NA62 & Kaon Experiments

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Outline:

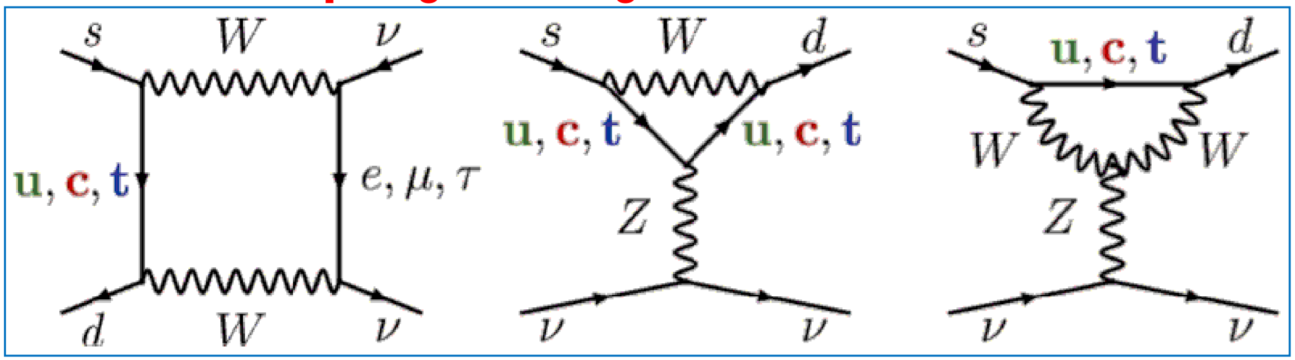
1) Ultra-rare $K \to \pi\nu\bar{\nu}$ decays: theory vs experiment.
2) NA62 and other $K_{\pi\nu\nu}$ experiments.
3) UK responsibilities within NA62.
4) NA62 programme beyond the flagship mode.
5) The long-term future.

PPAP Community Meeting

RAL • 22 July 2014

Flagship measurement: $K\rightarrow\pi\nu\bar{\nu}$

SM: box and penguin diagrams



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 ($K^+\rightarrow\pi^0 e^+\nu$).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from B–$\bar{\text{B}}$ mixing or $B^0\rightarrow\rho\gamma$.

SM branching ratios

Brod et al., PRD 83 (2011) 034030

Mode	$BR_{SM}\times10^{11}$
$K^+\rightarrow\pi^+\nu\bar{\nu}(\gamma)$	7.81±0.75±0.29
$K_L\rightarrow\pi^0\nu\bar{\nu}$	2.43±0.39±0.06

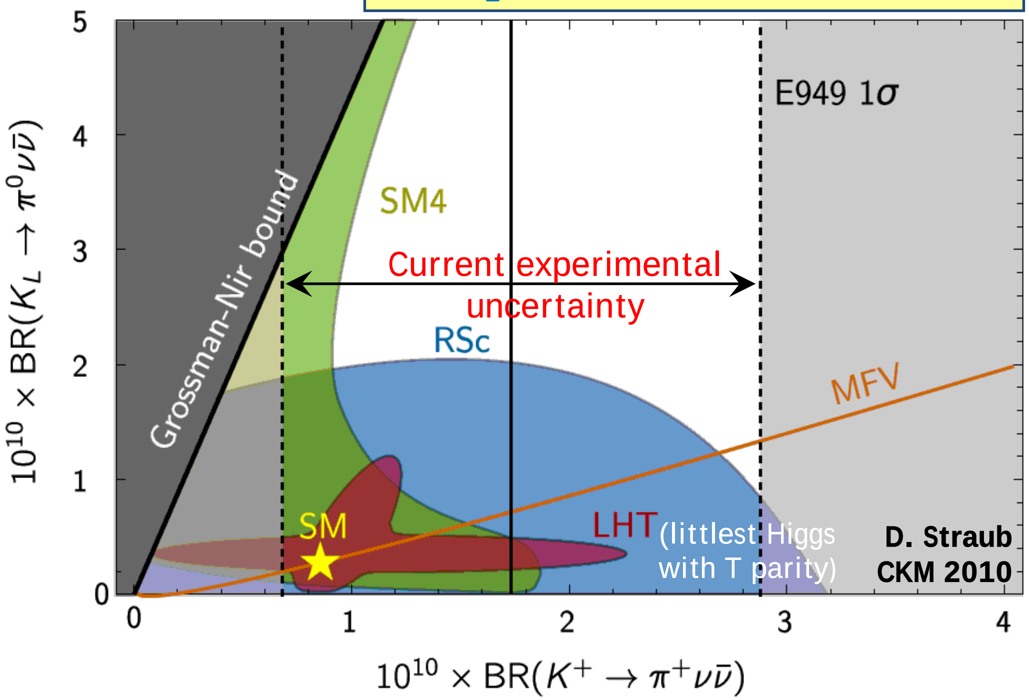
CKM parametric

Intrinsic

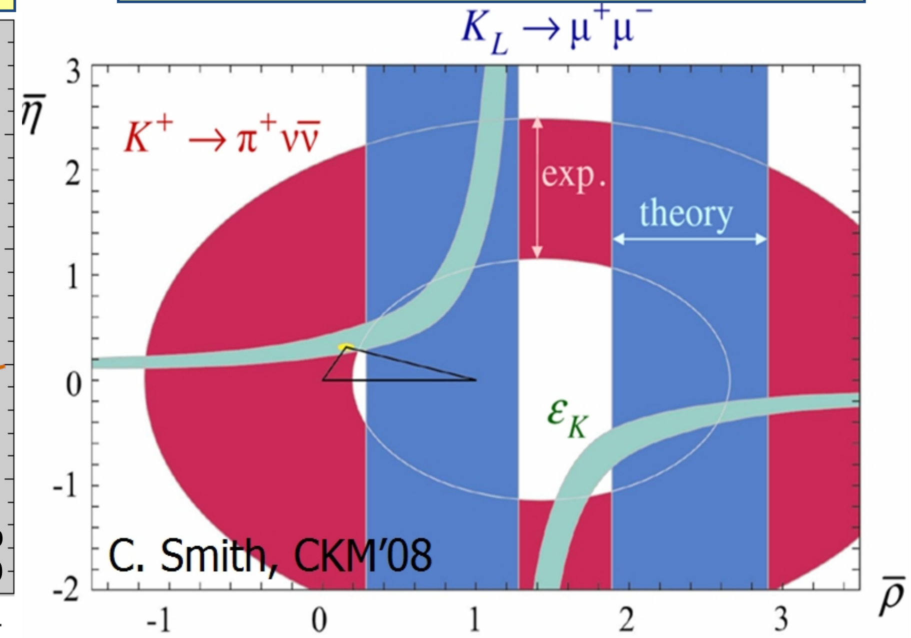
Theoretically clean,
almost unexplored,
sensitive to new physics.

