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Deep-Inelastic Scattering andRelater Subjects
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Latest results on rare decays at the NA62 experiment at CERN

On behalf of the NA62 collaboration

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Outline

- NA62 experiment overview
- Lepton flavour/number Violating decays
- Heavy Neutral Leptons (HNL) searches:
  - HNL production: $K^+ \to e^+ N$, $K^+ \to \mu^+ N$
- $K^+ \to \mu^+\nu\nu\nu$, $K^+ \to \mu^+\nu X$
- Summary

NA62 experiment (decay-in-flight)

- Main goal is measure ultra rare kaon decay $K^+ \to \pi^+ \nu\nu$ with 10% precision

- SM prediction:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

[Buras et al., JHEP 1511 (2015) 033]

- Experimental value

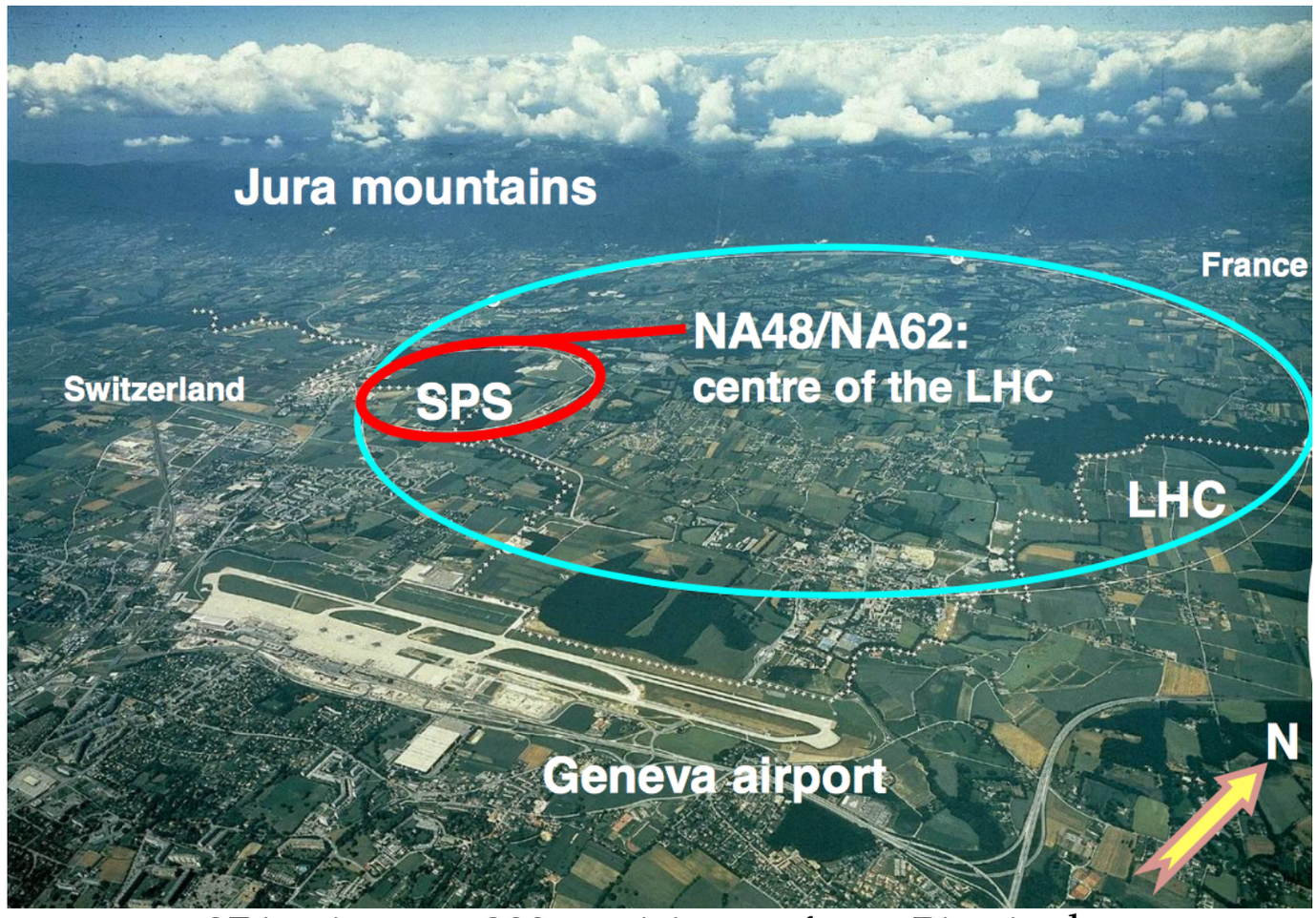
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

[E949/E787 PRL 101 (2008) 191802]

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

[NA62, JHEP06 (2021) 093]

- Sensitive to New Physics



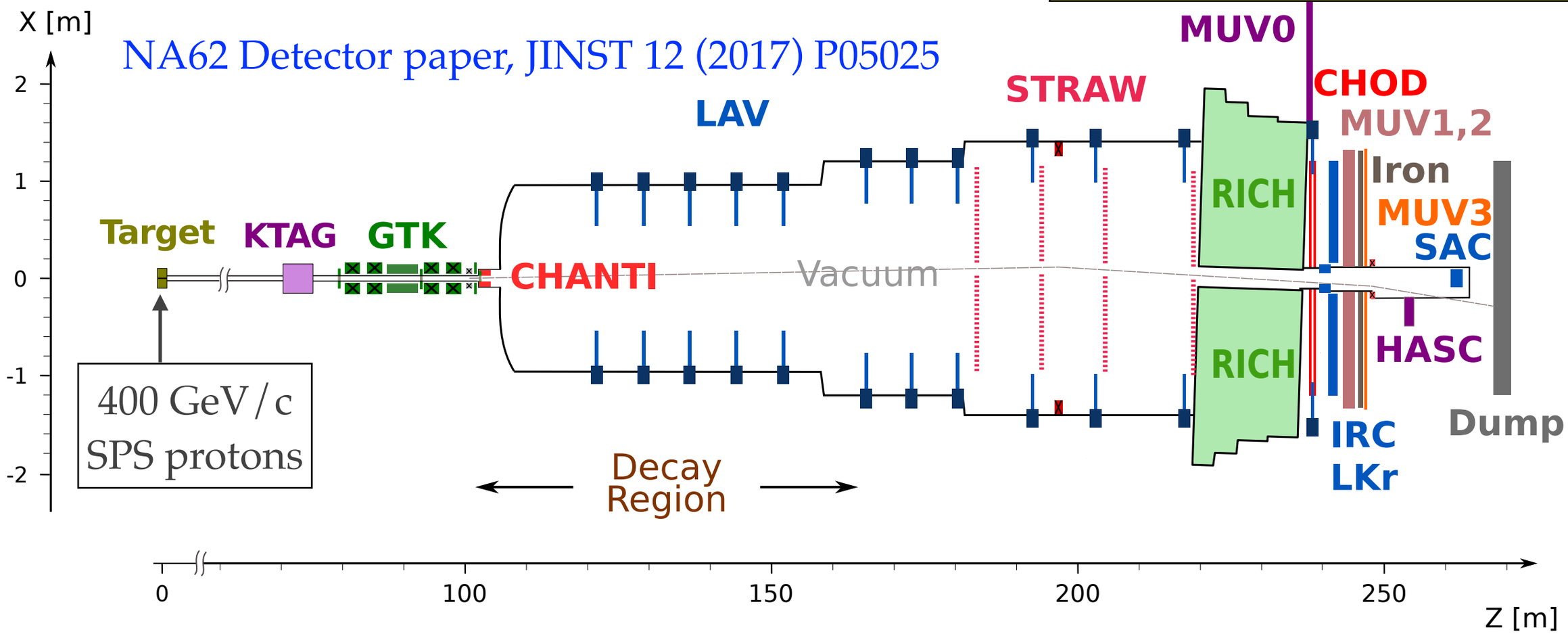
27 institutes, ~200 participants form: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax-GMU, Ferrara, Firenze,Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Torino, TRIUMF, Vancouver UBC

