Prospects in Kaon Decay Physics

H. Nanjo (Osaka University)

for the KOTO, LHCb, and NA62/KLEVER collaborations and the US Kaon Interest Group

Snowmass Summer Meeting 2022 2022/07/19

Snowmass White Paper

- https://arxiv.org/abs/2204.13394

Searches for new physics with high-intensity kaon beams

Contributed paper to Snowmass 2021

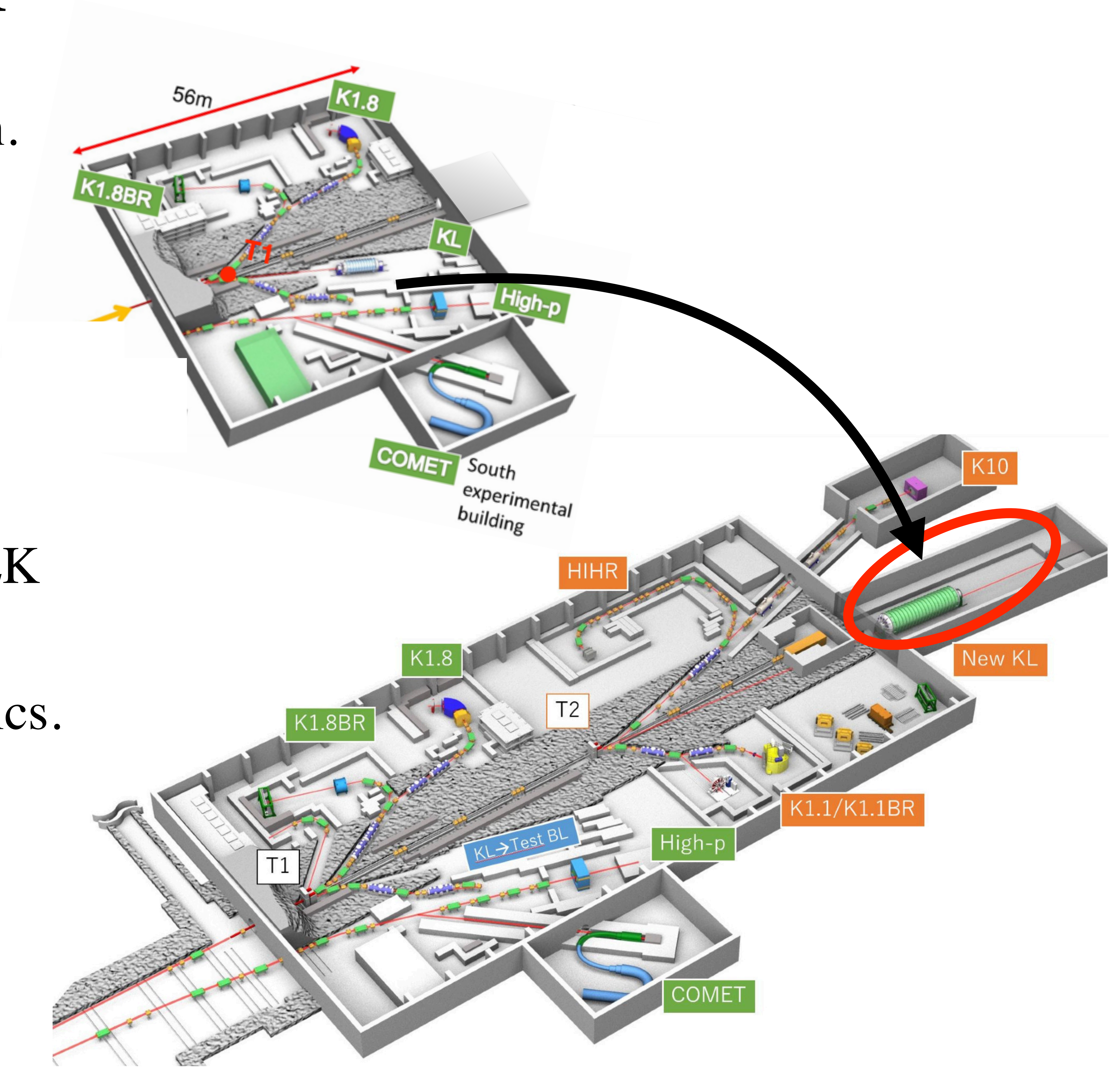
The KOTO[1], LHCb[2], and NA62/KLEVER[3] Collaborations
and the US Kaon Interest Group[4]

28 April 2022

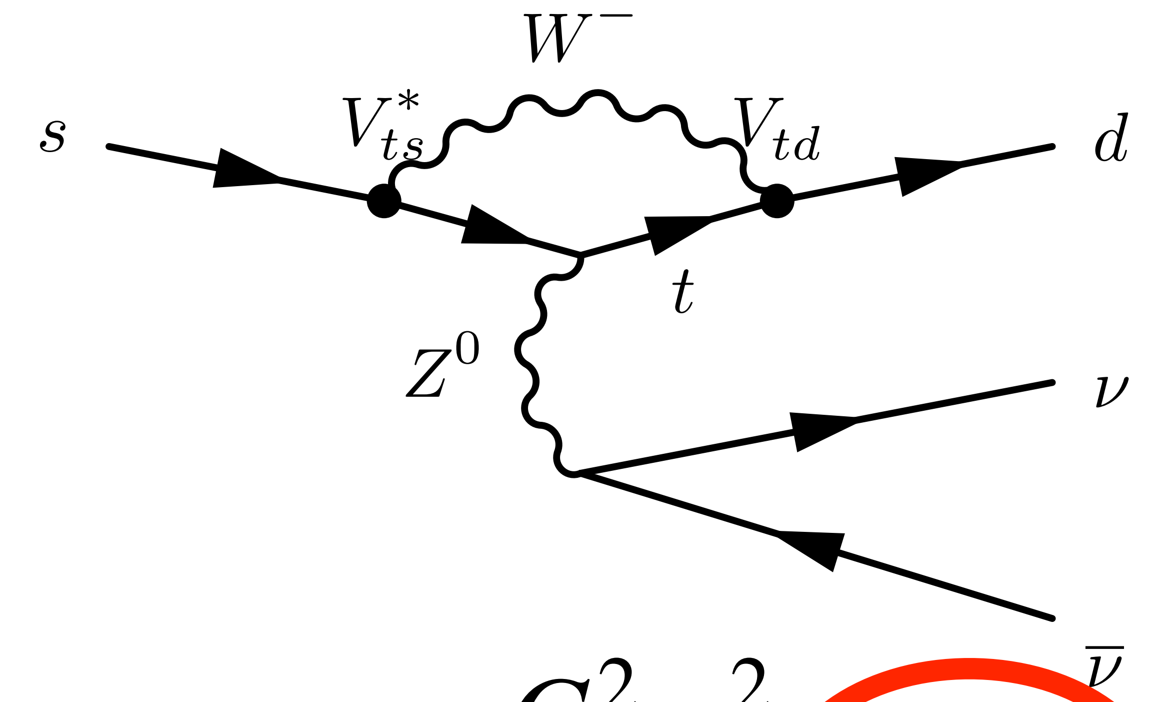
[4]W. Altmannshofer, L. Bellantoni, E. Blucher, G.J. Bock, N.H. Christ, D. Denisov, Y. Grossman, S.H. Kettell, P. Laycock, J.D. Lewis, H. Nguyen, R. Ray, J.L. Ritchie, P. Rubin, R. Tschirhart, Y. Wah, E. Worcester, E.D. Zimmerman;

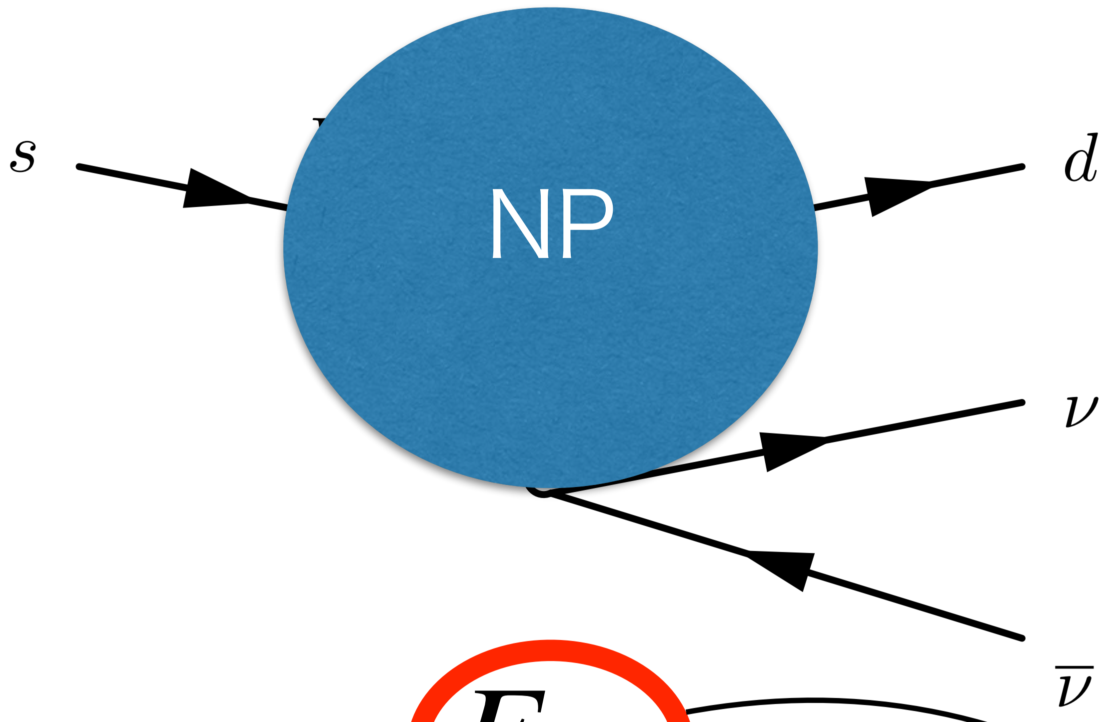
News on KEK Project Implementation Plan 2022

- KEK : Largest laboratory in particle physics in Japan.
- Released the project implementation plan in JFY2022-2027 at June 24.
  - https://www.kek.jp/wp-content/uploads/2022/07/KEK-PIP2022.pdf
  - Extension of J-PARC hadron experimental facility has been selected as the 1st priority project for KEK to make new budget requests.
  - This gives a large impact on the future Kaon physics.
    - KOTO step-2 is planned at the extend hadron experimental facility at J-PARC.
    - aiming at measurement of $\mathscr{B}(K_L \to \pi^0 \nu\nu)$ with ~40-event observation.



Kaon decay : s → d





$$\mathscr{M} \sim \frac{G_F^2 m_t^2}{16\pi^2}(V_{ts}^* V_{td}) + \frac{F_{NP}}{\Lambda^2}\alpha_{NP}^2$$

can be $\mathscr{O}(1)$

Characteristic structure !

$$\begin{array}{c|ccc} & d & s & b \\ u & 1 & \lambda & \lambda^3 \\ c & -\lambda & 1 & \lambda^2 \\ t & \lambda^3 & -\lambda^2 & 1 \end{array}$$

Dominant top contribution!

$\lambda \sim 0.23$

Most Suppressed!

$\times 1/100$

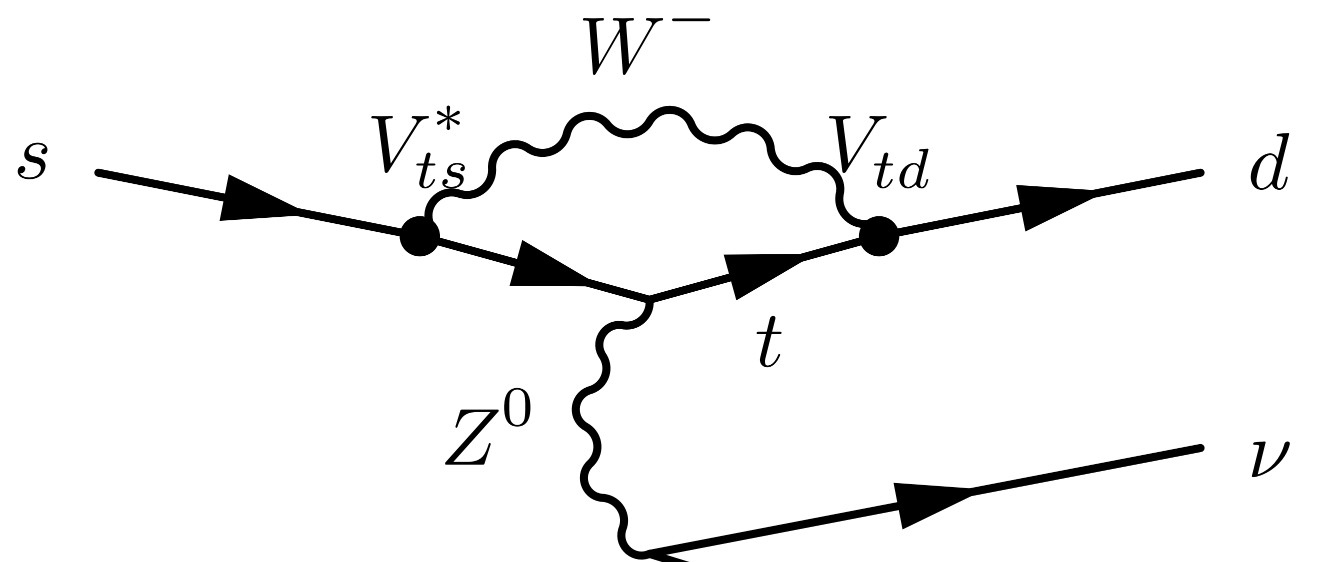
$$|V_{ts}^* V_{td}| \sim 5 \times 10^{-4} \ll |V_{tb}^* V_{td}| \sim 10^{-2} < |V_{tb}^* V_{ts}| \sim 4 \times 10^{-2}$$

s→d   b→d   b→s

s→d : SM : Flavor transition : Most suppressed
NP : Flavor transition : O(1)? → High energy scale O(100TeV)

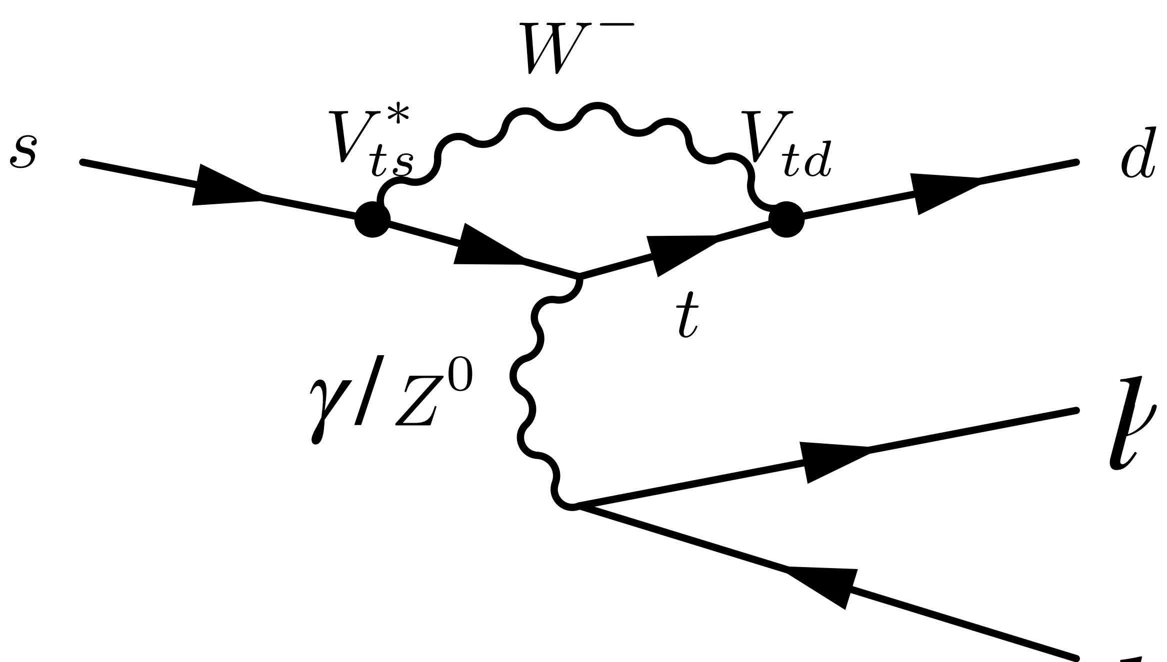
Rare kaon decay observables

$K \to \pi\nu\nu$



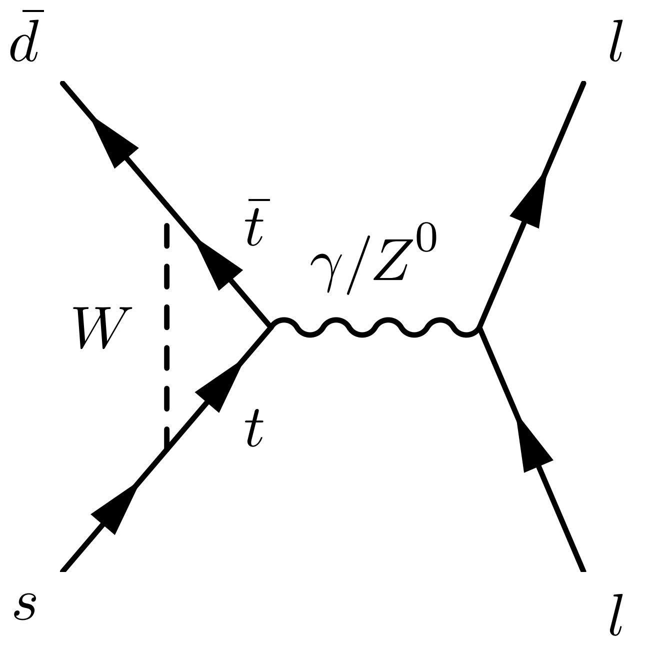
Golden mode
Short distance is dominant
Precise, Suppressed in SM
NP : $\mathcal{O}(100)$ TeV

$K \to \pi + [ee \text{ or } \mu\mu]$



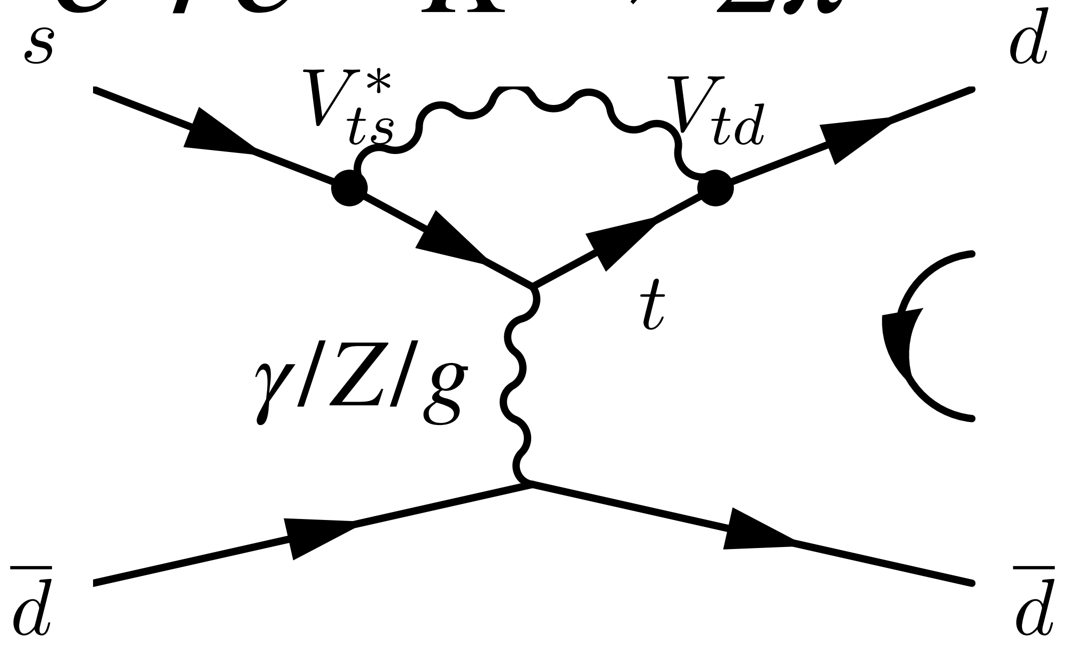
Suppressed in SM
Larger uncertainty in SM
Large room of search in K_L decay

$K \to \mu\mu$ or ee



Suppressed in SM
Large room of search
SD contribution can be extracted through interference

ϵ'/ϵ $K \to 2\pi^0$

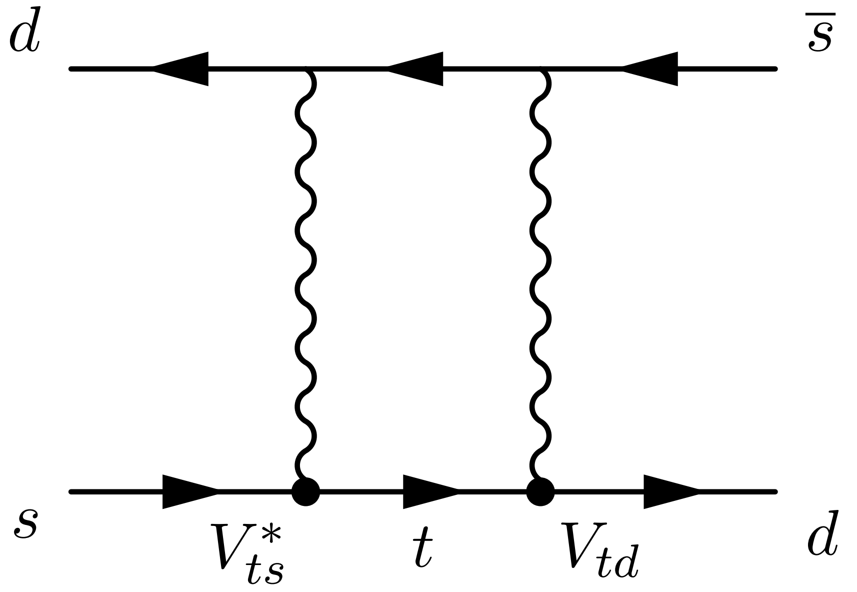


Re ϵ'/ϵ = $(16.6 \pm 2.3) \times 10^{-4}$
Consistent to SM : $(15 \pm 5) \times 10^{-4}$

Mode	SM	Measurment	
$K^+ \to \pi^+\nu\nu$	$(8.4 \pm 1.0) \times 10^{-11}$	$10.6^{+4.1}_{-3.5} \times 10^{-11}$	
$K_L \to \pi^0\nu\nu$	$(3.4 \pm 0.6) \times 10^{-11}$	$< 3 \times 10^{-9}$	$\not{CP}$
$K_L \to \pi^0 e^+e^-$	$3.54^{+0.98}_{-0.85}(1.56^{+0.62}_{-0.49}) \times 10^{-11}$	$< 2.8 \times 10^{-10}$	$\not{CP}$
$K_L \to \pi^0\mu^+\mu^-$	$1.41^{+0.28}_{-0.26}(0.95^{+0.22}_{-0.21}) \times 10^{-11}$	$< 3.8 \times 10^{-10}$	$\not{CP}$ w/ LD
$K_S \to \mu^+\mu^-$	$(5.18 \pm 1.50_{\mathrm{LD}} \pm 0.02_{\mathrm{SD}}) \times 10^{-12}$	$< 2.1 \times 10^{-10}$	$\not{CP}$ w/ LD

Dark sector : $K \to \pi\phi, K \to lN, K \to \gamma A', \cdots$
Lepton number/flavor violation : $K \to \pi l^+ l^+, K \to \pi l_\alpha l_\beta, \cdots$
Correlation to B-anomalies, g-2, …

ϵ_K $K^0 \leftrightarrows \overline{K}^0$

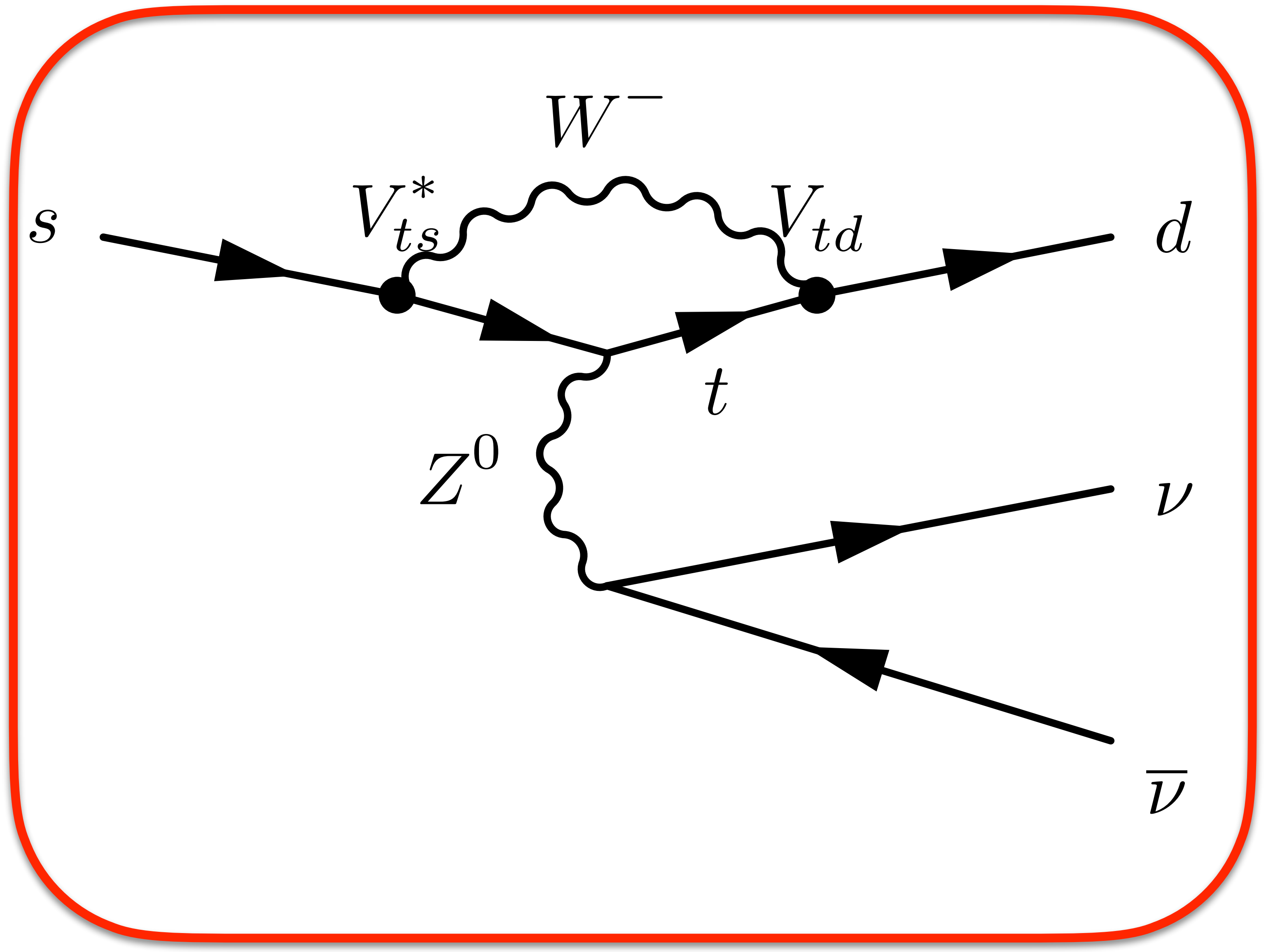


Constraining NP

Physics in $K \to \pi\nu\nu$

$K \to \pi\nu\nu$ in SM

	$K_L \to \pi^0\nu\bar{\nu}$	$K^+ \to \pi^+\nu\bar{\nu}$
Calculated BR (SM)	$(3.4 \pm 0.6) \times 10^{-11}$	$(8.4 \pm 1.0) \times 10^{-11}$
	Buras et al JHEP11(2015)33	
Theoretical error	Mainly Parameter error from CKM matrix elements	
	$< 2\,\%$	$< 4\,\%$
Quarks in loop	top	top, charm



Precise and Suppressed SM process(BG)
→BSM Physics search(Signal)😀

High energy reach fro NP
$\mathcal{O}(100)$ TeV

Correlation between K_L and K^+ in $K \to \pi\nu\nu$

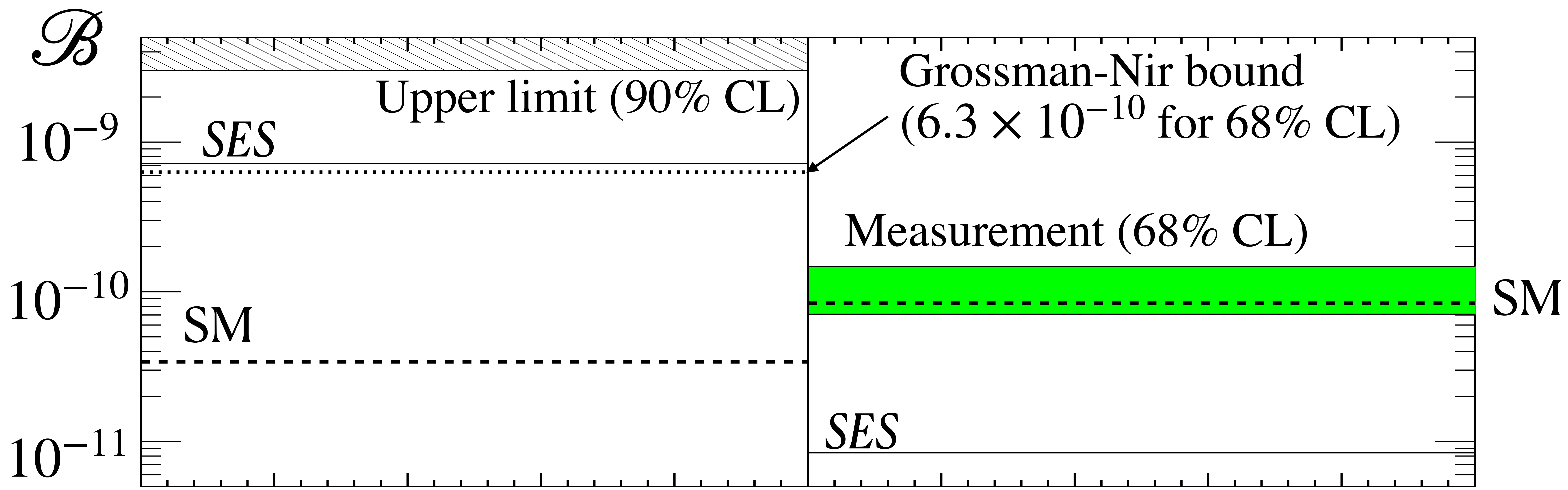
	$K_L \to \pi^0\nu\bar{\nu}$ $\left(K_L \sim (K^0 - \bar{K}^0)/\sqrt{2}\right)$	$K^+ \to \pi^+\nu\bar{\nu}$
Amplitude	$\propto \mathscr{A}_{s\to d} - (\mathscr{A}_{s\to d})^*$	$\propto \mathscr{A}_{s\to d}$
Width	$\propto (\mathrm{Im}\mathscr{A}_{s\to d})^2$	$\propto \lvert\mathscr{A}_{s\to d}\rvert^2$
CP	**CP violating**	