$K\to\pi\nu\bar{\nu}$: experiment vs theory

$BR(K_L\to\pi^0\nu\bar{\nu})$ vs $BR(K^+\to\pi^+\nu\bar{\nu})$



CKM unitarity triangle with kaons



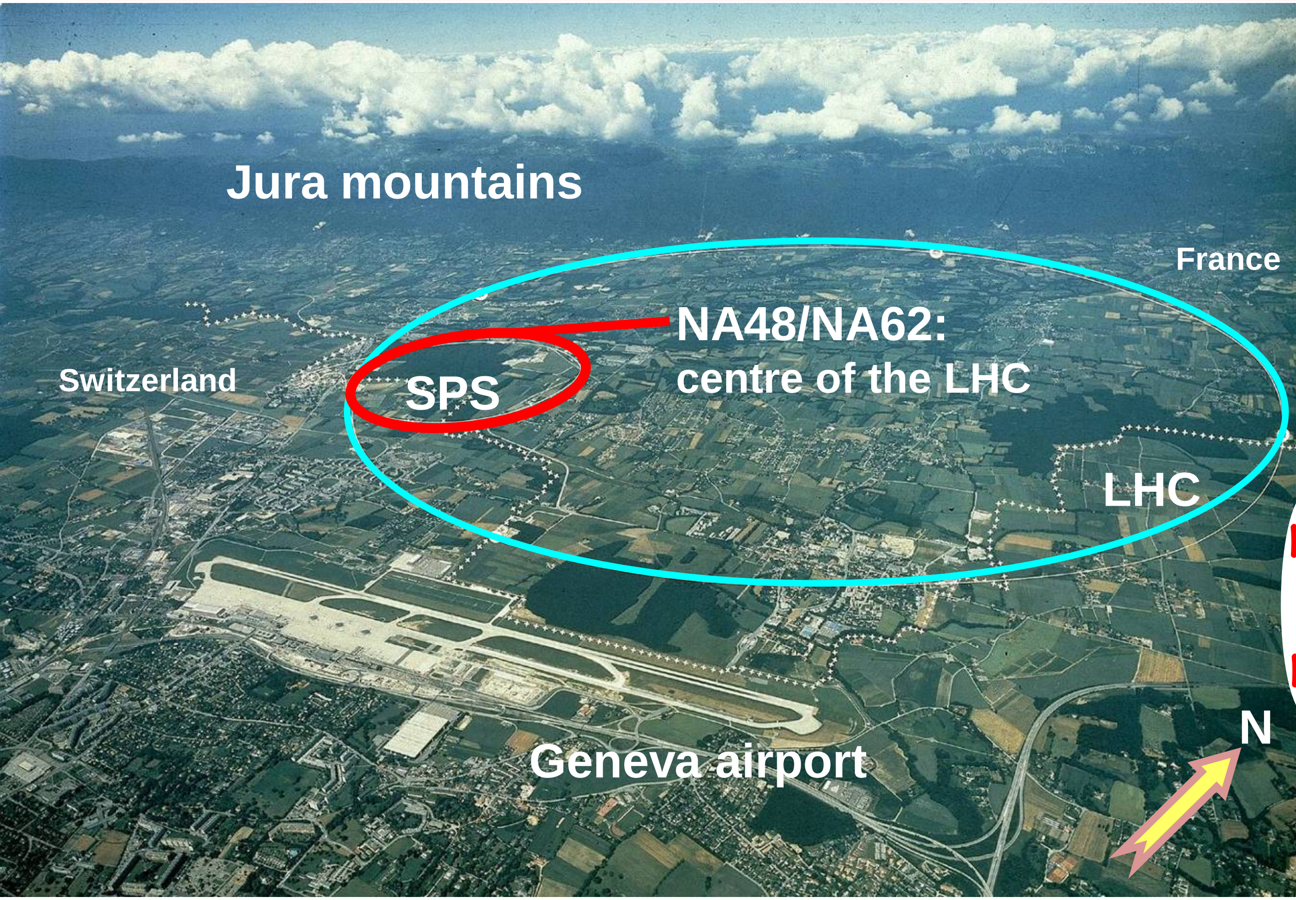
NA62 aim: collect O(100) SM $K^+\to\pi^+\nu\bar{\nu}$ decays with <20% background in 3 years of data taking using a novel decay-in-flight technique.

Signature: high momentum K^+ (**75GeV/c**) → low momentum π^+ (**15–35 GeV/c**).

Advantages: max detected K^+ decays/proton (**$p_K/p_0\approx0.2$**); efficient photon veto (**>40 GeV** missing energy); good π^+ vs μ^+ identification with RICH.

Un-separated beam (**6%** kaons) → higher rates, more background sources.

CERN NA48/NA62 experiments



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
- 2012: technical run
- *2014:* 1st $K^+\to\pi^+\nu\bar{\nu}$ run

Kaon decay in flight experiments.

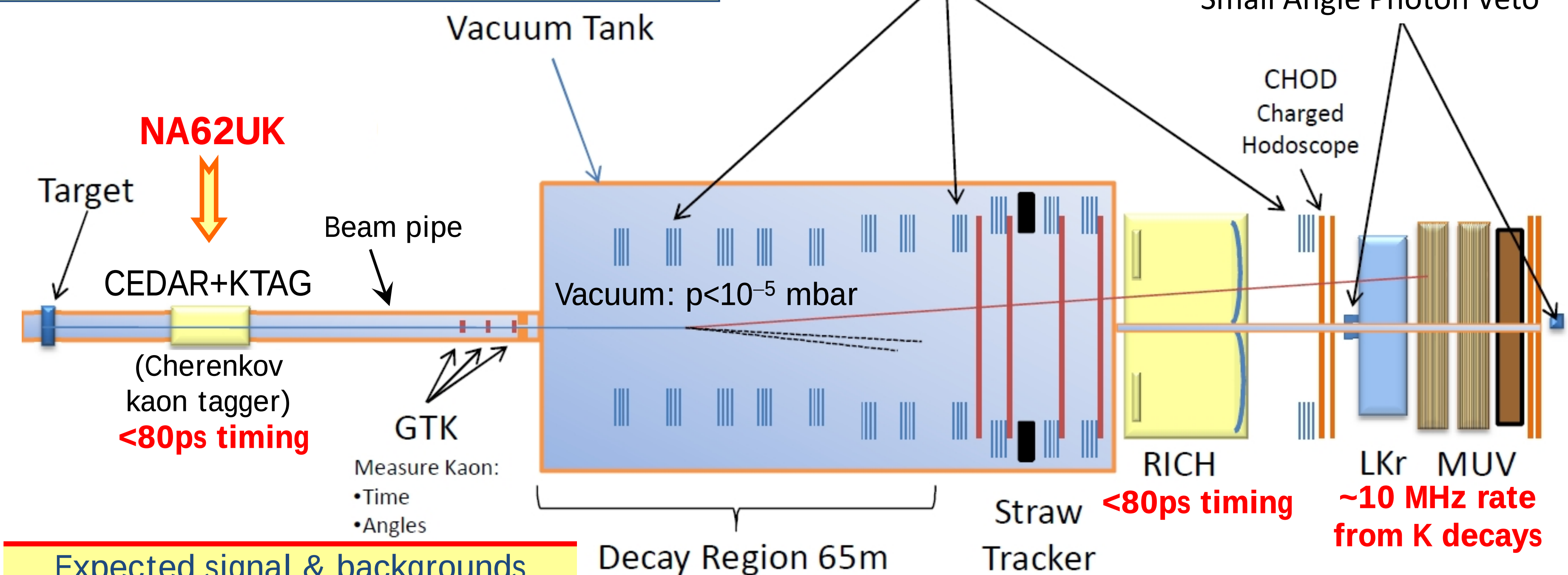
NA62: currently **~200** participants, **29** institutions.

