"NA62 results on heavy neutral leptons and $K^+ \to \pi^+ \nu \bar{\nu}$"

FCCP2017 Workshop
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Anacapri

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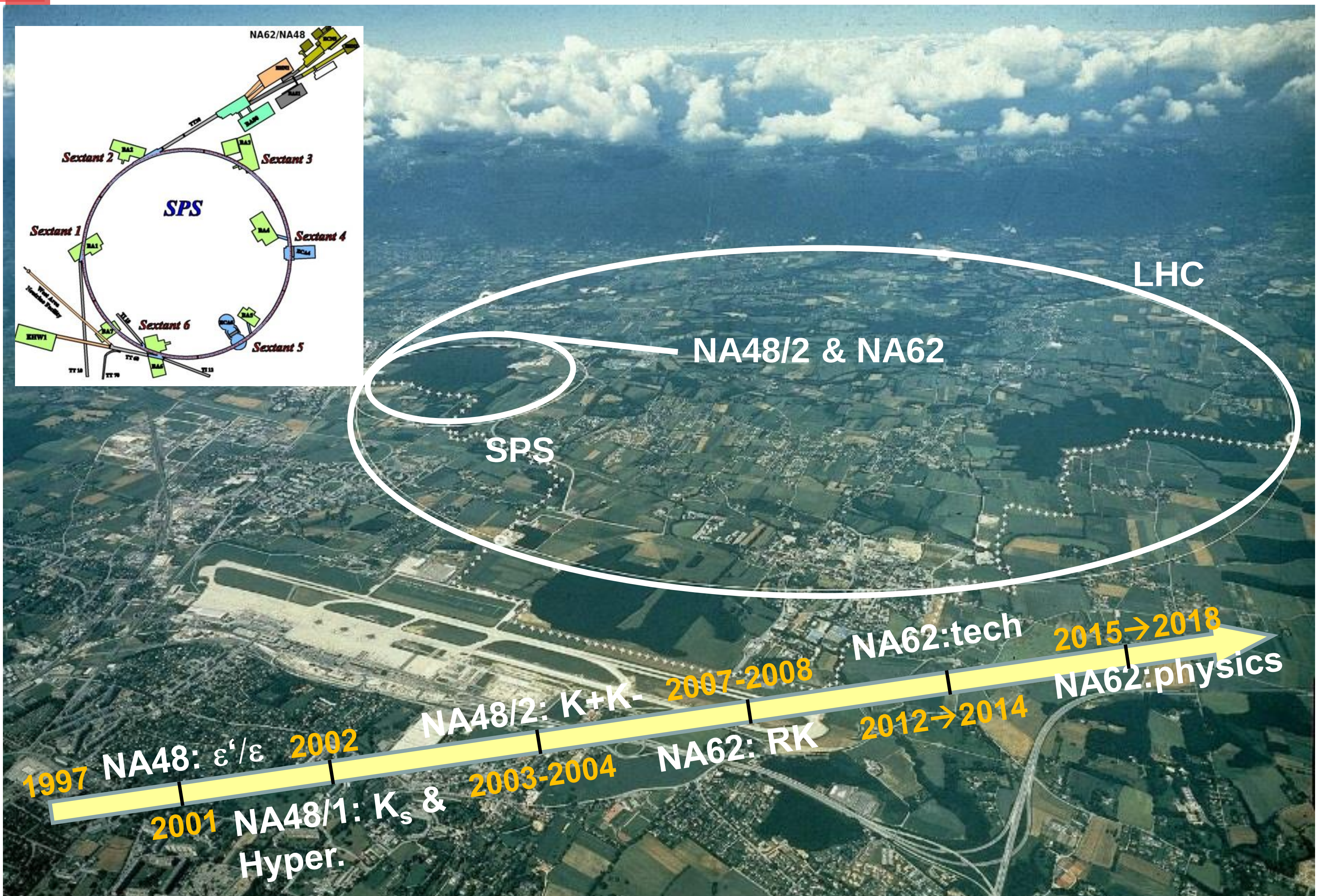
Kaon physics @ CERN



Why Kaons?

New Physics effects in flavour physics and search for exotics in mesons decays

Non-MFV: FCNC decays with high suppression in the standard model and clean theoretical prediction.

The $K\rightarrow\pi\nu\bar{\nu}$ has a very clean SM prediction (λ^5 suppression).

Clean environment in K: few decay channels, low background. Direct and indirect search for new states and DM portals.

MFV: helicity suppressed observables are sensitive to SUSY ($B\rightarrow ll$, $B\rightarrow l\nu$, $K\rightarrow l\nu$). LFV decays forbidden in SM.

Easier in K: the B decays are suppressed (Vub<<Vus). Cleaner environment to search for forbidden decays.

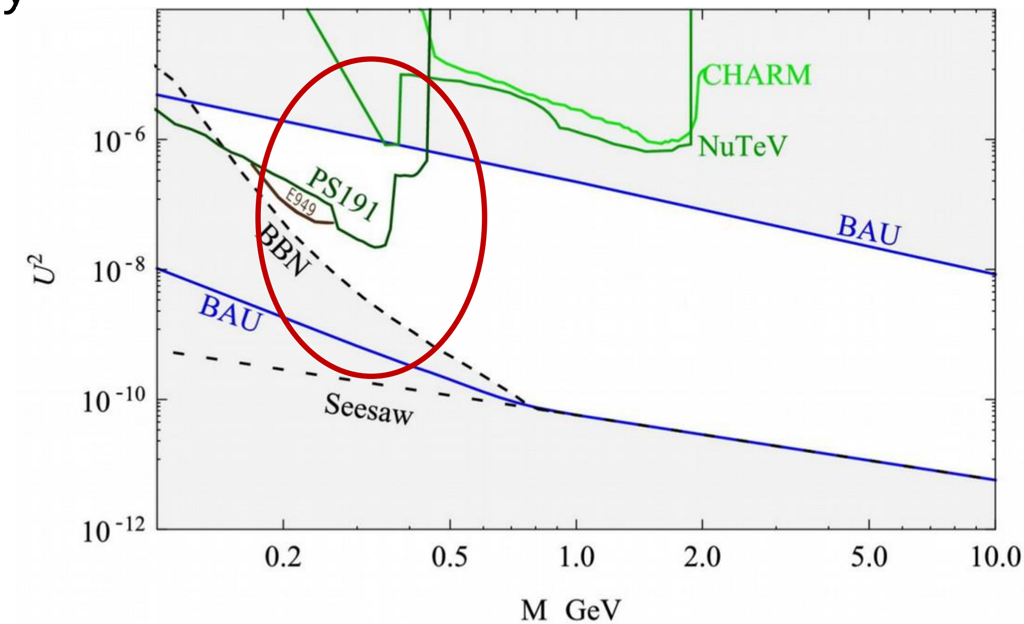
Kaon Factory: NA62 & NA48/2

→HEAVY NEUTRAL LEPTONS

→STATUS OF K→$\pi\nu\bar{\nu}$

HNL: Heavy Neutral Lepton

- Neutrino oscillations imply they are massive → No SM
- Dark Matter and Baryon asymmetry → No SM
- Majorana/Sterile neutrinos (HNL): Asaka-Shaposhnikov *[PLB 620 (2005) 17]* model (νMSM)
  - Three sterile (Majorana) neutrinos N1 is the lightest (dark matter) N2, N3 produce ν masses and solve SM neutrinos problems and Baryon asymmetry
- Inflatons: Shaposhnikov-Tkachev *[PLB 639 (2008) 414]*
  - Add a real scalar field (**inflaton** χ) to νMSM to explain Universe homogeneity and isotropy



- Short-lived sterile neutrinos/inflatons decay can be observed in **decay**: $\mathbf{K^+ \to \pi^+ N}$ with $\mathbf{N \to \mu^+\mu^-}$ or $\mathbf{K^+ \to \mu^+ N}$ with $\mathbf{N \to \pi^\pm \mu^\mp}$
- If kinematically allowed HNL can be observed in **production**

$$\Gamma(K^\pm \to l^\pm N) = \Gamma(K^\pm \to l^\pm \nu)\, \rho(m_N) |U_{l4}|^2$$

NA48/2: charged K CP violation

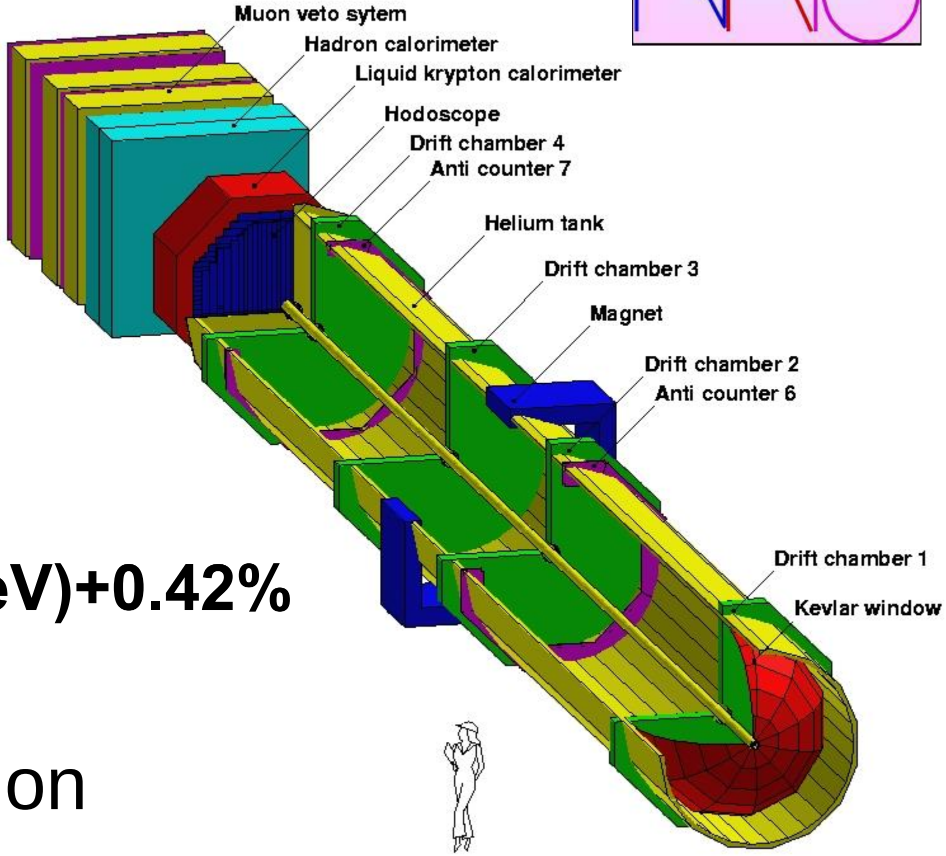
- K+/K- beams (60 GeV/c)
  - Produced in Be target from 400 GeV/c protons from SPS
- Main goal: study CP violation in **3π decays**
- Spectrometer: 4 DCH

$\sigma_P/p = 1.02\% + 0.044\%\ p(\mathrm{GeV})$

- LKr Calorimeter

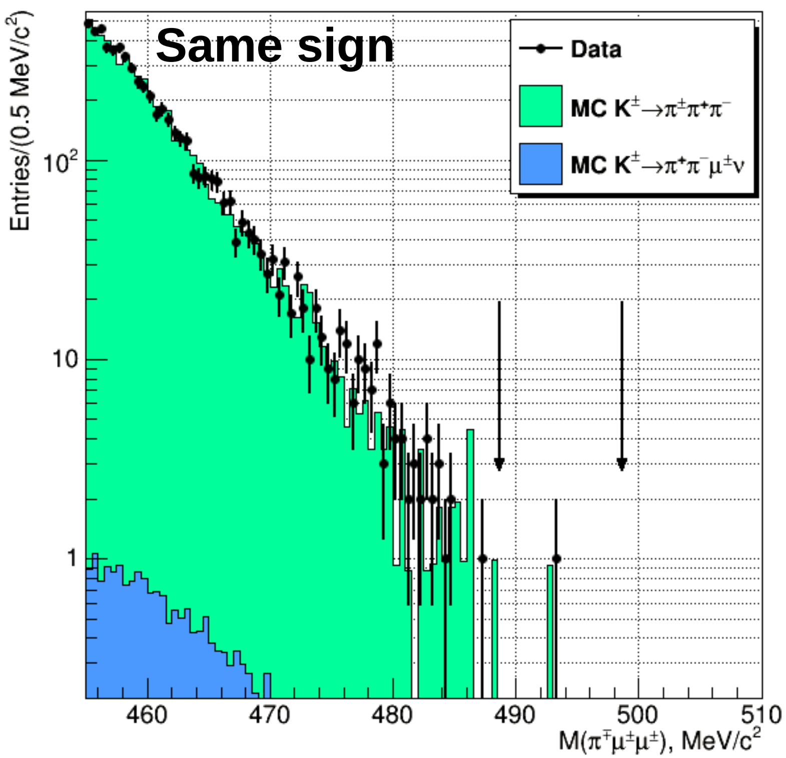
$\sigma_E/E = 3.2\%/\sqrt{E(\mathrm{GeV})} + 9\%/E(\mathrm{GeV}) + 0.42\%$

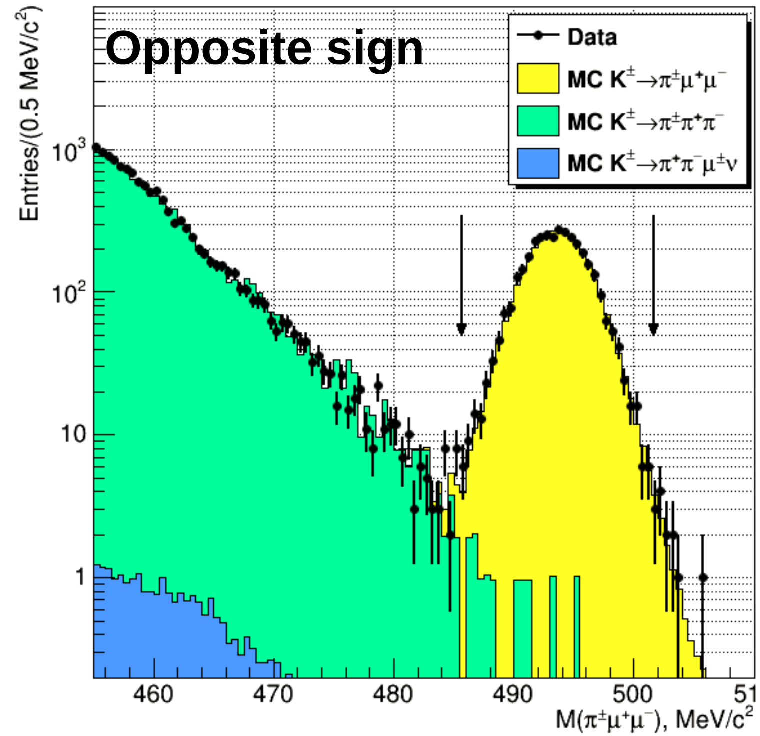
- Veto system, fast timing, flexible trigger configuration
- Data collected in 2003+2004



