KOTO Step2 experiment

Koji Shiomi 2021/07/08

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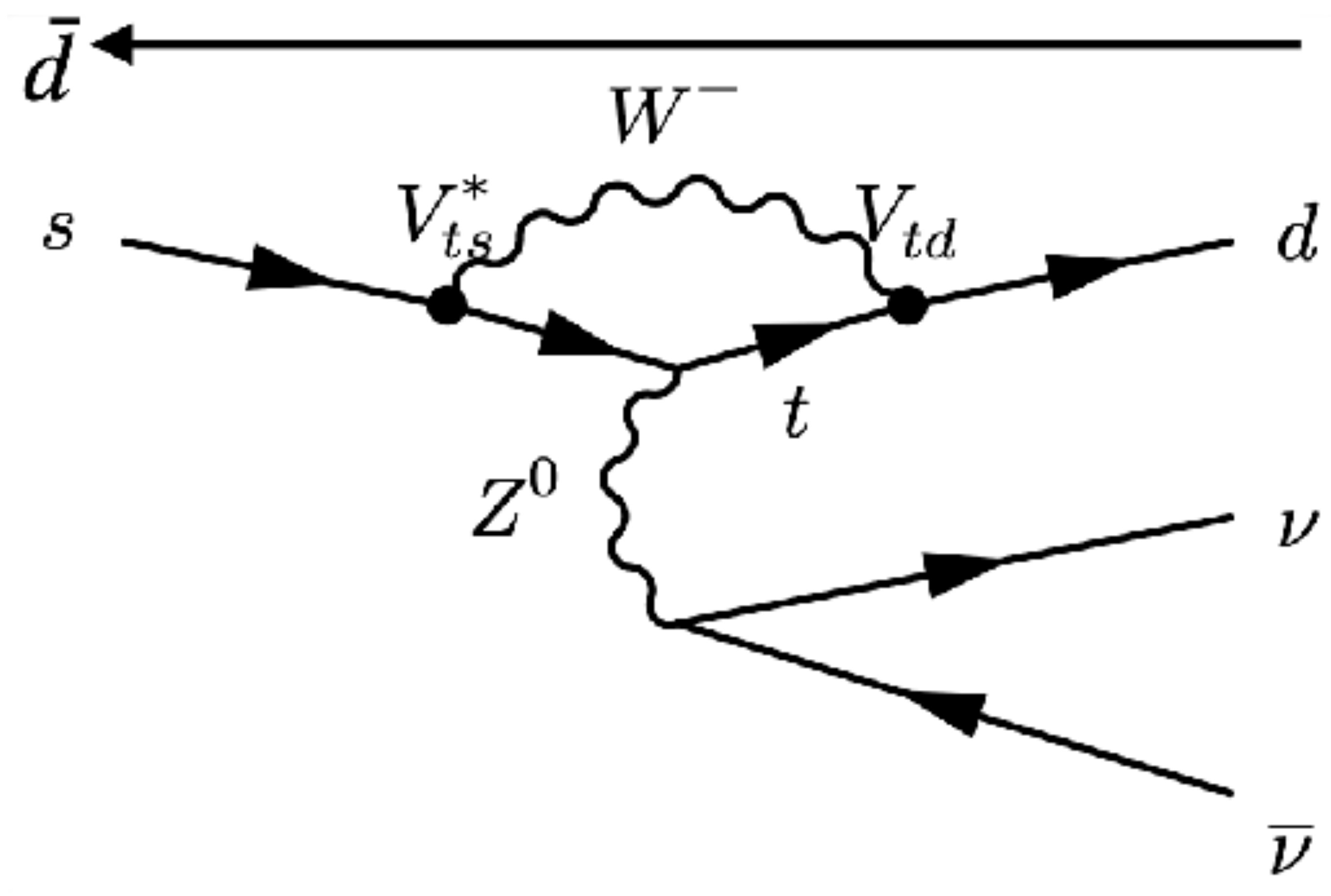
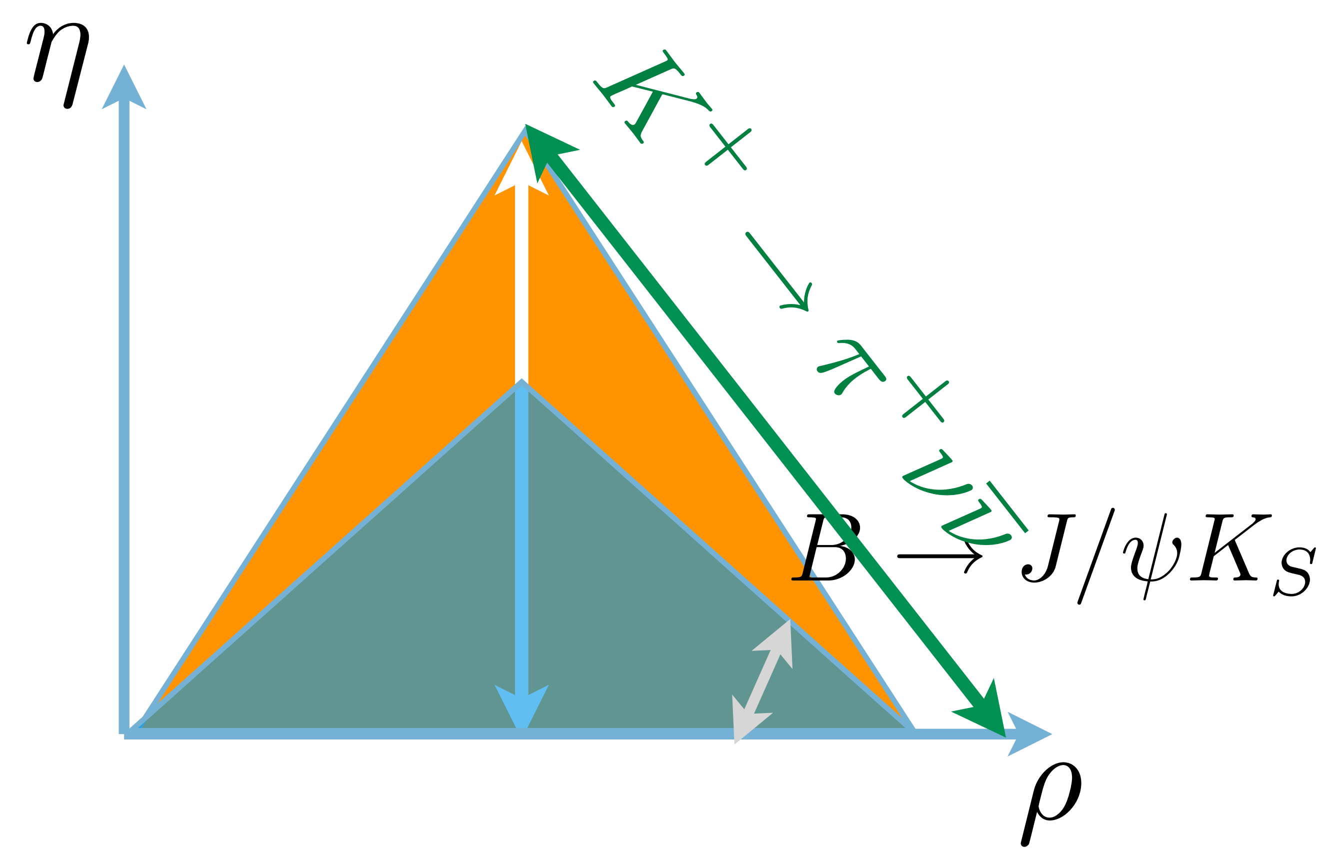
- Physics on $K_L \to \pi^0 \nu \nu$
- Experimental principle of the $K_L \to \pi^0 \nu \nu$ search
- KOTO experiment in Hadron Hall
- KOTO step2 in Extended Hadron Hall.
- Summary

Physics on $K_L \to \pi^0 \nu\,\nu$

- Breaks CP symmetry directory
  - $K_L \propto K^0 - \overline{K^0}$
  - $A_{K_L \to \pi^0 \nu \nu} \propto A_{s \to d} - (A_{s \to d})^* \propto \mathrm{Im}\, A_{s \to d}$
- Suppressed in the standard model (SM)
  - $BR(SM) = 3 \times 10^{-11} \propto \mathrm{Im}(V_{ts} V_{td}^*)^2$
- Small theoretical uncertainty (<2%)
  - Dominated by short distance interaction
  - Precisely estimated Hadron matrix by using the $K^+ \to \pi^0 e^+ \nu$ data

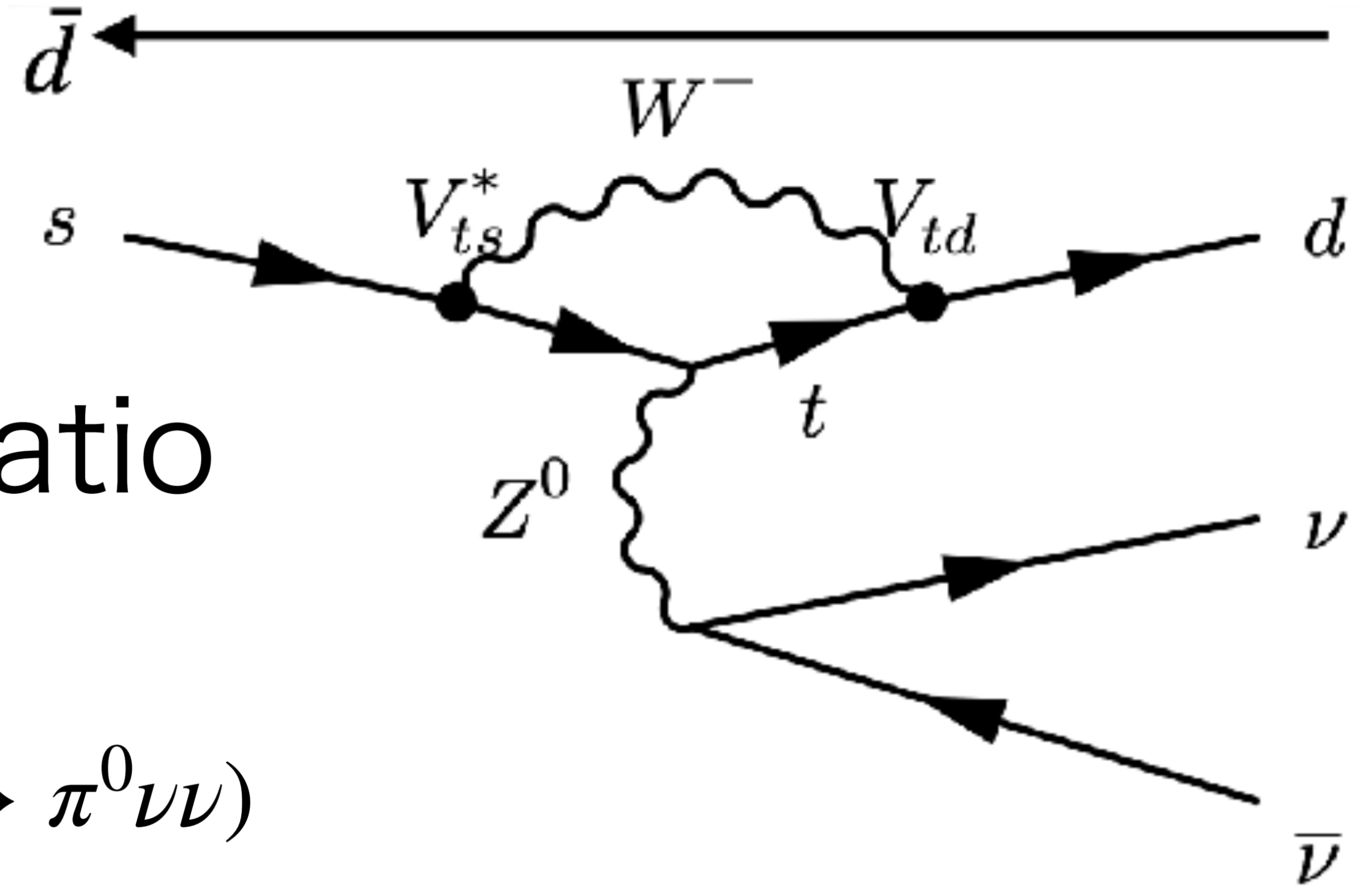


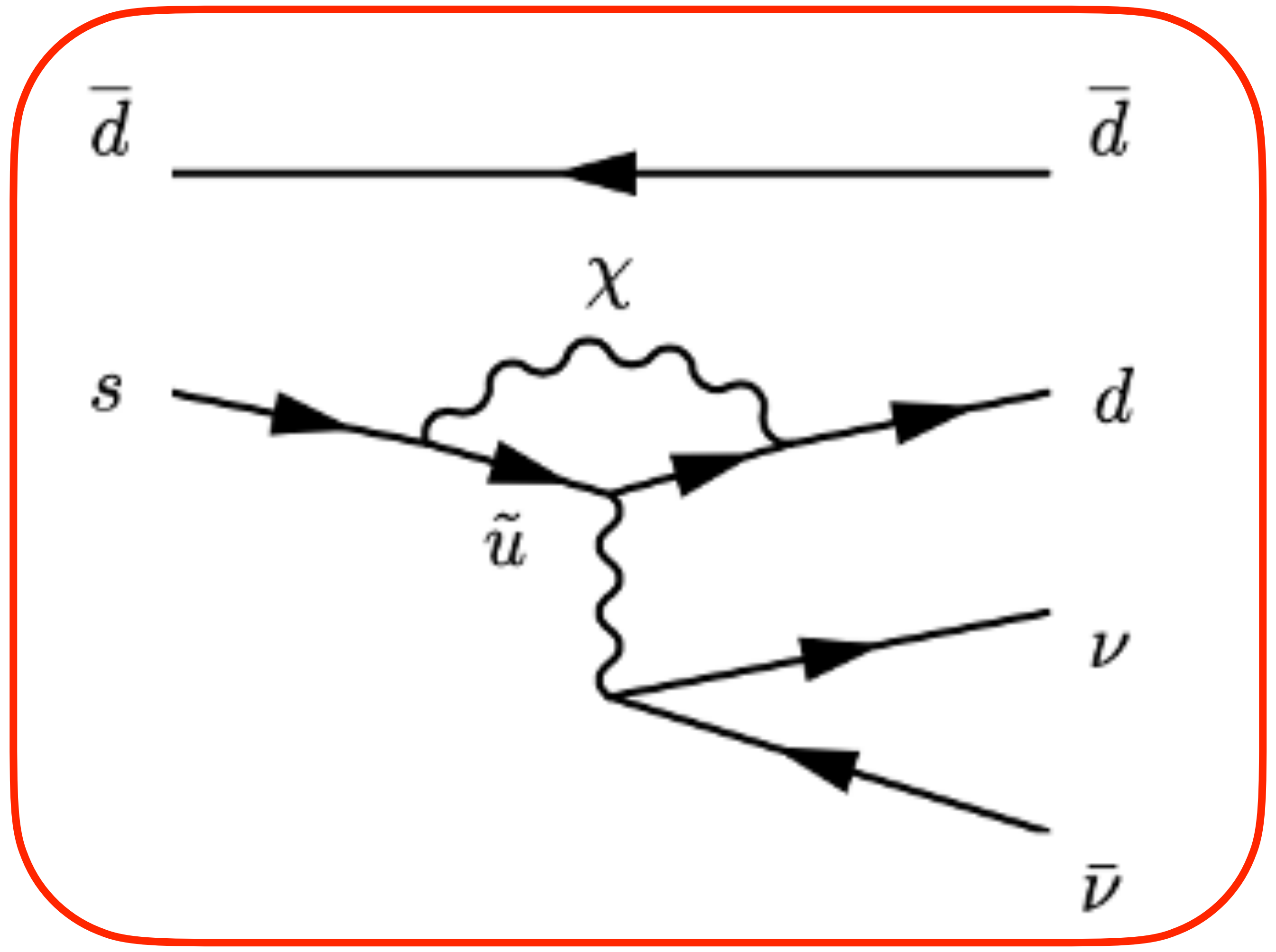


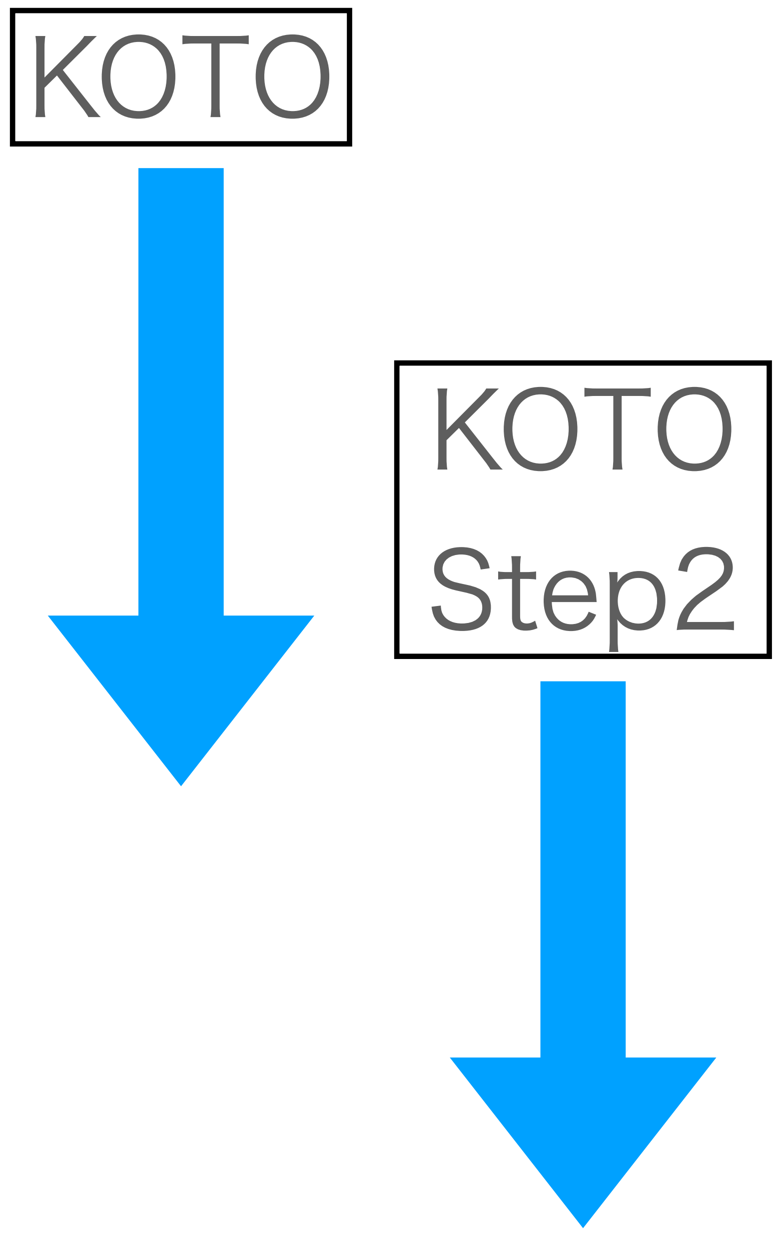
$$\begin{array}{c}
\begin{array}{c} \mathrm{u} \\ \mathrm{c} \\ \mathrm{t} \end{array}
\begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \boxed{\lambda^3 \quad -\lambda^2 \quad 1} \end{pmatrix} \\
\quad \mathrm{d} \qquad \mathrm{s} \qquad \mathrm{b}
\end{array}$$

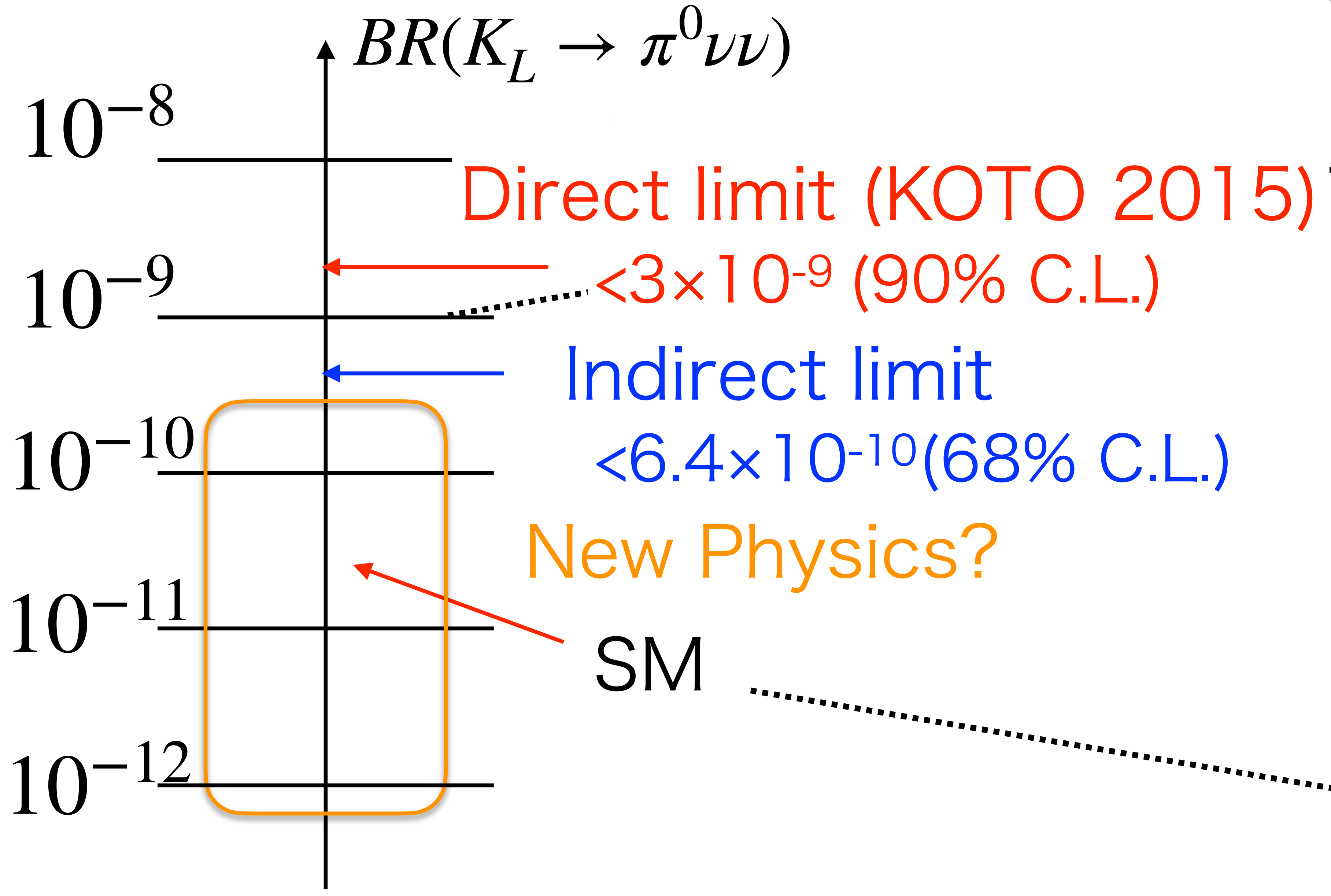
New Physics on $K_L \to \pi^0 \nu \nu$

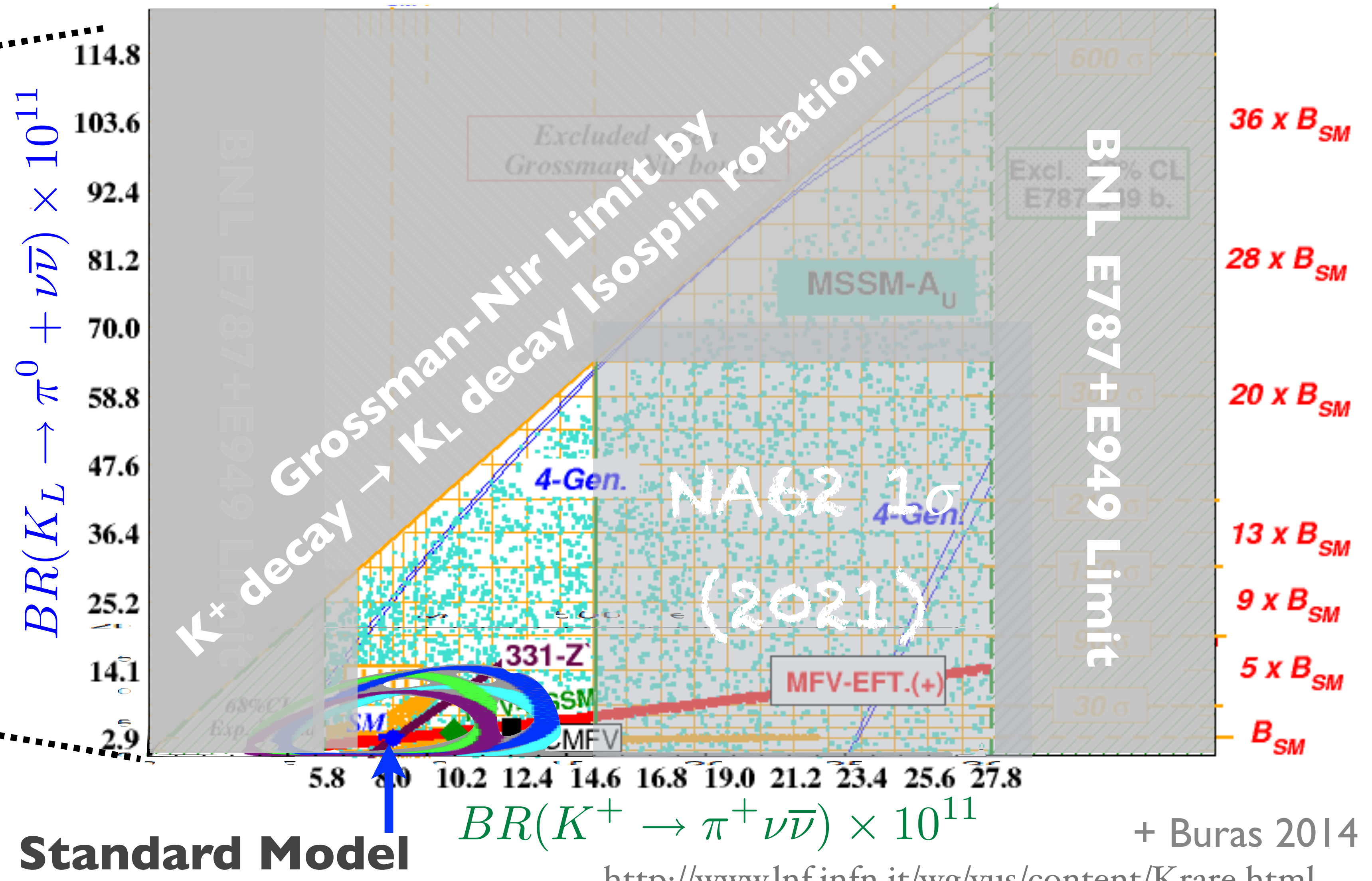
- Can appear in the loop
- Can enhance the branching ratio







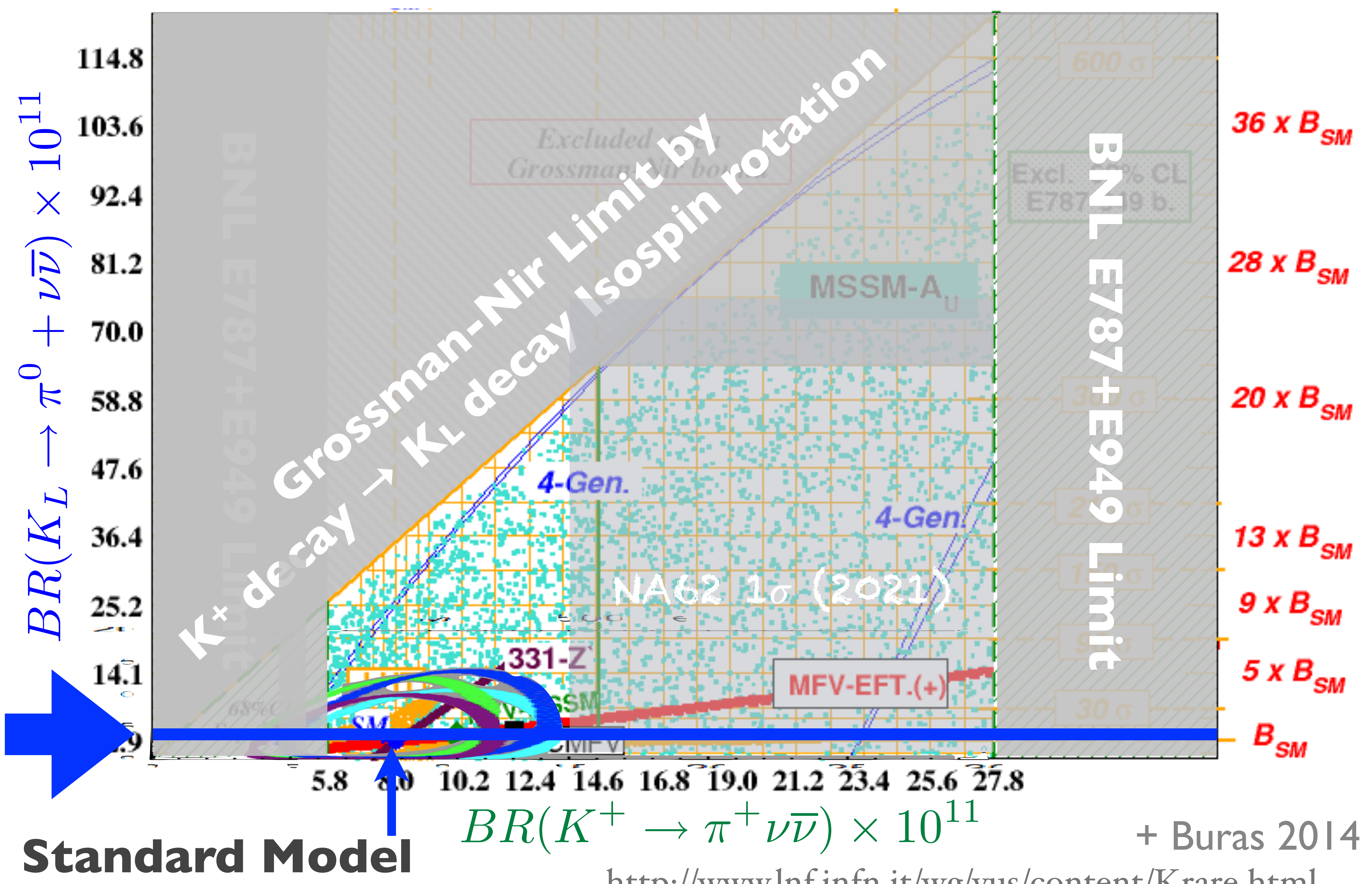




+ Buras 2014
http://www.lnf.infn.it/wg/vus/content/Krare.html

What we want to reach at KOTO step2

- Discovery
  - BR(KL→π ν ν)≒ (SM prediction)
    → ～5σ discovery
    →Measure BR with 30% accuracy
- New physics search
  - |Br(K_L→π^0ν ν)-SM|/SM >40%
    →Indicate new physics
- Measurement of SM parameters
  - Measure CKM parameter η
    representing the size of CP violation
    with 15% accuracy

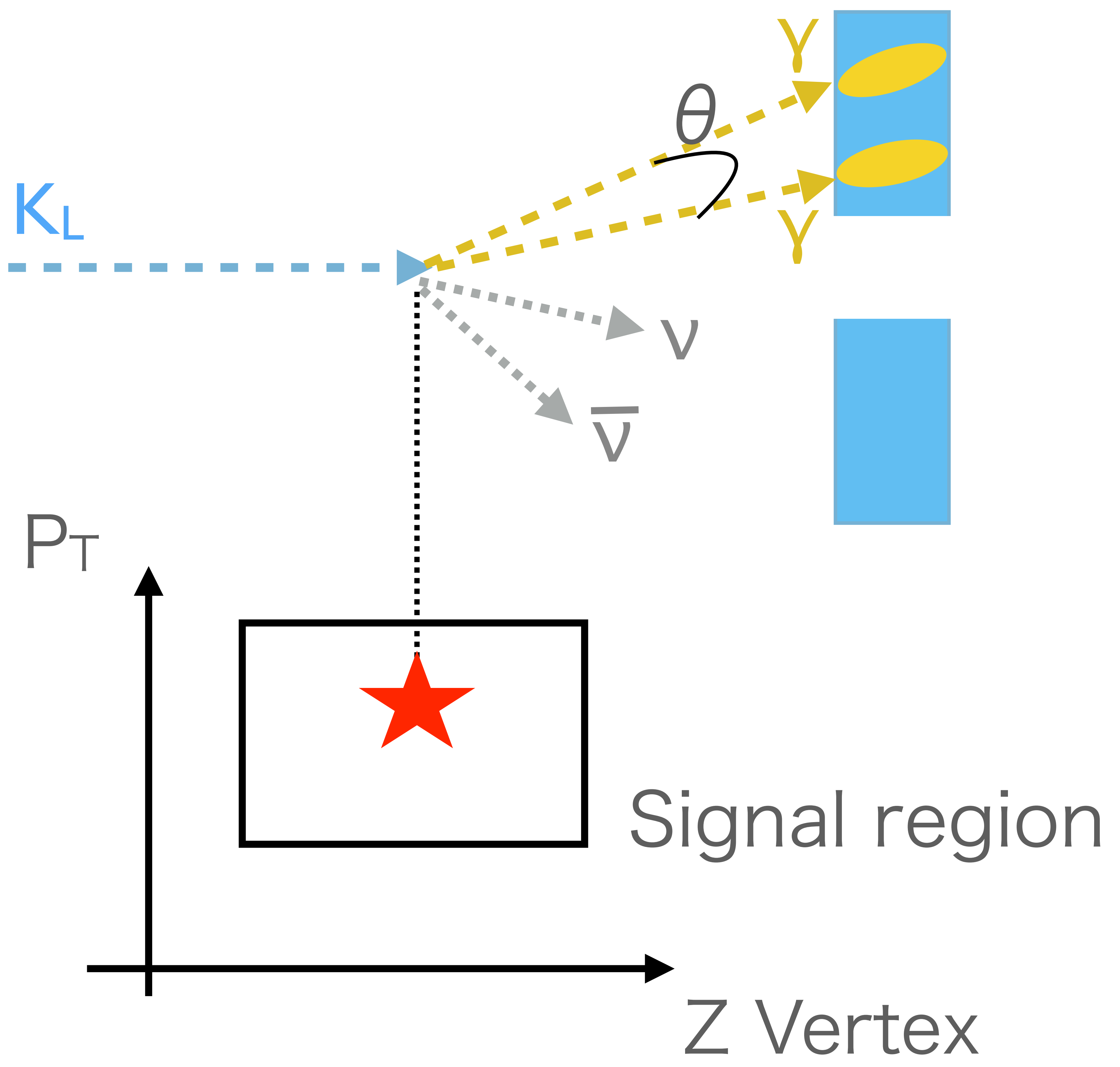


http://www.lnf.infn.it/wg/vus/content/Krare.html

How to search the $K_L \to \pi^0 \nu \nu$ decay

Experimental Principle

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



Assuming 2γ from π^0,
Calculate z vertex.

