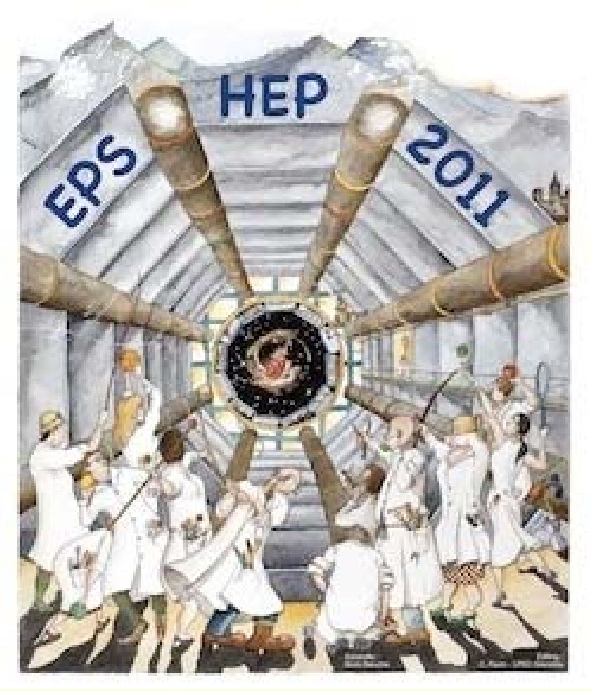
Kaon physics at CERN: recent results



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on behalf of CERN NA48 and NA62 collaborations

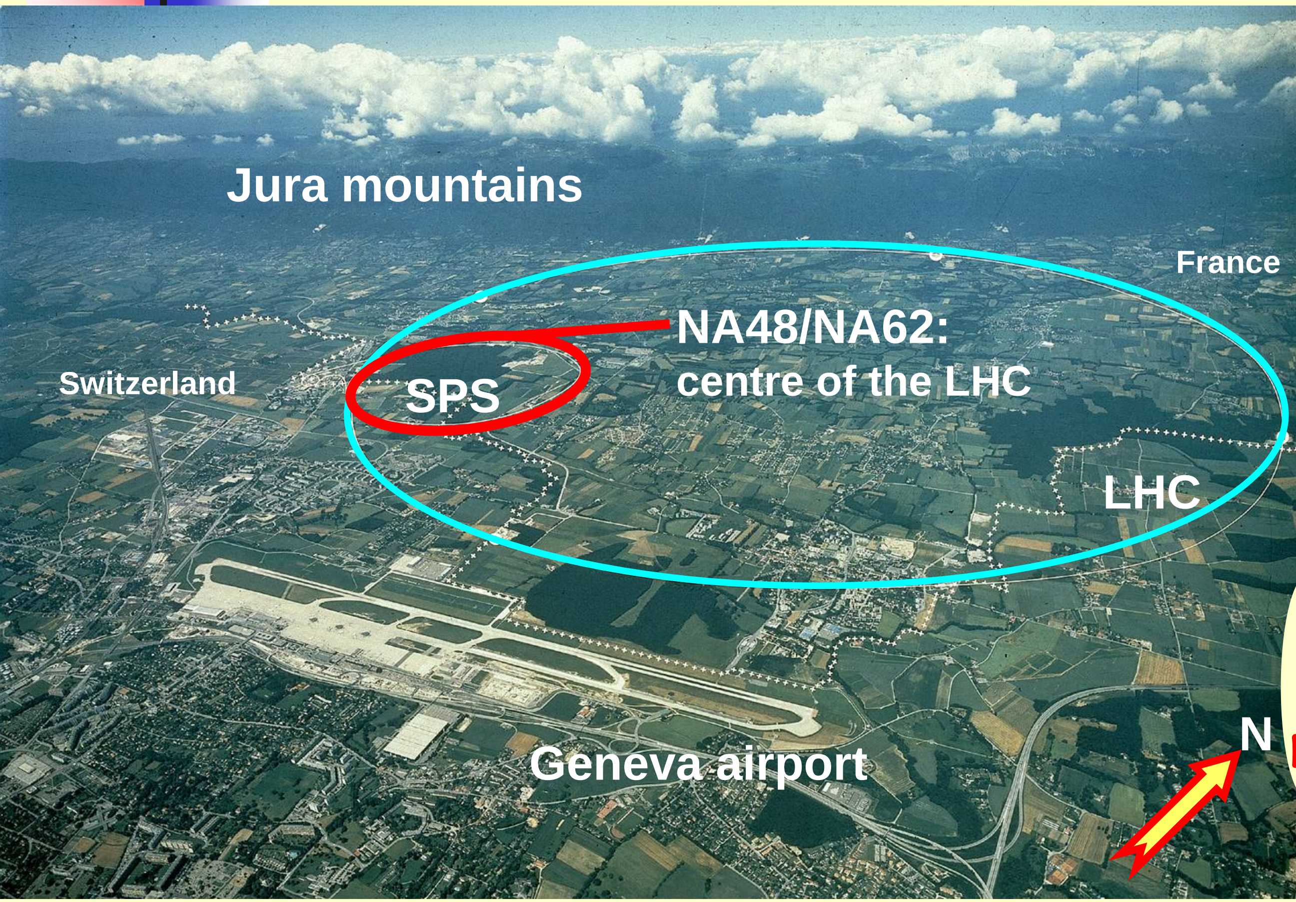
Outline:

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

European Physical Society HEP 2011 conference

Grenoble, France • 22 July 2011

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

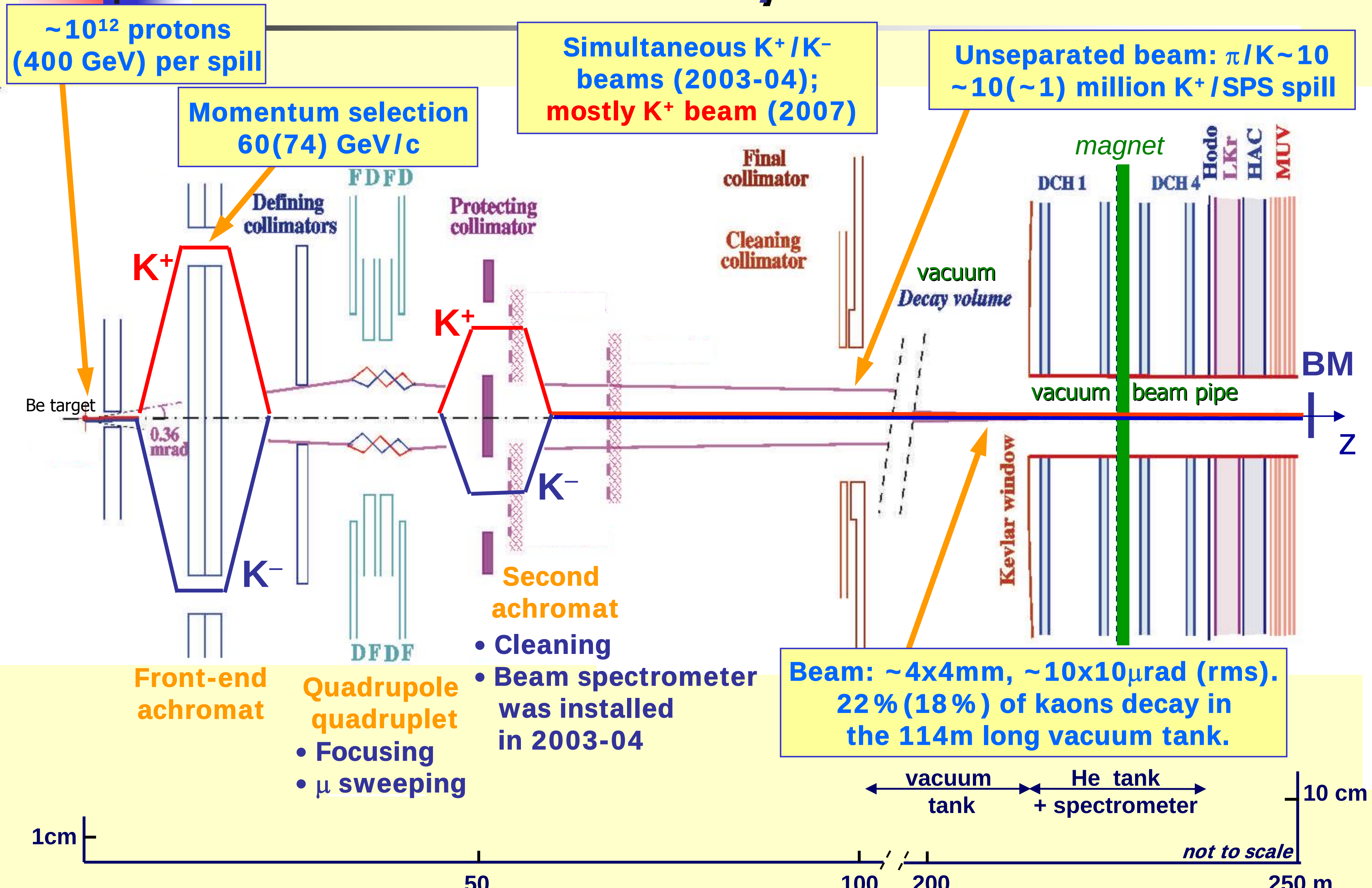
NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

