Searching for new physics at Kaon experiments at CERN

Chris Parkinson, on behalf of NA62

CLFV 2016

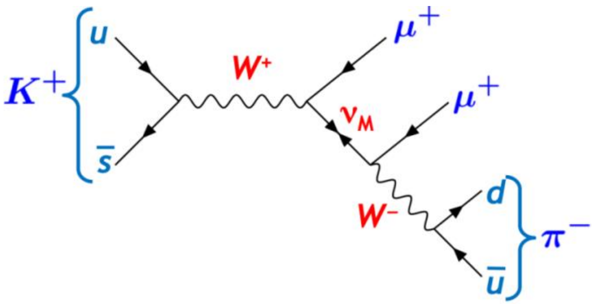
21st June 2016

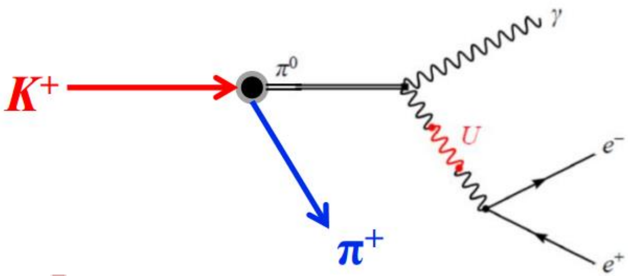
Outline

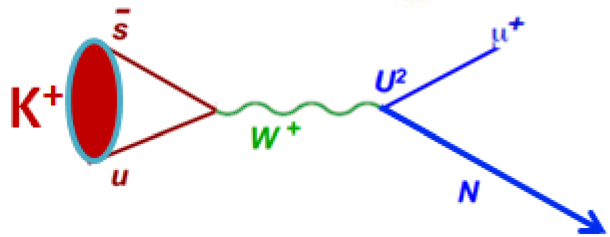
- An introduction to Kaon experiments at CERN
- Recent results (published or underway) from older Kaon experiments at CERN
- An introduction to the NA62 experiment
- Physics prospects of the NA62 experiment

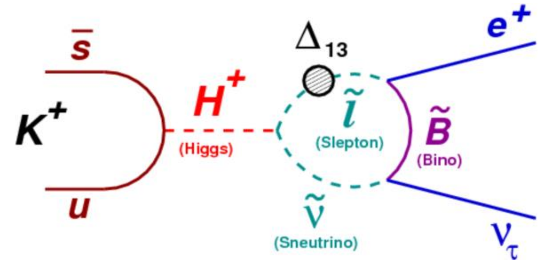
Why search for NP at Kaon experiments

- Many Kaon decays can proceed, or are enhanced, by contributions from new physics particles
- To study these (rare) processes, need **precise measurement** of **many Kaons** with **low backgrounds**
- Kaon experiments at CERN fulfil these characteristics, making Kaon experiments an ideal laboratory in which to search for new physics processes
- Kaon experiments are also π^0 factories ($K^+\rightarrow\pi^+\pi^0$ branching fraction = 20%)
- Results from CERNs Kaon physics programme:
  - Inflaton or heavy (majorana) neutrino in $K^+\rightarrow\pi\mu\mu$ decays (analysis completed, paper in preparation)
  - Dark photons in Dalitz decays of the π^0
  - Heavy neutrino production in $K^+\rightarrow\mu^+N$ decays (analysis underway)
  - Heavy neutrino, or other BSM particles, affecting the ratio of $K^+\rightarrow\mu^+\nu$ and $K^+\rightarrow e^+\nu$ branching fractions

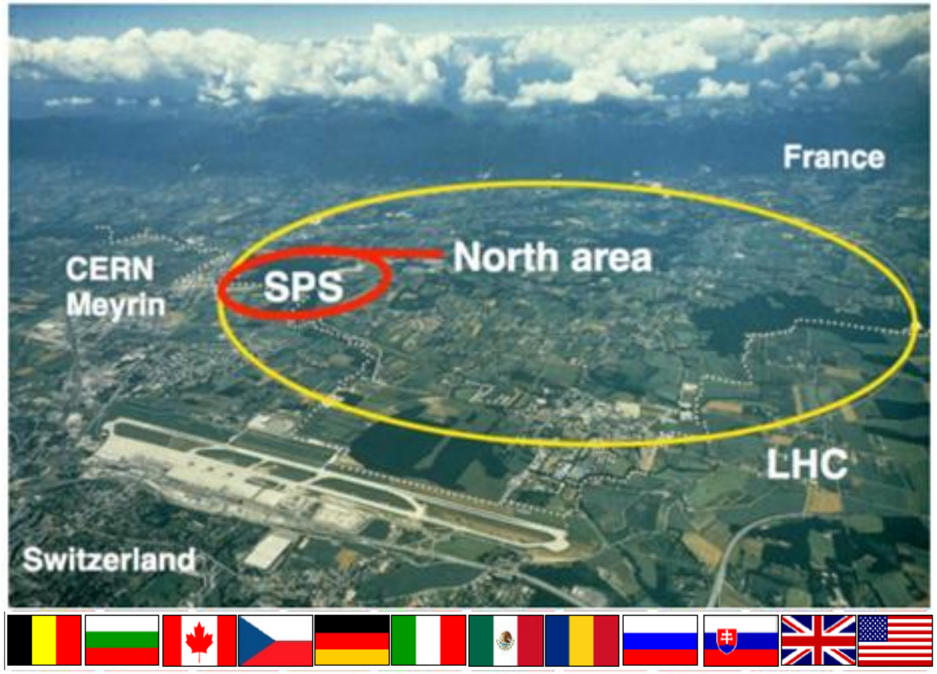








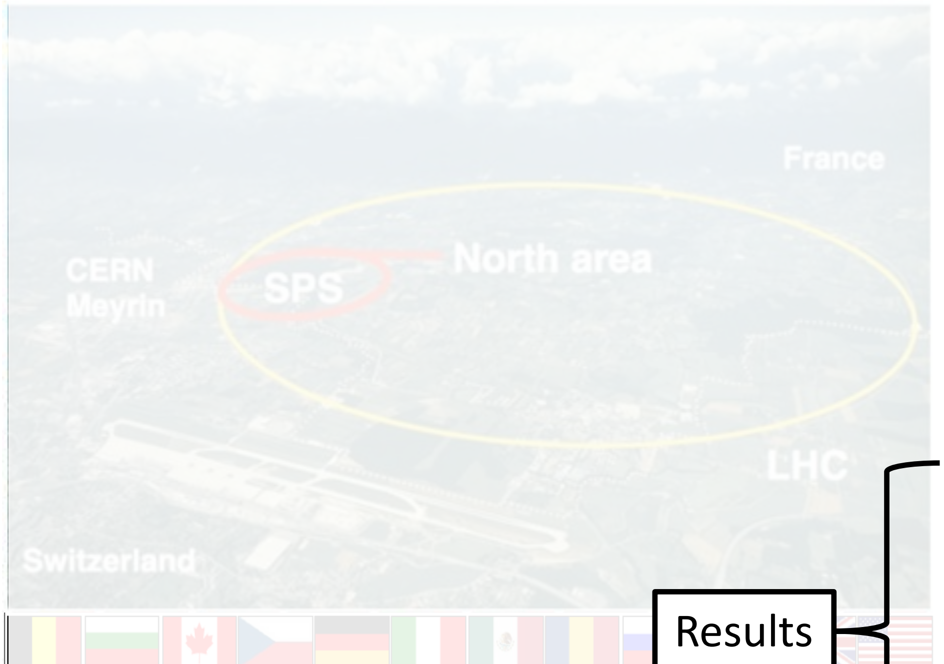
Kaon physics at CERN



NA62: ~200 participants of 29 institutions

Recent history of NA experiments		
1984 ↓ 1990	NA31 (K_S/K_L)	First evidence of direct CPV
1997 ↓ 2001	NA48 (K_S/K_L)	**Re ε'/ε** Discovery of direct CPV
2002	NA48/1 (K_S/hyperons)	Rare $\mathbf{K_S}$ and hyperon decays
2003 ↓ 2004	NA48/2 (K^+/K^-)	Direct CPV Rare $\mathbf{K^+}$ / $\mathbf{K^-}$ decays
2007 ↓ 2008	NA62 R_K phase (K^+/K^-)	$\mathbf{R_K = K^{\pm}_{e\nu}/K^{\pm}_{\mu\nu}}$
2014 ↓ 2018	NA62 (K^+)	$\mathbf{K^+ \to \pi^+ \nu\nu}$ Rare $\mathbf{K^+}$ and $\mathbf{\pi^0}$ decays

Kaon physics at CERN



NA62: ~200 participants of 27 institutions

Results

Prospects

Recent history of NA experiments		
1984 ↓ 1990	NA31 (K_S/K_L)	First evidence of direct CPV
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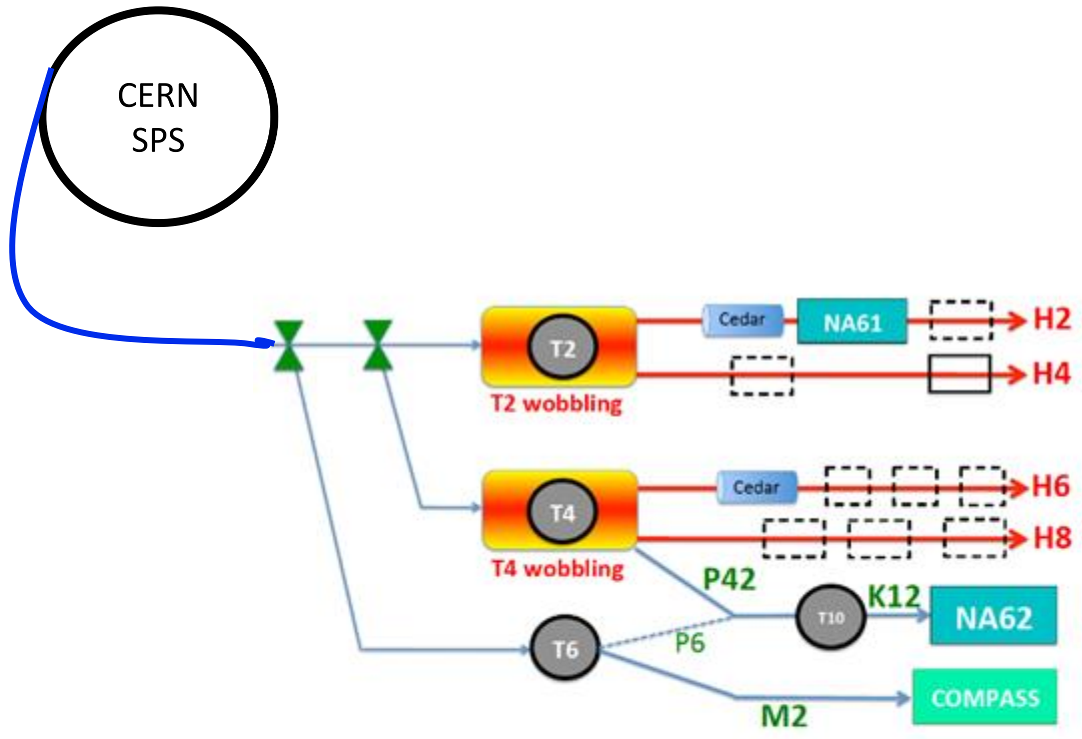
2002	NA48/1 (K_S/hyperons)	Rare K_S and hyperon decays
2003 ↓ 2004	NA48/2 (K^+/K^-)	Direct CPV Rare **K^+** / **K^-** decays
2007 ↓ 2008	NA62 R_K phase (K^+/K^-)	**$R_K = K^{\pm}_{e\nu}/K^{\pm}_{\mu\nu}$**
2014 ↓ 2018	NA62 (K^+)	**$K^+ \rightarrow \pi^+\nu\nu$** Rare **$K^+$** and **$\pi^0$** decays

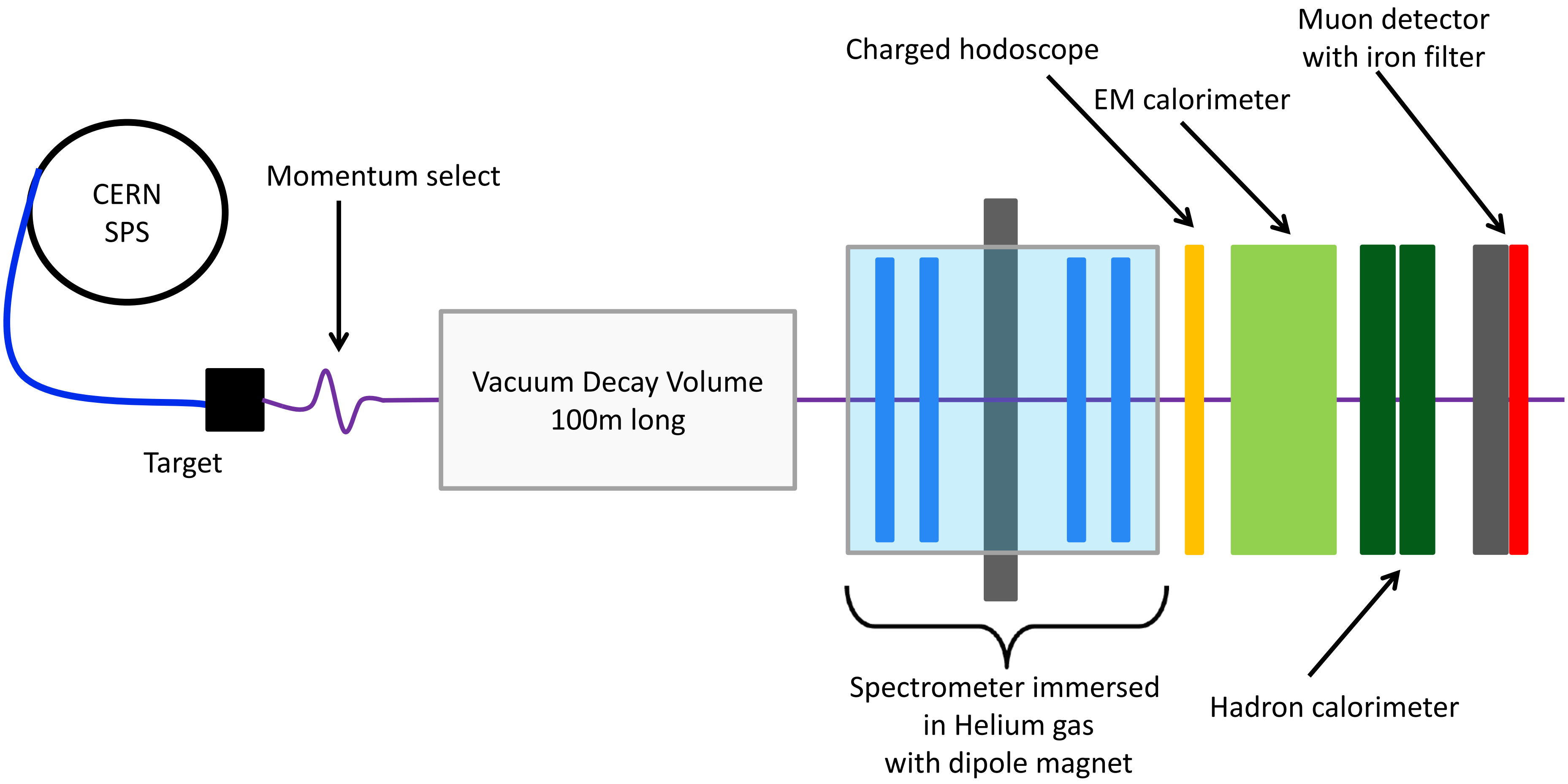
Kaon decay-in-flight experiments at CERN

