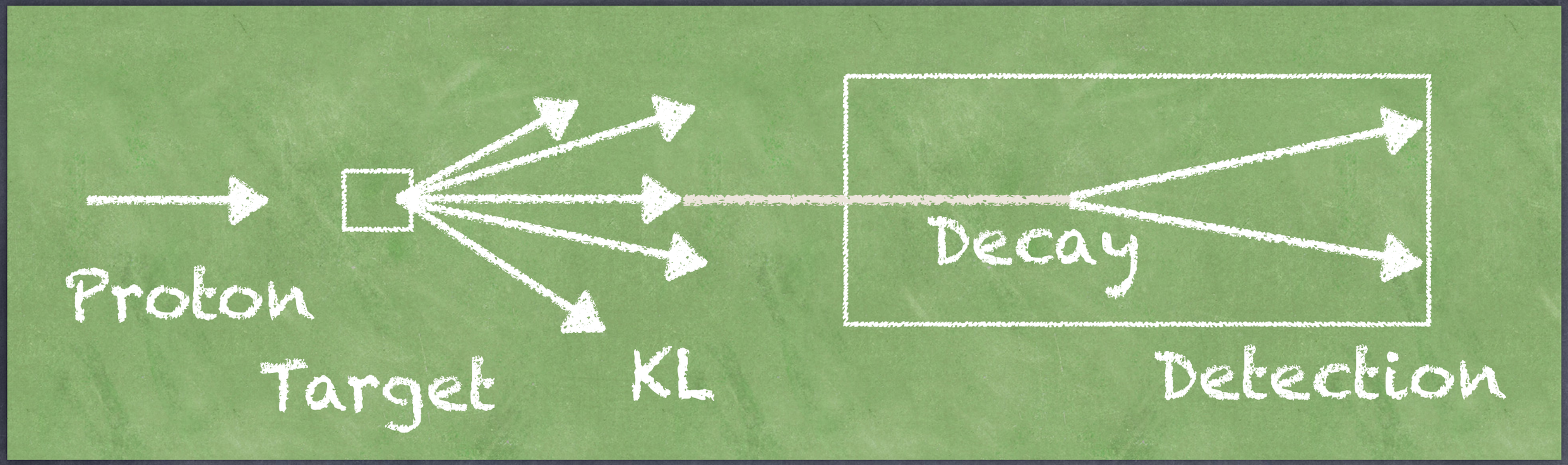
A future $K_L \to \pi^0 \nu\nu$ experiment at J-PARC

Tadashi Nomura (KEK/J-PARC)

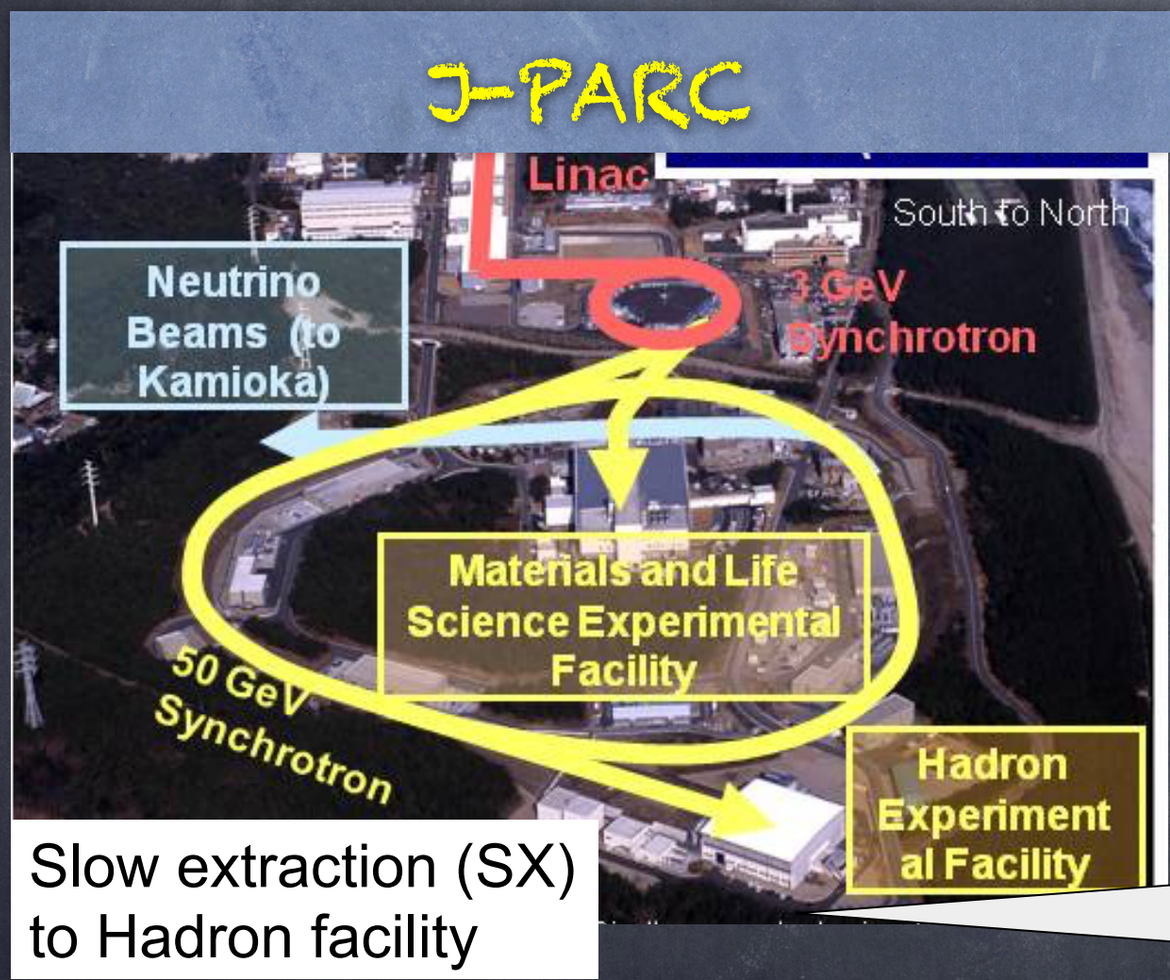
Kaon2019 @ Univ. of Perugia, September 13, 2019



Sensitivity is a function of

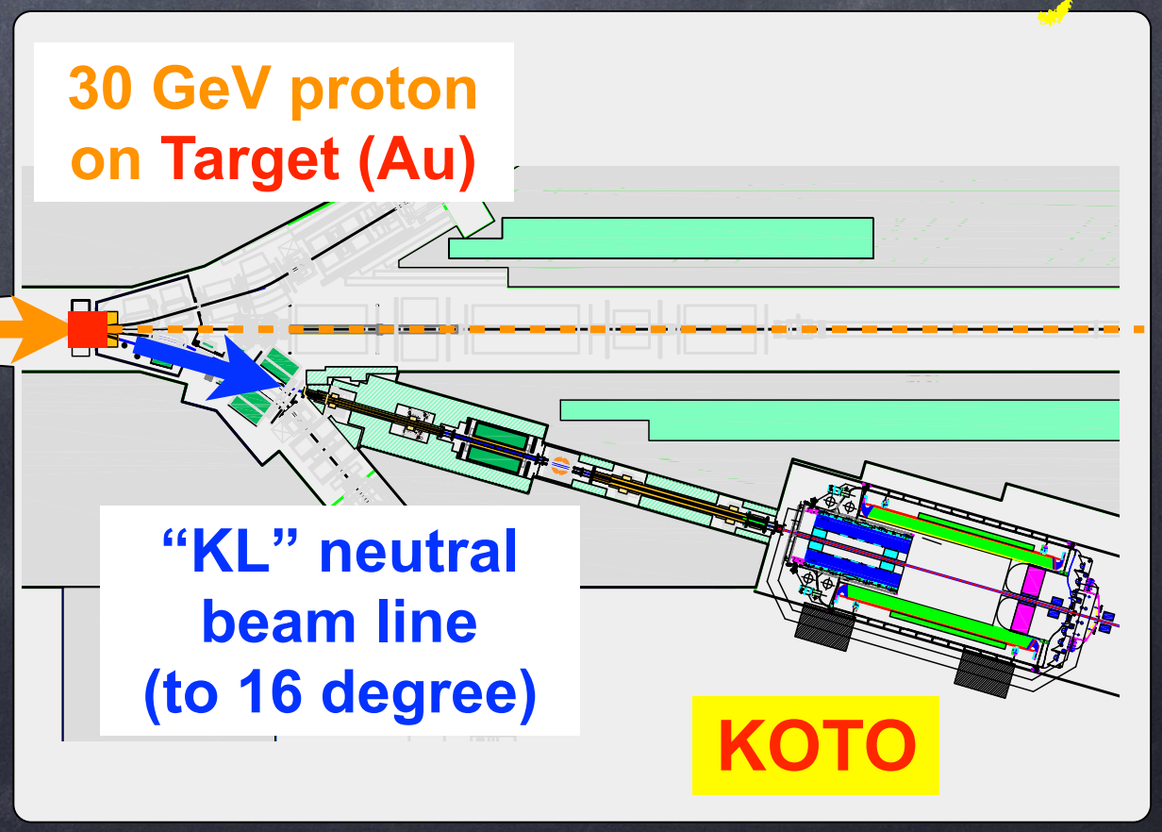
- Primary (proton) beam power
- KL yield @ experimental area
- Decay probability
- Acceptance for detection
- Running time

Current experiment "KOTO"

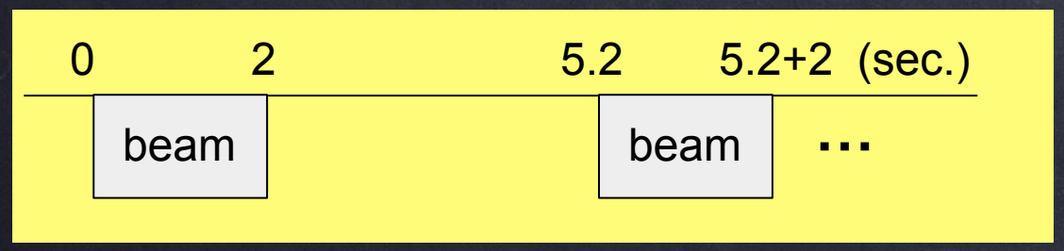


Proton beam power: 51kW (as of 2019)

