Searches for hidden sectors and lepton flavour violation in kaon decays at NA62

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on behalf of the NA62 collaboration

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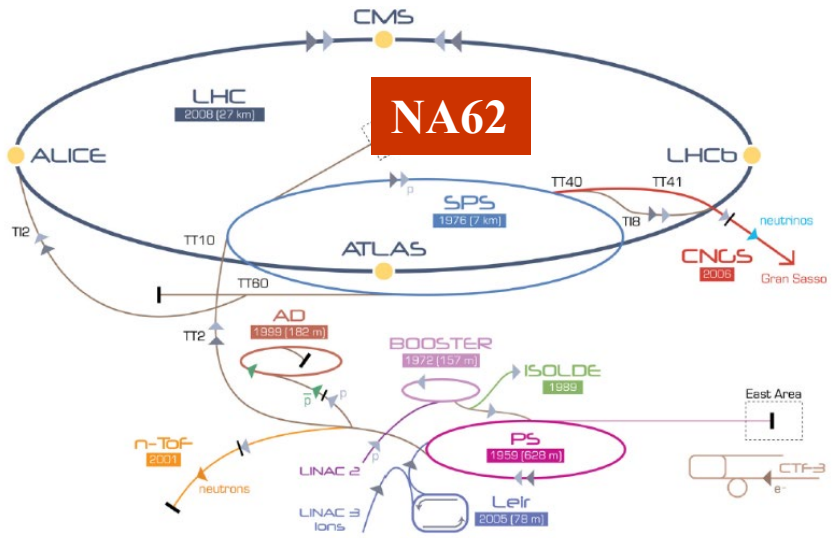
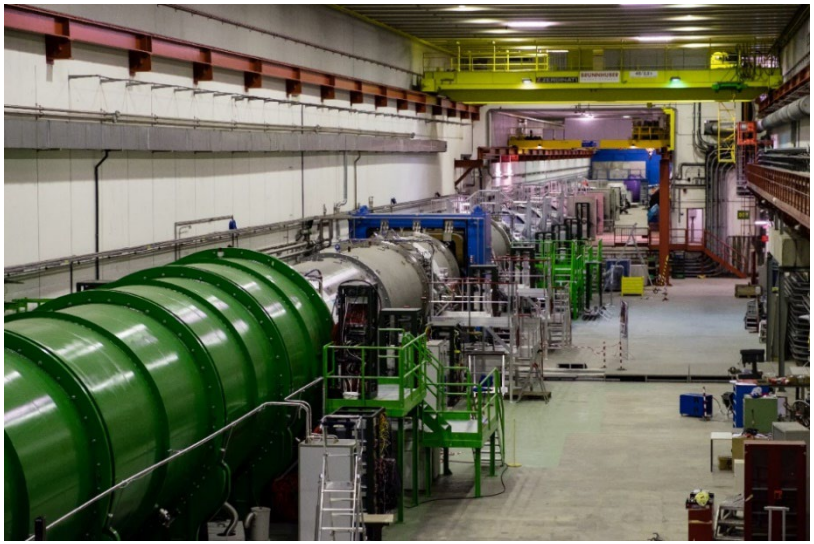
The NA62 experiment at CERN

A fixed target experiment at the CERN SPS dedicated to the study of rare decays in the kaon sector. Currently in NA62: ~300 participants, ~ 30 institutions from 11 countries





Main NA62 goal: BR($K^+ \to \pi^+ \nu\bar{\nu}$) measurement to 15% precision using the decay-in-flight technique.

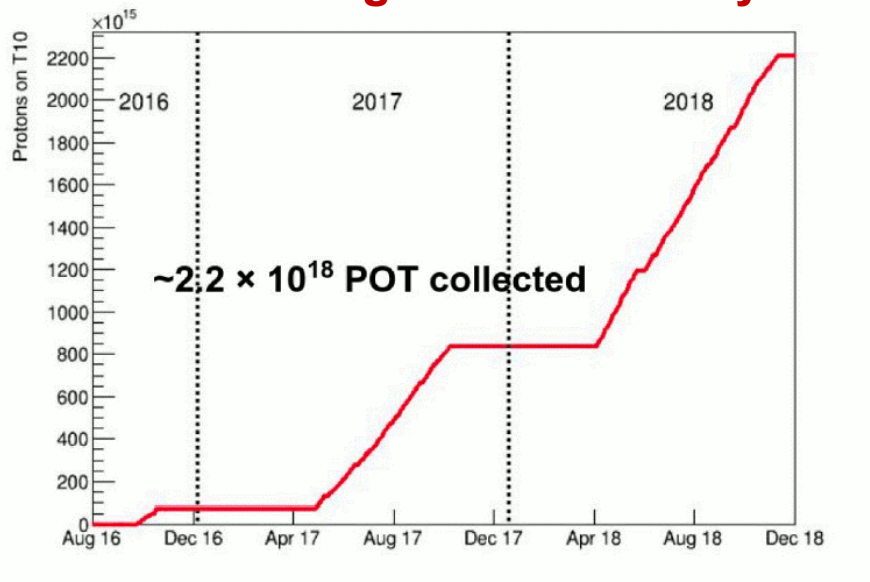
Searches for hidden sectors and lepton flavour violation in kaon decays — This talk

Searches of exotic decays with NA62 in beam-dump mode — See S. Ghinescu talk

NA62 timeline and datasets

- ✓ **Run 1 (2016−18): $N_K \sim 10^{13}$ useful K+ decays with the main trigger**
  - **Sample 2016 (30 days, ~1.3×10^{12} ppp): 2×10^{11} useful K^+ decays**
  - **Sample 2017 (160 days, ~ 1.9×10^{12} ppp): 2×10^{12} useful K^+ decays**
  - **Sample 2018 (217 days, ~ 2.3×10^{12} ppp): 4×10^{12} useful K^+ decays**
- ✓ **Run 2 (2021−…): in progress (up to 3×10^{12} ppp), approved till LS3**

Run 1 integrated luminosity



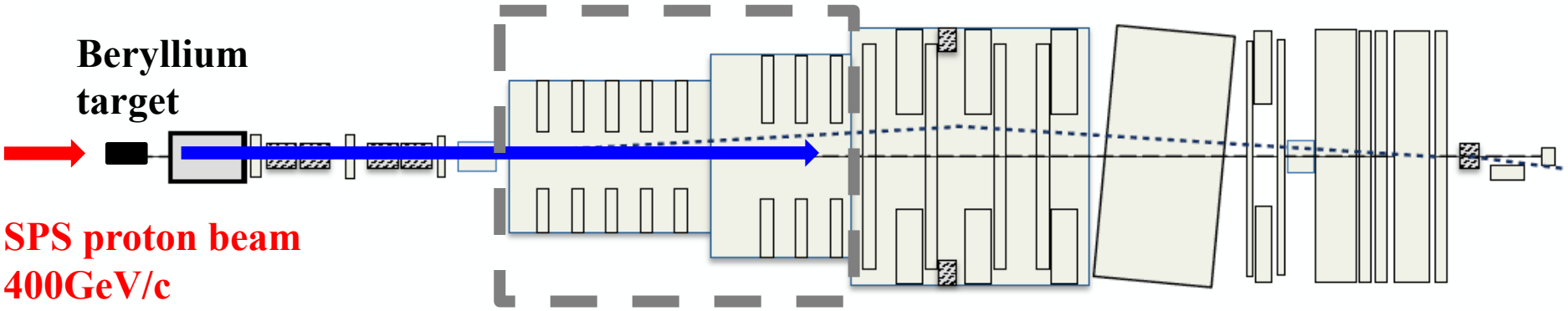
2014 Pilot Run	2015 Commissioning	2016 Commissioning + Physics Run	2017 - 2018 Physics Run	2019-2020 LS2	2021-LS3 Physics Run

Run 1 **Run 2**

Currently: ~2×10^{18} pot/year, ~5×10^{12} K^+ decays/year
Beam-dump mode: 4×10^{17} pot collected so far

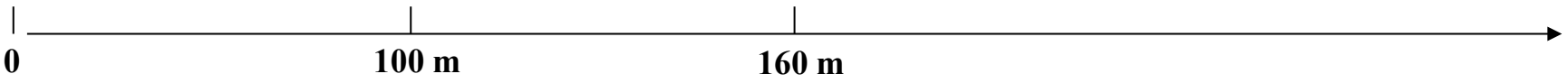
NA62 layout

Fiducial volume: 60 m $\mathcal{O}(10^{-6})$ mbar
~4 MHz of K^+ decays



SPS proton beam
400GeV/c
3×10^{12} PoT/spill
4.8 sec spill

Secondary beam
75 GeV/c, 1% bite, 60 × 30 mm²
K^+(6%)/π^+(70%)/p(24%)
Beam rate: 600 MHz

