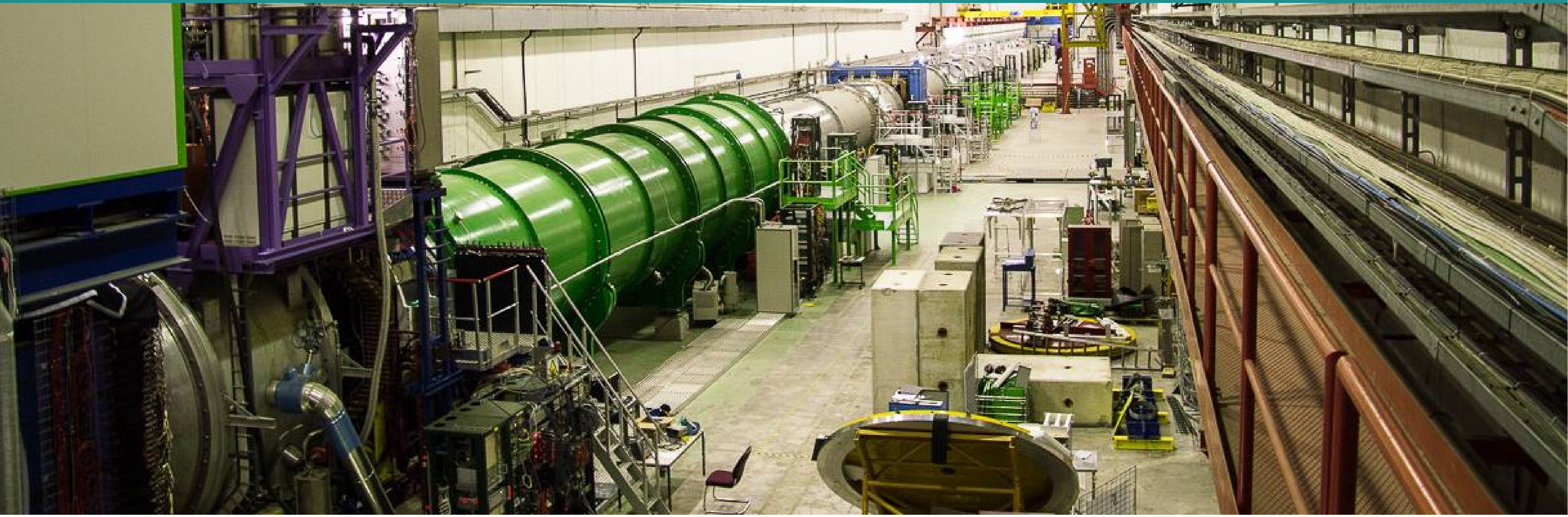
Latest results from NA62



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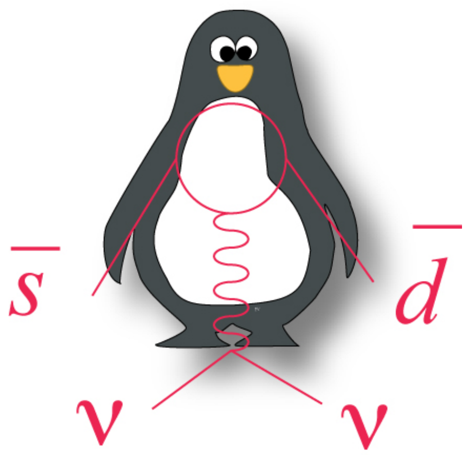
on behalf of the NA62 Collaboration

WIN 2019 - 27th International Workshop on Weak Interactions and Neutrinos – June 2019

Outline

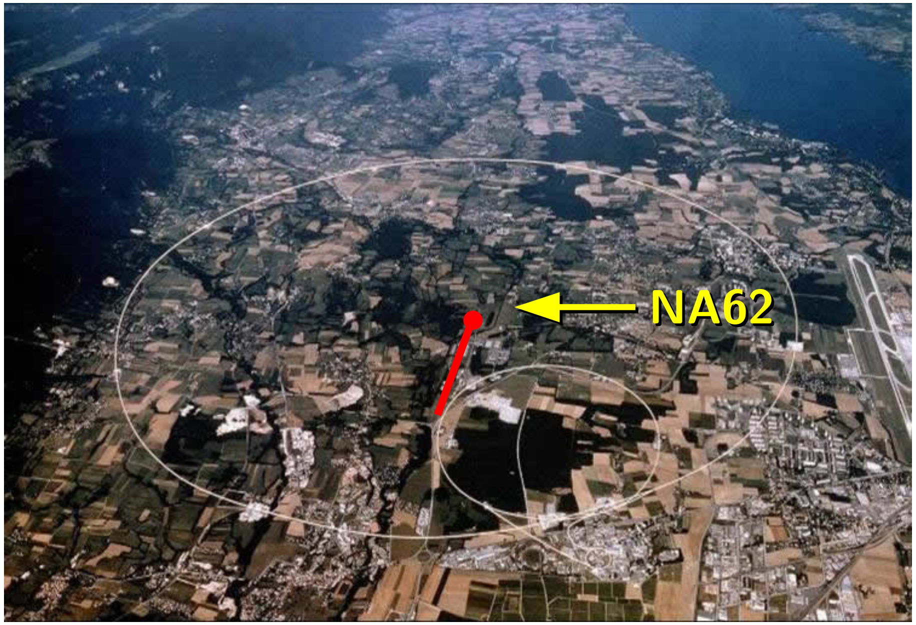
- The NA62 experiment
- The $K^+ \to \pi^+ \nu\bar{\nu}$ decay
- LNV/LFV searches



This talk will not cover NA62 searches for HNL, ALPs or dark photons (see Lorenza Iacobuzio's presentation)

The NA62 experiment

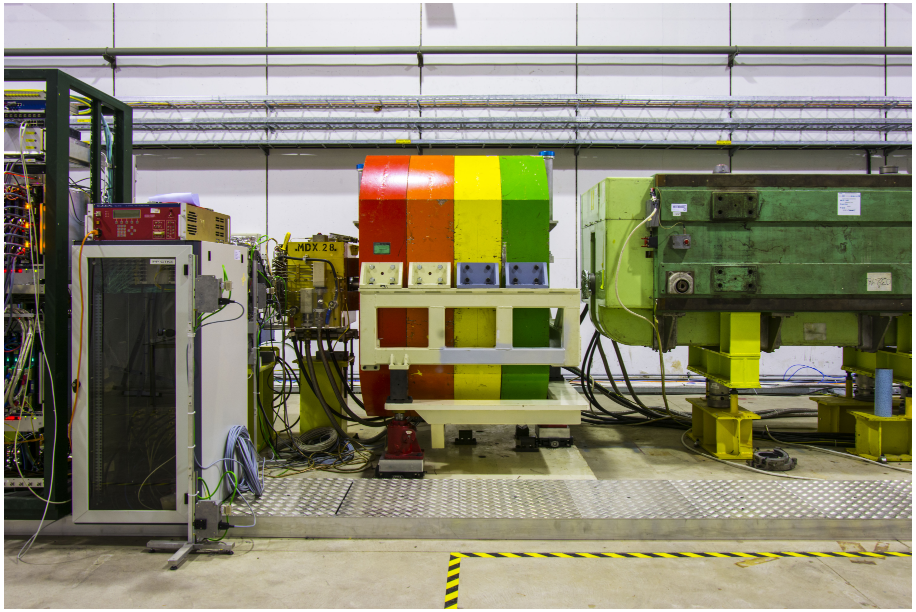
- Fixed target experiment, located in the North Area of the CERN SPS.
- Main goal: **BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)** with 10% precision.
- $BR_{th}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$
  [Buras et al., JHEP11(2015)033]
  $BR_{exp}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$
  [E949, Phys. Rev D 79, 092004 (2009)]
- ~200 participants from ~30 insitutes:
  Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC.



The NA62 experiment

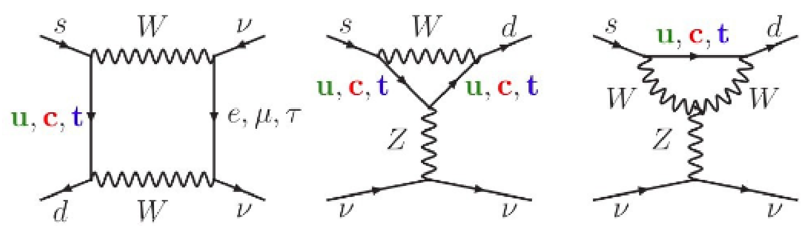
Status and timeline:

- 2016
  - Commissioning + 1st physics run.
  - First results presented in March 2018.
- 2017
  - Physics run, better collection efficiency for physics data.
  - 3 x 10^{12} K^+ decays recorded (> 20x more than 2016).
- 2018
  - Physics run, better shielding of upstream background.
  - 5 x 10^{12} K^+ decays recorded (> 40x more than in 2016).
- 2019 – 2020: LHC Long Shutdown 2.

