Precision Standard Model Tests with Kaons

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Flavour Physics and CP Violation 2007

Taipei, May 6, 2008

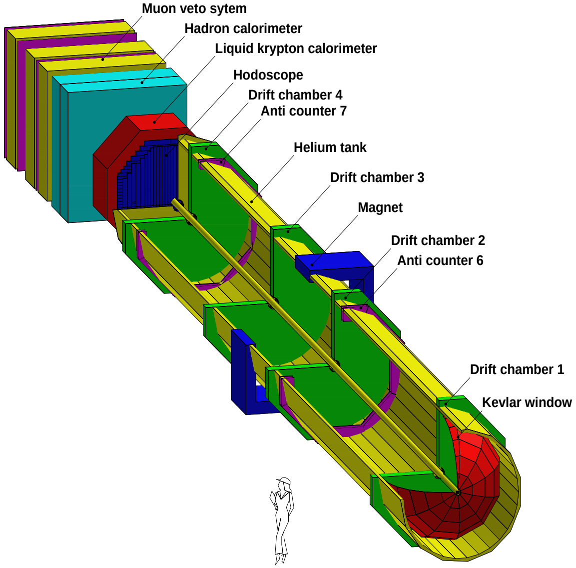
Overview

- **Flavour Physics . . .**
  - $|V_{us}|$ **from Semileptonic and Leptonic K Decays**
  - **Precise Measurement of Leptonic K Decays**
- **. . . and $\mathcal{CP}$ Violation**
  - **Search for Direct $\mathcal{CP}$ Violation in $K^\pm \rightarrow 3\pi$ Decays**
- **Not covered . . .**
  - **Precision Tests of ChPT in Kaon Decays**

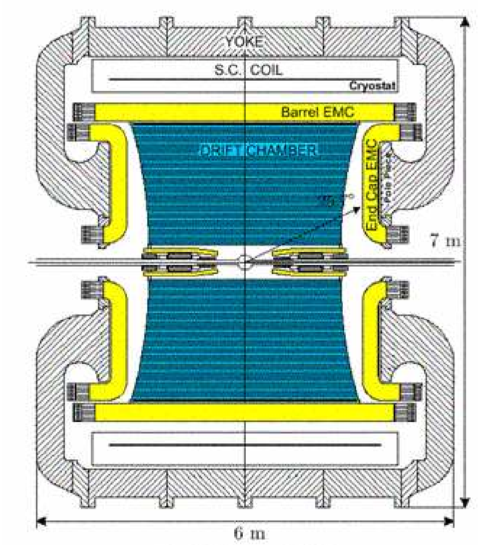
    $\pi\pi$ scattering amplitudes from K_{e4} and Cusp in $K \rightarrow 3\pi$,
    $K^+ \rightarrow \pi^+ e^+ e^-$, $K^+ \rightarrow \pi^+\pi^0\gamma$, $K^+ \rightarrow \pi^+\gamma\gamma$, $K_S \rightarrow \gamma\gamma$,
    and many more!

Experiments

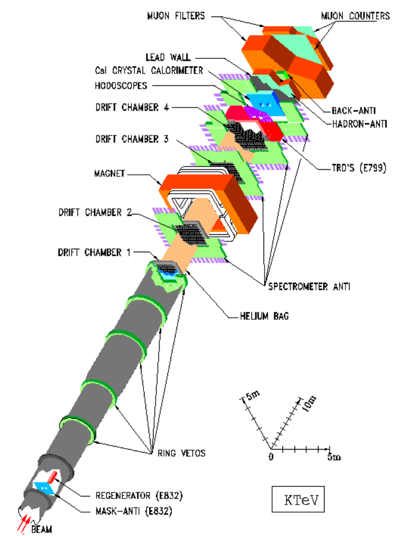
NA48



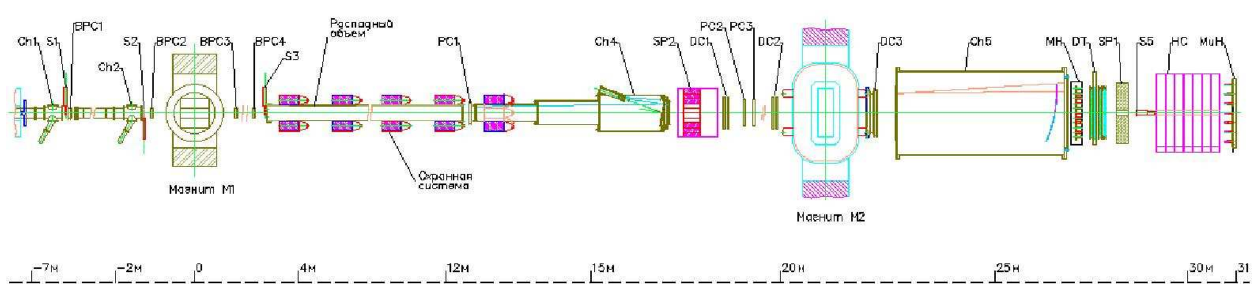
KLOE



KTeV



ISTRA+



Flavianet Kaon Working Group

http://www.lnf.infn.it/wg/vus/

FlaviA net

Working Group on Precise SM Tests in K Decays

FlaviA net

Kaon WG home
FlaviaNet home

Master Formulae
Branching Ratios
Lifetimes
Form Factors

Radiative Corrections
SU(3) Breaking Form Factors

Contacts

News
Talks
Acknowledgements

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Vladimir Obraztsov (Protvino)

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Patrizia De Simone (Frascati)

KTeV:
Sasha Glazov (DESY)

NA48:
Rainer Wanke (Uni. Mainz)
Michele Veltri (Uni. Urbino)
Mauro Piccini (CERN)

Theory:
Johan Bijnens (Lund)
Vincenzo Cirigliano (Los Alamos)
Juerg Gasser (Bern)
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$|V_{us}|$ Measurement from Semileptonic and Leptonic Kaon Decays

$|V_{us}|$ from Semileptonic Kaon Decays

$\mathbf{K_{l3}}$ master formula: $(K_{l3} \equiv K \to \pi l \nu;\, l = e, \mu)$

$$\Gamma(K_{l3(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 \, S_{EW} \, |V_{us}|^2 \, |f_+(0)|^2 I_K^l (1 + 2\delta^l_{SU(2)} + 2\delta^l_{EM})$$

with: $C_K^2 = 1$ for K^0, $= \frac{1}{2}$ for $K^\pm$.

$S_{EW} = 1.0232$: short-distance EW correction.

To be measured by experiment:

- $\Gamma(K_{l3(\gamma)})$: Decay rates including radiative γ's $\Longrightarrow$ BR's, τ's.
- I_K^l: Integral of form factors over phase space $\Longrightarrow$ slopes λ_+, λ_0.

To be determined by theory:

- $f_+(0)$: Hadronic matrix element at $q^2 = 0$ (different for $K^\pm$, K^0).
- $\delta^l_{SU(2)}$, δ^l_{EM}: Form factor corrections for $SU(2)$ breaking and long-distance EM interactions.