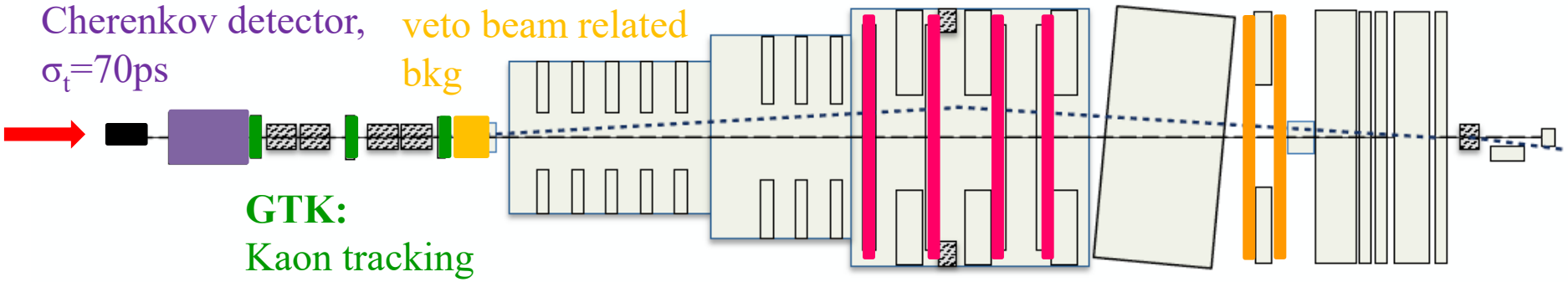


NA62 layout

KTAG
Kaon identification
Differential
Cherenkov detector,
σ_t=70ps

CHANTI:
scintillation rings to
veto beam related
bkg

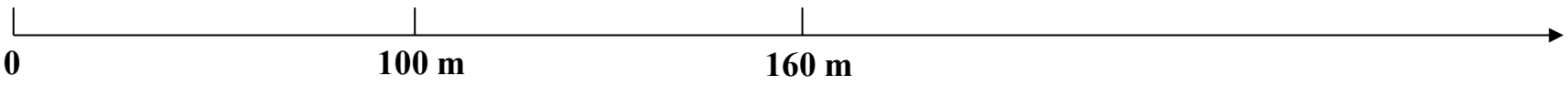
CHOD:
hodoscope



GTK:
Kaon tracking
Si pixel, 3
stations, σ_t=100
ps, σ_p/p=0.2%

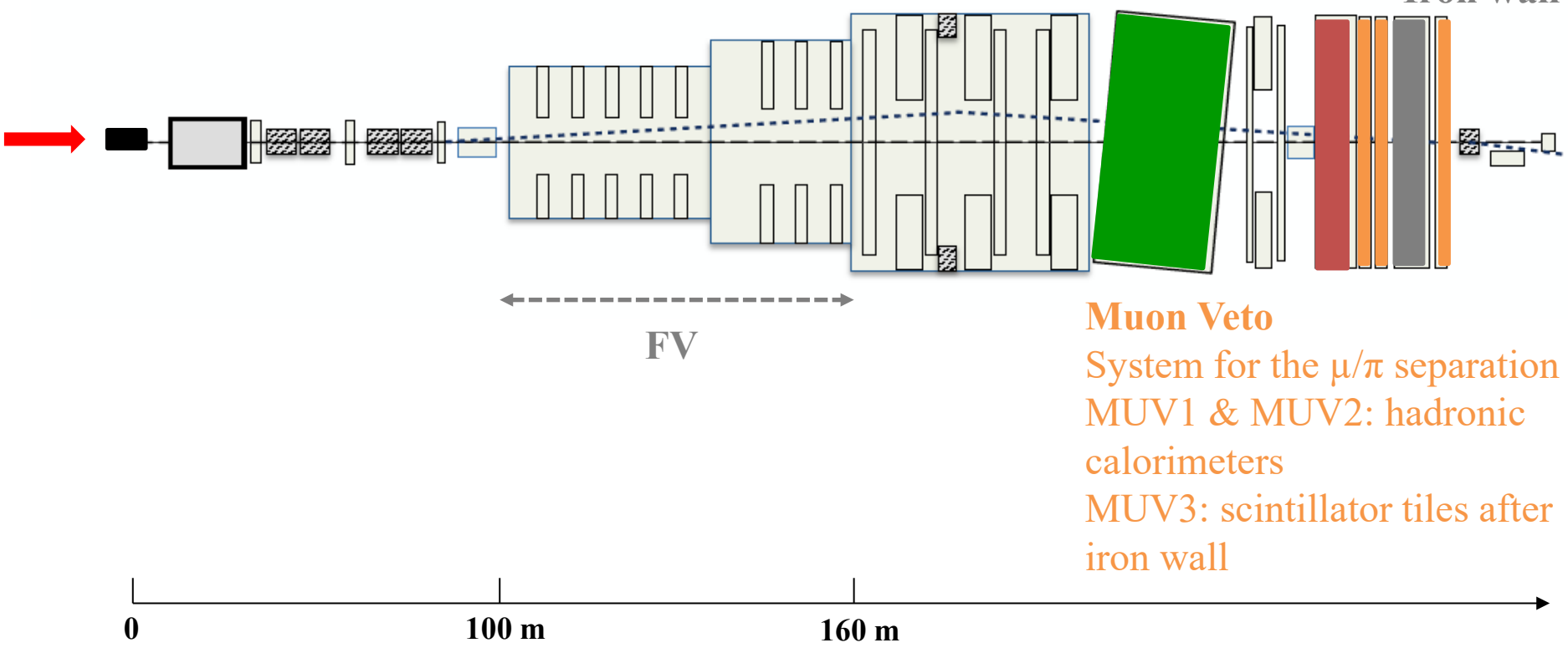
FV

STRAW:
Spectrometer for
downstream particle
tracking: 4 straw-tracker
stations, σ_p/p=0.3-0.4%



- **Kinematic reconstruction: $M^2_{miss}=(P_K-P_\pi)^2$, $\sigma_{M^2_{miss}}=10^{-3}$GeV^2/c^4 at $K^+\to\pi^+\pi^0$**
- **Time resolution to match beam and daughter particle information: ~100ps**

NA62 layout

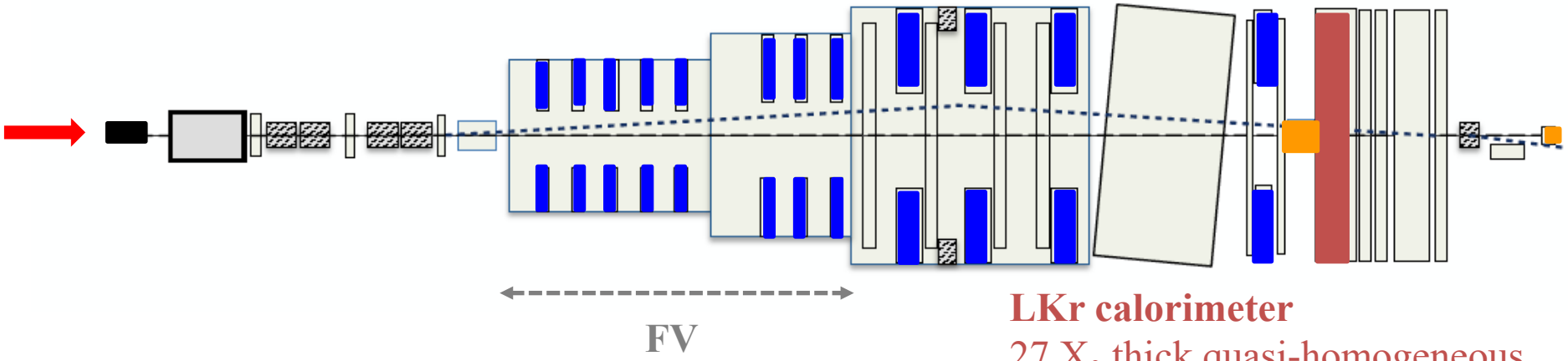


- **PID detectors to suppress bkg with μ^+or e^+ in the final state for the main analysis: μ vs π rejection of O(10^7) for 15 < p(π^+) < 35 GeV**

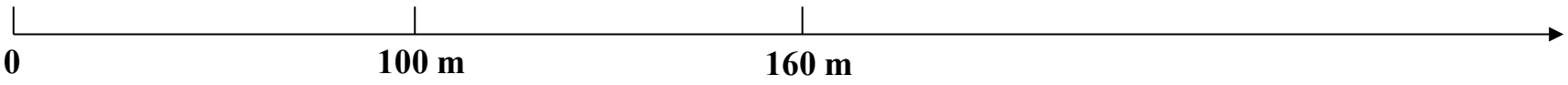
NA62 layout

Large Angle Veto (LAV)
12 stations with lead glass blocks
Covering angles $10 < \theta < 50$ mrad

Small angle veto (SAV)
Two shashlik calorimeters, IRC and SAC, to cover $\theta < 1$ mrad