See R.Fantechi's talk for more details about $K^+ \to \pi^+ \nu\nu$

The NA62 detector

Unseparated secondary beam:

- K^+(6%), π^+(70%), p(24%)
- 800 MHz rate; 45 MHz K^+ rate
- Momentum: 75 GeV/c



- Timing between sub detectors O(100 ps)
- Kaon ID and direction (KTAG, GTK)
- Particle ID and direction (STRAW, RICH, LKr, HASC, MUV): μ^+ rejection O(10^7)
- Photon veto (LAV, LKr, IRC, SAC): $\pi^0 \to \boldsymbol{\gamma\gamma}$ rejection O(10^7)

Data collection

2016: 30 days, 2×10^{11} useful kaon decays
2017: 161 days, 2×10^{12} useful kaon decays
2018: 217 days, 4×10^{12} useful kaon decays

Run1

2021: 85 days [10 beam dump]

Run2,
approved till LS3

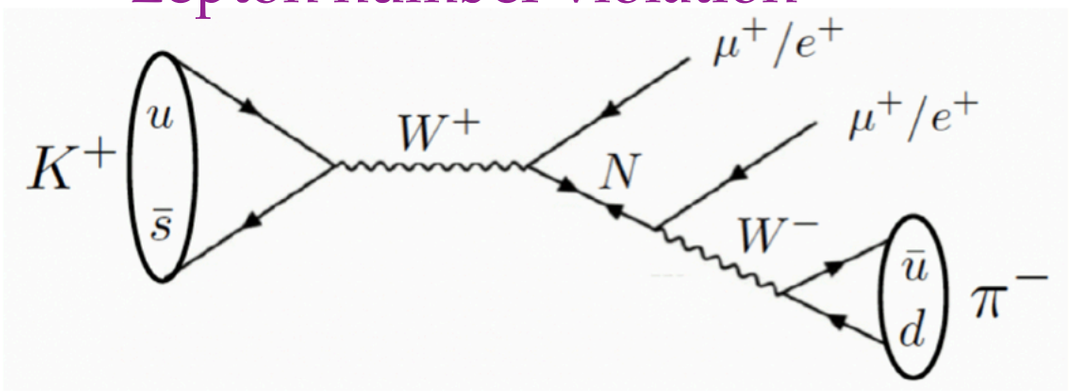
Trigger streams:

- $\pi\nu\nu$ trigger: 1 track, γ/μ veto
- Control trigger: samples for normalization, background estimation
- 3-track triggers: samples for lepton flavour violation study

Lepton Number/Flavour Violation

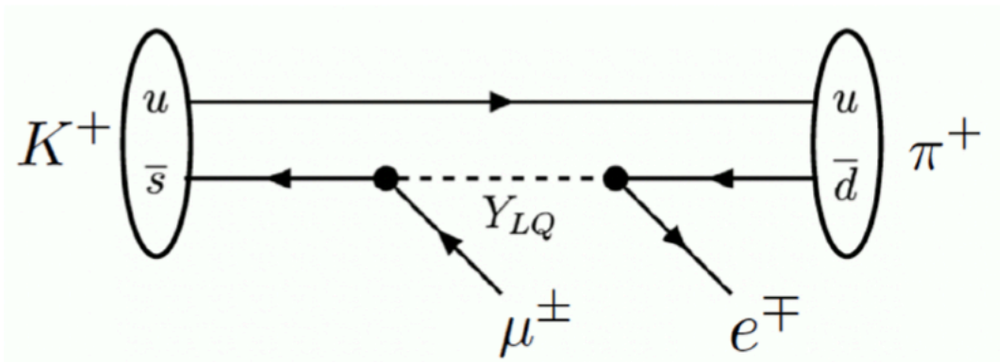
- Lepton number (L) and lepton flavour (L_e,L_μ,L_τ) are conserved quantities in the Standard Model
- Violation of these quantities is a clear indication of Physics Beyond the Standard Model

Lepton number violation



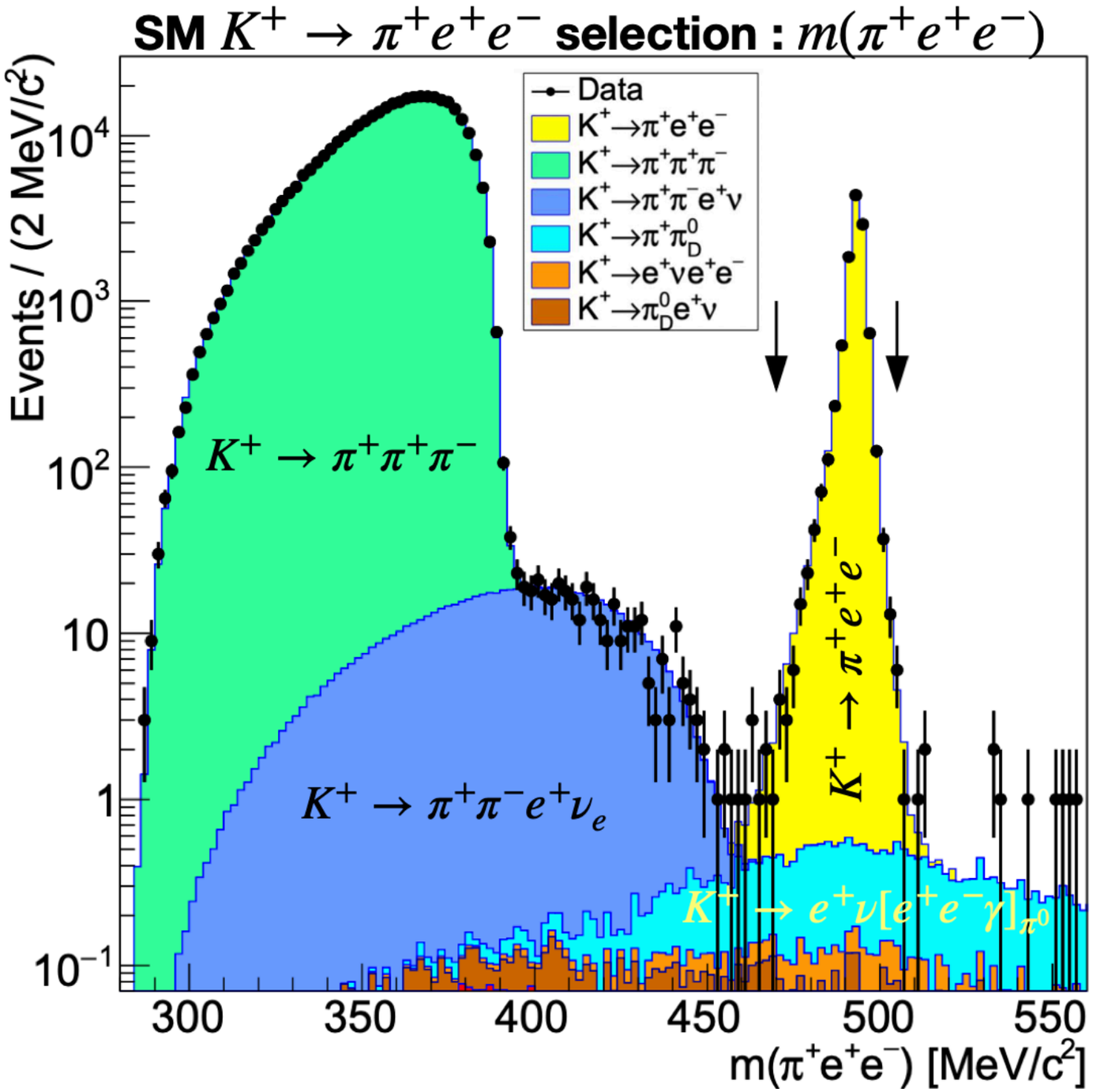
Seesaw mechanism provides a source of LNV through the exchange of Majorana neutrinos as in 0νββ decay [JHEP 0905 (2009) 030]

Lepton flavour violation



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]

