Physics beyond SM with kaons at NA62

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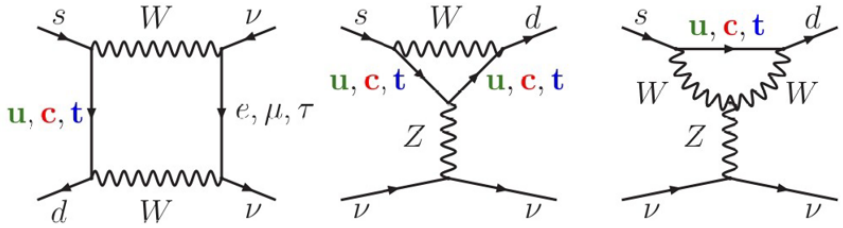
Outline

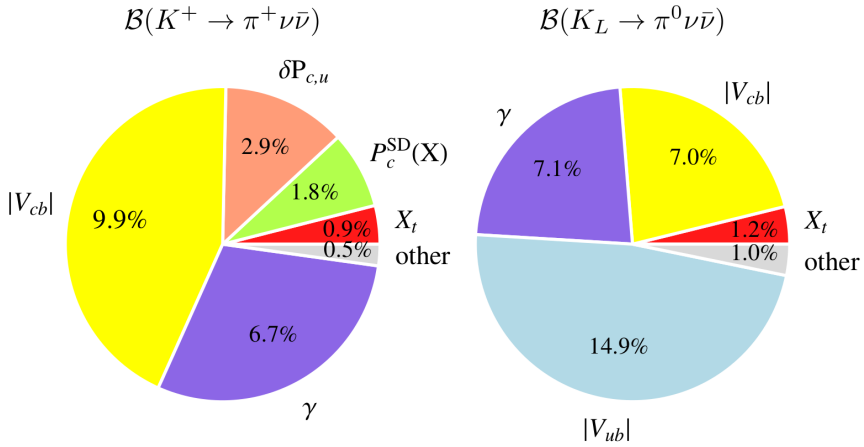
- **Theoretical motivation for $K \to \pi \nu \bar{\nu}$ decays**
- $K^+ \to \pi^+ \nu \bar{\nu}$
  - Experiment description
  - Results of 2016 data
  - Analysis of 2017 sample
  - Prospects for 2018 sample and future
- **Other Kaon decays at NA62 experiment**

Theoretical motivation - Standard Model

- **FCNC loop process**
  - **s → d coupling** and highest CKM suppression (BR∼ $|V_{ts} \times V_{td}|^2$)



- **Very clean theoretically**
  - Short distance contribution and no hadronic uncertainties
  - Hadronic matrix element extracted from well-known decay $K^+ \to \pi^0 e^+ \nu$
  - Theoretical error budget dominated by CKM parameters



- **SM predictions**
  [Buras et al., JHEP 1511 (2015) 033]

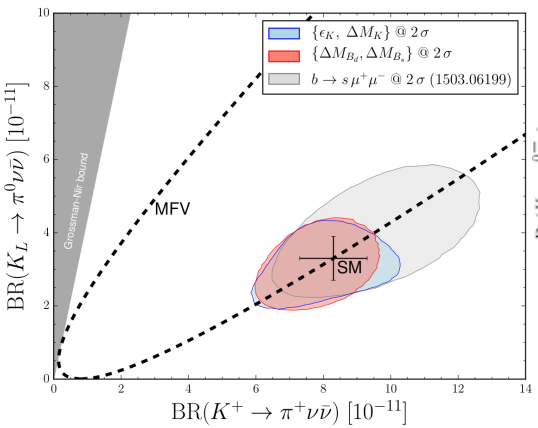
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11}$$

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

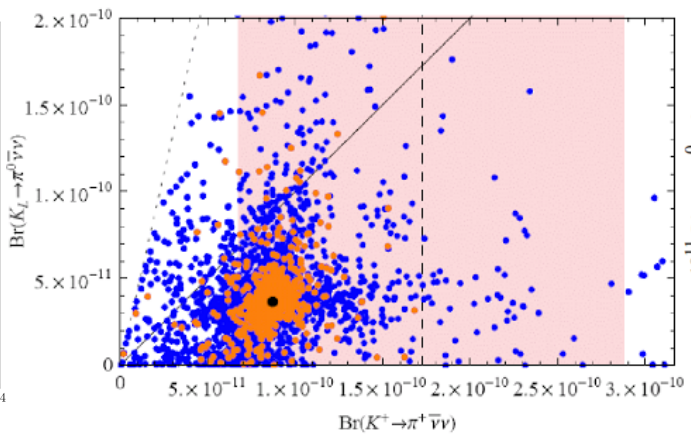
Theoretical motivation - Beyond the Standard Model

- Simplified Z, Z' models *[Buras, Buttazzo,Knegjens, JHEP 1511 (2015) 166]*
- Littlest Higgs with T-parity *[Blanke, Buras, Recksiegel, EPJ C76 (2016) no.4 182]*
- Custodial Randall-Sundrum *[Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]*
- MSSM non-MFV *[Blazek, Matak Int.J.Mod.Phys.A29 (2014) 1450162; Isidori et al. JHEP 0608 (2006) 064]*
- LFU violation models *[Isidori et. al., Eur. Phys. J. C (2017) 77]*
- Leptoquarks *[S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]*
- Constraints from existing measurements (correlations model dependent):
  Kaon mixing and CPV, CKM fit, K,B rare meson decays, NP limits from direct searches
- $K \to \pi\nu\bar{\nu}$ **can discriminate among different new physics scenarios**