- SPS Protons @ 400 GeV steered to Beryllium target (T10)
- Secondary hadron beam – 6% Kaons (70% pions, rest = protons, electrons*)

*electrons removed from beam before reaching NA62



The NA48/2 and $NA62_{RK}$ detector



The NA48/2 and NA62$_{RK}$ experiments

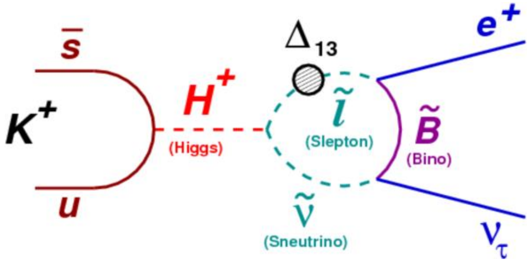
- The beam parameters were modified for the NA62$_{RK}$ experiment to give a more favourable environment for measuring R_K

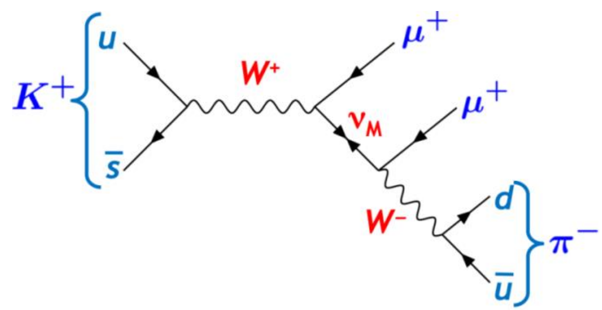
	NA48/2	NA62-RK
Data taking	2003-4	2007-8
Primary intensity (ppp)	7×10^{11}	7×10^{11}
Solid angle (μsr)	~0.4	~0.4
Beam momentum (GeV)	60	74
RMS momentum bite (GeV)	2.2	1.4
Spectrometer thickness, X_0	2.8%	2.8%
Spectrometer P_T kick, MeV	120	265
$M(K \rightarrow \pi^+\pi^+\pi^-)$ resolution, MeV	1.7	1.2
K decays in fiducial region	2×10^{11}	2×10^{10}

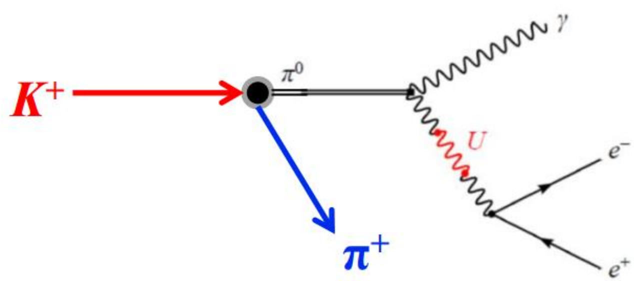
PHYSICS RESULTS FROM NA62$_{RK}$ AND NA48/2

Physics results from NA62$_{RK}$ and NA48/2

- Results from CERNs Kaon physics programme:
  1. Heavy neutrino and/or other BSM particles affecting the ratio of $K^+ \to \mu^+ \nu$ and $K^+ \to e^+ \nu$ branching fractions
  2. Inflaton or heavy Majorana neutrino in $K^+ \to \pi\mu\mu$ (analysis completed, paper draft in preparation)
  3. Dark photons in Dalitz decays of the π^0







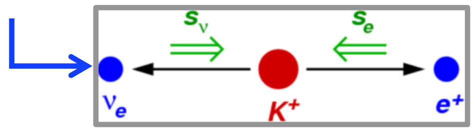
R_K at $NA62_{RK}$

- Value of R_K can be precisely calculated in the SM

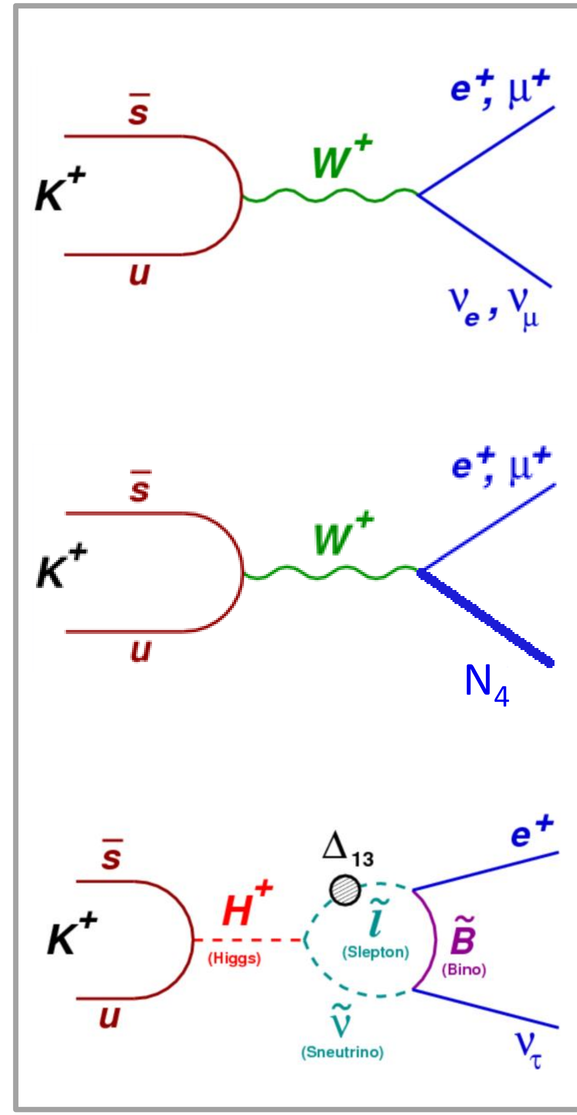
Helicity suppression ↓ — Radiative corrections ↓

$$R_K^{SM} \equiv \frac{\Gamma(K \to e\nu(\gamma_{IB}))}{\Gamma(K \to \mu\nu(\gamma_{IB}))} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_K^{EM}) = 2.477(1) \times 10^{-5}$$

PRL 99 (2007) 231801



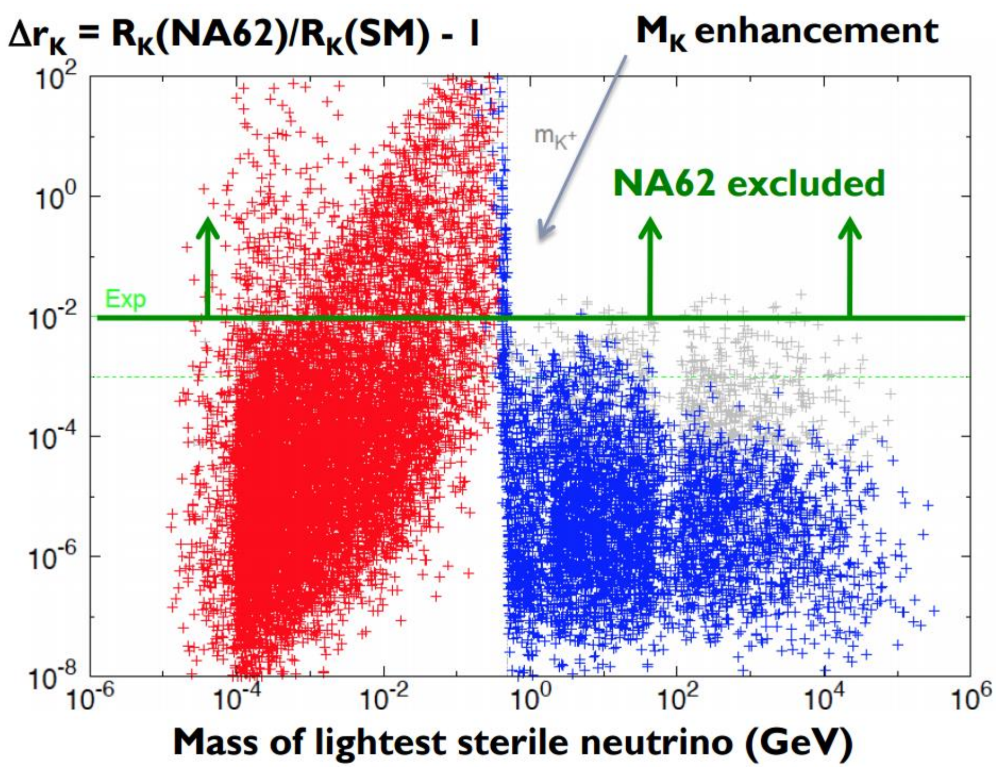
- R_K is sensitive to:
  - Ratio of mixing parameters of 4[th] neutrino $U_{e4}/U_{\mu4}$ [JHEP 1302 (2013) 048]
  - LFV loop diagrams in e.g. SUSY models at $O(10^{-3})$ [EPJ C72 (2012) 2228]



R_K at $NA62_{RK}$

- **World's most precise** measurement of R_K [PLB 719 (2013) 326]

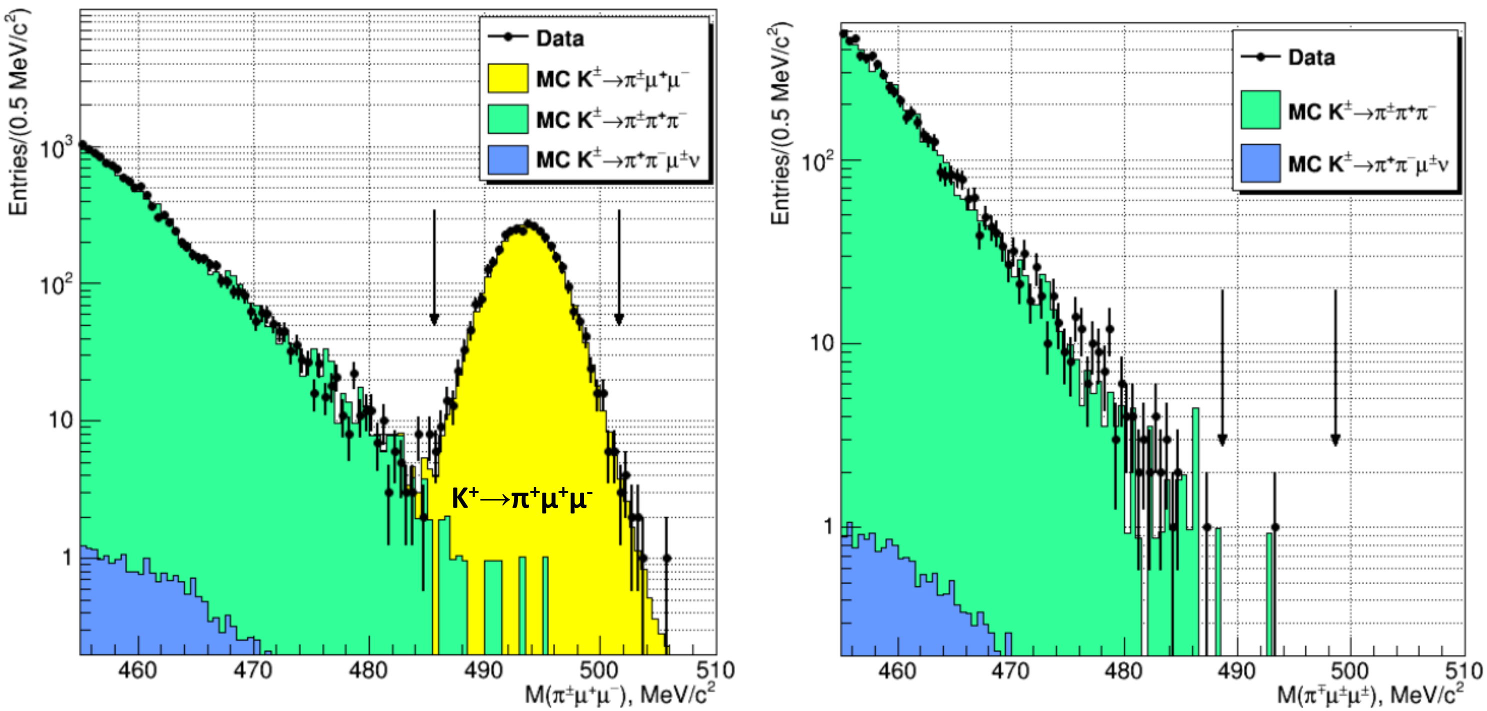
$R_K = 2.488(7)_{st}(7)_{sy} \times 10^{-5}$
$= 2.488(10) \times 10^{-5}$ 0.4% precision
$\Delta r_K = (4 \pm 4) \times 10^{-3}$



[Abada et al. JHEP 1402 (2014) 091]

Search for lepton number violation

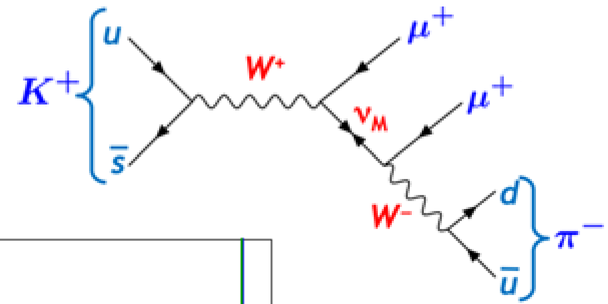
- The NA48/2 data contains ~3.5k $\mathbf{K^+ \to \pi^+ \mu^+ \mu^-}$ candidates [PLB697 (2011) 107]
- A re-analysis was made to improve the search for the $\mathbf{K^+ \to \mu^+ \mu^+ \pi^-}$ (LNV) decay