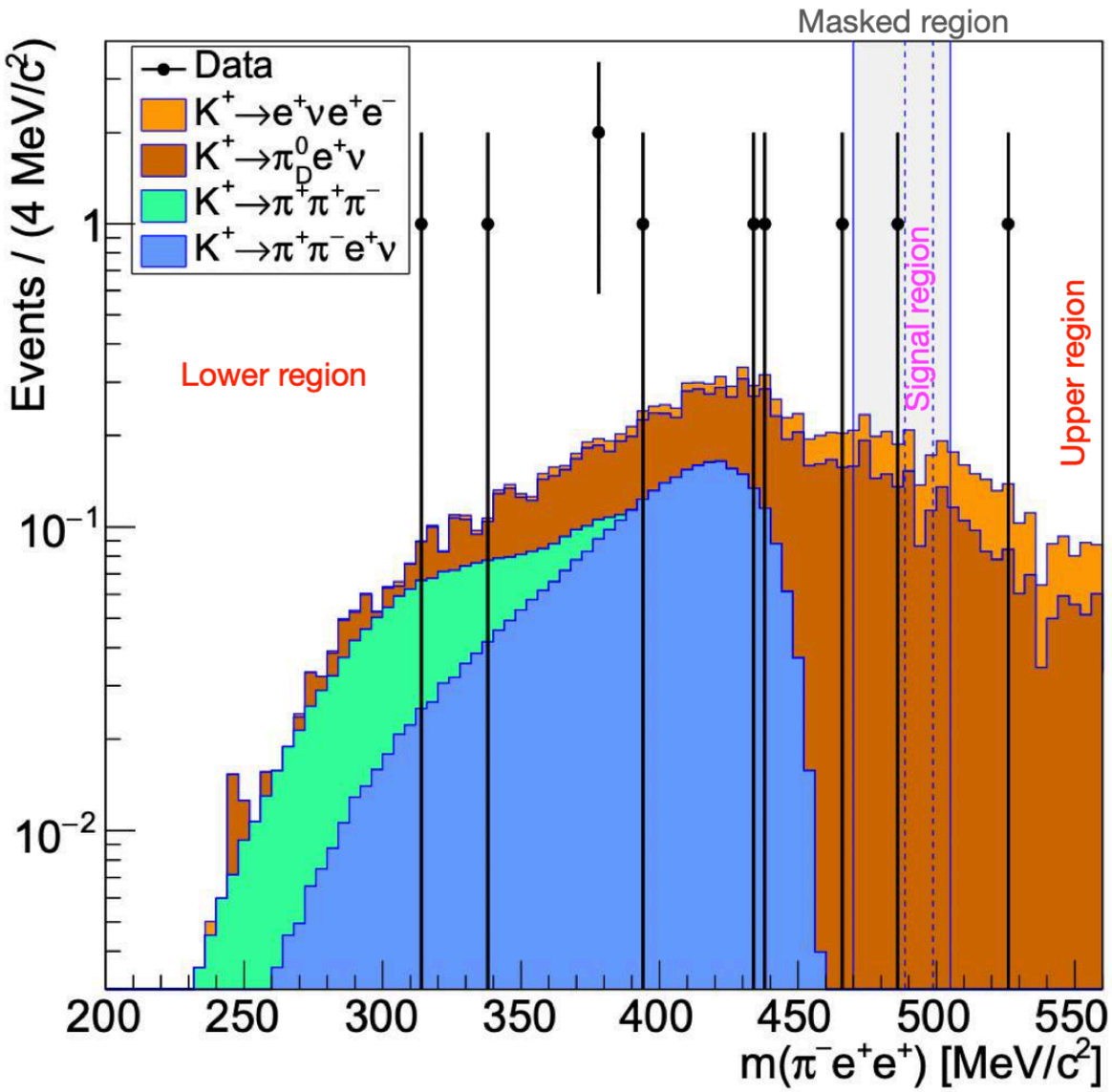
Searches for $K^+ \to \pi^-(\pi^0)e^+e^+$



Normalise to the SM $K^+ \to \pi^+e^+e^-$ with BR = $(3.00 \pm 0.09) \times 10^{-7}$.
11041 candidates are found — **world's largest sample**

New result: arXiv:2202.00331 [hep-ex]

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



Mode	Lower region	Upper region	Masked region	Signal region
$K^+ \to \pi^+\pi^+\pi^-$	0.9	–	–	–
$K^+ \to \pi^+\pi^-e^+\nu$	3.3	–	–	–
$K^+ \to \pi^+\pi^0_D$	–	0.02	0.01	–
$K^+ \to \pi^0_D e^+\nu$	3.7 ± 0.7	1.20 ± 0.24	1.23 ± 0.25	0.29 ± 0.06
$K^+ \to e^+\nu e^+e^-$	0.7 ± 0.1	0.76 ± 0.15	0.47 ± 0.09	0.14 ± 0.03
Total	8.6 ± 0.9	1.98 ± 0.39	1.71 ± 0.34	0.43 ± 0.09
Data	8	1	1	0

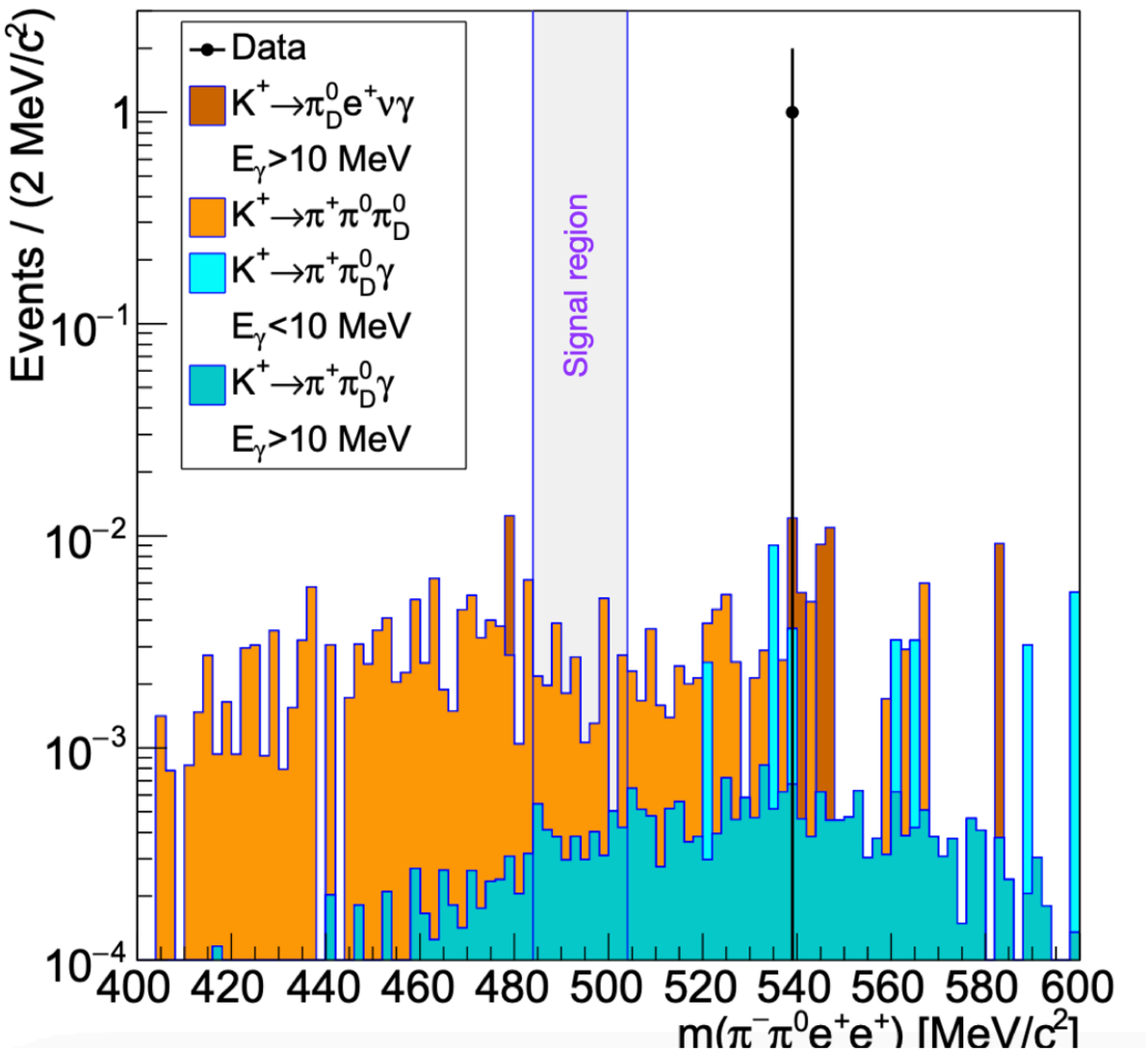
- Blind analysis method — validate background estimation in control regions.
- In signal region $n_{exp} = 0.43 \pm 0.09$, $n_{obs} = 0$

