



29th International Symposium on Lepton Photon Interactions at High Energies

5–10th August, 2019, Toronto, Canada



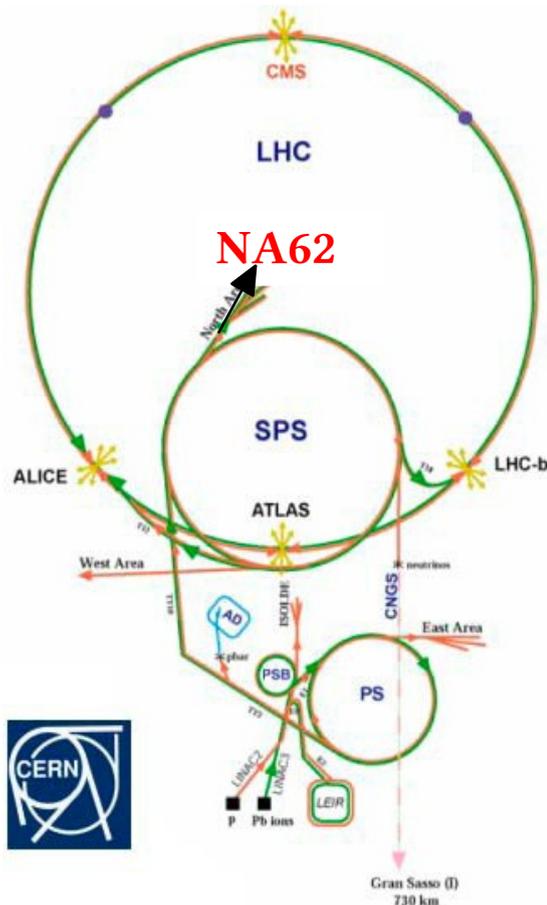
Physics beyond SM with kaons at NA62

Outline:

- ◆ The NA62 experiment at the CERN SPS
- ◆ $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with the 2017 data
- ◆ Results on LFV-LNV searches
- ◆ Conclusions and prospects

Speaker: Radoslav Marchevski
On behalf of the NA62 collaboration

The NA62 experiment



NA62 timeline

Dec 2008: NA62 Approval

2009 – 2014: Detector R&D and installation

2015: Commissioning

2016 – 2018: NA62 Run 1

2021 – 2023: NA62 Run2 (TBA)

NA62 primary goal: measurement of the ultra rare kaon decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

This talk

NA62 Collaboration consist of ~ 200 participants from: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Merced, Moskow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, Sofia, San Luis Potosi, Turin, TRIUMF, Vancouver UBC

The NA62 programme beyond $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

■ Standard kaon physics

★ Branching fraction measurements of all main K^+ decay modes

★ χ_{PT} : $K^+ \rightarrow \pi^+ \gamma \gamma$, $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$

★ Lepton universality: $R_K = \Gamma(K^+ \rightarrow e^+ \nu_e) / \Gamma(K^+ \rightarrow \mu^+ \nu_\mu)$

■ Rare and forbidden K^+ and π^0 decays

★ K^+ physics: $K^+ \rightarrow \pi^+ l^+ l^-$, $K^+ \rightarrow \pi^+ \gamma l^+ l^-$, $K^+ \rightarrow l^+ \nu \gamma$, [$l = e, \mu$]

★ **LNV/LFV searches**: $K^+ \rightarrow \pi^+ \mu^\pm e^\mp$, $K^+ \rightarrow \pi^- \mu^+ e^+$, $K^+ \rightarrow \pi^- l^+ l^+$ [$l = e, \mu$]

★ π^0 physics: $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow e^+ e^-$, $\pi^0 \rightarrow e^+ e^- e^+ e^-$, $\pi^0 \rightarrow \gamma \gamma (\gamma)$

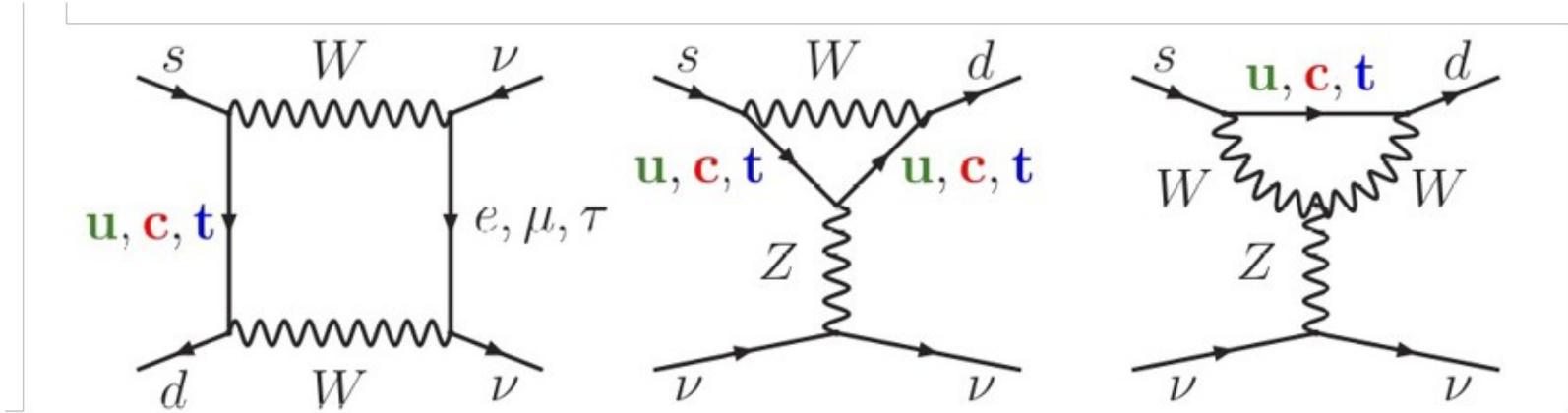
This talk 

■ Exotics searches

★ Heavy Neutral Lepton (HNL) production: $K^+ \rightarrow l^+ \nu_h$

★ Dark photon (A'): $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow A' \gamma$, $A' \rightarrow$ invisible

The FCNC process $K \rightarrow \pi \nu \bar{\nu}$



- FCNC loop processes: $s \rightarrow d$ coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with K_{l3} decays
- SM predictions: Buras. et. al., JHEP11(2015)033

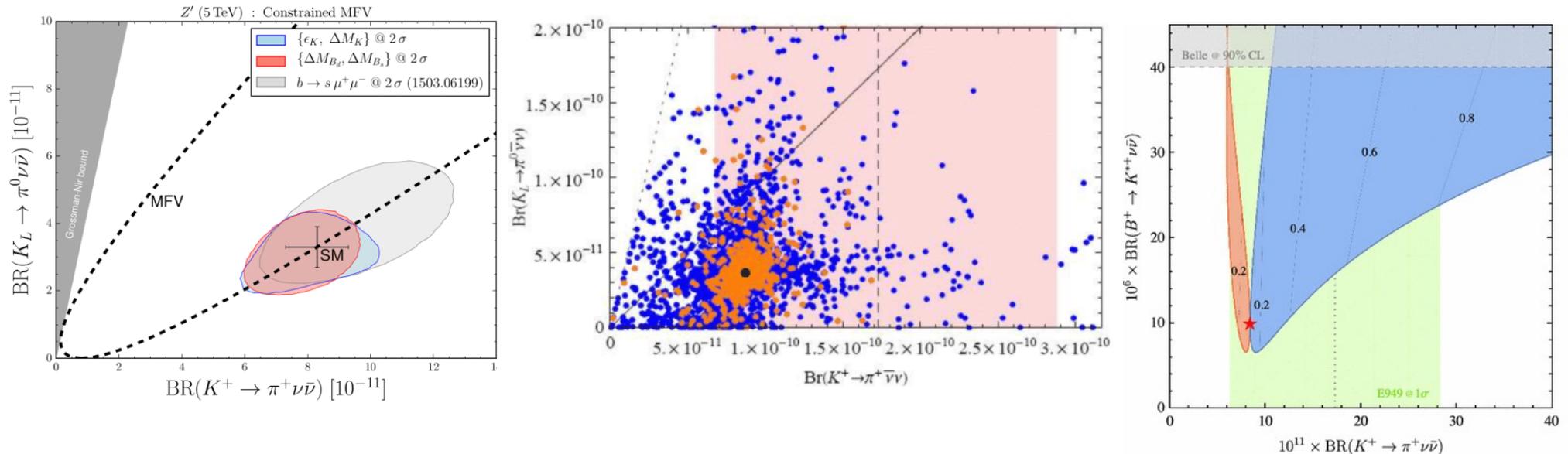
$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left(\frac{|V_{cb}|}{0.0407} \right)^{2.8} \left(\frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$$

$$BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \left(\frac{|V_{ub}|}{0.00388} \right)^2 \left(\frac{|V_{cb}|}{0.0407} \right)^2 \left(\frac{\sin \gamma}{\sin 73.2^\circ} \right)^2 = (3.4 \pm 0.6) \times 10^{-11}$$