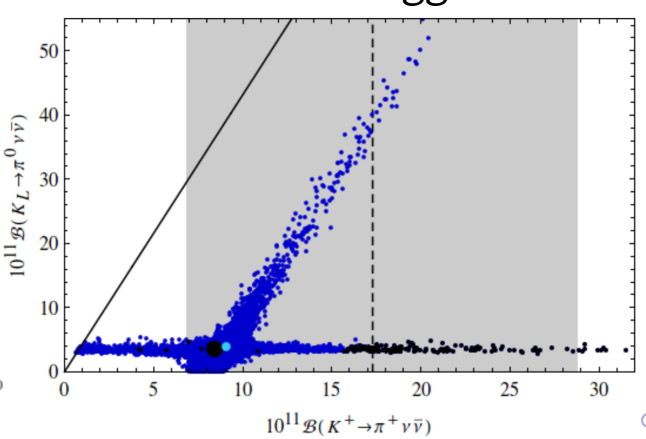
$Z'(5\,TeV)$ in ConstrainedMFV



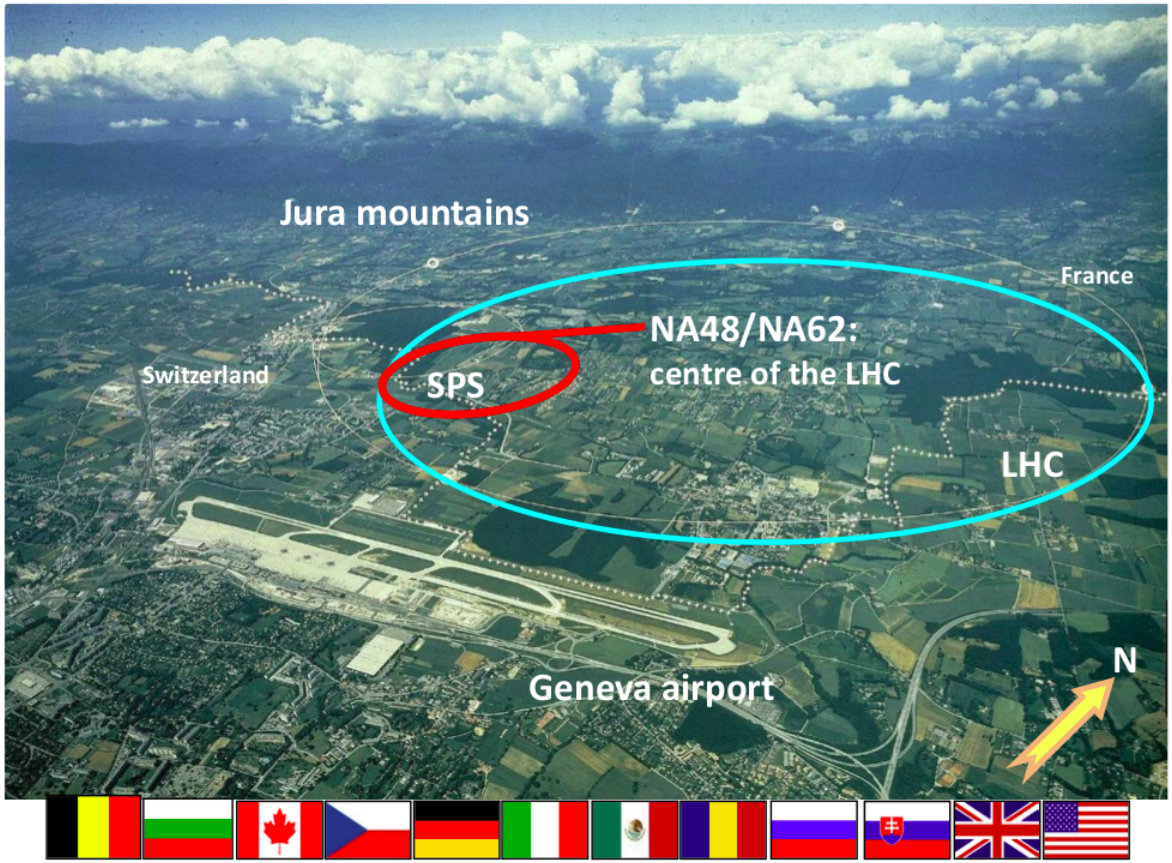
Randall – Sundrum



LittlestHiggs



Kaons at CERN



Kaon decay in flight experiments.
NA62: ~200 participants, ~ 30 institutes

Earlier: NA31

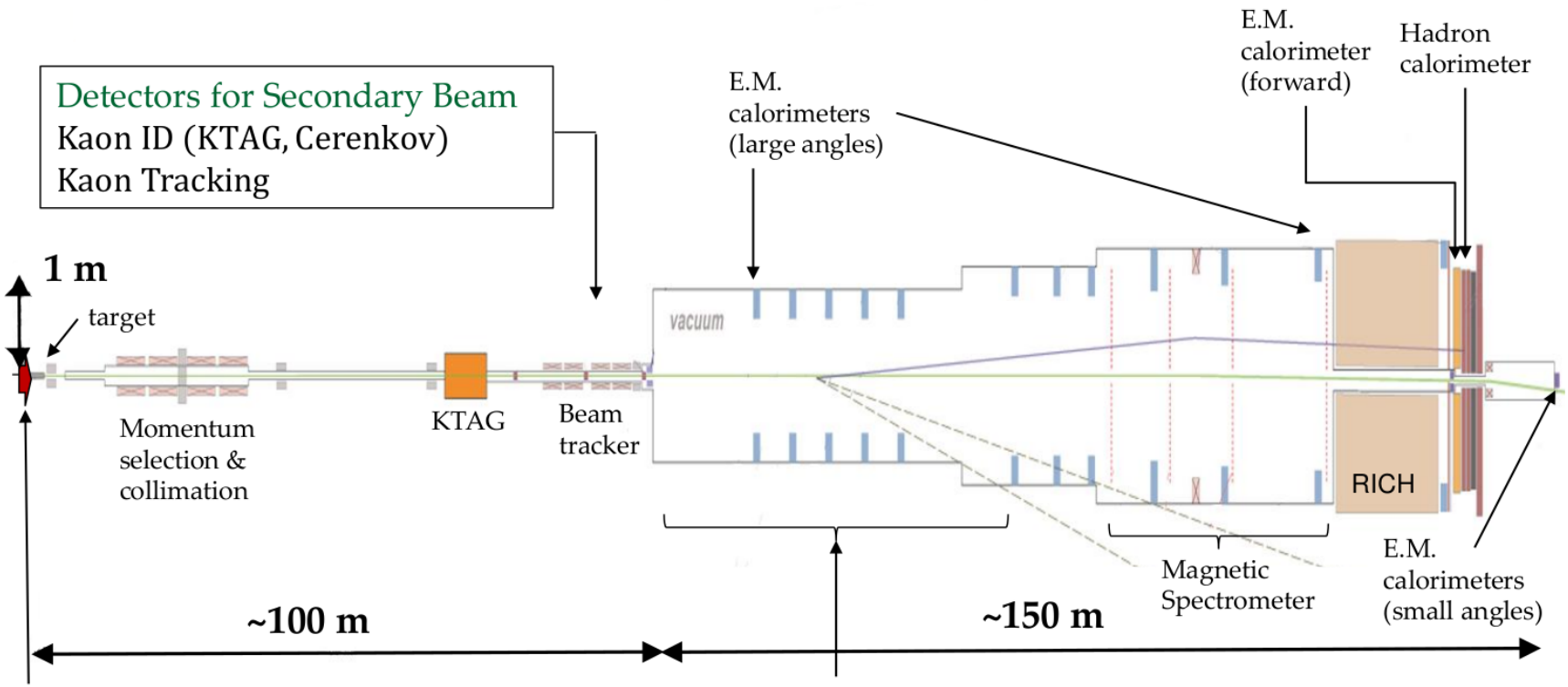
NA48 discovery of direct CPV	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 R_K phase	2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
	2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
NA62	2014: pilot run	
	2015: commissioning run	
	2016 – : $K^+\to\pi^+\nu\nu$ run	
	2017 – : $K^+\to\pi^+\nu\nu$ run	
	2018 – : $K^+\to\pi^+\nu\nu$ run	

Physics program of NA62 experiment

- **Main goal:**
  - Collect O(100) signal events $\Rightarrow 10^{13}$ Kaon decays
  - Measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) with 10% precision
- **Other program and future plans:**
  - Measure $|V_{td}|$ with $\sim$10% accuracy
  - Probe several NP scenarios in $K^+ \to \pi^+ \nu\bar{\nu}$
  - Probe NP in similar processes (e.g. $K^+ \to \pi^+ X$)
- **Beyond the baseline:**
  - χ_{PT} kaon decays: $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^+\pi^-\gamma$, $K^+ \to e^+\nu\gamma$, ...
  - R_K measurement, $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$
  - LFV/LNV and other decays with 3 tracks in the final state
    - Di-muon trigger stream: $\sim 2\times10^{12}$ K^+ decays; SES $\sim 10^{-11}$
    - Decays to μe and ee pairs: $\sim 5\times10^{11}$ K^+ decays; SES $\sim 10^{-10}$
    - Other 3-track decays: $\sim 5\times10^{10}$ K^+ decays; SES $\sim 10^{-9}$
  - Heavy Neutral Lepton (HNL) production: $K^+ \to \ell^+ \nu_h$
  - π^0 decays: $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-$, $\pi^0 \to e^+e^-e^+e^-$
  - Dark photon searches: $K^+ \to \pi^+\pi^0$, $\pi^0 \to A'\gamma$, $A' \to$ invisible
  - Exotic searches: Axion-like particles (ALP), $ALP \to \gamma\gamma$

NA62 Detector layout

- $\sim$ 5MHz of nominal K^+ decay rate



SPS proton
400 GeV
10^{12} p/s

Secondary Beam
$p = 75$ GeV/c
$\Delta p/p \sim 1\%$
X,Y Divergence < 100 µrad
$K(6\%), \pi(70\%), p(23\%)$
750 MHz
Beam size: 6.0 × 2.7 cm^2

