Search for $K^+ \to \pi^+ \nu\bar{\nu}$ at NA62

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on behalf of the NA62 Collaboration

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

Physics of fundamental Symmetries and Interactions - PSI2016
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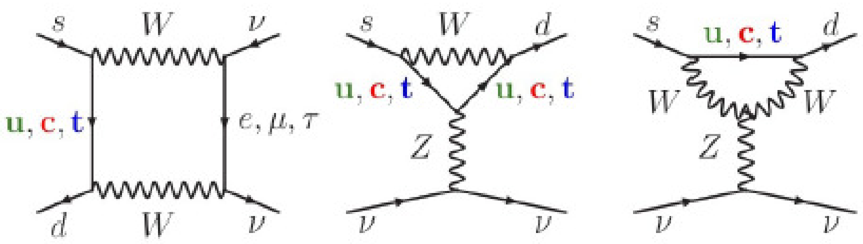
Outline

- $K^+ \to \pi^+ \nu\bar{\nu}$ theory (short reminder)
- NA62 detector layout
- Strategy for the measurement
- Other channels to be studied
- Prospects for the future
- Conclusions

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

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \cdot \left(\frac{V_{cb}}{0.0407}\right)^{2.8} \cdot \left(\frac{\gamma}{73.2^0}\right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11}$$

$$BR(K^0 \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \cdot \left(\frac{V_{ub}}{0.00388}\right)^{2} \cdot \left(\frac{V_{cb}}{0.0407}\right)^{2} \cdot \left(\frac{\sin\gamma}{\sin 73.2^0}\right)^{0.74} = (3.4 \pm 0.6) \cdot 10^{-11}$$

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

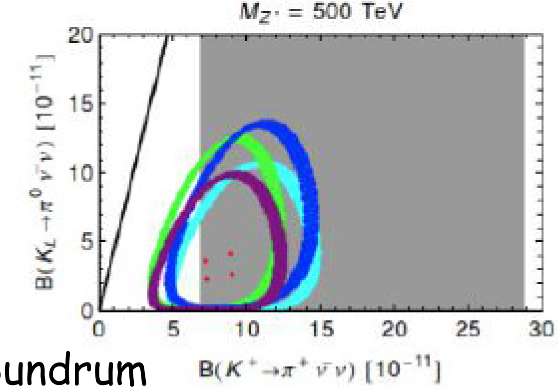
The combined measurement of K^+ and K_L modes could shed light on the flavour structure of NP (ΔS=2 / ΔS=1 correlation)

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

Simplified Z, Z' models

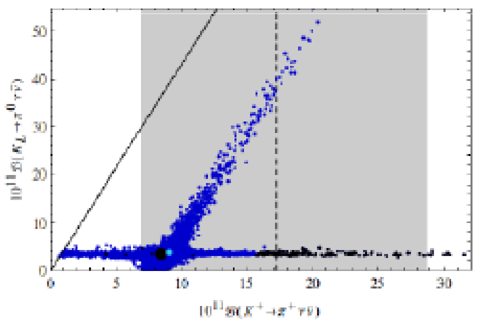
A. J. Buras, D. Buttazzo, R. Knegiens, JHEP 1511 (2015) 166

Z' model

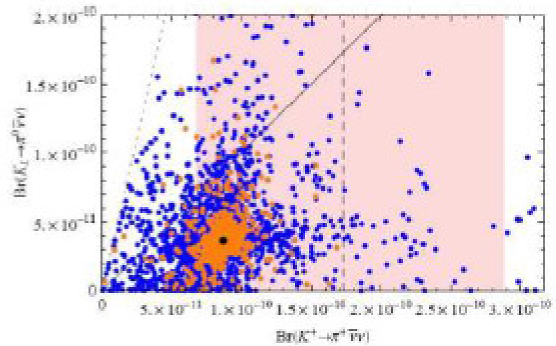


More specific NP models

Littlest Higgs with T-parity,
M. Blanke, A.J. Buras, S. Recksiegel,
EPJ C76 (2016) 182



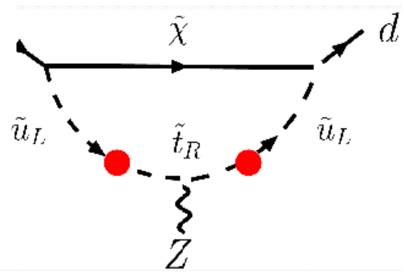
Custodial Randall-Sundrum
JHEP 0903 (2009) 108



- 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.



Today status of $K \to \pi\nu\bar{\nu}$

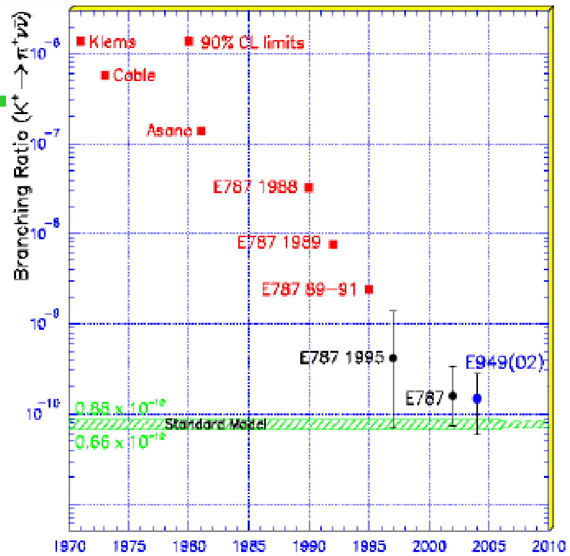
E787/E949 @Brookhaven: 7 candidates $K^+ \to \pi^+\nu\bar{\nu}$
2 experiments, stopped kaon technique

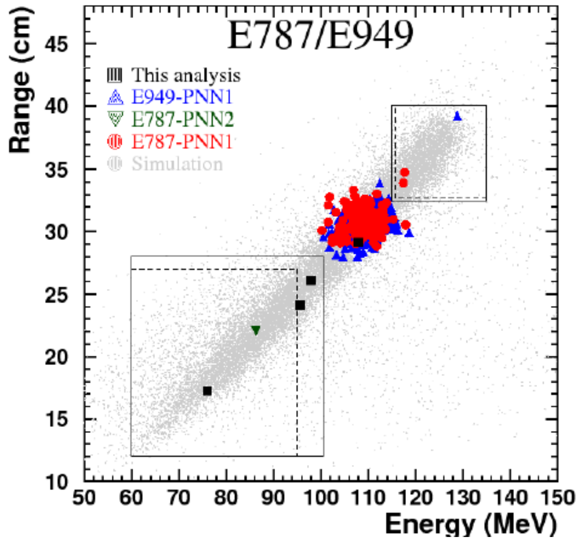
- Separated K^+ beam(710 MeV/c, 1.6MHz)
- PID: range (entire π+→μ+→e+decay chain)
- Hermetic photon veto system

