Rare Kaon Decay Experiments at CERN

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on behalf of NA48/2 and NA62 collaborations

Outline:

1) Introduction to CERN kaon programme
2) Search for lepton number violation at NA48/2
3) Leptonic kaon decays at NA62-R_K
4) Prospects for LFV searches at NA62
5) Summary

Charged Lepton Flavour Violation conference

Lecce, Italy • 7 May 2013

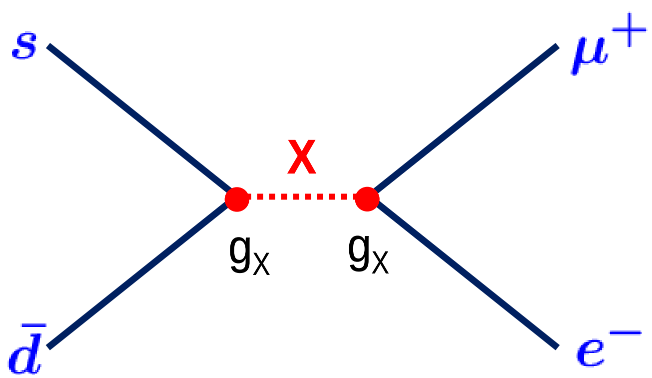
Introduction: LFV in K decays

Kaons historically competitive in searches for LFV phenomena:

- Copious production: high statistics.
- Simple decay topologies: clean experimental signatures.
- Source of tagged π^0 via $K^+ \to \pi^+\pi^0$, $K_L \to 3\pi^0$, ... :
  best limits for LFV π^0 decays.

High NP mass scales accessible for tree-level contributions

Example: $K_L \to \mu^+ e^-$



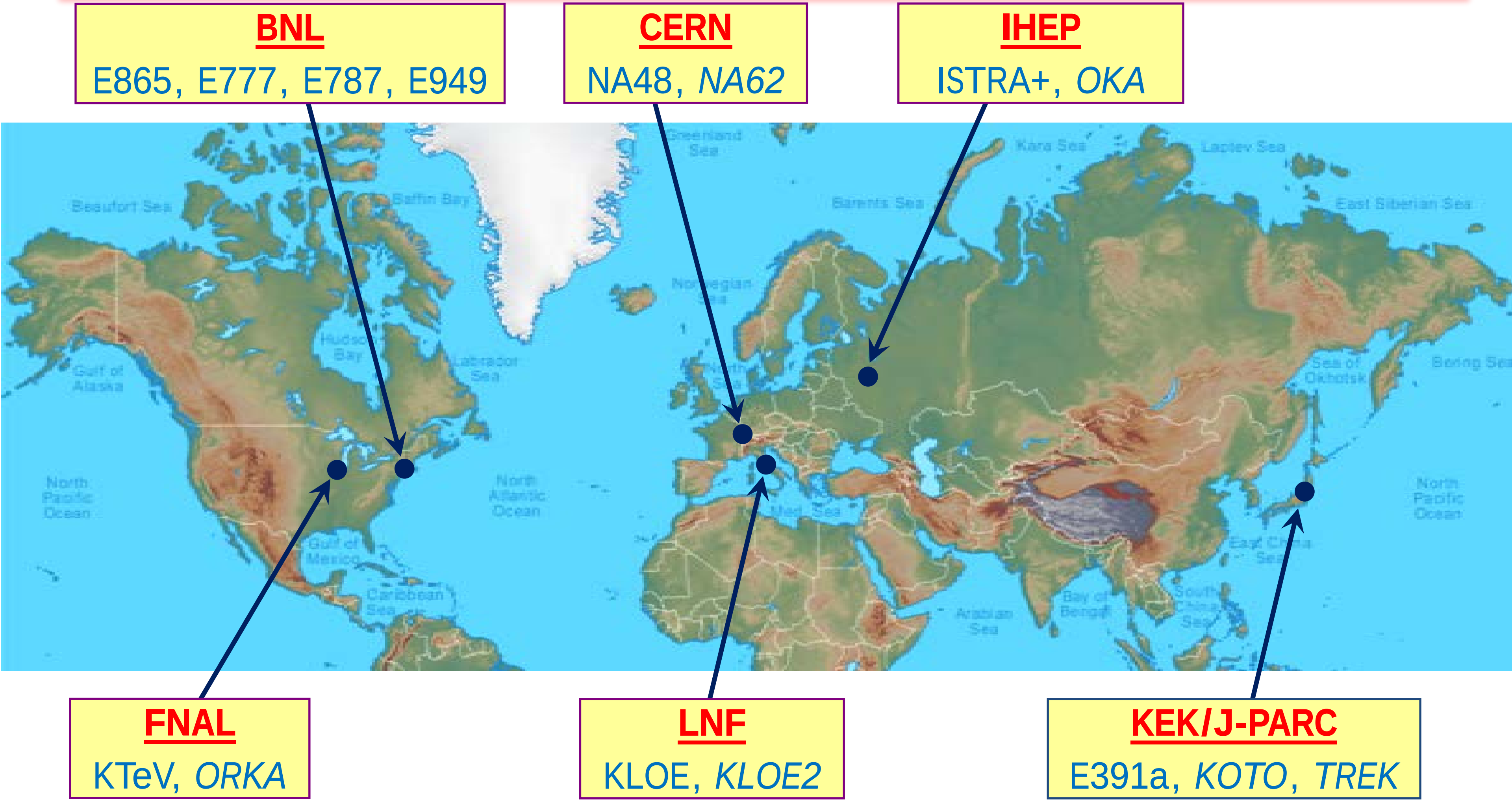
Dimensional argument:

$$\frac{\Gamma_X}{\Gamma_{SM}} \sim \left(\frac{g_X}{g_W} \cdot \frac{M_W}{M_X}\right)^4$$

For $g_X \approx g_W$ and $\mathcal{B} \sim 10^{-12}$,

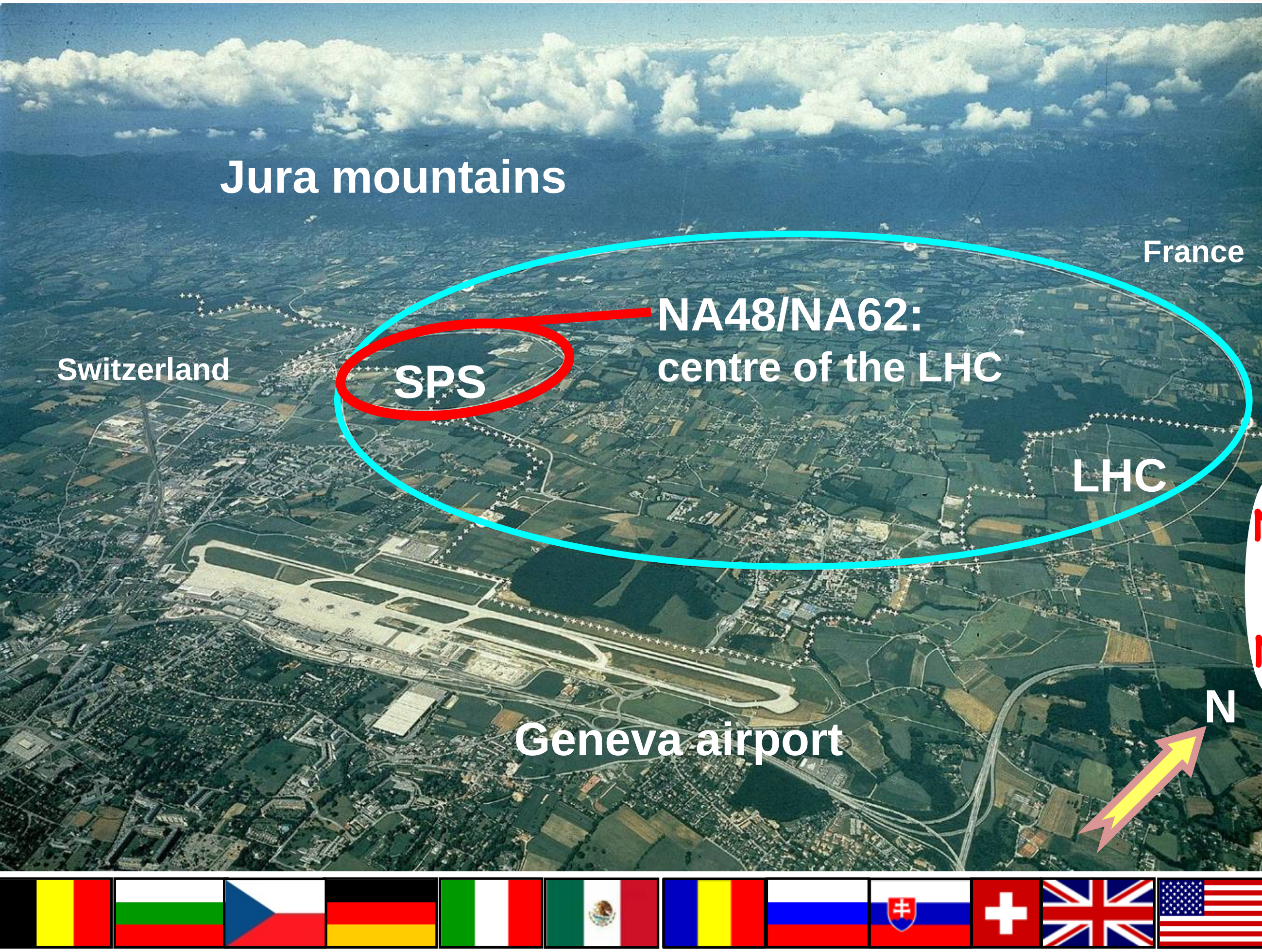
$$M_X \sim 100\ \text{TeV}$$

Kaon physics facilities



A variety of experimental techniques:
K decay-in-flight (e.g. CERN), stopped **K^+** and a ϕ factory

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: $K^\pm_{e2}/K^\pm_{\mu 2}$ | tests
- 2008: $K^\pm_{e2}/K^\pm_{\mu 2}$ | tests

NA62
- 2012: technical run
- *2014:* 1^{st} $K^+\rightarrow\pi^+\nu\bar{\nu}$ run

Kaon decay in flight experiments.
NA62: currently **~180** participants,
29 institutions, **12** countries

Recent $K^{\pm}$ experiments at CERN

Experiment	NA48/2 ($K^{\pm}$)	NA62-R_K ($K^{\pm}$)	*NA62* *(K^{+}; planned)*
Data taking period	**2003–2004**	**2007–2008**	**2014–2017**
Beam momentum, GeV/c	**60**	**74**	**75**
RMS momentum bite, GeV/c	**2.2**	**1.4**	**0.8**
Spectrometer thickness, X_0	**2.8%**	**2.8%**	**1.8%**
Spectrometer P_T kick, MeV/c	**120**	**265**	**270**
$M(K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-})$ resolution, MeV/c^2	**1.7**	**1.2**	**0.8**
K decays in fiducial volume	**1.9×10^{11}**	**2.5×10^{10}**	**1.2×10^{13}**
Main trigger	Three-track; **$K^{\pm}\to\pi^{\pm}\pi^{0}\pi^{0}$**	**$e^{\pm}$**	**$K_{\pi\nu\nu}$ + ...**

Same detector (NA48)

The new NA62 detector:

- beam spectrometer and kaon tagger;
- improved mass reconstruction and particle identification;
- hermetic photon veto.

LFV searches in $K^{\pm}$ and π^0 decays

Mode	UL at 90% CL	Experiment	Reference
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL E777/E865	PRD 72 (2005) 012005
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL E865*	PRL 85 (2000) 2877
$K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$	1.1×10^{-9}	CERN NA48/2	PLB 697 (2011) 107
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva-Saclay	PL 62B (1976) 485
$K^+ \to e^-\nu\mu^+\mu^+$	no data		
$\pi^0 \to \mu^+e^-$	3.6×10^{-10}	FNAL KTeV	PRL 100 (2008) 131803
$\pi^0 \to \mu^-e^+$	3.6×10^{-10}		

* CERN NA48/2 sensitivities for these 3 modes are similar to those of BNL E865

Expected NA62 single event sensitivities:
~10^{-12} for $K^{\pm}$ decays, **~10^{-11}** for π^0 decays.