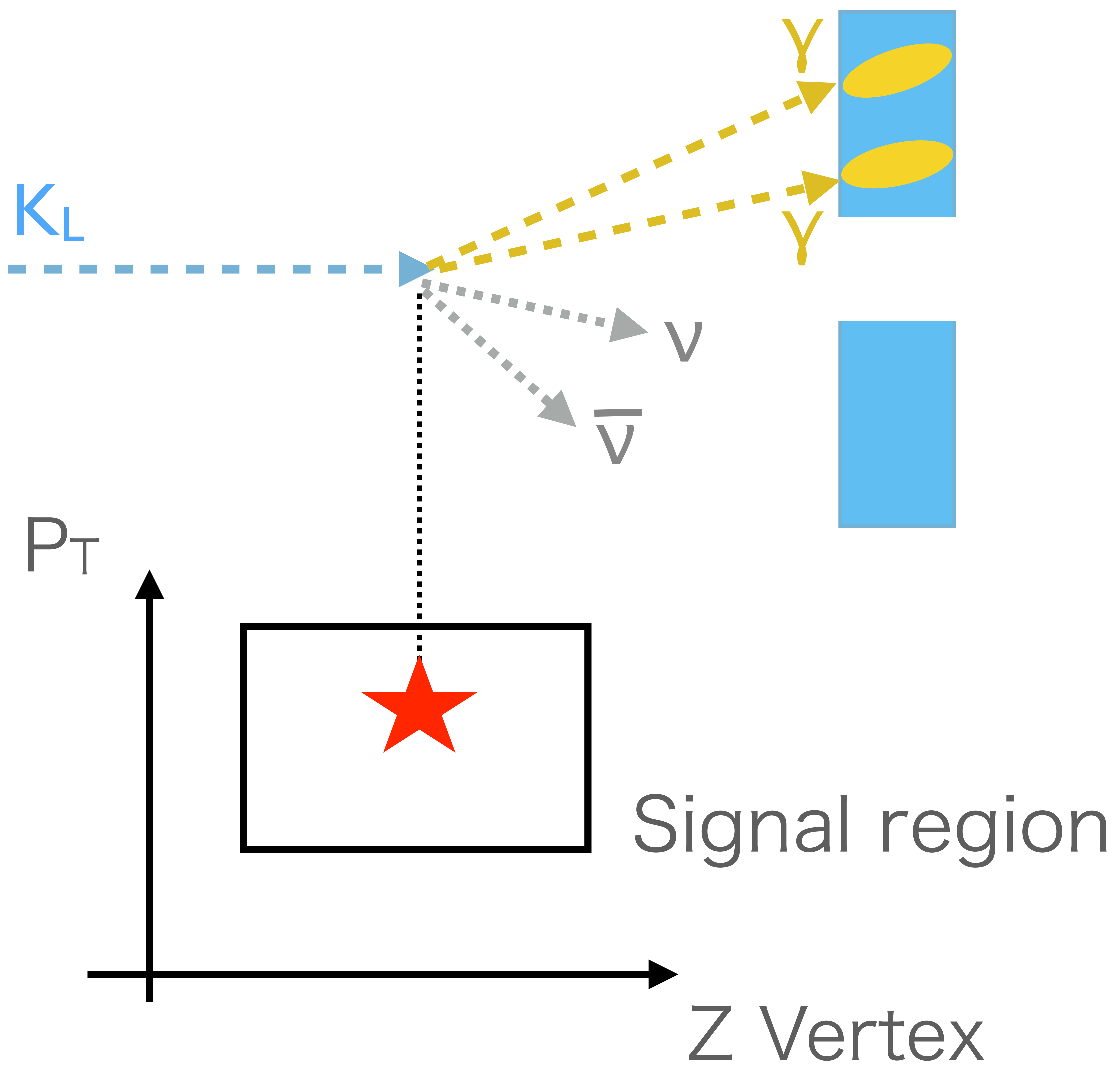
$$M^2(\pi^0)=2E_1E_2(1-\cos\theta)$$

Calculate π^0 transverse momentum

Experimental Principle

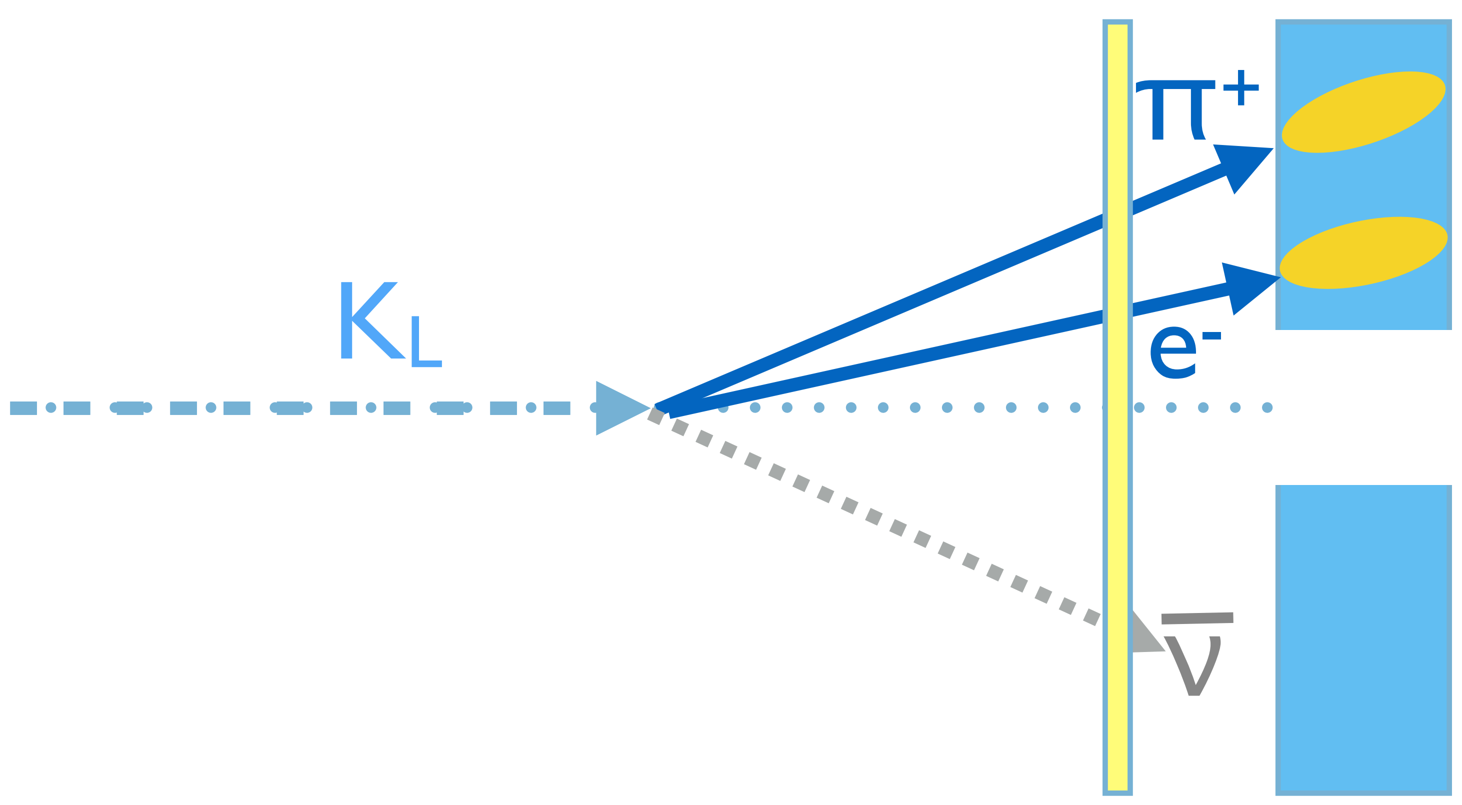
Suppression for background events

$K_L \to \pi^0 \nu \bar{\nu}$ BR=3×10^{-11}



$K_L \to \pi^+ e^- \overline{\nu}$ BR=4.0×10^{-1}

charged particles

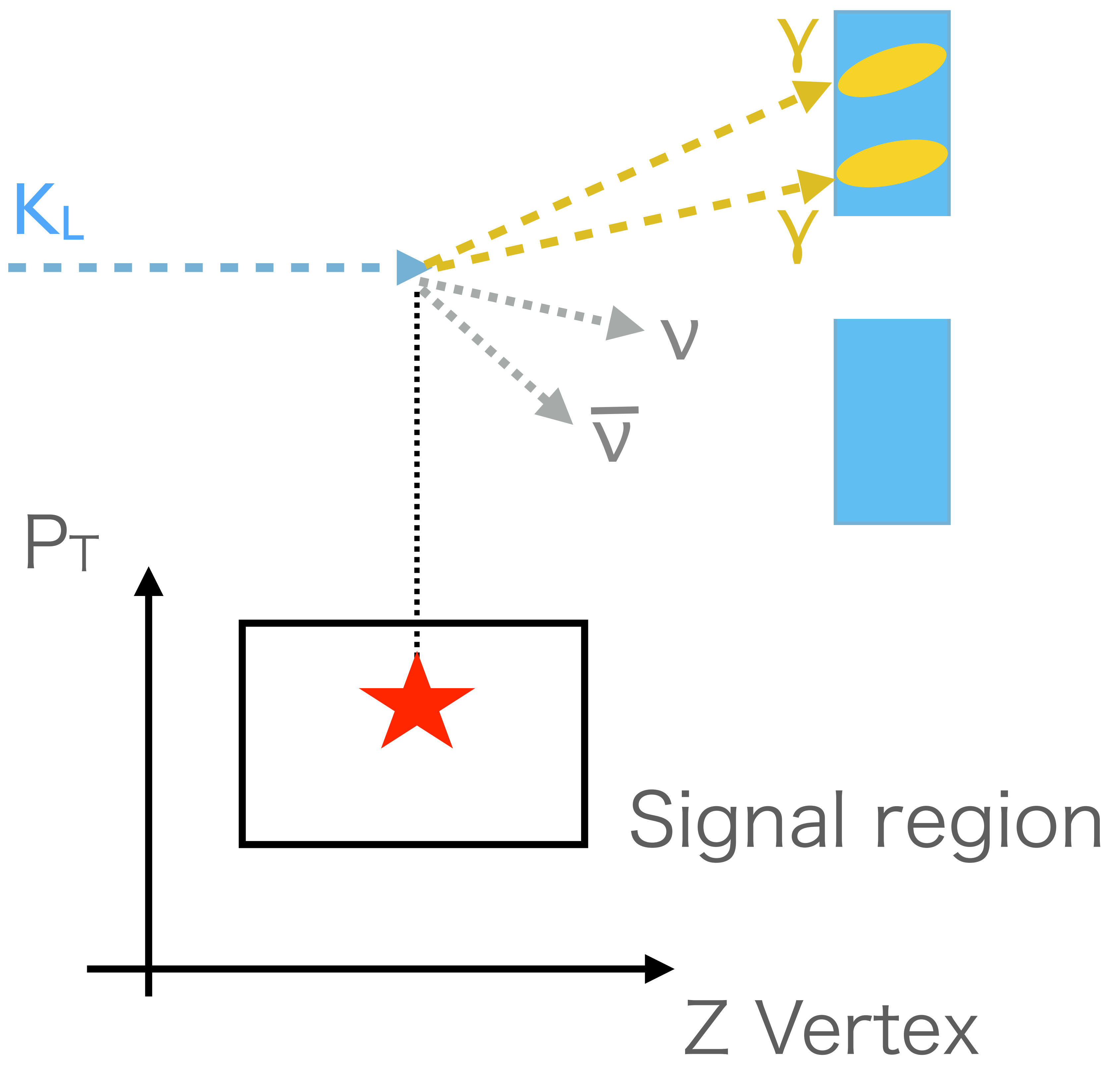


* Detect charged particles with plastic scintillators

Experimental Principle

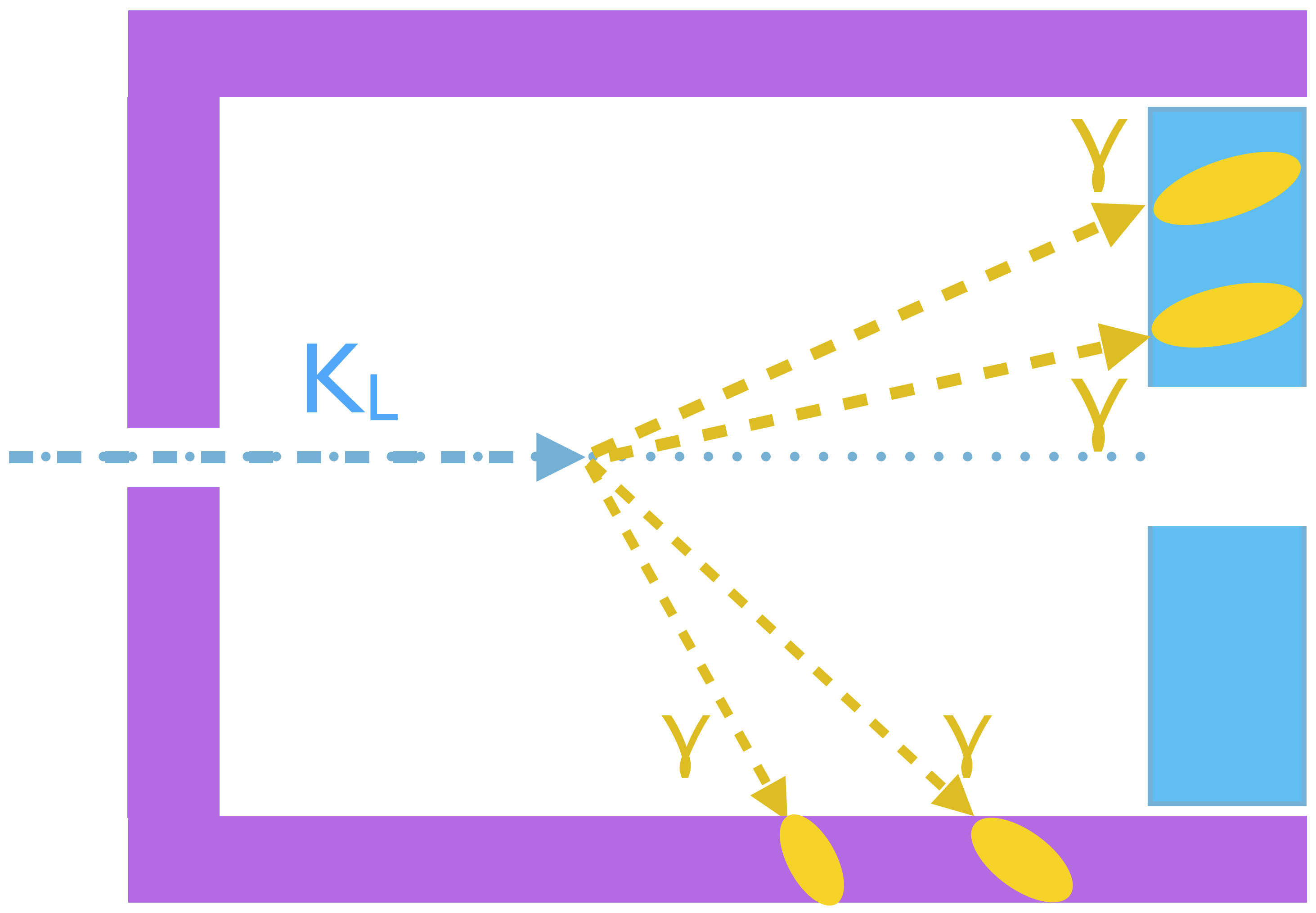
Suppression for background events

$K_L \to \pi^0 \nu \bar{\nu}$ BR=3×10^{-11}



$K_L \to \pi^0 \pi^0$ BR=8.6×10^{-4}

more photons

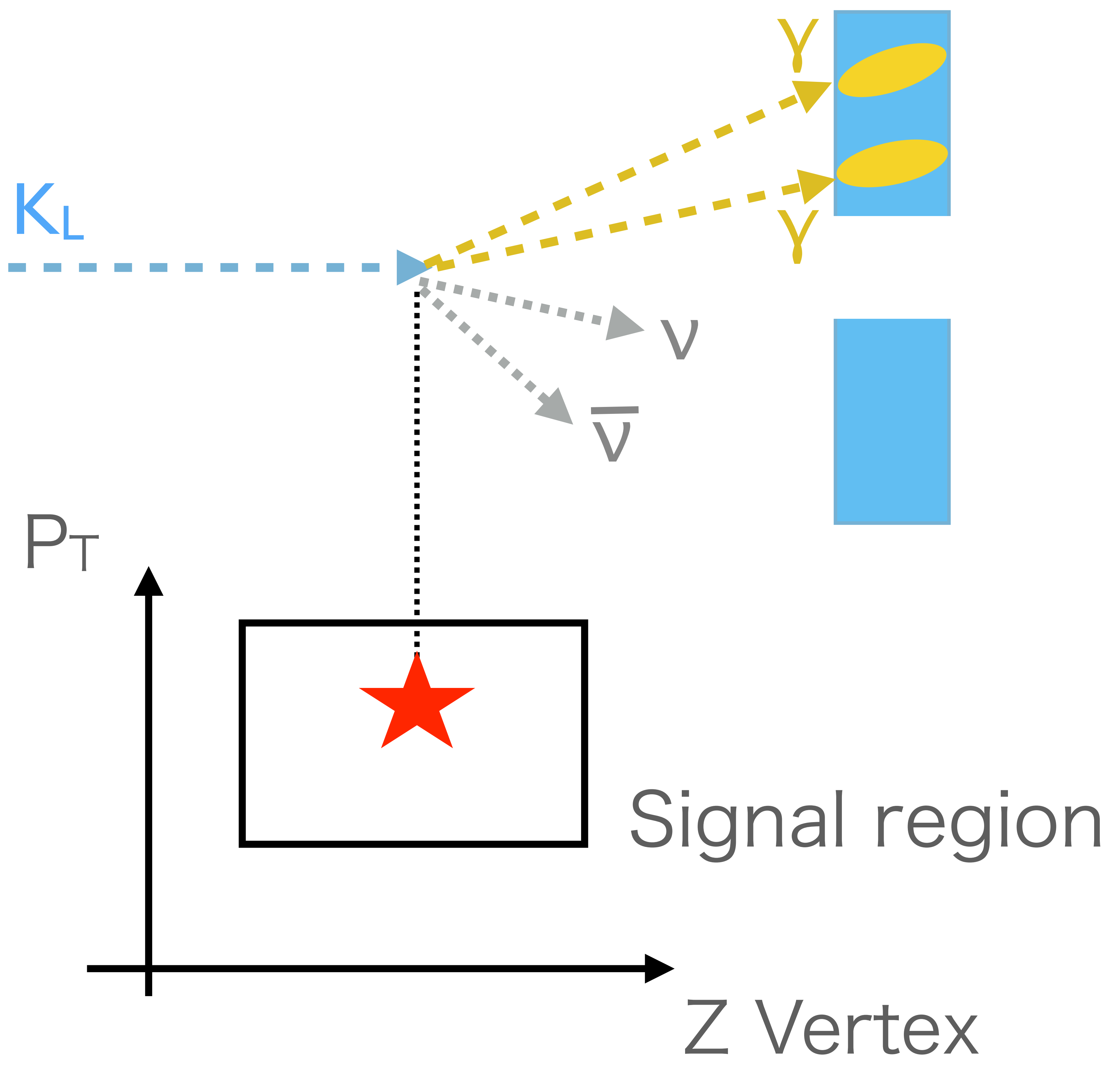


* Cover decay volume with veto detectors

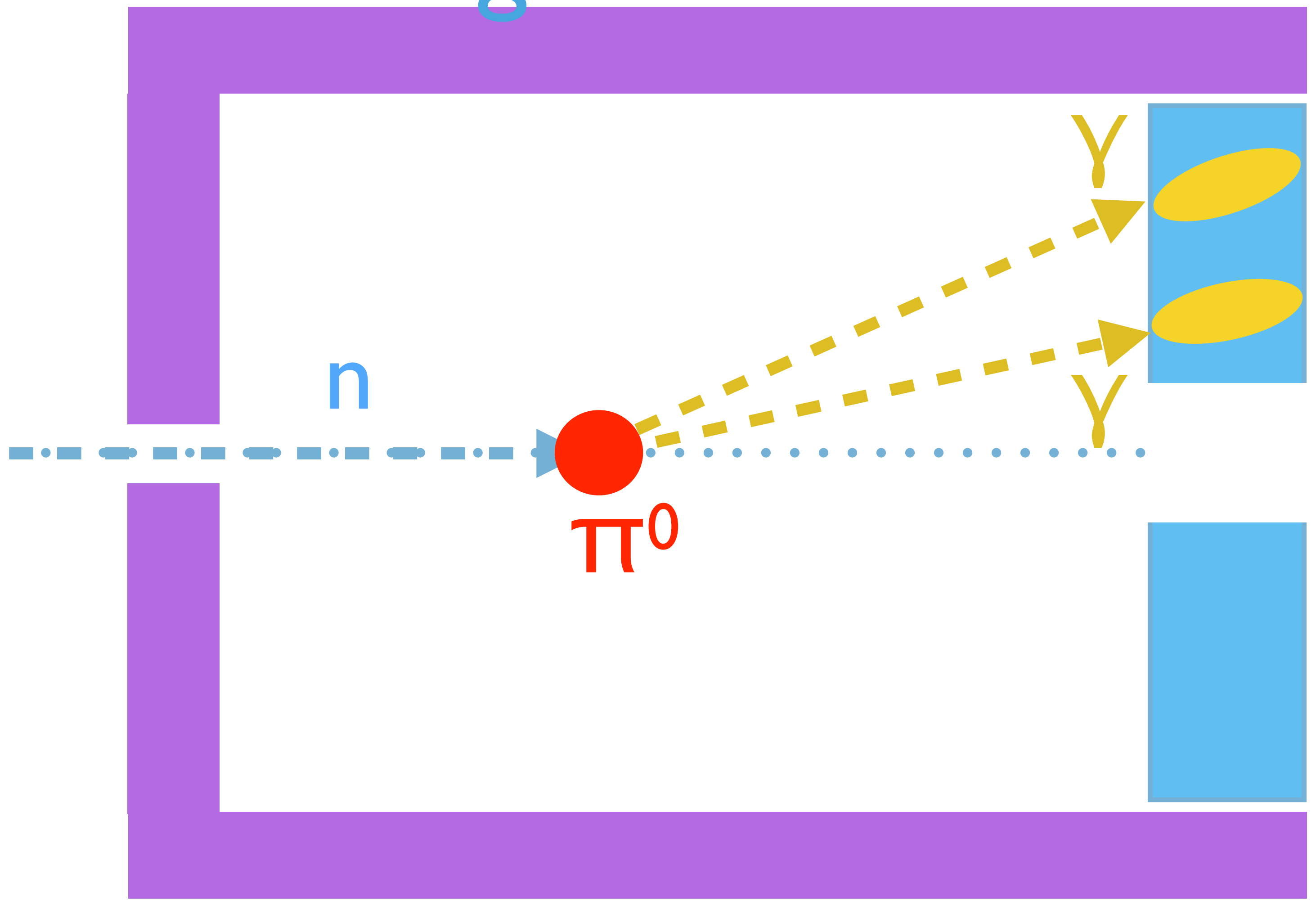
Experimental Principle

Suppression for background events

$K_L \to \pi^0 \nu \bar{\nu}$ BR=3×10-11



π0 Production through the interaction with residual gas

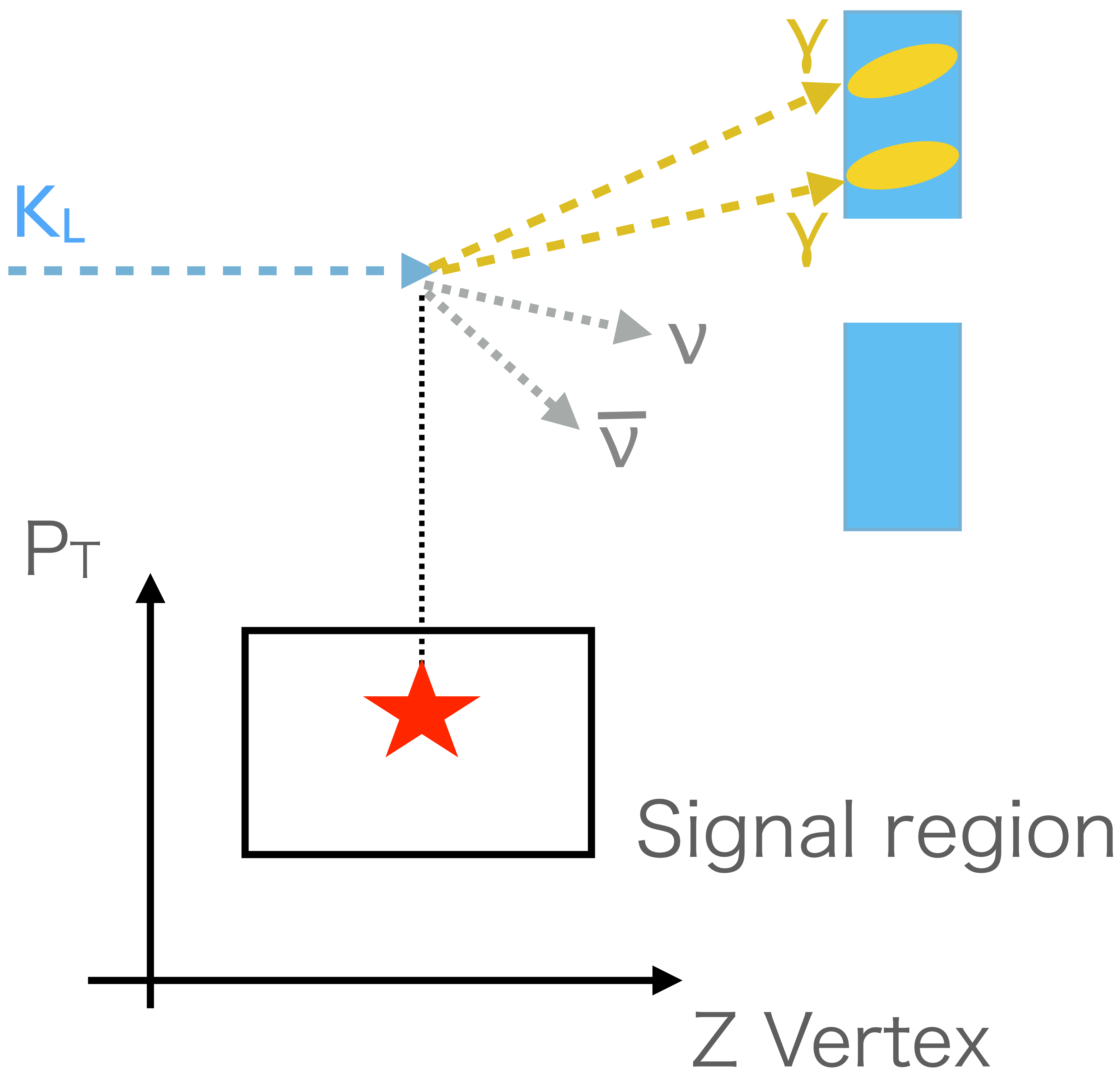


* Keep the decay volume to be high vacuum

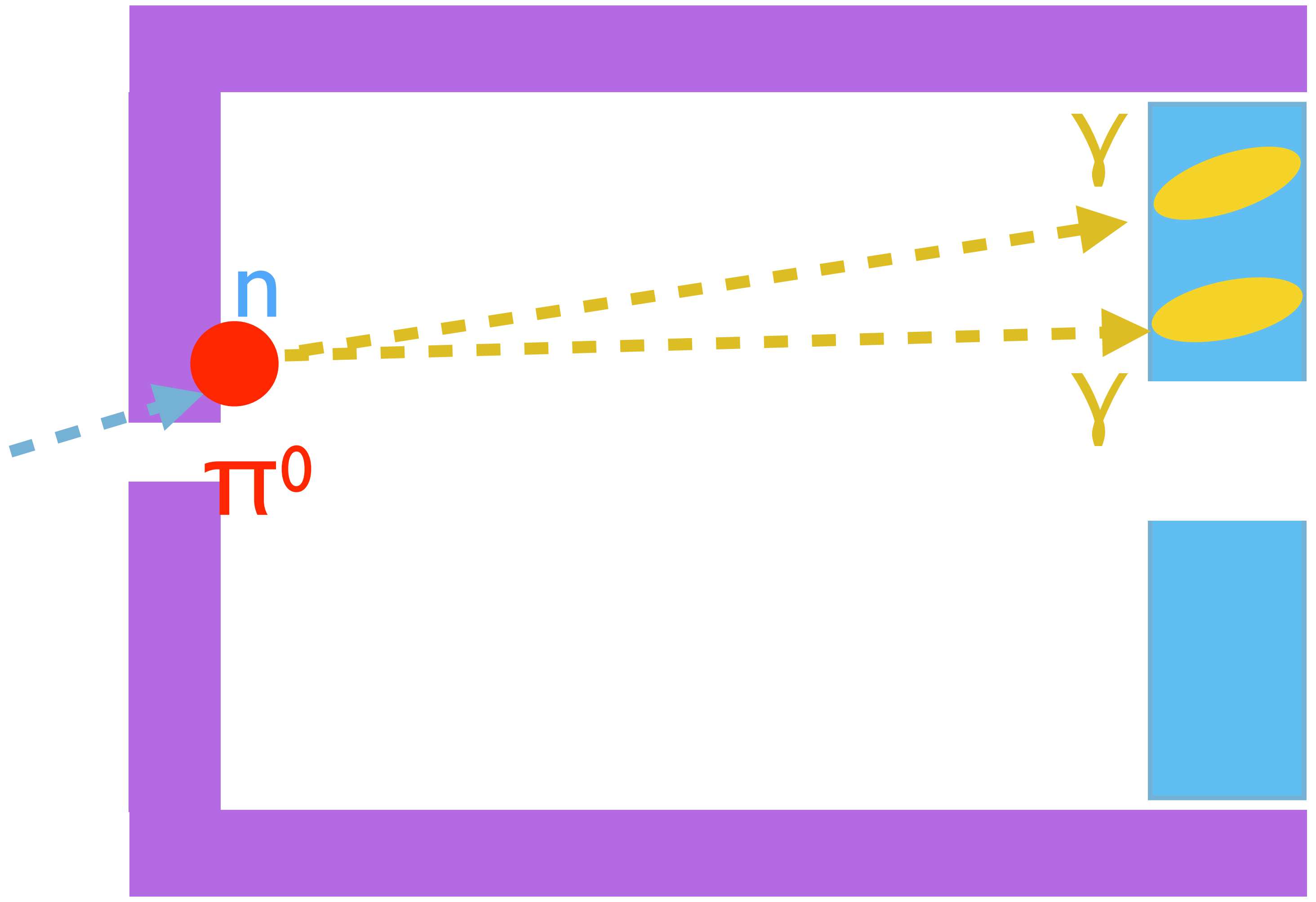
Experimental Principle

Suppression for background events

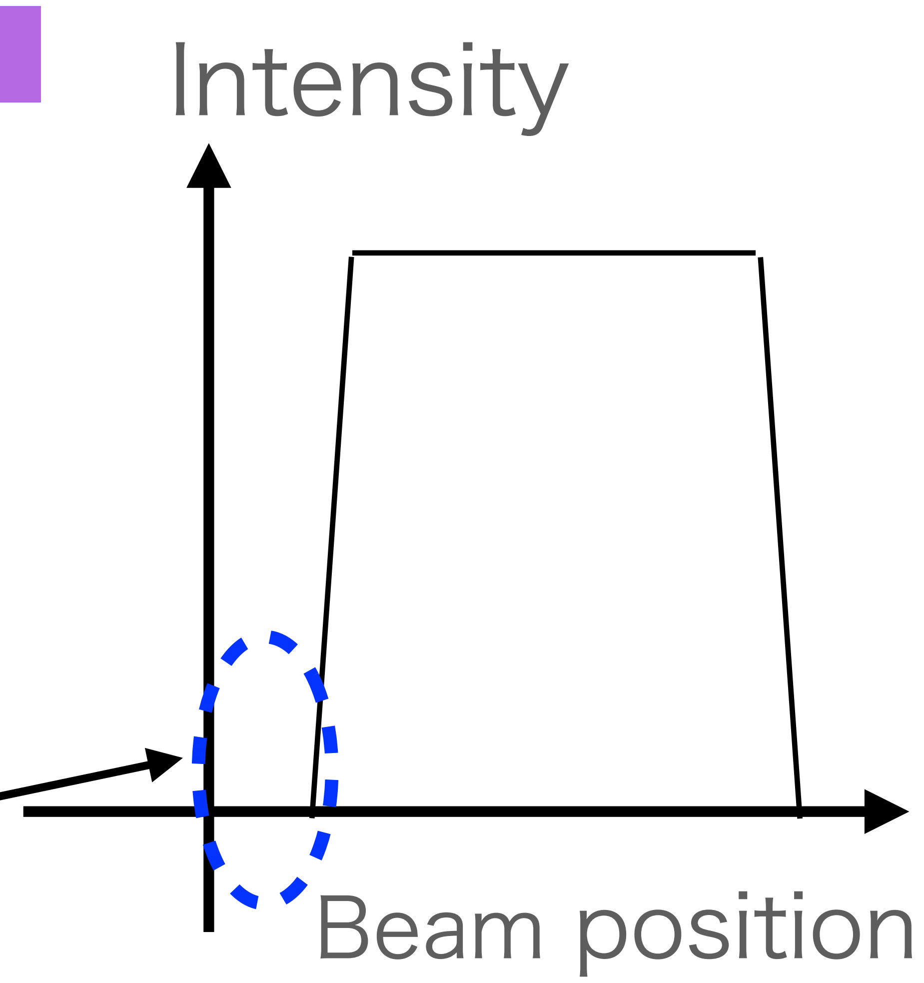
$K_L \to \pi^0 \nu \bar{\nu}$ $\boxed{BR=3\times10^{-11}}$



π0 Production through the interaction with detectors around the beam hole



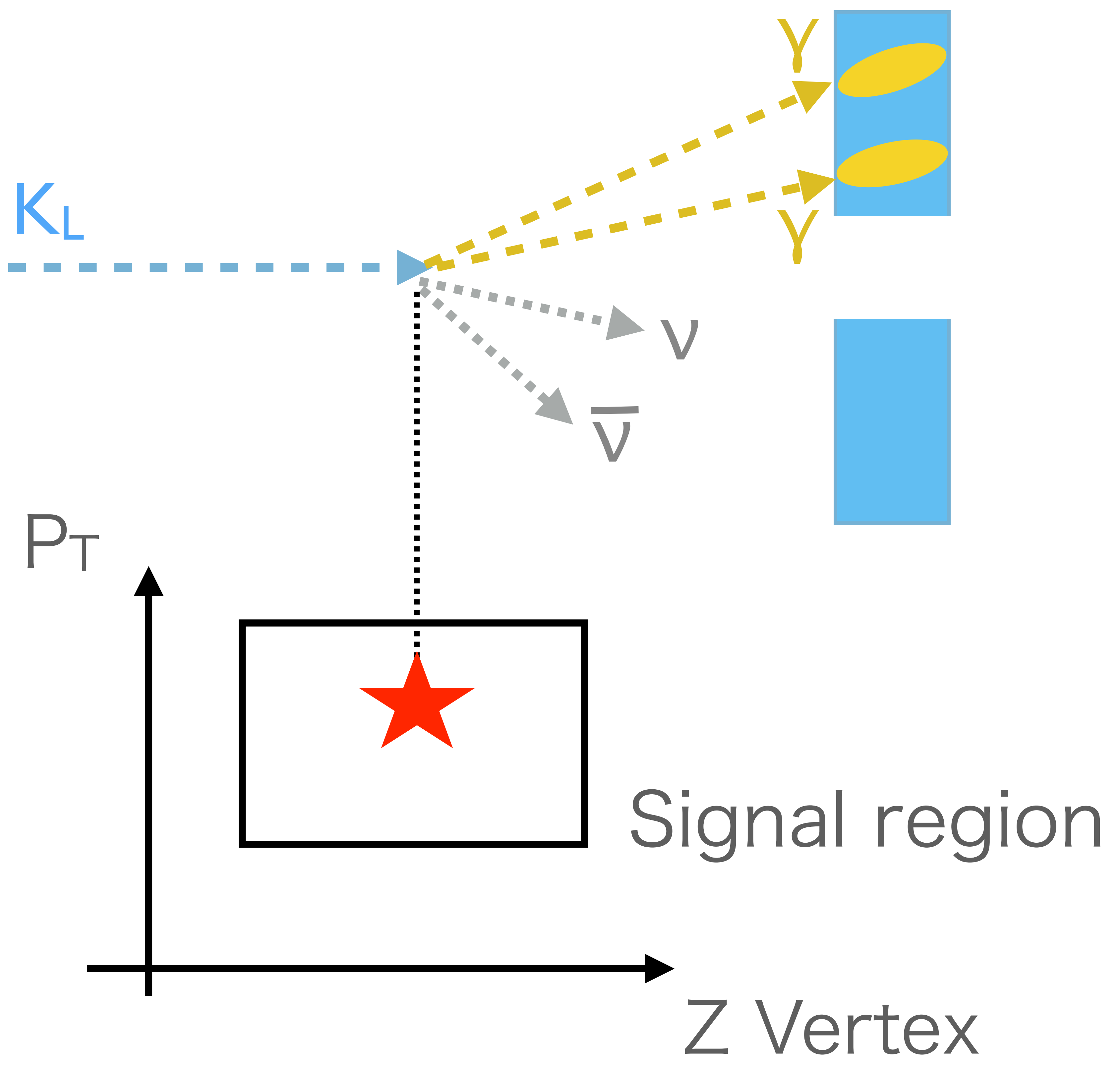
- Materials near the beam hole should be minimized
- Beam should be "well-shaped".
  - Ideally, No particles in "halo region"