Probability of all events to be background ~ 10^{-3}
Expected background: 2.6 events

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

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





E391a @ KEK: Phys. Rev. D81,072004 (2010)

$$BR(K_L \to \pi^0\nu\bar{\nu}) < 2.6\times 10^{-8} (90\%\ CL)$$

Preliminary from 2015 run of KOTO@JPARC:
arXiv 1609.03637

$$BR(K_L \to \pi^0\nu\bar{\nu}) < 5.1\times 10^{-8} (90\%\ CL)$$

NA62 goals and challenges

- Collection of O(100) $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events in two years of data taking
  - 10 % measurement of the branching ratio
  - This requires at least 10^{13} Kaon decays
  - In-flight decay technique
  - 75 GeV 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
  - Main contribution from $K_{\mu 2}$ (63%) and $K_{\pi 2}$ (21%)
  - Kinematics resolution
  - Efficient veto detectors
  - Particle ID
  - Precise timing

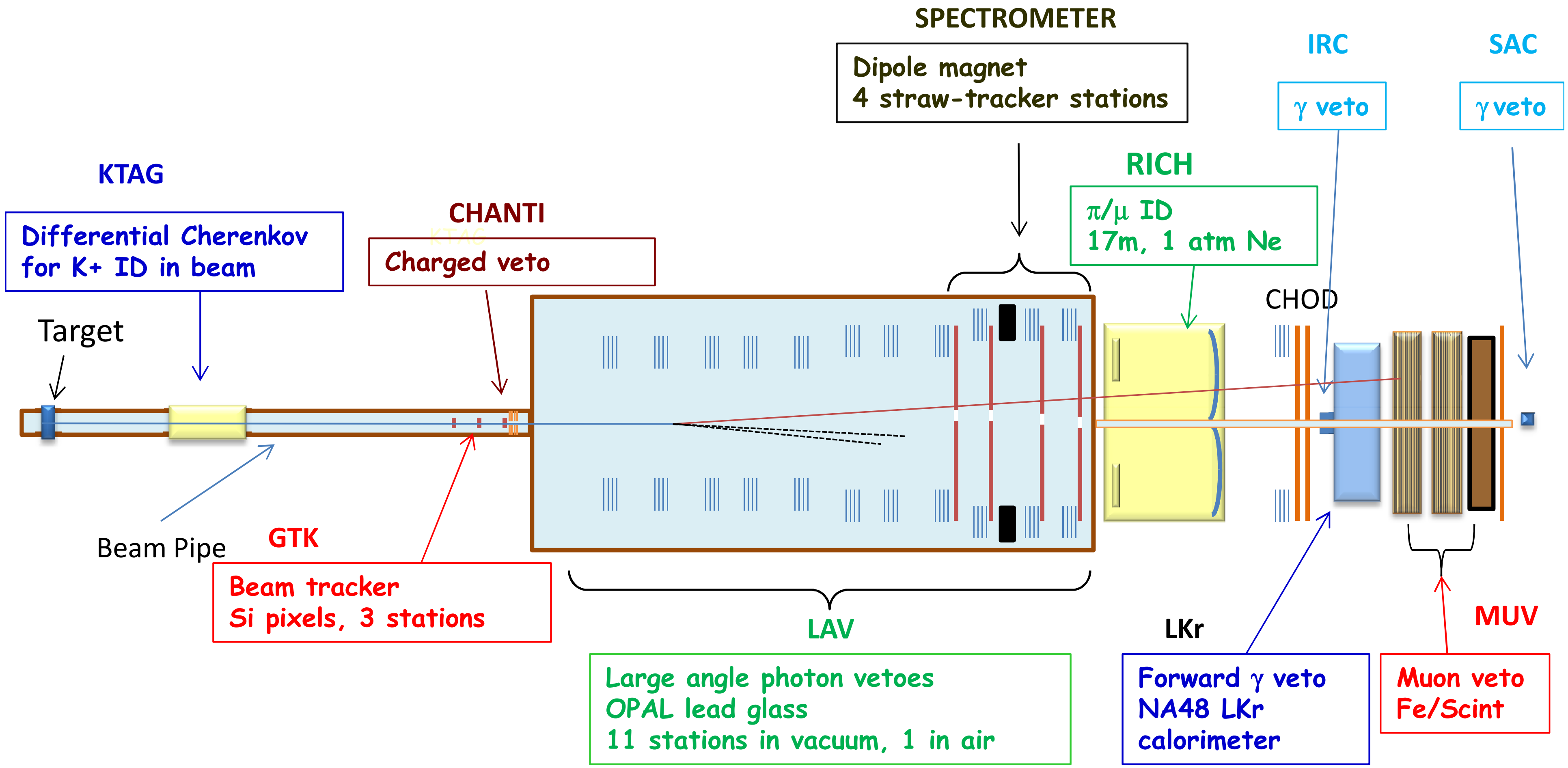
- Expected acceptance O (10%)

NA62 high-intensity kaon beam

- SPS primary proton beam @ 400 GeV/c
- Protons on target: 3×10^{12} / pulse
- Duty cycle ~ 0.3
- Simultaneous delivery to LHC
- Secondary charged beam 75 GeV/c
  - To optimize kaon production
- Momentum bite 1%
- X,Y divergence < 100 μrad