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

A factor of 4 improvement with respect to previous NA62 result with partial data set (2017 only):
PLB 797 (2019) 134794

New result: arXiv:2202.00331 [hep-ex]

Result for $K^+ \to \pi^-\pi^0 e^+ e^+$



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

- Blind analysis method — validate background estimation in control regions.
- In signal region $n_{exp} = 0.044 \pm 0.020$, $n_{obs} = 0$

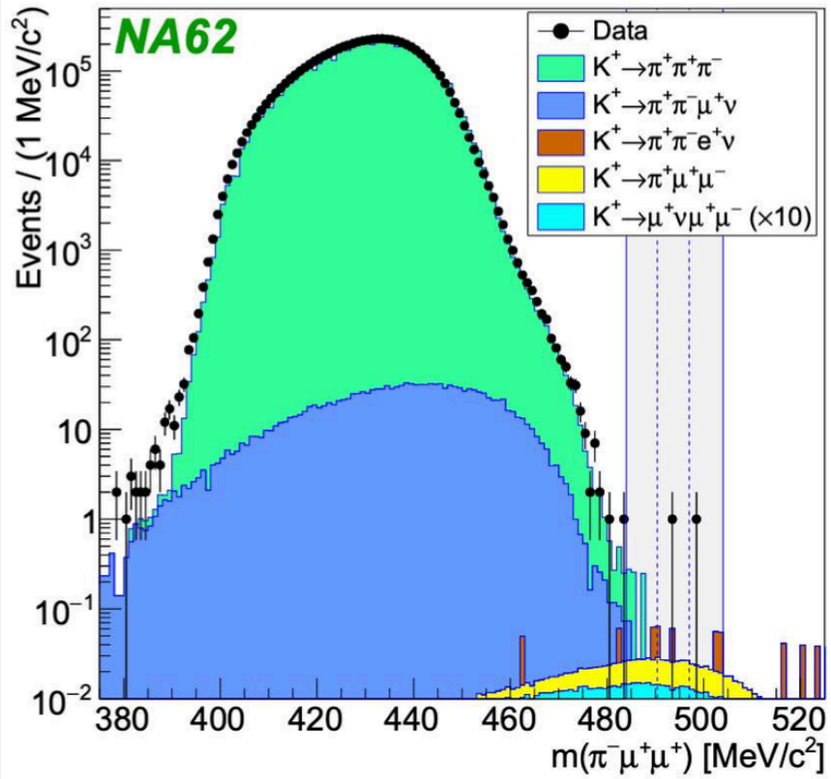
Set upper limit
$BR(K^+ \to \pi^-\pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ at 90% CL

First search for this LNV decay!

New result: arXiv:2202.00331 [hep-ex]

Other LNV/LNF decays

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



2017 data : $N_K = (7.94 \pm 0.23) \times 10^{11}$ (di-muon trigger)

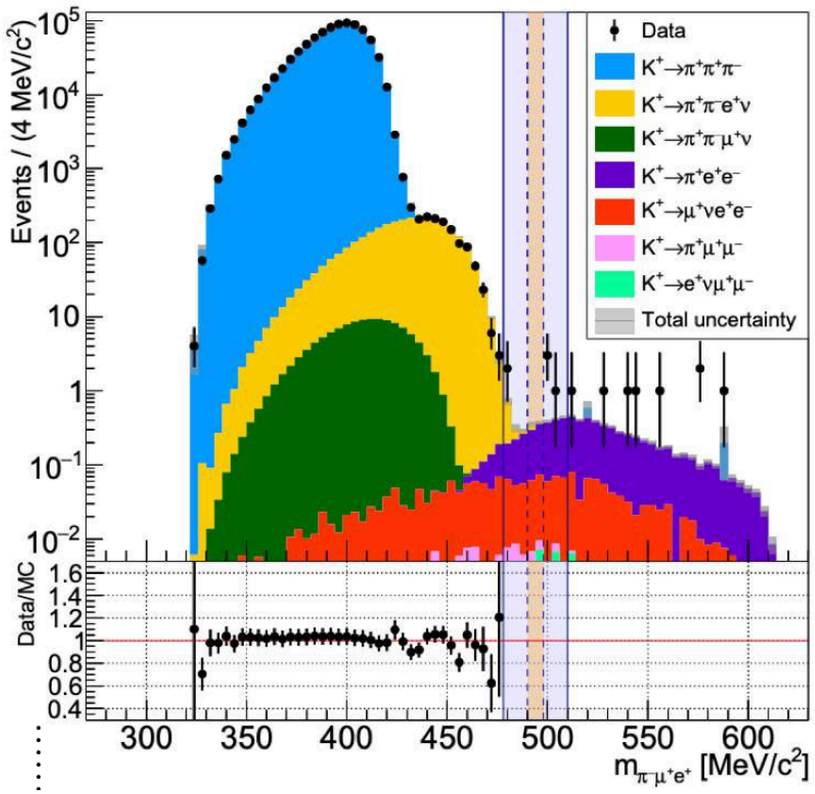
Expected background: 0.91 ± 0.41 Candidates observed: 1

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

[PLB 797 (2019) 134794]

Factor 2 improvement on NA48/2 limit [PLB 769 (2017) 67]

LNV/LFV : $K^+ \to \pi^-\mu^+e^+$



2017+18 data : $N_K = (1.33 \pm 0.02) \times 10^{12}$ (combine 3 triggers)

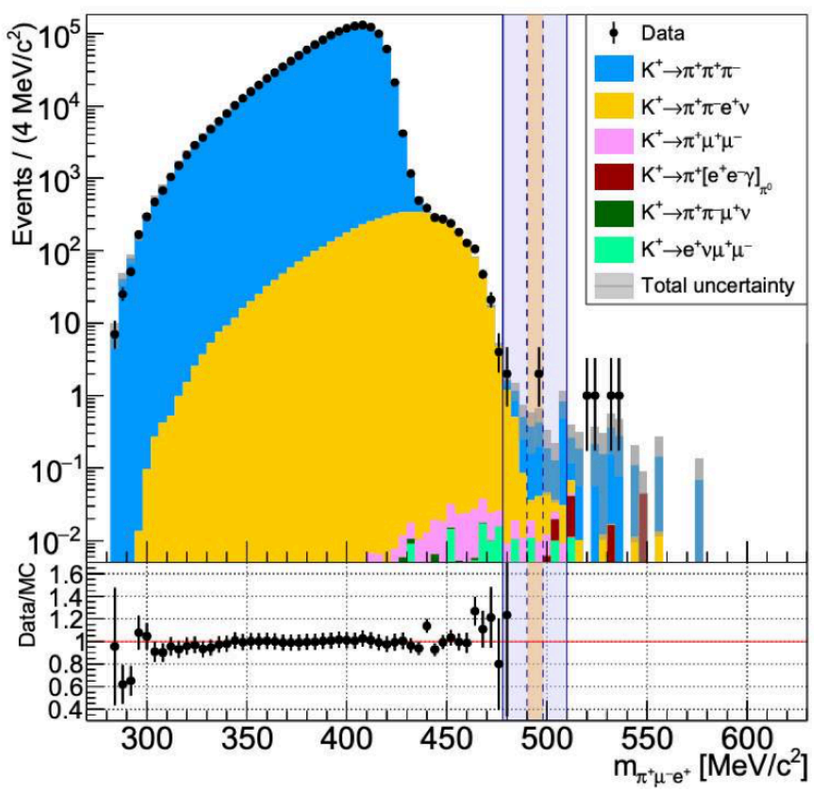
Expected background: 1.07 ± 0.20

Candidates observed: 0

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

[PRL 127 (2021) 131802]

LFV : $K^+ \to \pi^+\mu^-e^+$



Expected background: 0.92 ± 0.34

Candidates observed: 2

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

From $K^+ \to \pi^+\pi^0$, $\pi^0 \to \mu^-e^+$ search:

$\mathcal{B}(\pi^0 \to \mu^-e^+) < 3.2 \times 10^{-10}$ @ 90 % CL

Improve by approximately 1 order of magnitude on previous BNL E865 results [PRL 85 (2000) 2877].

