Missing Energy Decays @KOTO and NA62

H. Nanjo
(U. of Osaka)

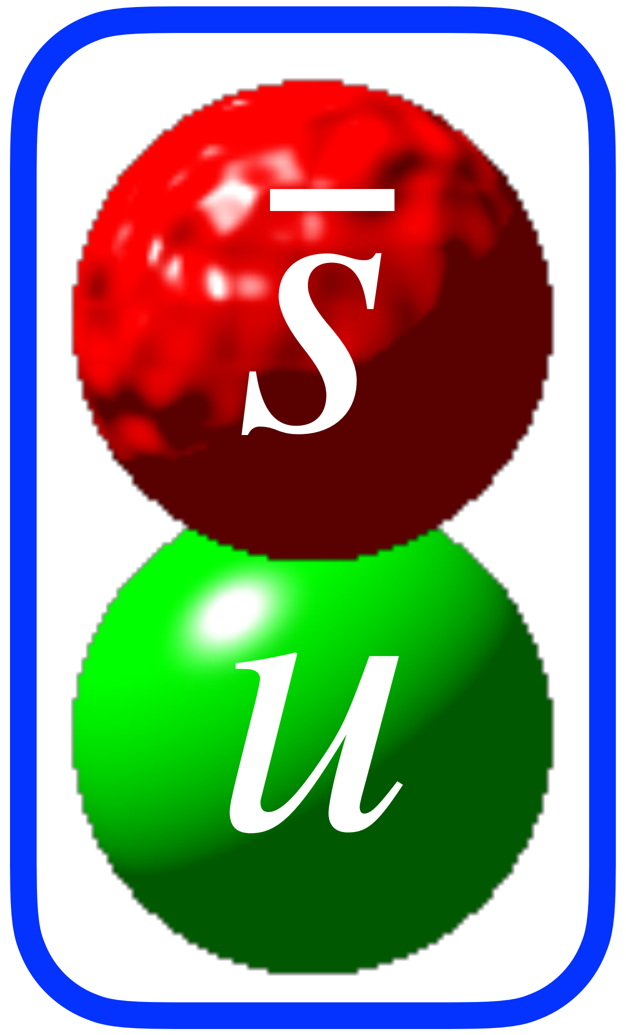
Belle II Physics Week Oct 7, 2025

Contents

- $s \to d\nu\bar{\nu} \to K^+ \to \pi^+\nu\bar{\nu},\ K_L \to \pi^0\nu\bar{\nu}$
  - Experimental status of NA62 and KOTO
  - Prospects of NA62, KOTO, and KOTO II
  - Slides from
    - J. Swallow, K. Ono, K. Massri, T. Nomura, and M. Raggi on KAON2025: https://indico.cern.ch/event/1485702/
    - F. Brizioli, C. Lin on HEF-ex 2025: https://kds.kek.jp/event/55177/

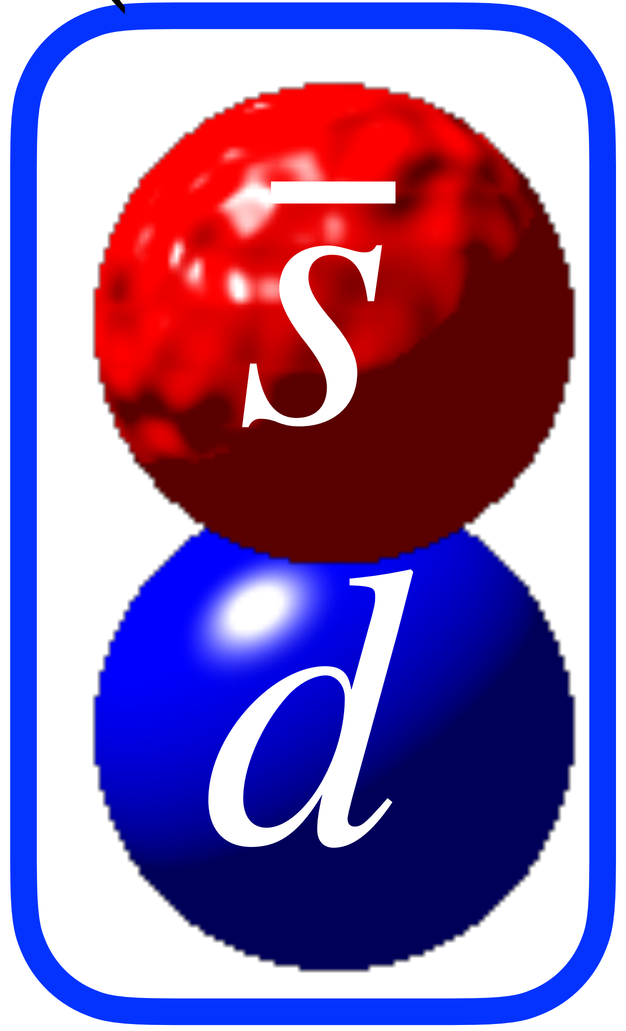
Kaon

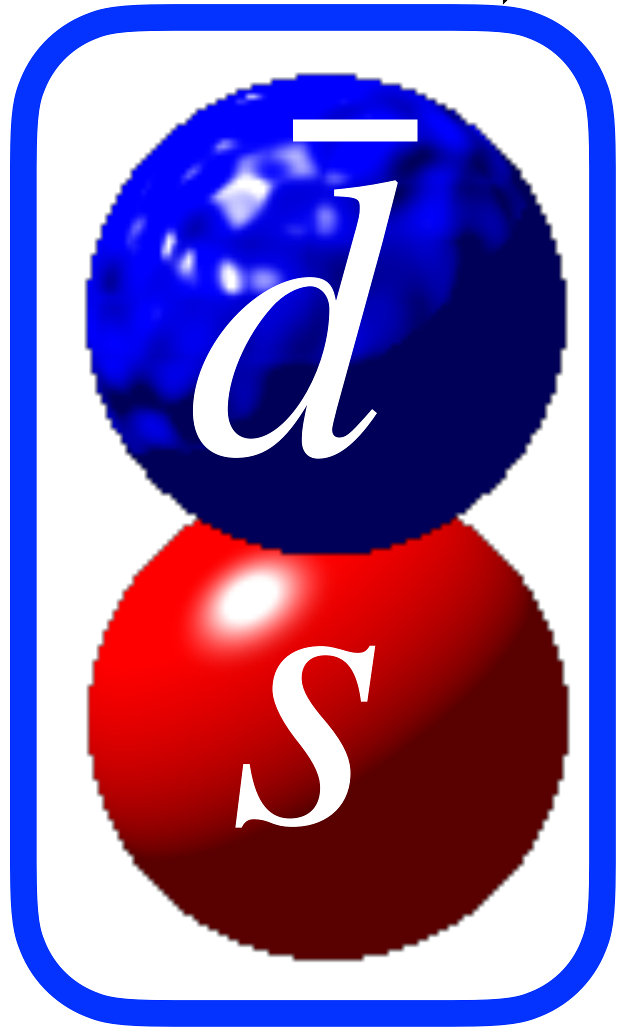
K^+



0.494 GeV, $c\tau = 3.7$ m

$$K_L \sim \frac{1}{\sqrt{2}}\left(K^0 - \bar{K}^0\right)$$

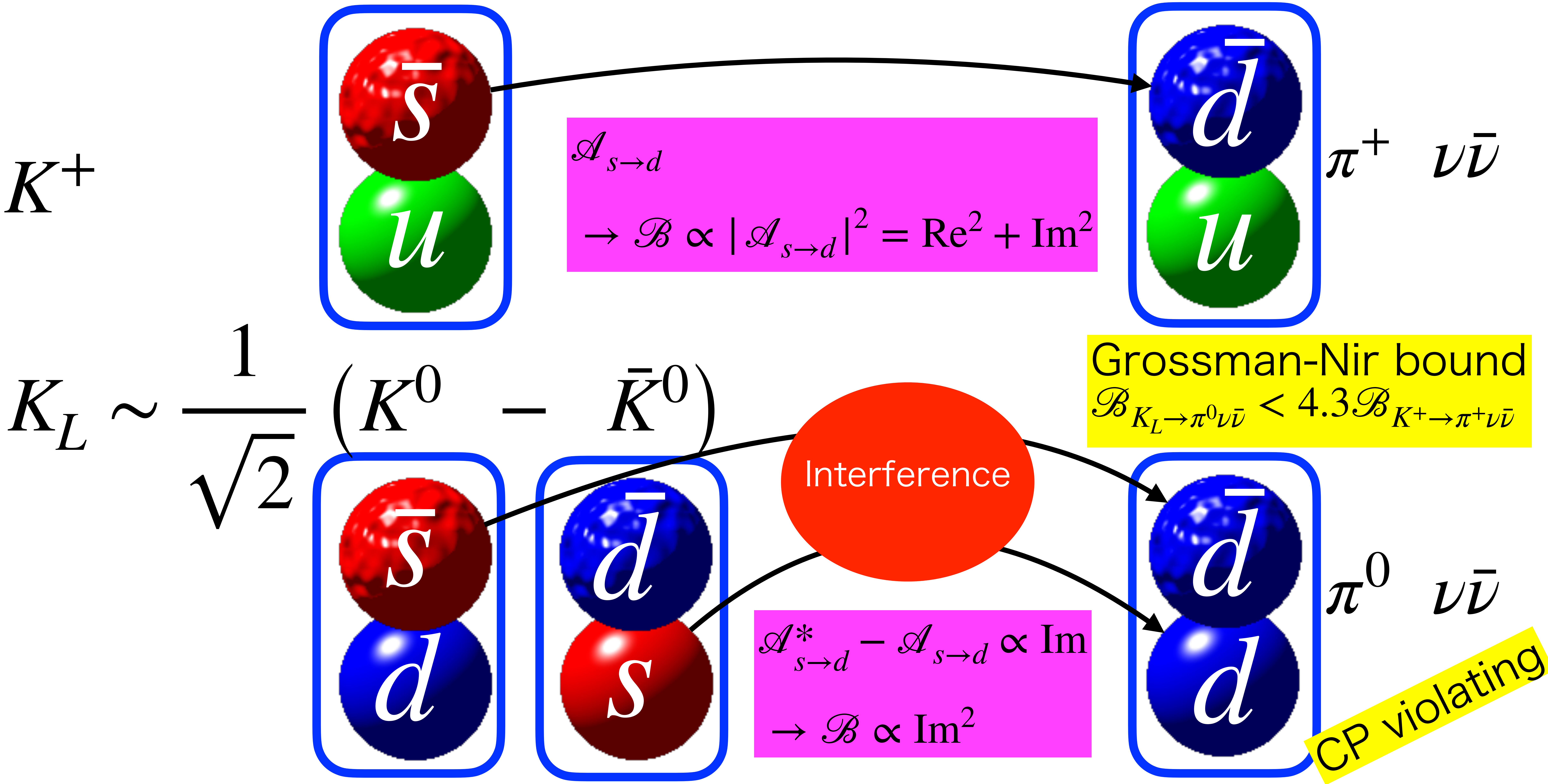




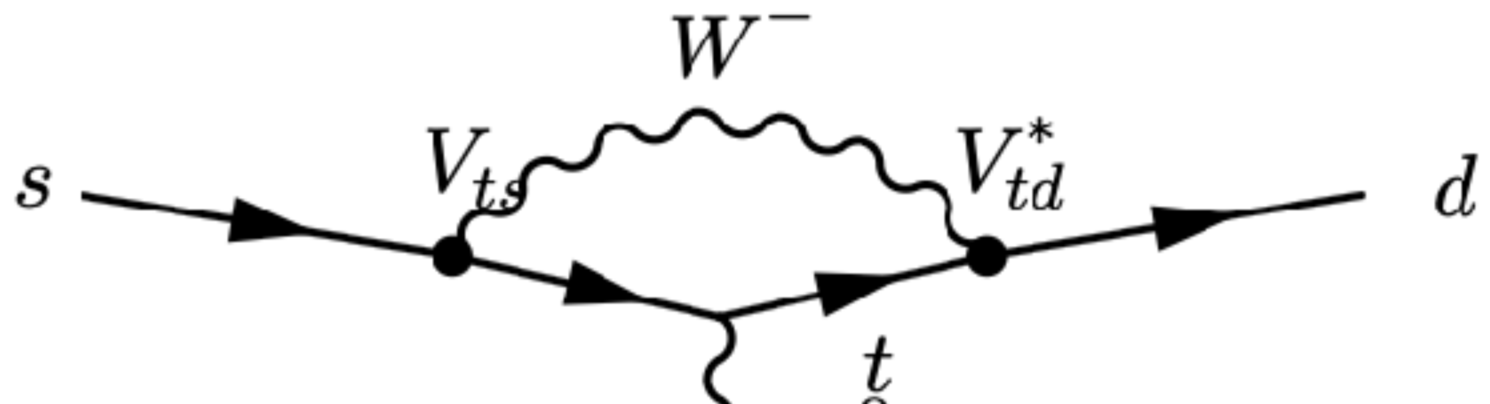
0.498 GeV, $c\tau = 15$ m

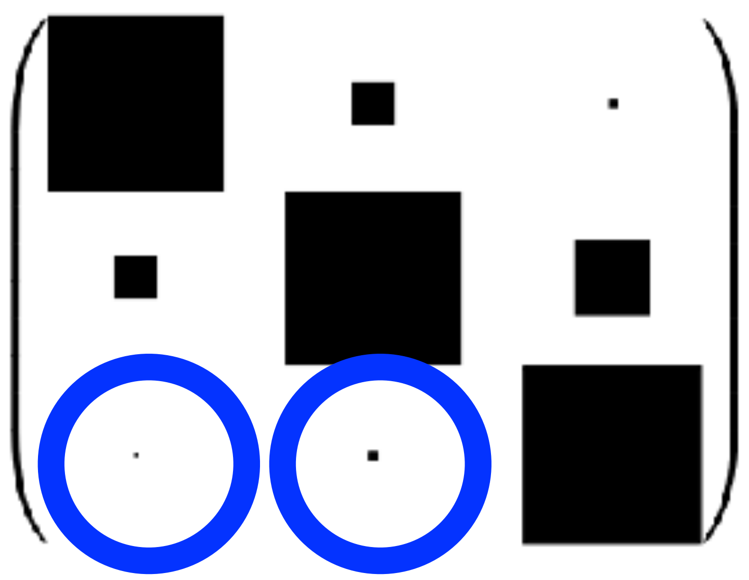
Both are Low mass
  Production is easier
  Decay is simpler
Both are Long lived
  Can be handled with beamline

$$s \to d\nu\bar{\nu}$$



$s \to d\nu\bar{\nu}$





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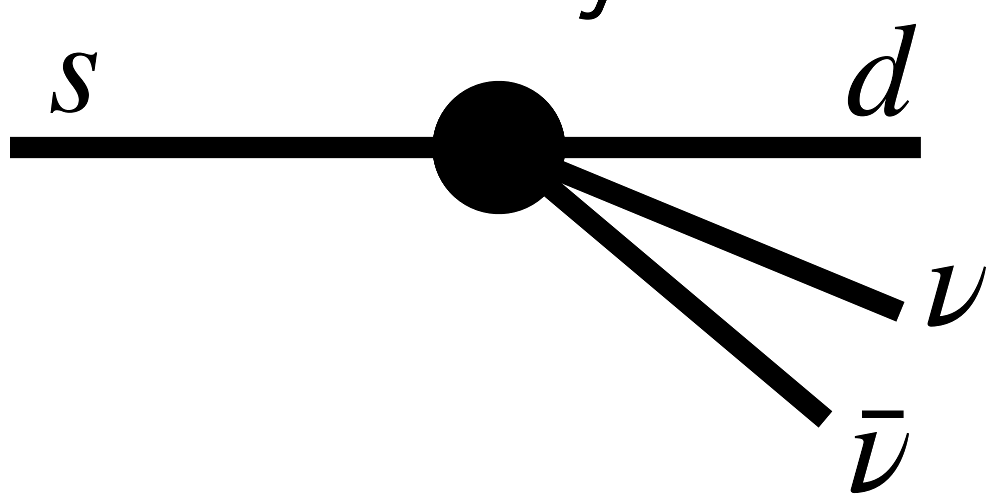
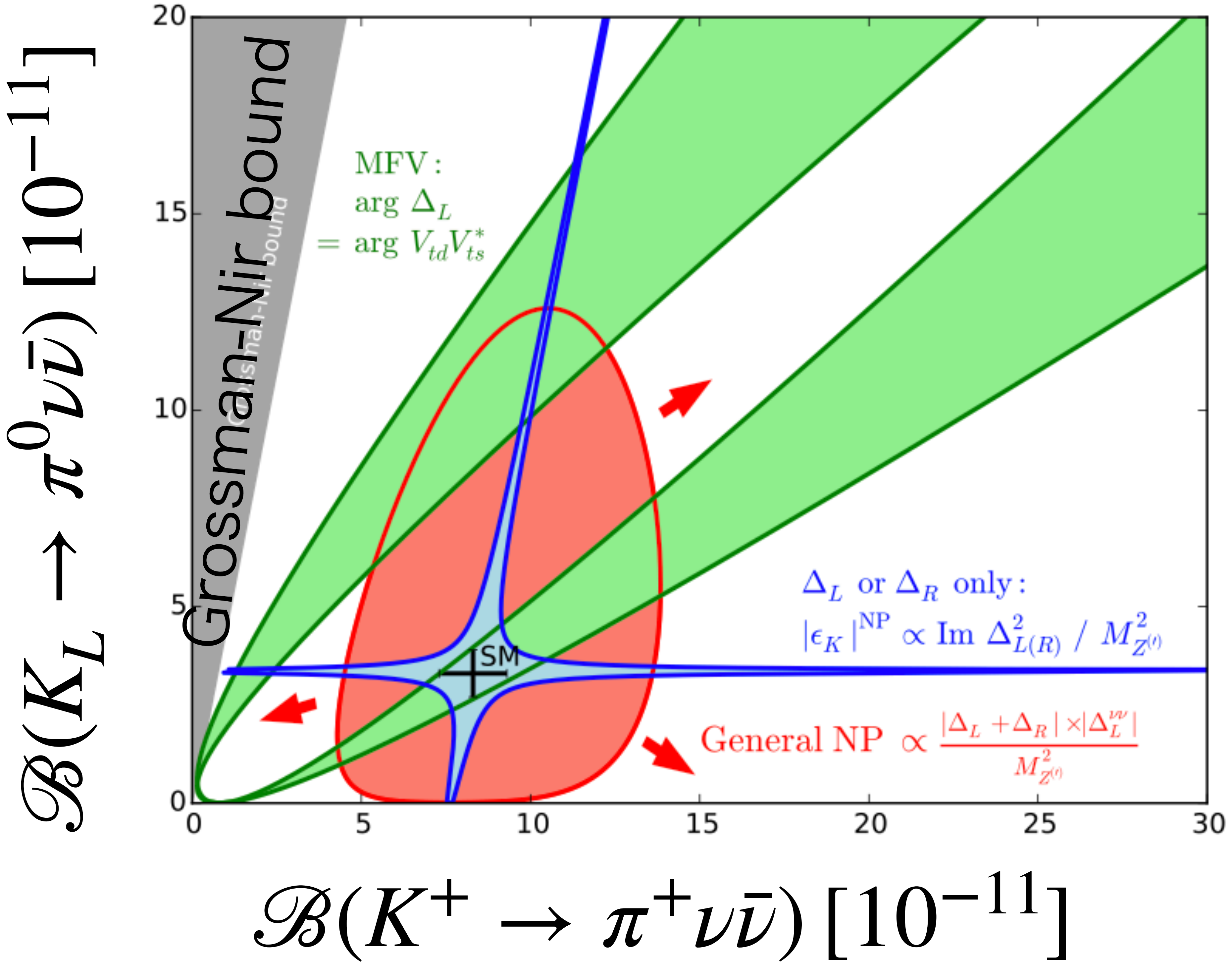
New Physics



