FUTURE EXPERIMENTS OF KAON PHYSICS

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA+
Cluster of Excellence

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FPCP 2024, Bangkok

May 29th, 2024

(Special thanks to Hajime Nanjo from KOTO II)

Golden Kaon Decays

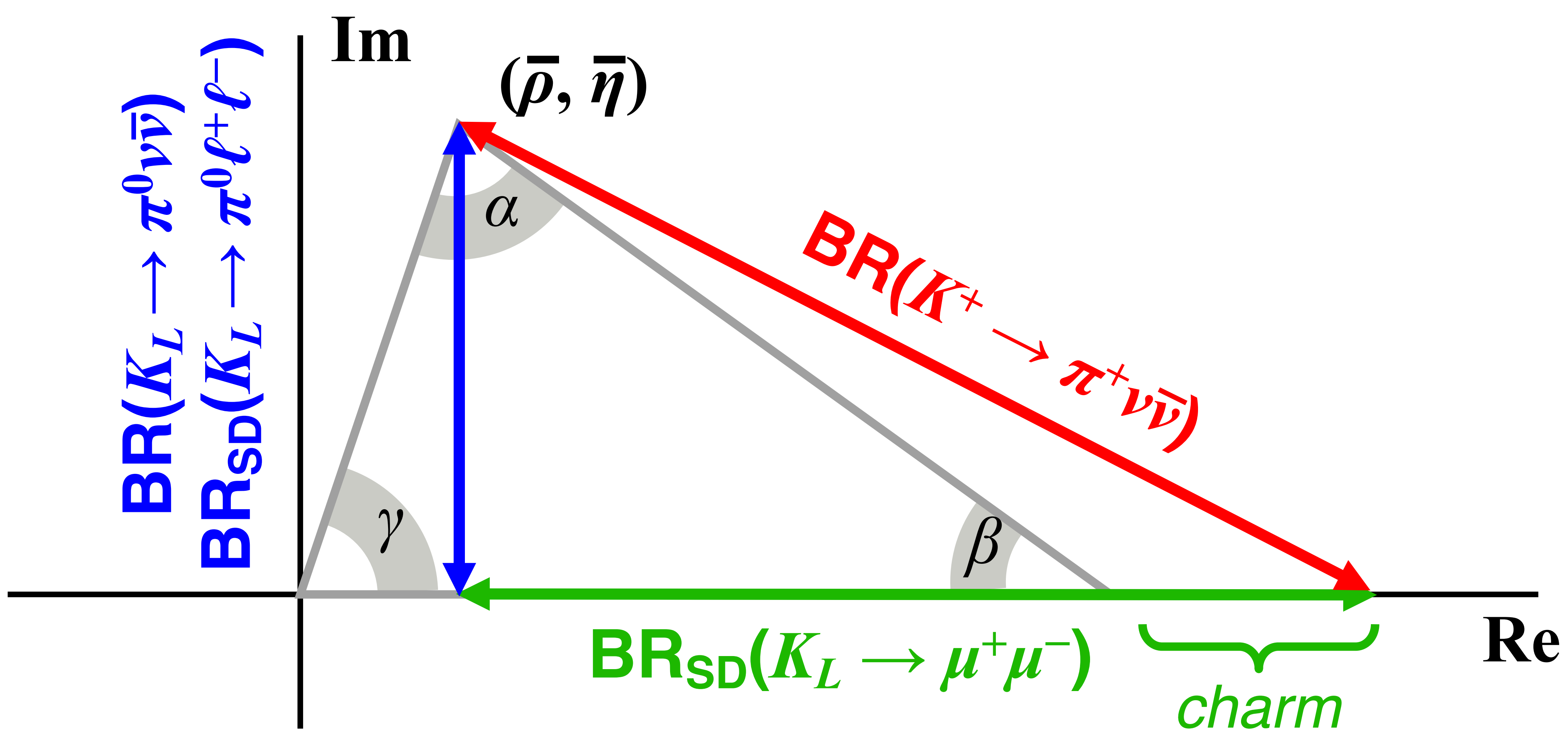
There is a handful of **"golden" Kaon decays**, which are very sensitive but also very rare.

- ▶ **Hadronic uncertainties small.**
- ▶ Almost **exact prediction by SM theory**.
- ▶ **Unique sensitivity to New Physics** because of **box & penguin diagrams**.

These are the decays to go for!

In addition:

Many other important Kaon decays
(LFV/LNV, $|V_{us}|$, Dark Matter searches, …)

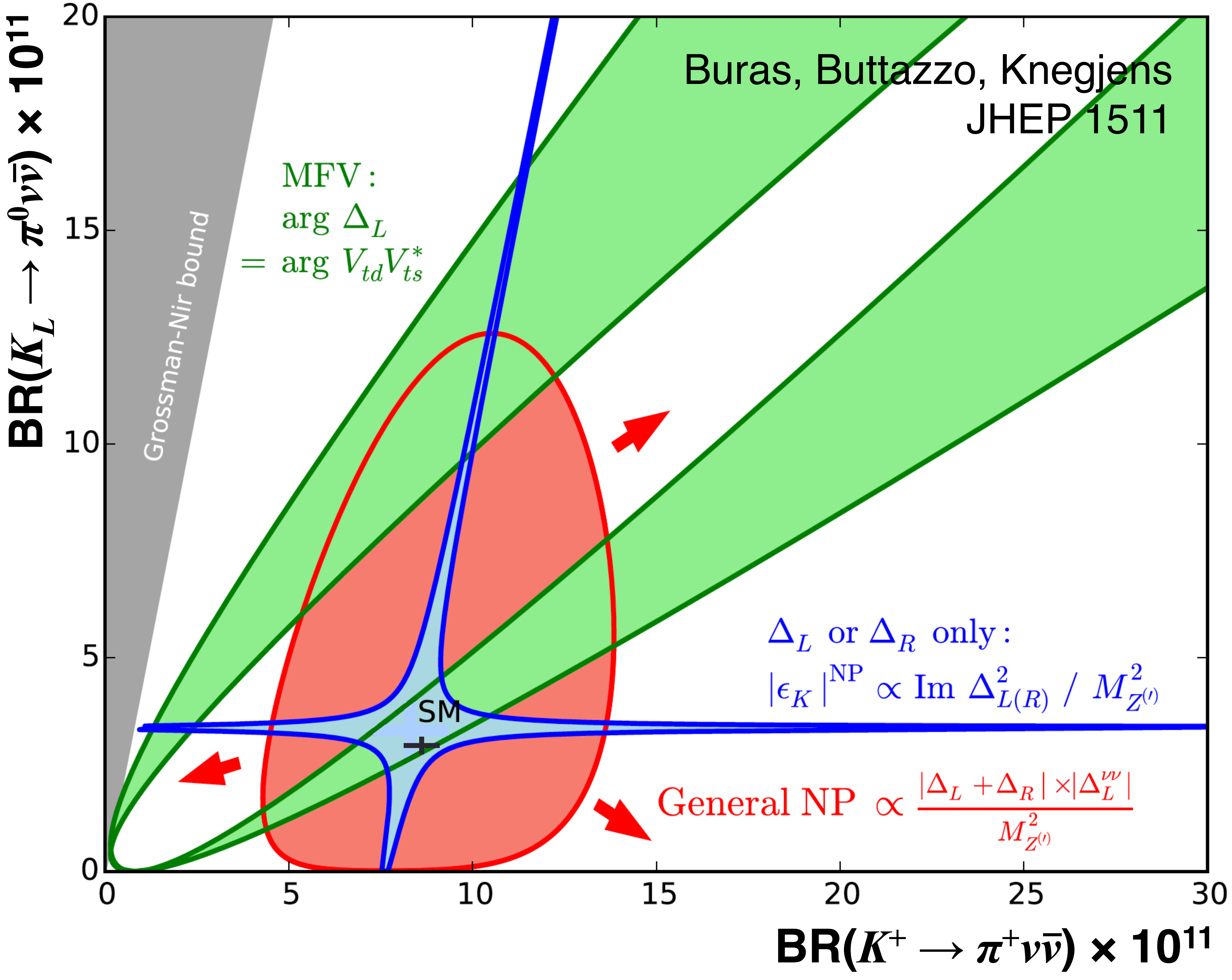


Decay	SM Branching Ratio
$K_L \to \pi^0 \nu \bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$ [1]
$K^+ \to \pi^+ \nu \bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$ [1]
$K_L \to \pi^0 \ell^+\ell^-$ (SD)	$(3.5 \pm ^{1.0}_{0.9}) \times 10^{-11}$ *ee*, [2]* $(1.4 \pm 0.3) \times 10^{-11}$ *μμ*, [2]*
$K_L \to \mu^+\mu^-$ (SD)	$(6.8 \pm ^{0.8}_{0.2}) \times 10^{-9}$ [3]*

[1] Buras, arXiv:2205.01118);
[2] Mescia, Smith, Trine, JHEP08 (2006) 088;
[3] Buras Fleischer, ASDHEP 15 (1998) 65;

* Assuming constructive interference with LD contribution.

Correlation between $K_L \to \pi^0 \nu \bar{\nu}$ and $K^+ \to \pi^+ \nu \bar{\nu}$



- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - Z/Z' models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints
  - Randall-Sundrum

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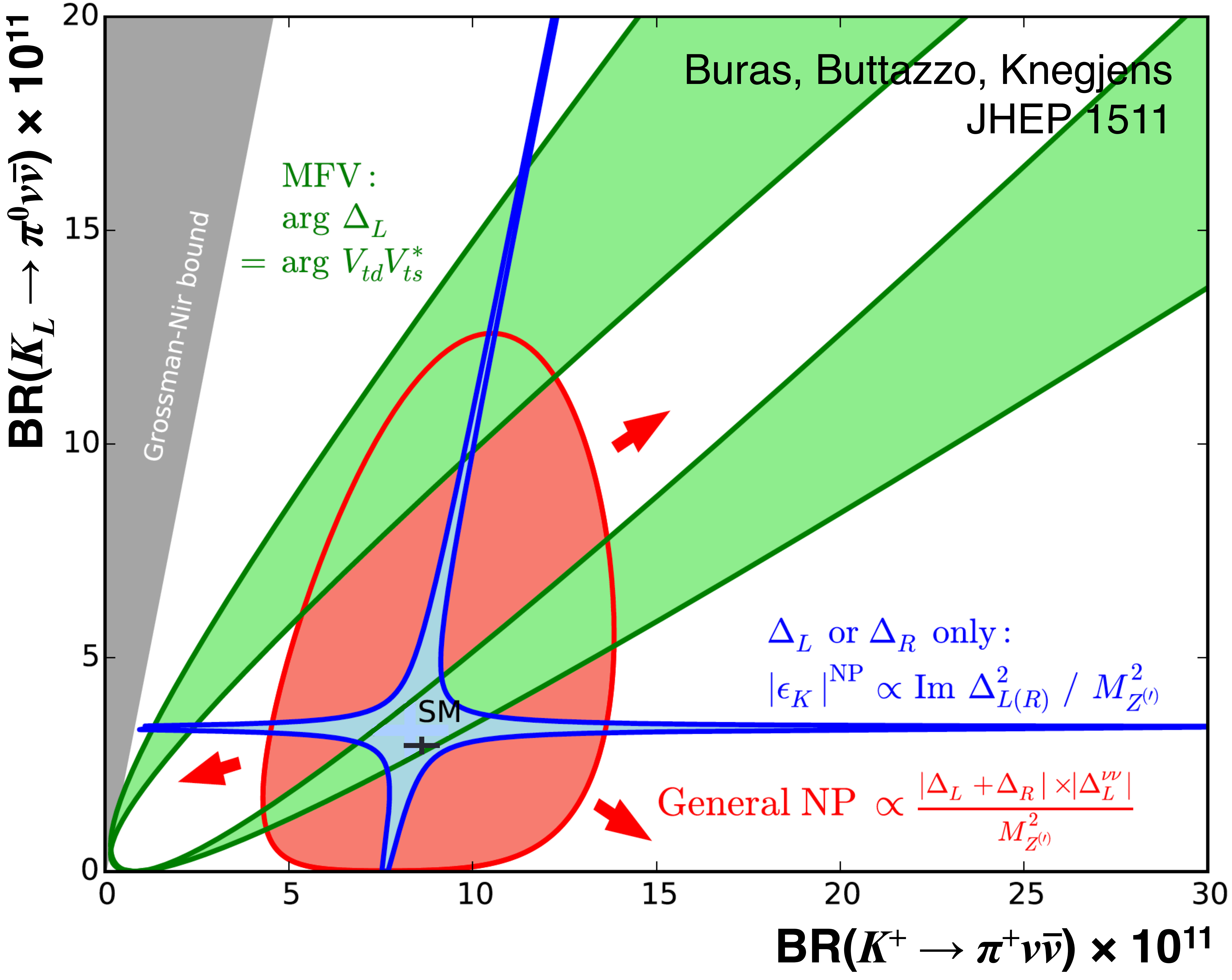


New Physics:

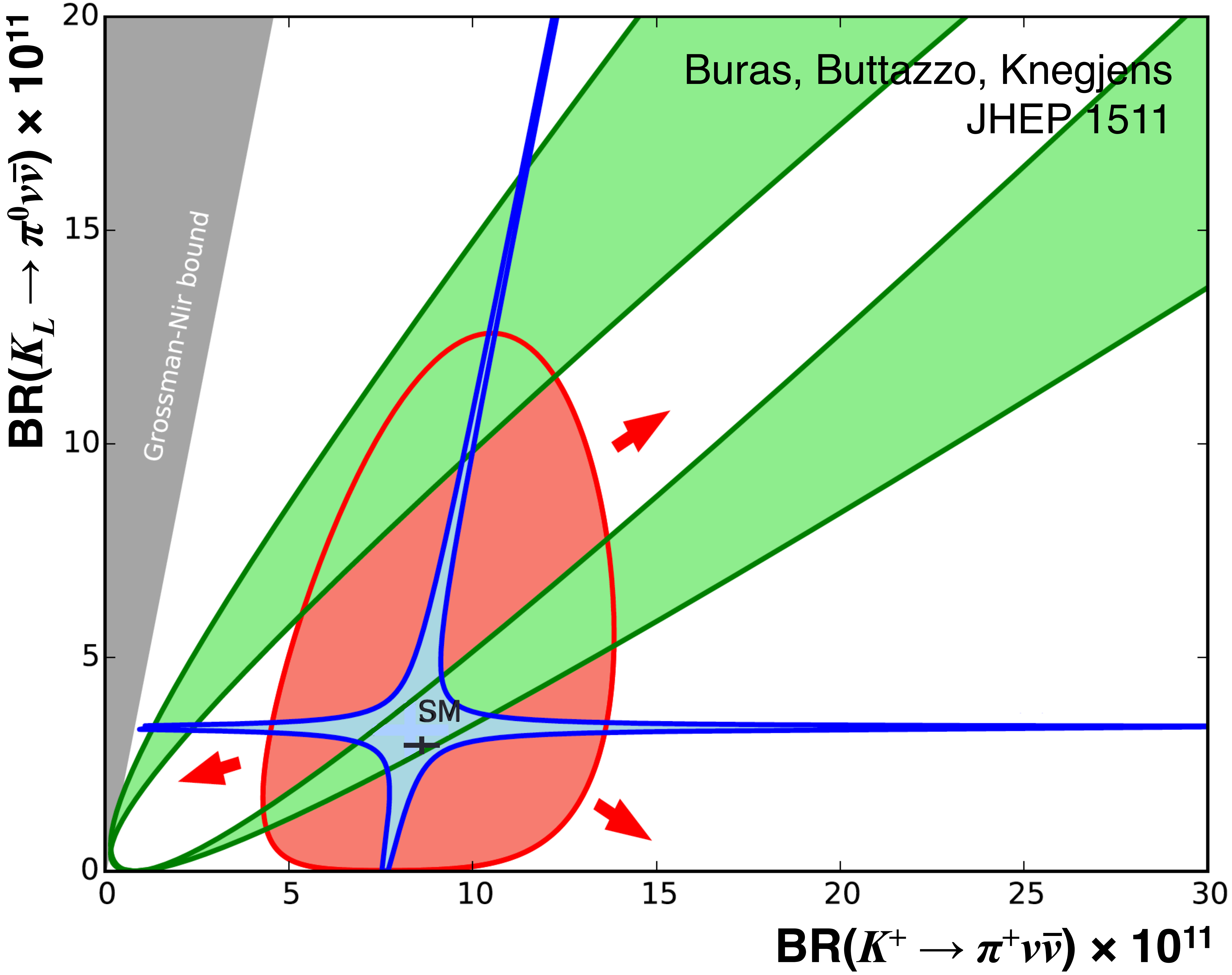
Branching ratio may become

- **larger** (constructive interference)
- **smaller** (destructive interference).

Necessary to measure both modes to nail down New Physics models.

The Landscape

Kaon Physics at the CERN SPS – NA62



- **Run 1: 2016-18**

  20 events (7 estimated bkg.)

  $Br(K^+ \to \pi^+ \nu\bar{\nu})$

  $= (10.6^{+4.0}_{-3.4}\,_{stat} \pm 0.9_{syst}) \times 10^{-11}$

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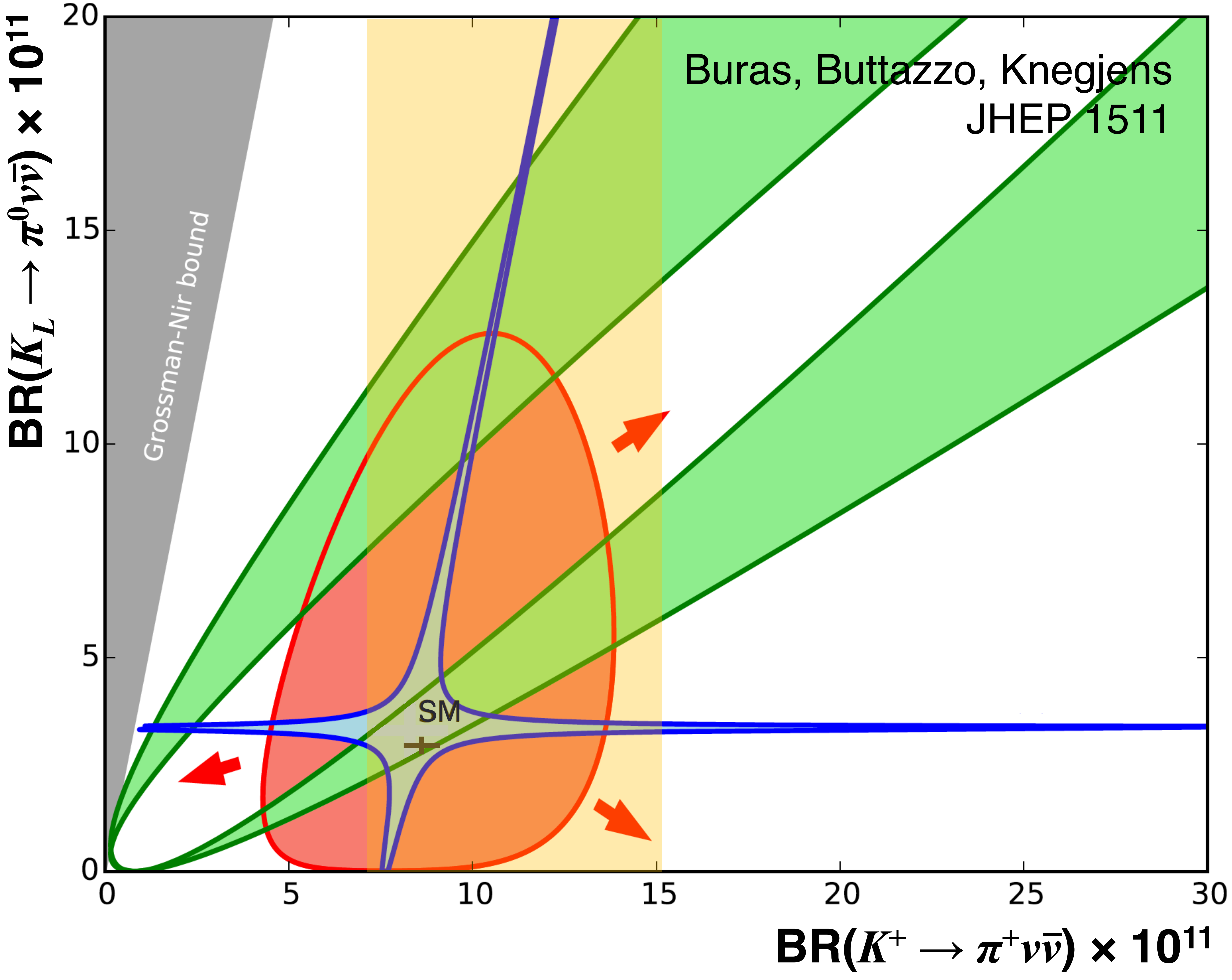
NA62 2016-18



