KOTO: Status and Future Prospects

Tadashi Nomura (KEK/J-PARC)

- Introduction and basics of the KOTO experiment
- Latest results from the 2021 data analysis
- Prospects

HQL2023 @ TIFR, Mumbai, India on November 28-December 2, 2023

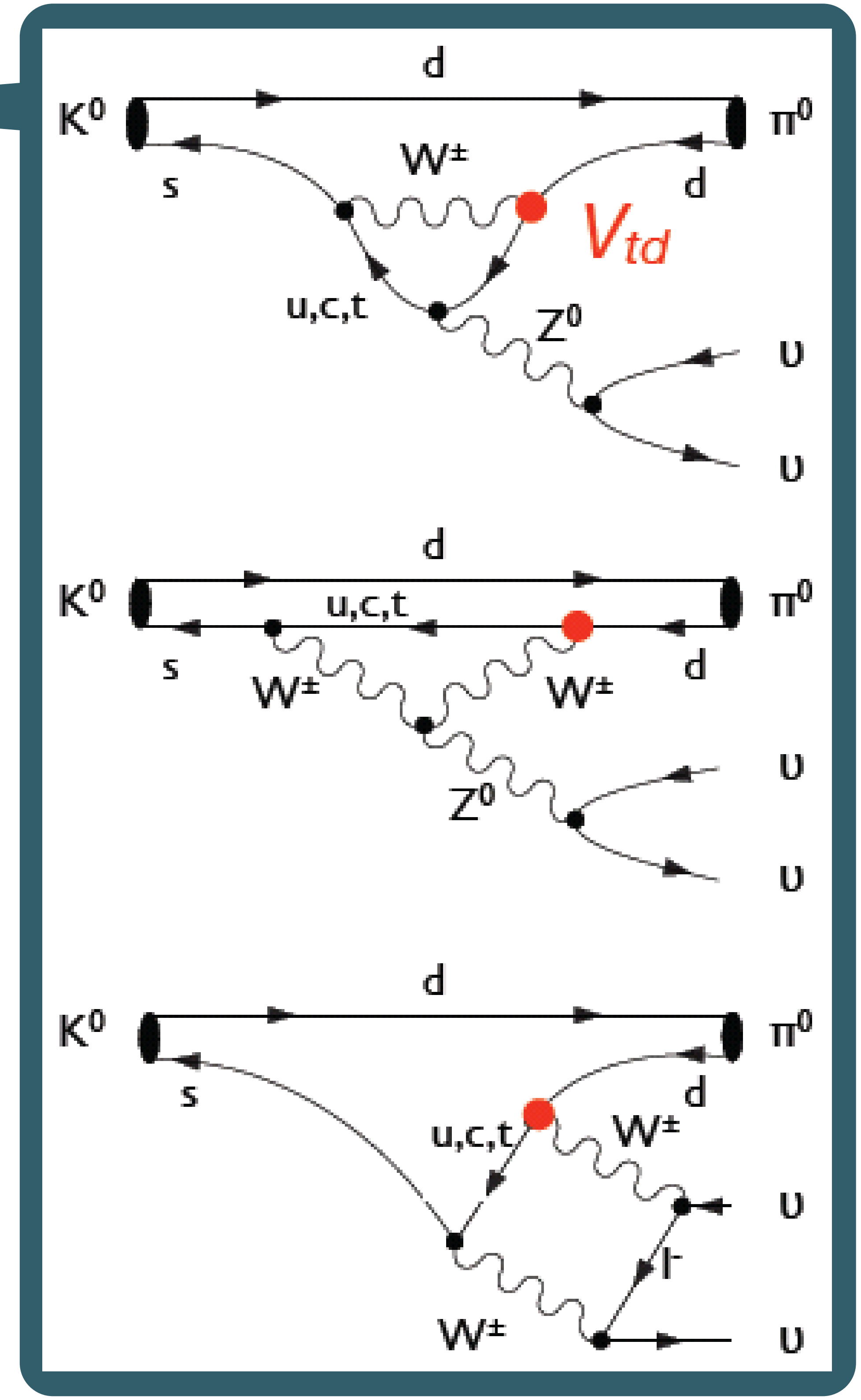
Physics in rare Kaon decays: K→πνν

- s-d transition via loop diagrams, Flavor Changing Neutral Current (FCNC) process

  ~ $A^2\lambda^5$
  ~ 10^{-4} suppression in SM

- $K_L \to \pi^0 \nu \bar{\nu}$ BR∝$\mathrm{Im}(A_{s\to dZ^*})^2$
  - Top quark dominates
  - $K^0 - \overline{K^0}$ superposition extracts imaginary part of the amplitude
  - **CP violating**

- $K^+ \to \pi^+ \nu \bar{\nu}$ BR∝$|A_{s\to dZ^*}|^2$
  - Top and charm contributes



K→πνν in the Standard Model (SM)

$K_L \to \pi^0 \nu\nu$

$$\mathcal{B}r(K_L \to \pi^0 \bar{\nu}\nu) = \kappa_L \left(\frac{\mathrm{Im}(V_{ts}^* V_{td})}{\lambda^5} X(x_t) \right)^2$$

$$BR_{SM}(K_L \to \pi^0 \nu\bar{\nu}) = (2.94 \pm 0.15) \times 10^{-11}$$

CKM uncertainties are dominant while intrinsic one ~2%.

$K^+ \to \pi^+ \nu\nu$

$$\mathcal{B}r\left(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)\right) = \kappa_+ (1 + \Delta_{EM})$$

$$\times \left| \frac{V_{ts}^* V_{td} X_t(m_t^2) + \lambda^4 \mathrm{Re} V_{cs}^* V_{cd} \left(P_c(m_c^2) + \delta P_{c,u} \right)}{\lambda^5} \right|^2$$

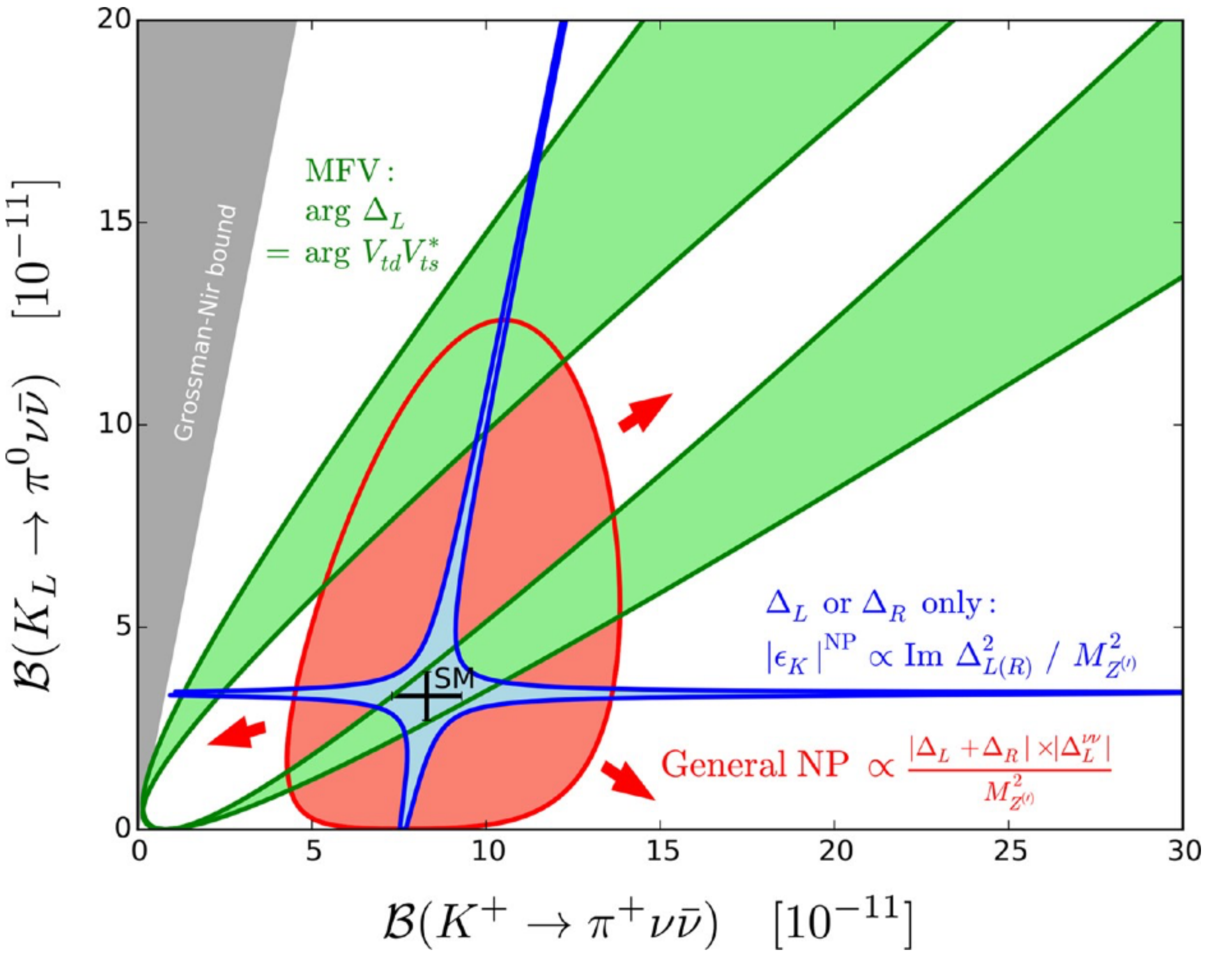
$$BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

BR_{SM} are quoted from Acta Phys. Pol. B 53, 6-A1 (2022)

Small theoretical uncertainty, suppressed in SM
⇒ Good probe to search for New Physics beyond SM

New physics can appear in the loop

Illustration of correlations in the BR($K^+ \to \pi^+ \nu\nu$) and BR($K_L \to \pi^0 \nu\nu$) plane



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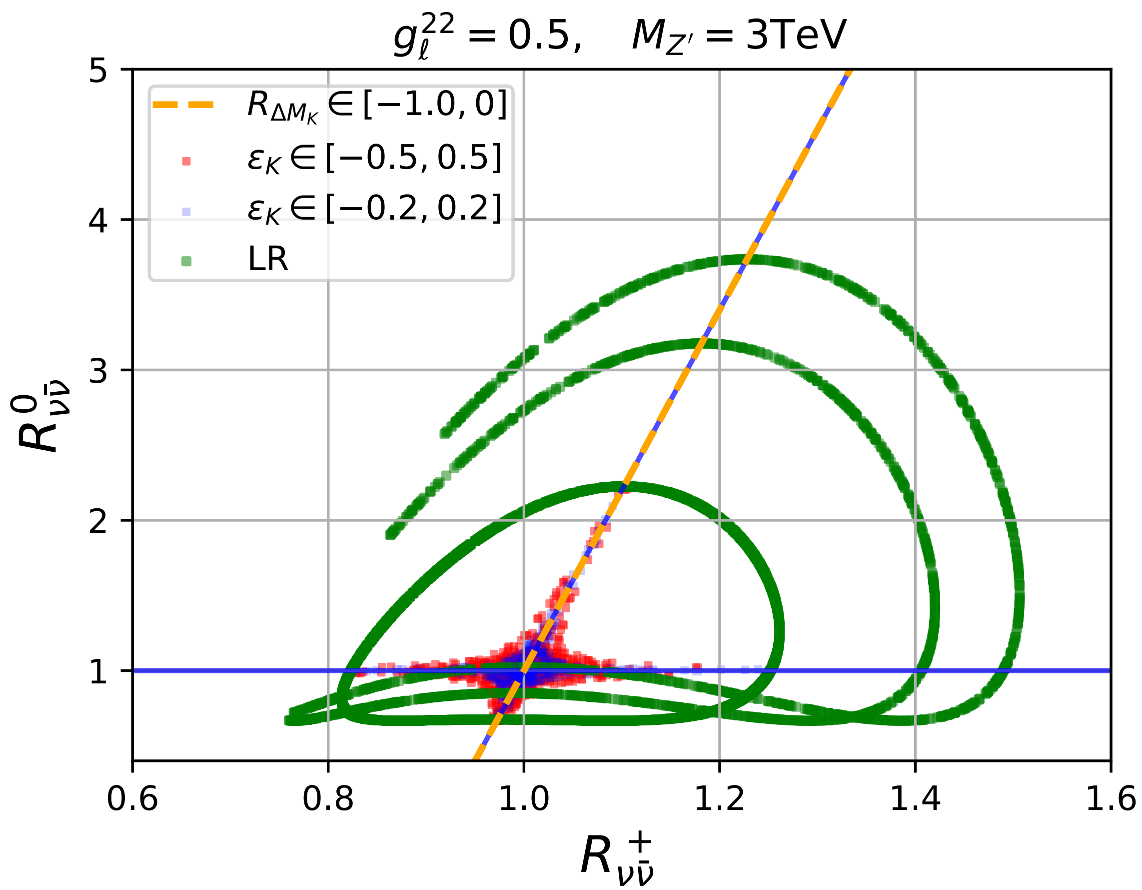
Z' models with LH and RH couplings



JHEP12 (2020) 097

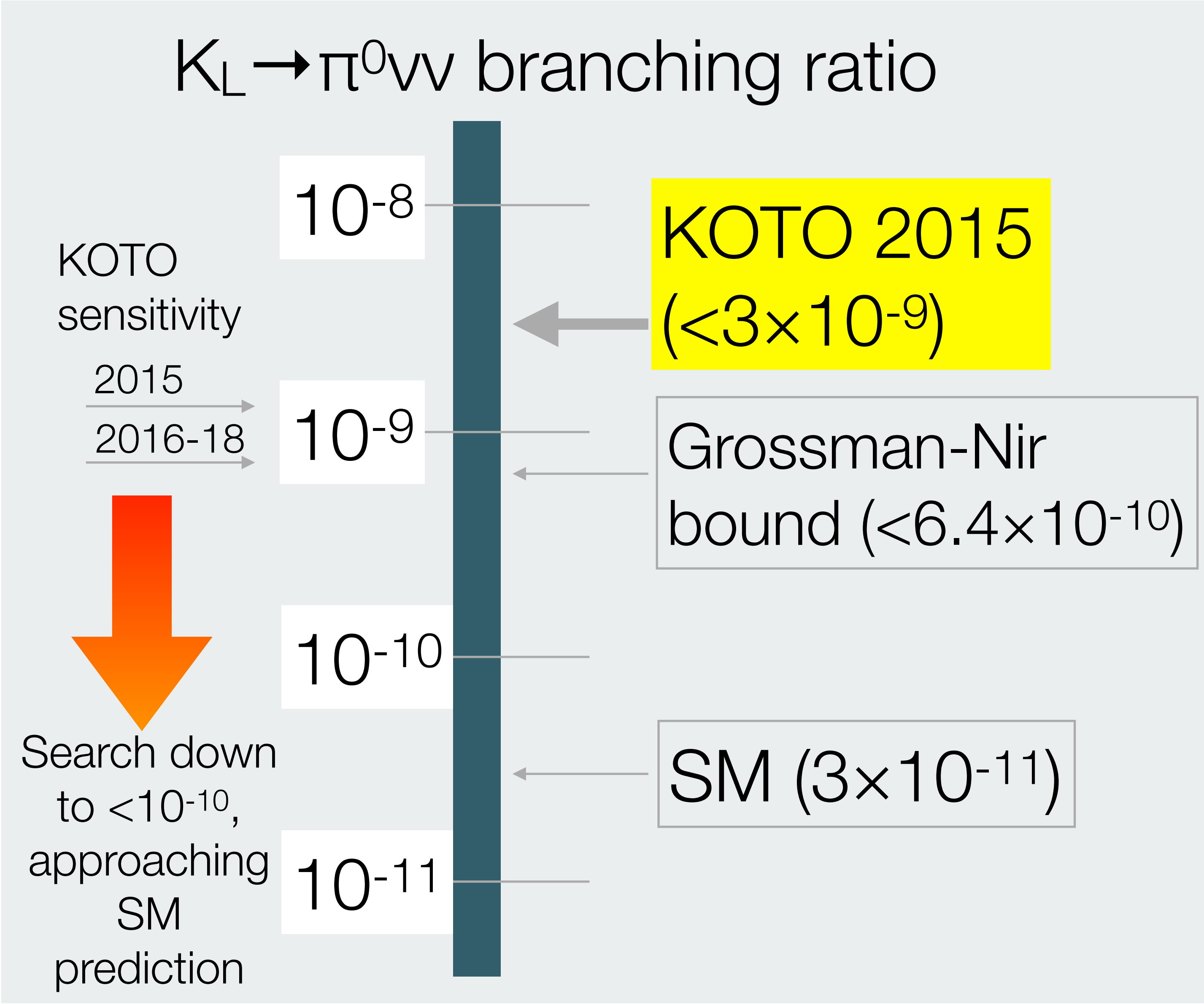
R^0,R^+: BR enhancements from SM for neutral and charged modes

BR($K_L \to \pi^0 \nu\nu$) can be enhanced to be O(10^{-10}).

- *Even in case that BR($K^+ \to \pi^+ \nu\nu$) is consistent with the SM prediction.*

KOTO experiment

$K_L \rightarrow \pi^0 \nu\nu$ study at J-PARC



Grossman-Nir bound: indirect limit from relation to $BR(K^+ \rightarrow \pi^+ \nu\nu)$;
Calc'd from NA62 results (2021) with 1σ region

KOTO collaboration

KOTO stands for **K0** at **To**kai.