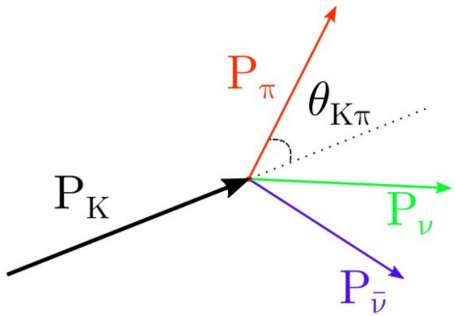
Kaon Decay
$\sim$5 MHz
$4.5 \times 10^{12}/year$
60 m length
10^{-6} mbar vacuum

Detectors for decay products
Charged particle tracking
Charged particle Time Stamping
Photon detection
Charged particle ID
Pion and muon identification

Analysis strategy for $K^+ \to \pi^+ \nu\bar{\nu}$

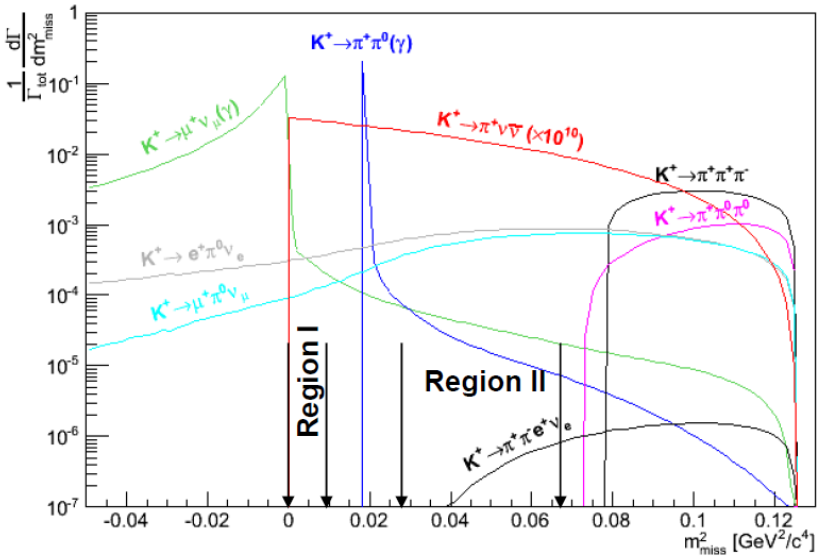
Kaon decays in flight

- **Signal:** Time and space $K^+ - \pi^+$ matching
- **Regions defined by:** $m^2_{miss} = (P_K - P_\pi)^2$
- The analysis is mostly cut based
- **Blind analysis:** Signal and background ctrl regions are kept blind throughout the analysis



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



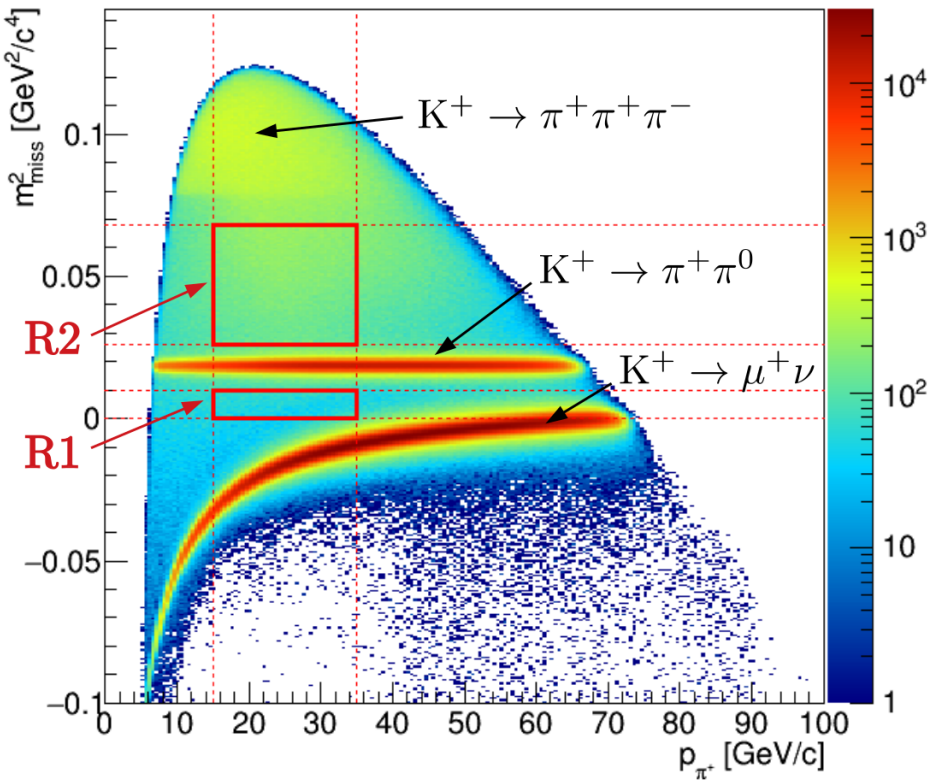
Requirements

- $\mathcal{O}(100\text{ps})$ timing between sub-detectors
- $\mathcal{O}(10^4)$ background suppression with kinematics
- $\mathcal{O}(10^7)$ μ-suppression $(K^+ \to \mu^+ \nu)$
- $\mathcal{O}(10^7)$ γ-suppression $(K^+ \to \pi^+ \pi^0 \ , \pi^0 \to \gamma\gamma)$

Event selection

Signal regions

- Three different ways to calculate m_{miss} to avoid mis-reconstruction:
  - $m^2_{miss} = (STRAW,\ GTK)$
  - $m^2_{miss} = (RICH,\ GTK)$
  - $m^2_{miss} = (STRAW,\ Beam)$