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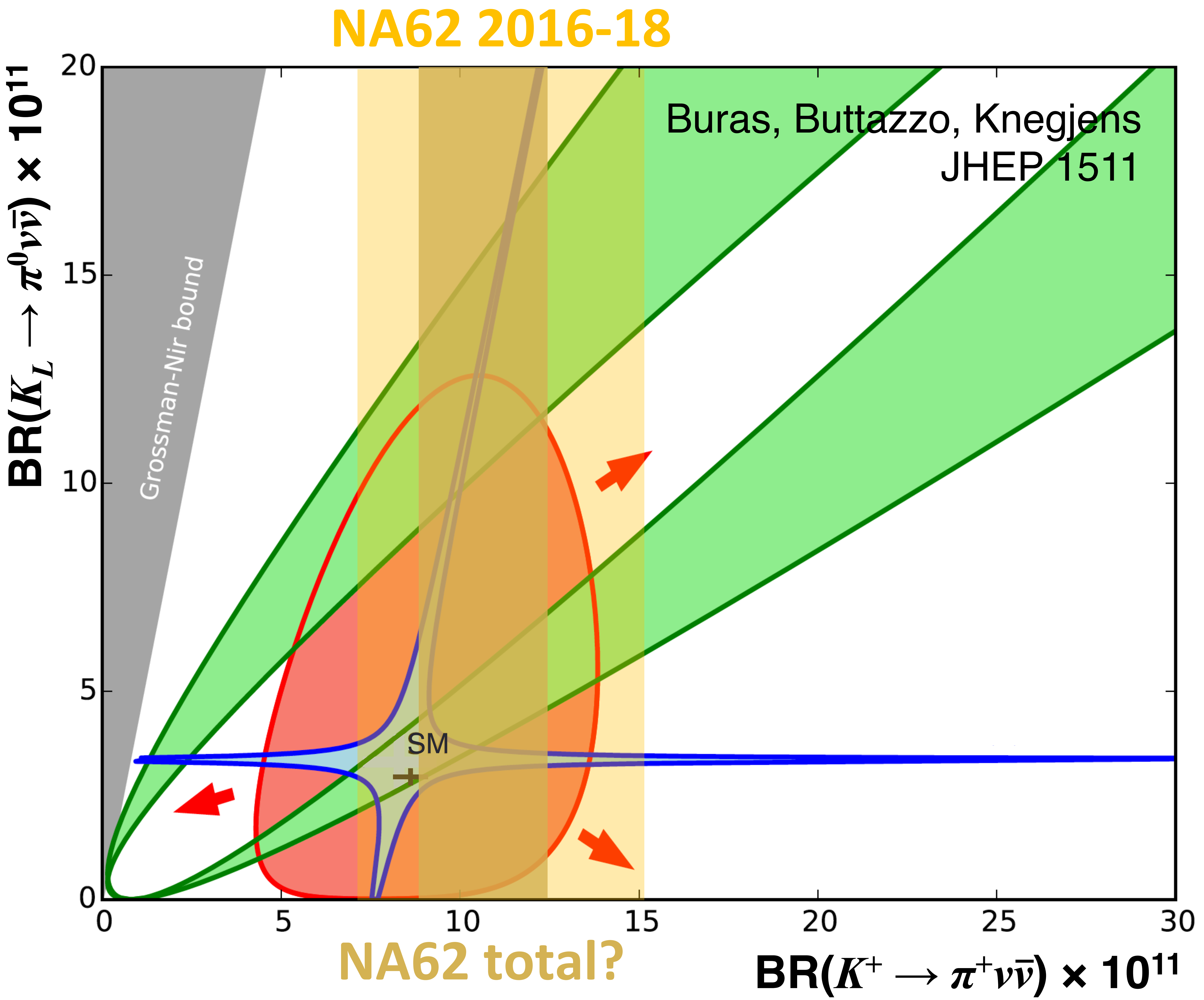

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- **All NA62: 2016-25** (up to LS 3)

  About 4-5 × N_K as for Run 1 with similar S/N ratio.

  → Total error of $\pm 1.8 \times 10^{-11}$ *(very rough estimation!)*

  - Assume same central value.

Kaon Physics at the CERN SPS – Future

Original Plan:

- **After end of NA62** new **H**igh-**I**ntensity **K**aon **E**xperiment (HIKE) , starting around 2030. Same experimental hall ECN3, many parts of the NA62 detector to be reused.
- **Phase 1:** **4 × increased K^+ intensity** → Measurement of **Br($K^+ \to \pi^+ \nu\bar{\nu}$)** to **± 5 %.**
- **Phase 2:** **High intensity K_L running** → $K_L \to \pi^0 \ell^+ \ell^-$ and other rare K_L decays.

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March 6, 2024, CERN decision:

No succession of NA62. Hall ECN3 shall be used for beam dump facility (SHiP).

"No decision on the physics, [but] *strategic decision*"

(CERN directorate, Mar 6th, 2024)

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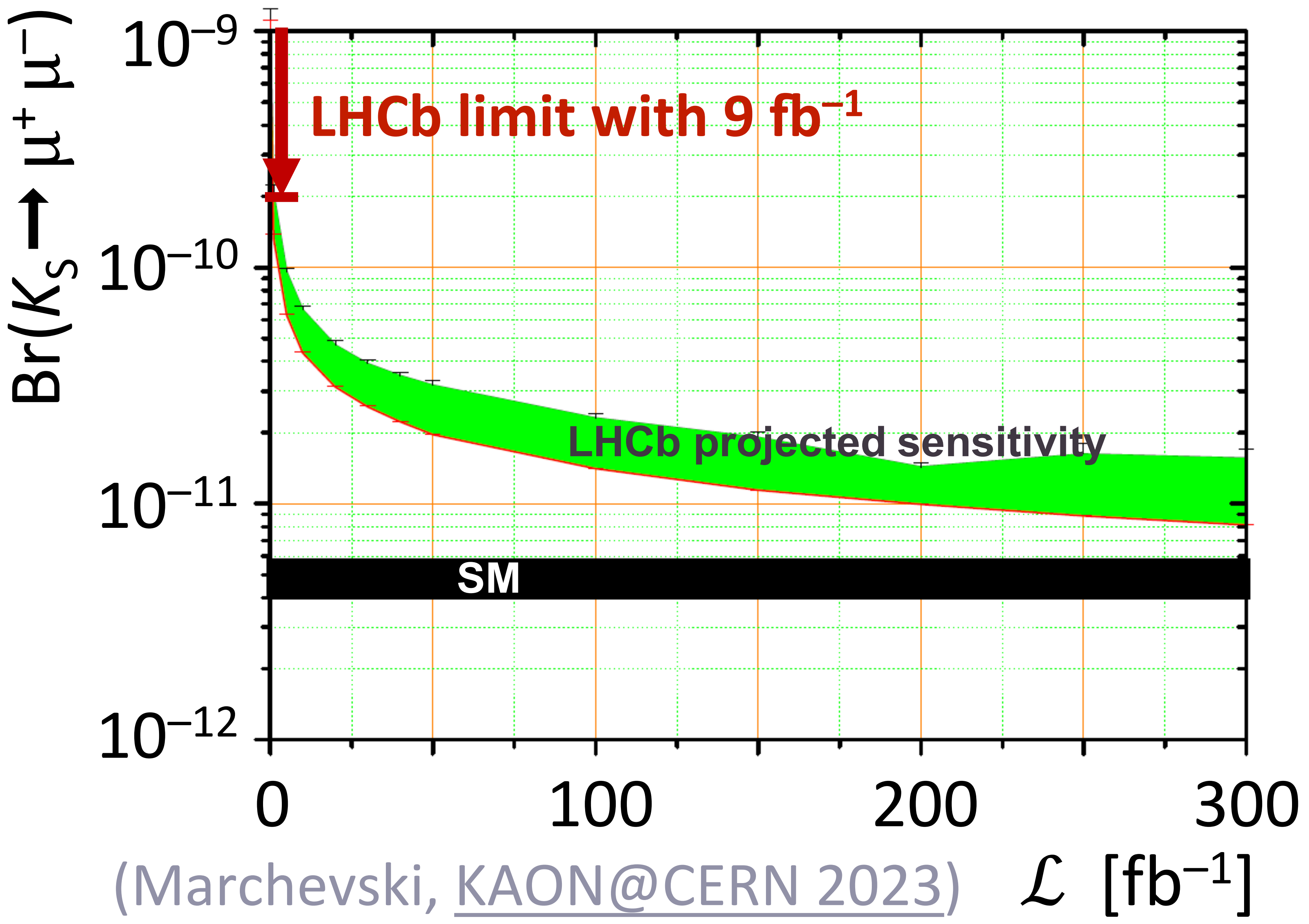
Bad day for Flavour Physics. Practically no other place at CERN for a Kaon experiment.

NA62 is going to say the last word on K^+ physics for many years (forever?).

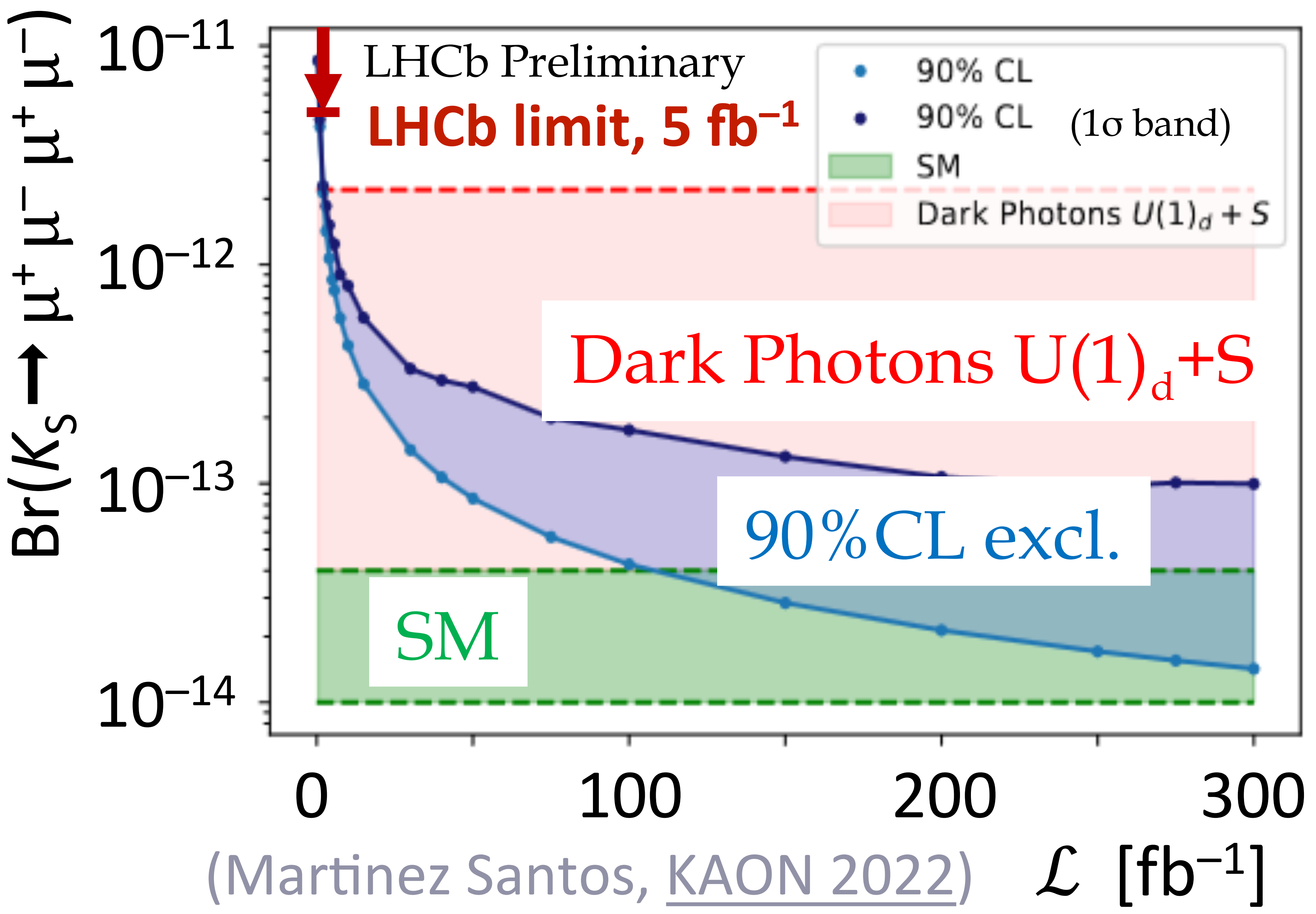
Other Kaon Physics at CERN?

LHCb competitive for K_S decays (displaced vertex) **with $\mu^\pm$ in the final state** (trigger):

- $K_S \to \mu^+\mu^-$ ➜ Important for $K_L \to \mu^+\mu^-$ interpretation, but other NP than $K_L \to \mu^+\mu^-$.
- $K_{S,L} \to \mu^+\mu^-\mu^+\mu^-$ ➜ Extremely suppressed in the SM → high NP sensitivity.
- $K_S \to \pi^0\mu^+\mu^-$ ➜ Very important for $K_L \to \pi^0\mu^+\mu^-$ interpretation.

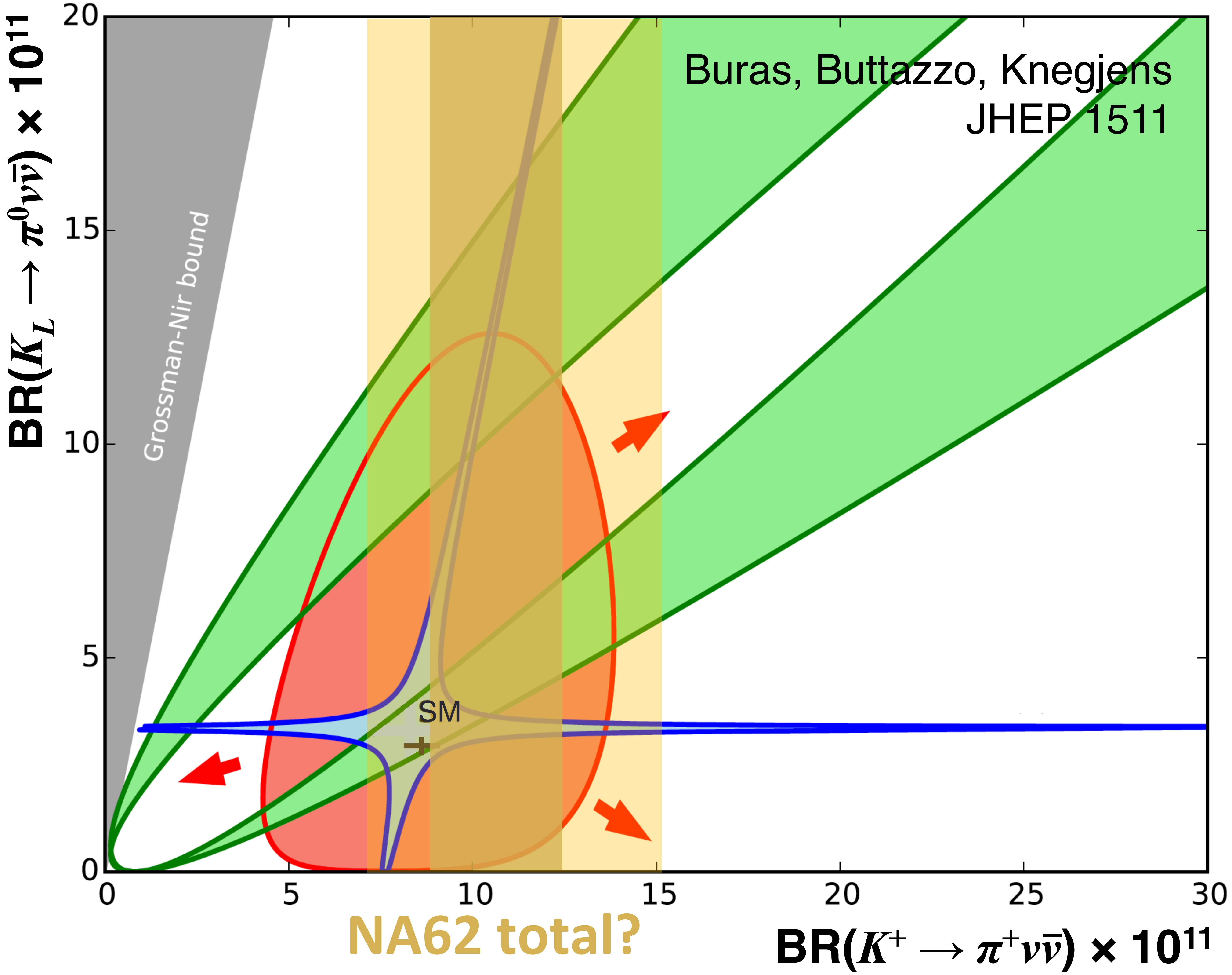


(Marchevski, KAON@CERN 2023)



(Martinez Santos, KAON 2022)

Kaon Physics at J-PARC – KOTO



- **2021 Data Analysis:**

  Preliminary **SES = 8.7×10^{-10}**,
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  → **Best upper limit** (preliminary):
  $Br(K_L \to \pi^0 \nu\bar{\nu}) < 2.0 \times 10^{-9}$

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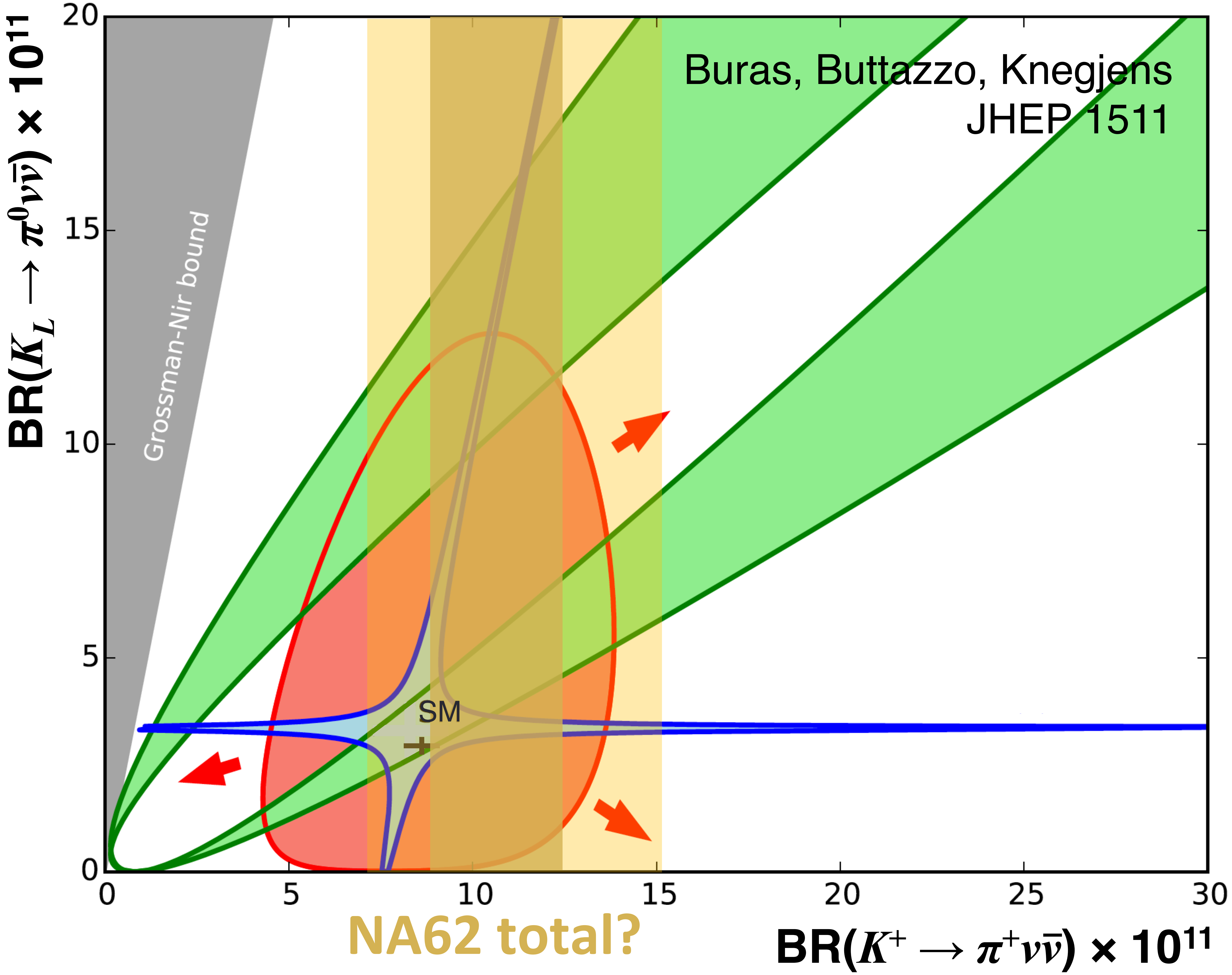

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  Better **Detector** (less bkgd.) & **DAQ** (ready for 100 kW beam).

