Overview of NA62 $K^+ \to \pi^+ \nu \bar{\nu}$ results

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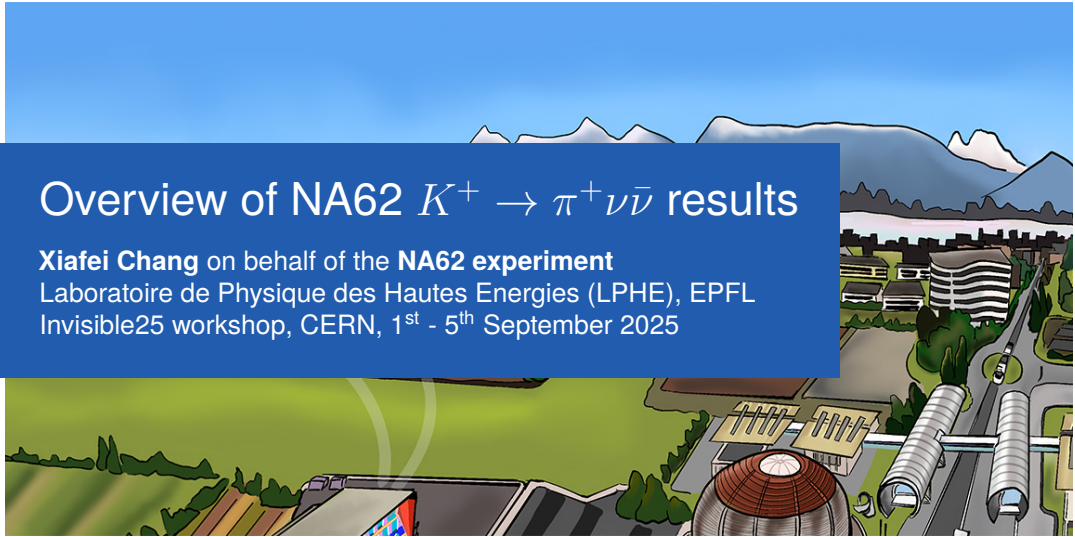
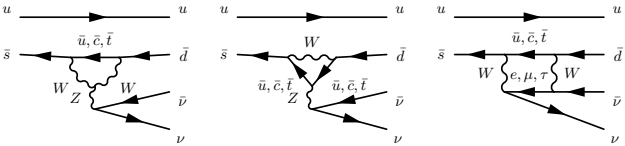
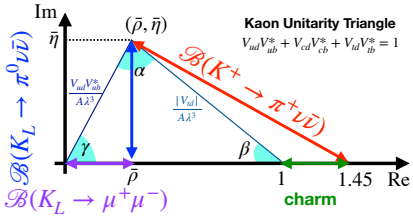
Laboratoire de Physique des Hautes Energies (LPHE), EPFL
Invisible25 workshop, CERN, 1st - 5th September 2025

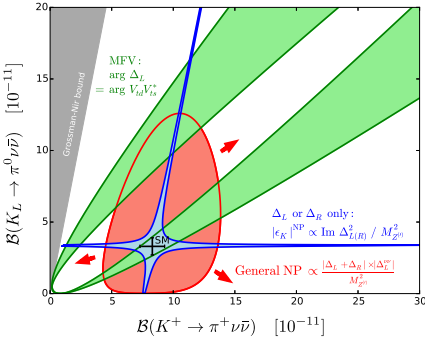


$K \to \pi\nu\bar{\nu}$: SM and beyond





- Flavor Changing Neutral Current;
- $\mathcal{B}(K \to \pi\nu\bar{\nu})$ highly supressed in SM
- Theoretically clean $\Rightarrow$ high precision SM predictions.
- **Correlation between neutral and charged modes**: minimum flavor violation, Z' model, etc. [JHEP 11 (2015) 166 ↗]
- **Correlation with $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$**: Lepton Flavor Universality violation [EPJC 77 (2017) 9, 618 ↗].
- **Hidden sector**: interpret $K \to \pi\nu\bar{\nu}$ results as $K \to \pi X$ searches.

