KOTO collaboration

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Status of $K_L \to \pi^0 \nu\nu$ Search

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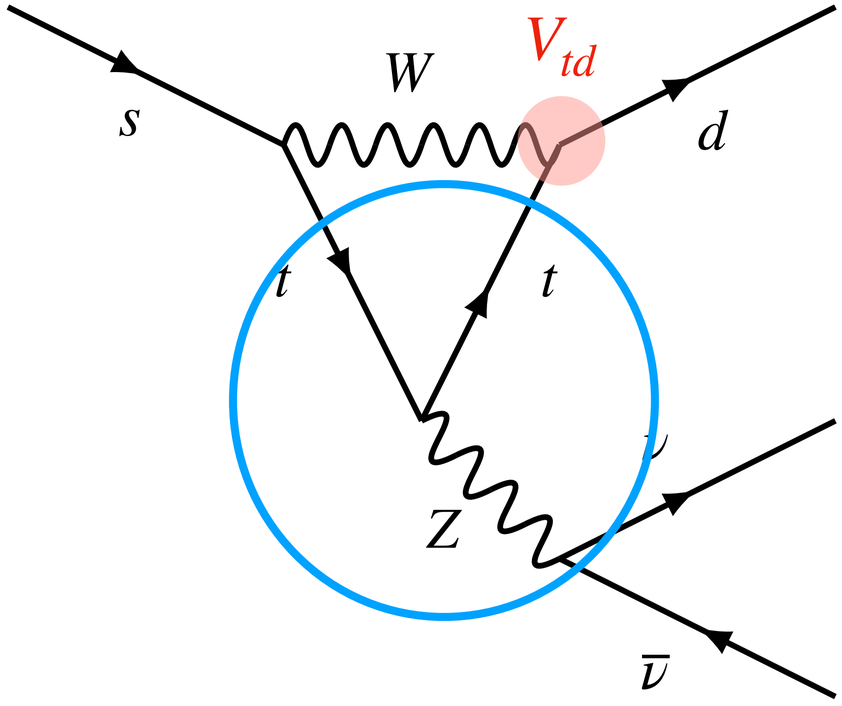
DISCRETE 2021

New Physics in Golden Mode $K_L \to \pi^0 \nu\nu$

New Physics hidden in FCNC process?



Clean & Rare $\Longrightarrow$ Sensitive to New Physics:

$$BR(K_L^0 \to \pi^0 \nu\bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$$

Grossmann-Nir bound (Model independent)

$$BR(K_L^0 \to \pi^0 \nu\bar{\nu}) \leq 4.3 \times BR(K^+ \to \pi^+ \nu\bar{\nu})$$

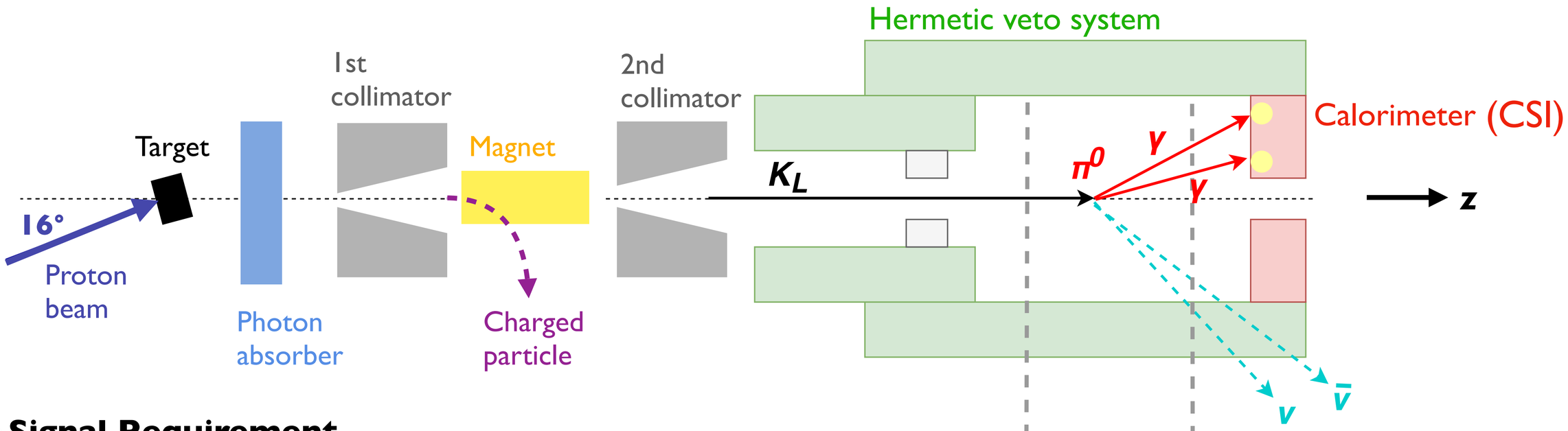
$$\leq 6.3 \times 10^{-10} \quad \text{(68\% C.L.)}$$

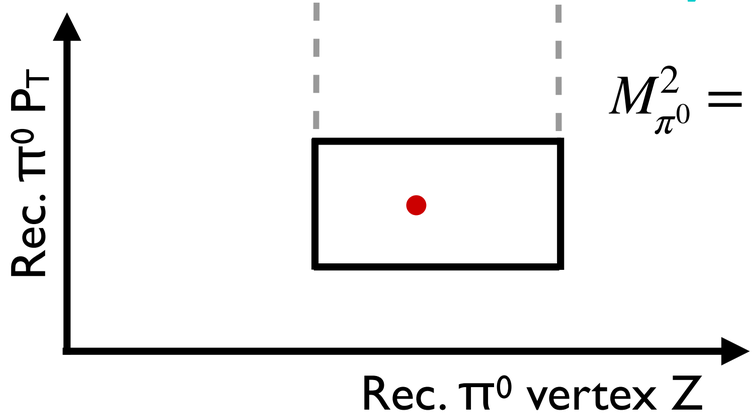
[JHEP 06 (2021) 093]

$\Longrightarrow$ Not applicable to $K_L \to \pi^0 X$, where $m_{X^0} \approx m_{\pi^0}$,

because this region is not experimentally examined.

The KOTO Experiment





$$M_{\pi^0}^2 = 2E_1E_2(1-\cos\theta_{12})$$

θ=θ(decay vertex)

- **Signal Requirement**
  - 2γ from π^0 on calorimeter
  - Missing P_T due to neutrinos.
  - Nothing else detected
- **Blind Analysis**
  - The distribution in the signal box is inaccessible.

