Results from NA62

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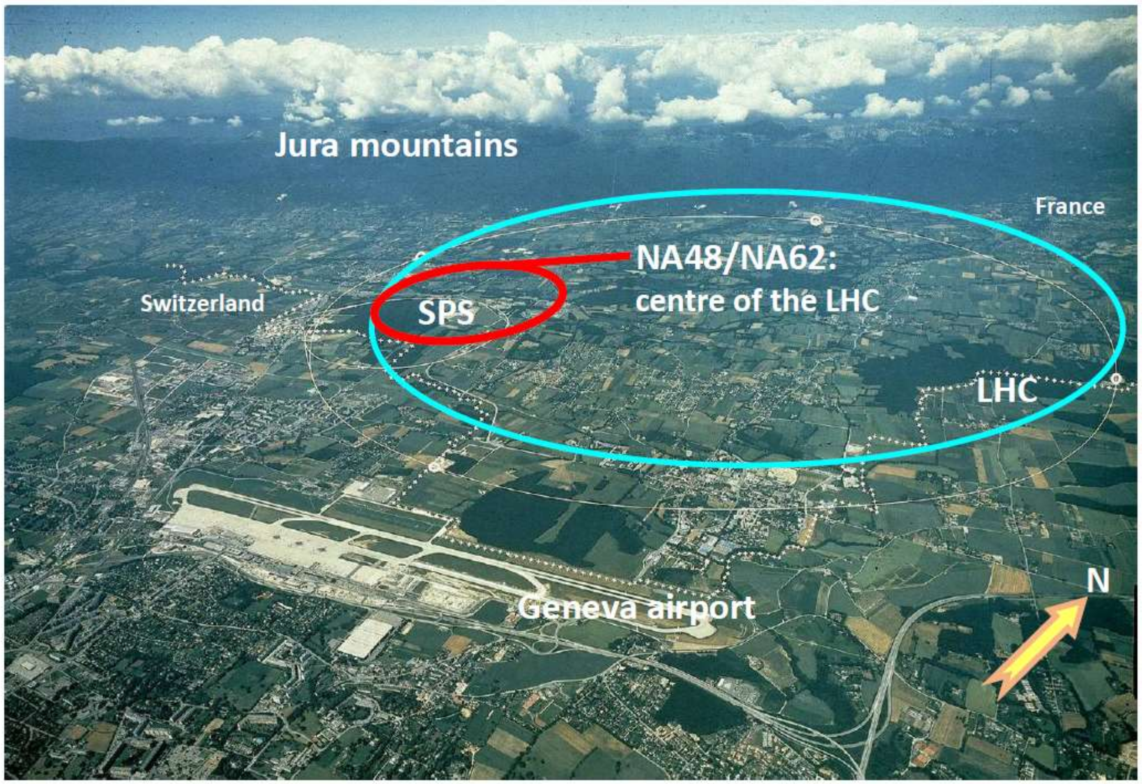
on behalf of the NA62 Collaboration

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax GMU, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosi, TRIUMF, Turin, Vancouver (UBC)
~200 participants

FPCP 2020
June 8th-12th, 2020

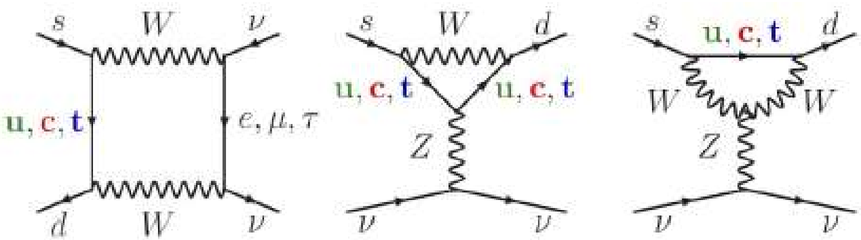
Kaon decays at CERN



Earlier: NA31

NA48 (discovery of direct CPV)	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 (R_K phase)	2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
	2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$	tests
NA62	2014: pilot run	
	2015: commissioning run	
	2016 – : $K^+\rightarrow\pi^+\nu\nu$ run	

$K^+ \to \pi^+ \nu\bar{\nu}$: clean theoretical environment



FCNC loop processes:
s->d coupling
Highest CKM suppression

Very clean theoretically
No hadronic uncertainties
Hadronic matrix element related to the precisely measured BR ($K^+ \to \pi^0 e^+ \nu$)

SM predictions [Buras et al. JHEP 1511 (2015) 33]

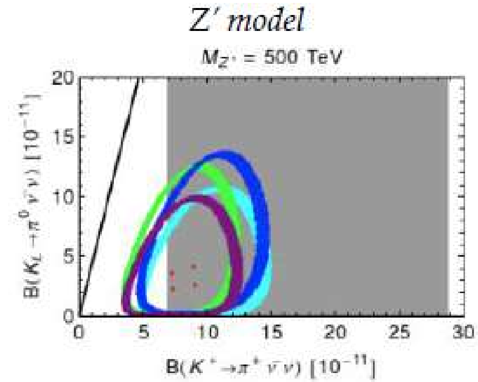
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \cdot \left(\frac{V_{cb}}{0.0407}\right)^{2.8} \cdot \left(\frac{\gamma}{73.2^0}\right)^{0.74} = (0.84 \pm 0.10) \cdot 10^{-10}$$

$$BR(K^0 \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \cdot \left(\frac{V_{ub}}{0.00388}\right)^{2} \cdot \left(\frac{V_{cb}}{0.0407}\right)^{2} \cdot \left(\frac{\sin\gamma}{\sin 73.2^0}\right)^{0.74} = (0.34 \pm 0.06) \cdot 10^{-10}$$

$K \to \pi\nu\nu$ are the most sensitive probes to NP models among B and K decays

The combined measurement of K^+ and K_L modes could shed light on the flavour structure of NP ($\Delta S=2$ / $\Delta S=1$ correlation)

$K \to \pi\nu\bar{\nu}$ NP sensitivity



Simplified Z, Z′ models

A. J. Buras, D. Buttazzo, R. Knegiens, JHEP 1511 (2015) 166

More specific NP models

Littlest Higgs with T-parity

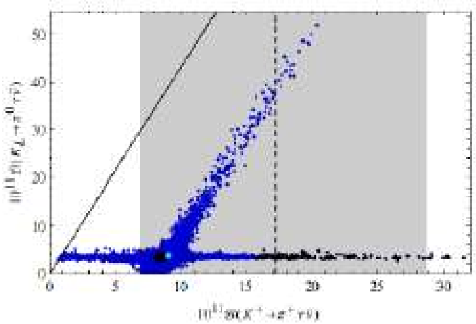
M. Blanke, A.J. Buras, S. Recksiegel, EPJ C76 (2016) 182

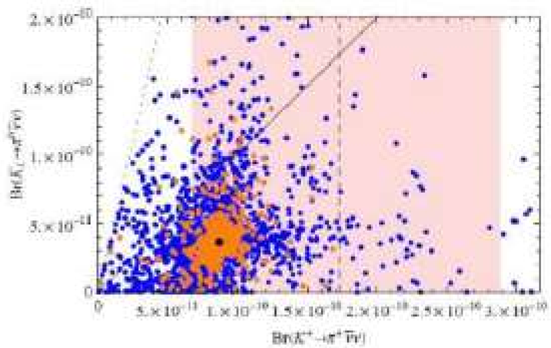
Custodial Randall-Sundrum

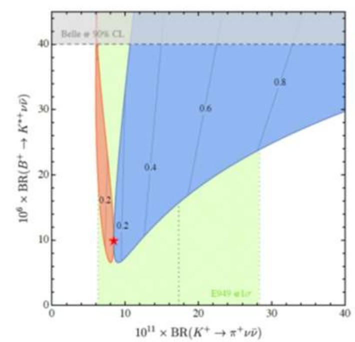
JHEP 0903 (2009) 108

LFU Violation

Isidori et al, EPJC (2017) 77



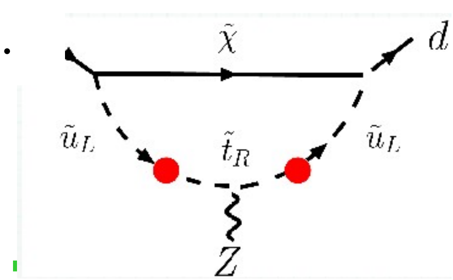




- Started to be probed at LHC, small effects in B physics.

Best probe of MSSM non-MFV [JHEP 0608 (2006) 064]

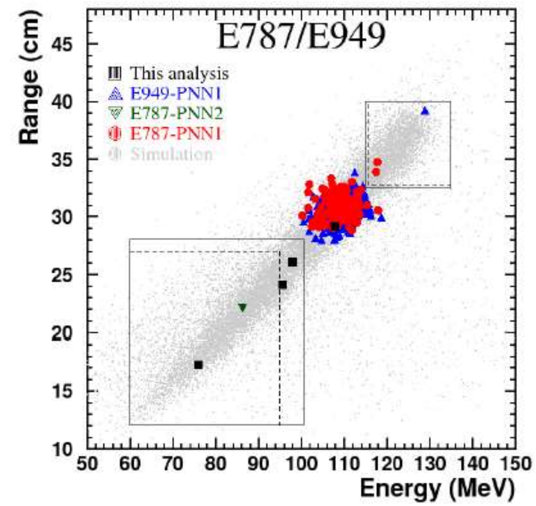
- E.g. non-MFV in up-squarks trilinear terms
- Still not excluded by the recent LHCb data.