NA62UK: Birmingham, Bristol, Glasgow, Liverpool.

NA62 detector & sensitivity

Un-separated hadron ($p/\pi^+/K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons
800MHz → 45MHz kaons → 5MHz decays

Total length: ~270m



Expected signal & backgrounds	
Signal	45 evt/year
$K^+\to\pi^+\pi^0$	4.3%
$K^+\to\mu^+\nu$	2.2%
$K^+\to$ 3 charged tracks	<4.5%
$K^+\to\pi^+\pi^0\gamma$	~2%
$K^+\to\mu^+\nu\gamma$	~0.7%
Total background	<13.5%

- **5×10^{12}** K^+ decays/year: record **$\sim10^{-12}$** sensitivity.
- Hermetic photon veto: **$\sim5\times10^{-8}$ $\pi^0\to\gamma\gamma$** suppression.
- Kinematics: **$\sim10^{-4}$** suppression of **$K^+\to\pi^+\pi^0$**.
- Technical run: **November 2012**.
- First run with full detector: **6 Oct – 13 Dec 2014**: low intensity, **~1** SM **$K_{\pi\nu\nu}$** event sensitivity.

NA62 installation

Large-angle photon installation

Cherenkov kaon tagger (CEDAR+KTAG)

Spectrometer and RICH

Other $K_{\pi\nu\nu}$ experiments

ORKA proposal @ FNAL (K^+)

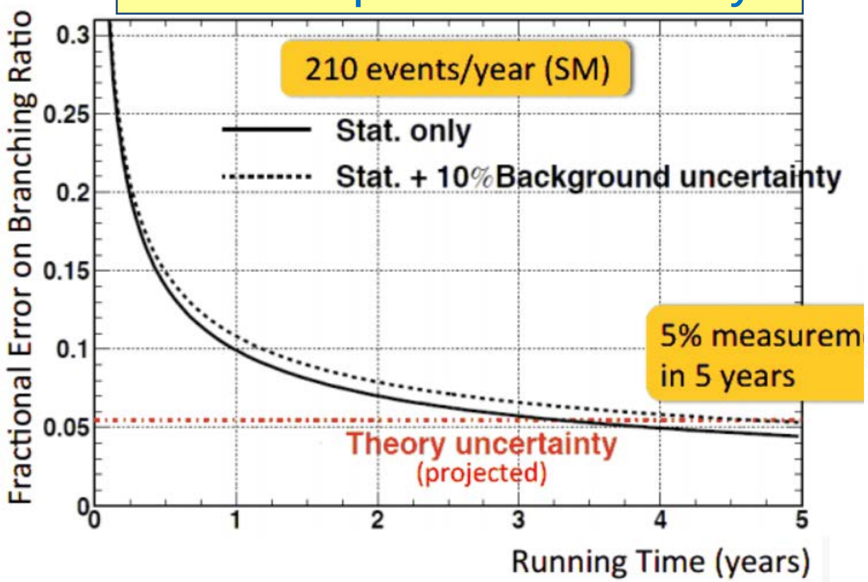
- Builds on BNL stopped-kaon technique.
- Goal: **$O(10^3)$** SM **$K^+\to\pi^+\nu\nu$** events.
- Higher sensitivity than NA62 due to more time scheduled for data taking.

22 May 2014: DOE P5 "cannot recommend moving ahead with ORKA at this time"

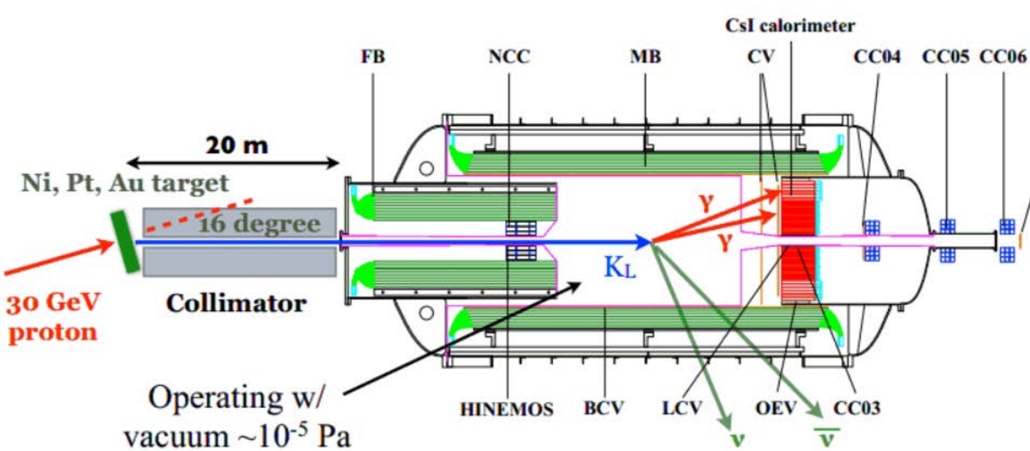
KOTO @ J-PARC (K_L):

- Builds on KEK E391a technique.
- E391a: **$BR<2.6\times10^{-8}$** @ 90%CL.
- Expect **$\sim10^3$** times higher sensitivity.
- Goal: **~3** SM **$K_L\to\pi^0\nu\nu$** events.
- Test run: **~100 hours** in **2013**.
- Test run results will be released soon.
- Data taking to be resumed: early **2015**.

ORKA expected sensitivity



"Two photons + nothing"



NA62: UK responsibilities

Hardware and trigger:

- **full responsibility** for the **KTAG subdetector**;
- development and operation of the **L0 muon trigger**;
- at a later stage, the **L0 KTAG trigger**.

Widening the physics programme:

- lepton flavour and number conservation tests in $K^+ \to \pi \ell \ell$ decays;
- lepton universality tests in $K^+ \to \ell^+ \nu$ decays;
- **peak searches**: heavy neutral leptons, the dark photon.

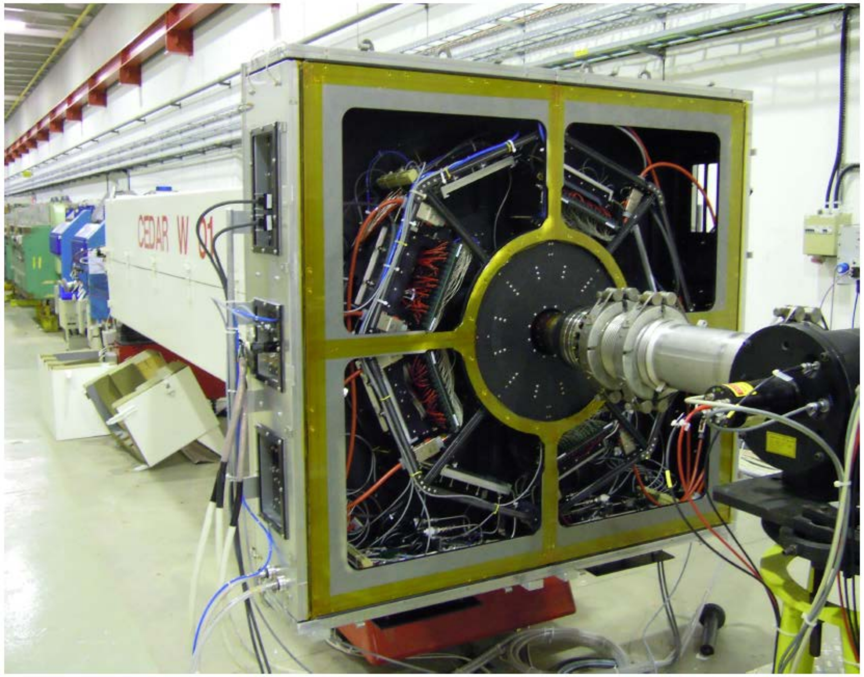
Coordination:

- co-convener of the **lepton flavour working group**;
- coordinator of the **NA62-R_K (2007 data) analyses**;
- **software coordinator**;
- chair of the **Conference Committee**;
- members of the **Editorial Board** (3 out of 10).

