Searches for dark sectors in kaon decays

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Focusing mainly on PBC benchmarks:

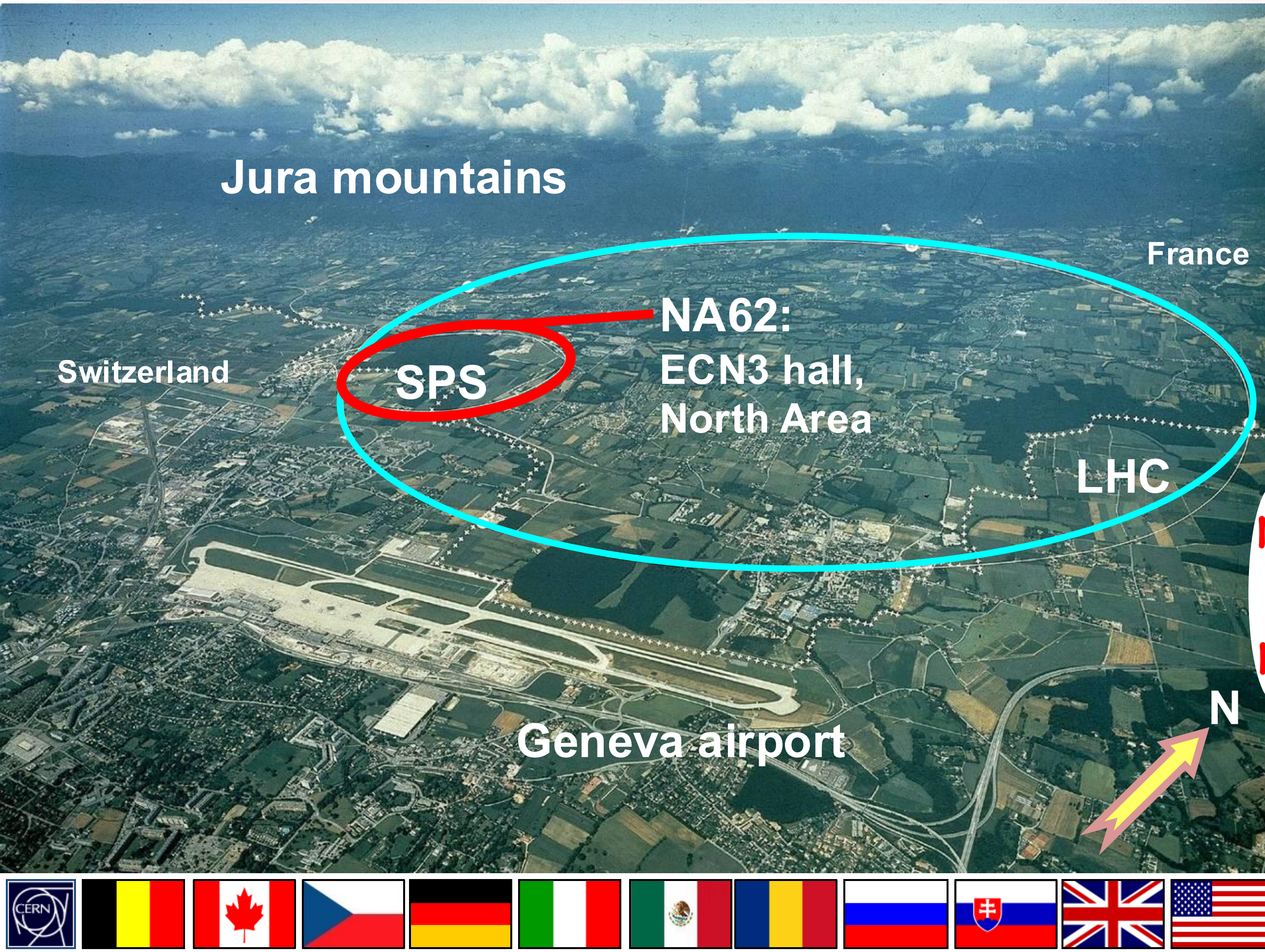
1) $K \to \pi X$: dark photon (BC2), dark scalar (BC4), ALP (BC10,11)
2) $\pi^0 \to \gamma A'$: visible dark photon (BC1)
3) $K^+ \to \ell^+ N$, $\pi^+ \to e^+ N$: heavy neutral leptons (BC6,7)
4) Other searches in kaon decays

Light Dark World Workshop

IFT Madrid • 18 September 2025

The NA62 experiment at CERN

Kaon experiments at CERN



Earlier: NA31

NA48 discovery of direct CPV	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 R_K run	2007: $K^\pm_{e2}/K^\pm_{\mu 2}$	tests
	2008: $K^\pm_{e2}/K^\pm_{\mu 2}$	tests
NA62	2015: commissioning	
	2016-18: physics run 1	
	2021-: physics run 2	

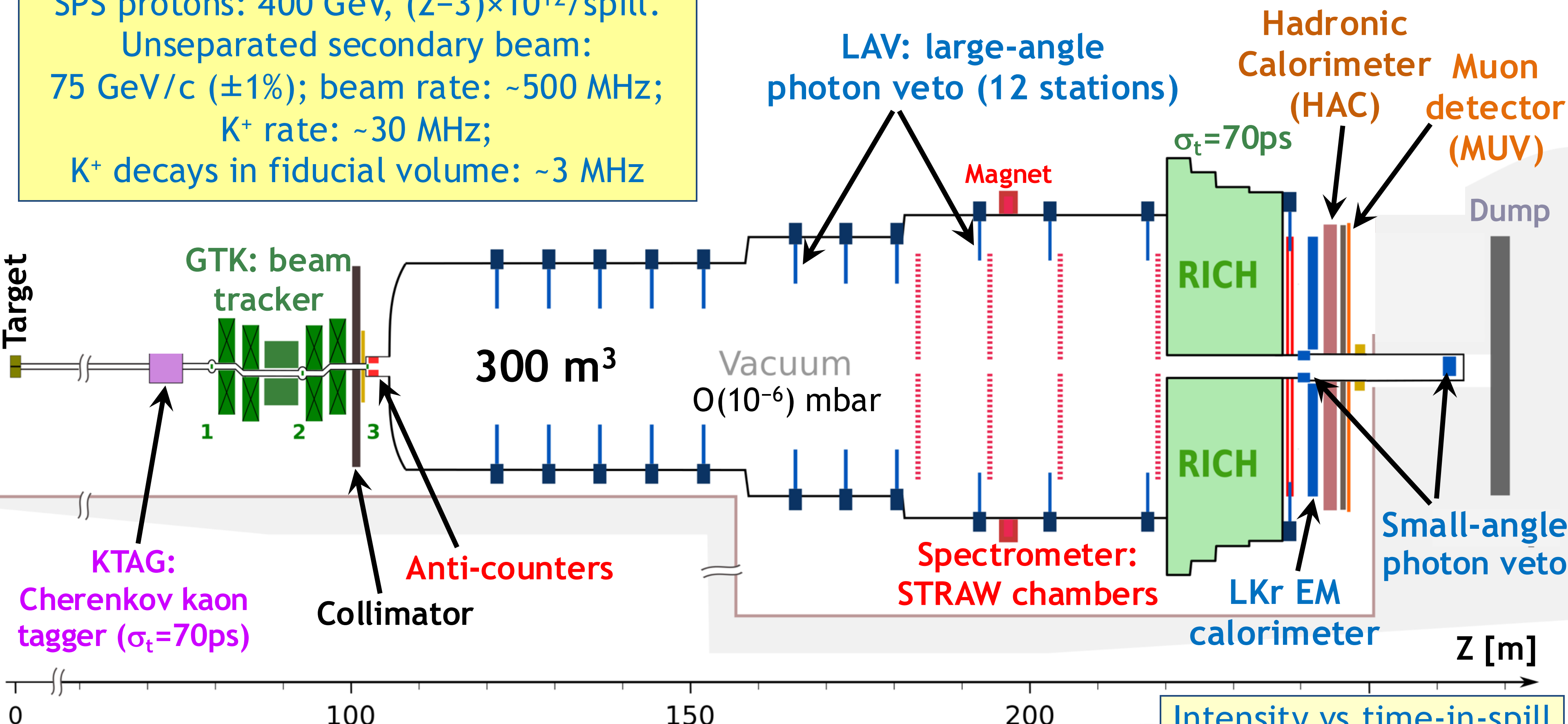
NA62: a multi-purpose K^+ (and π^0) decay experiment focused on $K^+\to\pi^+\nu\nu$ measurement to 15% precision.

Currently ~300 participants from ~30 institutions.

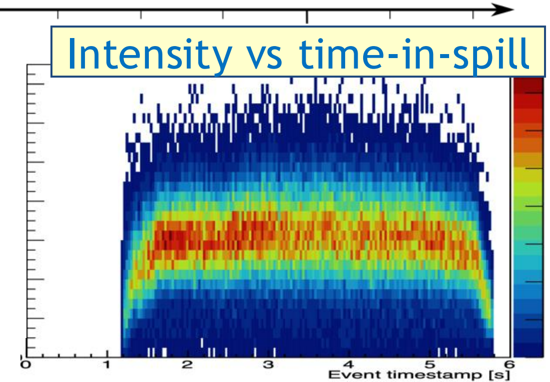
The NA62 experiment

JINST 12 (2017) P05025

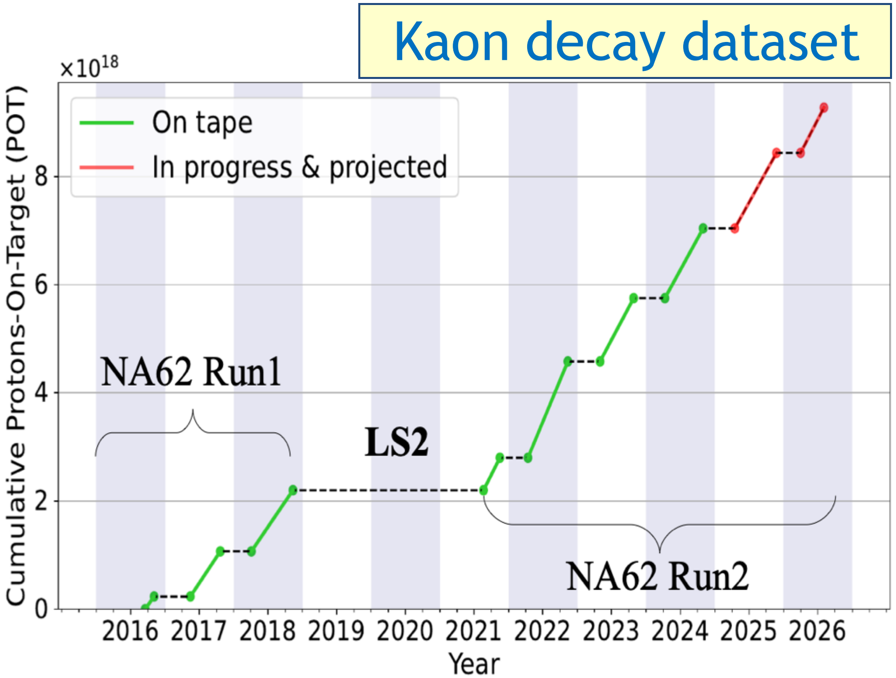
SPS protons: 400 GeV, (2−3)×10^{12}/spill.
Unseparated secondary beam:
75 GeV/c (±1%); beam rate: ~500 MHz;
K^+ rate: ~30 MHz;
K^+ decays in fiducial volume: ~3 MHz



- One year ≈ **1.5×10^{18}** protons on target ≈ **5×10^{12} K^+** decays.
- Beam structure: ideally, uniform over a **4.8 s** long spill.
- In practice, significant variations of instantaneous beam intensity during the spill.



NA62 datasets



Kaon decay dataset:

- ❖ Run 1 (2016–18): 850k good SPS spills in 420 days.
- ❖ Run 2 (2021–): 1.5M good SPS spills in 650 days, up to 2024.
- ❖ Data collection to continue until LS3 (up to 2026 inclusive).
- ❖ Broad programme: rare K^+/π^0 decays; LNV/LFV, hidden sectors.

Beam-dump dataset: 0.9×10^{18} pot, collected in 45 days.