KEK Tokai campus

Zoom

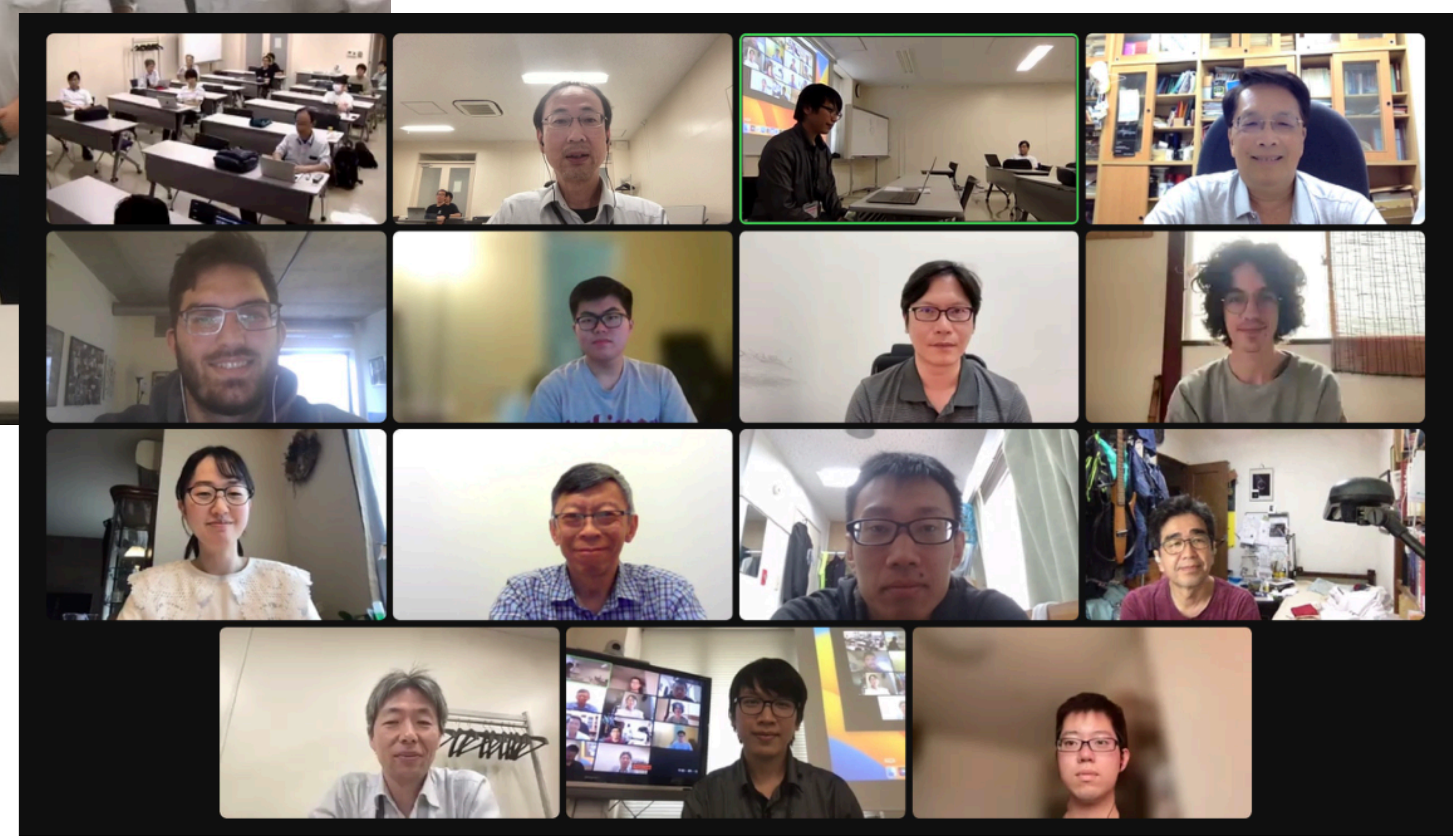
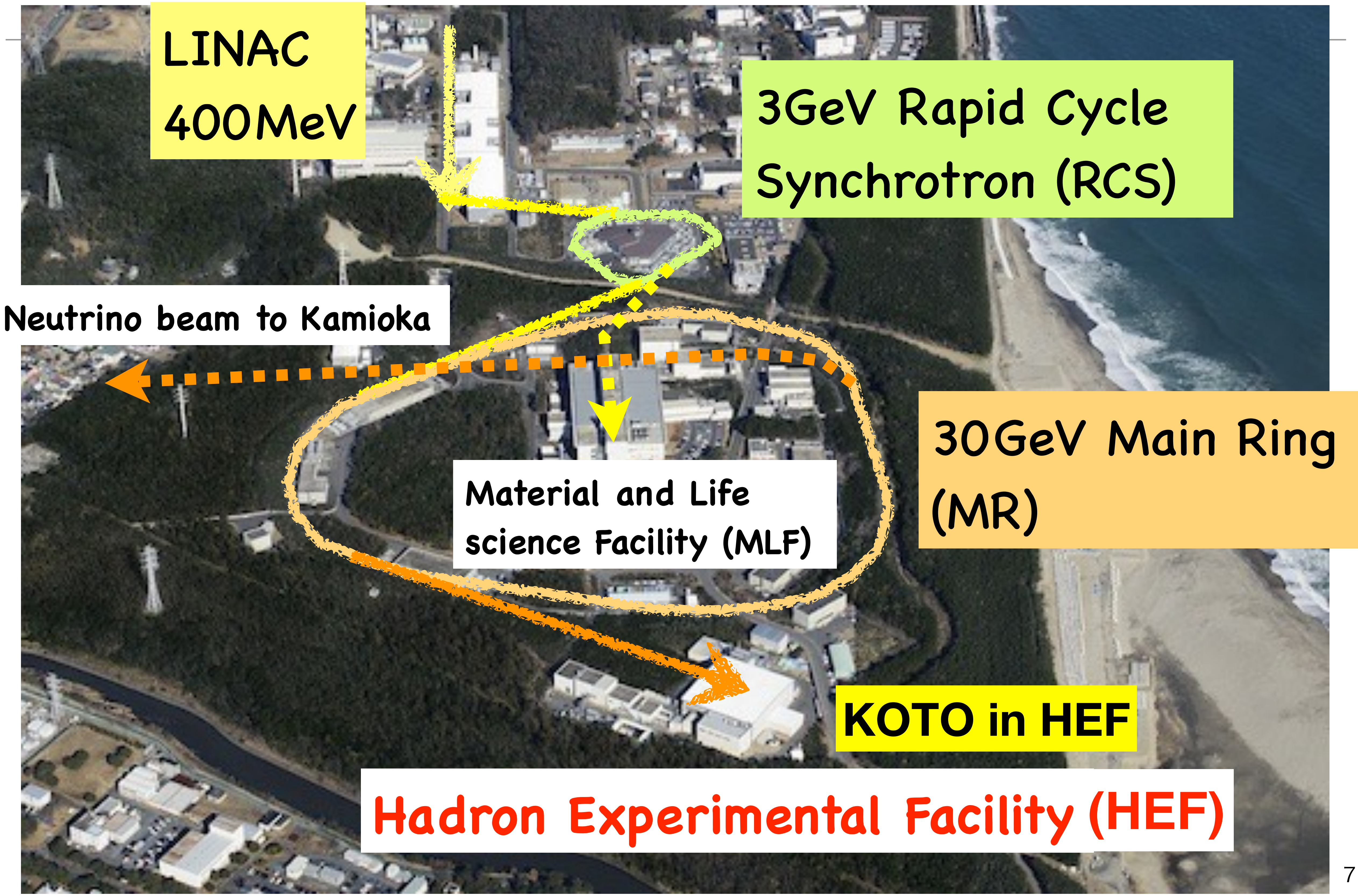


Photo @ collaboration meeting
on June 30 - July 2, 2023

KEK, NDA, Osaka, Saga, Yamagata,
Jeonbuk, Korea, NTU, Arizona State, Chicago, Michigan

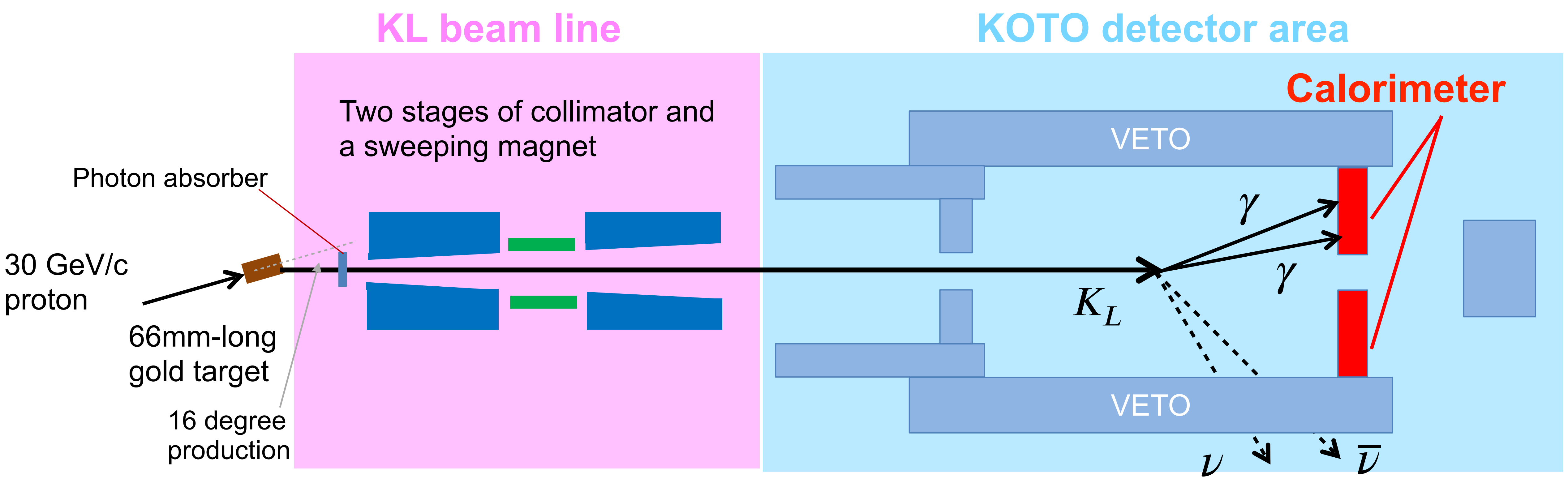
J-PARC

In Tokai-village, Ibaraki, Japan



Experimental principle

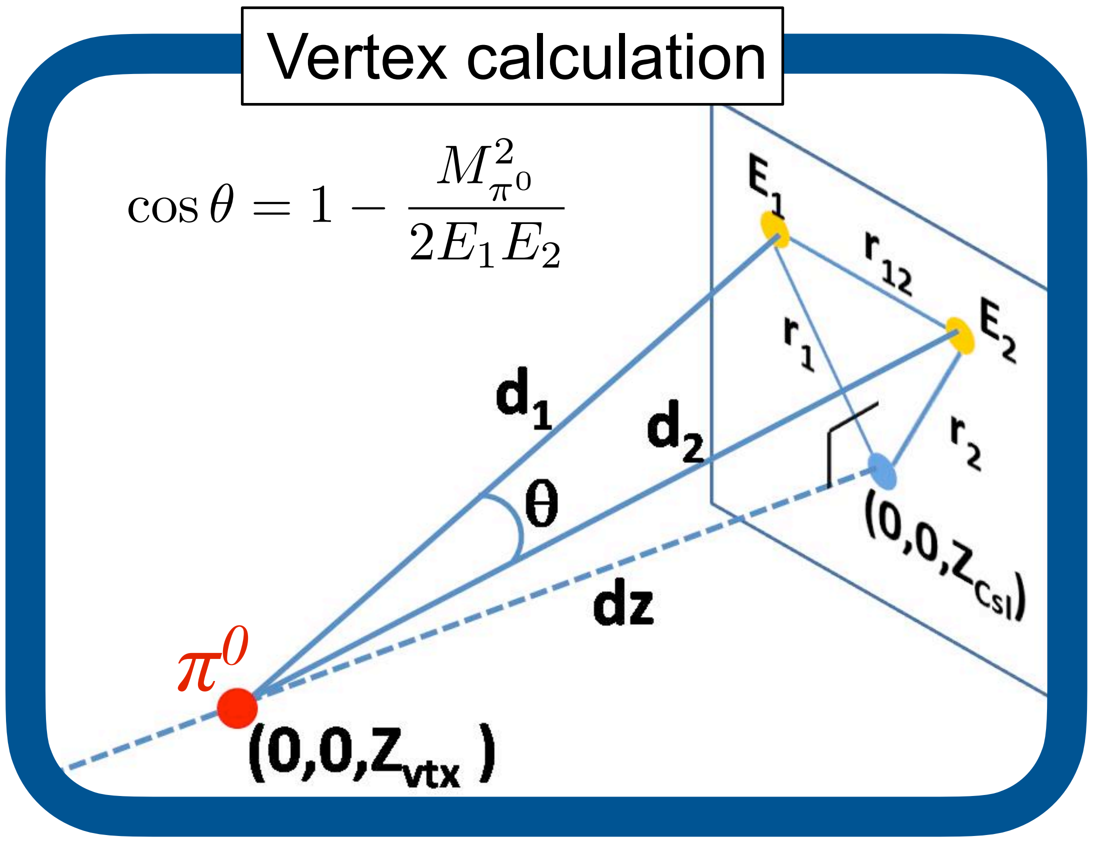
$$K_L \to \pi^0(\to 2\gamma)\ \nu\bar{\nu}\ (nothing)$$

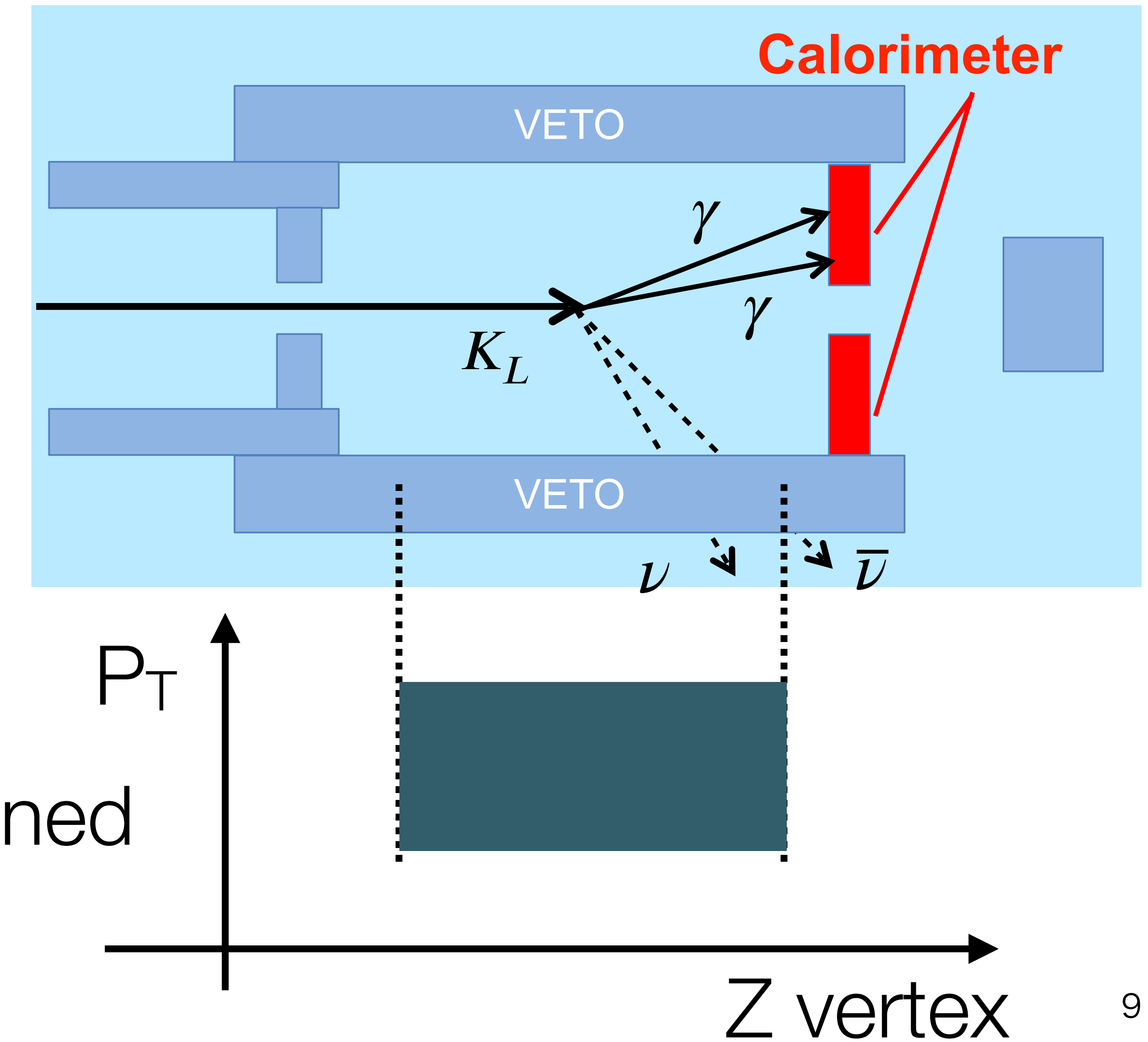


- 2γ in the calorimeter in the end-cap
- No extra particle, and thus no hit in veto detectors

Reconstruction of event kinematics

Calculate the π^0 **decay vertex** and **transverse momentum (P_T)** with 2γ energies and positions measured by the calorimeter

