Future prospects in Kaon physics

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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 $s \to d\nu\bar{\nu}$ 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 and in the ESPPU briefing book

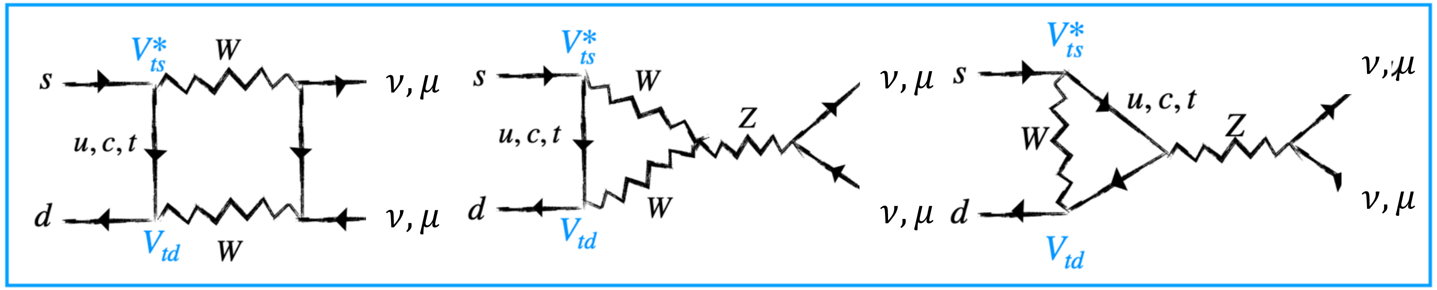
arXiv:2505.02568, arXiv:2503.22256, arXiv:2511.03883

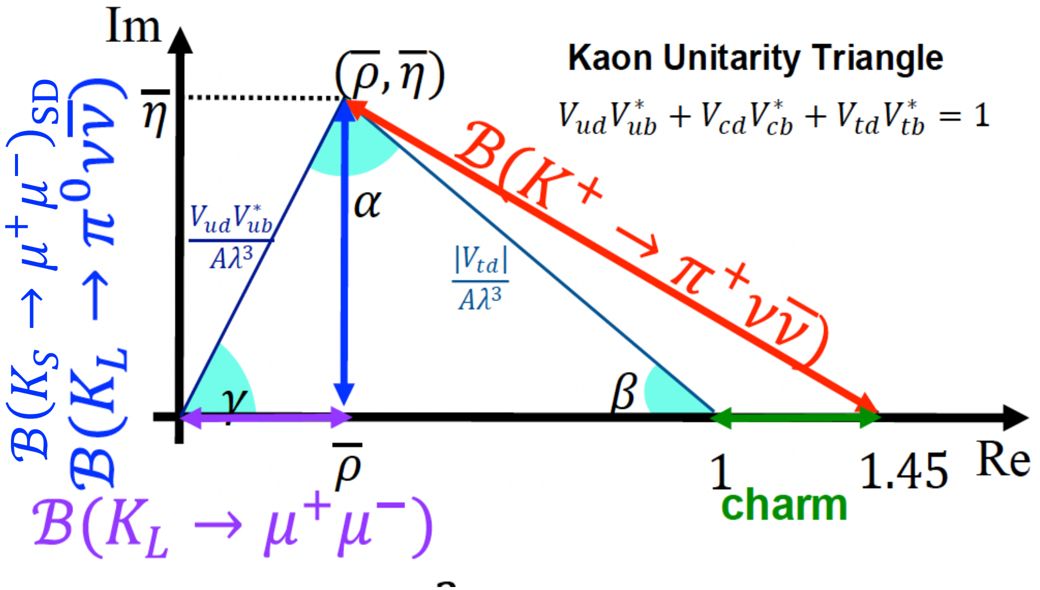
Gold-plated kaon observables

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

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

[JHEP 09 (2022) 148]

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

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

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

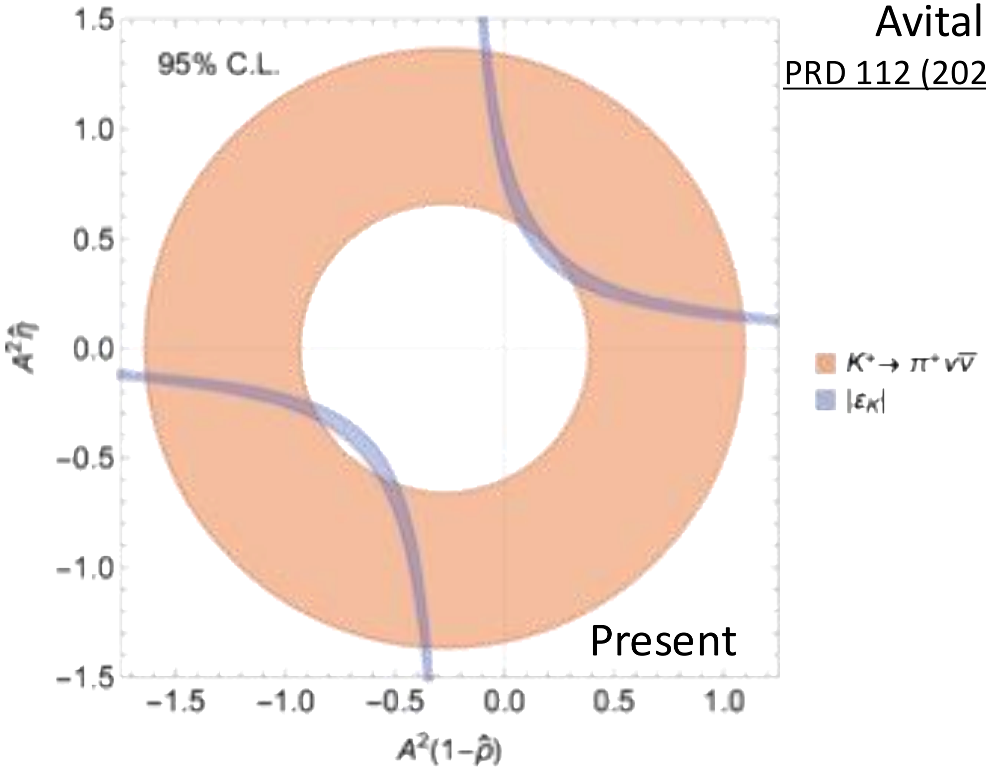
$\mathcal{B}(K_S \to \mu^+\mu^-)_{SD} = (1.6 \pm 0.1) \times 10^{-13}$ [JHEP 07 (2021) 103]

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



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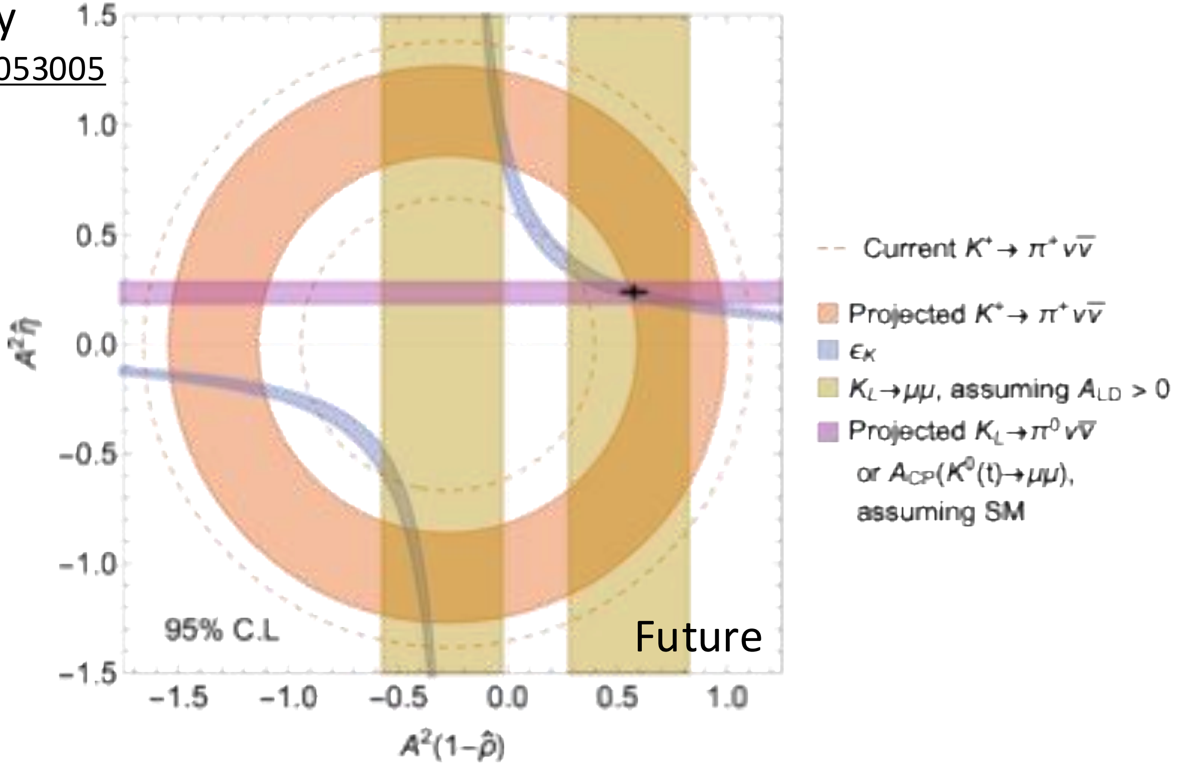


- Kaon physics can be used to independently determine 3/4 parameters of the CKM matrix w/o B physics input
- Presenting kaon information in the $(\hat{\rho}, \hat{\eta})$ plane → artificial error inflation due to $|V_{cb}|$ dependence
- More natural to present the kaon CKM information in the $(A^2(1-\hat{\rho}),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

