K decay measurements with the KLOE detector

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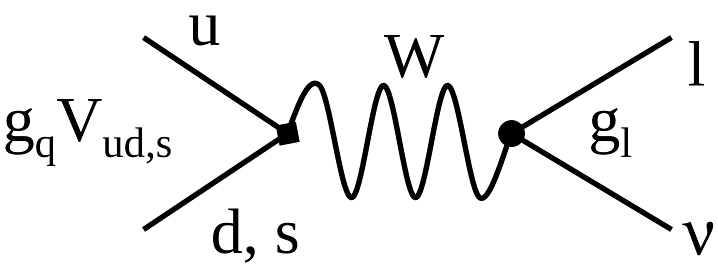
Precision test of SM with kaons

SM coupling to W → $g \times W_\alpha (\overline{U}_L V_{CKM} \gamma^\alpha D_L + \sum_{l=e,\mu,\tau} \bar{l}_L \gamma^\alpha \nu^l_L)$

- g → Same coupling for all fermions
- V_{CKM} → Unitary matrix
- L → Left-handed

K, π and nuclear β decays

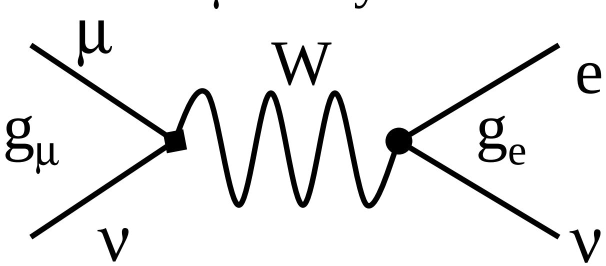


$(g_q g_l)^2 |V_{ud,s}|^2 / M_W^4$

Test of unitarity and universality

$(g_q g_l)^2 (|V_{ud}|^2 + |V_{us}|^2) = (g_\mu g_e)^2$

μ decay

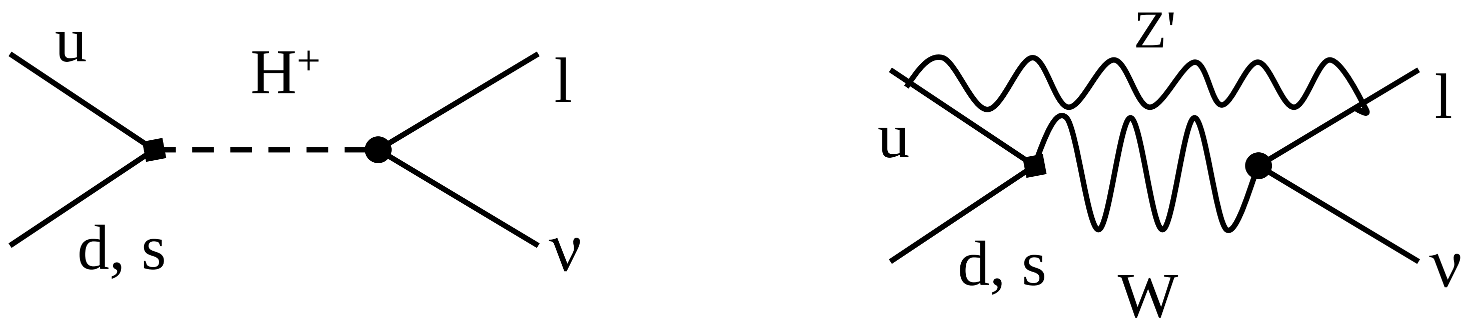


$(g_\mu g_e)^2 / M_W^4$

V_{ub} negligible

Precision test of SM with kaons

Believe in SM coupling to W: Test the presence of scalar and right-handed currents and presence of new gauge bosons.



With recent precise experimental results and progress in theoretical predictions (lattice QCD, ChPT ...), kaon physics allows us to test the Standard Model at permil level, and probe new physics at the TeV scale.

Semileptonic kaon decays

$$\Gamma(K_{l3(\gamma)}) = \frac{C_K^2 G_F^2 M_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_{Kl} (1+\delta_K^{SU(2)} + \delta_{Kl}^{EM})^2$$

- G_F^2: μ decay
- S_{EW}: Short distance EW correction
- δ_{Kl}^{EM}: Long distance EM correction
- $|f_+(0)|^2$: Form factor at zero momentum transfer
- I_{Kl}: Phase space integral
- $\delta_K^{SU(2)}$: SU(2)-breaking correction

For the extraction of $|V_{us}|$ we need to measure

Γ(Kl3): from measurement of BR's and lifetimes.

I_{kl}: from measurement of the t-dependence of form factors.

All measurements taking into account radiated photons.

Leptonic kaon decays

Ratio of K and π decay constants

EM correction

$$\frac{\Gamma(K_{\mu 2(\gamma)})}{\Gamma(\pi_{\mu 2(\gamma)})} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{m_K (1 - m_\mu^2 / m_K^2)^2}{m_\pi (1 - m_\mu^2 / m_\pi^2)^2} (1 + \delta)$$

Precise determination of the ratio $|V_{us}|/|V_{ud}|$ from $K_{\mu 2}$ and $\pi_{\mu 2}$ decay width.

Combine measurement from $K_{\mu 2}$, $\pi_{\mu 2}$, K_{e3}, $K_{\mu 3}$ and from nuclear β decays to test electron-muon and lepton-quark universality and the unitarity of the CKM matrix.

The KLOE experiment

Electromagnetic Calorimeter (pb/sci)

$\sigma(E)/E = 5.7\,\%/\sqrt{E(\mathrm{GeV})}$

$\sigma(t) = 57\ \mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 100\ \mathrm{ps}$

$\sigma(x) \sim 1\ \mathrm{cm}$

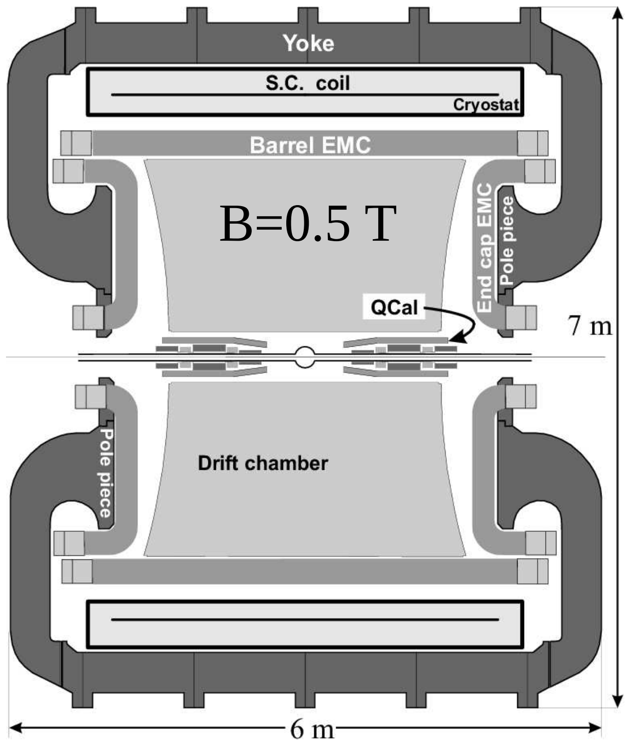
Drift Chamber (90%He 10% isobutane)

$\sigma_p/p = 0.4\,\%$ (tracks with $\theta > 45°$)

$\sigma_x^{hit} = 150\ \mu\mathrm{m}$ (xy), 2 mm (z)

$\sigma_x^{vertex} \sim 1\ \mathrm{mm}$

$\sigma(M_{\pi\pi}) \sim 1\ \mathrm{MeV}$



$K_S, K^+ \leftarrow \phi \rightarrow K_L, K^-$

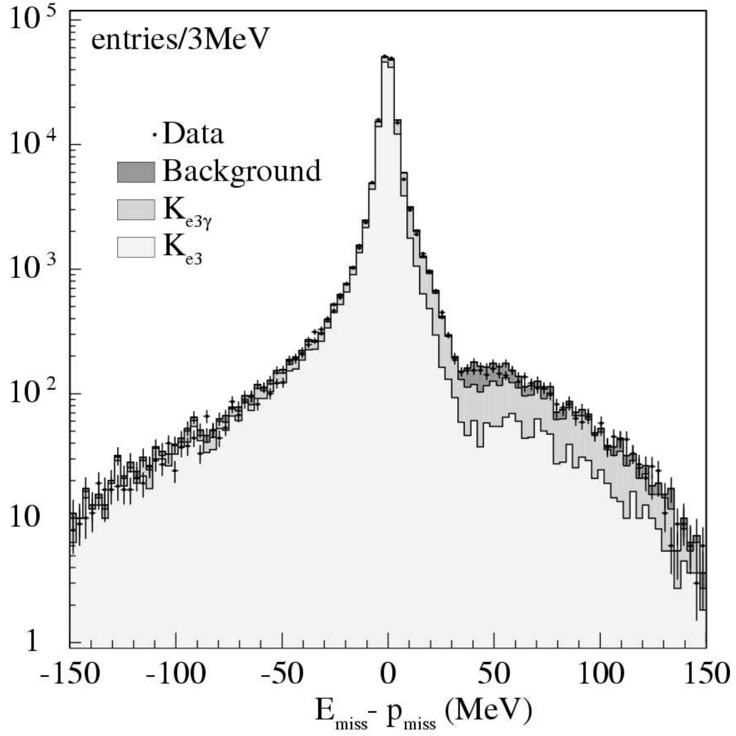
K^+K^-
BR~50%
p=127 MeV
$\lambda_\pm$=95 cm

