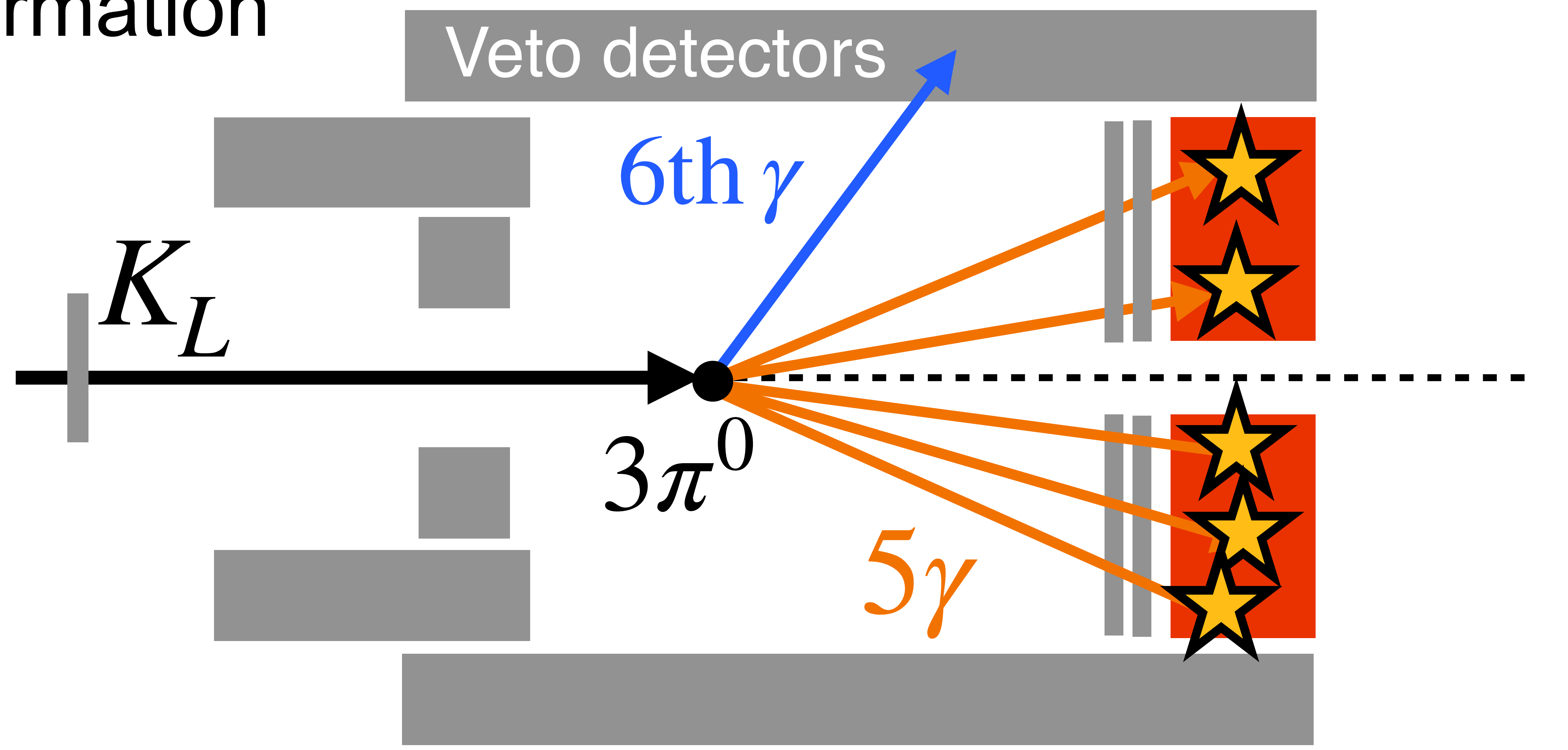
Photon inefficiency evaluation using 2024 data

Thanks to DAQ upgrade, we were able to accumulate 5γ data more effectively in 2024, 2025

→Evaluated photon inefficiency with data from 2024 data analysis

- Evaluate the inefficiency with $K_L \rightarrow 3\pi^0$ events with 5 clusters in CSI
  - Reconstruct energy of 6th γ(E_{γ_6}) and direction by using kinematic constraints with the 5γ information
  - Check the energy deposit in veto detector of the destination

Inefficiency = $\dfrac{N_{E_{dep}<\text{threshold}}}{N_{5\gamma\text{ in CSI}}}$



Photon inefficiency evaluation using 2024 data

In case of Barrel detector with incident γ energy $E_{\gamma_6} > 200\,\mathrm{MeV}$

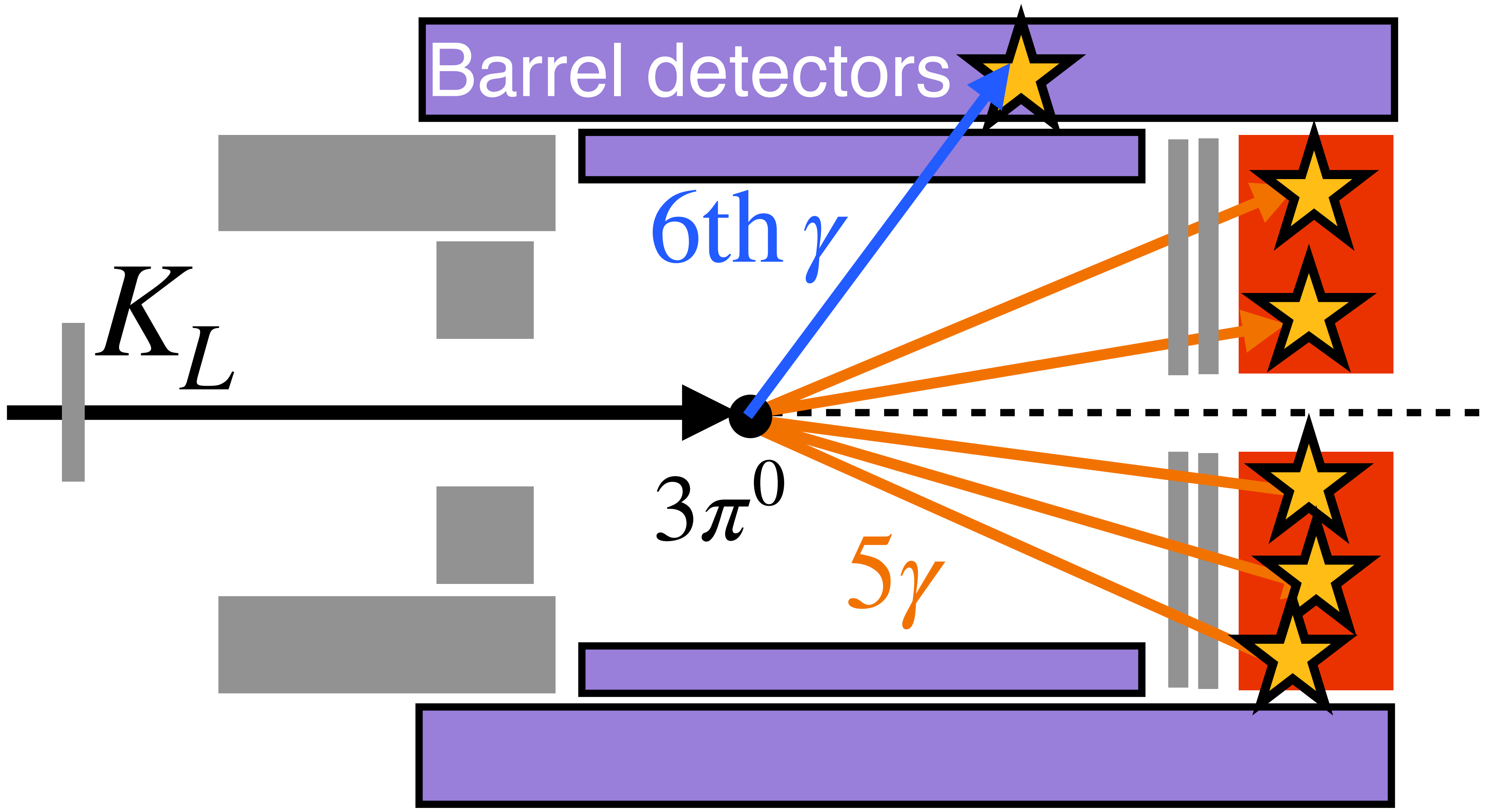
2021

$N_{E_{dep}<\mathrm{threshold}} = 1$

Corresponding inefficiency = $(4.8 \pm 4.8) \times 10^{-5}$

→ 100% statistical uncertainty

Inefficiency = $\dfrac{N_{E_{dep}<\mathrm{threshold}}}{N_{5\gamma\,\mathrm{in\,CSI}}}$