$K \rightarrow \pi \nu \bar{\nu}$ beyond the Standard Model

- 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]
- Simplified Z, Z' models [Buras, Buttazzo, Knecht, 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]
- Leptoquarks [S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]
- Constraints from existing measurements (correlations model dependent)

★ Kaon mixing, CKM elements, K, B rare meson decays, NP limits from direct searches

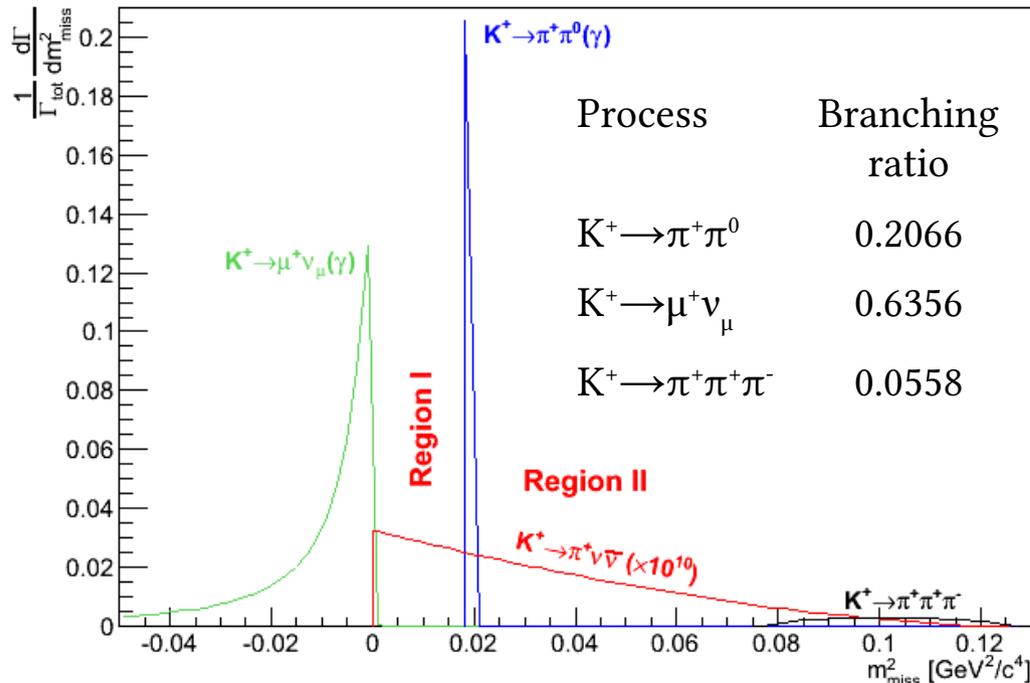
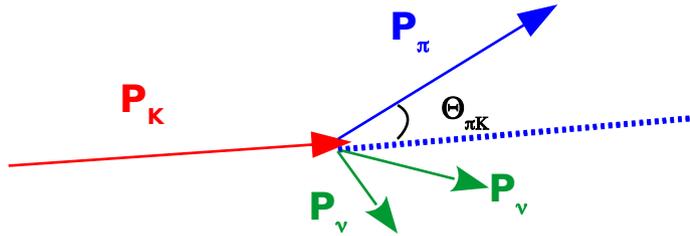


Analysis strategy

NEW

Decay in flight
technique

$$m_{\text{miss}}^2 = (\mathbf{P}_K - \mathbf{P}_{\pi^+})^2$$



Keystones of the analysis:

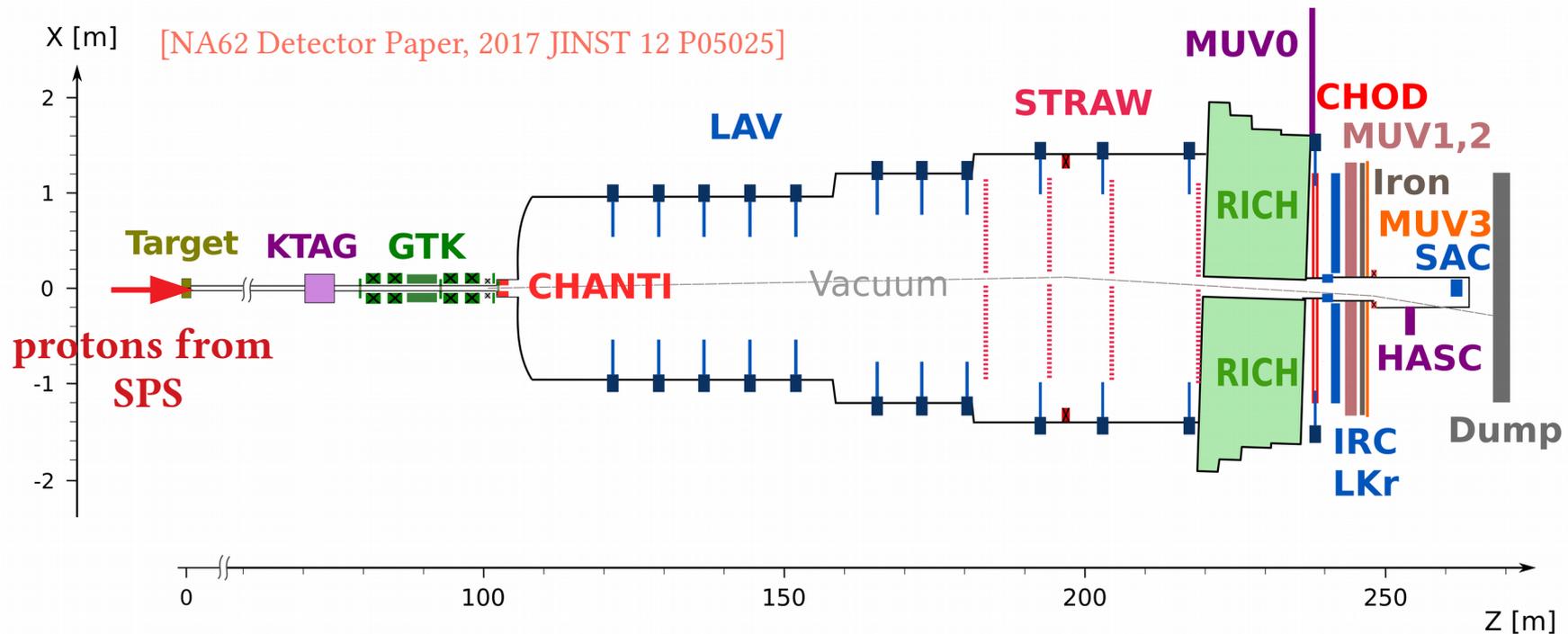
- ★ Timing between sub-detectors $\sim O(100 \text{ ps})$
- ★ Kinematic suppression $\sim O(10^4)$
- ★ Muon suppression $> 10^7$
- ★ π^0 suppression (from $K^+ \rightarrow \pi^+ \pi^0$) $> 10^7$

Signal and background control regions are kept blind throughout the analysis

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

- + Particle ID (Cherenkov detectors)
- Particle ID (Calorimeters)
- Photon veto

NA62 detector



■ SPS Beam:

- ★ 400 GeV/c protons
- ★ $2 \cdot 10^{12}$ protons/spill
- ★ 3.5s spill
- ★ $\sim 10^{18}$ POT/year