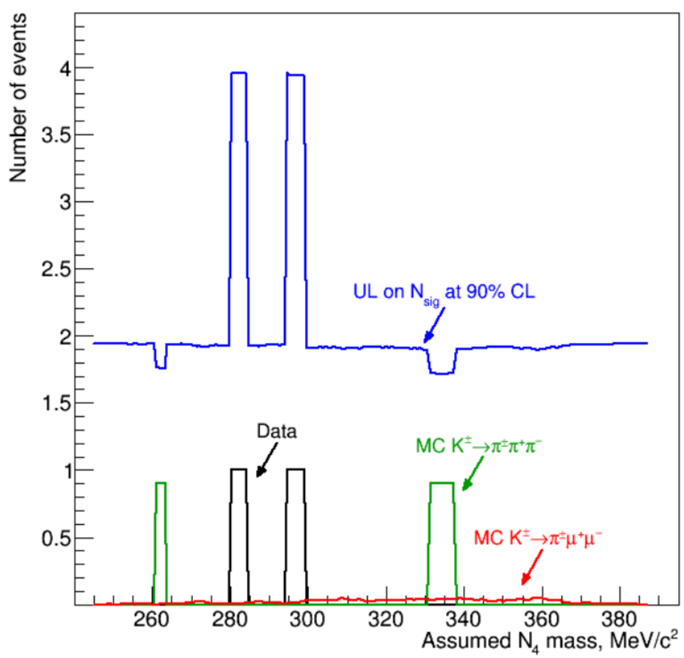


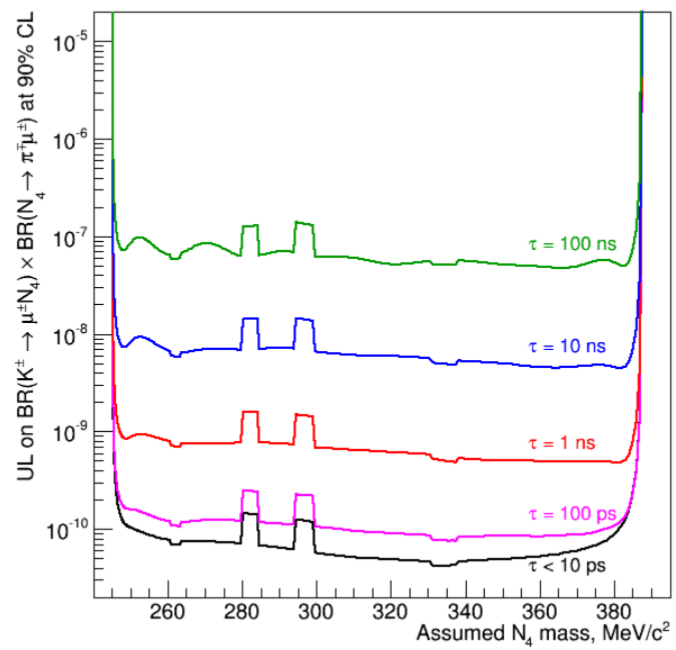
$N(\mu^\pm\mu^\pm) = 1$
$N_{bkg} = 1.16 \pm 0.87$ ⇒ $BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11}$ [90% CL]

Search for lepton number violating N

- Interpret the results as a search for Majorana neutrino [PLB 620 (2005) 17] mediating the $\mathbf{K^+ \rightarrow \mu^+(\mu^+\pi^-)}$ (LNV) decay
- Search is valid for N_M with $240 \approx m_N \approx 400$ MeV



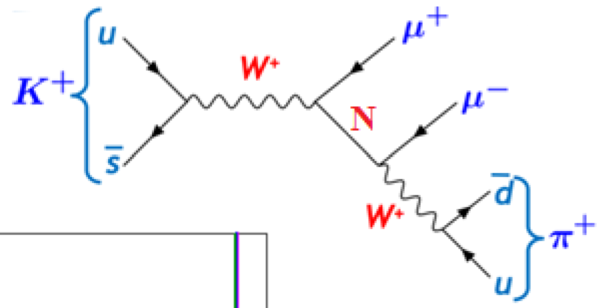


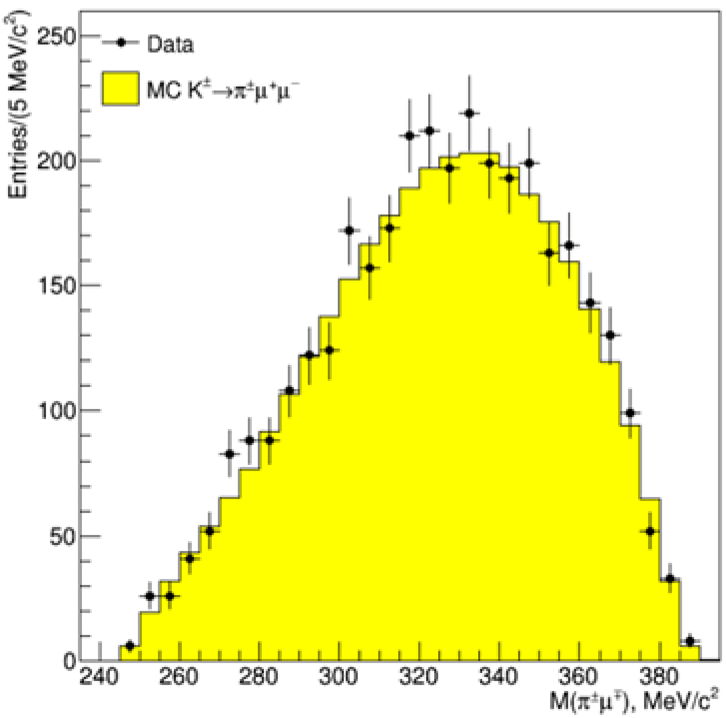


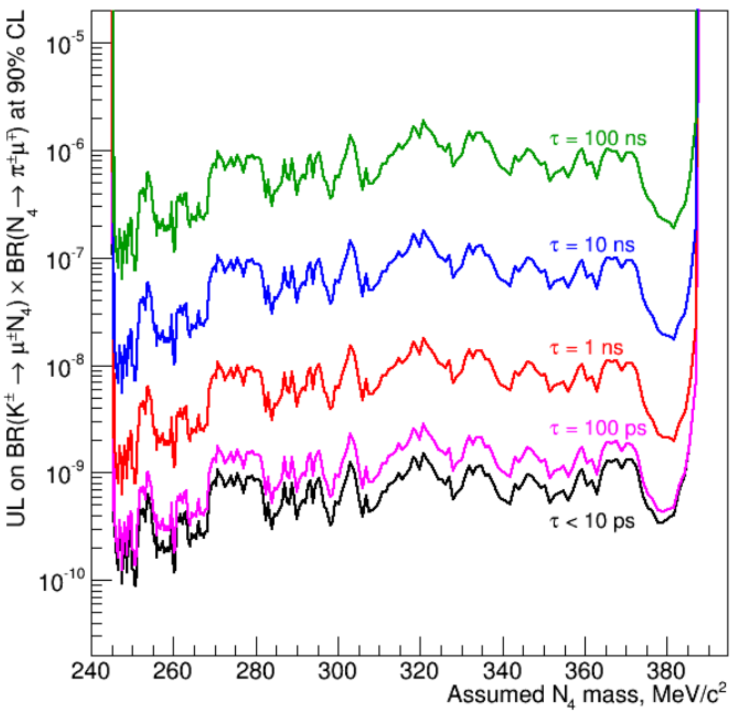
- For N_M with lifetime τ=100ps, **production x decay** limits set at ~10^{-10} (90% CL)

Search for lepton number conserving N

- Interpret the results as a search for heavy neutrino [PLB 620 (2005) 17] mediating the **$K^+ \to \mu^+(\pi^+\mu^-)$** (LNC) decay
- Peak search in the **$\pi^+\mu^-$** mass distribution



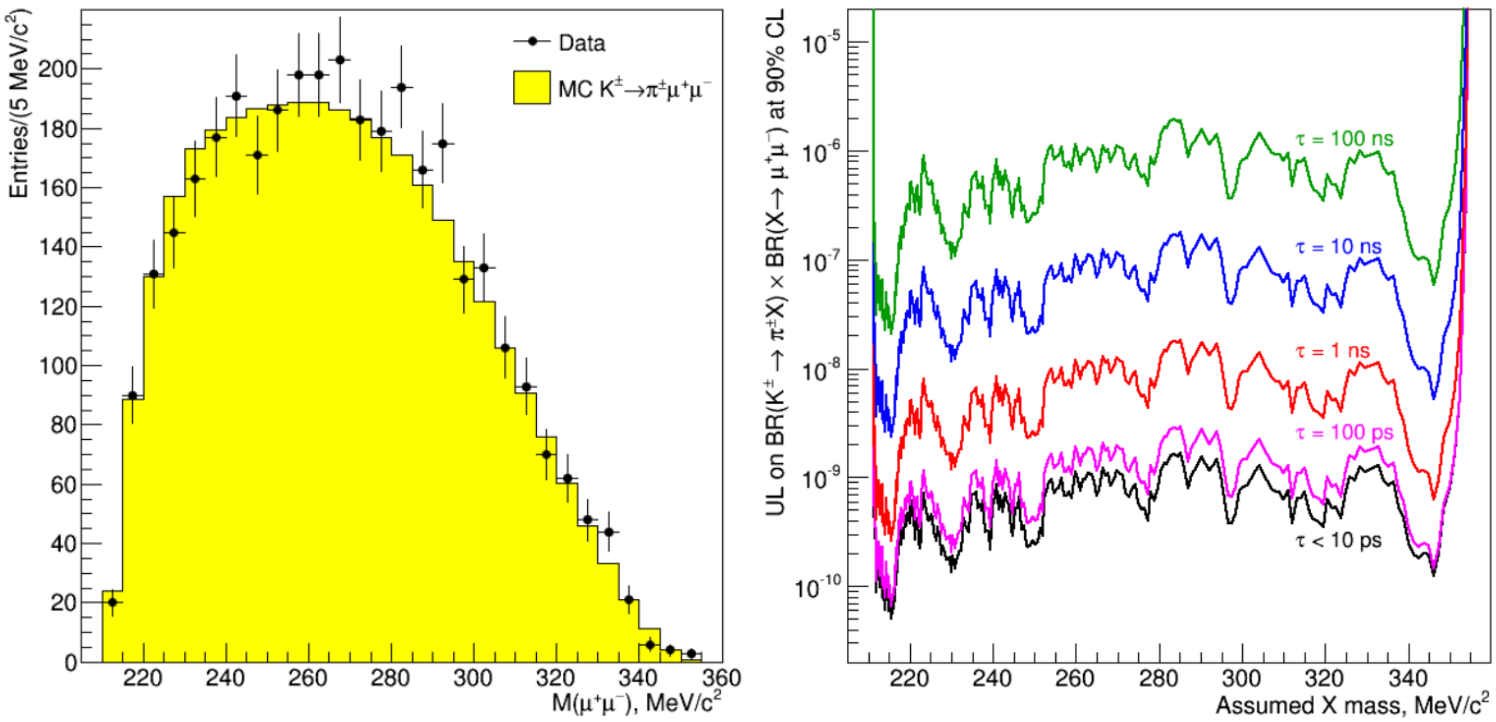




- For N_M with lifetime τ=100ps, **production x decay** limits set at ~10^{-9} (90% CL)

Search for inflatons

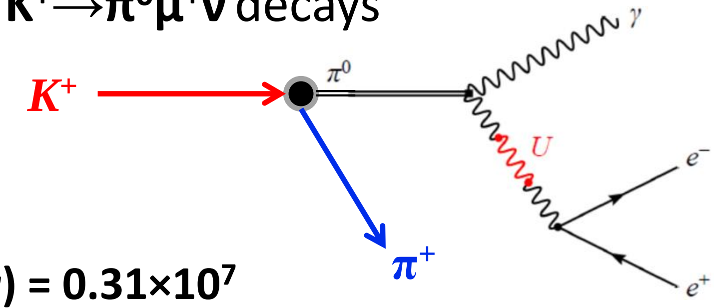
- Interpret the results as a search for inflatons [PLB 639 (2006) 414] mediating the **$K^+ \to \pi^+(\mu^+\mu^-)$** (LNC) decay
- Peak search in the **$\mu^+\mu^-$** mass distribution



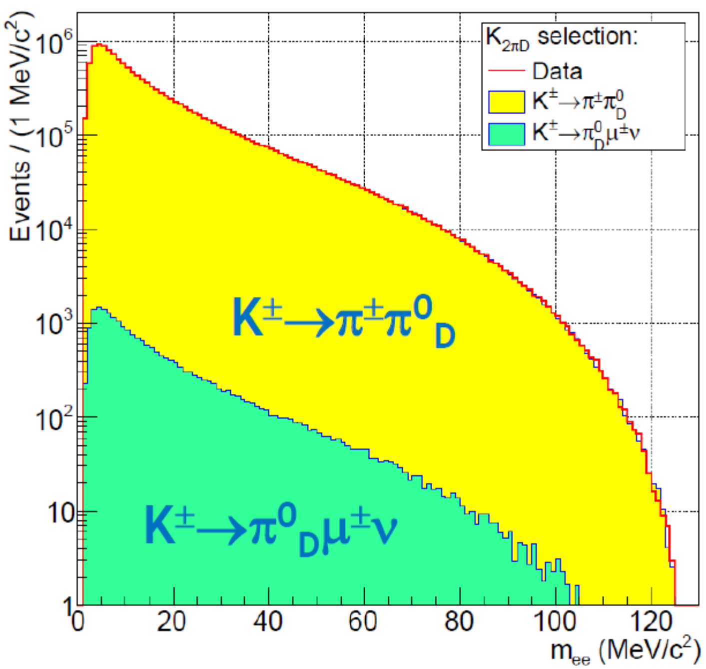
- For X with lifetime τ=100ps, **production x decay** limits set at ~10^{-9} (90% CL)

Search for dark photons

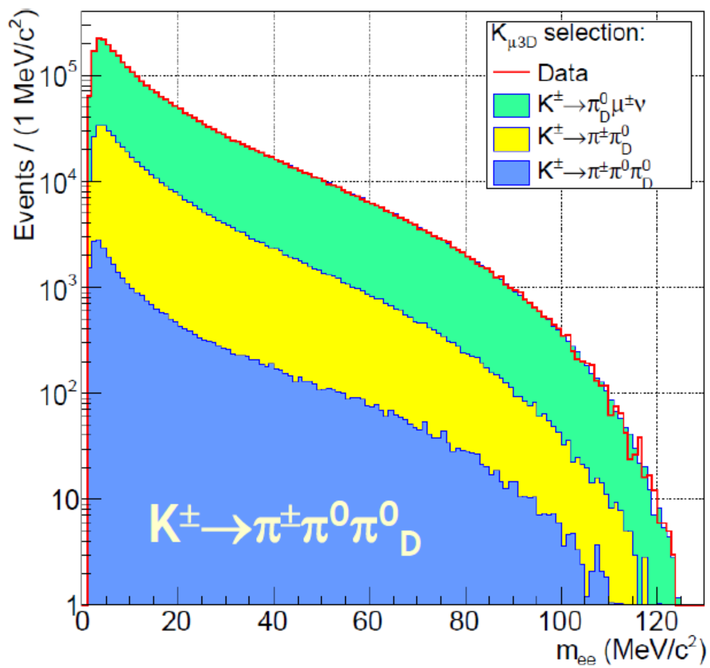
- The **$\pi^0 \rightarrow \gamma ee$** decay can be mediated by a **dark photon (A', U)**
- Can be isolated in NA48/2 data via **$K^+ \rightarrow \pi^+\pi^0$** and **$K^+ \rightarrow \pi^0\mu^+\nu$** decays
- Peak search in the **e^+e^-** mass distribution