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

NA62 talk by P.Valente
- 2007–2013: design & construction
- 2012: first 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

NA48/2 $K^{\pm}$ beam line



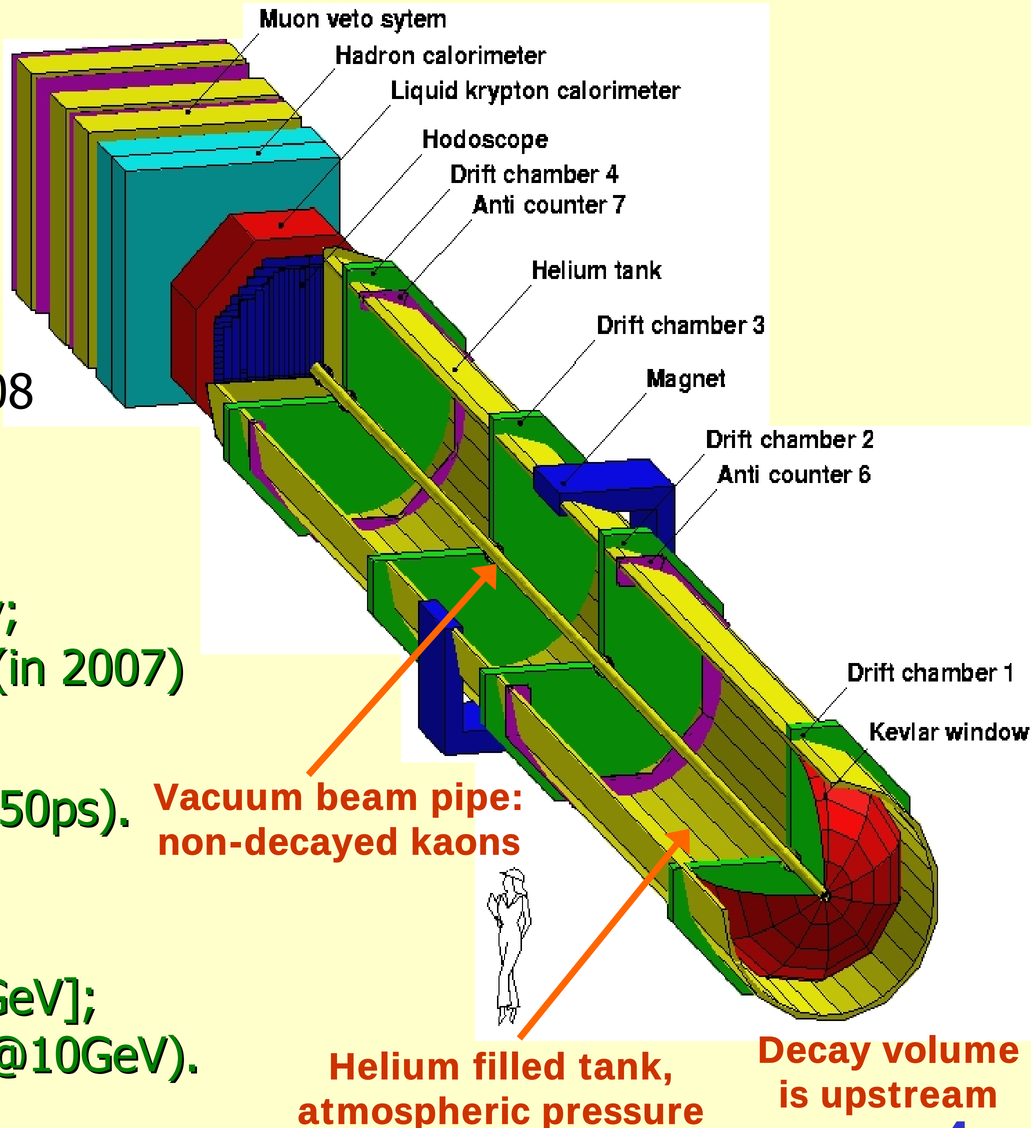
The detector

Data taking

- NA48/2:
  ~six months in 2003-04.
- NA62 (R_K phase):
  ~4 months in 2007;
  ~2 weeks (systematics studies) in 2008

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];
  $\sigma_x=\sigma_y=4.2\text{mm}/E^{1/2} + 0.6\text{mm}$ (1.5mm@10GeV).



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

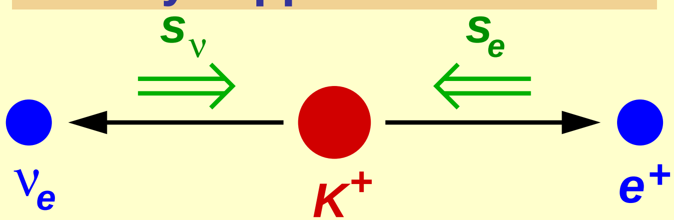
Lepton Flavour Universality (LFU): not a fundamental law (violated in ν sector).
New physics models (2HDM, SUSY, SM4): significant LFU violation.

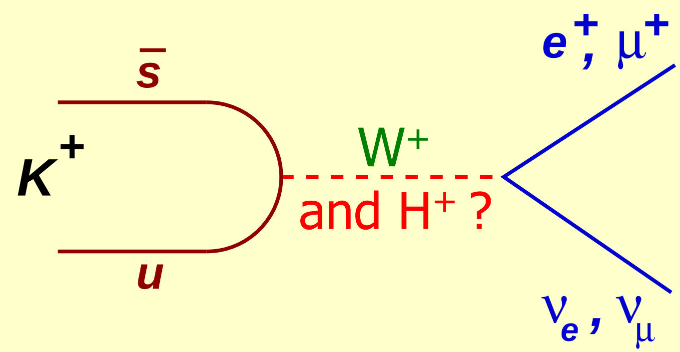
Observable sensitive to LFU violation:

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

Radiative correction (well known, few %)

Helicity suppression: f~10^{-5}





- SM prediction: excellent sub-permille accuracy: free of 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.

$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$
PRL99 (2007) 231801

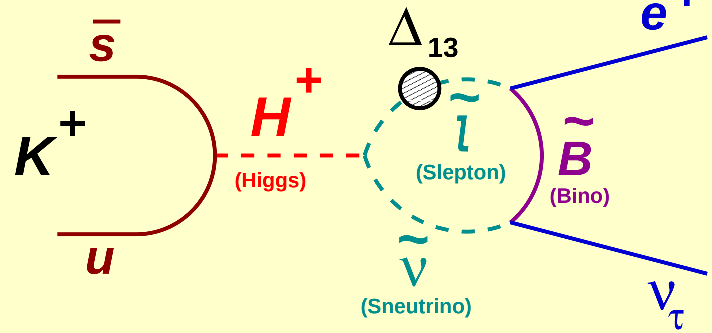
$R_K = K_{e2}/K_{\mu 2}$ beyond the SM

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

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

uniquely sensitive to slepton mixing

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

→ Possibly the first evidence for the charged Higgs boson.

~1% effect in large $\tan\beta$ regime with a massive $H^\pm$

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

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

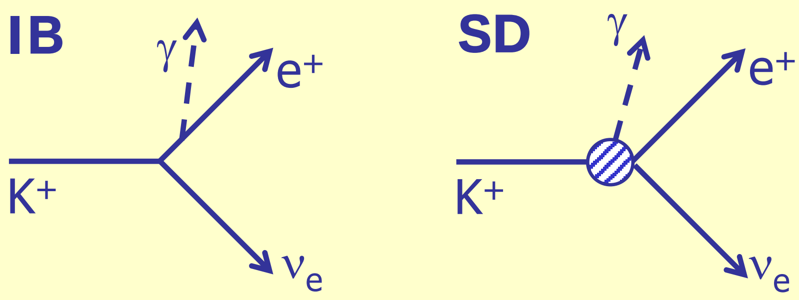
$B_{\mu\nu}/B_{\tau\nu}$ → ~50% enhancement;

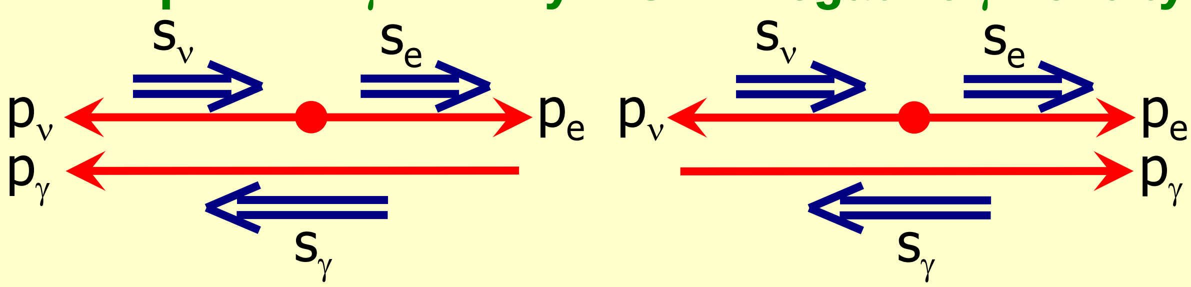
$B_{e\nu}/B_{\tau\nu}$ → enhanced by ~one order of magnitude.

