Experimental perspectives in Kaon physics

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Why kaons?

- <u>Important questions we still haven't answered:</u> What is origin of the SM flavour structure?
  - hierarchies of the fermion Yukawa couplings and mixing parameters, observed matter-antimatter asymmetry, etc…

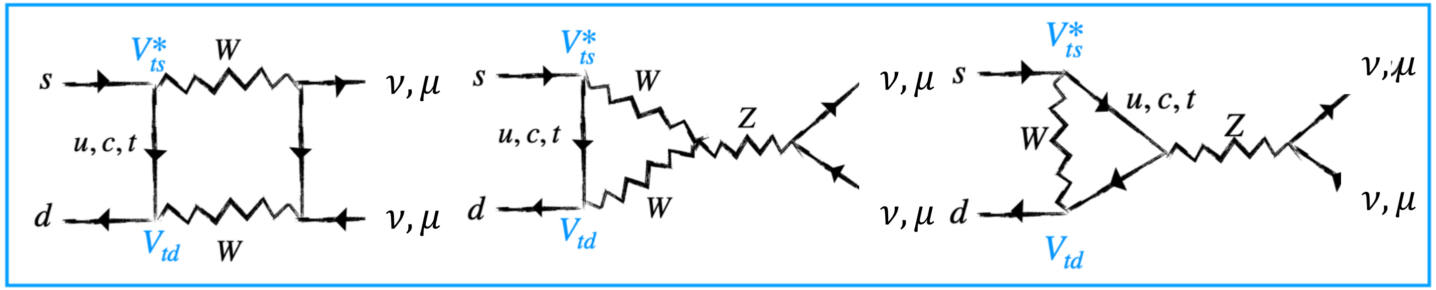
- Rare $s \to d\nu\bar{\nu}$ and $s \to d\ell^+\ell^-(\ell = e, \mu)$ transitions in the kaon sector offers insight into the SM flavour structure
  - Flavour Changing Neutral Currents (FCNCs) forbidden at tree level → **loop + CKM suppression**
  - several golden-plated observables: **dominated by Short Distance (SD) physics** → Precisely known theoretically **High NP sensitivity up to $\mathcal{O}(100\ \mathrm{TeV})$**
  - 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

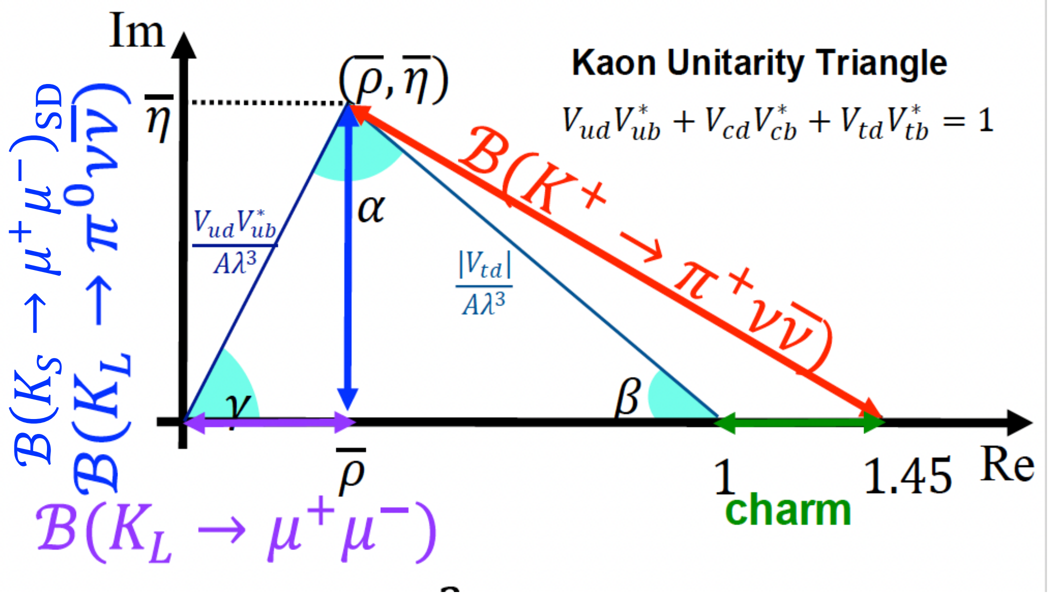
- Details on the motivation and prospects for kaon physics can be found in the input submitted to the European strategy by the kaon physics community

arXiv:2505.02568, arXiv:2503.22256

Gold-plated kaon observables

Gold-plated observables
$K^+ \to \pi^+ \nu\bar{\nu}, K_L \to \pi^0 \nu\bar{\nu}$
$K_S - K_L \to \mu\mu$ interference





Theoretical status

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (7.86 \pm 0.61) \times 10^{-11}$

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

[JHEP 09 (2022) 148]

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

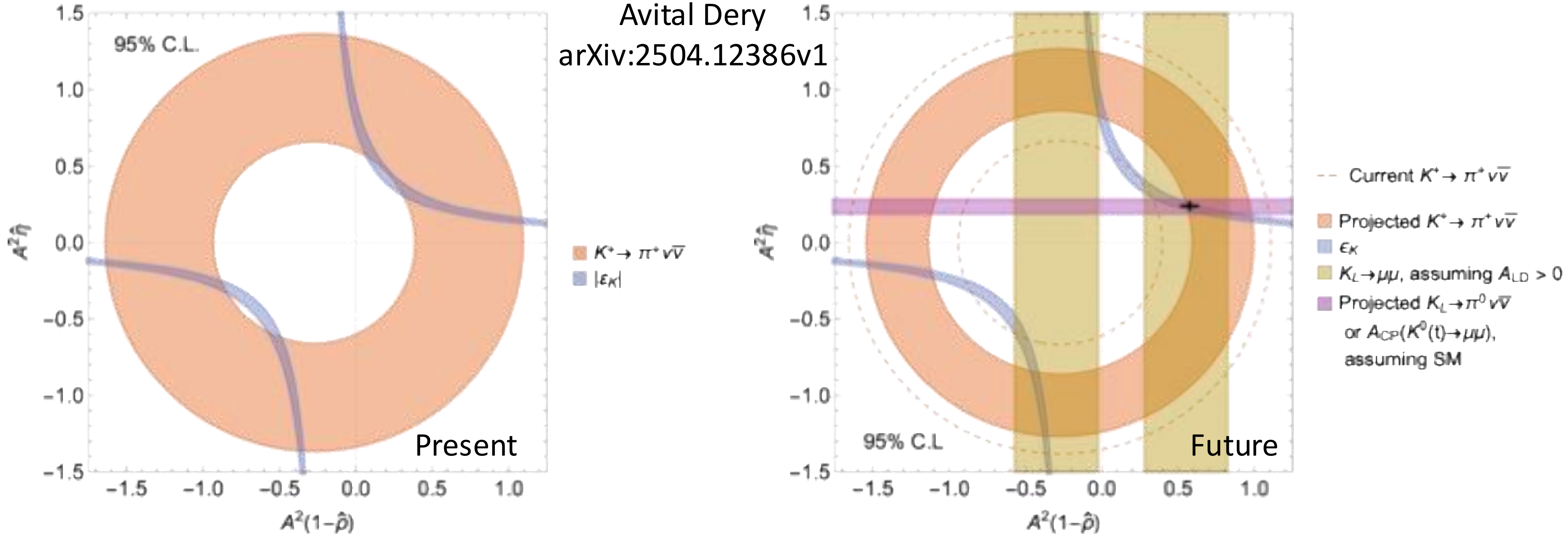
$\mathcal{B}(K_S \to \mu^+\mu^-)_{SM} = (5.18 \pm 1.50) \times 10^{-12}$ [PRL 119 201802 (2017)]

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

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

Gold-plated kaon observables: CKM tests

Avital Dery
arXiv:2504.12386v1



- Kaon physics can be used to independently determine 3/4 parameters of the CKM matrix w/o B physics input
- Presenting kaon information in the $(\hat{\rho}, \hat{\eta})$ plane → artificial error inflation due to $|V_{cb}|$ dependence
- More natural to present the kaon CKM information in the $(A^2(1-\hat{\rho}), A^2\hat{\eta})$ plane → avoid B physics input
- Test of the CKM picture exclusively with loop observables in the kaon sector!

Testing the CKM mechanism across the different flavour sectors important

Experimental status of rare kaon observables

Main players

$K_{S(L)}$ decays

More details in
Jacopo Pinzino's talk

K^+ decays

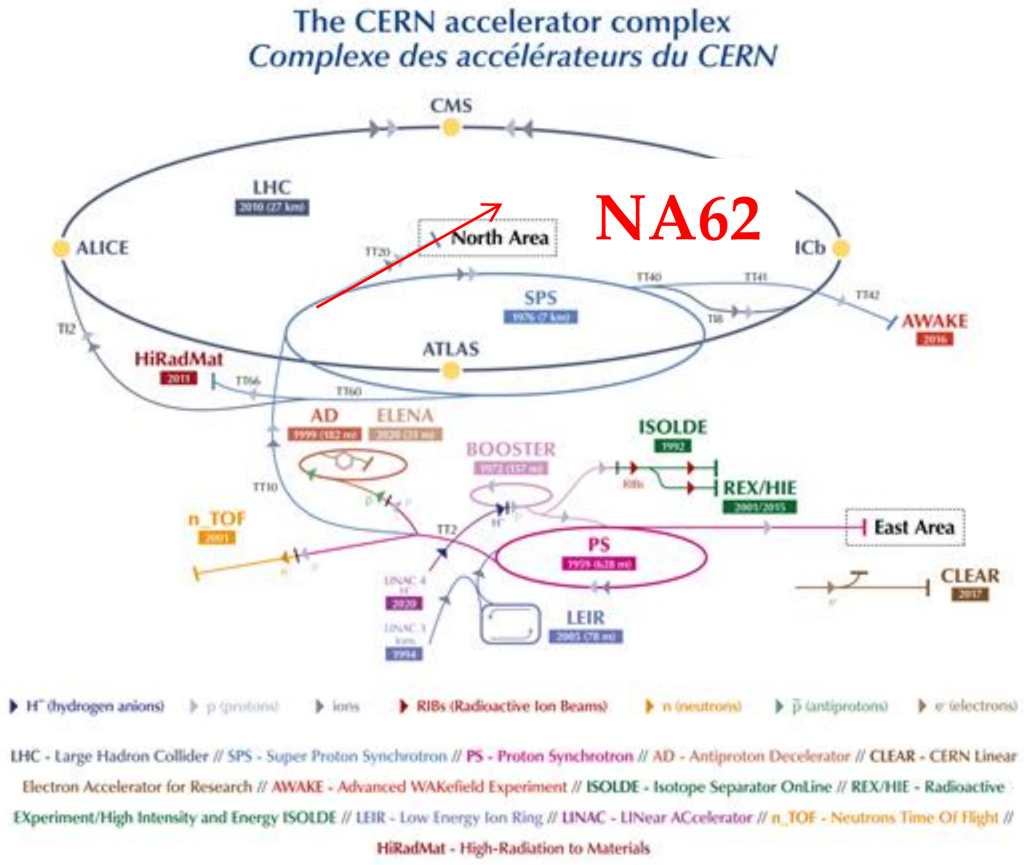
More details in
Yu-Chen Tung's talk

K_L decays

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

NA62 experiment

$K_{L,S}$	$K_{L,S}$	K_S	$K^{\pm}$	K^+	K^+	K^+
NA31	NA48	NA48/1	NA48/2	NA62 – R_K	NA62 Run1	NA62 Run2
1986 – 88	1997 – 2001	2002	2003 – 4	2007 – 8	2016 – 18	2021 –