→ *NA62 should be able to improve on all these decay modes*

Searches for Lepton Number Violation at NA48/2

Data taking: 2003–2004

NA48/2 and NA62-R_K detector

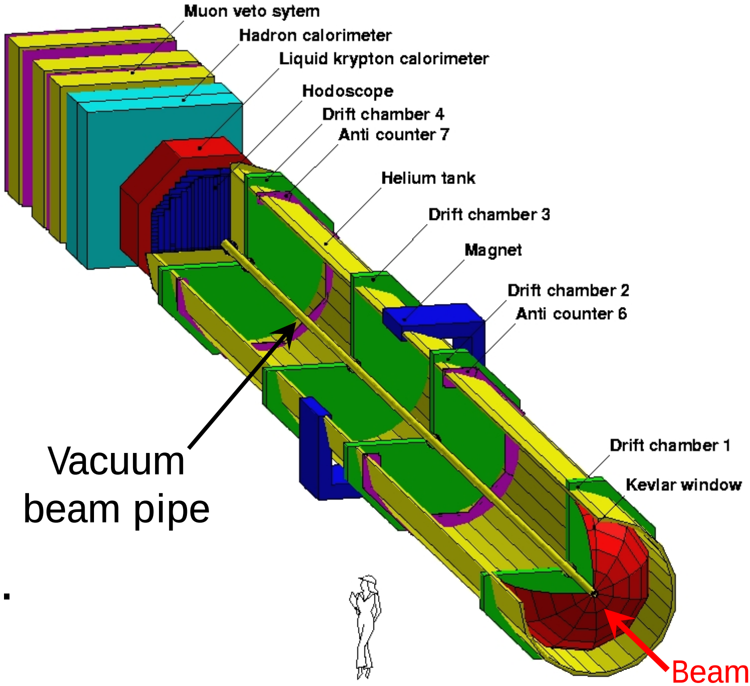
2003–2008: charged kaon beams,
the NA48 detector

Narrow momentum band $K^{\pm}$ beams:
P_K= 60 (74) GeV/c, $\delta P_K/P_K$ ~ 1% (rms).

- **NA48/2:** six months in 2003–04;
- **NA62-R_K:** four months in 2007.

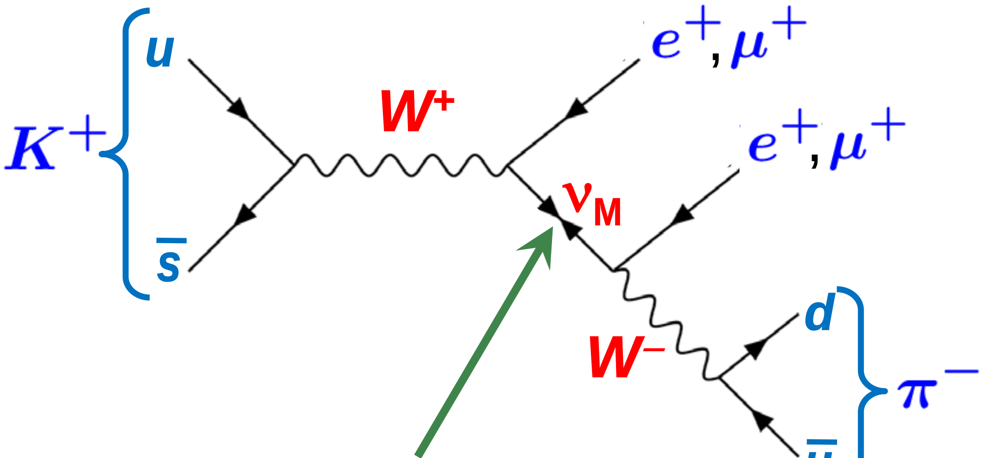
Principal subdetectors:

- Magnetic spectrometer (4 DCHs)
  4 views/DCH: redundancy $\Rightarrow$ efficiency;
  $\delta p/p = 0.48\% + 0.009\%p$ [GeV/c] (in 2007)
- Scintillator hodoscope
  Fast trigger, 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];
  $\sigma_x=\sigma_y=4.2mm/E^{1/2} + 0.6mm$ (1.5mm@10GeV).



