The most recent results from NA62

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on behalf of the NA62 Collaboration

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Seeking new physics through Flavour

Flavour physics is a special laboratory to look for physics beyond the Standard Model (SM)

- Loops are sensitive to the presence of new physics
- In rare processes new interactions can give major contributions
- New interactions can have different symmetries with respect to the SM

Two strategies:

- Search for deviations with respect to SM predictions

  $\rightarrow$ e.g. specific Flavour Changing Neutral Current (FCNC) processes
- Search for processes forbidden by (accidental) symmetries of the SM

  $\rightarrow$ e.g. Lepton Number (LN) and Lepton Flavour (LF) violating decays

Seeking new physics through kaon decays

Strange particles provided many building blocks in the construction of the SM

Kaon physics continues to help building the SM

Recent NA62 results covered in this talk

FCNC:

- $K^+ \to \pi^+ \nu\bar{\nu}$ very clean theoretically ← the main reason of NA62
- $K^+ \to \pi^+ \mu^+ \mu^-$ looking for new physics beyond the branching ratio

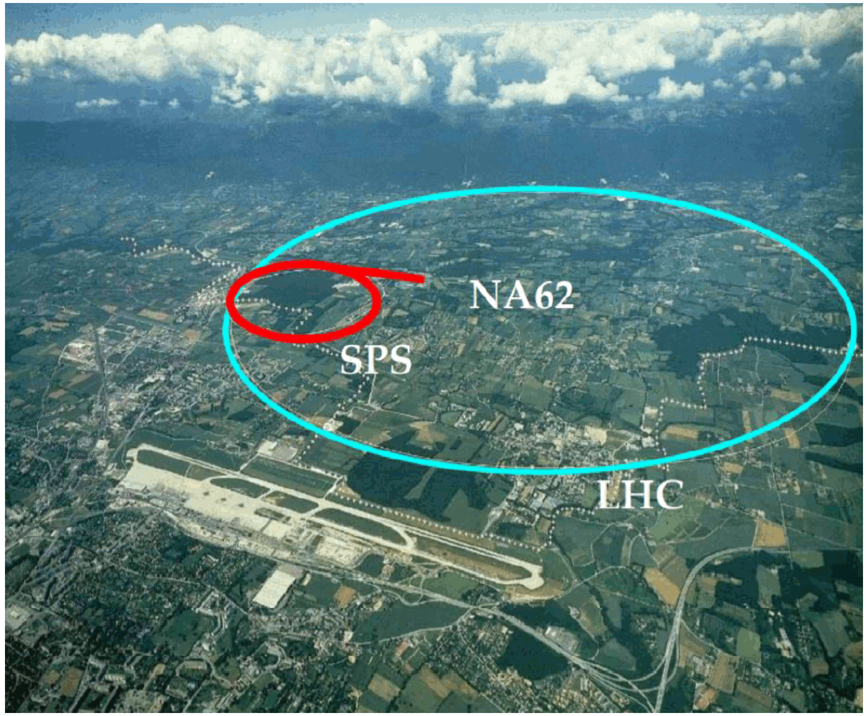
LNV, LFV:

- $K^+ \to \pi^- e^+ e^+$
- $K^+ \to \pi^- \pi^0 e^+ e^+$
- $K^+ \to \pi^- \mu^+ e^+$
- $K^+ \to \pi^+ \mu^- e^+$

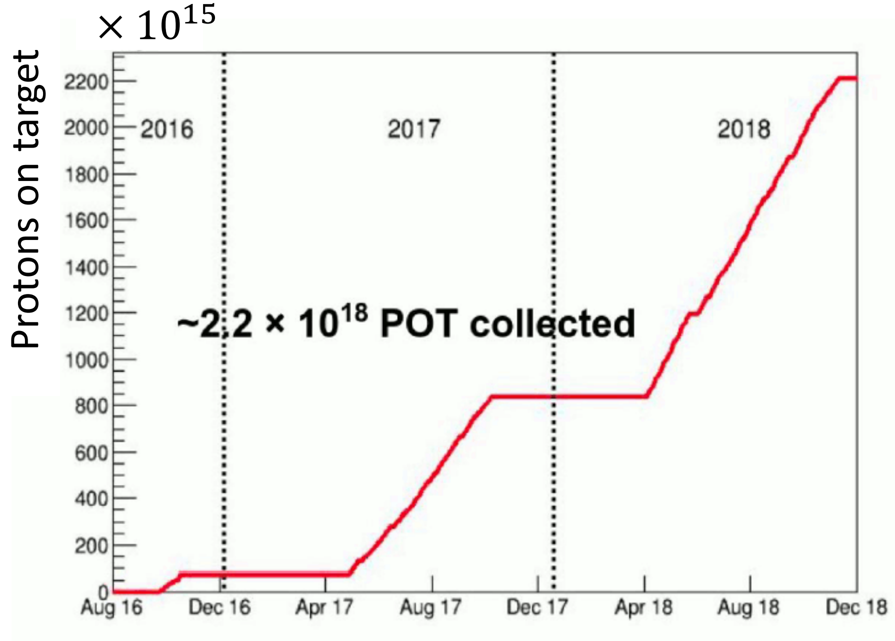
new results

NA62 experiment @ CERN Super Proton Synchrotron

Fixed target experiment installed in the CERN North Area



400 GeV/c protons from SPS hitting a beryllium target

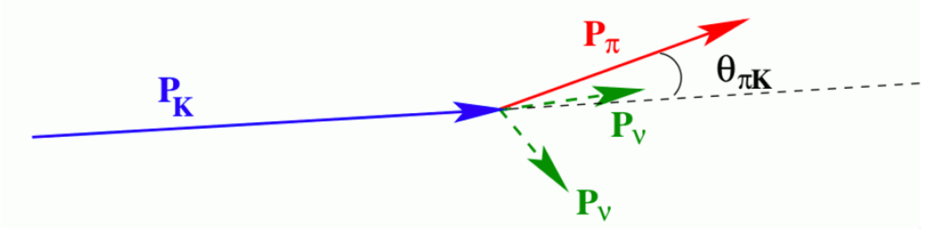


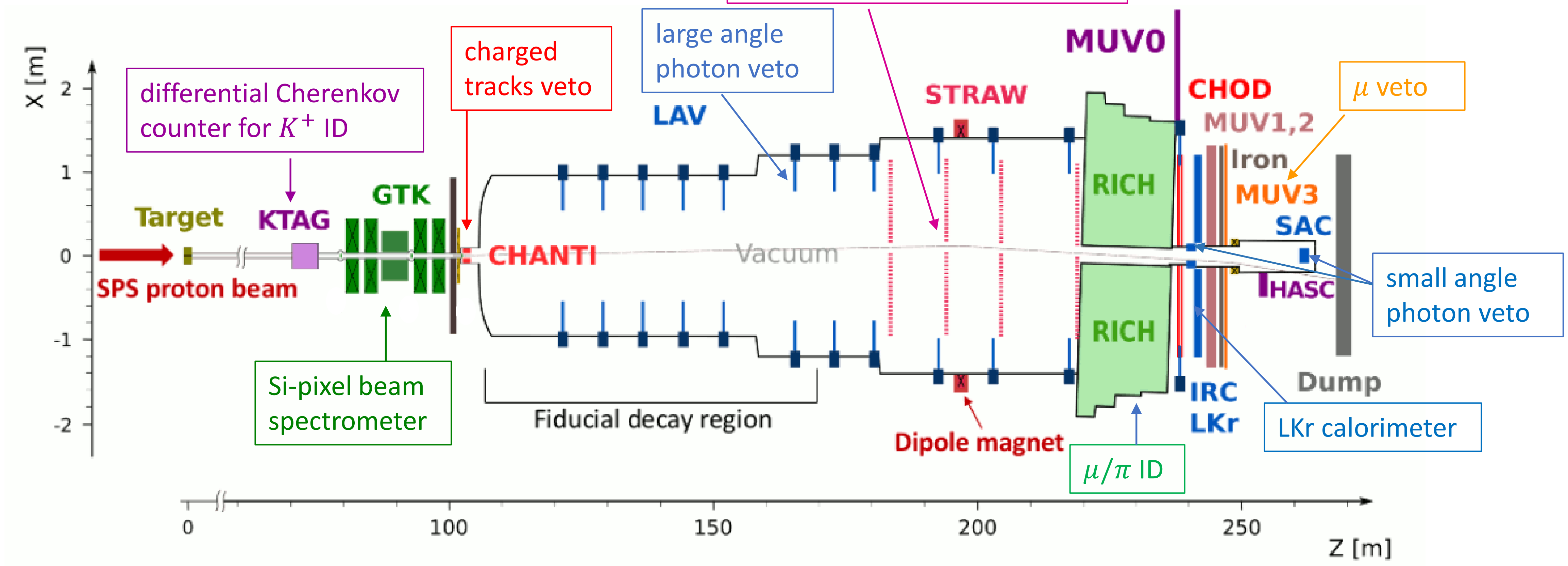
- Run1: 2016, 2017, 2018
- Run2: in progress, from 2021 till LS3

	2016	2017	2018
% of nominal intensity	40	60	60-70
K^+ decays in fiducial volume	$\sim 2\times10^{11}$	$\sim 2\times10^{12}$	$\sim 4\times10^{12}$

NA62 beam and detector

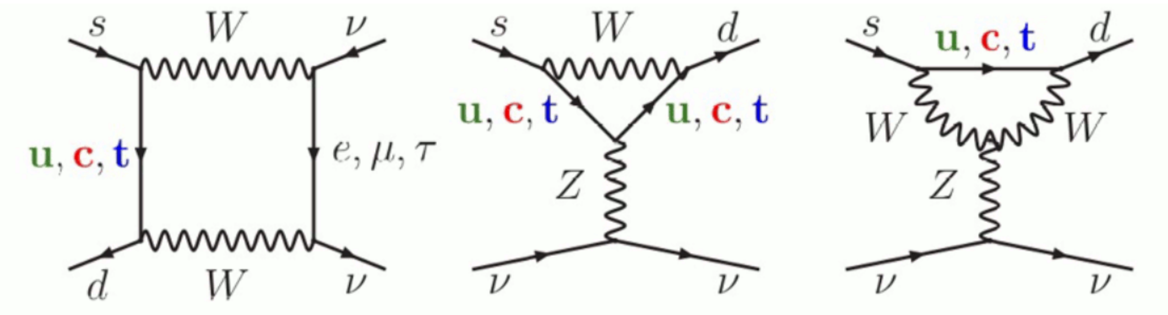
[2017 JINST 12 P05025]





- Secondary hadron 75 GeV/c beam: 70% pions, 24% protons, 6% kaons
- 60 m long fiducial region, ~ 5 MHz K^+ decay rate, vacuum ~ $O(10^{-6})$ mbar