Sensitive probe to NP



- NP can contribute as an interference: $\mathscr{A}_{\rm SM} + \mathscr{A}_{\rm NP}$
  on top of suppressed and accurately predicted SM contribution
  - Dominant top quark contribution
    $\to s \to t \to d$ is most suppressed with CKM
  - Dominant short-distance contribution
  - Hadron matrix element can be obtained from tree-level decays.
- NP may give a correlation to other flavor observables.
- NP may have LFU violation from $\nu_i\bar{\nu}_i$ or LNV from $\nu\nu$, or $s \to dX$

Mode	SM Branching Ratio [1]	SM Branching Ratio [2]
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$
$K_L \to \pi^0\nu\bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$

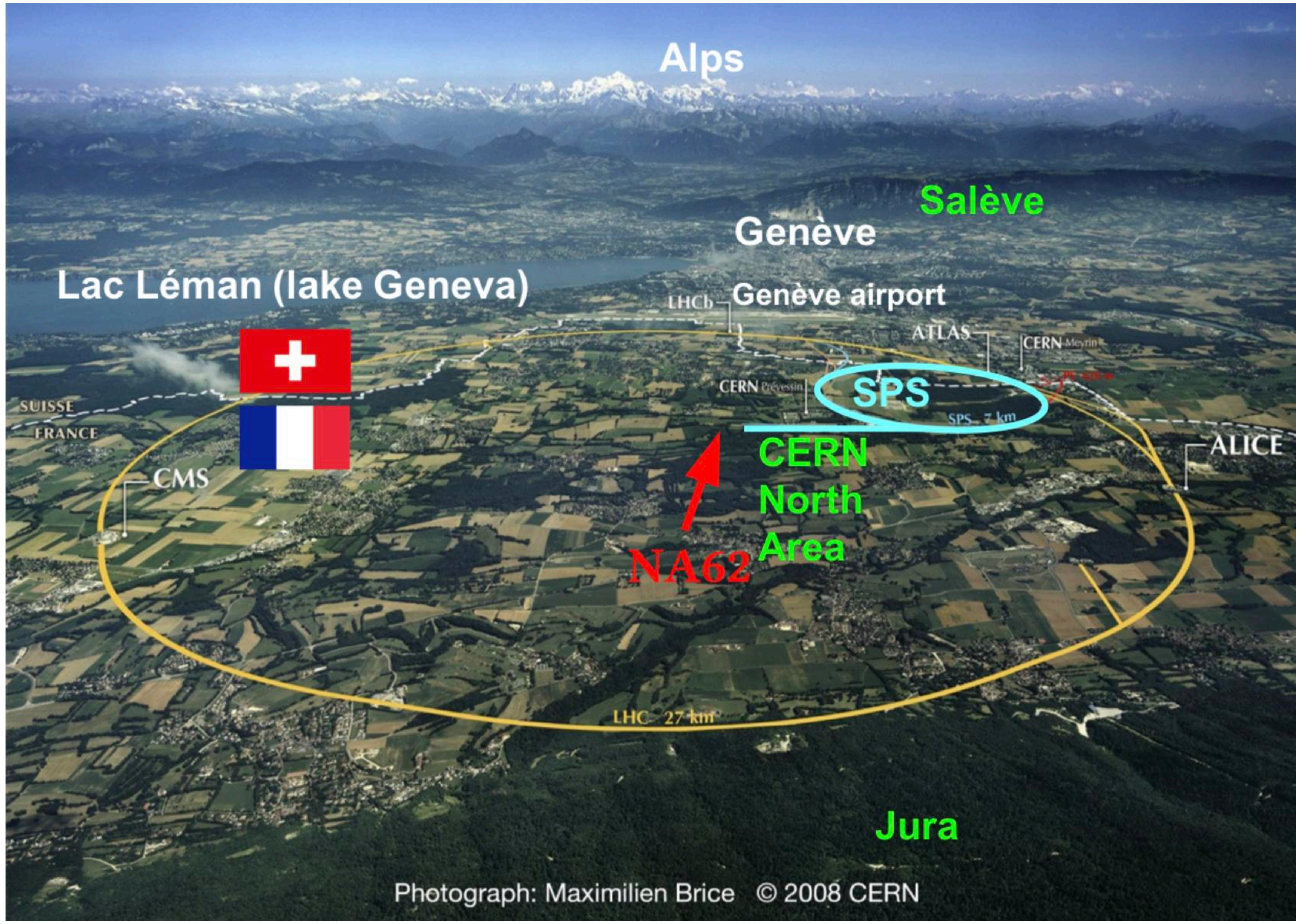
Recent SM calculations [1:Buras et al. EPJC 82 (2022) 7, 615][2:D'Ambrosio et al. JHEP 09 (2022) 148]
(Differences in SM calculations from choice of CKM parameters: see [Eur.Phys.J.C 84 (2024) 4, 377])

5-10% precision

NA62 experiment: $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu})$

The NA62 experiment at CERN

~200 collaborators from ~30 institutions.



- **Primary goal: measurement of** $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$
- **New Technique:** K^+ decay-in-flight
- **Run1 results:** [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- **Broader physics programme:**
  - **Precision measurements of kaon and pion decays**
  - **HNL and LNV/LFV searches in kaon decays**
  - **Hidden Sector searches with kaons and in dump mode**
- **Data taking**
  - 2016 Commissioning + Physics run (45 days).
  - 2017 Physics run (160 days).
  - 2018 Physics run (217 days).
  - 2021 Physics run (85 days [10 beam dump]). } Latest result
  - 2022 Physics run (215 days). }
  - 2023 Physics run (150 days [10 beam dump]).
  - 2024 Physics run (204 days [12 beam dump, 7 low int.]).
  - 2025 Physics run (~210 days ongoing, April-November)
  - 2026 Physics run (~120 days foreseen, starting in March)

	LS2 (upgrades)	Latest result			LS3

2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

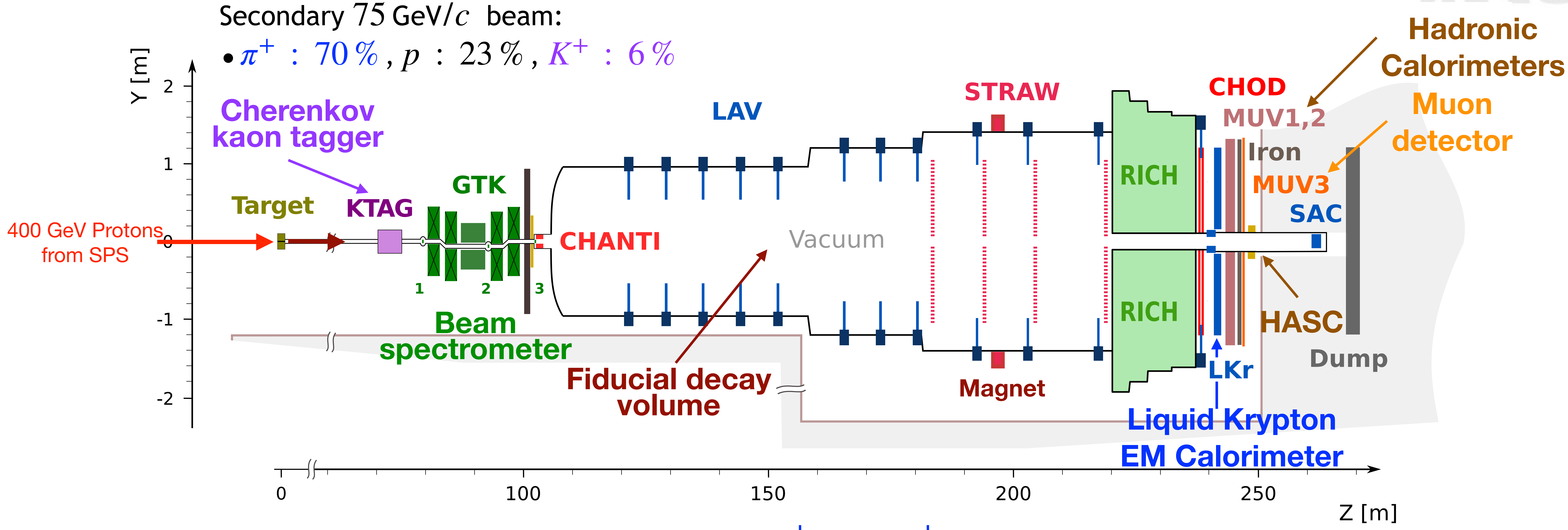
Latest result: JHEP 02 (2025) 191

NA62 beamline & detector

[JINST 12 (2017) 05, P05025]

Secondary 75 GeV/c beam:

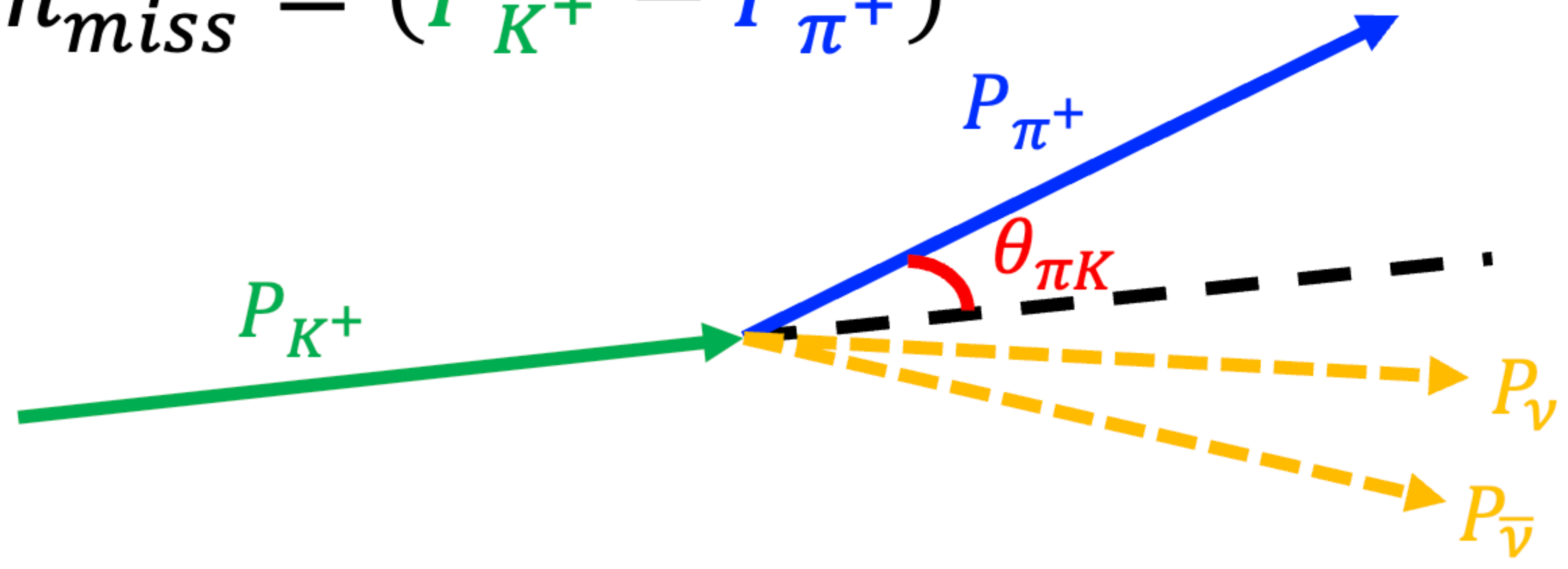
- π^+ : 70 %, p : 23 %, K^+ : 6 %

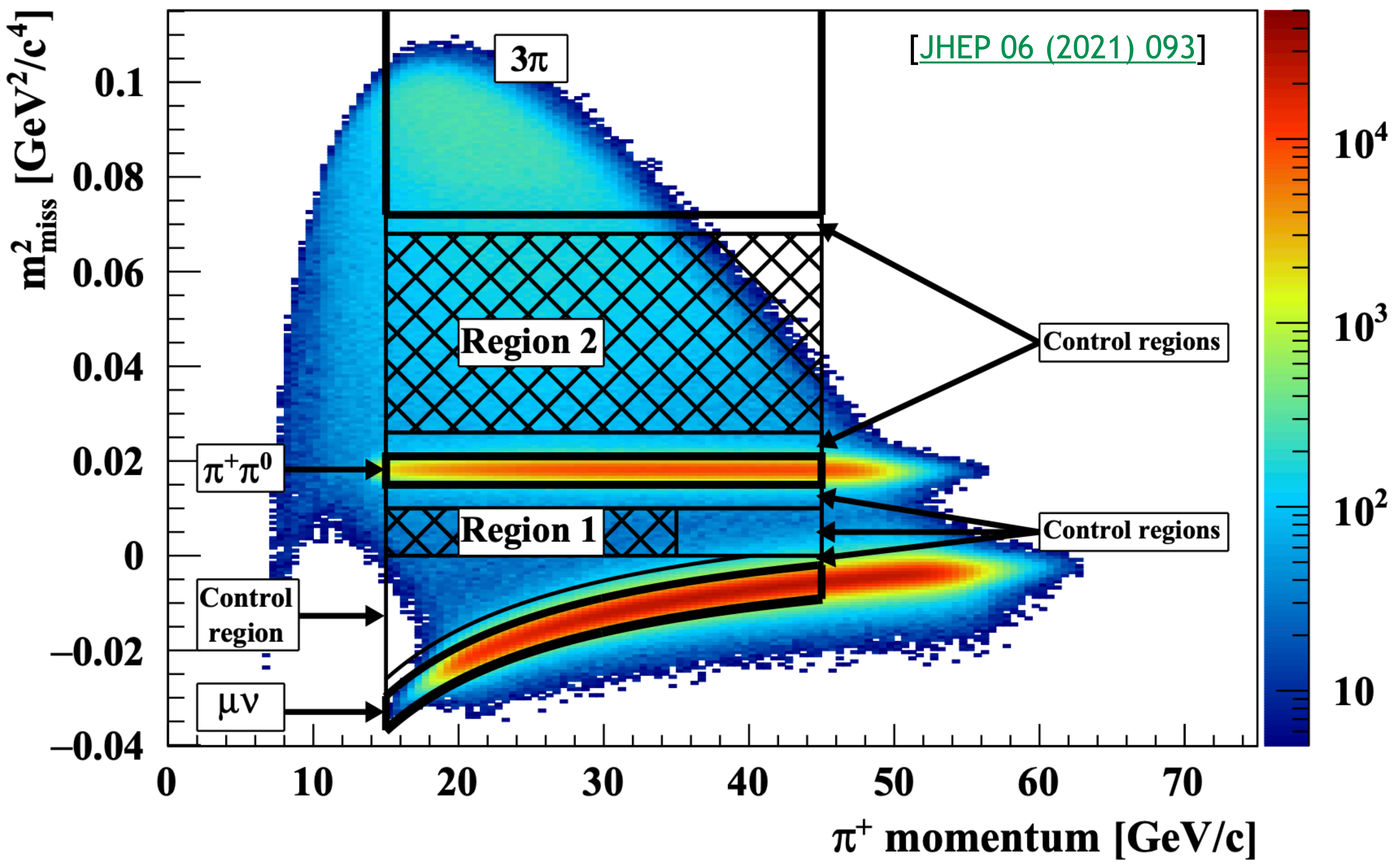


- Designed & optimised for study of $K^+ \to \pi^+ \nu \bar{\nu}$:
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV,LKr,IRC,SAC (γ)

Kinematics

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





π^+ momentum range: 15—45 GeV/c

NA62 Performance Keystones:

- $\mathcal{O}(100)\, ps$ timing between detectors
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $> 10^7$ muon rejection
- $> 10^7$ rejection of π^0 from $K^+ \to \pi^+\pi^0$ decays

Decay mode	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	$(63.56 \pm 0.11)\,\%$
$K^+ \to \pi^+\pi^0$	$(20.67 \pm 0.08)\,\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\,\%$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$ [SM]