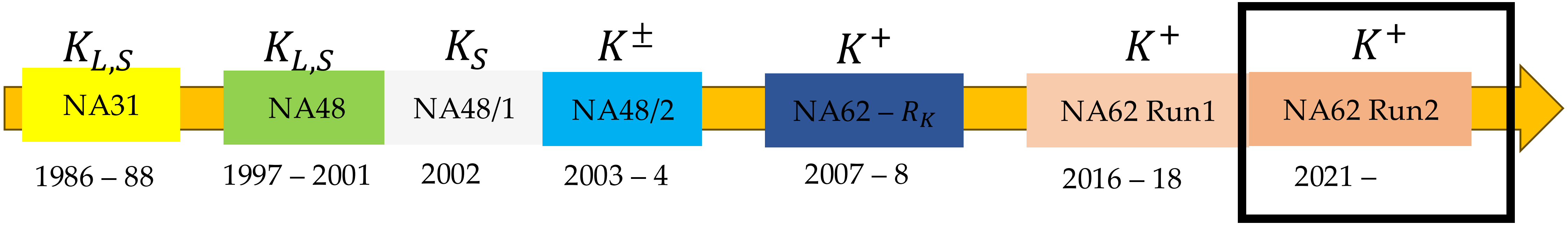


~ 200 physicists from 30 institutions

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

This talk

NA62 experiment



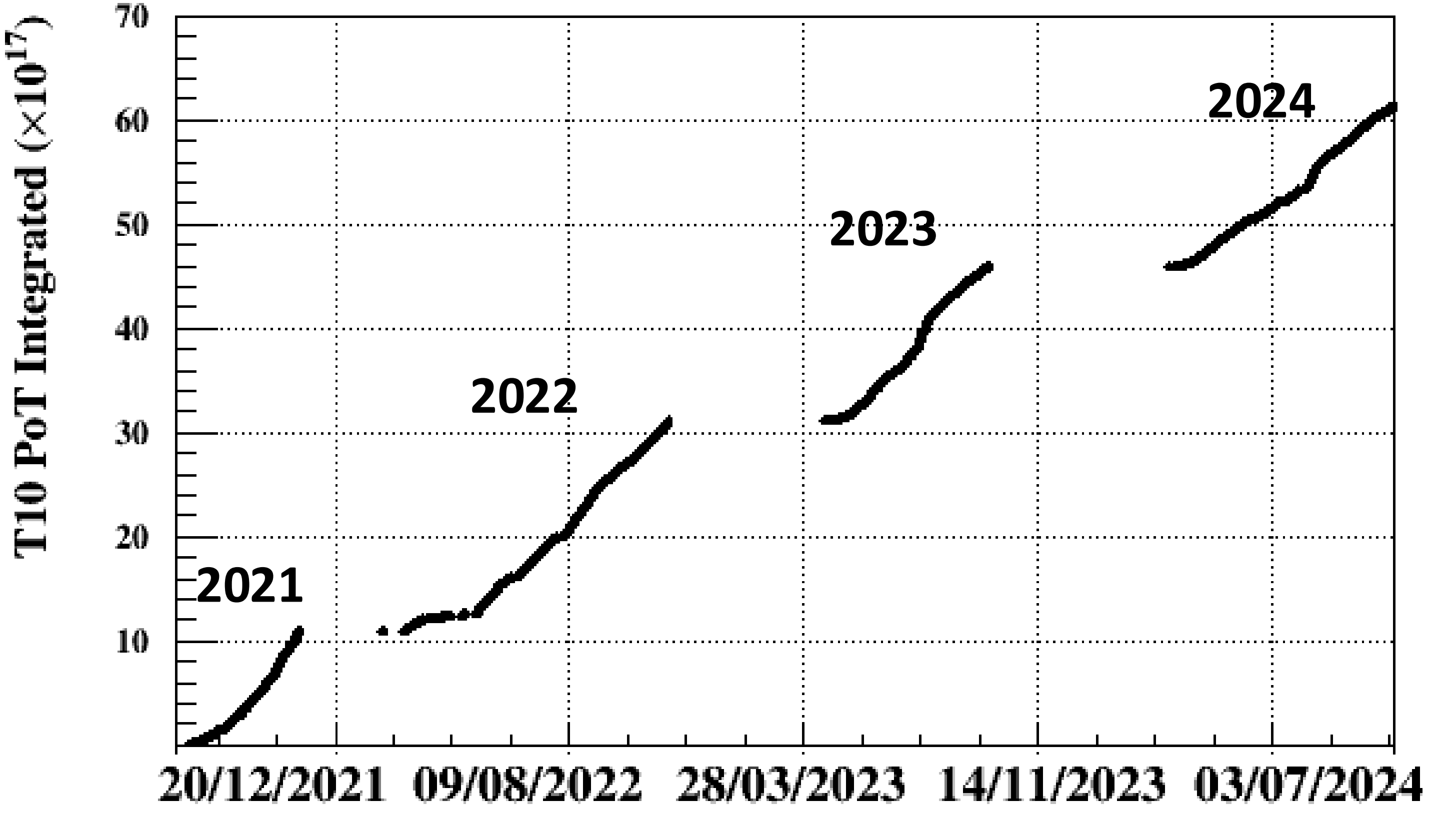
2016 – 18: ~ 0.9×10^6 spills collected

~ 22×10^{17} PoT delivered

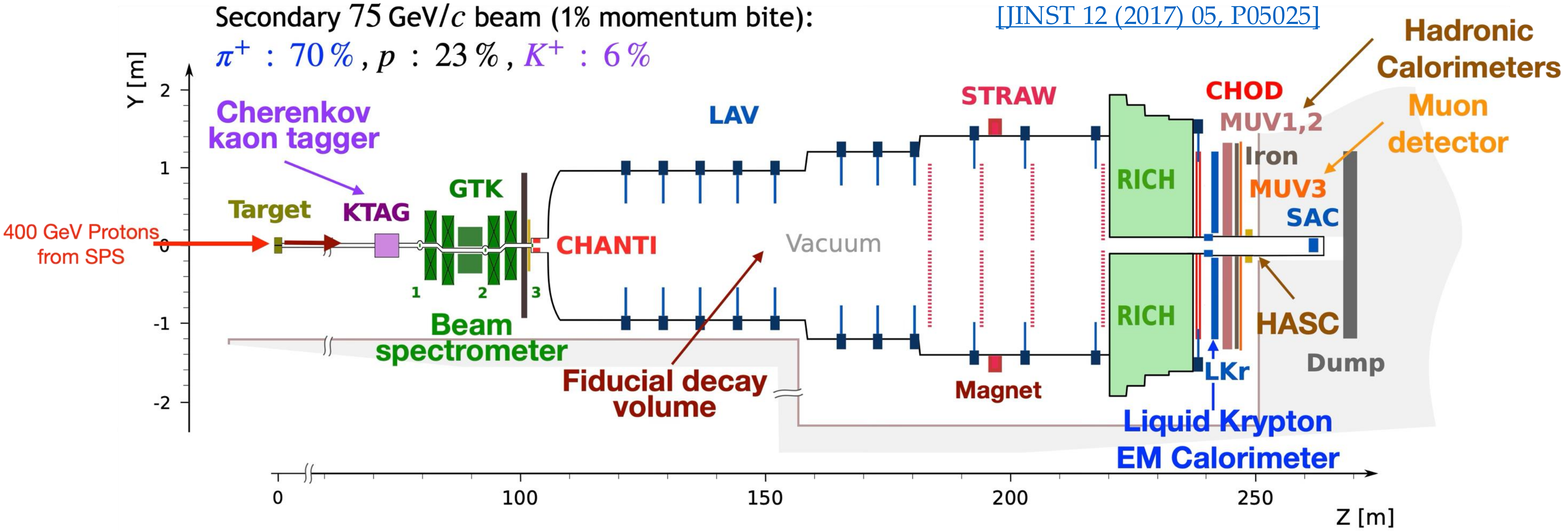
> 3σ $K^+ \to \pi^+ \nu \bar{\nu}$ evidence

[JHEP06(2021)093]

2021 – present: ~1.5×10^6 spills collected

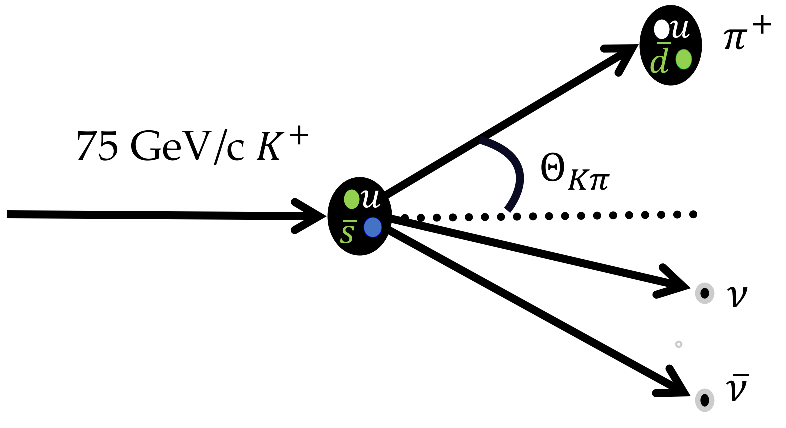


The NA62 detector



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

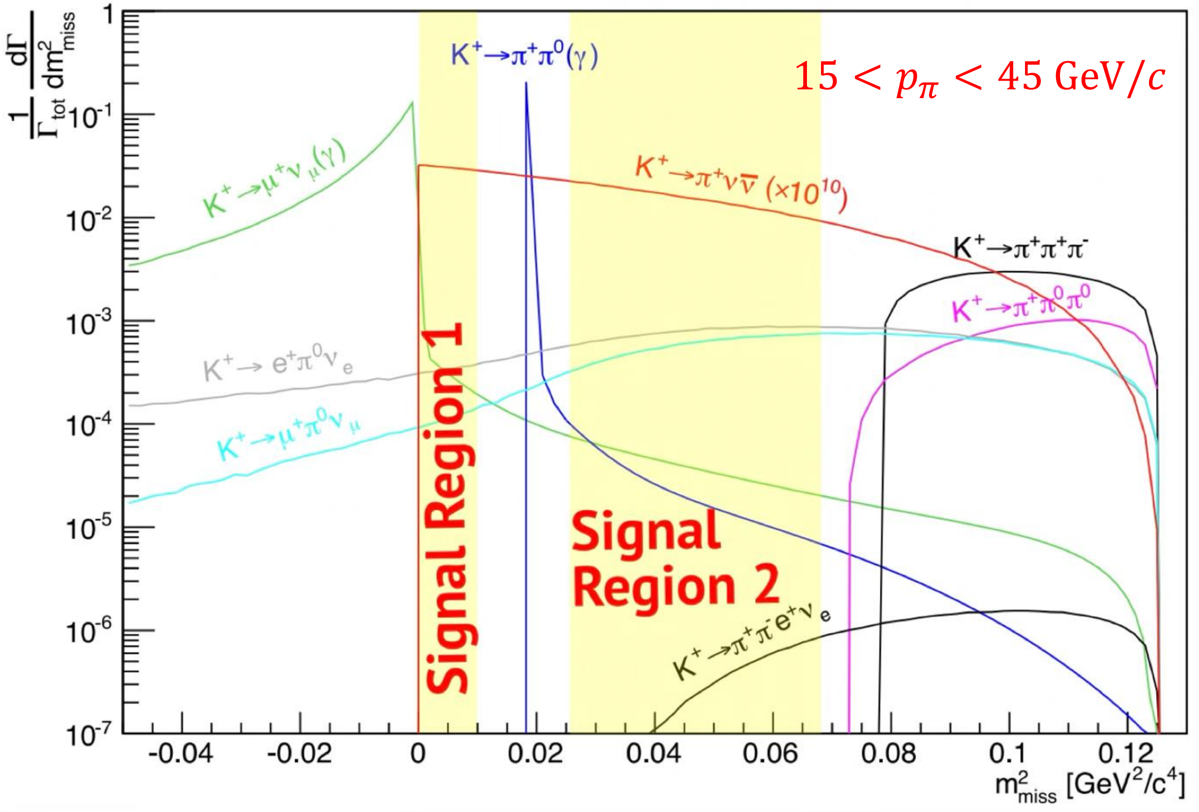
Analysis strategy



Squared missing mass (mass of the $\nu\bar{\nu}$ pair):

