Searches for feebly interacting particles at the NA62 Experiment

Dario Soldi
Istituto Nazionale di Fisica Nucleare - Torino, Italy

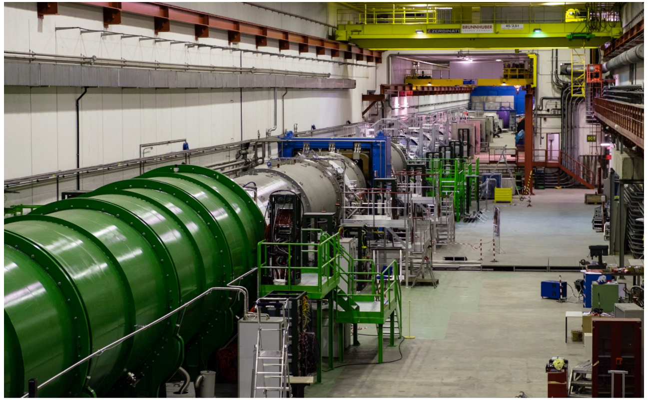
on Behalf of the NA62 Collaboration

16th Patras Workshop on Axions, WIMPs and WISPs

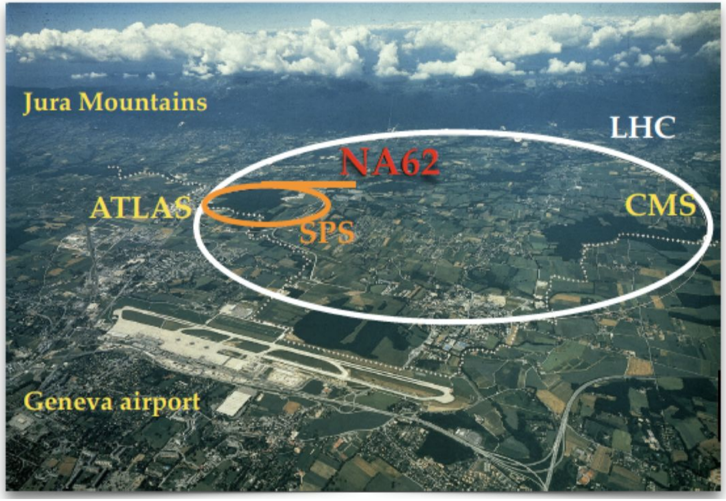
A Kaon Factory at CERN SPS

NA62 Main Goal:
the measurement of BR($K^+ \to \pi^+ \nu\nu$) with a precision better than 10%
(SM BR $\mathcal{O}(10^{-10})$)

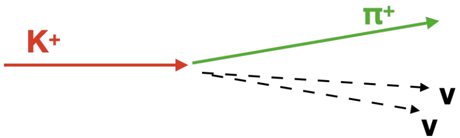
High intensity beam: least 10^{13} K^+ decays are required



- 400 GeV/c primary proton beam
- 3×10^{12} protons/pulse
- 40 cm beryllium target
- 75 GeV/c unseparated hadrons beam:
  - π+, K+ (6%), protons ($\Delta p/p \pm 1\%$)
- 4.8×10^{12} K+ decays/year



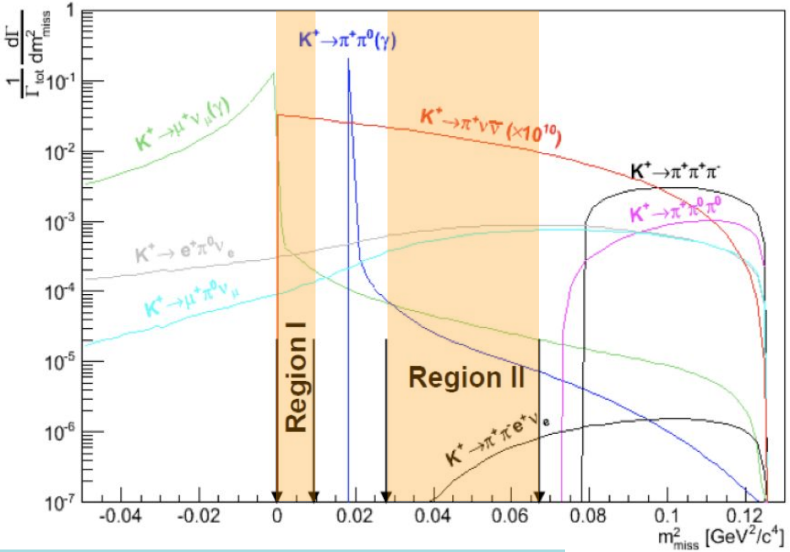
The NA62 strategy



$$m^2_{miss} = (p_K - p_\pi)^2$$

Kaons with high momentum.
Decay in flight technique.
Signal signature: K^+ track + π^+ track + missing energy

2 signal regions, on each side of the $K^+ \rightarrow \pi^+\pi^0$ peak
(to eliminate 92% of the K^+ width)



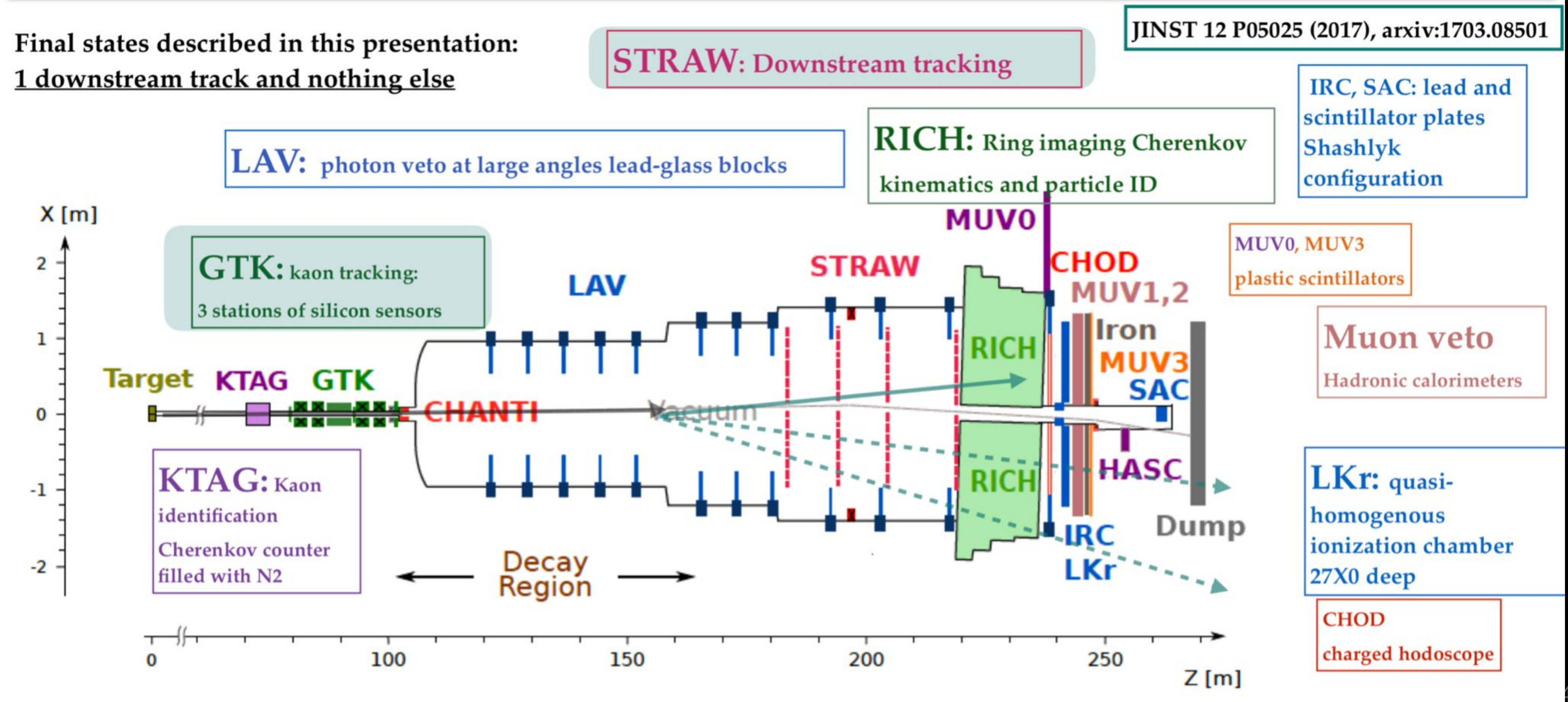
Main background sources:

Decay	BR	Main Rejection Tools
$K^+ \rightarrow \mu^+\nu_\mu(\gamma)$	63%	μ-ID + kinematics
$K^+ \rightarrow \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \rightarrow \pi^+\pi^+\pi^-$	6%	multi-track + kinematics
$K^+ \rightarrow \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \rightarrow \pi^0 e^+\nu_e$	5%	e-ID + γ-veto
$K^+ \rightarrow \pi^0\mu^+\nu_\mu$	3%	μ-ID + γ-veto

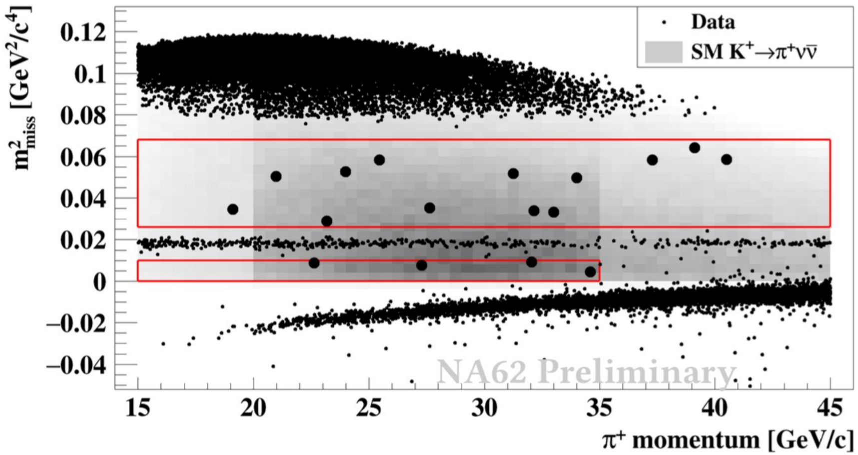
Key performances to deal with the backgrounds:

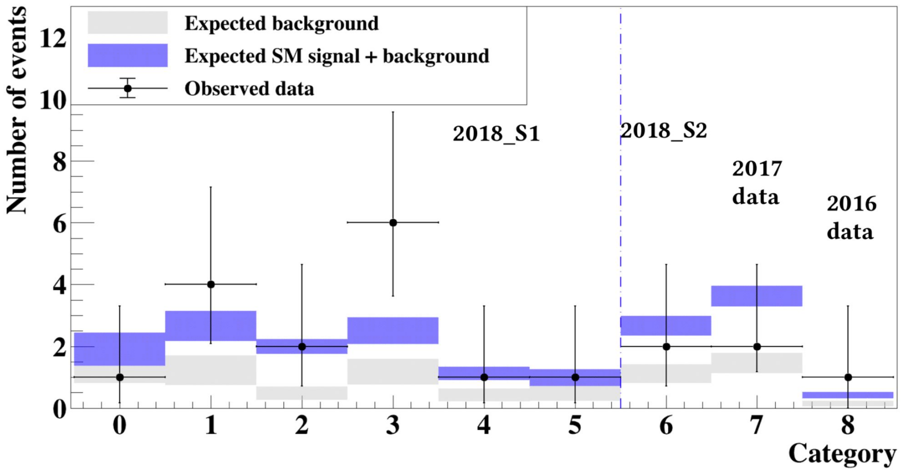
- O(100 ps) timing;
- $O(10^4)$ background suppression with kinematics;
- $O(10^7)$ μ-suppression;
- $O(10^7)$ γ-suppression;

The NA62 detector

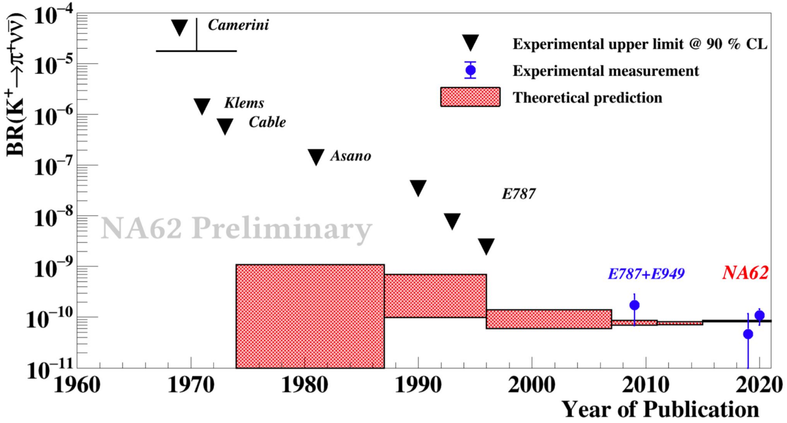


The π^+vv interlude





5.3 background + 7.6 SM signal events expected, 17 events observed



NA62 Run1(2016 + 2017 + 2018) result:

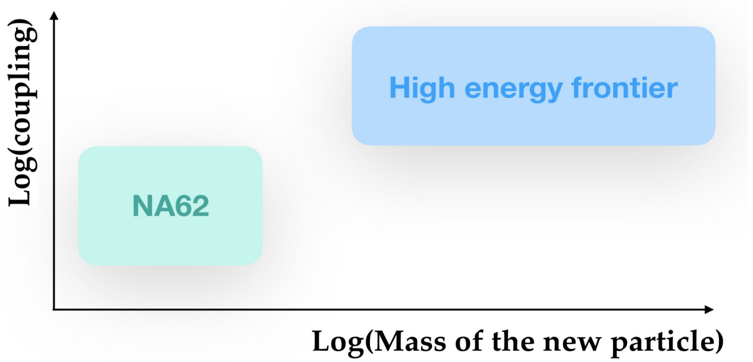
- $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5\,stat.} \pm 0.3_{syst.}) \times 10^{-11} (3.5\sigma \text{ significance})$

The invisible feebly interacting particles at NA62

Searches for a new exotic particle X produced in Kaon decays through detecting missing mass:

- X decaying to invisible particles (neutrinos or dark matter)
- X So long-lived to escape the apparatus

1 track + missing mass: similar signature to the golden mode K+ → π+vv 💪



the lifetime τ must be considered

Complementary to colliders!

