Kaon experiments at CERN

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__Outline:__

1) Ultra-rare $K\to\pi\nu\bar{\nu}$ decays: theory and experiment.
2) NA62 at CERN: towards a $K^+\to\pi^+\nu\bar{\nu}$ measurement.
3) Lepton flavour programme at NA62.

IoP Joint HEPP and APP Meeting • QMUL
3 April 2010

$K\to\pi\nu\bar{\nu}$: introduction

Theoretically clean, sensitive to new physics, almost unexplored

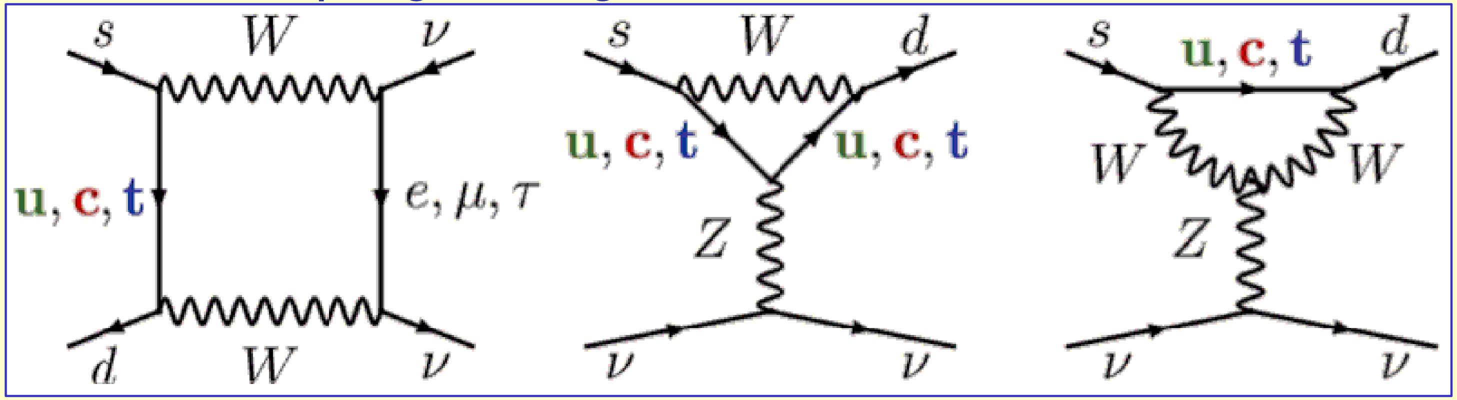
Ultra-rare decays with
the highest CKM suppression:
$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$

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

SM: box and penguin diagrams



- 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 $\delta|V_{td}|/|V_{td}|=7\%$.

$K^+ \to \pi^+ \nu\bar{\nu}$: BNL E787/E949

($K_L \to \pi^0 \nu\bar{\nu}$ never observed)

Technique: K^+ decay at rest.

Data taking: E787(1995–98), E949(2002).

Incoming K^+ (710 MeV/c) stopped in target (1.6MHz).

PID: range (entire $\pi^+ \to \mu^+ \to e^+$ decay chain).

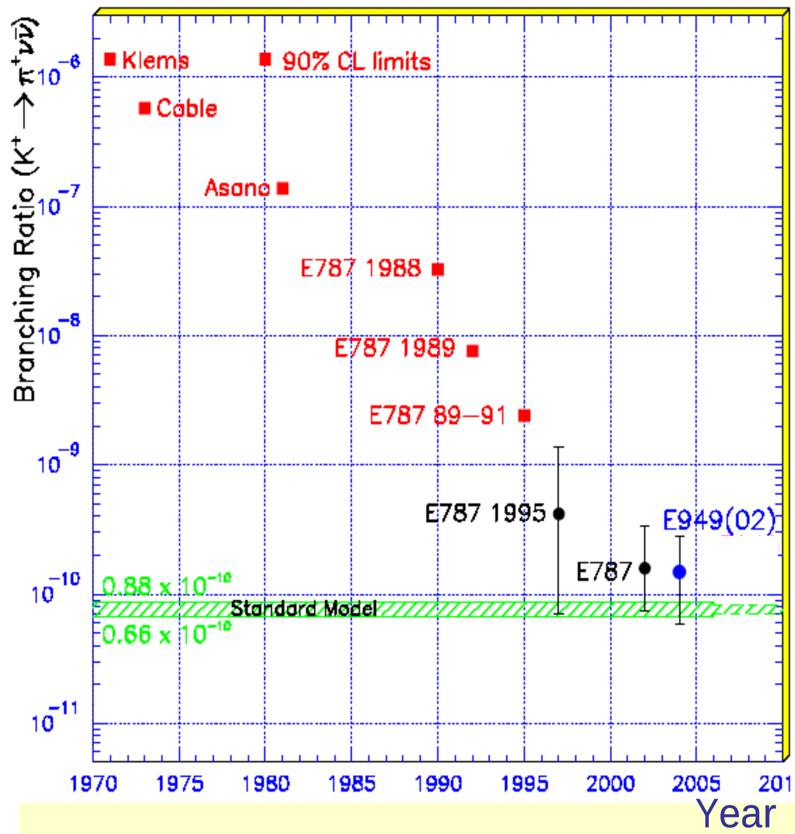
Hermetic photon veto system.