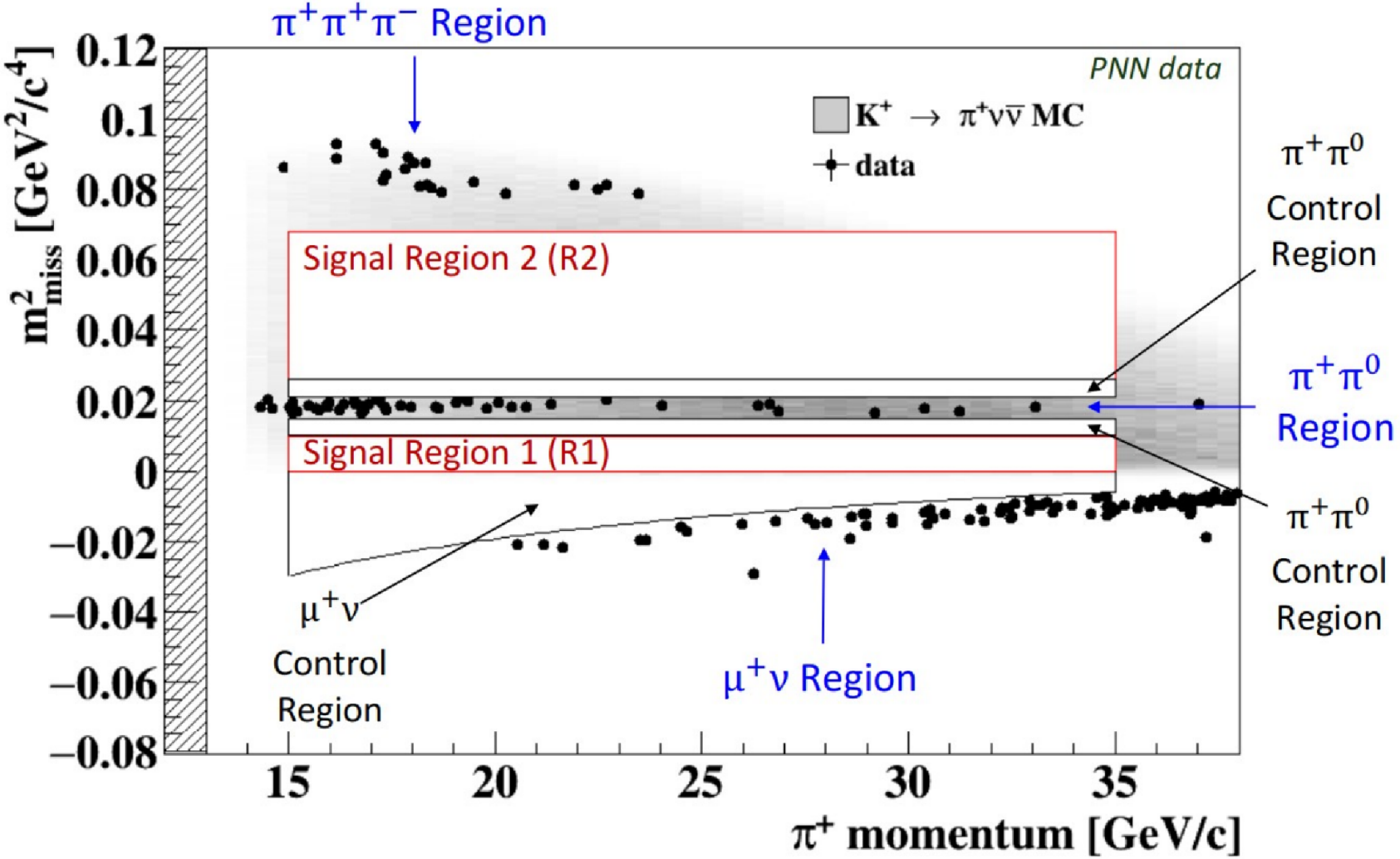
Selection

- Single track in final state topology
- π^+ identification
- Photon rejection
- Multi-track rejection
- $105 < Z_{vertex} < 165$ m
- $15 < P_{\pi^+} < 35$ GeV/c
  (best μ/π discrimination in RICH
  & to leave at least 40 GeV of E_{miss})

Performance

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

Results of the selection - 2016 Data



Single event sensitivity - 2016 Data

SES ingredients

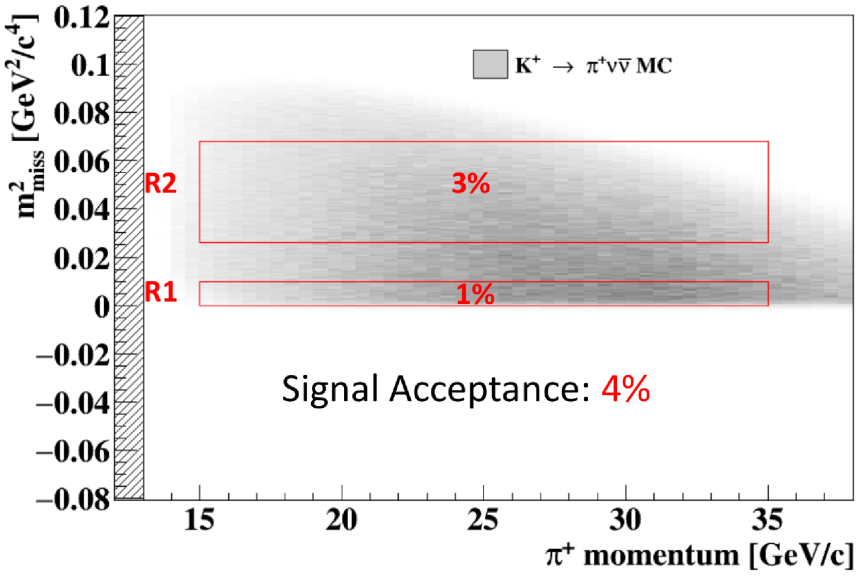
- N_K from $K^+ \to \pi^+\pi^0$ control trigger: $(1.21 \pm 0.02) \times 10^{11}$
- $K^+ \to \pi^+ \nu\bar{\nu}$ acceptance: $(4.0 \pm 0.1) \times 10^{-2}$
- Random Veto Efficiency: 0.76 ± 0.04
- Trigger Efficiency: 0.87 ± 0.2

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

j = π⁺ momentum bin

- N_K: number of K^+ decays
- $A^j_{\pi\nu\nu}$: signal acceptance
- ϵ^j_{RV}: random veto efficiency
- ϵ^j_{trig}: trigger efficiency

SES: $3.15 \pm 0.01_{stat} \pm 0.24_{syst} \times 10^{-10}$

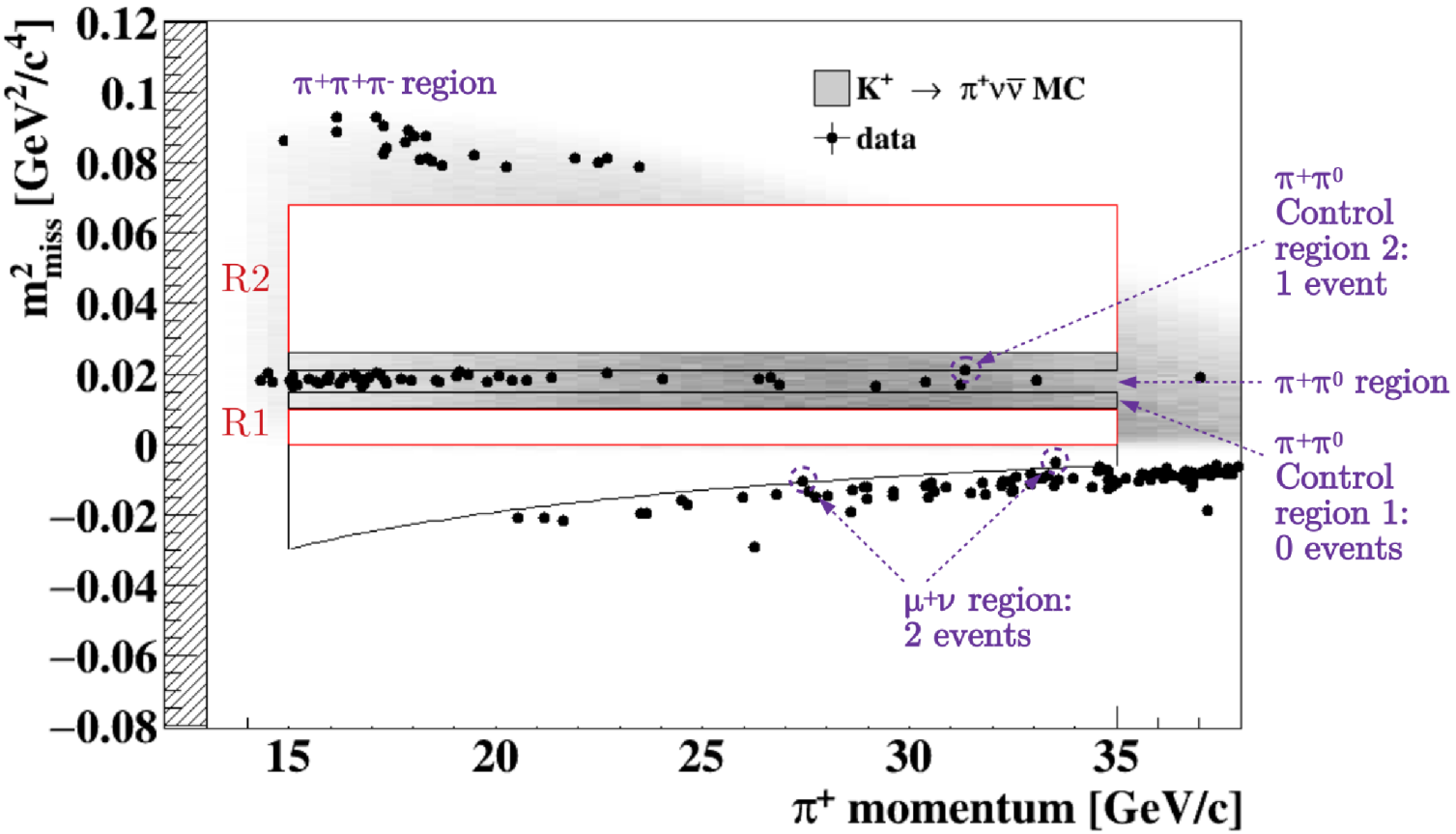


Process	Expected events in R1+R2
$K^+ \to \pi^+\nu\bar{\nu}$	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.020 \pm 0.003_{stat}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

