Lepton flavour and number violation with K decays at CERN

Evgueni Goudzovski

(Université Catholique de Louvain)

email: goudzovs@mail.cern.ch

Outline:

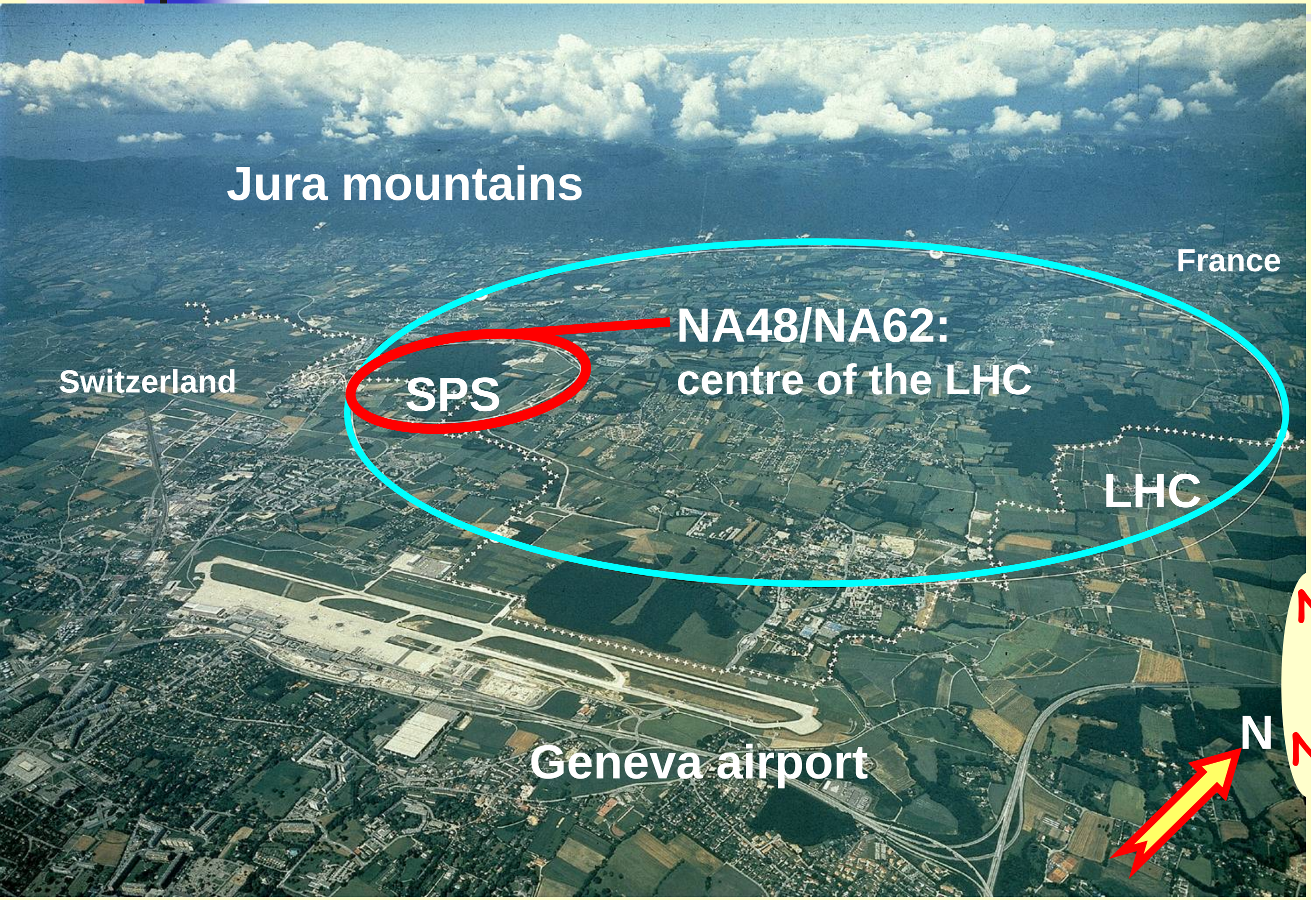
1) The NA48/NA62 experiments at CERN;
2) Lepton flavour universality test with $K^+ \to e^+\nu / K^+ \to \mu^+\nu$ decays;
3) Search for the lepton number violating $K^+ \to \pi^-\mu^+\mu^+$ decay;
4) Conclusions.

46th Rencontres de Moriond (EW session)

La Thuile, Italy • 16 March 2011

NA48/NA62 experiments at CERN

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

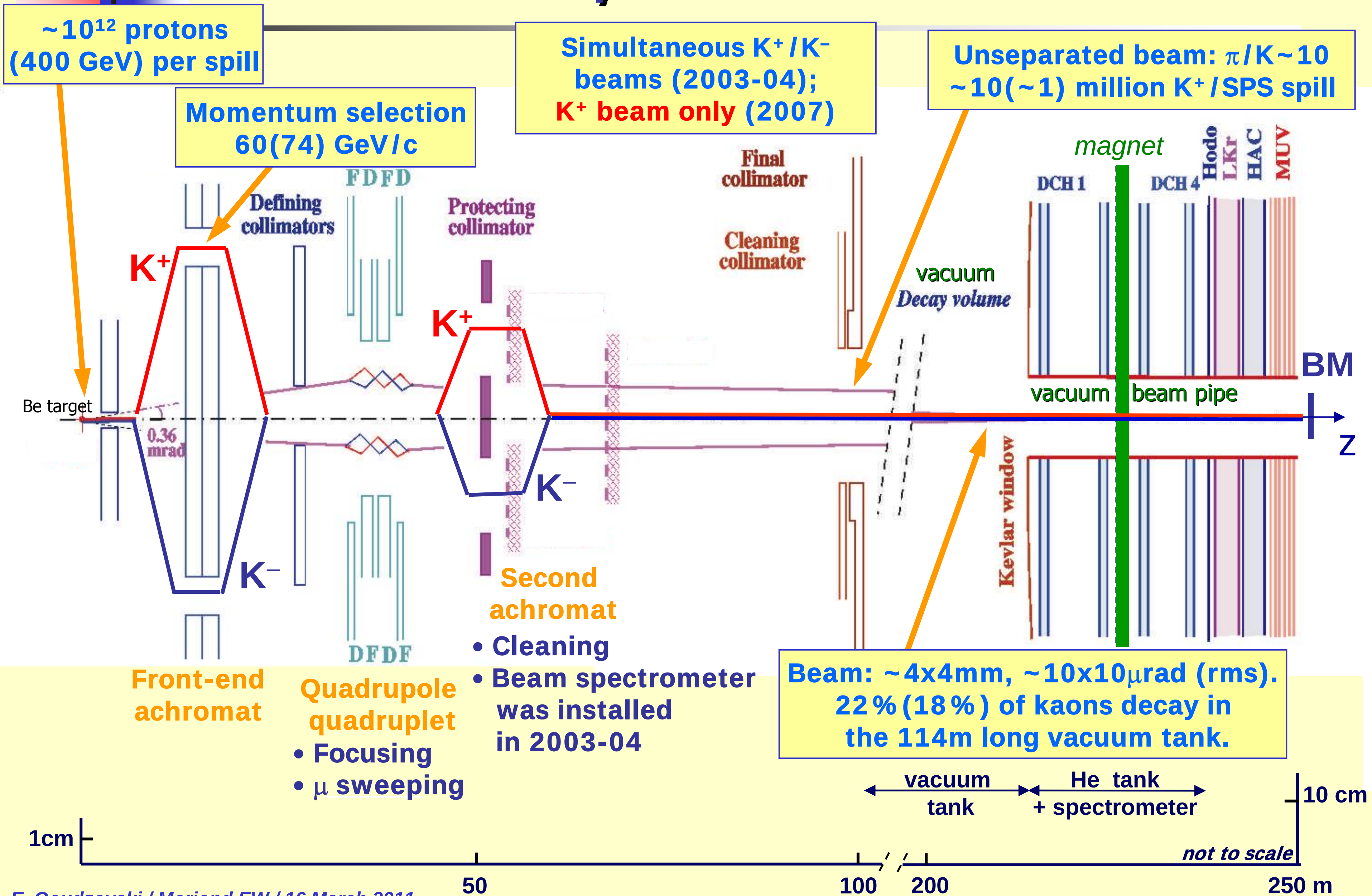
NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 (phase I)
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

NA62 (phase II)
- 2007–2012: design & construction
- 2013(?)–2016: $K^+ \to \pi^+ \nu\bar{\nu}$ data taking

