NA62 & Kaon Experiments

Evgueni Goudzovski

(University of Birmingham)

eg@hep.ph.bham.ac.uk

Outline:

1) Ultra-rare $K\to\pi\nu\bar{\nu}$ decays: theory vs experiment.
2) NA62 experiment and NA62UK.
3) Planned $K\to\pi\nu\bar{\nu}$ measurements in Japan and US.
4) Summary.

PPAP Community Meeting

University of Birmingham • 18 September 2012

Key low energy observables

[G. Isidori, ESPP 2012, Kraków]

- γ from tree ($B \to DK$, ...) — S-LHCb
- $|V_{ub}|$ from exclusive semi-leptonic B decays — S-Bfactory [SuperKEKB & SuperB]
- $B_{s,d} \to l^+l^-$ — S-LHCb + ATLAS & CMS
- CPV in B_s mix. [ϕ_s] — S-LHCb + ATLAS & CMS
- $B \to K^{(*)}\, l^+l^-, \nu\nu$ — S-LHCb / S-Bfactory
- $B \to \tau\nu, \mu\nu$ (+D) — S-Bfactory
- $K \to \pi\nu\nu$ — Kaon beams [NA62, KOTO, ORKA]
- CPV in charm — S-LHCb / S-Bfactory

UK involvement

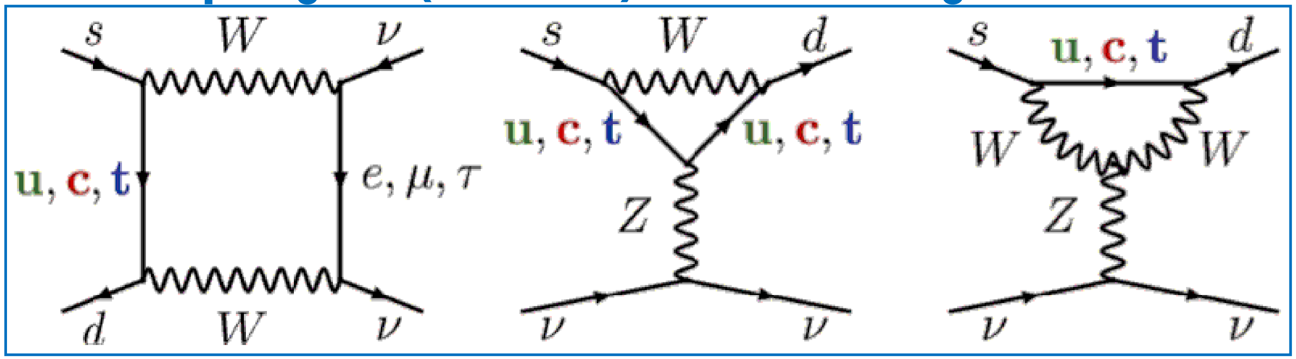
(worldwide effort: $K^{\pm}$ and K_L decays)

❖ Complementarity between low-energy and high-p_T physics.

❖ Complementarity among the different low-energy facilities.

$K\to\pi\nu\bar{\nu}$ within the SM

SM: EW penguin (dominant) and box diagrams



Ultra-rare decays with the highest CKM suppression:

$A_{s\to d} \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$

- Hadronic matrix element can be related to measured quantities ($K\to\pi e\nu$ form factors).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from B–$\bar{B}$ mixing and $B^0\to\rho\gamma$.
- $\delta BR/BR = 10\%$ would lead to $\delta|V_{td}|/|V_{td}| = 7\%$.

SM branching ratios

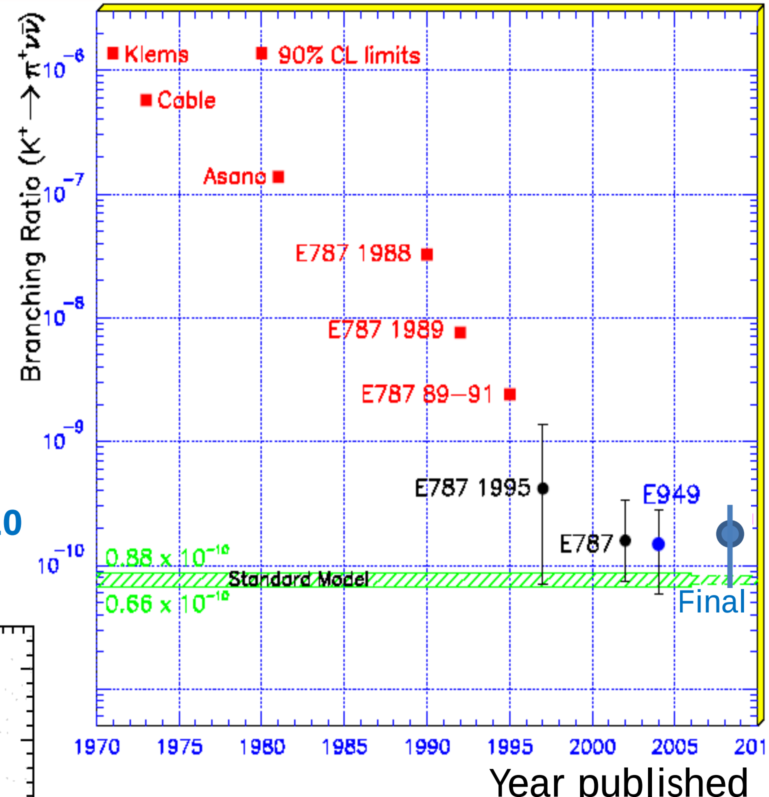
(Brod et al., PRD83 (2011) 034030)

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

CKM parametric — Intrinsic

Theoretically clean;
sensitive to new physics;
almost unexplored

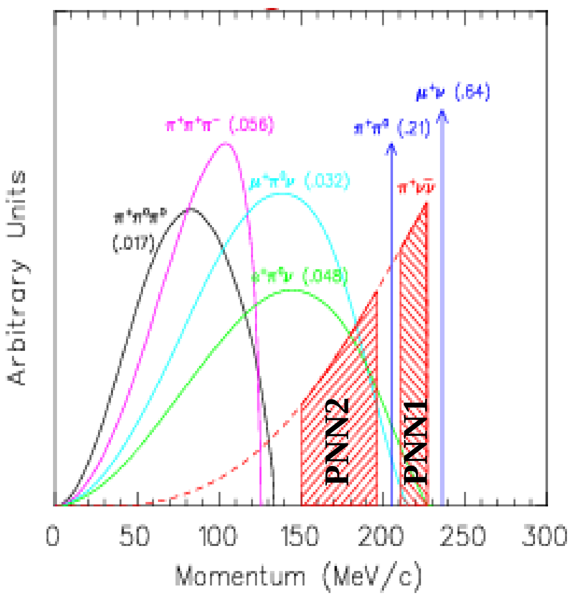
$K^+ \to \pi^+ \nu\bar{\nu}$: E747/E949 @ BNL

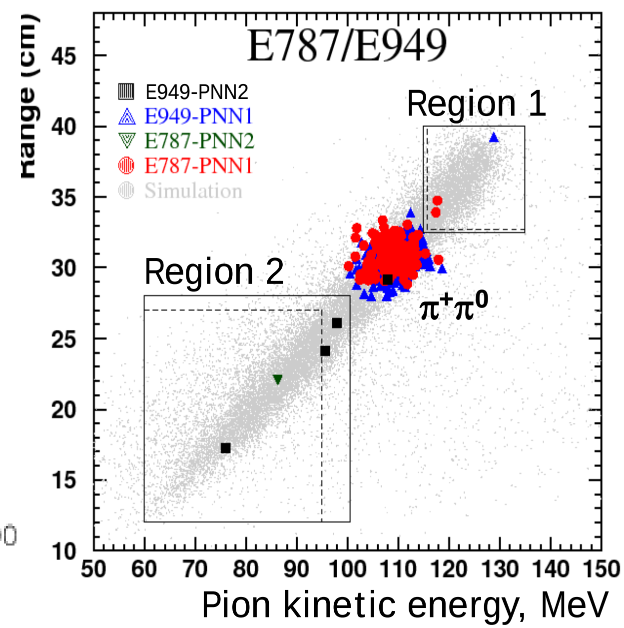


Technique: decays of stopped K^+

Data taking: E787 (1995–98), E949 (2002).
Separated K^+ beam (710 MeV/c, 1.6MHz).
PID: range (entire $\pi^+ \to \mu^+ \to e^+$ decay chain).
Hermetic photon veto system.

Observed candidates: 7
Expected background: 2.6
Final result: **$BR = (1.73^{+1.15}_{-1.05})\times10^{-10}$**
PRD79 (2009) 092004



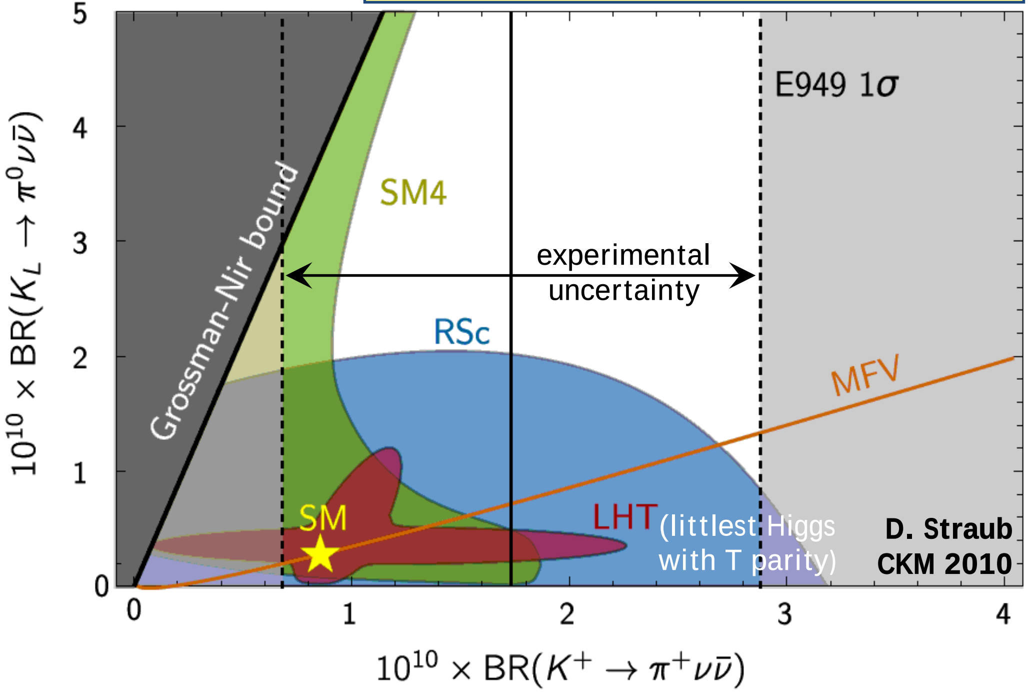


Limitations:

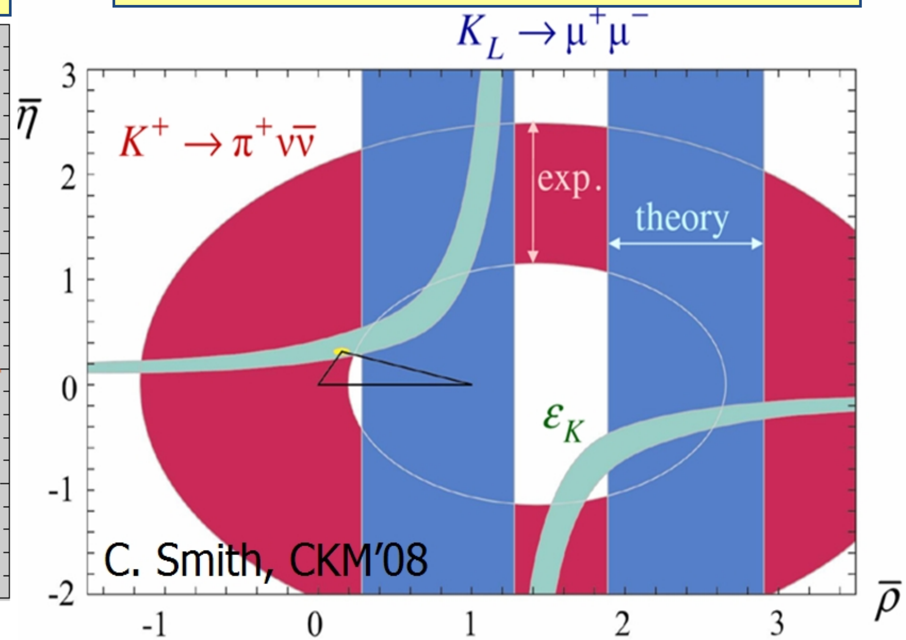
- Low acceptance (~1%).
- Significant background (~30%) due to π scattering in the target.

Current experimental status

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



CKM unitarity triangle with kaons



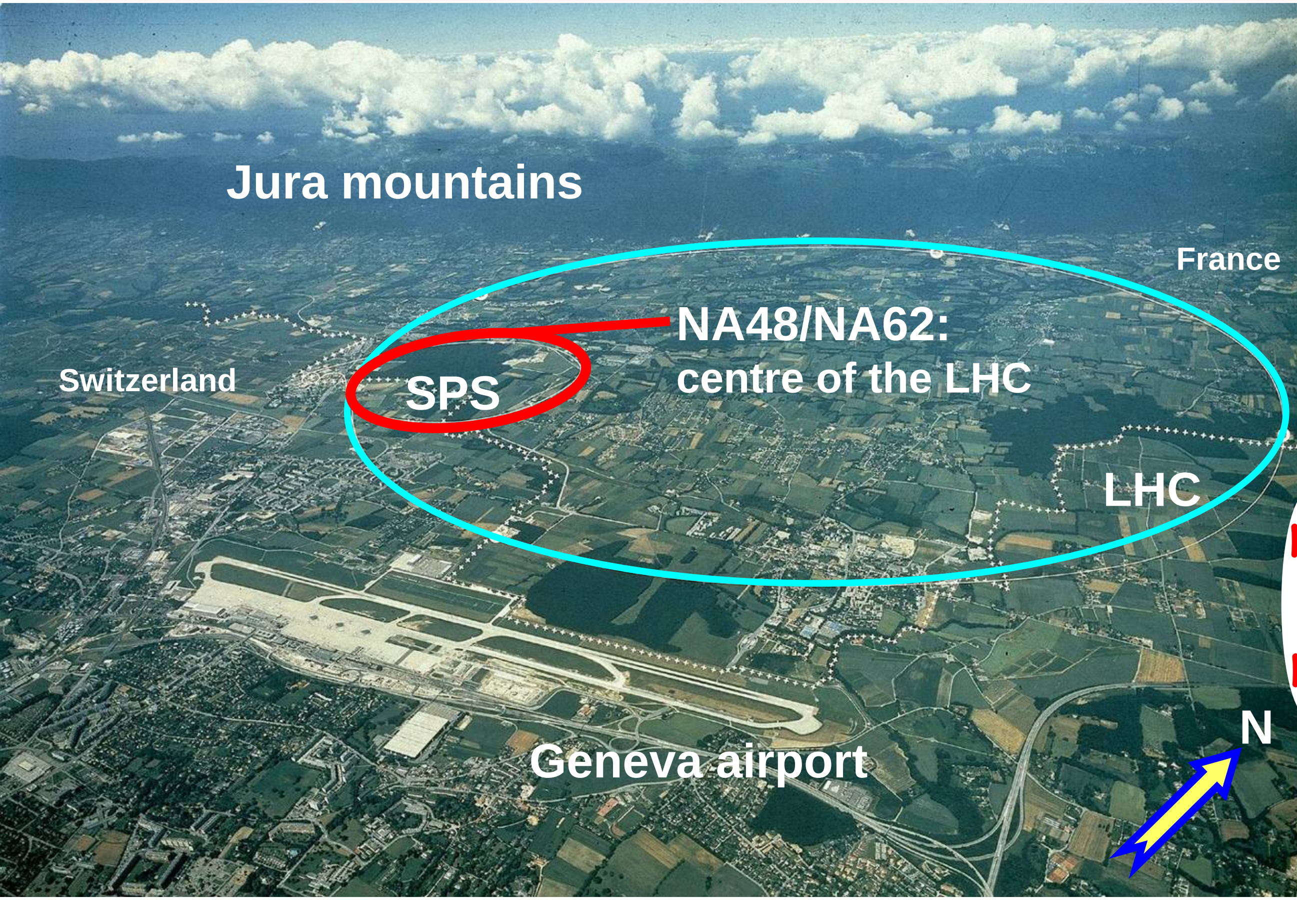
NA62@CERN aims to reach ~10% precision with O(100) SM $K^+ \to \pi^+ \nu\bar{\nu}$ events in 2 years, and is the first decay-in-flight $K^+ \to \pi^+ \nu\bar{\nu}$ experiment.

Decay signature: high momentum K^+ (75GeV/c) → low momentum π^+ (15-35 GeV/c).

Advantages: max detected K^+ decays/proton ($p_K/p_0 \approx 0.2$); high acceptance (~10%); efficient photon veto (>40 GeV missing energy); good π^+/μ^+ identification by RICH.

However, un-separated beam (6% kaons) → higher rates in beam tracker.

NA62 @ 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

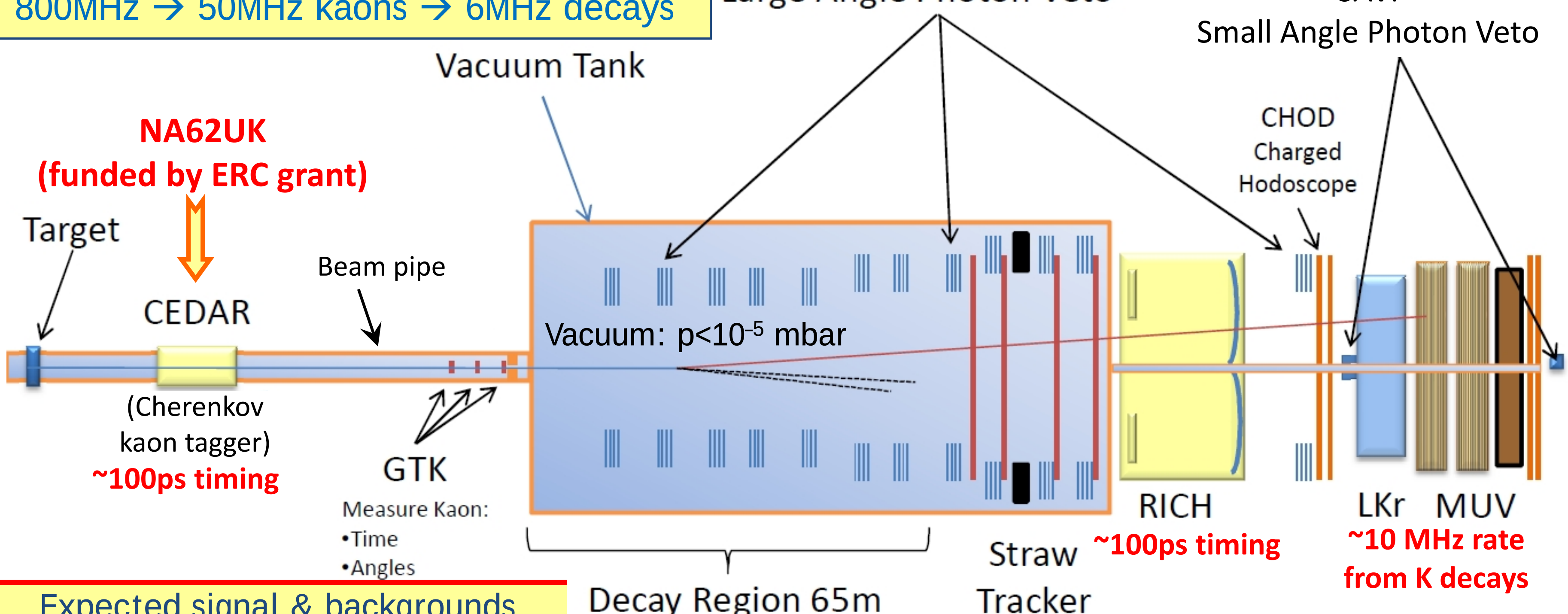
NA62
- *2012:* 1st technical run
- *2014:* 1st physics run

28 institutions, **12** countries, **187** participants.

NA62UK collaboration (**19** participants):
Birmingham, Bristol, Glasgow, Liverpool.

NA62 detector & sensitivity

Un-separated hadron ($p/\pi^+/K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons
800MHz → 50MHz kaons → 6MHz decays



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 SES of $\sim10^{-12}$.
- Hermetic photon veto: $\sim5\times10^{-8}$ $\pi^0\to\gamma\gamma$ suppression.
- Kinematics: $\sim10^{-4}$ suppression of $K\to\pi^+\pi^0$.

- First technical run: **29 Oct – 3 Dec 2012**.
- Physics data taking: after LHC LS1 (first physics run in **late 2014**).

