



Istituto Nazionale di Fisica Nucleare



Searches for new physics in kaon decays

Paolo Massarotti (massarotti@na.infn.it)

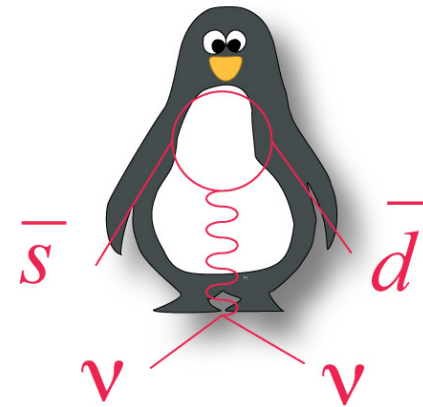
Università degli studi di Napoli Federico II and INFN Napoli

on behalf of the NA62 collaboration

QCD 2024, Montpellier

Outline

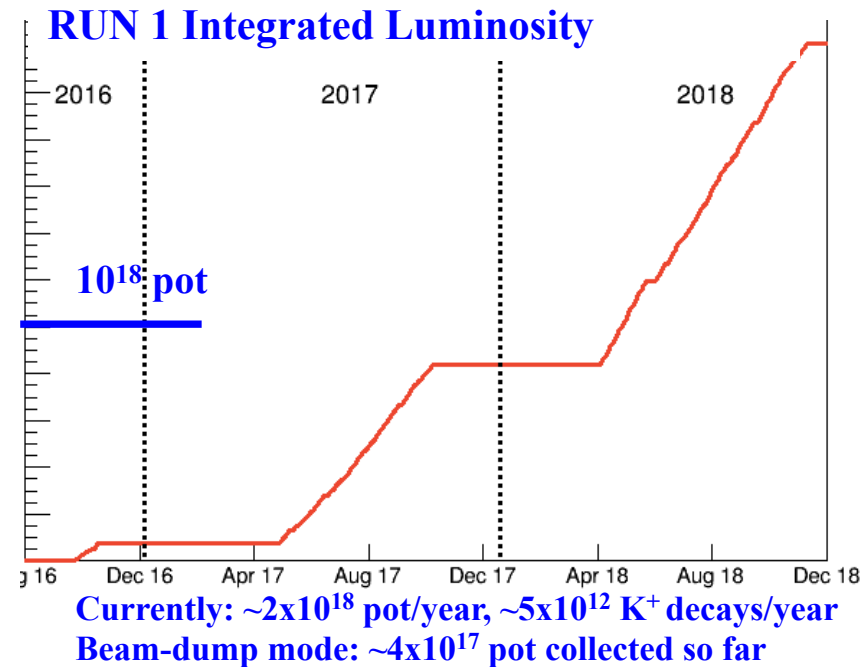
- The NA62 experiment
- Experimental setup
- Hidden sector
 - $K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$
 - $A' \rightarrow l^+ l^-$
- LFV or LNV
 - $K^+ \rightarrow \mu^- \nu e^+ e^+$
 - $K^+ \rightarrow \pi^0 \pi \mu e$
- Conclusions



NA62 experiment at CERN

NA62 is located in the North Area at CERN:

- ✓ Fixed target experiment with kaon decay-in-flight
- ✓ Main goal: $\text{BR}(\text{K}^+ \rightarrow \pi^+ \nu \bar{\nu})$ with **15% precision**
[PLB791 (2019) 156-166, JHEP11 (2020), JHEP06 (2021)]
- ✓ Primary beam: **400 GeV/c protons** from SPS
- ✓ Secondary beam: **75 GeV/c positive charged particle (6% K^+)**



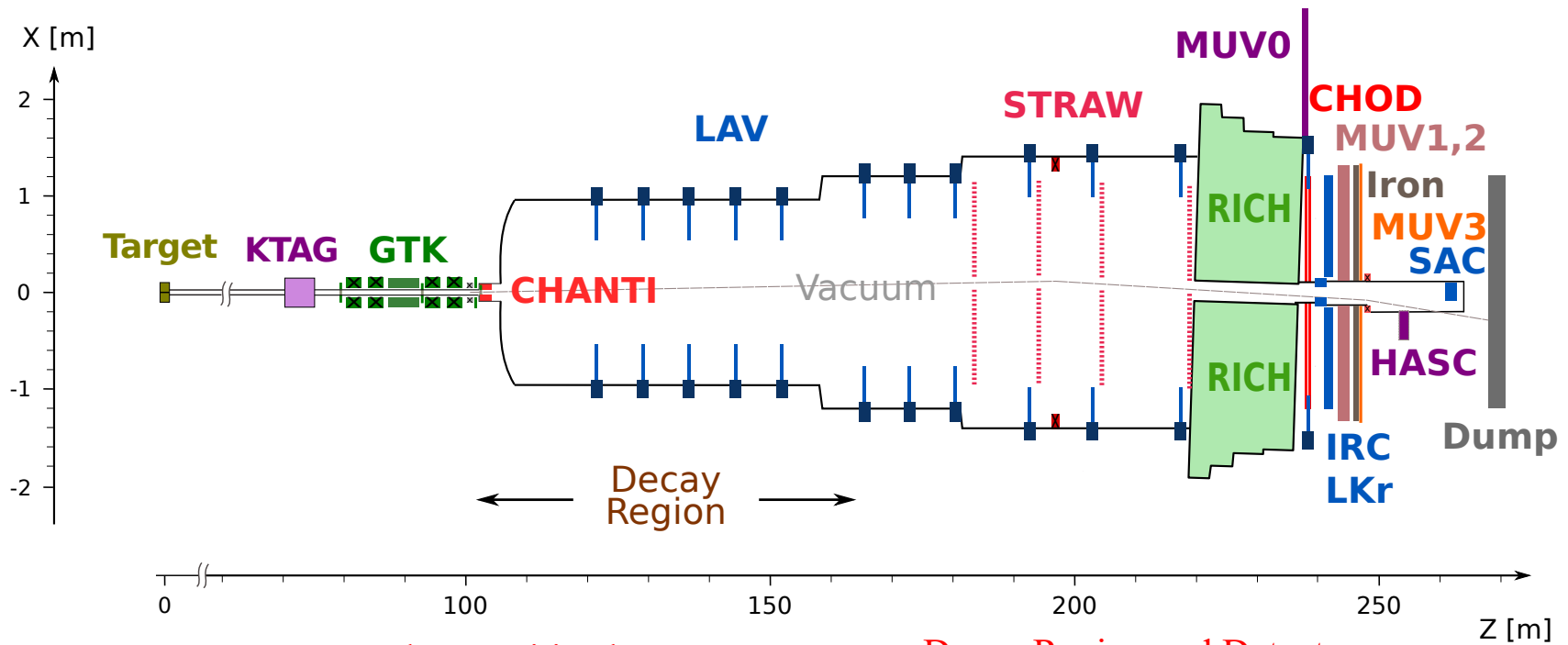
NA62 collaboration: ~ 200 participants from ~ 30 institutions:

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Marseille, Moscow, Munich-Garching, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Torino, TRIUMF, Vancouver UBC

Timeline

2009 – 2014	2014 – 2015	2016 – 2018	2021 – 2025
Construction and installation	Technical runs	Physics runs	Physics runs

NA62 beam and detector



SPS Beam

Secondary positive beam

Decay Region and Detectors

400 GeV/c protons

75 GeV/c momentum, 1% bite

Fiducial region 60 m

3.5s spill

100 μ rad divergence (RMS)

