


# Kaon physics

Radoslav Marchevski

**EPFL**

*WIN25 Conference*  
University of Sussex, UK, June 9-13, 2025

# Why kaons?

- Important questions we still haven't answered: What is origin of the SM flavour structure?
  - hierarchies of the fermion Yukawa couplings and mixing parameters, observed matter-antimatter asymmetry, etc...
- Rare  $s \rightarrow d\nu\bar{\nu}$  and  $s \rightarrow d\ell^+\ell^-$  ( $\ell = e, \mu$ ) transitions in the kaon sector offers insight into the SM flavour structure
  - Flavour Changing Neutral Currents (FCNCs) forbidden at tree level → **loop + CKM suppression**
  - several golden-plated observables: **dominated by Short Distance (SD) physics** 
  - tests of low-energy hadronic theories and methods (lattice QCD, ChPT, dispersive analysis, etc...)
  - direct and indirect searches for NP through LFV and LNV processes
  - sensitive direct searches for Feebly Interacting Particles (FIPs) below the EW scale
- Details on the motivation and prospects for kaon physics can be found in the input submitted to the European strategy by the kaon physics community

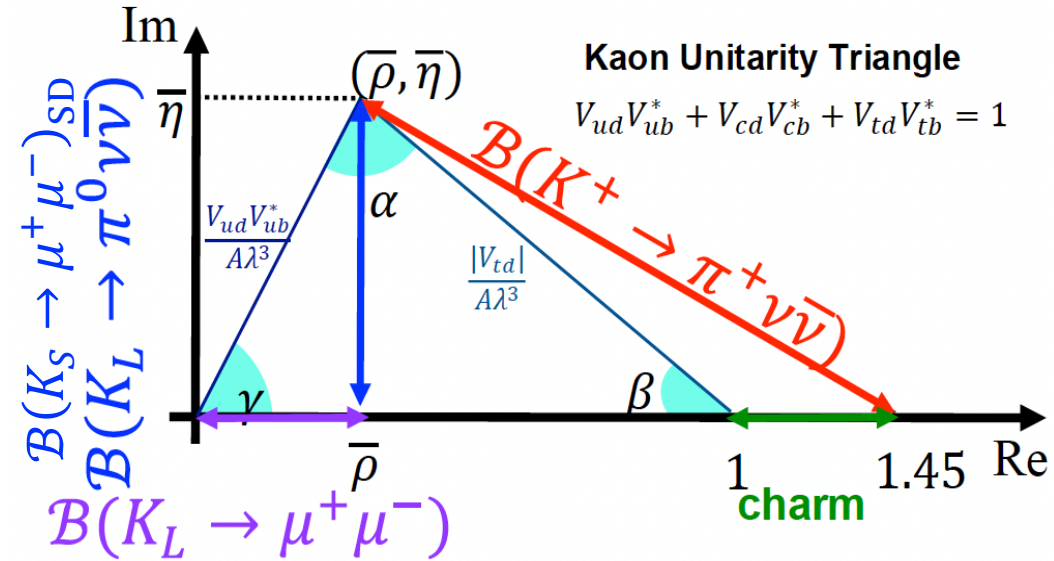
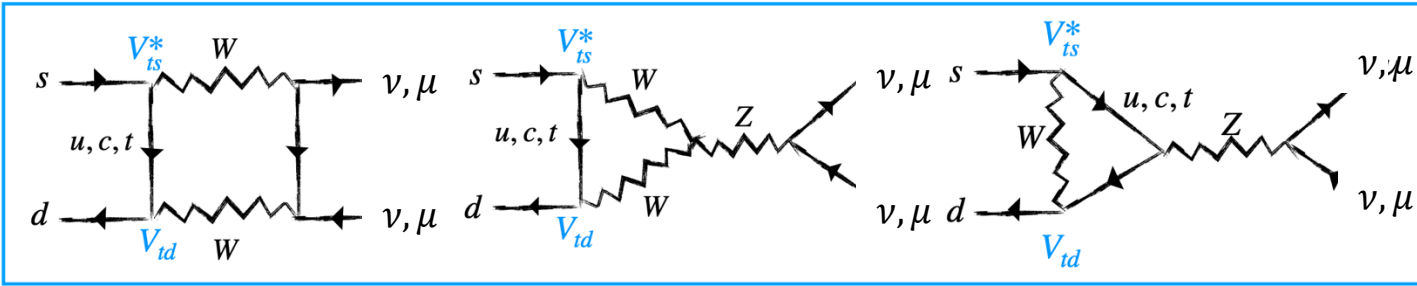
Precisely known  
theoretically  
**High NP sensitivity  
up to  $\mathcal{O}(100 \text{ TeV})$**

[arXiv:2505.02568](https://arxiv.org/abs/2505.02568), [arXiv:2503.22256](https://arxiv.org/abs/2503.22256)

# Gold-plated kaon observables

## Gold-plated observables

$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}$   
 $K_S - K_L \rightarrow \mu\mu$  interference



## Theoretical status

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} = (7.86 \pm 0.61) \times 10^{-11} \quad \text{[JHEP 09 (2022) 148]}$$

$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{SM}} = (2.68 \pm 0.30) \times 10^{-11}$$

Processes sensitive to interaction of all three generations of quarks and leptons

$$\mathcal{B}(K_S \rightarrow \mu^+ \mu^-)_{\text{SM}} = (5.18 \pm 1.50) \times 10^{-12} \quad \text{[PRL 119 201802 (2017)]}$$

$$\mathcal{B}(K_S \rightarrow \mu^+ \mu^-)_{\text{SD}} = (1.6 \pm 0.1) \times 10^{-13} \quad \text{[JHEP 07 (2021) 103]}$$

Access via the study of time-dependent decay rates  
 $K^0 - \bar{K}^0$  interference effect  
 [JHEP 07 (2021) 103]

# Experimental status of rare kaon observables

## Main players



$K_{S/L}$  decays



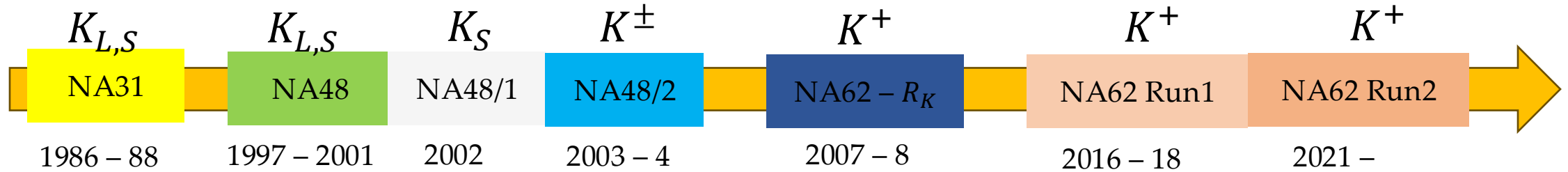
$K^+$  decays



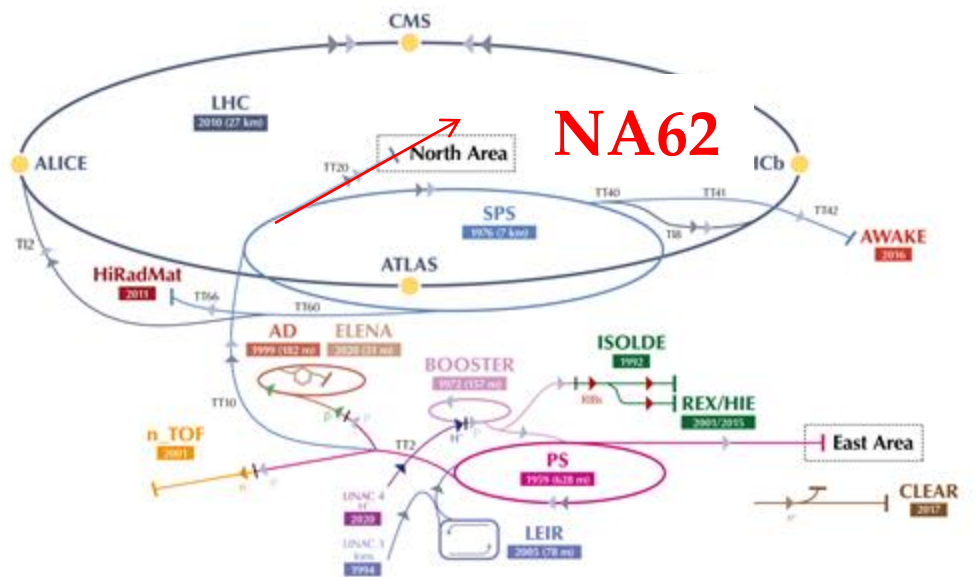
$K_L$  decays

This talk will focus on recent experimental results and prospects for rare kaon decay measurements primarily by NA62 but also KOTO and LHCb

# NA62 experiment



The CERN accelerator complex  
Complexe des accélérateurs du CERN

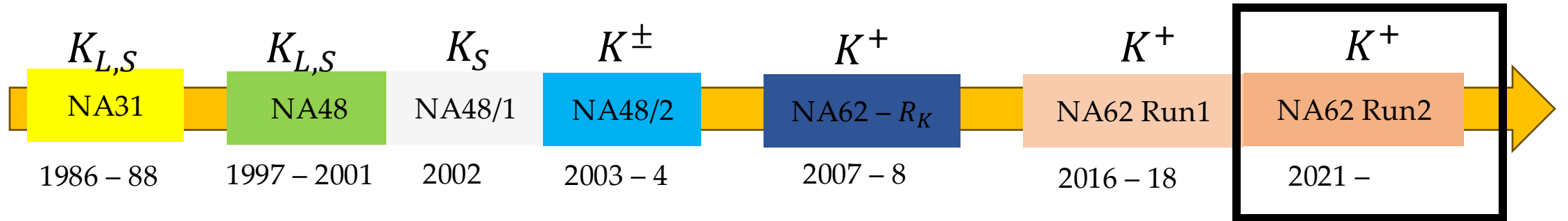


- Long tradition of kaon experiments at CERN
  - NA62 main target:  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay measurement
  - Broad physics program:
    - Rare  $K^+$  decays (e.g.  $K^+ \rightarrow \pi^+ \gamma \gamma$ )
    - LFV/LNV searches
    - Exotic decays
- This talk**

▶ H<sup>-</sup> (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶  $\bar{p}$  (antiprotons) ▶ e (electrons)  
 LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear  
 Electron Accelerator for Research // AWAKE - Advanced WAKEfield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive  
 Experiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n\_TOF - Neutrons Time Of Flight //  
 HiRadMat - High-Radiation to Materials