NA62UK responsibilities & funding

Key UK responsibilities

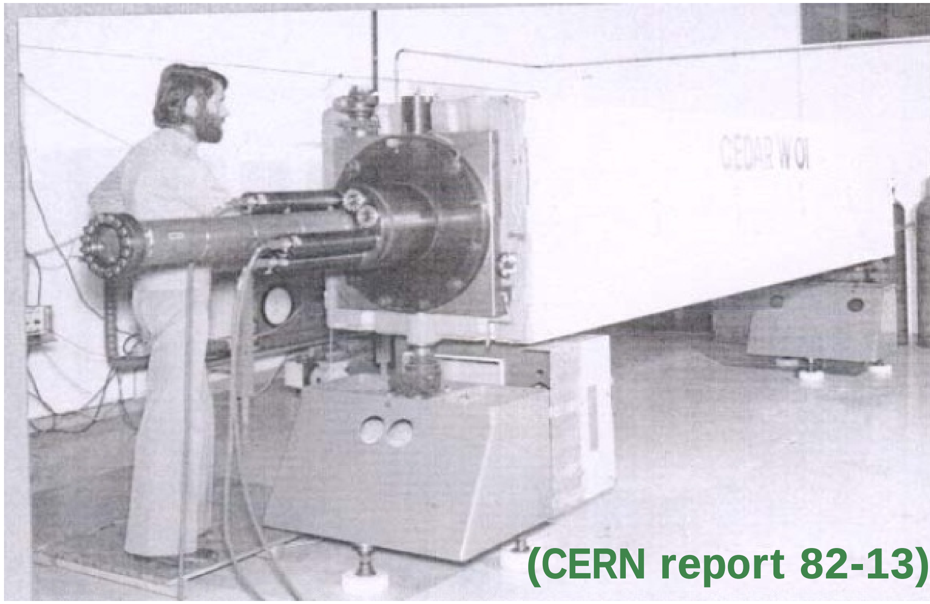
- Construction & operation of the KTAG subdetector (incl. project leader)
- Co-convener of lepton flavour & exotics working group
- Coordinator of the 2007 data set analyses
- Software coordinator (from 2013)
- Leading role in computing (collaboration with GridPP)
- Conference Committee chair; 3 (out of 10) Editorial Board members

NA62UK funding

- European Union:
  - ERC Advanced Grant (2011–2016; ~£2M)
  - Marie Curie Fellowship (2011–2012)
- Royal Society:
  - 2 University Research Fellowships (most recent from 2012)
- STFC:
  - Responsive RA (2008–2010)
  - Common Fund (from 2011)
  - Fractions of academic staff and RA (from 2012)
  - Rutherford Fellowship (from 2013)

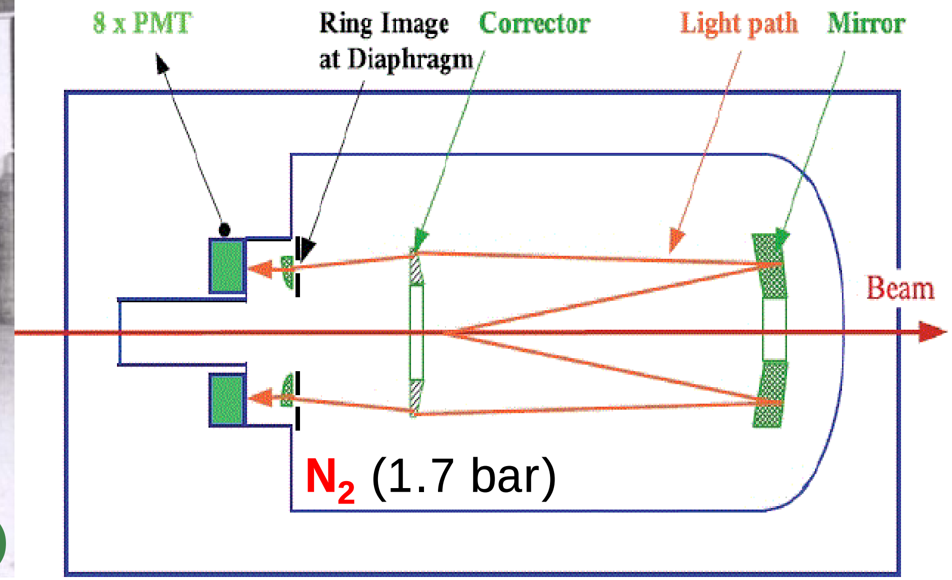
UK hardware contribution: KTAG

CEDAR: beam differential Cherenkov counter



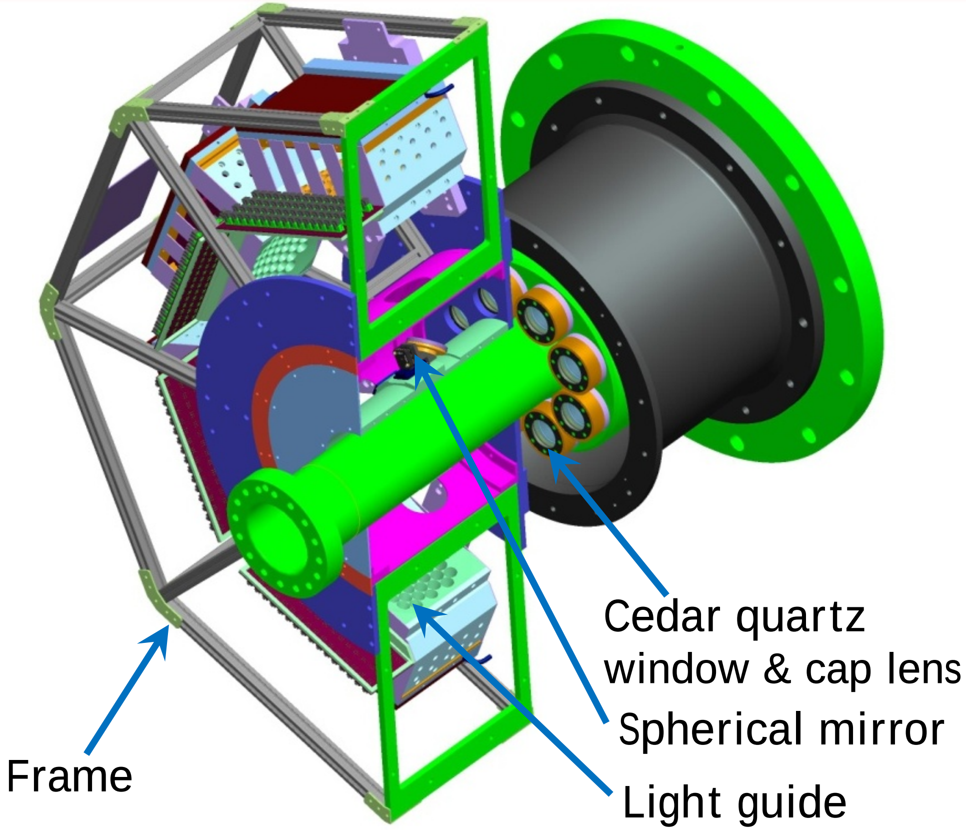
(CERN report 82-13)

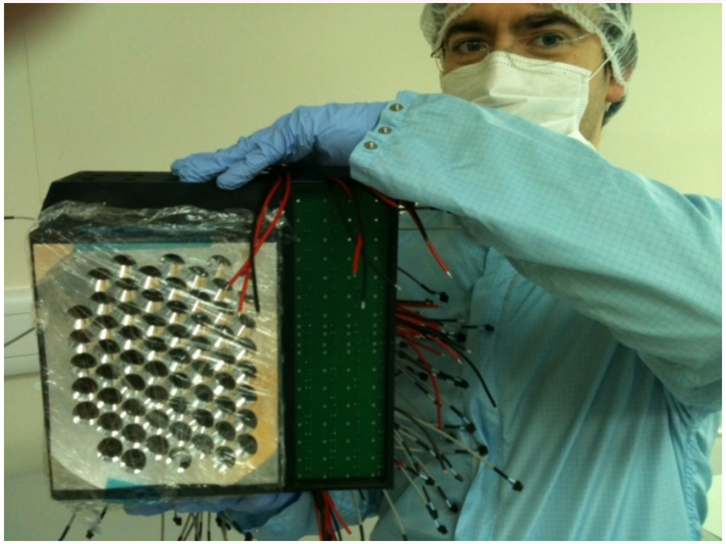
Principle of operation

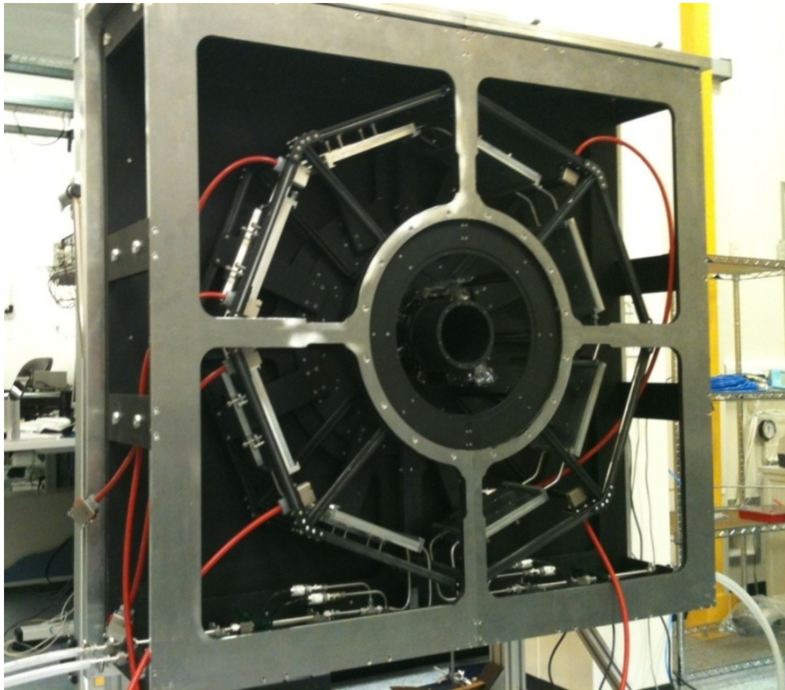


- Kaons: **minority particles** in the unseparated NA62 hadron beam (~6%).
- **Beam kaon tagging** is crucial for background suppression.
- CEDAR counters developed at CERN in 1980s for signal rates below **1 MHz**.
- Upgrade for the NA62 K^+ rate of **50 MHz**:
  the **KTAG detector** replacing the old PMTs and readout.
- New optical system: **8** octants with **64** Hamamatsu PMTs (R7400-U03) each.
- Cedar operation with **H_2 gas**: reduces thickness from $4\%X_0$ to $0.7\%X_0$.

