(Semi)leptonic kaon decays: experimental results & prospects

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Outline:

1) Overview of recent and planned kaon experiments;
2) Global analysis of (semi)leptonic kaon decay data;
3) CKM unitarity and SM tests;
4) Summary and prospects.

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Lattice QCD meets Experiment • University of Glasgow

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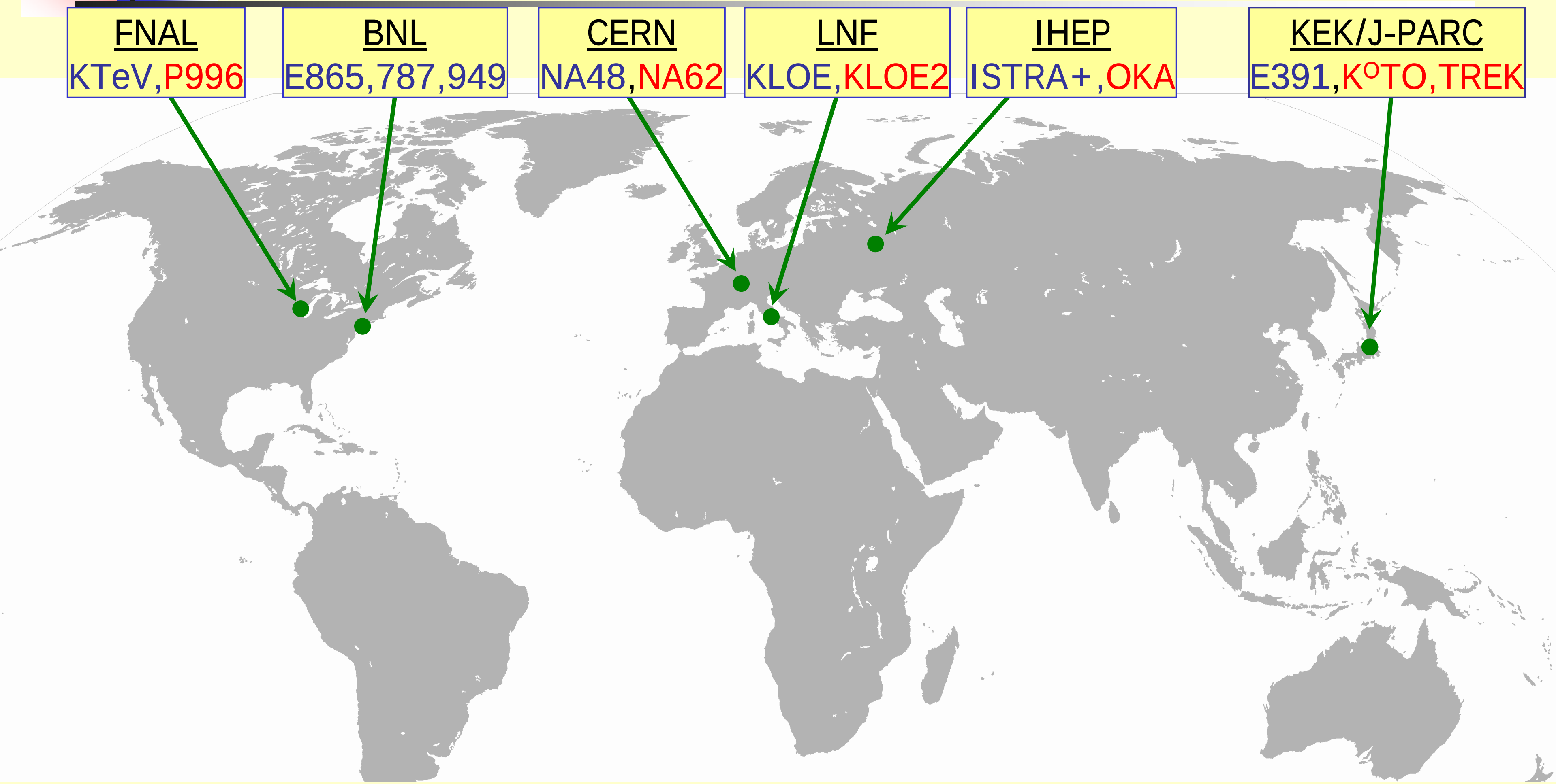
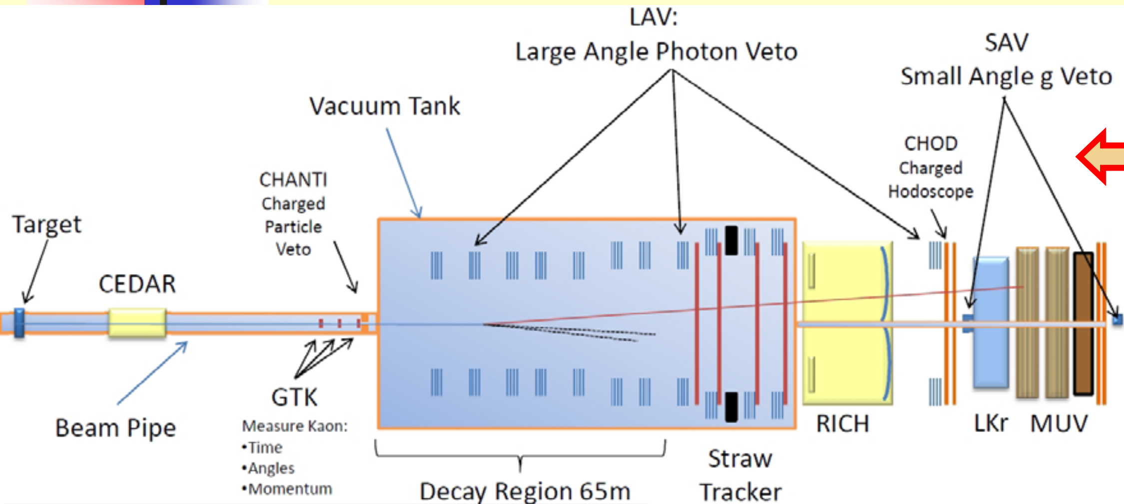
Overview of kaon experiments