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

π^+ mass hypothesis

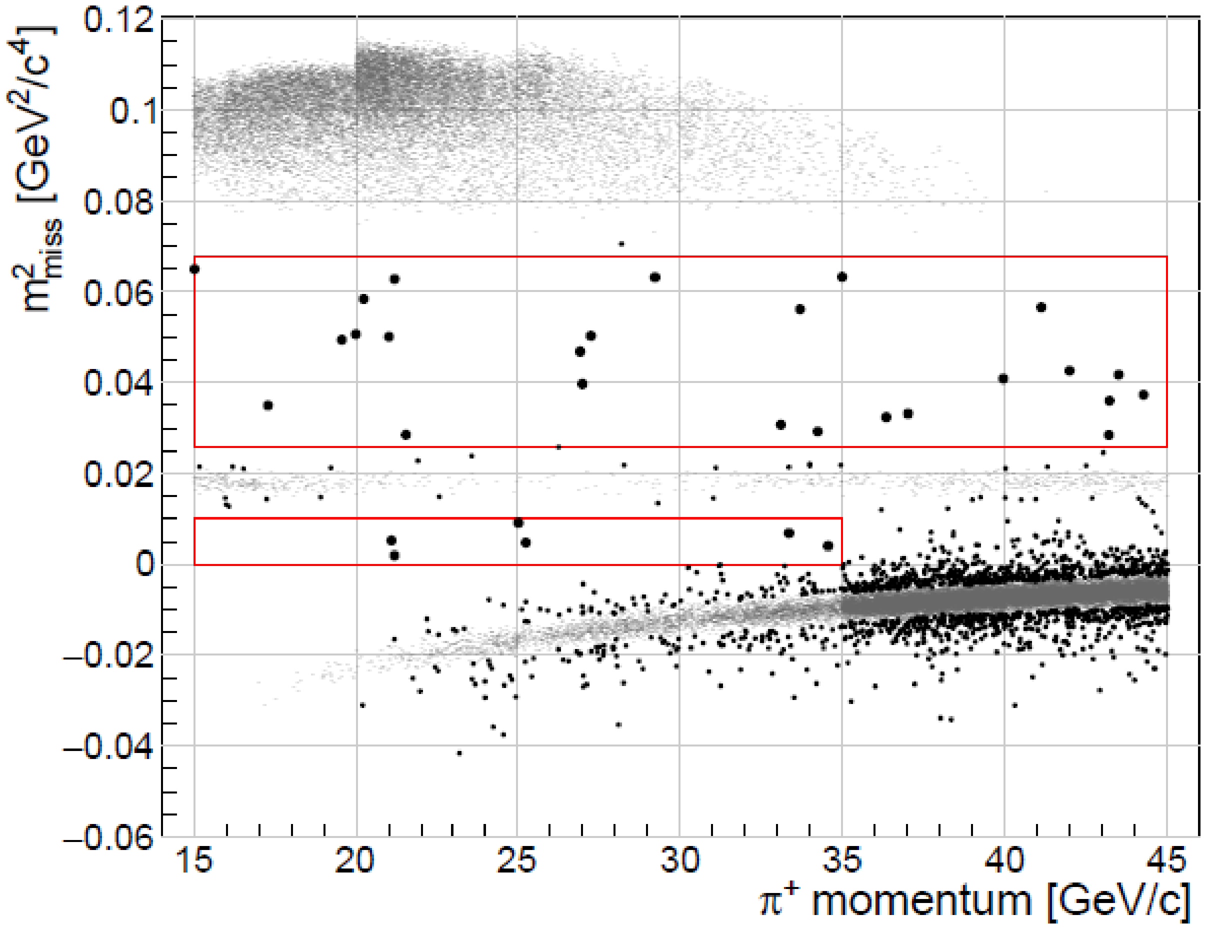


- Highly boosted decay: (75 ± 1) GeV/c K^+ $(\gamma \sim 150)$
- Large undetectable missing energy carried away by the neutrinos
- All energy from visible particles must be detected
- π^+ momentum range 15 – 45 GeV/c ($E_{miss} > 30$ GeV)
- Hermetic detector coverage and O(100%) detector efficiency needed

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

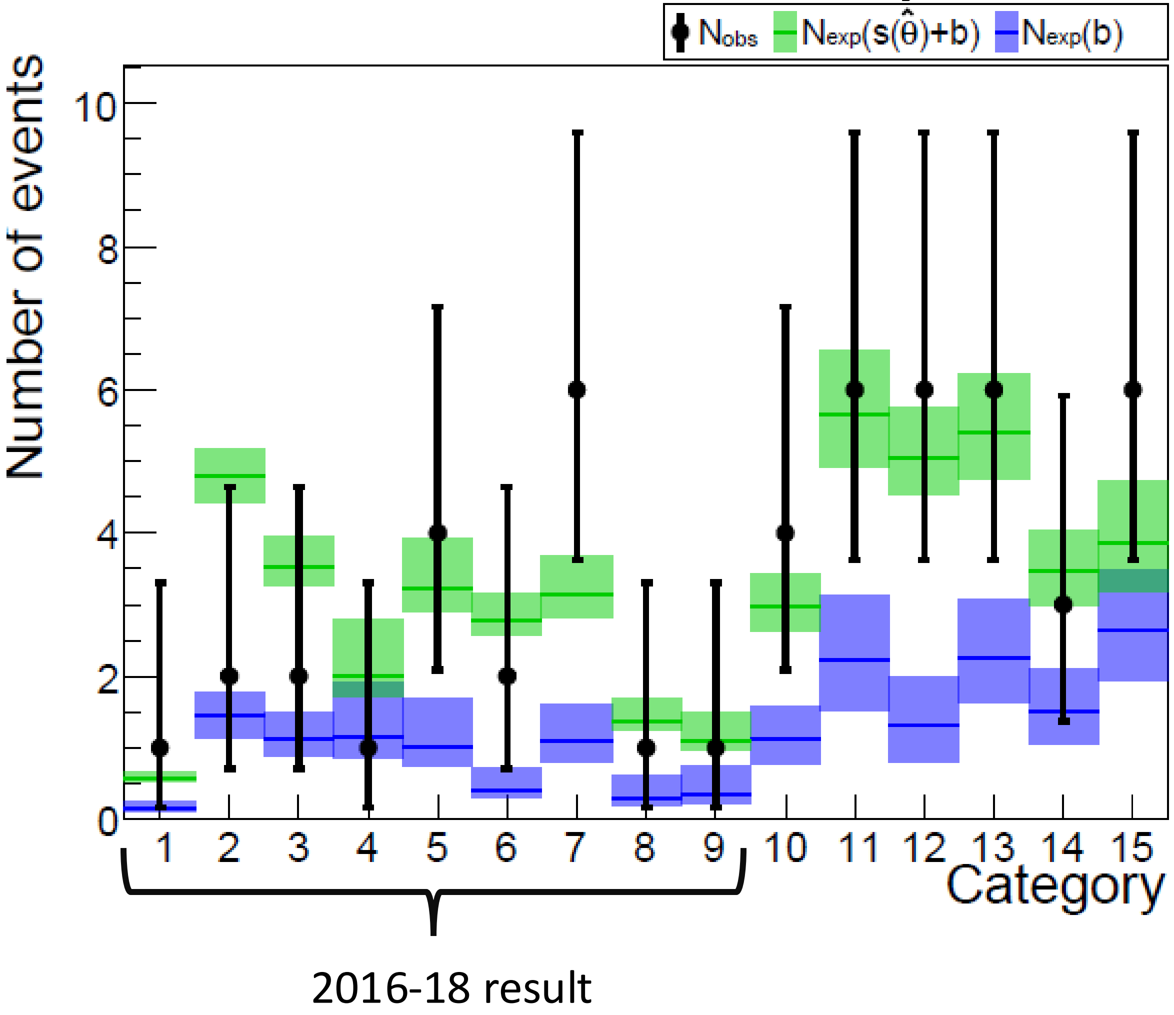
$K^+ \to \pi^+\nu\bar{\nu}$ results: Run II

2021-2022 data



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

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



Combined events 2016-2022

Expected SM signal: $N^{SM}_{\pi\nu\bar{\nu}} \approx 20$

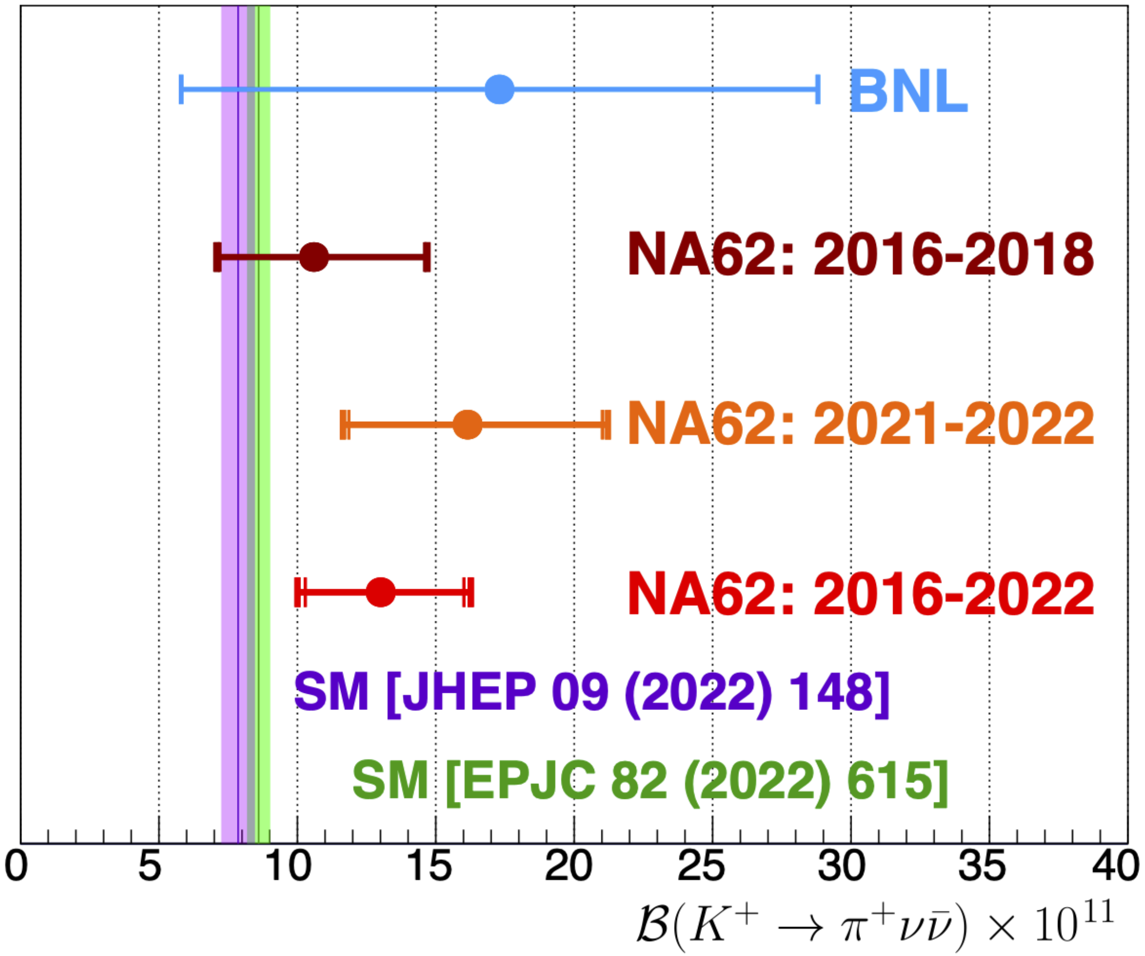
Expected background: $N_{bg} = 18^{+3}_{-2}$

Observed: $N_{obs} = 51$

Results in context

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

- $\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$
  JHEP 06 (2021) 093
- $\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = \left(16.2^{+5.1}_{-4.5}\right) \times 10^{-11}$
- $\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$
  JHEP 02 (2025) 191