In the Hadron Facility



SX cycle



From Accelerator report for J-PARC PAC in July 2019

J-PARC mid-term plan

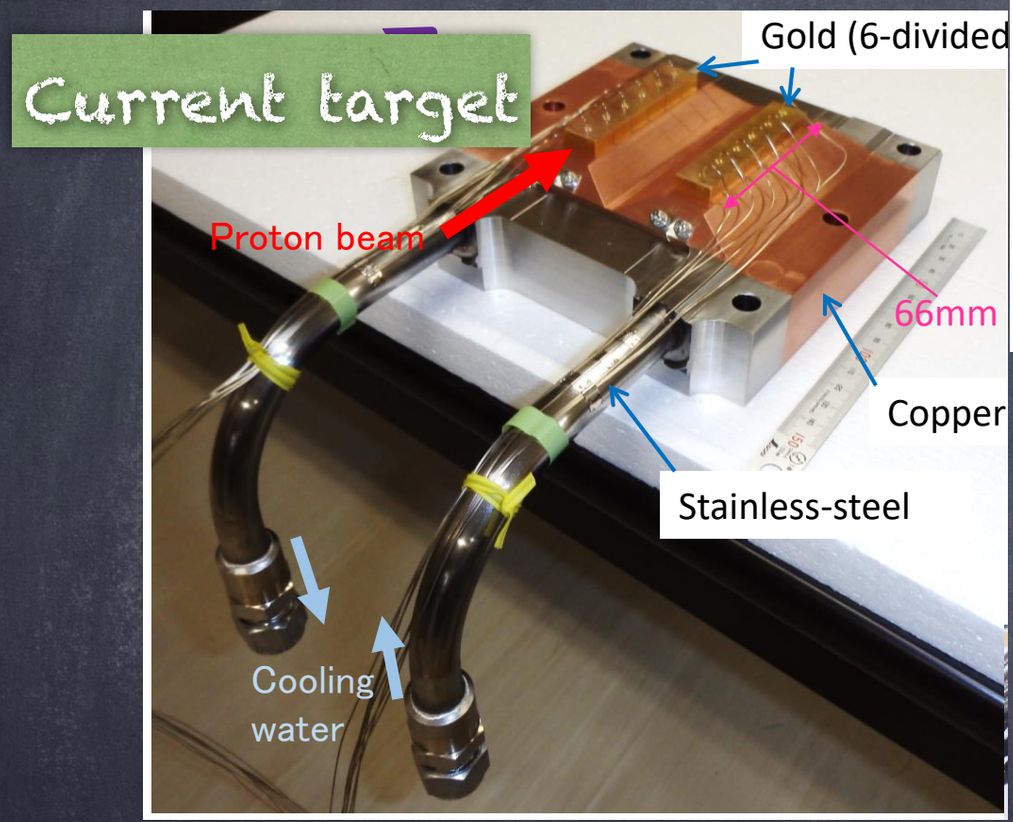
Mid-term plan of MR

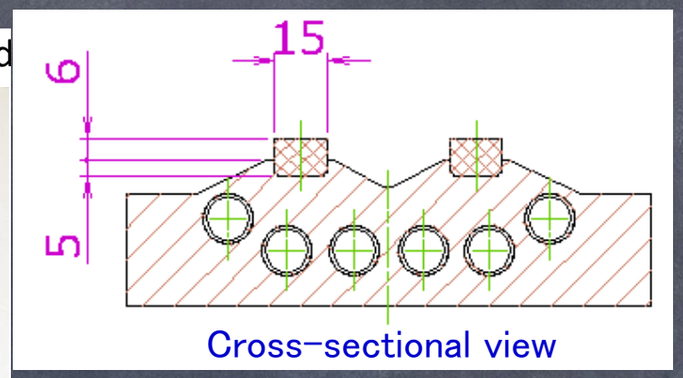
FX: The higher repetition rate scheme : Period 2.48 s —> 1.3 s for 750 kW.
(= shorter repetition period) —> 1.16 s for 1.3 MW
SX: Mitigation of the residual activity for 100kW

JFY	2017	2018	2019	2020	2021	2022	2023	2024
Event	New buildings		HD target		Long shutdown			
FX power [kW]	475	>480	>480	>480		>700	800	900
SX power [kW]	50	50	50	70		>80	>80	>80
Cycle time of main magnet PS New magnet PS	2.48 s	2.48 s	2.48s	2.48s		1.32s	<1.32 s	<1.32 s
		Mass production installation/test						
High gradient rf system 2nd harmonic rf system								
		Manufacture, installation/test						
Ring collimators	Add.collimators (2 kW)				Add.colli. (3.5kW)			
Injection system FX system	Kicker PS improvement, Septa manufacture /test							
	Kicker PS improvement, FX septa manufacture /test							
SX collimator / Local shields						Local shields		
Ti ducts and SX devices with Ti chamber	Ti-ESS-1	(Ti-ESS-2)						

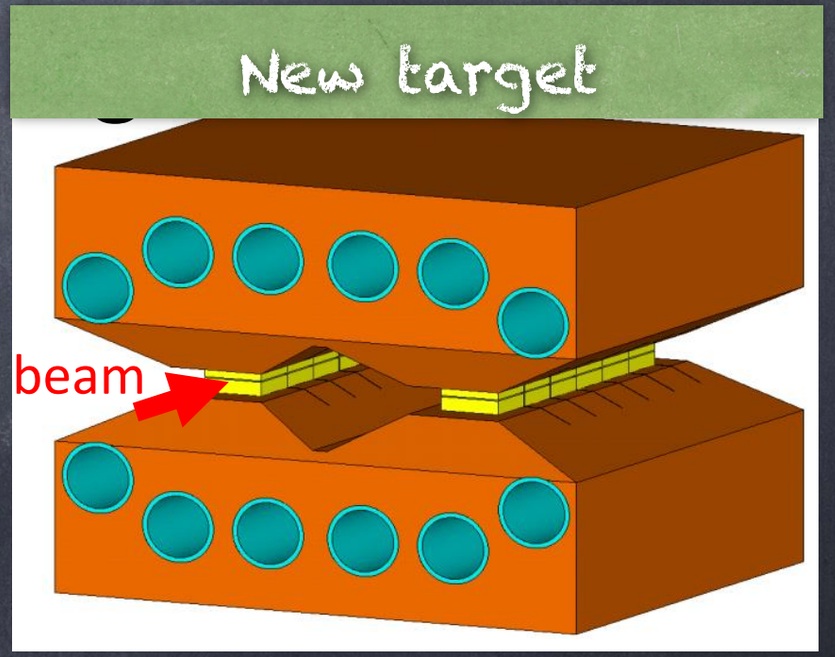
JFY2019

Target Upgrade





Cooling on both top and bottom



Acceptable beam power => up-to 95kW

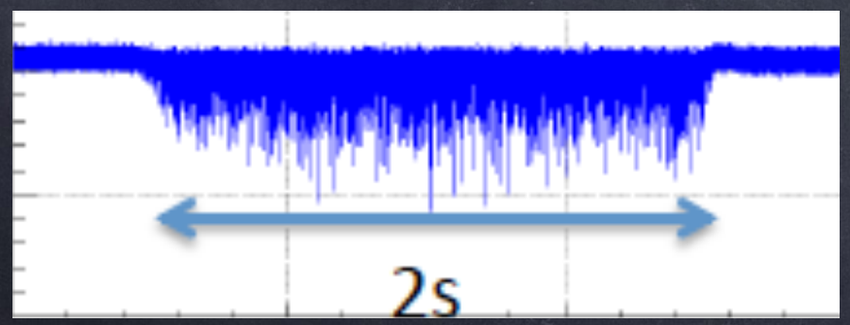
JFY2021

New MR Power Supply

- Shorter cycle time (=higher repetition)
  - 5.2->4sec for slow extraction (SX)

=> Higher beam power: toward 100kW

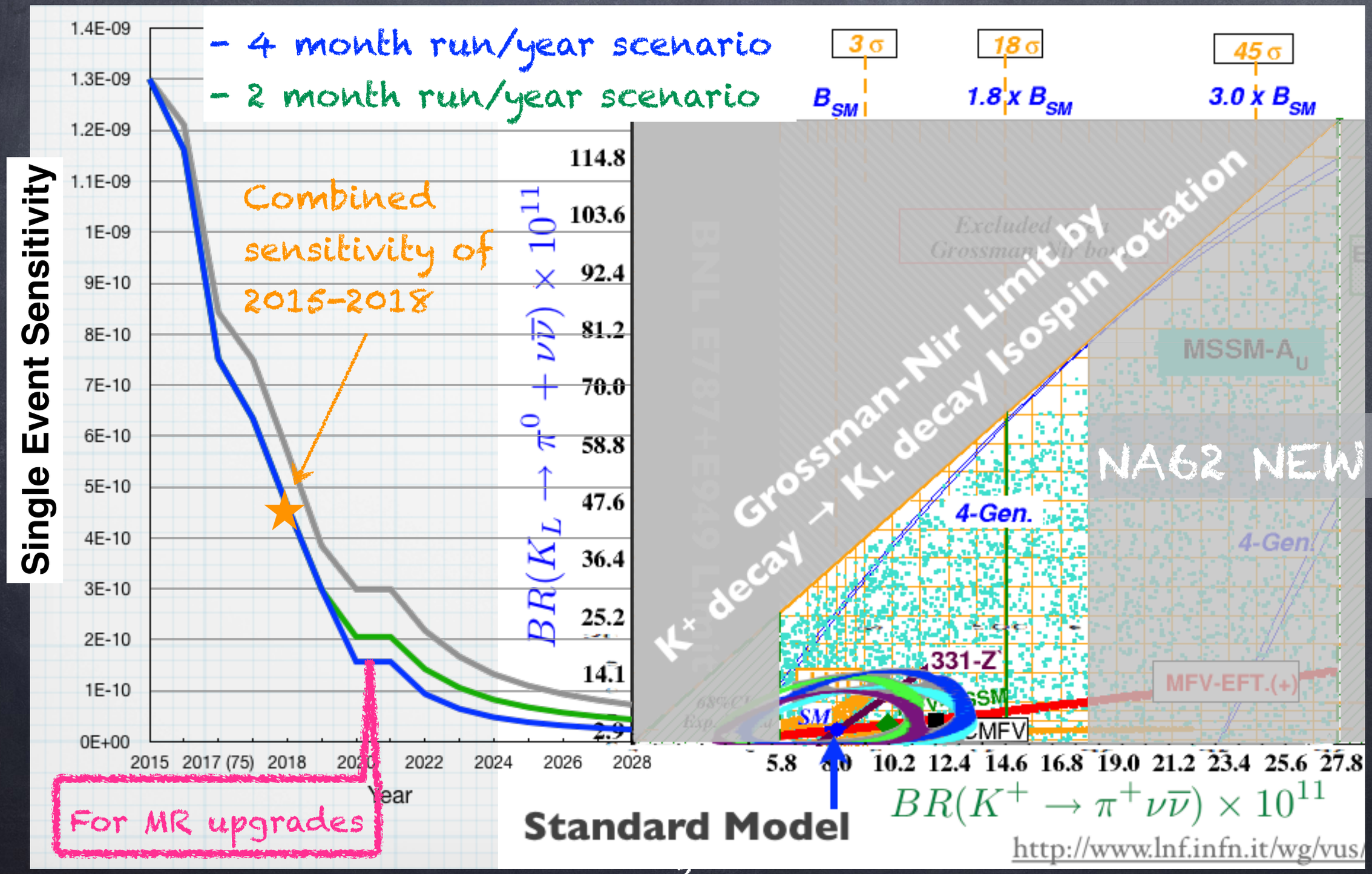
- Lower ripple noises



Beam structure in 2018

=> Smooth SX beam

KOTO Sensitivity projection



Will KOTO reach enough?

- Given KL flux, running time, KOTO may reach close to the Standard Model sensitivity (3×10^{-11}) but it will take long time, by 2025 or around.
- In addition, it is not enough to claim the OBSERVATION.

Next step

- We now start considering seriously a new experiment that can observe 100 SM events
  - A concept was described in the KOTO proposal in 2006, as "Step-2".