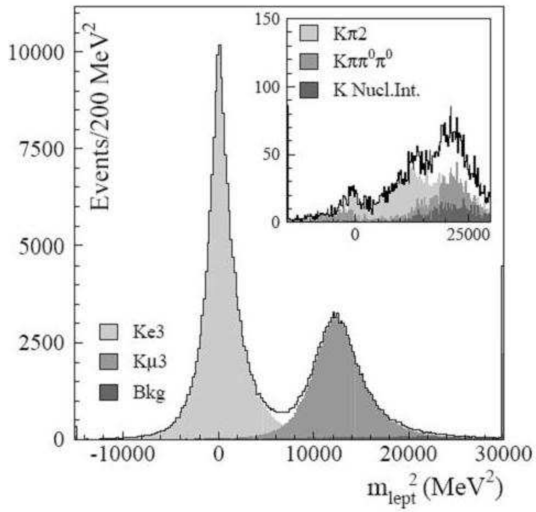
Direct Measurements of Kaon Branching Fractions

Several new data on main kaon branching fractions last year:

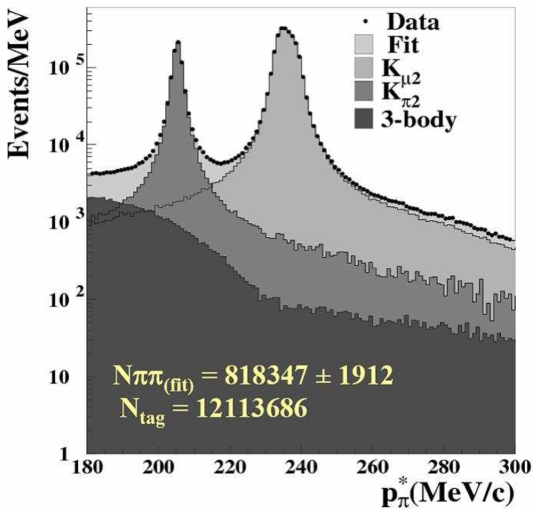
- **NA48/2:** $\mathbf{K^{\pm}_{e3}/\pi^{\pm}\pi^{0}}$, $\mathbf{K^{\pm}_{\mu 3}/\pi^{\pm}\pi^{0}}$ published last year.
- **ISTRA+:** $\mathbf{K^{-}_{e3}/\pi^{-}\pi^{0}}$ updated.
- **KLOE:**
  - Can measure ***absolute*** branching fractions $\Longrightarrow$ $\mathbf{K_{e3}, K_{\mu 3}, 2\pi, 3\pi, \mu\nu, \ldots}$
  - New precise $\mathbf{K_{L,S}}$, $\mathbf{K^{\pm}}$ **lifetime** measurements.

Global *Flavianet* fit to all data

KLOE K^{+}_{l3}

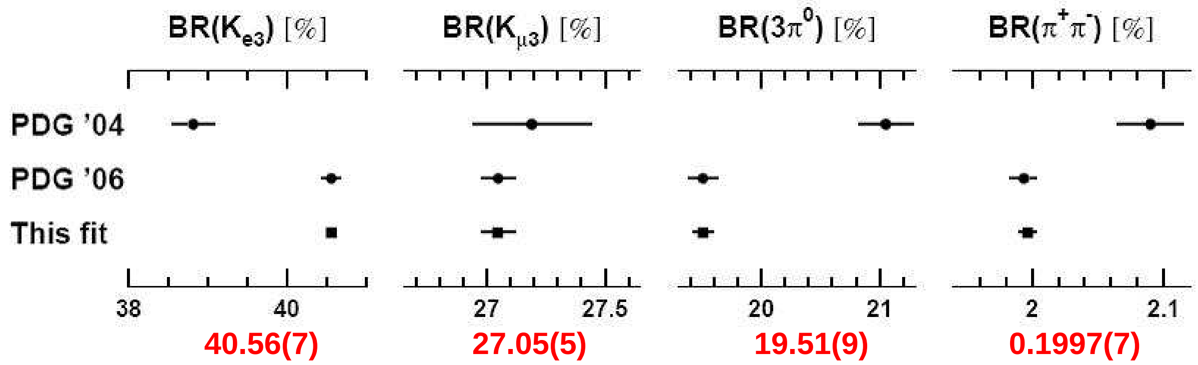


KLOE $K^{+}_{2\pi}$ (prel.)

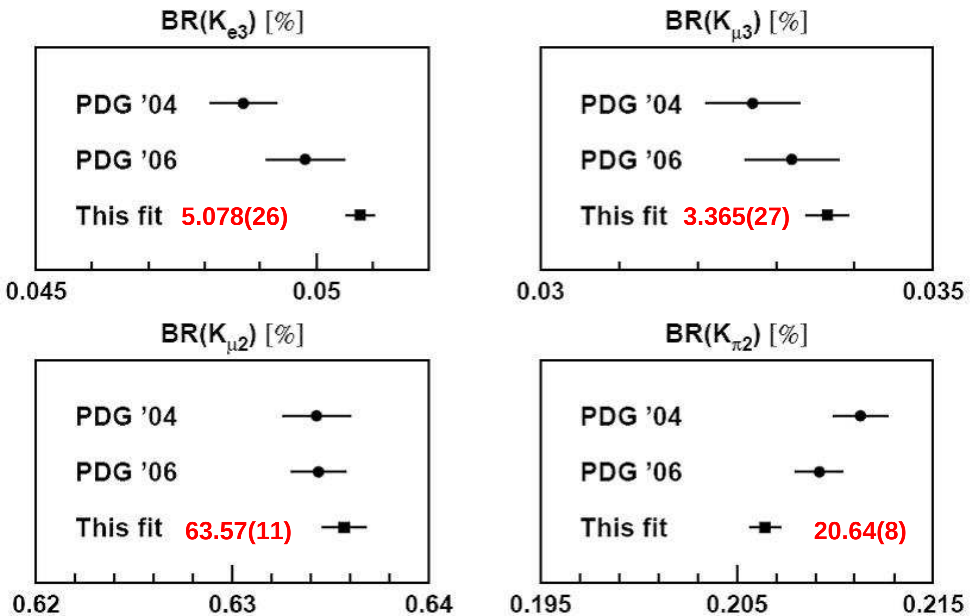


Fit to Kaon Branching Fractions

Main K_L branching fractions:



Main $K^\pm$ branching fractions:



$\Longrightarrow$ **New KLOE $\pi^+\pi^0$ BR significantly shifts all K^+ results!**

$|V_{us}|$ Determination

Global *Flavianet* fit to all Kaon data

- Includes: All $K^{\pm}$, K_L, K_S BR's, form factor slopes, lifetimes.

(M. Antonelli *et al.*, arXiv:0801.1817 [hep-ph])

$K_{L,S}$

18 input measurements:

5 KTeV ratios
NA48 K_{e3}/2t and $\Gamma(3\pi^0)$
4 KLOE BRs
KLOE, NA48 $\pi^+\pi^-/K_{l3}$
KLOE, NA48 $\gamma\gamma/3\pi^0$
PDG ETAFIT for $\pi^+\pi^-/\pi^0\pi^0$
KLOE τ_L from $3\pi^0$
Vosburgh '72 τ_L

1 constraint: ΣBR=1

K^{+-}

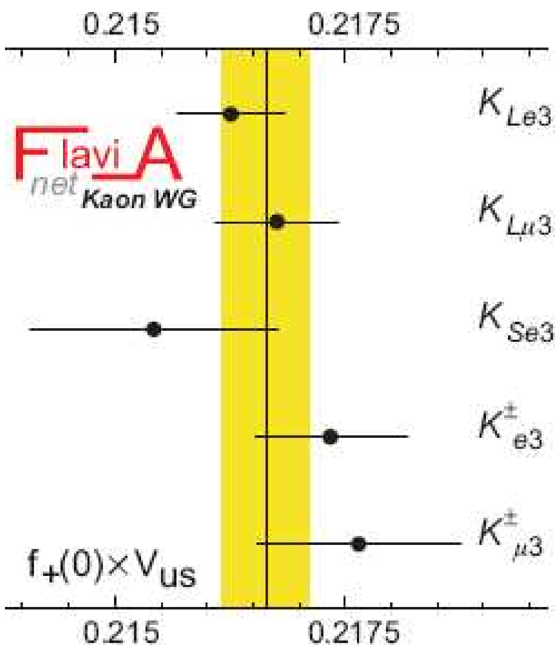
26 input measurements:

5 older τ values in PDG
2 KLOE τ
KLOE BR($\mu\nu$)
KLOE $Ke3$, $K\mu3$ BRs
ISTRA+ $K_{e3}/\pi\pi^0$
NA48/2 $K_{e3}/\pi\pi^0$, $K_{\mu3}/\pi\pi^0$
E865 K_{e3}/Kdal
KLOE $\pi\pi^0$
3 old $\pi\pi^0/\mu\nu$
2 old $Ke3$/2 body
3 $K\mu3/Ke3$ (2 old)
2 old + 1 KLOE results on 3π