Major recent & future K experiments



NA62, K^OTO, P996 aim at the "golden modes" $K\rightarrow\pi\nu\nu$.
Several experiments plan $|V_{us}|$ measurements with (semi)leptonic decays: lattice QCD is a crucial ingredient!

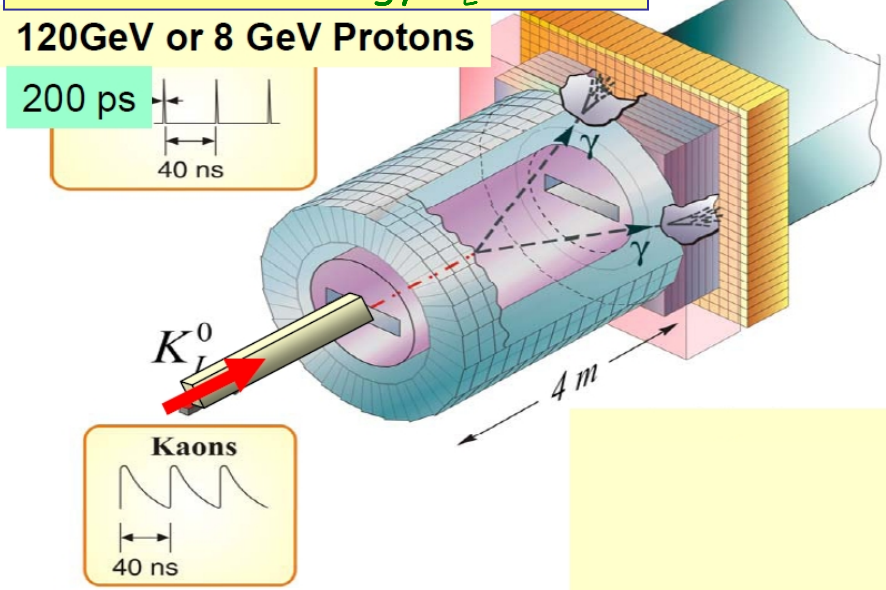
Future $K_{\pi\nu\nu}$ experiments

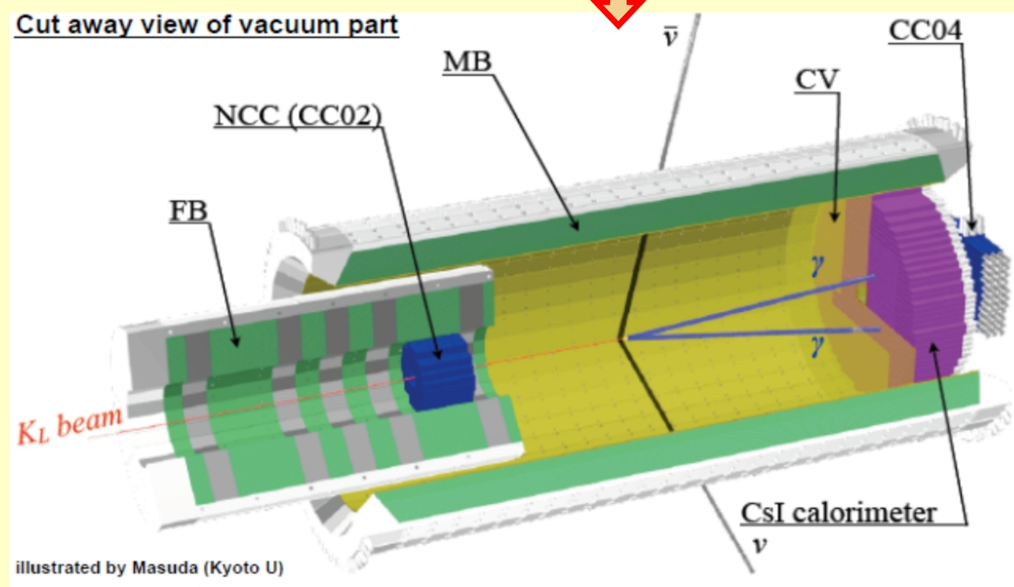


NA62@CERN: decays in flight
Unseparated 75 GeV K^+ beam
Starting in 2013

KOTO@J-PARC: decays in flight
30 GeV K_L beam
Expect to reach $K_L \to \pi\nu\nu$ SES
Starting in 2011