NA62 LNV/LNF summary

	Previous UL @ 90% CL	NA62 UL @ 90%CL		
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data → 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 → improved by factor 12	NEW ! arXiv:2202.00331
$K^+ \to \pi^- \pi^0 e^+ e^+$	no limit	8.5×10^{-10}	Run1 data	NEW ! arXiv:2202.00331
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data → improved by factor 12	PRL 127 131802 (2021)
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data → improved by factor 8	PRL 127 131802 (2021)
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data → improved by factor 13	PRL 127 131802 (2021)
$K^+ \to \pi^+ \mu^+ e^-$	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 $\sim 5 \times 10^{-11}$	

Heavy Neutral Leptons (HNL)

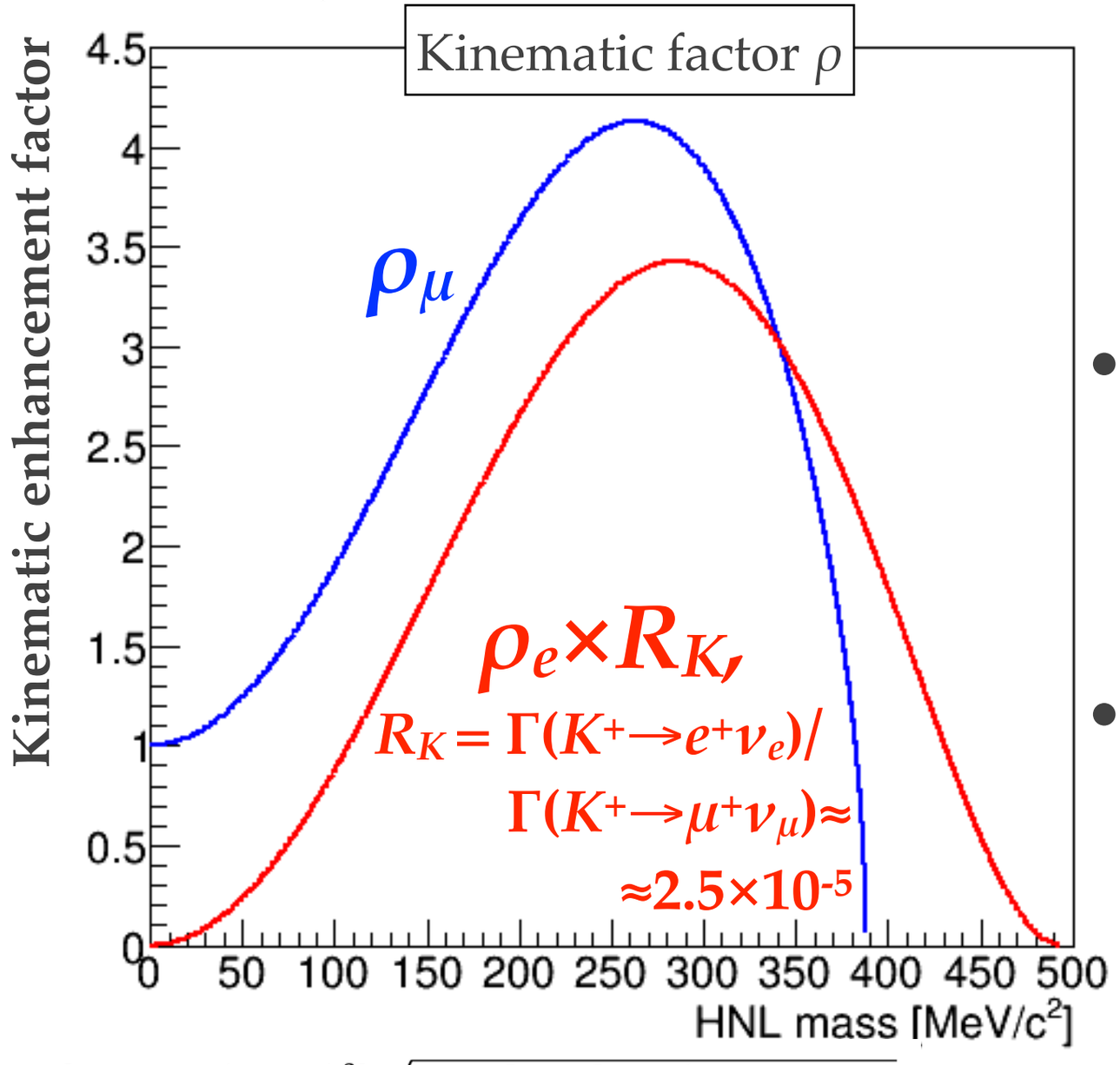
- The νMSM (Asaka et al., Phys.Lett.B 620 (2005) 17) is an extension of the SM to explain simultaneously neutrino oscillations, dark matter and baryon asymmetry of the Universe.
  - SM + 3 right-handed sterile neutrinos:
    - N_1: m_1 ~ 10 keV — dark matter candidate
    - $N_{2,3}$: $m_{2,3}$ ~ 100MeV — 100 GeV — baryon asymmetry
- GeV-scale HNLs can be observed via their production and decay (both searches are possible at NA62)

HNL production in K^+ decays

$$\Gamma(M^+ \to l^+ \nu_H) = \rho \times \Gamma(M^+ \to l^+ \nu_l) \times |U_{lH}|^2$$

O(1)

R.E.Shrock, Phys.Rev.D24 1232 (1981)