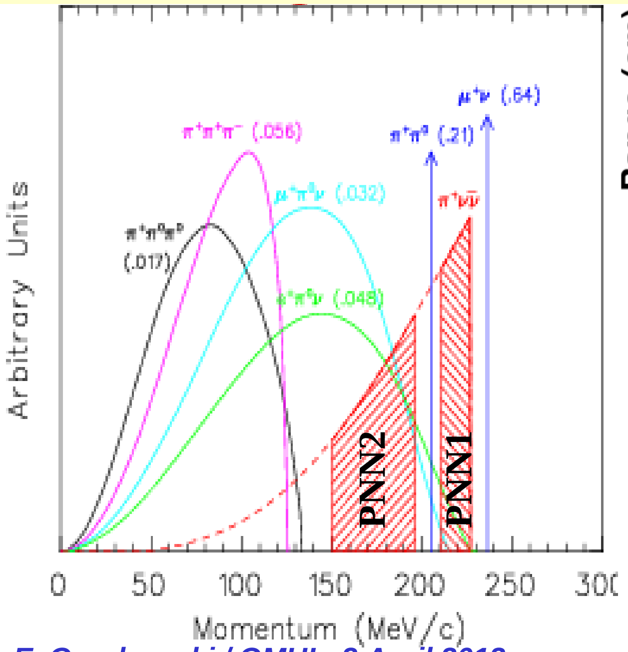
Observed candidates: 7

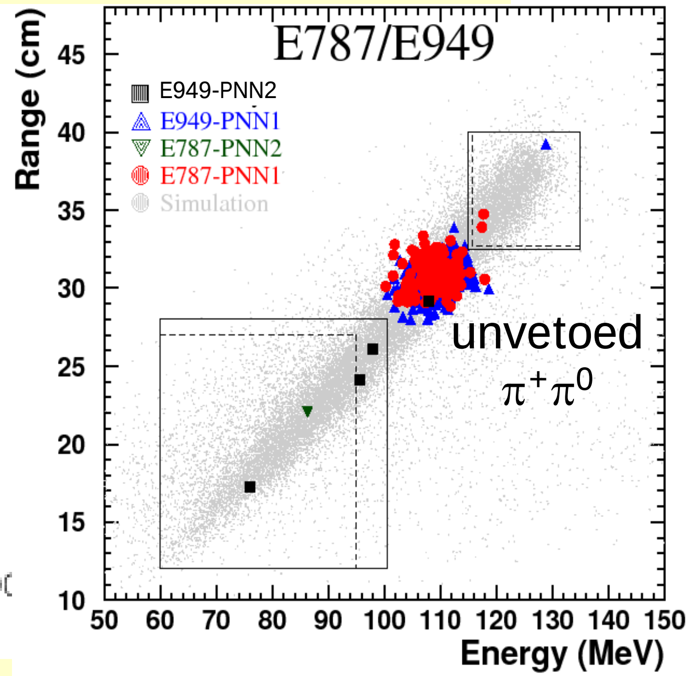
Expected background: 2.6

Final result: $BR = (1.73\,^{+1.15}_{-1.05}) \times 10^{-10}$

PRL 101 (2008) 191802, PRD 79 (2009) 092004





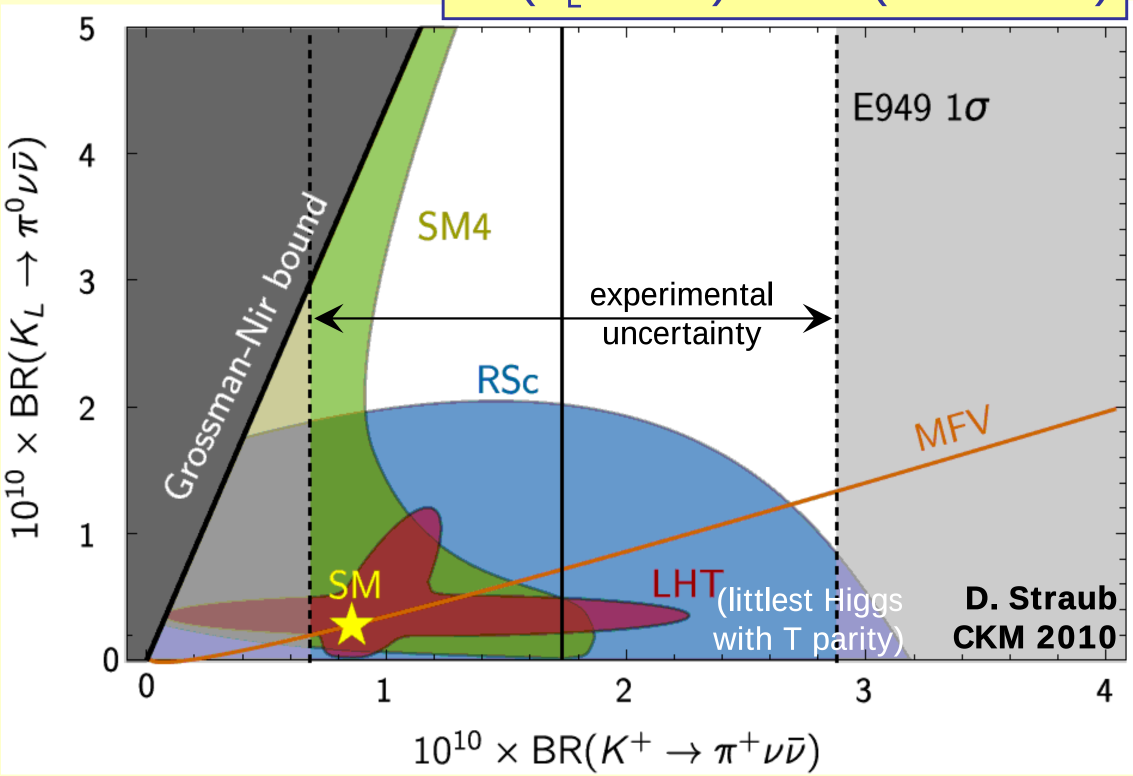


Drawbacks of the method:

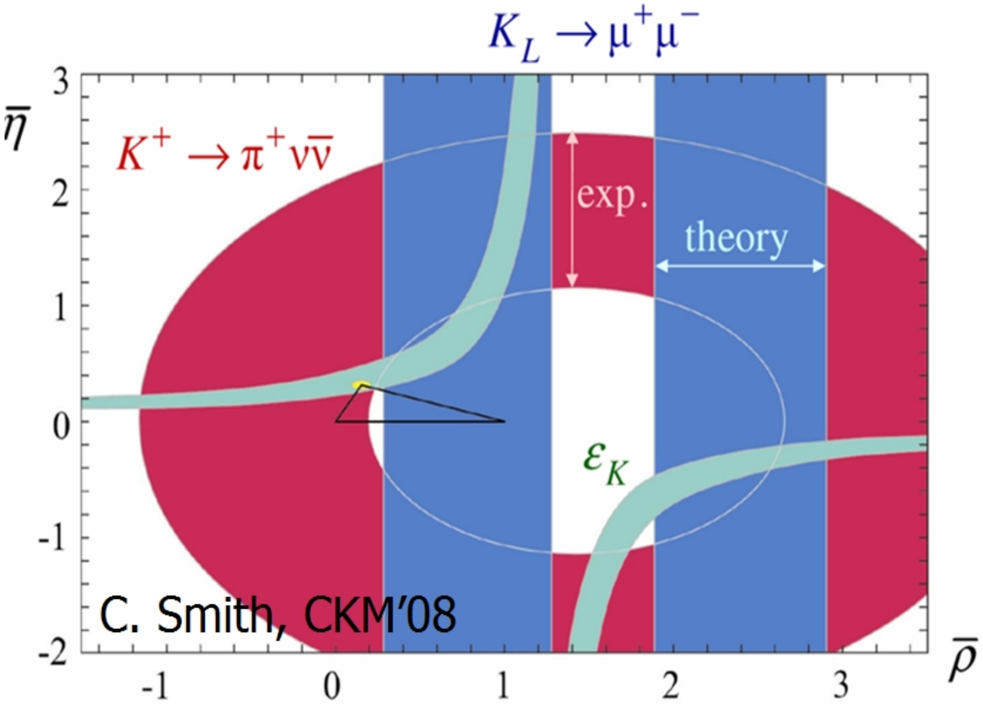
- Low acceptance (~1%);
- significant background (~30%) due to π scattering in the target.