Previous status of $K^+ \to \pi^+\nu\bar{\nu}$

E787/E949 @Brookhaven: 7 candidates $K^+ \to \pi^+\nu\bar{\nu}$
2 experiments, stopped kaon technique

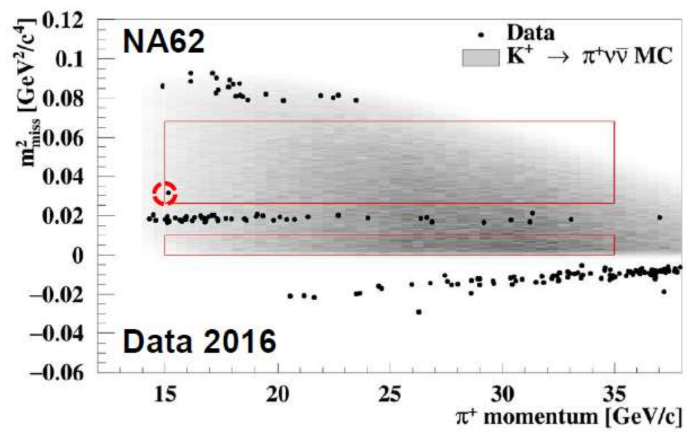
- Separated K^+ beam (710 MeV/c, 1.6MHz)
- PID: range (entire π+→μ+→e+ decay chain)
- Hermetic photon veto system



$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Phys. Rev. D77,052003 (2008), Phys. Rev. D79,092004 (2009)

NA62, result from 2016 data:
1 event observed
Background: $0.15 \pm 0.09_{stat} \pm 0.01_{syst}$ events



$$BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10} (95\%\ CL)$$

Phys. Lett. B 791 (2019) 156

NA62 goals and challenges

- Measurement of the $K^+ \rightarrow \pi^+ \nu\nu$ branching ratio
  - This requires at least 10^{13} Kaon decays
  - In-flight decay technique
  - 75 GeV/c beam helps in background rejection
    - Event selection with P_π<35 GeV/c
    - i.e. $K_{\pi 2}$ decays have around more than ~40 GeV of electromagnetic energy
    - $O(10^{12})$ rejection factor of common K decays

Good tracking devices

Accurate measurement of the kaon momentum
Accurate measurement of the pion momentum
Missing mass cut: $O(10^5)$ rejection on $K_{\mu 2}$, $O(10^4)$ on $K_{\pi 2}$

Veto detectors

Photons: to reduce the background by a factor of 10^8
Muons: add a rejection factor of $O(10^5)$

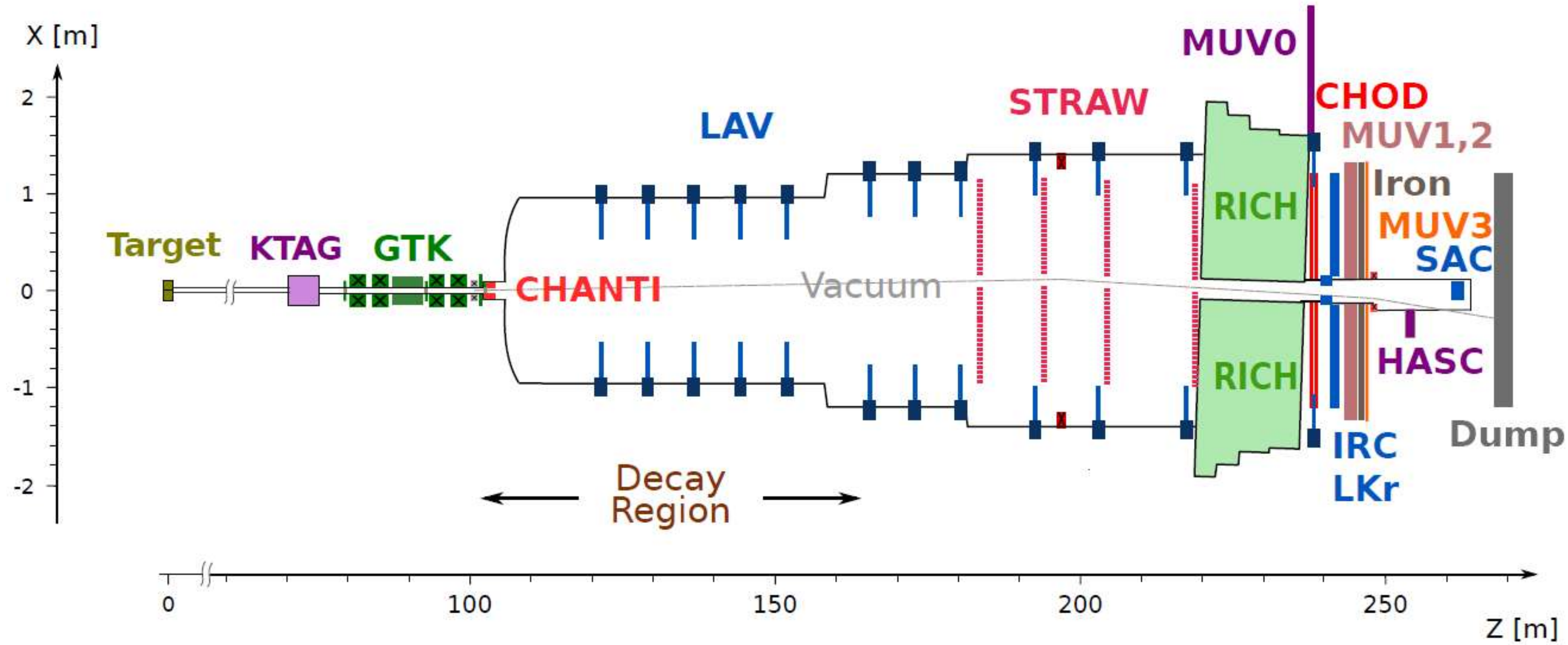
Particle identification

Identify kaons in the beam
Identify positrons
Additional π/μ rejection [$O(10^2)$]

Precise sub-ns timing

Kaon-pion time association
To reduce pileup

The NA62 detector



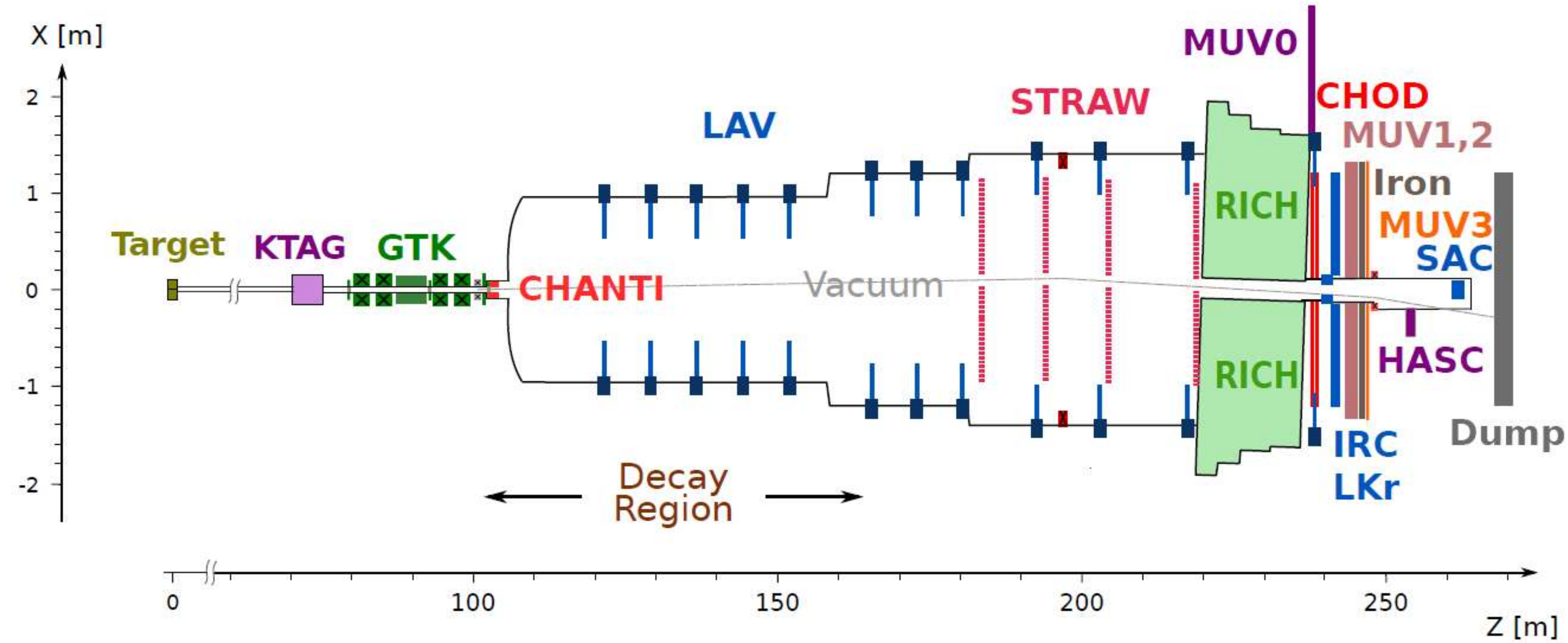
Beam	
Momentum	75 GeV/c, 1% bite
Divergence (RMS)	100 μrad
Transverse Size	60 × 30mm^2
Composition	K+ 6%, π+ 70%, p 24%
Nominal Intensity	33 × 10^{11} ppp (750 MHz at GTK3)

Fiducial region

60 m decay region
10^{-6} mbar vacuum
Downstream rate ~ 10 MHz

Detector description:
JINST 12 P05025 (2017), arxiv:1703.08501

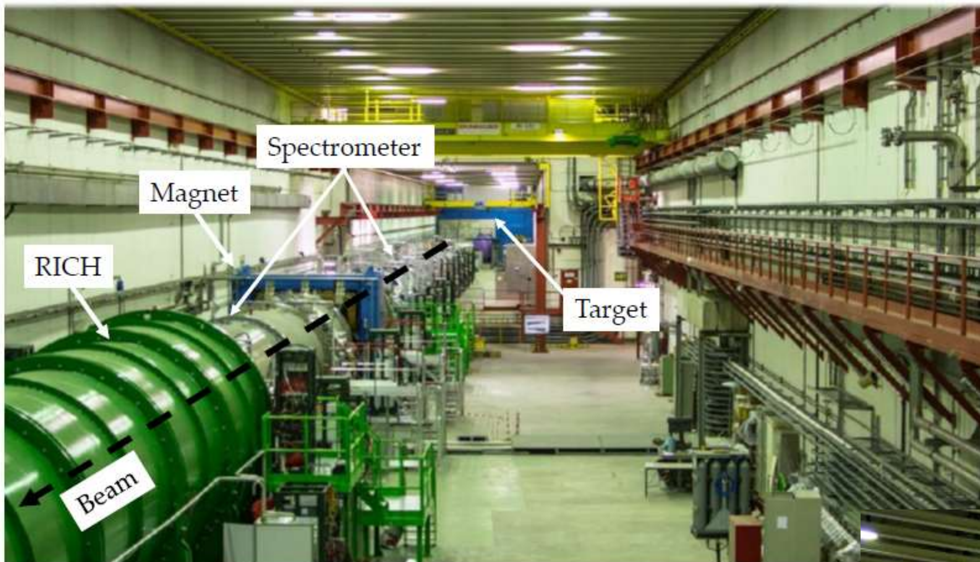
The NA62 detector



Upstream detectors (K^+)	
KTAG	Differential Cherenkov counter for K^+ ID
GTK	Silicon pixel beam tracker
CHANTI	Veto for inelastic beam-GTK3 interactions