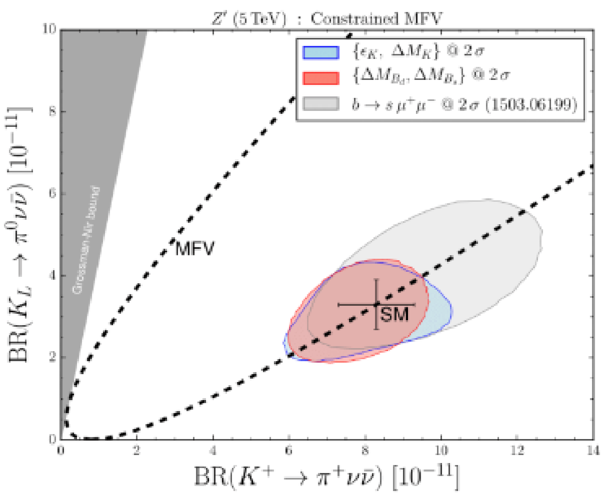


$K^+ \to \pi^+ \nu\bar{\nu}$: theoretical framework

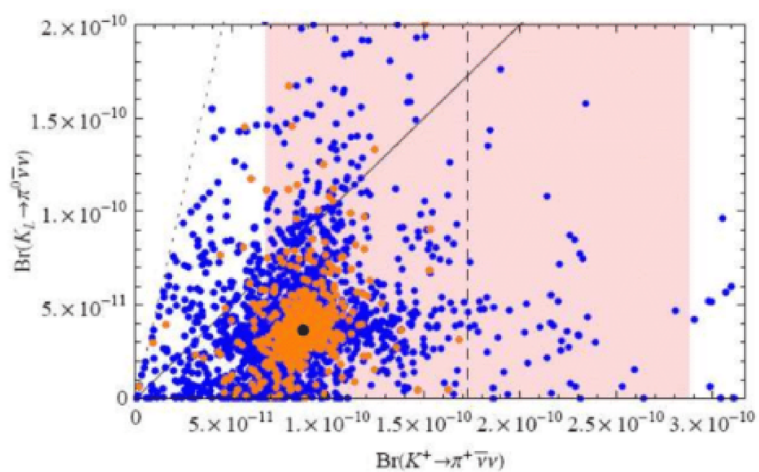
- FCNC processes dominated by Z penguin and box amplitudes: s→d coupling and highest CKM suppression.
- Theoretically clean.



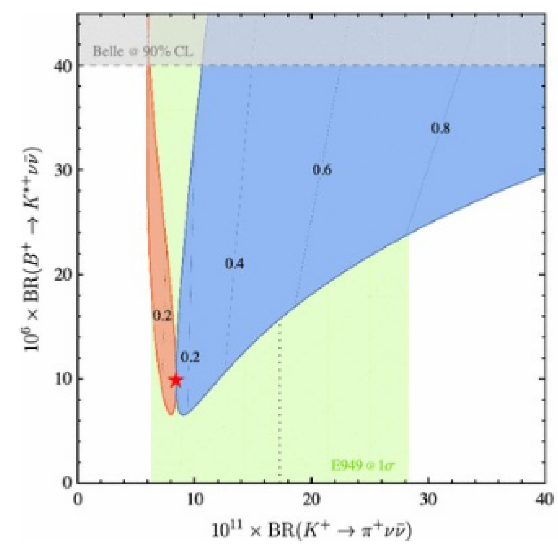
Z'(5 TeV) in Constrained MFV



Randall Sundrum



LFU violation



- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM Analysis [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27], [Isidori et al. JHEP 0608 (2006) 064]
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- LFU violation models [Isidori et al., Eur. Phys. J. C (2017) 77: 618]

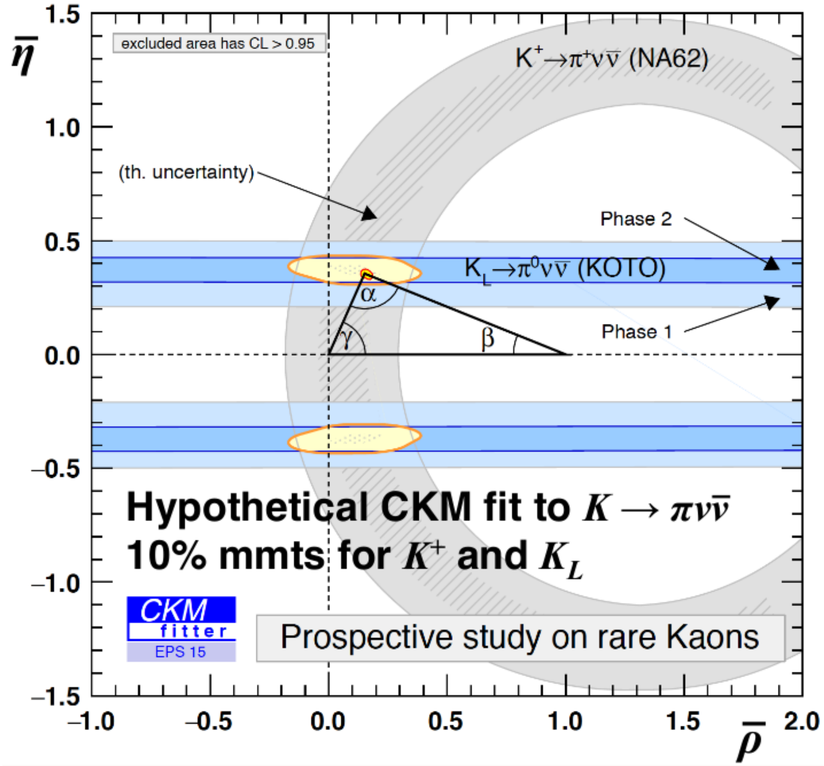
$K^+ \to \pi^+ \nu\bar{\nu}$: theoretical framework

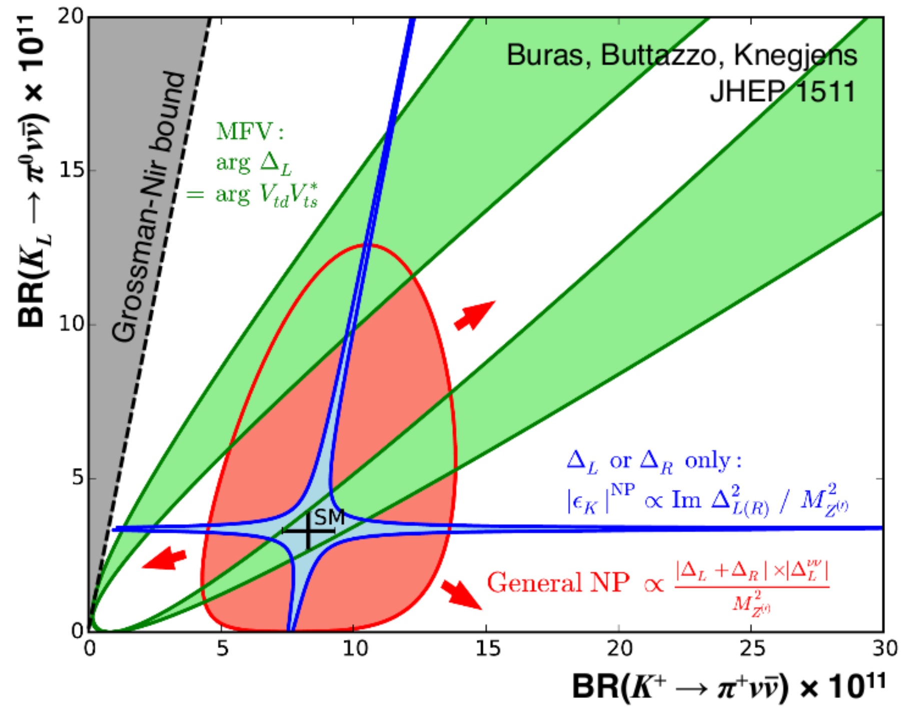
- Measuring both $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ can provide the CKM unitarity triangle independently from the B inputs.
- Dominant uncertainties for SM BR from CKM matrix elements.