OUTLINE:

- K+ → π+X, X → invisible/visible with the full 2016-2018 data
- K+ → π+π0 (or X with mX ~ mπ0), X/π0 → invisible with 2017 data
- K+ → μ+vX, X → invisible with the full 2016-2018 data
- K+ → lN - Heavy Neutral Leptons

$K^+ \rightarrow \pi^+ X$, X invisible

Motivation: feebly interacting new particle X in $K+ \rightarrow \pi+X$ foreseen in several models

The ***scalar portal*** couples the dark sector to the Higgs boson via the bilinear H†H operator of the SM. The minimal scalar portal model involves one extra singlet field S and two types of couplings, μ and λ:

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H.$$

hS coupling

It can lead to pair-production of S but cannot induce its decay.

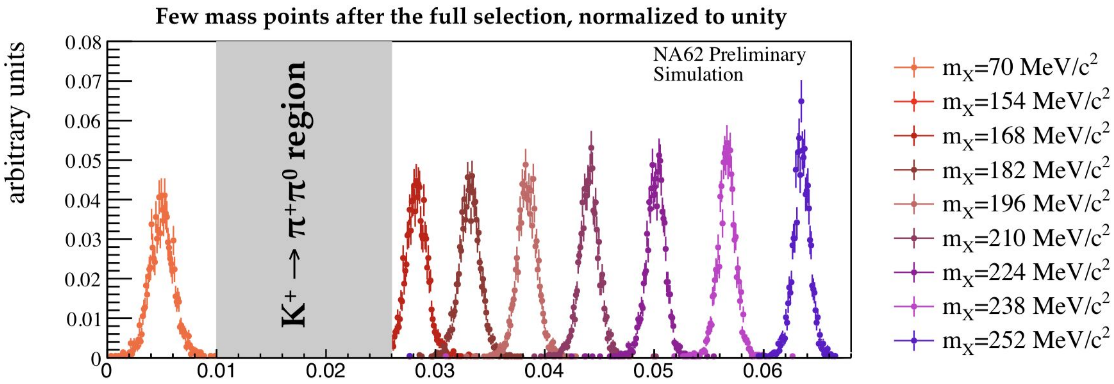
Pseudo-scalar:
Axion-like particles (ALPs)
QCD axion, Axiflavon (m~0)

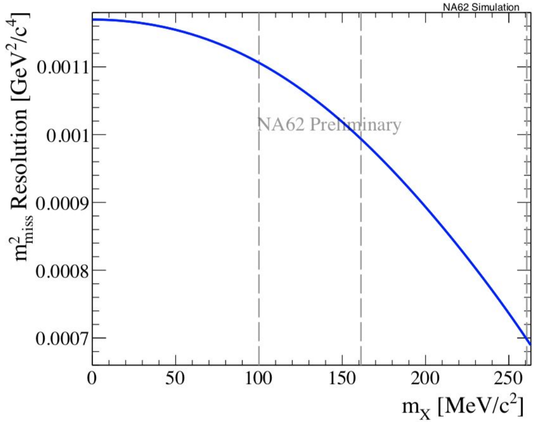
PBC: J Beacham *et al* 2020 *J. Phys. G: Nucl. Part. Phys.* 47 010501

NA62: arXiv: 2103.15389 [hep-ex]

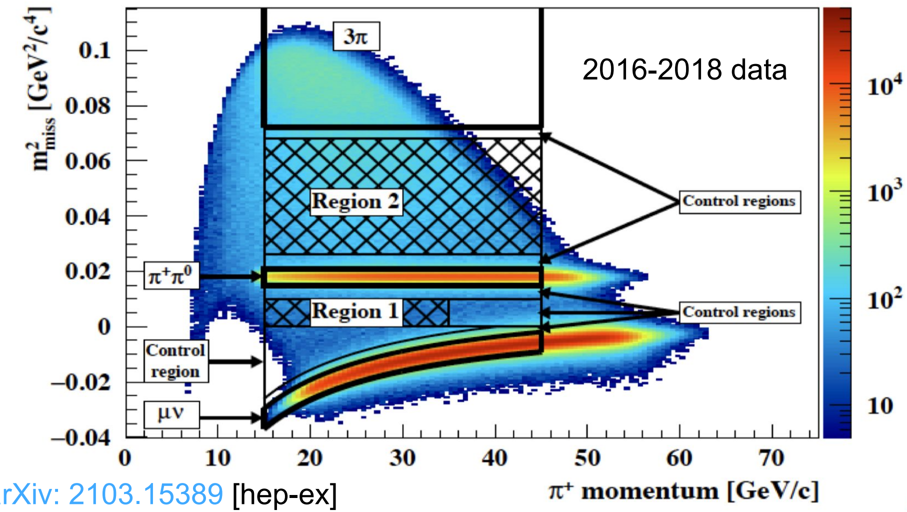
same analysis of K-> πvv:

- Use exactly the same selection, normalization and background evaluation;
- Generate signal with two body decay for 200 mass hypotheses to compute acceptance and resolution in m2miss



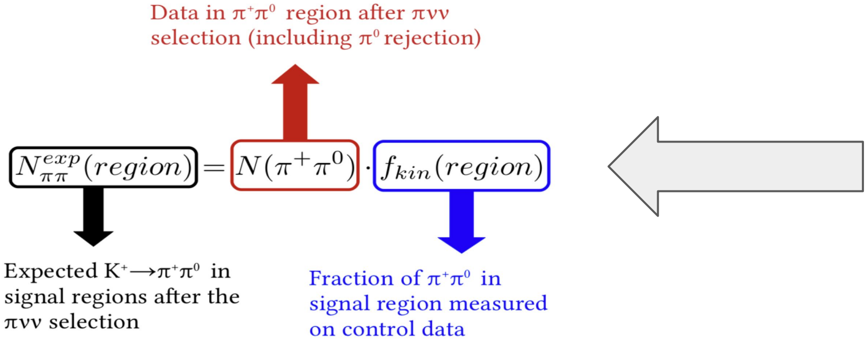


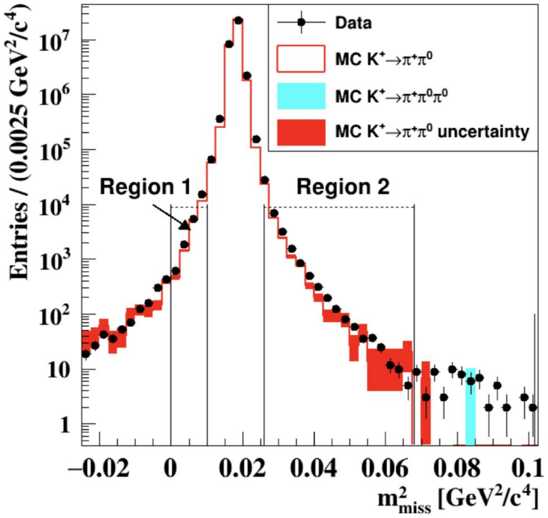
$K^{+} \rightarrow \pi^{+}X$, X invisible - the Analysis



arXiv: 2103.15389 [hep-ex]