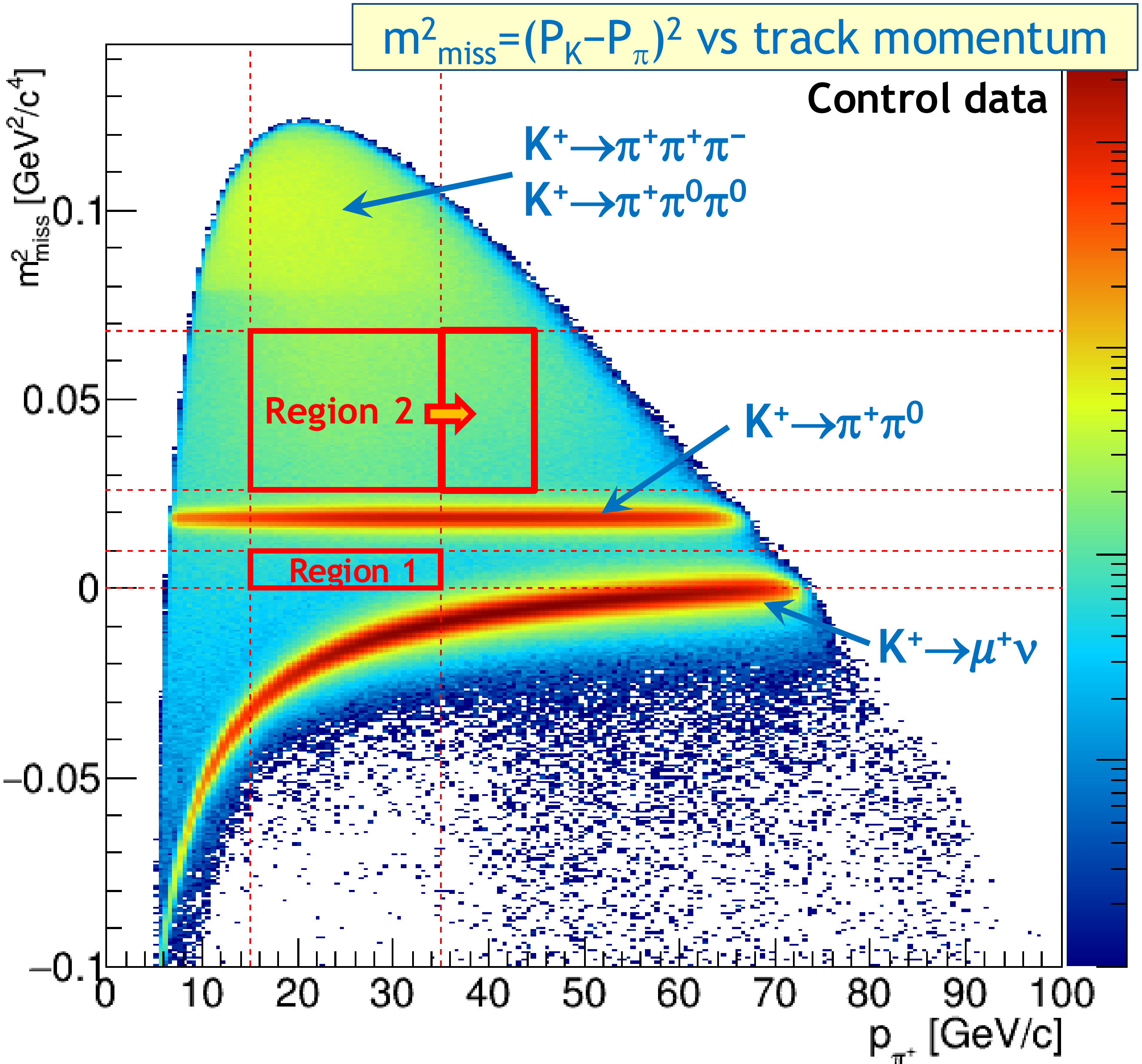
$K^+ \to \pi^+ X$ at NA62

[arXiv:2507.17286]

Invisible X, from the $K^+ \to \pi^+ \nu\nu$ measurement *[JHEP 02 (2025) 191]*
- BC2 (invisible dark photon),
- BC4 (dark scalar);
- BC10 (ALP with fermion coupling);
- BC11 (ALP with gluon coupling).

Visible X, from $K^+ \to \pi^+ \mu^+ \mu^-$ and $K^+ \to \pi^+ \gamma\gamma$ measurements *[JHEP 11 (2022) 11; PLB850 (2024) 138513]*

$K^+ \to \pi^+\nu\nu$ measurement principle



Main K^+ decay modes (>90% of BR) rejected kinematically.

Resolution on m^2_{miss}: $\sigma = 1.0\times10^{-3}$ GeV^4/c^2.

Measured kinematic background suppression:

- ✓ $K^+ \to \pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+ \to \mu^+\nu$: 3×10^{-4}.

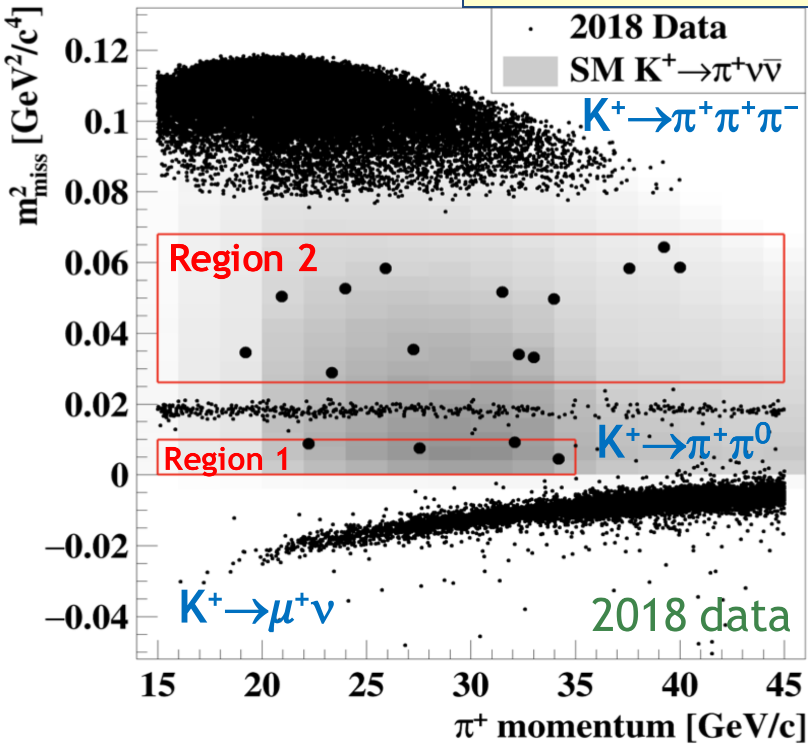
Further background suppression:

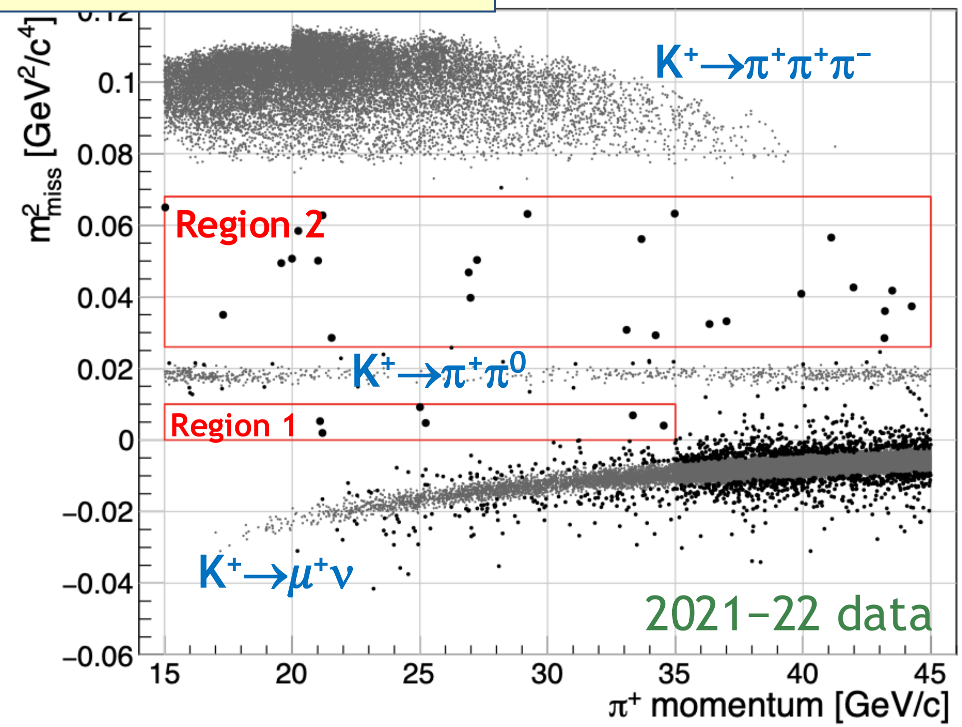
- ✓ PID (calorimeters & RICH): μ suppression 1.3×10^{-8}, π ID efficiency = 73%.
- ✓ Hermetic photon veto: $\pi^0 \to \gamma\gamma$ rejection factor = 1.7×10^{-8}.

$K^+ \to \pi^+ \nu\nu$ result (2016–22 data)

m^2_{miss} vs pion momentum

JHEP 02 (2025) 191





The 2016–22 dataset: 51 signal candidates; expected background: 18^{+3}_{-2}

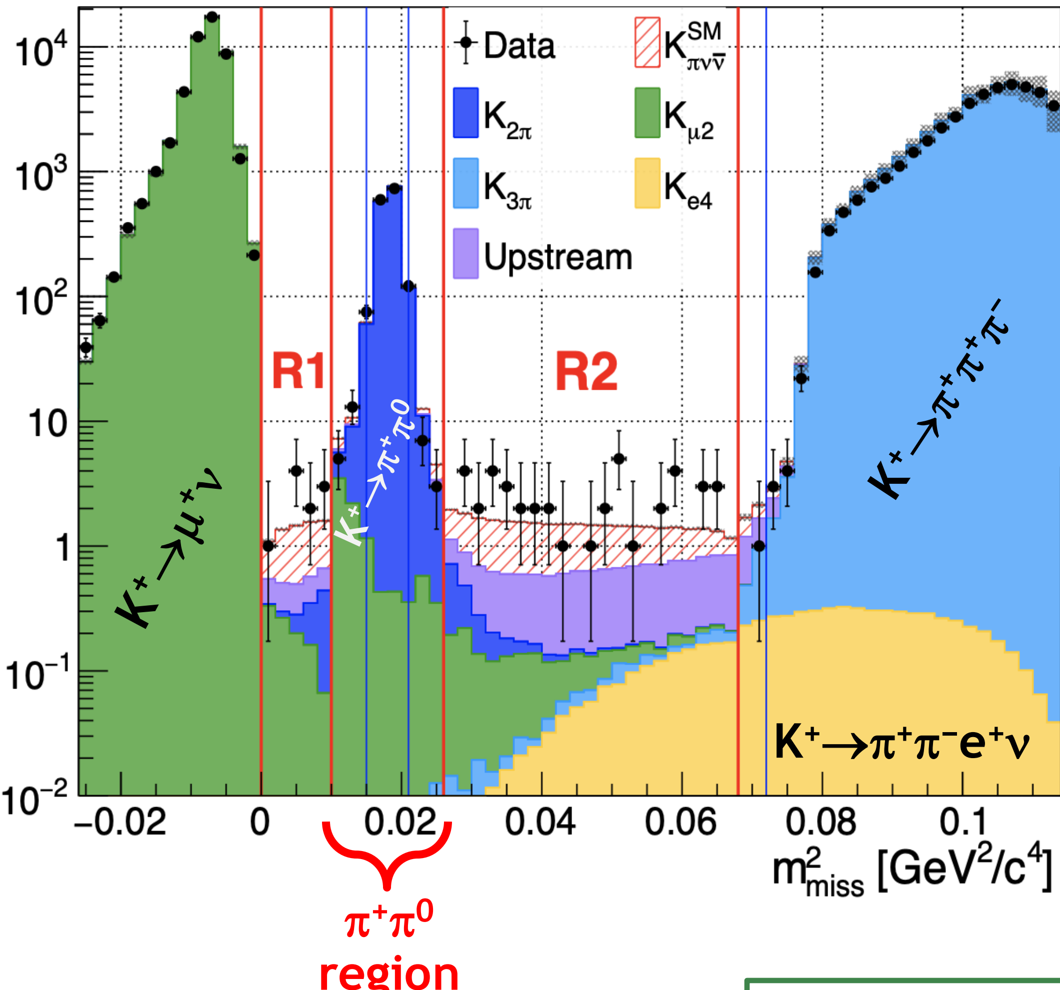
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(13.0^{+3.0}_{-2.7}\Big|_{\mathrm{stat}}{}^{+1.3}_{-1.3}\Big|_{\mathrm{syst}}\right) \times 10^{-11} = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$$

- *The rarest particle decay ever observed* with $>5\sigma$ significance.
- Consistent with the SM expectation within 1.7σ.

Search for $K^+ \to \pi^+ X_{inv}$ at NA62

JHEP 02 (2021) 201; arXiv:2507.17286

Squared missing mass (2016–22 data)



Peak search in $K \to \pi\nu\nu$ regions: **0–110 MeV** and **154–260 MeV**.