K^+ decay rate ~ 5 MHz

60x30 mm² transverse size

Vacuum $\varnothing 10^{-6}$ mbar

$K^+(6\%)/\pi^+(70\%)/p(24\%)$

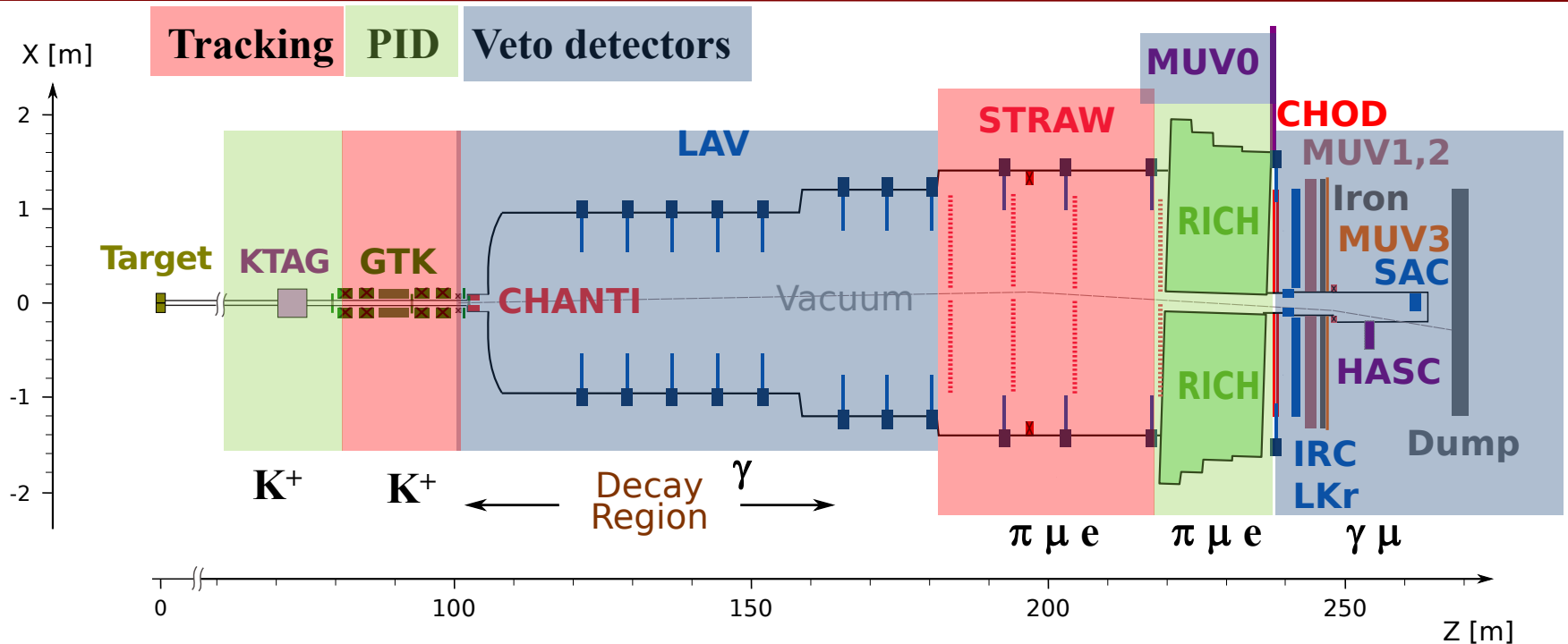
Si pixel beam tracker + Straw tracker

750 MHz at GTK3

LKr Calorimeter from NA48

Cerenkov counter for K id RICH for e/ π/μ id

NA62 beam and detector



SPS Beam

400 GeV/c protons
3.5s spill

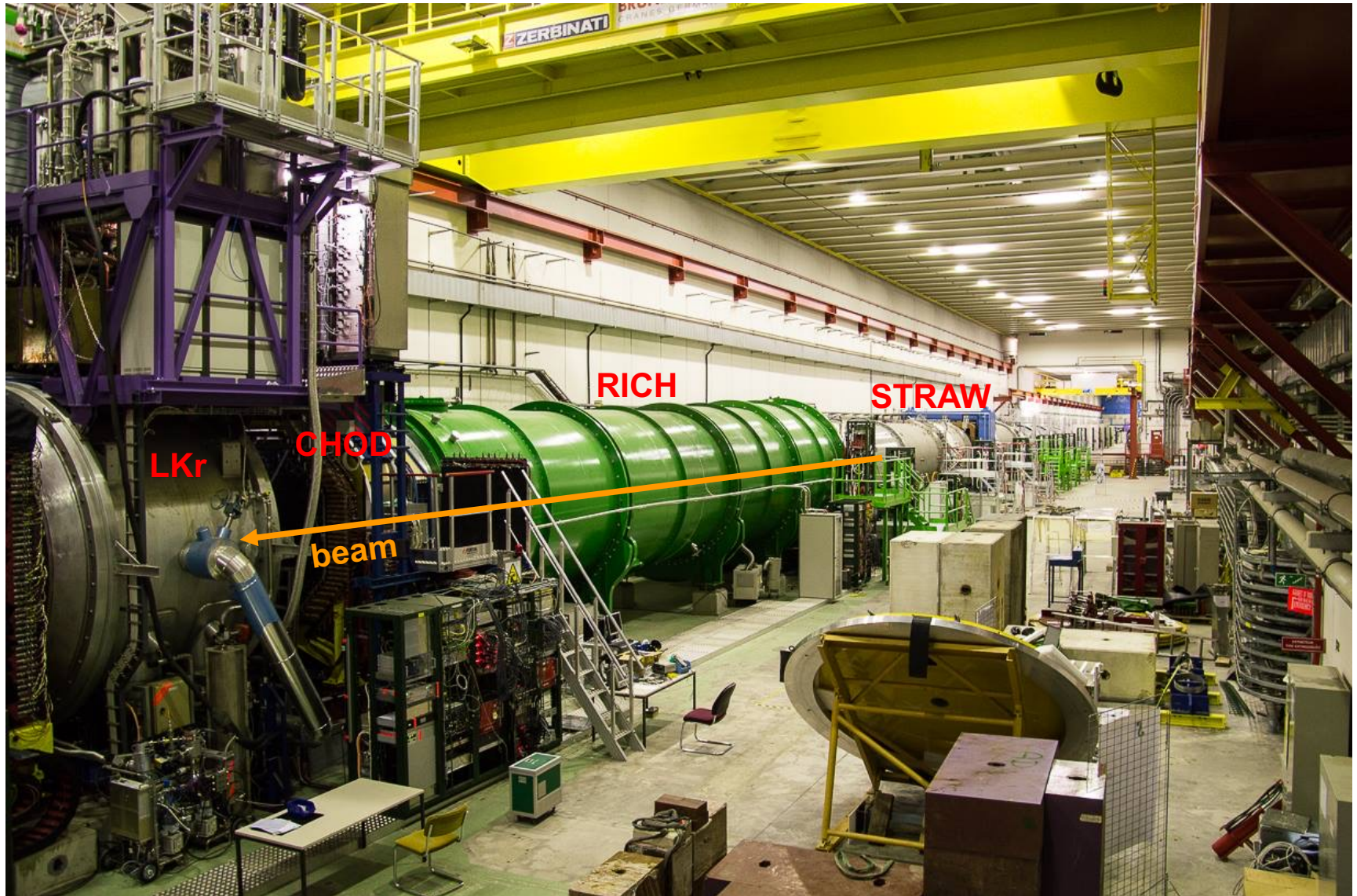
Secondary positive beam

75 GeV/c momentum, 1% bite
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Decay Region and Detectors

Fiducial region 60 m
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Cerenkov counter for K id RICH for $e/\pi/\mu$ id

NA62 Detector



$$\mathbf{K^+ \longrightarrow \pi^+ e^+ e^- e^+ e^-}$$

$K^+ \rightarrow \pi^+ X X$ motivation

Searches for production of dark-sector in meson decays have been focused on the production of a single particle, which is either invisible or decays into lepton or photon pairs (not on the pair-production of dark states)

Two-fold interest in the context of dark sector:

- A short-lived QCD axion:
 - plausible explanation for the “17 MeV anomaly” in the mass spectra of the e^+e^- pairs produced in the de-excitation of ^8Be , ^4He and ^{12}C nuclei
[Phys. Rev. D105 (2022) 015017]
 - assuming $m_a = 17 \text{ MeV}/c^2$, $B(K^+ \rightarrow \pi^+ a a) > 2 \times 10^{-8}$ is predicted
[Phys. Rev. D 103(2021)055018), (Eur. Phys. J. C83 (2023) 230)]
- Dark scalar S , and a dark photon A' with masses satisfying the condition $m_S \geq 2m_{A'}$, and $K^+ \rightarrow \pi^+ S$, $S \rightarrow A' A'$, $A' \rightarrow e^+ e^-$
[Phys. Rev. D105 (2022) 015017]

$K^+ \rightarrow \pi^+ X X$ selection (1)

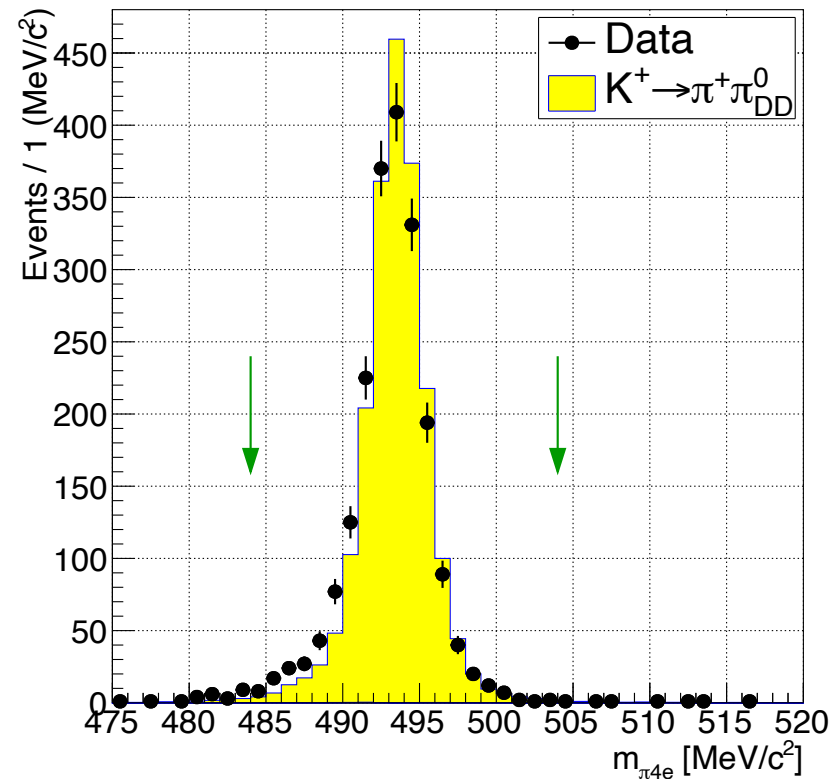
The data sample analysed is obtained from 8.3×10^5 SPS spills recorded in 2017–2018; $K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$ ($K_{\pi 4e}$) rate is normalised to decay $K^+ \rightarrow \pi^+ \pi_{DD}^0$ ($K_{2\pi DD}$) which allows a first order cancellation of detector and trigger inefficiencies.

➤ STRAW information only, to avoid loss in signal acceptance:

- vertices are reconstructed by extrapolating STRAW tracks backward
- 5 tracks,
- p-track in the range 5–45 GeV/c.
- each pair of tracks should be separated by at least 15 mm in each STRAW chamber plane, to suppress photon conversions and fake tracks

➤ Invariant mass $m_{\pi 4e}$ used to distinguish between signal and bkg

- Three assignments of the π^+ mass to one of the positively charged tracks are considered. The mass assignment corresponding to the minimal value of $|m_{\pi 4e} - m_K|^2$ is chosen



$K^+ \rightarrow \pi^+ X X$ selection (2)

The data sample analysed is obtained from 8.3×10^5 SPS spills recorded in 2017–2018. $K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$ ($K_{\pi 4e}$) rate is normalised to decay $K^+ \rightarrow \pi^+ \pi_{DD}^0$ ($K_{2\pi DD}$) which allows a first order cancellation of detector and trigger inefficiencies.

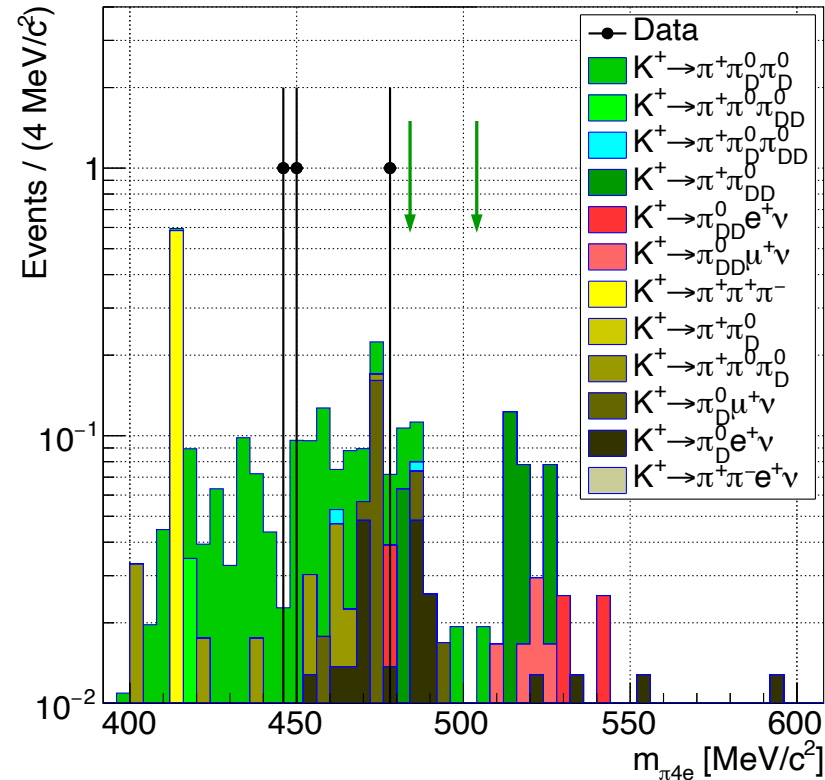
➤ Discriminating kinematic variable and blind analysis strategy

- Signal region kept masked until the completion and validation of the background evaluation

➤ For $K_{\pi 4e}$

- $|m_{4e} - m_{\pi 0}| > 10 \text{ MeV}/c^2$
- consistency of the two reconstructed $e^+ e^-$ mass for each X mass hypothesis $|m_{ee} - m_X| < 0.02 m_X$
- $p_\pi > 10 \text{ GeV}/c$.