The decay $K \to \pi\nu\bar{\nu}$

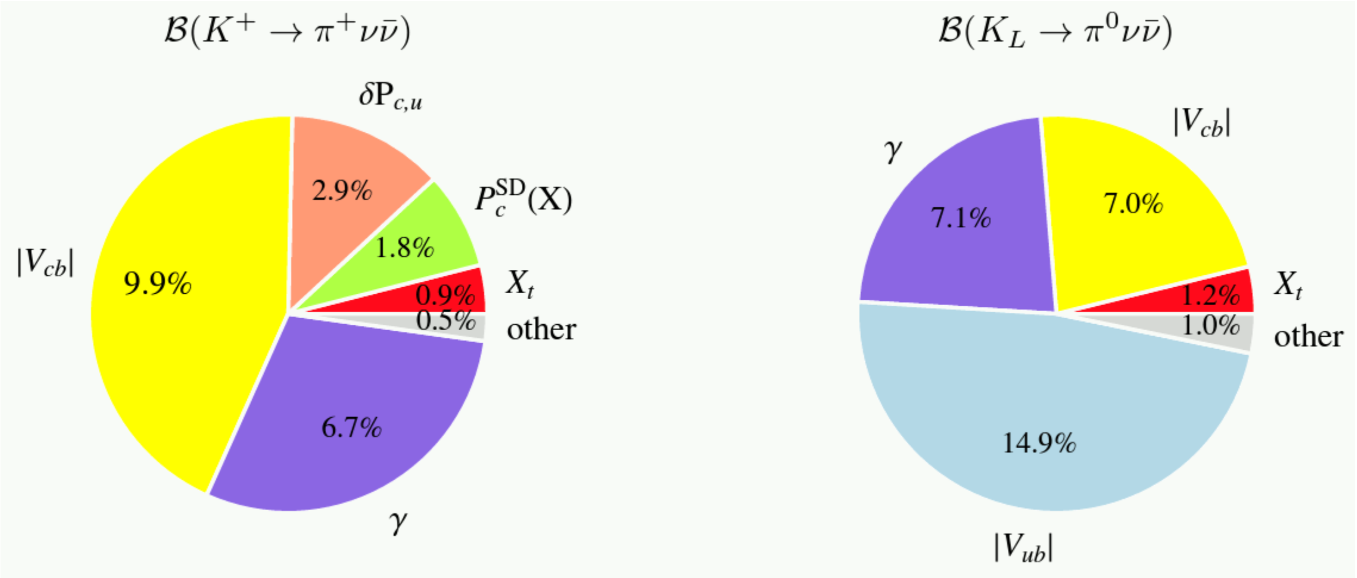


- FCNC process with highest CKM suppression
- Exceptional SM precision
- Basically free from hadronic uncertainties

SM branching ratios: [arXiv:2109.11032]

$K^+ \to \pi^+\nu\bar{\nu}(\gamma) = (8.60 \pm 0.42) \times 10^{-11}$

$K_L \to \pi^0\nu\bar{\nu} = (2.94 \pm 0.15) \times 10^{-11}$

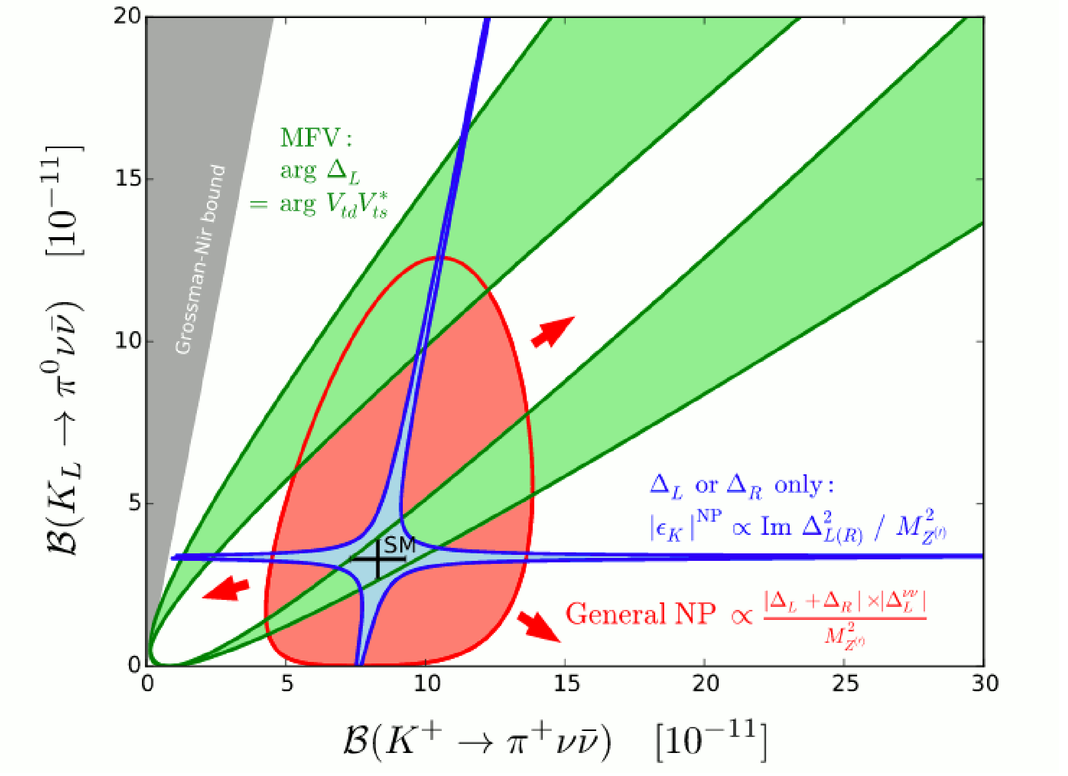


Theoretical error budget [JHEP11 (2015) 033]

K → $\pi\nu\bar{\nu}$: an example of sensitivity to new physics

Correlations are model-dependent

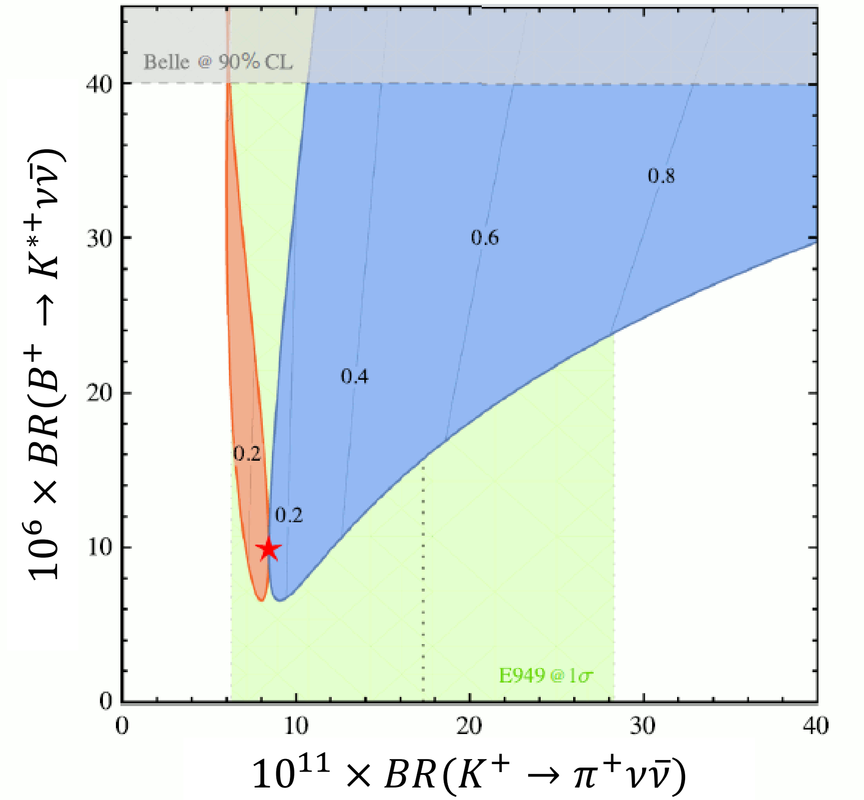
[JHEP11 (2015) 166]



- Models with MVF
- Z/Z' models with pure LH/RH couplings, Littlest Higgs with T parity
- Randall-Sundrum

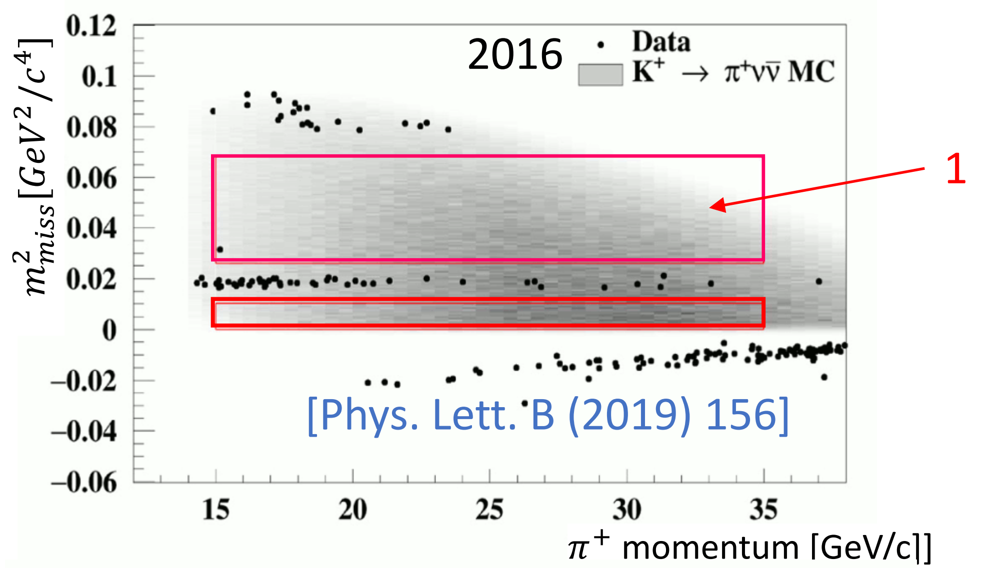
Important to look at the global picture (K, D and B)

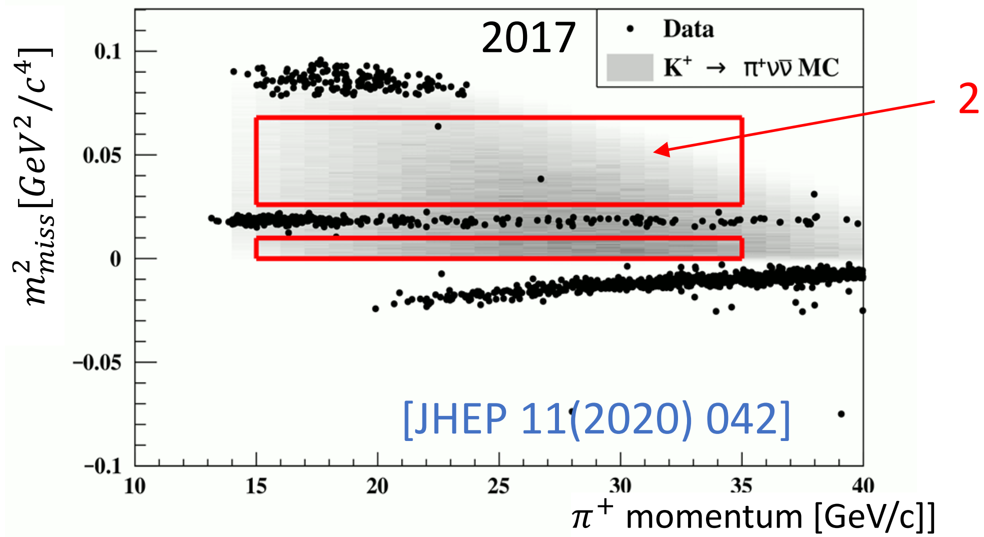
[Eur. Phys. J. C (2017) 77:618]