Experimental status of rare kaon observables

Main players

$K_{S(L)}$ decays

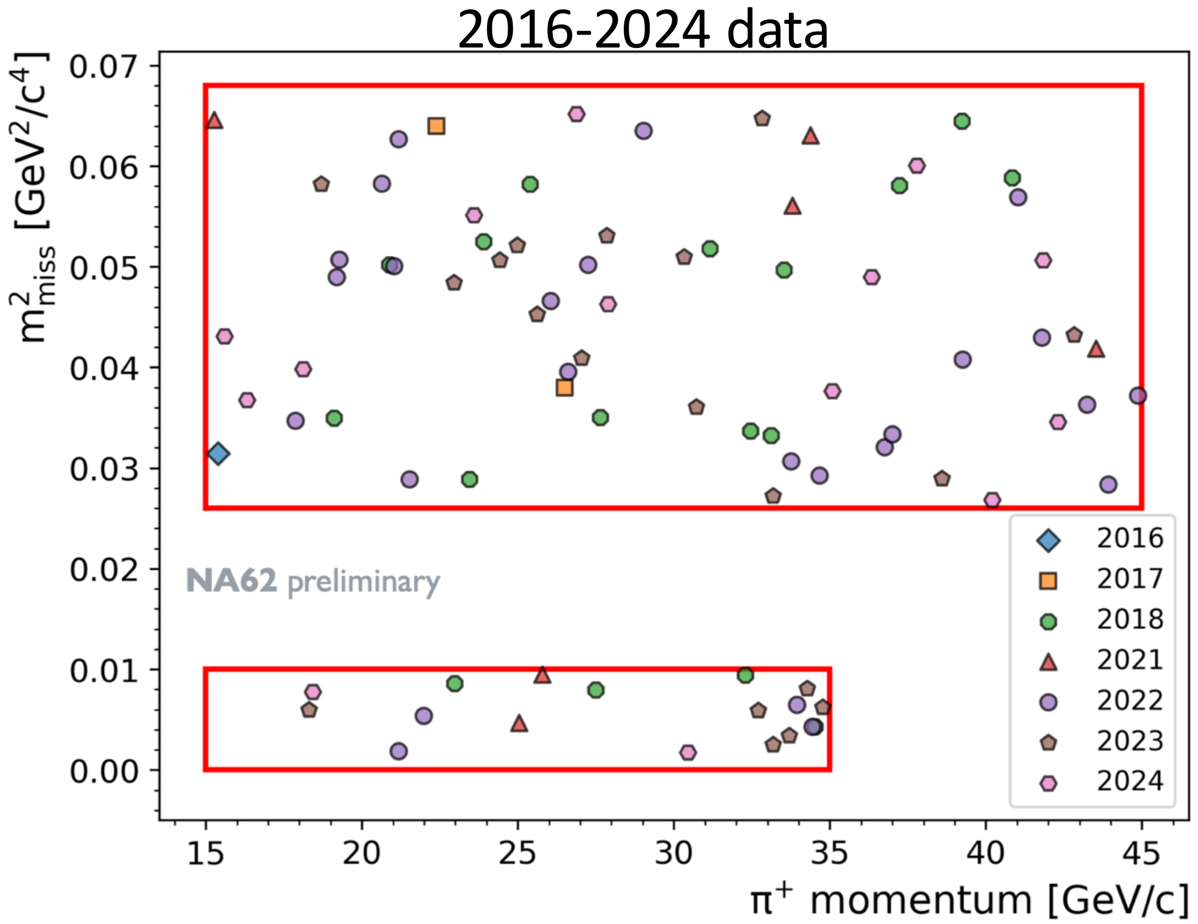
?

K^+ decays

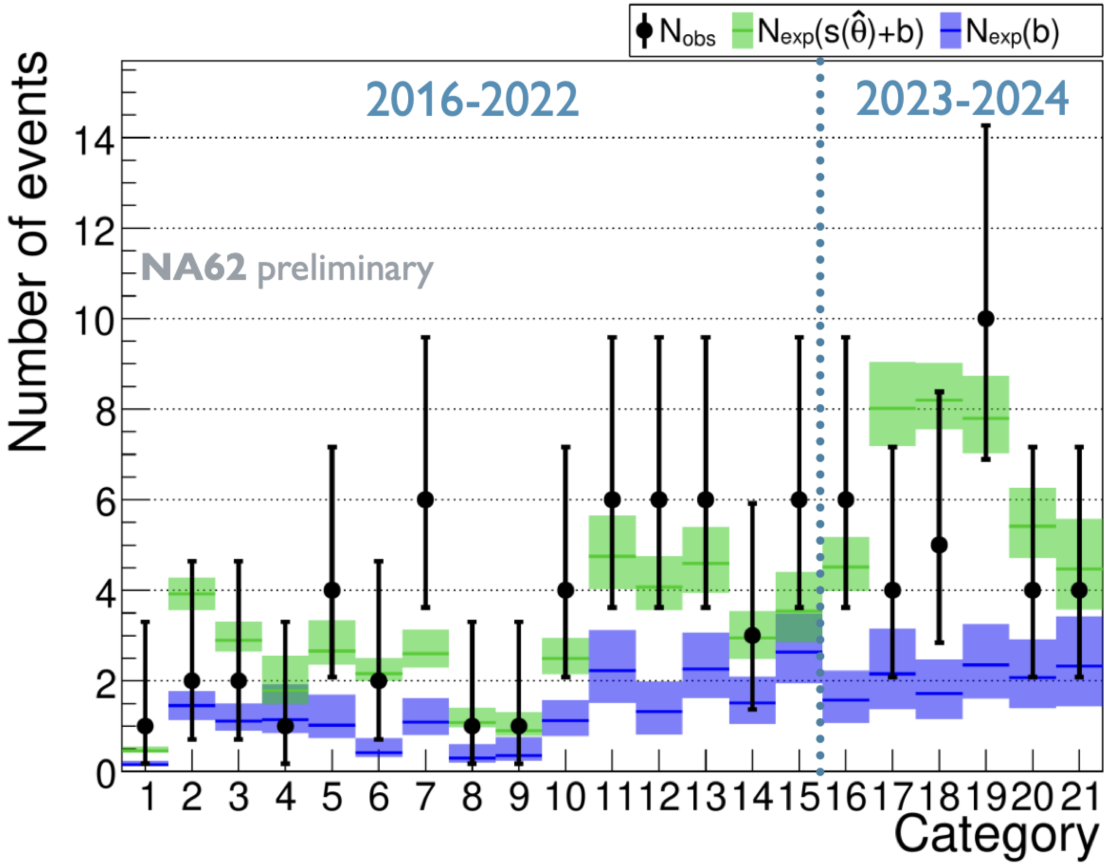
K_L decays

This talk will focus on recent experimental results and prospects for rare kaon decay measurements by NA62, KOTO, LHCb (and even FCC-ee)

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



$$\mathcal{B}^{16-24}_{\pi\nu\bar{\nu}} = \left(9.6^{+1.9}_{-1.8}\right) \times 10^{-11}$$



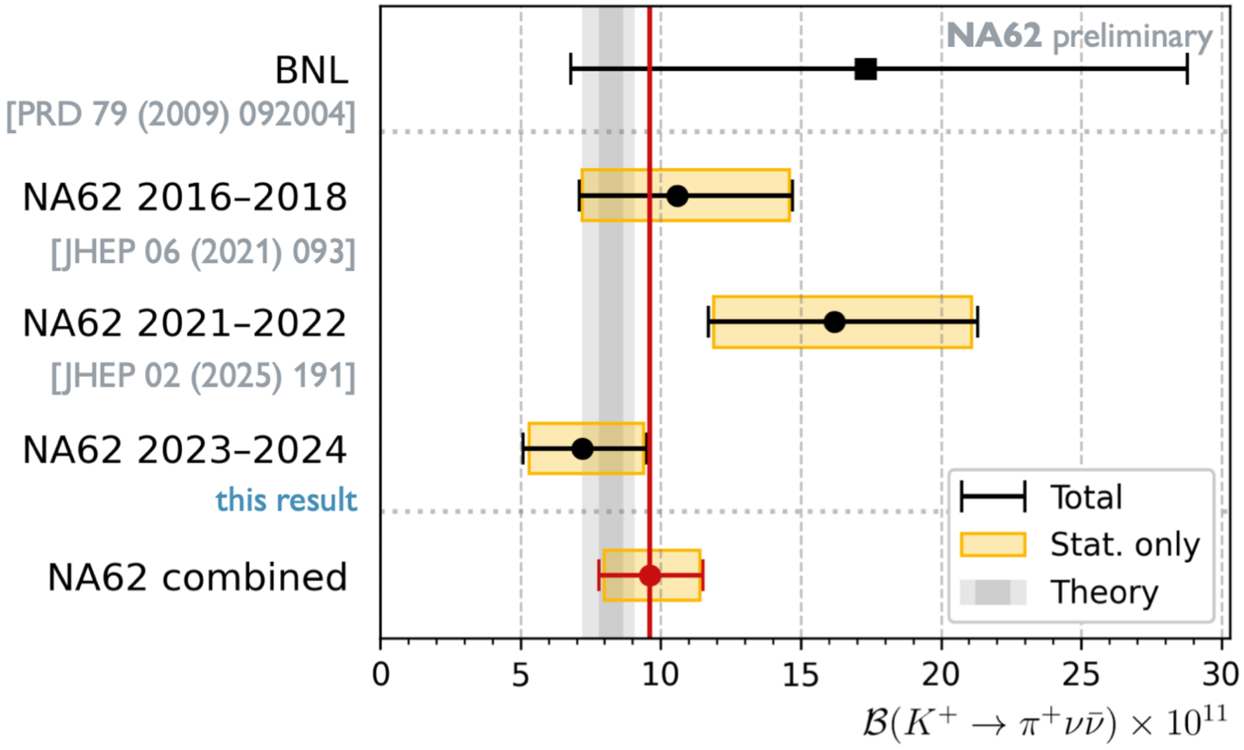
Combined events 2016-2024

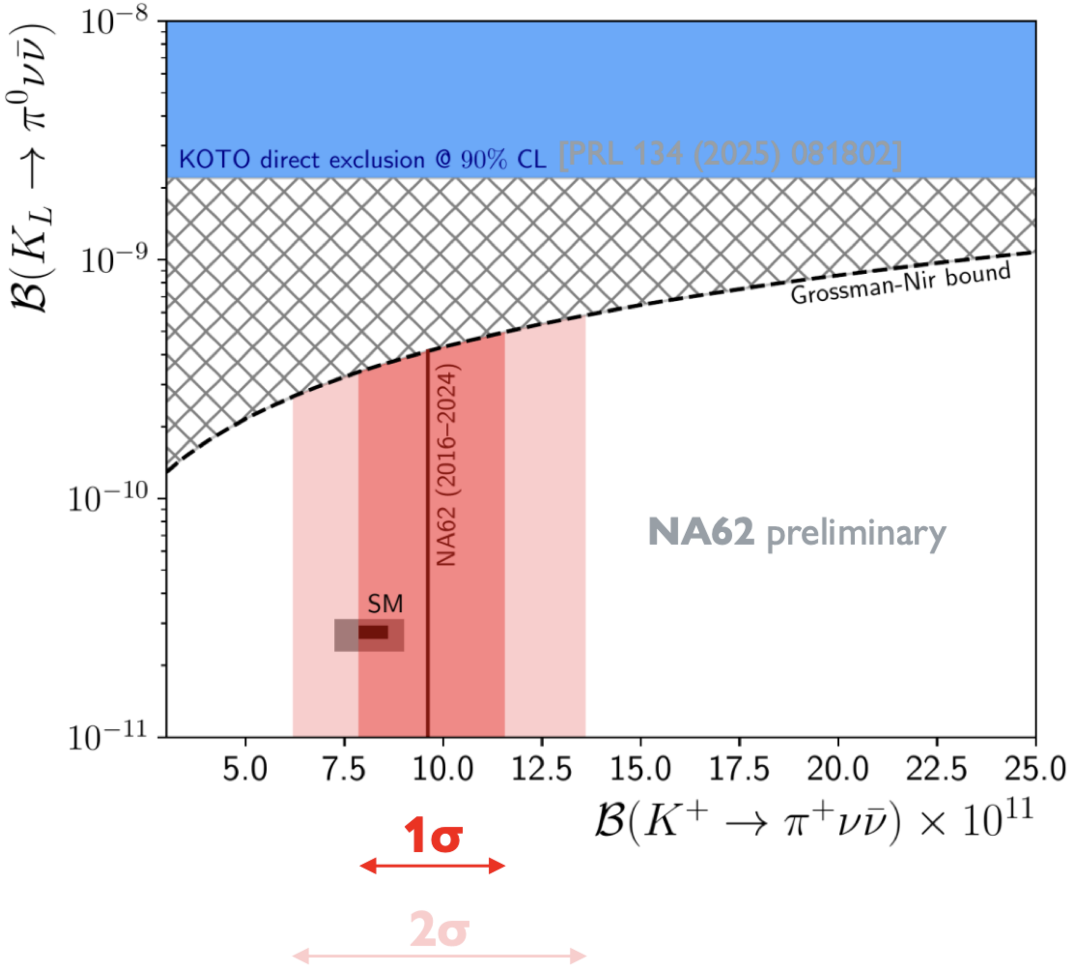
Expected SM signal: $N^{SM}_{\pi\nu\bar{\nu}} \approx 43 \pm 1$