K_SK_L
BR~30%
p=110 MeV
λ_s=0.6 cm λ_L=340 cm

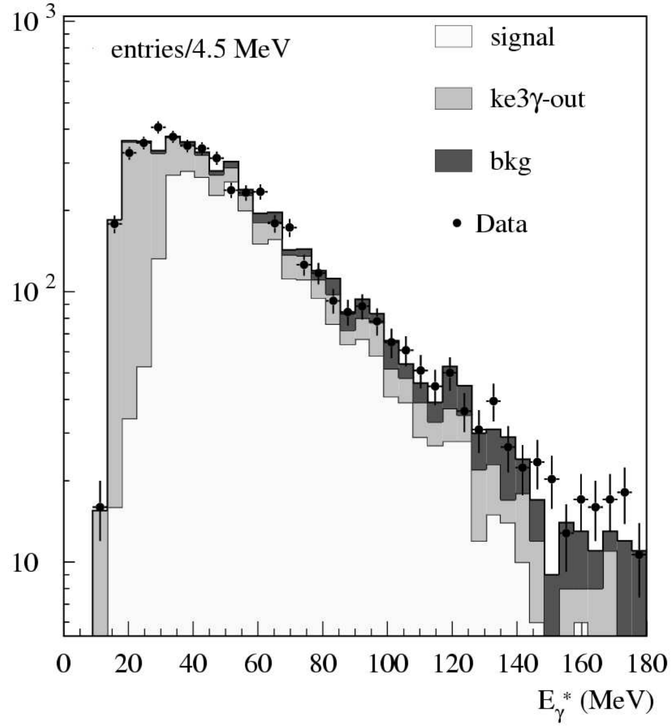
Integrated luminosity
$L=2.5\ \mathrm{fb}^{-1}$
About $2.5\times10^9\ K_SK_L$

Simulation of the final state photon

Enriched Ke3 sample



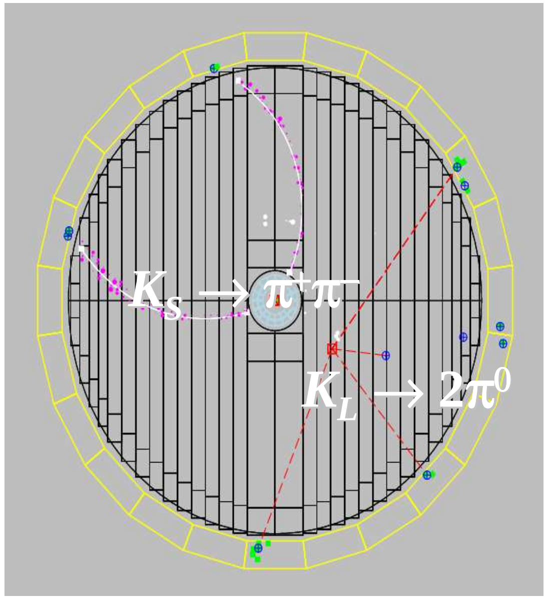
Direct measurement of E_γ in Ke3

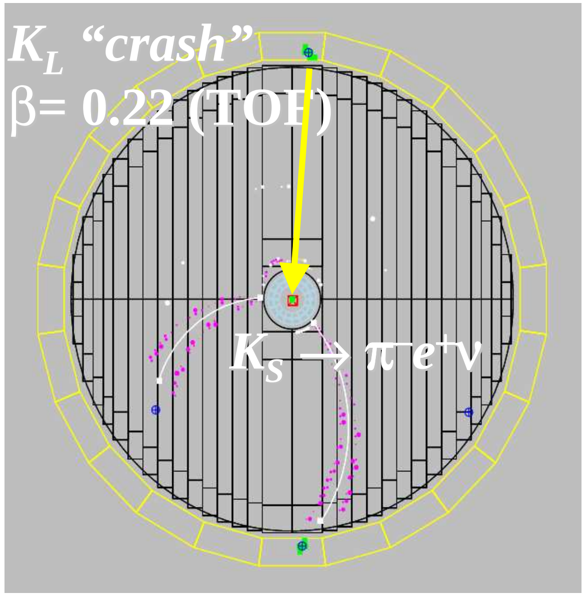


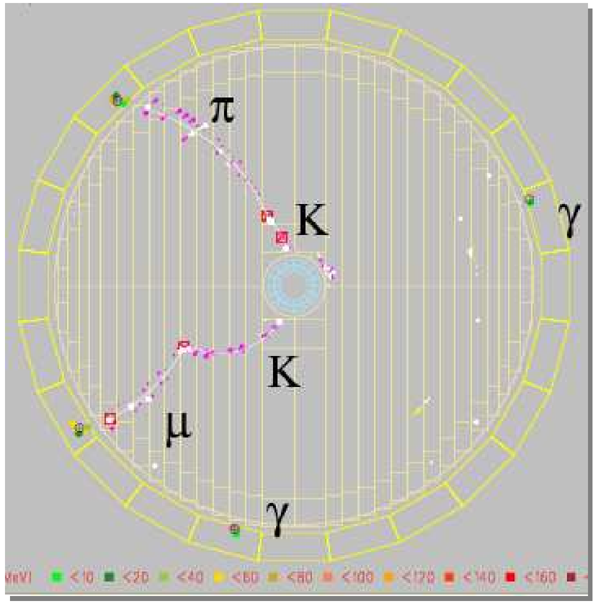
Emission of final state photon included in the KLOE simulation.

All measurements are inclusive of the final state radiation.

Kaon Tag







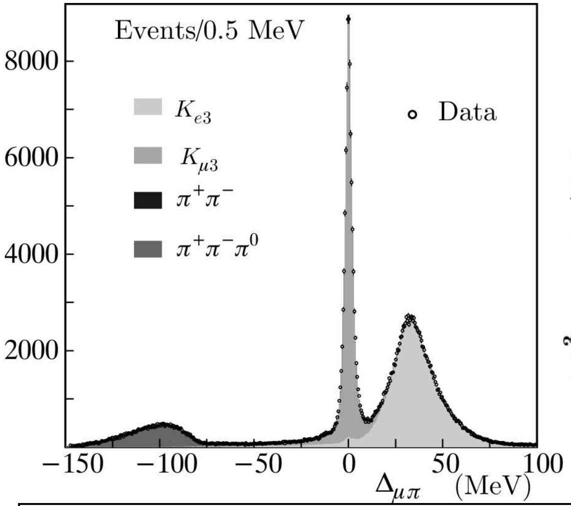
K_L tagged by $K_S \to \pi^+\pi^-$
Efficiency ~ 70%
$\sigma(P_K)$ ~ 1 MeV

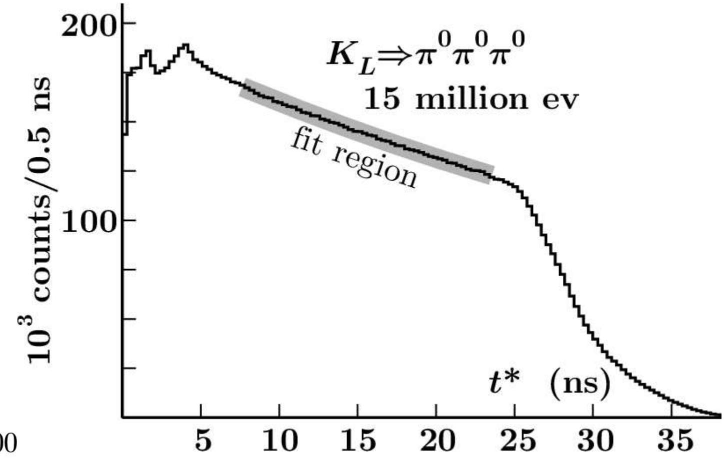
K_S tagged by K_L
interaction in EmC
Efficiency ~ 30%
$\sigma(P_K)$ ~ 1 MeV

