Experimental Prospects on Kaon Physics

A. Ceccucci

FCCP2025, Anacapri

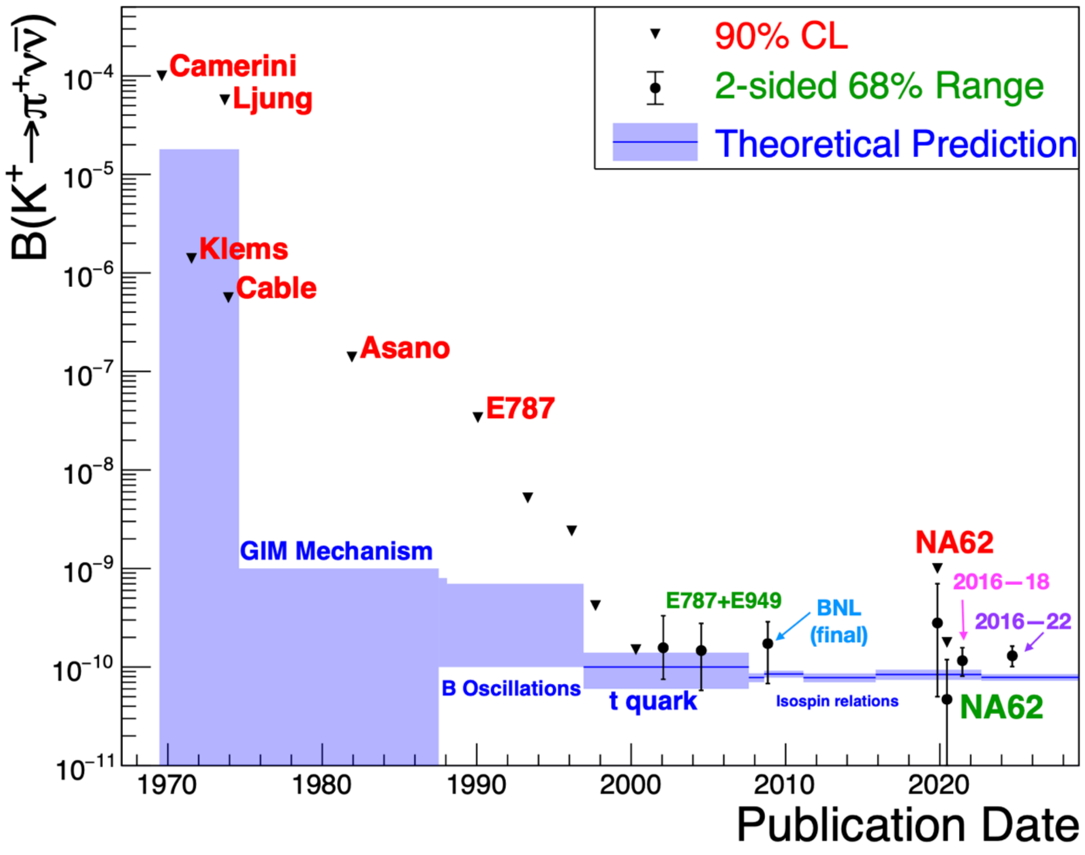
KAON XIII Mainz 2025 (KAON25)

- A very thoughrough conference, full programme including experiments, lattice, phenomenology etc:

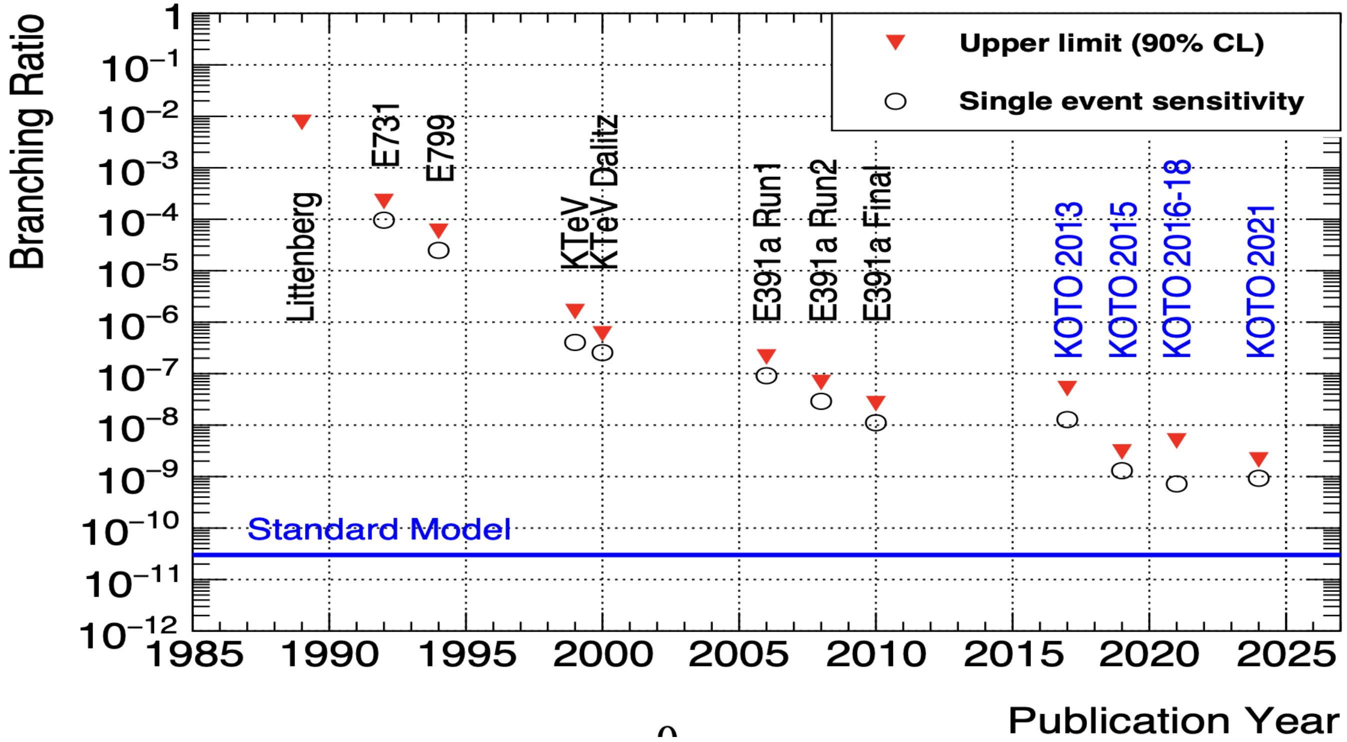
https://indico.cern.ch/event/1485702/

- One full session devoted to future plans, in a nutshell:
  - Completion of NA62 data taking: August 2026
  - Completion KOTO data taking: approx 2030
  - KOTO II received Stage 1 (scientific) approval
  - Competitive LHCb Kaon programme thanks to software triggers and upgrades
- Kaon physics is a vast domain, I focus here on short-distance dominated rare decays

$K \rightarrow \pi\nu\bar{\nu}$ (PNN): A Long Game...