  → **Expected in total:**

  Br Sensitivity ~ 1×10^{-10}

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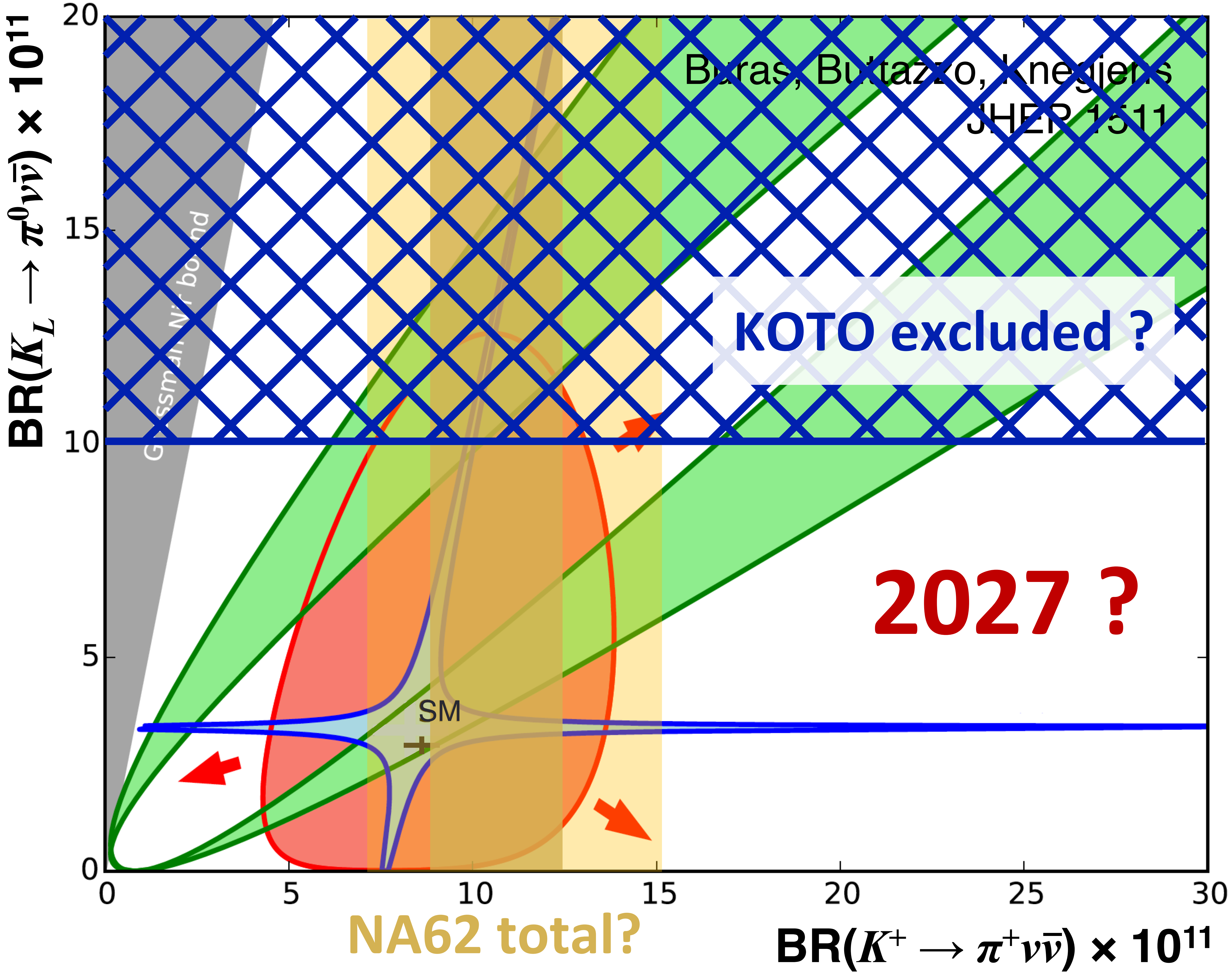

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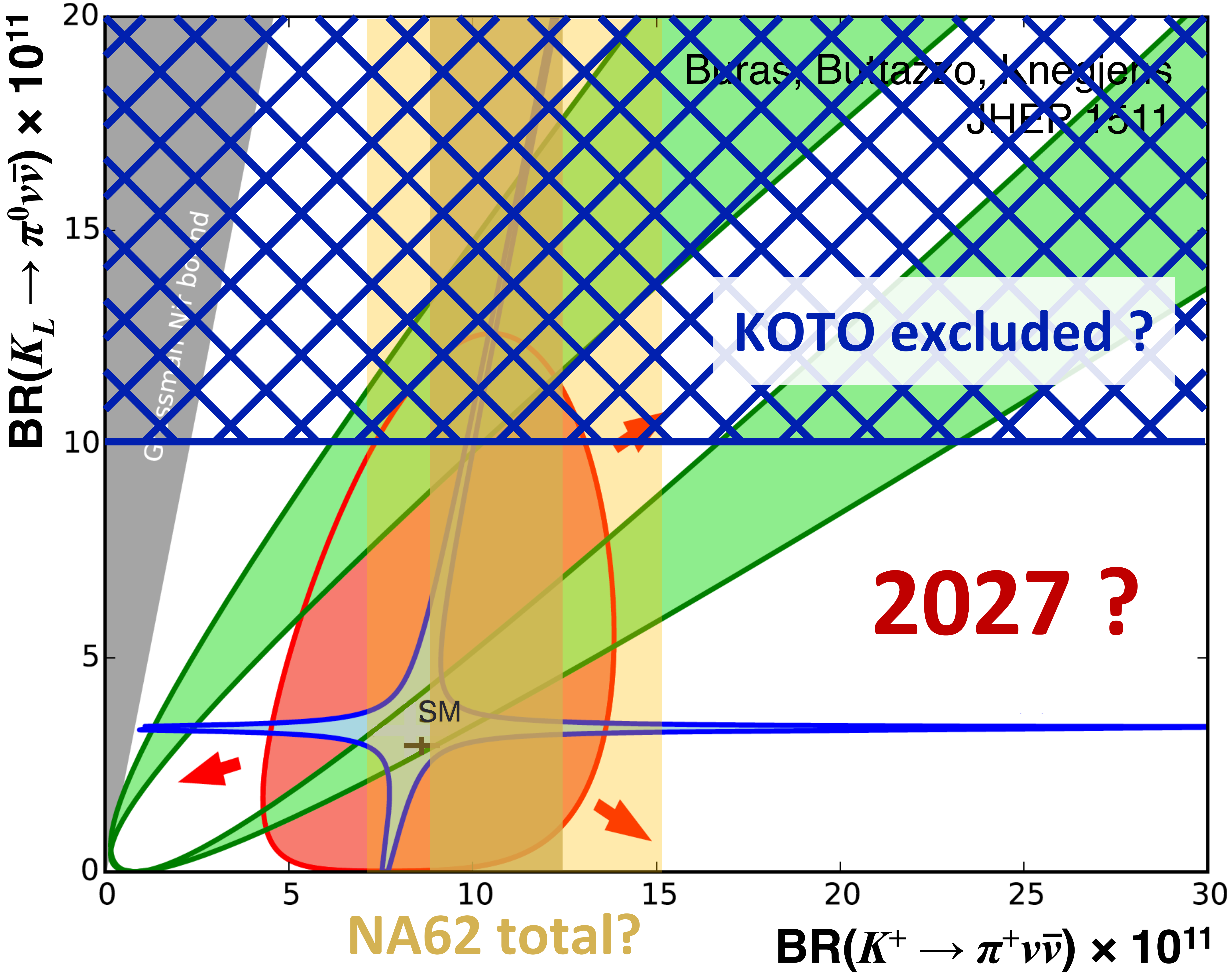
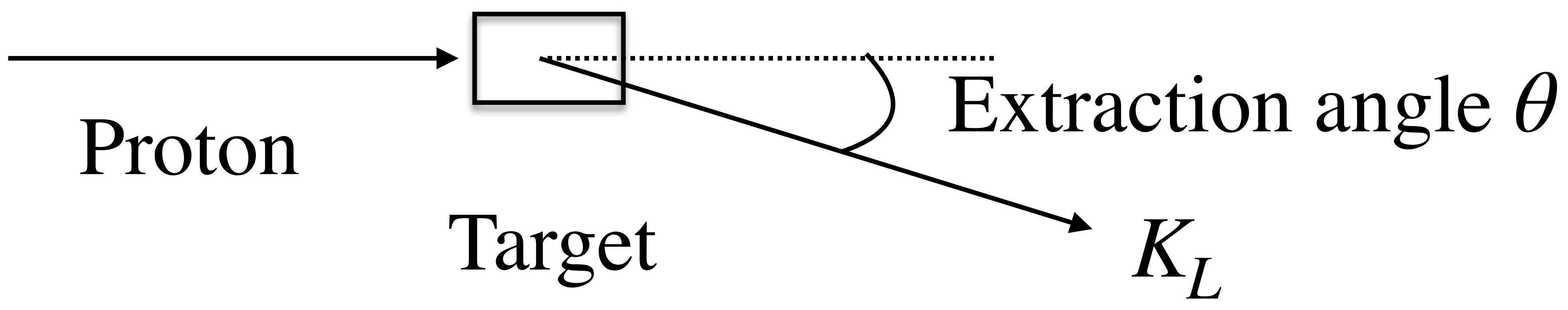


- If no NP at $Br(K_L \to \pi^0 \nu\bar{\nu}) \sim 10^{-10}$
  → **10 × more sensitivity needed**
  to close in on SM or NP.
  (This also holds for NP at 10^{-10},
  for nailing down the NP model!)
- **New beamline & detector**
  - **Higher beam intensity**
  - **Better bkg suppression**

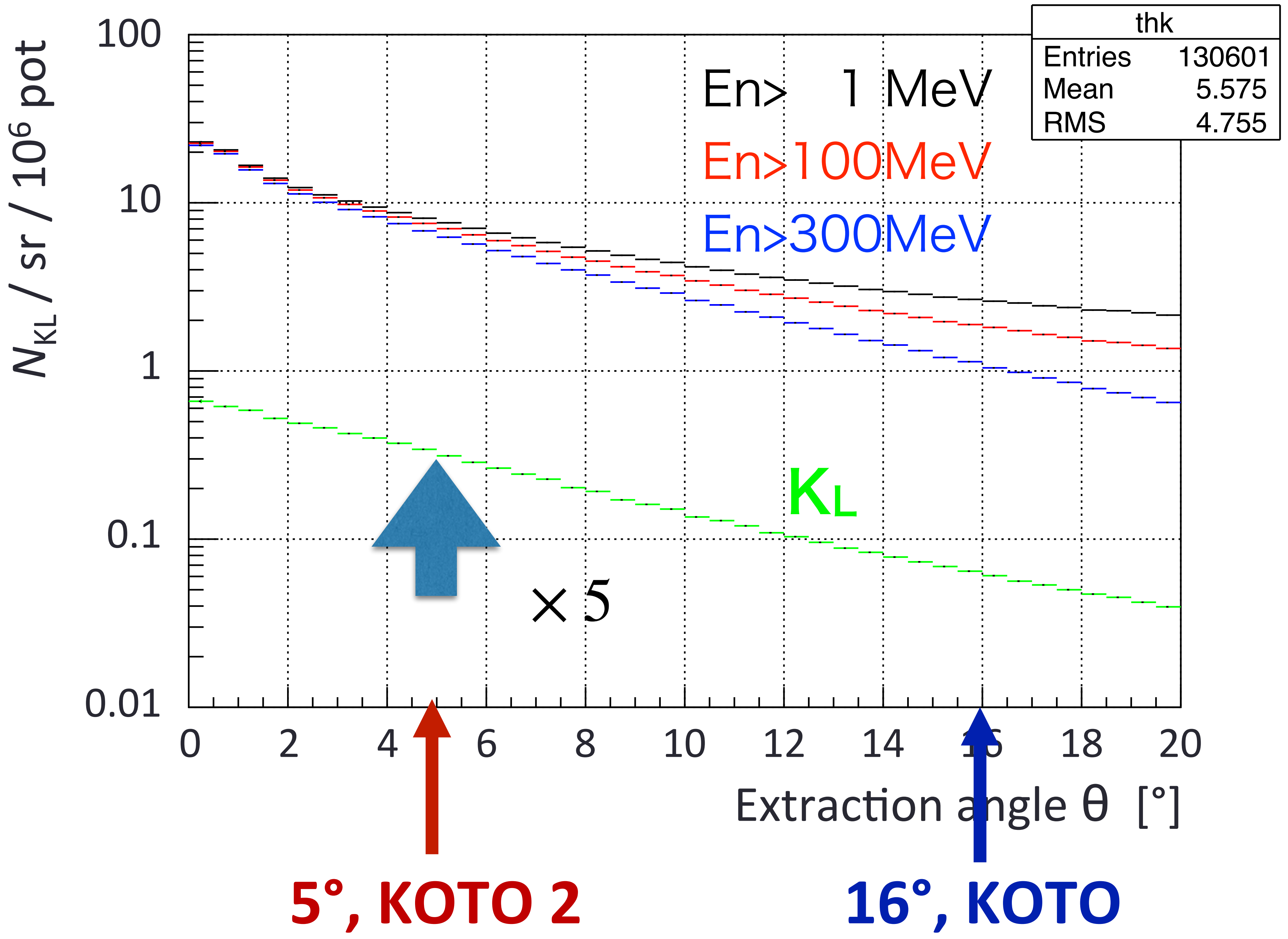
KOTO – Step 2

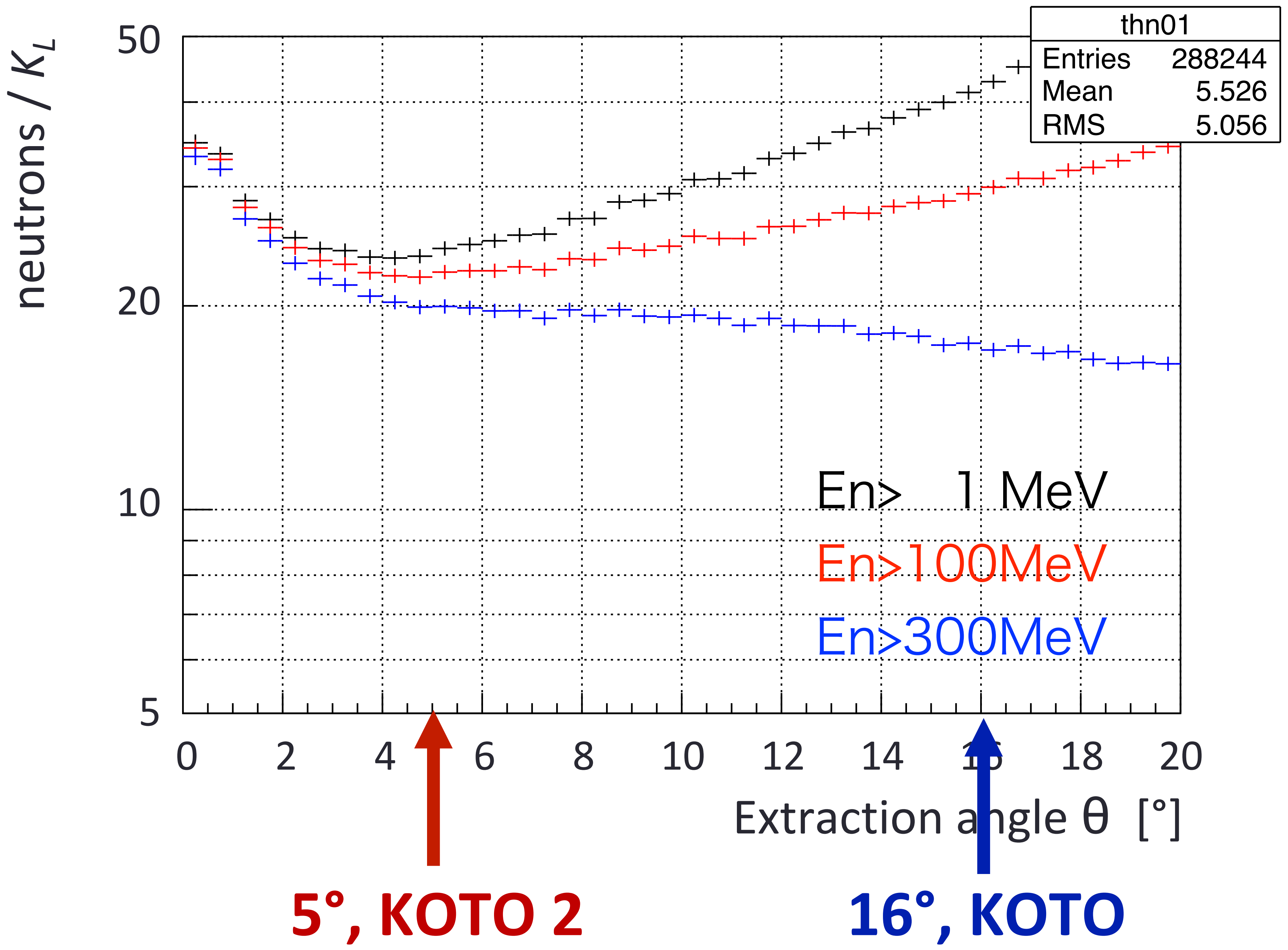
Increased K_L Intensity by smaller Extraction Angle