KTAG construction: completed







- CEDAR installed in NA62 beam line: **14 Sep 2012**.
- Fully assembled KTAG (2012 configuration) shipped from Liverpool to CERN: **16 Sep 2012**.
- Installation at CERN: **18–21 Sep 2012**.
- Start of the technical run: **29 Oct 2012**.

NA62 physics: UK leadership

- **Lepton Flavour Universality tests**

$R_K = BR(K^+ \to e^+\nu)/BR(K^+ \to \mu^+\nu)$.
Technique established during earlier phase.
Expected NA62 precision: $\delta R_K/R_K < 0.2\%$.
Competitors: TREK@J-PARC, ORKA@FNAL.
(both with stopped kaons)

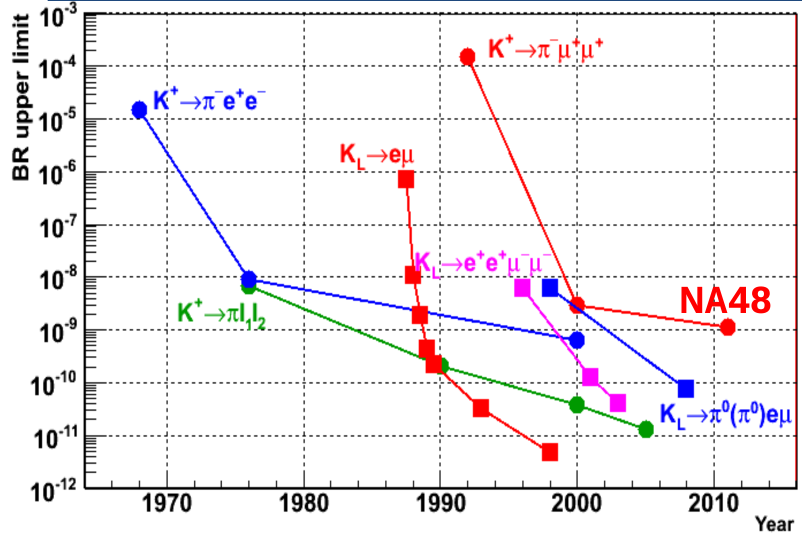
- **Lepton flavour/number violation**

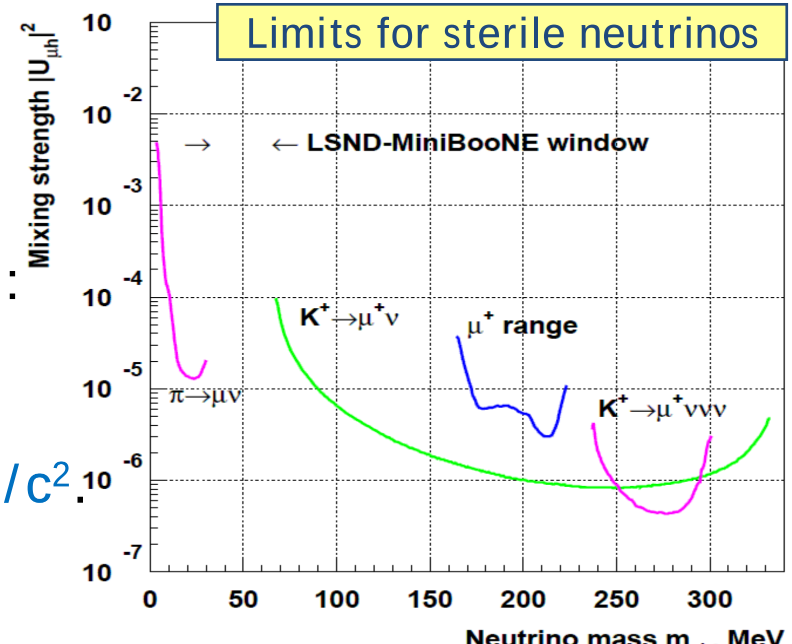
$K^+ \to \pi^+\mu^+e^-$, $K^+ \to \pi^+\mu^-e^+$, $K^+ \to \pi^-\mu^+e^+$,
$K^+ \to \pi^-\mu^+\mu^+$, $K^+ \to \pi^-e^+e^+$, $\pi^0 \to e^+\mu^-$, ...
Current upper limits: $\sim 10^{-9}$ ... 10^{-11}.
Foreseen NA62 limits: $\mathbf{\sim 10^{-12}}$.

- **Search for heavy sterile neutrinos** ($m_\nu < m_K$):

$K^+ \to \mu^+\nu_H$ via missing mass or $\nu_H \to \nu\gamma$ decay.
Possible interpretation of LSND/MiniBooNE results: existence of neutrino with $m \sim 60 MeV/c^2$.
S.N.Gninenko, PRD83 (2011) 015015

LFV/LNF decays: BR upper limit vs year



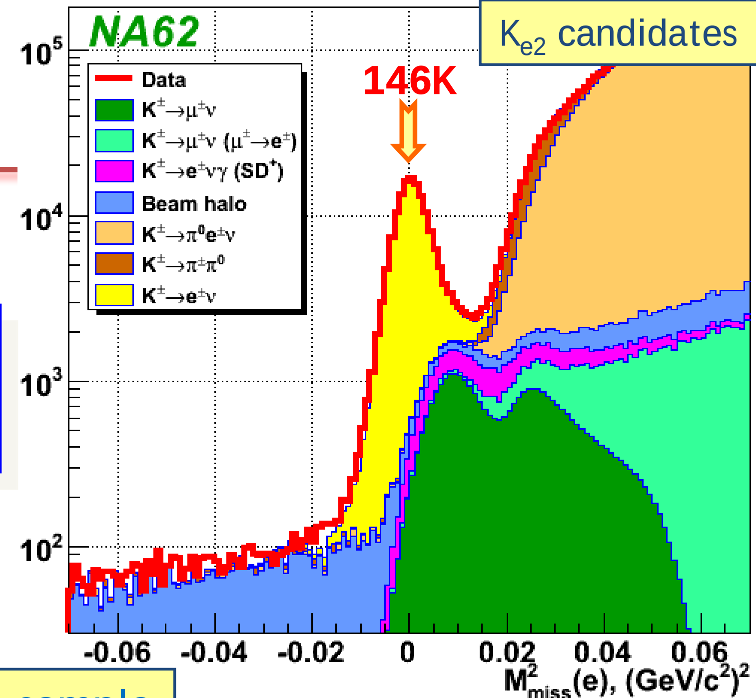


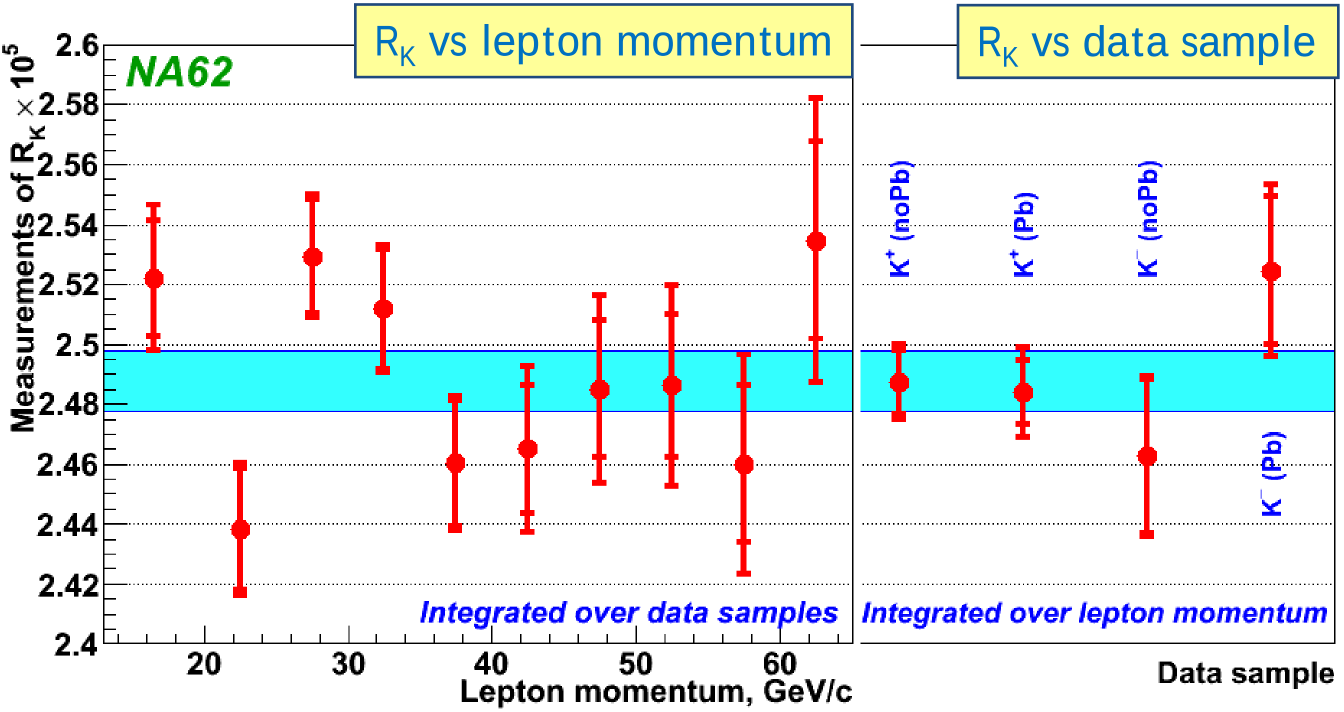
NA62 (R_K phase) result

Measurement with the full NA62 2007 data set:

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

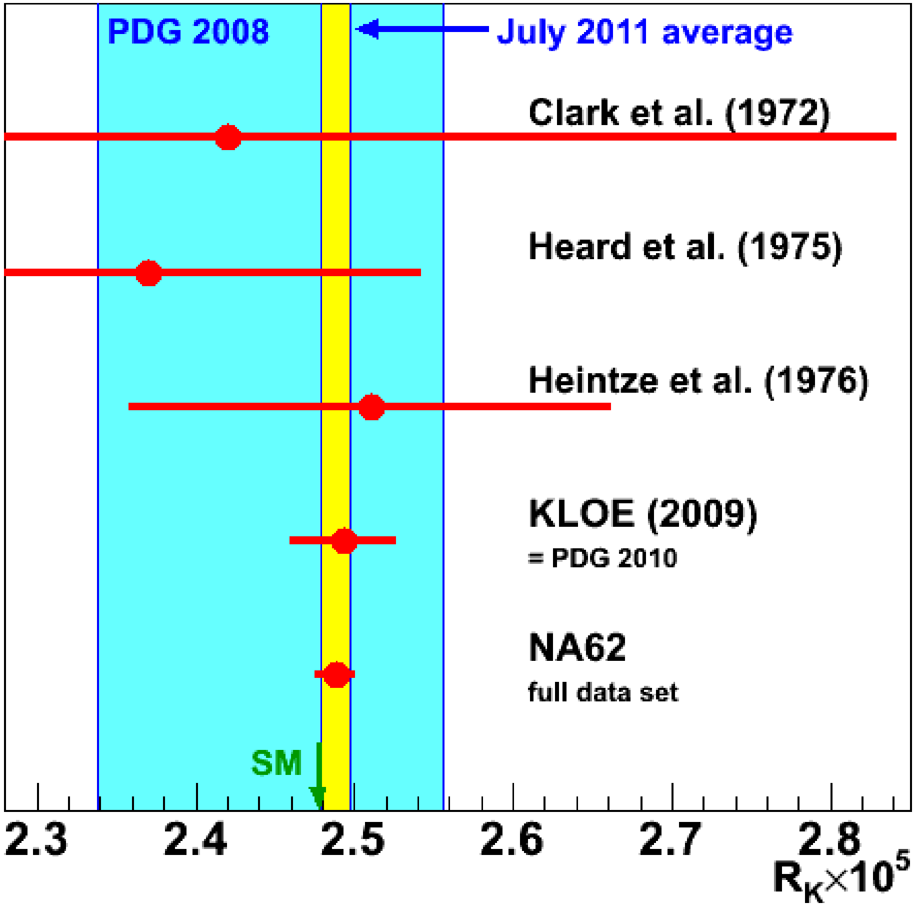
Partial (40%) data set: PLB 698 (2011) 105.
Full data set: results to be published soon.
Analysis led by the Birmingham group.

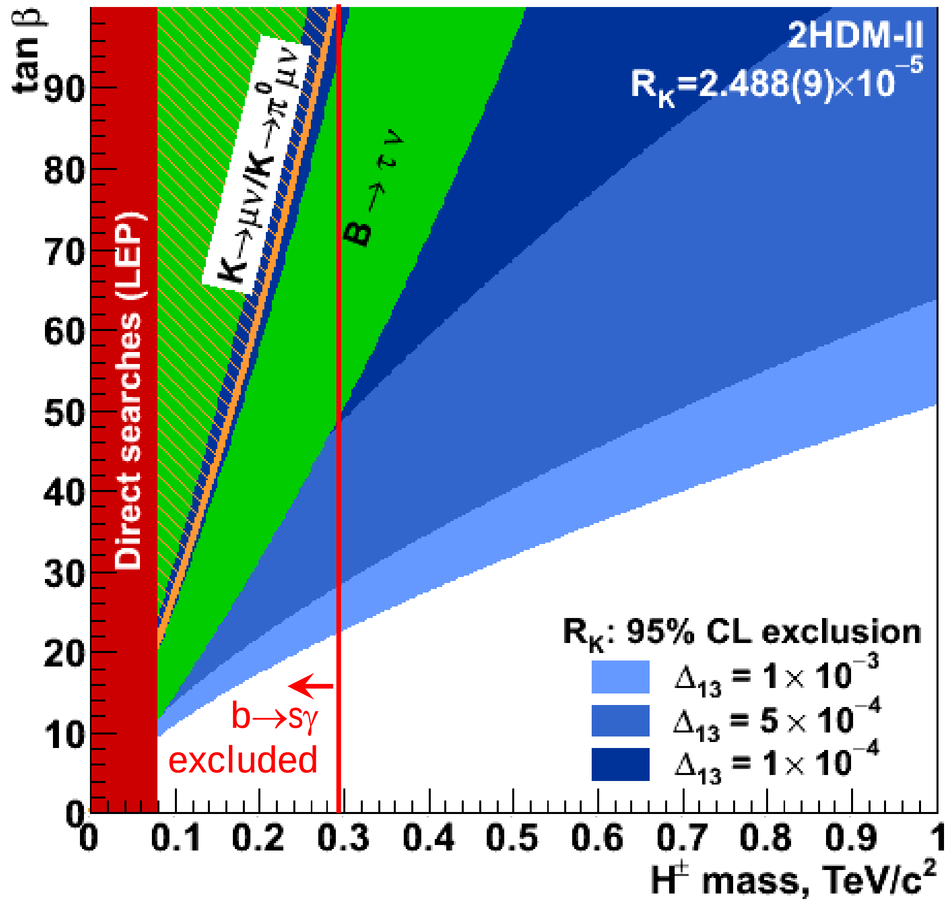




Uncertainty source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$ background	0.004
$K^\pm \to e^\pm \nu \gamma$ (SD+)	0.002
$K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$	0.003
Beam halo background	0.002
Matter composition	0.003
Acceptance correction	0.002
DCH alignment	0.001
Electron identification	0.001
1TRK trigger efficiency	0.001
LKr readout efficiency	0.001
Total uncertainty	0.010

R_K world average





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

Other limits on 2HDM-II:
PRD 82 (2010) 073012.

SM with 4 generations:
JHEP 1007 (2010) 006.

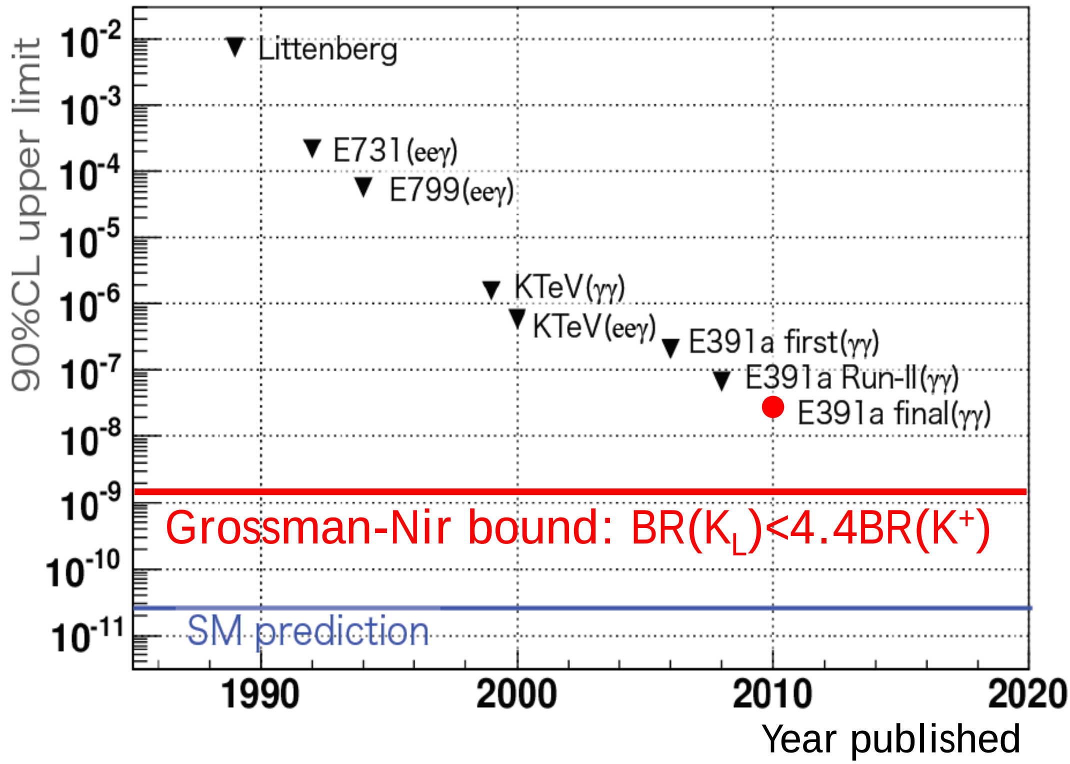
$K_L \to \pi^0 \nu\bar{\nu}$: E391a @ KEK

Technique: K_L beam (~2 GeV/c)

Data taking: 2005.
Pencil K_L beam (2.5×10^{18} PoT).
CsI calorimeter + hermetic Pb/Sci/WLS fiber photon veto.

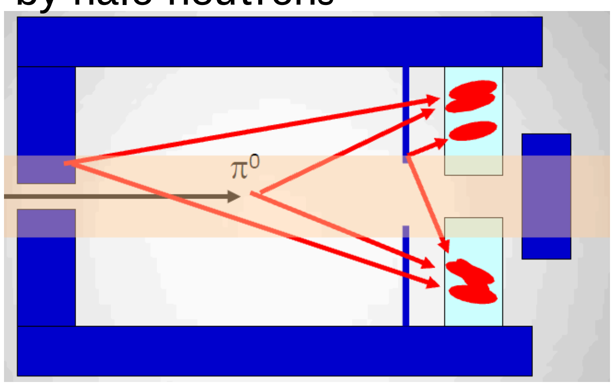
Observed candidates: 0
Expected background: 0.87 ± 0.41

Final result: PRD81 (2010) 072004
$BR(K_L\to\pi^0\nu\nu)<2.6\times10^{-8}$ @90%CL

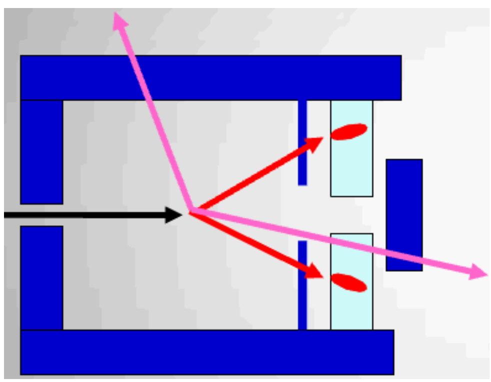


Principal backgrounds:

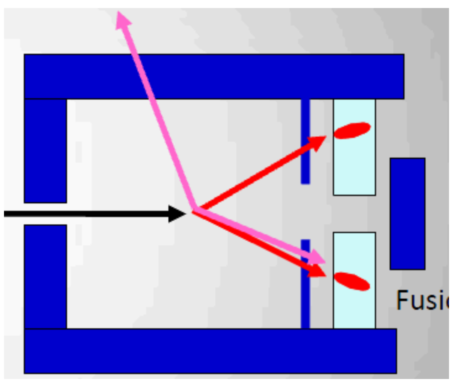
Dominant: π^0/η production by halo neutrons