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2°}\right]^{0.74}$$

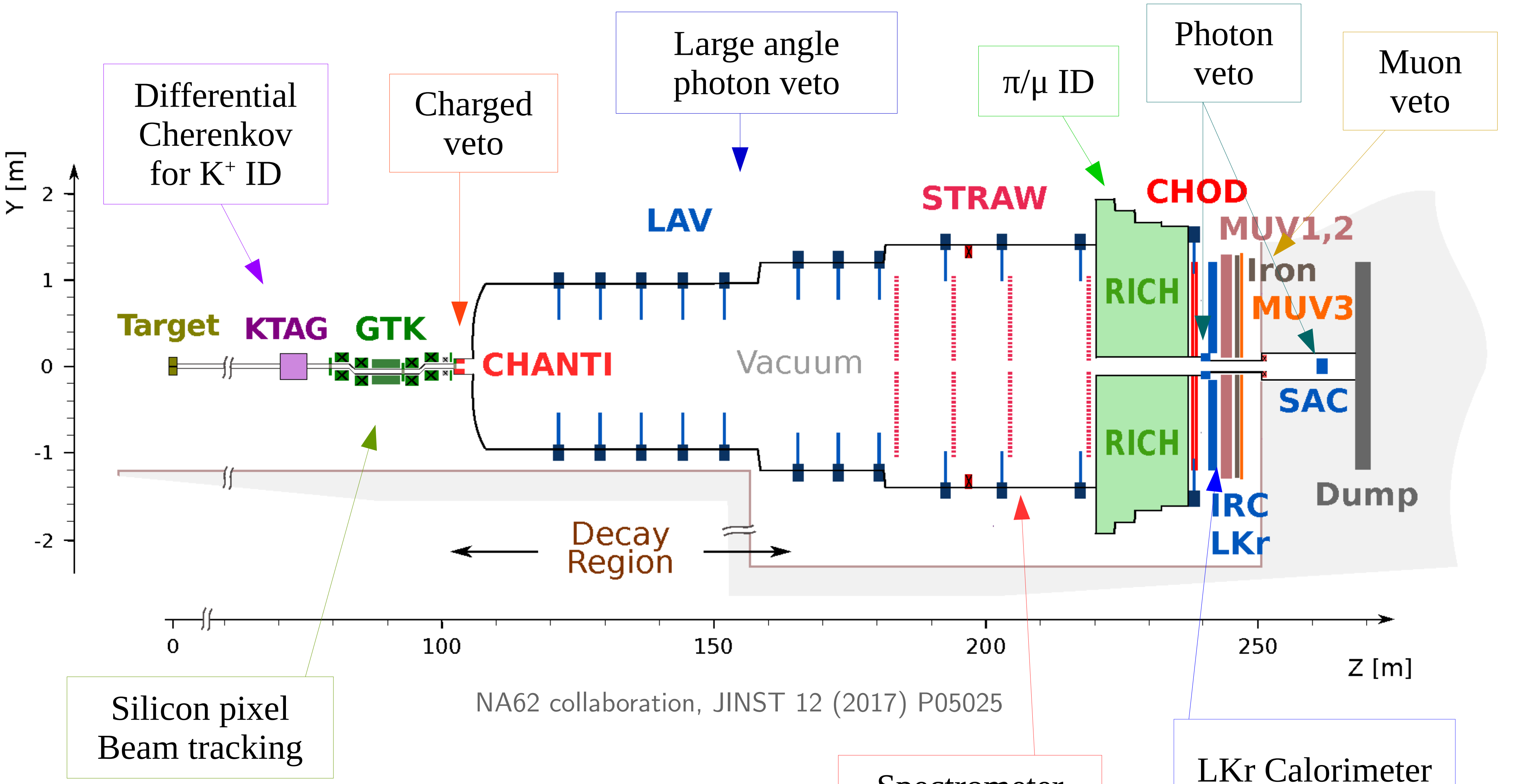
$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2°}\right]^{2}$$