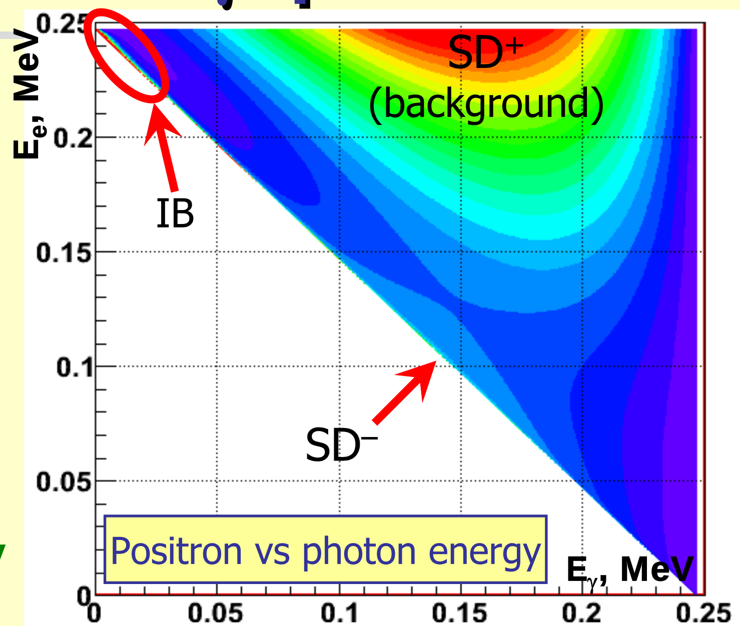
Out of reach: $Br^{SM}(B_{e\nu}) \approx 10^{-11}$

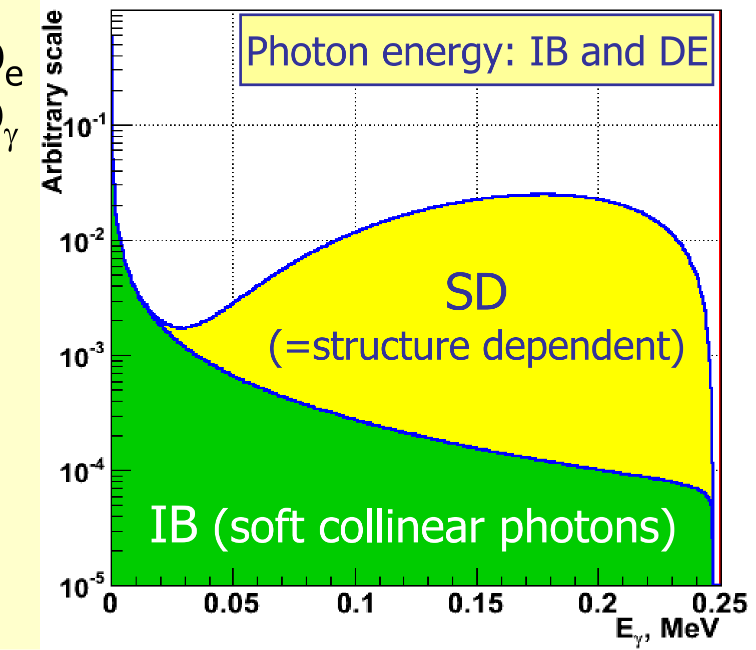
Radiative $K^+ \to e^+\nu\gamma$ process

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









SD radiation is not helicity suppressed.
KLOE measurement of the form factor leads to
BR(SD+, full phase space) = $(1.37\pm0.06)\times10^{-5}$.
(EPJC64 (2009) 627)

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

Measurement strategy

(1) $K_{e2}/K_{\mu 2}$ candidates are collected concurrently:
→ no kaon flux measurement; several systematic effects cancel at first order
(e.g. reconstruction/trigger efficiencies, time-dependent effects).

(2) Counting experiment, independently in 10 lepton momentum bins
(owing to strong momentum dependence of backgrounds and event topology)

$$R_K = \frac{1}{D} \cdot \frac{N(K_{e2}) - N_B(K_{e2})}{N(K_{\mu 2}) - N_B(K_{\mu 2})} \cdot \frac{A(K_{\mu 2}) \times f_\mu \times \varepsilon(K_{\mu 2})}{A(K_{e2}) \times f_e \times \varepsilon(K_{e2})} \cdot \frac{1}{f_{LKr}}$$

- $1/D$: prescaling of $K_{\mu 2}$ trigger
- $N(K_{e2})$, $N(K_{\mu 2})$: numbers of selected K_{l2} candidates
- N_B: numbers of background events
- A: geometric acceptance correction
- f_μ, f_e: particle ID eff (measured)
- ε: trigger eff (measured)
- f_{LKr}: LKr readout efficiency (measured)

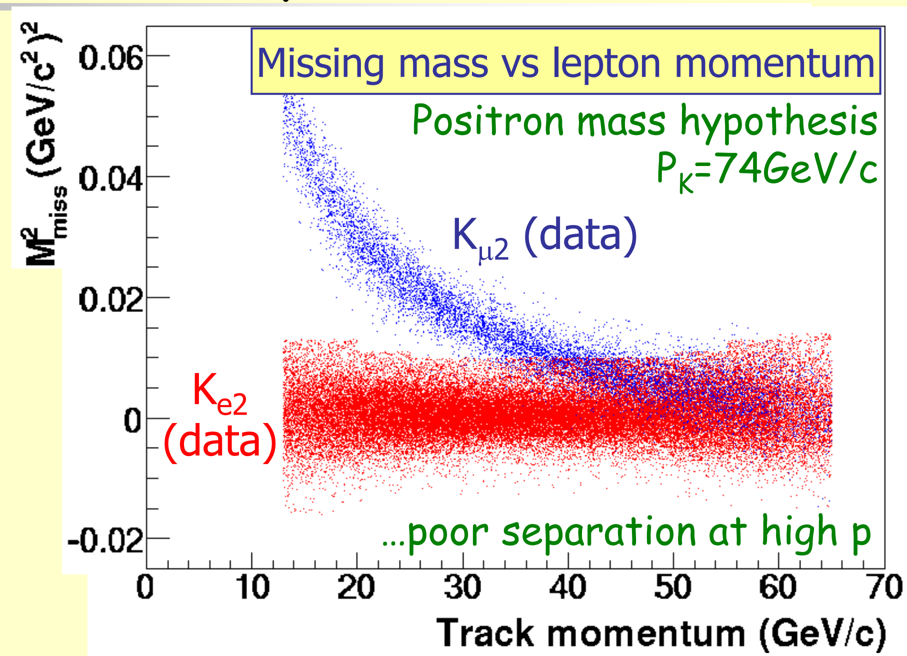
MC simulations used to a limited extent

(3) Data-driven beam halo background subtraction:
→ Alternating K^+/K^- beams (K^+: 66%, K^-: 7%, simultaneous: 27%);
→ K^+ only sample used to measure background in K^- sample & vice versa.

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

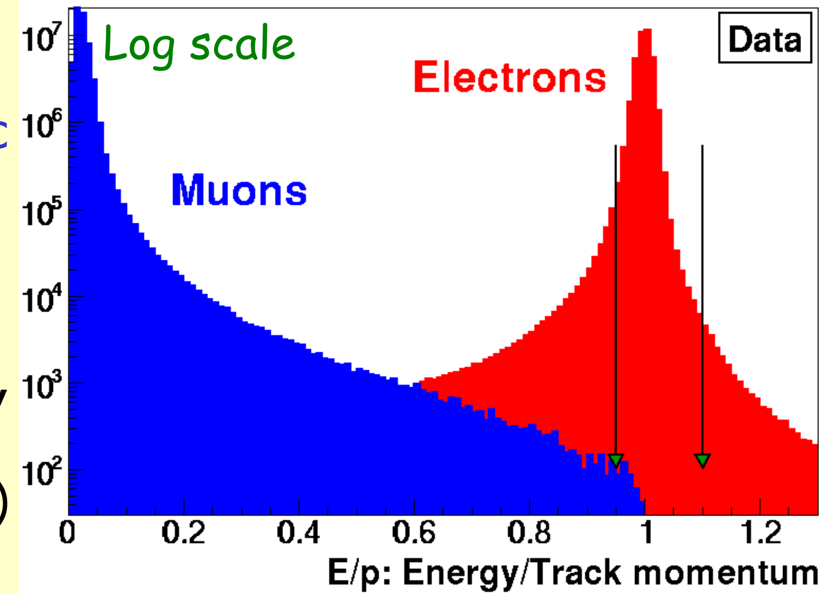
Lepton identification

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 ($\sim 10^6$)