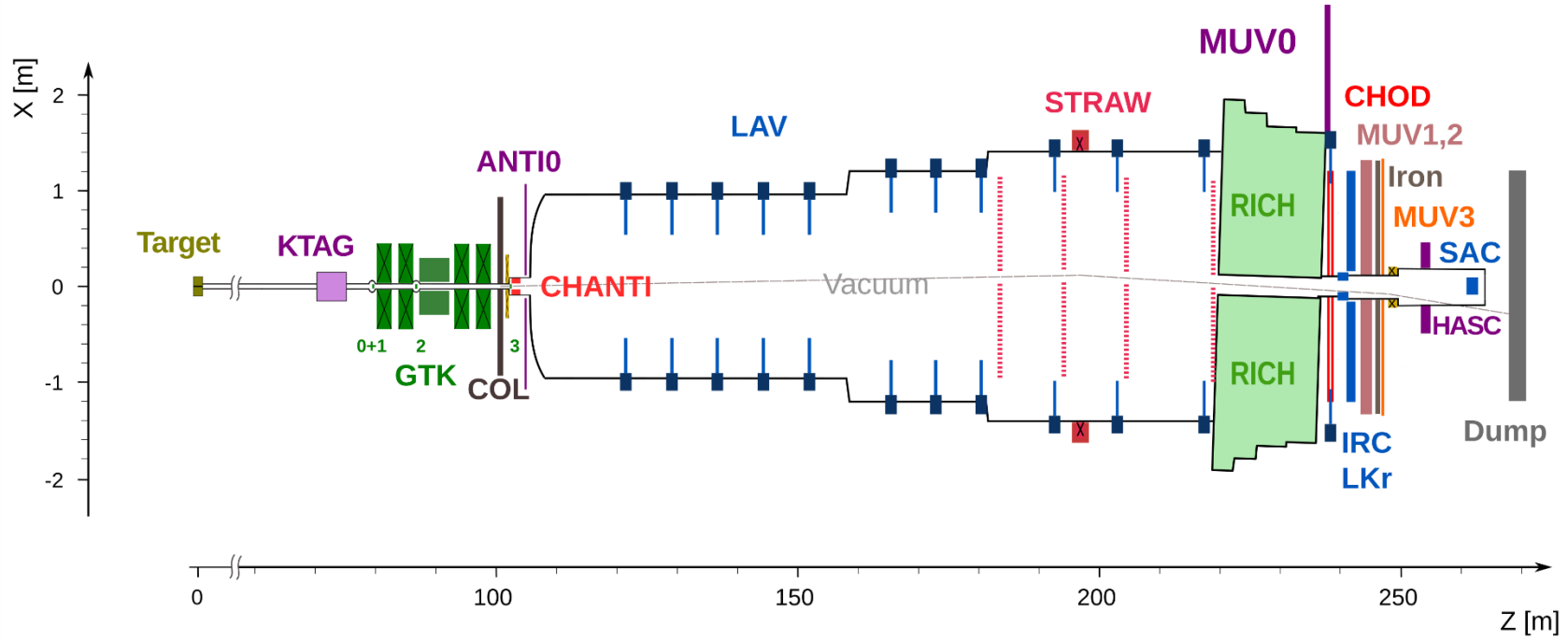


LKr calorimeter
27 X_0 thick quasi-homogeneous LKr electromagnetic calorimeter detects photons in $1 < \theta < 10$ mrad



- **Photon vetoes to suppress bkg with π^0 in the final state for the main analysis: 10^8 rejection of π^0 for $E(\pi^0) > 40$ GeV**

NA62 layout



Performances

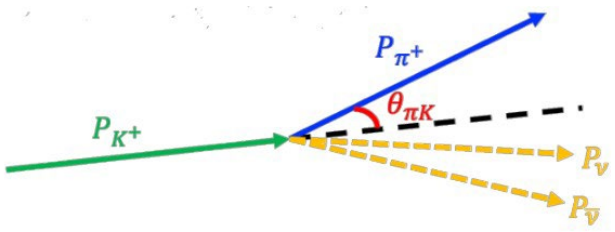
- ✓ **Excellent time resolution $\mathcal{O}$(100 ps) to match beam and daughter particle information**
- ✓ **Kinematics: rejection of main K modes 10^4 via kinematics reconstruction**
- ✓ **PID capability: μ vs π rejection of O(10^7) for $15 < p(\pi^+) < 35$ GeV**
- ✓ **High-efficiency veto: 10^8 rejection of π^0 for $E(\pi^0) > 40$ GeV**

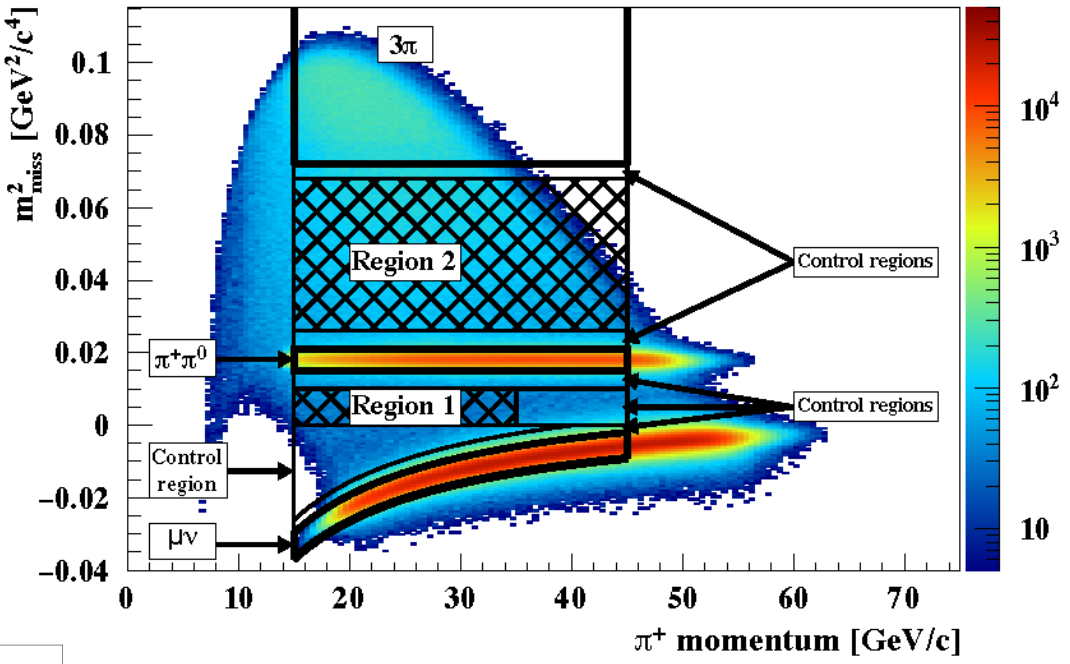
The beam and detector of the NA62 experiment at CERN, 2017 JINST 12 P0502

NA62 $K^+ \to \pi^+ \nu\bar{\nu}$ result - Run 1

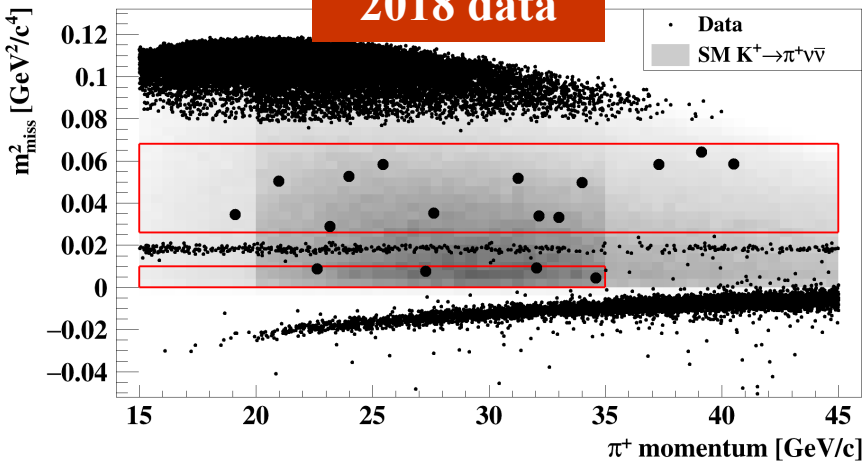
Signal: BR = (8.4 ± 1.0) × 10^{-11}

K^+ track in, π^+ track out
No other particles in final state
$m^2_{miss} = (P_K - P_\pi)^2$





2018 data



JHEP 06 (2021) 093

NA62 Run 1:
Expected SM sig: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
Expected bkg: $7.03^{+1.05}_{-0.82}$ evts
20 events observed

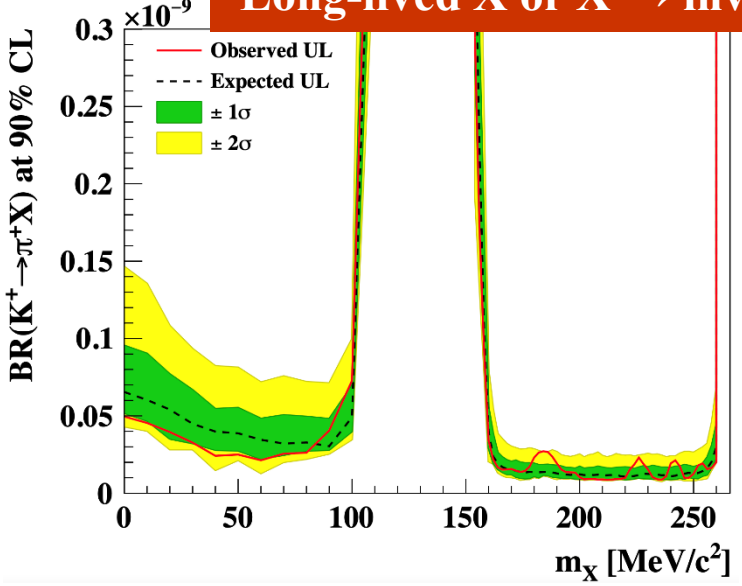
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4}\,|_{stat} \pm 0.9_{syst}\right) \times 10^{-11} \quad (3.4\sigma \text{ significance})$$