LNV & LNC selection in NA48/2 (2003+2004)

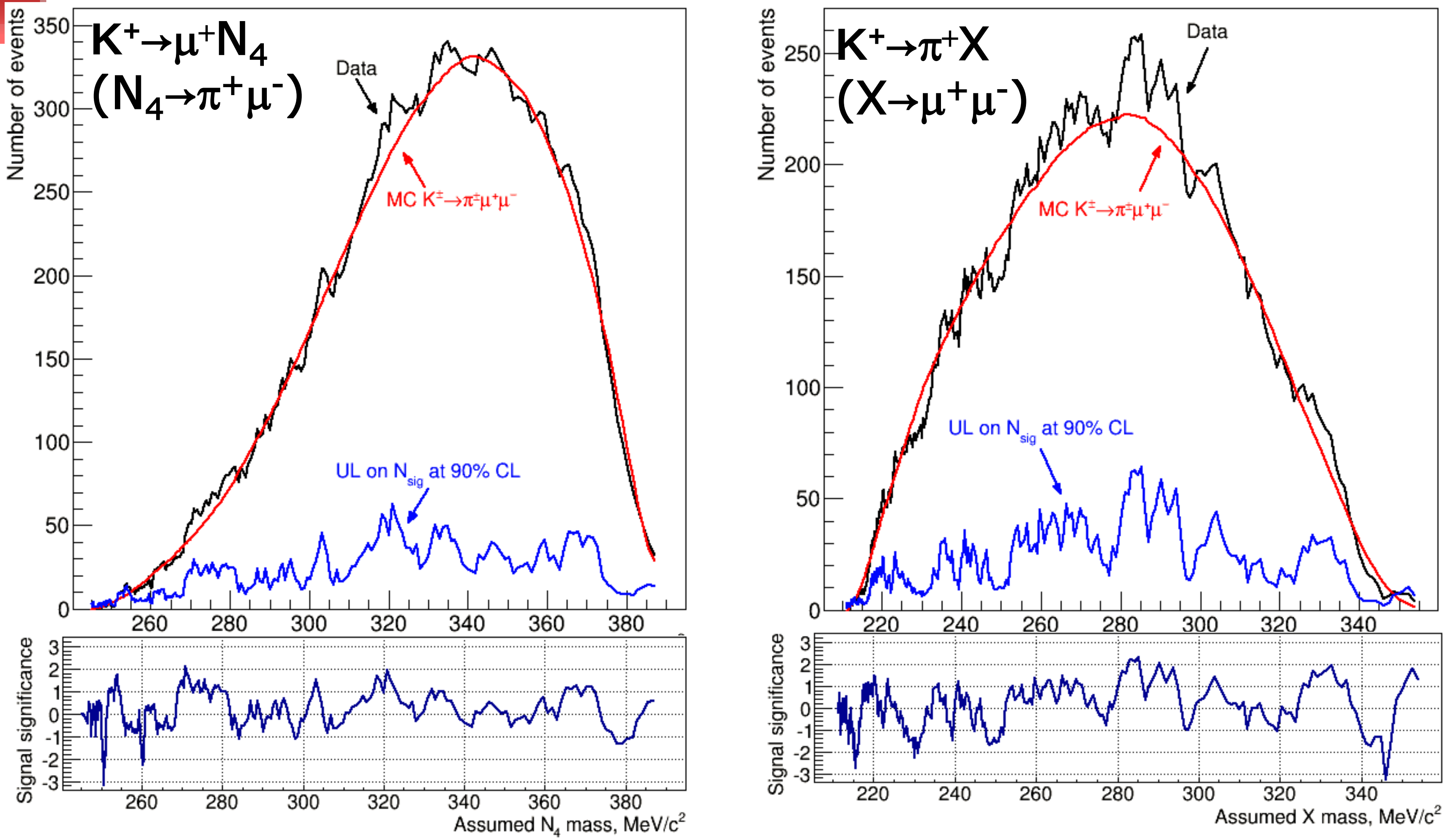
- 3 track topology
  - Opposite/same sign muons
  - No missing momentum
  - Total mass close to K mass (5 MeV/c^2)
- Background:
  - $K_{3\pi}$, $K_{\mu 4}$





- **1.64×10^{11} K** decays in fiducial region
  - Opposite sign: **3489** events ((0.36±0.10)% bkg)
  - Same sign: **1** events (1 bkg)

LNC: mass scan

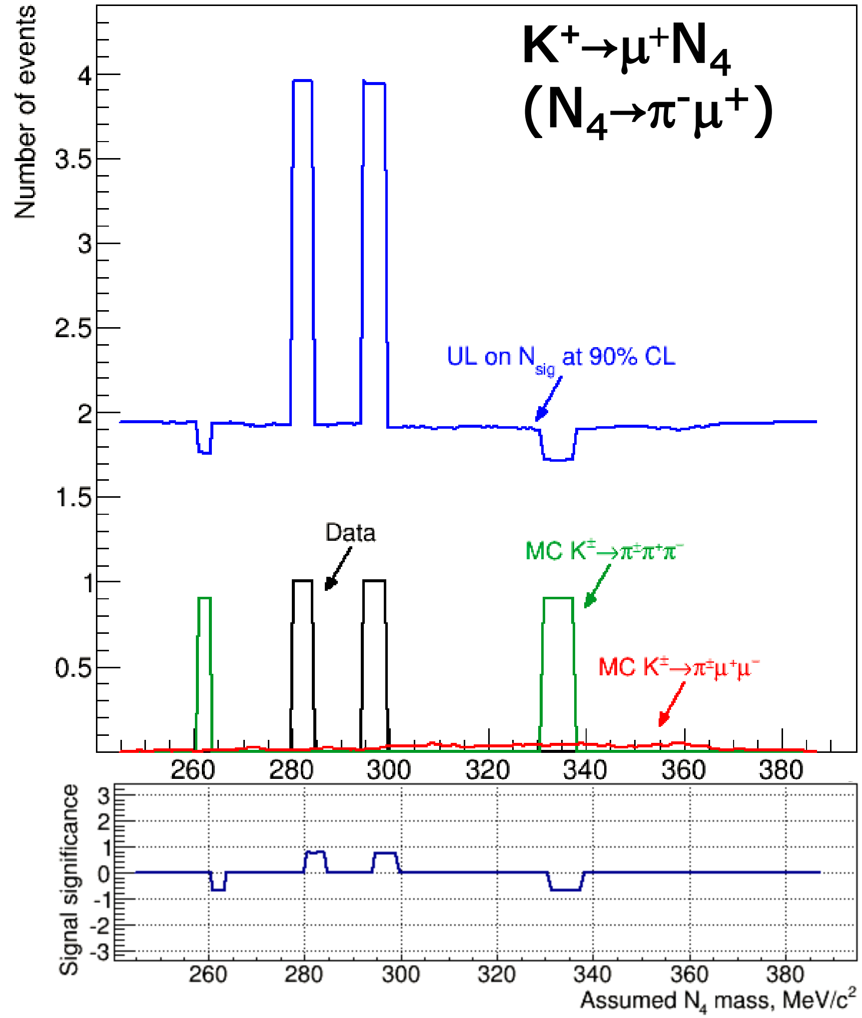


- Mass scan:
  - About **280** mass bins
  - The signal significance never exceed 3σ: **no signal observed**

$$z = \frac{n_{obs} - n_{exp}}{n_{obs} \oplus n_{exp}}$$

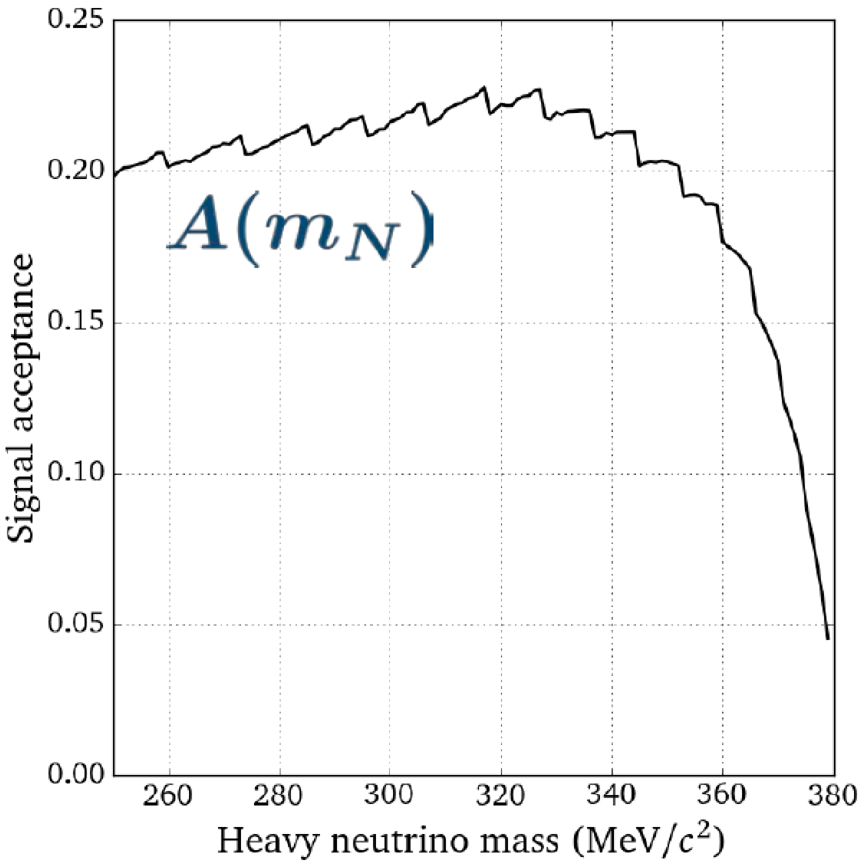
LNV: mass scan

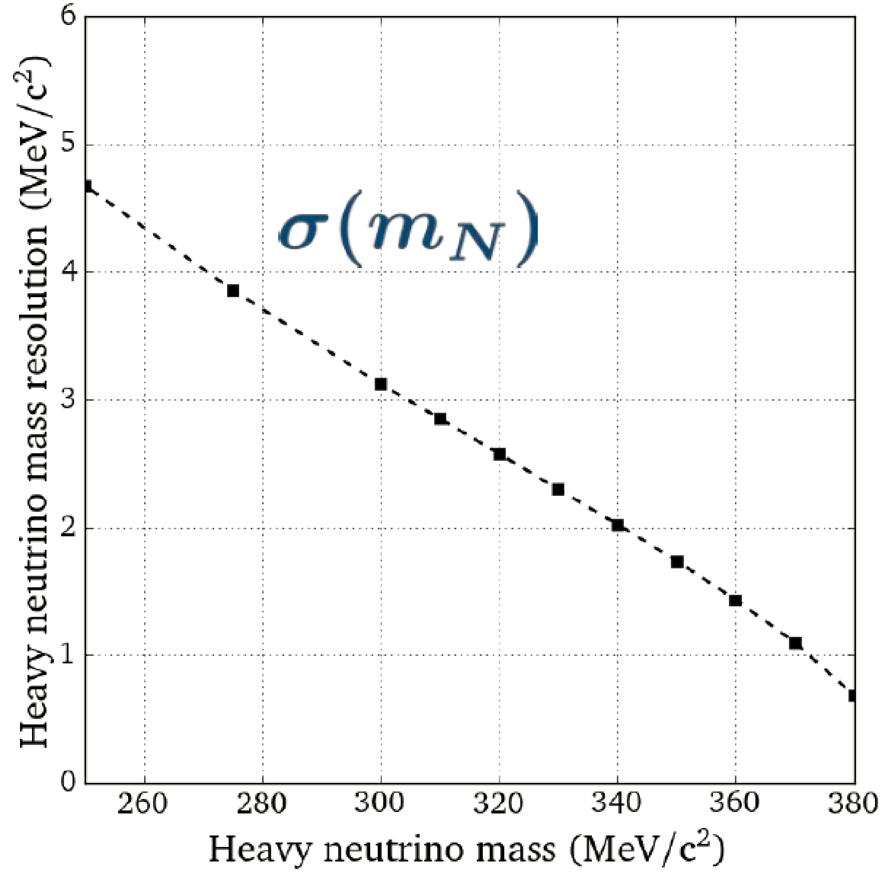
- **UL 8.6x10^{-11} @ 90% CL**
- Mass scan:
  - About **280** mass bins
  - The signal significance never exceed 3σ: **no signal observed**
- Both for opposite/same sign muons the acceptance is studied as a function of the heavy neutrinos/inflaton lifetime



Phys. Lett. B769 (2017) 67-76

Search for HNL in NA62-RK (2007)





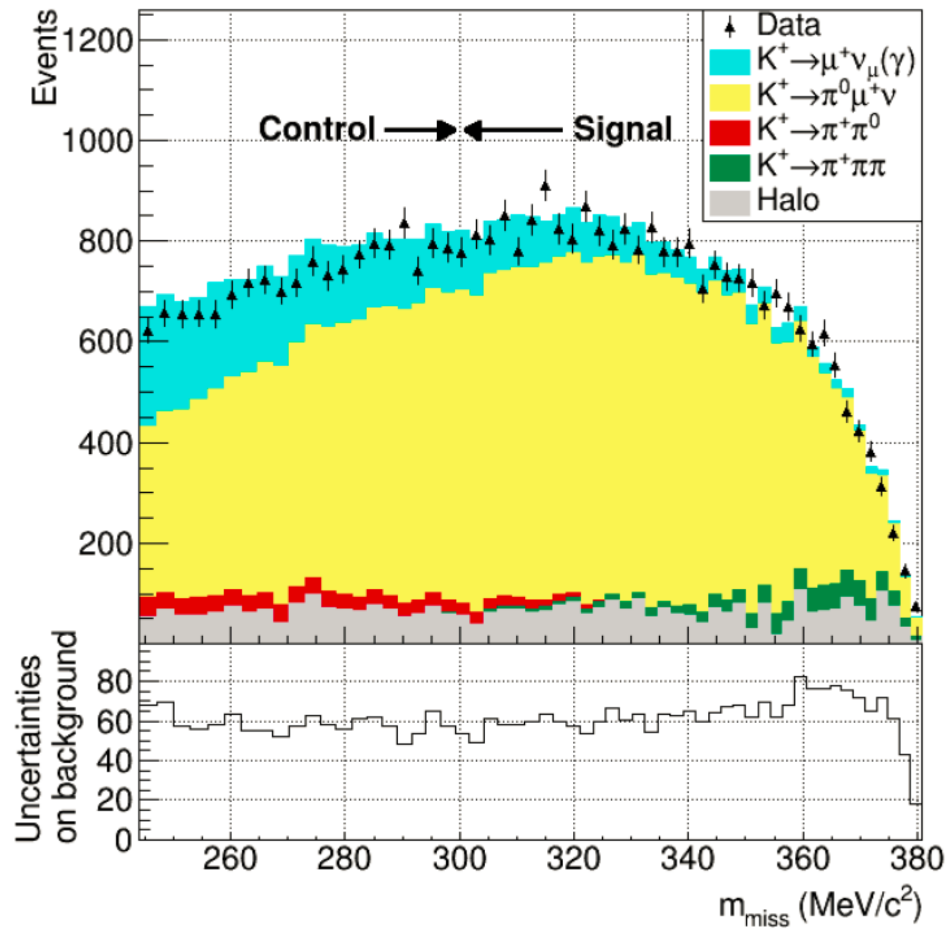
- (almost) Same detector as in NA48/2, run dedicated to measure R_K
- **~6·10^7 K** collected (D=150 with 1-μ track trigger)
- Study the missing mass in **$K^+ \to \mu^+ N$:** HNL in production
- Good acceptance and resolution in a wide range of HN masses