$K_L \to \pi^0 \nu\nu$ Result Based on 2016 - 2018 Data

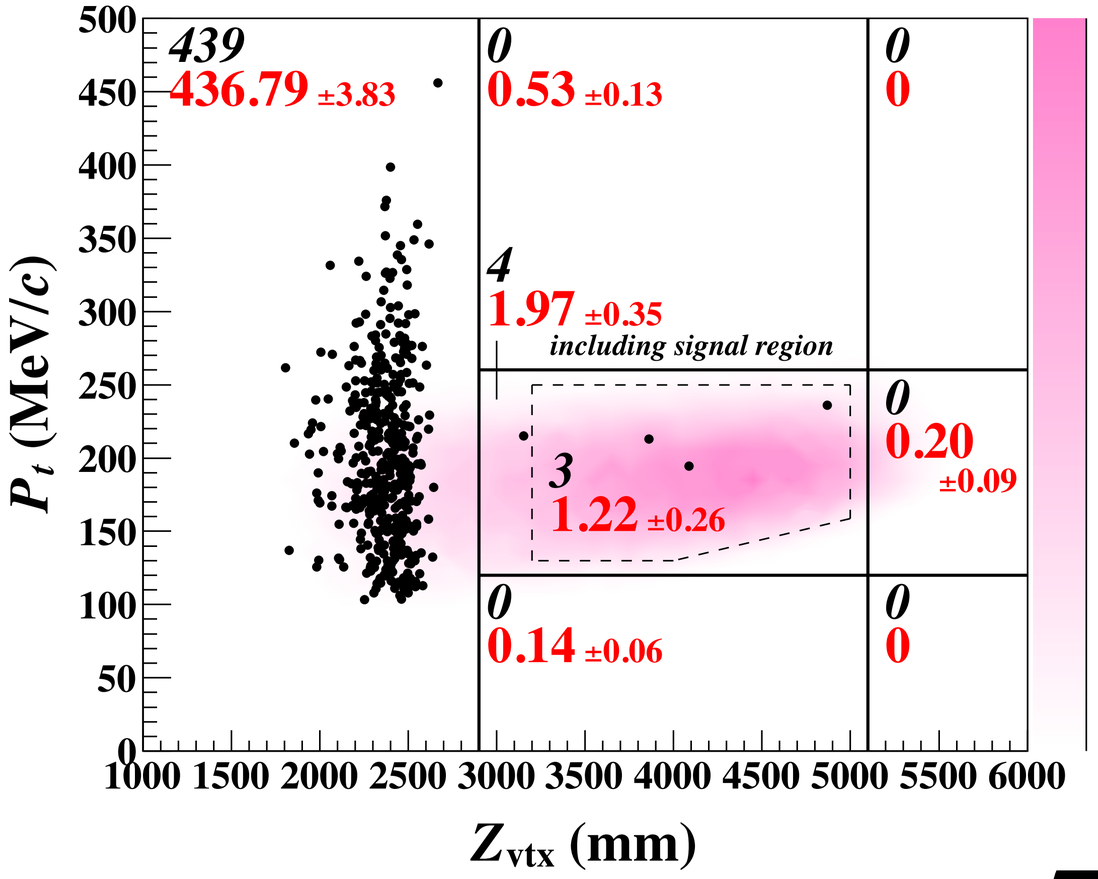
- **SES = (7.20 ± 0.05$_{stat}$ ± 0.66$_{syst}$) × 10^{-10}**
- **BR($K_L \to \pi^0 \nu\nu$) < 4.9 × 10^{-9} (90% C.L.)**
  - Based on three observed candidate events.

	Source		Number of events
	K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
2nd		$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
		Other K_L decays	0.005 ± 0.005
1st	$K^\pm$		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

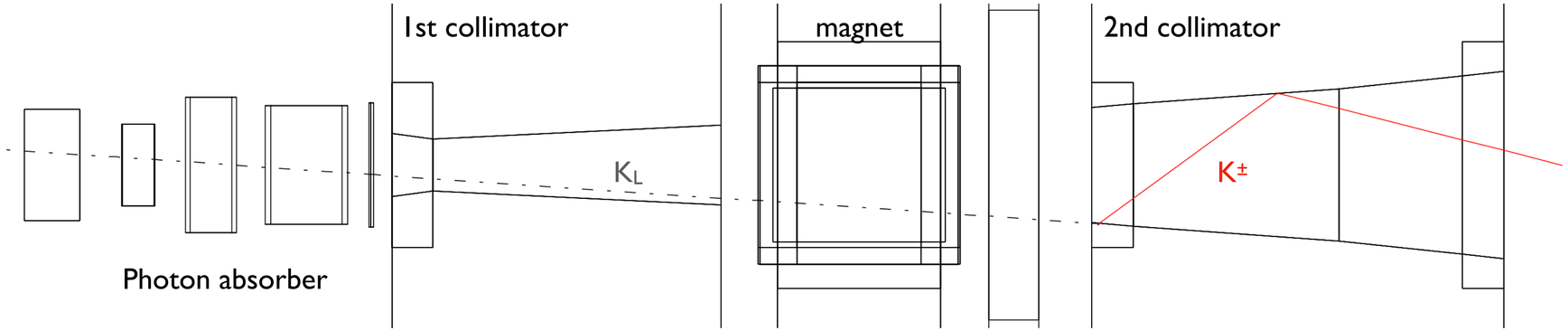
[a]Background sources studied after looking inside the blind region.

Observed
Expected

[PRL 126, 121801 (2021)]



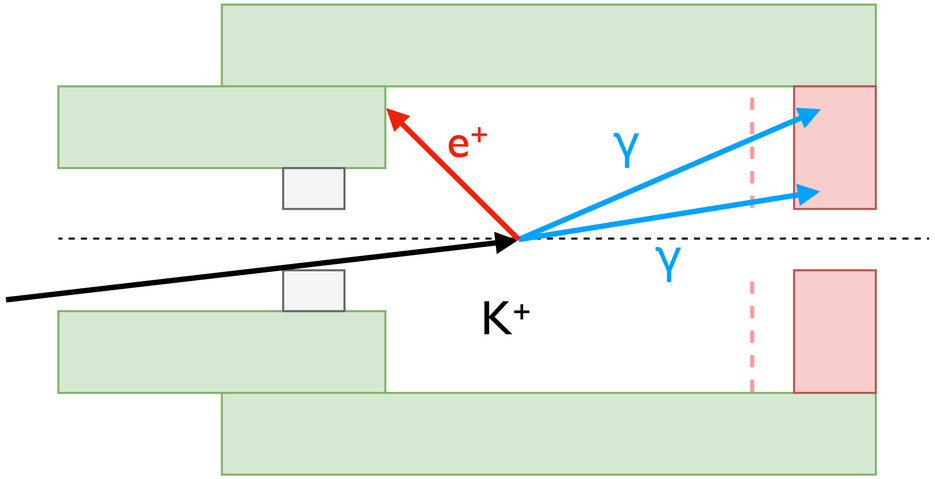
Primary Background: K^+ Decay



K^+ can be produced @ 2nd collimator

$K^+ \rightarrow \pi^0 e^+ \nu$ background can be threatening.

- π^0 kinematics is similar with signal.
- Inefficiency of backward e^+ is large.