NA48/2: $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$

$$K^+ \to \pi^- \ell_1^+ \ell_2^+, \quad \ell = e, \mu$$



Neutrino propagator

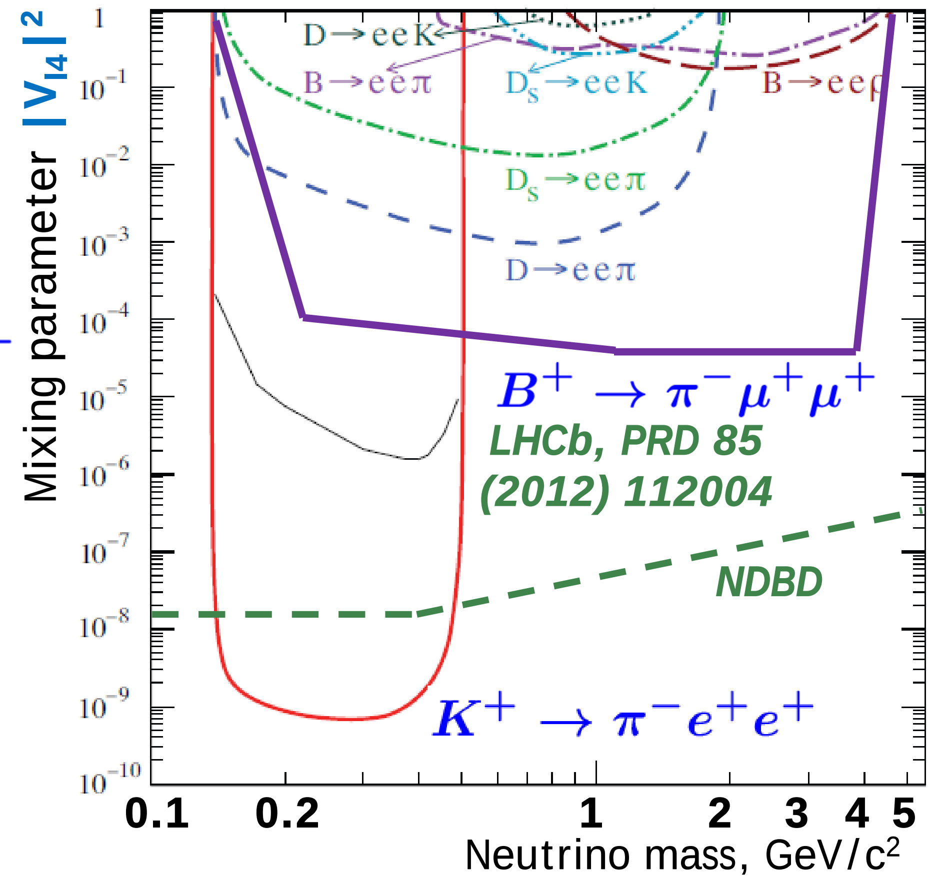
$$\frac{1}{q^2 - m_\nu^2}$$

→ resonant enhancement for

$$m_\pi \lesssim m_\nu \lesssim m_K$$

Littenberg and Shrock, PLB491 (2000) 285

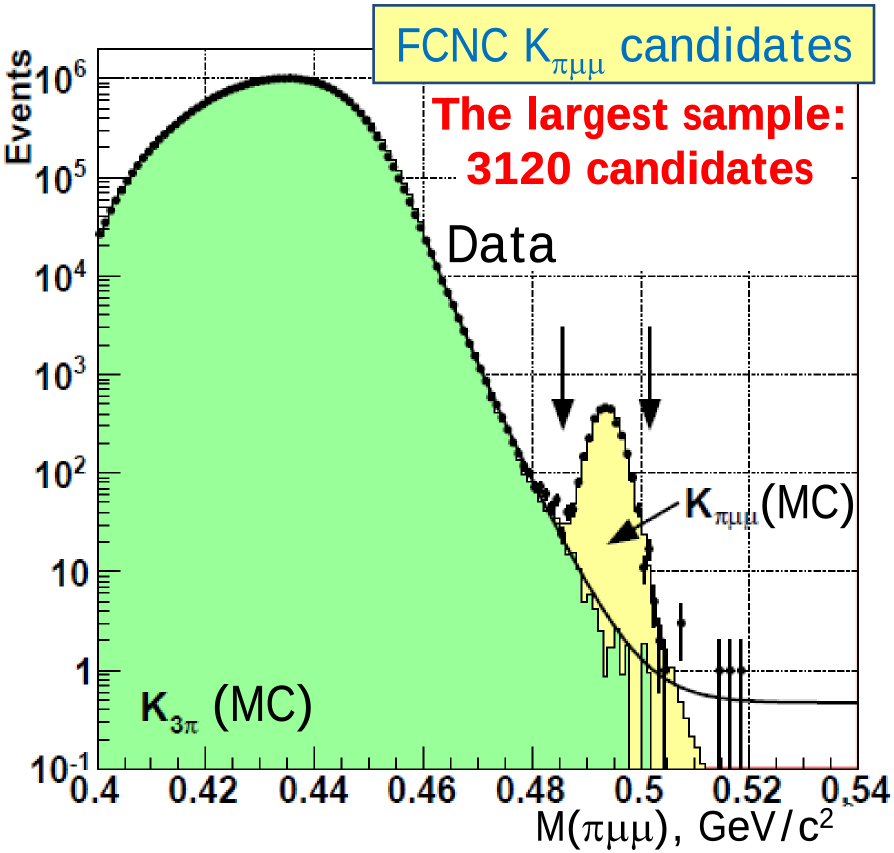
Majorana neutrino exclusion regions

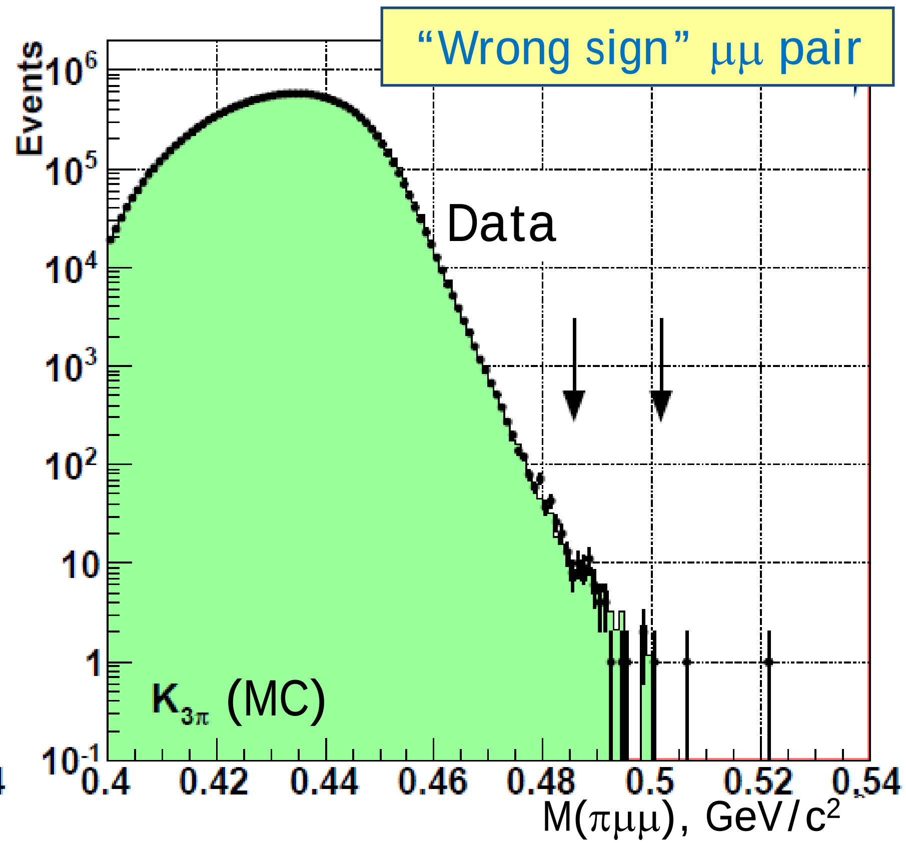


Plot from Atre et al., JHEP 0905 (2009) 030

NA48/2 $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$ upper limit

PLB 697 (2011) 107



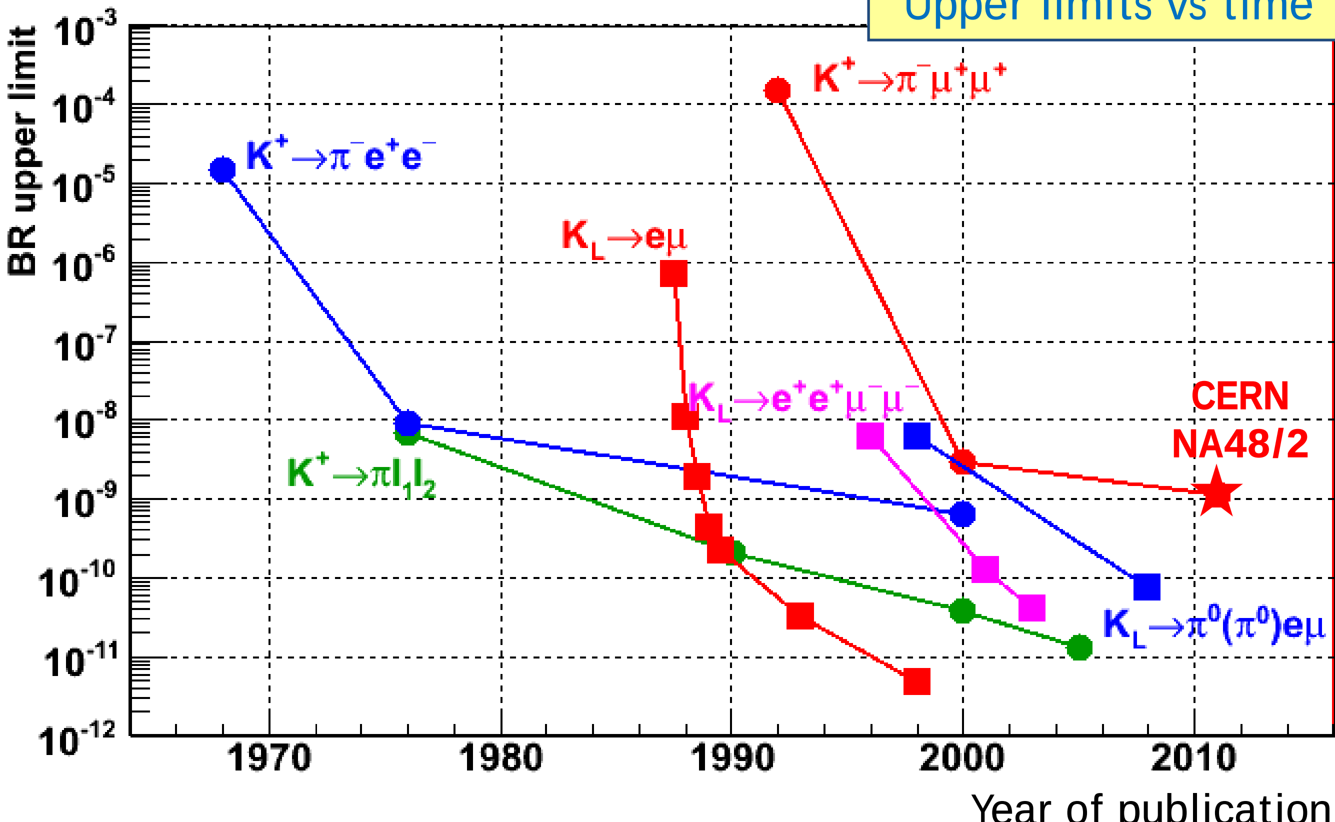


N_{data} = 52
N_{bkg} = 52.6±19.8$_{syst.}$ ⟹ $\mathcal{B}(K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1\times10^{-9}$ **@90% CL**

- ❖ Precision limited by background from $\pi^{\pm}\to\mu^{\pm}\nu$, despite **SES ≈ 3×10^{-11}**.
- ❖ Flat phase space assumed (rather than Majorana neutrino exchange).

NA48/2 $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$ upper limit

Upper limits vs time



$$\mathcal{B}(K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1\times 10^{-9}$$

- Previous BNL E865 limit improved by a factor **~3**.
- By-product of the $K^{\pm}\to\pi^{\pm}\mu^{\pm}\mu^{\mp}$ analysis: non-optimized procedure.
- A dedicated re-analysis has a potential sensitivity of **$\sim 10^{-10}$**.

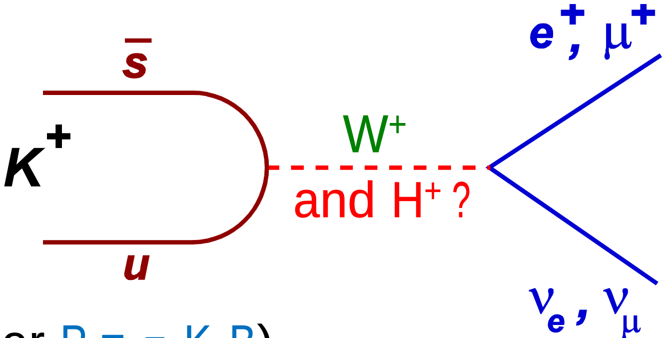
Leptonic Kaon Decays at NA62-R_K

Data taking: 2007–2008

Leptonic meson decays

Light leptons: SM contribution suppressed by angular momentum conservation

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



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, PRD 48 (1993) 2342;
Isidori, Paradisi, PLB 639 (2006) 499

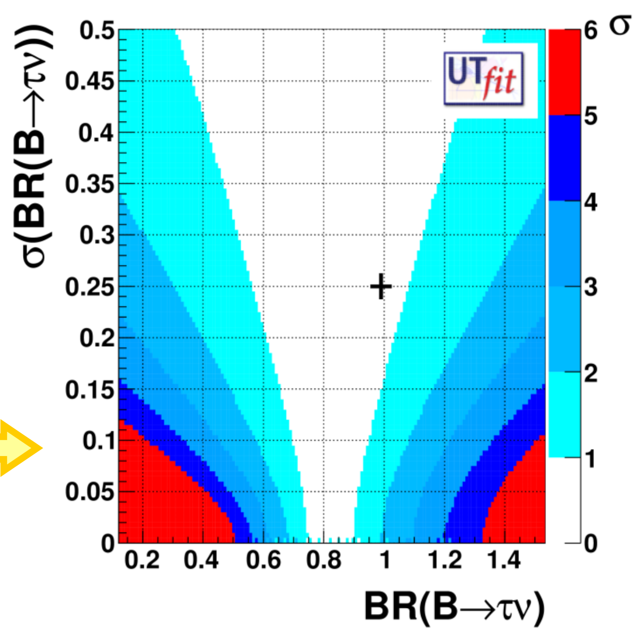
$\pi^+\to l^+\nu$: $|\Delta\Gamma/\Gamma_{SM}| \sim 2(m_\pi/m_H)^2\, m_d/(m_u+m_d)\, \tan^2\beta \sim 10^{-4}$
$K^+\to l^+\nu$: $|\Delta\Gamma/\Gamma_{SM}| \sim 2(m_K/m_H)^2 \tan^2\beta \sim 10^{-3}$

... smaller than SM prediction uncertainties (f_P, V_{CKM})

Potentially larger effect in $B^+\to\tau^+\nu$:

Experiment: $BR_{exp}(B^+\to\tau^+\nu) = (0.99\pm0.25)\times10^{-4}$

SM: $BR_{SM}(B^+\to\tau^+\nu) = (0.83\pm0.08)\times10^{-4}$



(UTfit, winter 2013)

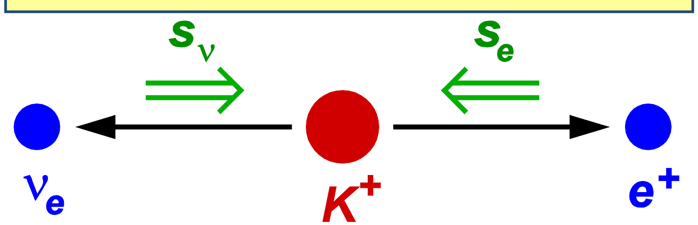
$R_K = BR(K_{e2})/BR(K_{\mu 2})$ in the SM

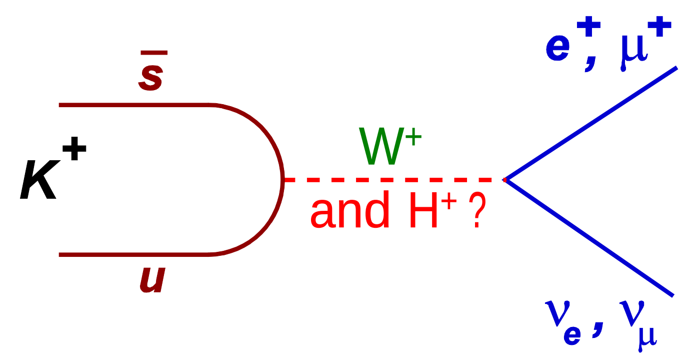
Lepton Universality test:

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

Radiative correction (well known, few %)

Helicity suppression: f~10^{-5}





- **SM**: excellent sub-permille accuracy, not obstructed by hadronic uncertainties.
- Measurements of R_K and R_π have long been considered as LU tests.
- **Suppression of the SM contribution**: potentially accessible NP contributions.

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

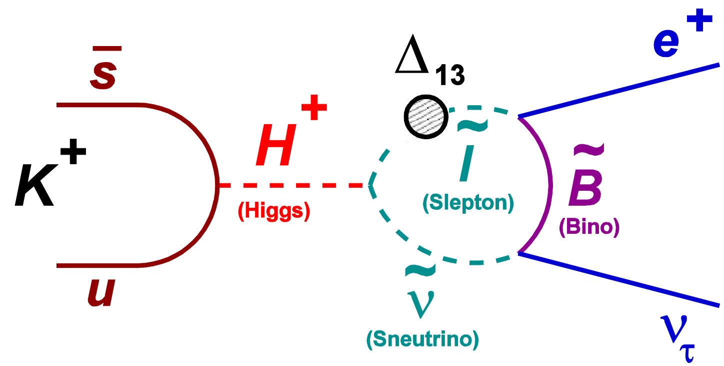
Cirigliano and Rosell, PRL99 (2007) 231801

R_K beyond the SM

2HDM - tree level

$K^\pm \to l^\pm\nu$ can proceed via charged Higgs $H^\pm$ (in addition to $W^\pm$) exchange

→ 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 and Petronzio, PRD 74 (2006) 011701, JHEP 0811 (2008) 042

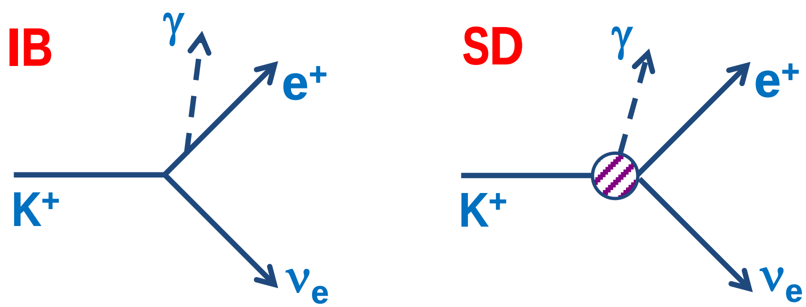
$$R_K^{LFV} \approx R_K^{SM}\left[1+\left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{M_e^2}\right)|\Delta_{13}|^2\tan^6\beta\right]$$

⇒ sensitive to slepton mixing

- MSSM: **~1%** effect possible
  Girrbach and Nierste, arXiv:1202.4906
- However limited by the recent $B_{(S)}\to\mu^+\mu^-$ measurements
  Fonseca, Romão and Teixeira, EPJC 72 (2012) 2228
- Sensitive to SM extensions with 4th generation, sterile neutrinos
  Lacker and Menzel, JHEP 1007 (2010) 006; Abada et al., JHEP 1302 (2013) 048

The radiative $K^{\pm}\rightarrow e^{\pm}\nu\gamma$ decay

R_K is inclusive of IB radiation by definition.
SD: background.

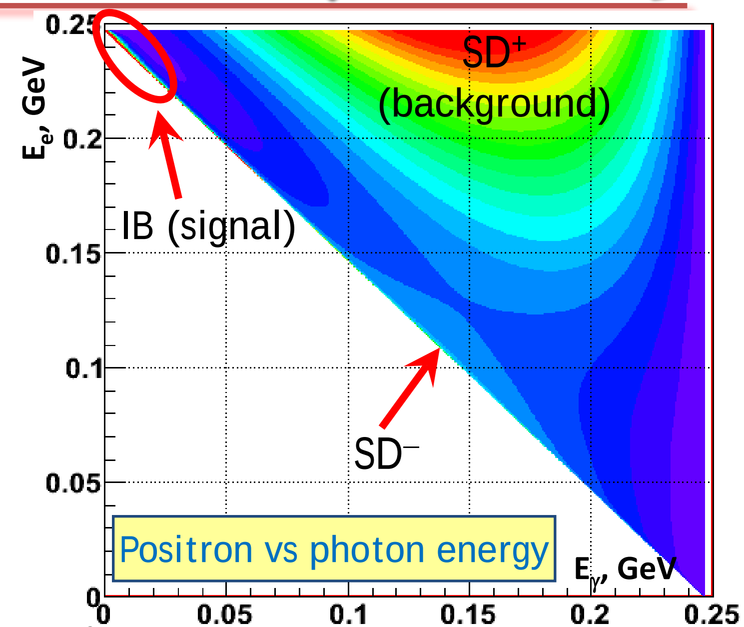


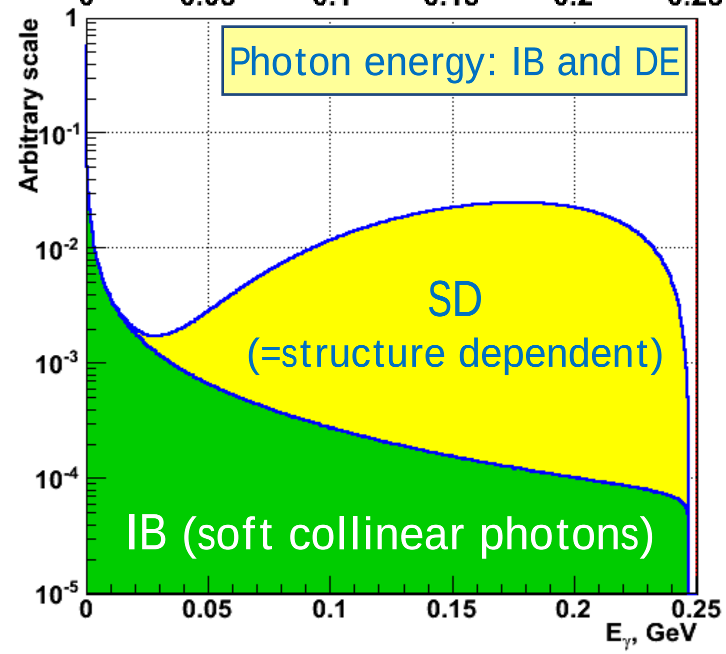
SD component is not helicity suppressed:
$BR(K^{+}\rightarrow e^{+}\nu\gamma$ SD) ~ $BR(K^{+}\rightarrow e^{+}\nu)$

Background subtraction uses external input:
KLOE measurement of the form factor leads to
$BR(SD^{+}) = (1.37\pm0.06)\times10^{-5}$.

