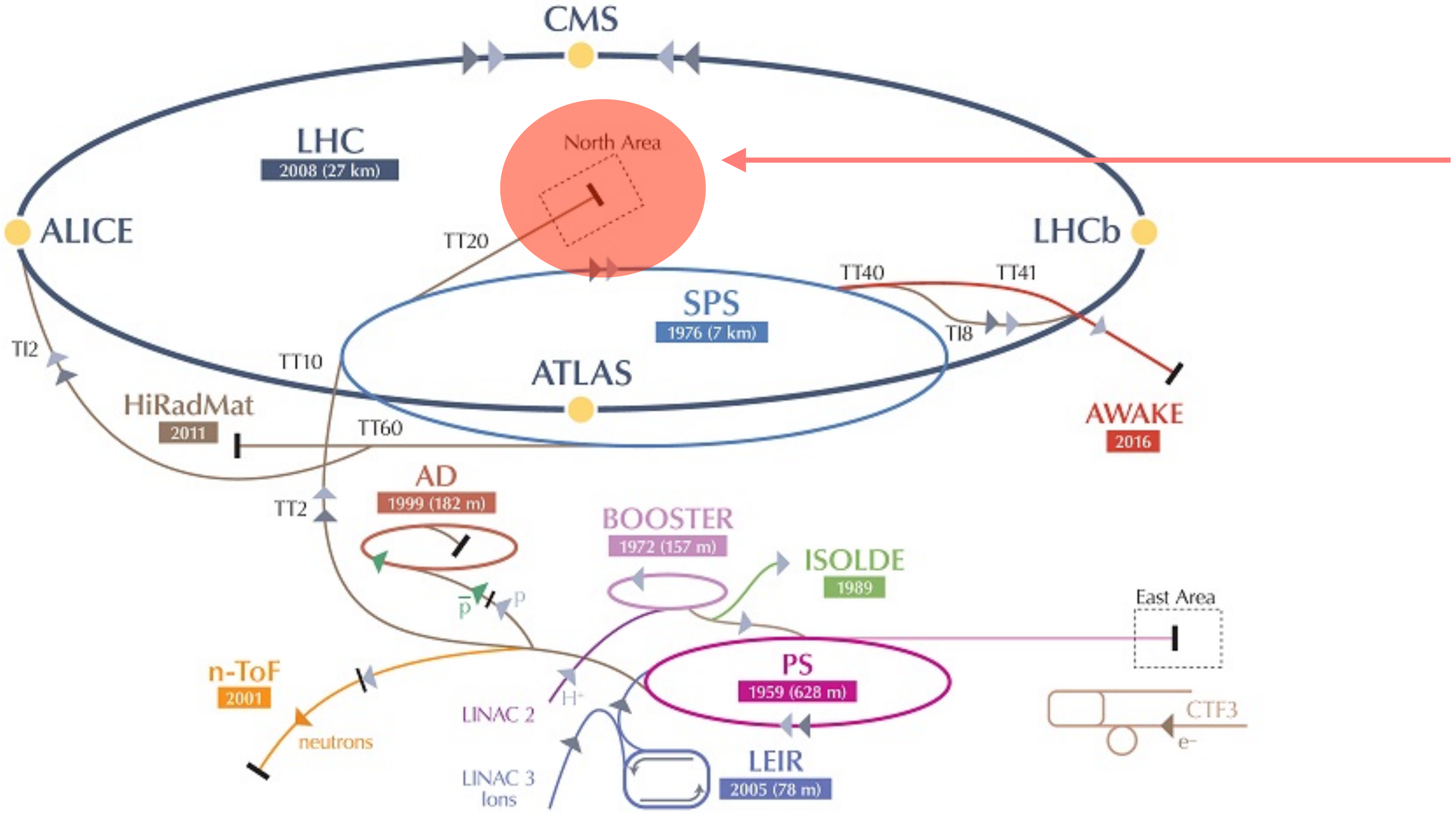
Flavor Physics and CP violation (FPCP) conferences



at

Recent Kaon results at NA62

10 June 2021

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on behalf of NA62 collaboration

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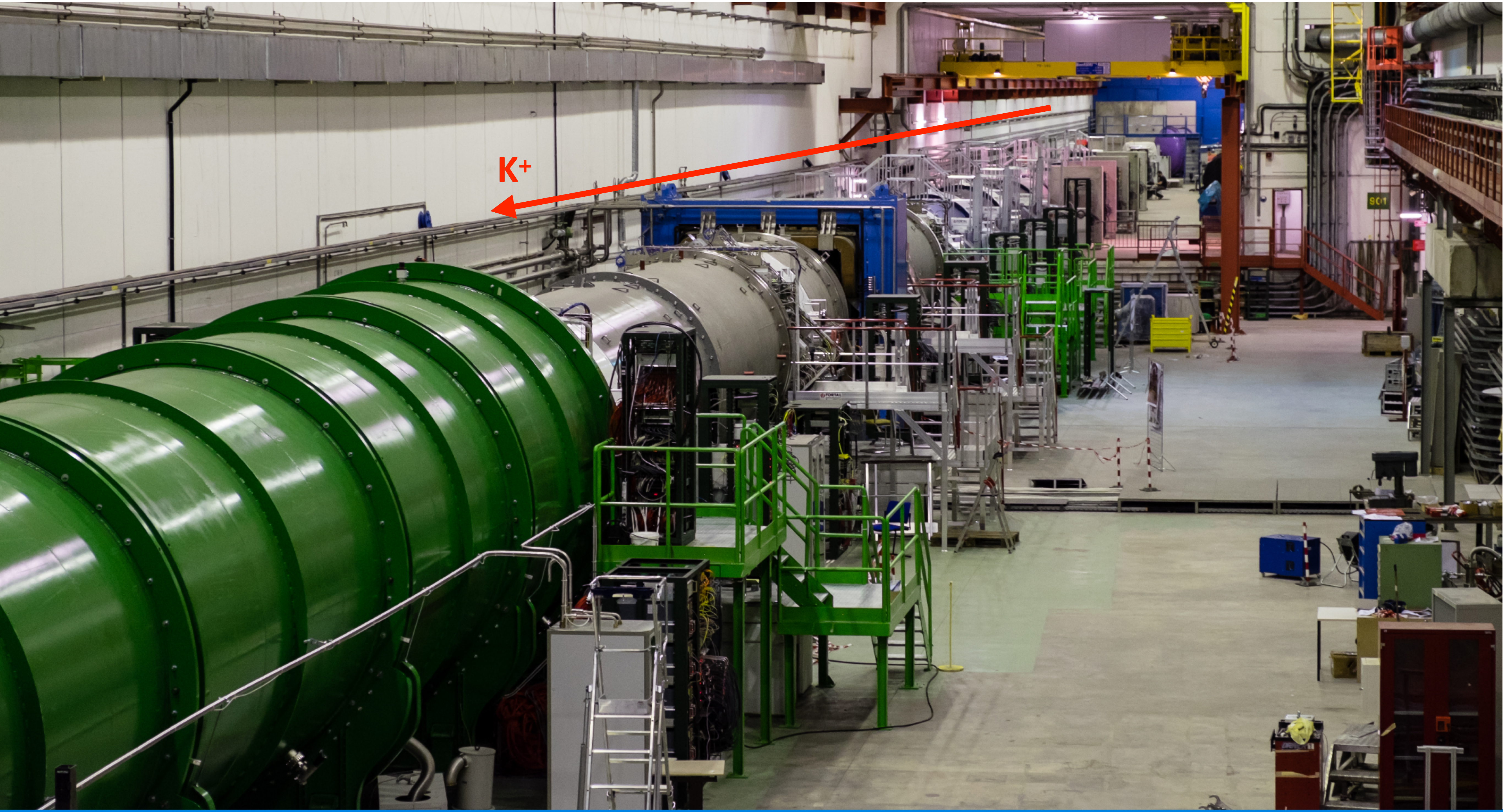
NA62 Experiment

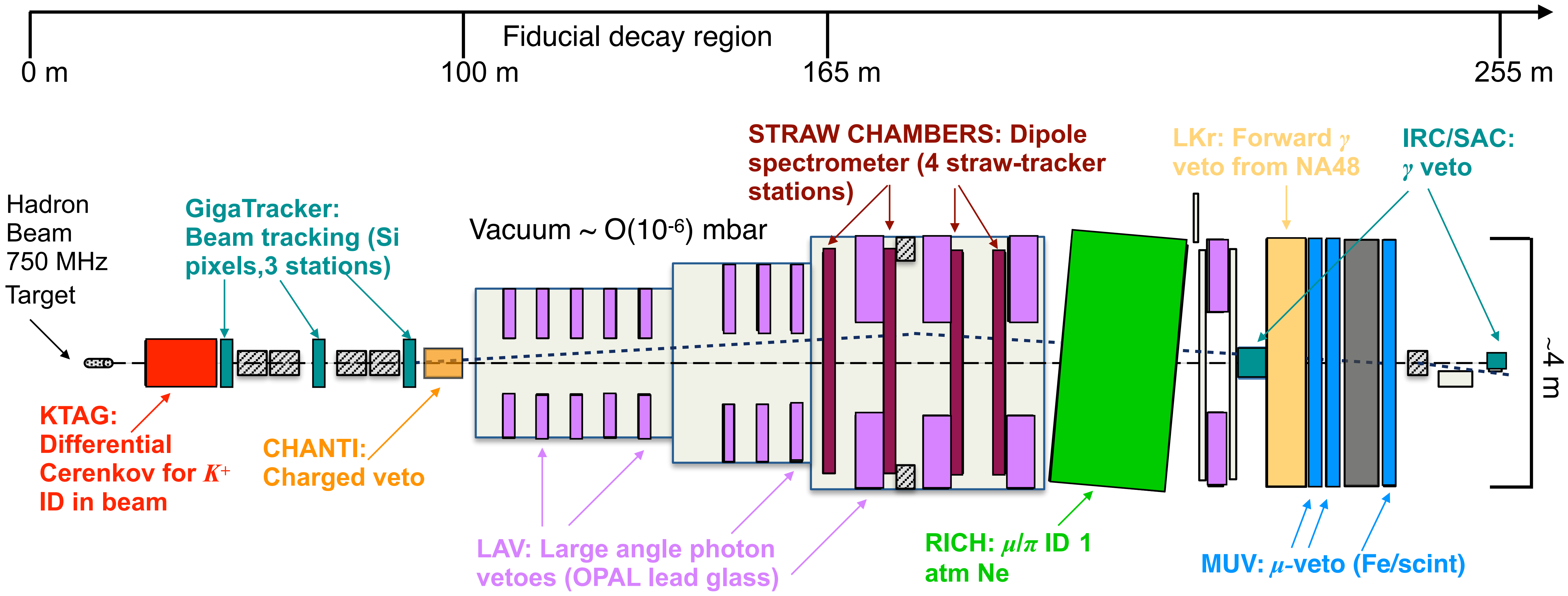
ECN3: CERN-SPS extraction line in the North Area.