$K_{\mu 2}$ 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

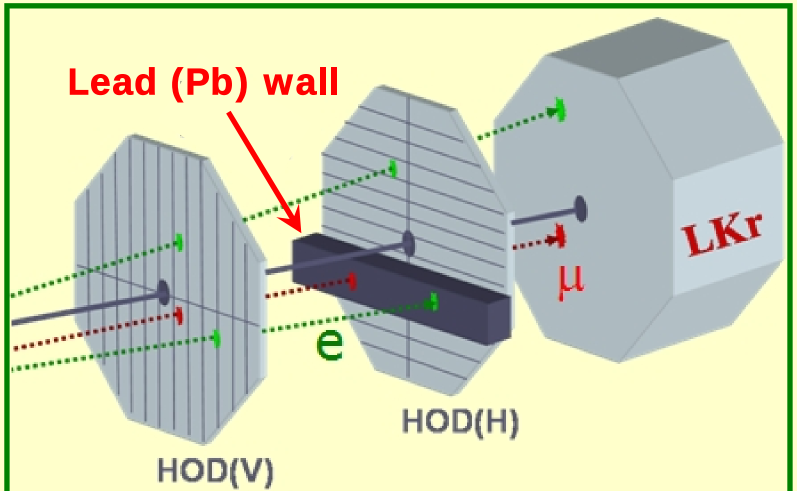
Direct measurement of $P_{\mu e}$

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

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

$P_{\mu e}$ 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

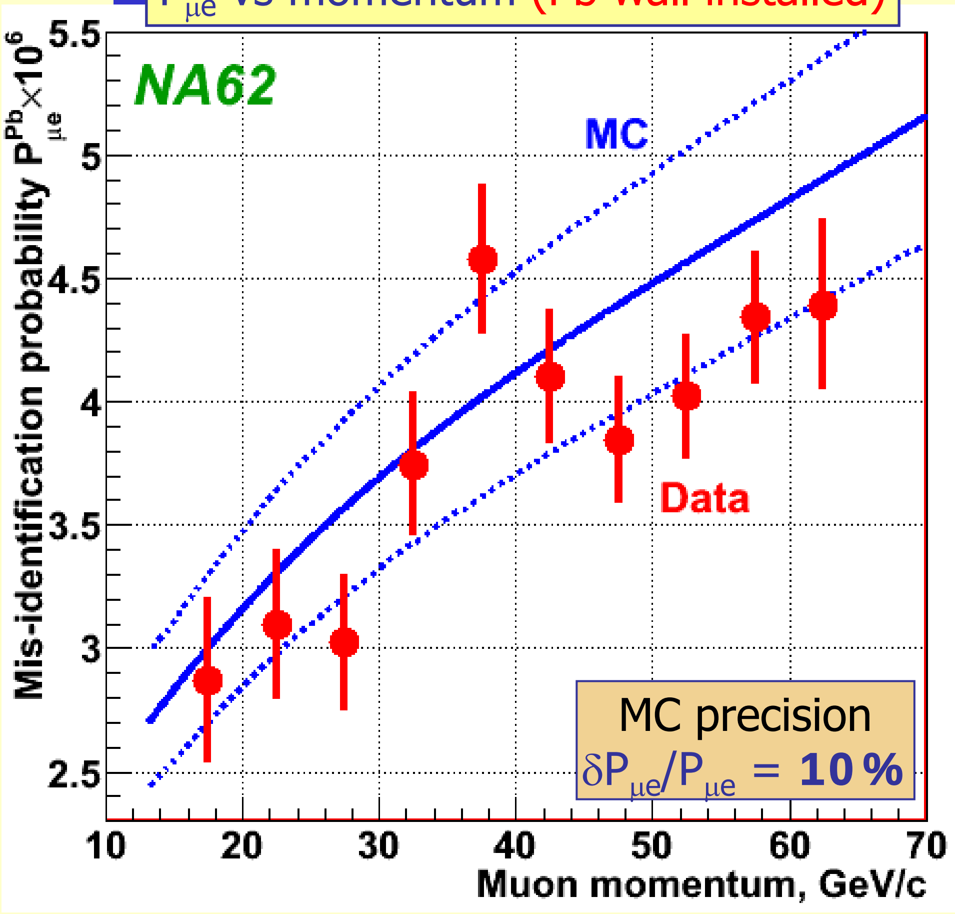


Thickness:	$9.2X_0$ (Pb+Fe)
Width:	240cm (=HOD size)
Height:	18cm (=3 counters)
Area:	~20% of HOD area
Duration:	~50% of R_K runs

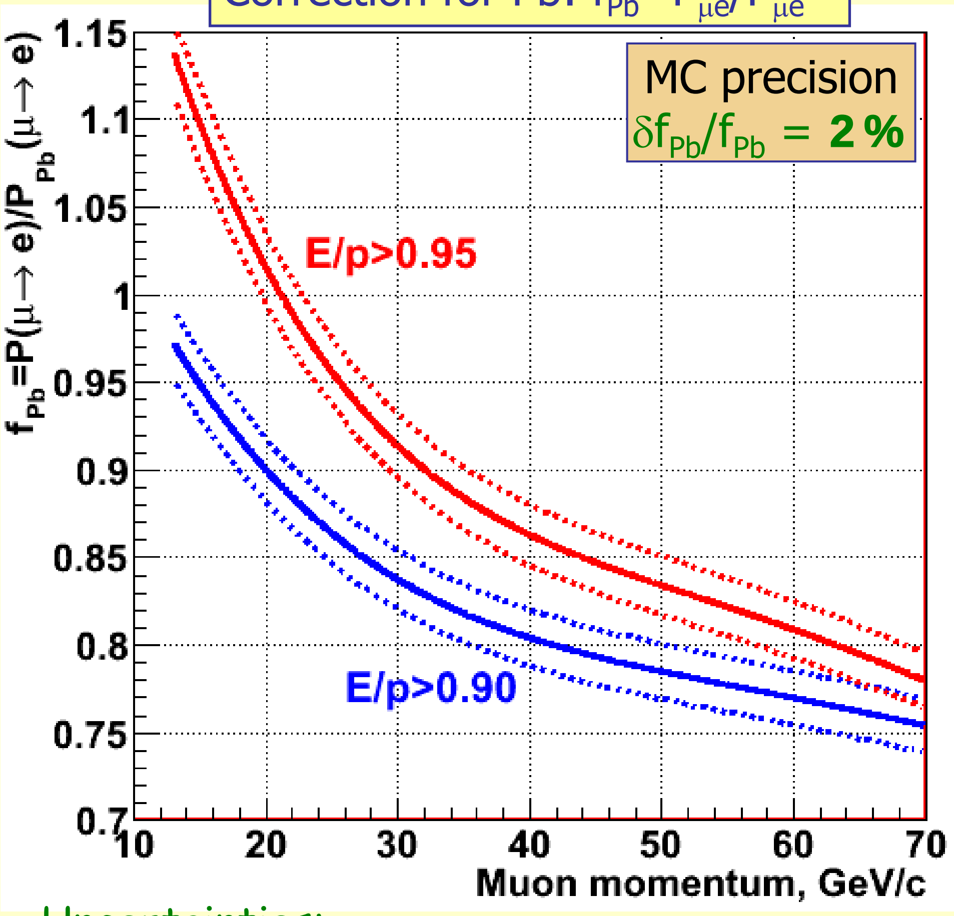
4 data samples with different background conditions:
K^+(Pb), K^+(noPb),
K^-(Pb), K^-(noPb).

