SEARCH FOR K^+ DECAYS TO A LEPTON AND INVISIBLE PARTICLES

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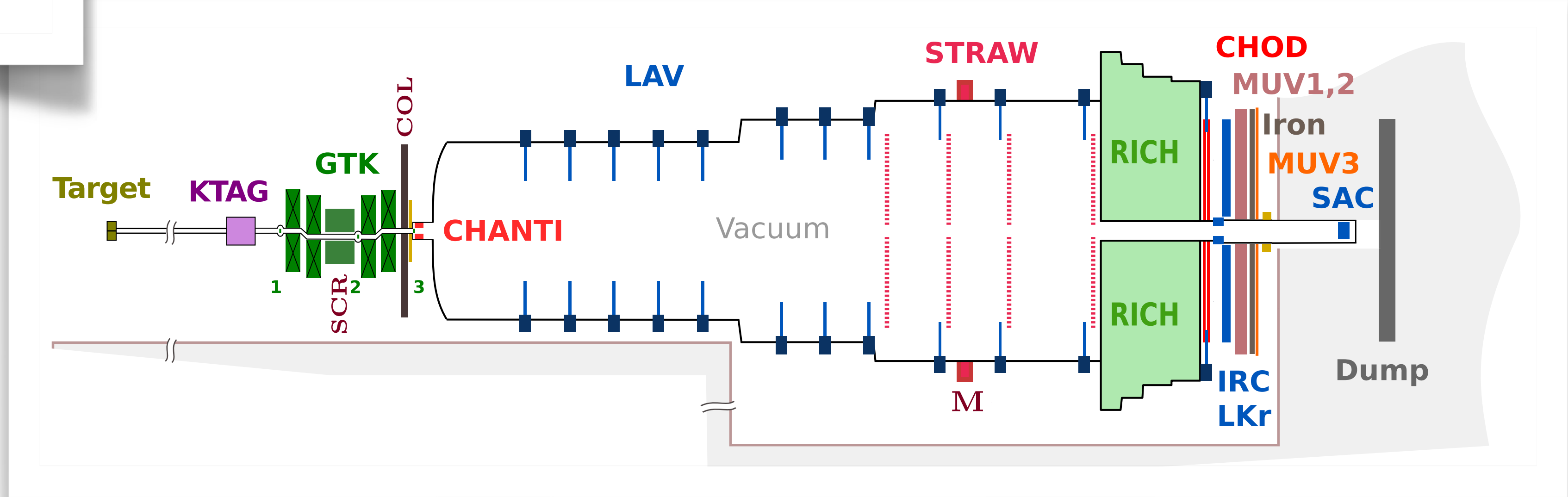
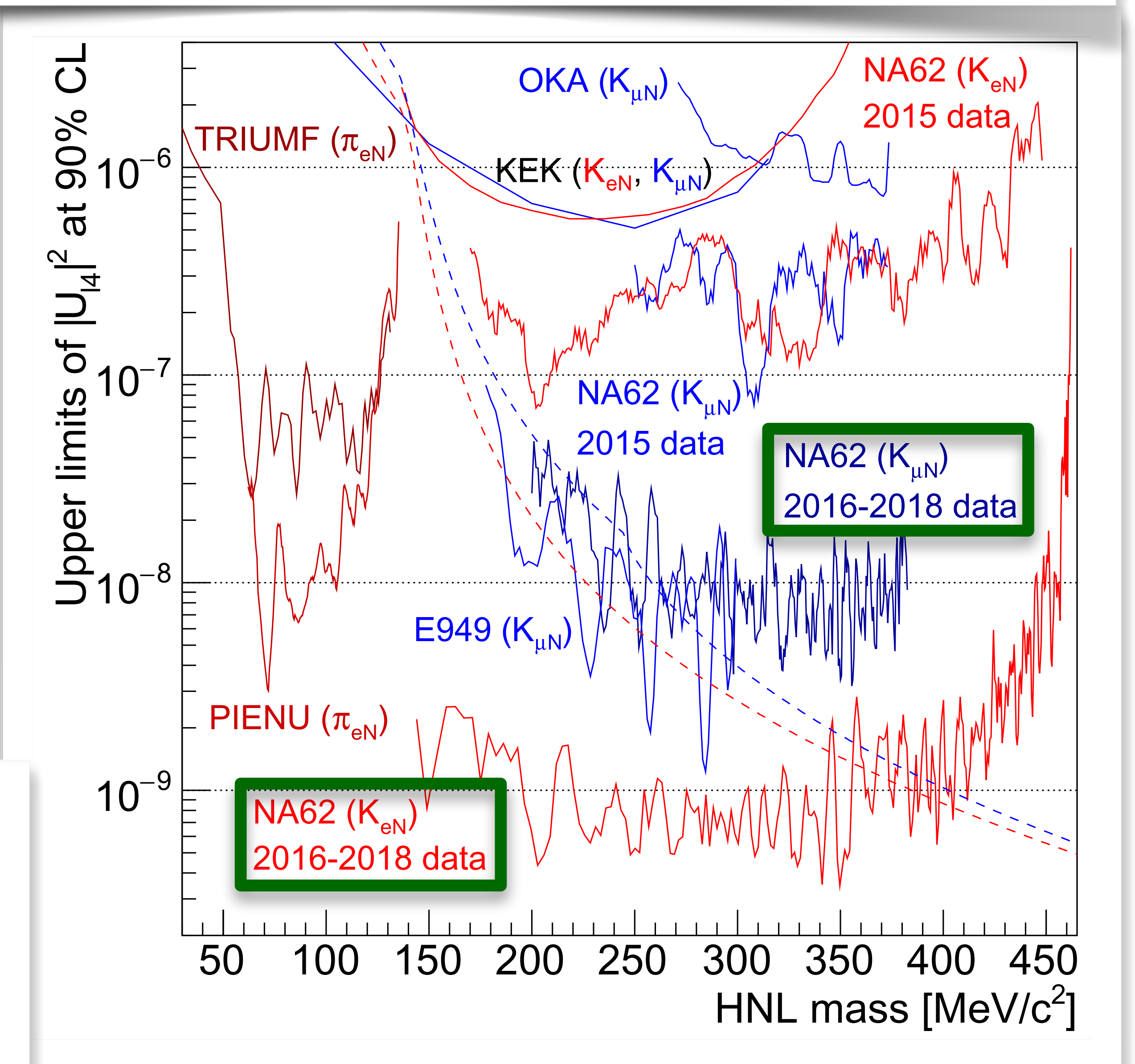
PRISMA+

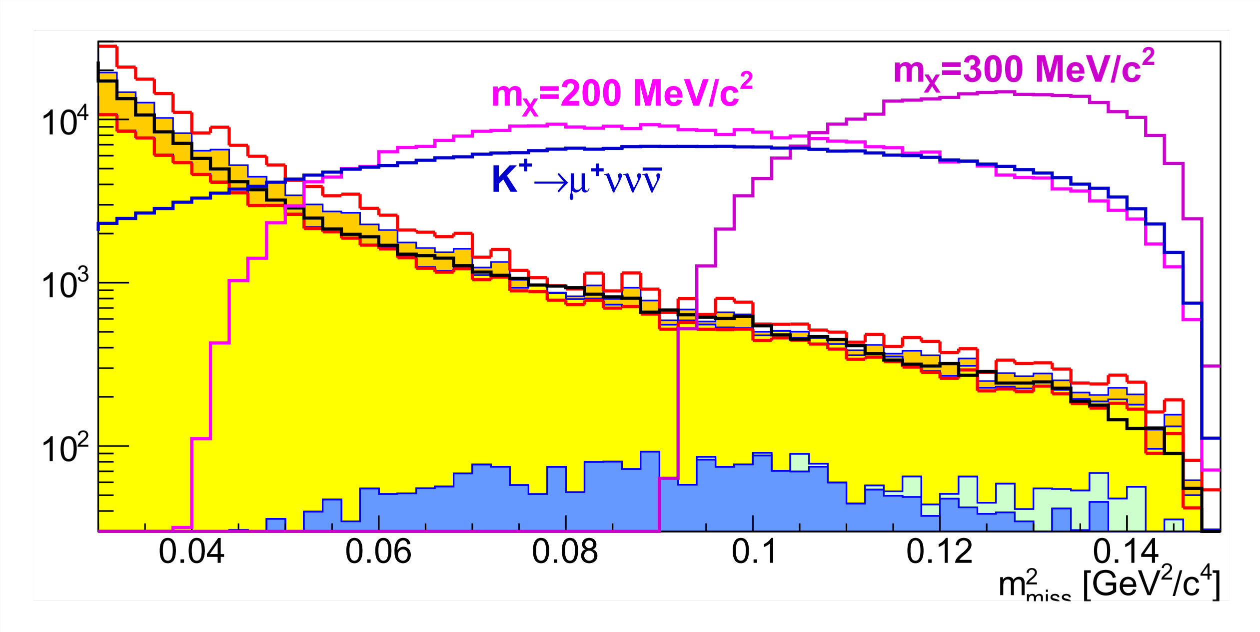
Outline

- Heavy Neutral Leptons
- The NA62 Beam and Detector
- Search for HNLs in $K^+ \to e^+ N$ and $K^+ \to \mu^+ N$.
- Search for $K^+ \to \mu^+ \nu \nu \bar{\nu}$ and $K^+ \to \mu^+ \nu X$.

$$\nu_\alpha = \sum_{i}^{3+k} U_{\alpha i} \nu_i \quad (\alpha = e, \mu, \tau); \;\; k = 3$$







Heavy Neutral Leptons (HNLs) and the *ν*MSM

Standard Model very successful, but fails to explain:

- Neutrino masses
- Baryon asymmetry
- Dark matter

➜ **νMSM extension** („*neutrino minimal SM extension*",
Asaka, Shaposhnikov, PLB 620 (2005) 17):

- Introduce **3 right-handed (sterile) neutrinos N_i** which may mix with the classical, active neutrinos.

$$\nu_\alpha = \sum_{i}^{3+k} U_{\alpha i} \nu_i \quad (\alpha = e, \mu, \tau); \;\; k = 3$$

- **See-saw mechanism** with **lightest N_1 mass of $\mathcal{O}$(10 keV)** → ***dark matter candidate.*** N_2 and N_3 masses of $\mathcal{O}$(100 MeV - 100 GeV).
- **Yukawa couplings** in the range 10^{-11} to 10^{-6}.