400 GeV primary protons from SPS —> 40 cm beryllium target —> 75 GeV positive secondary beam

- 750 MHz total particle rate in secondary beam: 45 MHz of K^+ (6%)



NA62 setup



- **High-performance EM calorimeter**
- **High-rate, precision tracking**
- **Redundant particle ID & μ vetoes**
- **Hermetic photon vetoes**

Trigger system flexibility and detector performances make NA62 ideal for many other measurements besides BR($K^+ \to \pi^+ \nu\nu$)

The large data sample collected by NA62 in 2016-2018 provides sensitivities to rare kaon decays with branching ratios as low as 10^{-11}.

A general purpose experiment

Flavour Physics

Search for New Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Experiment main goal:

$$BR(K^+ \to \pi^+ \nu \bar{\nu})$$

Search for lepton flavour and number violation, rare and forbidden decays:

$$K^+ \to \pi^\pm \mu^\mp e^+$$

$$K^+ \to \pi^- l^+ l^+$$

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

$$(K^+ \to \pi^+ \pi^0)\, \pi^0 \to \text{invisible}$$

Hidden sector Physics

Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

Dark Photon(**DP**), Axion Like Particle (**ALPs**), Dark Scalar (**S**), Heavy neutral Lepton(**N**)

$$K^+ \to l^+ N$$

Searches in K decays are complementary to searches in B-physics and in pure leptonic processes

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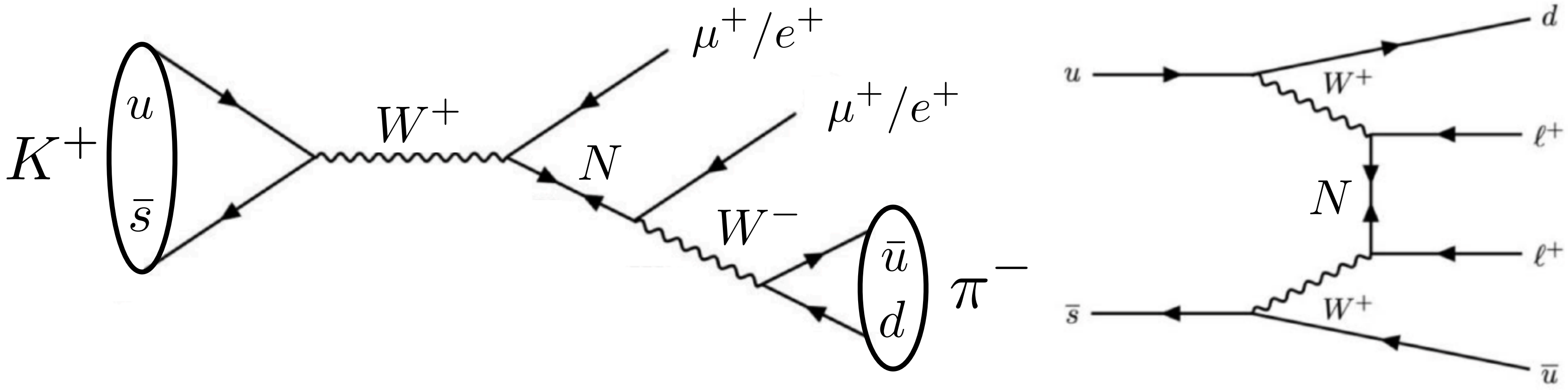
LFV & LNV in Kaon decays

Some BSM theories foresee a violation of **Lepton Number** (L) and **Lepton Flavor** ($L_{e,\mu,\tau}$) conservation laws that in the SM are not imposed by any local gauge symmetry.

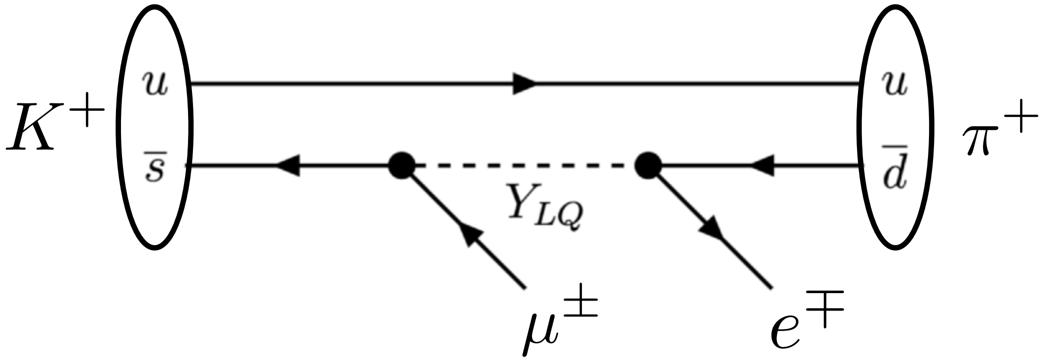
- **Lepton number violation:**



$$\Delta L = 2$$

see-saw mechanism via exchange of Majorana neutrinos (JHEP05(2009)030)

- **Lepton flavour violation:**



$$\Delta L_\mu = \pm 1$$

$$\Delta L_e = \mp 1$$

Mediated at three level by…

… ***leptoquark*** that can couples with different fermion families (10.1007/JHEP12(2019)089)

… or ***new heavy Z' boson*** with family non-universal coupling (arxiv.org/abs/hep-ph/9809526)

An observation of the following decays would be an interesting hint of new physics

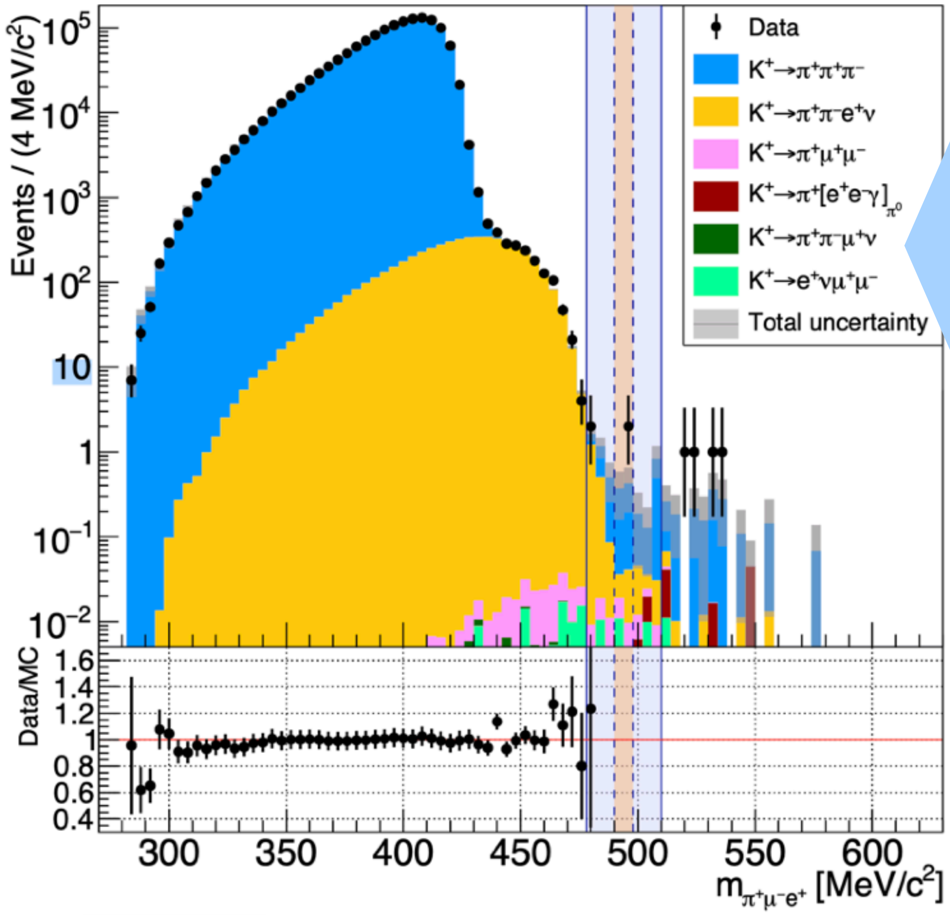
$K^+ \longrightarrow \pi^+\mu^-e^+$, $K^+ \longrightarrow \pi^-\mu^+e^+$