Buras et al., JHEP 1551



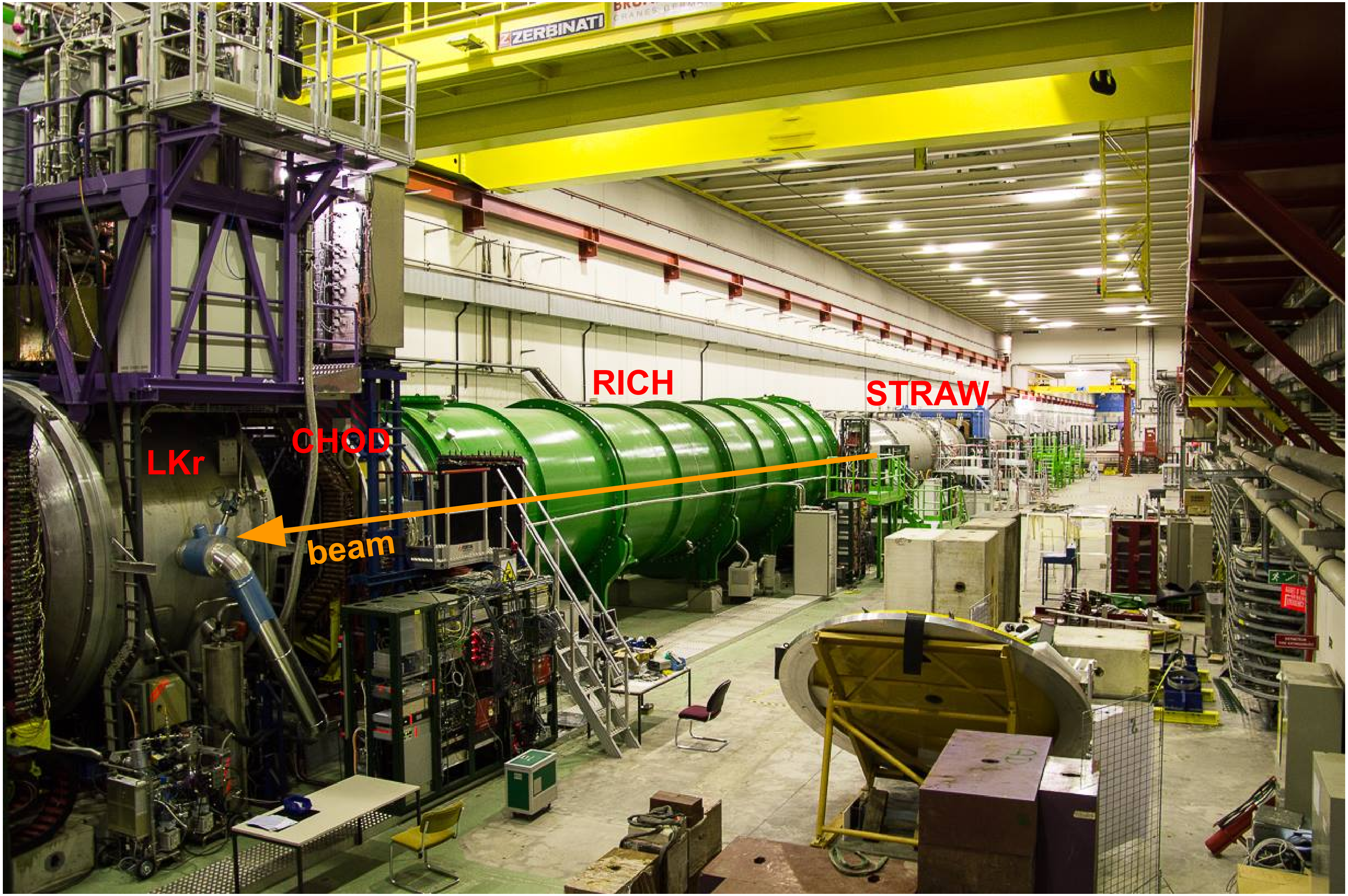


NA62 detector



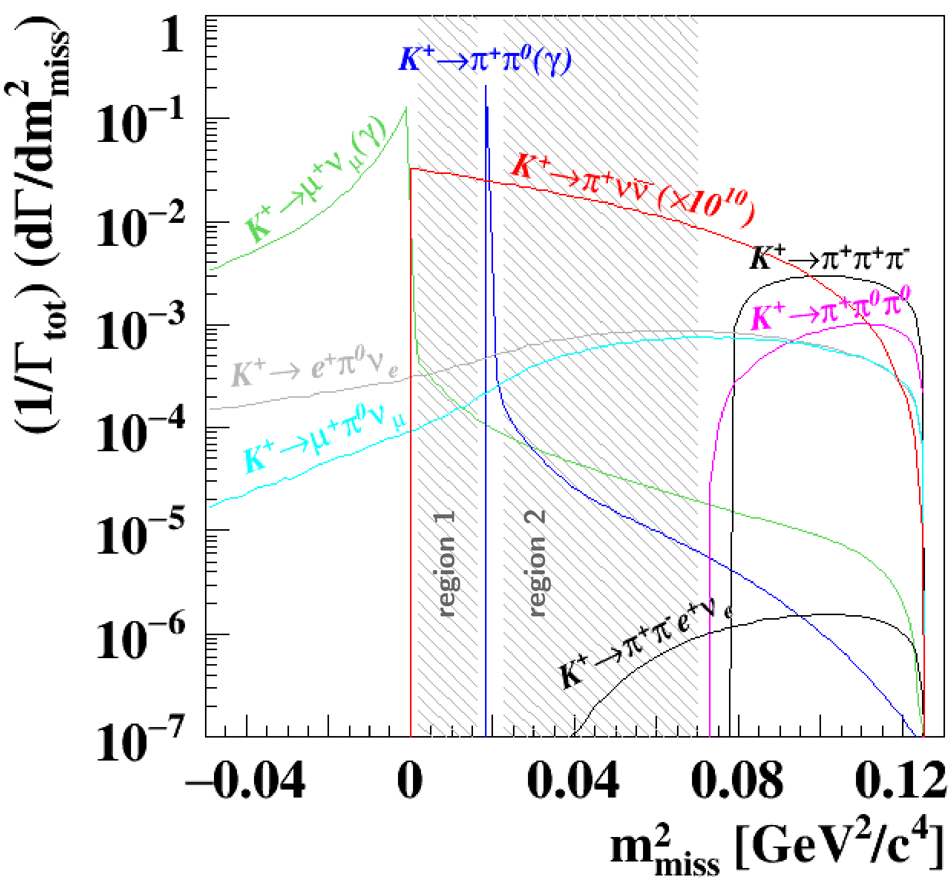
- Primary beam: 400 GeV/c protons from SPS.
- Secondary beam: 75 GeV/c positively charged particles, 70% π^+, 23% p, 6% K^+.

NA62 detector



$K^+\to\pi^+\nu\bar{\nu}$: decay in flight technique at NA62

Main background sources



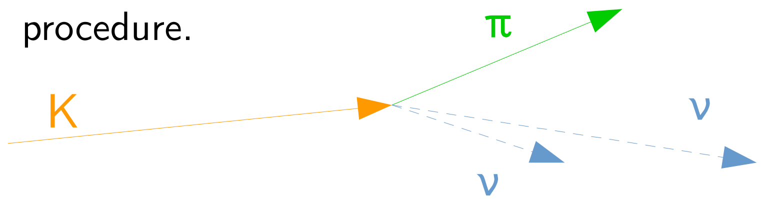
Decay mode	BR	Main rejection tools
$K^+\to\mu^+\nu(\gamma)$	63%	μ–ID + kinematics
$K^+\to\pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+\to\pi^+\pi^+\pi^-$	6%	multi + kinematics
$K^+\to\pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+\to\pi^0 e^+\nu_e$	5%	e–ID + γ-veto
$K^+\to\pi^0\mu^+\nu_\mu$	3%	μ–ID + γ-veto

- The squared missing mass is the main variable used to kinematically separate signal from background:

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

$$15\ \text{GeV/c} < P_{\pi^+} < 35\ \text{GeV/c}$$

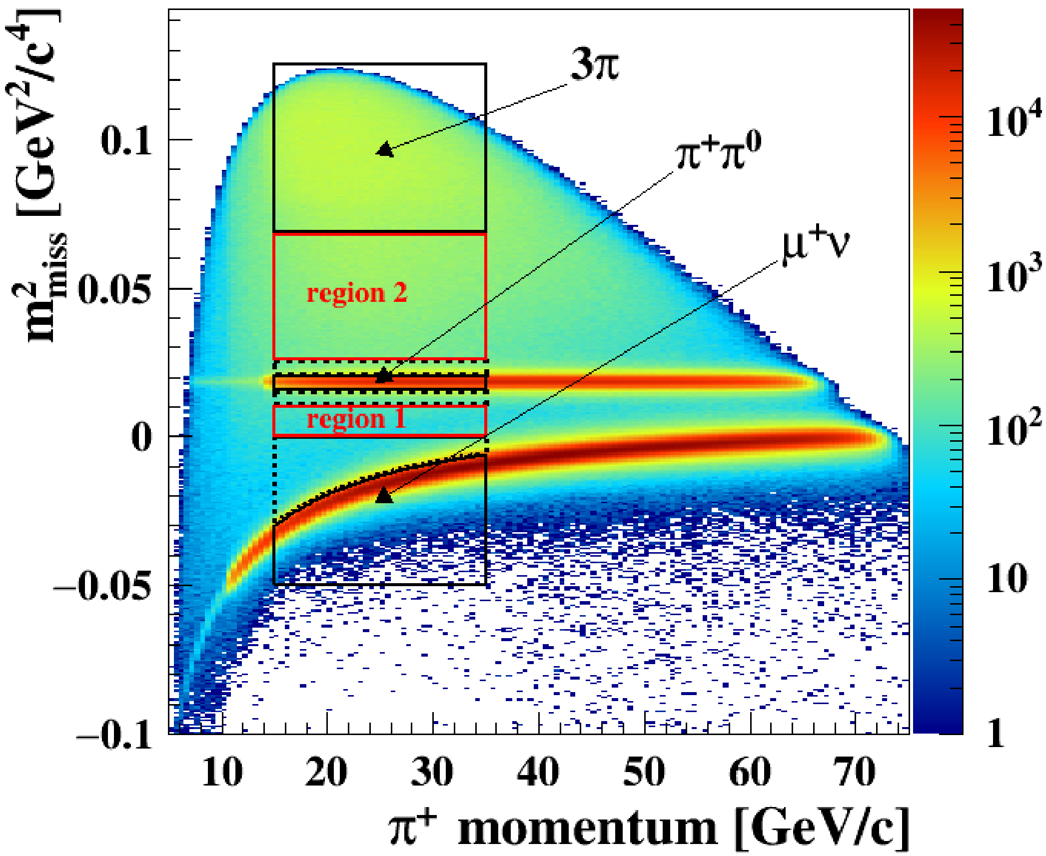
- Two signal region on each side of the K→π+π0 peak.
- Cut based analysis (mostly), blind analysis procedure.



- Requirements:
  - O(100 ps) timing between sub-detectors
  - O(10^4) background suppression with kinematics
  - O(10^7) background muon suppression ($K^+\to\mu^+\nu_\mu$)
  - O(10^7) photon suppression ($K^+\to\pi^+\pi^0$)

$K^+ \to \pi^+ \nu \bar{\nu}$: signal and control regions

- Two signal regions kept blinded
- In order to evaluate the background from K decays, the tails of the distribution are extrapolated into the signal regions.
- The control regions are kept blinded too, to validate the procedure.