EPJC 64 (2009) 627

Background: **$B/(S+B) = (2.60\pm0.11)\%$**

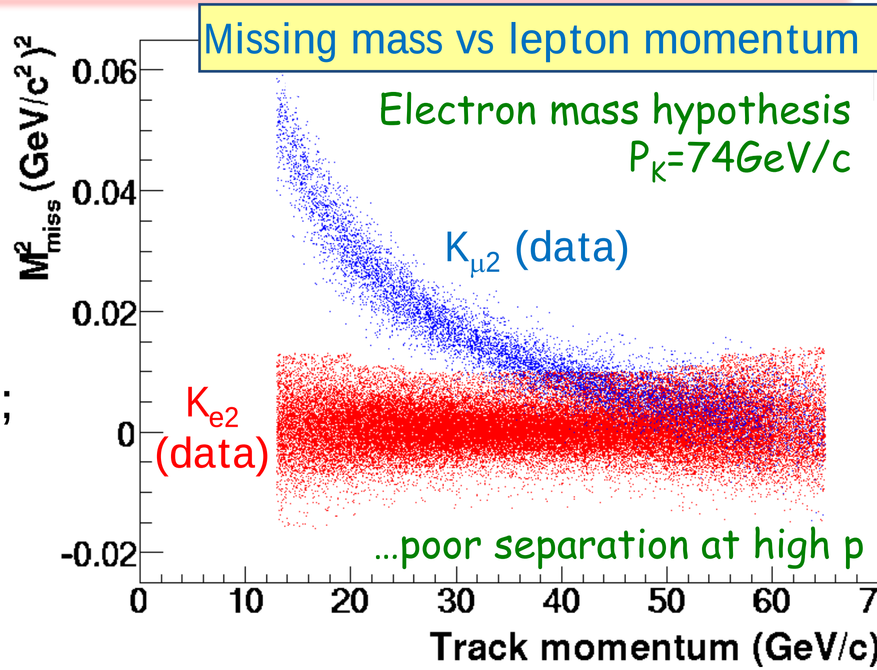




K_{e2} vs $K_{\mu2}$ selection

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: $13\text{GeV}/c<p<65\text{GeV}/c$.



Kinematic identification

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

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

→ sufficient $K_{e2}/K_{\mu2}$ separation at $p_{lepton}<30\text{GeV}/c$

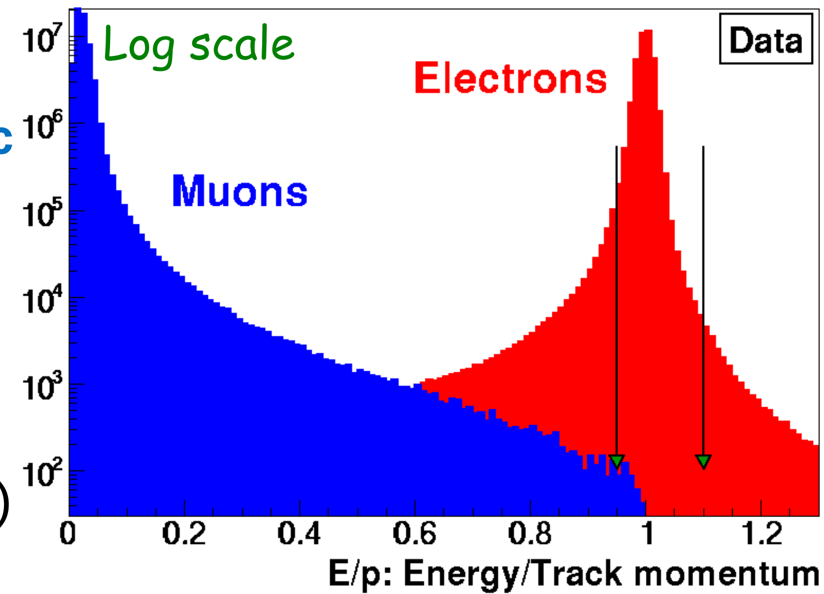
Lepton identification

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

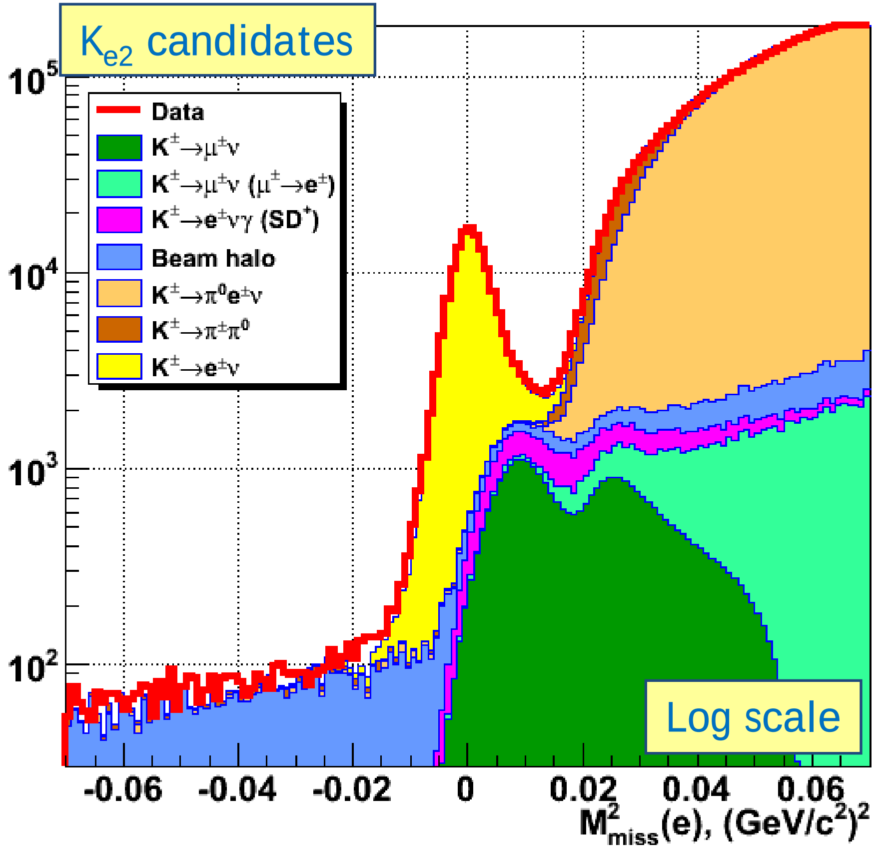
(0.90 to 0.95)<E/p<1.10 for electrons,

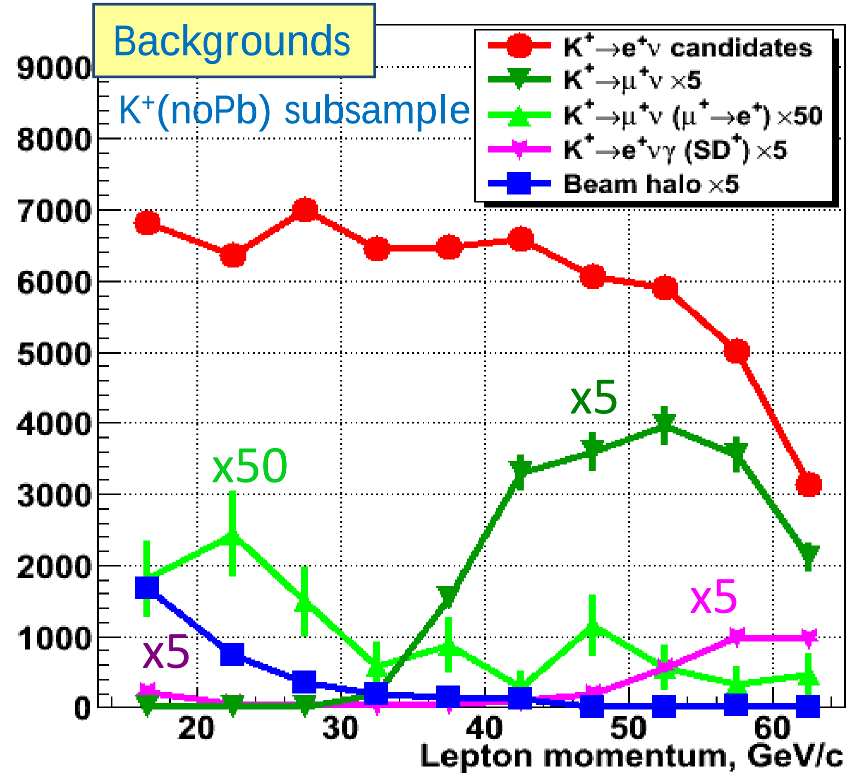
E/p<0.85 for muons.

→ powerful $\mu^\pm$ suppression in $e^\pm$ sample ($\sim 10^6$)



The K_{e2} sample





145,958 $K^{\pm}\to e^{\pm}\nu$ candidates.
Background: $B/(S+B)=(10.95\pm0.27)\%$.
Electron ID efficiency: $(99.28\pm0.05)\%$.

Source	B/(S+B)
$K_{\mu2}$	$(5.64\pm0.20)\%$
$K_{\mu2}$ ($\mu\to e$)	$(0.26\pm0.03)\%$
$K_{e2\gamma}$ (SD)	$(2.60\pm0.11)\%$
$K_{e3(D)}$	$(0.18\pm0.09)\%$
$K_{2\pi(D)}$	$(0.12\pm0.06)\%$
Opposite sign K	$(0.04\pm0.02)\%$
Muon halo	$(2.11\pm0.09)\%$
Total	$(10.95\pm0.27)\%$

