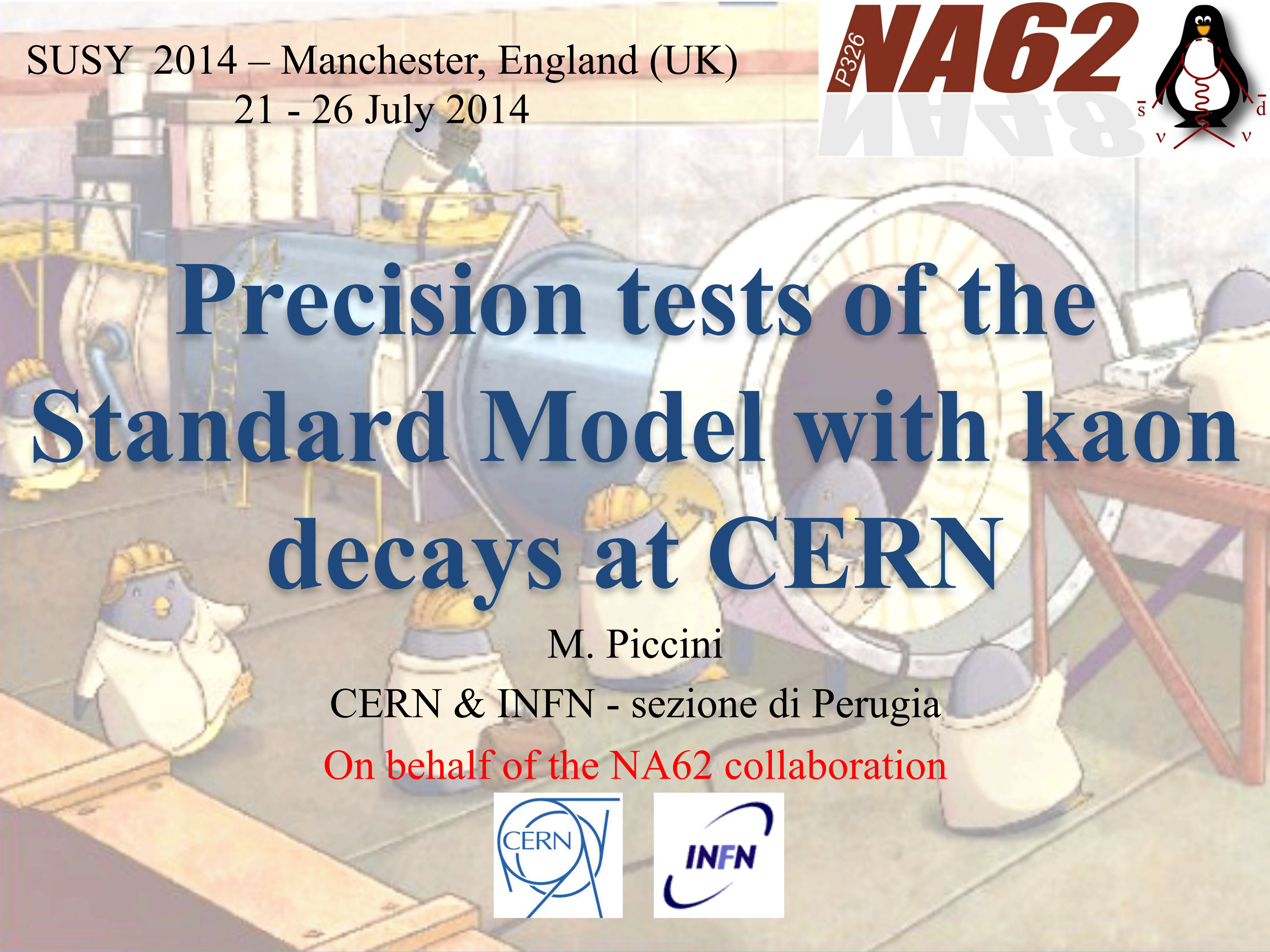


SUSY 2014 – Manchester, England (UK)
21 - 26 July 2014

Precision tests of the Standard Model with kaon decays at CERN

M. Piccini
CERN & INFN - sezione di Perugia
On behalf of the NA62 collaboration

Introduction

- Higgs found! Great success of the Standard Model!
- (Still) No evidence of new particles

    the Standard Model may be a self-consistent weakly coupled effective field theory up to very high scales without adding new particles up to the Plank mass scale (!).

Is this the end of the story? No!

- Experimental "evidence" of new physics

    Neutrino oscillations: tiny masses and flavour mixing

    Baryon asymmetry of the universe: CKM is not enough to explain all the CP violation;

    Dark matter;

    Dark Energy;

- Theoretical "evidence" of new physics

    SM flavour structure;

    Hierarchy problem;

    Strong CP problem;

precision tests of SM → direct and **indirect** search of new physics

Kaons at CERN - SPS

Kaons:

- **Theoretical cleanliness** unmatched
- The SM at E~M_K is remarkably **simple** (at least the EW part)
- Breaks of many symmetries: **C, P, CP, flavour**
- Extreme **hard-GIM SM-suppressed** FCNC decays

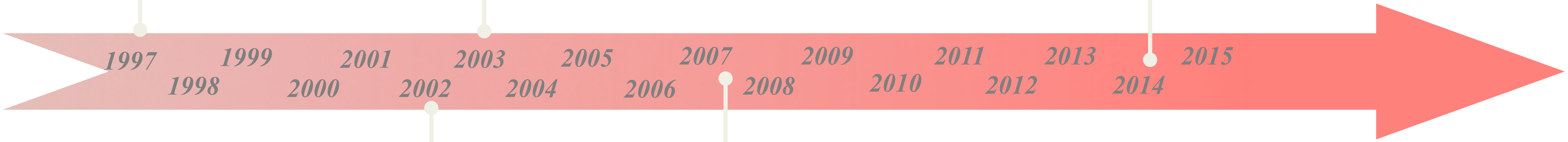
- Simple event topologies gives **clean experimental signature**
- **Few decay** channels
- Availability of **high intensity beams**

NA48 (1996-2001): search for direct CP violation in neutral kaon

NA48/2 (2003-2004): Direct CP violation in charged kaon and rare decays

NA62 (2014-…): BR($K^+ \rightarrow \pi\nu\bar{\nu}$)

