NP Limits from Kaon Decays

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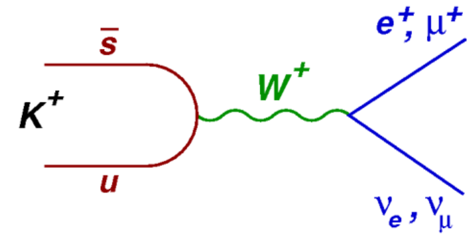
On behalf of the NA48-NA62 collaborations

Outline

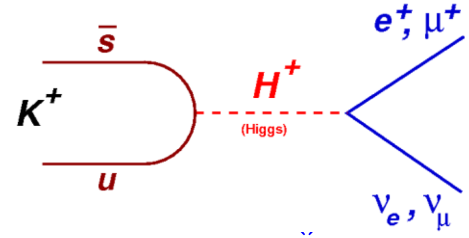
- New Physics and K decays.
- Test of lepton flavour universality with NA62 @ CERN.
- Studies of lepton number violation with NA48/2 @ CERN.
- The future of Kaon physics with NA62.

$P^+ \to l^+\nu$ Decays and Sensitivity to NP

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



- Beyond SM [PRD 48 (1993) 2342; Prog. Theor. Phys. 111 (2004) 295]:
  - Models with 2 Higgs doublets (e.g. 2HDM-II MSSM)
    - Sizeable effects at tree-level correction: $\Delta\Gamma/\Gamma_{SM}$ proportional to $\tan^2\beta$ and to $(m_{P+}/m_{H+})^2$.
  - Examples of possible theoretical deviations ($\Delta\Gamma/\Gamma_{SM}$) : (m_{H+} = 500 GeV/c^2, $\tan\beta$ = 40)
    - $\pi^+ \to l^+\nu$ -2×10^{-4}, $K^+ \to l^+\nu$ -0.3%
    - $D^+_s \to l^+\nu$ -0.4%, $B^+ \to l^+\nu$ -30%



- Best experimental limits [PRD82 (2010) 073012; Barlow, CKM2010] :
  - $Br(B^+ \to \tau^+\nu)_{exp} = (1.64 \pm 0.34) \times 10^{-4}$ [HFAG]
  - About 3σ discrepancy between measured value and preferred one from global CKM fit [UTfit, CKMfitter, ICHEP2010].

$K^+ \to \mu^+\nu$ Sensitivity to NP [EPJ C69 (2010) 399]

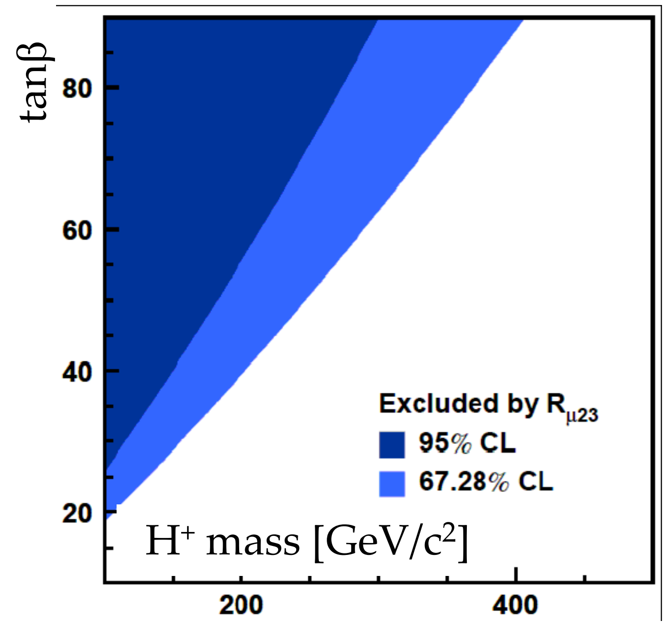
- Quantity: $$R_{\mu 23} = \underbrace{\left(\frac{f_K/f_\pi}{f_+(0)}\right)^{-1}}_{1.} \left(\underbrace{\left|\frac{V_{us}}{V_{ud}}\right| \frac{f_K}{f_\pi}}_{2.}\right)_{\mu 2} \frac{\overbrace{|V_{ud}|_{0^+\to 0^+}}^{4.}}{\underbrace{[|V_{us}|f_+(0)]_{\ell 3}}_{3.}}$$

1. Lattice QCD
2. Extracted from BR($K^+ \to \mu^+ \nu$) measurement (permille precision) [KLOE]
3. Extracted from BR($K \to \pi l \nu$) measurements (<1% precision) [KLOE, NA48,KTeV]
4. Average from nuclear β decays [PRC 79 (2009) 055502]

- Theoretical expectations:
  - SM: $R_{\mu 23} = 1$
  - Beyond SM: charged Higgs tree level current.

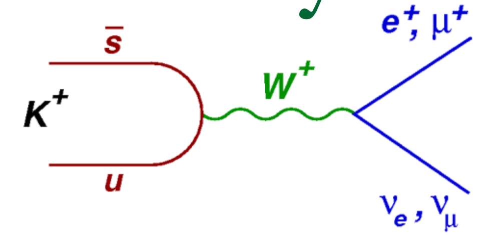
$$R_{\mu 23} \approx \left| 1 - \frac{m^2_{K^+}}{m^2_{H^+}} \frac{\tan^2\beta}{1+\epsilon_0 \tan\beta} \right|$$

- Experimental result:
  - $R_{\mu 23} = 0.999(7)$
  - Exclusion limits in m_{H^+} /tanβ plane



$R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$: Theory

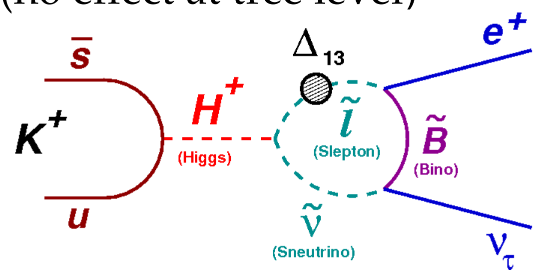
- SM: $$R_K = \frac{\Gamma(K^\pm \to e^\pm \upsilon)}{\Gamma(K^\pm \to \mu^\pm \upsilon)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot \left(1 + \delta R_K^{\text{rad.corr.}}\right)$$



  - Prediction: $R_K = (2.477 \pm 0.001) \times 10^{-5}$ [Phys. Lett. 99 (2007) 231801]
    - Hadronic uncertainties cancel in the ratio.
    - Strong helicity suppression.
    - Radiative correction (few %) due to $K \to e\nu\gamma$ (IB) included by definition in R_K

- Beyond SM:
  - Model with 2 Higgs doublets (e.g. 2HDM-II MSSM) and LFV sources in the right-handed slepton sector [PRD 76 (2006) 011701].
    - Potentially sizeable effects at 1-loop level at large tanβ (no effect at tree level)

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



    - Sensitivity: up to % level after tuning of the parameters: experimentally accessible
    - Higher enhancement in B sector , but experimentally challenging