Search for HNL in NA62-RK (2007)

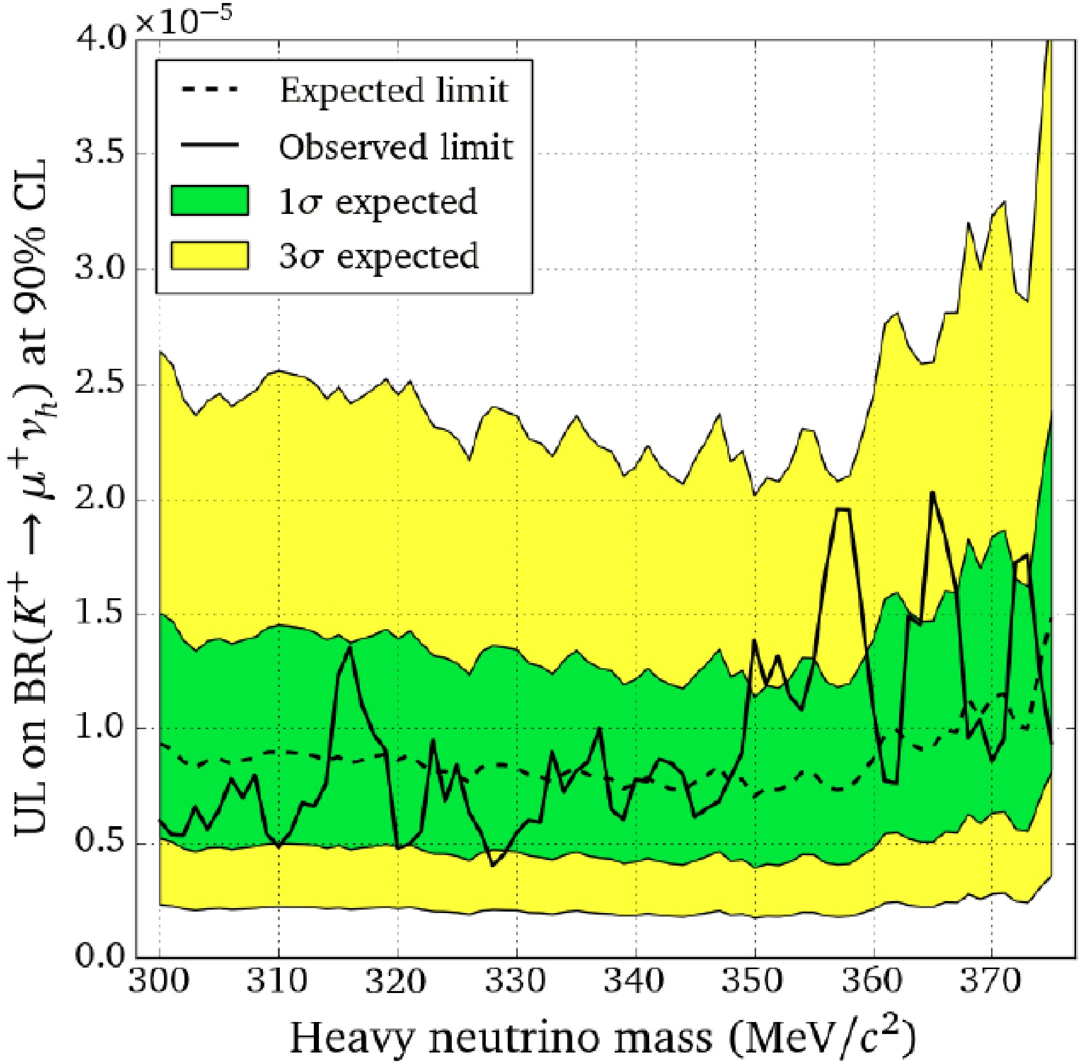
- 9.45×10^6 events in the final plot (acceptance 25%)
- Scan in bins of 1 MeV/c^2 of missing mass

$$m_{miss} = \sqrt{(P_K - P_\mu)^2}$$

- Mass range **(300-375) MeV/c^2**
- Search window defined by mass resolution

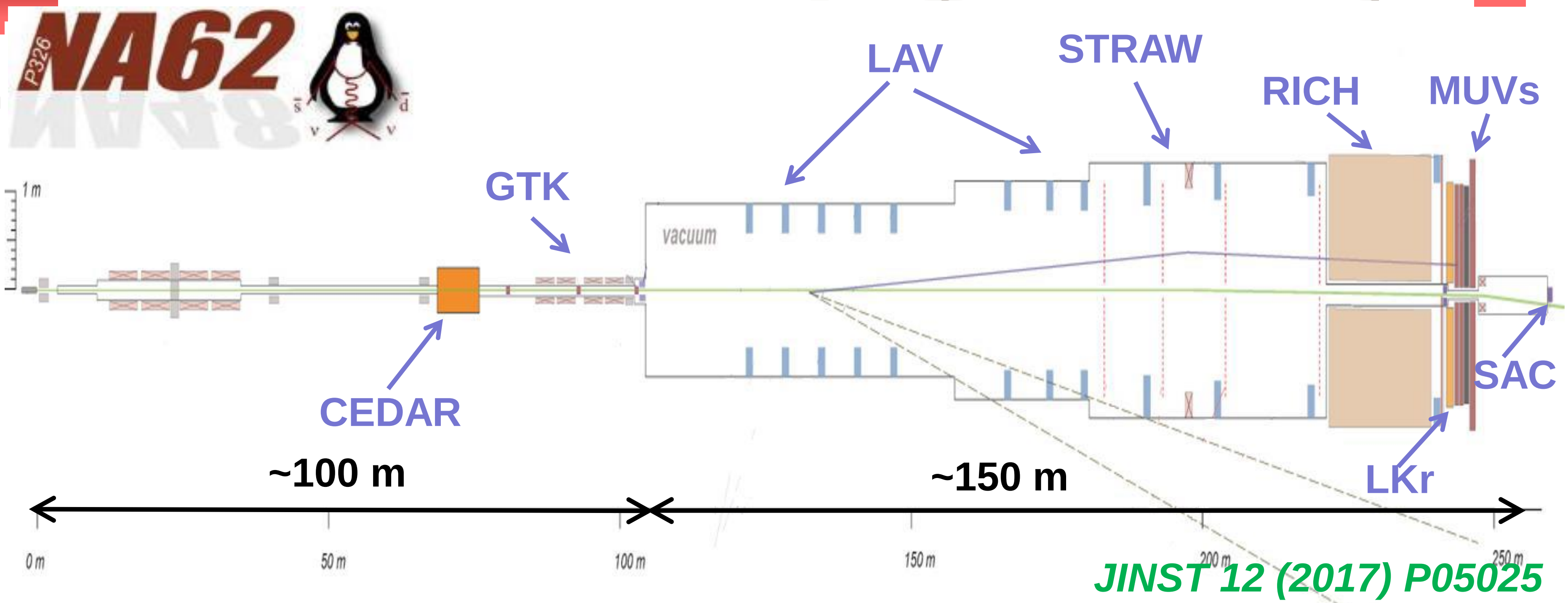


- Rolke-Lopez method used to extract the upper limit
- **No HNL signal found** with significance of 3σ



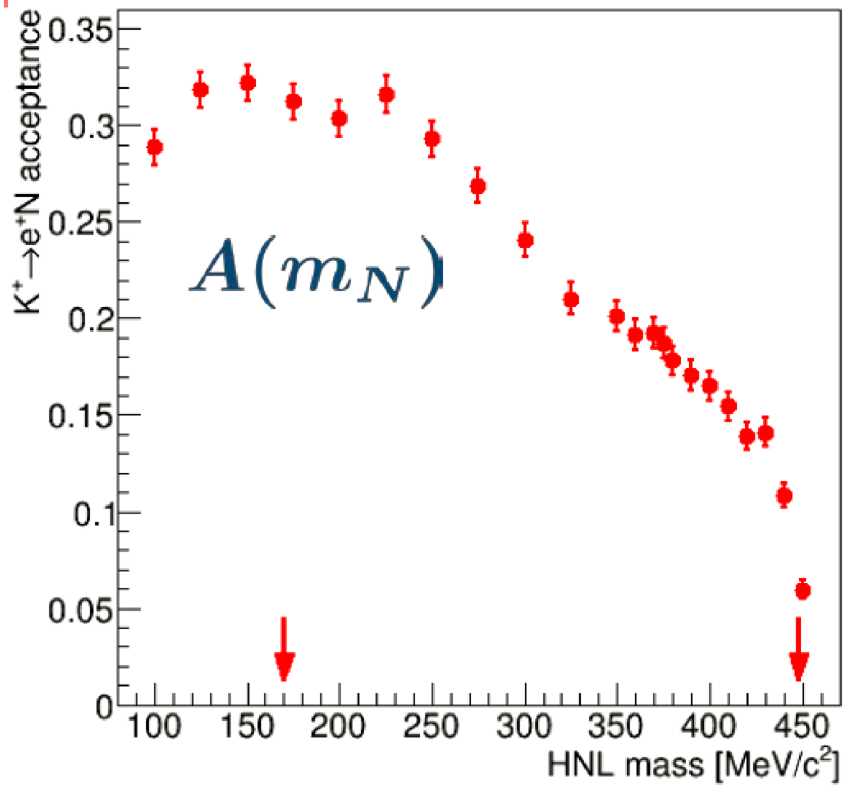
Phys. Lett. B772 (2017) 712-718

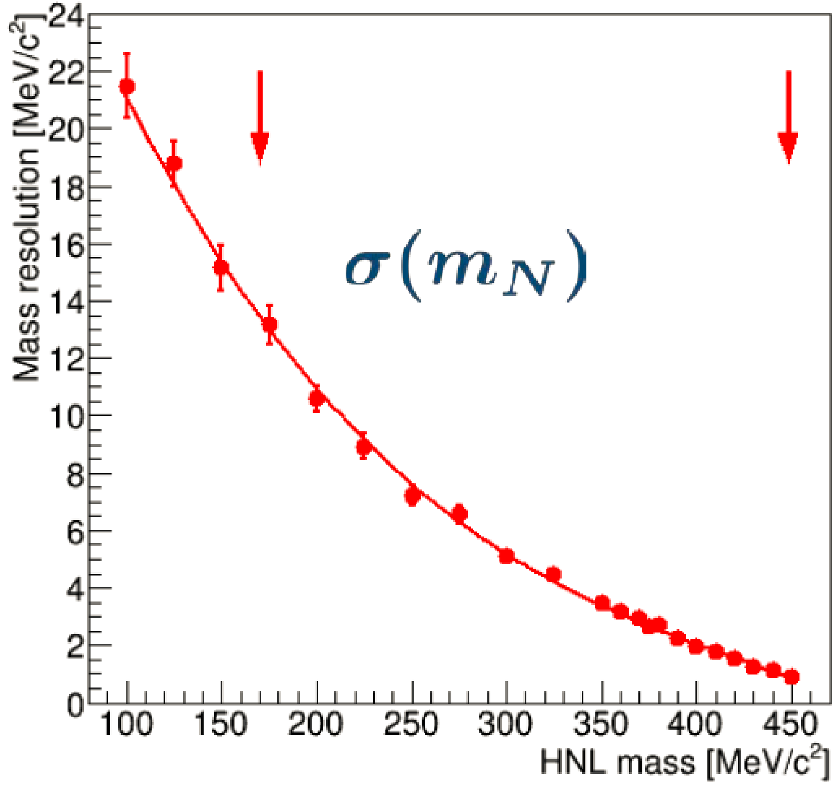
NA62: ultra-rare decays



- 75 GeV/c hadron beam (~8% K) from 400 GeV/c p from SPS
  - Total rate ~800 MHz, 10^{12} pot, 3.5 s spill
- Complete kinematics, quasi-hermetic veto system, PID system, calorimeters
- Main goal: **$K^+ \rightarrow \pi\nu\bar{\nu}$ O(100) events with decay in flight**
  - 10^{13} K+ decays, 10% acceptance, bkg rejection $>10^{12}$

Search for HNL in NA62 (2015)