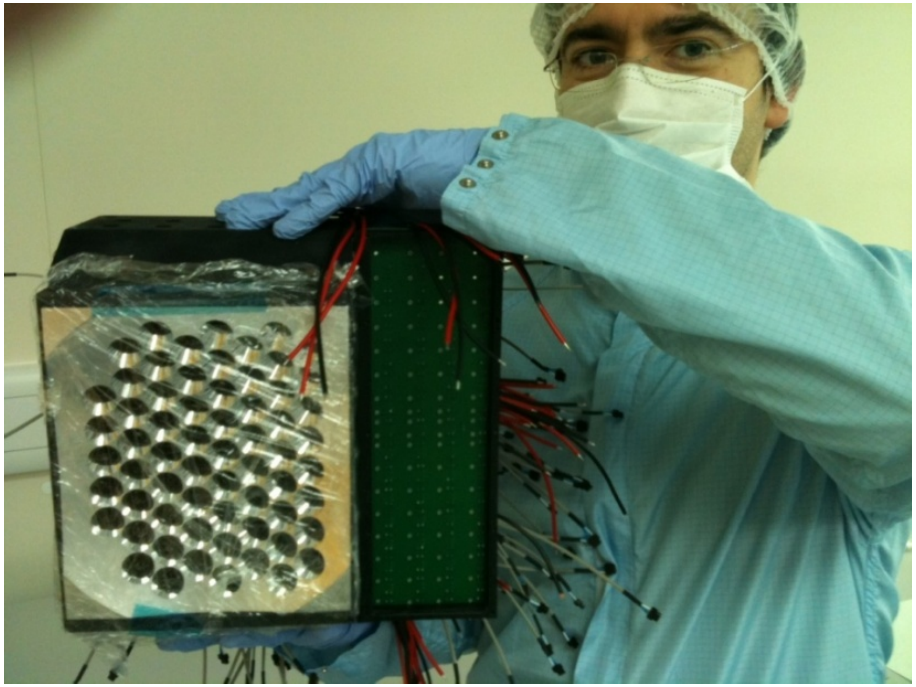
KTAG: technical run 2012

- NA62 technical run with partial setup: **November 2012**.
- Most subdetectors installed, none in its final version.
- Beam intensity: **~2%** of the nominal.
- KTAG: **4** sectors of out **8** instrumented;
  32 PMTs/sector (will be **48** in 2014, to up **64** foreseen).
- Validation of KTAG operation, finalization of the design.

CEDAR+KTAG installed in the beam line

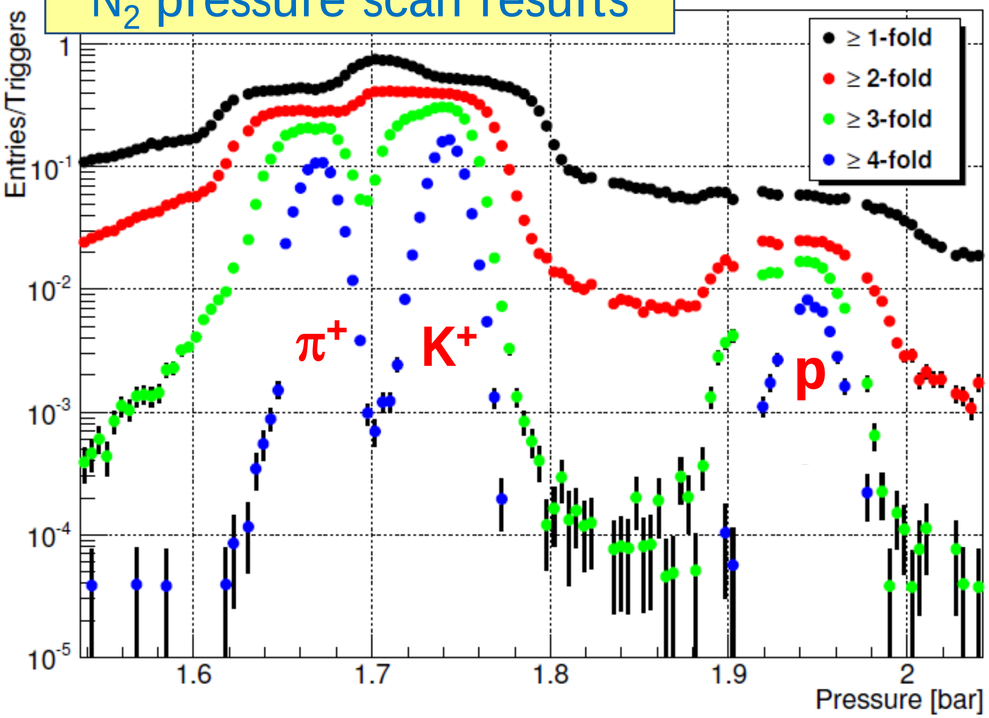


One of the eight "light boxes"