Grossman-Nir bound :
(Isospin symmetry in ΔI=1/2 process)

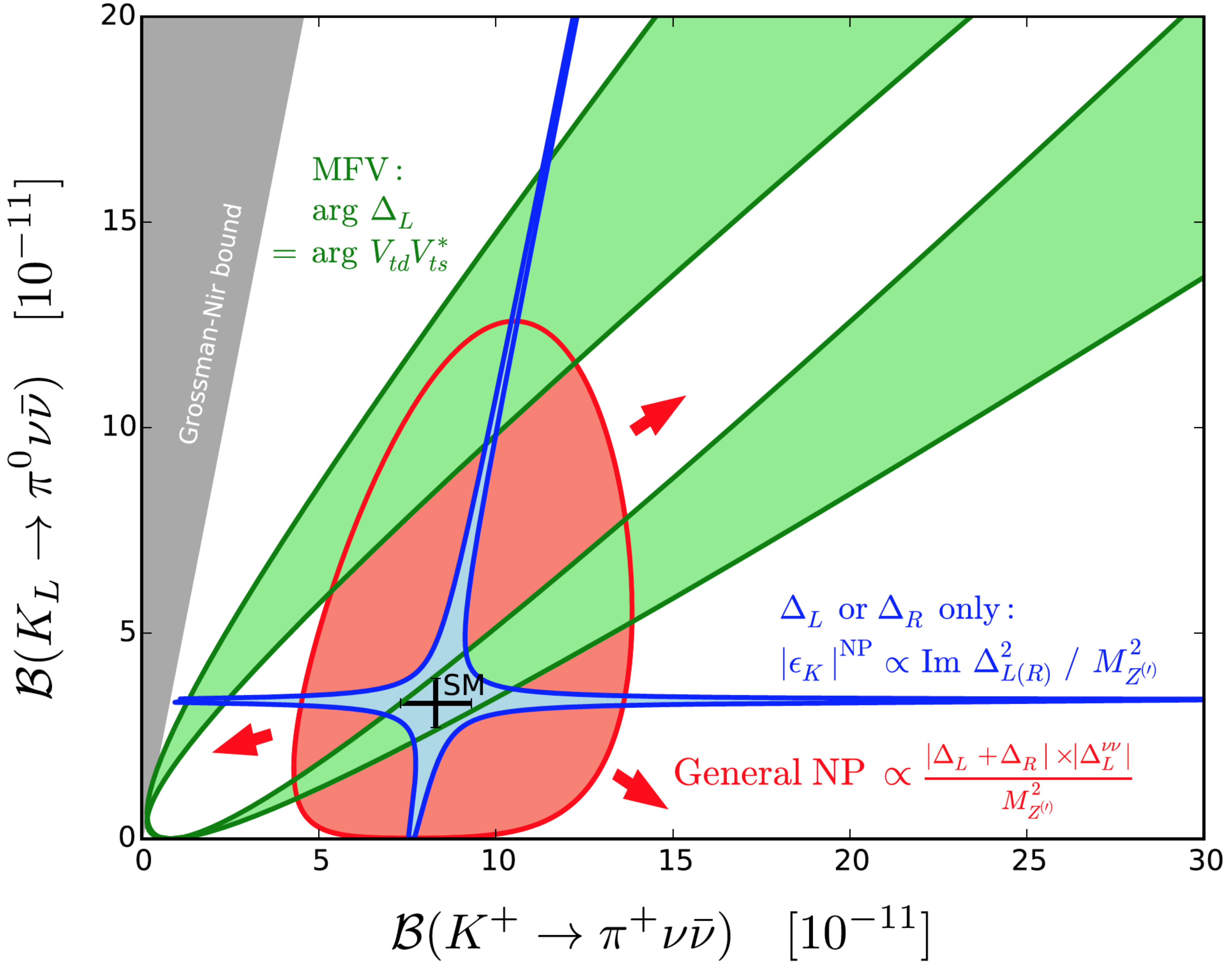
$\mathscr{B}(K_L) < 4.3 \times \mathscr{B}(K^+)$

Experimental status on $K \to \pi\nu\nu$

	$K_L \to \pi^0 \nu\bar{\nu}$	$K^+ \to \pi^+ \nu\bar{\nu}$
Experiments	J-PARC KOTO	CERN NA62
Branching ratio	$< 3.0 \times 10^{-9}$ (90 % CL) *PRL* 122, 021802 (2019)	$(10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$ (68 % CL)
Single Event Sensitivity *(SES)*	7.2×10^{-10} *PRL*. 126 (2021) 12, 121801	0.84×10^{-11} *JHEP* 06 (2021) 093

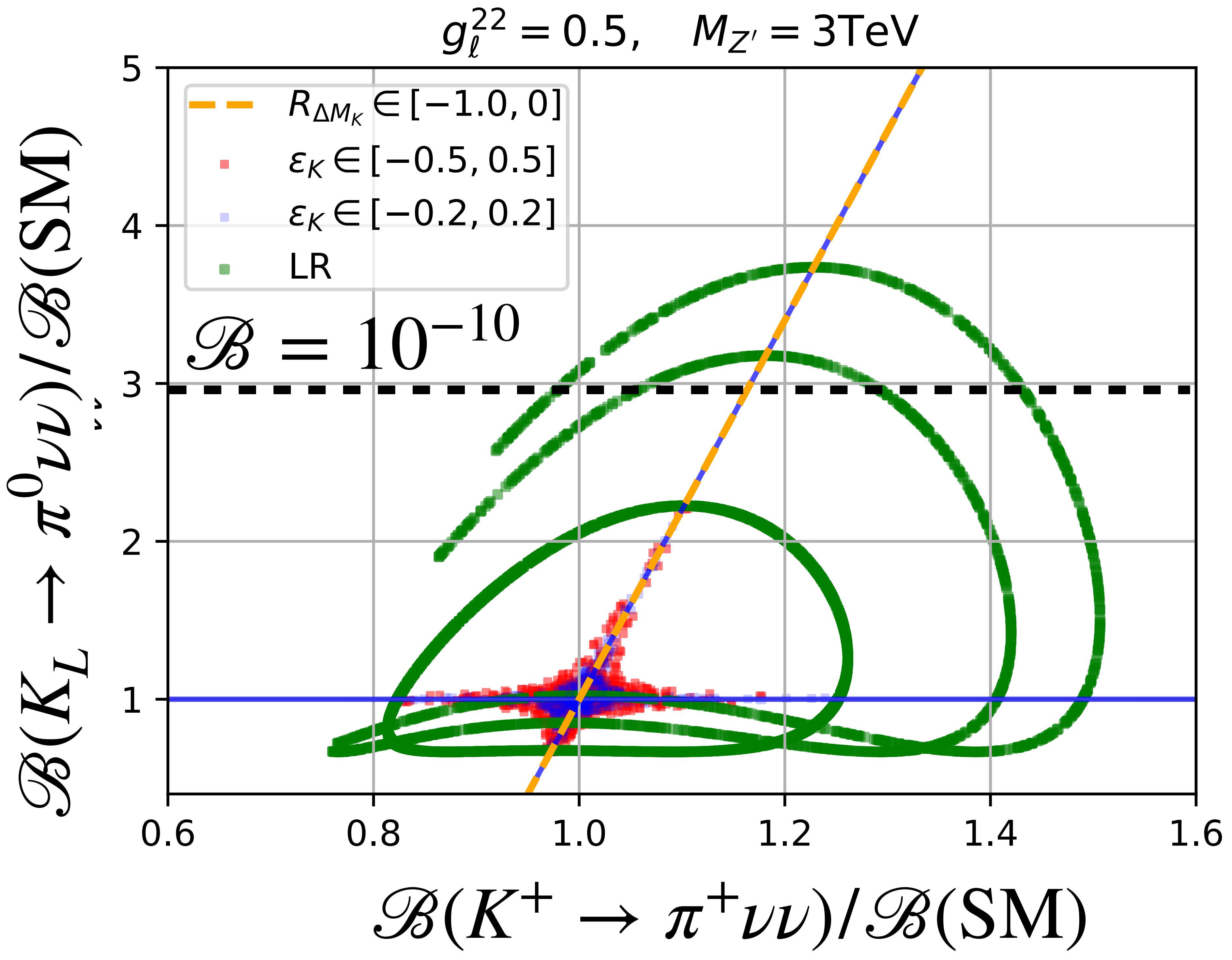


New physics contributions



Z', leptoquark, SUSY, charged Higgs…

JHEP12(2020)097

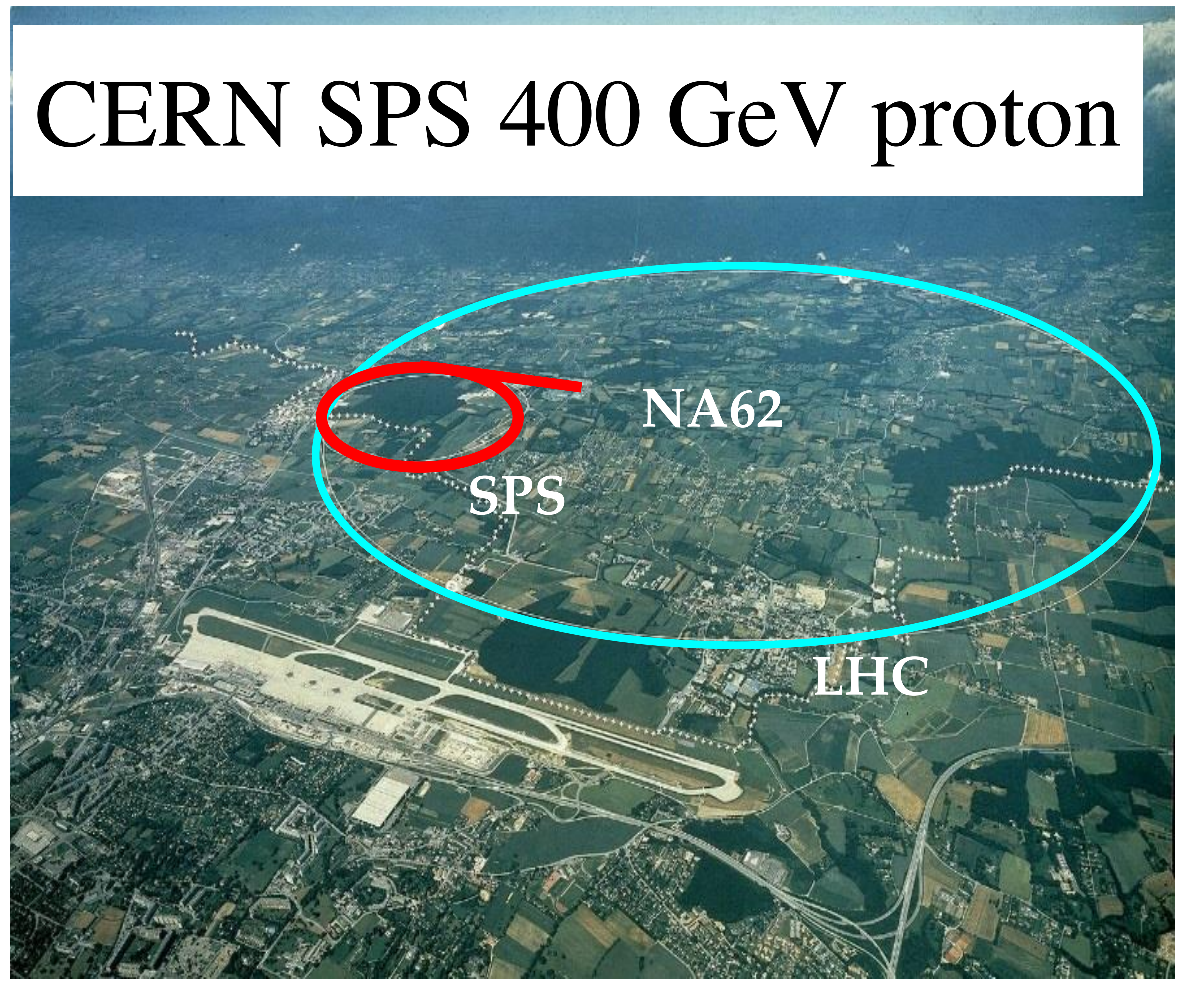


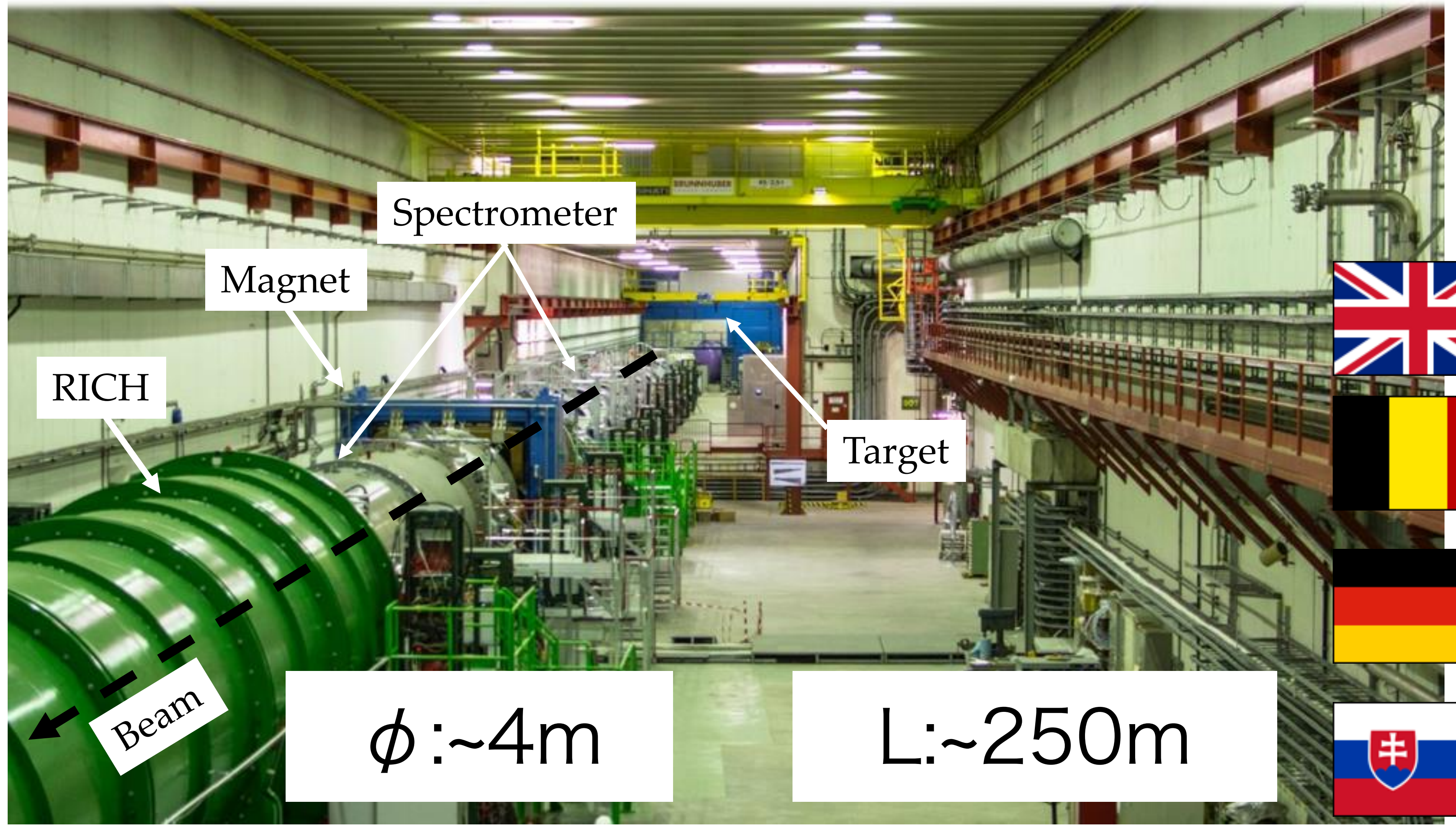
Flavor-violating Z' coupling

On-going experiments for $K \to \pi\nu\nu$

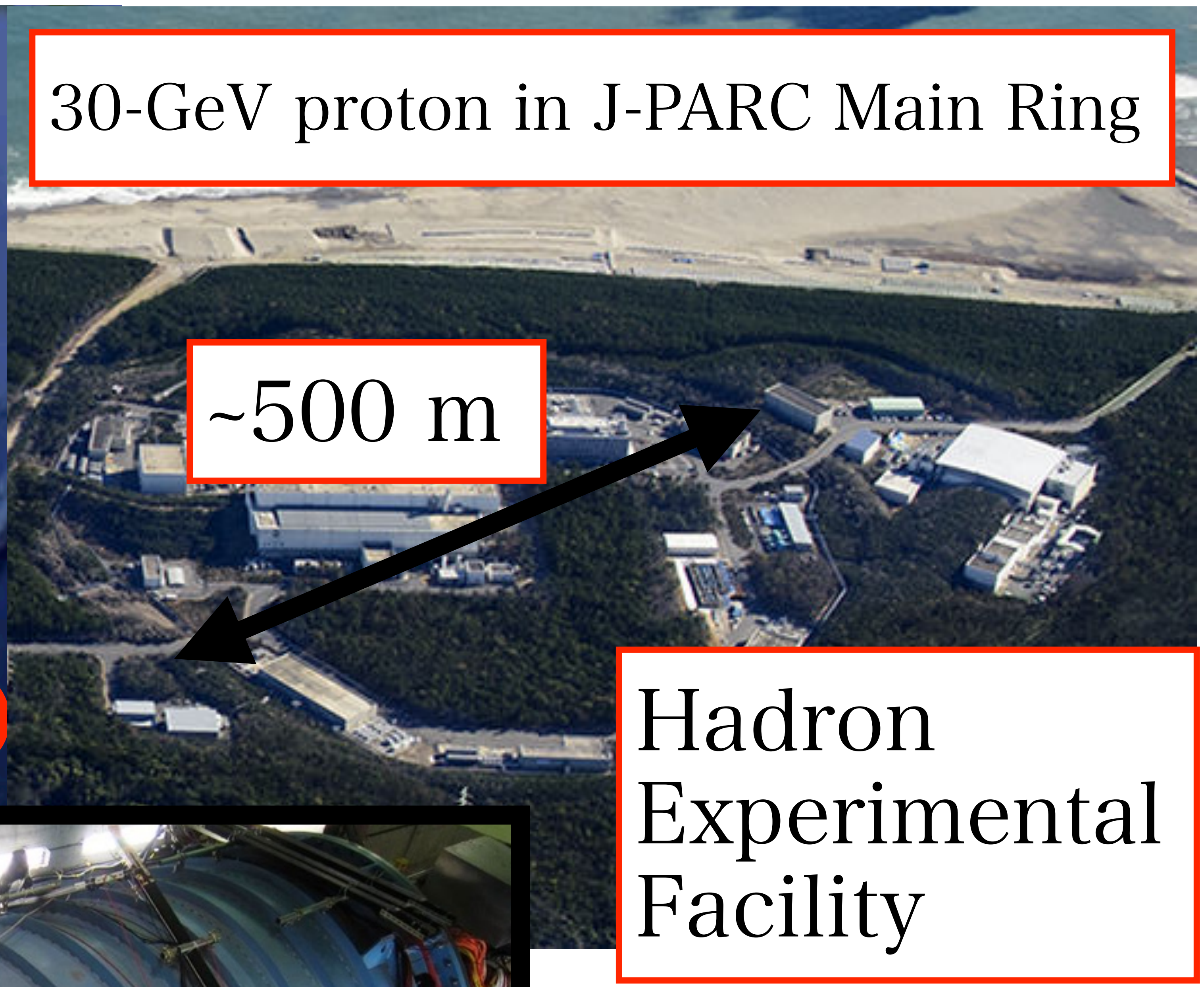
US is contributing both.

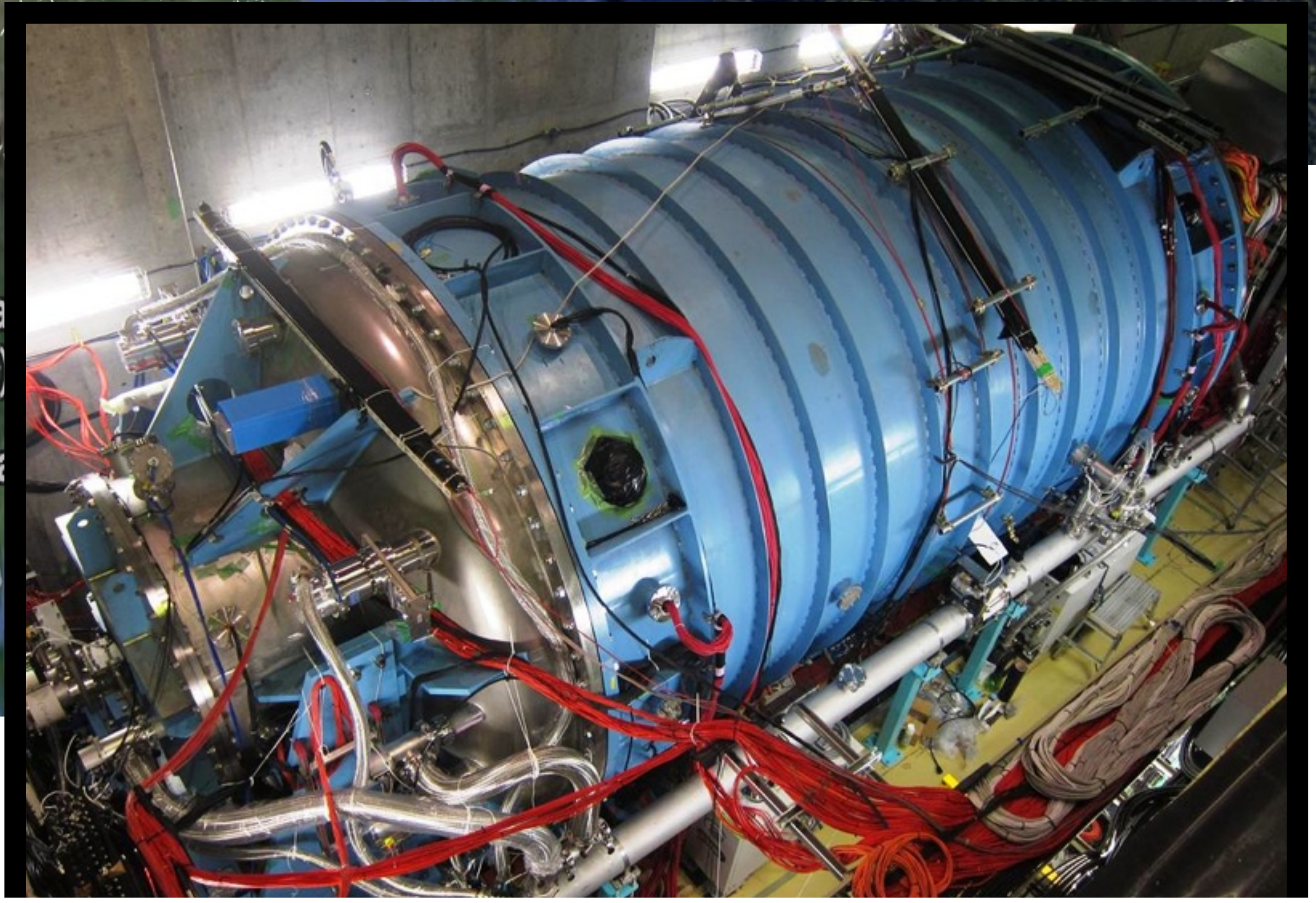
NA62 experiment : $K^+ \to \pi^+\nu\bar{\nu}$