- New interactions responsible for LFUV coupling mainly to the third generation of left-handed fermions
- EFT with new interaction satisfying an approximate $U(2)_q \times U(2)_l$ flavour symmetry

NA62: $K^+ \to \pi^+ \nu\bar{\nu}$ 2016+2017 data

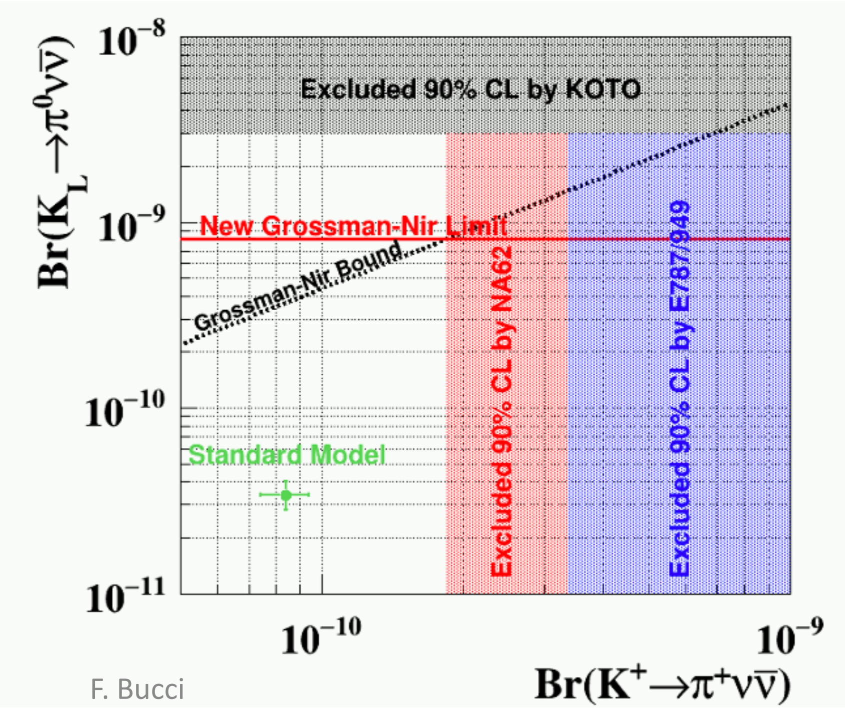




2016 + 2017 data

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) < 1.78 \times 10^{-10}\ (90\%\ CL)$$
$$= 0.48^{+0.72}_{-0.48} \times 10^{-10} (68\%\ CL)$$

Grossman-Nir limit: $BR(K_L \to \pi^0 \nu\bar{\nu}) < 7.8 \times 10^{10} (90\%\ CL)$



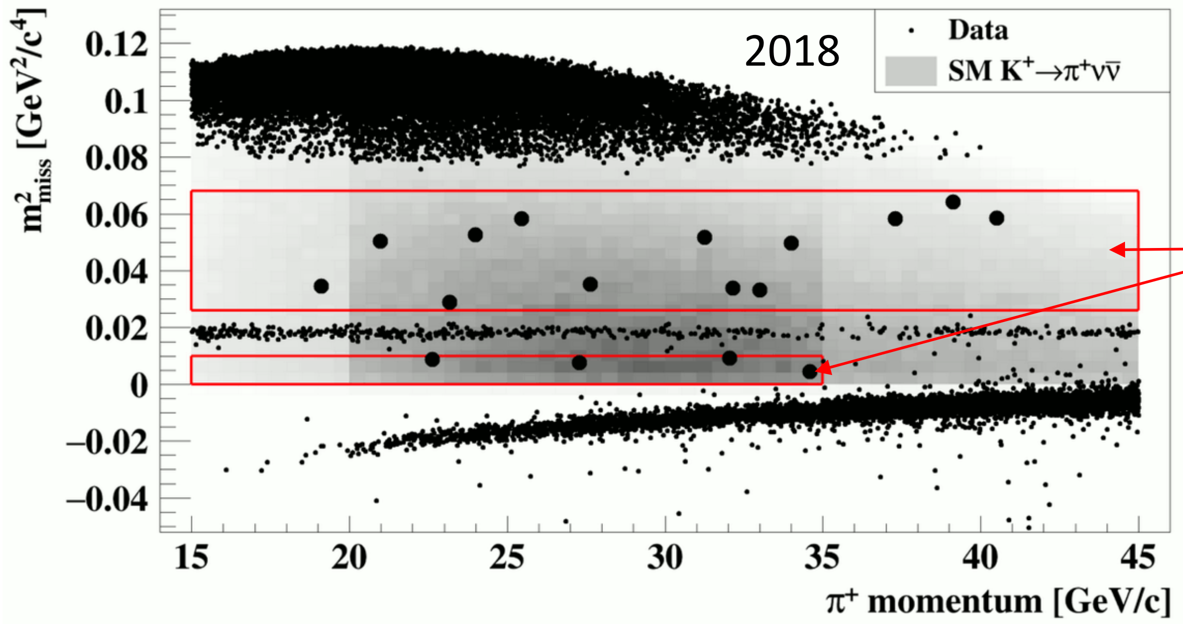
Grossman-Nir bound

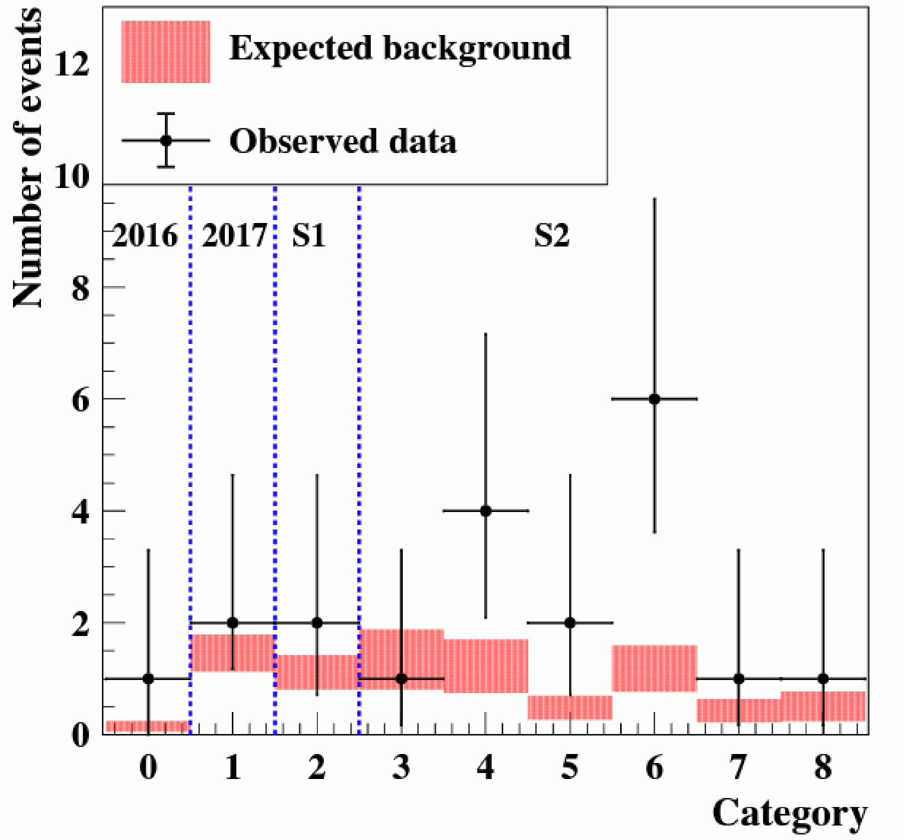
(model independent)

$$\frac{BR(K_L \to \pi^0 \nu\bar{\nu})}{BR(K^+ \to \pi^+ \nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \le 1$$

NA62: $K^+ \to \pi^+ \nu \bar{\nu}$ 2016+2017+2018 data(RUN1)

[JHEP 06 (2021) 093]





2016 + 2017 + 2018 data

$N_{obs}(Run1) = 20$

$BR(K^+ \to \pi^+ \nu \bar{\nu}) = \left(10.6^{+4.0}_{-3.4}\ _{stat} \pm 0.9_{syst}\right) \times 10^{-11}$ 68% CL

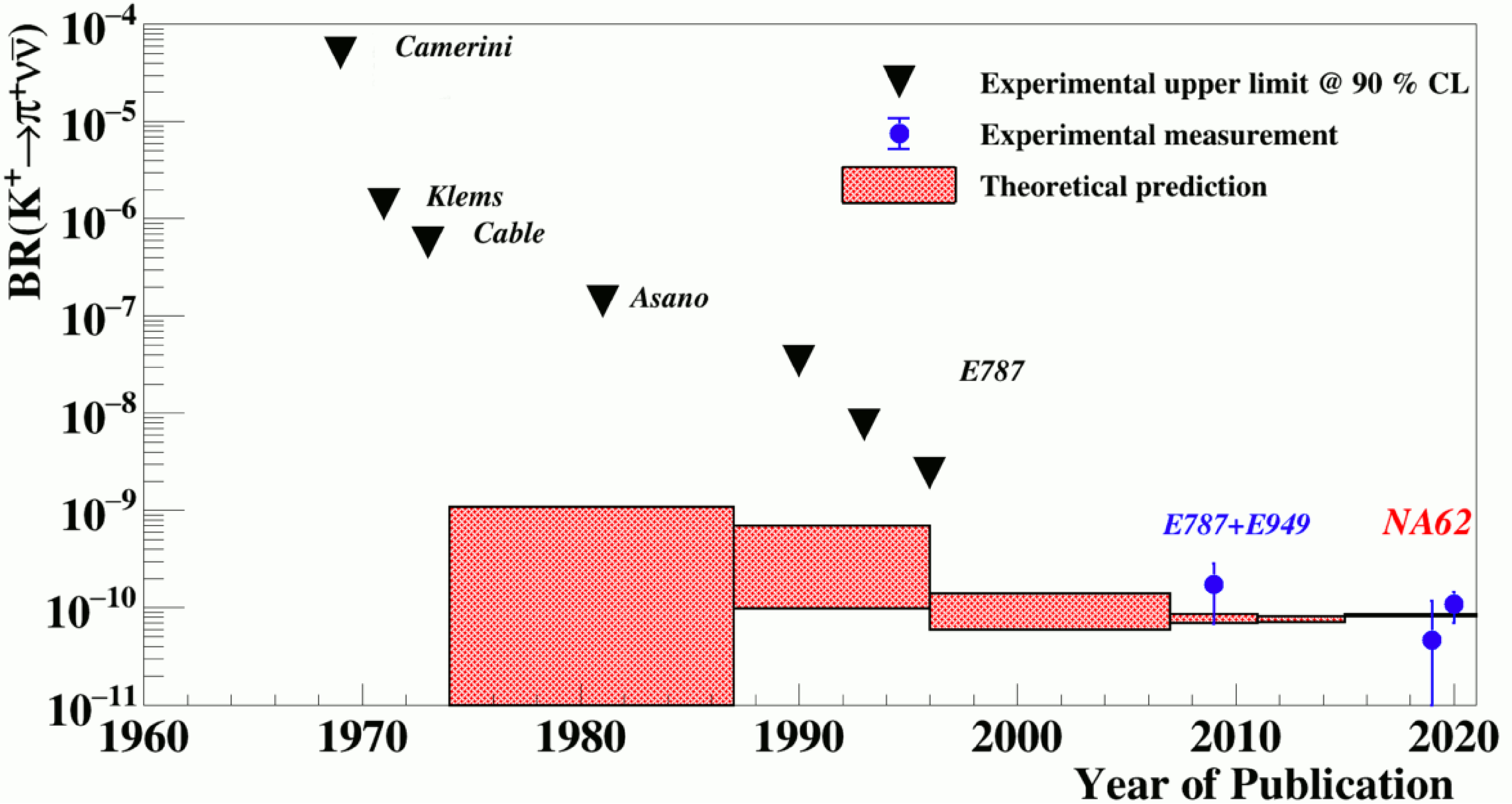
Most precise measurement of the decay rate to date