Buras et al. EPJC 82 (2022) 7, 615

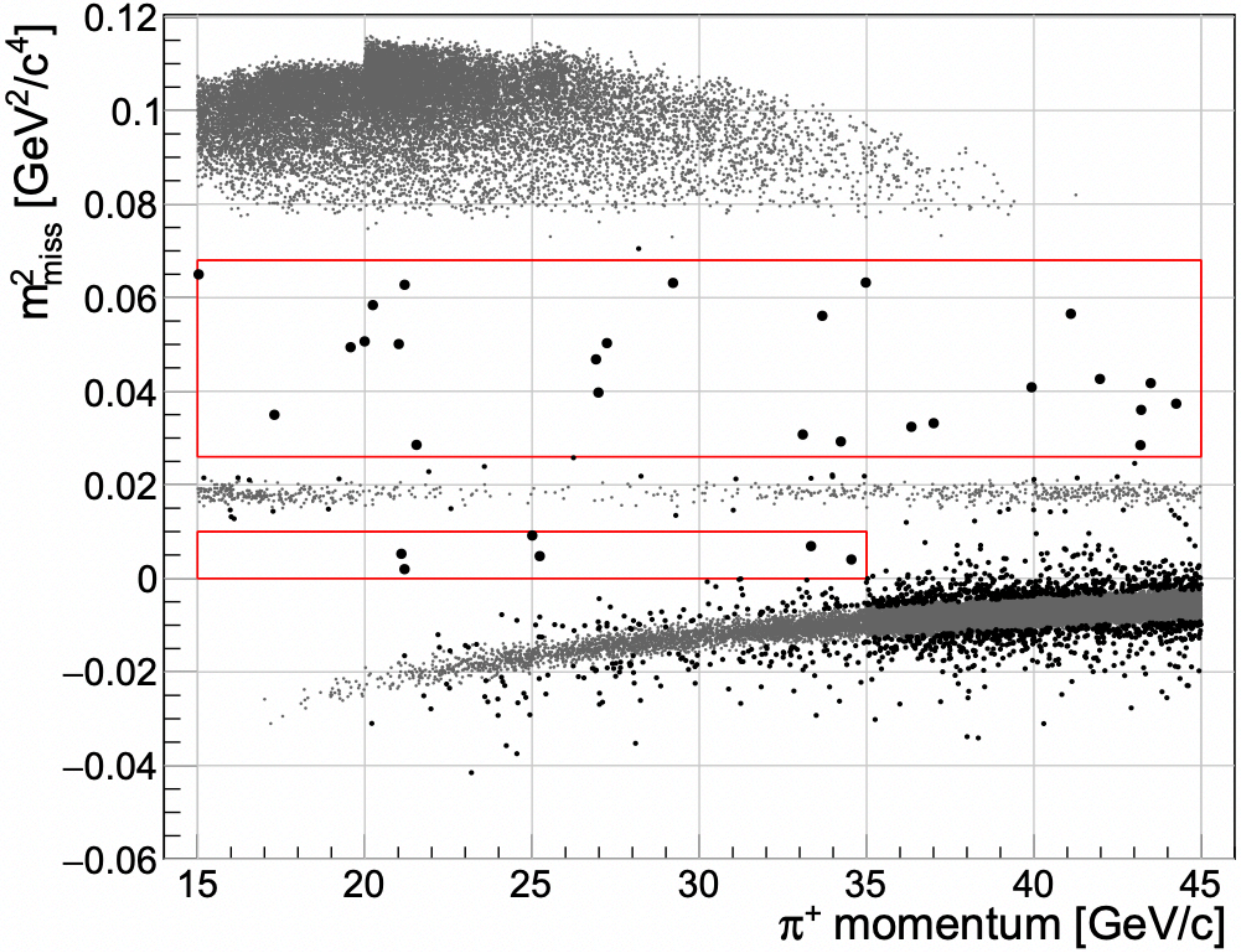
Signal regions

Expected SM signal, $N_{\pi\nu\bar{\nu}}^{SM} \approx 10$

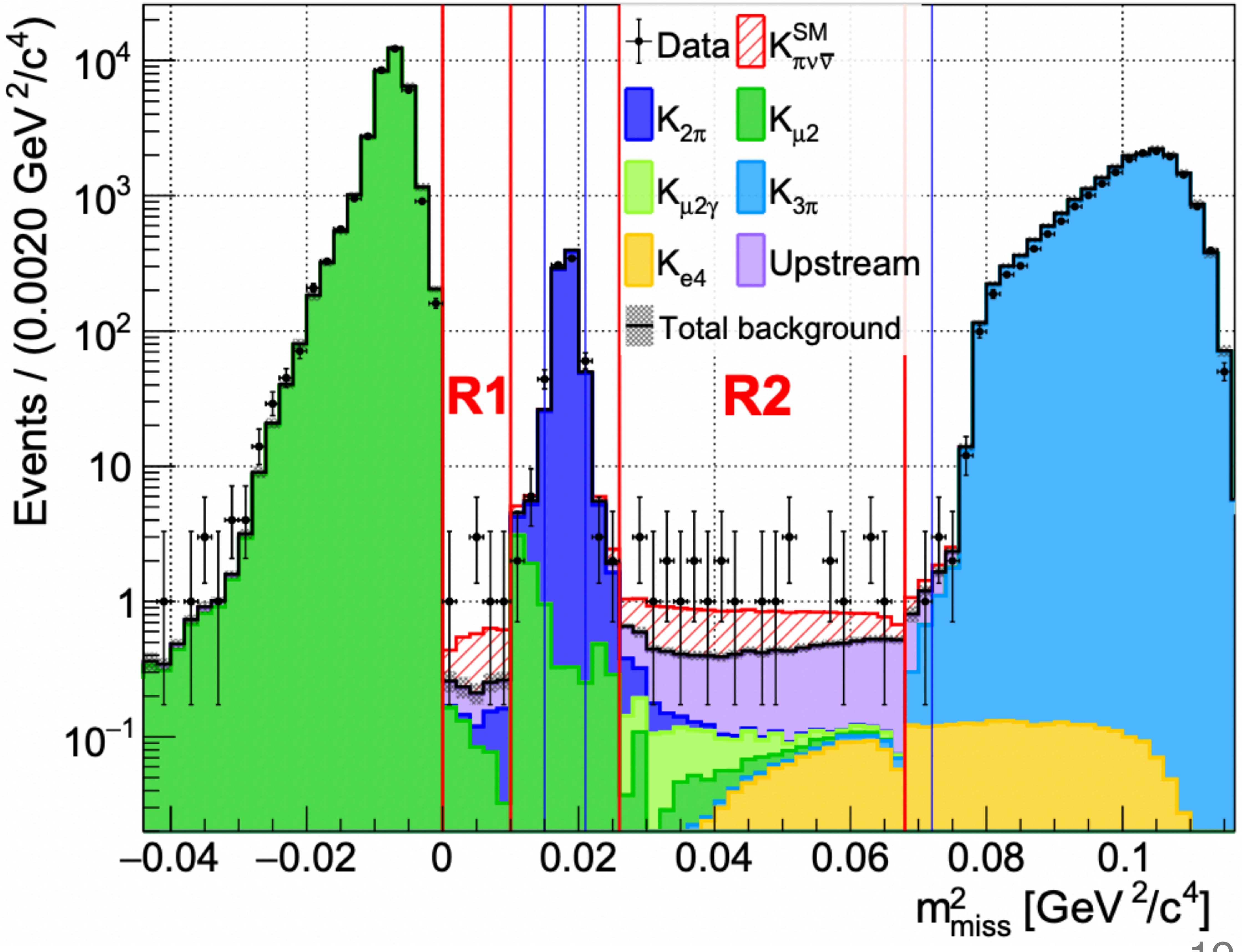
Expected background, $N_{bg} = 11.0^{+2.1}_{-1.9}$

Observed, $N_{obs} = 31$

2021—22 data



1D projection with differential background predictions & SM signal expectation [not a fit]:



Summary of expectations

Backgrounds

$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \pi^+\pi^0$	0.76 ± 0.04
$K^+ \to \pi^+\pi^0\gamma$	0.07 ± 0.01
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \mu^+\nu$	0.87 ± 0.19
$K^+ \to \mu^+\nu\gamma$	0.82 ± 0.43
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$ (From MC)	$0.89^{+0.34}_{-0.28}$
$K^+ \to \pi^0\ell^+\nu$ (From MC)	< 0.001
$K^+ \to \pi^+\gamma\gamma$ (From MC)	0.01 ± 0.01
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

Signal Sensitivity

$$\mathcal{B}_{SES} = (0.85 \pm 0.03) \times 10^{-11}$$

$$N^{SM,exp}_{\pi\nu\bar{\nu}} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}}$$

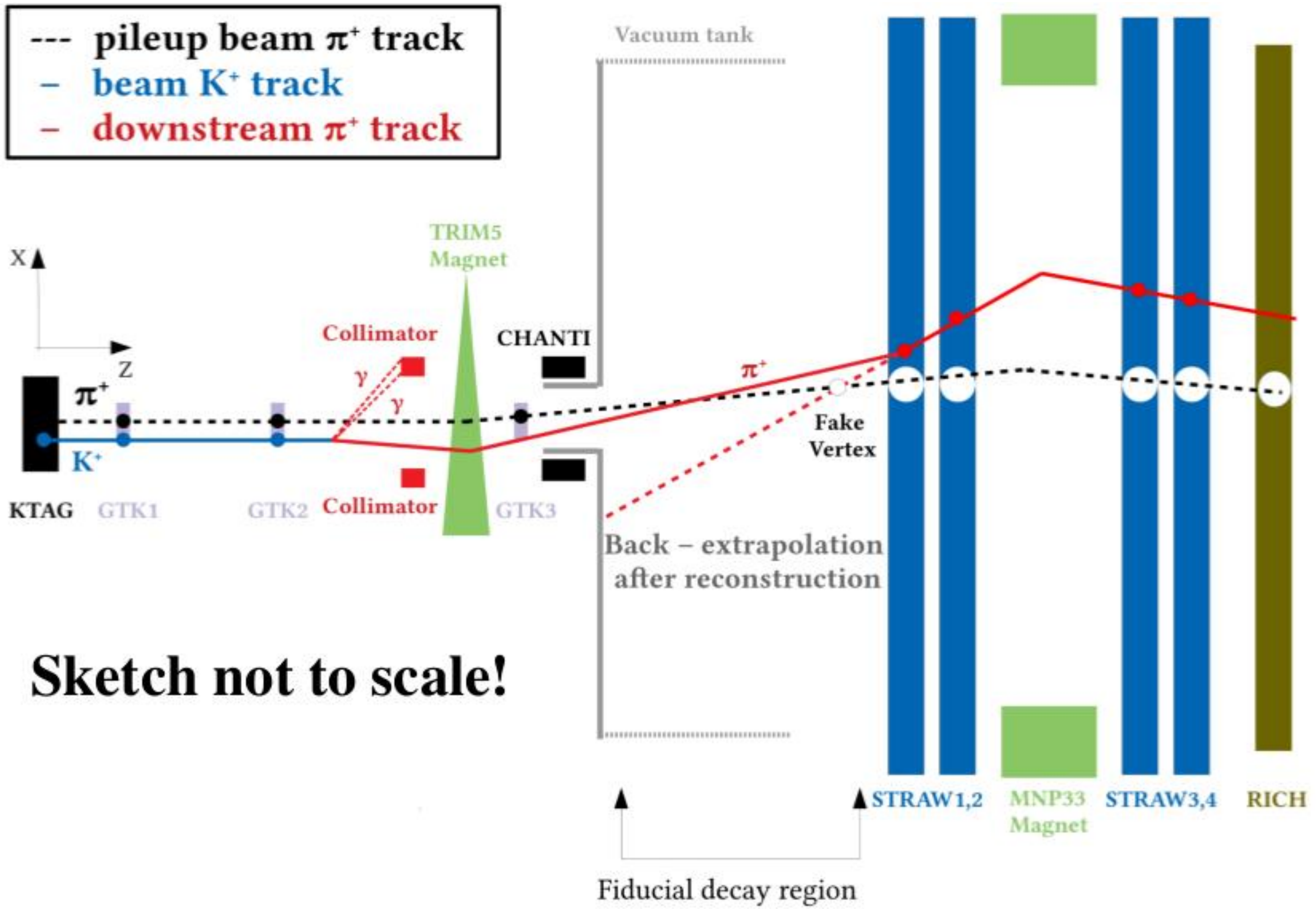
Assuming $\mathcal{B}^{SM}_{\pi\nu\bar{\nu}} = 8.4 \times 10^{-11}$:
2021–22: $N_{\pi\nu\bar{\nu}} = 9.91 \pm 0.34$
c.f. 2016–18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

→ Expected signal doubled by including 2021–22 data

- $N^{SM}_{\pi\nu\bar{\nu}}$ per SPS spill: 2.5×10^{-5} in 2022
  - c.f. 1.7×10^{-5} in 2018. ⇒ **signal yield increased by 50%.**
- Sensitivity for BR $\sim \sqrt{S+B}/S = 0.5$
  - **Similar but improved with respect to 2018 analysis for same amount of data.**

Upstream background mechanism

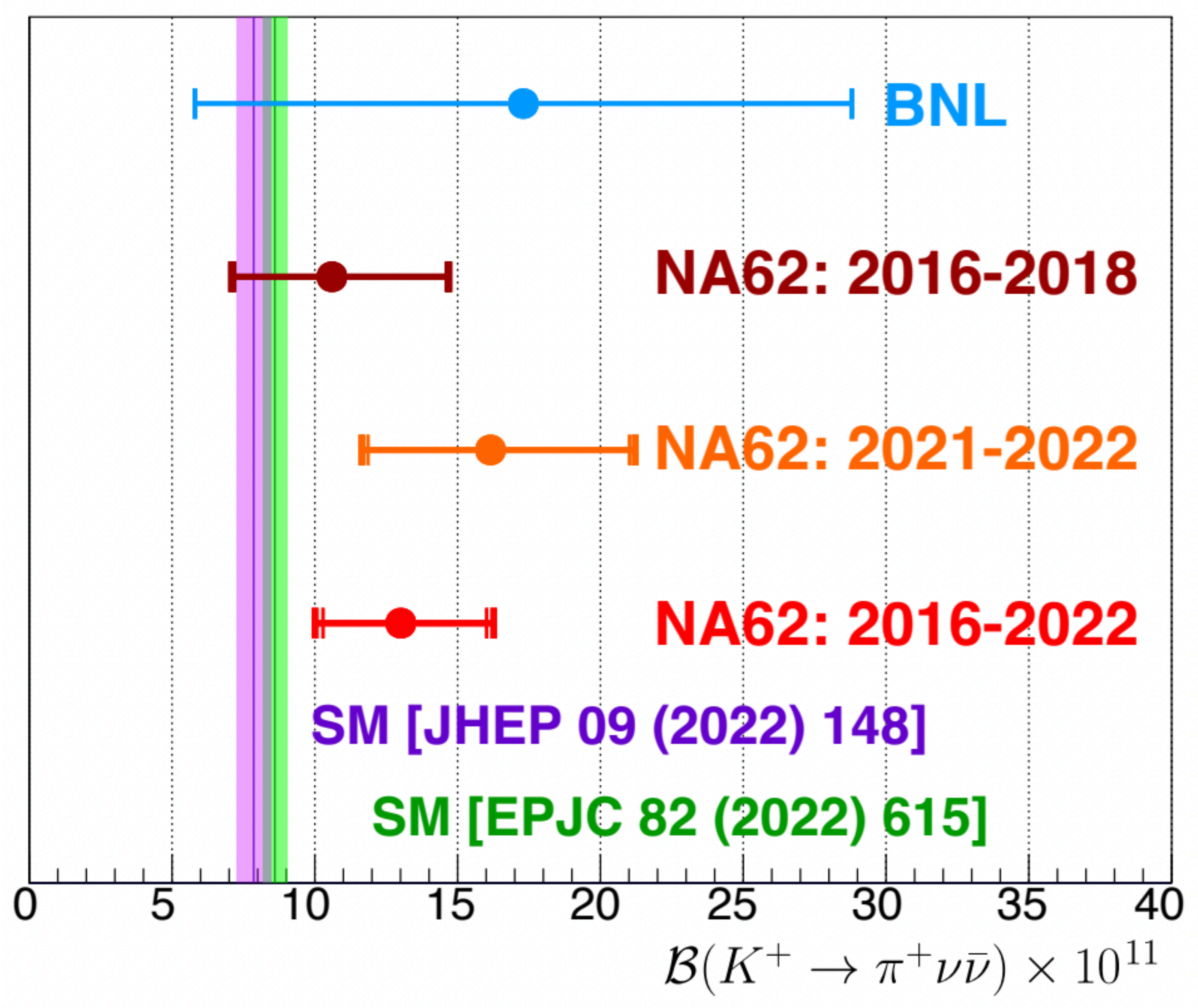
- A kaon decays upstream the fiducial decay region
- Only a π+ enters the fiducial decay region
- There is an in-time pileup beam particle (in GTK)
- The upstream π+ is scattered in the first STRAW chamber, and a fake vertex in the fiducial decay region is reconstructed

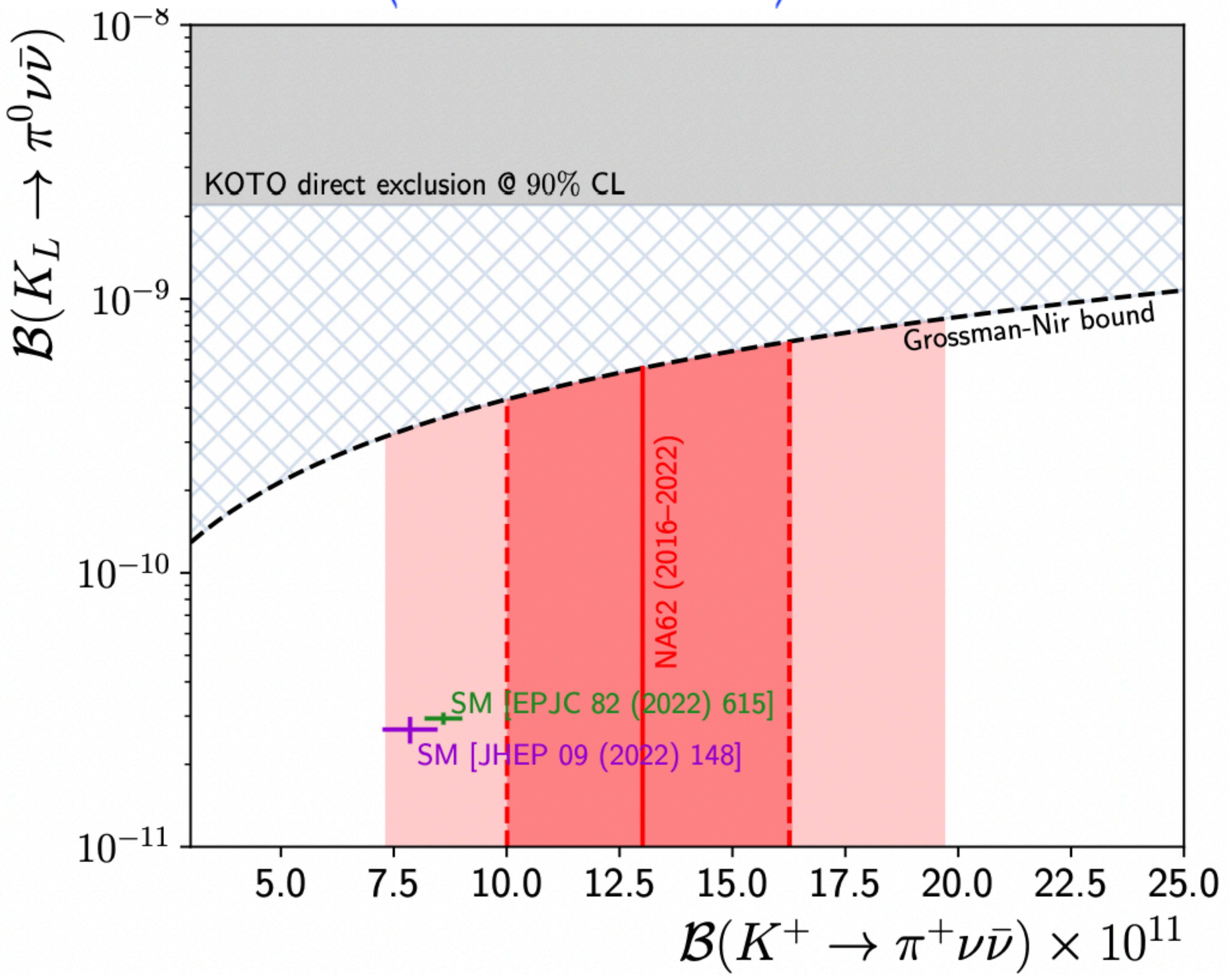


Sketch not to scale!