<u>NA62:</u> 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

NA48/NA62 K⁺ beam line



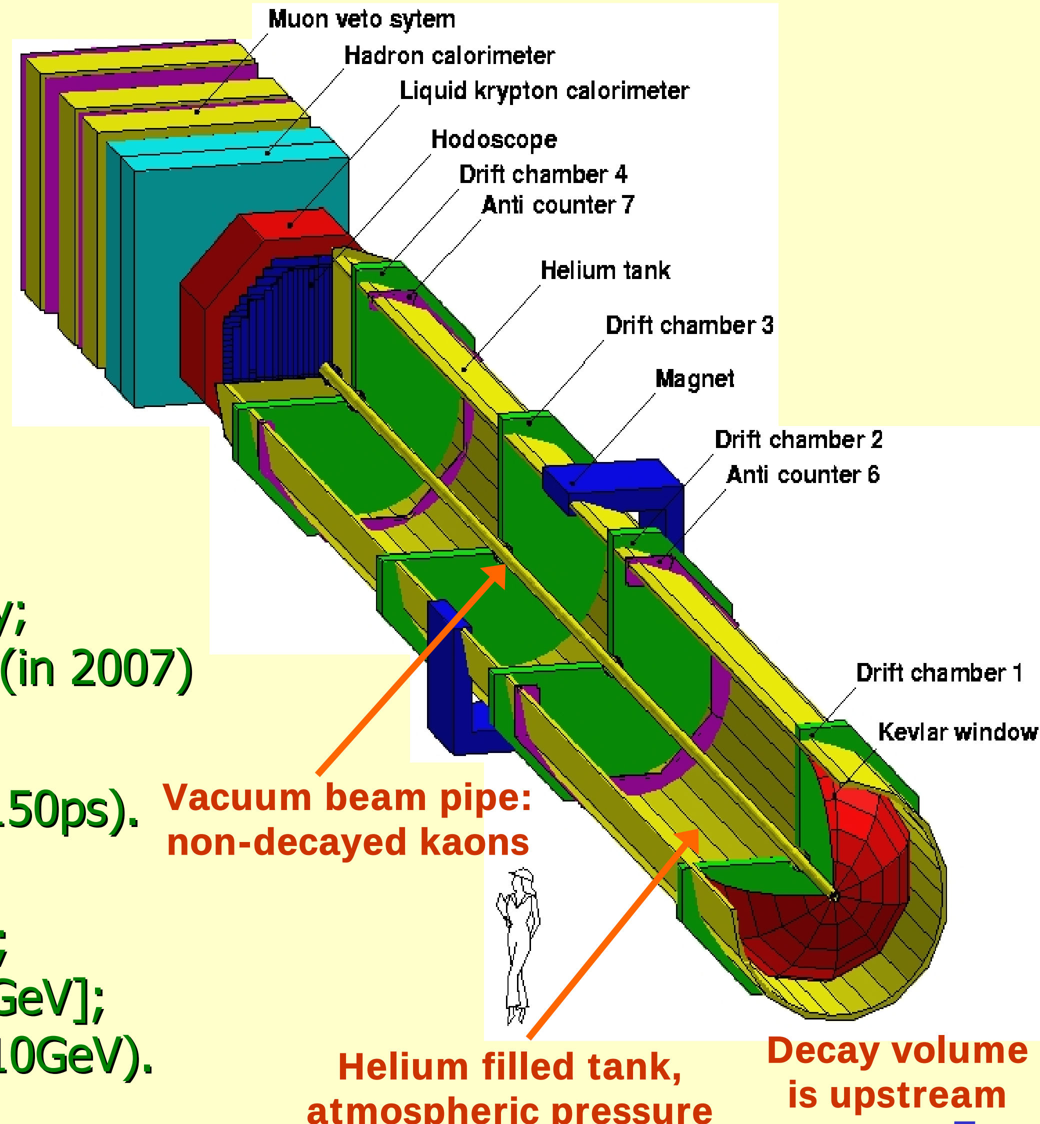
The detector

Data taking

- NA48/2:
  ~six months in 2003-04.
- NA62 (phase I):
  ~four months in 2007.

Principal subdetectors for R_K:

- Magnetic spectrometer (4 DCHs):
  4 views/DCH: redundancy ⇒ efficiency;
  $\Delta p/p = 0.47\% + 0.020\%{*}p$ [GeV/c] (in 2007)
- Hodoscope
  fast trigger, precise t measurement (150ps).
- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  $\sigma_E/E = 3.2\%/E^{1/2} + 9\%/E + 0.42\%$ [GeV];
  $\sigma_x=\sigma_y=0.42/E^{1/2} + 0.6$mm (1.5mm@10GeV).

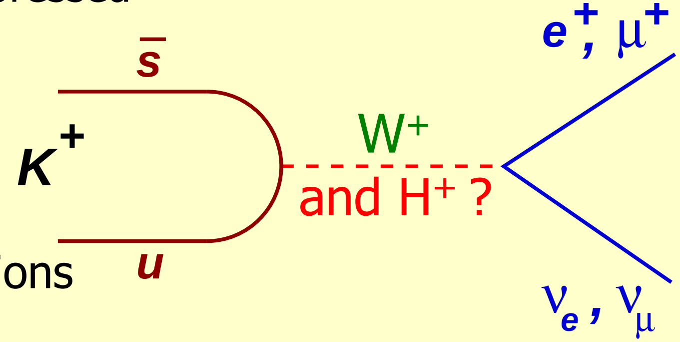


Lepton flavour universality in $K^+ \to l^+ \nu$ decays

Leptonic meson decays: $P^+ \to l^+\nu$

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 tree level charged Higgs ($H^\pm$) exchange contributions

PRD48 (1993) 2342; Prog.Theor.Phys. 111 (2004) 295

(numerical examples for M_H=500GeV/c^2, $\tan\beta = 40$)

$\pi^+\to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_\pi/m_H)^2\, m_d/(m_u+m_d)\, \tan^2\beta \approx -2\times10^{-4}$

$K^+\to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_K/m_H)^2 \tan^2\beta \approx -0.3\%$

$D^+_s\to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_D/m_H)^2 (m_s/m_c) \tan^2\beta \approx -0.4\%$

$B^+\to l\nu$: $\Delta\Gamma/\Gamma_{SM} \approx -2(m_B/m_H)^2 \tan^2\beta \approx -30\%$

$H^\pm$ exchange in $B^+\to\tau^+\nu$ (R. Barlow, CKM 2010, arXiv:1102.1267)

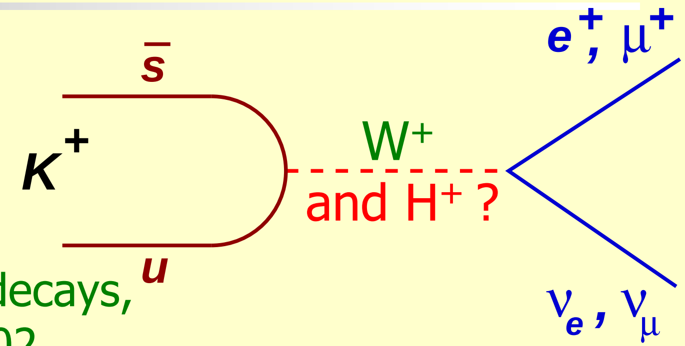
BaBar+Belle: $Br_{exp}(B\to\tau\nu) = (1.64\pm0.34)\times10^{-4}$
(HFAG)

Standard Model: $Br_{SM}(B\to\tau\nu) = (1.20\pm0.25)\times10^{-4}$
(f_B from HPQCD, $|V_{ub}|$ from HFAG)

~3σ discrepancy between $B_{\tau\nu}$ measurement and expectation from a global CKM fit
[UTfit, CKMfitter, ICHEP2010]

$K_{\mu 2}$: sensitivity to new physics

Comparison of $|V_{us}|$ determined from helicity-suppressed $K_{\mu 2}$ decays vs helicity-allowed K_{l3} decays



To reduce uncertainties of hadronic and EM corrections to $K_{\mu 2}$:

$$R_{\mu 23} = \left(\frac{f_K/f_\pi}{f_+(0)}\right)^{-1} \left(\left|\frac{V_{us}}{V_{ud}}\right| \frac{f_K}{f_\pi}\right)_{\mu 2} \frac{|V_{ud}|_{0^+\to 0^+}}{[|V_{us}|f_+(0)]_{\ell 3}}$$

- Lattice QCD input: $\left(\frac{f_K/f_\pi}{f_+(0)}\right)^{-1}$
- Measured with $K_{\mu 2}/\pi_{\mu 2}$: $\left(\left|\frac{V_{us}}{V_{ud}}\right| \frac{f_K}{f_\pi}\right)_{\mu 2}$
- Measured with $K\to\pi\mu\nu$: $[|V_{us}|f_+(0)]_{\ell 3}$
- $|V_{ud}|_{0^+\to 0^+}$: average from nuclear β decays, PRC79 (2009) 055502

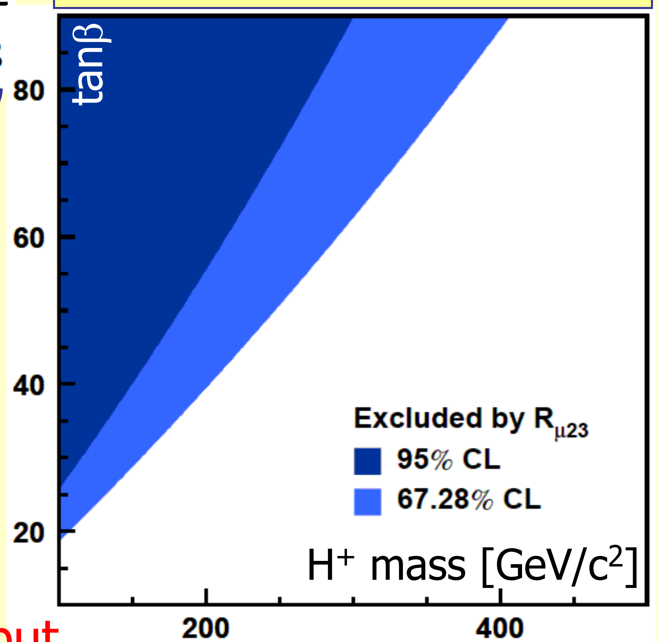
SM expectation: $R_{\mu 23} = 1$.