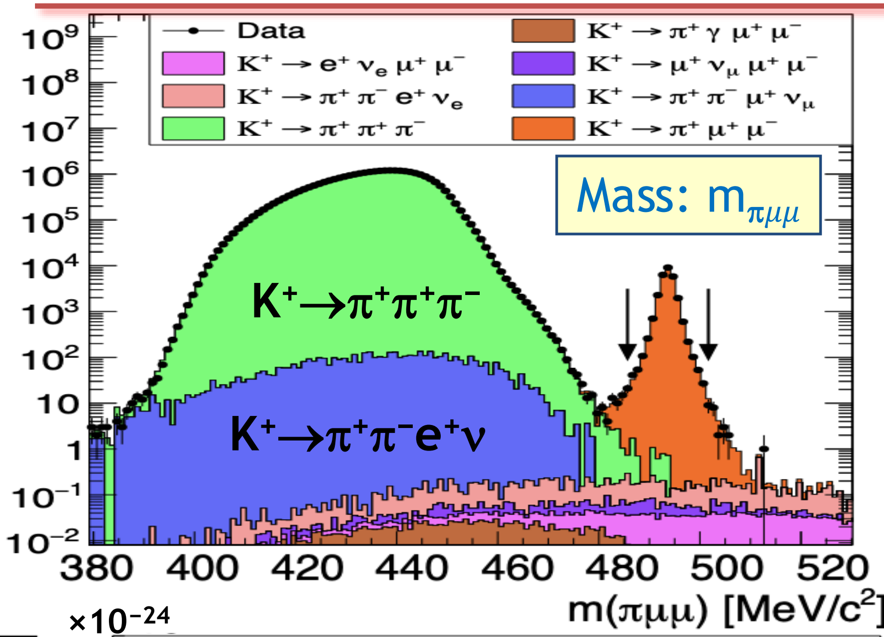
- ✓ Main background: $K^+ \to \pi^+ \nu\nu$.
- ✓ Limits on $BR(K_{\pi X})$ of $O(10^{-11})$.

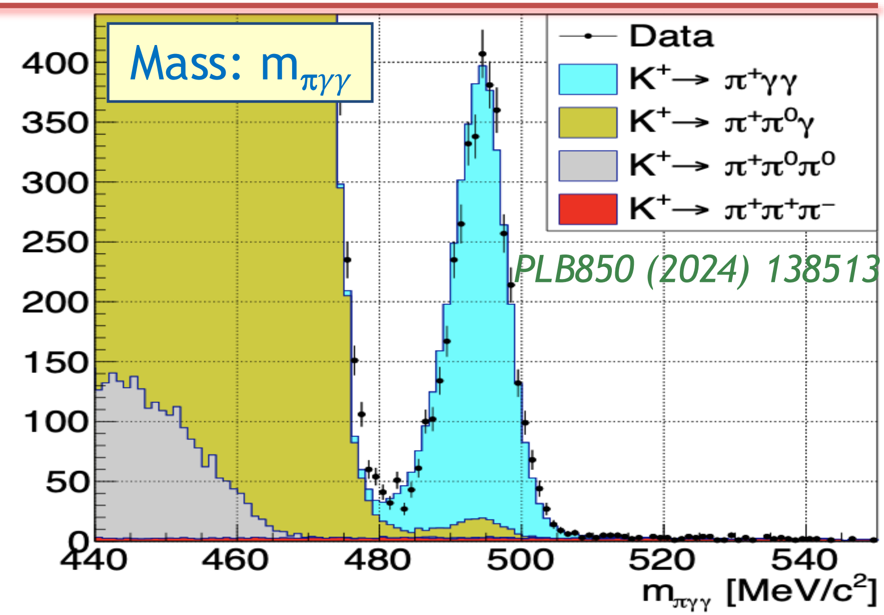
Search for $\pi^0 \to$ **invisible**:

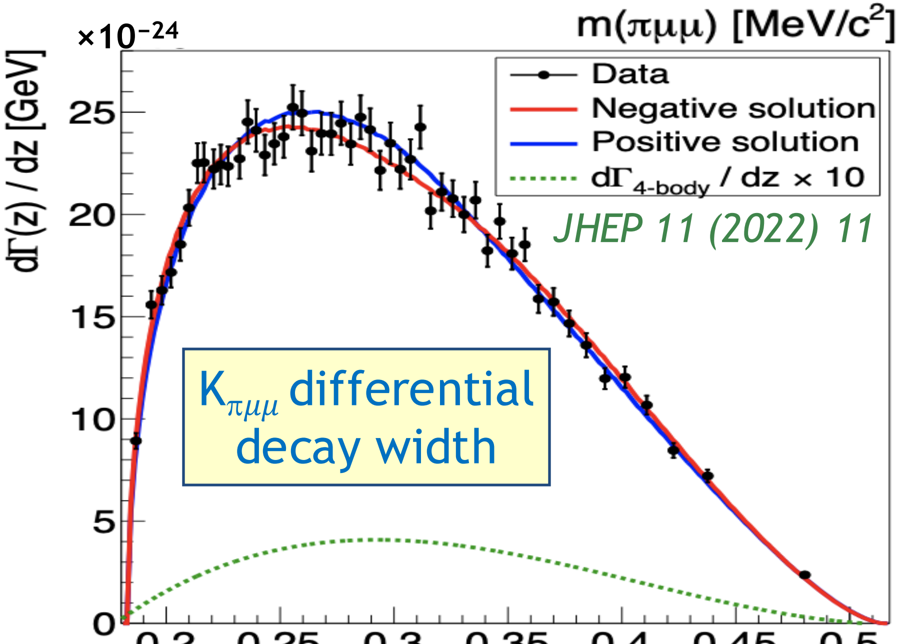
- ✓ Negligible SM rate ($\pi^0 \to 4\nu$).
- ✓ Observation = BSM physics.
- ✓ Interpretation as $K^+ \to \pi^+ X$, with m_X between R1 and R2.
- ✓ Using **10%** of Run 1 dataset; 4×10^9 tagged π^0 mesons.
- ✓ Optimised π^+ momentum range to reduce $\pi^0 \to \gamma\gamma$ background.
- ✓ Expected $\pi^0 \to \gamma\gamma$ events: 10^{+22}_{-8}, events observed: **12**.

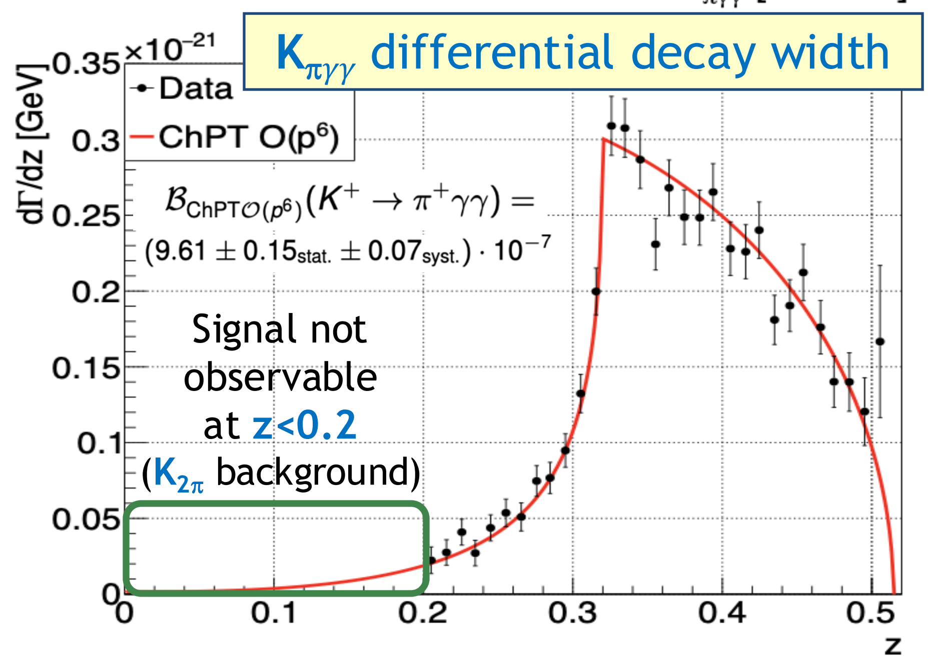
$BR(\pi^0 \to inv) < 4.4 \times 10^{-9}$ at 90% CL

Peak searches: $K^+\to\pi^+\mu^+\mu^-$, $K^+\to\pi^+\gamma\gamma$



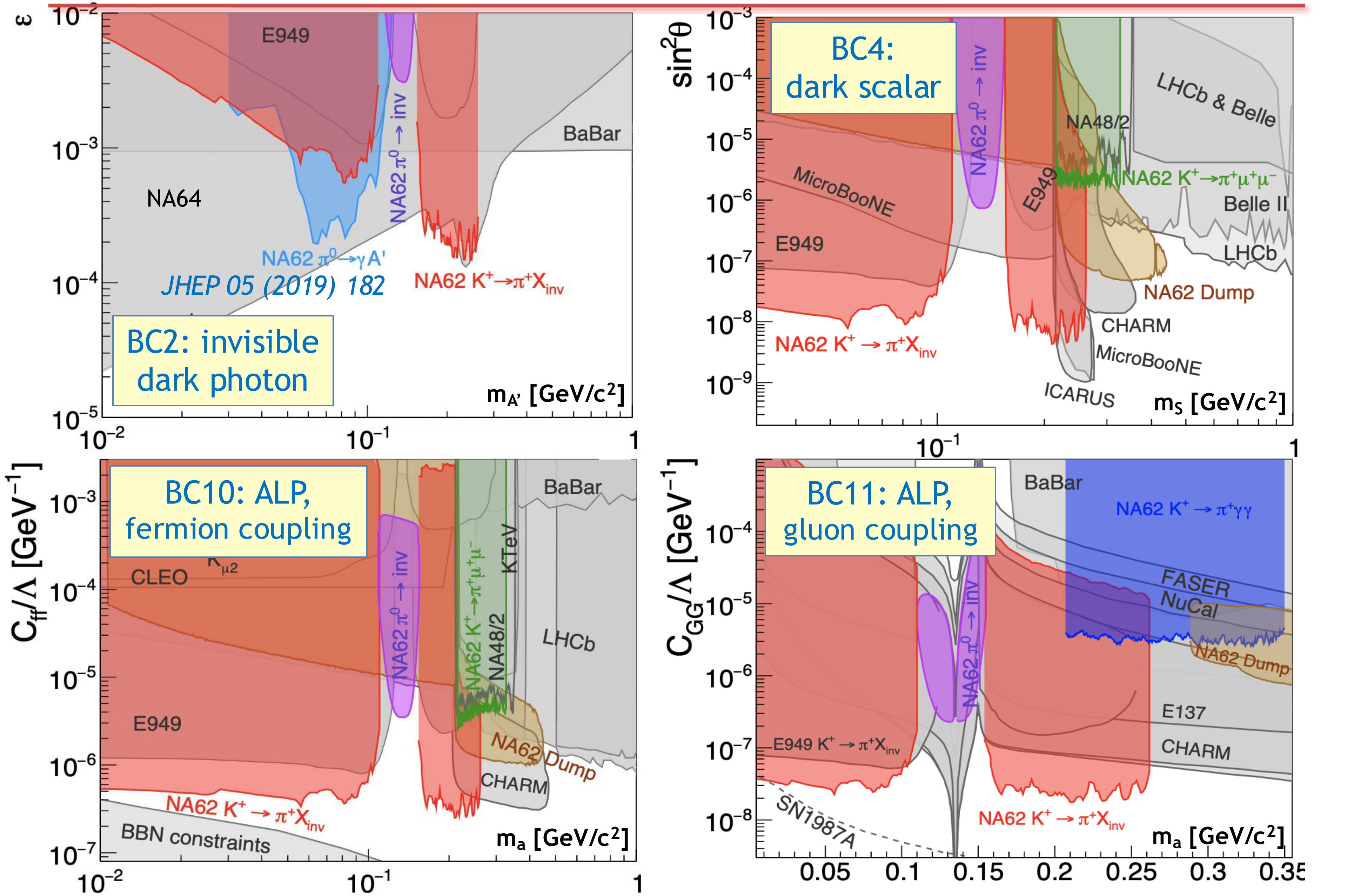






[arXiv:2507.17286]