2024

$N_{E_{dep}<\mathrm{threshold}} = \mathbf{12}$

Preliminary

Corresponding inefficiency = $(5.5 \pm 1.6) \times 10^{-5}$

→ ***Reduced statistical uncertainty by ~ 30%***

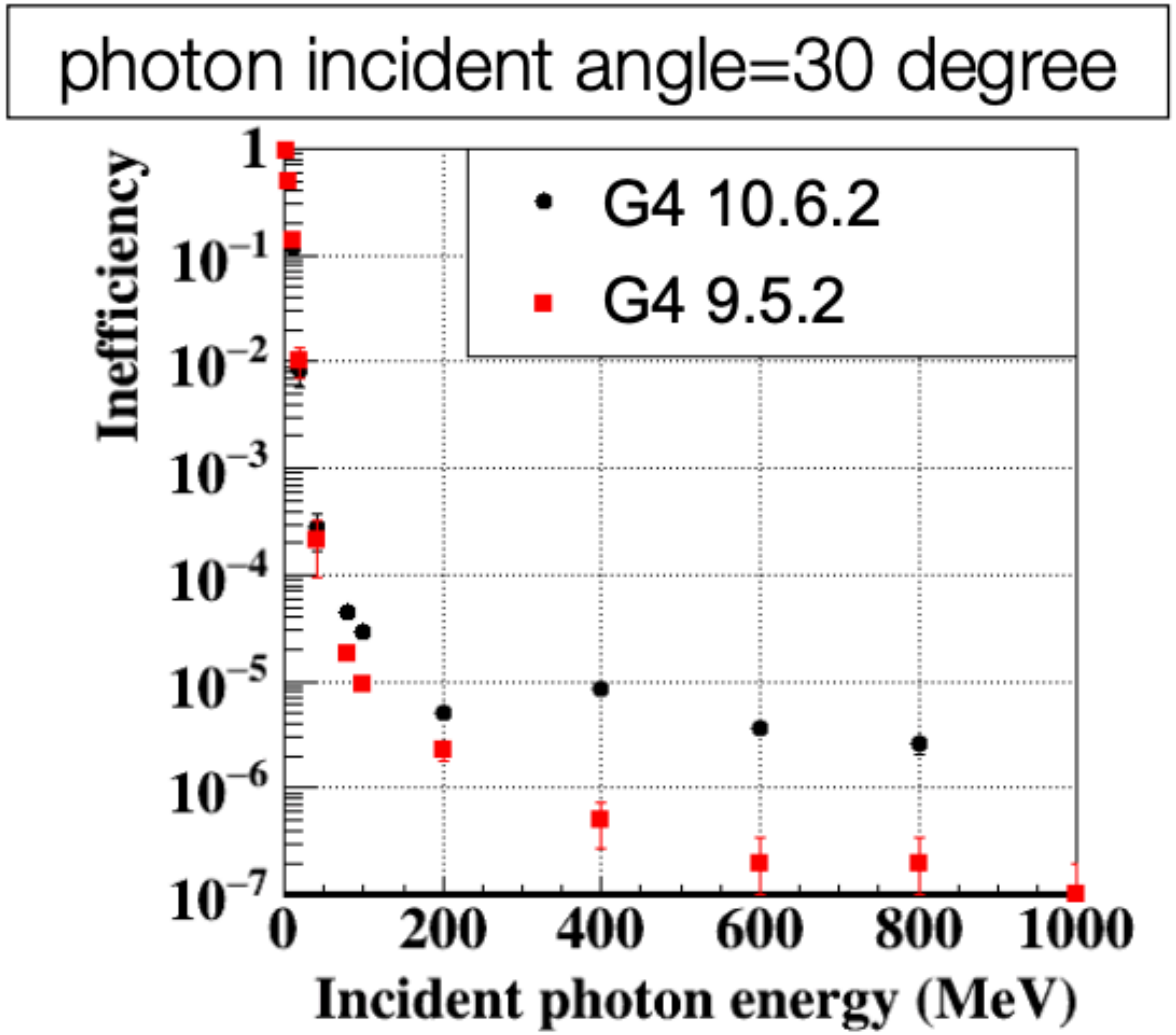
- Expect to reduce the statistical uncertainty of photon inefficiency by ~10% with 2024+2025 data

Photon inefficiency of the barrel detector with different Grant4 versions

Geant4-based MC simulation shows model dependance in the photon inefficiency

- The difference come from the difference of the model for photo nuclear interaction
- In $K_L \to 2\pi^0$ BG, we relied on MC simulation, but we don't know which model is true.

Data-driven evaluation is needed



* *No difference appears when photo-nuclear interaction is turned off.*

Quick check of 5γ data (2)

In case of Barrel detector with incident γ energy $E_{\gamma_6} > 200\,\mathrm{MeV}$

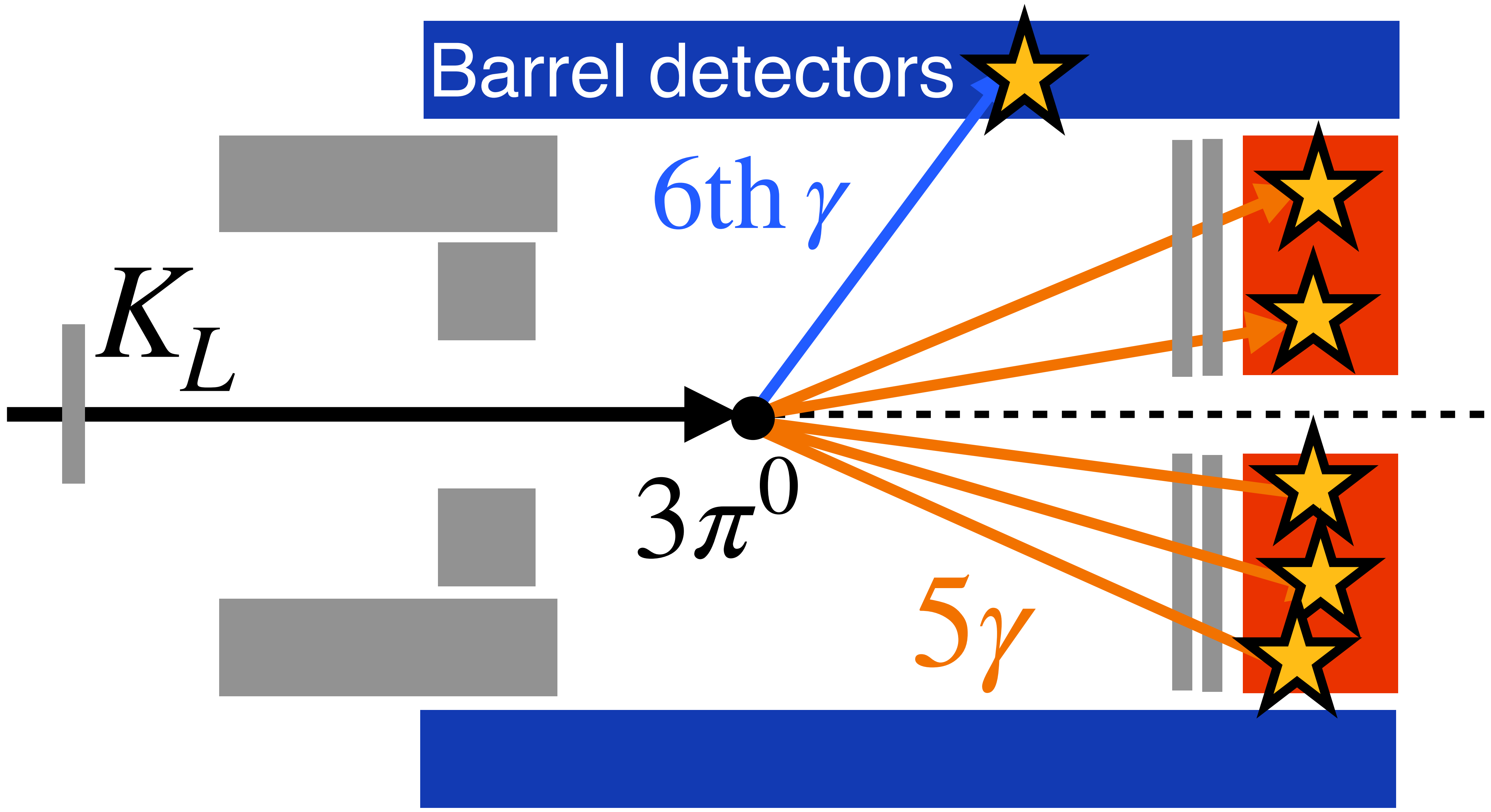
2021

$N_{E_{dep}<\mathrm{threshold}} = 1$

Corresponding inefficiency = (4.8 ± 4.8) × 10^{-5}

→ 100% statistical uncertainty

Inefficiency = $\dfrac{N_{E_{dep}<\mathrm{threshold}}}{N_{5\gamma\,\mathrm{in\,CSI}}}$