$N(K^+ \rightarrow \pi^+\pi^0) = 1.38\times10^7$



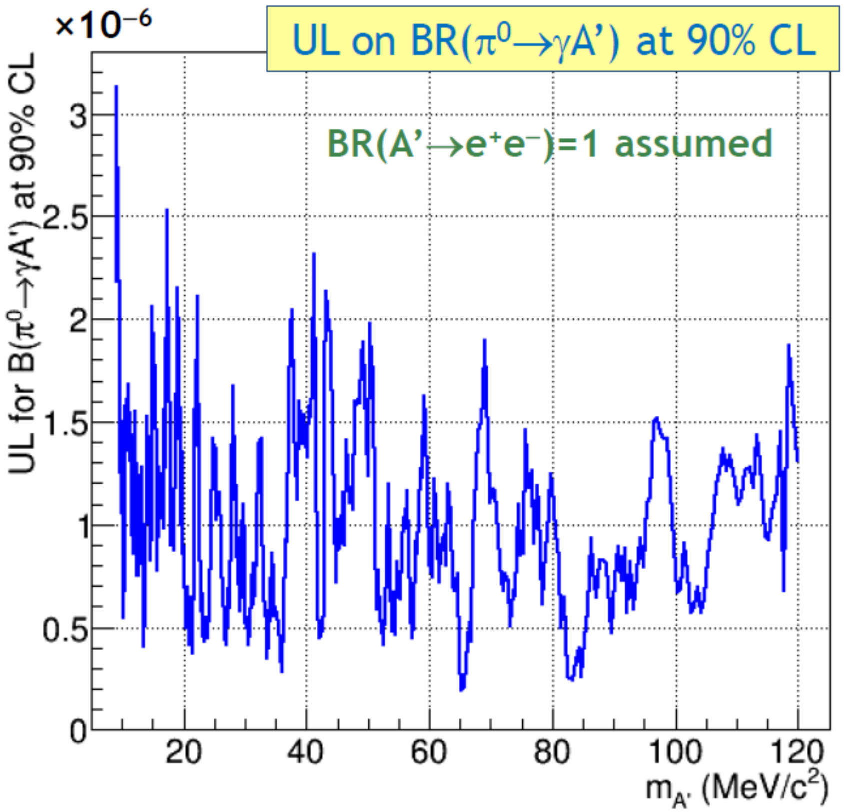
$N(K^+ \rightarrow \pi^0\mu^+\nu) = 0.31\times10^7$

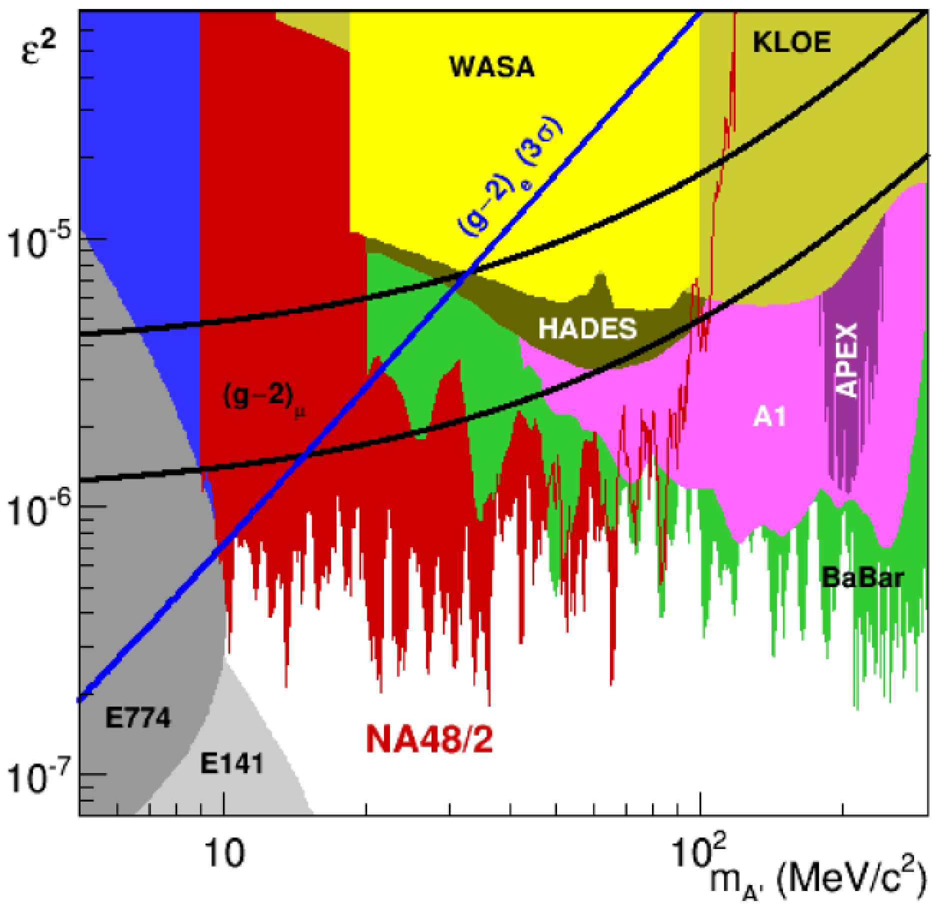


[PLB 746 (2015) 178-185]

Search for dark photons

- No local significance greater than 3σ → no hint of the dark photon





- NA48/2 constraints exclude dark photon explanation of the $(g\text{-}2)_\mu$ discrepancy [PLB 746 (2015) 178-185]

THE NA62 EXPERIMENT

NA62 and exotic searches

- The NA62 detector is primarily designed to collect 100 $K^+ \rightarrow \pi^+ \nu\nu$ events with only 10 background events
- Since the $K^+ \rightarrow \pi^+ \nu\nu$ branching fraction is $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$ this implies a huge number of K^+ decays and background reduction at the level of 10^{-12} [Buras et. al.]

- This requires:
  - A more intense secondary beam from the target

  … which implies a stringent trigger system based on detectors with excellent timing resolution
  - Efficient vetoing of photons (particularly from π^0 decays), electrons, and muons
  - Accurate momentum and energy measurement of kaon decay products

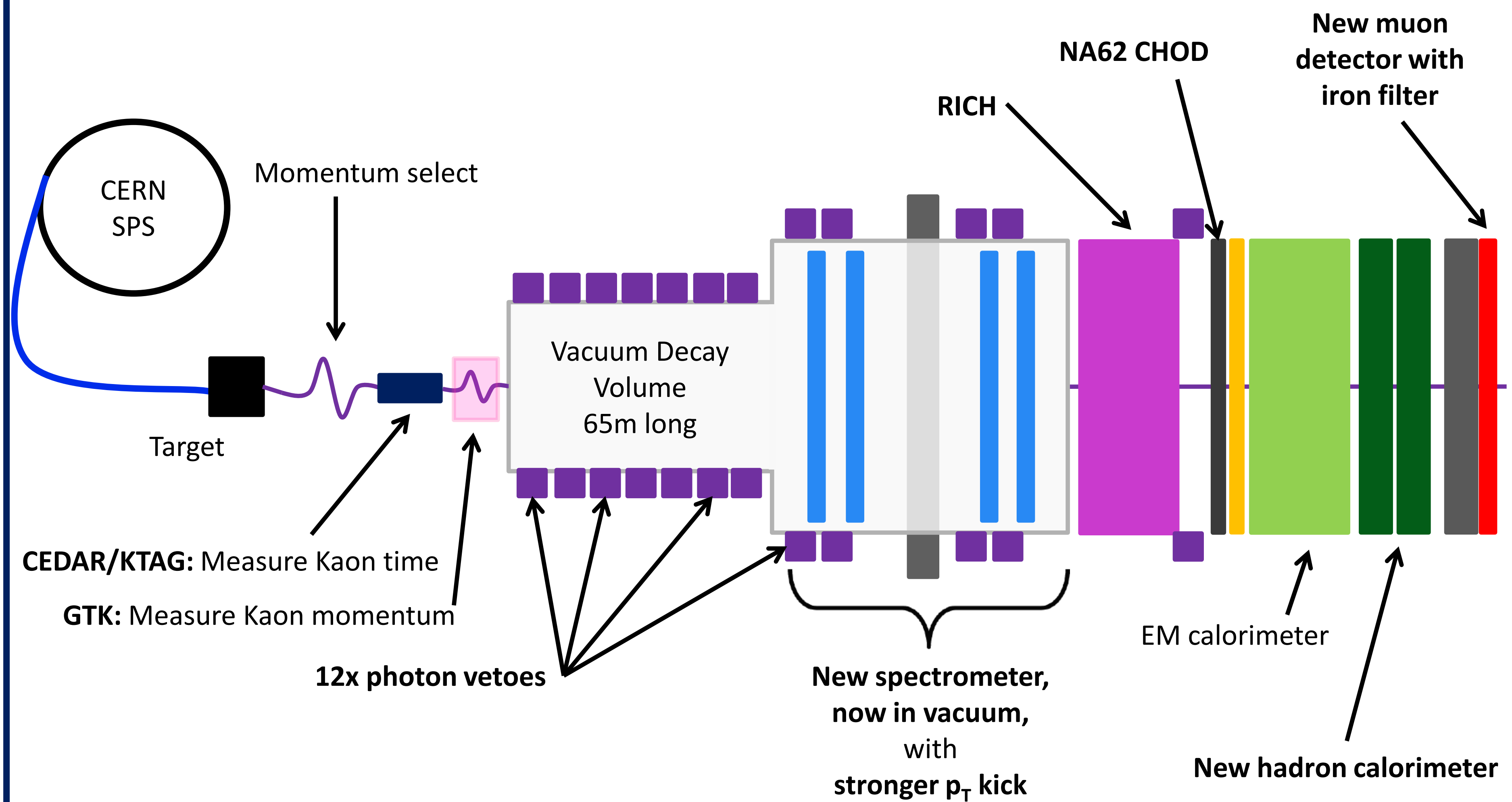
- These requirements (often inverted!) also make NA62 the perfect laboratory for searches for exotic particles
  - Development of a trigger strategy for exotic processes is critical

Kaon decay-in-flight experiments at CERN

- Beam intensities raised by about 4x
- 30x larger acceptance (solid angle) due to improved beamline optics

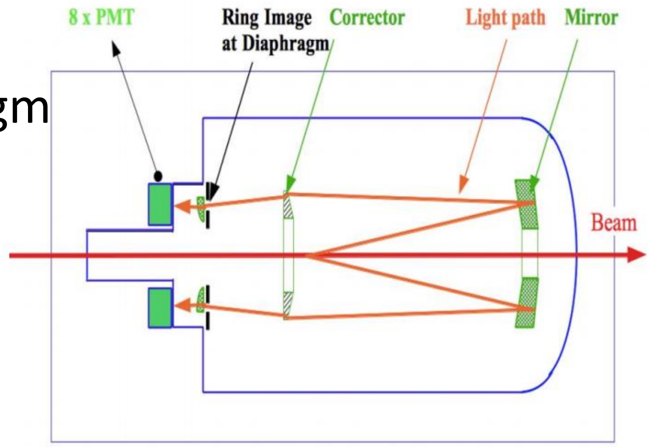
	NA48/2	NA62-RK	NA62
Data taking	2003-4	2007-8	**2014-18**
Primary intensity (ppp)	7×10^{11}	7×10^{11}	**3×10^{12}**
Solid angle (μsr)	~0.4	~0.4	**~12.7**
Beam momentum (GeV)	60	74	75
RMS momentum bite (GeV)	2.2	1.4	0.8

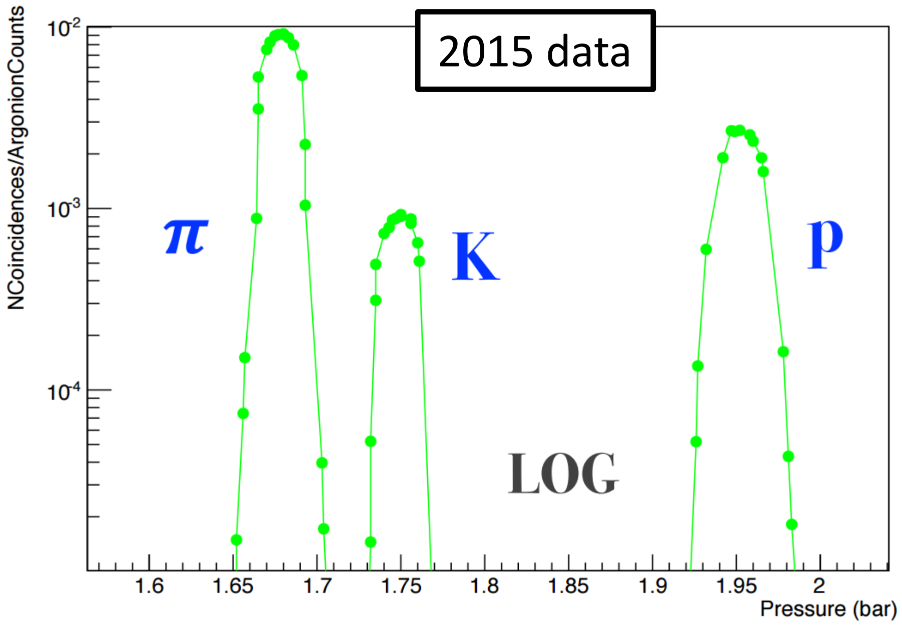
The NA62 detector



K^+ tagging – CEDAR/KTAG

- Kaons are tagged with the **CEDAR/KTAG** system
- **CEDAR** – collects Cherenkov light with fixed diaphragm
- **KTAG** – 8-fold PMT array with **σ_t ≈80 ps**
- Nominal Kaon rate ≈ **45 MHz**





STRAW spectrometer

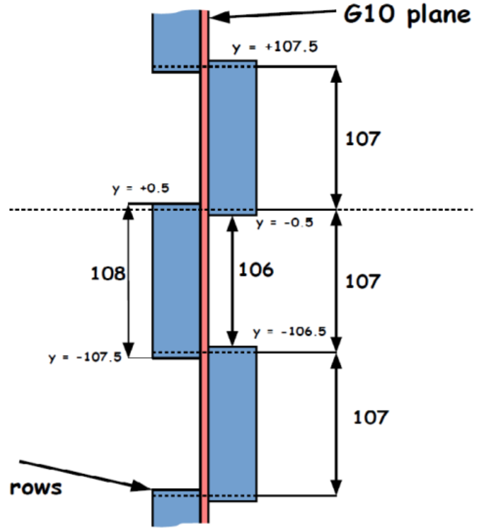
- Position and momentum of π^+ measured by the **STRAW** spectrometer
- Straw tubes operated in vacuum – very low material budget