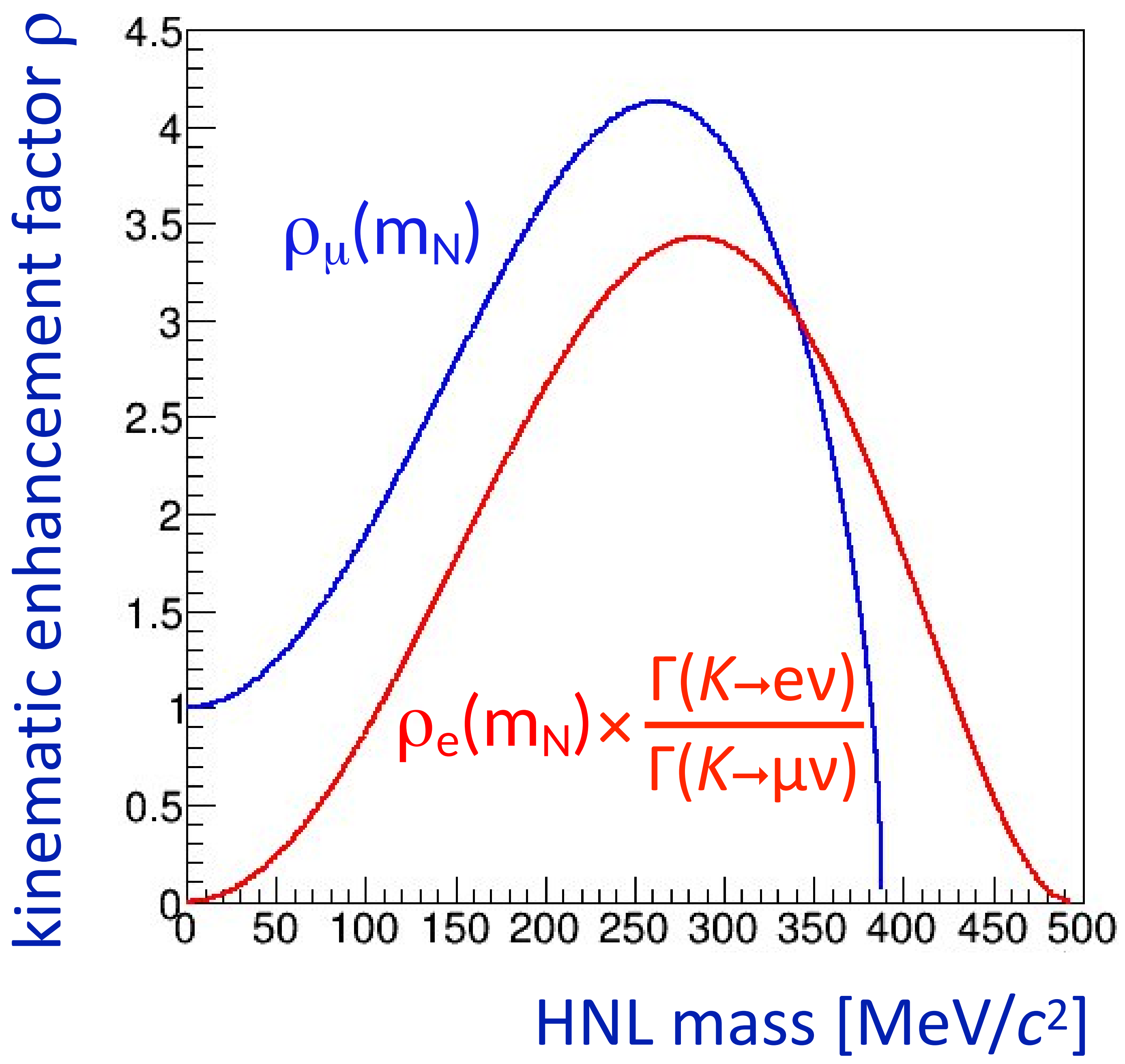
HNL Production in K^+ Decays

If HNLs exist, they would be produced in processes containing active neutrinos with a rate proportional to the mixing parameters $|U_{l4}|^2$ (only considering $k = 1$ here).

- Masses up to 0.5 GeV are observable in Kaon decays.
- **Master formula:** (Shrock, PLB 96 (1980) 159)

$$\mathcal{B}(K^+ \to \ell^+ N) = \mathcal{B}(K^+ \to \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{\ell 4}|^2$$

$\mathcal{O}$**(1)**



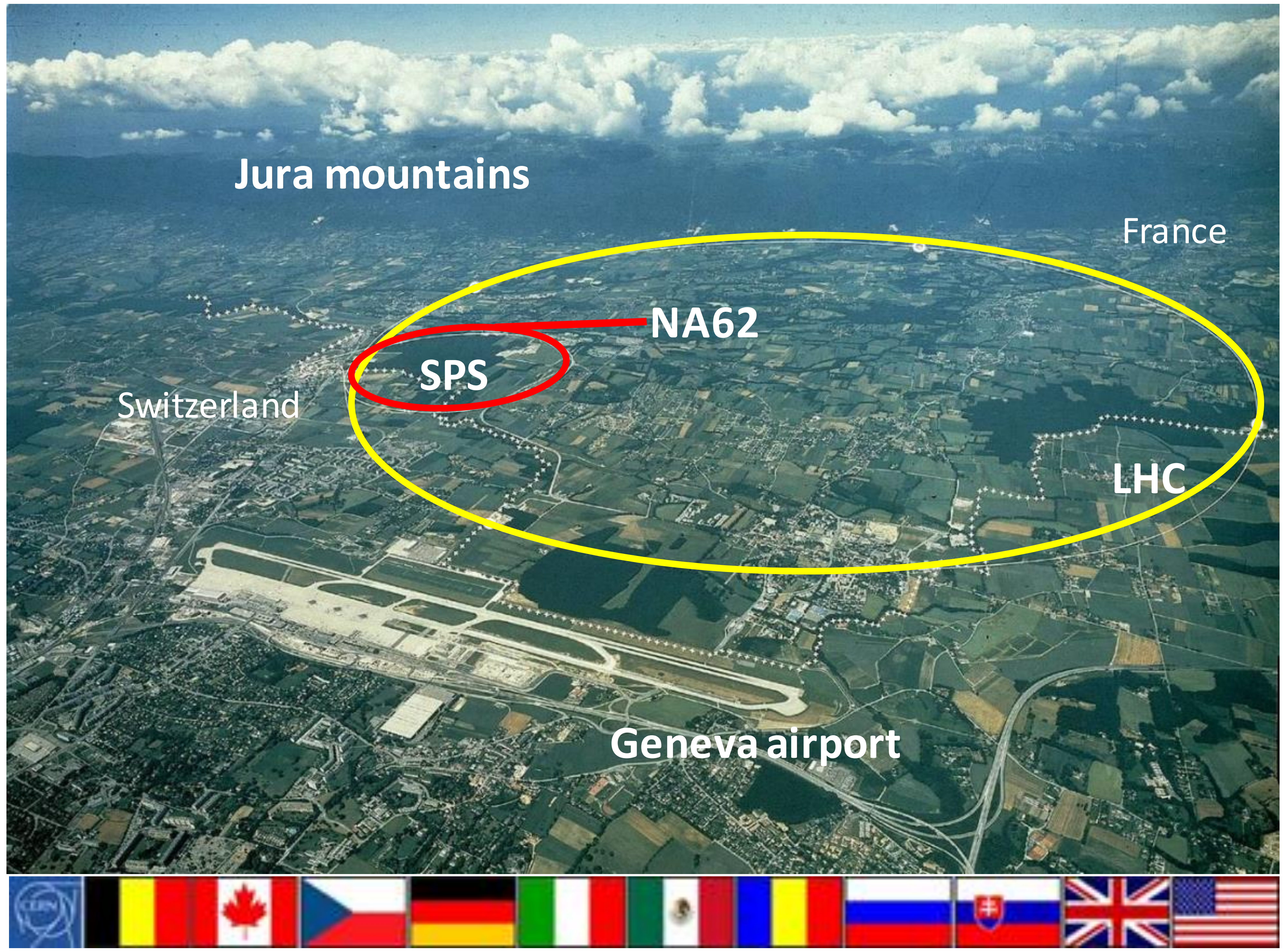
➜ Kinematic factor effectively cancels helicity suppression in electron channel!

➜ **Branching fractions $K^+ \to$ HNLs = $\mathcal{O}$(mixing parameter)**

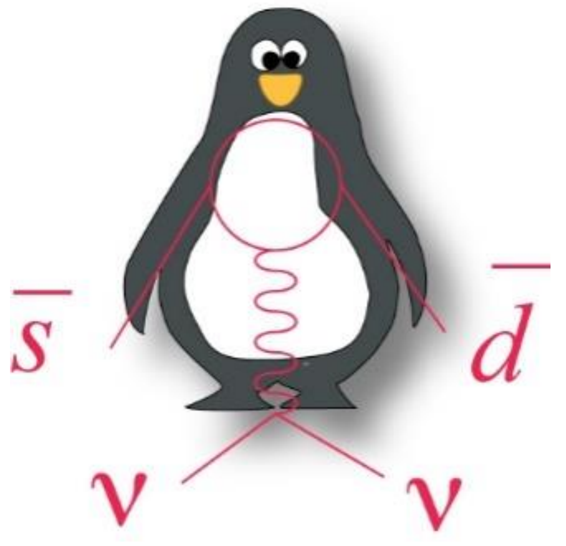
The NA62 Experiment

Fixed target Kaon experiment at the CERN SPS.