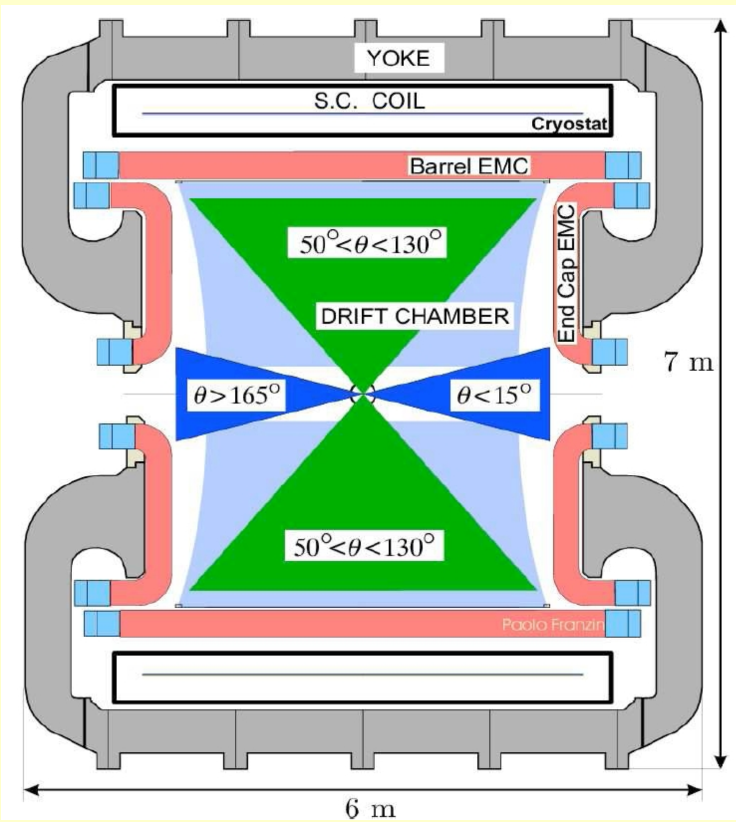
P966@FNAL: proposal
to collect ~10^3 $K_L \to \pi\nu\nu$ events
with a low-energy K_L beam



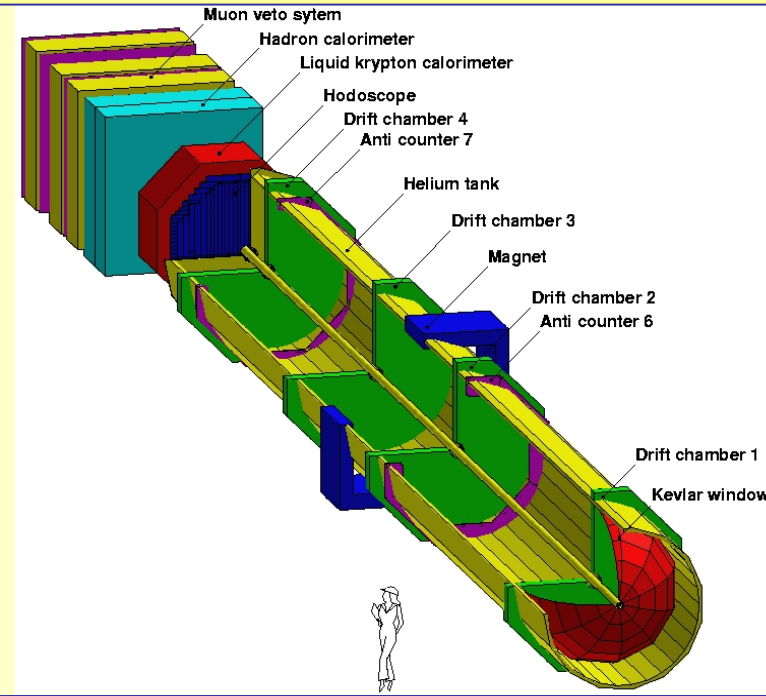


Other major experiments

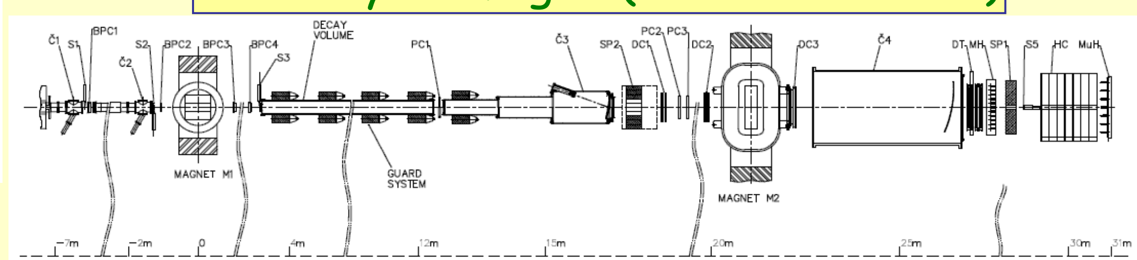
KLOE,KLOE-2@LNF Frascati:
low energy (~100 MeV) kaons
at DAFNE ϕ factory (e^+e^- at 1.02GeV)
KLOE: 2001-2005, KLOE2: 2010-



NA48/NA62-I@CERN:
K^0, $K^\pm$ decays in flight (~100 GeV beams)
1997-2007



ISTRA+,OKA@IHEP Protvino:
$K^\pm$ decays in flight (~26 GeV beams)



Global analysis of (semi)leptonic K decay data

$|V_{us}| f_+(0)$ from K_{l3} decays

$K \to \pi l \nu$ (K_{l3}) decays: ideal channels for $|V_{us}|$ determination

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

(with $K=K_S, K_L, K^+$; $l=e,\mu$; $C_K^2 = ½$ for K^+, $C_K^2 = 1$ for K^0)

Inputs from experiment

$\Gamma(K_{l3(\gamma)})$:
radiation-inclusive decays rates;
in practice, branching ratios & lifetimes.