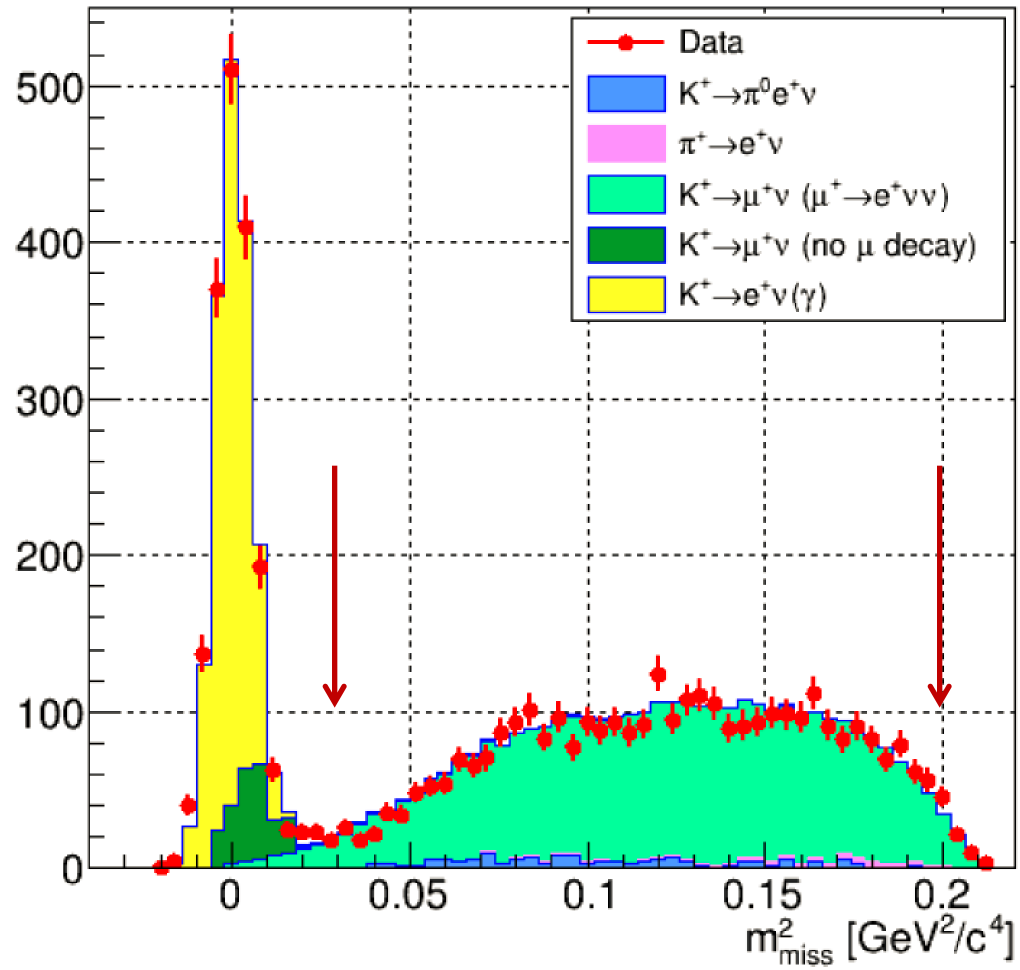
- HNL in production
- Search in the electron channel: **$K^+ \to e^+N$**
- ~3·10^8 K collected
- Muon channel suppressed by trigger

Search for HNL in NA62 (2015)

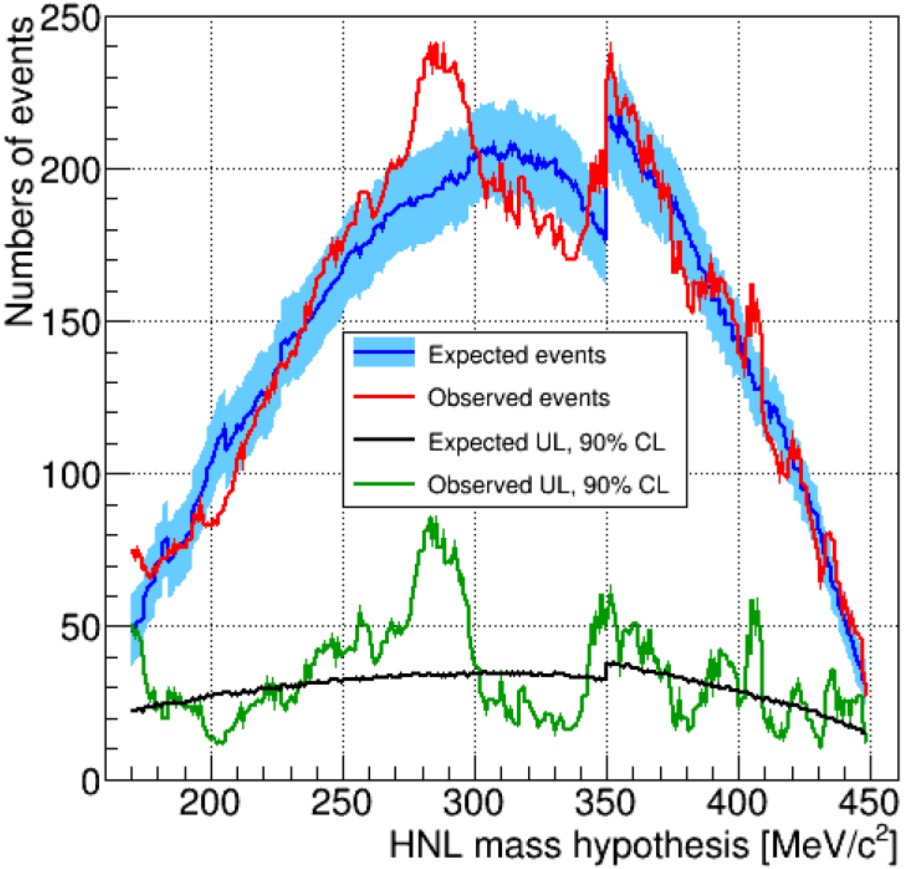
- Scan in bins of 1 MeV/c^2 of missing mass

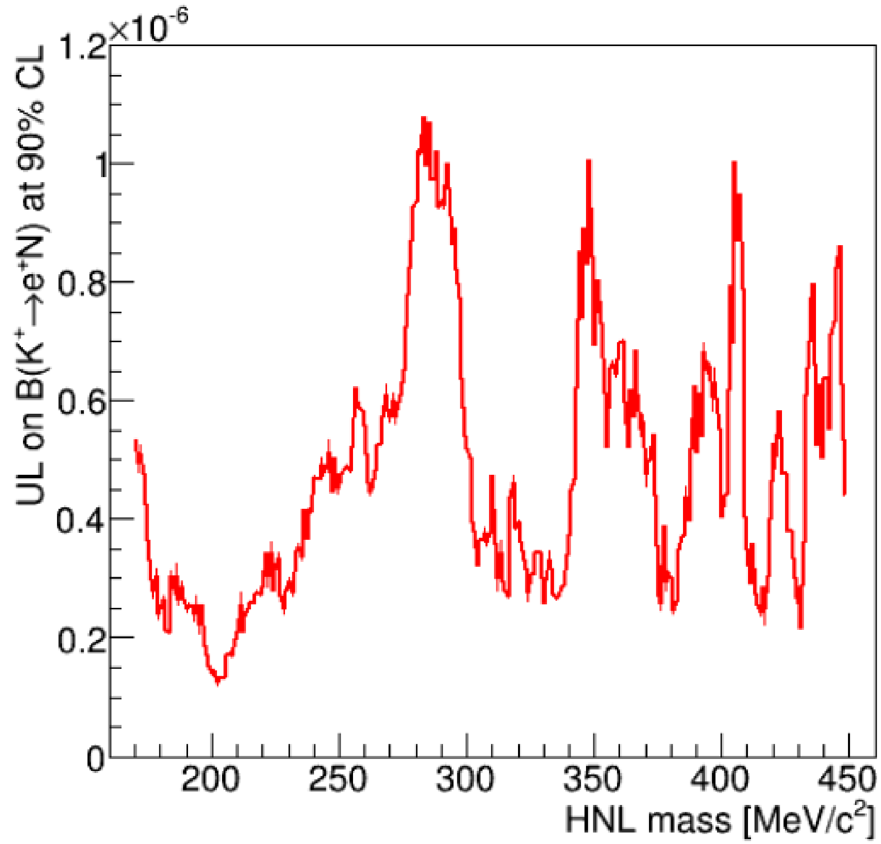
$$m^2_{miss} = (P_K - P_e)^2$$

- Mass range **(170-448) MeV/c^2**
- Search window defined by mass resolution



Search for HNL in NA62 (2015)





- Rolke-Lopez method used to extract the upper limit

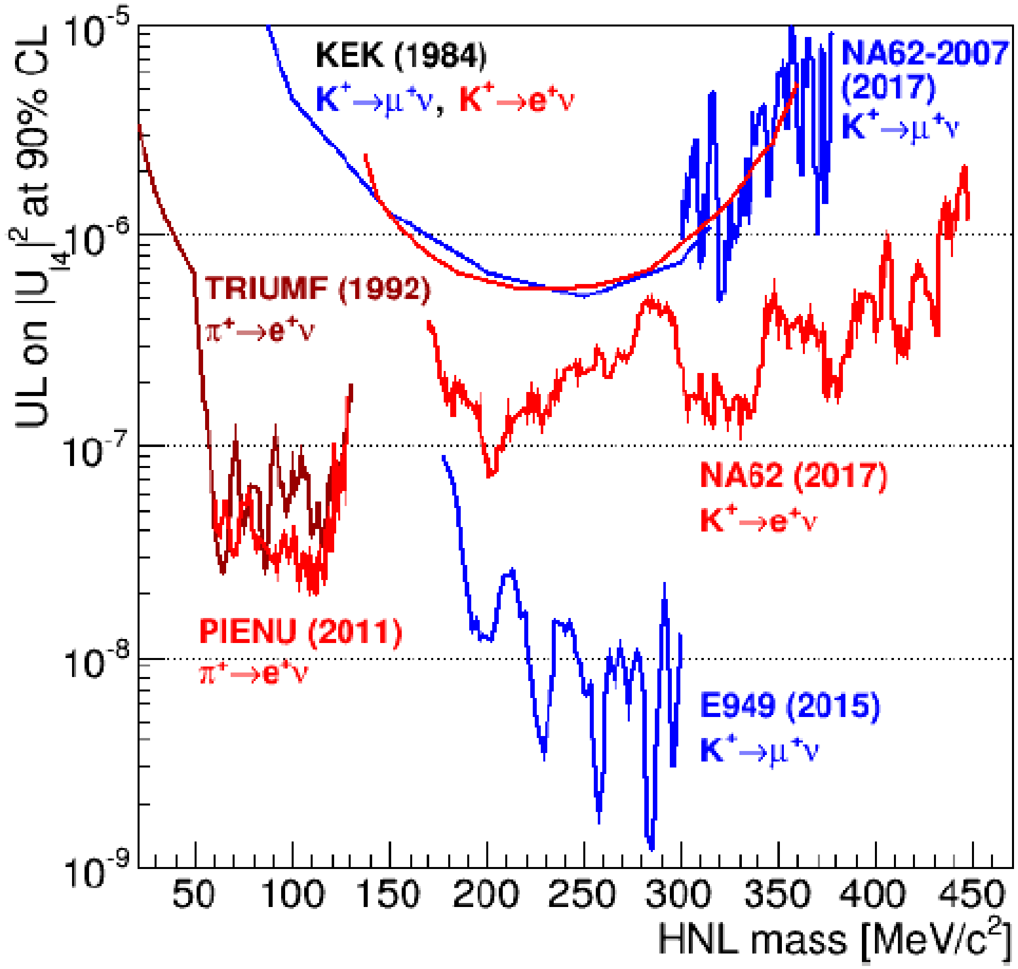
Paper in preparation

- **No HNL signal found** with significance of 3σ

Summary on HNL

In decay:

- **LNV $K^+ \to \pi^- \mu^+ \mu^+$** : UL 8.6×10^{-11} @ 90% CL
- Majorana sterile neutrinos **$K^+ \to \mu^+ N_4$ ($N_4 \to \pi^- \mu^+$)**, heavy sterile neutrinos **$K^+ \to \mu^+ N_4$ ($N_4 \to \pi^+ \mu^-$)**, inflatons **$K^+ \to \pi^+ X$ ($X \to \mu^+ \mu^-$)**: UL $\sim 10^{-10}$-10^{-9} for $\tau < 100$ ps
- Reached $O(10^{-4})$ limit on $|U_{\mu 4}|^2$ (for m_{N4} in **(245; 390) MeV/c^2** (also short-lived HNs))



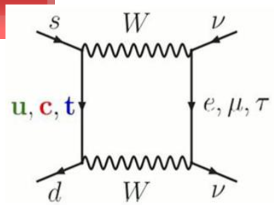
In production:

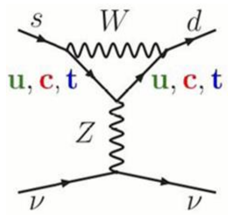
- Improved limits on $|U_{\mu 4}|^2$ for m_{N4} in **(300-375) MeV/c^2**
- New limits on $|U_{e4}|^2$ reaching $10^{-6} - 10^{-7}$ for m_{N4} in **(170-448) MeV/c^2**

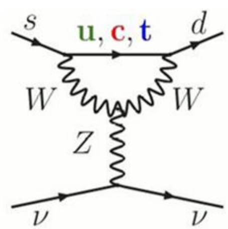
→HEAVY NEUTRAL LEPTONS

→STATUS OF $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

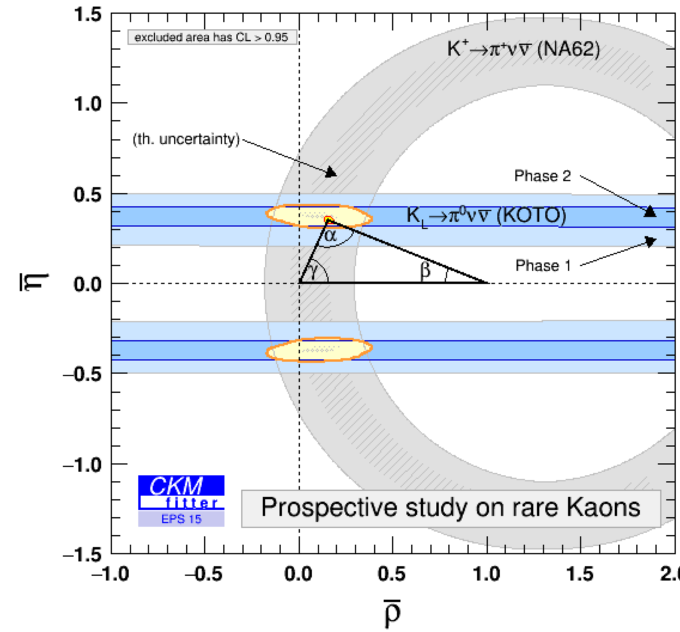
NA62: $K^+ \to \pi^+ \nu\bar{\nu}$







- $K \to \pi\nu\bar{\nu}$ is a "golden mode":
  - FCNC process: **s→d** coupling with highest suppression
  - Theoretically clean: hadronic matrix element measured with K_{l3}
  - The major contribution in the error for the prediction is parametric: V_{cb} and γ



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

$$= (8.4 \pm 0.6) \times 10^{-11}$$

[Brod, Gorbahn, Stamou, Phys. Rev.D 83, 034030 (2011)],[Buras et. al. arXiv:1503.02693]