R_K: Experiments

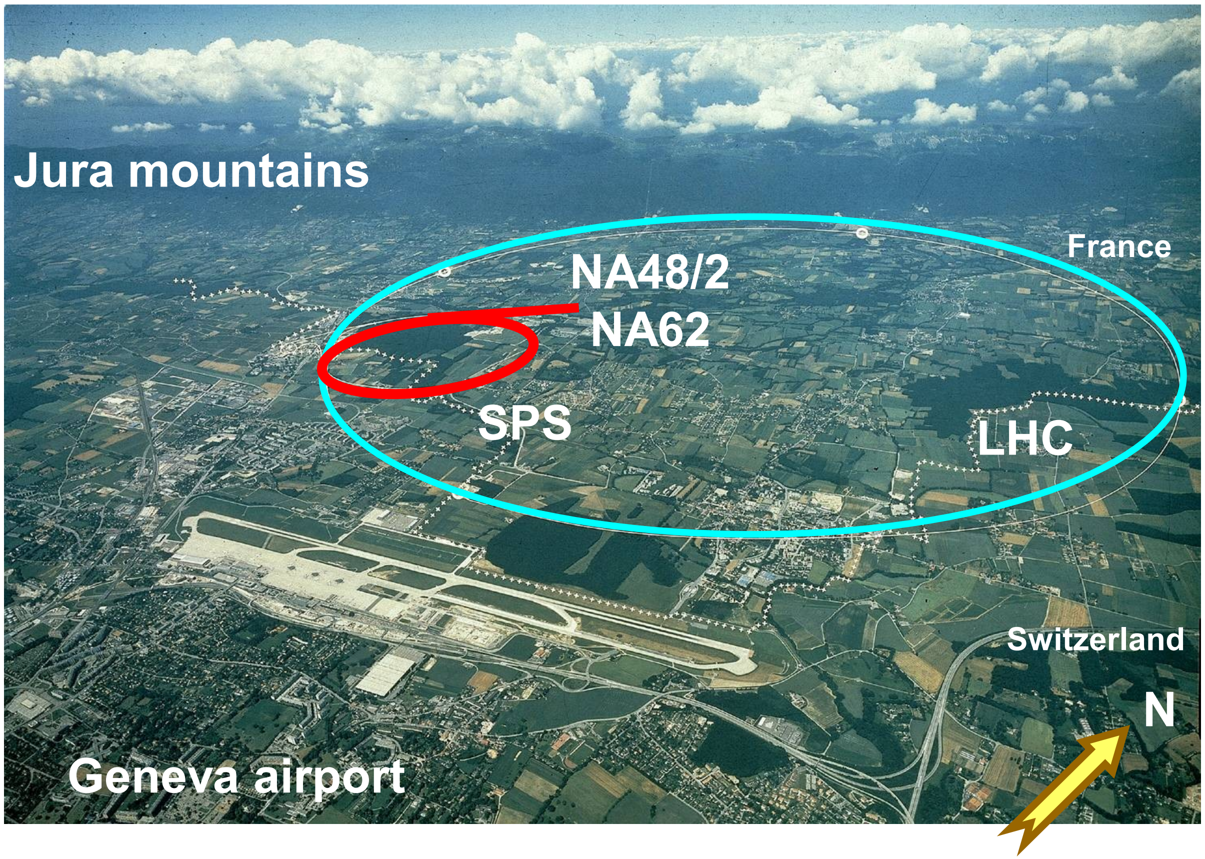
- PDG '08 [1970s measurement] : $R_K = (2.45 \pm 0.11) \times 10^{-5}$
  - $\delta R_K/R_K = 4.5\%$

- KLOE [Eur. Phys, J. C 65 (2010) 703]: $R_K = (2.493 \pm 0.031) \times 10^{-5}$
  - Data collected in 2001-2005
  - 13.8×10^3 $K \rightarrow e\nu$ decays and 16% background
  - $\delta R_K/R_K = 1.3\%$

- NA62 (phase I):
  - Dedicated 4 months data taking in 2007
  - Goals:
    1. 150×10^3 $K \rightarrow e\nu$ decays
    2. <10% background

  → $\delta R_K/R_K < 0.5\%$

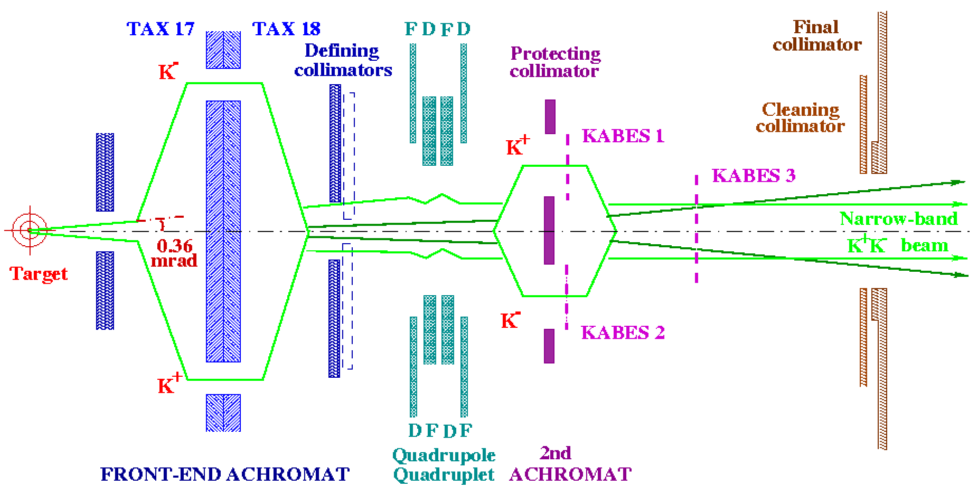
NA48 – NA62 Experiments @ CERN SPS

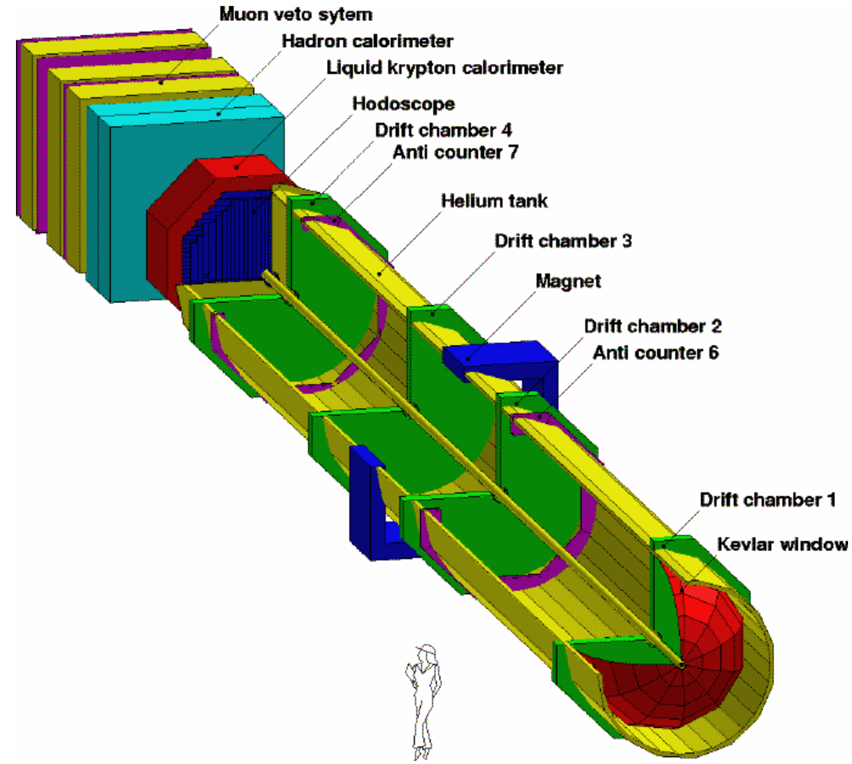


NA48	1997 ε'/ε run $K_L + K_S$
	1998 ε'/ε run $K_L + K_S$
	1999 ε'/ε run $K_L + K_S$; K_S Hi. Int.
	2000 K_L only ; K_S High Intensity ; *NO Spectrometer*
	2001 ε'/ε run $K_L + K_S$; K_S High Int.
NA48/1	2002 K_S High Intensity
NA48/2	2003 $K^{\pm}$ High Intensity
	2004 $K^{\pm}$ High Intensity
NA62 phase I	2007 R_K test -beam
	2008 R_K test -beam
NA62 phase II	2007-2012 Construction technical run
	2014- $K^+ \to \pi^+ \nu\nu$ run