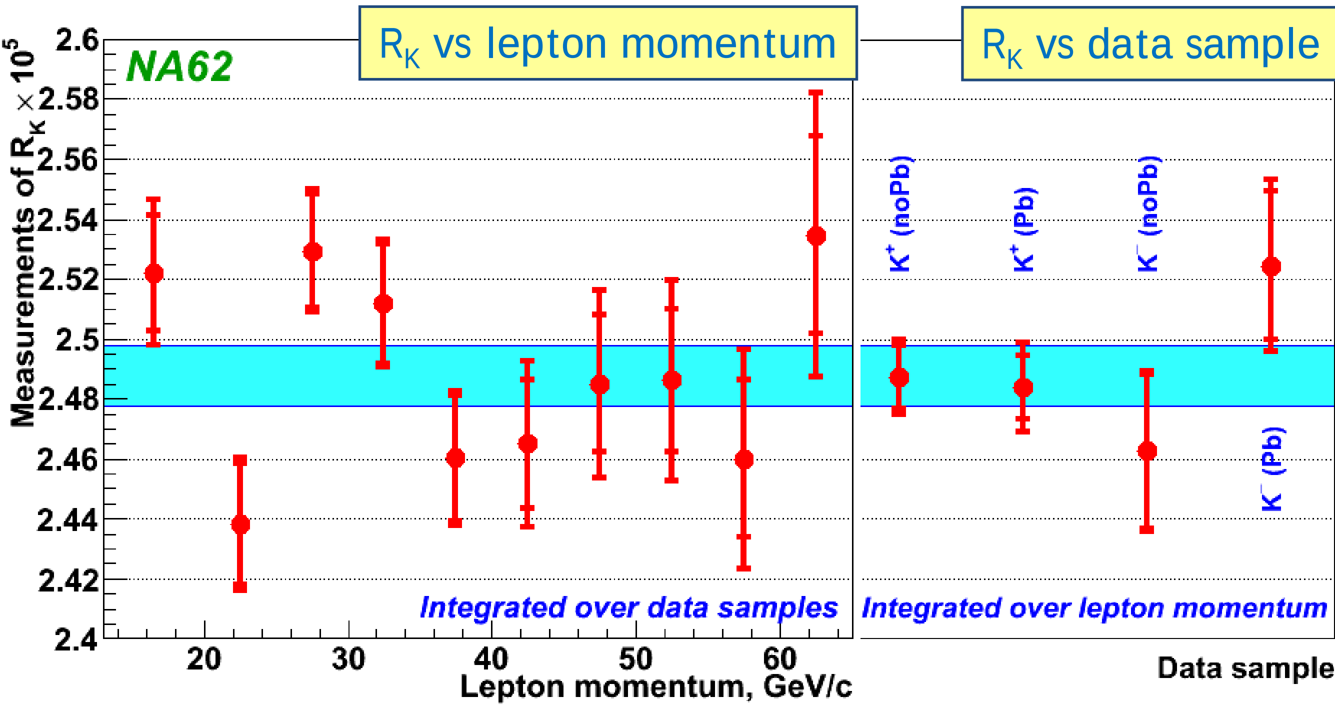
NA62-R_K final result

PLB 719 (2013) 326

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

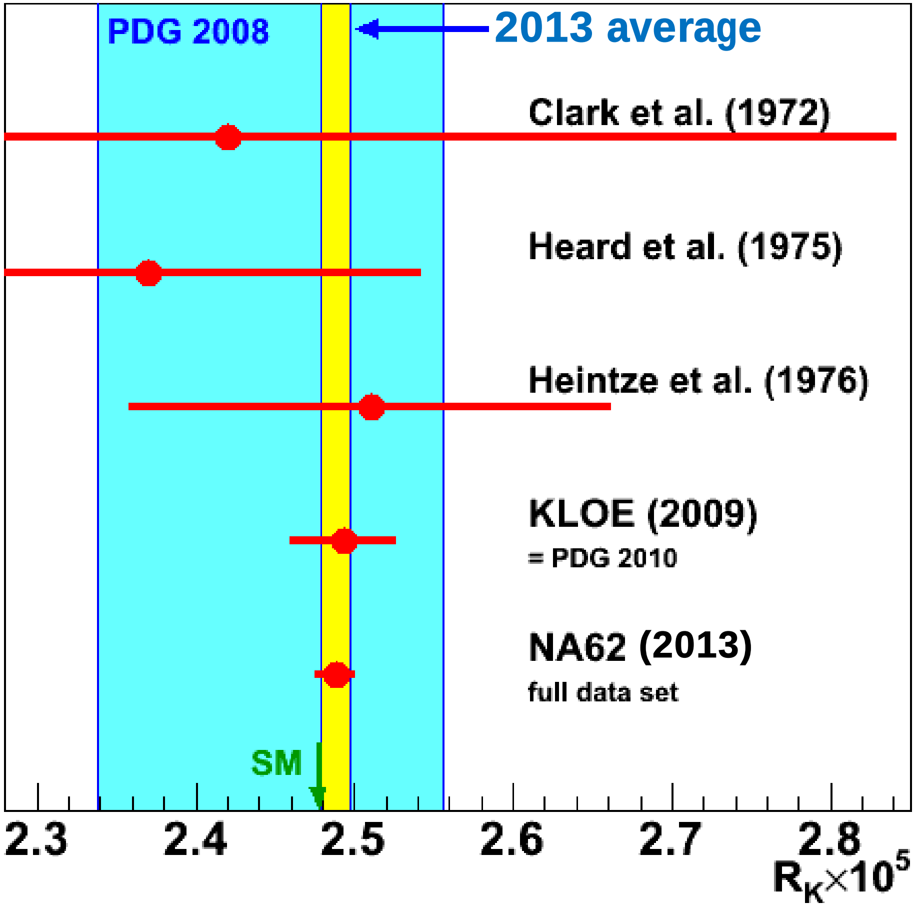
Fit over **40** measurements
(**4** data samples × **10** momentum bins)
including correlations: χ^2/ndf=47/39

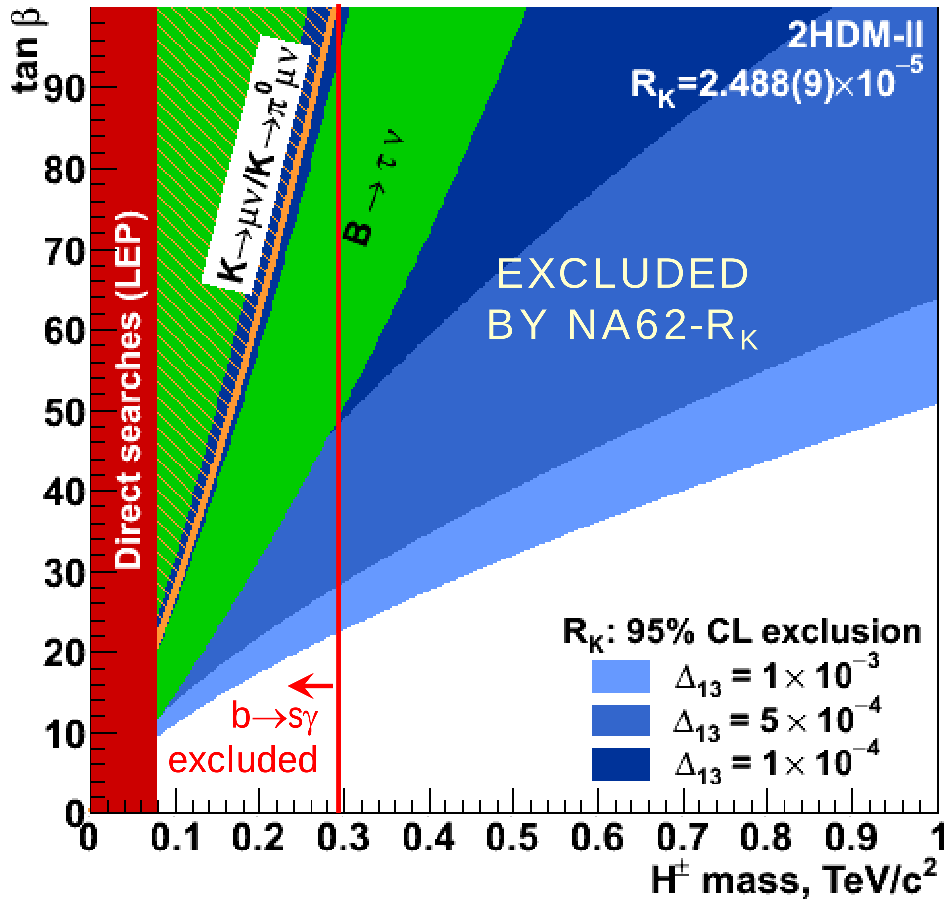
Uncertainty source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$ background	0.004
$K^\pm \to e^\pm \nu\gamma$ (SD$^+$)	0.002
$K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$	0.003
Beam halo background	0.002
Matter composition	0.003
Acceptance correction	0.002
DCH alignment	0.001
Electron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



NA62 prospects: improve the uncertainty by a factor ~2

R_K world average



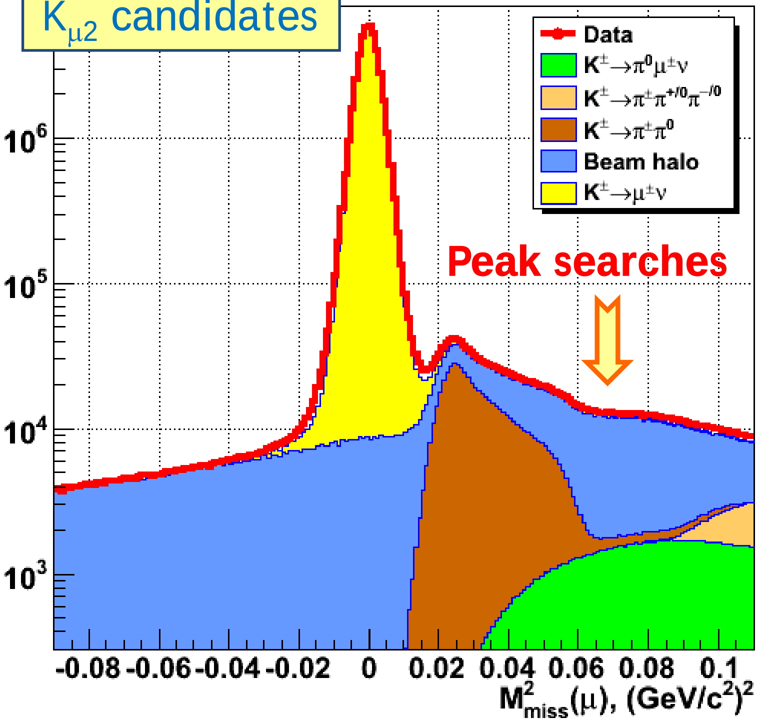


World average	$R_K\times10^5$	Precision
PDG 2008	2.447±0.109	4.5%
2013	2.488±0.009	0.4%

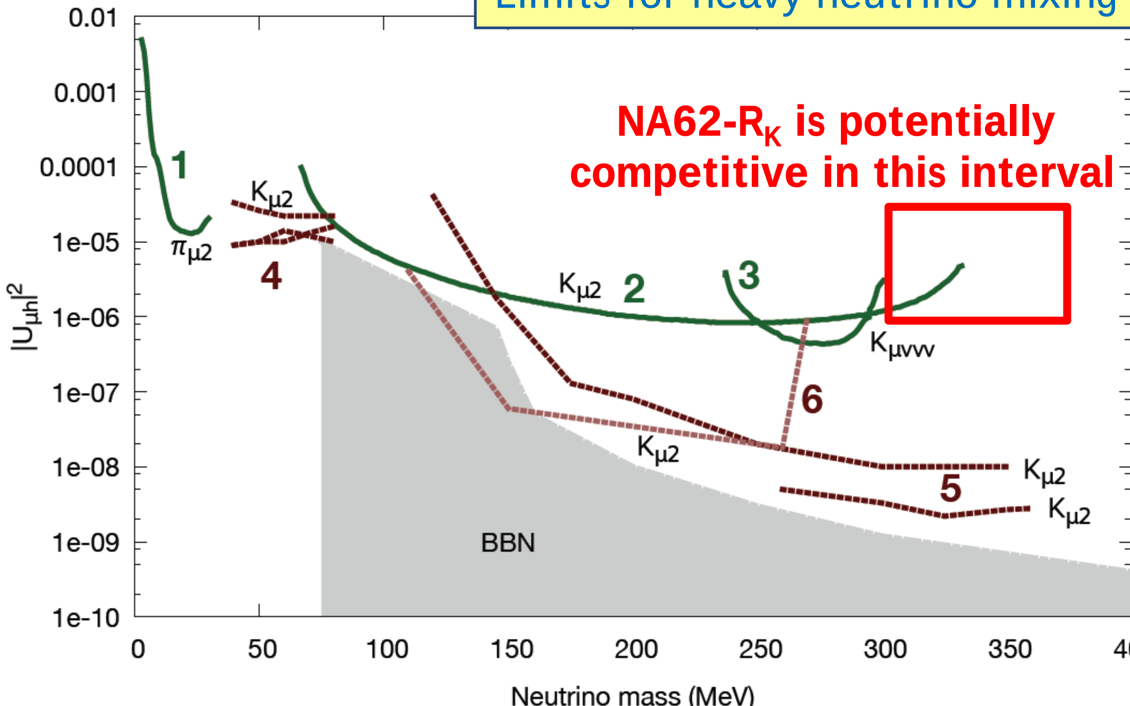
Other limits on 2HDM-II:
PRD 82 (2010) 073012.

$K_{\mu 2}$: heavy sterile neutrinos

$K_{\mu 2}$ candidates



Limits for heavy neutrino mixing



NA62-R_K subsample: 18.0M $K^+\to\mu^+\nu_\mu$.

→ Search for heavy sterile neutrino: $K^+\to\mu^+N$.

- NA62-R_K UL if no backgrounds: $|U_{\mu N}|^2<10^{-7}$, **100 MeV/c² < M_N < 380 MeV/c²**.
- Sensitivity is limited by background subtraction (mainly the beam halo).
- NA62-R_K can be competitive at high M_N.