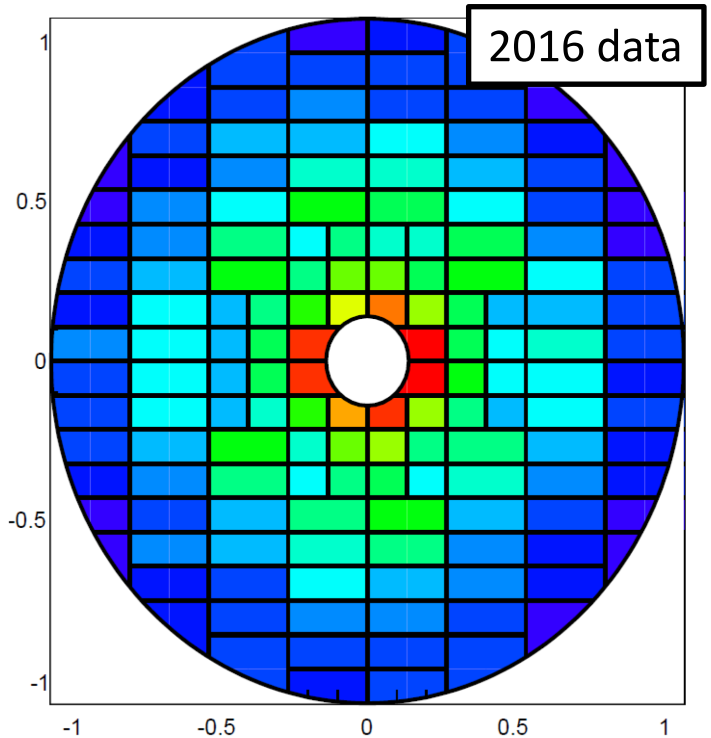
	NA48/2	NA62-RK	NA62
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV	120	265	270
$M(K \rightarrow \pi^+\pi^+\pi^-)$ resolution, MeV	1.7	1.2	0.8

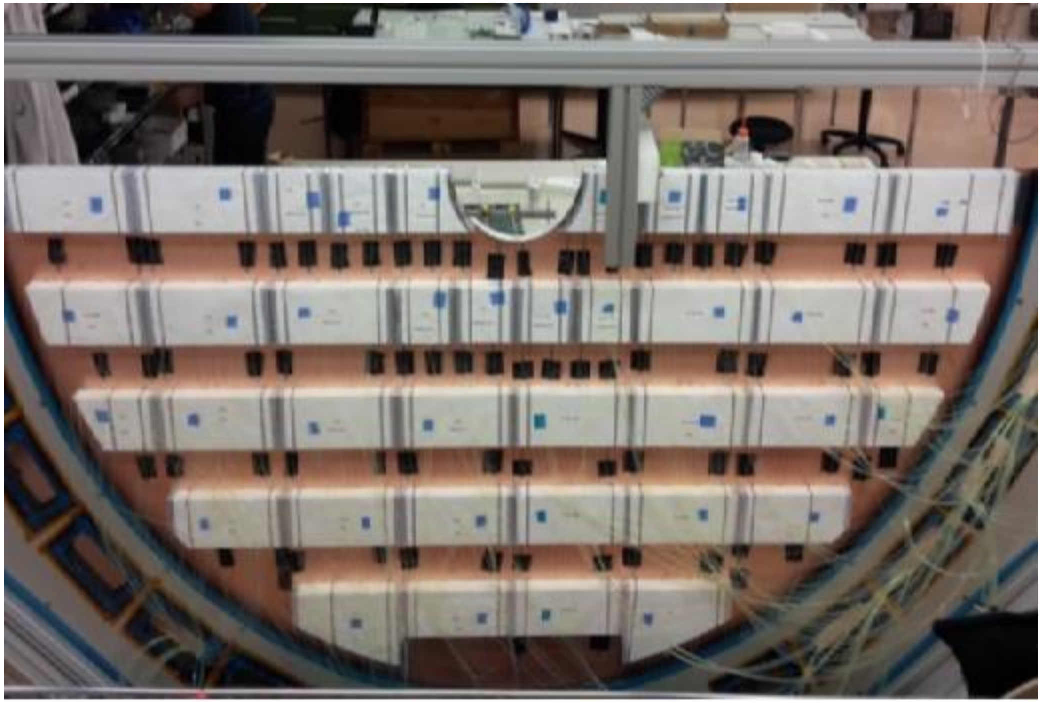
- **$\sigma_p/p \approx 0.32\% \oplus 0.008\%\ p$ [GeV/c]**
  - **Comparable momentum resolution to muons in LHCb [LHCb muons 2015]**

NA62 Charged Hodoscope

- NA62 Charged Hodoscope (NA62CHOD)
- New for 2016
- Designed as a simple charged particle trigger with time resolution of order ~1ns

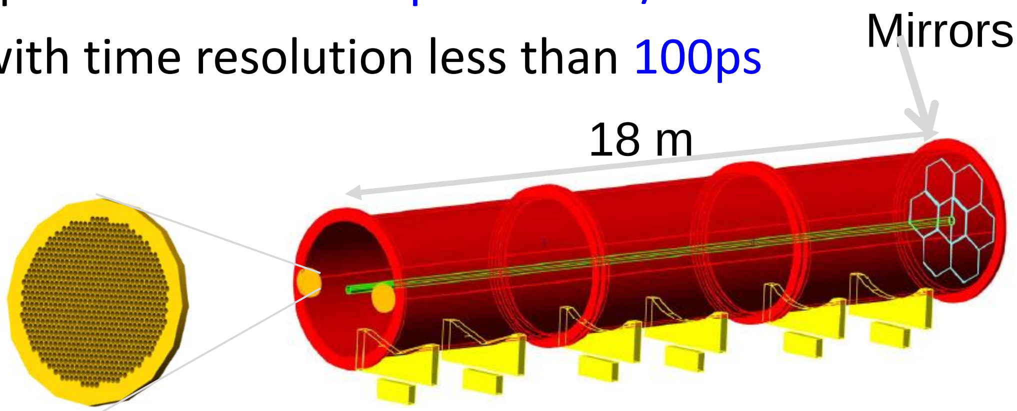


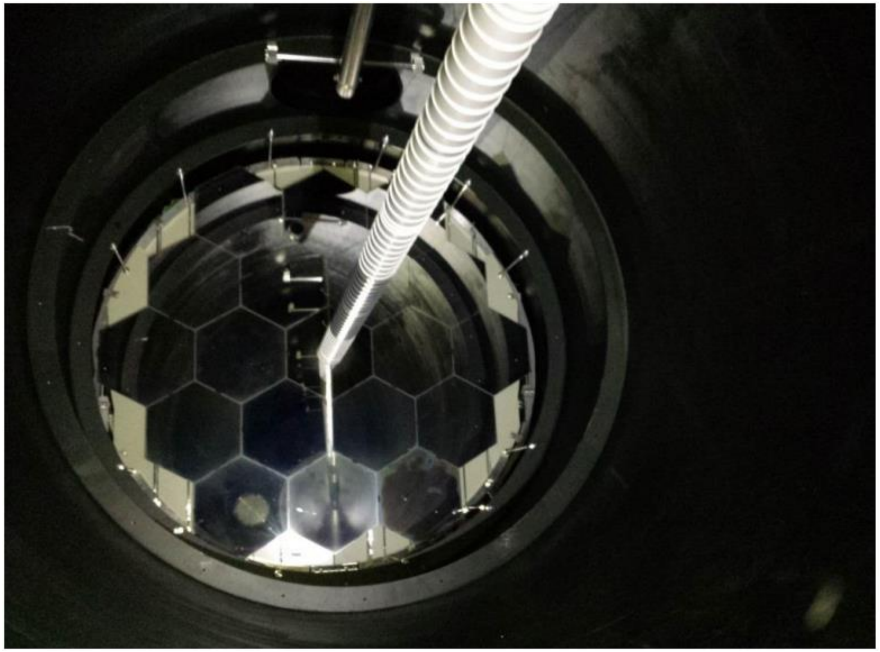




RICH detector

- Ring Imaging Cherenkov detector
- **Offline:** Particle identification for particles with 15 < p < 35 GeV/c
- **Trigger:** Charged particle trigger with time resolution less than 100ps





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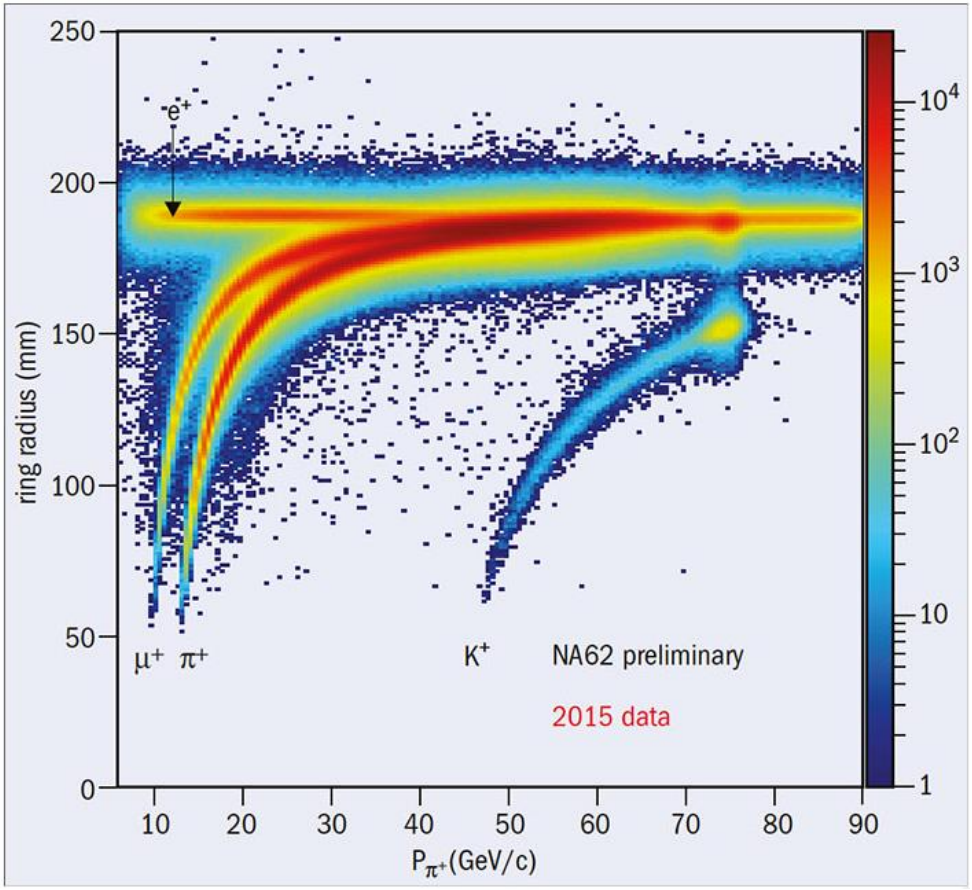
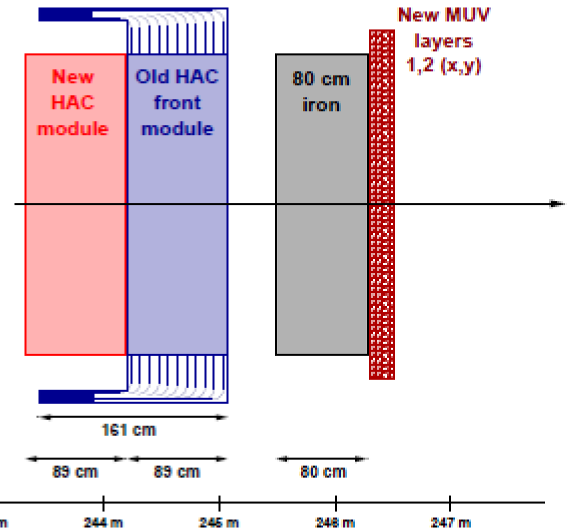
Plot from CERN Courier article

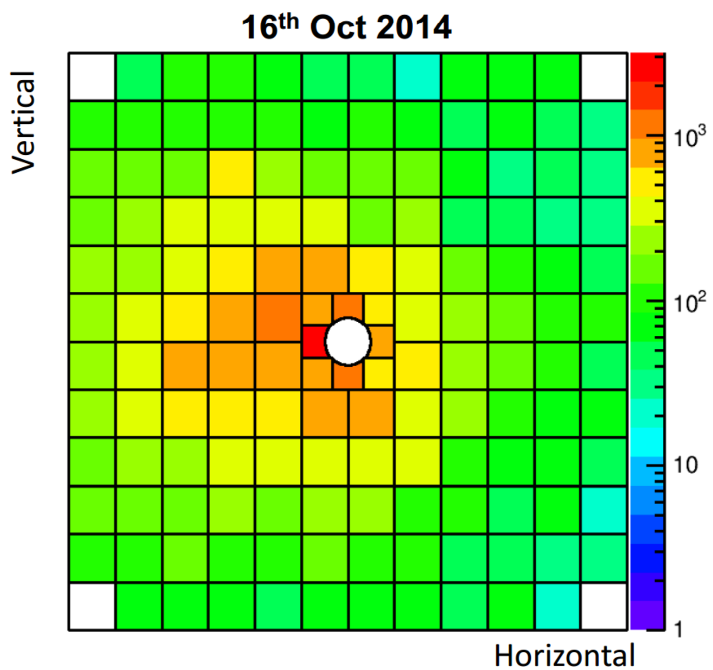


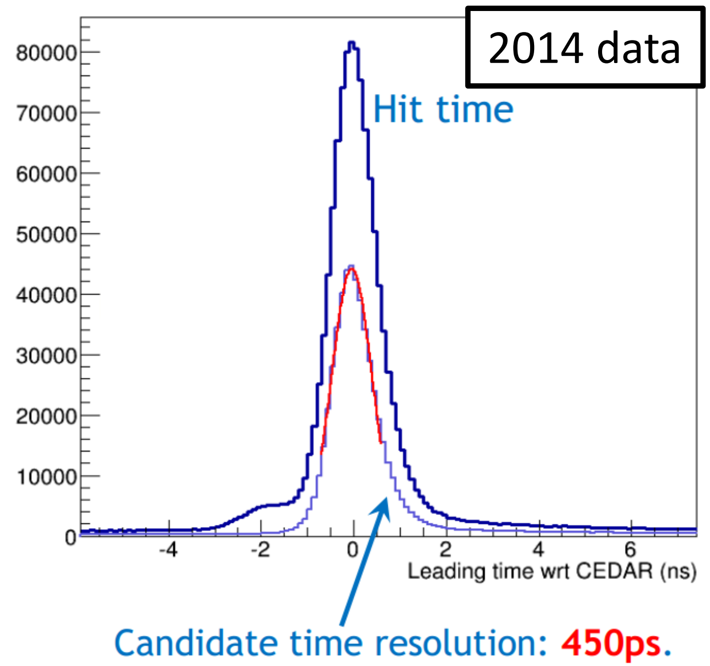
Muon veto system (MUV)