Situation after the BNL experiment

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



CKM unitarity triangle with kaons



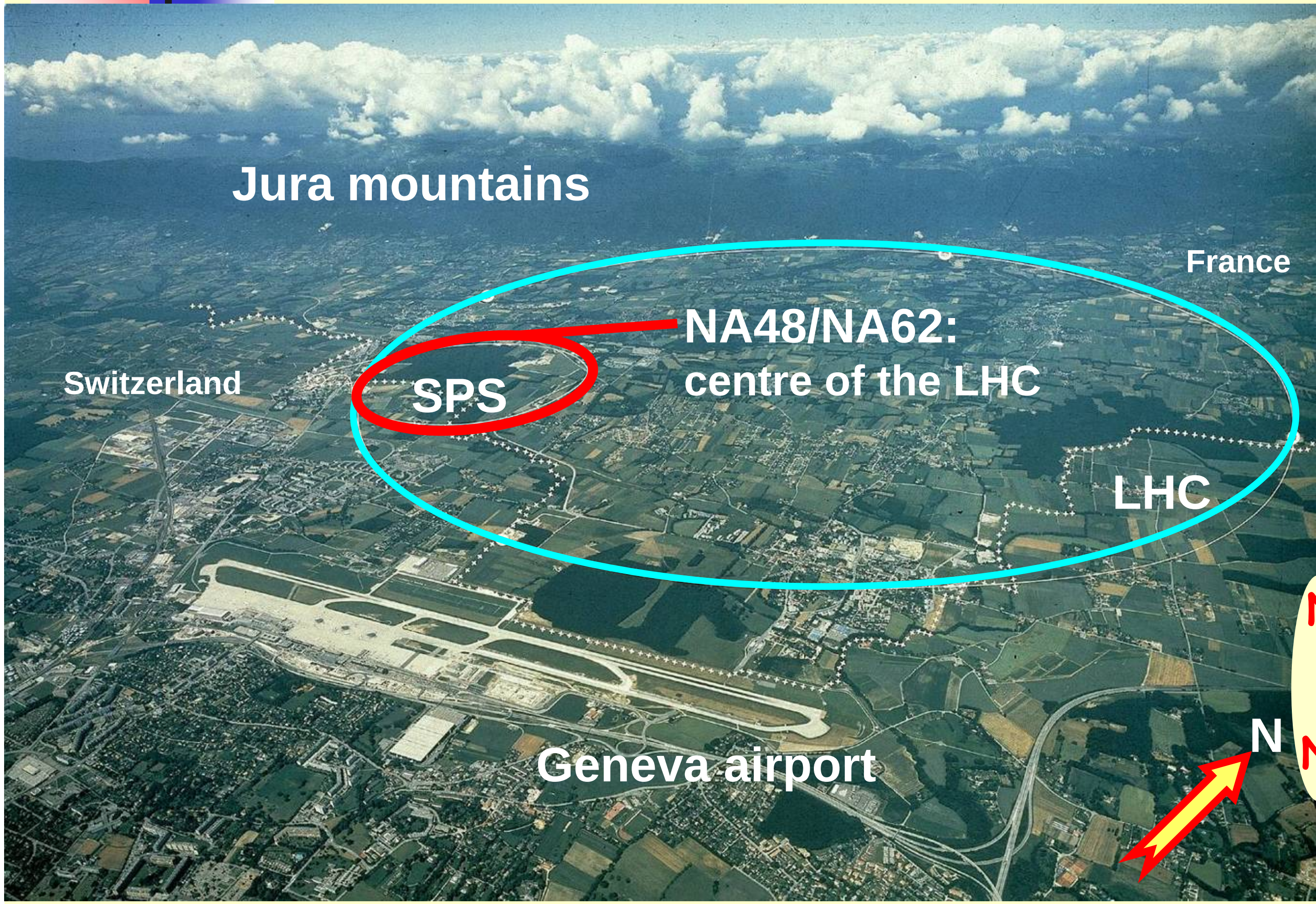
NA62@CERN aims to collect O(100) $K^+ \to \pi^+\nu\bar{\nu}$ decays with ~10% background in 2 years of data taking using a novel decay-in-flight technique.

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

Advantages: high K^+ production rate ($\sim p_K^2$); high acceptance (~10%); efficient photon veto (>40 GeV missing energy) + good π^+/μ^+ separation by RICH.

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

CERN NA48/NA62 experiments



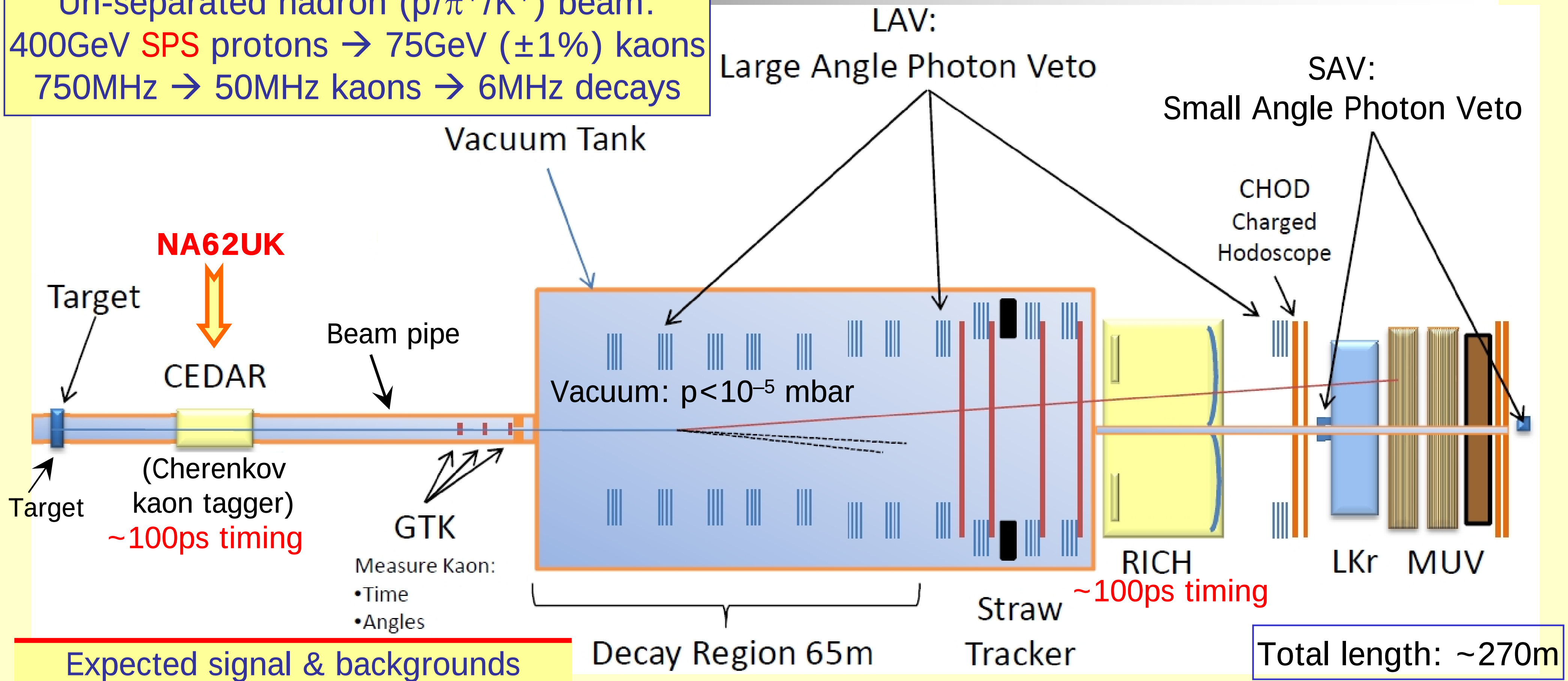
Earlier: NA31

- **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: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ | tests
  - 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ | tests
- **NA62**
  - 2007–2013: design & construction
  - 2012: first data taking