$K_L\to\pi^0\pi^0$ (2 lost photons)

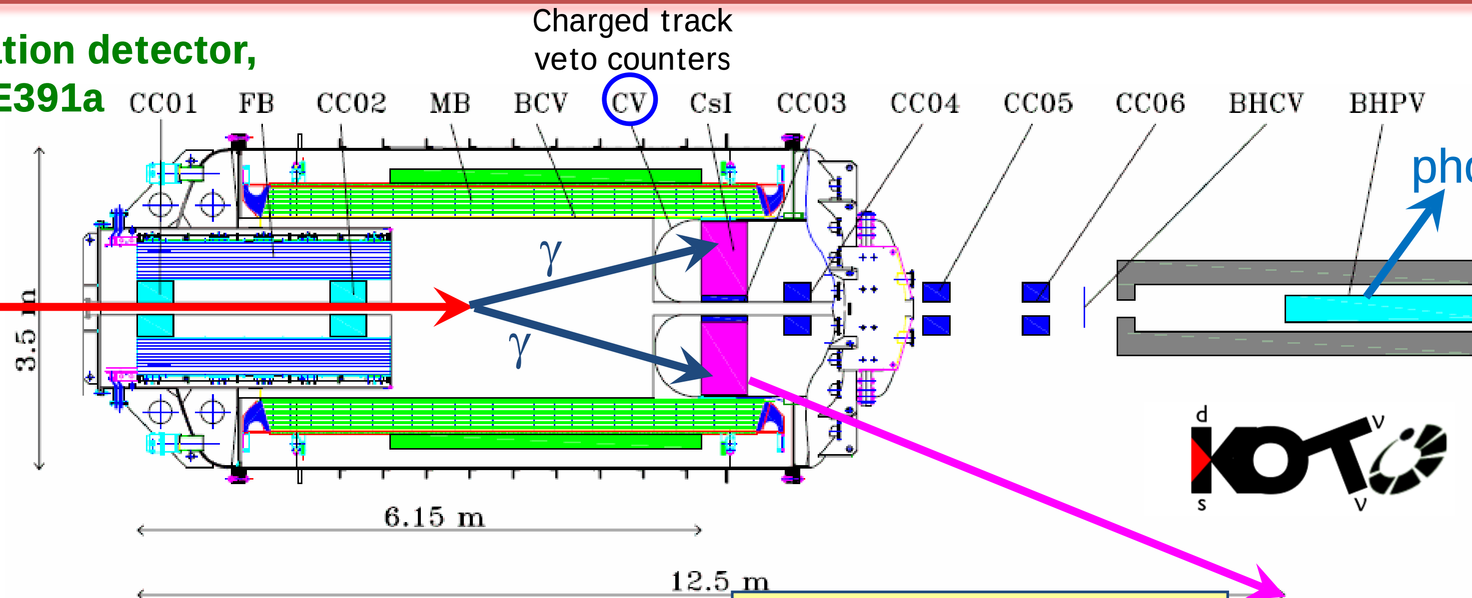


$K_L\to\pi^0\pi^0$ (merged clusters)



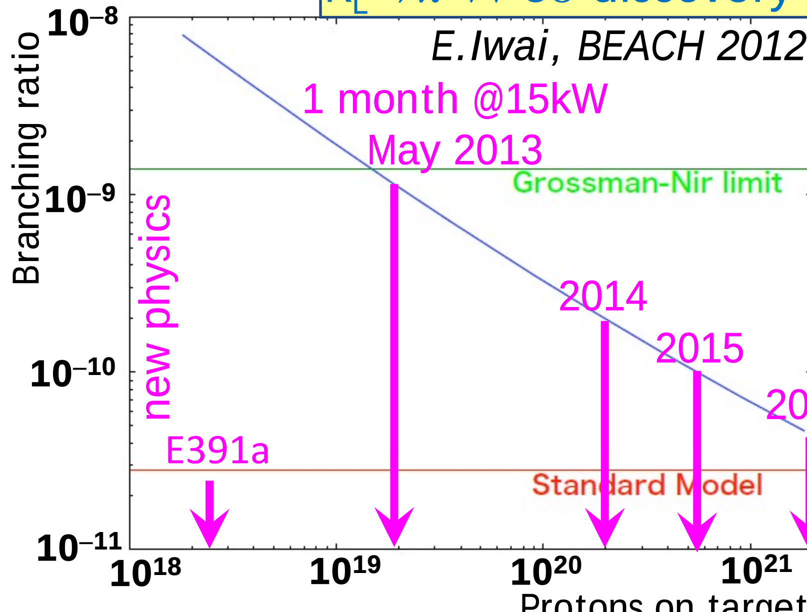
$K_L \to \pi^0 \nu \bar{\nu}$: KOTO @ J-PARC

2nd generation detector, builds on E391a



$27X_0$ CsI calorimeter: KTeV crystals, finer segmentation

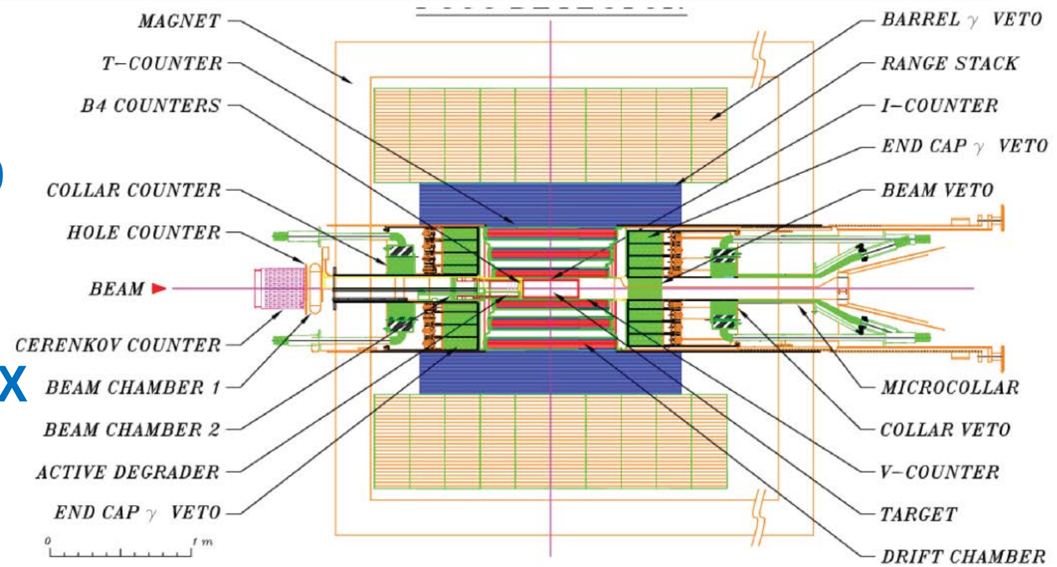
$K_L \to \pi^0 \nu \bar{\nu}$ 3σ discovery

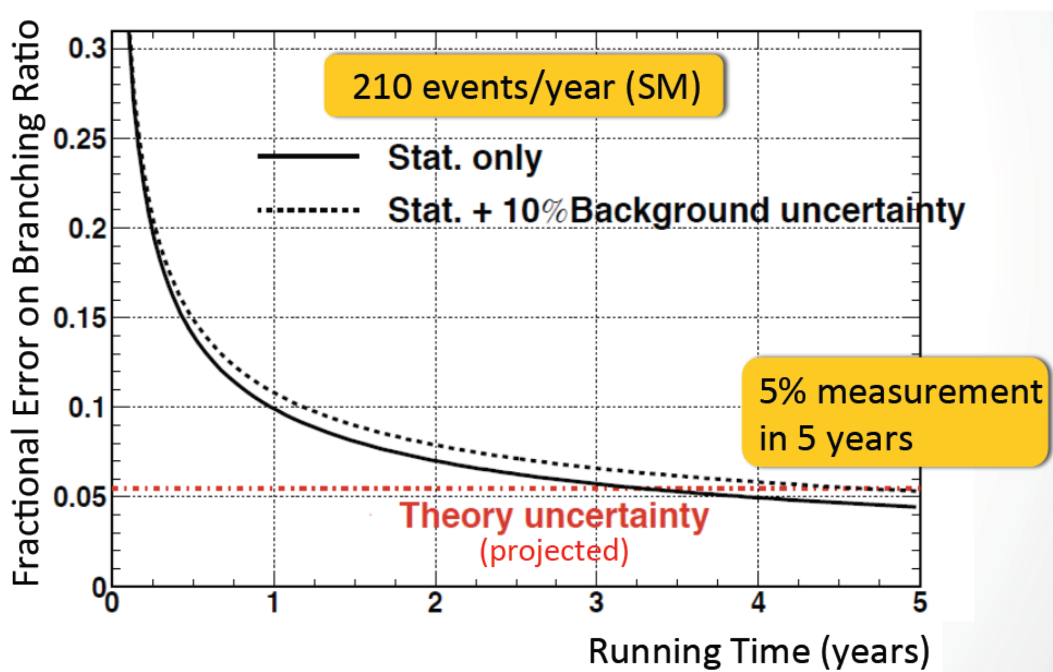


Signal & background (3 years) H. Nanjo, PoS(KAON09)047	
Signal	2.7
$K_L \to \pi^0 \pi^0$	1.7
Halo neutrons	0.4
Total background	2.1

$K^+ \to \pi^+ \nu\bar{\nu}$: ORKA @ FNAL

- Upgraded (4th generation) **BNL E949** detector installed at **FNAL** using the Main Injector proton beam.
- Foreseen at **"stage-0" of Project X** intensity frontier programme.
- Possible location: the **CDF hall** (re-use solenoid, cryogenics, …).
- Sensitivity improvements wrt BNL: **×10** (beam) and **×10** (detector).
- Possible start of data taking: **2016** (subject to DOE approval).
- **$O(10^3)$** SM **$K^+ \to \pi^+ \nu\bar{\nu}$** events in 5 years: **~5%** precision.

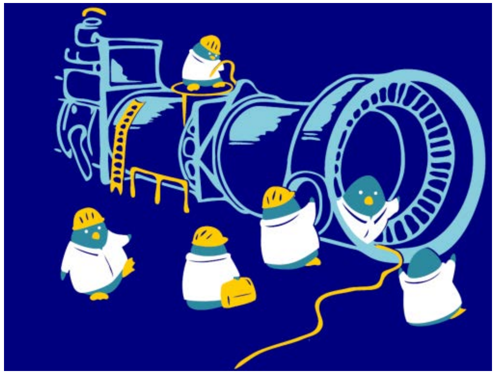




Summary

❖ Kaon physics worldwide is focused on ultra rare $K\to\pi\nu\bar{\nu}$ decays:
- a key flavour observable with unique sensitivity to non-SM physics;
- NP energy reach possibly superior to 14 TeV pp interactions.