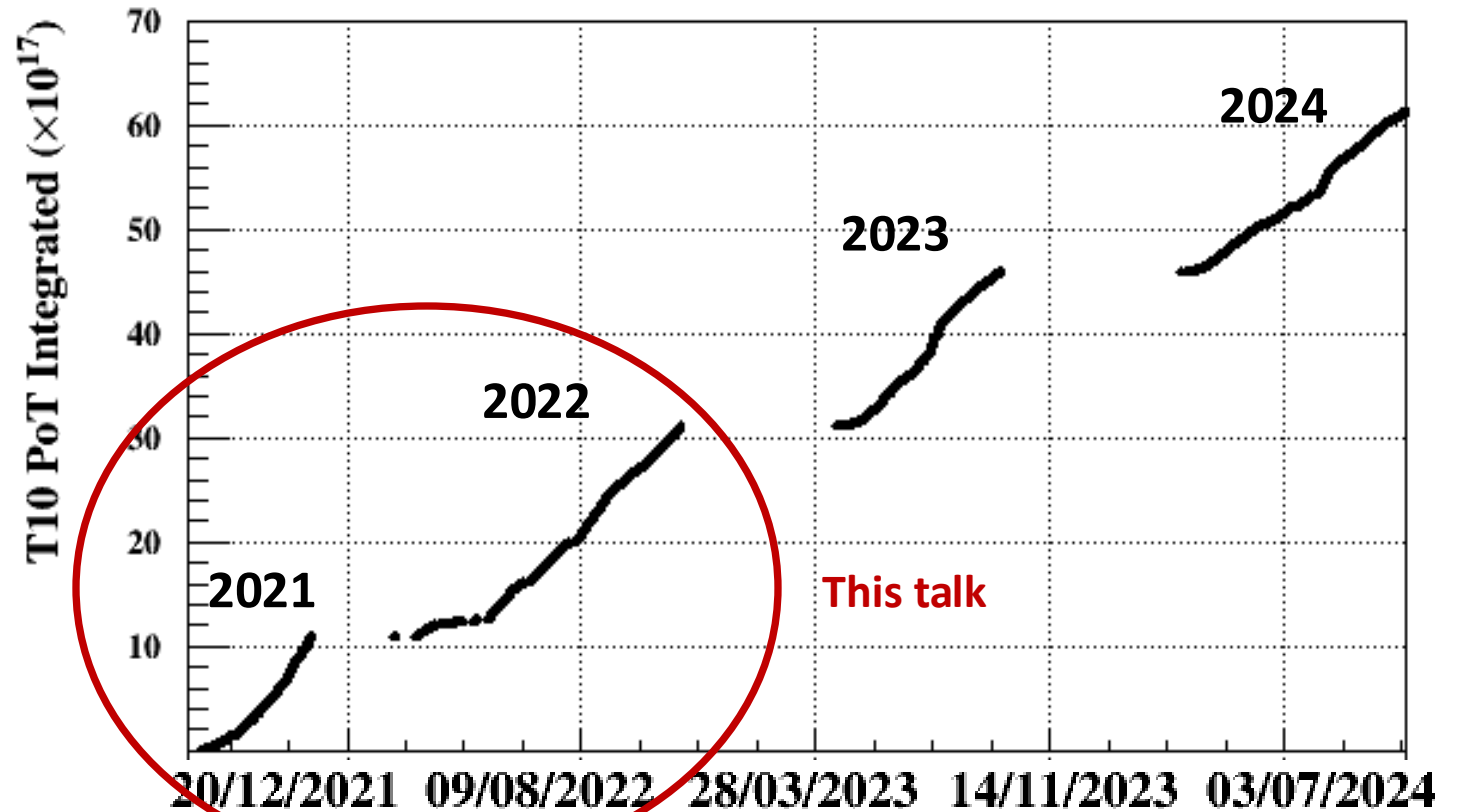
~ 200 physicists from 30 institutions

# NA62 experiment

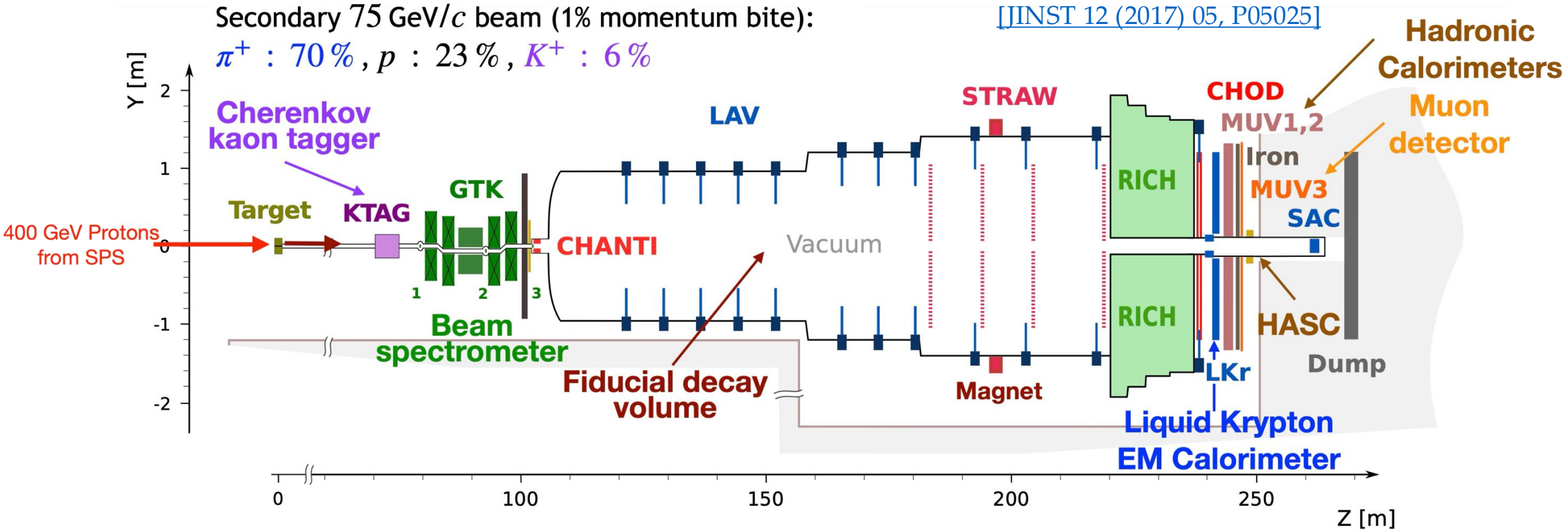


2016 – 18:  $\sim 0.9 \times 10^6$  spills collected  
 $\sim 22 \times 10^{17}$  PoT delivered  
 $> 3\sigma K^+ \rightarrow \pi^+ \nu \bar{\nu}$  evidence  
 [JHEP06(2021)093]

2021 – present:  $\sim 1.5 \times 10^6$  spills collected

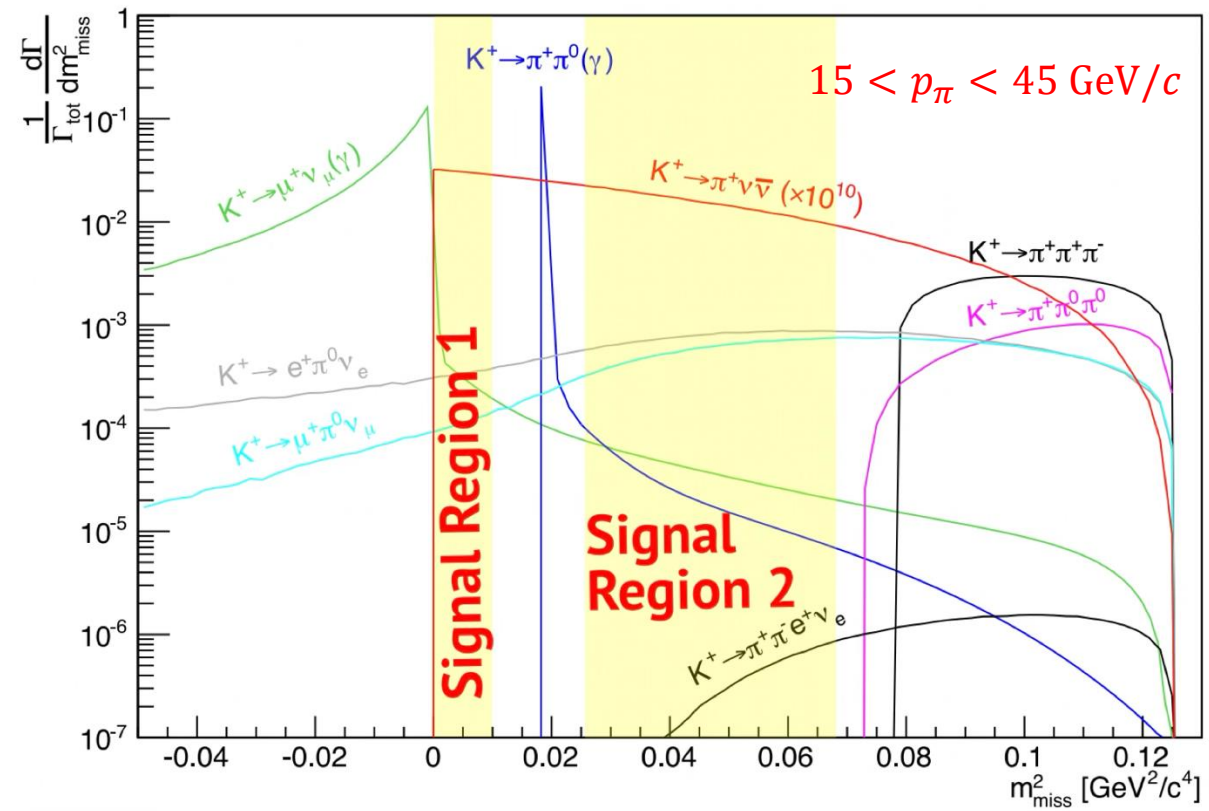
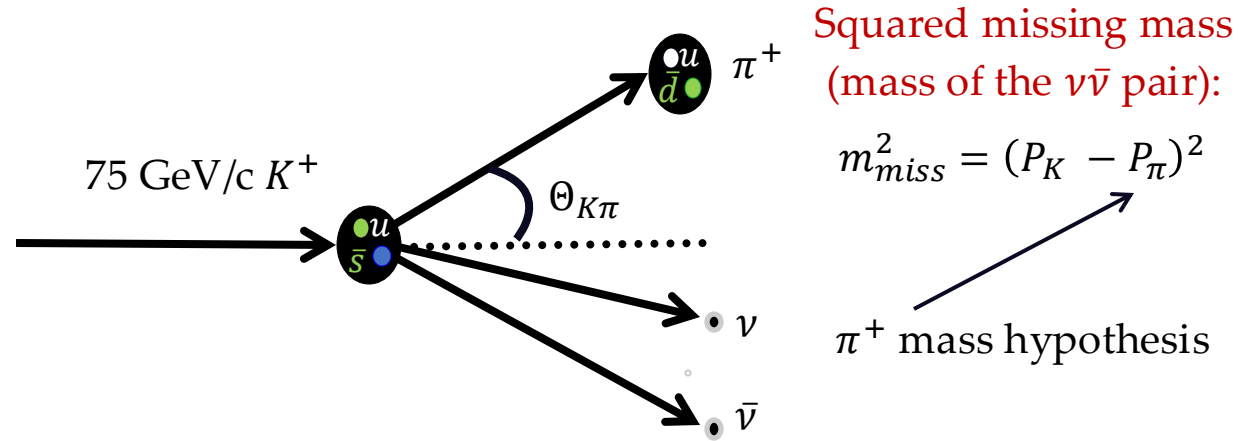


# The NA62 detector



- Designed and optimized to study  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decays
  - Particle tracking: beam particle (GTK) & downstream tracks (STRAW)
  - PID:  $K^+$  - KTAG,  $\pi^+$  - RICH, Calorimeters (LKr, MUV1/2), MUV3 ( $\mu$  detector)
  - Hermetic veto systems: CHANTI (beam interactions), LAV, LKr, IRC, SAC ( $\gamma$ )

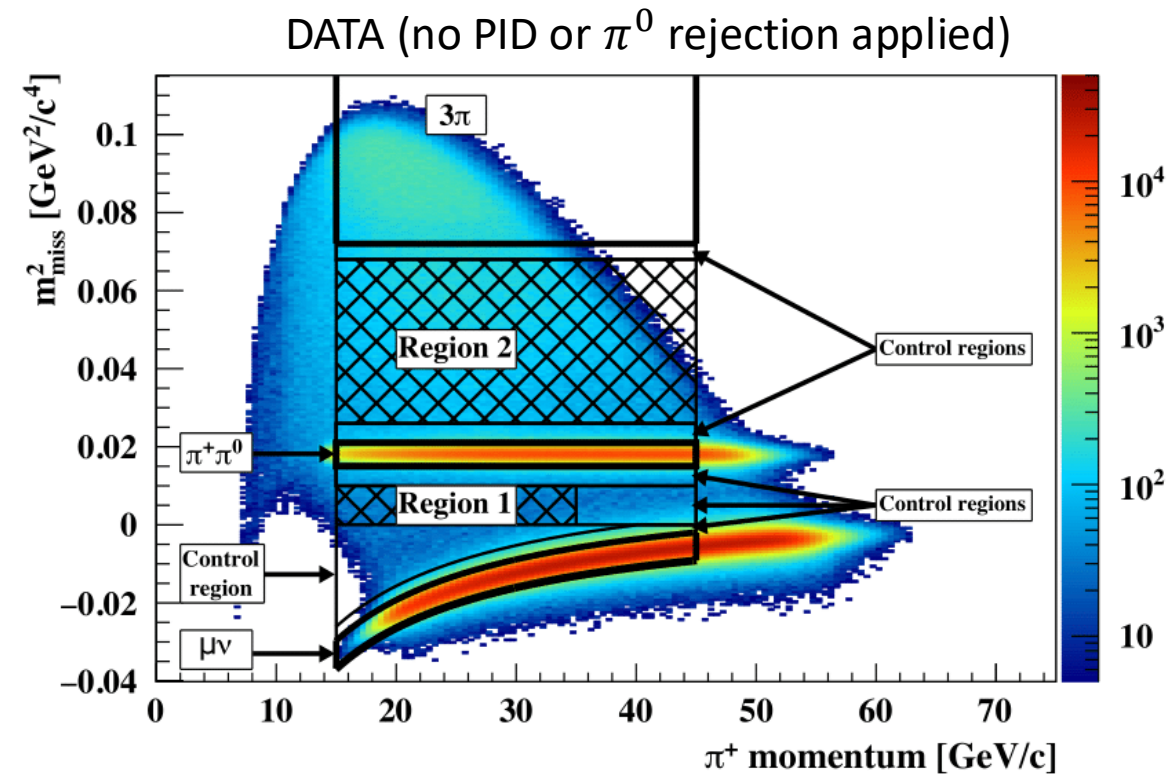
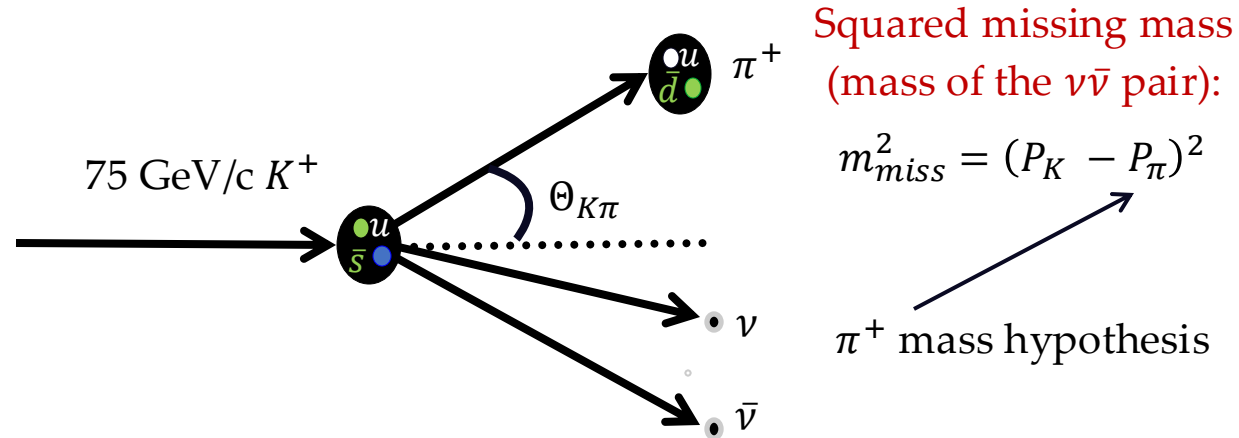
# Analysis strategy



- Highly boosted decay:  $(75 \pm 1) \text{ GeV}/c K^+$  ( $\gamma \sim 150$ )
- Large undetectable missing energy carried away by the neutrinos
- All energy from visible particles must be detected
- $\pi^+$  momentum range  $15 - 45 \text{ GeV}/c$  ( $E_{\text{miss}} > 30 \text{ GeV}$ )
- Hermetic detector coverage and  $O(100\%)$  detector efficiency needed

- Requirements:
  - Kinematic suppression –  $O(10^4)$
  - $\mu^+$  rejection –  $O(10^7)$
  - $\pi^0$  rejection –  $O(10^7)$
  - Time resolution –  $O(100 \text{ ps})$