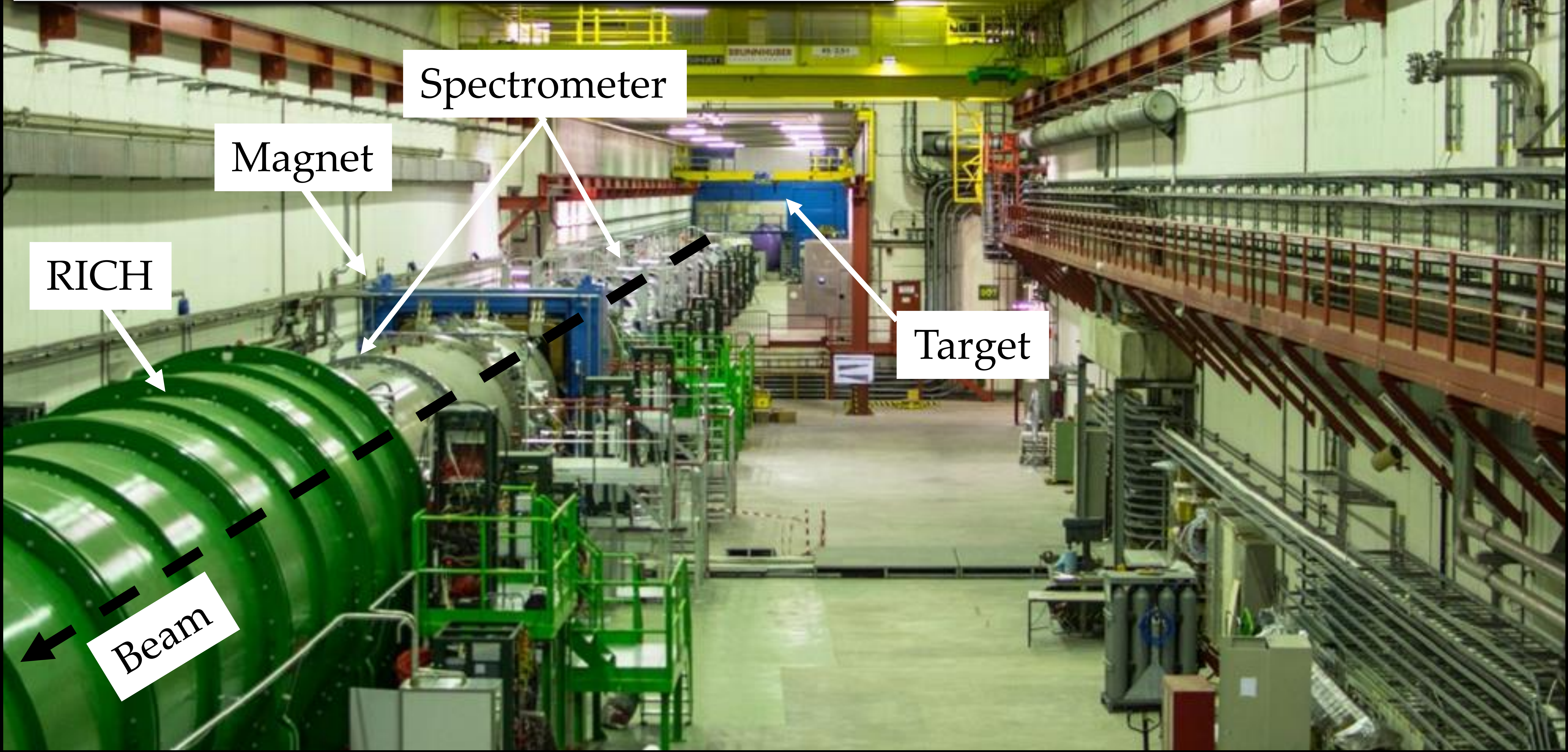
- **About 200 participants**
- **Main goal: Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$**



- 2008 — NA62 Approval
- 2009-2014 — Detector R&D and Installation
- 2014 — Pilot Run
- 2015 — Commissioning run
- 2016-2018 — Physics runs
- 2021-2023 — Physics runs (with upgrades)



The NA62 Beam and Detector



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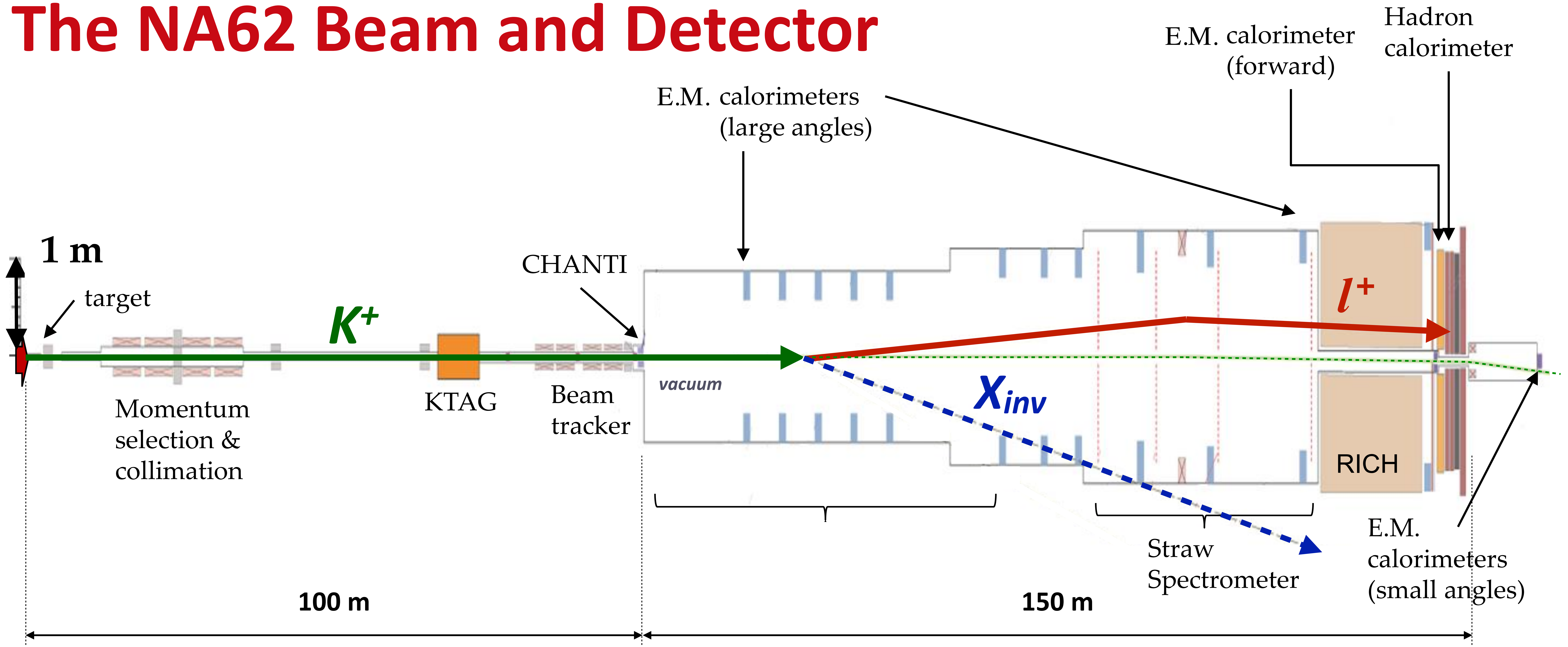

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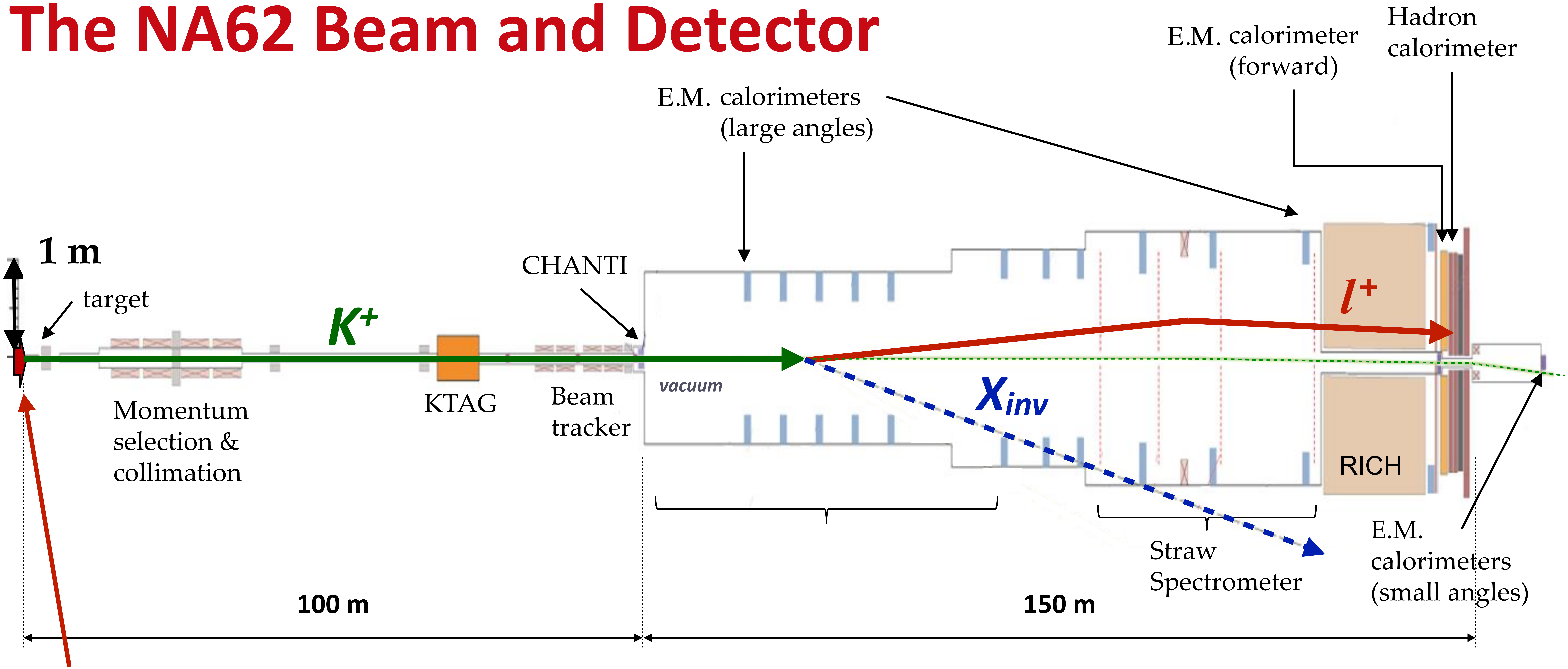