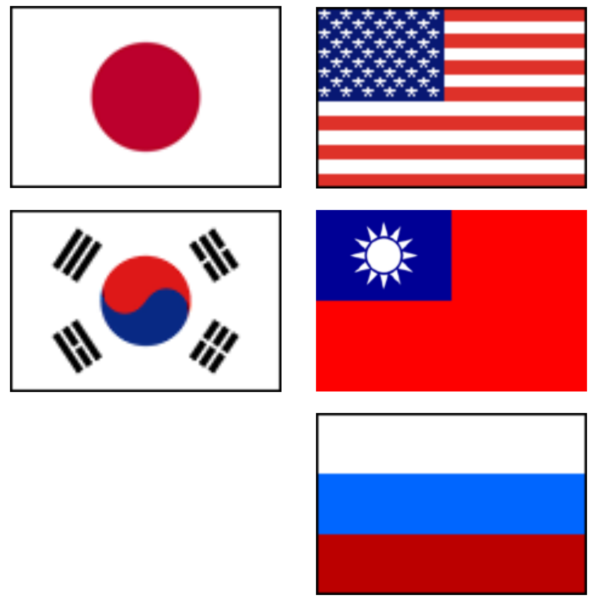


KOTO experiment : $K_L \to \pi^0\nu\bar{\nu}$



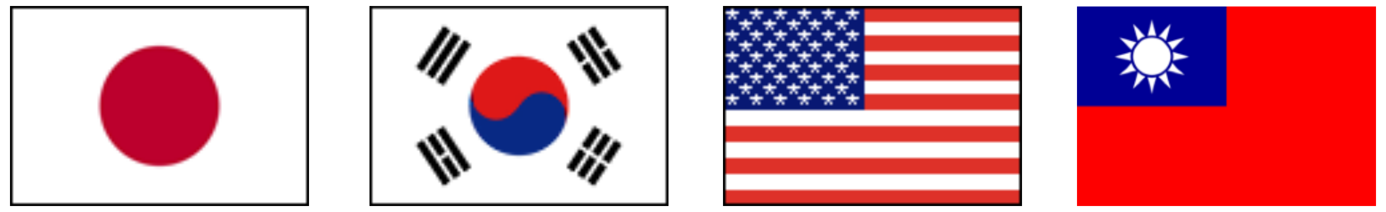


ϕ~4m, 8.5m-long vacuum tank

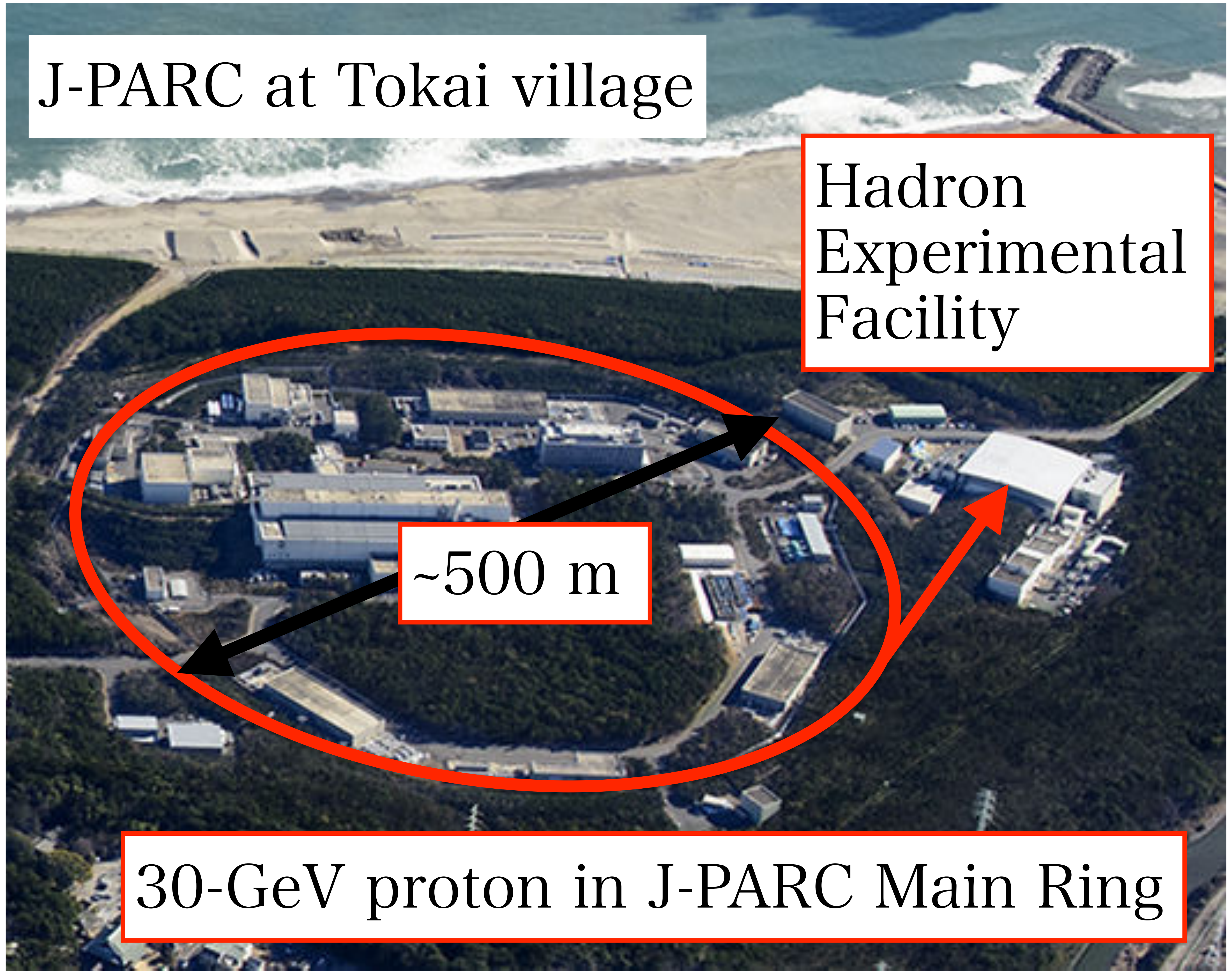


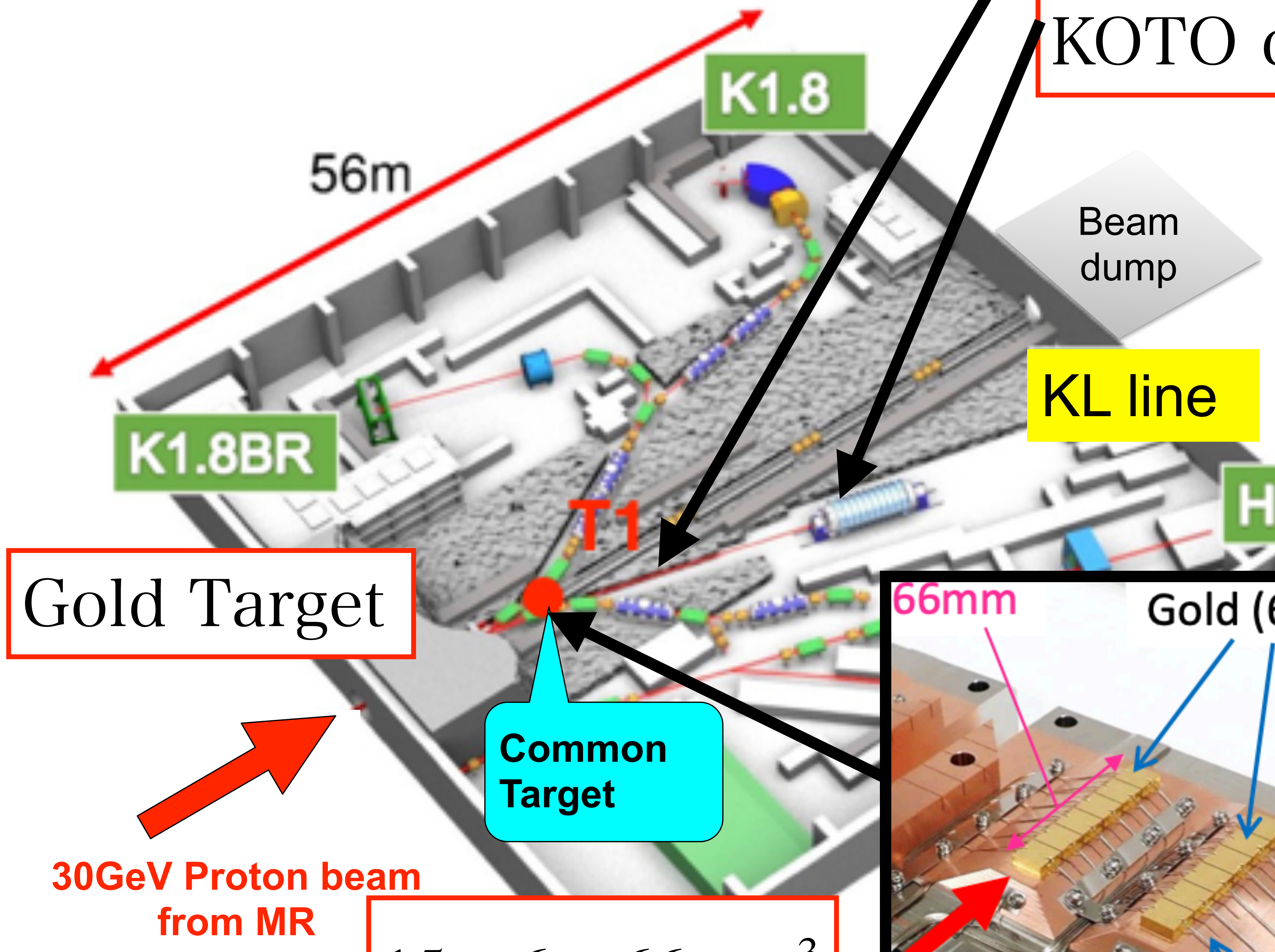
KOTO experiment at J-PARC

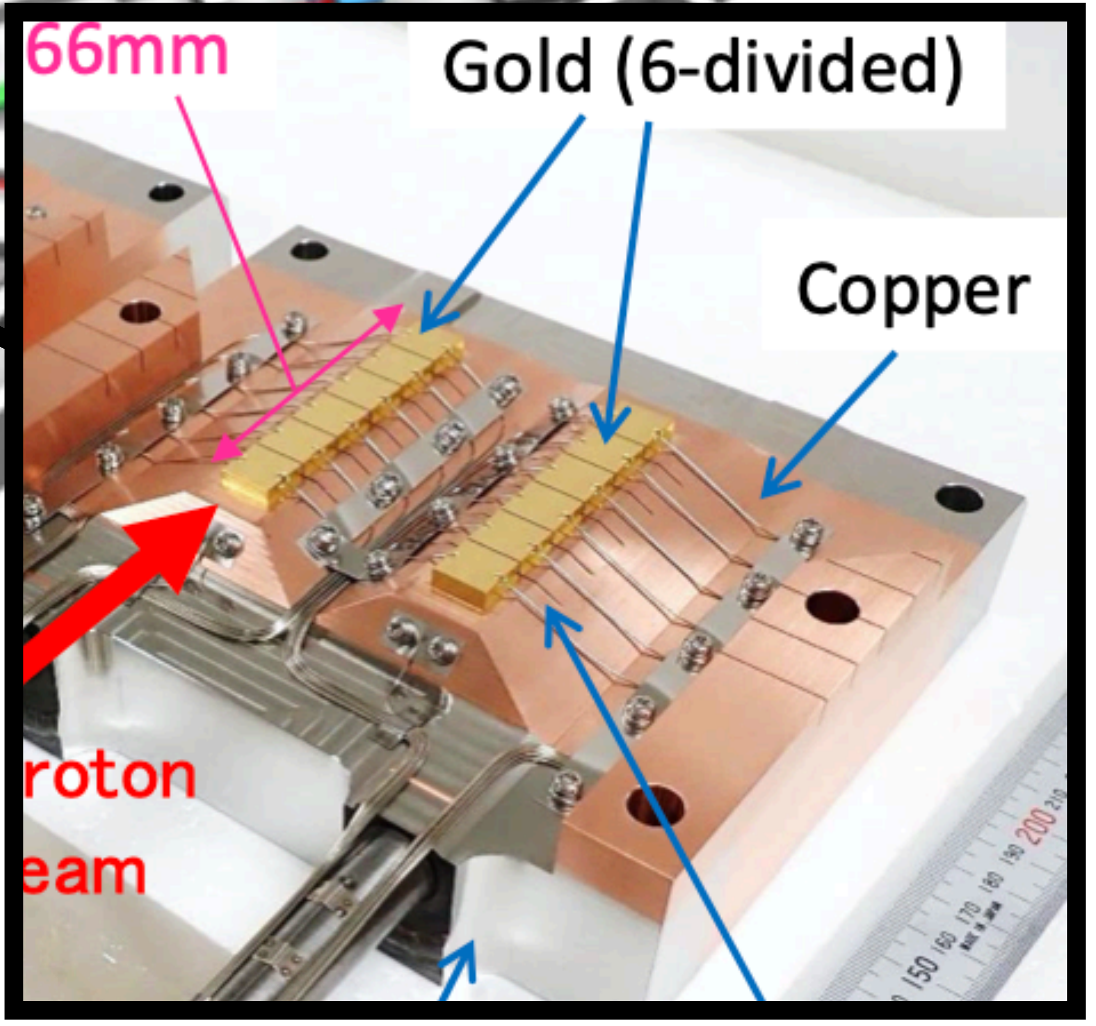
KOTO (K0 at Tokai)



search for $K_L \to \pi^0 \nu \bar{\nu}$



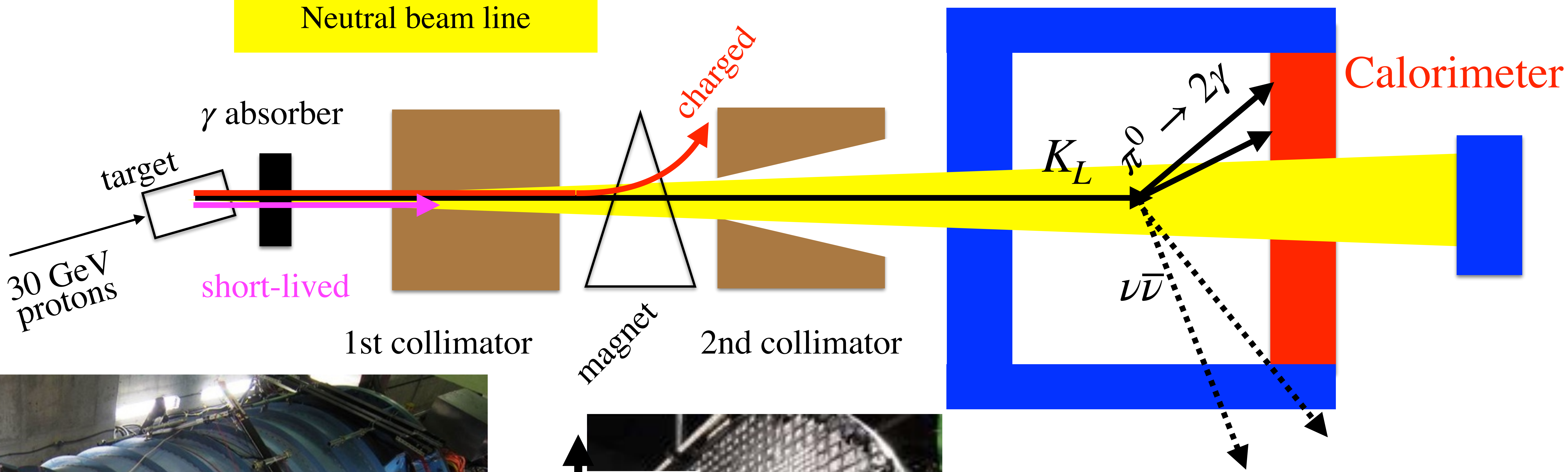


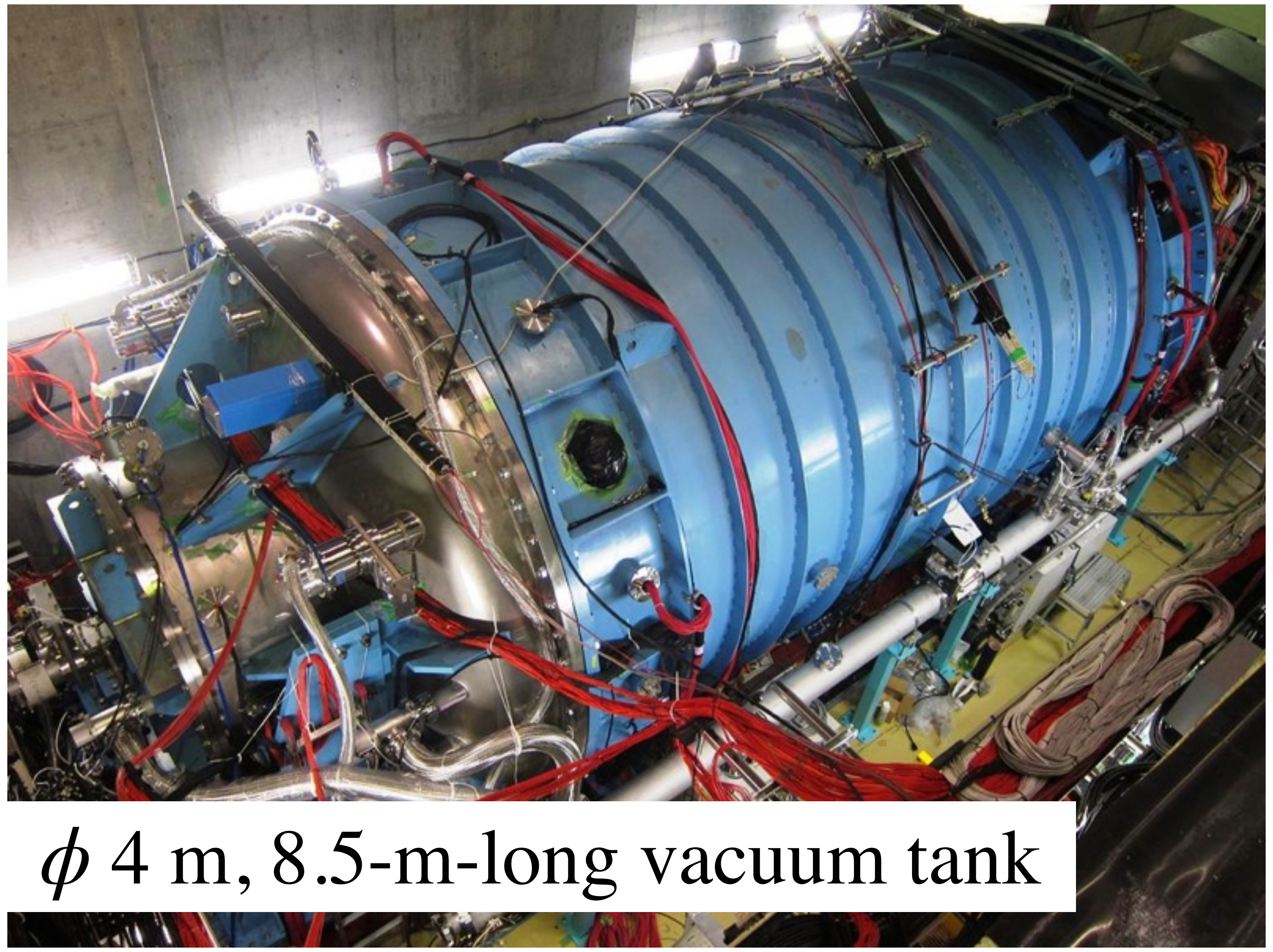


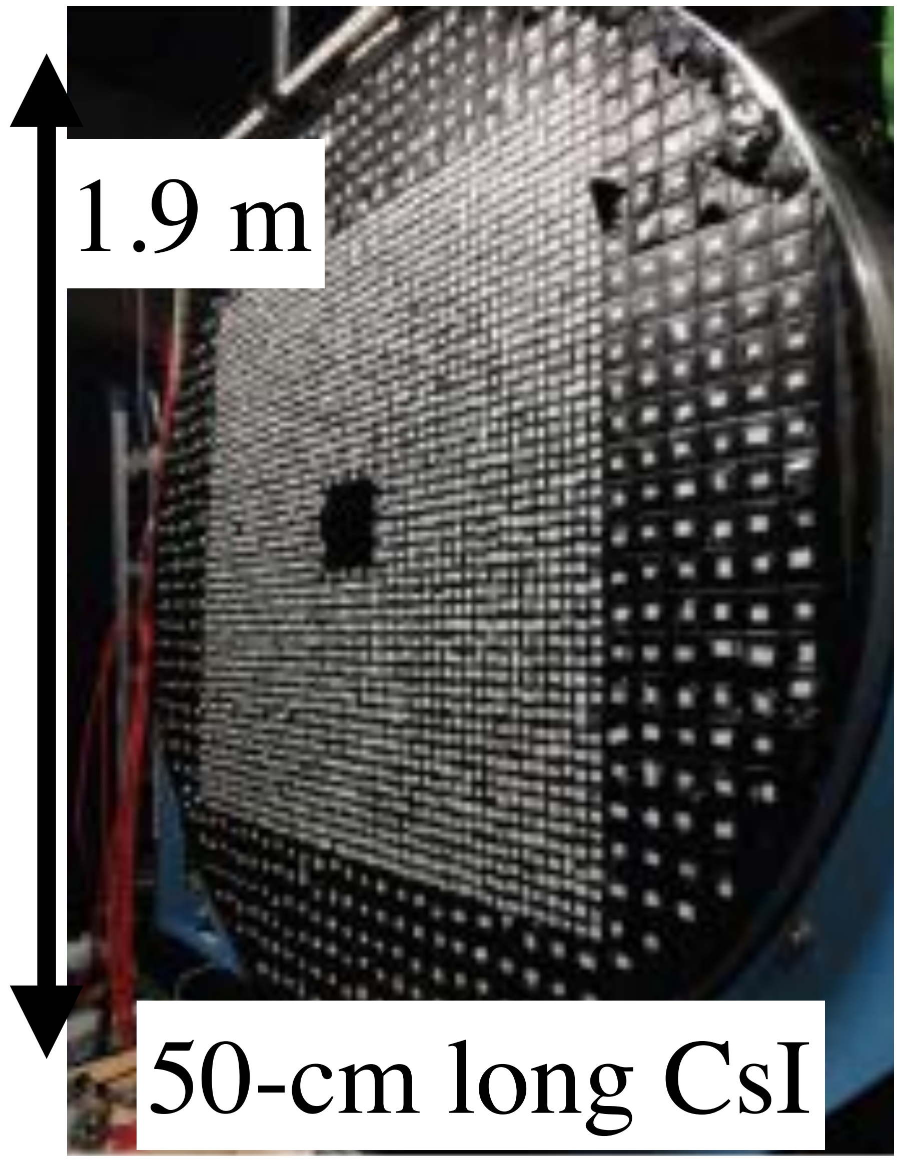
$15 \times 6 \times 66\,\mathrm{mm}^3$ gold target

Concept of the KOTO experiment

$K_L \to \pi^0 \nu \bar{\nu}$ $\pi^0 +$ nothing

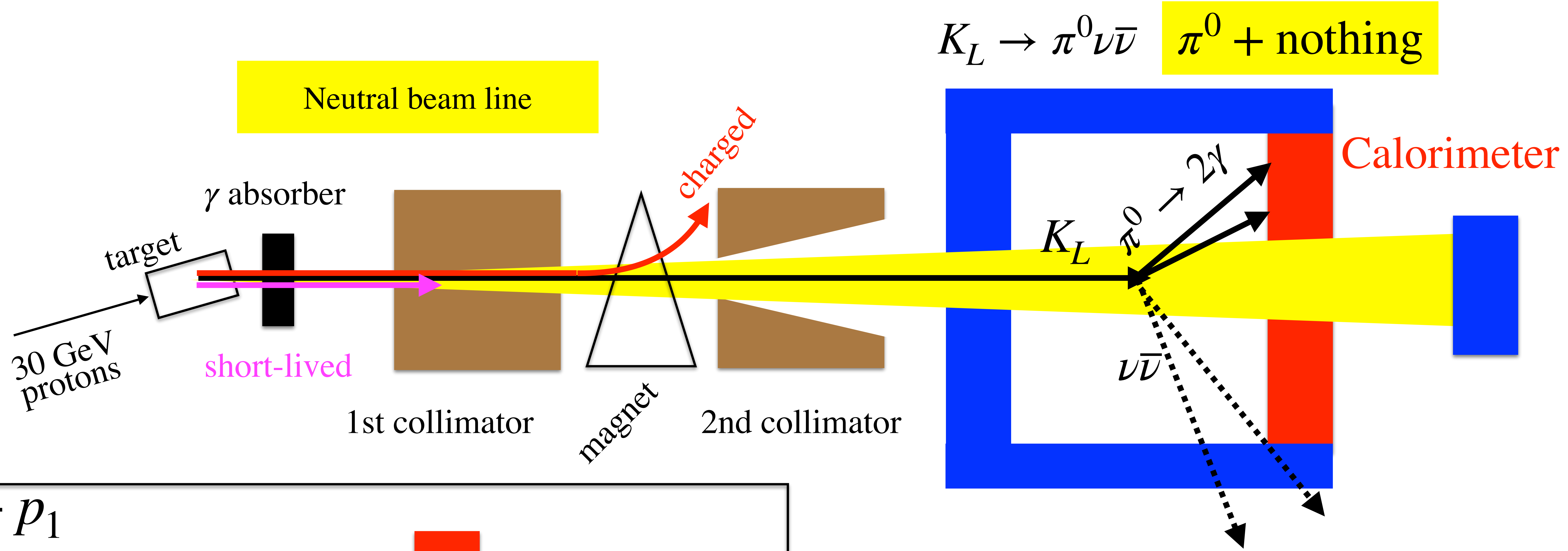






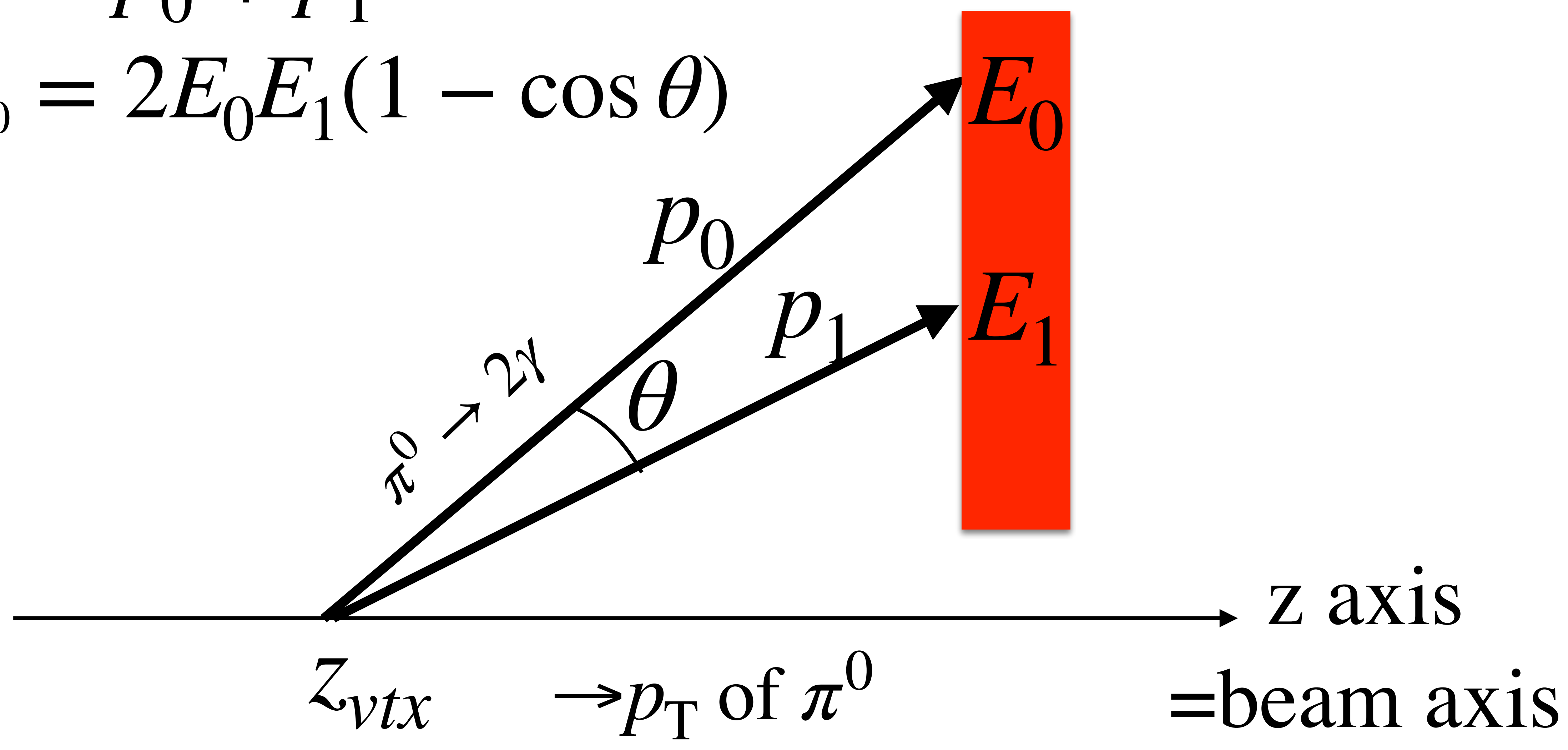
Diameter ~1.9 m
50-cm long CsI crystals
Cross section
2.5 cm × 2.5 cm
5 cm × 5 cm

Signal reconstruction



$$p_{\pi^0} = p_0 + p_1$$

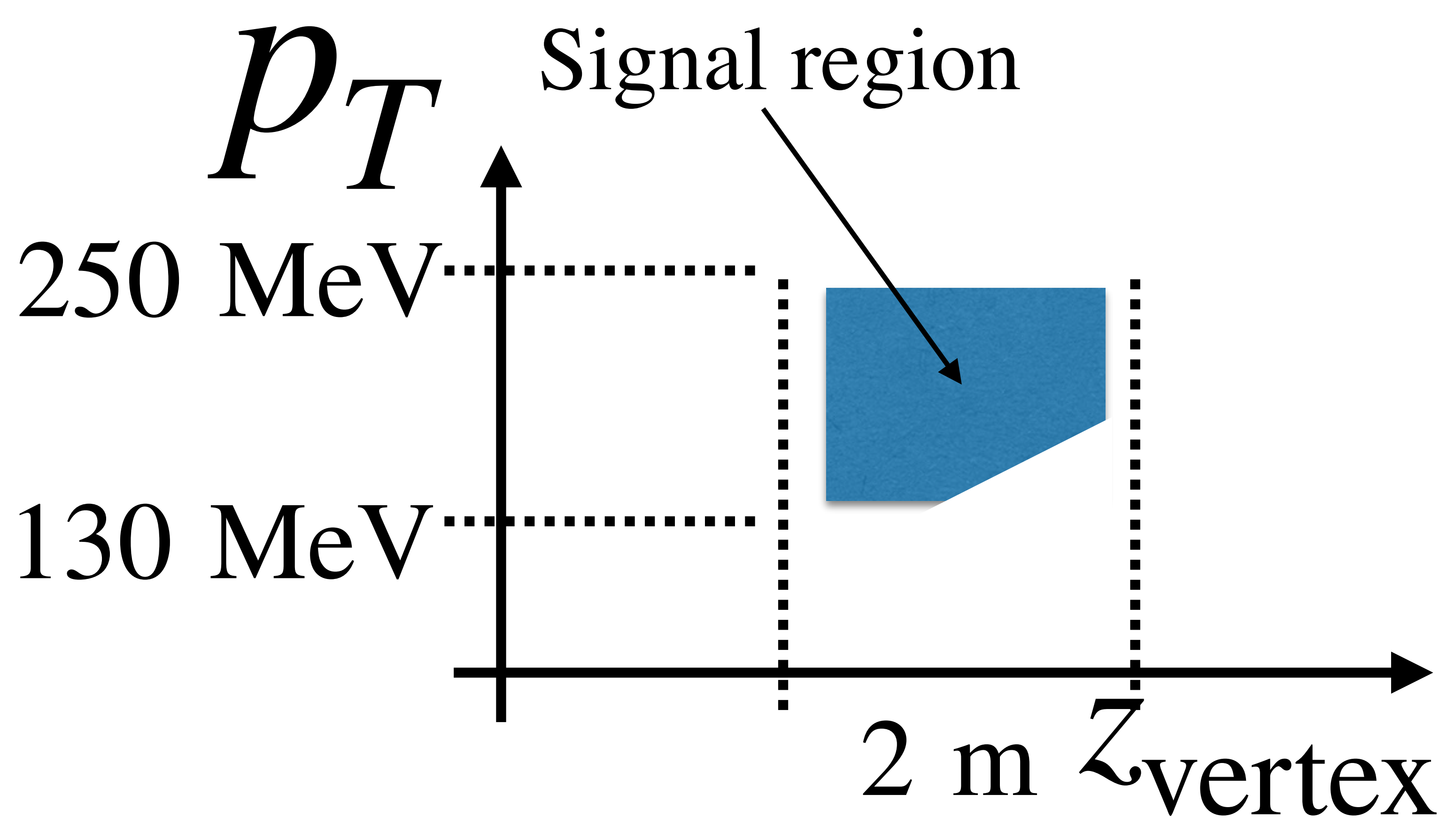
$$m_{\pi^0}^2 = 2E_0E_1(1 - \cos\theta)$$