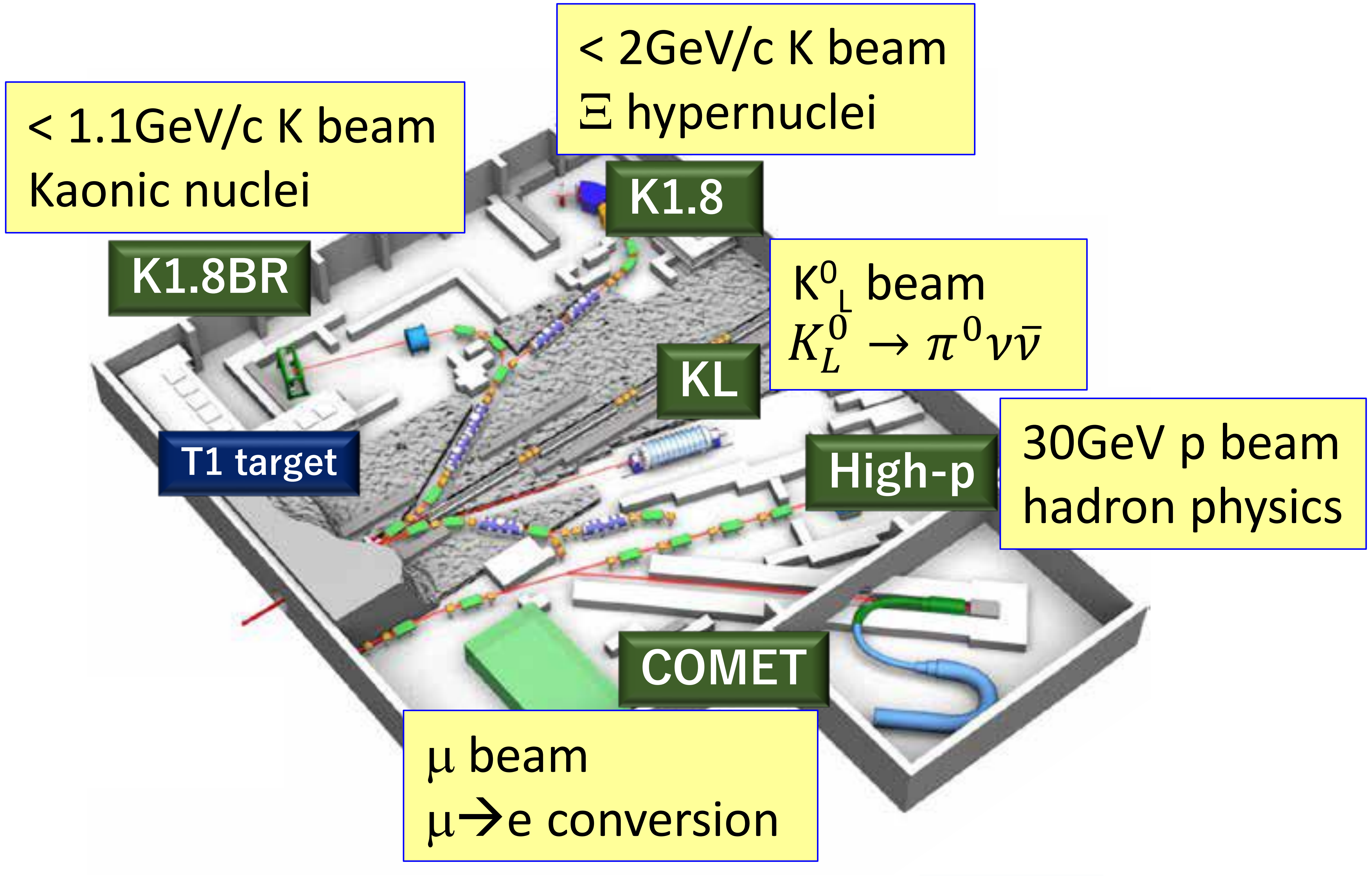
- Small extraction angle: High K_L flux, high momentum, high neutron background

→ **Optimum at θ ~ 5°**





Problem: Current KOTO Beamline



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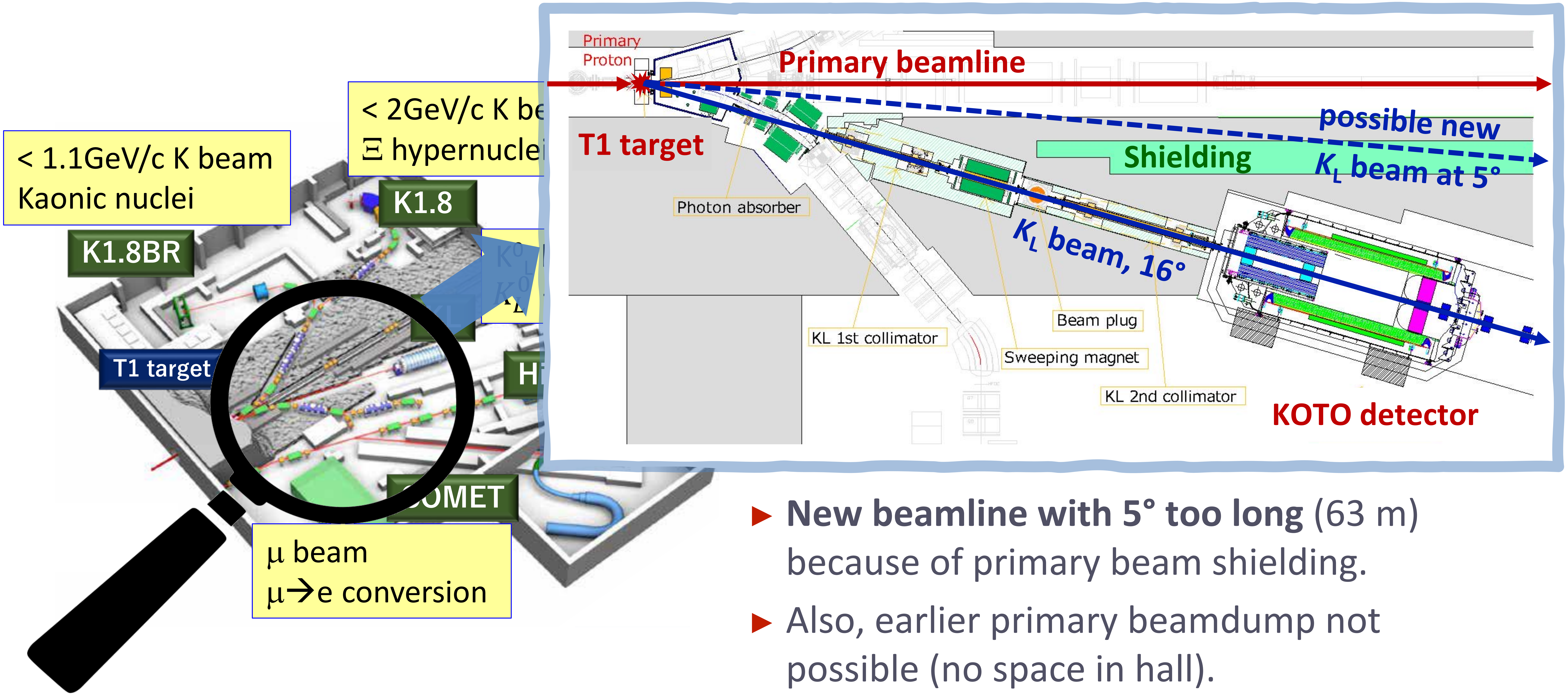
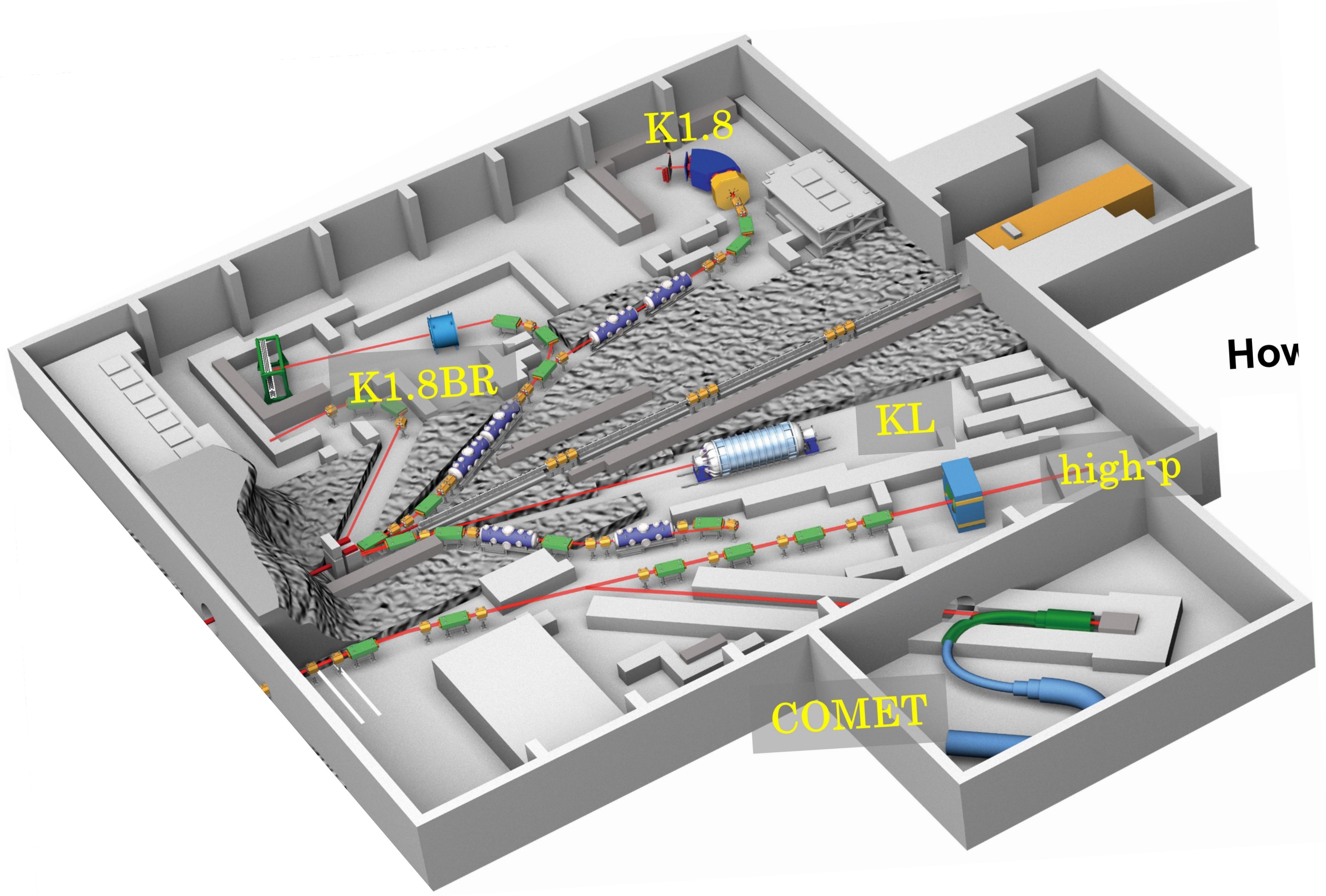


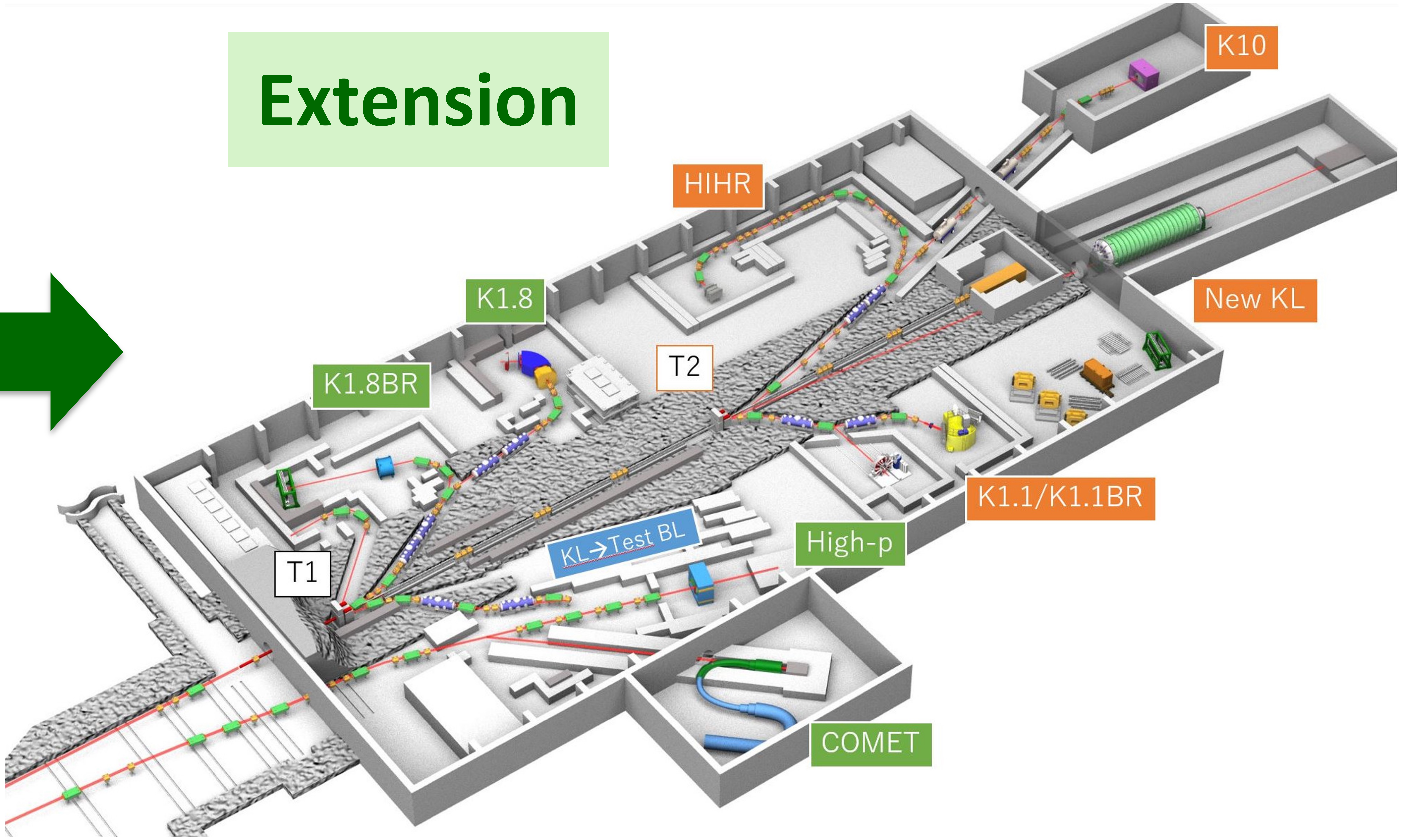
- **New beamline with 5° too long** (63 m) because of primary beam shielding.
- Also, earlier primary beamdump not possible (no space in hall).

J-PARC Hadron Facility Extension

Today

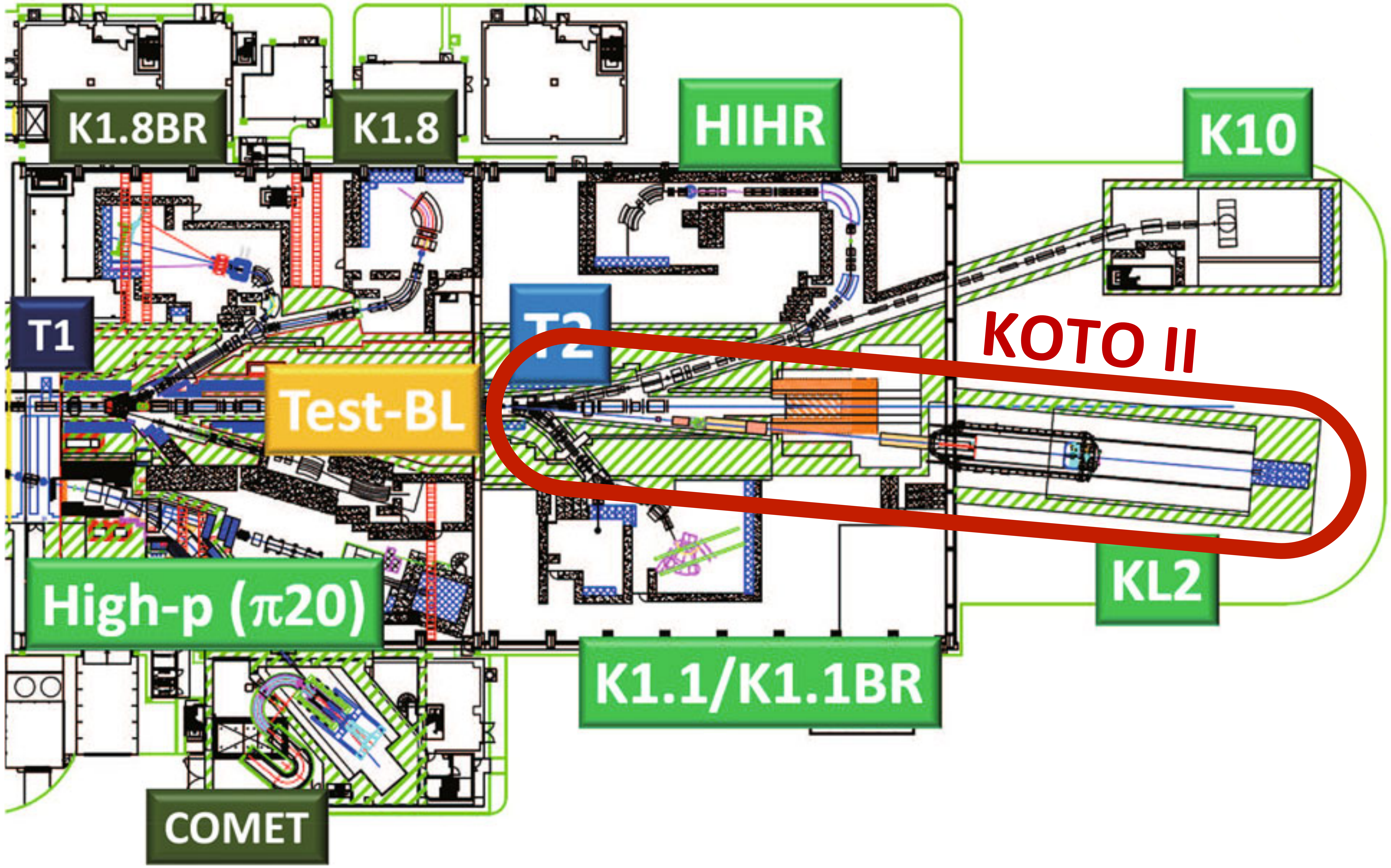


Extension



Extension is supported by KEK Project Implementation Plan 2022
→ Top priority to request new budget.