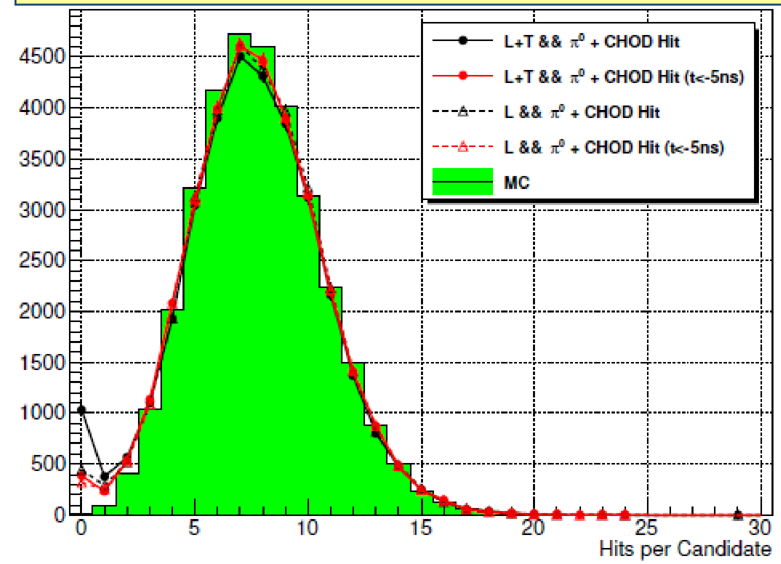


KTAG with 4 octants in 2012

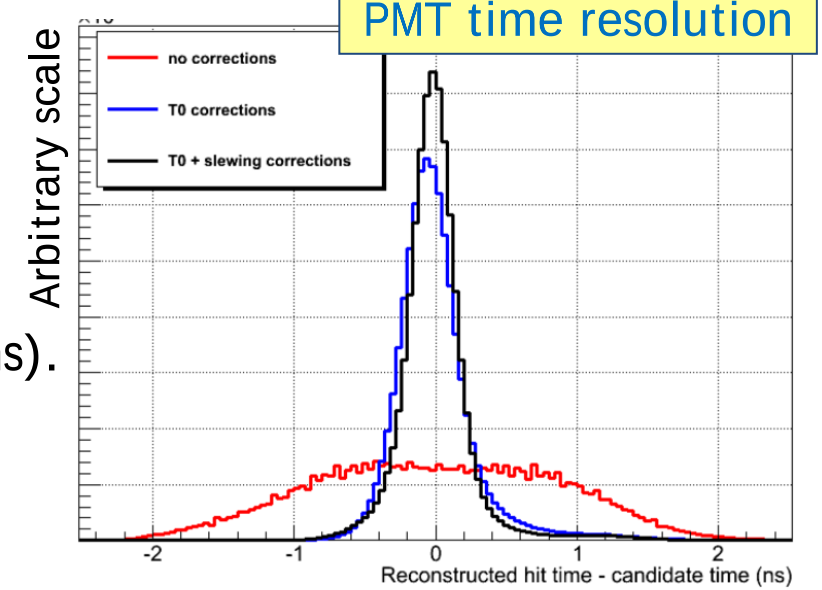
N_2 pressure scan results



Detected photons / beam particle



PMT time resolution



- Pion, kaon and proton peaks are resolved.
- Mean number of detected photons per beam particle: **~8**, similar to expectation.
- Measured PMT time resolution: **280 ps** (rms).
- Kaon tag resolution: **100 ps**, will be improved with the 8-sector setup.

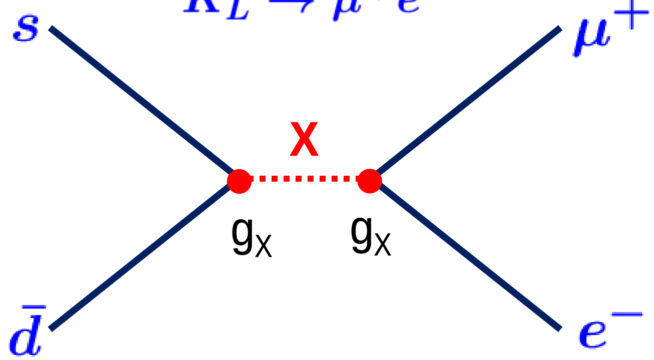
LFNV in $K^\pm$ and π^0 decays

NA62 single event sensitivities: **~10^{-12}** for $K^\pm$ decays, **~10^{-11}** for π^0 decays.
(modest L0 downscaling factors might be required for di-leptons)

Mode	UL at 90% CL	Experiment	Reference
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL E777/E865	PRD 72 (2005) 012005
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^\pm \to \pi^\mp\mu^\pm\mu^\pm$	1.1×10^{-9}	CERN NA48/2	PLB 697 (2011) 107
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva-Saclay	PL 62B (1976) 485
$K^+ \to e^-\nu\mu^+\mu^+$	no data		
$\pi^0 \to \mu^+e^-$	3.6×10^{-10}	FNAL KTeV	PRL 100 (2008) 131803
$\pi^0 \to \mu^-e^+$	3.6×10^{-10}	FNAL KTeV	PRL 100 (2008) 131803

* CERN NA48/2 sensitivities for these 3 modes are similar to those of BNL E865

$K_L \to \mu^+e^-$



Dimensional argument:

$$\frac{\Gamma_X}{\Gamma_{SM}} \sim \left(\frac{g_X}{g_W}\cdot\frac{M_W}{M_X}\right)^4$$

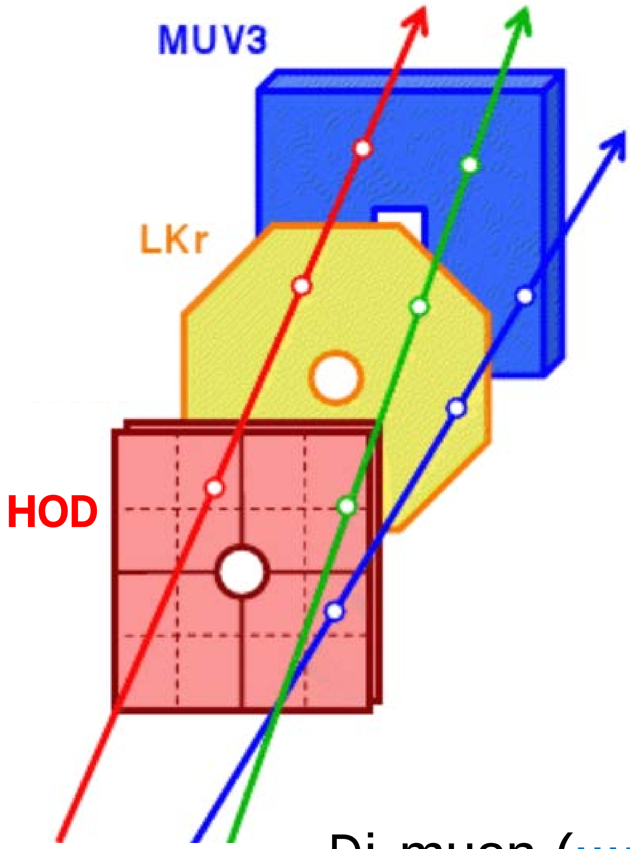
$$g_X \approx g_W \qquad \mathcal{B} \sim 10^{-12}$$

$$M_X \sim 100\ \text{TeV}$$

NA62 di-lepton L0 trigger

NA62 three-track decay rate upstream HOD: **F_{3track} = 640 kHz**

→ **Too high** to collect all three-track decays (the NA48/2 approach)



Birmingham-led effort: di-lepton L0 trigger

- **Q_N**: at least **N** hodoscope quadrants;
- **LKR(x)**: total LKr energy deposit of at least **x** GeV;
- **MUV_N**: hits in at least **N** MUV3 pads.

L0 trigger conditions for di-lepton collection:

ee pair:	$Q_2 \times$ LKR(10)
μe pair:	$Q_2 \times$ LKR(10) $\times$ MUV_1
$\mu\mu$ pair:	$Q_2 \times$ MUV_2

Di-muon ($\mu\mu$) rate dominated by accidentals;

ee and **μe** rates dominated by $K^+ \to \pi^+\pi^+\pi^-$ and $K^+ \to \pi^+\pi^0$.