$+$ form factor slopes

$|V_{us}|$ Determination

	BR [%]	$\mathbf{|V_{us}| \times f_+(0)}$	% err	% error from BR	% error from τ	% error from Δ
$\mathbf{K_L e3}$	$\mathbf{40.58(9)}$	$\mathbf{0.21625(60)}$	$\mathbf{0.28}$	0.09	0.19	0.15
$\mathbf{K_L \mu 3}$	$\mathbf{27.06(6)}$	$\mathbf{0.21675(66)}$	$\mathbf{0.31}$	0.10	0.18	0.15
$\mathbf{K_S e3}$	$\mathbf{0.0705(9)}$	$\mathbf{0.21542(134)}$	$\mathbf{0.67}$	0.65	0.03	0.15
$\mathbf{K^\pm e3}$	$\mathbf{5.078(25)}$	$\mathbf{0.21728(84)}$	$\mathbf{0.39}$	0.26	0.09	0.26
$\mathbf{K^\pm \mu 3}$	$\mathbf{3.365(27)}$	$\mathbf{0.21758(111)}$	$\mathbf{0.51}$	0.40	0.09	0.26
Average		$\mathbf{0.21661(47)}$				



Average: $\mathbf{|V_{us}| \times f_+(0) = 0.21661 \pm 0.00047}$

Use $\mathbf{f_+(0) = 0.964 \pm 0.005}$ from Lattice QCD (UKQCD/RBC 2007 $\Longrightarrow$ Talk F. Mescia)

$\mathbf{|V_{us}| = 0.2246 \pm 0.0012}$

(Error dominated by estimate of $f_+(0)$.)

$|V_{us}|$ Determination

Adding information from $\mathbf{K}^+ \to \mu^+\nu$ ($\mathbf{K}_{\mu 2}$):

- New BR from KLOE ($\sim 0.3\%$ precision) $+$ older values

  $\Longrightarrow$ Br$(\mathbf{K}^+ \to \mu^+\nu) = \mathbf{0.6357 \pm 0.0011}$

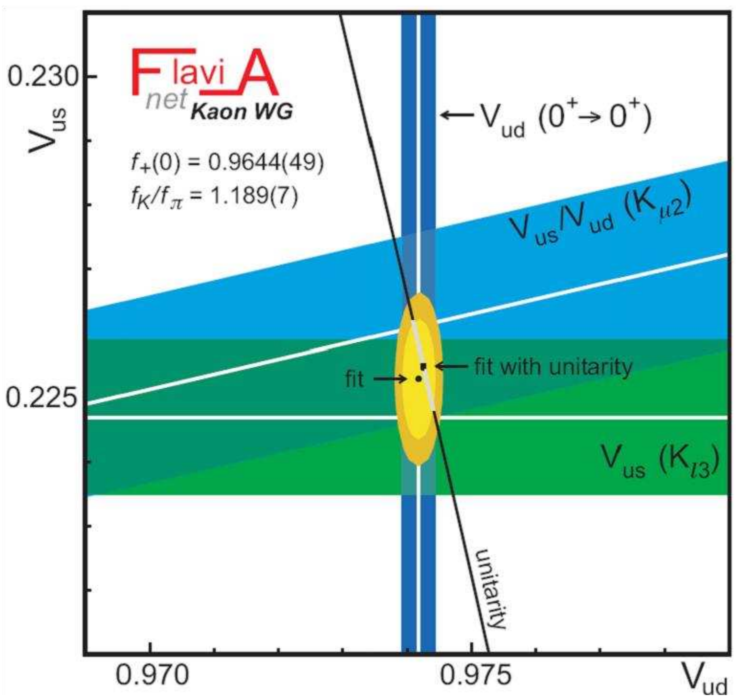
- Take $\tau_{\mathbf{K}^+}$ from Flavianet fit and build $\boldsymbol{\Gamma}(\mathbf{K} \to \mu\nu)/\boldsymbol{\Gamma}(\pi \to \mu\nu)$

  $(\Gamma(\pi_{\mu 2}) = 38.408(7)\ \mu\text{s}^{-1})$

$$\frac{|\mathbf{V_{us}}|}{|\mathbf{V_{ud}}|}\,\frac{\mathbf{f_K}}{\mathbf{f_\pi}} = \mathbf{0.2760 \pm 0.0006}$$

- Use $f_K/f_\pi = 1.189(7)$:
  (MILC-HPQCD 2007 $\Longrightarrow$ Talk F. Mescia)

$$|\mathbf{V_{us}}|/|\mathbf{V_{ud}}| = \mathbf{0.2321 \pm 0.0015}$$



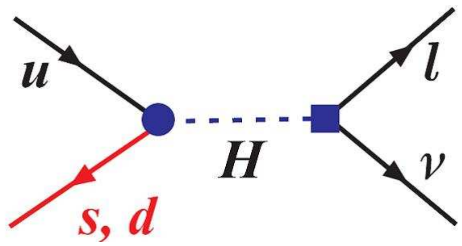
Very good agreement with $|\mathbf{V_{us}}|$ from $\mathbf{K_{l3}}$ and $|\mathbf{V_{ud}}|$ from $\mathbf{0^+ \to 0^+}$ transistions!

Higgs Mass Limit from $K_{\mu 2}$

Search for New Physics in $\mathbf{K_{\mu 2}}$:

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

$\Longrightarrow$ should be $\mathbf{1}$ in SM.



Higgs exchange in $\mathbf{K_{\mu 2}}$ would lower $\mathbf{R_{l23}}$:

(Isidori, Paradisi,PLB 639,2006)

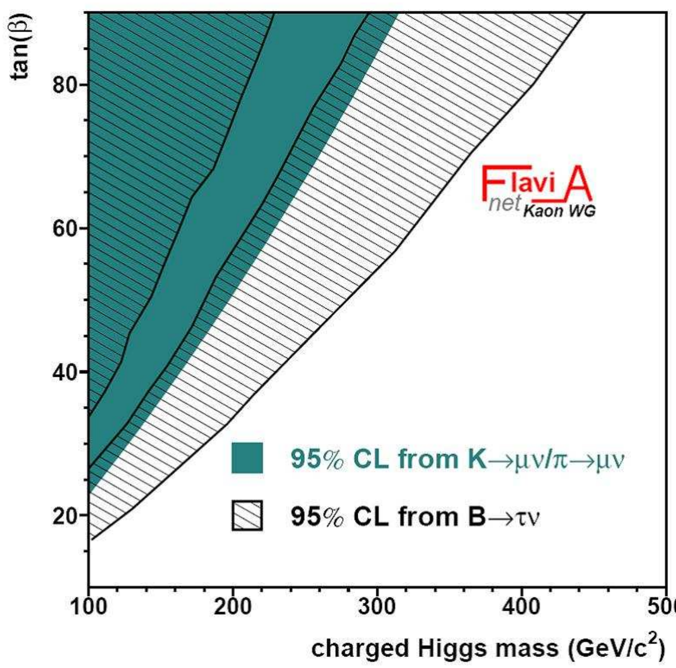
$$\mathbf{R_{l23}} = \left| 1 - \frac{\mathbf{m^2_{K^+}}}{\mathbf{m^2_{H^+}}} \left(1 - \frac{\mathbf{m^2_{\pi^+}}}{\mathbf{m^2_{K^+}}} \right) \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right|$$

$(\epsilon_0 \sim 0.01)$

Using experimental data, CKM unitarity for K_{l3} and $\frac{f_K}{f_\pi} / f_+(0)$ from the lattice:

$$\mathbf{R_{l23} = 1.004 \pm 0.007}$$

$\Longrightarrow$ **Limit on Higgs mass, covers gap from $\mathrm{B} \to \tau\nu$!**



$\mathbf{K_{e2}/K_{\mu 2}}$

Standard Model Prediction:

- $\mathbf{R_K} = \mathbf{\Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)}$ text book exercise for helicity suppression, but must include radiative corrections:

(Cirigliano, Rosell, PRL 99 (2007) 231801)

$$\mathbf{R_K} = R_K^{(0)}(1 + \delta R_K^{\text{rad.corr.}}) = 2.569 \times 10^{-5} \times (0.9640 \pm 0.0004)$$
$$= \mathbf{(2.477 \pm 0.001) \times 10^{-5}}$$

$\Longrightarrow$ **SM prediction has precision of 0.04%!**

Possibility for New Physics in $\mathbf{K_{e2}/K_{\mu 2}}$:

- **SUSY:** LFV $H^{\pm}$ couplings may enhance/lower SM K_{e2} decay width by up to $2-3\%$. (Masiero, Paradisi, Petronzio (2006))

PDG 2006: Three measurements from the 1970's

$$\mathbf{\Gamma(K_{e2})/\Gamma(K_{\mu 2}) = (2.45 \pm 0.11) \times 10^{-5}}$$

$K_{e2}/K_{\mu 2}$ — *Measurements*

Three new **preliminary measurements:**

- **NA48/2 (2003 data), presented in 2005:**
  - About 4000 signal events from normal running period.