2024

$N_{E_{dep}<\mathrm{threshold}} =$ **12**

Preliminary

Corresponding inefficiency = (5.5 ± 1.6) × 10^{-5}

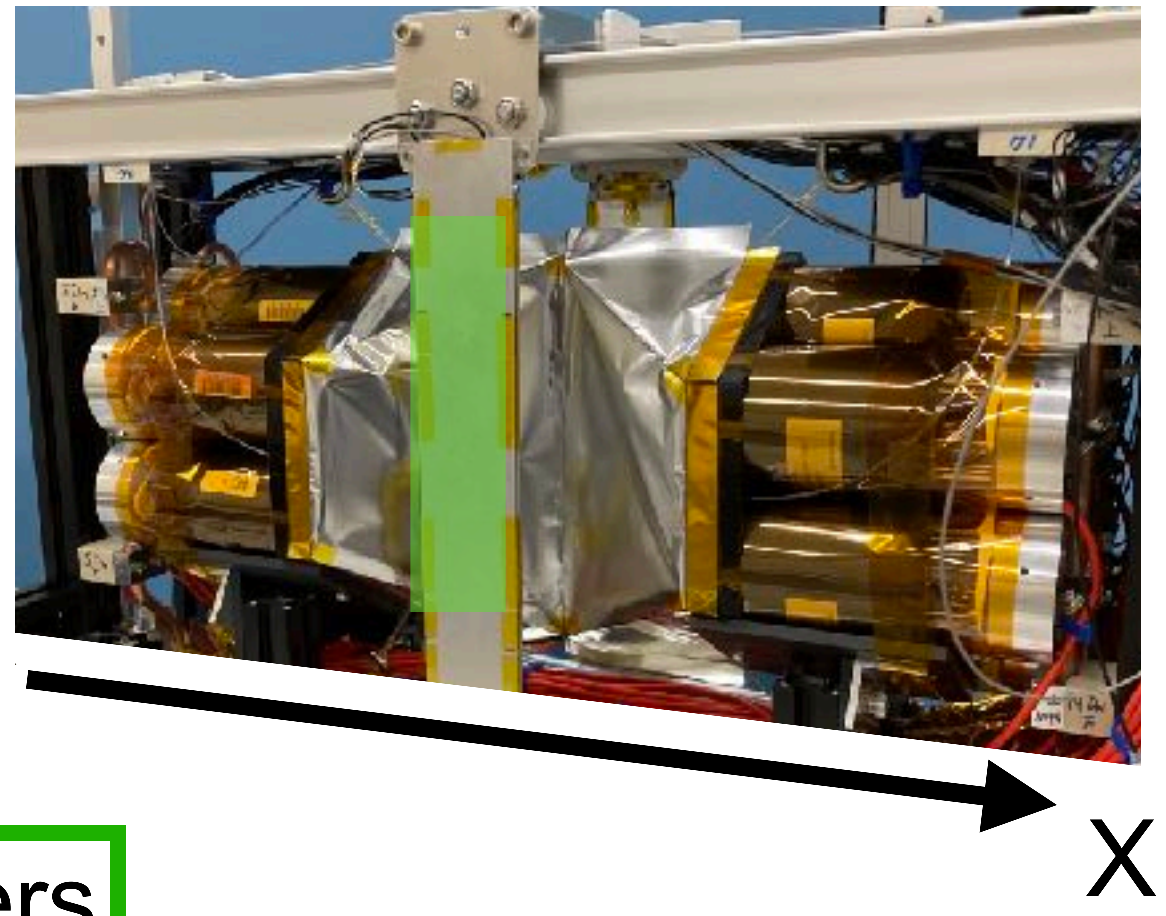
→ ***Reduced statistical uncertainty by ~ 30%***

Accumulated 5γ data × 20 more efficiently than before

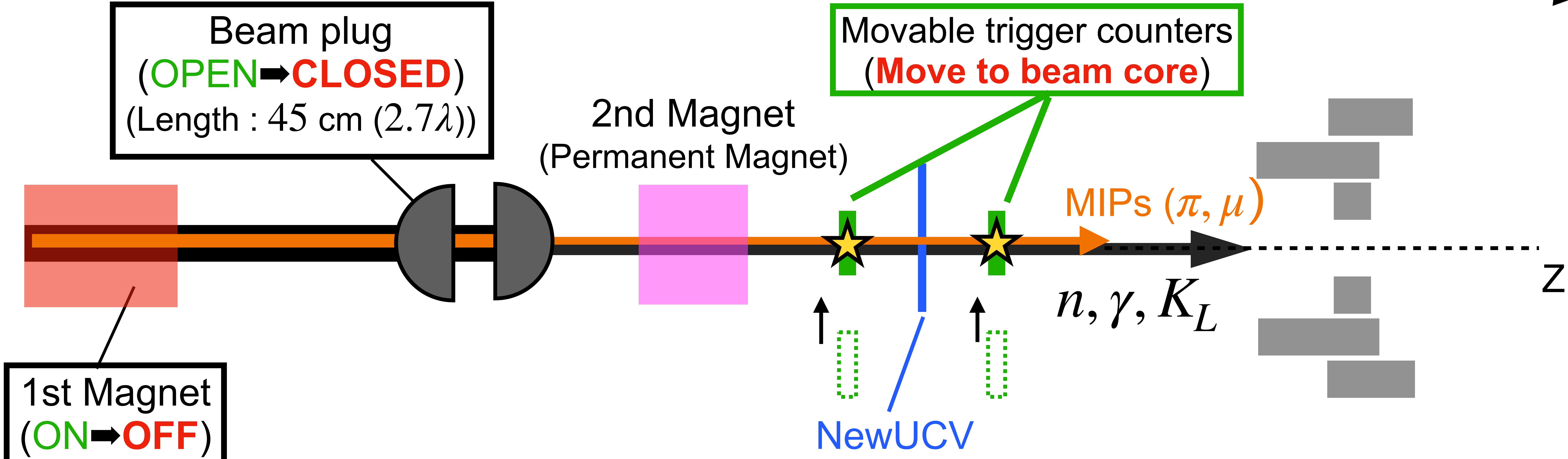
- Will accumulate more 5γ data in coming runs

Impact on NewUCV performance (1)

Evaluated UCV performance with the data collected in special condition



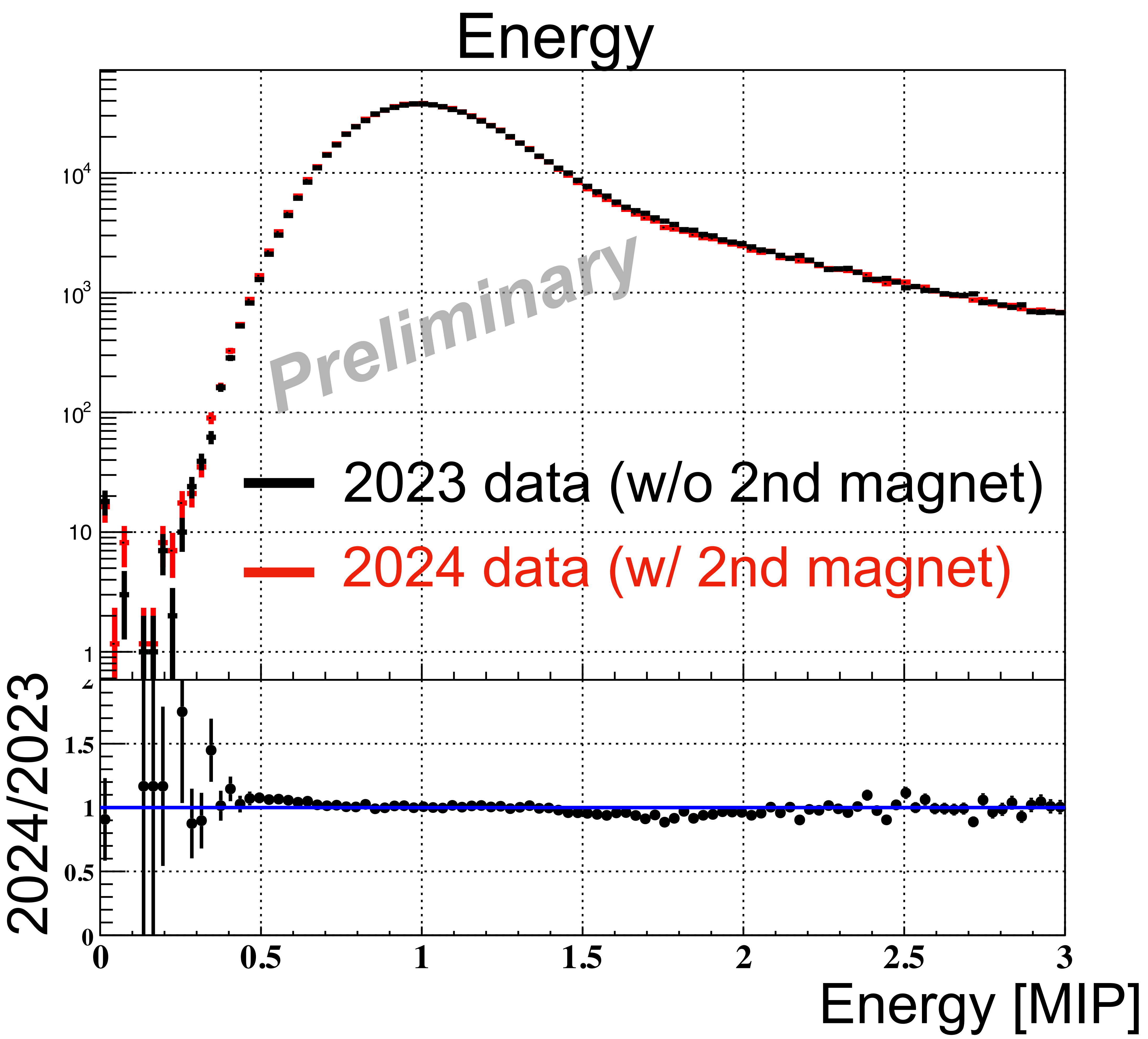
- Took the data with **special condition**

