Search for kaon decays with a pion and invisible particles at the NA62 experiment at CERN

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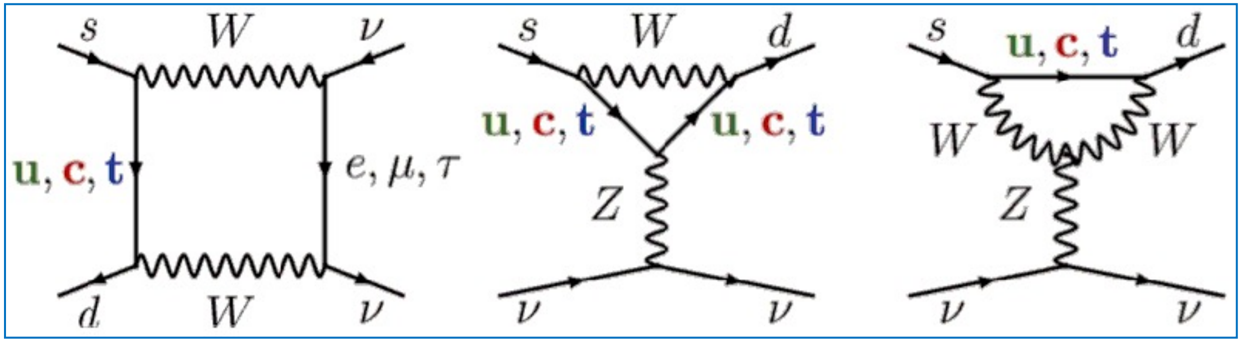
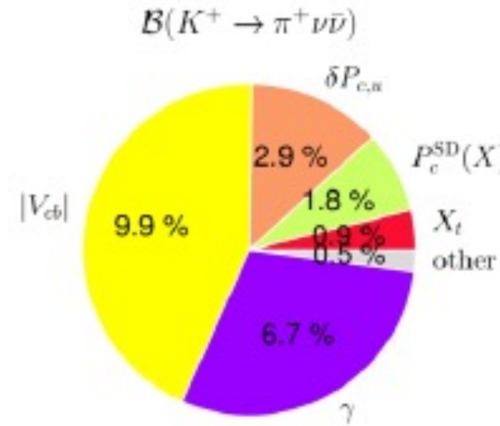
NA62 Spokesperson

The main physics goal

SM: box and penguin diagrams





Theoretical error budget
Buras. et. al., JHEP11(2015)033

Ultra-rare decays with
the highest CKM suppression:

$$A \sim (m_t/m_W)^2 |V^*_{ts} V_{td}| \sim \lambda^5$$

Hadronic matrix element related
to a measured quantity $(K^+ \rightarrow \pi^0 e^+ \nu)$.

Exceptional SM precision.
Free from hadronic uncertainties.

SM branching ratios
Buras et al., JHEP 1511 (2015) 033

Mode	$BR_{SM} \times 10^{11}$
$K^+ \rightarrow \pi^+ \nu\nu(\gamma)$	8.4±1.0
$K_L \rightarrow \pi^0 \nu\nu$	3.00±0.31

Theoretically clean, almost unexplored.
Sensitive to new physics, and to high-mass scale O(100) TeV

The unitary triangle

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

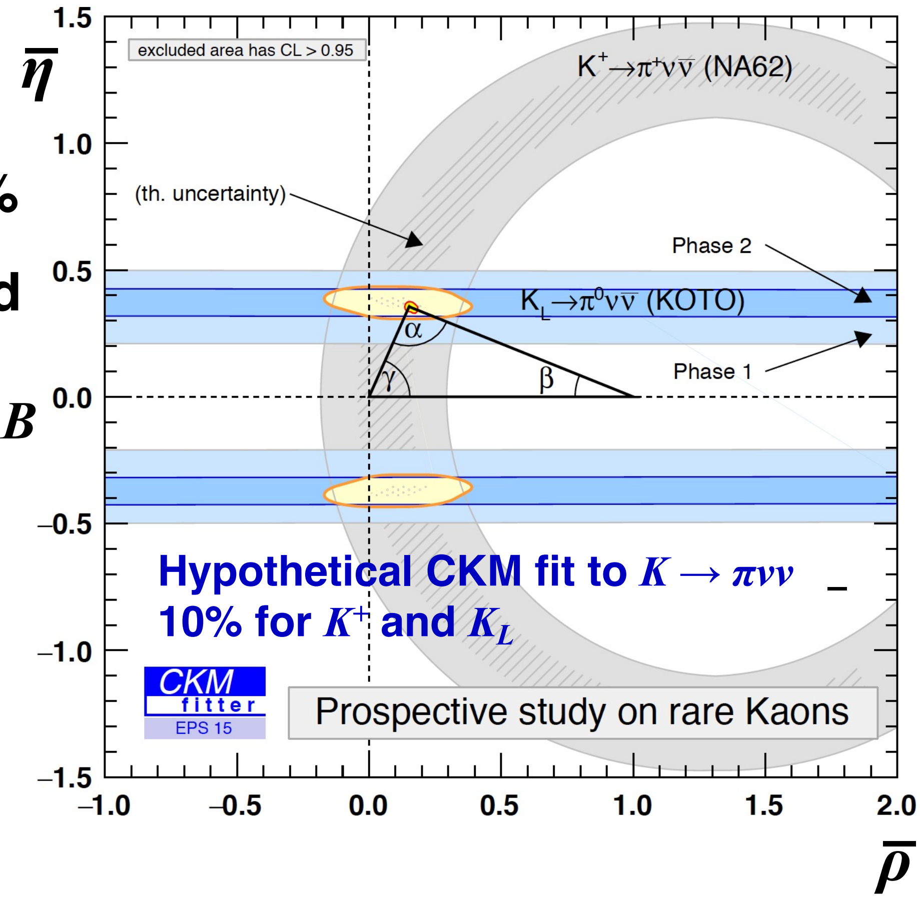
Buras et al., JHEP 1511

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

Dominant uncertainties for SM BRs are from CKM matrix elements

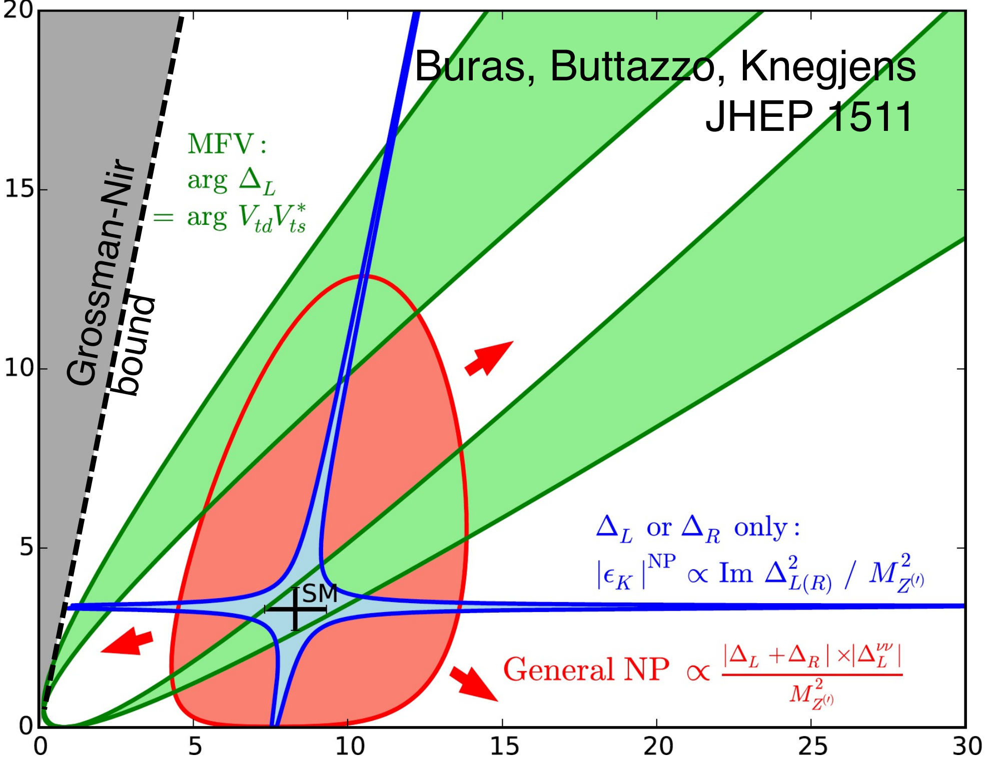
Intrinsic theory uncertainties 1.5-3.5%

Measuring BRs for both $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$ can determine the CKM unitarity triangle independently from B inputs:



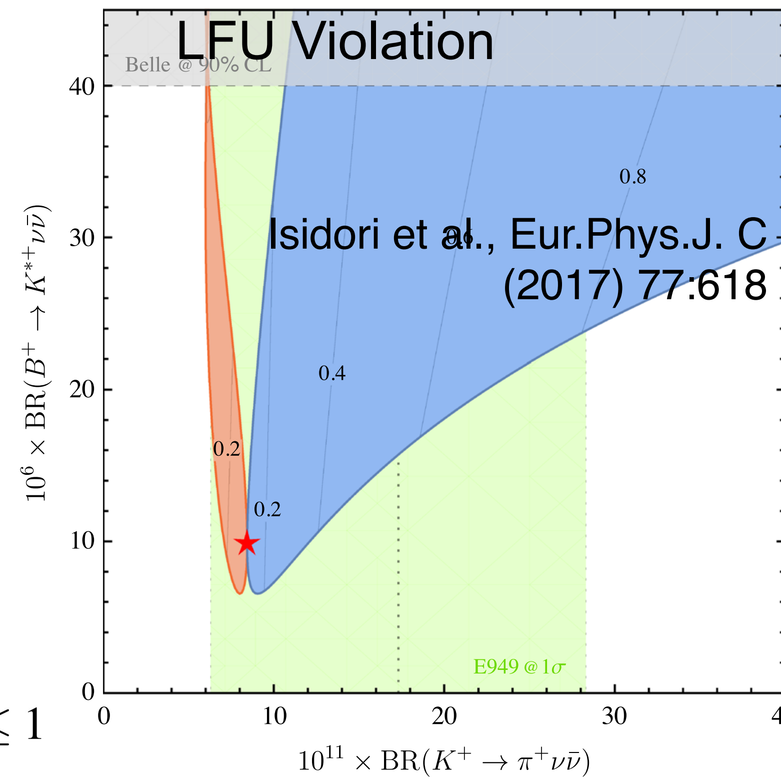
Sensitivity to O(100) TeV scale

$K^+ \to \pi^+ \nu\nu$ and new physics



High sensitivity to NP (non-MFV): significant variations wrt SM

New physics affects K^+ and K_L BRs differently



Models with CKM-like flavor structure

- Models with MFV

Models with new flavor-violating interactions in which either

LH or RH couplings dominate

- *Z*/*Z′* models with pure LH/RH couplings
- Littlest Higgs with *T* parity

Models without above constraints

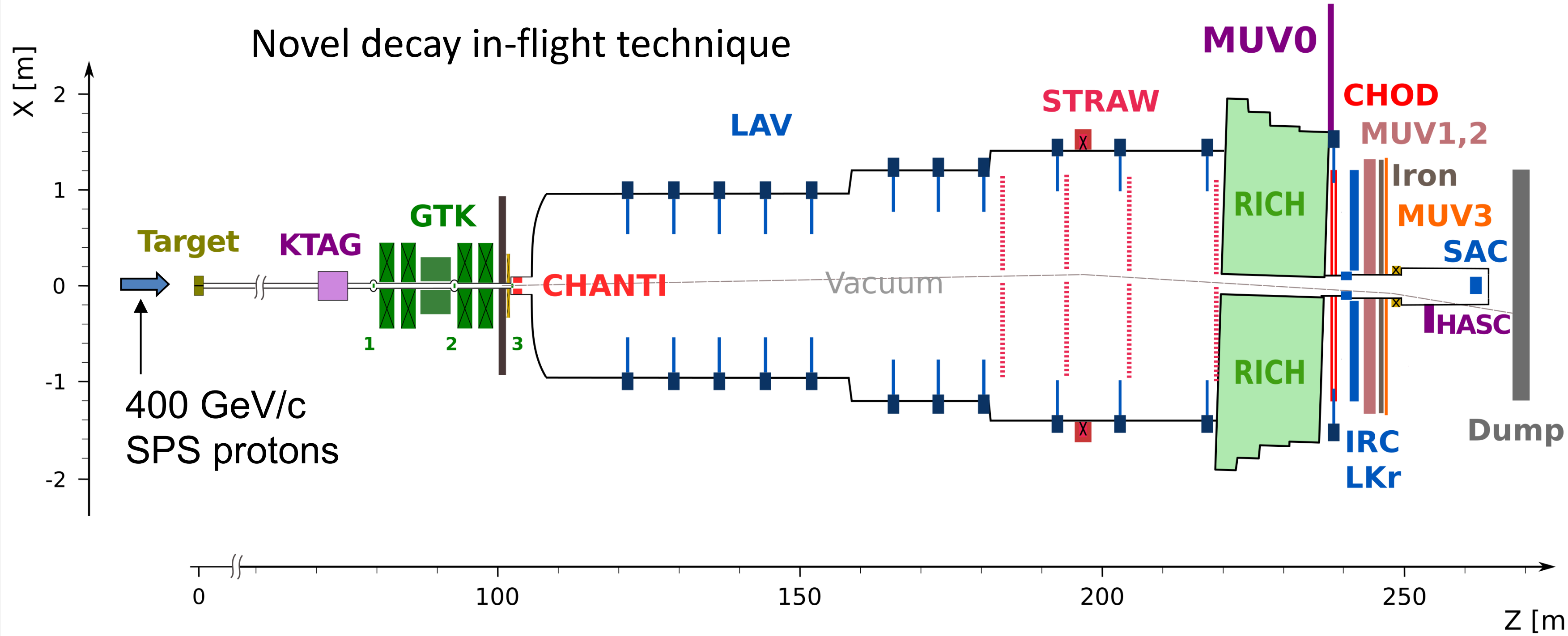
- Randall-Sundrum

Grossman-Nir bound

Model-independent relation

$$\frac{\text{BR}(K_L \to \pi^0 \nu\bar{\nu})}{\text{BR}(K^+ \to \pi^+ \nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \leq 1$$

NA62 beam and detector



SPS Beam:

400 GeV/c protons

2.10^{12} protons/spill

5s spill [3s eff.] / ~16 s

Decay Region:

60 m long fiducial region

~ 5 MHz K^{+} decay rate

Vacuum ~ O(10^{-6}) mbar

Secondary positive Beam:

75 GeV/c momentum, 1 % bite

100 μrad divergence (RMS)

60x30 mm^{2} transverse size

K^{+}(6%)/π^{+}(70%)/p(24%)