Charged Higgs mediated currents lead to

$$R_{\mu 23} \approx \left| 1 - \frac{m_{K^+}^2}{m_{H^+}^2} \frac{\tan^2\beta}{1+\epsilon_0 \tan\beta} \right|$$

Experiment: $R_{\mu 23} = 0.999(7)$, limited by lattice QCD input.

tanβ vs H^+ mass exclusion



[Flavianet Kaon WG, EPJC69 (2010) 399]

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

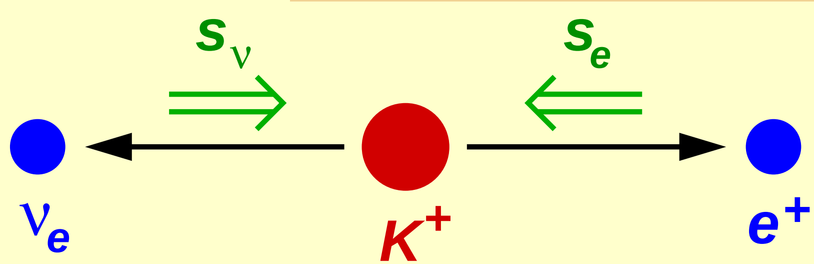
Observable sensitive to Lepton Flavour Violation:

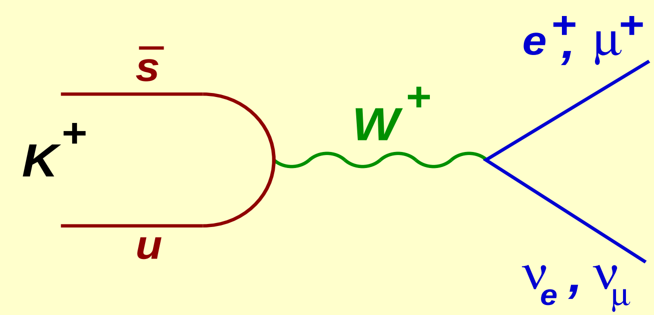
$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\mathrm{rad.corr.}})$$

(similarly, R_π in the pion sector)

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

Radiative correction (few %) due to $K^+ \to e^+ \nu \gamma$ (IB) process, by definition included into R_K





- 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 lepton universality.
- Understood recently: helicity suppression of R_K might enhance sensitivity to non-SM effects to an experimentally accessible level.

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

$R_\pi^{SM} = (12.352 \pm 0.001) \times 10^{-5}$

Phys. Lett. 99 (2007) 231801

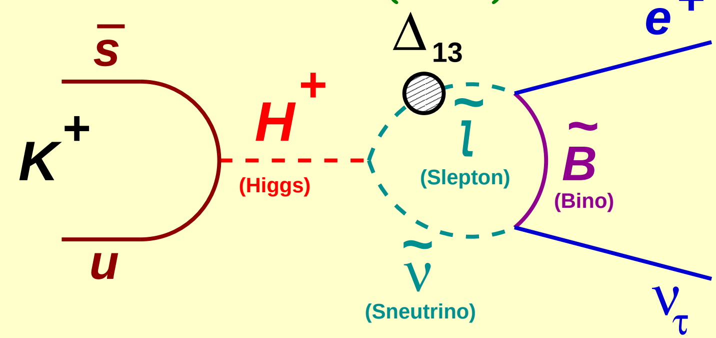
$R_K = K_{e2}/K_{\mu 2}$ beyond the SM

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

PRD 74 (2006) 011701,
JHEP 0811 (2008) 042



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

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

Up to ~1% effect in large (but not extreme) $\tan\beta$ regime with a massive $H^\pm$

Example:
($\Delta_{13}=5\times10^{-4}$, $\tan\beta=40$, $M_H=500$ GeV/c^2)
lead to $R_K^{MSSM} = R_K^{SM}(1+0.013)$.

Analogous SUSY effect in pion decay is suppressed by a factor $(M_\pi/M_K)^4 \approx 6\times10^{-3}$

Large effects in B decays due to $(M_B/M_K)^4 \sim 10^4$:

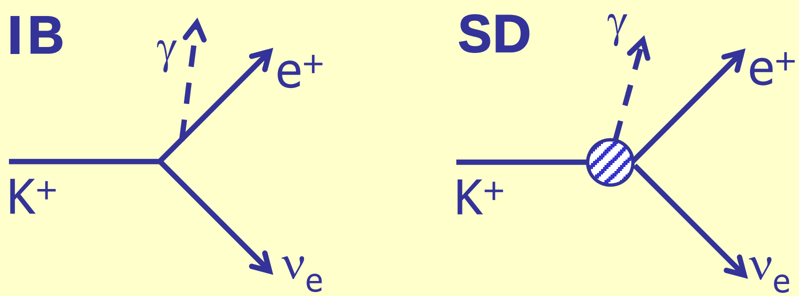
$B_{\mu\nu}/B_{\tau\nu}$ → ~50% enhancement;

$B_{e\nu}/B_{\tau\nu}$ → enhanced by ~one order of magnitude.

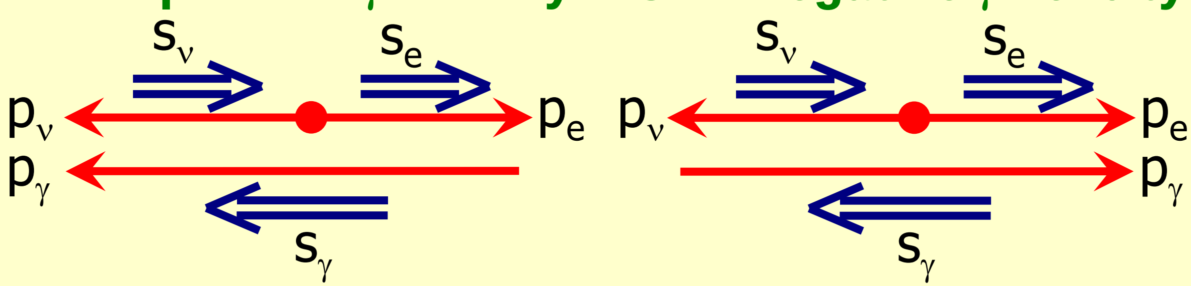
Out of reach: $Br^{SM}(B_{e\nu}) \approx 10^{-11}$

Radiative $K^+ \to e^+ \nu \gamma$ process

R_K is inclusive of IB radiation by definition. SD radiation is a background. INT is negligible.



SD+: positive γ helicity **SD−: negative γ helicity**



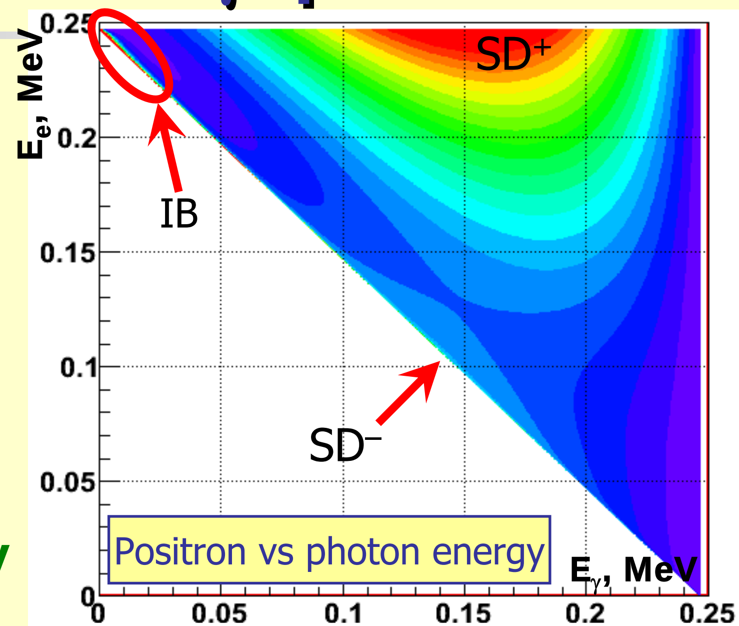
SD radiation is not helicity suppressed.