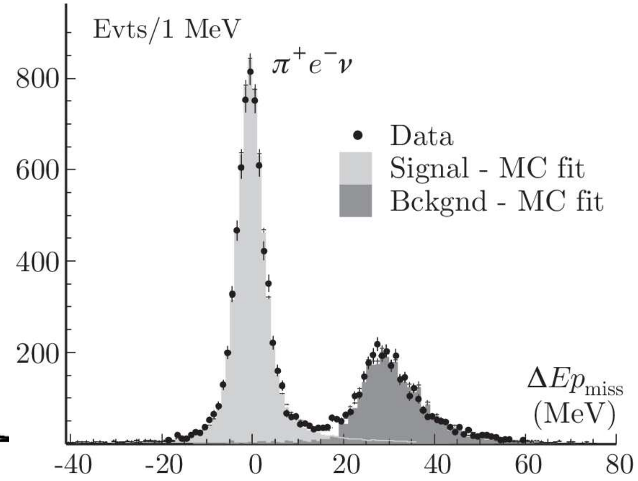
$K^\pm$ tagged by $K \to \mu\nu, \pi\pi$
identified by the secondary particle momentum in the K rest frame: $p^*(m_\pi)$
Trigger from the tag side.
ε_{Tag}~10%

Absolute BR's: $BR = N_{obs}/N_{tag}$

$K_{L,S}$ decays and K_L lifetime







13×10^6 K_L tagged decays.
BR for $3\pi^0$, $\pi^+\pi^-\pi^0$, Ke3 and Kμ3, identifying photons in the calorimeter and fit to E_{miss}-p_{miss} from p_{Trk}.
τ_L measurement from BR dependency on FV
$\Delta BR/BR=\Delta\tau_L\times0.0128\ ns^{-1} \oplus \sum BR=1$

Measurement of τ_L from proper decay-time ditribution for $K_L \rightarrow 3\pi^0$.
K_L vertex from photon time of flight and K_L direction.
8.5 million decays in $\sim0.4\lambda_L$.

400×10^6 $K_S K_L$
BR for $K_S \rightarrow \pi e \nu$
PID from time of flight.
13,500 Ke3 events selected.
Fit to E_{miss}-p_{miss}.
First measurement of the charge asymmetry
$A_S=(1.5\pm10)\times10^{-3}$

$K_{L,S}$ decays and K_L lifetime

$\chi^2/dof = 0.19/1$

BR(Ke3)	0.4008(15)
BR(Kμ3)	0.2699(14)
BR($3\pi^0$)	0.1996(20)
BR($\pi^+\pi^-\pi^0$)	0.1261(11)
BR($\pi^+\pi^-$)	$1.964(21)\times10^{-3}$
BR($\pi^0\pi^0$)	$8.49(9)\times10^{-4}$
BR(γγ)	$5.57(8)\times10^{-4}$
τ_L	50.84(23) ns

BR($\pi^+\pi^-$)	69.196(51)
BR($\pi^0\pi^0$)	30.687(51)
BR(Ke^+3)	$3.517(58)\times10^{-4}$
BR(Ke^-3)	$3.528(62)\times10^{-4}$

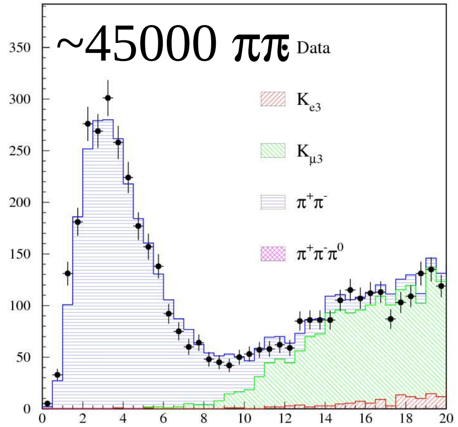
Only non-KLOE input

BR($\pi^0\pi^0$)/BR($\pi^+\pi^-$)=0.4391±0.0013

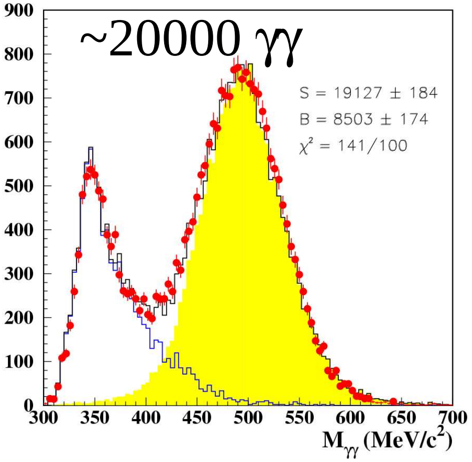
PDG ETAFIT

All correlations taken into account

Other KLOE inputs



$\sqrt{E_{miss}^2 + p_{miss}^2}\,(MeV)$



BR($K_S \rightarrow \pi^+\pi^-(\gamma)$)/BR($K_S \rightarrow \pi^0\pi^0$)=2.2549(54)

BR($K_L \rightarrow \gamma\gamma$)/($K_L \rightarrow 3\pi^0$)=0.00279(3)

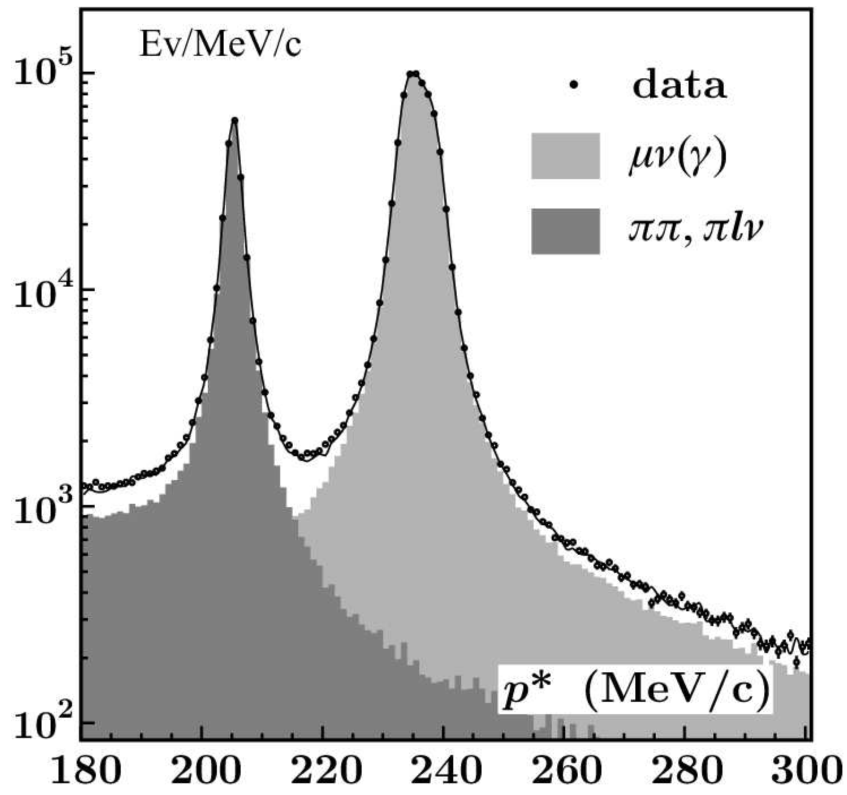
BR($K_L \rightarrow \pi^+\pi^-$)/($K_L \rightarrow \pi\mu\nu$)=0.007275(68)

The sum of measured K_S BR's is

$\sum BR \approx 1-5\times10^{-4}$

$K^+ \to \mu^+\nu$, $\pi^+\pi^0$

From 4 million tagged events.
Found ~865,000 Kμ2 events in
$225 < p^* < 400$ MeV
Absolute BR.
Counting by fit to p^* distribution.
Signal and background p^*-shapes, and efficiency from data control samples.
Small correction from MC checks, negligible dependence on $\tau_{\pm}$.