- Selection:
  - single track in final state
  - π^+ identification
  - photon rejection
  - 110 m < z_{vertex} < 165 m
  - 15 GeV/c < $p_{\pi+}$ < 35 GeV/c, in order to have at least E_{miss} = 40 GeV and have an optimal π/μ separation in the RICH.
- Performances:
  - $\varepsilon(\mu^+) = 10^{-8}$ (64% π^+ efficiency)
  - $\varepsilon(\pi^0) = 3 \cdot 10^{-8}$
  - $\sigma(m^2_{miss}) = 10^{-3}$ GeV^2/c^4
  - σ_t = O(100 ps)

$K^+ \to \pi^+ \nu\bar{\nu}$: Single Event Sensitivity (2016)

- N_K from $K^+ \to \pi^+\pi^0$ control trigger: $(1.21 \pm 0.02) \times 10^{11}$

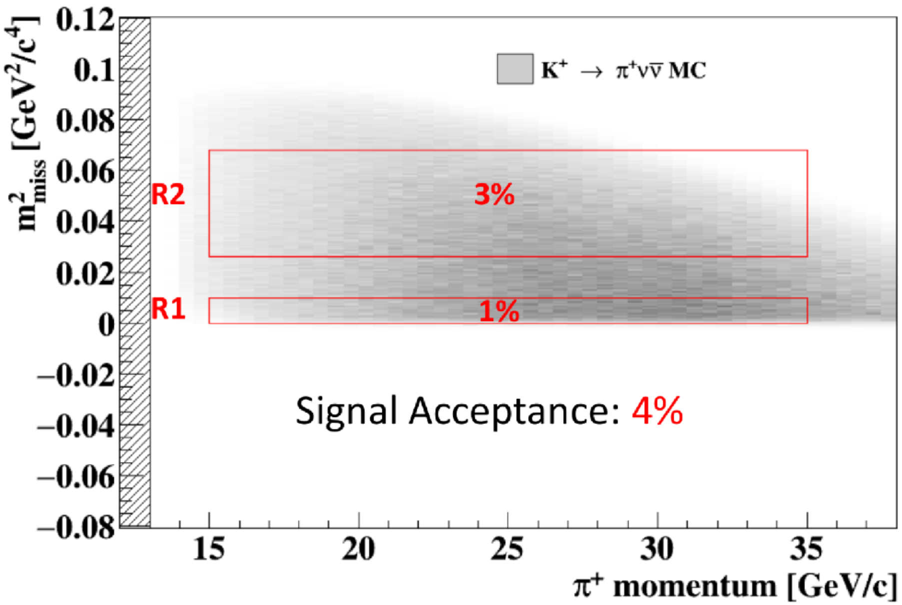
$$N_K = \frac{N_{\pi\pi} \cdot R}{A_{\pi\pi} \cdot BR_{\pi\pi}}$$ (R: reduction factor applied to CTRL trigger)

- $K^+ \to \pi^+ \nu\bar{\nu}$ acceptance: $(4.0 \pm 0.1) \times 10^{-2}$
- Random veto efficiency: 0.76 ± 0.04
- Trigger efficiency: 0.87 ± 0.2

$$SES = \frac{1}{N_K \cdot \sum_j \left(A^j_{\pi\nu\nu} \cdot \epsilon^j_{\text{trig}} \cdot \epsilon^j_{\text{RV}}\right)}$$

$$N^{\text{expected}}_{\pi\nu\nu}(\text{SM}) = \frac{BR_{\pi\nu\nu}(\text{SM})}{SES}$$

Source	δ SES (10^{-10})
Random veto	± 0.17
Definition of $\pi^+\pi^0$ region	± 0.10
Simulation of π^+ interactions	± 0.09
N_K	± 0.05
Trigger efficiency	± 0.04
Extra activity	± 0.02
GTK pileup simulation	± 0.02
Momentum spectrum	± 0.01
Total	± 0.24



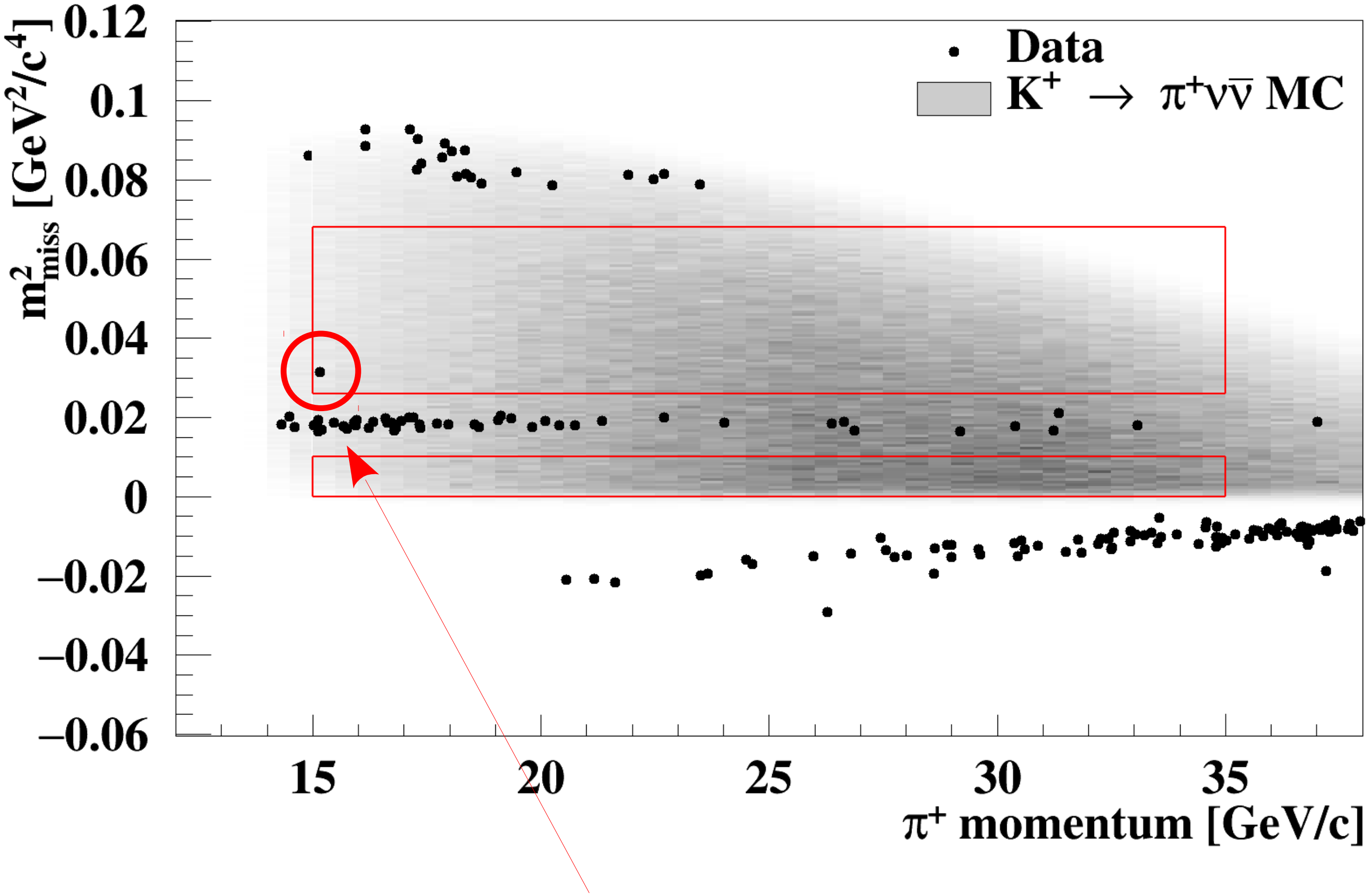
$$SES = (3.15 \pm 0.01_{\text{stat}} \pm 0.24_{\text{syst}}) \cdot 10^{-10}$$

$$N^{\text{expected}}_{\pi\nu\nu}(\text{SM}) = 0.267 \pm 0.001_{\text{stat}} \pm 0.020_{\text{syst}} \pm 0.032_{\text{extr}}$$

$K^+ \to \pi^+ \nu\bar{\nu}$: expected background (2016)

Process	Expected events in R1+R2
$K^+ \to \pi^+ \nu\bar{\nu}$	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
$K^+ \to \pi^+ \pi^0 (\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+ \nu (\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+ \pi^- e^+ \nu$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+ \pi^+ \pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}\vert_{stat}$

$K^+ \to \pi^+ \nu\bar{\nu}$: results (2016)



1 event observed in region 2!