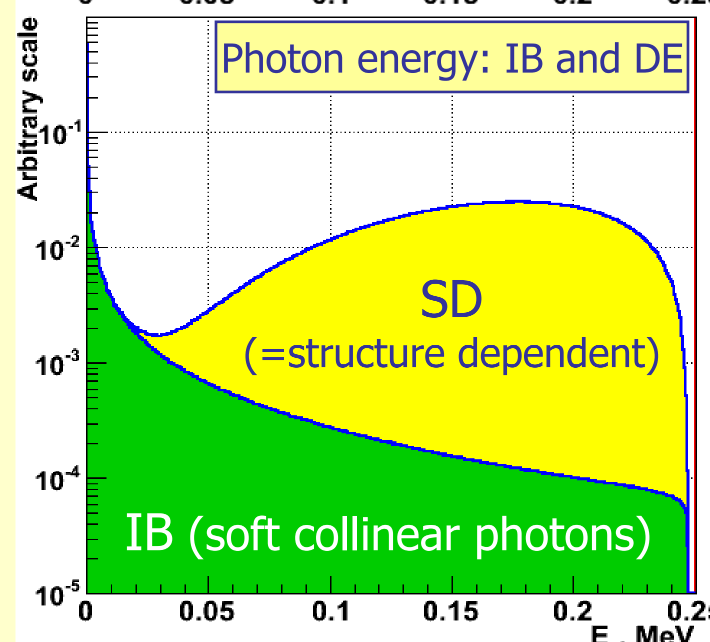
KLOE measurement of the form factor leads to

BR(SD+, full phase space) = $(1.37 \pm 0.06) \times 10^{-5}$.

(EPJC64 (2009) 627)

B/(S+B) = (1.07 ± 0.05)%

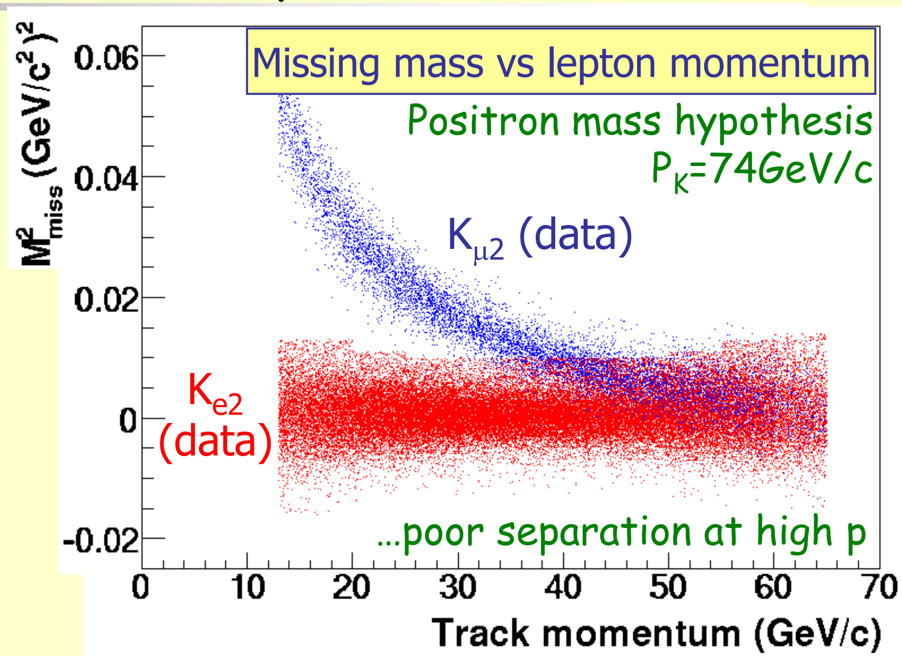




K_{e2} vs $K_{\mu 2}$ selection

Large common part (topological similarity)

- one reconstructed track (lepton candidate);
- geometrical acceptance cuts;
- K decay vertex: closest approach of lepton track & nominal kaon axis;
- veto extra LKr energy deposition clusters;
- track momentum: 13GeV/c<p<65GeV/c.



Kinematic identification

missing mass $M^2_{miss} = (P_K - P_l)^2$

P_K : average measured with $K_{3\pi}$ decays

→ Sufficient $K_{e2}/K_{\mu 2}$ separation at p_{track}<30GeV/c

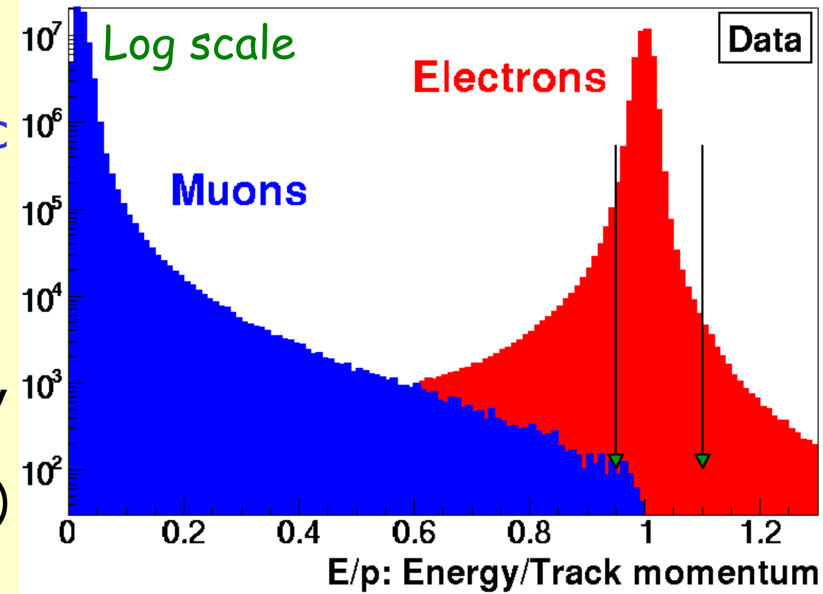
Lepton identification

E/p = (LKr energy deposit/track momentum).

(0.90 to 0.95)<E/p<1.10 for electrons,

E/p<0.85 for muons.

→ Powerful $\mu^{\pm}$ suppression in $e^{\pm}$ sample (~10^6)



$K_{\mu 2}$ background in K_{e2} sample

Main background source

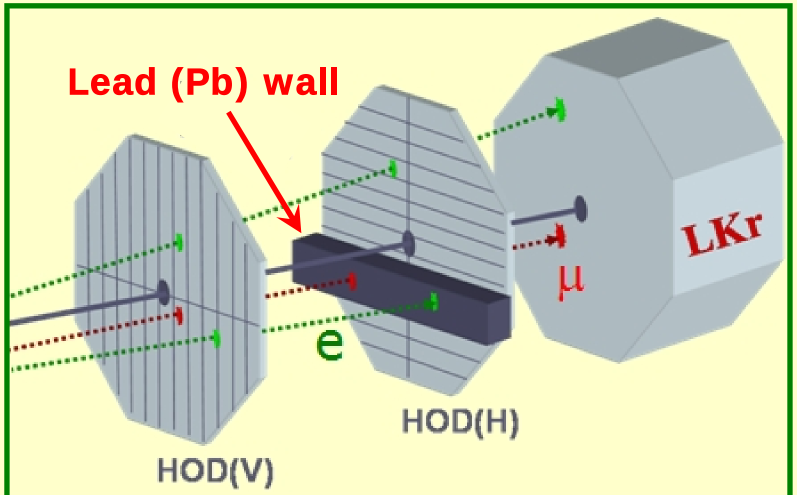
Muon 'catastrophic' energy loss in LKr by emission of energetic bremsstrahlung photons. $P_{\mu e} \sim 3\times10^{-6}$ (and momentum-dependent).

$P_{\mu e} / R_K \sim 10\%$:
$K_{\mu 2}$ decays represent a major background

Direct measurement of $P_{\mu e}$

Pb wall ($9.2X_0$) in front of LKr: suppression of $\sim10^{-4}$ positron contamination due to $\mu\rightarrow e$ decay.

$K_{\mu 2}$ candidates, track traversing Pb, $p>30$GeV/c, $E/p>0.95$: positron contamination $<10^{-8}$.