Joel Swallow @KAON25

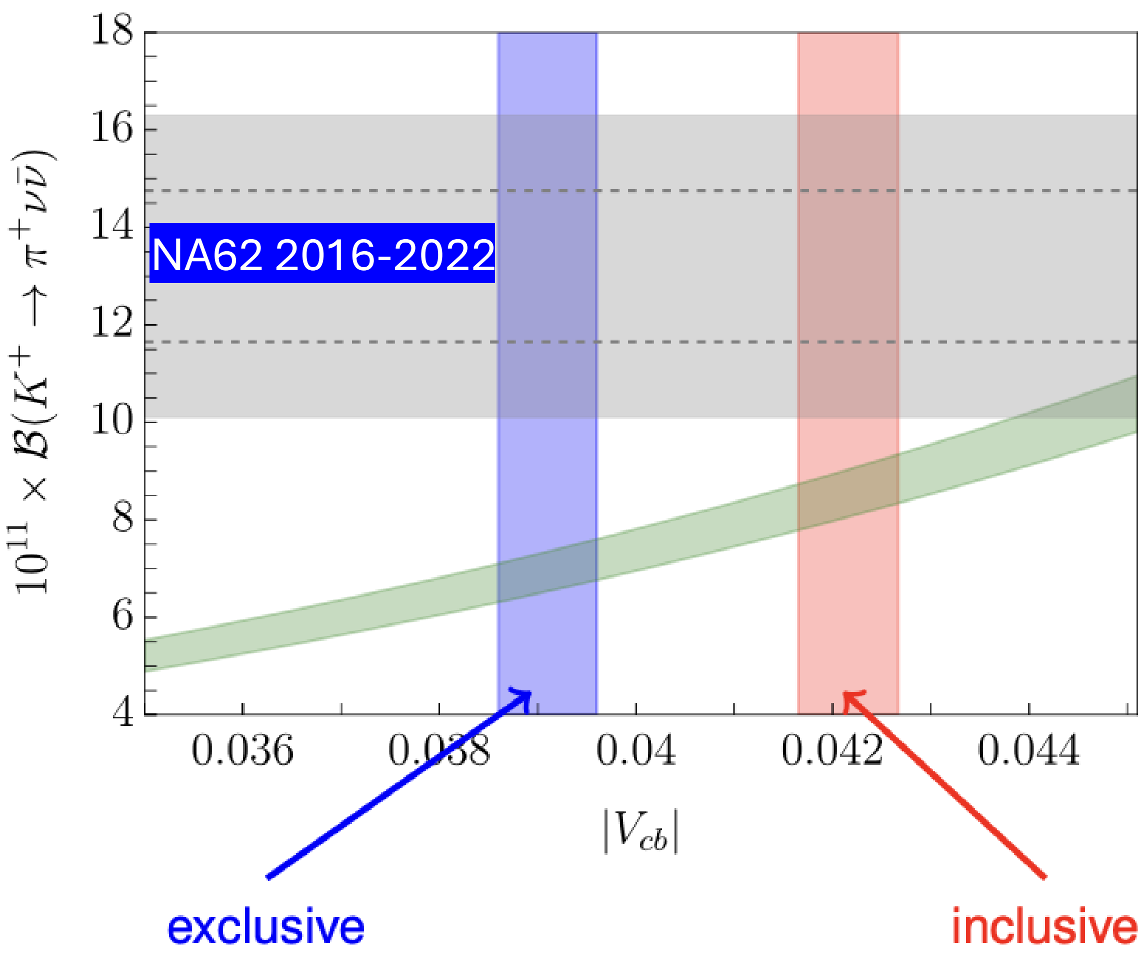


Keita Ono @KAON25

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |\lambda_{ts}|^2 \quad \lambda_{ts} \equiv \lambda |V_{cb}|^2 \left[(\bar{\rho} - 1) \left(1 - \frac{\lambda^2}{2}\right) + i\bar{\eta} \left(1 + \frac{\lambda^2}{2}\right) \right] + \mathcal{O}(\lambda^4)$$

Marzia Bordone@KAON2025

...beginning to provide quantitative tests



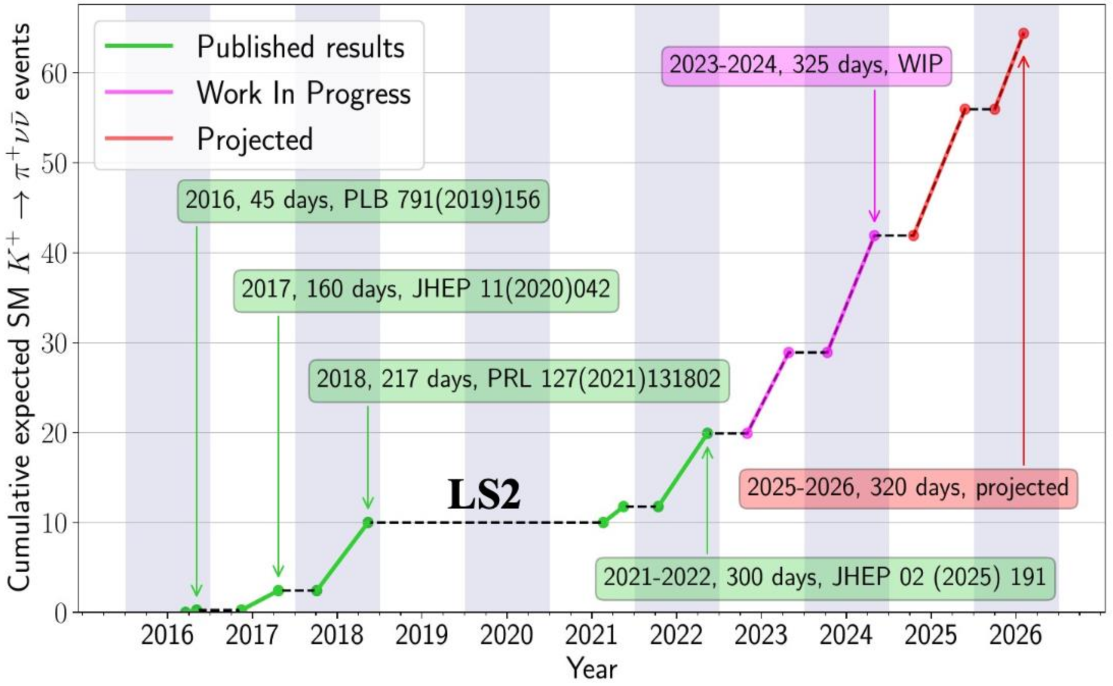
NA62 Projection, Karim Massri @KAON2025

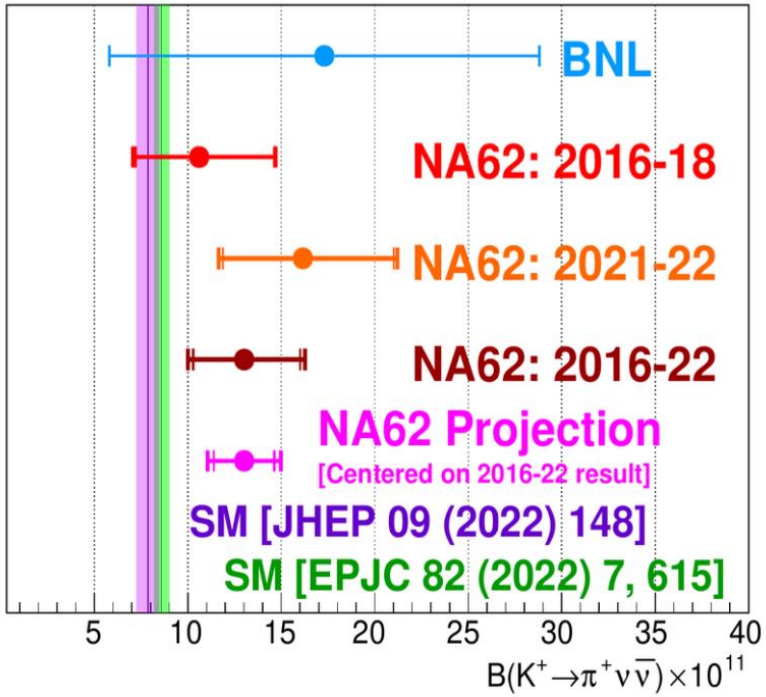
$K^+ \to \pi^+ \nu\bar{\nu}$: Final dataset projection

Latest $K^+ \to \pi^+ \nu\bar{\nu}$ result (2016-2022 data) discussed in detail **M. Zamkovsky**