# Analysis strategy



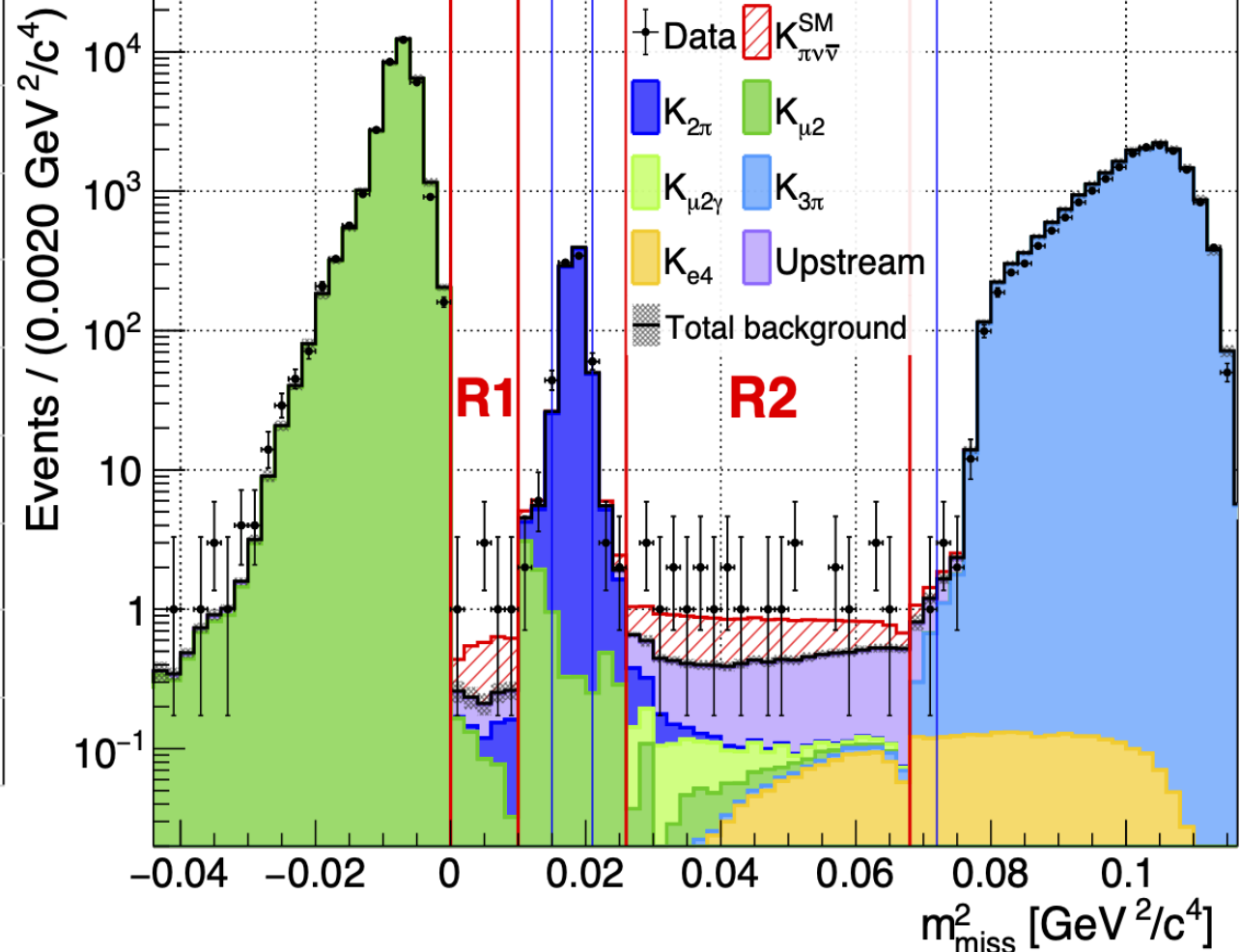
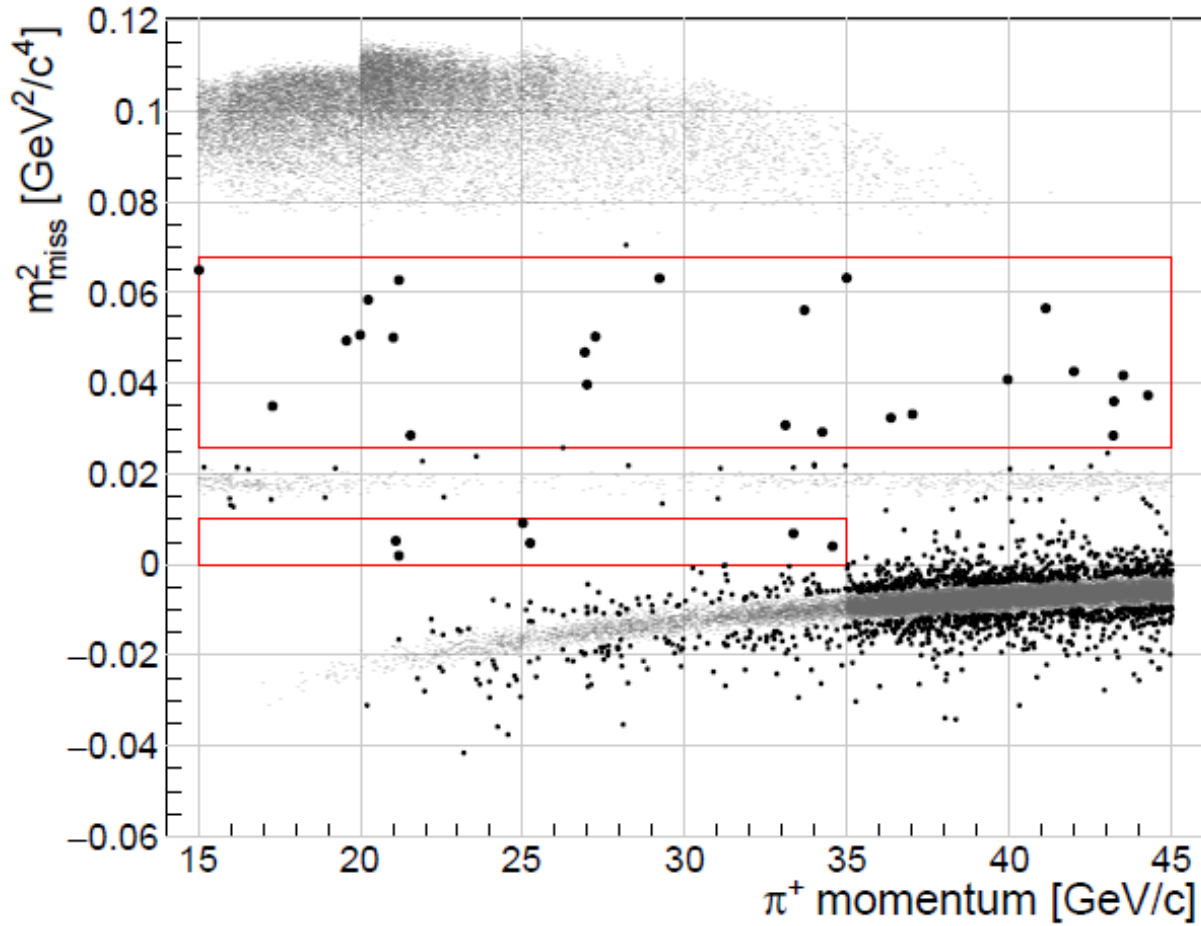
- Highly boosted decay:  $(75 \pm 1)$  GeV/c  $K^+$  ( $\gamma \sim 150$ )
- Large undetectable missing energy carried away by the neutrinos
- All energy from visible particles must be detected
- $\pi^+$  momentum range 15 – 45 GeV/c ( $E_{miss} > 30$  GeV)
- Hermetic detector coverage and O(100%) detector efficiency needed

- Requirements:
  - Kinematic suppression –  $O(10^4)$
  - $\mu^+$  rejection –  $O(10^7)$
  - $\pi^0$  rejection –  $O(10^7)$
  - Time resolution –  $O(100)$  ps

# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results: 2021-22 data

2021-2022 data

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



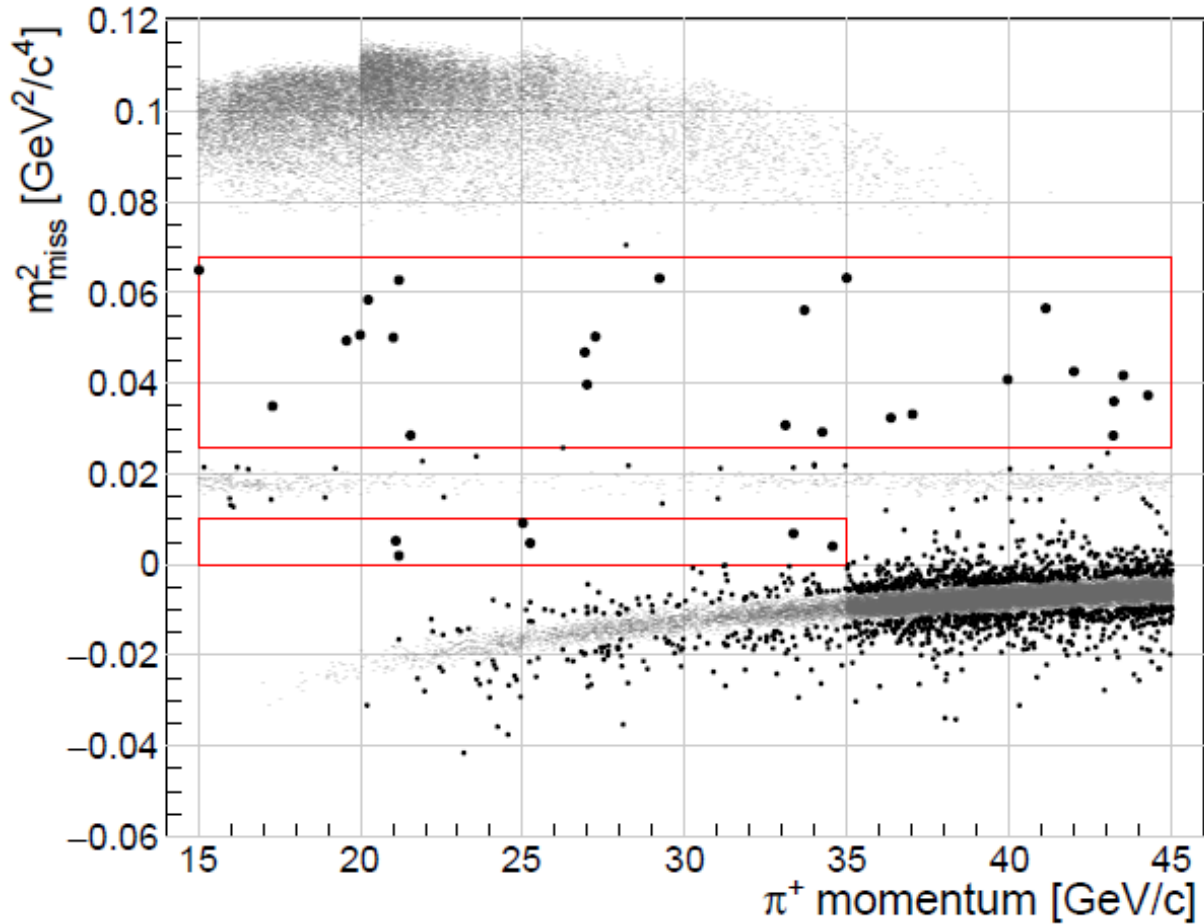
Expected SM signal:  $N_{\pi\nu\bar{\nu}}^{SM} \approx 10$

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

Observed:  $N_{obs} = 31$

# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results: 2021-22 data

2021-2022 data



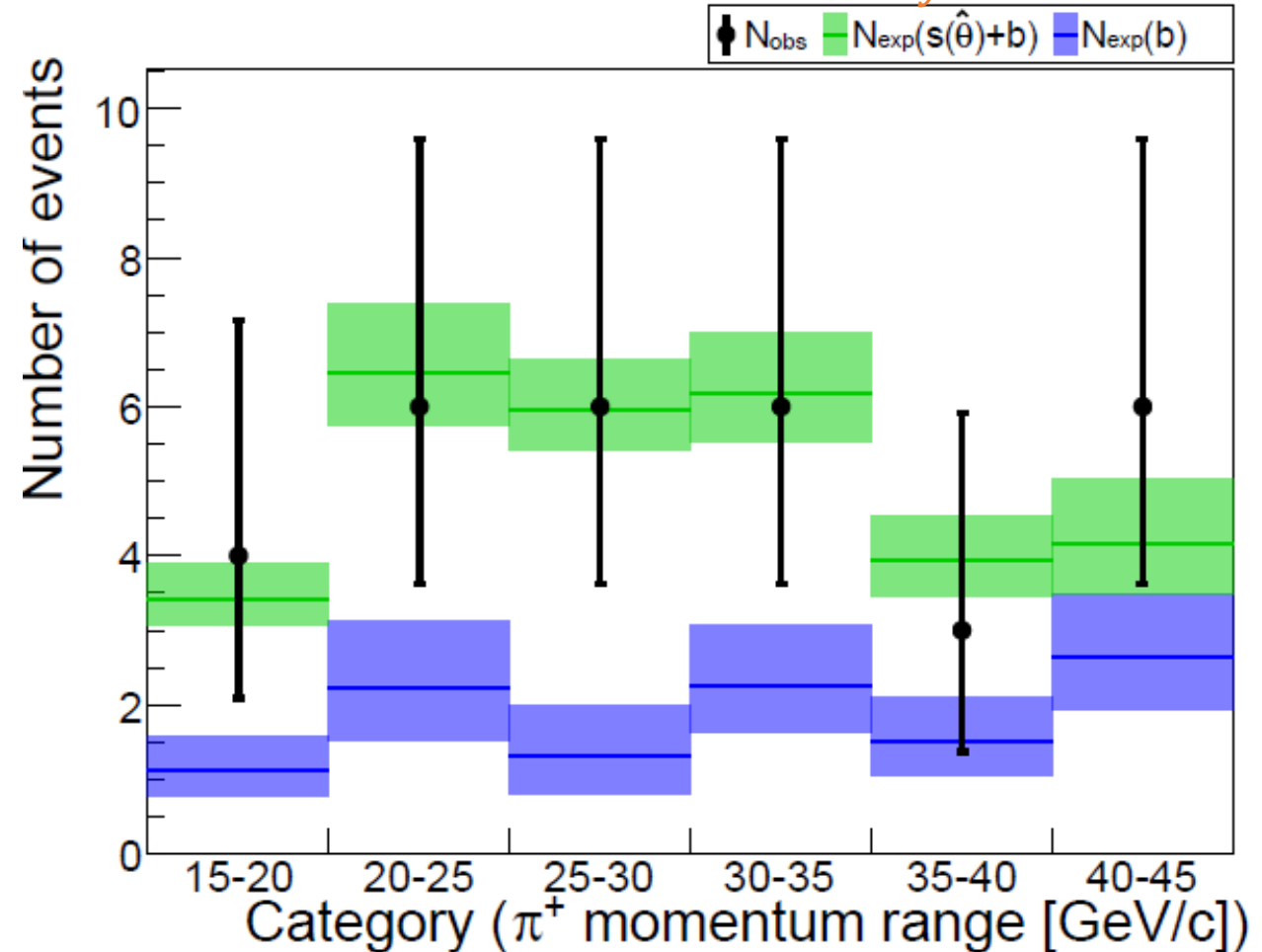
Expected SM signal:  $N_{\pi\nu\bar{\nu}}^{SM} \approx 10$

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

**Observed:  $N_{obs} = 31$**

Fit to  $\pi^+$  momentum with a profile likelihood ratio test statistics

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = \left( 16.2^{+4.9}_{-4.3} \left|_{stat} \begin{array}{c} +1.4 \\ -1.4 \end{array} \right|_{syst} \right) \times 10^{-11}$$