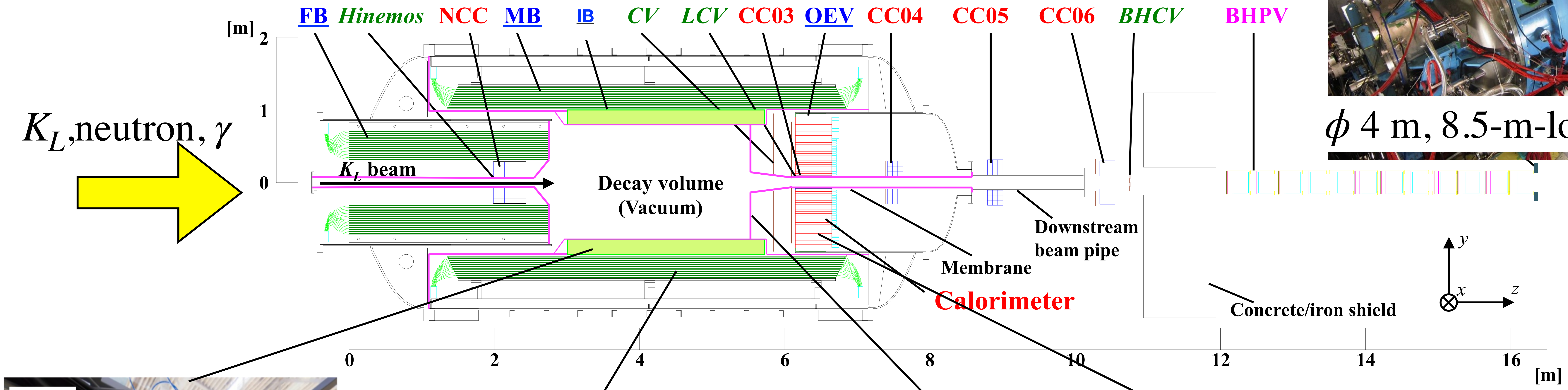
Assume the vertex on beam axis

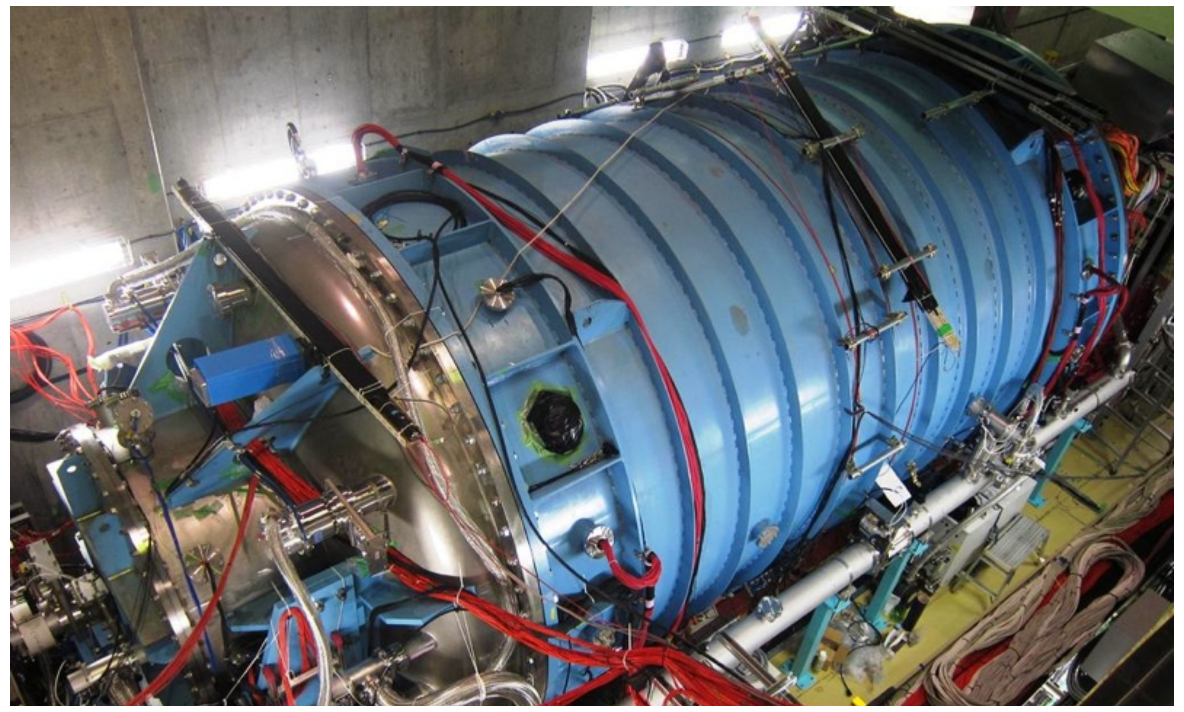
⇕

Narrow beam

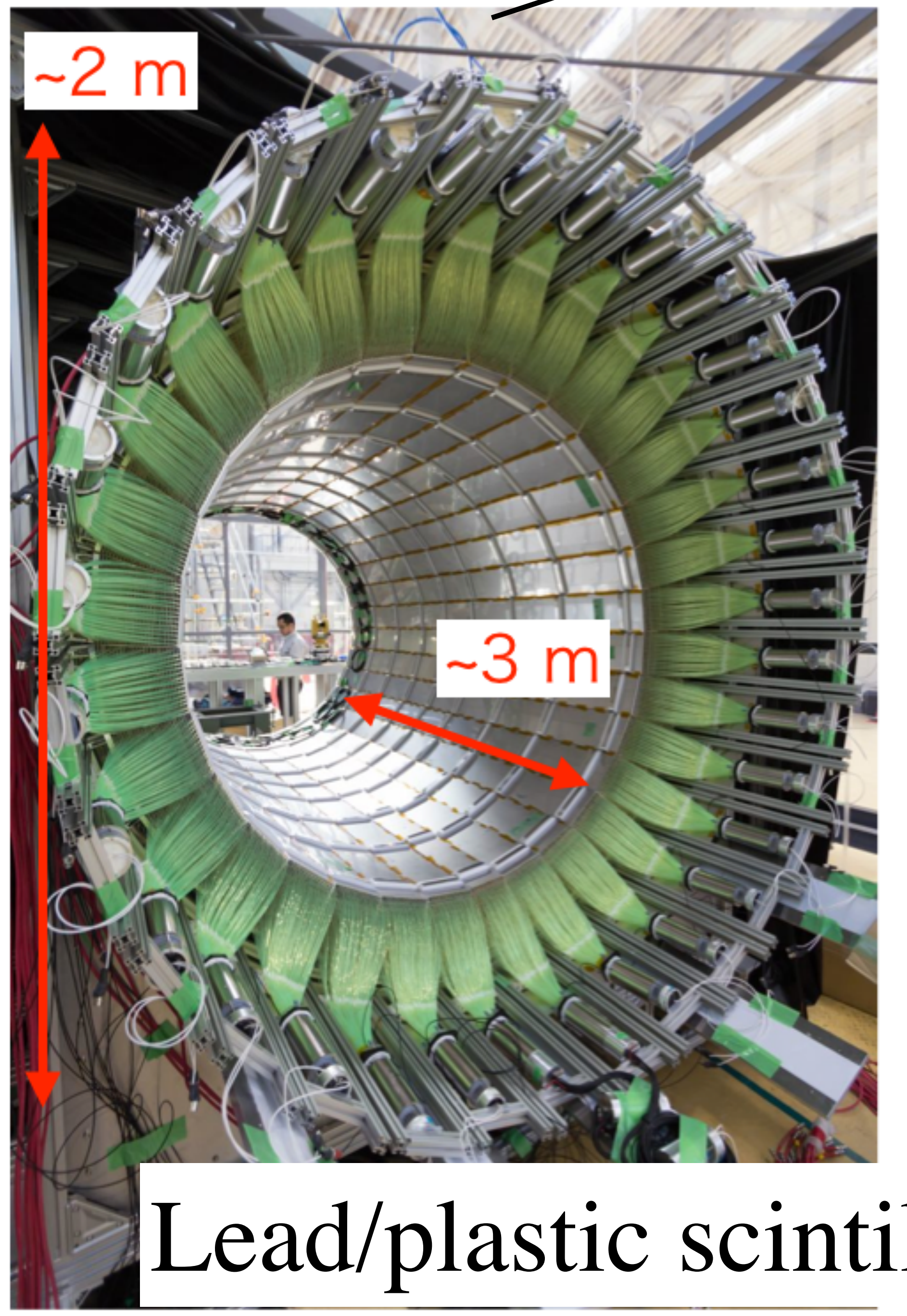


KOTO detector

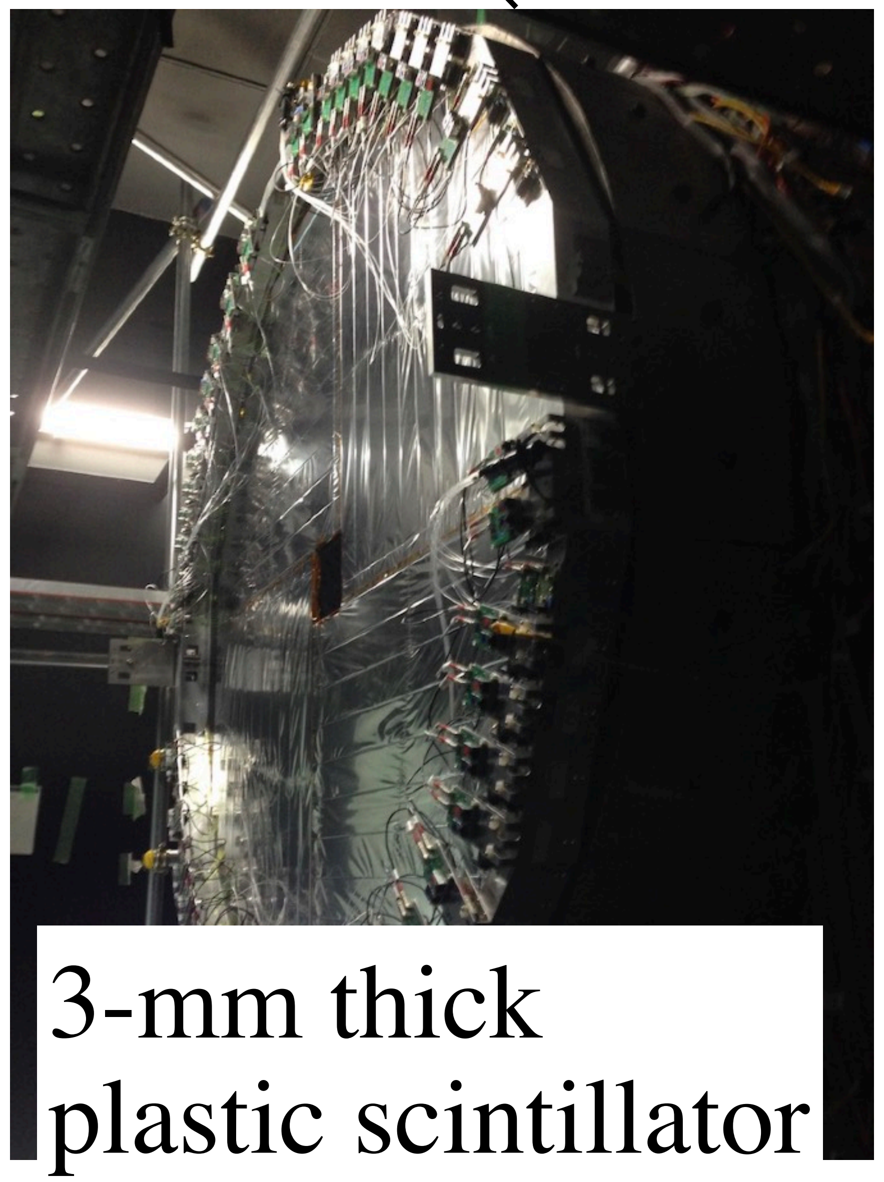




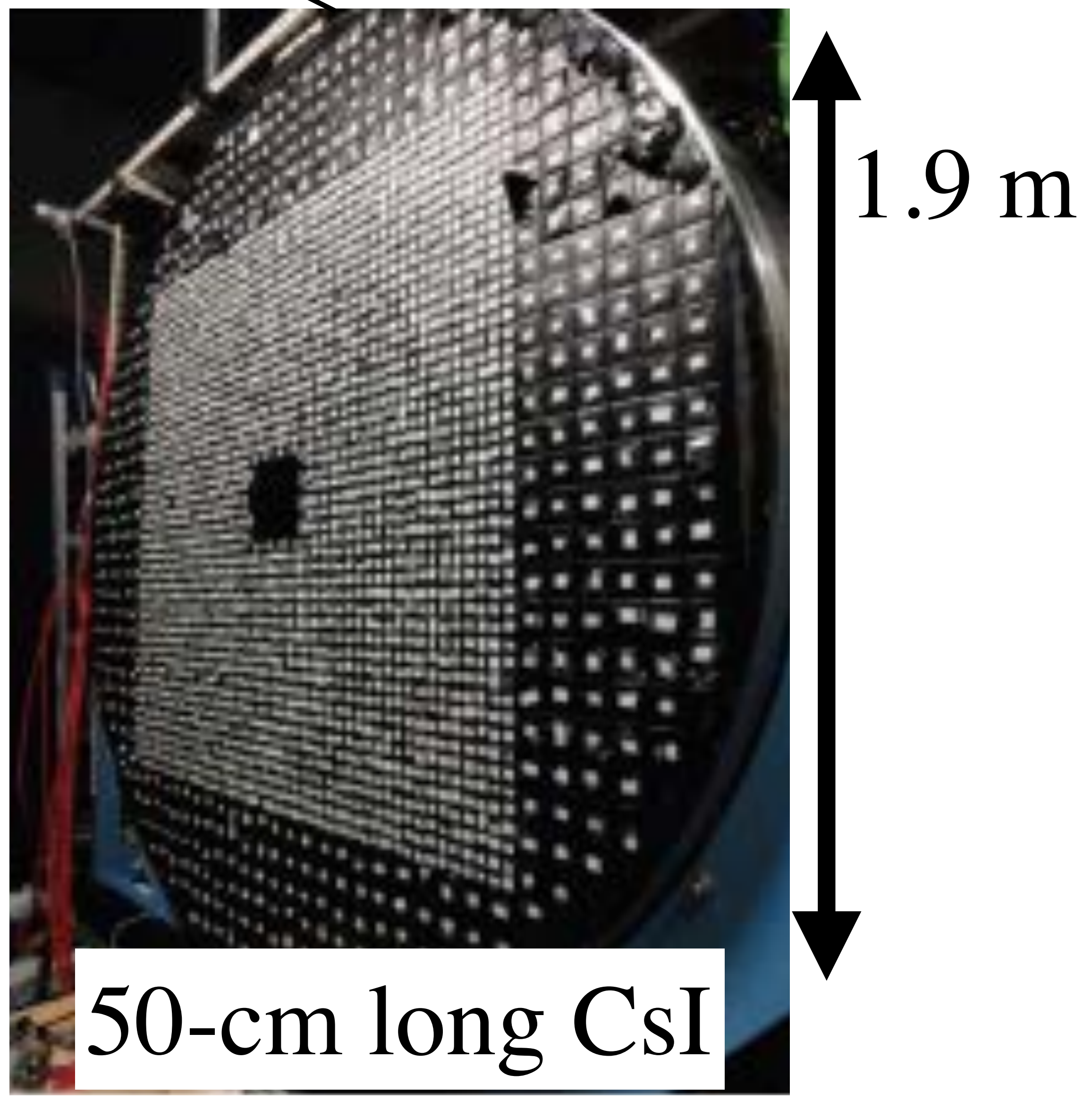
ϕ 4 m, 8.5-m-long vacuum tank



Lead/plastic scintillator sandwich counter



3-mm thick plastic scintillator

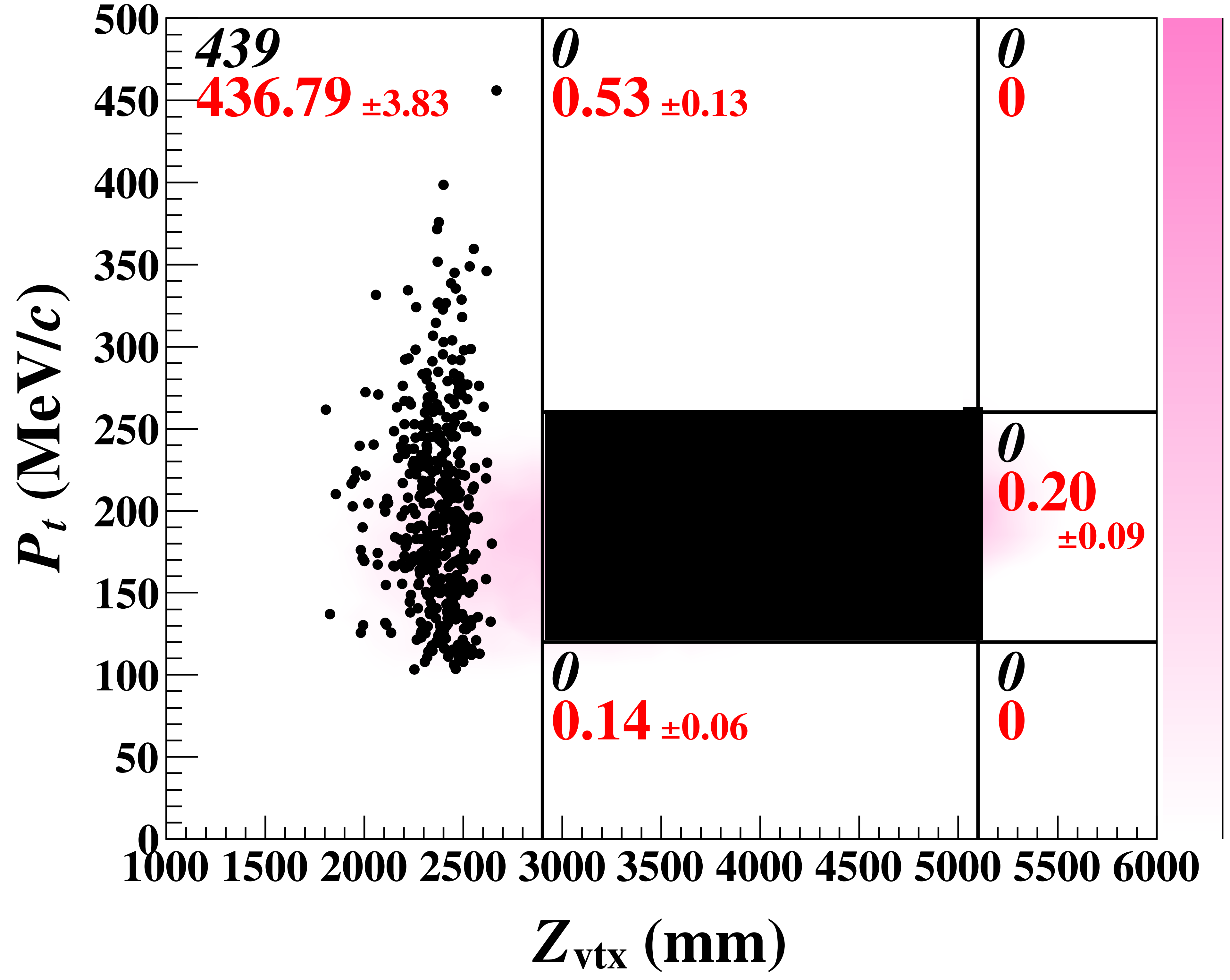


50-cm long CsI

Results of 2016-18 analysis

Phys.Rev.Lett.126(121801)(2021)

SES=$(7.20 \pm 0.05_{stat.} \pm 0.66_{syst.}) \times 10^{-10}$
3 events observed
$\mathscr{B}(K_L \to \pi^0 \nu\bar{\nu}) < 4.9 \times 10^{-9}$ (90 % CL)

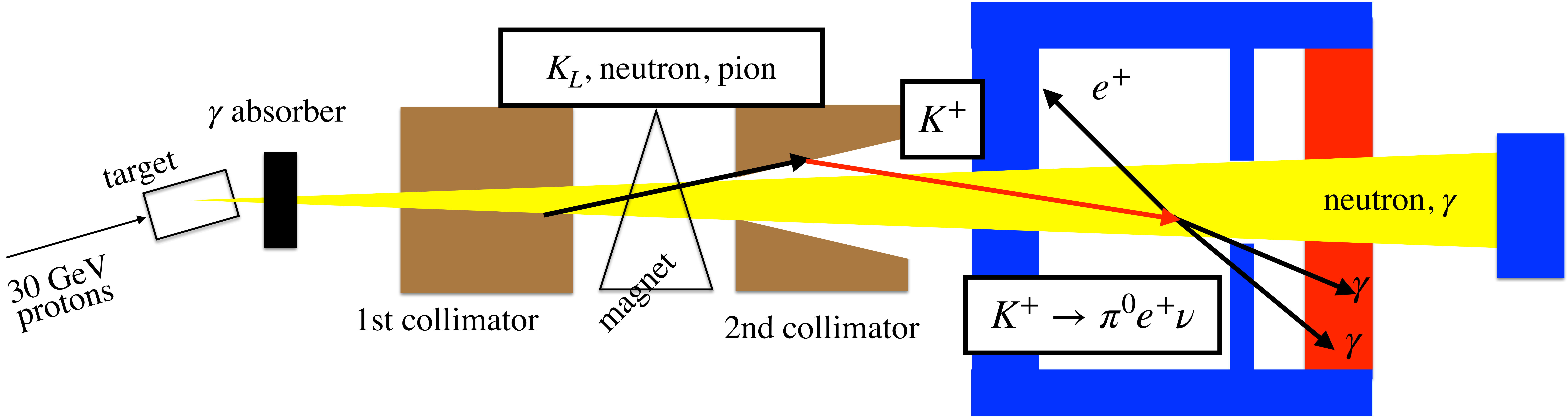


No events in the surrounding regions
except for the upstream region

- New background sources were found
- # of observed events is consistent to # of backgrounds