Final dataset (2016-2026) projection

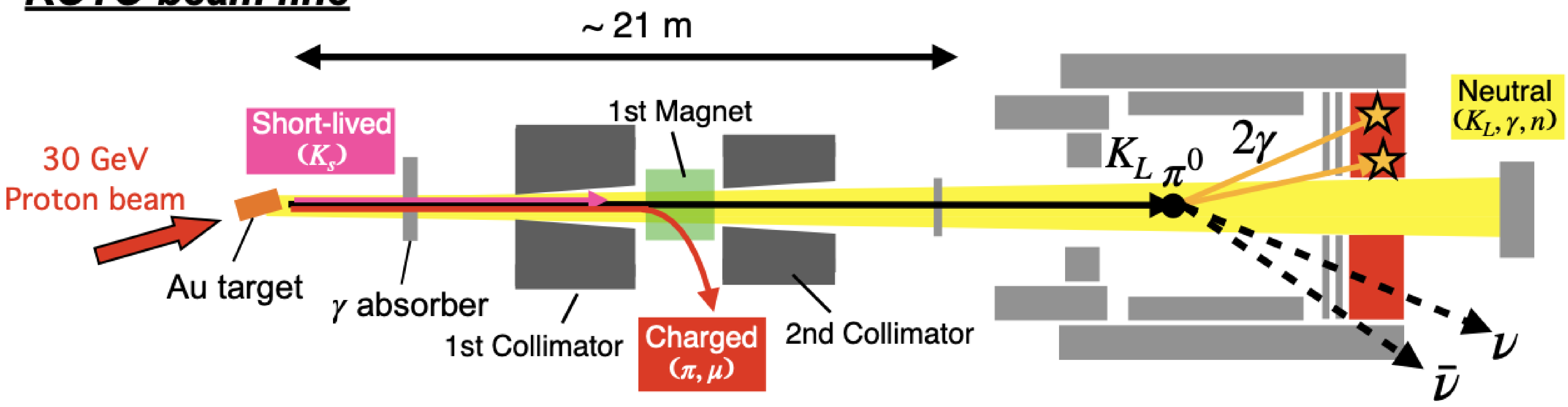
- Projected to be ~ 3x the 2016-2022 statistics (> 60 SM $K^+ \to \pi^+ \nu\bar{\nu}$)
- Assume same $N_{\pi\nu\nu}$ /day as 2024, assume same B/S as 2021-2022





Expect BR($K^+ \to \pi^+ \nu\bar{\nu}$) uncertainty < 20% (stats + analysis improvements)

KOTO beam line



Signature of $K_L \to \pi^0 \nu\bar{\nu}$

- 2γ from π^0 in electromagnetic calorimeter (CSI)
- Nothing else in veto detectors
- Missing momentum taken by $\nu\bar{\nu}$

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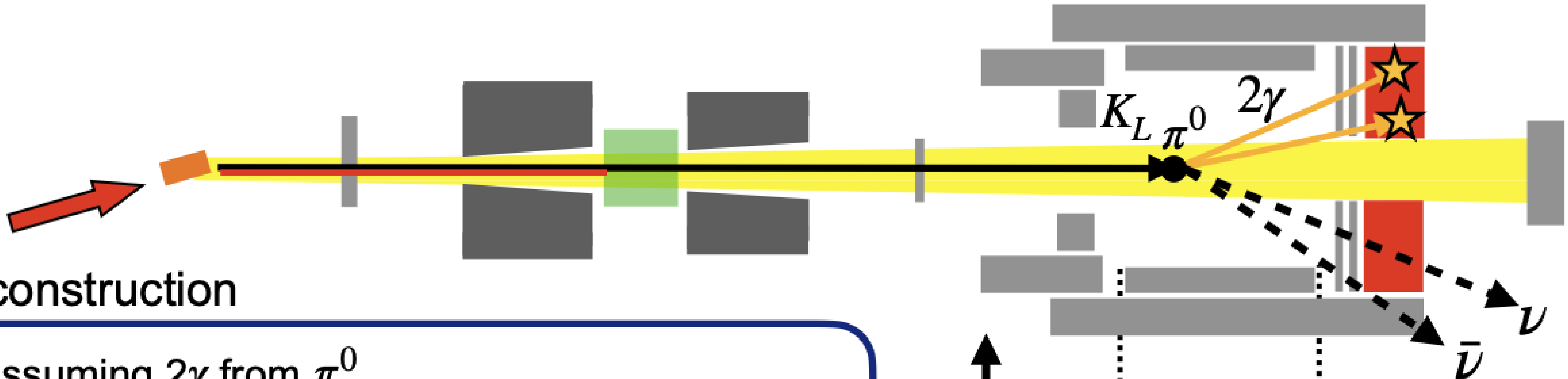
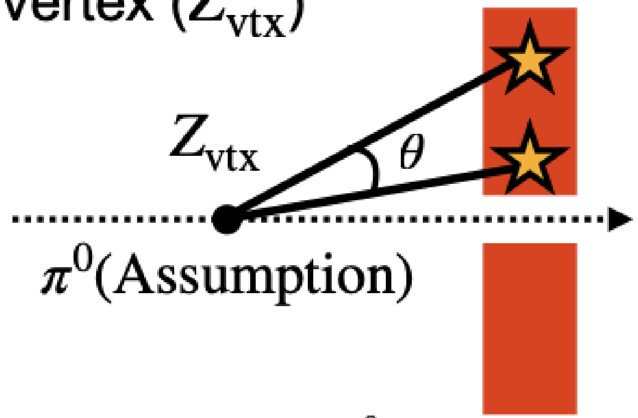


Reconstruction

- Assuming 2γ from π^0

  → Calculate Z vertex ($Z_{\rm vtx}$)

$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$



- Calculate π^0 transverse momentum ($p_t^{\pi^0}$)

Search for the signal in P_T vs Z plane

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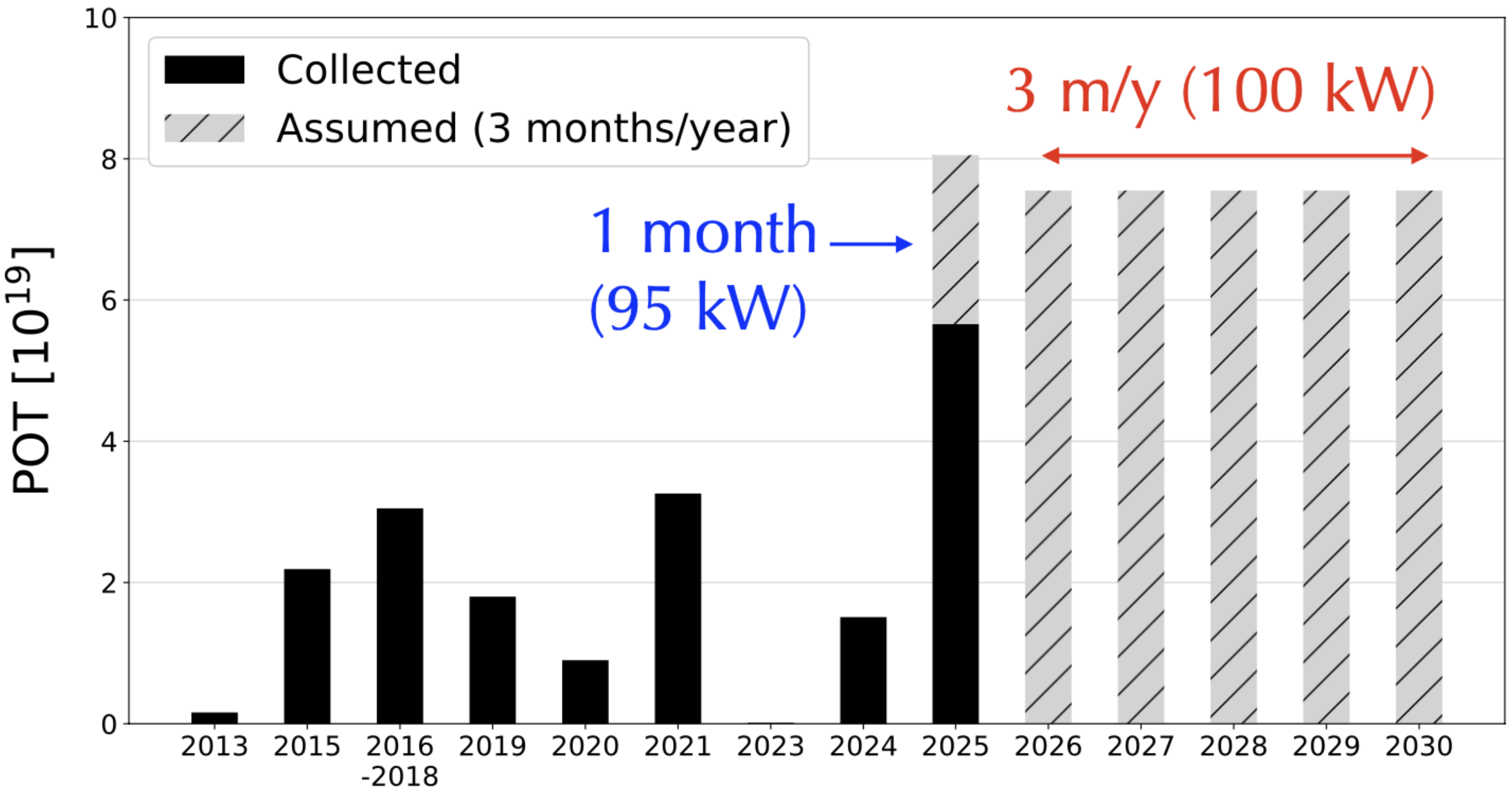
Expected protons on target (POT) KOTO



