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Search for K+ decays to a lepton and invisible particles

On behalf of the NA62 collaboration

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Outline

- NA62 experiment overview
- 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

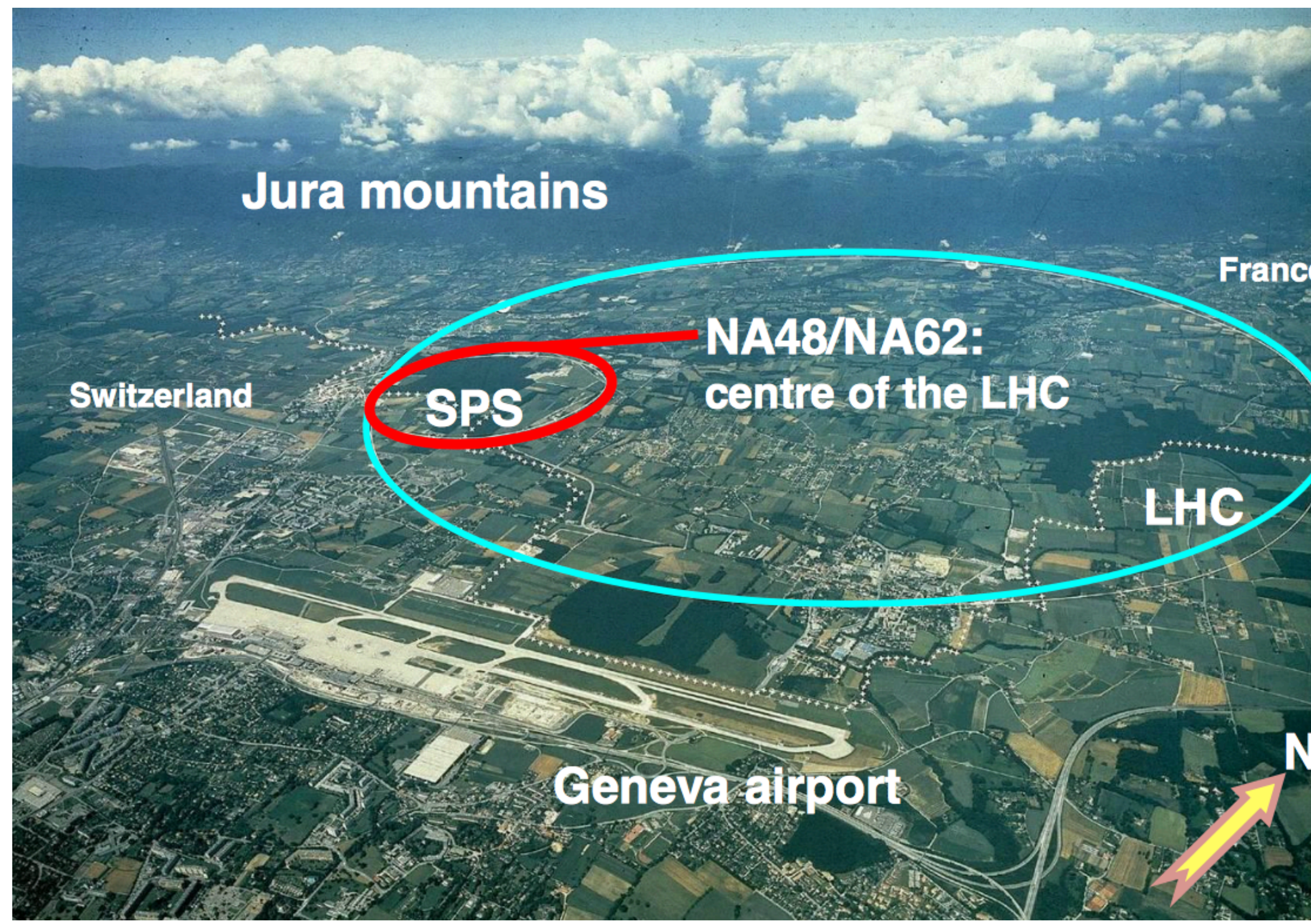
$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