Results in context

$\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-3.0}) \times 10^{-11} = \left(13.0 \left(^{+3.0}_{-2.7}\right)_{stat} \left[^{+1.3}_{-1.3}\right]_{syst}\right) \times 10^{-11}$





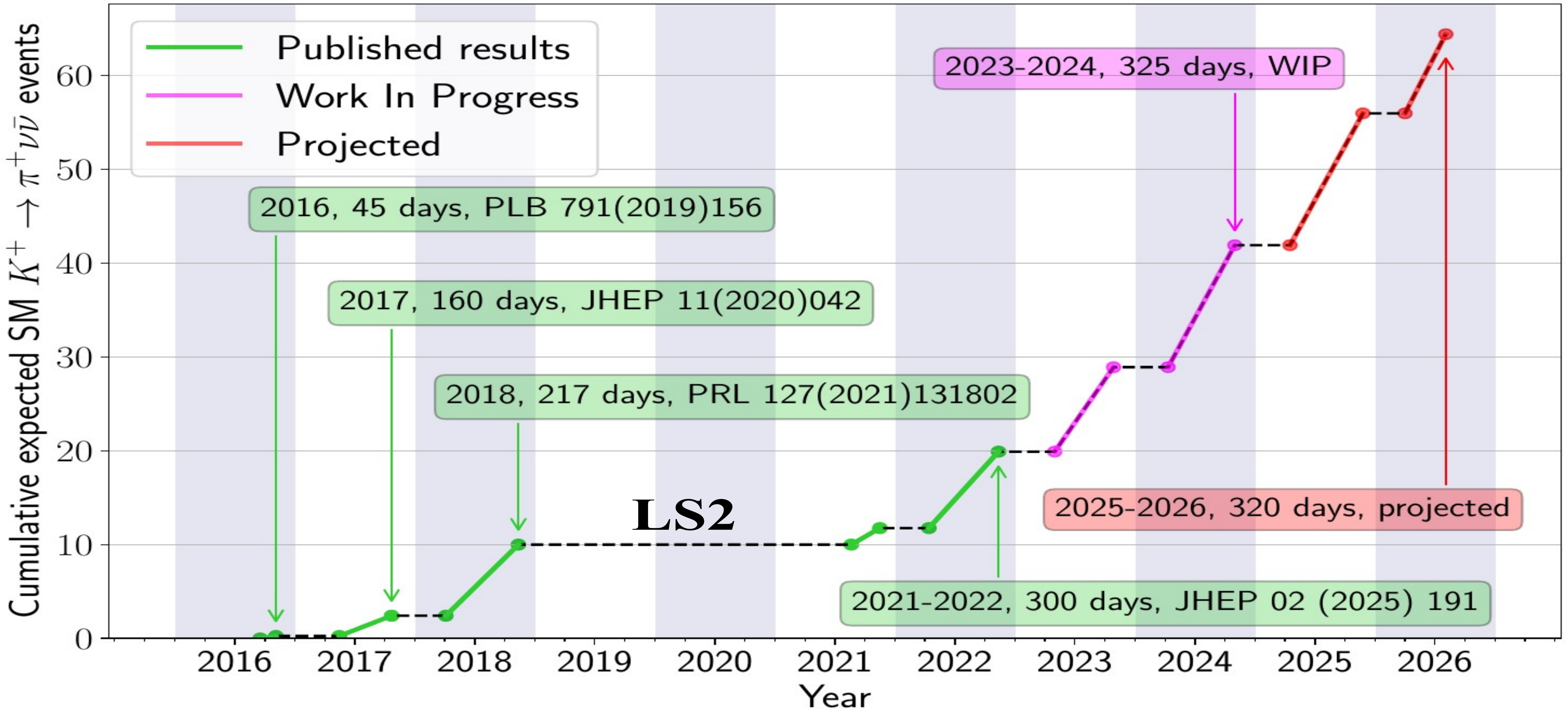
- NA62 results are consistent. Fractional uncertainty decreased: 40% to 25%
- Central value moved up (now 1.5—1.7σ above SM)
- Bkg-only hypothesis rejected with significance Z>5
  - **Observation of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay with BR consistent with SM prediction, within 1.7σ**
  - **Need full NA62 data-set to clarify SM agreement or tension**

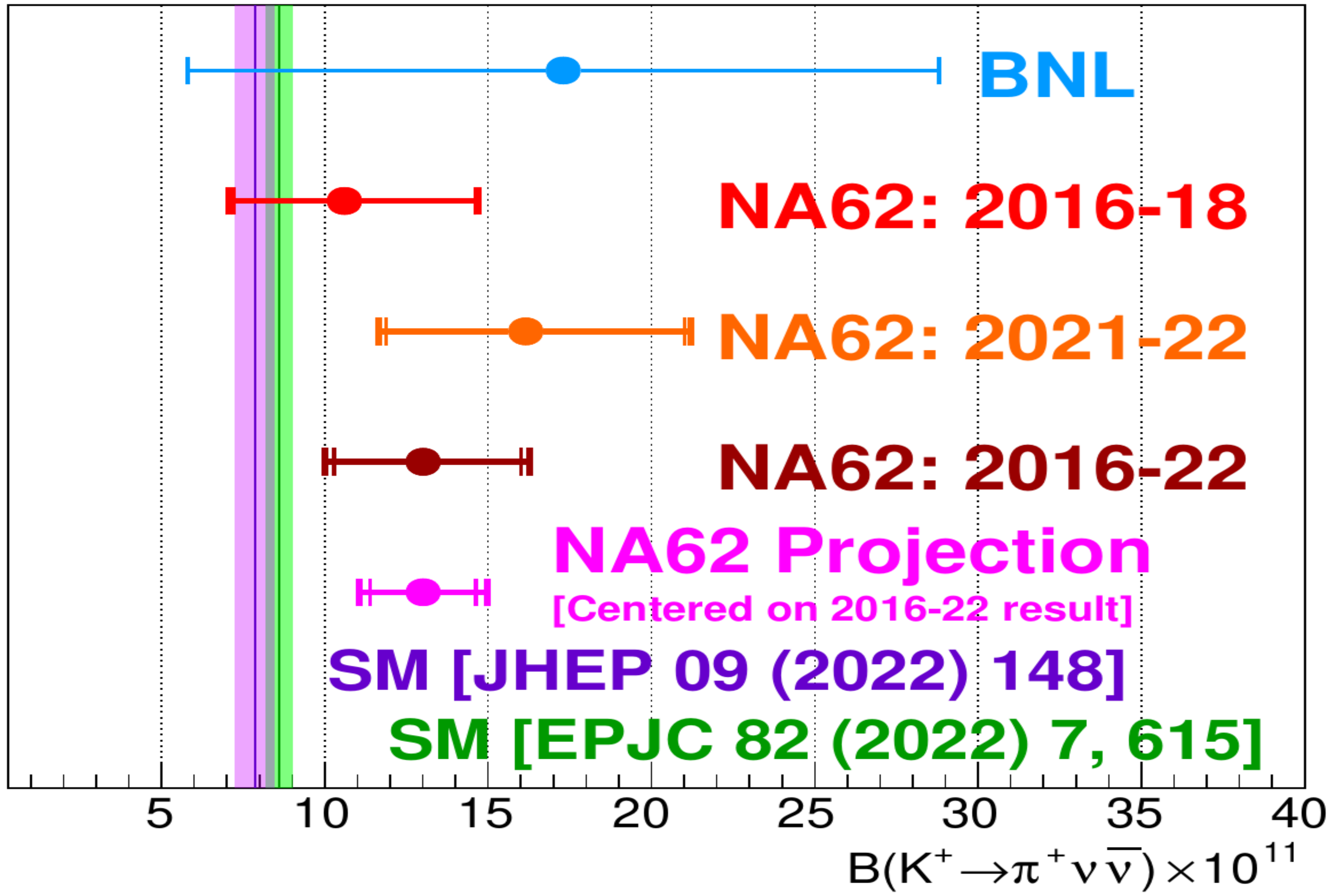
$K^+\to\pi^+\nu\bar{\nu}$: Final dataset projection

Latest $K^+\to\pi^+\nu\bar{\nu}$ result (2016-2022 data) discussed in detail in J. Swallow's talk

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



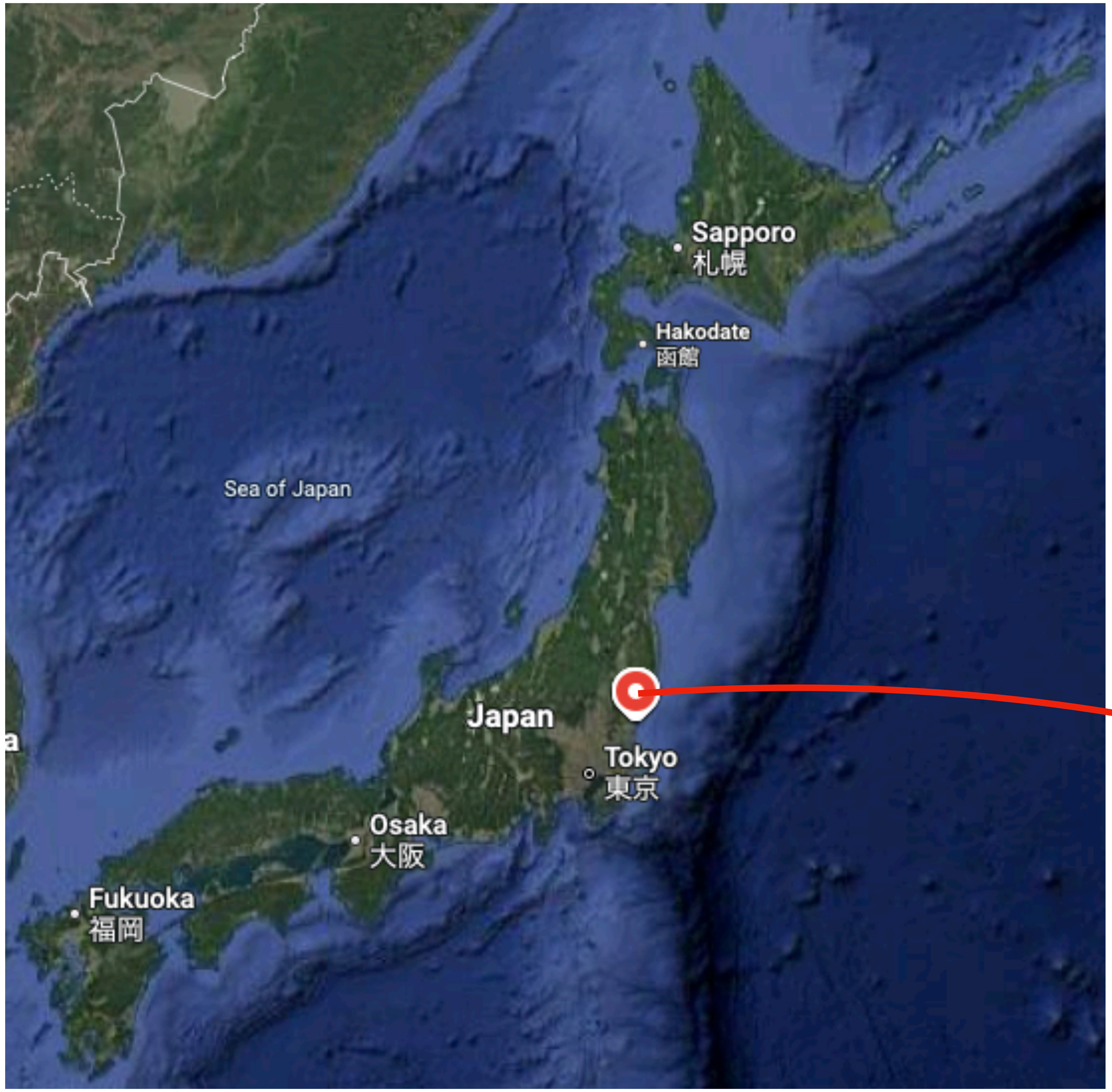


Expect BR($K^+\to\pi^+\nu\bar{\nu}$) uncertainty < 20% (stats + analysis improvements)

KOTO experiment: $\mathscr{B}(K_L \to \pi^0 \nu \bar{\nu})$

J-PARC KOTO experiment

Search for $K_L \to \pi^0 \nu \bar{\nu}$ at J-PARC



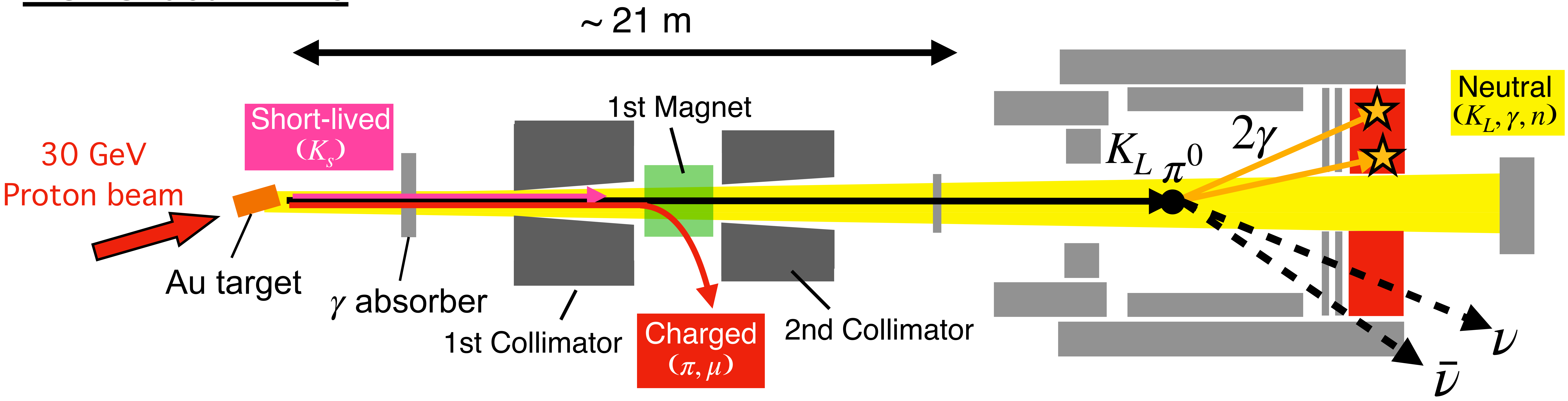
Japan Korea Taiwan U.S.