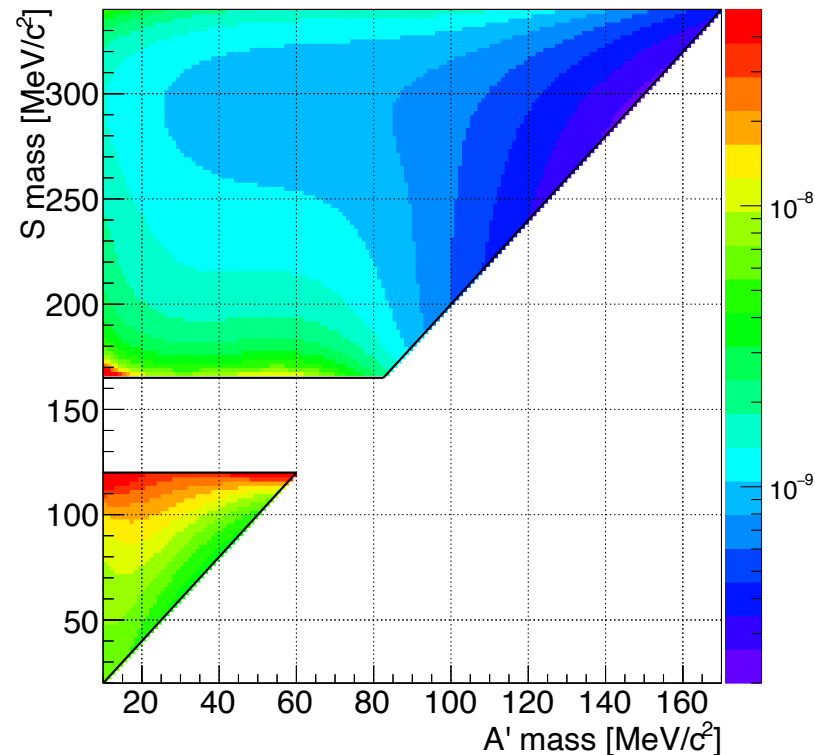
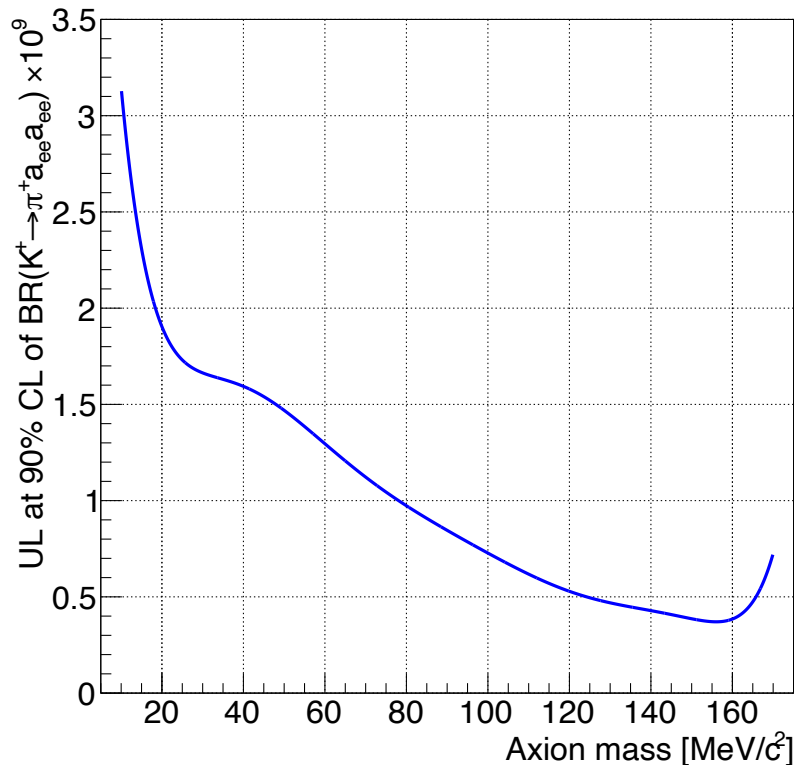
➤ For $K_{2\pi DD}$ $|m_{4e} - m_{\pi 0}|^2 < 10 \text{ MeV}/c^2$



$K^+ \rightarrow \pi^+ X X$ results

Uniform phase space assumed for K^+ decays, isotropic decays of dark states

No data observed in the Signal Region



Upper limits at 90% CL at the level of 10^{-9} for the branching ratios of two prompt decay chains involving pair-production of hidden-sector mediators.

The QCD axion is excluded as a possible explanation of the 17 MeV anomaly

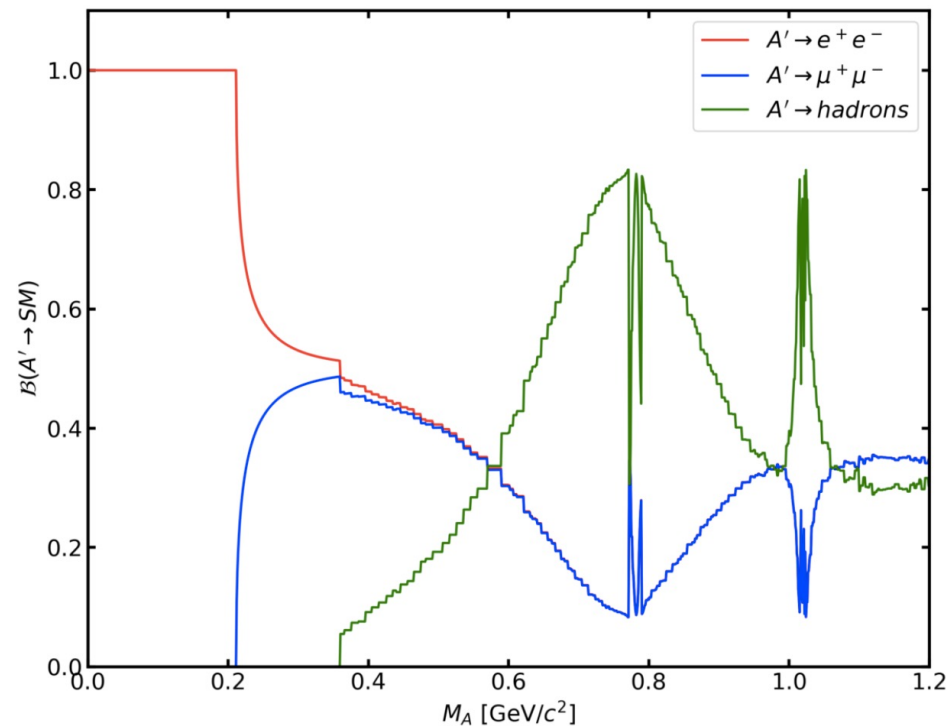
[Physics Letters B 846 (2023) 138193]

$$A' \rightarrow l^+ l^-$$

$A' \rightarrow l^+ l^-$ motivation

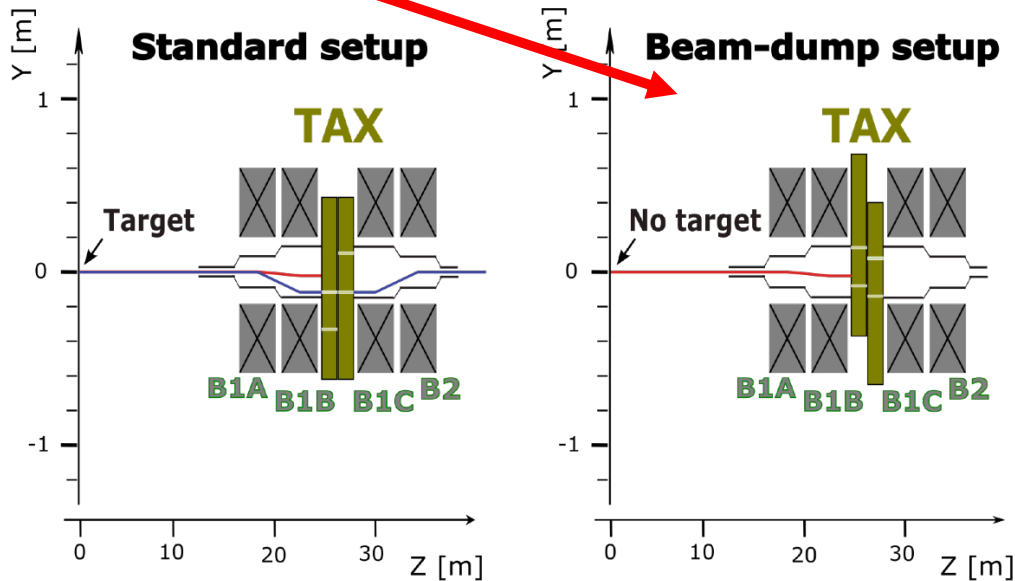
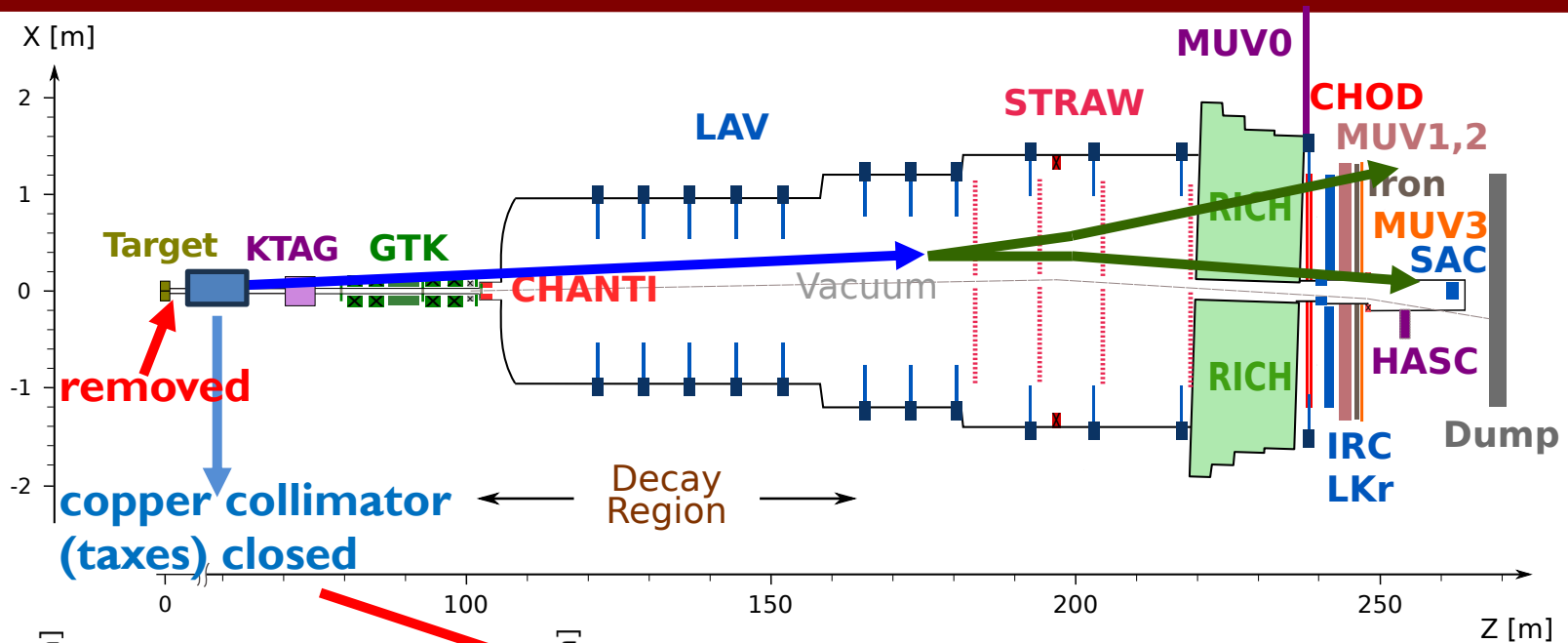
$$\mathcal{L} \propto -\epsilon \frac{1}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}$$

New U(1) gauge-symmetry
 A' vector mediator field
interaction between A'_μ and the SM
hypercharge $B_{\mu\nu}$ via kinetic-mixing



In the mass range $< 700 \text{ MeV}/c^2$, Dark Photon
decay width dominated by $l^+ l^-$ final states

NA62 beam dump configuration



In 2021, NA62 collected $1.40 \pm 0.28 \times 10^{17}$ POT.