J-PARC Hadron Facility Extension



Extraction angle:

From 16° (KOTO)
to 5° (KOTO II)

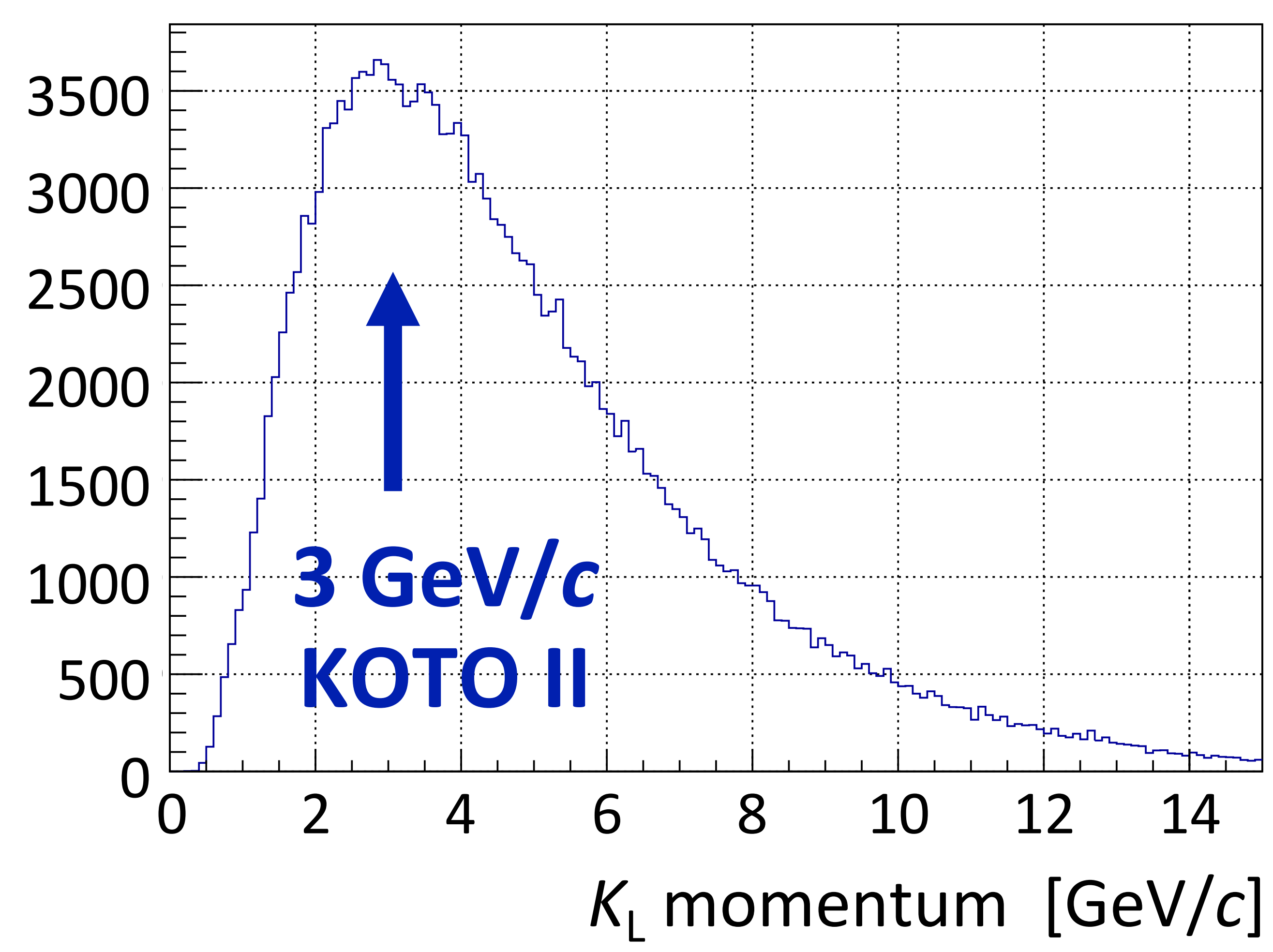
+ $5 \times K_L$ intensity
(@ same stereo angle)
$2 \times K_L$ momentum

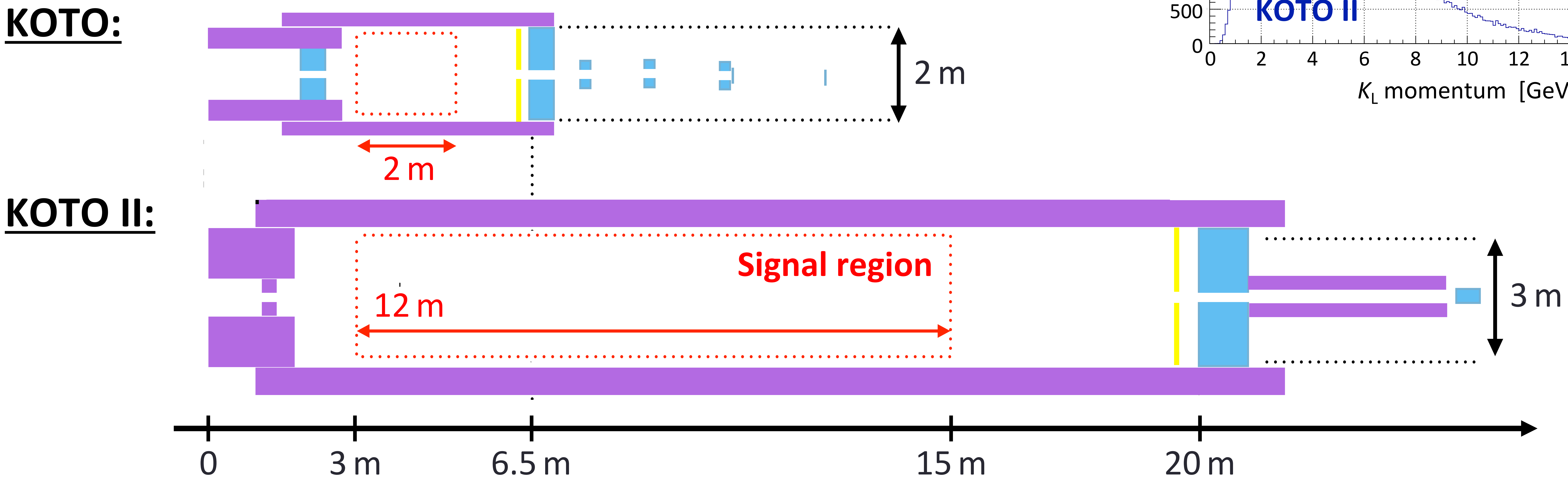
– Smaller stereo angle
Larger decay length
(larger $\gamma c\tau$)

KOTO II Detector

Peak K_L momentum: 1.4 GeV/c (KOTO) → **3 GeV/c (KOTO II)**

- **Larger decay volume:** 2 m → **12 m length**
- **Larger calorimeter:** 2 m → **3 m diameter**





KOTO II Expected Signal Yield

Comparison KOTO – KOTO II

	KOTO	KOTO II	K II/K I
K_L yield (arb. units)	1	2.6	**2.6**
Decay probability	3.3 %	10 %	**3**
Geom. acceptance	26 %	24 %	**0.9**
Selection efficiency	3 %	26 %	**8.7**
1 – Accidental loss	64 %	39 %	**1.7**
1 – Backsplash loss	50 %	91 %	**1.8**
Total improvement			**190**

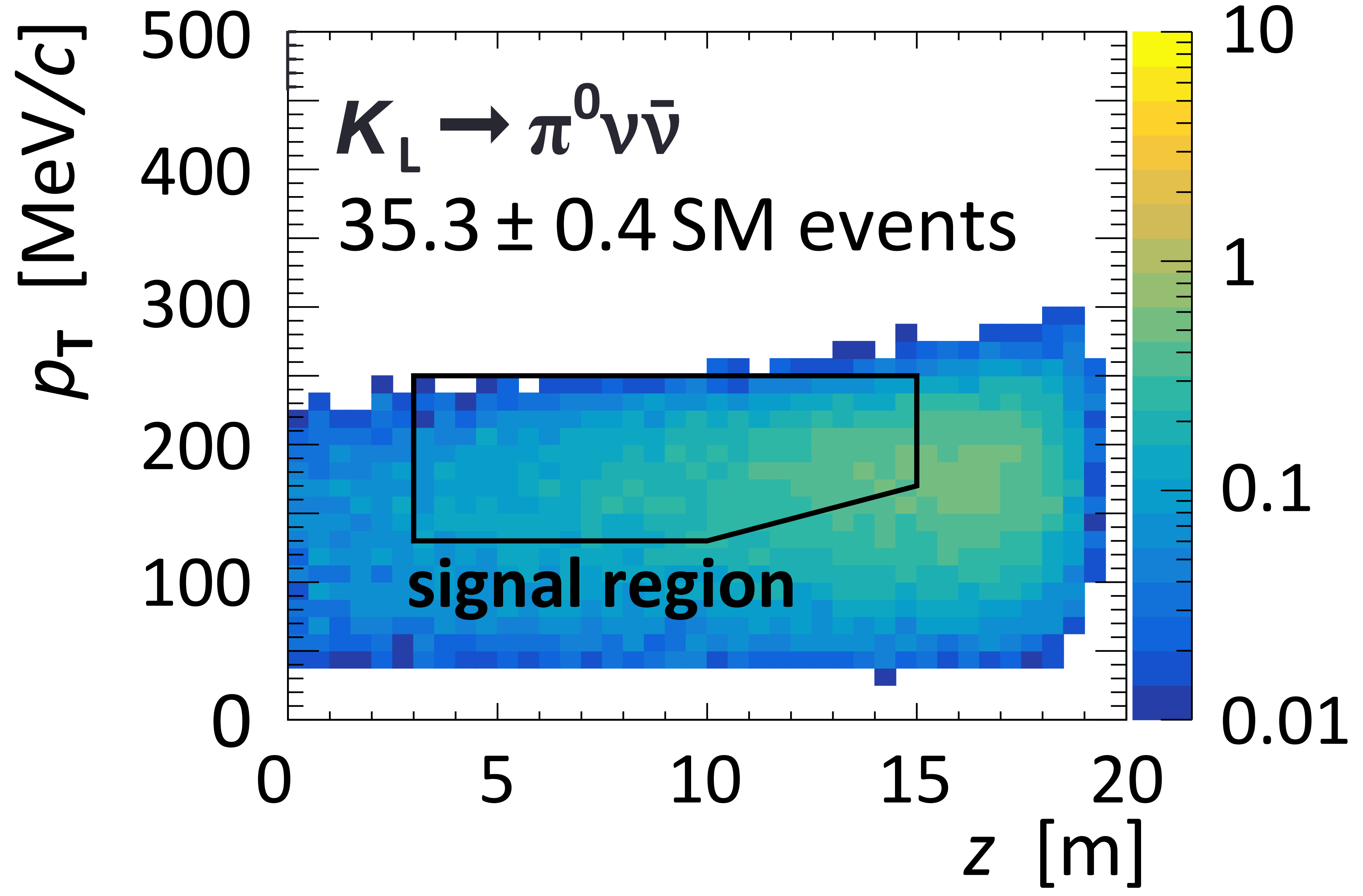
KOTO II 190 × more sensitive than KOTO

Assuming:

- **Beam power: 100 kW** (as in KOTO)
- **Running time: 3×10^7 s**

→ **6.3×10^{20} pot**

→ **35 expected SM $K_L \to \pi^0 \nu\bar{\nu}$ events**



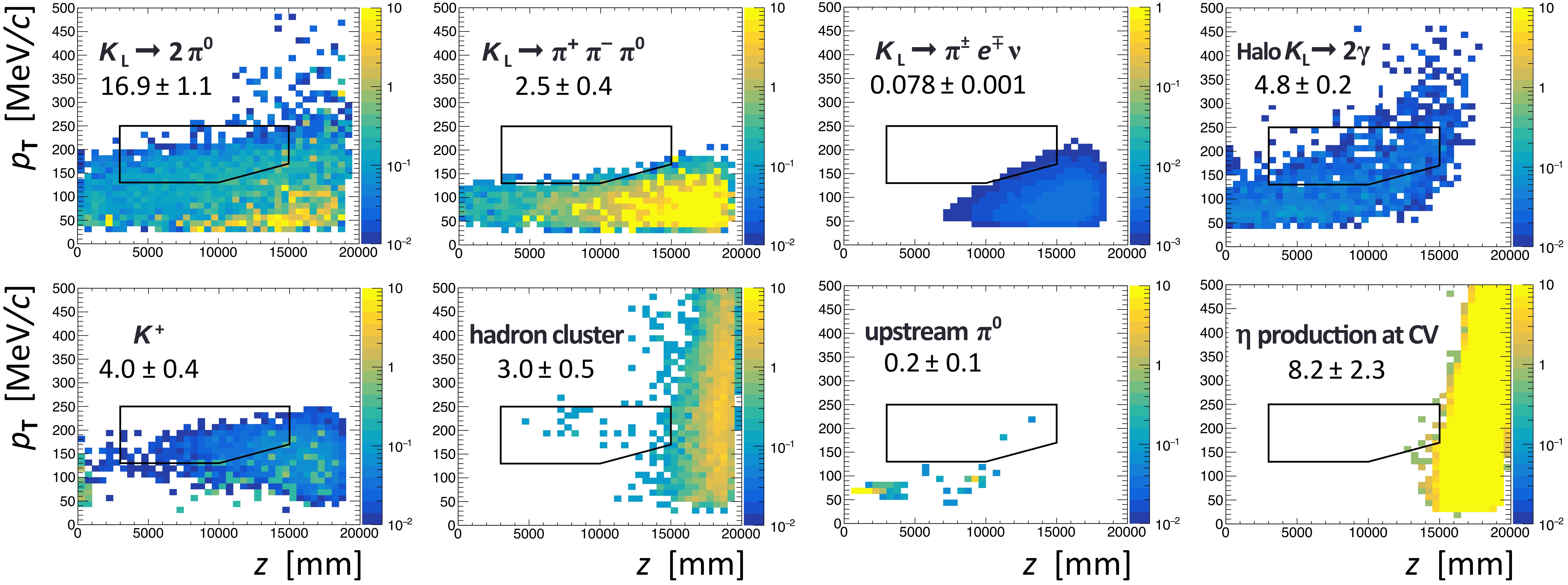
KOTO II Expected Background

Same assumptions (6.3×10^{20} pot):

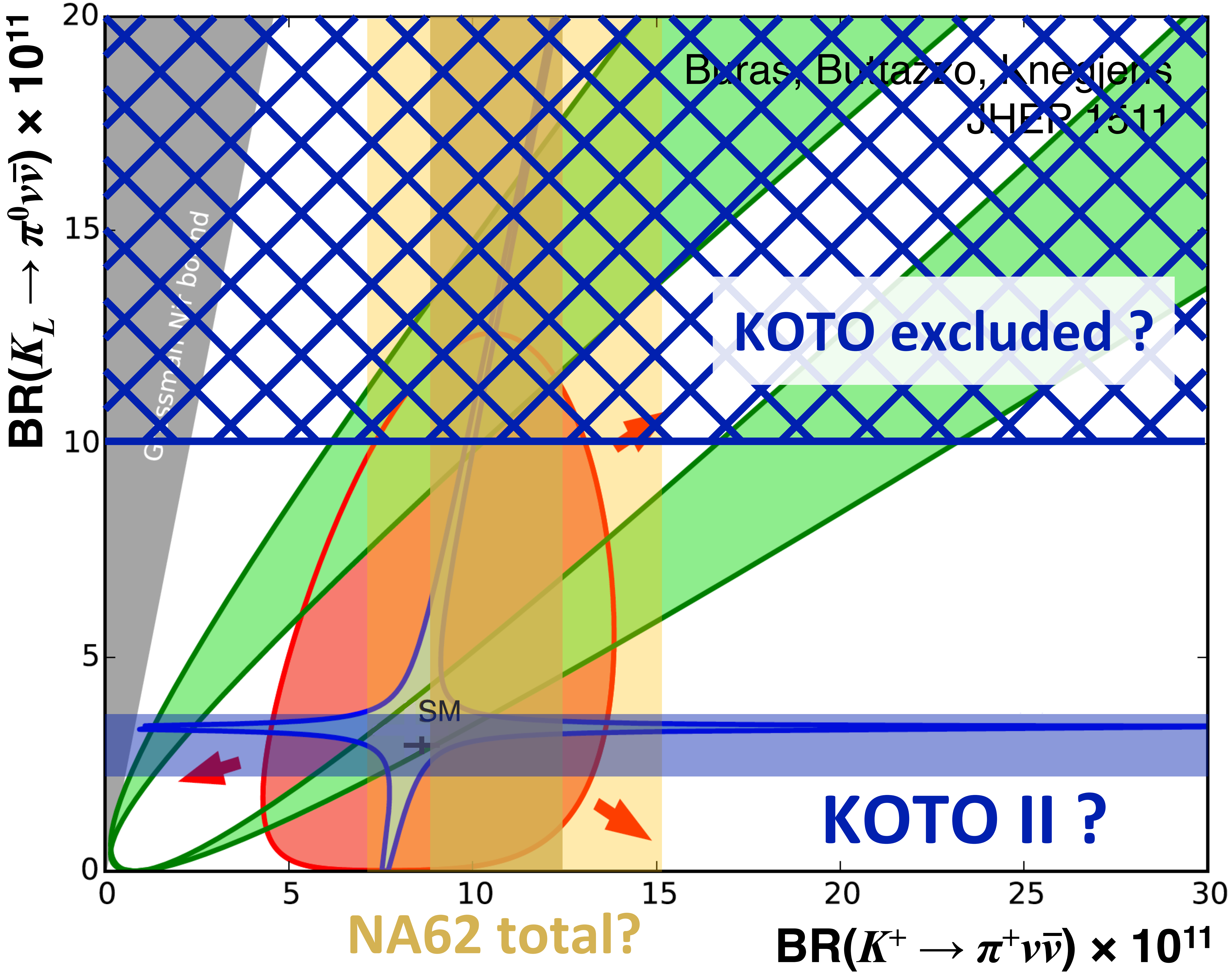
→ 40 ± 3 expected background events

Signal/Background ~ 0.9

→ 5.6 σ observation for SM $K_L \to \pi^0 \nu \bar{\nu}$



KOTO II Sensitivity



Assumptions:

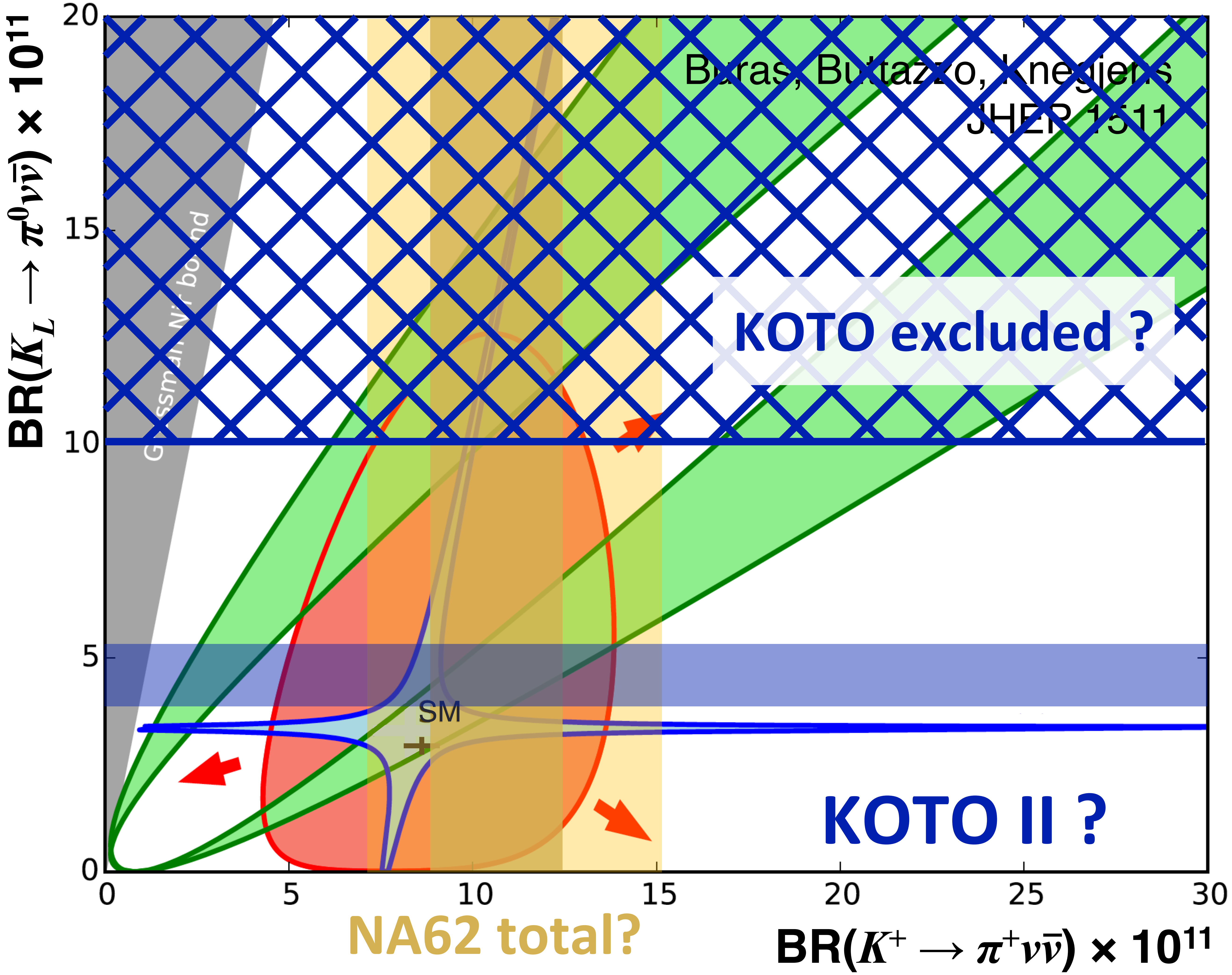
- 100 kW beam
- 3×10^7 s
- SES = 8.5×10^{-13}, S/B = 0.9

→ **35 SM signal events**
40 background events

→ **ΔBr/Br ≈ 25 %**
for SM value of Br.