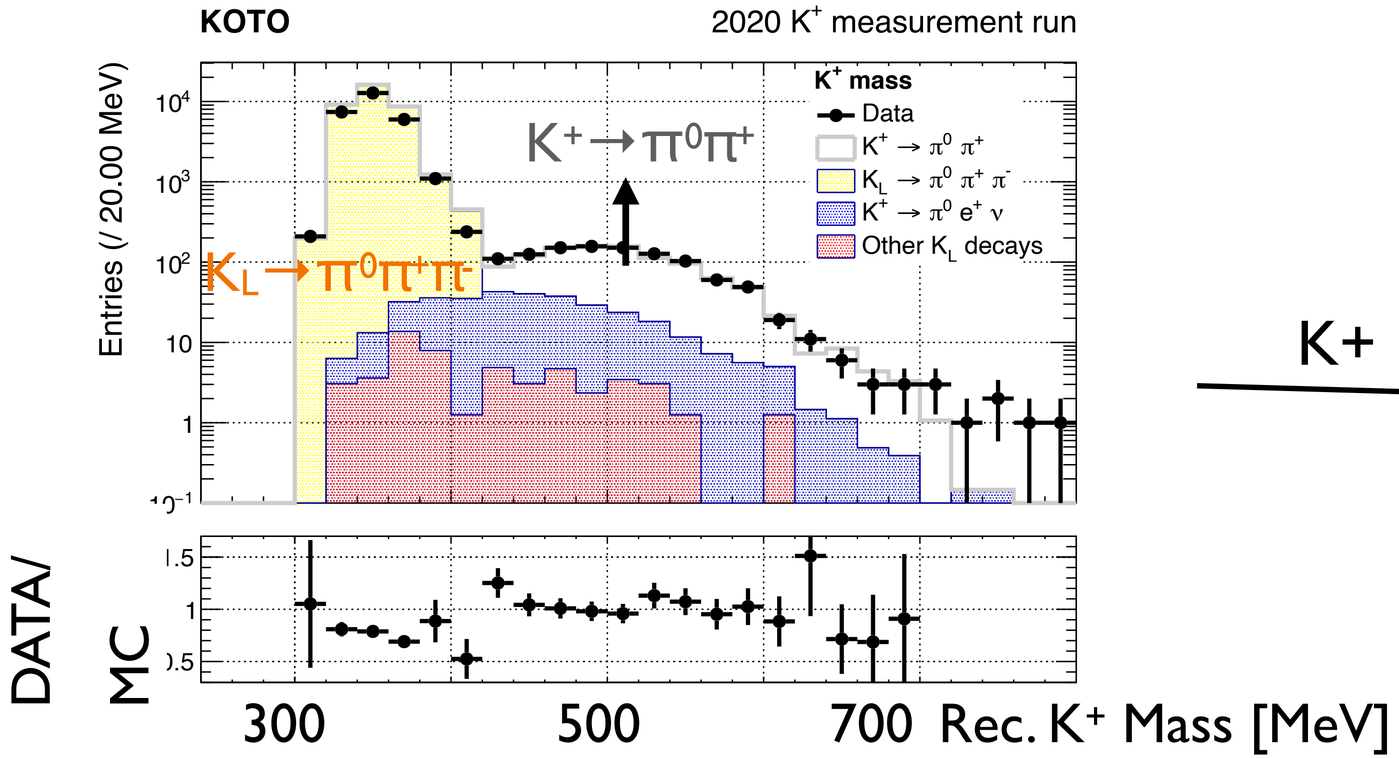


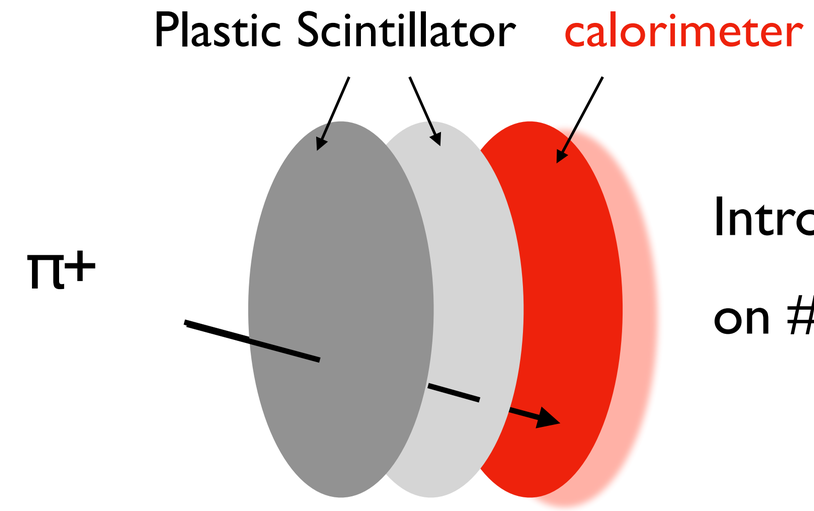
K^+ Flux Measurement at 2020 Special Run

Reconstruct $K^+ \rightarrow \pi^0\pi^+$ (BR ~ 20%)

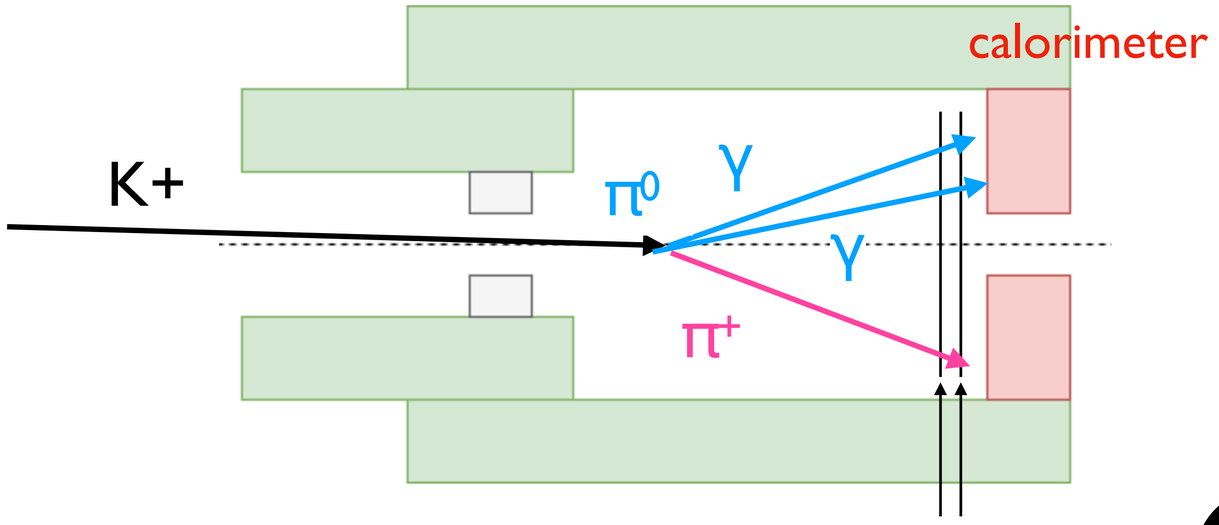
for K+ flux measurement.

K^+ / K_L flux ratio = $(2.6 \pm 0.1) \times 10^{-5}$.