$SES = \left(0.839 \pm 0.053_{syst}\right) \times 10^{-11}$

$N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

$N^{exp}_{bkg} = 7.03^{+1.05}_{-0.82}$

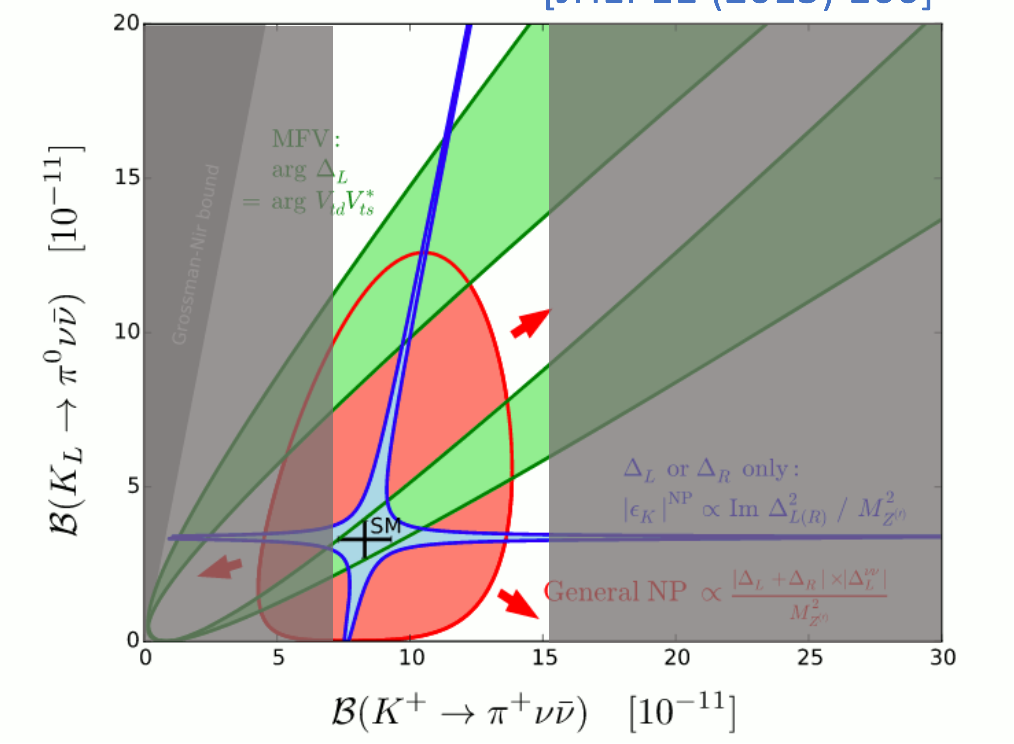
History of $K^+ \to \pi^+ \nu \bar{\nu}$ measurement



Implications of $K^+ \to \pi^+ \nu\bar{\nu}$ measurement and prospects

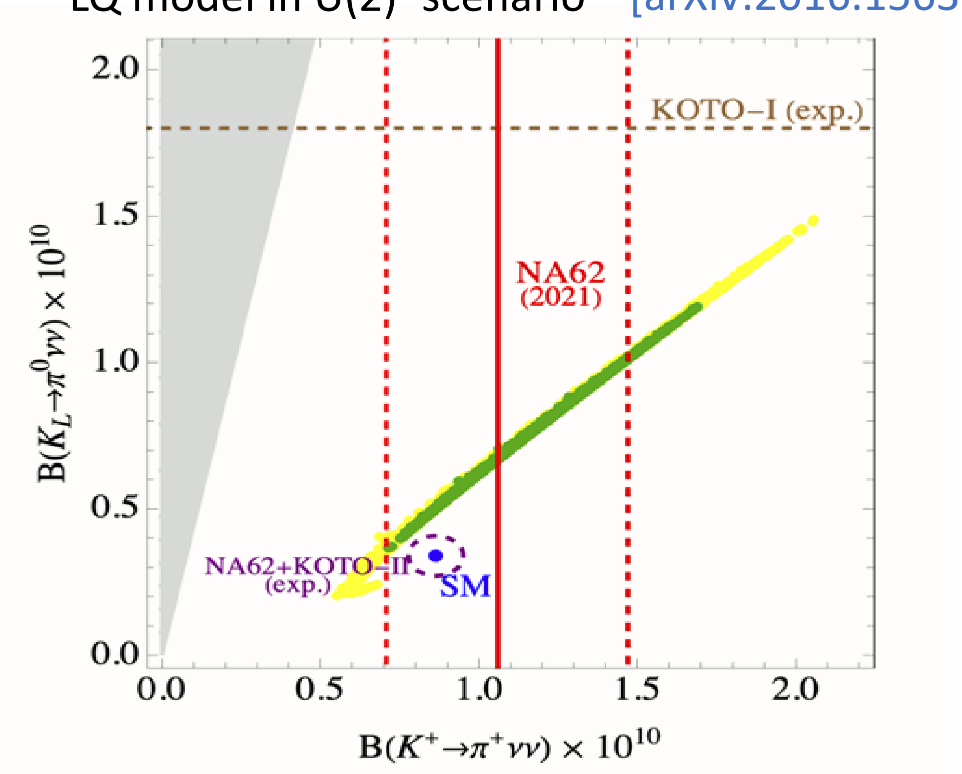
Part of the parameters space is already ruled out

[JHEP11 (2015) 166]



Next target: reach at least ×3 improved precision to match theoretical uncertainty $\mathcal{O}(10\%)$ by LS3

LQ model in U(2)^5 scenario [arXiv:2016.15630]



The dotted purple circle is the predicted precision of the high intensity kaon experiments of the future

$K^+ \to \pi^+\mu^+\mu^-$: Theory

Sensitive to new physics, LFU test together with electron channel

- FCNC decay mediated by the virtual photon exchange $K^+ \to \pi^+\gamma^* \to \pi^+\mu^+\mu^-$
- Long-distance hadronic contributions
- Differential decay width expressed in term of the Dalitz variables $z = m^2_{\mu^+\mu^-}/M^2_K$ and $x = m^2_{\pi^+\mu^+}/M^2_K$

Nucl. Phys. B291 (1987) 692-719, Phys.Part. Nucl. Lett. 5 (2008) 76-84

$$\frac{d^2\Gamma(x,z)}{dxdz} = \frac{d^2\Gamma_0(x,z)}{dxdz} \times \left(1 + \delta(x,z)\right)$$

Radiative corrections
Eur. Phys. J. C70 (2010) 219-231

$$\frac{d^2\Gamma_0(x,z)}{dxdz} = \frac{\alpha^2 M_K}{8\pi(4\pi)^4}\left[(2x + z - 2 - 2r_\mu^2)(-2x - z + 2r_\mu^2) + z(z - 2 - 2r_\pi^2)\right]|W(z)|^2$$

Form factor parametrized at NLO in ChPT
JHEP 08 (1998) 004

$$W(z) = G_F M_K^2(a + bz) + W^{\pi\pi}(z)$$

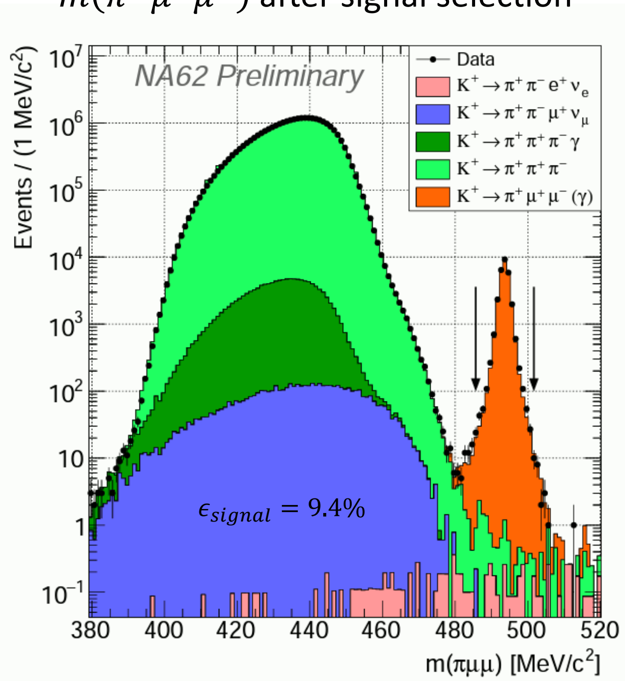
FF parameters

Pion loop term from
$K^+ \to \pi^+\pi^+\pi^-$

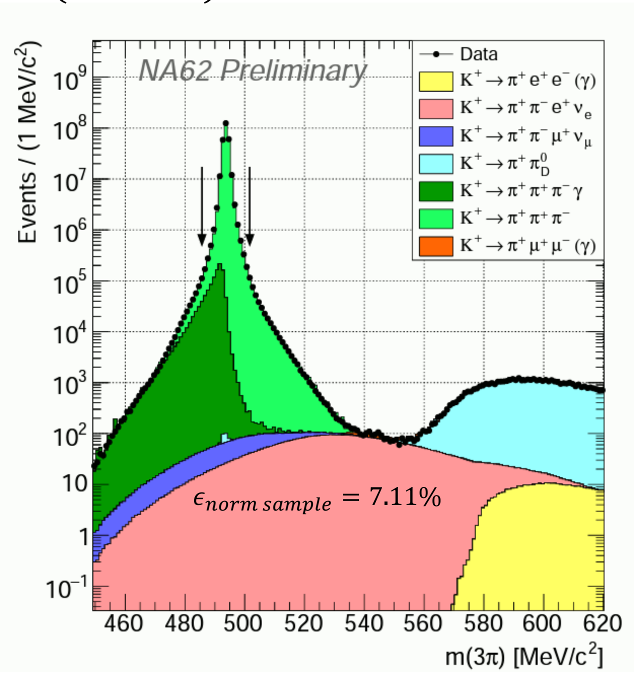
$K^+ \rightarrow \pi^+\mu^+\mu^-$: Analysis

- Analysis performed on NA62 2017+2018 data set
- $K^+ \rightarrow \pi^+\pi^+\pi^-$used as normalization decay
- $N_{selected\ signal} = 28011$ (~ 9 × more than NA48/2), $N_{expected\ bkg} = 12.5 \pm 1.7(stat.)12.5(syst.)$
- FF parameters measured by reweighting the MC z spectrum to best fit the data