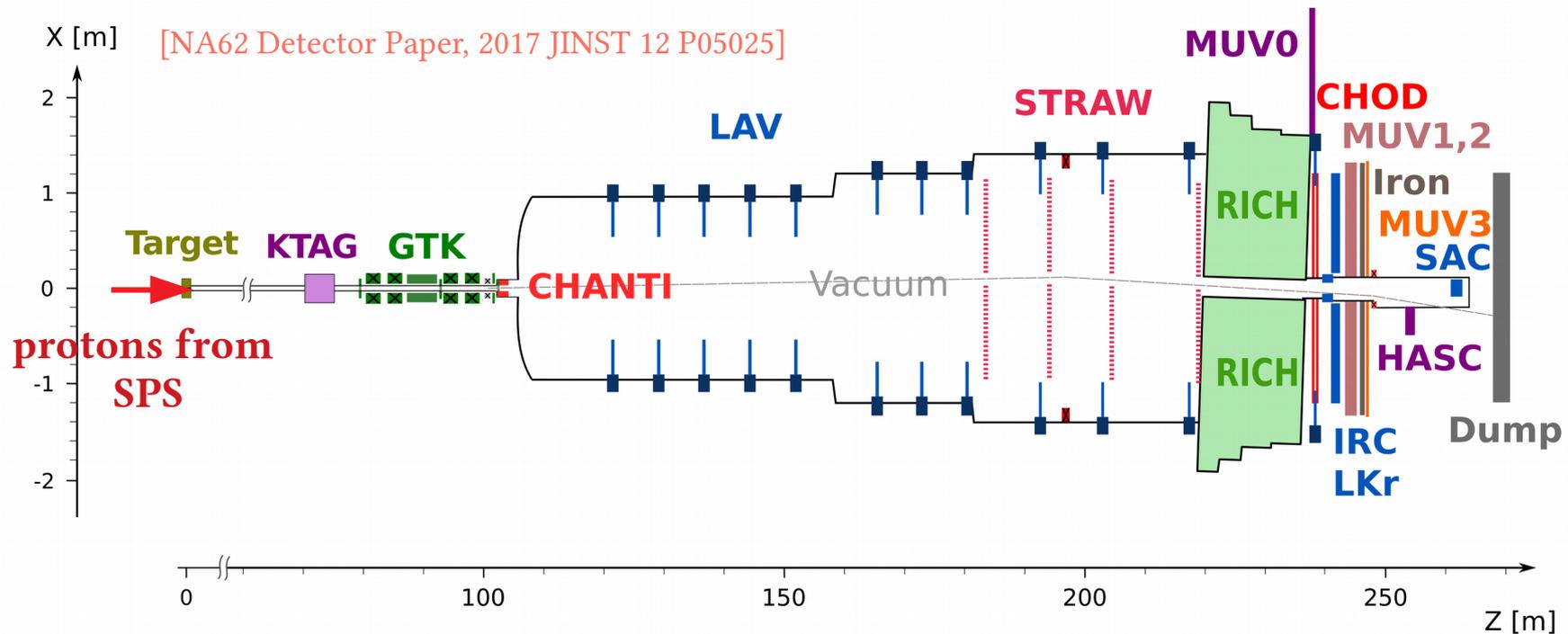
■ Secondary positive Beam:

- ★ 75 GeV/c momentum, 1 % bite
- ★ 100 μ rad divergence (RMS)
- ★ 60x30 mm² transverse size
- ★ $K^+(6\%)/\pi^+(70\%)/p(24\%)$
- ★ 750 MHz of particles at GTK3

■ Decay Region:

- ★ 75 m long fiducial region
- ★ ~ 5 MHz K^+ decay rate
- ★ Vacuum $\sim O(10^{-6})$ mbar

NA62 detector



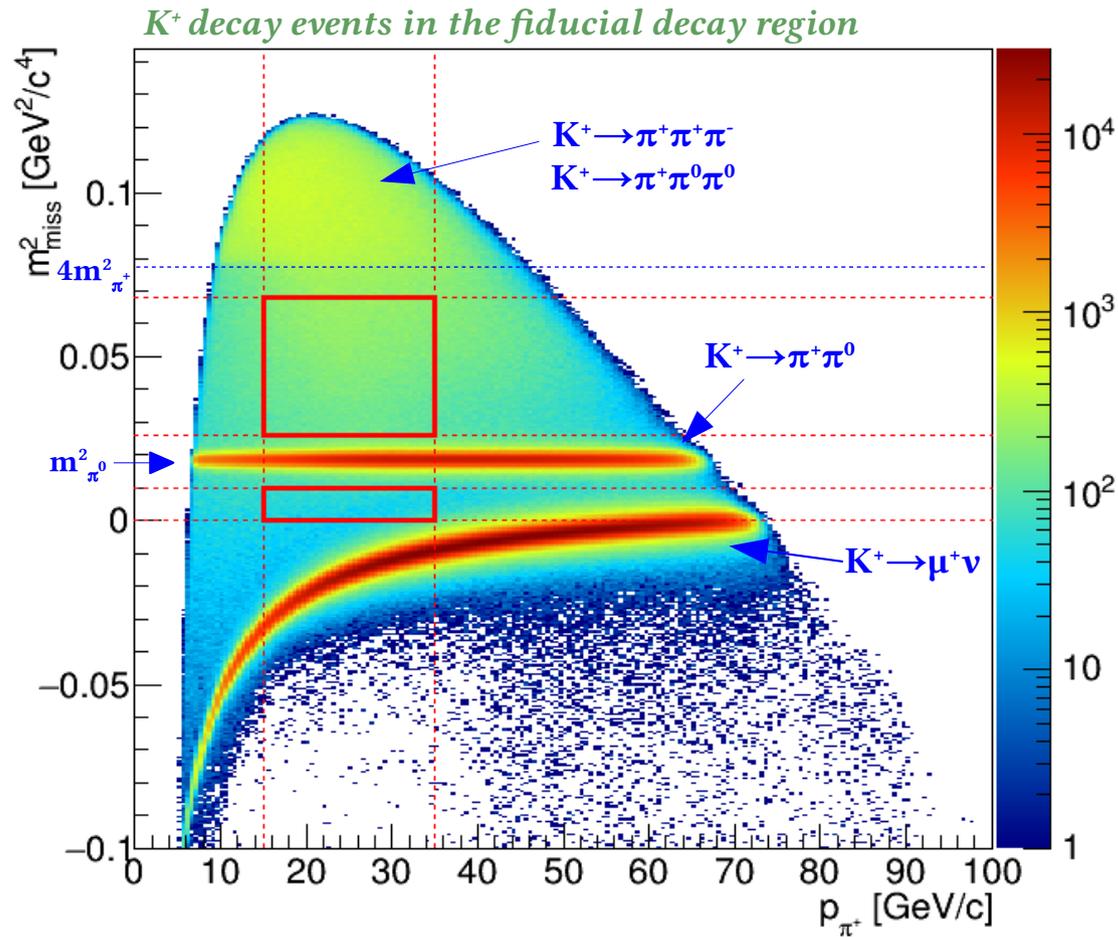
■ Upstream detectors (K^+):

- ★ **KTAG:** Differential Cherenkov counter for K^+ ID
- ★ **GTK:** Si pixel beam tracker
- ★ **CHANTI:** Anti-counter for inelastic beam-GTK3 interactions

■ Decay Region detectors (π^+):

- ★ **STRAW:** track momentum spectrometer
- ★ **CHOD:** Scintillator hodoscopes
- ★ **LKr/MUV1/MUV2:** Calorimetric system
- ★ **RICH:** Cherenkov counter for $\pi/\mu/e$ ID
- ★ **LAV/SAC/IRC:** Photon veto detectors
- ★ **MUV3:** Muon veto