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

Charged kaon background



$K^\pm$ generated in the 2nd collimator due to hadronic interaction

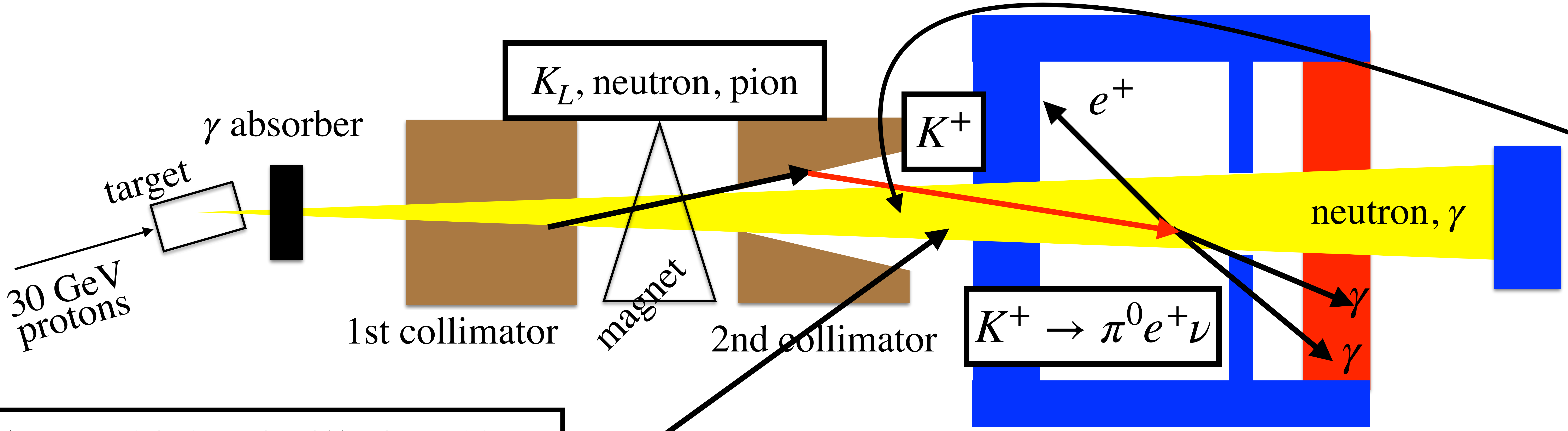
Flux : $K^+/K_L \sim 10^{-5}$

$\mathscr{B}(K^\pm \to \pi^0 e^\pm \nu) = 5\,\%$

Backward-going $e^\pm$ → low energy → missed due to the detector inefficiency

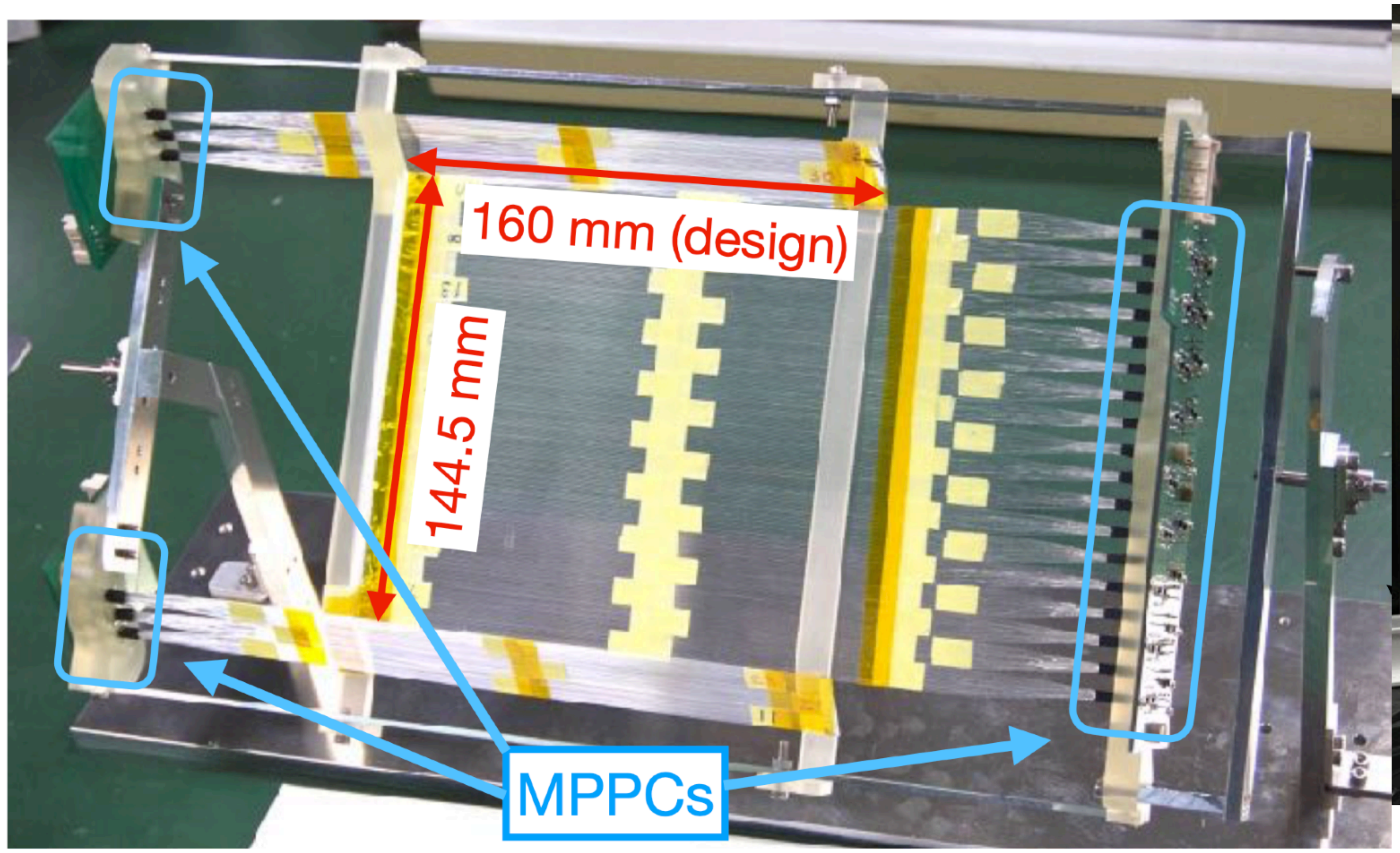
π^0 kinematics is similar to the signal

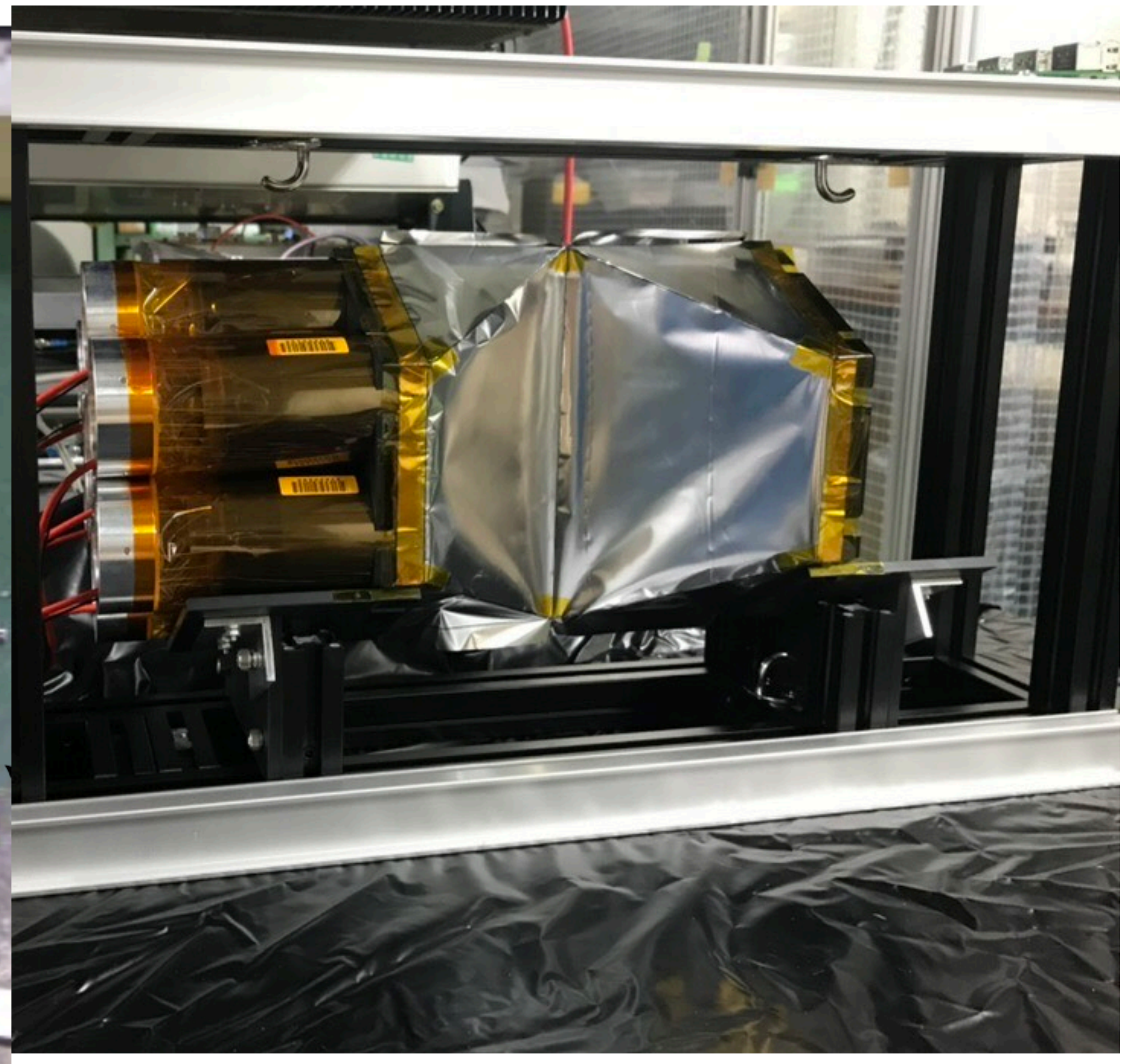
Measure against charged kaon background



Installation of additional magnet planned in 2023
$\rightarrow \times 1/10$

0.5-mm-thick scintillation fibers



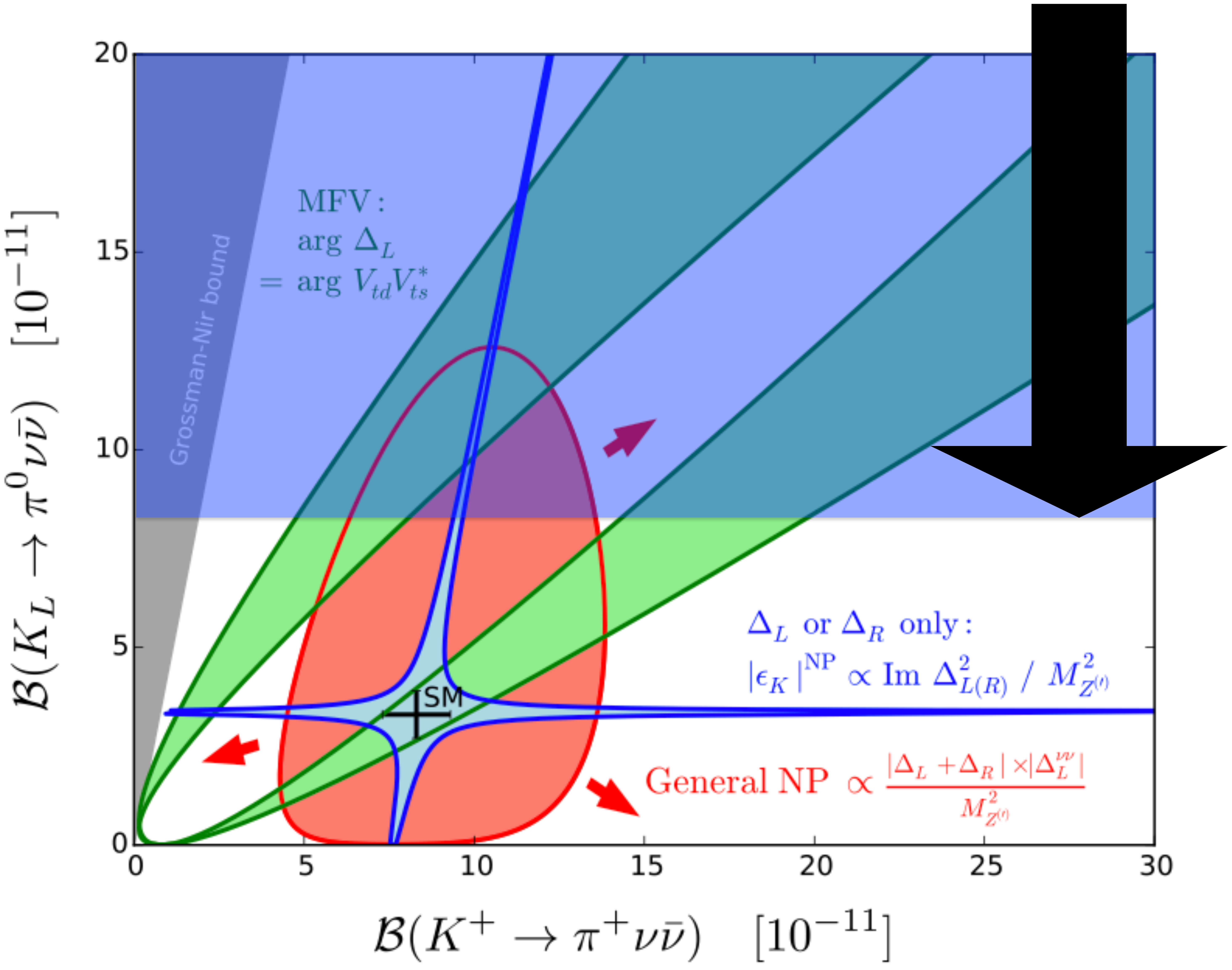


0.2-mm-thick scintillator
$\rightarrow \times 1/100$

Expected reduction
$\times 1/1000$ in total

0.02 events in SM sensitivity

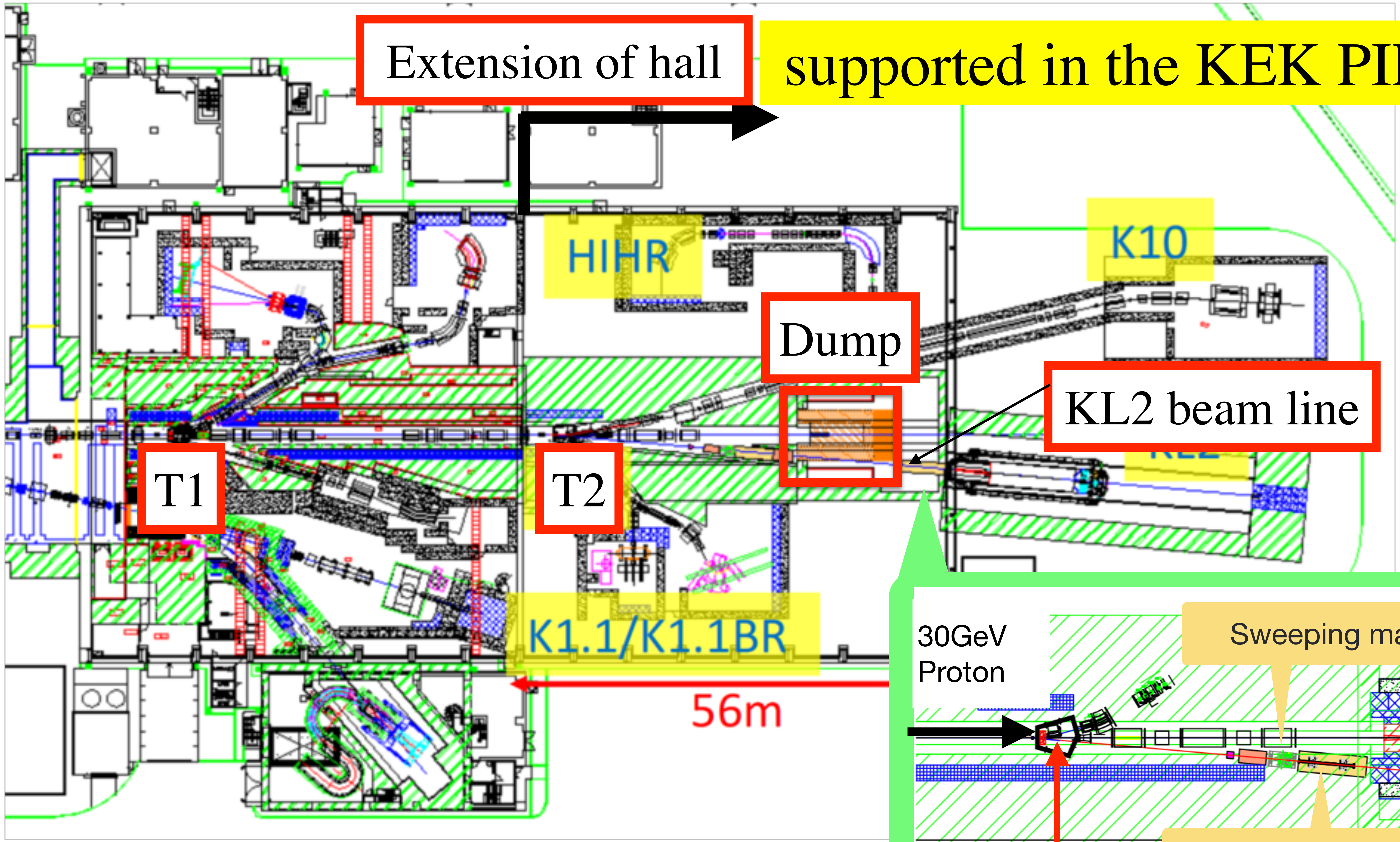
Prospects for KOTO



KOTO will reach $O(10^{-11})$ sensitivity in 3-4 years

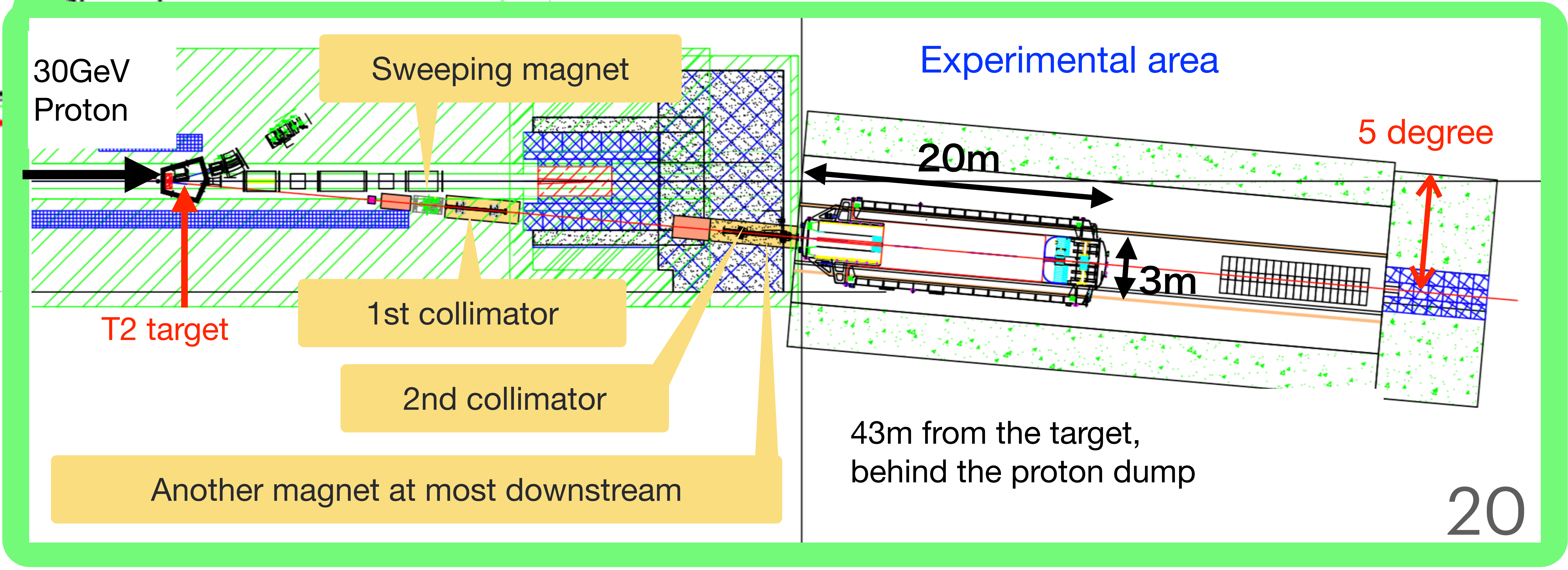
Upper limits or a few events with # of backgrounds ~ 0
Saturation of sensitivity

KOTO step-2 with extension of hadron experimental facility



Extraction angle: 16° → 5°

Higher momentum &
higher intensity K_L

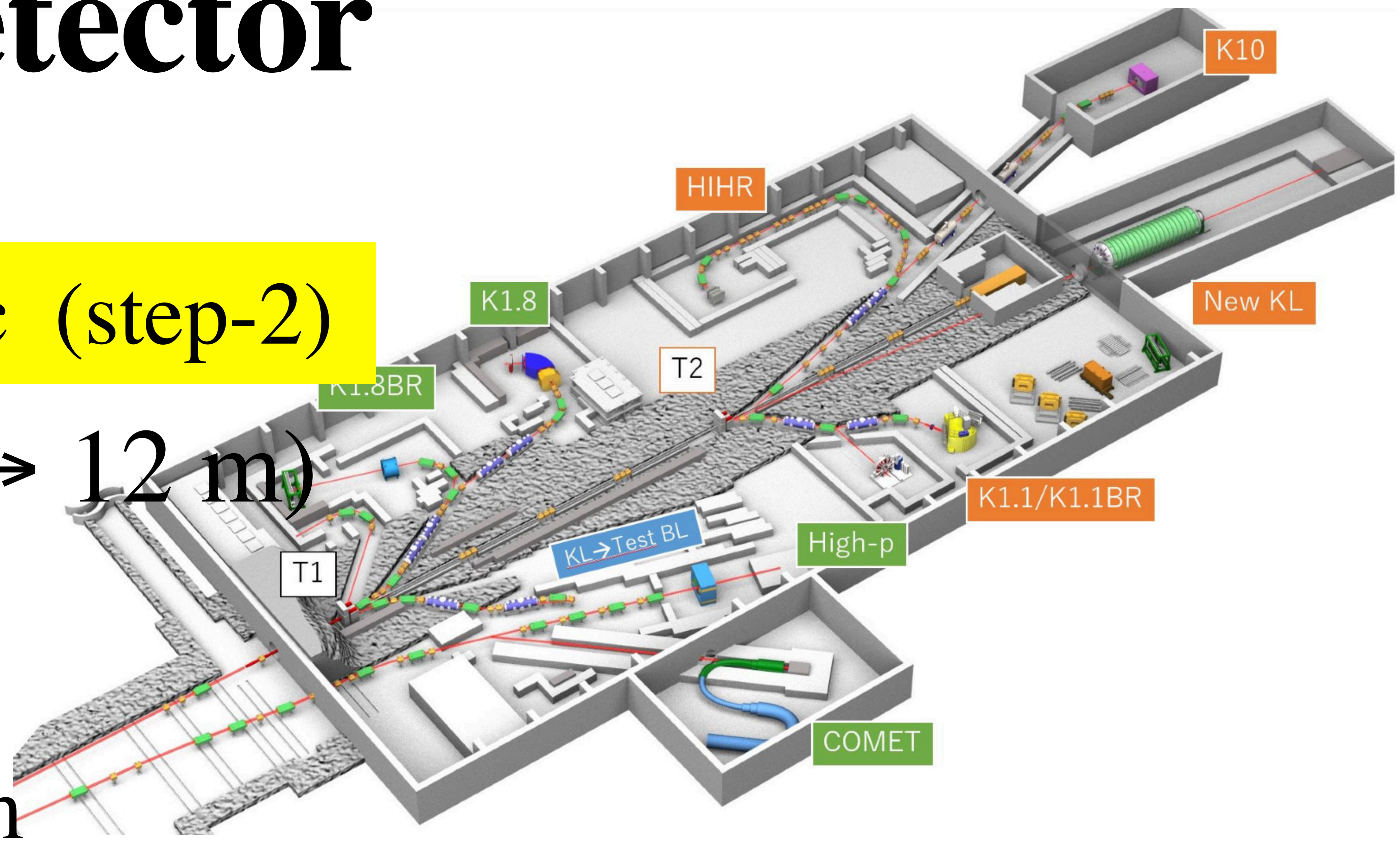


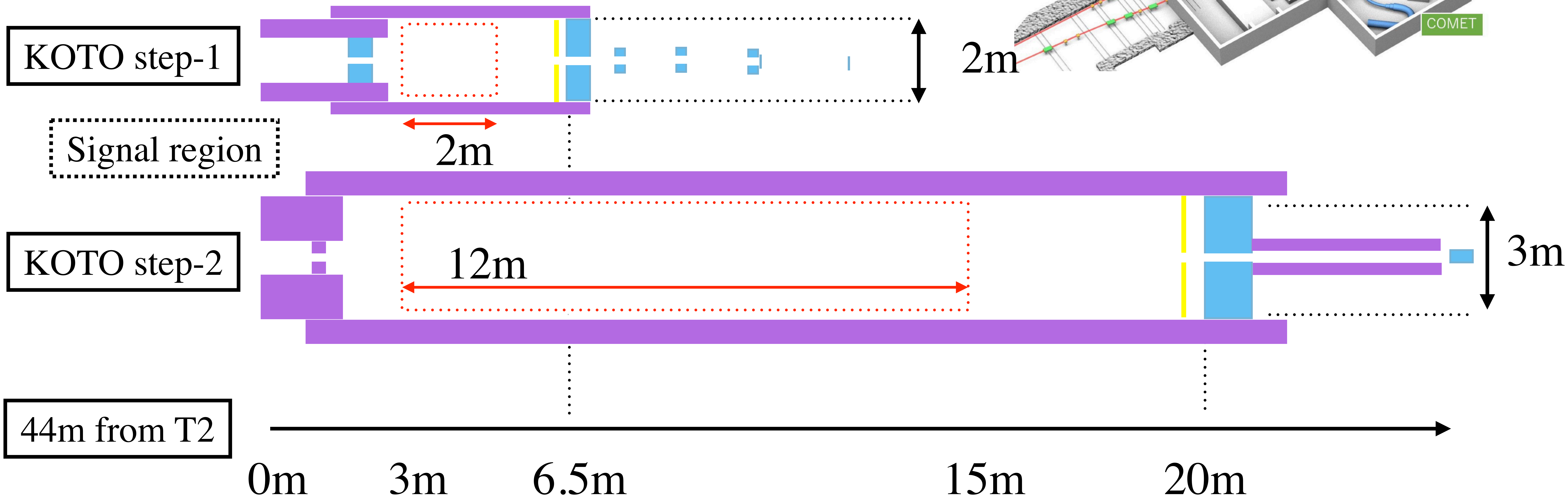
KOTO Step-2detector

Peak K_L momentum : 1.4 GeV/c (step-1) → 3 GeV/c (step-2)

Possible to use longer decay volume (2 m → 12 m)

Larger diameter calorimeter (2 m → 3 m)

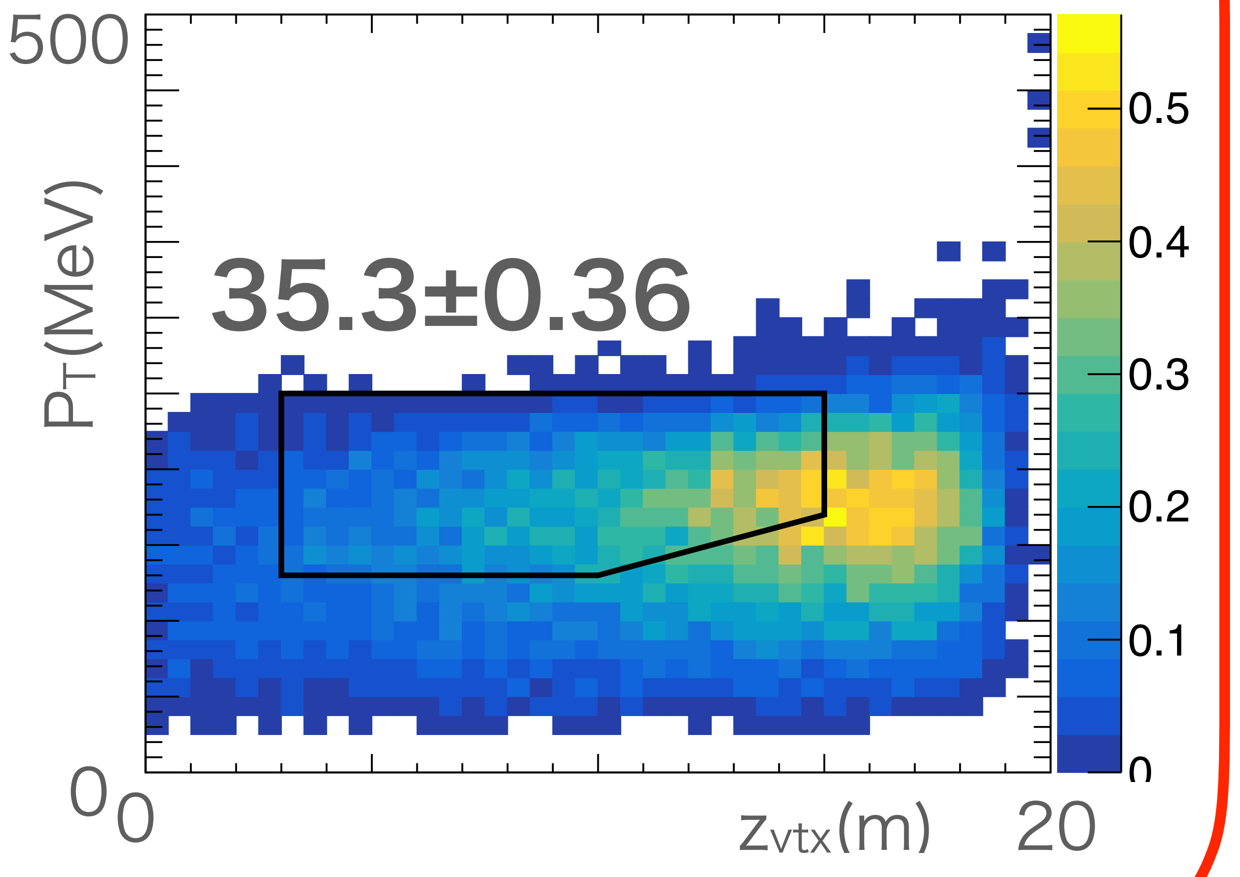


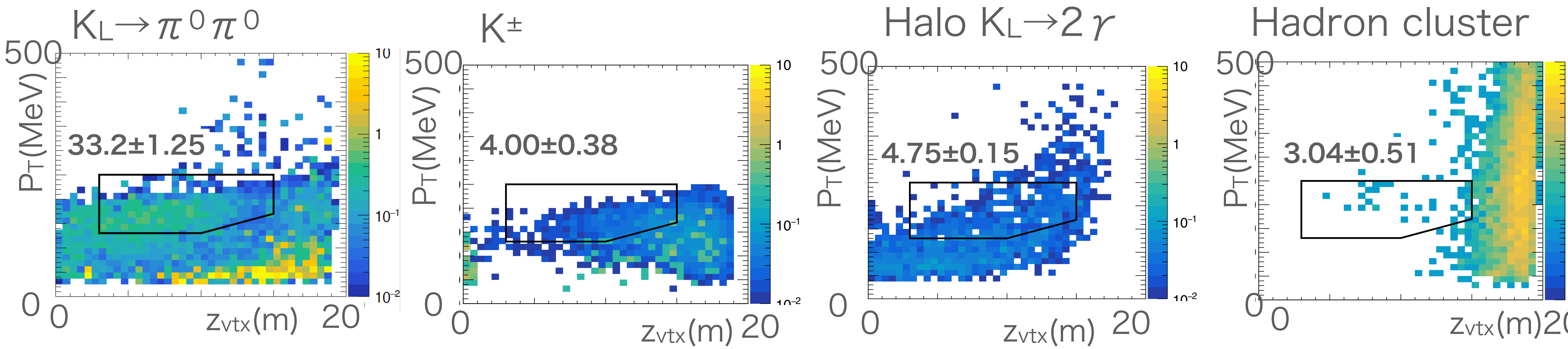


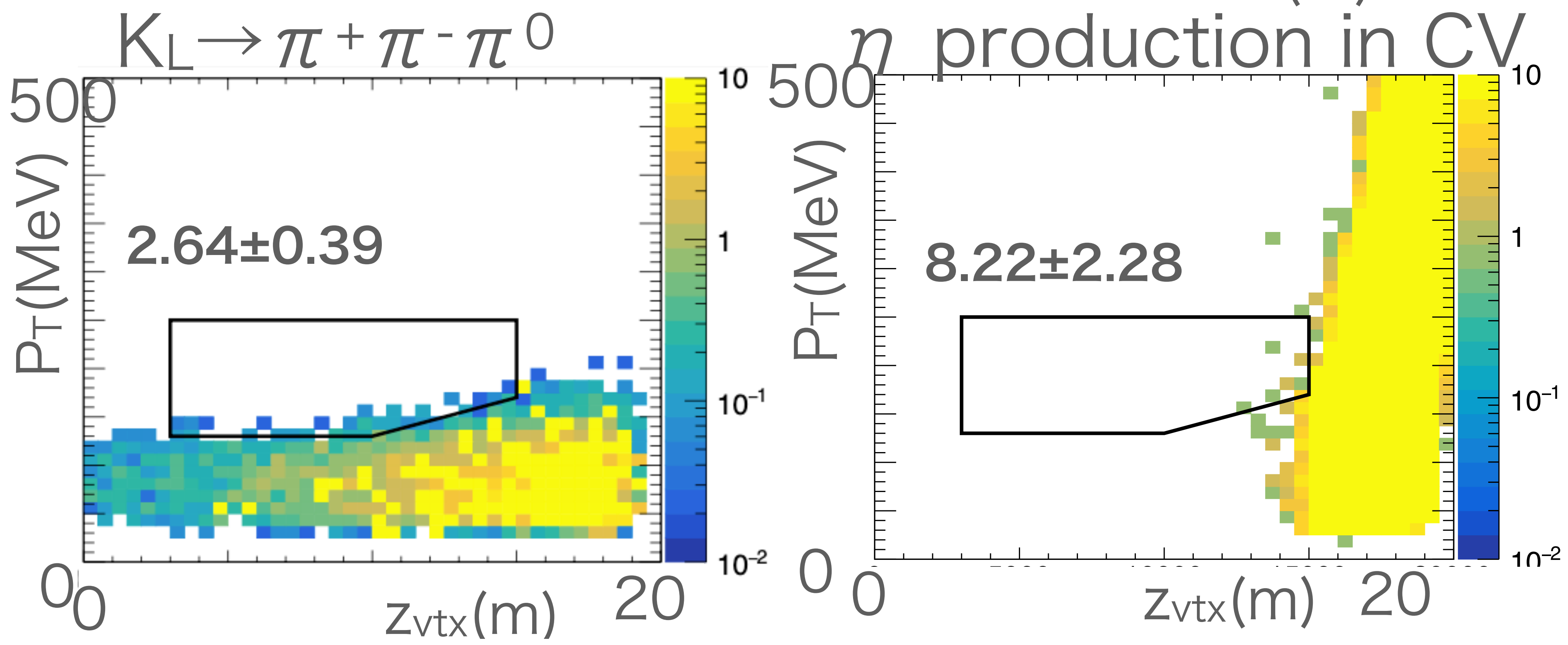
Signal / Background / Sensitivity

arXiv : 2110.04462

$K_L \to \pi^0 \nu \overline{\nu}$





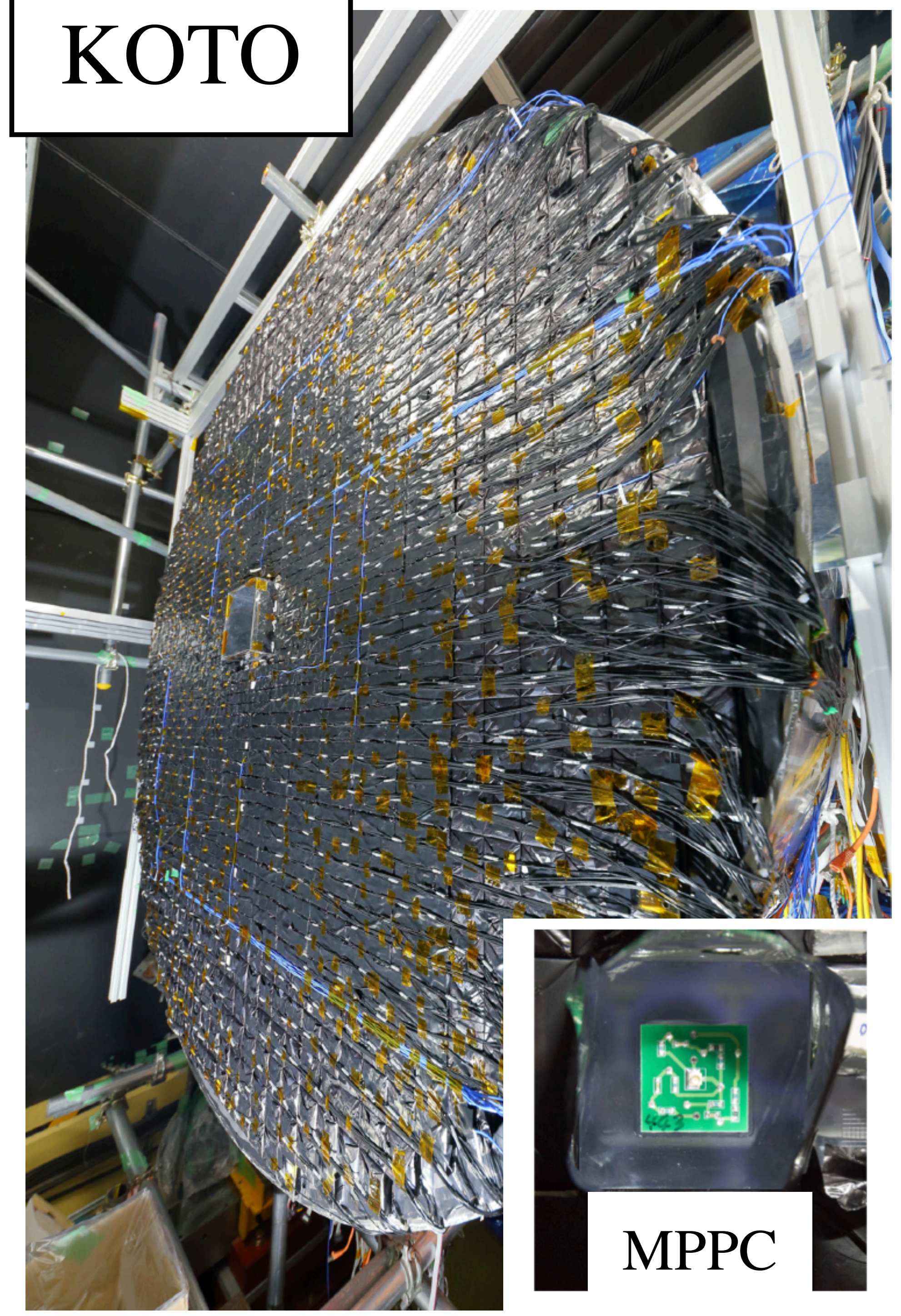


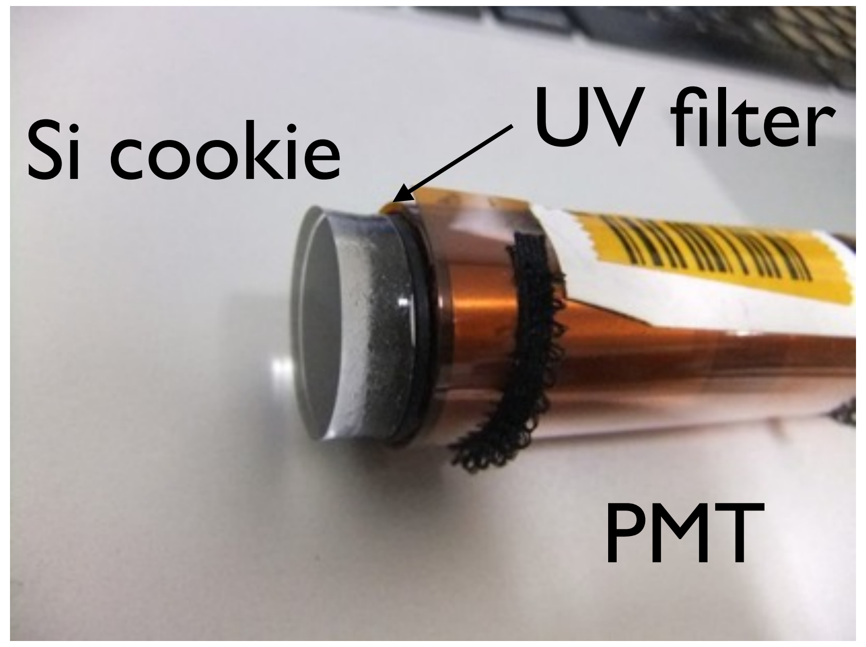
# of signal events : 35
# of background events : 56
S/N = 0.63
→ 4.7σ observation