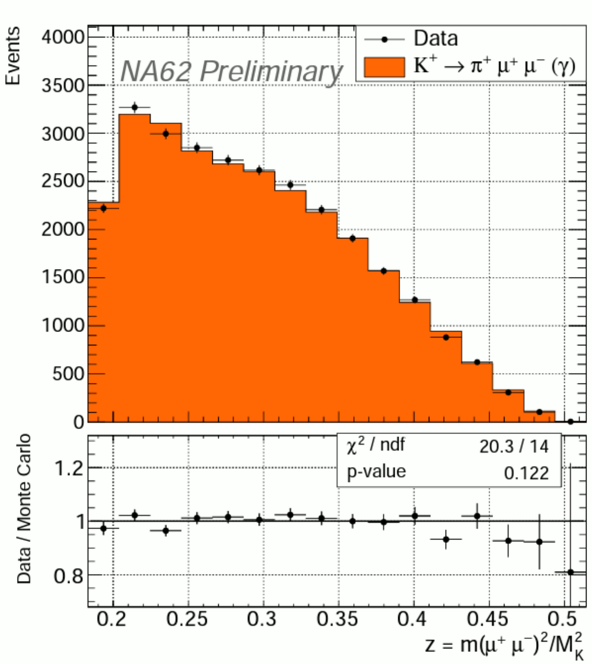
$m(\pi^+\mu^+\mu^-)$ after signal selection



$m(\pi^+\pi^+\pi^-)$ after normalization selection



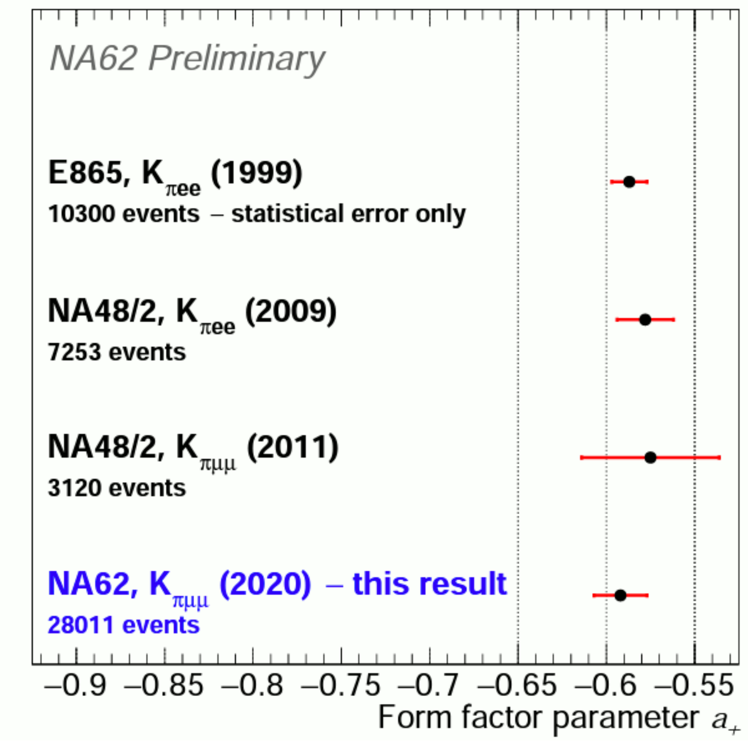
z spectrum of signal candidate events with MC reweighted to best fit the data



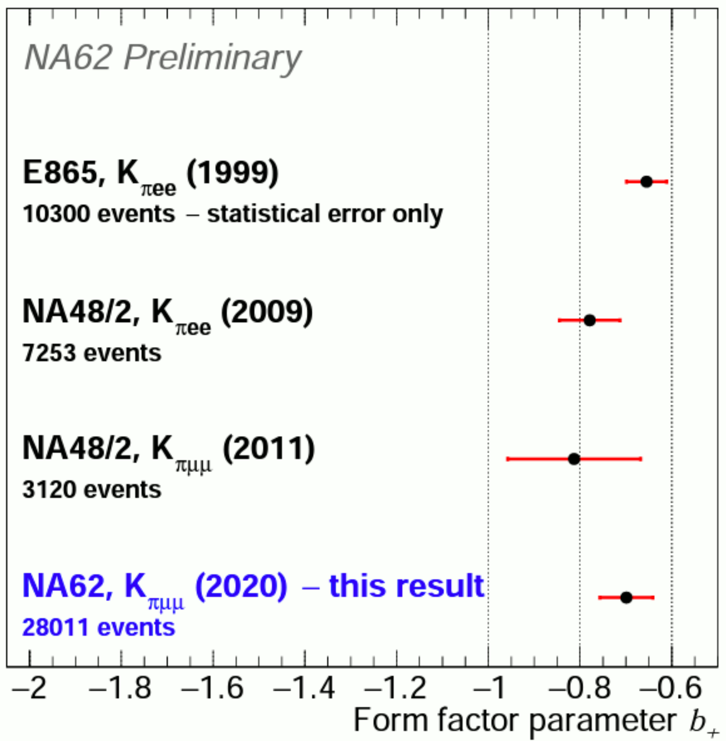
$K^+ \rightarrow \pi^+\mu^+\mu^-$: Results (2017+2018 data set)

Model dependent

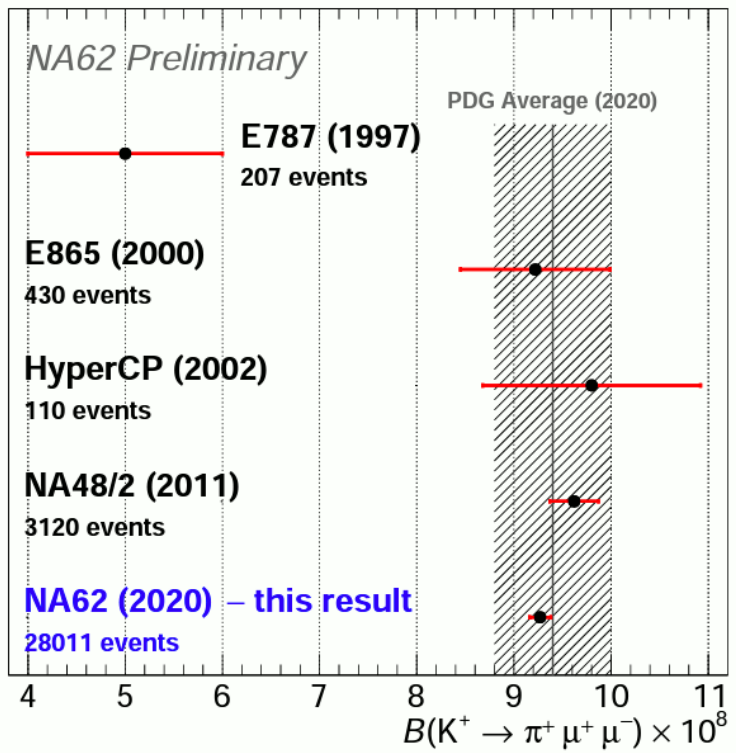
$a = -0.592 \pm 0.015$



$b = -0.699 \pm 0.058$



$BR(K^+ \rightarrow \pi^+\mu^+\mu^-) = (9.27 \pm 0.11) \times 10^{-8}$



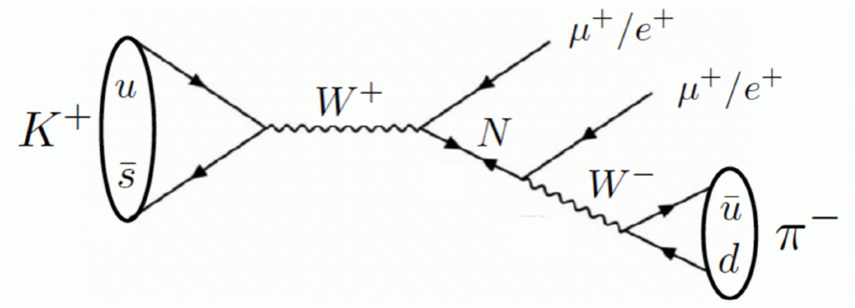
Analysis performed on the full NA62 Run 1 data set
Forward-backward asymmetry measured
} paper in preparation

Revised, more stringent trigger for di-muon and di-electron in 2021

LNV and LFV in kaon decays

- Lepton Number (L) and Lepton Flavor (L_e,L_μ,L_τ) are accidentally conserved quantities within the SM
- Violation of these conservation laws is a clear indication of BSM physics
- Searches for LNV and LFV kaon decays are powerful probes of BSM theories at mass scales up to $\mathcal{O}$(100 TeV)

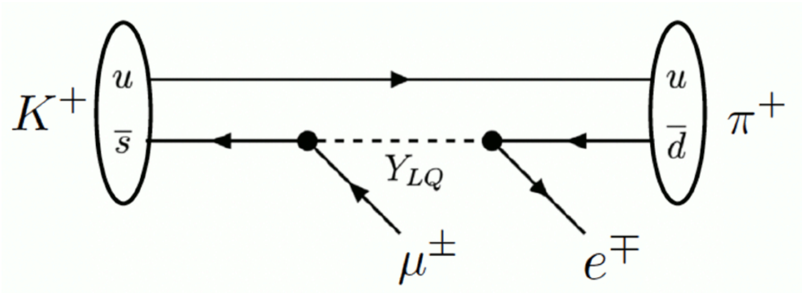
Lepton number violation (LNV)



Seesaw mechanism provides a source of LNV through the exchange of Majorana neutrinos as in $0\nu\beta\beta$ decay

[JHEP 0905 (2009) 030]

Lepton flavour violation (LFV)



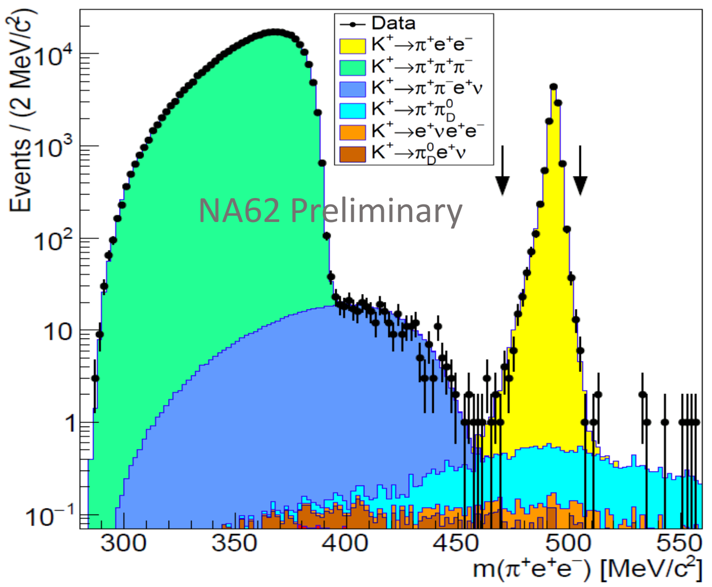
LFV processes can occur via the exchange of leptoquarks, of a Z′boson, or in SM extensions with light pseudoscalar bosons

[JHEP 10 (2018) 148, Rev. Mod. Phys. 81, 1199 (2009), JHEP 01 (2020)158]

$K^+ \to \pi^- e^+ e^+$ (LNV) [arXiv.2202.00331]