Signal selection



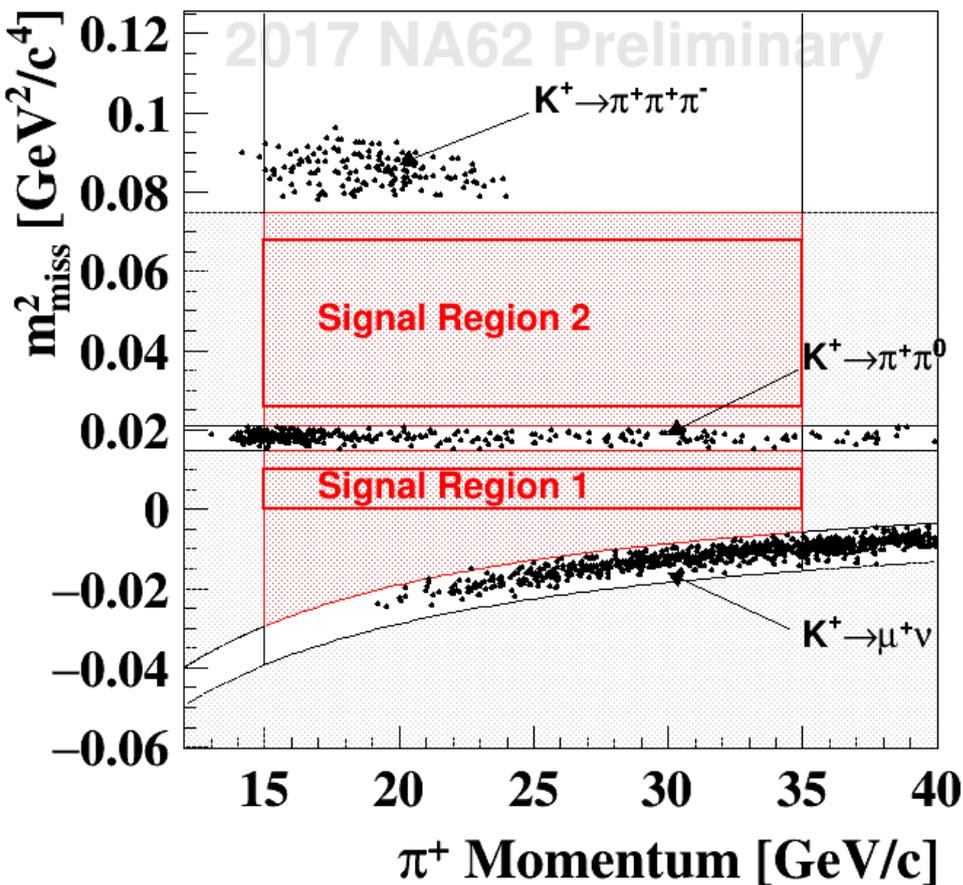
Selection criteria

- ★ single track decay topology
- ★ π^+ identification
- ★ photon rejection
- ★ multi-track rejection

Performance

- ★ $\epsilon_{\mu^+} = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
- ★ $\epsilon_{\pi^0} = (1.4 \pm 0.1) \cdot 10^{-8}$
- ★ $\sigma(m_{\text{miss}}^2) = 1 \cdot 10^{-3} \text{ GeV}^2/c^4$
- ★ $\sigma_T \sim O(100 \text{ ps})$

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with the 2017 data

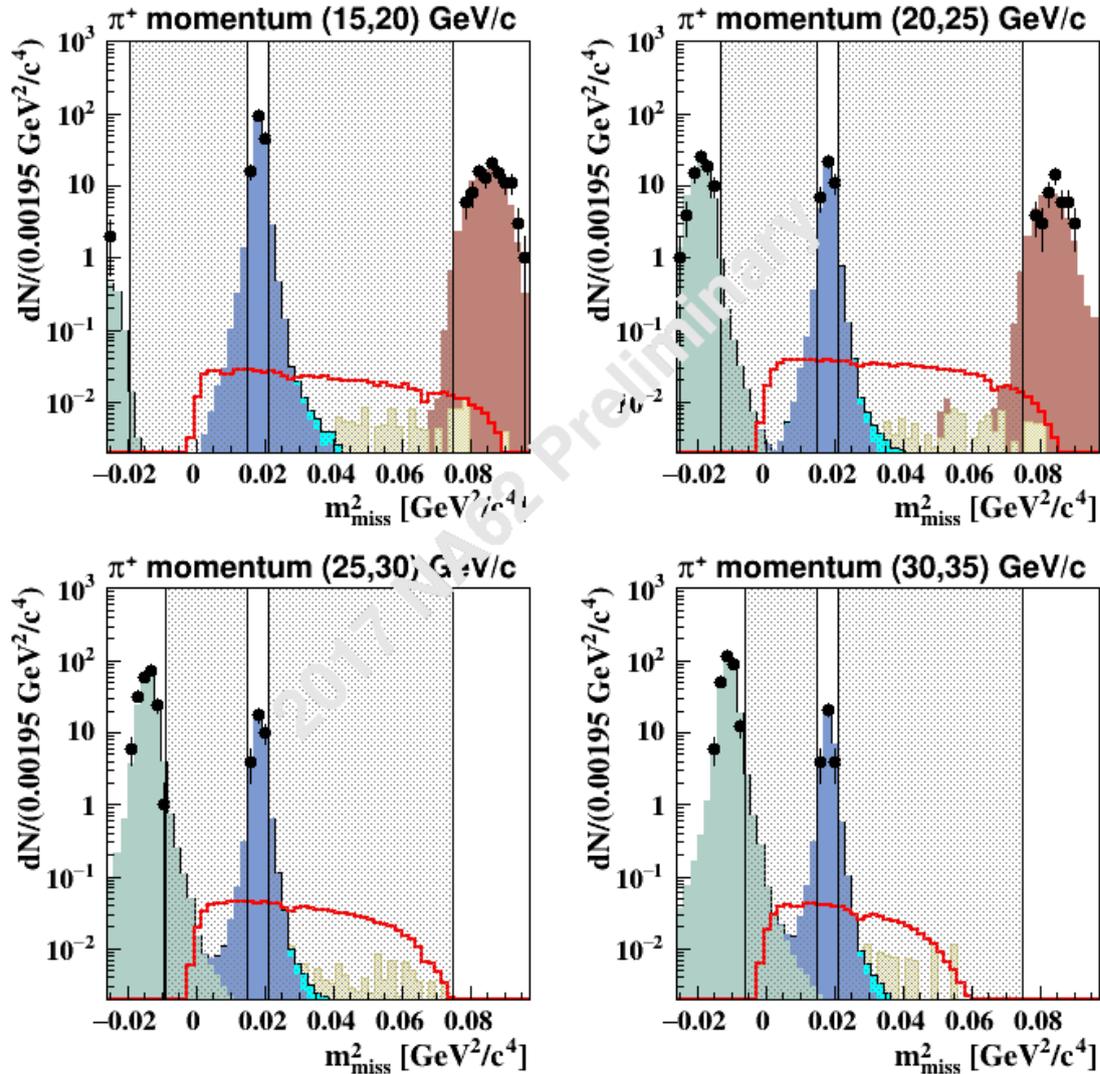


- Selection similar to that in 2016
 - ★ Performances in line with expectation
 - ★ Improved LKr reconstruction
 - ★ Improved π^0 rejection by a factor of 2
 - ★ Improved pileup treatment
- Signal and background control regions blinded until completion of the analysis

Figures of merit for the analysis:

- ◆ $N_K = 1.3(1) \times 10^{12}$ (about 10 times the 2016 data set)
- ◆ $SES = 0.34(4) \times 10^{-10}$ (scales linearly with intensity)
- ◆ Expected SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events: 2.5(4)

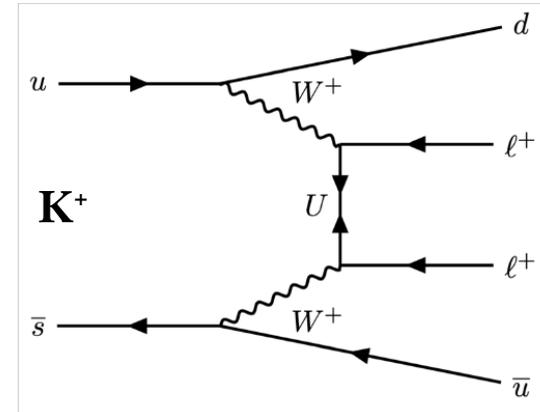
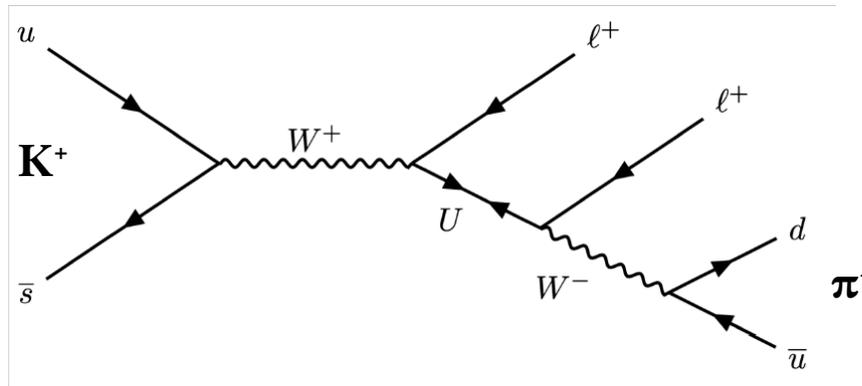
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ background



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

- Detailed comparison between signal and background models
 - ★ Shapes depend on the π^+ momentum
 - ★ Background distributions normalized separately
 - ★ Signal normalized to SM expectations
- Remarkable agreement across all momentum bins