Muon mis-identification

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



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

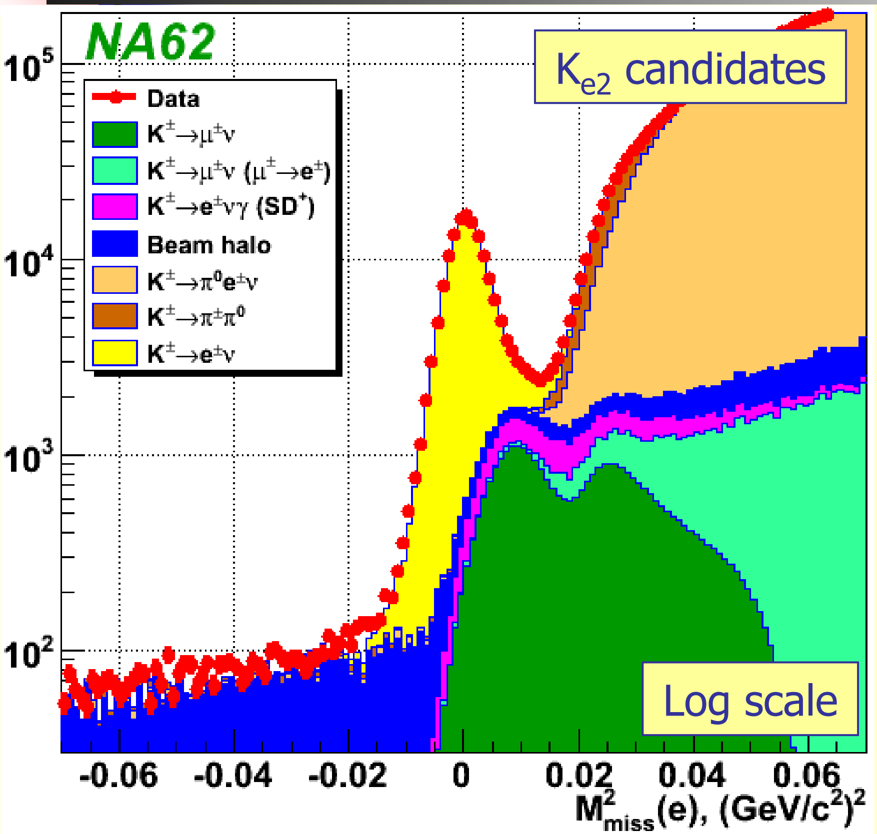


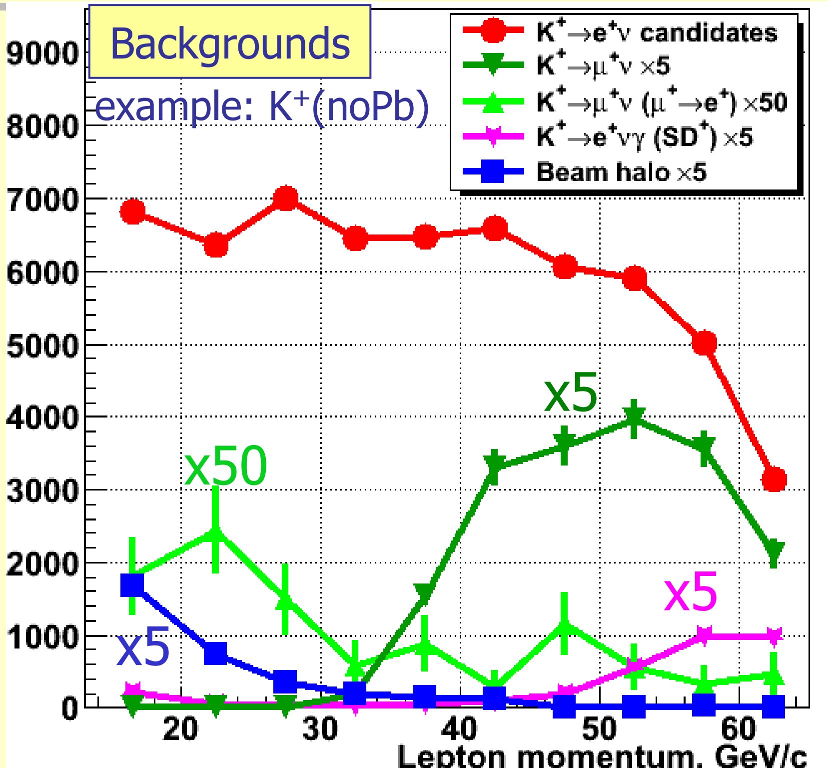
Result: B/(S+B) = (5.64±0.20)%

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} sample





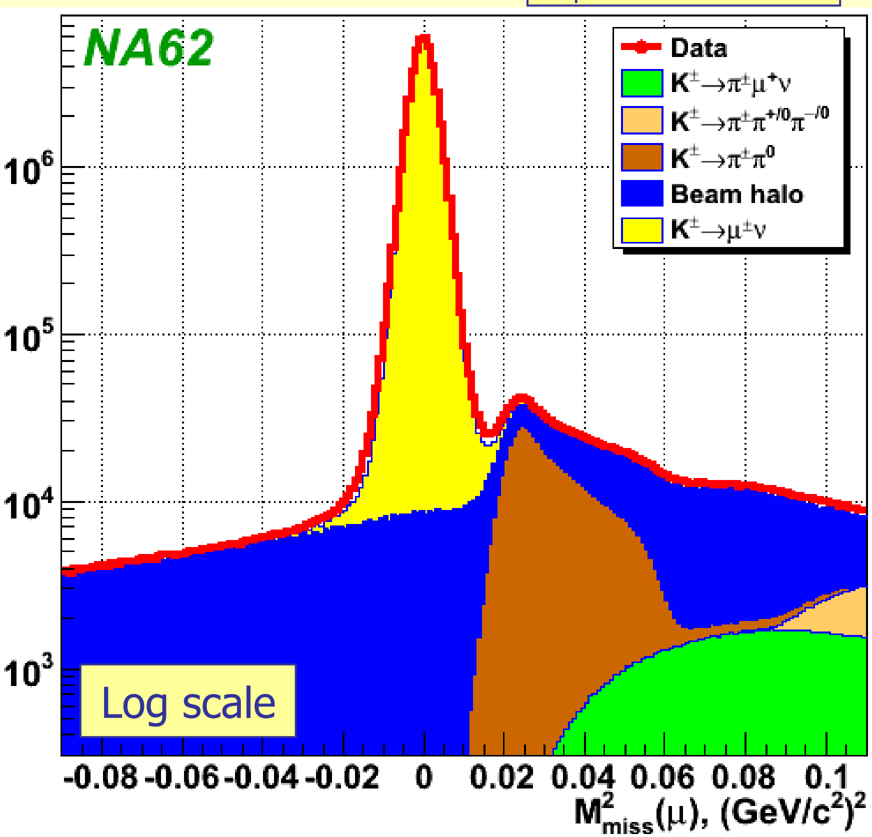
145,958 $K^{\pm}\to e^{\pm}\nu$ candidates.
Background: B/(S+B)=(10.95±0.27)%.
Electron ID efficiency: (99.28±0.05)%.

cf. KLOE: 13.8K candidates,
~90% electron ID efficiency, 16% background

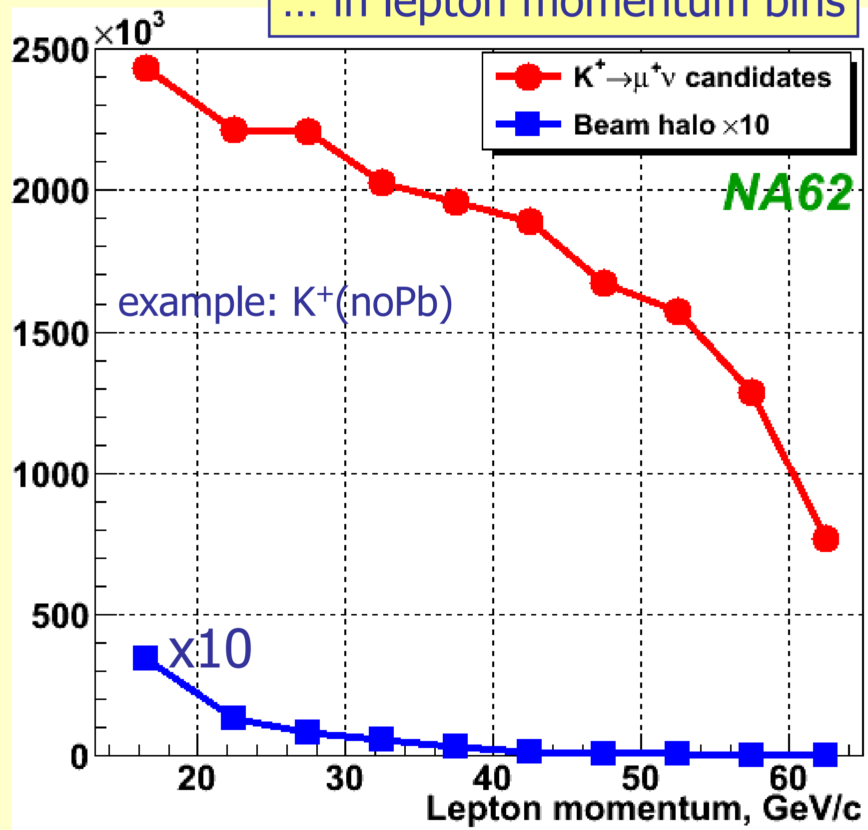
Source	B/(S+B)
$K_{\mu2}$	(5.64±0.20)%
$K_{\mu2}$ ($\mu\to e$)	(0.26±0.03)%
$K_{e2\gamma}$ (SD+)	(2.60±0.11)%
$K_{e3(D)}$	(0.18±0.09)%
$K_{2\pi(D)}$	(0.12±0.06)%
Wrong sign K	(0.04±0.02)%
Beam halo	(2.11±0.09)%
Total	(10.95±0.27)%