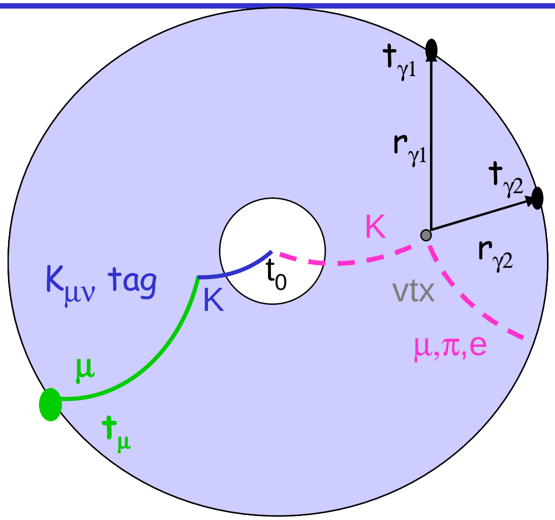
$BR(K^+ \to \mu\nu(\gamma)) = (0.6366 \pm 0.0017)$

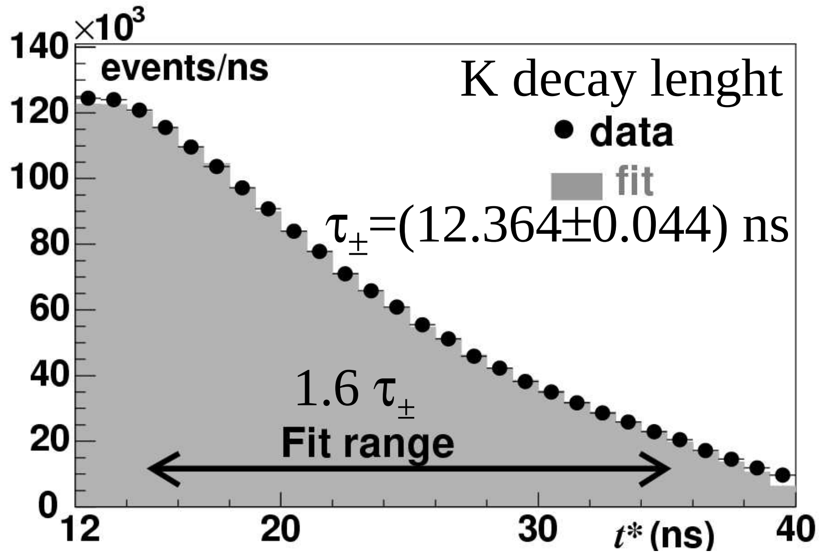
Same method used to measure $BR(\pi^+\pi^0)$.

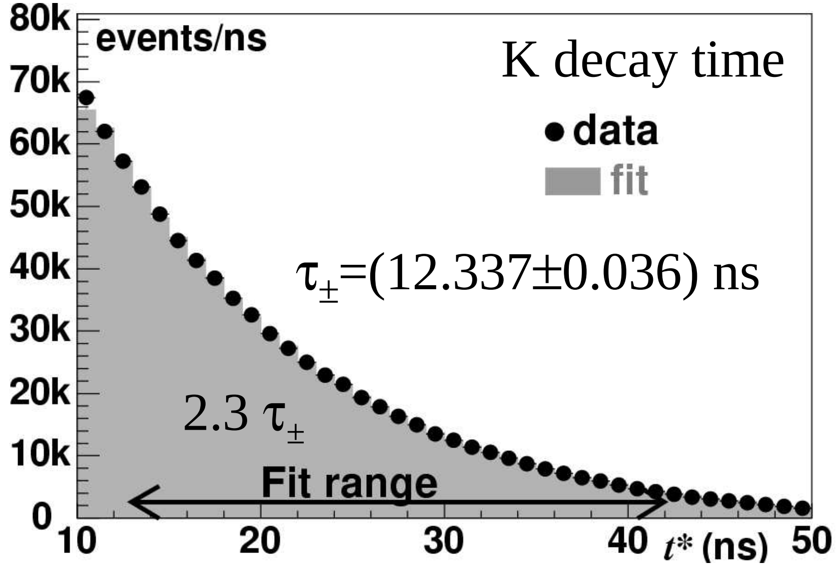
$BR(K^+ \to \pi^+\pi^0(\gamma)) = (20.65 \pm 0.05_{stat} \pm 0.08_{syst})\%$

-1.2% of PDG 2006, shifts NA48/2 and ISTRA+ Kl3 measurements

$K^{\pm}$ lifetime







With 12 million tagged K, use 2 methods:

K decay lenght $t^{*} = \sum \Delta L / (\gamma_K \beta_K c)$

from DC info, taking into account dE/dX.

K decay time $t^{*} = (t_\gamma - L_\gamma / c)/\gamma_K$

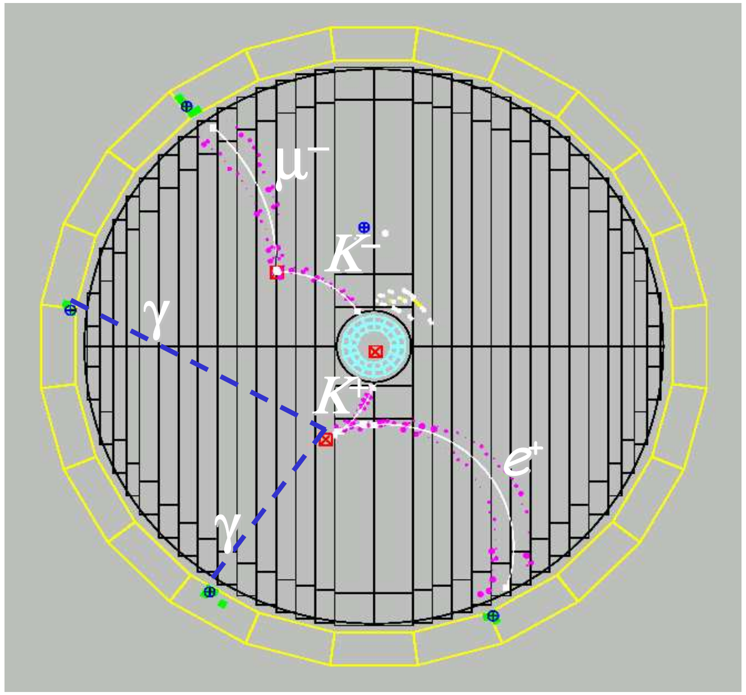
from calorimeter info, measure photon time of flight.

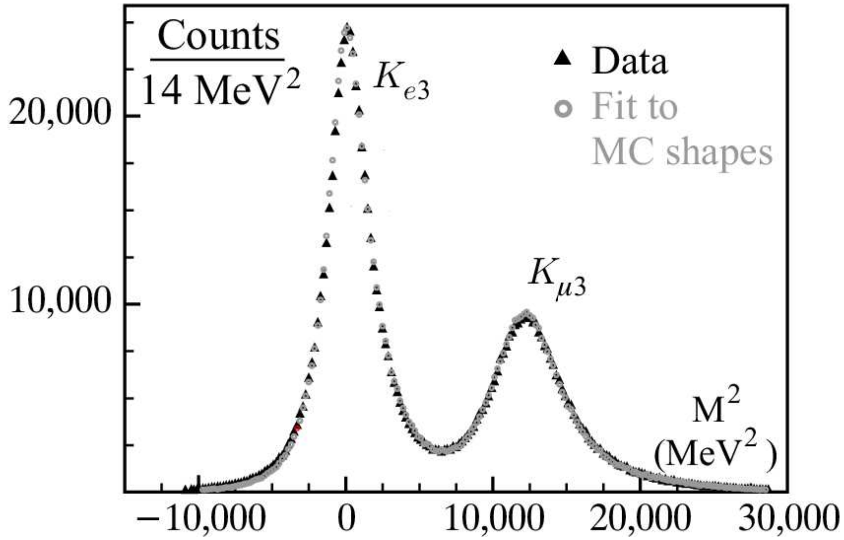
$\tau_{\pm}$=(12.347±0.030) ns

τ_{-}/τ_{+} = 1.004±0.004

PDG average 12.385(25) ns but CL 0.2%

$K^{\pm}$ semileptonic decays





$$m_l^2 = p_l^2\left[\frac{c^2}{L_l^2}(t_l - t_K)^2 - 1\right]$$

60 million tagged events.
Apply kinematic cuts to reject background. Reconstruct photons and measure t_K from tof.
Measure lepton mass from tof and track momentum measurement.