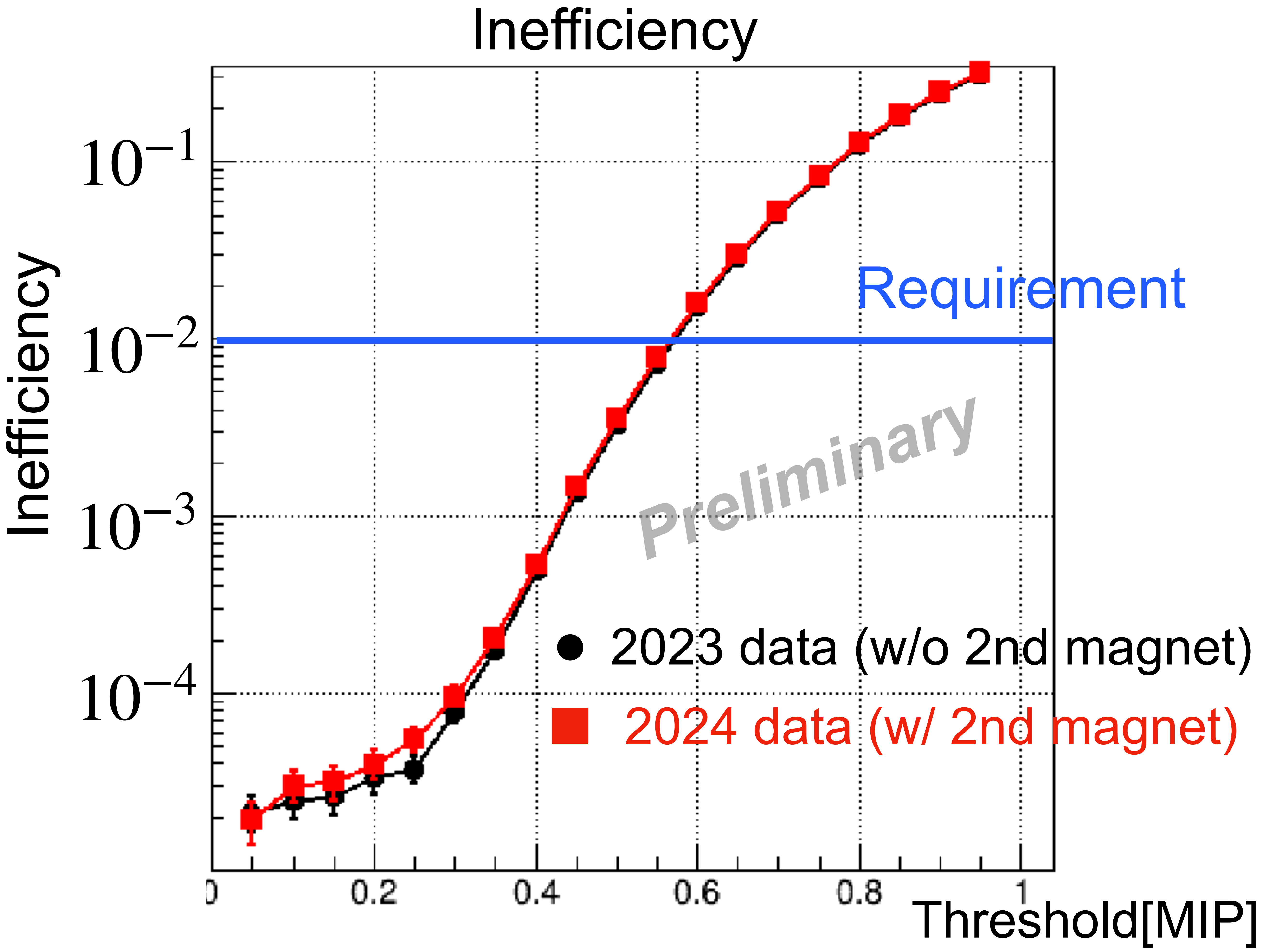


- Evaluated the performance against MIPs by tagging them with movable trigger counters

Impact on NewUCV performance (2)

- Compared the performance with 2023 data (w/o 2nd magnet)