$K^+ \to \pi^+ X_{inv}$: a $K^+ \to \pi^+ \nu\bar{\nu}$ spin-off

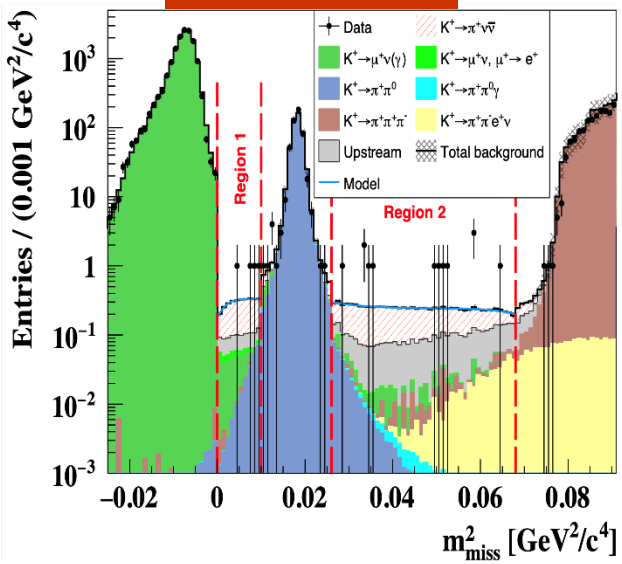
JHEP 06 (2021) 093

- **Signal regions R1,R2: peak search for $K^+ \to \pi^+ X$ (X =invisible), $0 \leq m_X \leq 110$ MeV/c² and $154 \leq m_X \leq 260$ MeV/c².**
- **Acceptance scan over m_X and τ_X**
- **Main background: $K^+ \to \pi^+ \nu\bar{\nu}$**

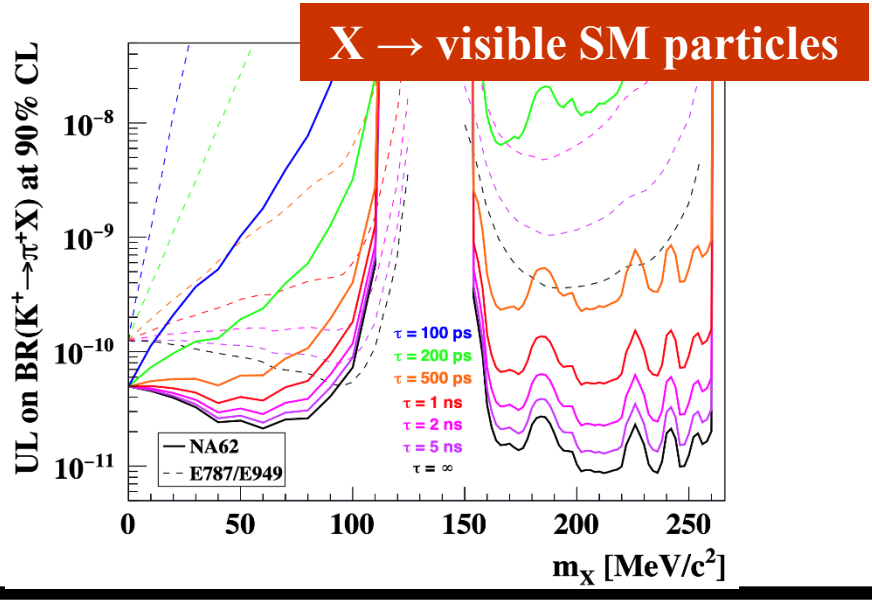
Long-lived X or X → invisible



2018 data



X → visible SM particles



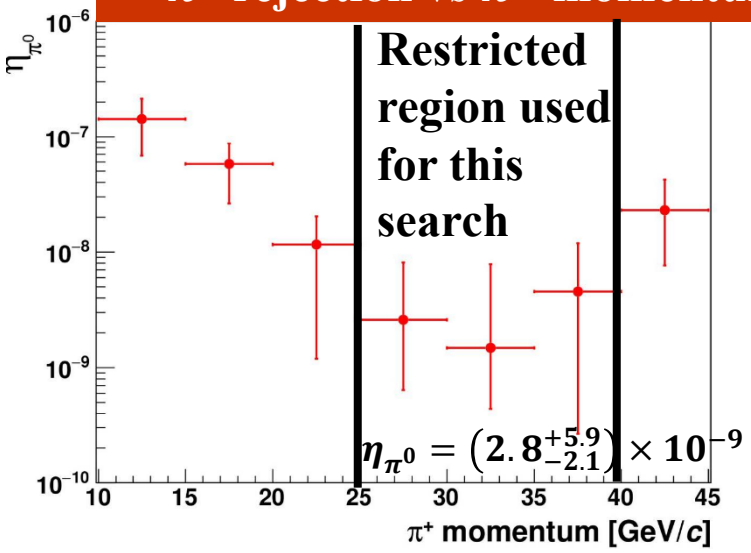
$K^+ \to \pi^+\pi^0, \pi^0 \to inv$: a $K^+ \to \pi^+\nu\bar{\nu}$ spin-off

JHEP 02 (2021) 201

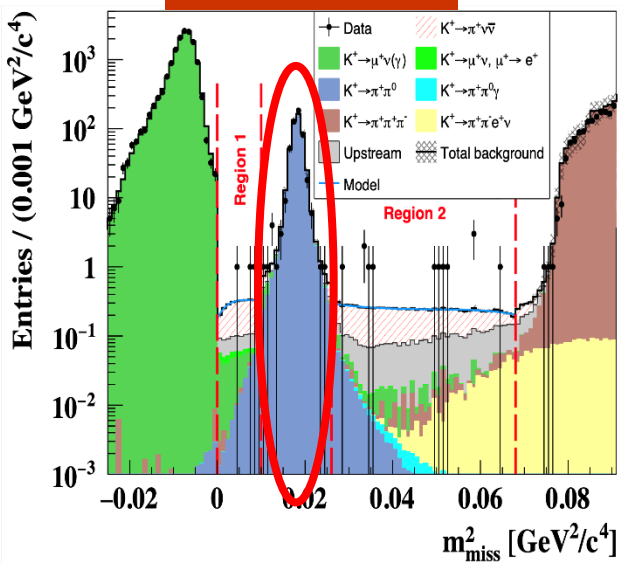
Search for $\pi^0 \to invisible$ in the $\pi^+\pi^0$ region (~10% of Run1 data):

- **Negligible SM rate ($\pi^0 \to 4\nu$)**
- **Observation = BSM physics.**
- **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**
- **Expected $\pi^0 \to \gamma\gamma$ events: 10^{+22}_{-8}, events observed: 12.**