Counting from fit to m^2_l distribution.
300,000 Ke3 and 160,000 Kμ3.
Using lifetime from KLOE:

BR(Ke3)=(4.972±0.053)%
BR(Kμ3)=(3.237±0.039)%

Form Factor: K^0e3

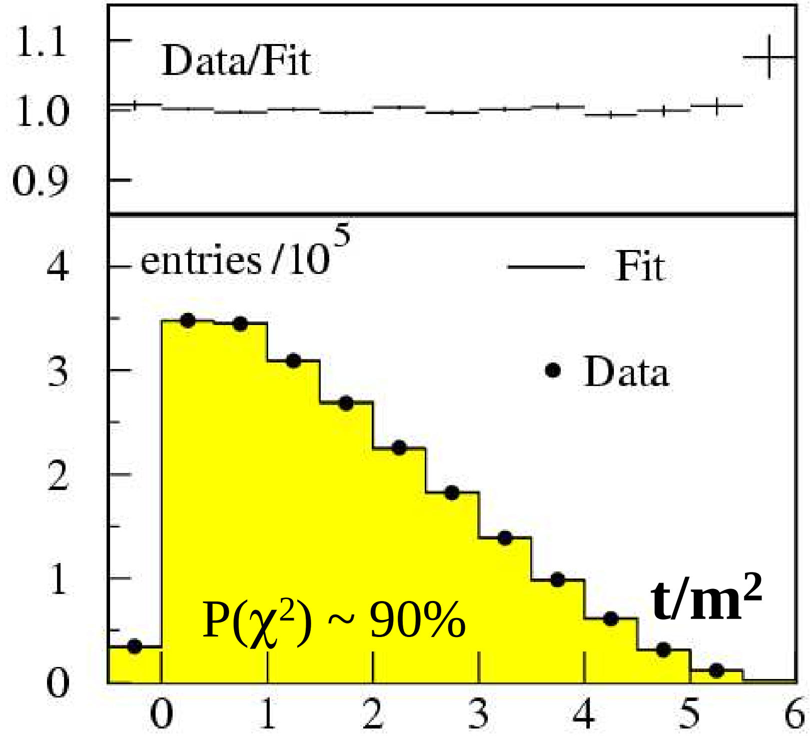
High purity Ke3 sample, 2 million events, selected by kinematics and time of flight.
e/π by tof → measure $t=(p_K-p_\pi)^2$
Independent measurement for the two charge modes.
Ke3 sensitive only to vector FF.

$$\tilde{f}_+(t) = 1 + \lambda'_+ \frac{t}{m_\pi^2} + \frac{1}{2}\lambda''_+ \left(\frac{t}{m_\pi^2}\right)^2$$

$\lambda'_+ = (25.5 \pm 1.5_{stat} \pm 1.0_{syst}) \times 10^{-3}$

$\lambda''_+ = (1.4 \pm 0.7_{stat} \pm 0.4_{syst}) \times 10^{-3}$

Correlation –0.95

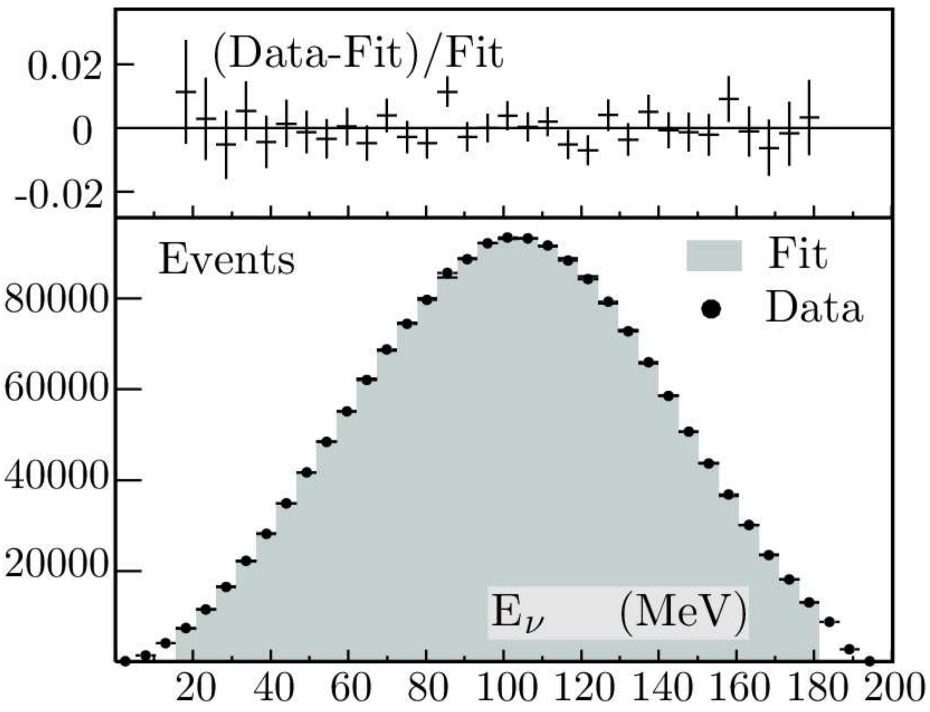


Pole parametrization: $P(\chi^2)$ ~ 92%

$M_V = (870 \pm 6_{stat} \pm 7_{syst})$ MeV

Form Factor: $K^0\mu 3$

1.8 million $K\mu 3$ selected.
Sensitive to both vector and scalar FF's.
Bakground rejection with kinematic cuts and tof.
Difficult π/μ separation: Fit to E_ν spectrum, less sensitive (errors 2-3 times larger) →combined fit with Ke3 data.
Large correlations: impossible to measure λ_0''.



$$\lambda_0=(15.4\pm 2.2)\times 10^{-3}$$

λ'_+	λ''_+	λ_0
1	-0.95	0.29
	1	-0.38

$$\chi^2/\text{ndf} = 2.3/2$$

Form Factors

New parametrizations based on dispersive relations (Bernard, Oertel, Passemar, Stern) and Kπ scattering data: f_+ and f_0 depend only on parameters λ_+ and λ_0 respectively.

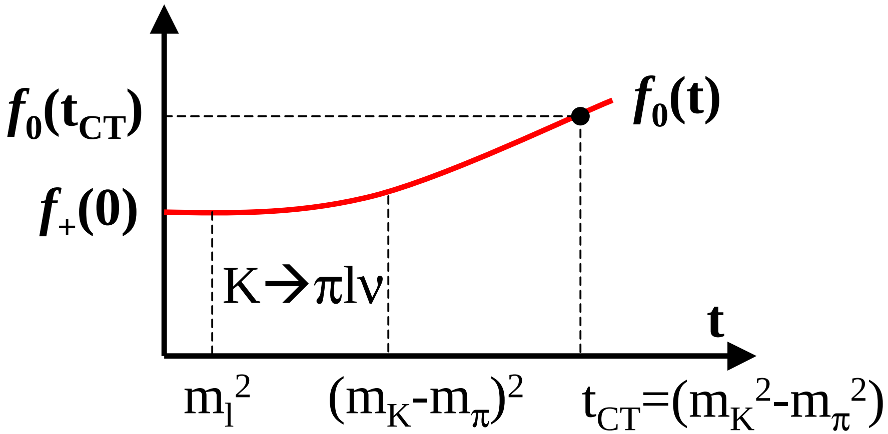
$$\lambda_+=(25.7\pm0.6_{stat+syst})\times10^{-3}$$
$$\lambda_0=(14.0\pm2.1_{stat+syst})\times10^{-3}$$

χ^2/ndf =2.6/3
Correlation –0.26

Phase-space integrals change by 0.04% and 0.09% for Ke3 and Kμ3.

Test of lattice QCD

Callan-Treiman
$f_0(t_{CT})=f_K/f_\pi+\Delta_{CT}$
Δ_{CT} $O(10^{-3})$ (Gasser, Leutwyler)
$f_K/f_\pi=1.189\pm0.007$ (HPQCD/UKQCD)



$$f_+(0)=0.967\pm0.025$$

Compare with $f_+(0)=0.9644\pm0.0049$ (RBC/UKQCD)

KLOE main publications related to V_{us}

Neutral Kaons

τ_L	PLB626 (2005) 15	$d\tau/\tau$~0.5%
K_L BR's	PLB632 (2006) 43	dBR($\pi l\nu$)/BR~0.4-0.5%
Ks→$\pi e\nu$	PLB636 (2006) 173	dBR($\pi e\nu$)/BR~1.3%

Form factors

Ke3 FF	PLB636 (2006) 166	$d\lambda'/\lambda'$~7% $d\lambda''/\lambda''$~50%
Kμ3 FF	JHEP 12 (2007) 105	$d\lambda_0/\lambda_0$~14% dI/I~0.3-0.5%

Charged Kaons

$\tau^{\pm}$	JHEP 01 (2008) 073	$d\tau/\tau$~0.25%
K^+→$\mu\nu$	PLB632 (2006) 76	dBR/BR~0.26%
$K^{\pm}$→ $\pi l\nu$	JHEP Accepted	dBR($\pi l\nu$)/BR~1.1%