Downstream detectors (π^+)	
STRAW	Track spectrometer
CHOD	Scintillator hodoscopes
LKr/MUV1/MUV2	Calorimetric system
RICH	Cherenkov for $\pi/\mu/e$ ID
LAV/LKr/IRC/SAC	Photon veto
MUV3	Muon veto

NA62 runs



2014: Pilot run

2015: Commissioning run

2016: Commissioning and physics run

Result published:
Phys. Lett. B 791 (2019) 156
arXiv.1811.08508

2017: 160 days of data taking

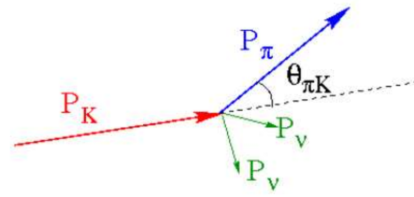
This talk, paper in preparation

2018: 217 days of data taking

Analysis on going

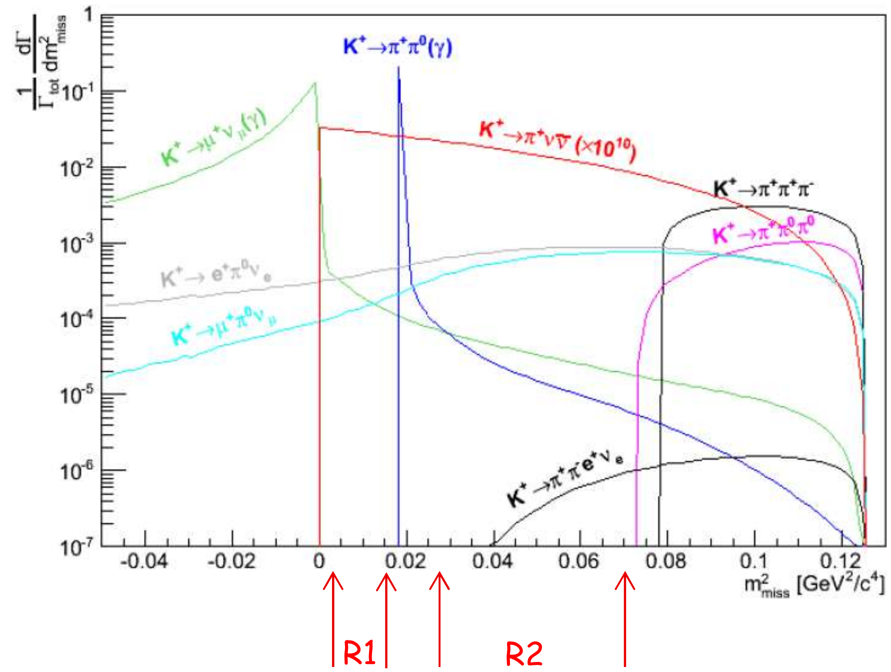
K^+ decay in-flight

- Signature: one incident kaon, 1 charged output track
- Missing mass distributions: $m^2_{miss} = (P_K - P_{track(hyp\ \pi^+)})^2$
- Define two regions in m^2_{miss} to accept candidate events
- 65 m long decay fiducial region, $15 < P\pi < 35$ GeV/c
- Particle ID (Cherenkov detectors, calorimeters)
- Photon Veto



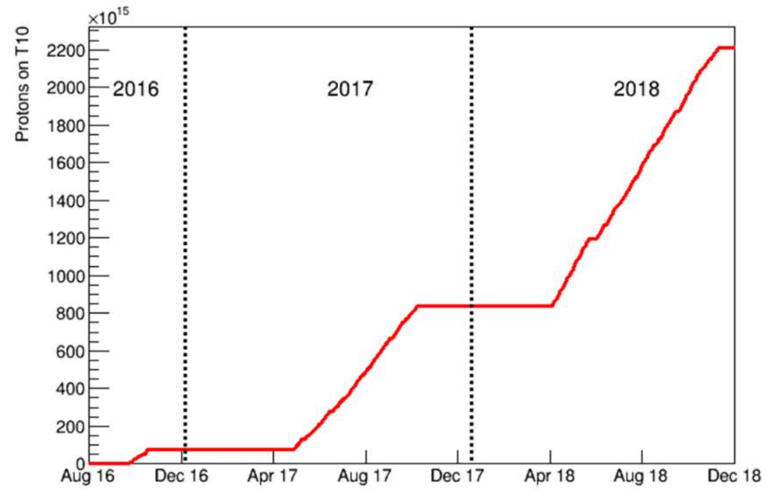
- Backgrounds:
  - Accidental beam activity
  - K+ decay modes:

$K^+ \to \pi^+\pi^0\ (\gamma)$ Br = 0.2067
$K^+ \to \mu^+\nu\ (\gamma)$ Br = 0.6356
$K^+ \to \pi^+\pi^+\pi^-$ Br = 0.0558
$K^+ \to \pi^+\pi^-e^+\nu$ Br = 4.25×10^{-5}



2017 data analysis

- $19 \cdot 10^{11}$ ppp on target
- $2 \cdot 10^{12}$ K^+ decays useful for $\pi\nu\nu$
- Blind analysis procedure
  - Signal and control regions kept masked for the whole analysis
- Main trigger streams:
  - $\pi\nu\nu$, control
- Offline analysis
  - $\pi\nu\nu$ sample
  - Control samples
    - $K^+ \rightarrow \pi^+\pi^0$
    - $K^+ \rightarrow \mu^+\nu$
    - $K^+ \rightarrow \pi^+\pi^+\pi^-$



Analysis steps

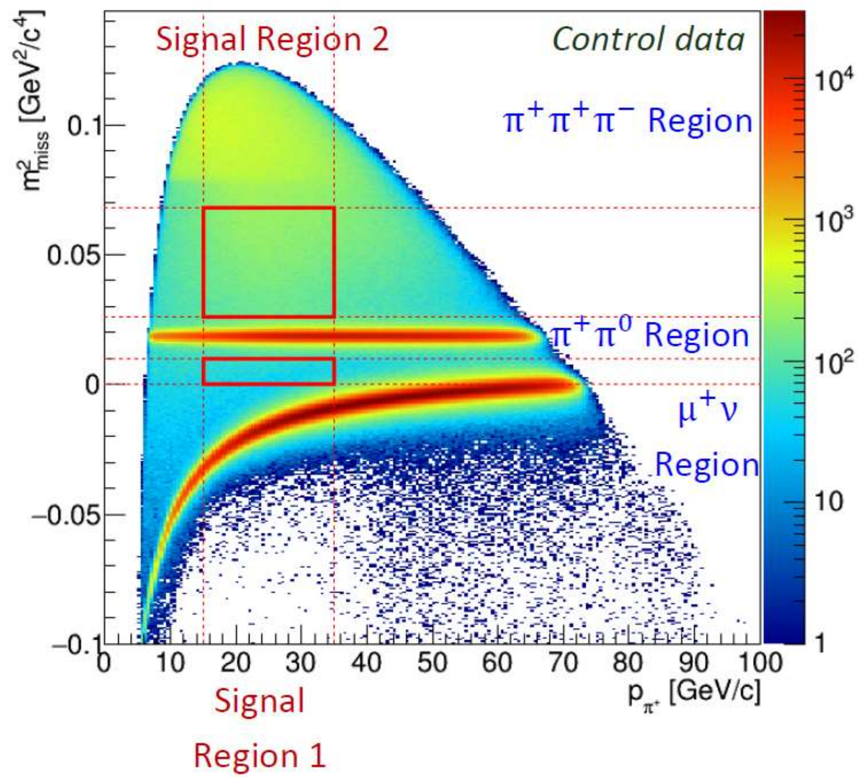
- Selection
- Determination of single event sensitivity (SES)
- Estimation and validation of the expected background
- Un-blinding of the signal regions and results

Kaon decay selection

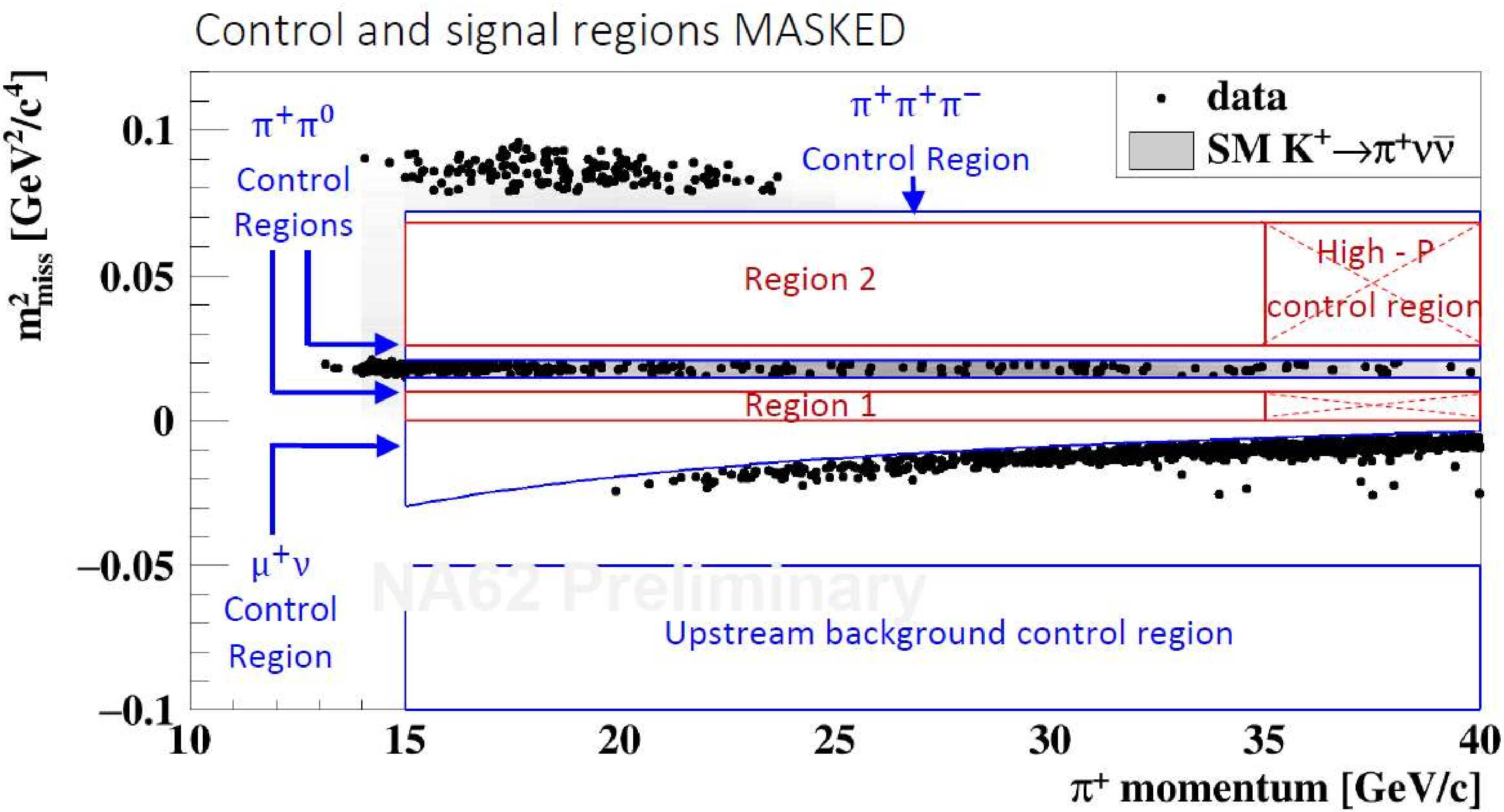
- Selection
  - K^+ decay into one charged particle
  - π^+ identification
  - Photon rejection
  - Multi track rejection