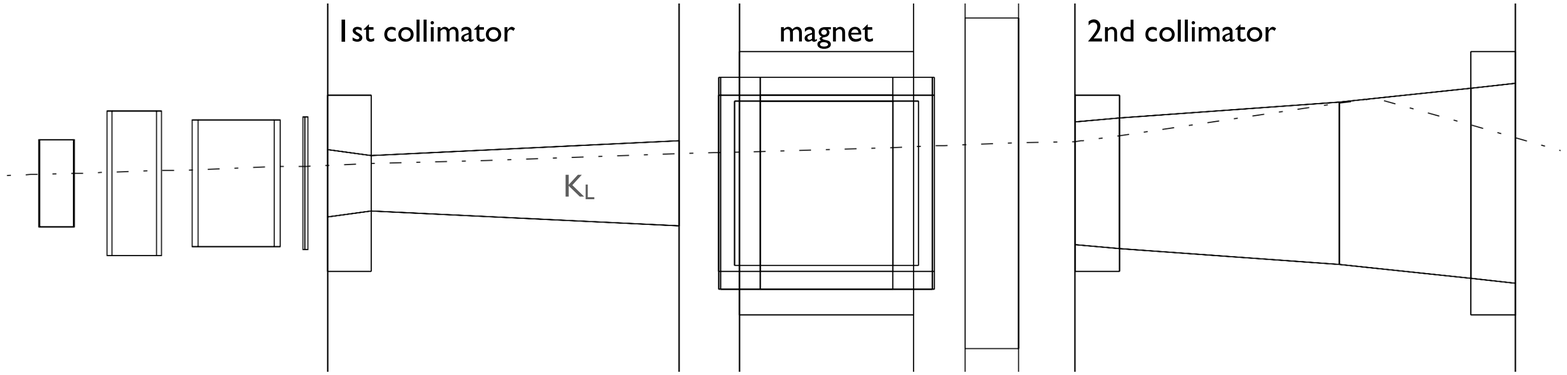




Introduce trigger based on #(Charge tracks)



2nd Largest Background: Halo K_L Decay

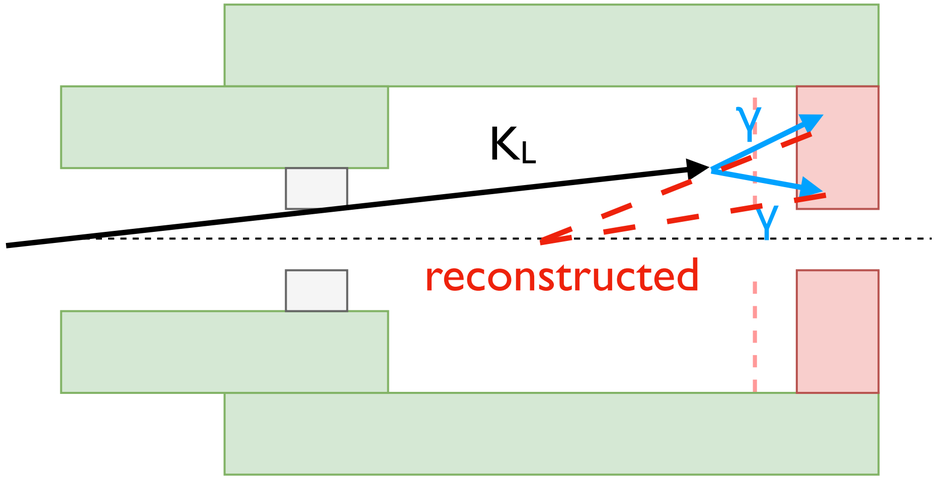


Elastic scattering

at collimator or photon absorber.

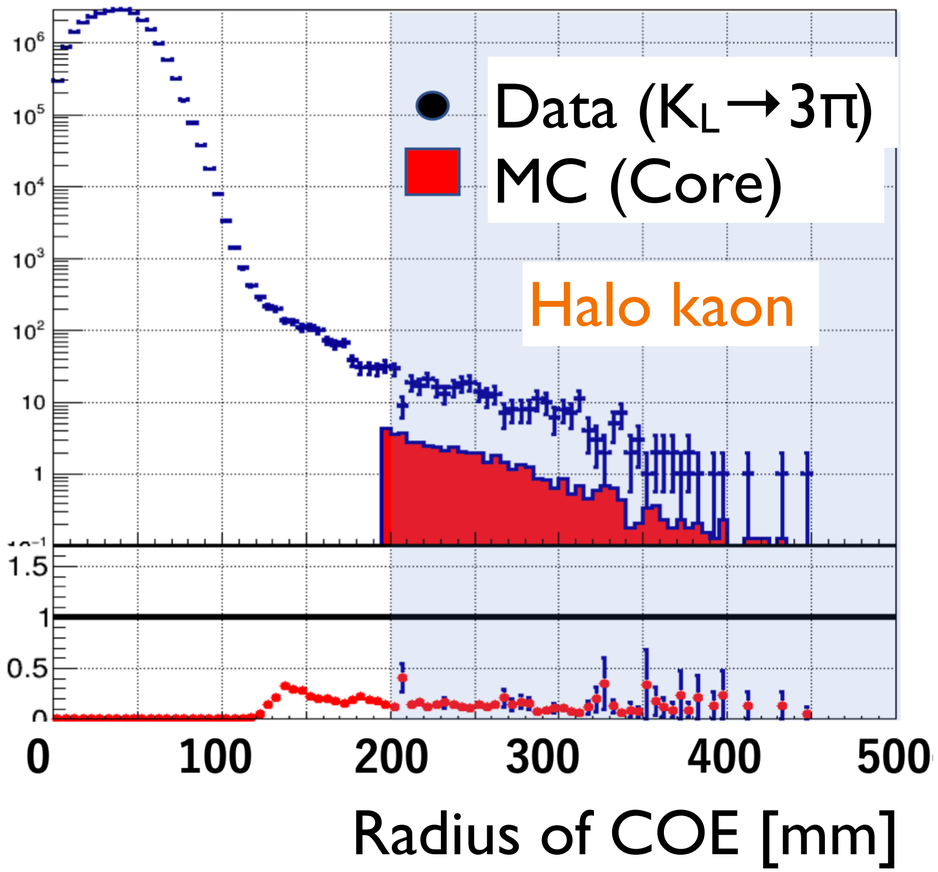
Downstream off-axis $K_L \rightarrow 2\gamma$ decay can be threatening.

- π^0 mass assumption leads to the upstream shift.
- The off-axis decay is misinterpreted as large P_T.