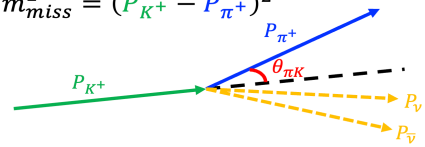


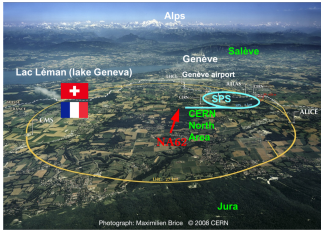
[JHEP11(2015)166]

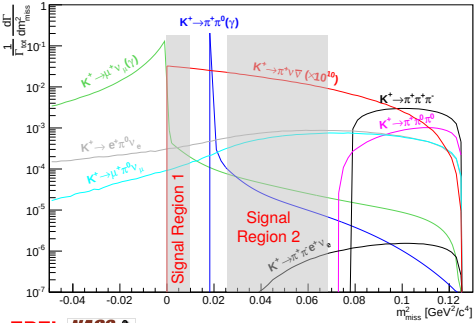
$K^+ \to \pi^+ \nu\bar{\nu}$ @ NA62

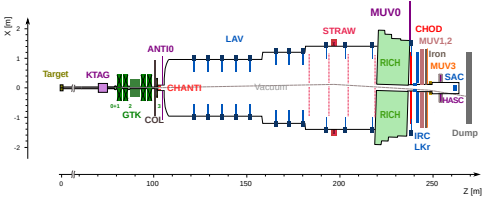
[PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]	LS2 (upgrades)	[JHEP 02 (2025) 191]	WIP		LS3
2016 2017 2018	2019 2020	2021 2022	2023 2024	2025 2026	

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







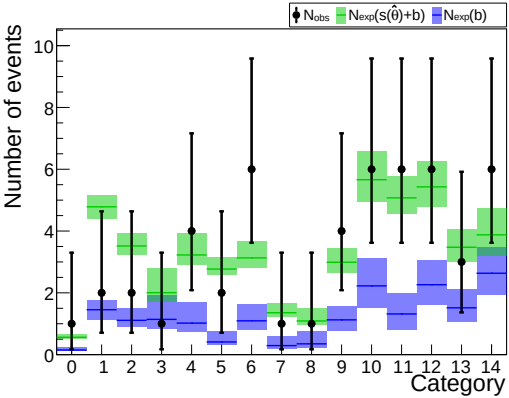


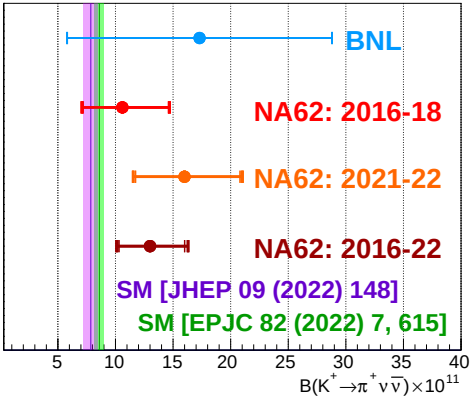
$\mathcal{O}(10^4)$ background suppression from kinematics;
$\mathcal{O}(10^8)$ muon rejection & photo veto from detector.

$K^+ \to \pi^+ \nu\bar{\nu}$ @ NA62: latest results

[JHEP 02 (2025) 191]

- Integrated 2016–2022 dataset: $N_{bg} = 18^{+3}_{-2}$, $N^{SM}_{\pi\nu\bar{\nu}} \sim 20$, $N_{obs} = 51$.