LFV/LNV $K^+ \rightarrow \pi^- l^+ l^+$



- Conservation of lepton number (L_e, L_μ, L_τ) not a fundamental symmetry of the SM
- LNV, LFV predicted in various beyond SM scenarios
- $K^+ \rightarrow \pi^- l^+ l^+$ decays
 - ★ $\Delta L = 2$ processes: $\Delta L_\mu = 2, \Delta L_e = 2$ for $l = \mu, e$
 - ★ Proceed via Majorana neutrinos U [[JHEP 0905 \(2009\) 030](#), [PLB 491 \(2000\) 285-290](#)]

Experimental status (results @ 90% CL):

- ◆ $\text{BR}(K^+ \rightarrow \pi^- e^+ e^+) < 6.4 \times 10^{-10}$ [[BNL E865](#), [PRL 85 \(2000\) 2877](#)]
- ◆ $\text{BR}(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 8.6 \times 10^{-11}$ [[CERN NA48/2](#), [PLB 769 \(2017\) 67](#)]

LNV/LFV searches @ NA62

- Subset of 2017 data: ~ 3 months of data taking
- Blind analysis procedure
- Dedicated trigger lines: multi-track final states with e^\pm or μ^\pm

Trigger line	Requirements	Data samples
Di-muon	3 tracks, 2 muon candidates	SM $K^+ \rightarrow \pi^+\mu^+\mu^-$ & LNV $K^+ \rightarrow \pi^-\mu^+\mu^+$
Multi track e	3 tracks, > 20 GeV energy deposit in LKr	SM $K^+ \rightarrow \pi^+e^+e^-$ & LNV $K^+ \rightarrow \pi^-e^+e^+$
Multi-track	3 tracks, minimum bias	Control samples for background studies

- Corresponding SM decay modes used for normalization

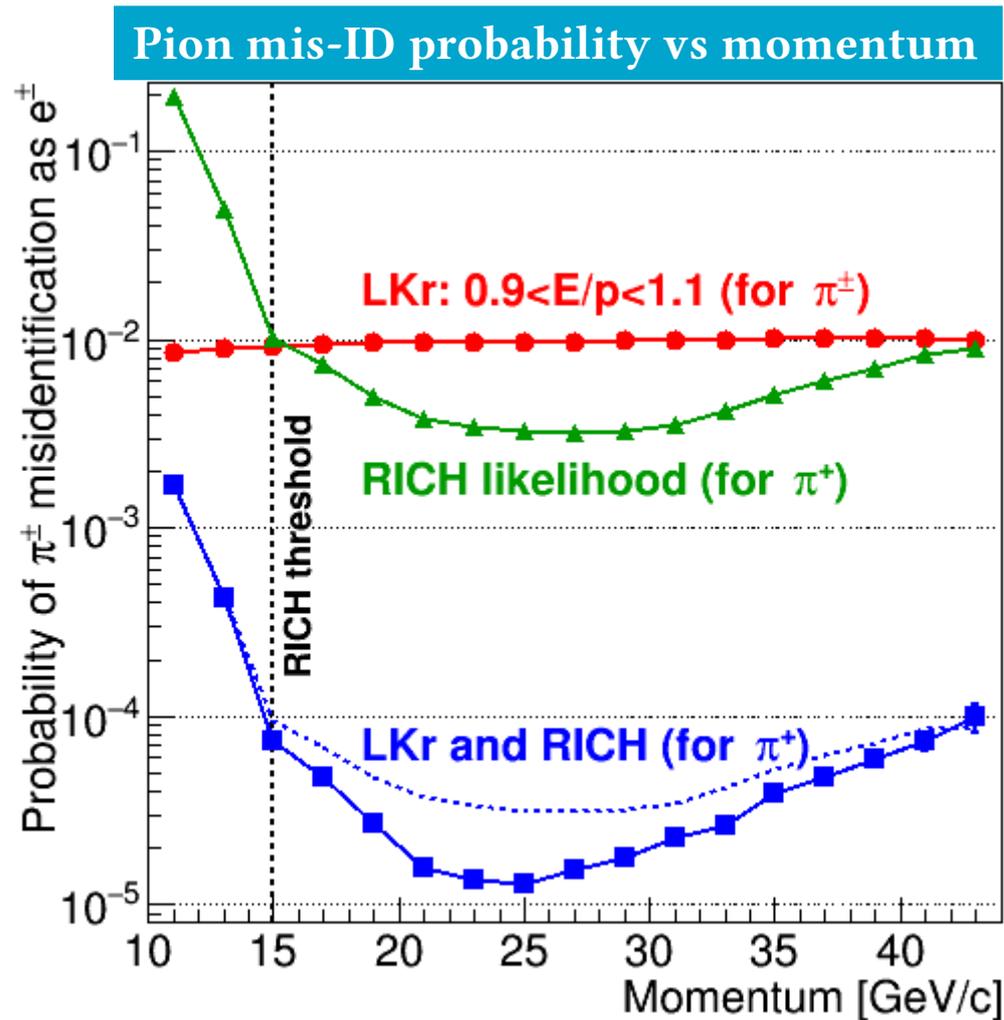
- ★ Almost identical selection (differs by track charge)
- ★ Cancellation between the dominant systematic uncertainties (trigger/detector efficiency/ pileup)

◆ $\text{BR}(K^+ \rightarrow \pi^+e^+e^-) = (3.00 \pm 0.09) \times 10^{-7}$ [PLB 677 (2009) 246]

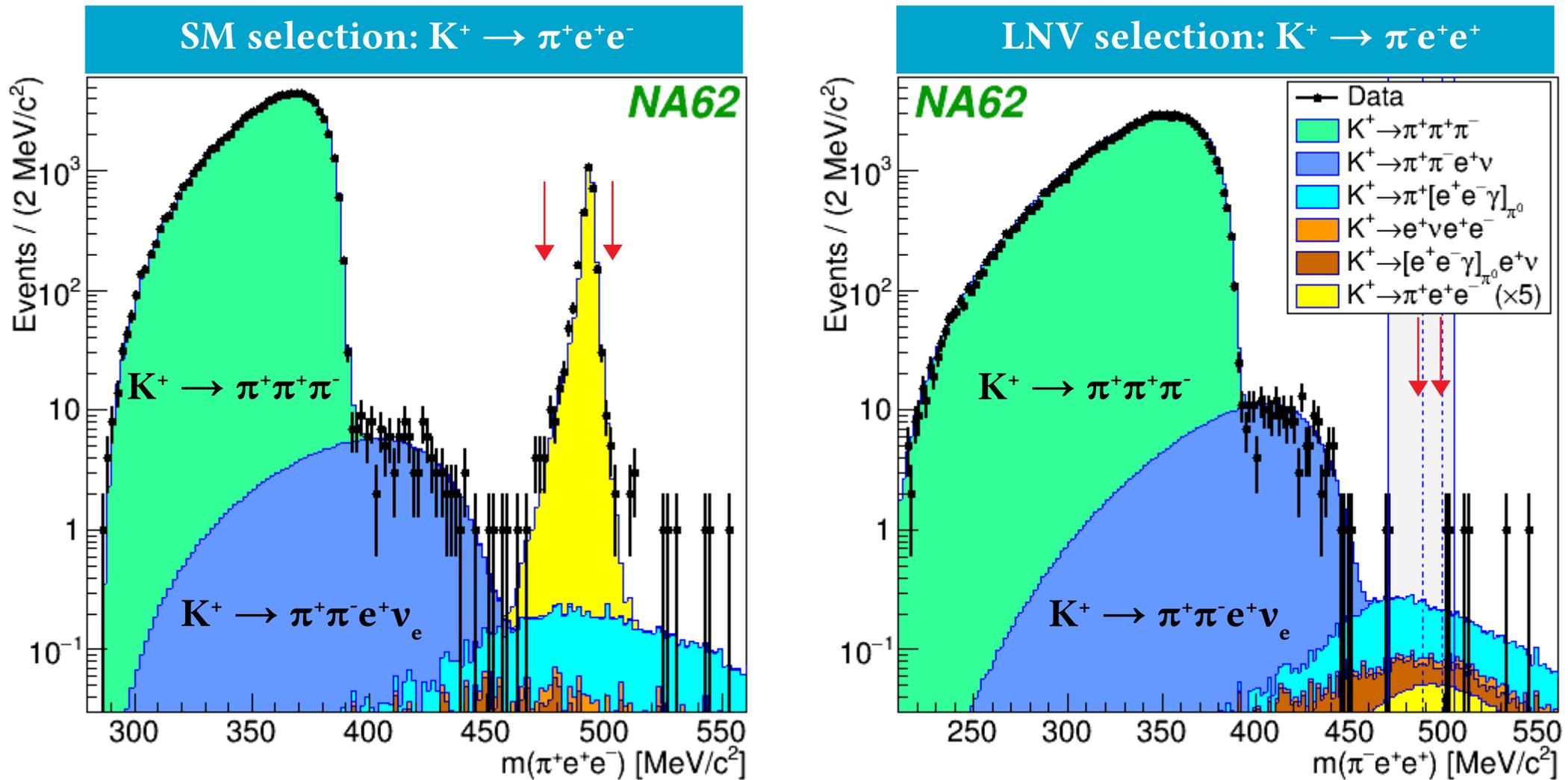
◆ $\text{BR}(K^+ \rightarrow \pi^+\mu^+\mu^-) = (0.962 \pm 0.025) \times 10^{-7}$ [PLB 697 (2011) 107]