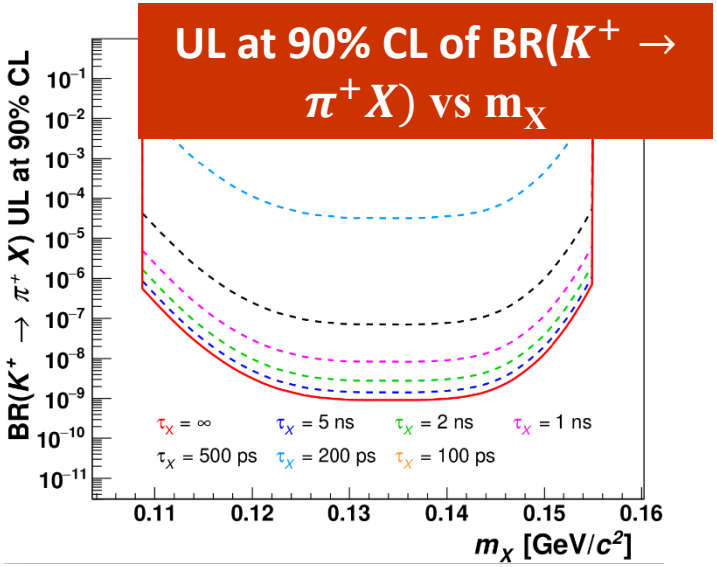
π^0 rejection vs π^+ momentum



2018 data



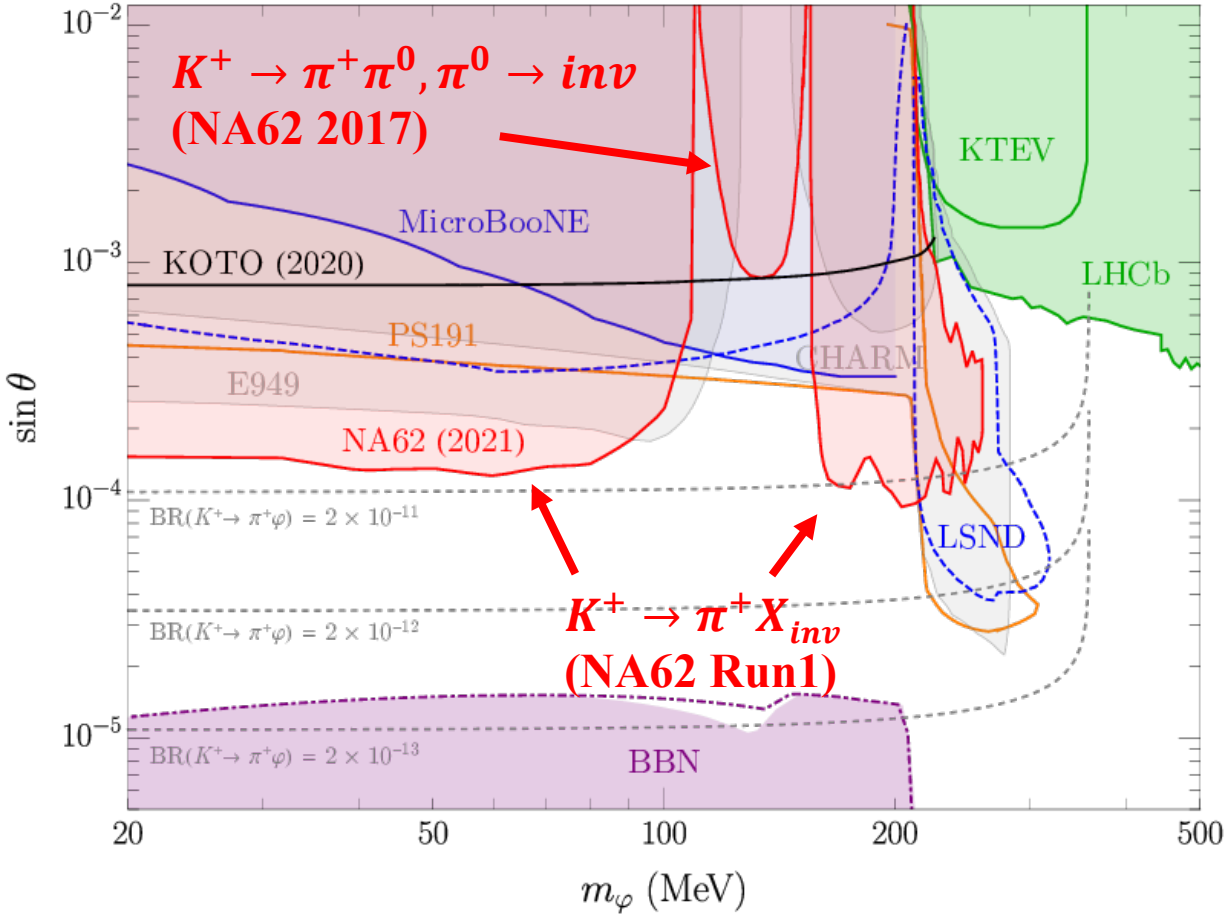
UL at 90% CL of BR($K^+ \to \pi^+X$) vs m_X



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

Limits on BRs for $K^+ \to \pi^+ X_{inv}$ and $K^+ \to \pi^+\pi^0, \pi^0 \to inv$ translate to parameter space for hidden-sector portals

Interpretation shown here: dark scalar below the K mass



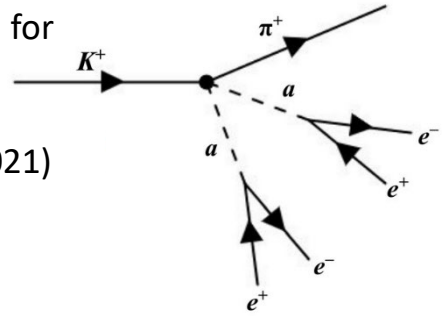
Rept.Prog.Phys. 86(2023)016201

Hidden sectors with $K^+ \to \pi^+ e^- e^+ e^- e^+$

- ✓ **SM decay: $BR_{SM}(K_{\pi 4e})=(7.2\pm0.7)\times10^{-11}$ [Husek, PRD106 (2022)]**
- ✓ **Channel with pair production of dark mediators $K^+ \to \pi^+ X(\to e^- e^+)\, X(\to e^- e^+)$:**

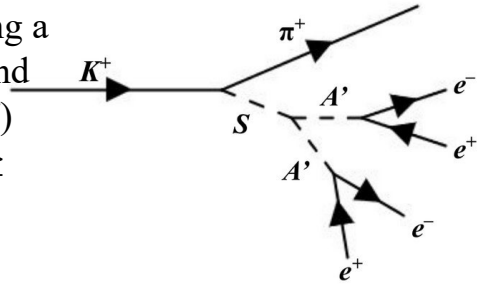
QCD Axion Like Particle (ALP):

- Explains the "17 MeV anomaly" for atomic nuclei
- Expect $K^+ \to \pi^+ aa$ >2×10^{-8} for m_a=17 MeV. [Alves, PRD103 (2021) 055018; Hostert and Pospelov, PRD105 (2022) 015017]

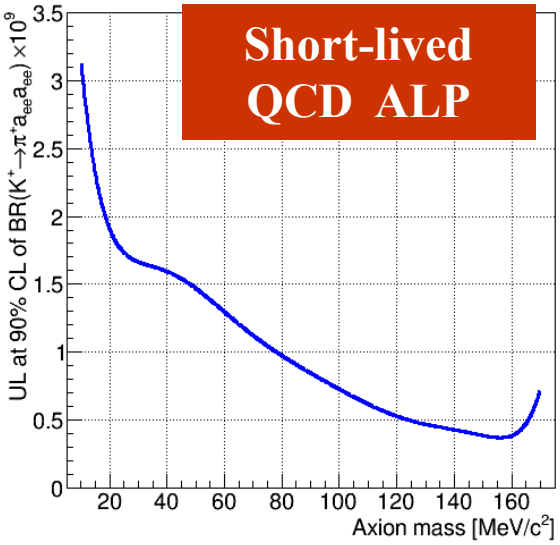


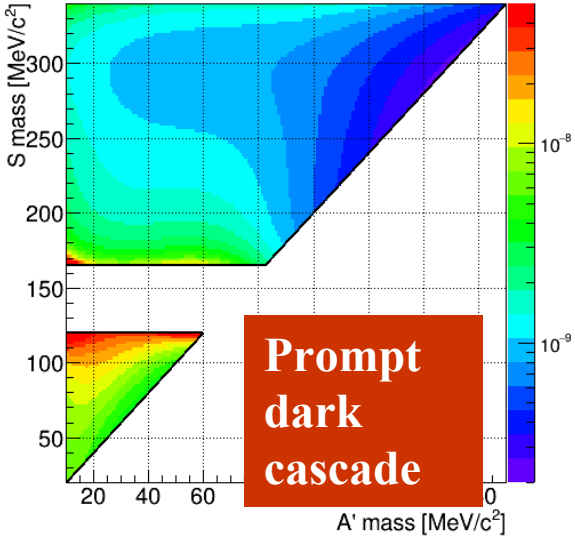
Prompt dark cascade process:

Scenario involving a dark scalar (S), and a dark photon (A′) with masses $m_S \geq 2m_{A'}$ (Phys. Rev. D105 (2022) 015017)



- ✓ **For the SM decay, $BR_{SM}(K_{\pi 4e}) < 1.4\times10^{-8}$ at 90% CL**
- ✓ **Upper limits at 90% CL are obtained at the level of 10^{-9} for the BR of the two prompt decay chains involving hidden-sector mediators.**
- ✓ **QCD axion is excluded as explanation of the 17 MeV anomaly**