For 33x10^{11} ppp on T10

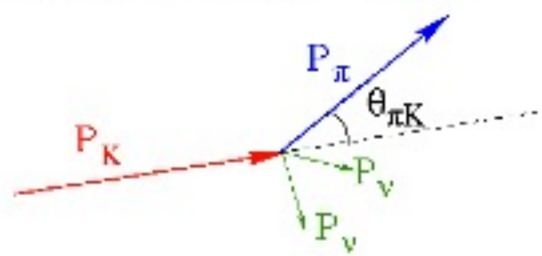
→ 750 MHz at GTK3

Detector and Performances:
JINST 12 (2017) P05025

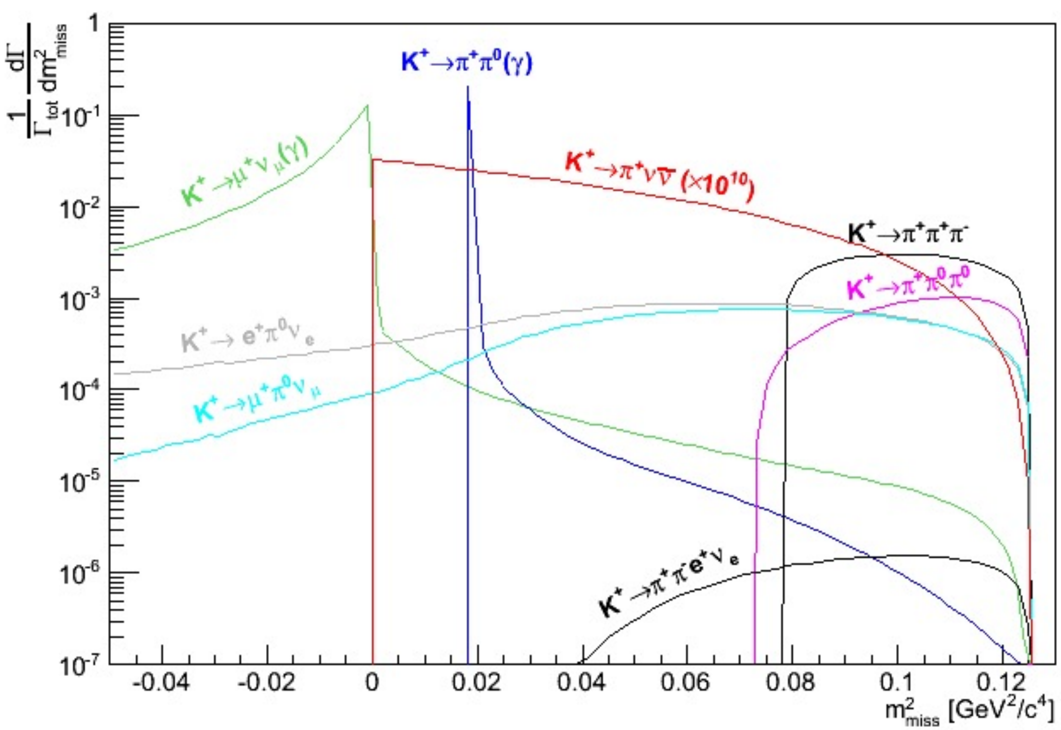
Data taking periods so far

Decay in flight technique @NA62

$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$

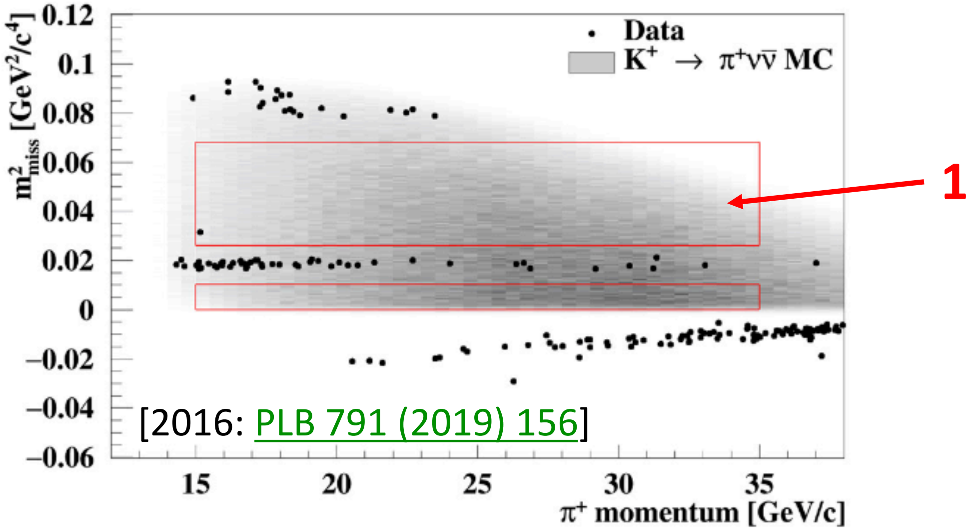


$15 < P(\pi^+) < P_{max}$ GeV/c
to ensure several tens of GeV of missing energy
+ Particle ID (calorimeters + Cherenkov + muonID)
Photon veto



Background rejection:
- O(100 ps) timing between sub-detectors
- O(10^4) background suppression from kinematic conditions
- $>10^7$ muon suppression
- $>10^7$ π^0 suppression (from $K^+ \rightarrow \pi^+\pi^0$)

2016 + 2017 data



2016 + 2017 data

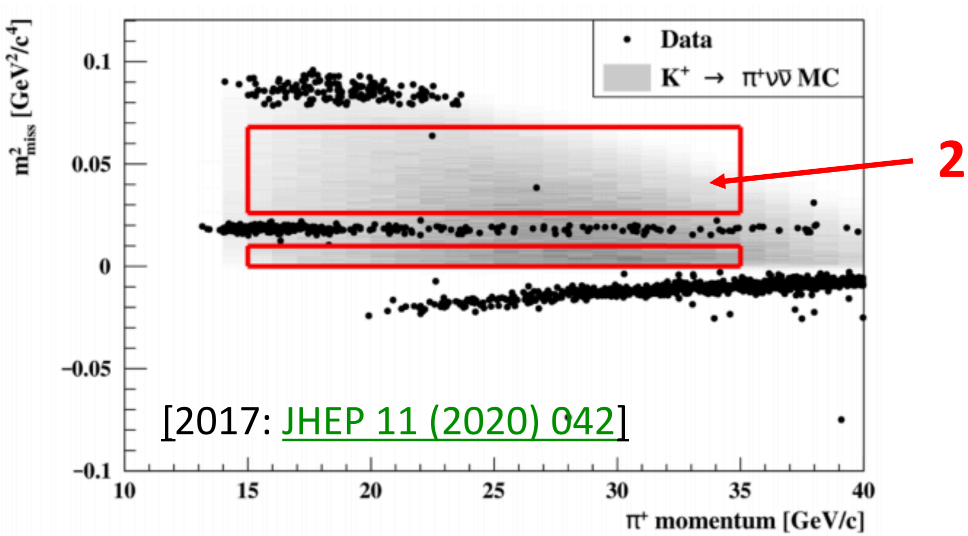
BR($K^+ \to \pi^+ \nu\nu$)

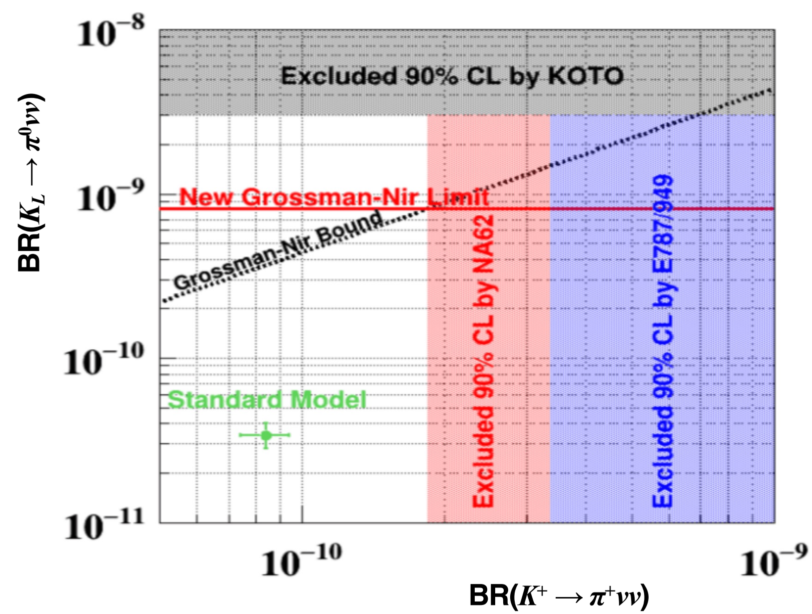
$< 1.78 \times 10^{-10}$ (90%CL)

$= 0.48^{+0.72}_{-0.48} \times 10^{-10}$ (68% CL)

Grossman-Nir limit on BR($K_L \to \pi^0 \nu\nu$):