NA48/2 – NA62 Beam Line and Detector

- Simultaneus $K^{\pm}$ beams:
  - $P_K = 60 \pm 3$ GeV/c (NA48/2)
  - $P_K = 75 \pm 2$ GeV/c (NA62)





- Detectors:
  - Magnetic Spectrometer:
    - $\sigma(P)/P = 1.0\% \oplus 0.044\, P(\text{GeV/c})\%$ (NA48/2)
    - $\sigma(P)/P = 0.48\% \oplus 0.009\, P(\text{GeV/c})\%$ (NA62 phase-I)
  - Hodoscope: Fast trigger for charged particles and timing for the event ($\sigma(t) = 200$ ps)
  - Liquid Kripton e.m. calorimeter (LKr): $\sigma(E)/E = 3.2\%/\sqrt{E} \oplus 90\text{ MeV}/E \oplus 0.42\%$

R_K: NA62 Measurement Strategy

- $K^+ \to e^+\nu$ (K_{e2}) , $K^+ \to \mu^+\nu$ ($K_{\mu2}$) collected simultaneously:
  - No dependence on K flux
  - Cancellation of several effects at first order

$$R_K = \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu2}) - N_B(K_{\mu2})} \; \frac{A(K_{e2}) \times f_\mu \times \varepsilon(K_{\mu2})}{A(K_{\mu2}) \times f_e \times \varepsilon(K_{e2})} \; \frac{1}{f_{LKr}} \; \frac{1}{D}$$

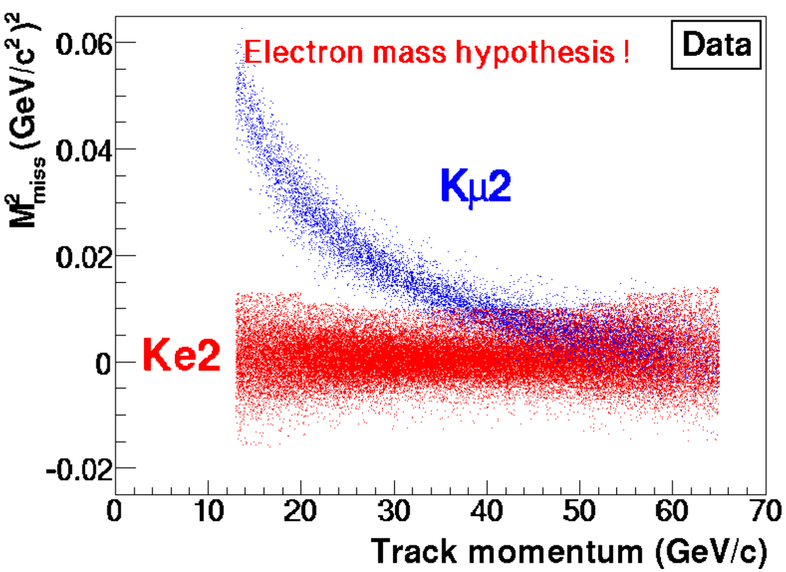
  - $N(K_{e2})$, $N(K_{\mu2})$: selected candidates
  - $N_B(K_{e2})$, $N_B(K_{\mu2})$: background, evaluated with data and/or MC
  - $A(K_{e2})$, $A(K_{\mu2})$: geometrical acceptance (MC), track reconstruction efficiency (MC/data)
  - f_e, f_μ: particle ID efficiency, evaluated with data
  - $\varepsilon(K_{l2})$: trigger efficiency, evaluated with data
  - f_{LKr} : global e.m. calorimetric inefficiency, evaluated with data
  - D : downscaling factor of $K_{\mu2}$, evaluated with data

- Analysis in 10 lepton momentum bins.

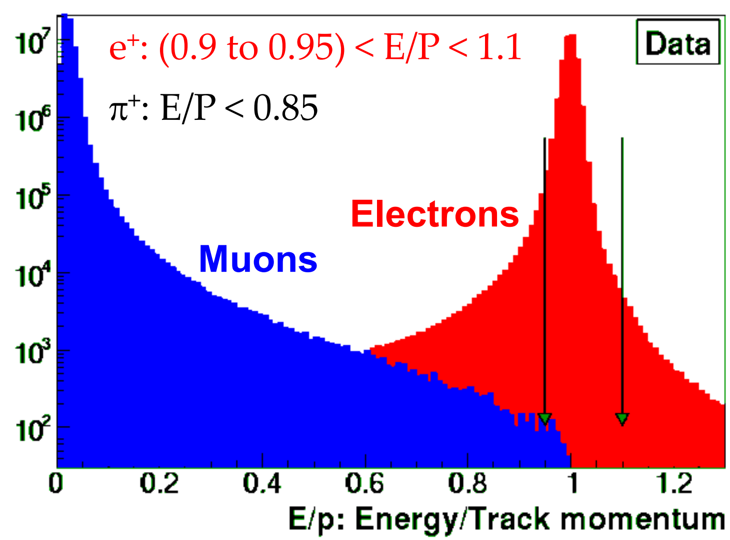
R_K Measurement: K_{e2} and $K_{\mu 2}$ Selection

- Common selection criteria:
  - $<P_K>$ reconstructed from $K^+ \to \pi^+\pi^+\pi^-$.
  - 1 track in the acceptance of the subdetectors downstream.
  - Decay vertex in the fiducial region upstream.
  - Photon veto using LKr downstream.

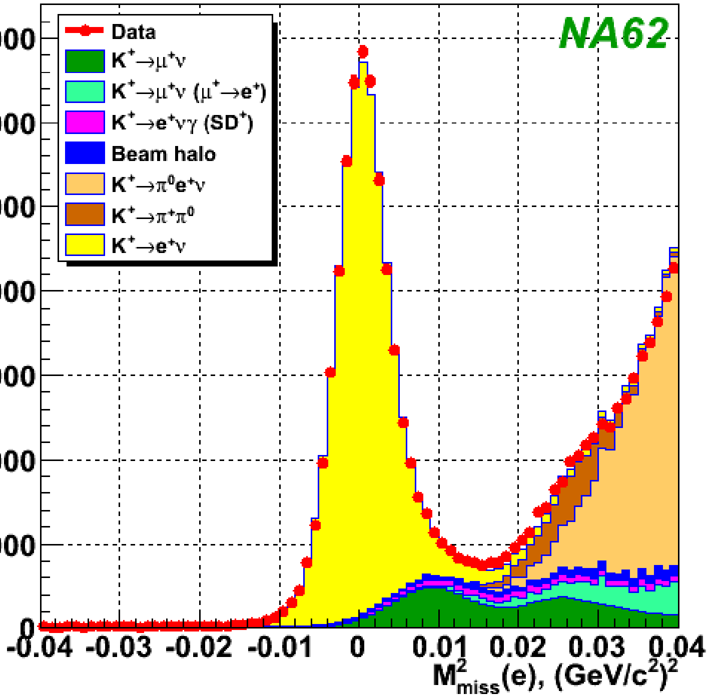
- Kinematic separation:
  - $M^2_{miss} = (P_K - P_l)^2$ (e^+ hypothesis)