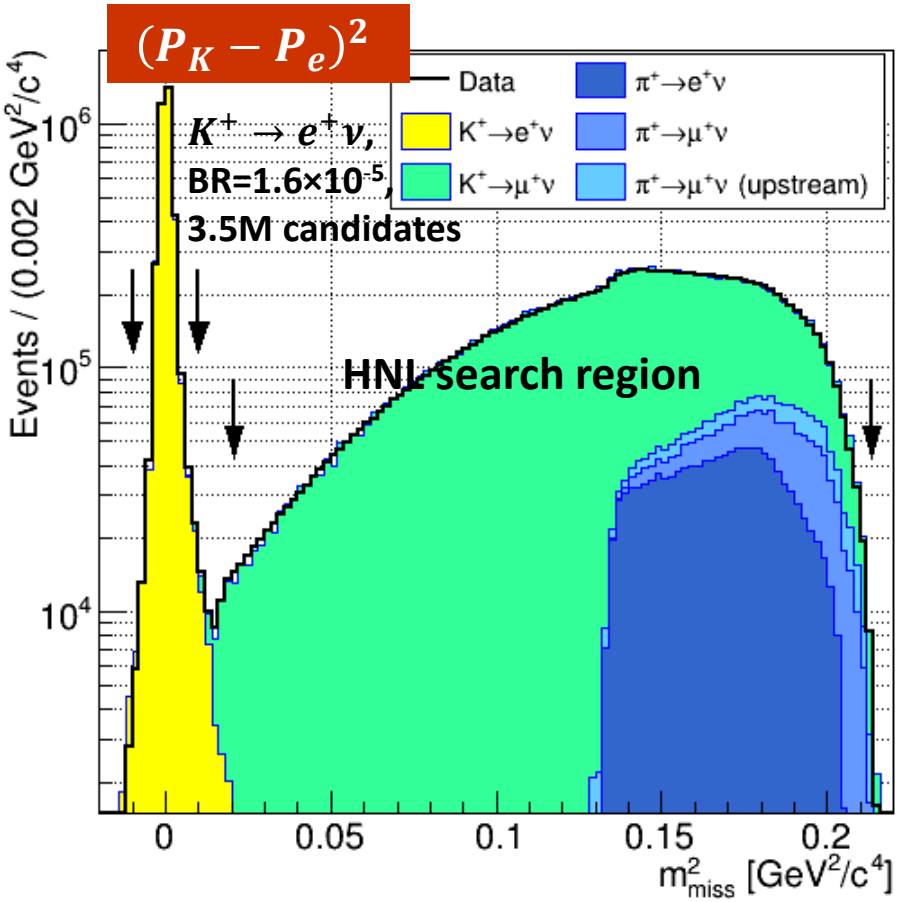




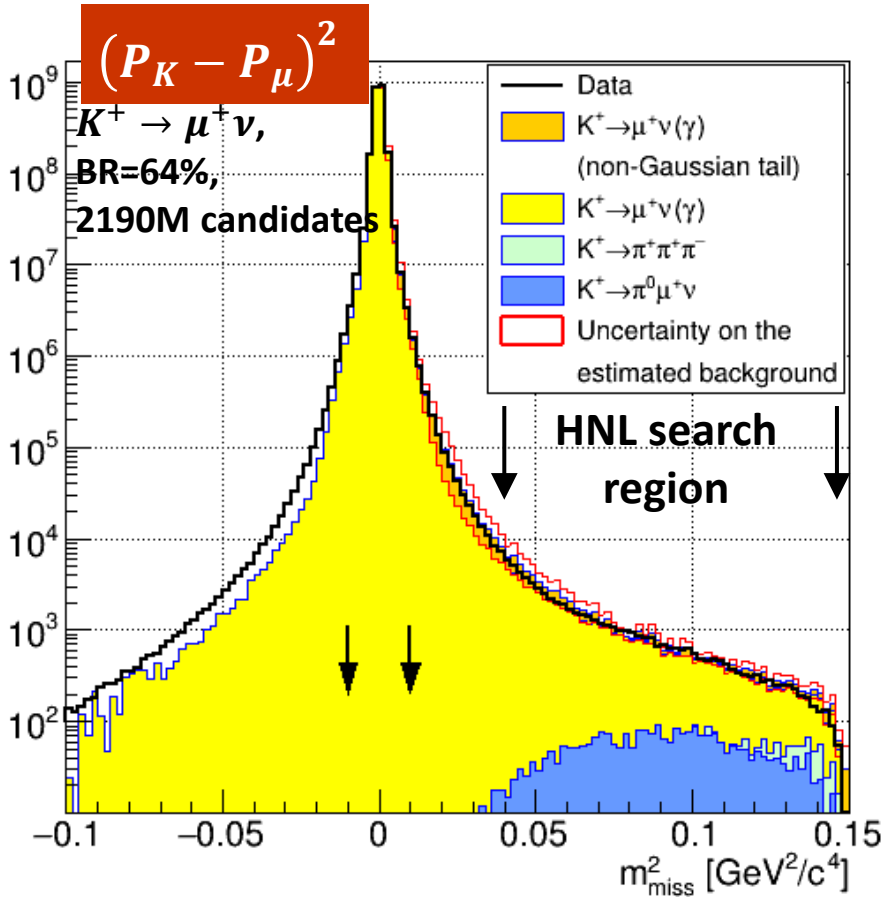
PLB846 (2023) 138193

HNL production at NA62

- Numbers of K^+ decays in fiducial volume: $N_K = 3.5 \times 10^{12}$ in e^+ mode; $N_K = 4.3 \times 10^9$ in μ^+ mode
- Squared missing mass $m^2_{miss} = (P_K - P_l)^2$ using STRAW and GTK detectors
- HNL production signal: a spike above continuous missing mass spectrum

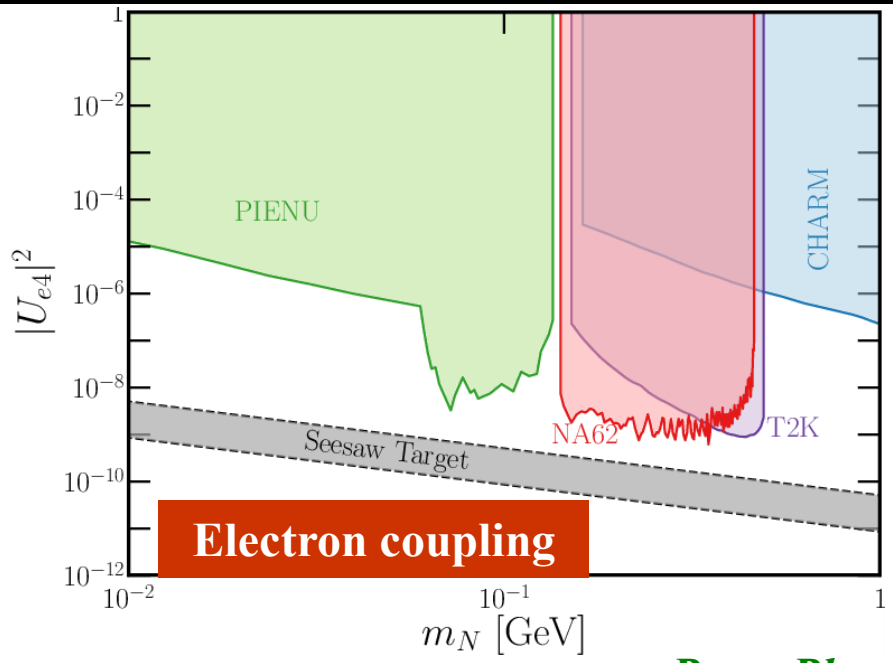


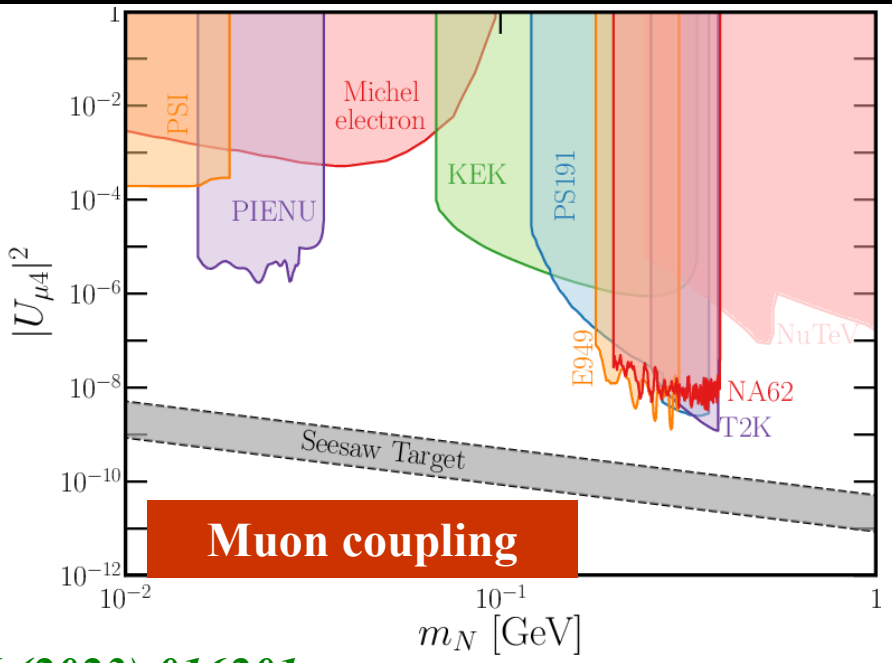
PLB 807 (2020) 135599



PLB 816 (2021) 136259

HNL results





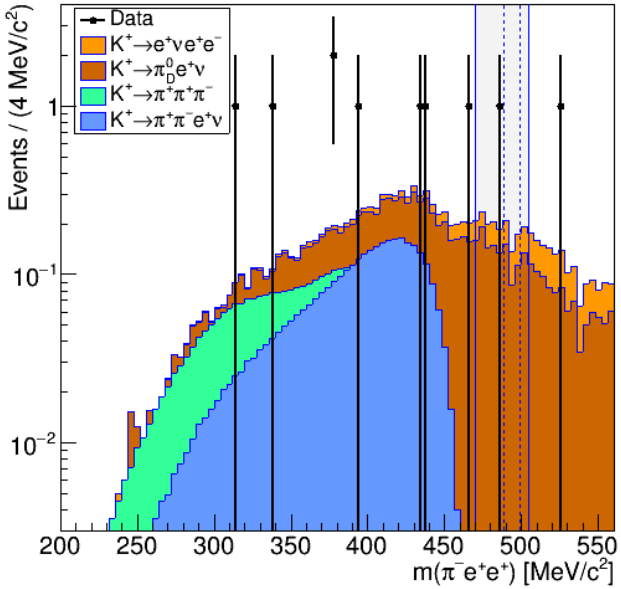
Prog. Phys. 86 (2023) 016201

- ✓ For $|U_{e4}|^2$, complementary to search for $\pi^+ \to e^+ N$ at PIENU.
- ✓ For $|U_{\mu 4}|^2$, complementary to search for $K^+ \to \mu^+ N$ at BNL-E949.
- ✓ In both cases, complementary to HNL decay searches at T2K.
- ✓ Future pion experiments might reach the seesaw bound.
- ✓ With slight modifications to the $K^+ \to \mu^+$N analysis, upper limits at 90% CL on BR($K^+ \to \mu^+ \nu X$) - with X a scalar or vector mediator in the mass range 10-370 MeV/c^2 - from $\mathcal{O}(10^{-5})$for low m_X values to $\mathcal{O}(10^{-7})$for high m_X values. Also a 90% CL upper limit at 1.0×10^{-6} on the BR($K^+ \to \mu^+ \nu\nu\bar{\nu}$) is obtained - *PLB 816 (2021) 136259*