$|V_{us}|$ and lepton universality @ KLOE arXiv:0802.3009

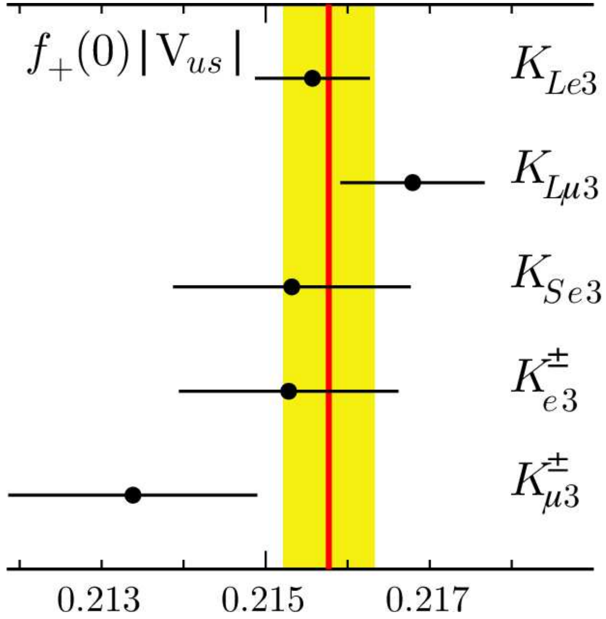
$f_+(0)\times|V_{us}|$ from KLOE results

K_{Le3}	0.2155(7)
$K_{L\mu3}$	0.2167(9)
K_{Se3}	0.2153(14)
$K^{\pm}_{e3}$	0.2152(13)
$K^{\pm}_{\mu3}$	0.2132(15)

$f_+(0)\times|V_{us}|=0.2157\pm0.0006$

All correlations taken into account

Only non-KLOE input τ_s



χ^2/ndf =7.0/4 (13%)

Comparing charged and neutral K decays: δSU(2)=1.67(62)% (theory 2.36(22)%)

Test of lepton universality:

$$r_{\mu e} = \frac{\left|f_+(0)\times V_{us}\right|^2_{\mu3}}{\left|f_+(0)\times V_{us}\right|^2_{e3}} = \frac{g^2_\mu}{g^2_e}$$

$r_{\mu e}=1.000\pm0.008$

From π and τ decays → ±0.4%

Test of CKM unitarity with KLOE results

Using

From lattice QCD:

$f_+(0)$=0.9644±0.0049 (RBC/UKQCD)

f_K/f_π=1.189±0.007 (HPQCD/UKQCD)

From $0^+ \to 0^+$ nuclear β decays

$|V_{ud}|$=0.97418±0.00026

And using $\Gamma(\pi \to \mu\nu)$:

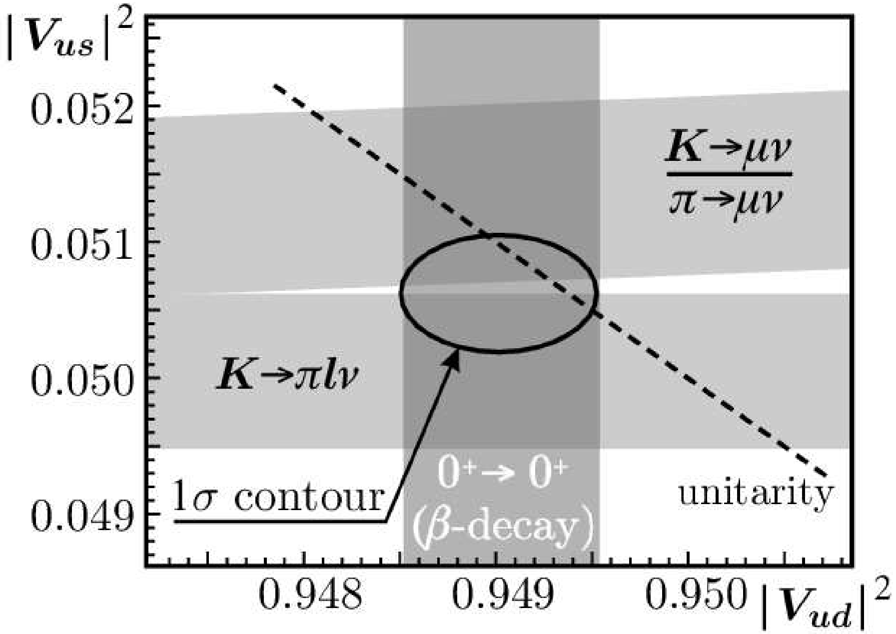
From Kl3 decays:

$|V_{us}|$=0.2237±0.0013

$|V_{ud}|^2+|V_{us}|^2-1$=-0.0009±0.0008

From Kμ2:

$|V_{us}|^2/|V_{ud}|^2$=0.0541±0.0007



Combined fit result:

χ^2/ndf =2.34/1 (13%)

$|V_{us}|$=0.2249±0.0010

$|V_{ud}|$=0.97417±0.00026

$|V_{ud}|^2+|V_{us}|^2-1$=0.0004±0.0007

Unitarity condition verified to 0.1%

Bounds on new physics from $K_{\mu 2}$ decay

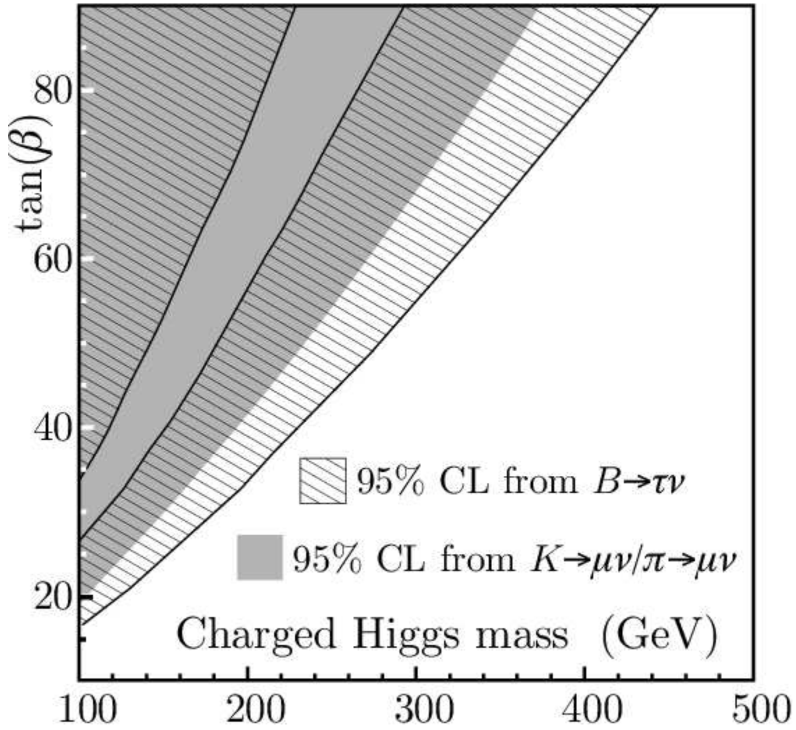
From previous results:

$$R_{l23} = \left| \frac{V_{us}(K_{\mu 2})}{V_{us}(K_{l3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\mu 2})} \right|$$

Unity in SM, affected by presence of scalar or right-handed currents.

$$R_{l23} = \left| 1 - \frac{m_{K+}^2}{m_{H+}^2} \left(1 - \frac{m_{\pi+}^2}{m_{K+}^2} \right) \frac{\tan^2\beta}{1+\varepsilon_0 \tan\beta} \right|$$

(Isidori, Paradisi)



We obtain:

$R_{l23}=1.008\pm0.008$

This places bounds on the charged Higgs mass and $\tan\beta$.
Competitive and complementary to B decays.

Bounds on new physics from K_{e2} decay

$R_K = \Gamma(K \rightarrow e\nu) / \Gamma(K \rightarrow \mu\nu)$

Accurate SM determination (0.04%)