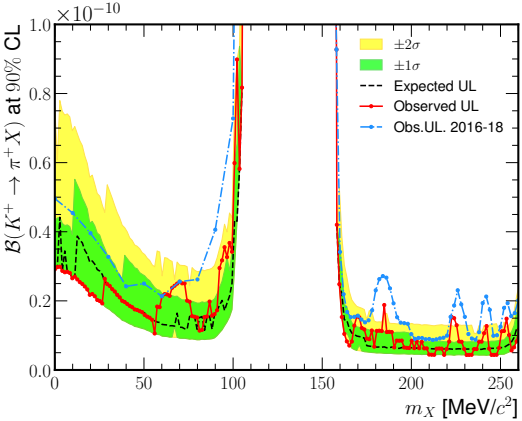
$$\mathcal{B}_{16-22}(K^+ \to \pi^+\nu\bar{\nu}) = (13.0^{+3.0}_{-2.7}|_{stat}\ ^{+1.3}_{-1.3}|_{syst}) \times 10^{-11} = (13.0^{+3.3}_{-3.0}) \times 10^{-11}.$$

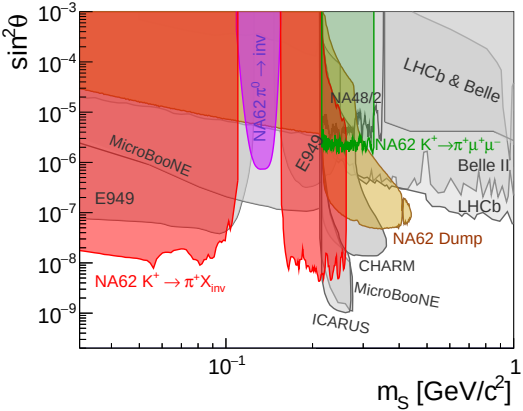
5σ observation! BR consistent with SM (within 1.7σ).

Search for $K^+ \to \pi^+ X$ @ NA62

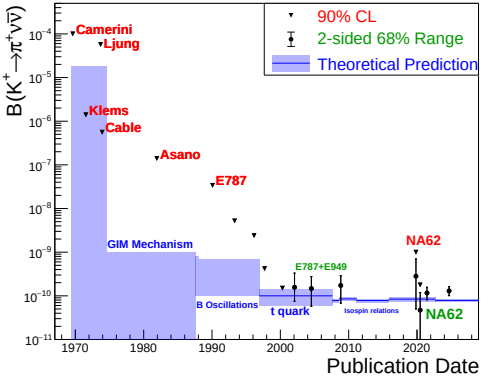
[arXiv:2507.17286v1]

- Interpret $K^+ \to \pi^+ \nu\bar{\nu}$ results as a search for $K^+ \to \pi^+ X$.
- Model independent upper limits on $\mathcal{B}(K^+ \to \pi^+ X)$.
- Exclude parameter space in benchmark models: BC2, **BC4**, BC10, BC11, etc.





Conclusion

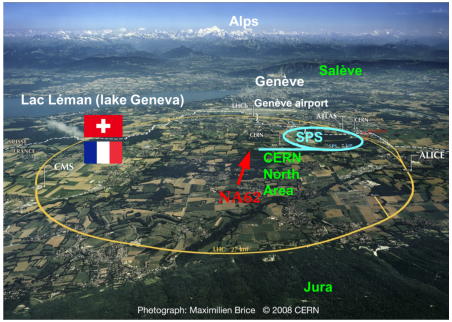


- First observation of $K^+ \to \pi^+ \nu\bar{\nu}$ decay with combined NA62 2016–2022 dataset.
- The smallest branching ratio ever observed at $5\ \sigma$ significance.
- Branching ratio consistent with SM prediction within 1.7σ.
- $K^+ \to \pi^+ X$ searches provide new limits in parameter space in benchmark hidden-sector models.
- NA62 2023–2024 data analysis is working in progress. Current statistics will be doubled.
- NA62 will continue to take data until 2026.