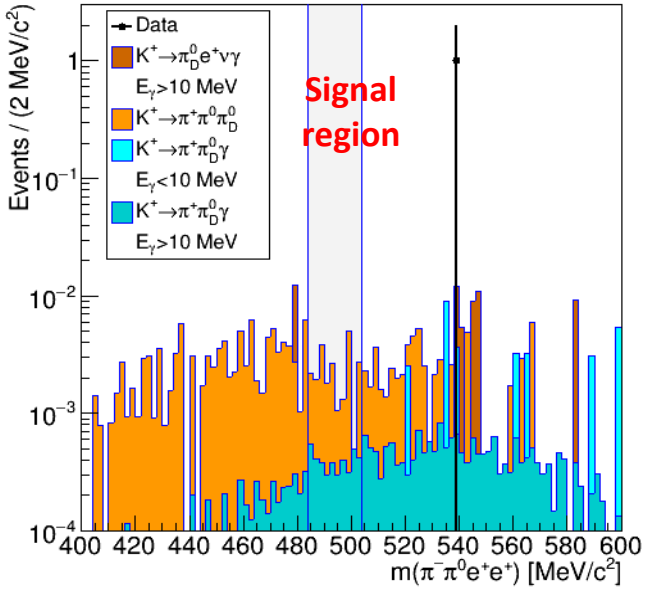
Search for LNV in $K^+ \to \pi^-(\pi^0)e^+e^+$

- Whole NA62 Run1 data set analysed.
- $K^+ \to \pi^+e^+e^-$ as normalization channel.
- K^+ decays in the FV: $(1.015\pm0.032)\times10^{12}$
- Invariant mass m($\pi^-e^+e^+$) and m($\pi^-\pi^0e^+e^+$) used to select signal.
- $K^+ \to \pi^-e^+e^+$: (LKr + RICH)-based e^+ ID to suppress π^0 Dalitz decay and $K^+ \to \pi^+e^+e^-$ with $\pi^+ \to e^+$ and e^-/π^- misID
- $K^+ \to \pi^-\pi^0e^+e^+$: π^0 reconstructed in LKr calorimeter via the $\pi^0 \to \gamma\gamma$ decay.

m($\pi^-e^+e^+$) Signal region



m($\pi^-\pi^0e^+e^+$)



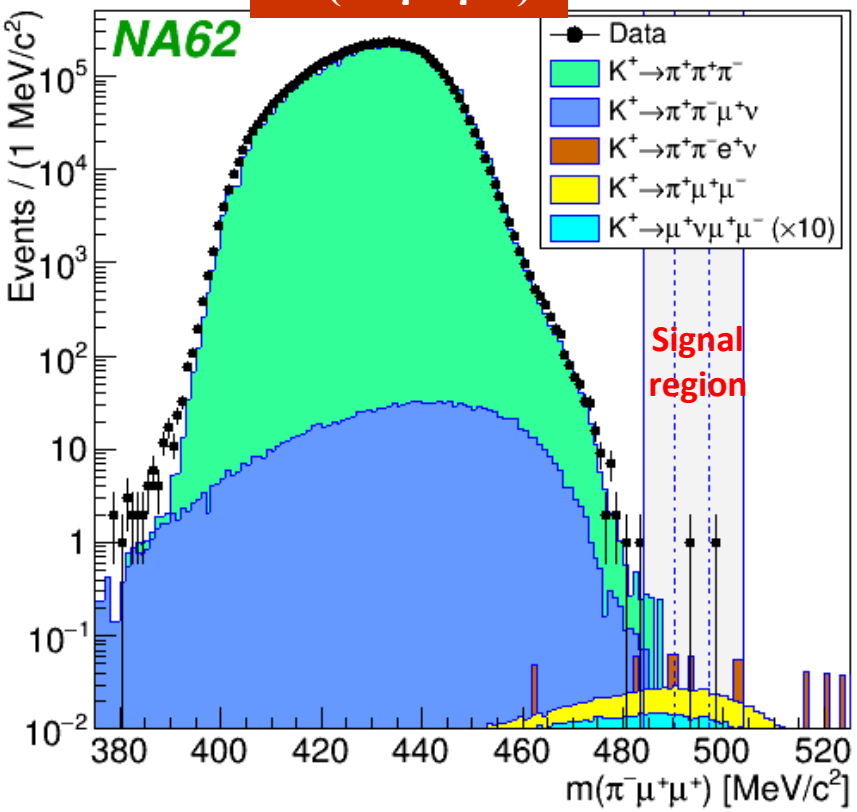
Exp. background:0.43±0.09 evt
Candidates observed: 0
BR($K^+ \to \pi^-e^+e^+$)<5.3×10^{-11} at 90% CL

Exp. background:0.044±0.020 evt
Candidates observed: 0
BR($K^+ \to \pi^-e^+e^+$)<8.5×10^{-10} at 90% CL

PLB830 (2022) 137172

Search for $K^+ \to \pi^-\mu^+\mu^+$ and $K^+ \to \mu^-\nu e^+e^+$

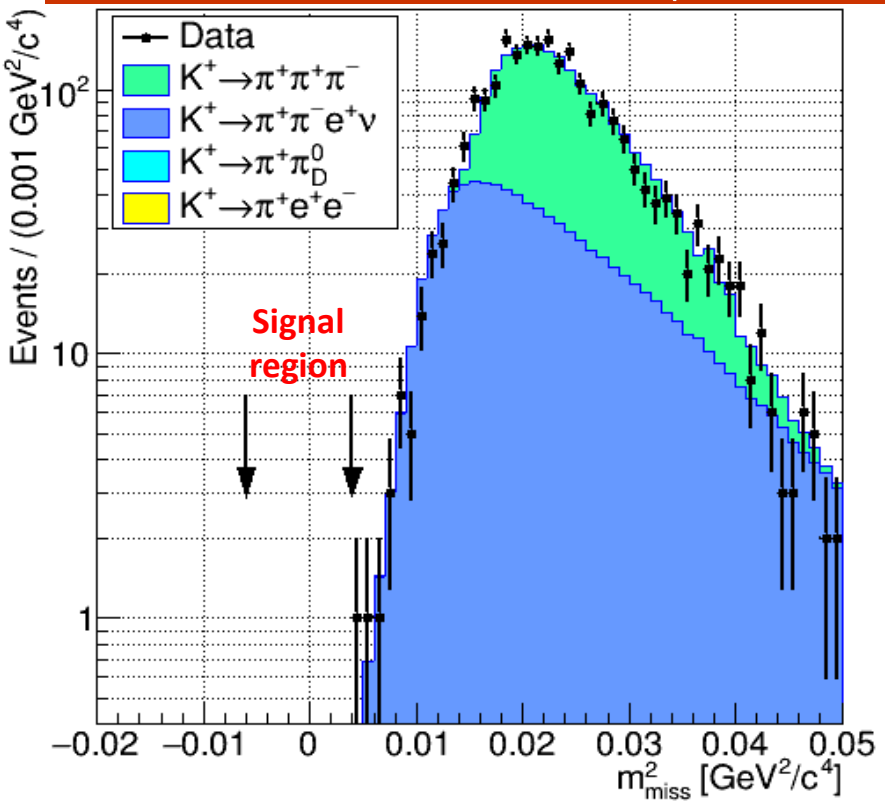
m($\pi^-\mu^+\mu^+$)



Exp. background:0.91±0.41 evt
Candidates observed: 1
BR($K^+ \to \pi^-\mu^+\mu^+$) < 4.2×10^{-11} at 90% CL