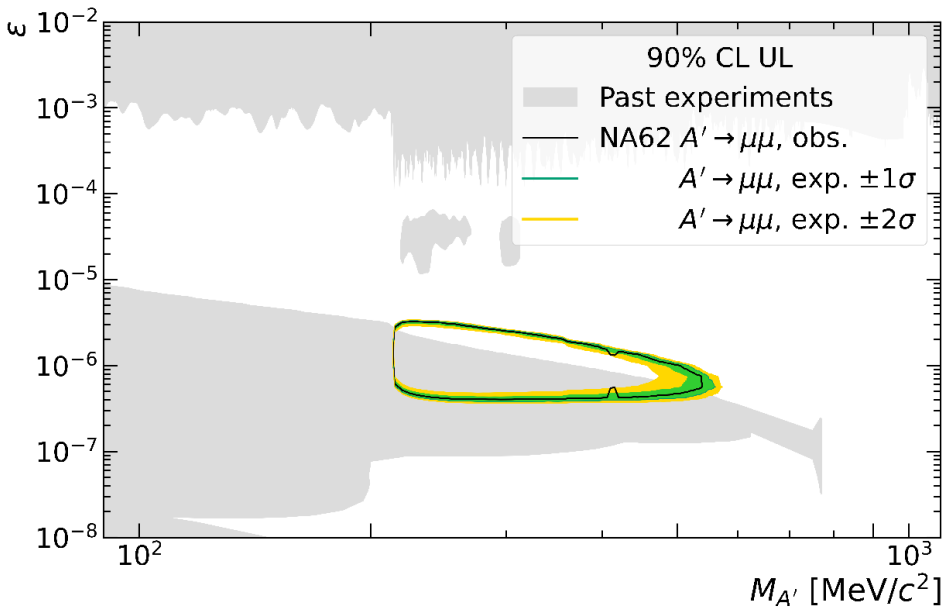
$A' \rightarrow l^+ l^-$ selection

Signal selection

- l^+l^- vertex reconstructed within the NA62 decay region and pointing back to the proton beam interaction point at the TAXes
- CR and SR masked until the analysis strategy is frozen
- Bkg estimated selecting single tracks in a data sample orthogonal to the one used for the analysis
- $A' \rightarrow \mu^+\mu^-$ result also interpreted in terms of the emission of axion-like particles in a model-independent approach, improving on previous limits for masses below $280 \text{ MeV}/c^2$

$A' \rightarrow l^+ l^-$ results

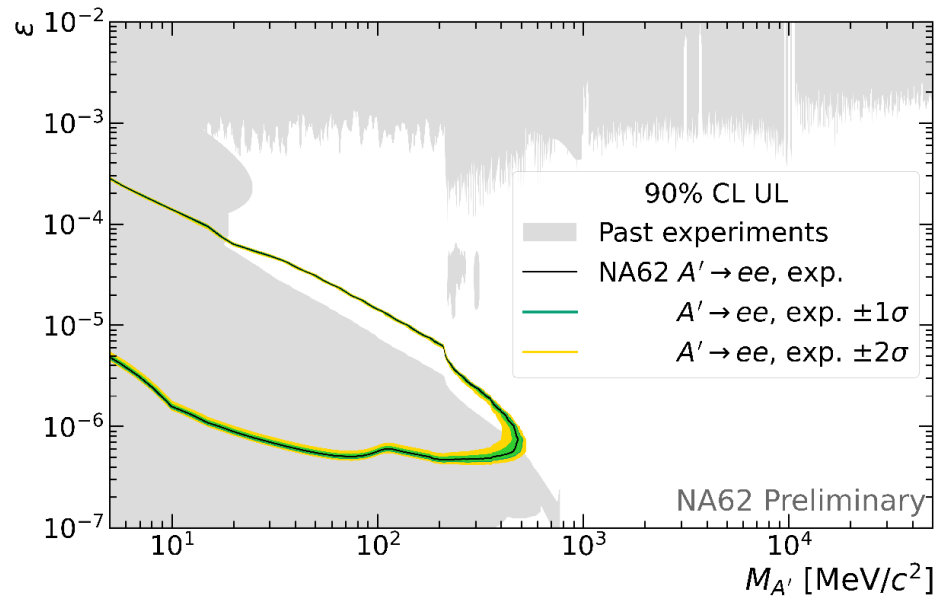
90% CL upper limits exploring new regions of the parameter space ϵ , $M_{A'}$,



$A' \rightarrow \mu^+ \mu^-$

1 event observed in the SR
corresponding to 2.4σ global significance

[JHEP 09 (2023) 035]



$A' \rightarrow e^+ e^-$

0 event observed in both CR and SR
(NA62 preliminary)

[arXiv.2312.12055[, accepted by PRL]

**Search for LFV
and LNV @ NA62**

Search for LFV and LNV @ NA62

A large dataset of K^+ decays to lepton pairs in 2016–2018, using dedicated trigger.

➤ UL of the branching ratios of the LNV decays

- $K^+ \rightarrow \pi^- (\pi^0) e^+ e^+$ [Phys. Lett. B 830 (2022) 137172]
- $K^+ \rightarrow \pi^- \mu^+ \mu^+$ [Phys. Lett. B 797 (2019) 134794]
- $K^+ \rightarrow \pi^- \mu^+ e^+$ [Phys. Rev. Lett. 127 (2021) 131802]

➤ UL of the branching ratios of the LFV decays

- $K^+ \rightarrow \pi^+ \mu^- e^+$ [Phys. Rev. Lett. 127 (2021) 131802]
- $\pi^0 \rightarrow \mu^- e^+$ [Phys. Rev. Lett. 127 (2021) 131802]

$K^+ \rightarrow \mu^- \nu e^+ e^+$ and $K^+ \rightarrow \pi^0 \pi \mu e$ decay are forbidden in the SM by either lepton number (LN) or lepton flavour (LF) conservation

For the first one the current UL of the branching fraction is 2.1×10^{-8} at 90% CL

[Phys. Lett. B 62 (1976) 485. Prog. Theor. Exp. Phys. 2022 (2022) 083C01]

$$K^+ \rightarrow \mu^- \nu e^+ e^+$$

$K^+ \rightarrow \mu^- \nu e^+ e^+$ selection

$K^+ \rightarrow \mu^- \nu e^+ e^+$ rate ($K_{\mu\nu ee}$) is normalised to decay $K^+ \rightarrow \pi^+ e^+ e^-$ ($K_{\pi ee}$) which allows a first order cancellation of detector and trigger inefficiencies.

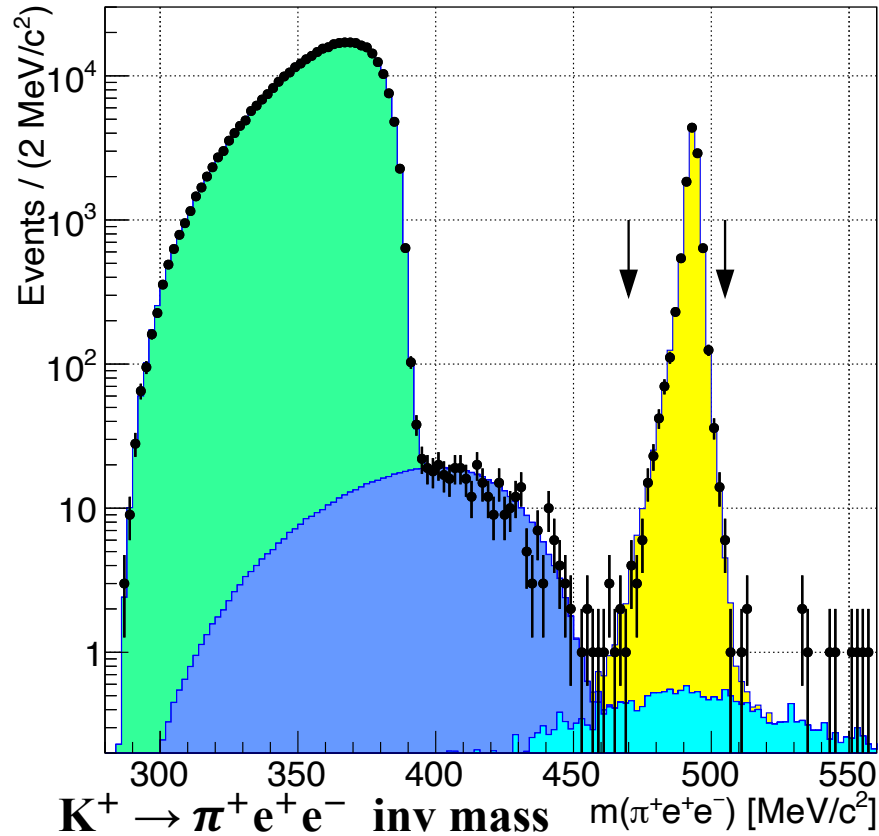
Common selection

- **3-track vertices extrapolating STRAW tracks into the FV with $6 < p < 44 \text{ GeV}/c$**
- **PID is based on the ratio E/p**
 - π is identified by $E/p < 0.85$ no in-time signal in MUV3
 - μ is identified by $E/p < 0.2$ in-time signal in MUV3
 - e is identified by $0.9 < E/p < 1.1$
- **For $K_{\pi ee}$**
 - $|p_{\text{vtx}} - p_{\text{beam}}| < 2 \text{ GeV}/c$,
 - $m_{ee} > 140 \text{ MeV}/c^2$,
 - $470 \text{ MeV}/c^2 < m_{\pi ee} < 505 \text{ MeV}/c^2$
- **For $K_{\mu\nu ee}$**
 - $p_{\text{beam}} - p_{\text{vtx}} > 10 \text{ GeV}/c$,
 - $-0.006 \text{ GeV}^2/c^4 < m_{\text{miss}}^2 < 0.004 \text{ GeV}^2/c^4$