$K^+ \to l^+ \nu_H$, $l = e, \mu$

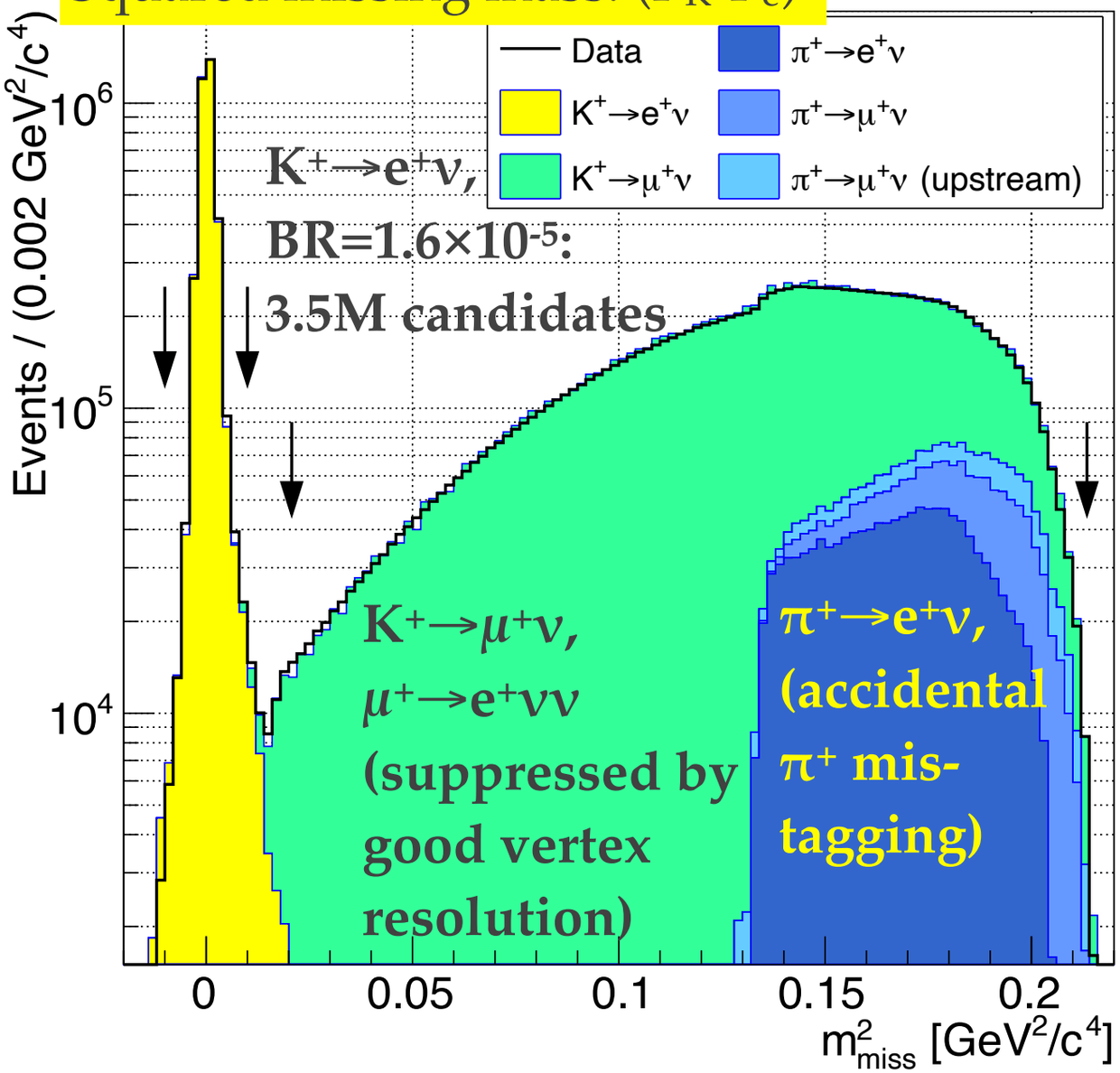
- HNL production is enhanced kinematically with respect to SM decays, except near kinematic endpoints
- Enhancement ~10^5 in the $K^+ \to e^+ \nu_H$ case as the helicity suppression is relaxed

$$\rho = \frac{[x+y-(x-y)^2]\sqrt{1+x^2+y^2-2(x+y+xy)}}{x(1-x)^2}, \quad x = m_l^2/m_M^2 \ , \ y = m_{\nu_H}^2/m_M^2$$

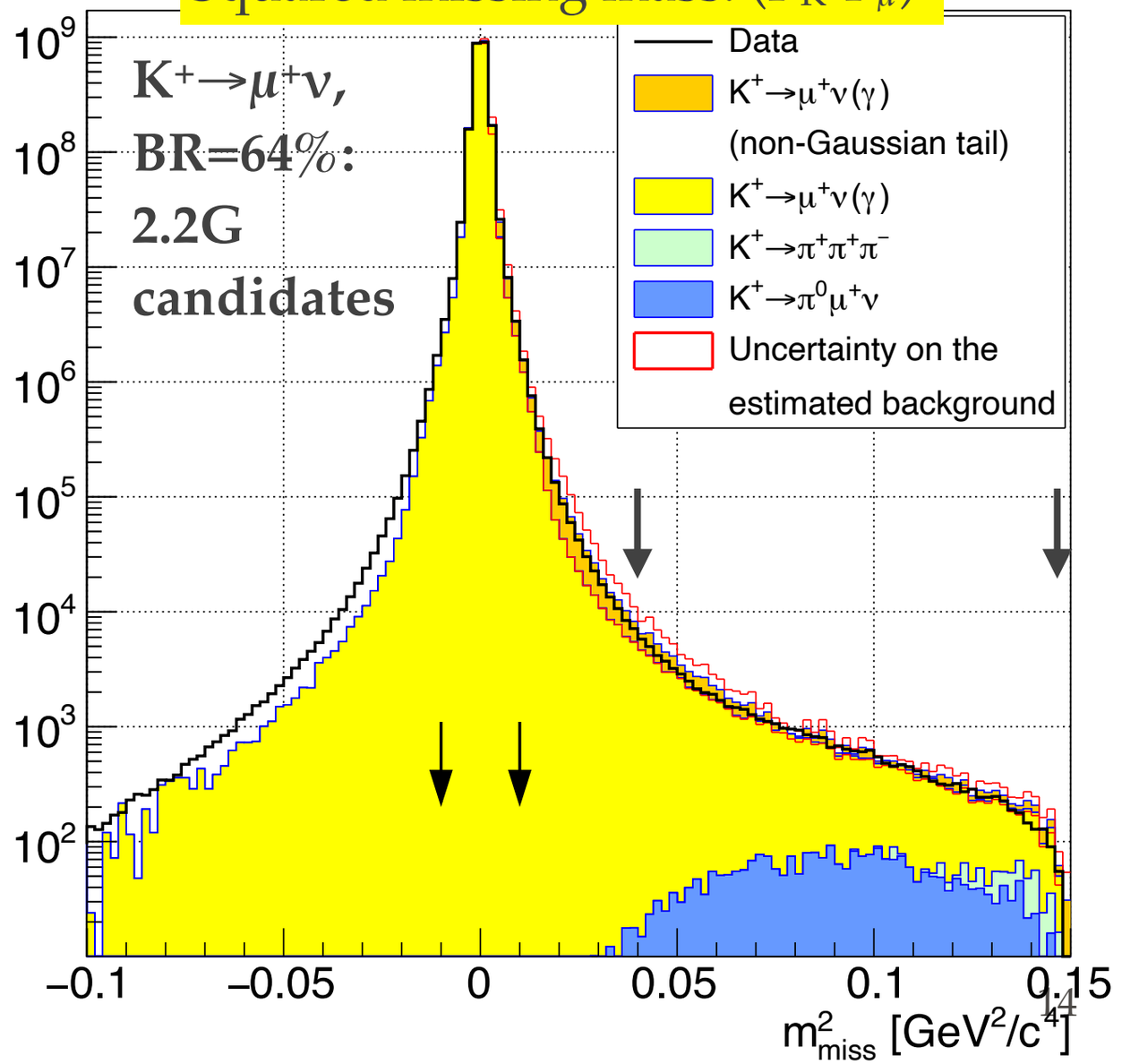
Heavy Neutral Leptons (HNL)

- Triggers: the main $K_{\pi\nu\nu}$ for $K^+ \to e^+ \nu_H$, Control/400 for $K^+ \to \mu^+ \nu_H$
- Number of kaon decays in the fiducial volume:
  $(3.52 \pm 0.02) \times 10^{12}$ for $K^+ \to e^+ \nu_H$, $(1.14 \pm 0.02) \times 10^{10}$ for $K^+ \to \mu^+ \nu_H$
- Peak search in the missing mass distribution $(P_K - P_l)^2$, P_K is kaon four-momentum, P_l is lepton four-momentum, use GTK and STRAW