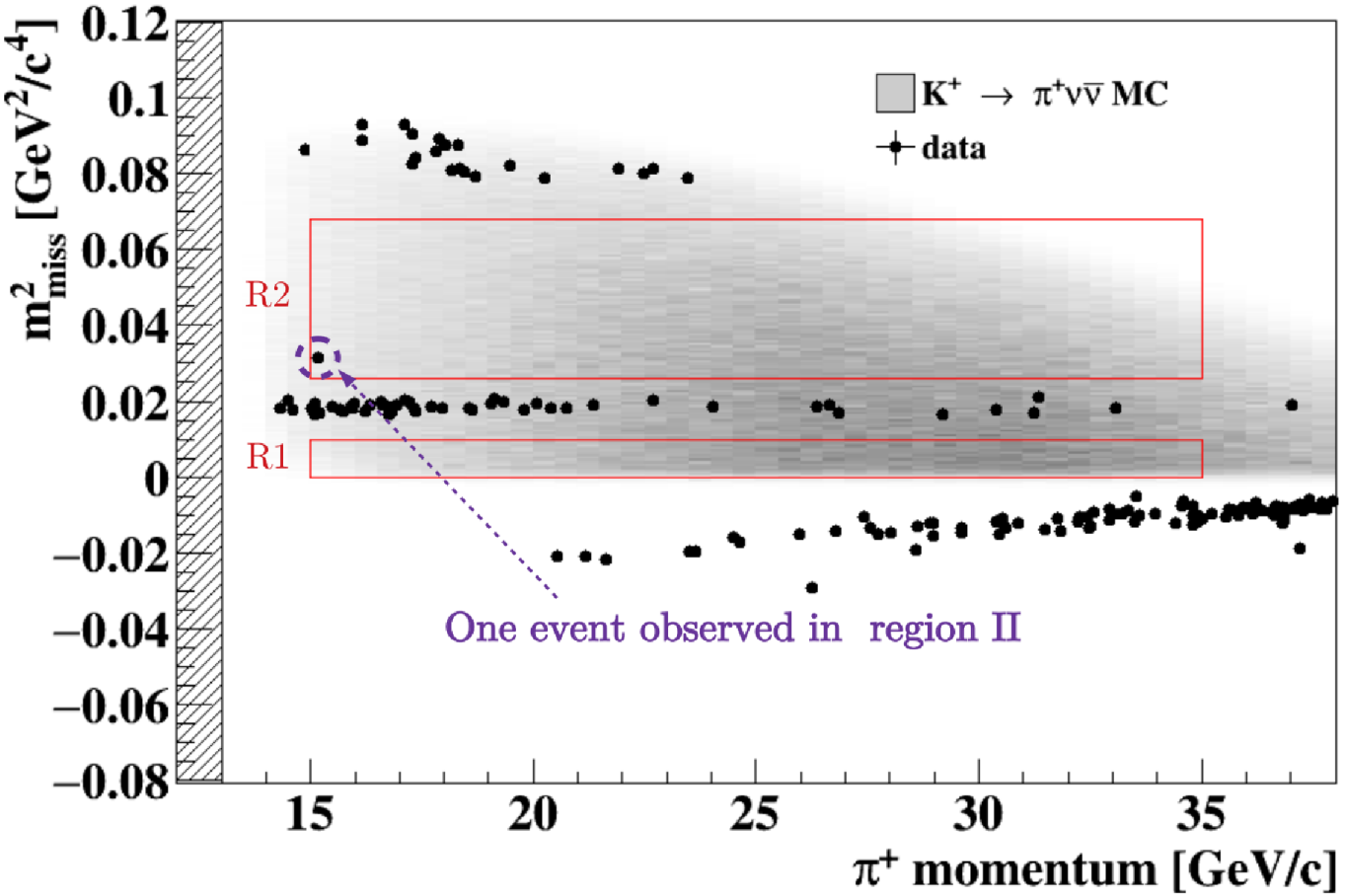
Source	δ SES (10^{-10})
Random veto	±0.17
Definition of $\pi^+\pi^0$ region	±0.10
Simulation of π^+ interactions	±0.09
N_K	±0.05
Trigger efficiency	±0.04
Extra activity	±0.02
GTK pileup simulation	±0.02
Momentum spectrum	±0.01
Total	±0.24

Expected background in control regions

	$\pi^+\pi^0$		$\mu^+\nu$
CR1	$0.52 \pm 0.08_{stat} \pm 0.03_{syst}$	CR	$1.02 \pm 0.16_{stat}$
CR2	$0.94 \pm 0.14_{stat} \pm 0.05_{syst}$		