Photo@Collaboration meeting on June 2025

K. Ono

Experimental principle

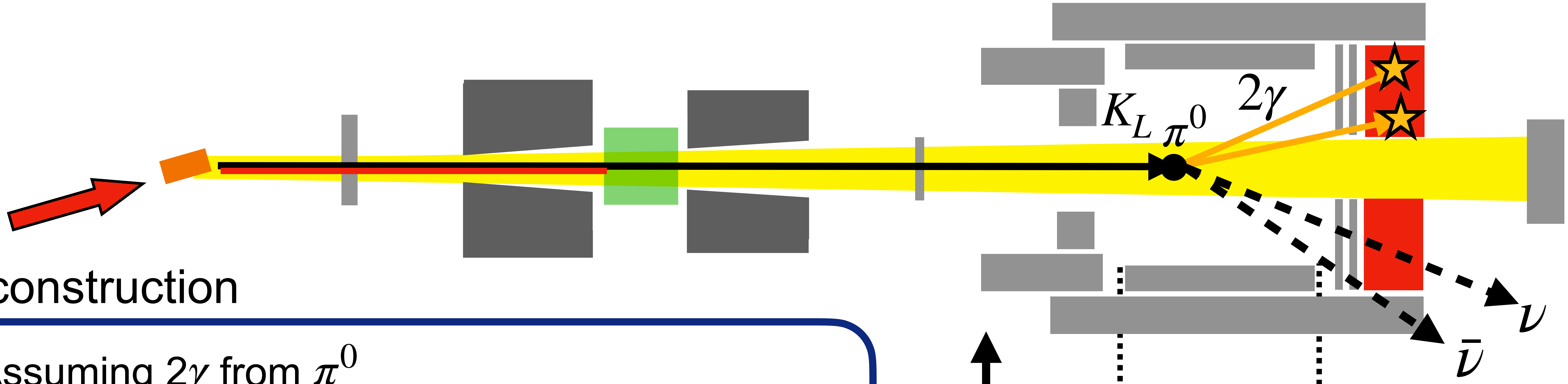
KOTO beam line



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 $\nu\bar{\nu}$

Event reconstruction

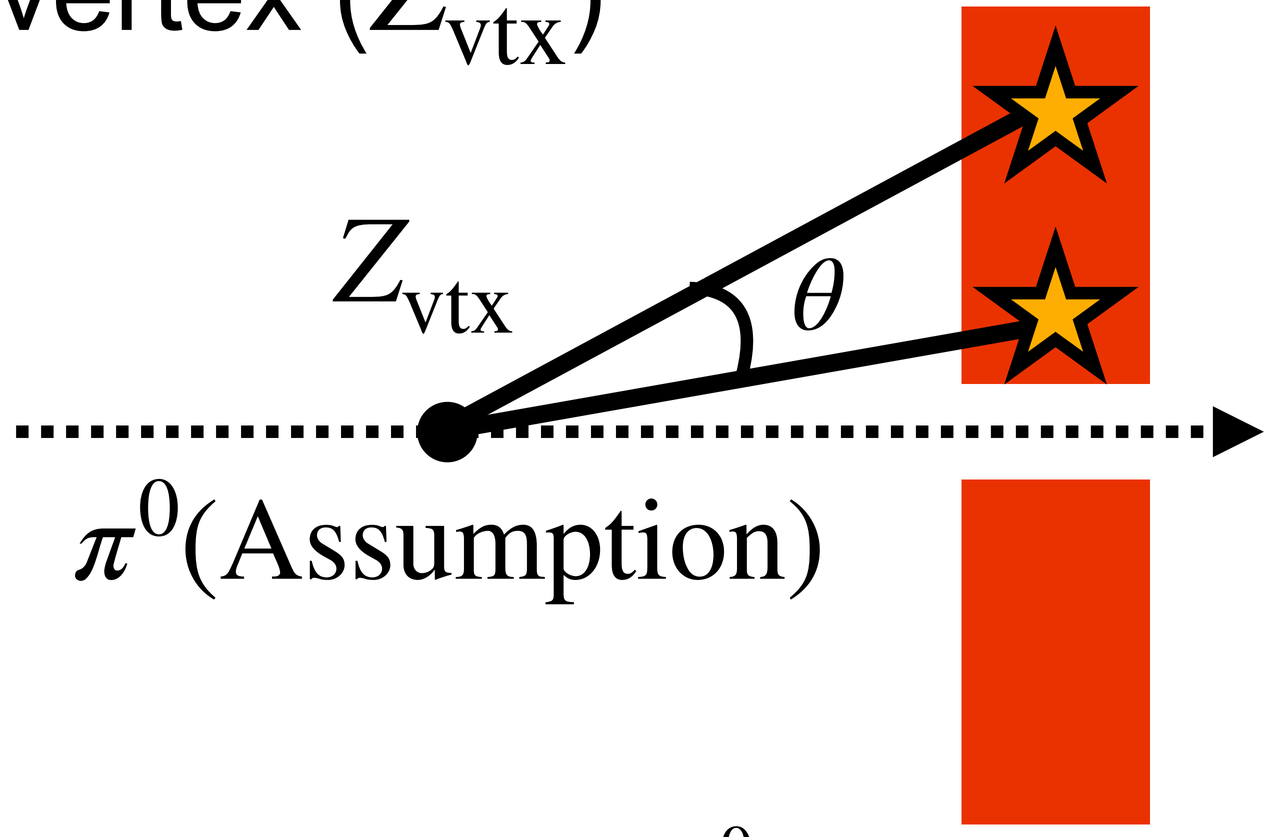


Reconstruction

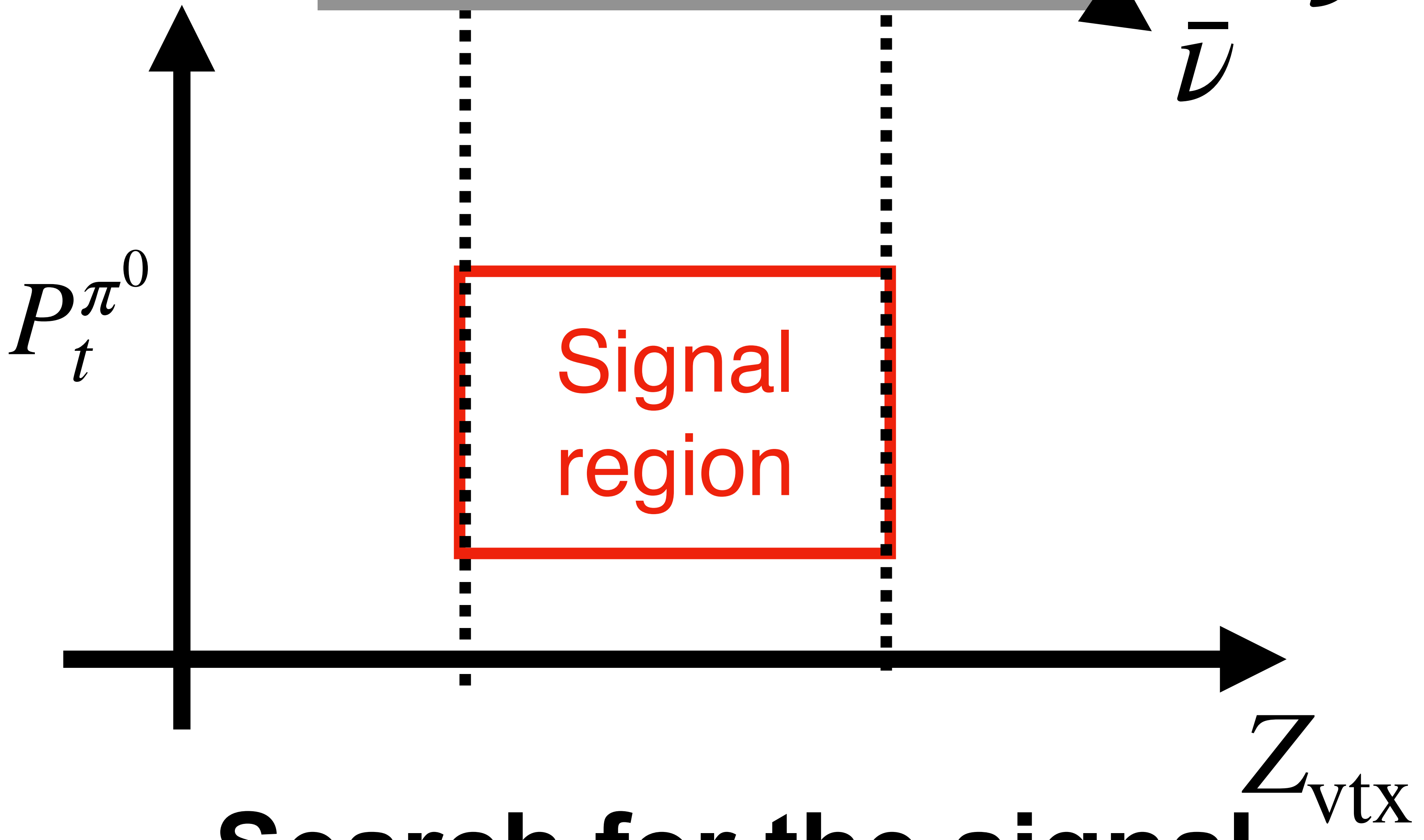
- Assuming 2γ from π^0

  → Calculate Z vertex (Z_{vtx})

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



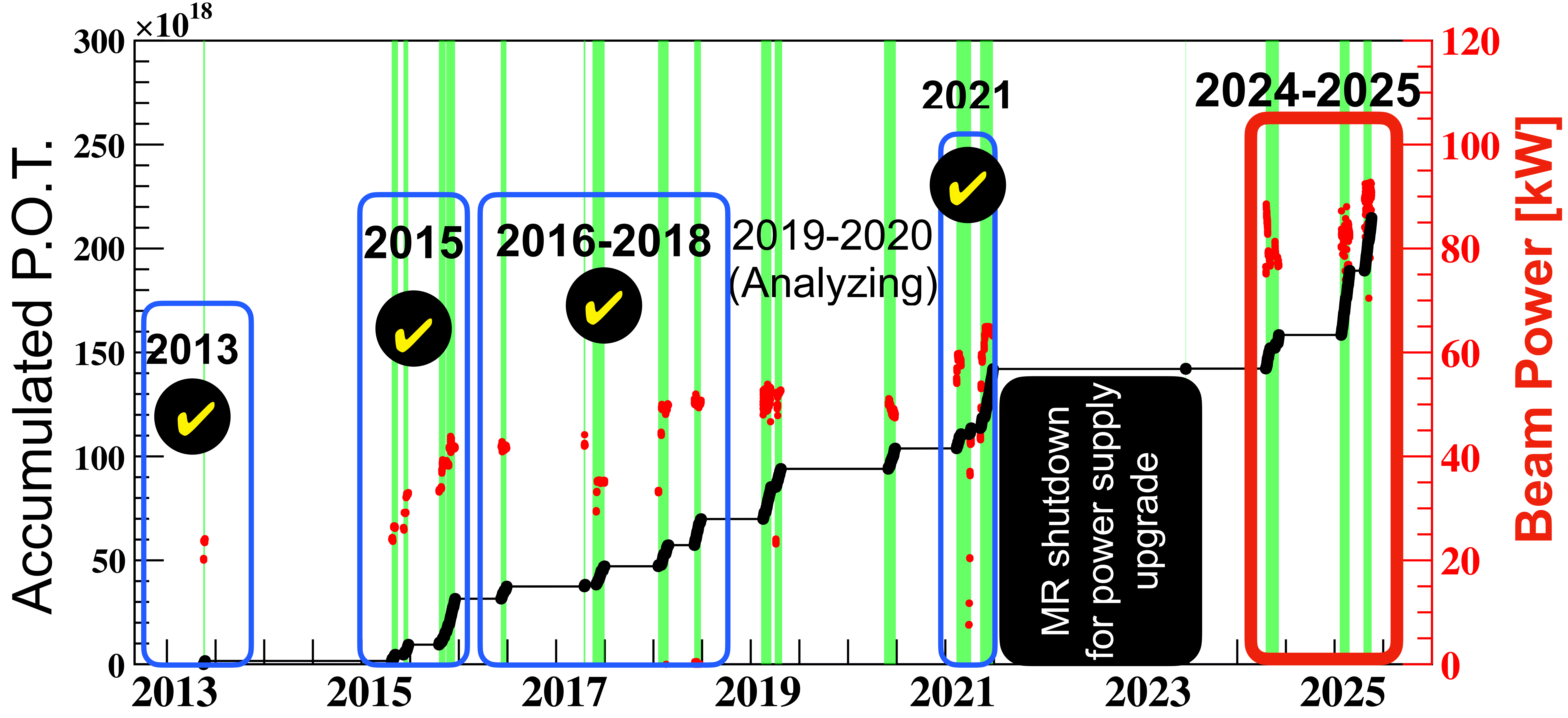
- Calculate π^0 transverse momentum ($p_t^{\pi^0}$)



Search for the signal in P_T vs Z plane

K. Ono

History of data taking



- Beam power gradually increased : 64kW(2021) → 80kW (2024) → 92kW (2025)

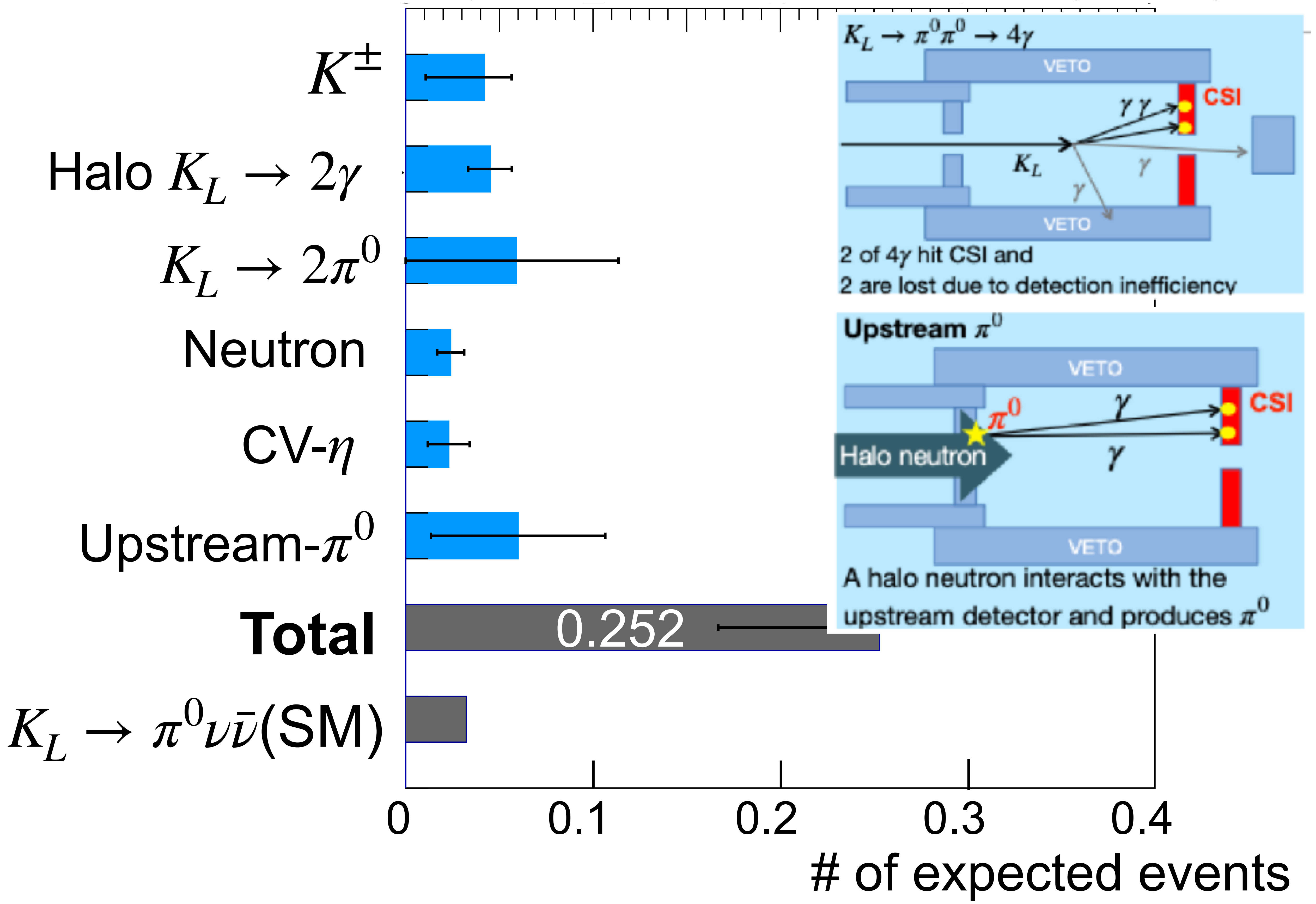
Higher repetition cycle
5.2 s → 4.2 s

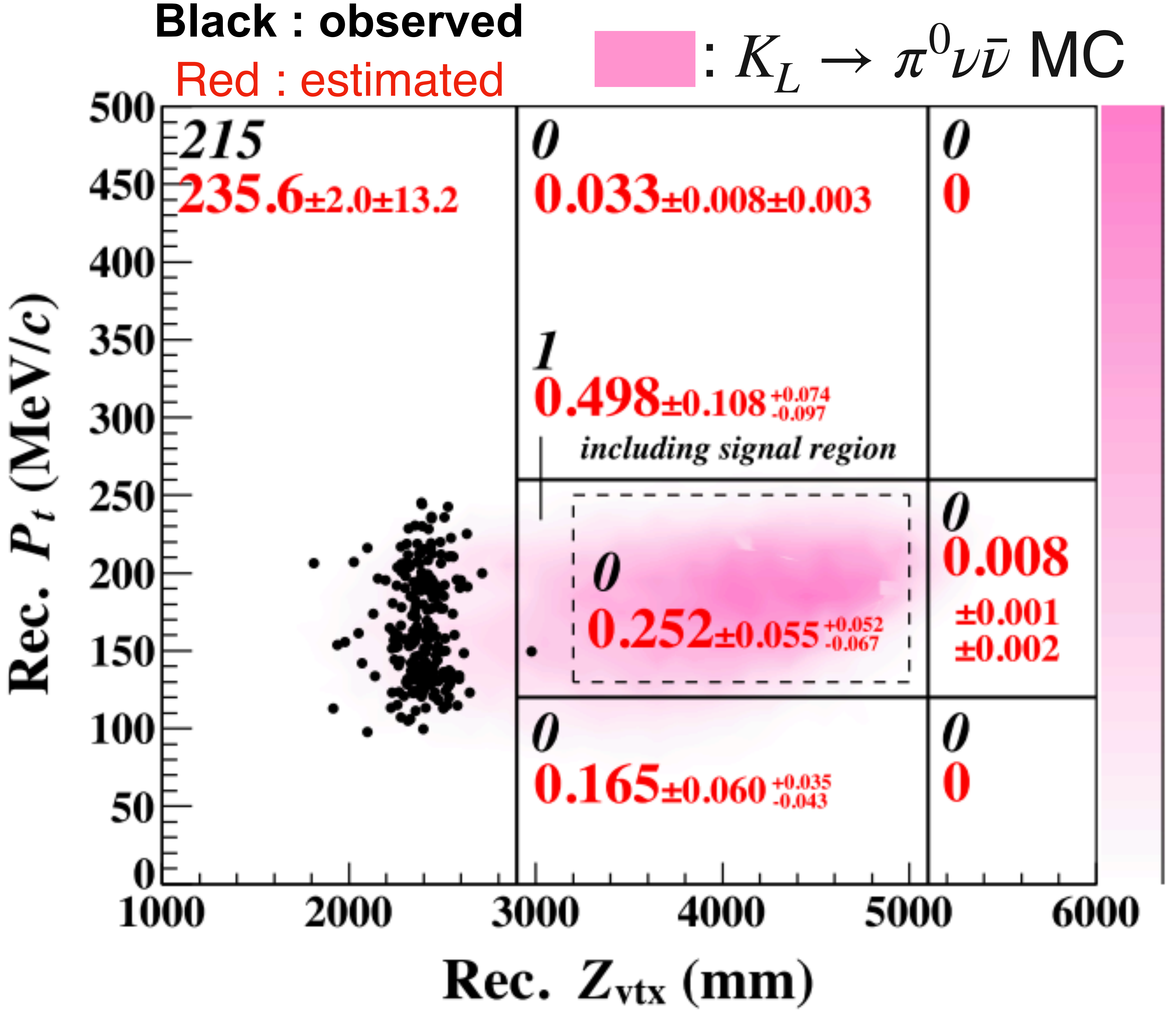
- We have collected approximately twice the statistics compared to the 2021 data in 2024, 2025