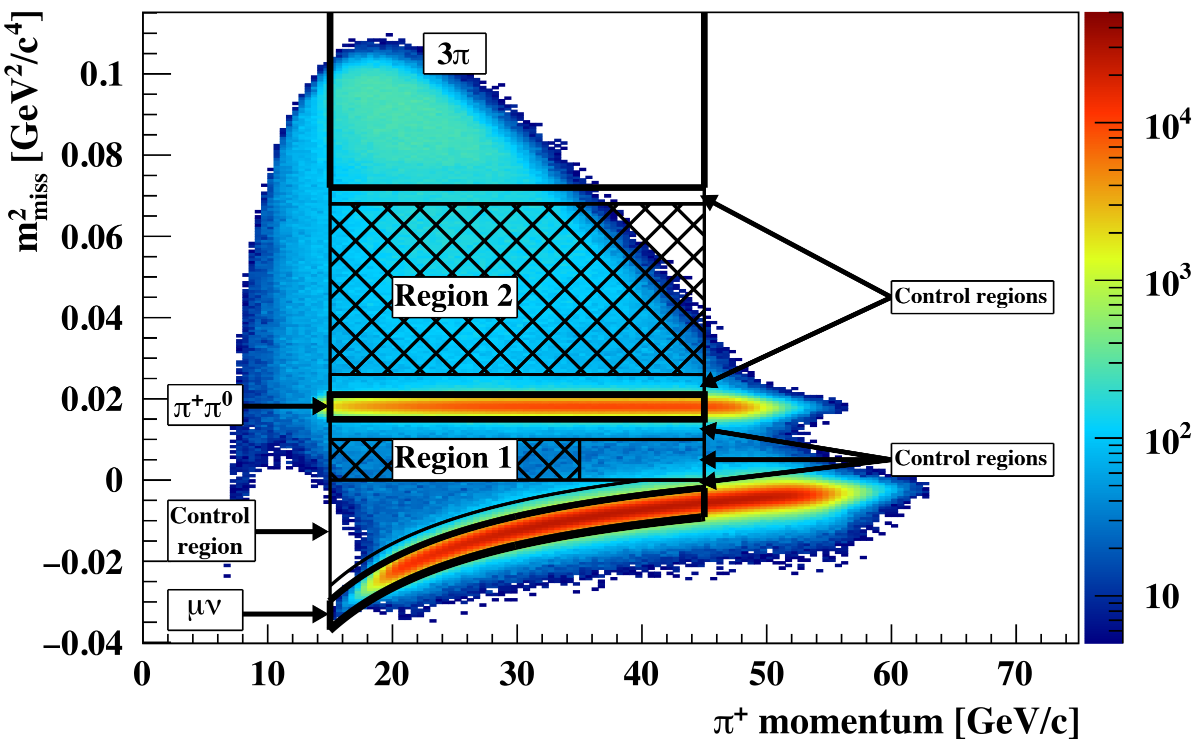
$< 7.8 \times 10^{-10}$ (90%CL)





Signal selection

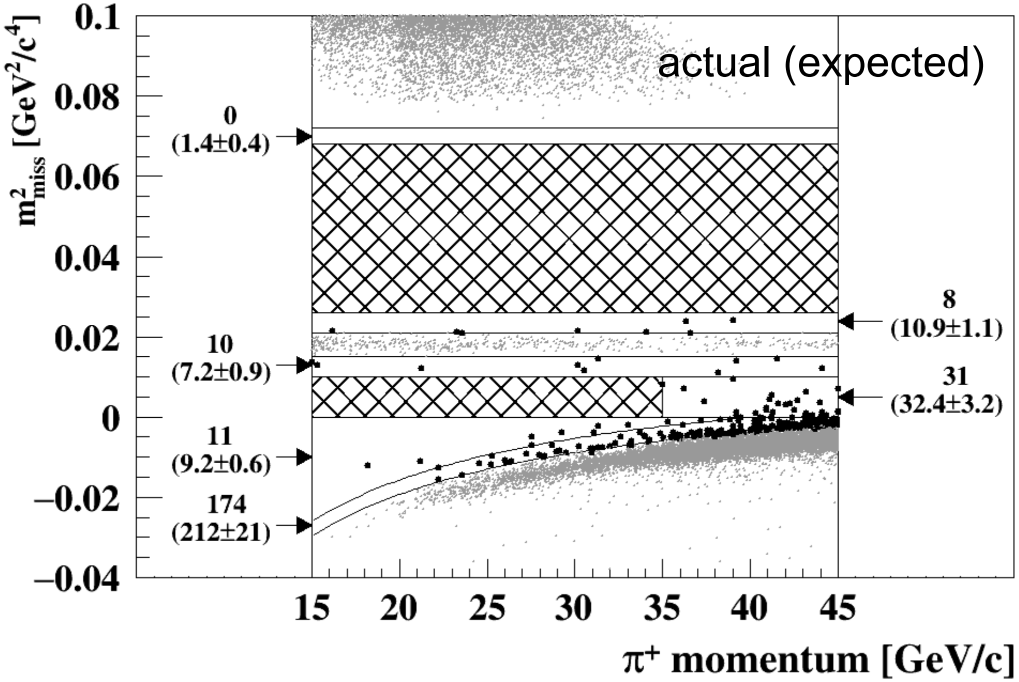
2018 data divided into two subsets, S1 (before, 20%) and S2 (after, 80%) installation of the new final collimator.
S2 is divided into six categories corresponding to 5 GeV/c bins of pion momentum in 15–45 GeV/c range.
S1 is a separate category integrated over pion momentum.
Dedicated selection applied to each category improves signal sensitivity



Control regions are used to validate the background estimates

Improvements led to sizable increase in signal acceptance, while keeping same level of S/B ratio

Background evaluation

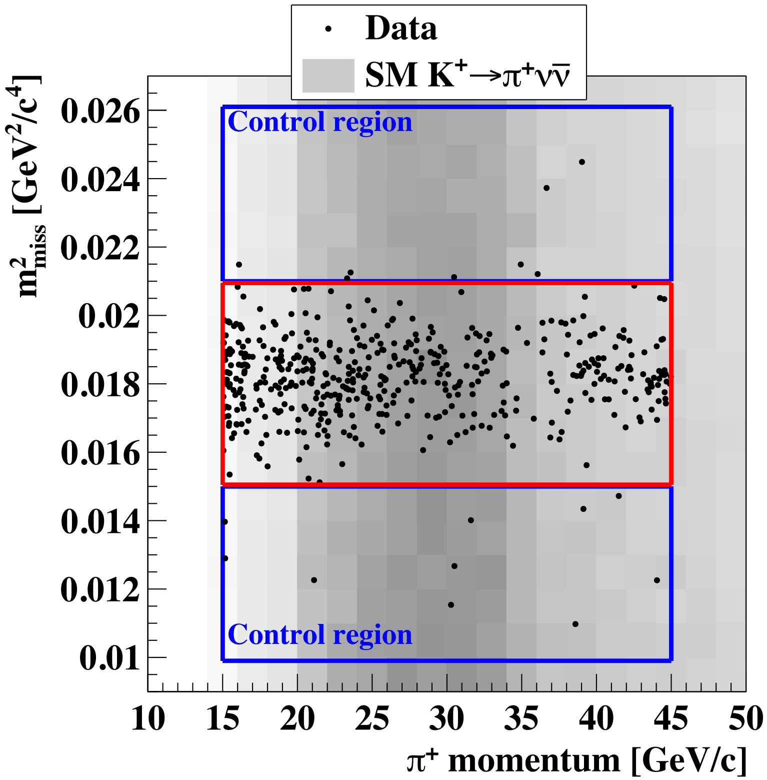


Background expected in Signal Regions S1 and S2:

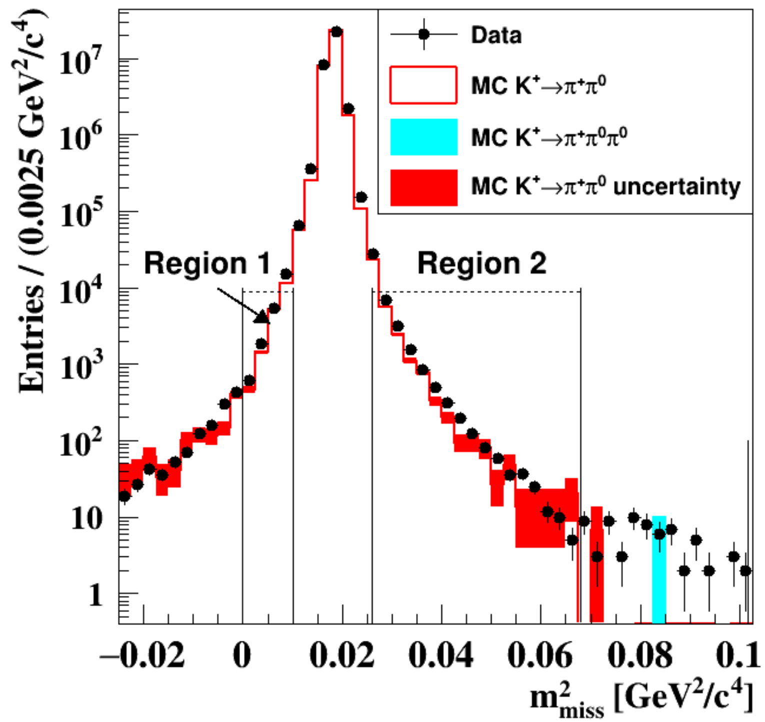
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