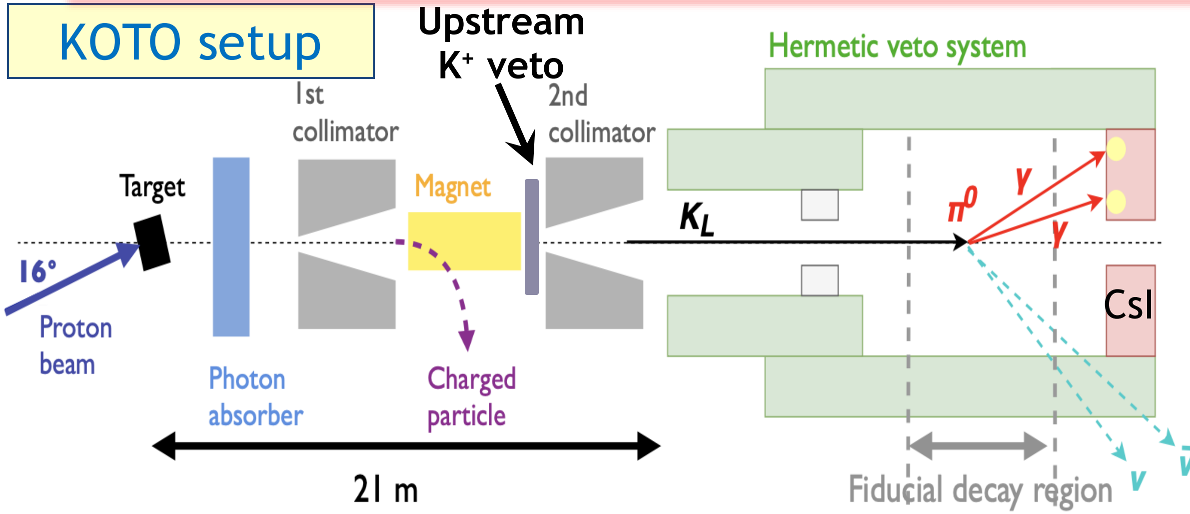
Summary of $K^+ \to \pi^+ X$ results



$K_L \to \pi^0 X_{inv}$ at KOTO

KOTO experiment at J-PARC

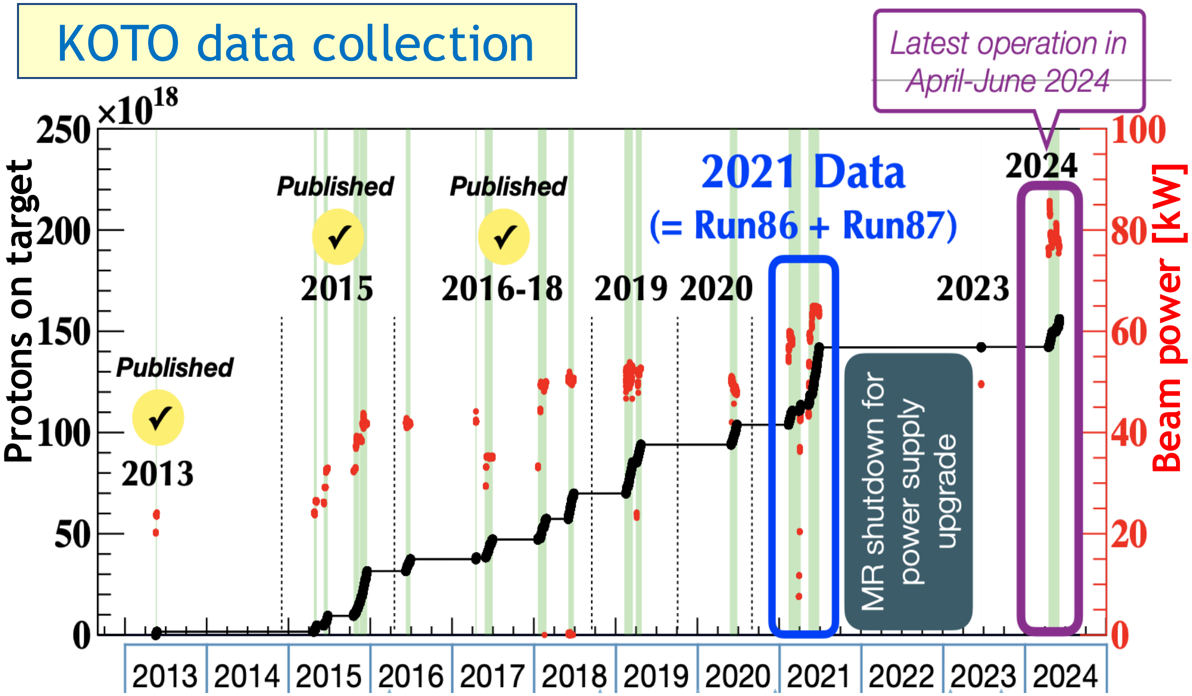
KOTO setup



Primary KOTO goal: search for $K_L \to \pi^0 \nu \bar{\nu}$, single-event sensitivity $<10^{-10}$

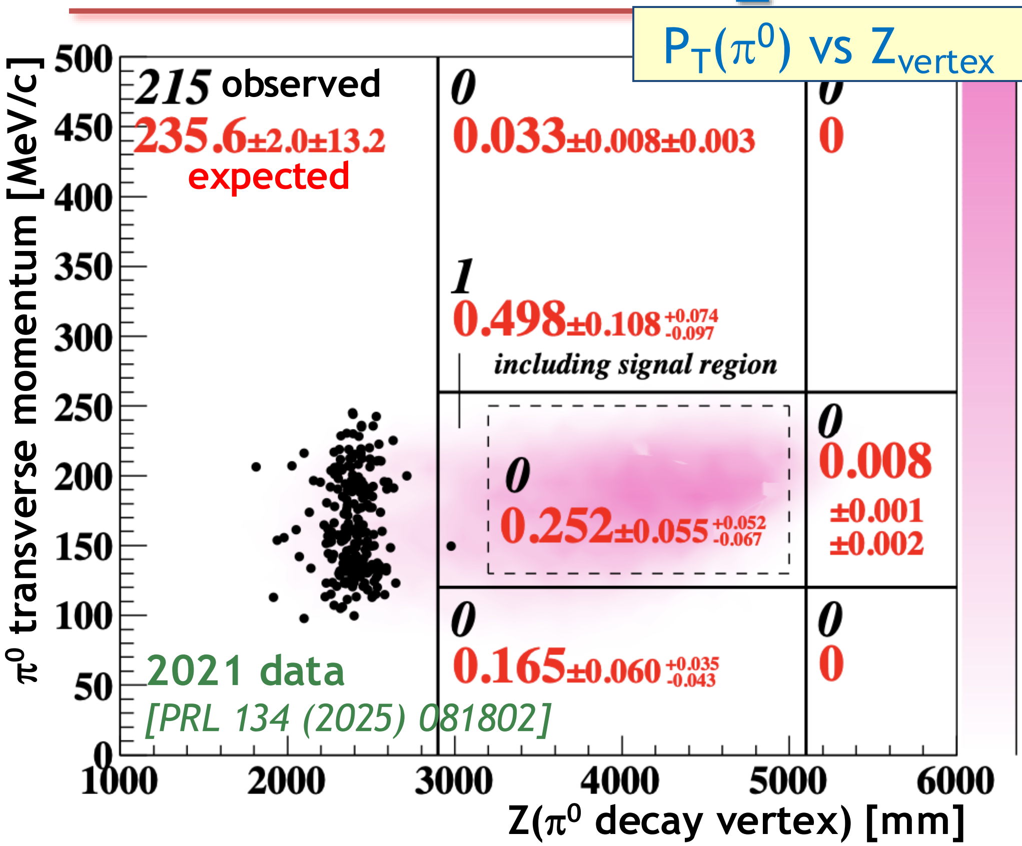
- Primary proton beam: **30 GeV**; **60 kW = 6.6×10^{13}/5.2 s**.
- Secondary K_L beam: peak momentum **1.4 GeV/c**.
- Beam composition: K_L, neutrons, photons.
- Decay region length: **~2 m**.
- Hermetic photon detector, including CsI calorimeter.
- Progressive improvements to the setup; upstream K^+ veto installed in **2020**.

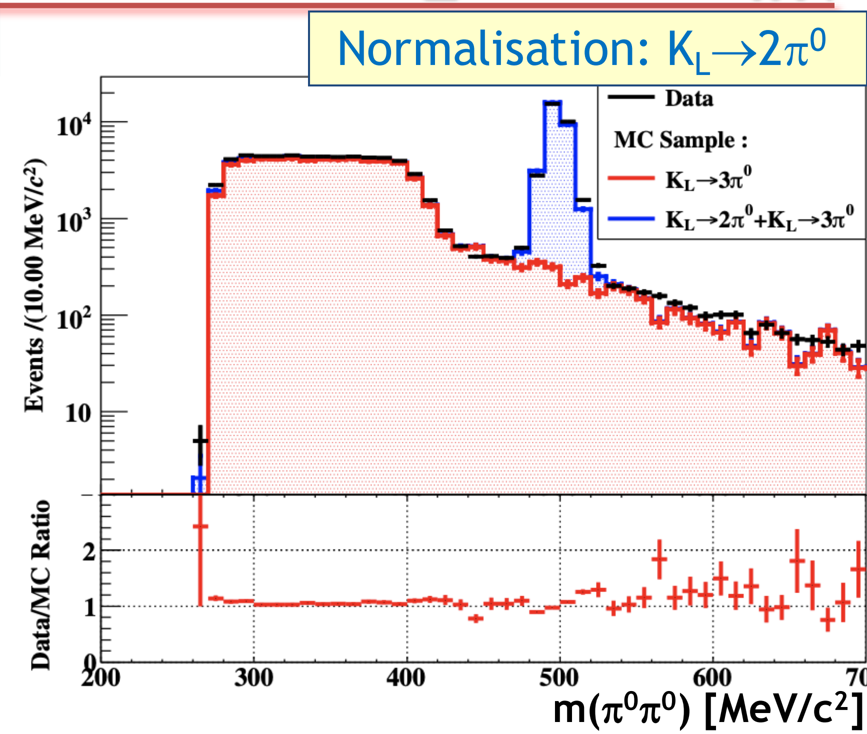
KOTO data collection

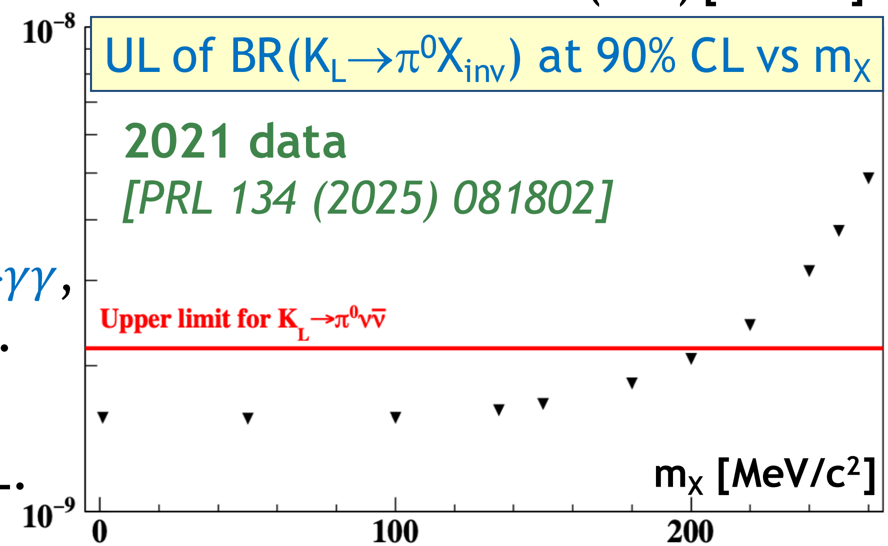


PRL 122 (2019) 021802
PRL 126 (2021) 121801
PRL 134 (2025) 081802

KOTO: $K_L \to \pi^0 \nu\nu$ and $K_L \to \pi^0 X_{inv}$







- Single-event sensitivity: $BR_{SES} = 9.3 \times 10^{-10}$ ($\approx 30 \times BR_{SM}$).
- Background: 0.252 events ($K_L \to 2\pi^0$, $K_L \to \gamma\gamma$, $K^+ \to \pi^0 e^+ \nu$, upstream π^0, hadron clusters).
- No candidates observed in the data.
- Result: $BR(K_L \to \pi^0 \nu\nu) < 2.2 \times 10^{-9}$ at 90% CL.

$\pi^0 \to \gamma A', A' \to e^+e^-$ at NA48/2

Dark photon production and decay (BC1):
peak search in the $K^+ \to \pi^+\pi^0_D \to \pi^+(\gamma e^+e^-)$ spectrum

[PLB746 (2015) 178]

NA48/2 at CERN: the π^0_D sample

$K^\pm$ decays in fiducial volume: $N_K = 1.6\times10^{11}$.

Two exclusive selections

$K^\pm\to\pi^\pm\pi^0_D$ selection:

- $|m_{\pi\gamma ee}-m_K|<20$ MeV/c^2;
- $|m_{\gamma ee}-m_{\pi0}|<8$ MeV/c^2;
- no missing momentum.