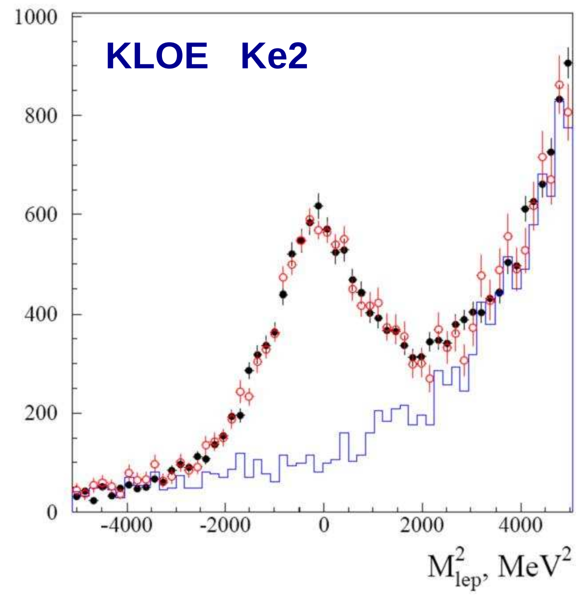
$$\mathbf{\Gamma(K_{e2})/\Gamma(K_{\mu 2}) = (2.416 \pm 0.043 \pm 0.024) \times 10^{-5}}$$

- **NA48/2 (2004 data), presented last year:**
  - About 4000 signal events from special minimum bias trigger.
  - Uncorrelated with 2003 measurement.

$$\mathbf{\Gamma(K_{e2})/\Gamma(K_{\mu 2}) = (2.455 \pm 0.045 \pm 0.041) \times 10^{-5}}$$

- **KLOE, presented last year:**
  - About 8000 events from 1.7 fb^{-1}.

$$\mathbf{\Gamma(K_{e2})/\Gamma(K_{\mu 2}) = (2.55 \pm 0.05 \pm 0.05) \times 10^{-5}}$$

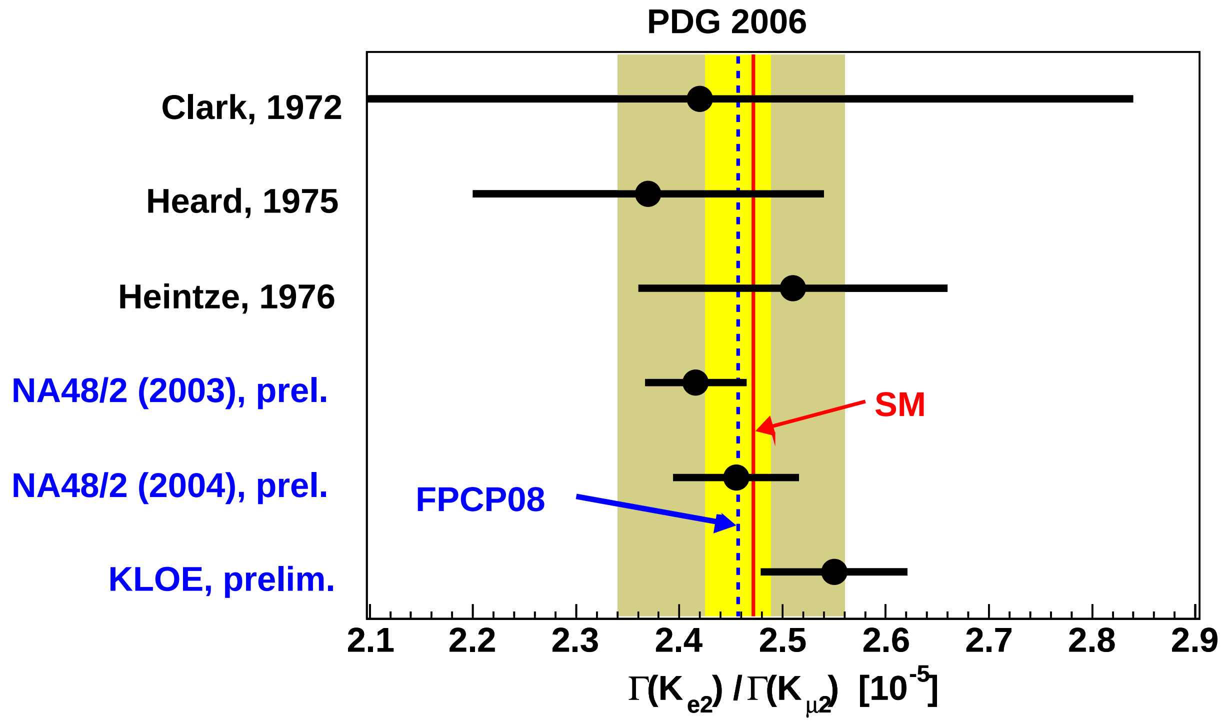


$K_{e2}/K_{\mu 2}$ — *Measurements*

Combine all preliminary results and PDG2006:

$$\boxed{\Gamma(\mathrm{K_{e2}})/\Gamma(\mathrm{K_{\mu 2}}) = (2.457 \pm 0.032) \times 10^{-5}} \quad (\chi^2/n_{\mathrm{dof}} = 2.44/3)$$

- Huge improvement w.r.t PDG 2006, $\sigma_{\mathrm{rel.}} = 1.3\%$ now!
- Perfect agreement with SM expectation.

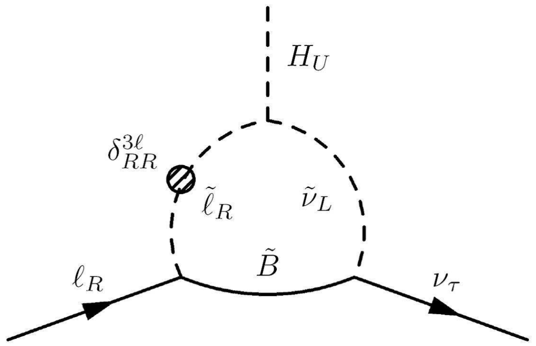


$K_{e2}/K_{\mu 2}$ — Restrictions on New Physics

Limit on LFV in $H^{\pm}$ coupling:

(Masiero, Paradisi, Petronzio, PRD 74, 2006)

LFV Yukawa coupling:

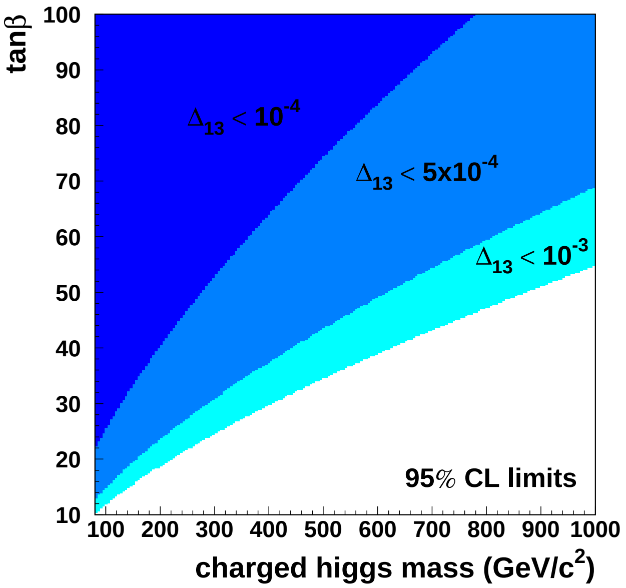


$$l H^{\pm} \nu_\tau \;\rightarrow\; \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \, \Delta_{13} \, \tan^2\beta$$