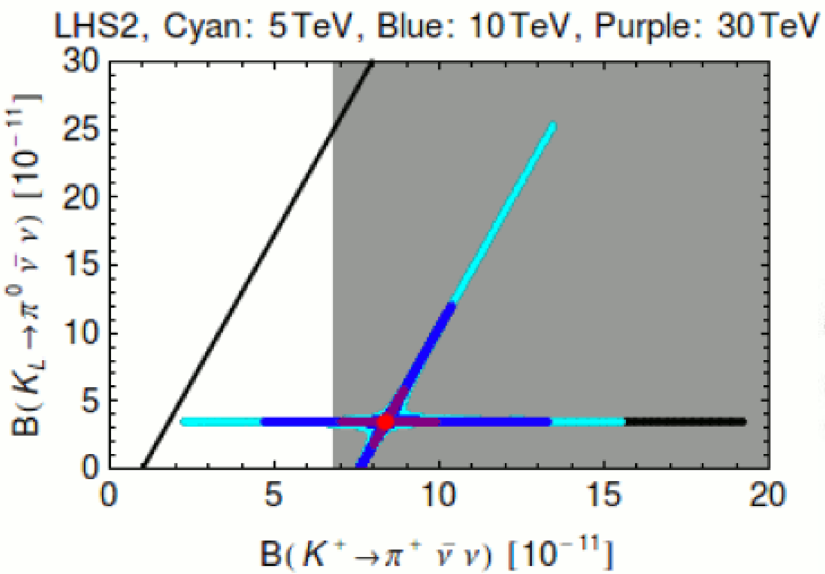
- Present experimental result (E949 - 7 events)

$$BR\left(K^+ \to \pi\nu\bar{\nu}\right) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

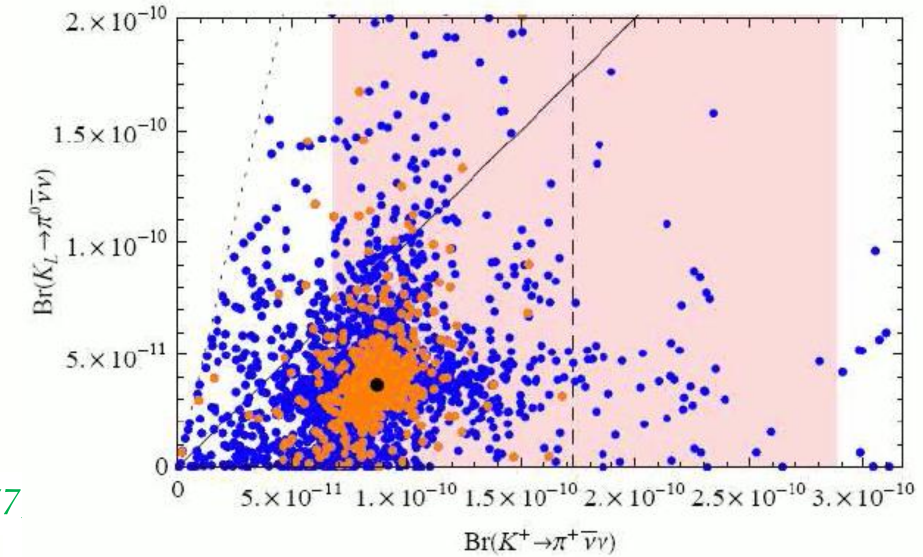
[Phys. Rev. D 79, 092004 (2009)]

NA62: new physics

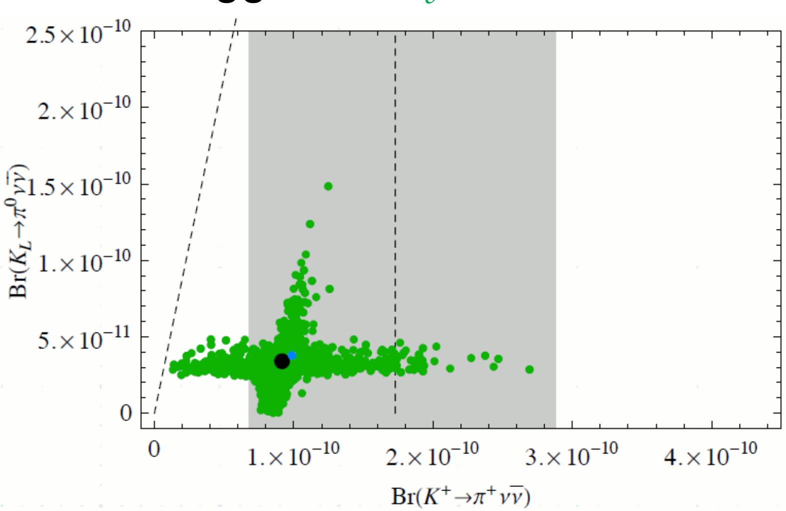
Z′ model *[A. J. Buras, F. De Fazio and J. Girrbach JHEP 1302 (2013) 116]*

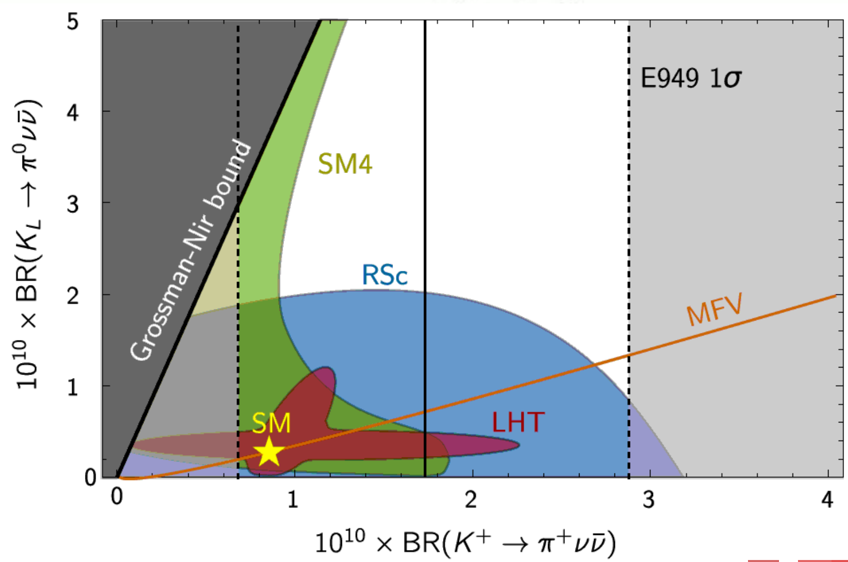


Randall-Sundrum *[JHEP 0903 (2009) 108]*



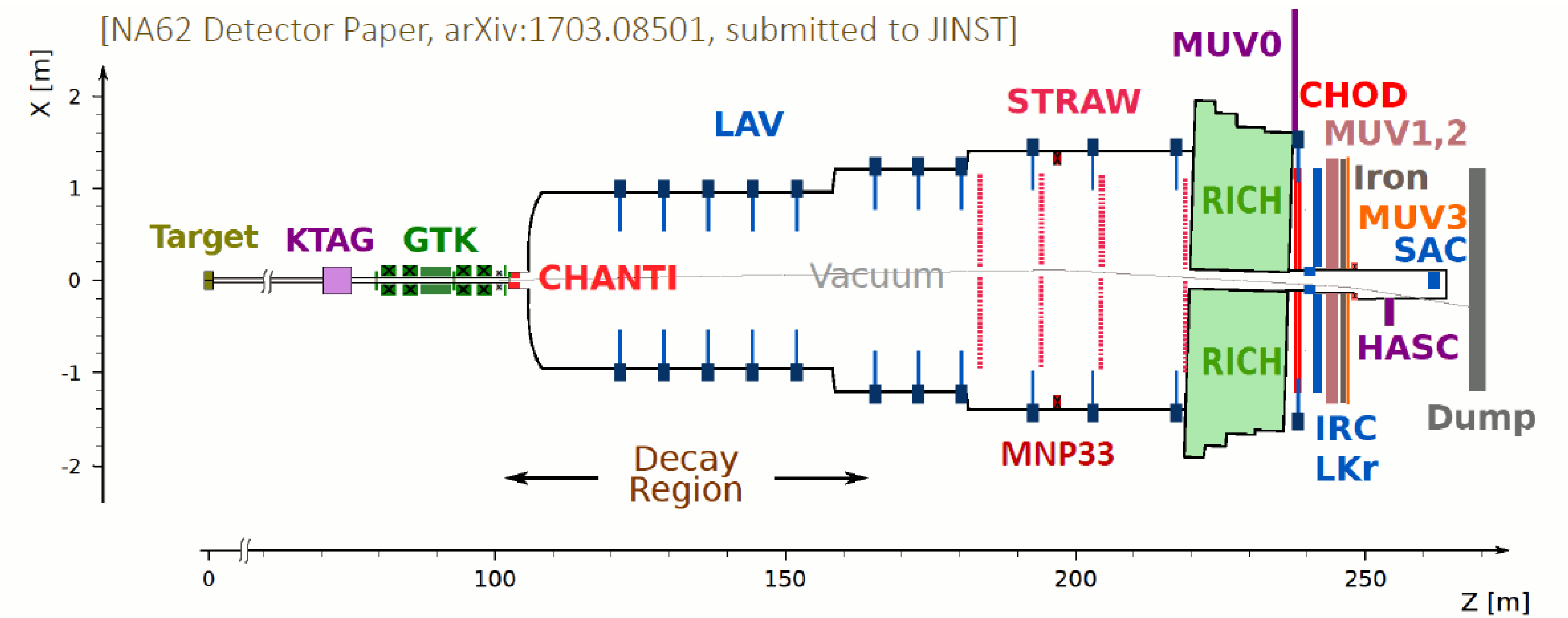
Littlest Higgs *[Acta Phys. Polon. B41 (2010) 657*





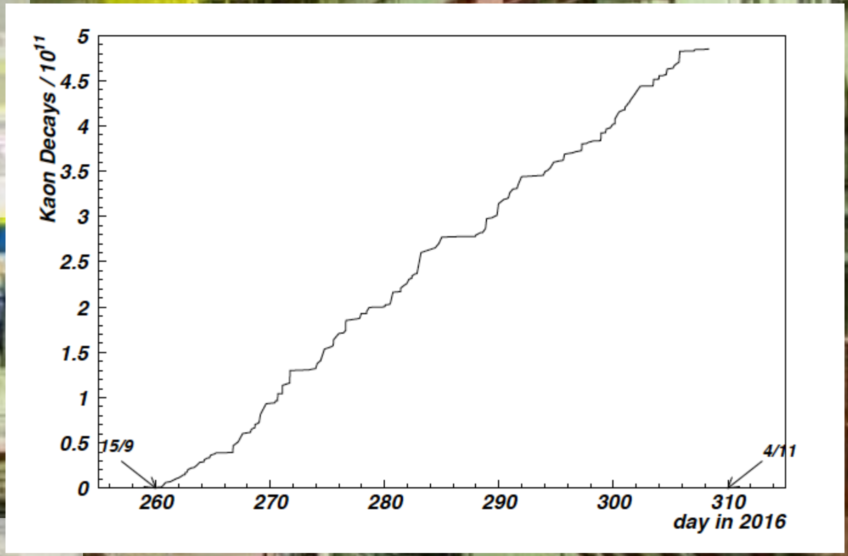
[See Tappei Kitahara]

NA62 Detector



NA62: runs

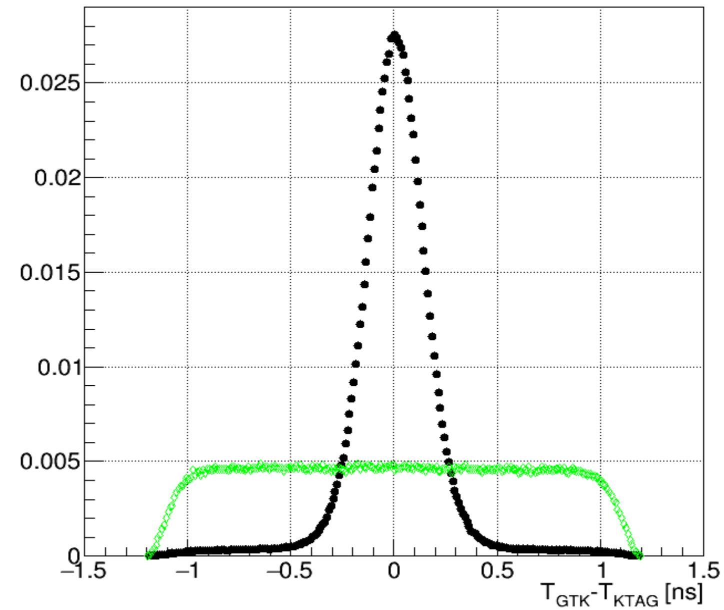
<2015: Technical and pilot runs
2015: commissioning run
2016: commissioning+physics run
2017: physics run
2018: physics run

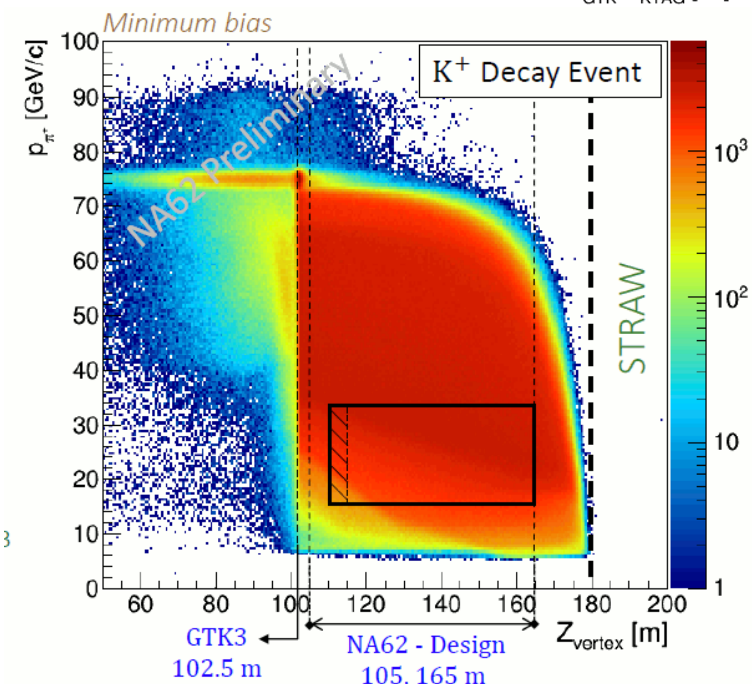


2016
~75 days : detectors commissioning
~50 days: GTK commissioning and physics for exotics
~50 days: $\pi\nu\nu$ data taking
4×10^{11} K^{+} decays collected, with 13×10^{11} ppp (40% nominal intensity)

$\pi\nu\bar{\nu}$ selection

- Decay in flight (75 GeV Kaons):
  - Maximize K yield wrt protons
  - High π^0 momentum (easier to veto main background)
  - Exploit pion missing mass
- K/π matching:
  - Good time resolution (~80 ps on K and ~150 ps on π)
  - Spatial matching based on CDA (GTK and STRAW): σ(cda)~1.5 mm
- Decay region: 115<Z<165 m
  - Defined by GTK3 and margin to avoid early decays
  - CHANTI to veto interaction in GTK3
  - Momentum : $15<p_\pi<35$ GeV/c