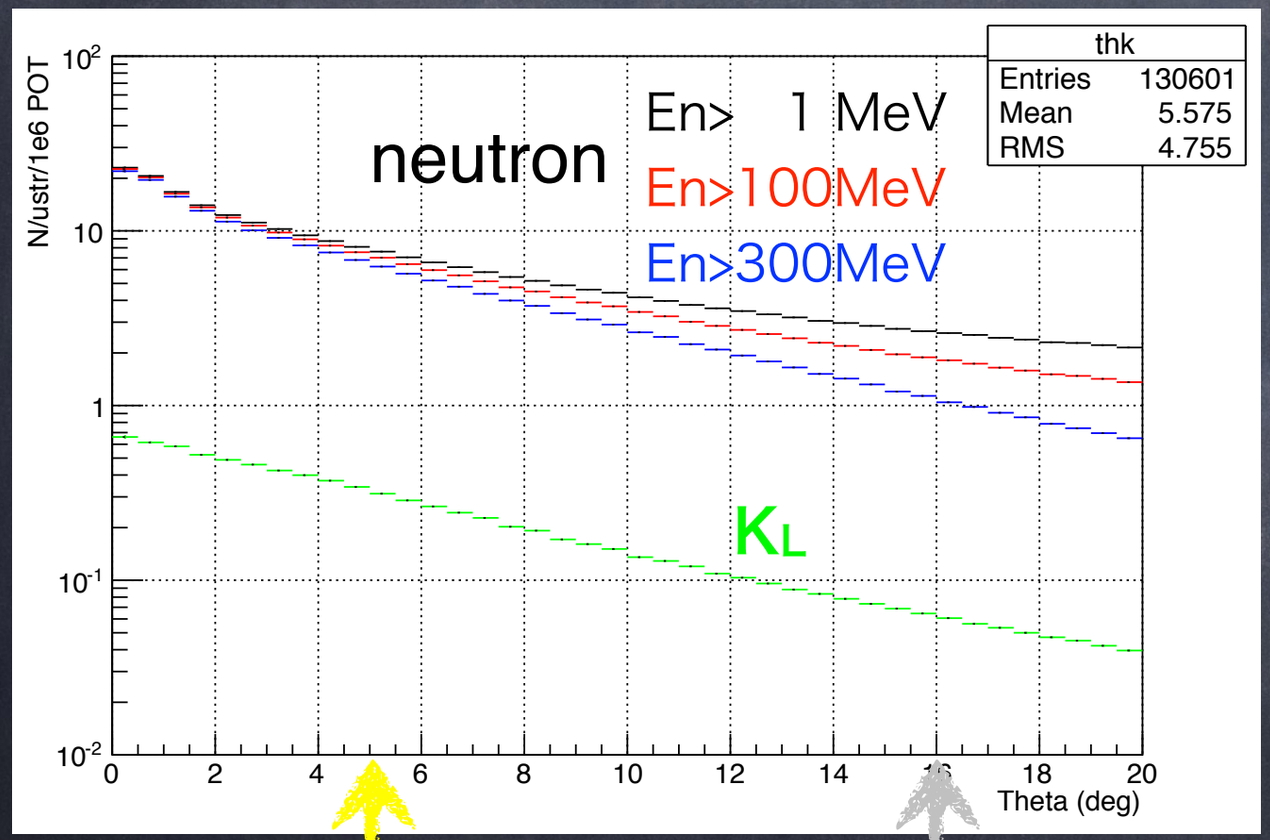
Keys for KOTO Step-2

- To obtain higher kaon flux, a smaller production angle is preferable;
  16 degree in KOTO => 5 degree
- To catch more kaon decays, a larger and longer detector is necessary
  2m-diameter end-cap in KOTO => 3m
  2m-long fiducial region in KOTO => 13m
  (A harder KL spectrum is better.)

Yield, n/K vs angle

(Target simulation)