Lepton-flavour violating term: Δ_{13}

(should be $\leq 10^{-3}$ from EW theory, but $\neq 0$)

Limit on LFV in K_{e2} converts to limit on $\Delta_{13} = \Delta_{13}(M_{H^{\pm}}, \tan\beta)$:



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

$K_{e2}/K_{\mu2}$ — Comparison with $B \to \tau\nu_\tau$

Compare again with $\mathrm{B}^\pm \to \tau^\pm\nu_\tau$:

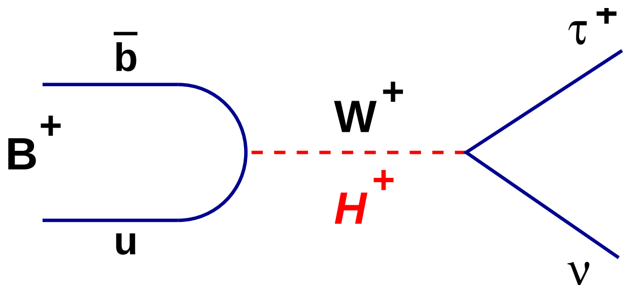
- In $\mathrm{B}^\pm \to \tau^\pm\nu_\tau$: no LFV required
  $\Longrightarrow$ No Δ_{13} term
- Dependency on $M_{H^\pm}$, $\tan\beta$:
  (Isidori, Paradisi,PLB 639,2006)

$$\frac{\mathrm{Br_{SUSY}}}{\mathrm{Br_{SM}}} = \left[1 - \left(\frac{m_B^2}{M_{H^\pm}^2}\right)\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right]^2$$

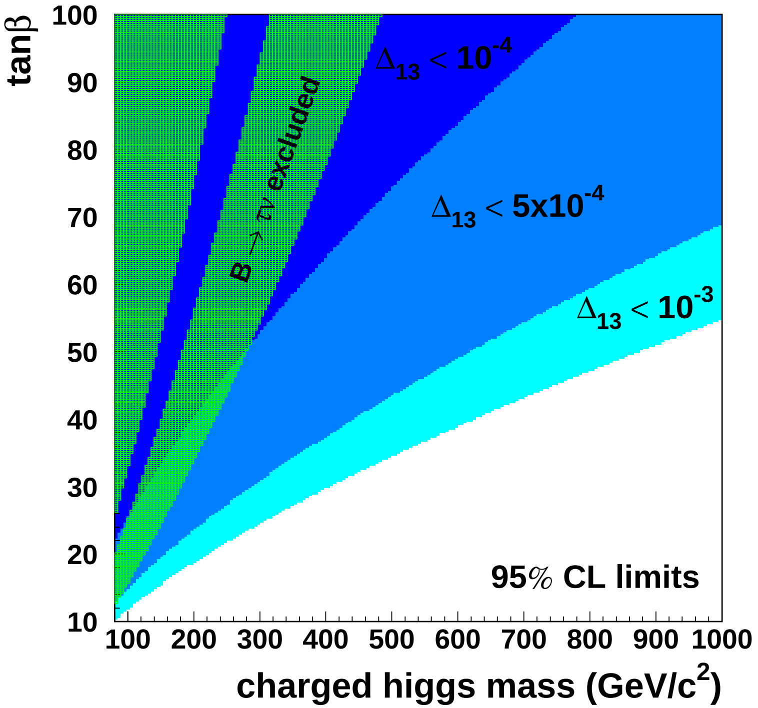
$(\epsilon_0 \sim 0.01)$

For non-tiny Δ_{13}:

Sensitivity to $\mathrm{H}^\pm$ in $\mathrm{K_{e2}/K_{\mu2}}$
better than in $\mathrm{B} \to \tau\nu_\tau$!



$\mathrm{Br}(B \to \tau\nu) = (1.42 \pm 0.44)\cdot 10^{-4}$
(current BaBar/Belle average)



$K_{e2}/K_{\mu 2}$ — *Near Future*

KLOE:

- Has $\sim 20\%$ more data on tape.
- Another $\sim$ **3000 events** with other reconstruction method.
- Improve MC statistics & systematics

$\Longrightarrow$ Should arrive at $\sigma_{\text{rel}}(\mathbf{R_K}) \sim \pm\mathbf{1}\%$.

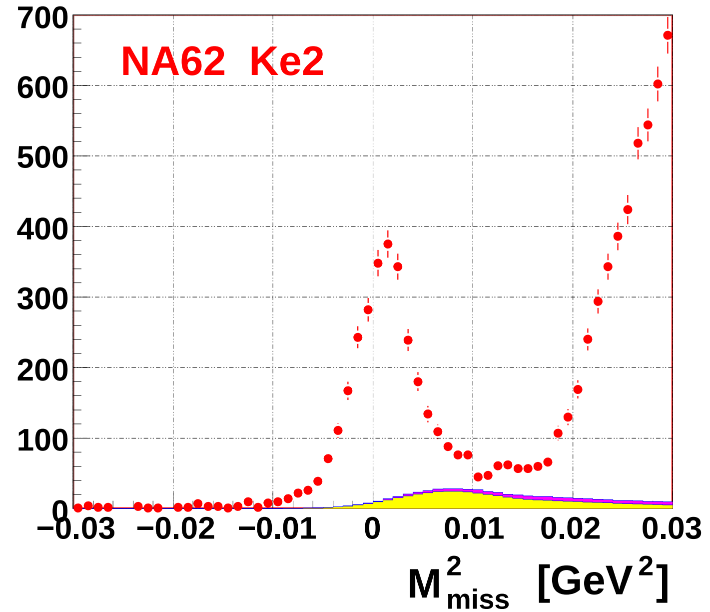
NA62: (also known as NA48/3)

- Similar setup as for NA48/2 (2004) prel. measurement, most parts of existing NA48 apparatus re-used.
- Special 4-month run period in 2007

  $\Longrightarrow$ $\sim$ **120 000 $\mathbf{K_{e2}}$ decays.**

$\Longrightarrow$ Goal: $\sigma_{\text{rel}}(\mathbf{R_K}) \sim \pm(\mathbf{0.3} - \mathbf{0.4})\%$.

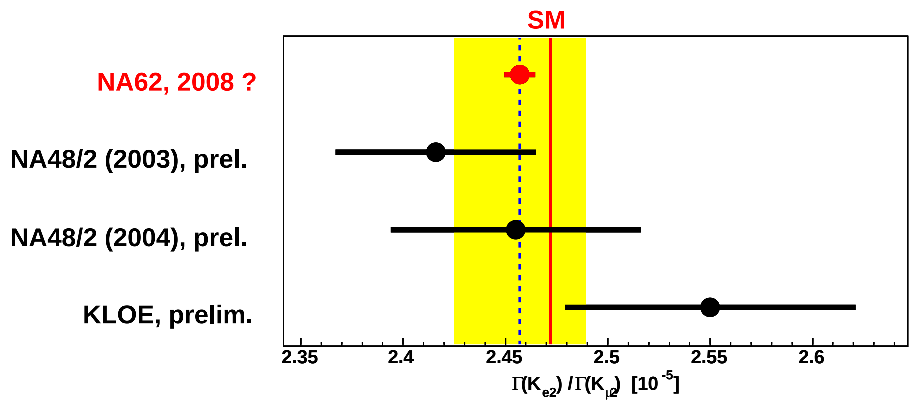
3% of NA62 statistics



$K_{e2}/K_{\mu2}$ — *Expectations*

Expected precision on $K_{e2}/K_{\mu2}$:

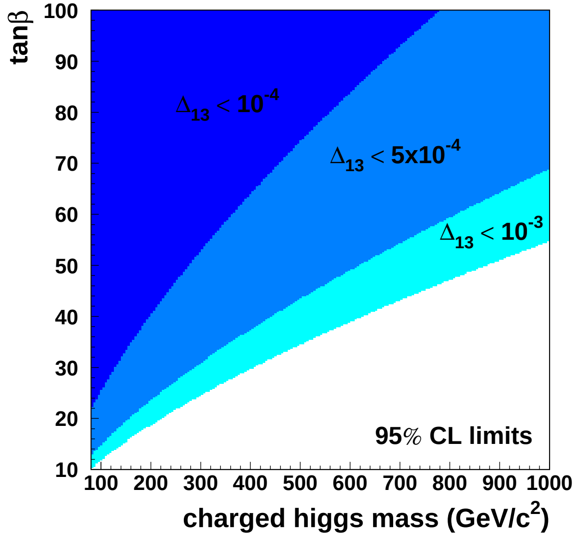
- Statistical: $\pm\mathbf{0.28\%}$
- Systematic: $\leq \pm\mathbf{0.2\%}$



Overall expected reach:

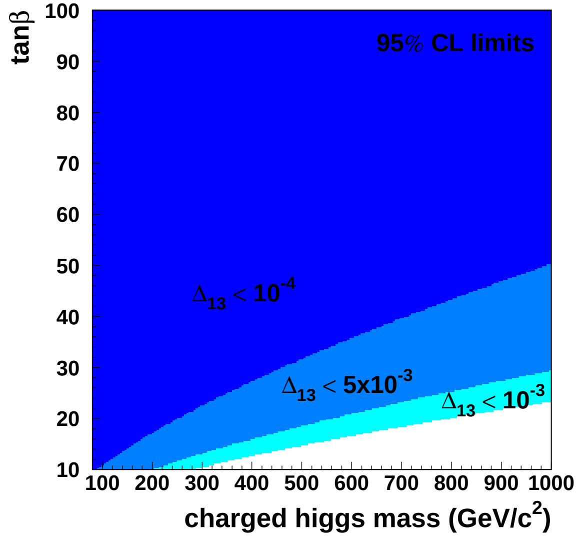
$$\sigma(\mathbf{R_K})/\mathbf{R_K} \approx \pm\mathbf{0.32\%}$$

FPCP08:



FPCP09 ?!

same R_K central value



Search for Direct CP Violation in $K^{\pm} \to 3\pi$ Decays

Search for $\mathcal{CP}$ Violation in $K^\pm \to \pi^\pm\pi\pi$

$\mathcal{CP}$ violation in $\mathbf{K^\pm \to 3\pi}$:

- Possibility for **direct $\mathcal{CP}$ violation** in the $K^\pm$ system:
  - — SM $\sim \mathcal{O}(10^{-5} - 10^{-6})$ (Gamiz, Prades, Scimeni, JHEP 10 (203) 042).
  - — New Physics could boost it up to $\mathcal{O}(10^{-4})$.

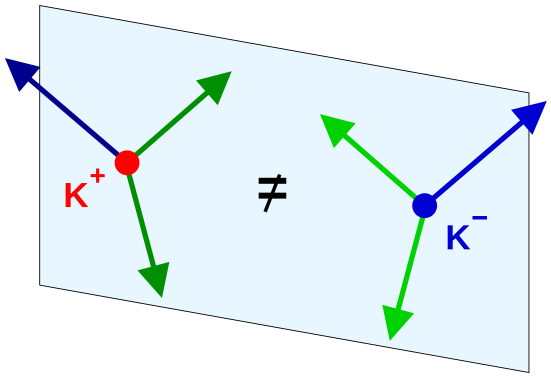
  (Experimental limit so far: $\mathcal{O}(10^{-3})$.)

Method:

- Rate asymmetry $\mathbf{\Gamma(K^+) \neq \Gamma(K^-)}$ experimentally not simple.
- **Better:** Measure difference in **Dalitz plot slopes!**
- $\mathbf{K^\pm \to \pi^\pm\pi\pi}$ **matrix element:**