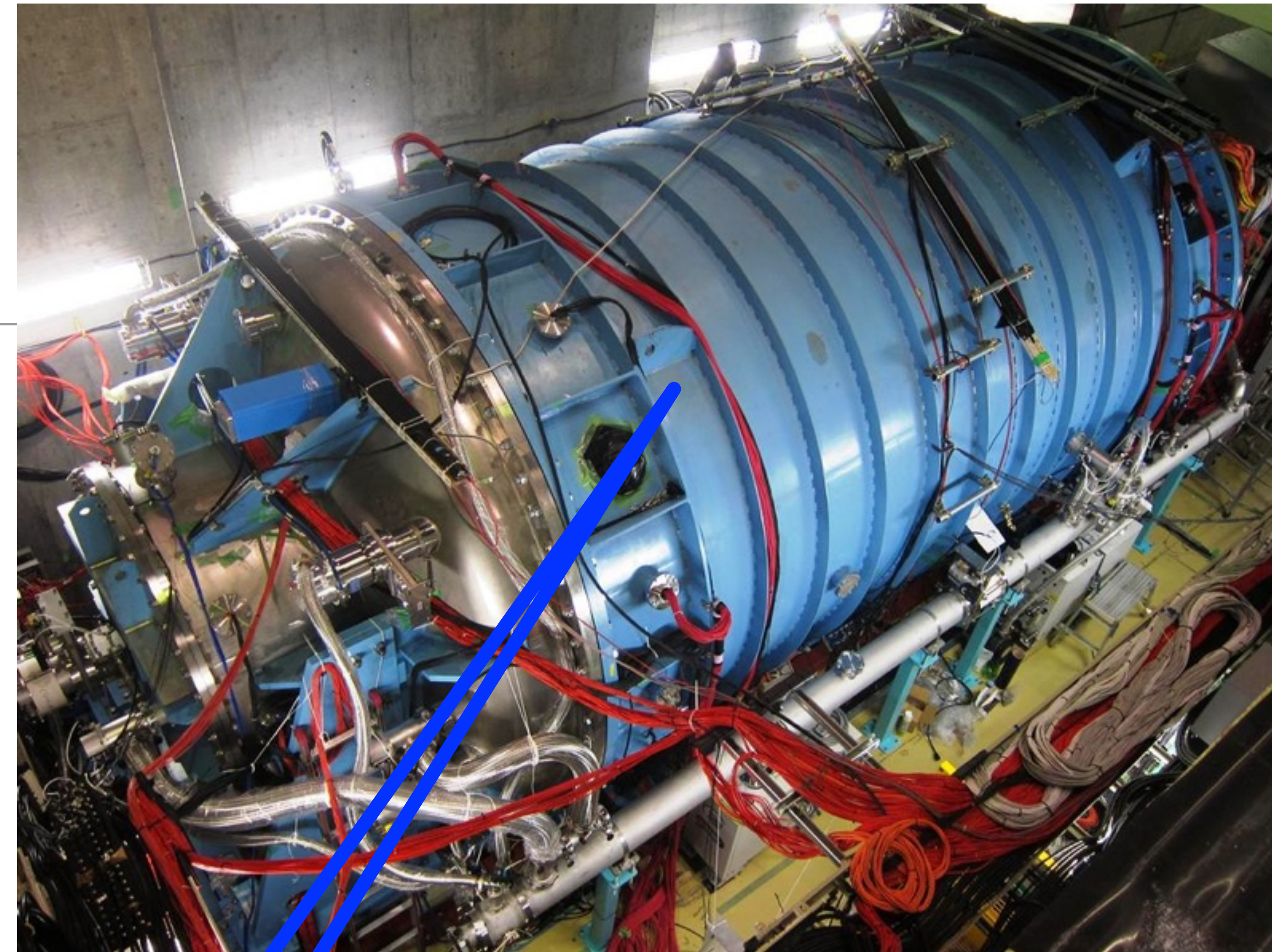


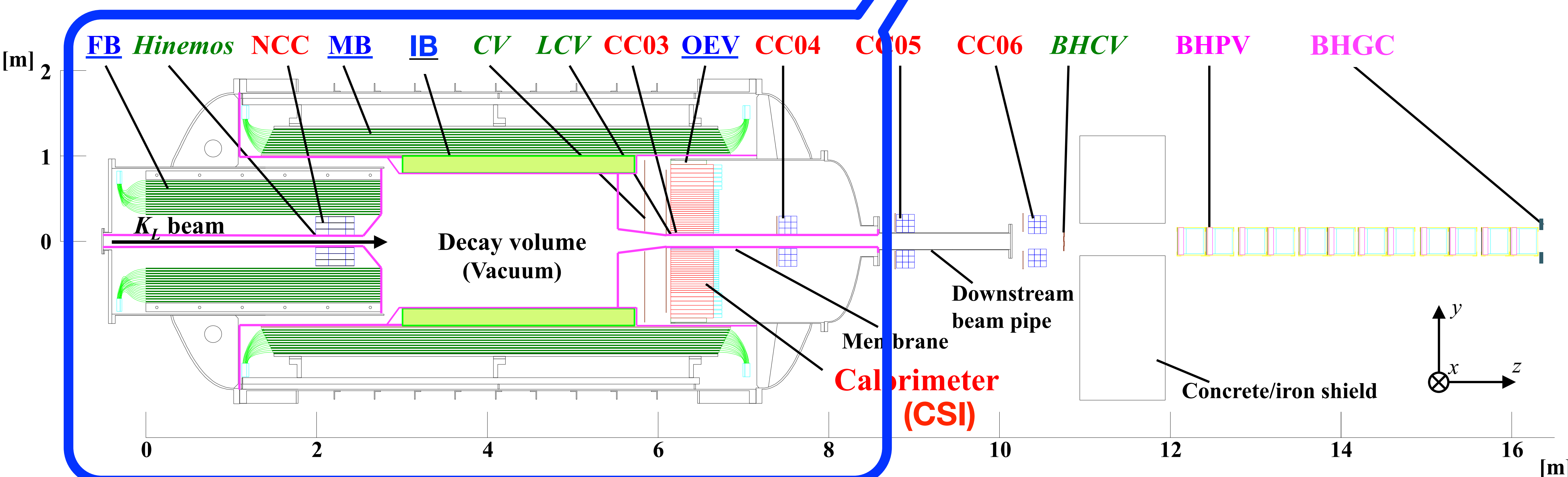


The signal region is defined on P_T vs Z plane

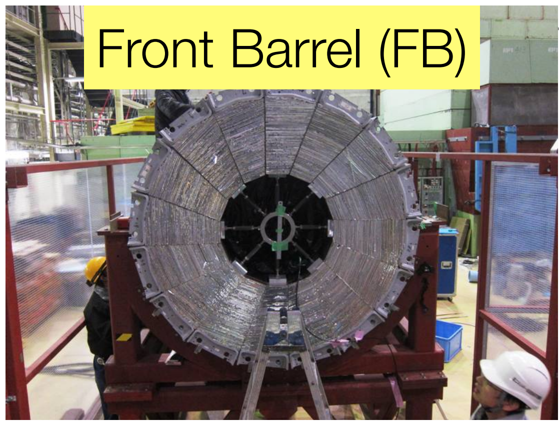
KOTO detector

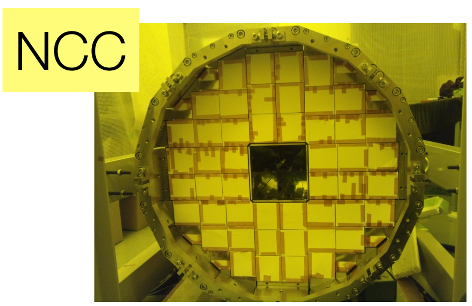
The core part of the detector, surrounding the K_L decay region, are located inside the vacuum tank.

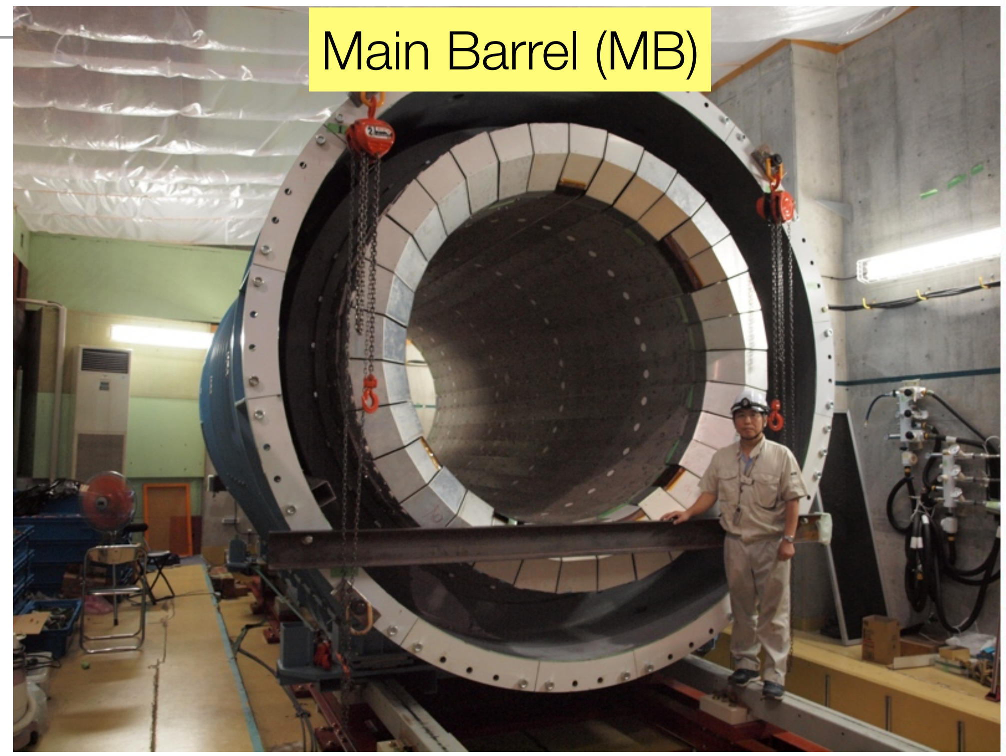


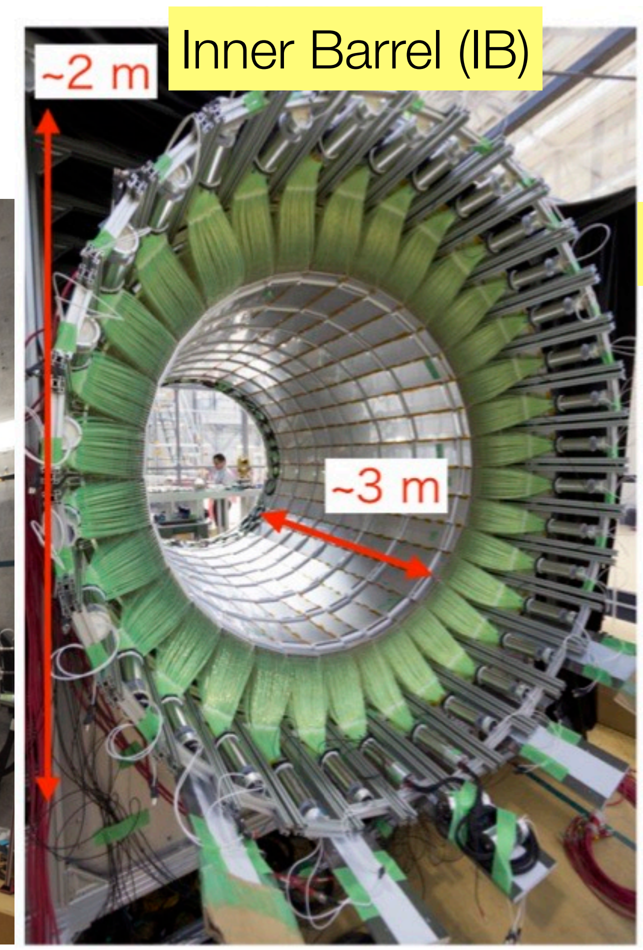


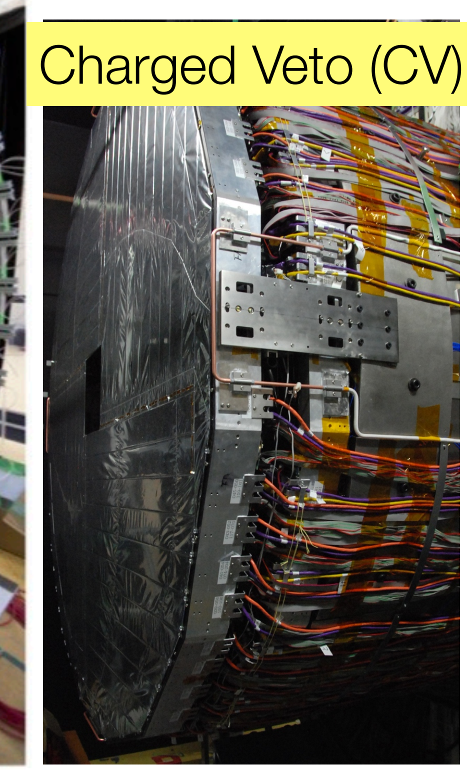
KOTO detector

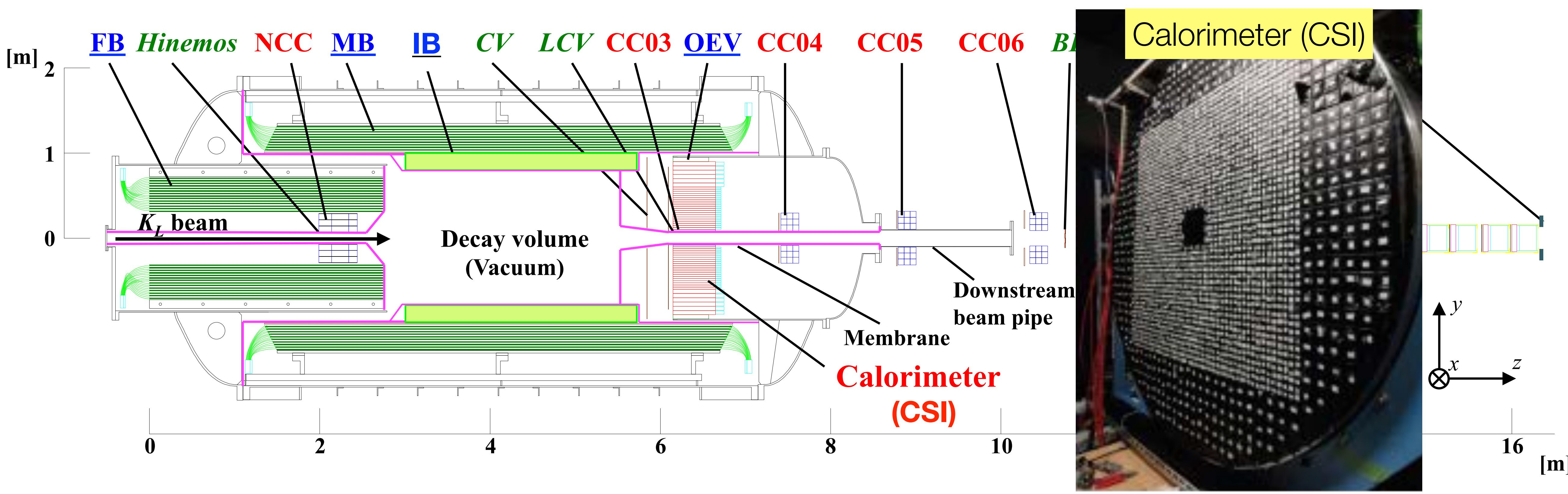








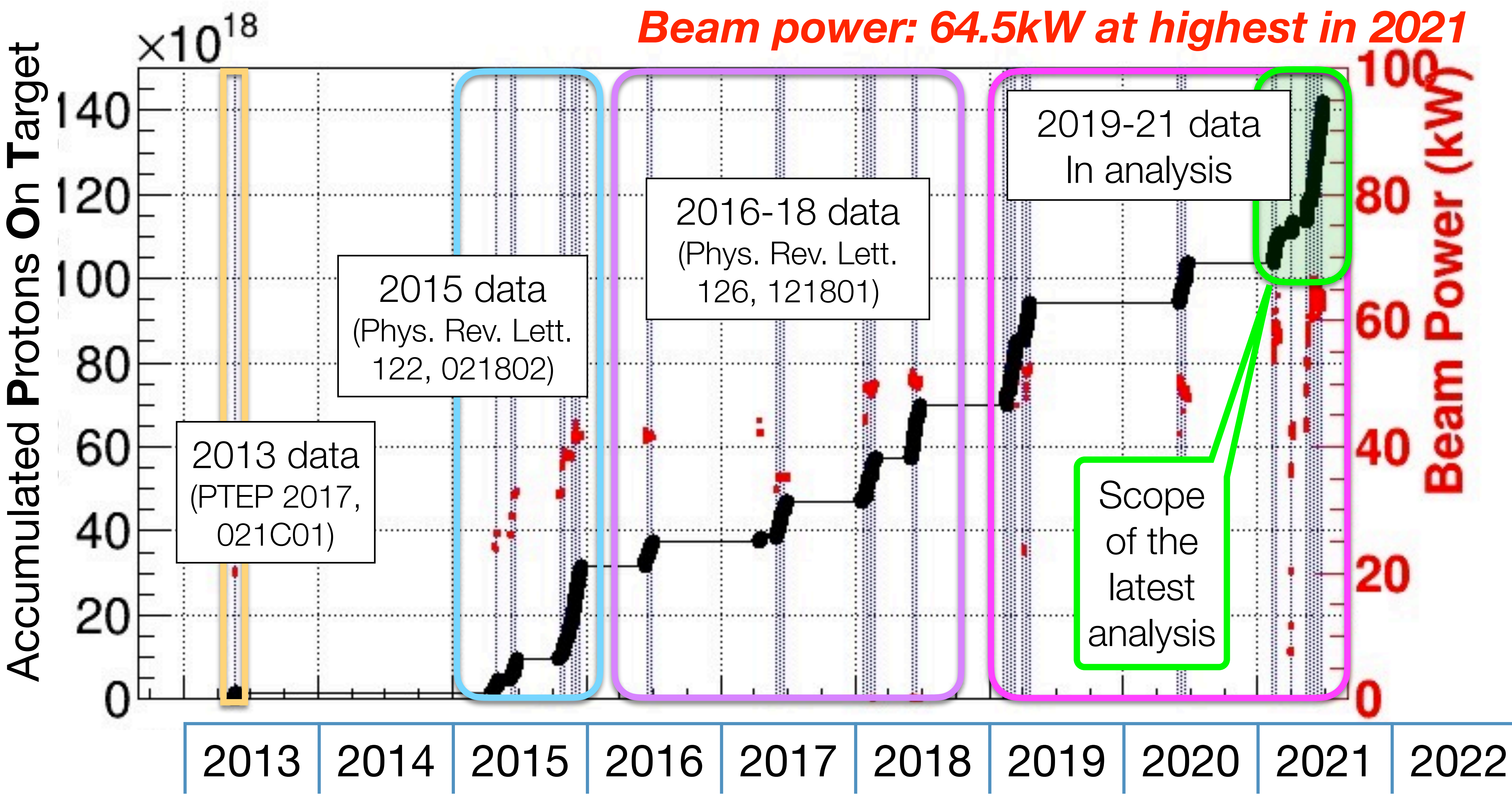




KOTO latest results
- From KOTO 2021 Data Analysis

P.O.T. = Protons On Target

KOTO data accumulation history



Detector upgrades

Additional barrel-type veto (IB)