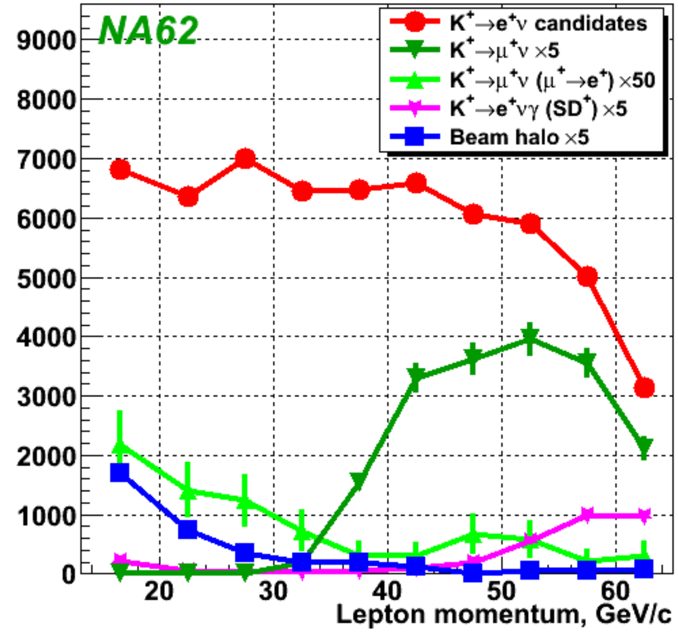


- Lepton identification:
  - E/P = ratio between LKr energy deposit and track momentum measured with the spectrometer



R_K Measurement: Signal and Background



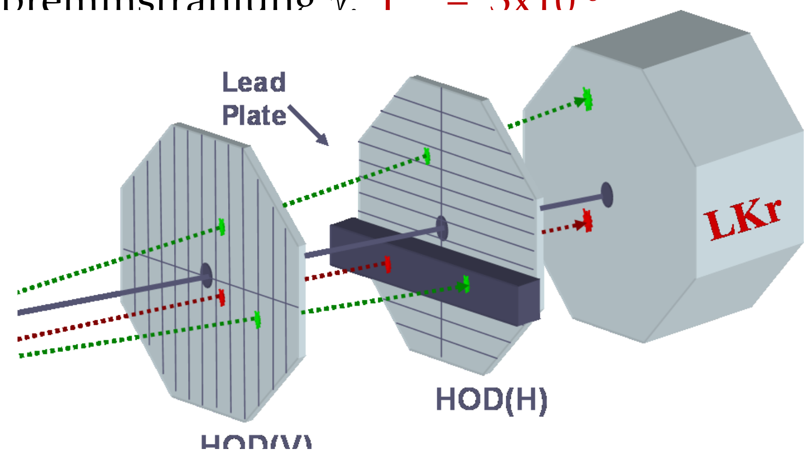


- 40% of the total 2007 data analyzed:
  - 59'813 $K^+ \to e^+\nu$ (K_{e2}^+) candidates
  - $(99.27 \pm 0.05)\%$ e^+ ID efficiency (measured using $K^+ \to \pi^0 e^+\nu$ and $K_L \to \pi^\pm e^\mp \nu$)
  - $(8.71 \pm 0.24)\%$ B/(S+B) in K_{e2}^+ sample
  - 18.03M $K^+ \to \mu^+\nu$ ($K_{\mu 2}^+$) candidates
  - $(0.38 \pm 0.24)\%$ B/(S+B) in $K_{\mu 2}^+$ sample

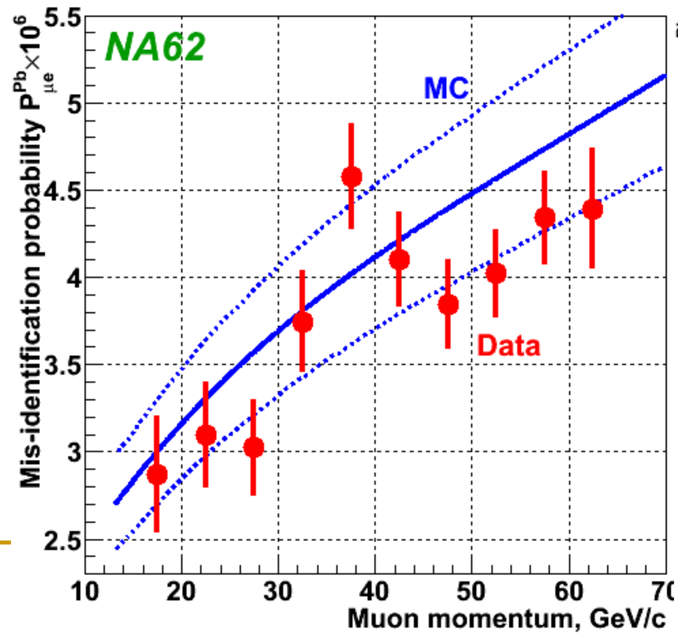
Decay	B/(S+B)
$K^+ \to \mu^+\nu$	$(6.11 \pm 0.22)\%$
$K^+ \to \mu^+\nu$ ($\mu \to e$)	$(0.27 \pm 0.04)\%$
$K^+ \to e^+\nu\gamma$ (SD+)	$(1.07 \pm 0.05)\%$
$K^+ \to \pi^0 e^+\nu$	$(0.05 \pm 0.03)\%$
$K^+ \to \pi^+\pi^0$	$(0.05 \pm 0.03)\%$
Beam halo	$(1.16 \pm 0.06)\%$

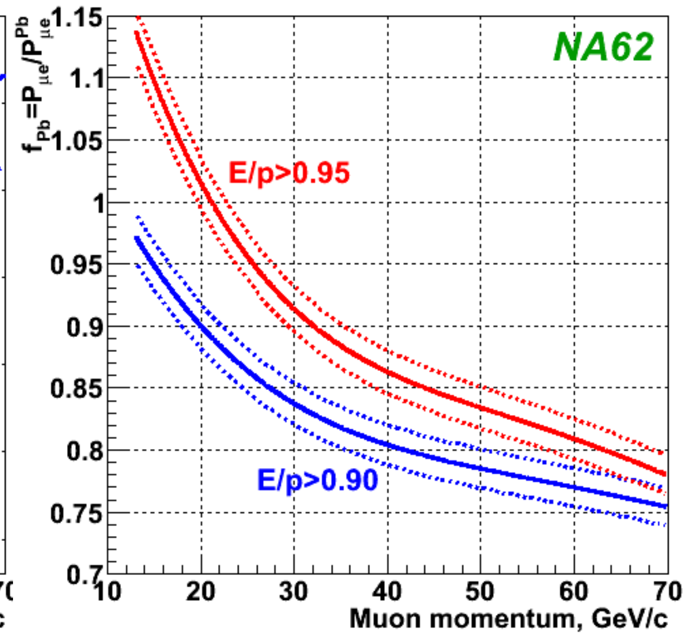
R_K Measurement: Background Analysis

- $K^+ \to \mu^+\nu$ background in K_{e2}^+: source
  - μ catastrophic energy loss in LKr by emission of a bremmstrahlung γ: $P = 3\times10^{-6}$
- $K^+ \to \mu^+\nu$ background in K_{e2}^+: measurement
  - Lead plate in front of LKr ($9.2X_0$, 20% total area) in order to provide pure μ sample in the LKr.
  - $P_{\mu e}$ measured on the selected pure μ sample
  - $P_{\mu e}$ corrected with Geant4 MC for μ energy loss and bremmstrahlung in the lead plate.