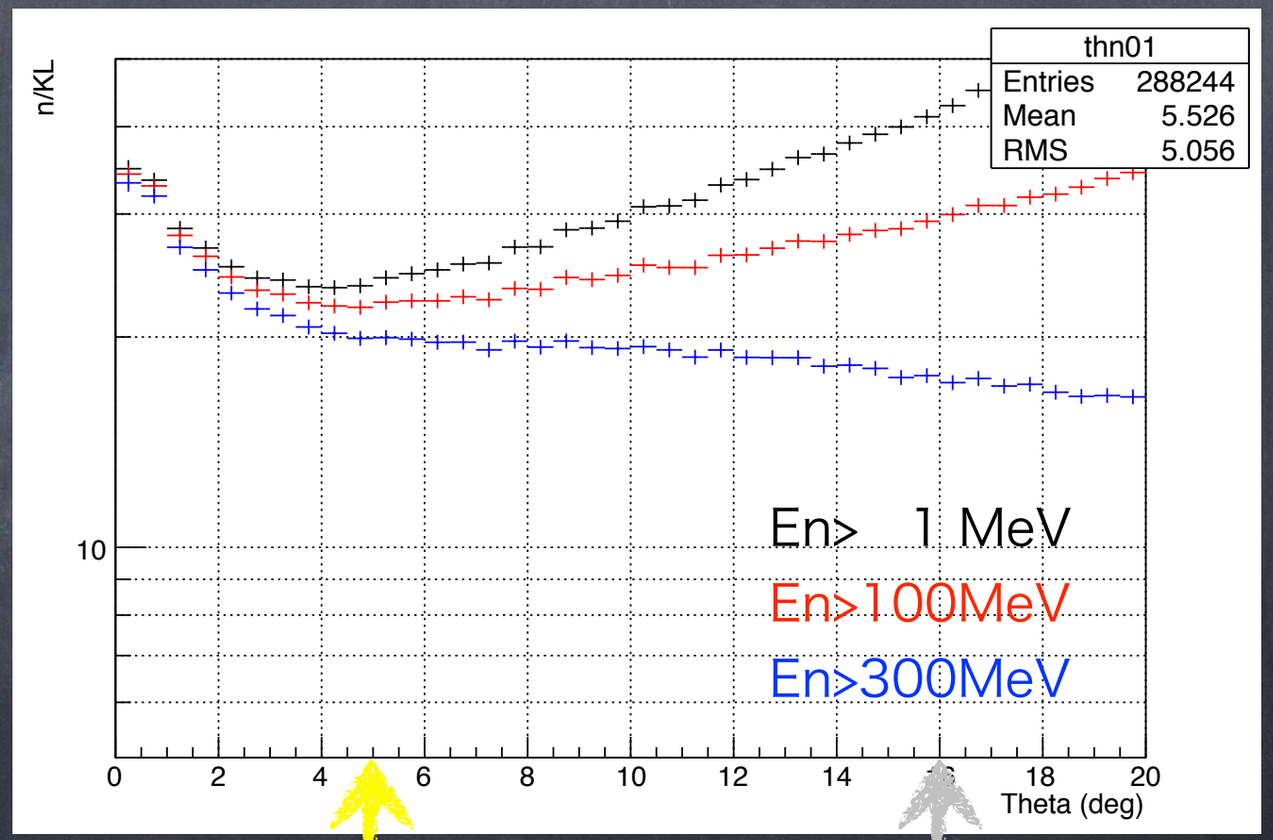
Yield



5 degree
Step 2

16 degree
KOTO

n/KL ratio

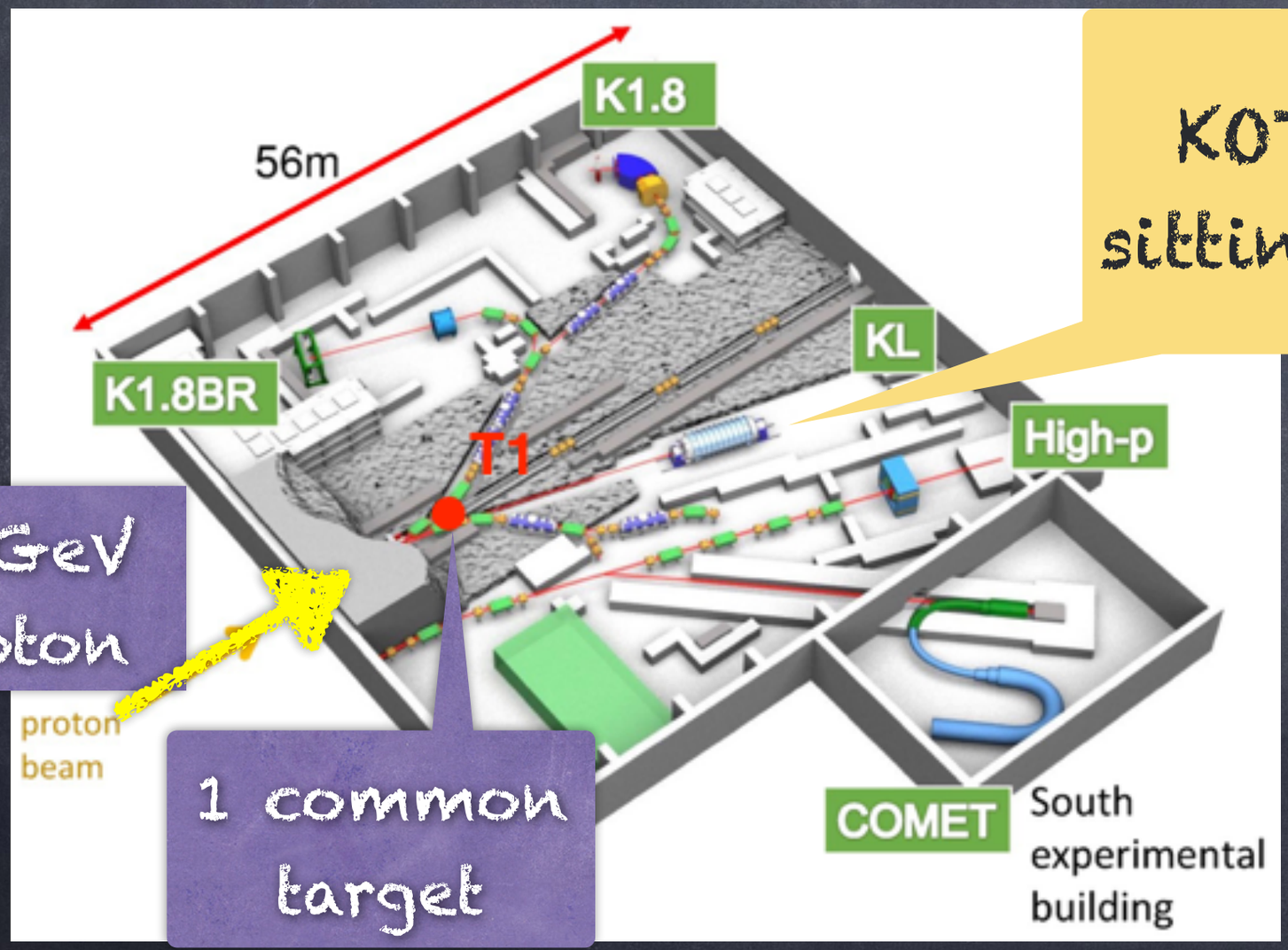


5 degree
Step 2

16 degree
KOTO

Experimental hall now

Hadron Experimental Facility



KOTO is sitting here

30GeV proton

1 common target

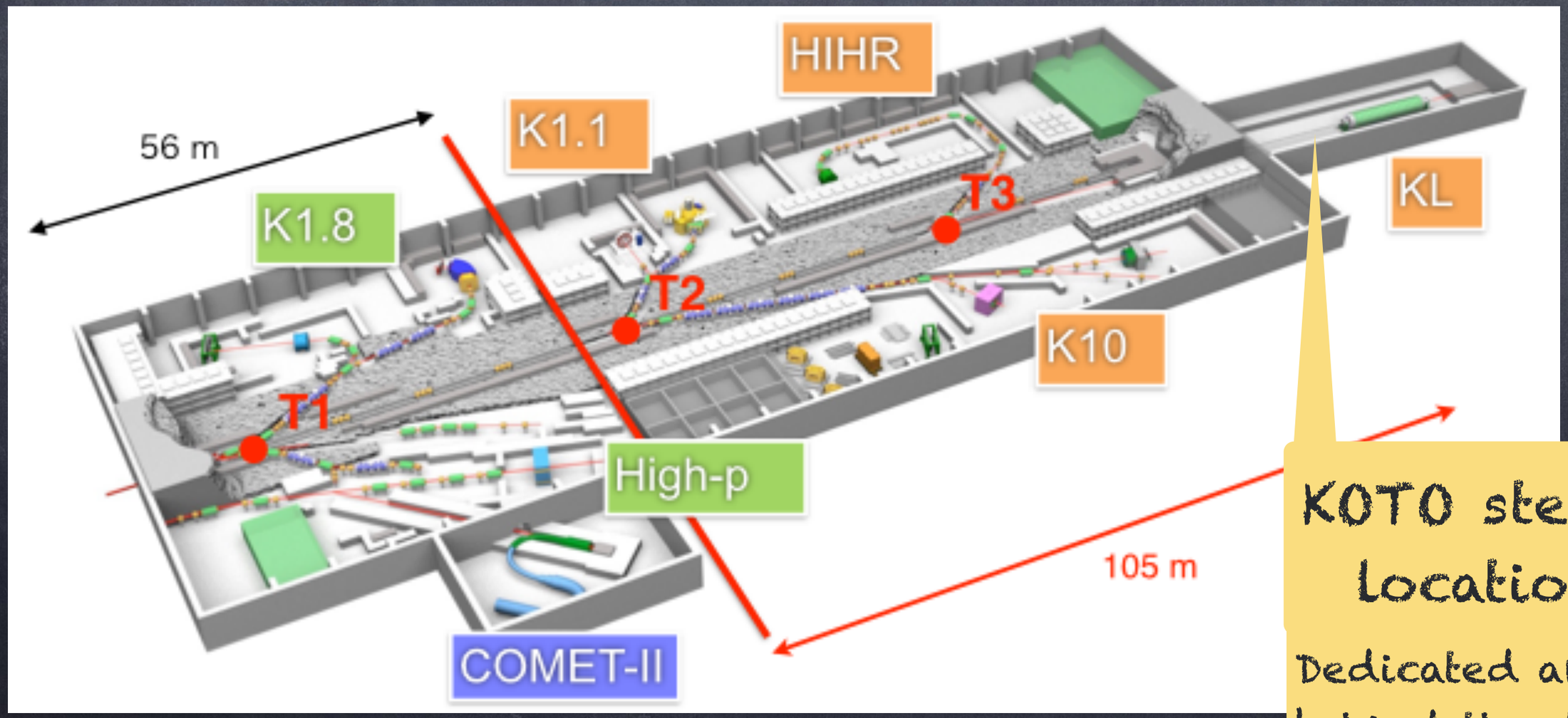
To accommodate our ideas, a facility upgrade is necessary.

Gray region: cutaway view inside the radiation shield

Hadron Hall Extension

Extend Hadron Experimental Facility

More targets, more beam lines



KOTO step-2 location

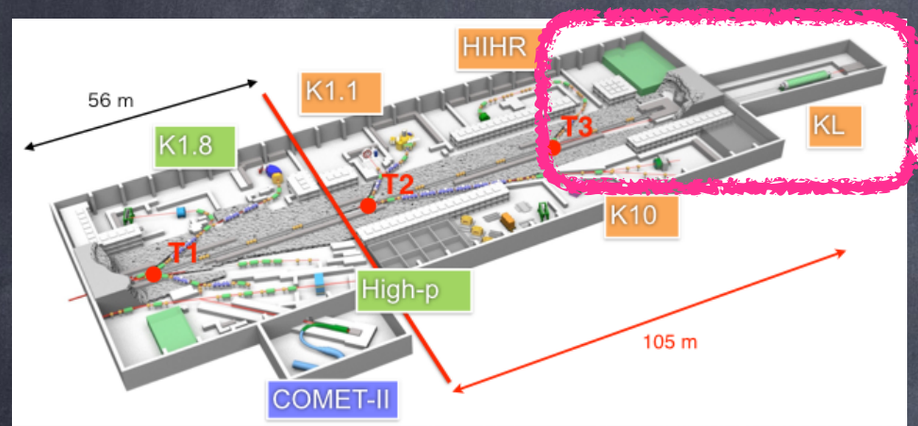
Dedicated annex behind the dump

Side Story

Hadron Hall Extension

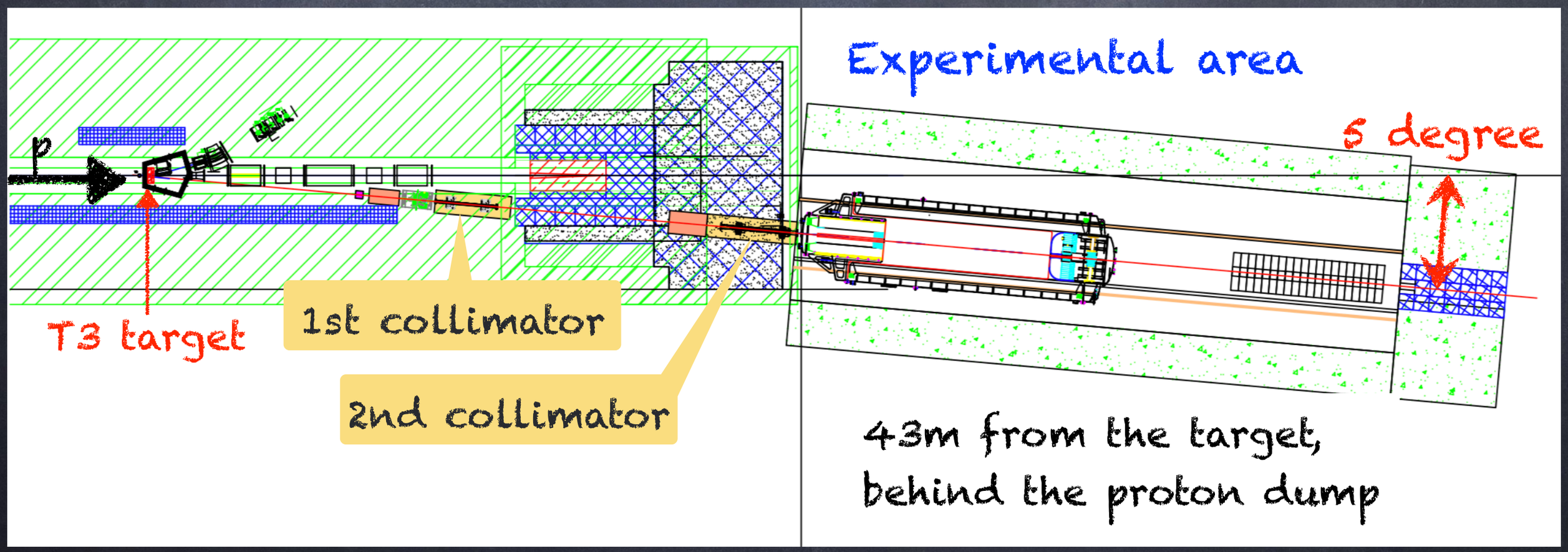
- The Extension of the Hadron Facility is a joint project with nuclear physics community.
  - KOTO step-2 is one of the flagships of the project.
- It is on the list of KEK future large-scale projects, though the assigned priority is not so high at this moment.
- Making a staging plan toward full construction.

Possible beam line



Minimum set as KOTO

- 2 stages of collimator
- 1 sweeping magnet
- Photon absorbing (Pb)

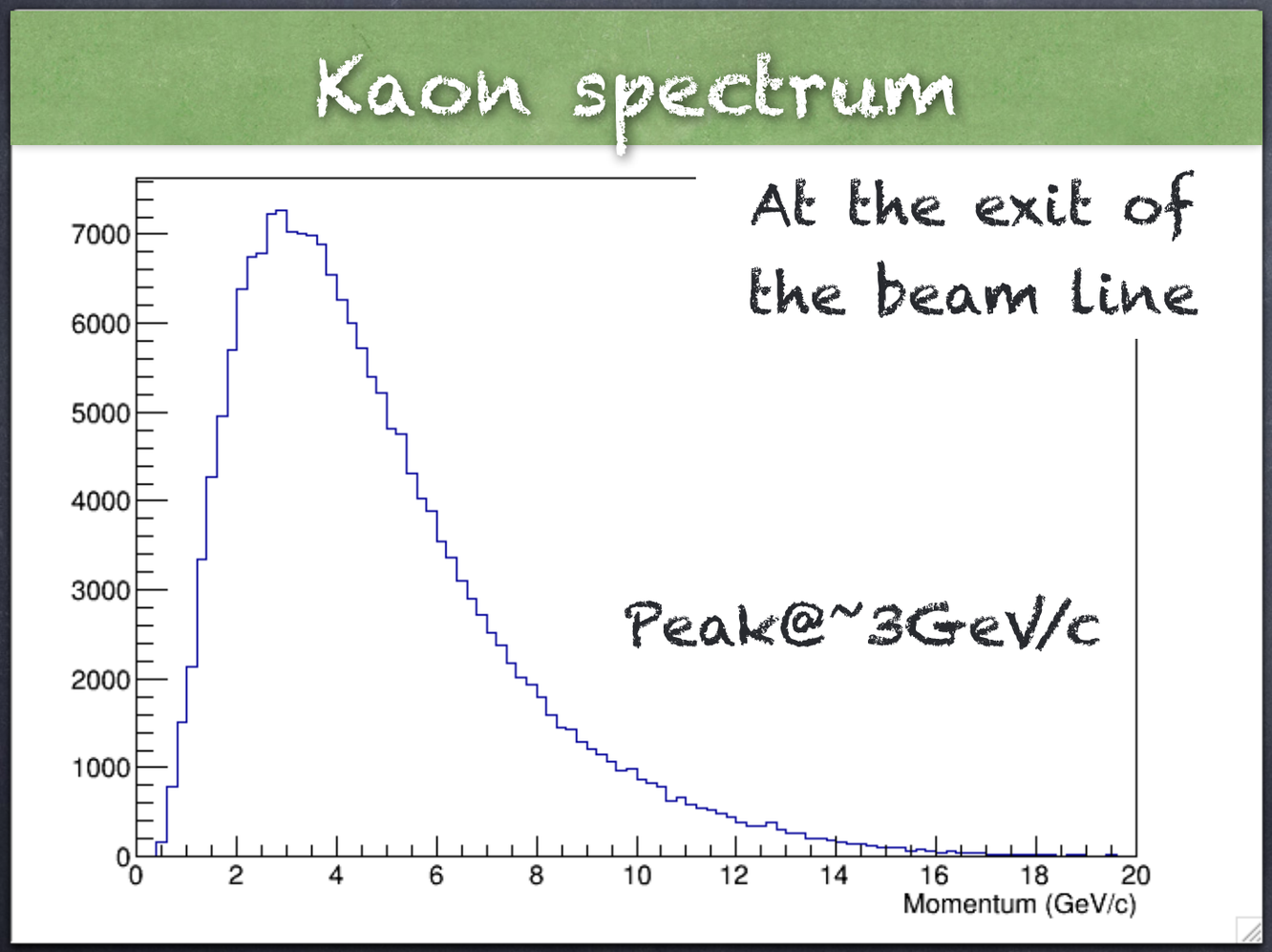


Working assumption (Beam)