NA62: Birmingham, Bristol, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, Glasgow, IHEP Protvino, INR Moscow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin

NA62: sensitivity

Un-separated hadron ($p/\pi^+/K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons
750MHz → 50MHz kaons → 6MHz decays



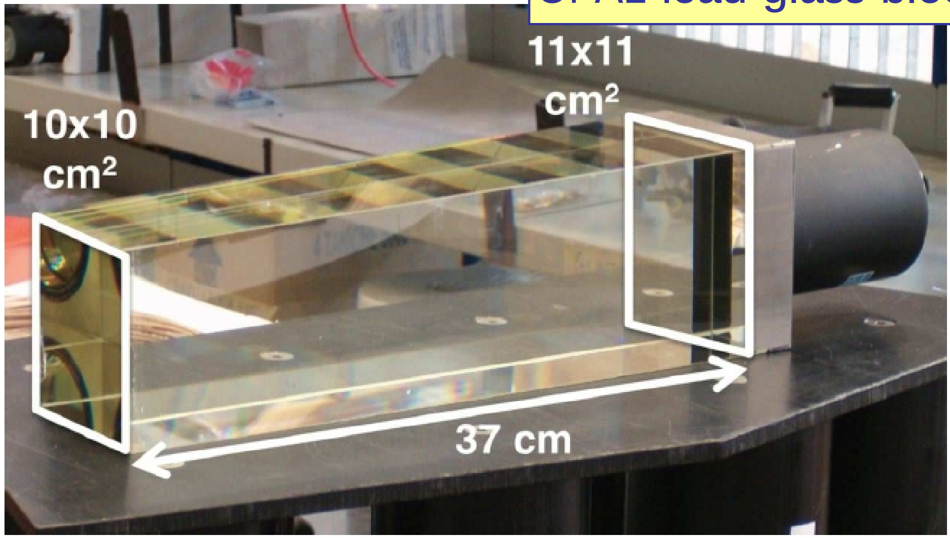
Expected signal & backgrounds	
Signal	45 evt/year
$K^+\to\pi^+\pi^0$	4.3%
$K^+\to\mu^+\nu$	2.2%
$K^+\to$ 3 charged tracks	<4.5%
$K^+\to\pi^+\pi^0\gamma$	~2%
$K^+\to\mu^+\nu\gamma$	~0.7%
Total background	<13.5%

- 5×10^{12} K^+ decays/year → record SES of $\sim10^{-12}$;
- Hermetic veto: $\sim5\times10^{-8}$ suppression of $\pi^0\to\gamma\gamma$;
- Kinematics: $\sim10^{-4}$ suppression of $K\to\pi^+\pi^0$.

- Construction in progress; first technical run in 2012;
- Physics data taken driven by CERN accelerator schedule.

Construction of LAV detectors

OPAL lead glass blocks



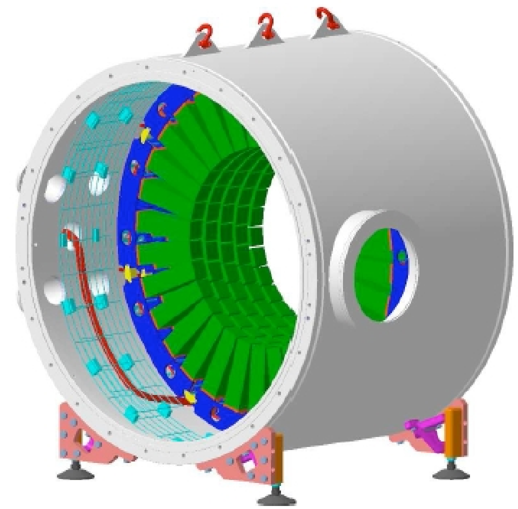
Detector:

- 12 stations;
- 4 block types:
  inner radii vary from 537 to 1072mm;

Each station:

- 4 or 5 staggered layers;
- 160 to 256 Pb glass blocks.