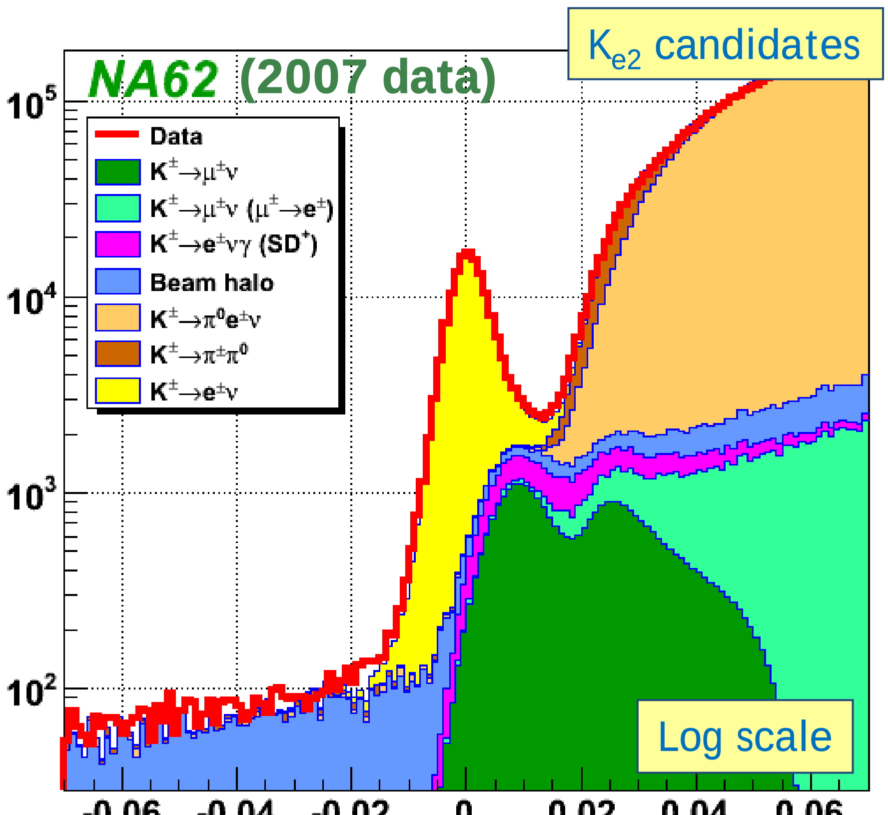
Total rate **F ~ 100 kHz**: charge blind di-lepton collection is feasible.

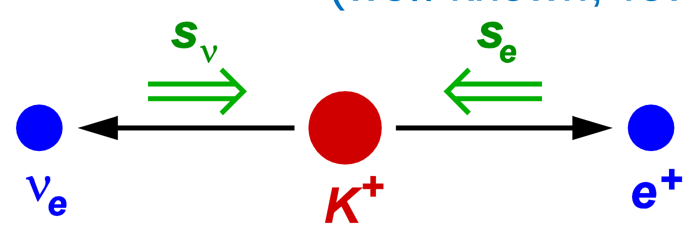
NA62-R_K: lepton universality

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \underbrace{\frac{m_e^2}{m_\mu^2}}_{\text{Helicity suppression: } f\sim10^{-5}} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot \underbrace{(1+\delta R_K^{\text{rad.corr.}})}_{\text{Radiative correction (well known, few \%)}}$$

Helicity suppression: f~10^{-5}

Radiative correction (well known, few %)





$R_K^{SM} = (2.477\pm0.001)\times10^{-5}$

Cirigliano and Rosell, PRL99 (2007) 231801

O(1%) effects due to sterile neutrinos or LFV

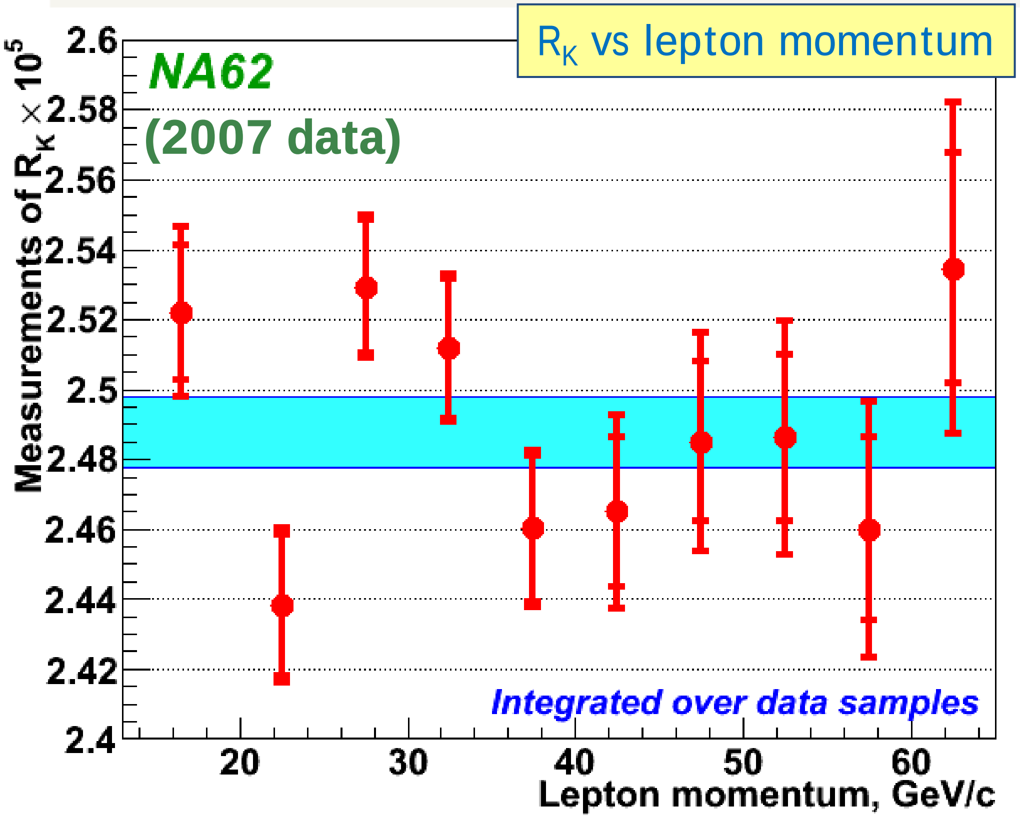
Lacker and Menzel, JHEP 1007 (2010) 006;
Abada et al., JHEP 1302 (2013) 048;
Girrbach and Nierste, arXiv:1202.4906

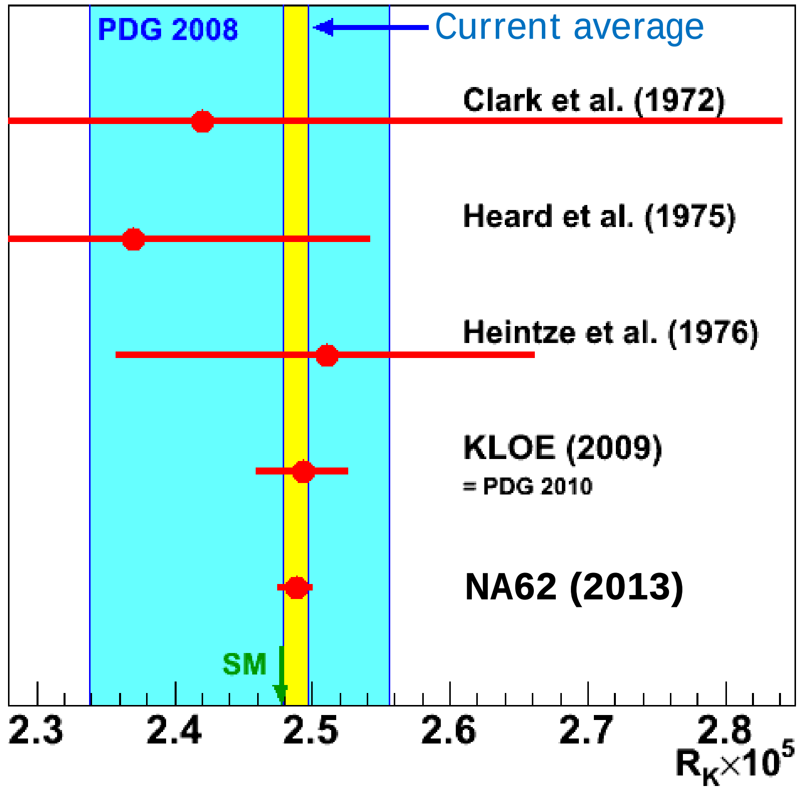
NA62-R_K 2007 data set:
145,958 $K^\pm \to e^\pm \nu$ candidates.
Background: $B/(S+B)=(10.95\pm0.27)\%$.
Electron ID efficiency: $(99.28\pm0.05)\%$.