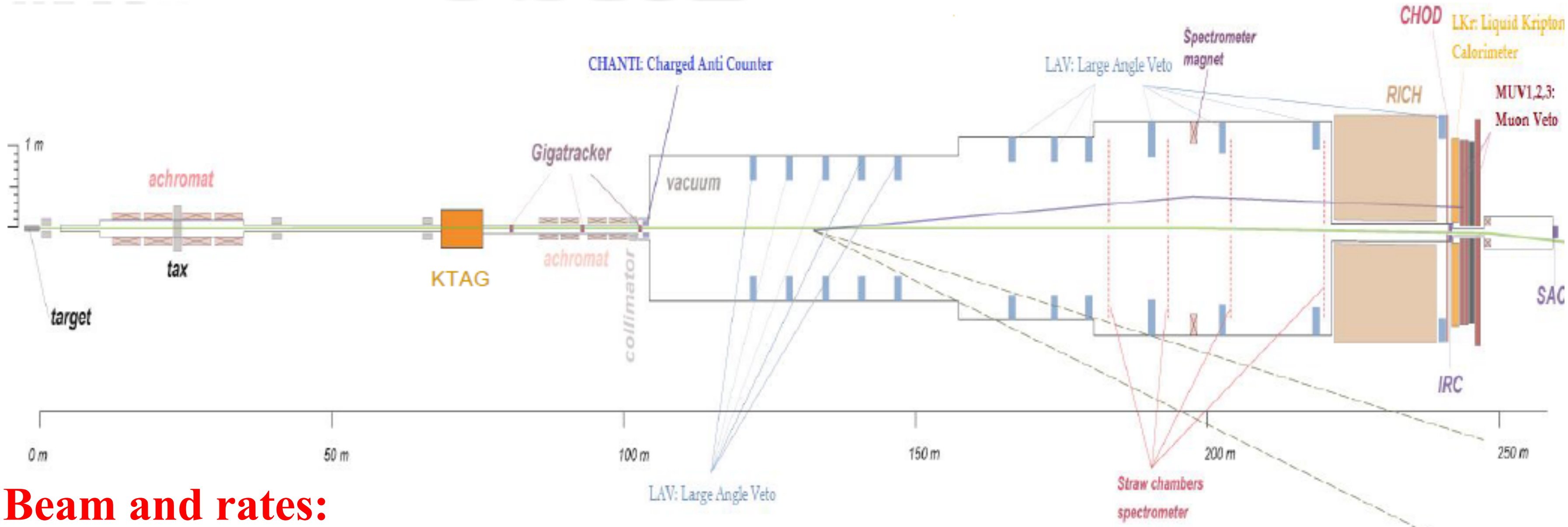
Talk by A. Buras SUSY 2014



NA48/1 (2002): Rare Ks and hyperon decays

NA62-RK (2007-2008): LFV in leptonic charged kaon decays

NA62



Beam and rates:

SPS proton beam @400 GeV/c, 1.1×10^{12} protons on beryllium target.

75 GeV/c (±1%) hadron beam (6% kaons).

~750 MHz on beam spectrometer, ~10 MHz kaon decays on main detectors downstream.

60 m decay volume.

Key factors:

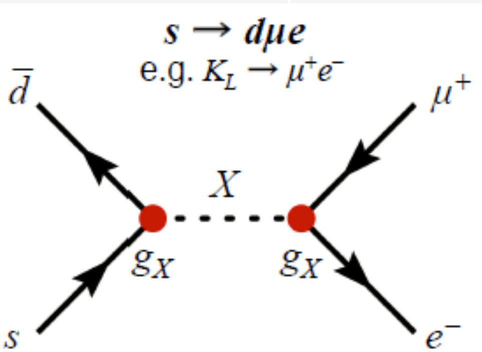
Reconstruction and identification of particles on both initial and final states (redundancy)

- **Kinematics rejection factor**:
  5×10^3 $K^+ \rightarrow \pi^+\pi^0$, 1.5×10^4 $K^+ \rightarrow$ 75 GeV/c
- **Photon veto**: 10^8 on $\pi^0 \rightarrow \gamma\gamma$ (LAV, LKR, SAC, IRC).
- **Muon ID**: 10^7 (RICH, MUV).

Goal: 10% acceptance on signal
O(100) events of $K^+ \rightarrow \pi\nu\bar{\nu}$ in 2 years

LFNV in kaon decays

Process	Violates	90% C.L. limit	Experiment	Year
$K^+ \to \pi^+ \mu^+ e^-$	LF	$< 1.3 \times 10^{-11}$	E865	2005
$K^+ \to \pi^+ \mu^- e^+$	LF	$< 5.2 \times 10^{-10}$		2000
$K^+ \to \pi^- \mu^+ e^+$	LF , LN	$< 5.0 \times 10^{-10}$		2000
$K^+ \to \pi^- e^+ e^+$	LN	$< 6.4 \times 10^{-10}$		2000
$K^+ \to \pi^- \mu^+ \mu^+$	LN	$< 1.1 \times 10^{-9}$	NA48/2	2011
$K^+ \to \mu^- \nu e^+ e^+$	LN	$< 2.0 \times 10^{-8}$	Geneva-Saclay	1976
$\pi^0 \to \mu^- e^+$	LF	$< 3.4 \times 10^{-9}$	KTEV	2000
$\pi^0 \to \mu^+ e^-$	LF	$< 3.8 \times 10^{-10}$		2000
$\pi^+ \to \mu^- e^+ e^+ \nu$	LF	$<1.6 \times 10^{-6}$	JINR-SPEC	1991



Example:
(dimensional argument)

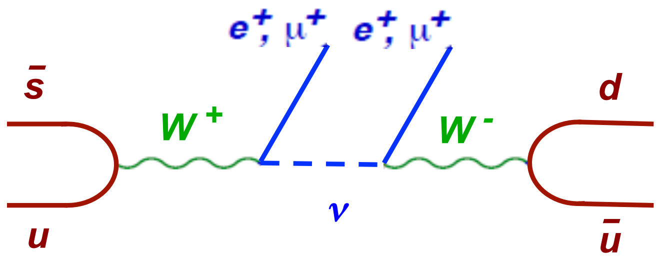
$$\frac{\Gamma_{LFV}}{\Gamma_{LFC}} \sim O\left(\frac{g^2{}_X}{g^2{}_W} \cdot \frac{M^2{}_W}{M^2{}_X}\right)$$

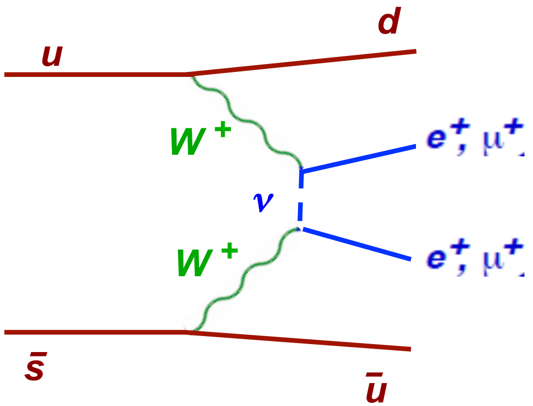
- NA62 will collect: $\sim 10^{13}$ K decays and $\sim$ **2.5×10^{12}** π^0 decays in two years of data taking
- Single event sensitivity: $\sim 10^{-12}$ for K^+, $\sim 10^{-11}$ for π^0

$K^+ \to \pi^- \mu^+ \mu^+$

- LFV possible at tree level;
- $|\Delta L|=2$ transition mediated by Majorana neutrino;
- Unique opportunity to study neutrino-less double beta decay in second generation;
- For some LFV SM extension the foreseen rate is close to the present experimental limit

[Phys. Lett. B 491 (2000) 285]





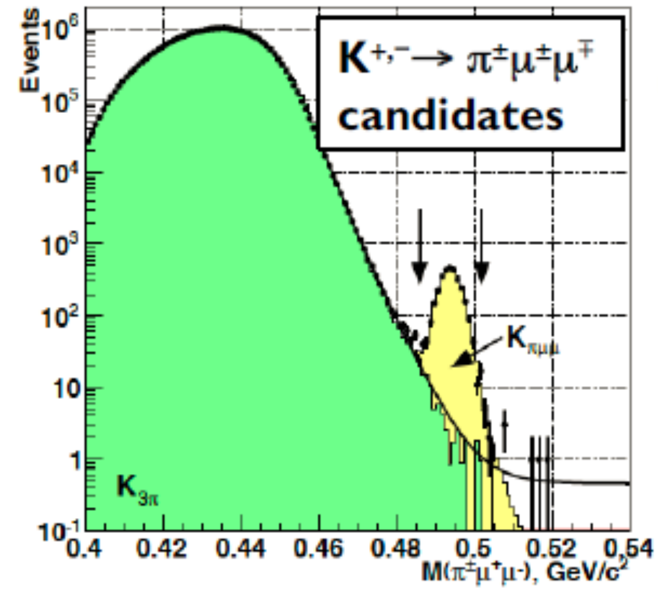
Upper limit before NA48/2 (E867):