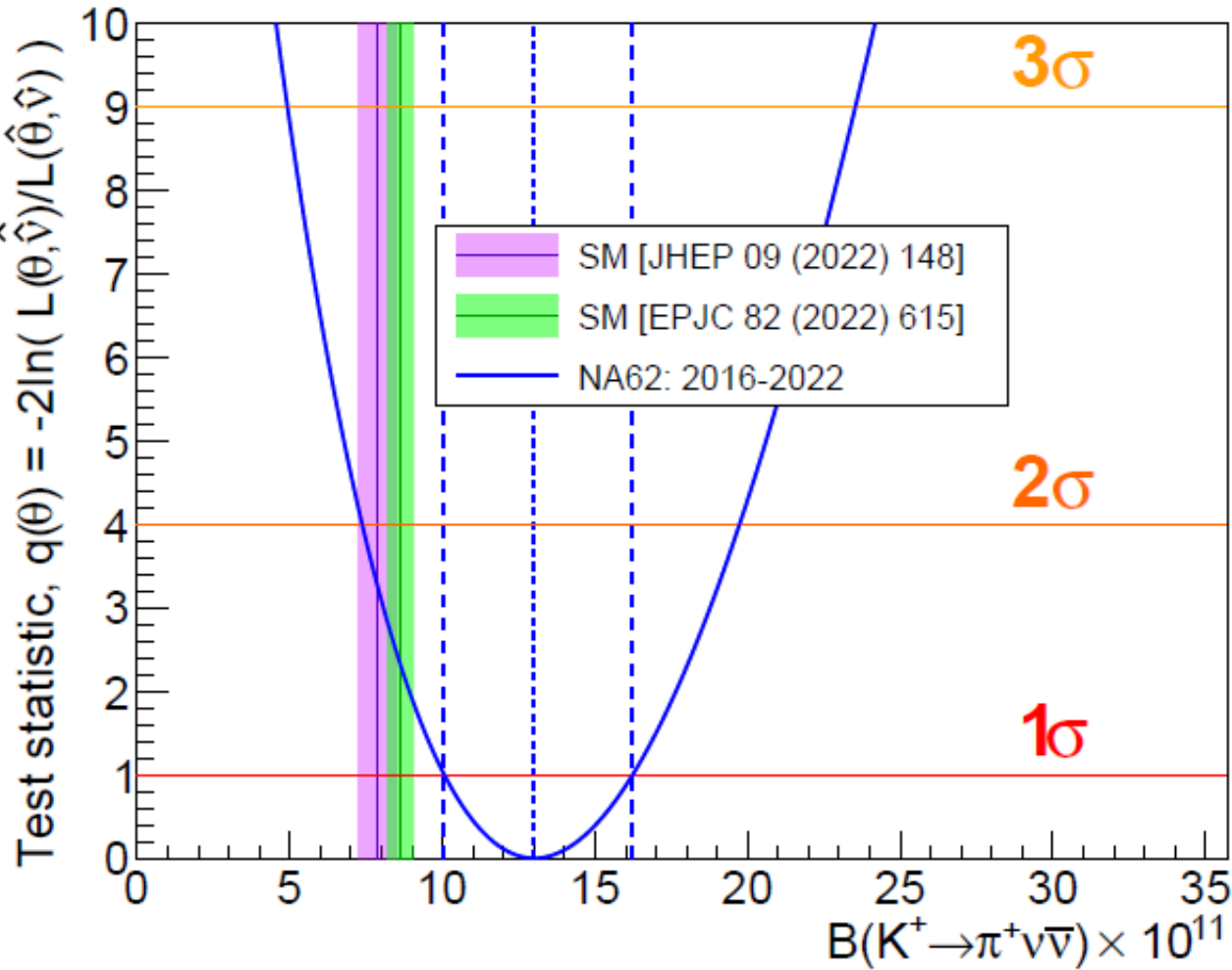


# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results: combined 2016-22 result

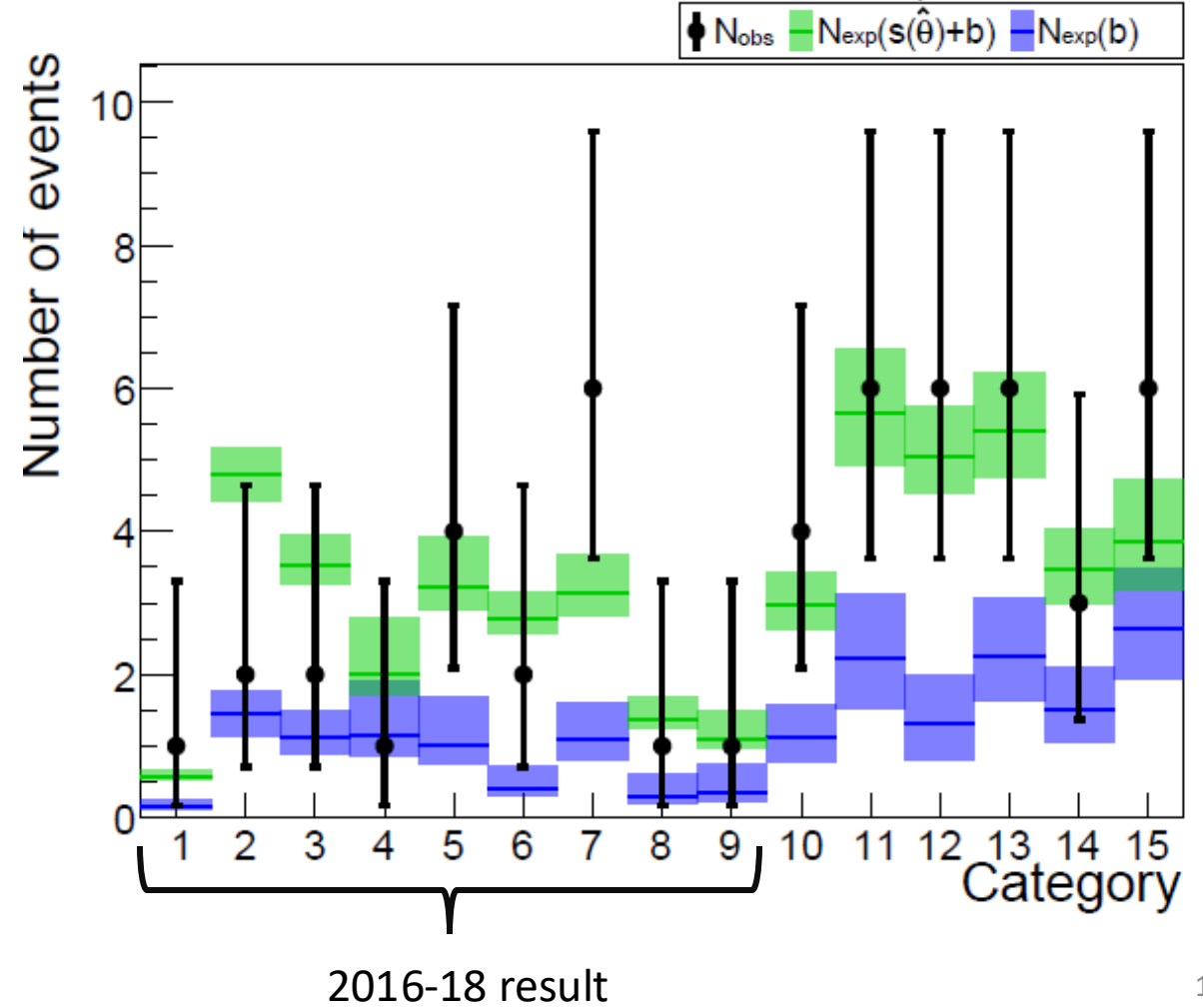


**b-only hyp. rejection significance:  $Z > 5\sigma$**

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left( 13.0_{-2.7}^{+3.0} \Big|_{stat} \quad +1.3_{-1.3} \Big|_{syst} \right) \times 10^{-11}$$



Expected SM signal:  $N_{\pi\nu\bar{\nu}}^{SM} \approx 20$   
 Expected background:  $N_{bg} = 18_{-2}^{+3}$   
**Observed:  $N_{obs} = 51$**



# Results in context

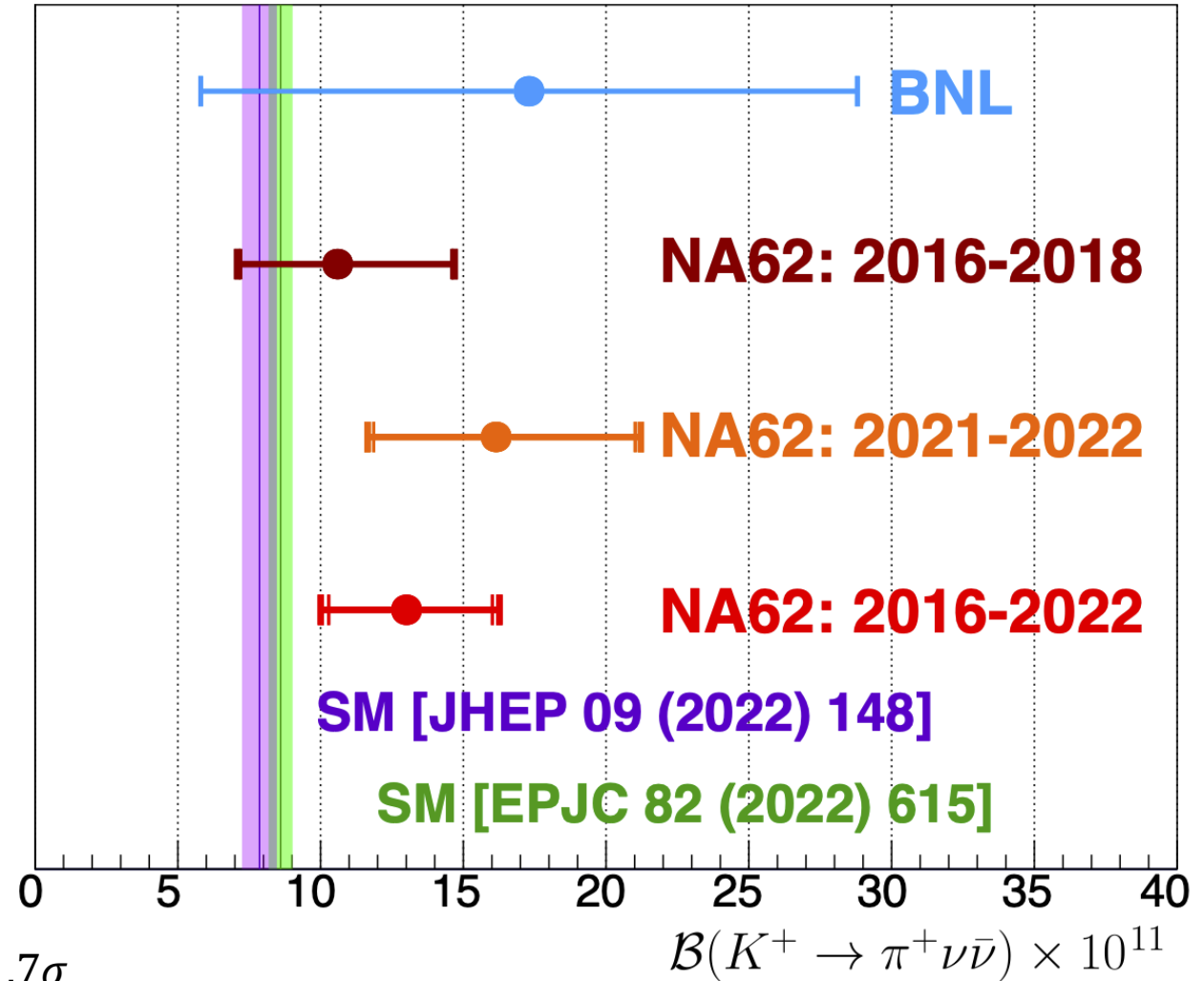
BNL E787/E949 experiment  
[Phys.Rev.D 79 (2009) 092004]

- $\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6_{-3.5}^{+4.1}\right) \times 10^{-11}$   
JHEP 06 (2021) 093

- $\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = \left(16.2_{-4.5}^{+5.1}\right) \times 10^{-11}$