- Performances
  - GTK-KTAG-RICH timing: O(100 ps)
  - π^+ ID: $\varepsilon_\mu = 10^{-8}$; $\varepsilon_{\pi+}$ ~64%
  - π^0 rejection $\varepsilon_{\pi 0}$ = ~$1.4 \cdot 10^{-8}$
  - $\sigma(m^2_{miss})$ ~ 10^{-3} GeV^2/c^4

Selected K^+ decays, before π^+ id and γ/multi rejection



Data after selection

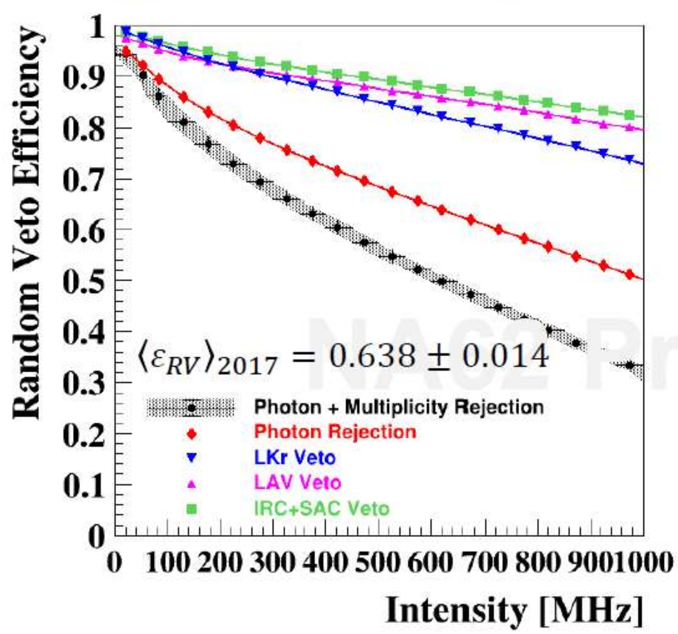


Single Event Sensitivity (SES)

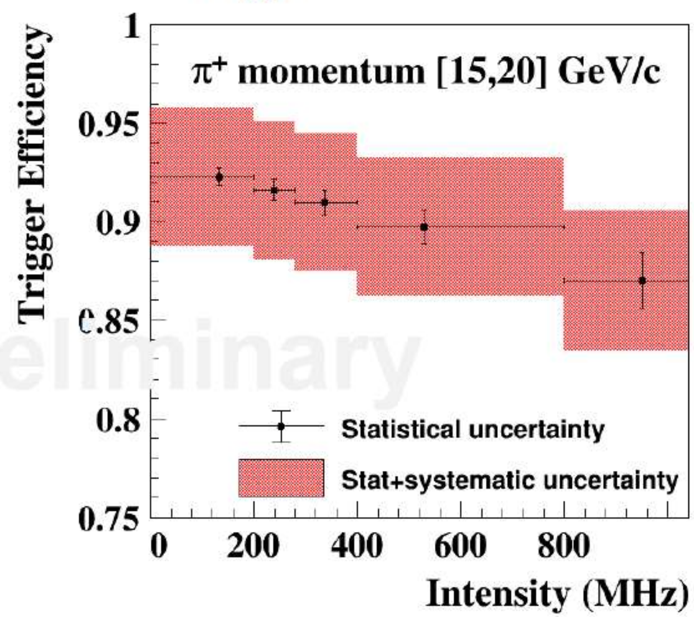
- Determine Kaon flux from $K^+ \rightarrow \pi^+\pi^0$ selected with control trigger (downscale 400)
- Use the same $\pi\nu\nu$ selection, but without photon and multiplicity rejection and with missing mass cut modified

$$N_{\pi\nu\nu}^{\exp} = N_{\pi\pi}\varepsilon_{RV}\varepsilon_{trig}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{BR(\pi\nu\nu)}{BR(\pi\pi)} \qquad SES = \frac{BR(\pi\nu\nu)}{N_{\pi\nu\nu}^{\exp}}$$

ε_{RV} measured on $K^+ \rightarrow \mu^+\nu$ data



$\varepsilon_{trigger}$ measured on data



Intensity measurements from the sidebands of the GTK

Single Event Sensitivity (SES)

Integrated over beam intensity and π^+ momentum

$$SES = (0.389 \pm 0.021) \times 10^{-10} \qquad N_{\pi\nu\nu}^{\exp} = 2.16 \pm 0.12 \pm 0.26_{ext}$$

External error from BR = 0.84 ± 0.10

Error budget	
Source	Uncertainty (10^{-10})
L0 trigger	± 0.015
Acceptance	± 0.012
Random veto	± 0.008
L1 trigger	± 0.003
Normalization background	negligible

$K^+ \to \pi^+\pi^0\ (\gamma)$ and $K^+ \to \mu^+\nu$ background

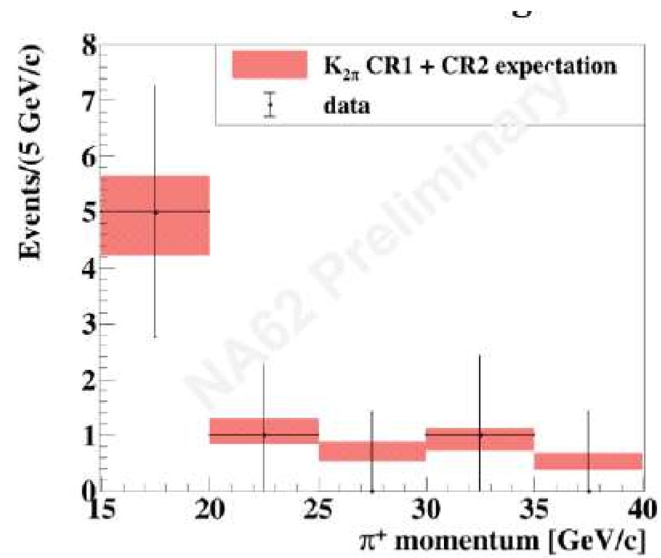
$$N_{\pi\pi}^{exp}(region) = N(\pi^+\pi^0) f^{kin}(region)$$

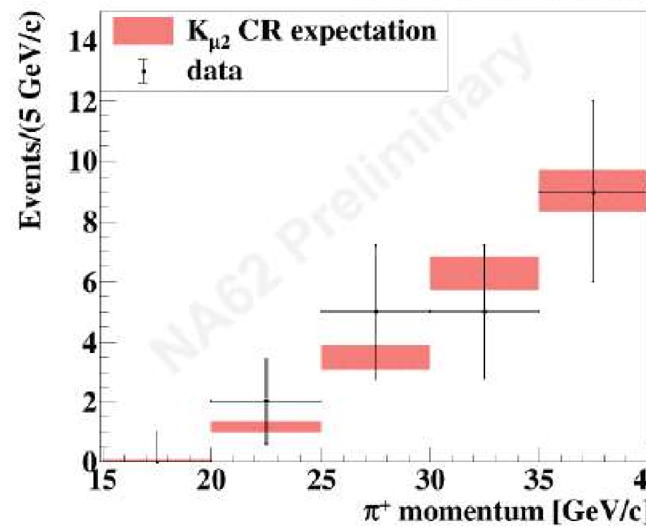
Expected events in the signal region, $\pi\nu\nu$ selection

Data in $\pi^+\pi^0$ ($\mu^+\nu$) region, $\pi\nu\nu$ selection (including π^0 rejection)