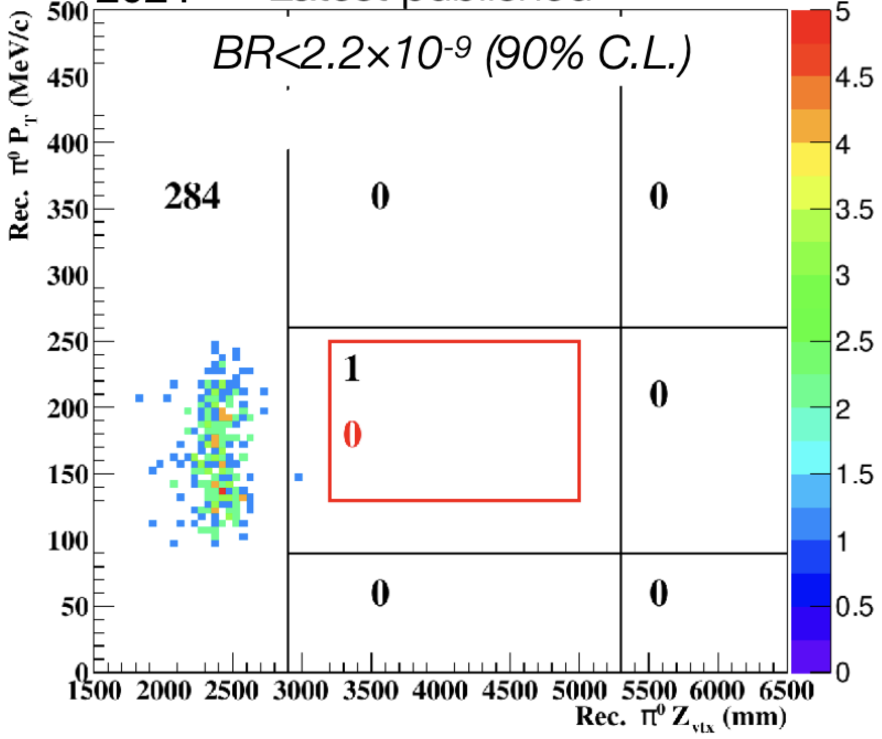
- If we assume 3 month (60 days net) per year, the accumulated POT will reach ×10 more than 2021 data around 2028. (Cf. SES(2021)=9.3×10^{-10})
  - Typical operation efficiencies (accelerator, DAQ, etc.) are taken in account.

Recap See slides by Ono (Osaka U)

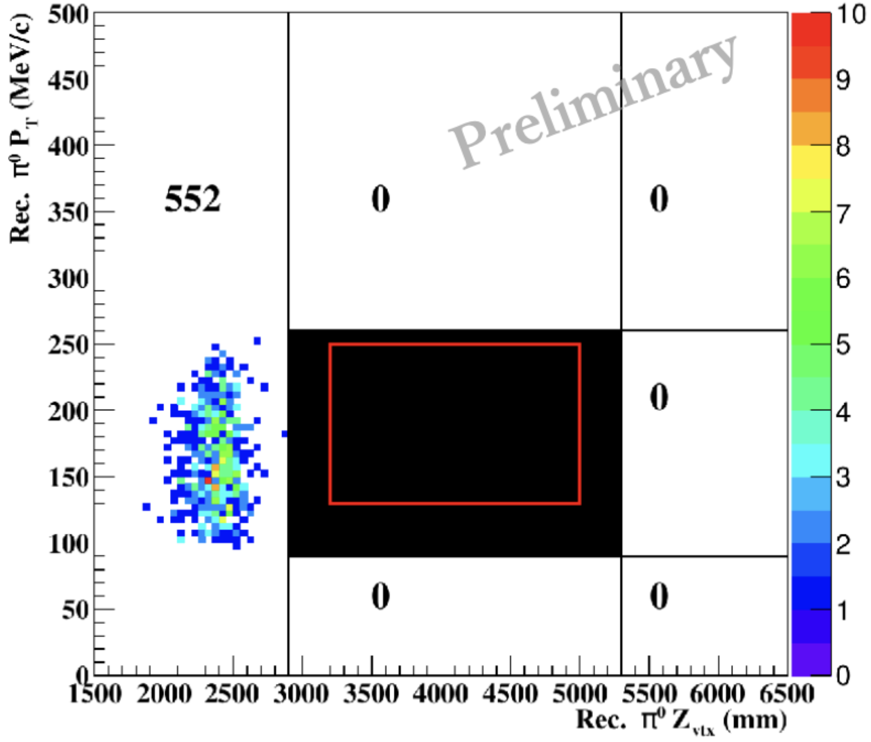
Latest status of the $K_L \to \pi^0 \nu\bar{\nu}$ search

Tadashi Nomura @KAON2025

2021 ←Latest published



2024-2025



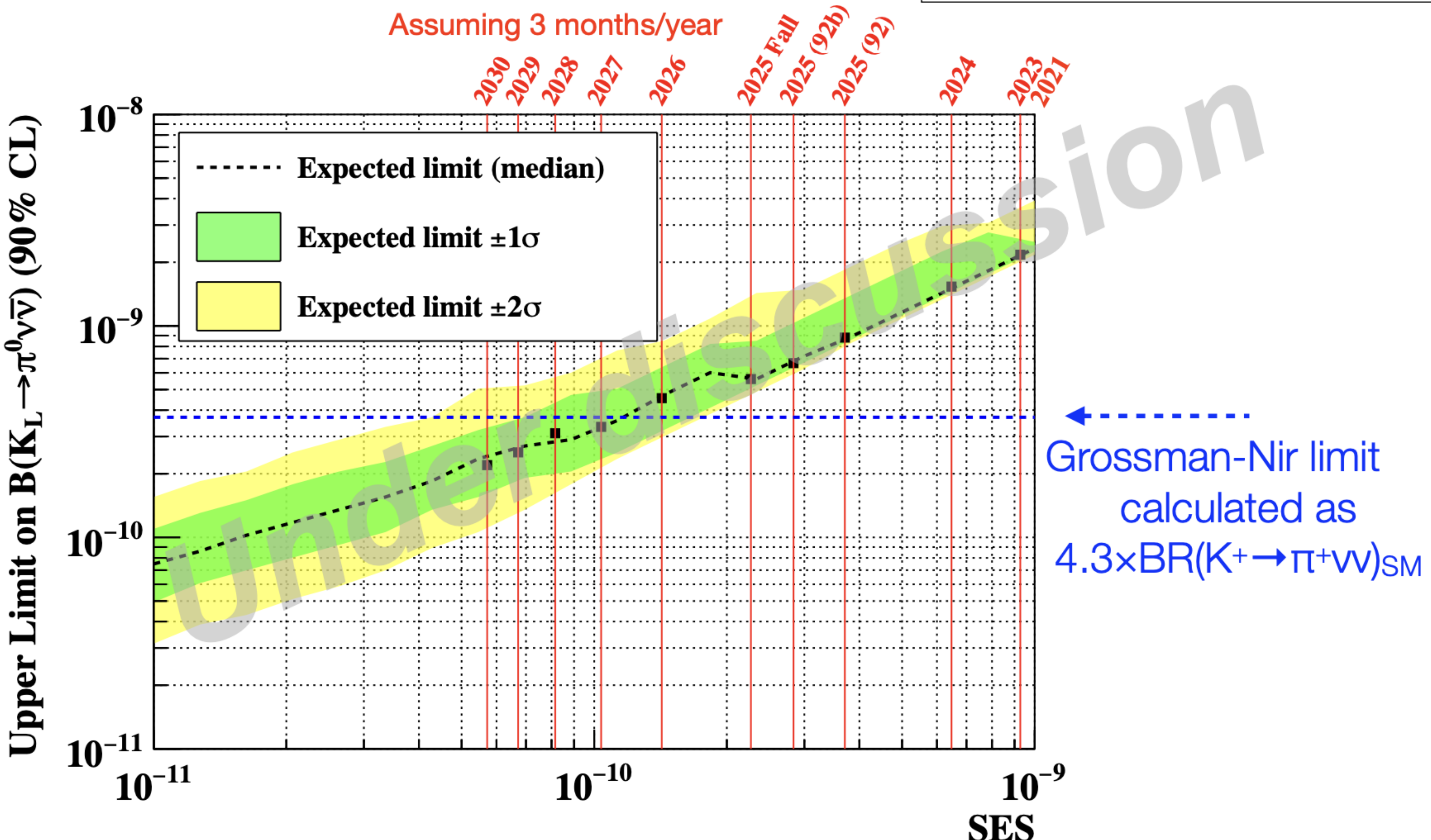
~×2 more data have been already accumulated in 2024-25