[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



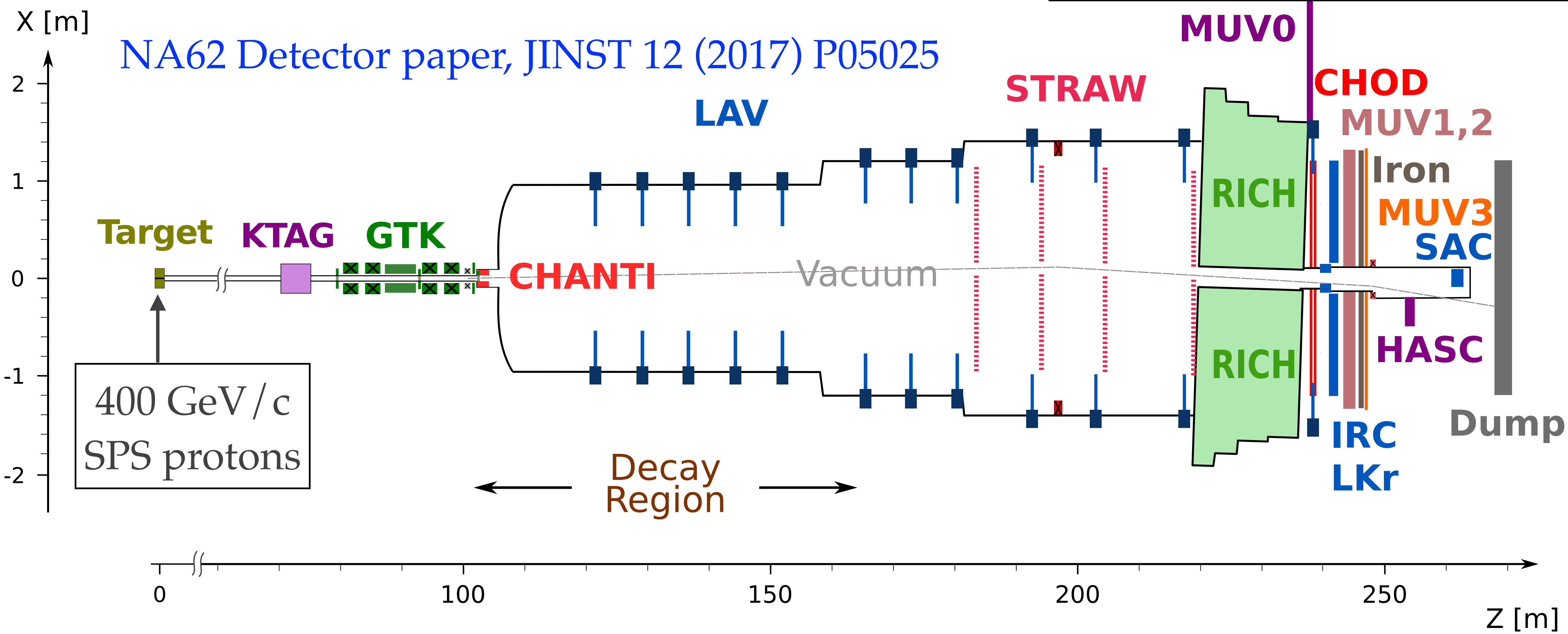
27 institutes, ~200 participants form: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax-GMU, Ferrara, Firenze,Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Torino, TRIUMF, Vancouver UBC

The NA62 detector

Unseparated secondary beam:

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

NA62 Detector paper, JINST 12 (2017) P05025



- 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): $\pi^0 \rightarrow \gamma\gamma$ rejection O(10^7)

Data collection

2014	2015	2016	2017	2018	2019-2020
Pilot Run	Commissioning	Commissioning + Physics Run	Physics Run	Physics Run	LS2 Long shutdown 2

2015: 1% of nominal intensity, 3×10^8 kaon decays
2016: 30 days, 40% of nominal intensity, 2×10^{11} useful kaon decays
2017: 161 days, 60% of nominal intensity, 2×10^{12} useful kaon decays
2018: 217 days, 60% of nominal intensity, 4×10^{12} useful kaon decays

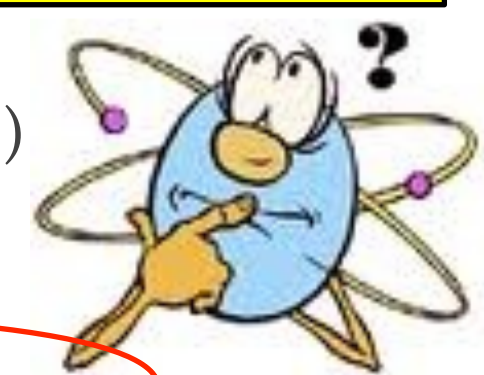
Trigger streams:

- $\pi\nu\nu$ trigger: 1 track, $\boldsymbol{\gamma}/\mu$ veto
- Control trigger: samples for normalization, background estimation
- 3-track triggers: samples for lepton flavour violation study

Beyond the Standard Model

Neutrino oscillation	Baryon asymmetry of the Universe	Dark matter and dark energy
		 

There is New Physics beyond the Standard Model, but we don't know exactly what is it



Search for New Physics:

- Study of rare decays of the SM particles (like $K^+ \to \pi^+ \nu\nu$)
  - PLB791 (2019) 156-166, JHEP11 (2020) 042, JHEP06 (2021) 093 ($K^+ \to \pi^+ \nu\nu$)
- Search for new particles (HNL, ALP, dark photon etc.)
  - **PLB807 (2020) 135599, PLB816 (2021) 136259 (HNL)**
  - JHEP 05 (2019) 182, JHEP02 (2021) 201, JHEP03 (2021) 058 (other exotic)
- Search for forbidden (in the SM framework) processes
  - PLB 797 (2019) 134794 (LNV in K^+ decays)

All methods are available at NA62

This talk

Heavy Neutral Leptons (HNL)