$I_{Kl}(\lambda)$:
Phase space integrals;
λs parameterize form factor dependence on momentum transfer $t=(P_K-P_\pi)^2$.
E.g. Taylor expansion parameterization:
$(\lambda_+', \lambda_+'')$ for K_{e3}, $(\lambda_+', \lambda_+'', \lambda_0')$ for $K_{\mu3}$.

Inputs from theory

S_{EW}=1.0232(3):
short-distance EW correction

$f_+(0)$:
vector form factor at zero momentum transfer (t=0)

$\Delta^{SU(2)}$ and Δ^{EM}:
channel-dependent isospin breaking and long-distance EM corrections

$|V_{us}|$ from K_{l3}: recent history

2002: (PDG 2004) — $|V_{ud}|^2 + |V_{us}|^2 - 1 = -0.0035(15)$.
A 2.3σ hint for CKM unitarity violation.

2003: BNL E865 measured higher $BR(K^+_{e3})=0.0513(10)$. ← 1.9 %
Start of the $|V_{us}|$ revolution:
first modern measurement, consistent with unitarity.

2004-present: Many new measurements (KLOE, KTeV, ISTRA+, NA48)

- BRs, lifetimes, form factor shapes;
- Much higher statistical precision than early measurements;
- Adequate treatment of radiative corrections;
- Correlations between measurements properly reported.

2008-beyond: Value of $|V_{us}|$ used in precision tests of the SM

FlaviaNet Kaon WG [www.lnf.infn.it/wg/vus]
arXiv:0801.1817 + update arXiv:1005.2323

BR & τ measurements: K_L

FlaviaNet'10 fit: 21 input measurements (published final results, mostly 2003-06)

KLOE: 4 absolute BRs, $BR(\pi^+\pi^-)/BR(K_{l3})$, $BR(\gamma\gamma)/BR(3\pi^0)$, τ_{KL} with $K_L \to 3\pi^0$

KTeV: 5 ratios fo BRs, $BR(\pi^+\pi^-\gamma)/BR(\pi^+\pi^-)$, 2 meas. of $BR(\pi^+\pi^-\gamma_{DE})/BR(\pi^+\pi^-)$

NA48: $BR(K_{e3})/BR(2\text{-track})$, $BR(\pi^+\pi^-)/BR(K_{l3})$, $BR(\gamma\gamma)/BR(3\pi^0)$

PDG: $BR(\pi^0\pi^0)/BR(\pi^+\pi^-)$

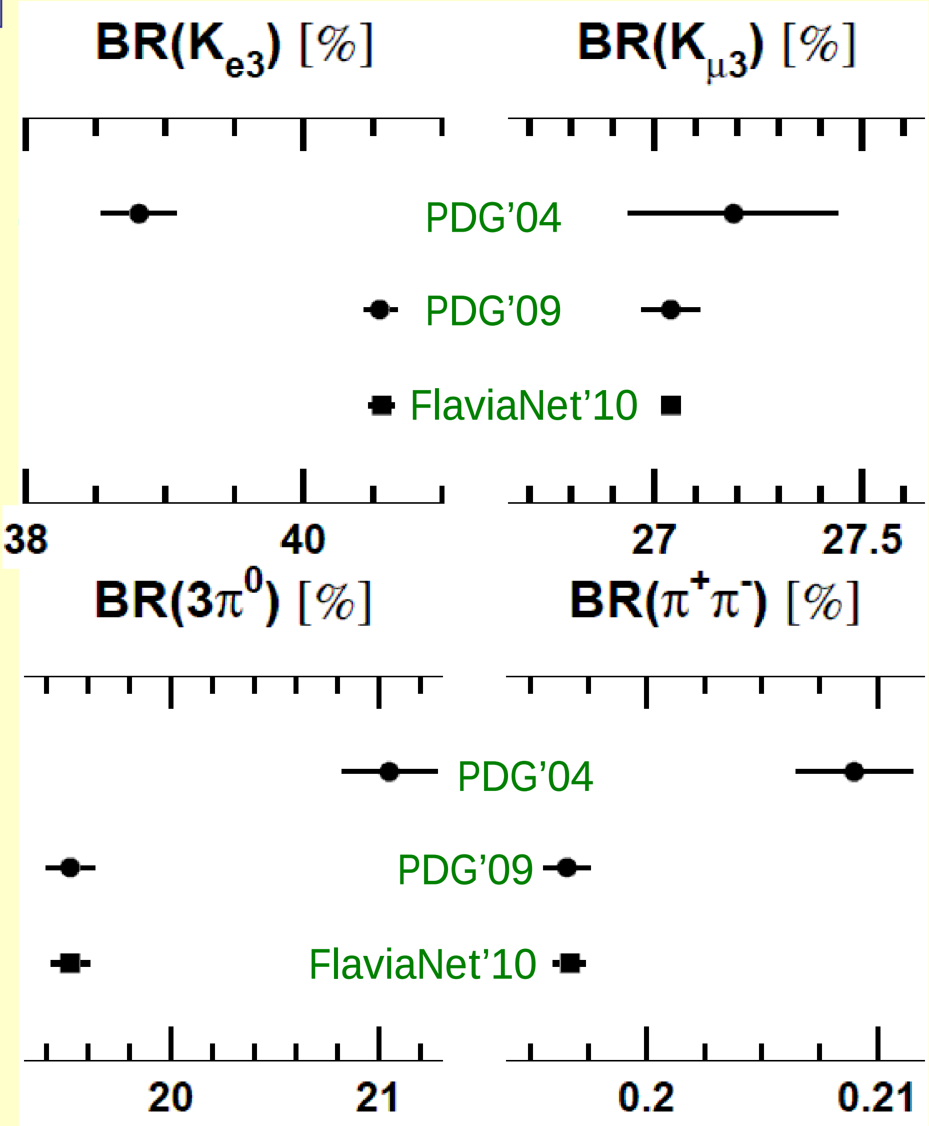
E731: $BR(\pi^+\pi^-\gamma_{DE})/BR(\pi^+\pi^-)$