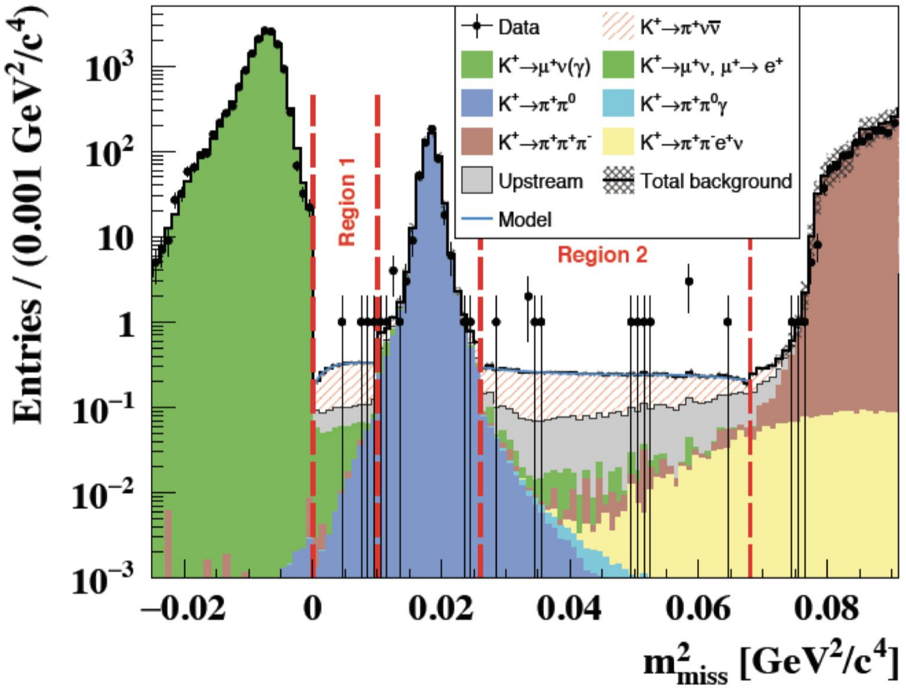
- Normalization to K+→ π+π0 decay
- efficiencies evaluated with data driven methods
- Data-driven background estimation
- Analysis binned in π+ momentum and beam intensity
- Control regions for validation





$K^+ \to \pi^+ X$, X invisible - the Analysis

2018 Dataset, for illustration



Background model

- shape: Parameterized with polynomial functions
- both in Region1 and Region2
- Background yield from πvv analysis, including K->πvv

Signal model

- shape: Gaussian
- Efficiency and normalization obtained in bins of momentum and intensity, as in πvv analysis

Update with full dataset
arXiv: 2103.15389 [hep-ex]
Submitted to JHEP

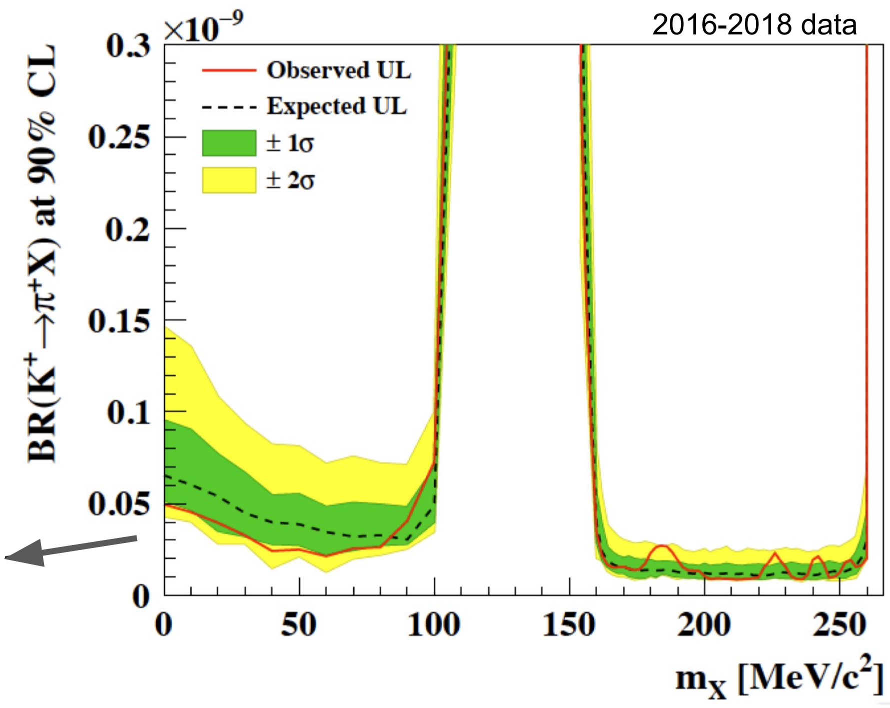
Looking for bumps in the mm^2_{miss} distribution

$K^+ \to \pi^+ X$, X invisible - the Analysis

Assumption: X decays to invisible particles, or it is so long-lived to escape the apparatus

- Shape analysis on m2miss;
- Fully frequentist approach;
- Profiled likelihood test statistic;
- Combination of the 2016-2018 datasets;

Sensitivity degrades at small mX because of resolution.
In particular, for axion models, half of the signal is cut away