$K_{\mu2}$ sample

$K_{\mu2}$ candidates



... in lepton momentum bins



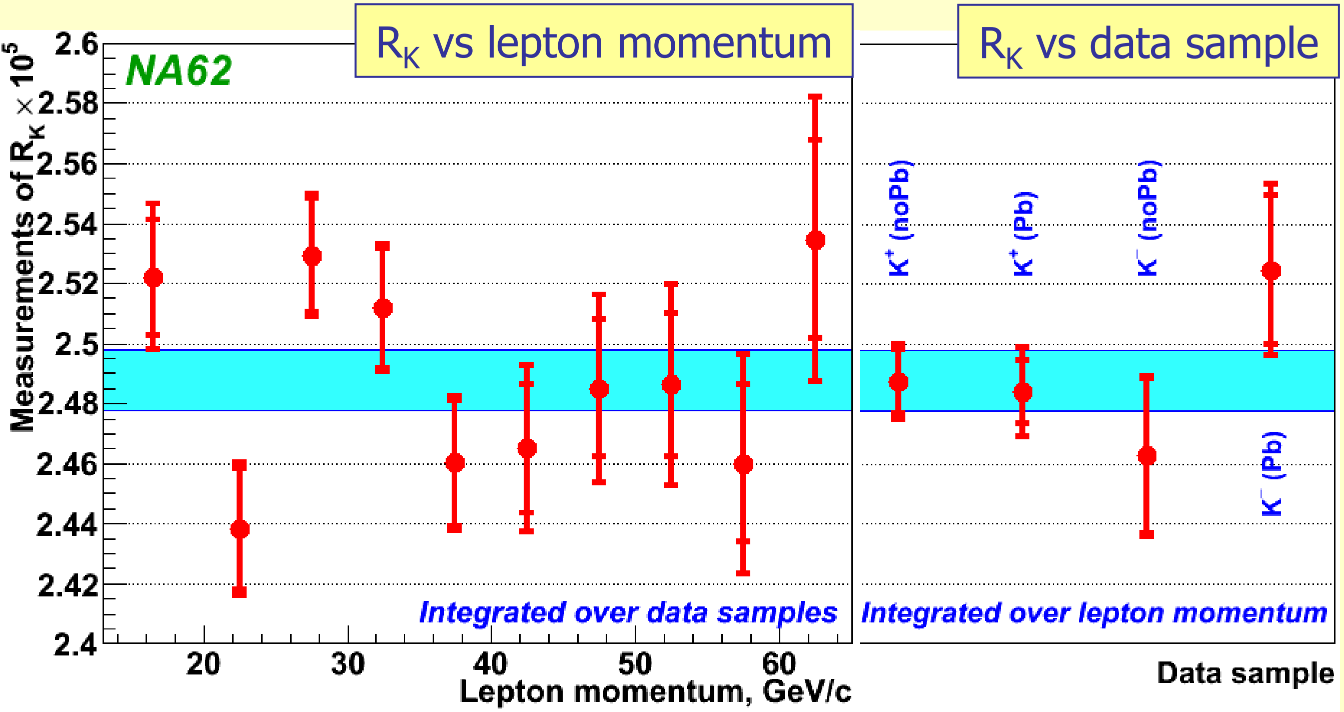
42.817M candidates (pre-scaled trigger).
B/(S+B) = (0.50±0.01)%,
background dominated by beam halo.

The result (full NA62 data set)

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

New result: July 2011

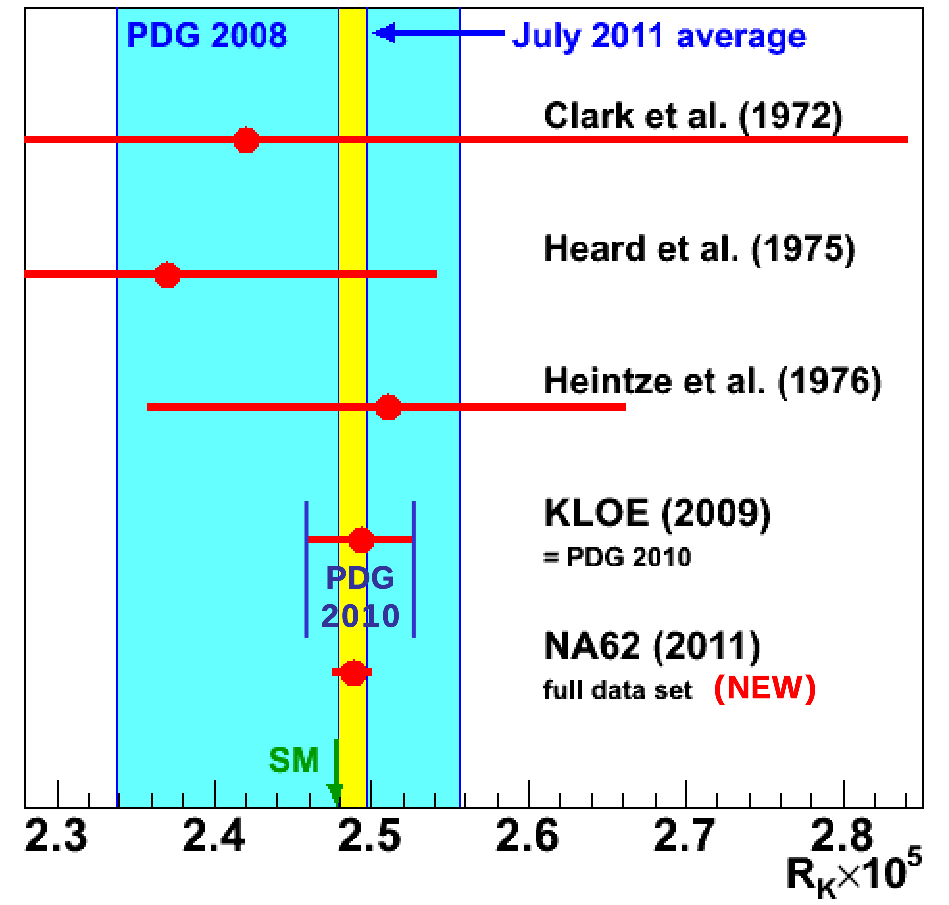
Fit over 40 measurements (4 data samples x 10 momentum bins) including correlations: $\chi^2/ndf=47/39$.

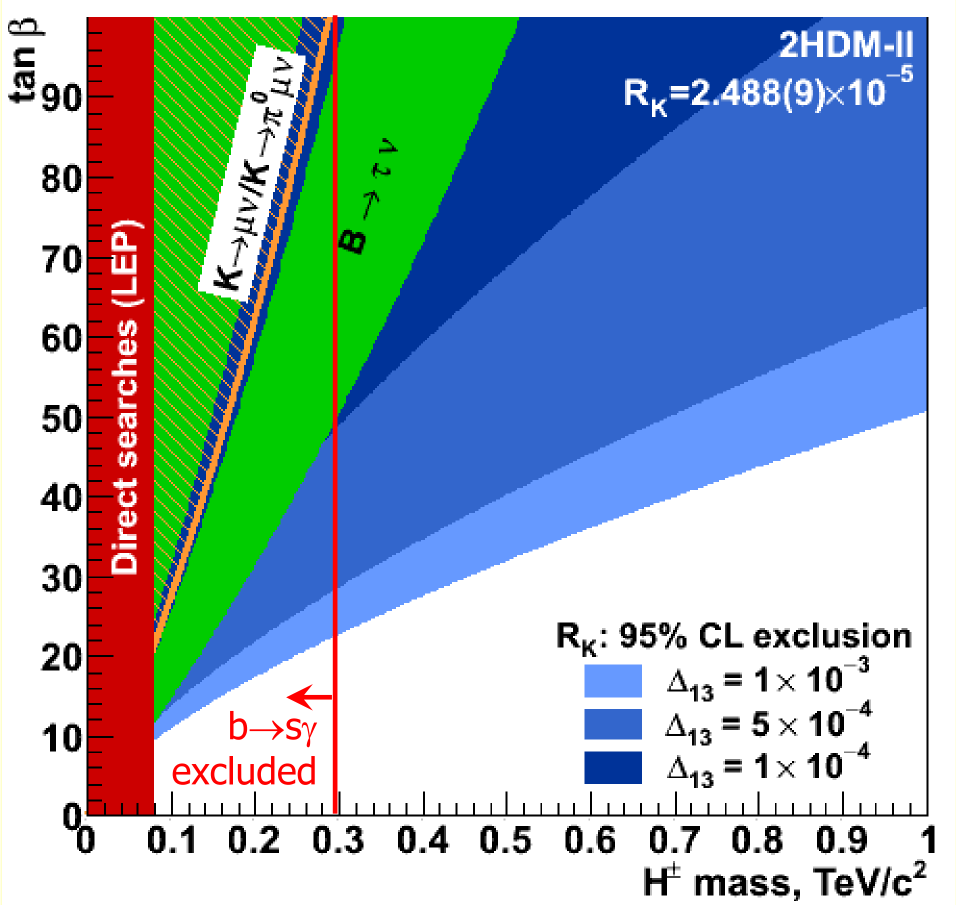


Uncertainty source	$\delta R_K \times 10^5$
Statistical	0.007
$K_{\mu 2}$ background	0.004
$K^\pm \to e^\pm \nu \gamma$ (SD$^+$)	0.002
$K^\pm \to \pi^0 e^\pm \nu$, $K^\pm \to \pi^\pm \pi^0$	0.003
Beam halo background	0.002
Helium purity	0.003
Acceptance correction	0.002
DCH alignment	0.001
Electron identification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

NA62 partial (40%) data set result: $R_K=(2.487 \pm 0.013) \times 10^{-5}$ [PLB698 (2011) 105]