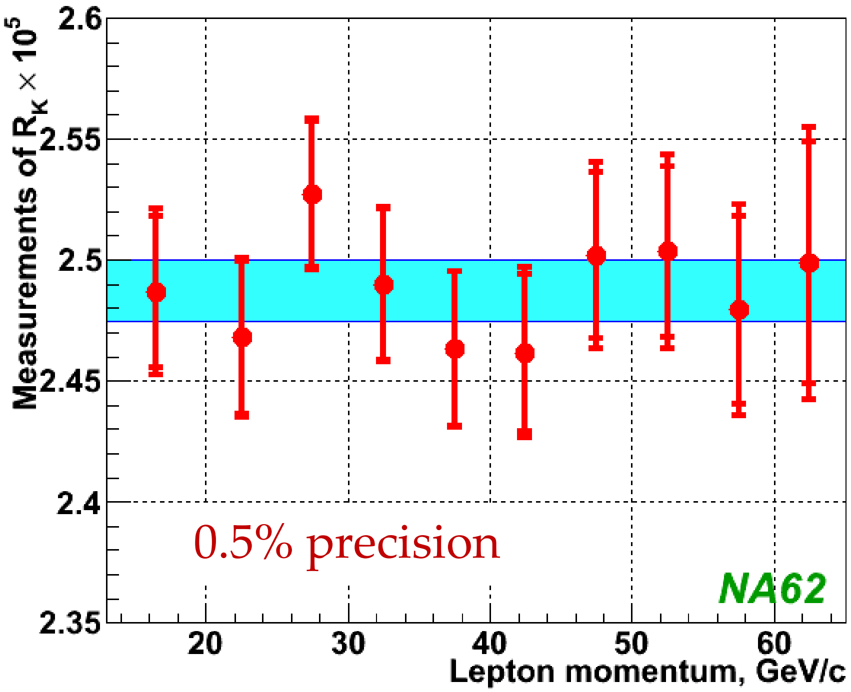


- Result:
  - B/(S+B) = (6.11±0.22)%
  - Uncertainty 3 times smaller than using MC only
  - $(\delta P_{\mu e}/ P_{\mu e})_{MC}$ ~10%
  - $(\delta f_{Pb}/f_{Pb})_{MC}$ ~2%





R_K Measurement: Final Result



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

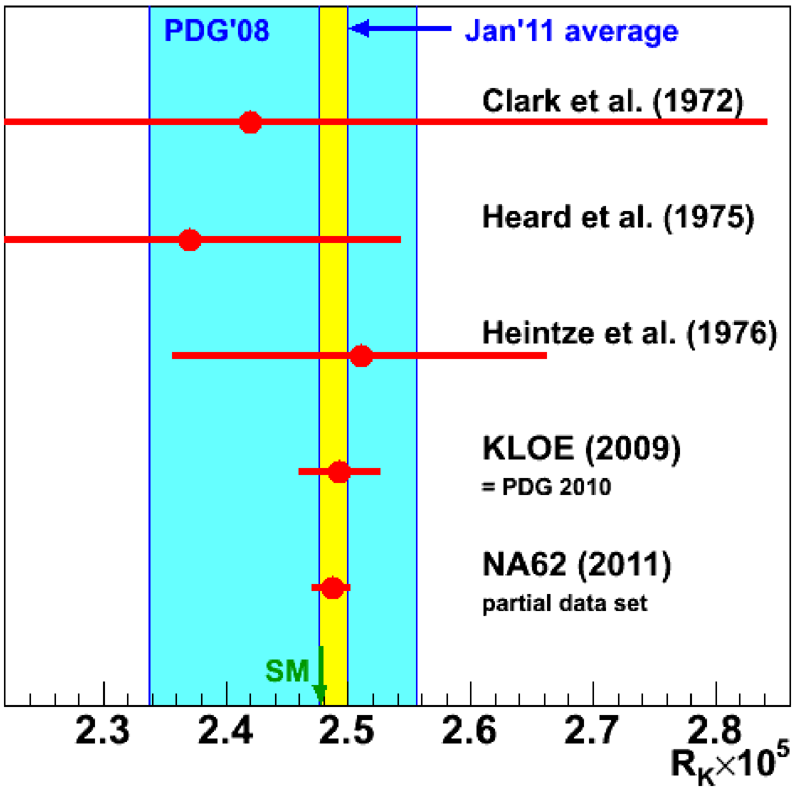
[Phys. Lett. B 698 (2011) 105]