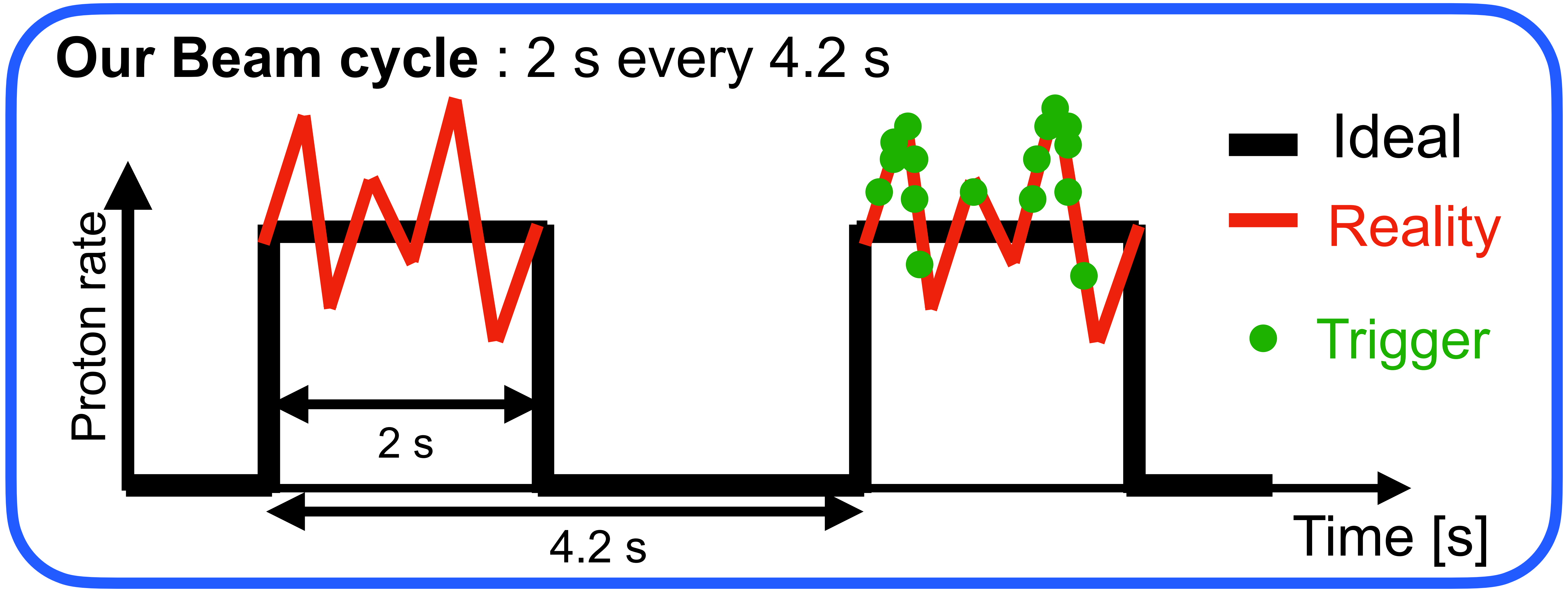


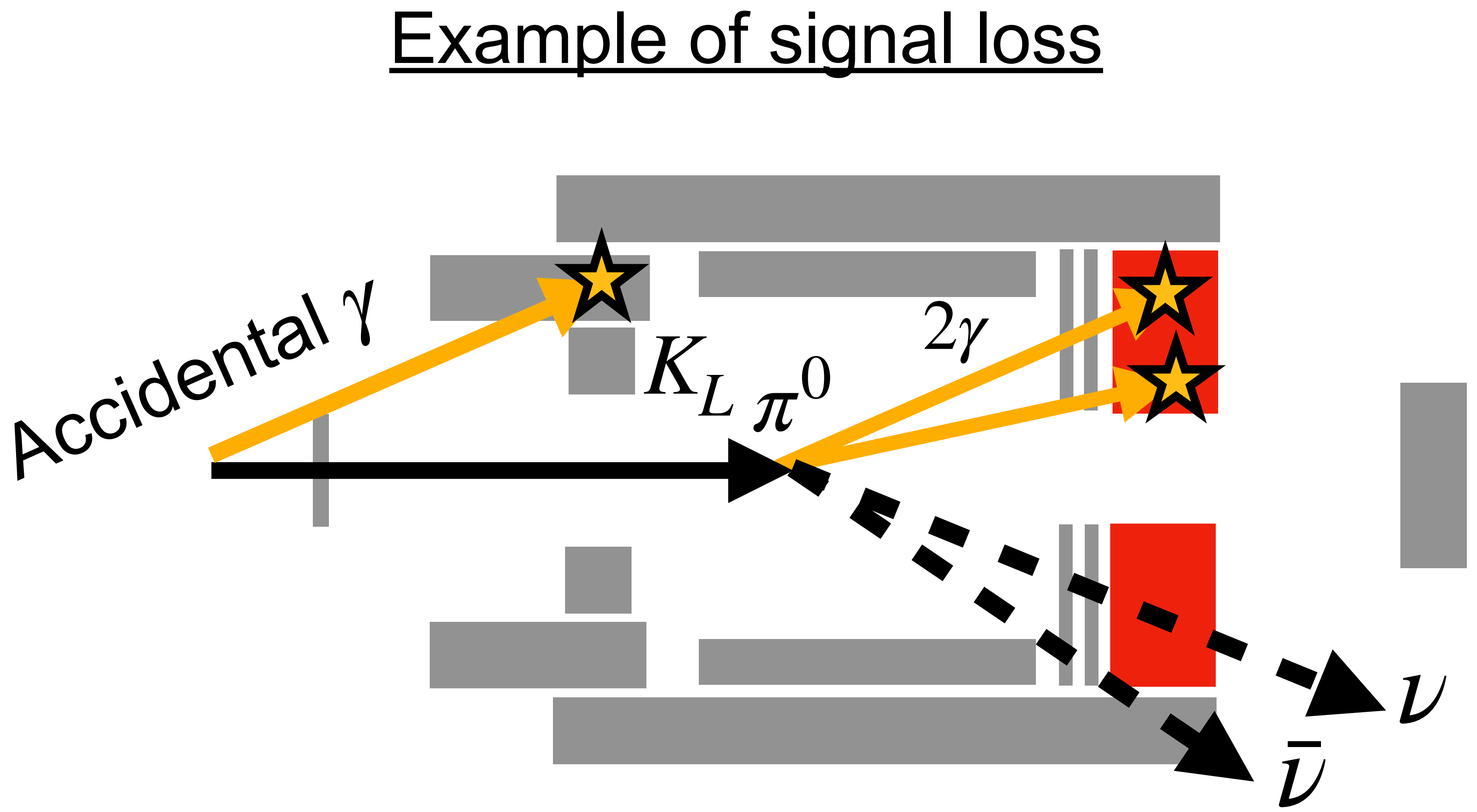
- UCV performance was consistent with 2023 data : Achieved 5×10^{-4} at 0.4 MIP threshold

=> Effect of magnetic field leakage was negligible

Status of 2025 data : Improvement of beam structure (1)

Tried to improve the beam structure in cooperation with the accelerator side





- If beam structure is bad, many triggers are issued during spiky condition

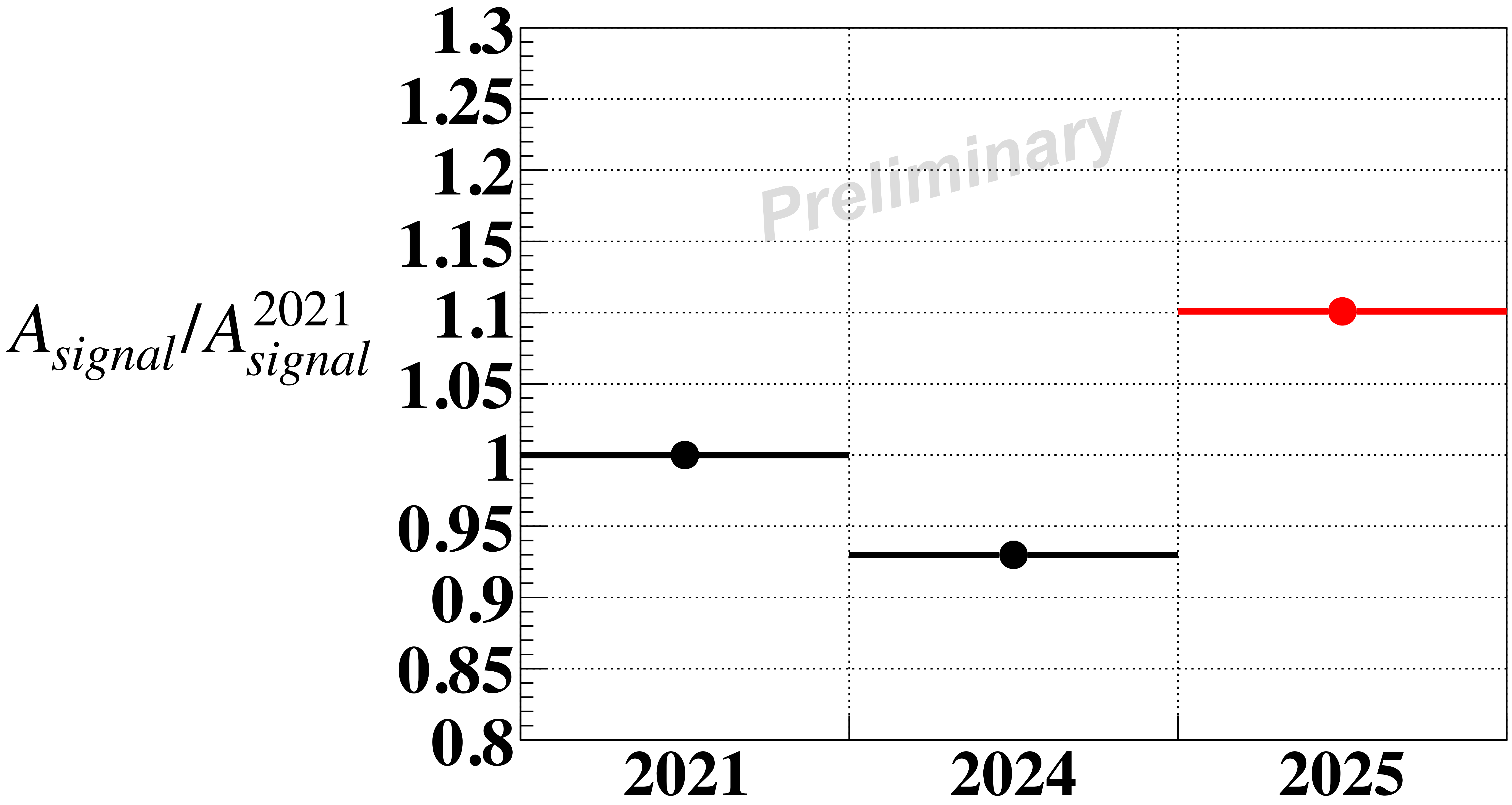
→ **Suffered from signal loss due to accidental hit in veto detectors**

Better beam structure = Larger signal acceptance

- As KOTO, implemented accidental hit monitor at HLT for the quick feedback to accelerator side

Status of 2025 data : Improvement of beam structure (2)

- Evaluated the gain of signal acceptance A_{signal} using MC overlaid accidental data