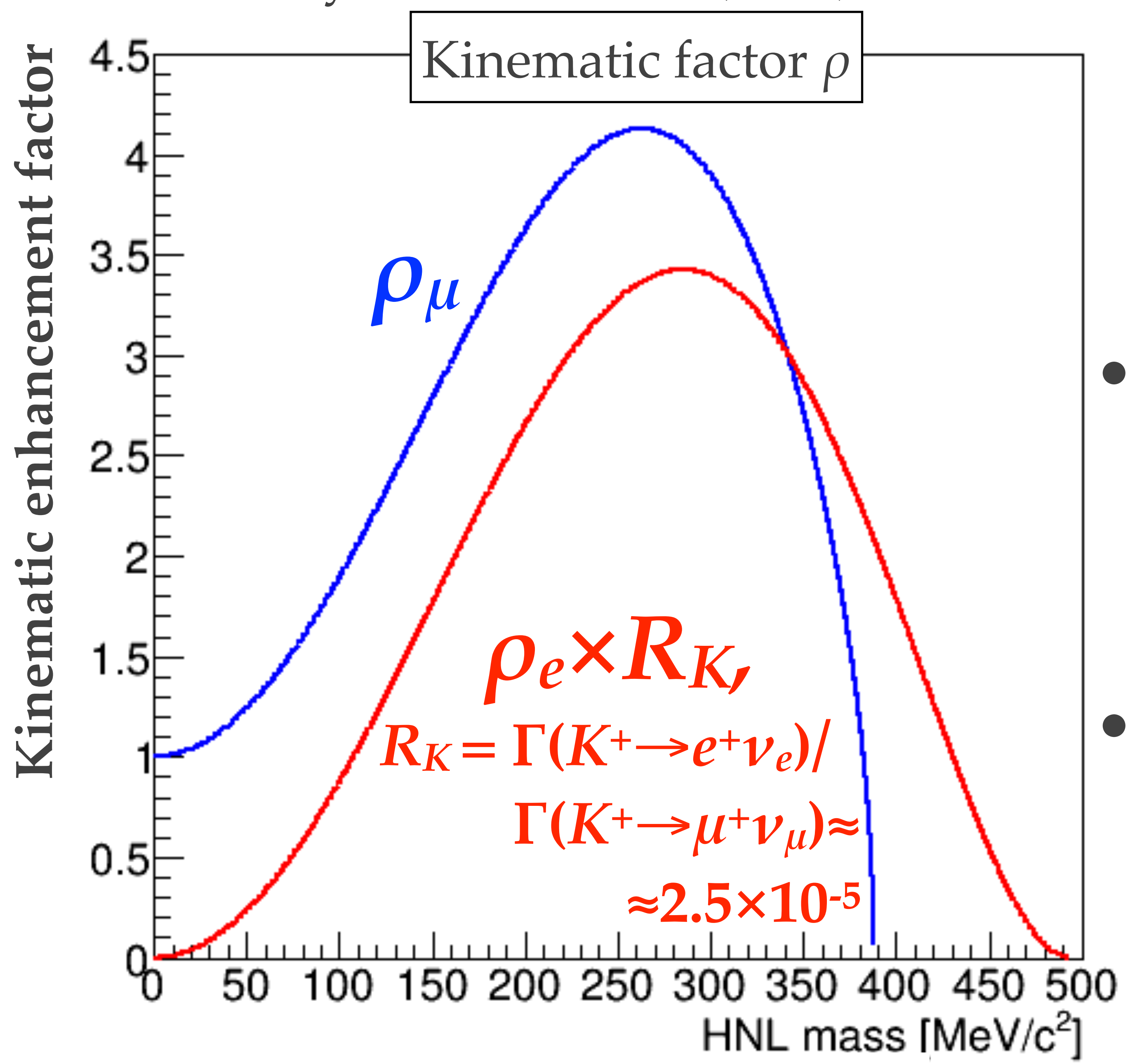
- The νMSM (Asaka et al., Phys.Lett.B 620 (2005) 17) is an extension of the SM to explain simultaneously neutrino oscillations, dark matter and baryon asymmetry of the Universe.
  - SM + 3 right-handed sterile neutrinos:
    - N_1: $m_1 \sim 10$ keV — dark matter candidate
    - $N_{2,3}$: $m_{2,3} \sim 100$MeV — 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)