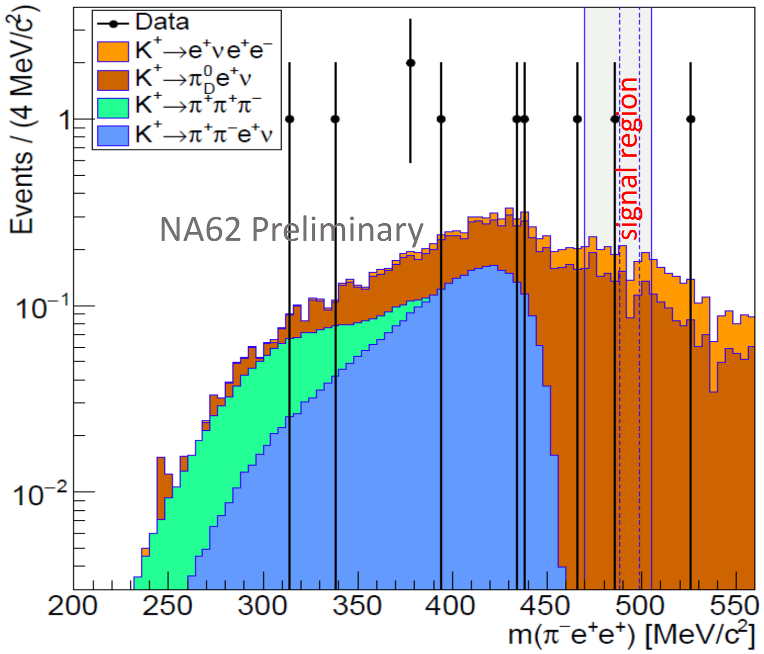
- Analysis based on the full NA62 Run1 data set
- $K^+ \to \pi^+ e^+ e^-$ used as normalization decay
- RICH-based e^+ identification used to suppress the dominant backgrounds from $K^+ \to \pi^+ \pi^0_D$ ($\pi^0_D \to e^+ e^- \gamma$) and $K^+ \to \pi^+ e^+ e^-$ decays with double $\pi^+ \to e^+$and $e^- \to \pi^-$ misidentification

SM selection: $m(\pi^+ e^+ e^-)$



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

LNV selection: $m(\pi^- e^+ e^+)$



Expected bkg events: 0.43 ± 0.09

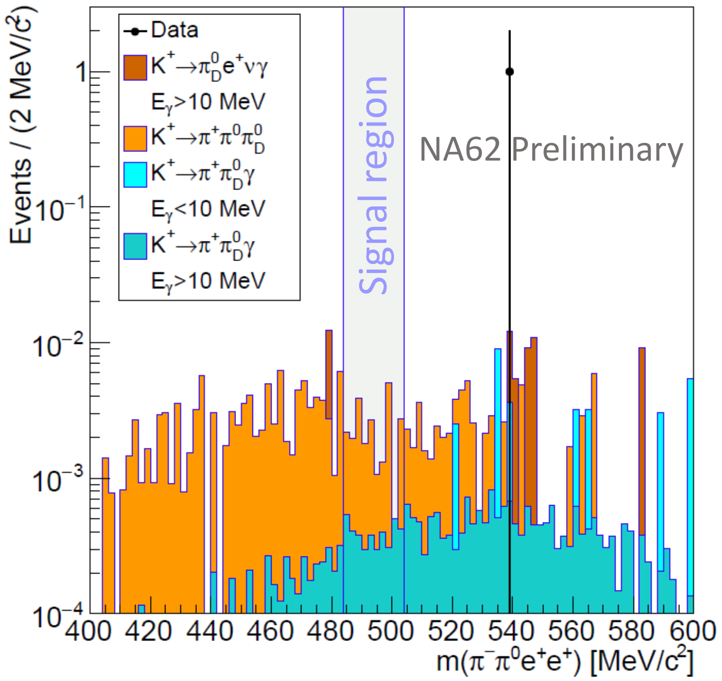
Observed signal cand events: 0

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

$K^+ \to \pi^-\pi^0 e^+ e^+$(LNV) [arXiv.2202.00331]

- Analysis based on the full NA62 Run1 data set
- $K^+ \to \pi^+ e^+ e^-$ used as normalization decay
- π^0 is reconstructed by its prompt $\pi^0 \to \gamma\gamma$ decay

LNV selection: $m(\pi^-\pi^0 e^+ e^+)$



Mode	Control region	Signal region
$K^+ \to \pi^+\pi^0\pi^0_D$	0.16 ± 0.01	0.019
$K^+ \to \pi^+\pi^0_D\gamma$	0.06 ± 0.01	0.004
$K^+ \to \pi^0_D e^+\nu\gamma$	0.05 ± 0.02	–
$K^+ \to \pi^+\pi^0 e^+ e^-$	0.01	0.001
Pileup	0.20 ± 0.20	0.020 ± 0.020
Total	0.48 ± 0.20	0.044 ± 0.020
Data	1	0

Expected bkg events: 0.044 ± 0.020
Observed signal cand events: 0
$BR(K^+ \to \pi^-\pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ at 90% CL

First search for this mode

$K^+ \to \pi^-\mu^+e^+$ LNV and $K^+ \to \pi^+\mu^-e^+$ $(\pi^0 \to \mu^-e^+)$ LFV

- Analysis based on the NA62 2017+2018 data set
- $K^+ \to \pi^+\pi^+\pi^-$ used as normalization decay. K^+decays in FV: $(1.07 \pm 0.20) \times 10^{12}$
- 3 charged tracks consistent with $\pi^\mp\mu^\pm e^+$ final states coming from K^+decay
- Invariant mass $m_{\pi\mu e}$used to distinguish between signal and background ($\sigma_{m_{\pi\mu e}} = 1.4$ MeV/c^2)
- To search for the decay chain $K^+ \to \pi^+\pi^0(\pi^0 \to \mu^-e^+)$ the reconstructed mass of μe pair required to be consistent with π^0 mass

Main background contributions arise from K^+decays followed by:

- particle misidentification

$\pi^\pm \Rightarrow e^\pm$ $(4-5) \times 10^{-3}$ $\quad$ $e^\pm \Rightarrow \pi^\pm$ $(1-3) \times 10^{-2}$

$\pi^\pm \Rightarrow \mu^\pm$ $(2-3) \times 10^{-3}$ $\quad$ $\mu^\pm \Rightarrow \pi^\pm$ 1.5×10^{-3}

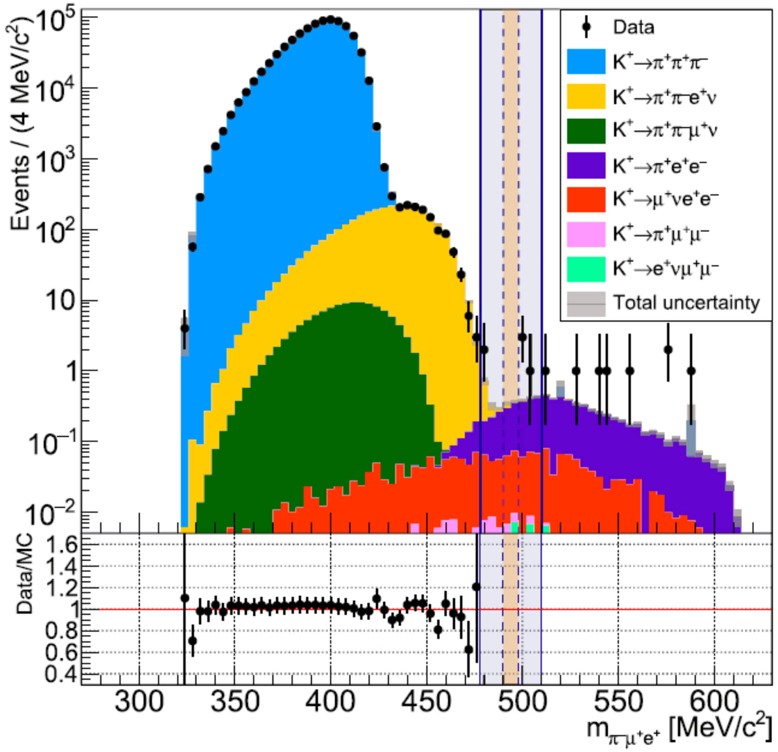
- $\pi^\pm \to l^\pm\nu_l$ $(l = \mu, e)$ decays in flight

$K^+ \to \pi^-\mu^+e^+$ LNV and $K^+ \to \pi^+\mu^-e^+$ $(\pi^0 \to \mu^-e^+)$ LFV

[PRL 127 (2021) 131802]

Expected bkg events: 1.07 ± 0.20

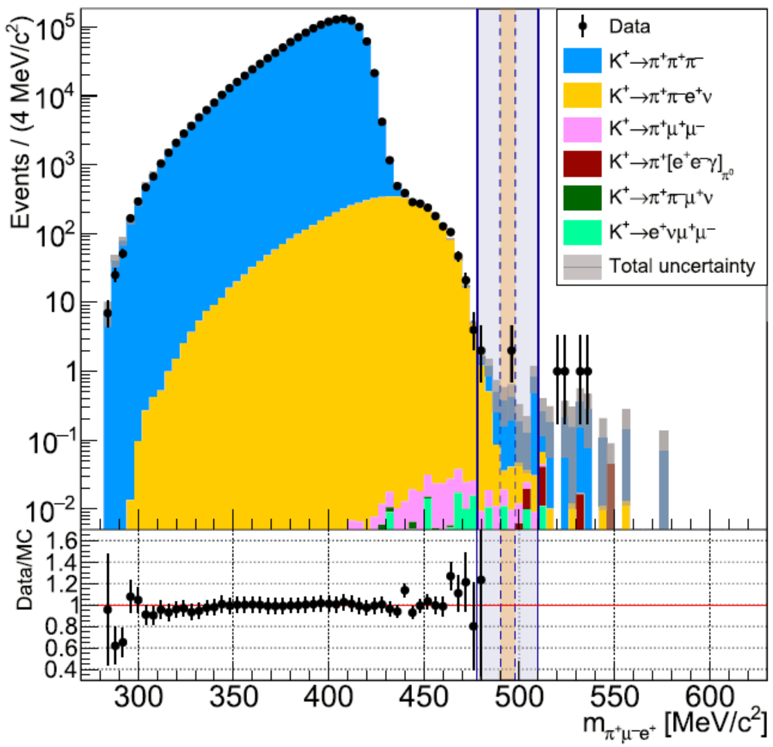
Observed $K^+ \to \pi^-\mu^+e^+$ cand events: 0



$BR(K^+ \to \pi^-\mu^+e^+) < 4.2 \times 10^{-11}$ at 90% CL

Expected bkg events: 0.92 ± 0.20

Observed $K^+ \to \pi^+\mu^-e^+$ cand events: 2



$BR(K^+ \to \pi^+\mu^-e^+) < 6.6 \times 10^{-11}$ at 90% CL

$BR(\pi^0 \to \mu^-e^+) < 3.2 \times 10^{-11}$ at 90% CL

NA62 LNV and LFV Results

	Previous UL @ 90% CL	NA62 UL @ 90%CL		
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data $\to$ improved by factor 2	Phys. Lett. B 797 (2019) 134794
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	5.3×10^{-11}	Run1 data $\to$ improved by factor 12	NEW ! arXiv:2202.00331
$K^+ \to \pi^-\pi^0e^+e^+$	no limit	8.5×10^{-10}	Run1 data	
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data $\to$ improved by factor 12	PRL 127 131802 (2021)
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data $\to$ improved by factor 8	
$\pi^0 \to \mu^-e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data $\to$ improved by factor 13	
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	-	sensitivity similar to previous search	
$\pi^0 \to \mu^+e^-$	3.8×10^{-10}	-	sensitivity similar to previous search	
$K^+ \to \mu^-\nu e^+e^+$	2.1×10^{-8}	-	Ongoing analysis on 2017 data: SES $\sim 1 \times 10^{-10}$	
$K^+ \to e^-\nu\mu^+\mu^+$	no limit		Ongoing analysis on 2017 data: SES $\sim 5 \times 10^{-11}$	