Backgrounds and PID

- Main background from $K^+ \rightarrow \pi^+\pi^+\pi^-$ (BR~5.6%)
 - ★ Single/double mis-identification
 - $\pi^\pm \rightarrow e^\pm, \pi^\pm \rightarrow \mu^\pm$
 - ★ Pion decay in flight (9% probability in the NA62 fiducial volume)
 - $\pi^\pm \rightarrow \mu^\pm$ decay (99.9%)
 - $\pi^\pm \rightarrow e^\pm$ decay (1.2×10^{-4})
- Background study using data-driven methods and dedicated simulations
- Pion/electron identification
 - ★ By energy deposit in LKr (E/p)
 - ★ By RICH ring shape

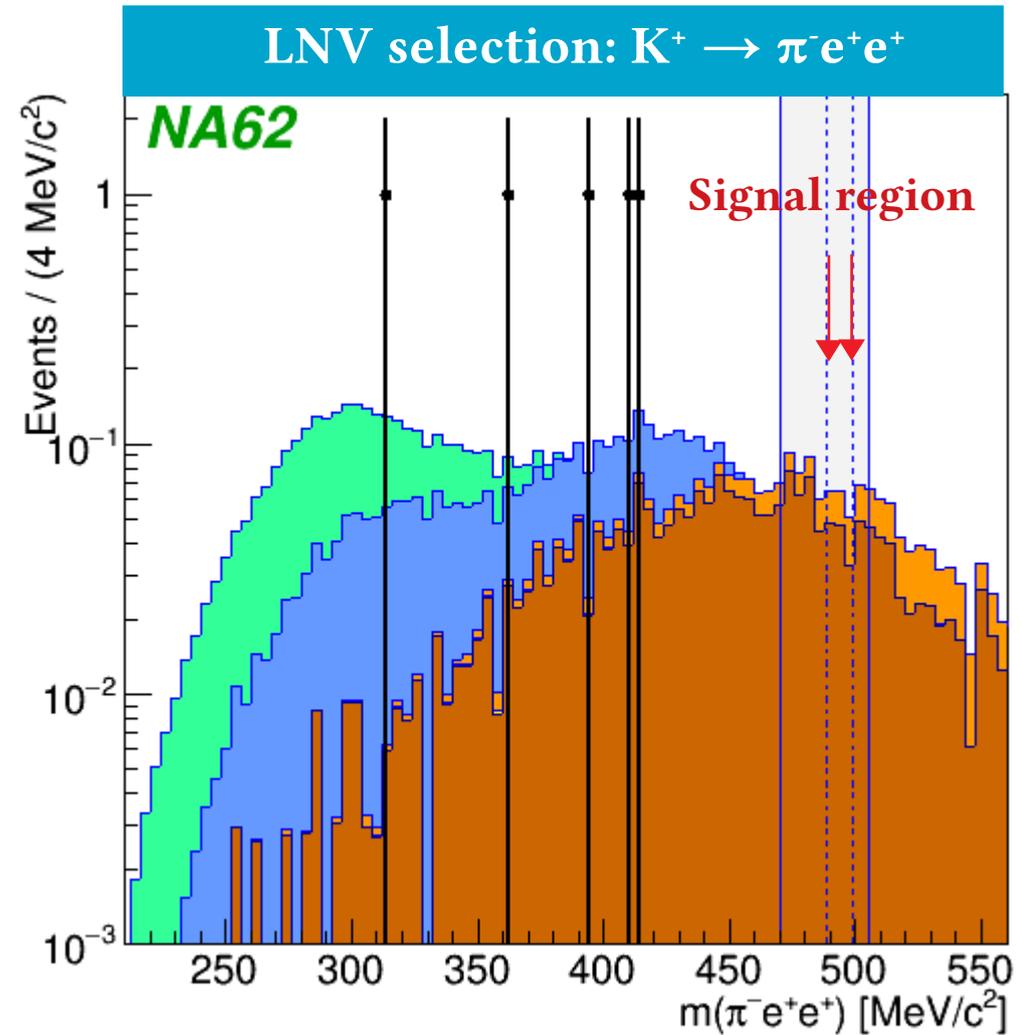
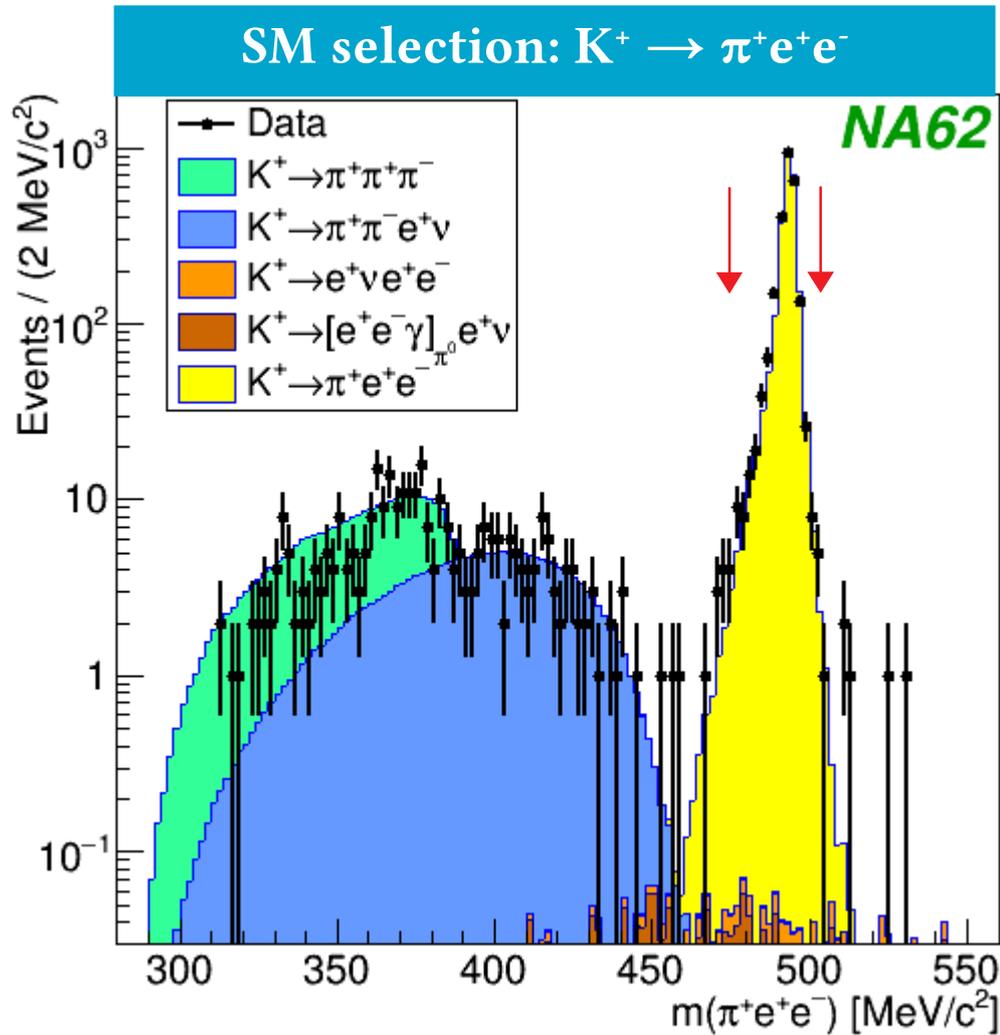


$K^+ \rightarrow \pi^- e^+ e^+$: auxiliary selection



- ◆ Auxiliary selection: pion/electron ID only with Lkr
- ◆ Validation of the background estimates in control mass regions
- ◆ LNV sensitivity limited by $K^+ \rightarrow \pi^+ [e^+ e^- \gamma]_{\pi^0}$ background