Calorimeter upgrade for n/γ separation

K± veto: UCV

1mmt

0.5mmt

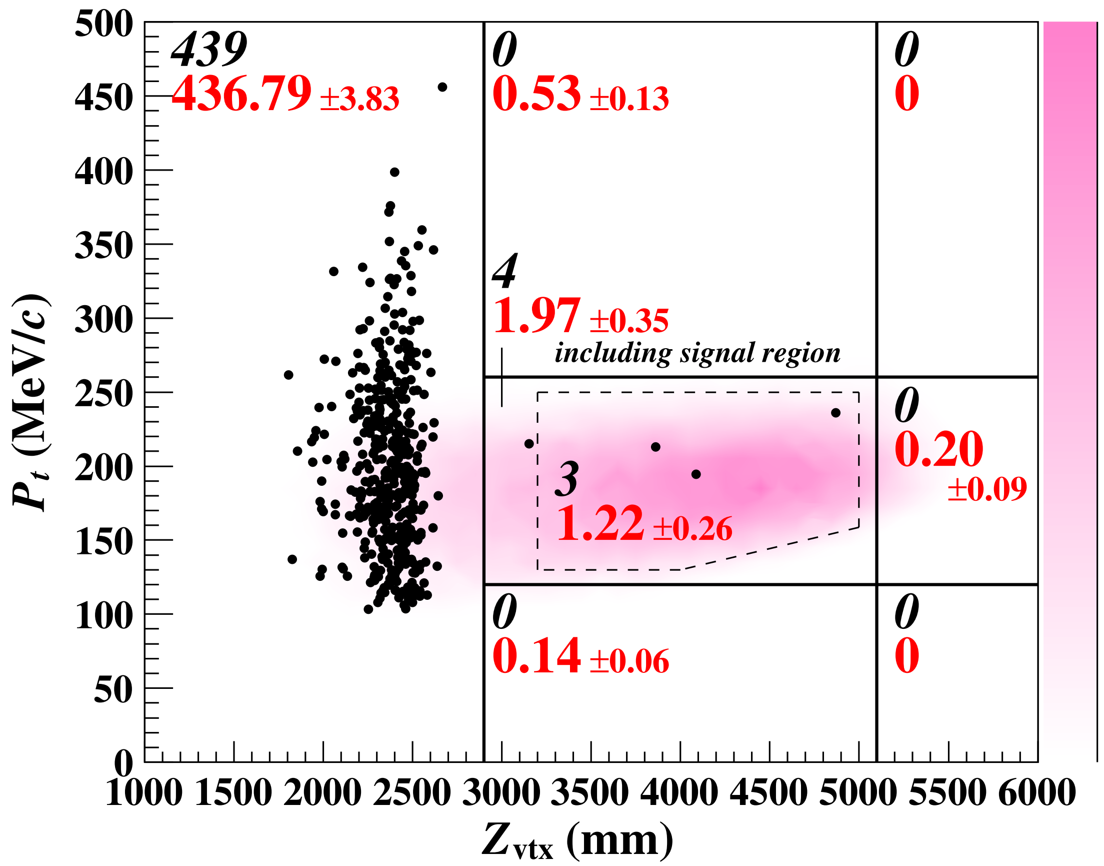
0.2mmt

Review of the previous analysis (2016-18 data)

<u>Final PT vs Z plot</u>

Black: observed
Red: expected BG
Contour: signal MC

Single Event Sensitivity = $(7.20 \pm 0.05_{stat} \pm 0.66_{syst}) \times 10^{-10}$



Background table

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

Newly evaluated backgrounds

$N_{observed}$ (=3) ⇔ Statistically consistent with N_{BG} (=1.22±0.26)

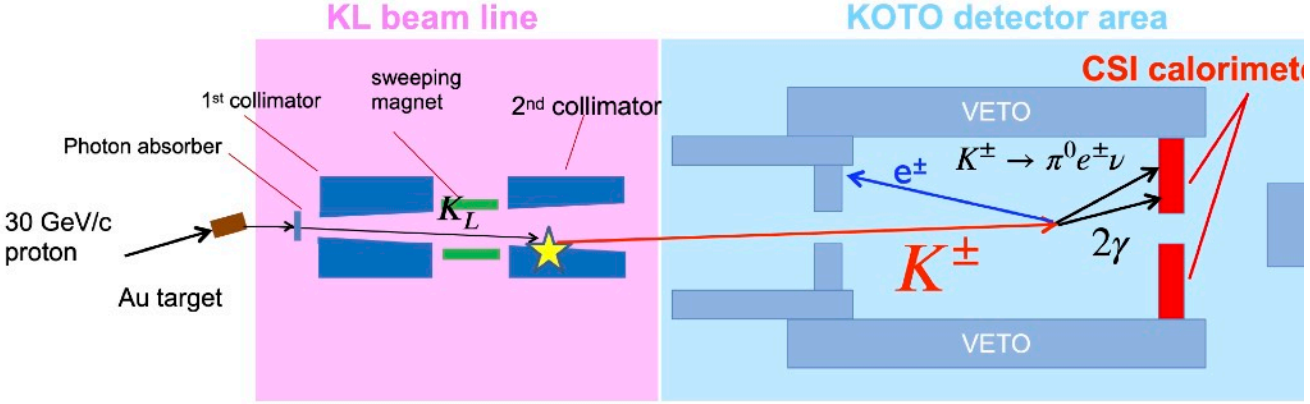
$BR(K_L \to \pi^0 \nu\nu) < 4.9 \times 10^{-9}$ (90% C.L.)

Better sensitivity but worse limit than the result from 2015 data

Must reduce $K^\pm$ and halo K_L backgrounds

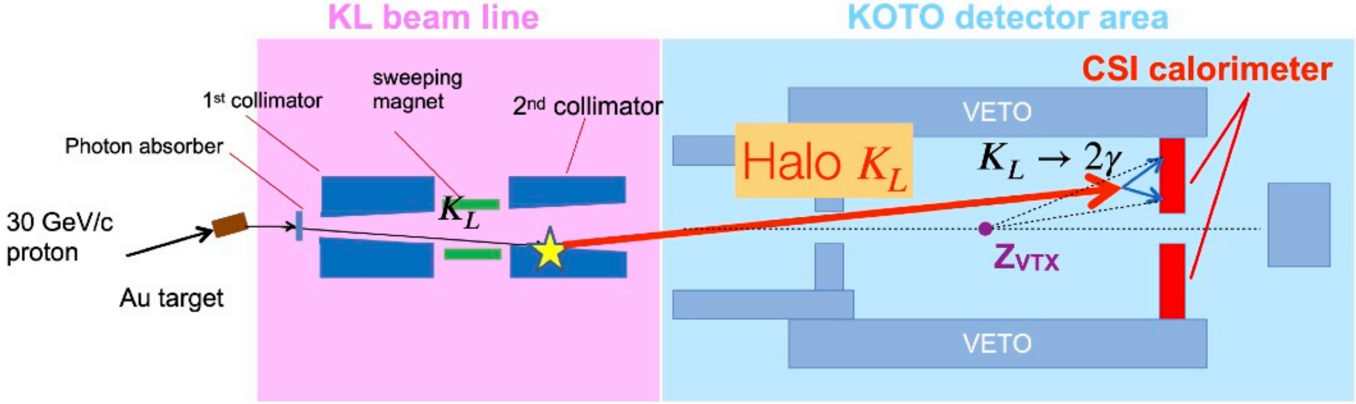
$K^{\pm}$ and halo $K_L \to 2\gamma$ backgrounds

$K^{\pm} \to \pi^0 e^{\pm} \nu$

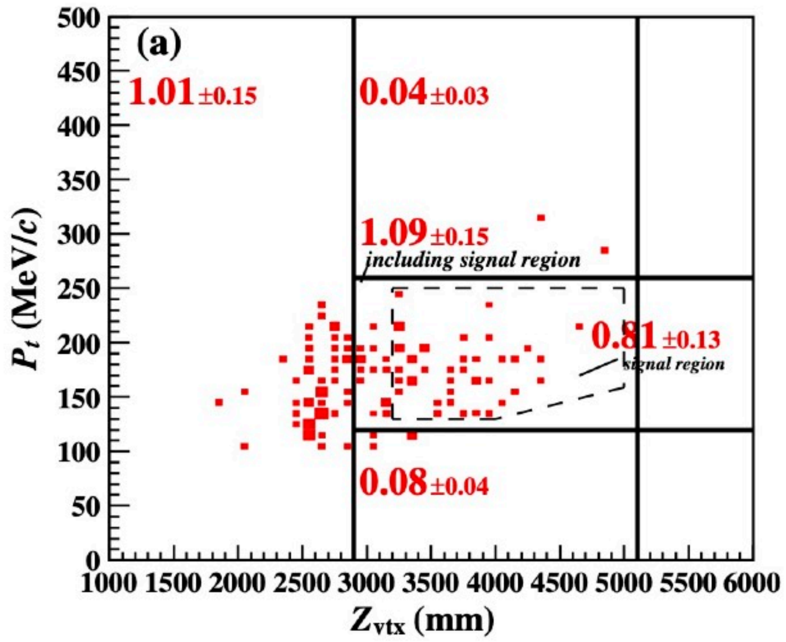


The interaction of K_L with the 2nd collimator produces $K^{\pm}$.

Halo $K_L \to 2\gamma$



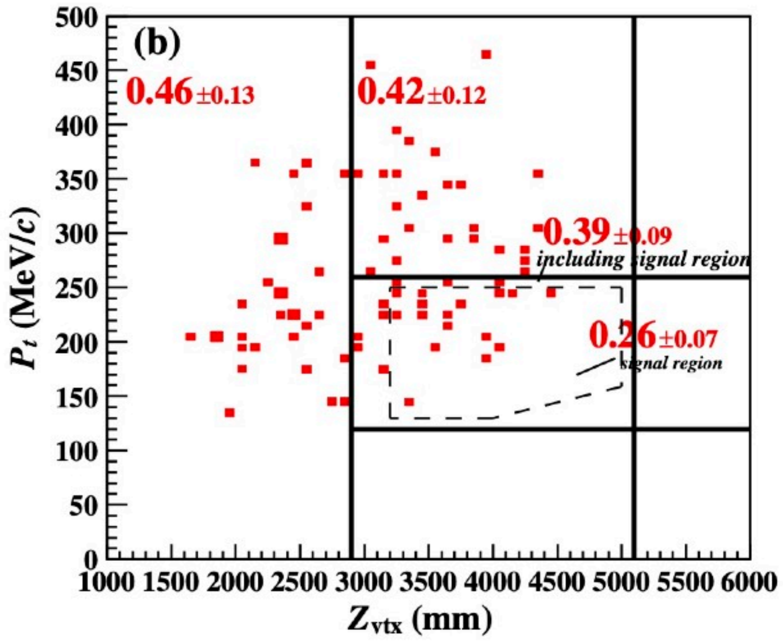
The interaction of K_L with the 2nd collimator produces halo K_L.



PT vs Z plots

Signal region

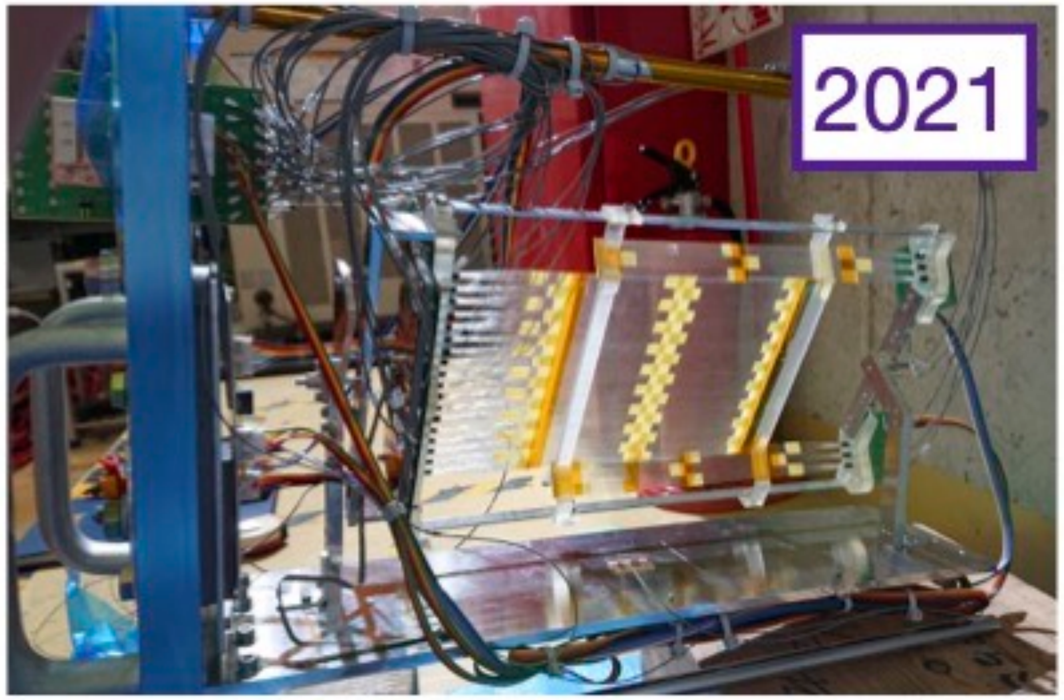
in 2016-18 analysis

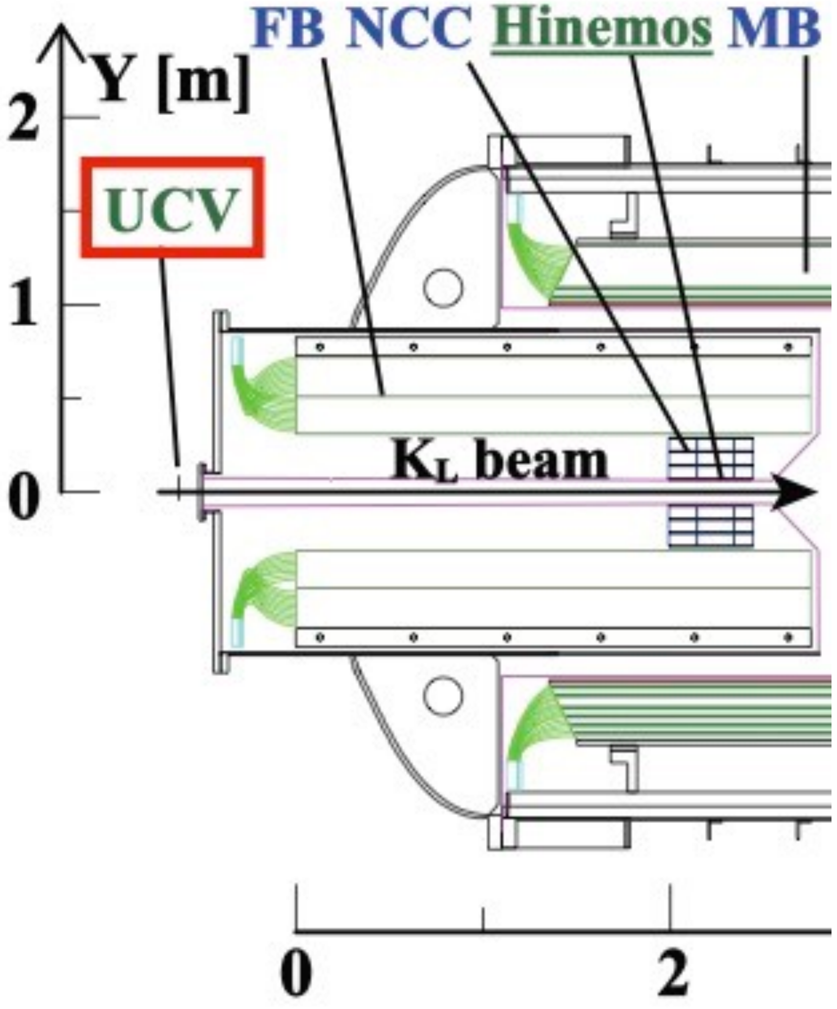


New in 2021 run:

UCV - Upstream Charged Veto

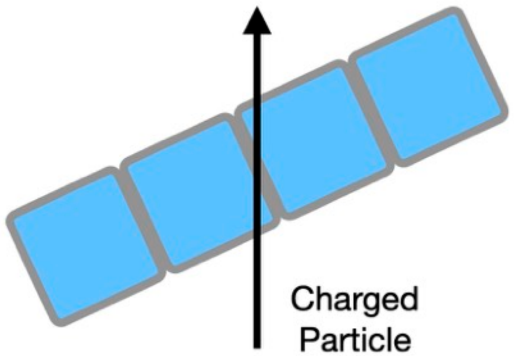
- For $K^{\pm}$ detection in the beam at the entrance of the KOTO detector
- A plane of square scintillation fibers, read by MPPC