- Kinematic variable used to distinguish between signal and background: **invariant mass** of the 3 selected tracks built under the π−μ−e hypothesis $M_{\pi\mu e}$ (σ_M~ 1.4 MeV)
- Normalized with $\mathbf{K^+ \rightarrow \pi^+\pi^+\pi^-}$ (cancellation of systematic effects: trigger efficiency, detector inefficiencies) $N_K = (1.32 \pm 0.01) \times 10^{12}$
- Main background: π mis-ID and decays in flight:

$$K \rightarrow \pi\pi\pi(\pi \rightarrow \mu\nu, \pi \Rightarrow e)\; K \rightarrow \mu\nu ee(e \Rightarrow \pi)$$
$$K \rightarrow \pi ee^+\nu(\pi \rightarrow \mu\nu, e \Rightarrow \pi)\; K \rightarrow \pi\pi e^+\nu(\pi \rightarrow \mu\nu \,\mathrm{or}\, \pi \Rightarrow \mu)$$

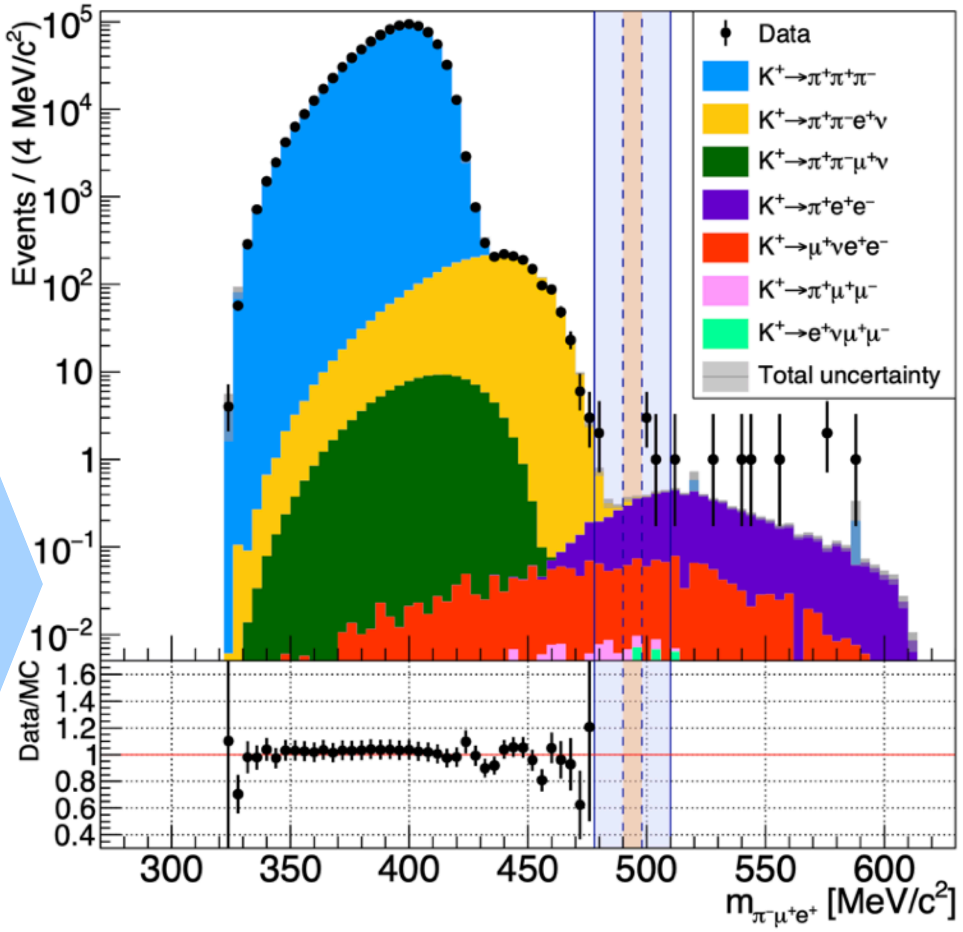
Blind analysis on
2017 + 2018 data

$$S.E.S. = \frac{1}{N_K \cdot A_s \cdot \epsilon_{trig}}$$



$$K^+ \rightarrow \pi^+\mu^-e^+$$
$$n_{bkg} = 0.92 \pm 0.34$$
$$n_{obs} = 2$$

$$K^+ \rightarrow \pi^-\mu^+e^+$$
$$n_{bkg} = 1.06 \pm 0.20$$
$$n_{obs} = 0$$

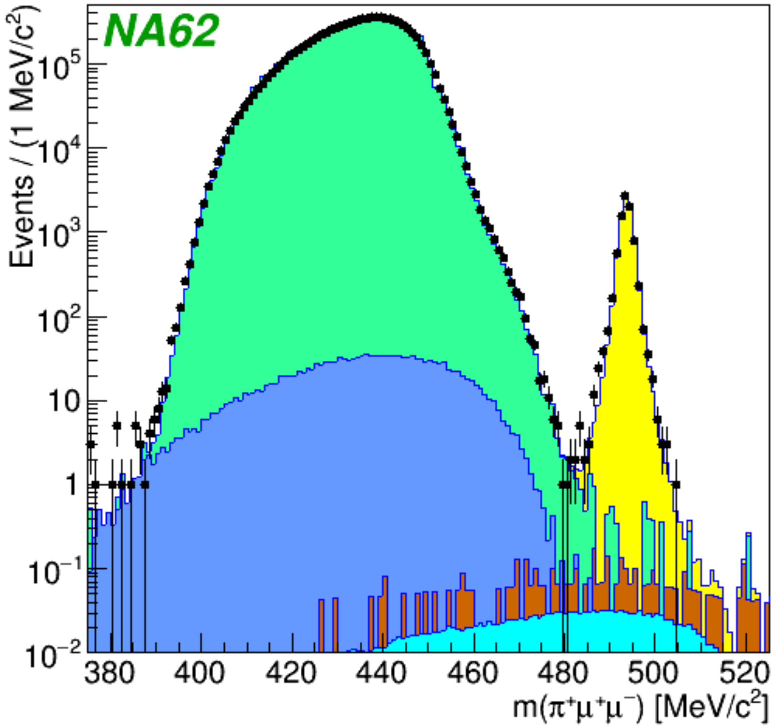


$$A_s(K^+ \rightarrow \pi^+\mu^-e^+) = (6.21 \pm 0.02)\%$$
$$S.E.S. = (1.44 \pm 0.05) \times 10^{-11}$$

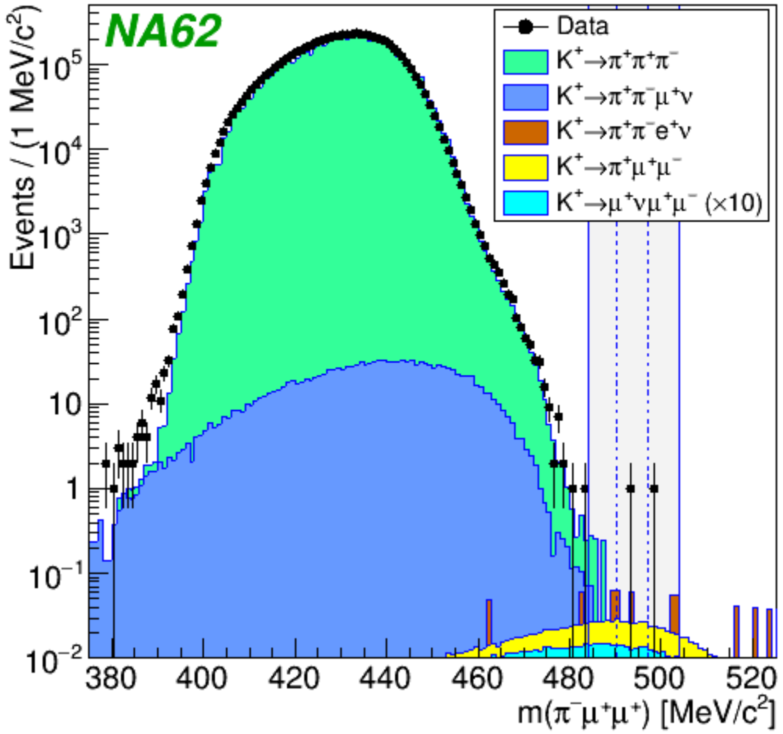
$$A_s(K^+ \rightarrow \pi^-\mu^+e^+) = (4.90 \pm 0.02)\%$$
$$S.E.S = (1.82 \pm 0.08) \times 10^{-11}$$

$K^+ \longrightarrow \pi^- \mu^+ \mu^+$, $K^+ \longrightarrow \pi^- e^+ e^+$

$K^+ \to \pi^+ \mu^+ \mu^-$ selection (SM)