Expected background: $N_{bg} = 30^{+4}_{-3}$

Observed: $N_{obs} = 84$

Results in context

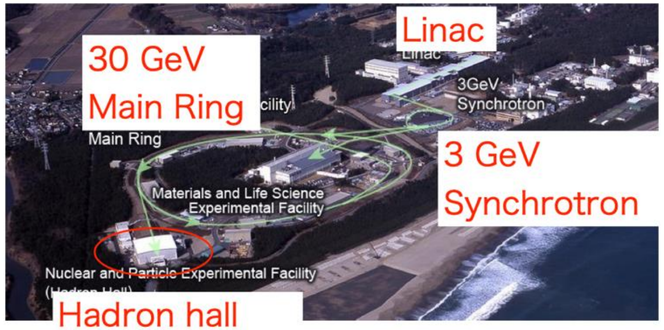


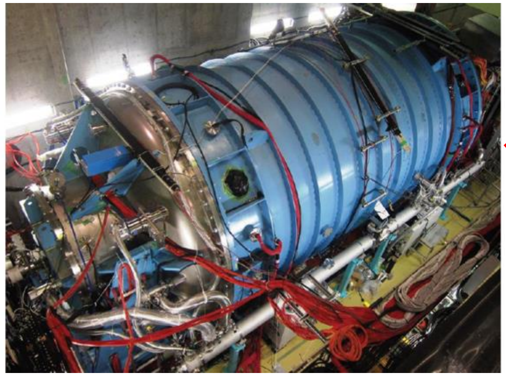


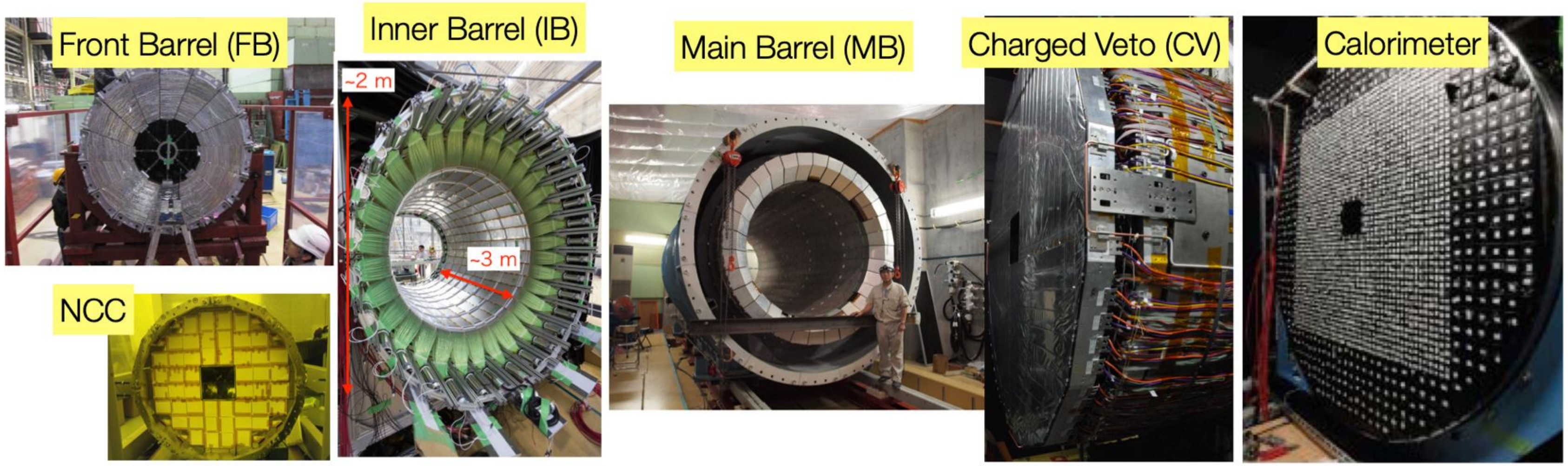
- NA62 results consistent with previous results
- Central value consistent with SM
- Fractional uncertainty decreased to slightly below **20%**
- Only about 2/3 of the complete NA62 dataset analysed (including data to be collected in 2026)
- **Final goal to reach precision of about 15% or better → stay tuned for more exiting results**

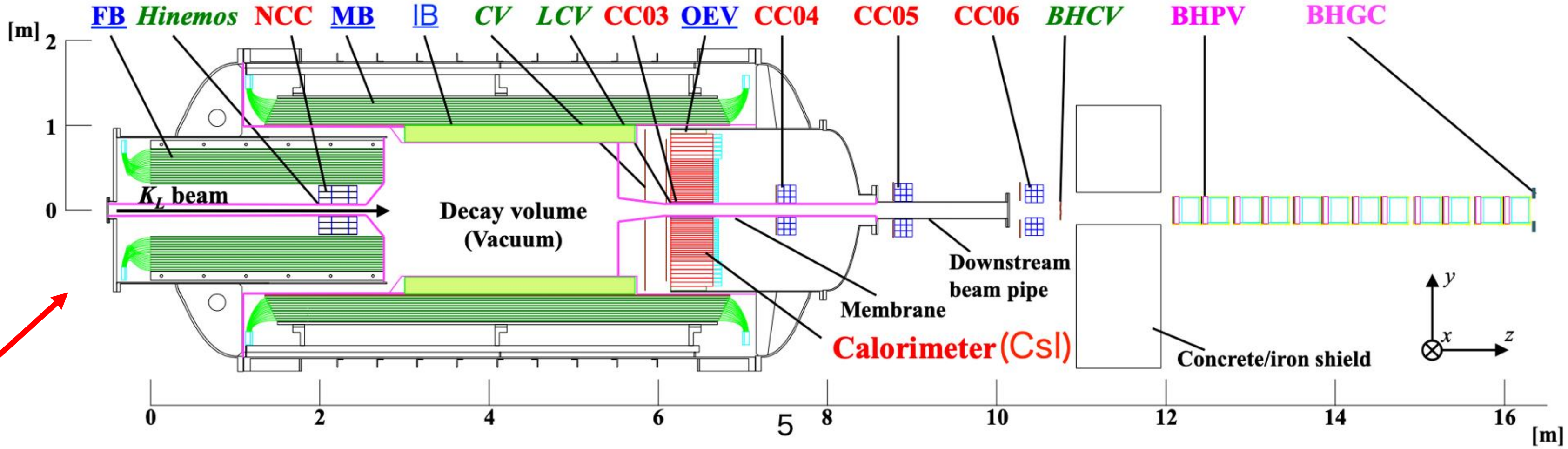
KOTO experiment: a search for $K_L \to \pi^0 \nu \bar{\nu}$