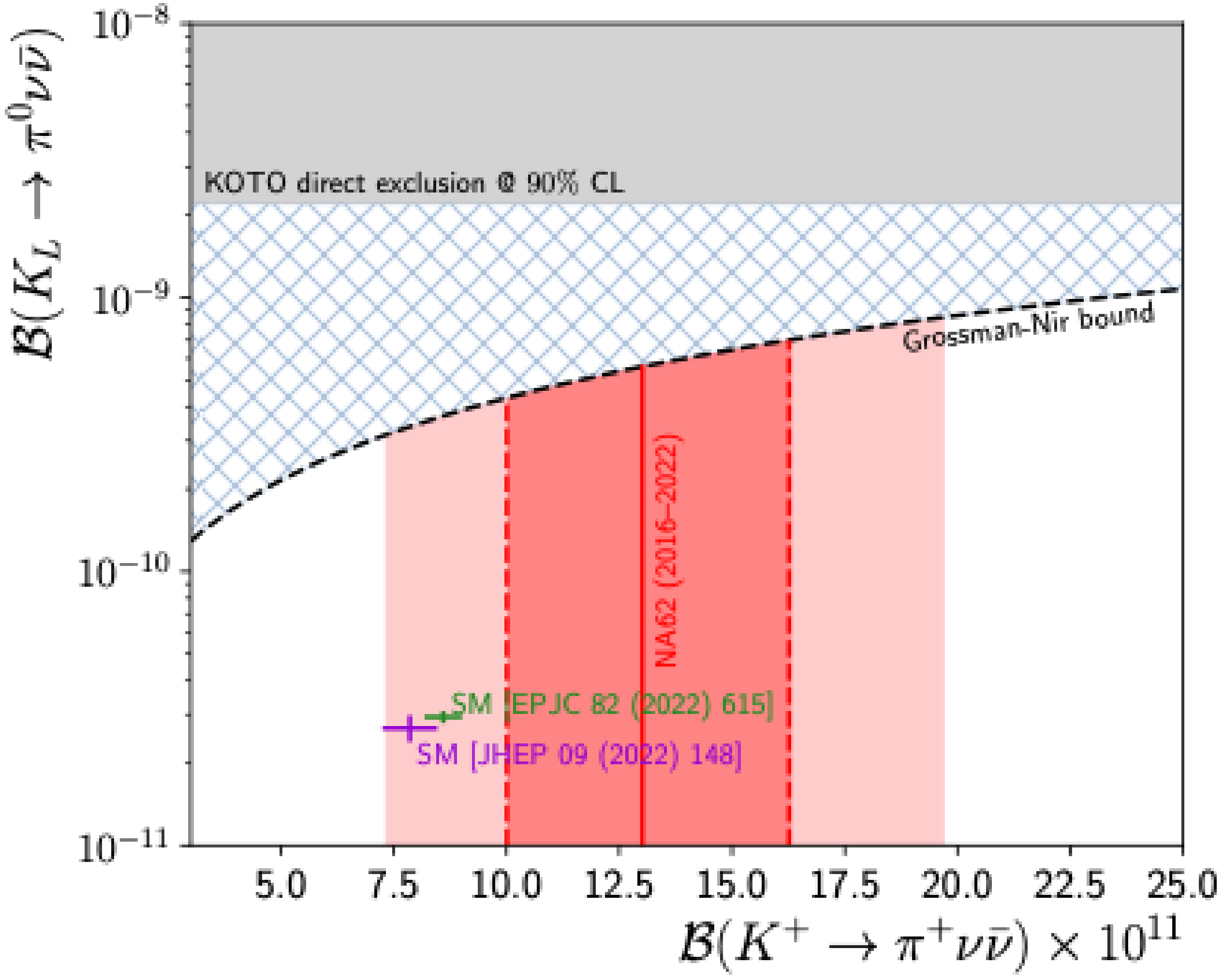


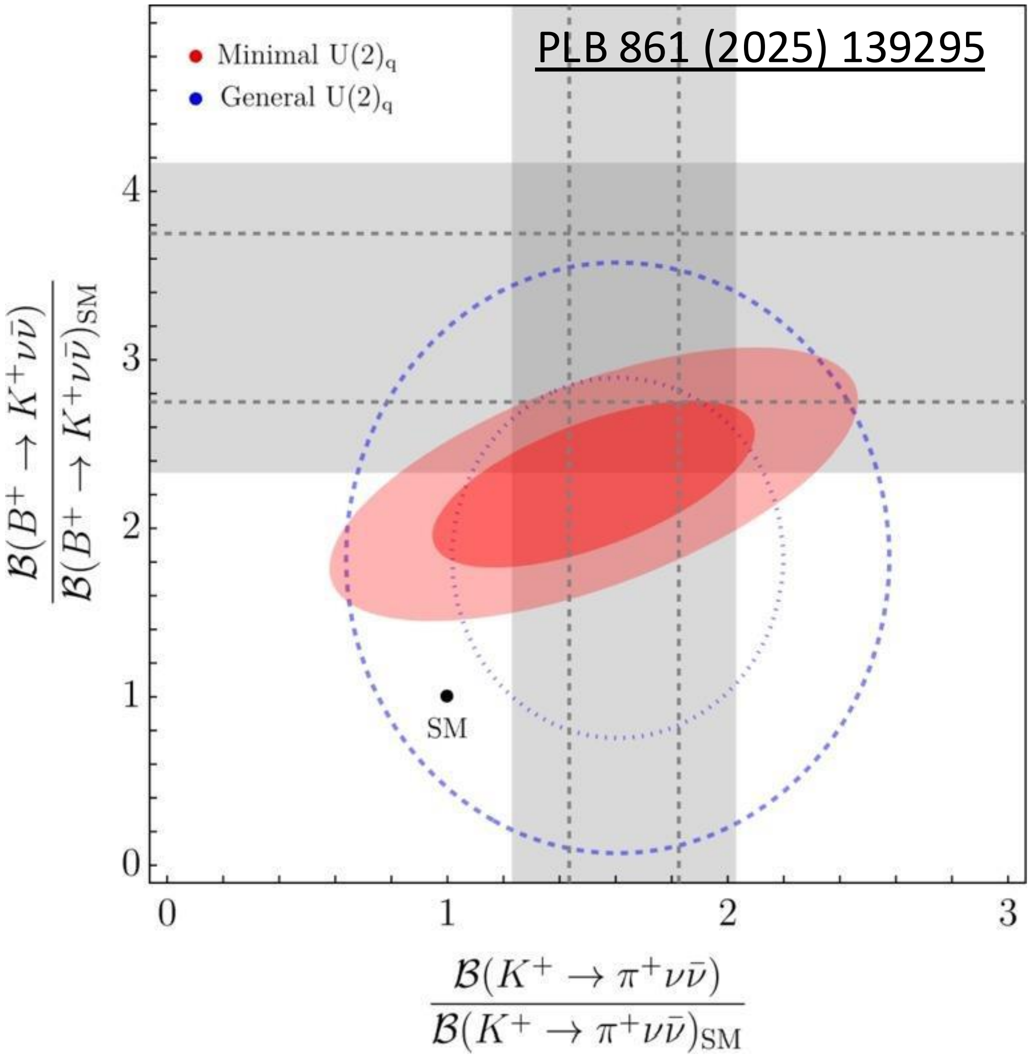
- NA62 results consistent with previous results
- Central value moved up but still consistent with SM within 1.7σ
- Fractional uncertainty decreased: **40% → 25%**
- Bkg-only hypothesis rejected with significance $Z > 5$
- **Three times more statistics expected with the complete NA62 dataset → stay tuned for more exiting results**

Results in context

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

JHEP02(2025)191





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

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

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

depend on external parameters (A, B, C)

- Two main kinematic variables used to describe the decay:

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

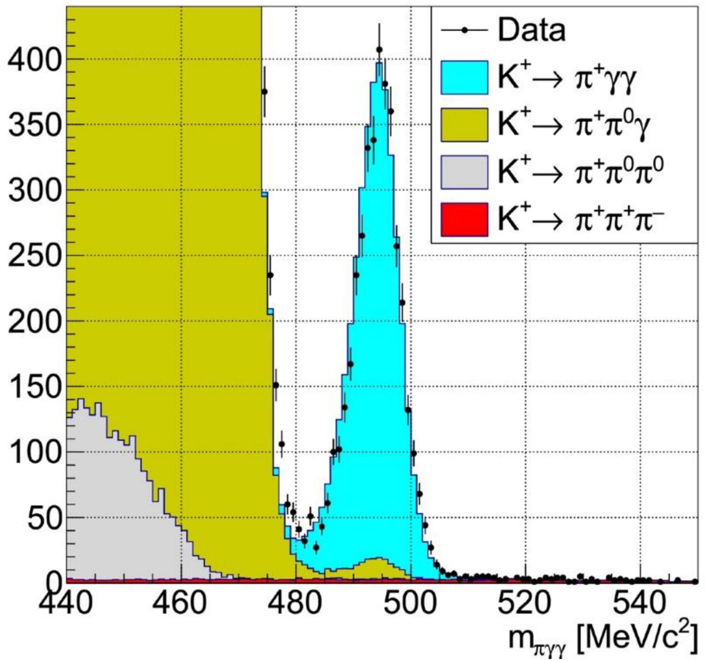
q_i – photon momenta

p – kaon momentum

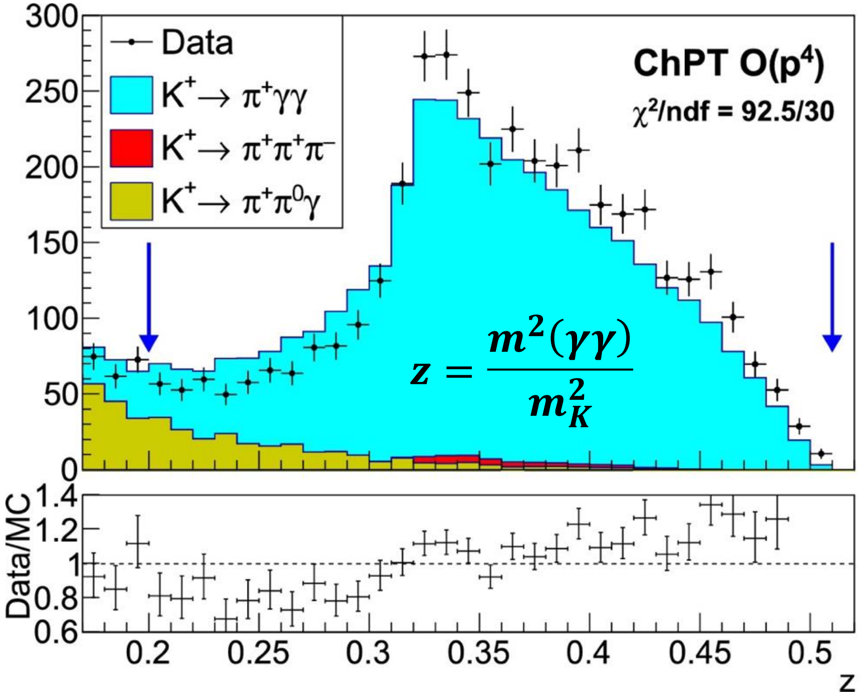
- Goal: Measurement of both $BR(K^+ \to \pi^+\gamma\gamma)$ and $\hat{c}$

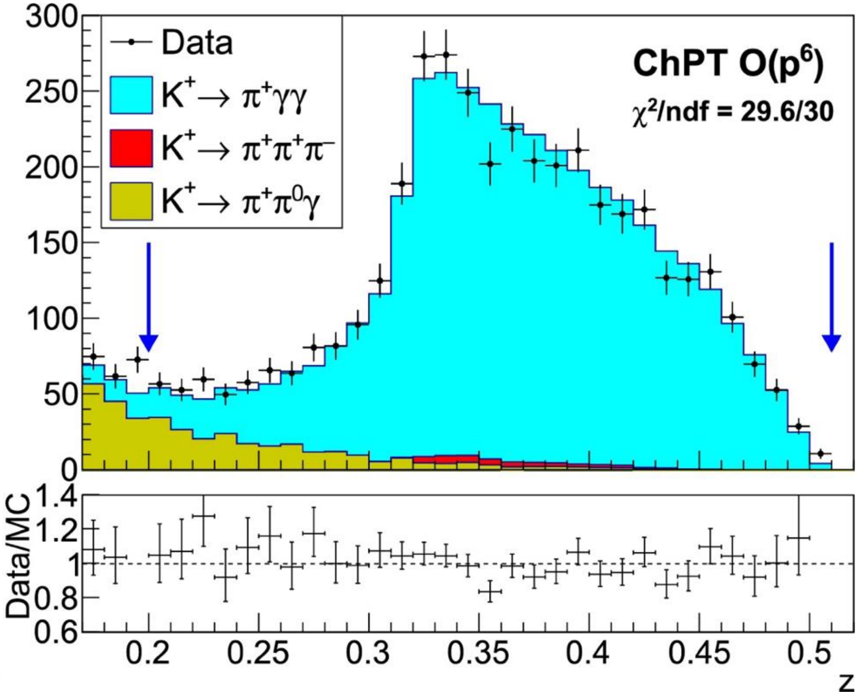
$K^+ \to \pi^+\gamma\gamma$ ($K_{\pi\gamma\gamma}$) decays