- MUV system formed of two calorimeters (MUV1, MUV2) plus a segmented layer of plastic scintillator (MUV3)



- **Offline:** MUV1&MUV2 provide muon rejection
- **Trigger:** MUV3 provides muon rejection with time resolution of ≈ **450 ps**
  MUV1 and **MUV2** information combined with **LKr**

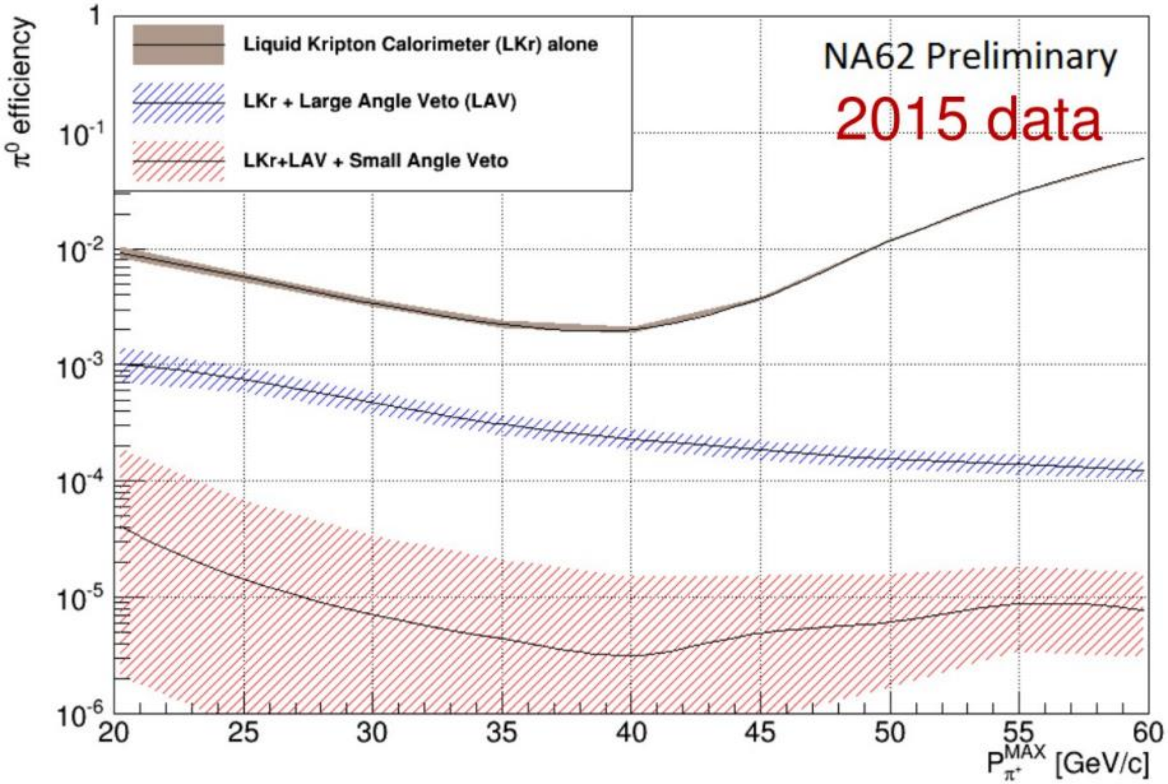




Hermetic photon veto

- Hermetic photon veto built from multiple detector systems
- **Small Angles Vetoes** (IRC and SAC) cover from 0 to 1.0 mrad
- The **LKr calorimeter** covers from 1.0 to 8.5 mrad
- **Large Angles Vetoes (LAV)** is formed of 12 stations, which are distributed along the experiment to cover from 8.5 to 50 mrad

- **Trigger:**
Information from **LAV12** is available
Information from **IRC** and **SAC** can be combined with the **LKr**



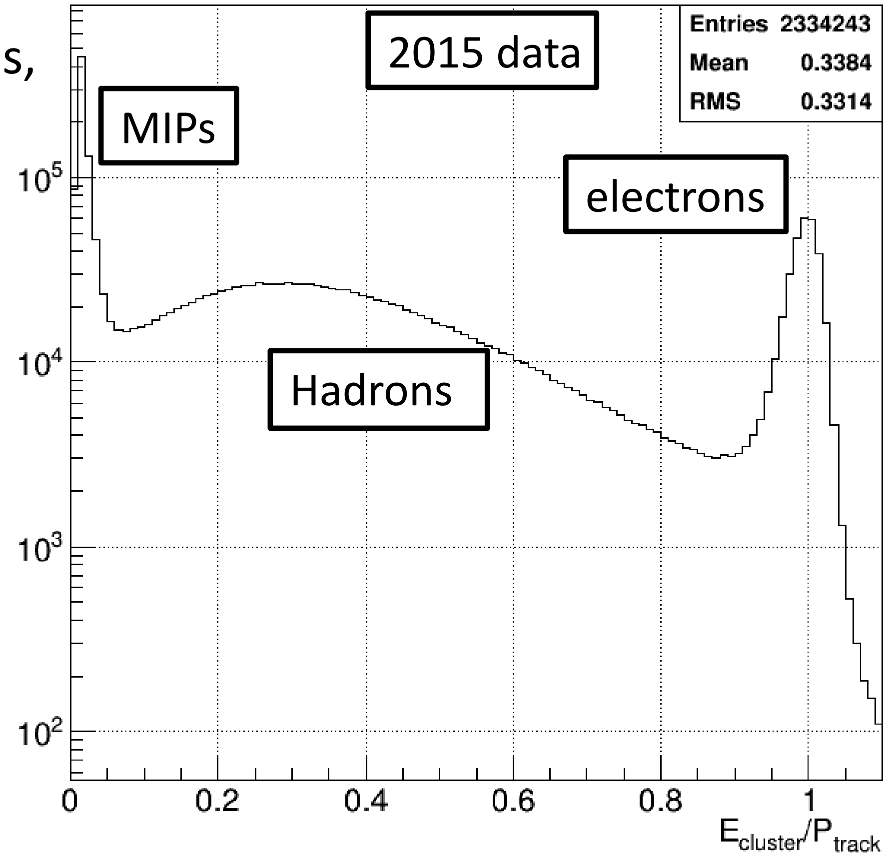
Electromagnetic calorimetry

- The **Liquid Krypton Calorimeter,** as used in NA48
- Measures particle energy with energy resolution comparable to e.g. CMS ECAL

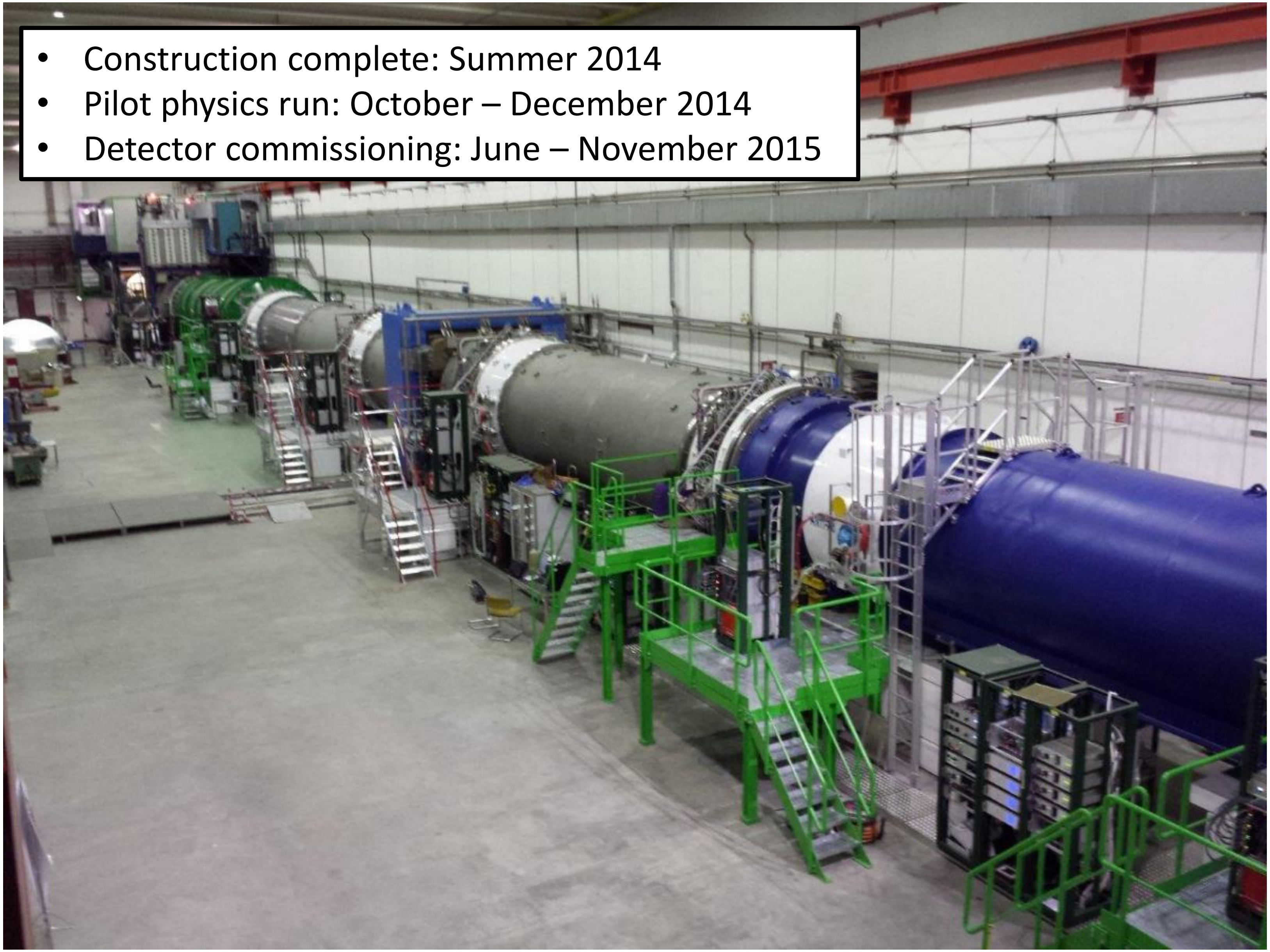
$$\frac{\sigma_E}{E} = \frac{3.2\,\%}{\sqrt{E(GeV)}} \oplus \frac{9\,\%}{E(GeV)} \oplus 0.42\,\%$$

($\sigma_E/E \approx 1\%$ at 10 GeV)

- **Offline:** provides separation of electrons, hadrons, and muons
- **Trigger:** total energy deposition information available

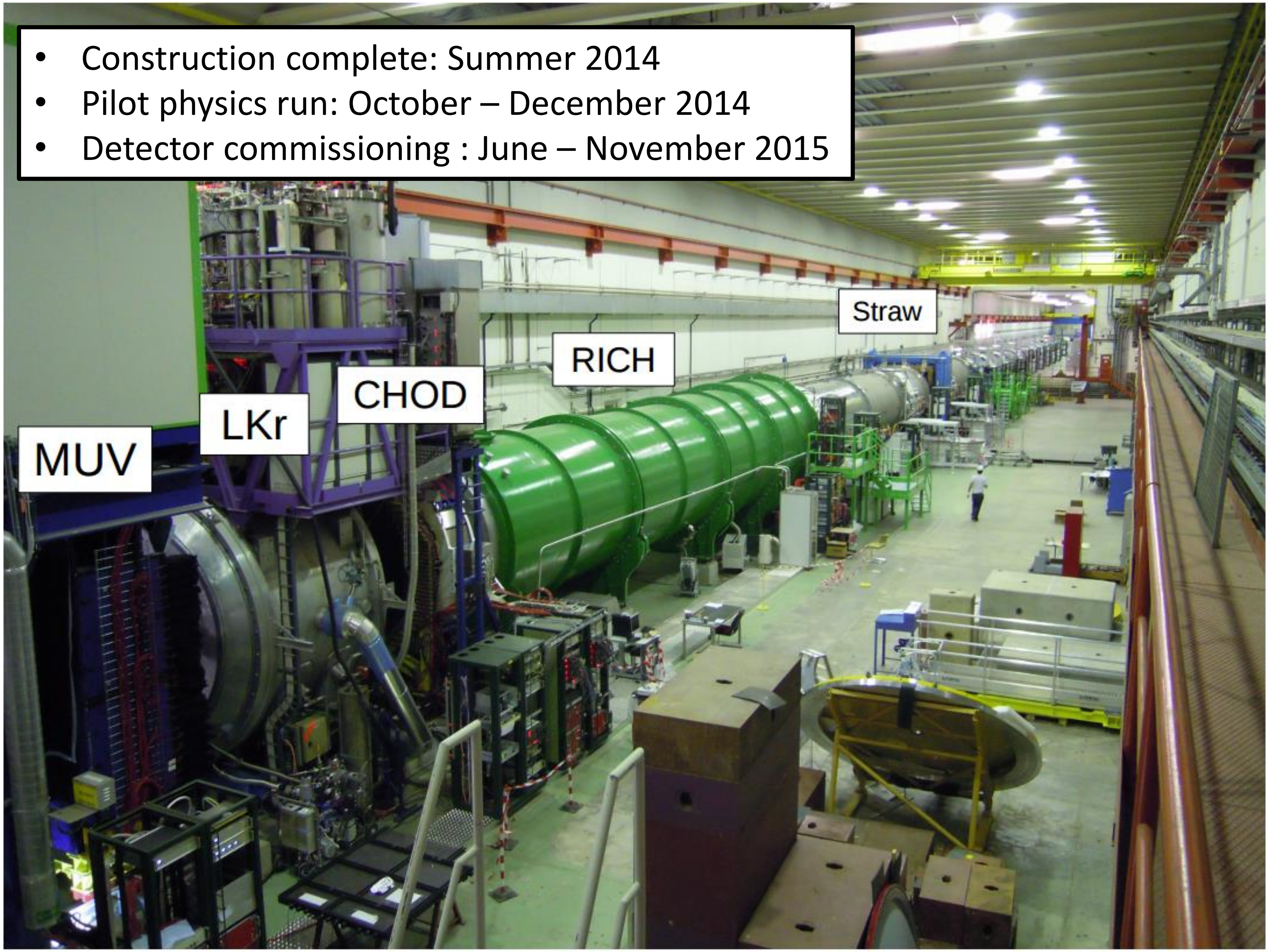


NA62



• Construction complete: Summer 2014
• Pilot physics run: October – December 2014
• Detector commissioning: June – November 2015