$K^+ \to \pi^+ X$, X visible, but not seen

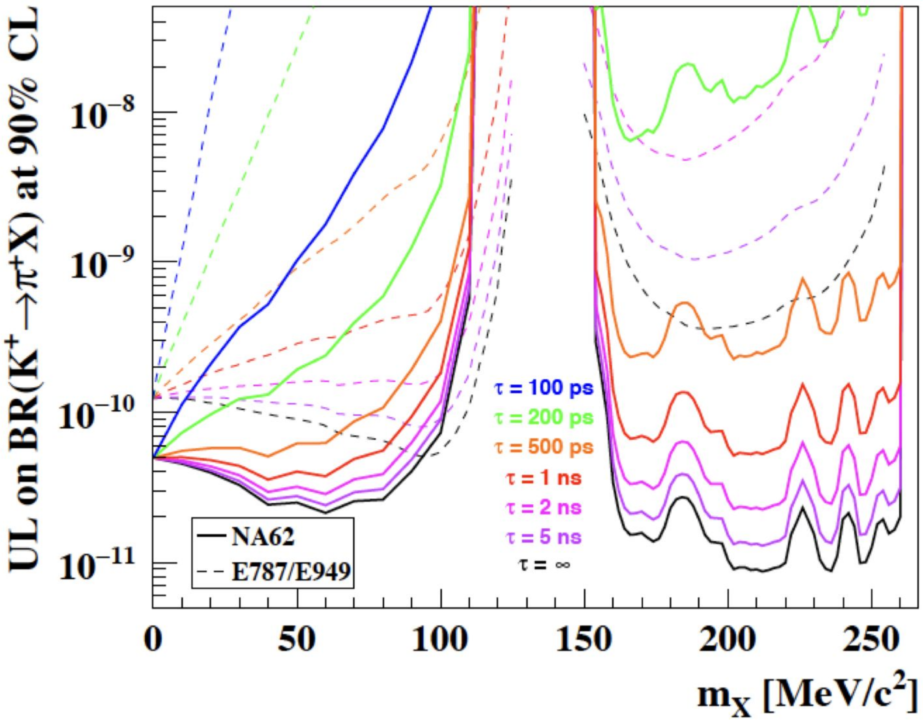
2016-2018 data

Assumption: X decays to visible Standard Model particles, but far from NA62.
If it decays inside NA62, the products are supposed to be vetoed.

$$P = e^{-\left(\frac{\Delta L}{\beta\gamma c\tau}\right)}$$

Dimensions of the experiment

cτ depends on the coupling parameters and the mass



Improved upper limit over a the range [0,100] MeV and [160,260] MeV

$K^+ \to \pi^+ S$, S scalar

Higgs mixing model

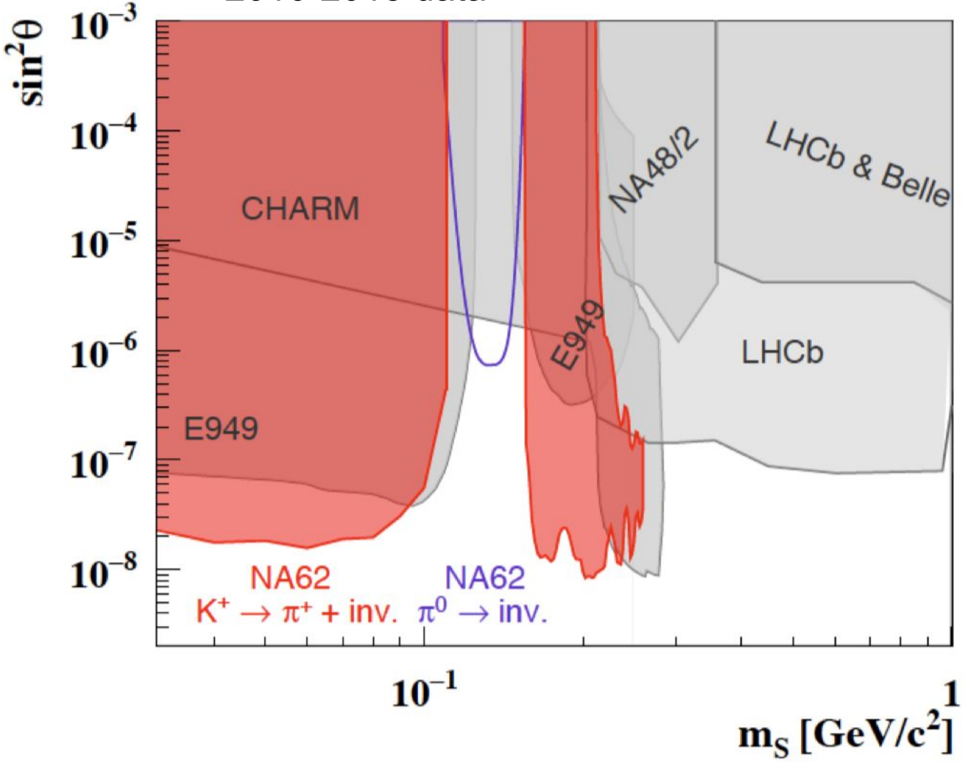
$$\mathcal{L}_{\text{scalar}} = -\left(\mu S + \lambda S^2\right) H^\dagger H$$
$$\lambda = 0$$
$$\mu = \sin\theta$$

The lifetime depends on $\sin\theta$ and m_S

S decay only in standard model particles

acceptance is reduced because the decay products (e or μ) are vetoed

2016-2018 data



$K^+ \rightarrow \pi^+ \pi^0 , \pi^0 \rightarrow$ inv.

- In principle $\pi 0 \rightarrow \nu\nu$ is not forbidden because of neutrino non-zero masses, but in the SM: BR($\pi 0 \rightarrow \nu\nu$) ~ O(10^{-24})
- Any observation → BSM
- The previous experimental limit is 2.7 10^{-7} at 90% CL, from BNL experiments

Measure possible thanks to the photon-hermeticity of NA62

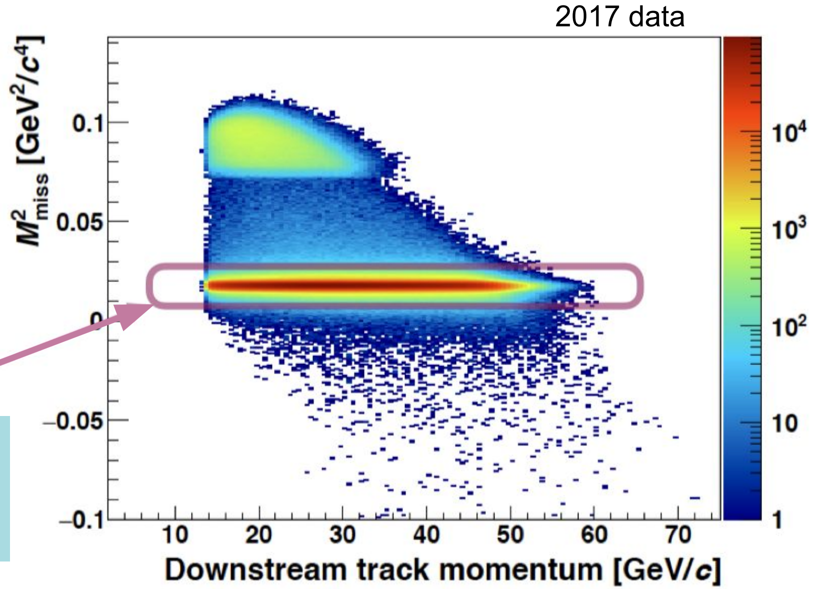
With the same analysis we can also search for

$$K^+ \rightarrow \pi^+ X, X \rightarrow \text{invisible, for } m_X \sim m_{\pi 0}$$

JHEP **02 (2021) 201**

2010.07644 [hep-ex]