NA62-R_K final result & prospects

$$R_K = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$$
$$= (2.488 \pm 0.010) \times 10^{-5}$$

PLB719 (2013) 326





World average	$R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
2013	2.488±0.009	0.4%

NA62 prospects:

improve precision by a factor **~2**.

Competitor: **TREK@J-PARC**

(stopped K^+; similar precision).

Heavy neutral leptons below M_K

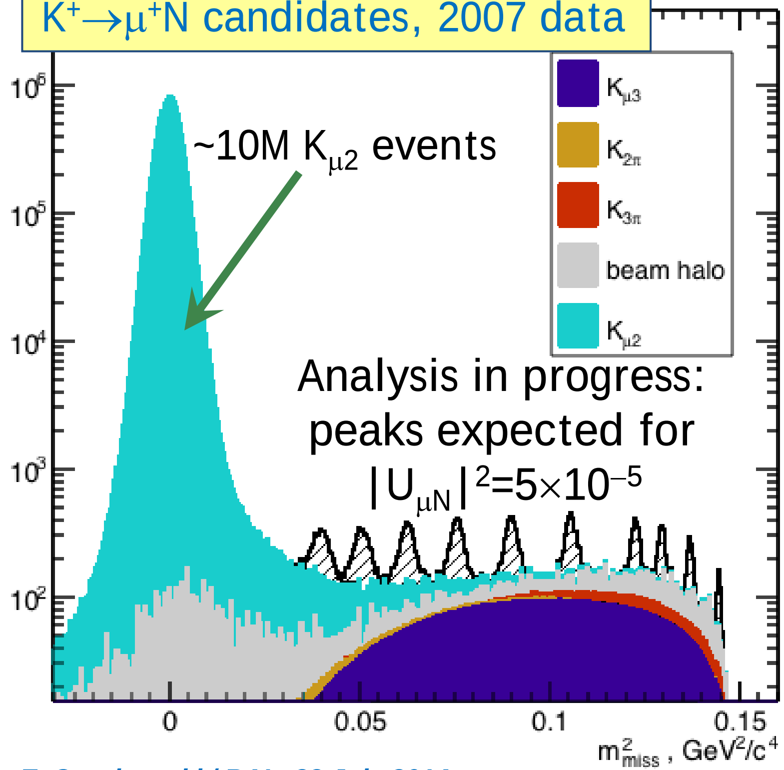
Neutrino minimal SM (**νMSM**):
3 heavy sterile RH Majorana νs (**$N_{1,2,3}$**).
m_1~10 keV/c²: dark matter candidate.
m_2~m_3~1 GeV/c²:
observable in **$K^\pm \to l^\pm N$**, **$D^\pm \to l^\pm N$** decays.

Asaka & Shaposhnikov, PLB620 (2005) 17

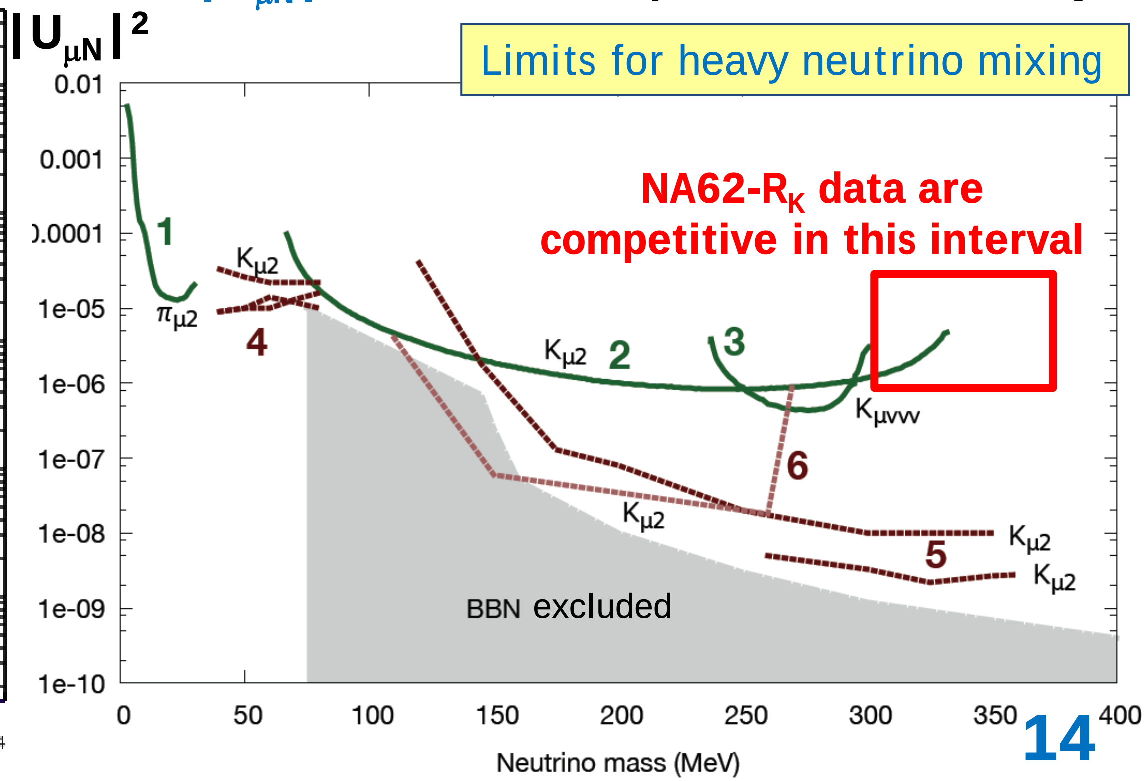
NA62-R_K subsample: ~10M **$K^+ \to \mu^+\nu_\mu$**.
"Peak search" for HNL: **$K^+ \to \mu^+ N$**.

- Sensitivity is limited by background fluctuation (mainly beam halo).
- Competitive at **$0.30 < M_N < 0.38$ GeV/c²**.
- **NA62:** larger sample and smaller bkg., **$|U_{\mu N}| \sim 10^{-8}$** sensitivity in wider mass range.

$K^+ \to \mu^+ N$ candidates, 2007 data



Limits for heavy neutrino mixing



Long-term future

❖ **Run 2014–2017**: dedicated to $K^+ \to \pi^+ \nu\nu$ (**~100** SM events) and other rare/forbidden K^+ and π^0 decays, likely with incremental hardware upgrades.