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



PLB850 (2024) 138513

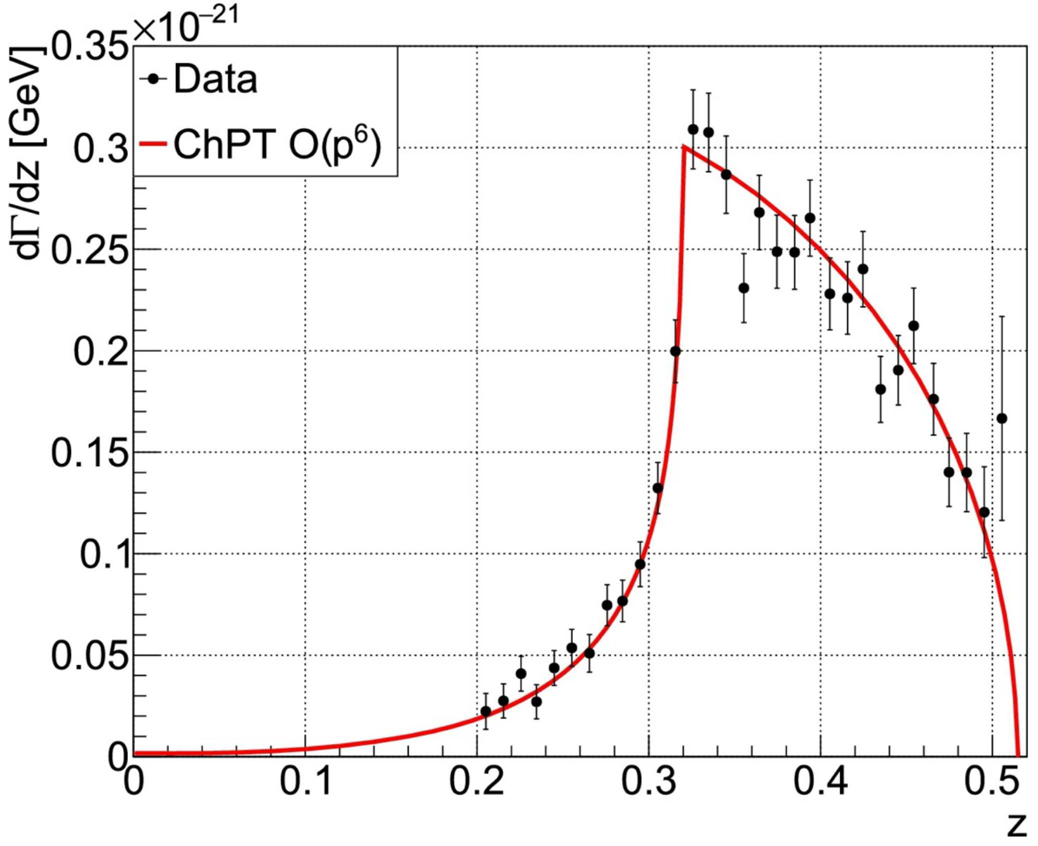


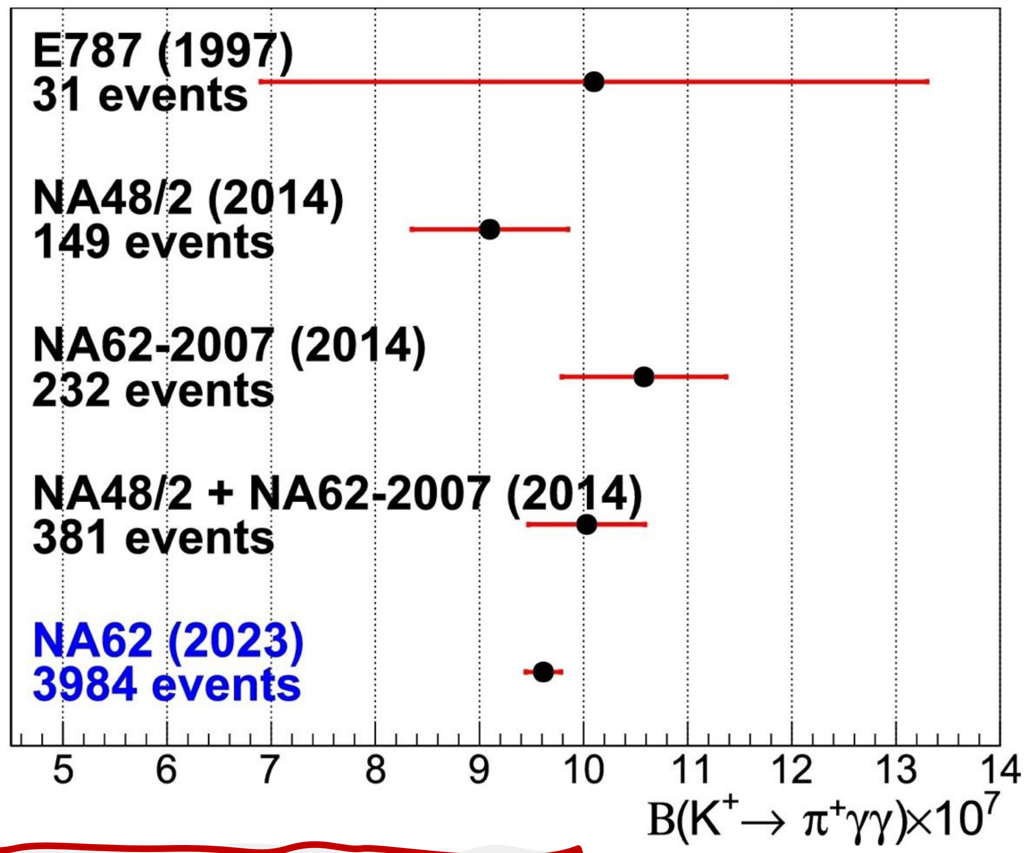


Expected background: $N_{bg} = 291 \pm 14$

Candidates observed: $N_{obs} = 3984$

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





PLB850 (2024) 138513

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

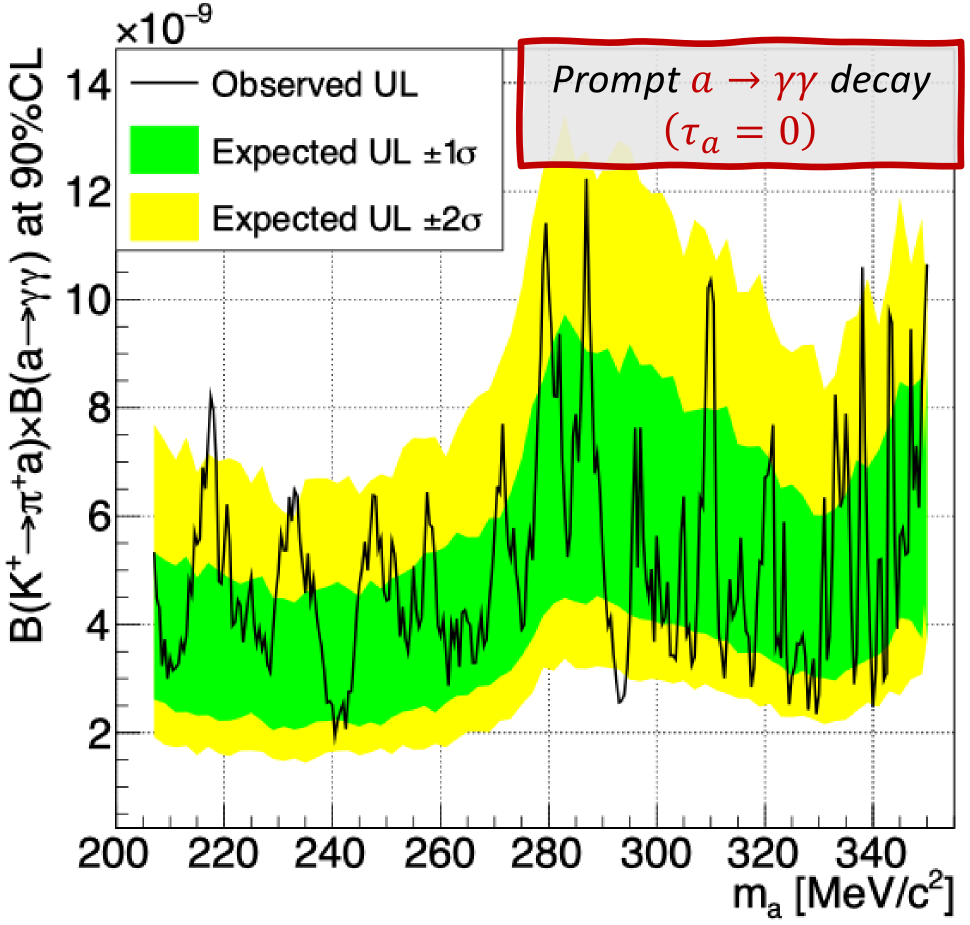
$$\mathcal{B}_{ChPT\ \mathcal{O}(p^6)}(K^+ \to \pi^+\gamma\gamma) = (9.61 \pm 0.15_{stat} \pm 0.07_{syst}) \times 10^{-7}$$

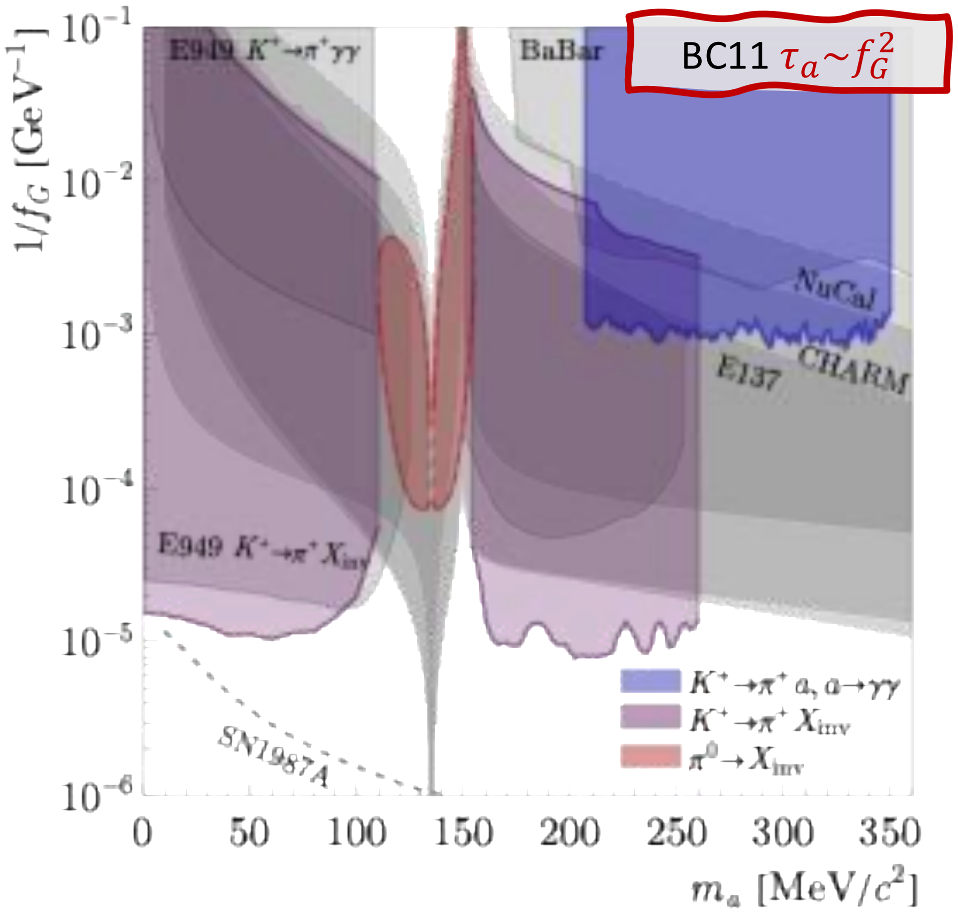
$$\mathcal{B}_{MI}(K^+ \to \pi^+\gamma\gamma | z > 0.2) = (9.46 \pm 0.19_{stat} \pm 0.07_{syst}) \times 10^{-7}$$

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

PLB850 (2024) 138513

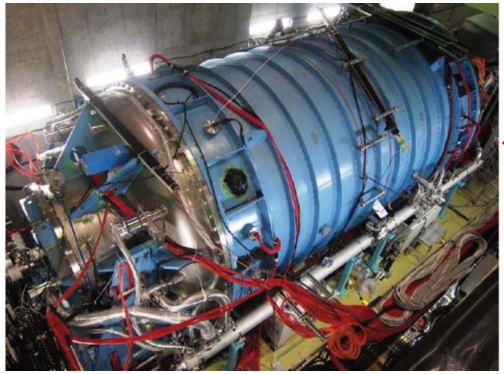
- Peak search over $m_a = \sqrt{(P_K - P_\pi)^2}$ in the range $207 - 350\ \mathrm{MeV/c^2}$ in steps of $0.5\ \mathrm{MeV/c^2}$
- m_a resolution: $2.0 - 0.2\ \mathrm{MeV/c^2}$ varying across the search range
- For each m_a hypothesis background estimated from simulations and UL set using CLs