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

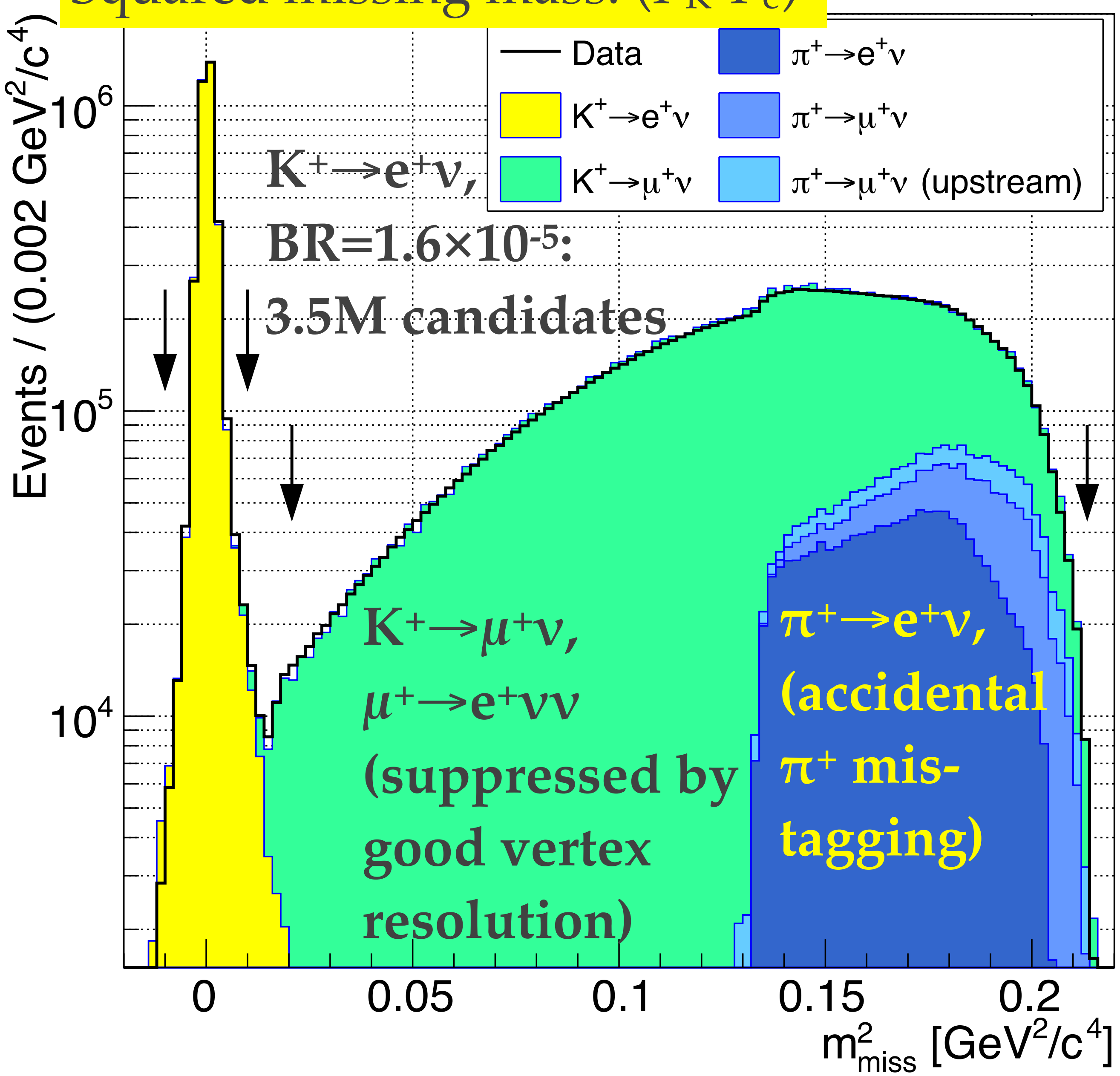
- HNL production is enhanced kinematically with respect to SM decays, except near kinematic endpoints
- Enhancement ~10^5 in the $K^+ \to e^+\nu_H$ case as the helicity suppression is relaxed