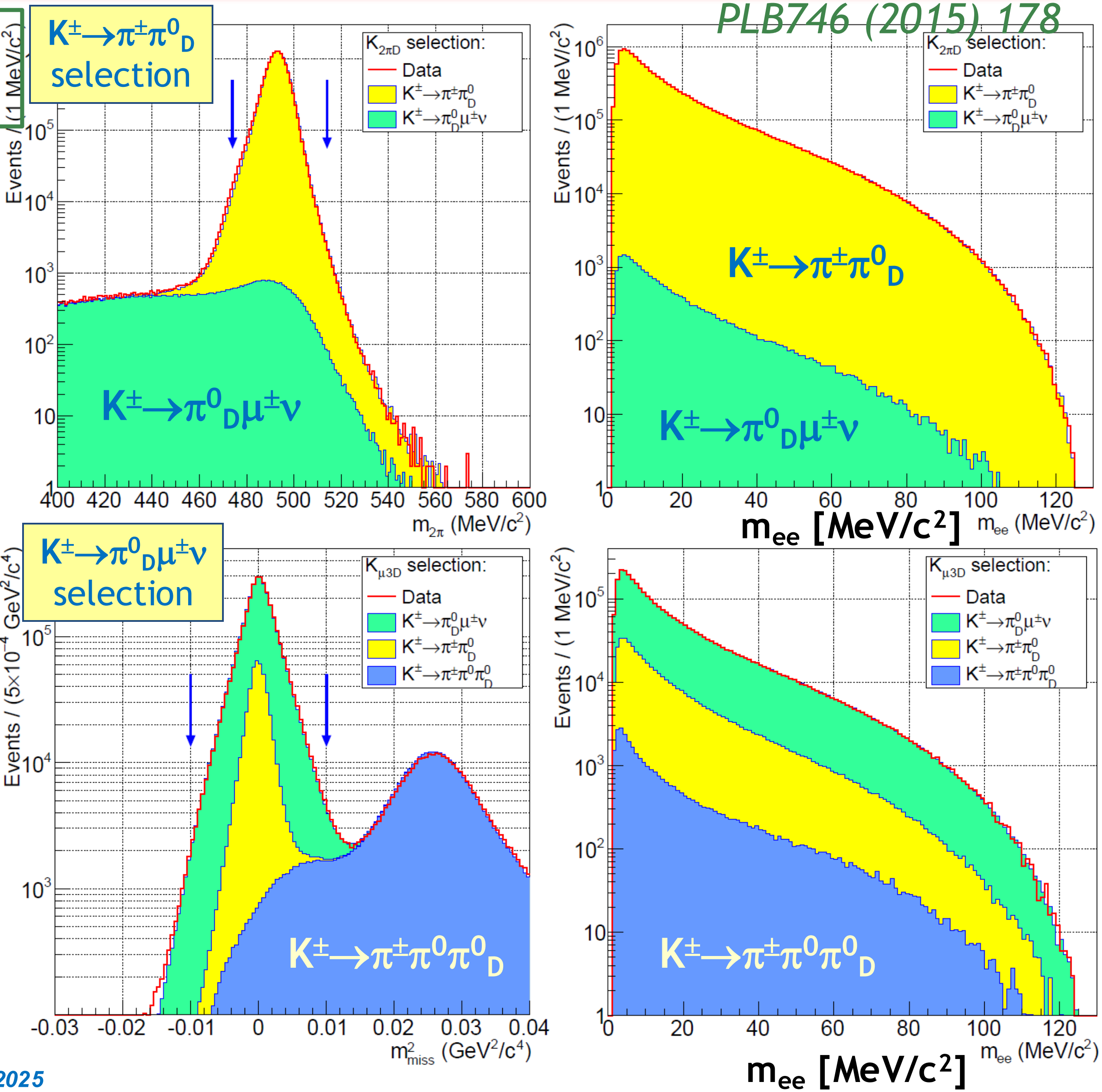
$K^\pm\to\pi^0_D\mu^\pm\nu$ selection:

- $m_{miss}^2 = (P_K-P_\mu-P_{\pi0})^2$ compatible with zero;
- $|m_{\gamma ee}-m_{\pi0}|<8$ MeV/c^2;
- non-zero missing total & transverse momentum.

Reconstructed π^0_D decay candidates:

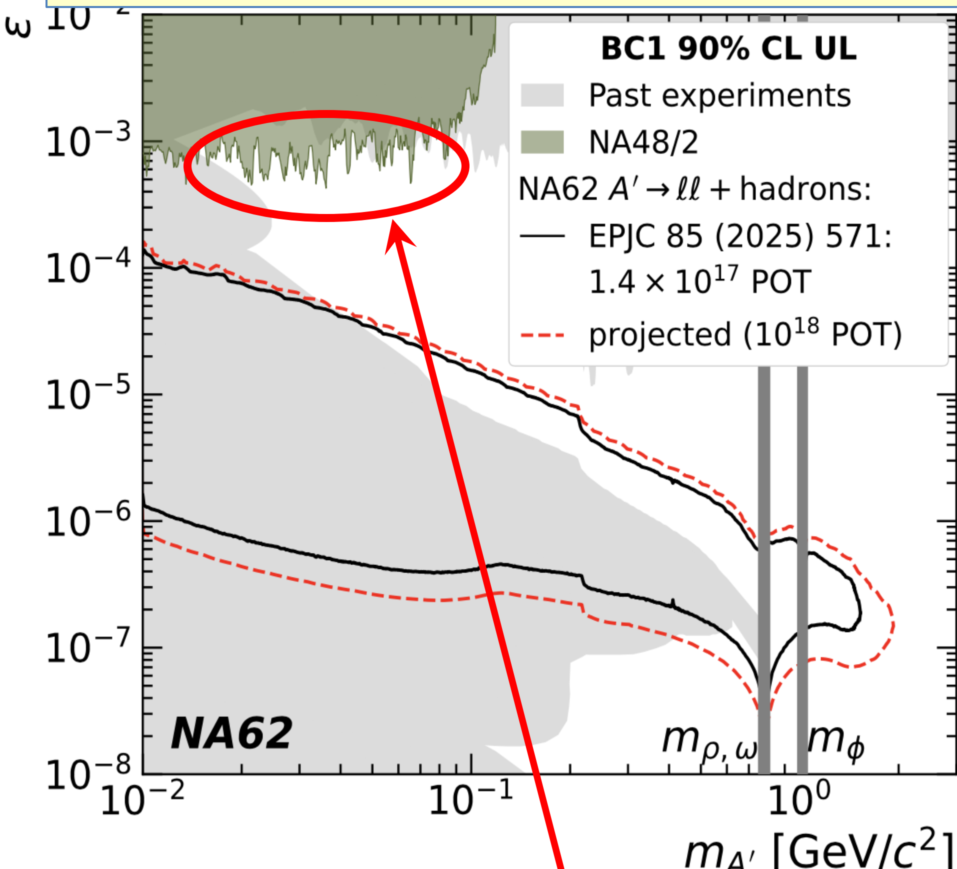
- $N(K_{2\pi D}) = 1.38\times10^7$,
- $N(K_{\mu3D}) = 0.31\times10^7$,
- total $= 1.69\times10^7$.

PLB746 (2015) 178



Dark photon: results & prospects

BC1: exclusion of DP coupling vs $m_{A'}$



To be improved by NA62

Further opportunities:

NA62 dataset is ~10 times larger than NA48/2 with improved m_{ee} resolution: expect order of magnitude improvement on BR($\pi^0 \to \gamma A'$) and ε^2.

In mass range $m_{\pi 0} < m_{A'} < 2m_\mu$, the $K^+ \to \mu^+ \nu A'$, $A' \to e^+e^-$ channel is potentially competitive.

[Krnjaic et al., RL124 (2020) 041802]

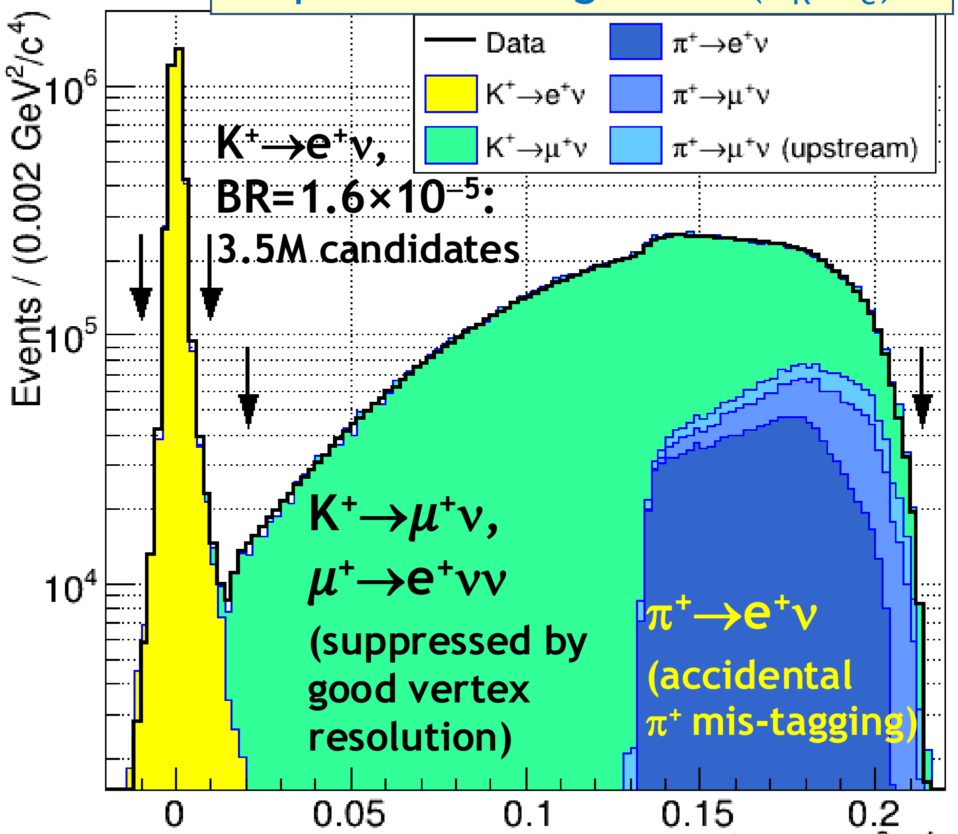
$K^+, \pi^+ \to \ell^+ N$ at NA62: HNL production (BC6,7)

PLB807 (2020) 135599, *PLB816 (2021) 136259*, *arXiv:2507.07345*

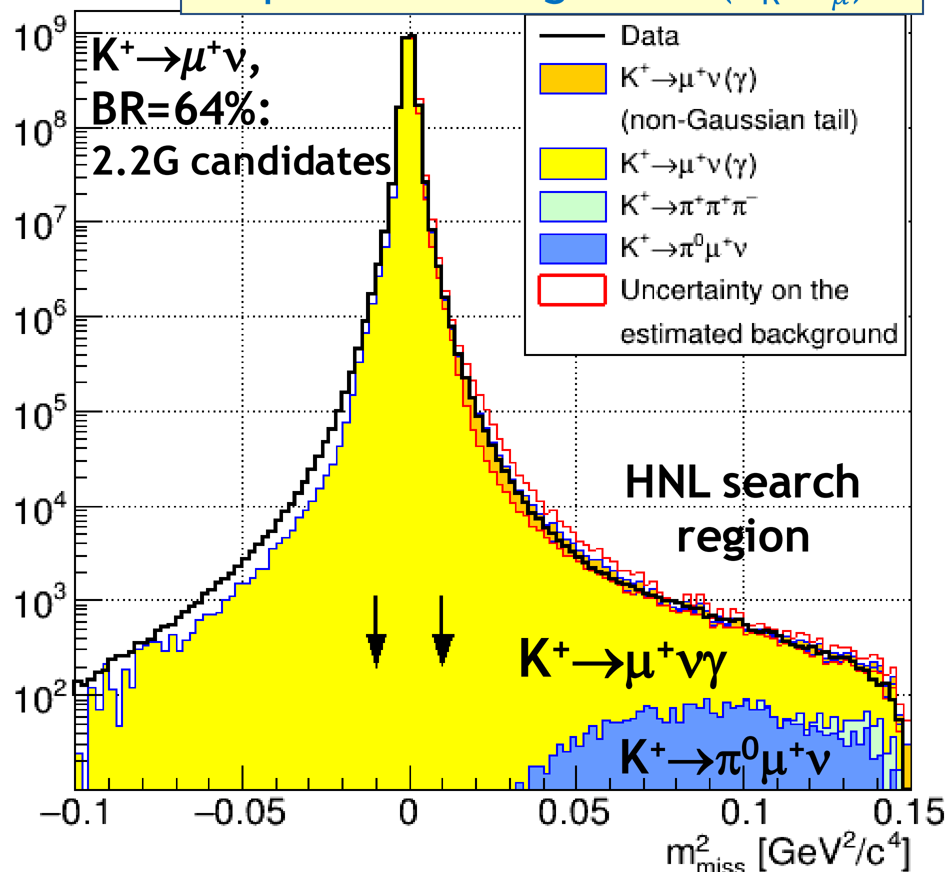
HNL production in kaon decays

- Trigger lines: $K_{\pi\nu\nu}$ for $K^+\to e^+N$; Control/400 for $K^+\to\mu^+N$. *PLB807 (2020) 135599* *PLB816 (2021) 136259*
- Run 1 dataset; numbers of K^+ decays in fiducial volume: $N_K=3.5\times10^{12}$ in the positron case; $N_K=4.3\times10^{9}$ in the muon case.
- Squared missing mass: $m^2_{miss}=(P_K-P_\ell)^2$, using GTK and STRAW trackers.
- HNL production signal: **a spike above continuous missing mass spectrum**.