SPS LS2: 2018–2019

❖ **Run 2020–2023** (non-exclusive) possibilities:

a) Upgrades to improve precision on $K^+ \to \pi^+ \nu\nu$ (**~1000** SM events).

b) Switch to neutral beam to pursue $K_L \to \pi^0 \ell^+ \ell^-$ and prototype studies for $K_L \to \pi^0 \nu\nu$. Need **~10** times higher SPS proton intensity (**~10^{13} ppp**), well within SPS capability. **A dedicated working group set up.**

c) Optimize for **heavy neutral lepton** searches (trigger, shielding upstream of the decay volume, …).

SPS LS3: 2024

❖ **Run 2025–2028** possibility:

Next generation $K_L \to \pi^0 \nu\nu$ experiment: significant detector R&D required.

Summary

- Improving the experimental precision on **BR($K\to\pi\nu\bar{\nu}$)** remains among the priority issues in flavour physics.

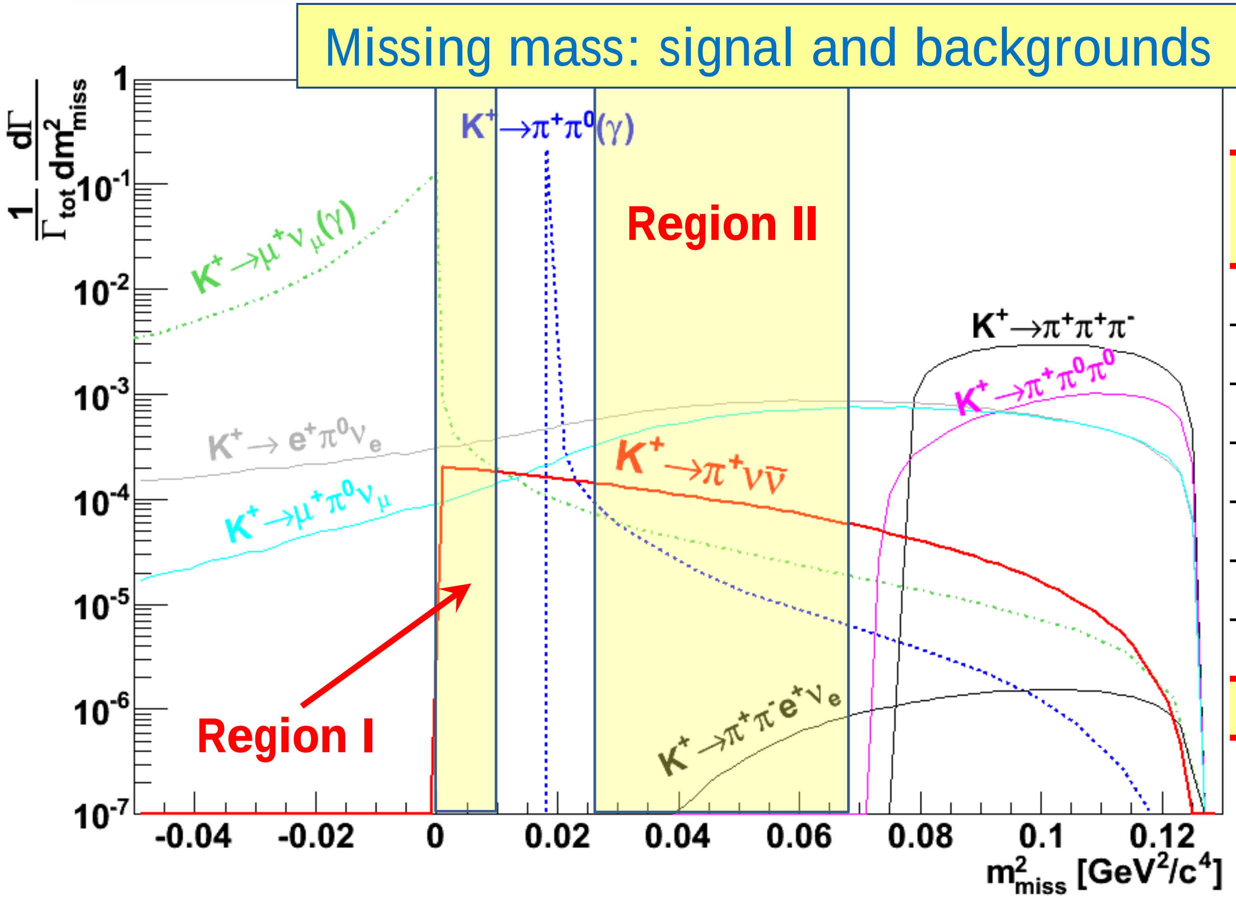
- The first **NA62 physics run** (at lower intensity) with the complete detector is starting in **October 2014**.

- The **KTAG** sub-detector (**UK responsibility**) delivered on time. KTAG test in 2012: main performance parameters are as expected.

- **UK groups** play a key role in shaping a **wider NA62 programme** (CLFV, lepton universality, heavy neutral leptons) and publishing results based on existing **K^+** data sets (2003, 2004, 2007).

Spares

NA62: $K_{\pi\nu\nu}$ signal region



Signal & backgrounds (events/year)	
Signal	45
$K^+ \to \pi^+\pi^0$	5
$K^+ \to \mu^+\nu$	1
$K^+ \to \pi^+\pi^+\pi^-$	<1
Other 3-track decays	<1
$K^+ \to \pi^+\pi^0\gamma$ (IB)	1.5
$K^+ \to \mu^+\nu\gamma$ (IB)	0.5
Total background	**<10**

92% of total **BR(K^+)**:

- Outside the signal kinematic region.
- Signal region is split into **Region I** and **Region II** by the **$K^+ \to \pi^+\pi^0$** peak.

8% of total **BR(K^+)** including multi-body:

- Span across the signal region (not rejected by kinematic criteria).
- Rejection relies on **vetoes**, **PID**.

NA62: from K^+ to K_L

- Possibility of a neutral beam foreseen in the NA62 Technical Proposal: minor changes to production angle and upstream beam optics
- Running for $K_L \to \pi^0 \nu\nu$ or $K_L \to \pi^0 \ell^+ \ell^-$ will require a **substantial increase** in primary intensity, but well within what the SPS can provide.

	NA62 K^+ beam	Future NA62 K_L beam
Primary intensity (ppp)	3×10^{12}	2.4×10^{13}
Production angle (mrad)	0	2.4
Angular acceptance (μsr)	12.7	0.125
Momentum	(75 ± 1) GeV/c	97 GeV/c (mean)
Rates in fiducial volume, MHz	$525(\pi)+70(p)+45(K^+)$	$2000(\gamma)+800(n)+90(K_L)$
K decays in fiducial volume	4.5 MHz (4.5×10^{12}/year)	0.9 MHz (0.9×10^{12}/year)

TREK (E36) at J-PARC

Running starts in **FY 2014/15**. Short-term goals:

1) $R_K=\Gamma(K_{e2})/\Gamma(K_{\mu2})$ at **0.25%** precision;

2) Heavy sterile neutrino: $BR(K^+\to\mu^+N)\sim10^{-8}$.

3) Dark photon ($\varepsilon^2\sim10^{-6}$): $K^+\to\mu^+\nu U$, $U\to e^+e^-$.