Vosburgh (1972): τ_{KL}

Free parameters: 9 main BRs, lifetime τ_{KL}.
Constraint: $\Sigma BR_i = 1$.
Fit quality: $\chi^2/ndf=19.8/12$ (P=7.1%).
Cf. PDG'09: $\chi^2/ndf=35.7/17$ (P=0.5%).

~5σ shifts wrt PDG'04: many new results, elimination of old results with no radiative corrections or not reporting correlations.

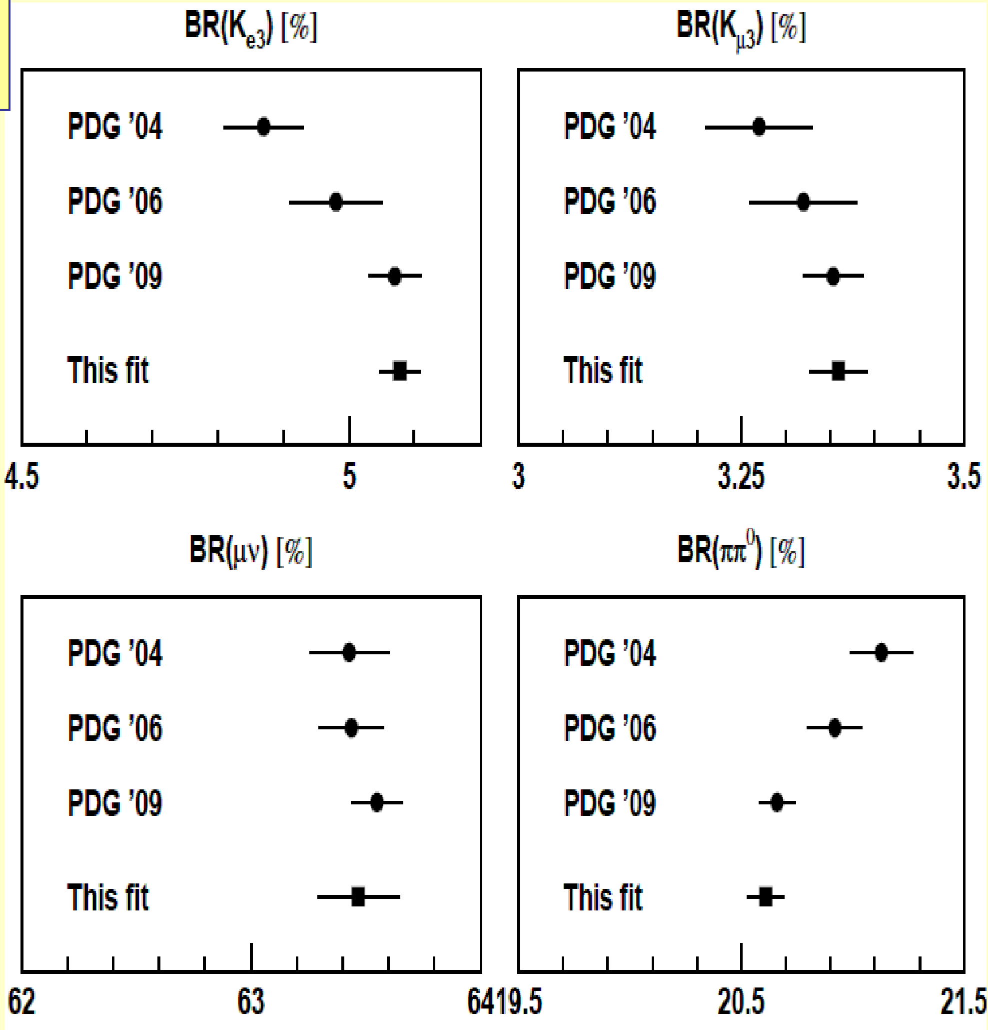
Evolution of main K_L BRs



BR & τ measurements: $K^{\pm}$

FlaviaNet'10 fit: 17 input measurements (many 2000s but also earlier results)

Evolution of main $K^{\pm}$ BRs



KLOE: 5 absolute BRs, τ_K with $K^{\pm}\to\mu^{\pm}\nu$

NA48/2: BR(K_{e3})/BR($\pi^{\pm}\pi^0$), BR($K_{\mu3}$)/BR($\pi^{\pm}\pi^0$),

E865: BR(K_{e3})/BR($\pi^{\pm}\pi^0$+$K_{\mu3}$+$K_{3\pi}$, π^0 Dalitz)

KEK246: BR(K_{e3})/BR($K_{\mu3}$)

Early: BR($K_{3\pi}$), 3 meas. of τK,
3 meas. of BR($K\to\mu\nu$)/BR($\pi^{\pm}\pi^0$)

Free parameters: 6 main BRs, lifetime τ_K.
Constraint: $\Sigma BR_i = 1$.
Fit quality: χ^2/ndf=25.8/11 (P=0.7%).
Cf. PDG'09: χ^2/ndf=52/24 (P=0.1%).