Note that some selection criteria, which are not ready for the 2024-25 data analysis, are not applied for comparison in both plots.

KOTO Projection, Tadashi Nomura @KAON2025

[Example]
Discussion based on modified-frequentist method (CL_s method)

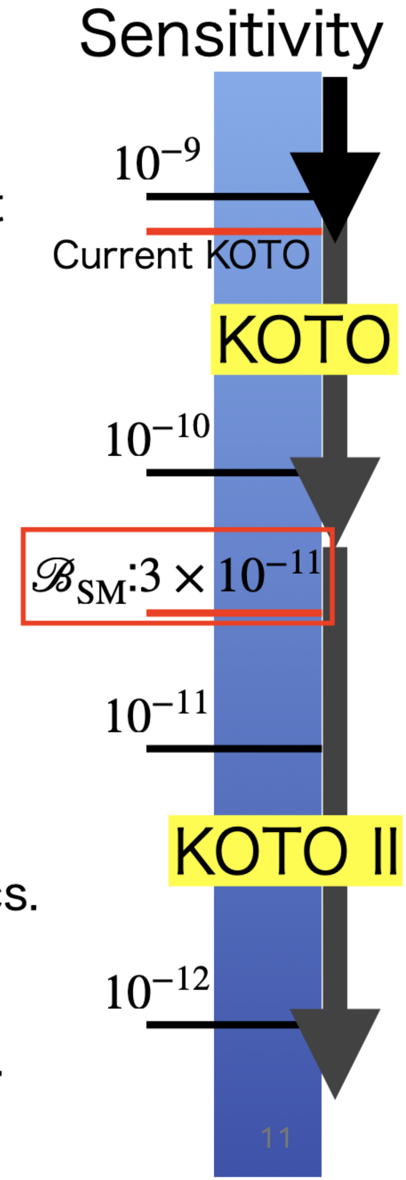
Limit vs SES considering BGL



H. Nanjo @KAON2025

KOTO II experiment

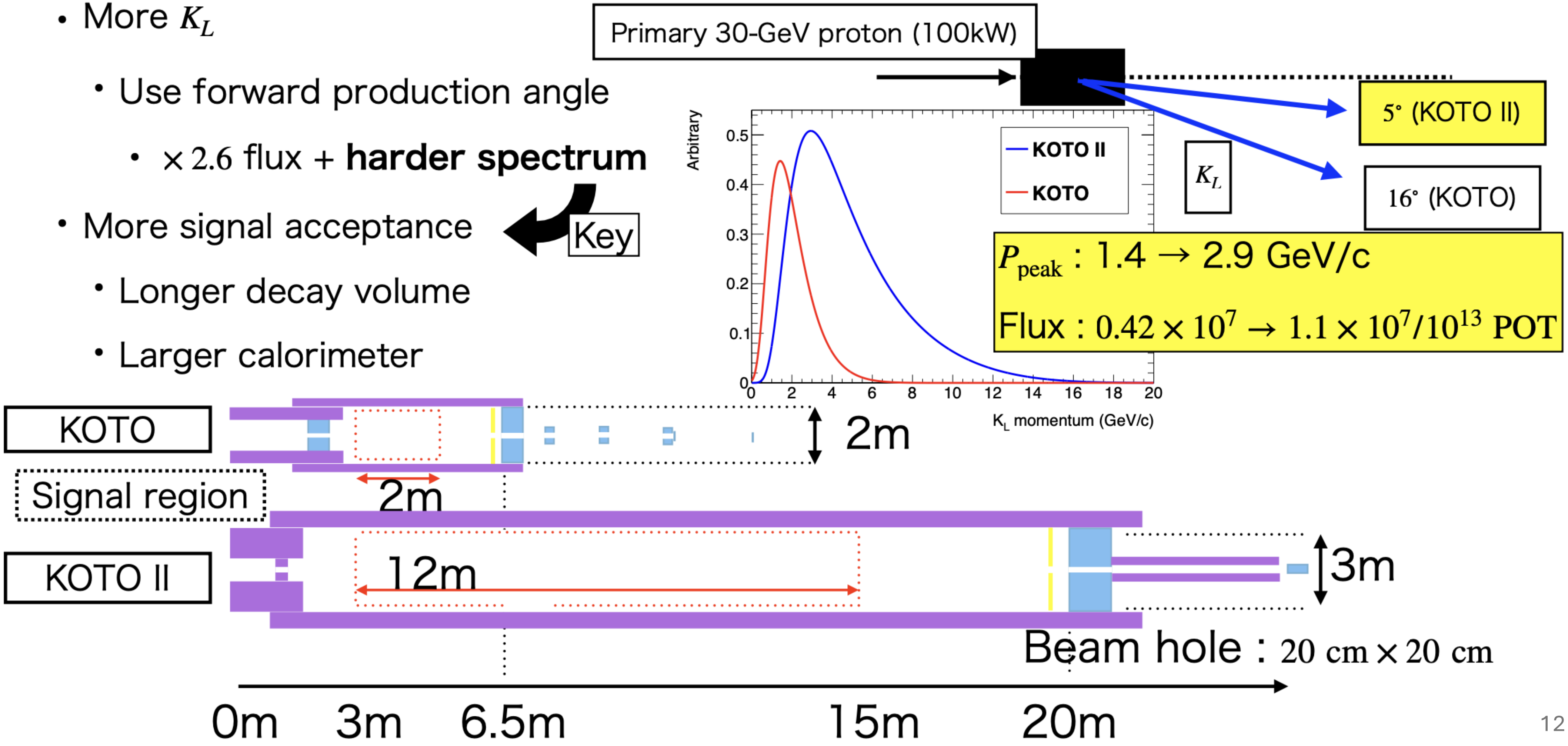
- Next-generation experiment to measure $\mathscr{B}(K_L \to \pi^0 \nu \bar{\nu})$ with x100 improvement
  - J-PARC 30 GeV proton→ Slow Extraction to Hadron Experimental Facility
  - K_L beam at 5 degrees from a proton target
  - Searches for new physics beyond the standard model
  - Discovery of $K_L \to \pi^0 \nu \bar{\nu}$ with $> 5\sigma$ significance
- KOTO II will be
  - a world center of experimental kaon physics.
  - indispensable in the quest for a complete understanding of flavor dynamics.
  - combining efforts from kaon community worldwide to have more physics.
    $K_L \to \pi^0 \ell^+ \ell^-$, other K_L decays, dark photons, axions, and axion-like particles.