Fraction of $\pi^+\pi^0$ ($\mu^+\nu$) in signal region measured on control data

$$N_{\mu\nu}^{exp}(region) = N(\mu^+\nu) f^{kin}(region)$$

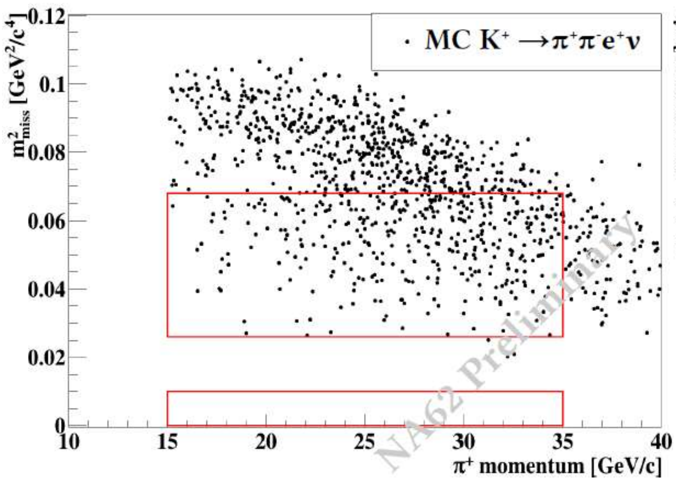


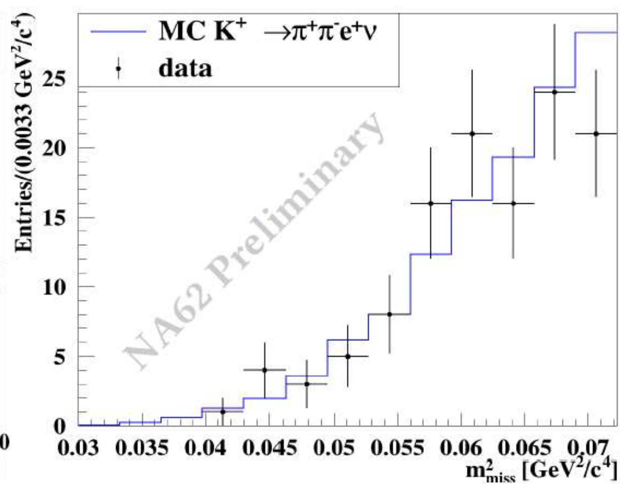


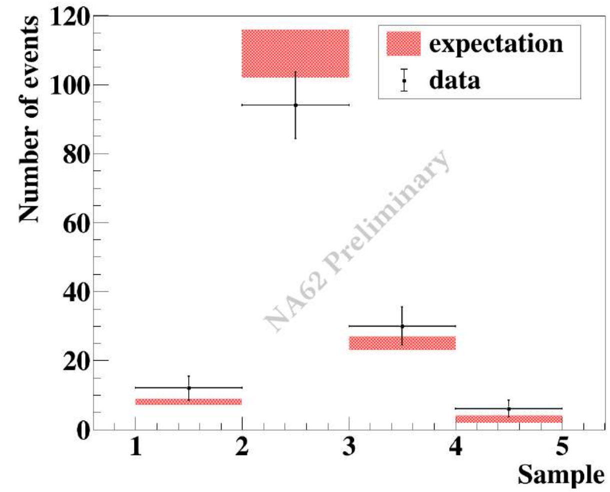
$K^+ \to \pi^+\pi^-e^+\nu$ (K_{e4}) background

- Measured branching ratio: 4.247(24) · 10^{-5}
- Topology-correlated kinematics spanning Region 2
- MC-based background estimation, 2·10^9 events generated
- Validation of MC done with data using enriched $K^+ \to \pi^+\pi^-e^+\nu$ sample

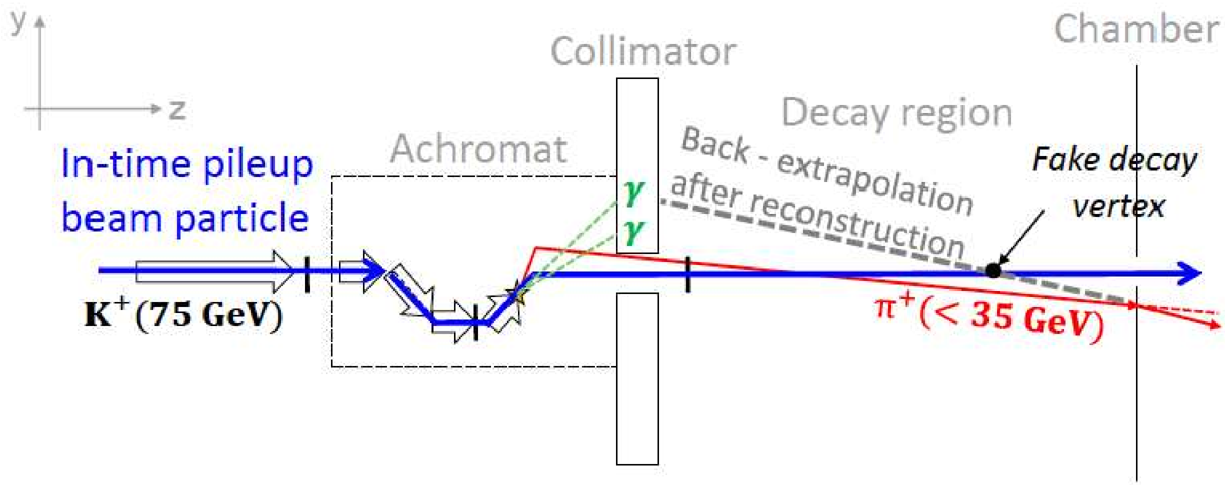
$$N_{Ke4}^{bg} = 0.12 \pm 0.05_{st} \pm 0.03_{sy}$$







Upstream background



K⁺ decay/interaction in the achromat
Photons blocked by the collimators

π⁺ detected in the straw, but it has scattered

← Use inverted K-π matching to counts event from data

Back extrapolation gives a fake vertex in the fiducial zone with an in-time pileup K⁺

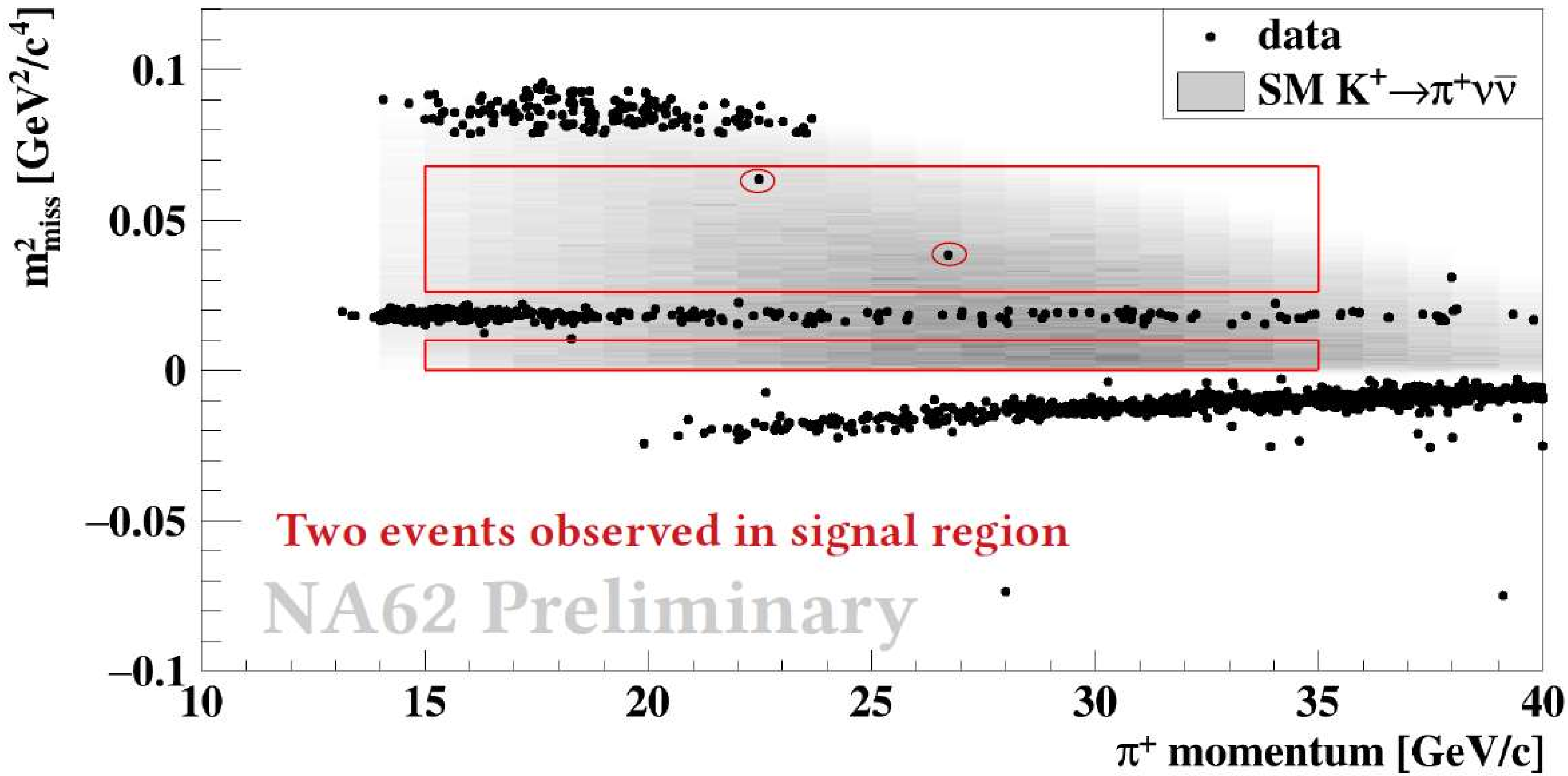
← Estimation of the probability of occurrence from data/MC

$$N^{bg}_{upstream} = 0.9 \pm 0.2_{st} \pm 0.2_{sy}$$

Background summary

Process	Expected events in R1+R2
$K \to \pi\nu\nu$ (SM)	$2.16 \pm 0.12_{stat} \pm 0.26_{ext}$
Total Background	$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$
$K^+ \to \pi^+\pi^0 (\gamma)$	$0.29 \pm 0.03_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu (\gamma)$	$0.15 \pm 0.02_{stat} \pm 0.04_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.02 \pm 0.02_{syst}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.012 \pm 0.05_{stat} \pm 0.03_{syst}$
$K^+ \to \ell^+\pi^0\nu$	Negligible
Upstream background	$0.9 \pm 0.2_{stat} \pm 0.2_{syst}$

Opening the box



$K^+ \rightarrow \pi^+\nu\nu$ 2016+2017 result

	2017	2016
Observed candidates	2	1
Single event sensitivity	$(0.389 \pm 0.021)\cdot 10^{-10}$	$(3.15 \pm 0.24)\cdot 10^{-10}$
Expected SM signal	$2.16 \pm 0.12 \pm 0.26_{ext}$	$0.27 \pm 0.02 \pm 0.03_{ext}$
Expected background	1.5 ± 0.3	0.15 ± 0.09

Upper limits (CLs methods)

Observed

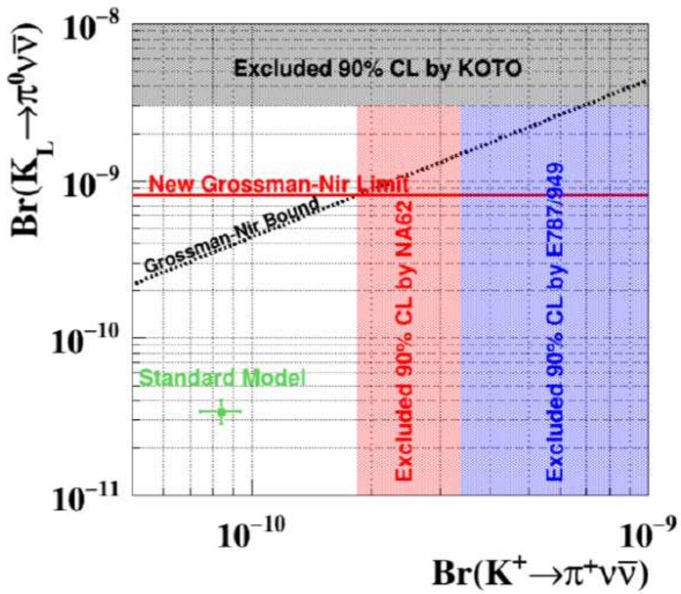
$BR(K \rightarrow \pi\nu\nu) < 1.85\cdot 10^{-10}$ @ 90% CL