$\sim$ 1 order of magnitude improvements compared to previous searches

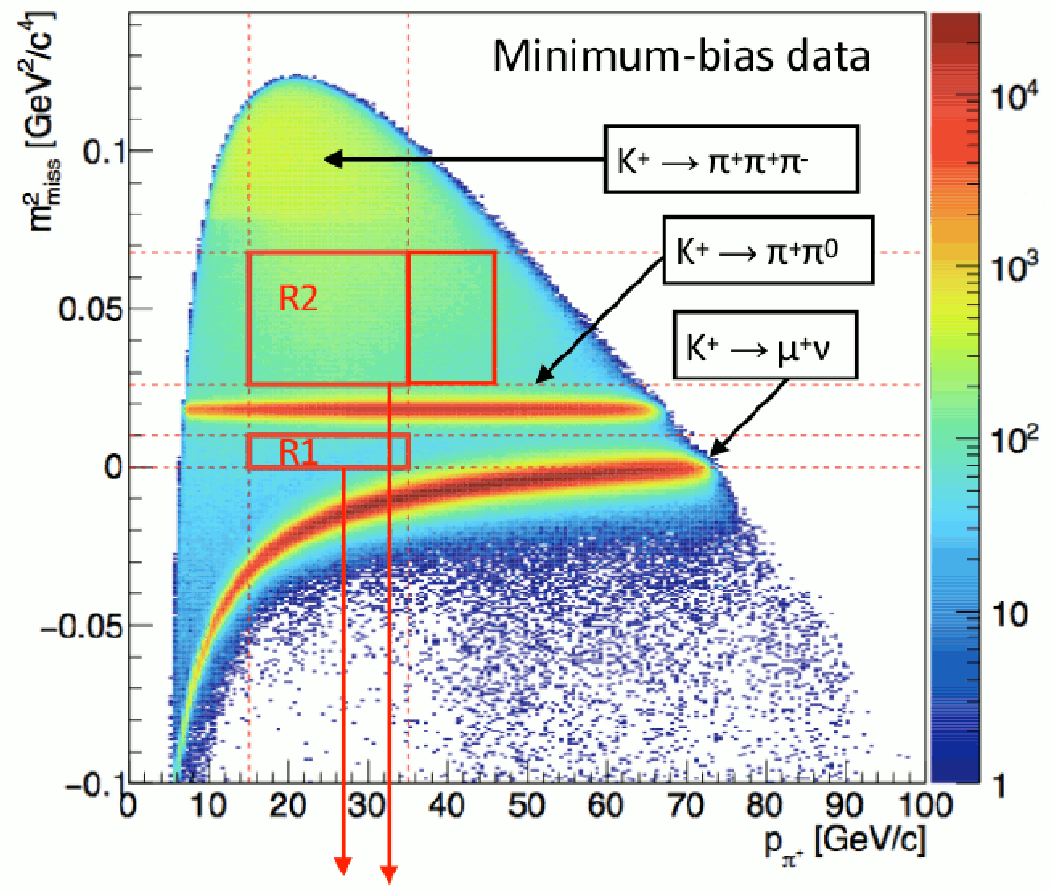
Conclusions

- Kaon rare decays are an excellent portal to explore physics beyond the Standard Model
- NA62 Run1 data set collected in 2016-2018 contains $\sim 6 \times 10^{12}\ K^+$ decays in flight
- A strong kaon physics program is going on
- NA62 data taking was resumed in 2021 and will continue till LS3 at higher beam intensity, with updated detectors and trigger lines
- The short term goal is to have $BR(K^+ \to \pi^+ \nu\bar{\nu})$ measured to 10% by LS3
- In parallel, compelling measurements: FCNC decays other than $K^+ \to \pi^+ \nu\bar{\nu}$, LFV, LNV, Exotics, HNL,..

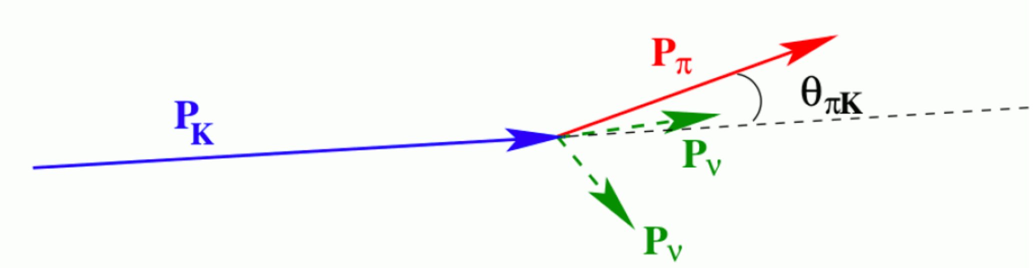
Spare

NA62: Decay in flight

$$m^2_{miss} = (p_K - p_\pi)^2$$



Kinematic cuts to define signal regions R1 and R2



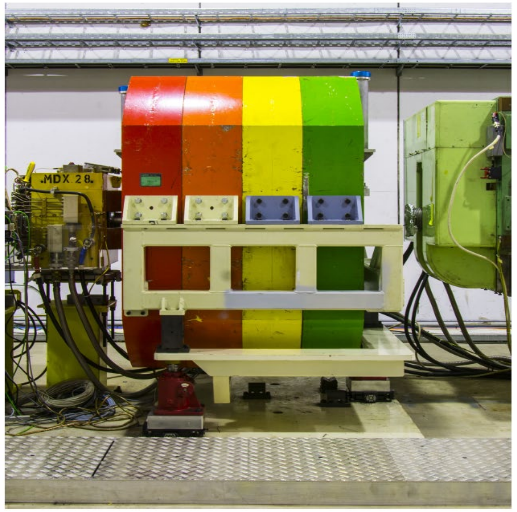
K^+ main (background) decays

Decay channel	Branching ratio
$K^+ \to \mu^+\nu$ ($K_{\mu 2}$)	$(63.56 \pm 0.11) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^0$ ($K_{2\pi}$)	$(20.67 \pm 0.08) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^+\pi^-$ ($K_{3\pi}$)	$(5.583 \pm 0.024) \cdot 10^{-2}$
$K^+ \to \pi^+\pi^- e^+\nu$ (K_{e4})	$(4.247 \pm 0.024) \cdot 10^{-5}$

NA62: Upstream decays

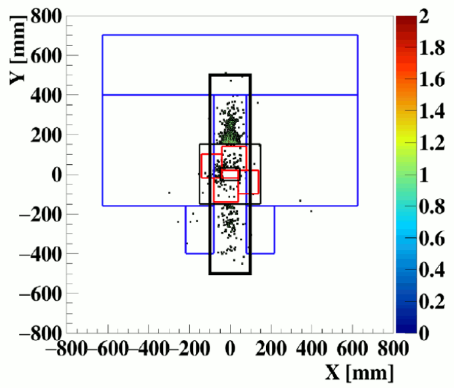
OLD COL

NEW COL (from June 2018)

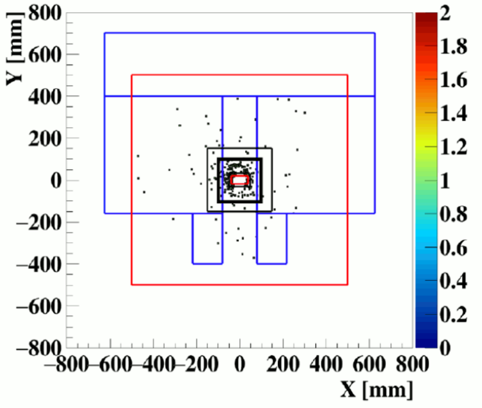


Track extrapolation at collimator in enriched sample of upstream events
Red boxes: collimator coverage

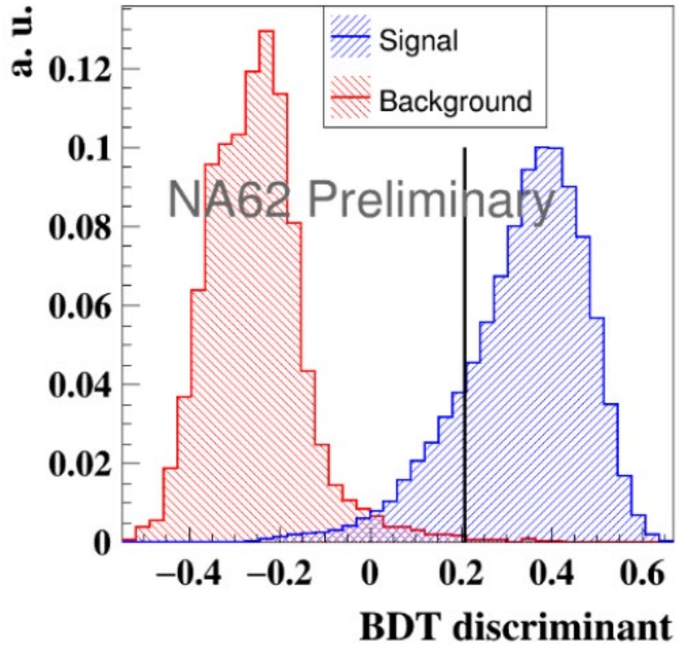
OLD COL



NEW COL



Both samples normalized to 1



$\epsilon(sig) \sim 83\%$ @ $\epsilon(bkg) \sim 0.5\%$

BDT (NEW COL) based on:

- X,Y at Collimator
- Vertex
- Track slope

NA62 2018 Data: Signal efficiency

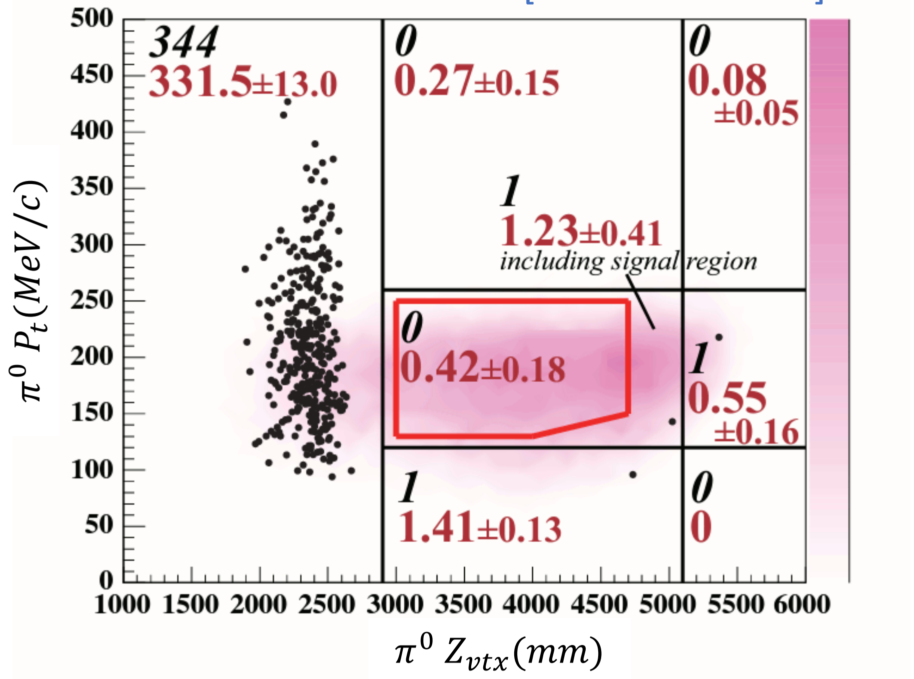
Sizeable improvements in 2018 data analysis (hardware and software)