$K^+ \to \pi^- \mu^+ \mu^+$ selection

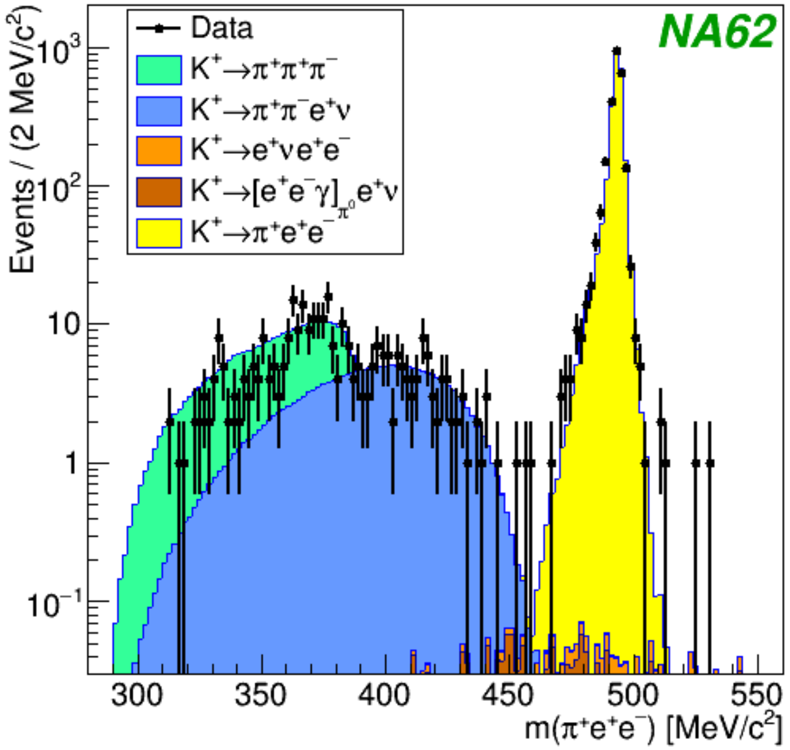


- Normalized with $K^+ \to \pi^+ \mu^+ \mu^-$ channel from the same sample

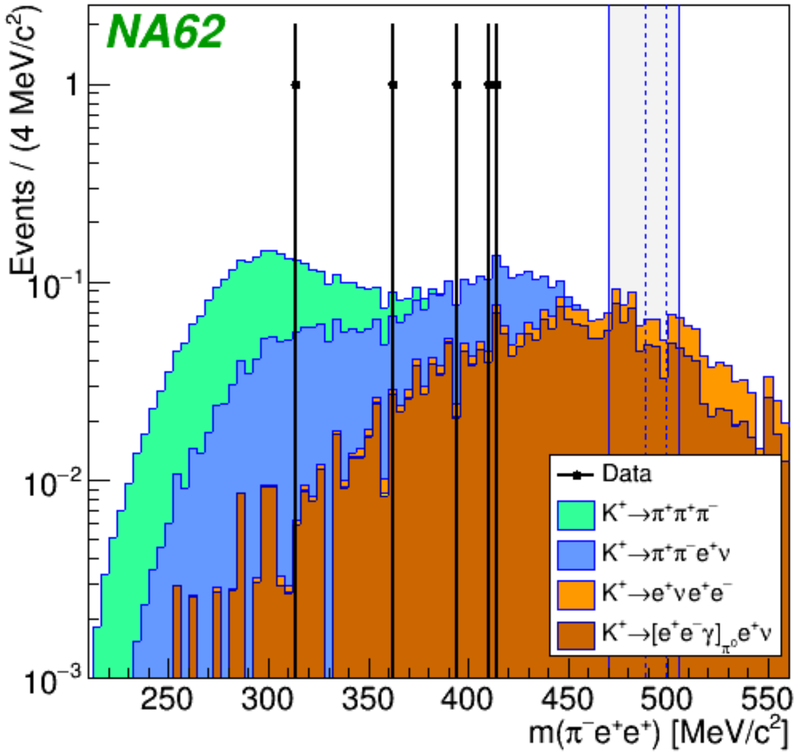
$$N_K = (7.94 \pm 0.09_{stat} \pm 0.21_{ext}) \times 10^{11}$$
$$A_s = 9.81\%$$
$$S.E.S. = (1.28 \pm 0.04) \times 10^{-11}$$
$$n_{bkg} = 0.91 \pm 0.41$$
$$n_{obs} = 1$$

Blind analysis on 2017 data

$K^+ \to \pi^+ e^+ e^-$ selection (SM)



$K^+ \to \pi^- e^+ e^+$ selection



- Normalized with $K^+ \to \pi^+ e^+ e^-$ channel from the same sample

$$N_K = (2.14 \pm 0.04_{stat} \pm 0.06_{ext}) \times 10^{11}$$
$$A_s = 4.98\%$$
$$S.E.S. = (0.94 \pm 0.03) \times 10^{-10}$$
$$n_{bkg} = 0.16 \pm 0.03$$
$$n_{obs} = 0$$

LFV & LNV: NA62 BR upper limits

	Previous UL @ 90% C.L	**NA62 UL @ 90% C.L**	
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11} (NA48/2, CERN)	4.2×10^{-11} ◊	2017 data → improved by a factor 2
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10} (E865, BNL)	2.2×10^{-10} ◊	2017 data → improved by a factor 3
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10} (E865, BNL)	$4.2 \times 10^{-11} \ast$	2017+2018 data → improved by a factor 12
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10} (E865, BNL)	$6.6 \times 10^{-11} \ast$	2017+2018 data → improved by a factor 8
$K^+ \to \pi^+ \mu^+ e^-$	1.3×10^{-11} (E865, BNL)	-	sensitivity similar to the previous searches
$K^+ \to \mu^- \nu e^+ e^+$	2.1×10^{-8} (Geneva-Saclay)	-	Ongoing: 2017 data $S.E.S \sim 1 \times 10^{-10}$
$K^+ \to e^- \nu \mu^+ \mu^+$	no limit	-	Ongoing: 2017 data $S.E.S \sim 1 \times 10^{-11}$

$K^+ \to \pi^+ \pi^0$, $\pi^0 \to \mu^- e^+$ $BR(\pi^0 \to \mu^- e^+) < 3.4 \times 10^{-9}$(E865, BNL) $< 3.2 \times 10^{-10}$(NA62) $\ast$

Large improvements on most of the LN & LF violating
K$^+$ decays → sensitivity up to 10^{-11}

Stay tuned: new results will come

$\ast$ [arXiv:2105.06759v1] ◊[arXiv:1905.07770v2]

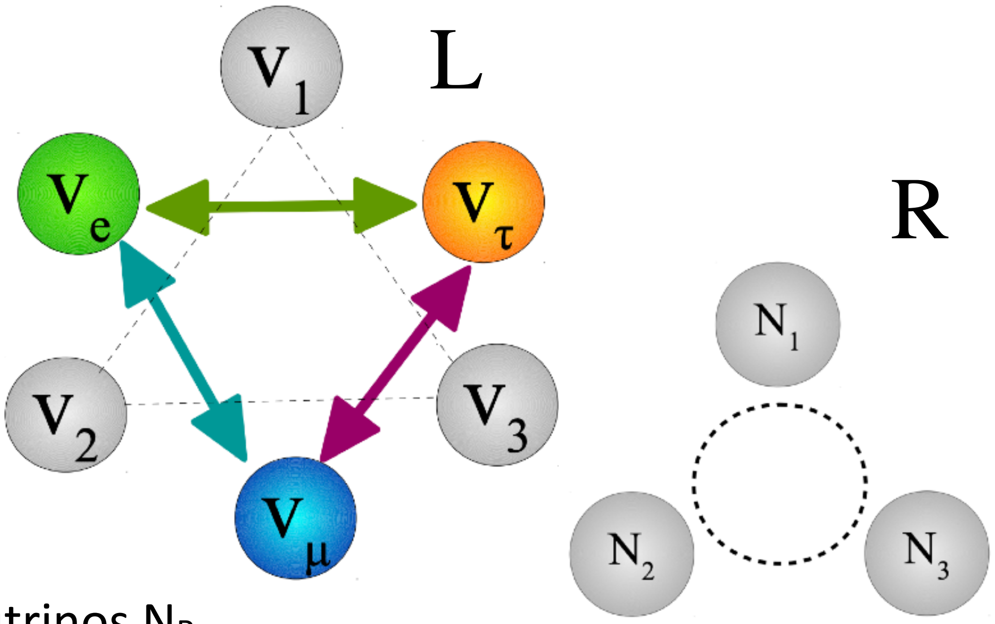
Heavy Neutral Lepton

Right handed neutrino or heavy neutral leptons (HNLs) are included in several extension of the SM

Possibility of sterile neutrino mass states:

$$\nu_\alpha = \sum_{i=1}^{3+k} U_{\alpha_i} \nu_i \;\; (\alpha = e, \mu, \tau)$$

"natural" explanation for the small ν_L mass



νMSM: minimal extension of the SM adding 3 sterile Majorana neutrinos N_R (Asaka and Shaposhnikov, PLB 631 (2005) 151) able to explain ν masses, oscillations, baryogenesis and dark matter

- Lightest: $m_1 \sim 10$ KeV/c^2 → Dark Matter candidate
- $m_{2,3} \sim 100$ MeV/c^2 - 100 GeV/c^2 → Seasaw for ν_S: baryon asymmetry

NA62: sensitivity for masses **below the K^+ mass**

NA62 search for HNL produced in K^+ decays: **$K^+ \to \mu^+N$, $K^+ \to e^+N$** due to mixing with SM neutrinos

$$BR(K^+ \to l^+N) = BR(K^+ \to l^+\nu) \cdot \underbrace{\rho_l(m_N)}_{\text{phase-space kinematic factor}} \cdot \underbrace{|U_{l4}|^2}_{\text{mixing strength}}$$

Helicity suppression relaxed in **$K^+ \to e^+ N$** case: factor $\sim 10^5$ enhancement