❖ Construction of the NA62 detector for measurements of ultra rare K^+ decays is at advanced stage:
- 9 new detectors + several upgraded detectors;
- NA62UK: significant hardware and computing contributions, physics leadership;
- KTAG detector built in UK and shipped to CERN;
- technical (physics) runs in **2012** (**2014–2016**).



❖ Consolidation of the UK leadership in NA62 in the longer term: funds for enhancement of the UK role in the physics exploitation.
→ *Occasion for STFC to broaden UK physics programme at a modest investment*

❖ The NA62 enthusiasm is shared by:
KOTO@J-PARC (K_L: 2013–2017), ORKA@FNAL (K^+: 2016–2021?), …

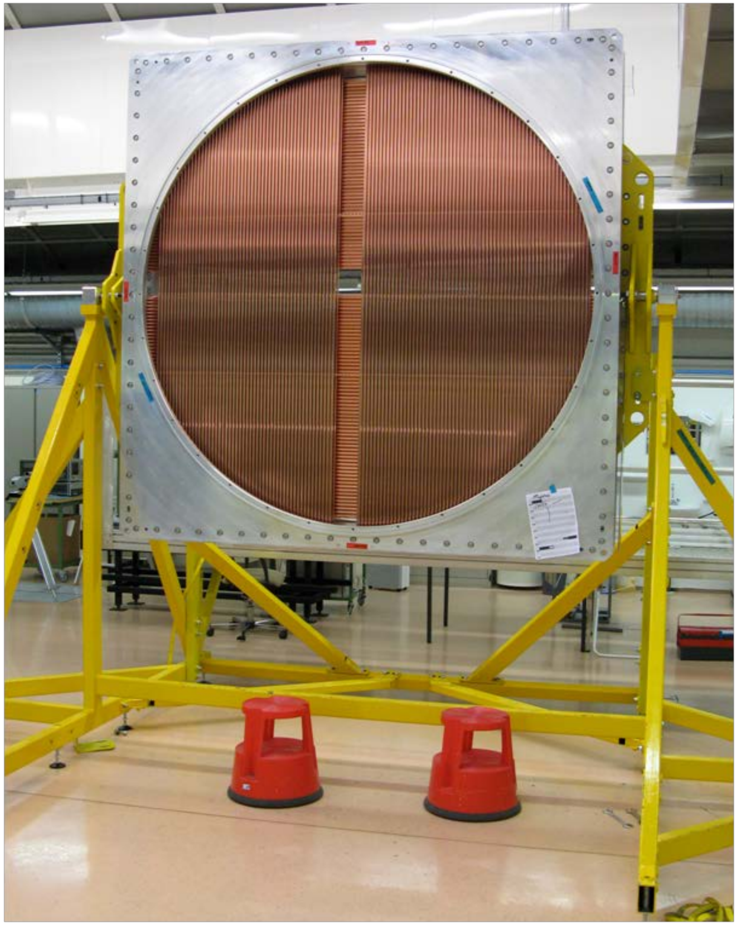
Spares

NA62 straw tracker

Magnetic spectrometer:

- ❖ Minimum material: $0.5\%X_0$ per chamber.
  … 4 straw chambers operating in vacuum.
- ❖ 1 chamber = 4 views (x, y, u, v);
  1 view = 4 straw layers.
- ❖ Momentum resolution: $\sigma(p)/p \sim 0.3\%$.
- ❖ Angular resolution: < 60μrad.
- ❖ Vertex reconstruction: $\sigma_{CDA} \sim 1$ mm.
- ❖ Max rate per straw: 0.5 MHz.

A straw chamber assembled at CERN

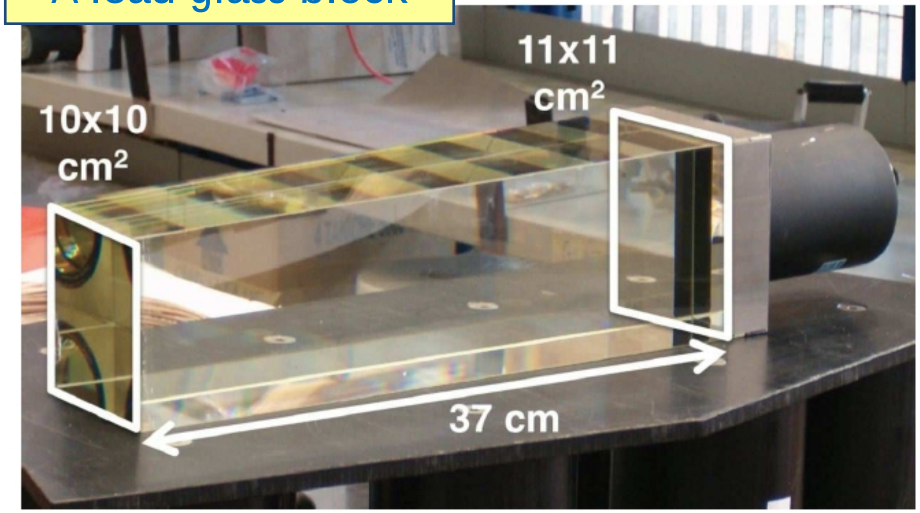


Straw tubes:

- ❖ Length: 2.1 m, diameter: 9.8 mm.
- ❖ Spatial resolution: < 130 μm.
- ❖ ~1800 straw tubes / chamber.
  - ❑ 36 μm Cu/Au-coated mylar foils;
  - ❑ Gas: Ar (70%) / CO_2 (30%) @ 1 atm.

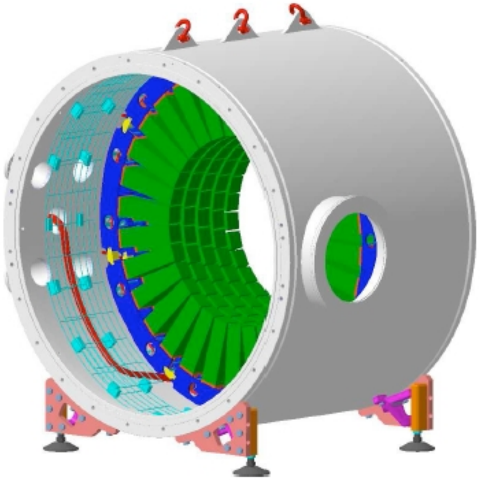
NA62 large angle vetoes (LAV)

A lead glass block



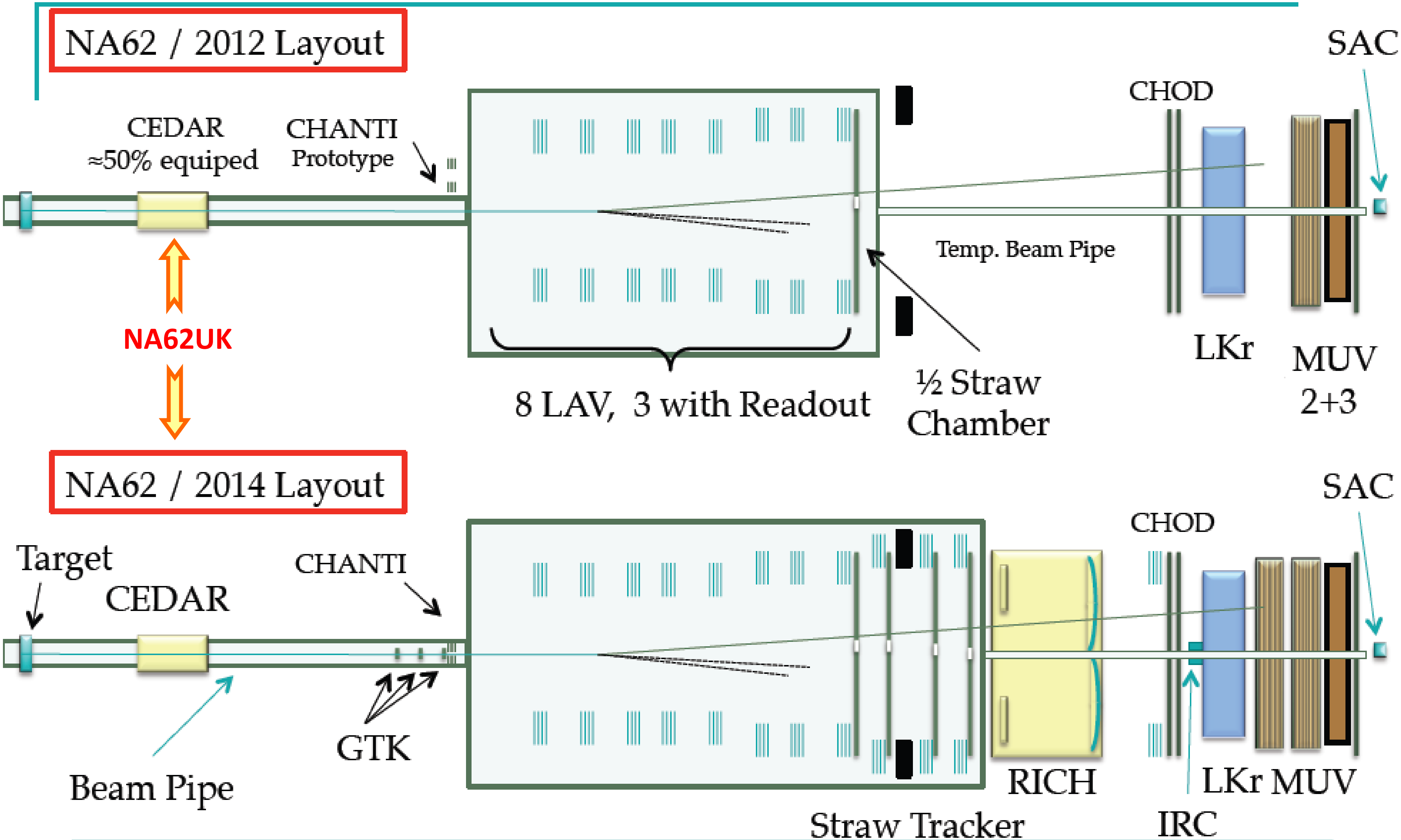
- 12 stations in total (11 in vacuum);
- Each station: 4 or 5 staggered layers, ~$20X_0$,160 to 256 Pb glass blocks.
- Lead glass blocks from the former OPAL EM calorimeter.
- ~2500 blocks in total (of 4 types);
- Coverage in the region 8.5-50 mrad.