SPS protons
400 GeV/*c*
10^{12} *protons*/s

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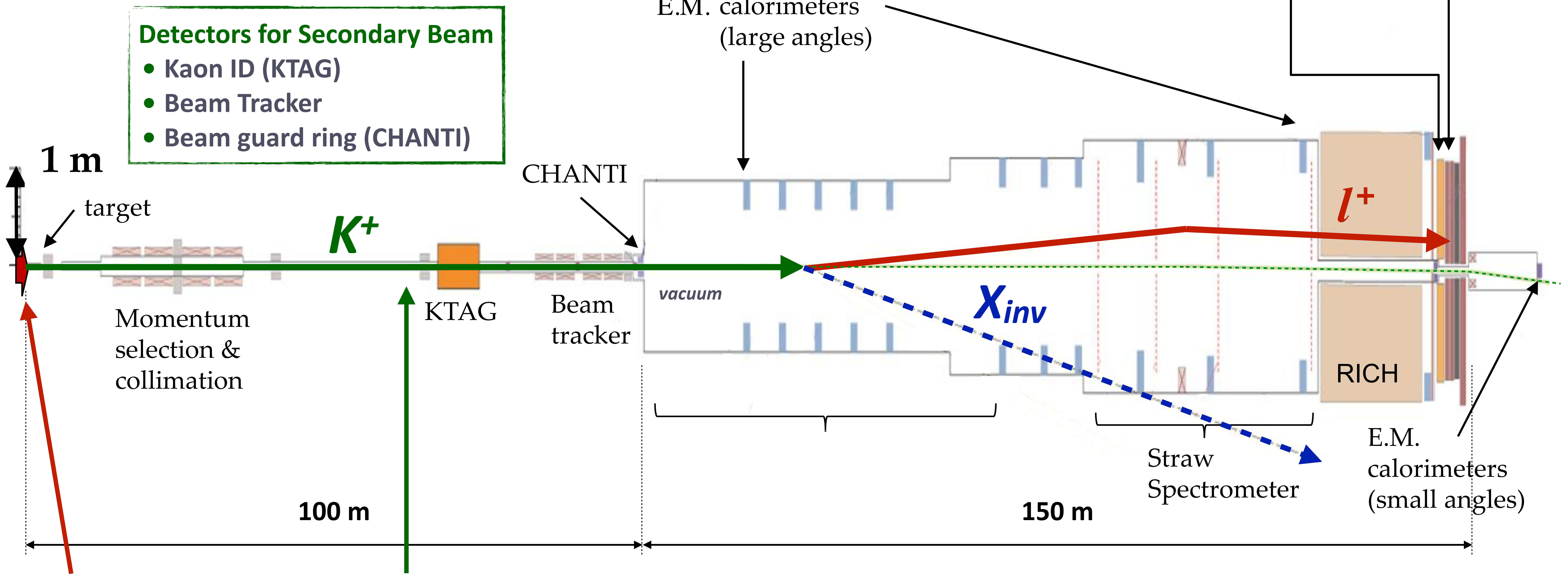

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Secondary beam
75 GeV/c, 750 MHz
K^+ (6%), π^+ (70%), p (23%)

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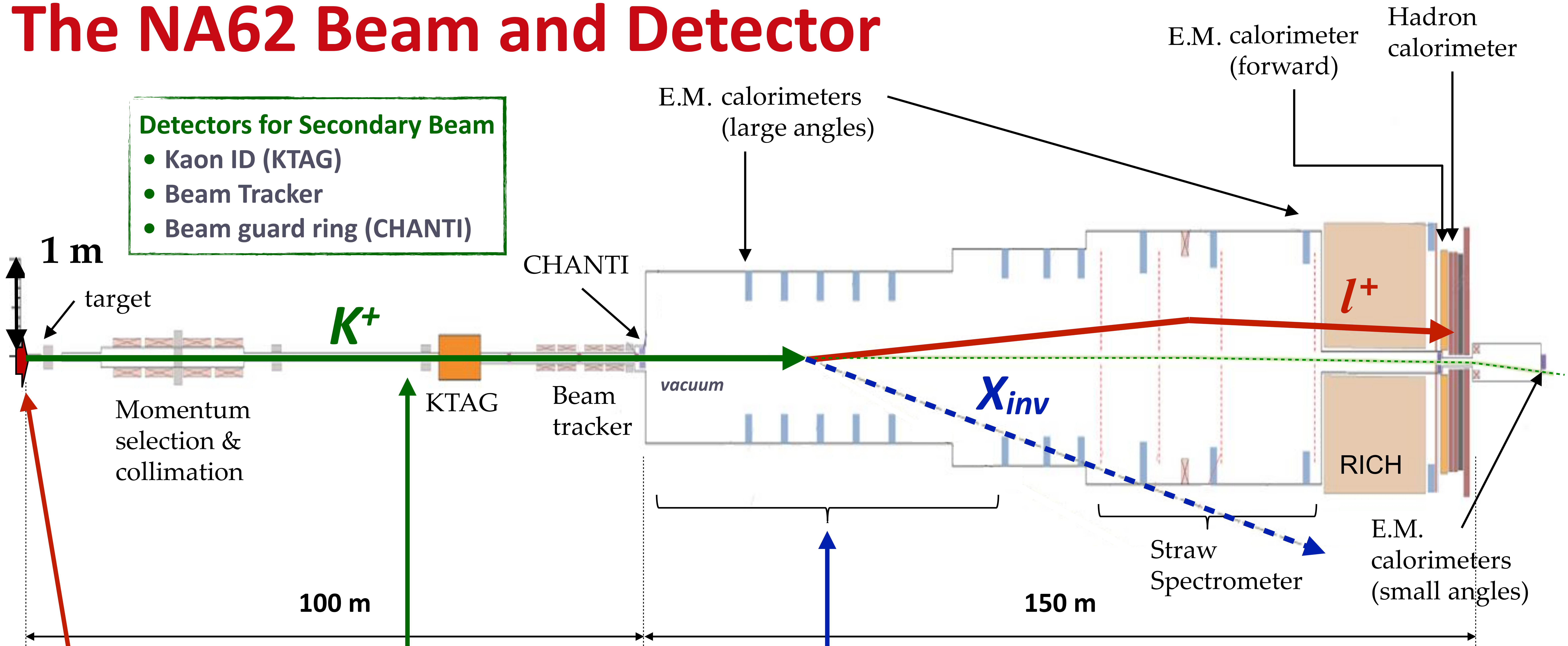


SPS protons
400 GeV/*c*
10^{12} *protons*/s

Secondary beam
75 GeV/*c*, 750 MHz
K^+ (6%), π^+ (70%), p (23%)

K^+ decay
60 m long
~ 5 MHz

Detectors for Decay Products
- Charged Particle Tracking
- Photon Detection
- Particle ID

Data Collection

Statistics, up to CERN Long Shutdown 2:

- **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:

- **$K^+ \to \pi^+ \nu\bar{\nu}$ trigger:** 1 track, γ/μ veto, used for **e^+ channels**. No downscaling.
- **Control trigger/400:** Single charged particle in the CHOD acceptance *(minimum bias)*, used for **μ^+ channels**. Downscaled by **$D = 400$**.

Searches for HNLs in $K^+ \rightarrow e^+N$ and $K^+ \rightarrow \mu^+N$ Decays

Search for $K^+ \to e^+N$ and $K^+ \to \mu^+N$

Measurement of **squared missing mass** from K^+ and *lepton* **4-momenta:**

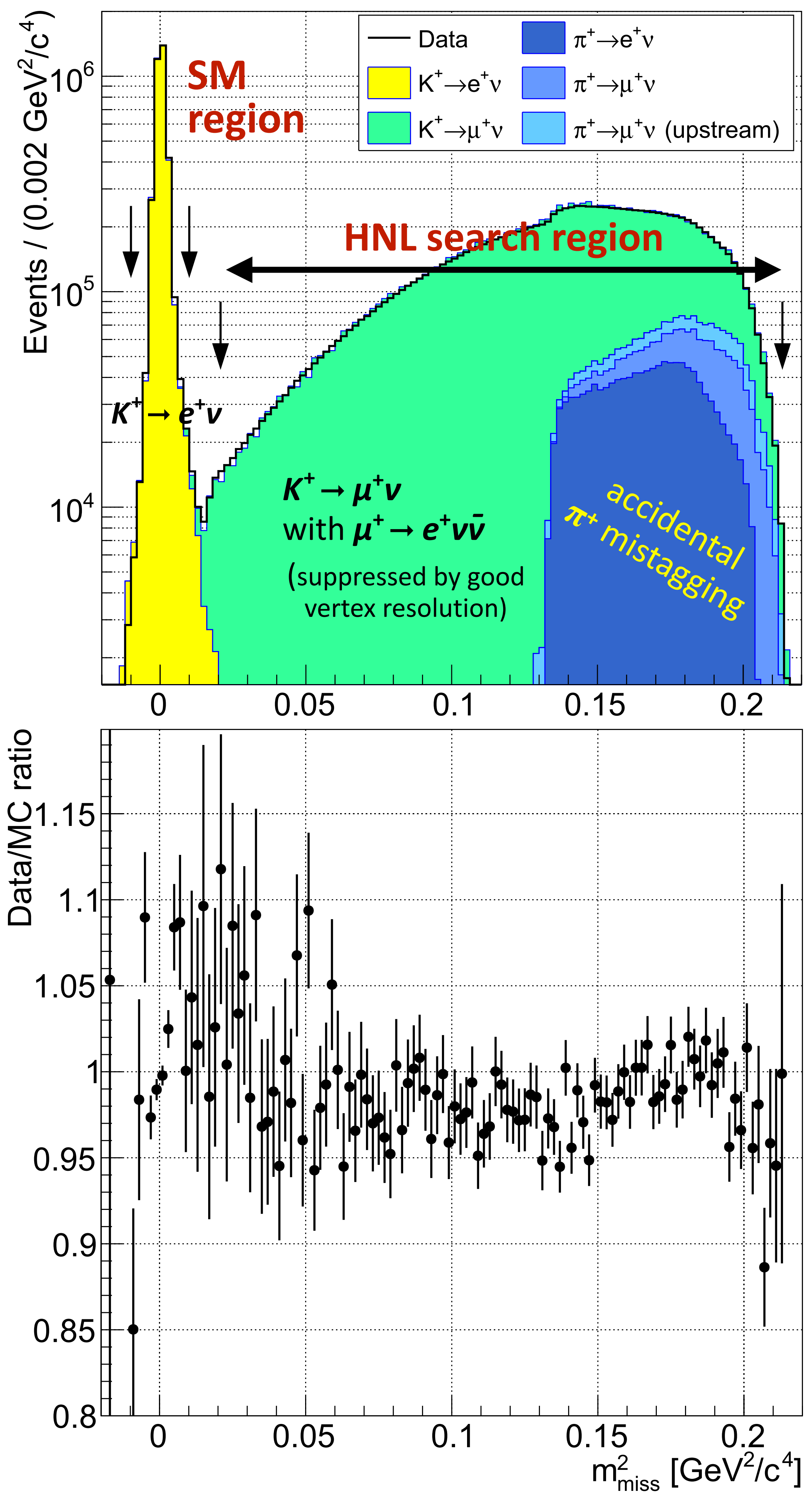
$$m^2_{miss} = (p_{K^+} - p_{lepton})^2$$
$$= \text{mass}^2 \text{ of invisible particle}$$

➜ **HNL signal:** sharp peak in m^2_{miss} spectra.