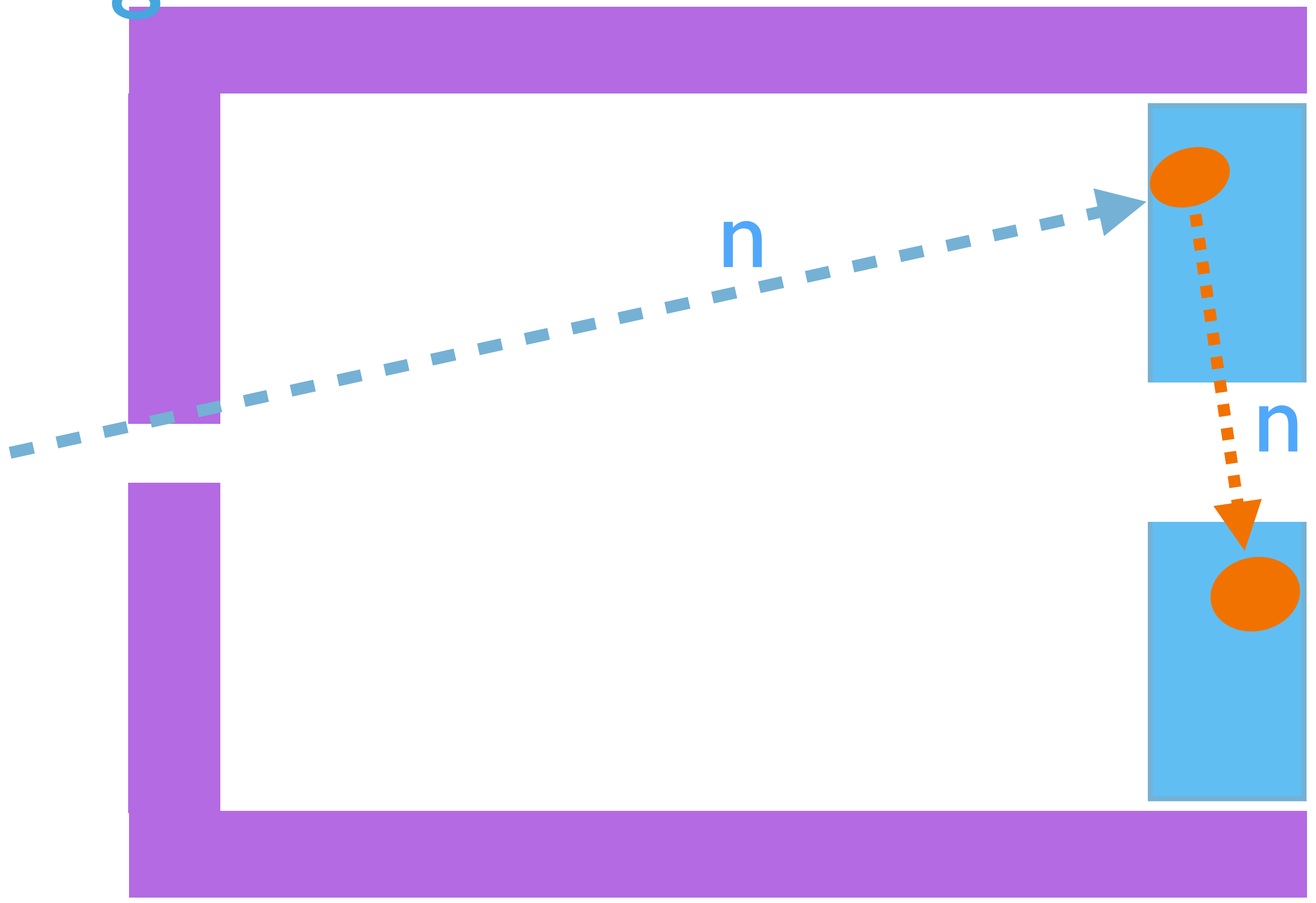
Experimental Principle

Suppression for background events

$K_L \to \pi^0 \nu \bar{\nu}$ $\boxed{BR=3\times10^{-11}}$

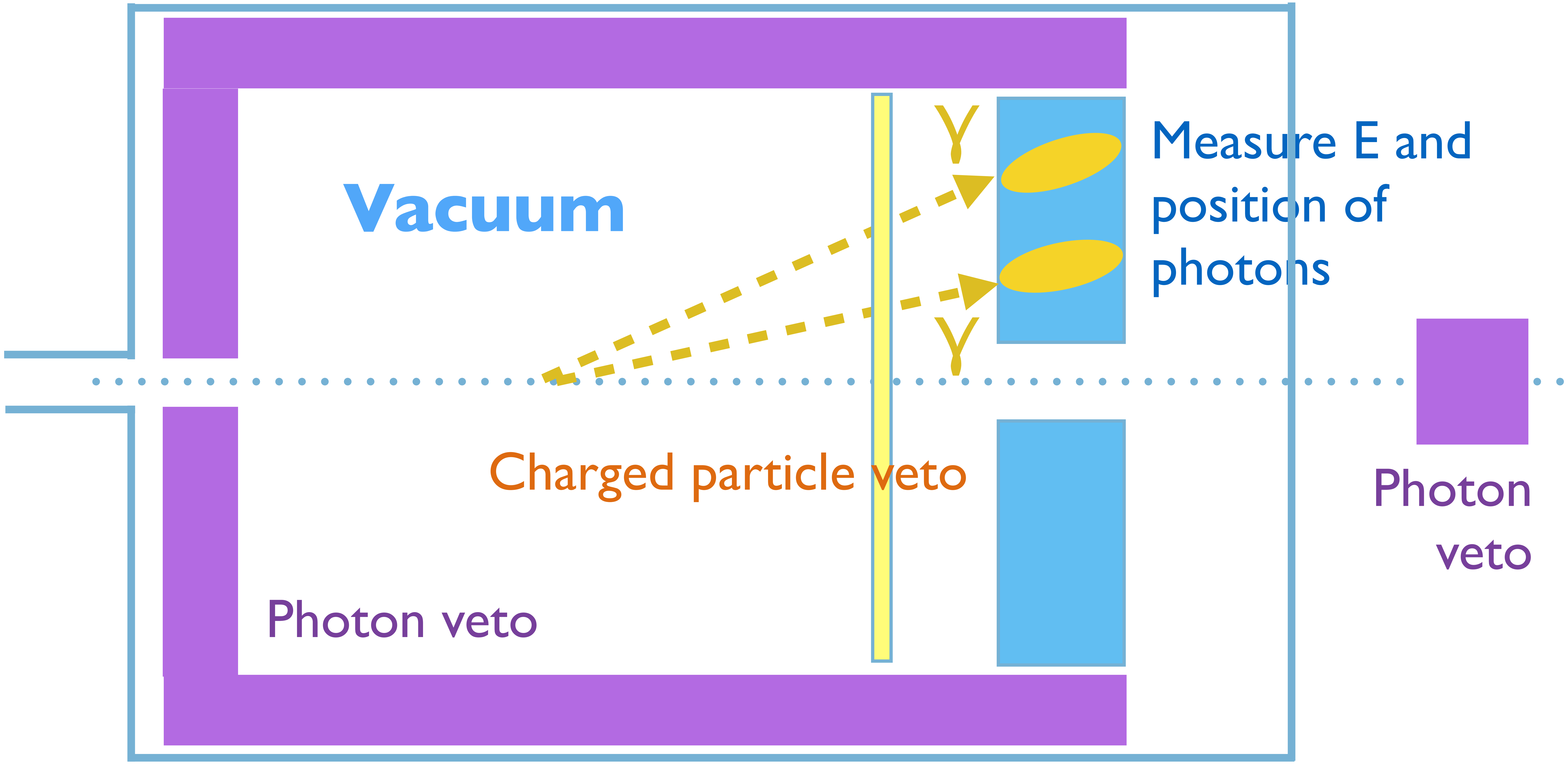


Neutron make 2 clusters through hadronic interactions



* Discriminate "neutron cluster" from "photon cluster"

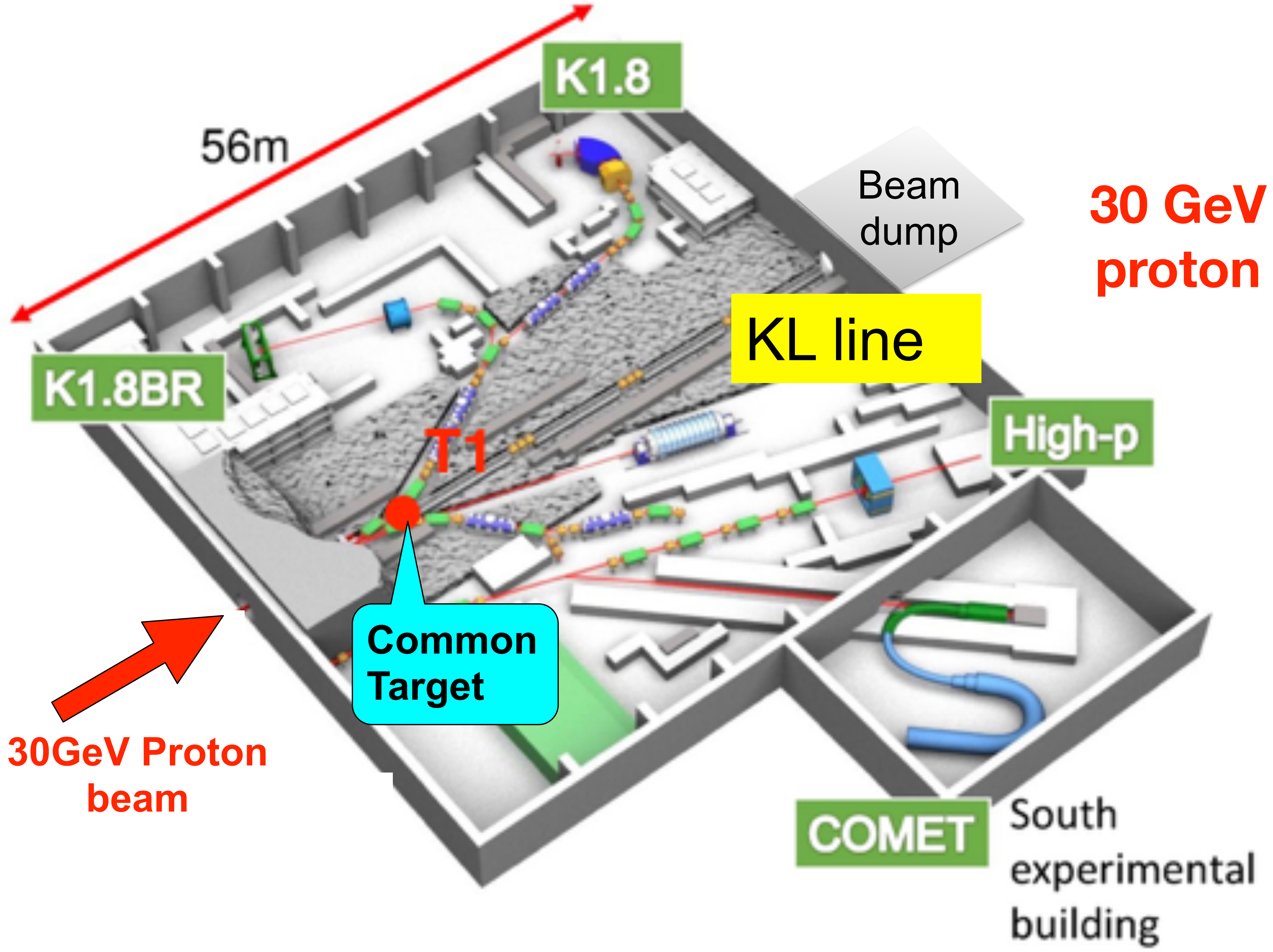
Basic detector design

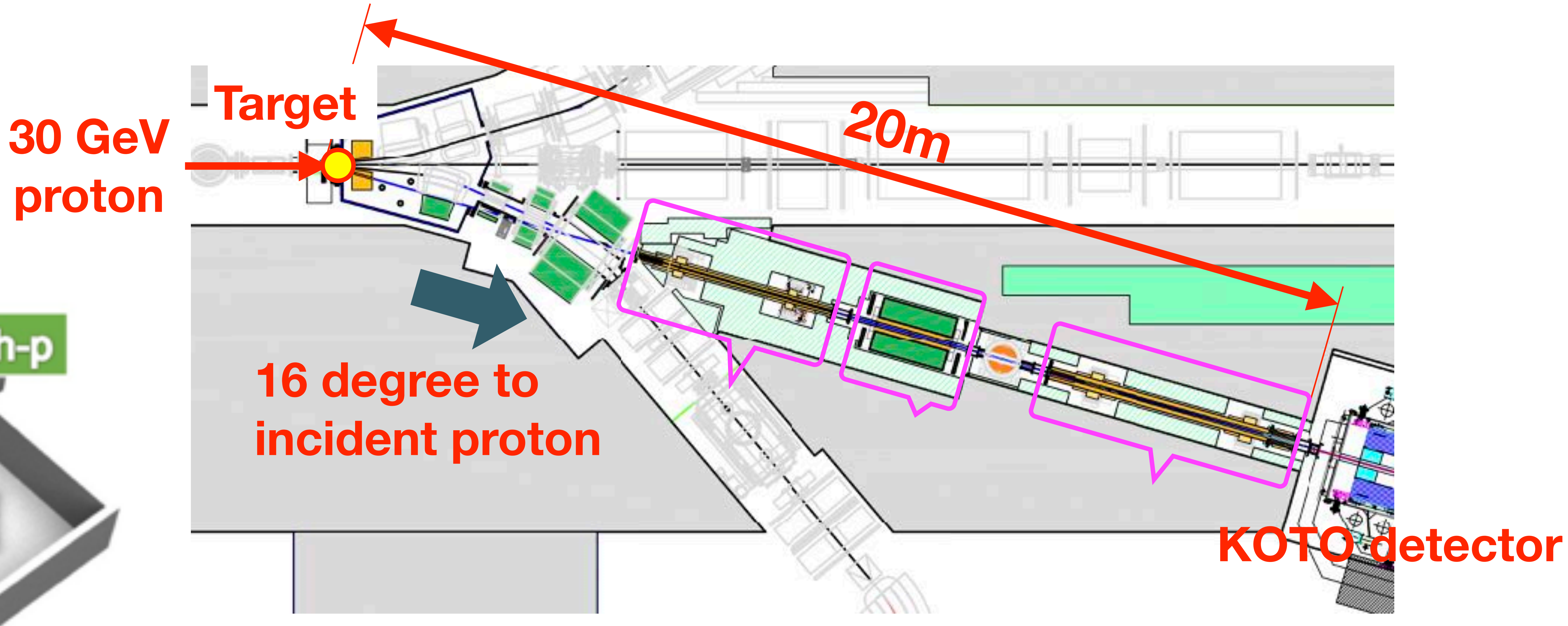


KOTO experiment
in Hadron Hall

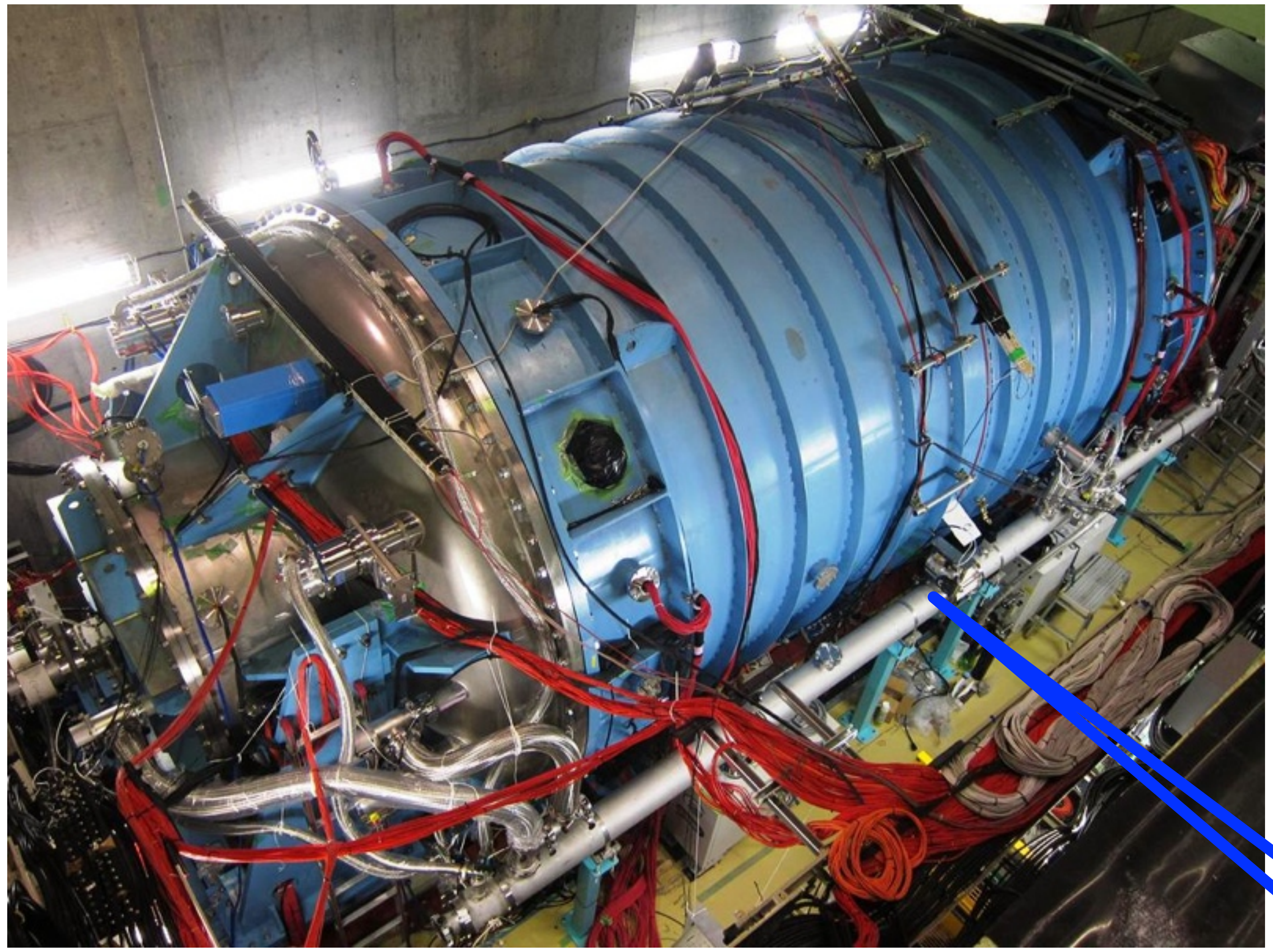
KOTO experiment

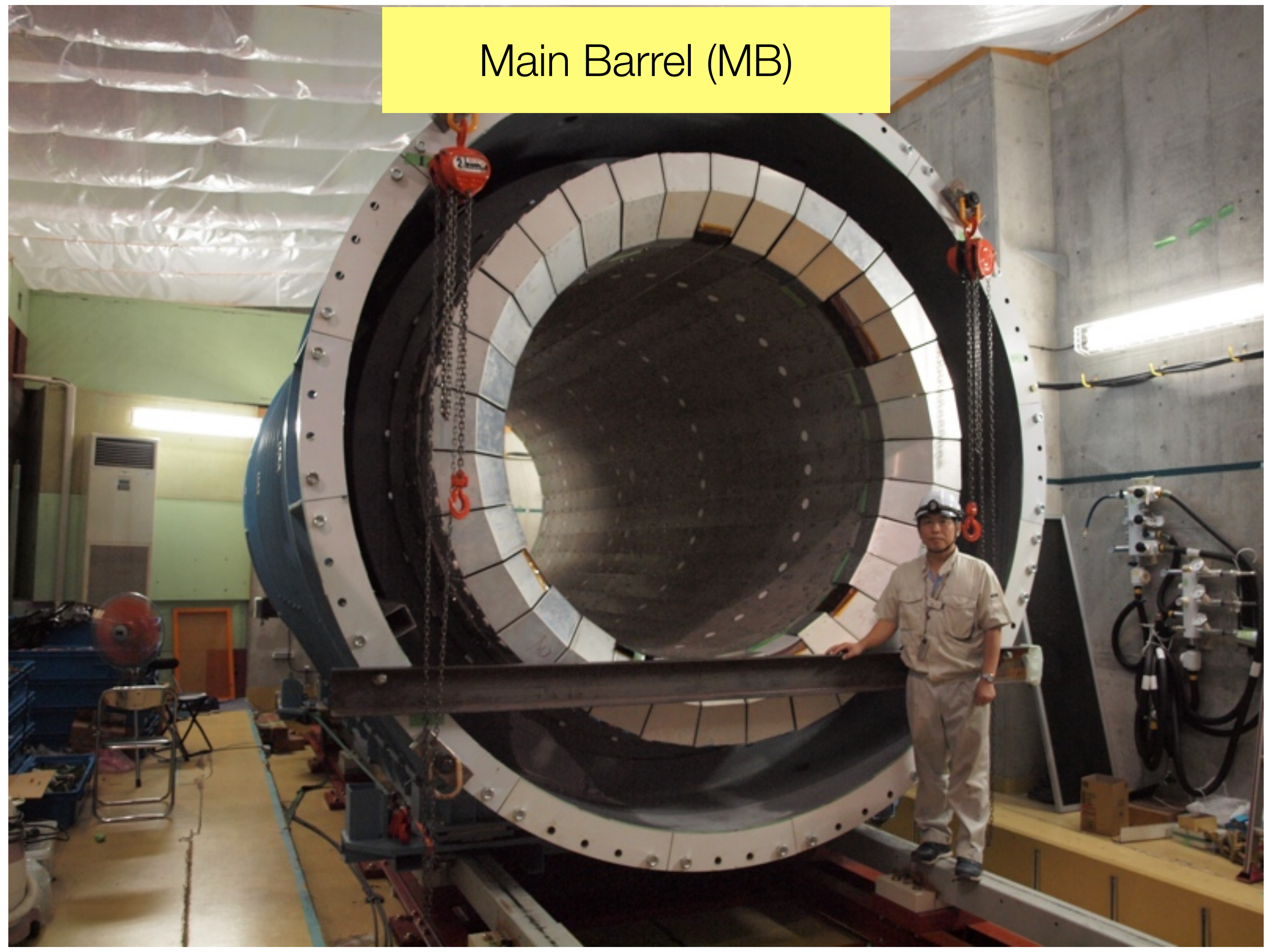
$K_L \rightarrow \pi^0 \nu \nu$ decay search @ Hadron Experimental Facility

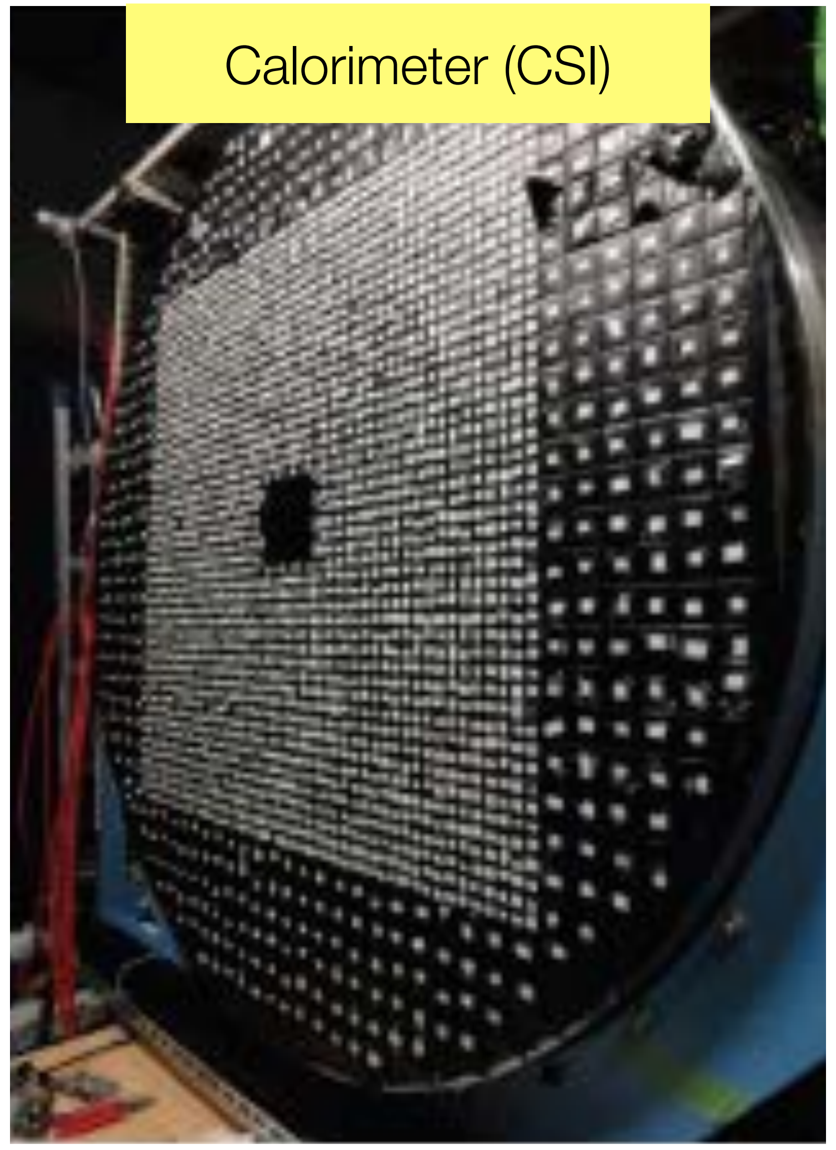


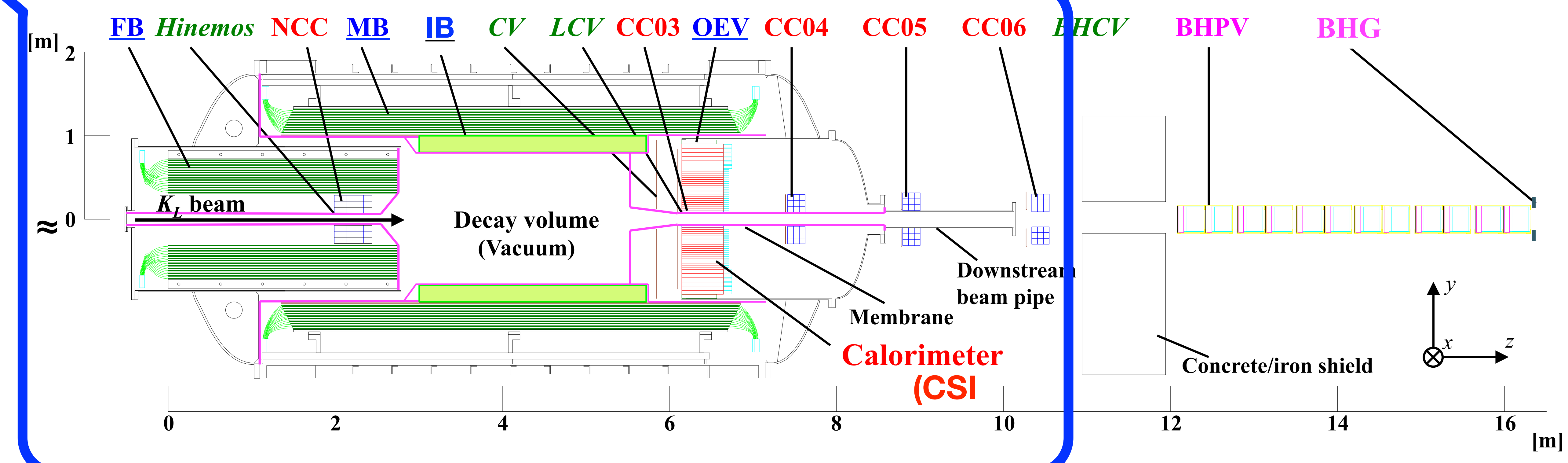


KOTO detector

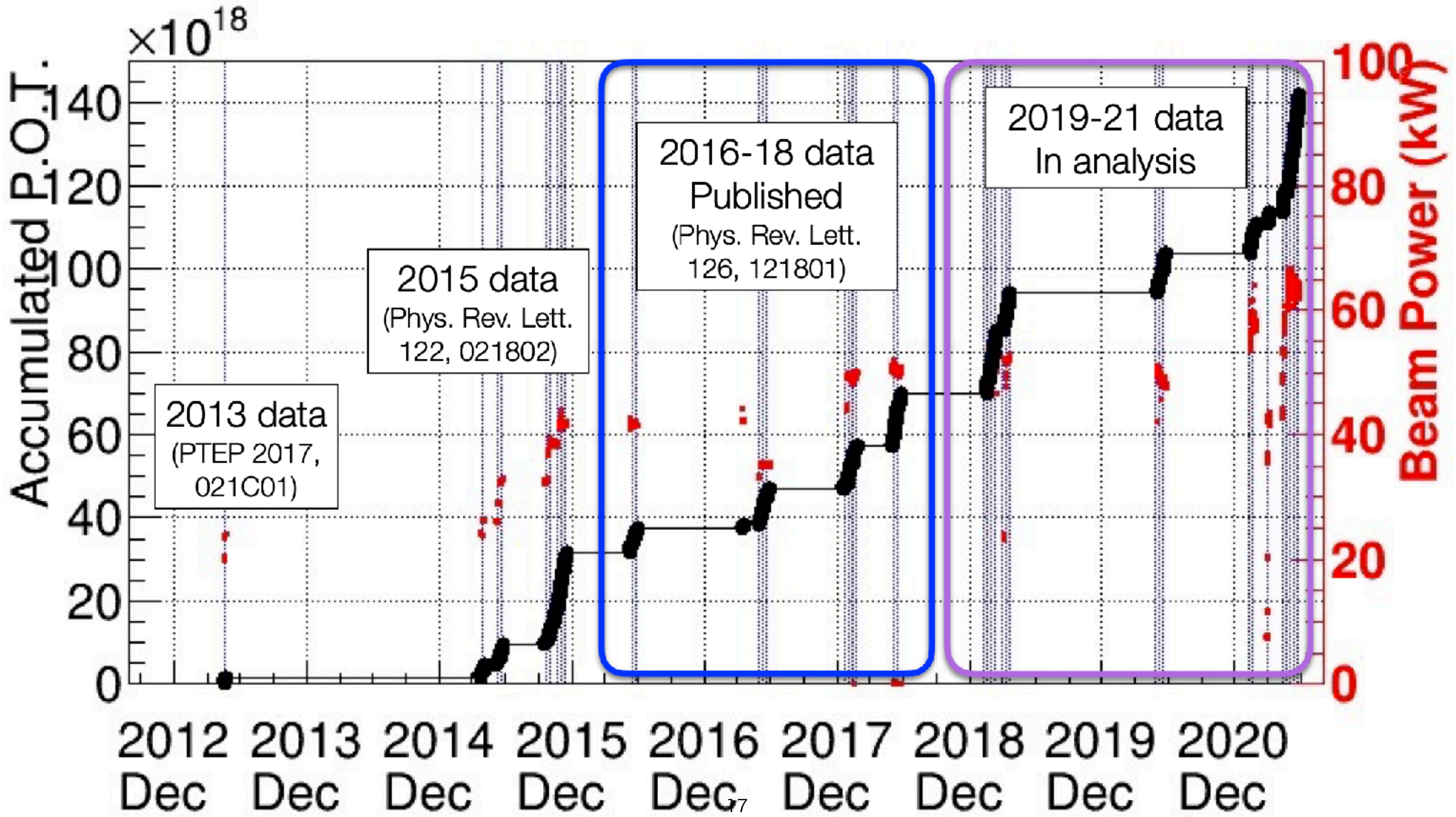








KOTO data taking



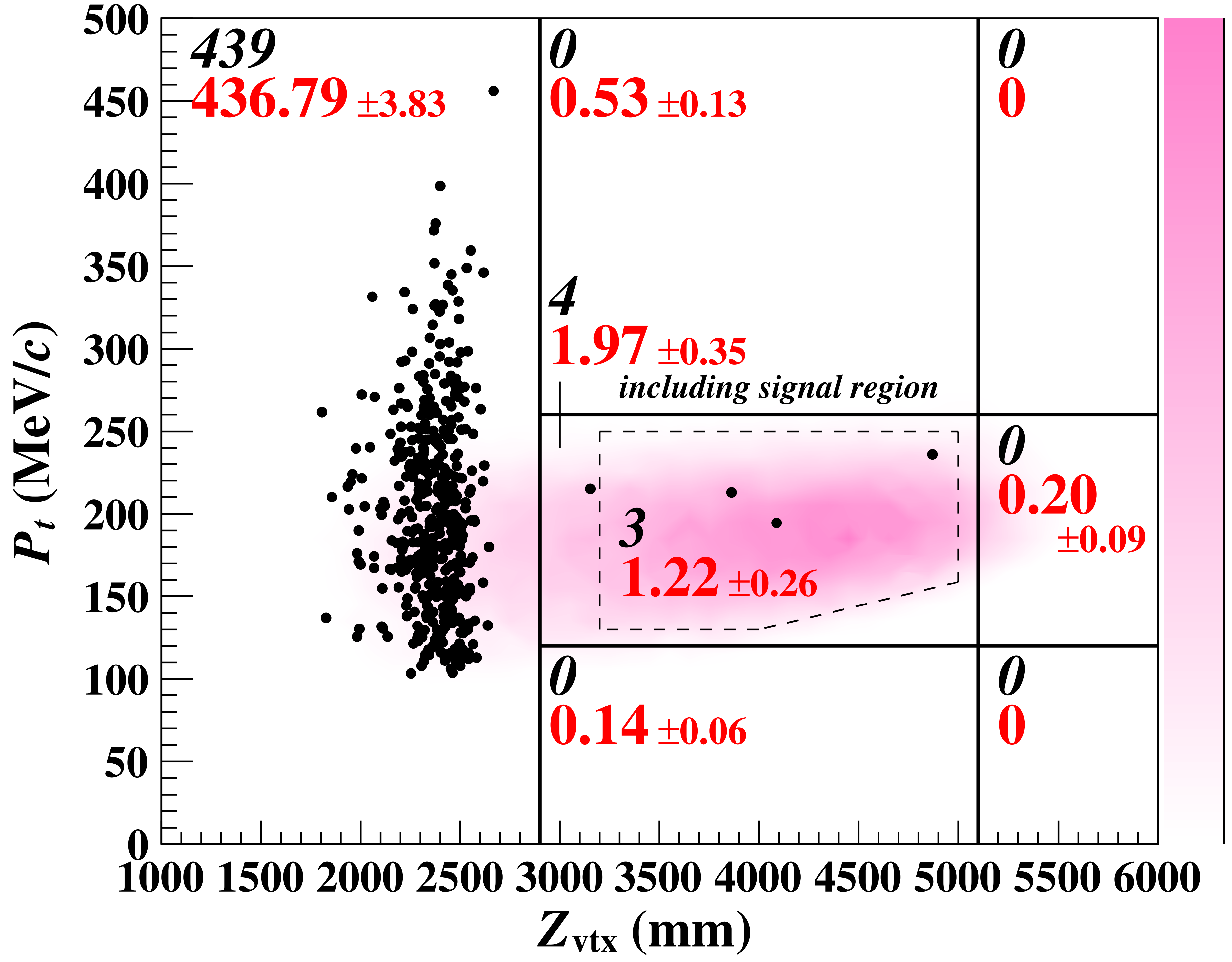
The latest results of KOTO

2016-2018 data analysis

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

Final PT vs Z plot

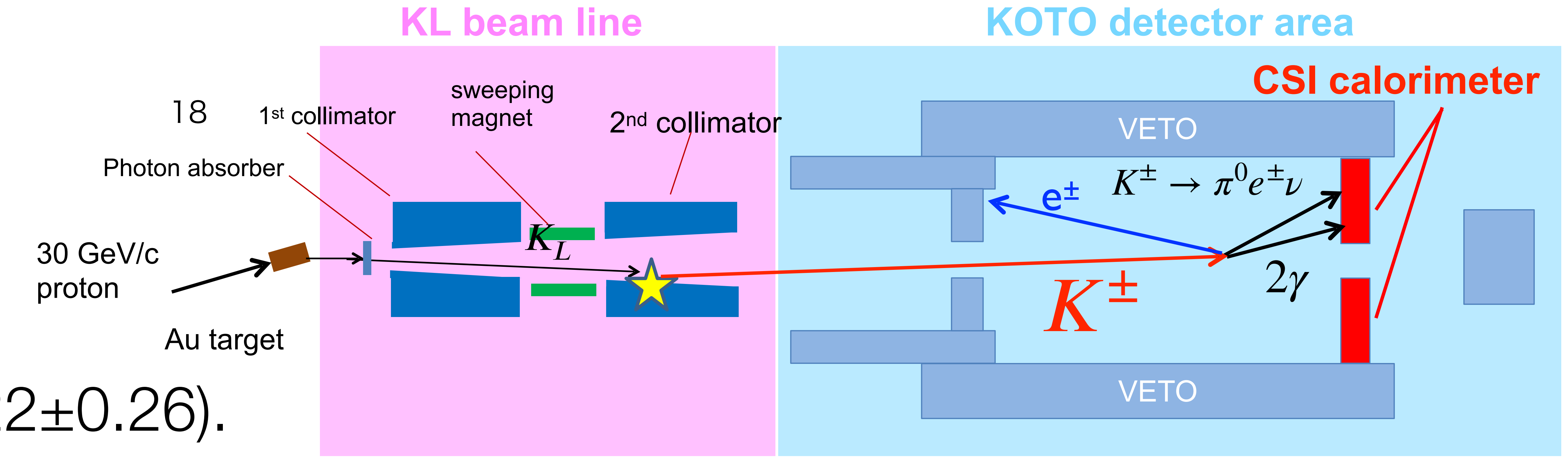
Black: observed, Red: expected BG, Contour: signal MC