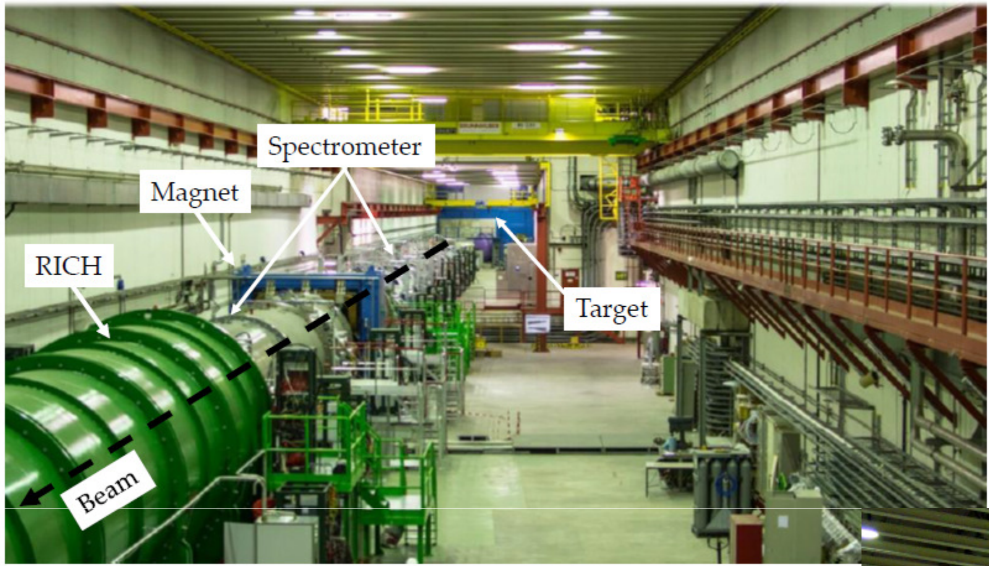
- Size @ beam tracker: 6.0×2.7 cm^2
- Rate @ beam tracker: 750 MHz
- 6% K^+ (others: 70% π^+, 24%proton)
- Rate downstream 10 MHz (mainly K^+ decay)
- K decay rates: 4.5×10^{12} /year
  - In a 60 m decay volume
  - 10^{-6} mbar vacuum

The NA62 detector



← Beam detectors →← Decay products detectors →

The NA62 detector



Where we are now

- Beam line, detectors, trigger and DAQ commissioned

- Data taking
  - 2014: detector commissioning
  - 2015: trigger commissioning, beam line commissioning up to the nominal intensity, detector performance studies
  - 2016: high level software trigger commissioning, full commissioning of the beam tracker, physics data taking on-going

- Data samples
  - 2015: Low intensity, minimum bias trigger for detector performance studies
  - 2016: $\pi^+ \nu\bar{\nu}$ and not $\pi^+ \nu\bar{\nu}$ (exotics) data up to 40% intensity

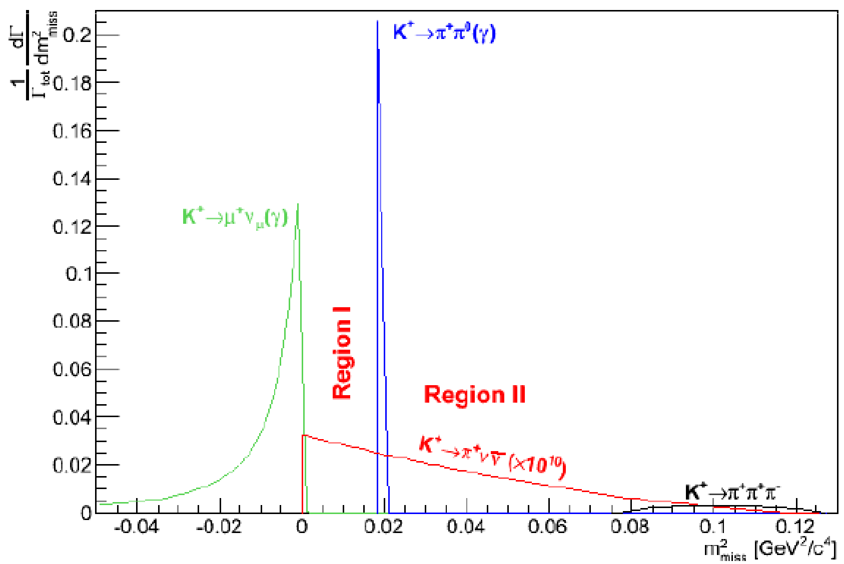
Guiding principles for the detectors

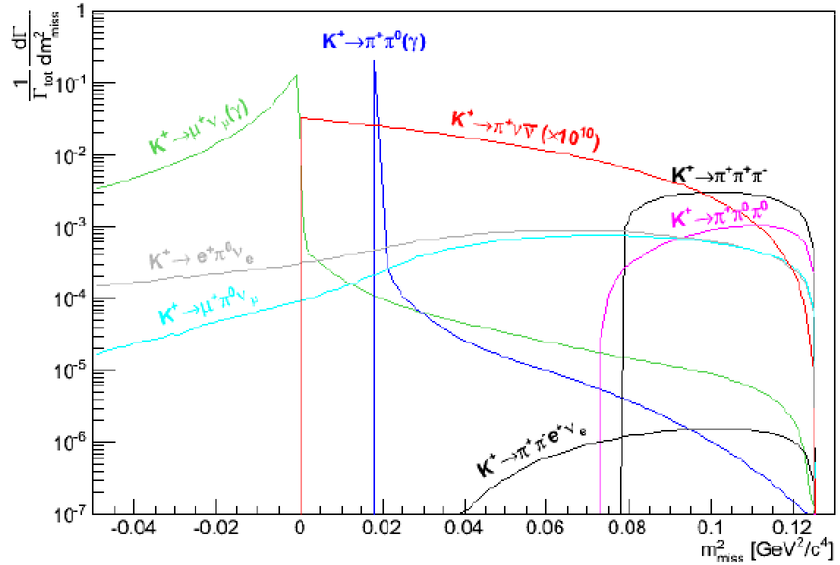
- Good tracking devices
  - Accurate measurement of the kaon momentum
  - Accurate measurement of the pion momentum
  - Missing mass cut: $O(10^5)$ rejection factor on $K_{\mu 2}$, $O(10^4)$ on $K_{\pi 2}$
- Veto detectors
  - For photons to reduce the background by a factor of 10^8
  - For muons add 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
  - To associate in time the kaon with the decay products
  - To reduce random veto