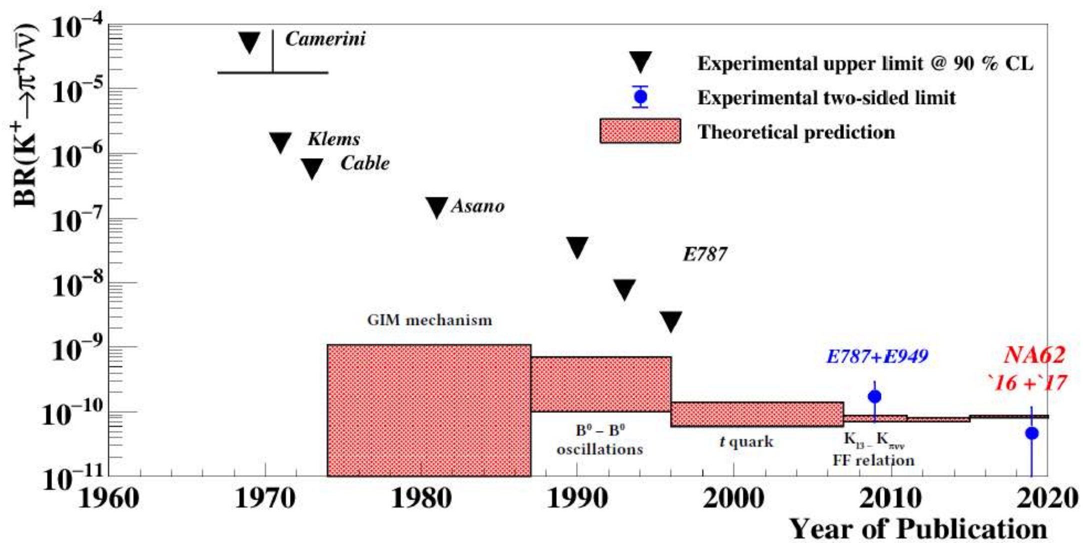
Expected (bkg only)

$BR(K \rightarrow \pi\nu\nu) < 1.32\cdot 10^{-10}$ @ 90% CL

Two sides 68% band $BR(K \rightarrow \pi\nu\nu) = (0.47^{+0.72}_{-0.47})\cdot 10^{-10}$

$K^+ \to \pi^+\nu\nu$ 2016+2017 result





Analysis improvements

- The used event selection aimed for the highest background rejection
  - Strong cuts, acceptance reduced to a few %
- Reoptimization of the analysis to improve signal efficiency:
  - Optimization of signal region and optimization of PID
  - Improvements of selection against upstream background
- Signal improvement by a factor ~2
- Background level scales accordingly
- More optimizations being studied
  - Improvement of upstream background using a BDT with pion informations
  - Improve the K-π matching, with a better likelihood or with neural networks
  - Reduce the random veto (42% loss in 2018) by
    - optimising photon rejection in LAV
    - developing LKr reconstruction specific for veto purpose
    - refining event reconstruction in small angle calorimeters
    - optimising multiplicity rejection algorithm

Improvements for the next runs

- Few additions to the experimental setup
  - Rearrangement of the beam line around the achromat and addition of a 4^{th} GTK station
    - To improve the efficiency of K-π matching
    - To improve the rejection of the upstream background
  - Addition of a veto counter before and after the final collimator
    - To improve the rejection of the upstream background
  - Installation of a large scintillator tile hodoscope in front of the decay volume
    - To improve background rejection in dump mode
    - To reduce the trigger rate in some rare decay modes
  - Addition of a second HASC module
    - To further reduce photon background

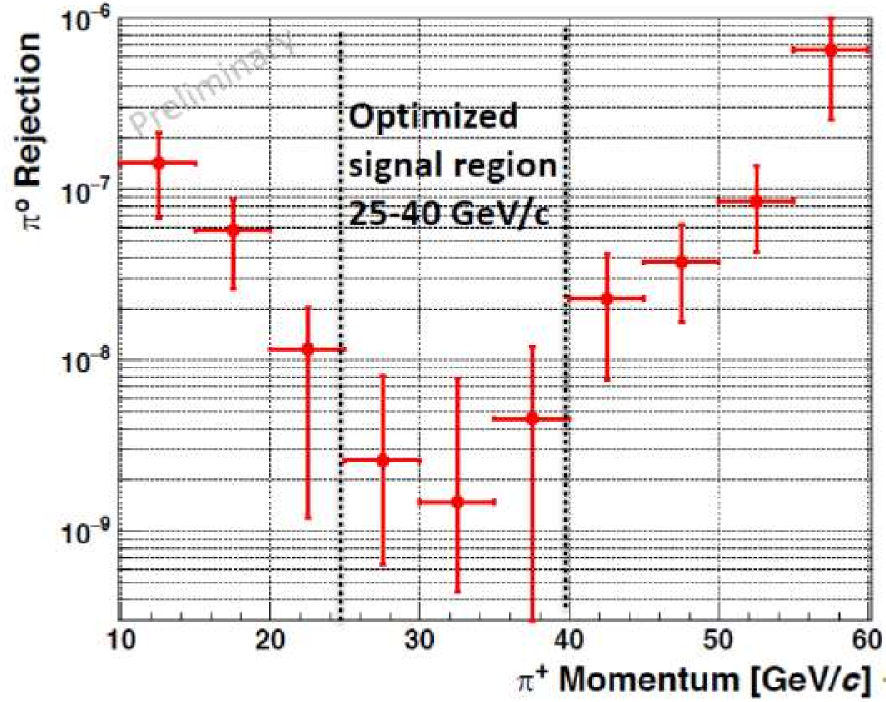
- Plan to run from 2021 to 2024

$\pi^0 \to$ invisible

- In the SM, BR($\pi^0 \to \nu\nu$) ~ O(10^{-24}), so any observation $\to$ BSM
- Present limit is $2.7 \cdot 10^{-7}$ at 90% CL, from BNL experiments
- Profit from hermetic photon veto
- Same $\pi\nu\nu$ selection and trigger
- Evaluate a-priori the π^0 suppression in $\pi^+\pi^0$ kinematic region
- Use $\pi^0 \to \gamma\gamma$ as normalization channel

- Expected background: 10^{+22}_{-8} events
- Observed: 12 events

Paper in preparation



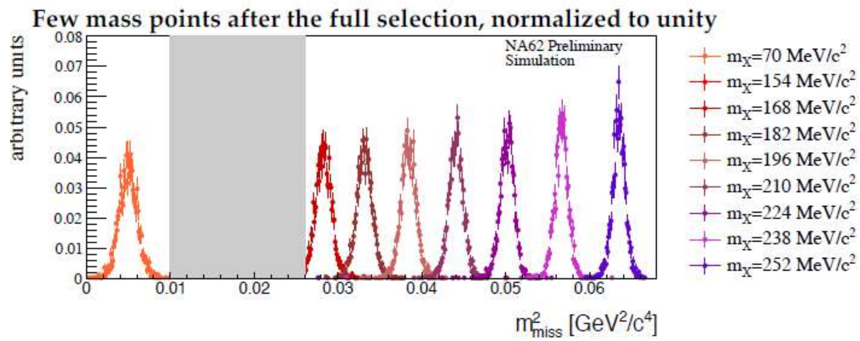
Preliminary result: BR($\pi^0 \to \gamma\gamma$) < $4.4 \cdot 10^{-9}$ @ 90% CL

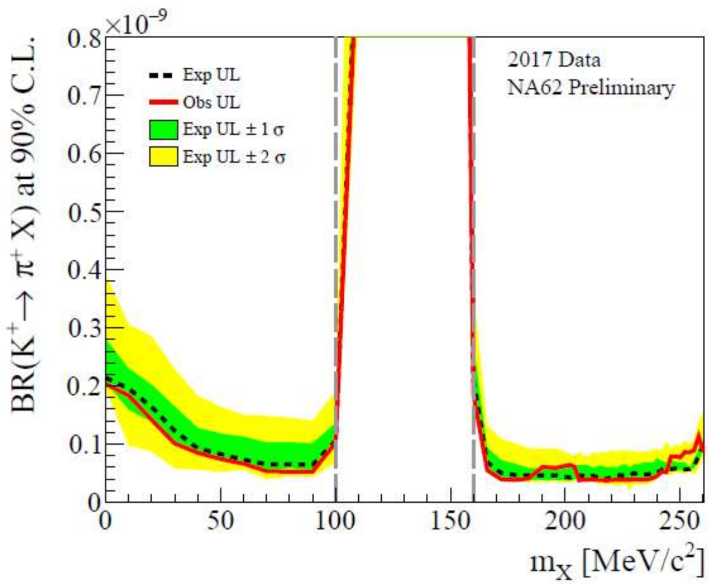
A factor 60 better wrt to previous measurements

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

- Search for feebly interacting particles in several models
  - Dark scalar mixing with Higgs boson
  - Scalars, like Alps, QCD axion, axiflavon
- Use the same selection, normalization and background evaluation of $\pi\nu\nu$ analysis
- Generate signal with two body decay for 200 mass hypotheses to compute acceptance
- Shape analysis on m^2_{miss}
- Fully frequentist approach, profiled likelihood test statistic

- Background parameterized with polynomial functions from $\pi\nu\nu$ analysis
- Signal shape: Gaussian, number of expected signal events obtained as in $\pi\nu\nu$ analysis.