$K^+ \to \mu^+ N$, $K^+ \to e^+ N$

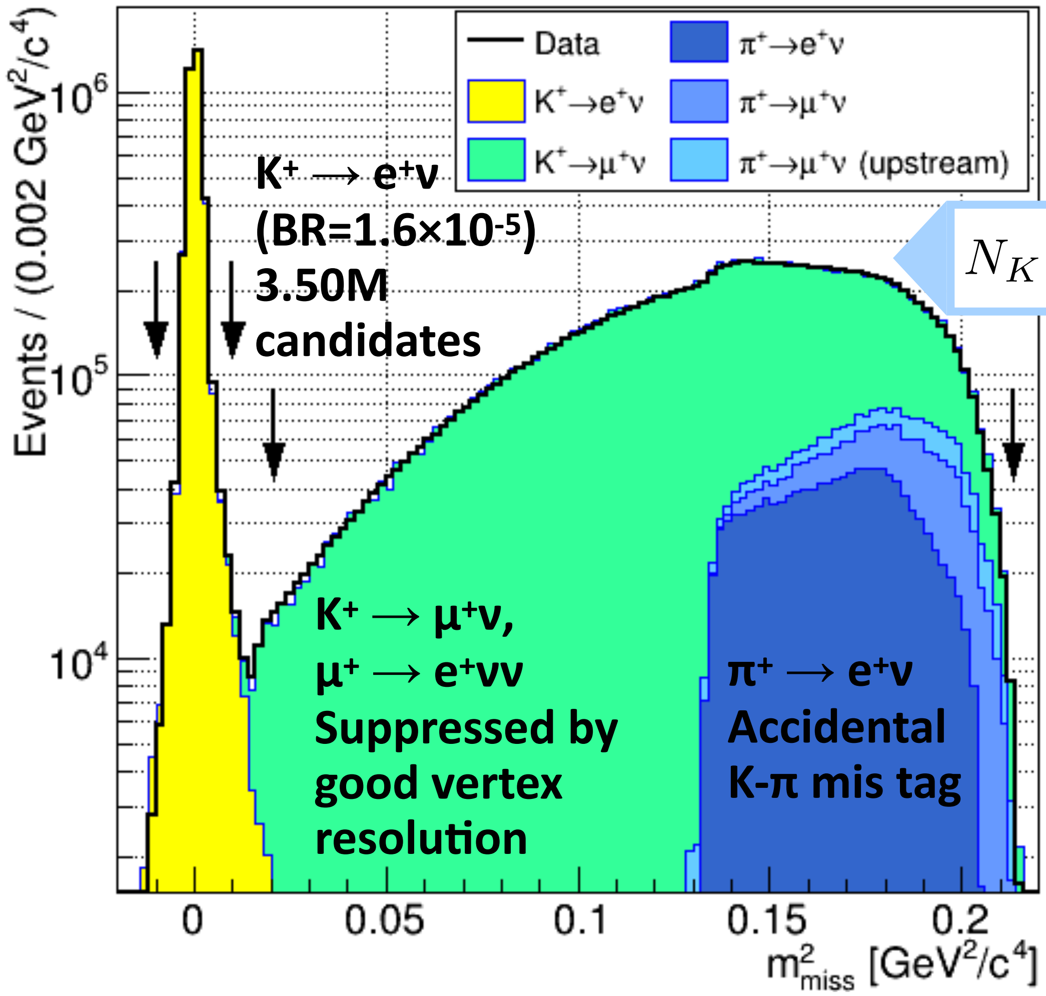
Analysis Strategy: searching for excess of events in missing mass spectrum

- count n_{sig} in sliding mass window across m^2_{miss}
- for each **HNL mass hypothesis**: $|m_{miss} - m_{HNL}| < 1.5\ \sigma_m$

  (σ_m = mass resolution evaluated from simulations - $m_{3\pi}$ for $K^+ \to \pi^+\pi^+\pi^-$)
- Convert n_{sig} to limit on $|U_\ell|$ comparing observed and expected events

$$m^2_{miss} = (P_K - P_{\mu/e})^2 = m^2_N$$

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



$K^+ \to e^+\nu$ ($BR=1.6\times10^{-5}$) 3.50M candidates

$K^+ \to \mu^+\nu$, $\mu^+ \to e^+\nu\nu$ Suppressed by good vertex resolution

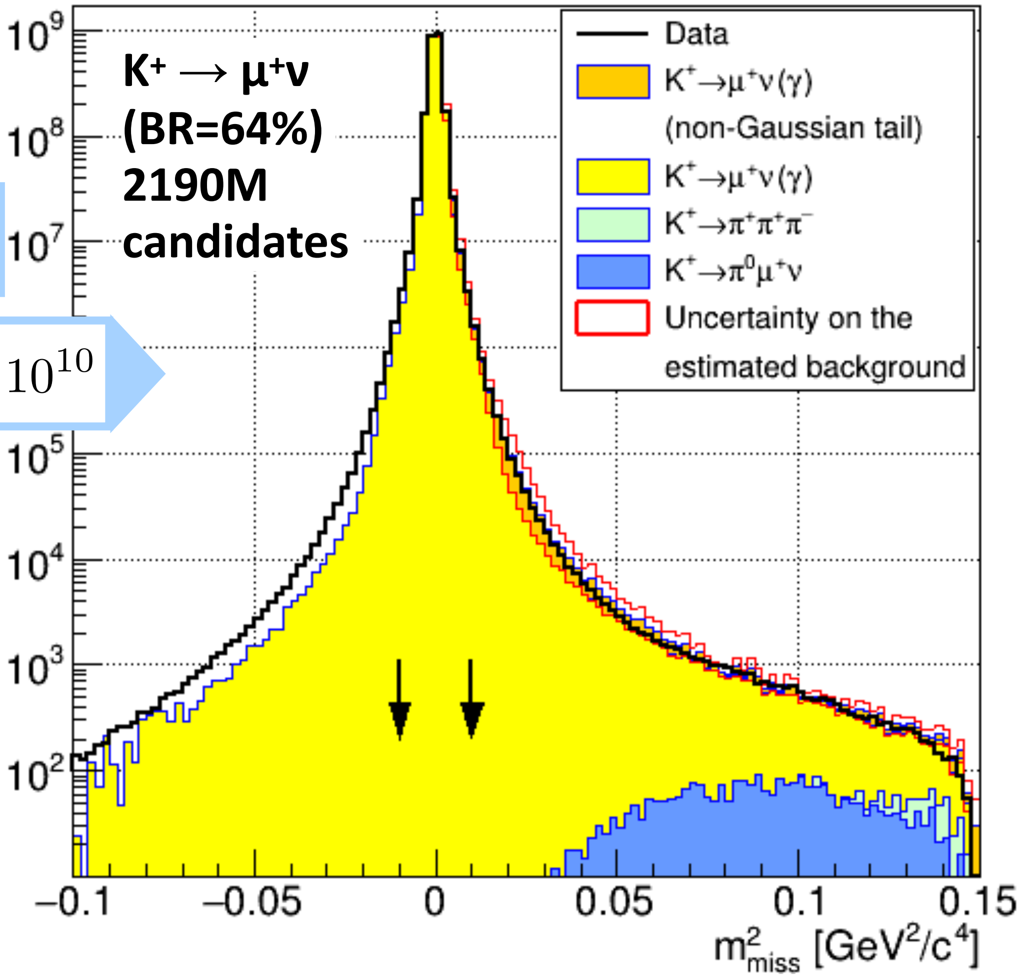
$\pi^+ \to e^+\nu$ Accidental K-π mis tag

Number of K^+ decays in FV:

$$N_K = (3.52 \pm 0.02) \times 10^{12}$$

$$N_K = (1.14 \pm 0.02) \times 10^{10}$$

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



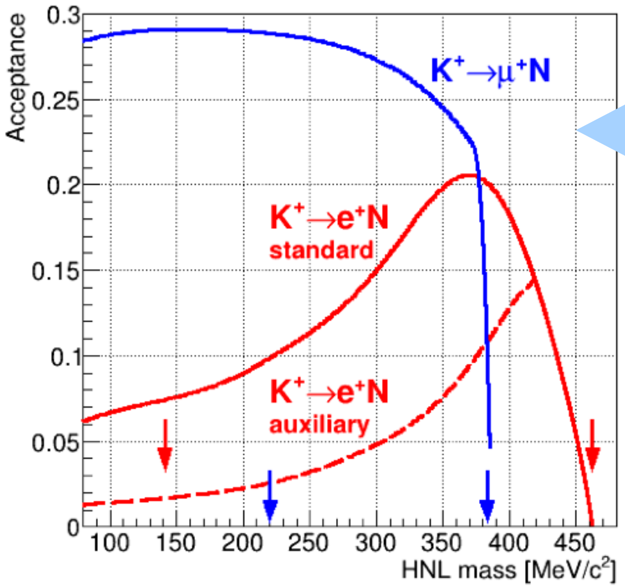
$K^+ \to \mu^+\nu$ ($BR=64\%$) 2190M candidates

- **Background** in each mass hypothesis **from the data** (sidebands fit)

$$BR_{SES} = 1/(N_K \times A) \ \Rightarrow\ |U_{l4}|^2_{SES} = BR_{SES}/(BR(K^+ \to l^+\nu) \times \rho_l(m_N))$$