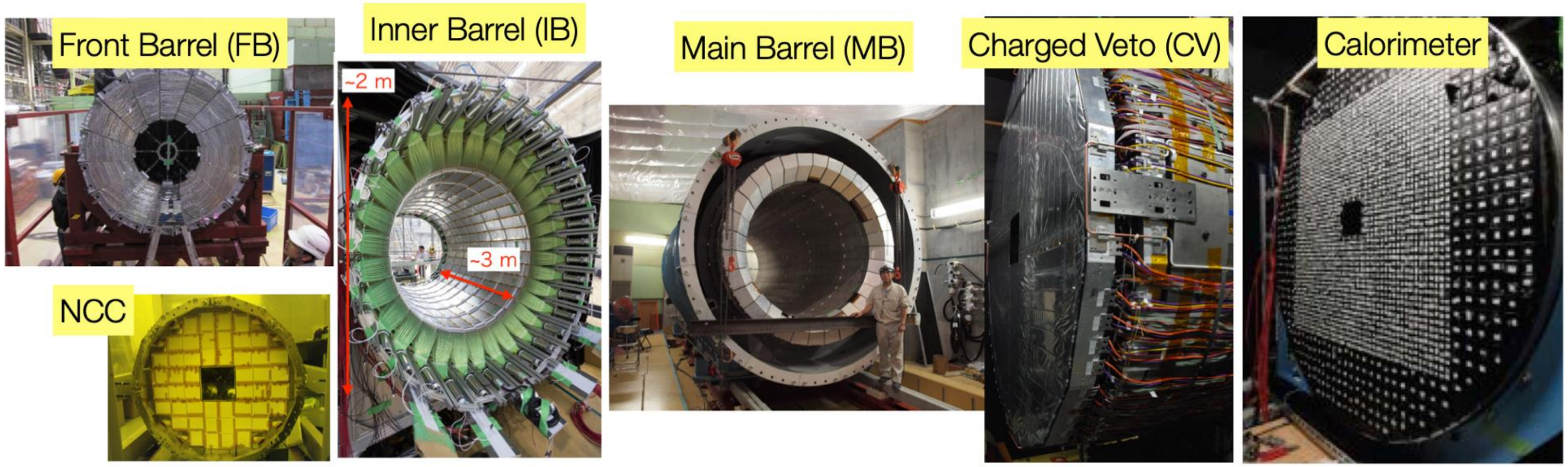


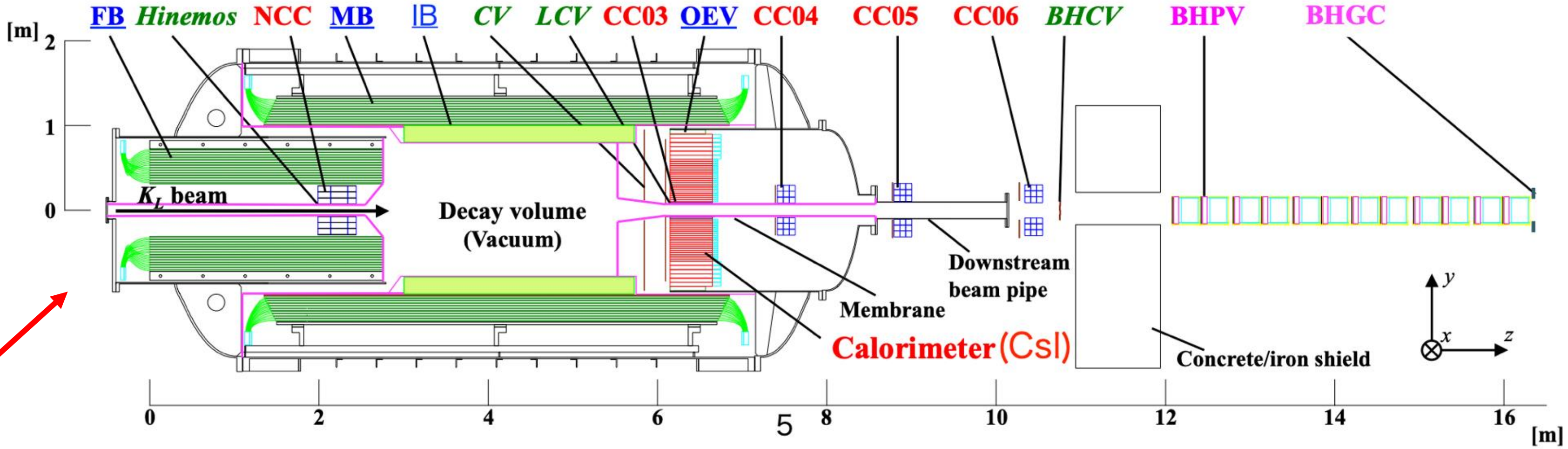


KOTO experiment: a search for $K_L \to \pi^0 \nu \bar{\nu}$

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







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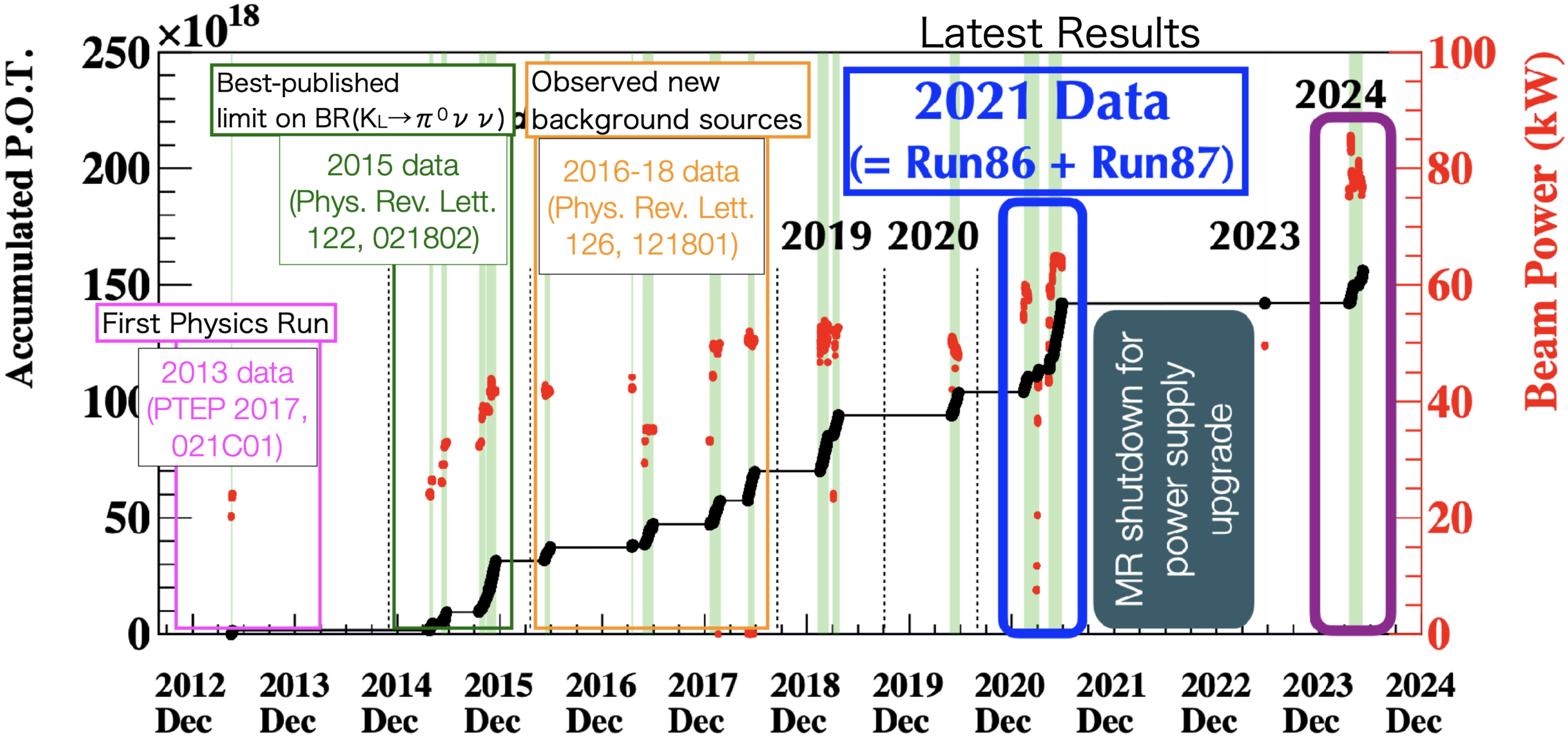
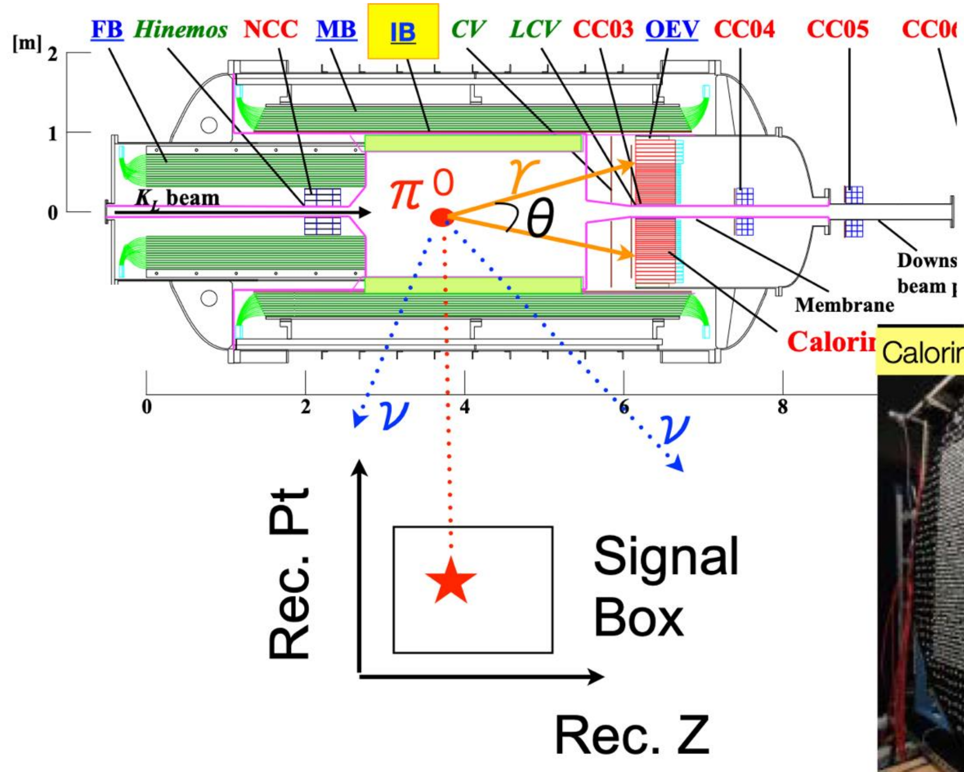
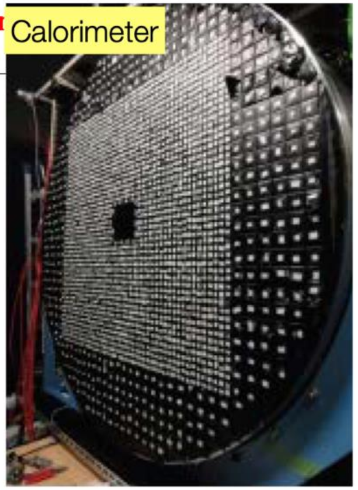