BEAM	KOTO	Step-2
Beam power	(50->100kW)	100kW
Target	60mmL gold	102mmL gold
Production angle	16 degree	5 degree
Beam line length	20m	43m
Solid angle	7.8 μsr	4.8 μsr

KL flux and spectrum

Simulation result



N(KL) = $1.1\times10^{7}/2\times10^{13}$ POT

<=> KOTO N(KL) = ~$4.2\times10^{6}/2\times10^{13}$ POT

cf. 100kW = $100\times10^{3}/1.6\times10^{-19}/30\times10^{9}$ = 2.1×10^{13} protons/s

Expected yield

Simulation result

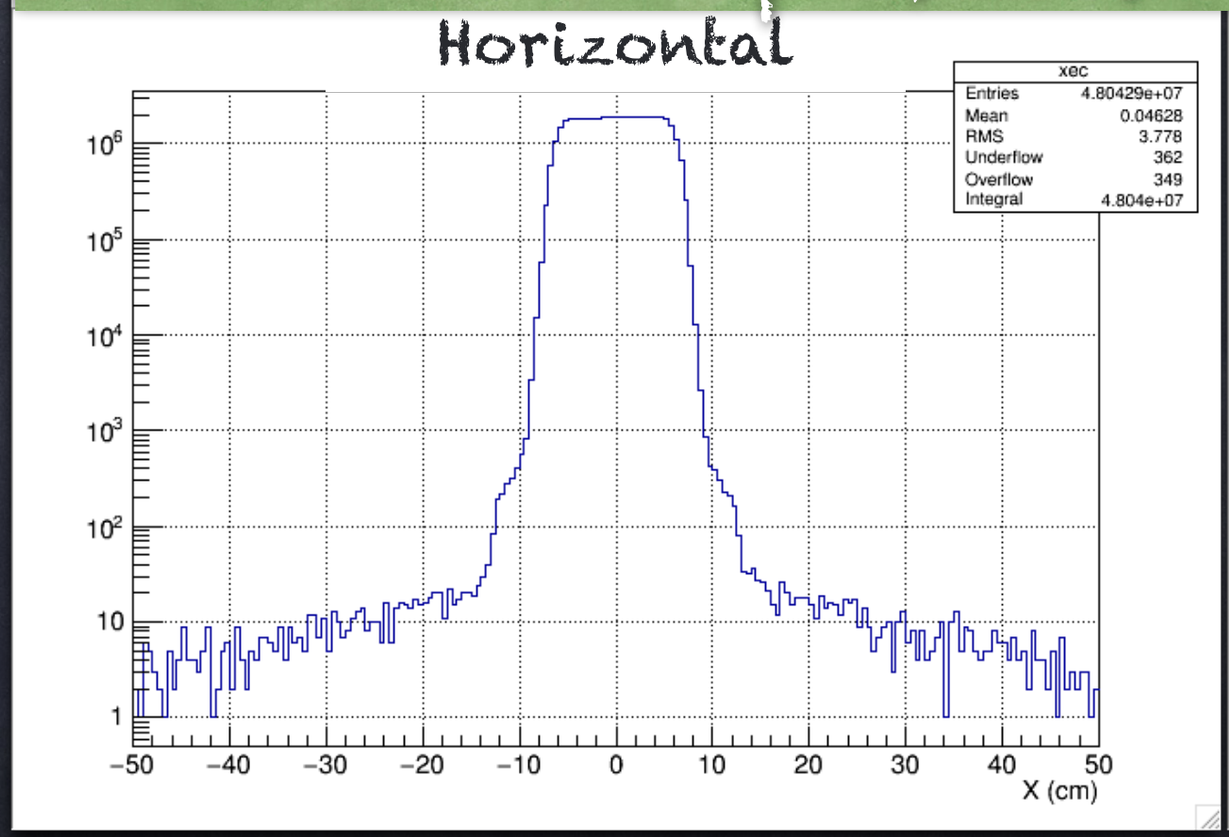
KL		$1.1\times10^{7}/2\times10^{13}$ POT
Photon	>10MeV	$5\times10^{7}/2\times10^{13}$ POT
	>100MeV	$1\times10^{7}/2\times10^{13}$ POT
Neutron	>0.1GeV	$3\times10^{8}/2\times10^{13}$ POT
	>1GeV	$2\times10^{8}/2\times10^{13}$ POT

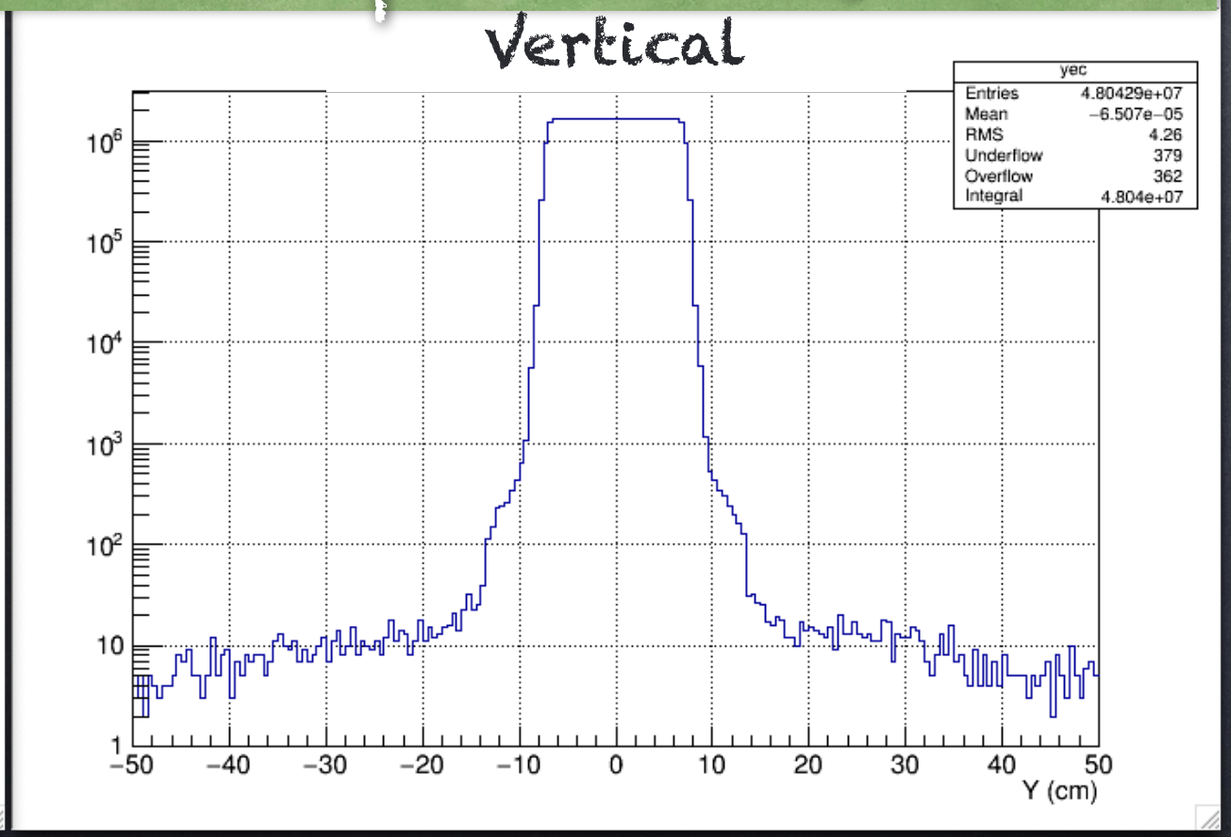
Tough for in-beam detectors ...

Beam profile and halo

Simulation result

Neutron profile (at end-cap detector)





N(halo)/N(core) = 1.8×10^{-4}

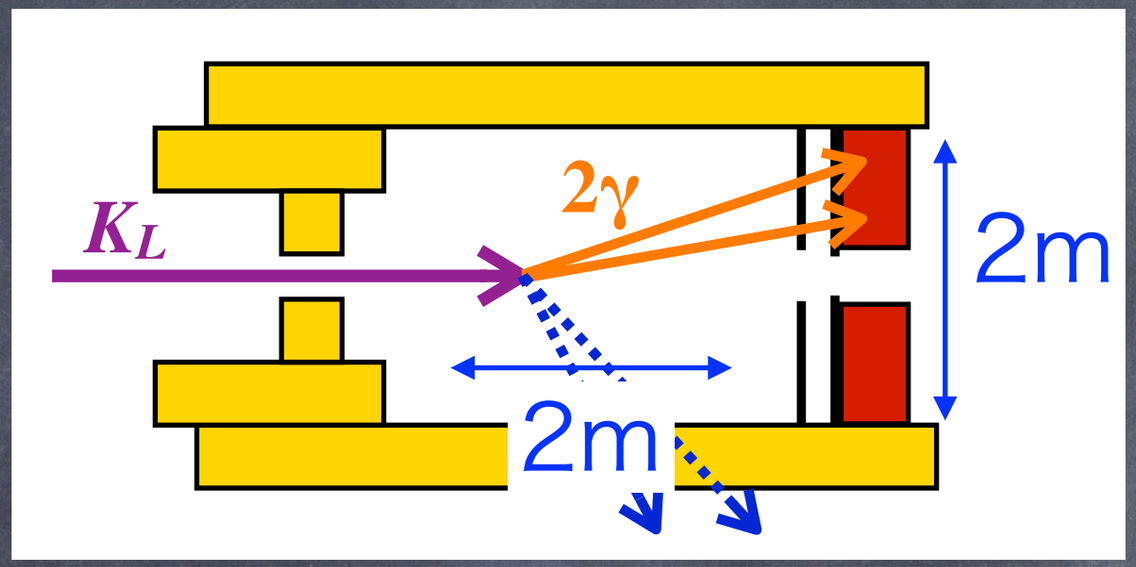
Here, core (halo) = "inside (outside) ± 10cm"

Working assumption (Detector)