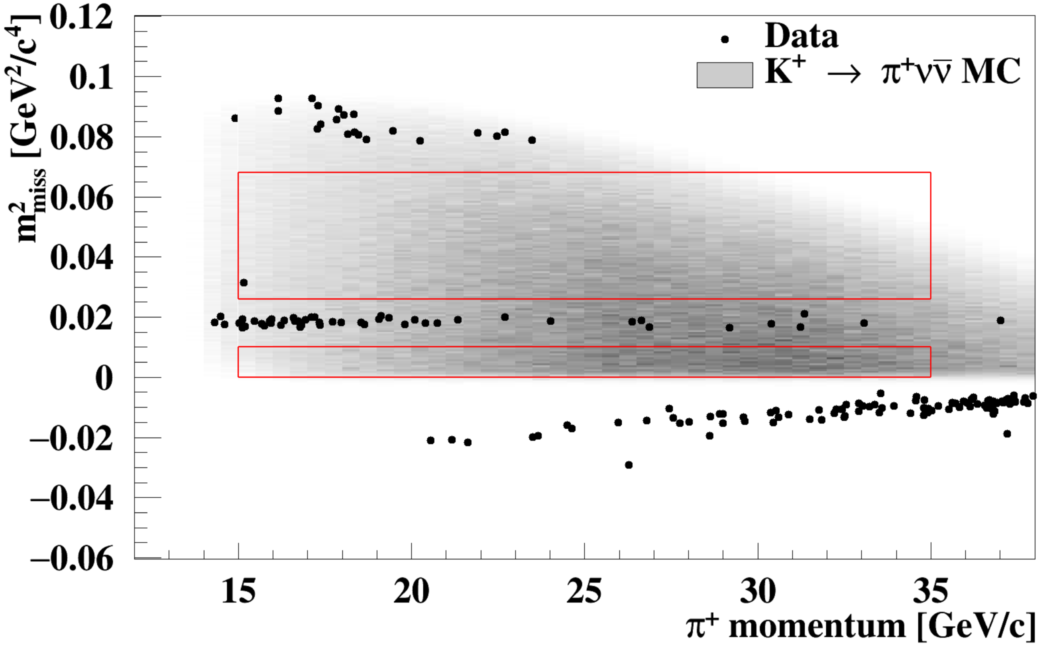
Signal events expected in signal region (SM)

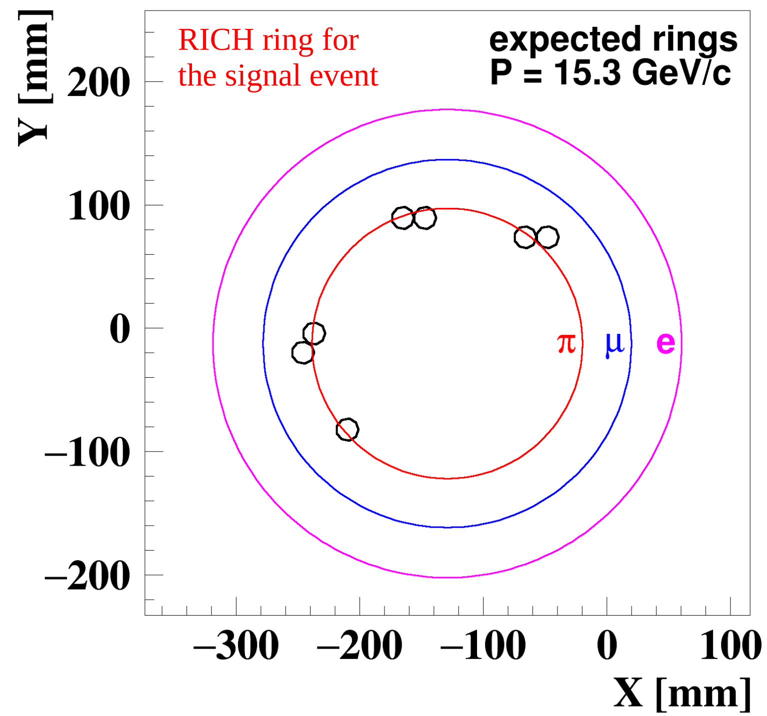
$$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{extr}$$

Background events expected in signal region

$$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$$

$K^+ \to \pi^+ \nu\bar{\nu}$: results (2016)





- Upper limits on the Branching Ratio: $BR(K^+ \to \pi^+ \nu \bar{\nu}) < 11 \cdot 10^{-10}$ @90%CL

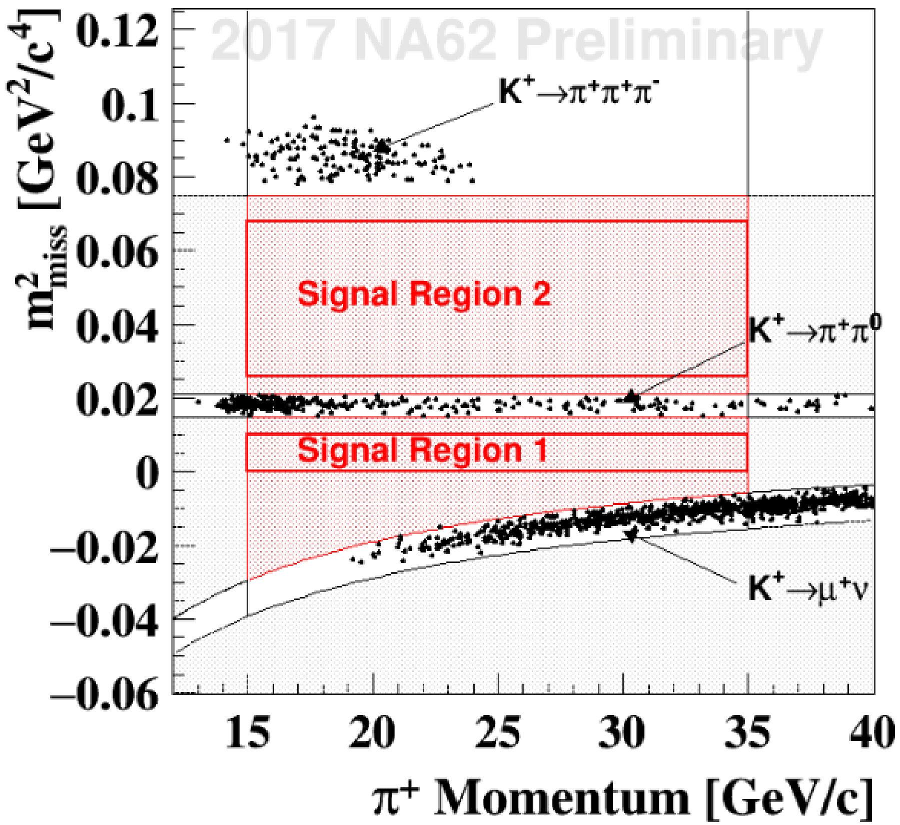
  $BR(K^+ \to \pi^+ \nu \bar{\nu}) < 14 \cdot 10^{-10}$ @95%CL

- Standard Model prediction on the Branching Ratio:

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (0.84 \pm 0.10) \cdot 10^{-10}$$

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

- Higher beam intensity
- 2016-like selection
- Performances are comparable to 2016
  - Better pile-up treatment in IRC/SAC
  - 40% better π^0 rejection (does not depend on intensity)
  - Slightly improved usage of RICH variables.
- 2 signal regions, like in 2016
- 3 control regions used to evaluate the background
- Signal and control regions kept masked, as well as the region below the $K \to \mu\nu$ used to validate the upstream background.



Process	Expected events in signal regions
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.35 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.16 \pm 0.01_{stat} \pm 0.05_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.22 \pm 0.08_{stat}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.015 \pm 0.008_{stat} \pm 0.015_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	$0.012 \pm 0.012_{syst}$
Upstream Background	Analysis on–going

Single Event Sensitivity

$N_K = (1.3 \pm 0.1) \cdot 10^{12}$ (~10 × 2016)

$SES = (0.34 \pm 0.04) \cdot 10^{-10}$ (scales linearly with intensity)

$N^{expected}_{\pi\nu\nu}(SM) = 2.5 \pm 0.4$

$K^+ \to \pi^+ \nu\bar{\nu}$: conclusions

- One event observed in region 2 in 2016
- This result is compatible with the Standard Model:

  $$BR(K^+ \to \pi^+ \nu \bar{\nu}) < 14 \cdot 10^{-10} \quad @95\% CL$$

  - Published here: [Phys. Lett. B 791 (2019) 156-166]

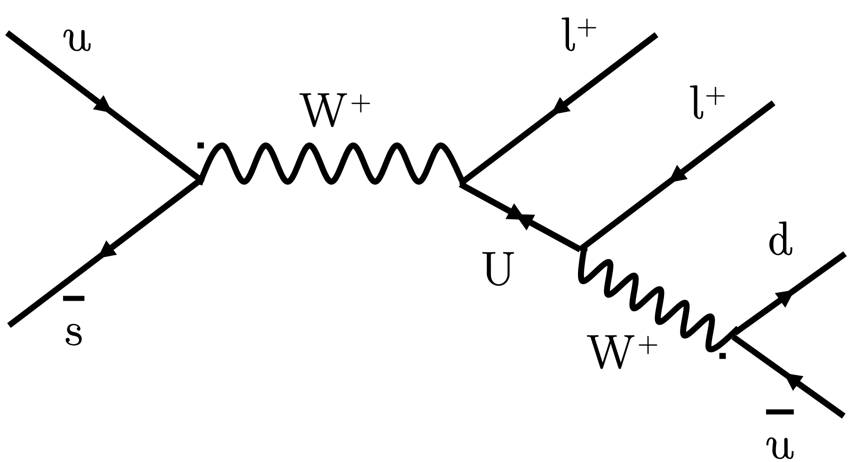
- The analysis of 2017 data is ongoing and results are expected very soon.
  - A factor 10 with respect to 2016 is expected from statistics
  - Signal over background ratio does not degrade with intensity
  - Strong effort to improve the analysis