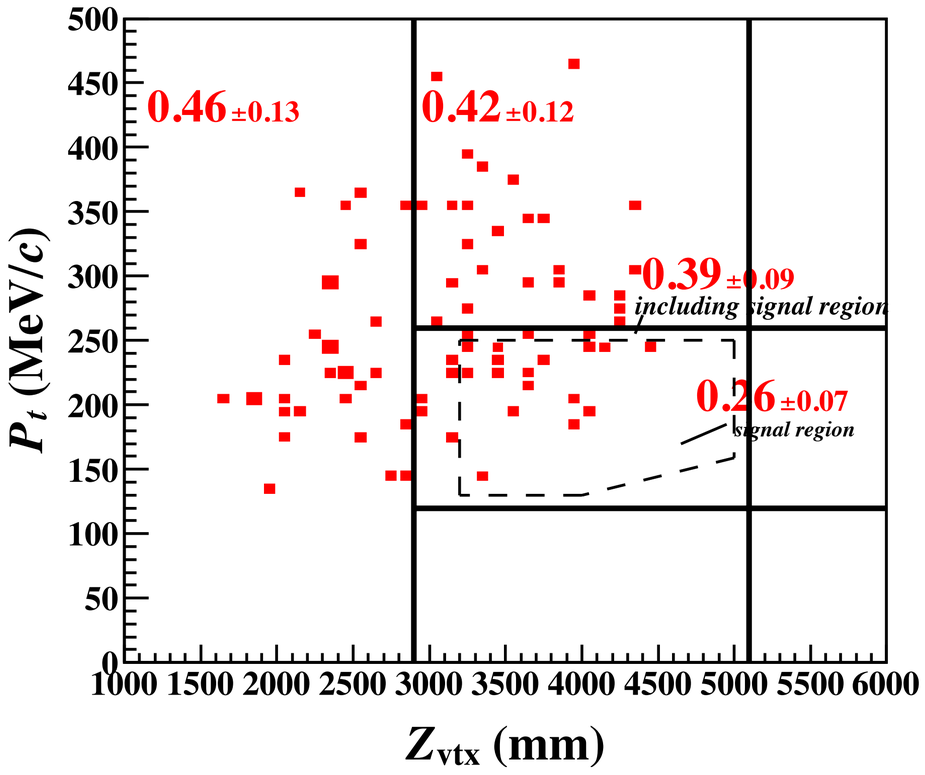
2nd Largest BGL: Halo $K_L \rightarrow 2\gamma$ Background Level

$$R_{COE} = \frac{\sqrt{(\sum E_i x_i)^2 + (\sum E_i y_i)^2}}{\sum E_i}$$



After the correction through R_{COE},

halo $K_L \rightarrow 2\gamma$ BGL is predicted to be (0.26 ± 0.07).

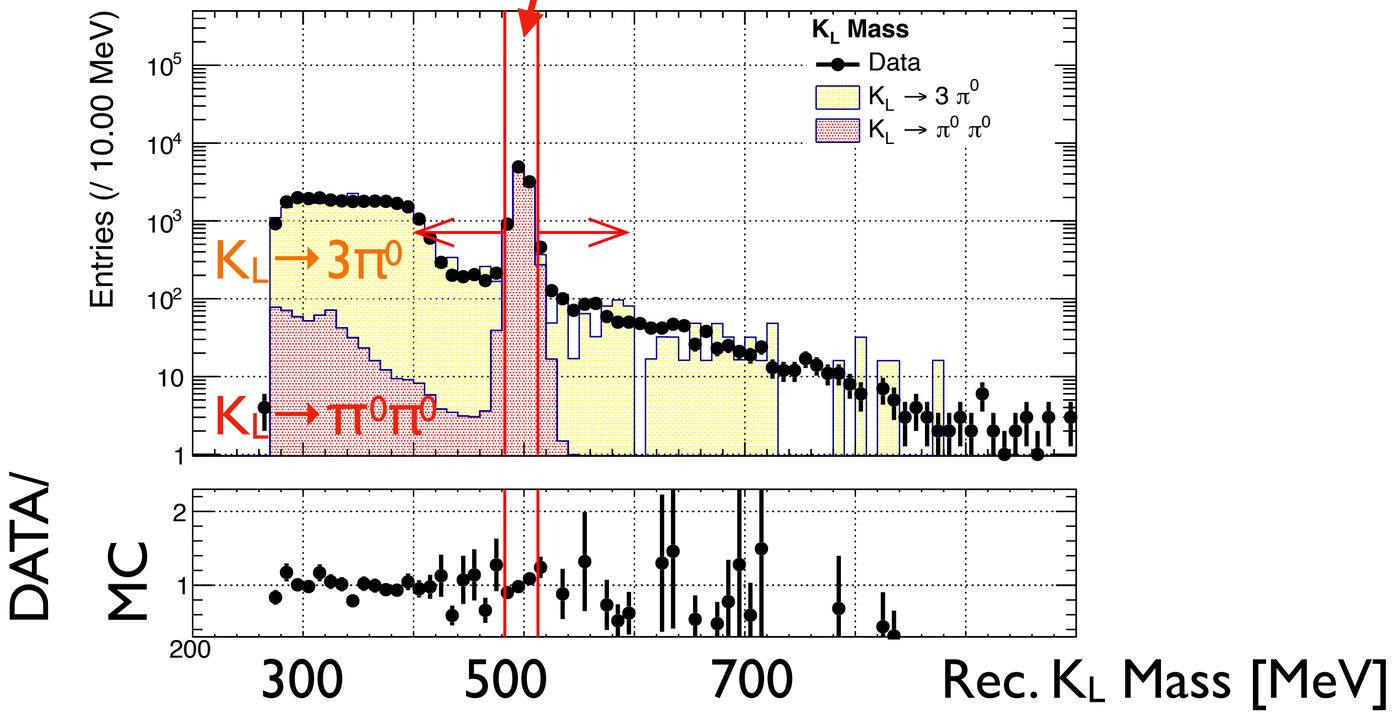


$K_L \rightarrow \pi^0 X$ Interpretation

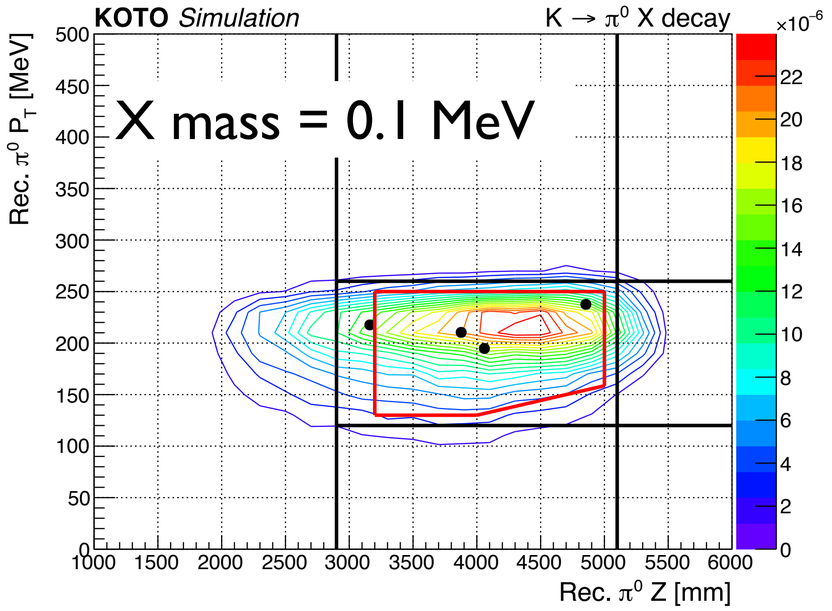
- X with mass range of 0.1 — 280 MeV.
- X can decay into $e^+ e^-$ pair with lifetime range 0.1 — 5 ns