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

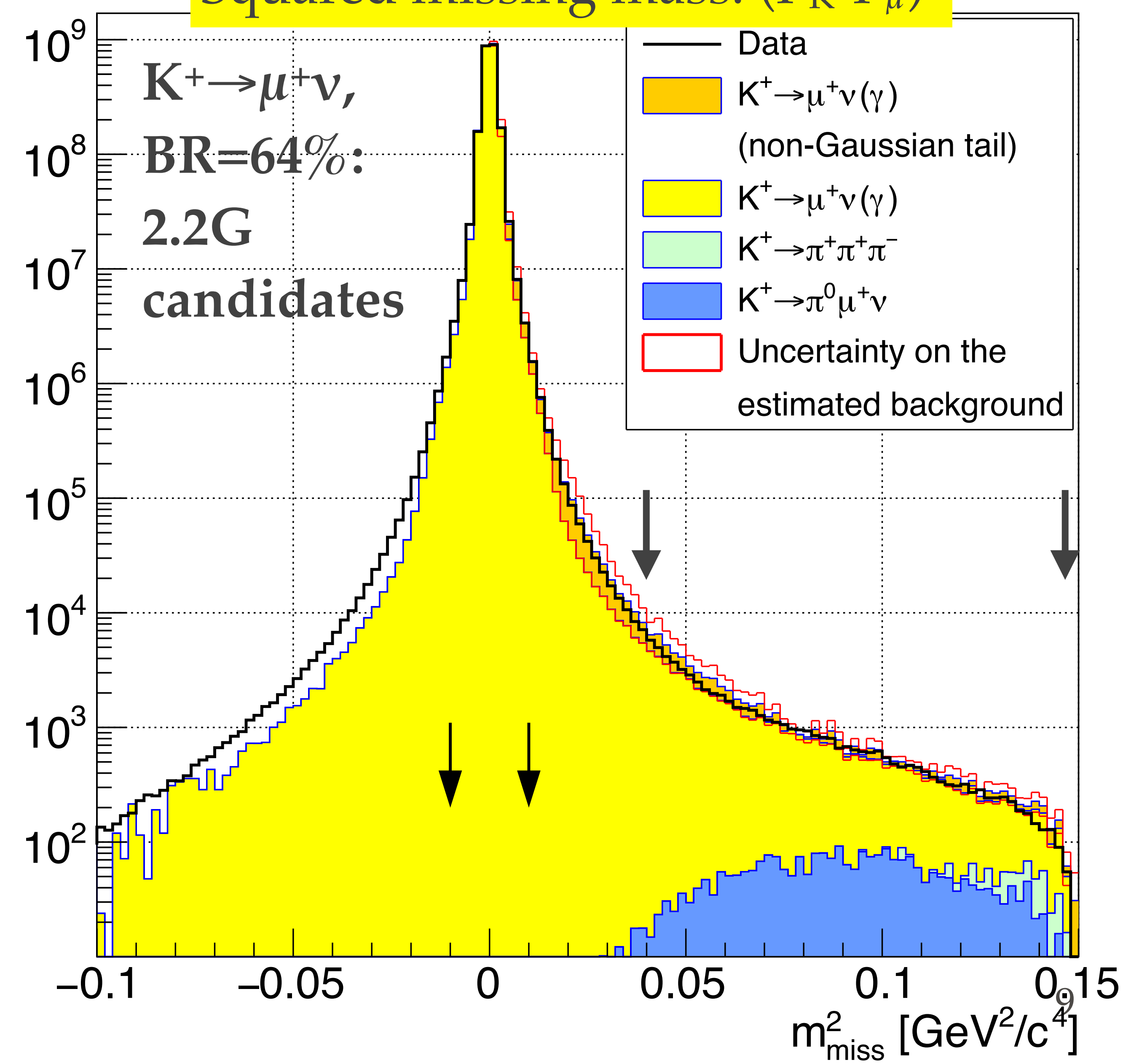
Heavy Neutral Leptons (HNL)

- 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: $(3.52\pm0.02)\times10^{12}$ for $K^+\to e^+\nu_H$, $(1.14\pm0.02)\times10^{10}$ 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