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

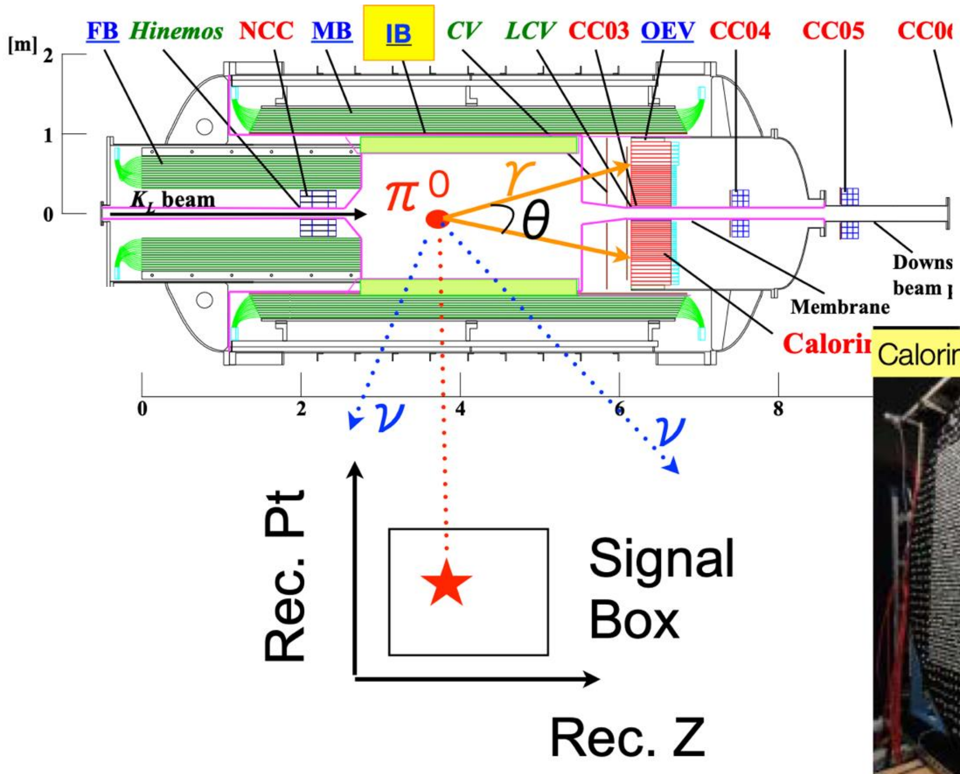


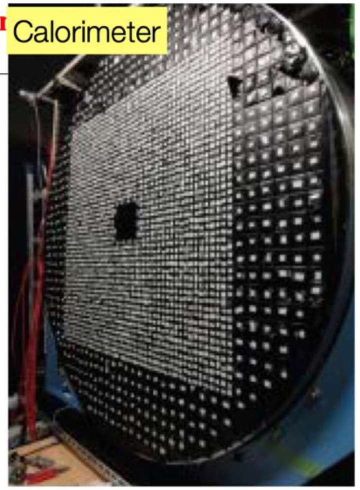






KOTO experiment: a search for $K_L \to \pi^0 \nu\bar{\nu}$

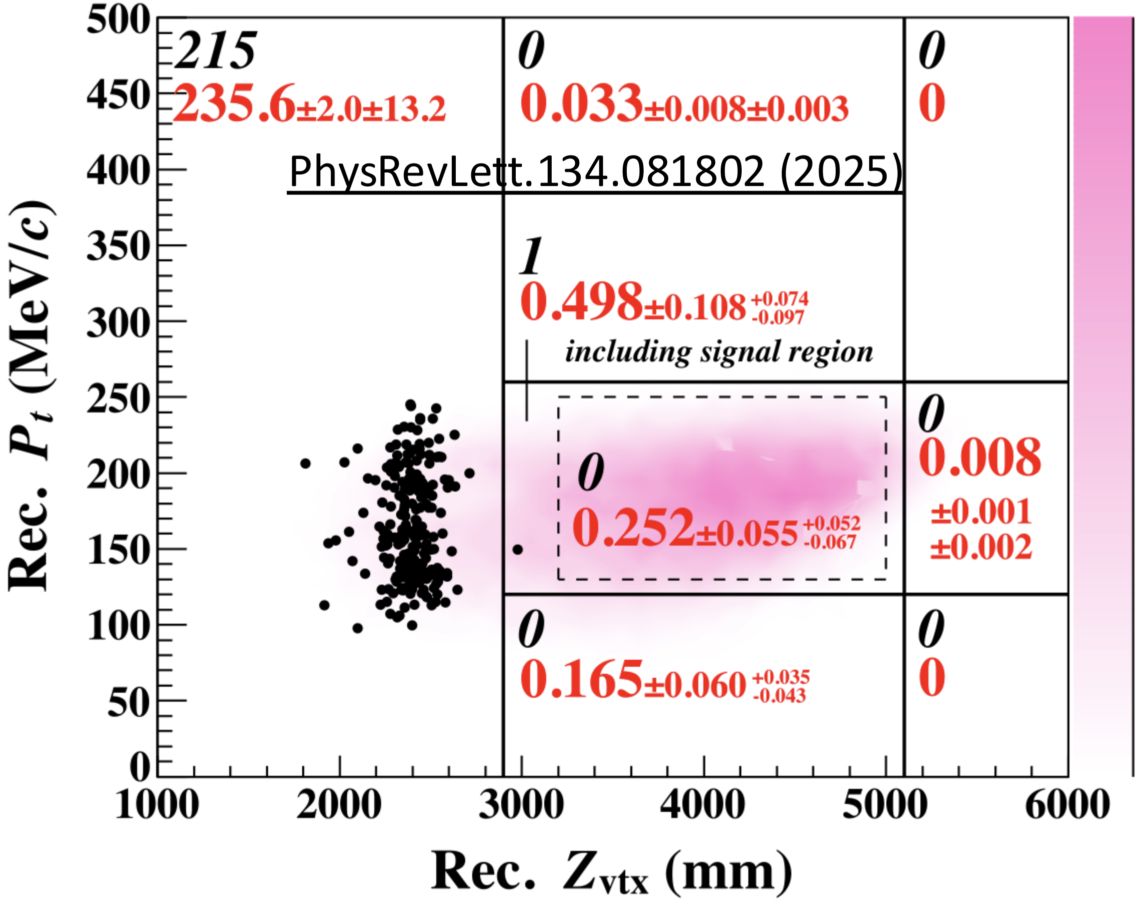




Experimental technique

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

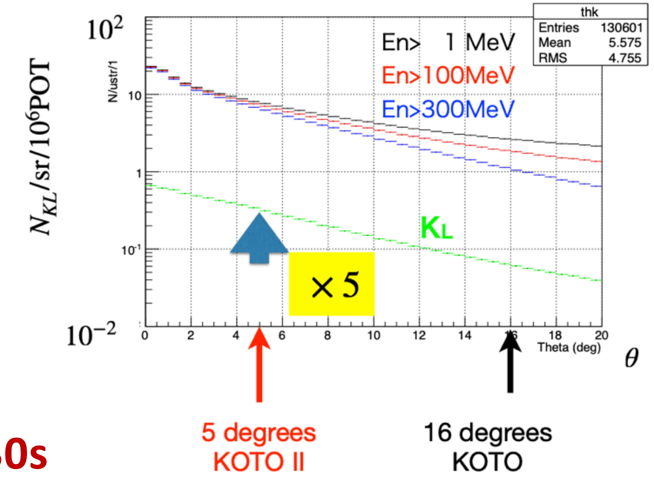
$$m^2(\pi^0) = 2E_1E_2(1 - \cos\theta)$$

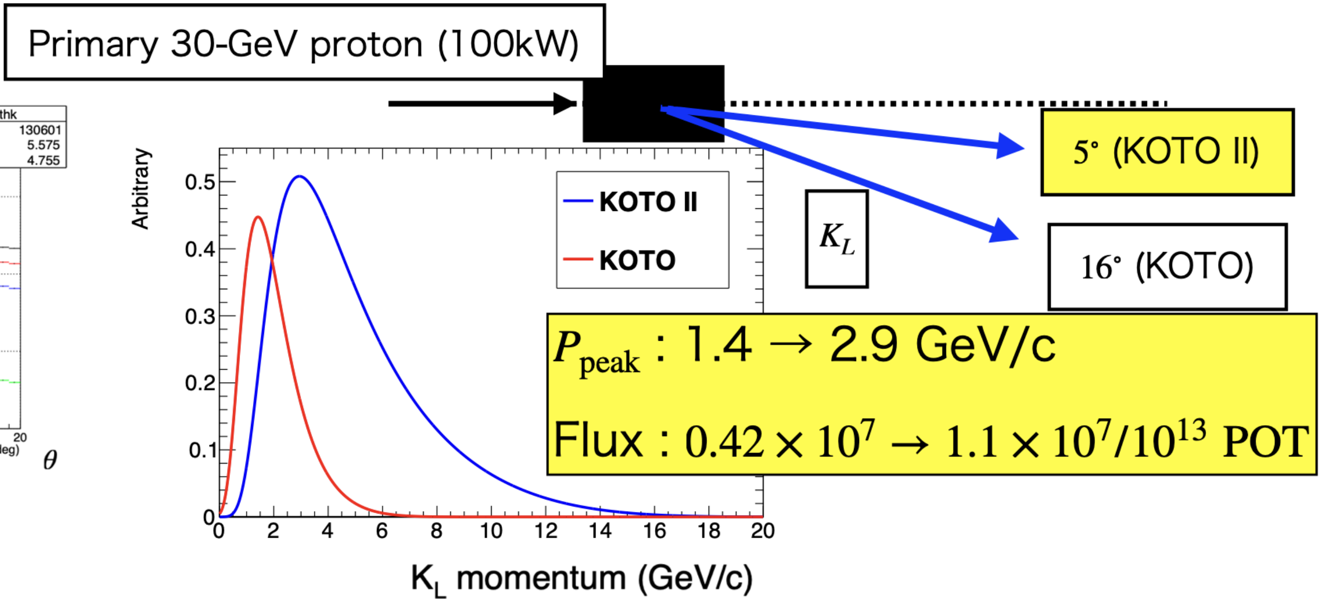


- $SES = (9.33 \pm 0.06_{stat} \pm 0.84_{syst}) \times 10^{-10}$
- No observed events in the signal region
- **$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) < 2.1 \times 10^{-9}$ at 90% CL**