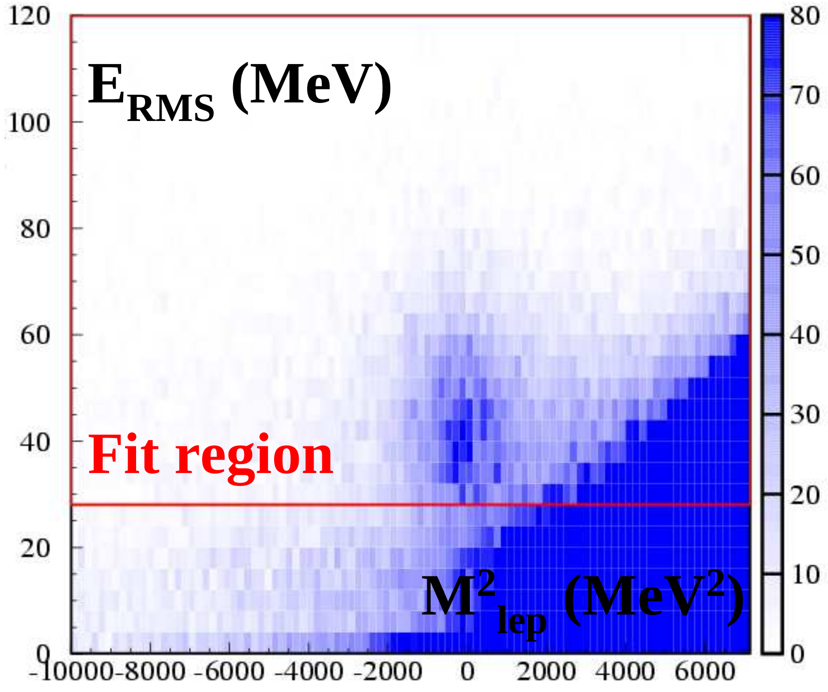
New physics effects up to 1%

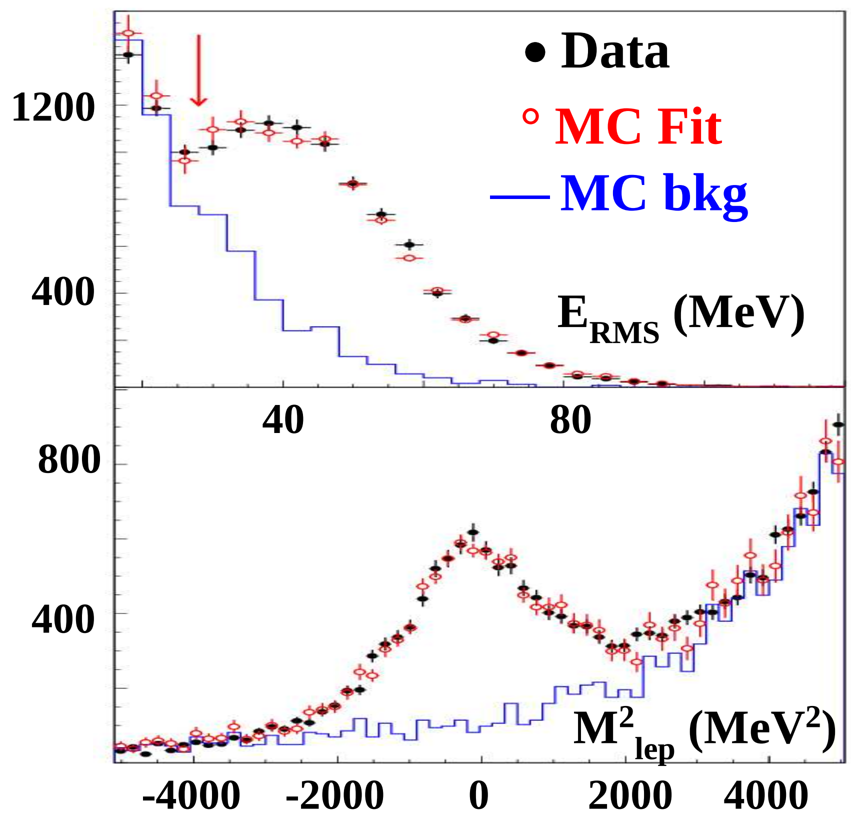
(Masiero, Paradisi, Petronzio).

$$R_K^{LFV} \approx R_K^{SM} \left[1 + \frac{m_K^4}{m_H^4} \frac{m_\tau^2}{m_e^2} \left|\Delta_R^{31}\right|^2 \tan^6 \beta \right]$$

$BR(K \rightarrow e\nu) \sim 10^{-5}$ at most 4×10^4 events. No tag requested.

Background from Kμ2, selection using DC info (M_{lep}^2) and calorimeter PID:



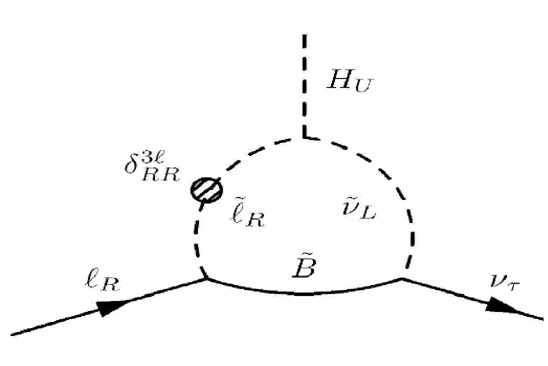


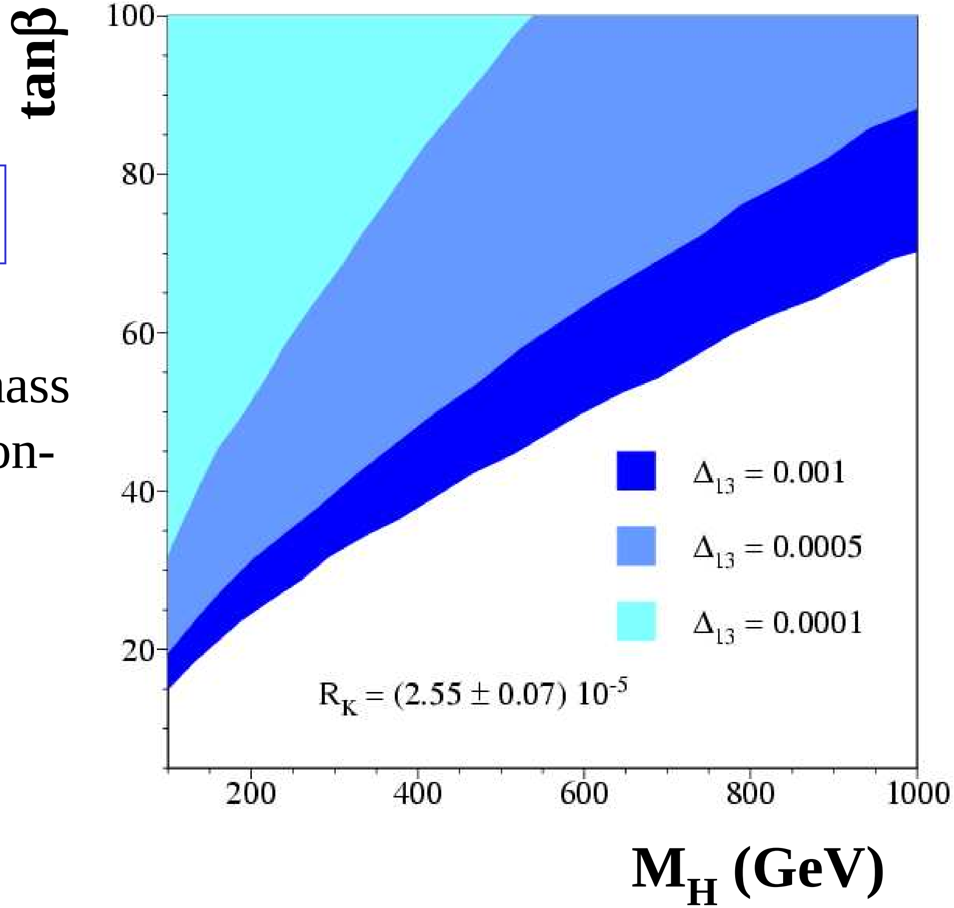
Bounds on new physics from K_{e2} decay

Preliminary KLOE result with ~ 8100 observed events:

$$R_K=(2.55\pm0.05_{stat}\pm0.05_{syst})\times10^{-5}$$

We place bounds on the charged Higgs mass and tanβ, for different values of the slepton-mass matrix element Δ_{13}.





SM: $2.477(1)\times10^{-5}$ (Cirigliano, Rosell)

NA48 preliminary: $2.43(4)\times10^{-5}$

Conclusion

We have measured:

- All the BR's for K_L K_S and $K^{\pm}$
- The form factor parameters in semileptonic K_L decays
- The K_L and $K^{\pm}$ lifetimes

We obtain $f_+(0)\times|V_{us}|=0.2157\pm0.0006$ with 0.3% accuracy

We test lepton universality: $r_{\mu e} = g_\mu^2/g_e^2 = 1.000\pm0.008$

We measured the ratio $|V_{us}/V_{ud}\times f_K/f_\pi|^2 = 0.7650\pm0.0033$ with 0.4% accuracy.

Using lattice QCD determinations for meson form factor and decay constants we obtain:

$|V_{us}|=0.2237\pm0.0013$ and $|V_{us}/V_{ud}|=0.2326\pm0.0015$ with 0.6% accuracy

Combining with a fit these results with the evaluation of $|V_{ud}|$ from nuclear β decay we obtain $|V_{us}|=0.2249\pm0.0010$ with 0.4% accuracy.