PLB797 (2019) 134794

Squared missing mass, $(P_K - P_\mu - P_{e1} - P_{e2})^2$

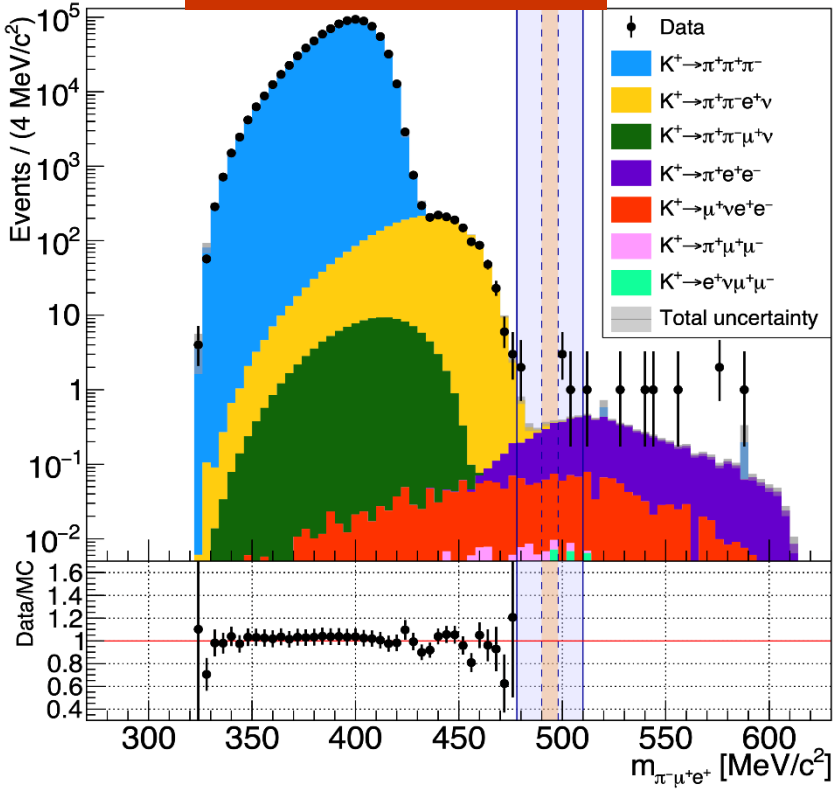


Exp. background:0.26±0.04 evt
Candidates observed: 0
BR($K^+ \to \mu^-\nu e^+e^+$) < 8.1×10^{-11} at 90% CL

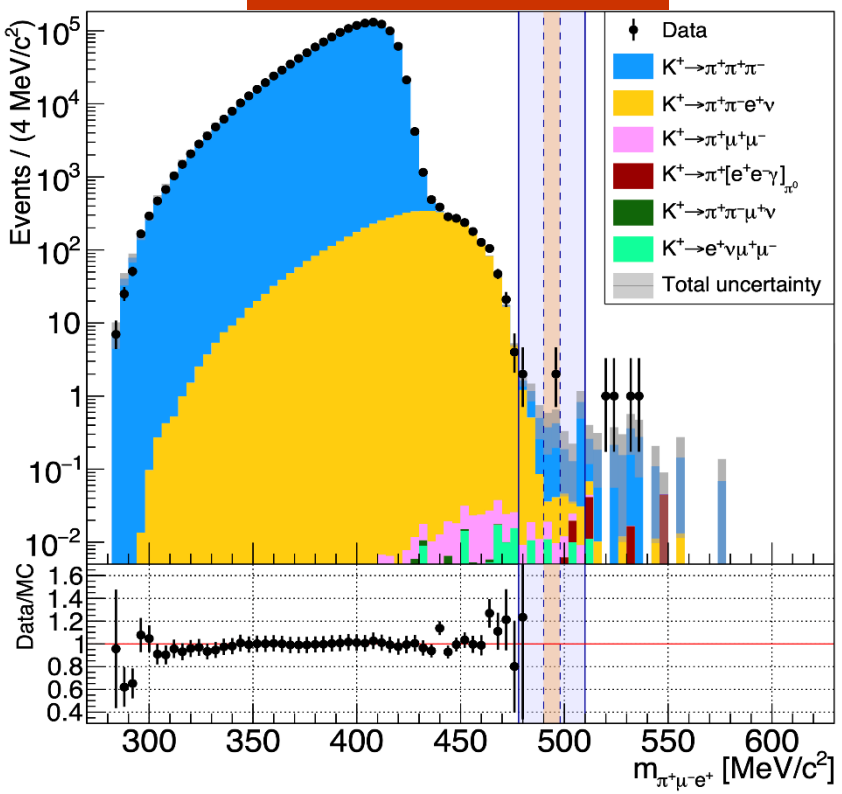
PLB838 (2023) 137679

Search for $K^+ \to \pi\mu e$ decays

LNV m($\pi^-\mu^+e^+$)



LFV m($\pi^+\mu^-e^+$)



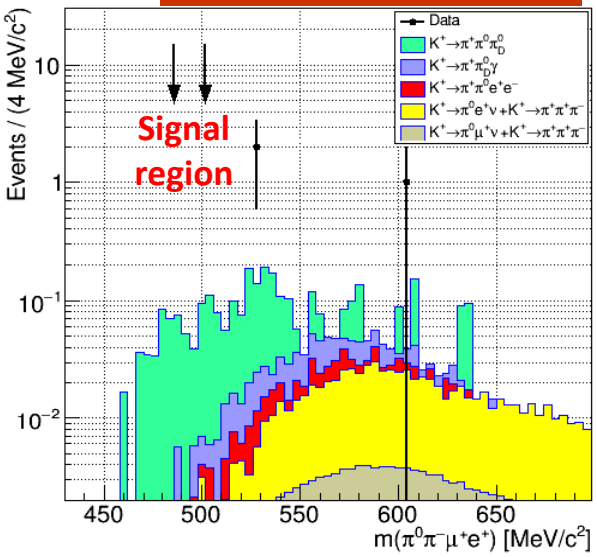
K^+ decays in FV: $(1.33\pm0.02)\times10^{12}$
Exp. background:1.07±0.20 evt
Candidates observed: 0
BR($K^+ \to \pi^-\mu^+e^+$) < 4.2×10^{-11} at 90% CL

Exp. background:0.92±0.34 evt
Candidates observed: 2
BR($K^+ \to \pi^+\mu^-e^+$) < 6.6×10^{-11} at 90% CL
BR($\pi^0 \to \mu^-e^+$) < 3.2×10^{-10} at 90% CL

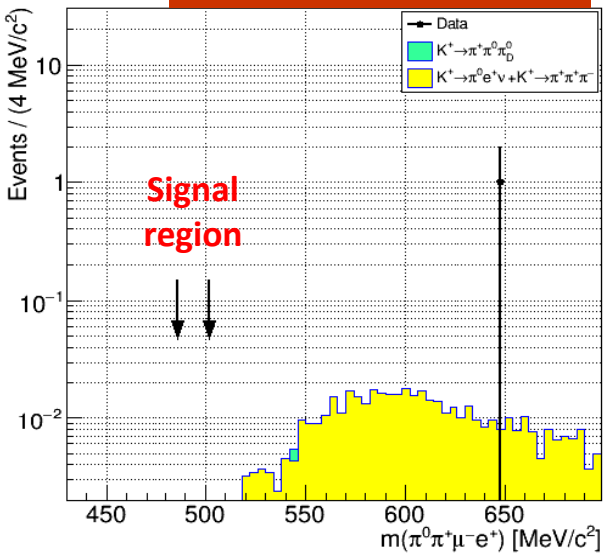
PRL 127 (2021) 131802

Search for $K^+ \to \pi^0\pi\mu e$ decays

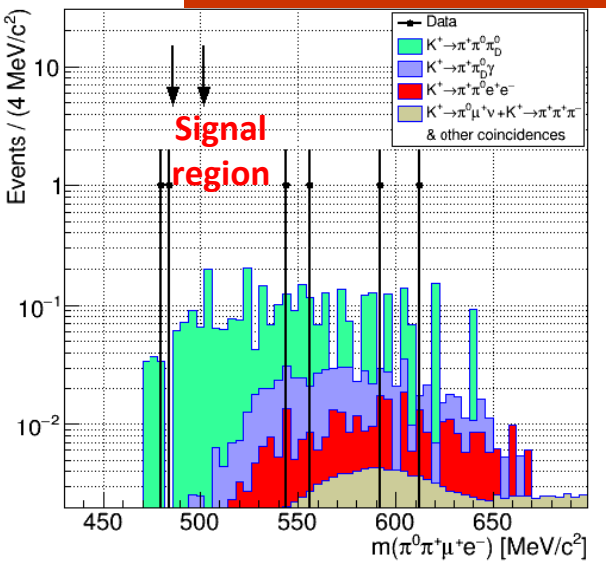
$m(\pi^0\pi^-\mu^+e^+)$



$m(\pi^0\pi^+\mu^-e^+)$



$m(\pi^0\pi^+\mu^+e^-)$



Mode	Expected background	Observed candidates	Upper limit of BR at 90% CL
$K^+ \to \pi^0\pi^-\mu^+e^+$	0.33±0.07	0	2.9×10^{-10}
$K^+ \to \pi^0\pi^+\mu^-e^+$	0.004±0.003	0	3.1×10^{-10}
$K^+ \to \pi^0\pi^+\mu^+e^-$	0.29±0.07	0	5.0×10^{-10}

New results to be published

Summary

- ✓ **The NA62 collaboration is continuing to fully exploit the data collected during Run 1 in 2016-2018 and it has the opportunity to directly search for a plethora of hidden sector particles and LNF/LNV decays in kaon physics**

- ✓ **NA62 LFV/LNV programme: stringent limits on 10 decay modes**

- ✓ **Searches for hidden sectors in kaon decays at NA62 address a range of PBC benchmark scenarios**
  - $K^+ \to \pi^+ X_{inv}$ **: dark scalar and ALP**
  - $K^+ \to l^+ N$ **: heavy neutral leptons**
  - **Non-minimal scenarios, e.g.** $K^+ \to \pi^+ aa$ **.**

- ✓ **NA62 at CERN is collecting data from 2016 till at least 2025**
  - **World's largest multi-purpose sample of** K^+ **decays**
  - **First measurement of the ultra-rare** $K^+ \to \pi^+ \nu\bar{\nu}$ **decay**