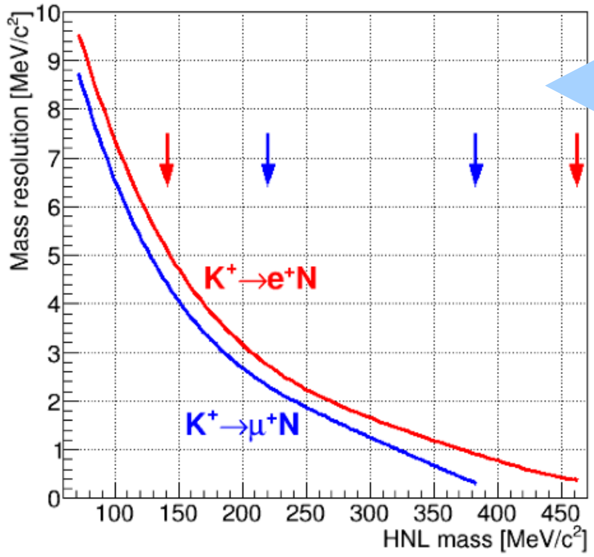
$$N_S = |U_{l4}|^2/|U_{l4}|^2_{SES}$$

Upper limits of $|U_{l4}|$



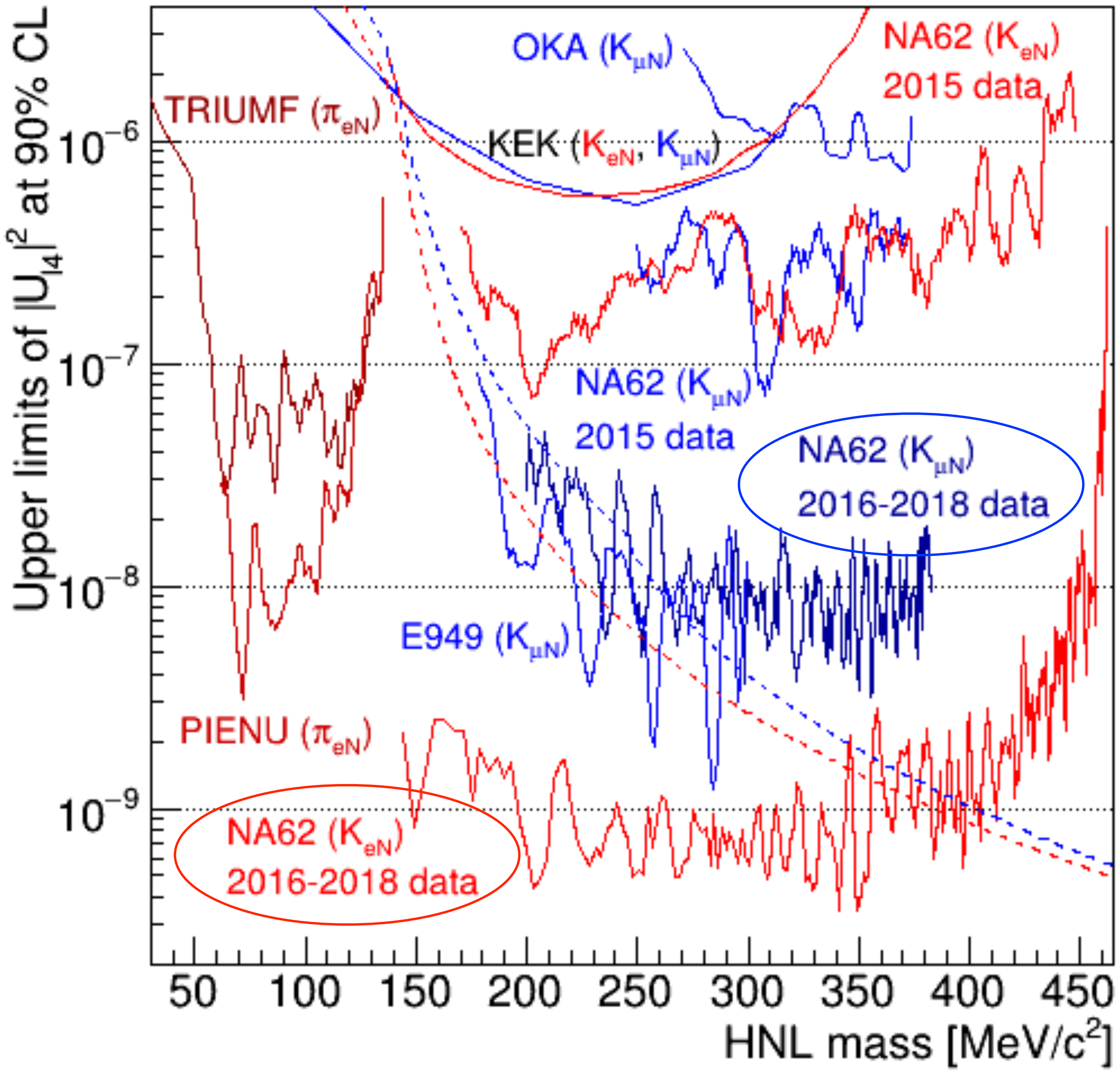
Acceptance vs HNL mass

Standard: p_e<30 GeV/c (Kπνν trigger)
Auxiliary: p_e<20 GeV/c (to remove "bump" near $\pi^+ \longrightarrow e^+\nu$ threshold)



HNL mass resolution vs mass

$|U_{l4}|^2$ limits vs m_{HNL} from production searches



- **O(10^{-9}) limits on $|U_{e4}|^2$** (PLB 807 (2020) 135599)

  Big Bang nucleosynthesis (BBN) allowed range (dashed lines) excluded up to 340 MeV/c^2

- **O(10^{-8}) limits on $|U_{\mu4}|^2$** (PLB 816 (2021) 136259)

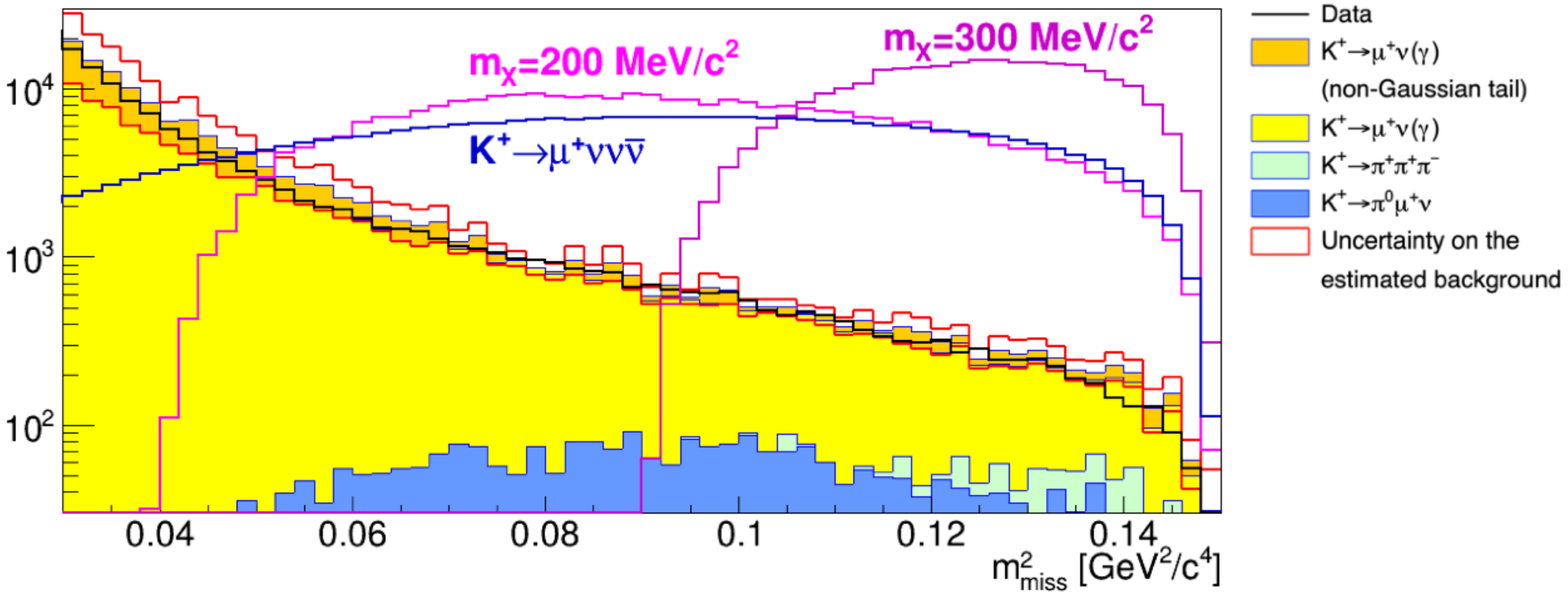
  Approached E949 sensitivity and extended search to 383 MeV/c^2

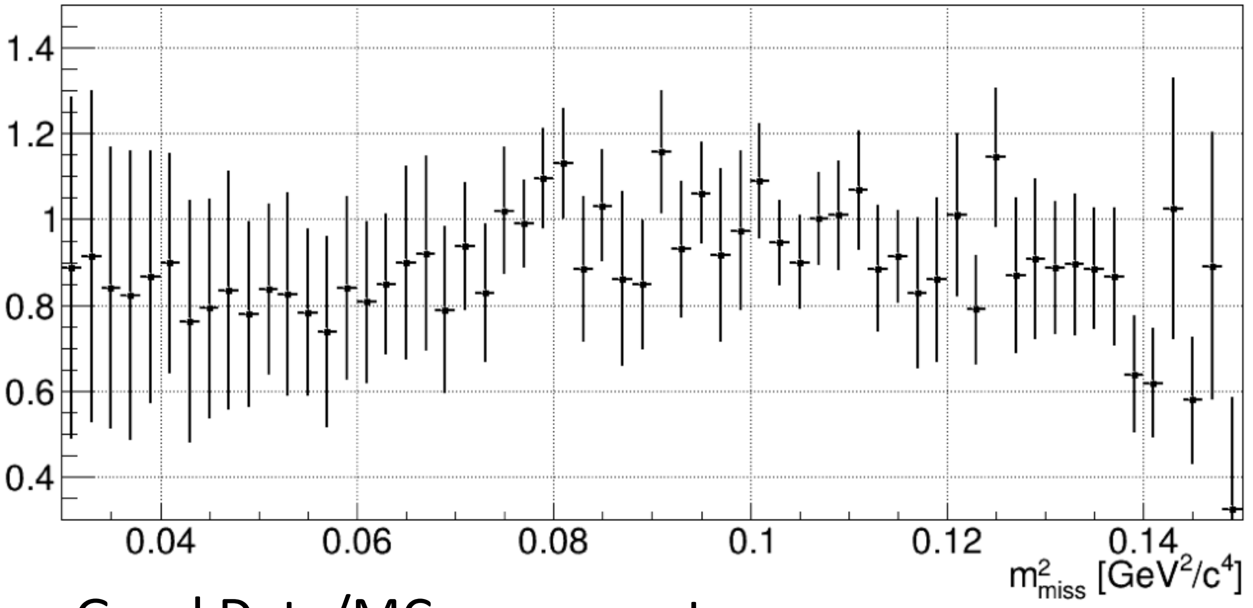
Full 2016-2018 dataset used for HNL production searches