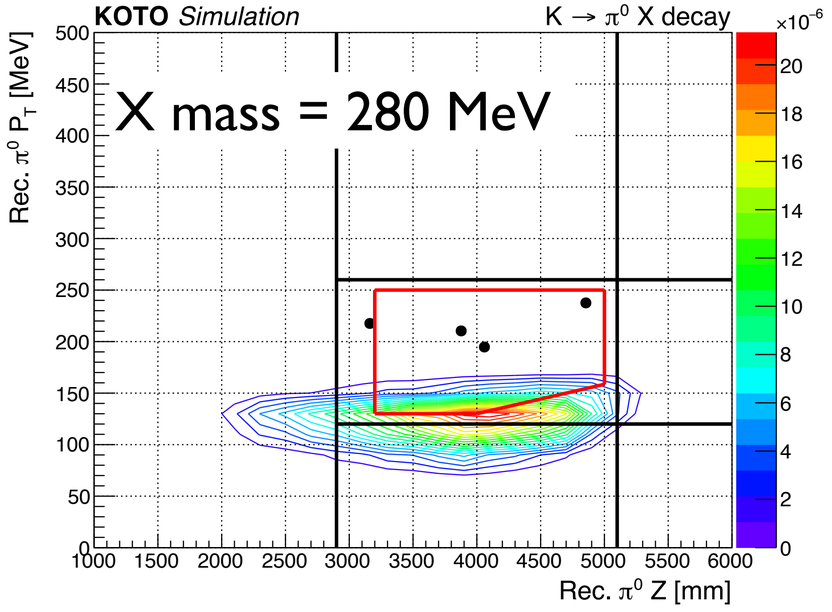
$$SES = 1/(N_{K_L} \times A_{sig})$$

Estimated by MC.



MC predictions





$K \to \pi^0 X$ Branching Ratio Result

$BR(K^+ \to \pi^+\pi^0, \pi^0 \to \text{invisible})$

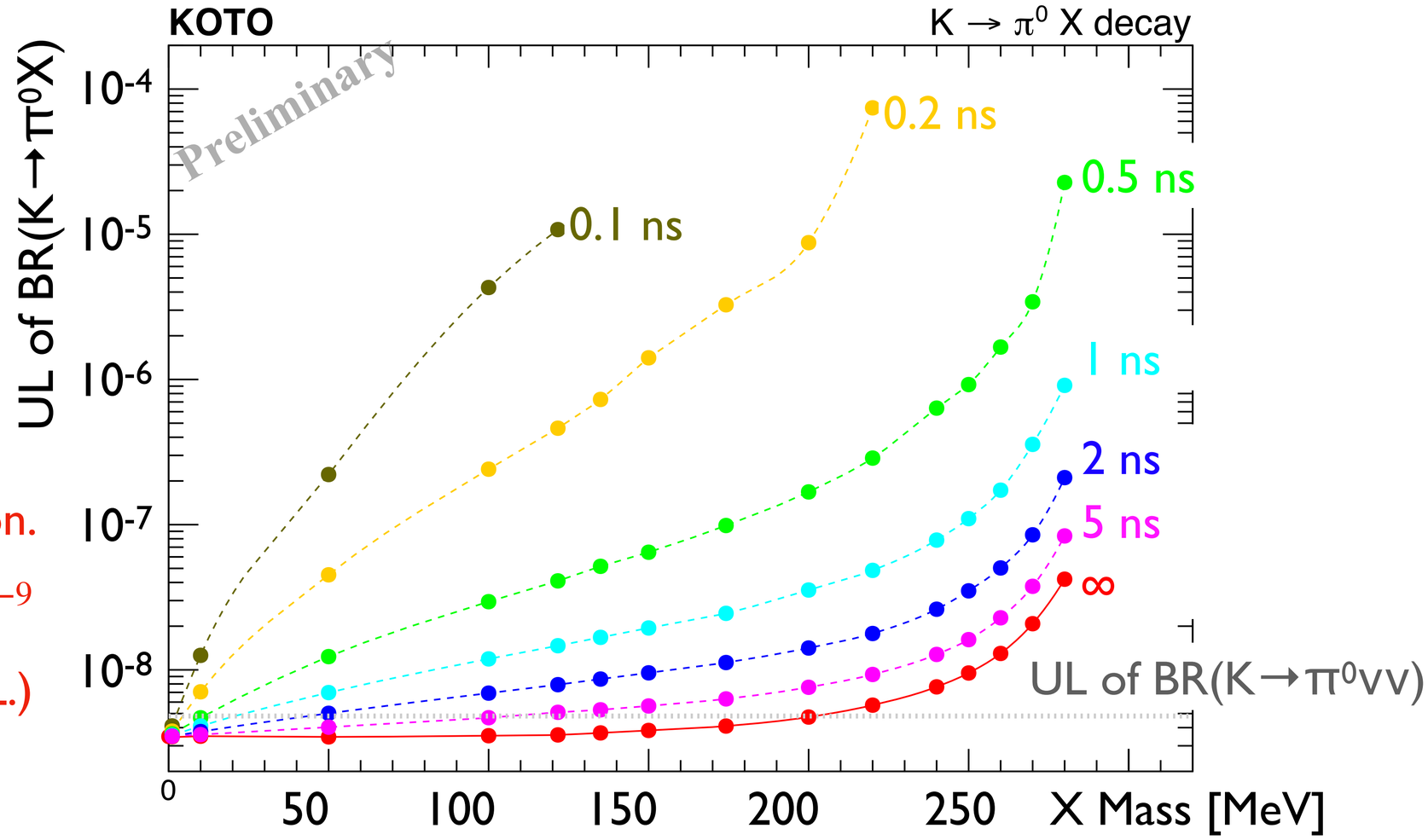
$< 4.4 \times 10^{-9}$ (90% C.L.)

[*JHEP* 02 (2021) 201]

KOTO further examines the M_π region.