Peak searches (long-lived ν_h)

1. PSI, PLB 105 (1981) 263.
2. KEK, PRL 49 (1982) 1305.
3. LBL, PRD 8 (1973) 1989.

Decay searches (short-lived ν_h)

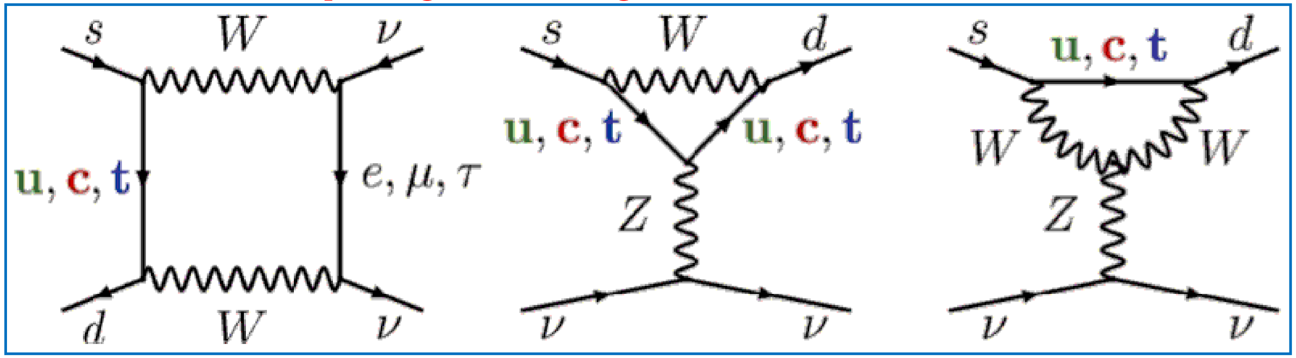
4. ISTRA+, PLB 710 (2012) 307.
5. CERN-PS191, PLB 203 (1988) 332
6. BNL-E949, preliminary

Prospects for LFV searches at the NA62 experiment

Expected data taking: 2014–2017

The challenge: $K \to \pi\nu\bar{\nu}$

SM: box and penguin diagrams



Ultra-rare decays with the highest CKM suppression:

$$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$$

- Hadronic matrix element related to a measured quantity ($K^+ \to \pi^0 e^+ \nu$).
- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from B–B mixing or $B^0 \to \rho\gamma$.
- Optimal probe for non-MFV *(Gino Isidori, ESPP open symposium 2012)*

SM branching ratios
Brod et al., PRD 83 (2011) 034030

Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	7.81±0.75±0.29
$K_L \to \pi^0 \nu\bar{\nu}$	2.43±0.39±0.06

CKM parametric ⇩ Intrinsic ⇩

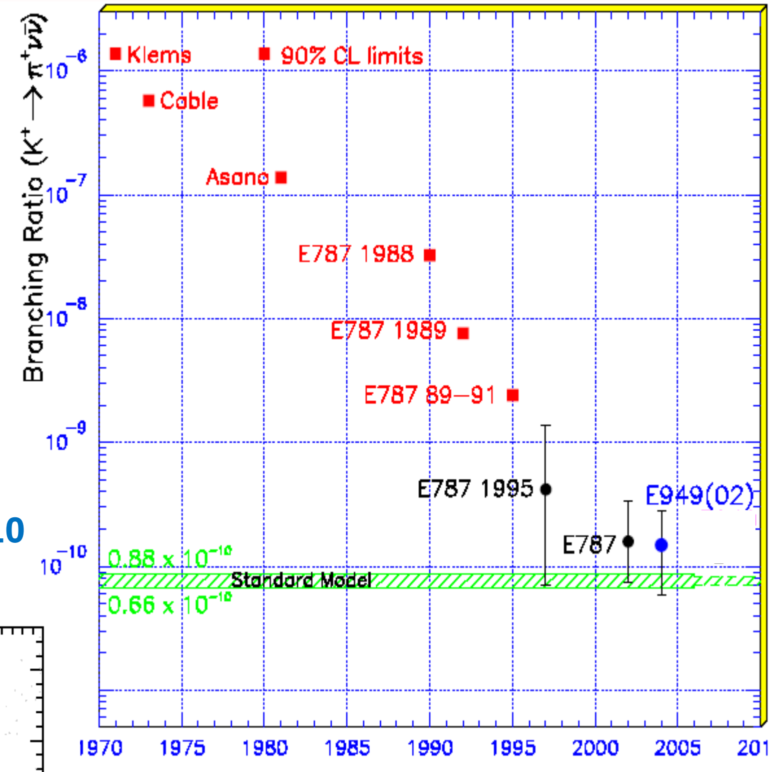
Theoretically clean, sensitive to new physics, almost unexplored

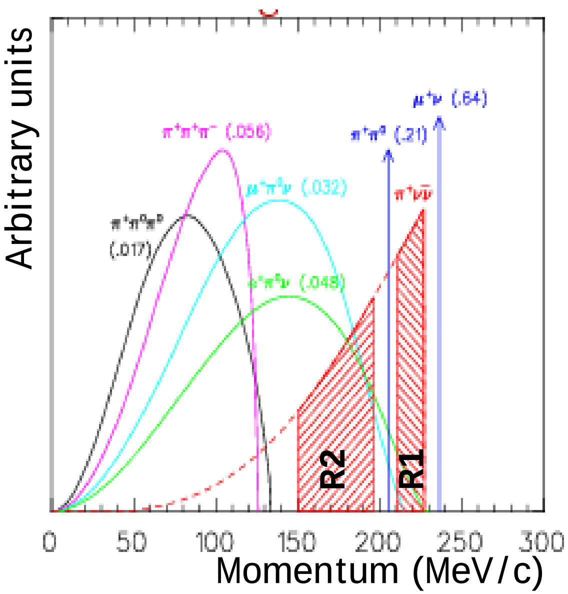
$K^+ \to \pi^+ \nu\bar{\nu}$ at BNL E747/E949

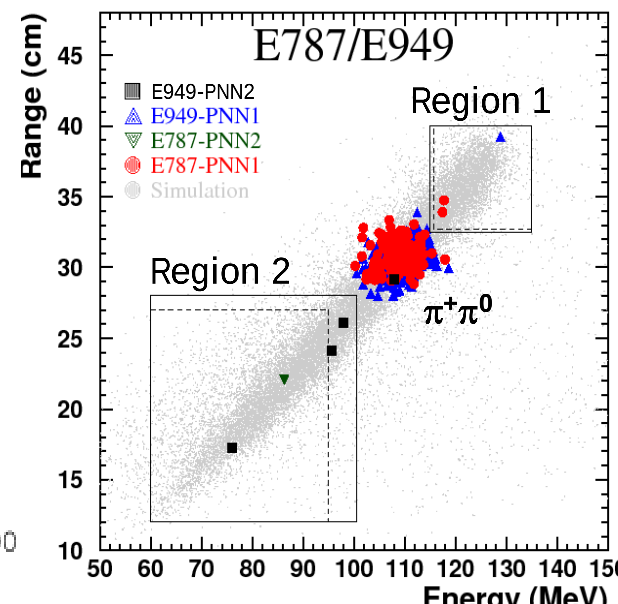
Technique: K^+ decay at rest

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





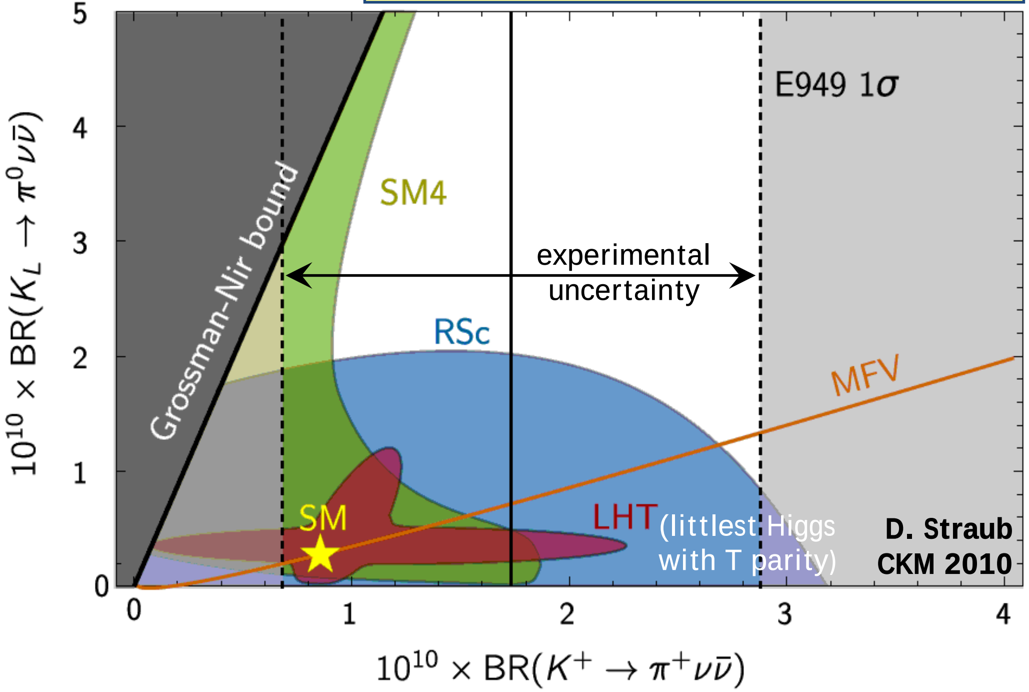


→ Significant background from the $K_{2\pi}$ decay (~30%) due to π^+ scattering in the target.

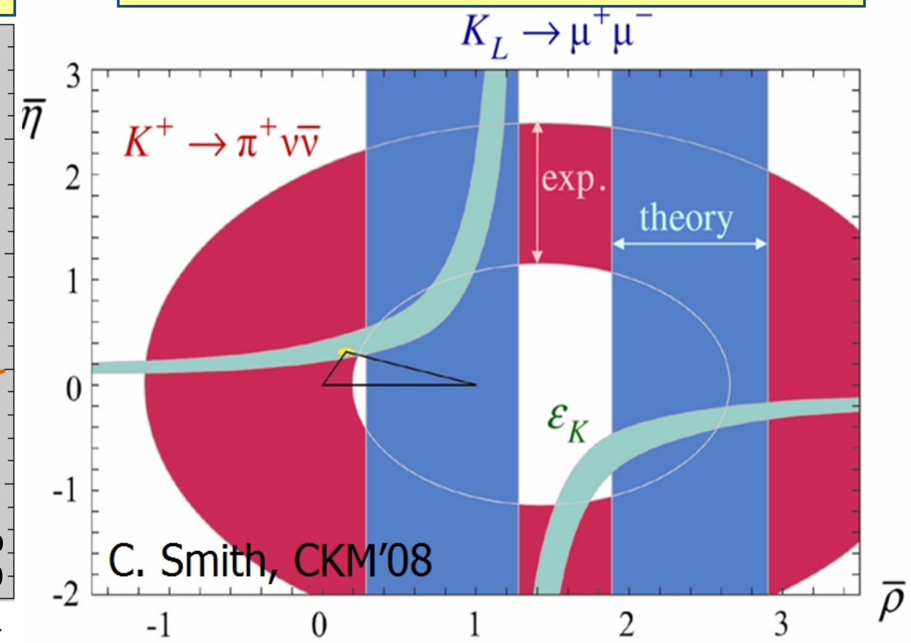
PRL 101 (2008) 191802; PRD 79 (2009) 092004

Experiment vs theory

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



CKM unitarity triangle with kaons



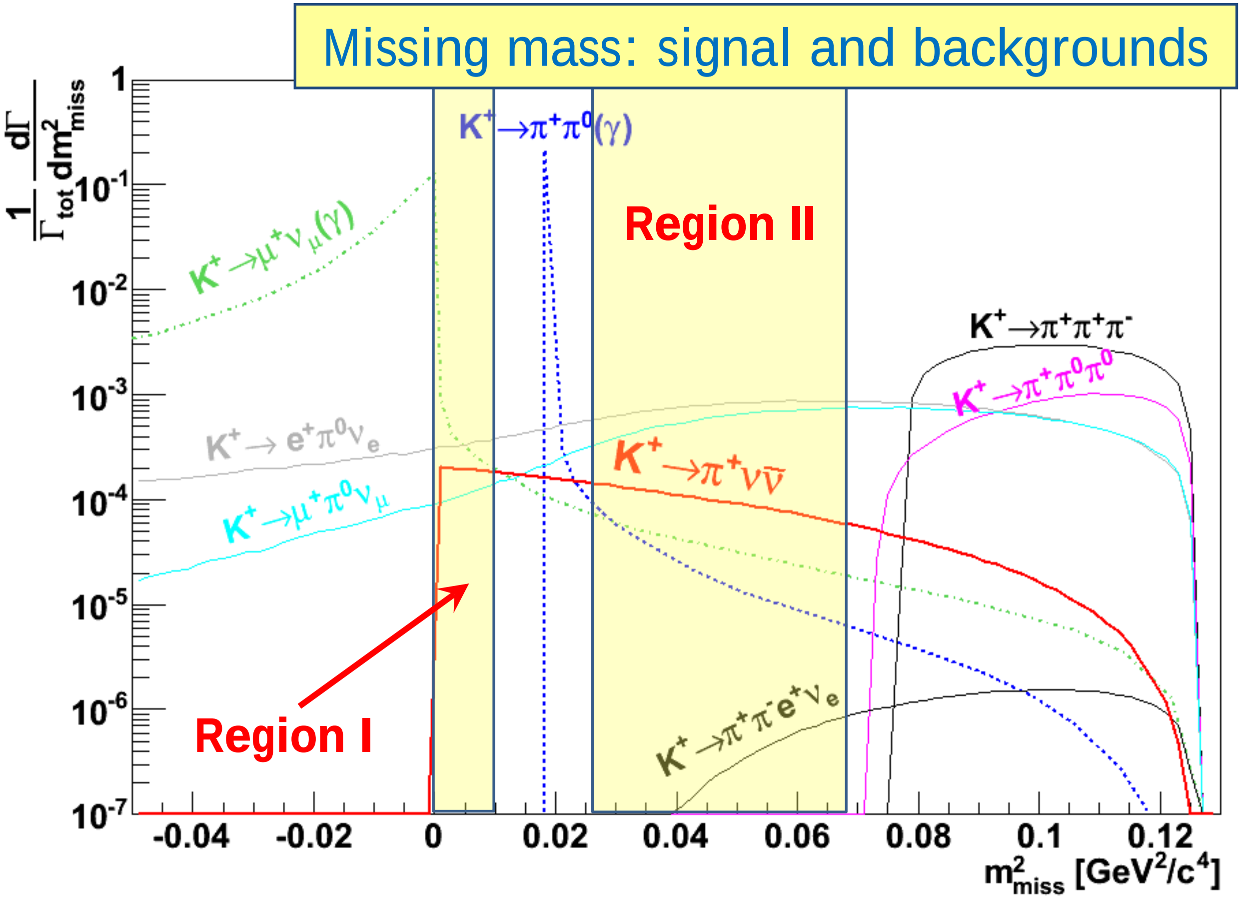
NA62 aim: collect O(100) SM $K^+ \to \pi^+ \nu\bar{\nu}$ decays with <20% background in 2 years of data taking using a novel decay-in-flight technique.