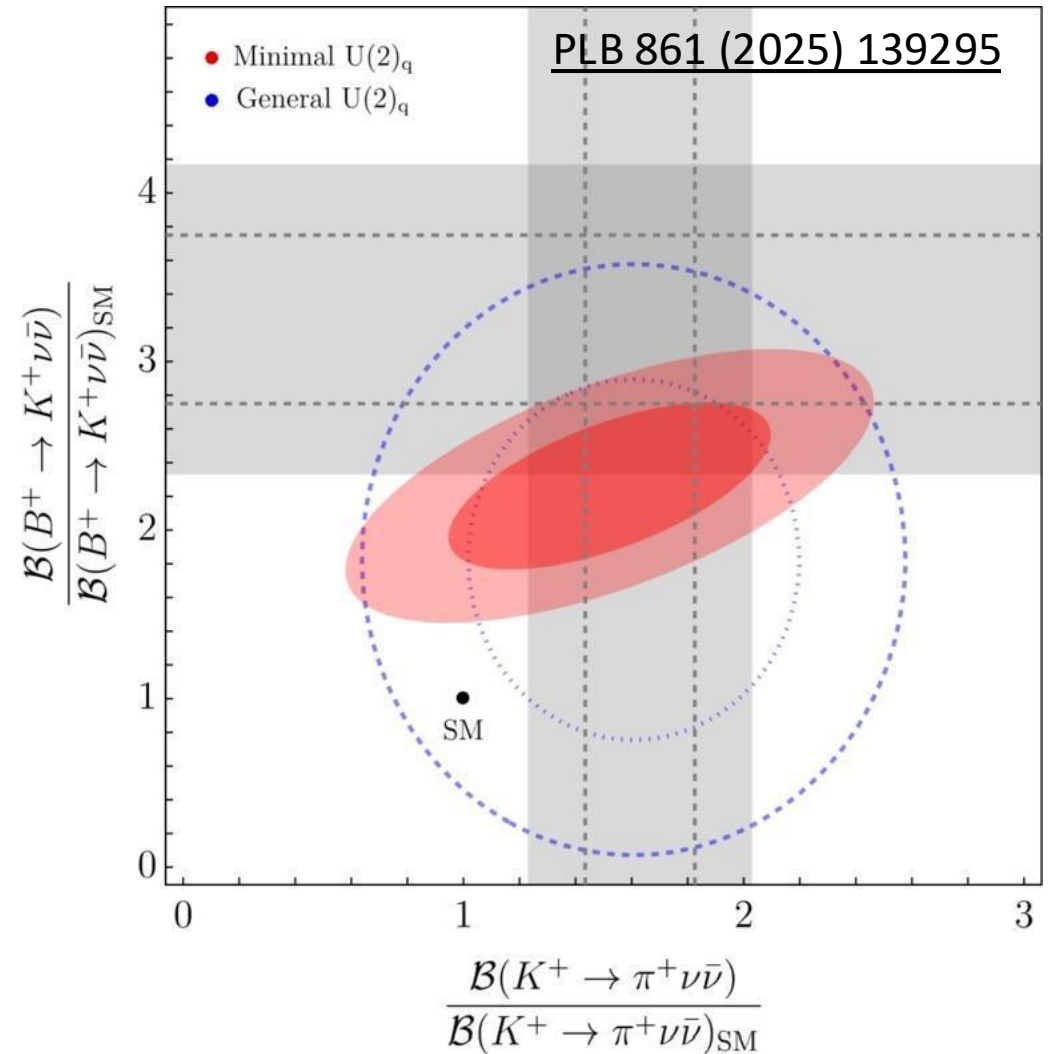
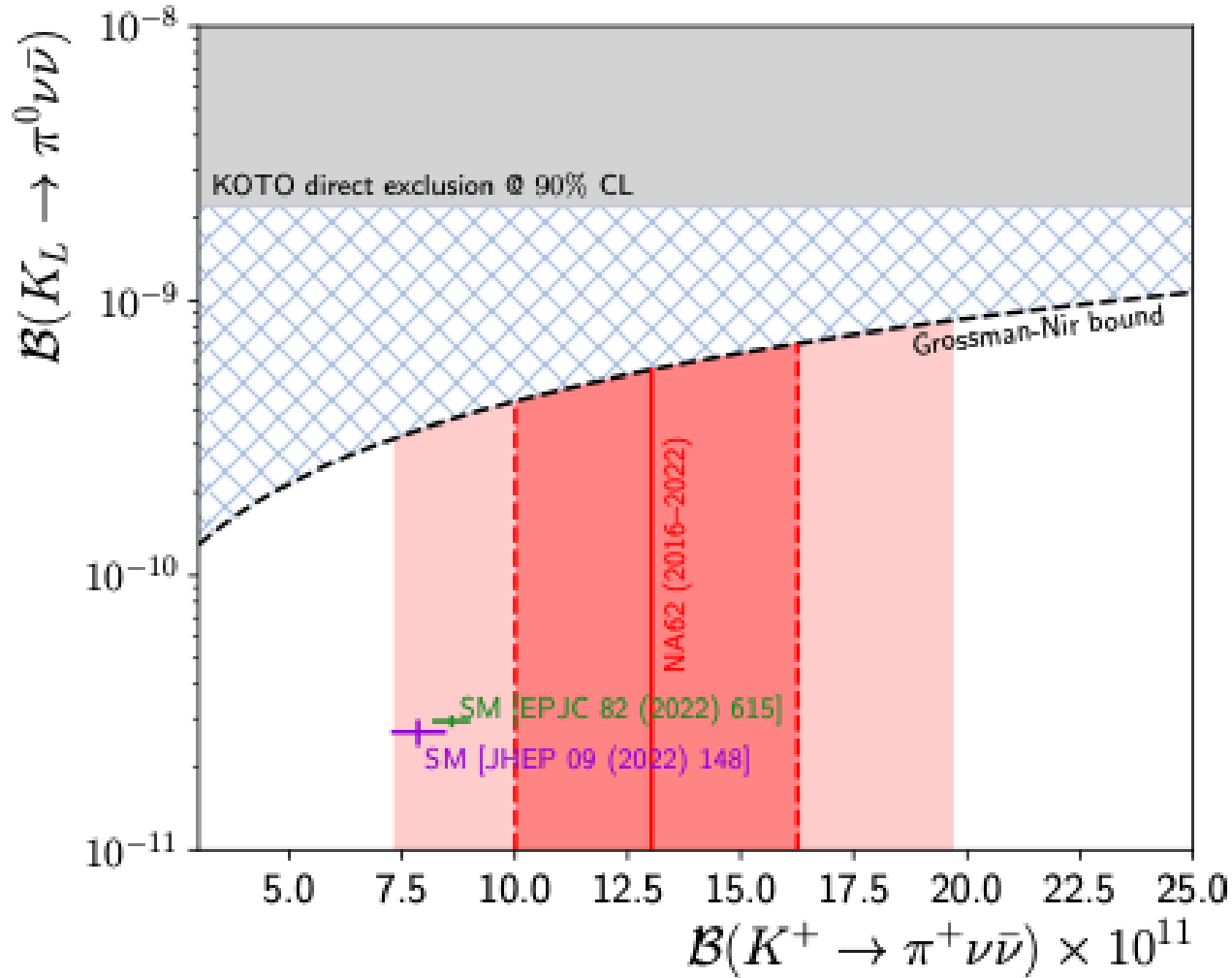
- $\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0_{-3.0}^{+3.3}\right) \times 10^{-11}$   
JHEP02(2025)191

- NA62 results consistent with previous results
- Central value moved up but still consistent with SM within  $1.7\sigma$
- Fractional uncertainty decreased: **40% → 25%**
- Bkg-only hypothesis rejected with significance  **$Z > 5$**



# Results in context

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left( \mathbf{13.0}^{+3.0}_{-2.7} \Big|_{stat} \quad \begin{matrix} +1.3 \\ -1.3 \end{matrix} \Big|_{syst} \right) \times \mathbf{10^{-11}} = \left( \mathbf{13.0}^{+3.3}_{-3.0} \right) \times \mathbf{10^{-11}} \quad \boxed{\text{JHEP02(2025)191}}$$



# $K^+ \rightarrow \pi^+ \gamma \gamma$ ( $K_{\pi\gamma\gamma}$ ) decays

- Rare decay that allows  $\chi_{PT}$  tests at  $O(p^6)$ : decay dominated by LD physics [PLB 386 403 (1996)]
- $BR(K^+ \rightarrow \pi^+ \gamma \gamma)$  at  $O(p^6)$  parametrized by a real parameter  $\hat{c}$

$$\frac{d^2\Gamma}{dydz}(\hat{c}, y, z) = \frac{m_K}{2^9 \pi^3} \left[ z^2 (|A(\hat{c}, z, y^2) + B(z)|^2 + |C(z)|^2) + \left( y^2 - \frac{1}{4} \lambda(1, r_\pi^2, z) \right)^2 |B(z)|^2 \right]$$

$\downarrow \qquad \qquad \downarrow \qquad \qquad \downarrow$   
 depend on external parameters

- Two main kinematic variables used to describe the decay:

$$z = \frac{m^2(\gamma\gamma)}{m_K^2}$$

$$y = \frac{p \cdot (q_1 - q_2)}{m_K^2}$$

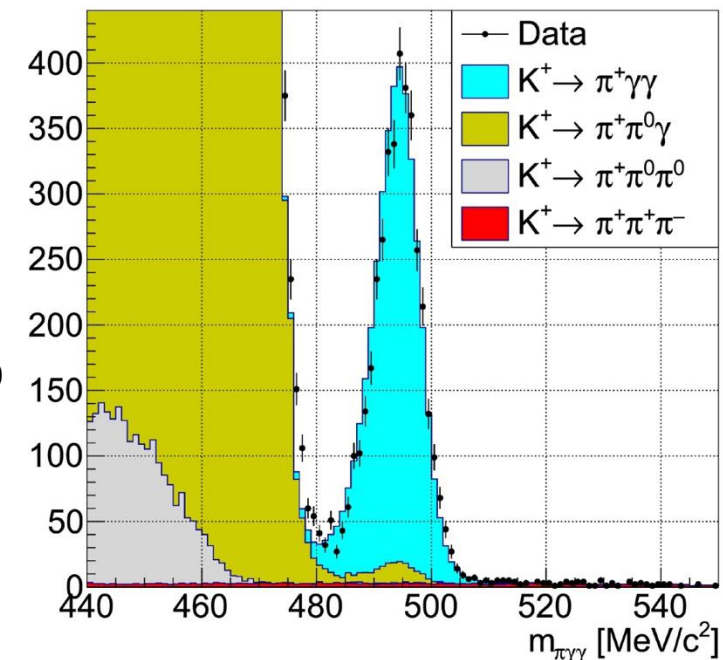
$q_i$  – photon momenta

$p$  – kaon momentum

- **Goal:** Measurement of both  $BR(K^+ \rightarrow \pi^+ \gamma \gamma)$  and  $\hat{c}$

# $K^+ \rightarrow \pi^+ \gamma \gamma$ ( $K_{\pi\gamma\gamma}$ ) decays

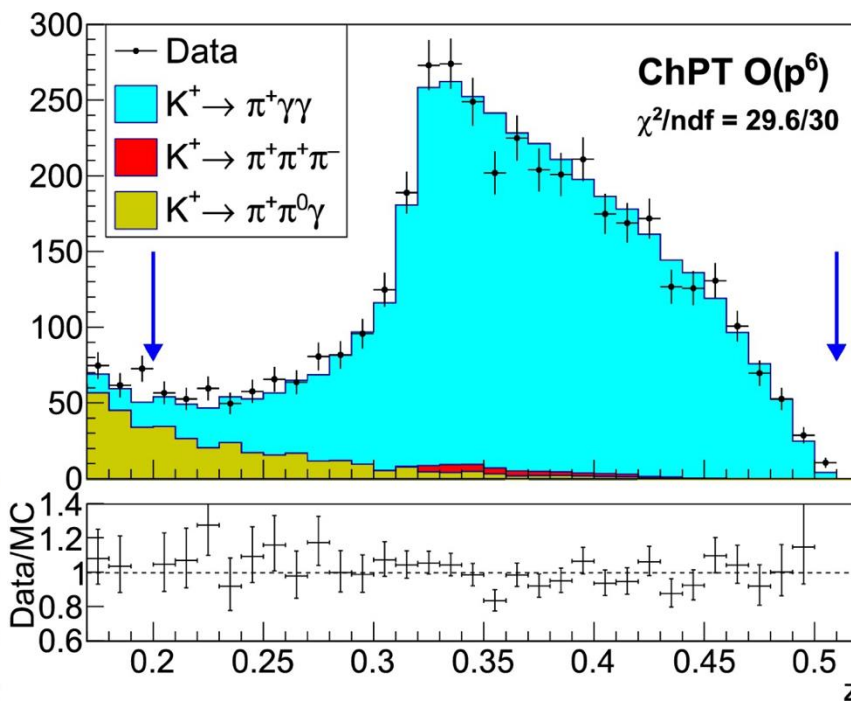
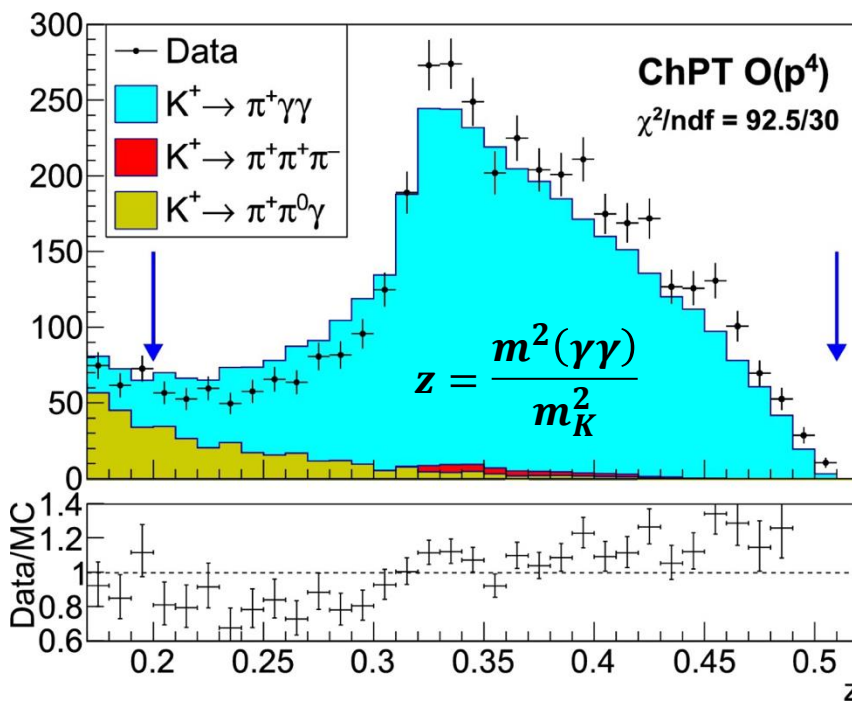
- Dedicated non-muon trigger lines used for this measurement
- The analysis is based on the data collected in 2017 and 2018
- **Normalisation channel:**  $K^+ \rightarrow \pi^+ \pi^0$  decay  $\rightarrow N_K^{eff} = (5.55 \pm 0.03) \times 10^{10}$
- $z$  computed using the  $K^+$  and  $\pi^+$  four-momenta (missing mass)