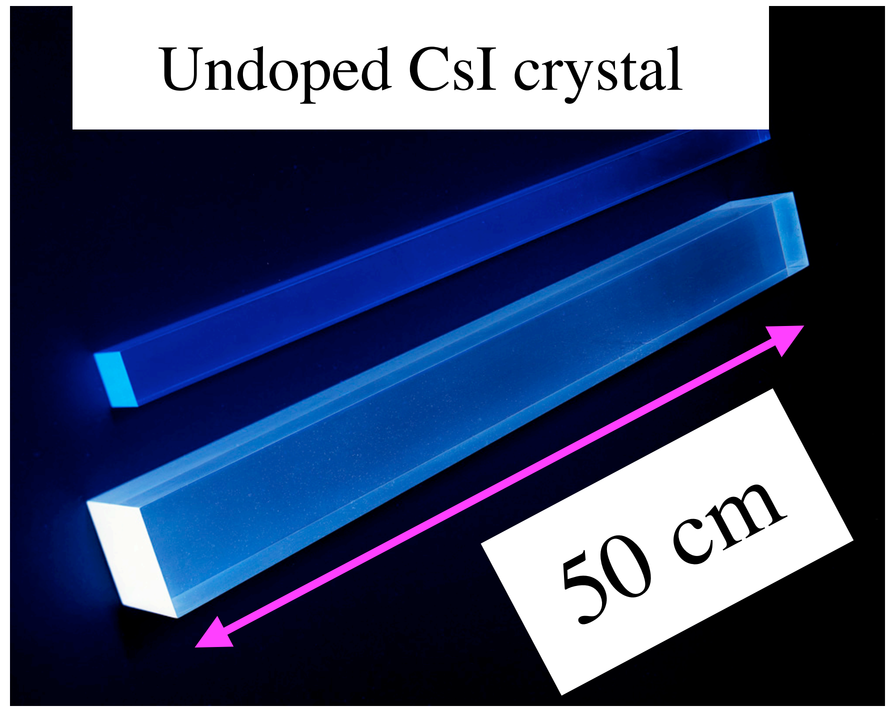
- $\Delta\mathscr{B}/\mathscr{B} = 27\,\%$ → CKM parameter : $\Delta\eta/\eta = 14\,\%$
- 44% deviation from SM→90%-CL indication of NP

Detector toward KOTO Step-2

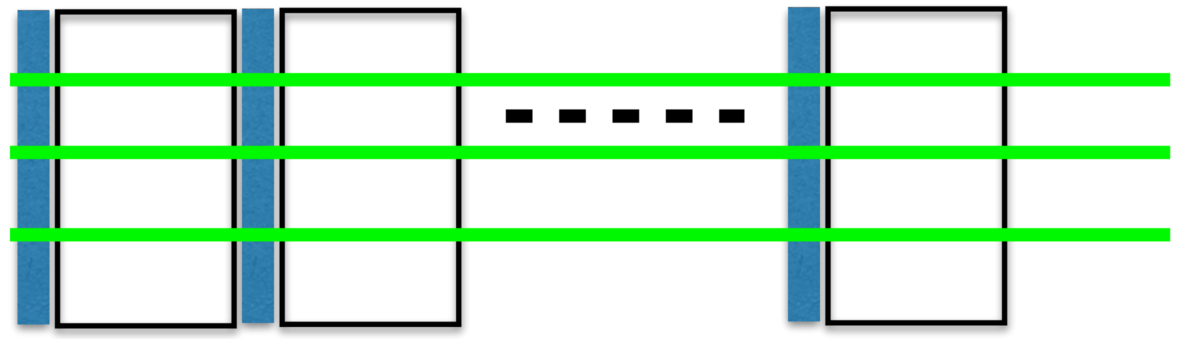
KOTO

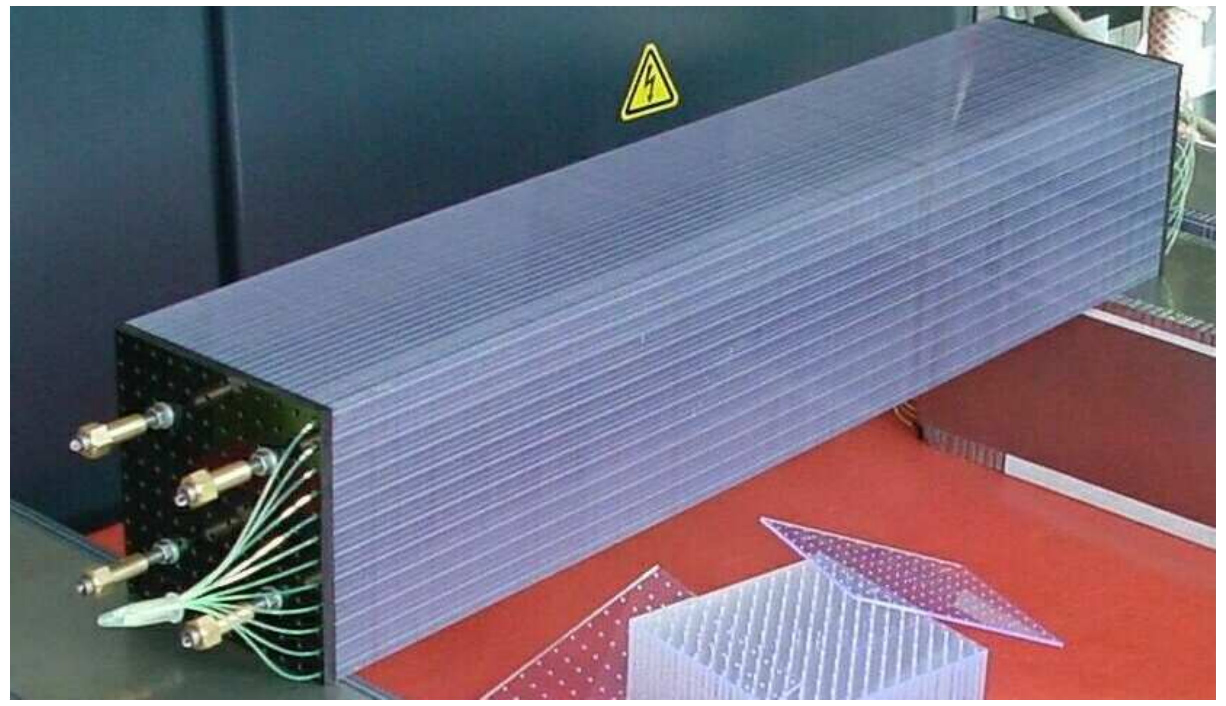






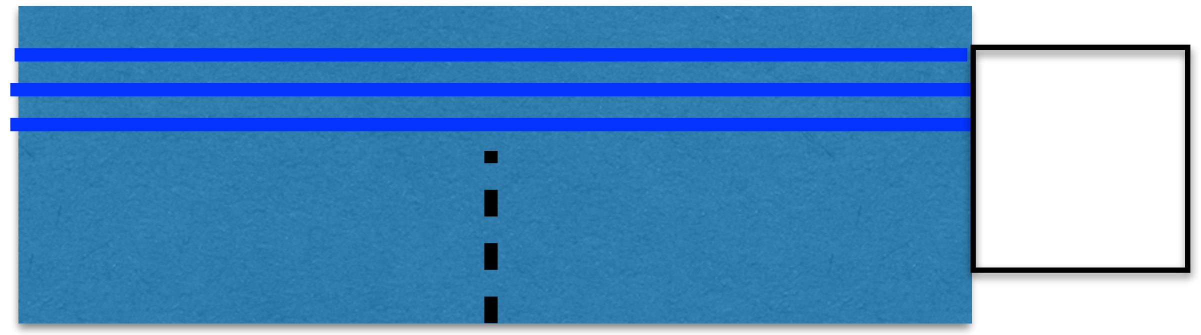
KOPIO

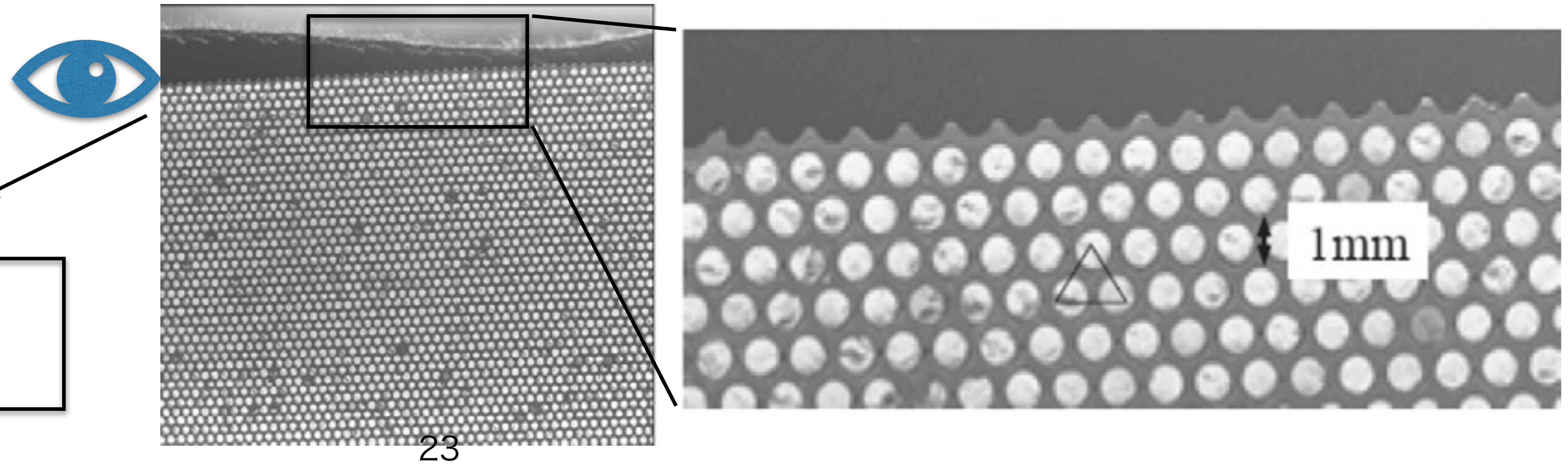




KLOE

Pb/Scintillating fiber (1mmϕ)



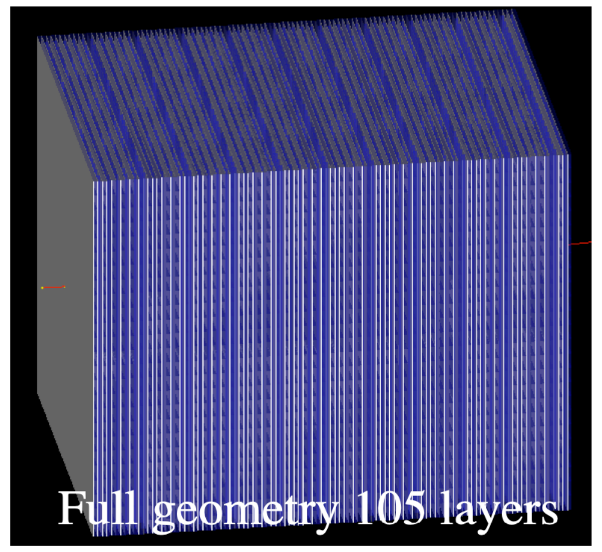


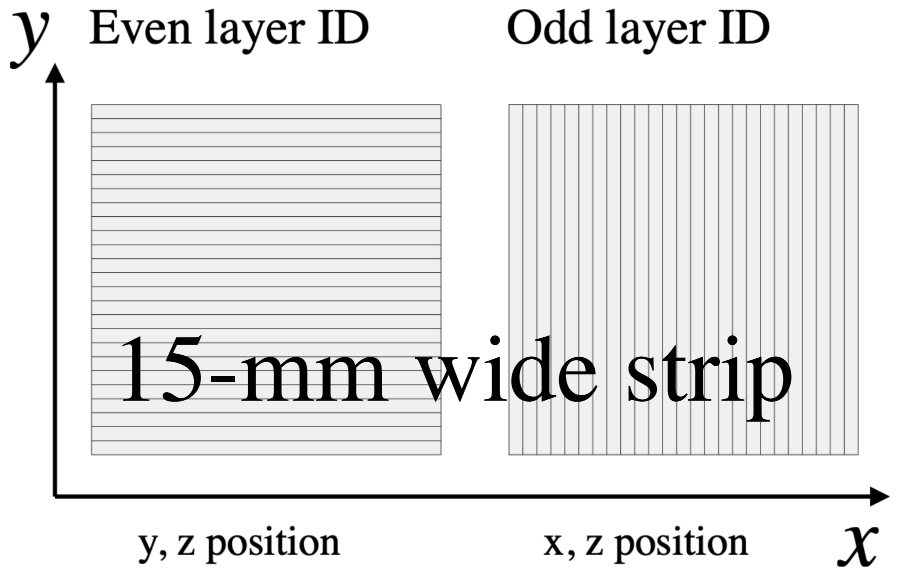
Low-mass fast charged particle veto

3 m in diameter
Timing resolution < 300 ps

Angle measurement capability

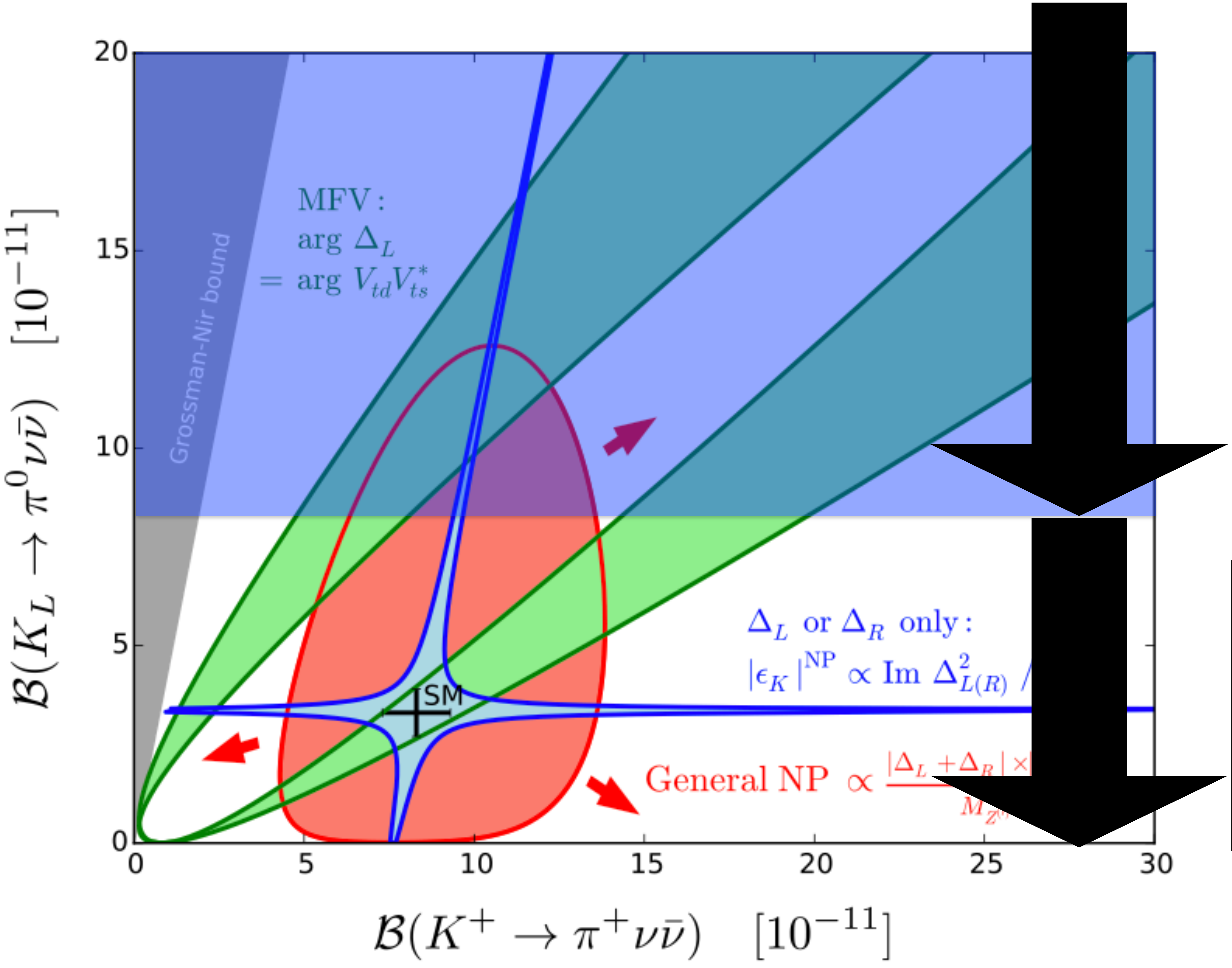
1-mm lead / 5-mm plastic scinti.
for upstream part of the calorimeter





MC Study to obtain incident angle
from shower development.
1-2 degree resolution so far
for 0.2-2 GeV photons

Prospects for KOTO to KOTO step-2

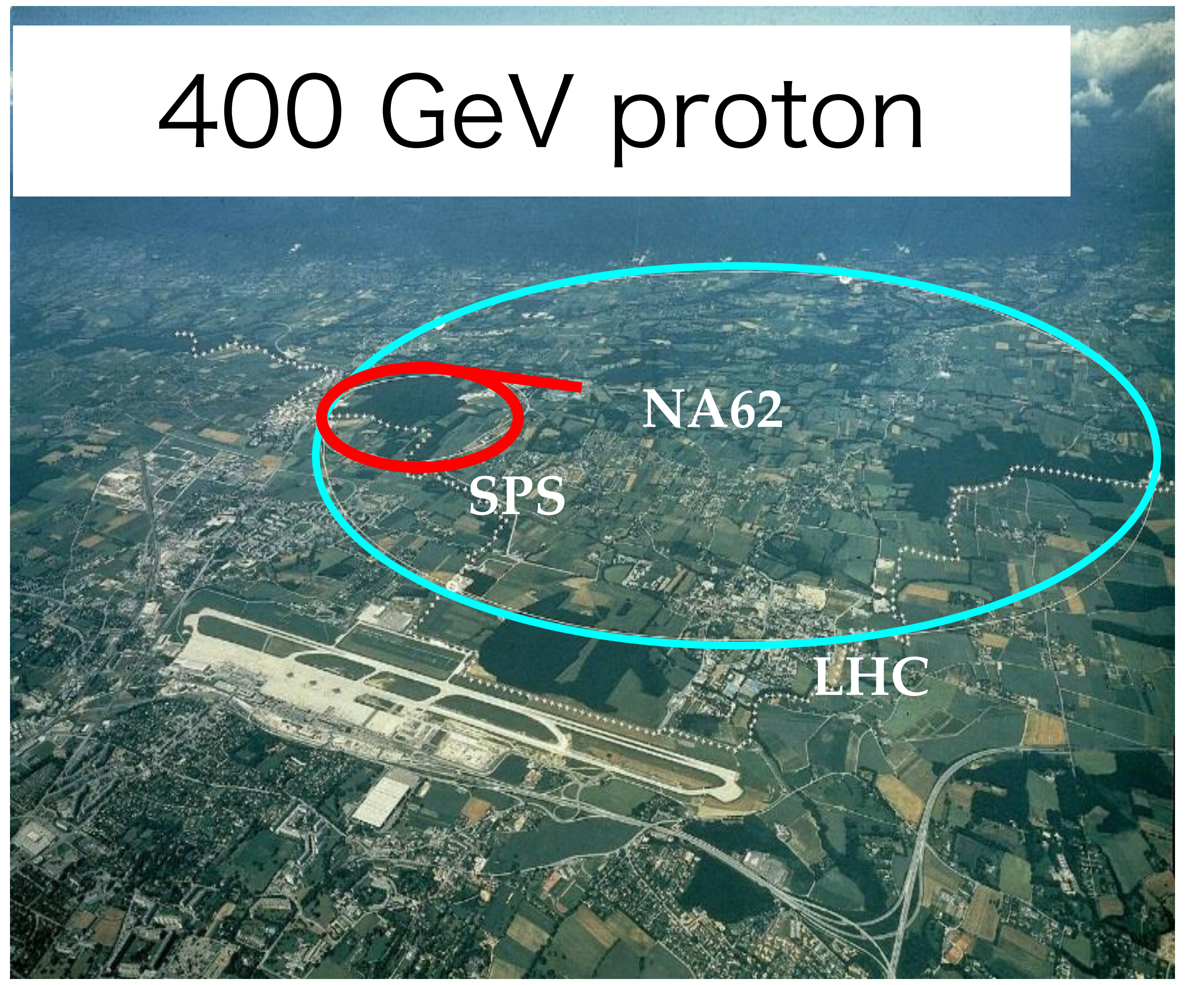


KOTO will reach $O(10^{-11})$ sensitivity

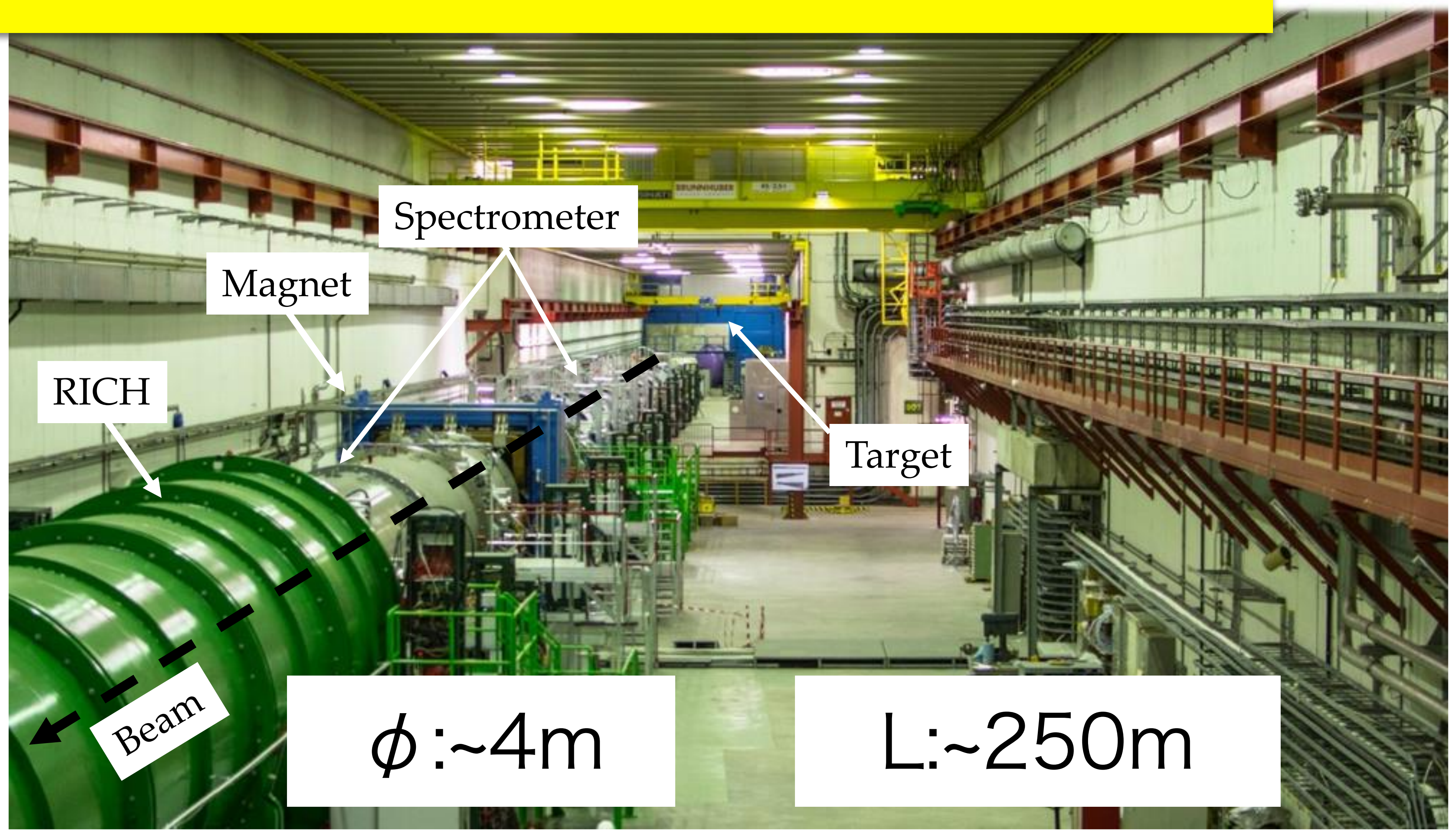
Upper limits or a few events with # of backgrounds ~ 0
Saturation of sensitivity

KOTO step-2 aims at measurements of $\mathscr{B}(K_L \to \pi^0 \nu\bar{\nu})$
~40 events in SM sensitivity
$O(10^{-13})$ sensitivity

NA62 experiment at CERN

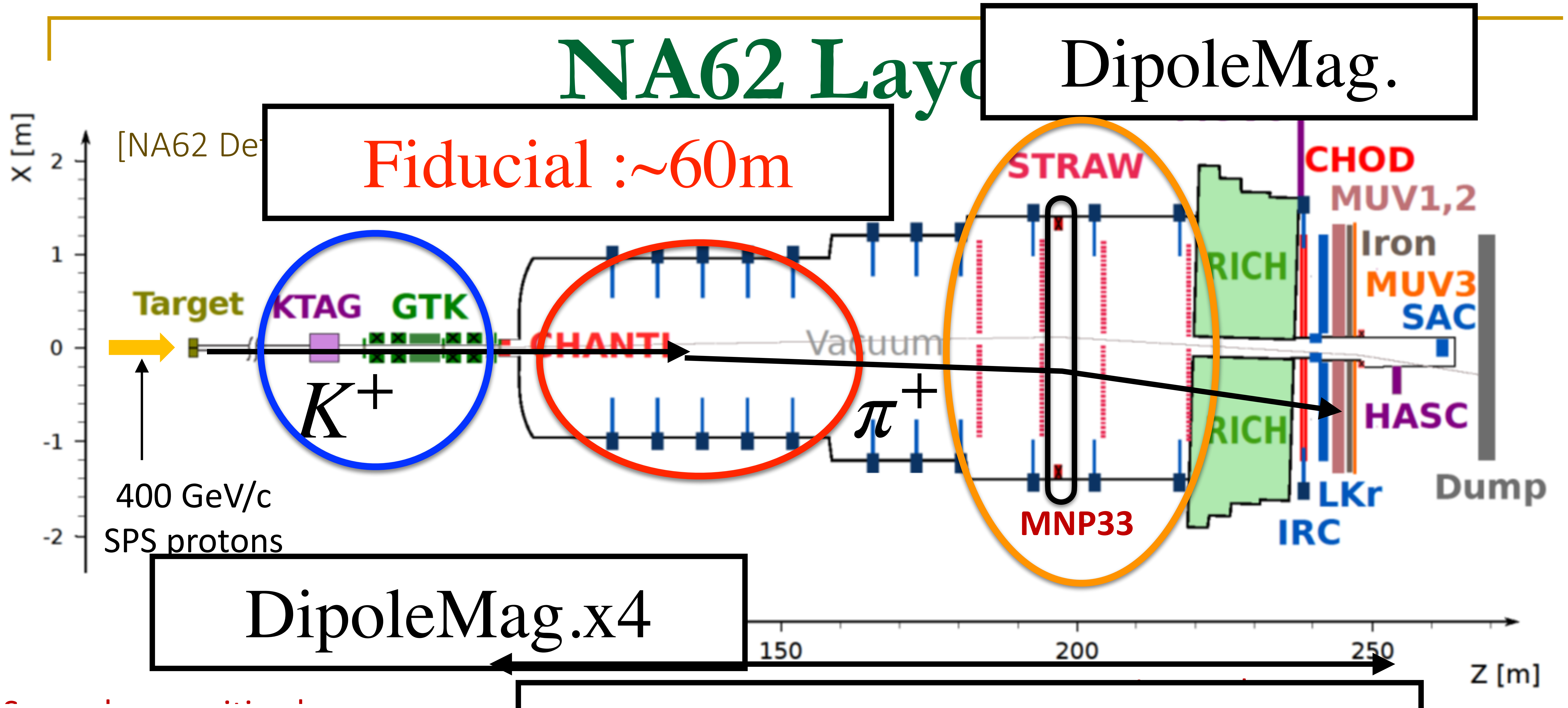


$K^+ \to \pi^+ \nu \bar{\nu} : K^+ \to \pi^+ +$ nothing



$K^+ \to \pi^+ \nu \bar{\nu}$ with NA62 experiment

400 GeV proton→75 GeV/c K+



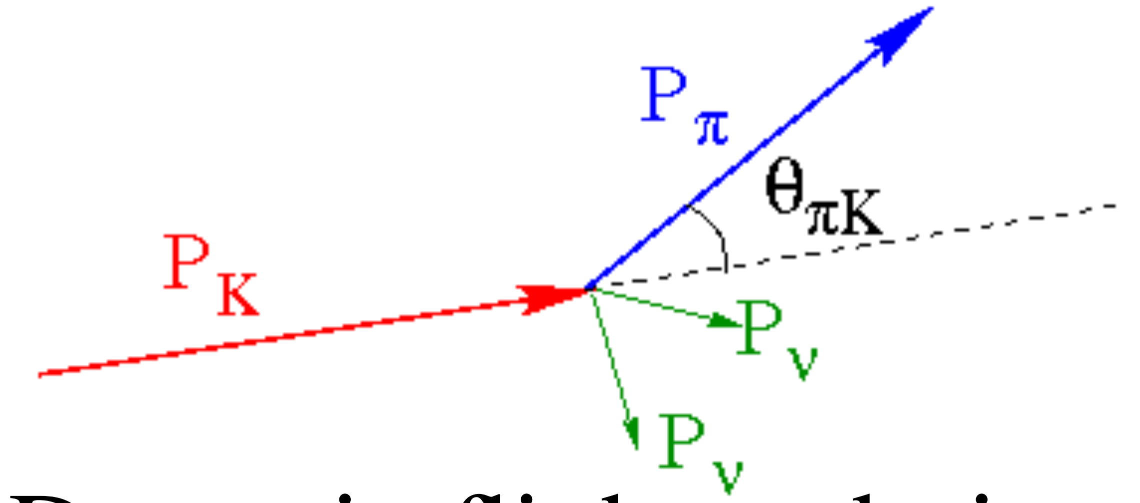
Fiducial :~60m

DipoleMag.