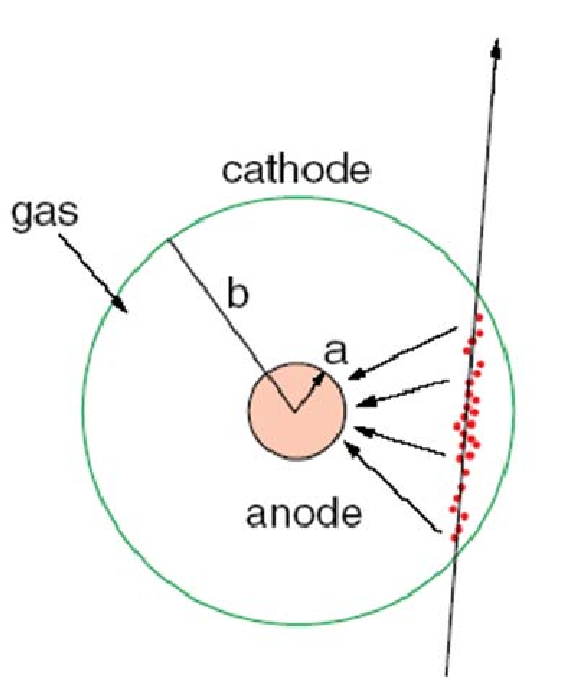
Station design



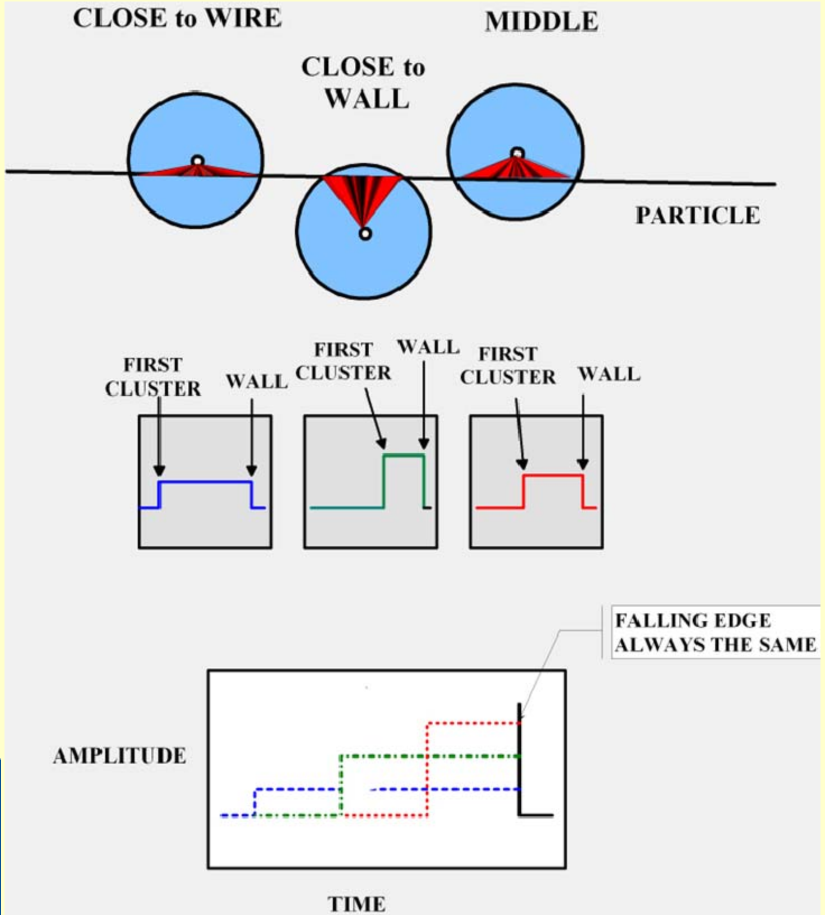
A LAV station constructed at Frascati

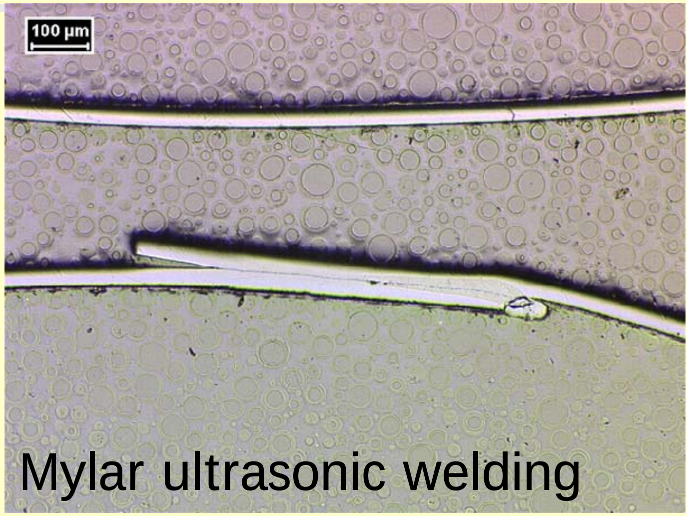
Construction of the straw tracker

to operate in vacuum

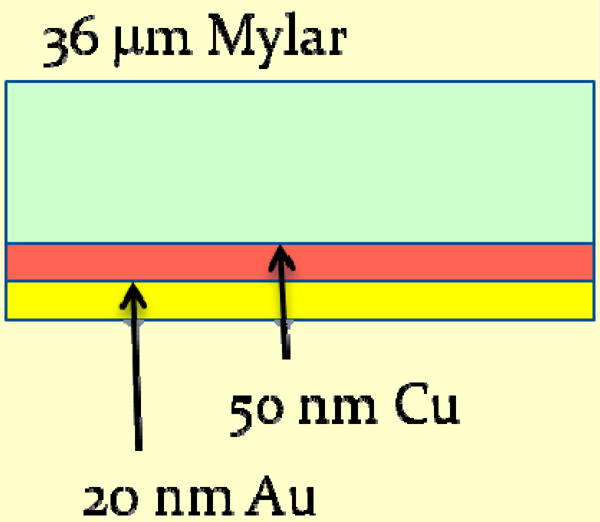


The straw principle:

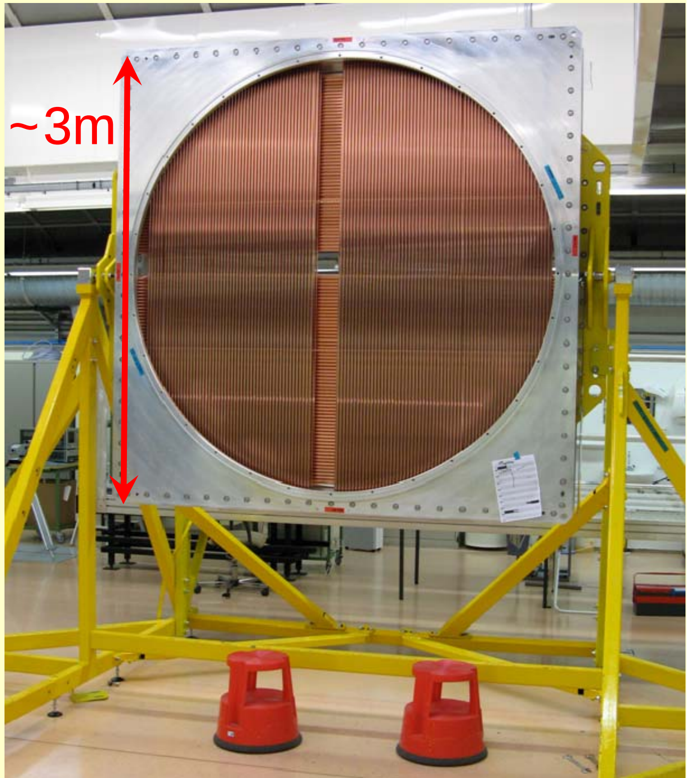




Mylar ultrasonic welding



- Falling edge has the same time for all straws on track;
- Rising edge and amplitude give the distance to wire.