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

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

Un-separated beam (6% kaons) → higher rates, additional backgrounds.

NA62: $K_{\pi\nu\nu}$ signal region



92% of total background ($K_{\mu2}$, $K_{2\pi}$, $K_{3\pi}$)

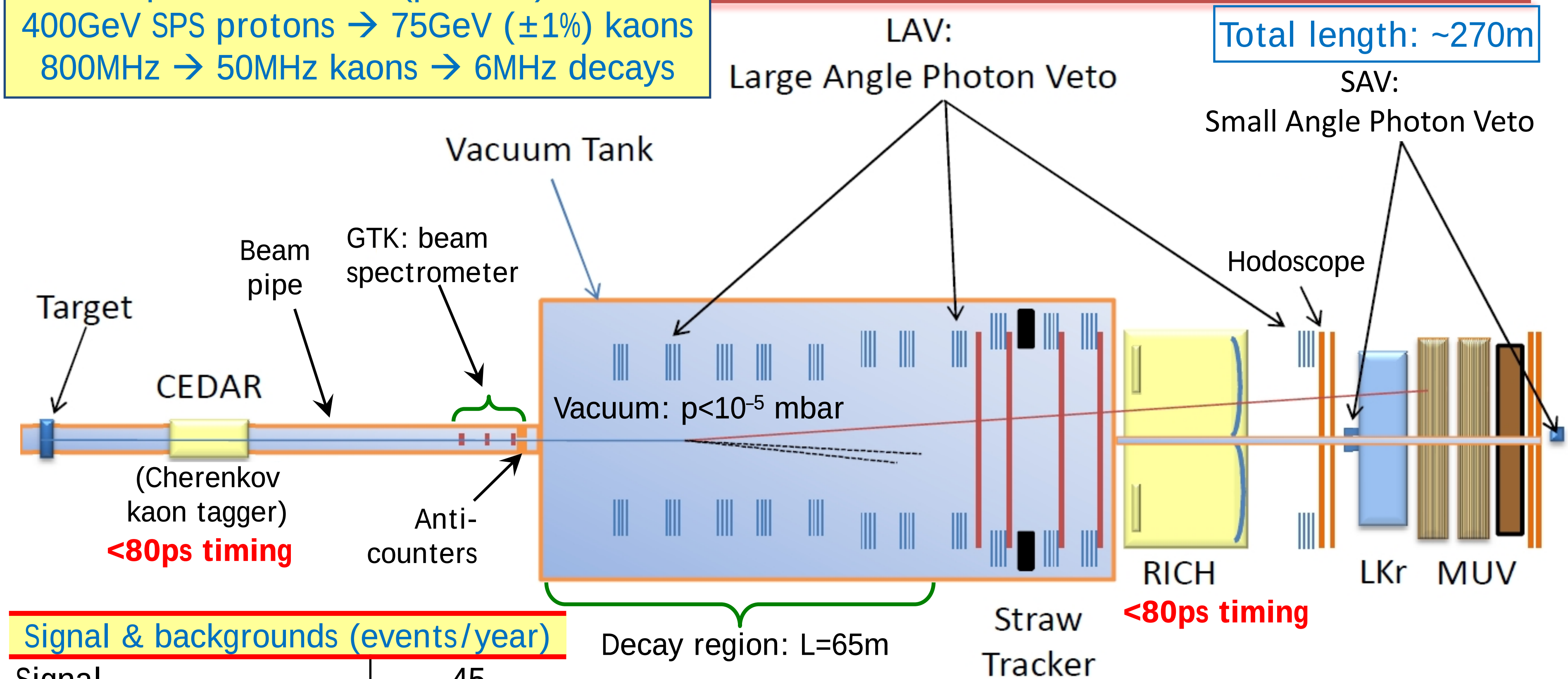
- Outside the signal kinematic region.
- Signal region is split into **Region I** and **Region II** by the $K^+\to\pi^+\pi^0$ peak.

8% of total background

- Span across the signal region
- Not rejected by kinematic criteria
- Rejection relies on vetoes/PID

NA62 detector

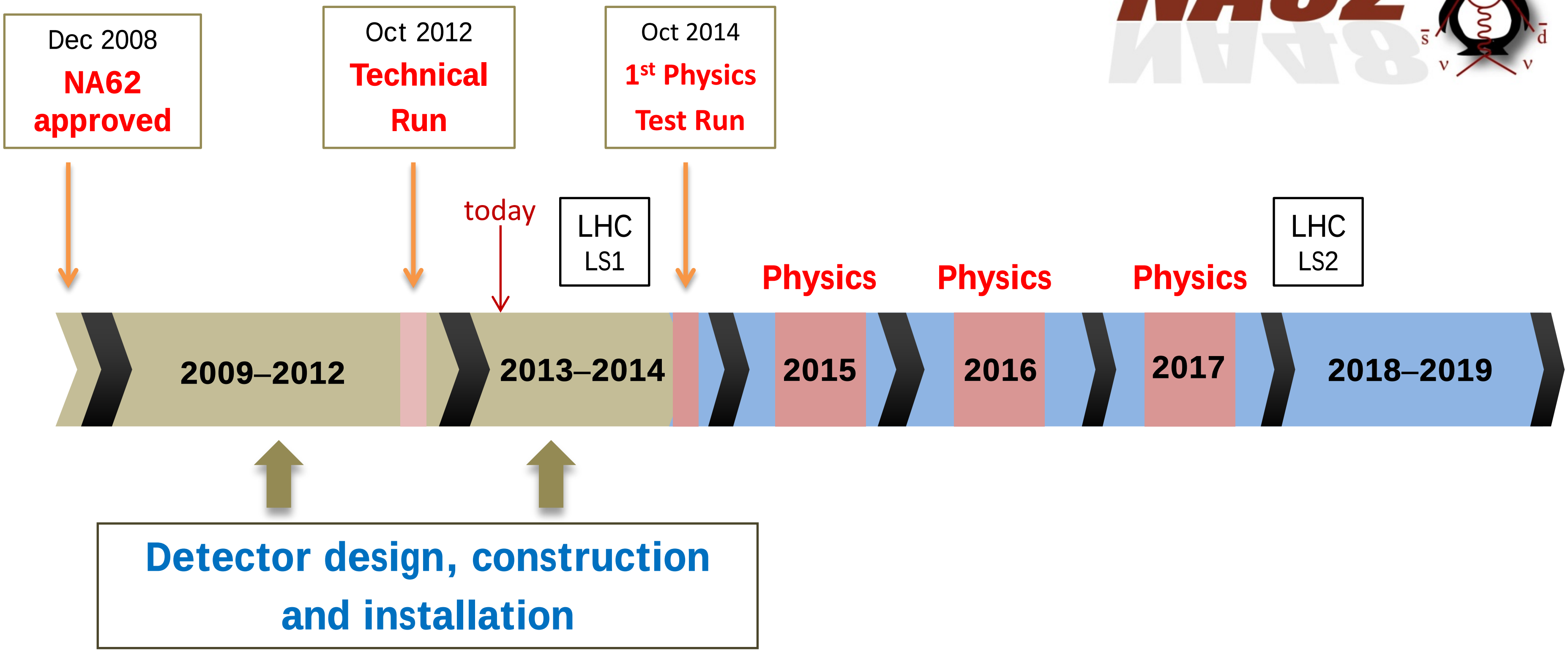
Un-separated hadron ($p/\pi^+/K^+$) beam:
400GeV SPS protons → 75GeV (±1%) kaons
800MHz → 50MHz kaons → 6MHz decays



Signal & backgrounds (events/year)	
Signal	45
$K^+\to\pi^+\pi^0$	5
$K^+\to\mu^+\nu$	1
$K^+\to\pi^+\pi^+\pi^-$	<1
Other 3-track decays	<1
$K^+\to\pi^+\pi^0\gamma$ (IB)	1.5
$K^+\to\mu^+\nu\gamma$ (IB)	0.5
Total background	**<10**

- Kinematic rejection factors (limited by beam pileup and tails of MCS): **5×10^3** for **$K^+\to\pi^+\pi^0$**, **1.5×10^4** for **$K\to\mu^+\nu$**.
- Photon veto: **~10^8** suppression of **$\pi^0\to\gamma\gamma$**.
- Particle ID: **~10^7** muon suppression.

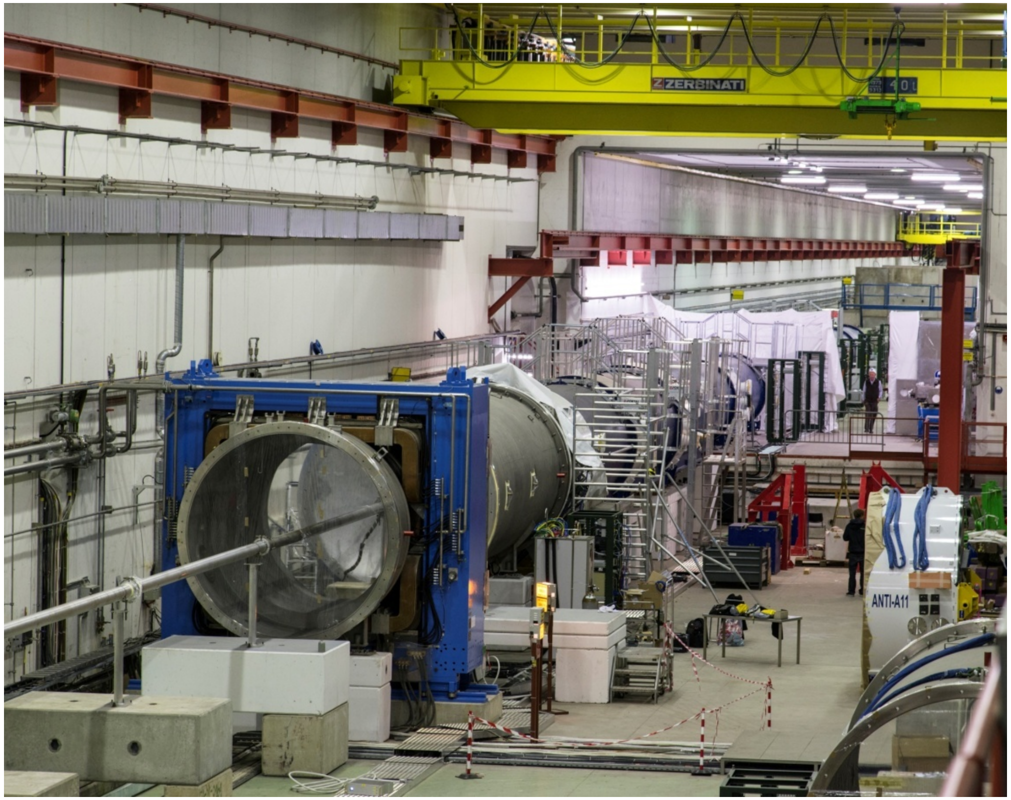
NA62 timeline



- 5 years of construction interleaved with a Technical Run in **October 2012**
- First Run with full detector in **2014**
- Plan 3 physics data taking runs before LHC Long Shutdown 2 (LS2)