Result - 2016 Data



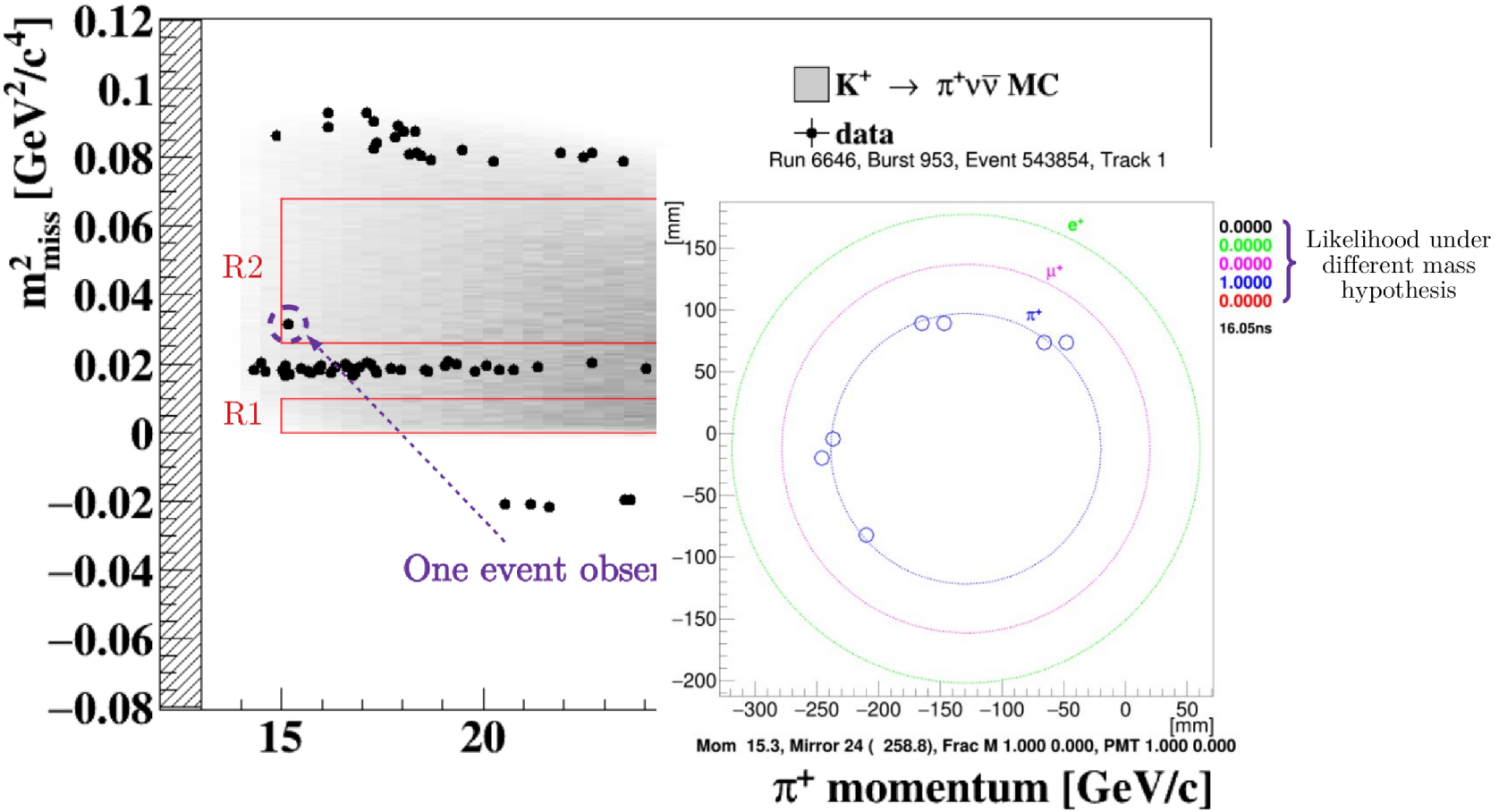
The results are compatible with the SM

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

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

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

Result - 2016 Data



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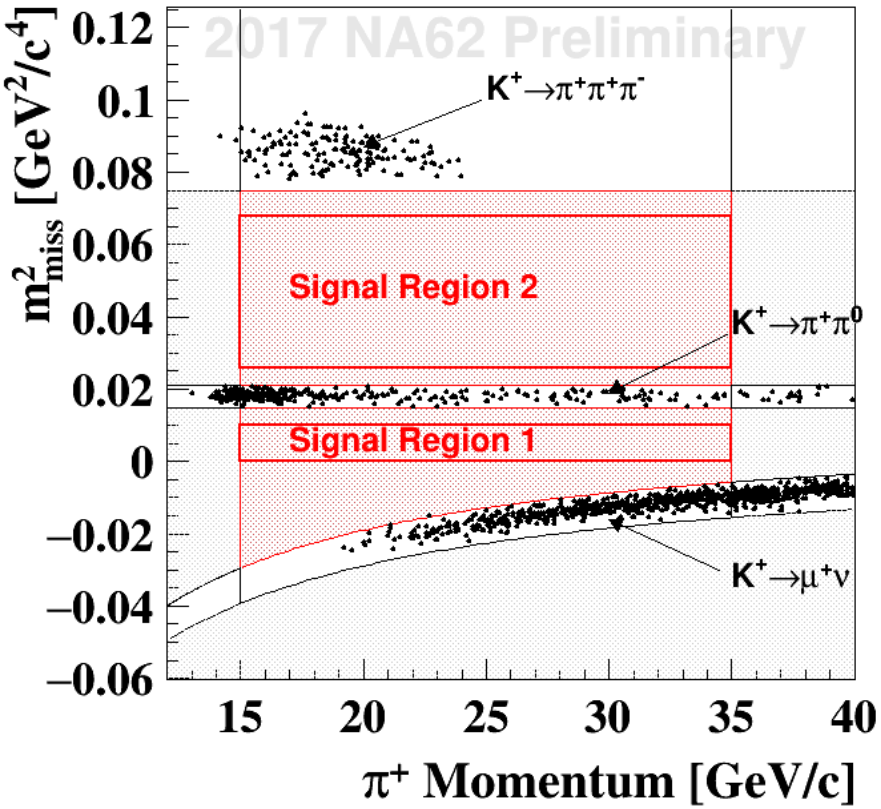
[Phys. Lett. B 791 (2019) 156-166]

Selection and SES

- 2016-like selection
- Comparable to 2016 analysis performance
  - Better treatment of pileup in IRC and SAC
  - 40% lower π^0 rejection inefficiency compared to 2016
  - Slightly improved usage of RICH variables

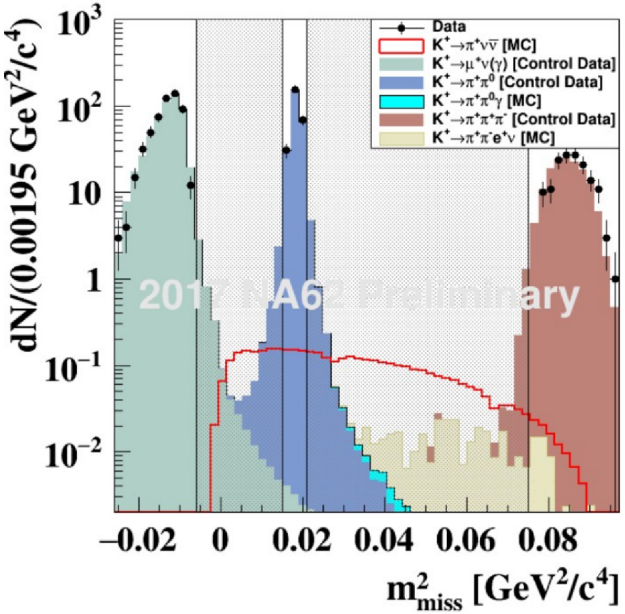


PRELIMINARY

N_K	$(13 \pm 1) \times 10^{11}$
SES	$(0.34 \pm 0.04) \times 10^{-10}$
Expected SM $K^+ \to \pi^+ \nu\bar{\nu}$	2.5 ± 0.4

Background summary

- 2017 data allows detailed comparison between data and background models
  - Shape differs between signal regions, and changes with pion momentum
- Good agreement between modeled m_{miss} and data confirms validity of estimated background from kaon decays

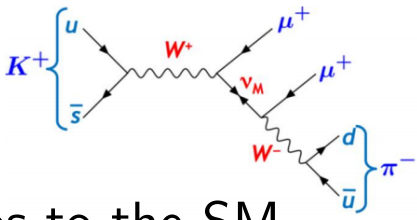


Process	Expected events in signal regions
$K^+ \to \pi^+ \nu\bar{\nu}$	2.5 ± 0.4 (Preliminary)
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.35 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.16 \pm 0.01_{stat} \pm 0.05_{syst}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.22 \pm 0.08_{stat}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.015 \pm 0.008_{stat} \pm 0.015_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to \ell^+\pi^0\nu_\ell$	$0.012 \pm 0.012_{syst}$
Upstream background	Analysis on-going

NP searches in kaon decays @NA62

- Search for Majorana neutrinos in LNV $K^+ \to \pi^- \ell^+ \ell^+$ decays

  [Asaka-Shaposhnikov model (νMSM) [Phys. Lett. B 620 (2005) 17]]



  - DM + Baryon Asymmetry + low mass of SM ν can be explained by adding three sterile Majorana neutrinos to the SM
  - Current limits *[[Phys. Lett. B 769 (2017) 67-76] for μμ set by NA48/2]*

$$\mathrm{BR}(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11} \quad @\ 90\%\ \mathrm{CL}$$
$$\mathrm{BR}(K^+ \to \pi^- e^+ e^+) < 6.4 \times 10^{-10}$$

- Search for resonances (N, X, etc.) in the opposite-sign leptons sample

  [Shaposhnikov-Tkachev model [Phys. Lett. B 639 (2006) 414]]

  - νMSM + real scalar field (inflaton X) with scale invariant couplings
  - Explains universe homogeneity and isotropy on large scales/structures on smaller scales
  - Current limits in opposite sign muons:
    - HN peak search in $\mathrm{K}^+ \to \mu^+(\pi^+\mu^-)$
    - Inflatons peak search in $\mathrm{K}^+ \to \pi^+(\mu^-\mu^+)$

    Limits set at $\sim 10^{-9}$ (90% CL) by NA48/2
  - Searches in $\mathrm{K}^+ \to \pi^+\mathrm{X}$, $\mathrm{X}^+ \to e^+e^-$