Background from Kaon decays and upstream events evaluated using data and control samples
Good agreement in control regions between expected and observed background events

Background evaluation, e.g $\pi^+\pi^0$



Control data used to study tails of distribution



$$N_{\rm decay}^{\rm exp} = N_{\rm bkg} \cdot f_{\rm kin}(\rm region)$$

Data driven background evaluation for all kaon decays (except $\pi\,\pi\,e\,\nu$)

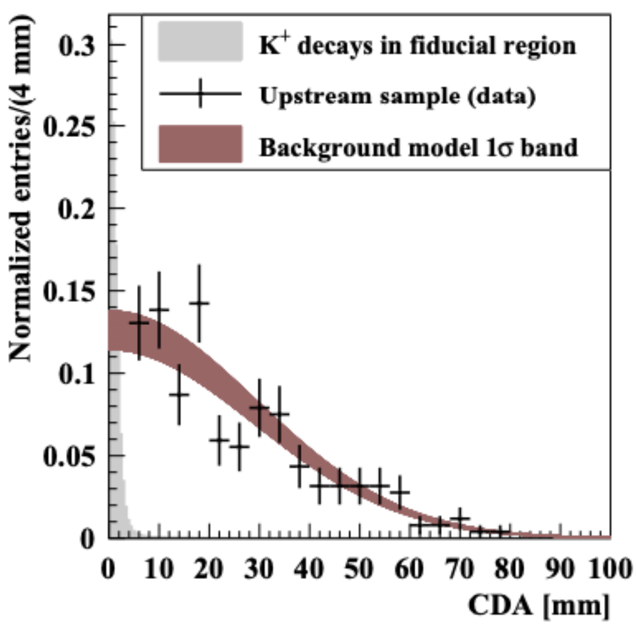
Upstream events rejection

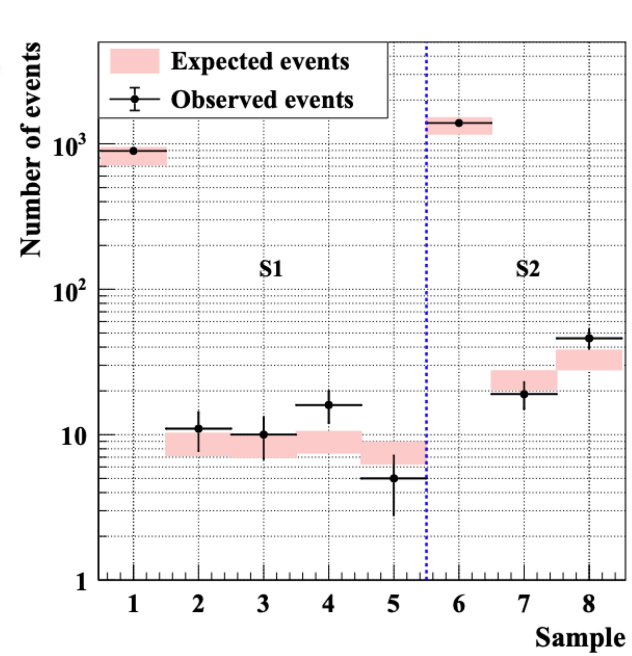
Early decays in upstream region, interaction with material plus beam pileup and scattering in STRAW1

BDT use possible only after installation of new collimator in 2018
K-pion matching conditions + geometrical variables
Signal training sample: MC simulation
Background training sample: out-of-time data

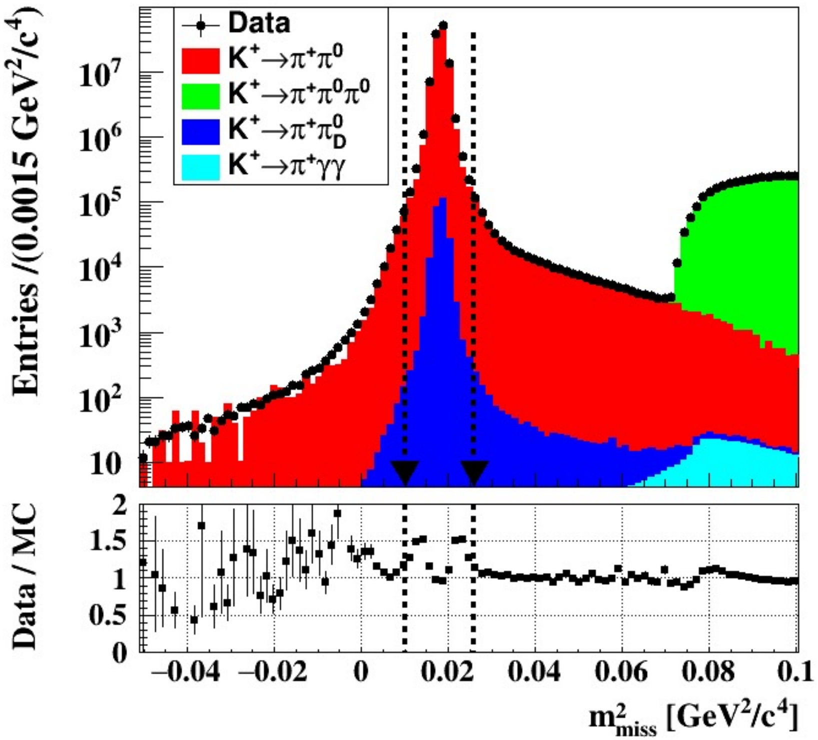
Increase signal acceptance keeping same B/S

Data driven procedure: control sample without time and K-pi matching requirements
Validated using inverted data samples enriched with upstream events





Normalization and Single Event Sensitivity



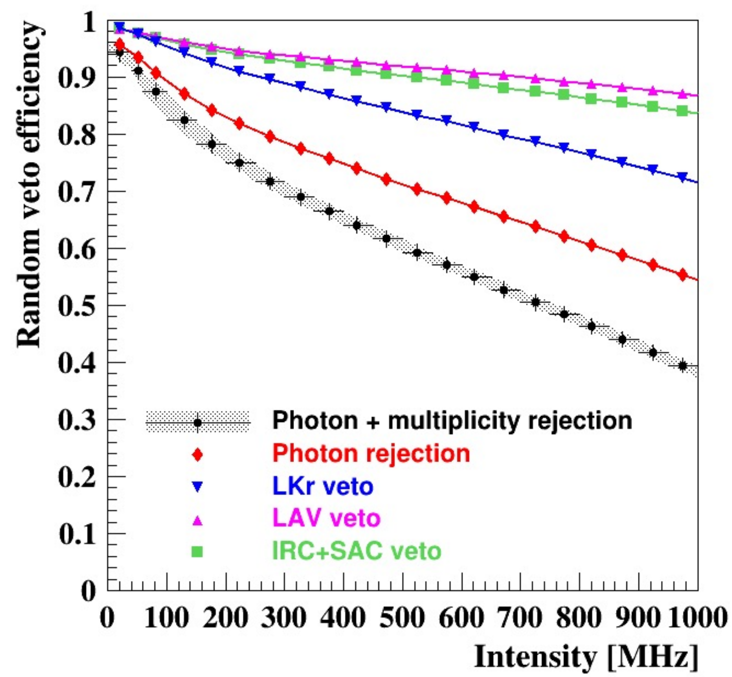
SES error budget:

Source	Relative uncertainty
trigger efficiency	5%
MC acceptance	3.5%
random veto efficiency	2%
normalization background	0.7%
instantaneous intensity	0.7%
Total	6.5%

$$N^{exp}_{\pi\nu\nu} \approx N_{\pi\pi} \cdot \epsilon_{trigger} \cdot \epsilon_{RV} \cdot \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \cdot \frac{Br(\pi\nu\nu)}{Br(\pi\pi)}$$