Uncertainties

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

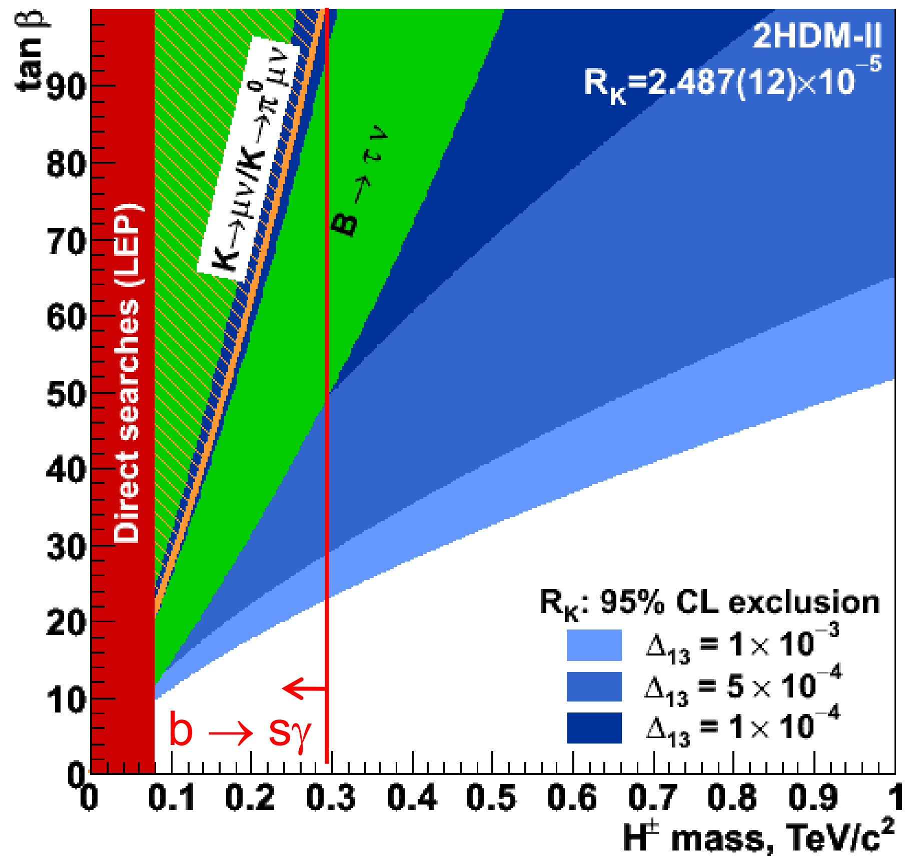
R_K Measurement: Discussion

- World average:
  - $R_K = (2.487 \pm 0.012) \times 10^{-5}$



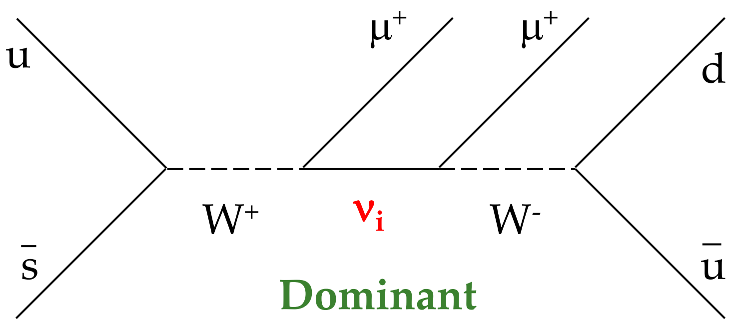
- Limits within 2HDM-II (with LFV)

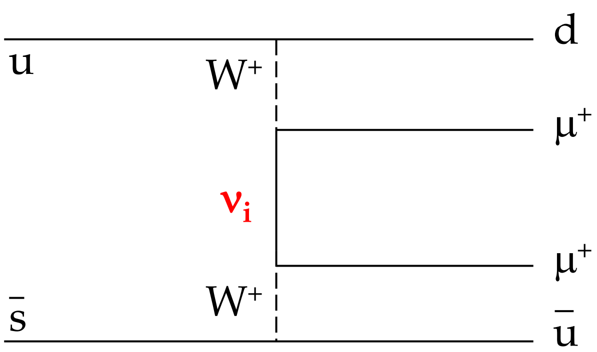
see also PRD 82 (2010) 073012



Lepton Number Violation: $K^+ \to \pi^- \mu^+ \mu^+$, $K^- \to \pi^+ \mu^- \mu^-$

- |ΔL| = 2 process
- Possible only if the ν is a Majorana particle (similar to the neutrinoless double β decay)
- Sensitive to the effective Majorana neutrino mass: $BR = 10^{-8} (\langle m_{\mu\mu}\rangle / TeV)^2$
  [PLB 479 (1000) 33; PRB 491 (2000) 285]

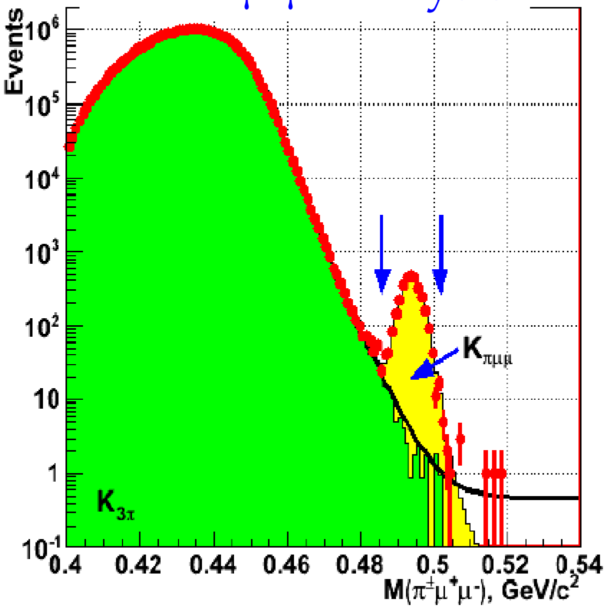




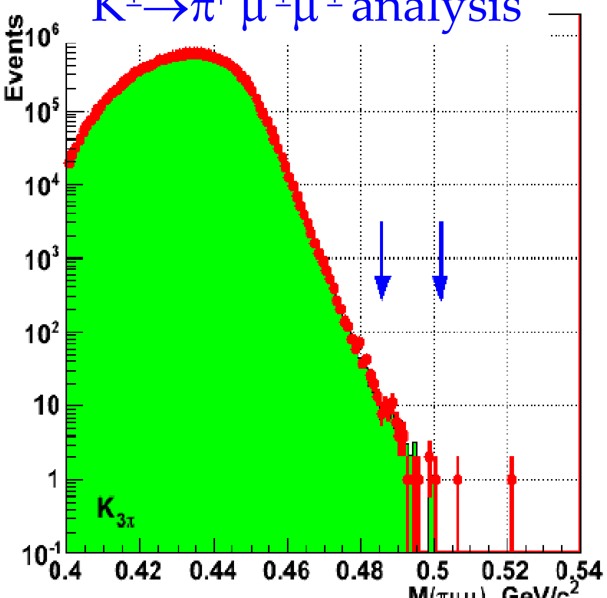
- Experiments:
- BNL E865: $BR(K^+ \to \pi^- \mu^+ \mu^+) < 3 \times 10^{-9}$ [PRL 85 (2000) 2877]
- NA48/2: 8 times larger statistics

NA48 Results [PLB 697 (2011) 107]

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



$K^\pm \to \pi^\mp \mu^\pm \mu^\pm$ analysis

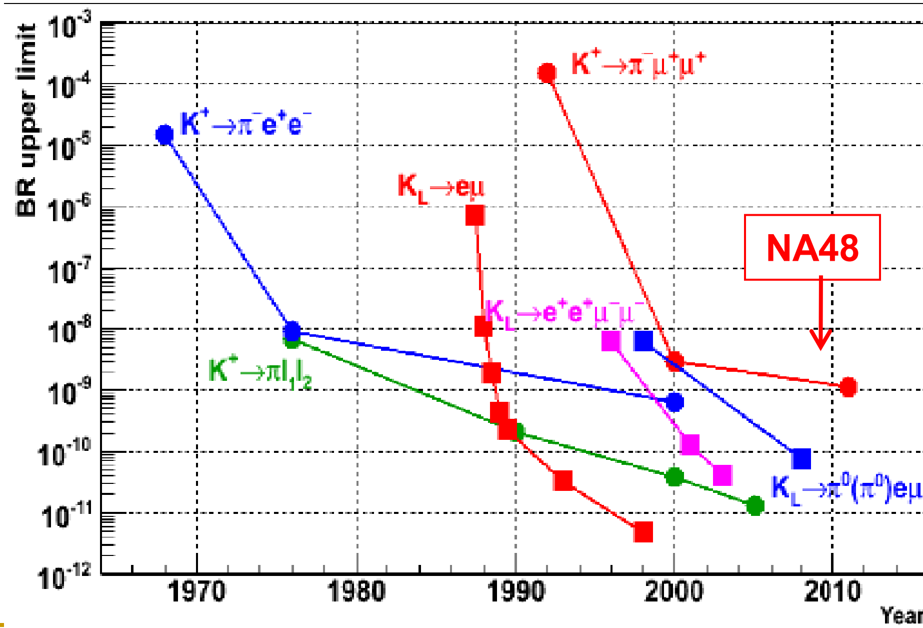


- $K^\pm \to \pi^\pm \mu^+ \mu^-$ analysis:
- 3120 candidates selected
- (3.3 ± 0.7)% background
- BR, CPV, FB asymmetries measured

- $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$ analysis:
- 52 data in signal region
- 52.6 ± 19.8 background expected