$K^+ \rightarrow \mu^- \nu e^+ e^+$ result

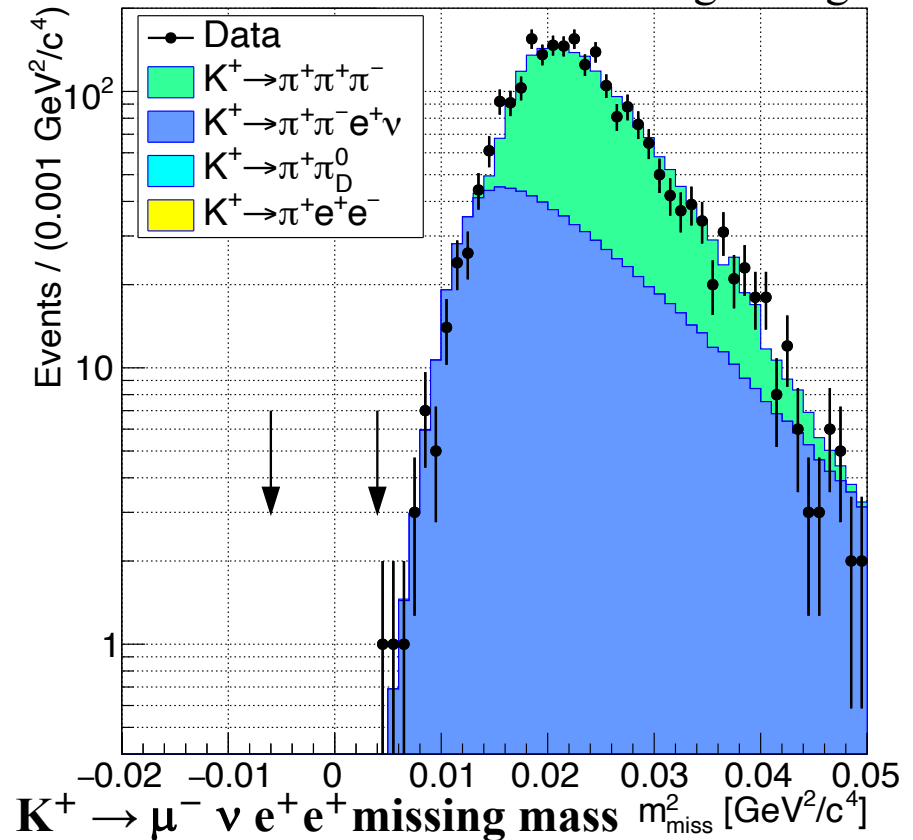
Normalisation selection

$N_{\pi e e} = 21401$



Signal selection ($N_B = 0.26 \pm 0.04$)

No candidate observed in the signal region



$\text{Br}(K^+ \rightarrow \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11}$ at 90% CL

[Physics Letters B 838 (2023) 137679]

$$K^+ \rightarrow \pi^0 \pi \mu e$$

$K^+ \rightarrow \pi^0 \pi \mu e$ selection

$K^+ \rightarrow \pi^0 \pi \mu e$ rate ($K_{\pi\pi\mu e}$) is normalised to $K^+ \rightarrow \pi^+ e^+ e^-$ ($K_{\pi ee}$) decay which allows a first order cancellation of detector and trigger inefficiencies.

Common selection

➤ **3-tracks vertex extrapolating STRAW trk into the FV with $6 < p < 65$ GeV/c**

➤ **PID is based on the ratio E/p**

- π is identified by $E/p < 0.85$, no in-time signal in MUV3
- μ is identified by $E/p < 0.2$ in-time signal in MUV3
- e is identified by $0.9 < E/p < 1.1$

➤ **For $K_{\pi ee}$**

- $|p_{\text{vtx}} - p_{\text{beam}}| < 2$ GeV/c,
- $470 < m_{\pi ee} < 505$ MeV/c²,

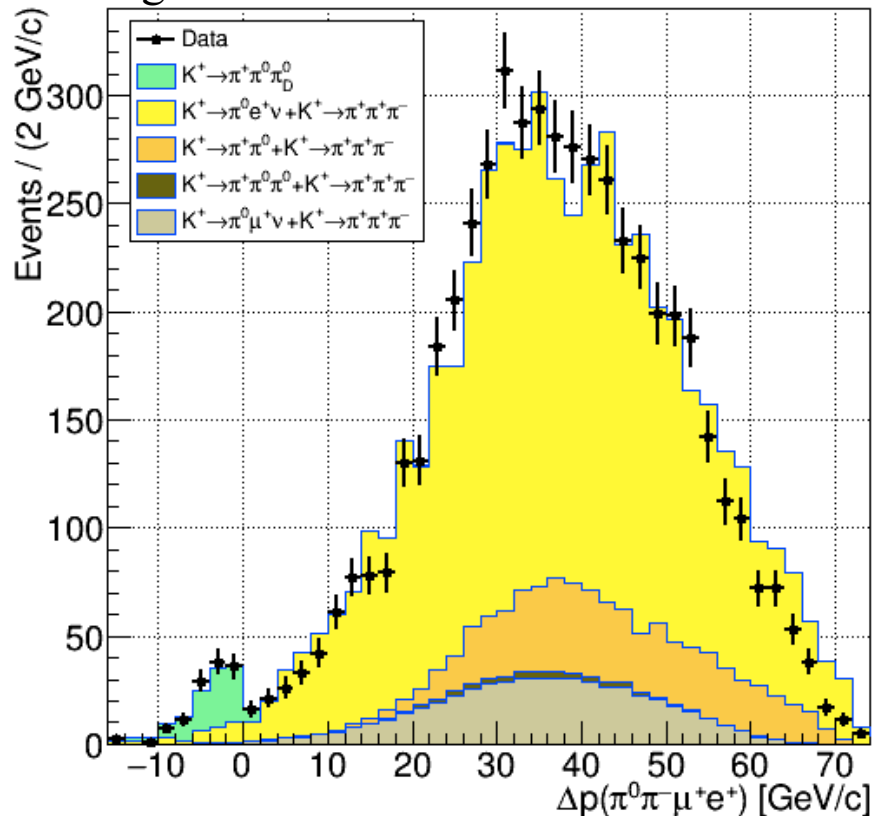
➤ **For $K_{\pi\pi\mu e}$**

- the 3-tracks vertex are π , μ and e
- one in-time π^0 reconstructed using LKr (neutral vertex)
- The charged and neutral are compatible within 8 m in Z
- $486 < m_{\pi\pi^0\mu e} < 502$ MeV/c²

Search for $K^+ \rightarrow \pi^0 \pi^- \mu^+ e^+$

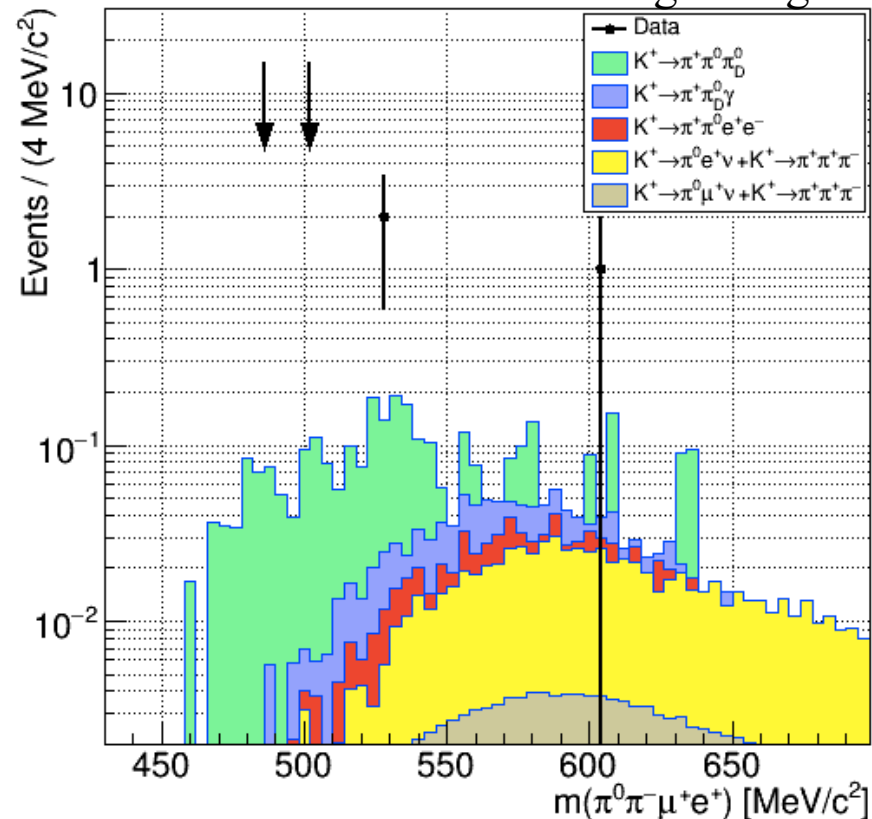
Control selection

For background normalisation and validation



Signal selection ($N_B = 0.33 \pm 0.07$)