Overview of 2021 data analysis

- Single Event Sensitivity (SES) $\mathrm{SES}_{2021} = (9.33 \pm 0.06_{\mathrm{stat}} \pm 0.84_{\mathrm{sys}}) \times 10^{-10}$

Summary of expected events inside signal region





Phys. Rev. Lett. 134, 081802 (2025)

- **No observed events inside signal region**

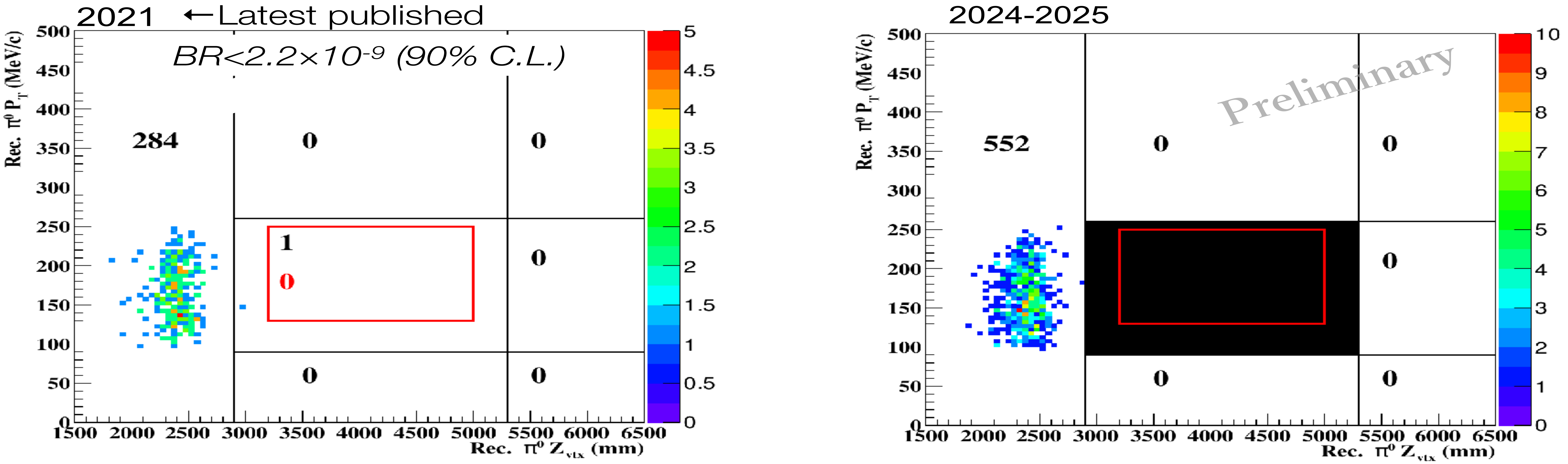
$$\mathscr{B}(K_L \to \pi^0 \nu \bar{\nu}) < 2.2 \times 10^{-9} \text{ (90\% C.L.)}$$

K. Ono

KOTO on-going analysis

Recap See slides by Ono (Osaka U)

Latest status of the $K_L \rightarrow \pi^0 \nu\nu$ search



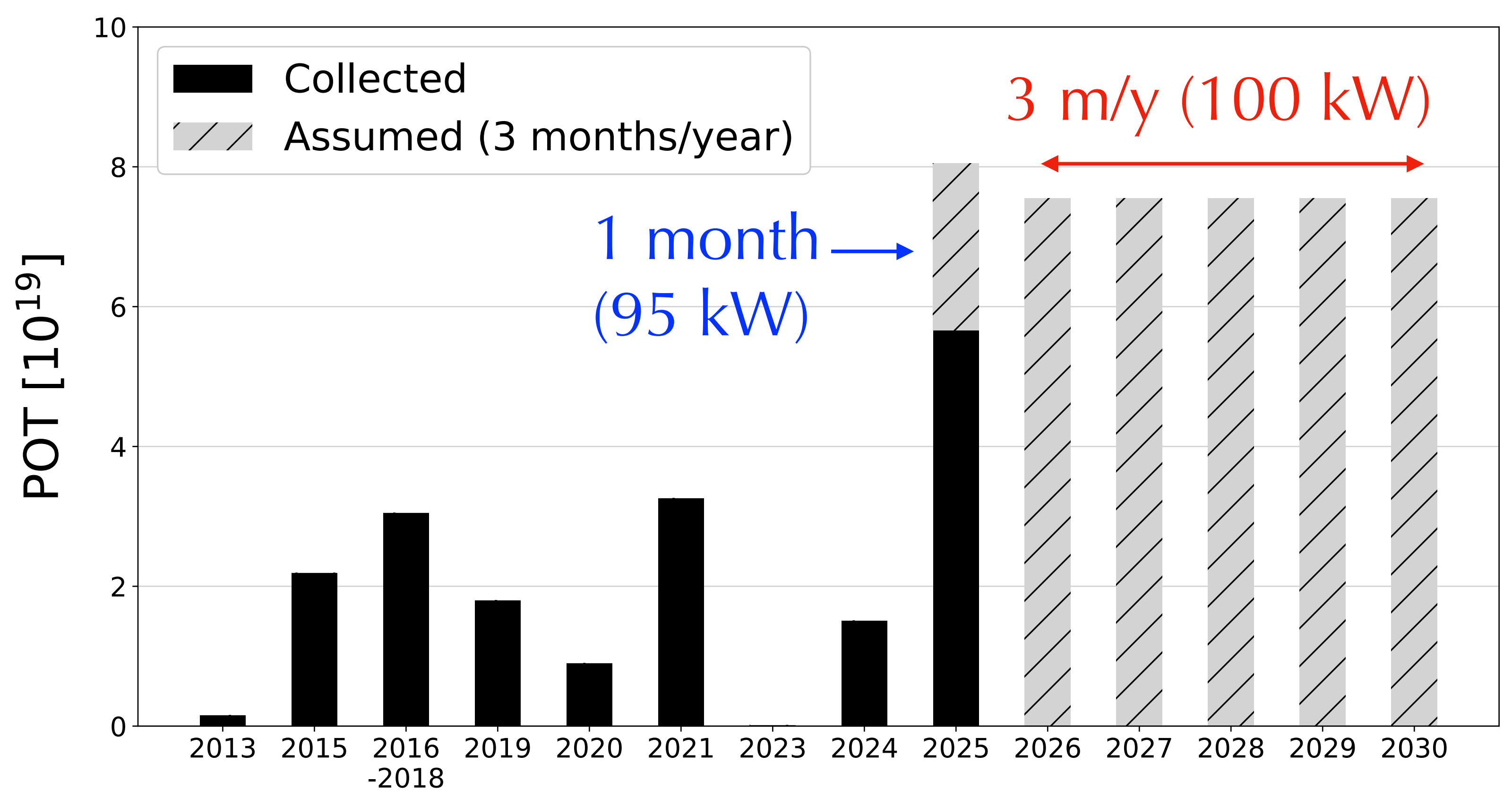
~×2 more data have been already accumulated in 2024-25

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

KOTO Prospects

- SES: 6×10^{-11}
- Expected # of BG=2.5
- 90% CL Upper limit ~2×10^{-10}

Expected protons on target (POT)

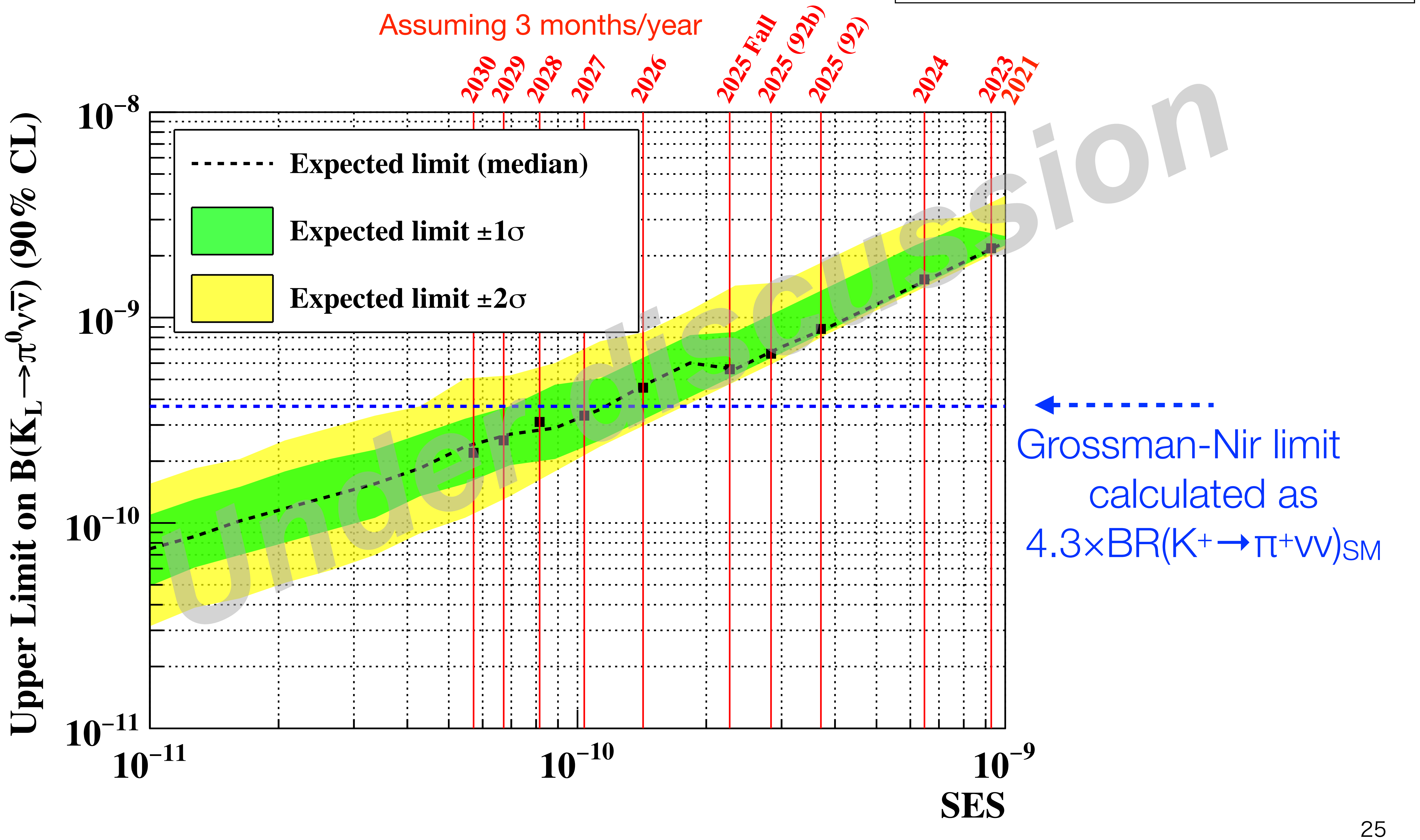


- If we assume 3 month (60 days net) per year, the accumulated POT will reach ×10 more than 2021 data around 2028. (Cf. SES(2021)=9.3×10^{-10})
  - Typical operation efficiencies (accelerator, DAQ, etc.) are taken in account.

20

Limit vs SES considering BGL

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

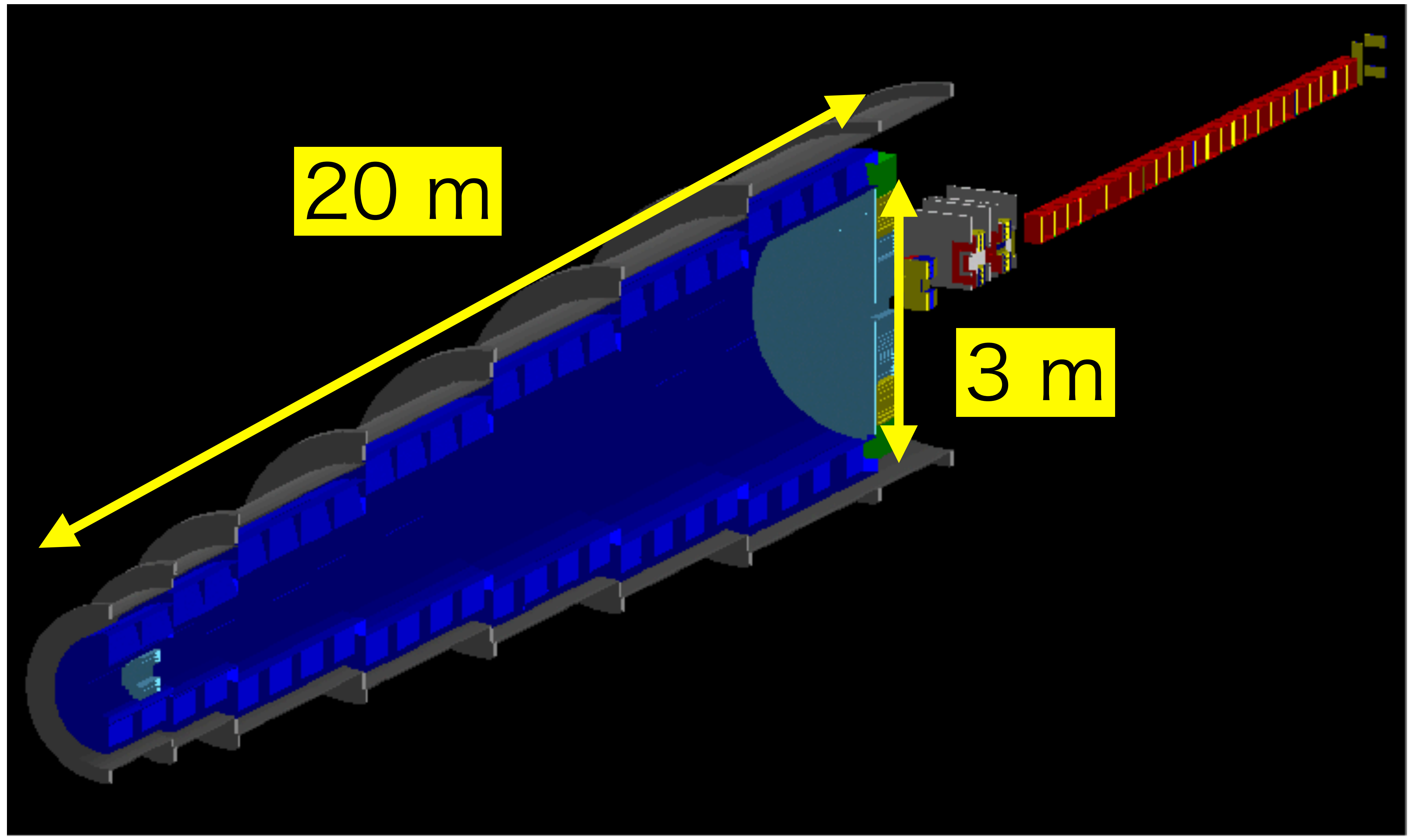


T. Nomura

J-PARC KOTO II experiment (E107)

- High flux and hard K_L with 5° production angle
- Large detector
- 35 signal (SM) and 40 background events with 3×10^7-s running time
- $> 5\sigma$ discovery、25% measurement of BR
- Scientifically approved (Stage-1 status)

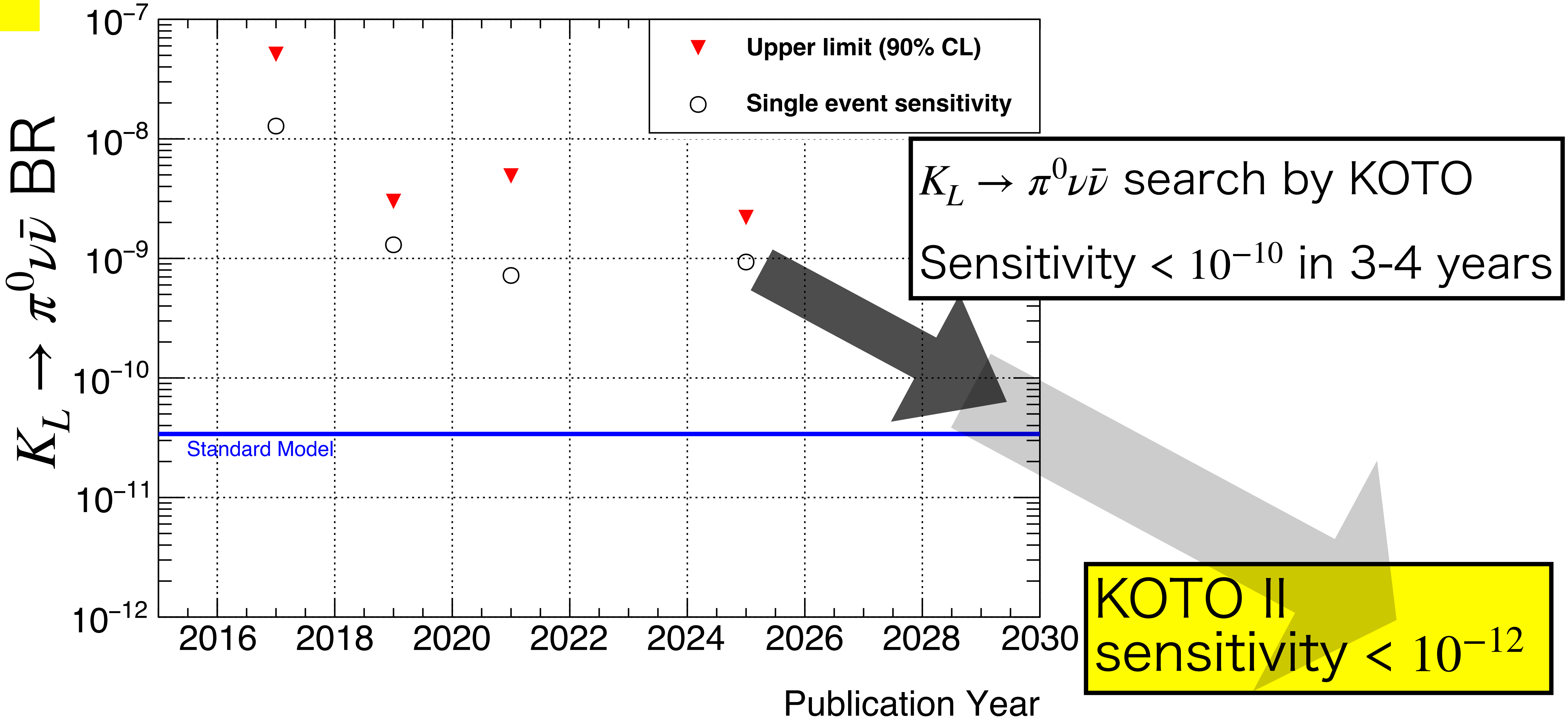
Only detected rare kaon decay program in 2030's so far