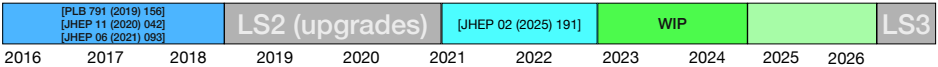
Backup slides

The NA62 experiment

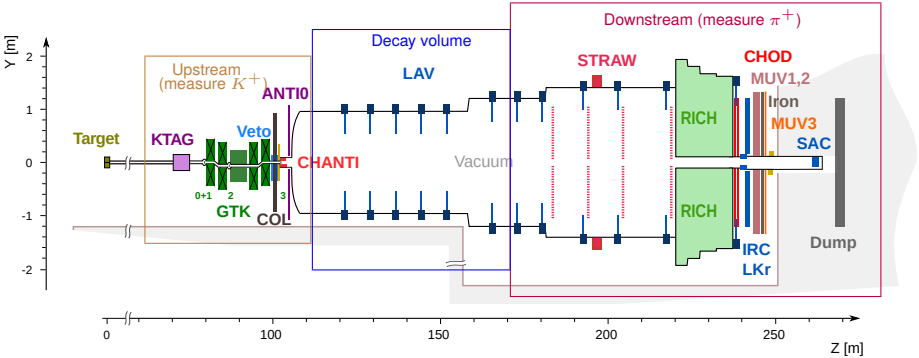
~300 collaborators from 31 institutions



- **Primary goal**: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ measurement;
- **New Technique**: K^+ decay-in-flight
- **Results**: [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093] [JHEP 02 (2025) 191].
- **Broader physics program**:
  - Rare K^+ decays ($K^+ \to \pi^+\gamma\gamma$, etc.)
  - LNV/LFV decays ($K^+ \to \pi^-(\pi^0)e^+e^+$, etc.)
  - Exotics (Dark photon, ALP, HNL, etc.)
  - Neutrino tagging.



The NA62 detector



- $400\ \mathrm{GeV}/c$ proton beam on beryllium target; secondary beam at $75\ \mathrm{GeV}/c$ with $6\%\ K^+$.
- **Particle tracking**: GTK - beam particle, STRAW - downstream tracks.
- **PID**: Cherenkov detectors (KTAG - K^+, RICH - π^+), calorimeters (LKr, MUV1,2), muon (MUV3)
- **Comprehensive veto system**:
  - Upstream: VetoCounter (early decays), CHANTI (beam interactions), ANTI0 (halo particles)
  - Downstream: LAV, LKr, IRC, SAC (photon), MUV0 (multiplicity), HASC (photon conversion)

- $\mathcal{O}(10^8)$ muon suppression, • $\mathcal{O}(10^8)$ photon (π^0) veto.

$K^+ \to \pi^+\nu\bar{\nu}$ analysis

Analysis Strategy

- Selections:
  - **Normalization** $K^+ \to \pi^+\pi^0$: 1 downstream track (only); identified as π^+; K^+–π^+ matching (space & time); upstream vetos.
  - **Signal** $K^+ \to \pi^+\nu\bar{\nu}$: normalization selection + full photon and detector multiplicity cuts (reject all extra activity).

$$\boxed{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \overbrace{(N_{SR}^{tot} - N_{SR}^{bg})}^{N_{SR}^{\pi\nu\bar{\nu}}} \cdot \mathcal{B}_{SES}.}$$

Observed events in signal region

Expected background

$$\mathcal{B}_{SES} = \frac{1}{N_K \varepsilon_{RV} \varepsilon_{trig} A_{\pi\nu\bar{\nu}}}, \quad N_K = \frac{N_{\pi\pi} D_0}{\mathcal{B}_{\pi\pi} A_{\pi\pi}}.$$

Number of normalization events

Downscaling factor of normalization trigger (generally 400)

Acceptance of normalization

Random veto efficiency

Trigger efficiency (ratio)

Signal selection acceptance

$K^+ \to \pi^+\pi^0$ branching ratio

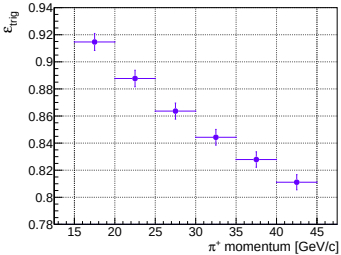
- Analysis is performed in bins of π^+ momentum (categories). Fitting all the categories to get the final $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$.