NA62



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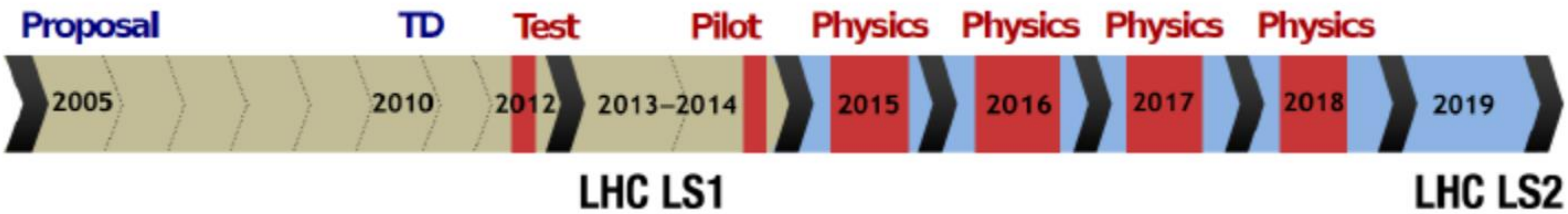
Solid angle (μsr)	~0.4	~0.4	**~12.7**
Beam momentum (GeV)	60	74	75
RMS momentum bite (GeV)	2.2	1.4	0.8
Spectrometer thickness, X_0	2.8%	2.8%	1.8%
Spectrometer P_T kick, MeV	120	265	270
$M(K \rightarrow \pi^+\pi^+\pi^-)$ resolution, MeV	1.7	1.2	0.8
K decays in fiducial region	2×10^{11}	2×10^{10}	**1.2×10^{13}**

NA62 data-taking – past, present and future



- 2014 – Pilot Physics run (initial setup of experiment, first look at data)
- 2015 – beam time mostly dedicated to TDAQ and detector commissioning, nevertheless, 10^{10} events collected at low intensity (1% of nominal) with minimum bias triggers
- 2016 to present – commissioning and data-taking with exotics trigger, at between 3% and 20% of nominal intensity
- 2016-2017-2018 – data-taking for $K^+ \rightarrow \pi^+ \nu\nu$, run exotics trigger in parallel

The NA62 L0 Trigger in 2016

- The lowest-level of the NA62 trigger system (L0) is implemented in hardware, based on FPGA technology

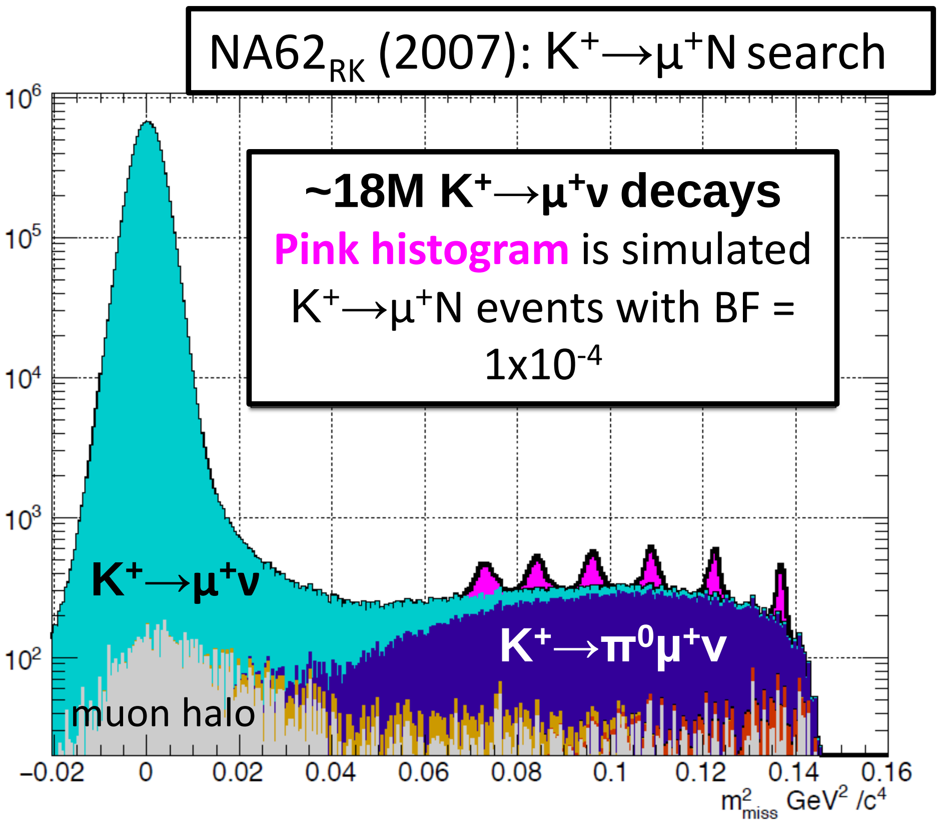
- **A multiple track trigger** (MT) can be built requiring signals in 10 RICH PMTs and two (NA62)CHOD quadrants
- **Dielectron trigger: multiple track +** more than 10GeV of energy in the LKr
- **Dimuon trigger: multiple track +** signals in two MUV3 tiles
- **LFV (muon-electron) trigger**: **multiple track +** more than 10GeV of energy in the LKr and signal in one MUV3 tile (selects **$K^+ \rightarrow \pi\mu e$** decays)

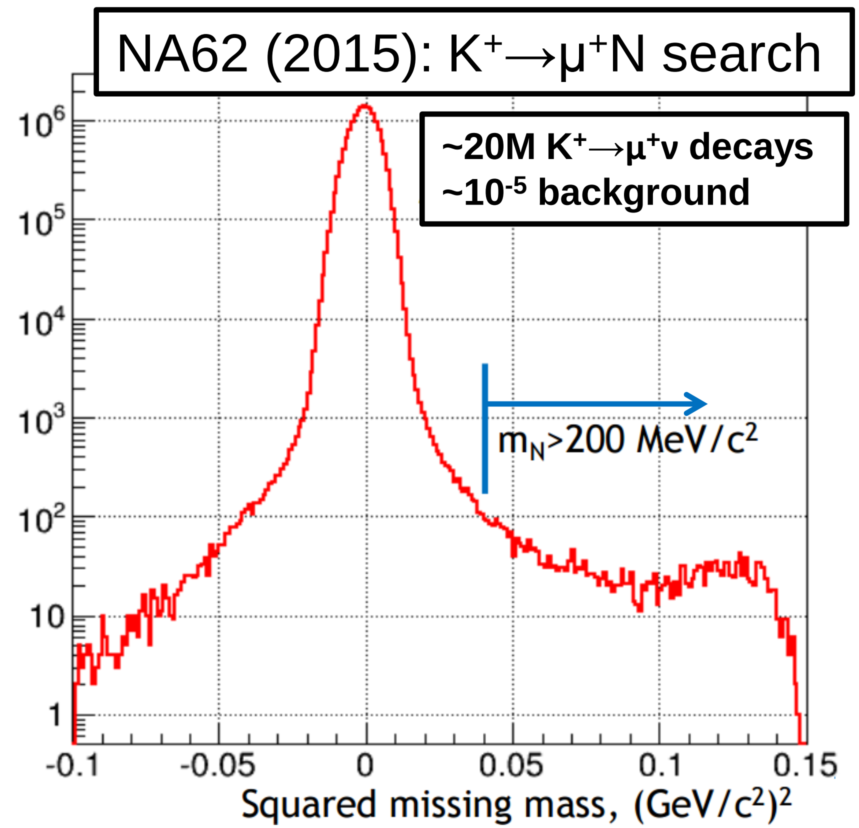
- In simulations the total rate from the above L0 triggers ~ few 100 kHz, which is sufficiently low to run in parallel to the $K^+ \rightarrow \pi^+ \nu\nu$ trigger
- Validation of the trigger rates with data is **currently underway**

PHYSICS PROSPECTS OF NA62

Searching for HNL production

- Can also search for production of HNL in $\mathbf{K^+\to\mu^+N}$ decays
- $\mathbf{K^+\to\mu^+N}$ events appear as peaks in the $\mathbf{K^+\to\mu^+\nu}$ squared missing mass spectrum
- Note: Production searches are model-independent





Searching for HNL production

- Can also search for production of HNL in $K^+ \to \mu^+ N$ decays
- Production searches are model-independent
- Most stringent limits are set by Kaon decay measurements

Global limits on $|U_{\mu4}|^2$ as a function of HNL mass

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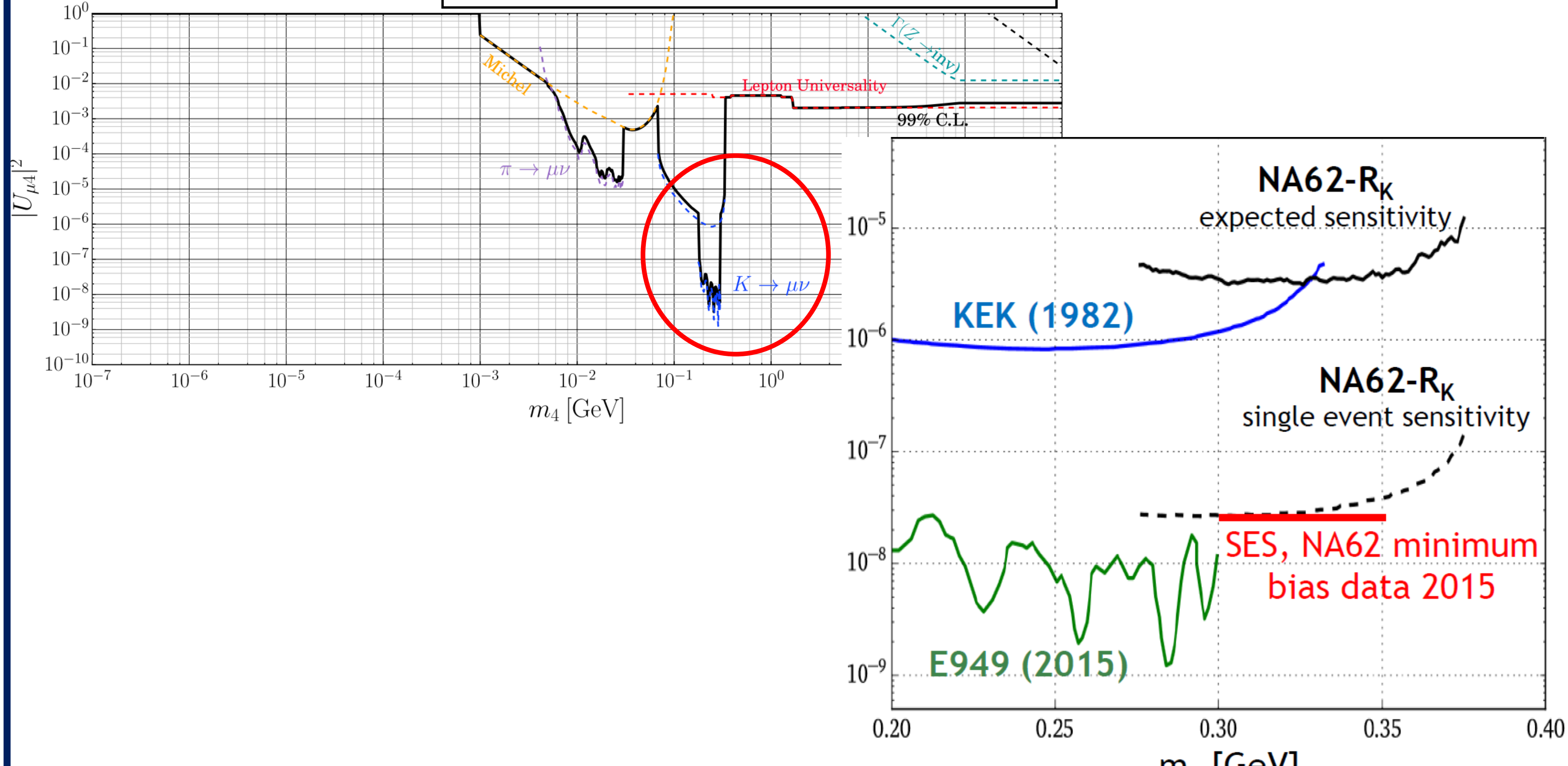
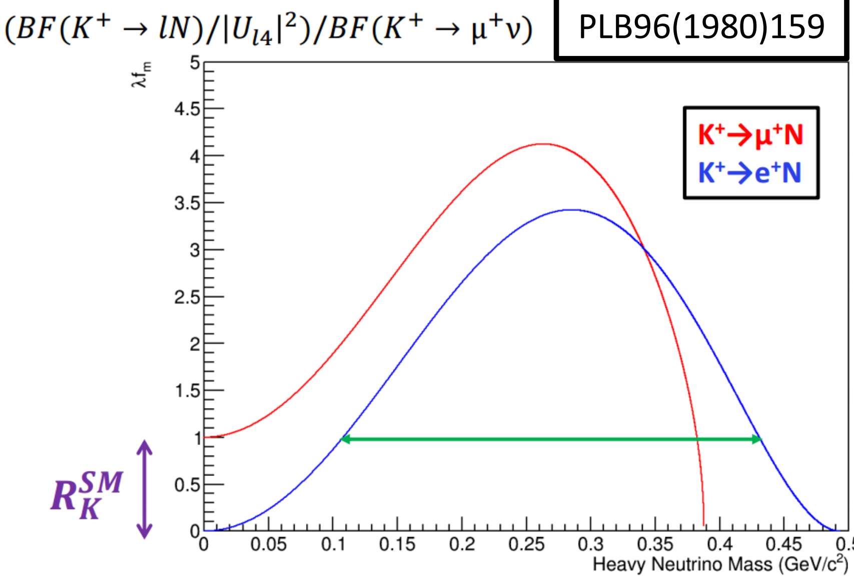
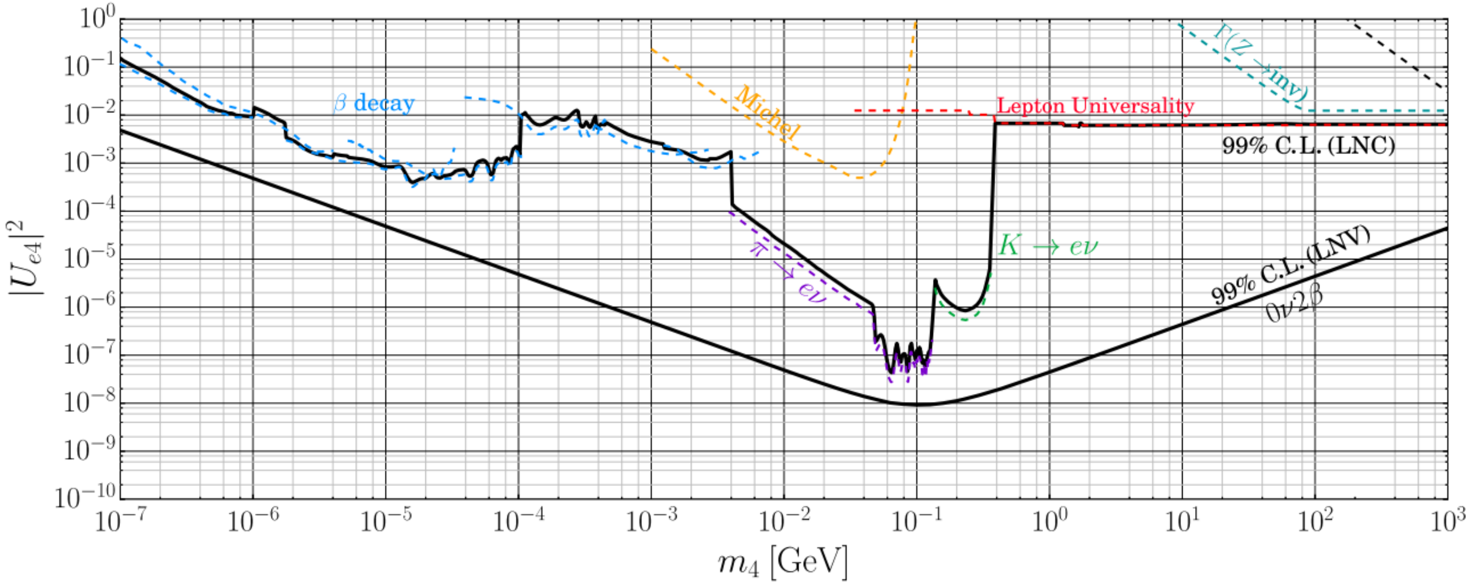