Search performed in a range of miss2 which is a background for πνν



$K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow$ inv. - strategy

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

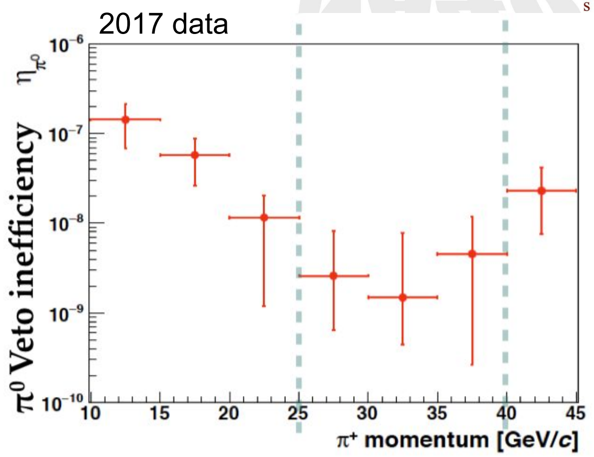
The main background is $K+ \rightarrow \pi+\pi 0$, $\pi 0$->γγ with undetected photons

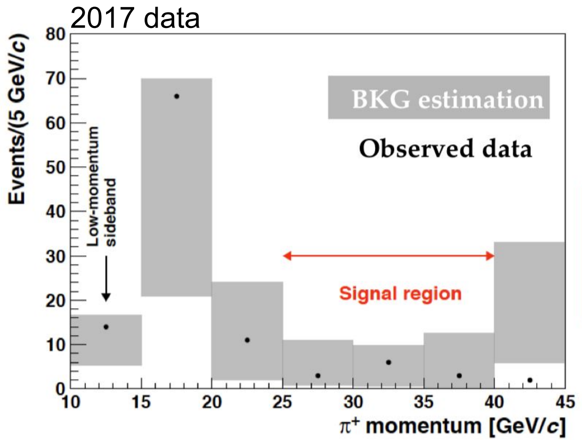
Counting experiment in the region: 25 < $p_{\pi+}$ < 40 GeV/c

and square missing mass in [0.015,0.021] GeV^2/c

$$\mathrm{BR}(\pi^0 \to \text{invisible}) \leq 4.4 \times 10^{-9} \quad \text{at } 90\% \text{ C.L.}$$

improvement of a factor 60 with respect to the previous experiments





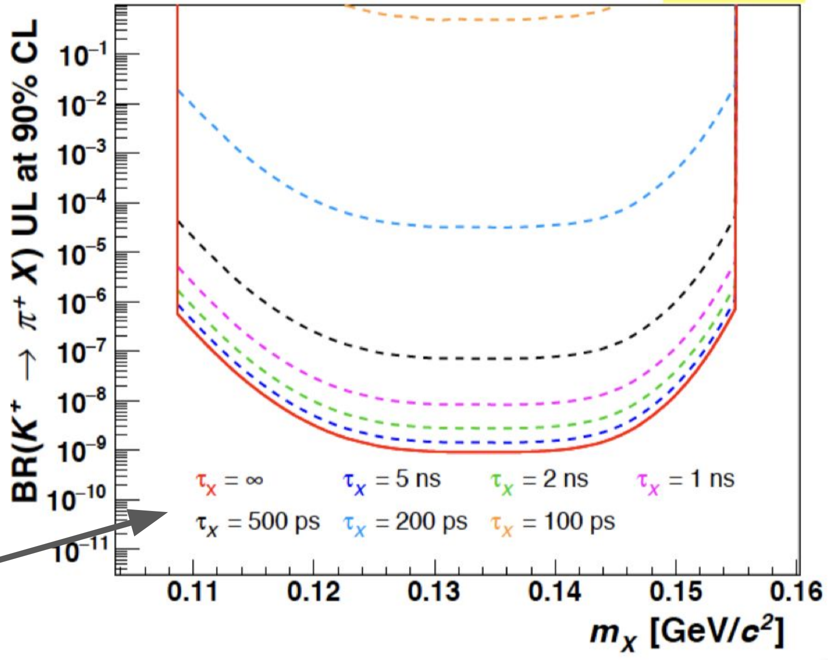
$K^+ \rightarrow \pi^+ X$, mX ~m$_{\pi 0}$

Model independent analysis for the upper limit of BR(K->π^+X)

$$BR(K^+ \rightarrow \pi^+ X) = \frac{N_s}{N_{K^+} \times R(m_X) \times \varepsilon_{sel} \times \varepsilon_{trig}}$$

Acceptance of the cut on m^2_{miss} depends on the mass hypothesis

2017 data



If X decays to visible particles inside the apparatus, the acceptance is reduced and the upper limit is weaker

$K+ \to \pi^+$ a , the ALP hypothesis

Phys.Lett.B 816 (2021) 136259

2101.12304 [hep-ex]

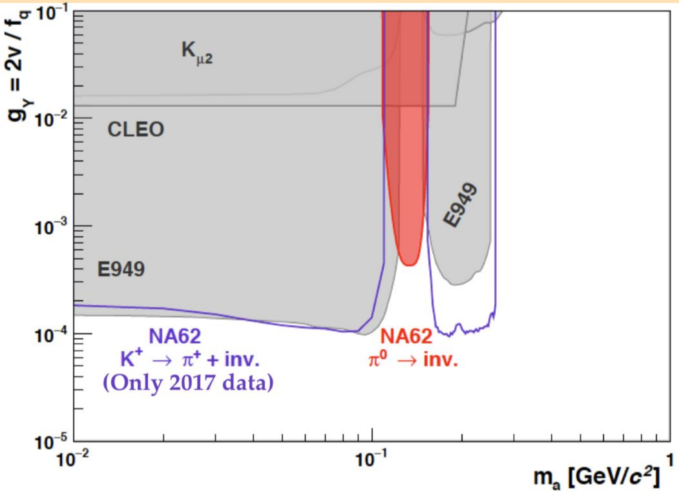
Pseudoscalar axion-like particle

$$\mathcal{L}_{\text{SM}} = \frac{\partial_\mu a}{f_\ell} \sum_\alpha \bar{\ell}_\alpha \gamma_\mu \gamma_5 \ell_\alpha + \frac{\partial_\mu a}{f_q} \sum_\beta \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta$$

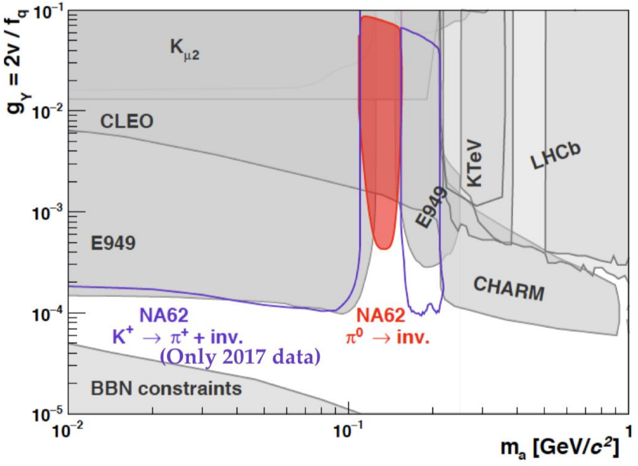
[J. Beacham et al., J. Phys. G 47 (2020) 010501] $f_q = f_\ell$