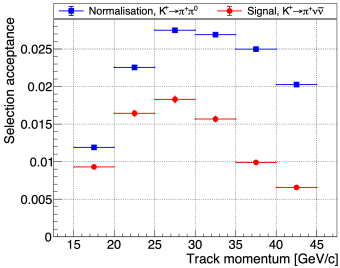
$K^+ \to \pi^+\nu\bar{\nu}$ analysis: signal sensitivity

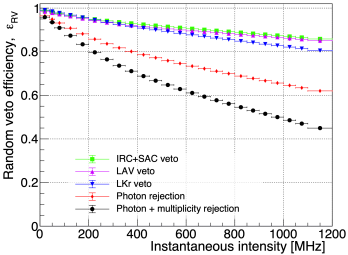
2021–2022 dataset [JHEP02(2025)191]

$N_{\pi\pi}$	$(1.953 \pm 0.005) \times 10^8$
$A_{\pi\pi}$	$(13.410 \pm 0.005)\%$
N_K	$(2.85 \pm 0.01) \times 10^{12}$
$A_{\pi\nu\bar{\nu}}$	$(7.62 \pm 0.22)\%$
ε_{RV}	$(63.2 \pm 0.6)\%$
ε_{trig}	$(85.9 \pm 1.4)\%$
$\mathcal{B}_{SES}$	$(8.48 \pm 0.29) \times 10^{-12}$
$N^{SM}_{\pi\nu\bar{\nu}}$*	9.91 ± 0.34

$$\mathcal{B}_{SES} = \frac{\mathcal{B}_{\pi\pi} A_{\pi\pi}}{N_{\pi\pi} D_0 A_{\pi\nu\bar{\nu}} \varepsilon_{RV} \varepsilon_{trig}}.$$







- 2016–2018 dataset: $N^{SM}_{\pi\nu\bar{\nu}} = (10.01 \pm 0.42)$.
- $+50\%$ signal yield, $\times 2$ better $\mathcal{B}_{SES}$ uncertainty.

* Using $\mathcal{B}^{SM}(K^+ \to \pi^+\nu\bar{\nu}) = 8.4 \times 10^{-11}$ [EPJC82(2022)615]

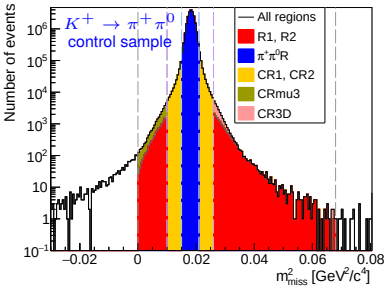
$K^+ \to \pi^+\nu\bar{\nu}$ analysis: background evaluation

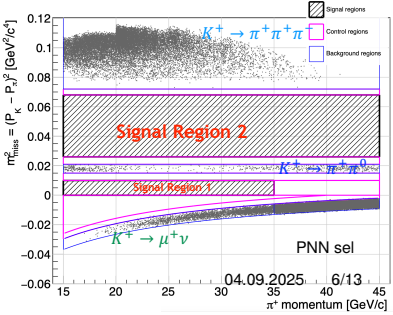
2021–2022 dataset [JHEP02(2025)191 ↗]

$$N_{bg} = N_{bgR}^{PNNsel} \cdot f_{tail} = N_{bgR}^{PNNsel} \cdot \frac{N_{SR}^{Ctrl}}{N_{bgR}^{Ctrl}}$$

- N_{bgR}^{PNNsel}: Number of events passing signal selection in background region
- N_{SR}^{Ctrl}: Control sample events in Signal Regions
- N_{bgR}^{Ctrl}: Control sample events in Background Region
- Backgrounds don't have a "tail" in m^2_{miss}: other distribution (CDA for upstream background) / simulation;