1 module ~ 1000 straws

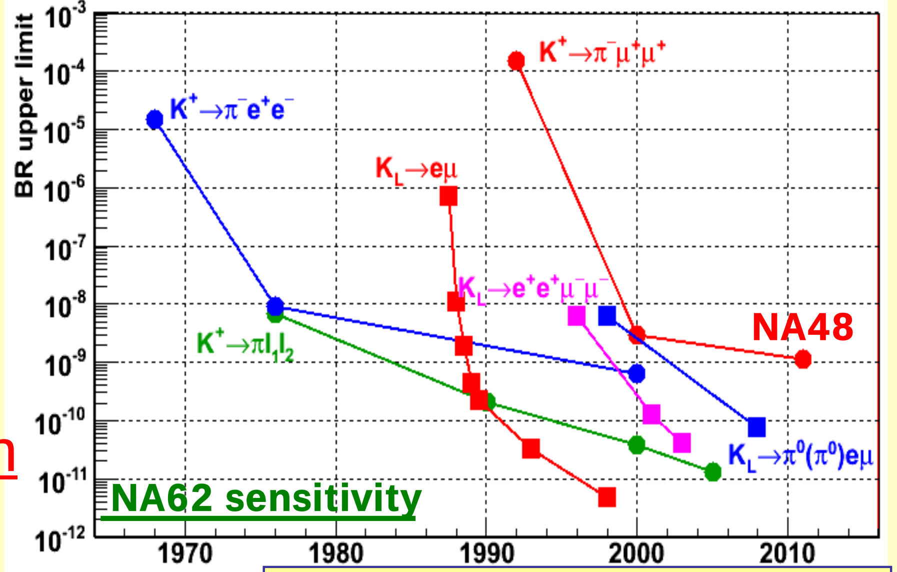
The wider NA62 programme

- Lepton Flavour Universality test
  $R_K = BR(K^+ \to e^+\nu)/BR(K^+ \to \mu^+\nu)$.
  Well established decay-in-flight technique.
  Expected NA62 precision: $\delta R_K/R_K < 0.2\%$.
  Competitor: TREK@J-PARC (stopped K^+).

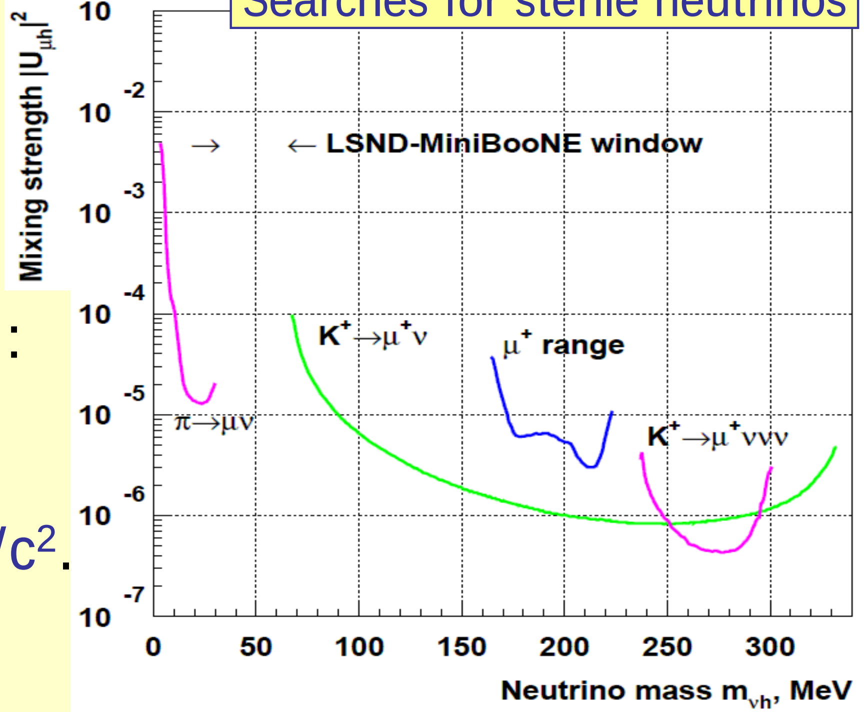
- Searches for lepton flavour/number violation
  $K^+\to\pi^+\mu^+e^-$, $K^+\to\pi^+\mu^-e^+$, $K^+\to\pi^-\mu^+e^+$,
  $K^+\to\pi^-\mu^+\mu^+$, $K^+\to\pi^-e^+e^+$.
  Current upper limits: $\sim10^{-10} \ldots 10^{-11}$.
  Expected NA62 limits
  (subject to trigger configuration): $\sim10^{-12}$.

- Searches 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 $m\sim60MeV/c^2$.
  S.N.Gninenko, PRD83 (2011) 015015

Searches for LFV/LNF: BR upper limit vs year



Searches for sterile neutrinos



Lepton Flavour Physics

(UK contribution to NA62)

Lepton Flavour Universality (LFU): not a fundamental law (violated in ν sector).
New physics models (2HDM, SUSY, SM4): significant LFU violation.

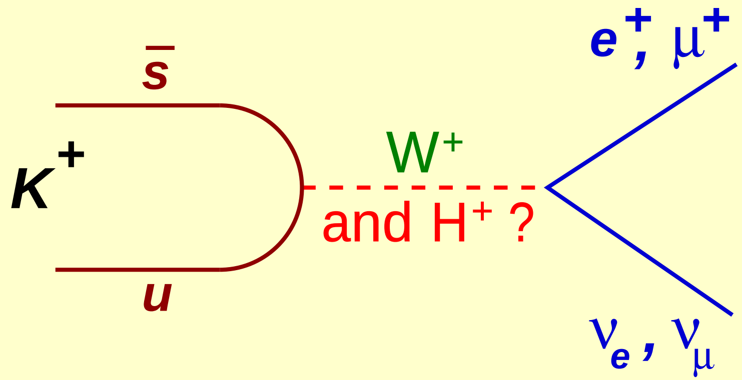
Observable sensitive to LFU violation:

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

Helicity suppression: $f \sim 10^{-5}$

Radiative correction (well known, few %)

- 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.



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

PL99 (2007) 231801

$R_K = K_{e2}/K_{\mu 2}$ beyond the SM

2HDM – tree level (including SUSY)

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

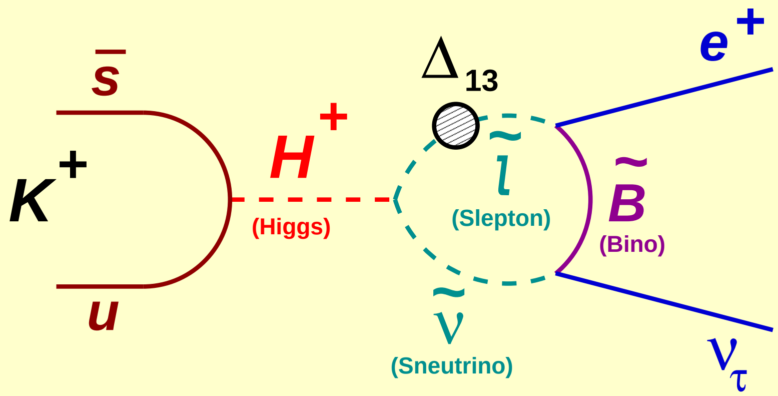
→ Does not affect the ratio R_K

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 et al., PRD 74 (2006) 011701,
Masiero et al., JHEP 0811 (2008) 042



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

→ ~$\tan^6\beta$, *cf.* $B_s \to \mu^+\mu^-$;

uniquely sensitive to slepton mixing

$\mathcal{O}(1\%)$ enhancement possible without contradicting any experimental constraints.