Thickness:	$9.2X_0$ (Pb+Fe)
Width:	240cm (=HOD size)
Height:	18cm (=3 counters)
Area:	~20% of HOD area
Duration:	~50% of R_K runs

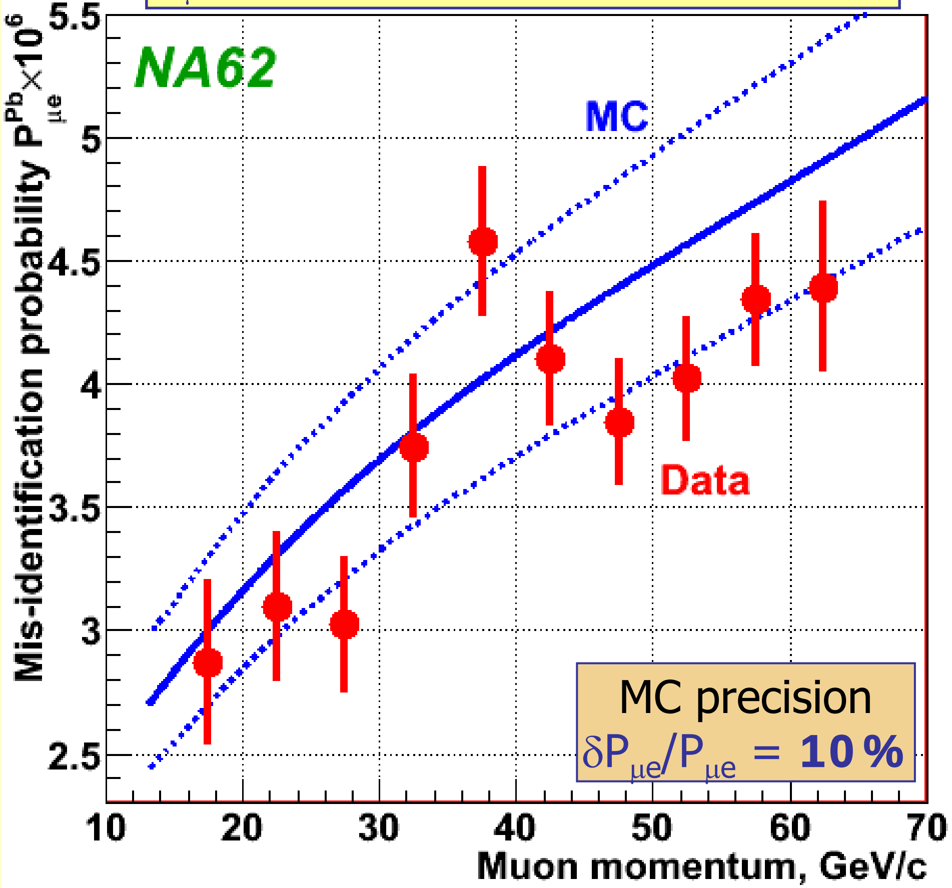
$P_{\mu e}$ is modified by the Pb wall:
→ ionization losses in Pb (low p);
→ bremsstrahlung in Pb (high p).

⇒ The correction $f_{Pb}=P_{\mu e}/P_{\mu e}^{Pb}$ is evaluated with a dedicated Geant4-based simulation

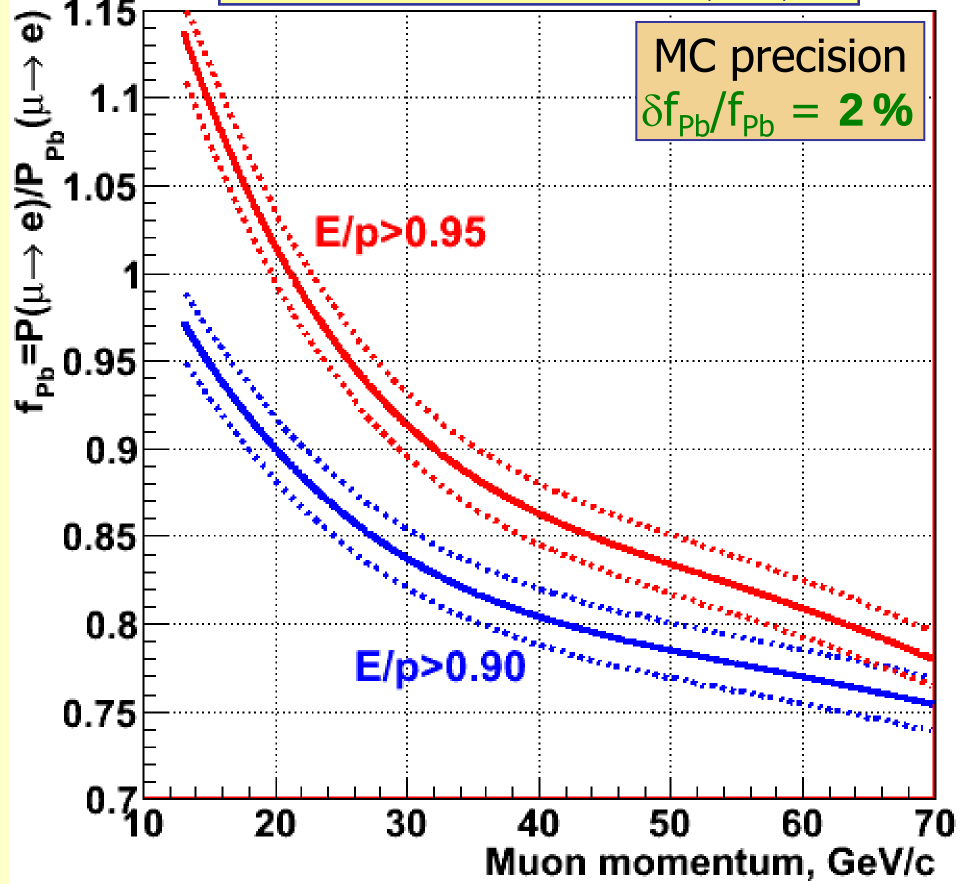
[Muon bremsstrahlung model:
Kelner et al., Phys. Atom. Nucl. 60(1997)576]

Muon mis-identification

$P_{\mu e}$ vs momentum (Pb wall installed)



Correction for Pb: $f_{Pb}=P_{\mu e}/P_{\mu e}^{Pb}$



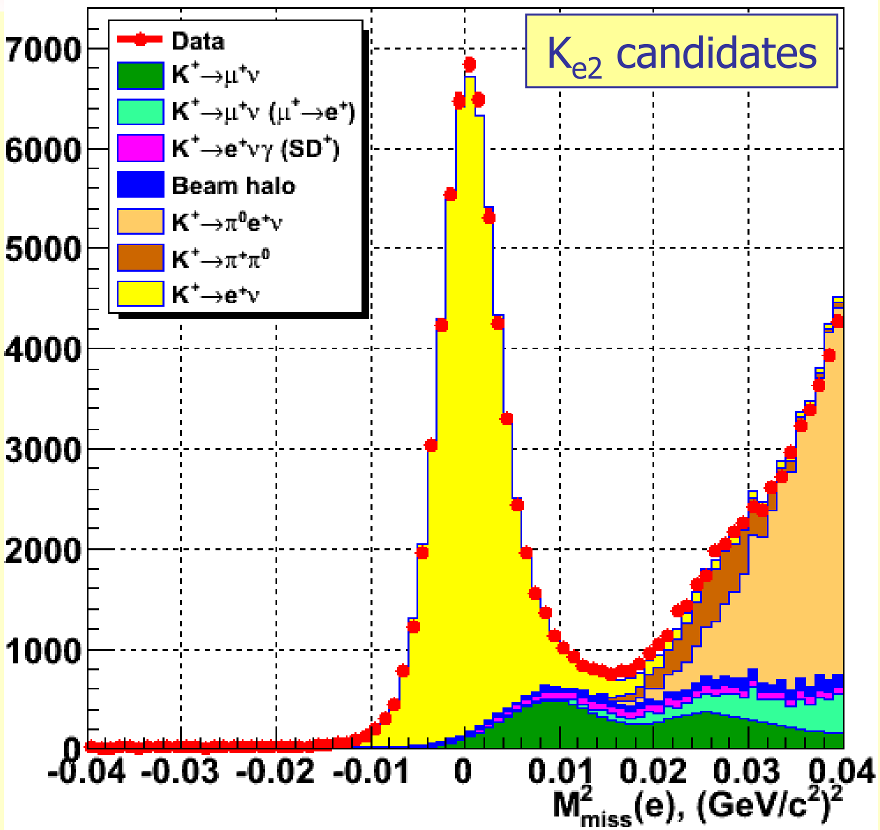
Result: $B/(S+B) = (6.11\pm0.22)\%$

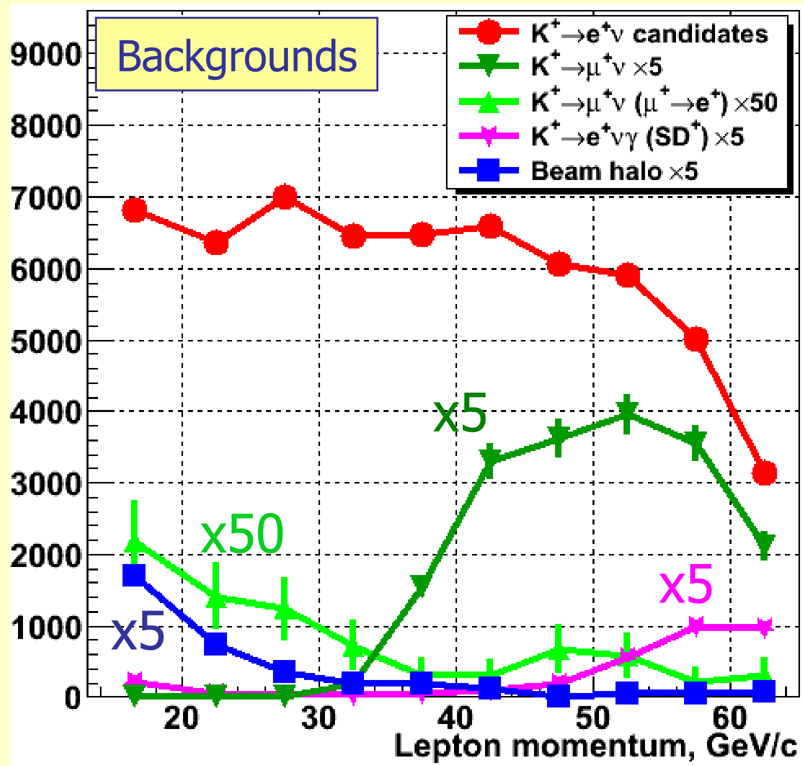
Uncertainty is ~3 times smaller than the one obtained solely from simulation

Uncertainties:
limited control data sample (0.16%),
MC correction δf_{Pb} (0.12%),
M^2_{miss} vs P_{track} correlation (0.08%).