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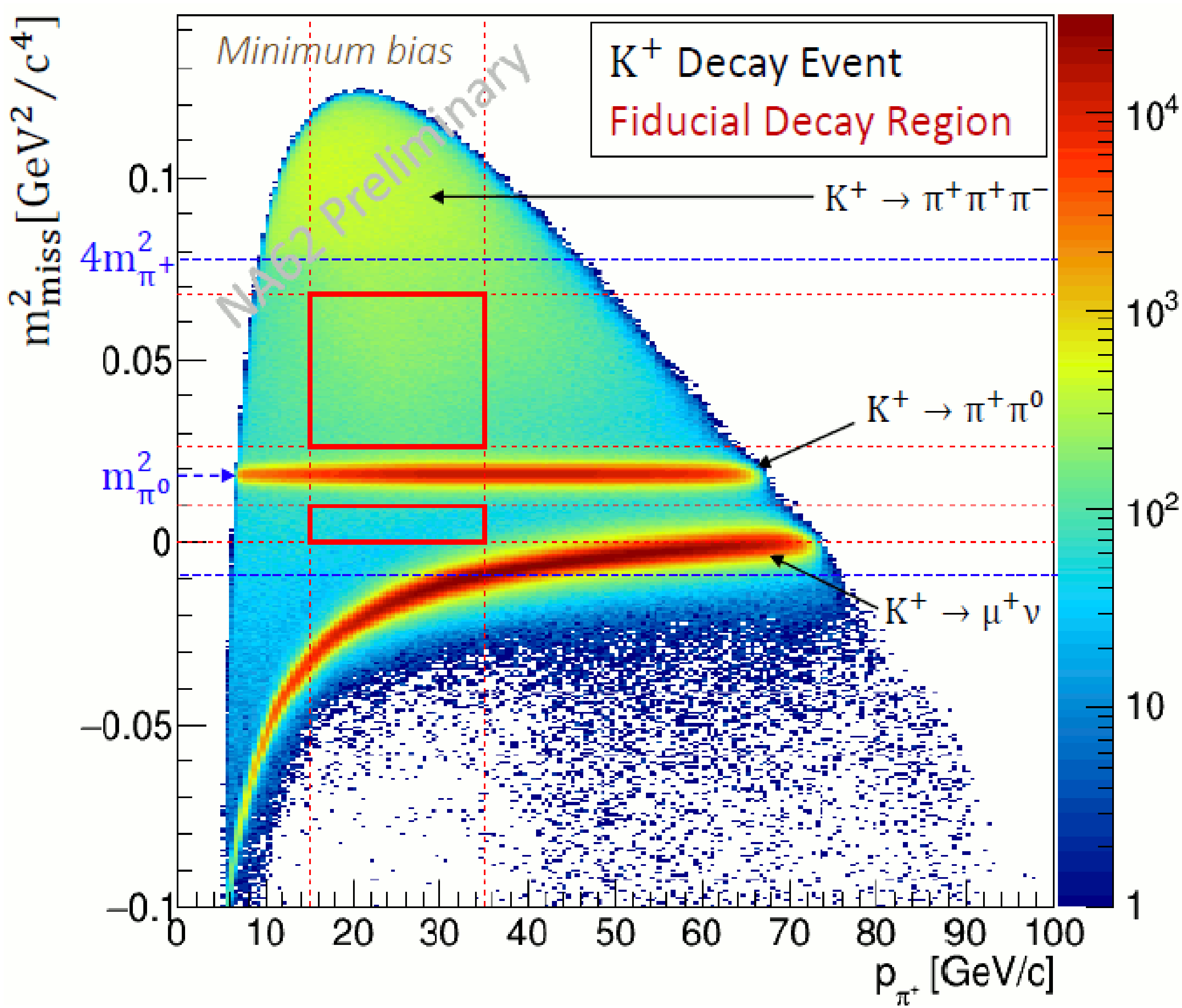
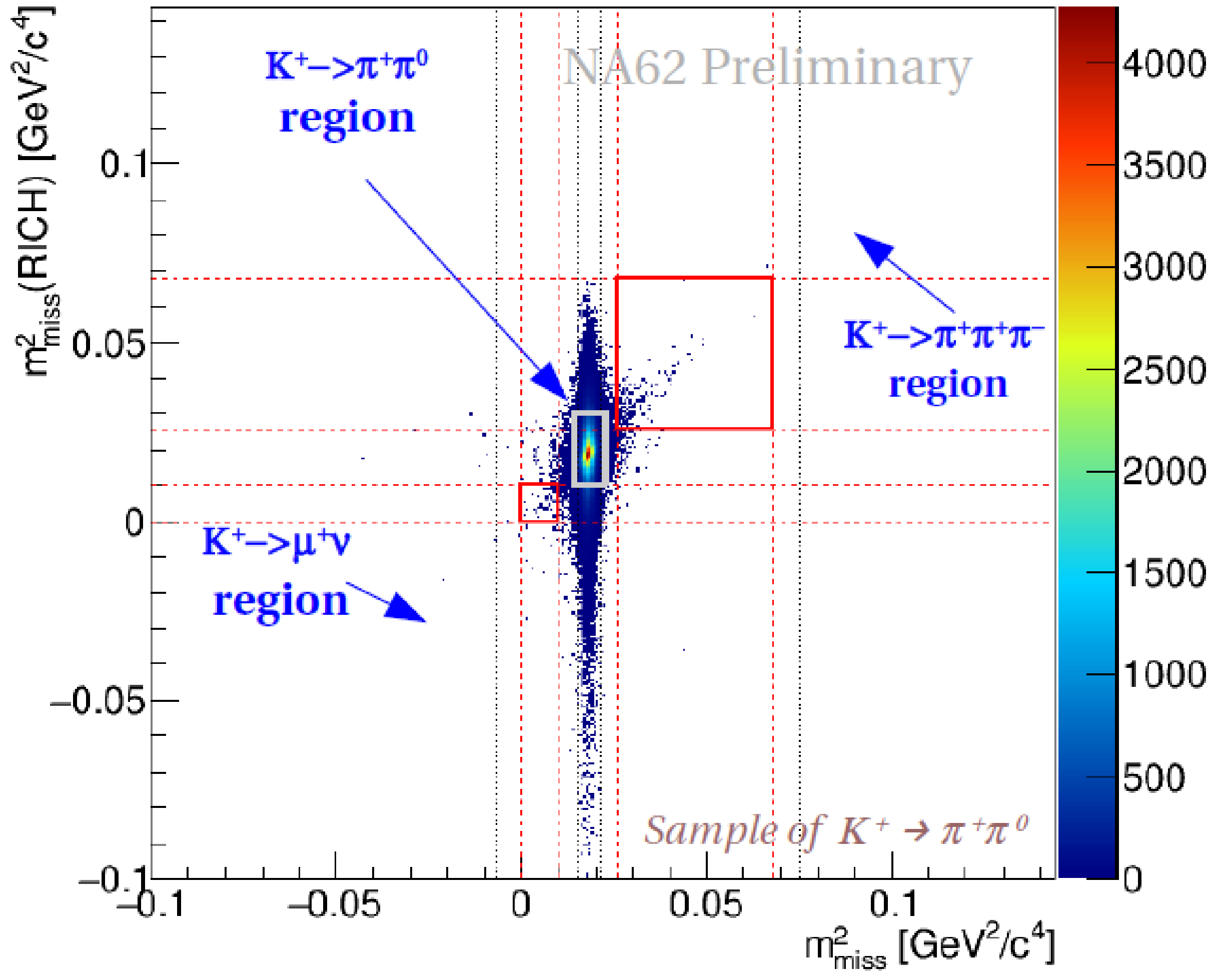
Signal regions

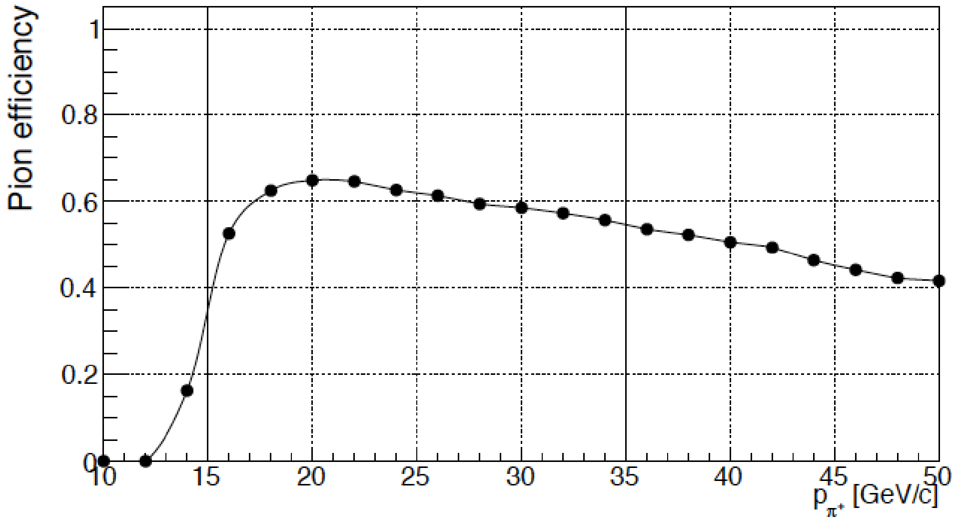


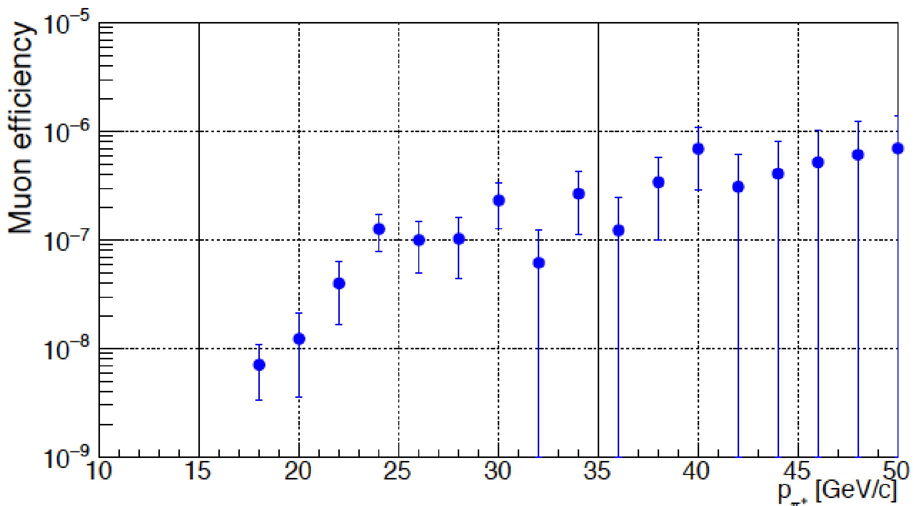
- Two different definition of **missing mass**: pion momentum measured with RICH and STRAW
- Kinematical rejection measured on data
- Remaining events in signal regions:
  - **$\pi^+\pi^0$: ~ 6x10^{-4} $\mu^+\nu$: ~ 3x10^{-4}**



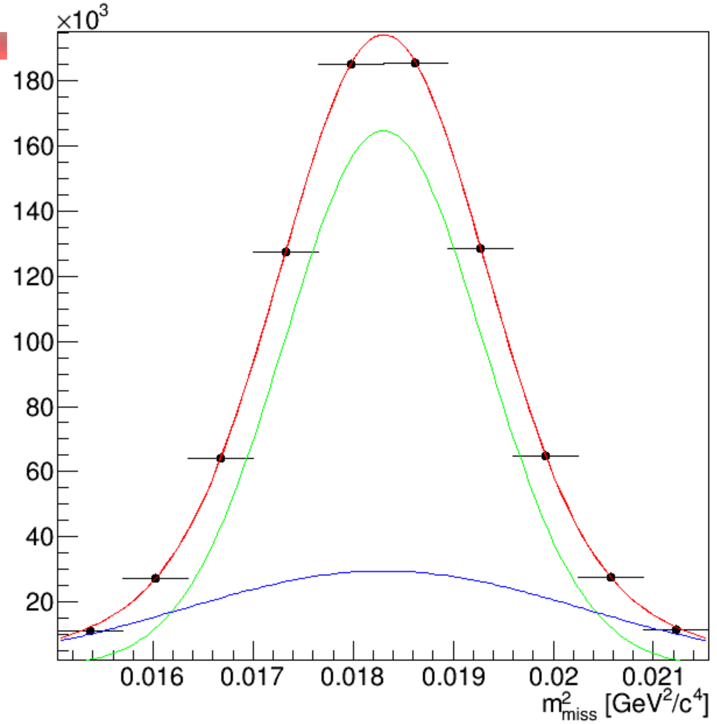
$\pi-\mu$ separation

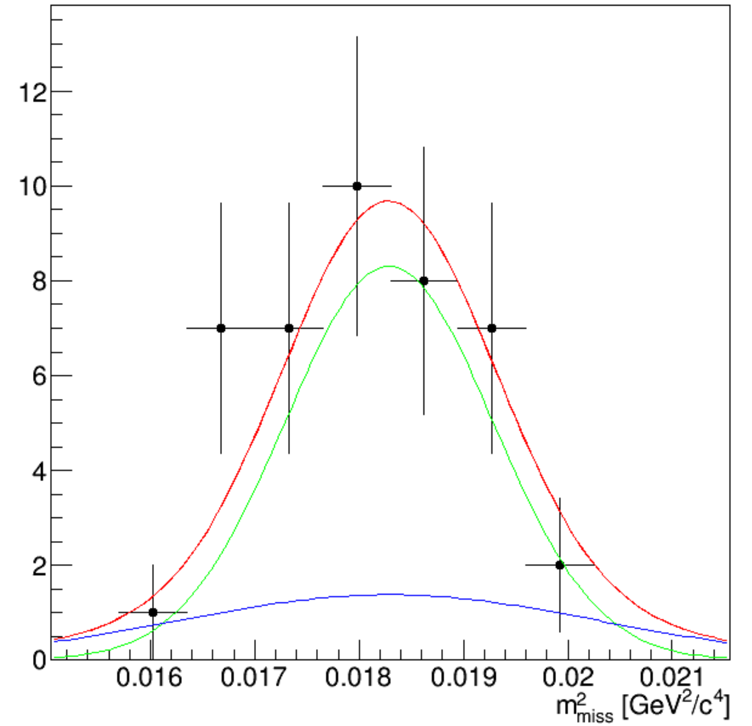
- PID with calos:
  - $\varepsilon(\mu)/\varepsilon(\pi)=10^{-5}/80\%$
  - LKR, MUV1,2
- PID with RICH:
  - $\varepsilon(\text{RICH}) = 90\%$
  - $\varepsilon(\mu)/\varepsilon(\pi)$=10-2/80%
- Separation measured with $K_{3\pi}$ and $K_{2\pi}$
- Discrimination studied as a function of momentum
- Muon suppression $\sim 10^{-7}$