R_K world average





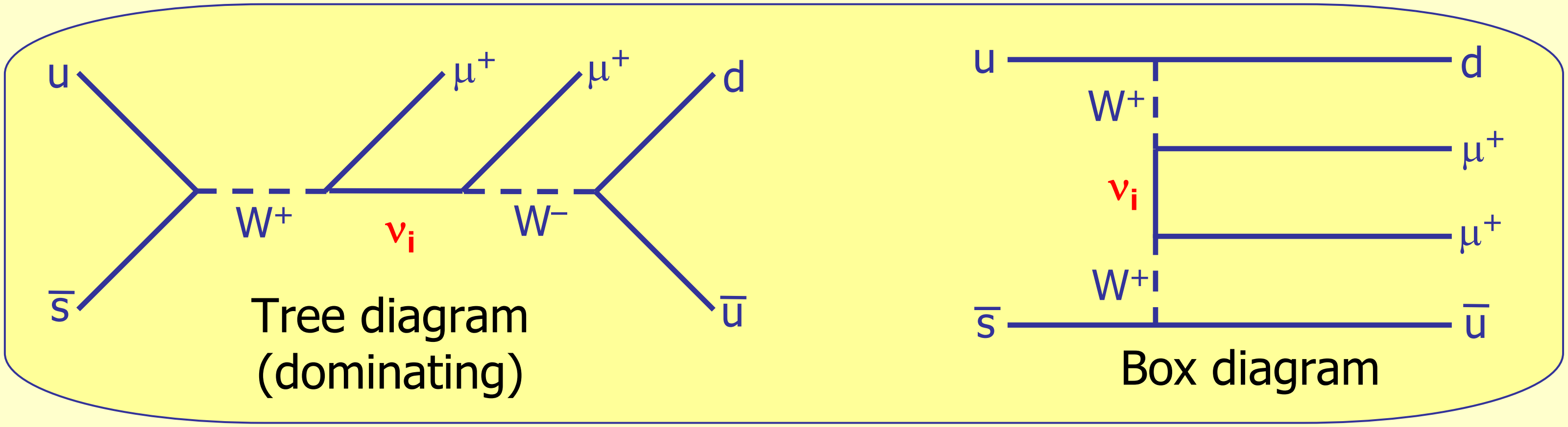
World average	$\delta R_K \times 10^5$	Precision
PDG 2008	2.447±0.109	4.5%
July 2011	2.488±0.009	0.4%

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

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

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

$K^+ \to \pi^- \mu^+ \mu^+$ 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, PLB491 (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

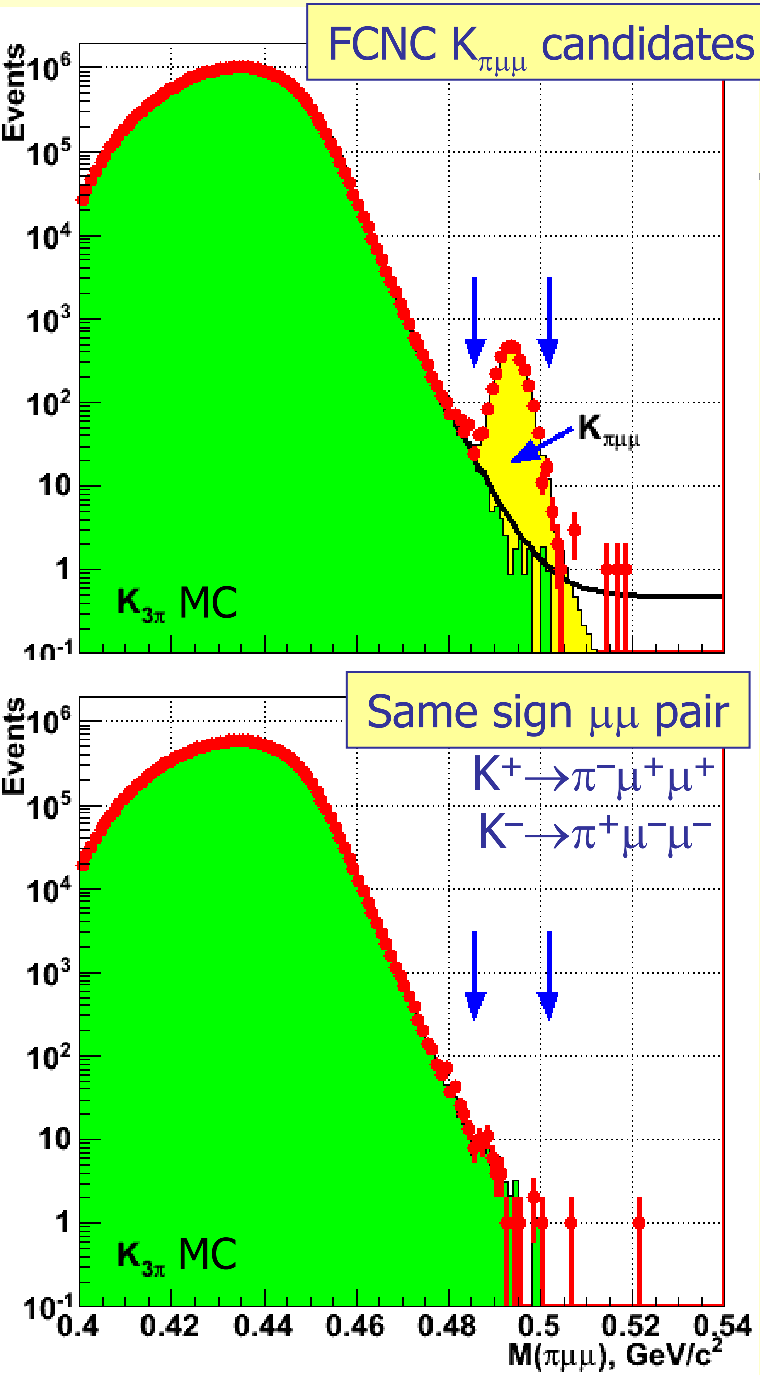
Best upper limits on LFV/LNV decays $K_{\pi ee}$, $K_{\pi\mu\mu}$, $K_{\pi\mu e}$ come from BNL E865.

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

→ NA48/2 is competitive for $K_{\pi\mu\mu}$ mode: ~8 times larger data sample ($K^\pm$ collected in 2003–04).

The NA48/2 limit

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.

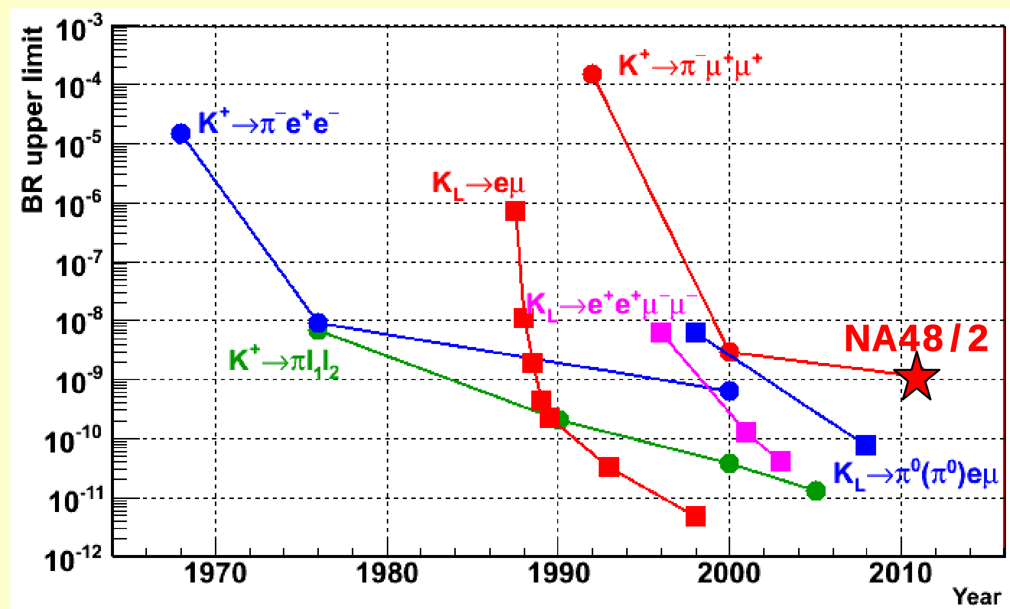
Lepton number violating decay:

N_{data} = 52

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

⇒ BR < 1.1×10^{-9} (90% CL)

A factor of 3 improvement on the upper limit for BR($K^+\to\pi^-\mu^+\mu^+$).