$$\mathbf{M(u,v) \sim 1 + g\,u + hu^2 + kv^2 + \cdots}$$

with: $u = (s_3 - s_0)/m_\pi^2$, $v = (s_2 - s_1)/m_\pi^2$



- **Direct $\mathcal{CP}$ violating asymmetry:**

$$\mathbf{A_g = \frac{g^+ - g^-}{g^+ + g^-} = \frac{2\,\Delta g}{g}}$$

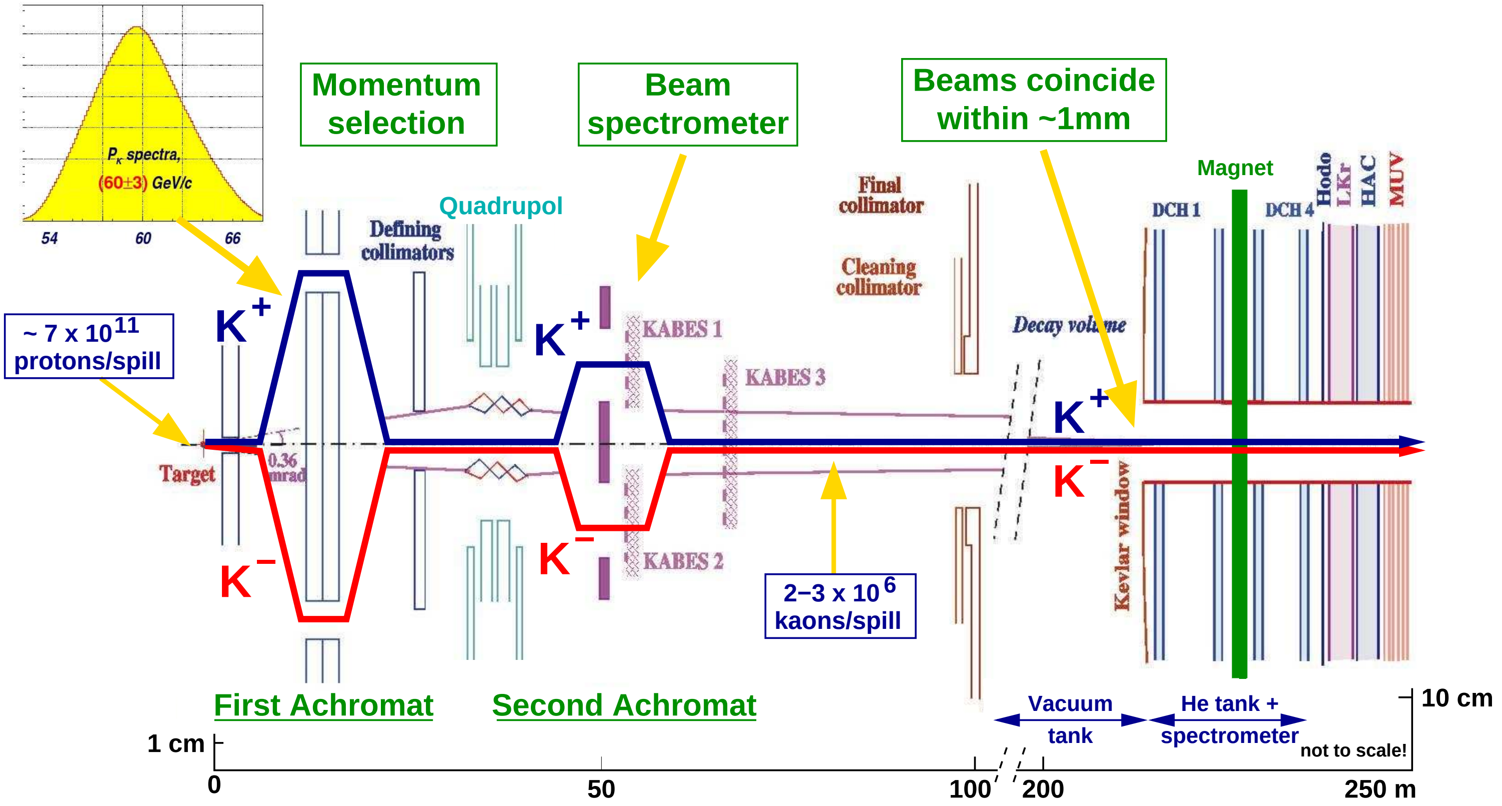
$g^+ \equiv g(K^+ \to \pi^+\pi\pi)$

$g^- \equiv g(K^- \to \pi^-\pi\pi)$

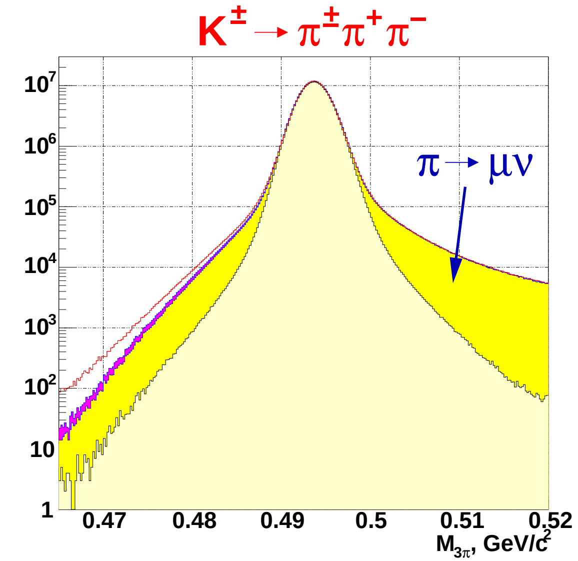
Search for $\mathcal{CP}$ Violation in $K^\pm \to \pi^\pm\pi\pi$

NA48/2 experiment in 2003/2004:

- **Simultaneous K^+** and **K^- beams** with $p_{K^\pm} = (60 \pm 3)$ GeV/c.
- Regular changes of achromat and spectrometer polarities to symmetrize beam and detector set-up.



Search for $\mathcal{CP}$ Violation in $K^{\pm} \to \pi^{\pm}\pi\pi$

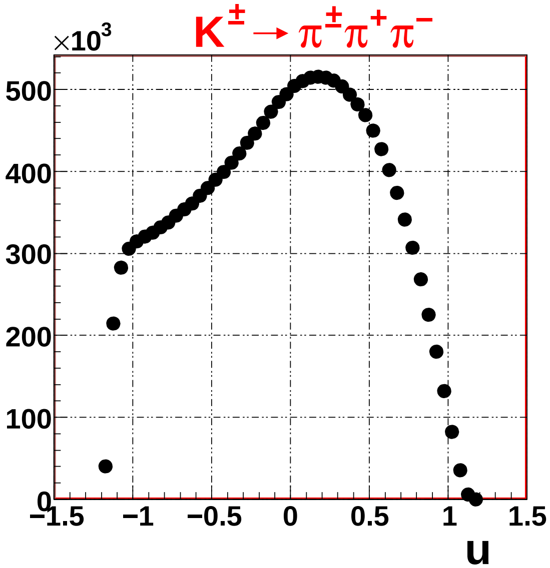


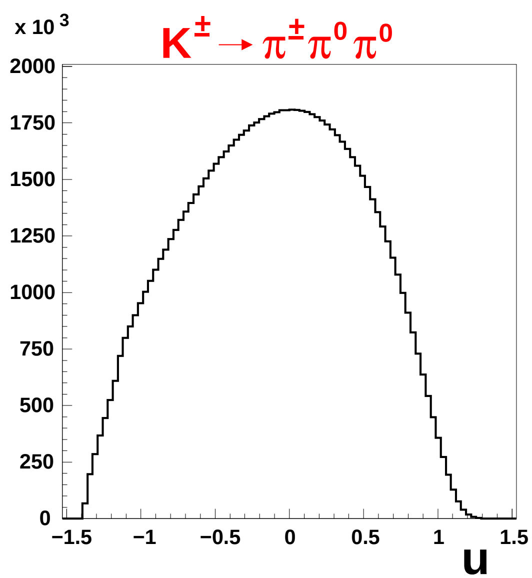
Total Yields: (practically bkg-free)

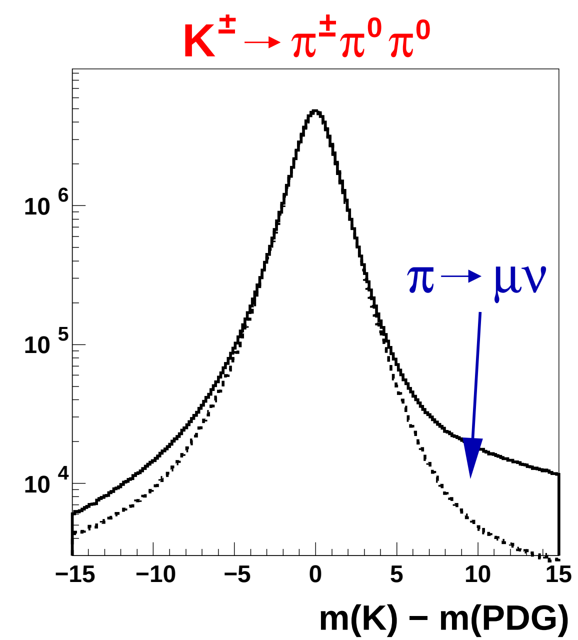
$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$: 3.1×10^{9} **events**

$K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$: 9.1×10^{7} **events**

u-spectra:

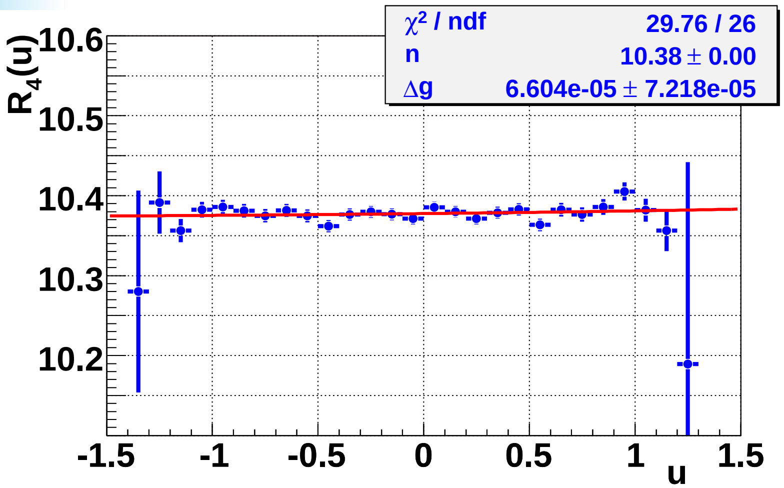




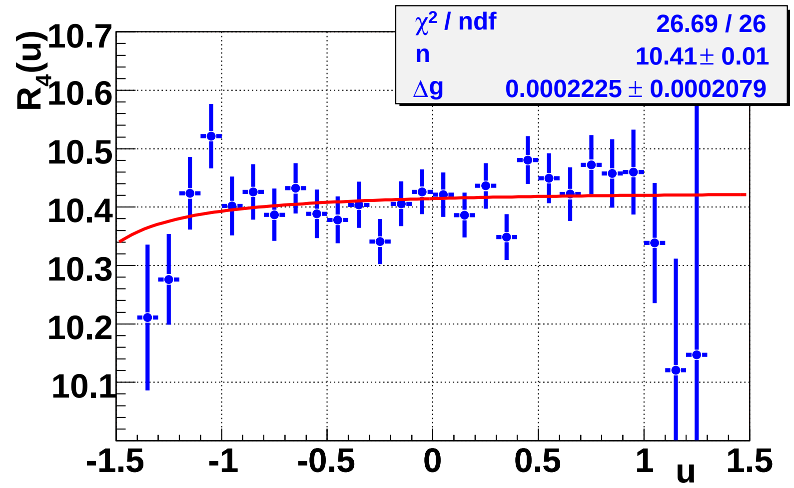


Search for $\mathcal{CP}$ Violation in $K^{\pm} \to \pi^{\pm}\pi\pi$

$\mathbf{K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}}$



$\mathbf{K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}}$



Final NA48/2 result for $\mathbf{K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}}$: (EPJ C52 (2007) 852)

$$\mathbf{A_g = (-1.5 \pm 1.5_{\text{stat}} \pm 0.3_{\text{trig}} \pm 0.6_{\text{syst}}) \times 10^{-4}}$$