Background Table

	Number of events
$K_L \to 3\pi^0$	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]
Hadron cluster	0.017 ± 0.002
CV η	0.03 ± 0.01
Upstream π^0	0.03 ± 0.03
	1.22 ± 0.26

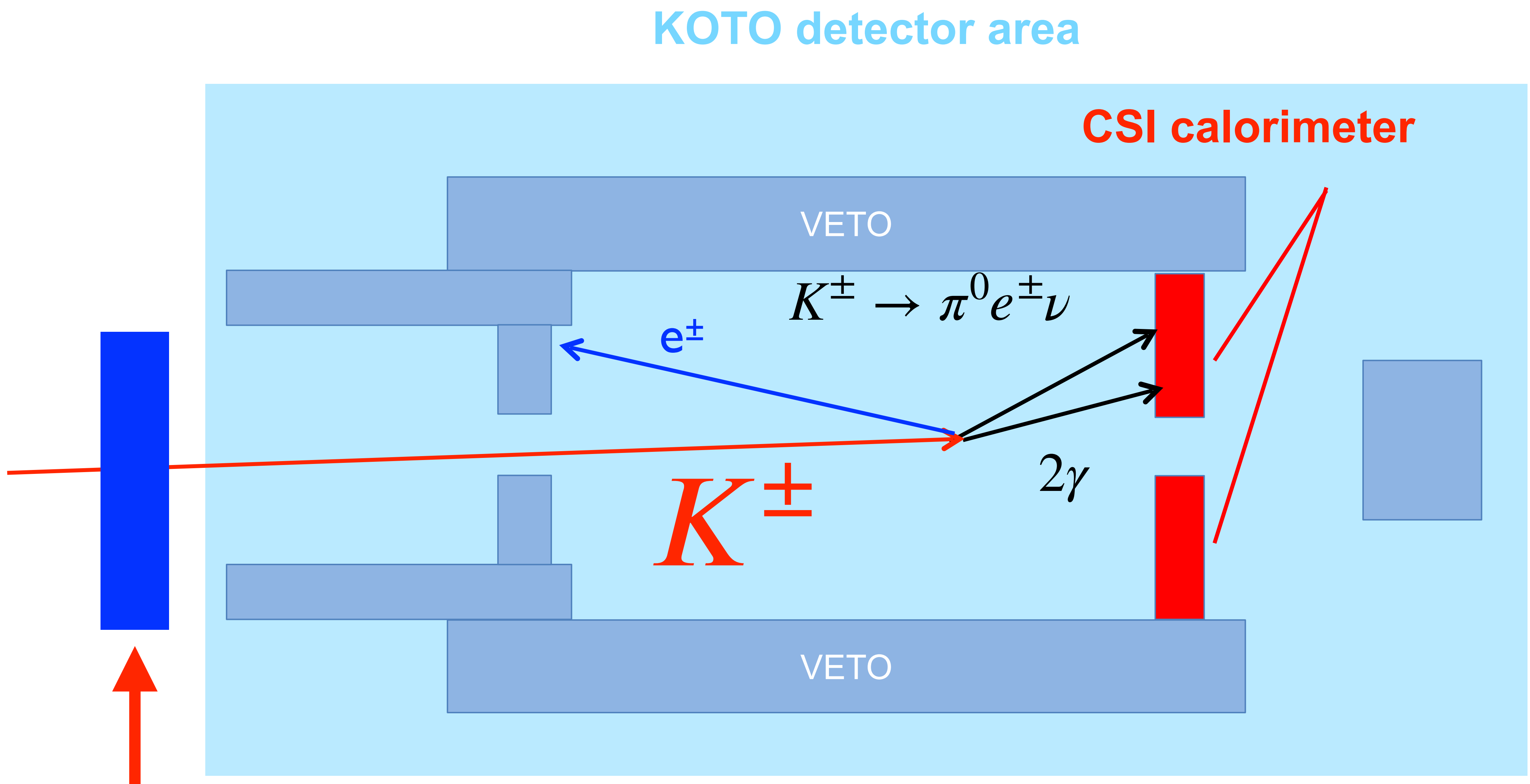
$K^{\pm} \to \pi^0 e^{\pm} \nu$ is the most serious contributor.

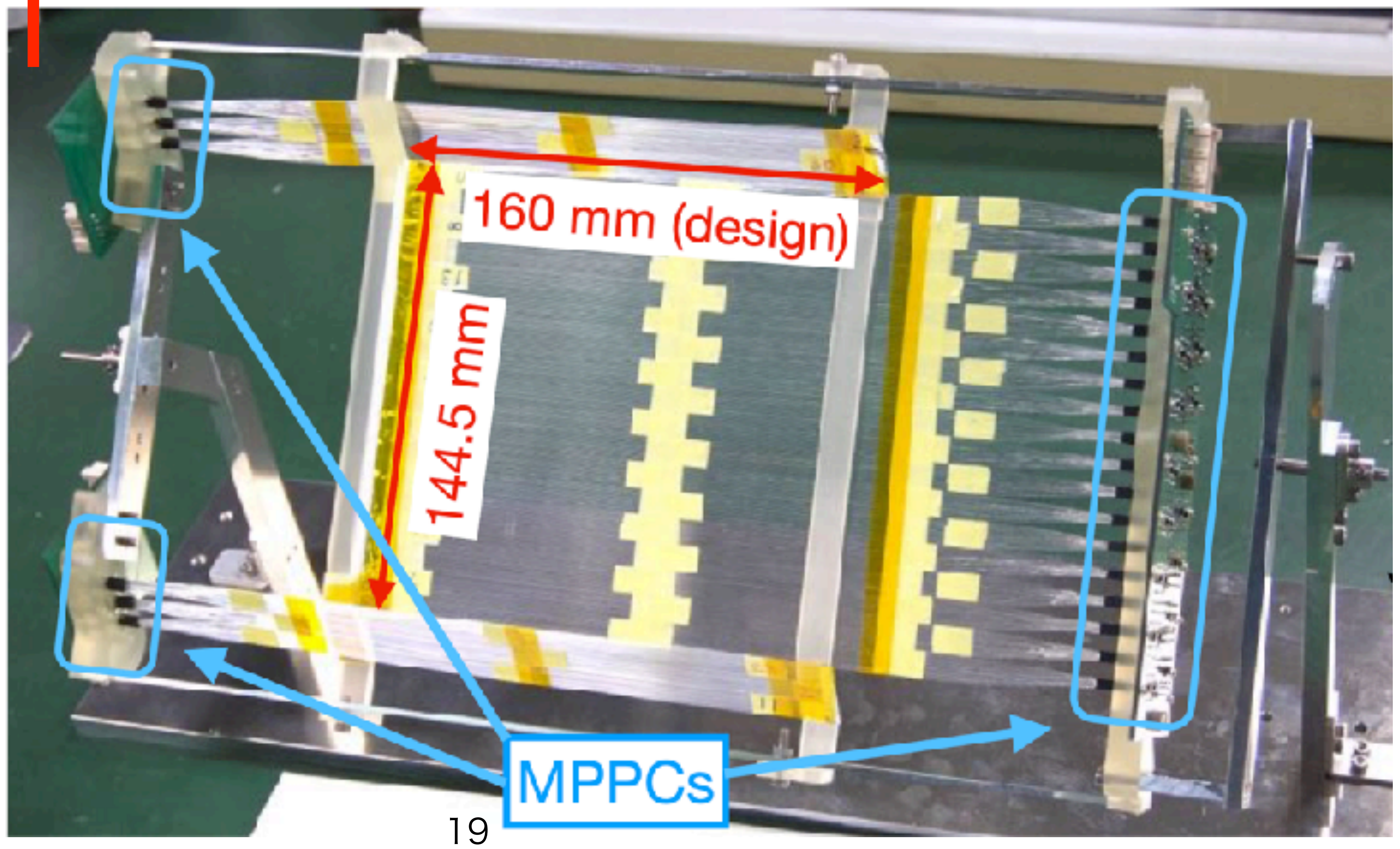


$N_{observed}$ (=3) is statistically consistent with N_{BG} (=1.22±0.26).

Prospects of KOTO

- Against K+ Backgrounds
  - Plate with 0.5-mm square scintillating fibers to detect K+ in beam (Efficiency ~ 95%)
  - Installed in 2021
  - Further upgrade study is on-going



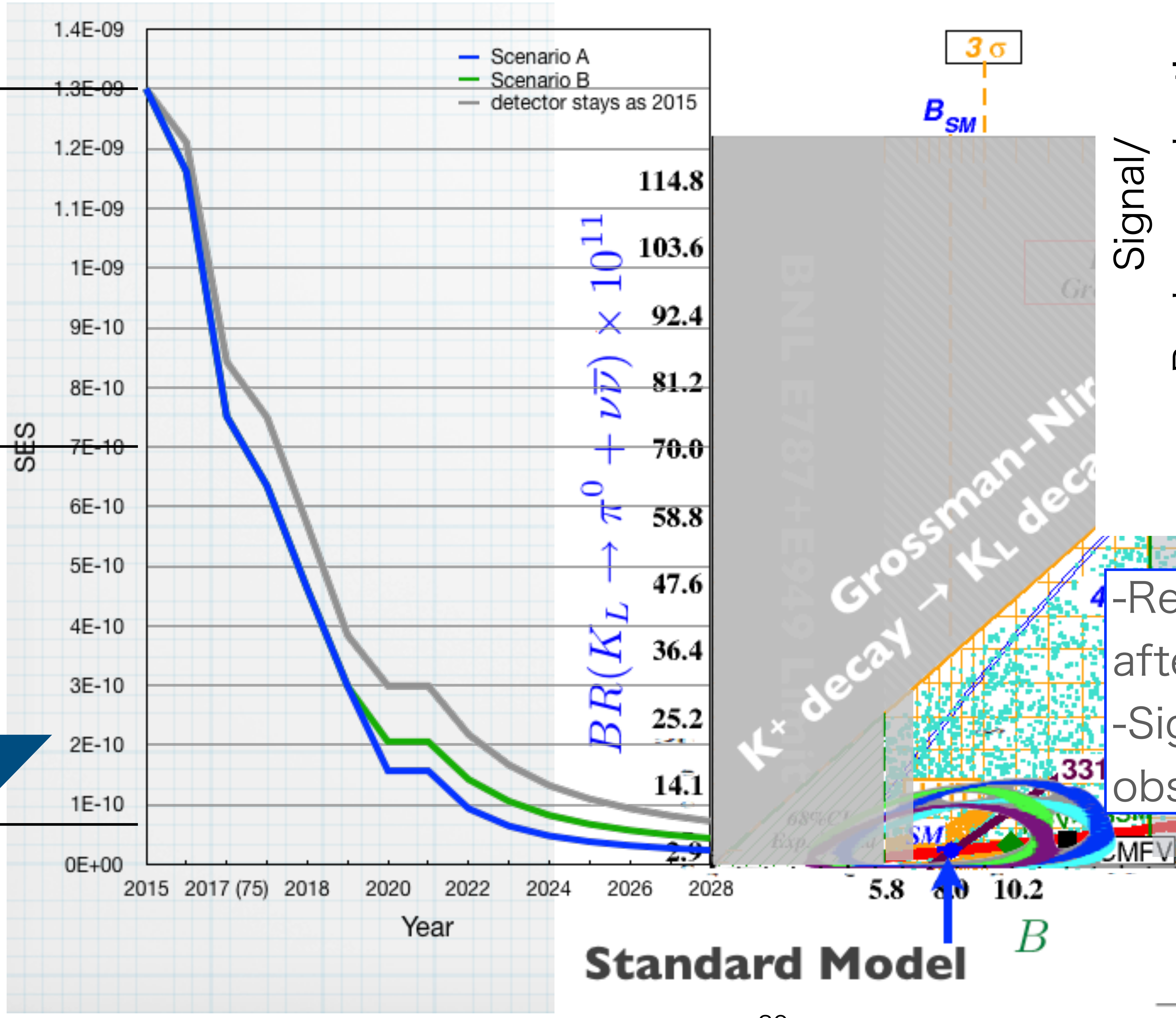


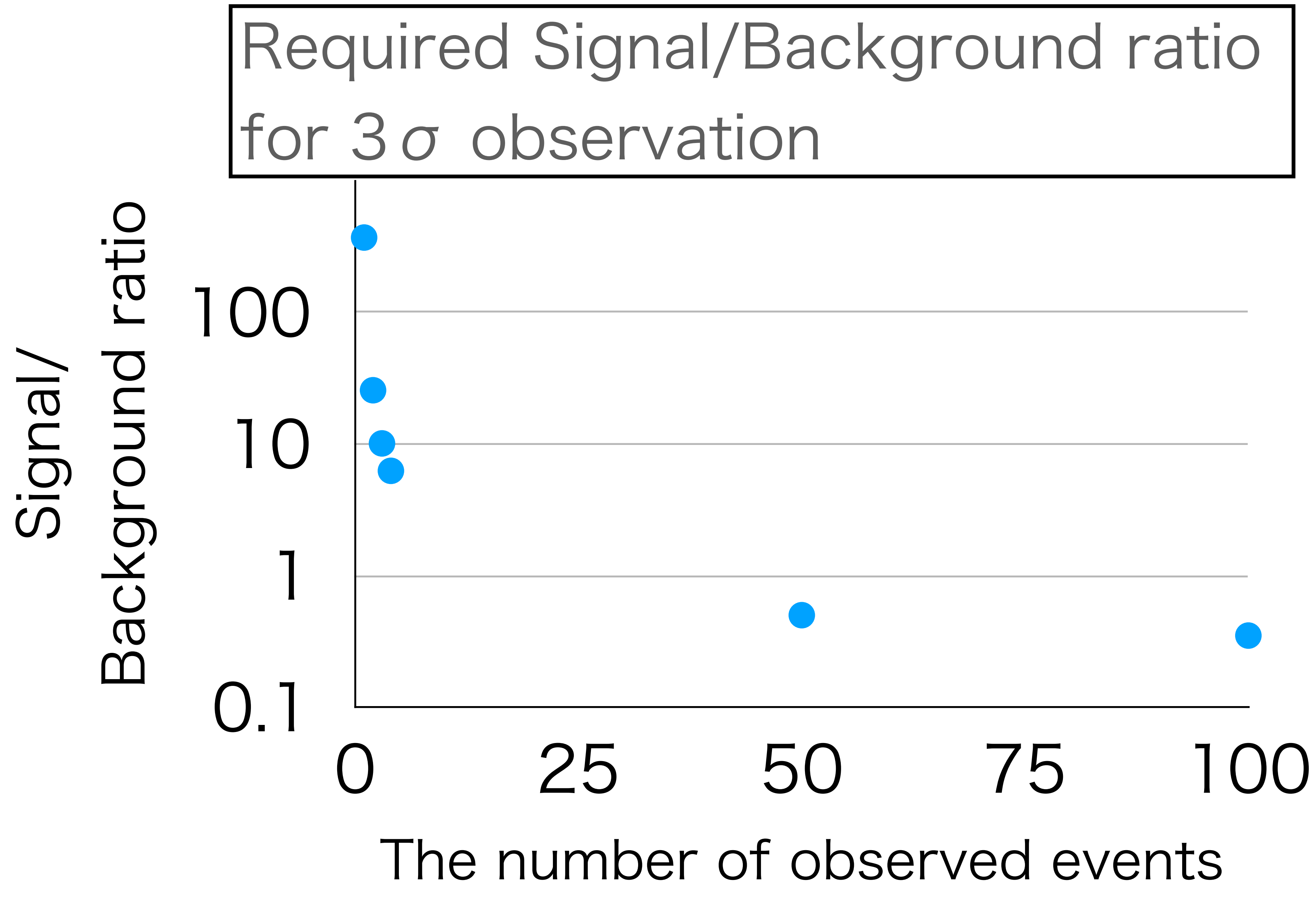
Prospects of KOTO

2015

2016-2018

By 2025
O(10^{-11})



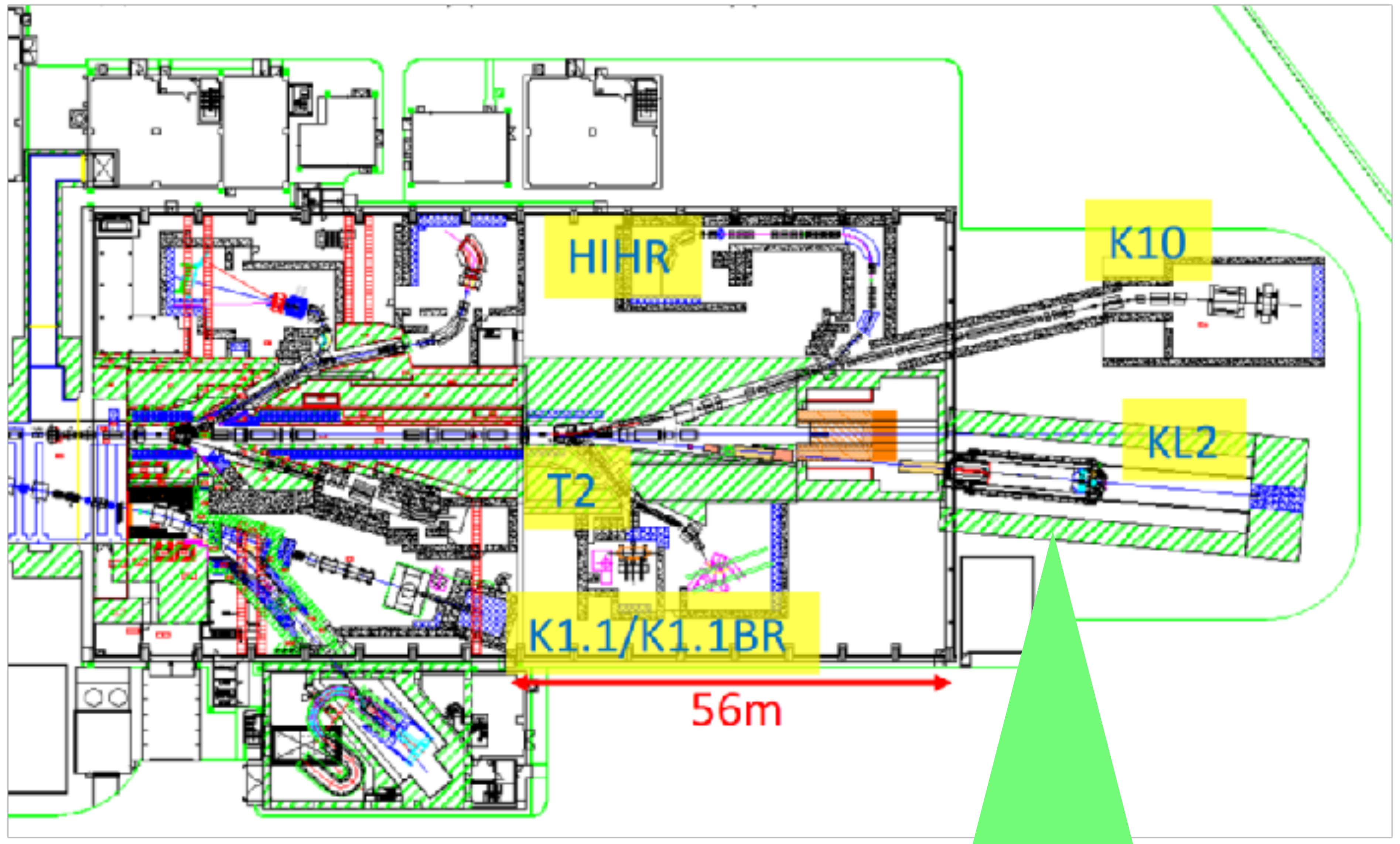


-Reachable sensitivity start to be saturated after reaching O(10^{-11})
-Signal background ratio required for 3σ observation is high if N_{obs} is a few events

Need a new experiment to get huge improvement

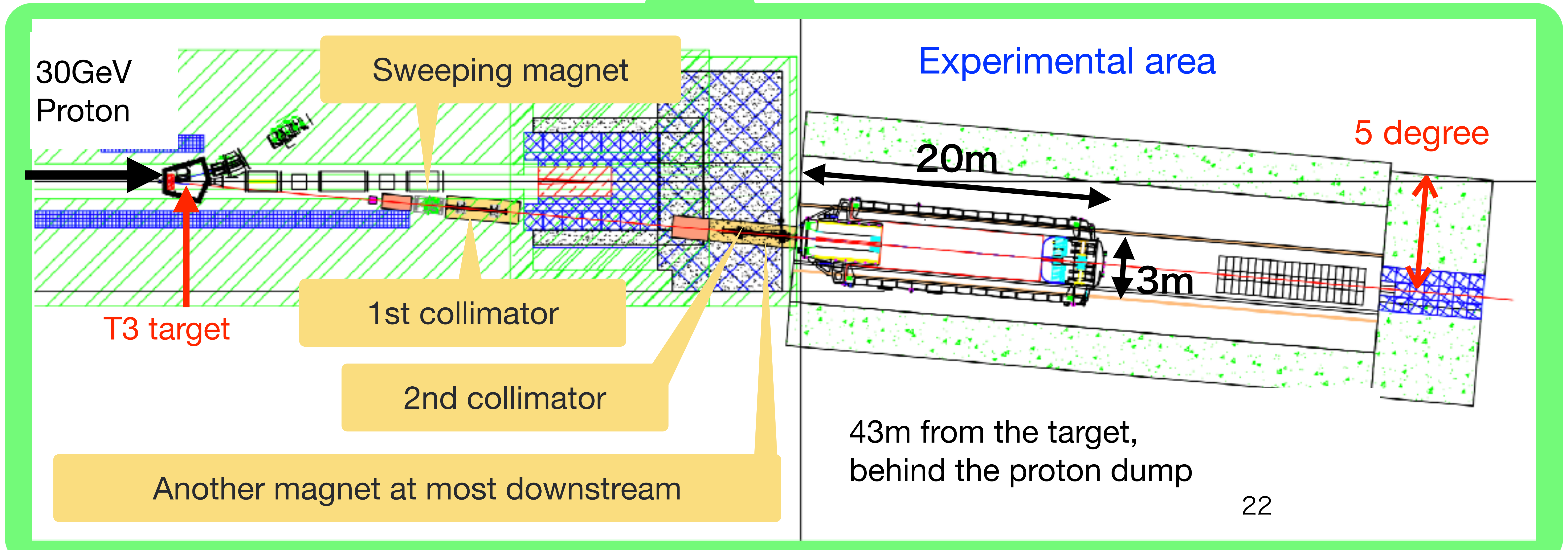
KOTO step2
in Extended Hadron Hall

KOTO Step2 in extended hadron hall



Measure branching ratio of the $K_L \rightarrow \pi^0 \nu\bar{\nu}$ decay with
- -Higher intensity K_L beam
- -Larger detector

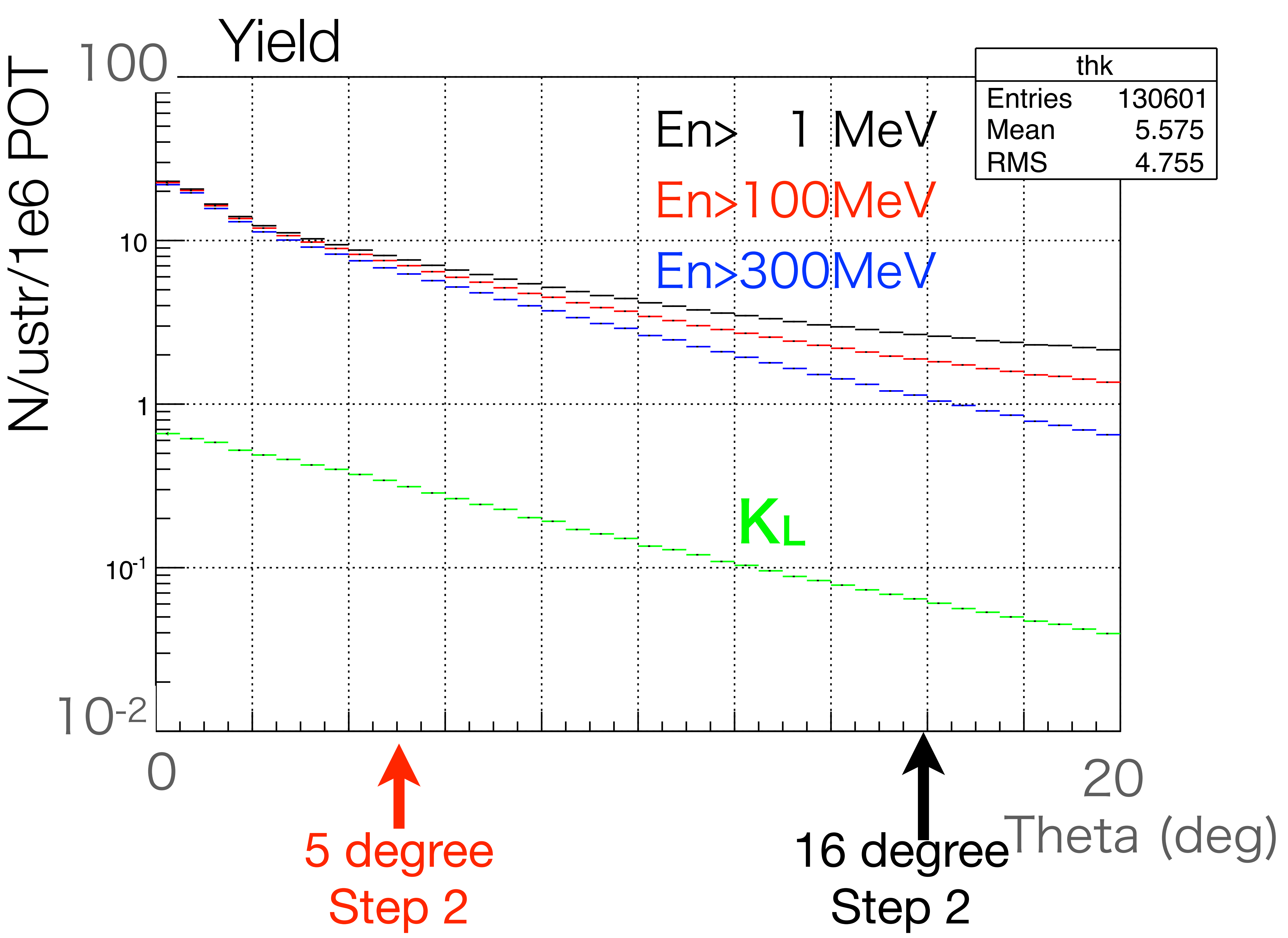
- ~50 SM events for 3×10^7 s run time with 100kW beam
- Signal-to-background ratio ~ 0.4

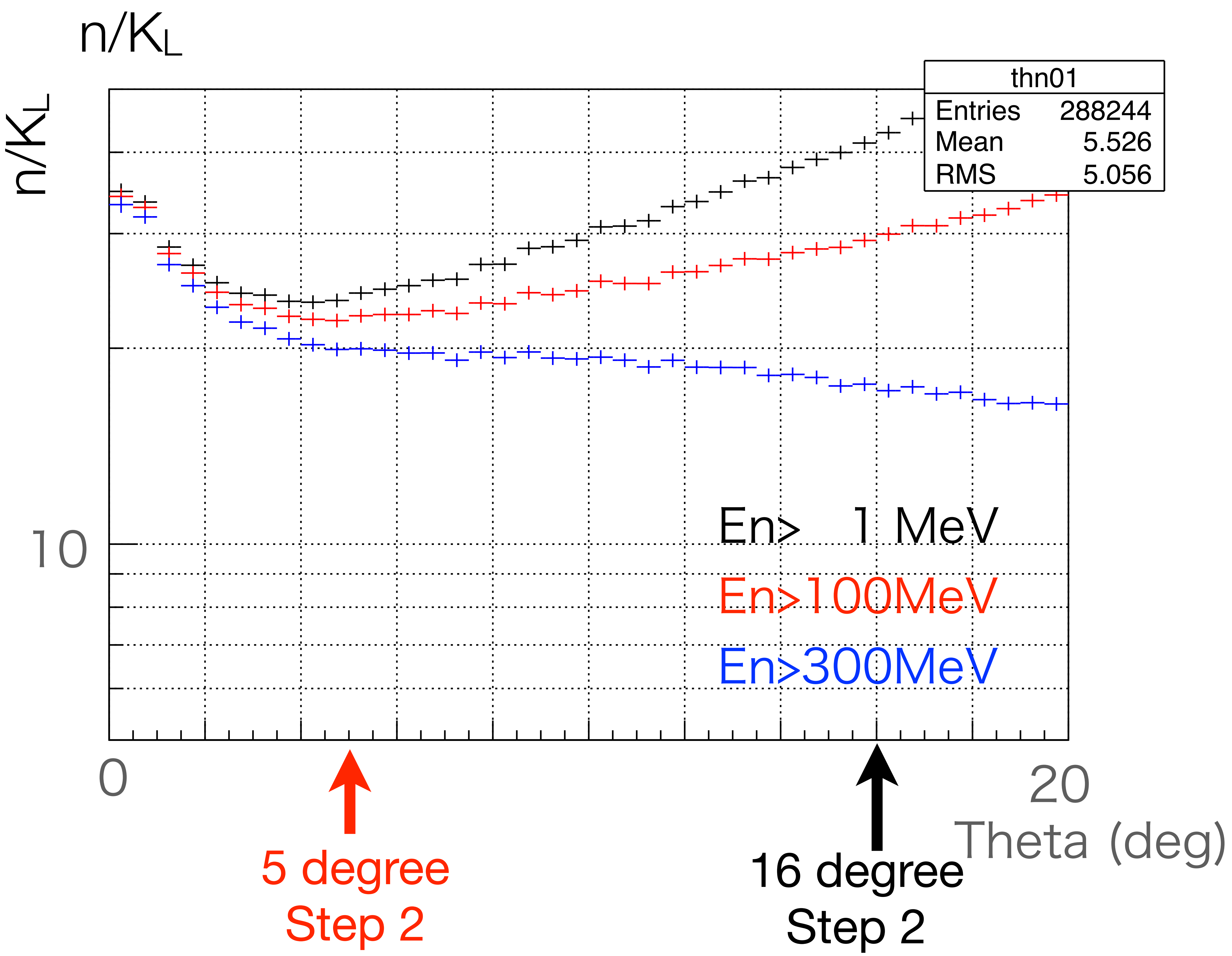


- $\mathrm{Br}(K_L \rightarrow \pi^0 \nu\bar{\nu}) \fallingdotseq \mathrm{SM}$
  $\rightarrow$ ~5σ discovery
- $|\mathrm{Br}(K_L \rightarrow \pi^0 \nu\bar{\nu}) - \mathrm{SM}|/\mathrm{SM} > 40\%$
  $\rightarrow$ Indication of new physics

A new KL beam line

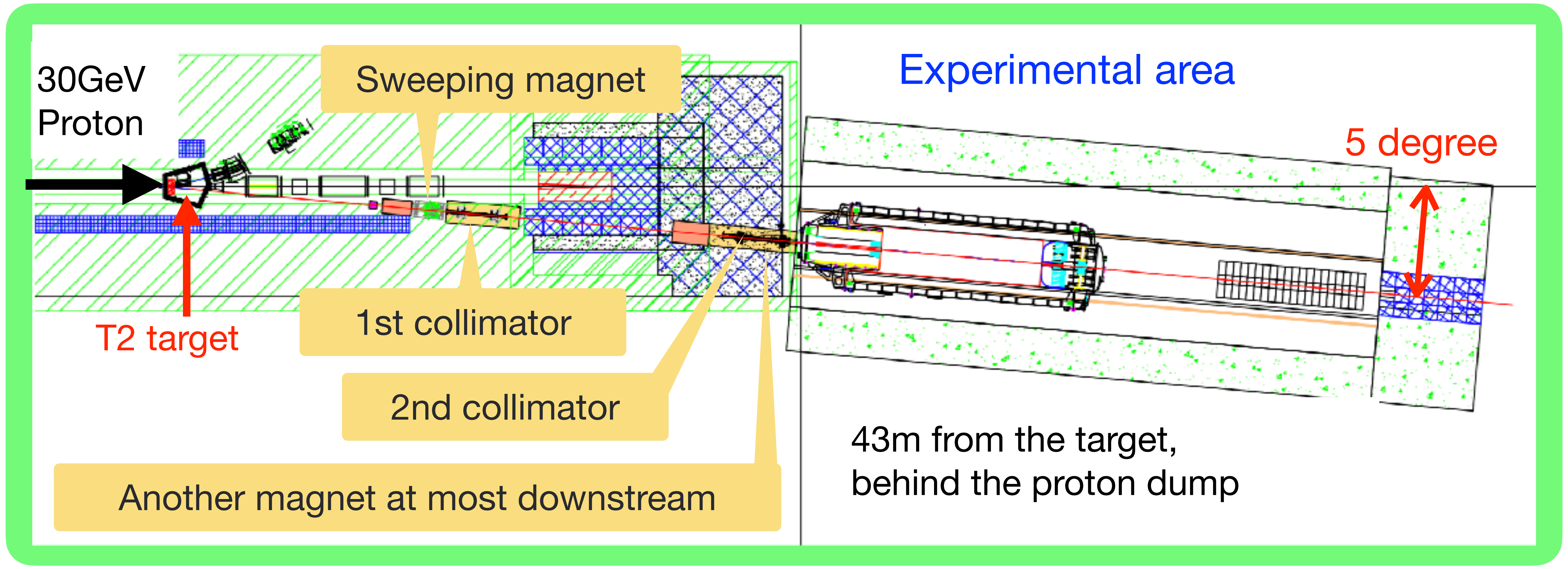
KL yield dependence on extraction angle

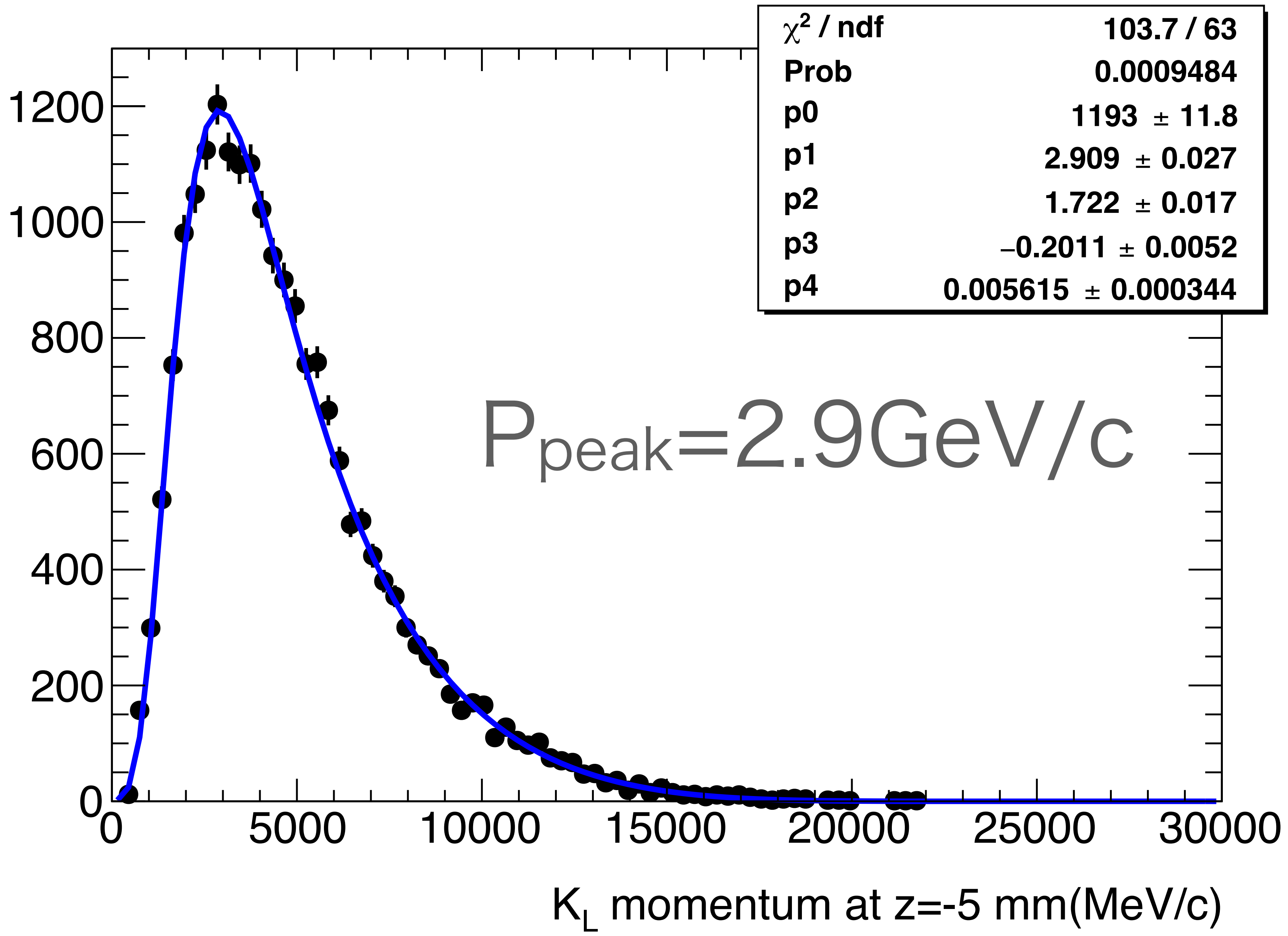




A new KL beam line

Basic design





- 5 degree production
- The beam line length is 43m.
  - Shorter than the original design by shortening the distance between the T2 target and the beam bump.
  - Need to discuss the detail with other groups
- KOTO-2 area is located behind the beam dump.