The measurement

- 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

- Backgrounds
  - K+ decay modes
  - Accidental beam activity



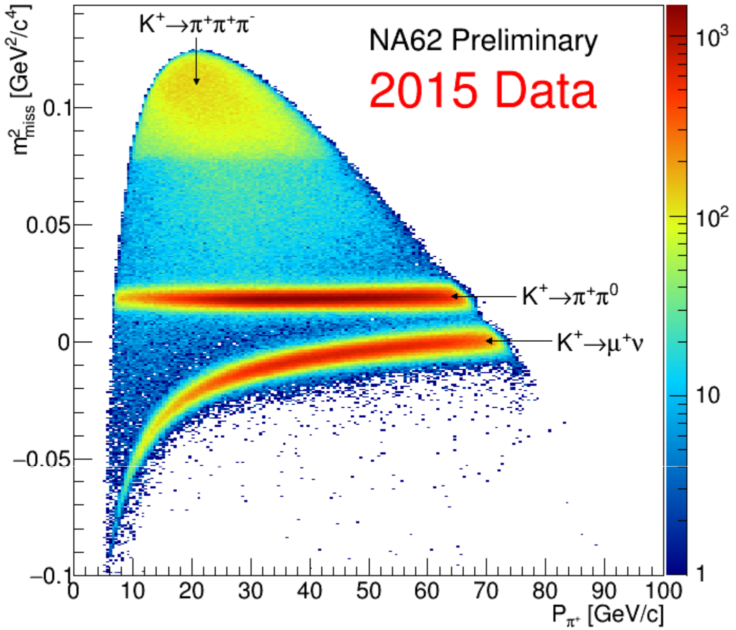


NA62 Sensitivity & background rejection

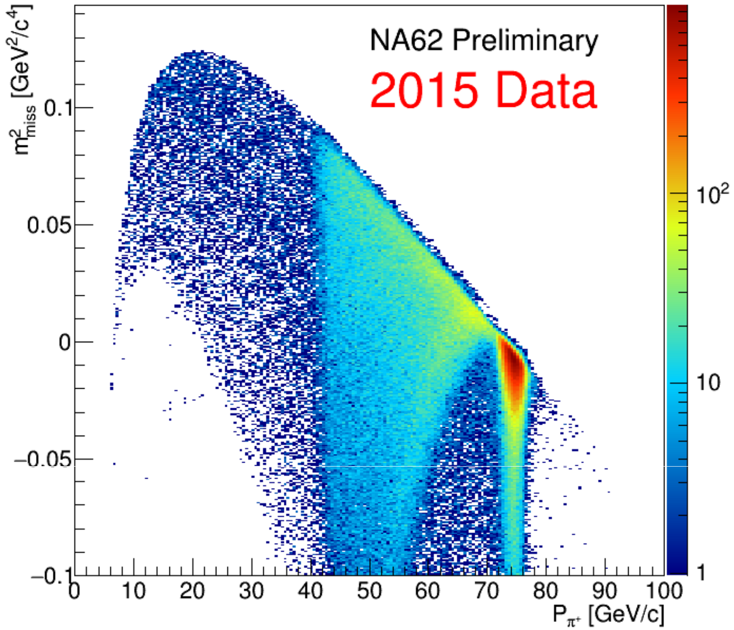
Decay	event/year
$K^+ \to \pi^+ \nu\nu$ [SM] (flux 4.5×10^{12})	45
$K^+ \to \pi^+ \pi^0$	5
$K^+ \to \mu^+ \nu$	1
$K^+ \to \pi^+ \pi^+ \pi^-$	< 1
Other 3 tracks decays	< 1
$K^+ \to \pi^+ \pi^0 \gamma$ (IB)	1.5
$K^+ \to \mu^+ \nu \gamma$ (IB)	0.5
$K^+ \to \pi^0 e^+ (\mu^+) \nu$, others	< 1
Total background	< 10

Kaon identification

KAON ID



Anti-KAON ID



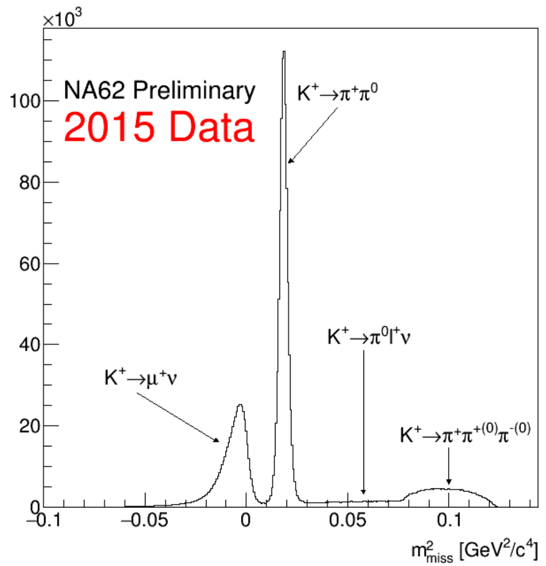
Use one-track selection:
Single track downstream, with matching energy in the calorimeters and matching a beam track
Kaon ID:
Signal in the Kaon ID matching a beam track
Decay vertex in the 65 m fiducial region

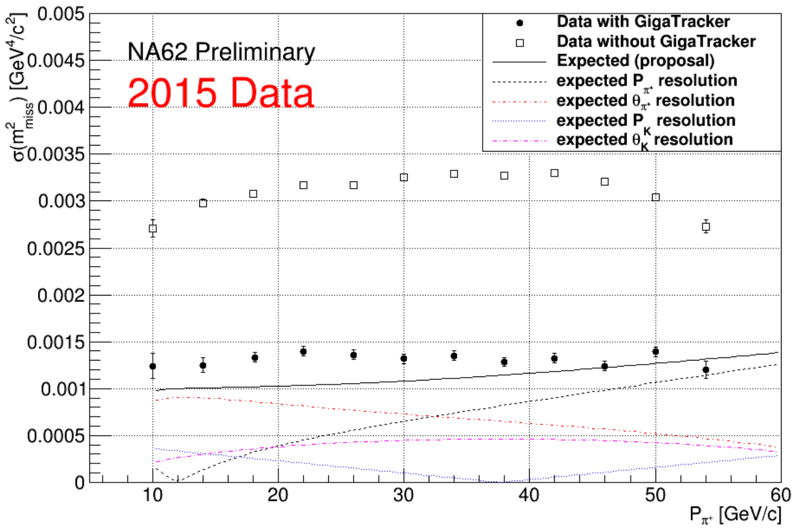
Time resolution close to design:

Kaon ID < 100 ps
Beam tracking < 200 ps
Decay track < 200 ps
Calorimeters <2 ns

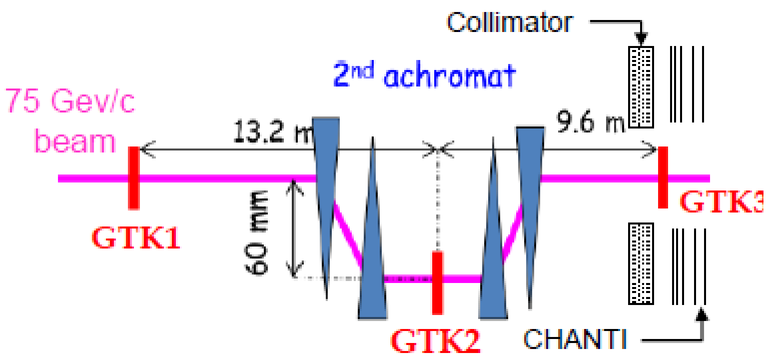
Kinematics

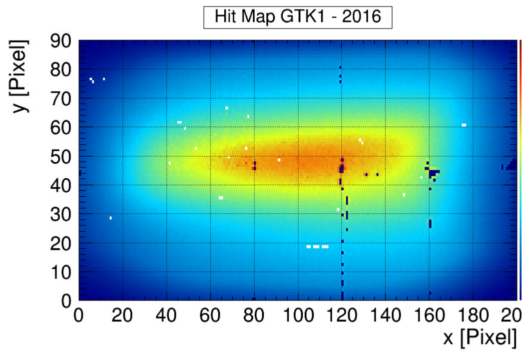
- Tracking uses Si pixels (GigaTracker) for the beam, straw tubes in vacuum + magnet for decay products
- $P\pi$ < 35 GeV/c for optimal $K_{\mu 2}$ rejection
- Resolution and kinematic suppression factor measured using $K^+ \to \pi^+\pi^0$ selected with the LKr calorimeter
- Resolution close to the design, measured suppression factor $O(10^3)$, prospect to reach the design figure with 2016 data

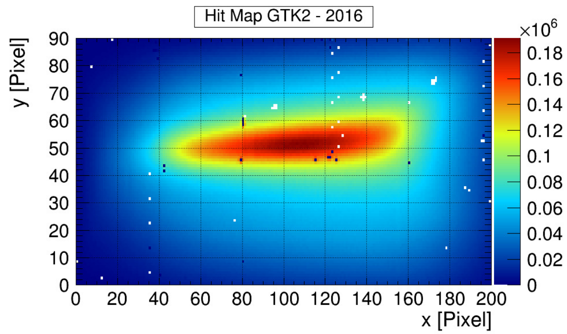




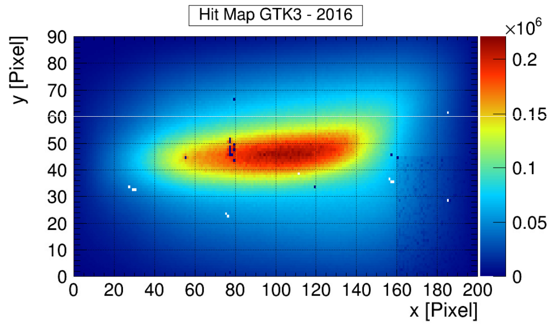
Beam tracker (Gigatracker)



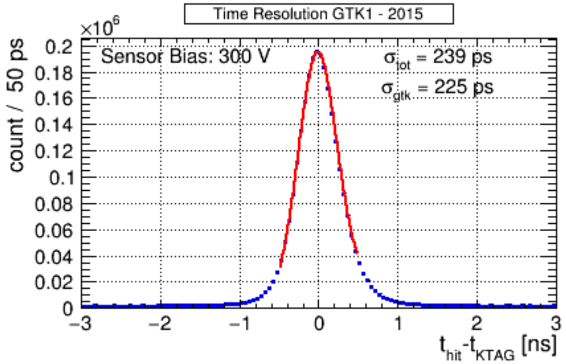




3 Si pixel station on the beam, each 0.5% X_0
300 x 300 μm^2 pixels, ~54000 pixels



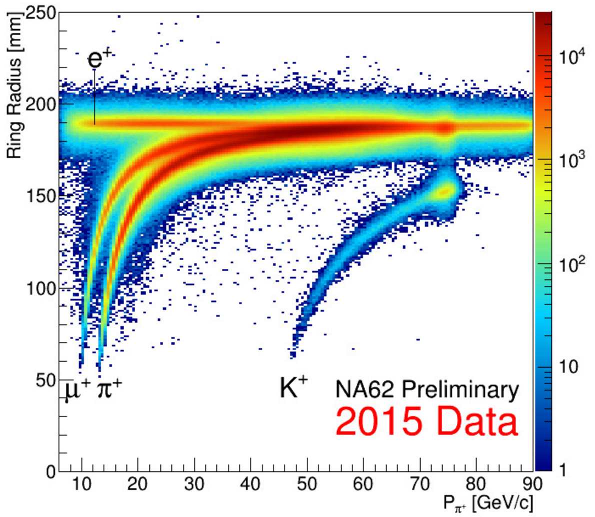
TDC readout chip on-sensor
Cooling using microchannel technique
Completely commissioned in 2016

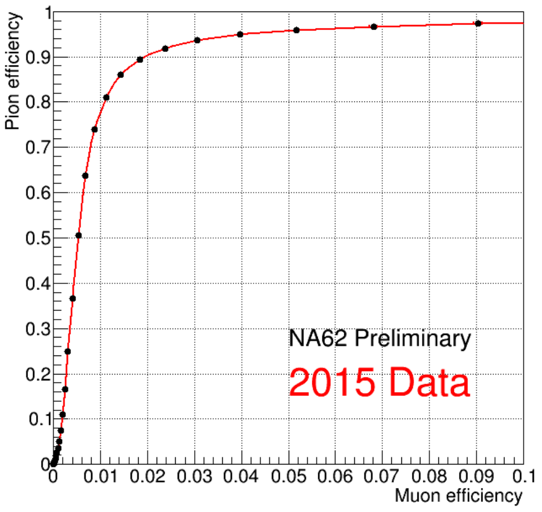


Measured performance in line with the design: $\sigma(t_{\text{beam track}}) < 200$ ps