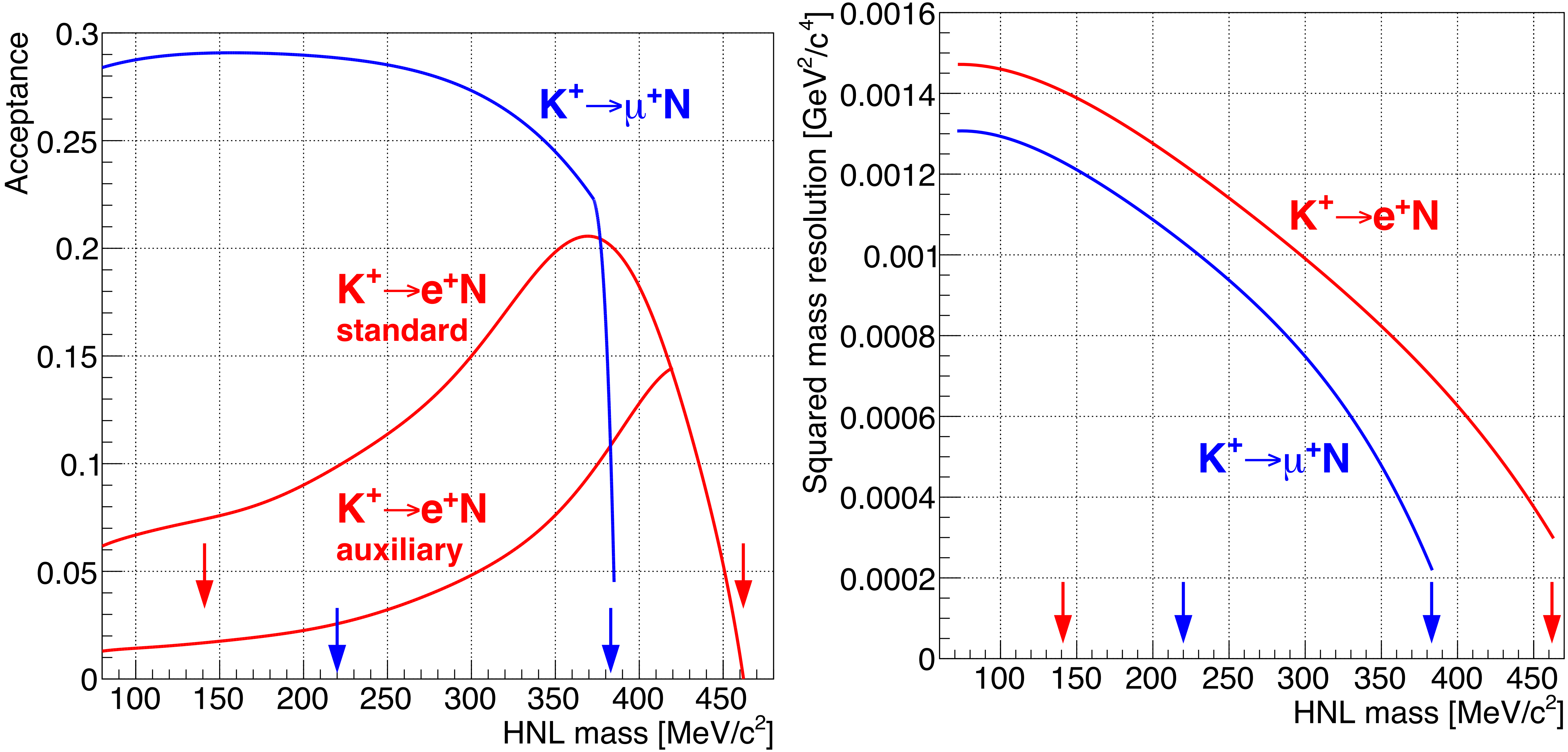
Squared missing mass: $(P_K-P_e)^2$



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



Acceptance and Resolution

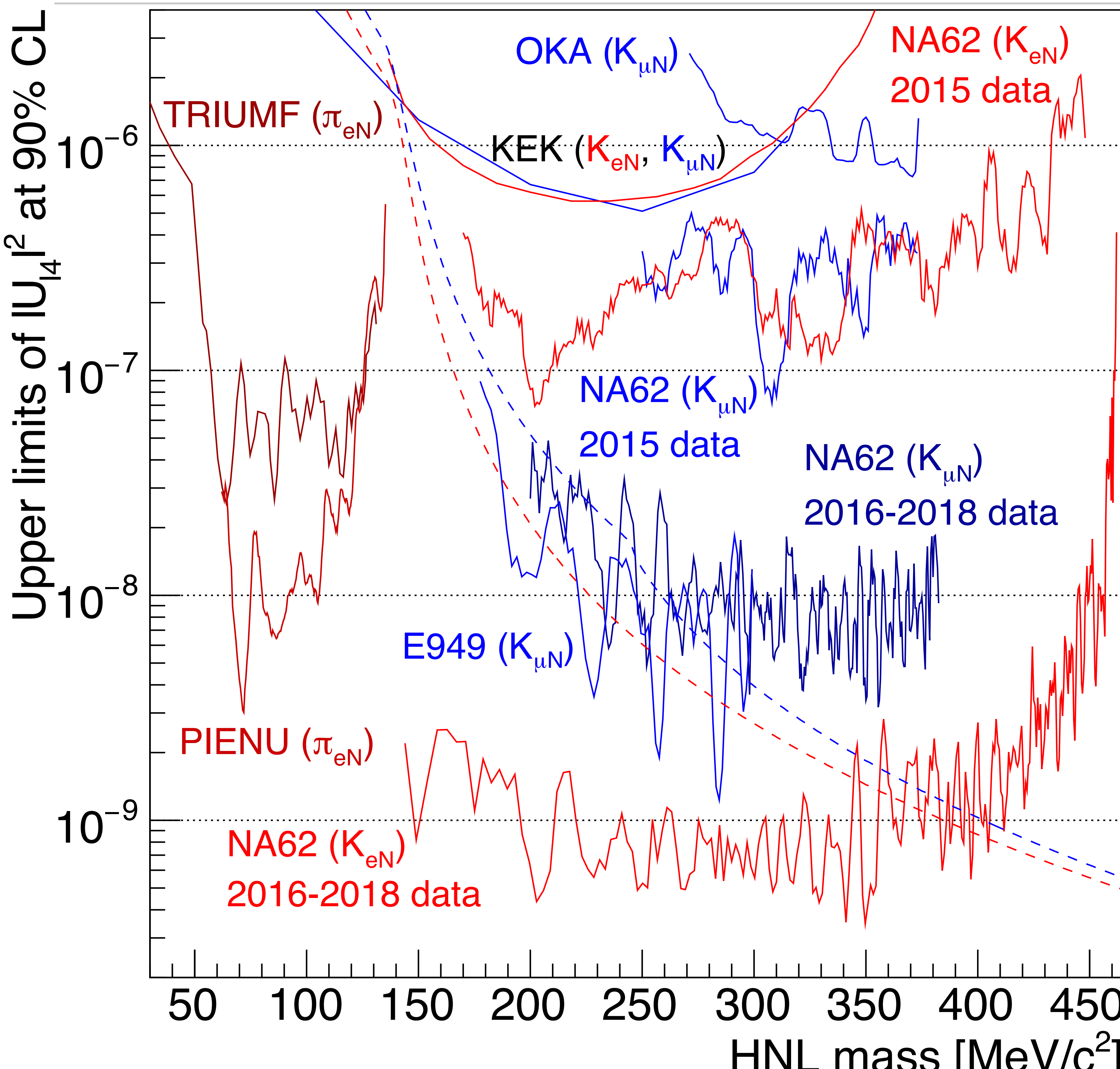


- Selection for each mass hypothesis includes a mass window condition $|m - m_{HNL}| < 1.5\sigma$ background is proportional to mass resolution
- Standard K_{e2} selection: $p_e < 30$ GeV/c (as in $K_{\pi\nu\nu}$ trigger)
- Auxiliary K_{e2} selection: $p_e < 20$ GeV/c — to remove “bump” near π_{e2} threshold