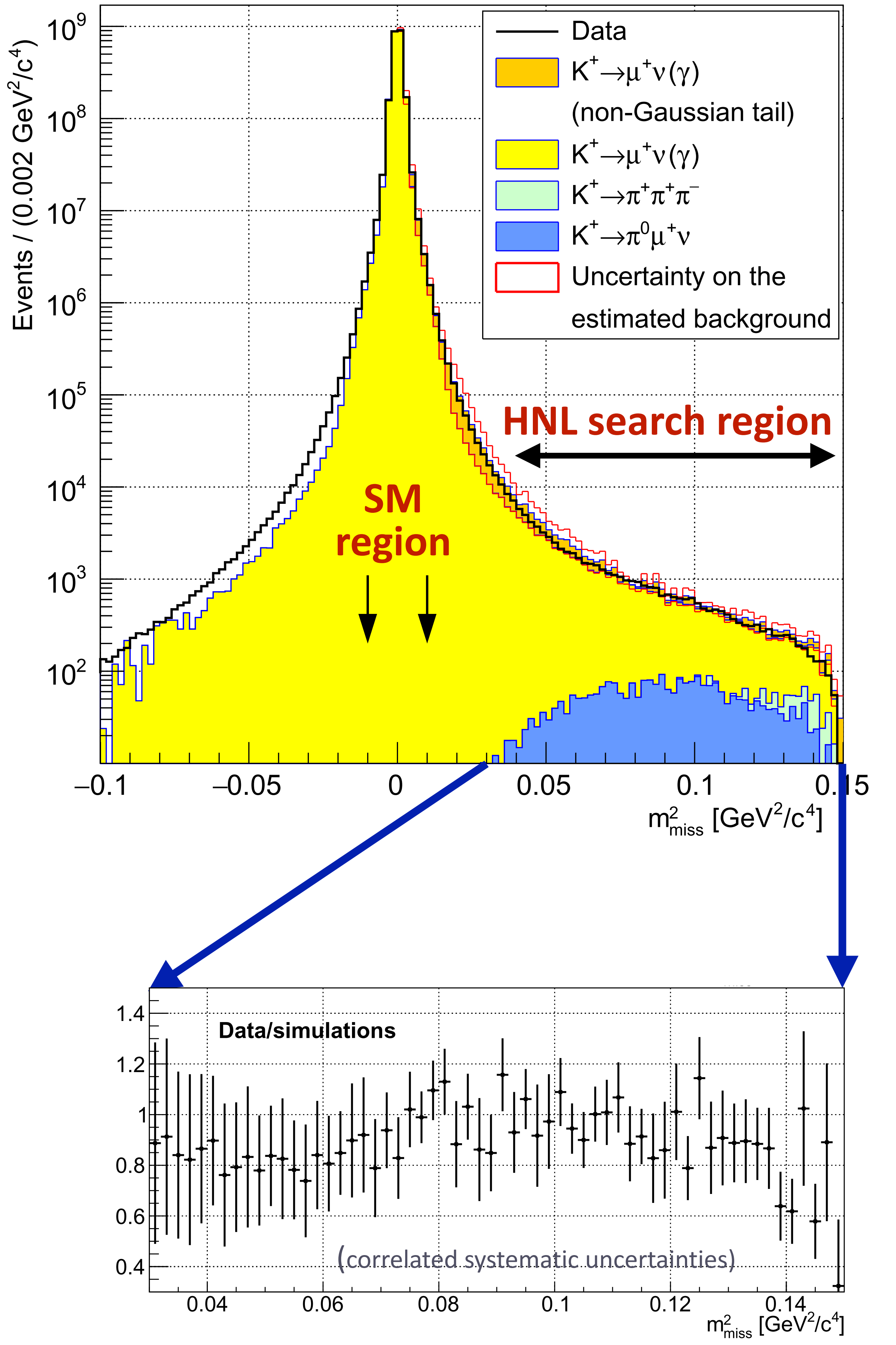
Selections & reconstruction fairly simple:

- K^+ and l^+ reconstruction & matching.
- Powerful **particle ID** (RICH, LKr, MUV).
- Vetoing of extra activity.

Search for $K^+ \to e^+N$



Search for $K^+ \to \mu^+N$



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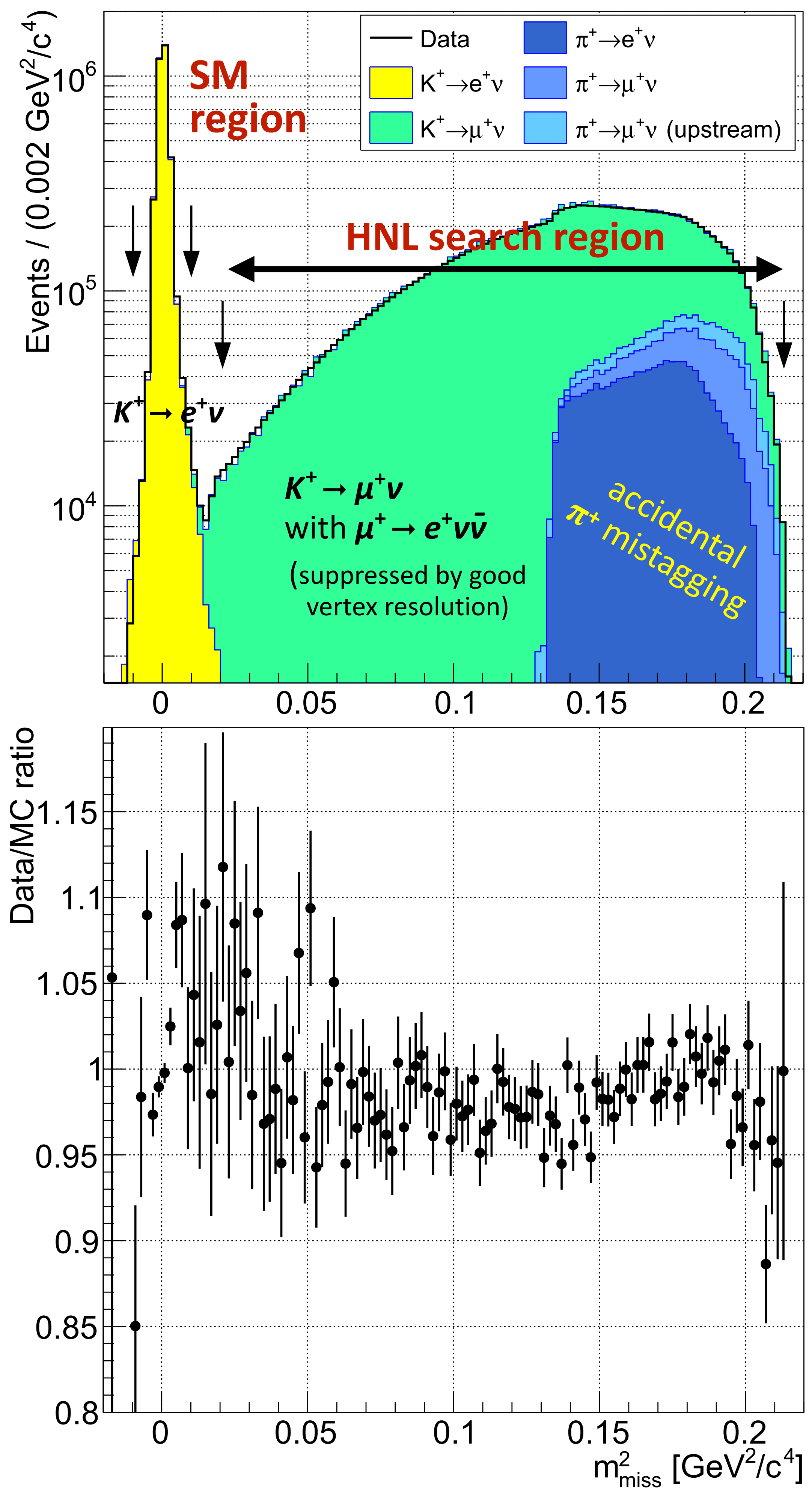
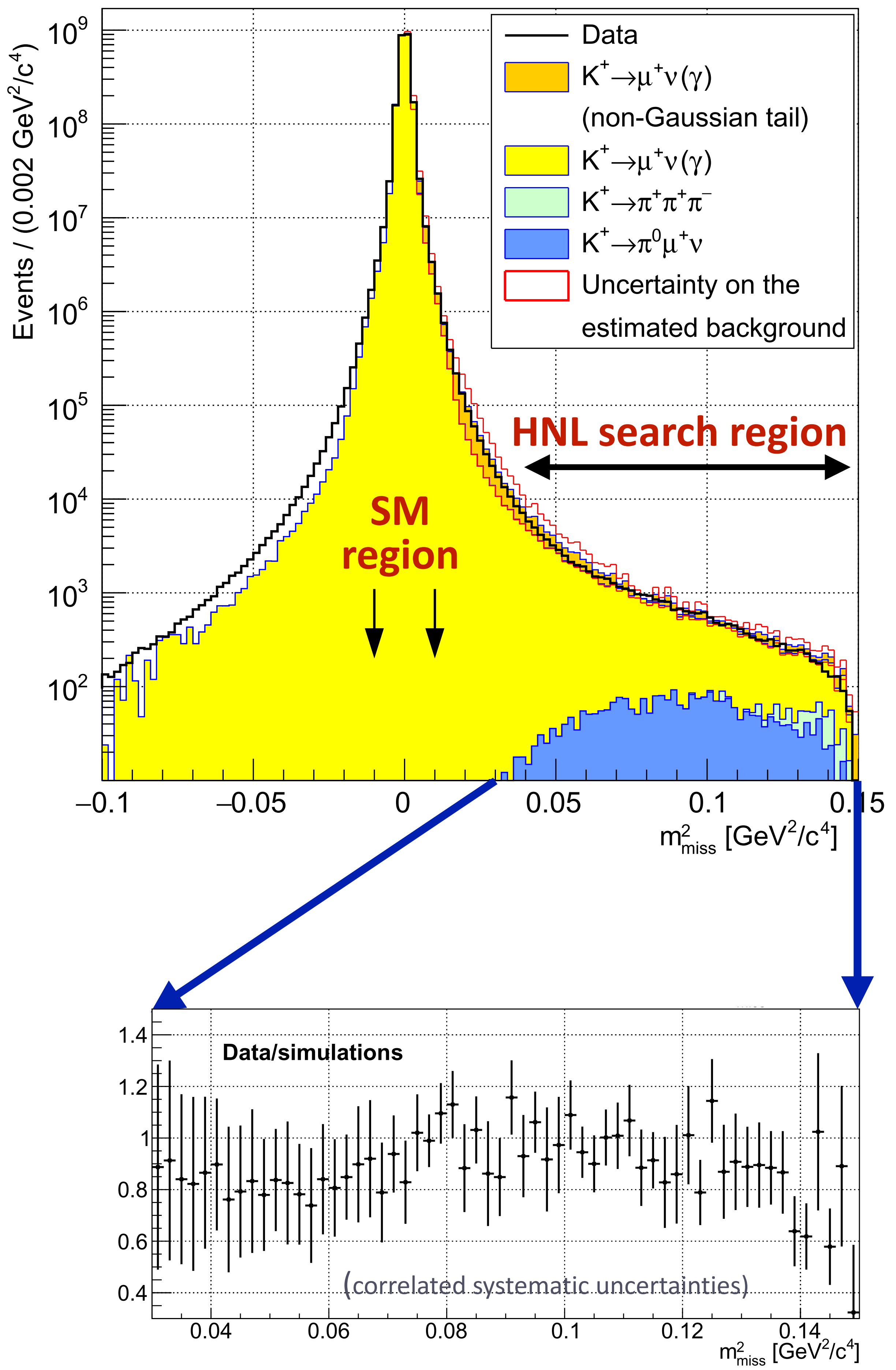
NA62 data:

	$K^+ \to e^+N$	$K^+ \to \mu^+N$
Trigger	$K^+ \to \pi^+\nu\bar{\nu}$	control (D=400)
N_K in fiducial volume	3.5×10^{12}	1.1×10^{10}
Selected SM decays	**3.5×10^6**	**2.2×10^9**

Search for $K^+ \to e^+N$



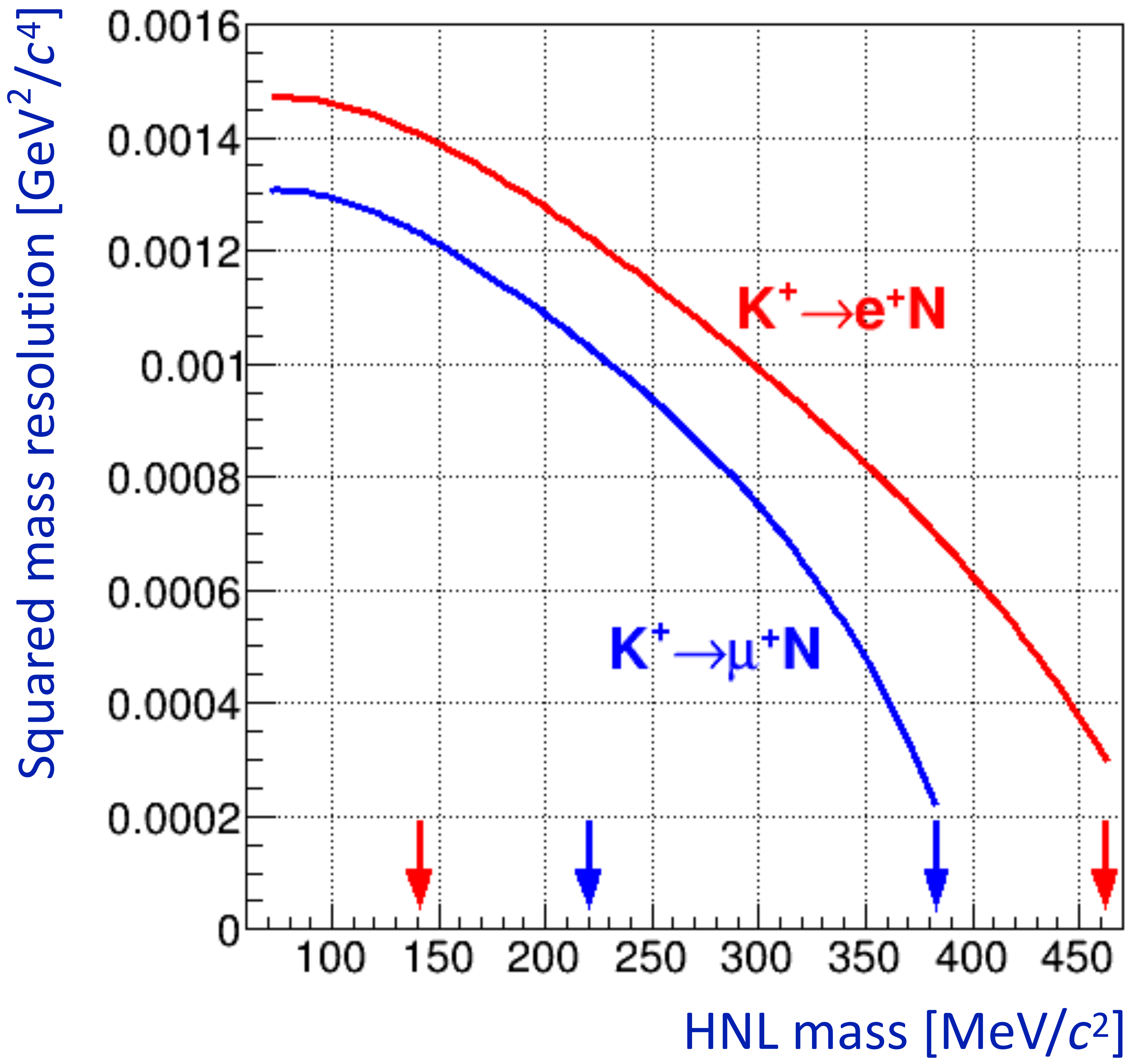
Search for $K^+ \to \mu^+N$



Limits on $K^+ \to e^+N$ and $K^+ \to \mu^+N$

Scan m^2_{miss} spectra over possible HNL masses,
based on the **missing-mass resolution $\sigma(m^2_{miss})$:**

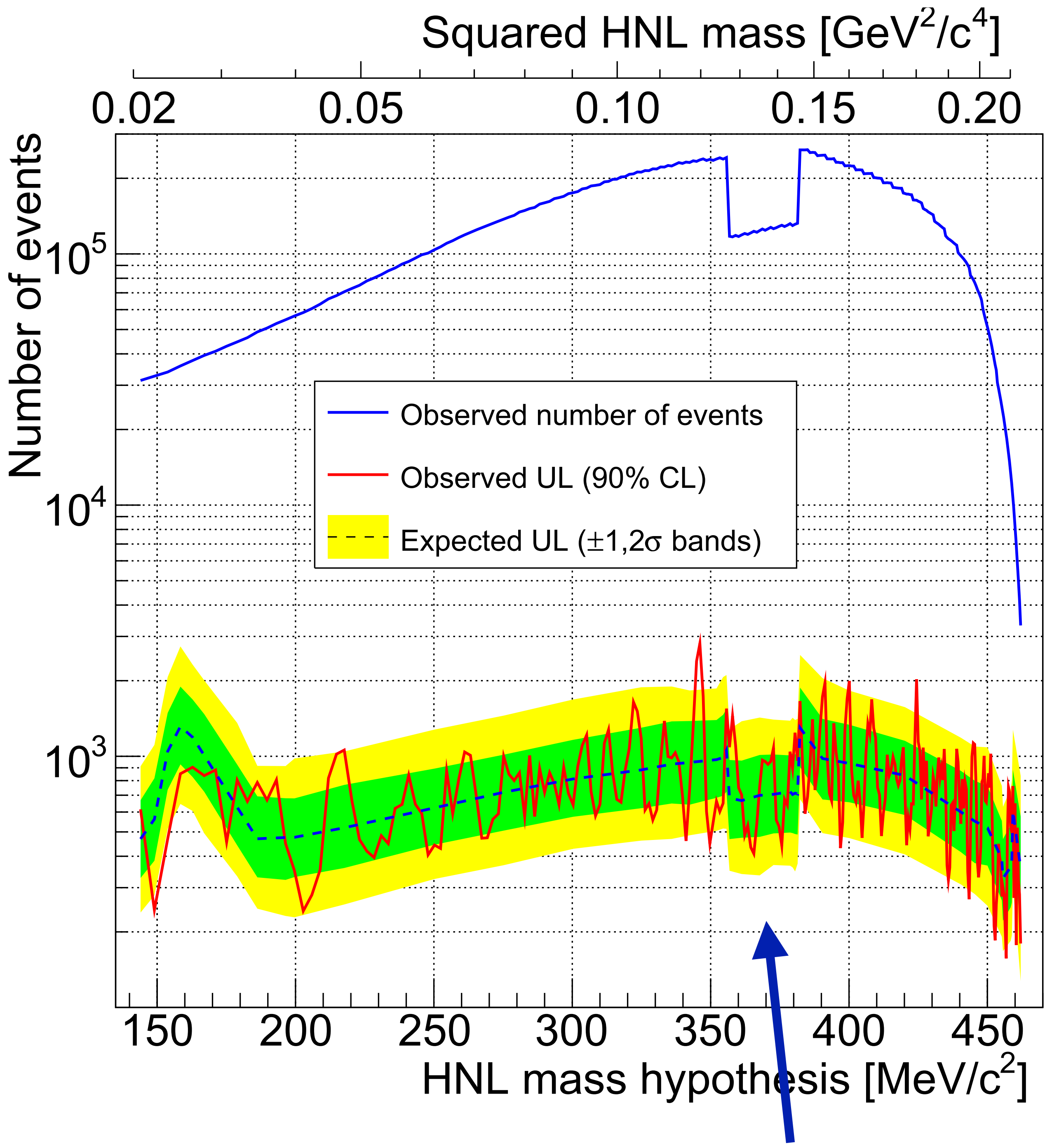
- The scan is performed in **step sizes of $\mathcal{O}$(1 MeV)**
  (depending on the mass or mass resolution).
- **At each scanned mass, a window of ± 1.5 σ** is put around the scanned mass value and the expected (SM) events are obtained from a polynomial fit to the sidebands.
- **Limits on $|U_{e4}|^2$ and $|U_{\mu4}|^2$:**
  CL_S comparison between observed and expected event numbers in each window.