M. J. Dolan et al., JHEP 03 (2015) 171
Used for BR and lifetime computation

If a decays to invisible particles,or it is so long-lived to escape the apparatus



If a decays to visible SM particles the acceptance is reduced because the decay products (e or μ) are vetoed



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

A possible explanation of the **anomalous muon magnetic momentum g-2** is the existence of a new light gauge boson

S.N. Gninenko and N.V. Krasnikov, *Phys.Lett.B* 513 (2001) 119, https://arxiv.org/pdf/hep-ph/0102222.pdf

In a scenario with dark matter freeze out, it could be a scalar or vector mediator of an hidden sector decaying to Dark Matter $X \to \chi\chi$

$K^+ \to \mu^+ \nu X$, with $X \to$ invisible, $\gamma\gamma$, $\mu^+\mu^-$

Work in progress

Same final state as
$K^+ \to \mu^+ N$, N: Heavy Neutral Lepton
One μ^+ and missing mass

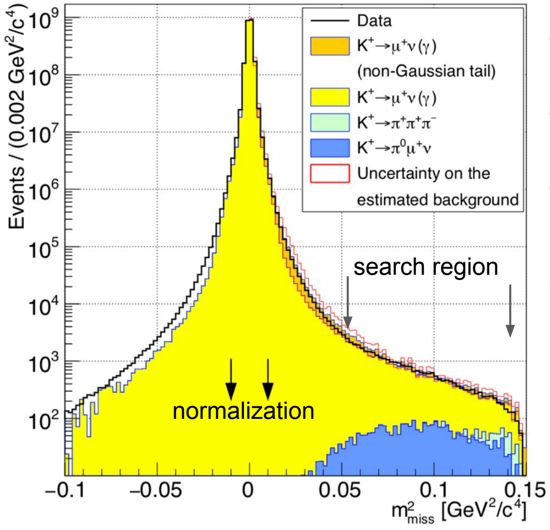
Phys.Lett.B **816 (2021) 136259**

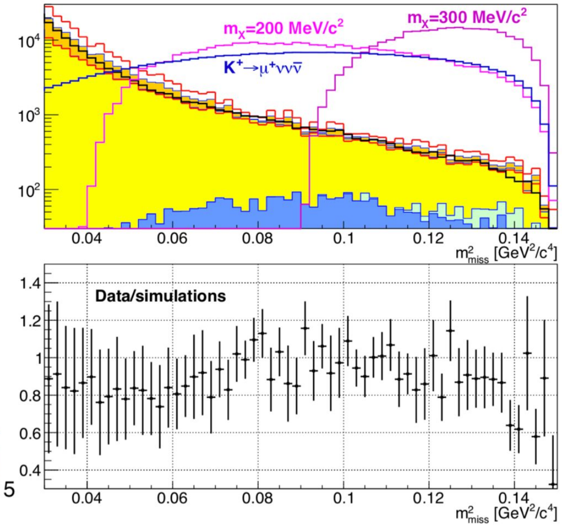
2101.12304 [hep-ex]

$K^+ \rightarrow \mu^+ \nu X$, X→invisible

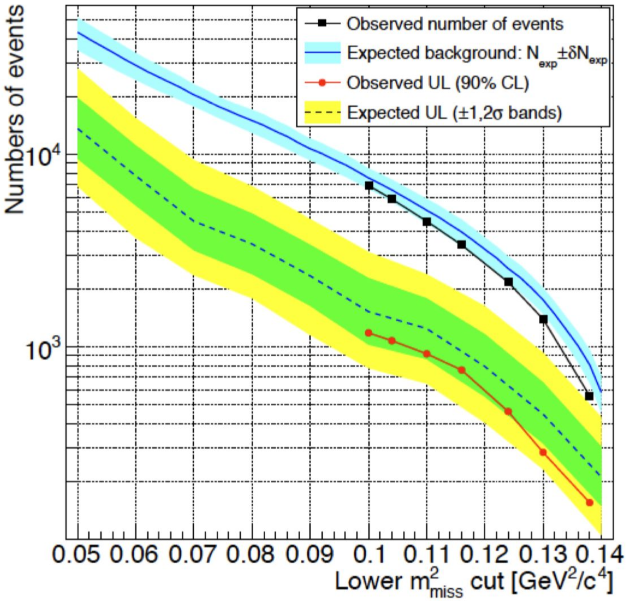
3 body decay → looking for modifications of the $m^2_{miss} = (p_K - p_\mu)^2$

2016 - 2018 data





2016 - 2018 data



Counting experiment with lower cut on m2miss optimized independently for each mass hypothesis, requiring the strongest upper limit

$K^+ \to \mu^+ \nu X$, X→invisible

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

Tested mass hypotheses from 10 to 370 MeV

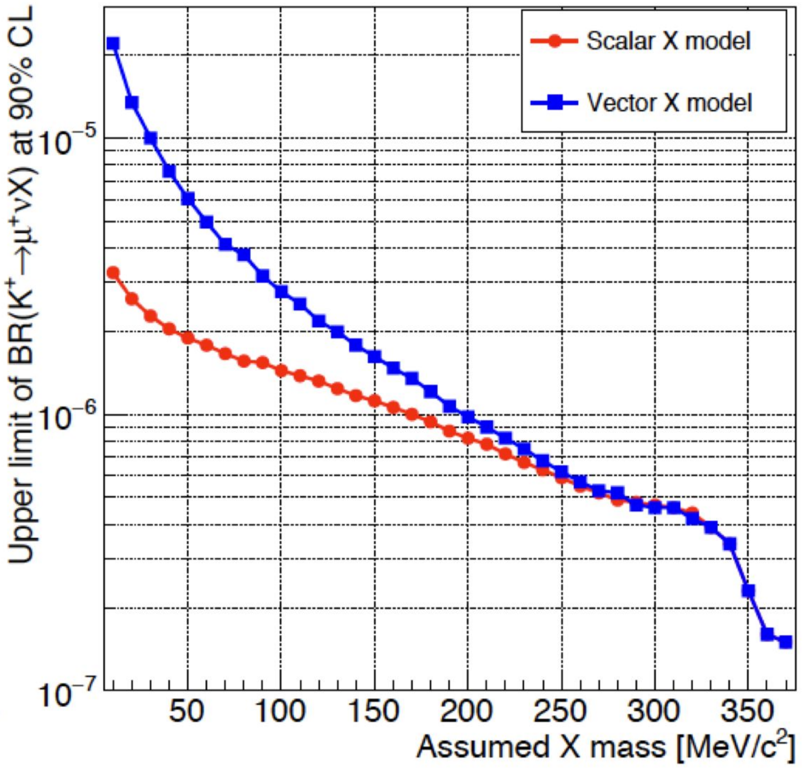
In the model with **scalar mediator**, the mean value of the m2miss is larger compared to the **vector mediator**