$K^+ \rightarrow \pi^- e^+ e^+$: standard selection



- ◆ SM $K^+ \rightarrow \pi^- e^+ e^-$ observed candidates: 2484
- ◆ $BR(K^+ \rightarrow \pi^- e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$
- ◆ K^+ decays in FV: $N_K = (2.14 \pm 0.07) \times 10^{11}$

- ◆ LKr + RICH used for pion/electron ID
- ◆ 10% loss of SES, but ~6 times lower background
- ◆ Better discovery potential for LNV

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

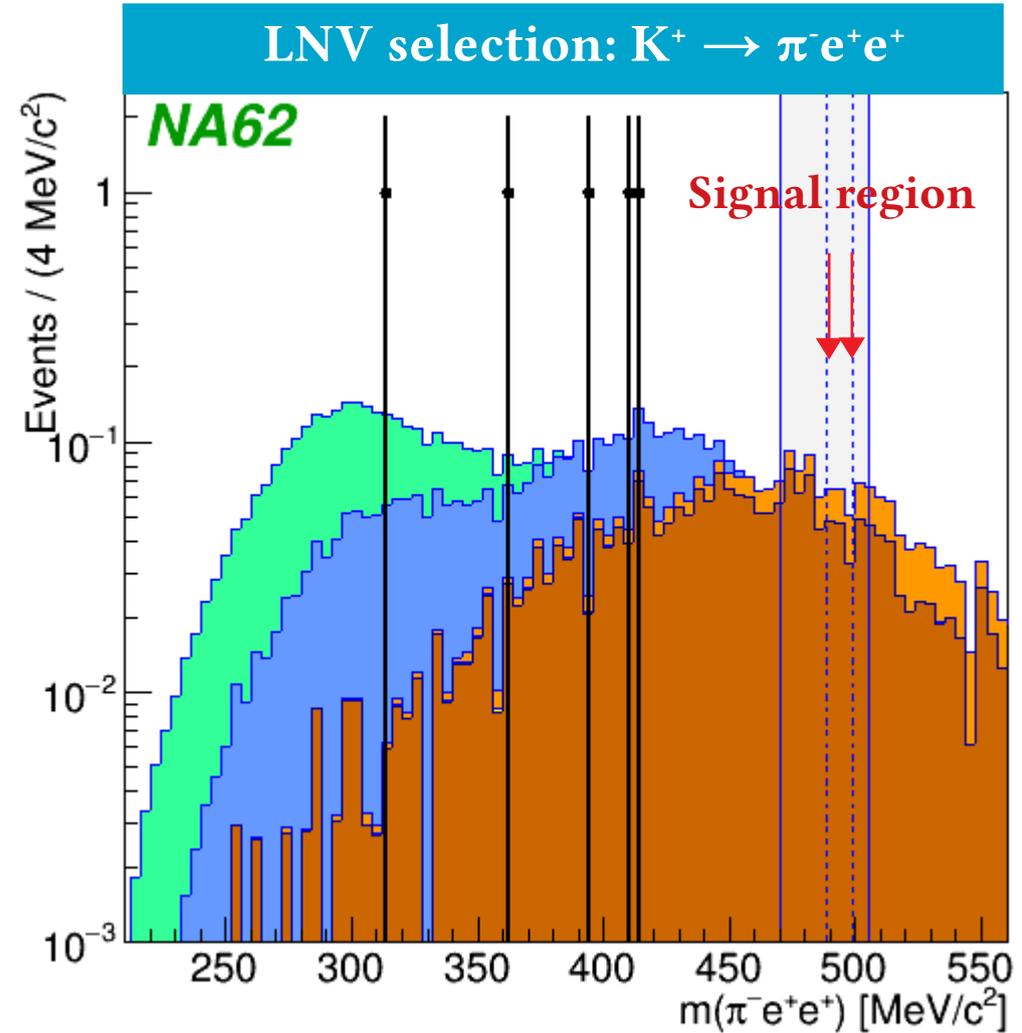
- Using $N_K = (2.14 \pm 0.07) \times 10^{11}$
- Signal acceptance: 4.98%

$$\text{SES} = (0.94 \pm 0.03) \times 10^{-10}$$

- Expected background in signal region

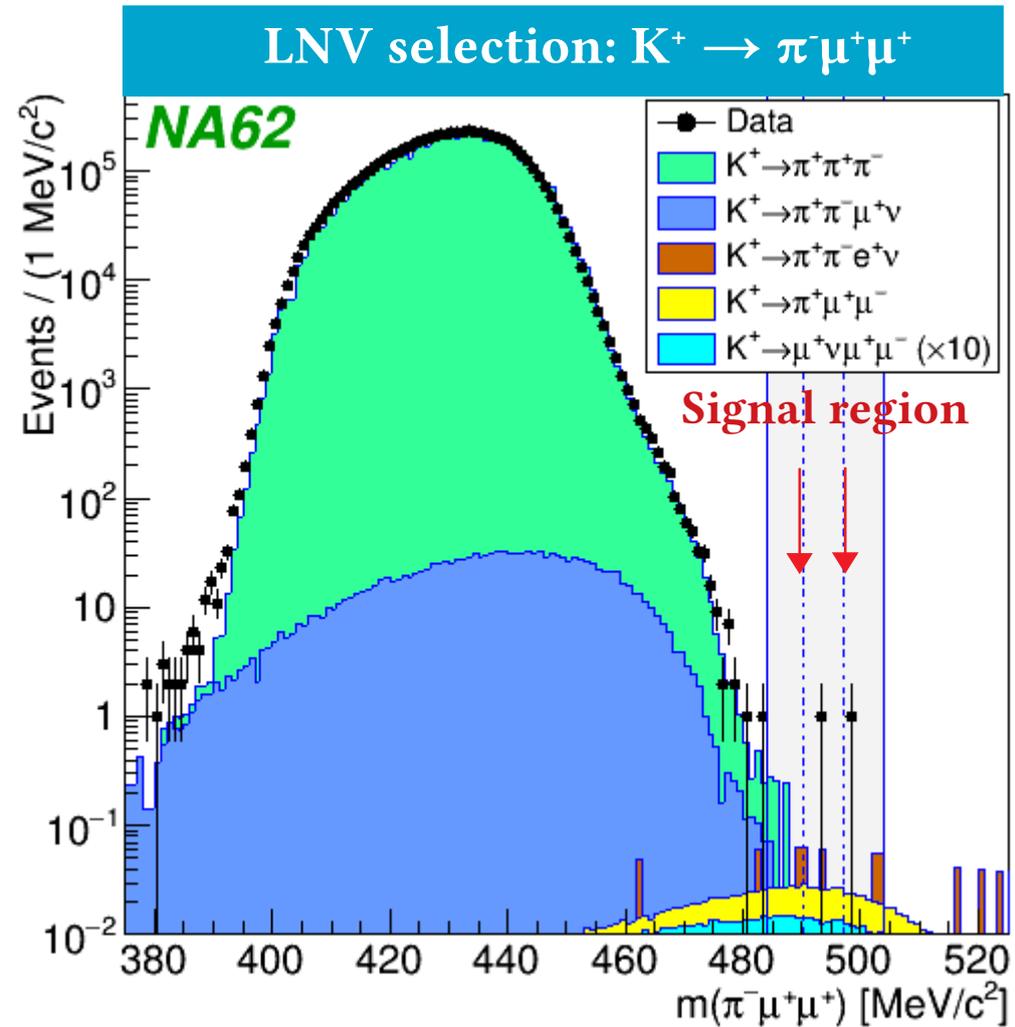
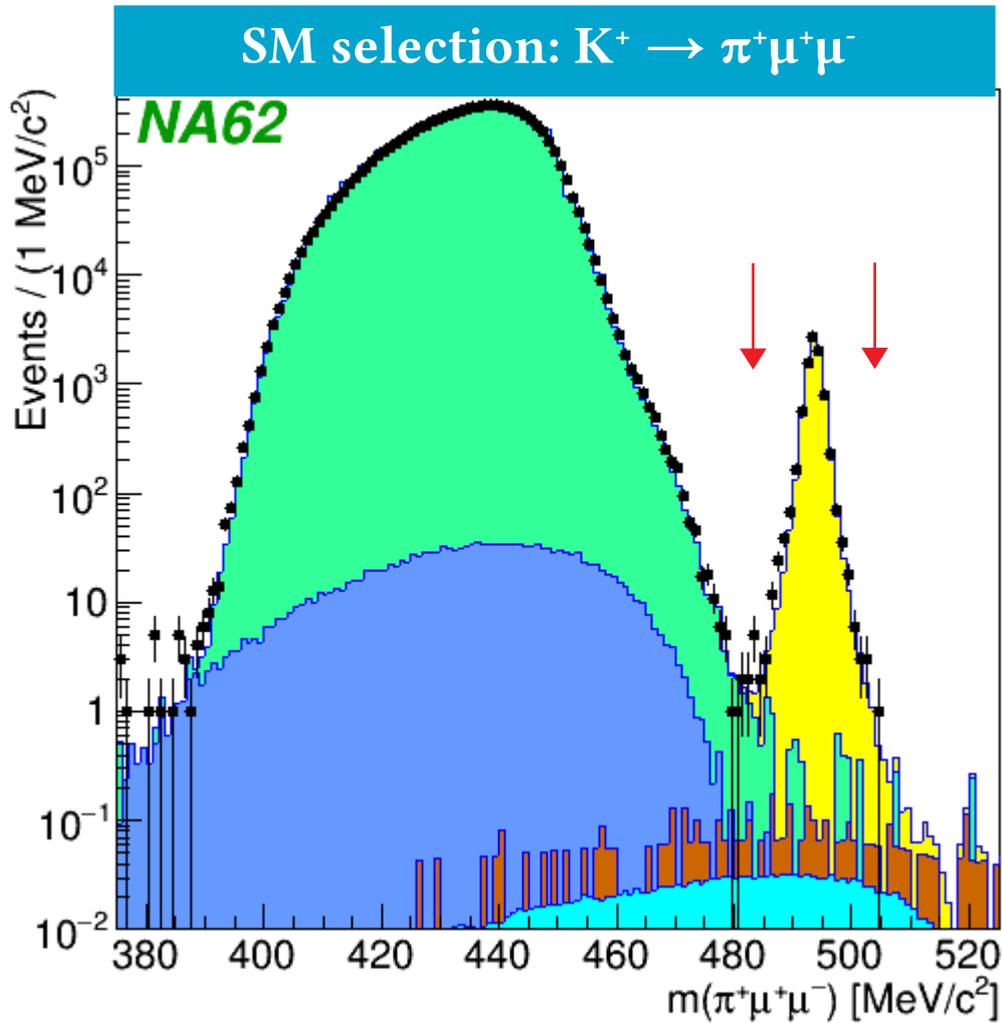
Process	Sig. Reg.
$K^+ \rightarrow e^+ \nu e^+ e^-$	0.12 ± 0.02
$K^+ \rightarrow [e^+ e^- \gamma]_{\pi^0} e^+ \nu$	0.04
Total	0.16 ± 0.03