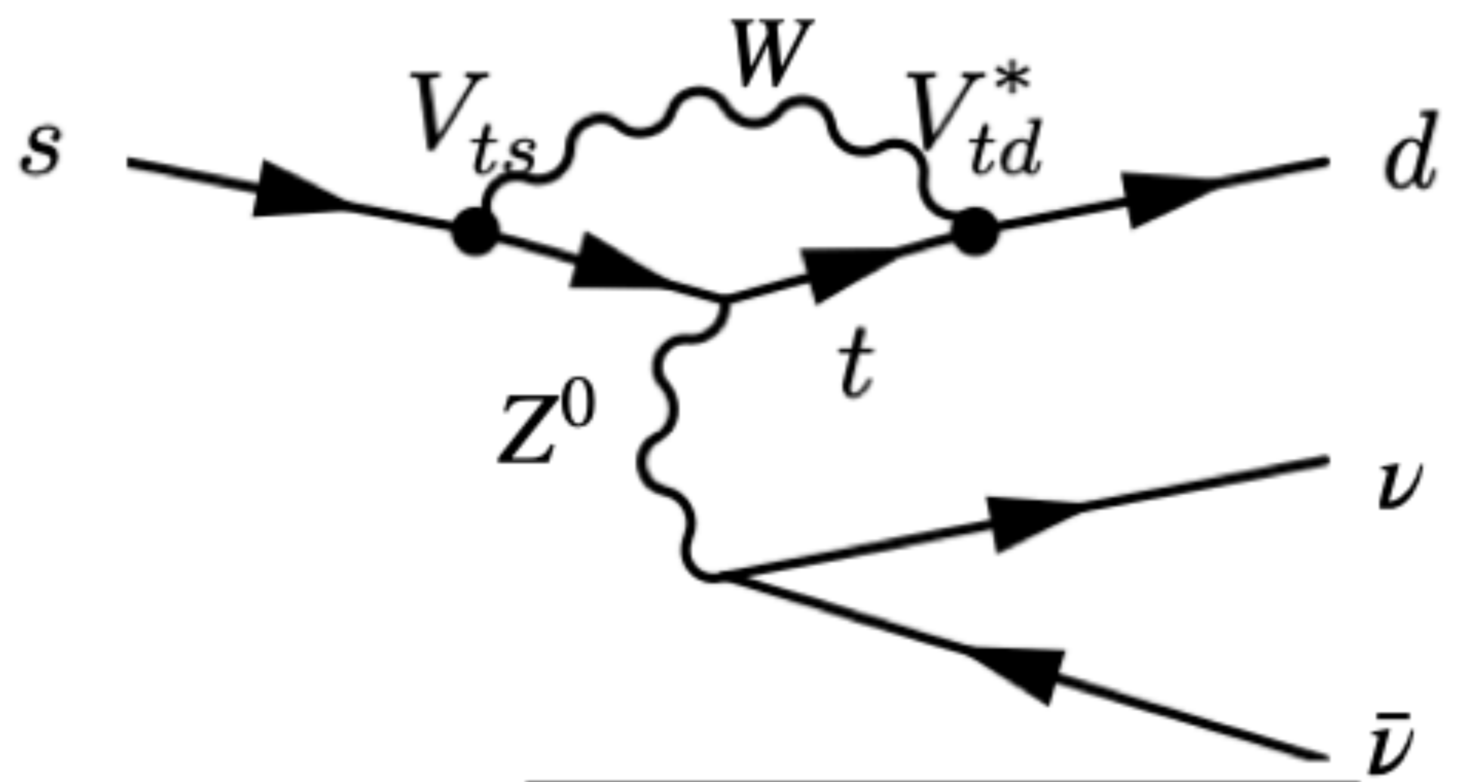


Signal acceptance was 10% better than 2021 (before MR power supply upgrade)
20% better than 2024

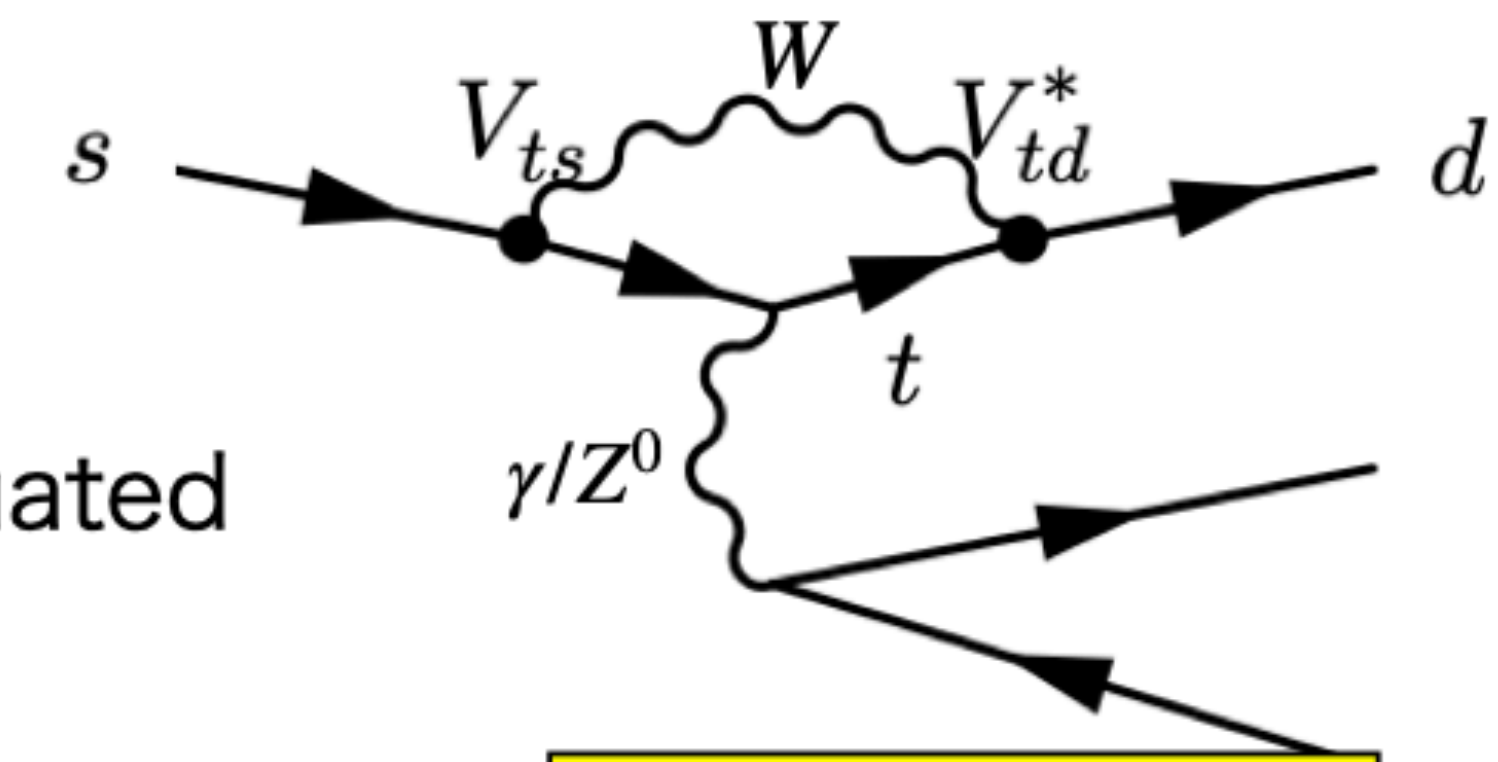
KOTO II

Major physics targets to explore new physics

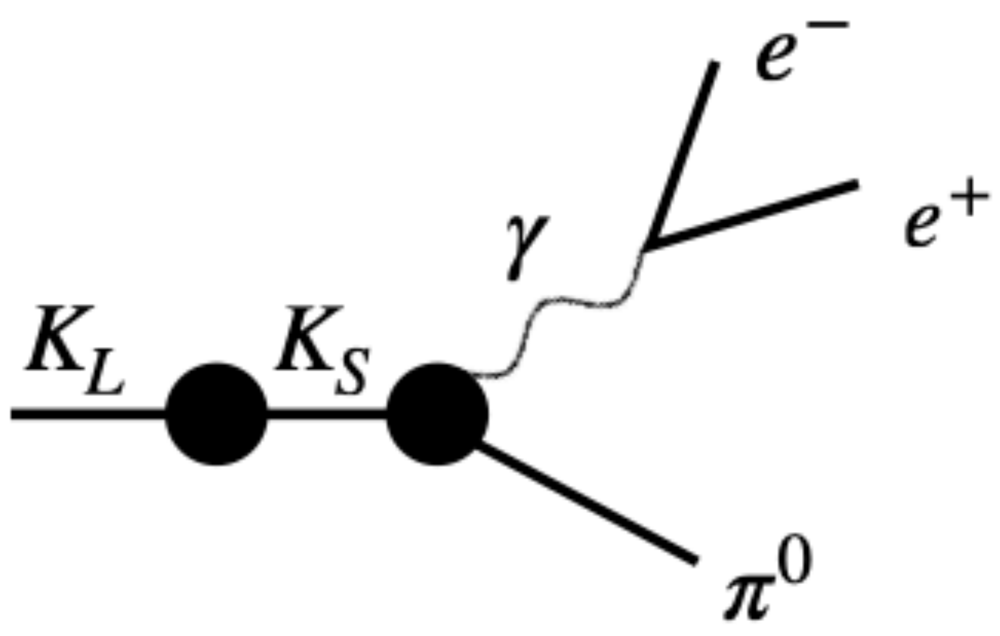
- $K_L \to \pi^0 \nu \bar{\nu}$ Eur. Phys. J. C (2023) 83:66
  - $\mathscr{B}^{\mathrm{SM}} = (2.94 \pm 0.15) \times 10^{-11}$
  - Theoretical uncertainty ~2%
- $K_L \to \pi^0 \ell^+ \ell^-$ JHEP 08 (2006) 088 positive interference is assumed
  - $\mathscr{B}^{\mathrm{SM}}_{\mathrm{K_L \to \pi^0 e^+ e^-}} = 3.54^{+0.98}_{-0.85} \times 10^{-11}$
  - $\mathscr{B}^{\mathrm{SM}}_{K_L \to \pi^0 \mu^+ \mu^-} = (1.41^{+0.28}_{-0.26}) \times 10^{-11}$
  - Long distance contribution can be evaluated with $K_S \to \pi^0 \mu^+ \mu^-$ from NA48/1 and the future LHCb