Searching for HNL production

- Lifting of the R_K-suppression by the HNL means there could be a similar number of **$K^+ \to e^+N$** events as **$K^+ \to \mu^+N$**
- Limits on **$K^+ \to e^+N$** are much weaker than those of **$K^+ \to \mu^+N$**
- **$K^+ \to e^+N$** background small enough for stringent limits to be set on this decay

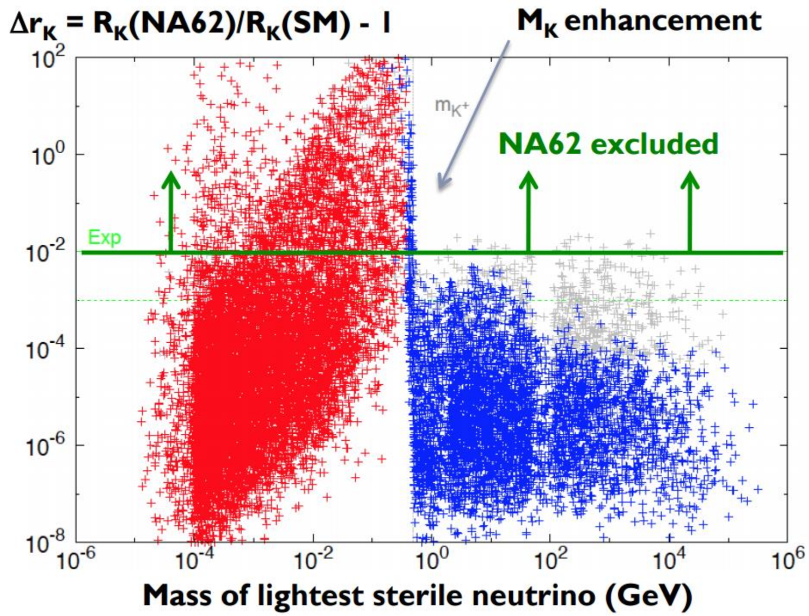
R. Shrock
PLB96(1980)159

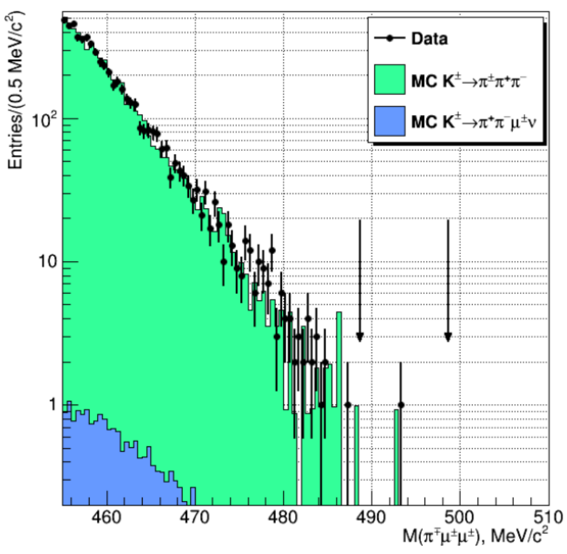


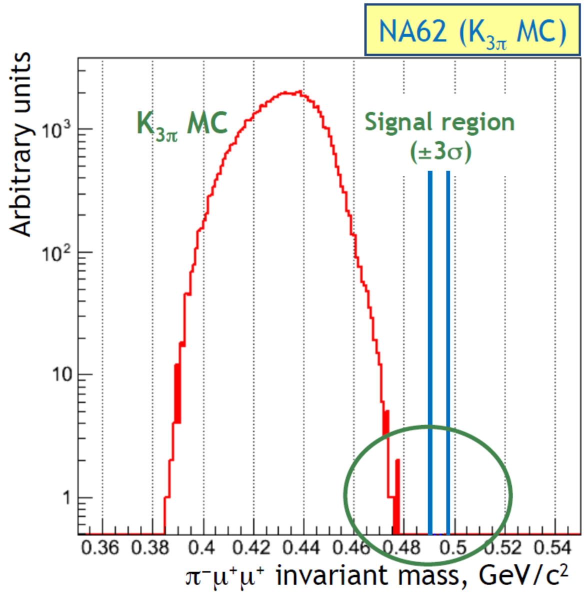


Physics prospects

- R_K measurement expected to improve by a factor of 2-4x at NA62
- Expect background reduction and larger sample of $\mathbf{K^+ \rightarrow \pi\mu\mu}$ decays, expect improved limits down to $\mathbf{10^{-12}}$





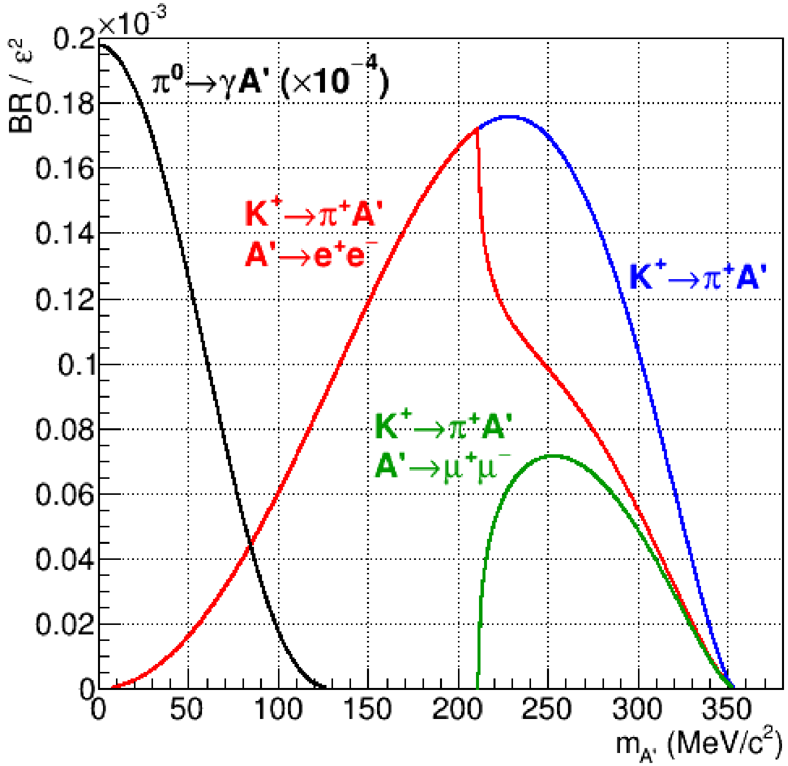


Physics prospects

- Searches for **$K^+ \rightarrow \pi\mu e$** have potential to probe to 10^{-12}

Mode	UL at 90% CL	Experiment	Reference
$K^+ \rightarrow \pi^+\mu^+e^-$	1.3×10^{-11}	E777/E865	PRD 72 (2005) 012005
$K^+ \rightarrow \pi^+\mu^-e^+$	5.2×10^{-10}	E865	PRL 85 (2000) 2877
$K^+ \rightarrow \pi^-\mu^+e^+$	5.0×10^{-10}		

- Sensitivity to dark photons with LFV couplings, masses from 100 to 350 MeV



Physics prospects

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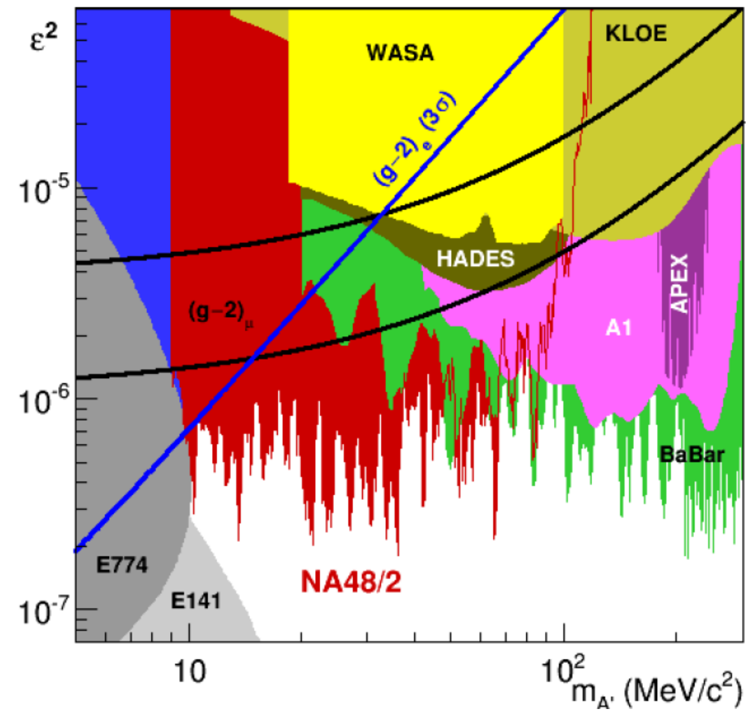
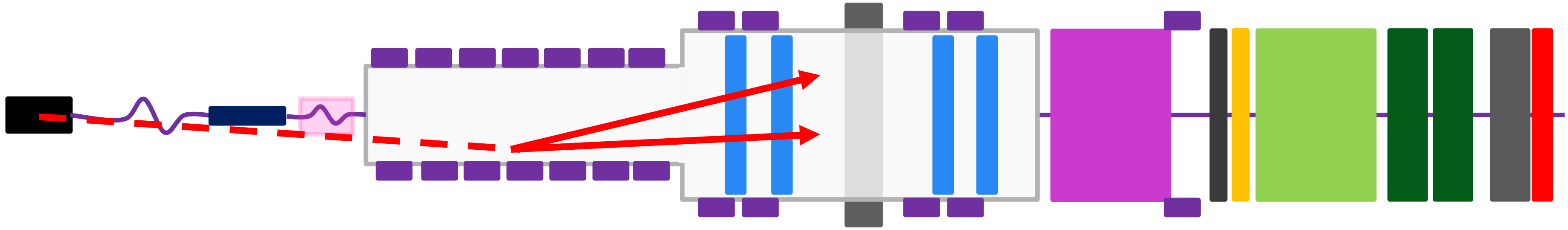
- Dark photon search in **$\pi^0 \rightarrow \gamma ee$** already background dominated, expect 10x improvement in limit

* plot contains published limits up to 2015

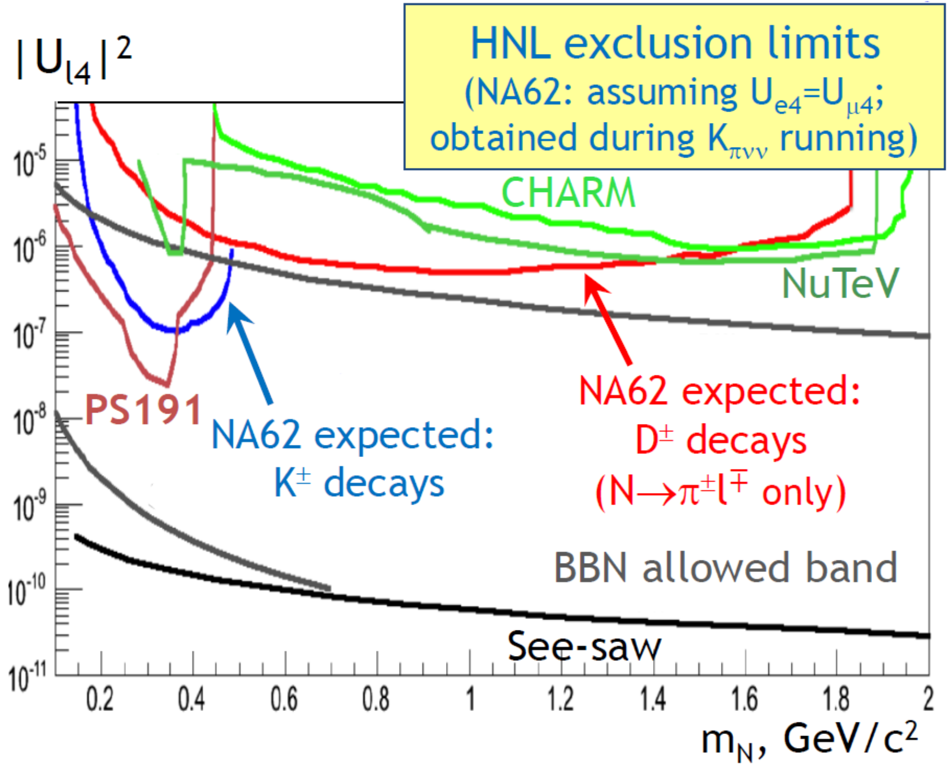


Searches for HNL from the target

- HNL can be produced in meson decays at the T10 target
- These HNL can then decay inside the NA62 fiducial volume



- With zero background events, can probe beyond current limits
- Proof-of-principle from 2016 data: searches for dark photon and axion (see link) production at the target. Prospects for these searches are currently being evaluated



Summary

- The long history of Kaon experiments at CERN continues with NA62

- The previous experiments, NA48/2 and NA62RK continue to produce results related to 'exotic' processes including: dark photons; inflatons; heavy (majorana) neutrinos in production and decay.
  - New world-best limits on the LNV decay $\mathbf{K^+ \to \mu^+ \mu^+ \pi^-}$

$N(\mu^\pm\mu^\pm) = 1$
$N_{bkg} = 1.16 \pm 0.87$ ⇒ $BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11}$ [90% CL]

- The NA62 experiment is a substantial upgrade over previous experiments, providing about 70x more kaon decays with much better background rejection

- There are planned and current searches for exotic processes at NA62

- Watch this space for more information!