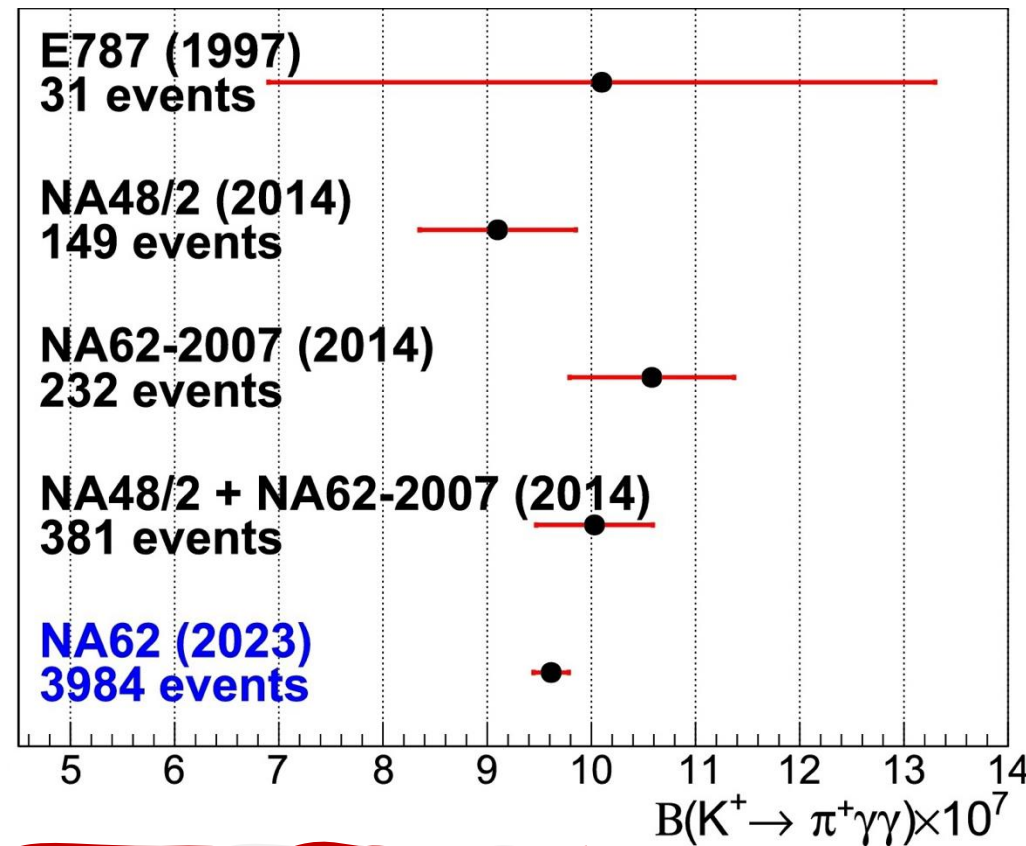
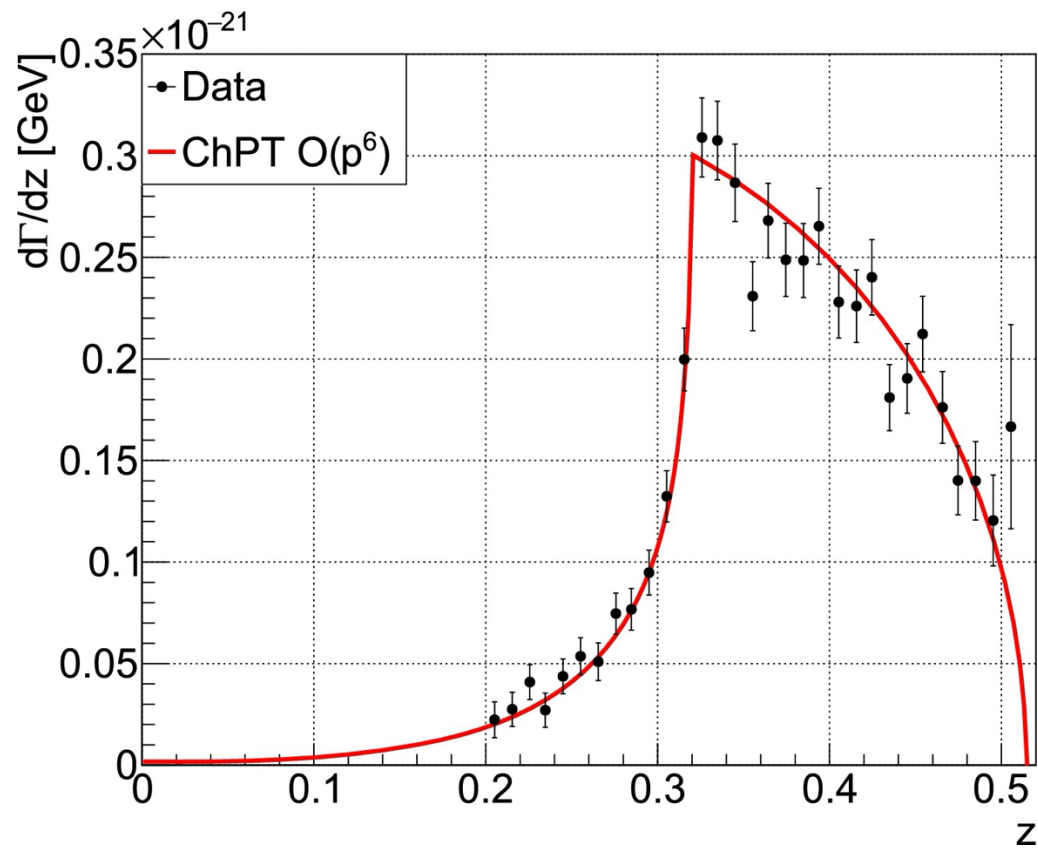
PLB850 (2024) 138513

Expected background:  $N_{bg} = 291 \pm 14$

**Candidates observed:  $N_{obs} = 3984$**



# $K^+ \rightarrow \pi^+ \gamma\gamma$ ( $K_{\pi\gamma\gamma}$ ) decays: results



$$\hat{c}_6 = 1.144 \pm 0.069_{stat} \pm 0.034_{syst}$$

$$\mathcal{B}_{ChPT O(p^6)}(K^+ \rightarrow \pi^+ \gamma\gamma) = (9.61 \pm 0.15_{stat} \pm 0.07_{syst}) \times 10^{-7}$$

$$\mathcal{B}_{MI}(K^+ \rightarrow \pi^+ \gamma\gamma | z > 0.2) = (9.46 \pm 0.19_{stat} \pm 0.07_{syst}) \times 10^{-7}$$

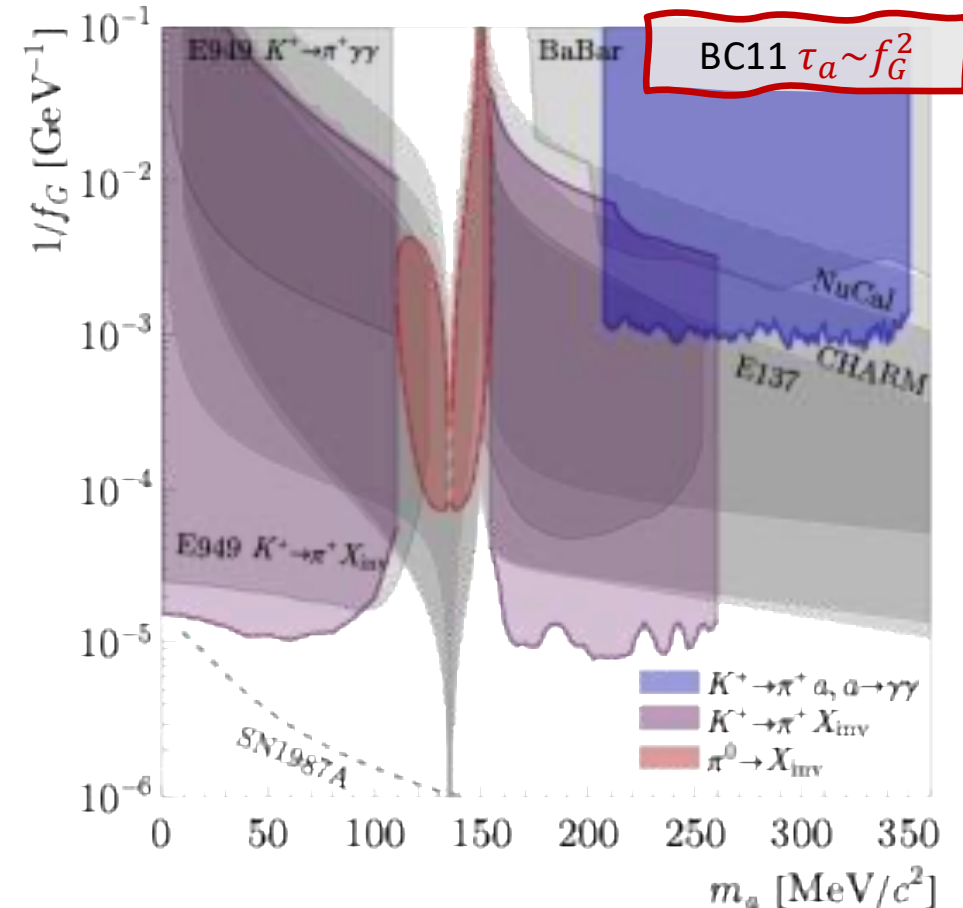
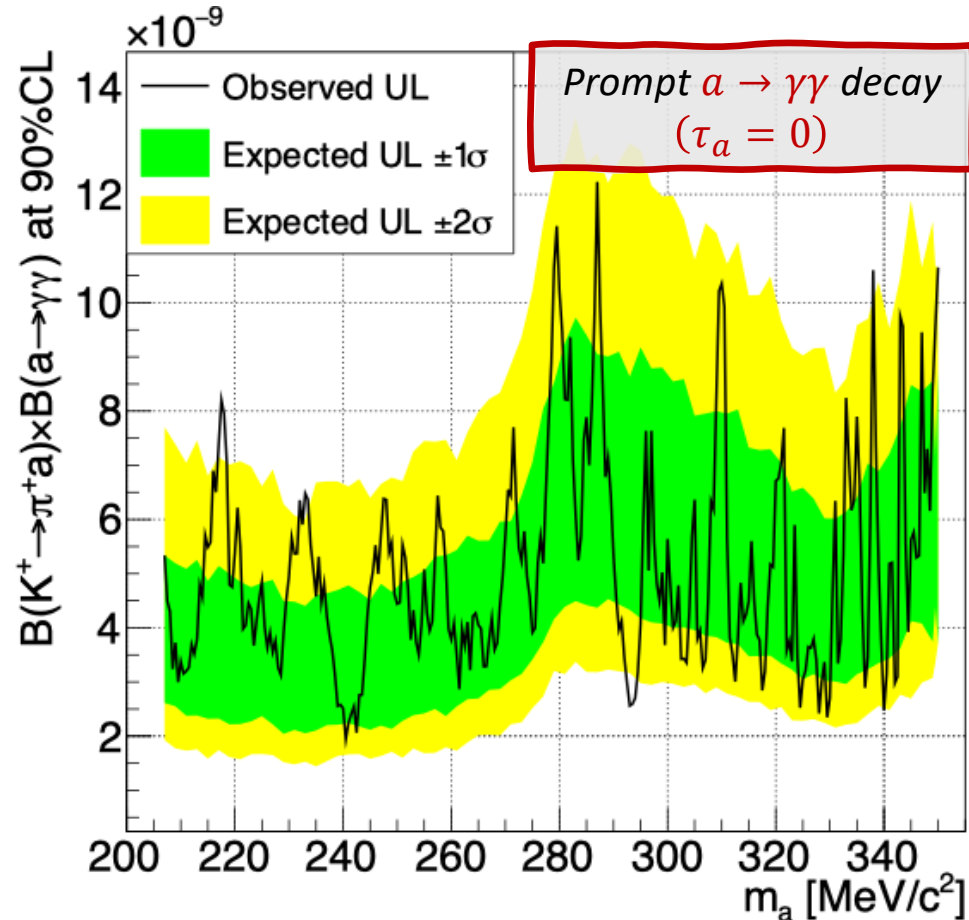
PLB850 (2024) 138513

# ALPs in $K^+ \rightarrow \pi^+ a, a \rightarrow \gamma\gamma$ decay

PLB850 (2024) 138513



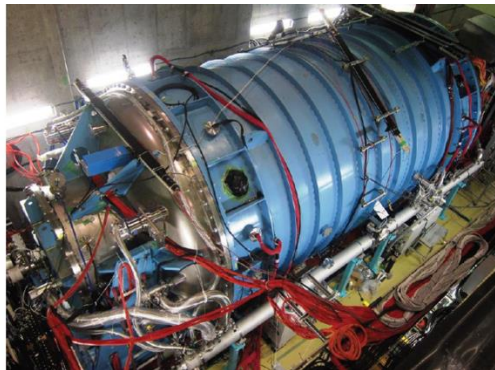
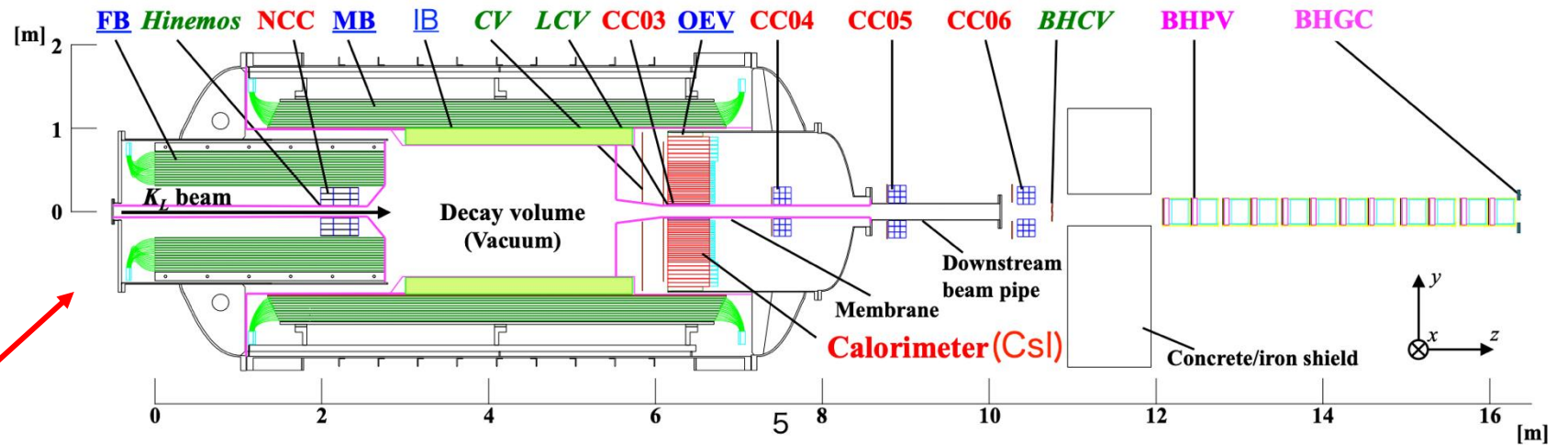
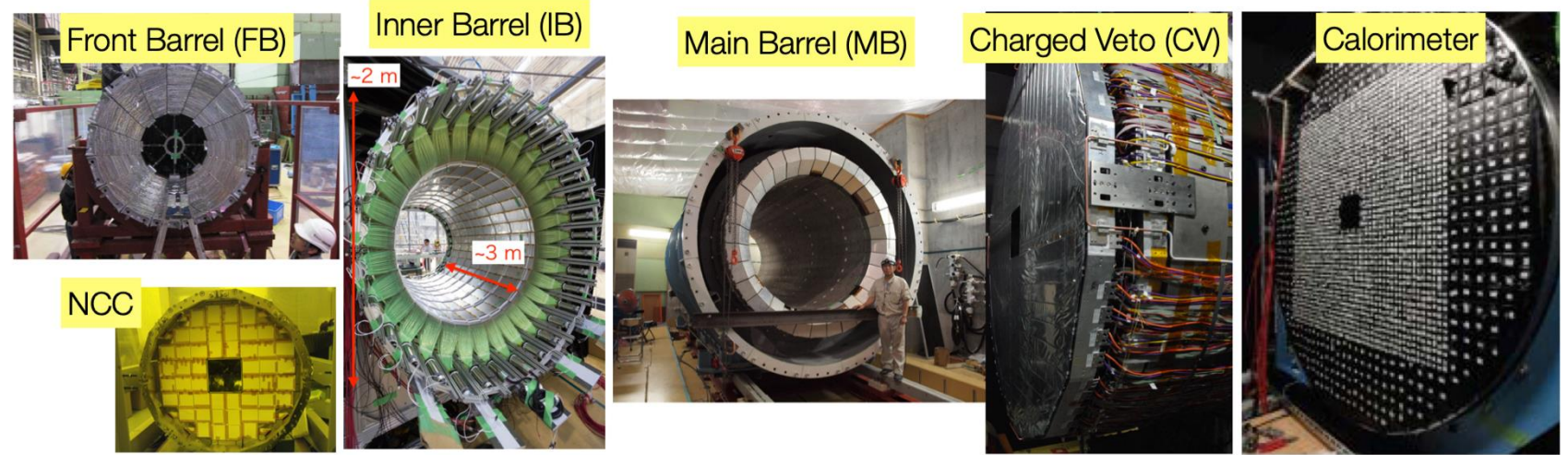
- Peak search over  $m_a = \sqrt{(P_K - P_\pi)^2}$  in the range 207 – 350 MeV/c<sup>2</sup> in steps of 0.5 MeV/c<sup>2</sup>
- $m_a$  resolution: 2.0 – 0.2 MeV/c<sup>2</sup> varying across the search range
- For each  $m_a$  hypothesis background estimated from simulations and UL set using CLs