Lepton Flavour Violation - selection

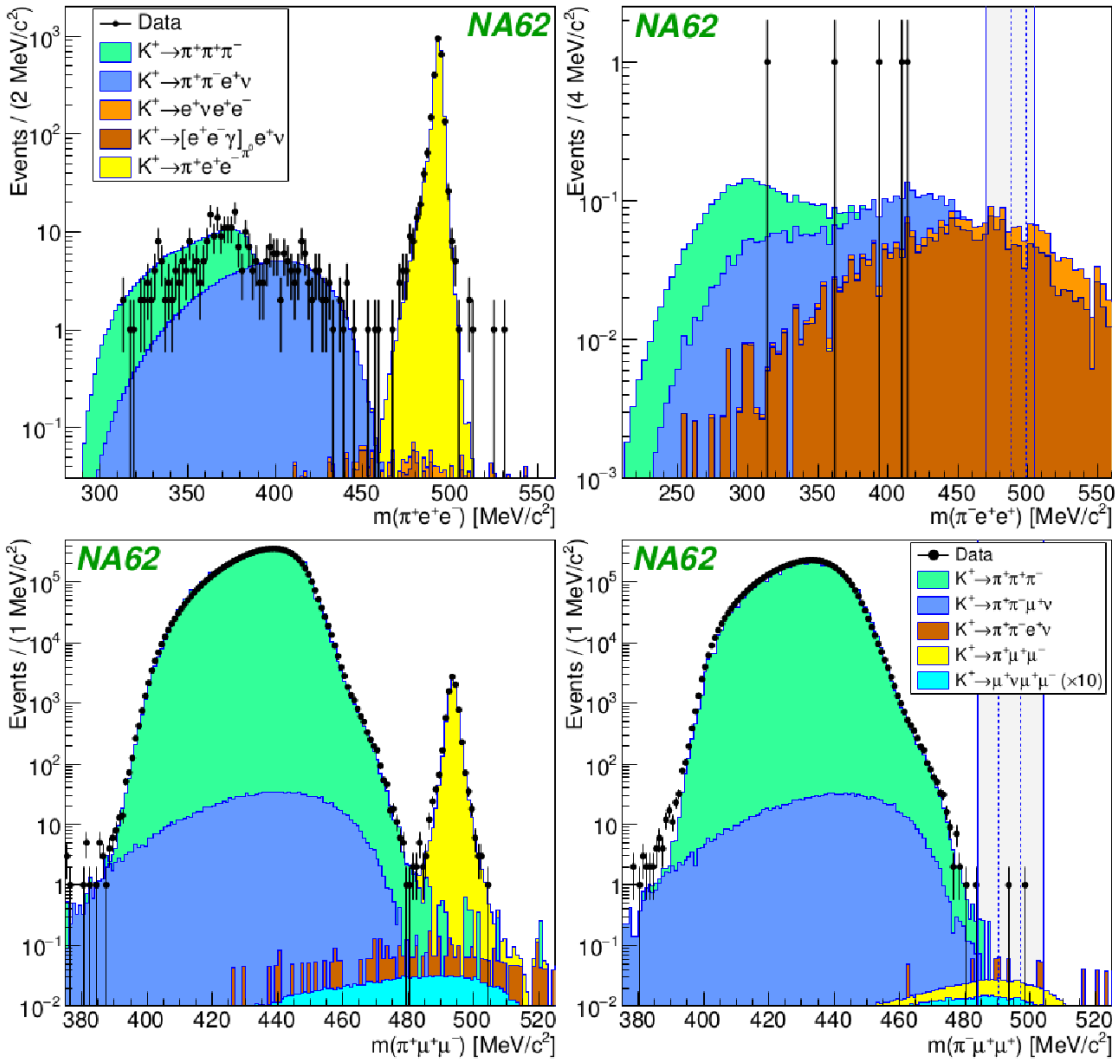
- Subset of 2017 data: $\sim$3 months of data taking
- Blind analysis procedure

- **Dedicated trigger:** multi-track final states with $e^{\pm}$ or $\mu^{\pm}$

Di-muon	3 tracks, 2 muon candidates
Multi-Track electron	3 tracks, 20 GeV deposit in LKr
Multi-Track	3 tracks, minimum bias

- **Corresponding SM channels used for normalisation**
  - Common event selection (differs by track charge)
  - Main systematic uncertainties cancel (trigger/detector efficiency/pileup)
- $\mathrm{BR}(\mathrm{K}^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$ *[Phys. Lett. B 677 (2009) 246]*
- $\mathrm{BR}(\mathrm{K}^+ \to \pi^+ \mu^+ \mu^-) = (0.962 \pm 0.025) \times 10^{-7}$ *[Phys. Lett. B 697 (2011) 107]*

Lepton Flavour Violation



$K^+ \to \pi^- e^+ e^+$ Signal Region

- Bkg. Prediction: $N_{SR}^{tot} = 0.16 \pm 0.03$
- Observed: $n_{SR} = 0$
- $N_K = (2.14 \pm 0.07) \times 10^{11}$
- $SES = (0.87 \pm 0.03) \times 10^{-10}$

$K^+ \to \pi^- \mu^+ \mu^+$ Signal Region

- Bkg. Prediction: $N_{SR}^{tot} = 0.91 \pm 0.41$
- Observed: $n_{SR} = 1$
- $N_K = (7.94 \pm 0.23) \times 10^{11}$
- $SES = (1.28 \pm 0.03) \times 10^{-11}$

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

NP searches in kaon decays @NA62

- Search for HNL in $K^+ \to l^+ N$ with undecayed N
  - $K^+ \to l^+ N$ events would appear as peaks in the $K^+ \to l^+ \nu$ m^2_{miss}
  - Searches are model independent

- Searches for LNV/LFV decays, SES achieved with the 2017 data

$$\left.\begin{array}{ll} \mathrm{BR}(\pi^- \mu^+ e^+) < 5.0 \times 10^{-10} & [\mathrm{LNV}] \\ \mathrm{BR}(\pi^+ \mu^- e^+) < 5.2 \times 10^{-10} & [\mathrm{LFV}] \end{array}\right\} \text{SES} \approx 5 \times 10^{-11} \text{ (factor} \sim 5 \text{ improvement on BNL-E865)}$$

$$\left.\begin{array}{ll} \mathrm{BR}(\pi^+ \mu^+ e^-) < 1.3 \times 10^{-11} & [\mathrm{LFV}] \\ \mathrm{BR}(\pi^0 \to \mu^\pm e^\mp) < 3.6 \times 10^{-10} & [\mathrm{LFV}] \end{array}\right\} \text{Not competitive yet}$$

- Searches for $K^+ \to \mu^- \nu e^+ e^+$, $K^+ \to e^- \nu \mu^+ \mu^+$ decays, SES from 2017 data