Mass scan

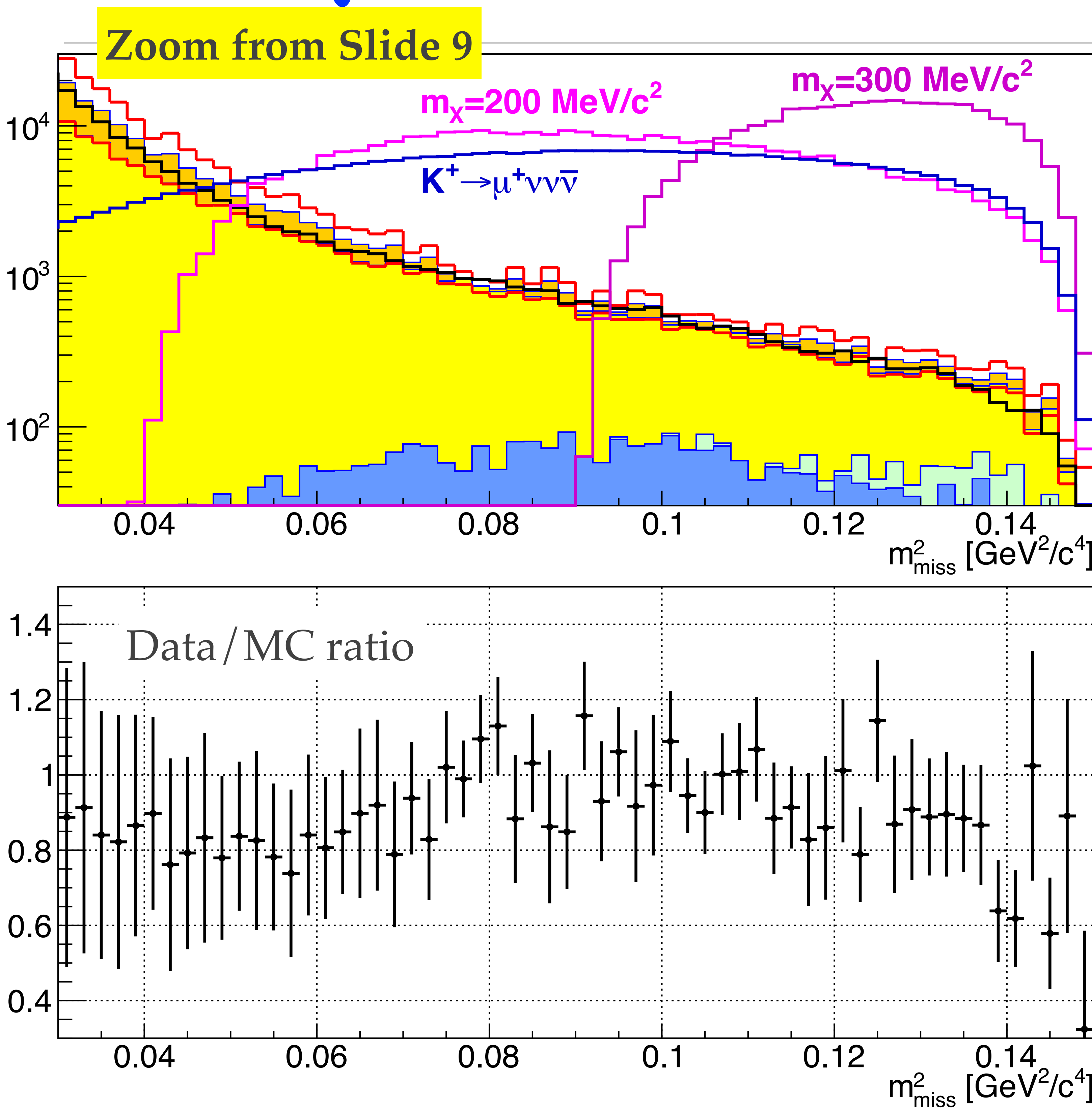
- **The procedure:**
  - HNL mass range 144–462 (200–384) MeV/c^2 in K_{e2} ($K_{\mu 2}$) case
  - Scan step: $\sigma/2$ in K_{e2} case; 1 (0.5) MeV/c^2 below (above) 300 MeV/c^2 in $K_{\mu 2}$ case
  - Number of mass hypotheses tested: 264 (269) in K_{e2} ($K_{\mu 2}$) case
  - Signal region half-width: 1.5σ
  - In each mass hypothesis m_0 background (and its stat.error) was determined from the data (polynomial fits in the sidebands: $1.5\sigma < |m - m_0| < 11.25\sigma$)
  - Limits on $|U_{14}|^2$: CLs comparison of observed with expected number of events
- **Systematic uncertainties on background estimates:**
  - **Background shape:** fits with 2nd vs 3rd polynomials
  - **Possible HNL signal in sidebands:** injection of artificial signals
  - Statistical uncertainties dominate; expected upper limits on $|U_{14}|^2$ typically degrade due to systematic errors