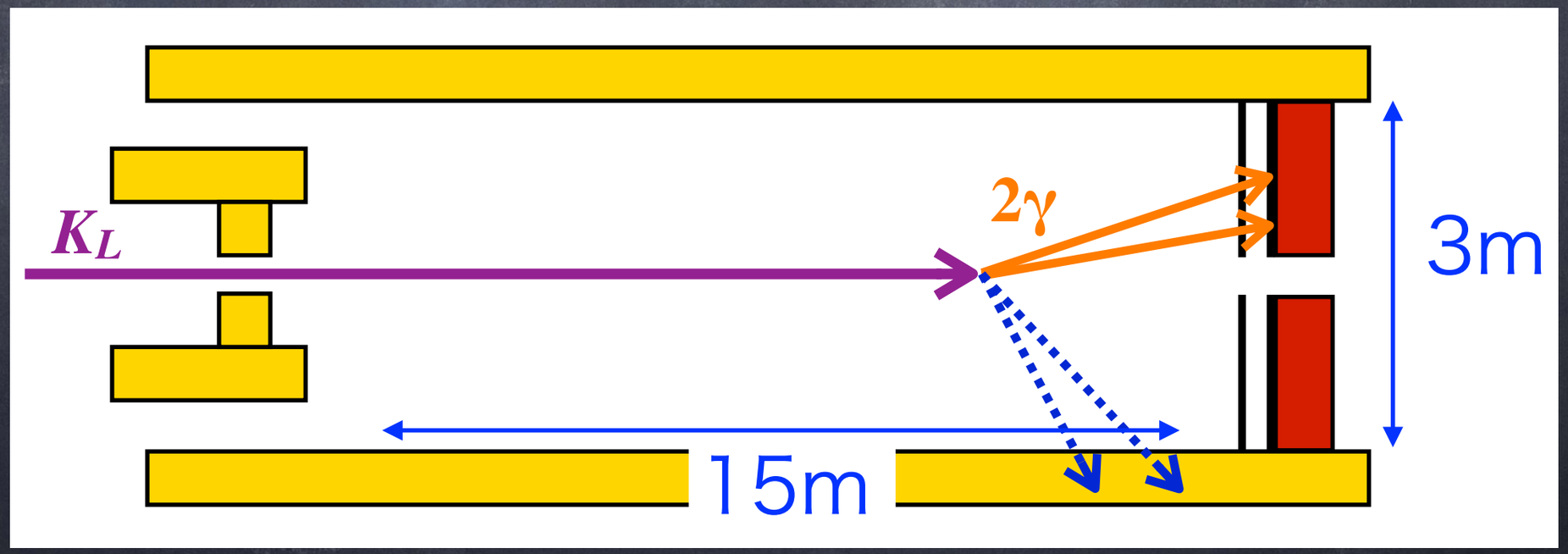
Detector	KOTO	Step-2
End-cap detector	2m diameter	3m diameter
Detector length (up-to end-cap)	~6m	~20m
Length of the Decay region	~2m	~15m
Beam hole at end-cap	~15cm sq.	~20cm sq.

Detector model

KOTO



KOTO Step-2



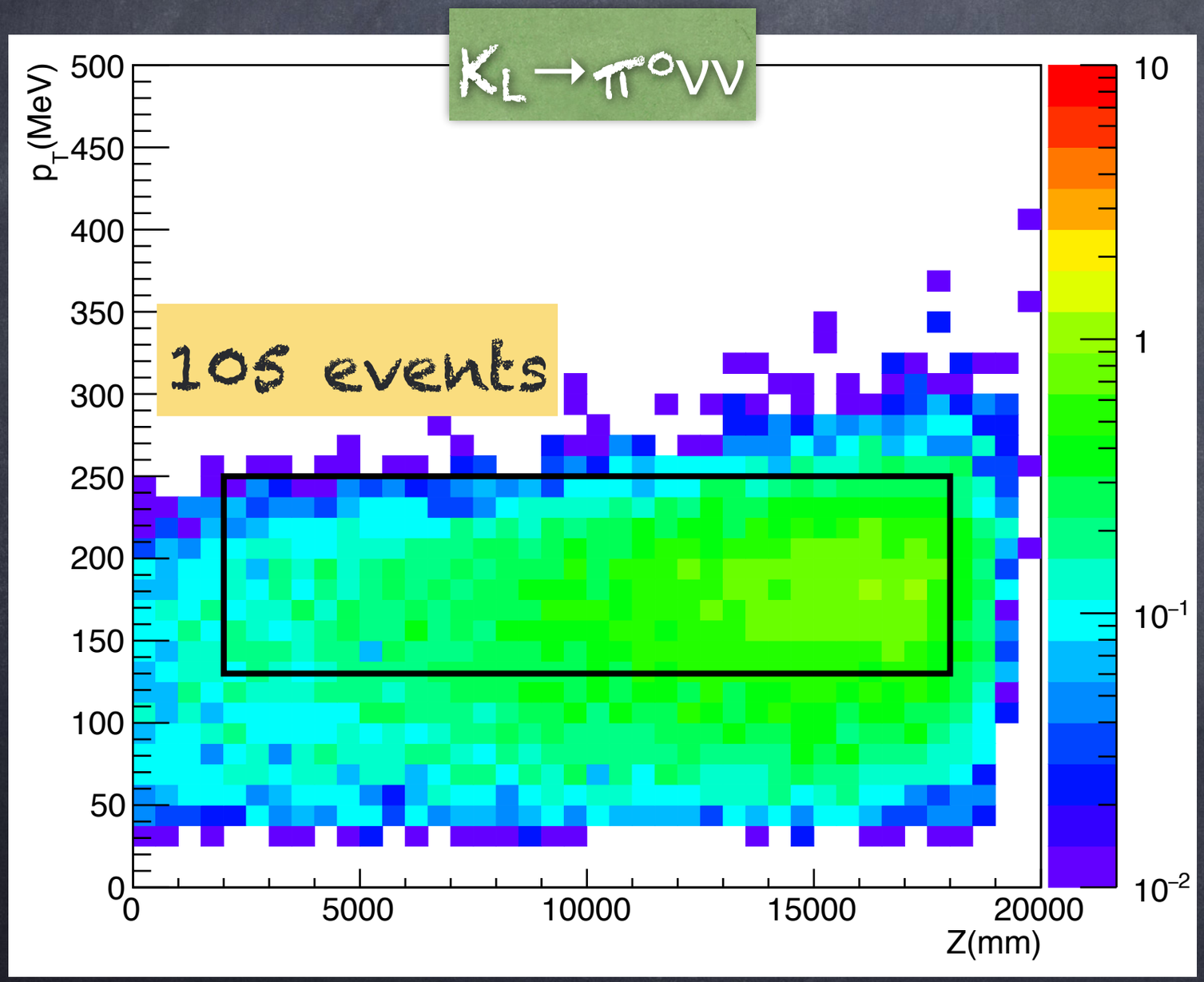
Sensitivity and BG

- Estimated by using "fast simulation"
  - Using inefficiency function for each assumed detector type.
  - Basic kinematic cuts used in KOTO are imposed.

NOT YET OPTIMIZED; JUST FOR DISCUSSION

Signal in PT-Z plot

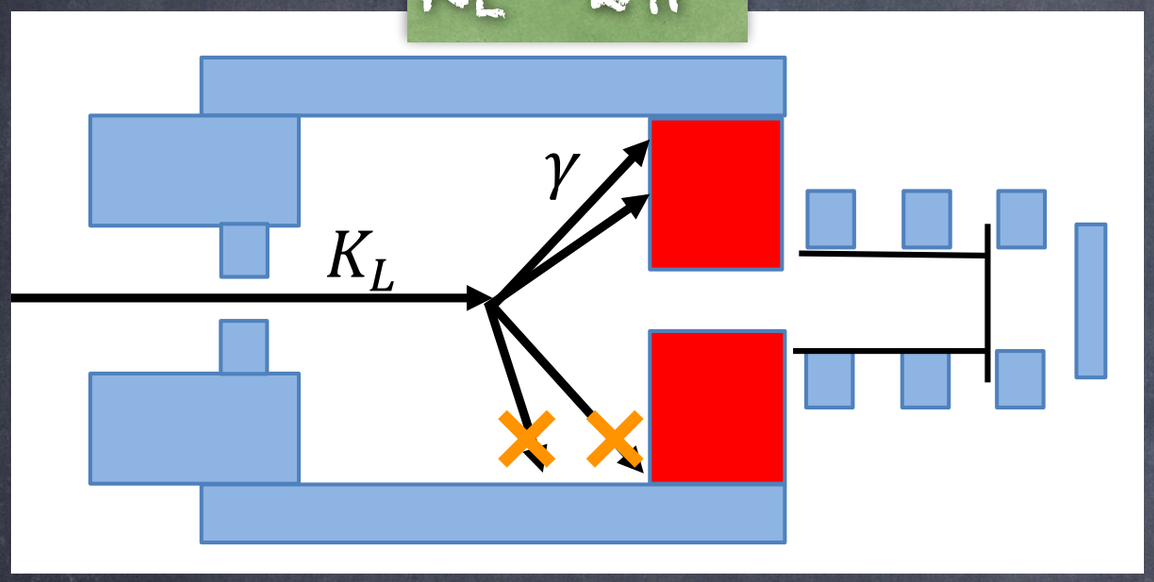
Scaled to equivalent protons for 100kW, 3 snow-mass year running



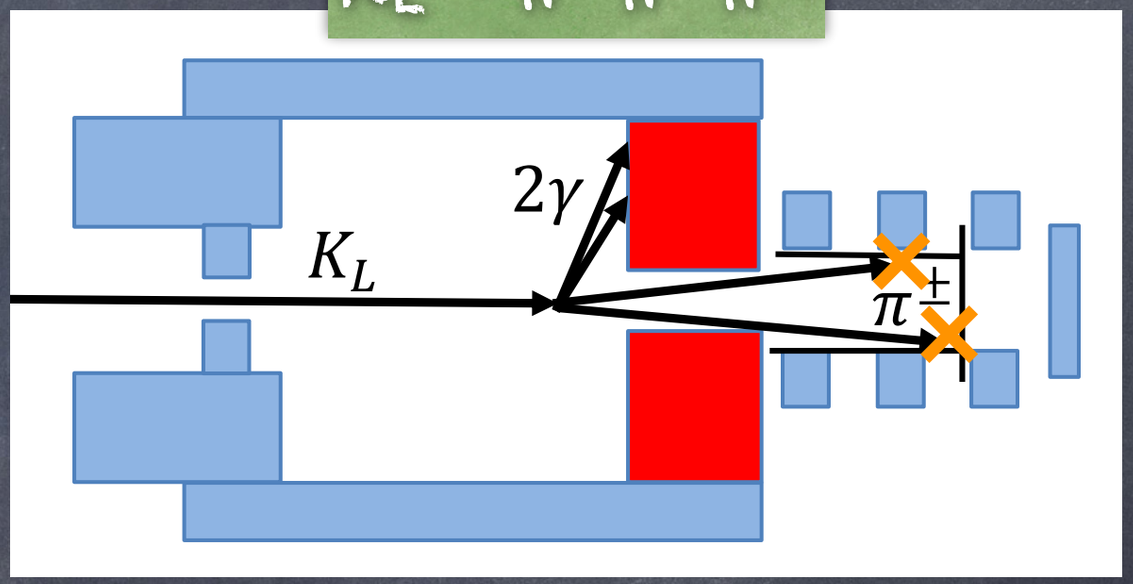
Here a simple rectangular signal box (Z=2 to 18m) is considered, but ...

In real life, Backgrounds!