γ vetos





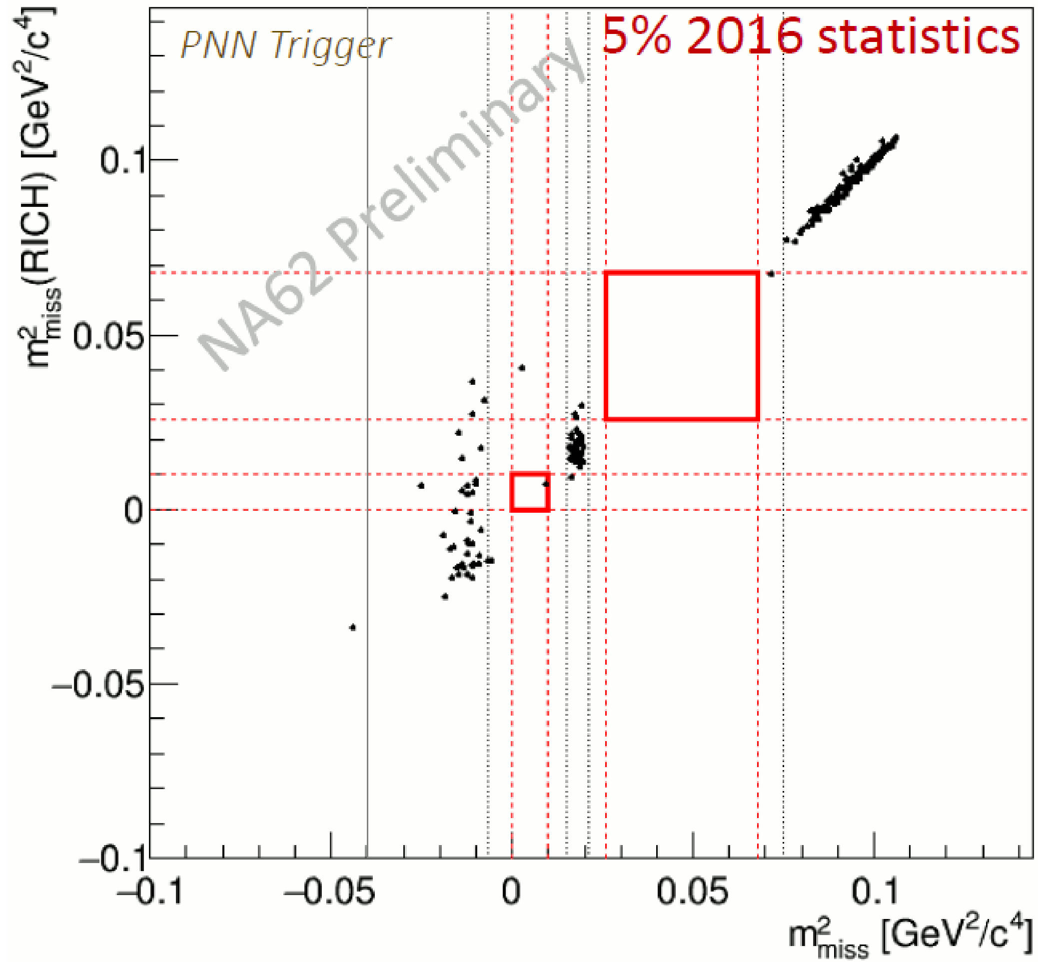
- SAC, IRC, LAV, LKR
- Goal: $O(10^{-7})$ to $O(10^{-8})$ rejection of π^0 from $K^+ \to \pi^+\pi^0$ decays.
- Measured π^0 rejection factor with the $K^+ \to \pi^+\nu\bar{\nu}$ selection: $\varepsilon = (1.2 \mp 0.2) \times 10^{-7}$.
- Random veto on signal measured with $K_{\mu 2}$: 16% at 40% intensity, can be improved.

Expected signal

- Flux measured from $\pi\pi^0$
- A($\pi\nu\nu$) from MC: **~3.3%**
- A(Norm) from MC: **~7%**
- Trigger efficiency, γ rejection, PID efficiency and background **measured on data**
- N(K) decays: **$2.3\text{x}10^{10}$**
- Expected SM $\pi\nu\nu$: **0.064 events (5% 2016 statistics)**
- Sensitivity of ~1 SM event in 2016

Preliminary results

- Background estimated with data driven method
  - $K^+ \to \pi^+\pi^0$: **0.024**
  - $K^+ \to \mu^+\nu$: **0.011**
  - $K^+ \to \pi^+\pi^+\pi^-$ **0.017**
  - **Beam-induced <0.005**
- **No events found in the signal region**
- Preliminary analysis: optimization in progress



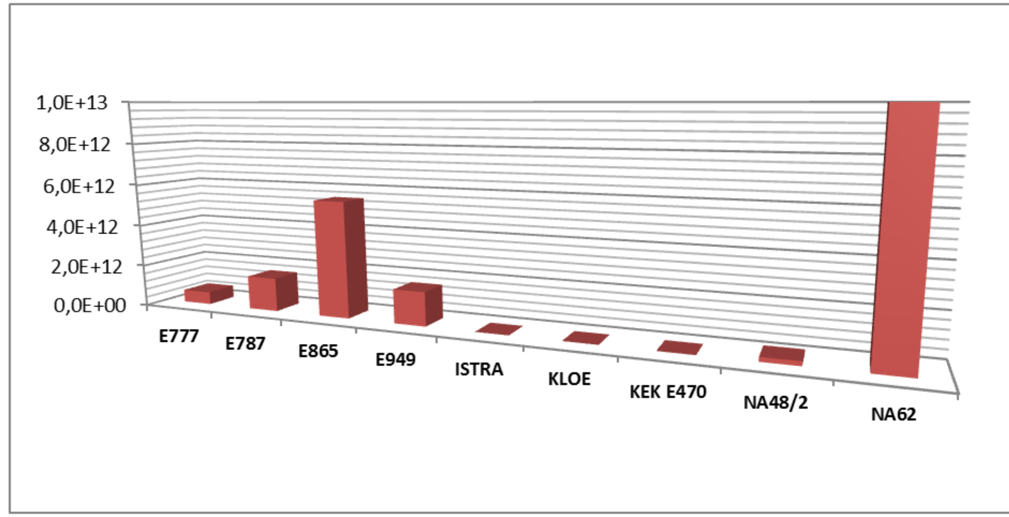
Conclusions

- **NA48/2, NA62-RK and NA62** have improved the limits on the search for Heavy neutral leptons both in decay and in production. NA62 (physics runs) will improve both statistics and systematics. Analysis on 2016 data on-going.
- **NA62** is taking data to search for ultra-rare $\pi^+\nu\bar{\nu}$ decay. The preliminary results show that the detector performs as expected even if the signal acceptance must be increased.
- Thanks to a very flexible trigger system, along with the main goal, other searches for dark matter portals (DP, HNL, ALPs) in medium mass region will be carried out with huge statistics and better resolution.

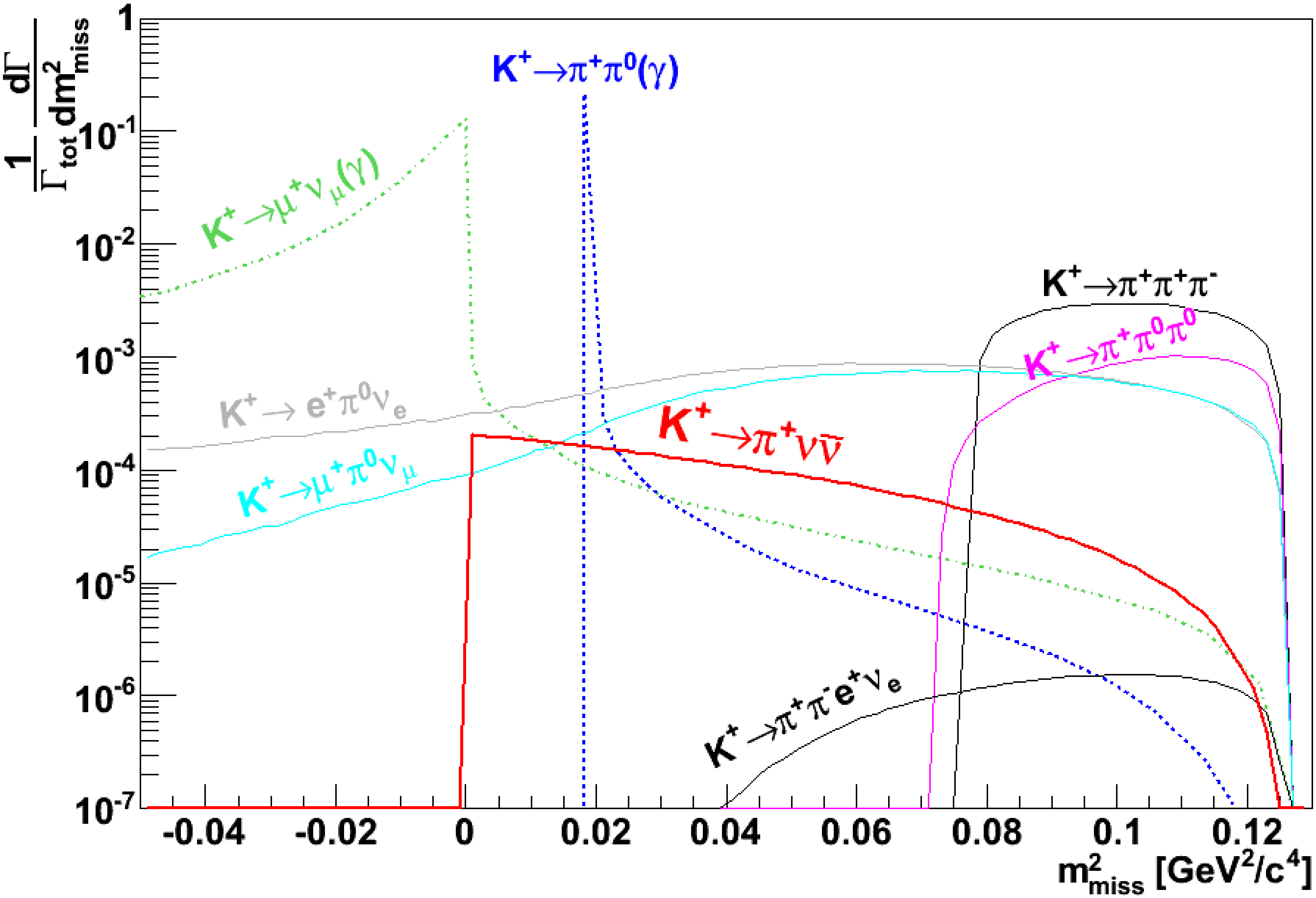
SPARE

NA62: Broad K decays program

- Unprecedented statistics for many K+ decay modes
- Key point: **digital trigger**
  - Very flexible
  - Trigger path in common with readout electronics (FPGA based)
  - GPU trigger



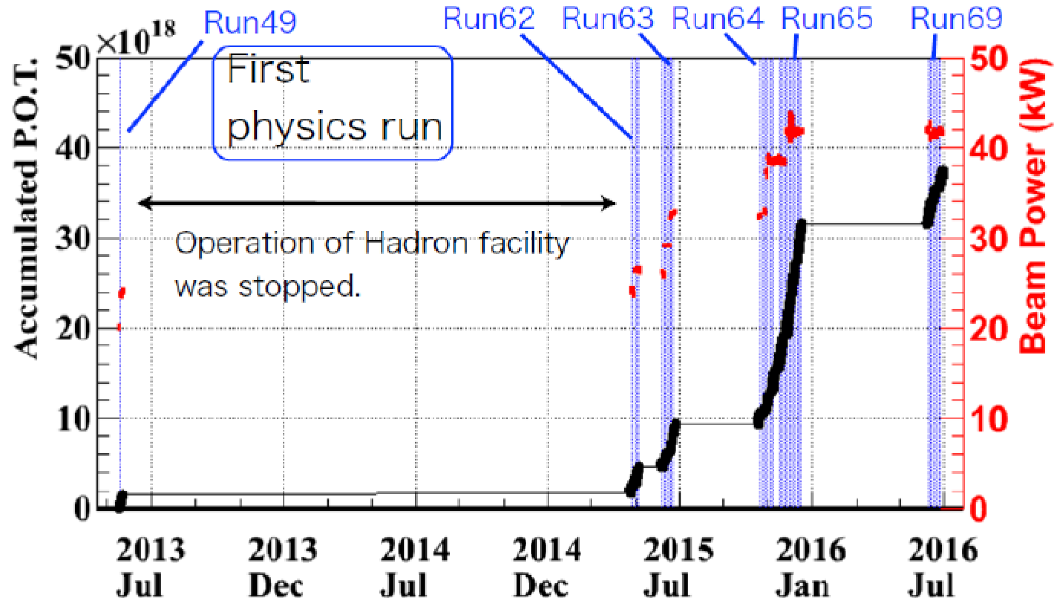
Process	Violates	90% C.L. limit	NA62 Acceptance
$K^+\to\pi^+\mu^+e^-$	LF	$< 1.3 \times 10^{-11}$	~10%
$K^+\to\pi^+\mu^-e^+$	LF	$< 5.2 \times 10^{-10}$	~10%
$K^+\to\pi^-\mu^+e^+$	LF , LN	$< 5.0 \times 10^{-10}$	~10%
$K^+\to\pi^-e^+e^+$	LN	$< 6.4 \times 10^{-10}$	~5%
$K^+\to\pi^-\mu^+\mu^+$	LN	$< 1.1 \times 10^{-9}$	~20%
$K^+\to\mu^-\nu e^+e^+$	LN	$< 2.0 \times 10^{-8}$	~2%
$\pi^0\to\mu^-e^+$	LF	$< 3.4 \times 10^{-9}$	~2%
$\pi^0\to\mu^+e^-$	LF	$< 3.8 \times 10^{-10}$	~2%
$\pi^+\to\mu^-e^+e^+\nu$	LF	$<1.6\times10^{-6}$	~2%