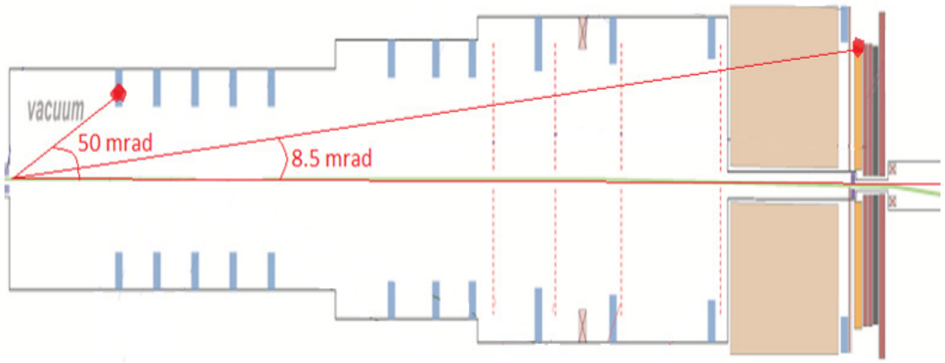
Decay products PID

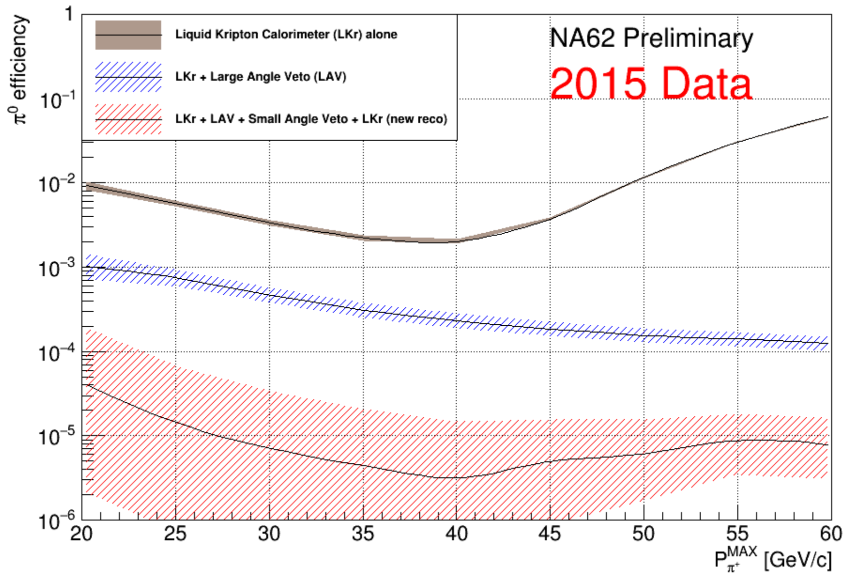
- Particle identification using RICH and calorimeters
- Suppress mainly $K_{\mu 2}$ with $O(10^7)$ π/μ separation
- $15 < P\pi < 35$ GeV/c for the best separation
- Evaluate suppression with clean samples of pion and muons
  - RICH: $O(10^2)$ π/μ separation, 80%(90%) efficiency 2015 (2016)
  - Calorimeters: $(10^4$-$10^6)$ μ suppression, (90%-40%) π^+ efficiency with cut analysis. Work going on for improvements





Photon rejection





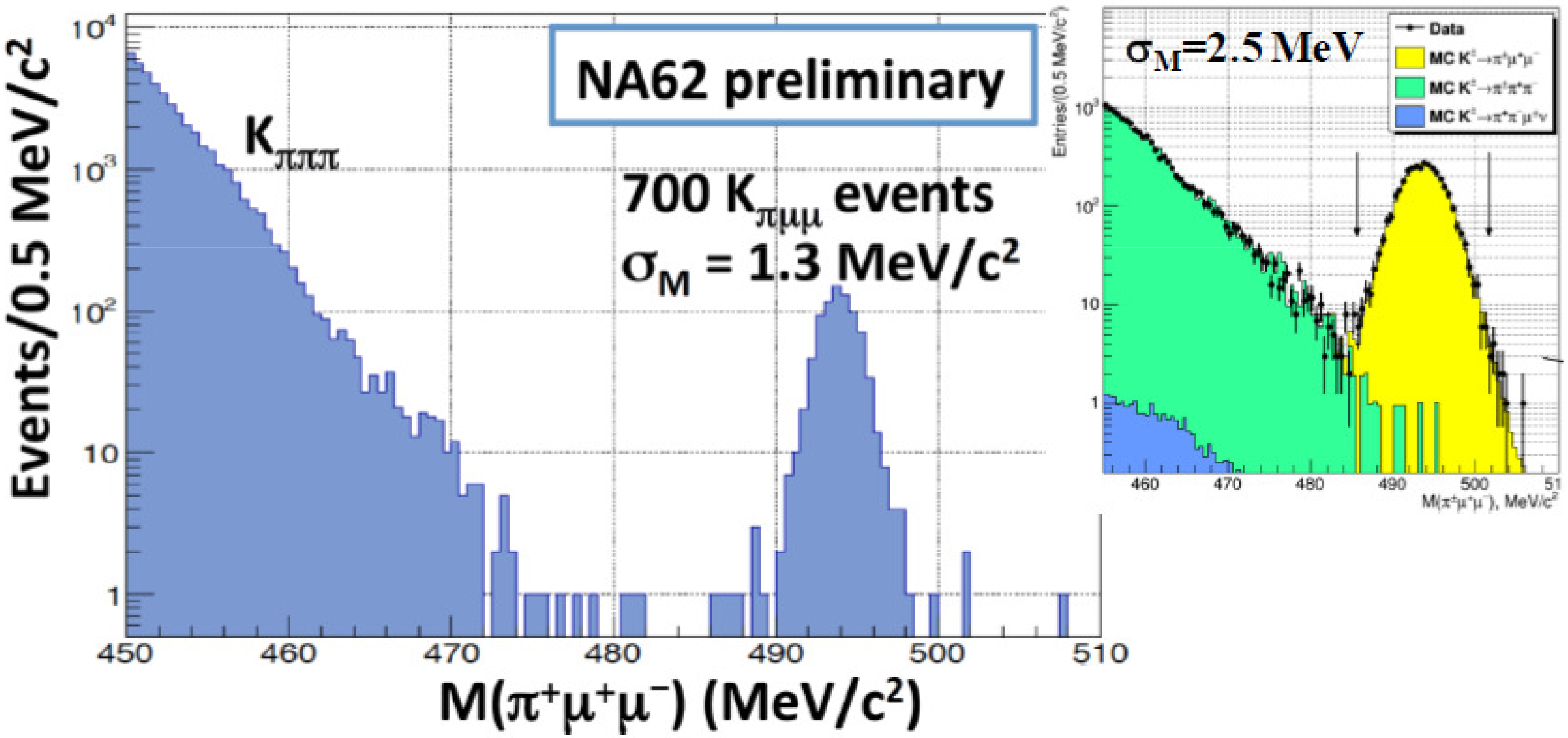
- Use EM calorimeters exploiting correlations between γs from π^0
- Hermetic coverage up to 50 mrad
- Goal: $O(10^8)$ π^0 rejection from $K^+ \to \pi^+\pi^0$
  - Thanks to the cut P_π <35 Gev $\to$ $E_{\pi 0}$ >40 Gev
- Kinematical selection of $\pi^+\pi^0$ decays to measure rejection
- $O(10^6)$ obtained with 2015 data, but statistically limited
- 2016 data already enough to address the $O(10^8)$ level.