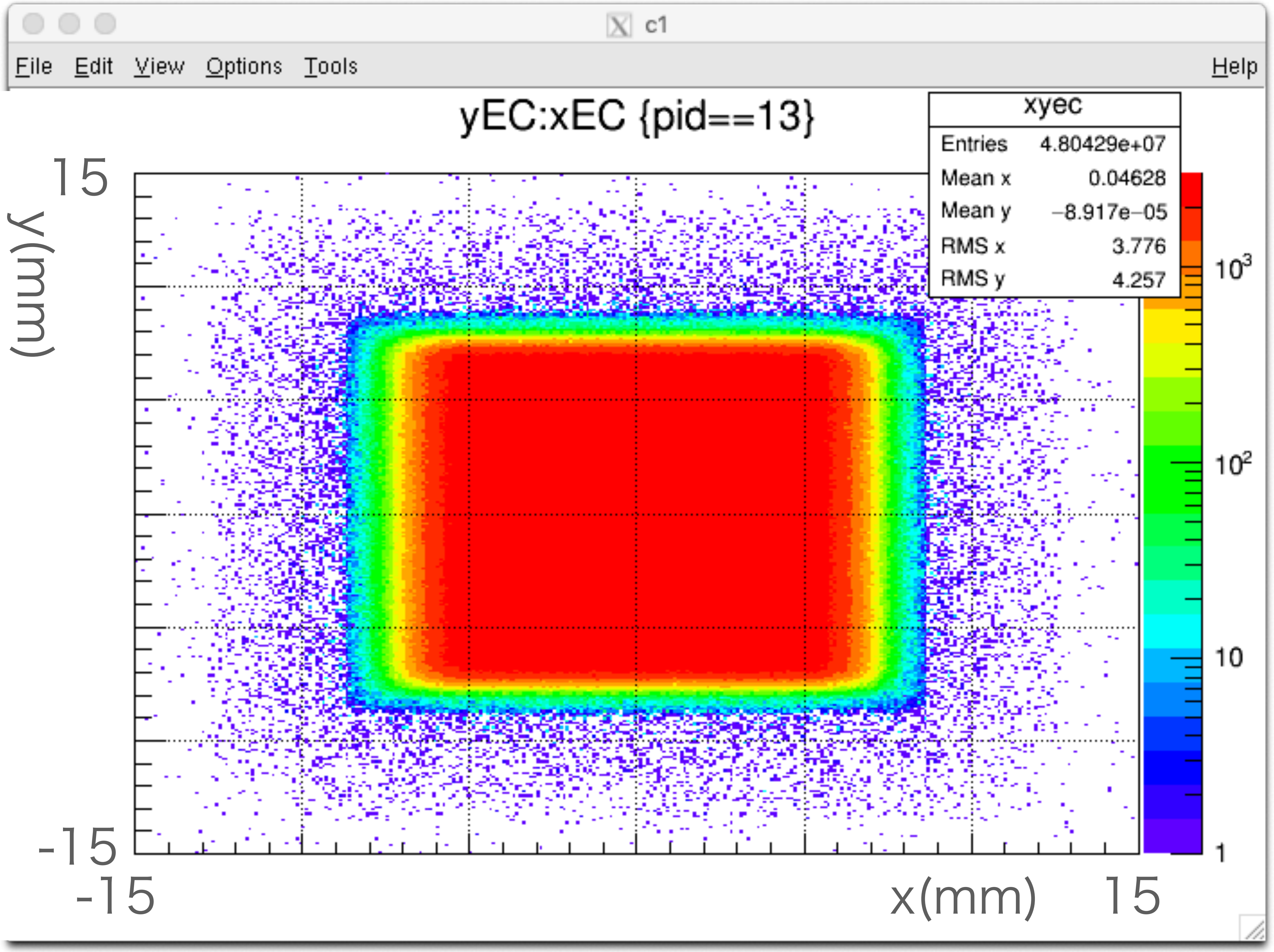
	KOTO	Step2	Gain for K_L yield
Production Angle	16 degree	5 degree	x5
Beam line Length	20m	43m	x0.8
Solid angle	7.8 μsr	4.8 μsr	x0.6

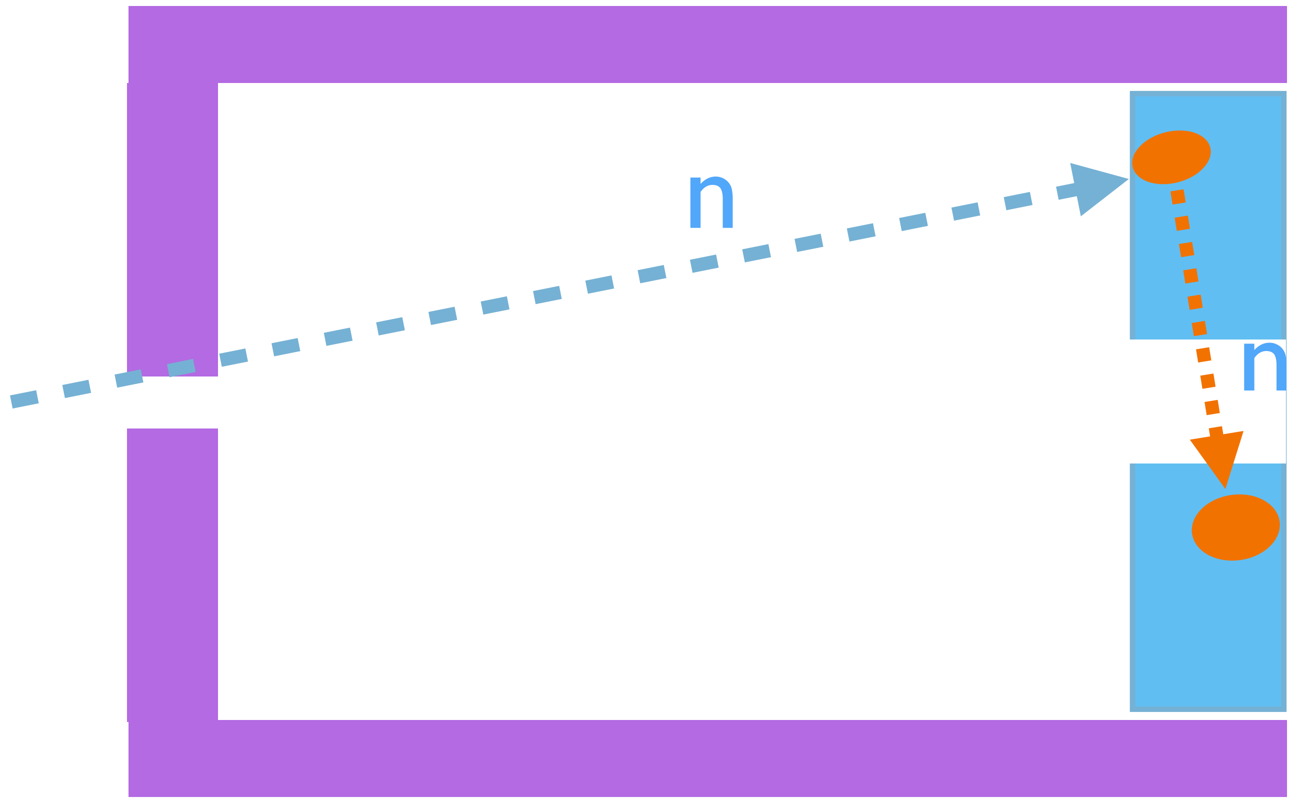
$N(K_L)= 1.1\times10^7/2\times10^{13}$ POT
→x 2.6 higher than KOTO (per POT)

A new KL beam line

Neutron profile

At Z=64m, Energy>0.3GeV





Halo=“outside ±10cm”

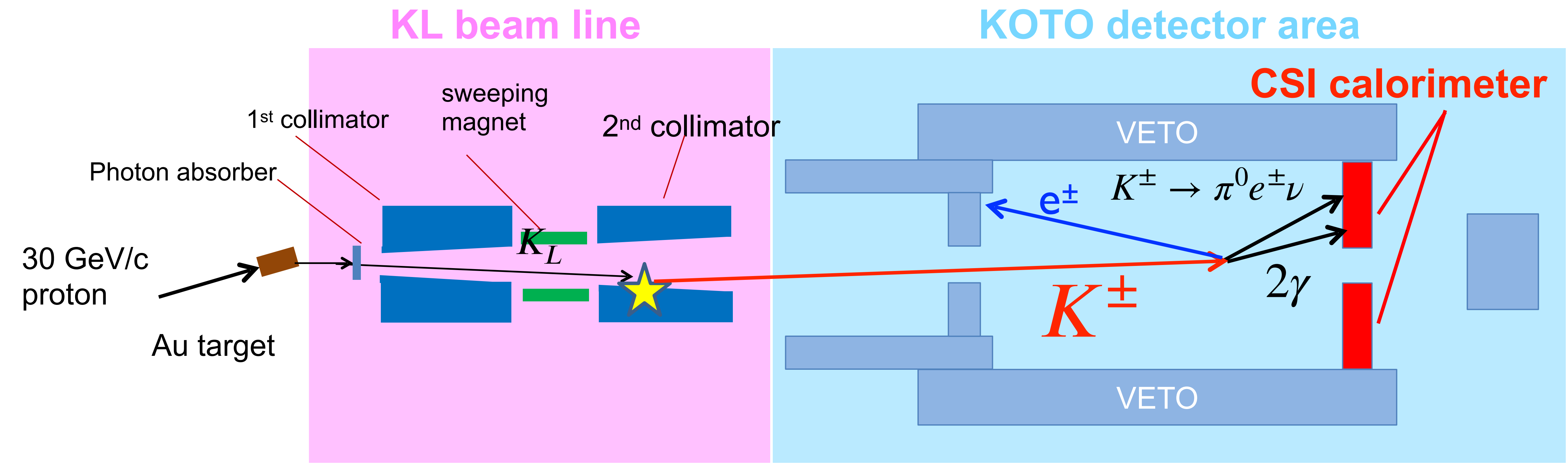
Core=“inside ±10cm”

Ratio (Halo/Core)=1.84(±0.02)x10^{-4}

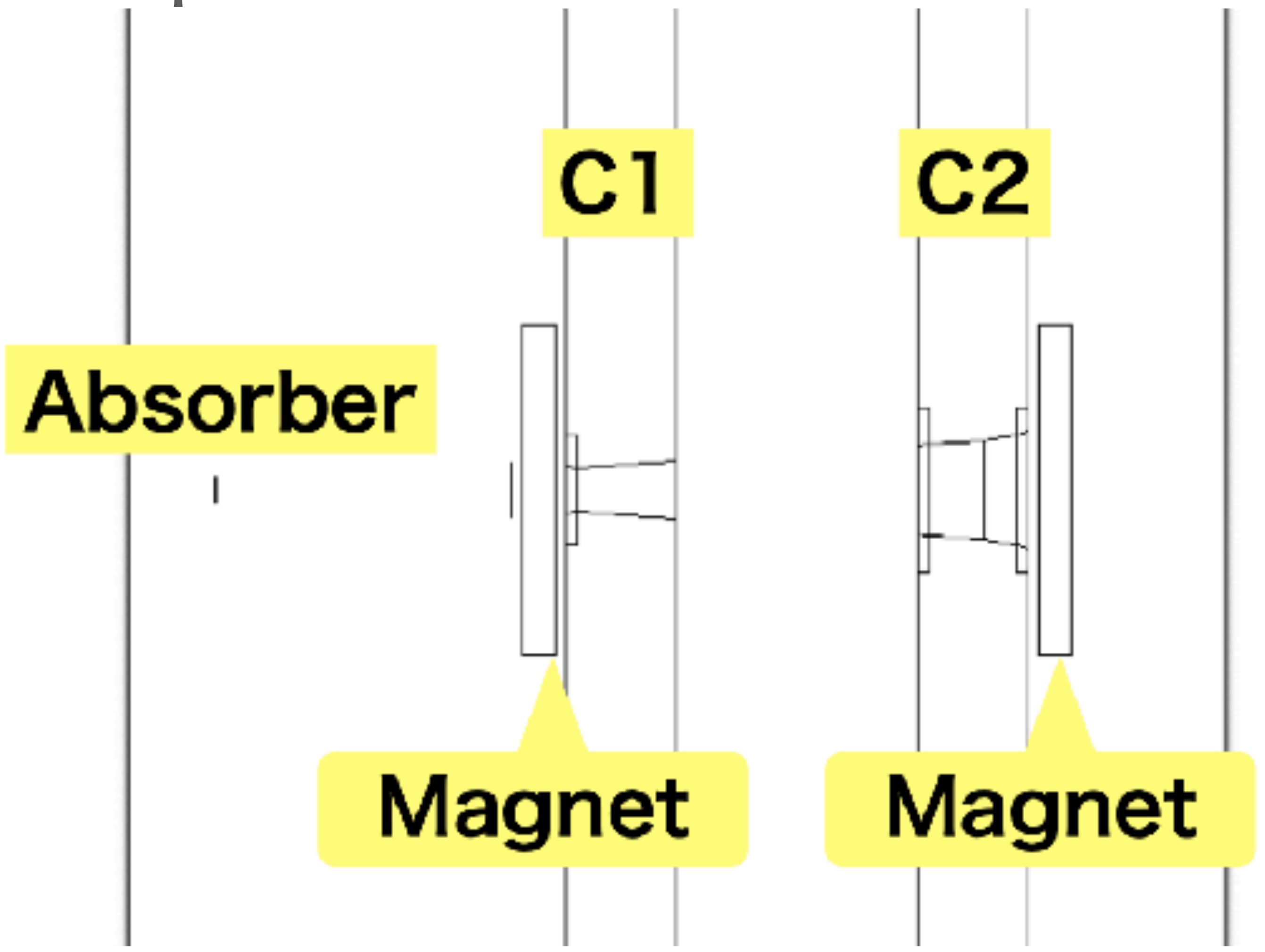
Can improve the Halo/Core ratio by optimizing the collimator shapes

A new KL beam line

Trial to reduce K± contamination



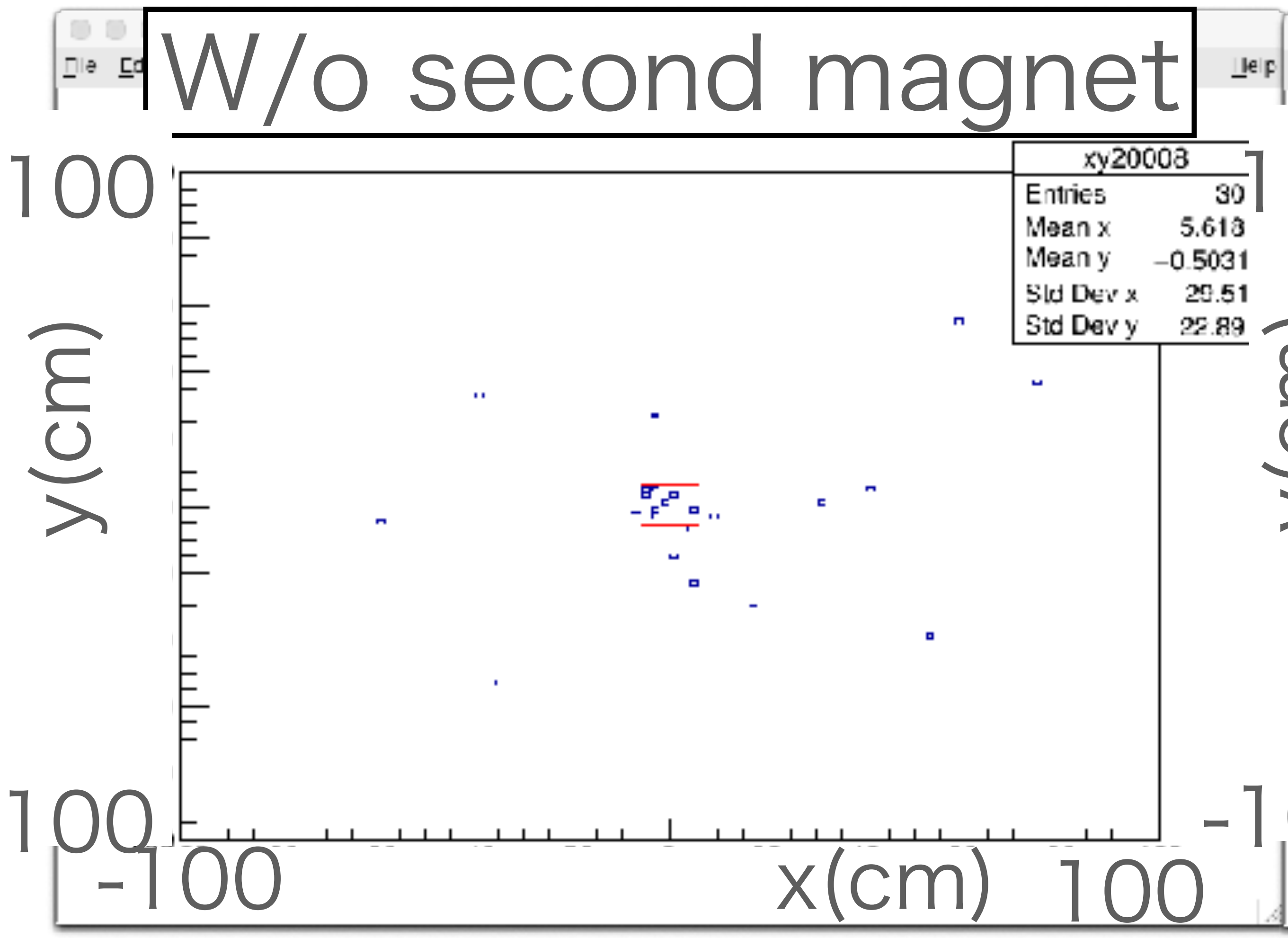
Setup for Monte carlo simulation

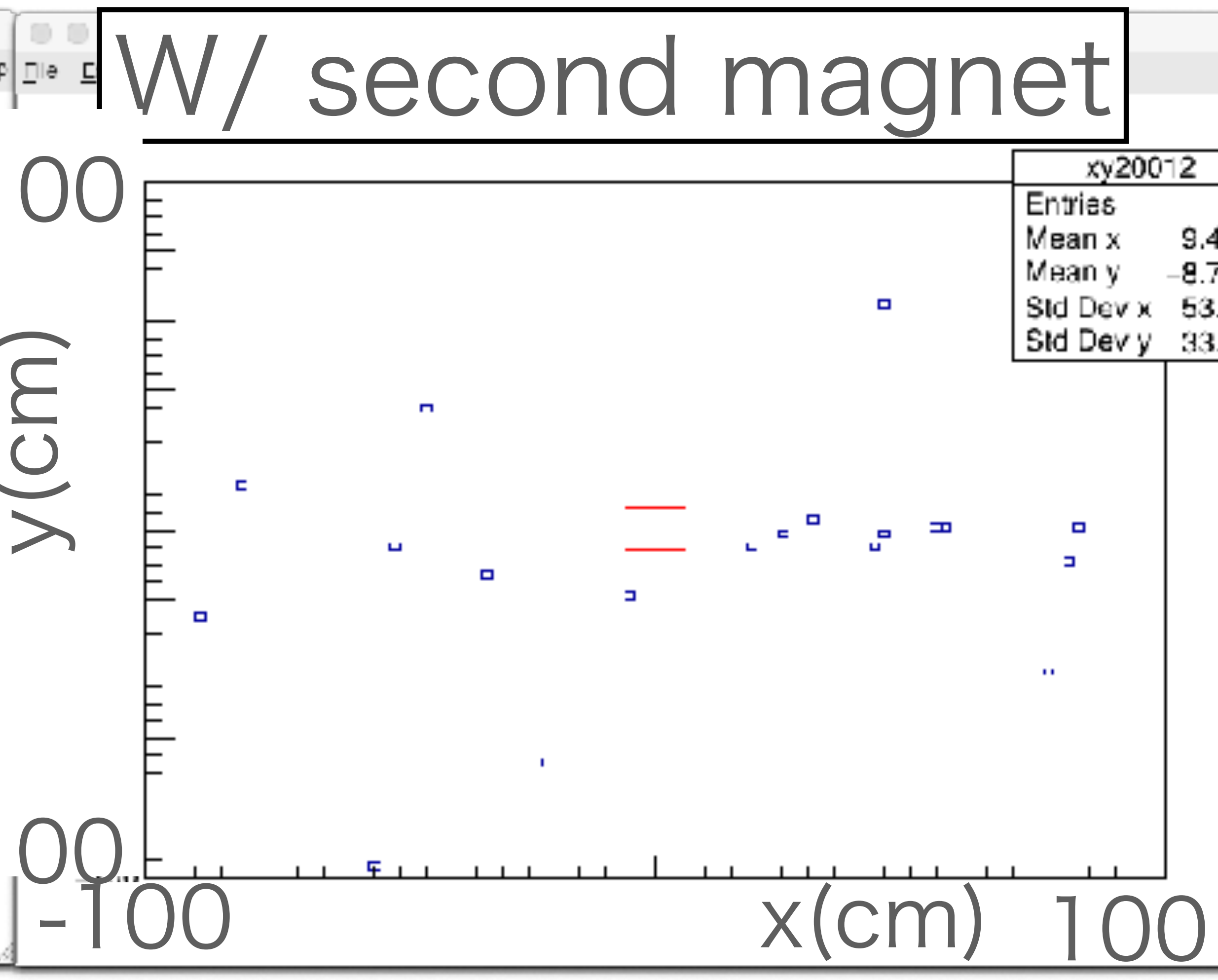


C1: 5m
C2: 5m

Magnet:
2T, L=1.5m
(Space=2m)

K± profile@ beam exit





Default setup

-R(K±/KL)=4.1×10^{-6}

With second magnet

-R(K±/KL)<1.1×10^{-6}

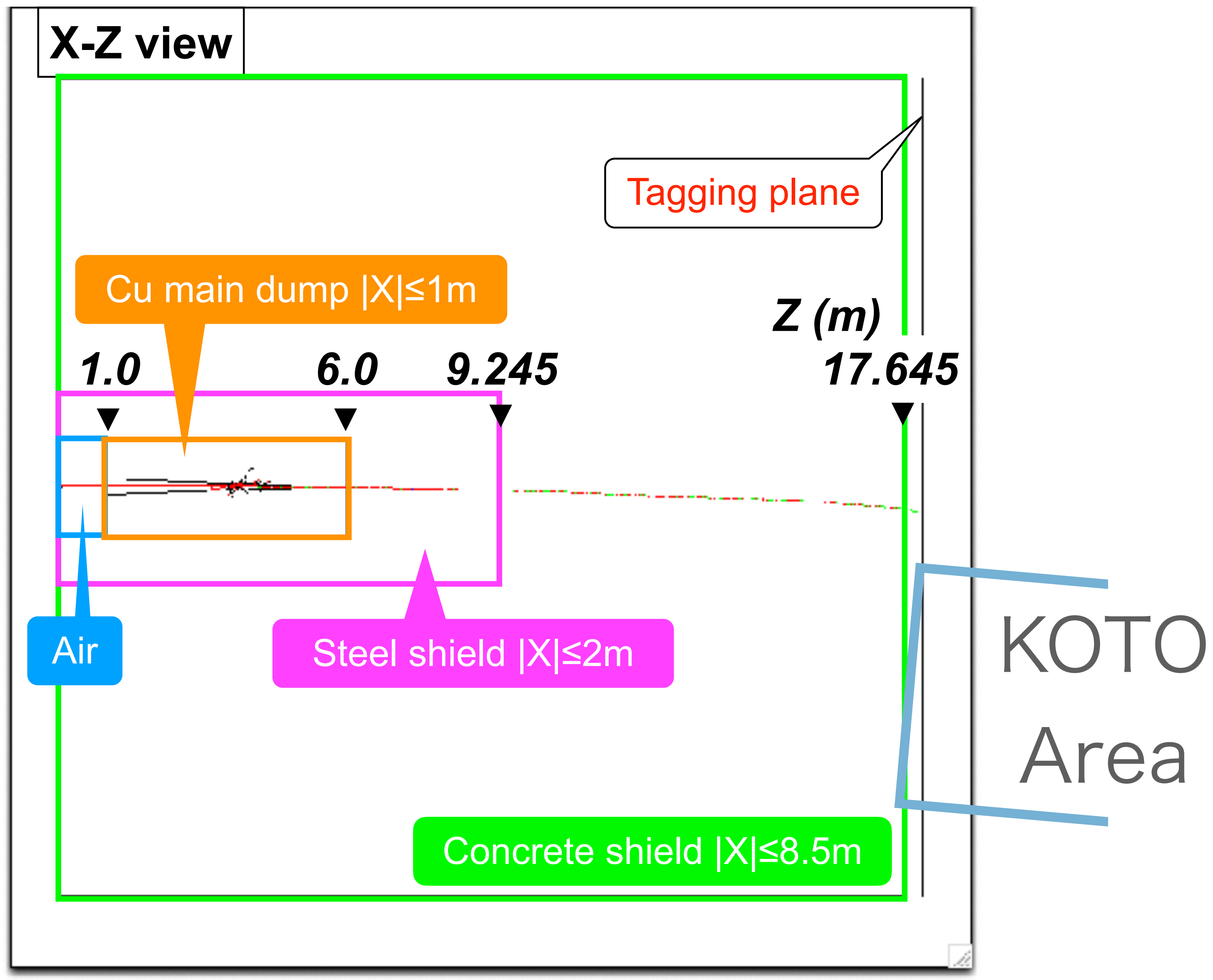
Optimization with higher MC samples are on going

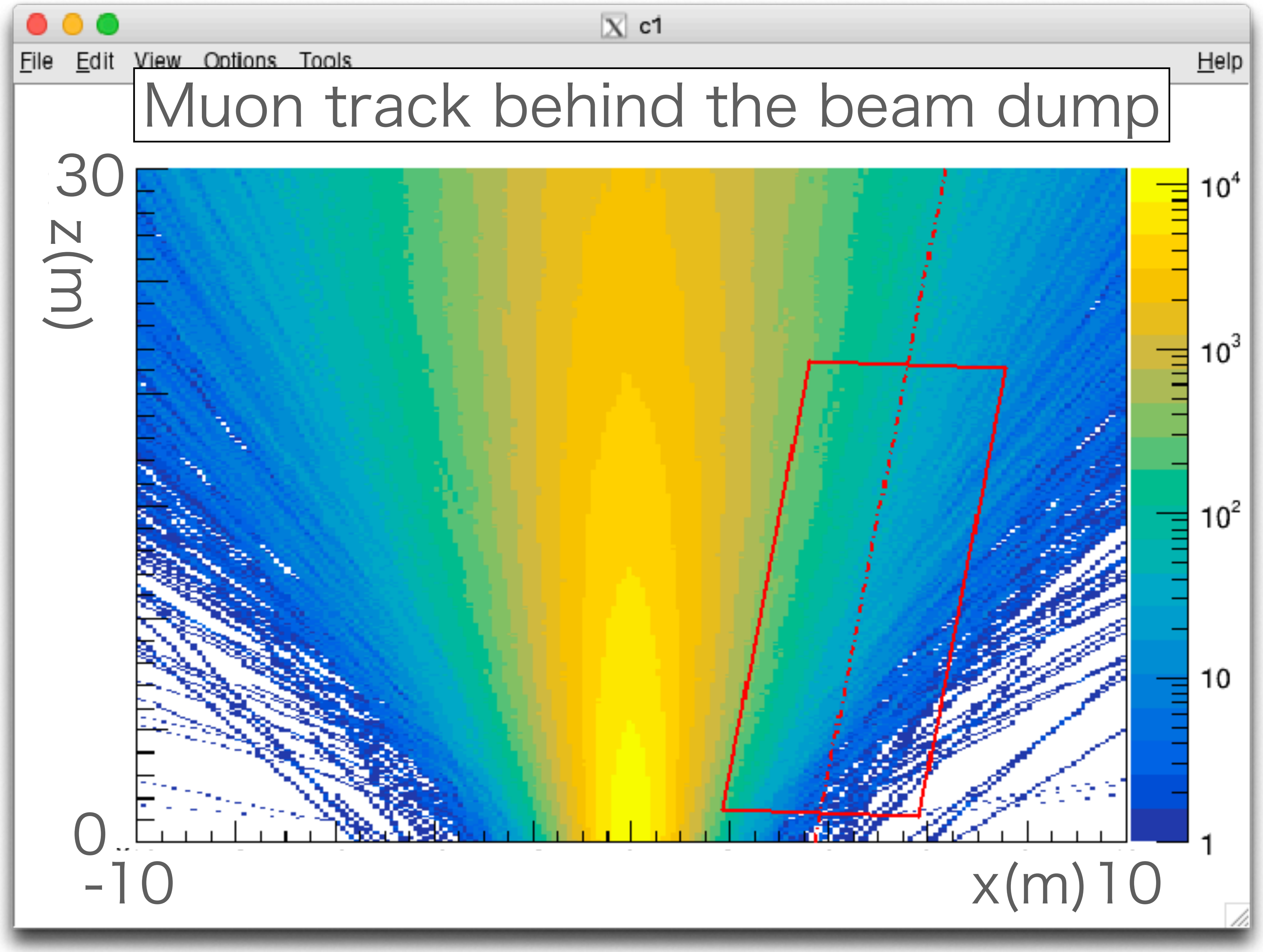
A new KL beam line

The effect of the beam dump

- K_L experimental area is just behind the beam dump

Simulation Setup for the effect of dump





Fill x and z position (extrapolated) when |y|<2m at the point

5 degree line from T2 target

Detector region D=4m, L=20m

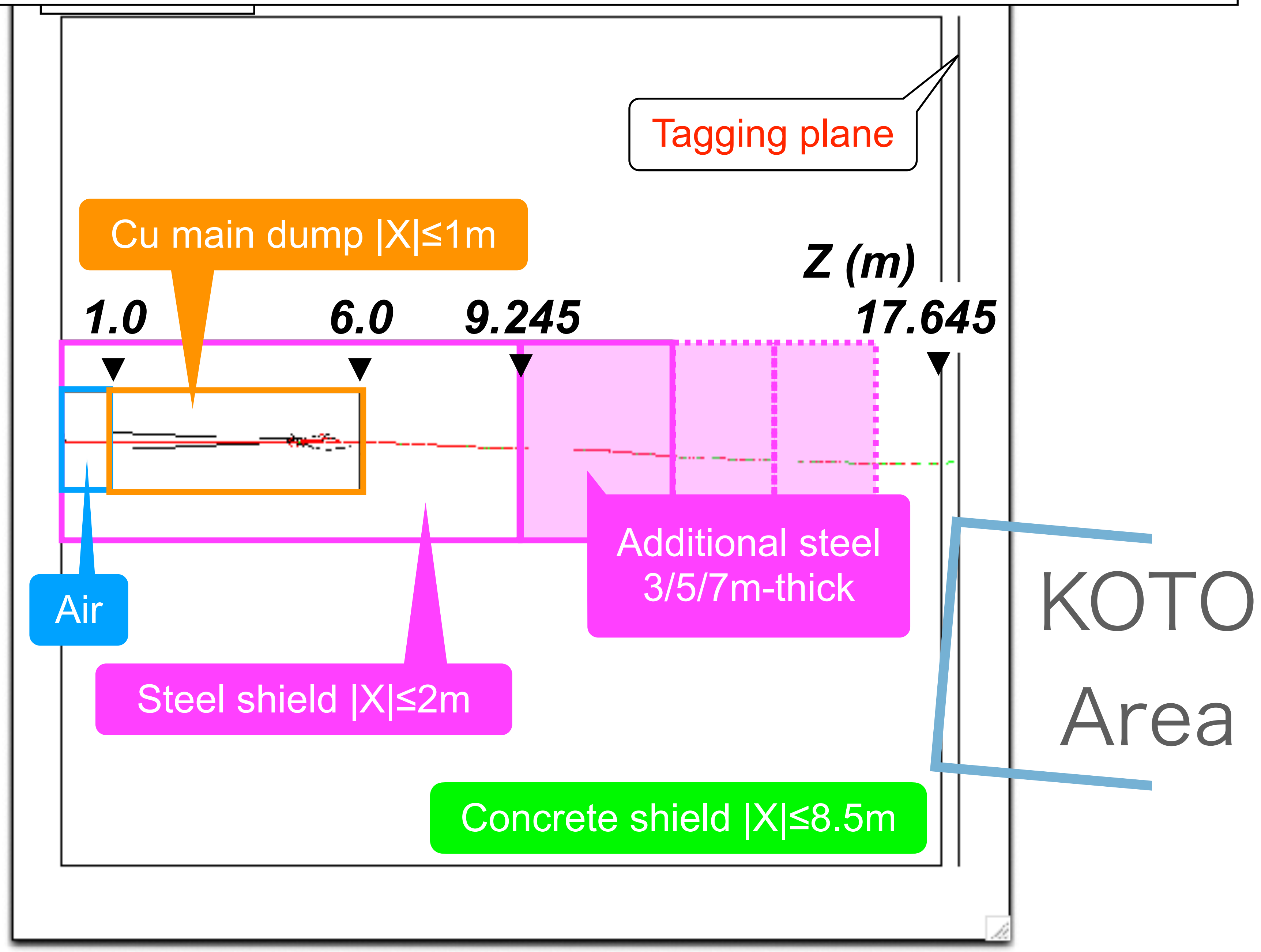
- **Muon rate over the detector will be 15 MHz !** (**)
- **Neutron rate is tolerable (∼25kHz)**