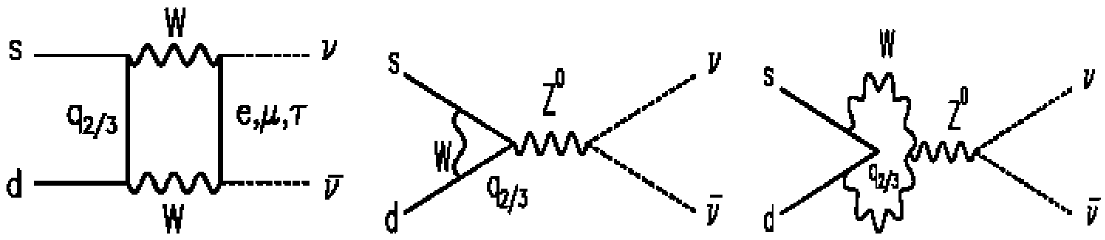
➡ **BR < 1.1x10^{-9} (90% CL)**

➡ **$\langle m_{\mu\mu} \rangle$ < 300 GeV (90% CL)**



The $K \to \pi\nu\bar{\nu}$ decays: a theoretical clean environment

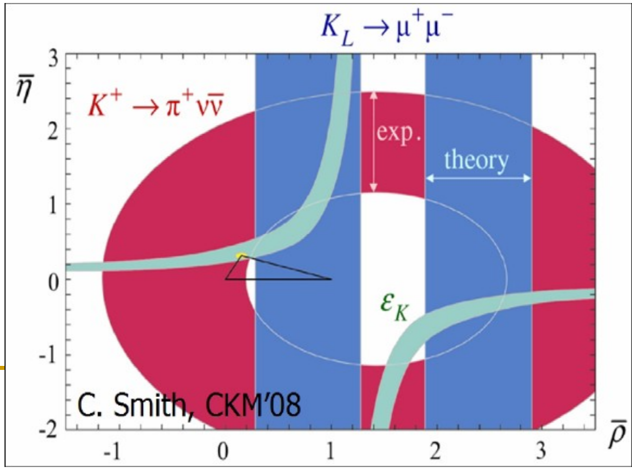
- FCNC loop processes: s→d coupling and highest CKM suppression



- Very clean theoretically: SD contributions dominate, hadronic matrix element can be related to measured quantites.
- BR proportional to $|V_{ts}{}^{*}V_{td}|^2$

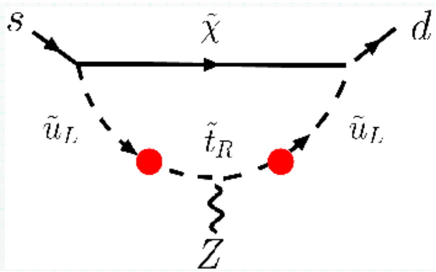
- SM predictions [Brod, Gorbahn, Stamou, arXiv:10009.0947] :
  - $BR(K^+ \to \pi^+\nu\bar{\nu}) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$
  - $BR(K_L \to \pi^0\nu\bar{\nu}) = (2.43 \pm 0.39 \pm 0.06) \times 10^{-11}$

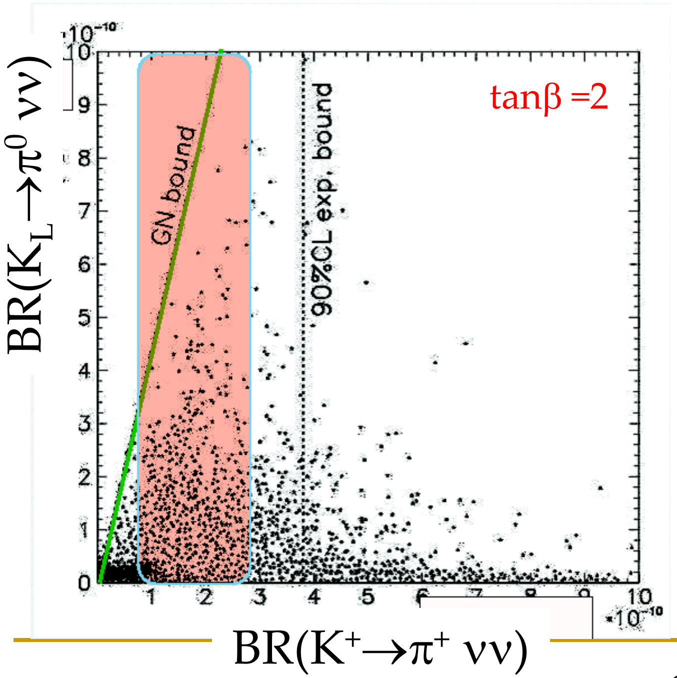
- Experimental results:
  - $BR(K^+ \to \pi^+\nu\bar{\nu}) = (1.73\,^{+1.15}_{-1.05}) \times 10^{-10}$ [E787, E959]
  - $BR(K_L \to \pi_0\nu\bar{\nu}) < 2.6 \times 10^{-8}$ [E391a]

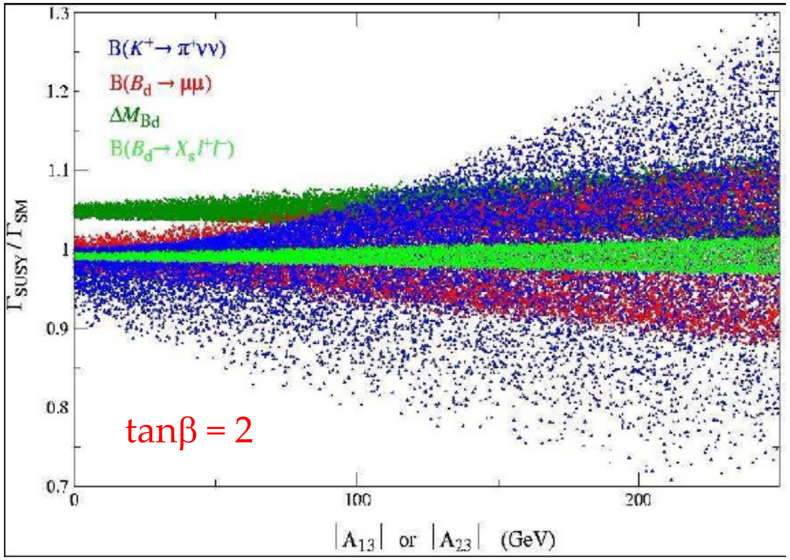


NP in $K \to \pi\nu\bar{\nu}$: MSSM with non-MFV breaking terms [JHEP 08 (2006) 064, NP B 714 (2005) 103]

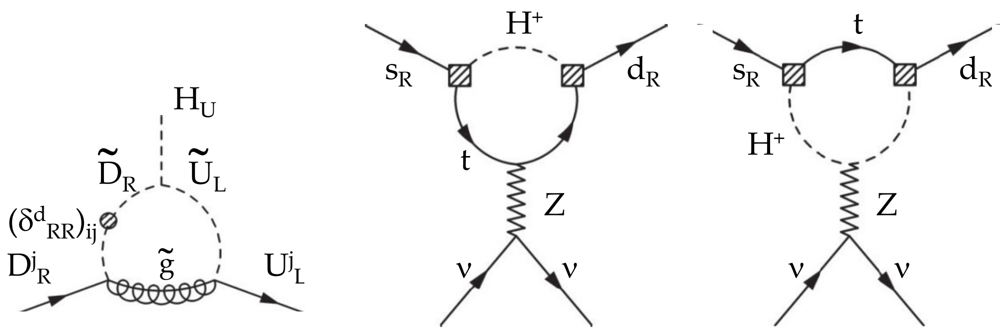
- Contribution from chargino/squark loops.
- Small tanβ scenario.
- Non-MFV in up-squarks trilinear terms.
- Maximal effects in $K \to \pi\nu\bar{\nu}$ decays
- Relatively slow decoupling (m^{-2}_{SUSY})