→ **New Physics at 90% CL with 40% deviation from SM.**

KOTO II Sensitivity



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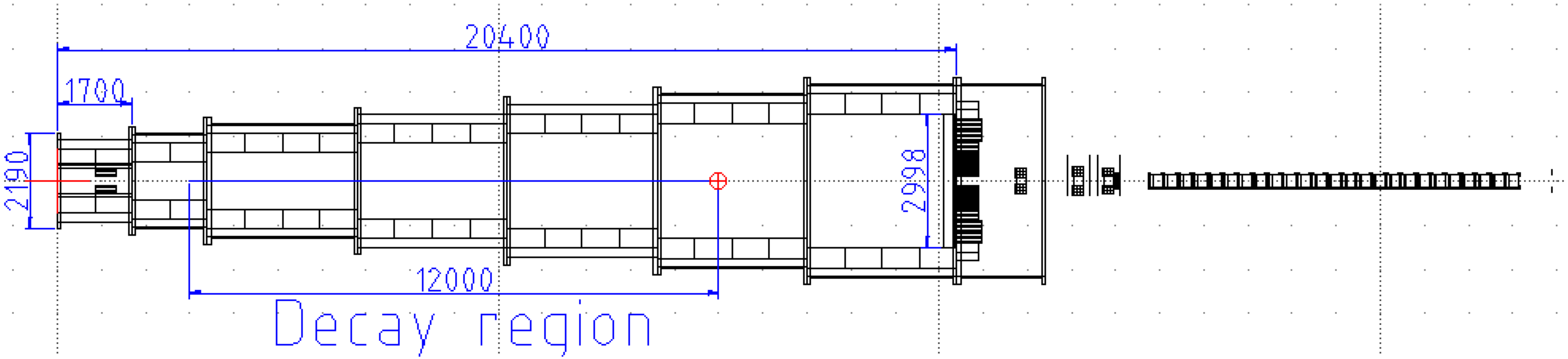
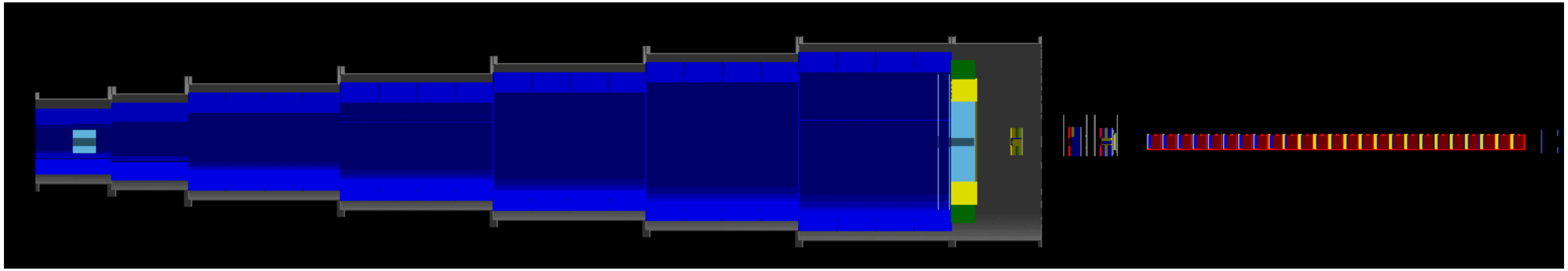
KOTO II Detector

Realistic detector layout for MC studies and Weight/Cost calculation.

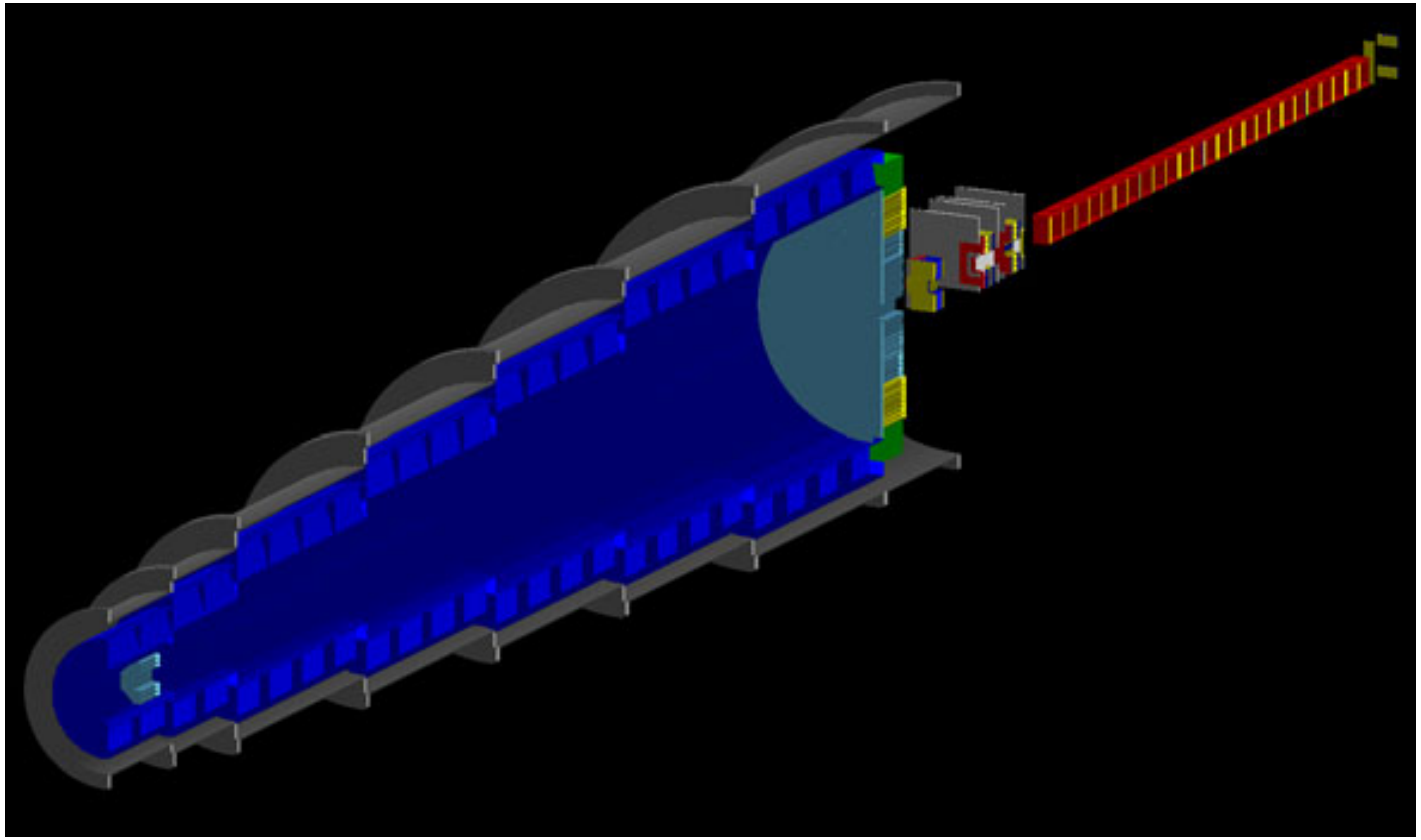
Still several subdetector options are being studied.





Tentative Barrel Veto Design

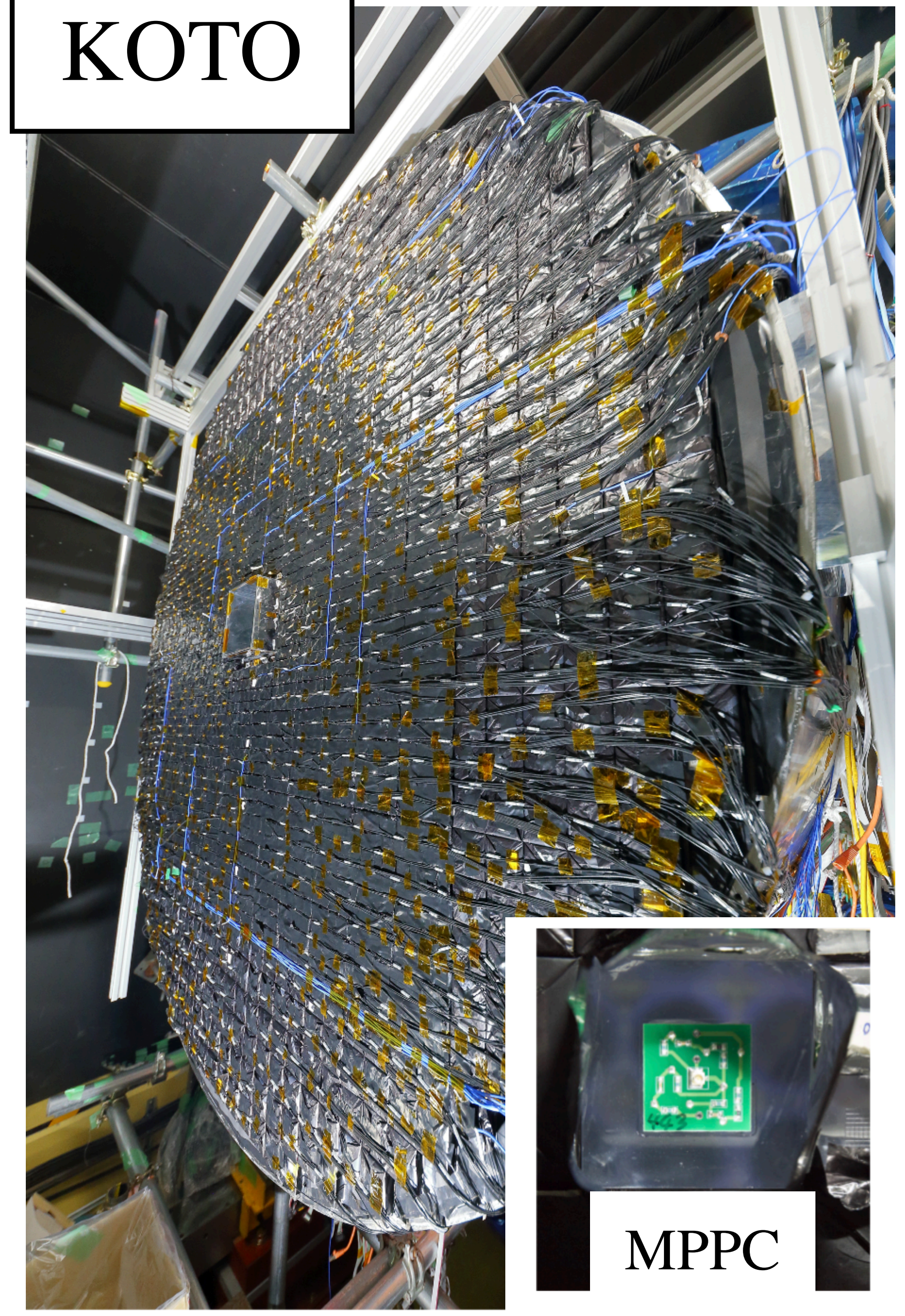
- **Scintillating layers perpendicular to *z***
  (similar to NA62 Large Angle veto), not parallel to *z* (KOTO).

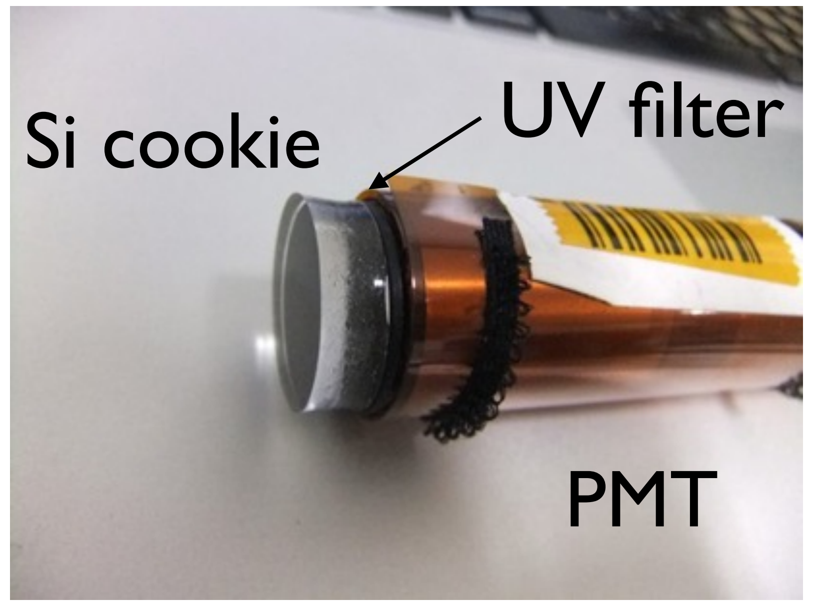


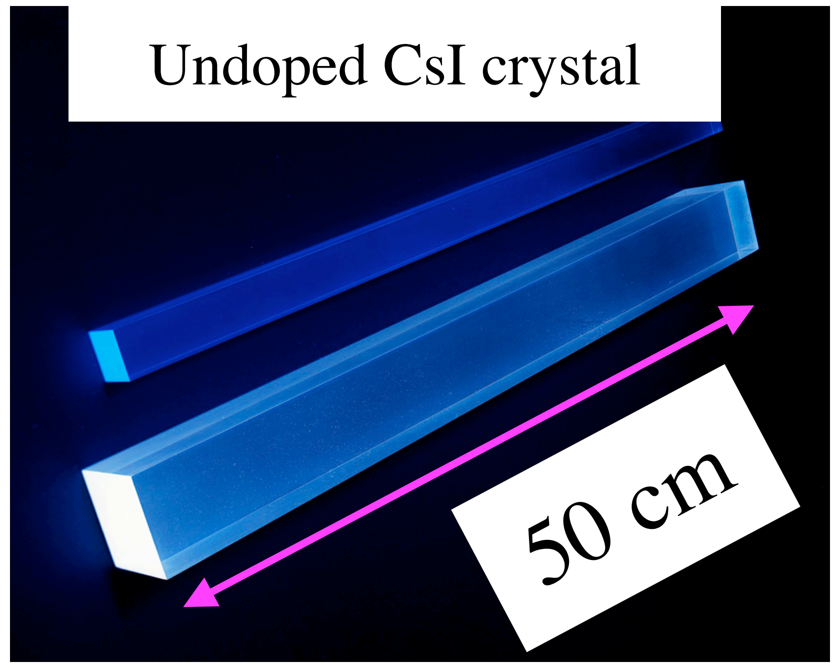
- Study of **B_4C mylar on lead layers** to absorb thermal neutrons.
- **First prototype of modular design** (1 mm lead + 5 mm plastic scintillator).

Several Calorimeter Options being studied

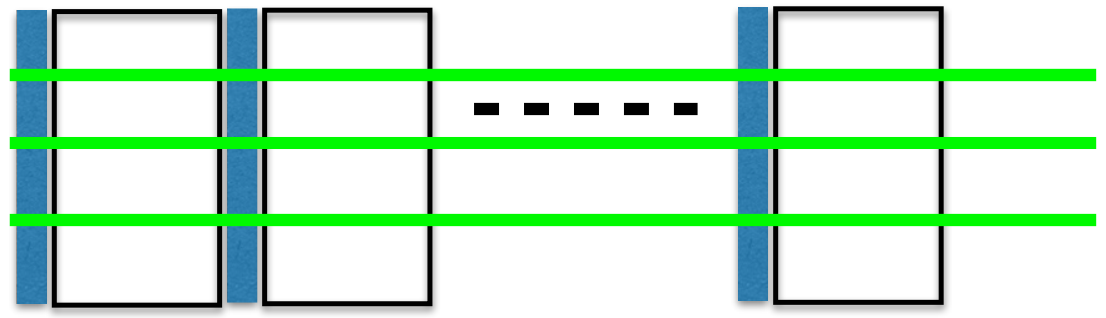
KOTO

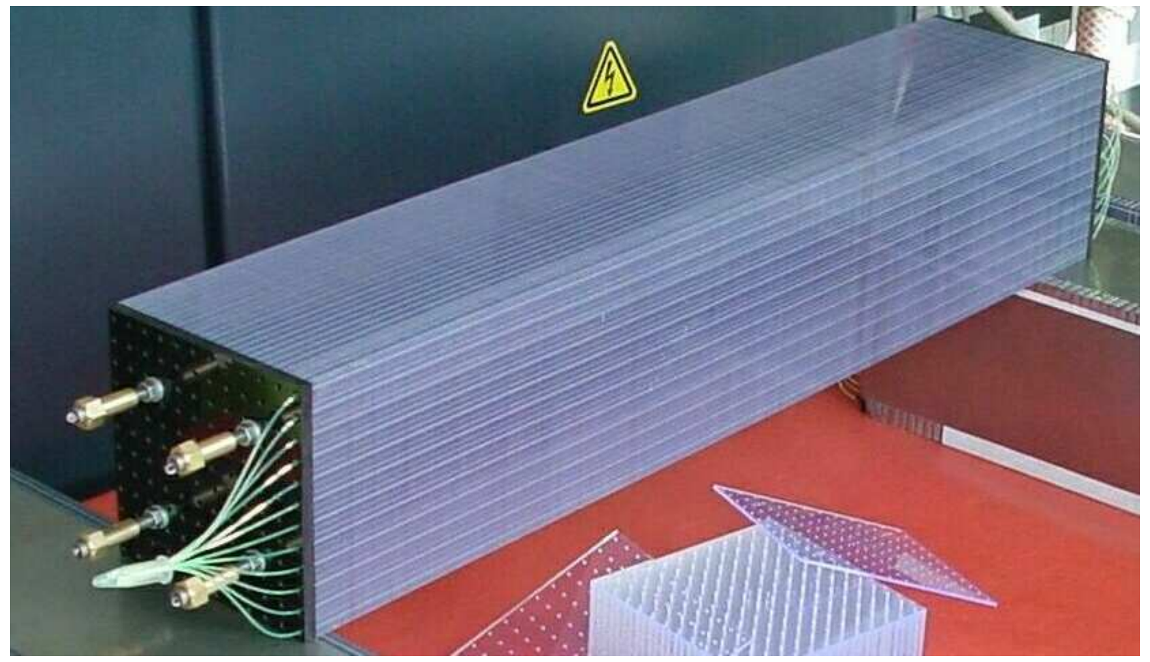






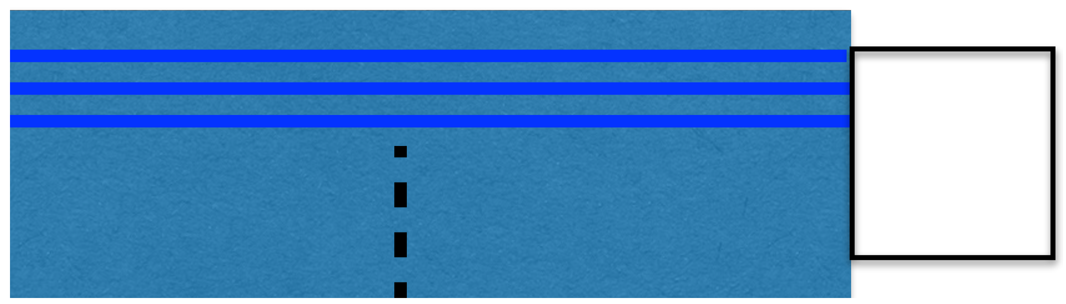
KOPIO

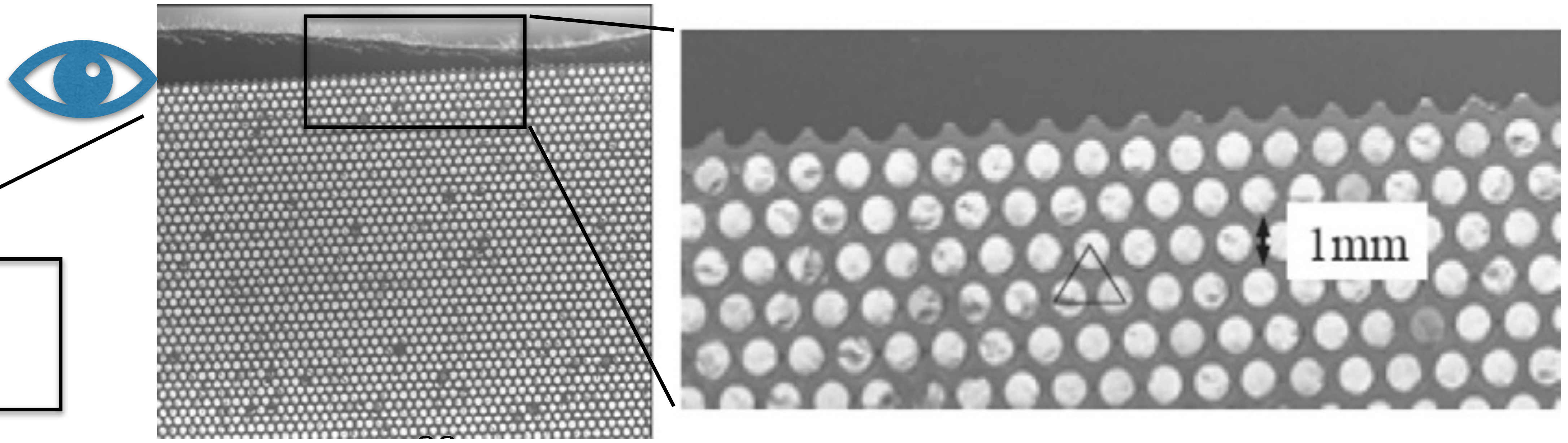




KLOE

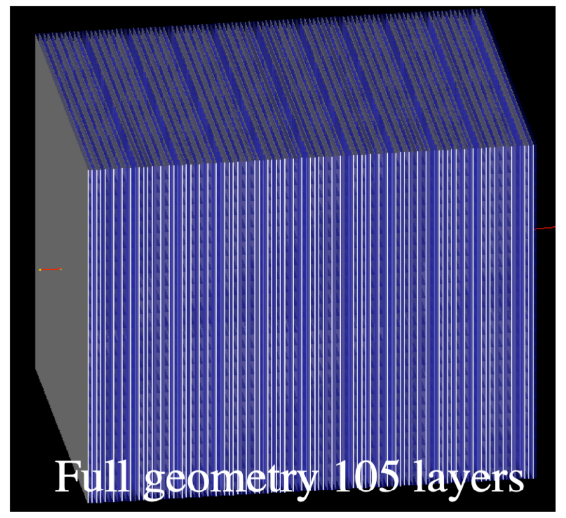
Pb/Scintillating fiber (1mmϕ)