$K^+ \longrightarrow \mu^+ \nu X$, X ⟶ invisible

With slight modification to the $K^+ \longrightarrow \mu^+ N$ analysis, the first search has been conducted of **$K^+ \longrightarrow \mu^+ \nu X$, where X is a scalar or a vector mediator.**

Background estimation from MC





Good Data/MC agreement

- Possible explanation of the anomalous muon magnetic momentum g-2: existence of a new light gauge boson

(*Phys.Lett.B* 513 (2001) 119)

- Could be a scalar or vector mediator of an hidden sector decaying to Dark Matter (X ⟶ xx)

(Phys. Rev. Lett. 124, 041802 (2020))

Mass hypotheses (m_X) equally spaced in **10-370 MeV/c^2** have been examined

- signal would manifest as an excess of data events over the estimated background
- 3 body decay, the signal has a broad distribution in

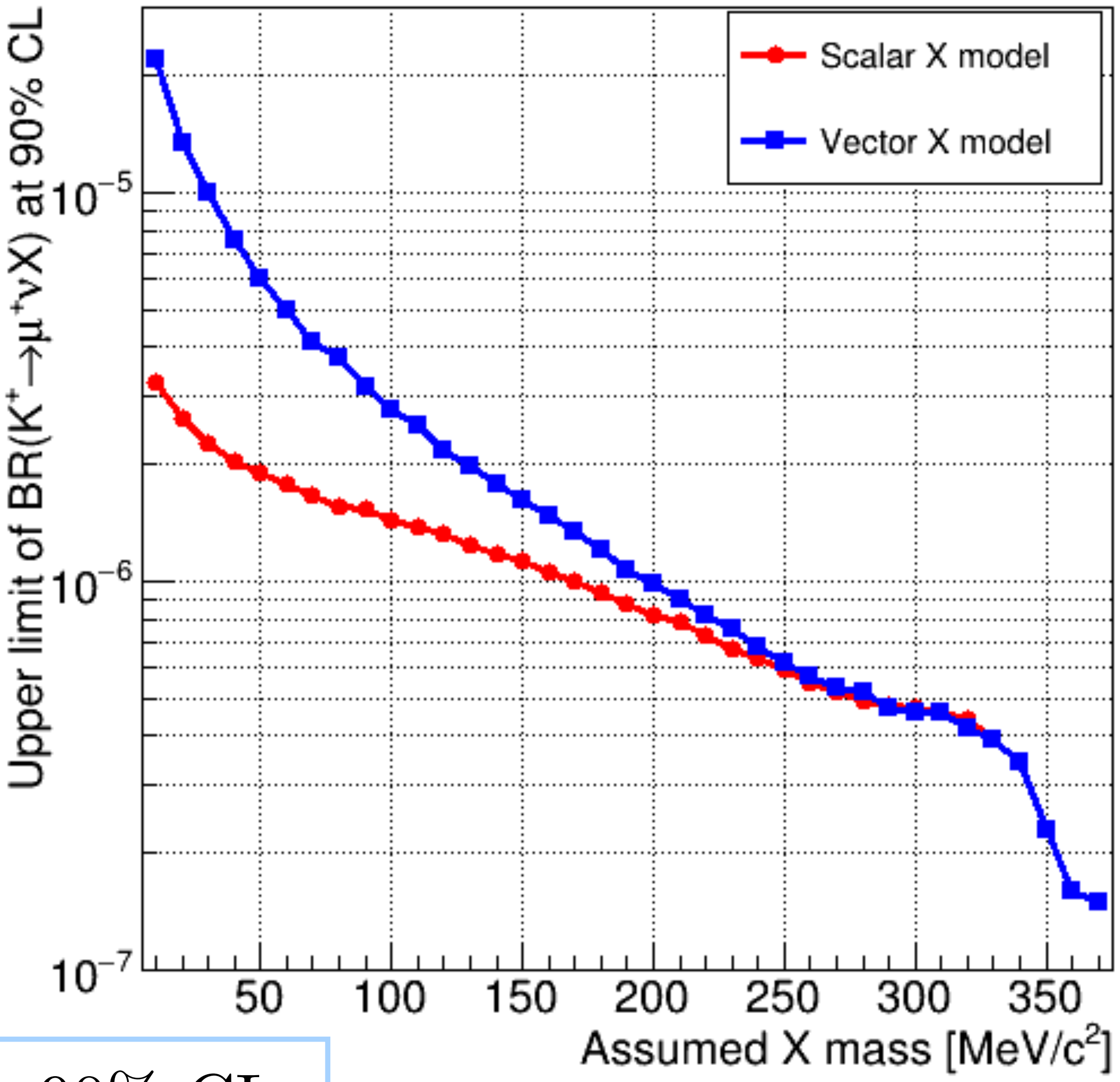
$$m^2_{miss} = (P_K - P_{\mu/e})^2$$

K⁺⟶μ⁺νX, X ⟶ invisible

Number of K decays in FV:

$$N_K = \frac{N_{SM}}{A_{SM} \cdot BR(K^+ \to \mu^+\nu)} = (1.14 \pm 0.02) \times 10^{10}$$

- Compare expected and observed number of event for each mass hypothesis and extract limit
- No signal observed
- The limits obtained in the **scalar mediator model** are stronger than those in the **vector mediator model** due to the larger mean value of m^2_{miss}
- This results is a stronger upper limit



With the same method an upper limit to the very rare SM decay has been established:

$$BR(K^+ \to \mu^+\nu\nu\bar{\nu}) < 1.0 \times 10^{-6} \text{ at } 90\% \text{ CL}$$

improving by a **factor of 2.4** on the most stringent previous limit obtained by the BNL-E949

[Phys. Rev. D94 (2016) 032012]

Search for $\pi^0 \to$invisible

$BR(\pi^0 \to \nu\nu) = O(10^{-24})$: **any observation would be a hint of New Physics**

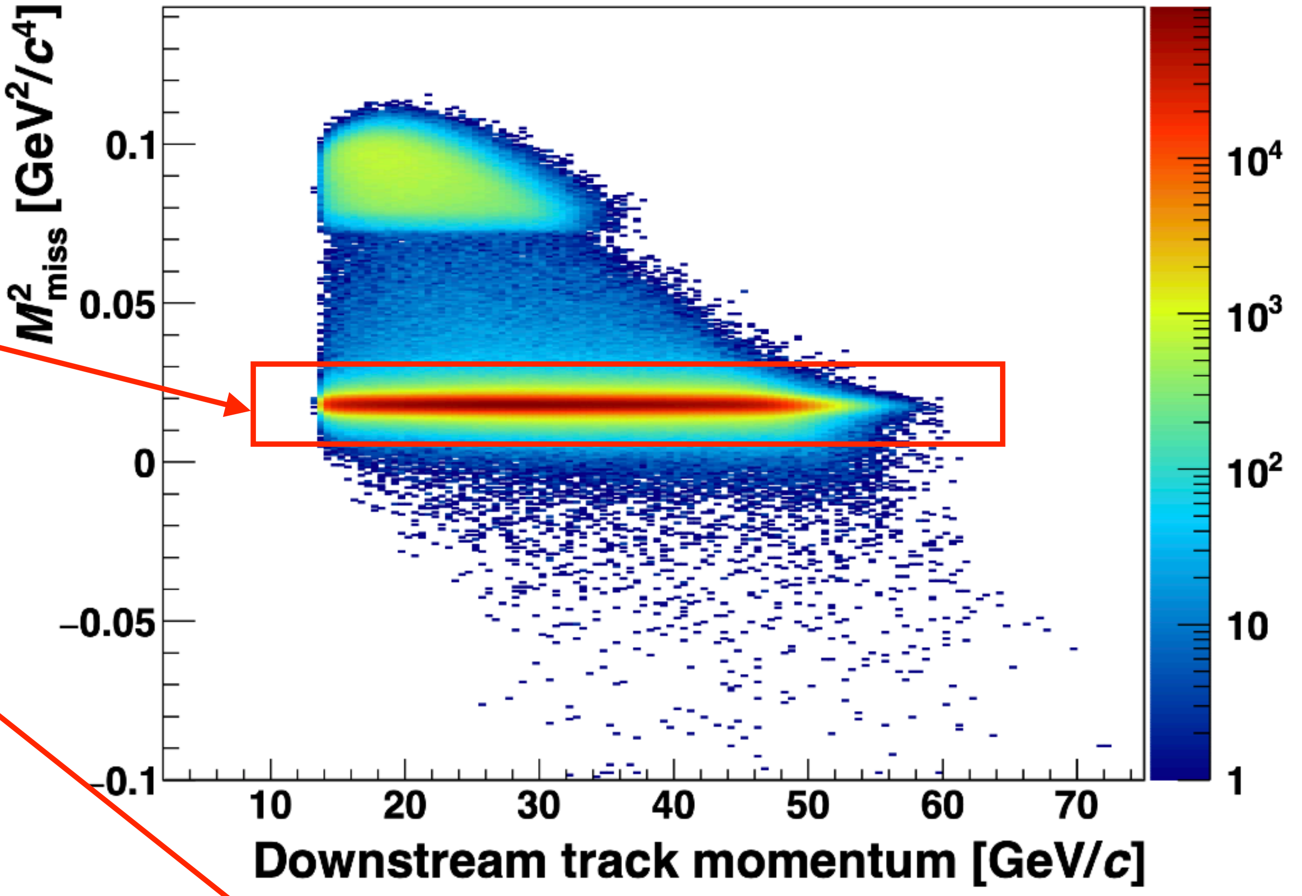
The hermetic photon veto in NA62, essential for the $K^+ \to \pi^+\pi^0$ rejection in the main $K^+ \to \pi^+\nu\nu$ analysis, allows for the search of the pion decay

$$K^+ \to \pi^+\pi^0(\gamma),\ \pi^0 \to \text{invisible}$$

Previous result from BNL (E949, PRD72 (2005)):

$$\mathrm{BR}(\pi^0 \to \mathit{invisible}) < 2.7 \times 10^{-7} \text{ at } 90\%$$