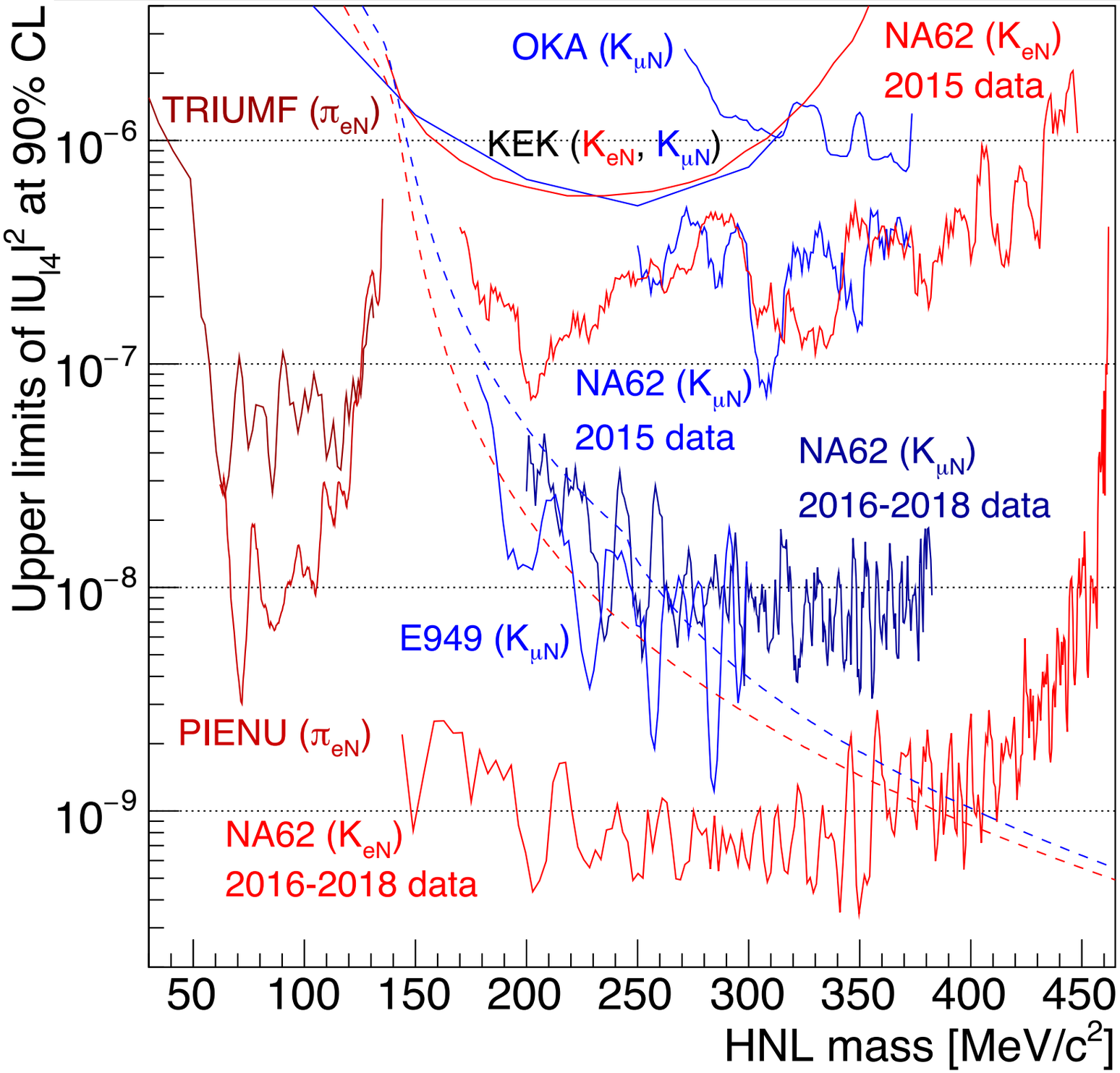
Squared missing mass: $(P_K - P_e)^2$



Squared missing mass: $(P_K - P_\mu)^2$



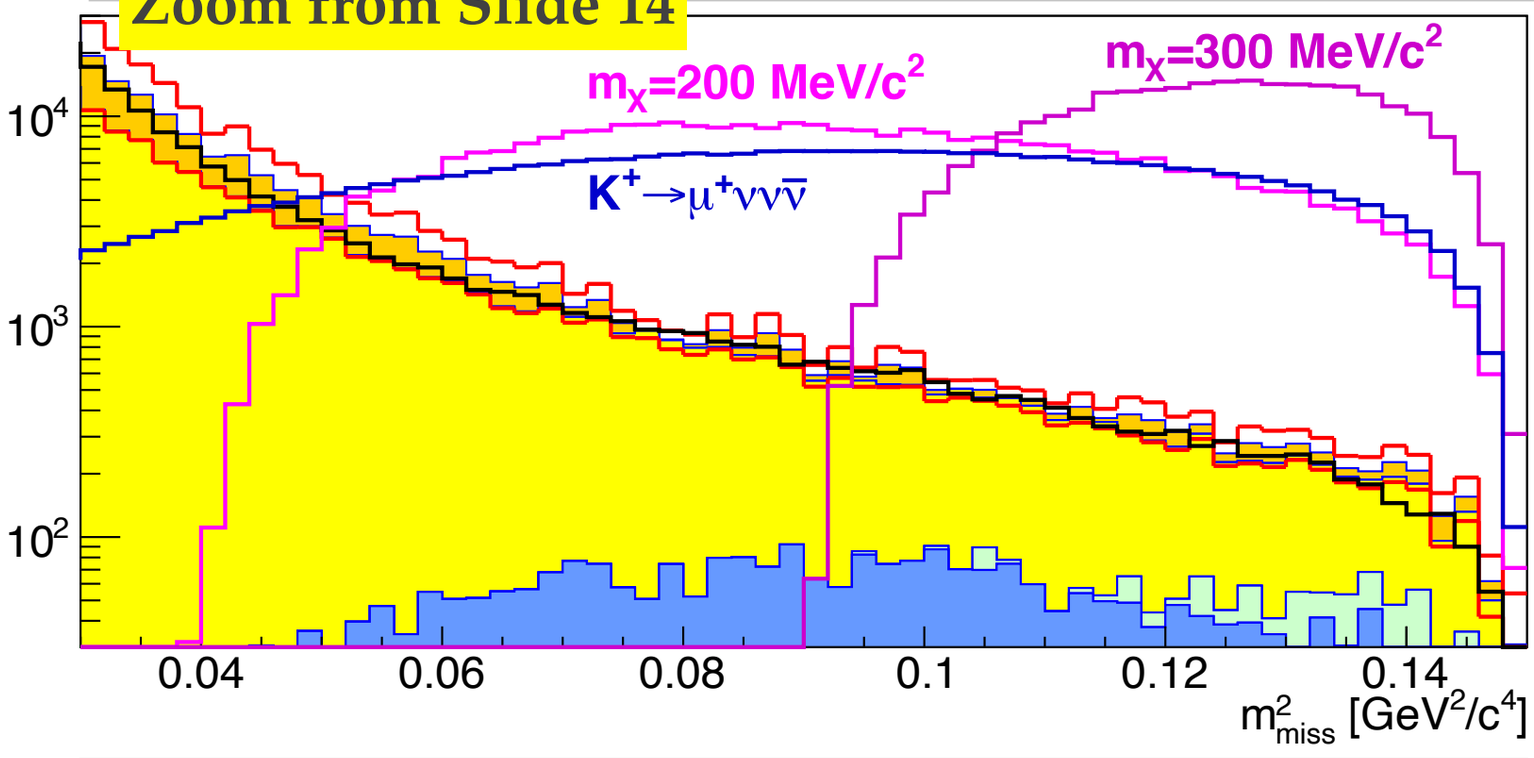
HNL Results

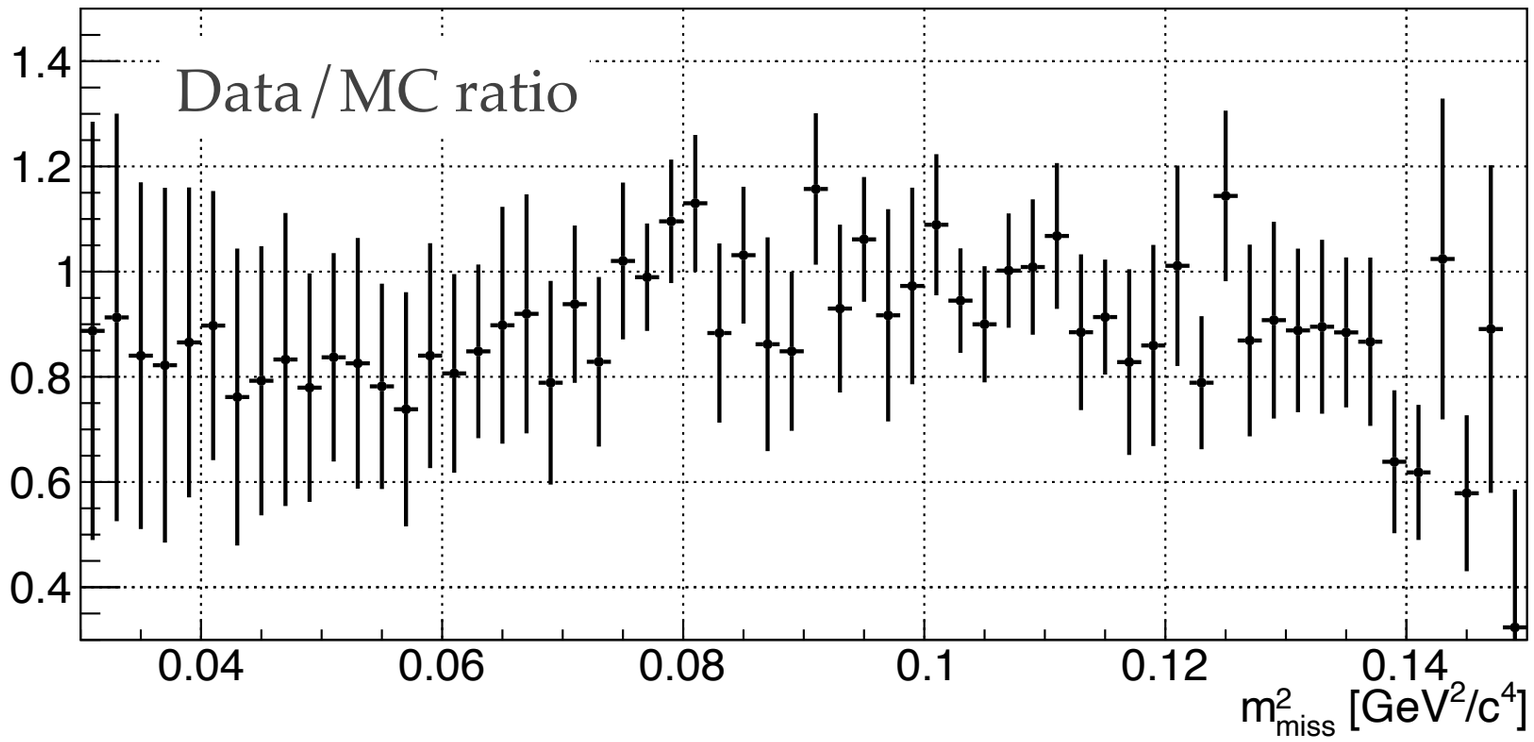


- No signal observed
- Full 2016-18 (RunI) data set is analyzed
- Close related study: $K^+ \to l^+ \nu\nu\nu$ and $K^+ \to l^+ \nu X$, X is invisible: predict background from MC simulation

$K^+ \to \mu^+ \nu\nu\nu$ and $K^+ \to \mu^+ \nu X$

Zoom from Slide 14





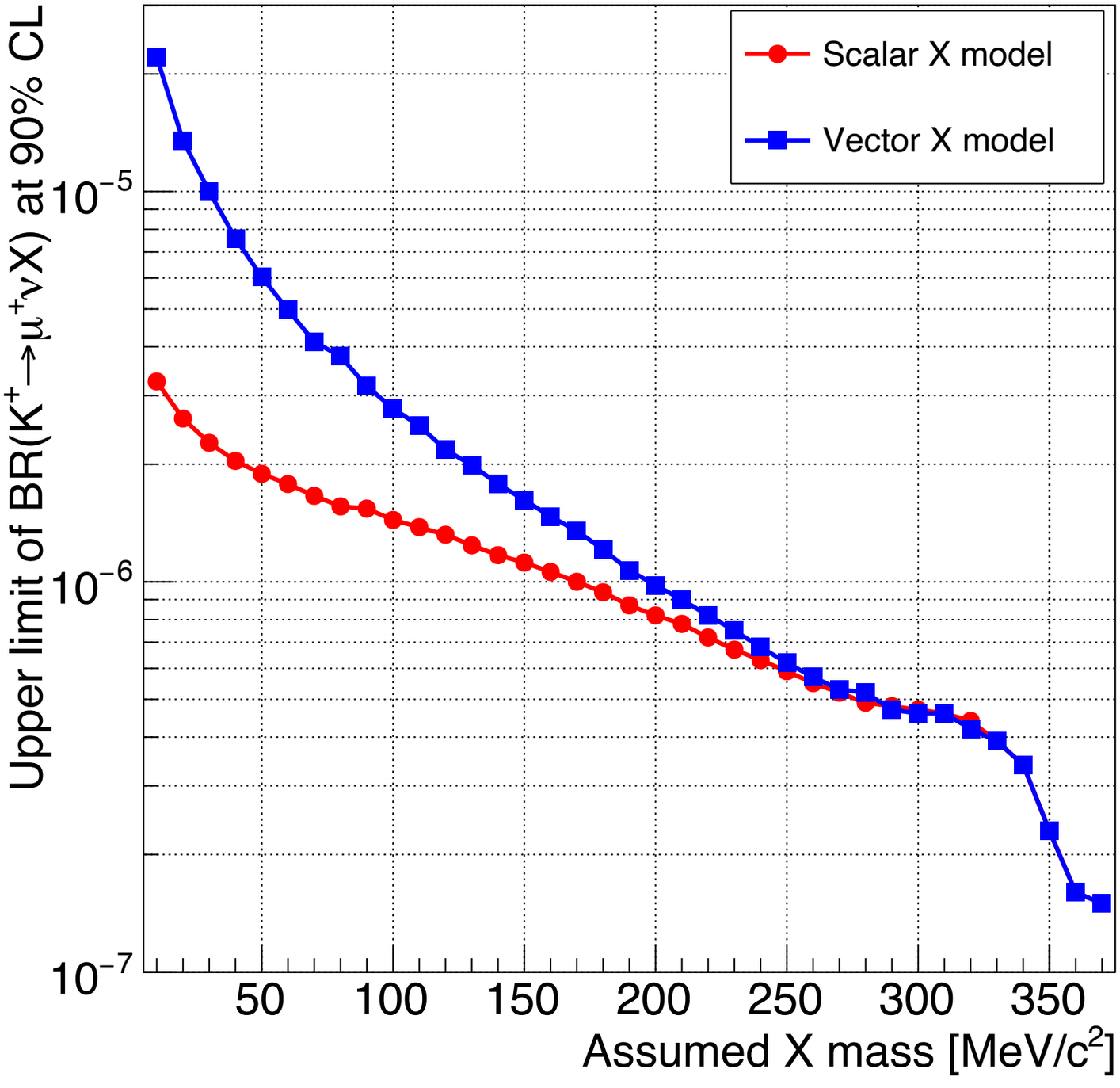
$K^+ \to \mu^+ \nu\nu\nu$

- Very rare in the Standard Model, BR: 1.6×10^{-16} [JHEP1610 (2016) 039]
- The current limit: $<2.4\times10^{-6}$ [E949, PRD94 (2016) 032012]
- Search region $m^2_{miss} > 0.1$ GeV$^2/c^4$ (optimized to extract strongest limit):
  - Observed events: 6894
  - Expected from MC: 7549±928
  - Set upper limit: 1.0×10^{-6} at 90%CL in the SM framework

$K^+ \to \mu^+ \nu X$, X is scalar or vector

- [PRL124 (2020) 041802]
- Mass range 10—370 MeV/c^2
- Compare expected and observed number of event for each mass hypothesis and extract limit.

$K^+ \to \mu^+ \nu X$ results



$K^+ \to \mu^+ \nu X$, X is scalar or vector

- No signal observed
- The limits obtained in the scalar model are stronger than those in the vector model due to larger mean m^2_{miss} value.

Summary

- The NA62 experiment is a powerful laboratory to make searches for exotic particles/processes
- World best upper limits on LNV/LNF kaon decays have been set
- World best upper limits on HNL mixing parameters have been set
- World best upper limit on BR($K^+ \to \mu^+ \nu\nu\nu$) has been set
- NA62 will continue to take data until LongShutdown3(LS3) — resumed in 2021