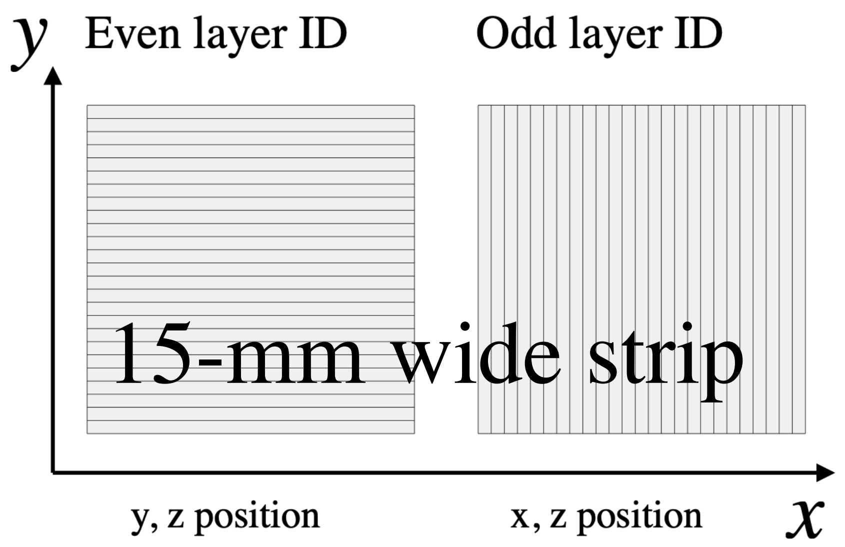




Angle measurement capability

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





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

KOTO II Status & Timeline

- Design of **Hadron Experimental Facility extension** and K_L **beamline** finished.
  → **Budget request is prepared.**
- Lots of detector R&D ongoing, everything on a good track.
- **KOTO running up to ~ 2026, KOTO II planned to start at 2030.**
- Trying to integrate more groups to have a more versatile detector.
  → **Dedicated workshop on July 27-30,2024 at J-PARC**

Kaons@J-PARC 2024 workshop

27–29 Jul 2024
Asia/Tokyo timezone

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Overview
Timetable
Access

Kaon physics is at a turning point. While the kaon rare decay experiments NA62 and KOTO are in full swing, the future experimental landscape is unclear. It's a good time to discuss the future of kaon physics with theorists and experimentalists.

Summary

Two running, dedicated Kaon experiments (NA62, KOTO) – will finish around **2026/27**.

→ **$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ to 15-20% precision, $K_L \rightarrow \pi^0 \nu\bar{\nu}$ sensitivity down to 1×10^{-10}.**

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  → **No Kaon experiment foreseen at CERN in the long-term future.**

- **KOTO II on track**, but still needs to be approved.
  - Hall & beamline design finished.
  - Detector options being studied and well on track.
  - **Aiming for ~ 35 SM $K_L \to \pi^0 \nu\bar{\nu}$ → Observation!**
  - Could be expanded for **more divers K_L physics.**

Summary

Two running, dedicated Kaon experiments (NA62, KOTO) – will finish around **2026/27**.

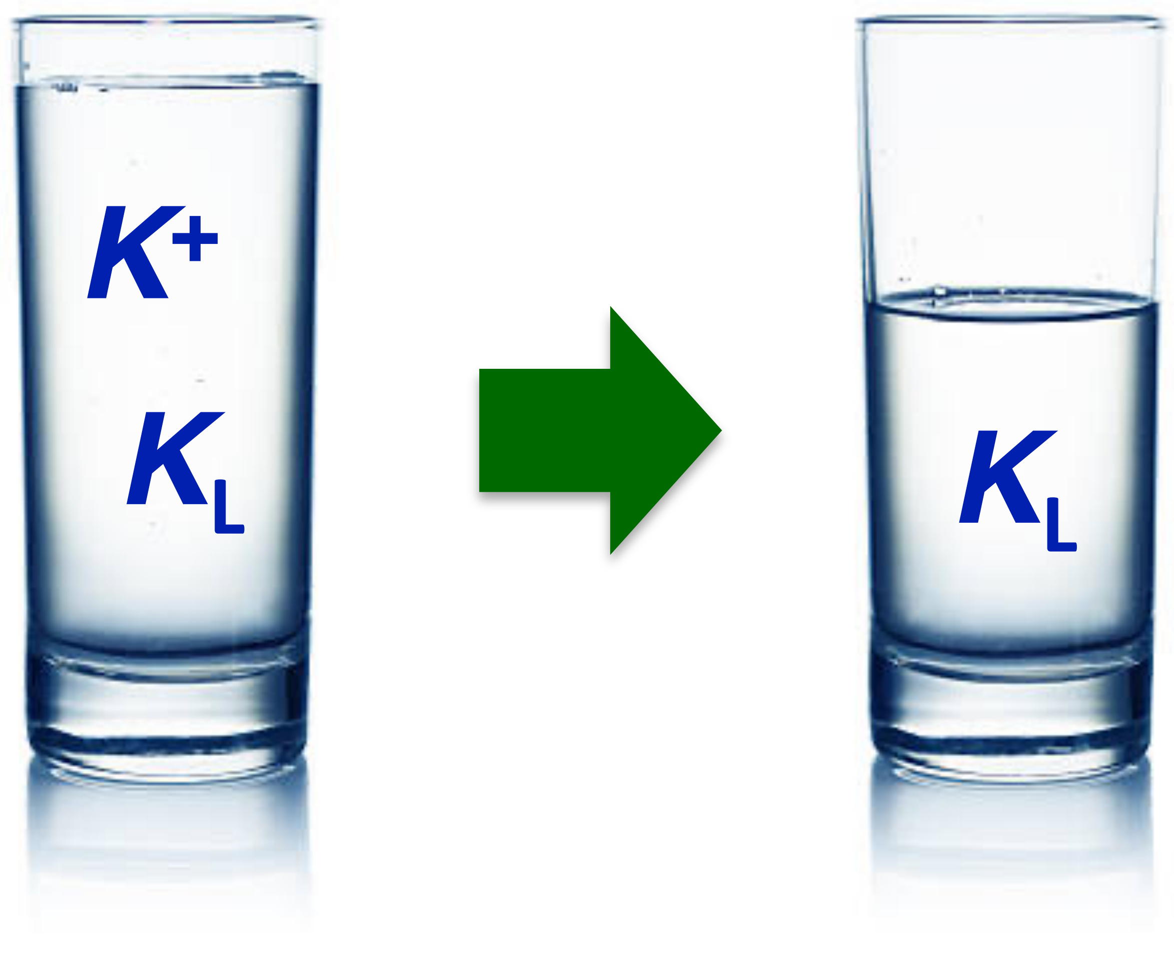
→ **$K^+ \rightarrow \pi^+\nu\bar{\nu}$ to 15-20% precision, $K_L \rightarrow \pi^0\nu\bar{\nu}$ sensitivity down to 1×10^{-10}.**

~~Two~~ One successor experiment~~s~~ (~~HIKE~~, KOTO II) planned to start around **2030**.

- *HIKE cancelled by CERN management in March 2024.*

→ **No Kaon experiment foreseen at CERN in the long-term future.**

- **KOTO II on track**, but still needs to be approved.
  - Hall & beamline design finished.
  - Detector options being studied and well on track.
  - **Aiming for ~ 35 SM $K_L \rightarrow \pi^0\nu\bar{\nu}$ → Observation!**
  - Could be expanded for **more divers K_L physics.**



Glass still more than half full!

Spares

Relations between rare Kaon decay Modes

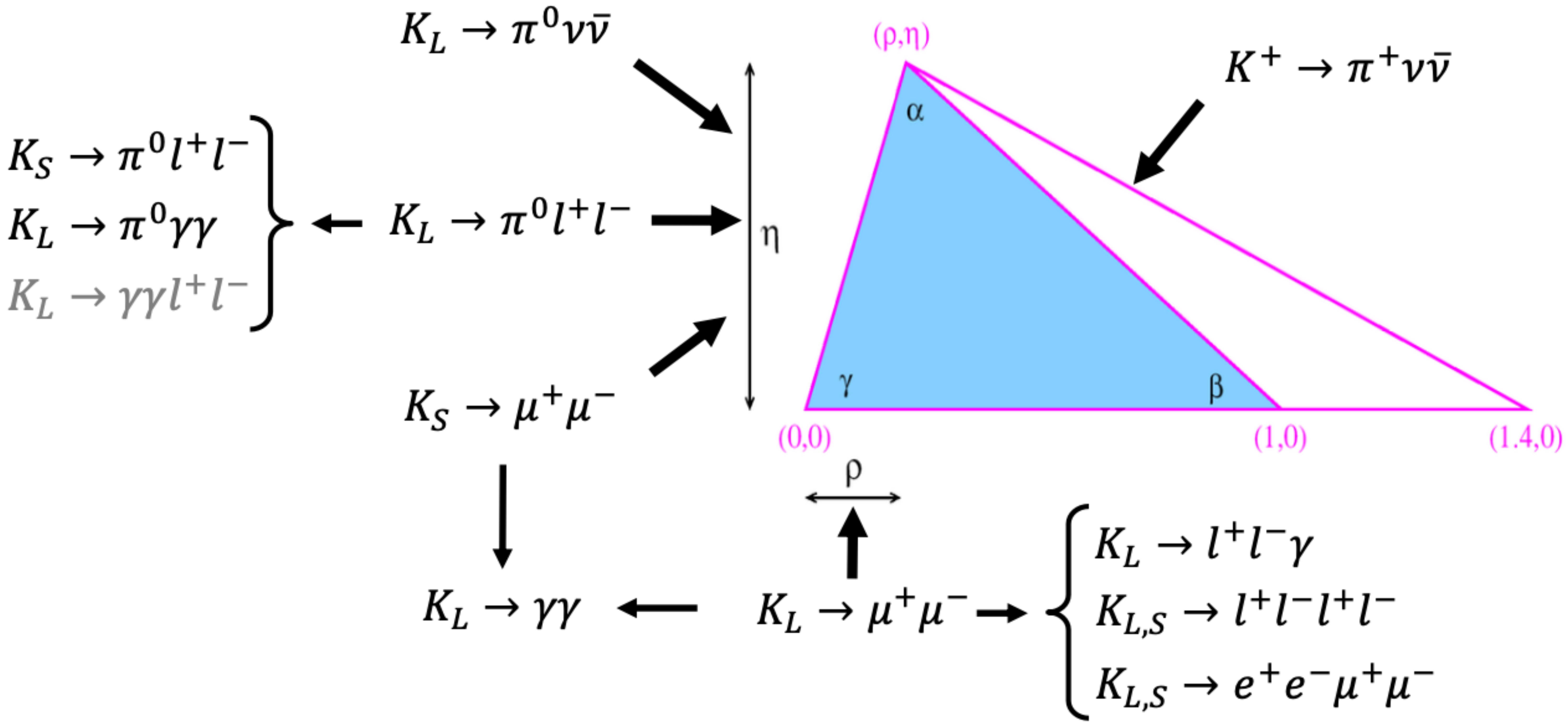
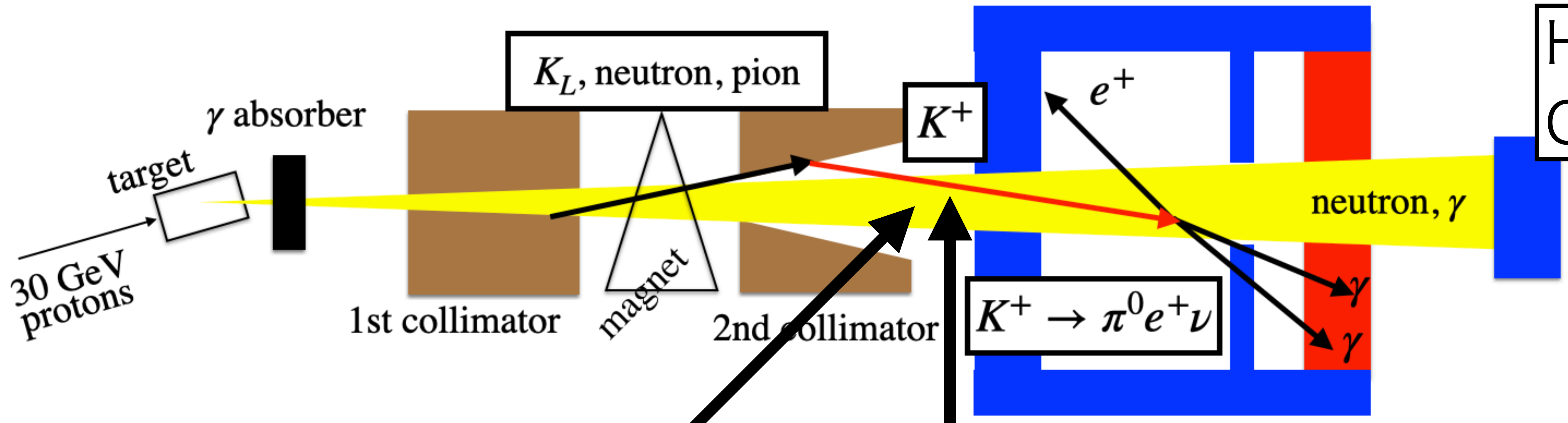


Figure 1: Relation between kaon rare decay modes and the parameters ρ and η of the unitary triangle (UT). The direct link between decay modes and the UT indicates short distance terms dependent on ρ or η contributing to the corresponding decay amplitudes. Decays not directly connected to the UT are relevant to interpret the experimental results of the decay modes to which they are related.

(HIKE Proposal, arXiv:2311.08231)

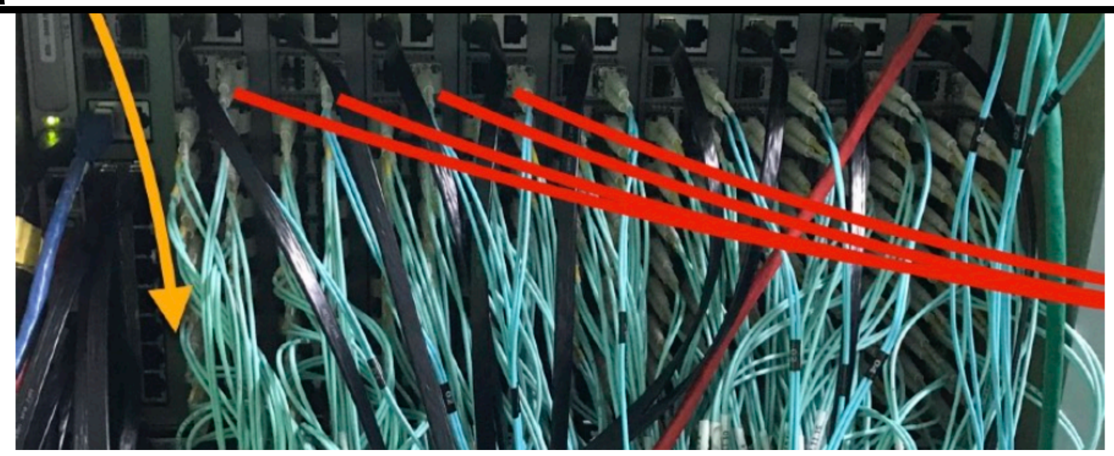
KOTO Detector and DAQ Upgrades since 2021