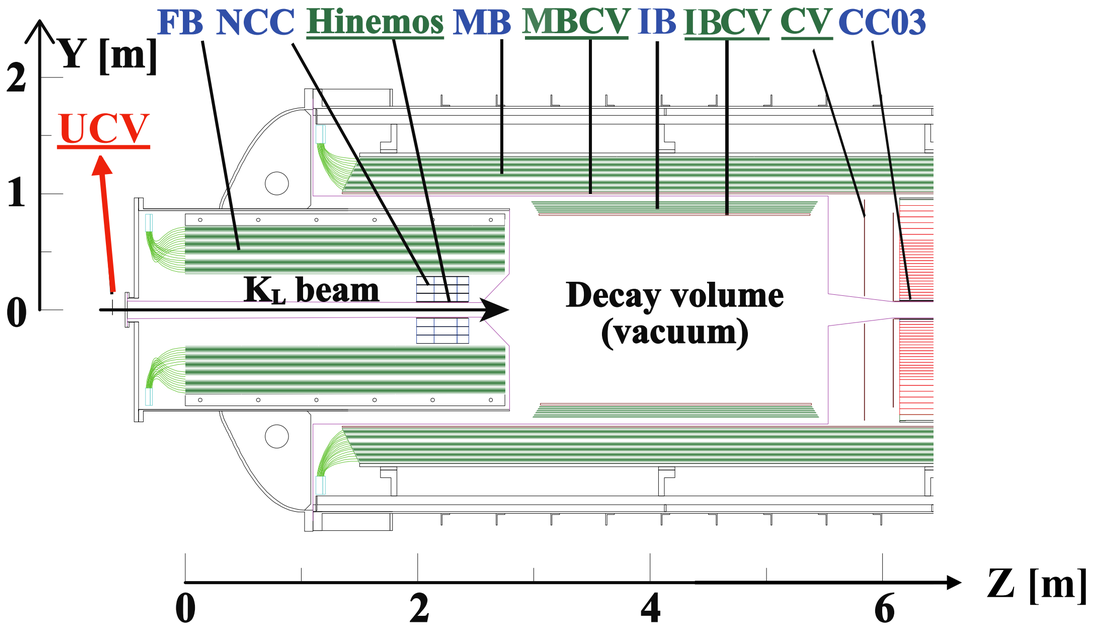
$$BR(K_L^0 \to \pi^0 X, M_X = M_{\pi^0}) < 3.7 \times 10^{-9}$$

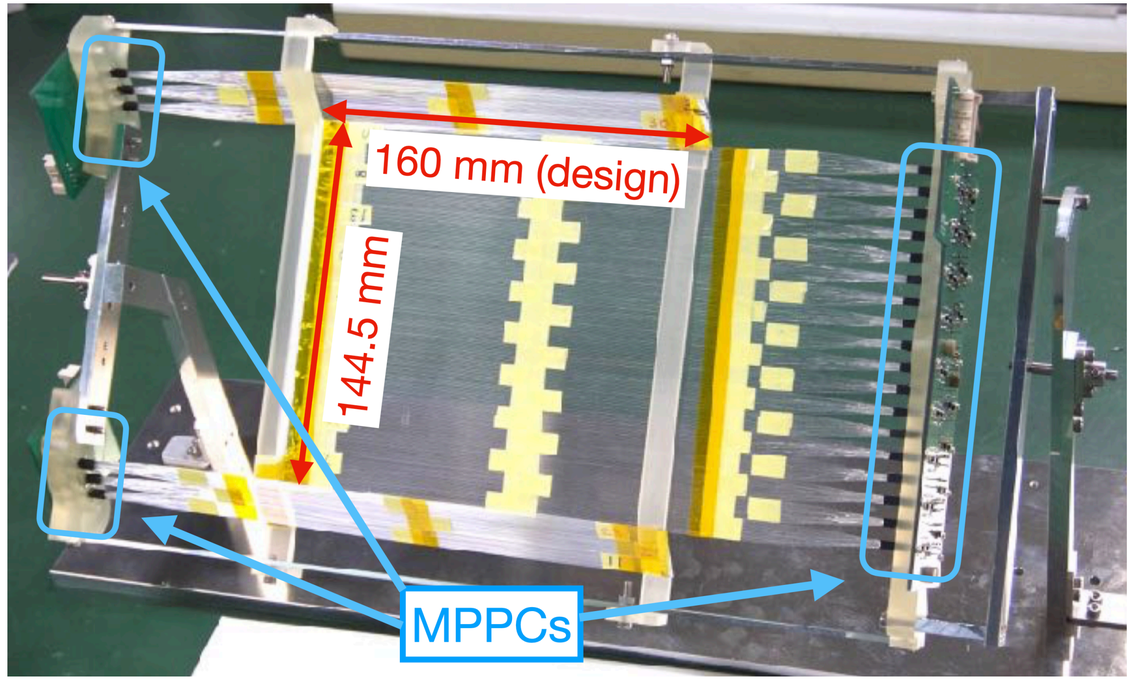
(Preliminary) (90% C.L.)



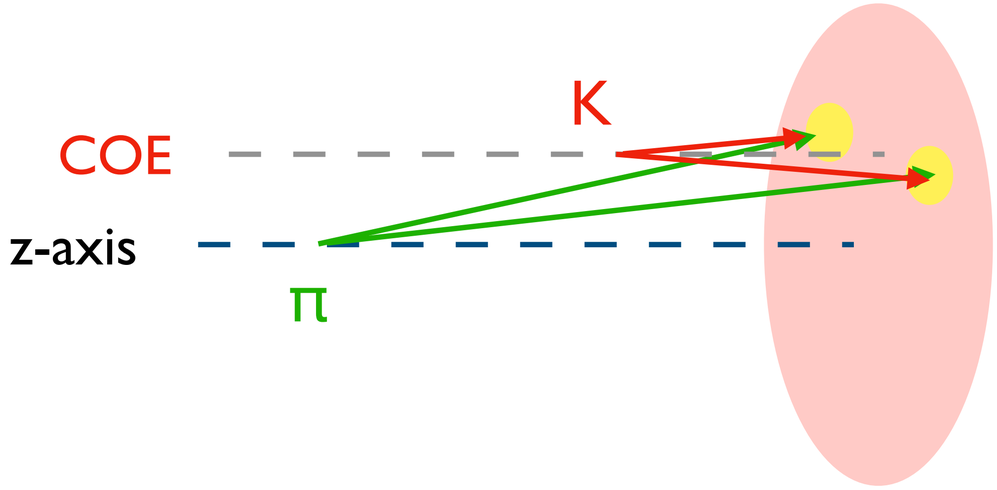
KOTO Next Step: K+ Background Suppression

- Upstream charged veto (UCV) counter was installed in 2021.
- Electron beam test showed 5% inefficiency.
  - BGL(K+ decay) ~ 20 → 1 at SM.