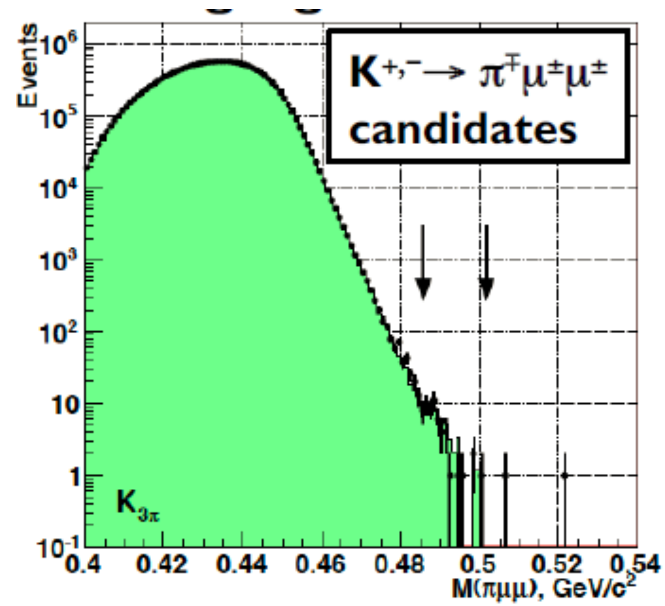
$Br(K^+ \to \pi^- \mu^+ \mu^+) < 3.0 \times 10^{-9}$ (90%C.L.)

[Phys. Rev. Lett. 85 (2000) 2877]

$K^+ \rightarrow \pi^- \mu^+ \mu^+$ in NA48/2

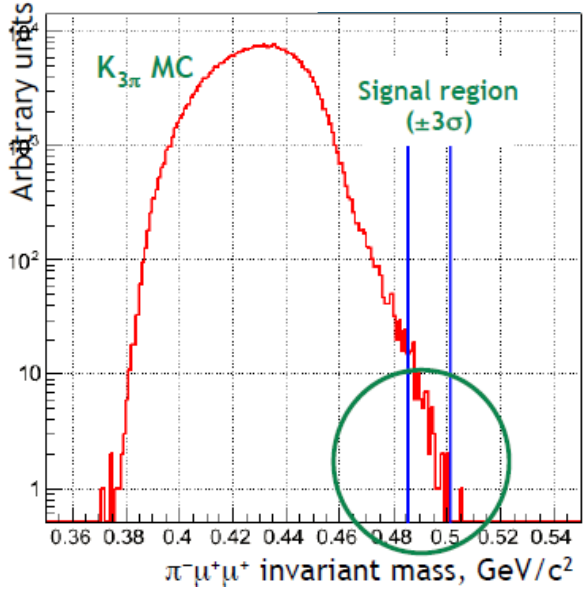
- Three tracks trigger based on charged hodoscope;
- Signal ($K^+ \rightarrow \pi^- \mu^+ \mu^+$) and normalization ($K^+ \rightarrow \pi^+ \pi^+ \pi^-$) selected concurrently with similar cuts to equalize the acceptance;
- Kinematical cuts studied on right sign ($K^+ \rightarrow \pi^+ \mu^+ \mu^-$) analysis
- 52 candidates in signal region with respect to an expected background of 52.6±19.8

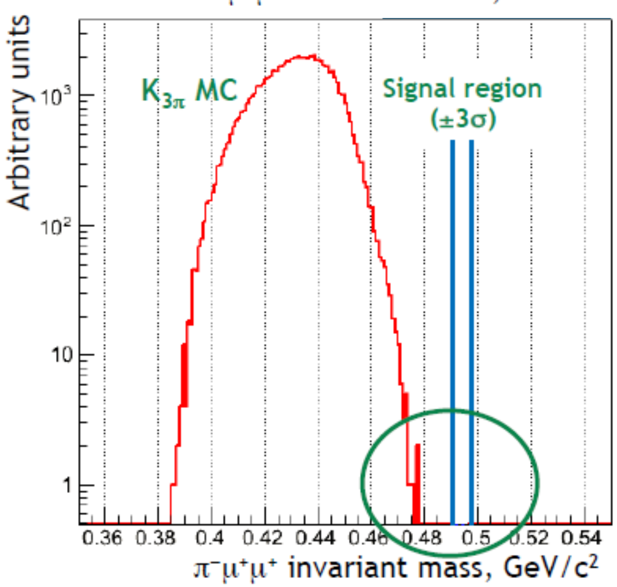




BR ($K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$) < 1.1×10^{-9} @ 90% CL
[Phys. Lett. B 697(2011)107]

$K^+ \to \pi^- \mu^+ \mu^+$ in NA62



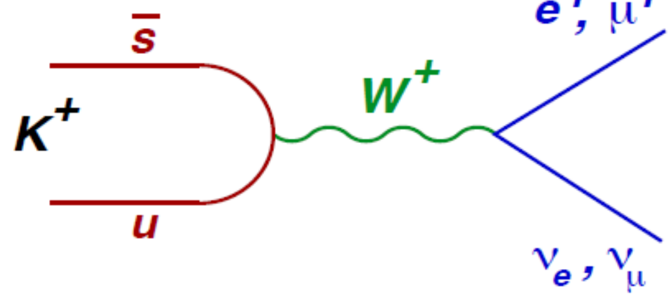


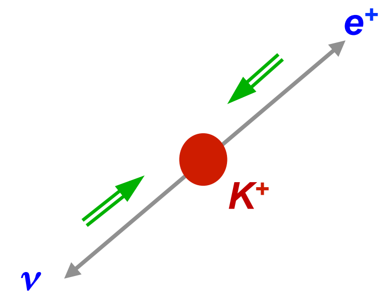
- In NA48/2 the main background was due to $\pi \to \mu\nu$ decay in flight in the spectrometer;
- The mass resolution on $\pi\mu\mu$ was 2.6 MeV/c^2;
- In NA62 negligible background is expected in the signal region, defined by a smaller invariant mass resolution (1.1 MeV/c^2);
- A factor of x100 or x1000 improvement could be achieved in NA62.

R_K in the SM

The ratio of kaon leptonic modes is extremely well predicted in the SM

- Helicity suppression;
- Hadronic uncertainties cancel in R_K ratio;
- Radiative correction are included in the RK definition and well computed in SM;





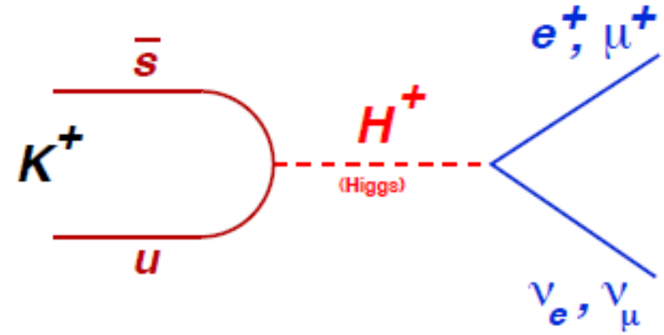
$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_K^{rad.corr.})$$

$R_K = (2.477 \pm 0.001)\text{x}10^{-5}$ *[V.Cirigliano, I.Rosell, Phys. Rev. Lett. 99 (2007) 231801]*

A precise measurement of R_K is a stringent test of the SM!