KOTO experiment: a search for $K_L \to \pi^0 \nu\bar{\nu}$

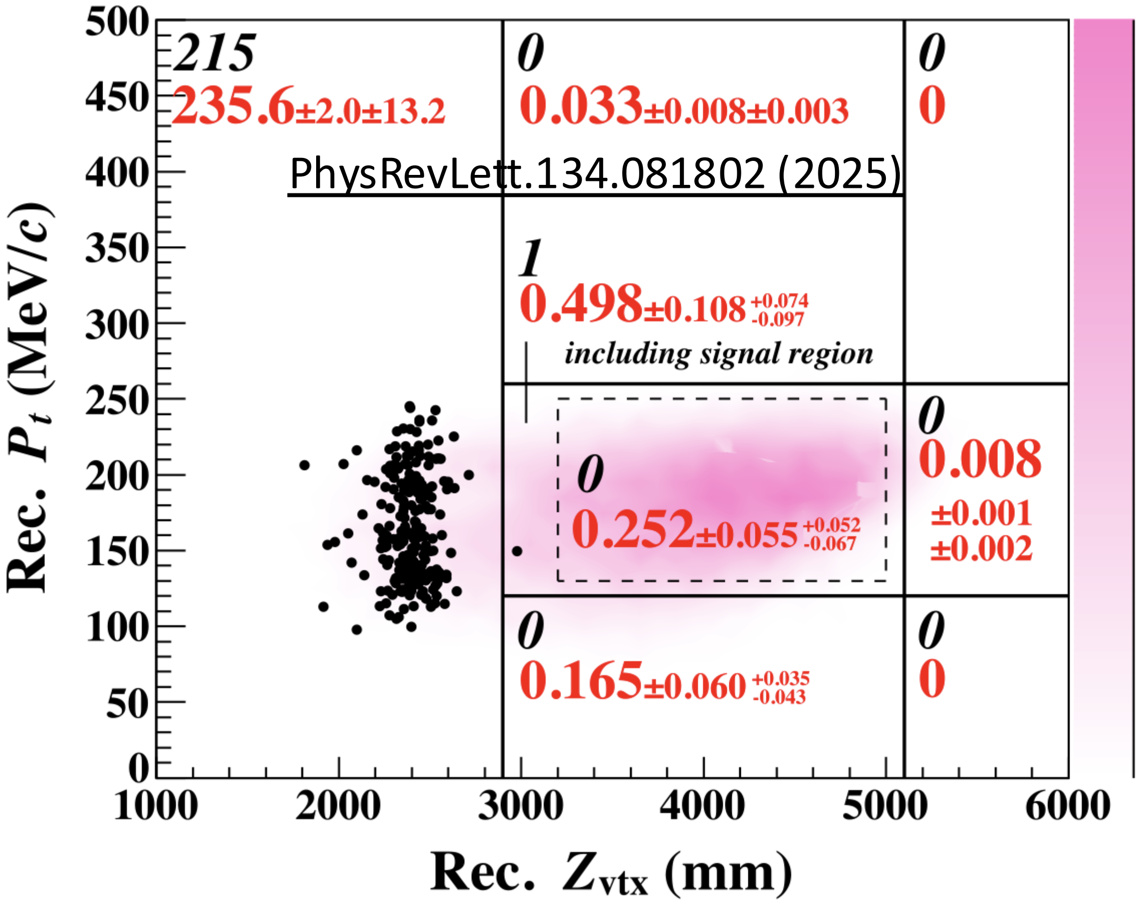




Experimental technique

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

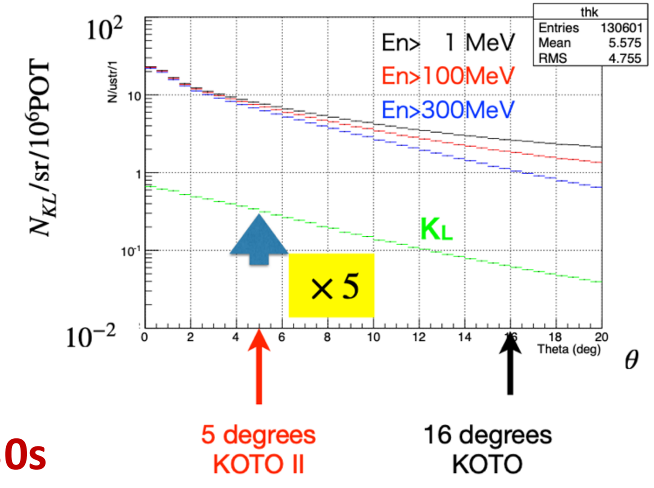
$m^2(\pi^0) = 2E_1E_2(1 - \cos\theta)$

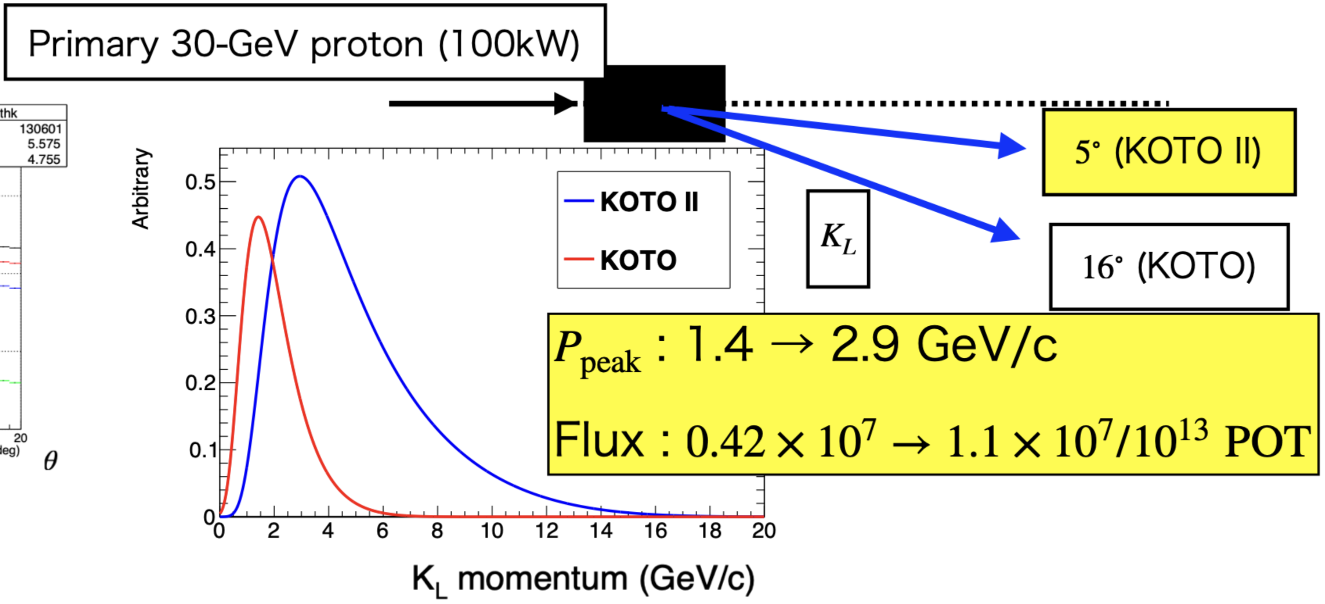


- $SES = (9.33 \pm 0.06_{stat} \pm 0.84_{syst}) \times 10^{-10}$
- No observed events in the signal region
- **$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 2.1 \times 10^{-9}$ at 90% CL**

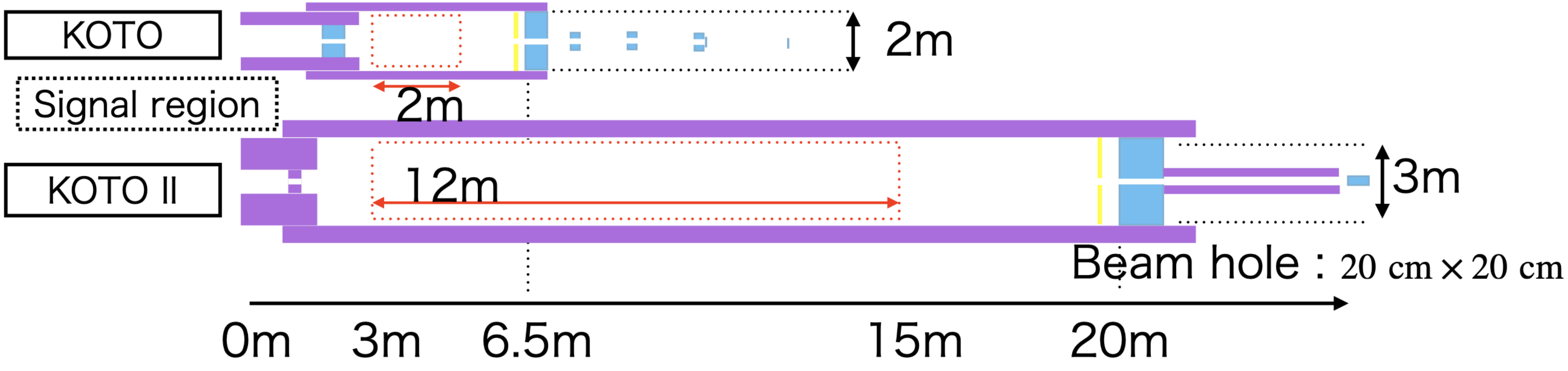
How to improve sensitivity: KOTO II

- More K_L → forward production angle
  - × 2.6 larger flux + **harder spectrum**
- Larger signal acceptance
  - longer decay volume
  - larger calorimeter