KOTO II vs. KOTO, H. Nanjo @KAON2025

Keys to Improve the sensitivity

- More K_L
  - Use forward production angle
    - $\times 2.6$ flux + **harder spectrum**
- More signal acceptance
  - Longer decay volume
  - Larger calorimeter

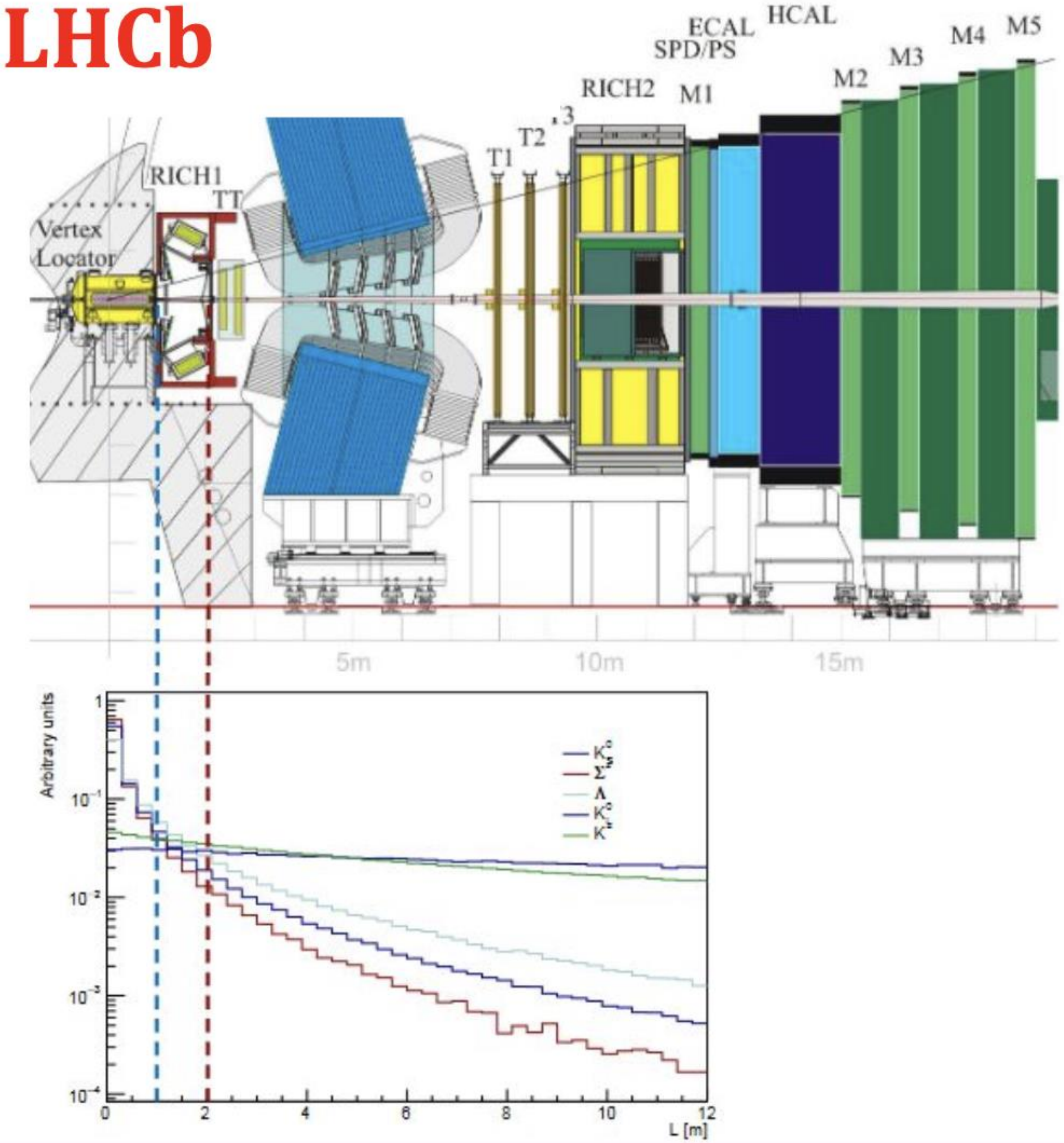


Conclusion

- KOTO II is a next generation experiment to measure $\mathscr{B}(K_L \to \pi^0 \nu\bar{\nu})$ in 2030s at J-PARC.
  - With the value of SM branching ratio and 3×10^7-s running time,
    - 35 signal and 40 background events are expected.
    - This gives >5σ discovery and $\Delta\mathscr{B}/\mathscr{B}$=25%.
  - It will be 90% indication of NP if observed $\mathscr{B}$ differs by 40% from the value in SM.
  - Measurement of another important mode $K_L \to \pi^0 \ell^+ \ell^-$ is planned.
  - The proposal of the KOTO II experiment was scientifically approved (Stage-1 status). Now : KOTO II = J-PARC E107
  - The **KOTO II collaboration** was formed.
  - The next goal
    - Make a strategy and breakthrough to prepare KL2 beam line.
    - More realistic detector design → TDR toward Stage-2 approval (full approval)

These are results of everyone's efforts,
but it is just the beginning.
Establish KOTO II experiment together!

LHCb



1 strange hadron / event produced at 13 TeV

$<p_t>$ ~0.08 GeV

Production rate compensates low trigger efficiency and long lifetime

Vast programme (mainly Run3):

$K_{S,L} \rightarrow \mu^+\mu^-$

$K_S \rightarrow \pi^0\mu^+\mu^-$

$K_S \rightarrow \mu^+\mu^-\mu^+\mu^-(e^+e^-)$

$K_S \rightarrow \pi^+\pi^-e^+e^-$

$K^+ \rightarrow \pi^+l^+l^-$

C. Lazzaroni, Lepton-Photon 2025

LHCb Upgrade1 done. Collect ~50 fb^{-1} at L = $2x10^{33}$ cm^{-2} s^{-1} in 2023-33.
LHCb Upgrade2: after 2035. Collect ~300 fb^{-1} .Pile-up: ~40, 200 Tb/s data, lots of R&Ds.

LHCb Sensitivity to Strange particles

(I am adapting material from the presentation of Luis Miguel Garcia Martin @KAON25)

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K^0_S \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K^0_S \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K^0_S \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K^0_S \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K^0_L \to \mu^+\mu^-$	~ 1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~ 3.0	~ 7.0
$K^+ \to \pi^+\pi^+\pi^-$	~ 2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~ 1.0	~ 4.0
$K^+ \to \pi^+\mu^+\mu^-$	~ 2	6.3 (2.3) $\times 10^{-3}$	0.030 (0.014)	~ 1.5	~ 4.5
$\Sigma^+ \to p\mu^+\mu^-$	~ 0.13	0.28 (0.28)	0.64 (0.64)	~ 1.0	~ 3.0
$\Lambda \to p\pi^-$	~ 0.45	0.41 (0.075)	1.3 (0.39)	~ 1.5	~ 5.0
$\Lambda \to p\mu^-\bar{\nu}_\mu$	~ 0.45	0.32 (0.31)	0.88 (0.86)	–	–
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~ 0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	–	–
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~ 0.03	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	–	–
$\Xi^- \to p\pi^-\pi^-$	~ 0.03	0.41(0.05)	0.94 (0.20)	~ 3.0	~ 9.0
$\Xi^0 \to p\pi^-$	~ 0.03	1.0 (0.48)	2.0 (1.3)	~ 5.0	~ 10
$\Omega^- \to \Lambda\pi^-$	~ 0.001	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~ 7.0	~ 20

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \pi^+\pi^-e^+e^-$	1	1.0 (0.18)	2.83 (1.1)	~ 2.0	~ 10
$K^0_S \to \mu^+\mu^-e^+e^-$	1	1.18 (0.48)	2.93 (1.4)	~ 2.0	~ 11
$K^+ \to \pi^+e^+e^-$	~ 2	0.04 (0.01)	0.17 (0.06)	~ 3.0	~ 13
$\Sigma^+ \to pe^+e^-$	~ 0.13	1.76 (0.56)	3.2 (1.3)	~ 3.5	~ 11
$\Lambda \to p\pi^-e^+e^-$	~ 0.45	$< 2.2 \times 10^{-4}$	~ 17 (< 2.2) $\times 10^{-4}$	–	–