BR & τ measurements: K_S

$|V_{us}|$ with K_S decays: the most recent development

KLOE (2006):

$BR(K_S \to \pi e \nu)$ / $BR(K_S \to \pi^+\pi^-)$ = $10.19(13) \times 10^{-4}$ ← **1.3 %** dominated by statistics

$BR(K_S \to \pi^+\pi^-)$ / $BR(K_S \to \pi^0\pi^0)$ = $2.2459(54)$

NA48 (2007):

$BR(K_S \to \pi e \nu)/BR(K_L \to \pi e \nu)$ = $0.993(34)$

NA48 (2002):

τ_{KS} = 89.598(70) ps

KTeV (2003):

τ_{KS} = 89.58(13) ps

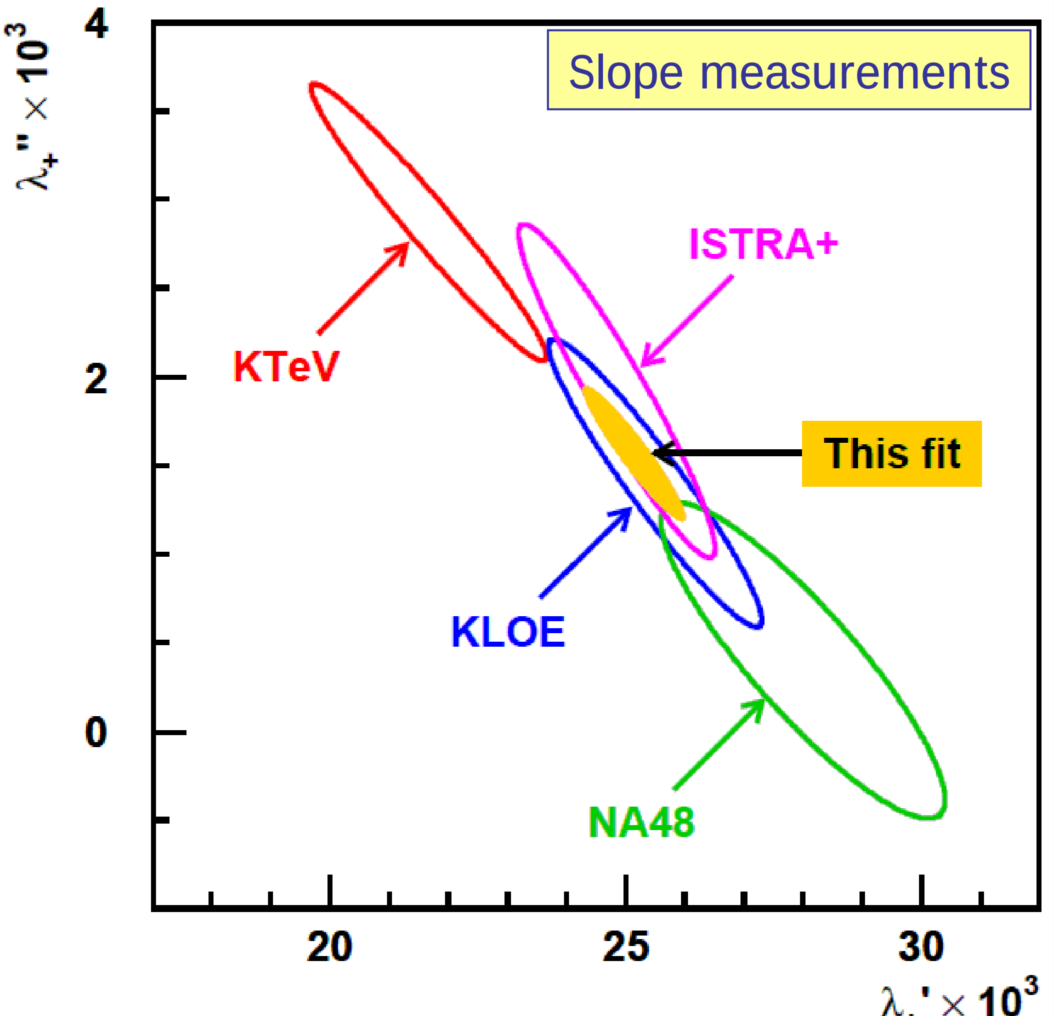
Assuming lepton universality
and using measured form factors:
$BR(K_{e3})/BR(K_{\mu3})$ = $0.6655(15)$

FlaviaNet'10 fit: 6 inputs.
Free parameters: 4 BRs and lifetime.
Constraint: $\Sigma BR_i = 1$.
$\chi^2/ndf = 0.015/1$ ($P=90\%$)