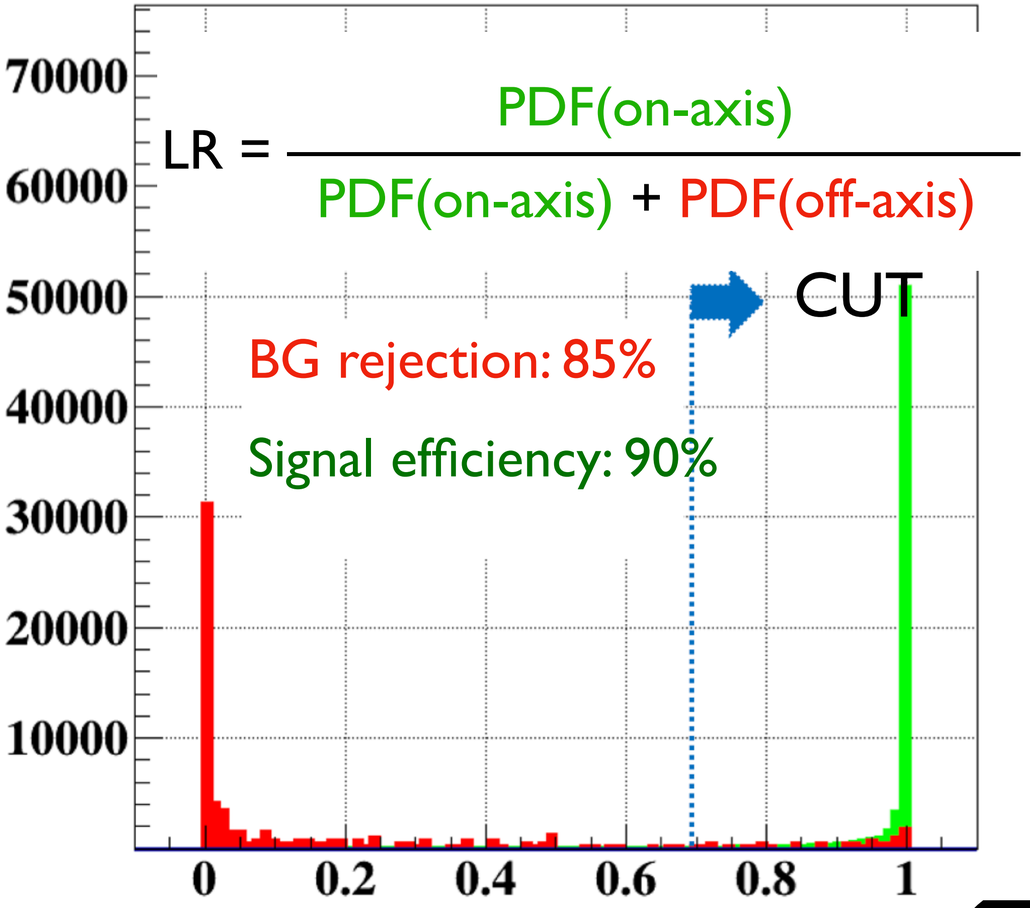




KOTO Next Step: Halo K_L Background Suppression

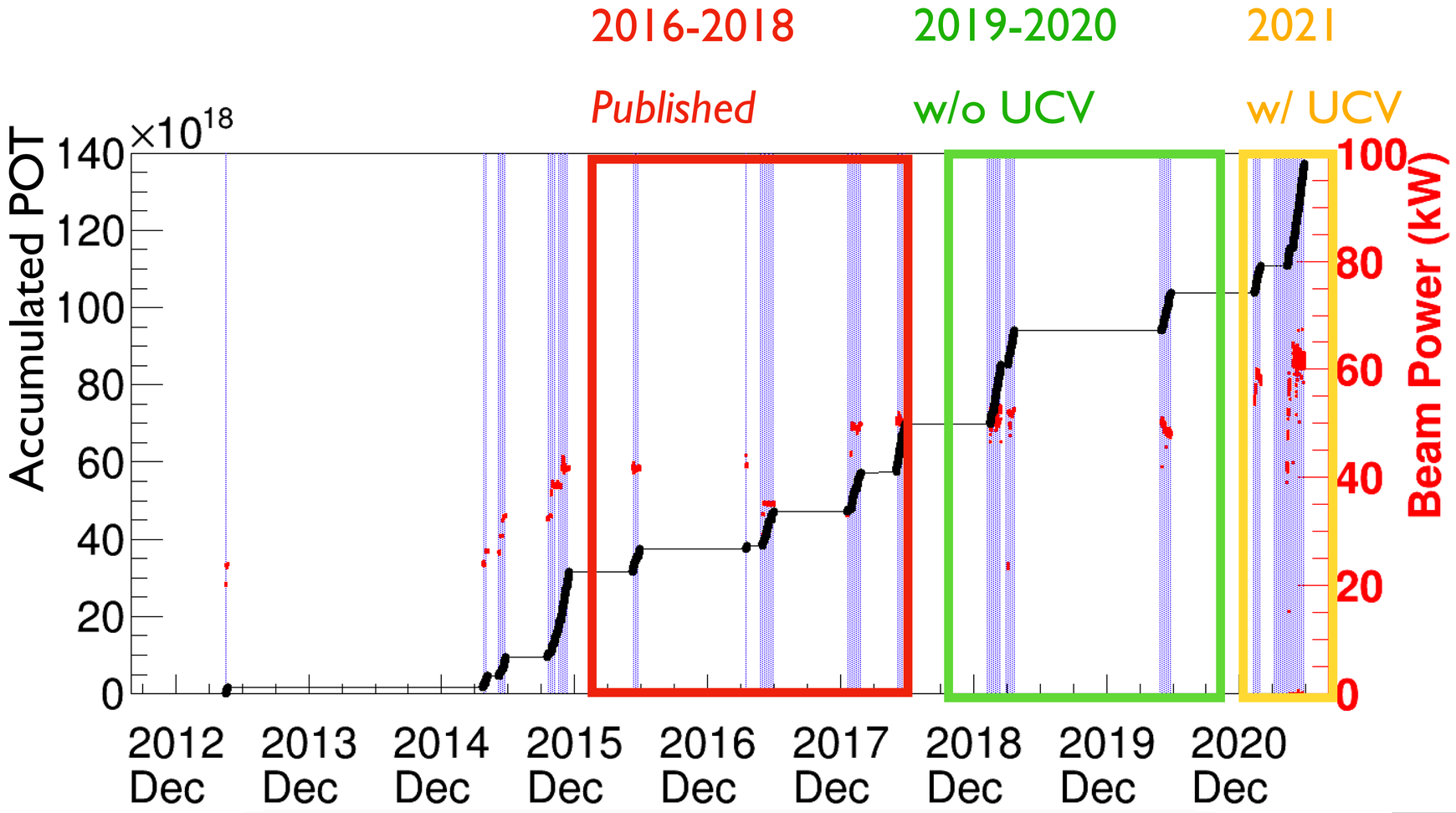


PDF(shower shape, incident angle)



KOTO Data Collection History and Future

- 2019 - 2020 w/o UCV data:
  Establish NN-based kinematic cut against K^+ background.
- 2021 w/ UCV
  Examine UCV performance.
- 2022 -
  Continuously collect data with beam power 60 - 100kW



* POT: proton on target

Summary

- $K_L \rightarrow \pi^0 \nu\nu$ analysis result based on 2016 - 2018 data was released in March 2021.
  $\Rightarrow$ Collimator-scattered K^+ and K_L particles are found to be threatening.

- An interpretation of $K_L \rightarrow \pi^0 X$ (where X is steady or decays to e^+e^- pair) is performed:
  In particular, BR($K_L \rightarrow \pi^0 X$, X is steady and $M_X = M_\pi$) < 3.7×10^{-9} (90% C.L.) [preliminary].

- An upstream plastic scintillator is implemented to suppress K^+ background.
  A shower shape algorithm is established to suppress halo K_L particles.

- Data collected during 2019 - 2021 is about doubled of the 2016 - 2018 data set and its analysis is now ongoing.

Supplement

K+ Background Level