$K^+ \to \pi^+ X$, X invisible - Results

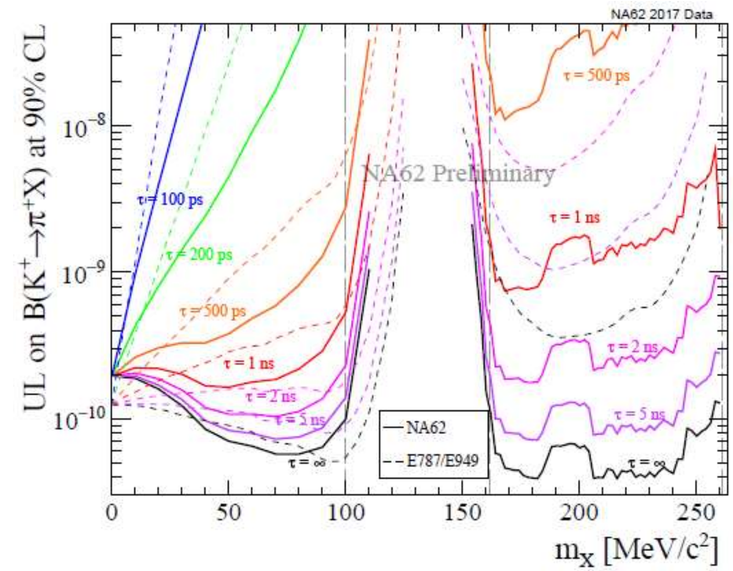
BR($K^+ \to \pi^+ X$) < $(0.5\text{-}2.0)\cdot 10^{-10}$ @ 90% CL for $m_X \in [0,100]$ MeV/c^2
BR($K^+ \to \pi^+ X$) < $(0.4\text{-}1.4)\cdot 10^{-10}$ @ 90% CL for $m_X \in [160,260]$ MeV/c^2

Paper in preparation

Assuming X decays to a visible SM particle, detected by NA62

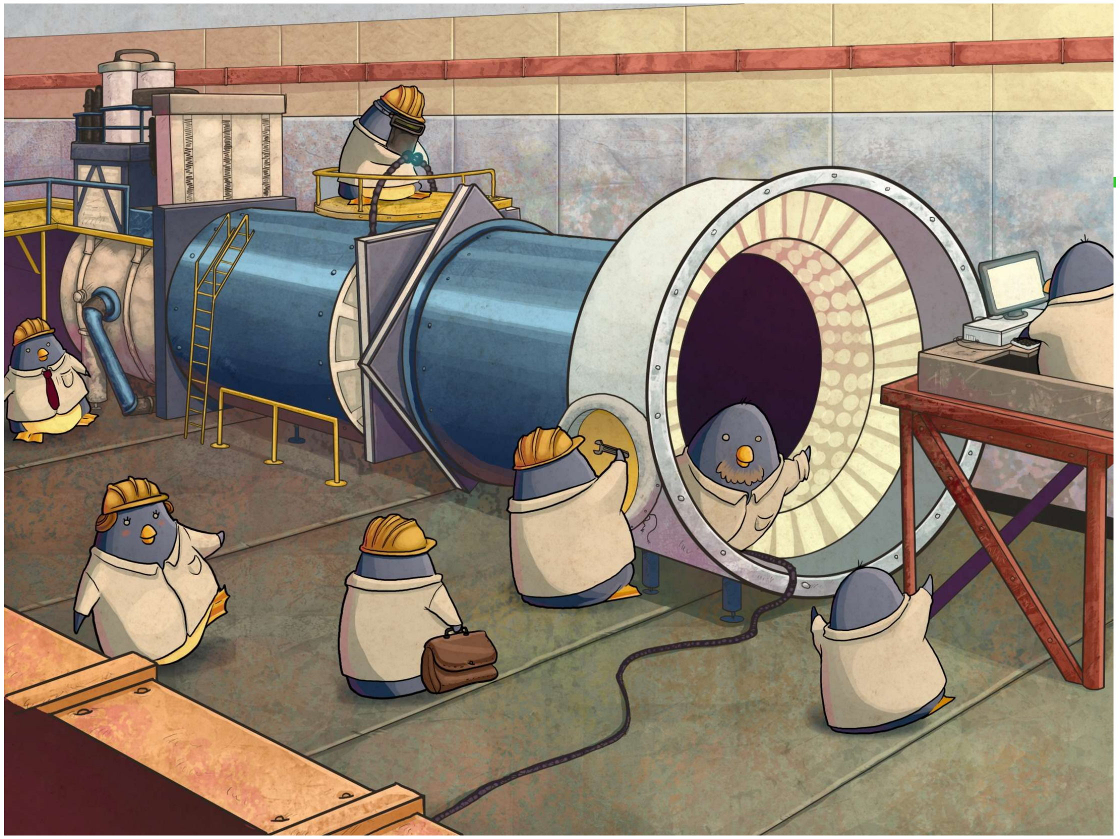
Evaluate the BR upper limit as a function of m_X

10 times better than E949 for $m_X \in [160,260]$

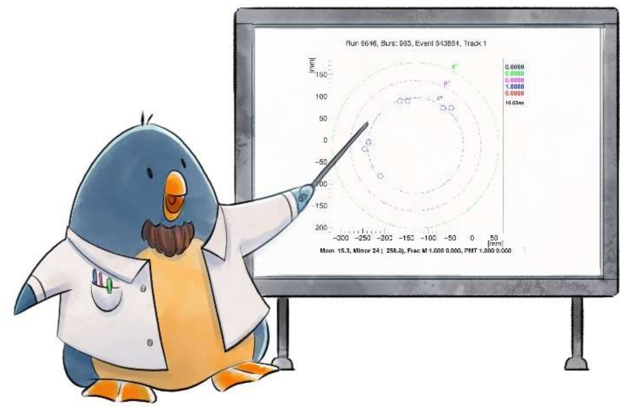


Conclusions

- A preliminary result from the analysis of the NA62 2017 data has been presented
  - 2 event found with an expected background of 1.5
  - The combination of 2016 and 2017 data gives an upper limit for the branching ratio of 1.85×10^{-10}
  - The two sides 68% band is $0.47^{+0.72}_{-0.47} \times 10^{-10}$
- The analysis of 2018 data is progressing
  - Improvements have been studied using the 2017 data
- The experimental setup is being updated for the next data taking (2012-2024)
- 2017 data have been used to search for exotic processes
  - 60 times improvement in the limit for $\pi^0 \to$ invisible
  - Improved limits on $K^+ \to \pi^+ X$, X invisible



Artist's view of the past installation activity…

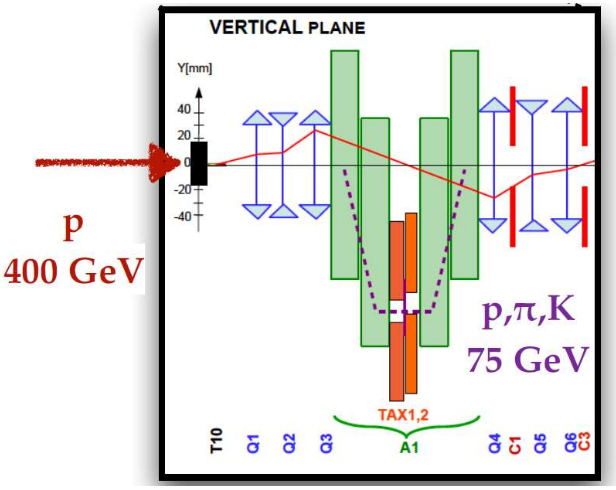


Thank you!

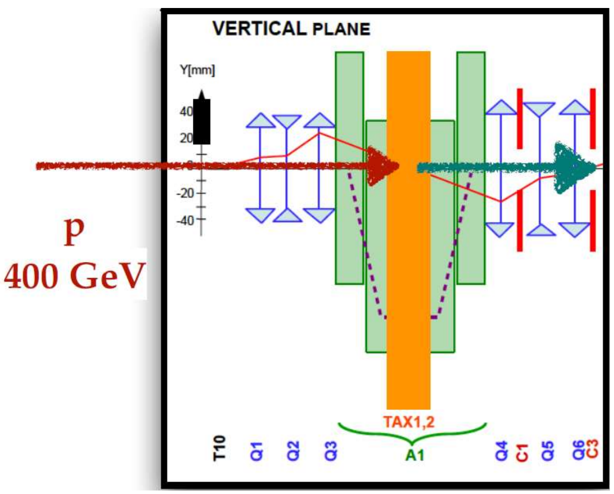
… and of the current analysis work…

Spares

Beam dump mode



Standard K+ mode



Dump mode

Dumping the beam ahead of the detector will allow to produce B, D and K mesons decaying promptly to exotics mediators and SM particles

Exotic particles could be produced also in the dump

Exotics searches extended up to m ~ 1.7 GeV

3×10^{16} POT has been collected in dump mode in 2017-2018. Analysis is ongoing to study the backgrounds

Runs in dump mode are foreseen during run 3 for a total of $O(10^{18})$ POT

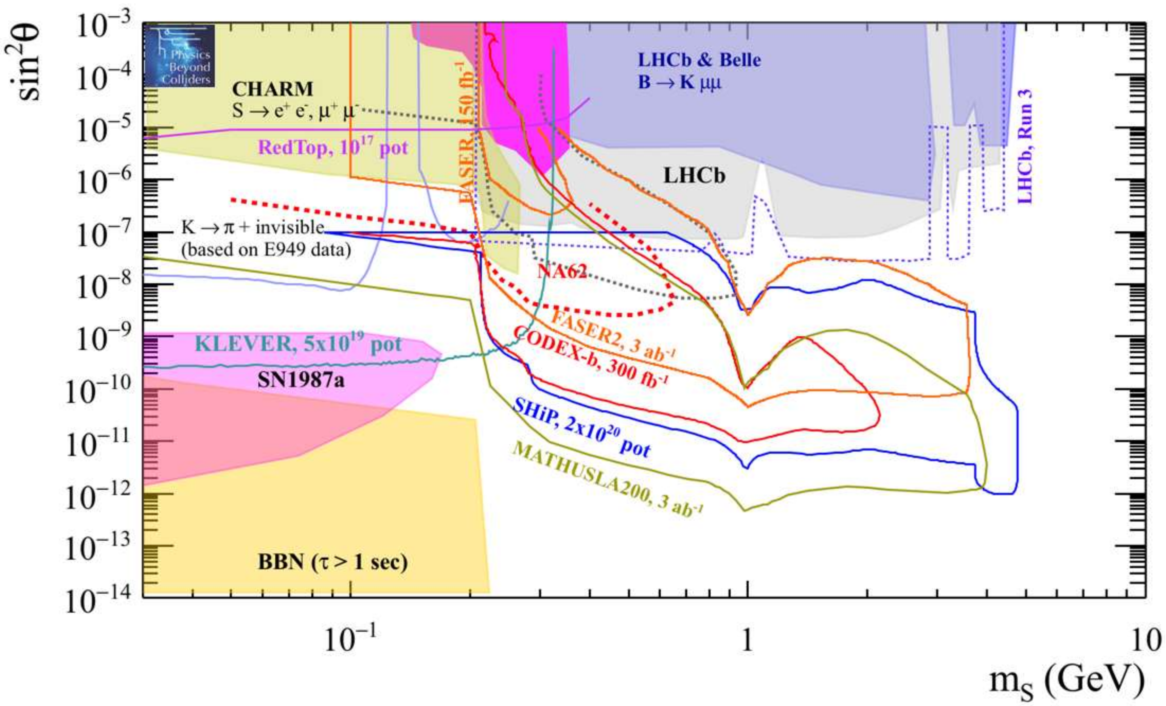
An additional veto counter ahead of the decay volume will improve the background rejection, mainly on not-closed channels