A new KL beam line

The effect of the beam dump

- KL experimental area is just behind the beam dump

Simulation Setup for the effect of dump with additional steel

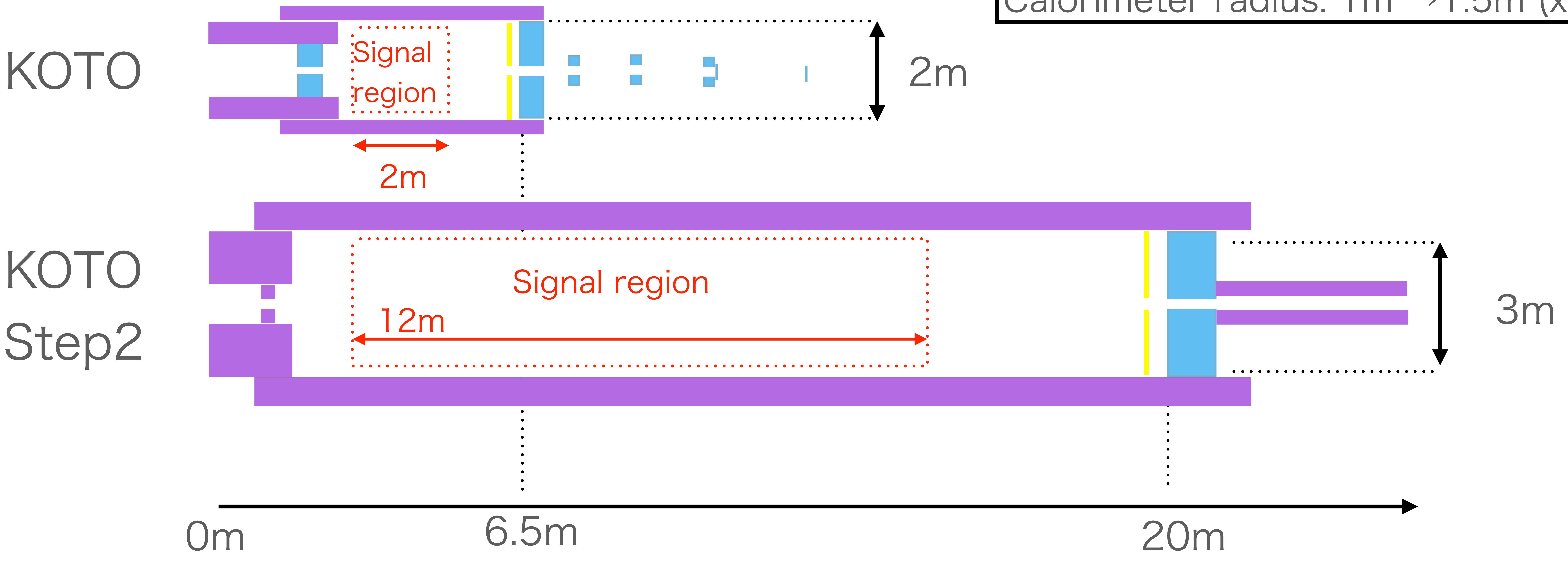


	Current dump	Additional 3m-thick steel	Additional 5m-thick steel	Additional 7m-thick steel
Counting rate @ 100kW	15 MHz	5.5 MHz	2.6 MHz	1.3 MHz

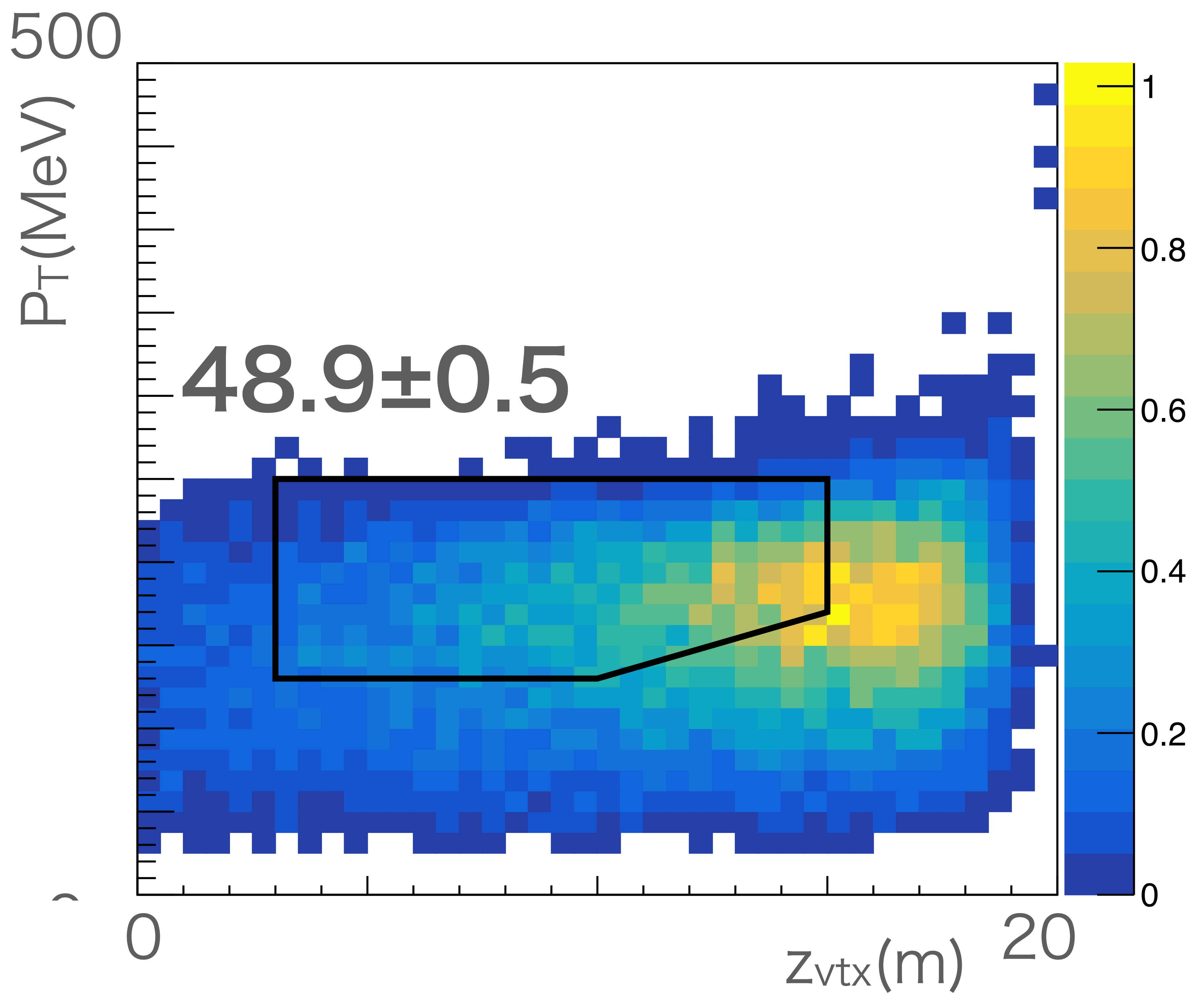
- **Muon rate can be reduce to 1.3 MHz with additional 7m-thick steel.**
- **Cooperate with the primary beam channel group to look for a good configuration**

Detector for KOTO step2

Signal region : 2m →12m (x6)
Calorimeter radius: 1m →1.5m (x.15)



Signal acceptance

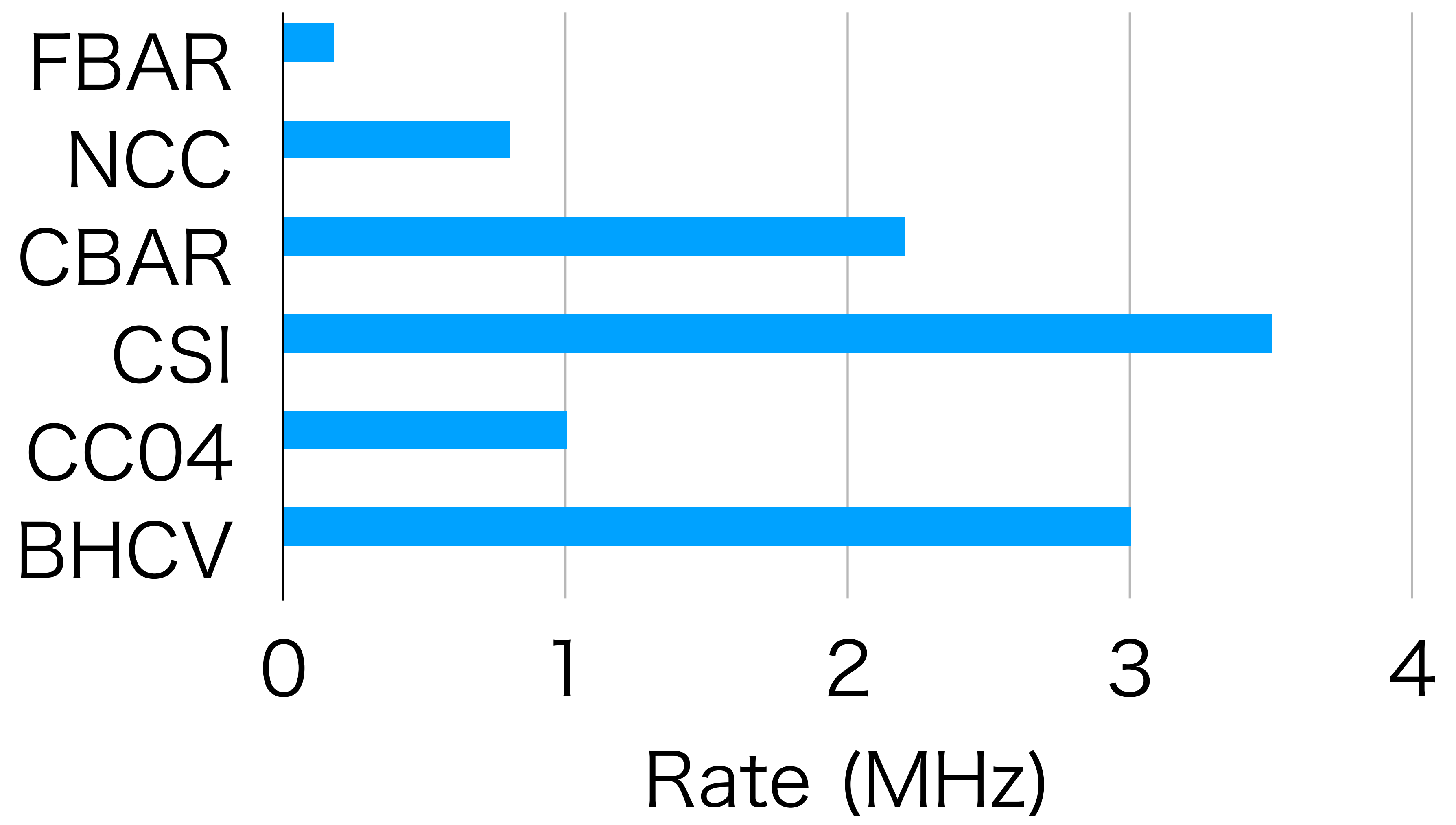


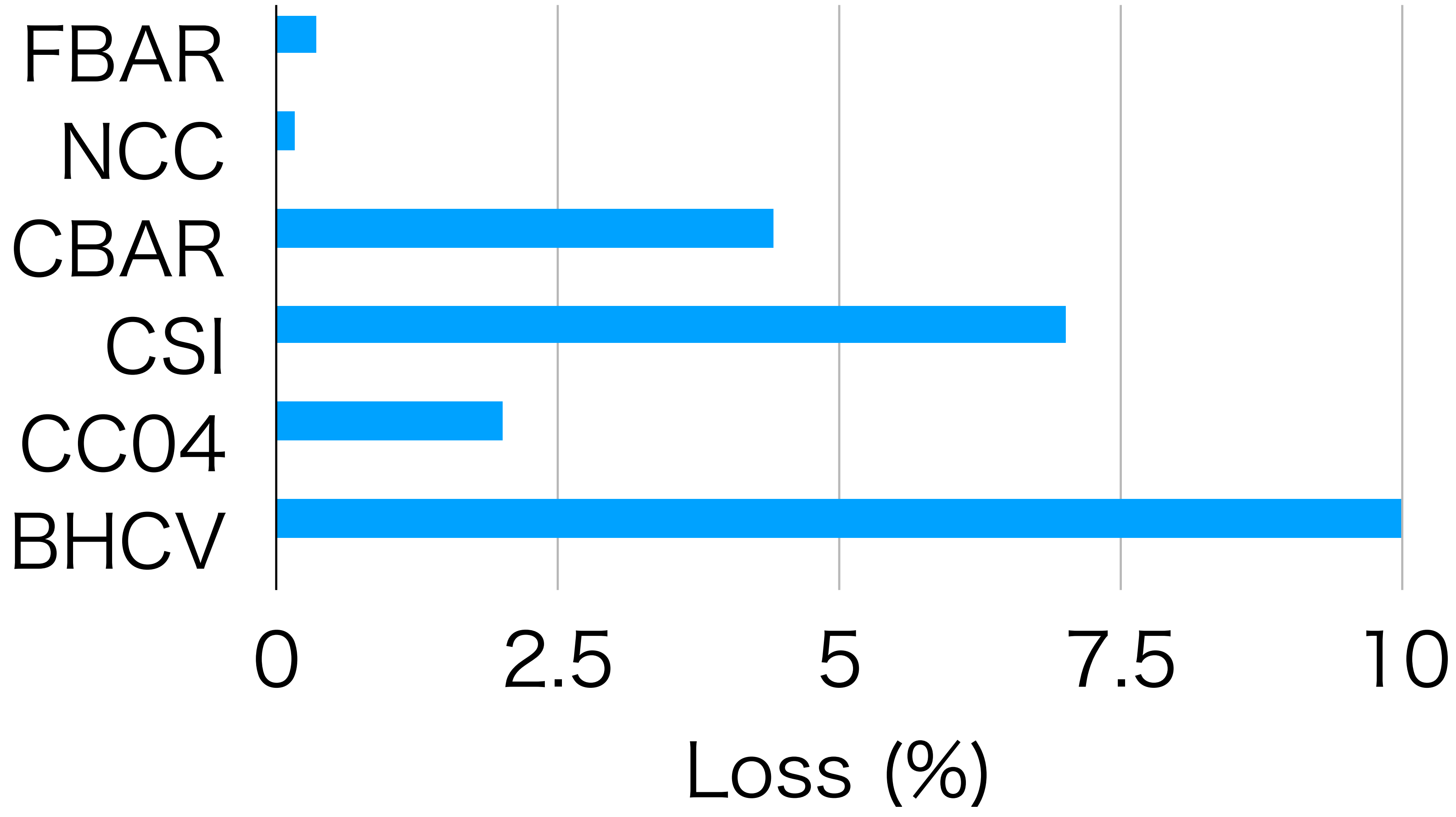
- Beam power: 100kW
- KL yield: $1.1\times10^{7}/2.1\times10^{13}$ POT → ×2.5 from KOTO
- Data taking : 3 Snowmass years ($3\mathrm{x}10^{7}$s)

	Decay Probability	Geometrical Acceptance	Cut efficiency	1- Accidental loss
KOTO Step2 Efficiency	10%	24%	26%	77%
KOTO Efficiency	3.3%	26%	3%	36%
Improvement factor	3	0.9	8.7	2.1