Limits on $K^+ \to e^+N$ and $K^+ \to \mu^+N$

$K^+ \to e^+N$:

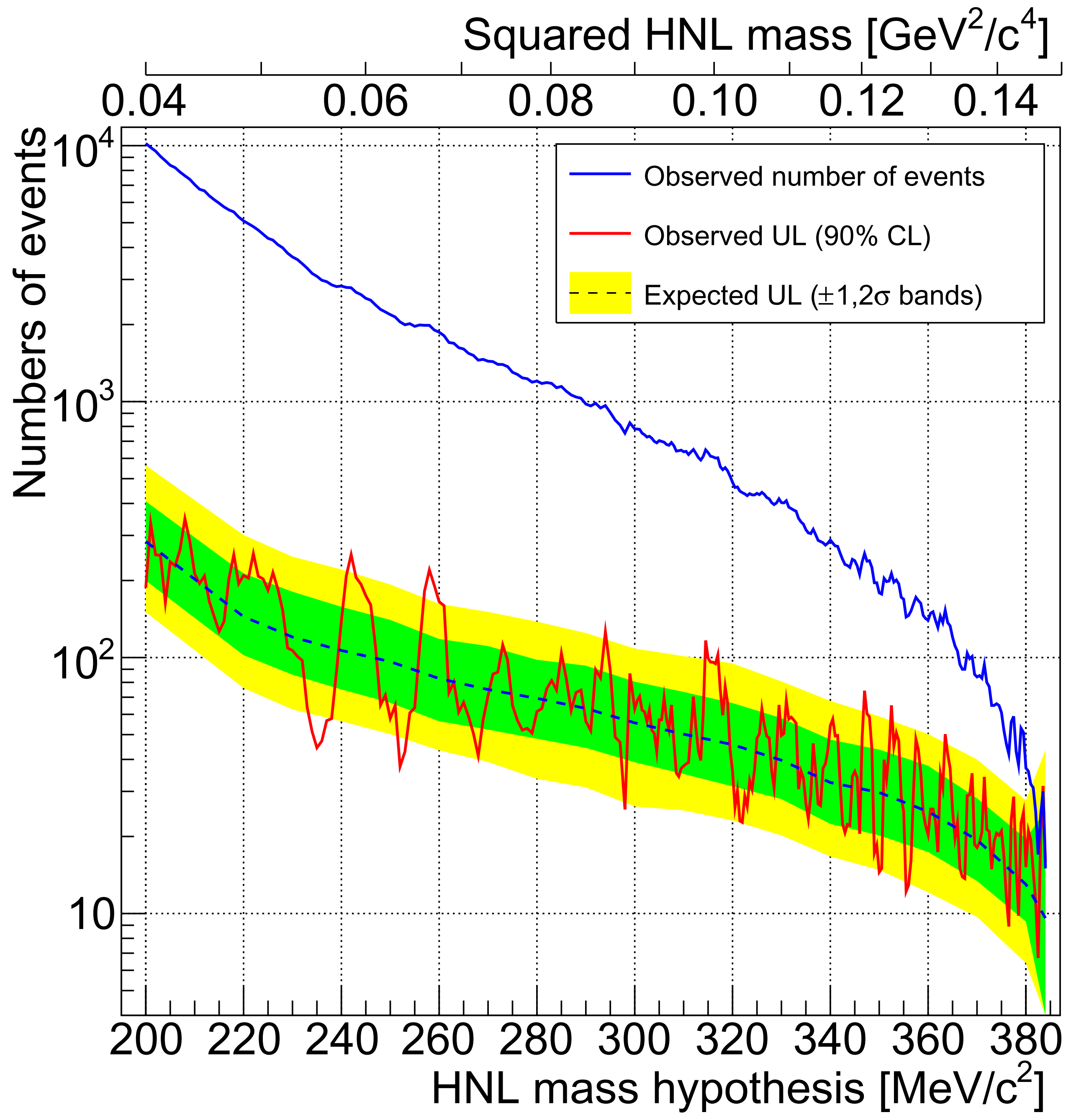
(PLB 807 (2020) 135599)



- Less sensitivity close to the π^+ decay threshold (stricter selection).
- Maximum significance: **3.6 σ** for m_N = 346 MeV.
- Accounting for look-elsewhere effect: **Global significance = 2.2 σ**.

$K^+ \to \mu^+N$:

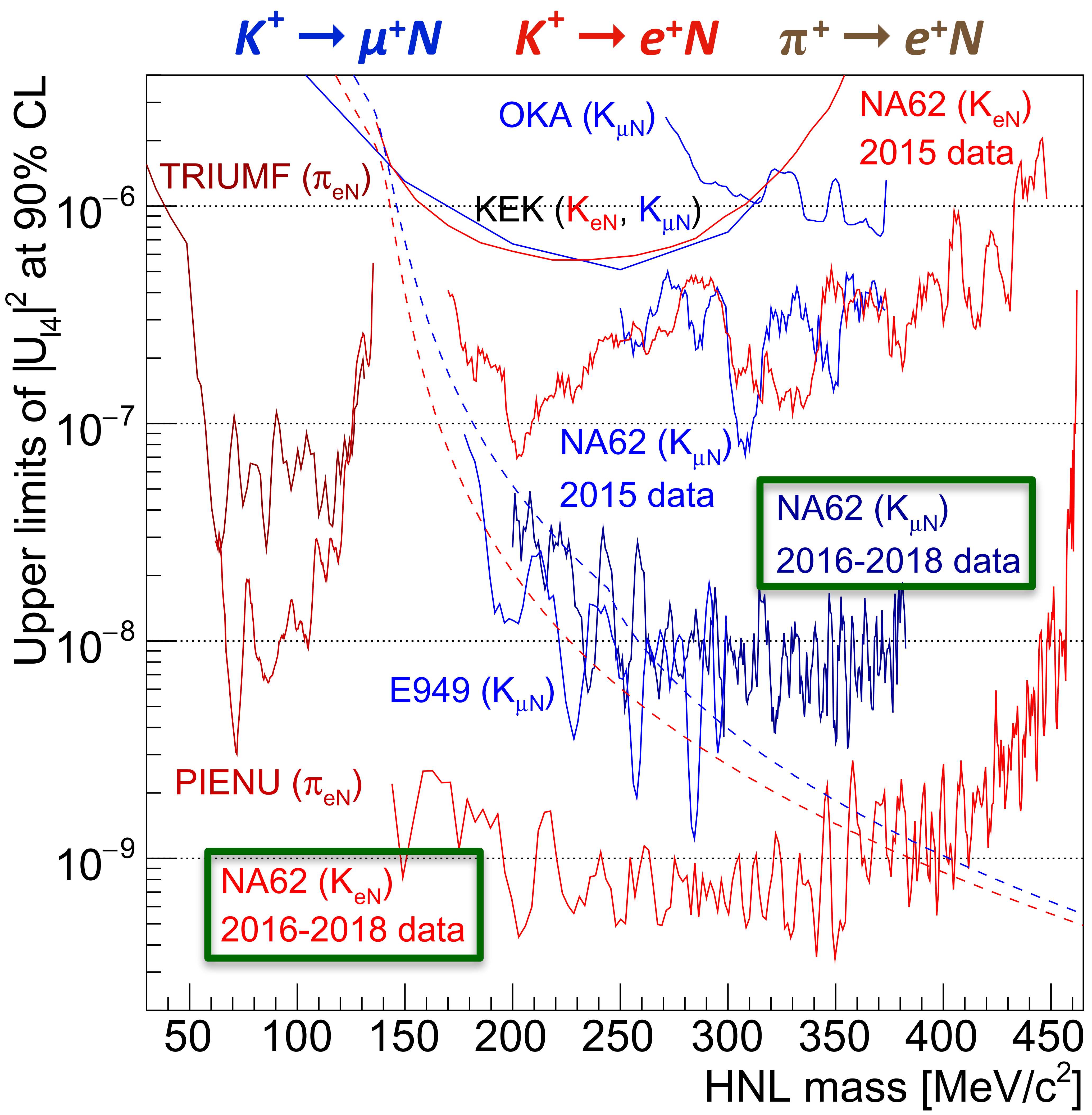
(PLB 816 (2021) 136259)



- **Local significance never exceeds 3 σ.**
  ➜ **no HNL production signals observed.**

Results of HNL Searches

- **No HNL signals observed in NA62.**
- Limits on $|U_{e4}|^2$ of $\mathcal{O}(10^{-9})$, limits on $|U_{\mu4}|^2$ of $\mathcal{O}(10^{-8})$.
- ***$K^+ \to e^+N$*:** Values favored by ***Big Bang Nucleo-synthesis (BBN) constraint*** (dashed red line) are excluded for HNL masses < 340 MeV.
- ***$K^+ \to \mu^+N$*:** Consistent with E949 and extending limits to higher HNL masses



Searches for $K^+ \to \mu^+ \nu \nu \bar{\nu}$ and $K^+ \to \mu^+ \nu X$

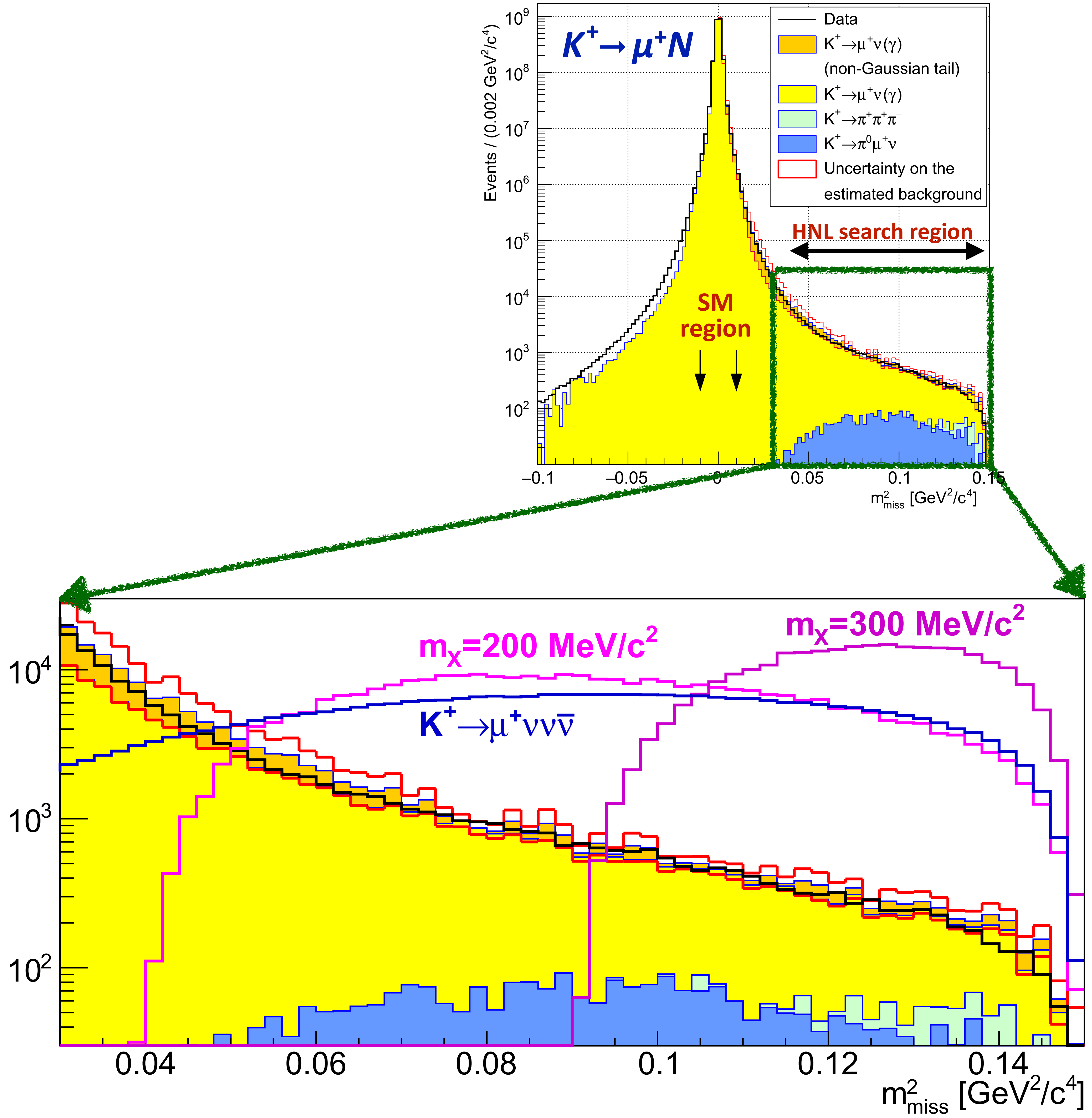
Searches for $K^+ \to \mu^+ \nu\nu\bar{\nu}$ and $K^+ \to \mu^+ \nu X$

$K^+ \to \mu^+ \nu\nu\bar{\nu}$:

- Very rare in the Standard Model:
  $Br \approx 1.6 \times 10^{-16}$
  (Gorbunov, Mitofanov, JHEP 10 (2016) 039).
- Current limit: $Br < 2.4 \times 10^{-6}$
  (E949, PRD 94 (2016) 032012).