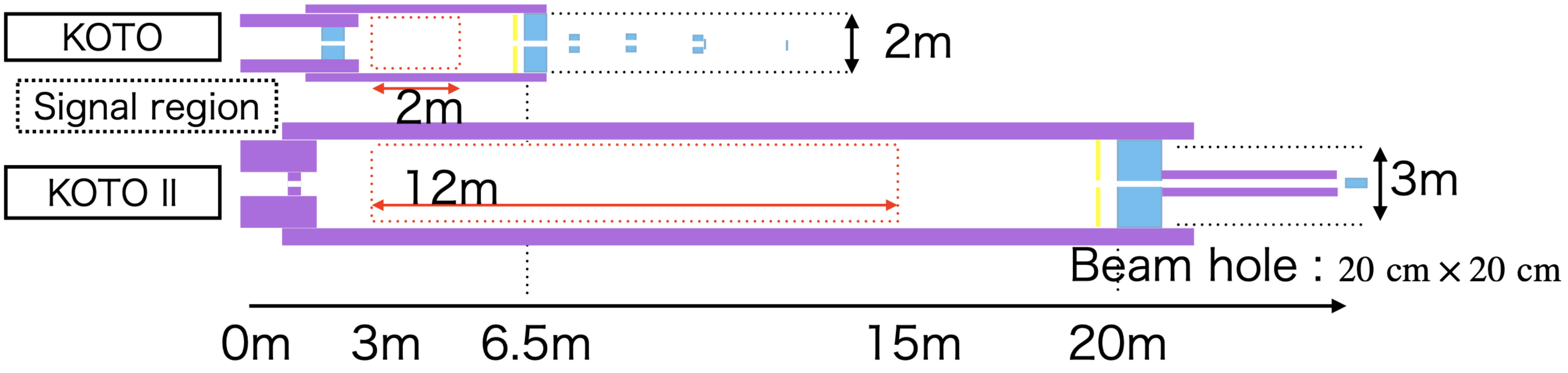
How to improve sensitivity: KOTO II

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

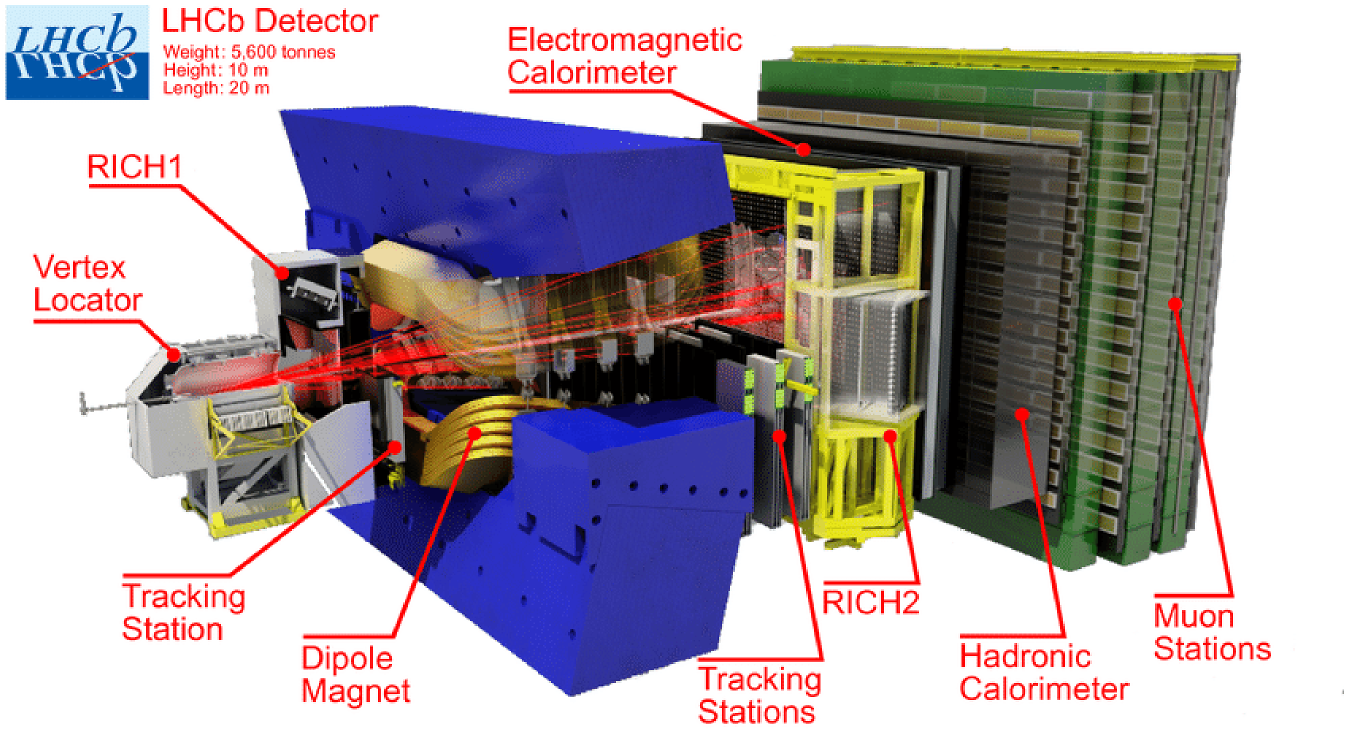




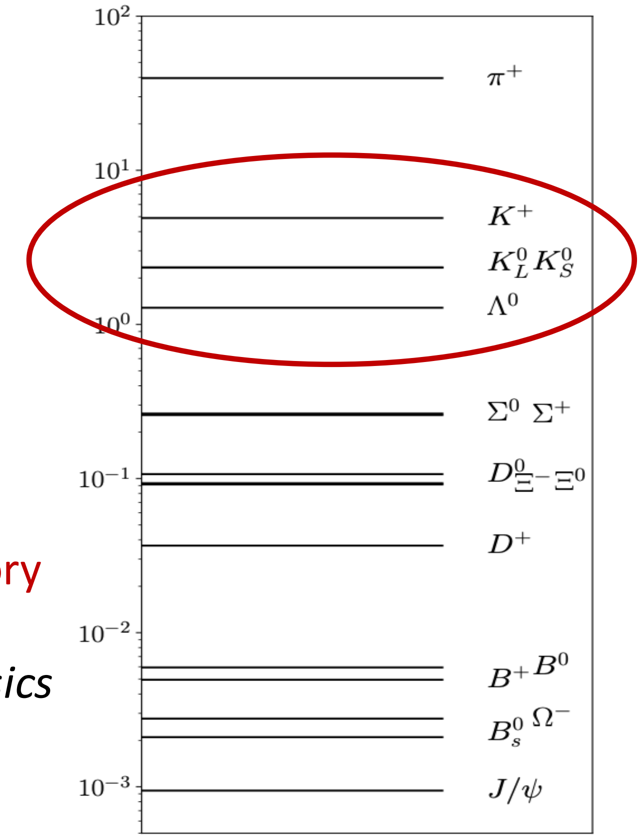
Proposed to start in the 2030s



Kaons at LHCb



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



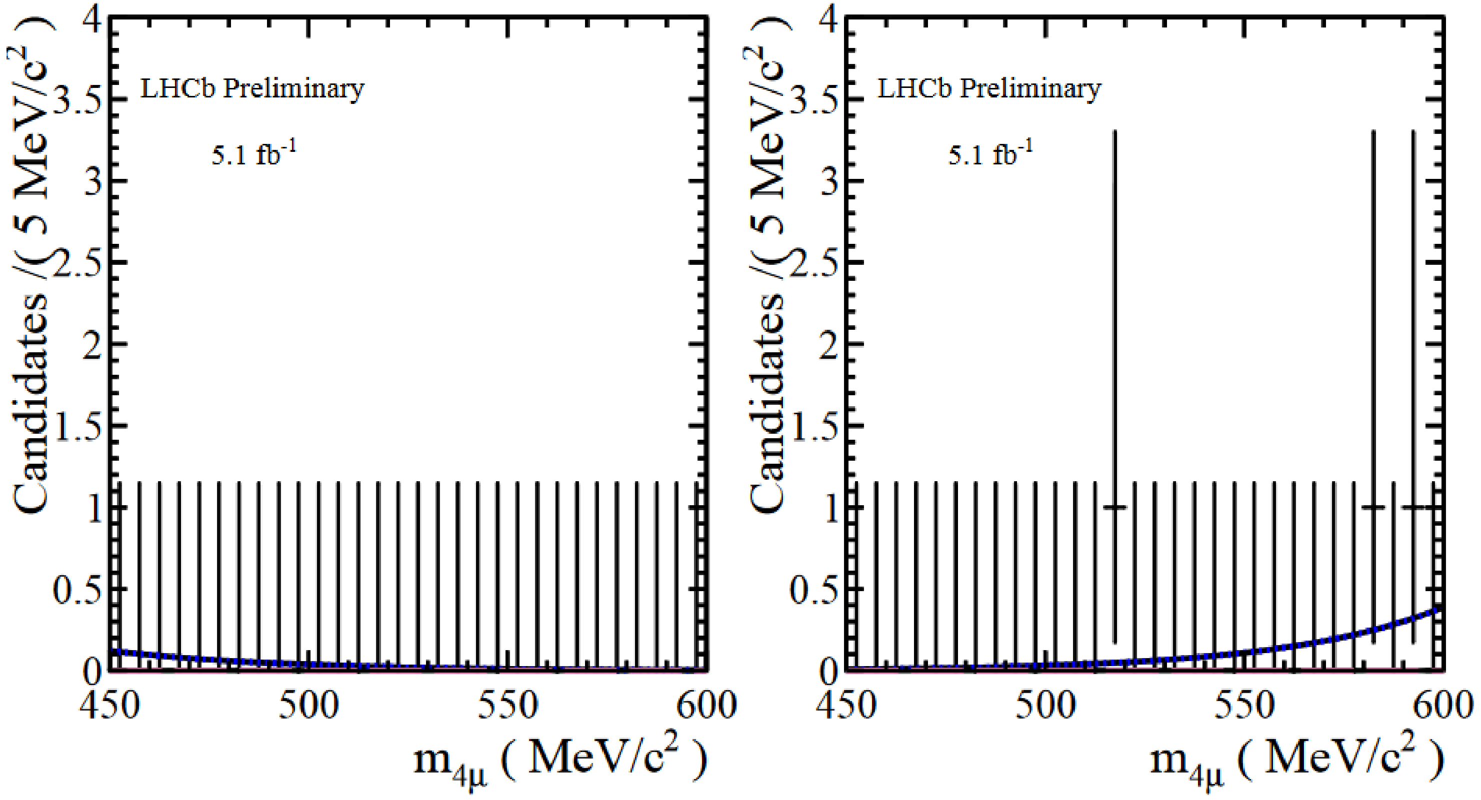
- Originally conceived as a B-meson factory: huge cross section for kaon production → K factory
- Fully software-based trigger introduced in Run 3 → $\mathcal{O}(100\%)$ *trigger efficiency for kaon physics*
- Unique opportunity to look for extremely rare kaon processes!

PRL 125 (2020) 231801

- **Flagship kaon mode:** $\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ @ 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 $K^0_{S(L)} \to \mu\mu\mu\mu$ decays, heavily suppressed in the SM: $10^{-13}(K^0_L), 10^{-14}(K^0_S)$
- Highly suppressed due to phase space
- No events found in signal region (Run 1 + 2)



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

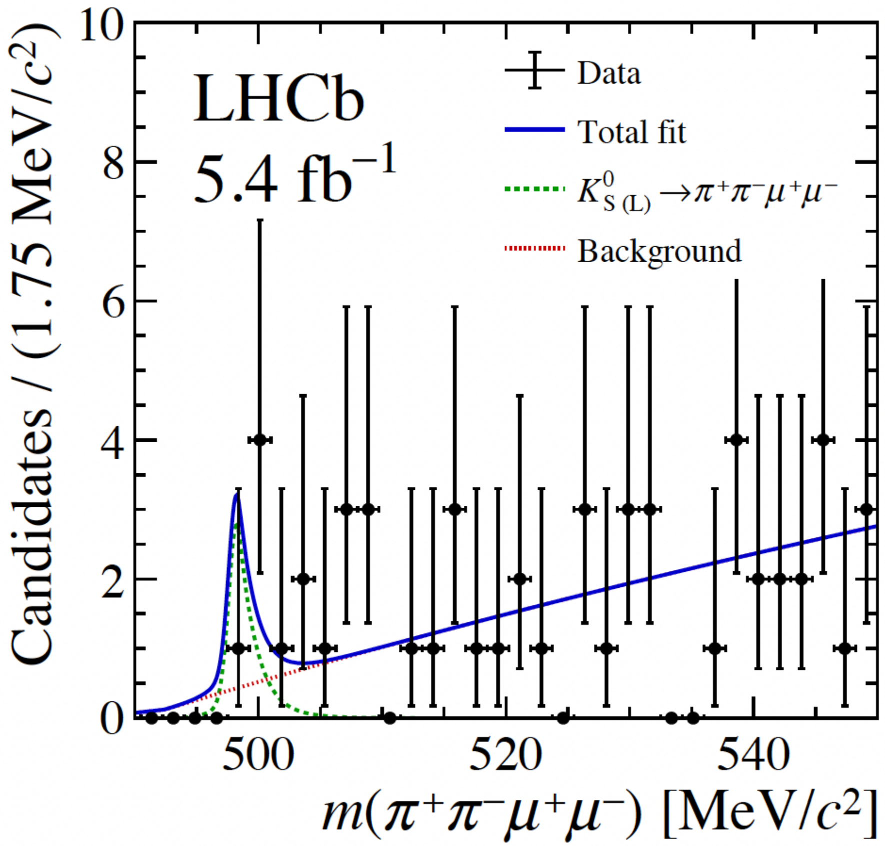
$$BR(K^0_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$$