No candidate observed in the signal region



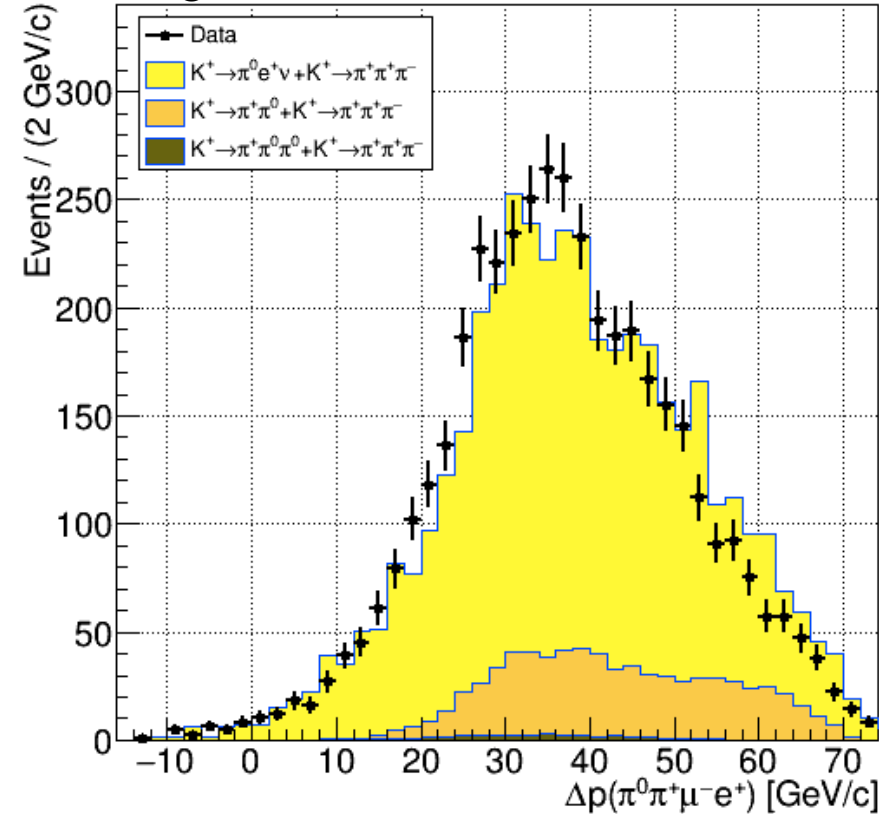
NA62 preliminary

$Br(K^+ \rightarrow \pi^0 \pi^- \mu^+ e^+) < 2.9 \times 10^{-10} @ 90\% CL$

Search for $K^+ \rightarrow \pi^0 \pi^+ \mu^- e^+$

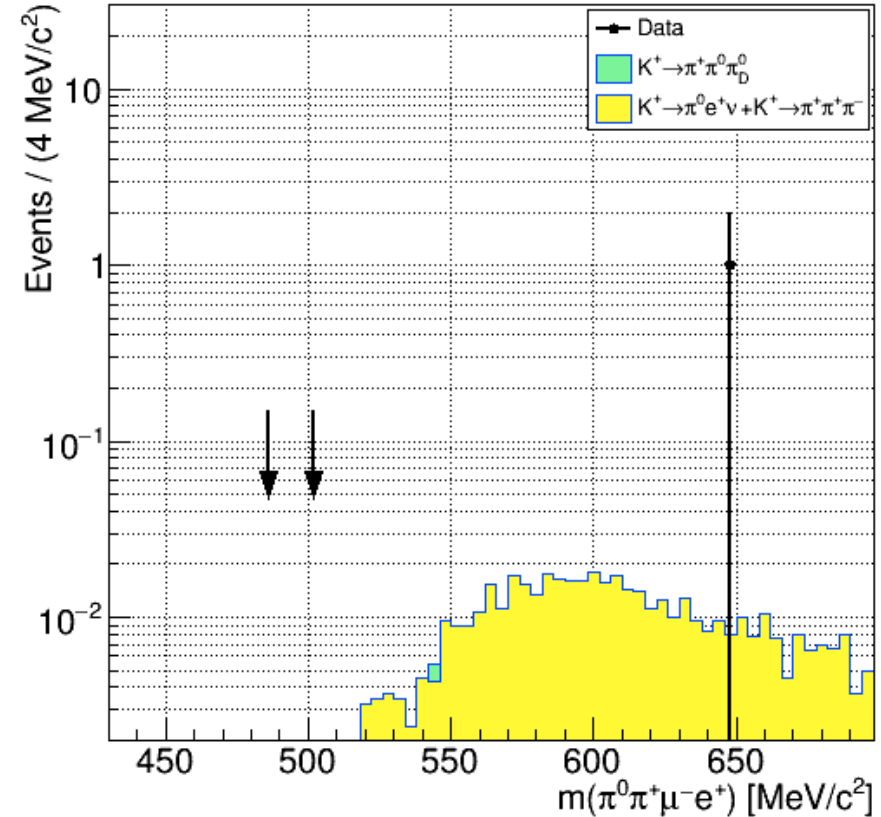
Control selection

For background normalisation and validation



Signal selection ($N_B = 0.004 \pm 0.003$)

No candidate observed in the signal region



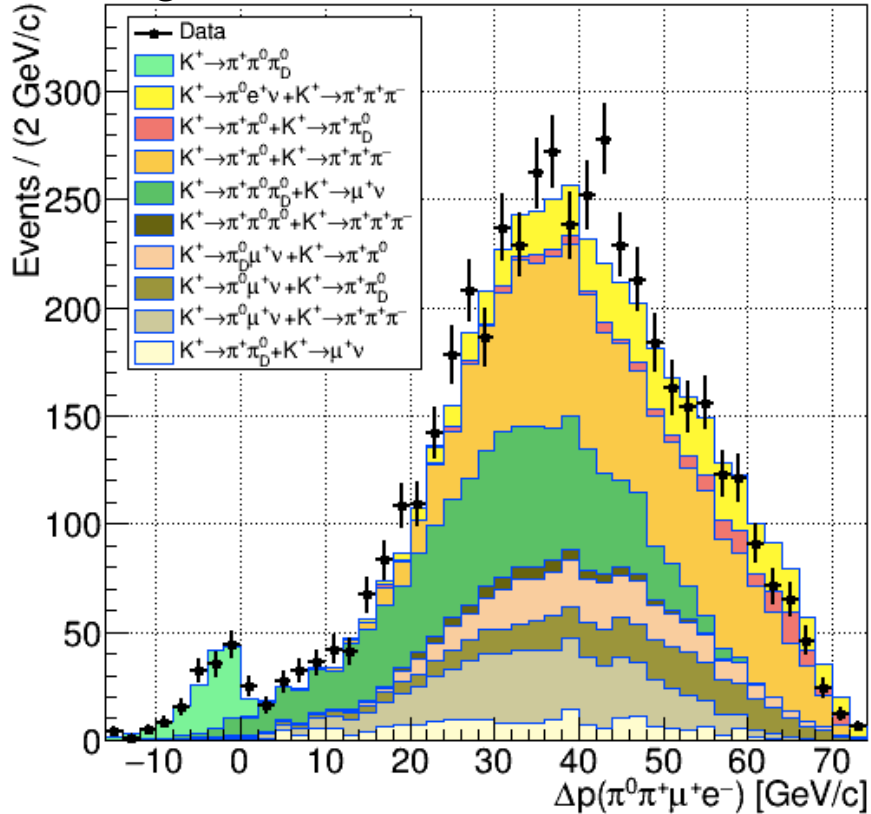
NA62 preliminary

$\text{Br}(K^+ \rightarrow \pi^0 \pi^+ \mu^- e^+) < 3.1 \times 10^{-10}$ @ 90% CL

Search for $K^+ \rightarrow \pi^0 \pi^+ \mu^+ e^-$

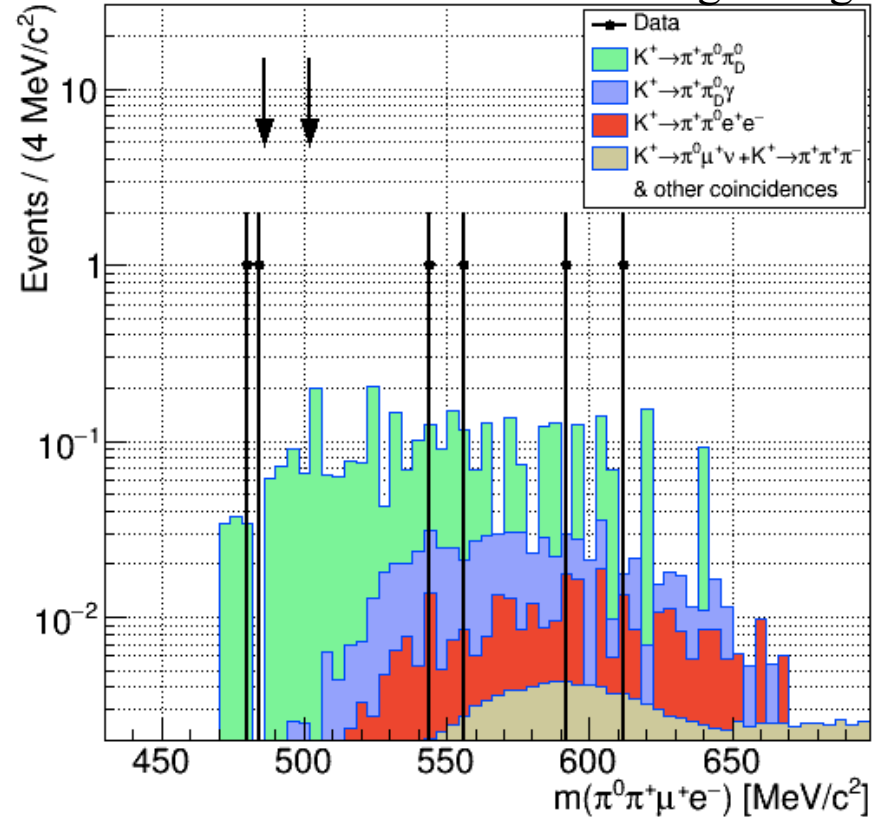
Control selection

For background normalisation and validation



Signal selection ($N_B = 0.29 \pm 0.07$)

No candidate observed in the signal region

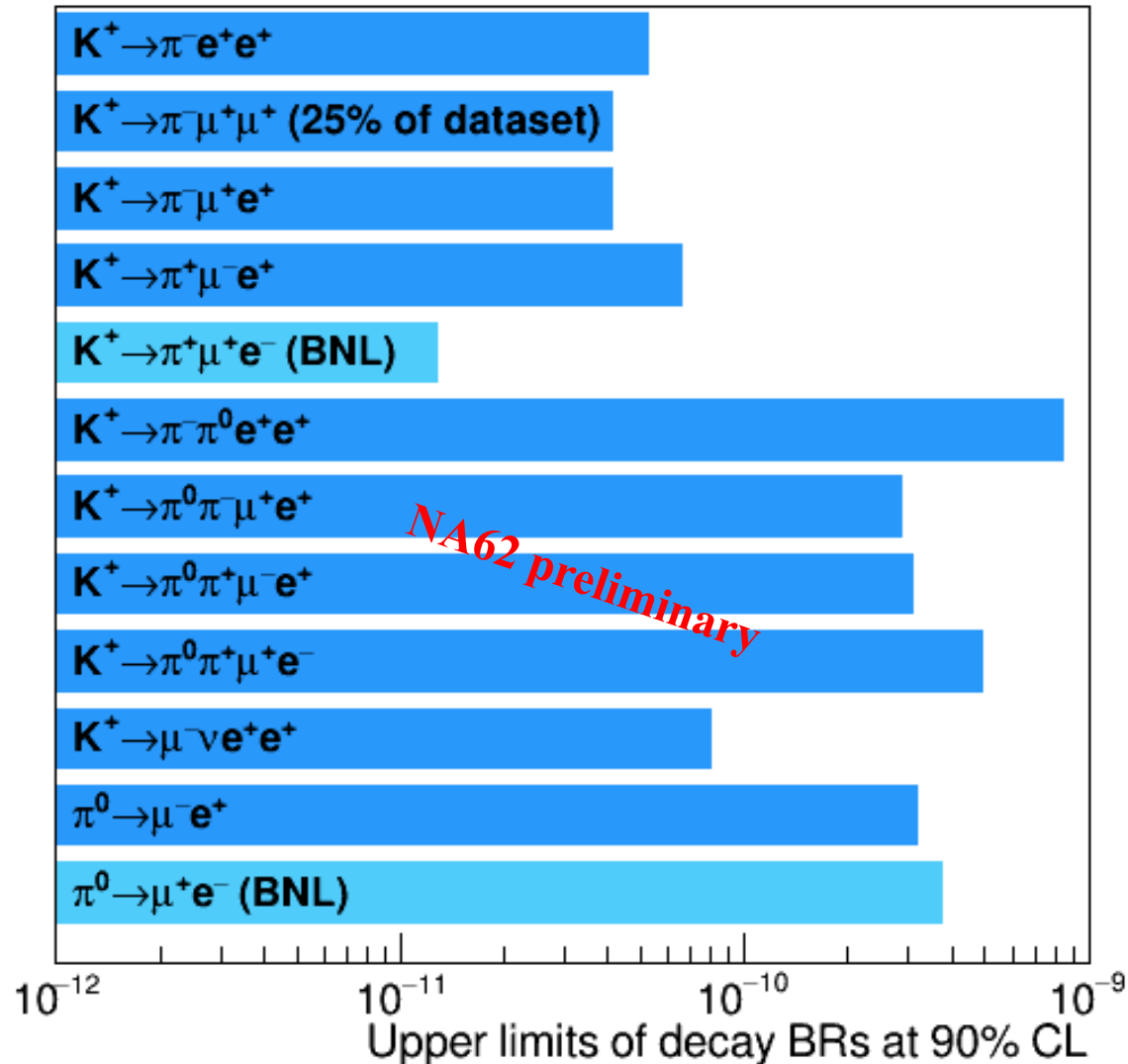


NA62 preliminary

$Br(K^+ \rightarrow \pi^0 \pi^+ \mu^+ e^-) < 5.0 \times 10^{-10} @ 90\% CL$

Summary: LFV/LNV decays

LNV/LFV K^+ and π^0 decays, NA62 Run 1



Conclusions

$\mathbf{K}^+ \rightarrow \pi^+ a a, a \rightarrow e^+ e^-$ and $\mathbf{K}^+ \rightarrow \pi^+ S, S \rightarrow A' A', A' \rightarrow e^+ e^-$ ULs have been set