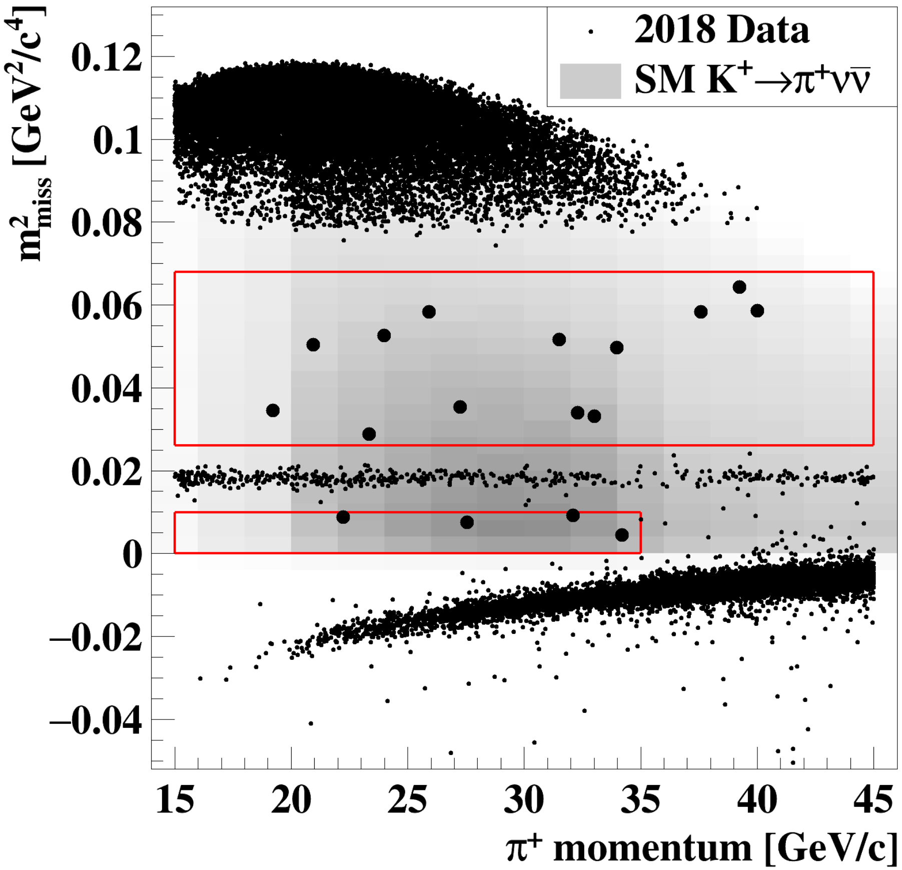
$A_{\pi\nu\nu}($ S1 $) \simeq 4.0\%$, $A_{\pi\nu\nu}($ S2 $) \simeq 6.4\%$

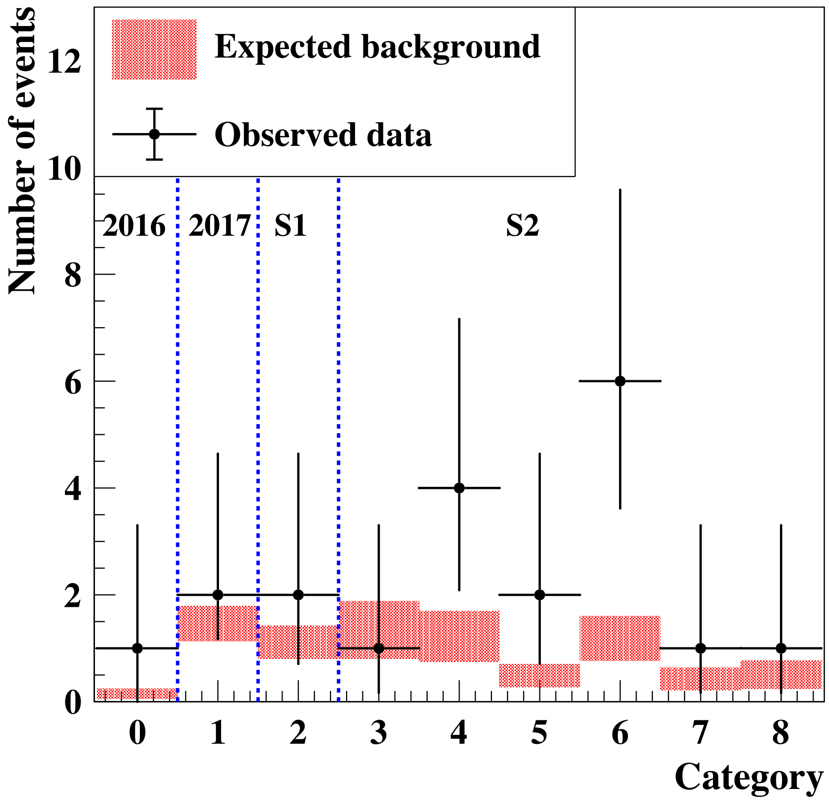
$$\text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}} = (1.11 \pm 0.07_{syst.}) \times 10^{-11}$$



Result: 2016+2017+2018 data

[JHEP 06 (2021) 093
arXiv:2103.15389]





$$SES = (0.839 \pm 0.053_{syst}) \times 10^{-11}$$

$$N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$$

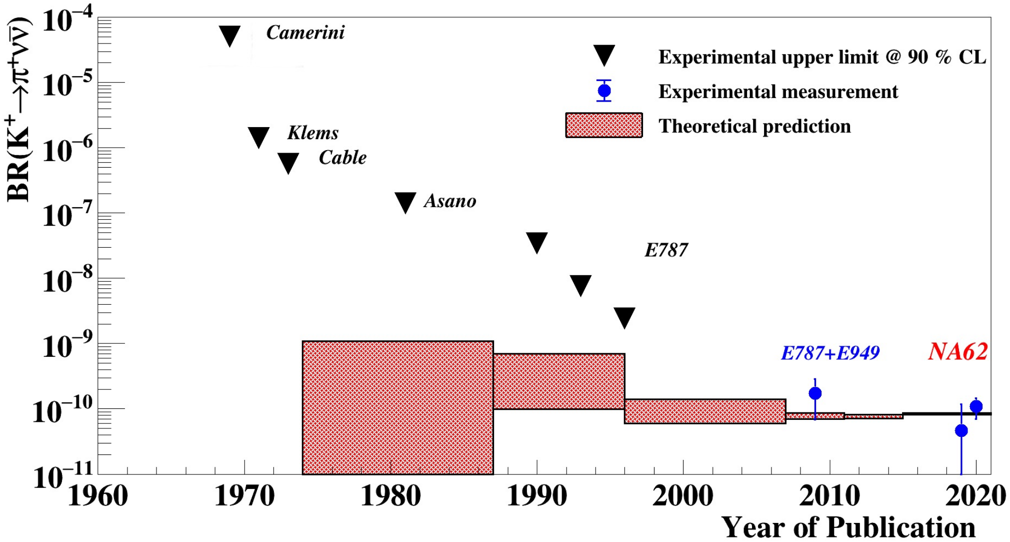
$$N^{exp}_{background} = 7.03^{+1.05}_{-0.82}$$

$$N_{obs} = 20$$

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

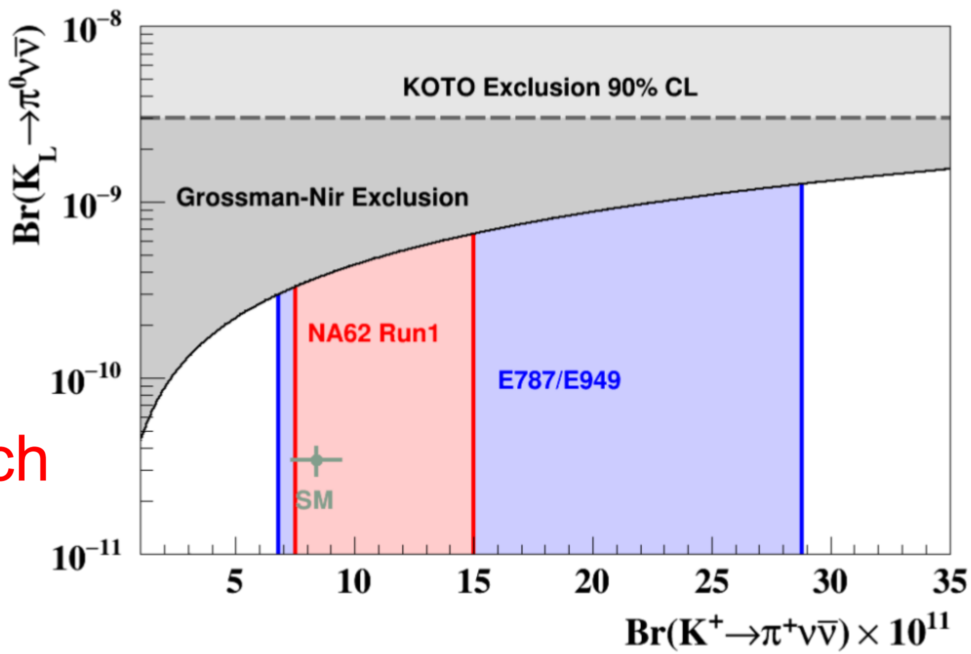
3.4σ significance

Implications of $K^+ \rightarrow \pi^+ \nu\nu$



Most precise determination of the decay rate to date

Provides strongest evidence so far (3.4 σ) for its existence



Part of parameter space already ruled out

Next target: at least x3 improved precision to match theoretical uncertainty by LS3