Observed candidates: 0



Set upper limit on BR using CLs statistical treatment:
 $\text{BR}(K^+ \rightarrow \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ at 90% CL

$K^+ \rightarrow \pi^- \mu^+ \mu^+$ search



- ◆ SM $K^+ \rightarrow \pi \mu^+ \mu^-$ observed candidates: 8357
- ◆ $\text{BR}(K^+ \rightarrow \pi \mu^+ \mu^-) = (0.962 \pm 0.025) \times 10^{-7}$
- ◆ K^+ decays in FV: $N_K = (7.94 \pm 0.23) \times 10^{11}$

- ◆ LKr + MUV3 used for pion/muon ID
- ◆ Background in SM signal mass region: 0.07%
- ◆ Background in the LNV selection due to pion decays in flight and $\pi^\pm \rightarrow \mu^\pm$ mis-ID

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

- Using $N_K = (7.94 \pm 0.23) \times 10^{11}$
- Signal acceptance: 9.81%

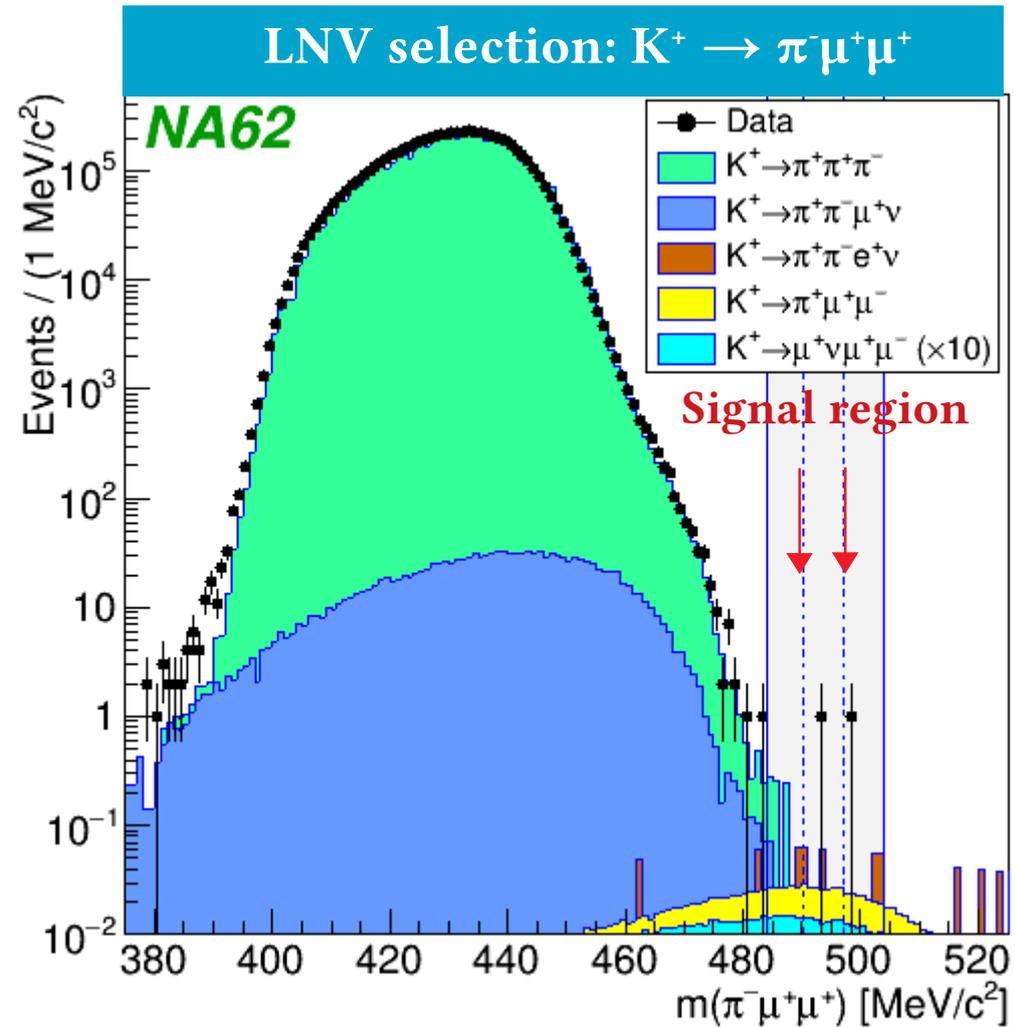
$$\text{SES} = (1.28 \pm 0.04) \times 10^{-11}$$

- Expected background in signal region

Process	Exp. in Signal Region
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	0.70 ± 0.40
$K^+ \rightarrow \pi^+ \pi^- \ell^+ \nu$	$0.06(7) \pm 0.05 \mu(e)$
$K^+ \rightarrow \pi^+ \mu^+ \mu^-$	0.08 ± 0.02
$K^+ \rightarrow \mu^+ \nu \mu^+ \mu^-$	0.01
Total	0.91 ± 0.41

Observed candidates: 1

Set upper limit on BR using CLs statistical treatment:
 $\text{BR}(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ at 90% CL



Summary and prospects

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ update of the analysis on the 2017 data set

- Number of kaons decays: $N_K = (1.3 \pm 0.1) \times 10^{12}$
- Single-event sensitivity in the 2017 data: $SES = (3.4 \pm 0.4) \times 10^{-11}$
- Expected signal: 2.5 ± 0.4 SM events
- Total background from K^+ decays: 0.76 ± 0.10
 - ★ Upstream background not included
- Final results from the 2017 data set expected later this year: **stay tuned!**

LFV/LNV

- Upper limits set with 80% of the 2017 NA62 data set
 - ★ $BR(K^+ \rightarrow \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ at 90% CL
 - ★ $BR(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ at 90% CL
- PLB 797 134794 (2019)

Factor 2-3 improvement over previous results [NA48/2 and BNL-E865]