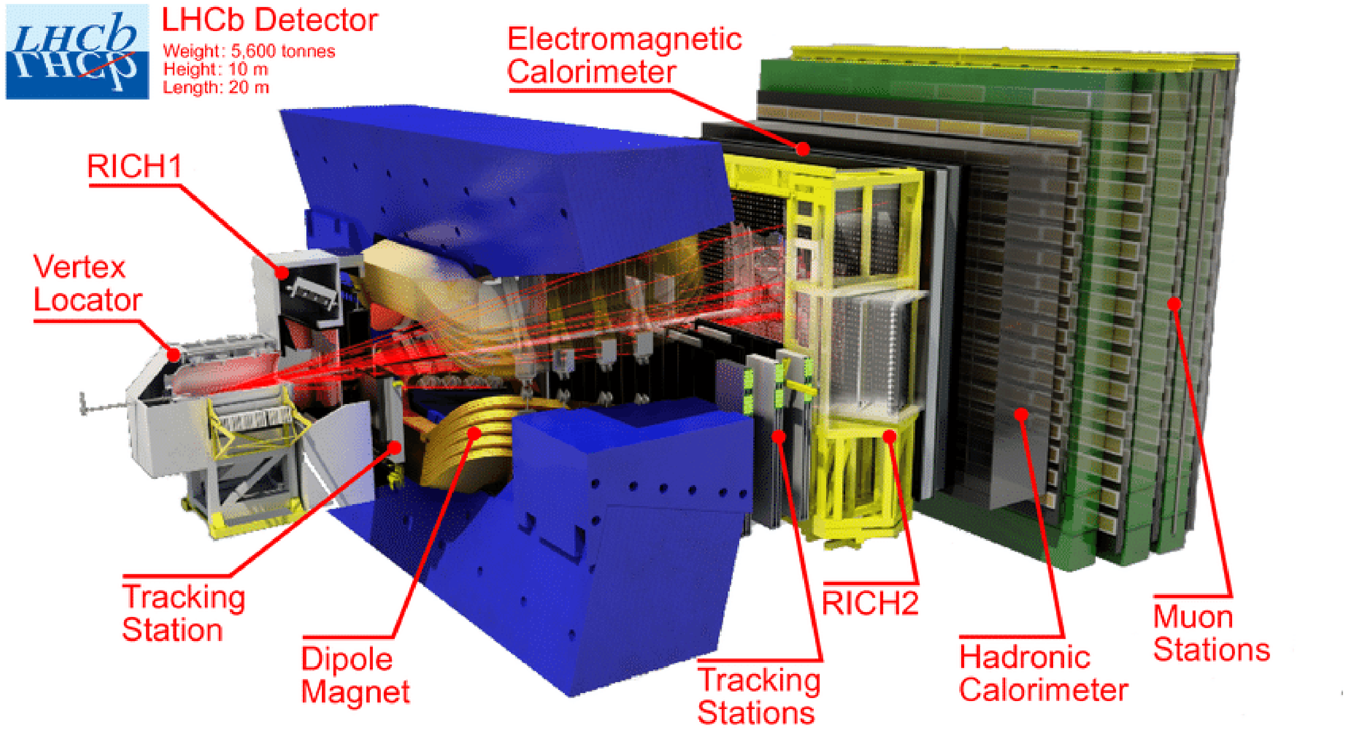




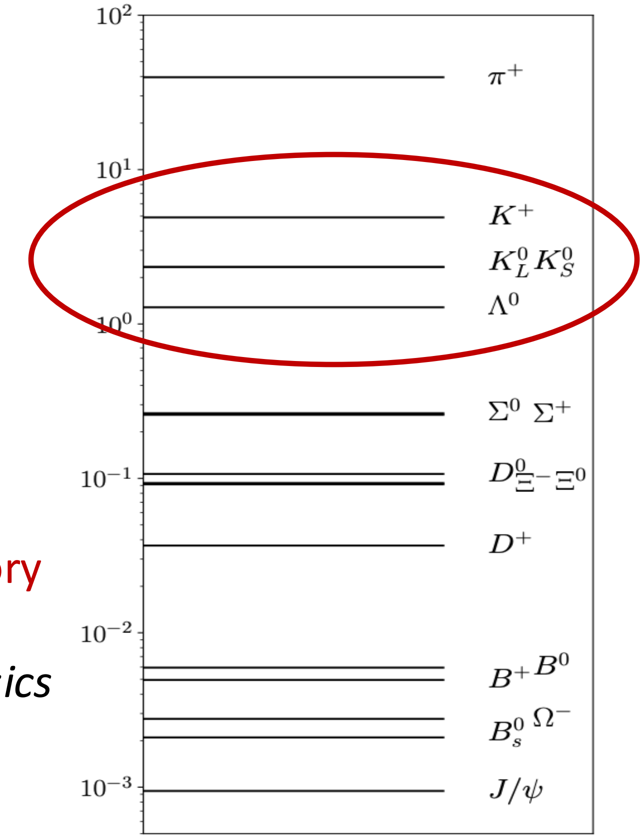
Proposed to start in the 2030s



Kaons at LHCb



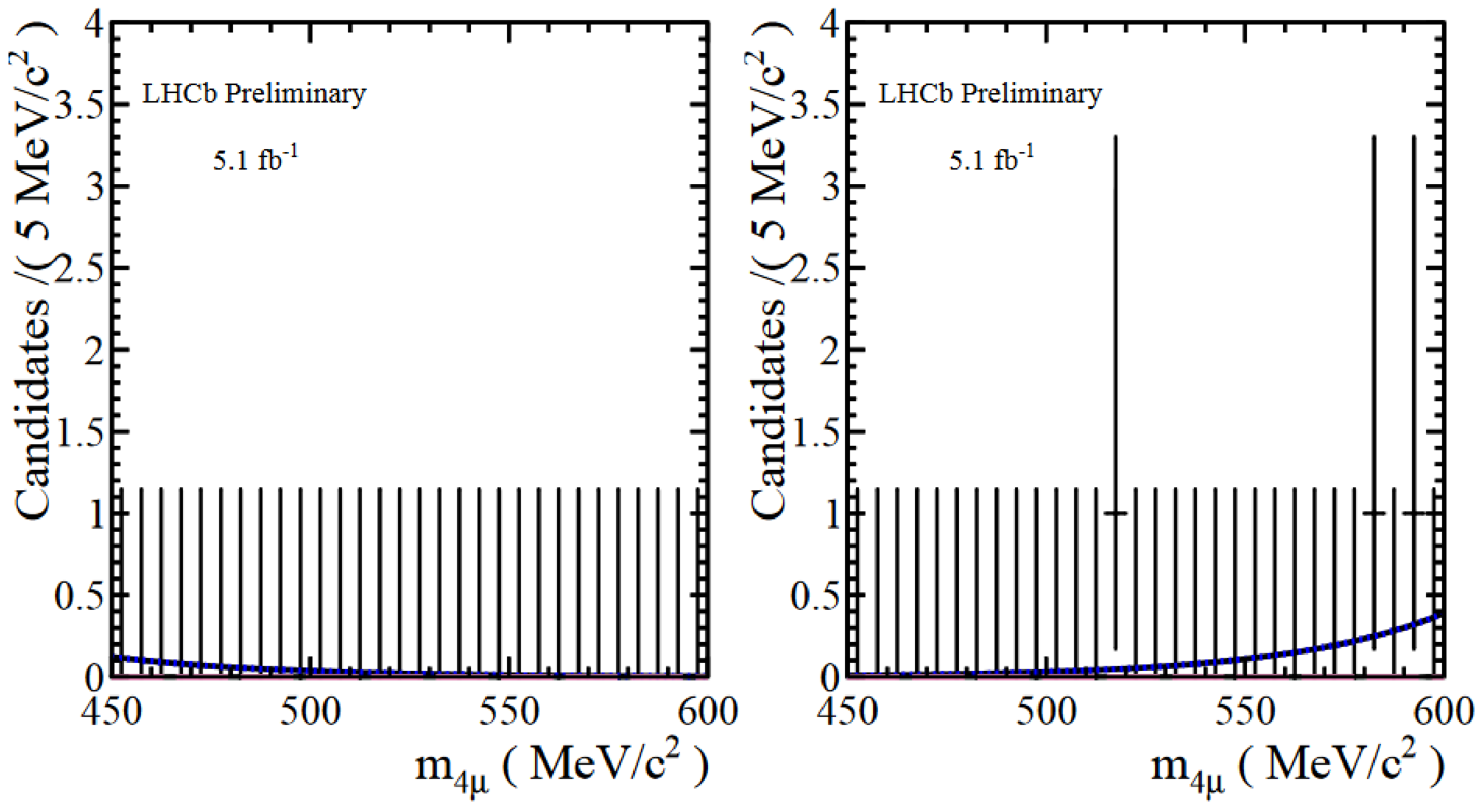
Multiplicity of particles produced in a single pp interaction at $\sqrt{s} = 13$ TeV within LHCb acceptance.



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

Rare kaon decays at LHCb

- Search for $K^0_{S(L)} \to \mu\mu\mu\mu$ decays, heavily suppressed in the SM: $10^{-13}(K^0_L), 10^{-14}(K^0_S)$
- No events found in signal region (Run 1 + 2)
- World's best (first) upper limits on these decays
- $K^0_{S(L)} \to \pi\pi\mu\mu$ search with Run 2 data ongoing (paper to appear in the following month)

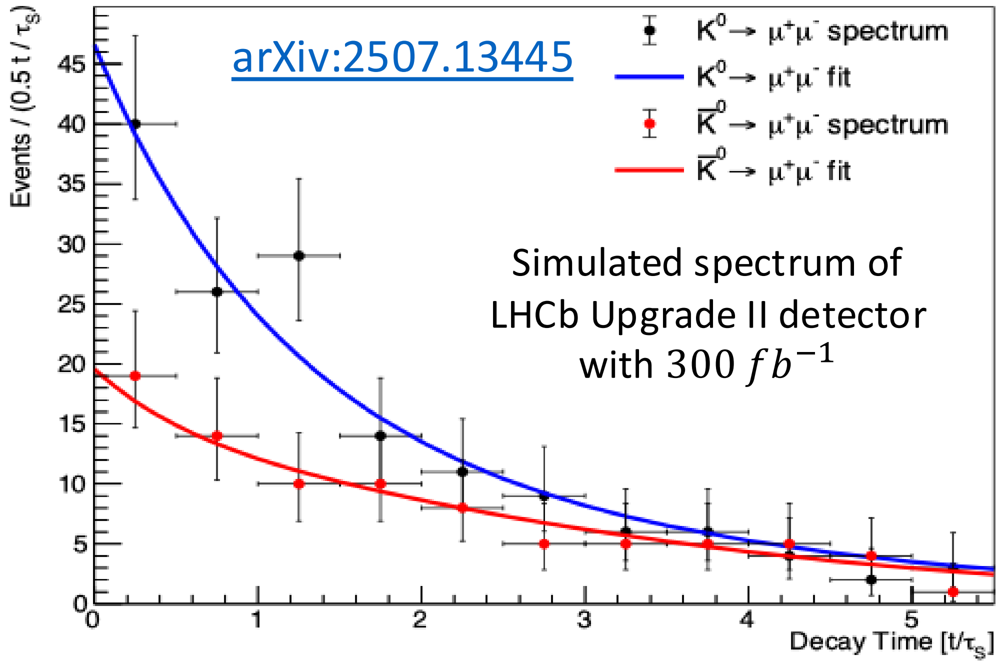


$$BR(K^0_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$$
$$BR(K^0_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$$

PRD 108 (2023) L031102

Plenty of kaon physics results to come from Run 3 data

Rare kaon decays at LHCb: future prospects



Time-dependent rate

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

$$\begin{aligned} C_L &= |A(K_L)_{\ell=0}|^2\,, \\ C_S &= |A(K_S)_{\ell=0}|^2 + \beta_\mu^2 |A(K_S)_{\ell=1}|^2\,, \\ C_{\text{Int.}} &= |A(K_S)_{\ell=0}||A(K_L)_{\ell=0}|\,, \\ \varphi_0 &= \arg\left[A(K_S)^*_{\ell=0}\, A(K_L)_{\ell=0}\right]. \end{aligned}$$

Short-distance CPV contribution

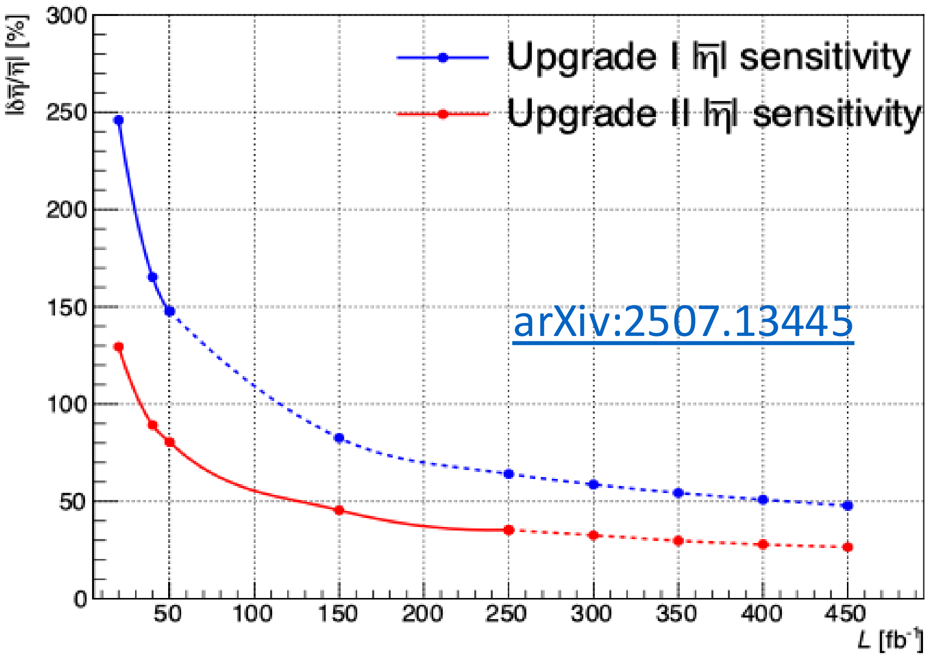
$$\Rightarrow C_{\text{Int.}} = C_L \sqrt{\frac{\tau_L}{\tau_S}\frac{\mathcal{B}(K_S \to \mu^+\mu^-)_{l=0}}{\mathcal{B}(K_L \to \mu^+\mu^-)}}$$

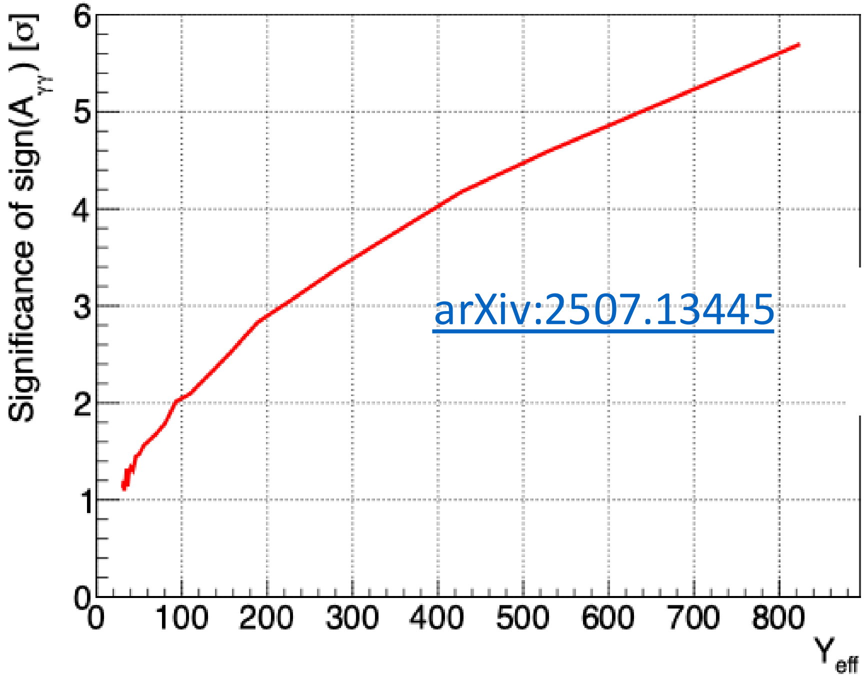
$$\mathcal{B}(K_S)_{\ell=0} = \frac{\beta_\mu \tau_S}{16\pi m_K}\left|\frac{2\, G_F^2 m_W^2}{\pi^2} f_K m_K m_\mu Y_t\right|^2 \cdot (\lambda^5 A^2 \bar{\eta})^2$$

- Measuring $K \to \mu^+\mu^-$ interference can give direct access to the short-distance component of $K_S \to \mu^+\mu^-$
- The strong phase φ_0 can be obtained from the measured rates of $K_L \to \gamma\gamma$ and $K_L \to \mu^+\mu^-$ [JHEP03(2023)014]
- Two unknown parameters: $\boldsymbol{C_S, C_{\text{Int.}}}$
- **Measurement of $C_{\text{Int.}}(|A(K_S)_{\ell=0}|)$ is a direct measurement of η**

Needs kaon tagging (ongoing effort)

Rare kaon decays at LHCb: future prospects





Tagging power — Effective signal yield

$$Y_{eff} = T_P S_{eff} = \varepsilon_T (1-2\omega)^2 \frac{S^2}{S+B} .$$

Tagging efficiency — Mistag probability

- Time-dependent information and K tagging can be used to measure the $K_S - K_L \to \mu^+\mu^-$ interference
- The studies show that LHCb Upgrade II might be able to achieve an uncertainty on $|\bar{\eta}|$ of $\sim 35\%$
  - development of kaon tagging (preliminary studies encouraging)
  - including downstream tracks in the analysis
  - improving lifetime acceptance with an improved Upstream Pixel (UP) detector
- LHCb would be able to resolve the sign of $A_{CP} \to$ sign of $A_{\gamma\gamma} \equiv A(K_L \to \gamma\gamma)$ @ at least 3σ

Summary and prospects

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