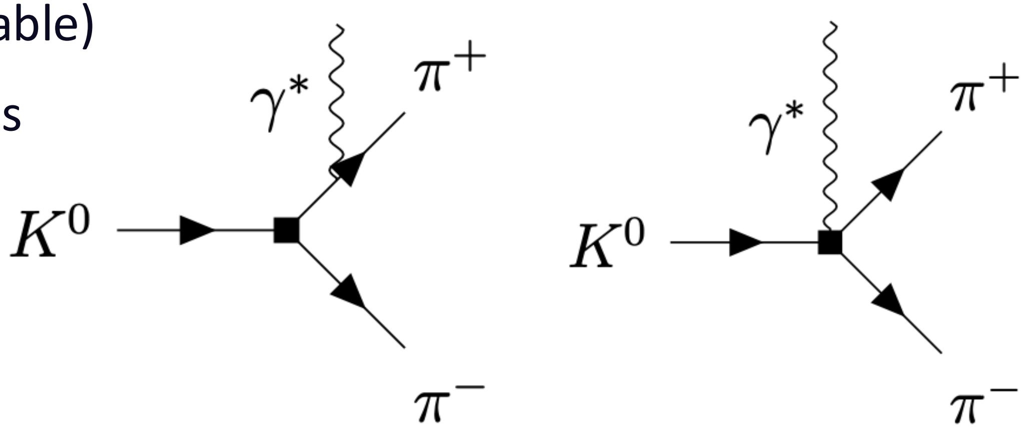
PRD 108 (2023) L031102

Plenty of kaon physics results to come from Run 3 data

Rare kaon decays at LHCb

- Search for $K^0_{S(L)} \to \pi\pi\mu\mu$ decays, heavily suppressed in the SM: $\sim 4 \times 10^{-14} (K^0_S)$
- Even larger suppression due to phase space (only 7 MeV available)
- More background than the 4μ modes due to presence of pions
- No significant signal found





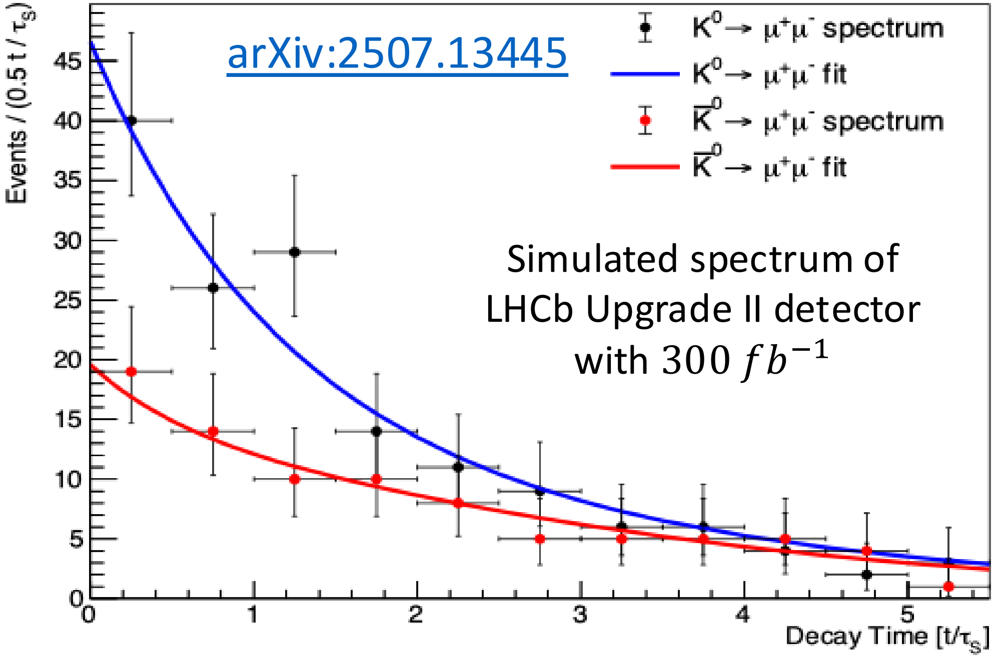
$BR(K^0_S \to \pi^+\pi^-\mu^+\mu^-) < 1.4 \times 10^{-9}$

$BR(K^0_L \to \pi^+\pi^-\mu^+\mu^-) < 6.6 \times 10^{-7}$

arXiv:2511.02619
Accepted by PRD

Plenty of kaon physics results to come from Run 3 data

Rare kaon decays at LHCb: future prospects



Time-dependent rate

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

$$C_L = |A(K_L)_{\ell=0}|^2\,,$$

$$C_S = |A(K_S)_{\ell=0}|^2 + \beta_\mu^2 |A(K_S)_{\ell=1}|^2\,,$$

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

$$\varphi_0 = \arg\left[A(K_S)^*_{\ell=0}\, A(K_L)_{\ell=0}\right].$$

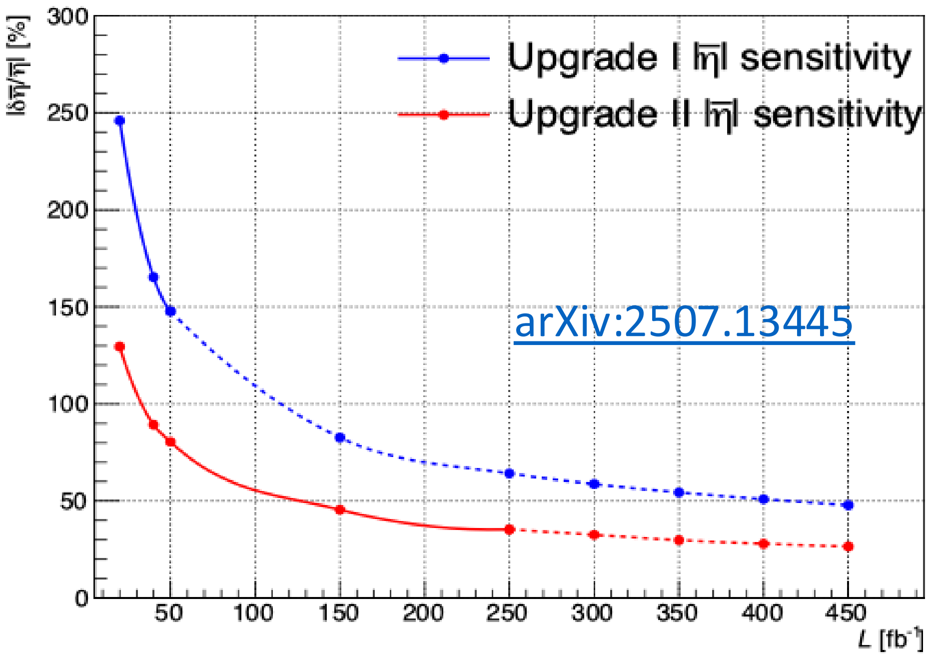
Short-distance CPV contribution

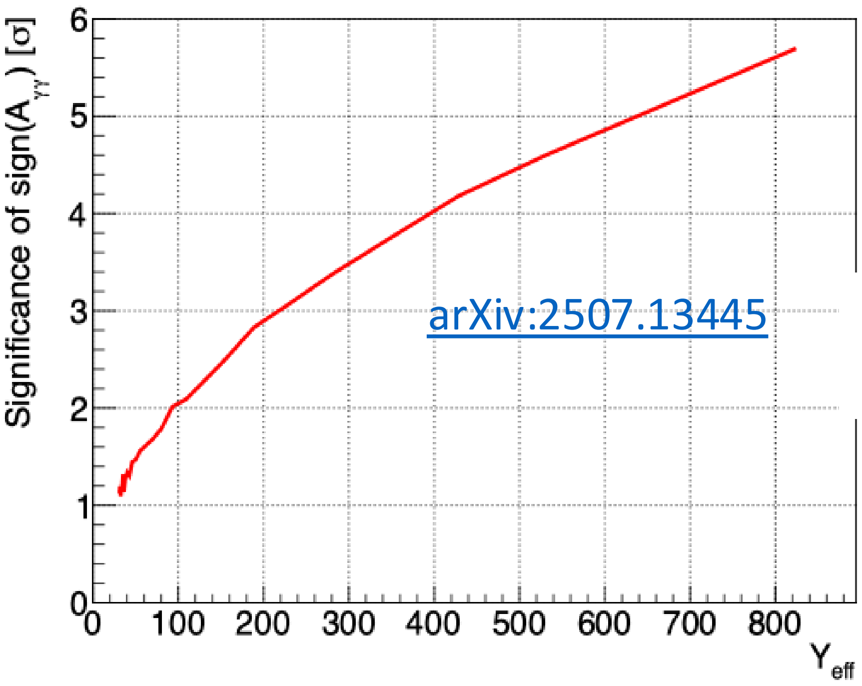
$$\mathcal{B}(K_S)_{\ell=0} = \frac{\beta_\mu \tau_S}{16\pi m_K}\left|\frac{2\,G_F^2 m_W^2}{\pi^2} f_K m_K m_\mu Y_t\right|^2 \cdot (\lambda^5 A^2 \bar{\eta})^2$$

- 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

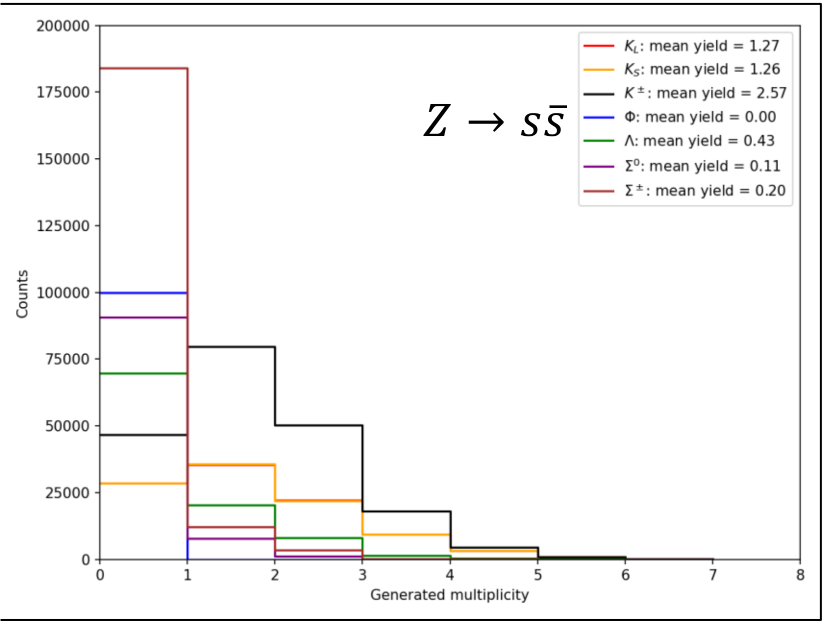
- Time-dependent information and K tagging can be used to measure the $K_S - K_L \to \mu^+\mu^-$ interference
- The studies show that LHCb Upgrade II might be able to achieve an uncertainty on $|\bar{\eta}|$ of $\sim 35\%$
    - development of kaon tagging (preliminary studies encouraging)
    - including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