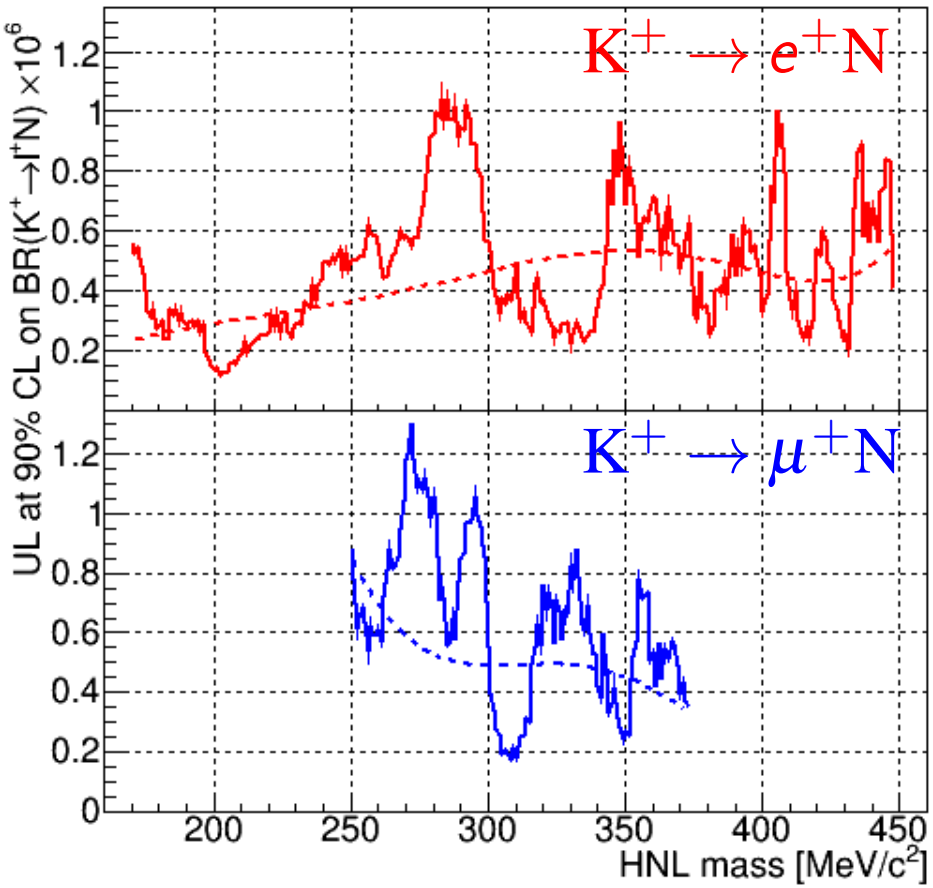
$K^+ \to \mu^- \nu e^+ e^+$ [LFV] SES $\approx 1 \times 10^{-10}$ - factor 100 improvement on PDG

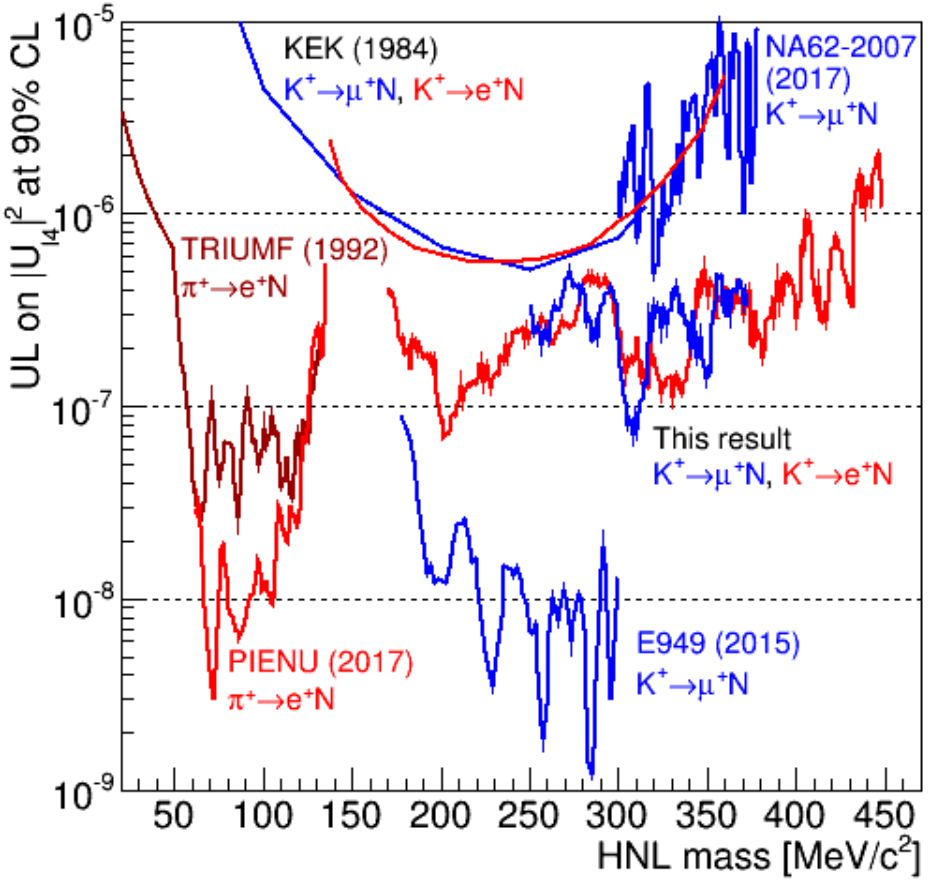
$K^+ \to e^- \nu \mu^+ \mu^+$ [LFV] SES $\approx 5 \times 10^{-11}$ - the first search for this mode

- The full 2016-18 dataset is ~ 3 times the size of 2017 dataset

Results of HNL search - 2015 data

- Local signal significance never exceeds 3σ: **no HNL signal is observed**
- Reached $10^{-6} - 10^{-7}$ limits for $|U_{e4}|^2$ in the 170-448 MeV/c^2 mass range
- Improved limits for $|U_{\mu 4}|^2$ for $300 \leq m_N \leq 373$ MeV/c^2
- **Major improvement foreseen** with high intensity NA62 data





[Phys. Lett. B 778 (2018) 137-145]

HNLs: prospects with full data set

- Data sample 2016-18 in comparison to data sample 2015:
  - Beam tracker (GTK) in operation:
    - a factor ~ 2 improved HNL mass resolution σ_m
    - lower background and broader mass range accessible
    - a factor ~ 3 lower background in the $K^+ \to e^+ N$ mode
      ($K^+ \to \mu^+ \nu$, $\mu^+ \to e^+ \nu\nu$: muon decays in flight rejected geometrically)
    - lower background from upstream decays in the $K^+ \to \mu^+ N$ mode
  - Much larger data sets:
    - $K^+ \to e^+ N$ mode: the main $K^+ \to \pi^+ \nu\nu$ trigger is used
      with reduced signal acceptance - max calorimetric energy = 30 GeV:
      expect $O(10^6)$ $K^+ \to e^+ \nu$ events, a factor ~ 1000 improvement
    - $K^+ \to \mu^+ N$ mode: down scaled control trigger (D=400):
      expect $O(10^9)$ $K^+ \to \mu^+ \nu$ events, a factor ~ 100 improvement
  - Expected sensitivities to $|U_{\ell 4}|^2$ with 2016-18 data:
    - better than 10^{-8} for both $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

Large data sets already collected; analysis is in progress

Conclusions for $K^+ \to \pi^+ \nu\bar{\nu}$ decays

- **NA62 BR($K^+ \to \pi^+ \nu\bar{\nu}$) measurement:**
  - Decay in flight technique works!
  - 1 event observed in 2016 data
  - BR($K^+ \to \pi^+ \nu\bar{\nu}$) $< 14 \times 10^{-10}$ @95% CL
    [Phys. Lett. B 791 (2019) 156-166]
  - Analysis of 2017 data is ongoing - Results expected in 2019
  - Precise evaluation of the total statistics collected in 2018 is under study
  - BR measurement expected in the next few years

Conclusions for other NA62 decay

- **Searches for LFV/LNV in 3-track decays:**
  - 3 months of 2017 data of 2 LNV/LFV decays improving over PDG limits *[Phys. Lett. B 797 134794 (2019)]*
  - $\mathrm{BR}(\mathrm{K}^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ @90% CL
  - $\mathrm{BR}(\mathrm{K}^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ @90% CL
  - ~ 3 times more data still to analyze
- **HNL result from the 2015 run:**
  - Search for HNL production in $\mathrm{K}^+ \to \ell^+ N$ decays with minimum bias data:
    $10^{-6} - 10^{-7}$ limits on $|U_{e4}|^2$ in mass range 170-448 MeV/c^2
    Improved limits for $|U_{\mu 4}|^2$ for $300 \leq m_N \leq 373$ MeV/c^2
    [Phys. Lett. B 778 (2018) 137-145]
  - Major improvement in HNLs foreseen with new data
- **Search for production of an invisible dark photon in π^0 decays:**
  - Improved previous limits over the mass range 60-110 MeV/c^2
  - Results published in *[JHEP 05 (2019) 182]*