NA62 through LS3

Plans for NA62 Run 2 (from LS2 to LS3):
Approved by CERN Research Board

NA62 has resumed data taking in July 2021

Key modifications to reduce background from upstream decays and interactions:

- Rearrangement of beamline elements
- Add 4th station to GTK beam tracker
- New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe

Run at ~nominal beam intensity

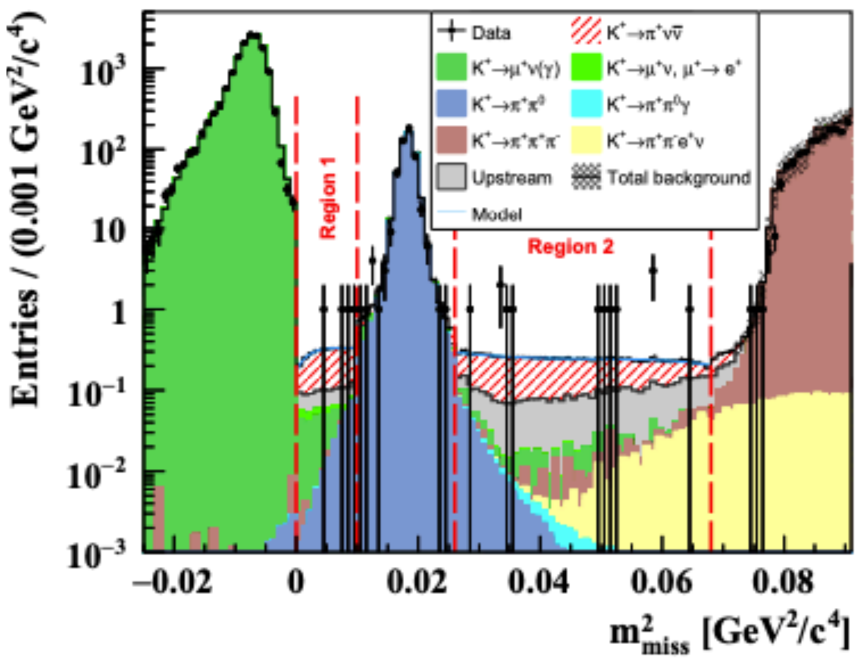
Expect to measure BR($K^+ \rightarrow \pi^+ \nu\nu$) to O(10%) by LS3

Search for $K^+ \to \pi^+ X$

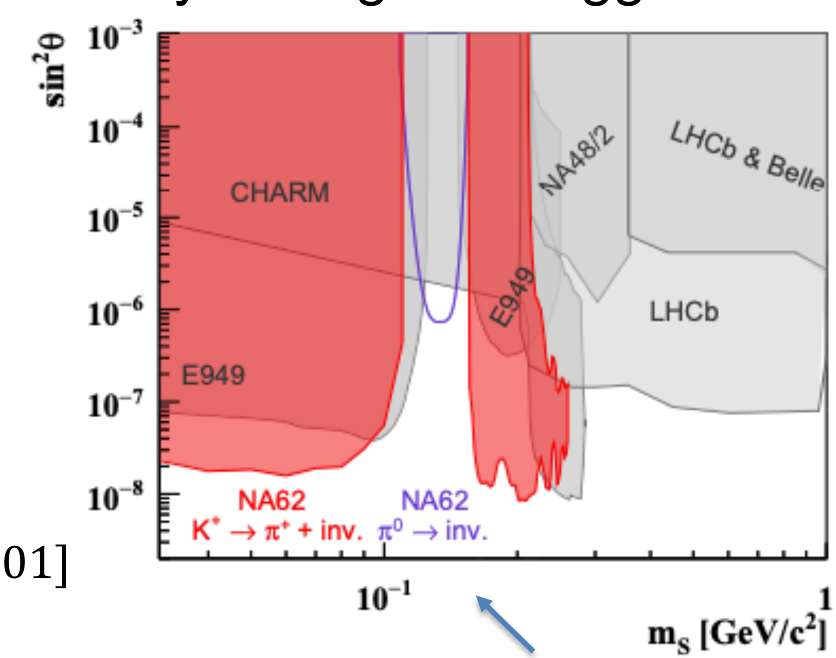
[JHEP 06 (2021) 093
arXiv:2103.15389]

Perform peak search considering **$K^+ \to \pi^+ \nu\nu$ as SM background**
Improvement on previous limit by factor ~4

Search for X scalar or pseudo-scalar



Dark Scalar, production and decay driven by mixing with Higgs boson

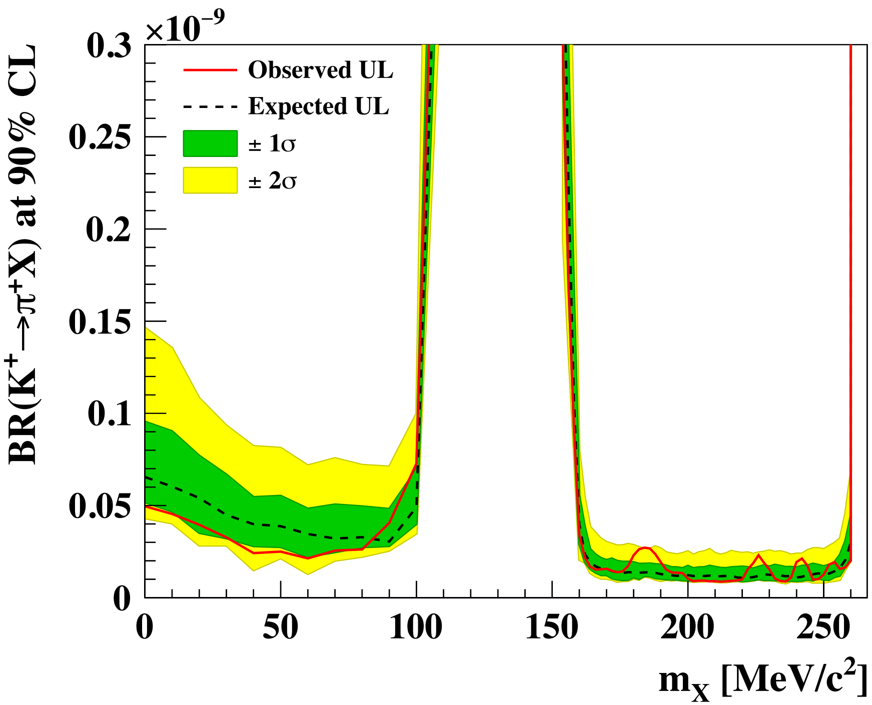


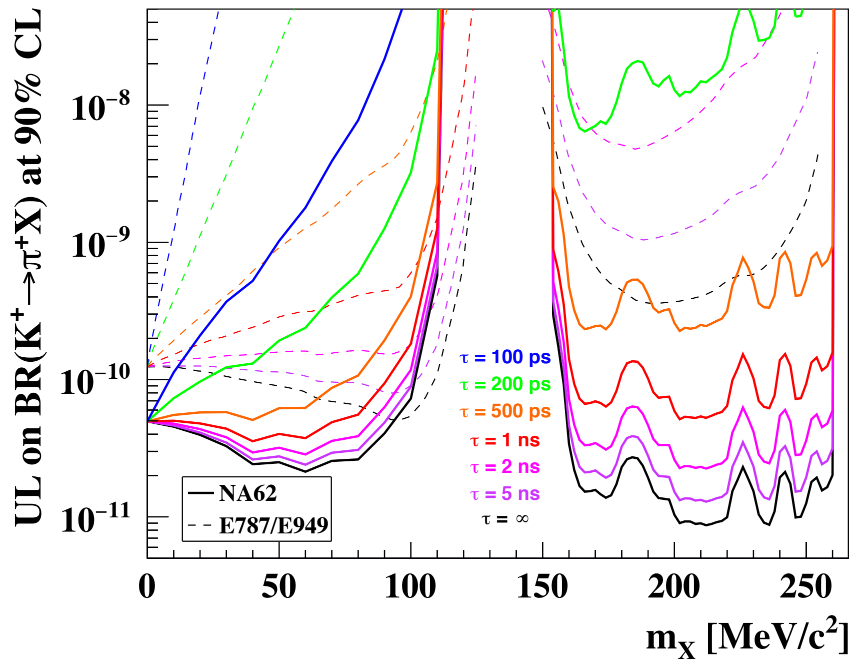
Also published: π^0 to invisibles [JHEP 02 (2021) 201] and π^+X 2017 data [JHEP 03 (2021) 058]