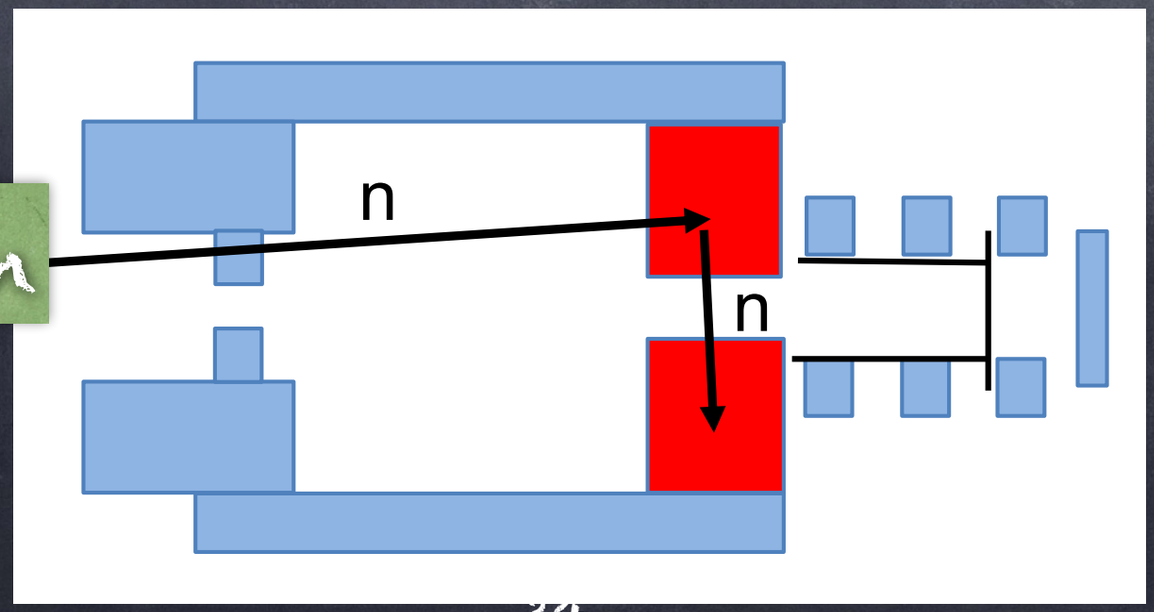
$K_L \to 2\pi^0$



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

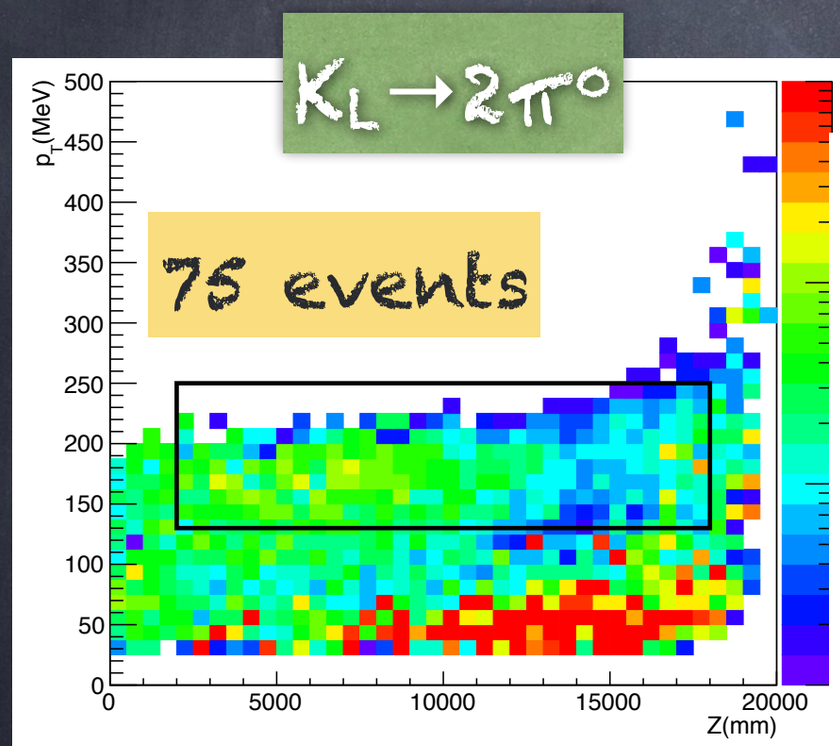


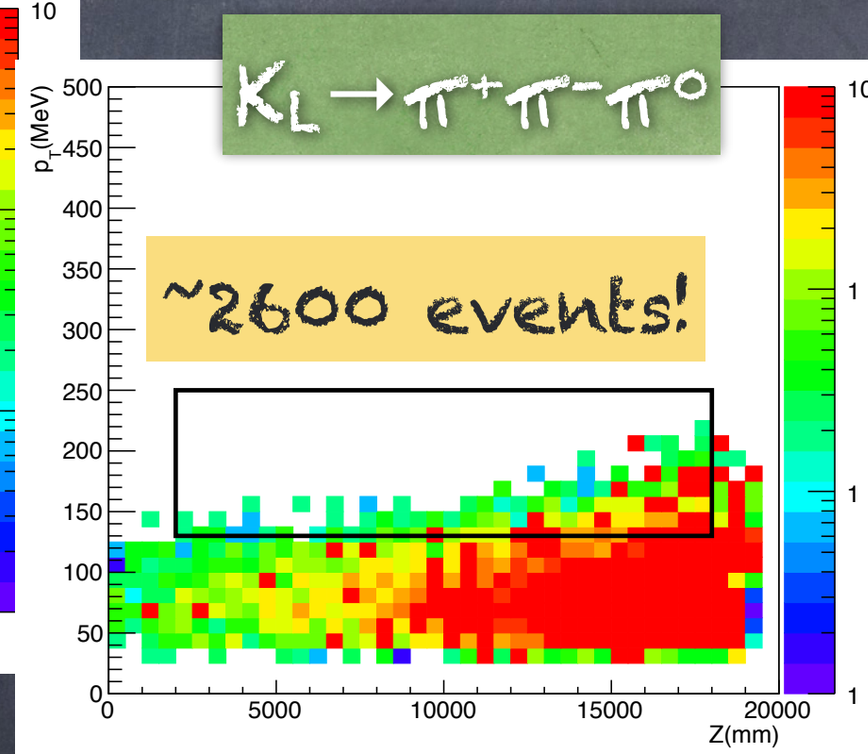
Neutron

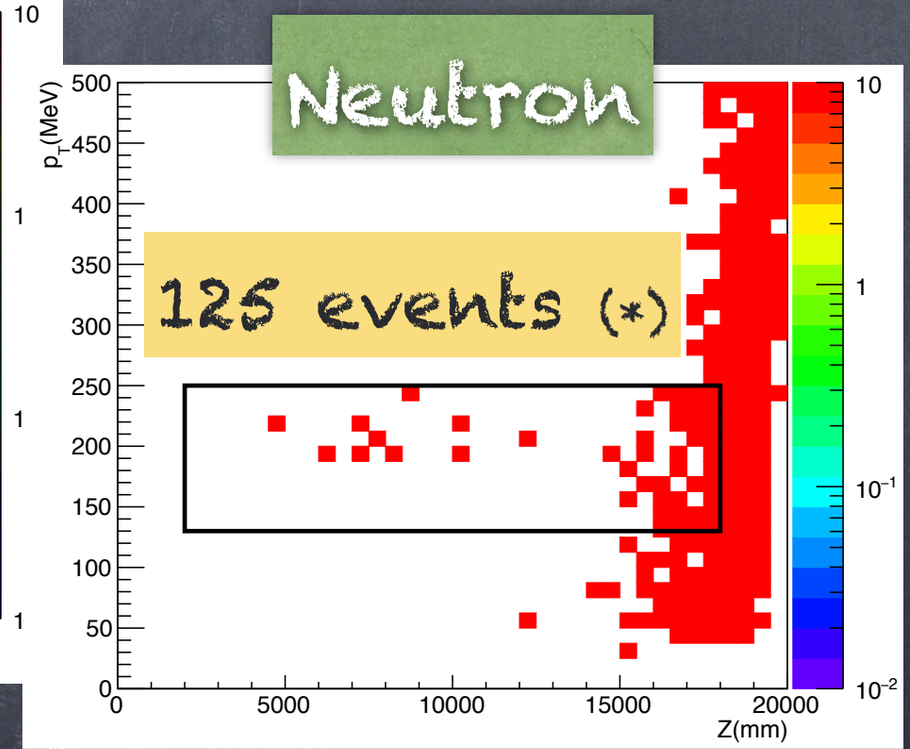


Backgrounds!

Full simulation for neutron interaction with the calorimeter





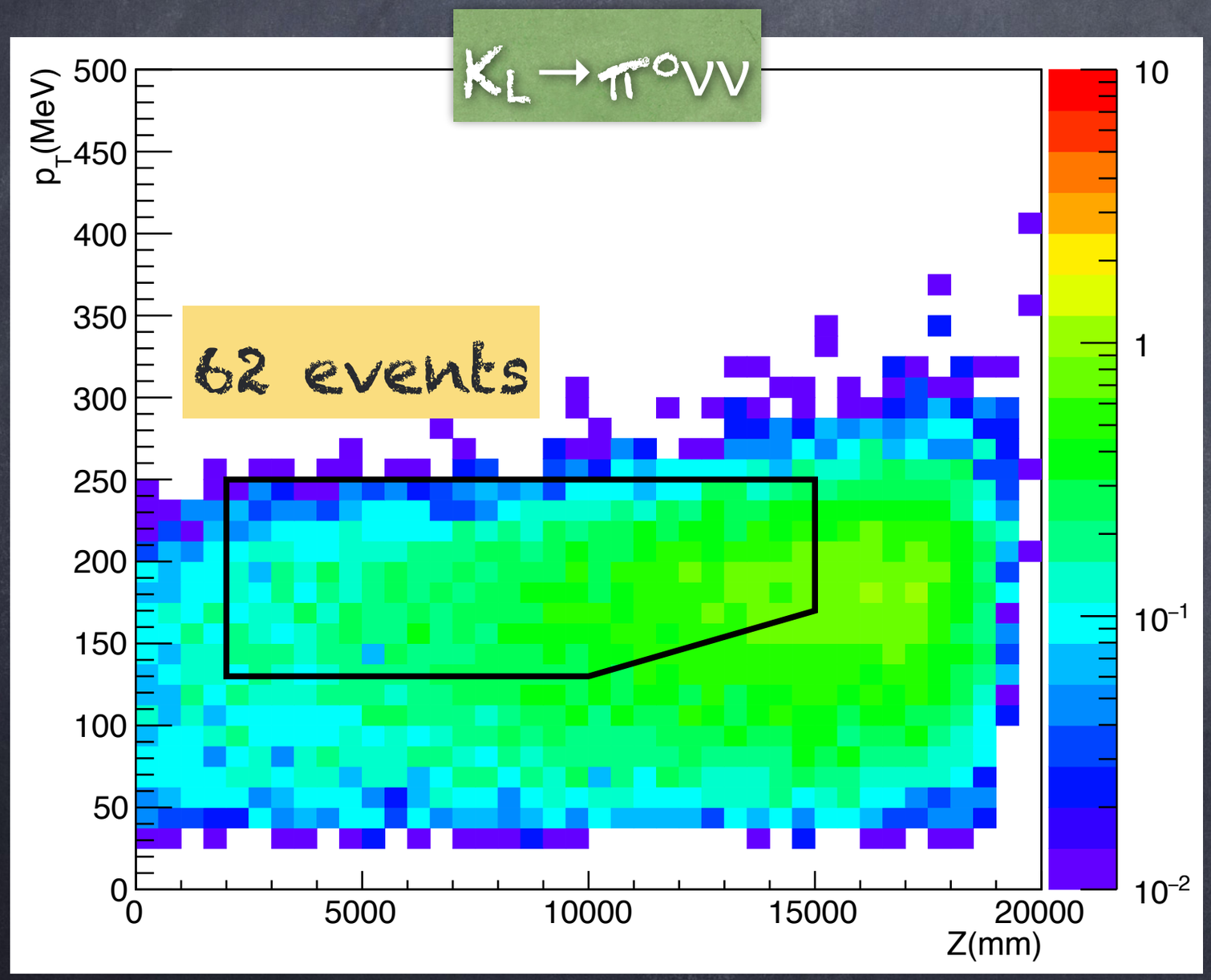


Assumed Veto threshold = 1MeV
(and 6 p.e. for in-beam detector)

(*) Achieved reduction of cluster shape cuts in 2016-18 data analysis (10^{-6}) is assumed.