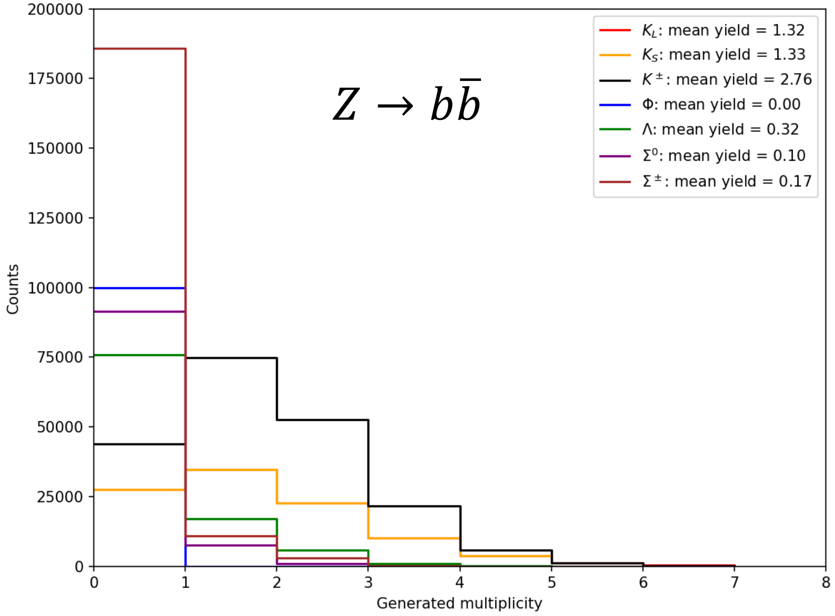
Kaon physics @ FCC-ee

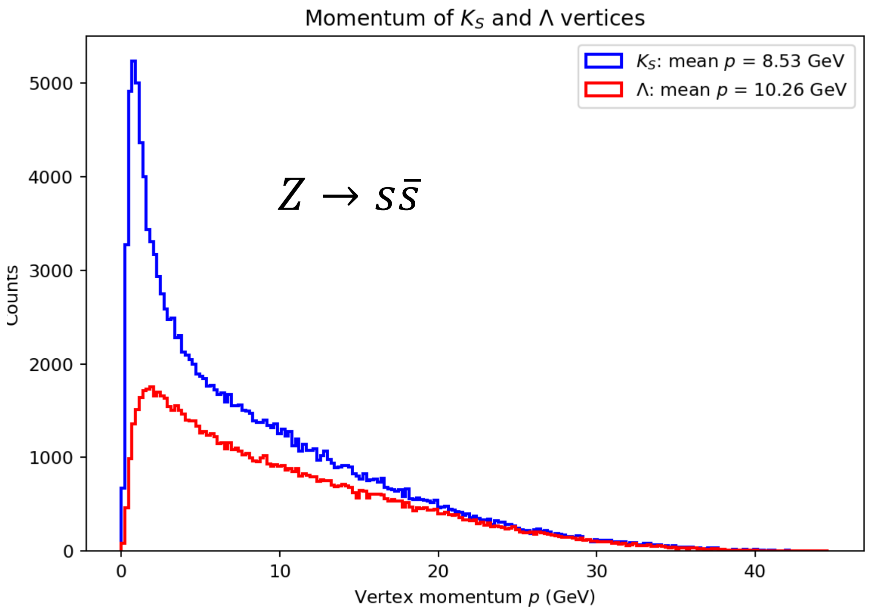
How many kaons will be produced at FCC-ee?

Kaon physics @ FCC-ee: production

DELPHES simulation
Results by Xunwu Zuo



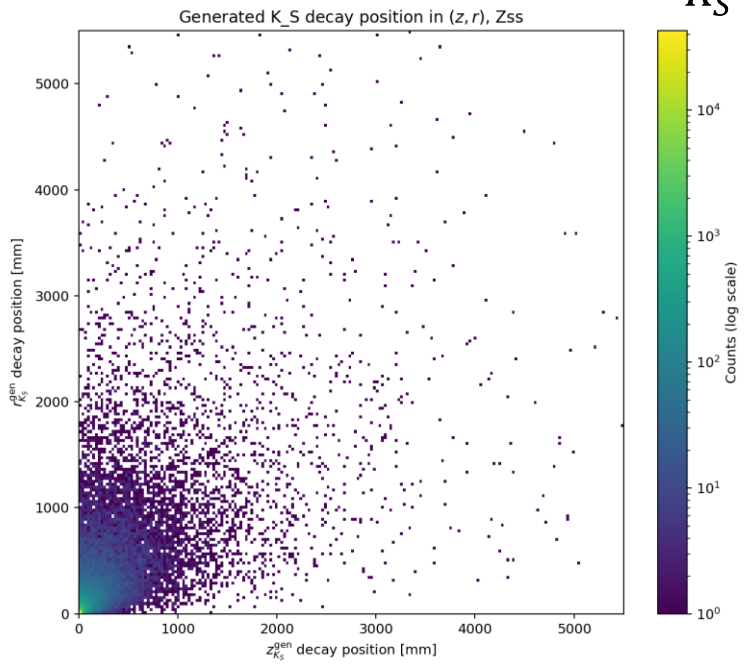


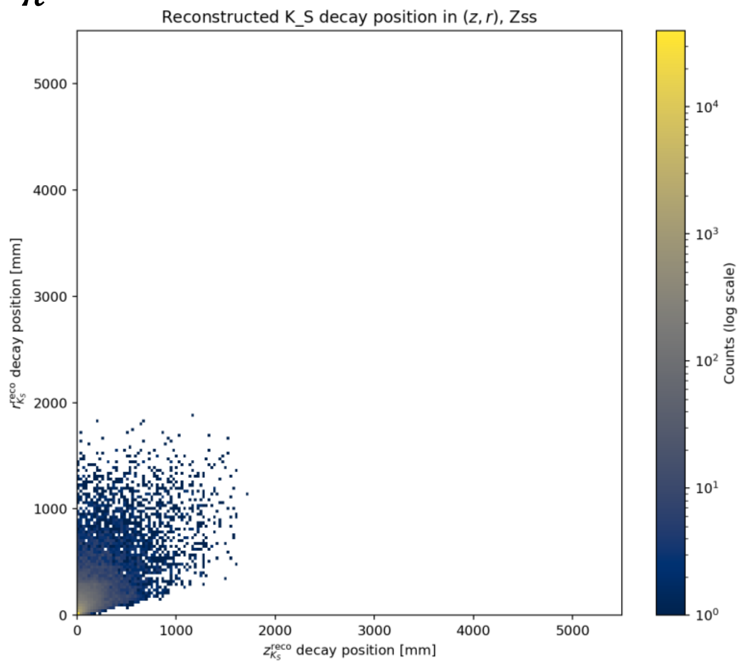


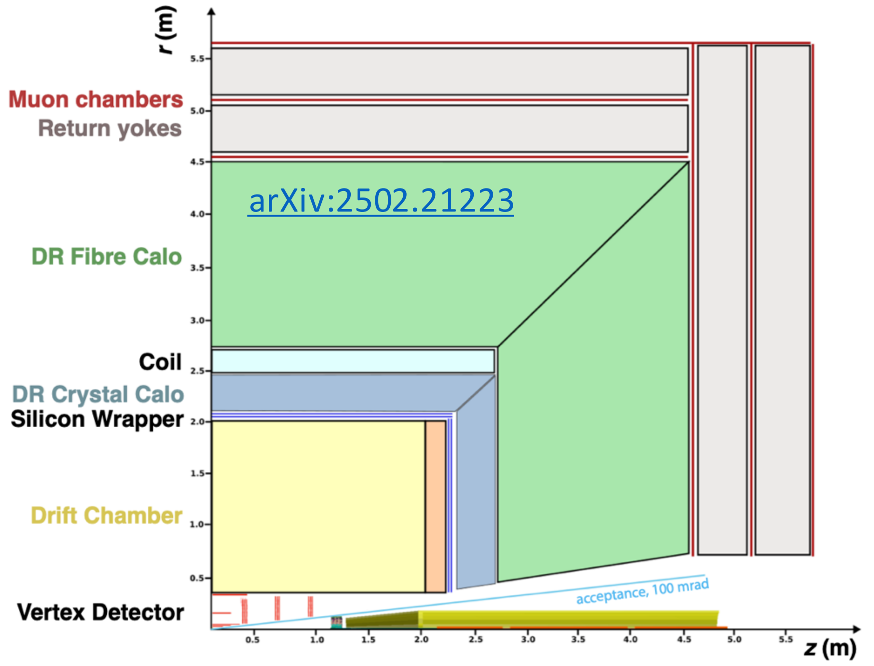
- Answer: at least one K_S per event for $Z \to q\bar{q}$ events: *a sample of more than* 10^{12} *neutral kaons*
- Could offer interesting prospects for precision studies due to the clean environment at FCC-ee
- Soft momentum spectrum for K_S and Λ's at production → "short" flight distance
- Large number of decays inside the vertex detector and tracker → large lifetime*acceptance could be expected
- For all plots I used as an example $Z \to s\bar{s}$ events but similar situation for all $Z \to q\bar{q}$ production mechanisms