(Sum of improvement factor on efficiency) × (Increase of KL yield)=120

Accidental loss

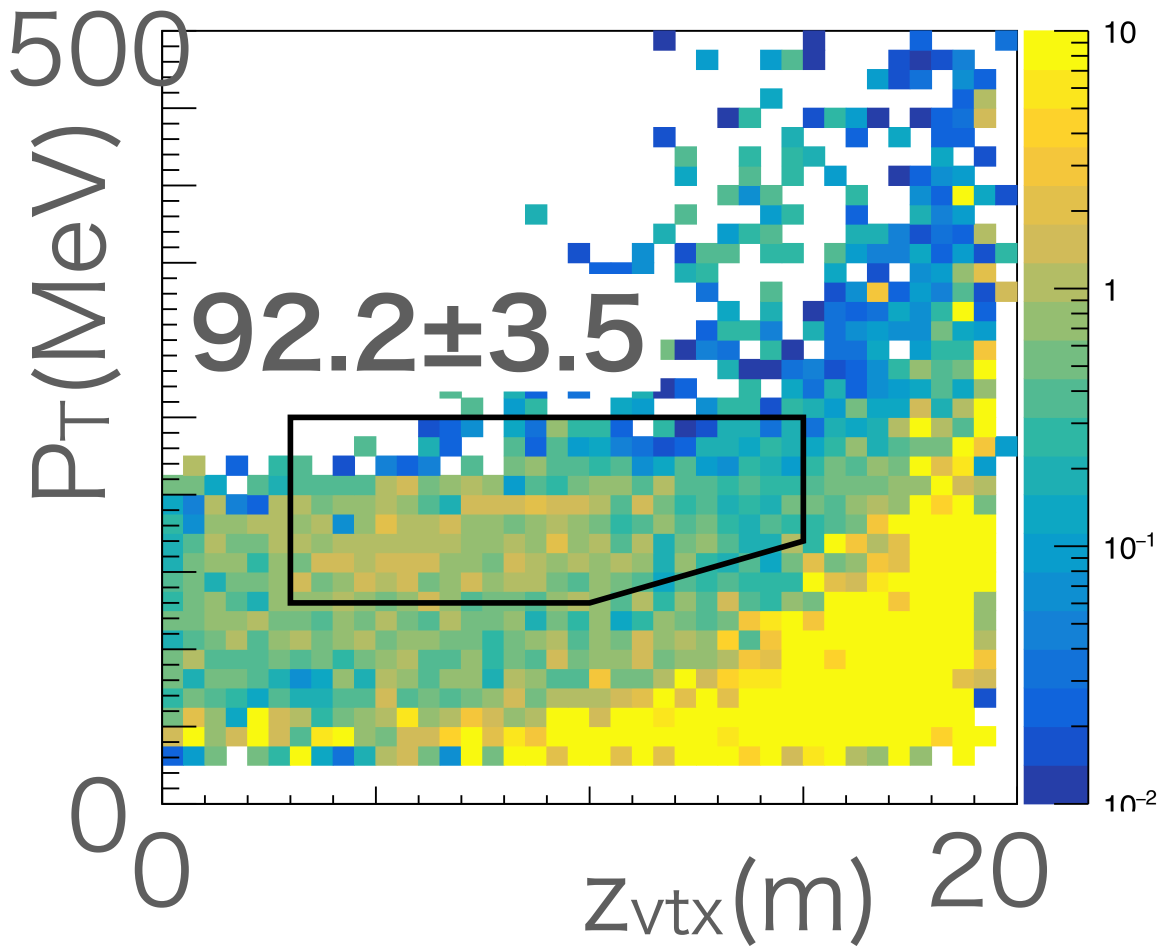


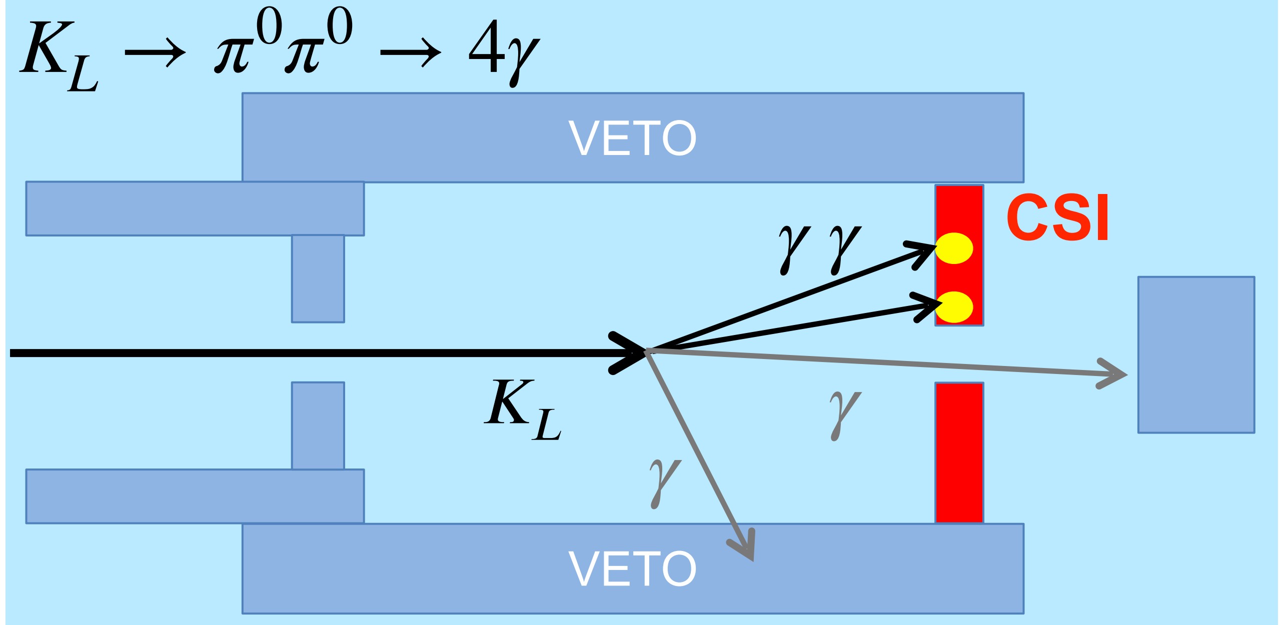


Accidental loss is 23% in total

BG estimation

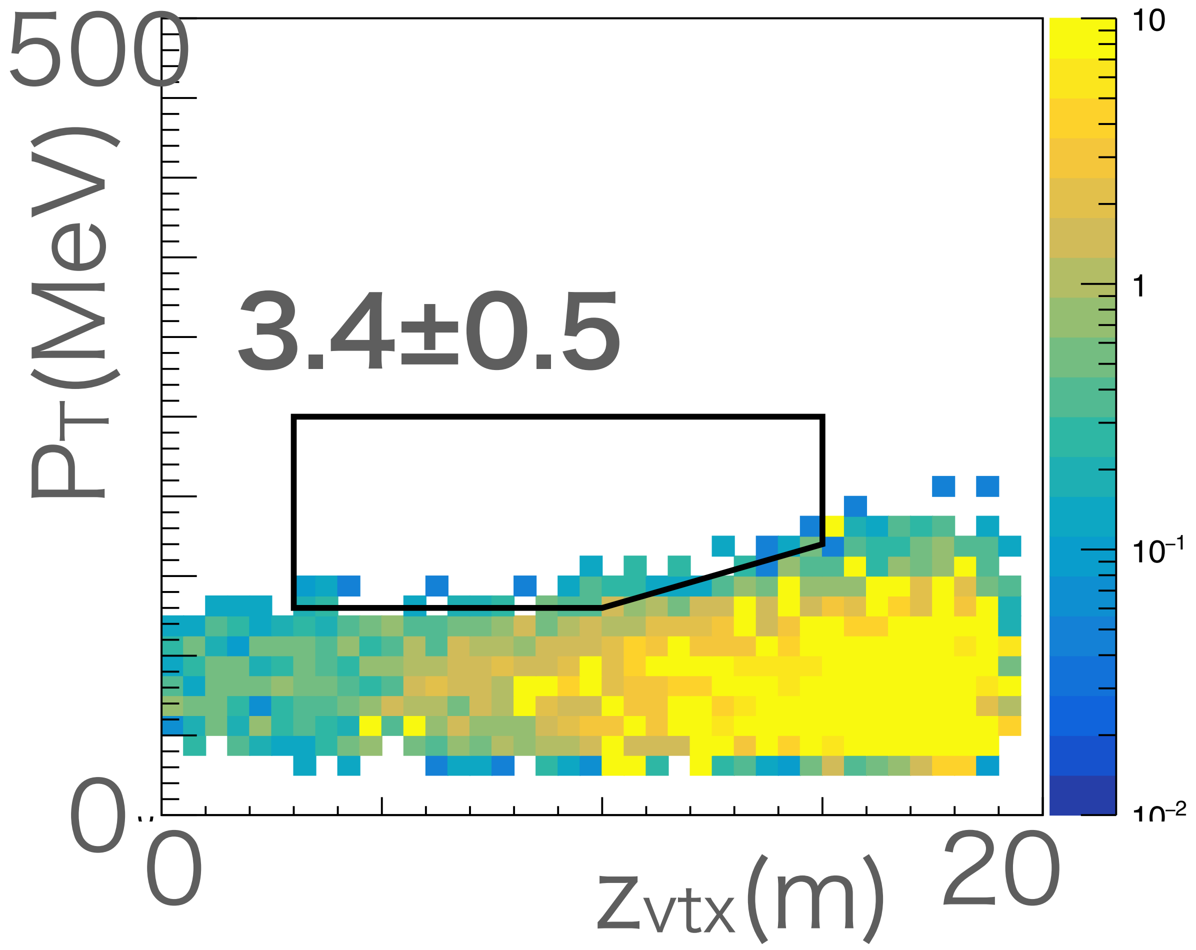
$K_L \rightarrow \pi^0\pi^0$

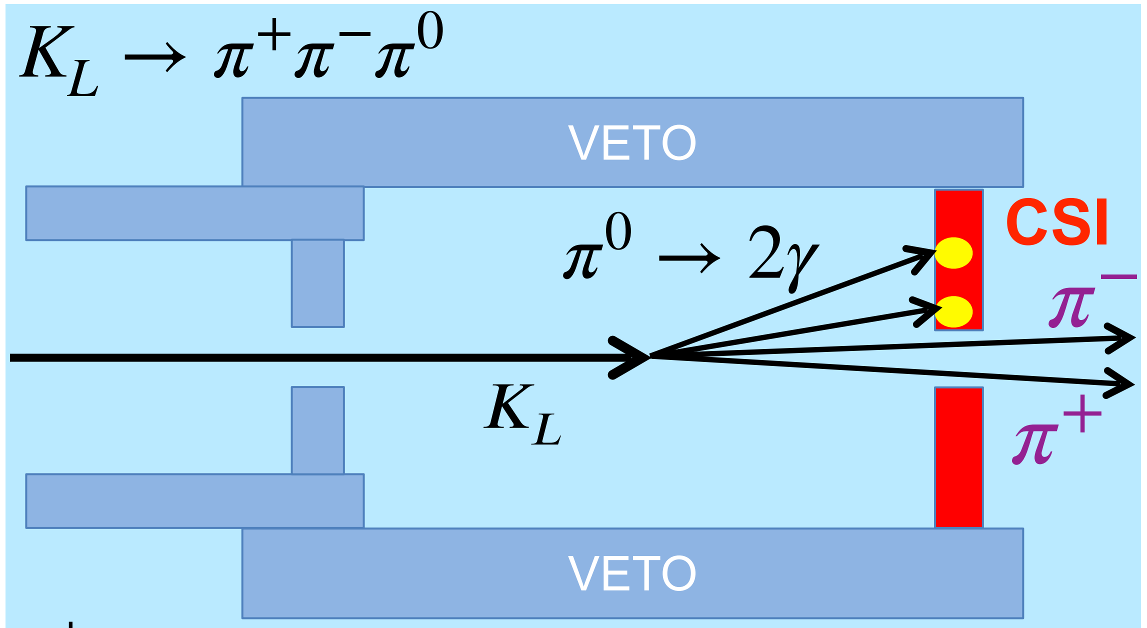




2 of 4γ hit CSI and
2 are lost due to detection inefficiency

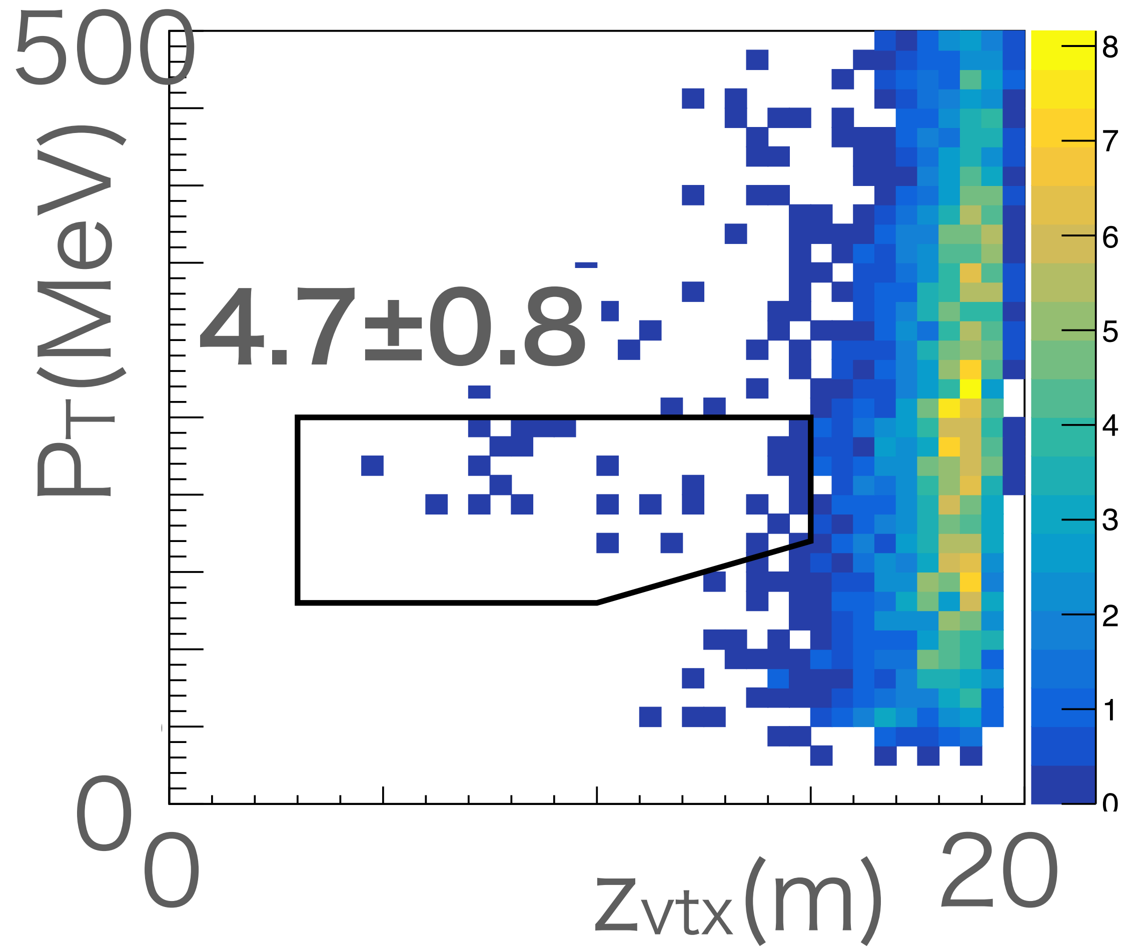
$K_L \rightarrow \pi^+\pi^-\pi^0$

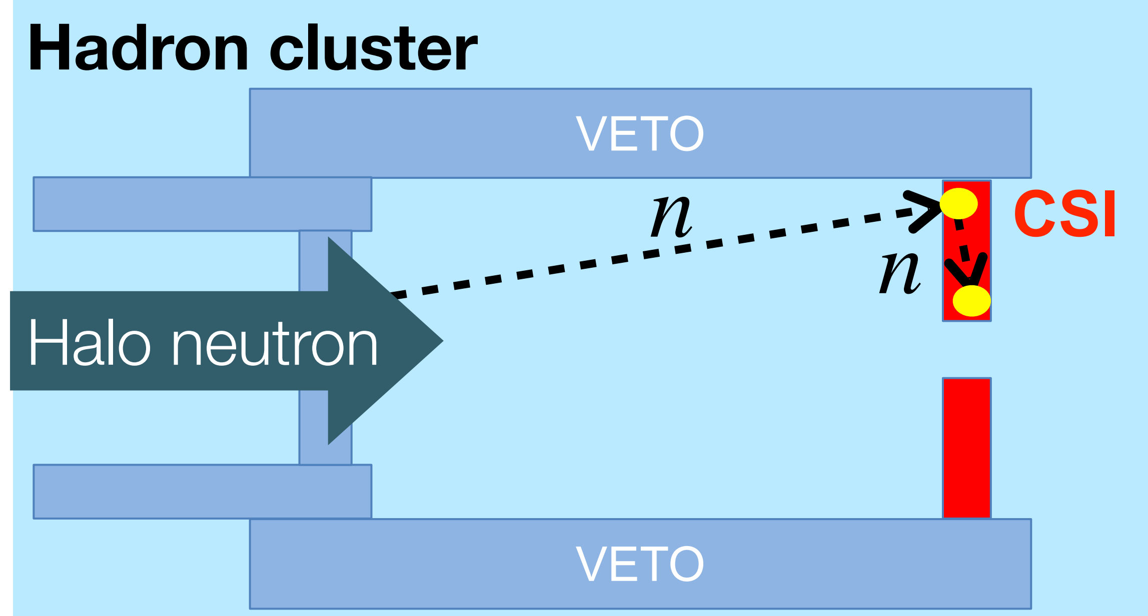




$\pi^\pm$ disappear in downstream beam pipe

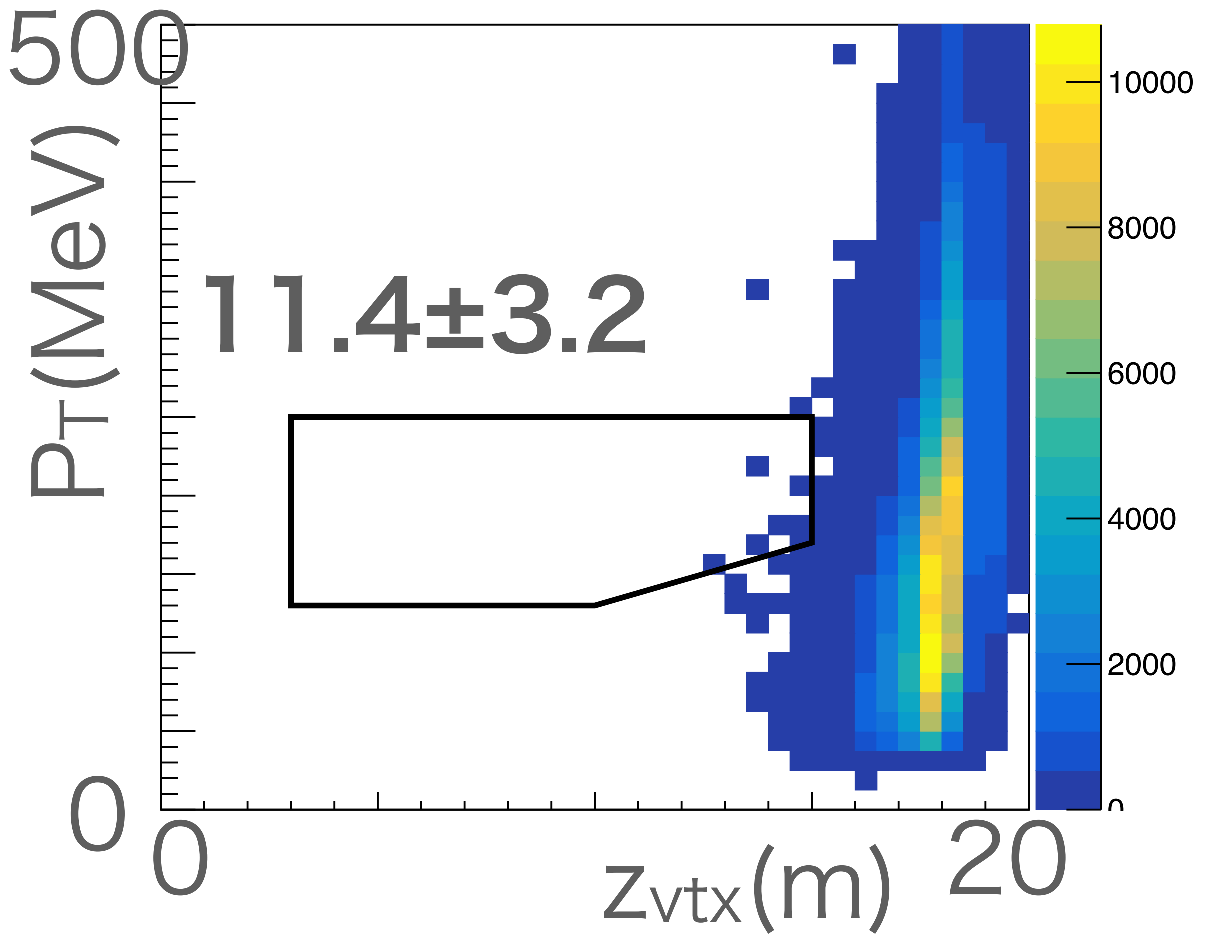
Hadron cluster

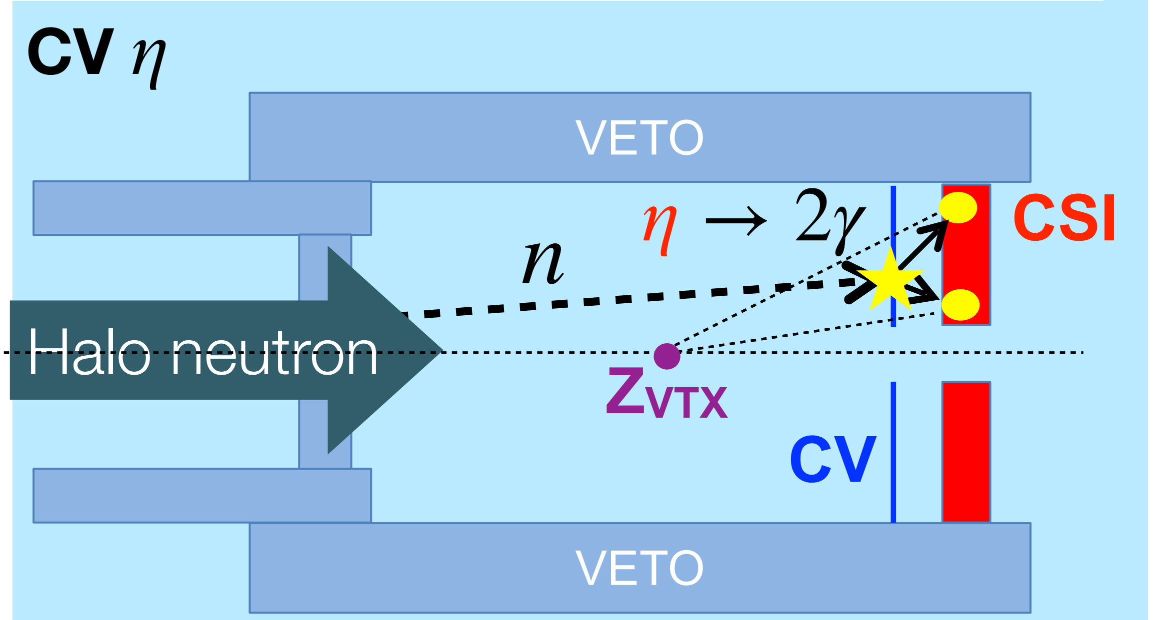




A halo neutron directly hit the calorimeter
and makes 2 clusters

η production in CV





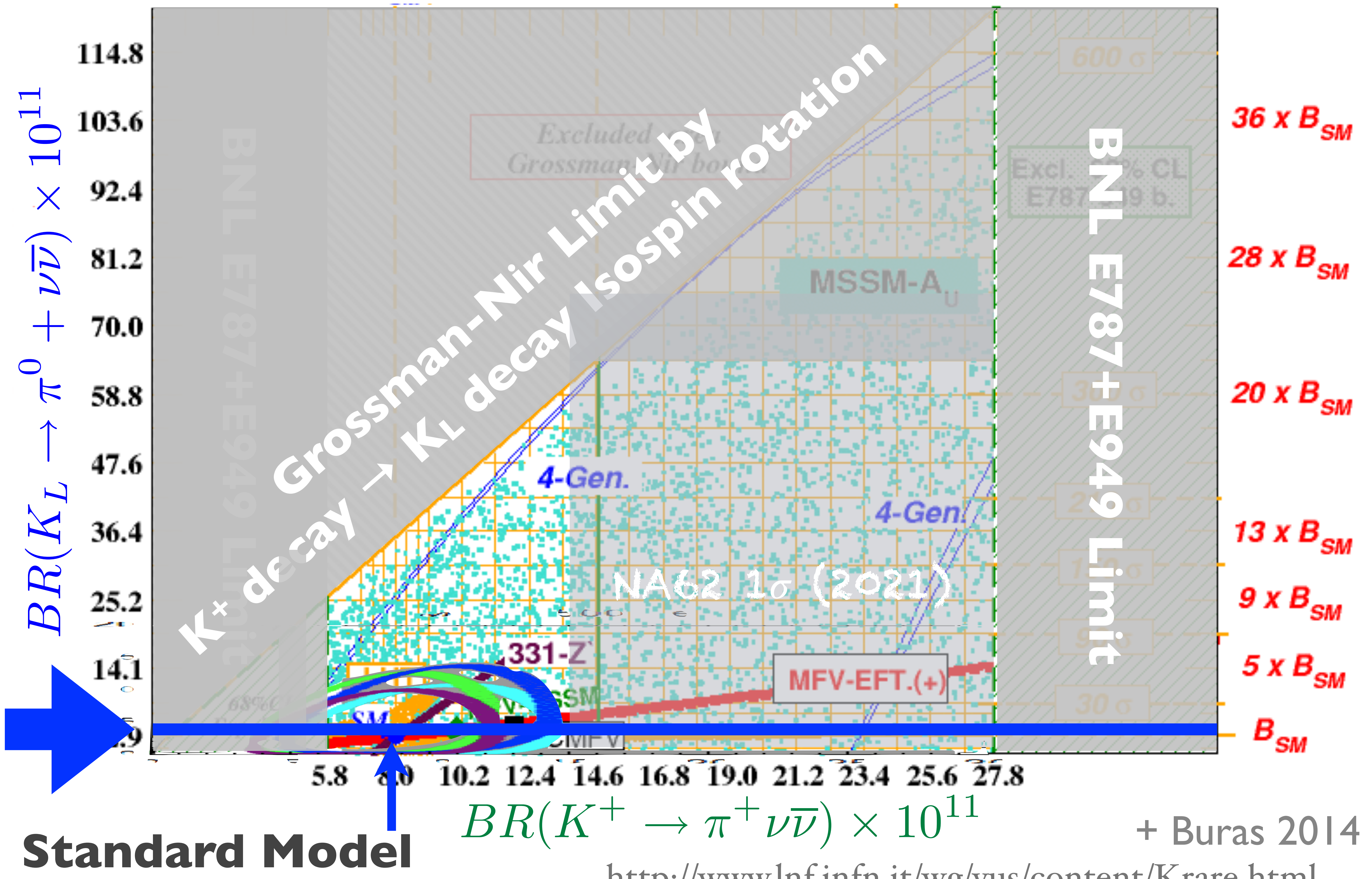
A halo neutron interacts with CV and
produces η →wrong vertex reconstruction

Signal :48.9±0.5 BG in total :111.7±4.8 S/N=0.44

What is achievable in KOTO step2

with 100KW beam and 3 years data taking

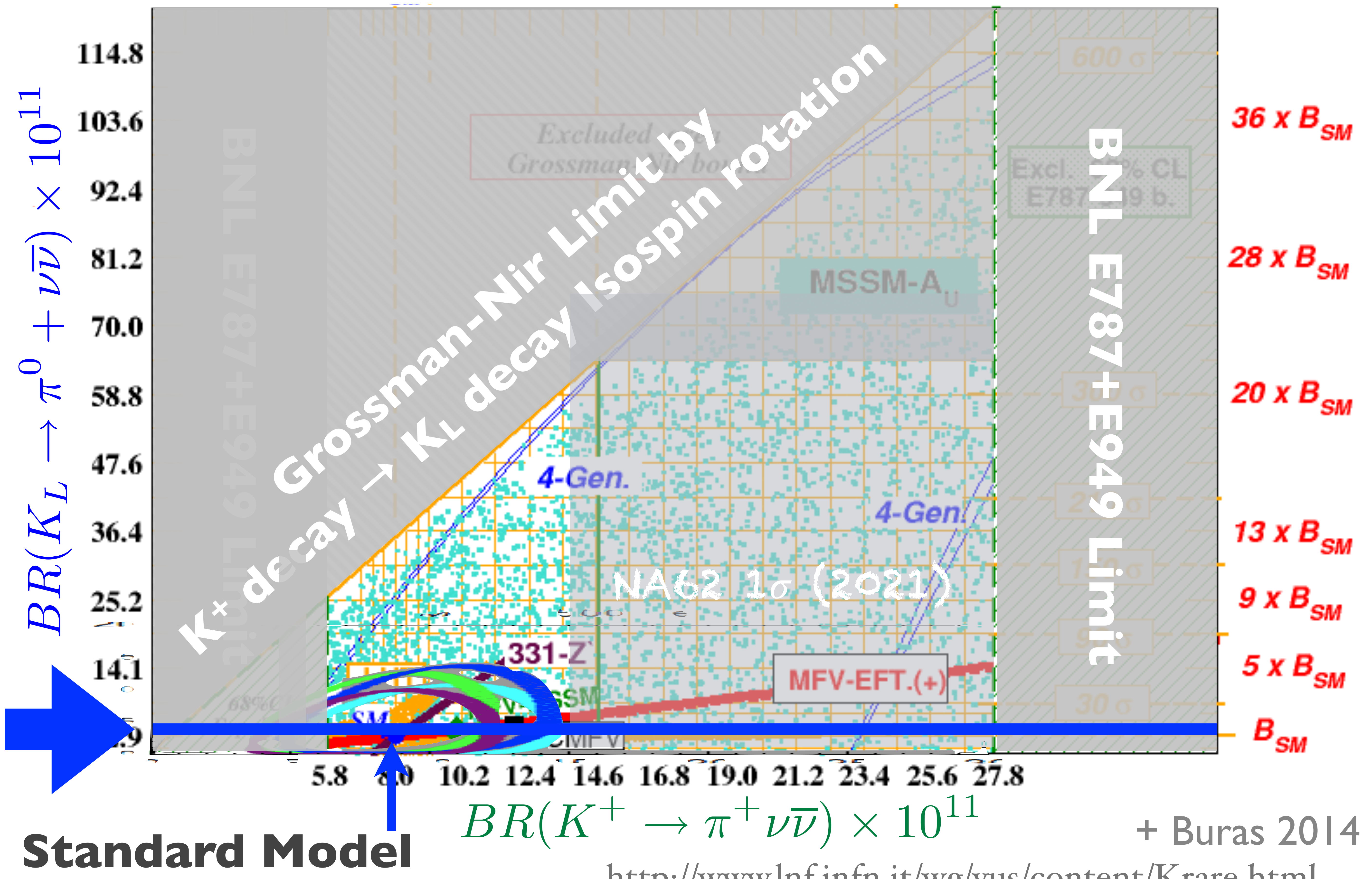
- Discovery
  - BR(KL→π ν ν)≒ (SM prediction)
    → ～5σ discovery
    →Observe 49 events with
    112 BG events
    →Measure BR with 30% accuracy
- New physics search
  - |Br(K$_L$→π^{0}ν ν)-SM|/SM >40%
    →Indicate new physics
- Measurement of SM parameters
  - Measure η with 15% accuracy



+ Buras 2014
http://www.lnf.infn.it/wg/vus/content/Krare.html

Summary

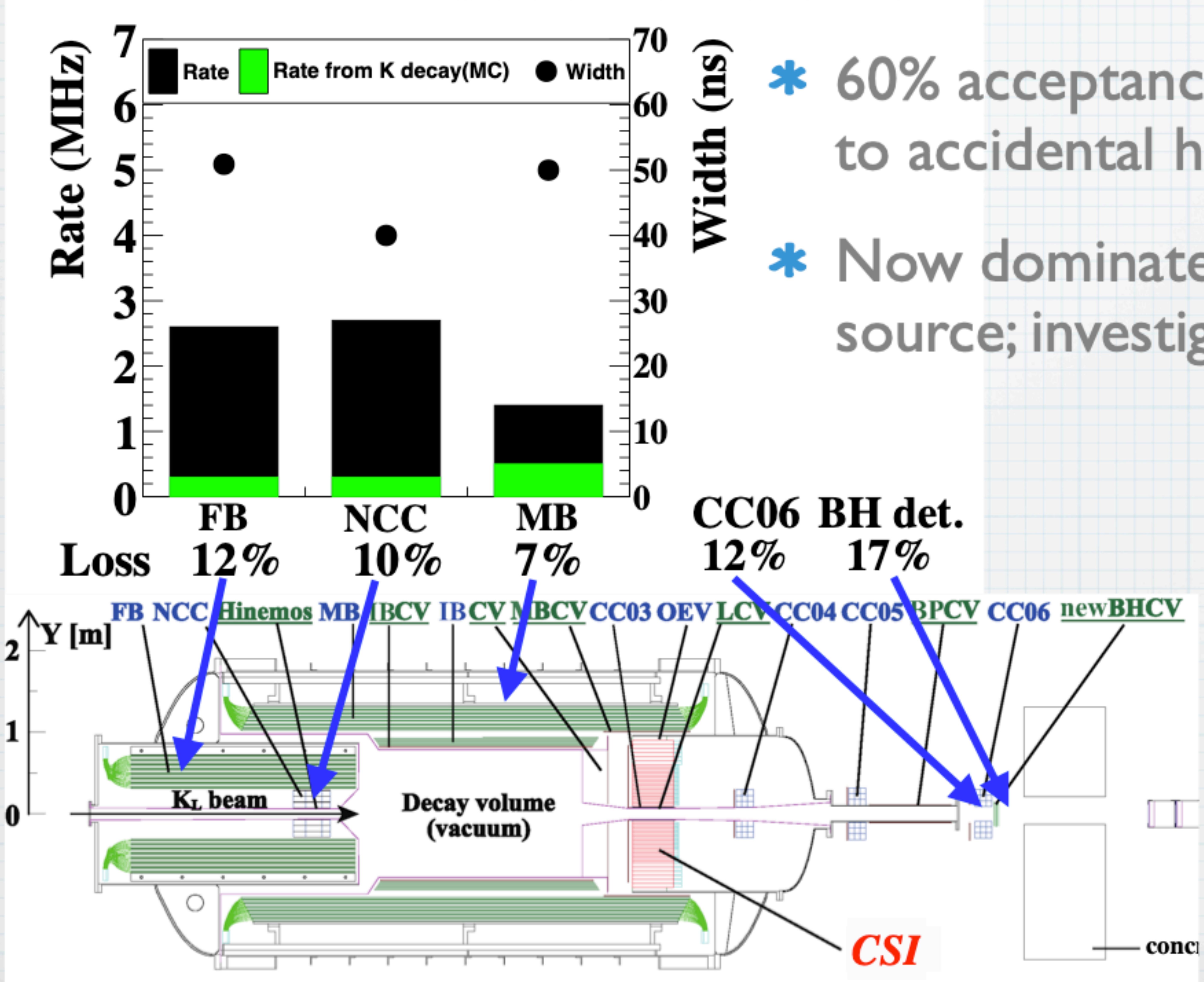
- $K_L \to \pi^0 \nu \nu$ decay is a powerful tool to search for new physics
- KOTO will reach the sensitivity of $O(10^{-11})$ around 2025.
- KOTO step2 have potentials
  - Discovery the $K_L \to \pi^0 \nu \nu$ signal with 5σ
  - Measure the branching ratio with 30% accuracy
  - Indicate new physics if $|Br(K_L \to \pi^0 \nu \nu)\text{-SM}|/\text{SM} > 40\%$



+ Buras 2014

http://www.lnf.infn.it/wg/vus/content/Krare.html

Accidentals

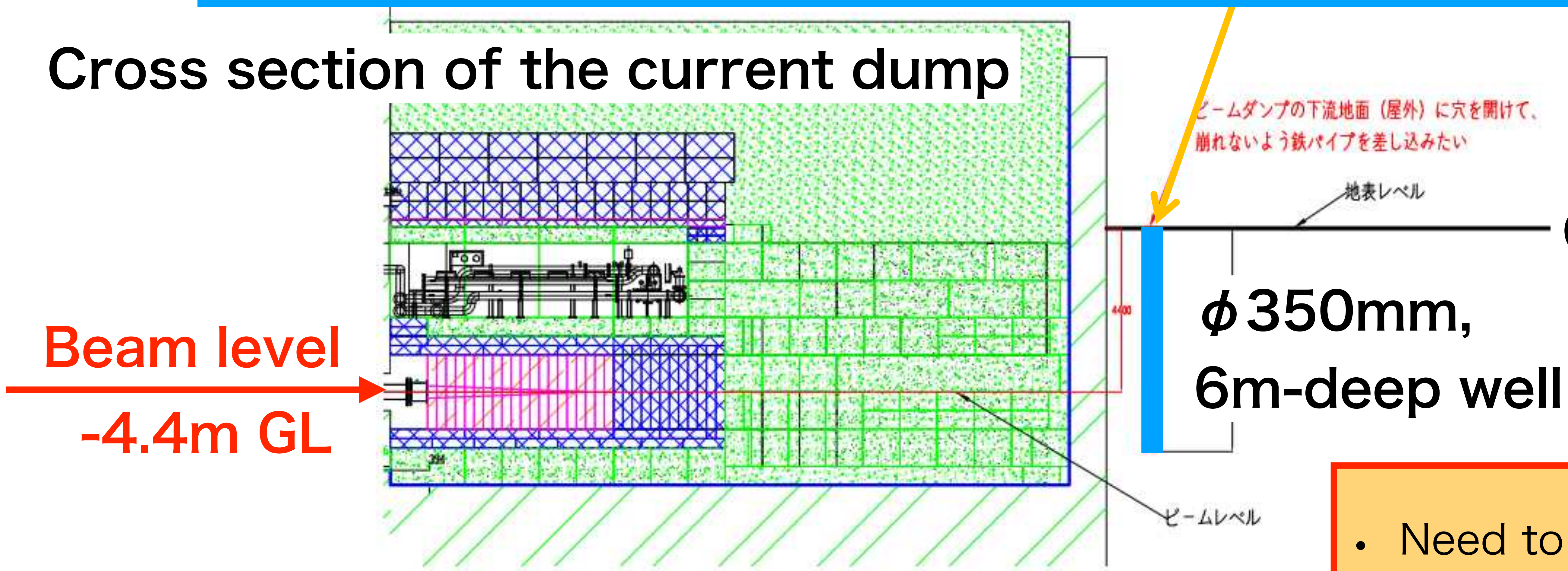


* 60% acceptance loss due to accidental hits
* Now dominated by non-K source; investigating

Muon flux measurement behind the current dump

Measurement in the well
(Under consideration)

Cross section of the current dump

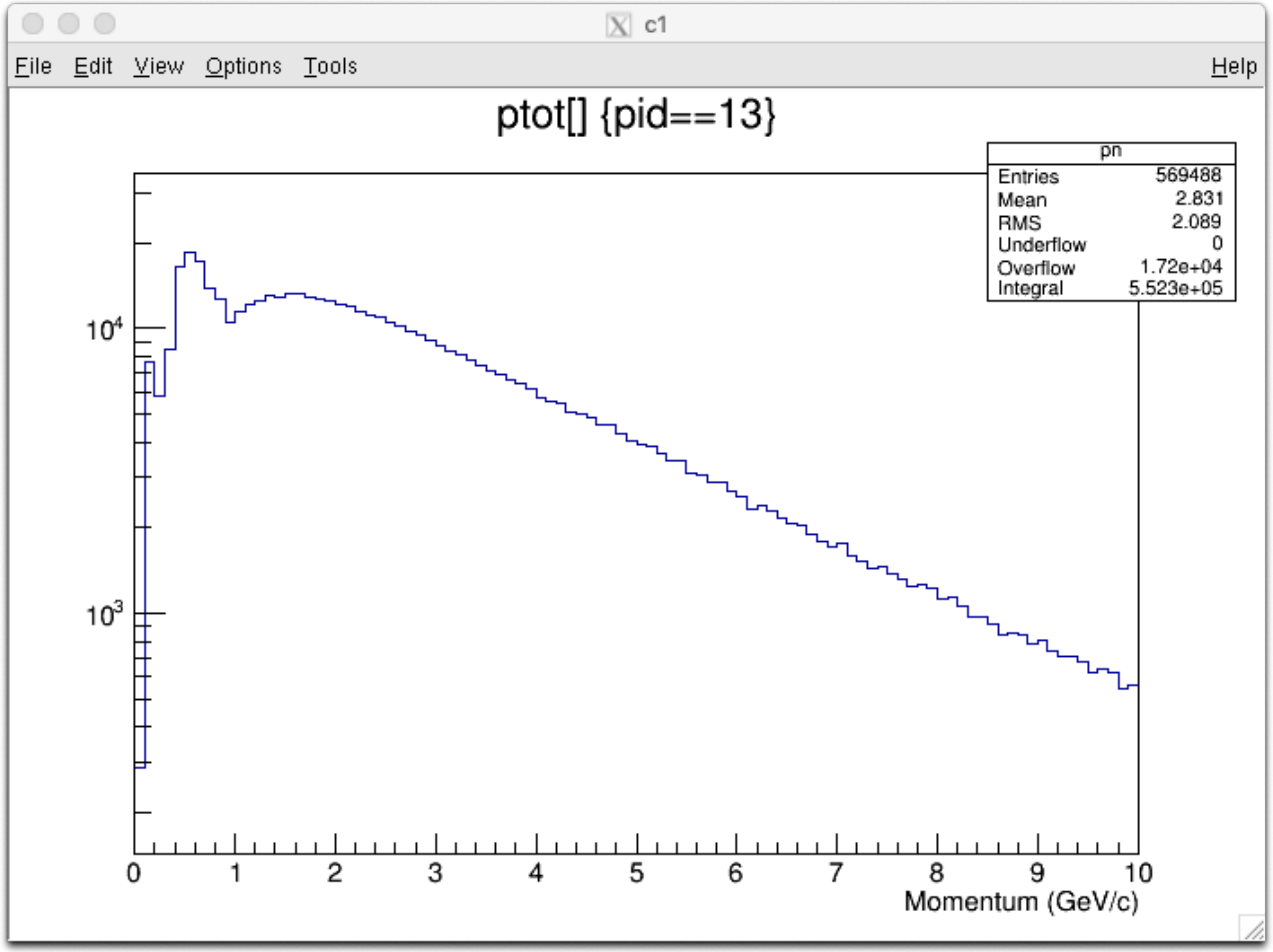


Want to prepare by the next beam time in 2022 if possible.
(Although no budget is allocated at the moment.)

- Need to dig a hole and insert a pipe
- Need to prevent spring water
- Need to have a rigid cover
- Watanabe-san started to discuss with facility department, radiation-safety division, and a company.

Neutron

At the exit of the beam line (Z=43m)

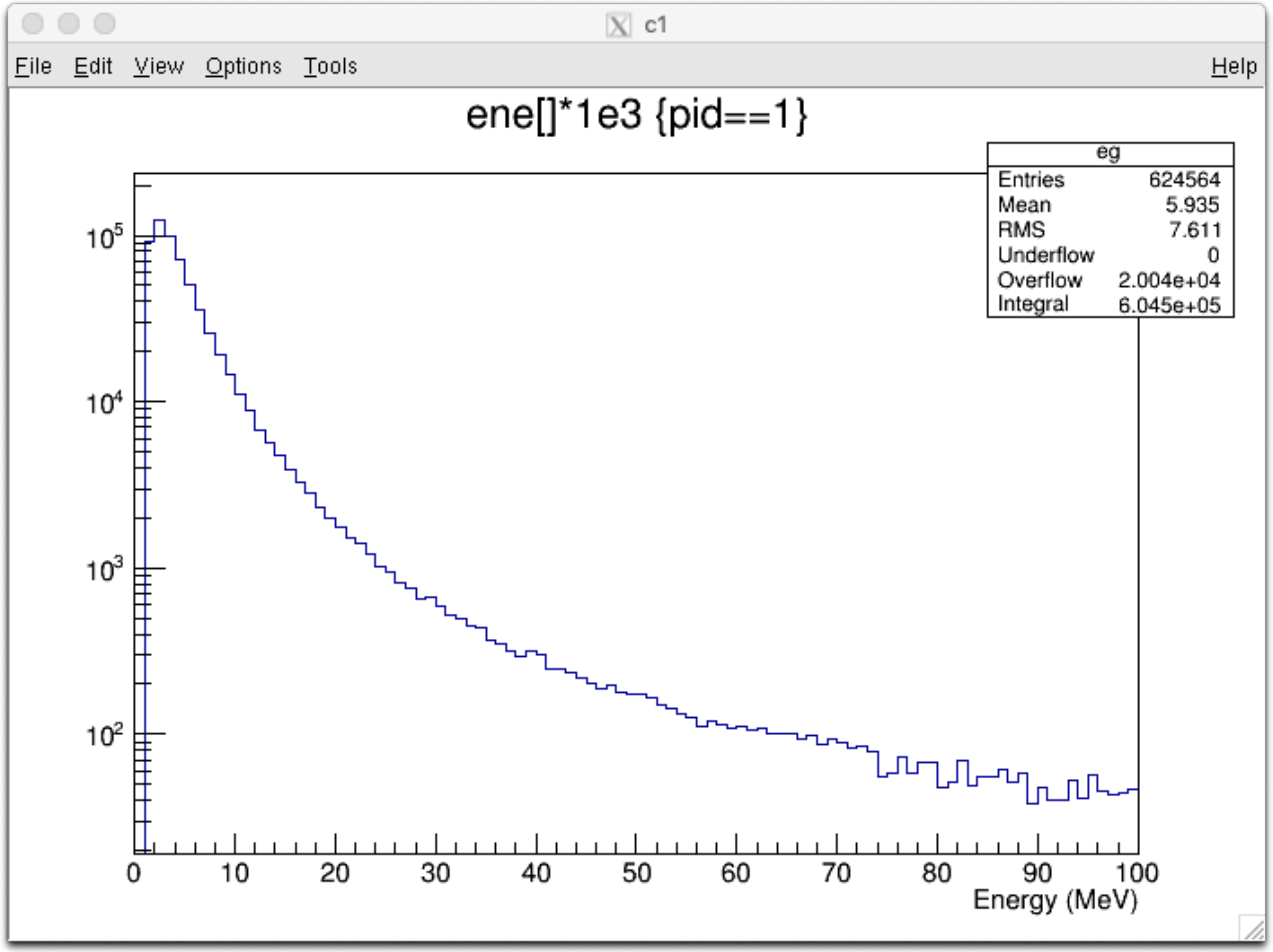


36×10^9 POT generated

Eth	N
On-spill ($/4.2 \times 10^{13}$ POT)	
>1MeV	569488 660MHz
>100MeV	540578 620MHz
>300MeV	480245 550MHz
>1GeV	370262 430MHz

Photon

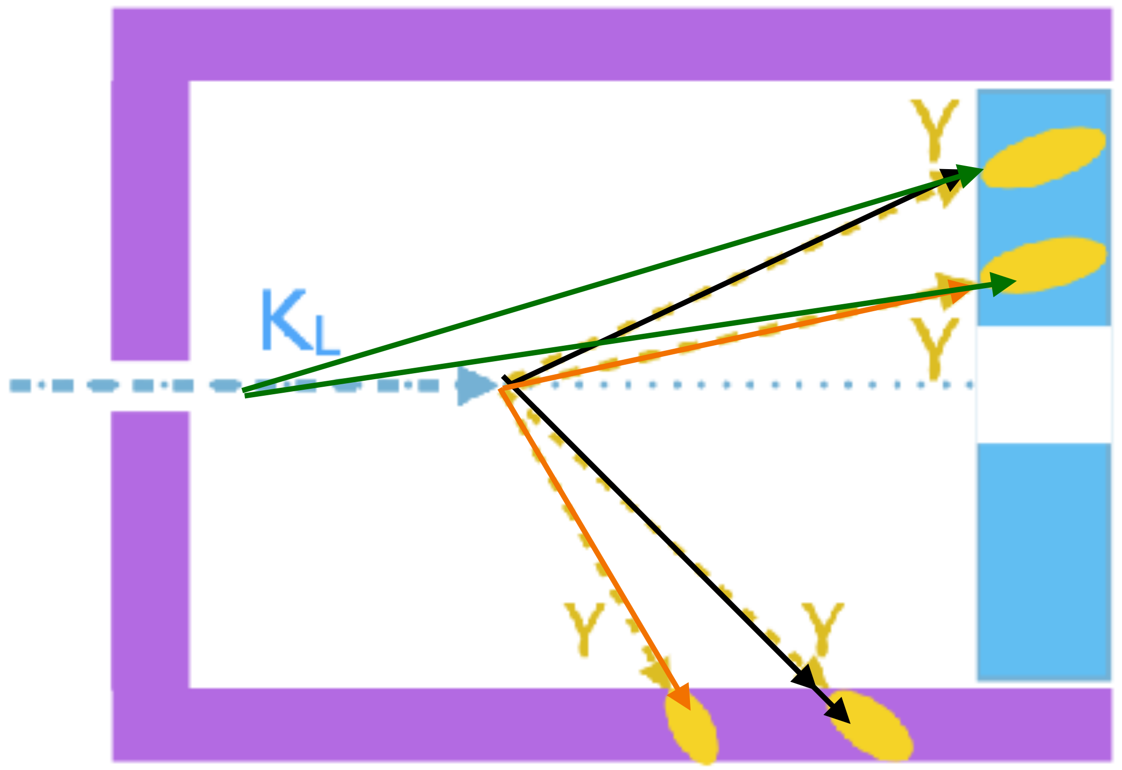
At the exit of the beam line (Z=43m)

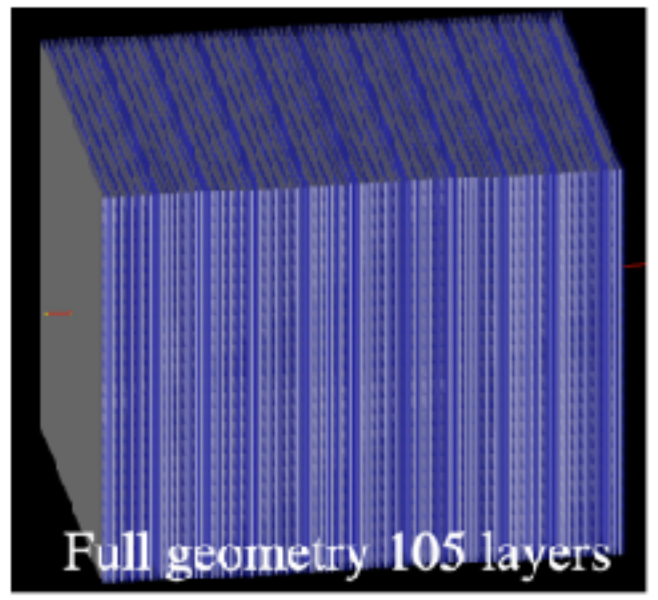


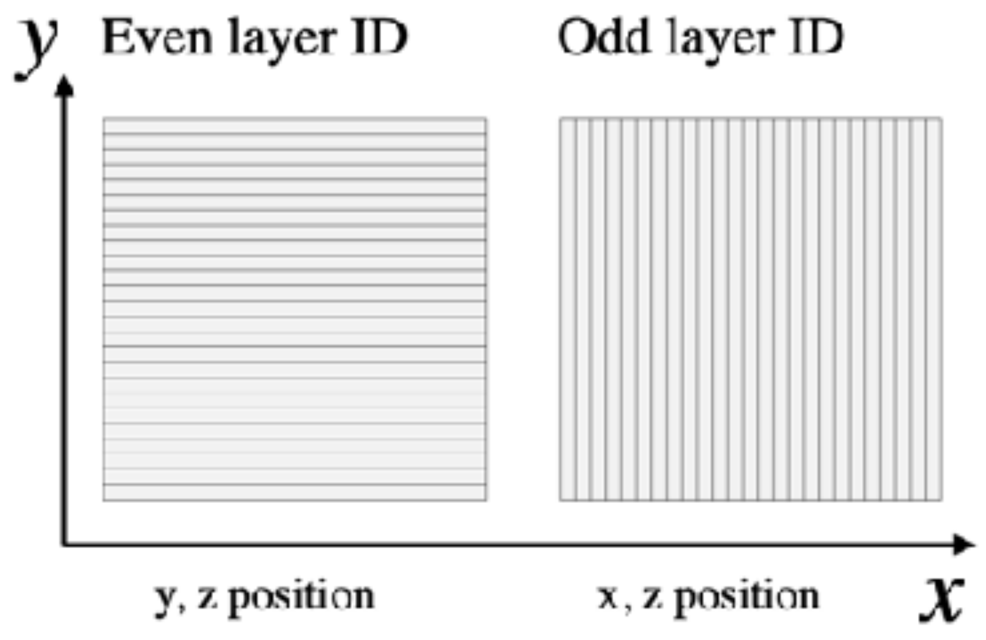
36×10^{9} POT generated

Eth	N
On-spill (/4.2×10^{13} POT)	
>1MeV	624564 720MHz
>10MeV	92471 110MHz
>100MeV	20035 23MHz