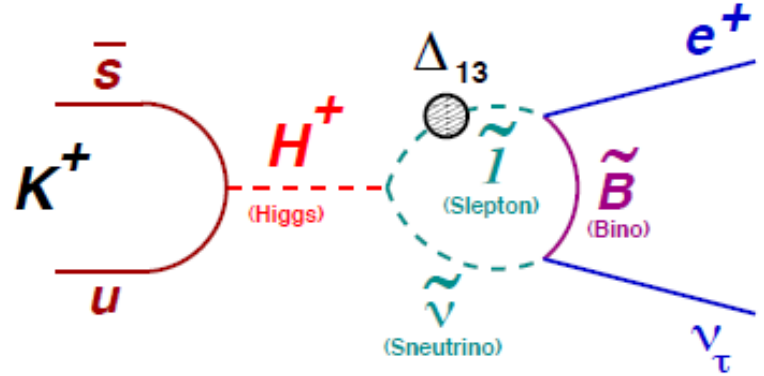
R_K beyond the SM

In several SM extensions the presence of LFV terms enhance the decay rate with sizeable effect:



$$R_K^{LFV} = \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma_{LFV}(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$

In model with 2 Higgs doublets (e.g. 2HDM-II MSSM) and LFV sources, for large tanβ contribution at the level of % is expected (one loop level):



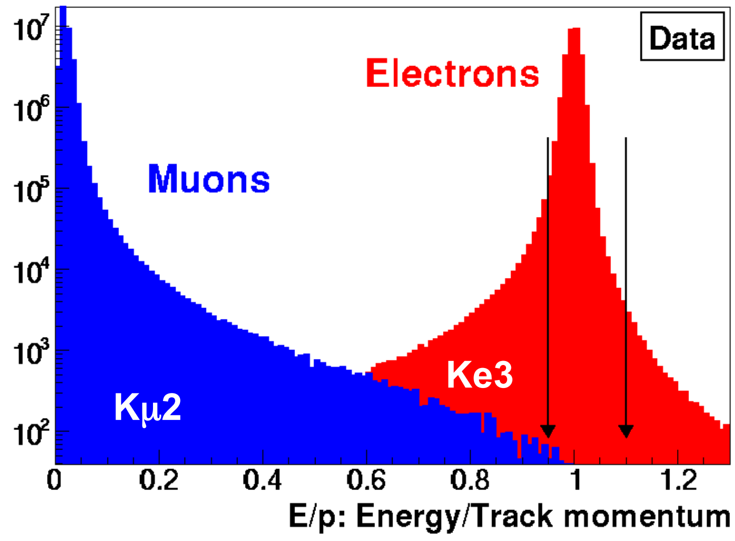
$$R_K^{LFV} \approx R_K^{SM}\left[1 + \left(\frac{m_K^{\ 4}}{m_{H^\pm}^{\ 4}}\right)\left(\frac{m_\tau^{\ 2}}{m_e^{\ 2}}\right)|\Delta_{13}|^2 tan^6\beta\right]$$

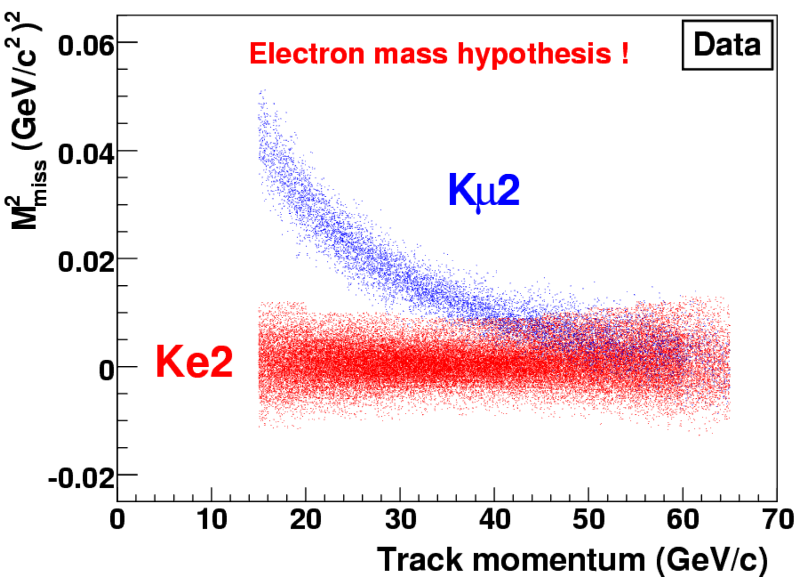
[Masiero et al., PRD 74 (2006) 011701]
[Masiero et al., JHEP 0811 (2008) 042]
[Girrbach, Nierste, arXiv:1202.4906]

K_{e2} and $k_{\mu 2}$ selection

- $K \rightarrow \mu\nu$ (**$K_{\mu 2}$**) and $K \rightarrow e\nu$ (**K_{e2}**) are collected simultaneously:
  - **1 track** in the spectrometer and in the acceptance of the electromagnetic calorimeter and muon counter;
  - **Decay vertex** well reconstructed in the decay region;
  - Forward **photon veto** using the electromagnetic calorimeter;
  - Track momentum: **13<p<65 GeV/c.**
- **$K_{\mu 2}$** and **K_{e2}** are separated by:
  - Different E/p:
    - ✓ electron if **(0.9 to 0.95)<E/p<1.1**,
    - ✓ muon if **E/p<0.85;**
  - Missing mass:

    $$M^2_{miss}=(P_K-P_i)^2 \text{ with } i=e \text{ or } \mu$$
- The analysis is done in **10 momentum bins**:
  - The selection criteria are tuned in each bin





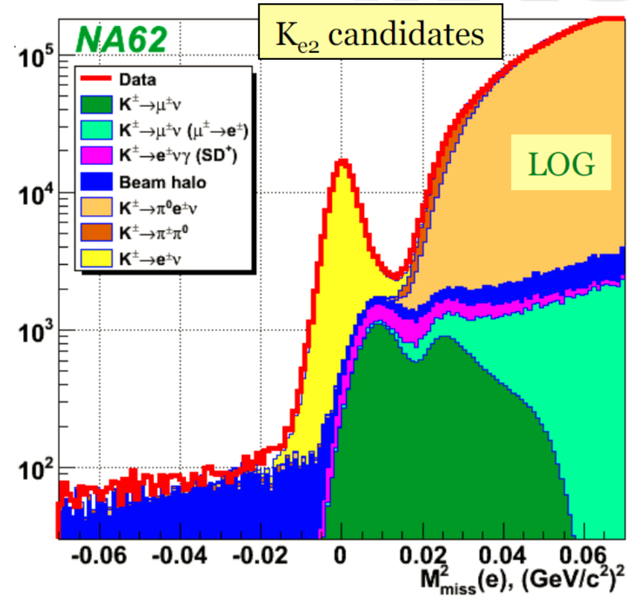
Data set

K_{e2}:

145958 events selected (more than a factor 10 with respect to the best previous measurement)