[Physics Letters B 846 (2023) 138193]

$A' \rightarrow \ell^+ \ell^-$ in beam-dump mode UL have been set, exploring new regions of the parameter space

[JHEP 09 (2023) 035]

$\mathbf{K}^+ \rightarrow \mu^- \nu e^+ e^+$ UL have been set

[Physics Letters B 838 (2023) 137679]

$\mathbf{K}^+ \rightarrow \pi^0 \pi \mu e$ UL have been set

NA62 Preliminary

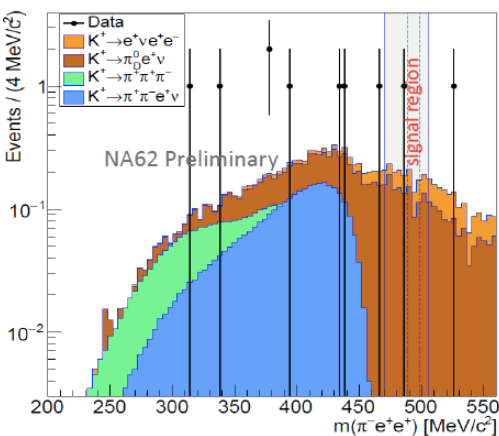
SPARE

Search for LNV and LNV @ NA62

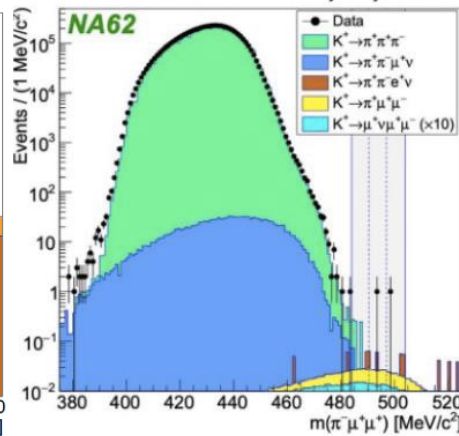
Previous UL @90% CL NA62 UL @90% CL

$K^+ \rightarrow \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data	PLB 797 (2019) 134794	<i>Factor 2 improvement</i>
$K^+ \rightarrow \pi^- e^+ e^+$	6.4×10^{-10}	5.3×10^{-11}	Run1 data	PLB 830 (2022) 137172	<i>Factor 12 improvement</i>
$K^+ \rightarrow \pi^- \pi^0 e^+ e^+$	no limit	8.5×10^{-10}	Run1 data	PLB 830 (2022) 137172	
$K^+ \rightarrow \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data	PRL 127 (2021) 131802	<i>Factor 12 improvement</i>
$K^+ \rightarrow \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data	PRL 127 (2021) 131802	<i>Factor 8 improvement</i>
$\pi^0 \rightarrow \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data	PRL 127 (2021) 131802	<i>Factor 13 improvement</i>

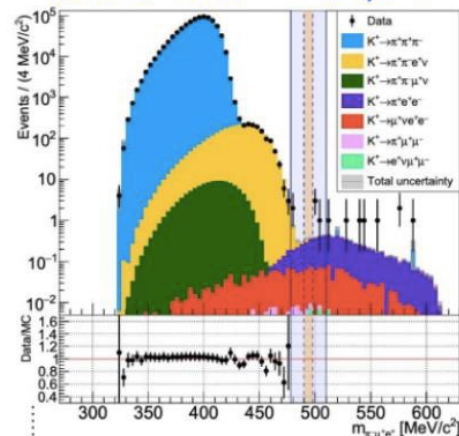
LNF: $K^+ \rightarrow \pi^- e^+ e^+$



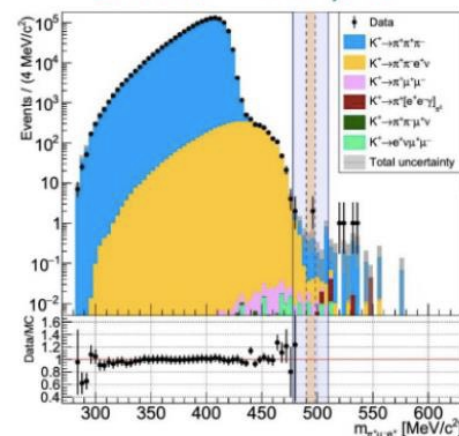
LNV: $K^+ \rightarrow \pi^- \mu^+ \mu^+$



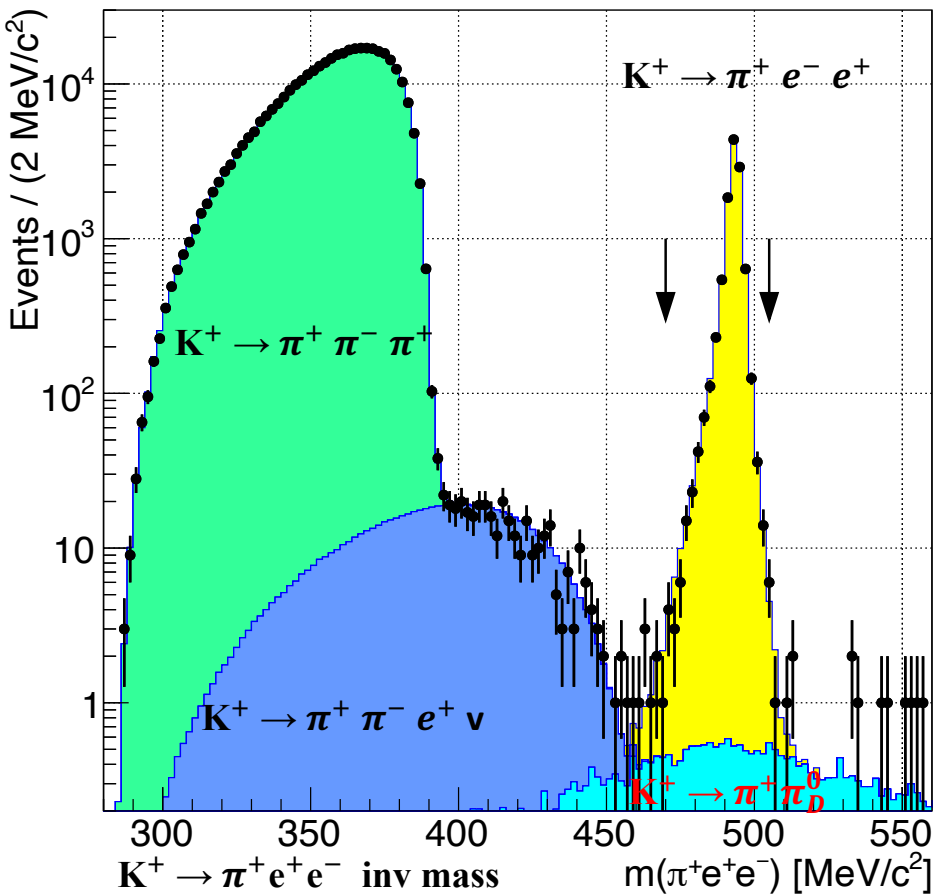
LNV/LFV: $K^+ \rightarrow \pi^- \mu^+ e^+$



LFV: $K^+ \rightarrow \pi^+ \mu^- e^+$



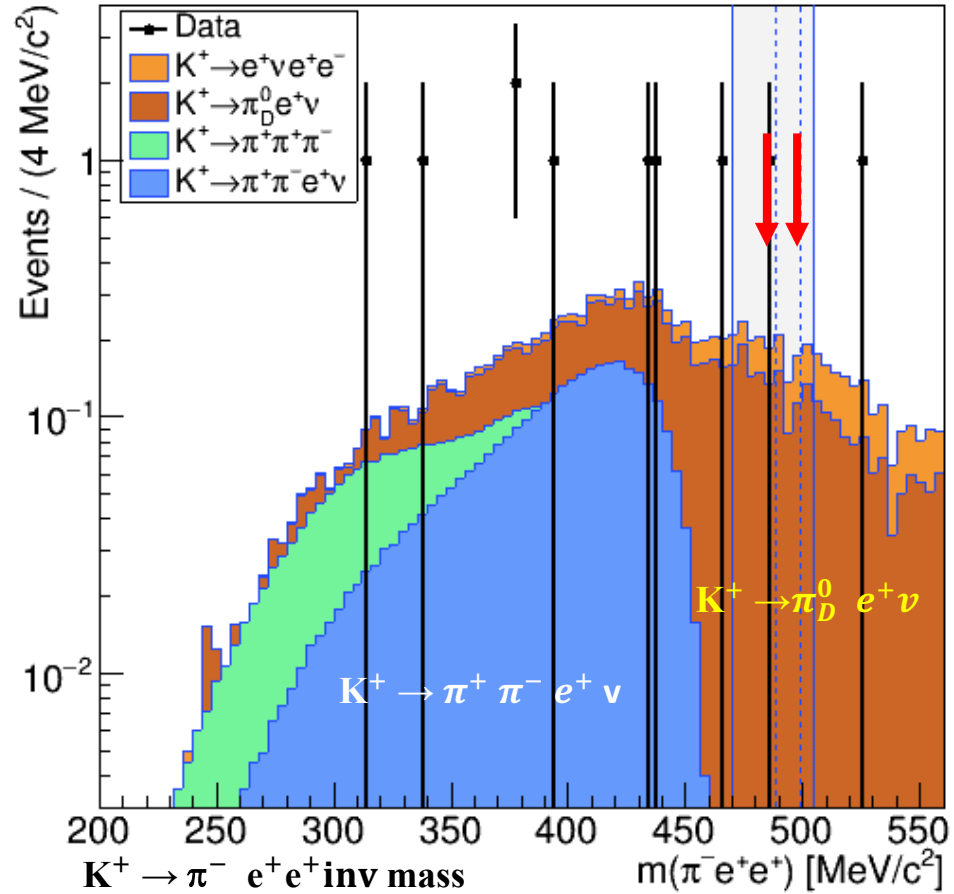
Search for $K^+ \rightarrow \pi^- e^+ e^+$



Candidates observed: 11041

$$\text{Br}(K^+ \rightarrow \pi^+ e^- e^+) = (3.00 \pm 0.09) \times 10^{-9}$$

K^+ decays in FV: $(1.015 \pm 0.032) \times 10^{12}$



Expected background: 0.43 ± 0.09 evt

Candidates observed: 0

$$\text{Br}(K^+ \rightarrow \pi^- e^+ e^+) < 5.3 \times 10^{-11} \text{ at } 90\% \text{ CL}$$

[PLB830 (2022) 137172]

$$\mathbf{K^+ \rightarrow \pi^+ \nu \bar{\nu}}$$

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Beyond SM

Precise SM predictions: [Buras. et. al., JHEP11(2015)033]

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ can discriminate among different NP scenarios