Angle measurement

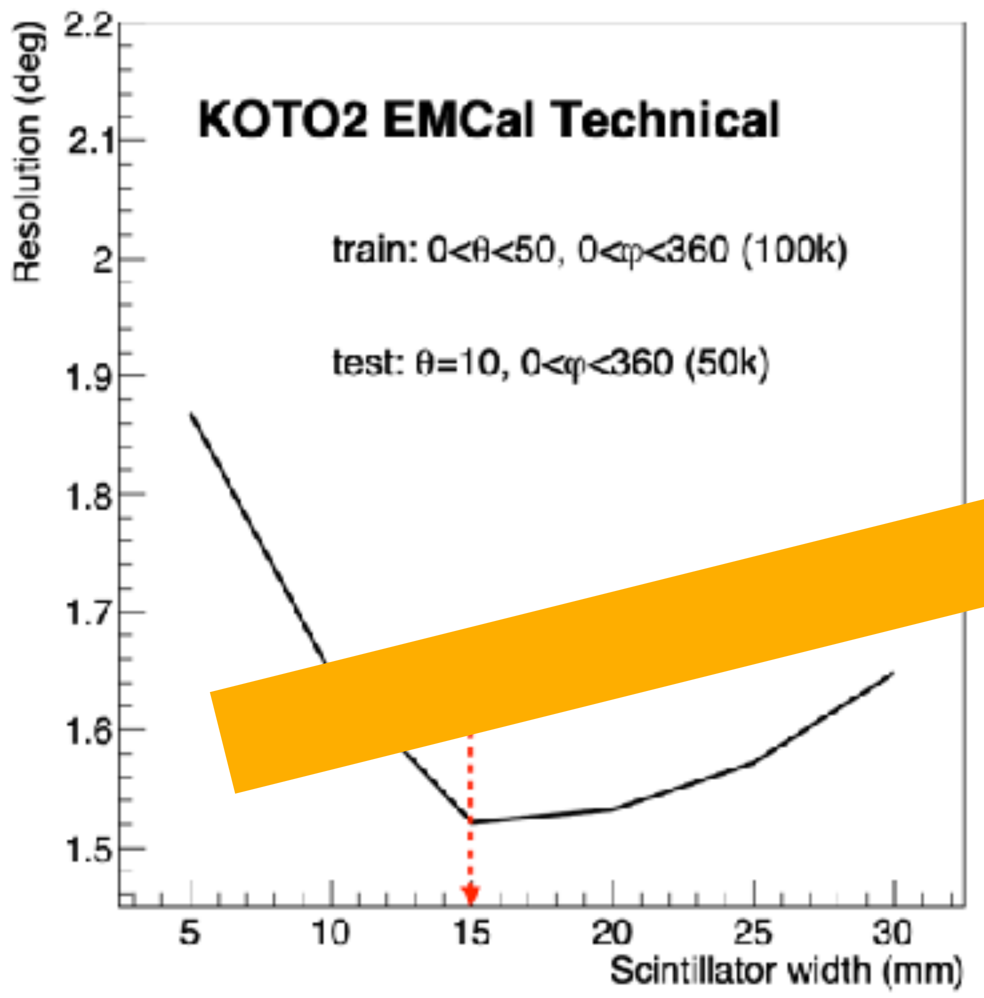


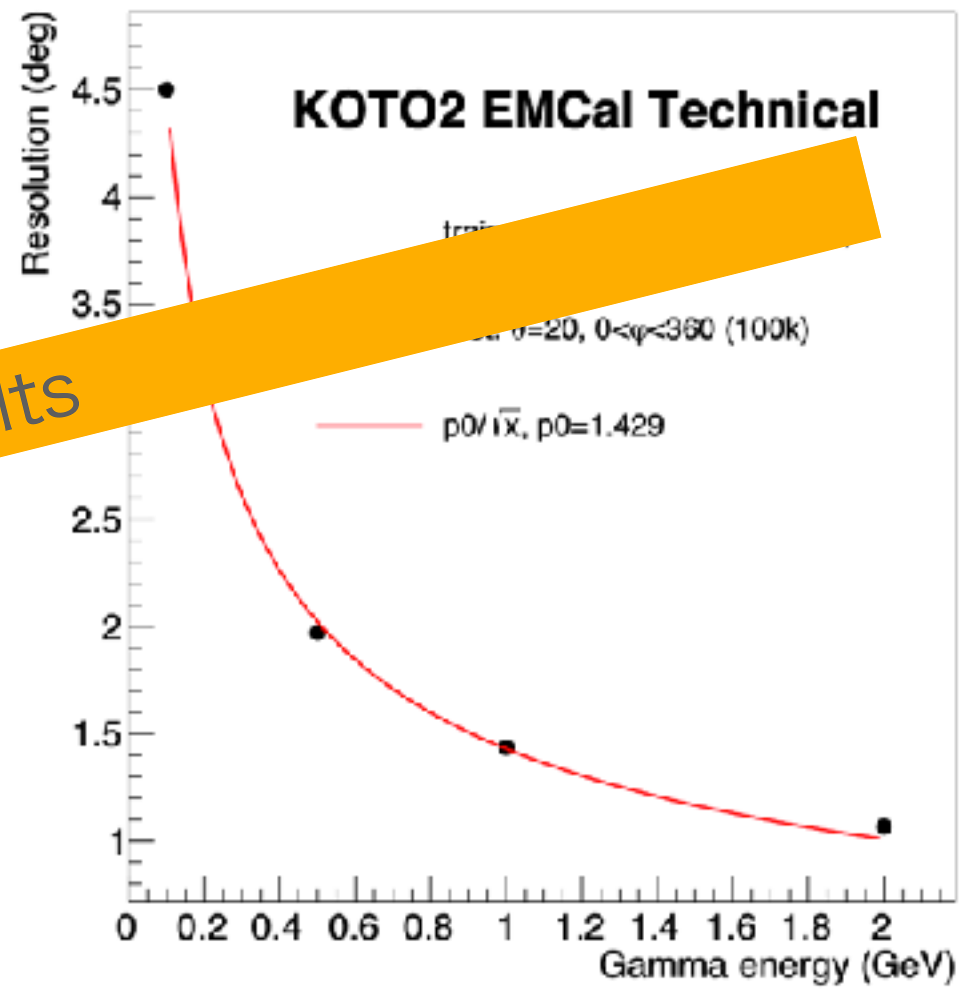




- Incorrect vertex reconstruction
  - Reject with two additional photons
  - Narrower veto window

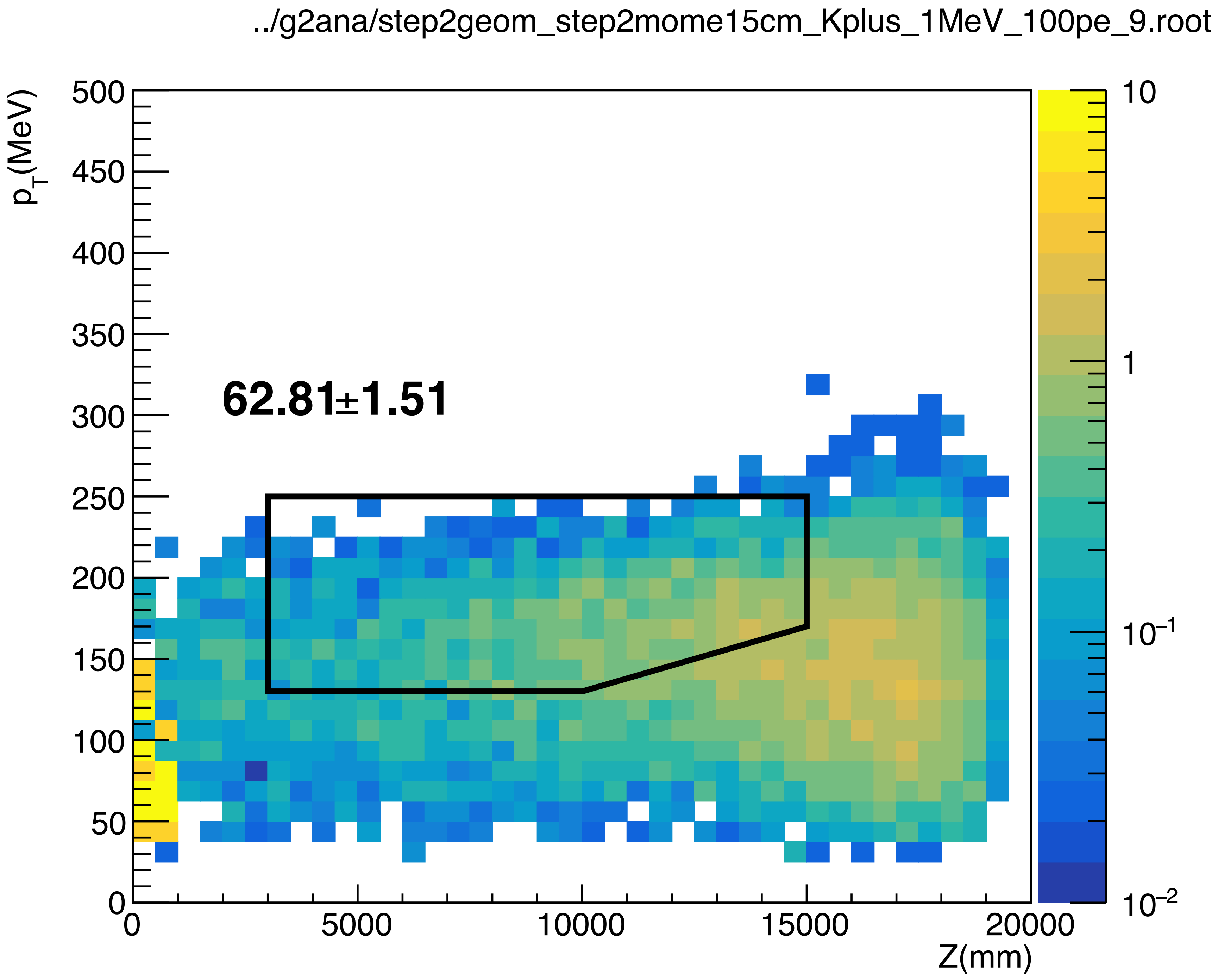
- Sampling calorimeter made of alternating lead and plastic scintillator
- Plastic scintillator is finely segmented in X- and Y-direction individually





- 15mm width of scintillator seems to be optimal
- 1.5 degree angular resolution for 1 GeV photon

Still detector optimization is on going.



$K^{\pm}/K_L = 4.1 \times 10^{-6}$

The same momentum spectrum as in K_L

Only Ke3 decay

With 0.9^4 additional cut acceptance

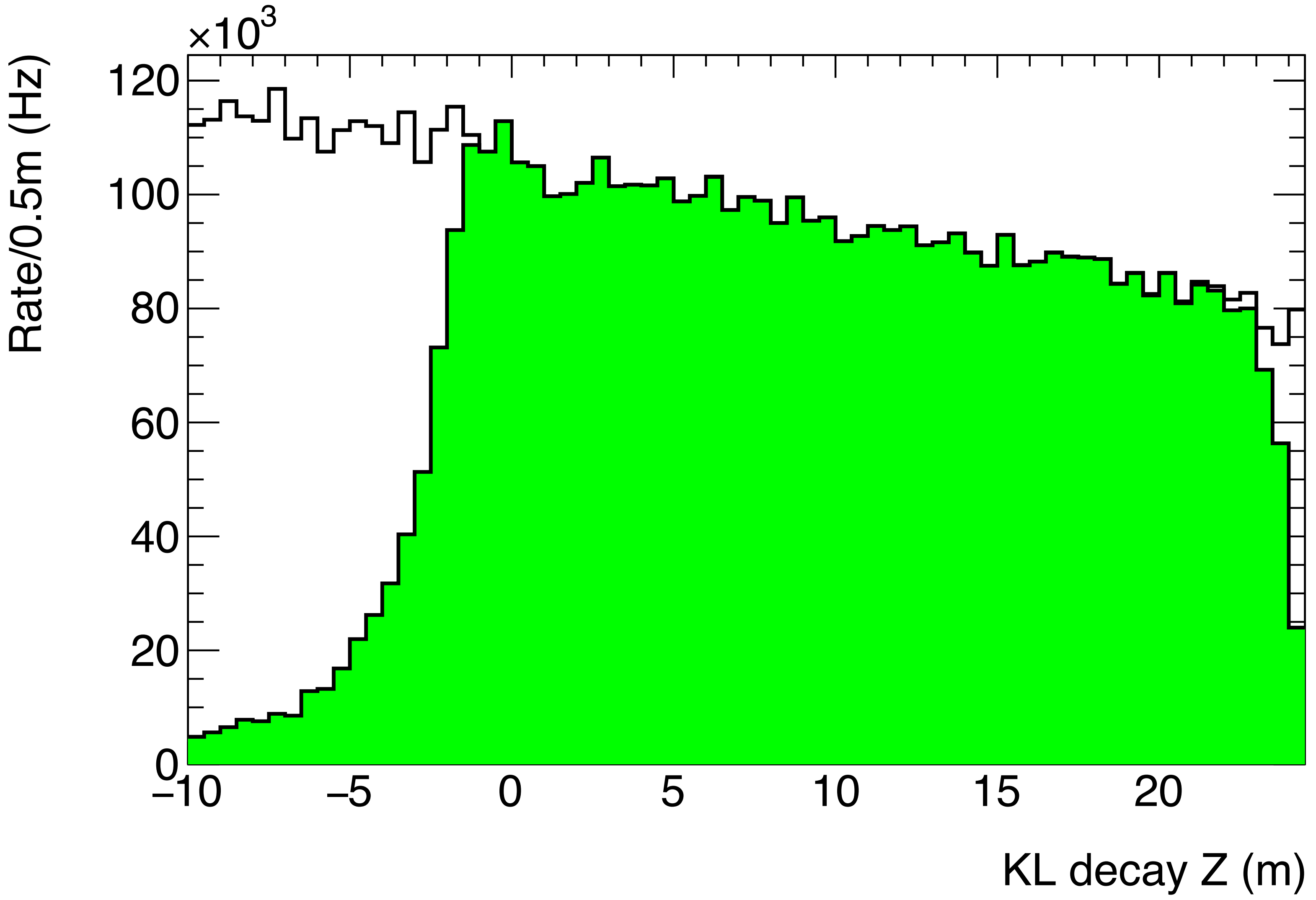
Second magnet : $\times 1/4$ or less → hope to be 1/10

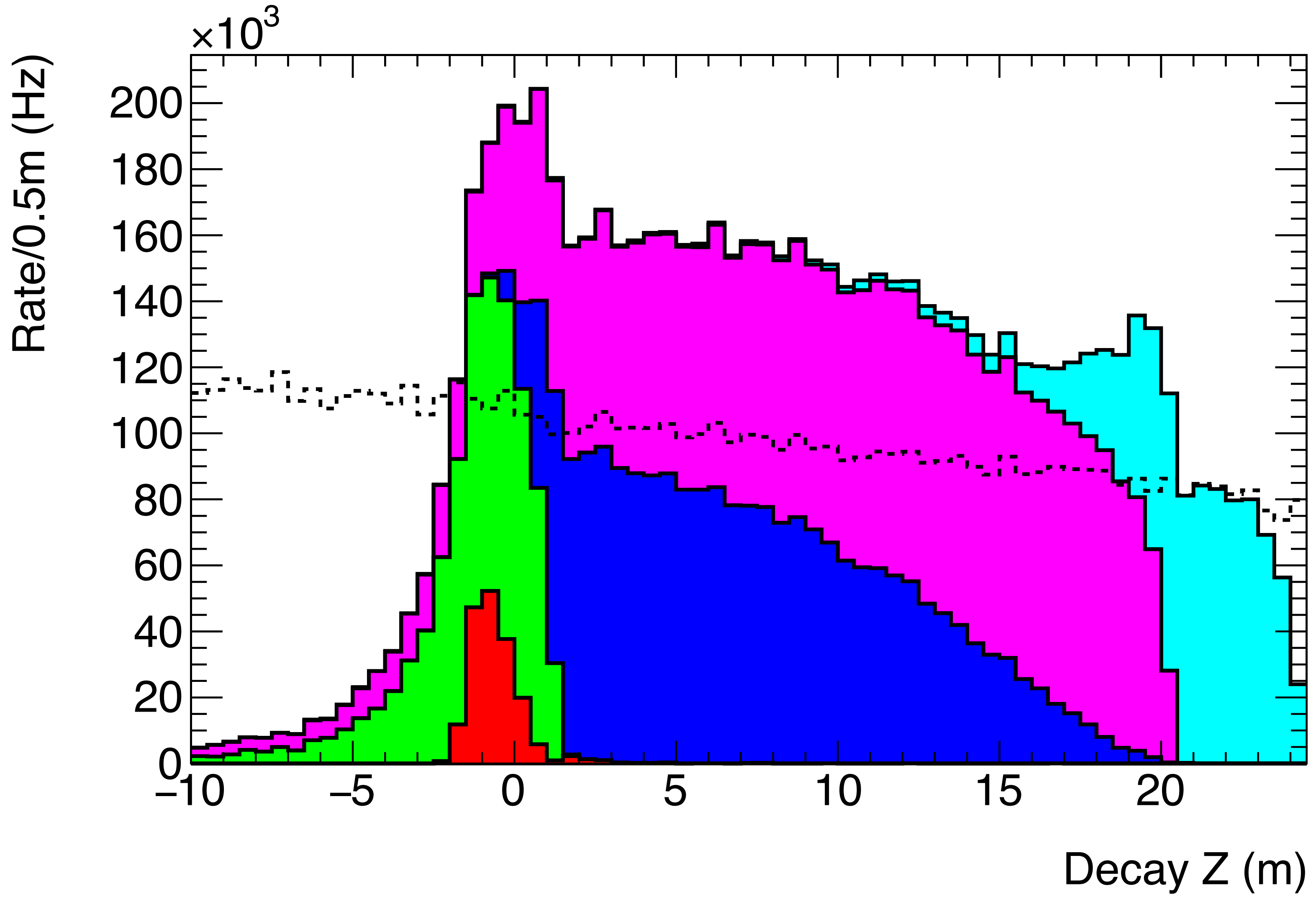
If more reduction is needed, we will have UCV

(with additional acceptance loss)

CBAR / newBHCV are responsible for the inefficiency of $e^{\pm}$

Accidental loss





- Hermetic detector = KL decay = hit somewher
- Which decay region → 30m

R_{incident}=100e3/(30e9*1.6e-19)*4.2/2.*11e7/2e14=24MHz

$$P_{\mathrm{decay}} = 1 - \exp\left(-\frac{30\ \mathrm{m}}{\beta\gamma c\tau}\right)$$ =1-exp(-30/(6*15))=0.28

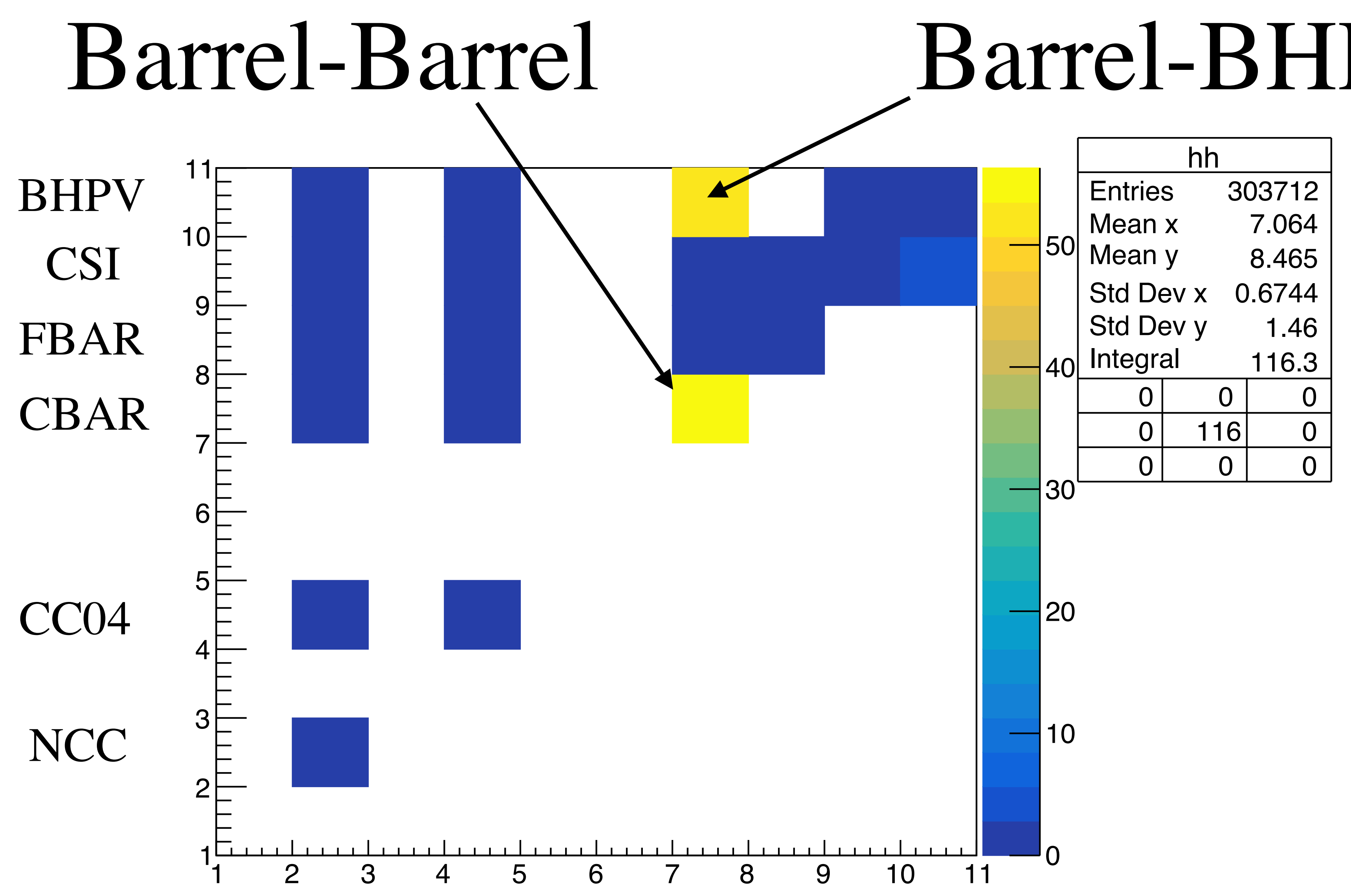
R_{decay}=24e6*0.28=6.7MHz

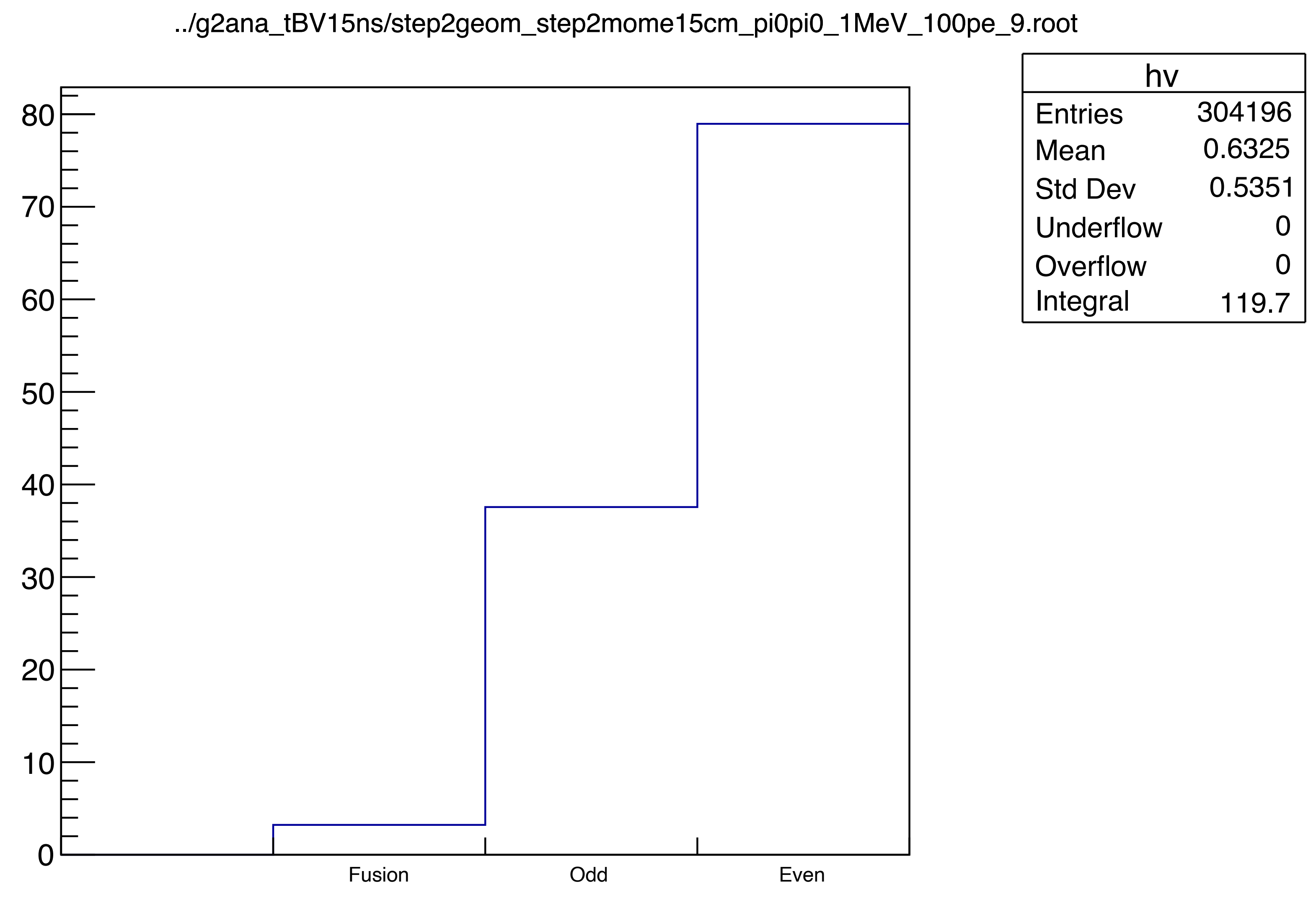
wR=20*ns * 6.7MHz =0.13 13% loss

Situation of $K_L \to 2\pi^0$ background

- Detector inefficiency is a key.

Contributing detector
for $K_L \to 2\pi^0$ background



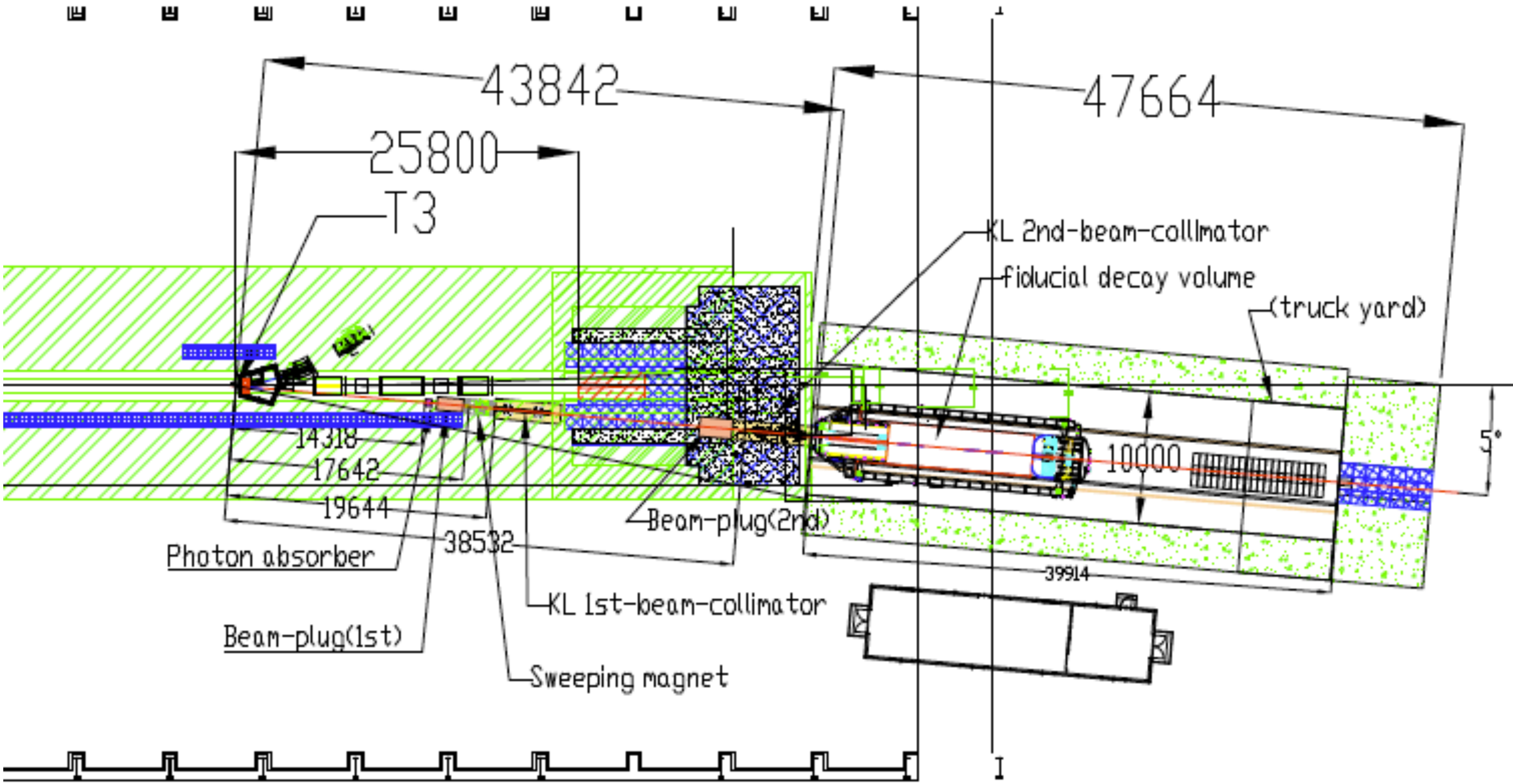


Fusion Odd Even

Effect of Barrel timing window, BHPV for $K_L \to 2\pi^0$

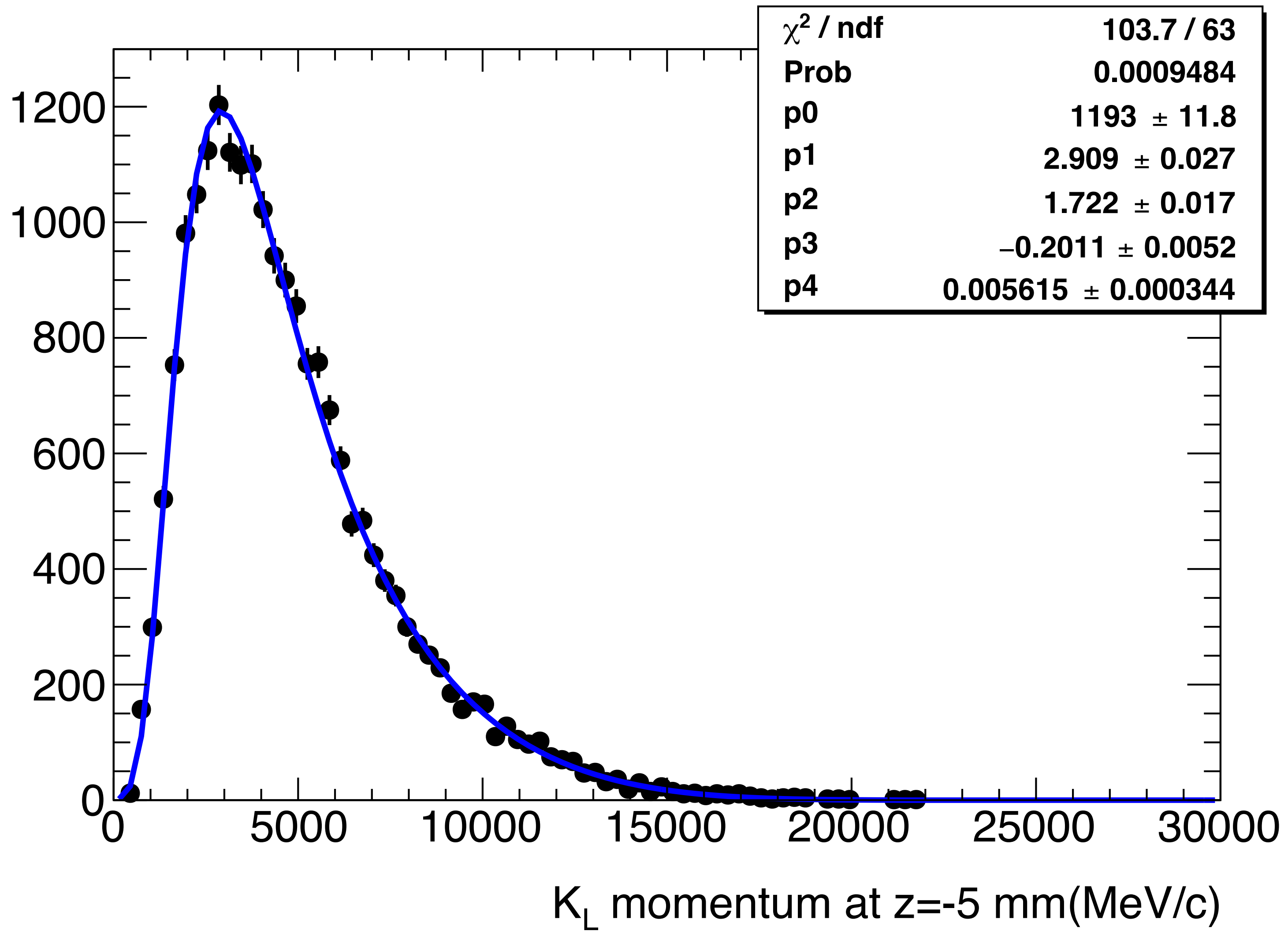
- Narrow barrel veto window is feasible.
  - Thanks to good timing variable
- BHPV would reduce # of BG.
  - 24 p.e. threshold is not effective.
  - Operation is difficult.
  - BHPV can be removed.

Barrel Timing Window	BHPV threshold	# of BG
20ns	—	120 ± 5
50ns	24p.e.	115 ± 4
50ns	12p.e.	90 ± 3
50ns	6p.e.	60 ± 2

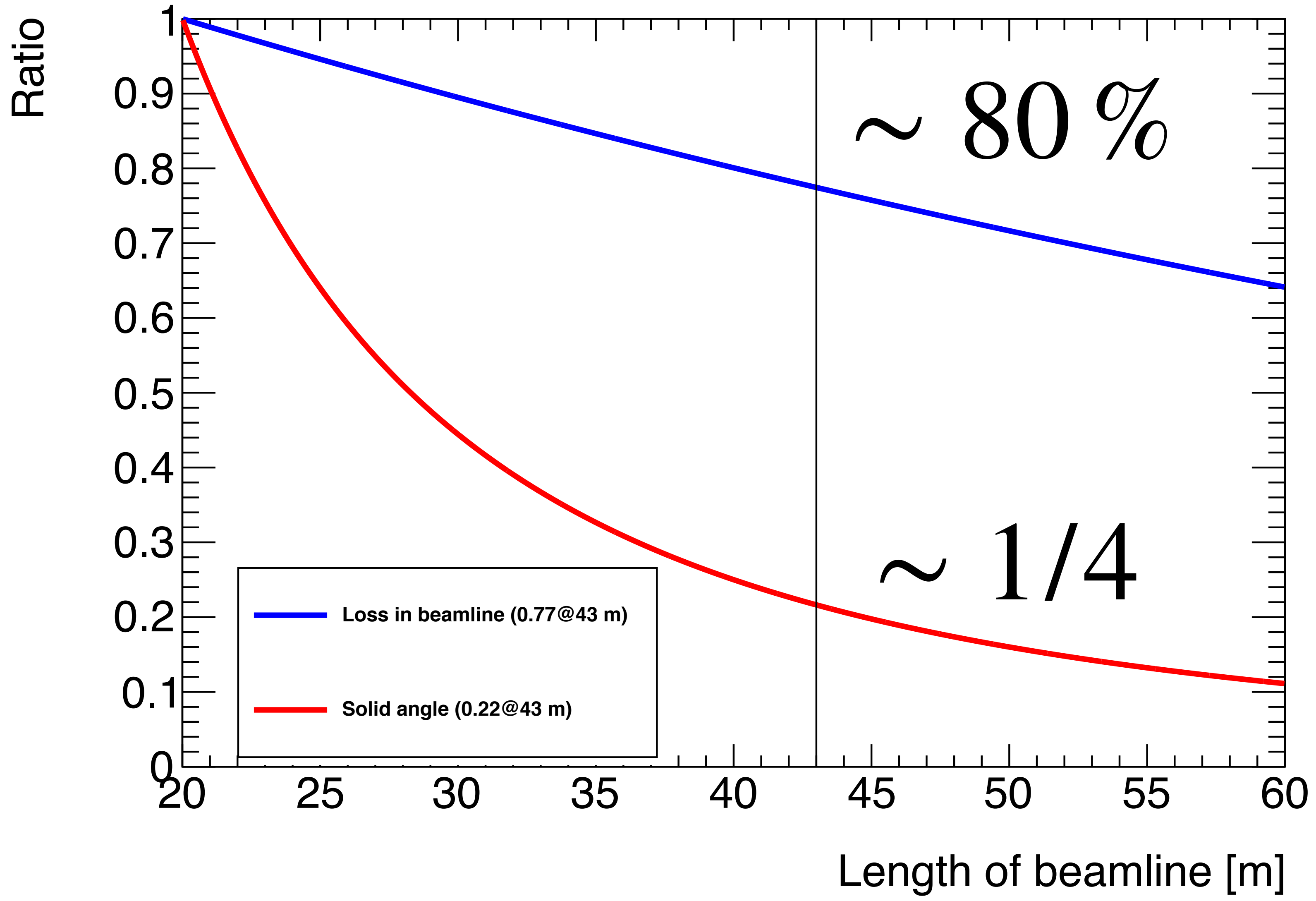


43842
47664
25800
T3
KL 2nd-beam-collimator
fiducial decay volume
(truck yard)
14318
17642
19644
38532
10000
5°
Beam-plug(2nd)
39914
Photon absorber
KL 1st-beam-collimator
Beam-plug(1st)
Sweeping magnet

High momentum KL



Extraction: 16°→5°: $\times \sim 5$



- $p_{\mathrm{peak}} = 2.9\,\mathrm{GeV}/c$
- $l = \gamma\beta c\tau \sim 6 \times 15\ \mathrm{m} = 90\ \mathrm{m}$

Beam size: 10cm→15cm: $\times 2$

Step1: $4.2 \times 10^7 / 2 \times 10^{14}$POT (measurement)

$\times 5 \times 1/4 \times 2 = 2.5$

Step2: $11 \times 10^7 / 2 \times 10^{14}$POT (Geant3 simulation)