# KOTO experiment: a search for $K_L \rightarrow \pi^0 \nu \bar{\nu}$



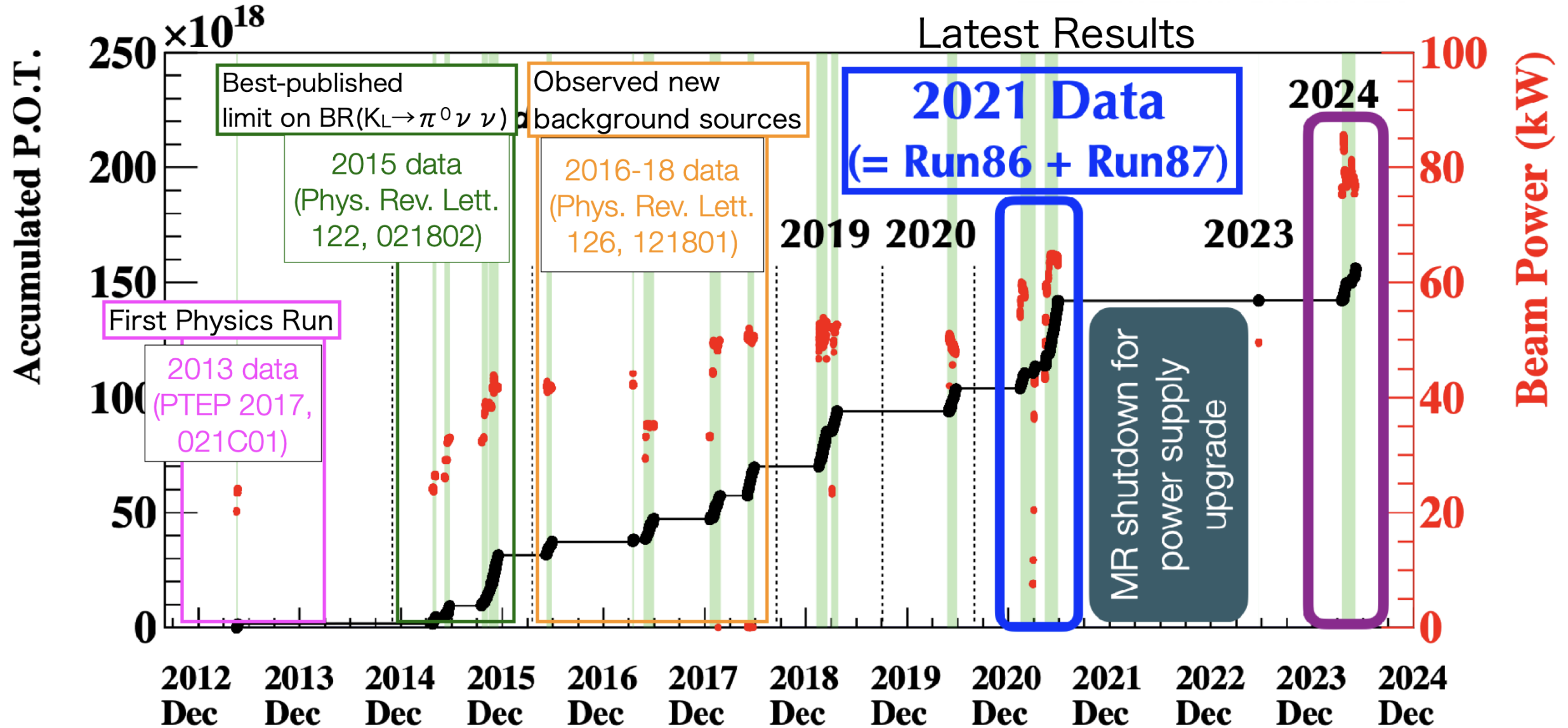
Search for  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  decay @ J-PARC



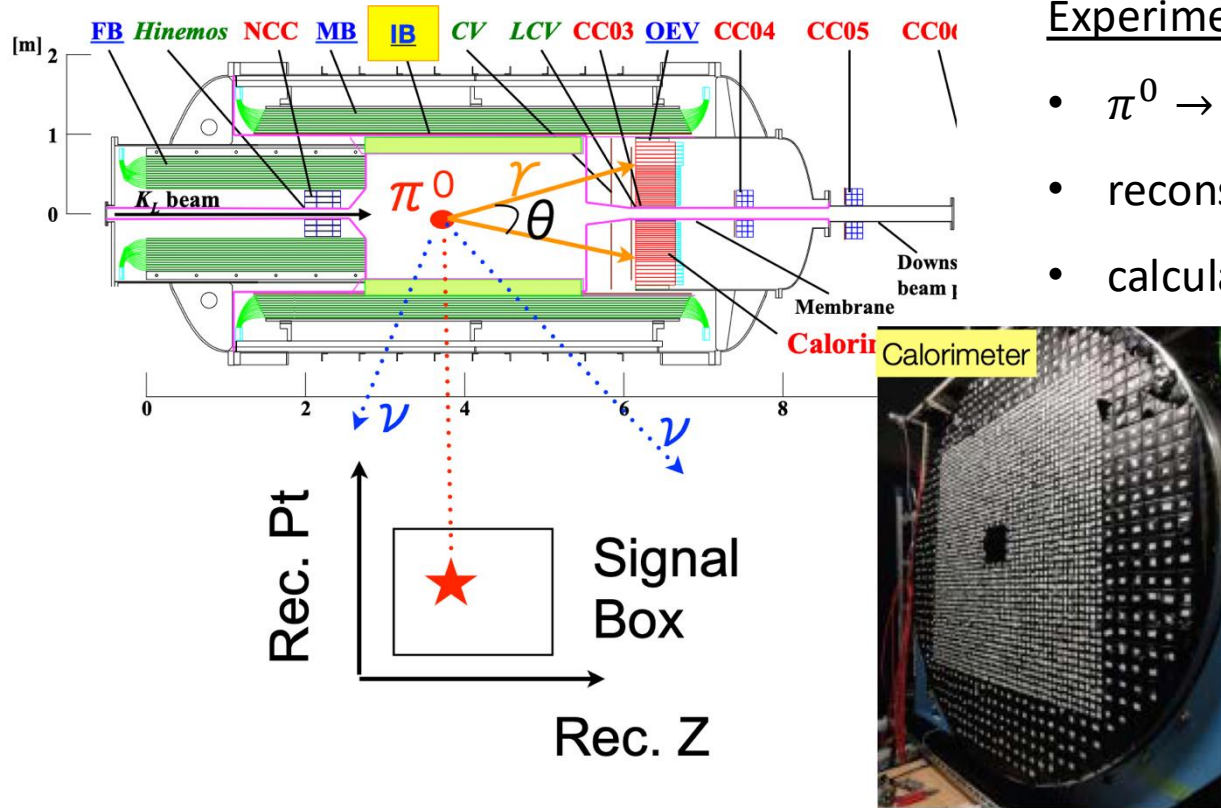
# KOTO experiment: a search for $K_L \rightarrow \pi^0 \nu \bar{\nu}$



Latest Results



# KOTO experiment: a search for $K_L \rightarrow \pi^0 \nu \bar{\nu}$



## Experimental technique

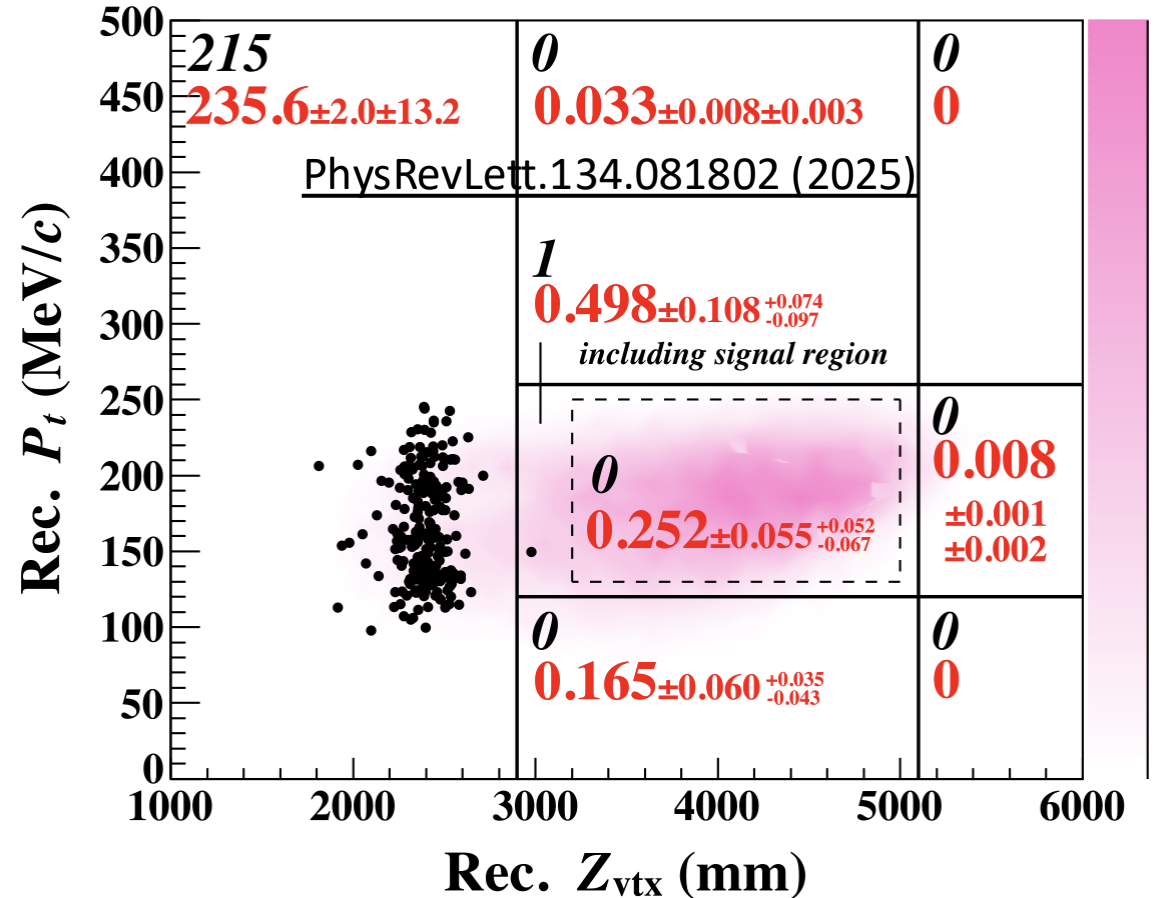
- $\pi^0 \rightarrow \gamma\gamma$  + no other particles (hermetic veto system)
- reconstruction assumes  $\gamma\gamma$  from  $\pi^0$  to calculate the  $Z_{vtx}$
- calculate  $\pi^0$  transverse momentum

$$m^2(\pi^0) = 2E_1E_2(1 - \cos\theta)$$

- $SES = (9.33 \pm 0.06_{stat} \pm 0.84_{syst}) \times 10^{-10}$

- No observed events in the signal region

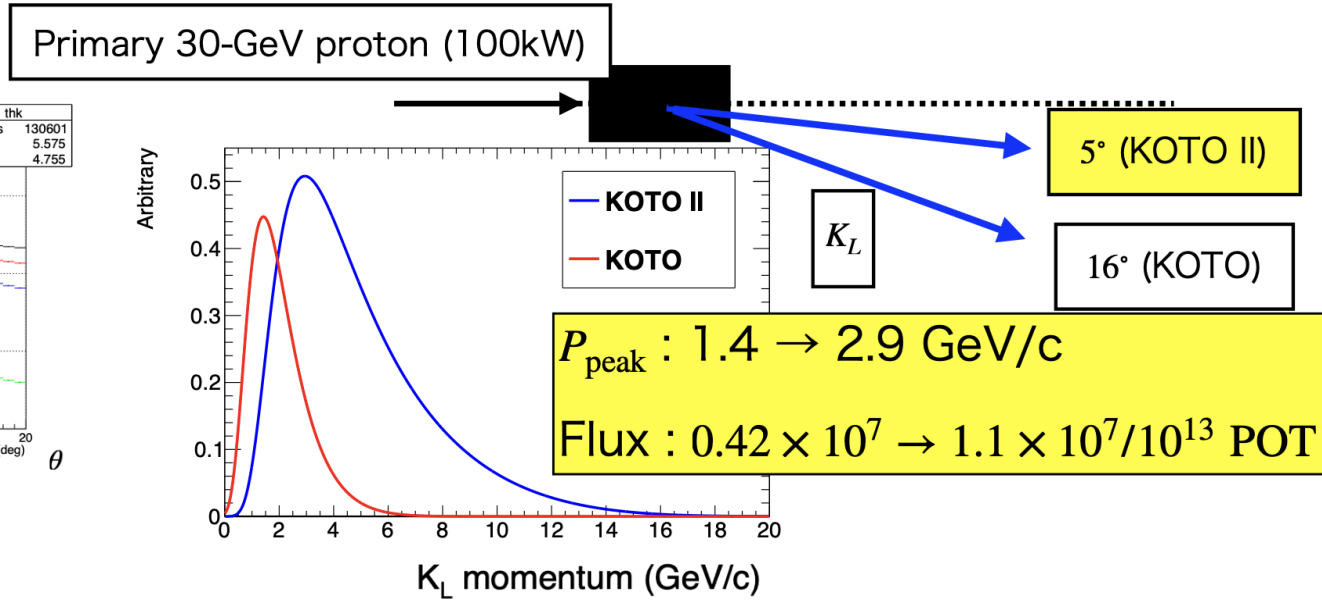
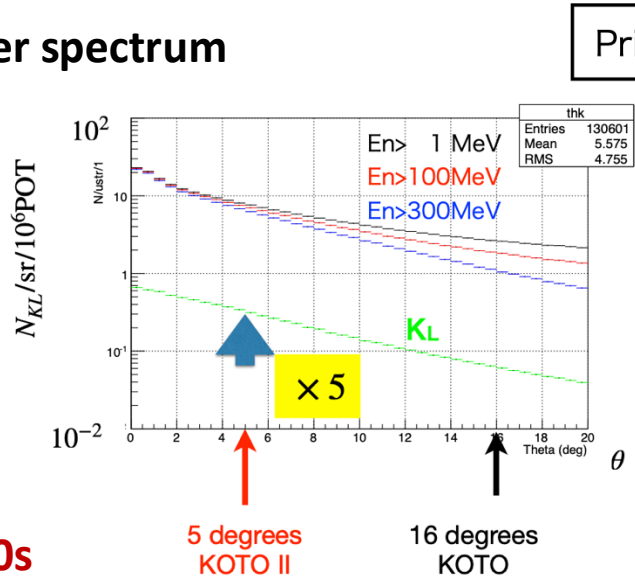
- $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.1 \times 10^{-9}$  at 90% CL