Stability checks:
vs lower E/p cut, upper HOD energy deposit.

K_{e2}: partial (40%) data set





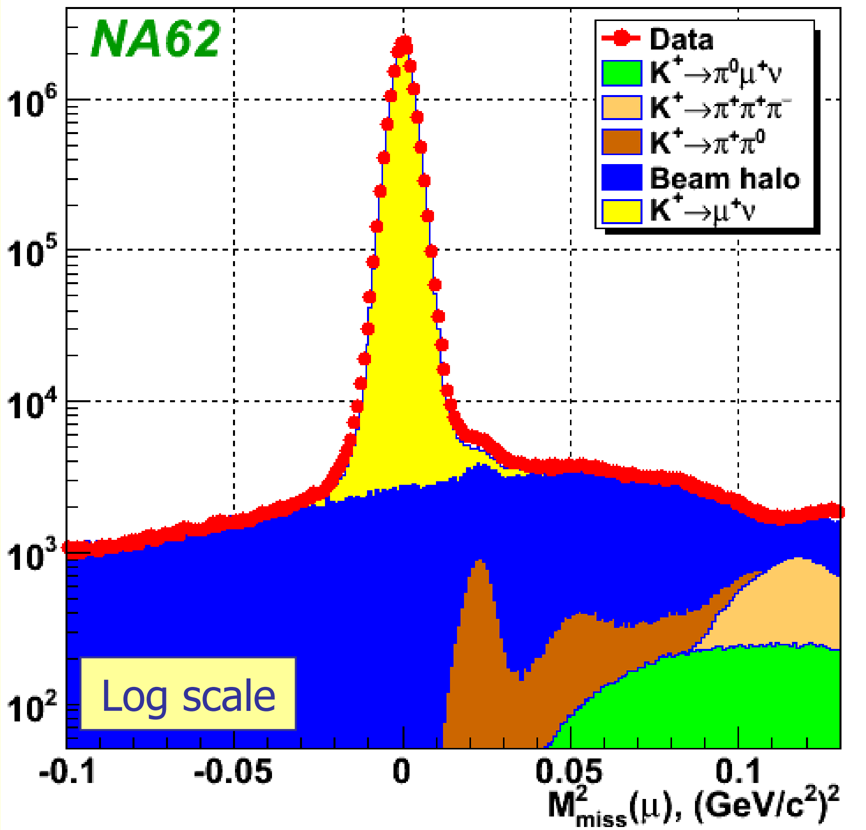
59,813 $K^+\to e^+\nu$ candidates.
Positron ID efficiency: (99.27±0.05)%.
B/(S+B) = (8.71±0.24)%.

cf. KLOE: 13.8K candidates (K^+ and K^-), ~90% electron ID efficiency, 16% background

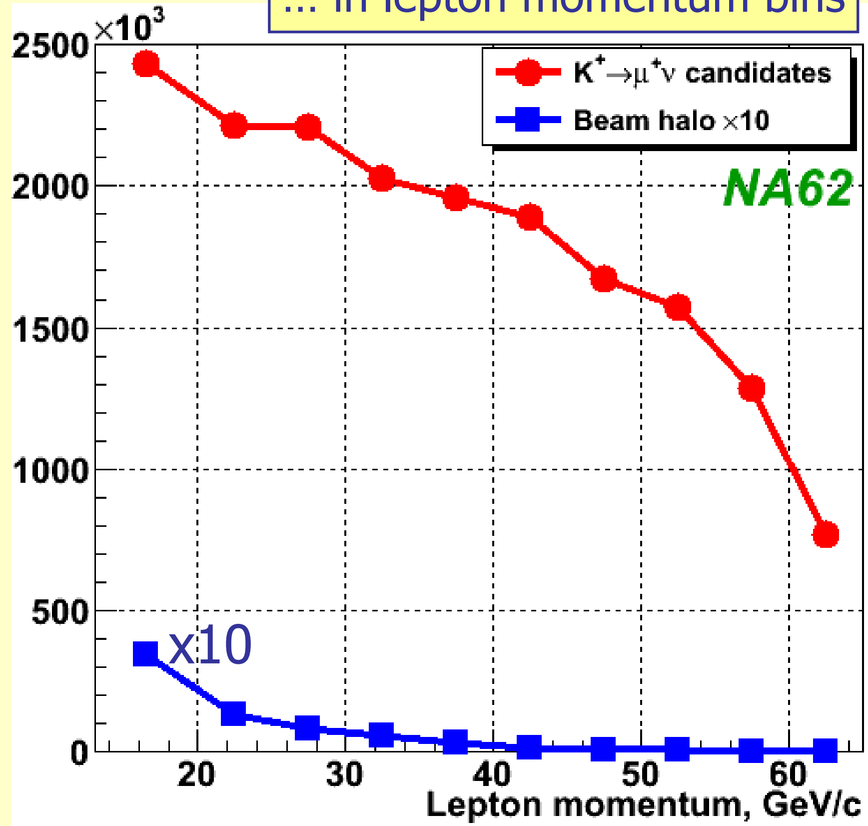
Source	B/(S+B)
$K_{\mu2}$	(6.11±0.22)%
$K_{\mu2}$ ($\mu\to e$)	(0.27±0.04)%
$K_{e2\gamma}$ (SD$^+$)	(1.07±0.05)%
$K_{e3(D)}$	(0.05±0.03)%
$K_{2\pi(D)}$	(0.05±0.03)%
Beam halo	(1.16±0.06)%
Total	(8.71±0.24)%

$K_{\mu2}$: partial (40%) data set

$K_{\mu2}$ candidates



… in lepton momentum bins



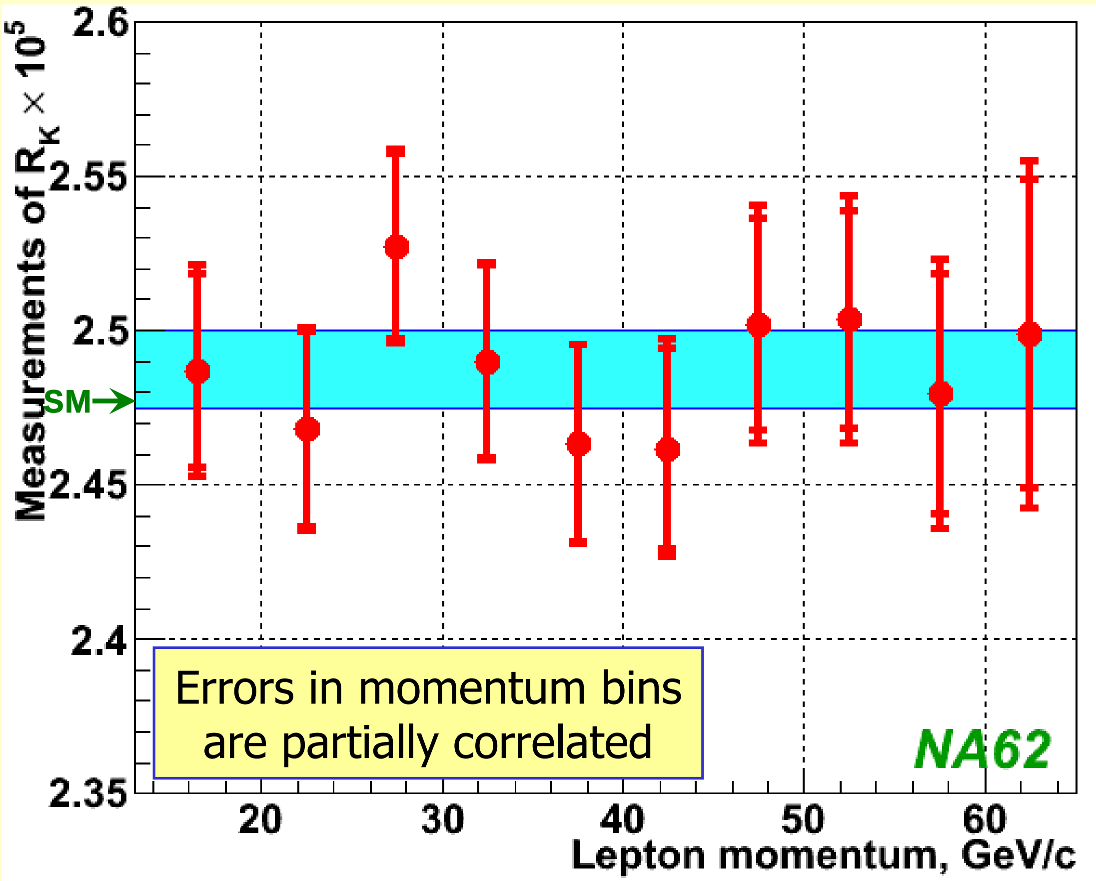
18.03M candidates (pre-scaled trigger).
$B/(S+B) = (0.38\pm0.01)\%$,
background dominated by beam halo.