Short distance



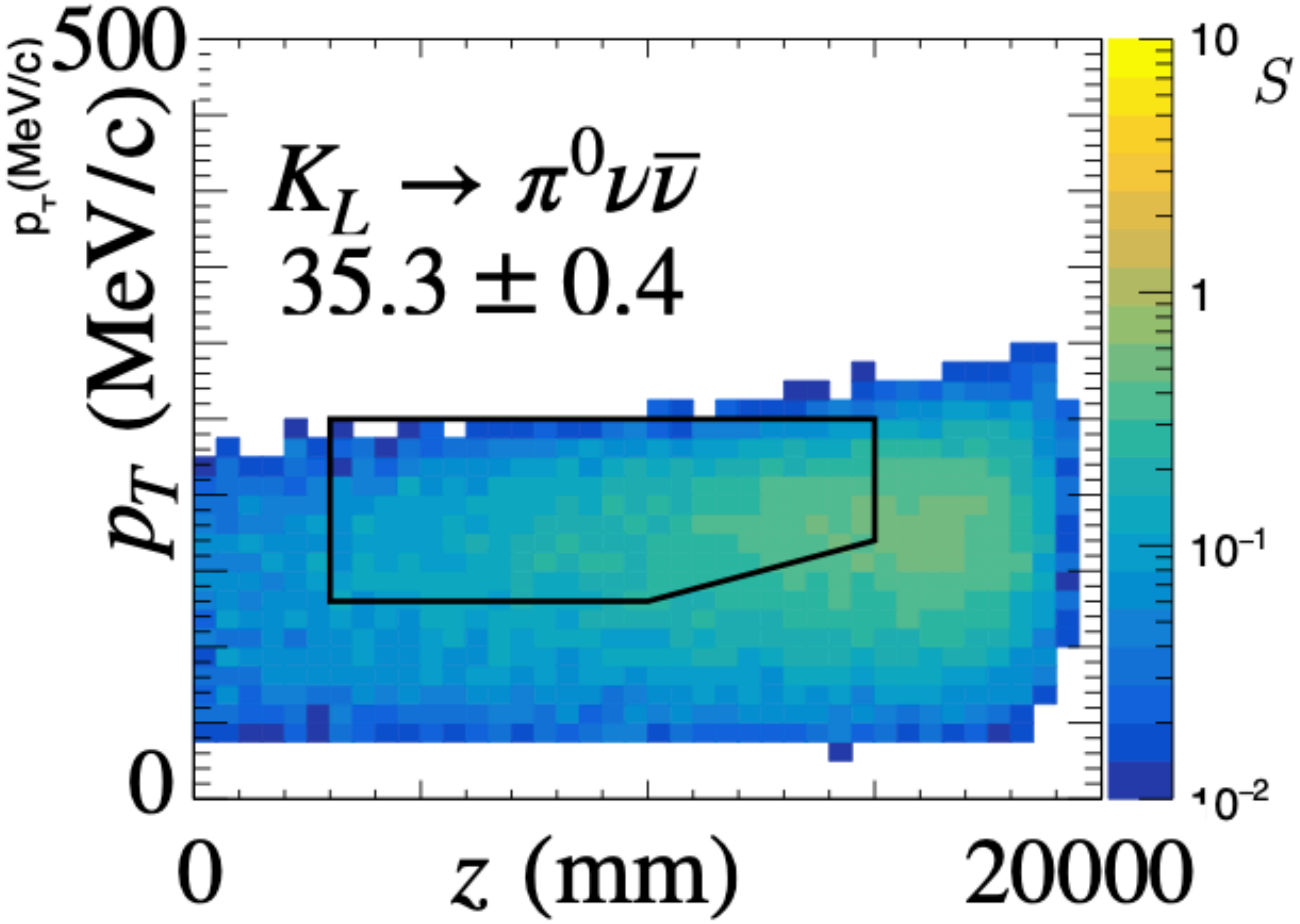
Short distance



Long distance

New physics contributes in the interference to the precise and suppressed SM contribution

Estimation of # of signal



$$S = \frac{(\text{beam power}) \times (\text{running time})}{(\text{beam energy})} \times (\text{number of } K_L/\text{POT})$$
$$\times P_{\text{decay}} \times A_{\text{geom}} \times A_{\text{cut}} \times (\text{1-accidental loss}) \times (\text{1-backsplash loss}) \times \mathcal{B}_{K_L \to \pi^0 \nu \bar{\nu}}$$
$$= \frac{(100\ \text{kW}) \times (3 \times 10^7\ \text{s})}{(30\ \text{GeV})} \times \frac{(1.1 \times 10^7 K_L)}{(2 \times 10^{13}\ \text{POT})}$$
$$\times 9.9\% \times 24\% \times 26\% \times (1 - 39\%) \times 91\% \times (3 \times 10^{-11})$$
$$= 35.$$

Beam power : 100 kW at the target
Running time : 3×10^7 s → POT : 6.3×10^{20}
# of events (SM) : 35 events

	KL yield	Decay Probability	Geometrical Acceptance	Cut efficiency	1- Accidental loss	1-Backsplash loss
KOTO		3.3%	26%	11%	29%	56%
KOTO II	×2.6	10%	24%	26%	61%	91%
Improvement factor	2.6	3.0	0.9	2.4	2.1	1.6

→SES: 8.5×10^{-13}

× 58 in total

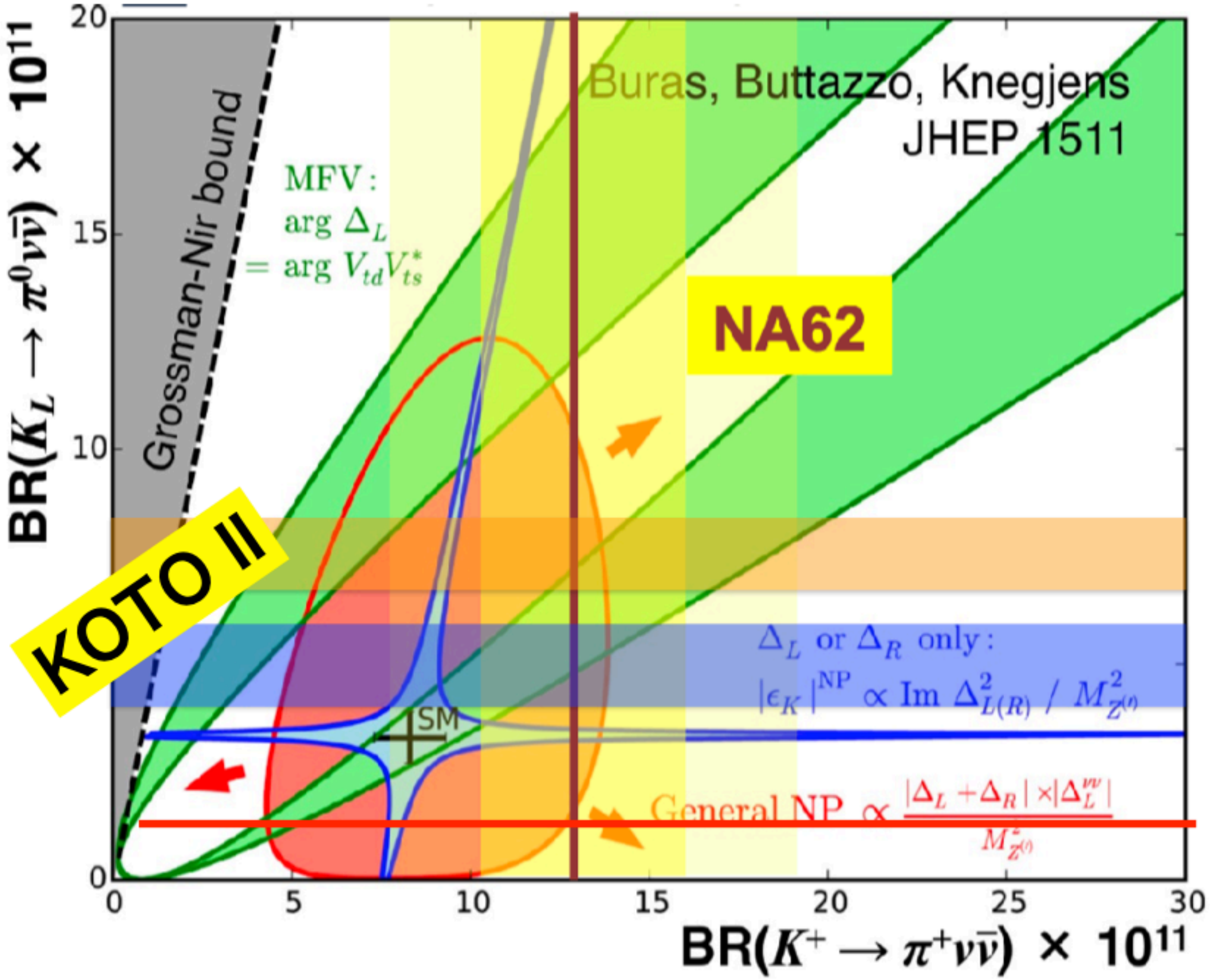
Estimation of # of background

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

>5 σ observation
for SM value of branching ratio

Impact of KOTO II for $K_L \to \pi^0 \nu \bar{\nu}$

Base design → better sensitivity with more studies



100-kW beam, 3×10^7 s $= 6.3 \times 10^{20}$ POT

SES: 8.5×10^{-13}, S/B=0.9

- 35 SM signal / 40 background events
  →5.6σ observation
- $\Delta\mathscr{B}/\mathscr{B} = 25\,\%$ for SM value of $\mathscr{B}$
- 40% deviation from SM
  →90%-CL indication of NP