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

- ***X*** is a scalar or vector particle
  (Krnjaic et al., PRD 124 (2020) 041802).



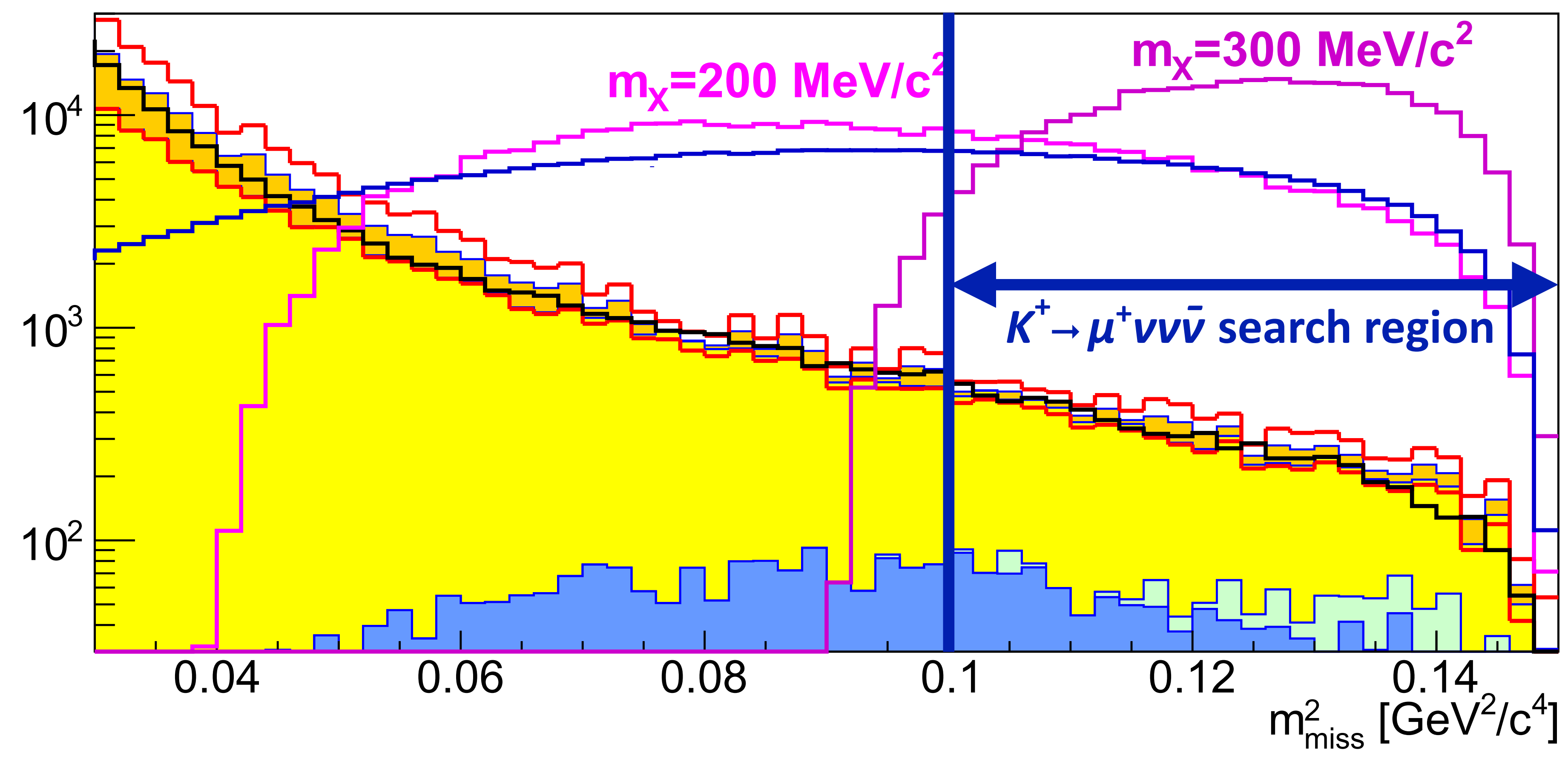
Searches for $K^+ \to \mu^+\nu\nu\bar{\nu}$ and $K^+ \to \mu^+\nu X$

(PLB 816 (2021) 136259)

$K^+ \to \mu^+\nu\nu\bar{\nu}$:

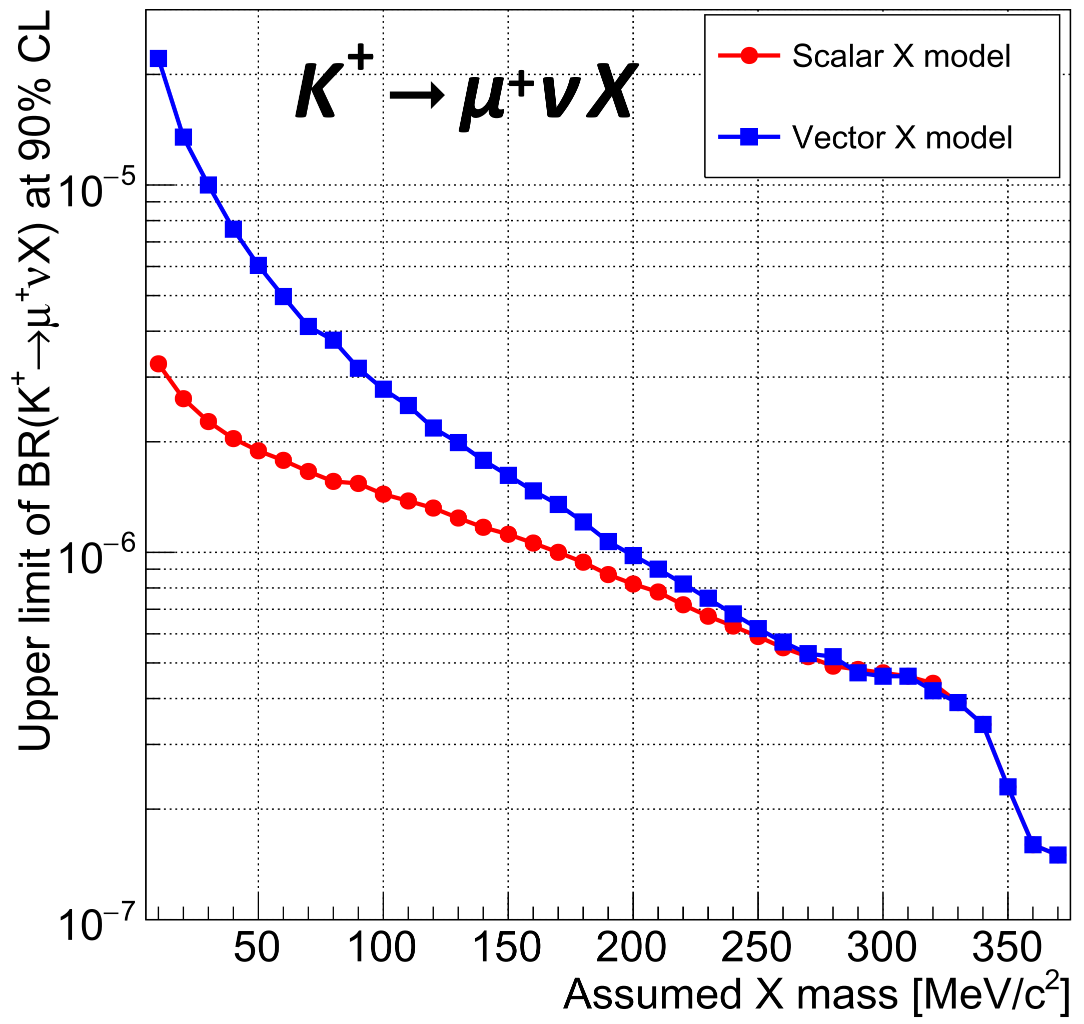
- Search region: $m^2_{miss} > 0.1\ \mathrm{GeV}^2/c^4$ (optimized for strongest limit extraction).
- **Observed events: 6894**
  MC expectation: 7549 ± 92

➜ **$\mathrm{Br}(K^+ \to \mu^+\nu\nu\bar{\nu}) < 1.0 \times 10^{-6}$ at 90% CL.**



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

- Limit extraction similar to $K^+ \to \mu^+ N$ in the mass range 10 – 370 MeV.
- **No signal observed.**
- **Upper limits of $\mathcal{O}(10^{-7} - 10^{-5})$.**



Conclusions & Outlook

- **World-best limits on HNL mixing parameters with full NA62 data set before LS2:**
  - ➜ $\mathcal{O}(10^{-9})$ limits on $|U_{e4}|^2$, $\mathcal{O}(10^{-8})$ limits on $|U_{\mu4}|^2$ (PLB 807 (2020) 135599, PLB 816 (2021) 136259).
- **Searches for $K^+ \to \mu^+ \nu\nu\bar{\nu}$ and $K^+ \to \mu^+ \nu X$ performed:**
  - ➜ Again world-best limits of $\mathcal{O}(10^{-7}) - \mathcal{O}(10^{-9})$ (PLB 816 (2021) 136259).
- **In 2021 NA62 started new data-taking period covering the full time up to LS3.**
  - ➜ Running at 30% higher beam intensity and collect $\mathcal{O}(10^{13})$ K^+ **decays.**
  - ➜ Plan to collect 10^{18} **protons-on-target in "dump mode"** → **further HNL searches.**