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \mu^+e^-$	1	1.0 (0.84)	1.5 (1.3)	~ 3.0	~ 8.0
$K^0_L \to \mu^+e^-$	1	3.1 (2.6) $\times 10^{-3}$	13 (11) $\times 10^{-3}$	~ 3.0	~ 7.0
$K^+ \to \pi^+\mu^+e^-$	~ 2	3.1 (1.1) $\times 10^{-3}$	16 (8.5) $\times 10^{-3}$	~ 2.0	~ 8.0

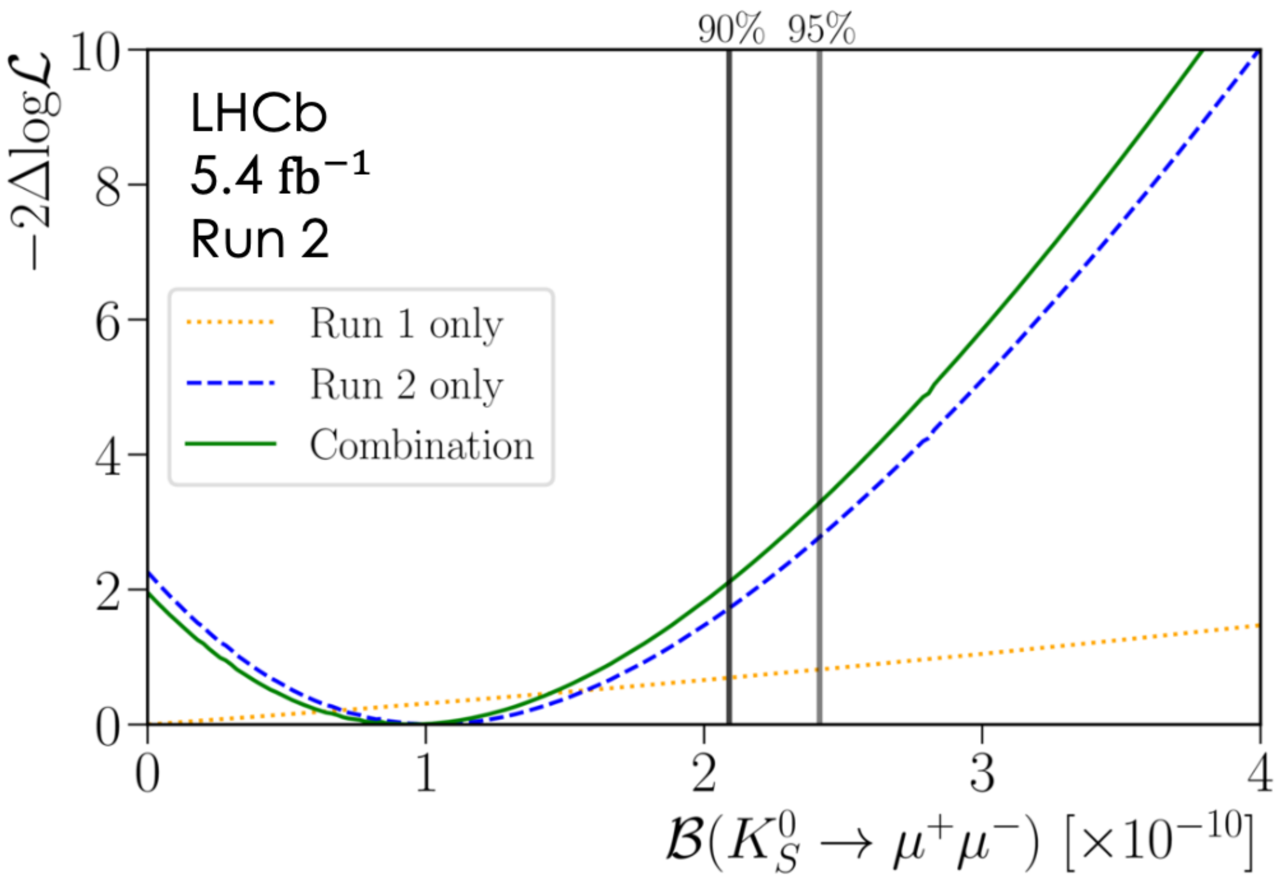
$\mathcal{R}$ – ratio of production w.r.t. K^0_S

ϵ – ratio of efficiencies w.r.t. $K^0_S \to \mu^+\mu^-$

JHEP05(2019)048

It was realised that a strong kaon programme can be realized in LHCb

LHCb example: $K_S \rightarrow \mu^+\mu^-$



$BR(K_S^0 \rightarrow \mu^+\mu^-)_{theo} \sim 10^{-12}$

$BR(K_S^0 \rightarrow \mu^+\mu^-) < 2.2 \times 10^{-10}$ @ 90% CL

PRL 125 (2020) 231801

- prospects to reach $O(10^{-11})$ sensitivity with Run 3 data (analysis ongoing)

JHEP 05 (2019) 048

Impressive limit, opening the way to phenomenological implications (see next)

$K(t) \to \mu^+\mu^-$

[D'Ambrosio, Kitahara, [arXiv: 1707.06999]]
[**AD**, Ghosh, Grossman, Schacht, [arXiv: 2104.06427]]

The $K \to \mu^+\mu^-$ system can be described by four parameters:

$|A(K_L)_{\text{CP-even}}|$ | $C_L = |A(K_L)_{\text{CP-even}}|^2$

$|A(K_S)_{\text{CP-odd}}|$ $\propto A^2\lambda^4\bar{\eta}$ | $C_S = |A(K_S)_{\text{CP-odd}}|^2 + \beta_\mu^2 |A(K_S)_{\text{CP-even}}|^2$

$|A(K_S)_{\text{CP-even}}|$ | $C_{\text{Int.}} = |A(K_S)_{\text{CP-odd}} A(K_L)_{\text{CP-even}}|$

$\varphi_0 = \arg\left(A(K_S)^*_{\text{CP-odd}} A(K_L)_{\text{CP-even}}\right)$ | φ_0

$$\frac{d\Gamma(K^0(\overline{K}^0))}{dt} = C_L e^{-i\Gamma_L t} + C_S e^{-i\Gamma_S t} \pm 2\, C_{\text{Int.}} \cos(\Delta M_K t - \varphi_0) e^{-i\Gamma t}$$

Interference term holds the CPV (SD) information

$$\frac{C_{\text{Int.}}^2}{C_L} = |A(K_S)_{\text{CP-odd}}|^2$$

Theoretically clean

The same effect induces A_{CP}: the difference between K^0 and $\overline{K}^0$ rates.

A new way to access η

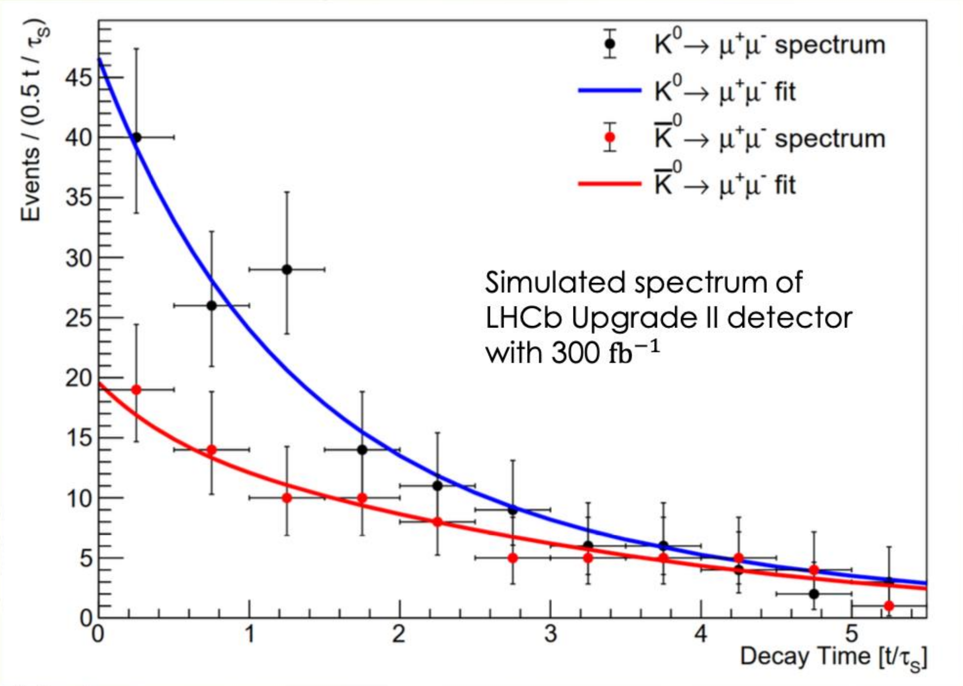
D'Ambrosio, Dery, Grossmann, Kitahara, Marchevski, Martinez Santos, Schacht