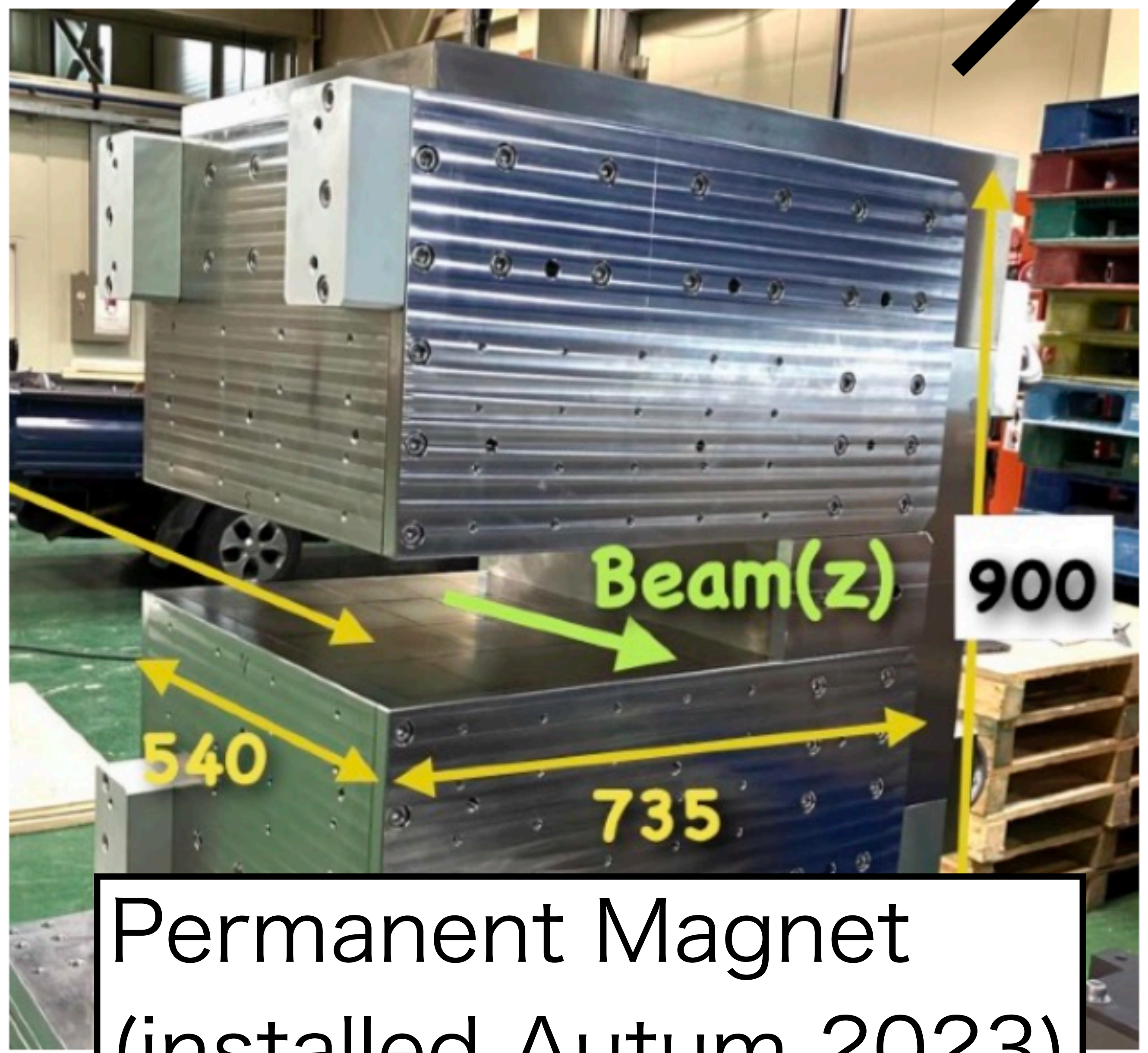
Background reduction



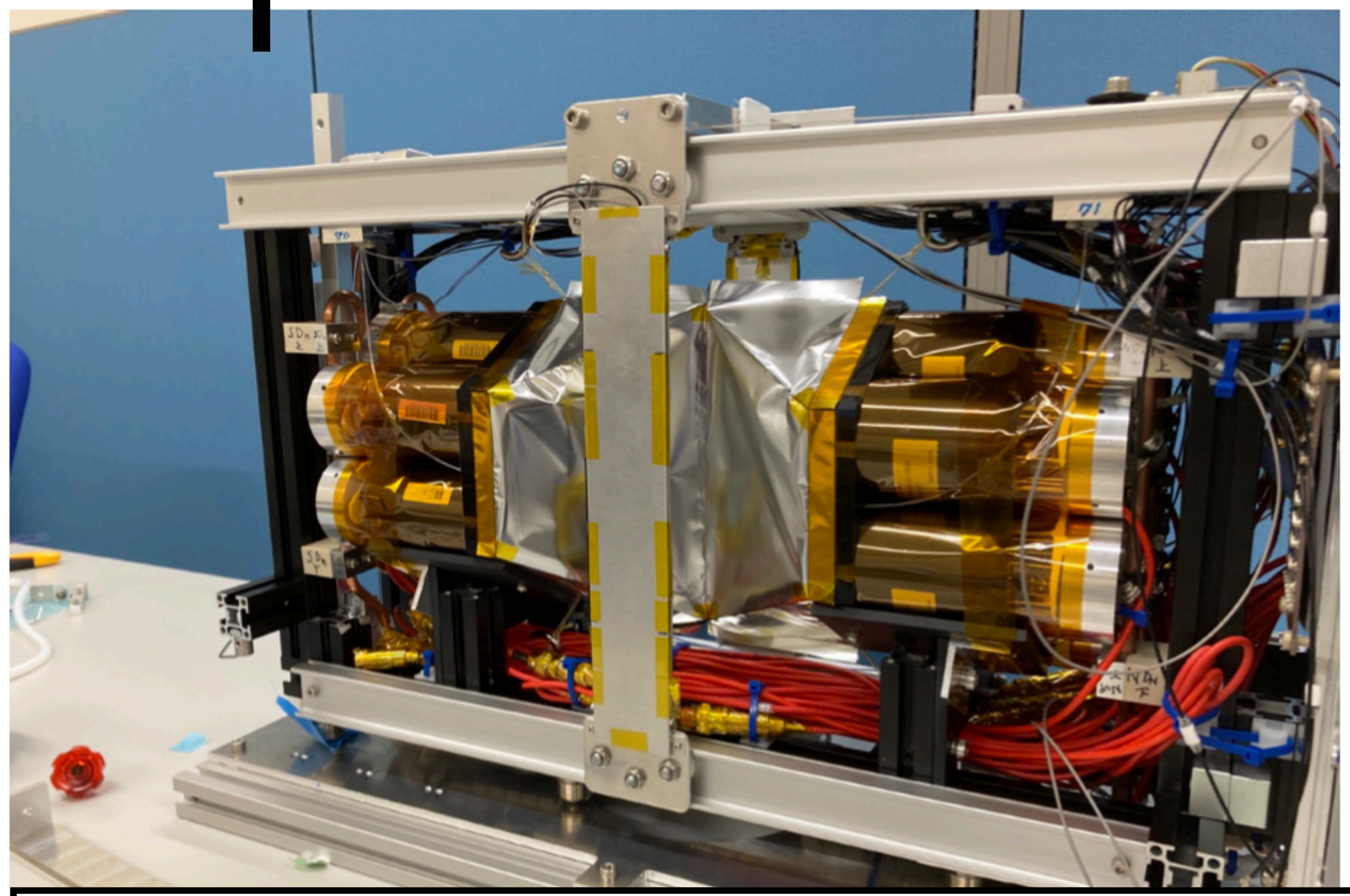
High power and quality beam

High speed DAQ ready for 100 kW beam
Optical fiber, FPGA, GPU/CPU L3

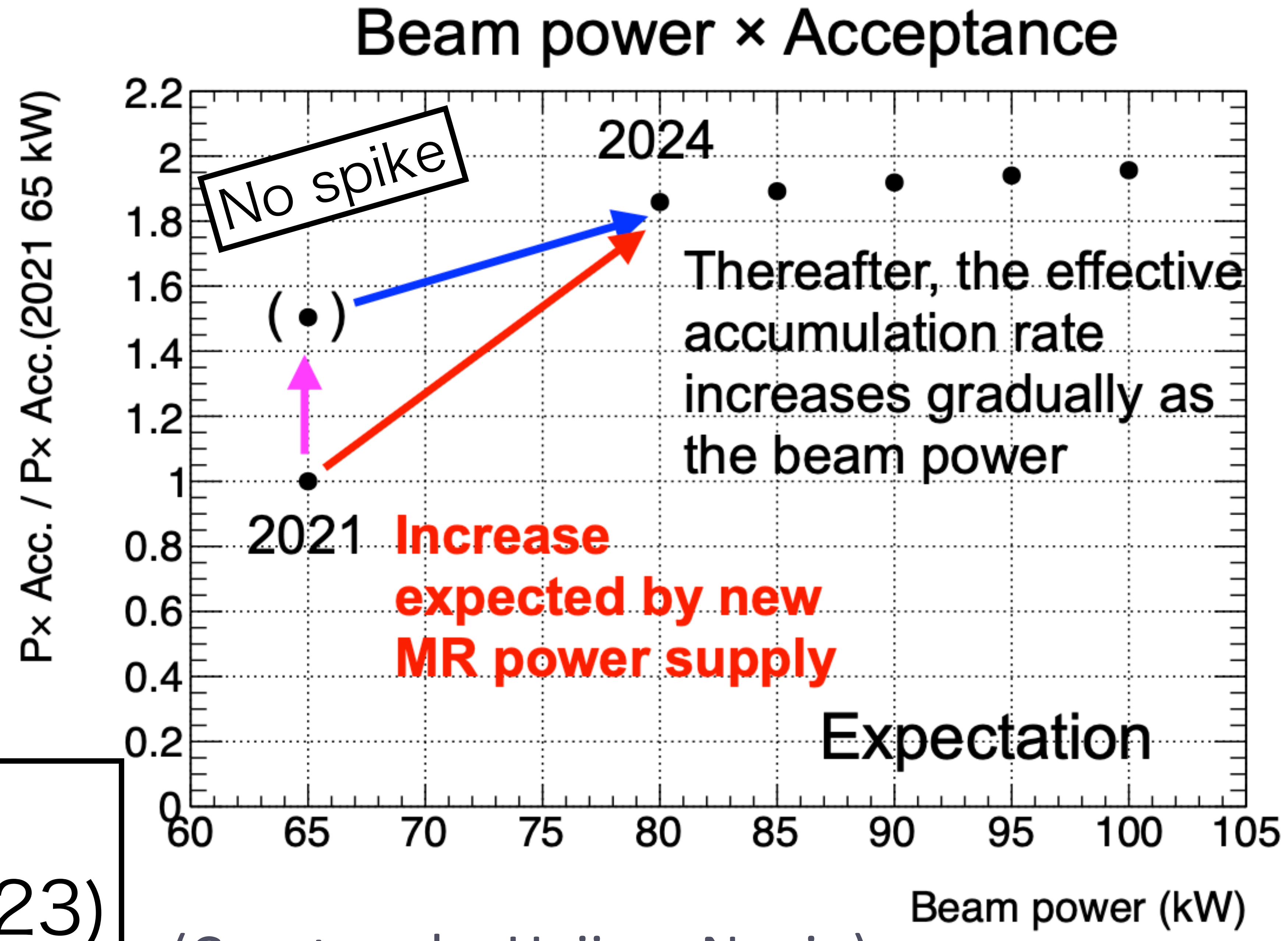




Permanent Magnet
(installed Autum 2023)



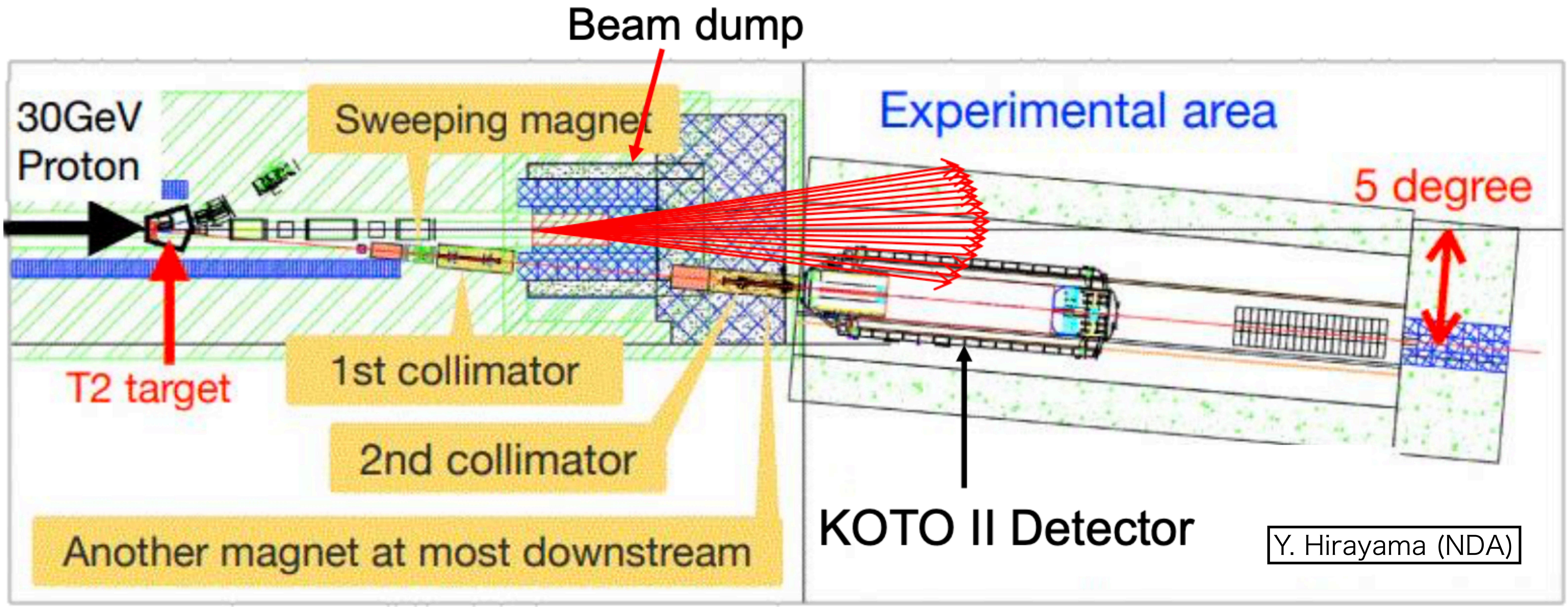
0.2-mm thick plastic scintillator
(new version installed Spring 2023)



(Courtesy by Hajime Nanjo)

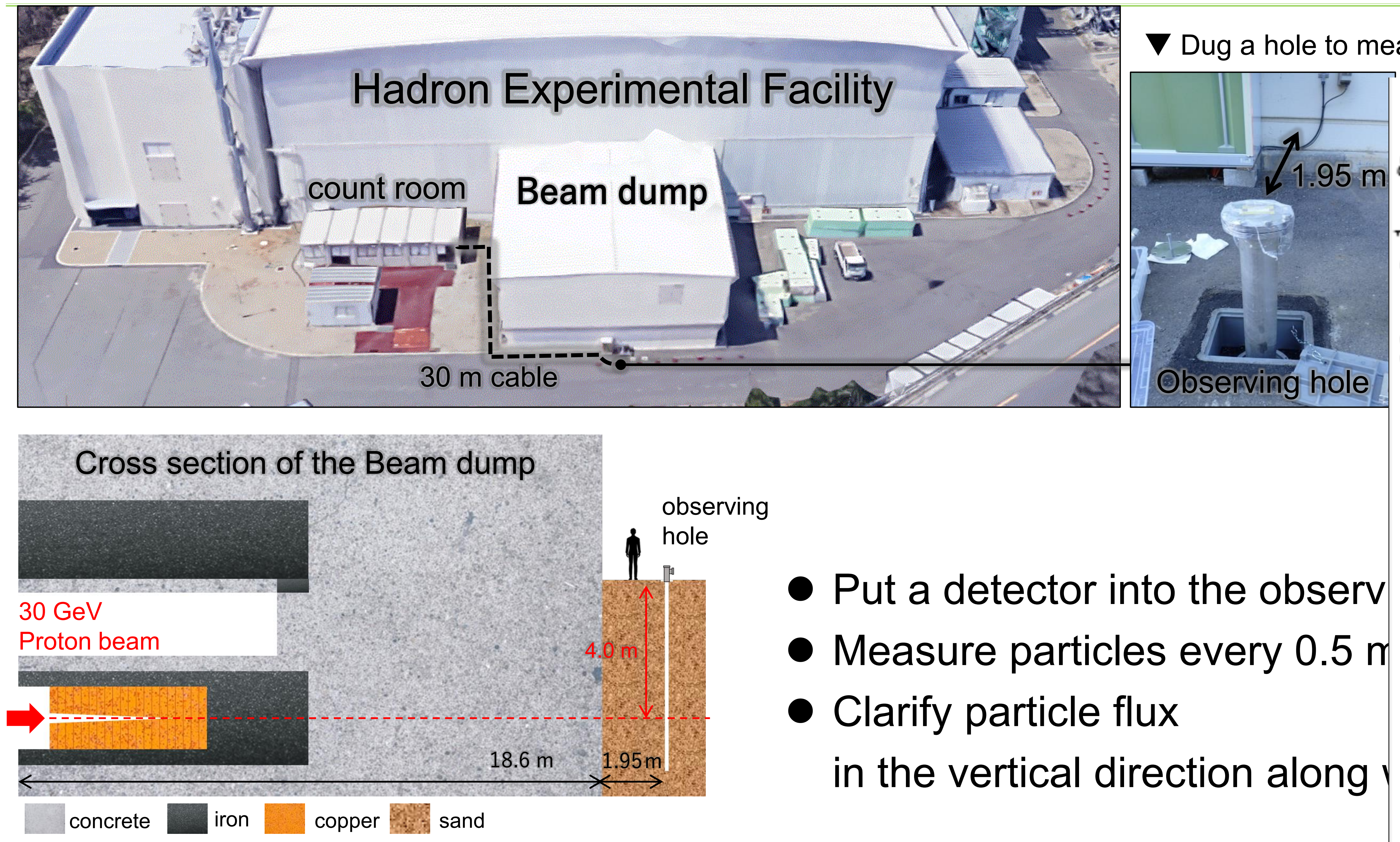
Muon Flux behind the Beamdump

KOTO II may suffer from high rate with particles from dump:



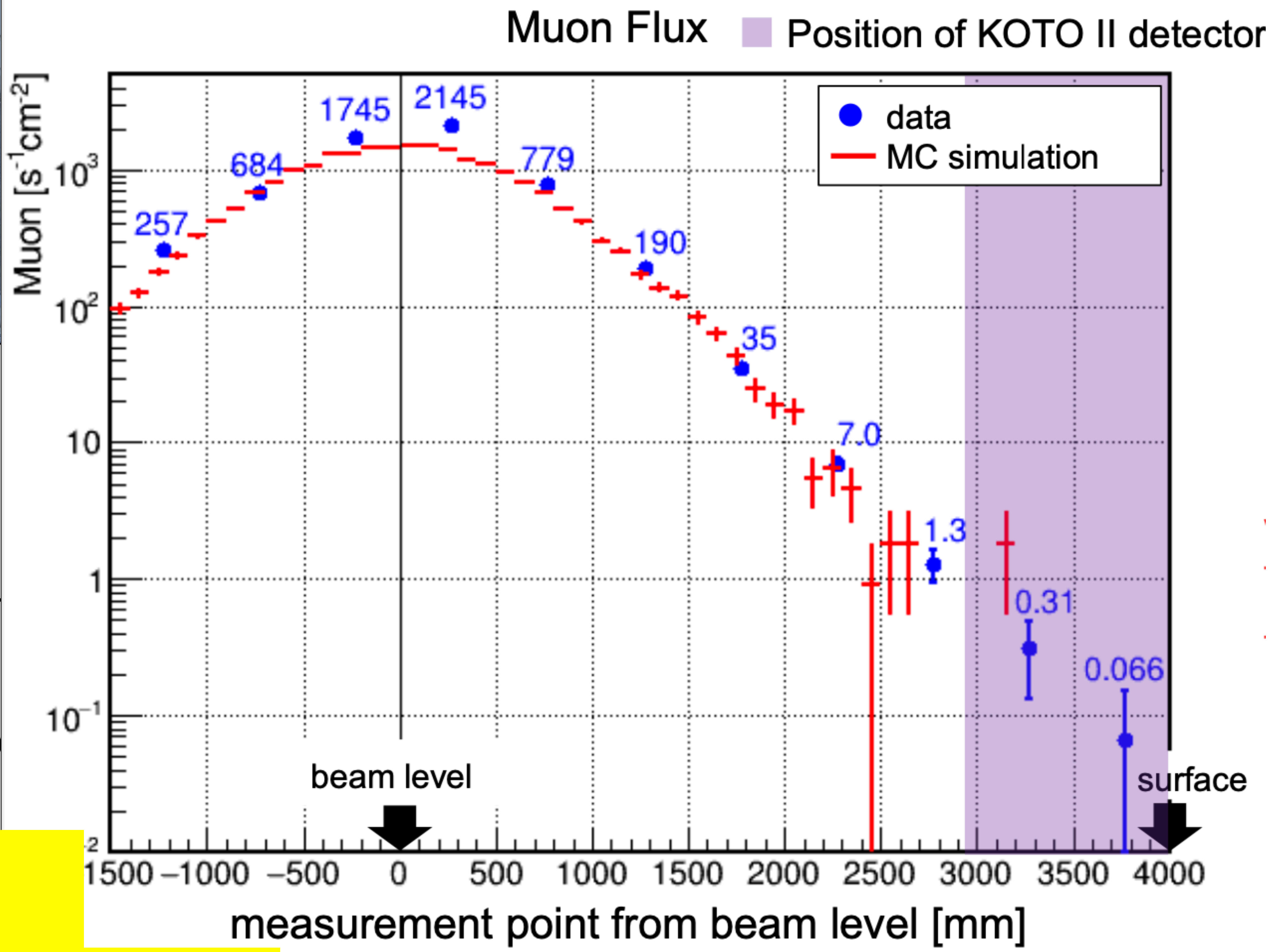
Muon Flux behind the Beamdump

Measured with the current beamdump.



- Put a detector into the observ
- Measure particles every 0.5 m
- Clarify particle flux in the vertical direction along v

Y. Hirayama (NDA)



Muon flux is as expected. →2.1 MHz at KOTO II
Will add 3-m thick iron shield at the dump → 0.4 MHz Fine!