Girrbach, Nierste, arXiv:1202.4906

SM with 4-th generation:

$R_K^{4SM} = R_K^{SM}\,(1-|U_{e4}|^2)/(1-|U_{\mu 4}|^2)$

Sub-percent precision on R_K provides non-trivial constraints on neutrino mixing

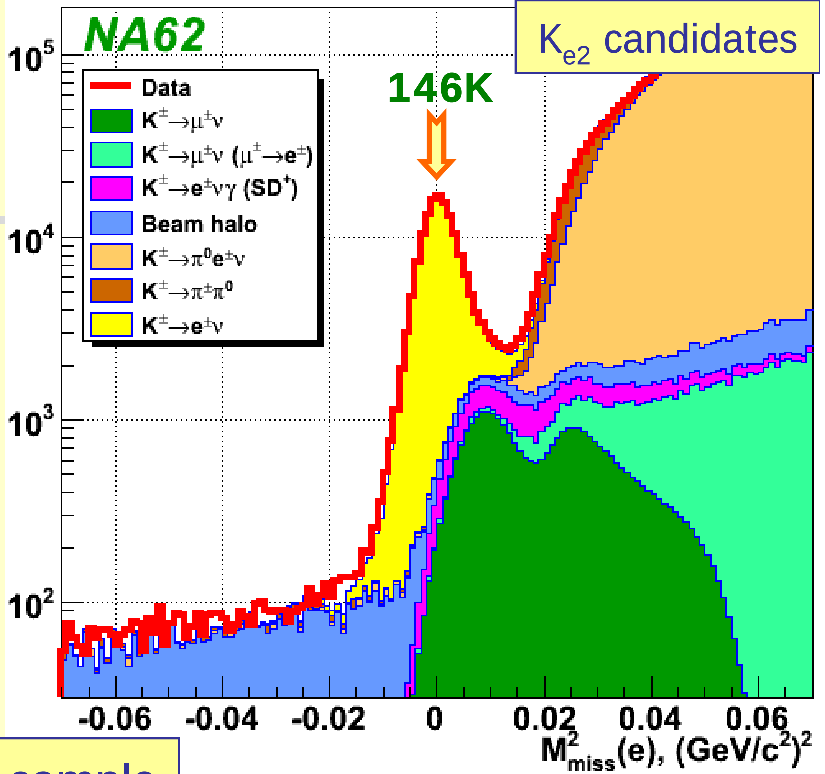
Lacker and Menzel, JHEP 1007 (2010) 006

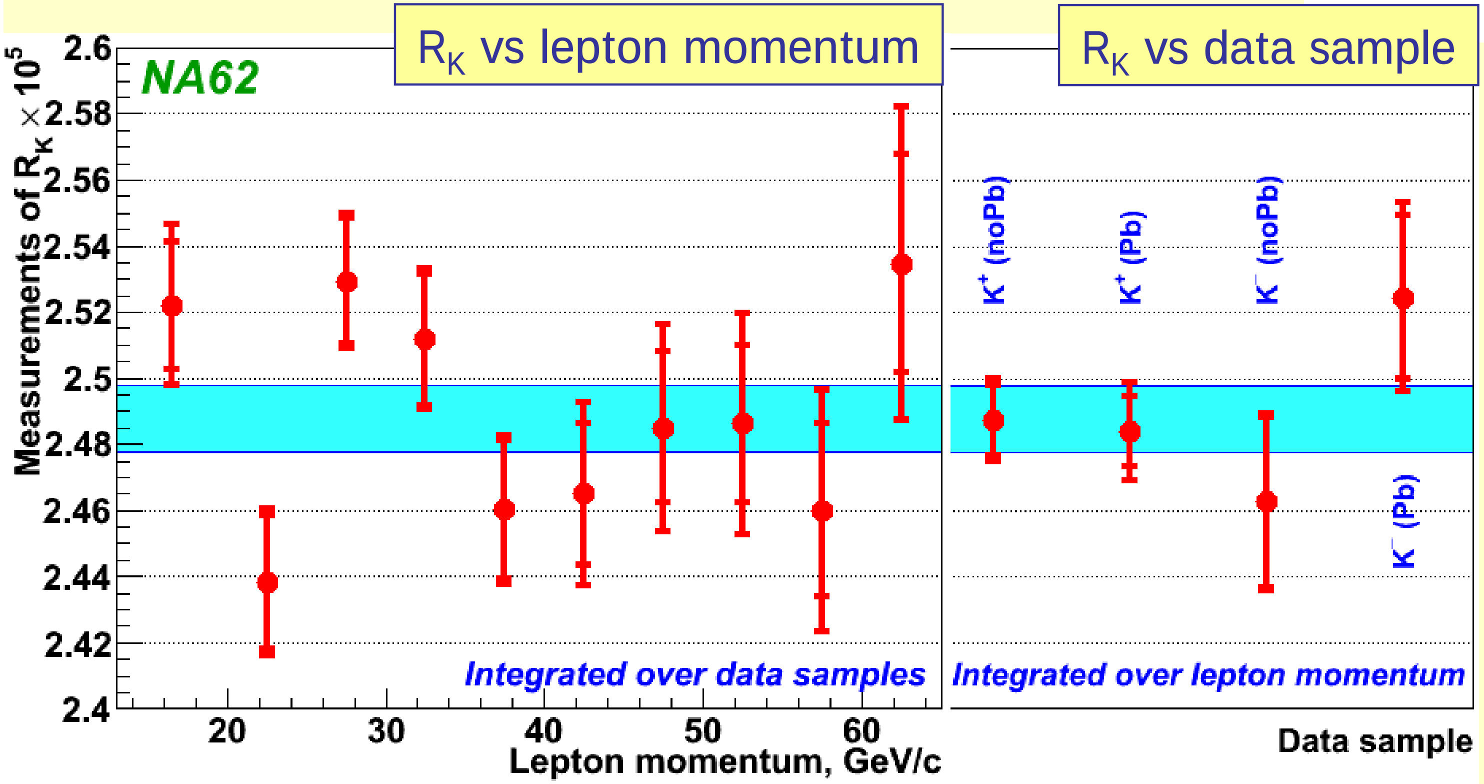
NA62 (R_K phase)

Final result with the full 2007 data set:

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

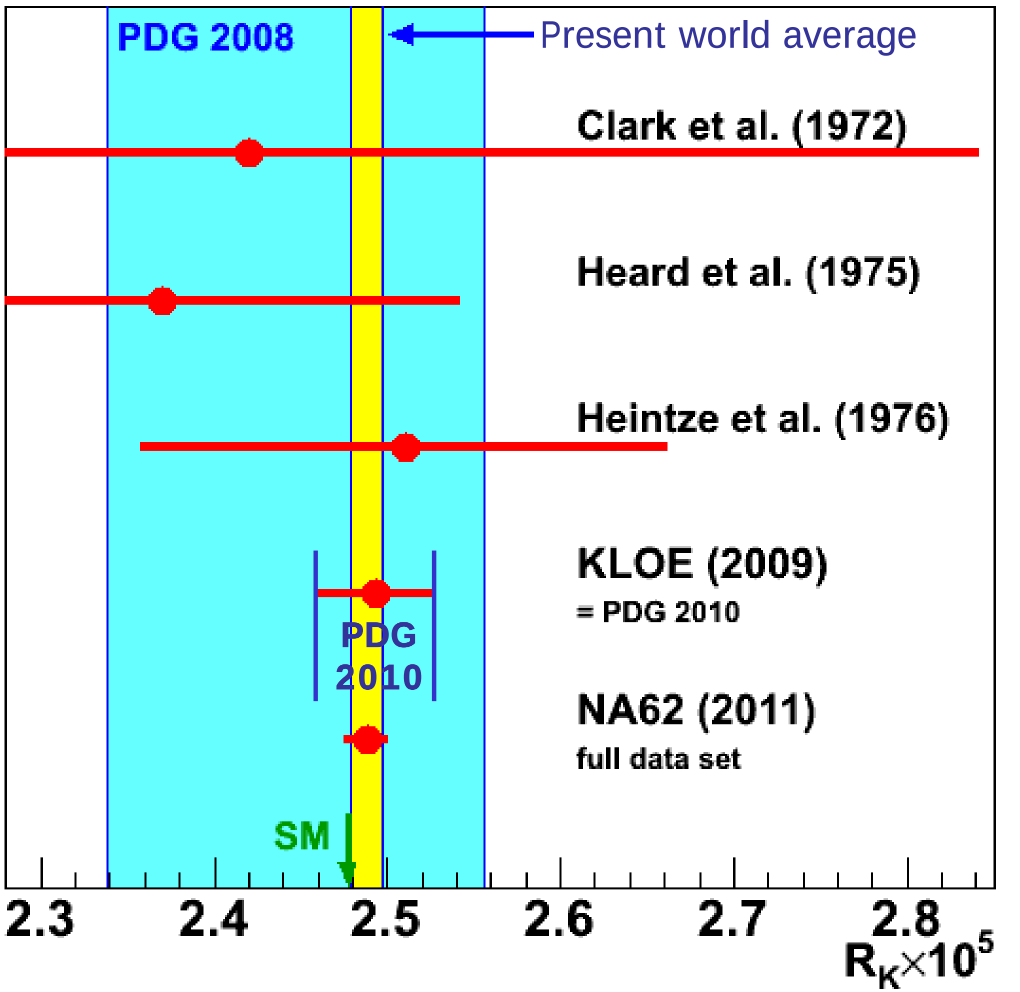
Partial (40%) data set: PLB 698 (2011) 105.
Full data set: paper to be submitted in April/May 2012.

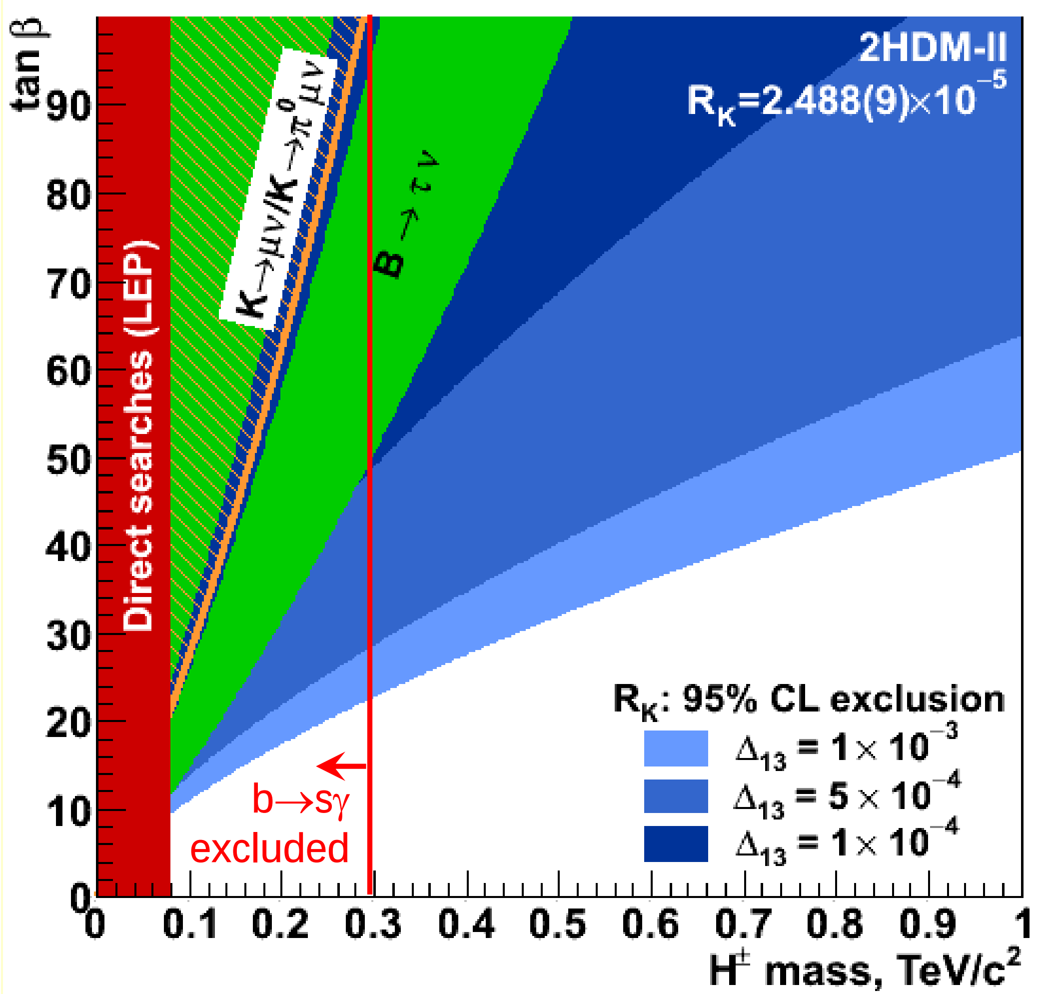




Uncertainty source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$ background	0.004
$K^\pm \to e^\pm \nu \gamma$ (SD^+)	0.002
$K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$	0.003
Beam halo background	0.002
Matter composition	0.003
Acceptance correction	0.002
DCH alignment	0.001
Electron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

Conclusions

- The $K\to\pi\nu\nu$ decays are extremely suppressed and precisely predicted within the SM.
  → unique sensitivity to new physics;
  → a way of pushing the energy frontier above 14 TeV pp interactions.

- NA62: first experiment aiming to measure $BR(K\to\pi\nu\bar{\nu})$ to ~10% precision.
  → a timely measurement complementary to the LHC programme.

- The NA62 programme spans well beyond the flagship decay mode.
  → lepton flavour and number violation,
  sterile neutrinos, rare and radiative decays, …

- Precise measurement of the helicity-suppressed ratio $R_K=\Gamma(K\to e\nu)/\Gamma(K\to\mu\nu)$ completed at the previous stage of NA62:
  → record precision; non-trivial bounds on the 2HDM parameters.