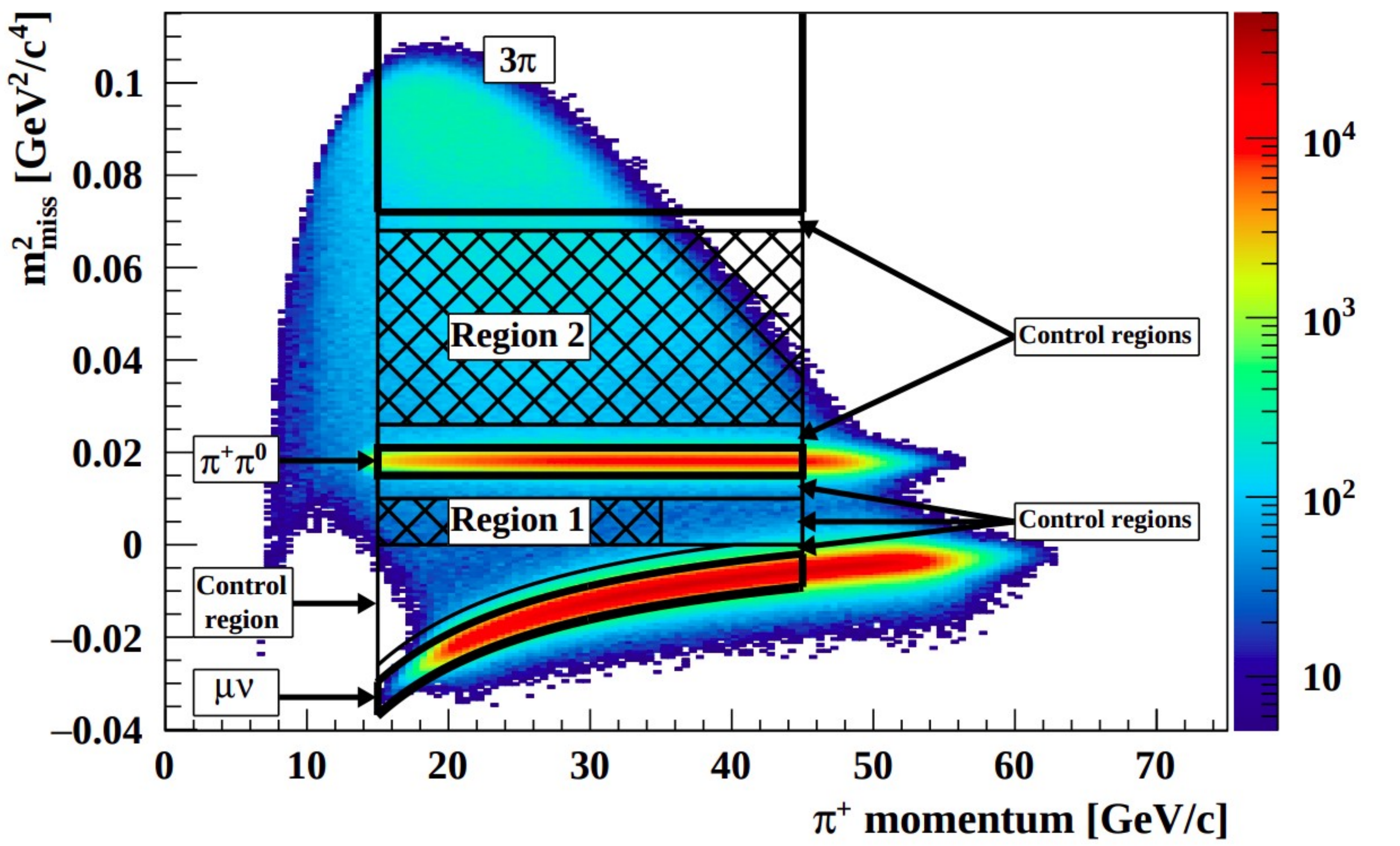
DipoleMag.x4

~150m veto sections

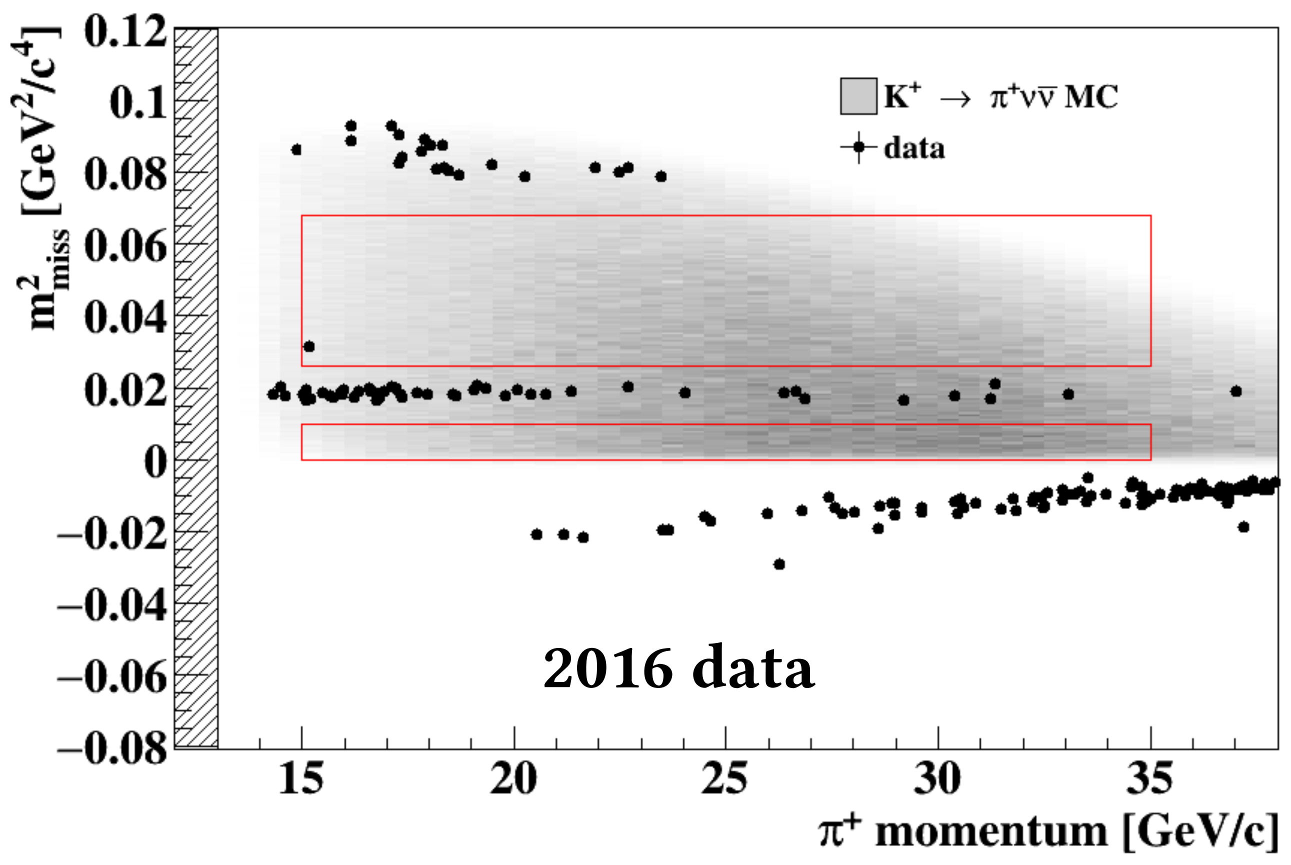
$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$

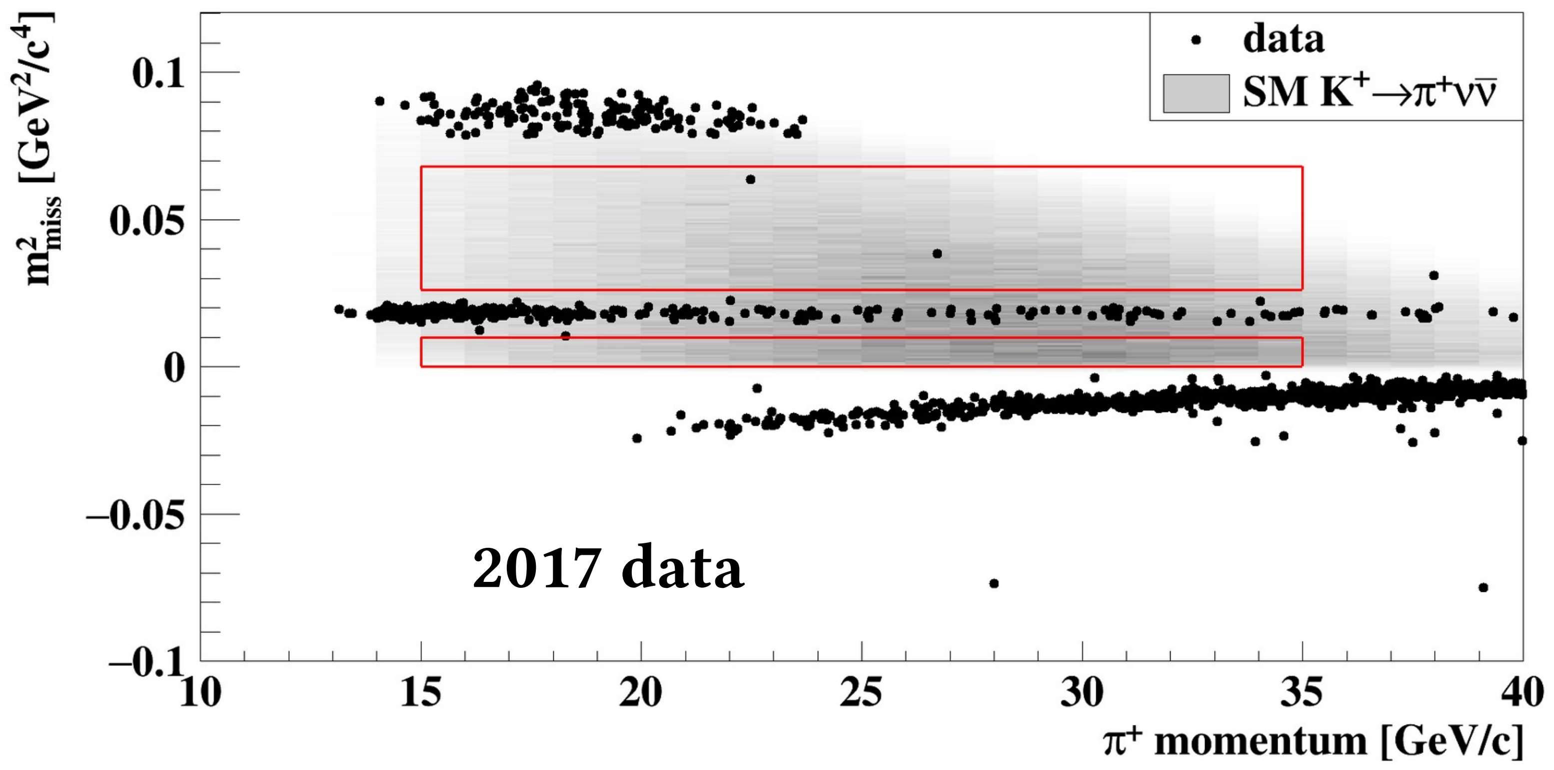


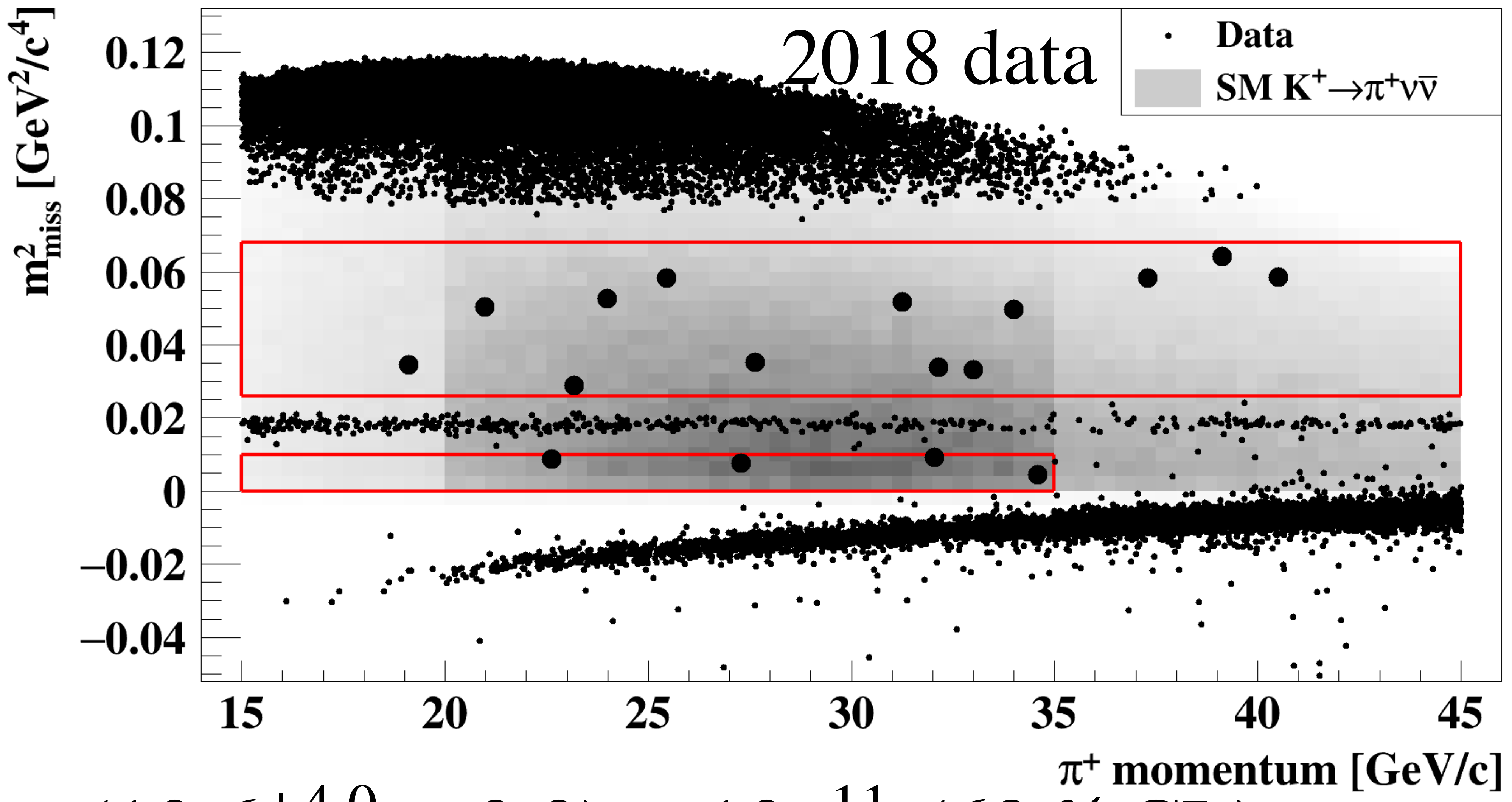
- Decay in flight technique
- High momentum K+(75GeV/c)
- K+ tracking w/ magnetic field → p_K
- π+ tracking w/ magnetic field → p_π



Results of NA62 run1 (2016-2018)







2016 : 1 event observed (*PLB* 791(2019) 156)

2017 : 2 events observed (*JHEP* 11(2020)042)

2018 : 17 events observed

In total 20 events observed

$$SES = (0.839 \pm 0.053_{\rm syst}) \times 10^{-11},$$

$$N^{\rm exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{\rm syst} \pm 1.19_{\rm ext},$$

$$N^{\rm exp}_{\rm background} = 7.03^{+1.05}_{-0.82}.$$

$\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$ (68 % CL)

→ 40% measurement

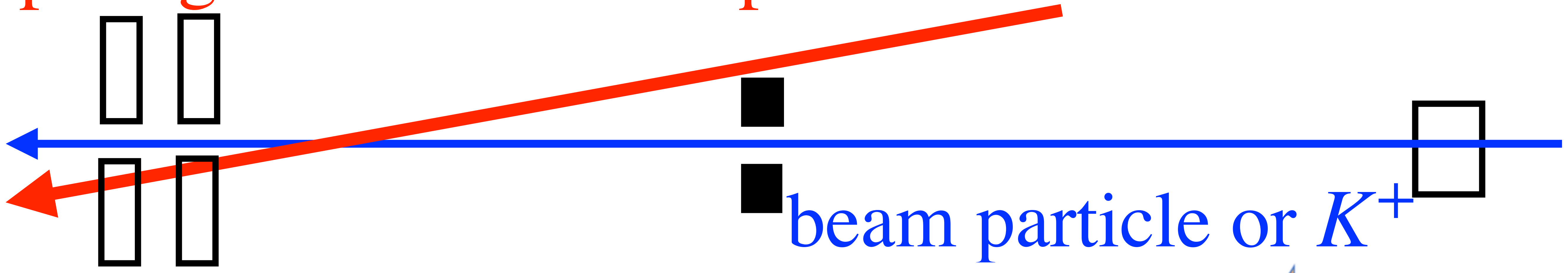
Observation with 3.4σ significance

Compatible with SM (8.4×10^{-11}) (*JHEP* 06 (2021) 093)

2018 : 17 events observed
: # of SM signal expected : 7.6
: # of BG expected : 5.4
: => 3.3 from upstream background (dominant)

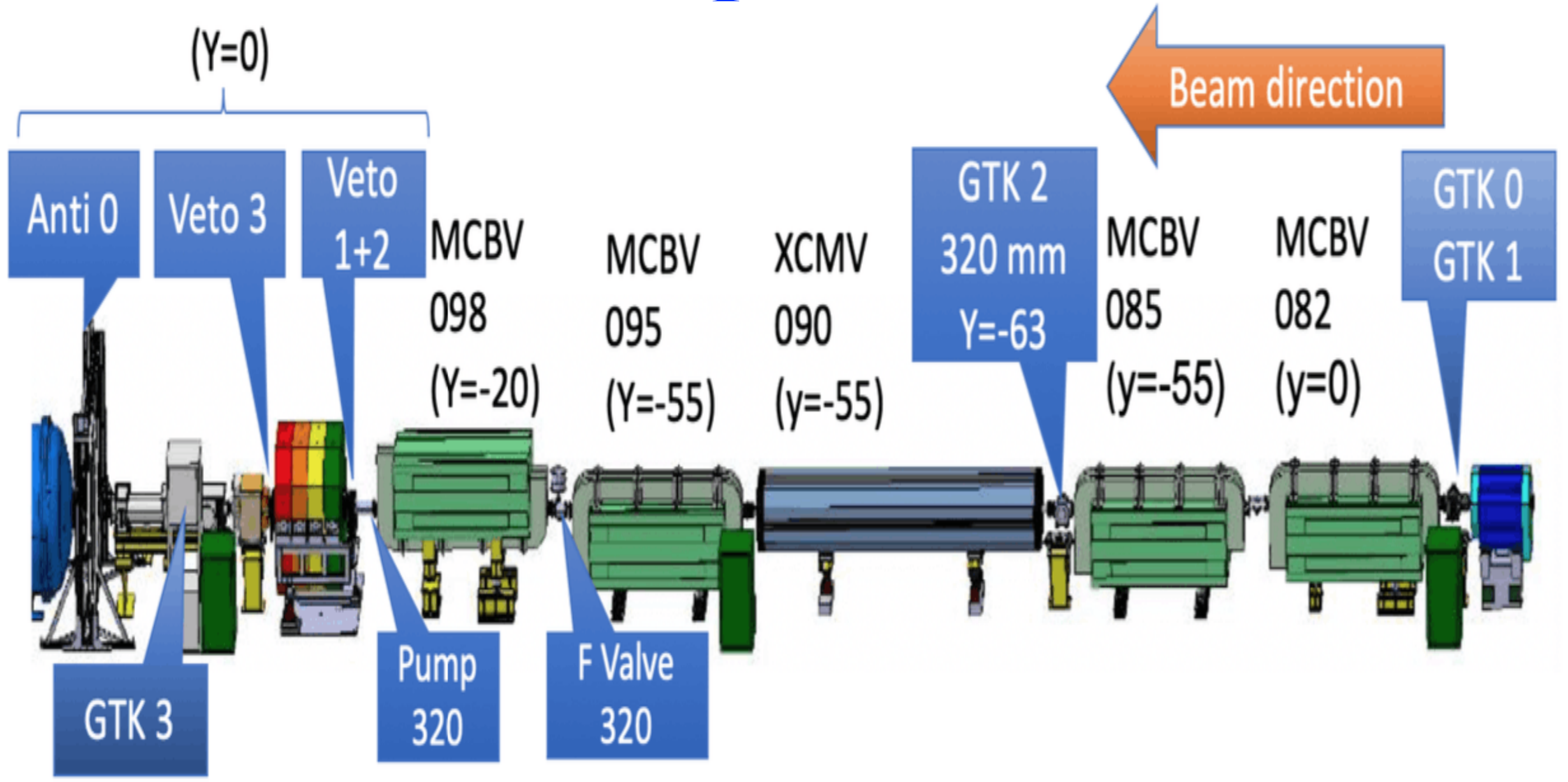
Measure against background

charged pion generated in the upstream



beam particle or K^+

Accidental coincidence or Decay



Larger collimator from 2018 to stop such charged pions
NA62 run2 : additional tracker (GTK 0) + veto

NA62 outlook

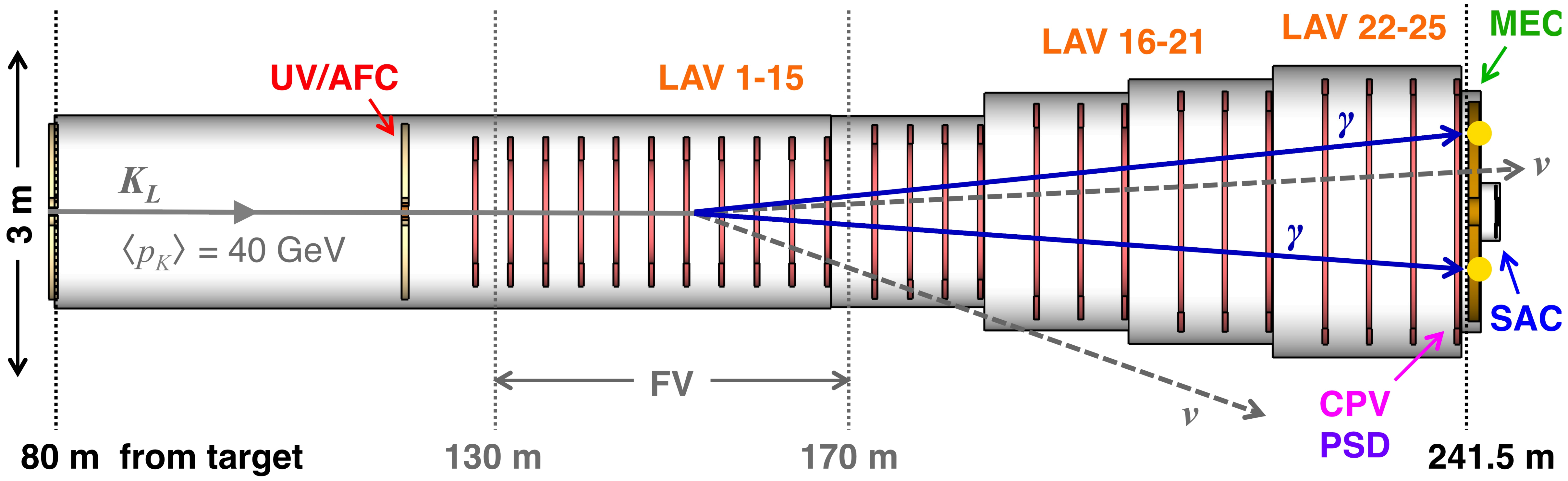
- Resumed data taking in July 2021 with the measure against the upstream background
- Running at higher beam intensity (70%→100%)
- NA62 was approved until LS3 (currently foreseen at the end of 2025)
- Expected order 10% measurement of $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu})$

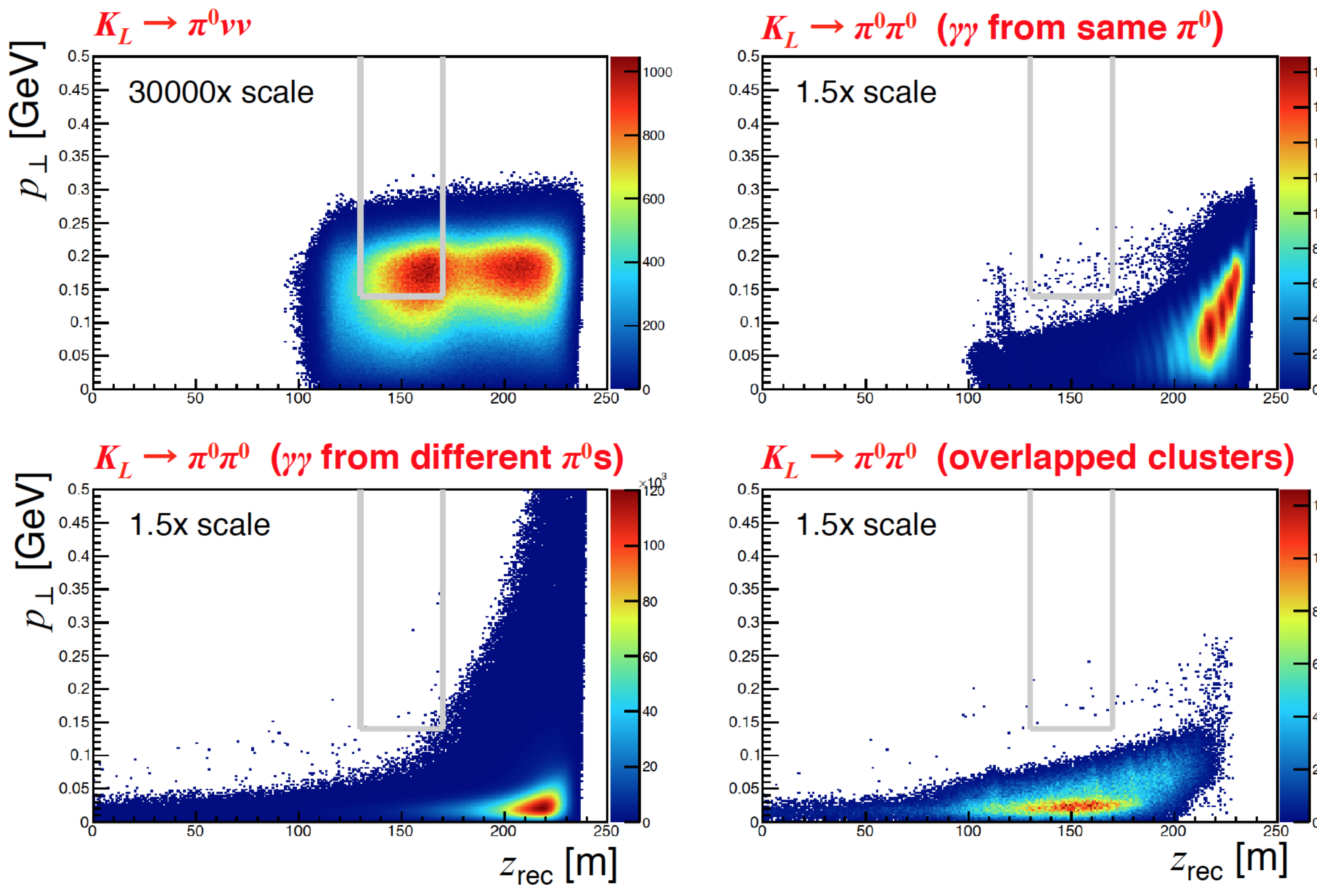
High Intensity Kaon Experiments (HIKE)

- After LS3, higher beam intensity at SPS
  - Plan to support both K^+ and K_L for long term plan until 2039.
  - 6×10^{18} pot/year ($\times 4$ increase) to measure $K^+ \to \pi^+ \nu \bar{\nu}$ at 5%
  - 1×10^{19} pot/year ($\times 6$ increase) to measure $K_L \to \pi^0 \nu \bar{\nu}$ at 20%
- Keys to handle the high rate
  - Accelerator : slow extraction with small beam loss, dump, target, radiation level
  - Improvements on the timing resolution is a key to handle high rate
  - Suppress $\Lambda \to n\pi^0$ background with longer beamline

$K_L \to \pi^0 \nu \bar{\nu}$ with HIKE (KLEVER)

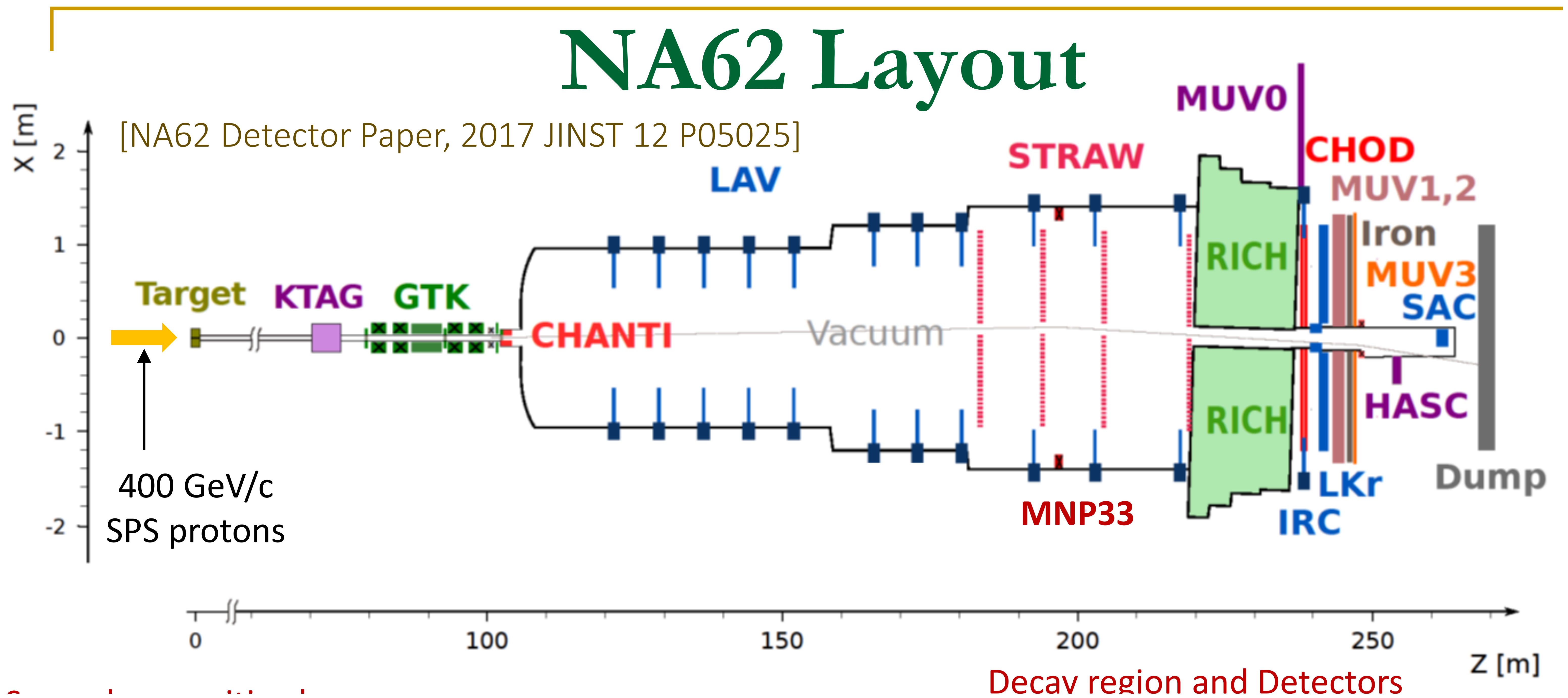
- $< p_{K_L} > \sim 40$ GeV/c
- 5 years running
- 60 SM events are expected with S/B=1.