Fit result:
$BR(K_{e3}) = 7.05(8) \times 10^{-4}$

Form factors with K_{e3}: $(\lambda'_+, \lambda''_+)$

Polynomial parameterization:
$f_+(t)/f_+(0) = 1 + \lambda'(t/m_\pi^2) + \frac{1}{2}\lambda''(t/m_\pi^2)^2 + \ldots$



Slope parameters x10^3

λ' = 25.1 ± 0.9
λ'' = 1.6 ± 0.4
$\rho(\lambda', \lambda'')$ = -0.94
χ^2/ndf = 3.5/6 (P=51%)

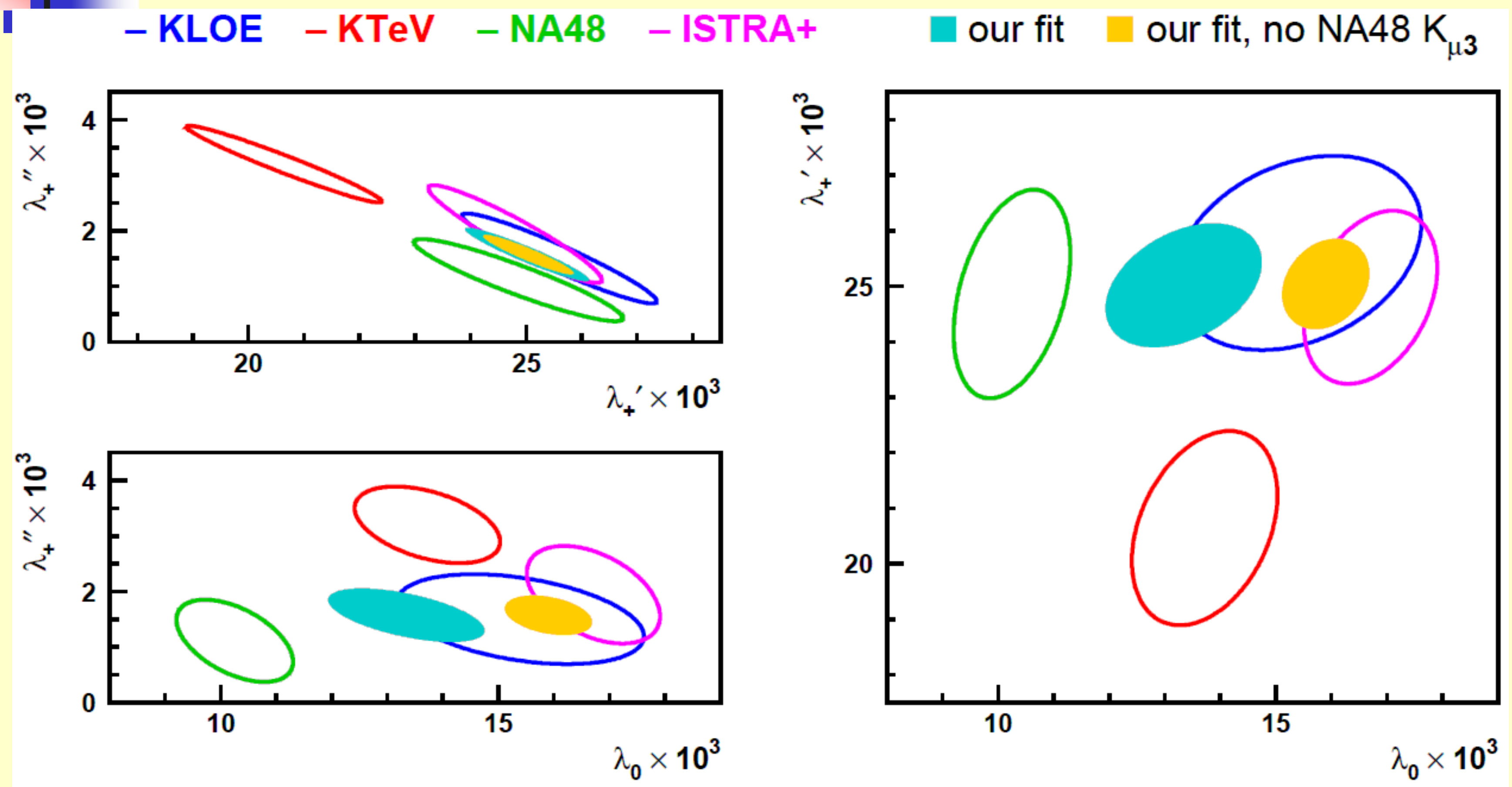
Phase Space Integrals:

$I(K^0_{e3})$ = 0.15463(21) ← 0.14%
$I(K^\pm_{e3})$ = 0.15900(22)

4σ significance of λ''