Not only $\pi\nu\bar{\nu}$

- Standard kaon physics
  - ChPT studies: $K^+ \to \pi^+ \gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+ e^-$, $K_{\ell 4}$
  - Precision test of lepton universality: $R_K=\Gamma(K \to e\nu(\gamma))/\ \Gamma(K \to \mu\nu(\gamma))$
- Searches for lepton-flavor or –number violating decays
  - $K^+ \to \pi^+ \mu e$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^- \ell^+ \ell^+$
- Search for heavy neutrinos
  - $K^+ \to \ell^+ \nu_h$ (inclusive)
  - ν_h from upstream K, D decays with $\nu_h \to \pi\,\ell$
- Search for heavy neutral leptons
- Search for long-lived dark sector particles
  - Dark photon γ' produced in π/ρ decays in target with $\gamma' \to \ell^+\ell^+$
  - Axion-like particle A^0 produced in target/beam dump, with $A^0 \to \gamma\gamma$
- π^0 decays
  - $\pi^0 \to$ invisible; $\pi^0 \to 3\gamma$, 4γ ; $\pi^0 \to \gamma'\gamma$

An example: $K^+ \to \pi \mu\mu$

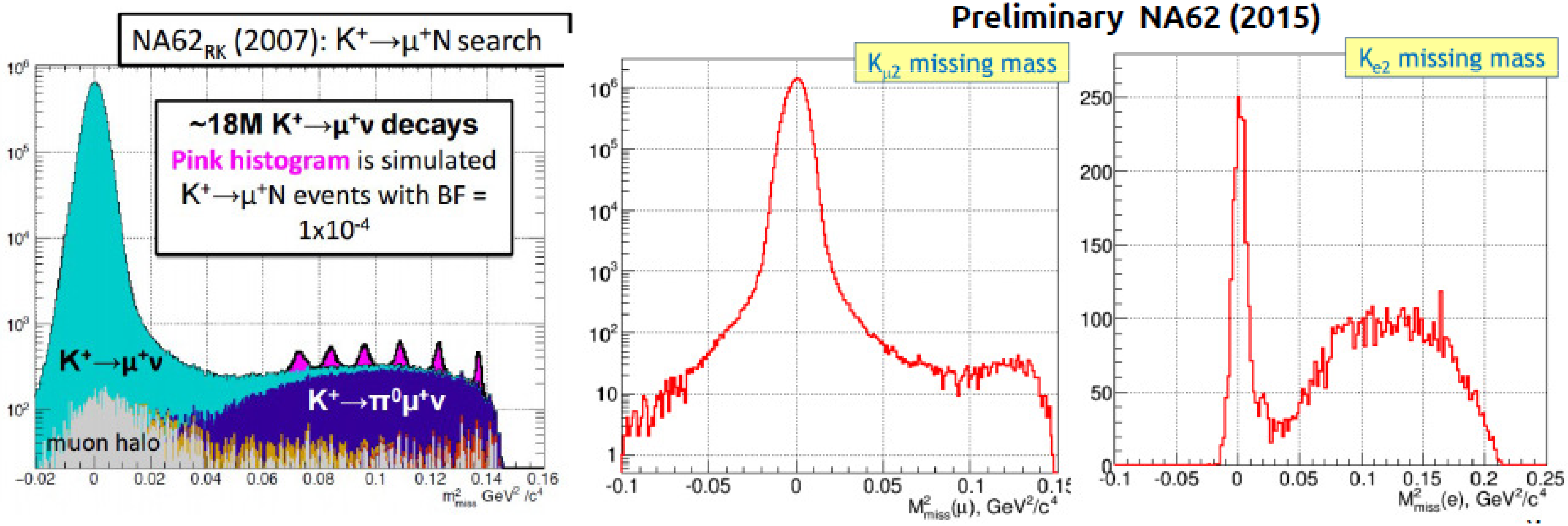
- Kaon physics: BR, form factors, charge asymmetry, FB asymmetry
- $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$: Lepton number violation
  - Possible if the neutrino is a Majorana particle



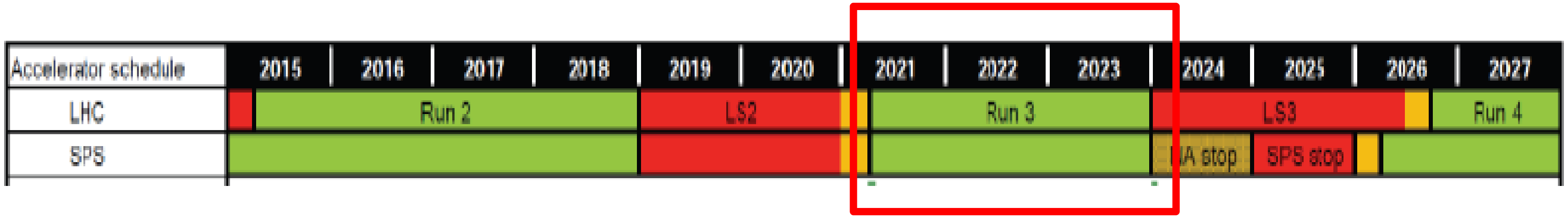
Mass resolution better by a factor ~2 with respect to NA48/2

An example: Heavy neutral leptons

- Heavy neutral leptons in $K^+ \to \ell^+ N$
- Can also search for HNL in $K^+ \to \ell^+ N$ where N does not decay inside the detector fiducial volume
- $K^+ \to \ell^+ N$ events would appear as peaks in the $K^+ \to \ell^+ \nu$ squared missing mass distribution
- Searches are model independent



Prospect for the future - Run 3



- With minimal/no upgrades of the present K^+ beam and detector
  - LFV/LNV high-sensitivity studies
    - $K^+ \to \pi^+ \mu e$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^- \mu^+ \mu^+$
  - ultra-rare/forbidden π^0 decays
    - μe, 3γ, 4γ, ee, $eeee$
- Year-long run in "beam-dump" mode
  - searches for MeV-GeV mass hidden-sector candidates
    - Dark photons
    - Heavy neutral leptons
    - Axion like particles, etc.