$K_S \to \mu^+\mu^-$: Prospects

arXiv:2507.13445

See A. Dery's talk

- $K^0 \to \mu^+\mu^-$ interference grants access to SD



Time-dependent rate

$$\frac{1}{\mathcal{N}}\frac{d\Gamma(\overset{(-)}{K}{}^0 \to \mu^+\mu^-)}{dt} = C_L\, e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t} \pm 2\, C_{\text{Int.}} \cos(\Delta M_K t - \varphi_0) e^{-\Gamma t}$$

$$C_L = |A(K_L)_{\ell=0}|^2\,,$$
$$C_S = |A(K_S)_{\ell=0}|^2 + \beta_\mu^2 |A(K_S)_{\ell=1}|^2\,,$$
$$C_{\text{Int.}} = |A(K_S)_{\ell=0}||A(K_L)_{\ell=0}|$$

Short-distance CPV contribution

- Also grants access to CKM η
- Time-dependence and Tagging required
- Benefit from extending acceptance (Downstream tracks)

LHCb Upgrade II might be able to achieve:

- $^{\delta\eta}/_{\eta}$ ~35%
- Sign of $A^{\mu}_{L\gamma\gamma}$ with at least 3σ

KAON2025

Possible future

Avital Dery @Kaon25

[arXiv: 2504.12386]

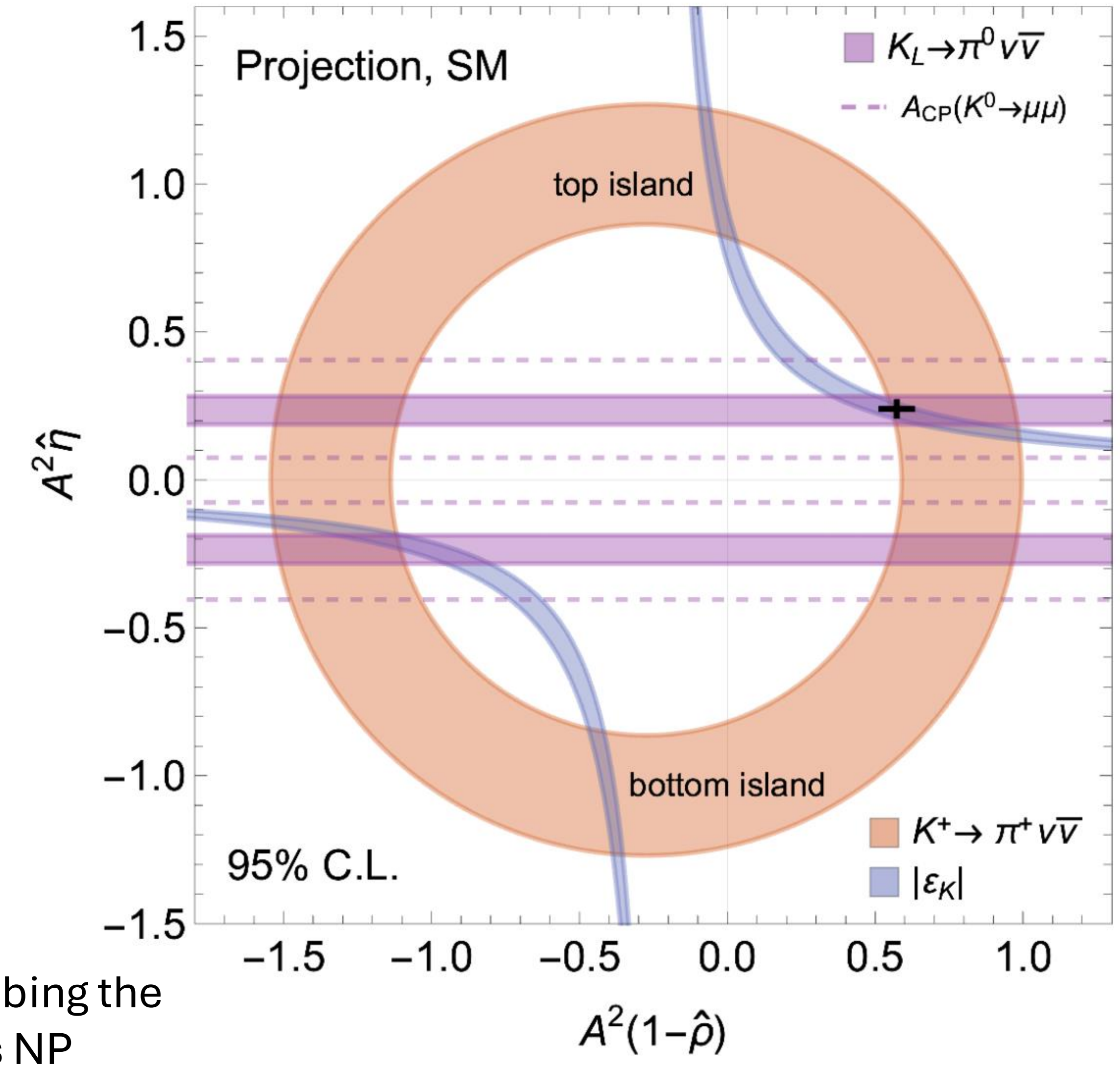
NA62 expectation:

15 % uncertainty on $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$

Planned KOTO II projection:

20 % uncertainty on $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$
=> A measurement of $(A^2\hat{\eta})$

Complementary measurement of $(A^2\hat{\eta})$ via $A_{CP}(K^0 \to \mu^+\mu^-)$ at LHCb



“Progress in rare kaon decays (exp+pheno+dispersion+Lattice) allows to start probing the kaon UT plane, with constraints sensitive to various NP operators, using vastly different experimental and theory techniques, complementing the B-physics CKM picture in a unique and crucial way”

Prospects

- Watch out for the final NA62 $K^+ \rightarrow \pi^+ \nu\nu$ result: if the mean value remains that of the result based on the 2016-2022 data sample, one could expect a three sigma deviation from SM prediction. To be compared with progress on $B \rightarrow K\nu\nu$ from Belle II
- Follow with attention the progress of KOTO towards SM sensitivities for $K_L \rightarrow \pi^0 \nu\nu$ over the next decade
- Support the new J-PARC initiative KOTO II. This is a significant step forward in term of investment and ambition
- Stay tuned: a strong kaon physics programme is taking shape in LHCb
- Look for new opportunities, for instance at FCC-hh injectors
- Be part of the global strategy of particle physics (see next)

arXiv:2503.22256v1 [hep-ph] 28 Mar 2025,
Submitted to ESPPU

CERN-TH-2025-066

Kaon Physics: A Cornerstone for Future Discoveries

The kaon community requests to

- protect and amplify the European kaon-physics programme, exploring opportunities for
  - $K^+ \to \pi^+ \nu \bar{\nu}$
  - $K_{S,L} \to \mu^+ \mu^-$ decay and interference,
- facilitate and support European contributions for KOTO II for $K_L \to \pi^0 \nu \bar{\nu}$ and $K_L \to \pi^0 \ell^+ \ell^-$, spanning both hardware and analysis development,
- maintain the European leadership on theory computations for kaon physics (phenomenology, dispersion theory, effective theory and lattice QCD, including high-performance computing).