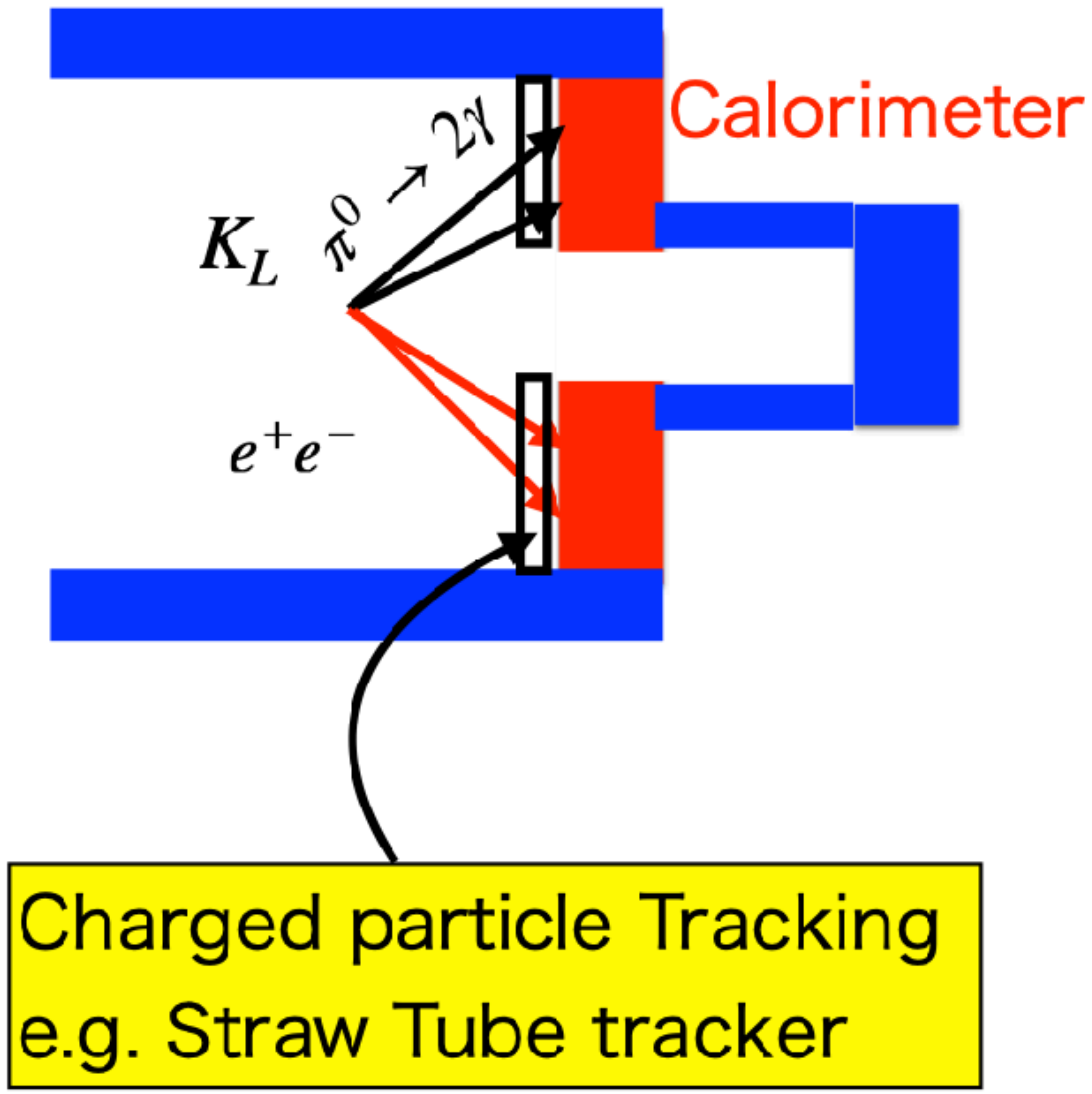
Example

250% deviation from SM

70% deviation from SM

May find NP effect

Measurement of BR of $K_L \to \pi^0 \ell^+ \ell^-$



- $K_L \to \pi^0 e^+ e^-$
- Additional charged particle tracker (Two layers)
- Vertex reconstruction with the two tracks
  → Better resolution
- Reconstruct K_L and π^0 with better resolution
  - BG : $K_L \to e^+ e^- \gamma\gamma$
- 3.6σ observation is expected in KOTO II
  → Discussion of further improvement
- $K_L \to \pi^0 \mu^+ \mu^-$ is also under study.

Correlations and prospects

May find NP effect with 3σ

depending on enhancement from NP and stat. fluctuation

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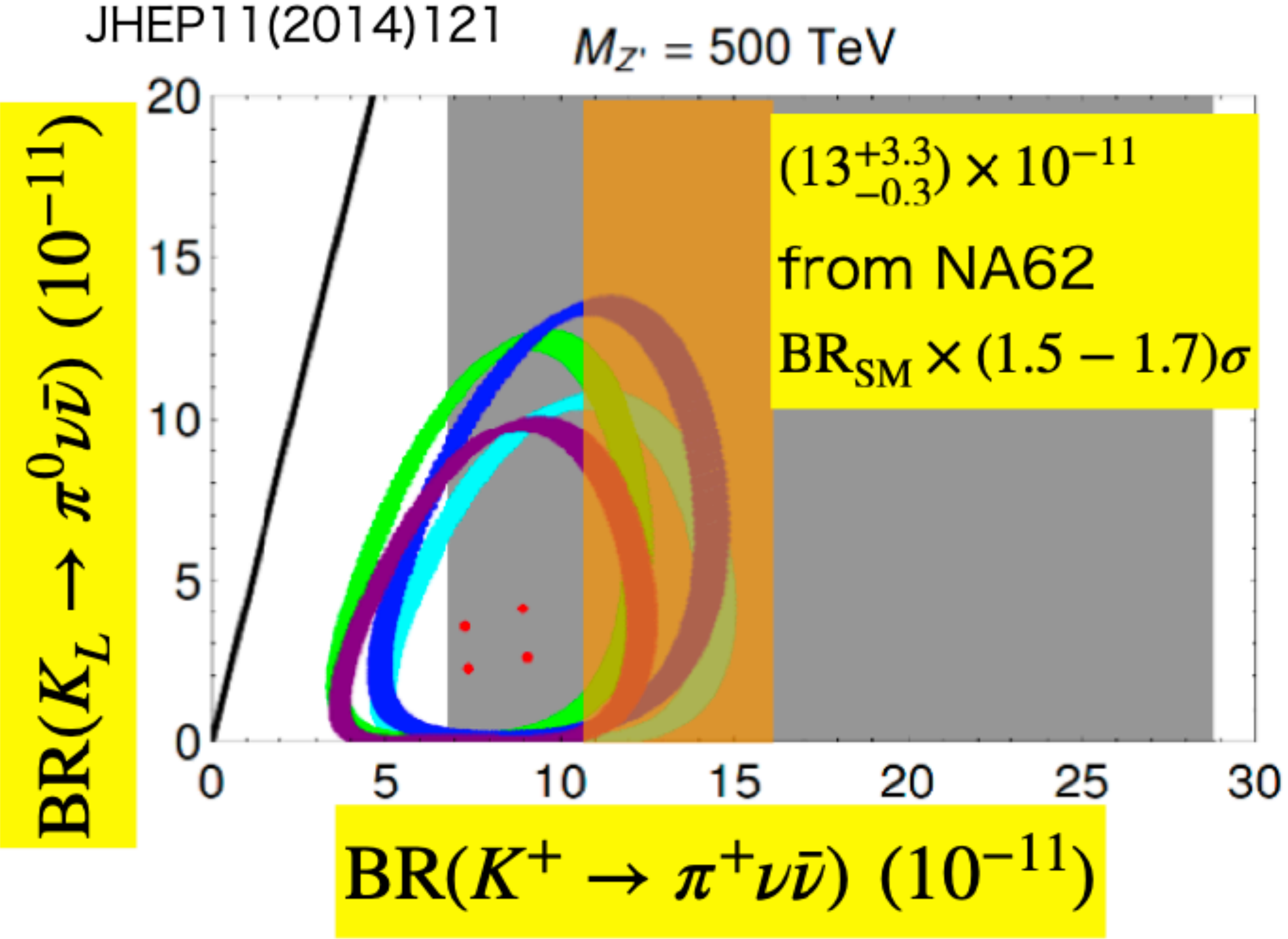

Phys.Lett.B 861 (2025) 139295