Prospect for the future - Run 4

- KLEVER: $K_L \rightarrow \pi^0 \nu\bar{\nu}$ at the SPS
  - A design study for an experiment to measure $K_L \rightarrow \pi^0 \nu\bar{\nu}$ at the CERN SPS

- High-energy experiment: complementary approach to KOTO
- Photons from K_L decays boosted forward
- Makes photon vetoing easier - veto coverage only out to 100 mrad
- Possibility to re-use LKr calorimeter and the NA62 experimental infrastructure

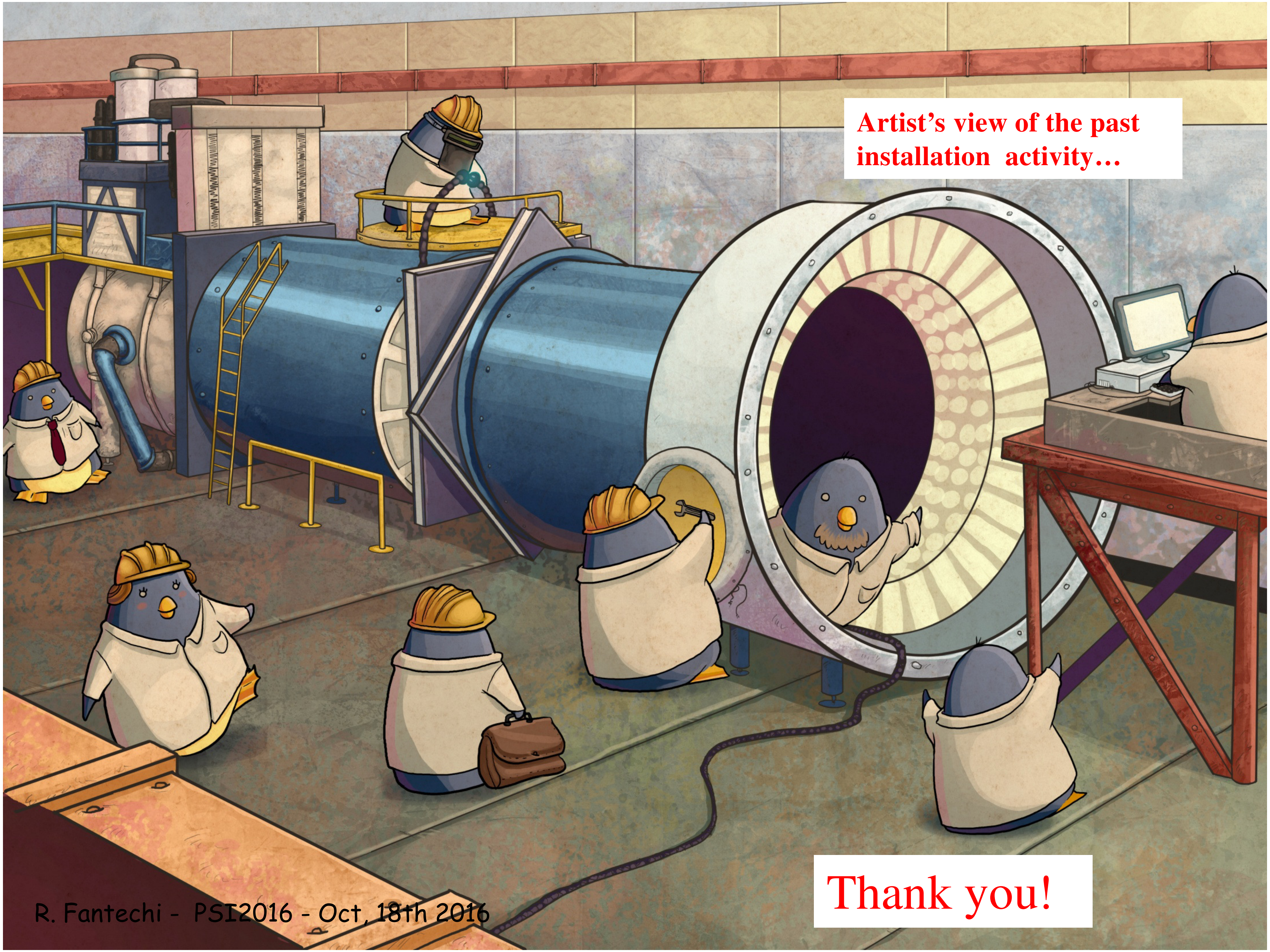
- The study has been presented at the CERN workshop "Physics beyond collider" in September 2016 and has been well received

$K_L \to \pi^0\nu\bar{\nu}$ at the SPS

- Many issues/questions raised by the study
  - Need for 3 10^{13} K_L decays for 100 events
    - 10^{19} pot/year on 5 years -> 2 10^{13} ppp (6x NA62 intensity)
    - Beam and experimental area need major upgrade
  - Fiducial volume similar to NA62
  - Active final collimator to veto upstream decays
  - New and many more large angle vetoes (100 mrad)
  - Small Angle vetoes insensitive to 3 GHz of beam neutrons
  - Charged vetoes in front of the LKr calorimeter
  - Optimize LKr efficiency and two cluster separation
  - Following NA62 experience, need to have electronics with a better behavior in radiation areas
  - Expected to have 60 SM events with S/B=1
    - Background studies still going on

Conclusions

- NA62 is taking data with the complete detector since 2015
- The data analysis up to now shows that the detector is behaving as expected and with the latest data we can address a sensitivity of less than 10^{-9} for $K^+ \to \pi^+ \nu\bar{\nu}$
- Data for exotics decays are being collected in parallel
- Data taking will continue at least up to LS2
- Plans are being prepared for Run 3 to study various types of exotic decays
- A preliminary study has been performed to assess the possibility to setup a detector for $K^0 \to \pi^0 \nu\bar{\nu}$ in Run 4


Artist's view of the past installation activity…
Thank you!
R. Fantechi - PSI2016 - Oct, 18th 2016