0.5mm-square fibers

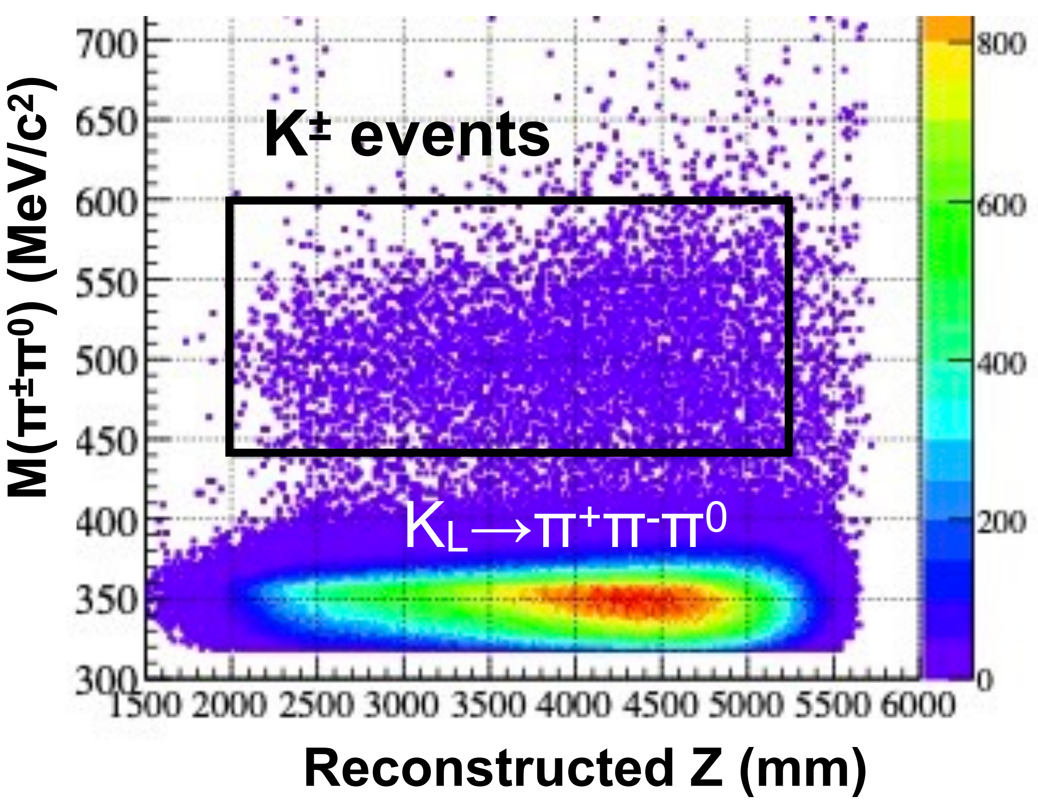
- Tilted 25 degree to reduce inefficiency due to fibers' inactive region (clad)

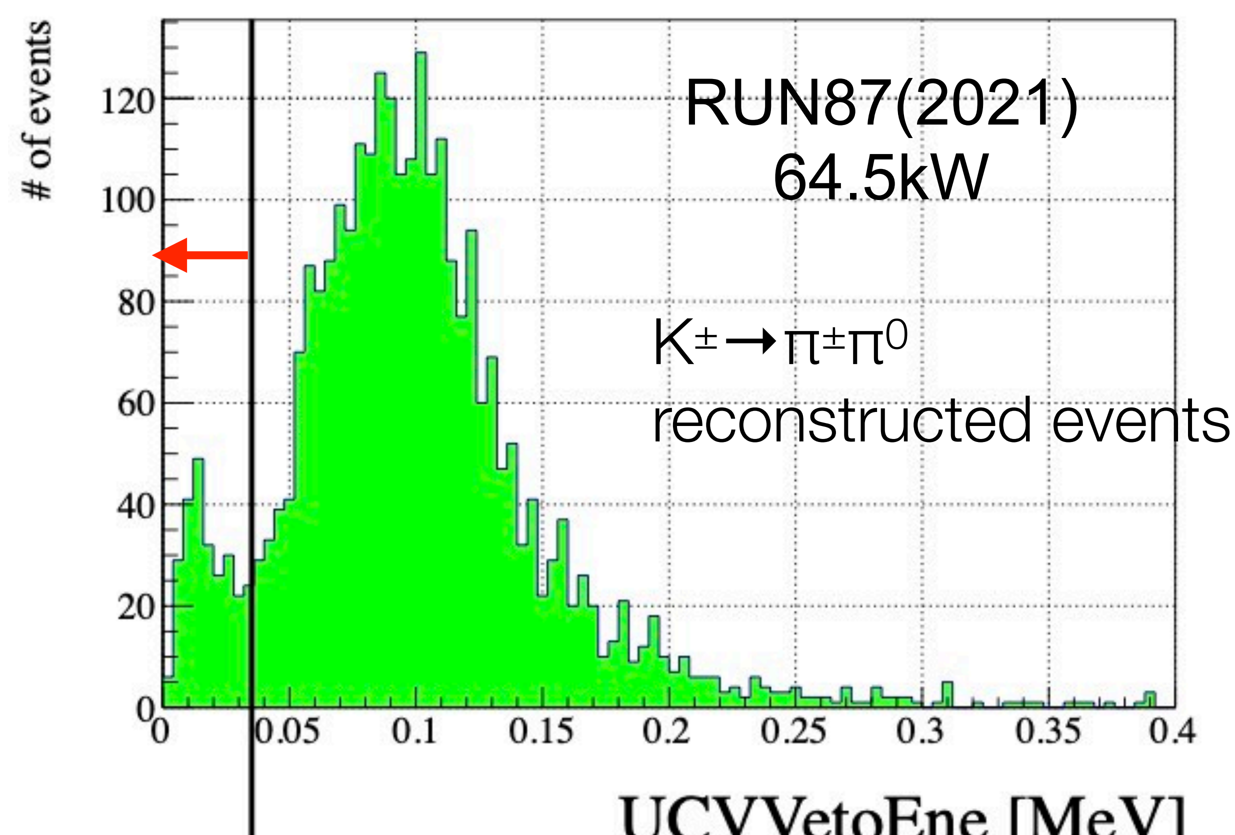


KOTO 2021 data analysis:

Evaluation of $K^{\pm}$ flux and rejection by UCV

- $K^{\pm}$ flux was evaluated by using control data which were simultaneously taken in physics run
  - 3-cluster trigger, collecting 2γ (from π^0)+$1\pi^{\pm}$





$K^{\pm}$ flux: $R(K^{\pm}/K_L)=3.3\times10^{-5}$

UCV detection inefficiency=7.8%

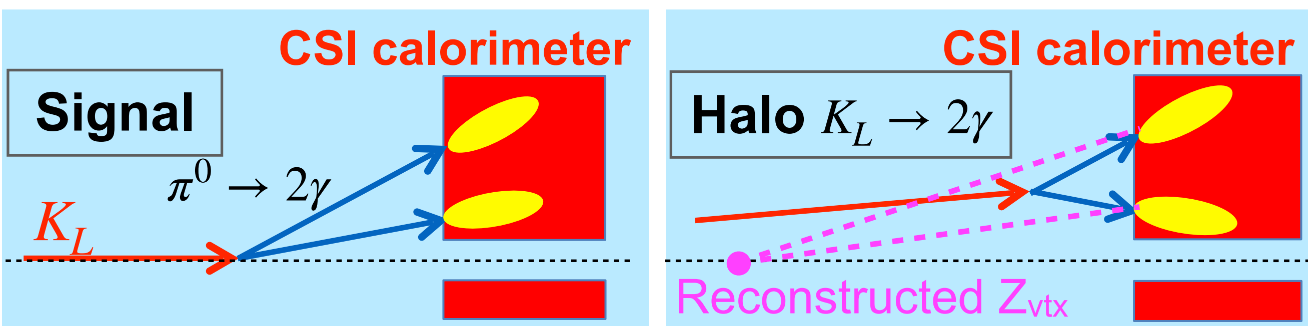
Corresponding to $K^{\pm}$ BG rejection by a factor of 12

New in 2021 data analysis:

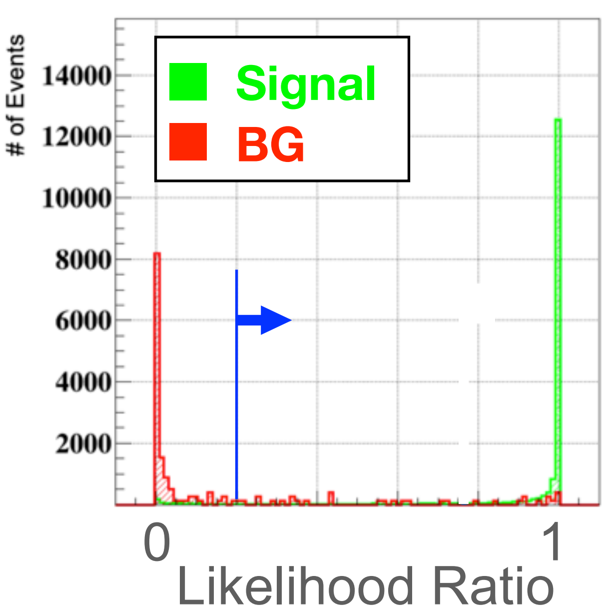
Analysis method to reject halo $K_L \to 2\gamma$

Shower shape likelihood

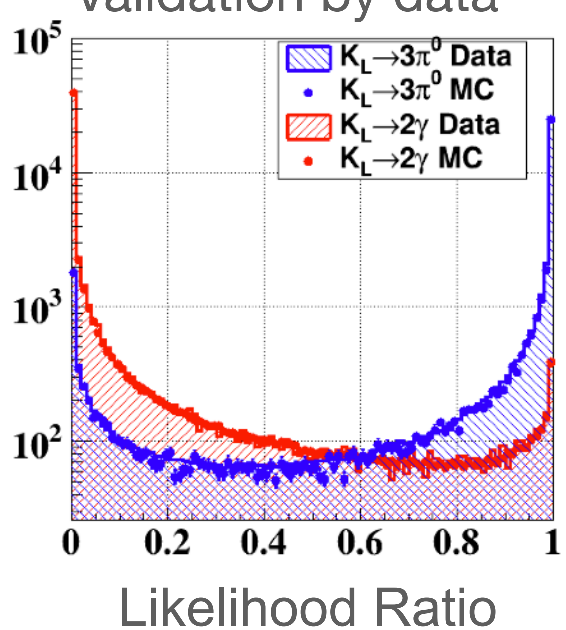
- Consistency between shower shape and reconstructed angle



Performance



Validation by data



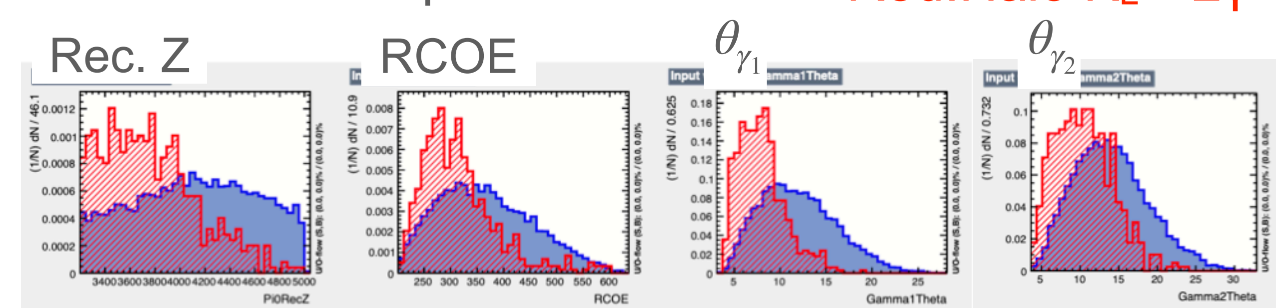
Kinematic MVA

- Multi-variable analysis by using kinematical variables

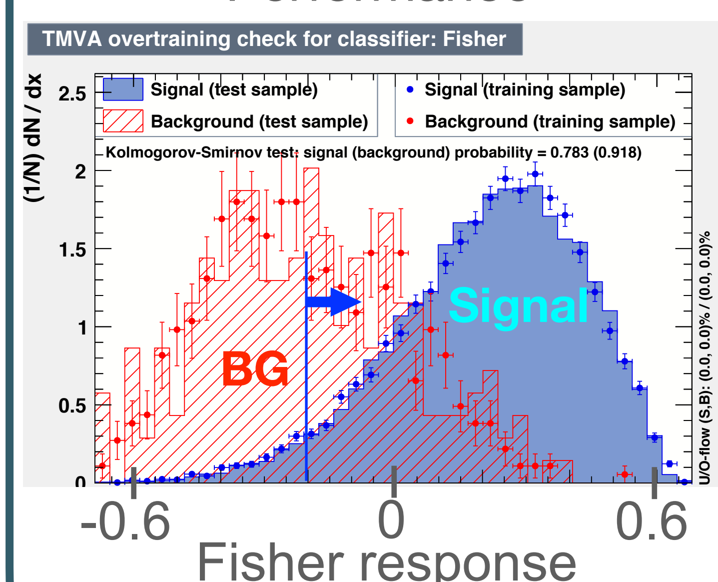
Blue:signal

Red:Halo $K_L \to 2\gamma$

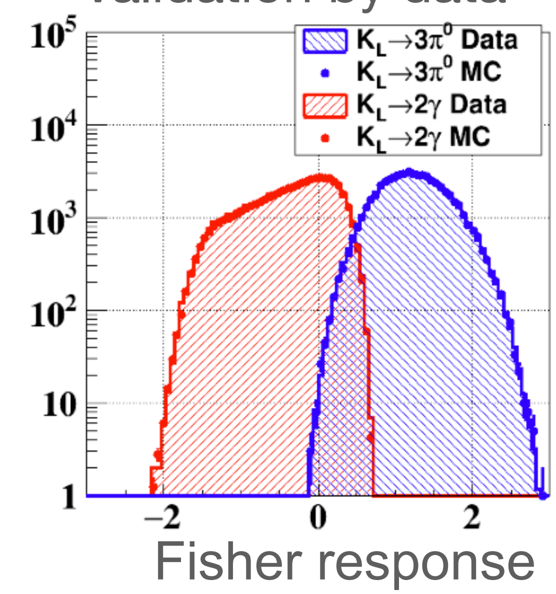
Distributions of input variables



Performance



Validation by data

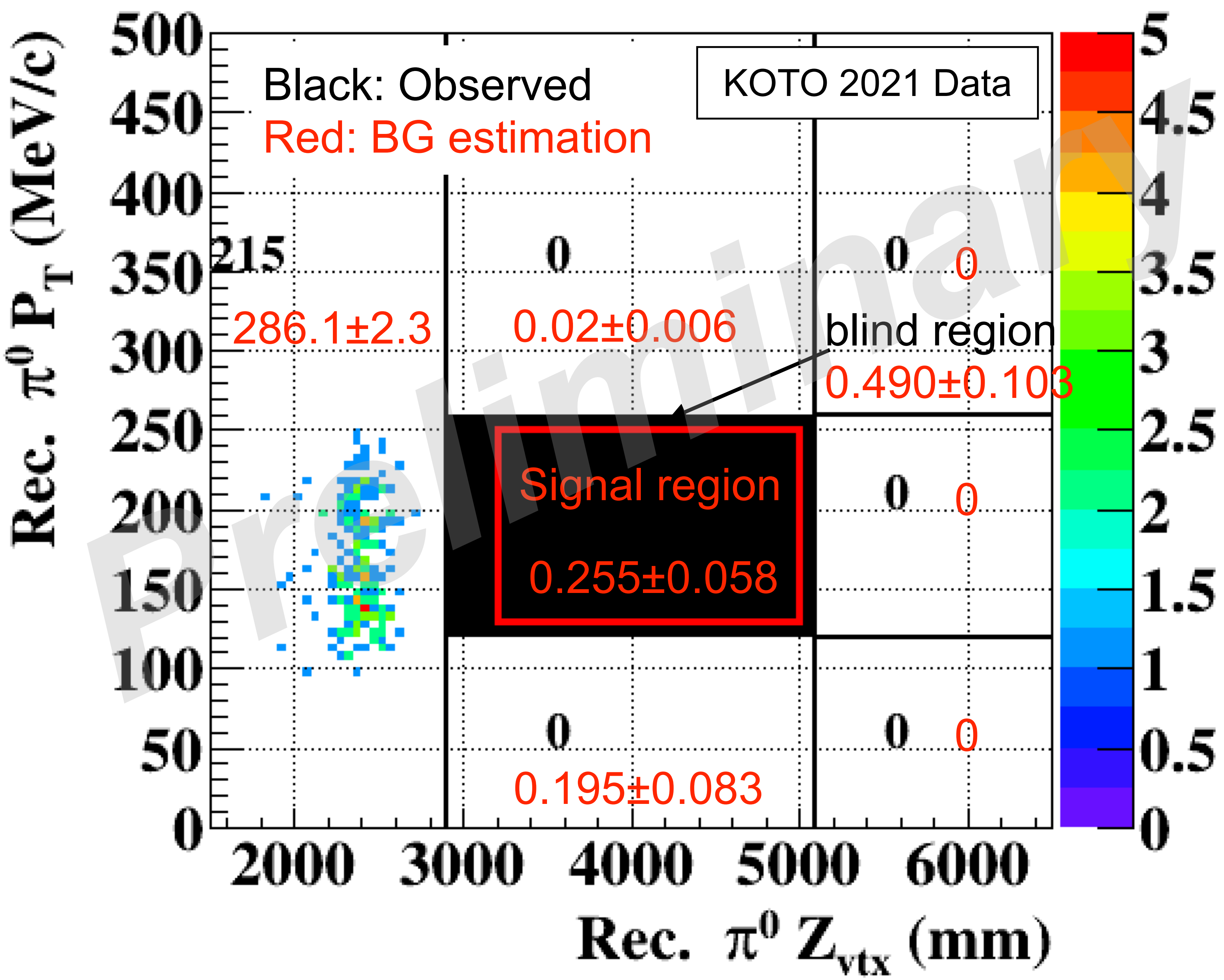


Reduce halo $K_L \to 2\gamma$ by a factor of 8, while signal efficiency = 94%

KOTO 2021 data analysis:

P_T vs Z plot after applying all the cuts

Single Event Sensitivity = 8.7 × 10^{-10}



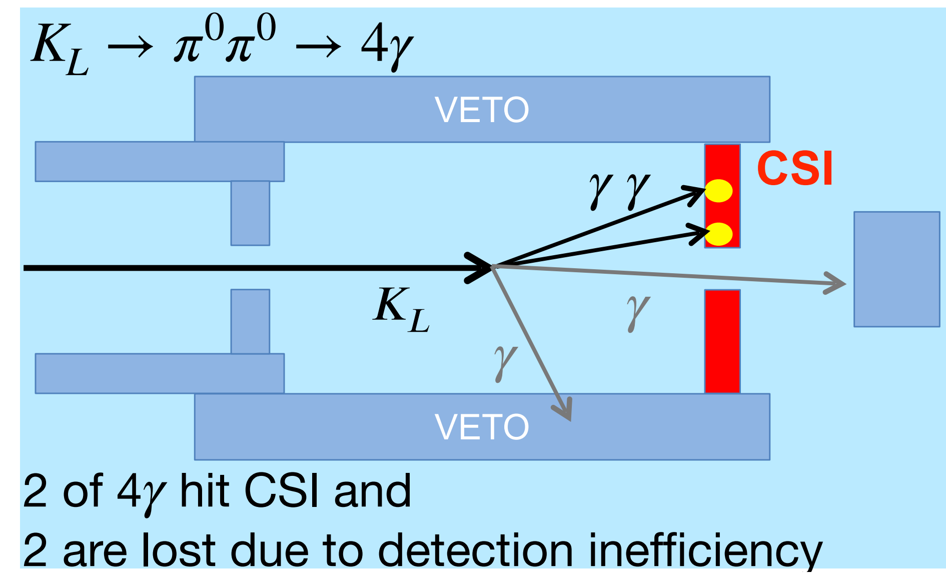
Background evaluations in detail:

$K_L \to 2\pi^0$ background

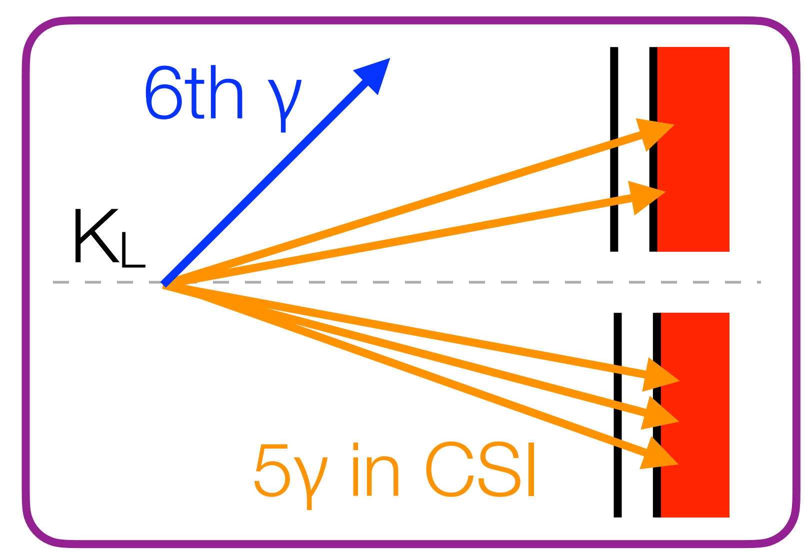
- Inefficiency of the photon detection is critical for $K_L \to 2\pi^0$ BG estimation.
  - We relied on the simulation in the past analysis but different versions of GEANT4 gave us different results.
  - Data-driven evaluations (and corrections) are needed.

- We use $K_L \to 3\pi^0$ events with 5γ in the calorimeter as evaluation samples.
  - Calculate energy (E_6) and direction of remaining 1γ by using kinematic constraints (vertex from $2\pi^0$ reconstruction, transverse momentum balance, K_L mass)
  - Check the energy deposit in the detector of destination

$K_L \to 2\pi^0$ background



Inefficiency evaluation by using $K_L \to 3\pi^0$



Inefficiency evaluation with 5γ data
Category: Barrel (IB or MB), high E

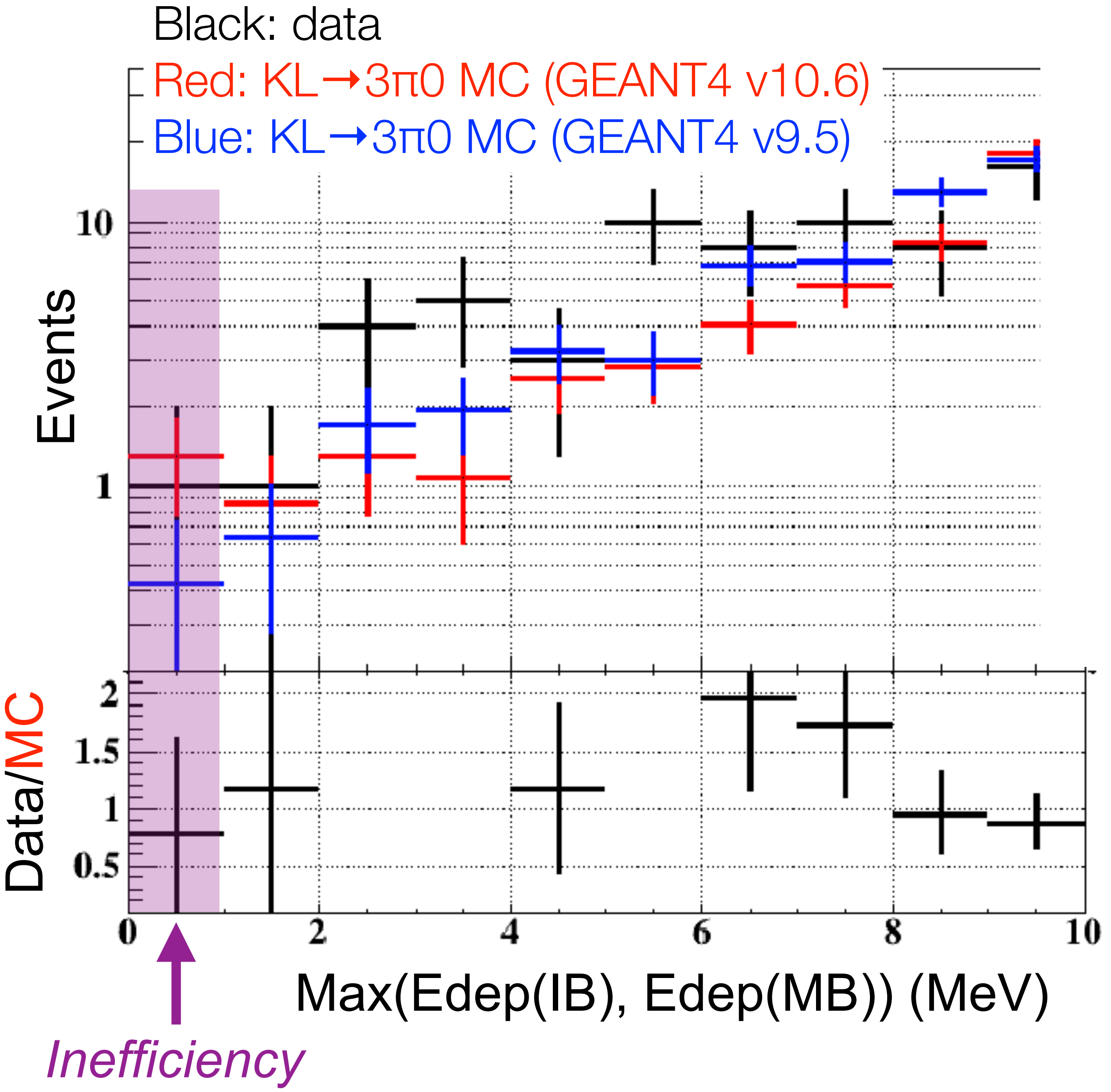
Reconstructed E_6: >200MeV
Destination: IB/MB region

Inefficiency event ≡ N(Edep<1MeV)

- **1 in data** (uncertainty is 100%)
  Corresponding inefficiency
  = $(4.8\pm4.8)\times10^{-5}$
- **1.3**±0.5 **in MC** - G4 v10.6
  (cf. 0.4±0.3 in G4 v9.5 MC)
  Corresponding inefficiency
  = $(6.2\pm2.5)\times10^{-5}$

MC-to-data correction factor:
1/1.3 = 0.77
Uncertainty: 100%
Limited by statistics of control data

Energy deposit (E_{dep}) in the barrel detectors



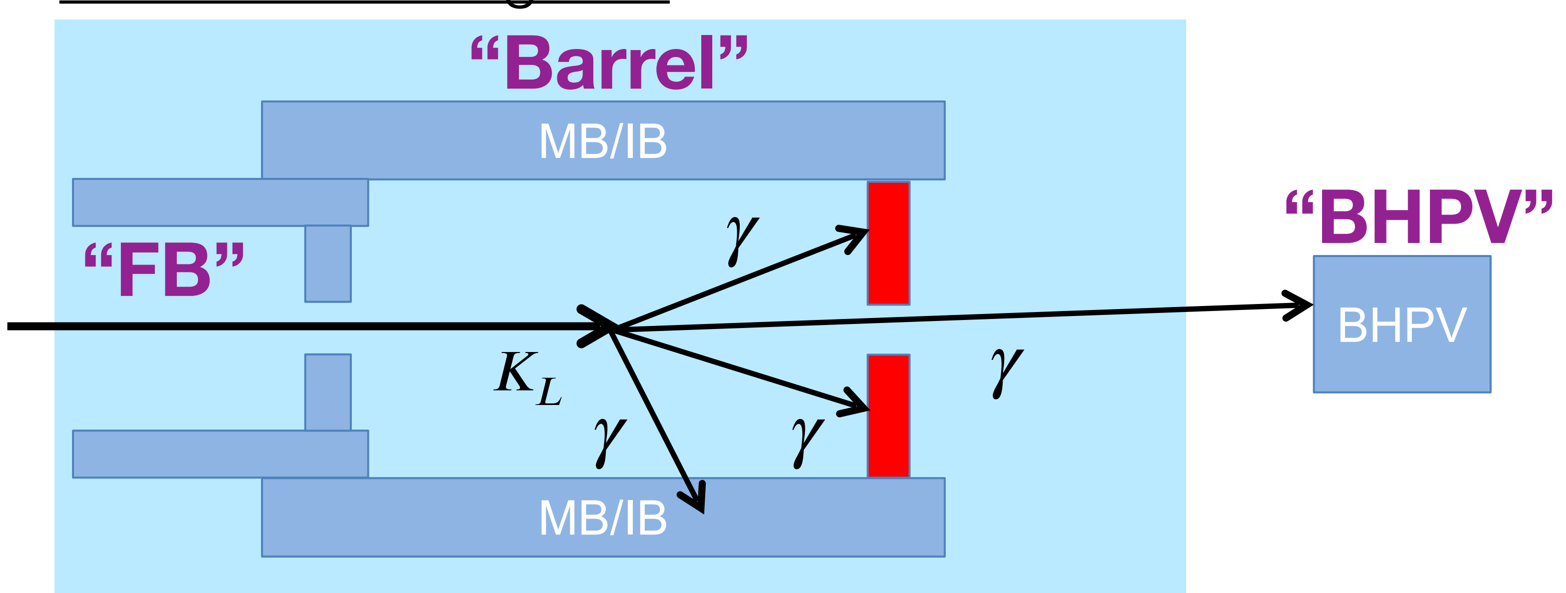
Background evaluations in detail:

$K_L \to 2\pi^0$ background with correction factors

- Applied the weight to BG events in MC, according to energies and destinations of missing photons in each event

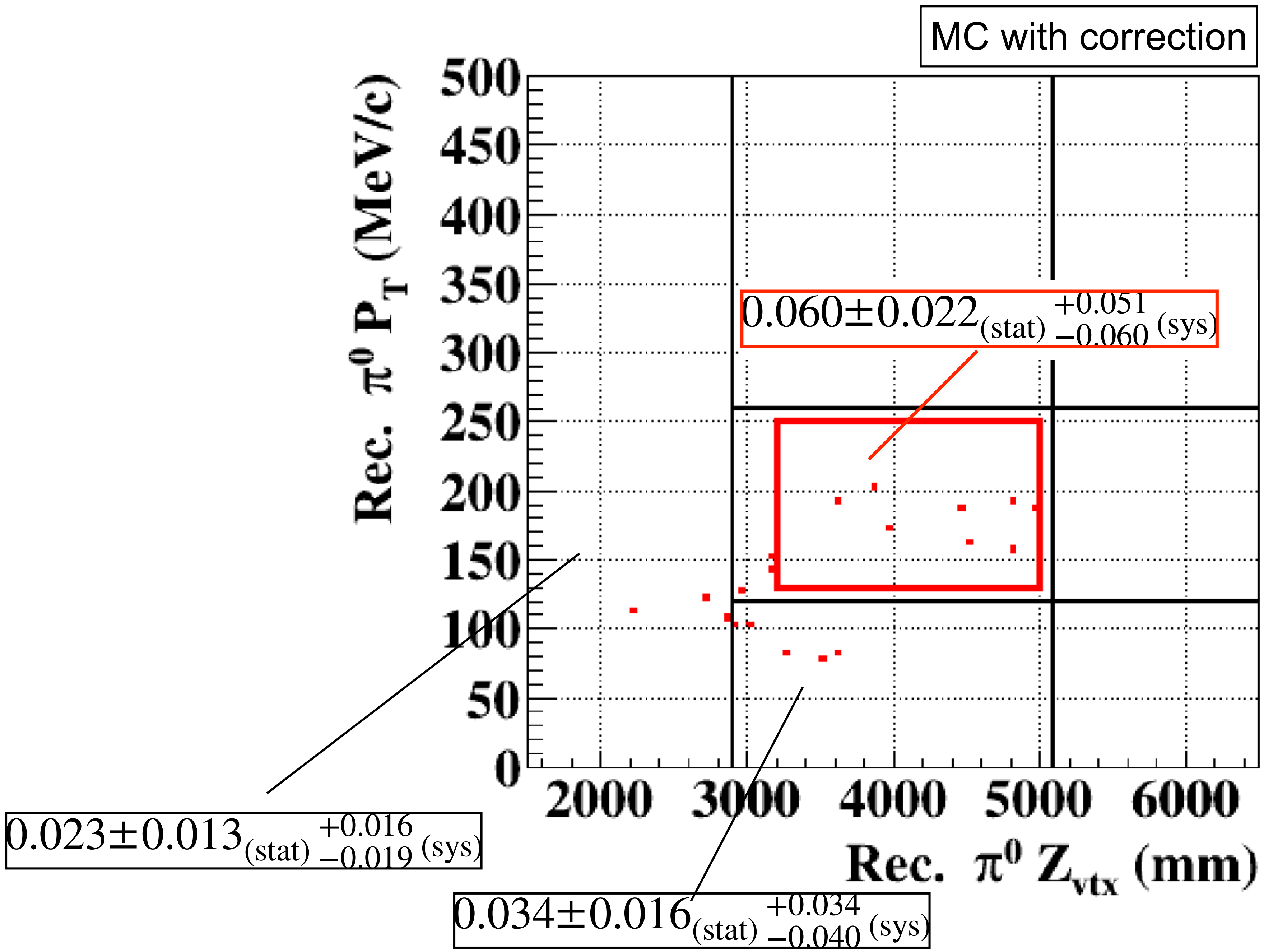
Category	Correction factor on inefficiency	Uncertainty (Stat error of 5γ data)
Barrel, high E	0.77	+85% / -100%
Barrel, low E	1.10	±9.9%
FB (upstream)	1.42	±12.6%
BHPV (downstream)	1.5	+42% / -51%

Destination categories



Background evaluations in detail:

$K_L \to 2\pi^0$ background on P_T vs Z plane



N_{BG}=0.060

($\Leftrightarrow$ $N_{BG,\text{ w/o correction}}$=0.049)

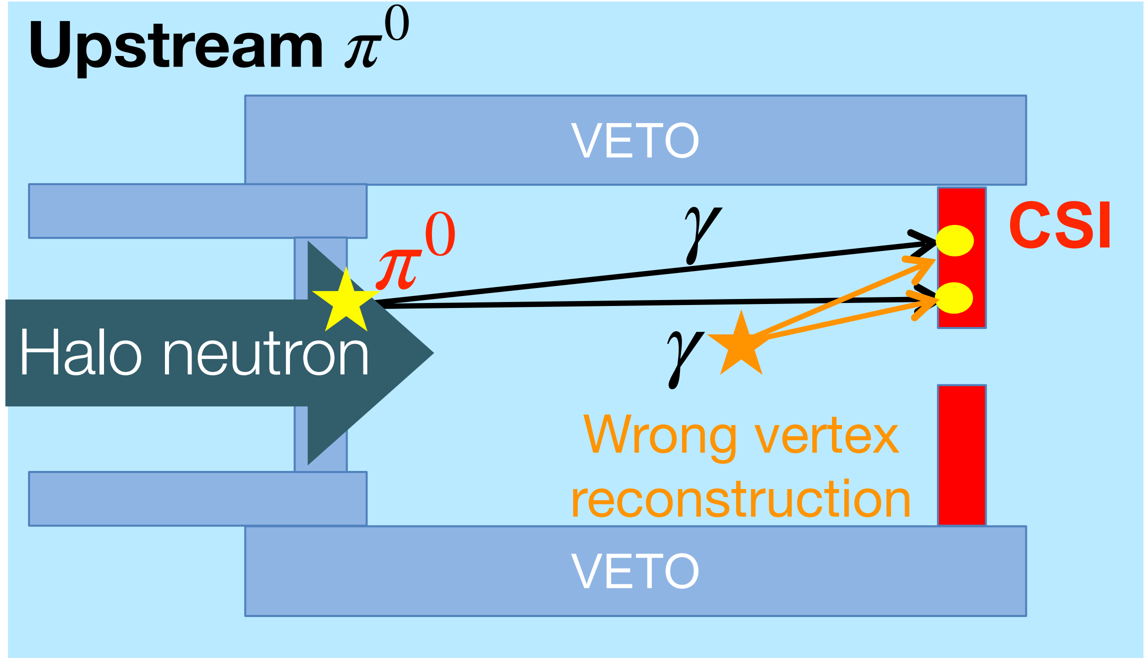
Background evaluations in detail:

Upstream π^0 background

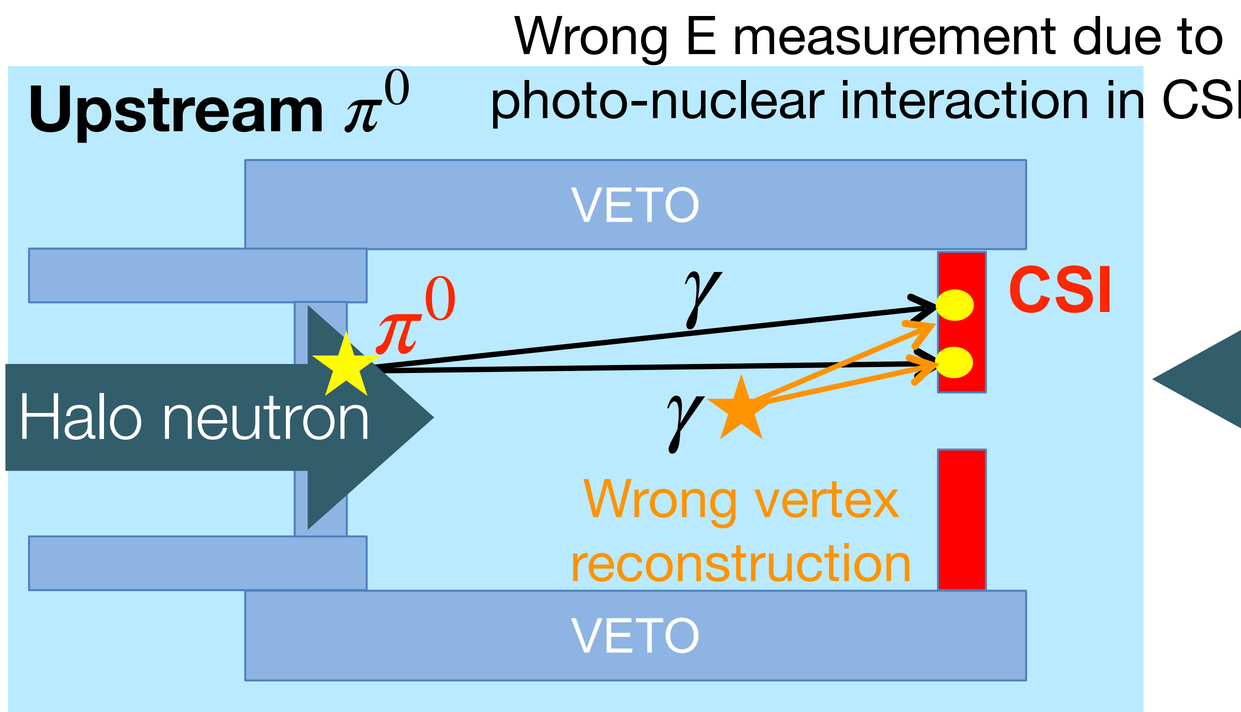
- π^0 can be produced by the interaction between halo neutrons and the upstream detector (NCC).
    - The reconstructed vertex must be around the NCC position, which is outside of the signal region.
    - If the measured photon energy is wrong ($E_{measured}<E_{true}$), the resultant reconstructed vertex can be inside the signal region.

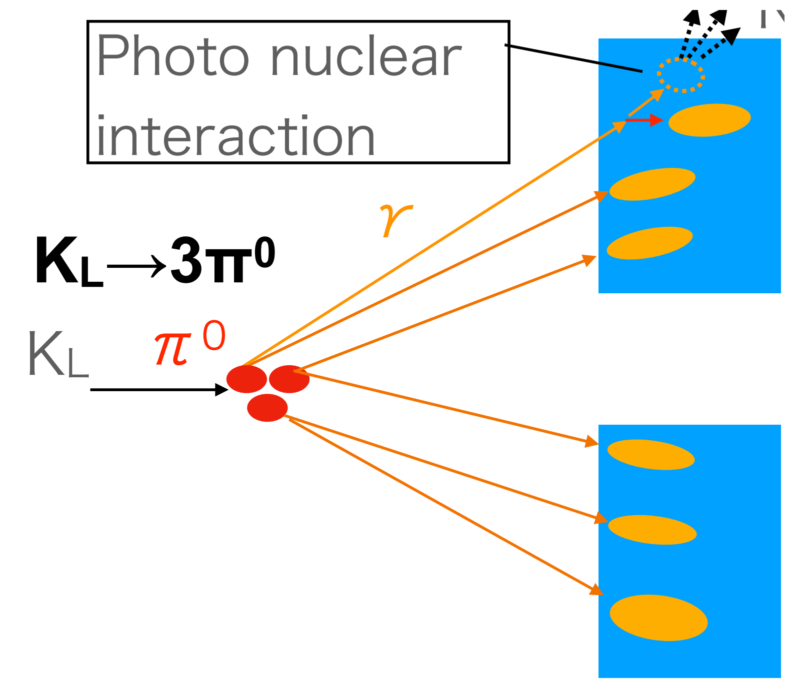
      This happens due to **photo-nuclear interactions in the calorimeter.**

      ➔ Need data-driven evaluations

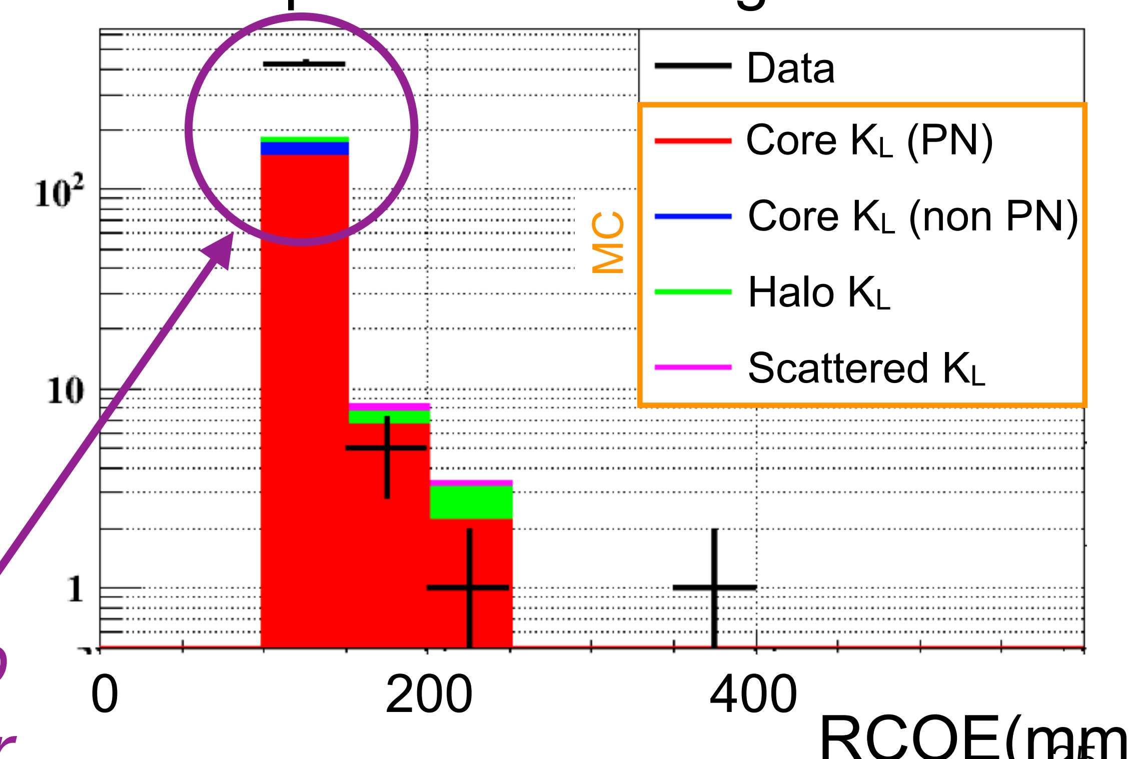


Data-driven evaluation of photo-nuclear interaction in the CsI calorimeter





6γ events with large COE



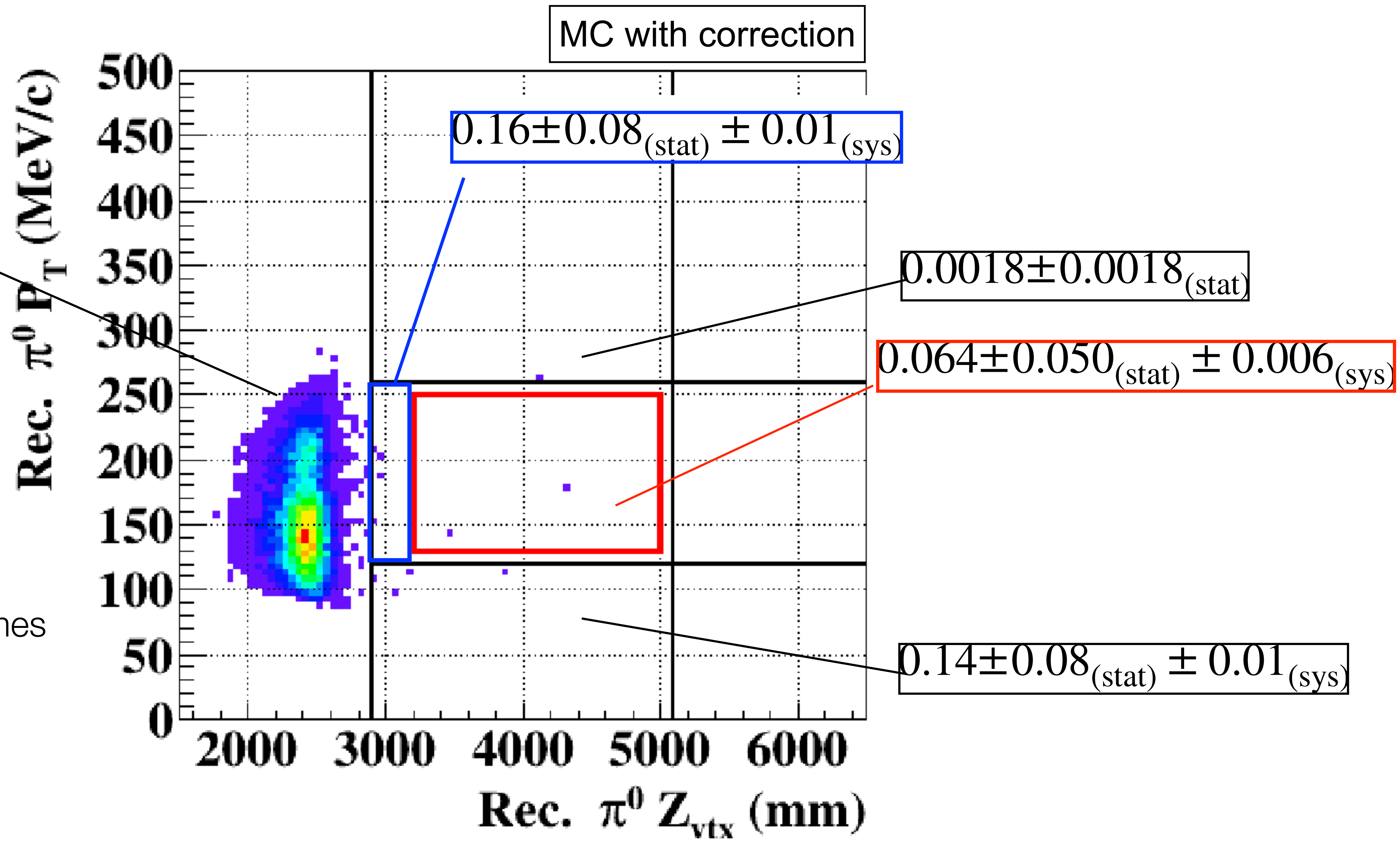
The MC reproducibility of the photo-nuclear interaction (PN) in the CsI calorimeter can be evaluated by using 6γ sample ($K_L \rightarrow 3\pi^0$).

- $M(6\gamma) \neq M_{K_L}$
- Large center of energies radius (RCOE)

This discrepancy was taken into account as the correction factor.

Background evaluations in detail:

Upstream π^0 background on P_T vs Z plane



$\Leftrightarrow N_{obs} = 215$

25% discrepancy comes from an imperfect reproducibility of π^0's kinematics in MC.

N_{BG}=0.064

($\Leftrightarrow$ $N_{BG,\ w/o\ correction}$=0.035)

KOTO 2021 data analysis:

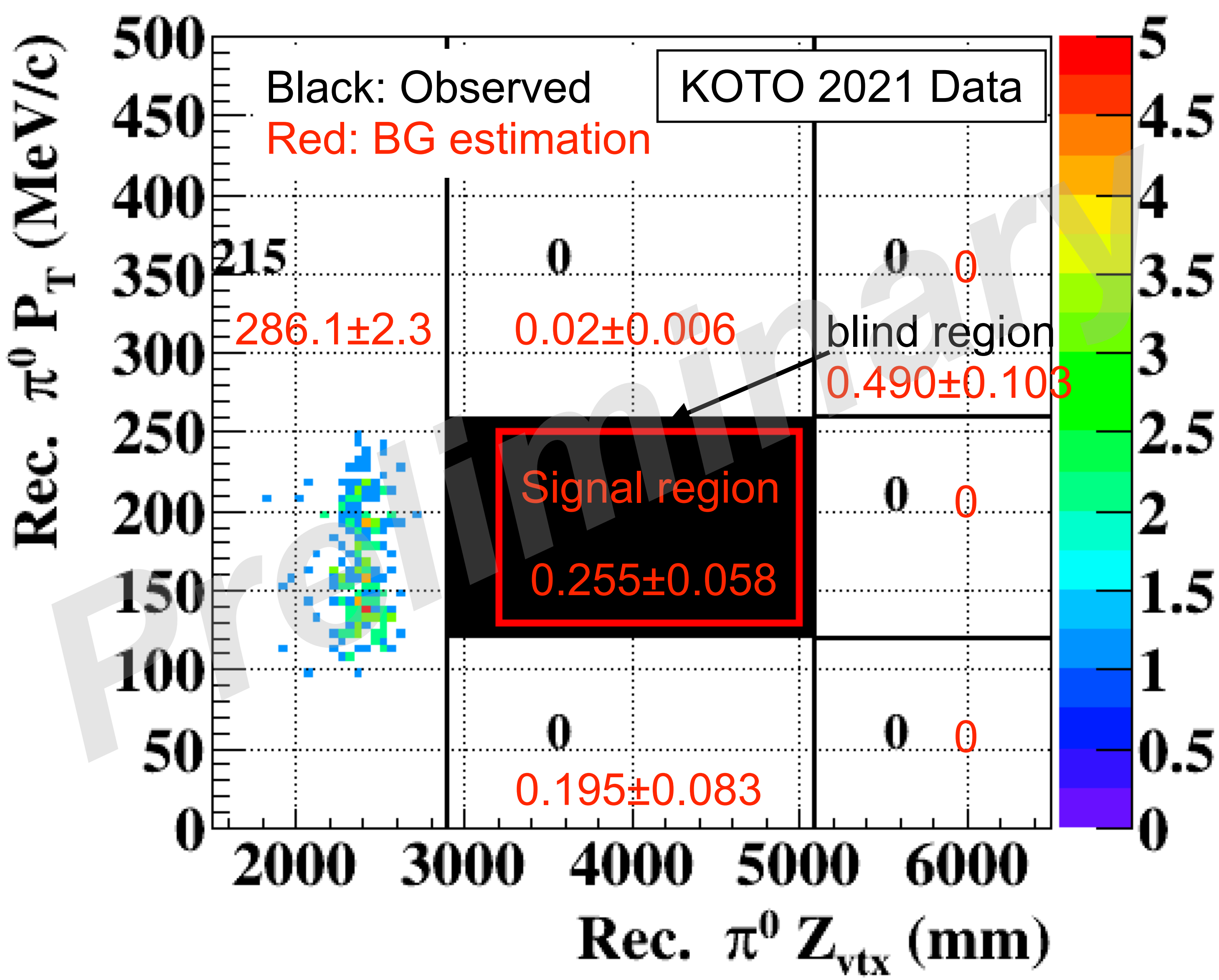
Summary of backgrounds

Source	Estimated value
Upstream π^0	$0.064 \pm 0.050\ (stat.) \pm 0.006\ (syst.)$
$K_L \to 2\pi^0$	$0.060 \pm 0.022\ (stat.)\ ^{+0.051}_{-0.060}\ (syst.)$
$K^\pm$	$0.043 \pm 0.015\ (stat.)\ ^{+0.004}_{-0.030}\ (syst.)$
Scattered and halo $K_L(\to 2\gamma)$	$0.022 \pm 0.005\ (stat.) \pm 0.004\ (syst.)$ $0.018 \pm 0.007\ (stat.) \pm 0.004\ (syst.)$
Hadron cluster BG	$0.024 \pm 0.004\ (stat.) \pm 0.006\ (syst.)$
η production in CV	$0.023 \pm 0.010\ (stat.) \pm 0.006\ (syst.)$
Sum	$0.255 \pm 0.058\ (stat.)\ ^{+0.053}_{-0.068}\ (syst.)$

KOTO 2021 data analysis:

Ready for opening the box

Single Event Sensitivity
$= 8.7 \times 10^{-10}$

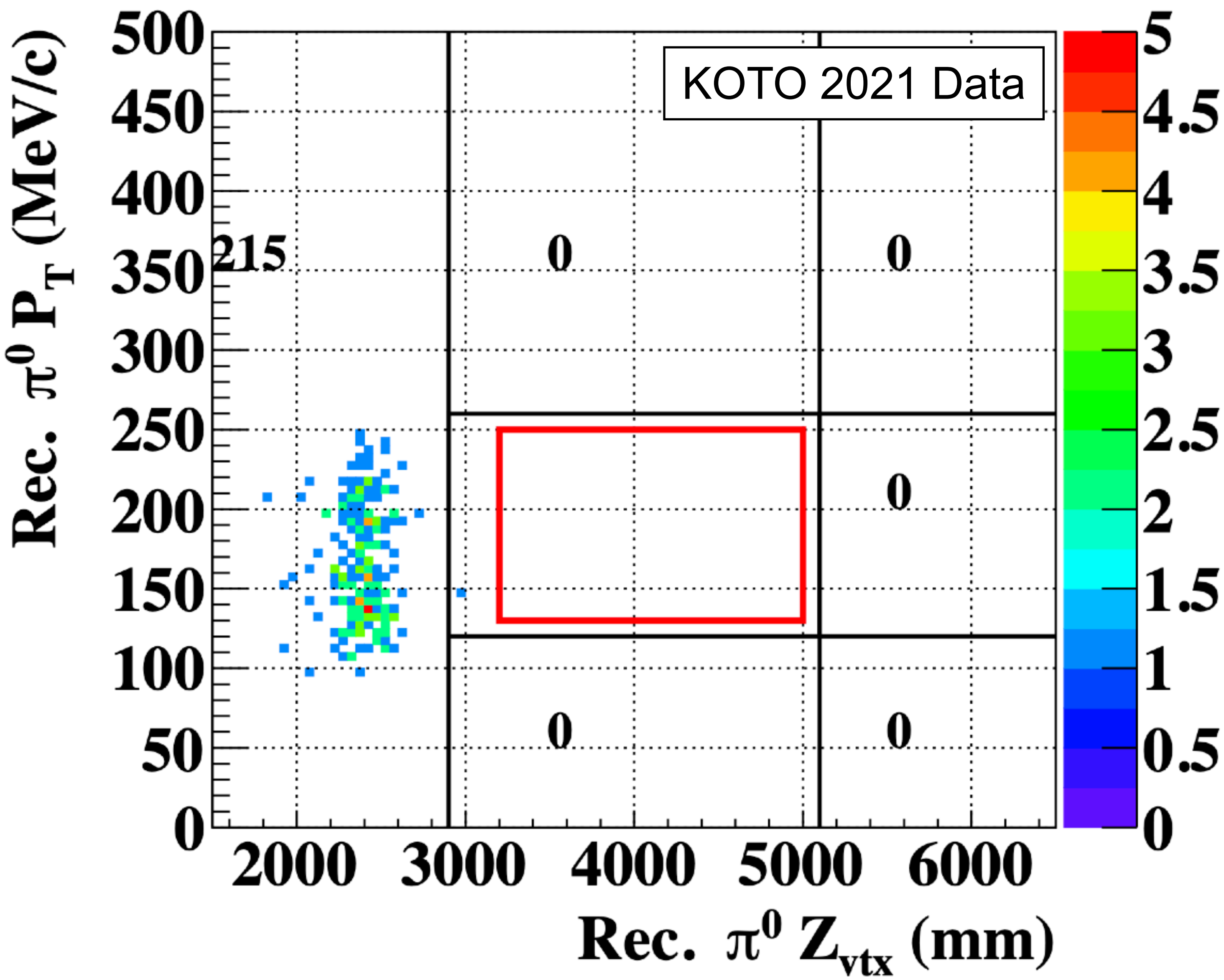


Preliminary

Results

- Unblinded the hidden region
  ➡**No signal candidates** were observed in the signal region.
- Set the upper limit to be
  BR($K_L \to \pi^0 \nu\bar{\nu}$) < 2.0×10^{-9}
  at 90% confidence level.
  - Corresponding to SES×2.3 based on Poisson statistics.

Preliminary



We are preparing the paper of this result.

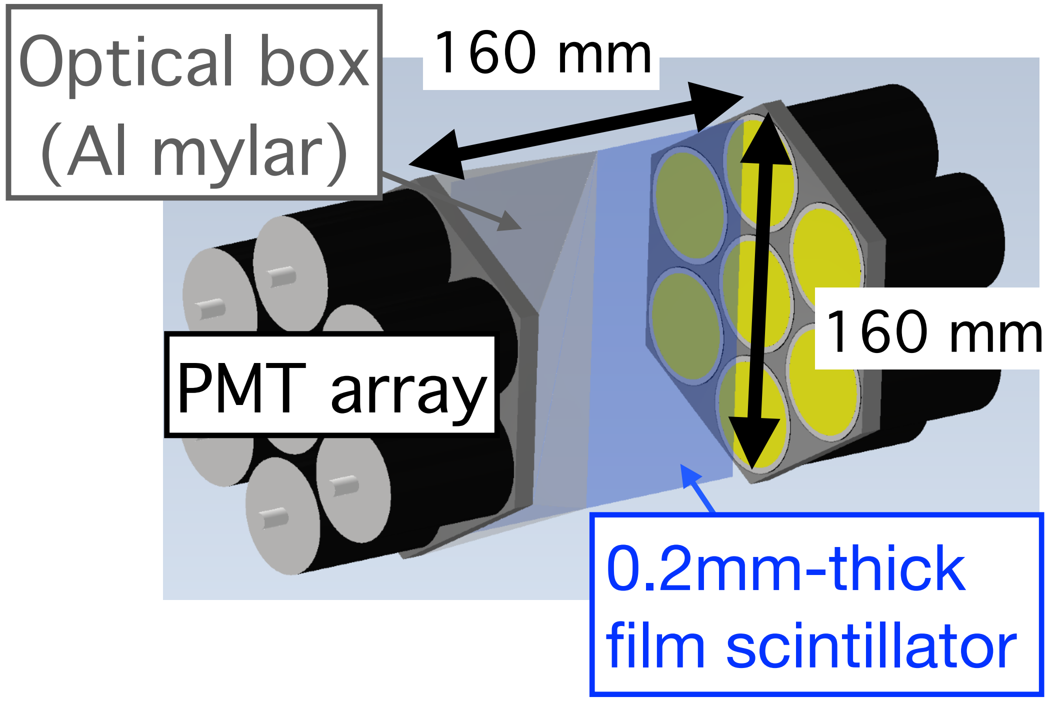
Prospects

Improvement after 2021 run

The MR accelerator was shutdown in 2021-22 for the magnet power supply upgrade.

- UCV upgrade
  - Less material and better efficiency
- DAQ upgrade
  - To prepare for a higher beam power, and to accommodate more control data simultaneously in physics run
  - Capable to handle ~×2 more trigger rate
- Beam line upgrade
  - 50-cm-long, 0.9-T permanent magnet has been installed at the end of the beam line to sweep out $K^{\pm}$.

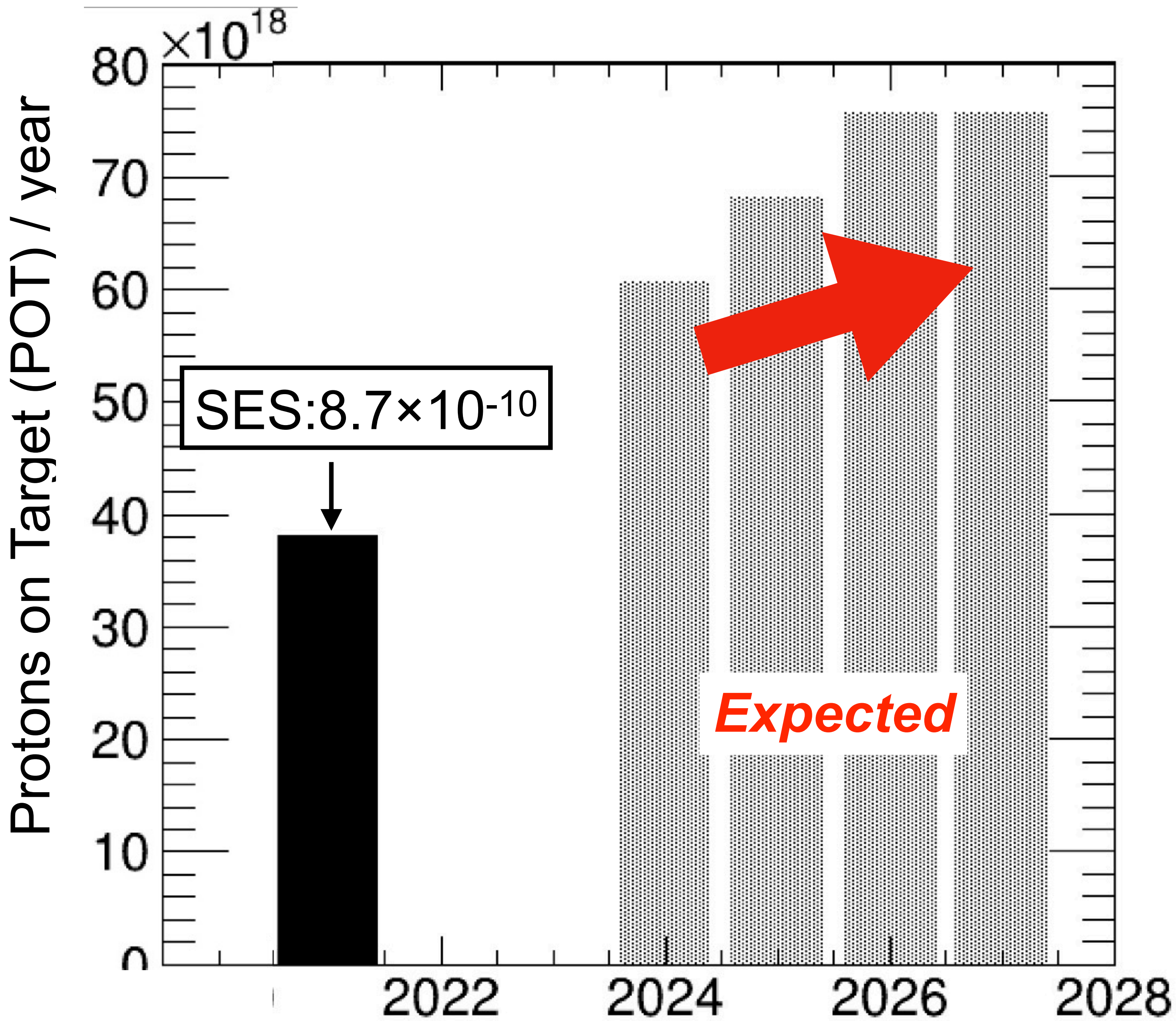
New UCV



>99.9% efficiency was achieved in a short run in June 2023

We are ready for next run.

KOTO expected sensitivity in the near future



The accumulated POT will be ×10 larger than 2021 in 4-5 years.

Assumption

- The beam power increases as 80→90→100kW.
- 60 days beam time / year.

➡ SES will reach the level better than 10^{-10}.

- The achievable sensitivity will be $(5\text{-}8)\times10^{-11}$.

Thanks to the MR power supply upgrade in 2021-22,

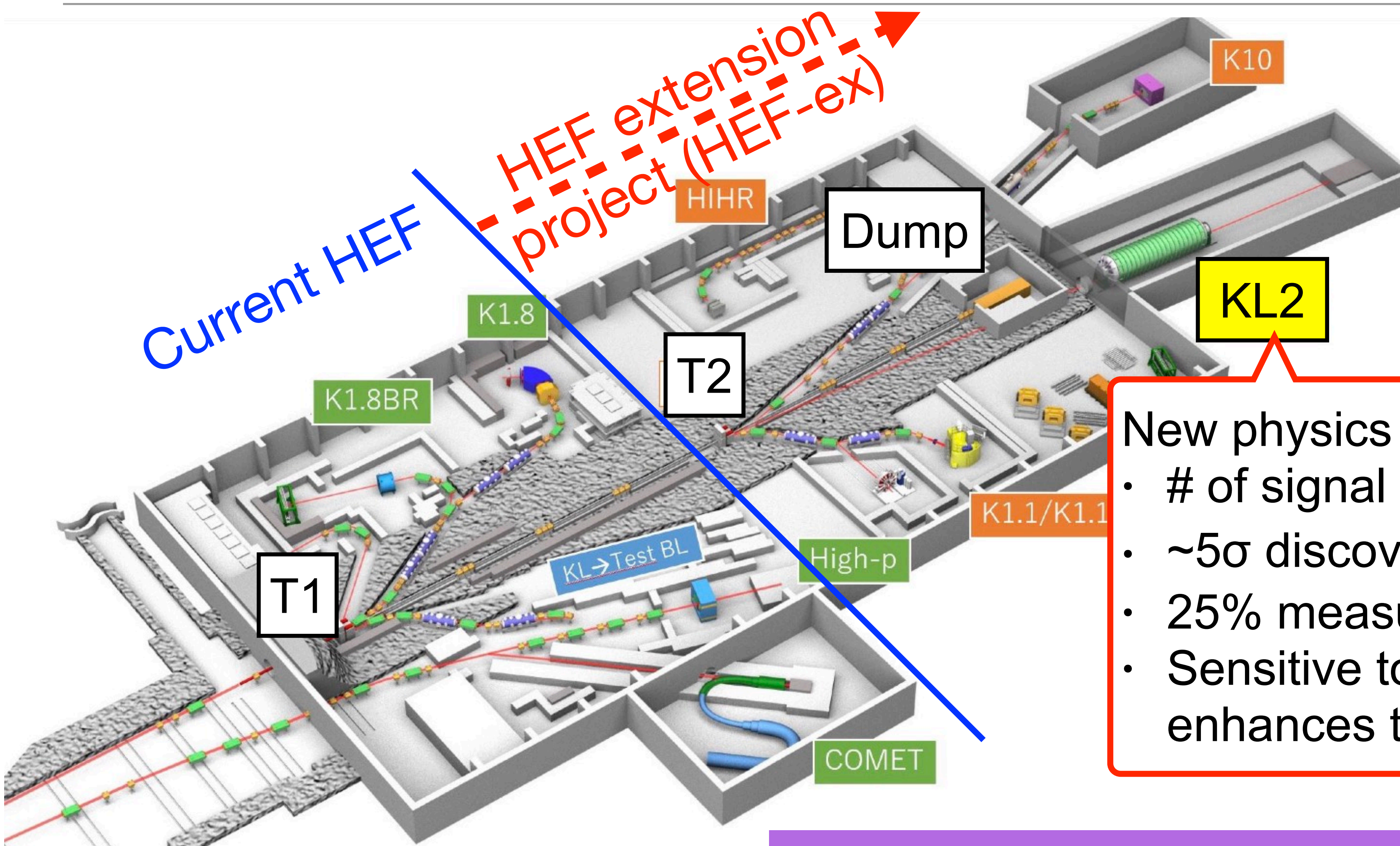
- A higher repetition (5.2s→4.2s cycle) can be adopted ➔ **Higher beam power**
  - 65kW in 2021 with 5.2s repetition → 80kW with 4.2s repetition
- A smoother time-structure beam is expected ➔ **Reduction of accidental loss**

And to go further, …
KOTO II in Extended Hadron Experimental Facility

Next generation $K_L \to \pi^0 \nu\nu$ experiment

HEF-ex is on top of the KEK-PIP 2022

- Expecting that programs in the new hall will be launched in 2030's



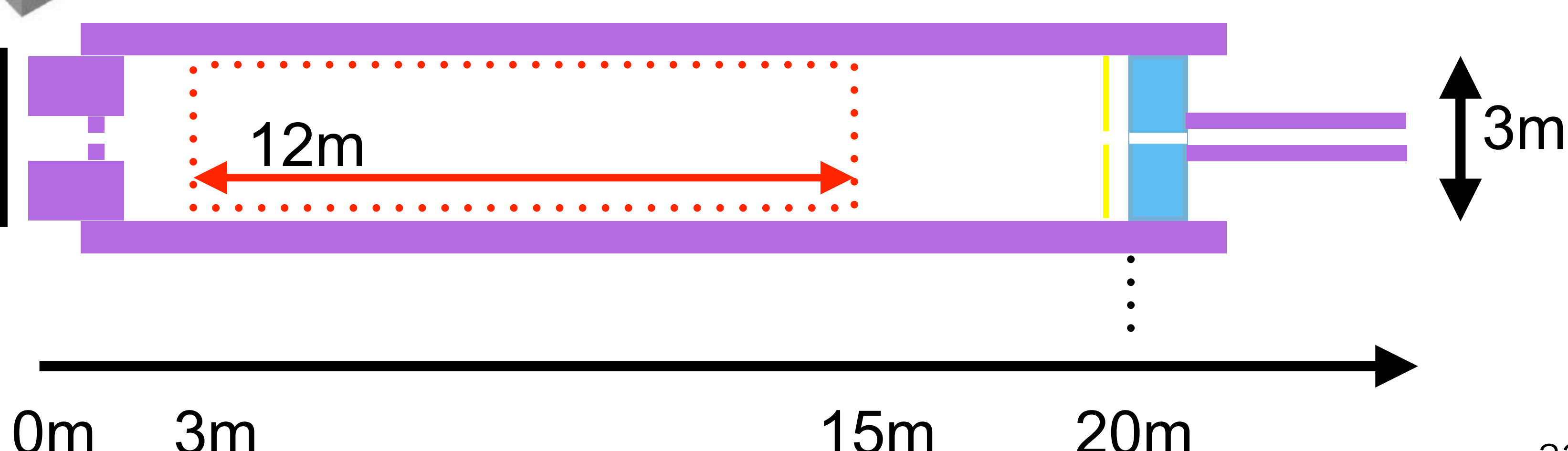
New physics search with

- # of signal ~35 (in SM) / # of BG ~30
- ~5σ discovery of $K_L \to \pi^0 \nu \overline{\nu}$ (in SM)
- 25% measurement of the BR (in SM)
- Sensitive to new physics that enhances the BR by >40%

- 5 degree production angle
- Larger and longer detector than KOTO

KOTO step-2

44m from T2



Summary

- KOTO concluded the 2021 data analysis
  - The single event sensitivity = 8.7×10^{-10},
    the expected number of backgrounds = 0.255
  - After opening the signal box, no candidate events were observed inside the signal box.
  - New upper limit: $BR(K_L \to \pi^0 \nu\bar{\nu}) < 2.0\times10^{-9}$ (90% C.L.) ***Preliminary***
- KOTO continues taking data and will reach the sensitivity level better than 10^{-10} in 4-5 years.
- Next generation experiment “KOTO II” is being discussed.
  - Aiming to observe >30 SM events with S/N ratio of 1