✓ **Models with CKM-like flavour structure**

[Buras, Buttazzo, knegjens, JHEP11(2015) 166]

✓ **Custodial Randall-Sundrum**

[Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]

✓ **MSSM analyses**

[Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],

[Isidori et al. JHEP 0608 (2006) 064]

✓ **LFU violation models**

[Isidori et al., Eur. Phys. J. C (2017) 77: 618]

✓ **Leptoquarks**

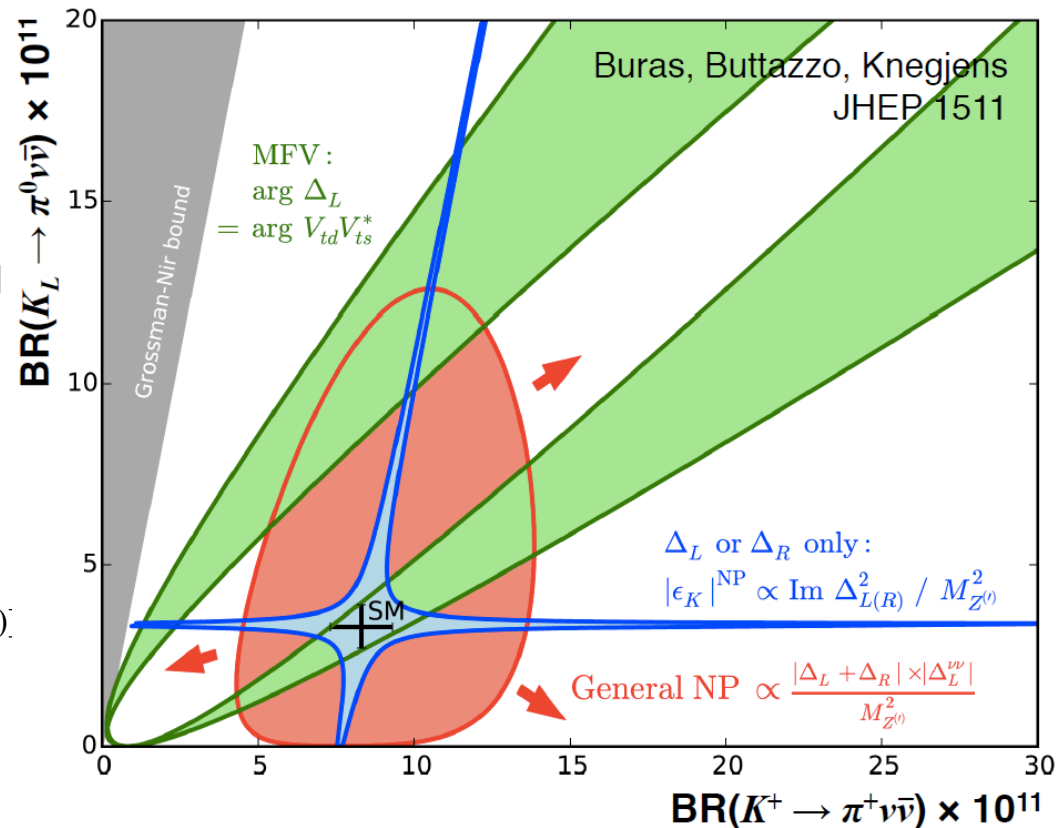
[S. Fajfer, N. Kosnik, L. Vale Silva, arXiv: 1802.00786v1 (2018)]

✓ **Simplified Z, Z' models**

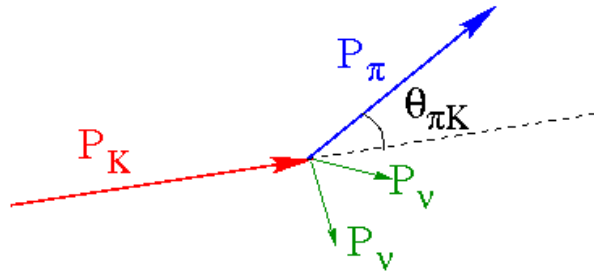
[Buras, Buttazzo, Knejiens, JHEP11(2015)166]

✓ **Littlest Higgs with T-parity**

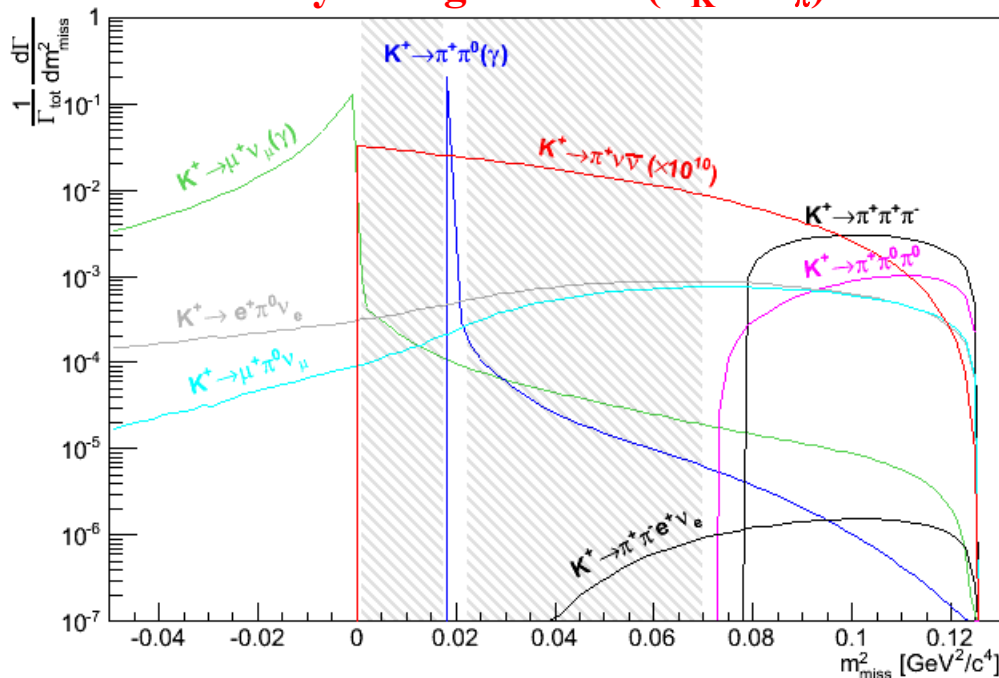
[Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]



Experimental Strategy



K decay in flight: $m^2 = (P_K - P_\pi)^2$



Performances

- Kinematic suppression $O(10^4)$
- Muon suppression $O(10^7)$
- π^0 suppression $O(10^7)$
- Timing between sub-detectors $O(100 \text{ ps})$

Selection

- K^+ , π^+ track reconstruction
- Track matching, vertex reconstruction
- π^+ identification, μ^+ rejection
- Multi-track rejection, photon veto
- Kinematics (m^2_{miss} , p_π)

Analysis

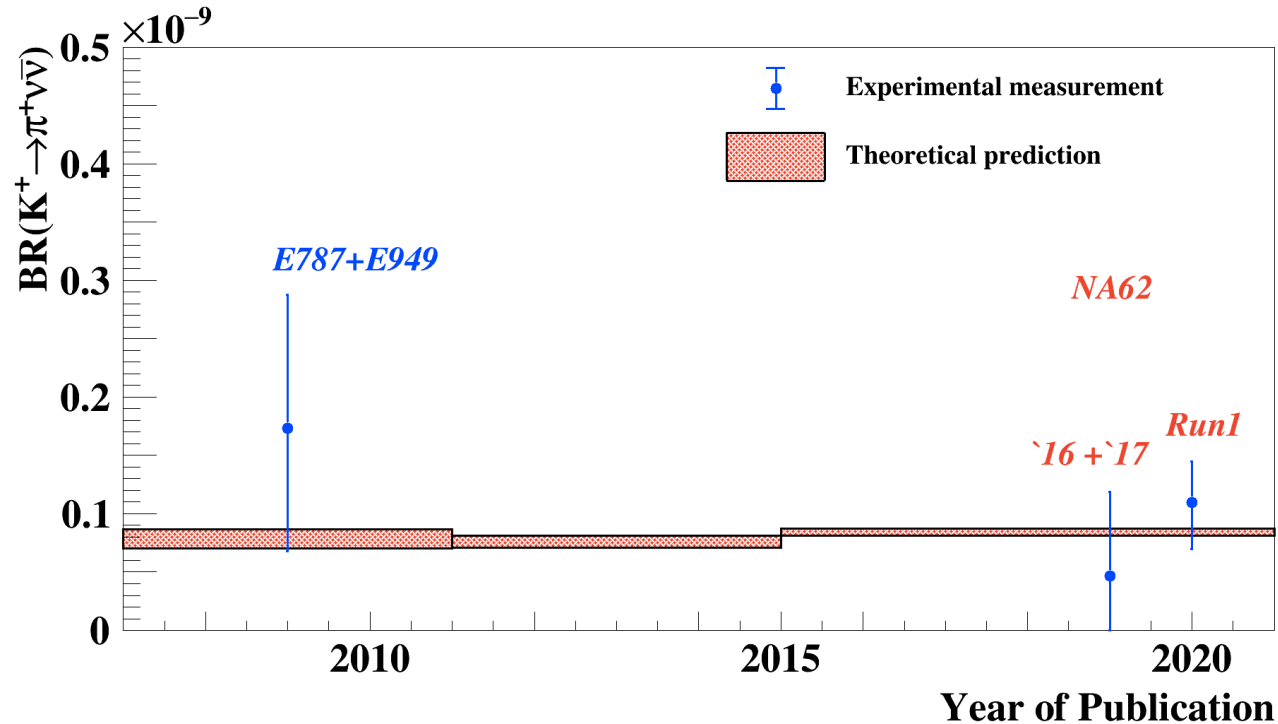
- Momentum range: $15 < p_\pi < 45 \text{ GeV}/c$
- Signal regions blinded during the analysis
- Data-driven background estimate
- 7 categories depending on hardware and momentum

RUN1 summary

$$N_{\pi\nu\nu}^{exp} \approx N_{\pi\pi} \epsilon_{trigger} \epsilon_{RV} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \implies \text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$

	2016 data	2017 data	2018 S1 data	2018 S2 data
$SES \times 10^{10}$	3.15 ± 0.24	0.39 ± 0.02	0.54 ± 0.04	0.14 ± 0.01
$A_{\pi\nu\nu} \times 10^2$	4 ± 0.4	3 ± 0.3	4 ± 0.4	6.4 ± 0.6
Expected SM signal	0.27 ± 0.04	2.16 ± 0.13	1.56 ± 0.10	6.02 ± 0.39
Expected background	0.15 ± 0.090	1.46 ± 0.30	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
Observed events	1	2	2	15
	<i>[PLB 791 (2019) 156-166]</i>	<i>[JHEP 11 (2020) 042]</i>	<i>[JHEP 06 (2021) 093]</i>	

RUN1 summary



Single Event Sensitivity: $(0.839 \pm 0.053_{\text{syst}}) \times 10^{-11}$

Expected SM signal events: $10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}}$

Expected background events: $7.03^{+1.05}_{-0.82}$

Observed events: 20

Significance: 3.4σ

$$Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.5 \text{ stat}} \pm 0.9_{\text{ syst}}) \cdot 10^{-11} (3.4 \sigma \text{ significance})$$