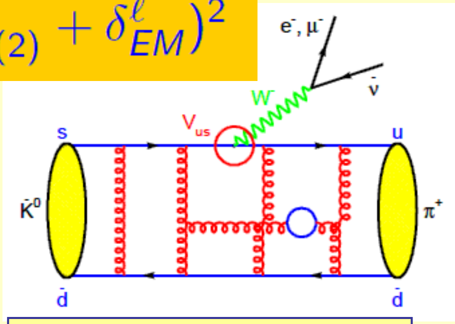
$K^\pm \to \pi^0 \mu^\pm \nu_\mu$ ($K_{\mu3}$) form factors

Most precise measurement of $|V_{us}|$: from $K \to \pi l \nu$ decays

$$\Gamma_{K\ell3(\gamma)} = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^\ell(\lambda_{+0}) (1 + \delta^\ell_{SU(2)} + \delta^\ell_{EM})^2$$

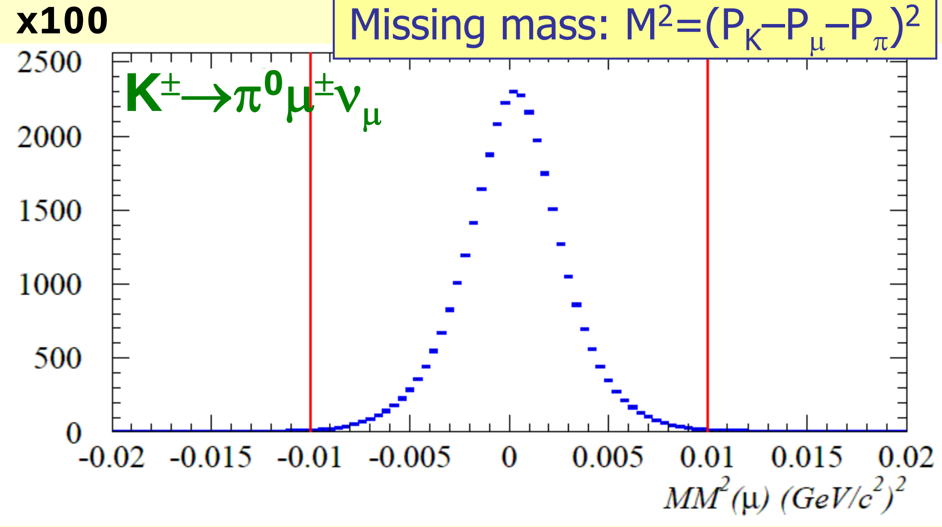
Decay rates

Phase space integrals depend on form factors



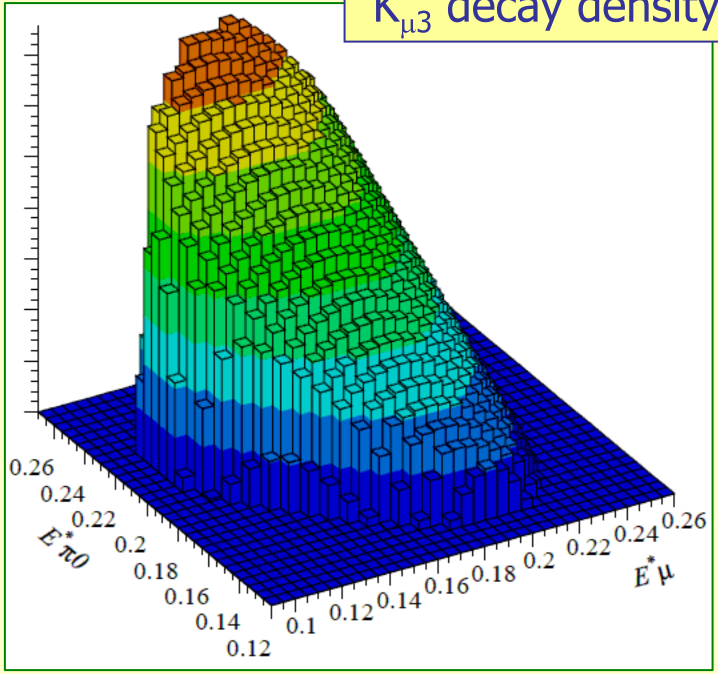
Data sample: NA48/2 2004 special run with a minimum bias trigger

Missing mass: $M^2=(P_K-P_\mu-P_\pi)^2$



→ 3.4×10^6 $K_{\mu3}$ candidates with 0.8% background

$K_{\mu3}$ decay density



$K_{\mu3}$ form factor fits

Form-factor parameterizations:

$$\bar{f}_{+,0}(t) = \left(1 + \lambda_{+,0}\ t/m_\pi^2\right)$$ LINEAR

$$\bar{f}_{+,0}(t) = \left[1 + \lambda'_{+,0}\ t/m_\pi^2 + \tfrac{1}{2}\ \lambda''_{+,0}\ (t/m_\pi^2)^2\right]$$ QUADRATIC

$$\bar{f}_{+,0}(t) = \frac{m_{V,S}^2}{m_{V,S}^2 - t}$$ POLE

$$f_0(t) = f_+(t) + \frac{t}{(m_K^2 - m_\pi^2)} f_-(t)$$

$$\bar{f}_+(t) = \exp\left[\frac{t}{m_\pi^2}(\Lambda_+ + \mathrm{H(t)})\right]$$ DISPERSIVE

$$\bar{f}_0(t) = \exp\left[\frac{t}{\Delta_{K\pi}}(\ln\mathrm{C} - \mathrm{G(t)})\right]$$

PLB 638(2006) 480
PRD 80(2009) 034034

$K_{\mu3}$ world data: polynomial parameterization

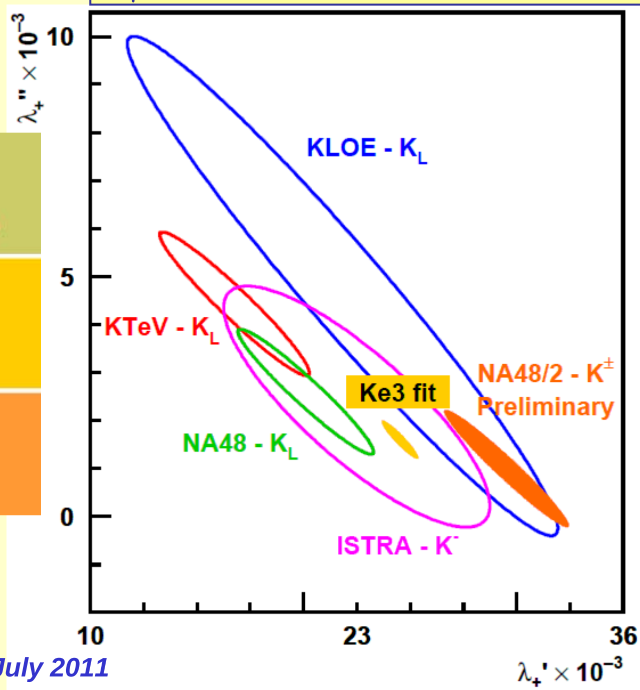
NA48/2 preliminary results

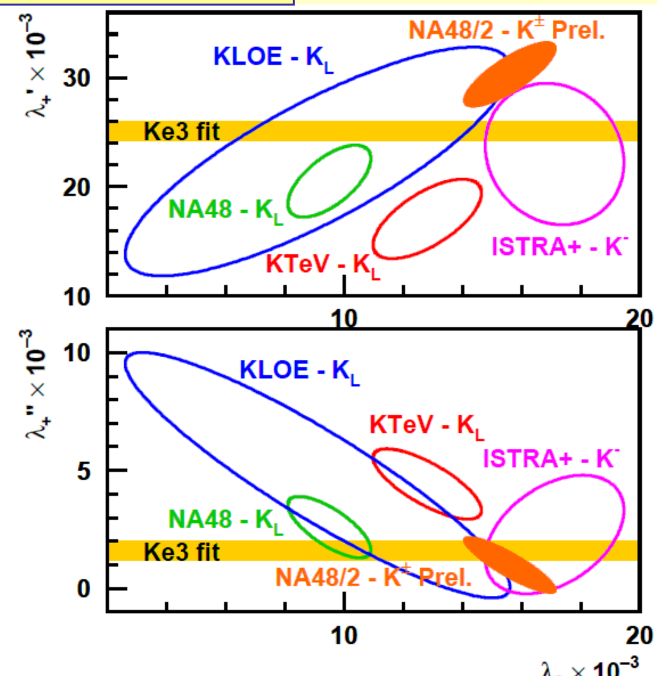
QUADRATIC ($\times 10^3$)		
λ'_+	λ''_+	λ_0
30.3±2.7±1.4	1.0±1.0±0.7	15.6±1.2±0.9

POLE (MeV/c^2)	
m_V	m_S
836±7±9	1210±25±10

DISPERSIVE ($\times 10^3$)	
Λ_+	$\ln C$
28.5±0.6±0.7±0.5	188.8±7.1±3.7±5.0

Further details:
M.Veltri, arXiv:1101.5031.





Summary

- New NA62 measurement of $R_K=BR(K_{e2})/BR(K_{\mu 2})$ presented.
  Combined experimental precision has improved
  by an order of magnitude over the last 3 years,
  but is still an order of magnitude worse than the SM prediction.

- R_K experiment and SM currently agree at 1.2σ level.

- NA48/2 upper limit on LNV $BR(K^+\to\pi^-\mu^+\mu^+)$ is an improvement
  by a factor of 3: $BR<1.1\times 10^{-9}$ → $\langle m_{\mu\mu}\rangle<300$ GeV at 90% CL.

- NA48/2 precisely measured the $K^{\pm}_{\mu 3}$ form factors:
  → further improvement in the determination of $|V_{us}|$.

Future plans of kaon physics at CERN:
talk by Paolo Valente, "Detector R&D and Data Handling" session