Squared missing mass: $(P_K-P_e)^2$

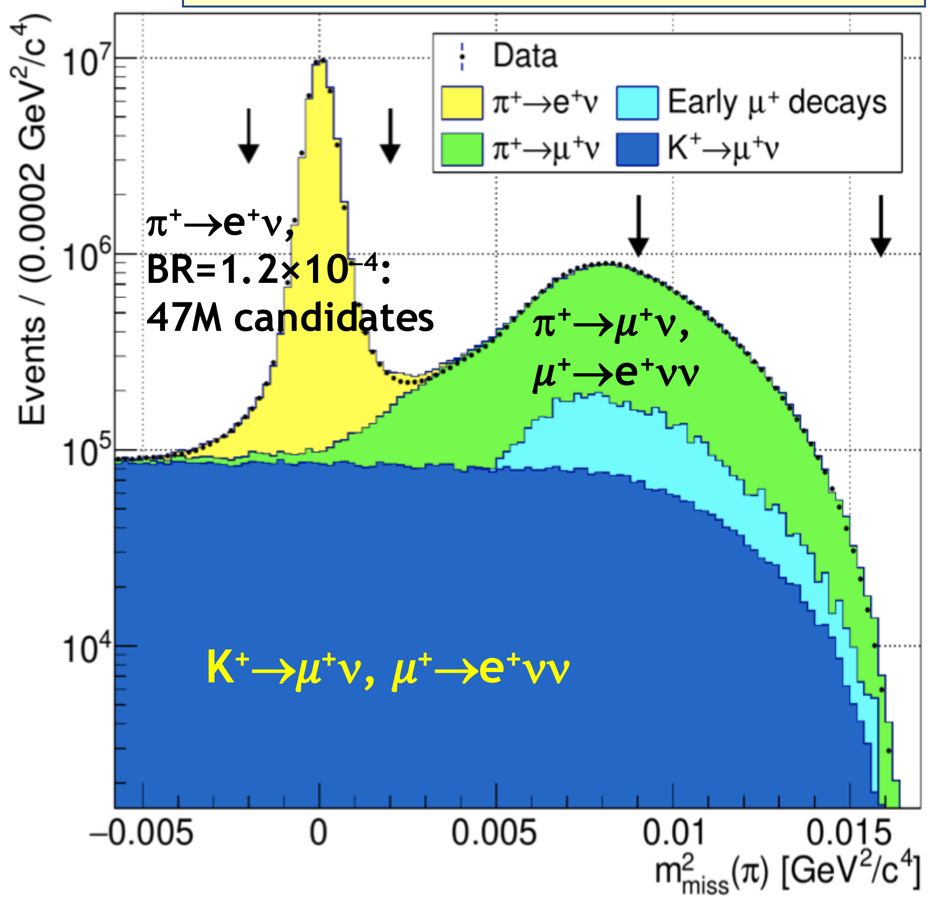


Squared missing mass: $(P_K-P_\mu)^2$

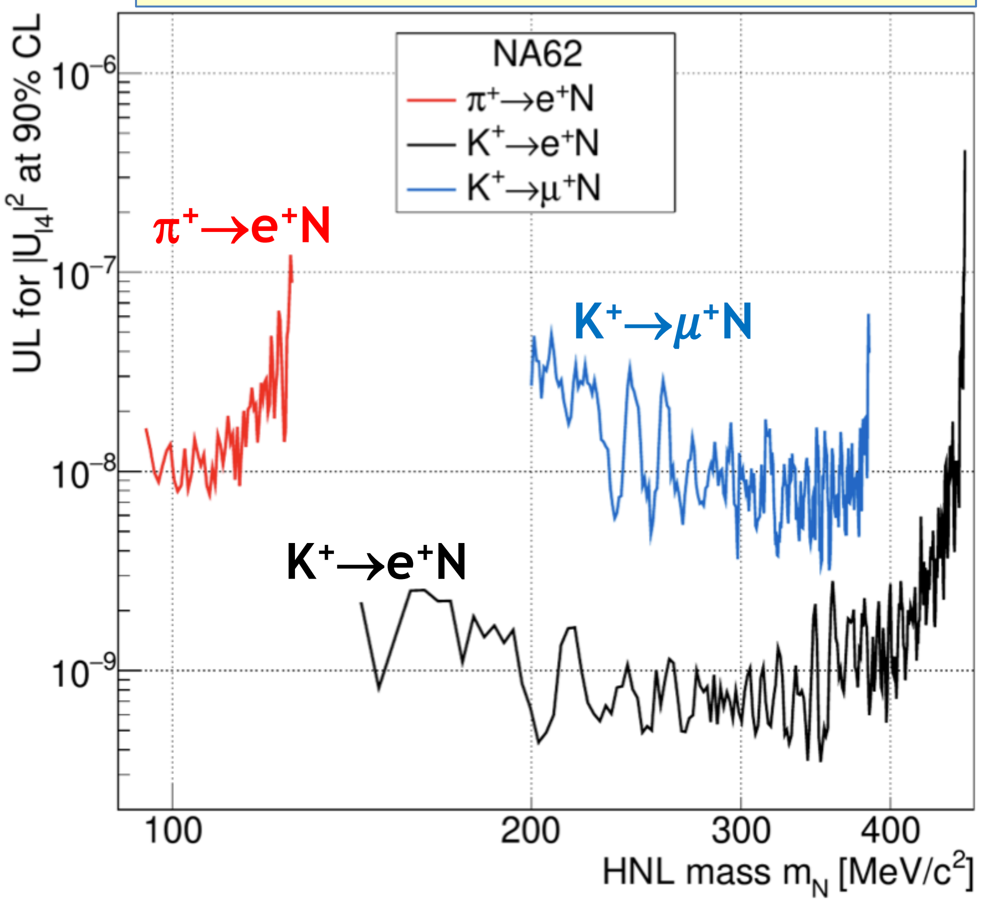


HNL production in pion decays

Squared missing mass: $(P_\pi - P_e)^2$



BC6,7: NA62 $|U_{\ell4}|^2$ limits vs m_{HNL}

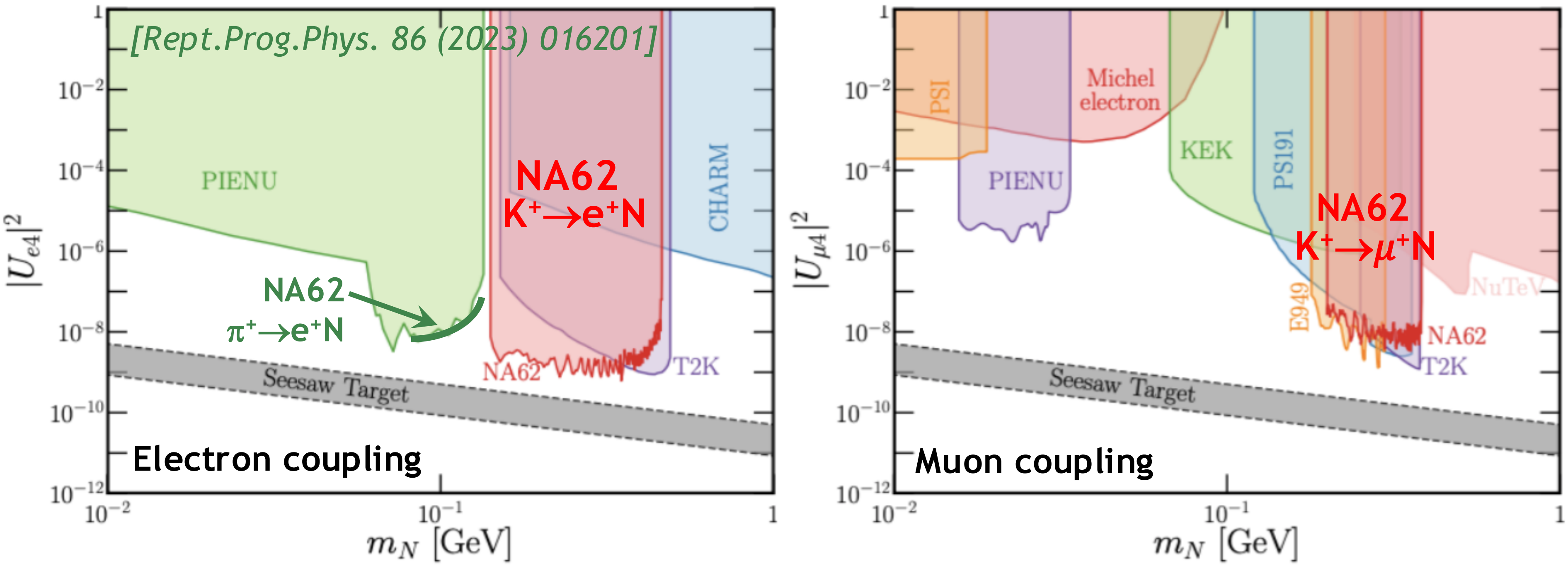


- The 2017−2024 dataset; $K_{\pi\nu\nu}$ trigger line (limited efficiency for beam pions).
- Number of π^+ decays in fiducial volume: $N_\pi = 6.5\times10^{12}$.
- Squared missing mass: $m^2_{miss} = (P_\pi - P_\ell)^2$, using GTK and STRAW trackers.

[arXiv:2507.07345]

HNL production: results

BC6,7: $|U_{\ell 4}|^2$ limits vs m_{HNL} from production & decay searches



- For $|U_{e4}|^2$, NA62 improves on the T2K and PIENU limits.
- For $|U_{\mu 4}|^2$, NA62 has similar sensitivity to T2K and BNL-E949.

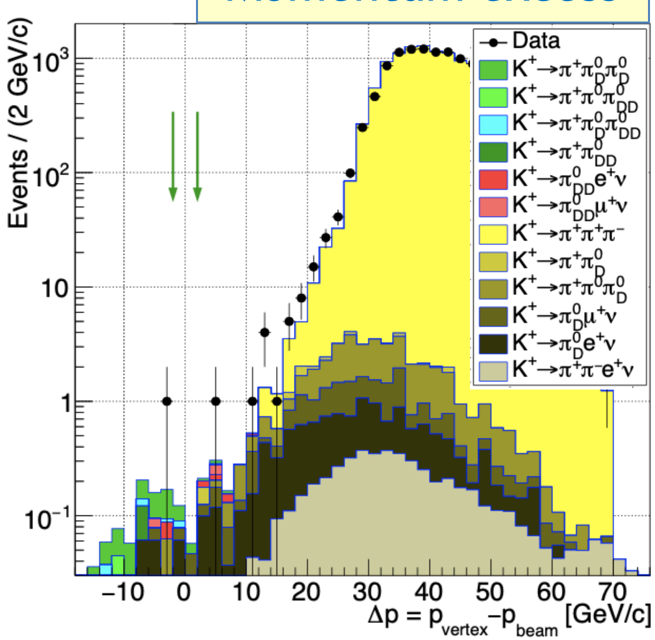
NA62 upper limit at 90% CL: **$BR(K^+\to\mu^+\nu\nu\nu)<1.0\times10^{-6}$**,
and similar limits of **$BR(K^+\to\mu^+\nu X_{inv})$**. *[PLB 816 (2021) 136259]*

Other searches in K decays

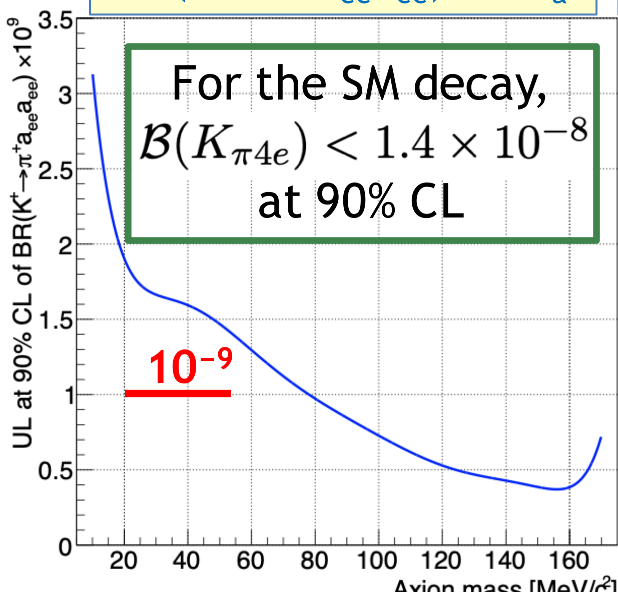
NA62: search for $K^+ \to \pi^+ X_{ee} X_{ee}$

- Run 1, multi-electron trigger, $N_K = 8.6 \times 10^{11}$. *PLB846 (2023) 138193*
- Production and prompt decays of axion pairs, $K^+ \to \pi^+ aa$, $a \to e^+e^-$: exclusion of the axion explanation for the "17 MeV anomaly".
  - ✓ Expect $BR(K^+ \to \pi^+ aa) > 2 \times 10^{-8}$ for $m_a = 17$ MeV.
    [Alves, PRD103 (2021) 055018; Hostert and Pospelov, PRD105 (2022) 015017]
- Prompt dark cascade involving a dark scalar (S) and dark photons (A'): $K^+ \to \pi^+ S$, $S \to A'A'$, $A' \to e^+e^-$.
- SM rate: $BR_{SM}(K^+ \to \pi^+ e^+ e^- e^+ e^-) = (7.2 \pm 0.7) \times 10^{-11}$ [Husek, PRD106 (2022) L071301]