J-PARC KOTO II (E107) (scientifically approved)

77 members + 2 observers
34 institutions, 11 countries

Spokespersons:
H. Nanjo (U. of Osaka) and C. Lazzeroni(U. of Birmingham)



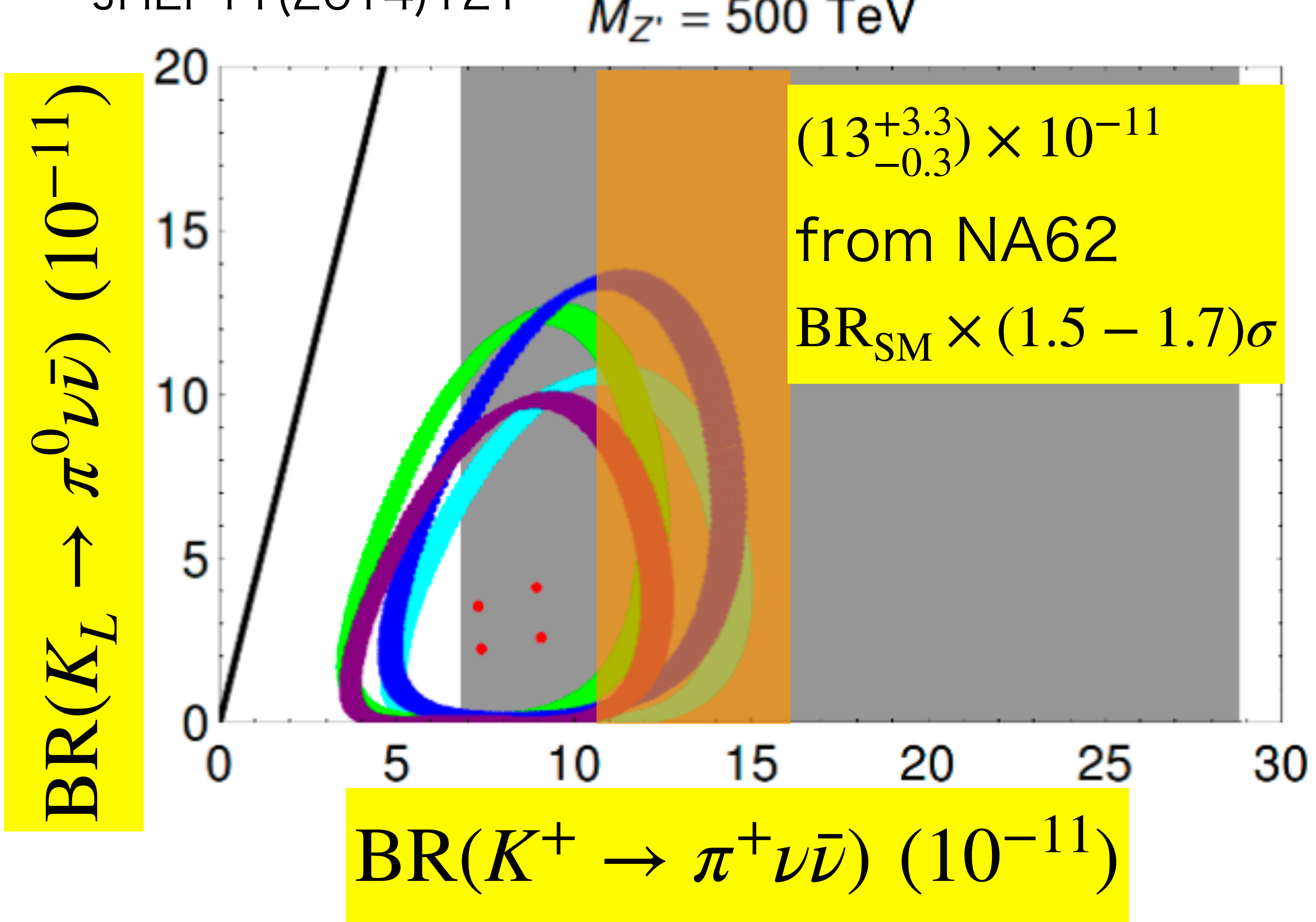
Preparation is on-going with new Asian, European, and US members. Be a world center of kaon physics!

Correlations and prospects

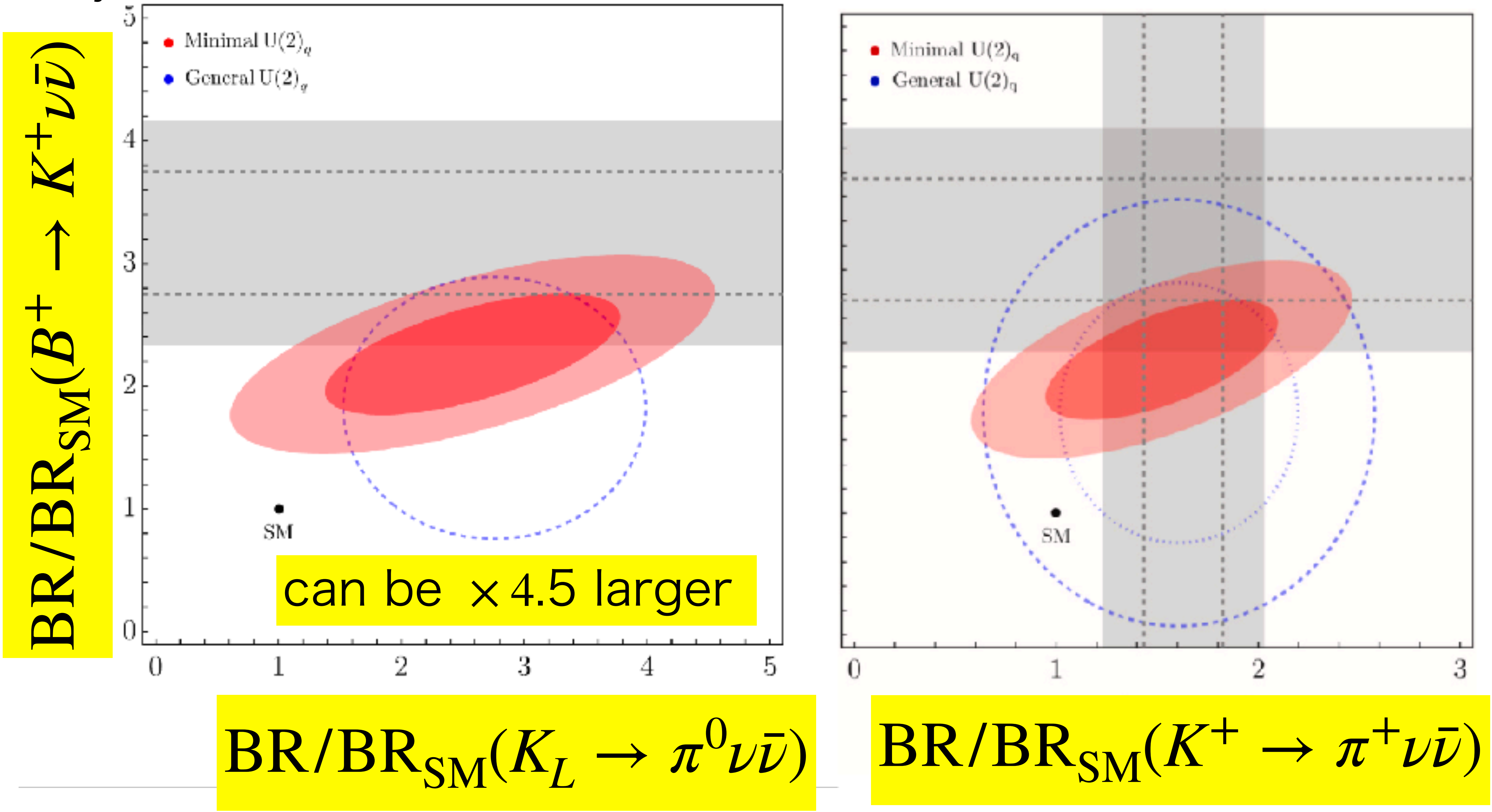
May find NP effect with 3σ

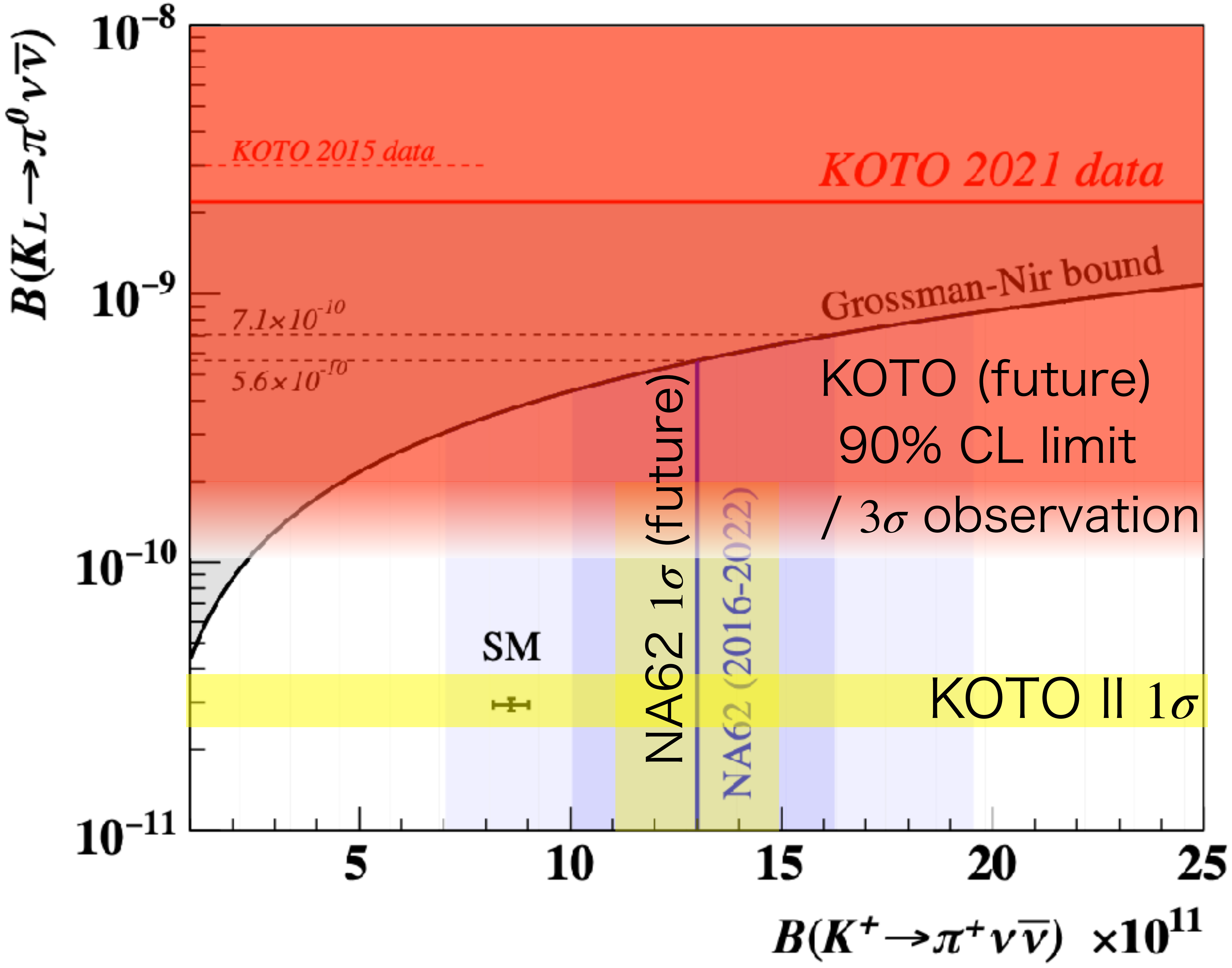
depending on enhancement from NP and stat. fluctuation

JHEP11(2014)121



Phys.Lett.B 861 (2025) 139295





Conclusion

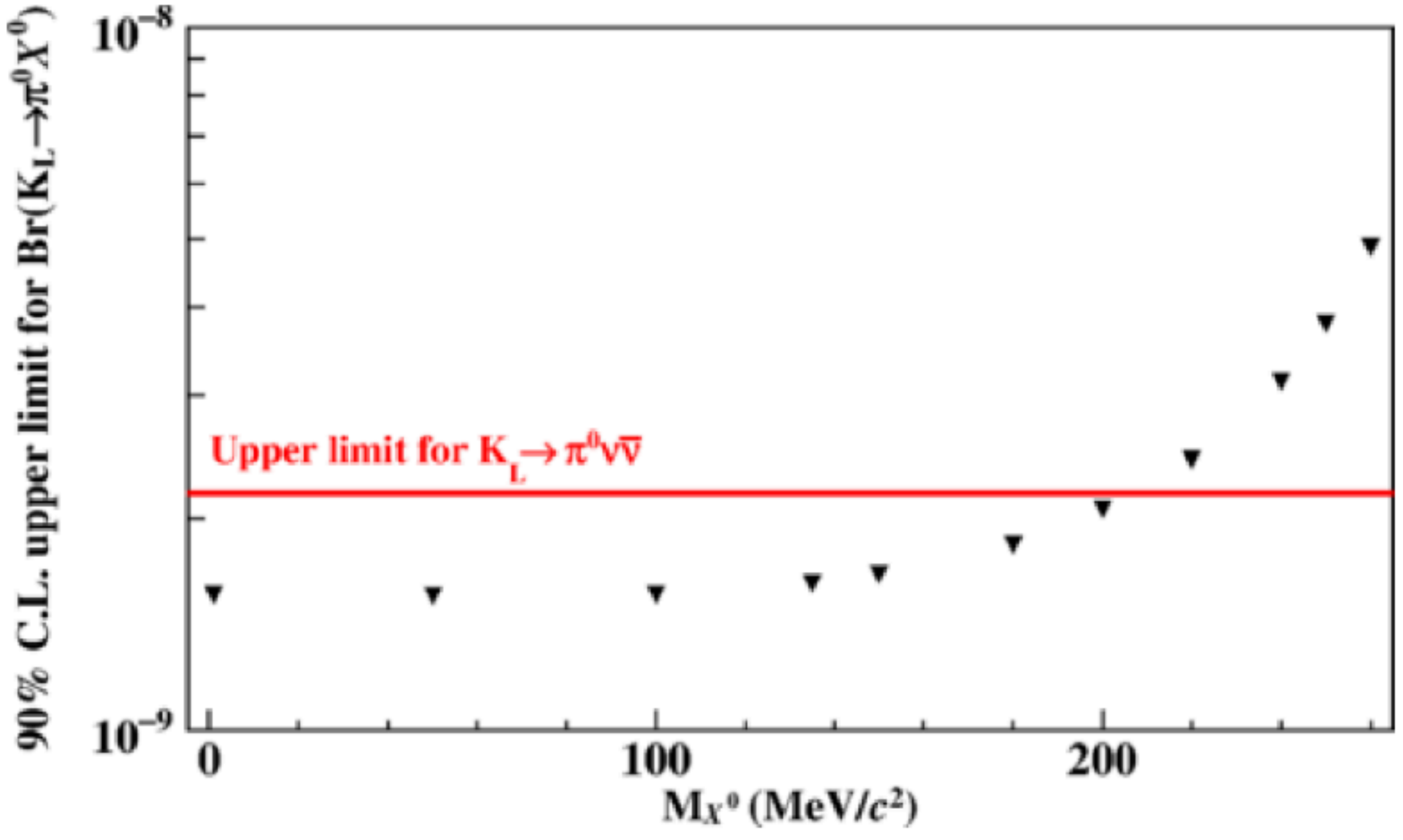
- NA62 and KOTO are improving the measurements.
- NA62
  - $\mathscr{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ was measured with 5σ combining 2016-2022 data analyses with 23% precision, with 1.5-1.7 σ larger than SM
  - will take data until 2026 before the LS3 improving the precision <20%
- KOTO
  - An upper limit 2.2×10^{-9} at 90% CL was obtained by analyzing data taken in 2021.
  - Analysis is on-going for data taken in 2024-2025 with ~x2 more data.
  - SES below 10^{-10} can be reached with more data taking in several years including additional data takin in 2025 in this Nov going beyond the Grossman-Nir bound.
- Synergies between the two and other flavors are interesting tougher with the uniqueness.