<u>Background sources (in %):</u>

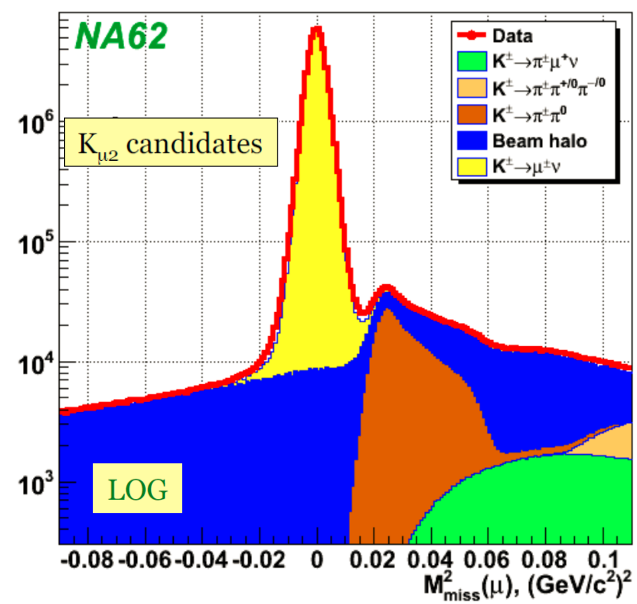
$K_{\mu 2}$	5.64±0.20
$K_{\mu 2}$ (μ decay)	0.26±0.03
$K_{e2\gamma}$ (SD+)	2.60±0.11
Beam halo	2.11±0.09
K_{e3}	0.18±0.09
$K_{2\pi}$	0.12±0.06
Wrong sign K	0.04±0.02
Total	**10.95±0.27**



$K_{\mu 2}$:

42.817 M events (with pre-scaled trigger)

Main background: beam halo muons (0.50±0.01)%

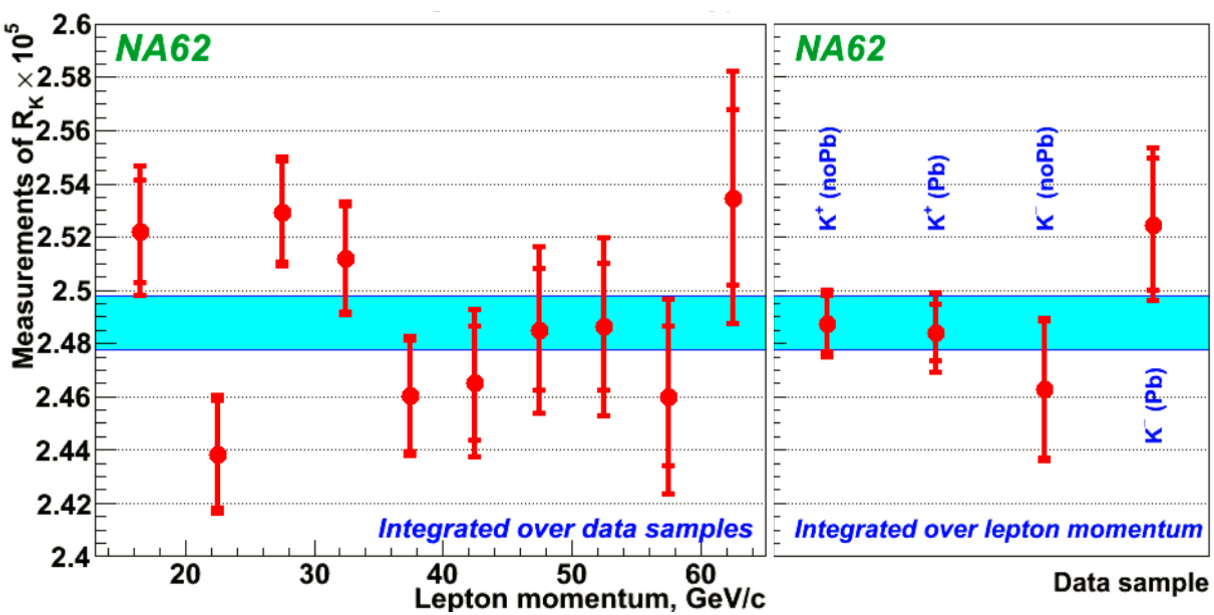


Final result

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

[Phys. Lett. B 719 (2013) 326]

- Analysis in 10 momentum bin and 4 data sub-samples ;
- Fit over 40 measurements: χ^2 = **47/39 ;**
- **0.4%** precision reached;
- Theoretical error still **one order of magnitude better.**



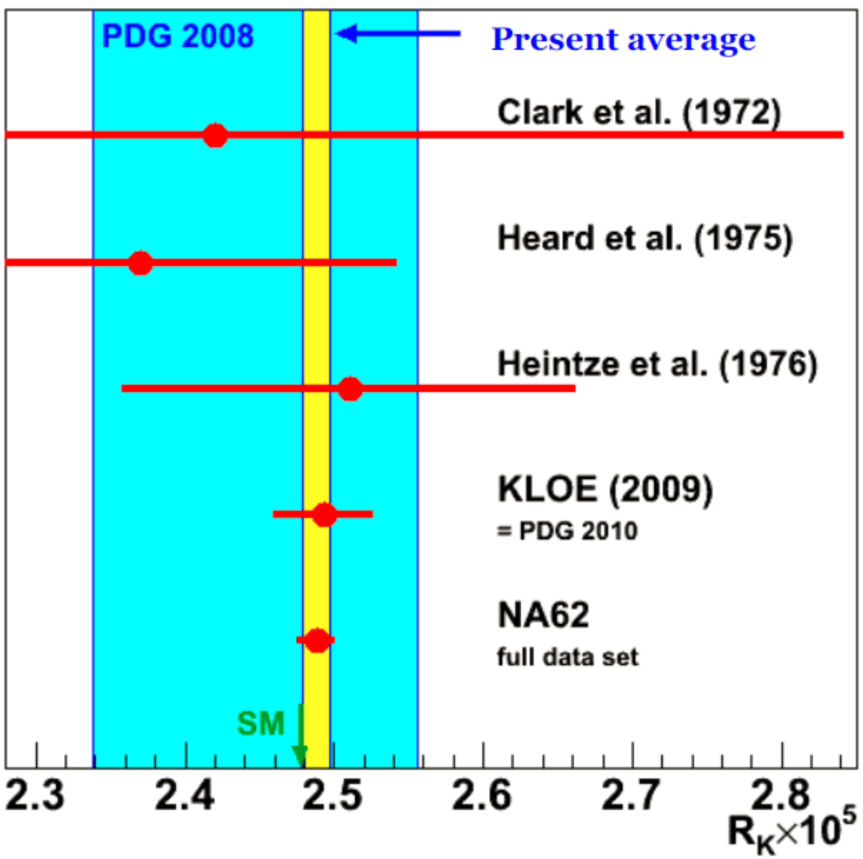
Source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$	0.004
$BR(K_{e2\gamma}SD+)$	0.002
Beam halo	0.002
K_{e3}, $K_{\pi 2}$	0.003
Material	0.002
Acceptance	0.002
DHC alignment	0.001
Electron ID	0.001
LKr read. ineff.	0.001
Trigger	0.001
Total	**0.010**