This results in a stronger upper limit for the scalar X model

New upper limit for the ultra-rare decay:

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

2016 - 2018 data



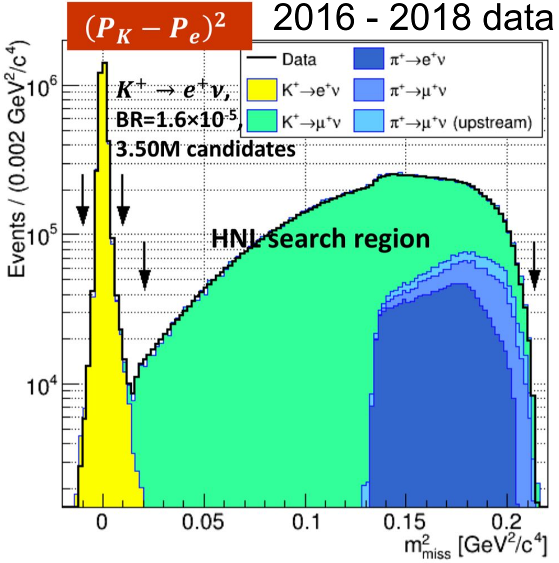
Heavy Neutral Leptons

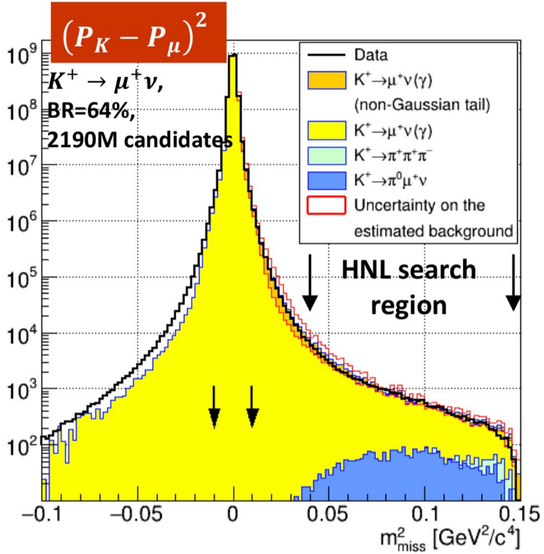
K+ → lN, with l= e or μ: two body decays looking for bumps

$$\mathrm{BR}(P^+ \rightarrow lN) = \mathrm{BR}(P^+ \rightarrow l\nu) \times \rho_l(m_N) \times |U_{l4}|^2$$

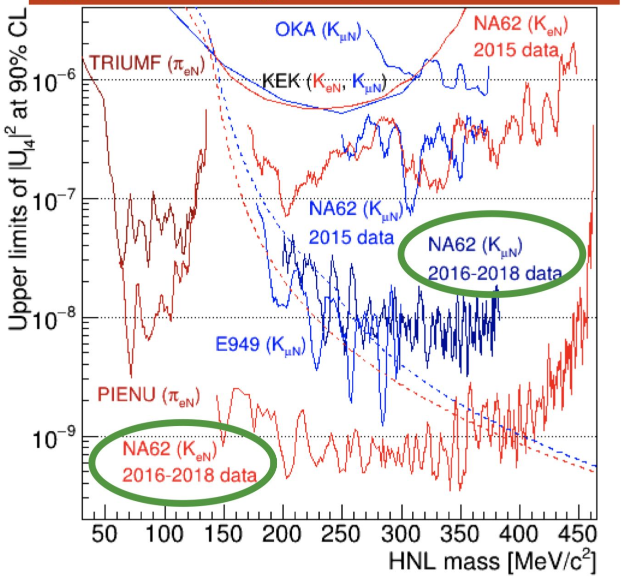
- HNL production is enhanced kinematically wrt SM decays
- Helicity suppression relaxed in the $K \rightarrow eN$ case: factor $O(10^5)$ enhancement

2016 - 2018 data





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



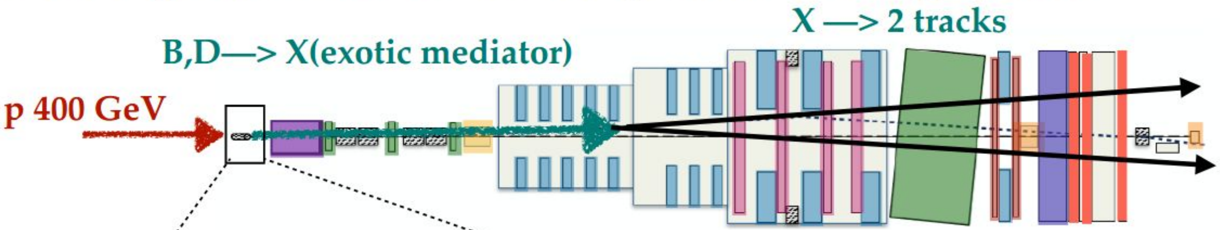
Conclusions

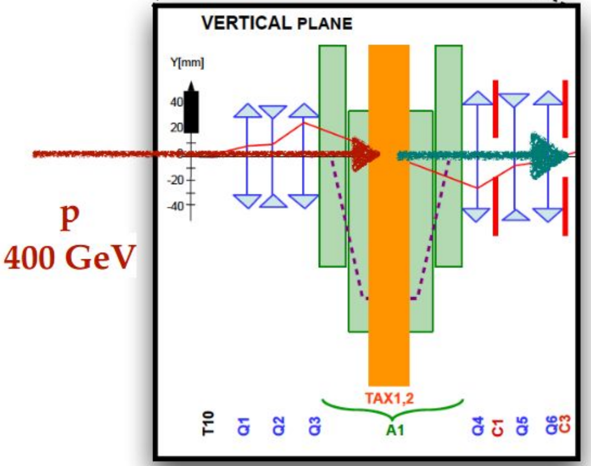
- NA62 is a detector built to measure the very rare decay K+->π+vv.
    - Nevertheless its characteristics and the beam intensity are such that stronger limits on feebly interacting particles are possible;
- New Limits on:
    - K+$\rightarrow\pi$+X, X$\rightarrow$ invisible, in almost the full the mass range ~[0, 250] MeV
    - K+ $\rightarrow$ π+π0 (or X with mX ~ mπ0), X/π0 $\rightarrow$ invisible
    - K+ $\rightarrow$ μ+vX , X$\rightarrow$invisible in the mass range [10, 370] MeV
    - Heavy Neutral Leptons: new limits in electron and muon flavors
- Ongoing analyses to finalize other searches with 2016-2018 dataset
- NA62 is ready for the new data taking (Kaon beam and beam dump), starting soon (July 2021)

NA62 in Dump Mode

Beam dump mode

B and D instantaneously decay to exotic mediators and SM particles which are stopped/deviated





Also $\gamma\gamma$ signature to search for ALPs from Primakoff

slide from Roberta Volpe