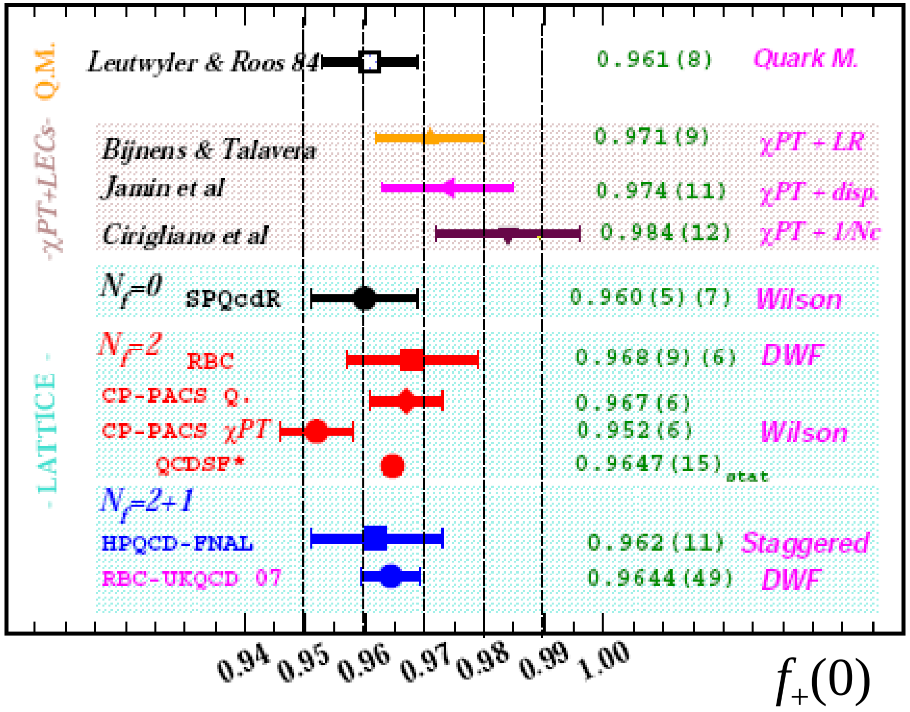
First-row CKM unitarity is satisfied to 0.1% (0.6σ)

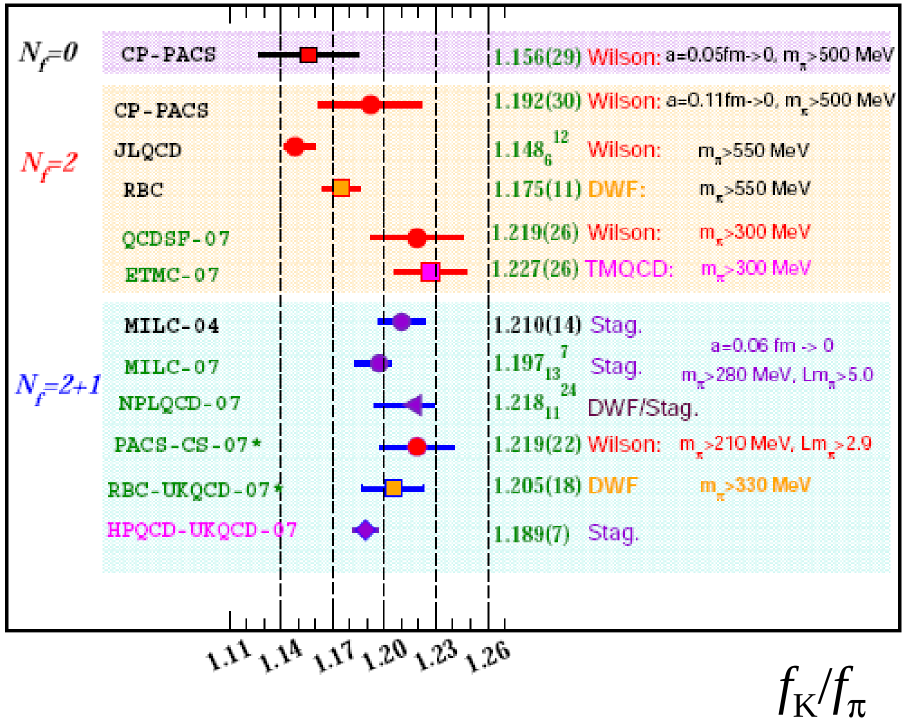
With our results we are able to exclude a large region in the m_{H+}-tanβ plane.

Preliminary results on the ratio BR(K→eν)/BR(K→μν) allow a test LFV and the exclusion of a large region in the m_{H+}-tanβ plane.

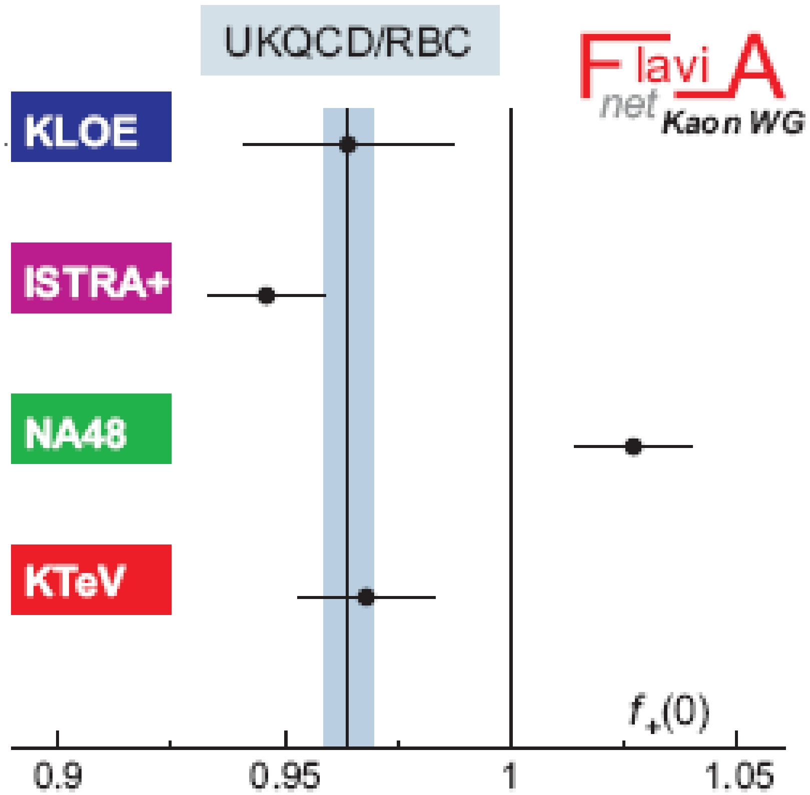
Complete dataset must still be analyzed, we expect improvements for lifetimes, BR's and FF parameters, as well as from the theory side (Lattice QCD, ChPT ......).

backup


Q.M.
χPT+LECs
LATTICE
Leutwyler & Roos 84
0.961(8)
Quark M.
Bijnens & Talavera
0.971(9)
χPT + LR
Jamin et al
0.974(11)
χPT + disp.
Cirigliano et al
0.984(12)
χPT + 1/Nc
N_f=0 SPQcdR
0.960(5)(7)
Wilson
N_f=2 RBC
0.968(9)(6)
DWF
CP-PACS Q.
0.967(6)
CP-PACS χPT
0.952(6)
Wilson
QCDSF*
0.9647(15)stat
N_f=2+1
HPQCD-FNAL
0.962(11)
Staggered
RBC-UKQCD 07
0.9644(49)
DWF
0.94 0.95 0.96 0.97 0.98 0.99 1.00
f+(0)


N_f=0
CP-PACS
1.156(29) Wilson: a=0.05fm->0, m_π>500 MeV
N_f=2
CP-PACS
1.192(30) Wilson: a=0.11fm->0, m_π>500 MeV
JLQCD
1.148 12 6 Wilson: m_π>550 MeV
RBC
1.175(11) DWF: m_π>550 MeV
QCDSF-07
1.219(26) Wilson: m_π>300 MeV
ETMC-07
1.227(26) TMQCD: m_π>300 MeV
N_f=2+1
MILC-04
1.210(14) Stag.
MILC-07
1.197 7 13 Stag.
a=0.06 fm -> 0
m_π>280 MeV, Lm_π>5.0
NPLQCD-07
1.218 24 11 DWF/Stag.
PACS-CS-07*
1.219(22) Wilson: m_π>210 MeV, Lm_π>2.9
RBC-UKQCD-07*
1.205(18) DWF m_π>330 MeV
HPQCD-UKQCD-07
1.189(7) Stag.
1.11 1.14 1.17 1.20 1.23 1.26
fK/fπ

backup


UKQCD/RBC
FlaviA net Kaon WG
KLOE
ISTRA+
NA48
KTeV
f+(0)
0.9
0.95
1
1.05