	2017	2018-OLDCOL	2018-NEWCOL
N_K	$(1.5 \pm 0.2) \cdot 10^{12}$	$(0.8 \pm 0.1) \cdot 10^{12}$	$(1.9 \pm 0.2) \cdot 10^{12}$
$A_{\pi\nu\nu}$	$(3.0 \pm 0.3)\%$	$(4.0 \pm 0.4)\%$	$(6.4 \pm 0.6)\%$
ε_{RV}	0.64 ± 0.01	0.66 ± 0.01	0.66 ± 0.01
ε_{trig}	0.87 ± 0.03	0.88 ± 0.04	0.88 ± 0.04
$N^{exp}_{\pi\nu\nu}(SM)$	2.16 ± 0.29	1.56 ± 0.21	6.02 ± 0.82
B/S	~ 0.7	~ 0.7	~ 0.7

Increase of signal efficiency with the same B/S ratio

KOTO: $K_L \rightarrow \pi^0 \nu \bar{\nu}$ Results

[PRL.122.021802]



2015 data:

$\text{SES} = 1.30 \times 10^{-9}$

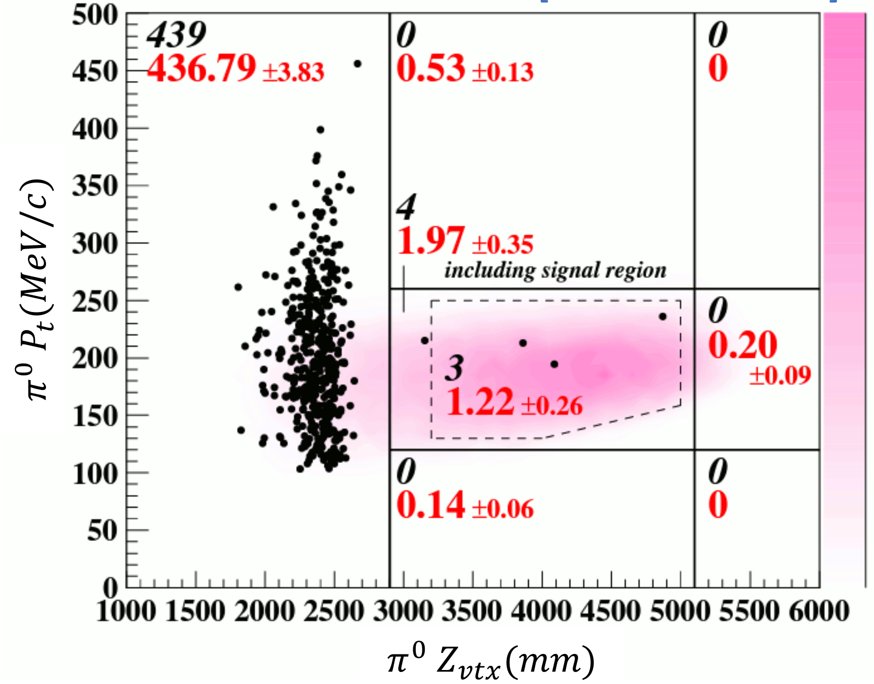
0.42 predicted bkg events

No events observed

$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9}$ (90% CL)

current best limit

[PRL.126.121801]



2016-2018 data:

$\text{SES} = 7.20 \times 10^{-10}$

1.22 predicted bkg events

(including newly-found backgrounds)

3 events observed

$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ (90% CL)

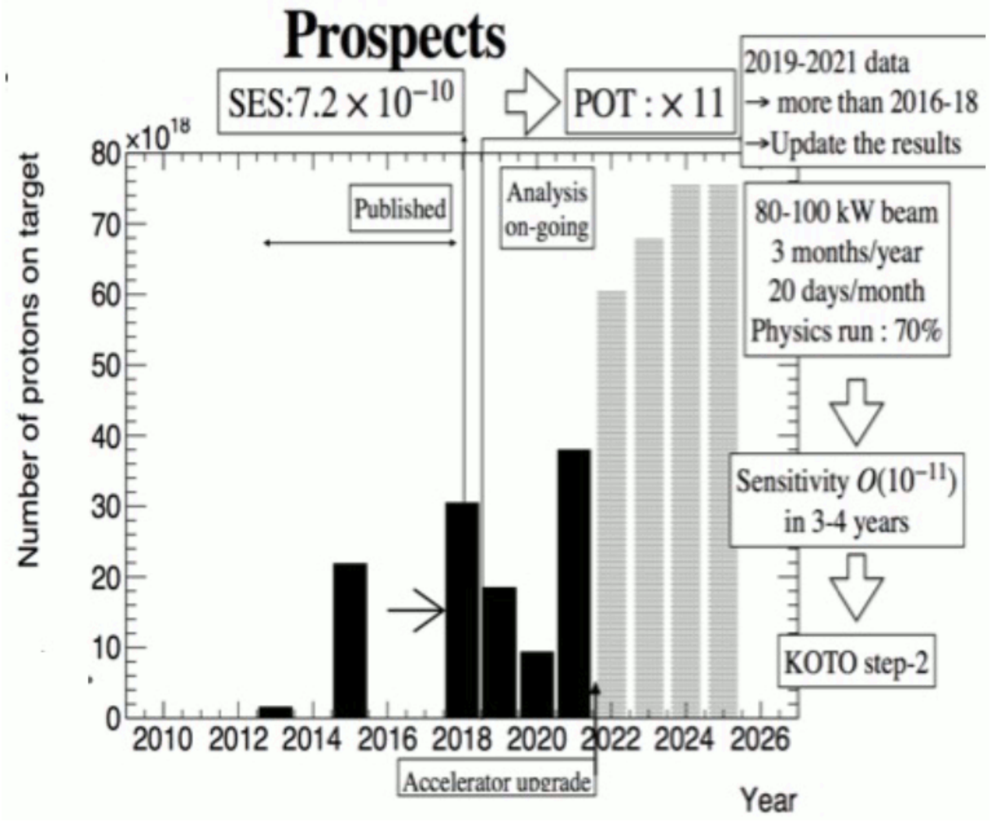
KOTO: $K_L \to \pi^0 \nu \bar{\nu}$ Prospects

2021-2022 shutdown:

- J-PARK main ring power supply upgrade
  Beam power 64kW $\rightarrow$ 80-100 kW
- KOTO DAQ upgrade
  event throughput $\times$ 4

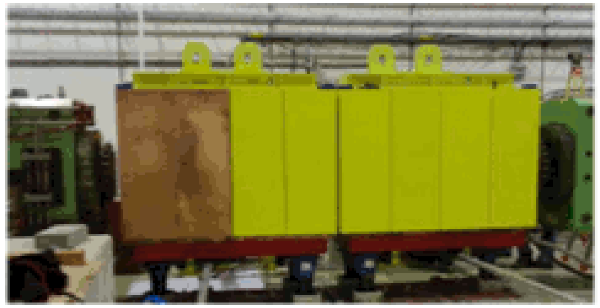
2022-2025:

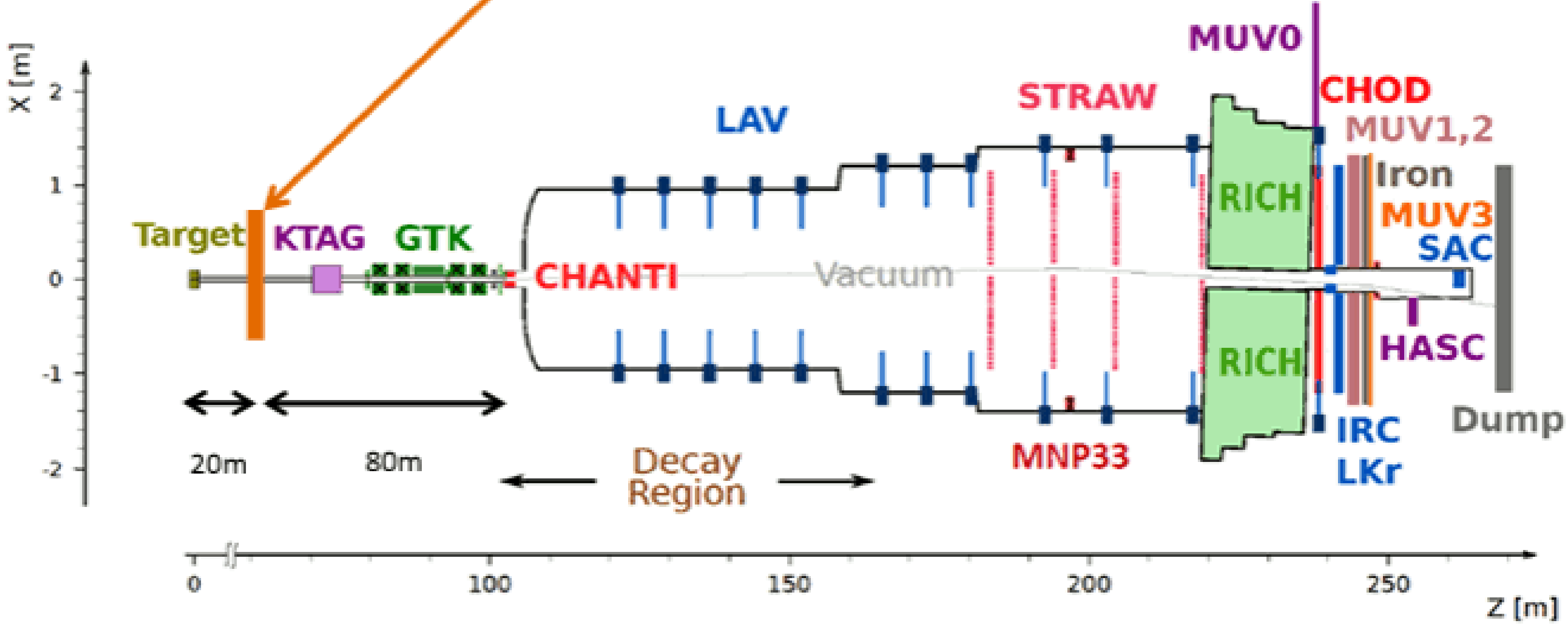
KOTO will collect $\times$ 11 more data
Projected SES $\mathcal{O}(10^{-11})$ by 2026



NA62 in dump mode

Beam defining collimators (TAX1 and TAX2)
~ 11 λ_I Cu-based can be used as a dump





Easy switch between K^+ beam and proton dump mode with TAXes