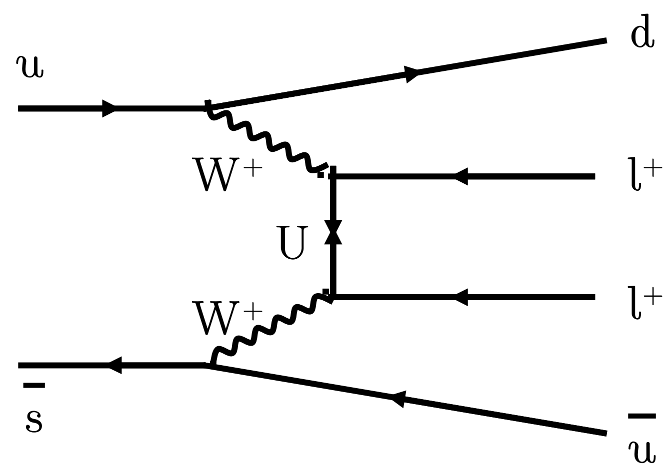
- Branching ratio measurement expected in the next few years.

LNV and LFV

- In the Standard Model, if neutrinos are massless, lepton flavour numbers (L_e, L_μ, L_τ) and the total lepton number (L) are conserved quantities.
- Neutrino oscillation experiments proved that individual lepton numbers are not conserved.
- Neutrino masses are non-zero and different, and the weakly interacting neutrinos are superpositions of the mass eigenstates.
- Oscillations don't necessarily imply the total lepton number violation, that is expected only if neutrinos are Majorana fermions.

- Violation of these conservation laws in models BSM via Majorana neutrinos (U).
- E.g. $K^+ \to \pi^- l^+ l^+$ (l = e, μ), with $\Delta L = 2$ and $\Delta L_e = 2$ or $\Delta L_\mu = 2$.
  [JHEP 0905 (2009) 030], [Phys.Lett. B491 (2000) 285-290]

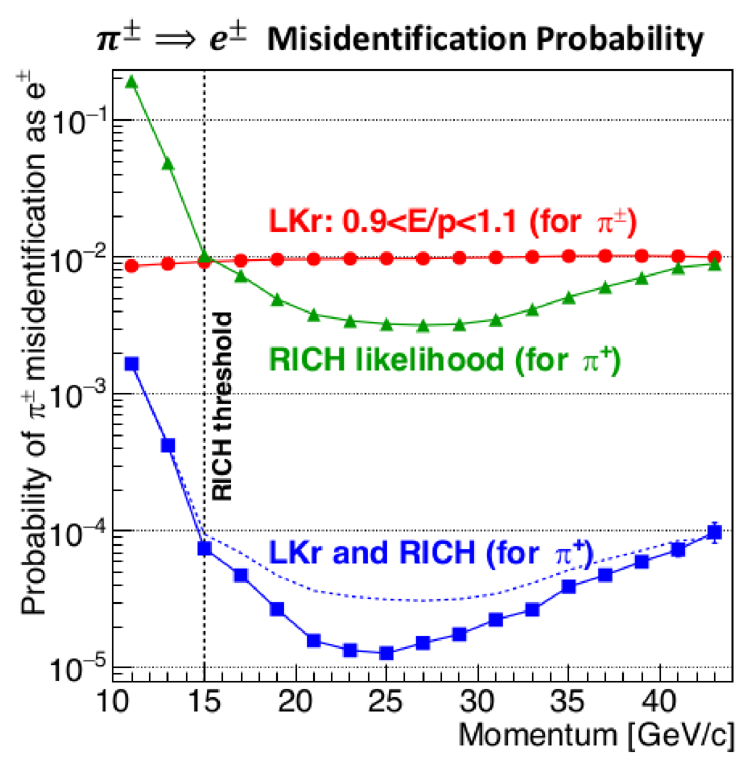




- Previous experimental results (@90% CL):
  - $BR_{th}\left(K^+ \to \pi^- e^+ e^+\right) < 6.4 \cdot 10^{-10}$ BNL E865 [PRL 85 2877 (2000)]
  - $BR_{th}\left(K^+ \to \pi^- \mu^+ \mu^+\right) < 8.6 \cdot 10^{-11}$ NA48/2 [Phys. Lett. B769 67 (2017)]

LNV and LFV: NA62 search

- Subset of 2017 data, corresponding to 3 months of data taking.
  - 3 times more data still to be analyzed.
- Blind analysis
- Normalization from corresponding SM channels
- Triggers: L0 (hardware) + L1 (software)
- Main background from π^+ misID and π^+ decays in flight (e.g. from $K^+ \to \pi^+\pi^+\pi^-$).

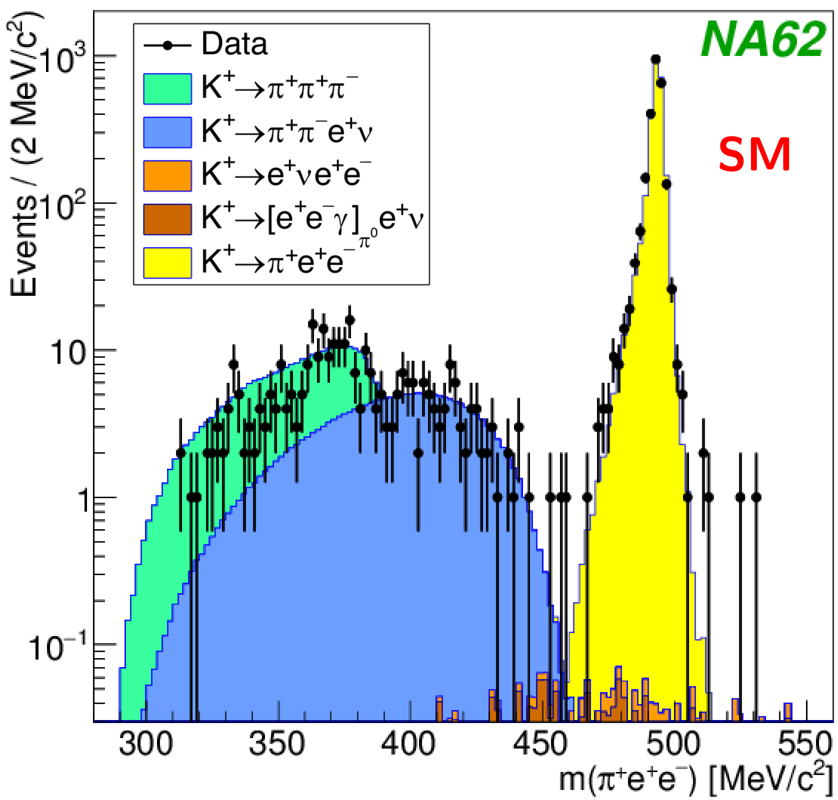


Trigger Name	Description	Use in LNV/LFV Searches
Di-Muon	3 tracks with 2 μ candidates (MUV3)	Collect SM $K^+ \to \pi^+\mu^+\mu^-$ & LNV $K^+ \to \pi^-\mu^+\mu^+$
Multi-Track e	3 tracks with 20 GeV energy deposit in LKr	Collect SM $K^+ \to \pi^+e^+e^-$ & LNV $K^+ \to \pi^-e^+e^+$
Multi-Track	Minimum bias 3-track trigger	Control samples for background studies