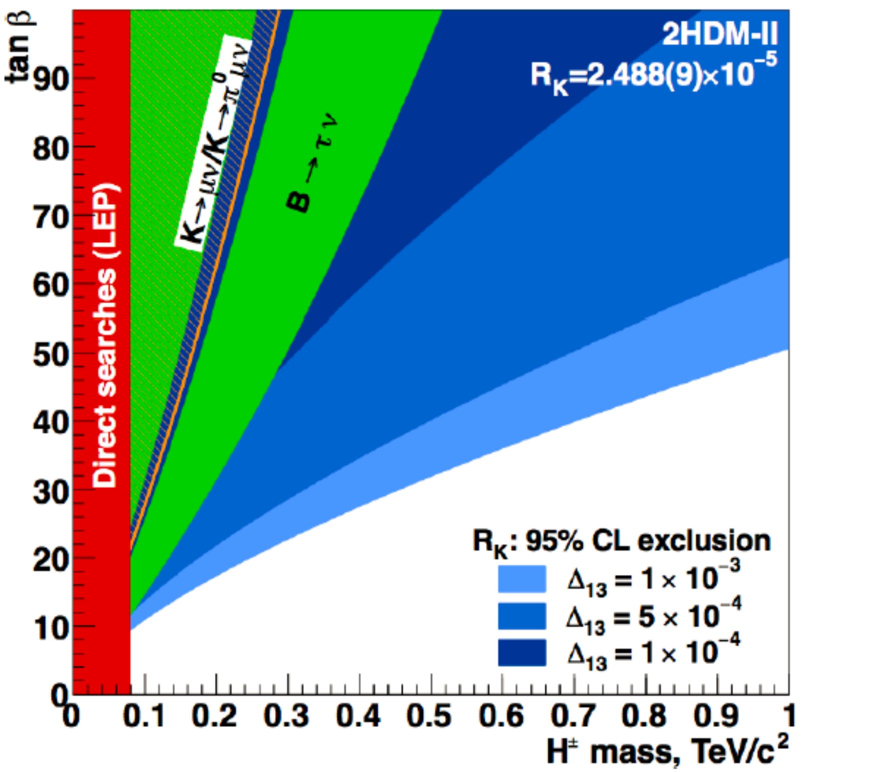
Word average

$R_K = (2.488 \pm 0.009) x 10^{-5}$

[our own average]

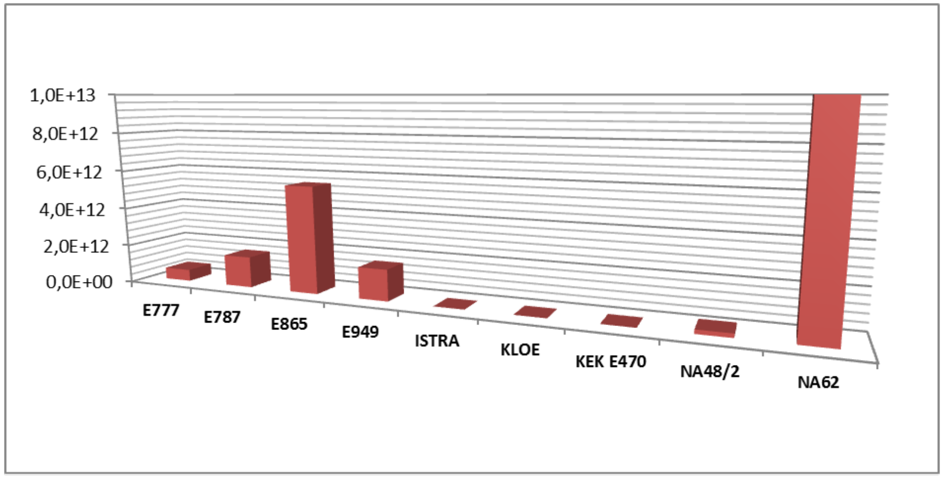
Precision of **0.4%**. In agreement with SM expectation within 1.2 σ





NA62: Statistical error at the 1‰ level achievable

Exotic and forbidden decays



- NA62 will collect an unprecedented amount of K^+ decays giving the possibility to re-measure rare decays properties and look for forbidden and exotic decays
- The NA62 trigger system is flexible and fully reconfigurable (based on FPGA)

	B865	E787	E949	NA62
Energy p	25.5 GeV	25.5 GeV	25.5 GeV	400 GeV
Protons ϕ	10^{13} in 2.8s/5.1s	~10^{13} /1.6s	~10^{13} /2.2 s	~10^{12} in 4.6s/16.8s
Energy K	6 GeV	700 MeV (stopped)	710 MeV (stopped)	75 GeV
Beam	71 MHz K, 1.4 GHz π, 0.7 GHz p	(2.5-4) MHz K with π/K = 0.25	6 MHz K with K/π~3	45 MHz K, 525 MHz π, 173 MHz protons
Decay region	5 m (6% kaon decay)	Stopped (20% kaon decay)	Stopped (20% kaon decay)	60 m (10% kaon decay)

NA62 decay list

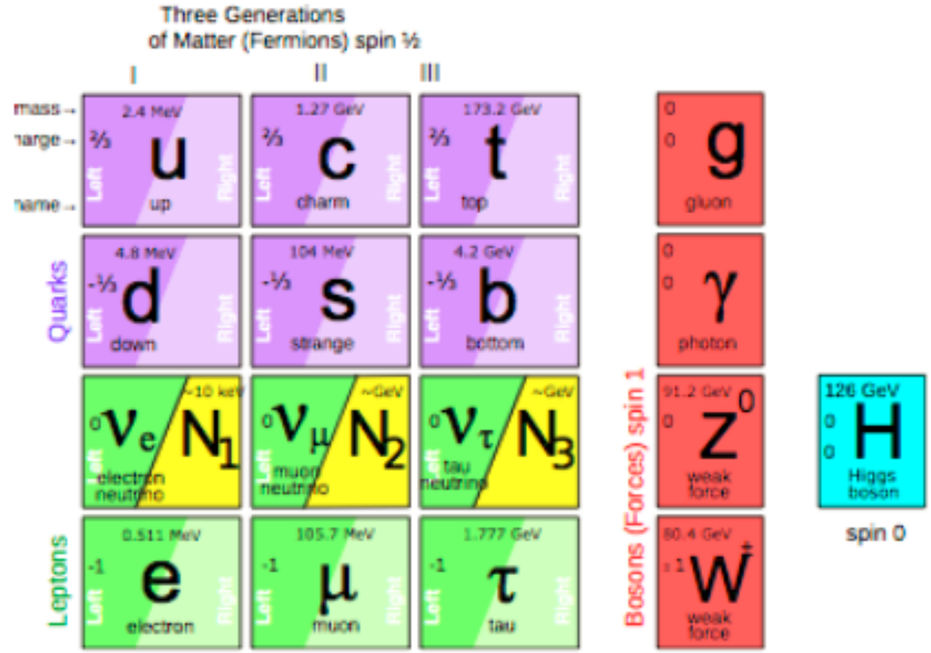
List (not complete) of forbidden and exotic decays:

Process	motivation	90% C.L. limit	Experiment	Year
$K^+ \to \pi^+ X^0$	New particle	$< 5.9 \times 10^{-11}$ $m_{X0}=0$	E787, E949	2002
$K^+ \to \pi^+ \chi\chi$	New particles	(several)	Example: E949	2008
$\pi^0 \to ee(\gamma)$	Dark force	(several)	(several)	--
$\pi^0 \to eeee$	T viol. in SI and EI	C=-0.77+-0.53	Samios et. al.	1962
$\pi^0 \to \gamma\gamma\gamma$	C violation	$< 3.1 \times 10^{-8}$	Crystal Box	1988
$\pi^0 \to \gamma\gamma\gamma\gamma$	light scalar	$< 2 \times 10^{-8}$	Crystal Box	1988
$\pi^0 \to \nu\bar{\nu}$	RH neutrino	$<2.7\times10^{-7}$	E949	2005
sgoldstino	New particle	$< 9 \times 10^{-6}$	Hyper-CP, ISTRA+	
$K^+ \to \pi^+\pi^+ e^- \nu$	$\Delta S != \Delta Q$	$< 1.2 \times 10^{-8}$	Geneva-Saclay	1976
$K^+ \to \pi^+\pi^+ \mu^- \nu$	$\Delta S != \Delta Q$	$< 3.0 \times 10^{-6}$	Birge et al.	1965
$K^+ \to \pi^+ \gamma$	Angular momentum	$< 2.3 \times 10^{-9}$	E949	2005