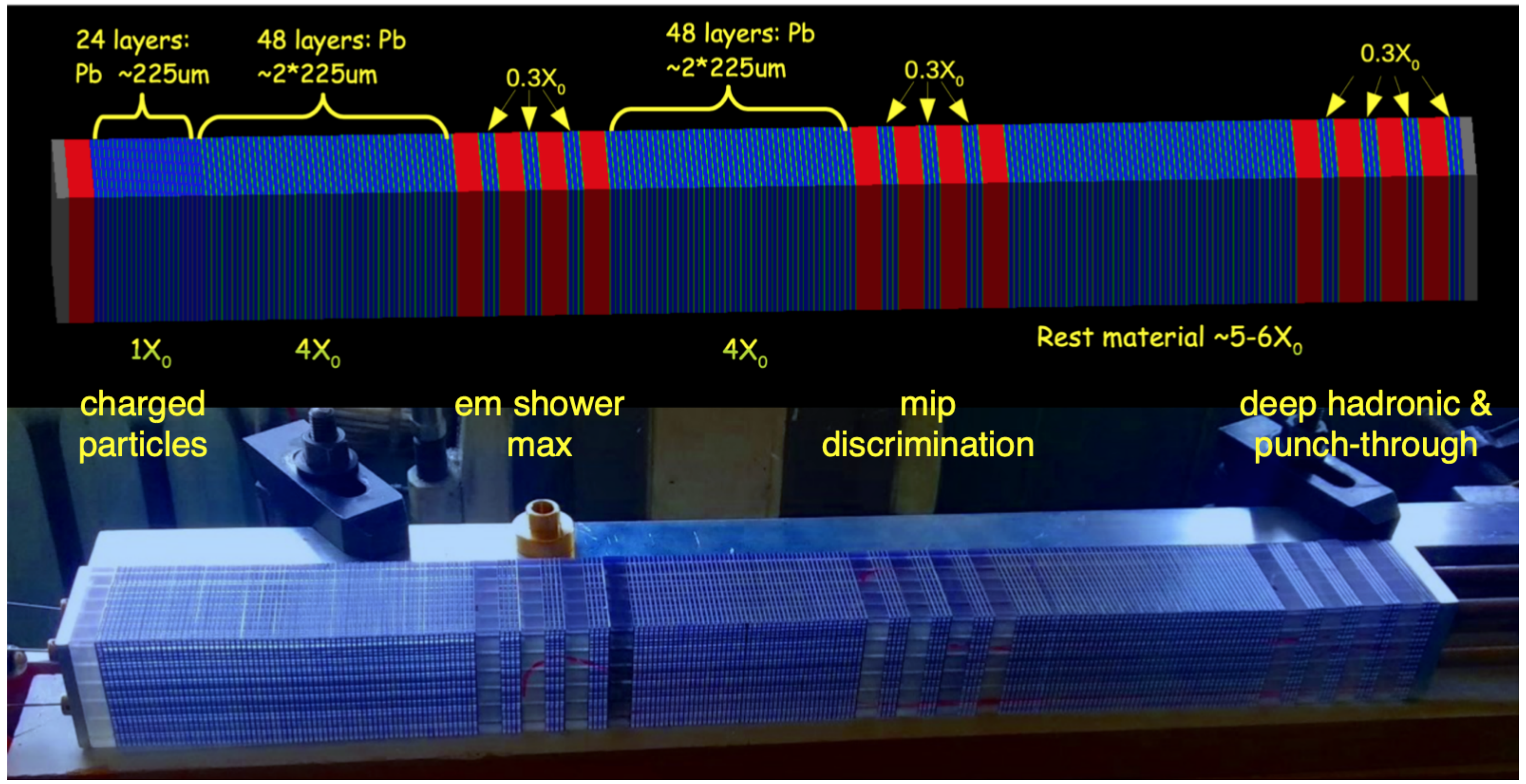
R&D for new detectors

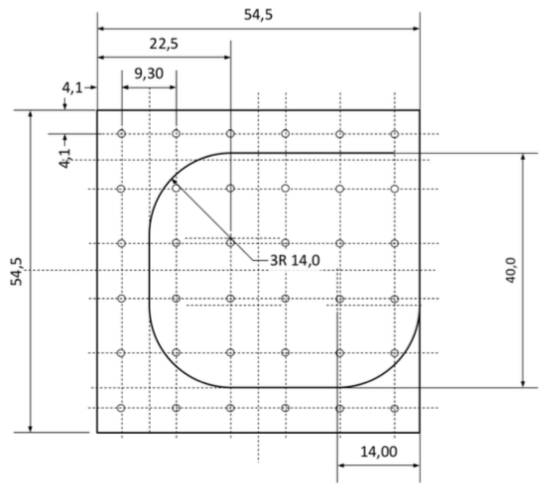
- New straw chamber with less diameter (~5 mm) and thinner wall (12 μm)
- Silicon pixel tracker (GTK) : planar, 3D, LGAD are being considered.
- Microchannel plate PMT for Cherenkov photon sensor

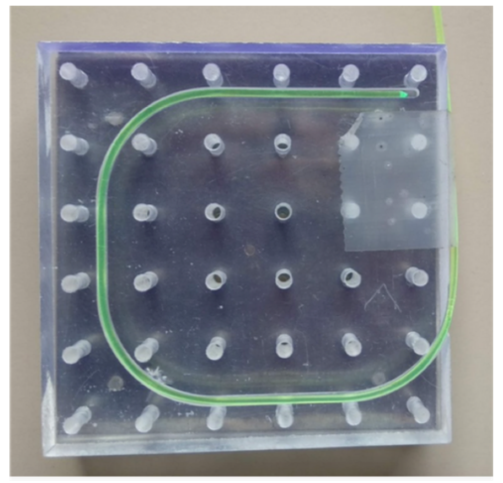


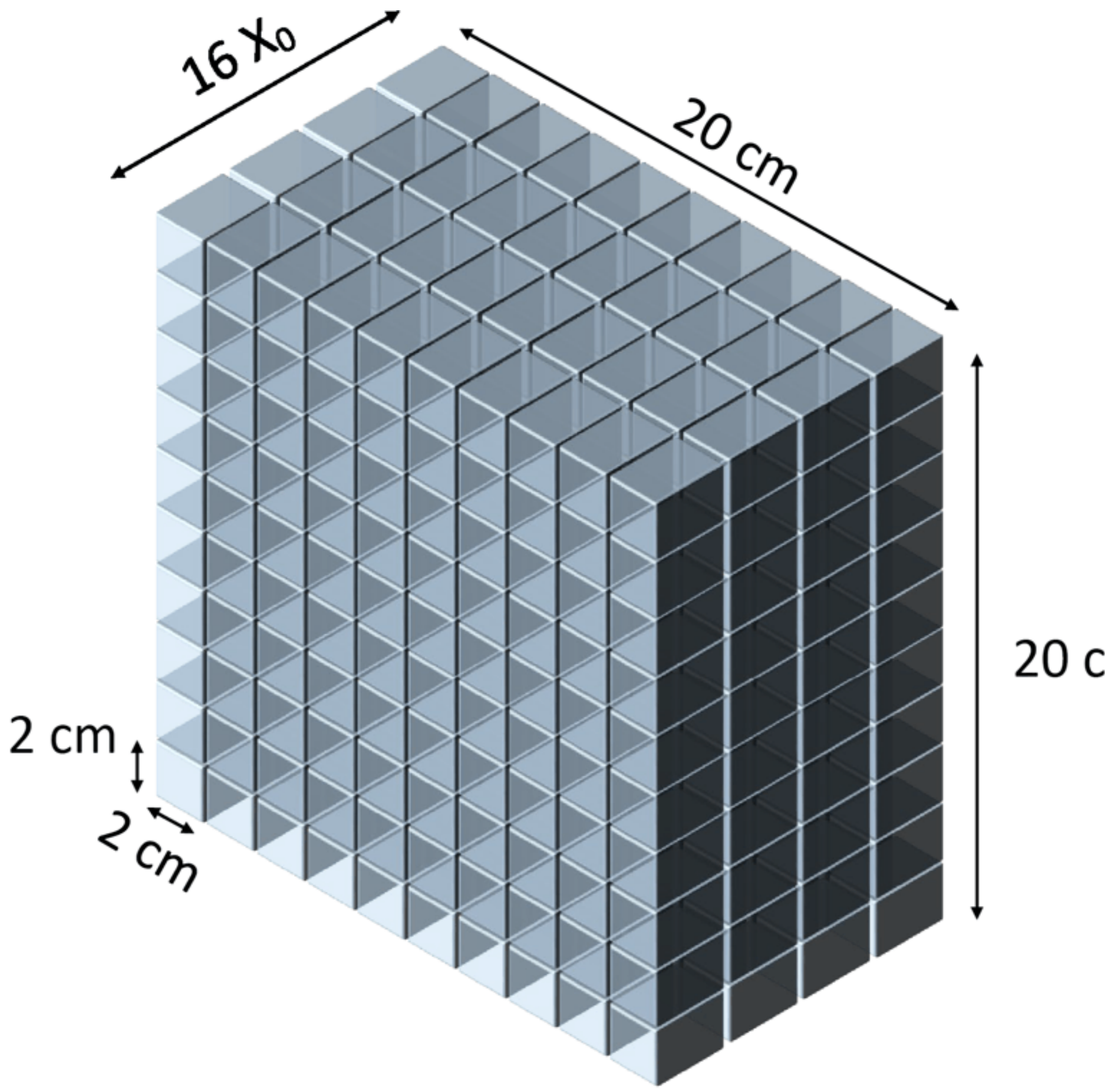
R&D for new detectors

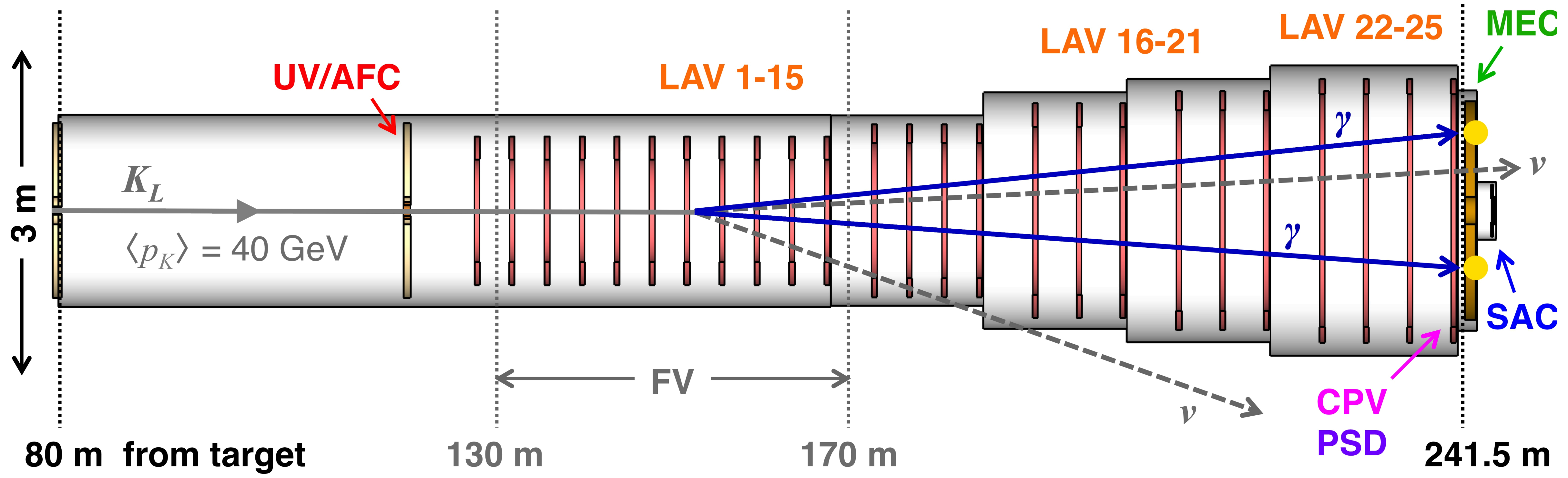
- MEC : Calorimeter with better timing resolution
  - Shashylic type
  - γ / neutron discrimination
- SAC: Tungsten / Silicon-pad sampling / Compact Cerenkov detector with 3D segmentation.
  - Crystal orientation →enhancement of photon conversion through coherent interaction





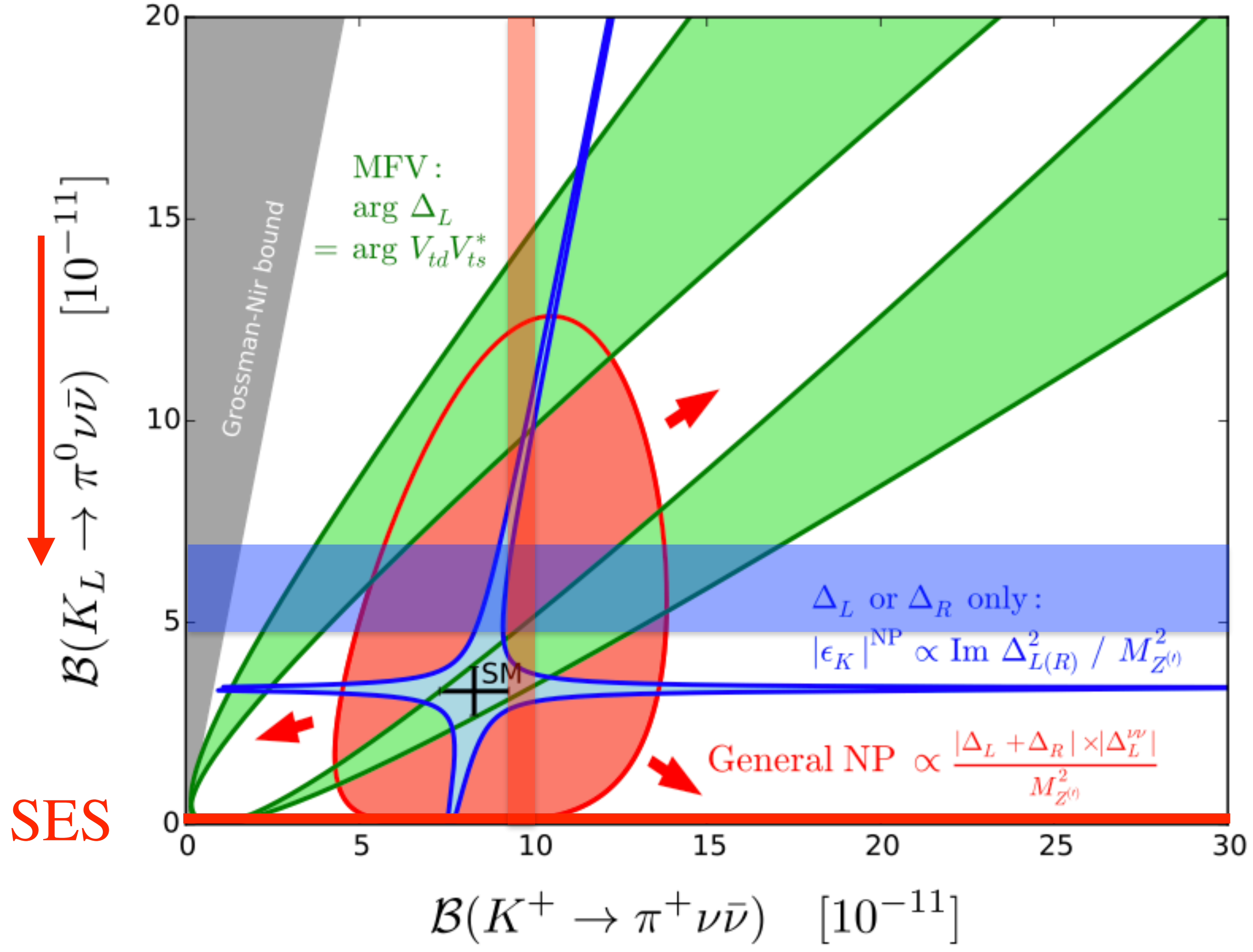


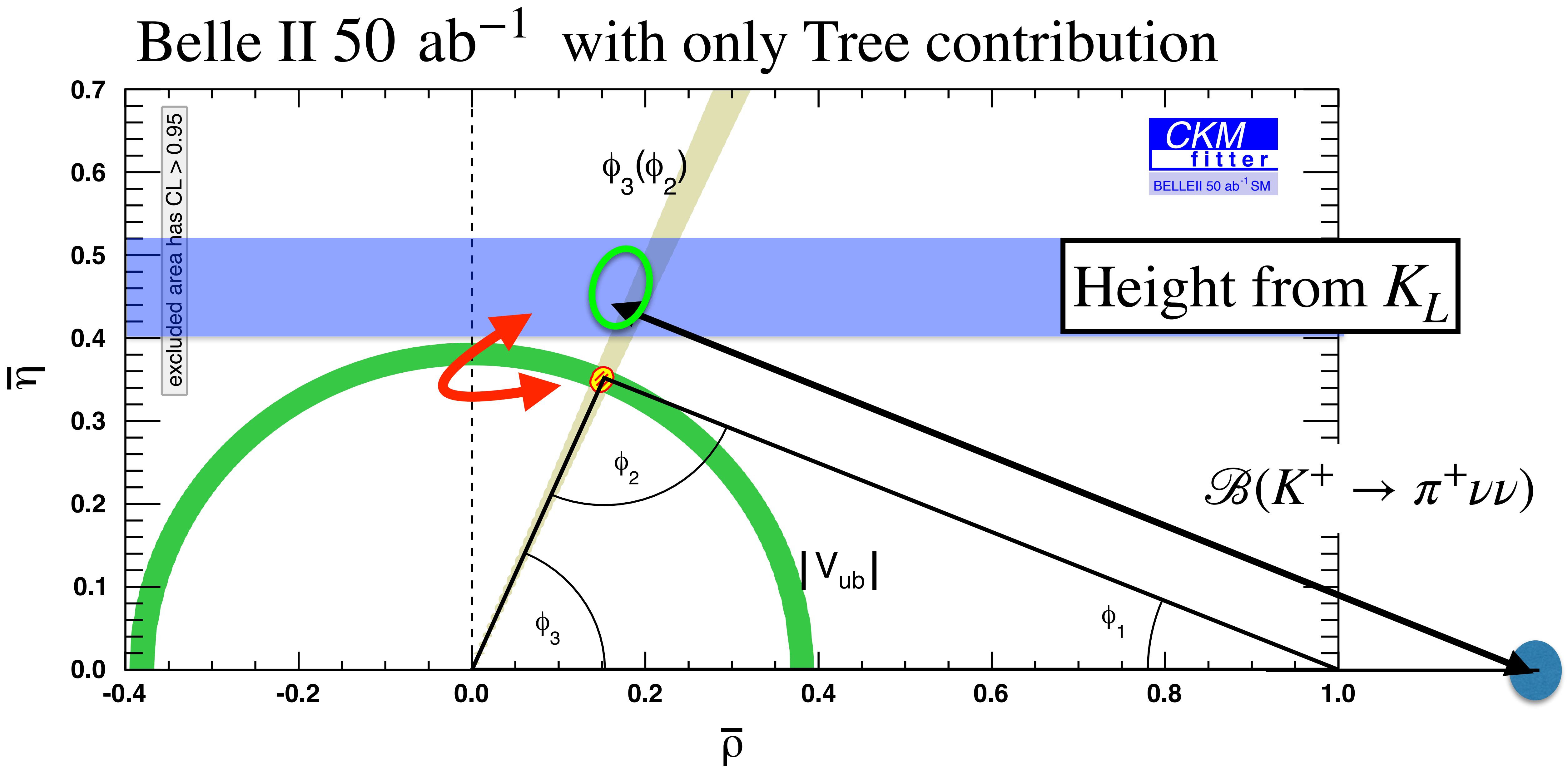




Impact of HIKE and KOTO Step-2

Just a case study:





May find new physics effect

K_S decays at LHCb

10^{13} K_S/fb^{-1} produced in LHCb acceptance

About 1 strange hadron per event!

Production rate compensates for low trigger efficiency and long lifetime

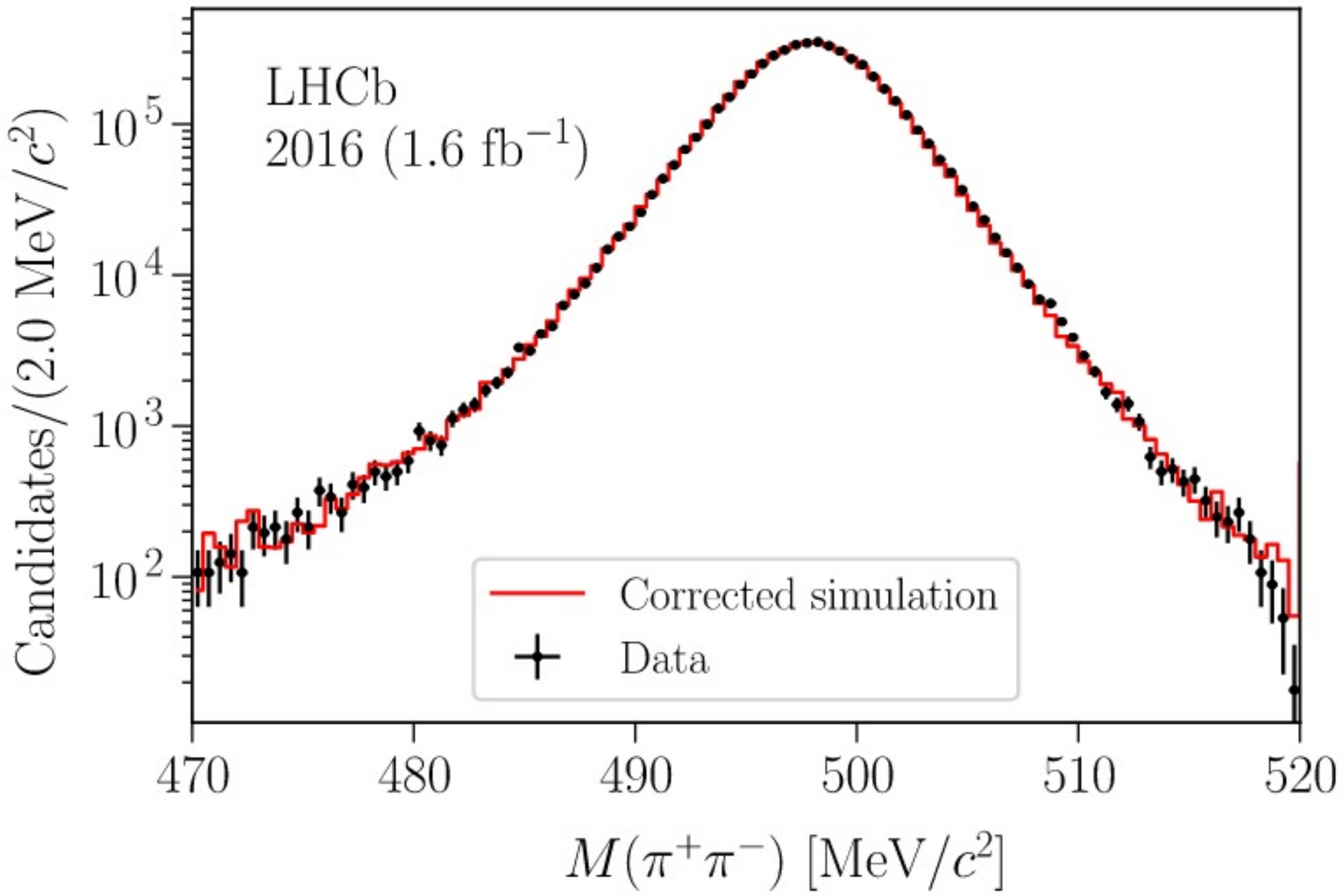
Vast K program for Run 3:

- $K_{S,L} \to \mu^+\mu^-$
- $K_S \to \pi^0\mu^+\mu^-$
- $K_S \to \pi^+\pi^-e^+e^-$
- $K_S \to \ell^+\ell^-\ell^+\ell^-$
- $K^+ \to \pi^+\ell^+\ell^-$
- + others

For example:

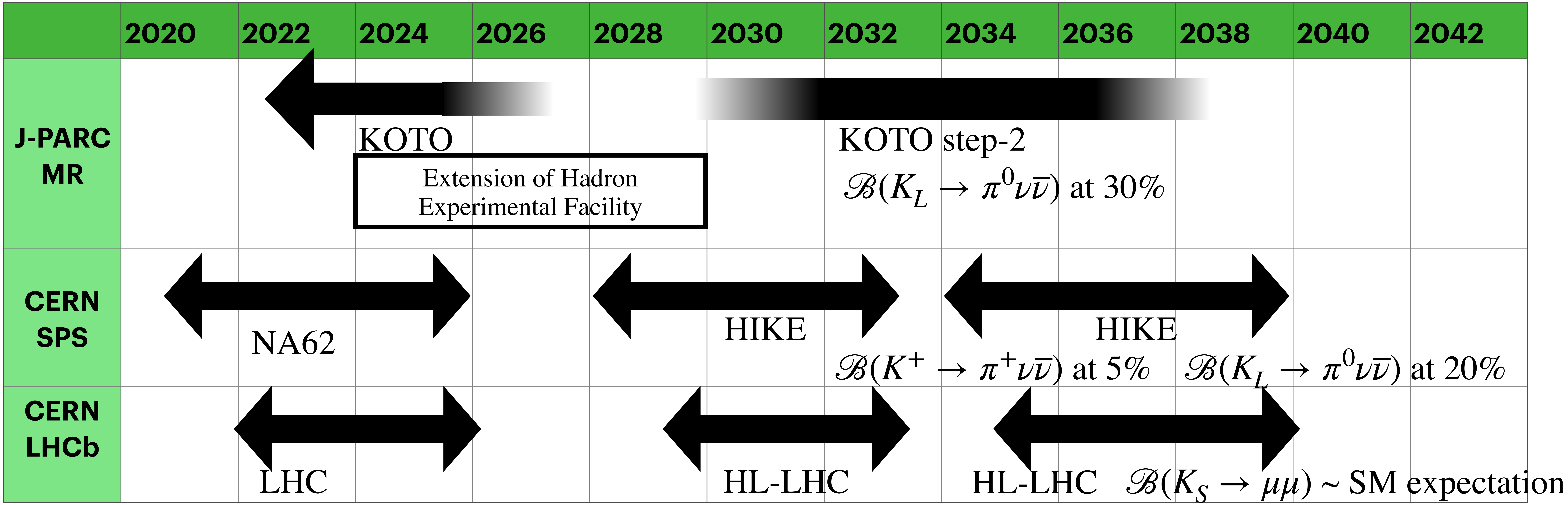
BR($K_S \to \mu^+\mu^-$) < 2.1 × 10^{-10} (90%CL)

PRL125 (2020) 231801



Invariant mass distribution for normalization mode

Long term timeline for a case study



- Current : Learning more with the on-going experiments. Develop high-performance detectors.
- ~2030s : Start new experiments.

Messages

- US groups are already contributing significantly to the existing kaon experiments.
- In a 2018 DOE KOTO review, the committee's report concluded that moving towards KOTO step-2 is well justified and that effort to recruit new collaborators is encouraged.
- It is important US groups keep such leading roles in the field toward the future.
- Many opportunities get involved are there for the current and future experiments with various R&D items.
  - Large size calorimeter with γ / neutron separation, Photon incident angle measurement, Fast-timing straw tubes, Low-mass fast charged particle counter including planar, 3D, LGAD sensors, Fast-timing photon sensor including MCP-PMT, Photon detector in high intensity neutral beam, …
- It is good timing to consider new experiments. We would like to have more brain storming with relaxed atmosphere. Is it assist these directions? Encouraging?
- Message at the spring meeting by Elizabeth Worcester
  - Participation in kaon experiments at JPARC and/or CERN is currently the only opportunity for US physicists to contribute to this vital area of research [...] the US HEP community is exploring possible expansions to our physics program that could be achieved with future upgrades to the Fermilab proton accelerator complex, envisioned to take place in the 2030s. This could include additional (next-next generation) experiments exploring the physics accessible with high-intensity kaon beams. The best way for the US HEP community to be well-positioned to take advantage of this opportunity would be to explore this physics and develop expertise in modern kaon experiments by participating in the international programs described in [the whitepaper].