Sensitivity to heavy neutrinos ($K^+\to\mu^+N$) is limited by beam halo and similar to that of Hayano et al., PLB49 (1982) 1305

NA62 final result (40% data set)

$R_K = (2.487 \pm 0.011_{stat} \pm 0.007_{syst}) \times 10^{-5}$
$= (2.487 \pm 0.013) \times 10^{-5}$

CERN-PH-EP-2011-004,
arXiv:1101.4805,
accepted by PLB

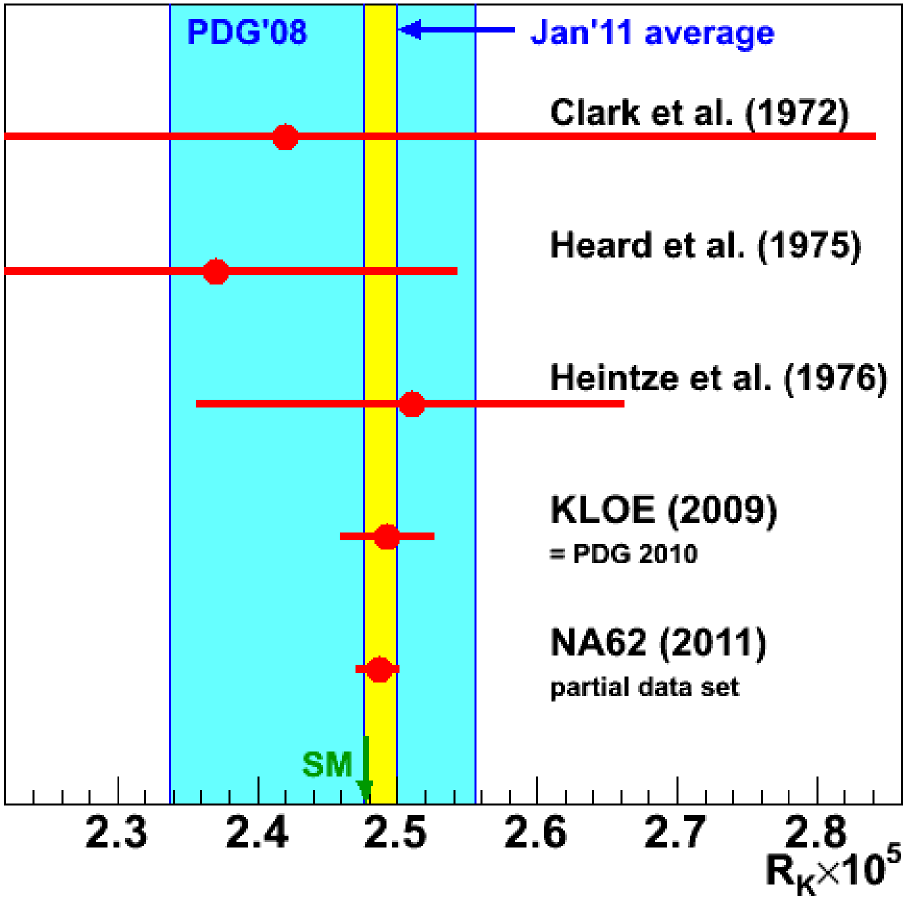


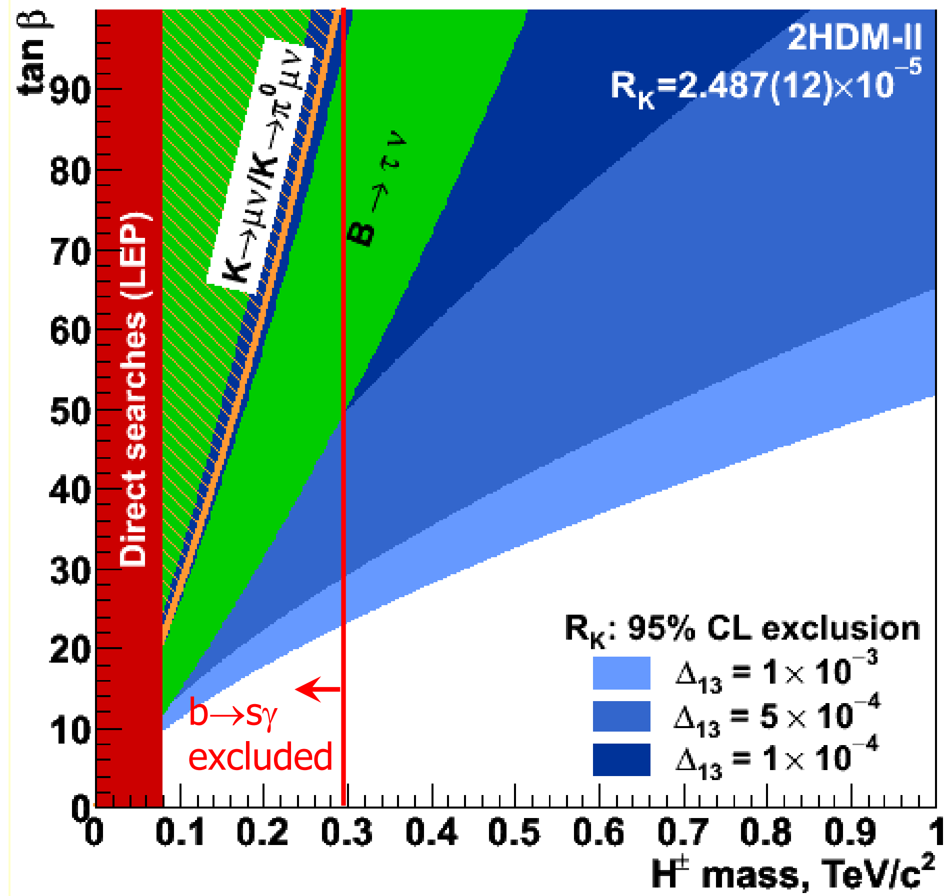
Uncertainties

Source	$\delta R_K \times 10^5$
Statistical	0.011
$K_{\mu 2}$	0.005
$K \to e^+ \nu \gamma$ (SD^+)	0.001
$K^+ \to \pi^0 e^+ \nu$, $K^+ \to \pi^+ \pi^0$	0.001
Beam halo	0.001
Helium purity	0.003
Acceptance correction	0.002
Spectrometer alignment	0.001
Positron ID efficiency	0.001
1TRK trigger efficiency	0.002
LKr readout efficiency	0.001
Total	0.013

Full NA62 data set: precision will be improved from 0.5% to 0.4%.

R_K world average





World average	$\delta R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
Today	2.487±0.012	0.5%

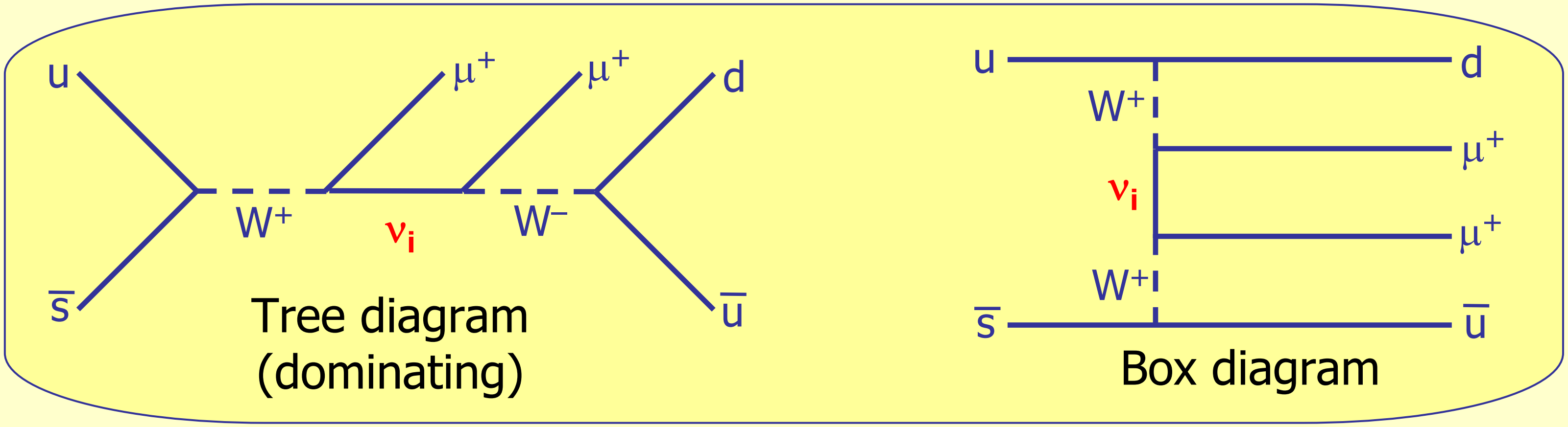
Other limits on 2HDM-II:
PRD 82 (2010) 073012.