Pentagon signal box

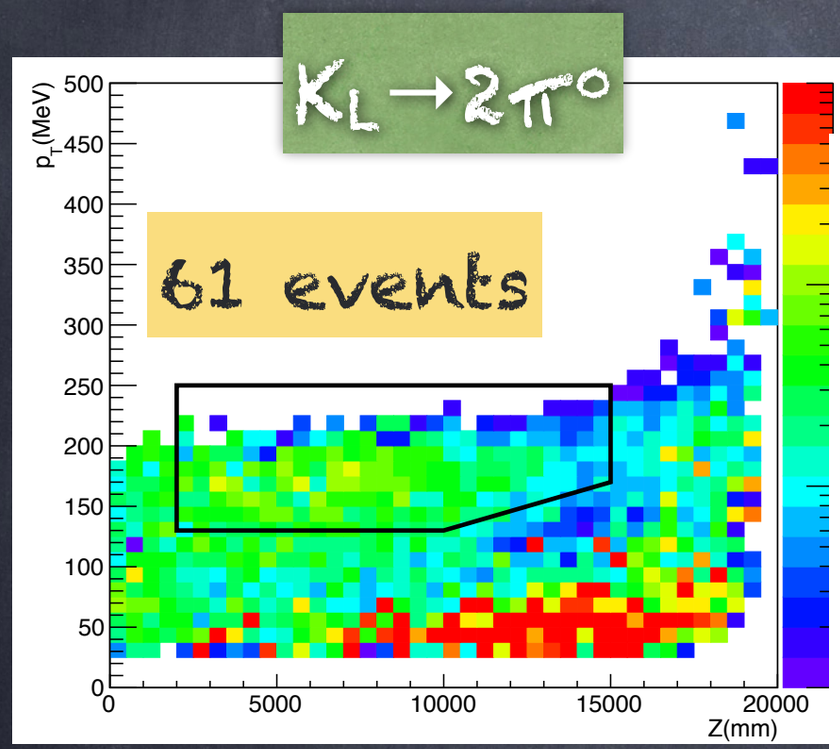
Scaled to equivalent protons for 100kW, 3 snow-mass year running

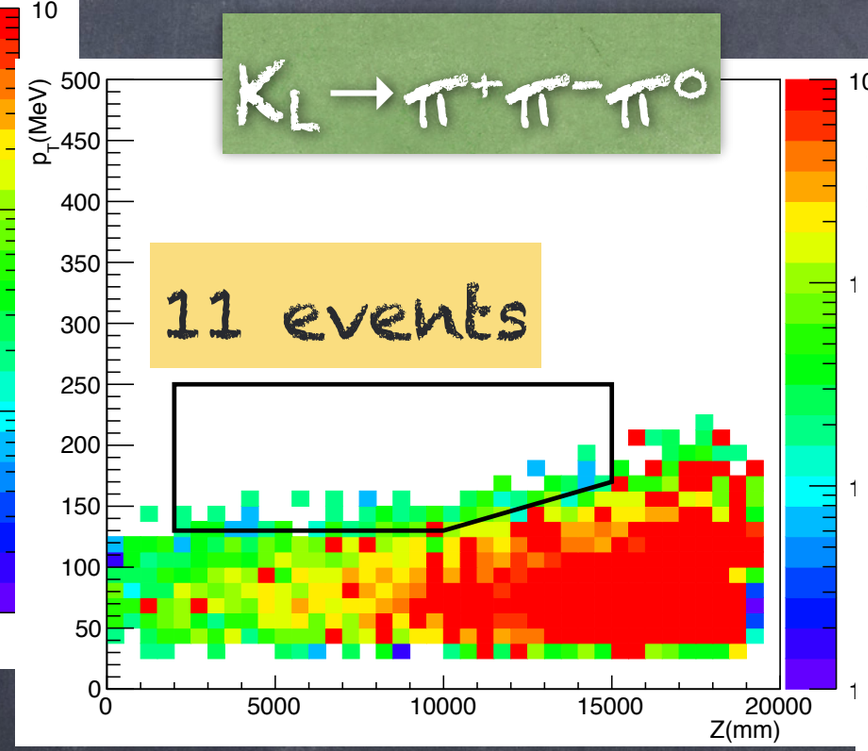


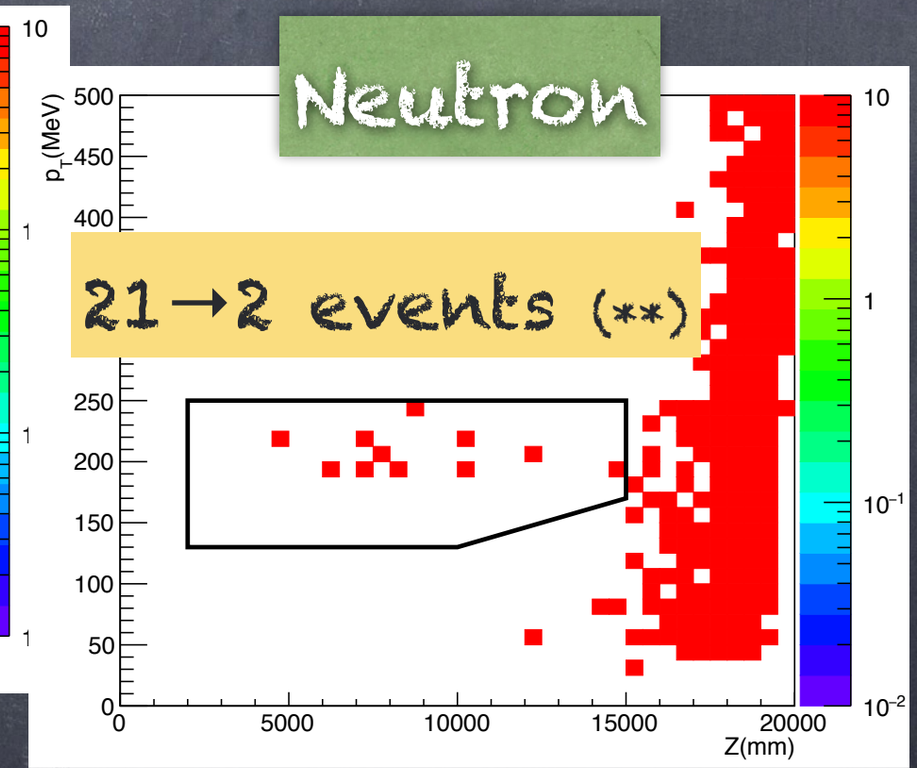
Pentagon signal box

- Cutting Z closed to the calorimeter
- Cutting low PT in large Z

BG with pentagon box







(**) In addition to 10^{-6} reduction by cluster shape cuts, the both-end readout calorimeter will provide 10^{-1} reduction.

Sensitivity and BG

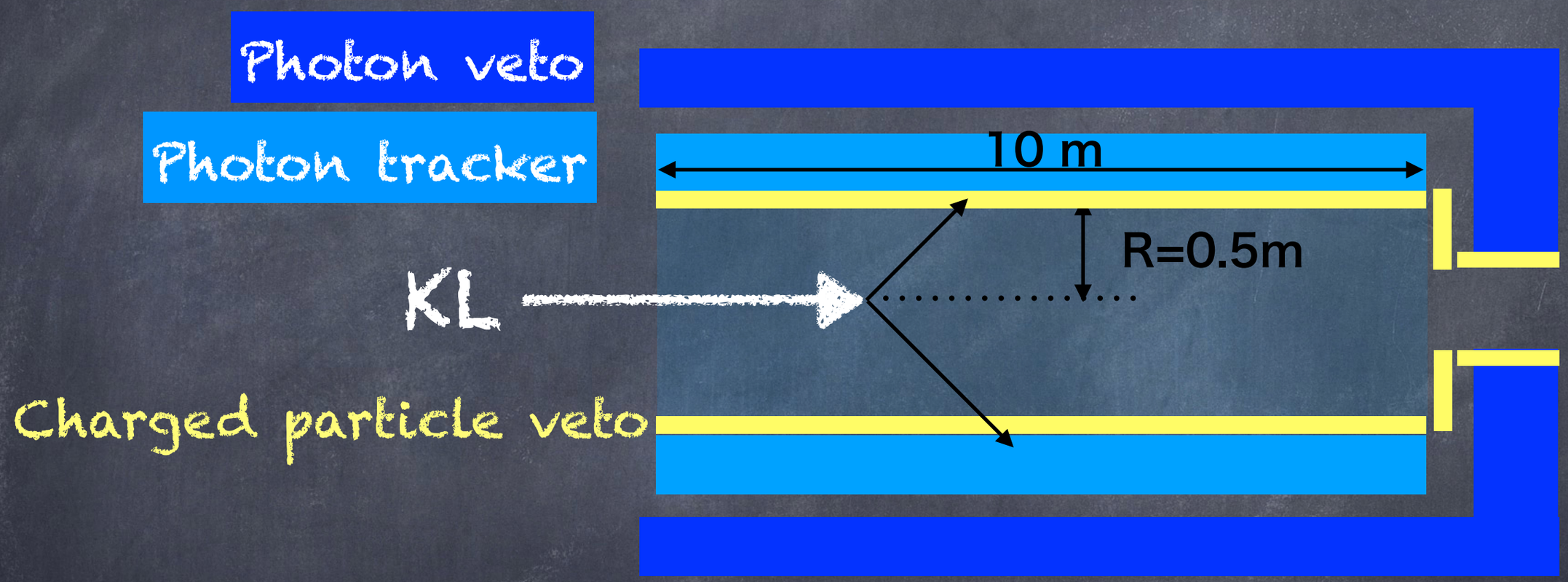
- ~60 SM events with S/N~1
  will be a baseline number.
- To be considered
  - In-beam detector performance
  - Signal loss due to accidental hits
  - ...

Yet another idea?

- The base line plan for Step 2 requires the extension of the facility.
- BUT, it as a whole will take a time and a large cost:
  7(?) years and ~200(?) Oku-Yen
- It is better we have an option that can be done without (full) extension...

Yet another idea?

"barrel detection"



- Decay probability : KOTO 3% -> THIS 19%
- Geometrical acceptance: KOTO 27% -> THIS 72%

×18 gain

Pros: Current beam line can be used.
Low momentum is OK. Extendable.

Cons: What detector??

Summary

- We start considering a future $K_L \to \pi^0 \nu\nu$ experiment at J-PARC that can observe O(100) SM events.
- With a simple working model, we expect ~60 SM events with S/N~1 with 100kW beam and 3 snow-mass years running.

Summary

- A base plan is considered as a part of the hadron facility extension project. We also consider a way to make new experiment without the extension as an option.
- For realization, many things we have to consider, many ideas we need.
  PLEASE JOIN US and have fun to think and carry out this challenging subject.