Search in the $m^2_{miss} = (P_K - p_\pi)^2$ range which is the background region for $K^+ \to \pi^+\nu\nu$ analysis



N_s = number of signal events after background subtraction from the observed number of candidate events

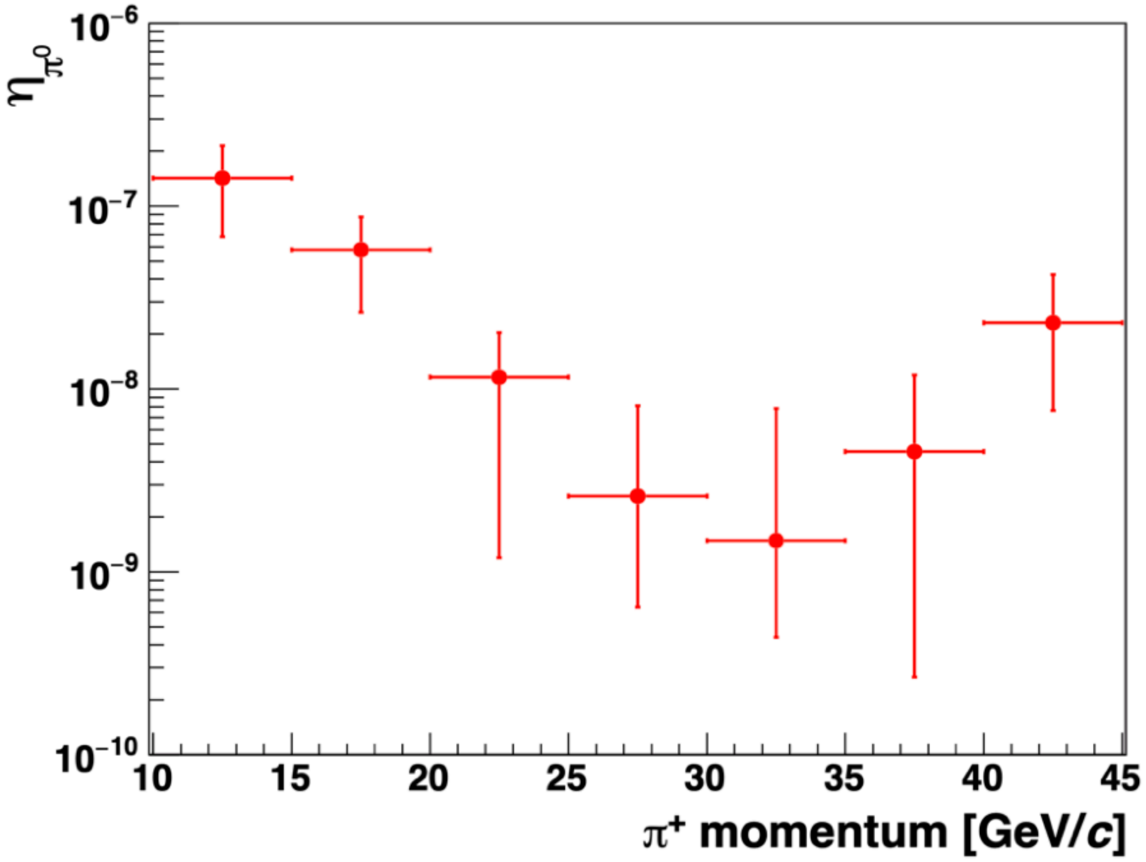
ε_{sel} , ε_{trig} = efficiencies of the signal-selection algorithm and the $\pi\nu\nu$ trigger, respectively

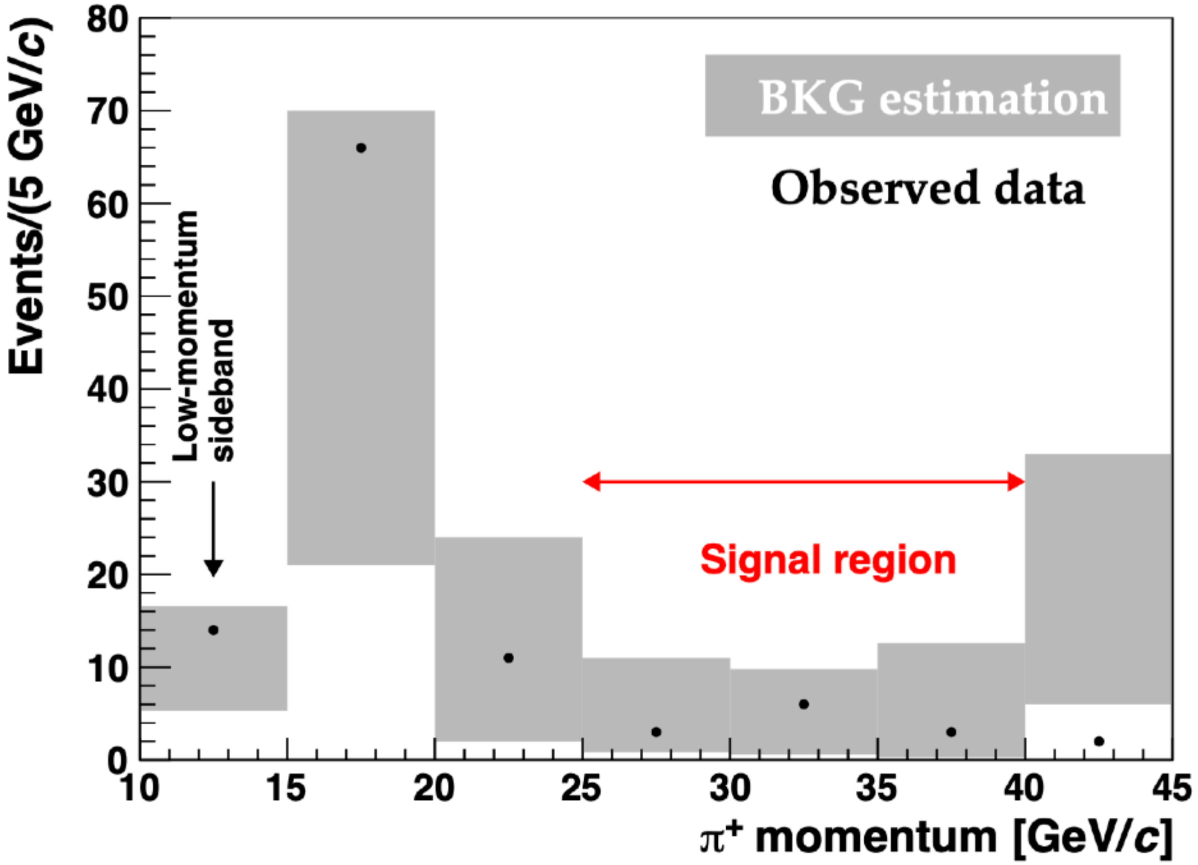
Analysis Strategy

$$\mathrm{BR}(\pi^0 \to \text{invisible}) = \mathrm{BR}(\pi^0 \to \gamma\gamma) \times \frac{N_s}{N_{\pi^0} \times \varepsilon_{\text{sel}} \times \varepsilon_{\text{trig}}}$$

Search for $\pi^0 \longrightarrow$invisible

- Main background: $K^+ \longrightarrow \pi^+ \pi^0, \pi^0 \longrightarrow \gamma\gamma$ with undetected photons
- π^0 rejection evaluation is crucial for this analysis
- π^0 suppression expected for $25 < P_{\pi+} < 40$ GeV/c —> $\eta_{\pi 0} = (2.8^{+5.9}_{-2.1}) \times 10^{-9}$
- Validation: on side bands with expected rejection $O(10^{-7})$ where $\pi^0 \longrightarrow$invisible excluded (BNL)
- Expected background: 10^{+22}_{-8} events
- Observed: 12 events





$$BR(\pi^0 \rightarrow invisible) < 4.4 \times 10^{-9} \ @ \ 90\% \ CL$$

JHEP 02 (2021) 201

60 times stronger than previous measurements

Conclusions

- **The NA62 experiment is a powerful laboratory to make searches for extremely rare kaon decays**
- **Results of recent searches with world best upper limit have been shown**
  - Large improvements on most of the **LNV** and **LFV K^+ decays → sensitivity up to 10^{-11}**
  - Improved up to two order of magnitude in **HNL** upper limits (to be improved with more statistics) **$O(10^{-9})$ limits on $|U_{e4}|^2$, $O(10^{-8})$ limits on $|U_{\mu4}|^2$**
  - The first search for **$K^+ \to \mu^+ \nu X$** decay has been performed together with **$K^+ \to \mu^+ \nu\nu\nu$** in the mass range 10-370 MeV/c^2: upper limits between **$O(10^{-7})$ and $O(10^{-5})$**
  - Upper limit on **$\pi^0 \to$ invisible** decay, **$O(10^{-9})$**, has been improved by a factor 60
- **NA62 will resume data taking on July 2021, till 2024: larger data sets will be available**

Further results will be obtained and new searches developed !

Thank you for your attention!
From the NA62 Collaboration