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

Lepton number violation: $K^+ \to \pi^- \mu^+ \mu^+$, $K^- \to \pi^+ \mu^- \mu^-$

Motivation

$K^+ \to \pi^- \mu^+ \mu^+$ proceeds if the neutrino is a Majorana particle:



$BR \approx 10^{-8} \times (\langle m_{\mu\mu} \rangle/\mathrm{TeV})^2$

[K. Zuber, PLB 479 (2000) 33;
L. Littenberg, R. Shrock,
PRB491 (2000) 285]

Analogously, neutrinoless double beta decay rate is $\sim\langle m_{ee} \rangle^2$.

$\langle m_{ll} \rangle = |\Sigma m_i U^2_{li}|$ is the effective Majorana neutrino mass

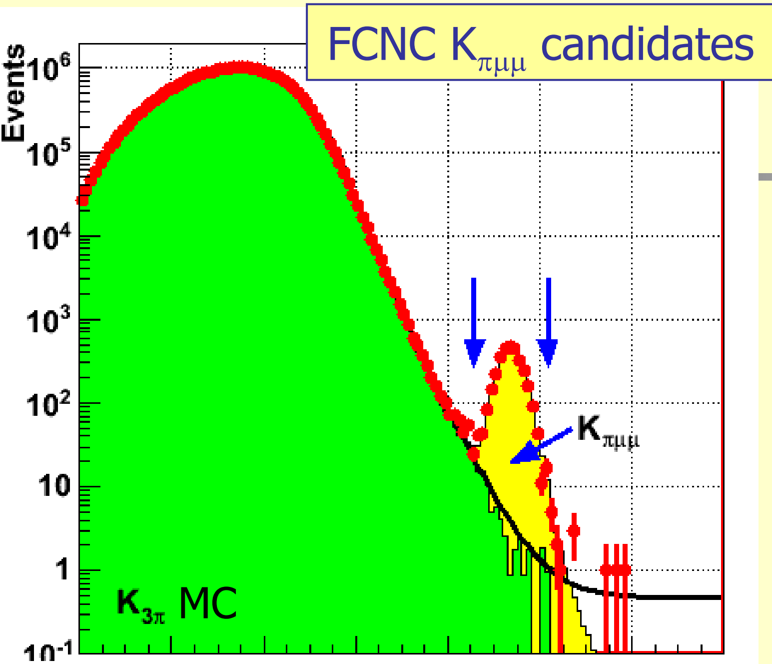
Best upper limits on LFV/LNV decays $K_{\pi ee}$, $K_{\pi\mu\mu}$, $K_{\pi\mu e}$ come from BNL E865.

The E865 $K_{\pi\mu\mu}$ limit, based on a (short) special run, is the weakest: $BR<3\times10^{-9}$.

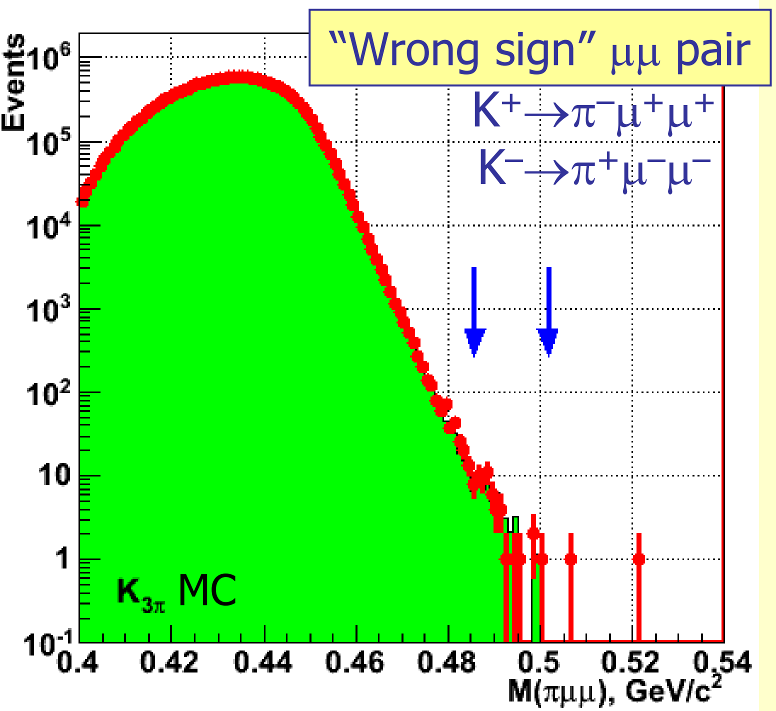
→ NA48 is competitive for $K_{\pi\mu\mu}$ mode: ~8 times larger data sample ($K^\pm$).

NA48 results

PLB 697 (2011) 107



$K^{\pm}\to\pi^{\pm}\mu^{+}\mu^{-}$ analysis: 3,120 candidates (~4 times world sample), (3.3±0.7)% background.
BR, CPV and FB asymmetries measured.

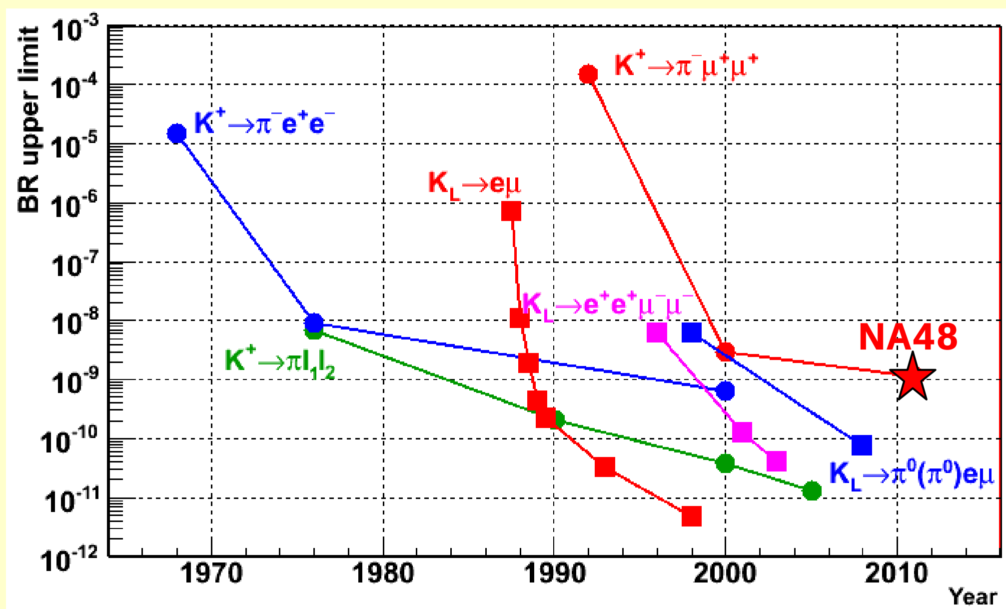


<u>Lepton number violating decay:</u>

$N_{data} = 52$
$N_{bkg} = 52.6\pm19.8_{syst.}$

BR < 1.1×10^{-9} (90% CL)

A <u>factor of 3</u> improvement on the upper limit for $BR(K^{+}\to\pi^{-}\mu^{+}\mu^{+})$.



Summary

- Combined experimental precision on $R_K=BR(K_{e2})/BR(K_{\mu2})$ has improved by an order of magnitude over the last 3 years, but is still an order of magnitude behind that of the SM prediction.
- R_K experiment and SM currently agree at 0.8σ level.
- Short (medium) term plans at NA62: improvement of the experimental uncertainty on R_K to 0.4% (0.2%) exploiting the decay-in-flight technique.
- Upper limit on LNV $BR(K^+\to\pi^-\mu^+\mu^+)$ improved by a factor of 3: $BR<1.1\times10^{-9}$ → $\langle m_{\mu\mu}\rangle<300$ GeV at 90% CL.

Other recent CERN NA48/NA62 results:
S.Balev @ La Thuile 2011; B.Bloch-Devaux @ Moriond QCD 2011