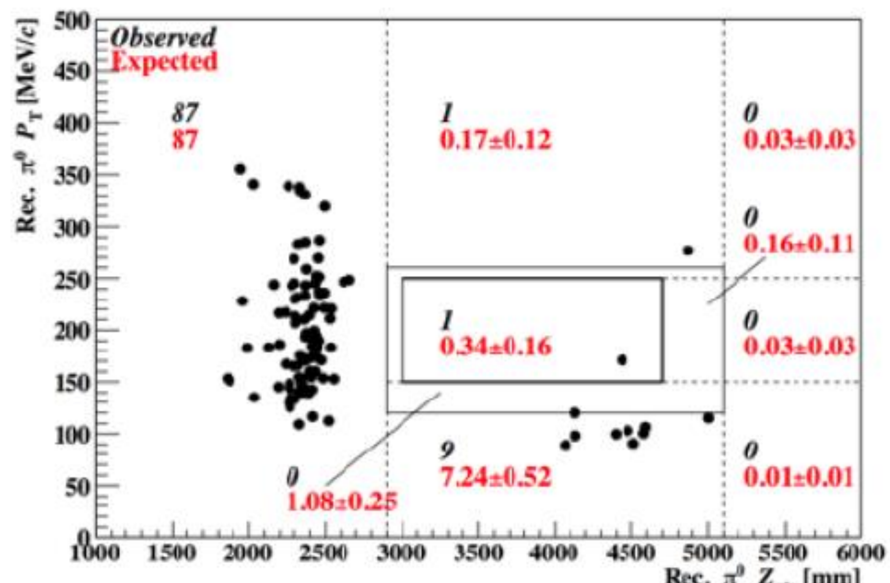
$\frac{1}{\Gamma_{tot}} \frac{d\Gamma}{dm^2_{miss}}$
$K^+ \to \pi^+ \pi^0 (\gamma)$
$K^+ \to \mu^+ \nu_\mu (\gamma)$
$K^+ \to \pi^+ \pi^+ \pi^-$
$K^+ \to \pi^+ \pi^0 \pi^0$
$K^+ \to e^+ \pi^0 \nu_e$
$K^+ \to \pi^+ \nu \bar{\nu}$
$K^+ \to \mu^+ \pi^0 \nu_\mu$
$K^+ \to \pi^+ \pi^- e^+ \nu_e$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12
m^2_{miss} [GeV^2/c^4]

KOTO

- Data from 2013 run: N KL ~2.4×10^{11}, S.E.S 1.3×10^{-8}
- BR $K_L \to \pi^0 \nu\nu < 5.1\times10^{-8}$ 90% C. L.
- Background in signal region dominated by neutrons
- Data from 2015 run: S.E.S 5.9×10^{-9} (prelim.)
- SM sensitivity in 2021

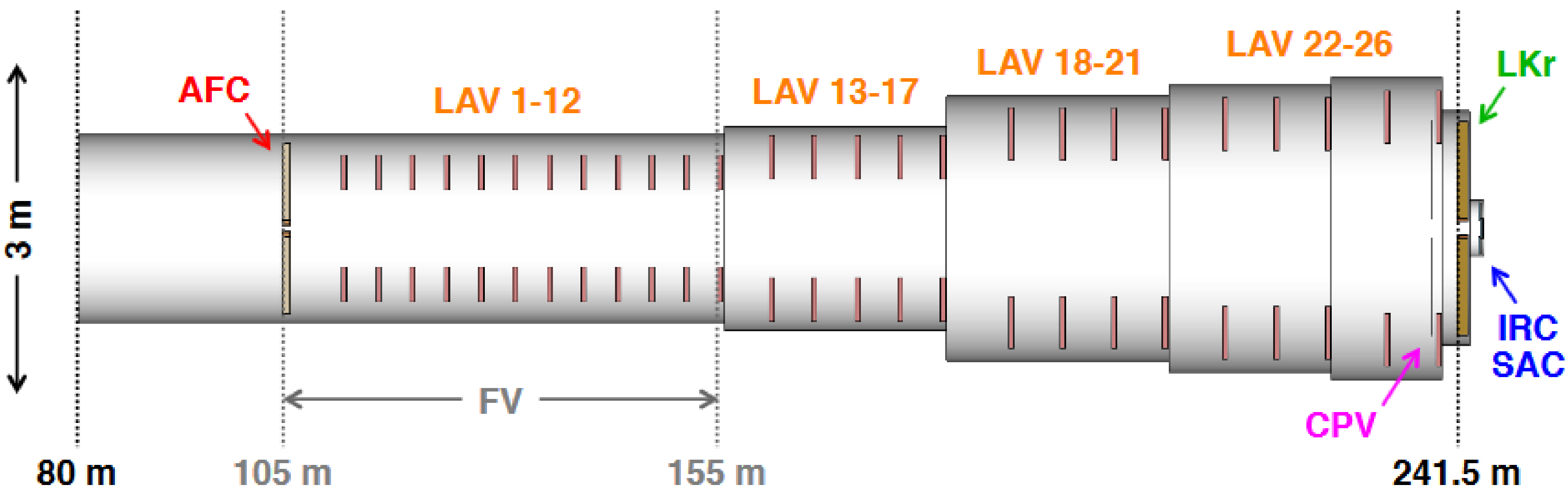


Background source	Number of events
$K_L \to 2\pi^0$	0.047 ± 0.033
$K_L \to \pi^+\pi^-\pi^0$	0.002 ± 0.002
$K_L \to 2\gamma$	0.030 ± 0.018
Pileup of accidental hits	0.014 ± 0.014
Other K_L background	0.010 ± 0.005
Halo neutrons hitting NCC	0.056 ± 0.056
Halo neutrons hitting the calorimeter	0.18 ± 0.15
Total	0.34 ± 0.16



$\pi^0\nu\nu$@CERN :KLEVER

2026→2029



For 60 SM events, need:

5×10^{19} pot

E.g. 2×10^{13} ppp/16.8 s × 5 yrs

$\langle p_K \rangle$ **= 70 GeV** for decays in FV

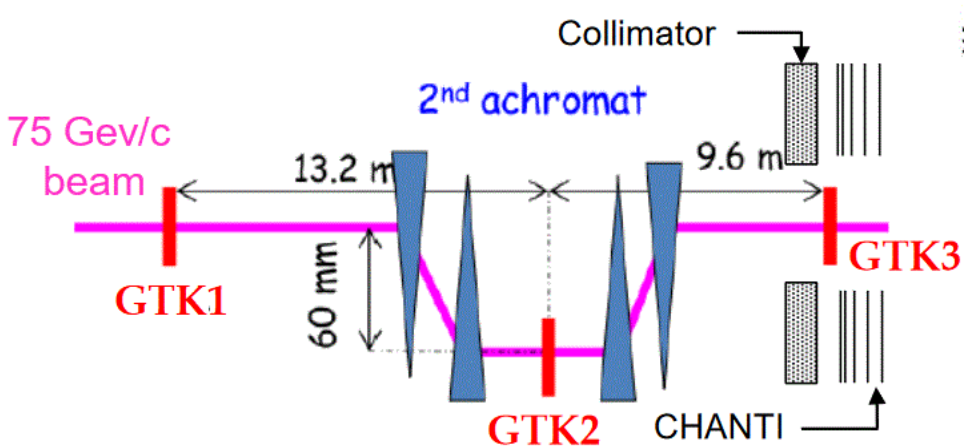
Photons from $K_L \to \pi^0\pi^0$ boosted forward for easier vetoing

Much higher energy than KOTO: Complementary approach

Main detector/veto systems:

AFC	Active final collimator/upstream veto
LAV1-26	Large-angle vetoes (26 stations)
LKr	NA48 liquid-krypton calorimeter
IRC/SAC	Small-angle vetoes
CPV	Charged-particle veto

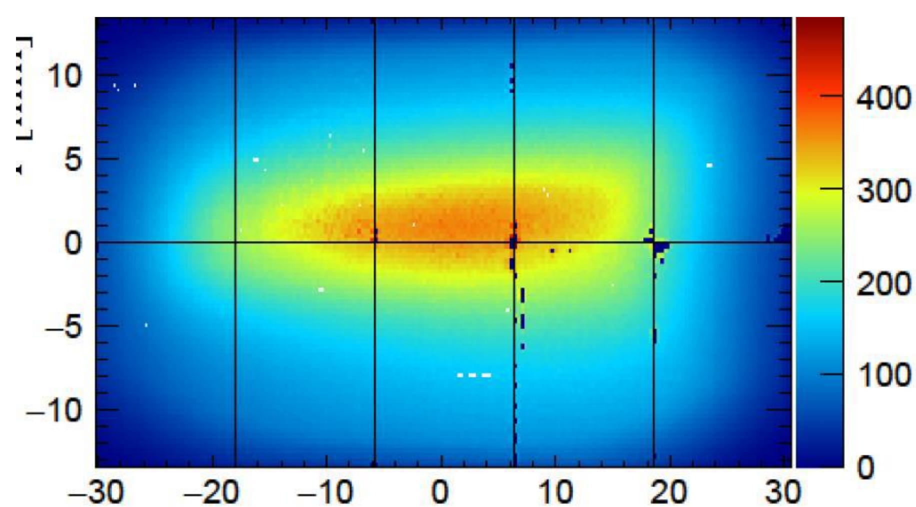
From M.Moulson

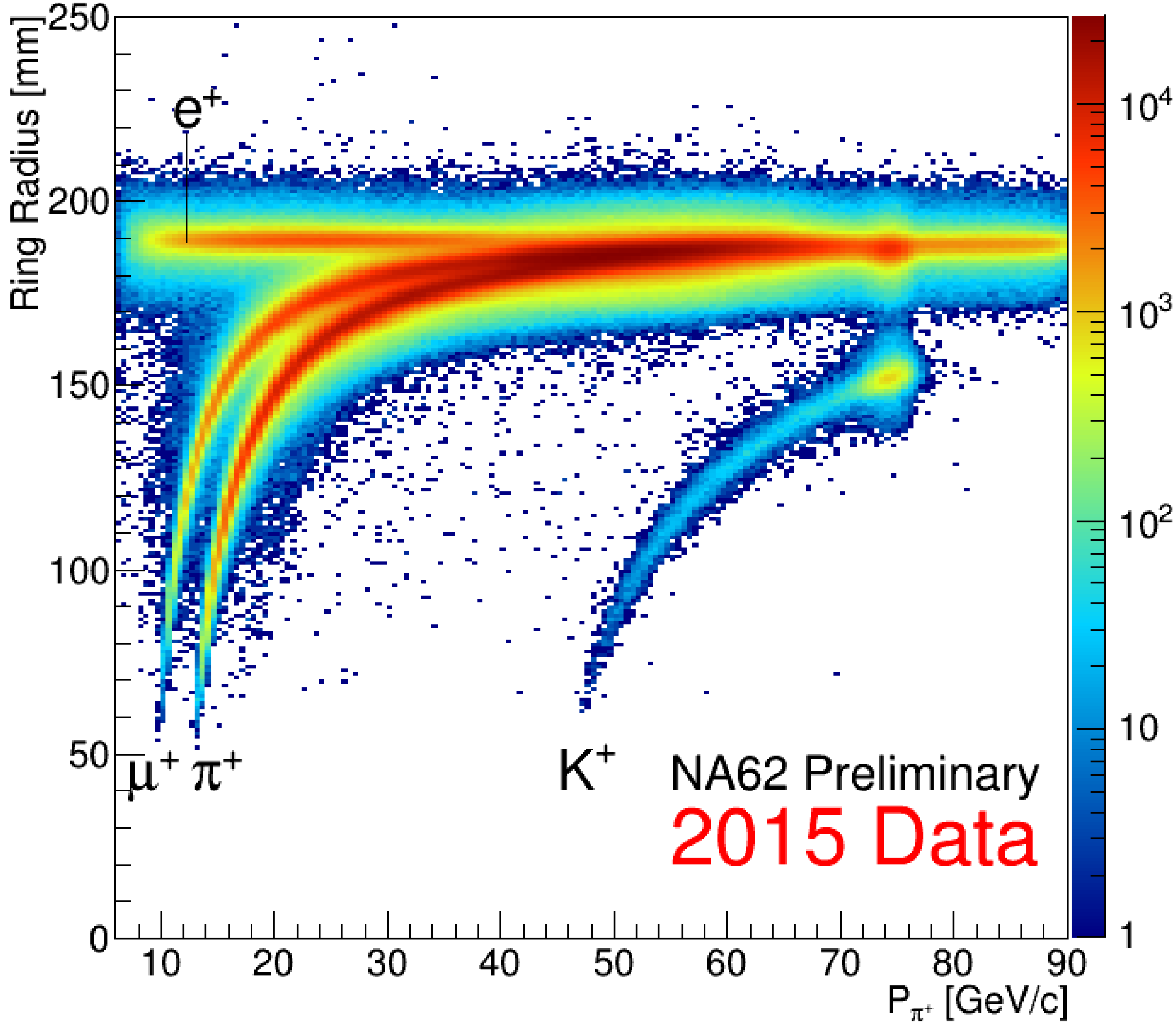


- Track reconstruction efficiency: 75%.
- Time resolution:100 ps.
- mis-tagging probability: 1.7%.

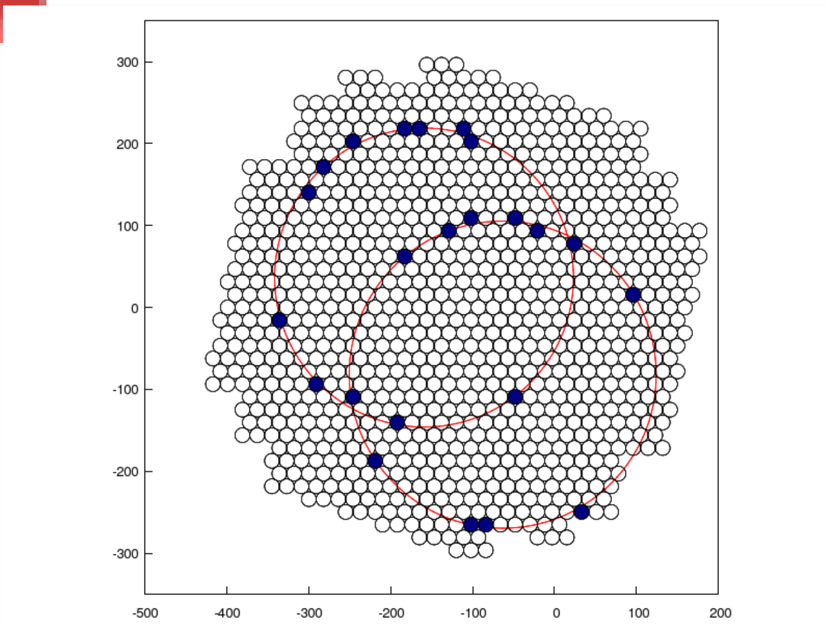
- Max. rate: 800 MHz.
- 54k pixels (300×300 μm^2).
- <0.5% X0 per station.

Performance at 40% beam intensity:




Ring Radius [mm]
250
200
150
100
50
0
10
20
30
40
50
60
70
80
90
P_π+ [GeV/c]
e+
μ+ π+
K+
10^4
10^3
10^2
10
1
NA62 Preliminary
2015 Data

GPU trigger: almagest algorithm



- Tesla K20
- Only computing time presented
- <0.5 us per event (multi-rings) for large buffers