Design of a station



A station constructed at LNF Frascati

NA62 technical run 2012



The NA62 experiment (R_K phase)

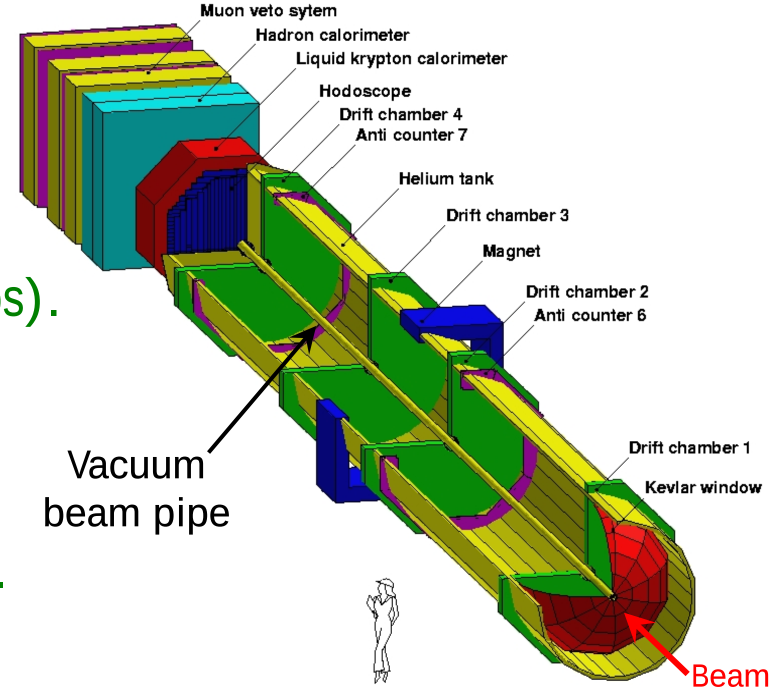
Beam line & setup:

from **the earlier NA48/2 experiment**.

- Simultaneous $K^{\pm}$ beams: 74 GeV/c (±1% RMS).
- Decay volume: 114 long vacuum tank.
- Data taking: 4 months in 2007 with a minimum bias trigger.

Principal subdetectors:

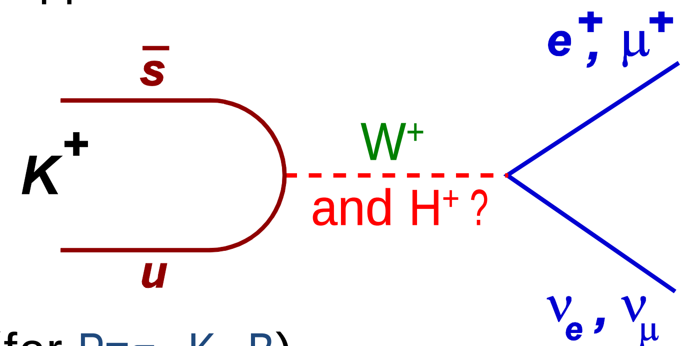
- **Magnetic spectrometer (4 DCHs):**
  4 views/DCH: redundancy ⇒ efficiency;
  $\Delta p/p = 0.47\% + 0.020\%*p$ [GeV/c]
- **Hodoscope**
  fast trigger, precise time measurement (150ps).
- **Liquid Krypton EM calorimeter (LKr)**
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ [GeV];
  $\sigma_x=\sigma_y=4.2\text{mm}/E^{1/2} + 0.6\text{mm}$ (1.5mm@10GeV).



Leptonic meson decays

Angular momentum conservation → SM contribution is suppressed

$$\Gamma(P^+ \to l^+\nu) = \frac{G_F^2 M_P M_l^2}{8\pi}\left(1 - \frac{M_l^2}{M_P^2}\right)^2 f_P^2 |V_{qq'}|^2$$



Models with 2 Higgs doublets (2HDM-II including SUSY): sizeable charged Higgs ($H^{\pm}$) exchange contributions.

$$\frac{\Gamma(P^\pm \to \ell^\pm\nu)}{\Gamma^{SM}(P^\pm \to \ell^\pm\nu)} = \left[1 - \left(\frac{M_P}{M_H}\right)^2 \frac{\tan^2\beta}{1+\varepsilon_0 \tan\beta}\right]^2$$

(for P=π, K, B)

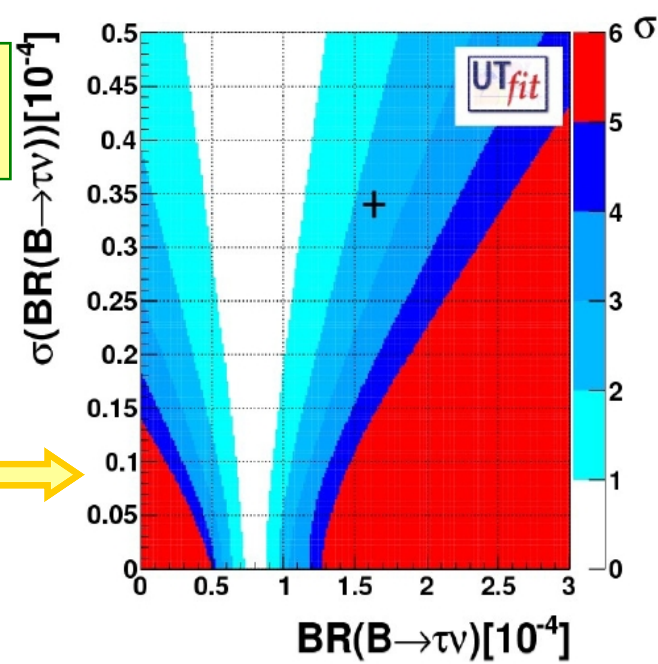
Hou, PRD48 (1993) 2342;
Isidori, Paradisi, PLB639 (2006) 499

$\pi^+ \to l\nu$: $|\Delta\Gamma/\Gamma_{SM}| \sim 2(m_\pi/m_H)^2\, m_d/(m_u+m_d)\, \tan^2\beta \sim 10^{-4}$
$K^+ \to l\nu$: $|\Delta\Gamma/\Gamma_{SM}| \sim 2(m_K/m_H)^2 \tan^2\beta \sim 10^{-3}$

… obstructed by hadronic uncertainties (f_P)

$H^\pm$ exchange in $B^+ \to \tau^+\nu$: UTfit; PLB687 (2010) 61

BaBar+Belle: $Br_{exp}(B\to\tau\nu) = (1.65\pm0.34)\times10^{-4}$
(PDG 2012)
Standard Model: $Br_{SM}(B\to\tau\nu) = (0.79\pm0.08)\times10^{-4}$
(UTfit, M.Bona, EPS 2011)



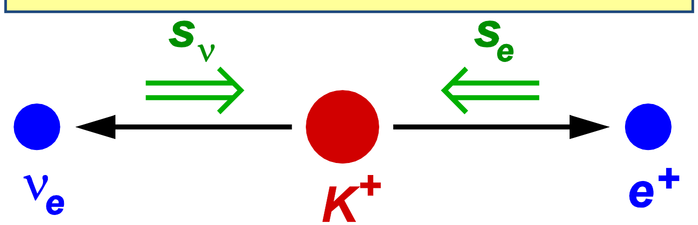
NA62: lepton flavour physics

Observable sensitive to Lepton Flavour Universality violation:

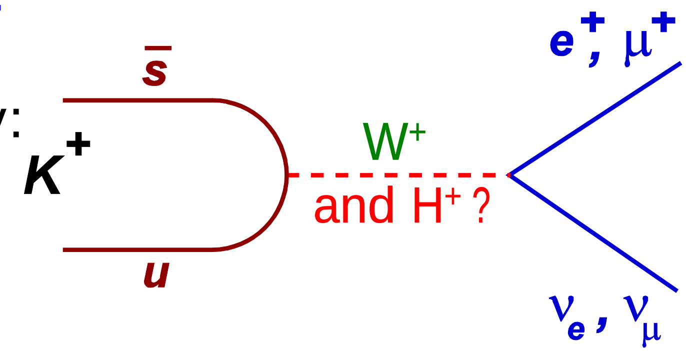
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot (1 + \delta R_K^{\mathrm{rad.corr.}})$$

Radiative correction (well known, few %)

Helicity suppression: f~10^{-5}



- **SM prediction:** excellent sub-permille accuracy: not obstructed by hadronic uncertainties.
- Measurements of R_K (and R_π) have long been considered as tests of LFU.
- NP contributions accessible experimentally due to the **suppression of the SM value**.



$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

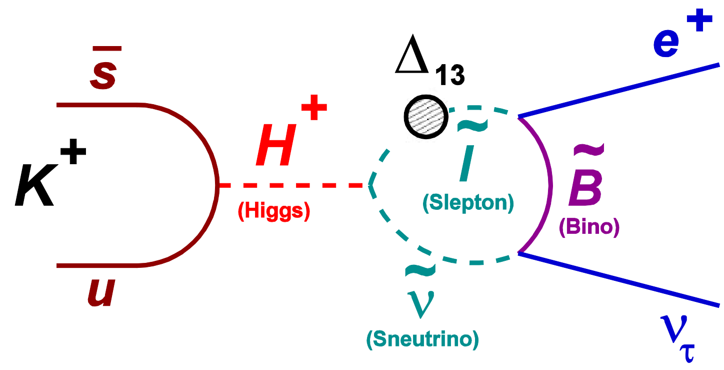
Cirigliano, Rosell, PRL99 (2007) 231801

$R_K = BR(K_{e2})/BR(K_{\mu 2})$ beyond SM

2HDM - tree level

K_{l2} can proceed via exchange of charged Higgs $H^\pm$ instead of $W^\pm$

→ Does not affect the ratio R_K



2HDM - one-loop level

Dominant contribution to R_K: $H^\pm$ mediated LFV (rather than LFC) with emission of ν_τ

→ R_K enhancement can be experimentally accessible

[Masiero, Paradisi, Petronzio, PRD 74 (2006) 011701, JHEP 0811 (2008) 042]

$$R_K^{LFV} \approx R_K^{SM}\left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2 \tan^6\beta\right]$$

⇒ sensitive to slepton mixing

~1% effect in Minimal Supersymmetric SM
[Girrbach, Nierste, arXiv:1202.4906]

Limited by recent $B_s \to \mu^+\mu^-$ measurements
[Fonseca, Romão, Teixiera, arXiv:1205.1411]

Sensitive to SM extensions with 4th generation
[Lacker, Menzel, JHEP 1007 (2010) 006]