Assuming X decays only to visible SM particles, with lifetime inversely proportional to the mixing parameter

Search for $K^+ \to \pi^+ X$

Perform peak search considering $K^+ \to \pi^+ \nu\nu$ as SM background





Stable or invisibly decaying

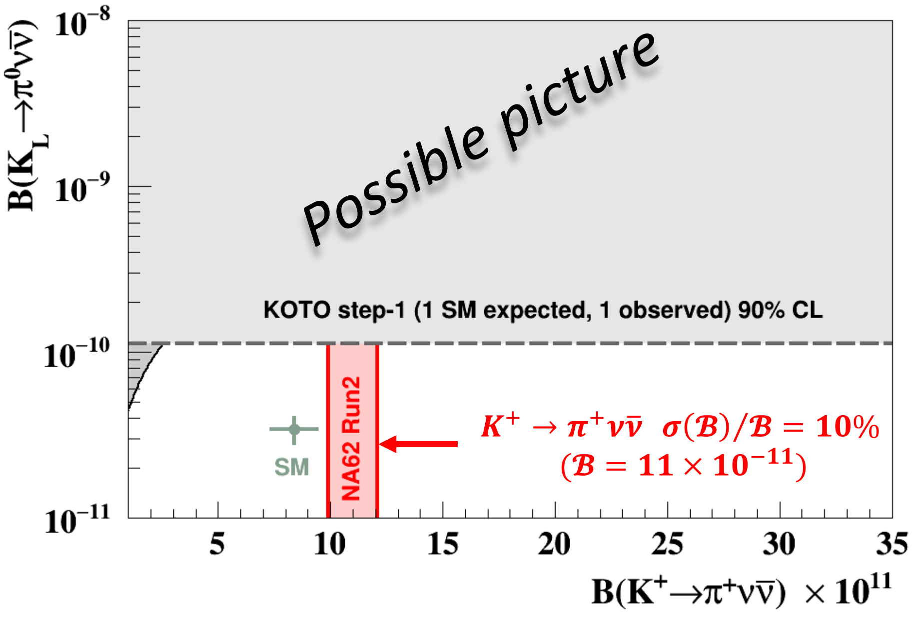
Decaying to visible SM particle

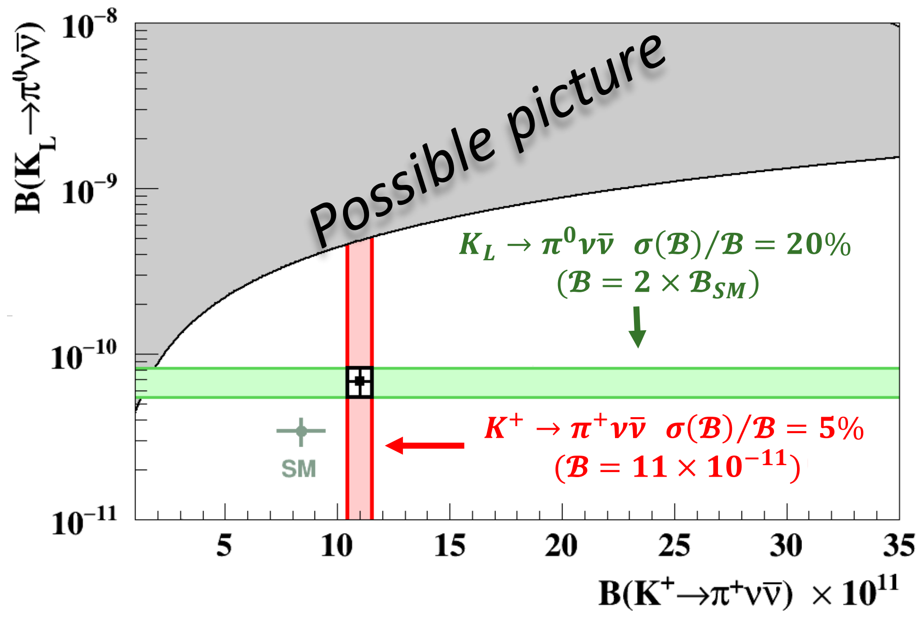
Improvement on previous limit by factor ~4

Sensitivity to X with shorter lifetimes substantially improved by extension of FV in S2 sample

Clear opportunity in the Kaon sector

Going beyond 10% measurement on $K^+ \to \pi^+ \nu\nu$
Precision measurements of $K \to \pi\nu\nu$ BRs can provide model-independent tests for new physics at mass scales of up to O(100 TeV)





Approach theory error, possibility to find clear evidence of deviation from SM

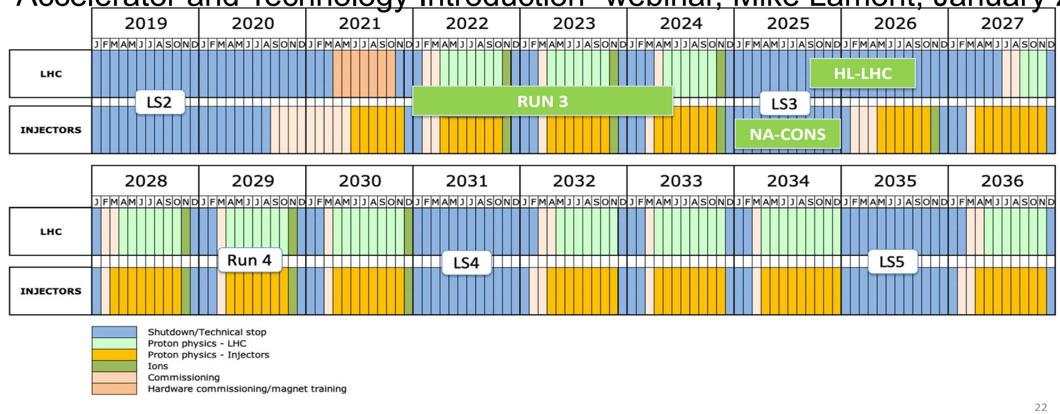
Integrated high-intensity Kaon programme at the SPS

EU Strategy deliberation document: **CERN-ESU-014**
“rare kaon decays at CERN” mentioned in Sec4
“Other essential activities for particle physics”

Long-term Physics Programme in NA-ECN3 to extend to FCC-ee

- $K^+ \to \pi^+ \nu\nu$
  $\sim 7 \times 10^{18}$ pot/year
  4x increase
- $K_L \to \pi^0 \nu\nu$
  1×10^{19} pot/year
  6x increase

“Accelerator and Technology Introduction” webinar, Mike Lamont, January 2021



Integrated programme with multiple phases, synergies with LHC
K^+ and K_L beams for precision measurement of $K \to \pi\nu\nu$
Study of other rare kaon decays, including K_L beam with tracking detector
Data taking in dump mode to reach 10^{19} POT to search for FIPs

Advantage of integrated approach: common upgrades for intensity and detectors between projects, more flexibility on schedule.

Summary

Kaon Physics is a portal to explore physics beyond the SM.

$K^+ \to \pi^+ \nu\nu$ analysis on Run1 data is completed with a World-leading measurement.

Excellent sensitivity to searches to pion and invisible particles

NA62 will take data until LS3, to approach theory precision

Plans for longer term high-intensity kaon beam experiments beyond LS3