Final NA48/2 result for $\mathbf{K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}}$: (as above)

$$\mathbf{A_g = (1.8 \pm 1.7_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-4}}$$

$\Longrightarrow$ **No indication for CP violation in $\mathbf{K^{\pm}}$ beyond the SM!**

Conclusions

- **$|\mathbf{V_{us}}|$ from $\mathbf{K_{l3}}$ Decays:**
  - New precise **BR measurements** from all experiments.
  - New $|\mathbf{V_{us}}|$ value: $|\mathbf{V_{us}}| = \mathbf{0.2246 \pm 0.0012}$
- **Ratio $\mathbf{\Gamma(K_{e2})/\Gamma(K_{\mu 2})}$:**
  - Two new preliminary results reported by KLOE and NA48/2.
    $\Longrightarrow$ **Precision on $\mathbf{\Gamma(K_{e2})/\Gamma(K_{\mu 2})}$** now **1.3%**.
  - Further improvement by KLOE and NA62 soon
    $\Longrightarrow$ Sensitivity to LFV in SUSY!
- **Search for CP violation in $\mathbf{K^+ \to 3\pi}$:**
  - Limits improved by one order of magnitude to $\mathcal{O}(10^{-4})$
    $\Longrightarrow$ **No sign for new physics.**

Spares

Form Factor Measurements

Measurement of form factors essential for

- Knowledge of phase space integral I_K^l for $|V_{us}|$ determination.
- Knowledge of detector acceptances for BR measurements.

$\mathbf{K_{l3}}$ **matrix element:**

$$\mathcal{M} \propto \mathbf{f_+(q^2)(p_K + p_\pi)^\mu \bar{u}_l \gamma_\mu (1+\gamma_5) u_v + f_-(q^2) m_l \bar{u}_l \gamma_\mu (1+\gamma_5) u_v}$$

Scalar form factor: $\mathbf{f_0(q^2) = f_+(q^2) + \frac{q^2}{m_K^2 - m_\pi^2} f_-(q^2)}$

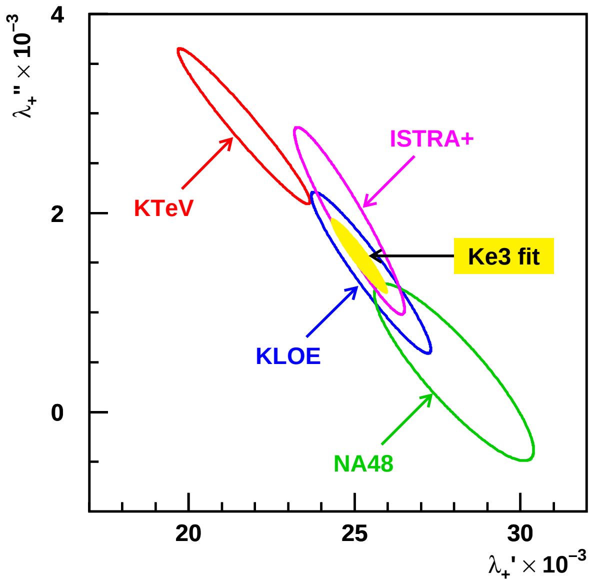
Common Parametrization used by all experiments:

- Quadratic expansion λ'_+, λ''_+ for **vector form factor** $\mathbf{f_+(q^2)}$.
- Linear expansion λ_0 for **scalar form factor** $\mathbf{f_0(q^2)}$ ($K_{\mu 3}$ only).

Form Factor Measurements

Current Data on K_{l3} form factor slopes by all 4 Experiments in 2004–07.

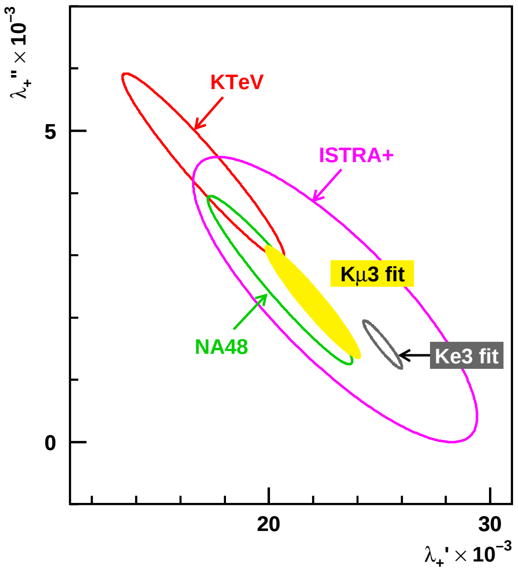
- $\mathbf{K_{e3}}$: Good agreement
- $\mathbf{K_{\mu 3}}$: Bad χ^2 due to λ_0 from NA48 $K_{L\mu 3}$

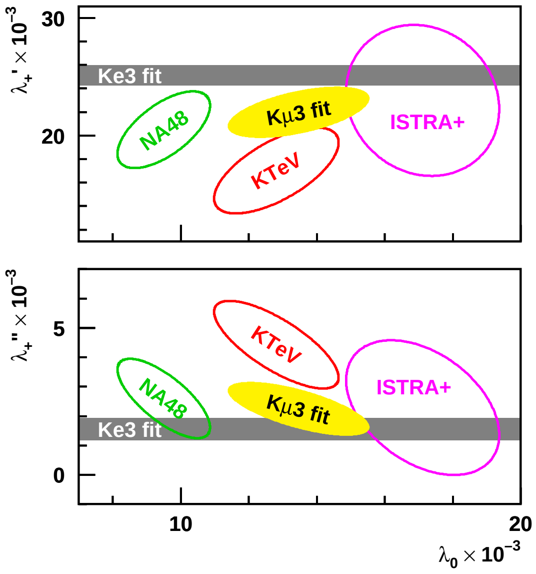


Combined fit:

(Includes scale factors due to $K_{\mu 3}$ disagreement)

$$\lambda'_+ = (24.9 \pm 1.1) \times 10^-3$$
$$\lambda''_+ = (1.6 \pm 0.5) \times 10^-3$$
$$\lambda_0 = (13.4 \pm 1.2) \times 10^-3$$





Corrections to K_{l3} Decay Rates

- **EM corrections** are small
  (Cirigliano et al. (2002), updated by Cirigliano, Neufeld; errors are taken as uncorrelated [has to be improved].)

	$\delta^{\mathbf{e}}_{\mathbf{EM}}$ [%]	$\delta^{\mu}_{\mathbf{EM}}$ [%]	$(\mathbf{1}+\delta^{\mu}_{\mathbf{K}})^{\mathbf{2}}/(\mathbf{1}+\delta^{\mathbf{e}}_{\mathbf{K}})^{\mathbf{2}}$
$\mathbf{K^0_{l3}}$	$+\mathbf{0.52(10)}$	$+\mathbf{0.80(15)}$	$\mathbf{1.006(4)}$
$\mathbf{K^{\pm}_{l3}}$	$+\mathbf{0.03(10)}$	$-\mathbf{0.12(15)}$	$\mathbf{0.997(4)}$

- **Phase space corrections** are large and depend on form factor slopes λ'_+, λ''_+, λ_0.
  Use form factor values from global Flavianet fit
  (assuming lepton universality in the slopes and taking correlations into account).

	$\mathbf{I^e_K}$	$\mathbf{I^{\mu}_K}$	$\mathbf{I^{\mu}_K/I^e_K}$
$\mathbf{K_{L,l3}}$	$\mathbf{0.15454(29)}$	$\mathbf{0.10209(31)}$	$\mathbf{0.6617(16)}$
$\mathbf{K^{\pm}_{l3}}$	$\mathbf{0.15889(30)}$	$\mathbf{0.10504(32)}$	$\mathbf{0.6611(16)}$