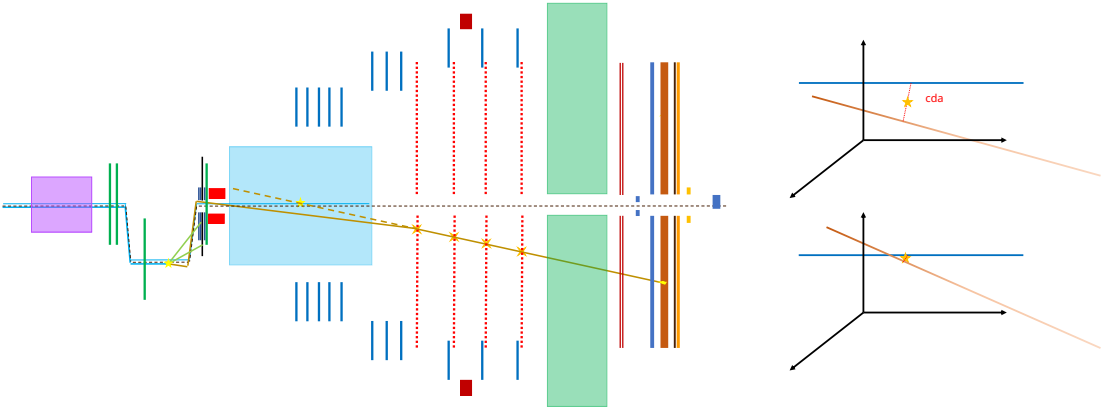
$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89^{+0.33}_{-0.27}$
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
$K^+ \to \pi^0 l^+\nu$	< 0.001
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$





$K^+ \to \pi^+ \nu \bar{\nu}$ analysis

Upstream background: the π^+ selected in downstream is originated from the upstream instead of a kaon decay in the decay region, and it's matched with an accidental beam K^+.

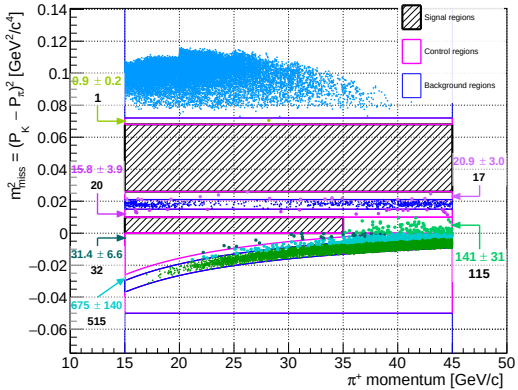


- Estimation of upstream background relies on the distribution of the Closest Distance Approach (CDA) of the pion track and the kaon track.