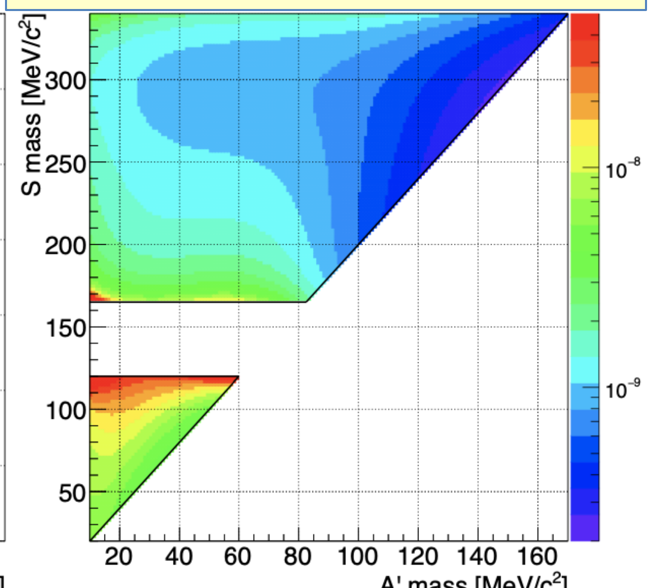
Momentum excess



UL at 90% CL of $BR(K^+ \to \pi^+ a_{ee} a_{ee})$ vs m_a



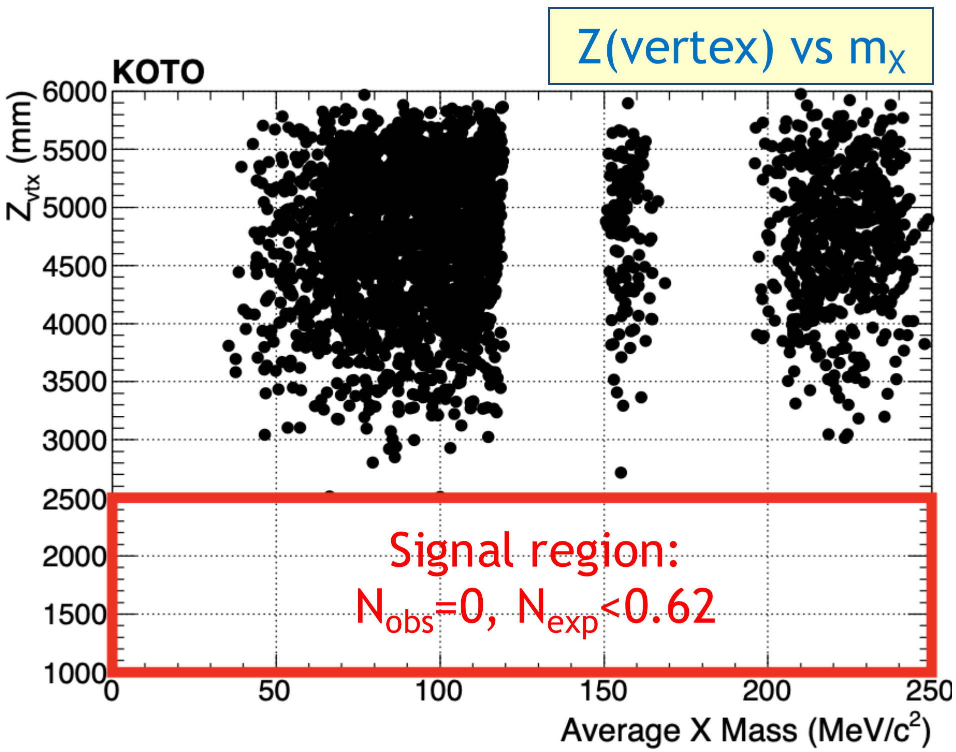
UL of $BR(K^+ \to \pi^+ S, S \to A'_{ee} A'_{ee})$ vs $(m_{A'}, m_S)$

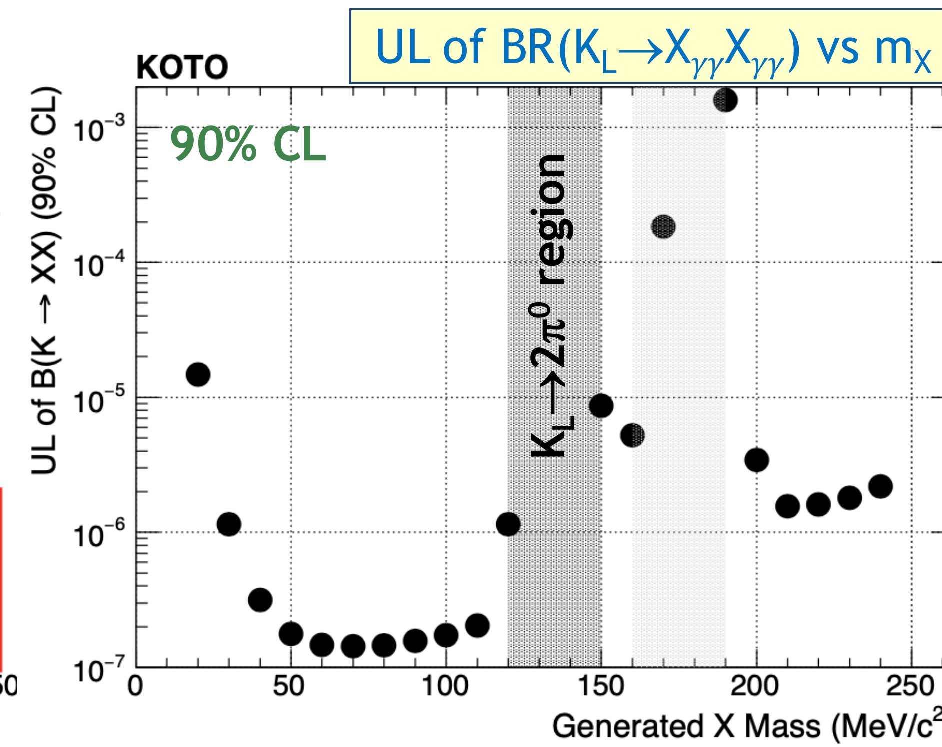


KOTO: search for $K_L \to X_{\gamma\gamma} X_{\gamma\gamma}$

PRL 130 (2023) 111801

- Dataset: one month (June **2018**), a dedicated trigger line.
- Proton beam power: **51 kW**; total exposure: **1.1×10^{19}** pot.
- Main background: $K_L \to 3\pi^0$; undetected photons or (double) cluster fusion.
- Signal acceptance reduced at $m_X > 150$ MeV/c^2 by anti-$K_L \to 3\pi^0$ selection.
- No data events observed in the signal region.





KOTO: search for $K_L \to \gamma A'$

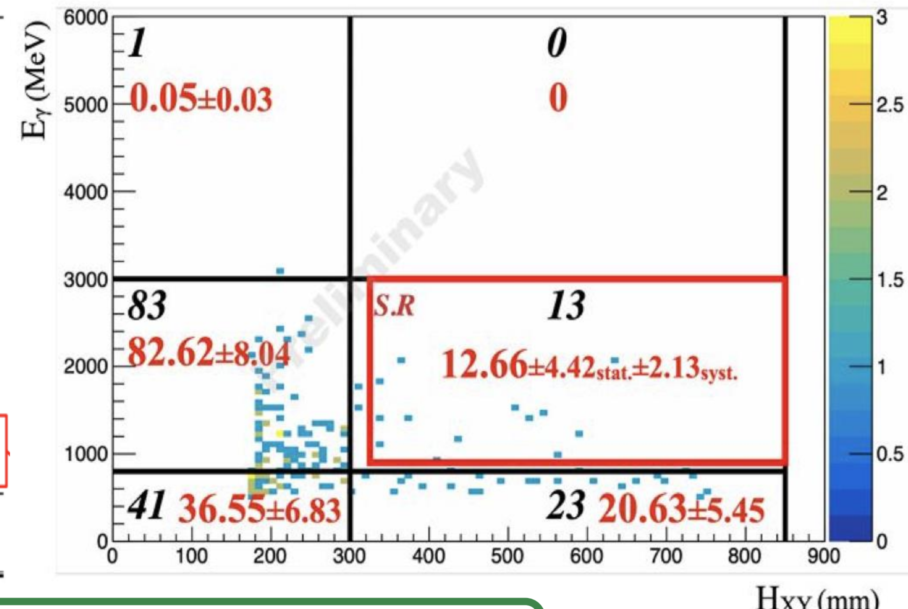
KOTO preliminary [T.Wu @ ICHEP 2024]

- Search for a *massless dark photon* (**A'**).
- Experimental signature: a single EM cluster in the final state.
- Dataset: a special sample (2 hours) collected in **2021**.
- Number of kaon decays: $N_K = 1.29\times10^{10}$.
- Single-event sensitivity: $BR_{SES} = (2.91\pm0.05)\times10^{-8}$.

Type	Source	Background Level
K_L^0 decay	$K_L^0 \to 2\gamma$	$1.09 \pm 0.12_{stat.} \pm 0.05_{syst.}$
	$K_L^0 \to 3\pi^0$	< 0.18 (90% C.L.)
	$K_L^0 \to 2\pi^0$	< 0.51 (90% C.L.)
	$K_L^0 \to \pi^\pm e^\mp \nu_e$	< 0.27 (90% C.L.)
	$K_L^0 \to \pi^\pm \mu^\mp \nu_\mu$	< 0.25 (90% C.L.)
	$K_L^0 \to \pi^+\pi^-\pi^0$	< 0.17 (90% C.L.)
Neutron		$11.57 \pm 4.42_{stat.} \pm 2.13_{syst.}$
Total (exclude sources without central value)		$12.66 \pm 4.42_{stat.} \pm 2.13_{syst.}$

PRELIMINARY

Black ⇒ Number Observed
Red ⇒ Number Expected (Bkg)



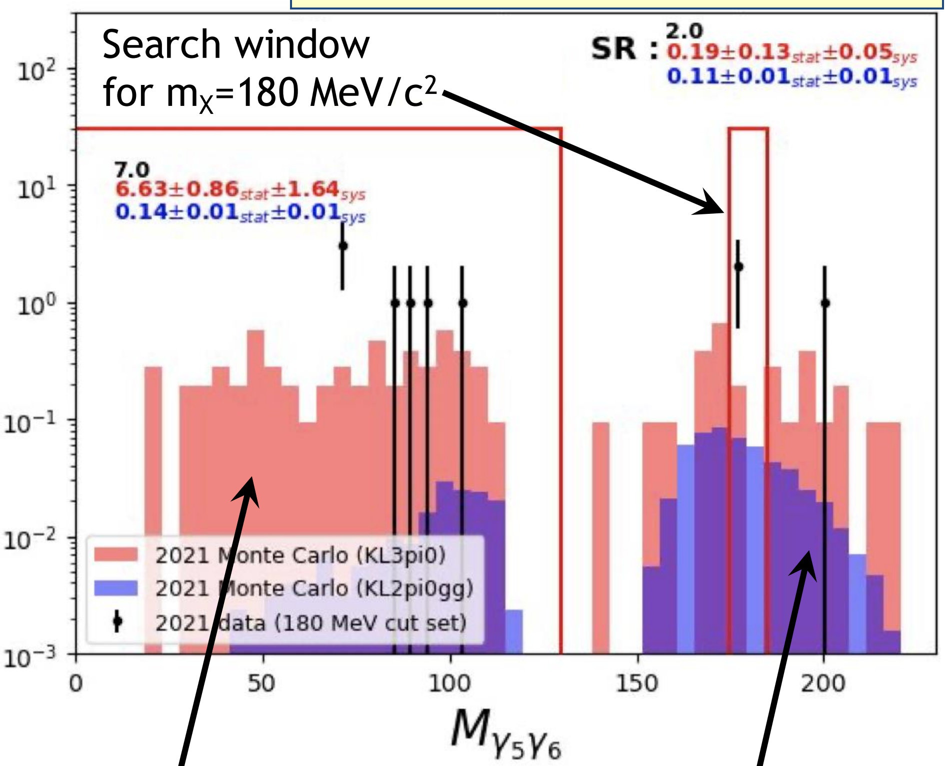
Result: $BR(K_L \to \gamma A') < 3.5\times10^{-7}$ at 90% CL

KOTO: search for $K_L \to \pi^0\pi^0 X_{\gamma\gamma}$

KOTO preliminary [J.Redeker @ Kaon 2025]

- The 2021 dataset is used.
- Number of kaon decays: $N_K = (4.27 \pm 0.31) \times 10^{12}$.
- Mass range probed: $160 \le m_X \le 220$ MeV/c^2, in 5 MeV/c^2 steps.