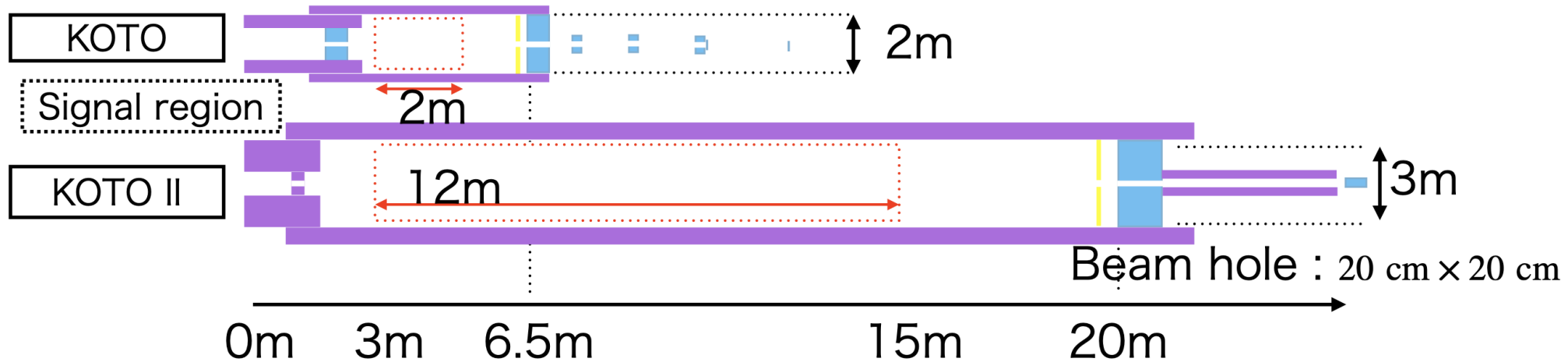
# How to improve sensitivity: KOTO II



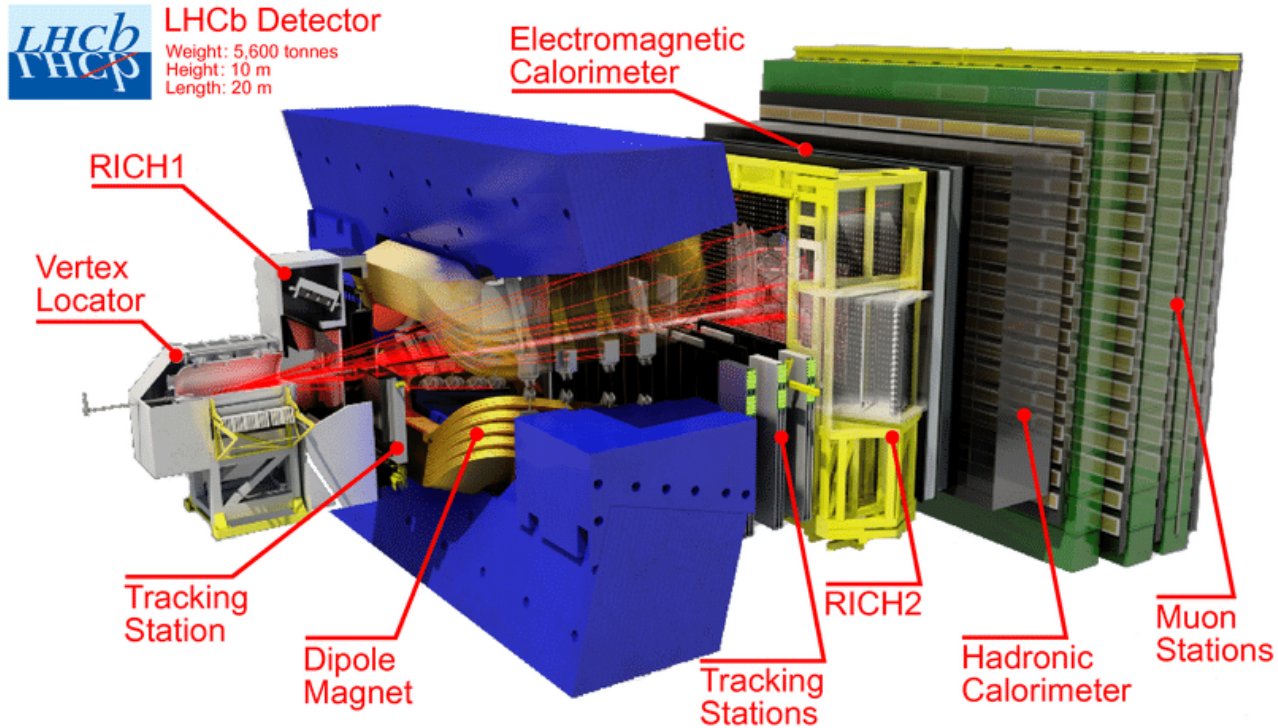
- More  $K_L \rightarrow$  forward production angle
  - $\times 2.6$  larger flux + **harder spectrum**
- Larger signal acceptance
  - longer decay volume
  - larger calorimeter



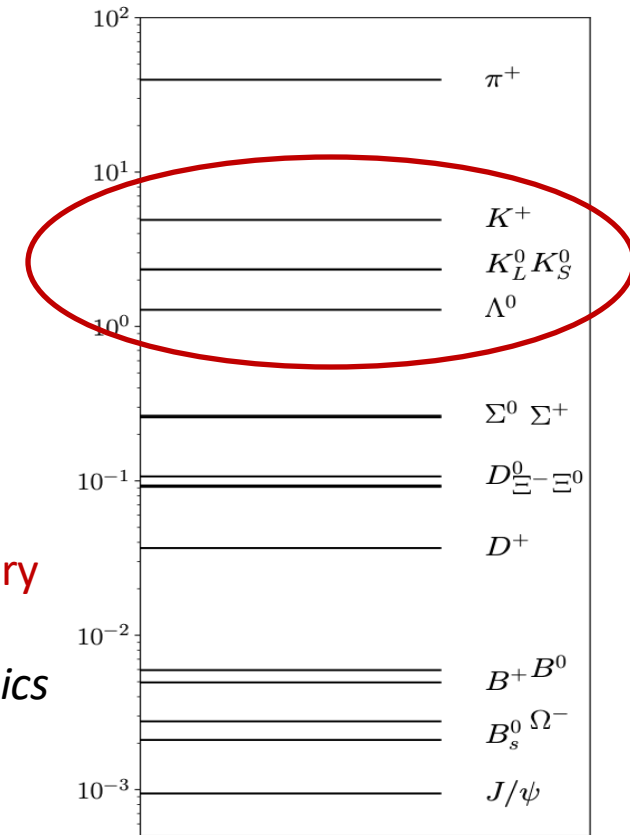
**Proposed to start in the 2030s**



# Kaons at LHCb



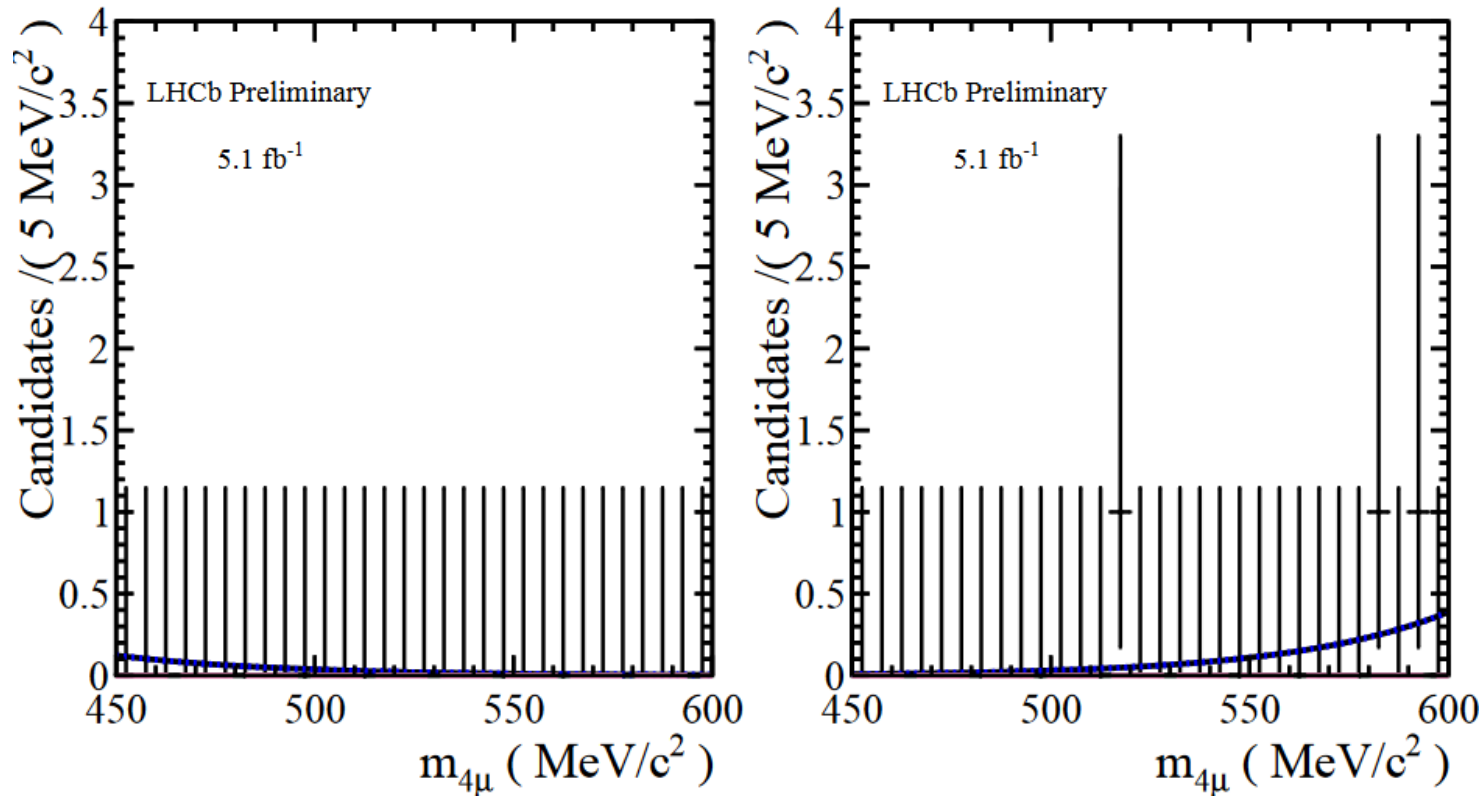
Multiplicity of particles produced in a single  $pp$  interaction at  $\sqrt{s} = 13$  TeV within LHCb acceptance.



- Originally conceived as a  $B$ -meson factory: **huge cross section for kaon production  $\rightarrow K$  factory**
- Fully software-based trigger introduced in Run 3  $\rightarrow \mathcal{O}(100\%)$  *trigger efficiency for kaon physics*
- **Unique opportunity to look for extremely rare kaon processes!**  
[PRL 125 \(2020\) 231801](https://arxiv.org/abs/2002.03311)
- **Flagship kaon mode:**  $\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10}$  @ 90% CL (Run 1 + 2)
  - **prospects to reach  $\mathcal{O}(10^{-11})$  sensitivity with Run 3 data (analysis ongoing)**

# Rare kaon decays at LHCb

- Search for  $K_{S(L)}^0 \rightarrow \mu\mu\mu\mu$  decays, heavily suppressed in the SM:  $10^{-13}(K_L^0), 10^{-14}(K_S^0)$
- No events found in signal region (Run 1 + 2)
- **World's best (first) upper limits on these decays**
- $K_{S(L)}^0 \rightarrow \pi\pi\mu\mu$  search with Run 2 data ongoing (stay tuned)



$$BR(K_S^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 5.1 \times 10^{-12}$$

$$BR(K_L^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 2.3 \times 10^{-9}$$

PRD 108 (2023) L031102

**Plenty of kaon physics results  
to come from Run 3 data**

# Summary and prospects

- Kaon physics remains highly relevant and complementary to other HEP efforts
  - $s \rightarrow d$  transitions offers unique opportunities to probe NP flavour structure at the multi-TeV scale
- Observation of the  $K^+ \rightarrow \pi^+ \bar{\nu} \nu$  decay by NA62 with BR consistent with the SM within  $1.7\sigma$ 
  - $\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = (13.0_{-2.9}^{+3.3}) \times 10^{11}$  [JHEP02\(2025\)191](#) (full NA62 data set needed to clarify SM agreement or tension)
  - rarest particle decay observed ( $Z > 5\sigma$ ) and the first with third generation leptons ( $\bar{\nu}_\tau \nu_\tau$ )
  - 2023 – 24 data same at the same order of the 2016 – 22 sample (analysis ongoing)
  - NA62 will take data until the start of LS3 (summer 2026)
- KOTO is making progress:  $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 2.1 \times 10^{-9}$  at 90% CL [PhysRevLett.134.081802 \(2025\)](#)
- LHCb can make an impact on rare  $K_S$  decays thanks to the huge strange cross section and fully software trigger in Run 3!
- NA62, KOTO, and LHCb are collecting data and would ensure a steady stream of kaon physics results in the coming years!