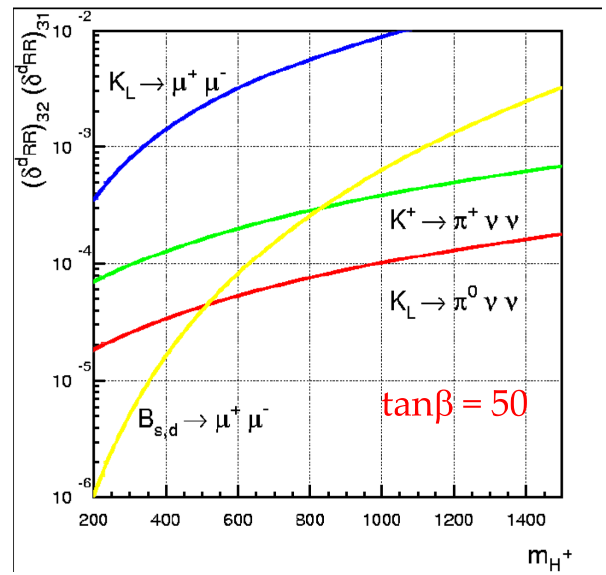




NP in $K\to\pi\nu\bar{\nu}$: MSSM with non-MFV breaking terms [PRD 73 (2006) 055017]



- Contribution from charged-Higgs/top quark loops at 3-loop level in standard loop expansion.
- Large $\tan\beta$ scenario.
- Non-MFV RR soft-breaking terms.
- Strong limits already assuming 10% SM BR variation.
- Slow decoupling with the charged-Higgs mass.



The NA62 Experiment for $K\rightarrow\pi\nu\bar{\nu}$: Goals

- Goal: 10% precision branching ratio measurement of $K^+\rightarrow\pi^+\nu\nu$
  - O(100) SM $K^+\rightarrow\pi^+\nu\bar{\nu}$ events (2 years of data taking)
  - % level systematics
- Requirements
  - Statistics:
    - BR(SM) ~ 8 x 10^{-11}
    - Acceptance: ~ 10%
    - K decays (2 years): 10^{13}
  - Systematics:
    - >10^{12} background rejection (i.e. <10% background)
    - <10% precision background measurement

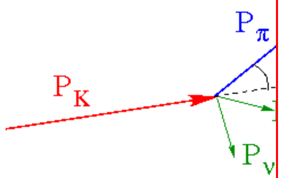
Kaon intensity Signal efficiency

Signal purity & detector redundancy

- Experimental technique
  - "High" momentum K^+ beam
  - Decay in-flight technique

The NA62 Experiment for $K \rightarrow \pi \nu \bar{\nu}$: Overview

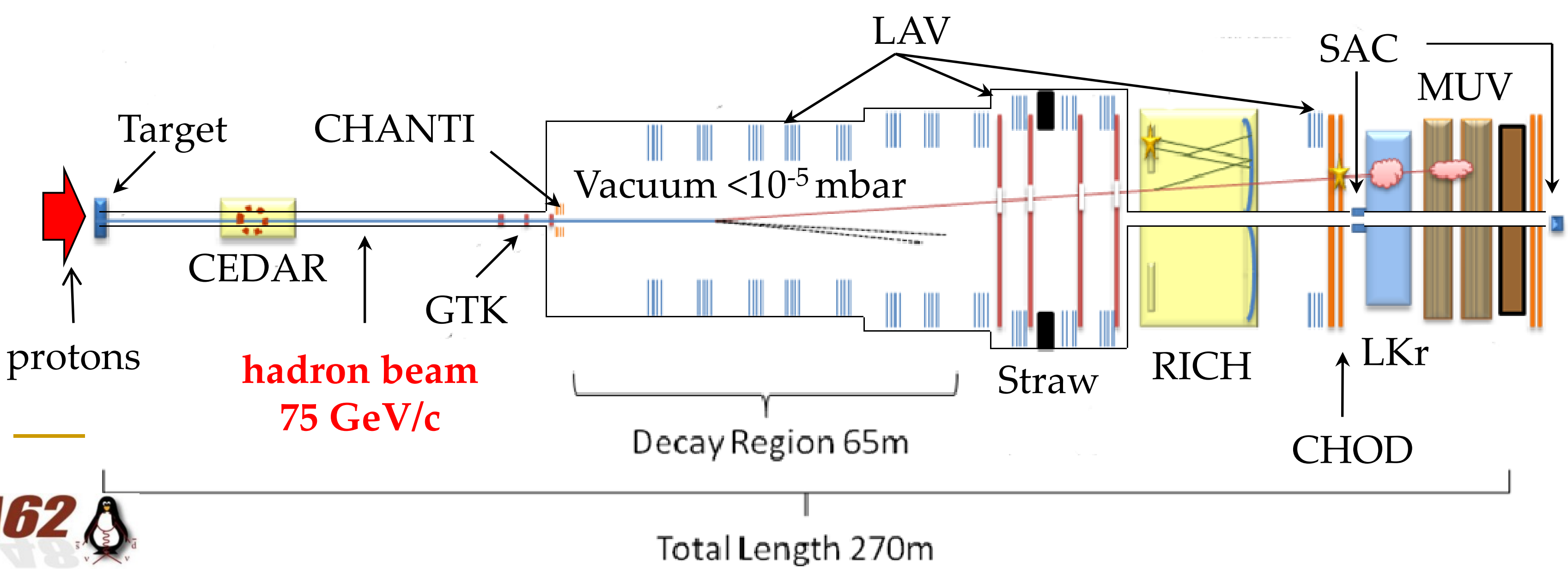
- Signal signature



- Background
  - All the K^+ d
  - Accidental single tracks

- Experimental principles
  - atic rejection
  - e timing
  - etoes
  - , e ID
  - rate 750 MHz
  - Downstream rate 10 MHz

- R&D finished in 2010
- 2010-2012: construction
- End 2012: first technical run
- Physics data taking to begin after CERN machine shutdown



Conclusions

- K decays are a very appealing laboratory to test NP effects
  - Good sensitivity and precise experimental results.
  - Complementarity to B physics in most of the cases.
- R_K measurement:
  - The NA62 measurement of R_K (40% of total data set) allows for a <0.5% relative precision, combined with the other world measurements.
  - The SM precision is still 1 order of magnitude better.
  - The complete NA62 data set will allow for a 0.4% precision.
  - NA62 phase-II could improve the precision down to 0.2% level.
- Studies of lepton number violation with NA48/2.
  - Upper limits on $BR(K^+ \to \pi^- \mu^+ \mu^+)$ improved of a factor 3.
- $BR(K^+ \to \pi^+ \nu\bar{\nu})$ measurement with NA62.
  - Compelling physics case thanks to the high sensitivity of this decay to NP.
  - 10% precision BR measurement in 2 years of data taking planned.
  - **Experiment under construction.**