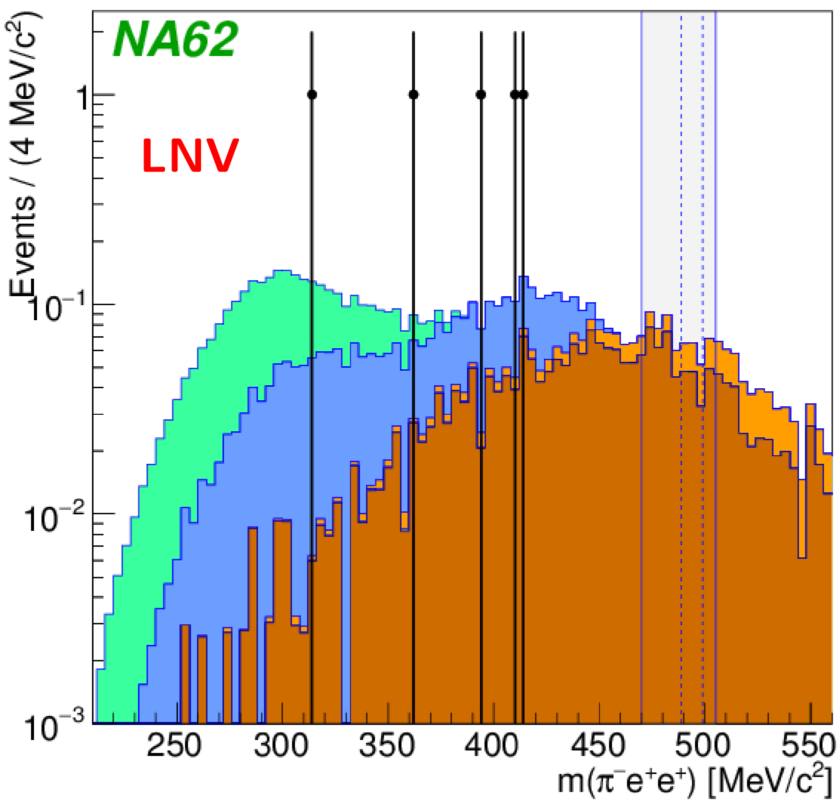
LNV and LFV: NA62 search

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

SM: $K^+ \to \pi^+ e^+ e^-$ (m_{ee} > 140 MeV/c^2)



LNV: $K^+ \to \pi^- e^+ e^+$ (no event observed)



- Bkg prediction: $N_{bkg} = 0.16 \pm 0.03$
- Observed: $n_{obs} = 0$
- $N_K = (2.14 \pm 0.07) \times 10^{11}$
- $SES = (0.94 \pm 0.03) \times 10^{-10}$

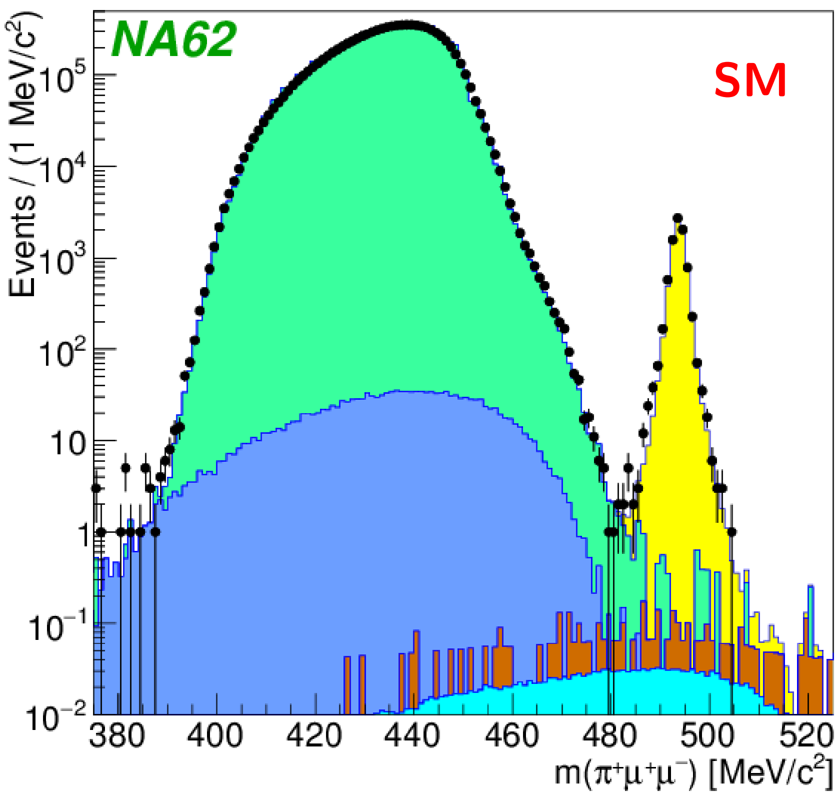
$BR(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ @90% CL

$PDG < 6.4 \times 10^{-10}$ @90% CL

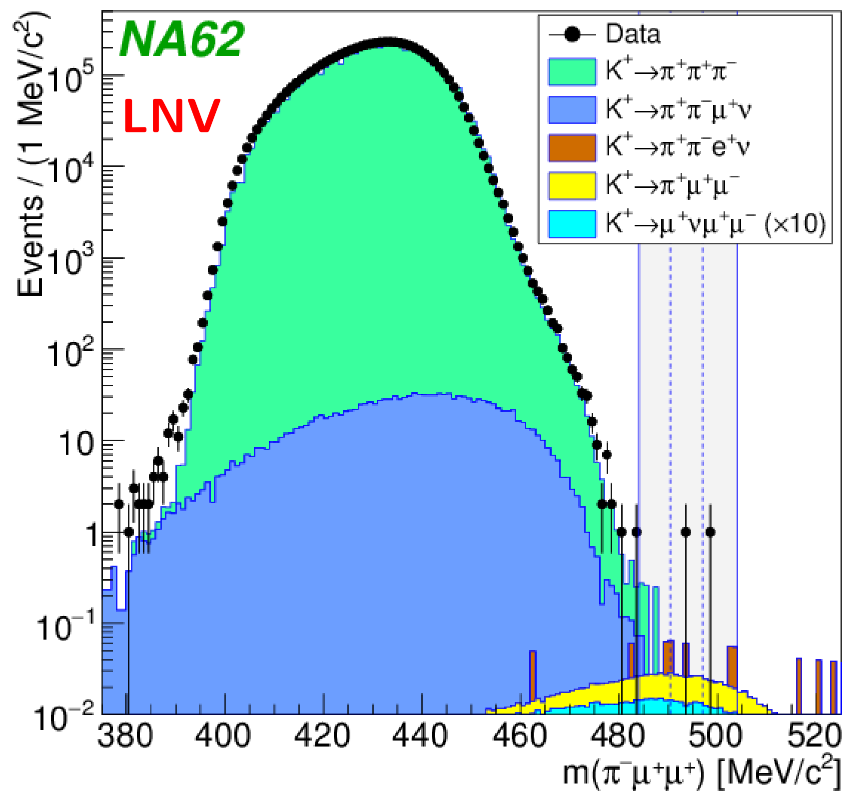
LNV and LFV: NA62 search

Search for $K^+ \to \pi^- \mu^+ \mu^+$

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



LNV: $K^+ \to \pi^- \mu^+ \mu^+$ (1 event observed)



- Bkg prediction: $N_{\mathrm{bkg}} = 0.91 \pm 0.41$
- Observed: $n_{\mathrm{obs}} = 1$
- $N_K = (7.94 \pm 0.23) \times 10^{11}$
- $SES = (1.28 \pm 0.03) \times 10^{-11}$

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

$$PDG < 8.6 \times 10^{-11} \text{@90\% CL}$$

LNV and LFV: results

- New NA62 results with a subset of 2017 data improve world upper limits on the BR of $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi^- \mu^+ \mu^+$.
- No new physics observed.
- Very low background in both searches.

Decay	BR UL @ 90% CL	PDG UL @ 90% CL
$K^+ \to \pi^- e^+ e^+$	2.2×10^{-10}	6.4×10^{-10} (E865)
$K^+ \to \pi^- \mu^+ \mu^+$	4.2×10^{-11}	8.6×10^{-11} (NA48/2)

arXiv:1905.07770

Conclusions

- The decay in flight technique to measure BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) works:
  - 1 event observed in 2016 data
  - $\mathrm{BR}\left(K^+ \rightarrow \pi^+ \nu \bar{\nu}\right) < 14 \cdot 10^{-10}$ @ 95% CL
  - 2017 analysis ongoing, BR measurement expected in a few years.

- First results from LNV/LFV searches improve world upper limits on the BR of the $K^+ \rightarrow \pi^- e^+ e^+$ and $K^+ \rightarrow \pi^- \mu^+ \mu^+$ decays (3x more data still to be analyzed).

- Running after LS2 will allow to fully exploit the possibilities of the detector with minimal upgrades.

THANK YOU!

NA62