Kaon physics @ FCC-ee: reconstruction

$K_S \to \pi^+\pi^-$

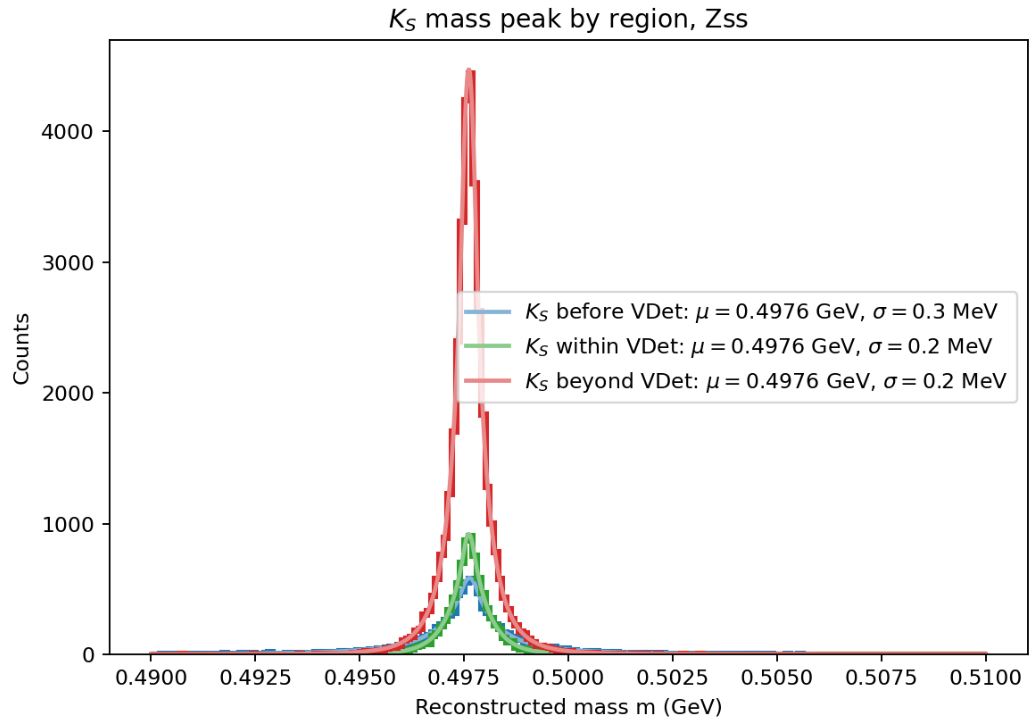


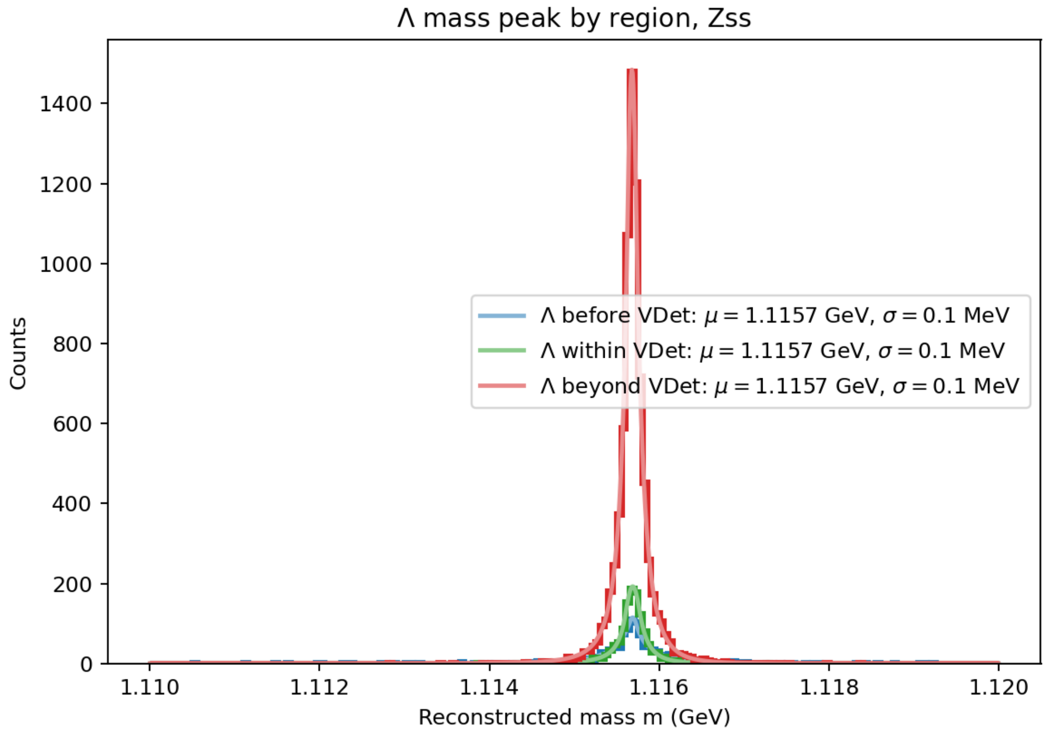




- IDEA detector concept used for the simulations
- Simple two-track vertex selection to check reconstructability for $K_S \to \pi^+\pi^-$ (proxy for $K_S \to \mu^+\mu^-$) and $\Lambda \to p\pi^-$ decays
- Lifetime-acceptance important to estimate what fraction of decays we can reconstruct and use for measurements

Kaon physics @ FCC-ee: mass resolution

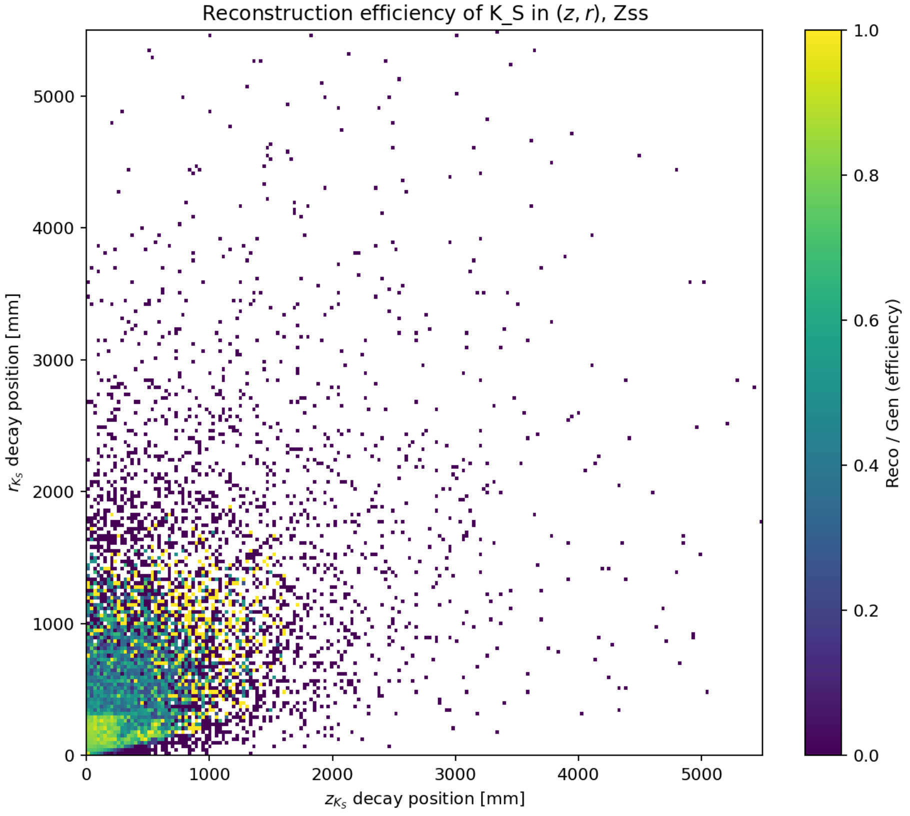


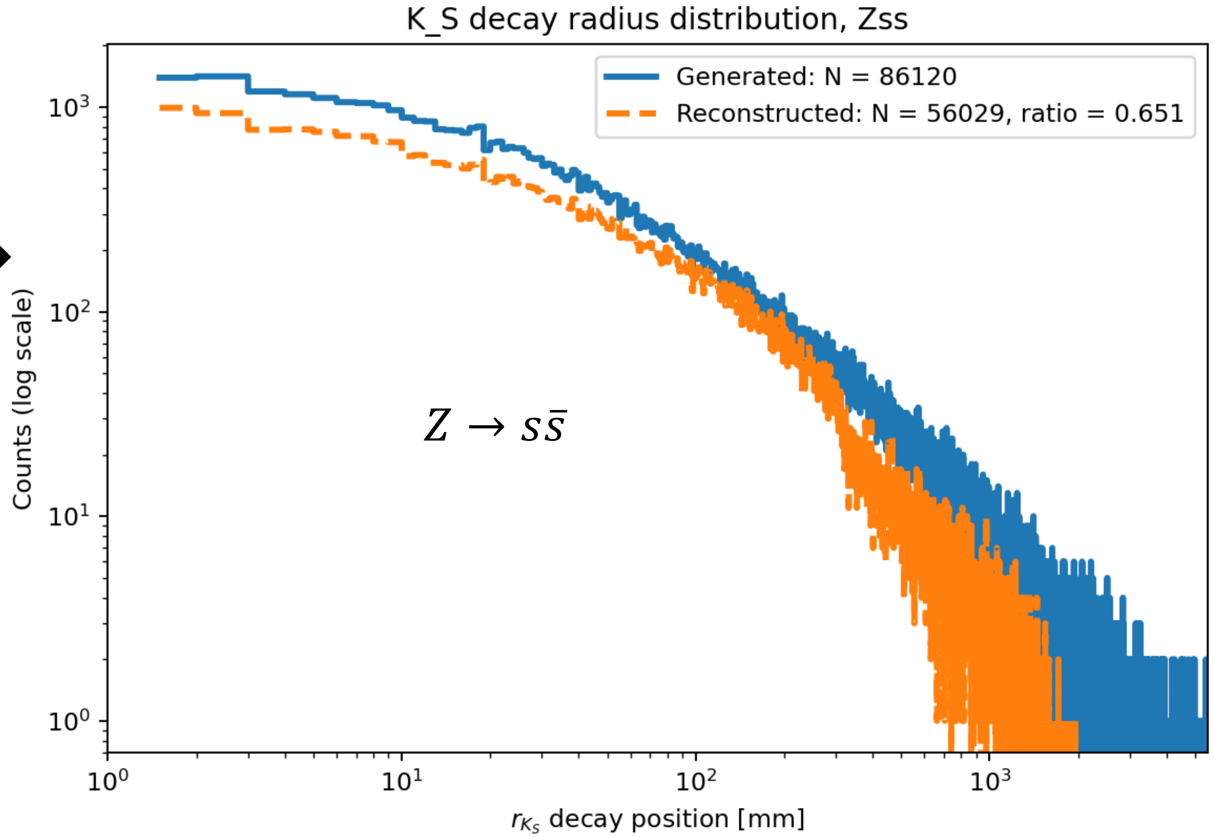


Situation looks promising

- Mass resolution seems pretty good (even too good): less than 1 MeV (to be investigated further)
- For comparison: at present LHCb's mass resolution with long tracks in Run 3 is between 3 and 4 MeV
- Mass resolution very important, especially for $K \to \mu^+\mu^-$ ($BR = 5 \times 10^{-12}$) measurement (mis-reconstructed $K \to \pi^+\pi^-$ ($BR = 69\%$) main bkg)

Kaon physics @ FCC-ee: lifetime-acceptance





- The soft momentum spectrum leads to large lifetime*acceptance for these decays
  - ~65% for $K_S \to \pi^+\pi^-$ (it should be the same for $K_S \to \mu^+\mu^-$)
- Tagging of the flavour of the decaying neutral kaon needs to be investigated to understand feasibility for A_{CP} measurements
- Next steps: complete the sensitivity to $K \to \mu^+\mu^-$ and extend the studies to three-body decays (e.g. $K \to \pi^0 l^+ l^-$)

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
  - $\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = (9.6^{+1.9}_{-1.8}) \times 10^{-11}$ (paper in preparation)
- 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!
- Clean environment at the FCC-ee and relatively large amount of kaons produced might offer interesting opportunities
- NA62, KOTO, and LHCb are collecting data and would ensure a steady stream of kaon physics results in the coming years!