Sterile neutrinos

Adding three right handed sterile Majorana neutrinos to SM it is possible to explain some of the open questions in particle physics:

- Matter-antimatter asymmetry (leptogenesis induces baryogenesis)
- Neutrino mixing
- Dark matter

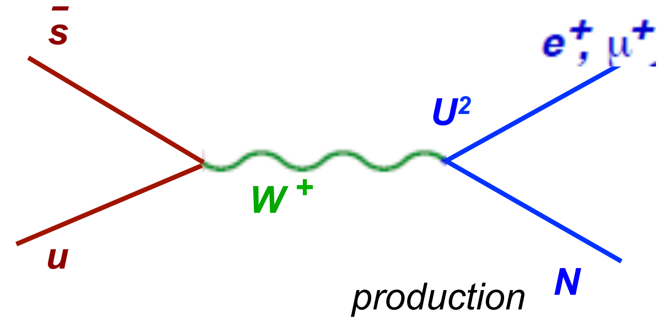


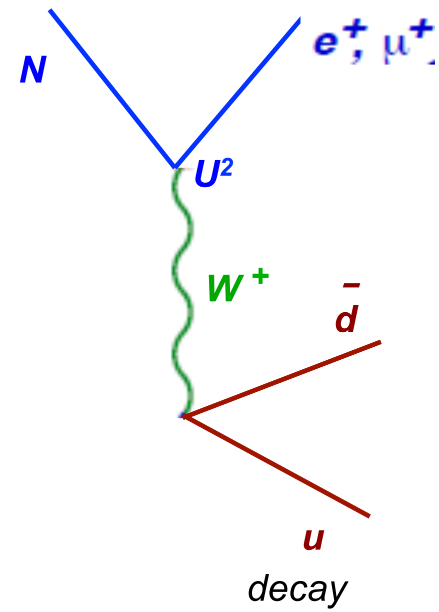
In the **Asaka-Shaposhnikov** model νMSM *[Phys. Lett. B 620 (2005) 17]*

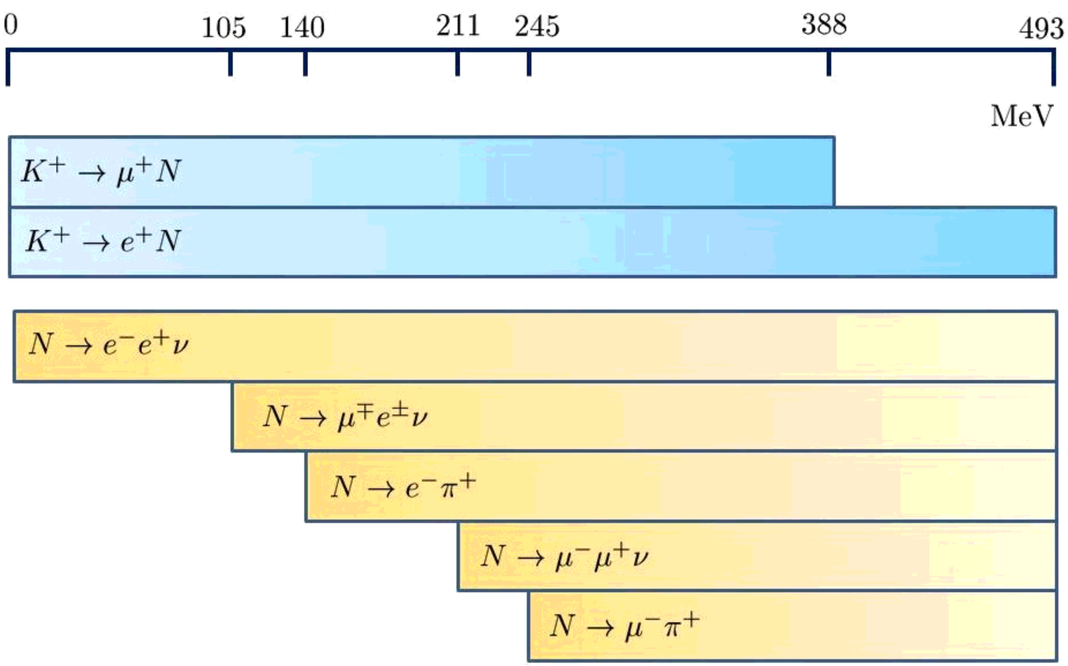
- N_1 is the lighter **O(keV)** → dark matter candidate
- N_2, N_3 are nearly degenerate **(100 MeV to few GeV)** to tune CPV-phases as extra-CKM sources of baryon asymmetry. $N_{2,3}$ produce standard neutrino masses through seesaw with a Yukawa coupling of the order of 10^{-8}

Sterile neutrinos in K

- The meson factories are an ideal place to produce and study heavy neutrinos ($N_{2,3}$);
- In principle several LFV decay modes accessible;
- The neutrinos mass accessible in kaon decays is limited by M_K