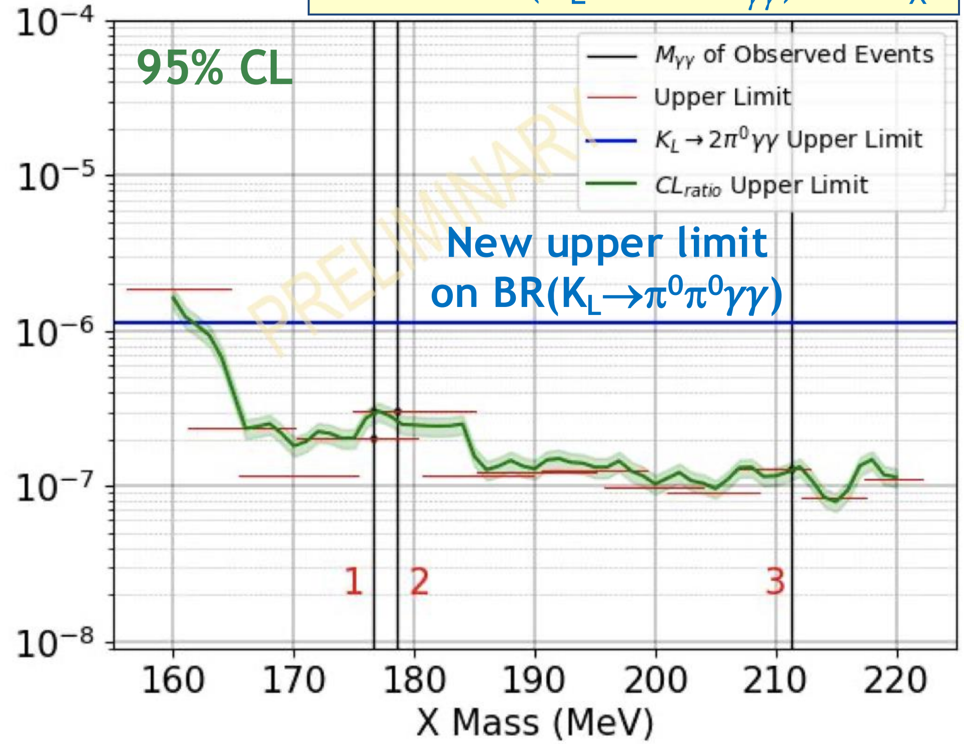
Di-photon mass spectrum



$K_L \to 3\pi^0$ background

$K_L \to 2\pi^0\gamma\gamma$ expectation

UL of BR($K_L \to \pi^0\pi^0 X_{\gamma\gamma}$) vs m_X

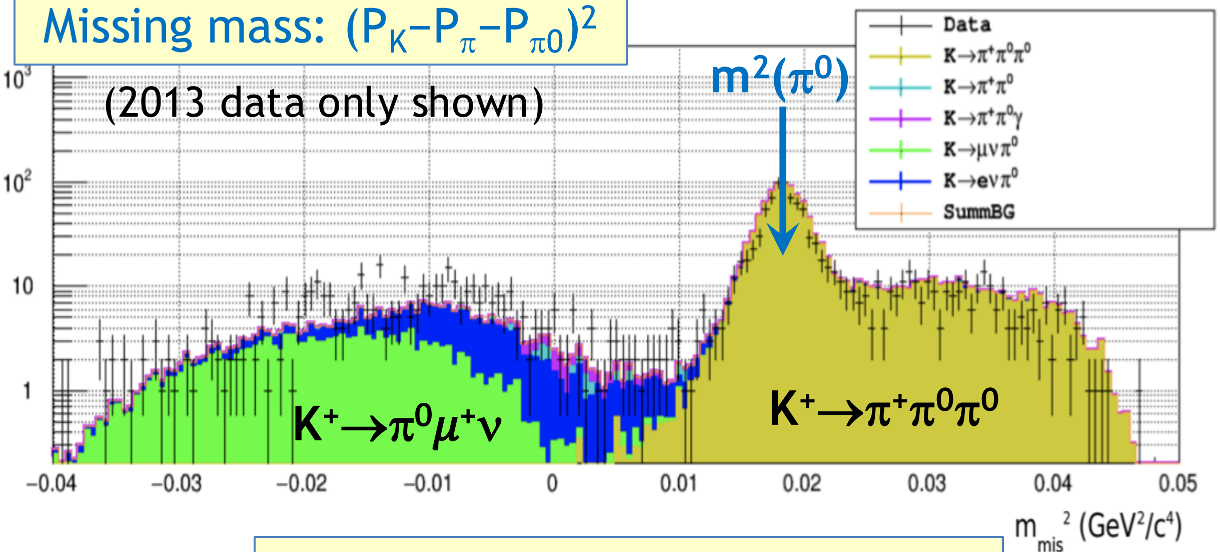


OKA at Protvino: $K^+ \to \pi^+\pi^0 X_{inv}$

EPJ C84 (2024) 3

Missing mass: $(P_K - P_\pi - P_{\pi 0})^2$

(2013 data only shown)



OKA experiment:

K^+ decays in flight,

18 GeV/c beam,

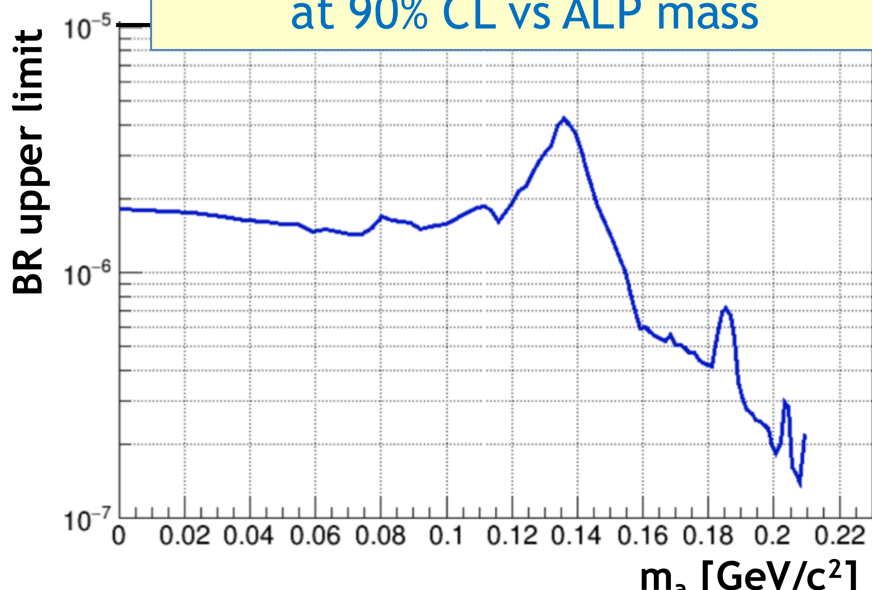
2012–2013 dataset.

$K^+ \to \pi^+\pi^0 a$ decay density:

Camalich et al.,

PRD 102 (2020) 015023

Upper limits of $BR(K^+ \to \pi^+\pi^0 a)$ at 90% CL vs ALP mass



$$\frac{d\Gamma(K^+ \to \pi^+\pi^0 a)}{ds} = \frac{1}{|F_{sd}^A|^2} \frac{(m_{K^+}^2 - s)^3}{1536\pi^3 m_K^5}\beta \times \left(F_p^2 + \beta^2 G_p^2 + 2\beta F_p G_p\right)$$

$$s = (p_{\pi_1} + p_{\pi_2})^2 \text{ and } \beta^2 = 1 - 4m_\pi^2/s$$

Prospects at NA62: upper limits of **O(10^{-7})** on **$BR(K^+ \to \pi^+\pi^0 a)$** with a downscaled control-trigger sample

Summary

❖ Rare kaon decays are a unique probe for new physics:
  - ✓ large decay samples are available (~10^{13} events);
  - ✓ relatively simple and clean final states, low backgrounds.

❖ Kaon experiments provide unique coverage of FIP phase space:
  - ✓ FIP production in K^+, π^+ and π^0 decays at NA62;
  - ✓ FIP production in K_L decays at KOTO;
  - ✓ FIP searches in dump mode at NA62 [Jan Jerhot's talk].

❖ Both NA62 and KOTO are collecting data:
new results at improved sensitivity are expected soon.

**New ideas very welcome,
please get in touch!**

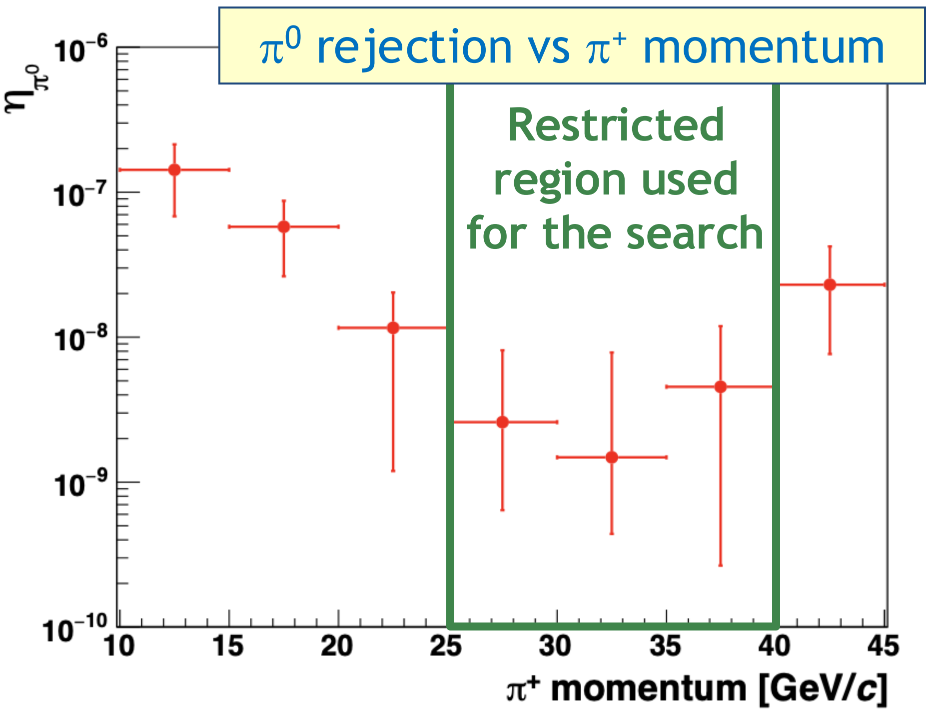
Spares

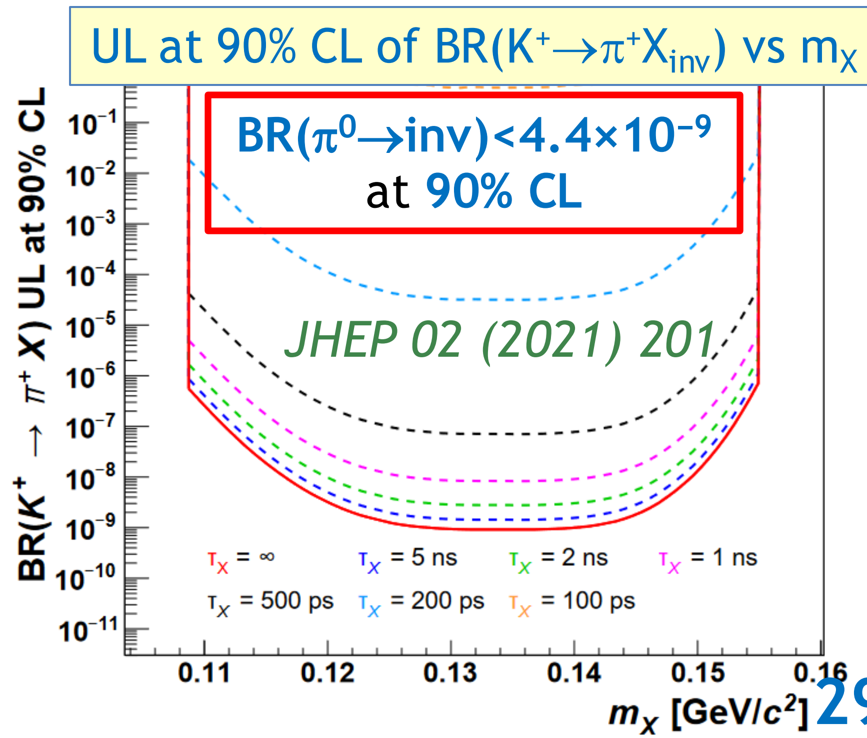
NA62: search for $\pi^0 \to$ invisible

- Rejection of ($K^+ \to \pi^+\pi^0(\gamma)$, $\pi^0 \to \gamma\gamma$) decays: simulations based on single-photon efficiency measurements with $K^+ \to \pi^+\pi^0$ decays.
- Rejection of $\pi^0 \to \gamma\gamma$ decays for $K^+ \to \pi^+\nu\nu$ analysis: $\varepsilon \approx 10^{-8}$.
- For $\pi^0 \to$ invisible search ($25 < p_\pi < 40$ GeV/c): $\varepsilon = (2.8^{+5.9}_{-2.1}) \times 10^{-9}$

<u>Search for $\pi^0 \to$ invisible:</u> (~10% of NA62 Run 1 dataset, 4×10^9 tagged π^0 mesons)

- $K_{\pi\nu\nu}$ trigger and selection used, with $0.015 < m^2_{miss} < 0.021$ GeV^2/c^4.
- Expected $\pi^0 \to \gamma\gamma$ events: 10^{+22}_{-8}, events observed: 12.





Dark photon lifetime

BC1 dark photon proper lifetime below the di-muon threshold:

$$c\tau_{A'} \approx 0.8\ \mu\text{m} \times \left(\frac{10^{-6}}{\varepsilon^2}\right) \times \left(\frac{100\ \text{MeV}}{m_{A'}}\right)$$

Mean path at $E_{A'}$=50 GeV
(max possible energy at NA48/2 and NA62):

$$L_{\max} \approx 0.4\ \text{mm} \times \left(\frac{10^{-6}}{\varepsilon^2}\right) \times \left(\frac{100\ \text{MeV}}{m_{A'}}\right)^2$$

- For $\varepsilon^2 > 10^{-7}$ and $m_{A'} > 10$ MeV/c^2, DP path length is negligible with respect to the resolution on the vertex longitudinal coordinate (~1 m).
- DP decay can be considered prompt.
- DP production and decay signature ($\pi^0 \to \gamma A'$, $A' \to e^+e^-$) is identical to that of the Dalitz decay, $\pi^0_D \to \gamma e^+e^-$.