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



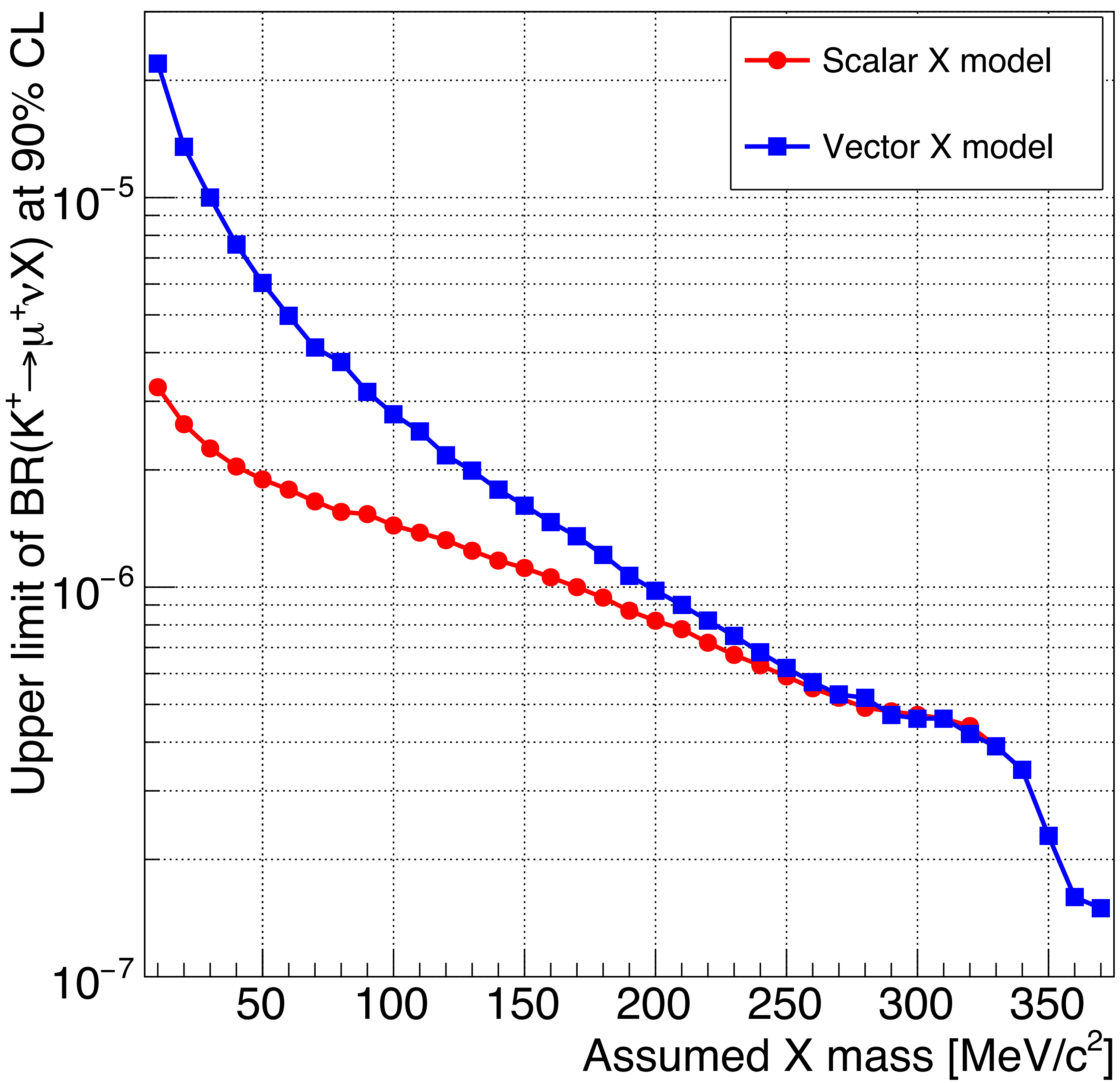
$K^+ \to \mu^+ \nu\nu\nu$

- 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



<u>$K^+ \to \mu^+ \nu X$, X is scalar or vector</u>

- 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 HNL mixing parameters have been set
- World best upper limit on BR($K^+ \to \mu^+ \nu\nu\nu$) has been set: 1.0×10^{-6}
- The first search for $K^+ \to \mu^+ \nu X$ decays has been performed in the mass range 10-370 MeV/c^2: upper limits between $O(10^{-7})$ and $O(10^{-5})$
- NA62 continue data taking since July 2021