Backup

$K \to \pi X$

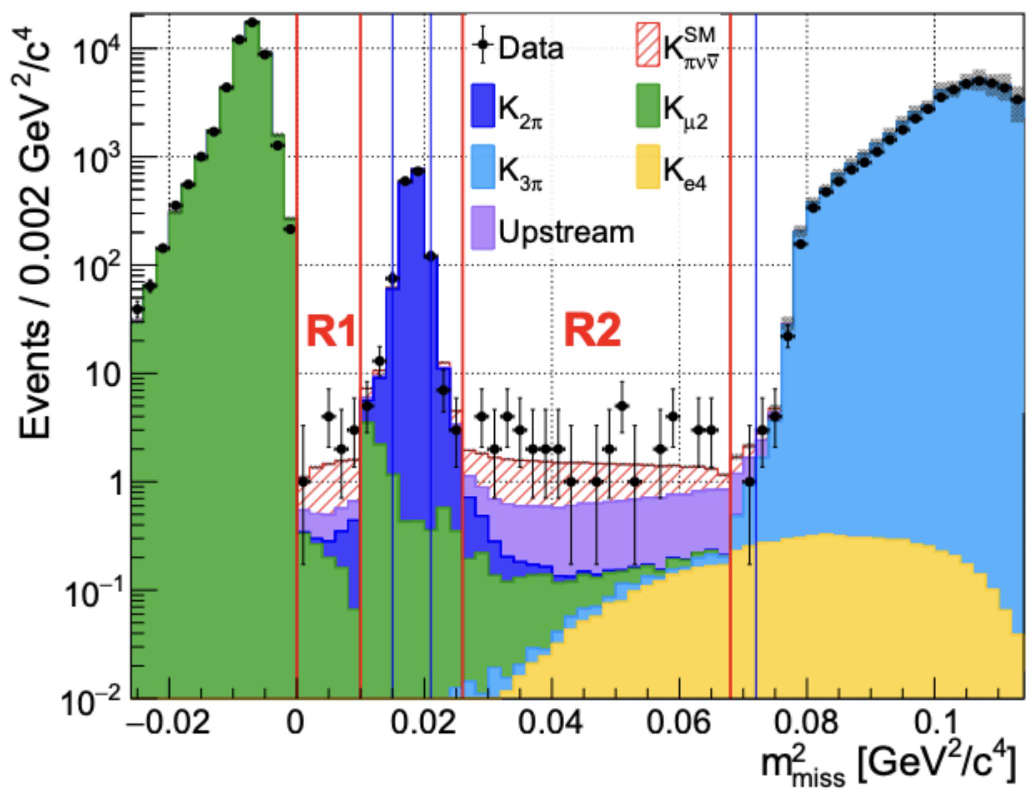
- Interpretation of an invisible boson X with mass of 135 MeV/c² (M_{π^0}):

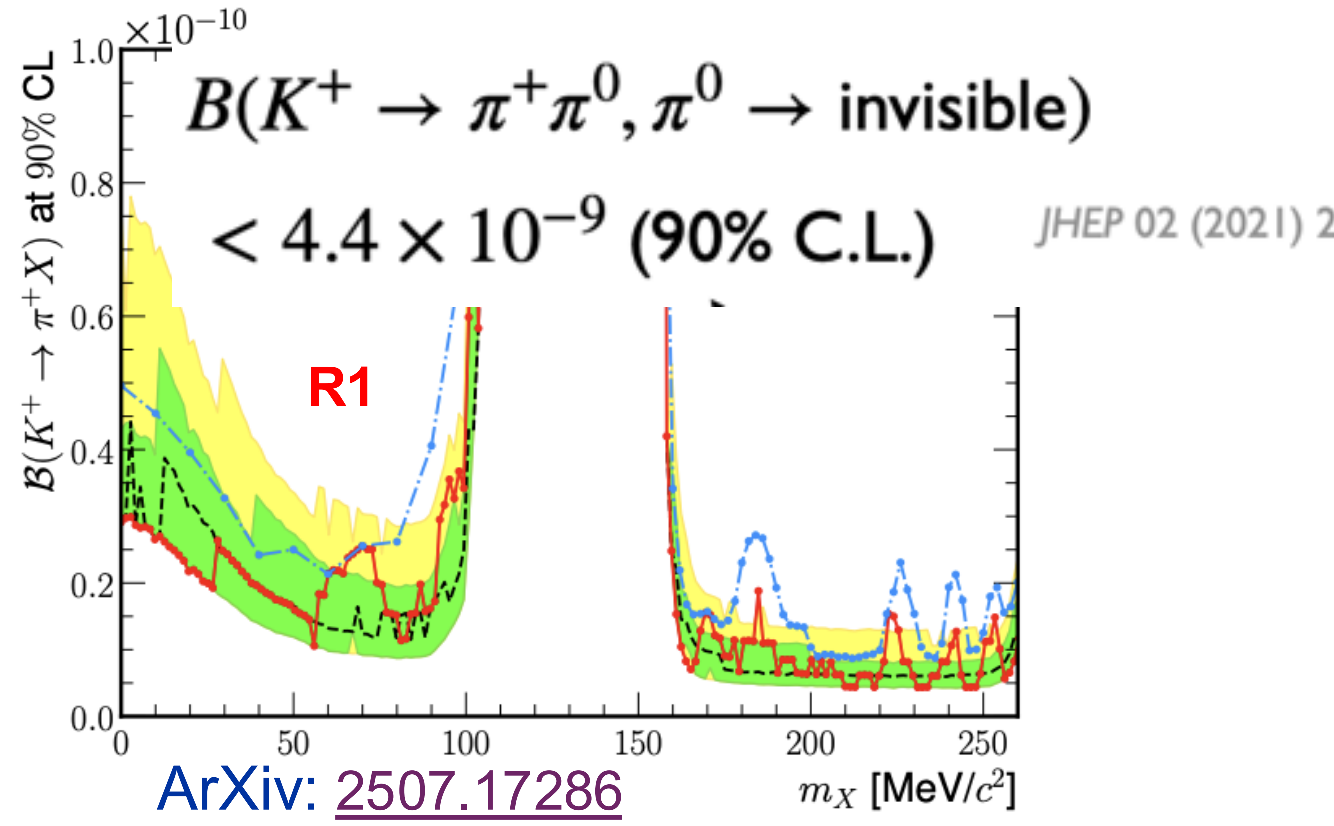
$B(K_L^0 \to \pi^0 X) < 1.6 \times 10^{-9}$ (90% C.L.)



C. Lin

From $K^+ \to \pi^+\nu\nu$ to $K^+ \to \pi^+ X$, $X \to$ invisible





ArXiv: 2507.17286

- Start from the m^2_{miss} spectrum used for the NA62 $K^+ \to \pi^+\nu\nu$ searches on 2016-22 data [JHEP 02 (2025) 191]
- Obtain the UL on the BR($K^+ \to \pi^+ X$) as function of X mass (p_X mom of X in the K rest frame):

$$\mathcal{B}(K^+ \to \pi^+ X) = \frac{p_X}{8\pi\Gamma_K m_K^2}|\mathcal{M}|^2 \qquad \Gamma_K = 5.32 \times 10^{-14}\,\mathrm{MeV}$$

- Recast the limit under different model assumptions (Vector, scalar, pseudoscalar) changing $|M|^2$
  - Add lifetime corrections to obtain visible decay limits for the same model.

Mauro Raggi | New physics searches with kaon and pion decays at NA62 09/09/2025 9

M. Raggi

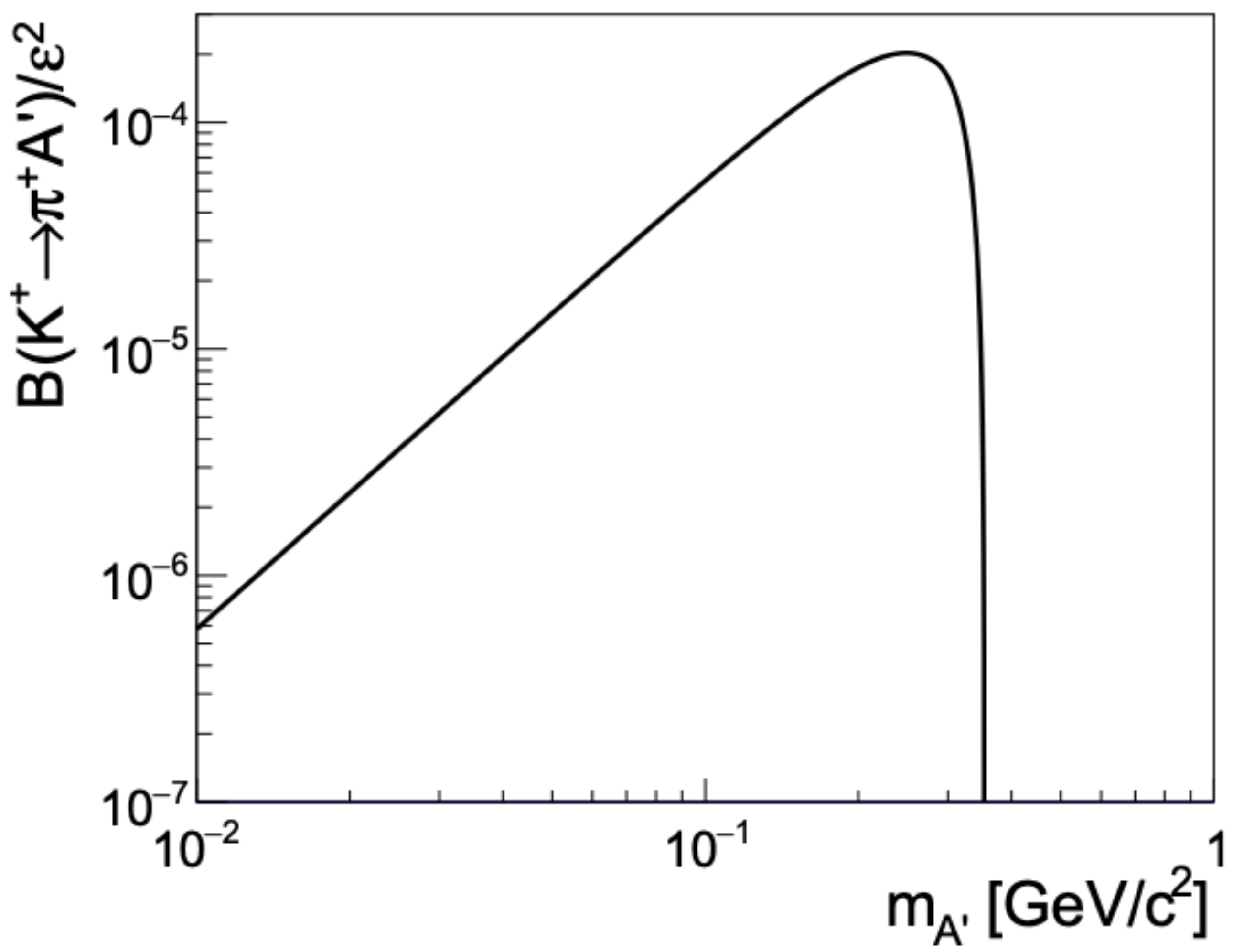
Interpretation on $K^+ \to \pi^+ X$

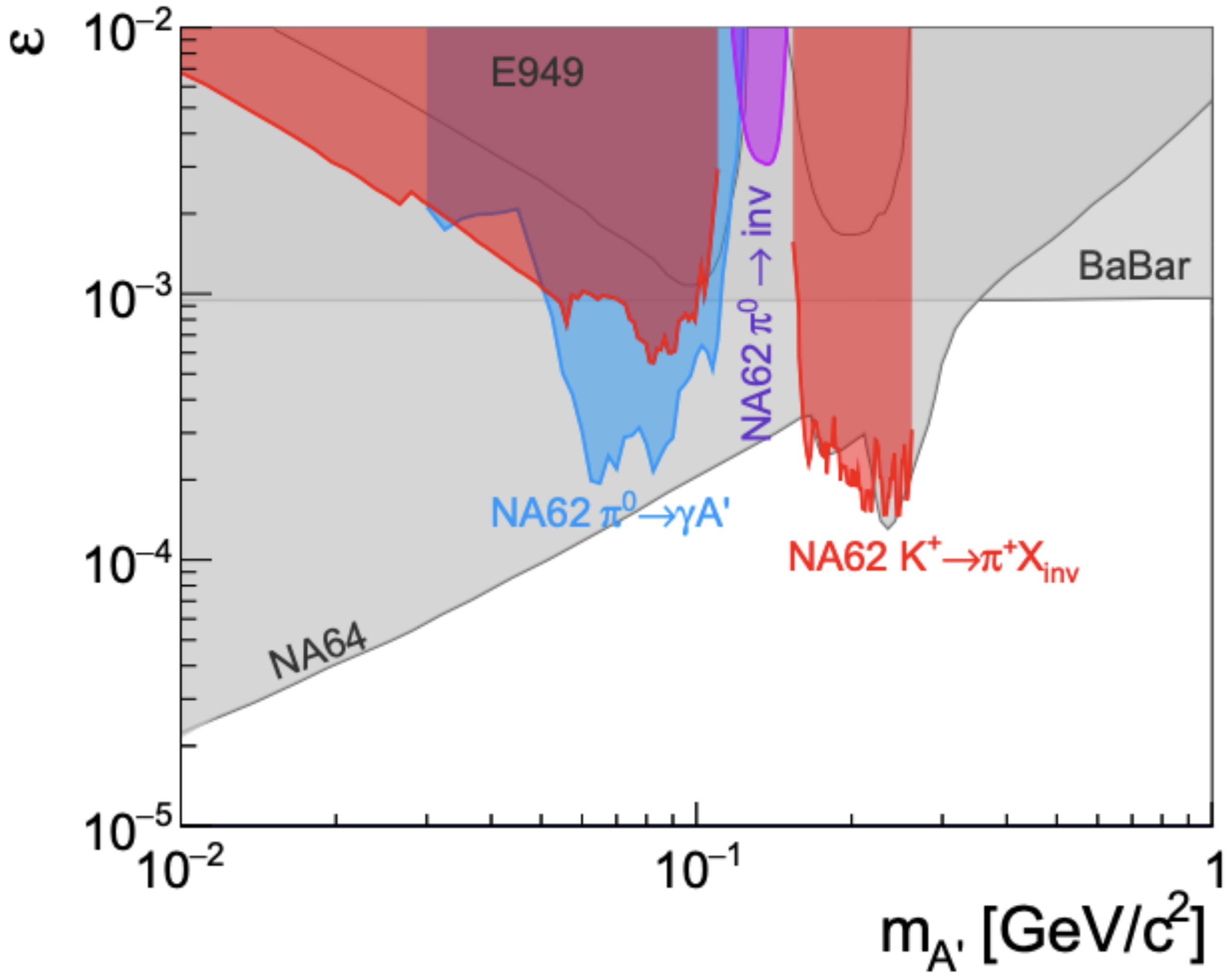
The vector portal: K⁺–>π⁺A', A'–>inv. decay BC2 NEW

$$\mathcal{B}(K^+ \to \pi^+ X) = \frac{p_X}{8\pi \Gamma_K m_K^2} |\mathcal{M}|^2$$

$$p_X = \sqrt{\lambda(m_K^2, m_\pi^2, m_X^2)/(2m_k^2)}$$

$$|\mathcal{M}| = \frac{e\varepsilon |W(z)| m_{A'}}{16\pi^2 m_K^2} \sqrt{\lambda(m_K^2, m_\pi^2, m_{A'}^2)}$$





- Based on full **2016-2022 NA62 data set**
  - Limit computed for the first time for NA62 ArXiv: 2507.17286
- **NA62 K⁺–>π⁺A' provides the best limit** in the region **160 MeV/c² < $m_{A'}$ < 200 MeV/c²**
  - The NA62 result improves by 1 order of magnitude the previous result by E949 based on $K^+ \to \pi^+ \nu\nu$
- An **improved result** is expected from **2016-2026 data sample** (x3 stat. see K. **Massri's talk**)
  - Dedicated analysis can further enhance the sensitivity

M. Raggi

Recap See also slides by Redeker (U Chicago)

Taken in our standard trigger mixing
Choices for trigger mixing or special run

Searches for decays other than $K_L \to \pi^0 \nu\nu$

1γ $K_L \to \gamma\bar{\gamma}$: Dark photon search — *T. Wu, Talk @ ICHEP2024*

- SES=2.9×10^{-8} (2 hours run), expected N_{BG}=12.7, observed 13 => BR<3.5×10^{-7} (90% CL) **Preliminary**

2γ $K_L \to \pi^0 X$ (X: invisible)

- Simple byproduct of $K_L \to \pi^0 \nu\bar{\nu}$ analysis

3γ $K_L \to \pi^0\gamma$: Violating Lorentz invariance — *N. Shimizu et al, PRD102, 051103 (2020)*

- (2016-18 data) SES=7.1×10^{-8}, estimated N_{BG}=0.34
  - No events observed, BR<1.7×10^{-7} (90% CL)

4γ $K_L \to \pi^0\pi^0\nu\bar{\nu}$ and $K_L \to \pi^0\pi^0 X$ (X: invisible) … taken in 2018; now revisited by a student in Taiwan G

4γ $K_L \to XX, X \to 2\gamma$ — *C. Lin et al, PRL130, 111801 (2023)*

- (2018 data) N_{BG}=0.61, No events observed.
- BR<(1-4)×10^{-7} (M_X: 40-110MeV/c^2), BR<(1-2)×10^{-6} (M_X: 210-240MeV/c^2)

6γ $K_L \to \pi^0\pi^0 X, X \to 2\gamma$ and $K_L \to \pi^0\pi^0\gamma\gamma$ **Preliminary** — **Talk by J. Redeker**

- (2021 data) BR<(0.8-3)×10^{-7} (M_X=170-220MeV/c^2), BR($K_L \to \pi^0\pi^0\gamma\gamma$)<$11.2\times10^{-7}$

6EM $K_L \to \pi^0 4e$

- (2018 data) No events observed, BR<4.1×10^{-7} (90% CL) **Preliminary** — *X. Li, Talk @ ICHEP2024*

4EM $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0 X, X \to e^+e^-$ … trial data taking in 2024/2025 runs — **Poster by Y. T. Su**

EM: γ or e+/e-

3EM $K_L \to \gamma X, X \to e^+e^-$ … trial data accumulation in 2025 run