NA62 installation

Vacuum tank view in 2012



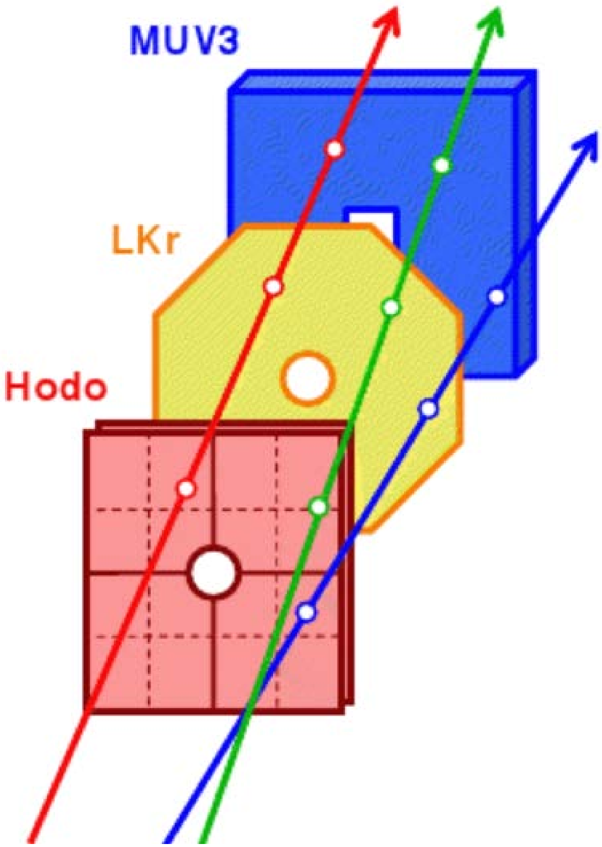
Photon veto (LAV) installation

Cherenkov kaon tagger (CEDAR+KTAG)

Triggering on lepton pairs

NA62 three-track decay rate upstream CHOD: **F_{3track} = 640 kHz**

→ **Too high** to collect all three-track decays (as NA48/2 did)



Available L0 trigger primitives:

- **Q_N**: at least N hodoscope quadrants;
- **$LKR_N(x)$**: at least N LKr clusters with energy E>x GeV;
- **MUV_N**: hits in at least N MUV3 pads.

Possible L0 triggers for LFV searches:

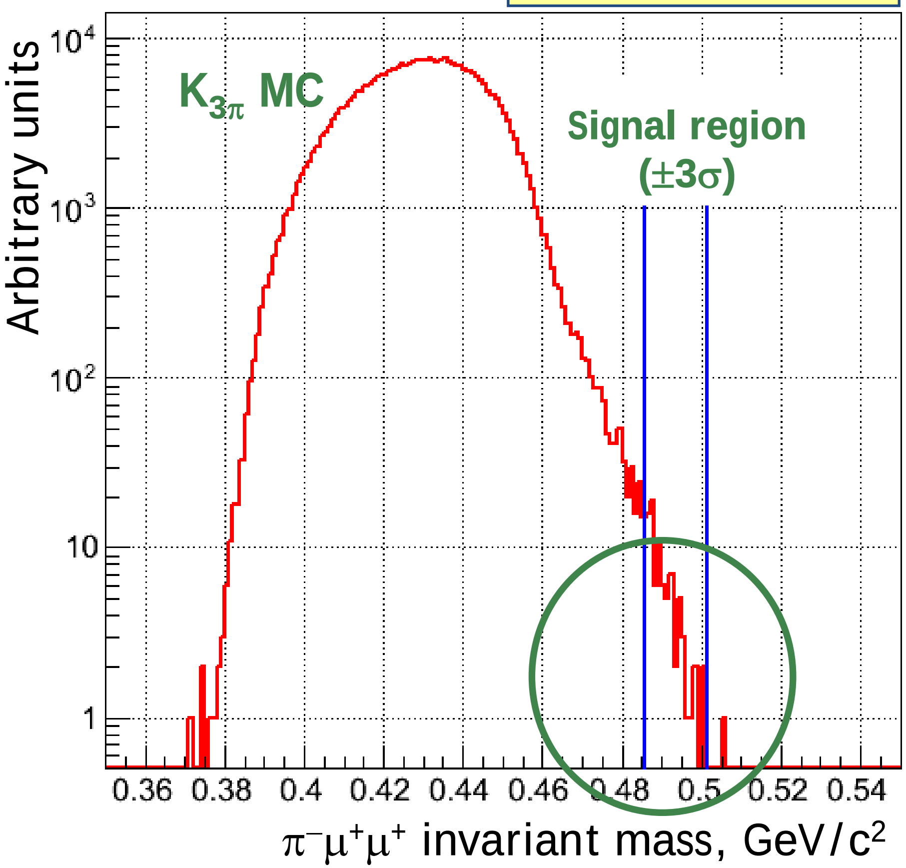
ee pair:	$Q_2 \times LKR_2(15)$
μe pair:	$Q_2 \times LKR_1(15) \times MUV_1$
$\mu\mu$ pair:	$Q_2 \times MUV_2$

Total lepton pair L0 rate (dominated by $K^+ \to \pi^+\pi^+\pi^-$): **F = few × 10 kHz**

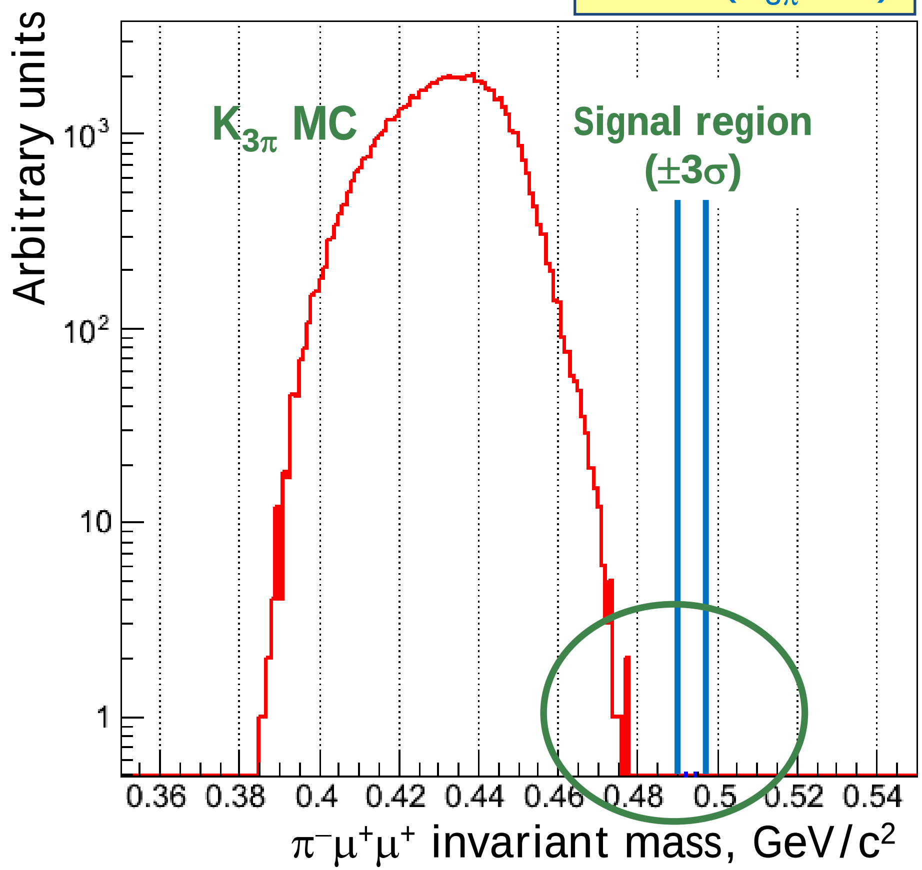
→ *Charge-blind lepton pair collection is feasible*

Example: $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$ at NA62

NA48/2 ($K_{3\pi}$ MC)



NA62 ($K_{3\pi}$ MC)



NA48/2: $K_{3\pi}$ background to $K_{\pi\mu\mu}$ due to $\pi^\pm \to \mu^\pm \nu$ decays in the spectrometer

NA62: no $K_{3\pi}$ background expected due to high spectrometer P_T (**270** vs **120 MeV/c**) and improved $\pi\mu\mu$ mass resolution (**1.1** vs **2.6 MeV/c²**)

Summary

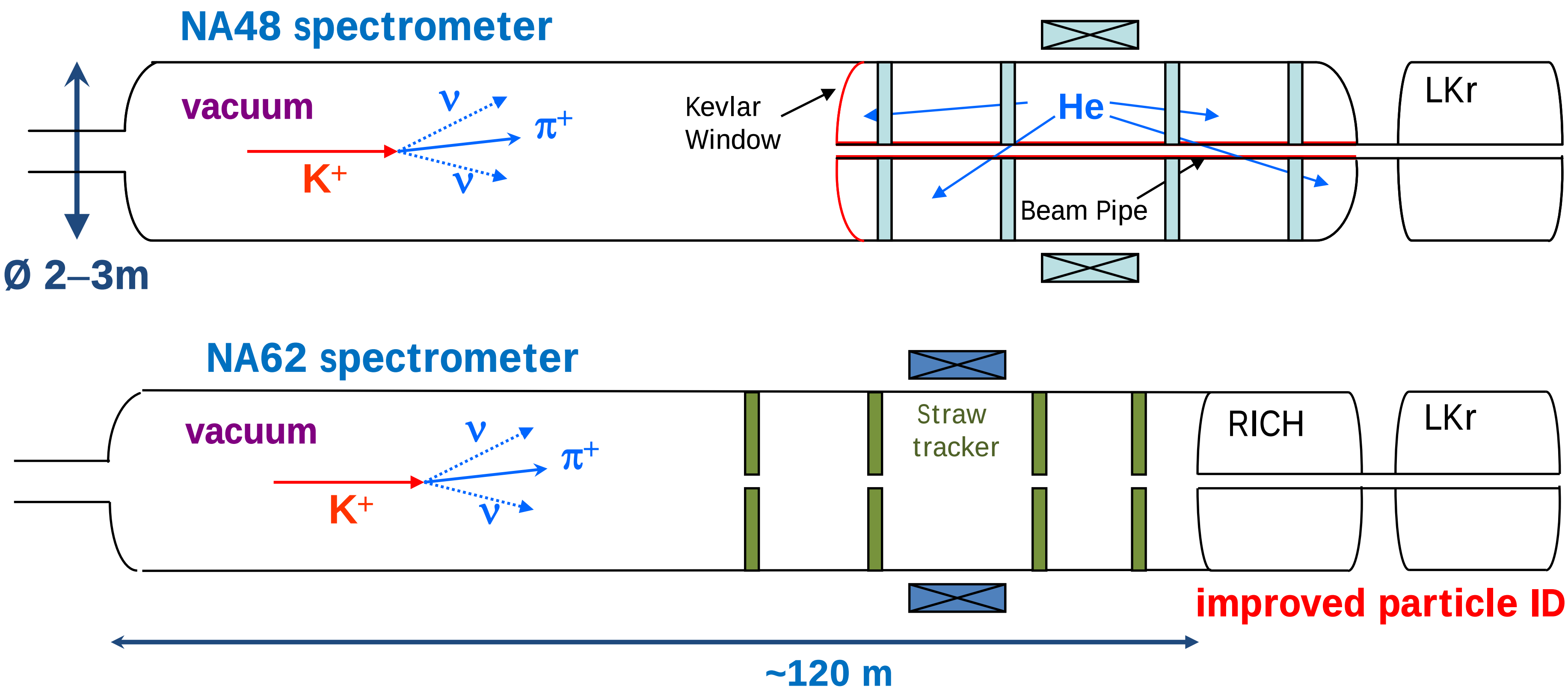
- **NA48/2** (2003–2004): a multi-purpose **$K^\pm$** experiment.
  - ✓ **$K^\pm$** physics at a new precision level (15 PL,EPJ papers so far);
  - ✓ sensitivity to LFV **$K^\pm$** decays: **$\sim 10^{-10}$**;
  - ✓ LNV: $\mathcal{B}(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 1.1 \times 10^{-9}$, proof of principle.

- **NA62-R_K** (2007–2008): minimum bias electron trigger.
  - ✓ world's largest sample of 0.15M **$K^\pm \to e^\pm \nu$** decay candidates;
  - ✓ LU test at record **0.4%** precision:
    $BR(K^\pm \to e^\pm \nu)/BR(K^\pm \to \mu^\pm \nu) = (2.488 \pm 0.010) \times 10^{-5}$;
  - ✓ also rare decays, heavy neutrinos.

- **NA62** (construction/commissioning)
  - ✓ expected single event sensitivity for **K^+** decays: **$\sim 10^{-12}$**;
  - ✓ excellent prospects to search for LFV **K^+, π^0** decays.

SPARES

NA62 vs NA48/2



NA62 will operate a straw tracker in vacuum:

- Spectrometer thickness reduced from **~2.8%X_0** (NA48) to **1.8%X_0** (NA62).
- Reduced multiple scattering: improved invariant mass resolutions.
- Reduced photon conversion.