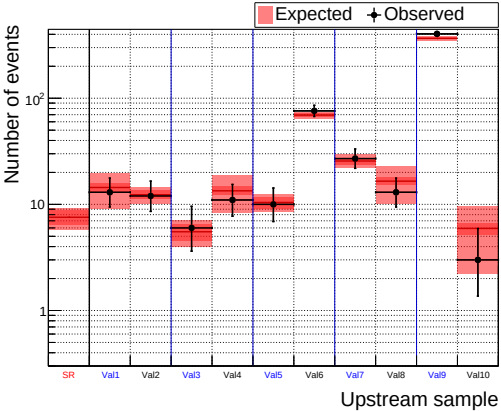
$K^+ \to \pi^+ \nu\bar{\nu}$ analysis

Validation of background evaluation

Control region prediction (colored) v.s. observation

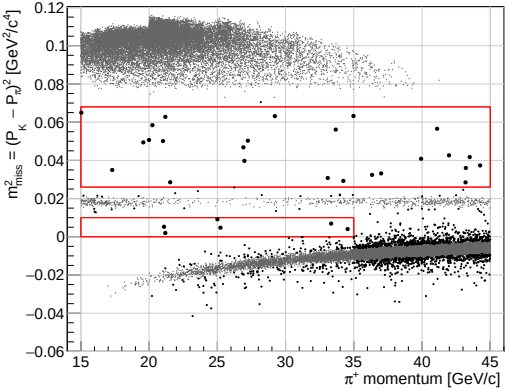


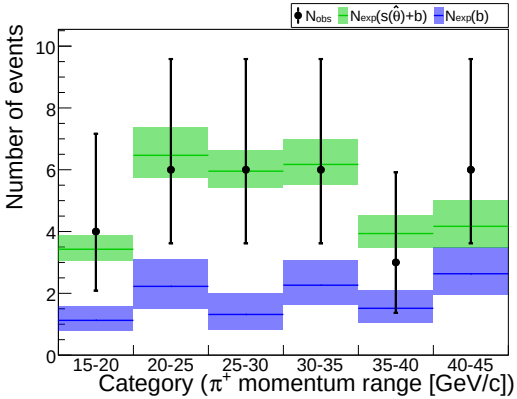
Upstream validation samples



$K^+ \to \pi^+ \nu\bar{\nu}$ analysis

2021–2022 dataset [JHEP02(2025)191 ↗]



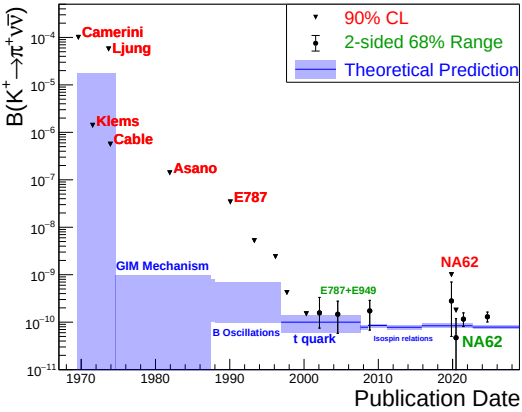


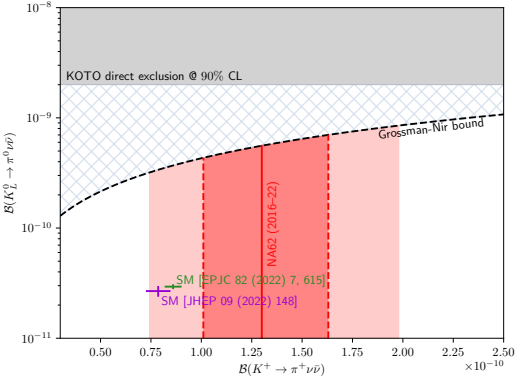
- Evaluated background $N_{bg}^{tot} = 11.0^{+2.1}_{-1.9}$,
- Expected SM signal $N_{\pi\nu\bar{\nu}}^{SM} \approx 10$,
- $\boldsymbol{N_{obs} = 31}$.

$$\mathcal{B}_{21-22}(K^+ \to \pi^+\nu\bar{\nu}) = (16.2^{+4.9}_{-4.3}|_{stat}\ ^{+1.4}_{-1.4}|_{syst}) \times 10^{-11} = (16.2^{+5.1}_{-4.5}) \times 10^{-11}.$$

$K^+ \to \pi^+ \nu\bar{\nu}$ analysis

Results in context





$K^+ \to \pi^+ \nu\bar{\nu}$ bibliography

Experiments:

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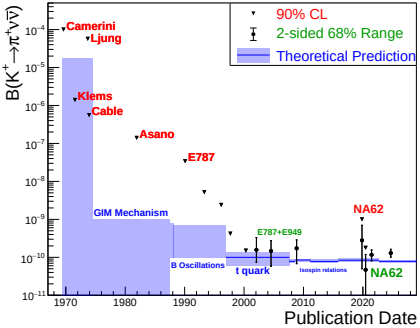
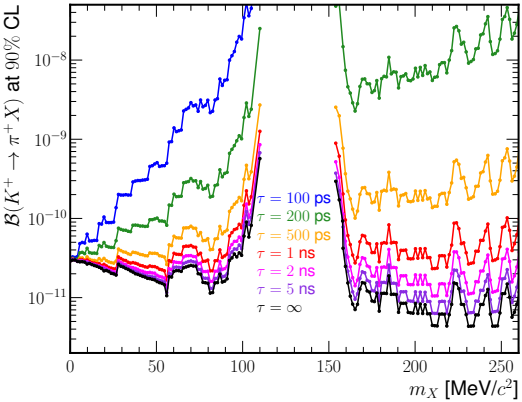
- Klems et al. [PRD 4 (1971) 66-80]
- Ljung et al. [PRD 8 (1973) 1307-1330]
- Cable et al. [PRD8 (1973) 3807-3812]
- Asano et al. [PLB 107 (1981) 159]
- E787 :
  - [PRL 64 (1990) 21-24]
  - [PRL 70 (1993) 2521-2524]
  - [PRL 76 (1996) 1421-1424]
  - [PRL 79 (1997) 2204-2207]
  - [PRL 84 (2000) 3768-3770]
  - [PRL 88 (2002) 041803]
- E949 (+E787):
  - [PRL 93 (2004) 031801]
  - [PRL 101 (2008) 191802]
- NA62:
  - 2016 data: [PLB 791 (2019) 156]
  - 2016+17 data: [JHEP 11 (2020) 042]
  - 2016–18 data: [JHEP 06 (2021) 093]
  - 2016–22 data : [JHEP 02 (2025) 191].

Theory:

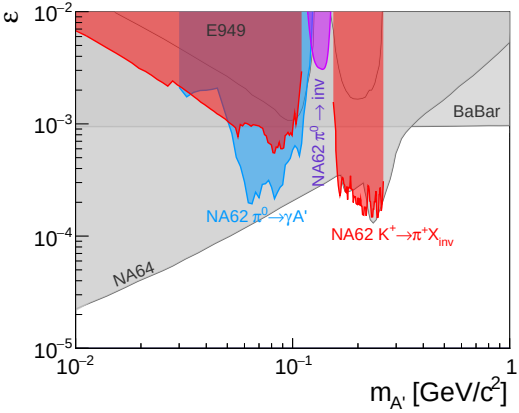
- [Phys.Rev. 163 (1967) 1430-1440]
- [PRD 10 (1974) 897]
- [Prog.Theor.Phys. 65 (1981)]
- [PLB 133 (1983) 443-448]
- [PLB 192 (1987) 201-206]
- [Nucl.Phys.B 304 (1988) 205-235]
- [PRD 54 (1996) 6782-6789]
- [PRD 76 (2007) 034017]
- [PRD 78 (2008) 034006]
- [PRD 83 (2011) 034030]
- [JHEP 11 (2015) 033]
- [JHEP 09 (2022) 148]



$K^+ \to \pi^+ X$ searches

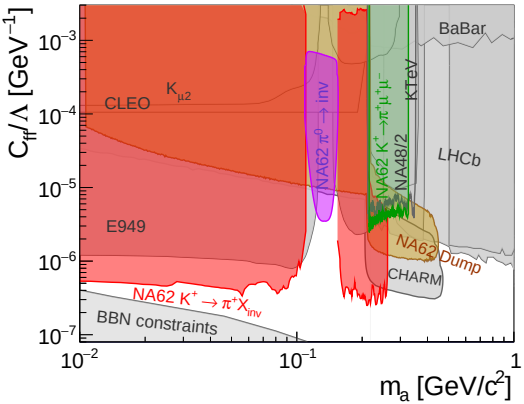


Upper limit for different X lifetime

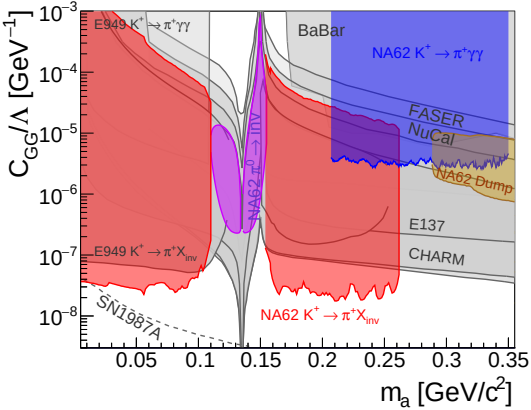


BC2

$K^+ \to \pi^+ X$ searches



BC10



BC11