Dark scalar

$S \to \mu^+\mu^-$

$(\mu S+\lambda S^2)H^\dagger H$
$\mu = \sin\theta$
$\lambda = 0$

Search for two opposite sign charged tracks in the NA62 fiducial volume



Expected 90% CL exclusion contours

- Including trigger/acceptance/selection efficiencies
- Assume zero background

Dark photon

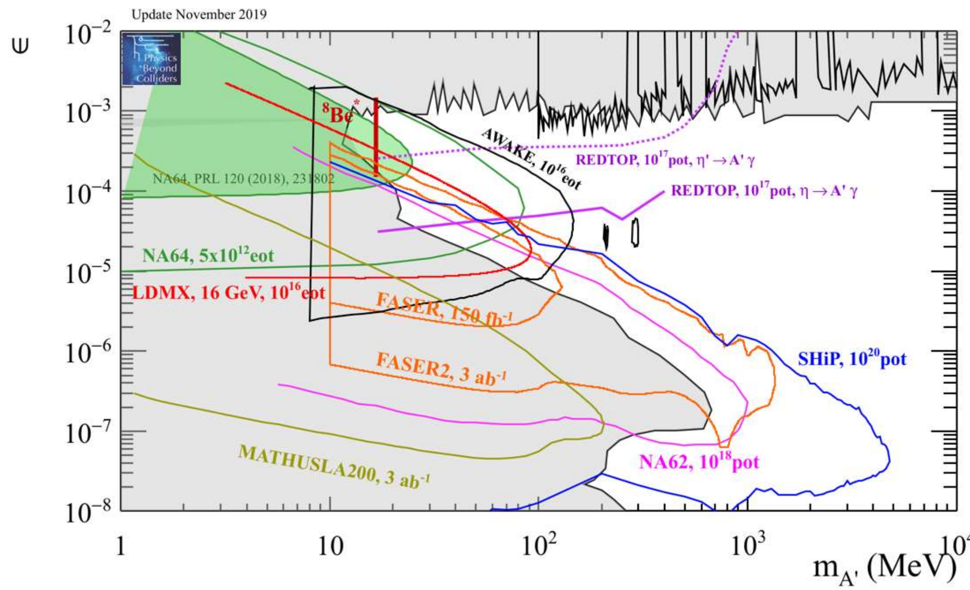
$A' \rightarrow e^+e^-$, $A' \rightarrow \mu^+\mu^-$

Search for two opposite sign charged tracks in the NA62 fiducial volume

Possible improvement on current limits

Here only p-Be target considered

Including direct QCD production of A' and A' production in the dump, the sensitivity will be higher



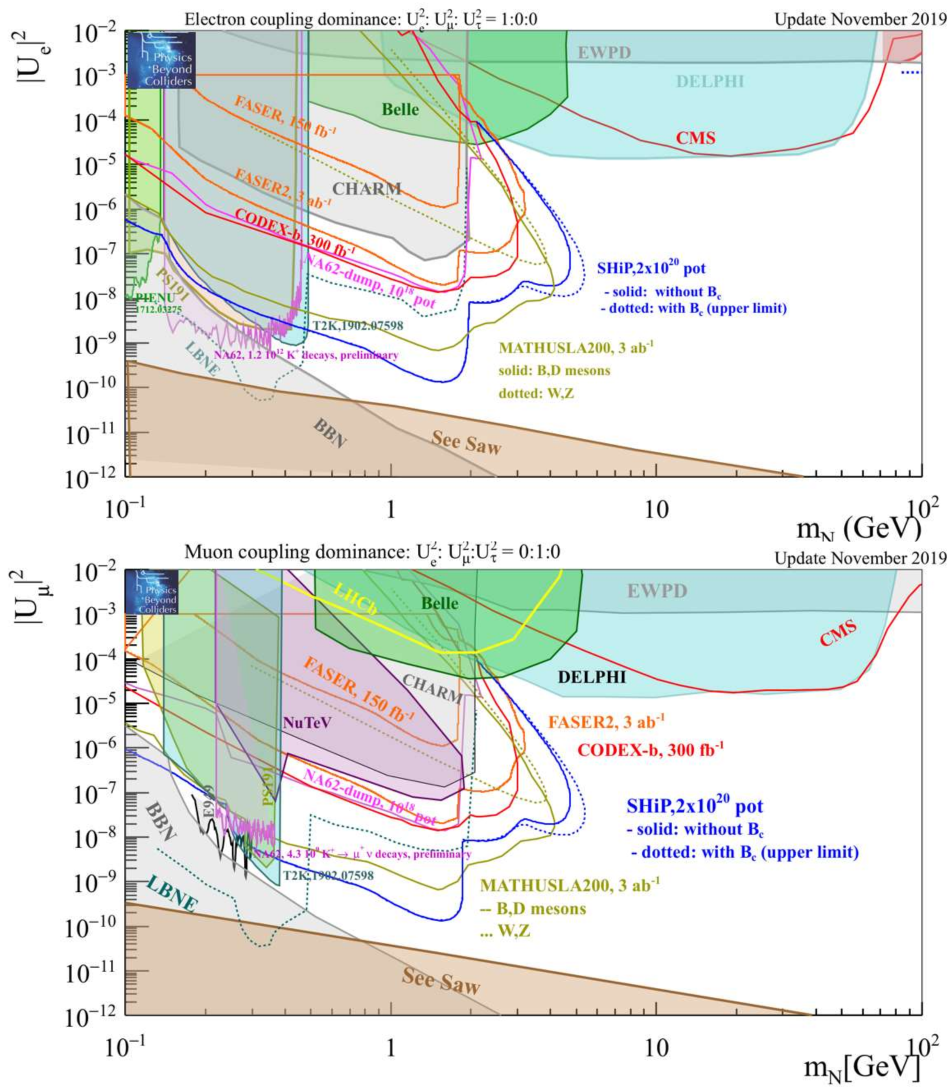
Expected 90% CL exclusion contours

- Including trigger/acceptance/selection efficiencies
- Assume zero background

Heavy neutral leptons

$D/D_s \to \ell^+ \nu_H,\ \nu_H \to \pi e,\ \nu_H \to \pi\mu$

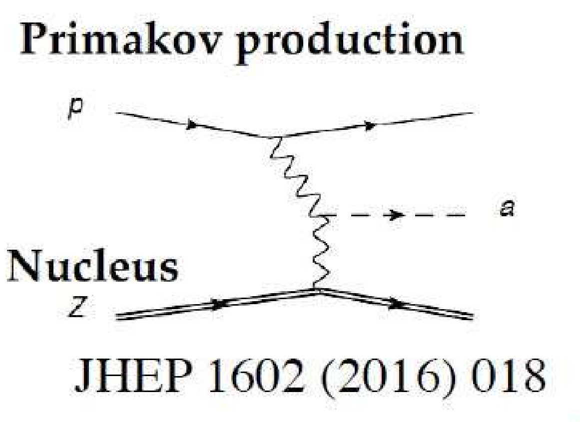
Also the τ coupling can be probed

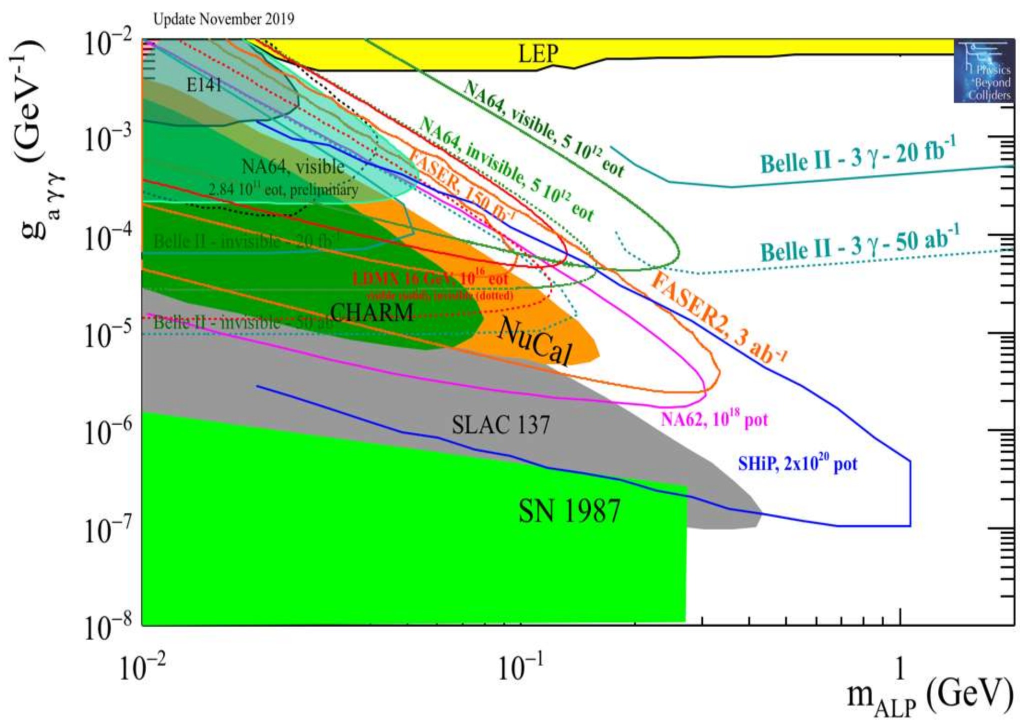


Expected 90% CL exclusion contours

- Including trigger/acceptance/selection efficiencies
- Assume zero background

Axion-like particles (ALPs)





Production via elastic scattering of beam protons on the dump

Coupling to photons is the main one

Search for decay $A \to \gamma\gamma$
Signature: 2 photons in the LKr calorimeter

Expected 90% CL exclusion contours
- Including trigger/acceptance/selection efficiencies
- Assume zero background