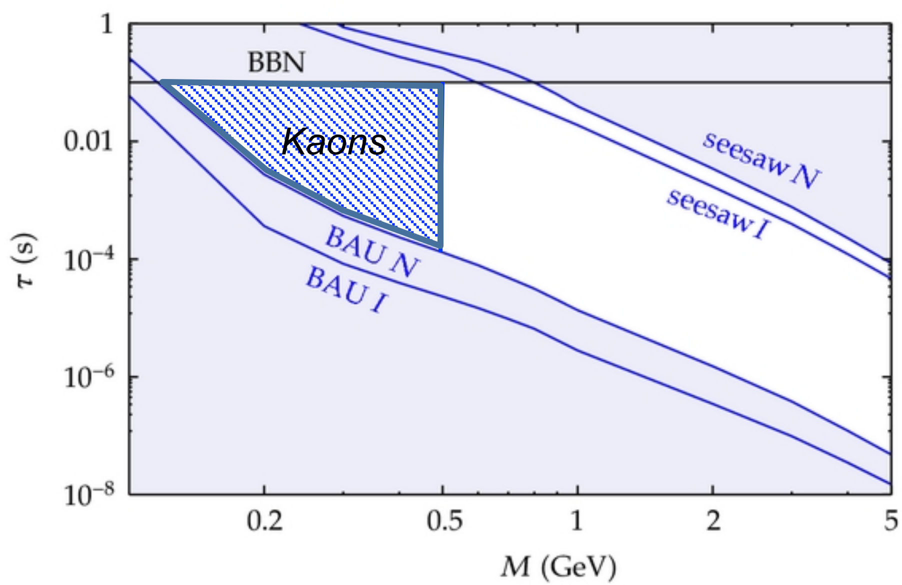


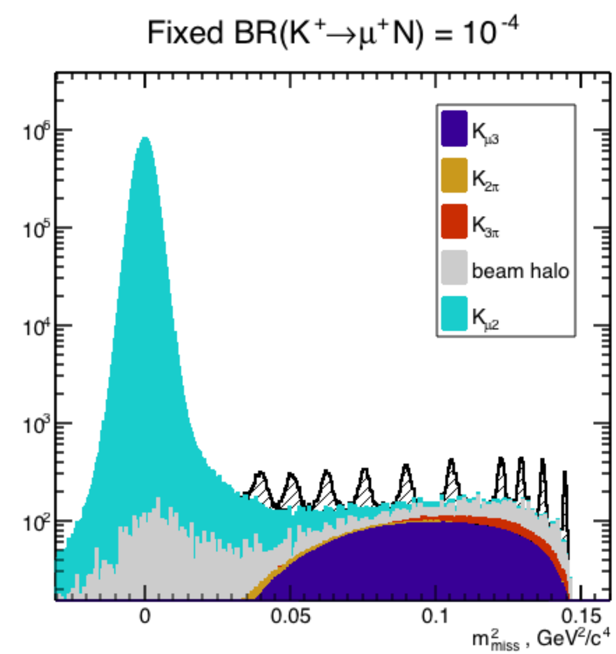




Sterile neutrino analysis

- The ongoing analysis in NA62-R_K is done assuming long lived heavy neutrinos → Missing mass analysis
- In NA62 higher statistics, better resolution on the invariant mass, better photon veto to control $K_{\mu3}$ and $K_{2\pi}$ backgrounds, will increase significantly the sensitivity;
- The kaons will help to cover the full parameters space in the regions allowed by general constraints.



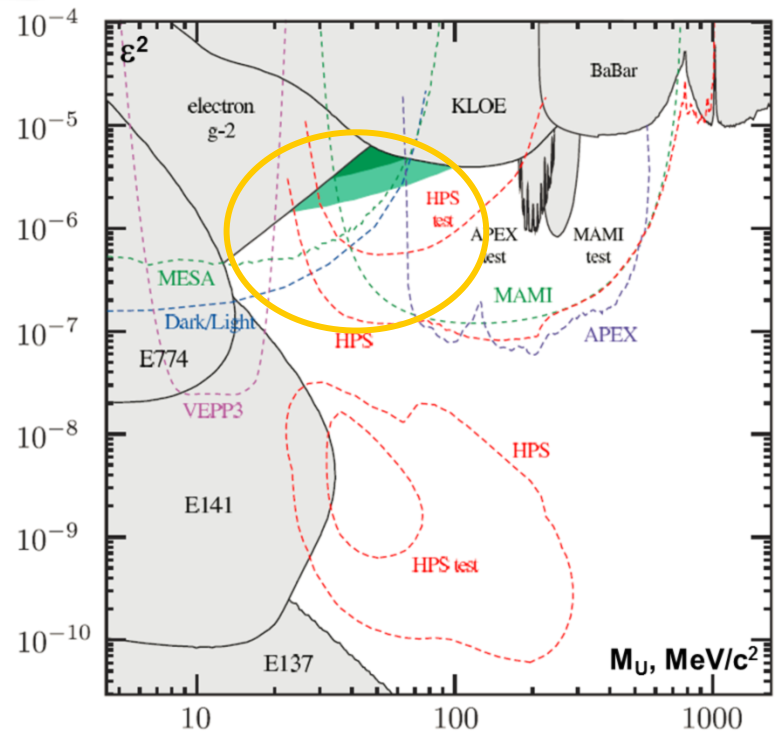


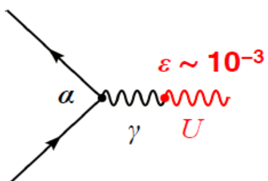
Dark photons

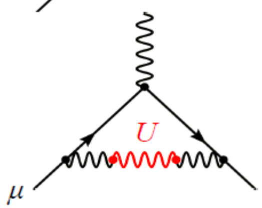
The search for the U boson (aka dark photon) is becoming interesting as possible explanation of several ***SM anomalies***:

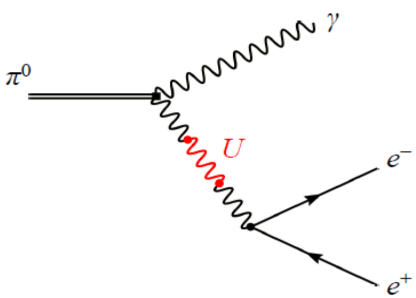
- PAMELA e^+ excess
- Dama/Libra dark matter signals

  [R. Bernabei et al., Eur. Phys. J. C56, 333 (2008)]
- 3.6σ anomalies in $(g-2)_\mu$









- Search in $\pi^0 \to U\gamma$ decays (with $U \to e^+e^-$)
  - NA62 will collect 10^8 $\pi^0 \to e^+e^-\gamma$ decays/year
  - M_{ee} resolution of 1 MeV
  - Sensitive to $\mathbf{M_U < 100}$ **MeV** with $\boldsymbol{\varepsilon^2 \sim 10^{-6}}$
- Analysis on the NA48/2 data ongoing
- NA62 will improve the NA48/2 upper limit.

Conclusions

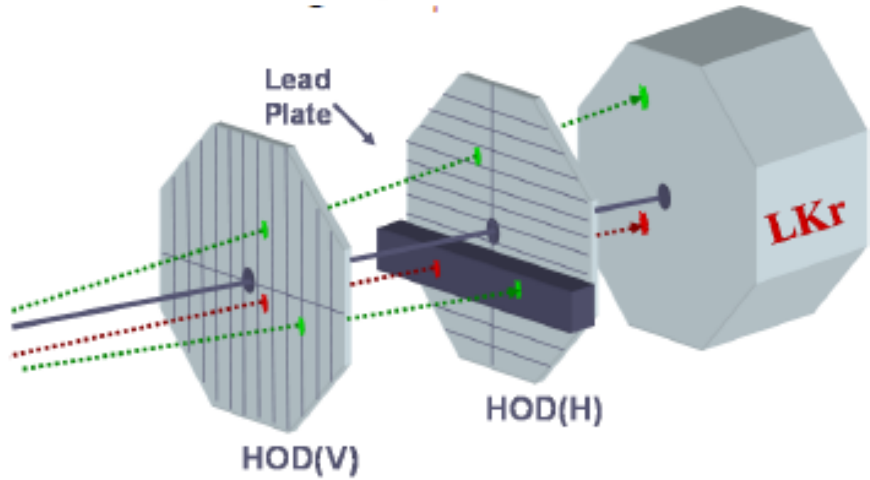
- The Kaons have written several chapters in particle physics:
  - ✓ Strangeness
  - ✓ Parity violation
  - ✓ Oscillation and regeneration
  - ✓ CP violation (indirect and direct!)
  - ✓ GIM mechanism
- The Kaons have still arrows in their quiver:
  - ✓ The $K \rightarrow \pi \nu \bar{\nu}$ is an unique laboratory to test new physics scenarios;
  - ✓ Other LFV, forbidden and exotics decays may shed new light on some obscure point of the SM;
  - ✓ NA62 will profit from high intensity hadron beam, flexible trigger configuration and ~10% acceptance on several decays; data taking will start next autumn

"It is important to cast as wide an experimental net as possible"
(M. Pospelov @ this conference)

We are part of this net and data taking will start in October 2014 !

SPARES

Main background to K_{e2}



The main background is given by $K_{\mu 2}$ in the K_{e2} sample

- ✓ μ catastrophic energy loss in LKr: $\mathbf{P_{\mu e}=3\cdot 10^{-6}}$
- ✓ Direct measurement of $P_{\mu e}$ selecting a pure μ sample
- ✓ Lead plate in front of LKr ($9.2X_0$, 20% of total area)
- ✓ Uncertainty on the evaluated $K_{\mu 2}$ background 3 times smaller with respect to MC only