Fits to pole and dispersive parameterizations lead to similar PSIs within 0.1%

Form factors, $K_{e3}+K_{\mu3}$: $(\lambda'_+,\lambda''_+,\lambda_0)$



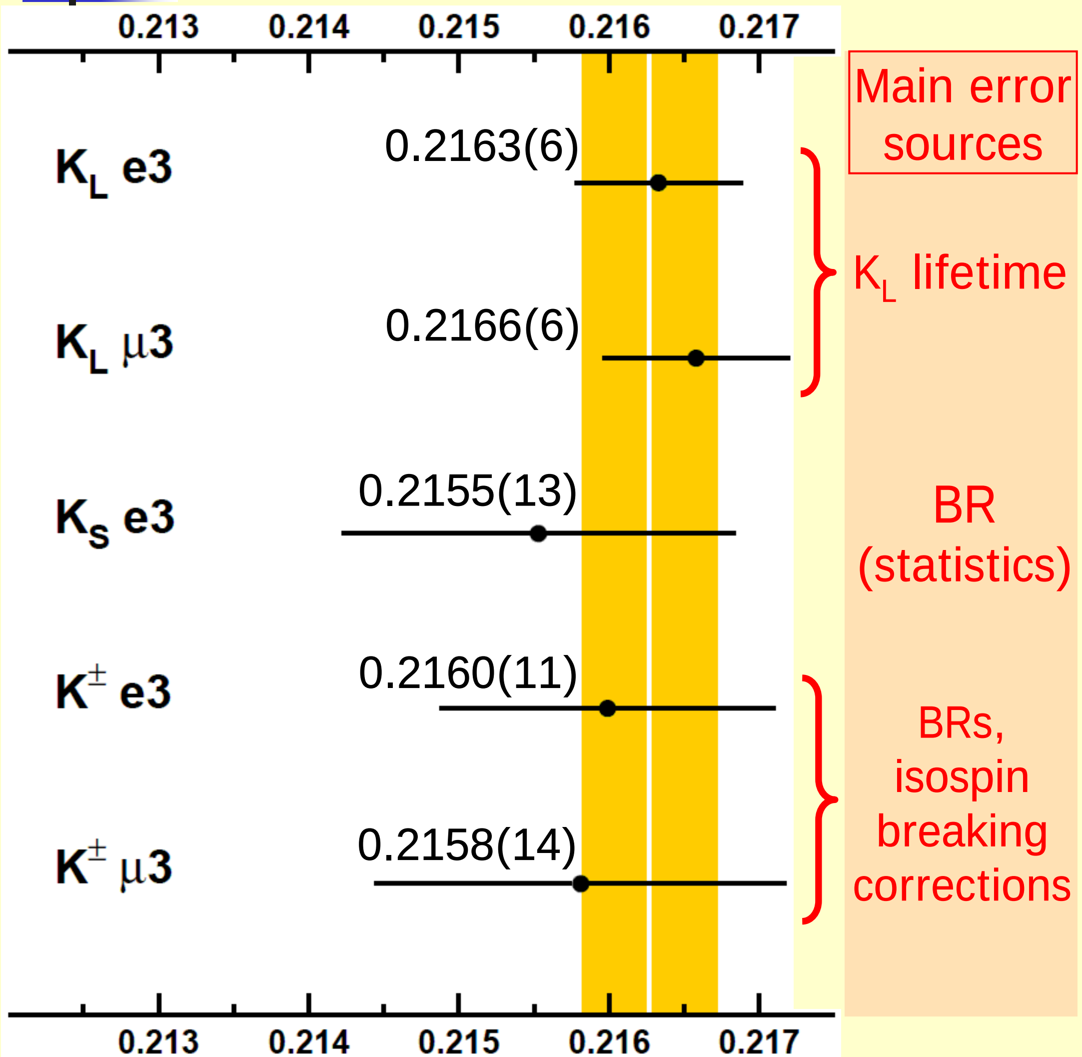
NA48 $K_{\mu3}$ measurement is inconsistent and has been excluded

χ^2/ndf=5.6/5 (P=34%)

<u>Phase Space Integrals:</u>

$I(K^0_{e3})$	= 0.15457(20)	$I(K^0_{\mu3})$	= 0.10266(20)
$I(K^\pm_{e3})$	= 0.15894(21)	$I(K^\pm_{\mu3})$	= 0.12564(20)

$|V_{us}|f_+(0)$ measurements with K_{l3}



Measurements of $|V_{us}|f_+(0)$

Global fit result:

$$|V_{us}|f_+(0) = 0.2163(5)$$

χ^2/ndf = 0.77/4
(P=94%)

0.23% relative precision

Prospects:

KLOE-2/step-0 alone expect 0.14% precision on $|V_{us}|f_+(0)$ by improving on $BR(K_{Se3})$ and K_L, $K^\pm$ lifetimes. (arXiv:1003.3868)

NA48/NA62 plan improvements on K^+ BRs and FFs.

$|V_{us}|/|V_{ud}|$ from $(K,\pi)\to\mu\nu$

SM ratio of radiation-inclusive leptonic decay widths:

$$\frac{\Gamma_{K\ell 2}}{\Gamma_{\pi\ell 2}} = \frac{|V_{us}|^2}{|V_{ud}|^2}\frac{f_K^2}{f_\pi^2}\frac{m_K(1-m_\ell^2/m_K^2)^2}{m_\pi(1-m_\ell^2/m_\pi^2)^2}(1+\delta_{\mathrm{EM}})$$

Extracted

Lattice QCD input

Long-distance EM correction

$$\delta_{\mathrm{EM}} = -0.0070(35)$$

(Marciano, PRL 93 (2004) 231803)

<u>Experimental input</u>

(1) from $K^\pm$ BR fit

$BR(K_{\mu 2})$ = 0.6347(18) ← **0.28%**

$\tau(K^\pm)$ = 12.384(15) ns

(2) from PDG 2009

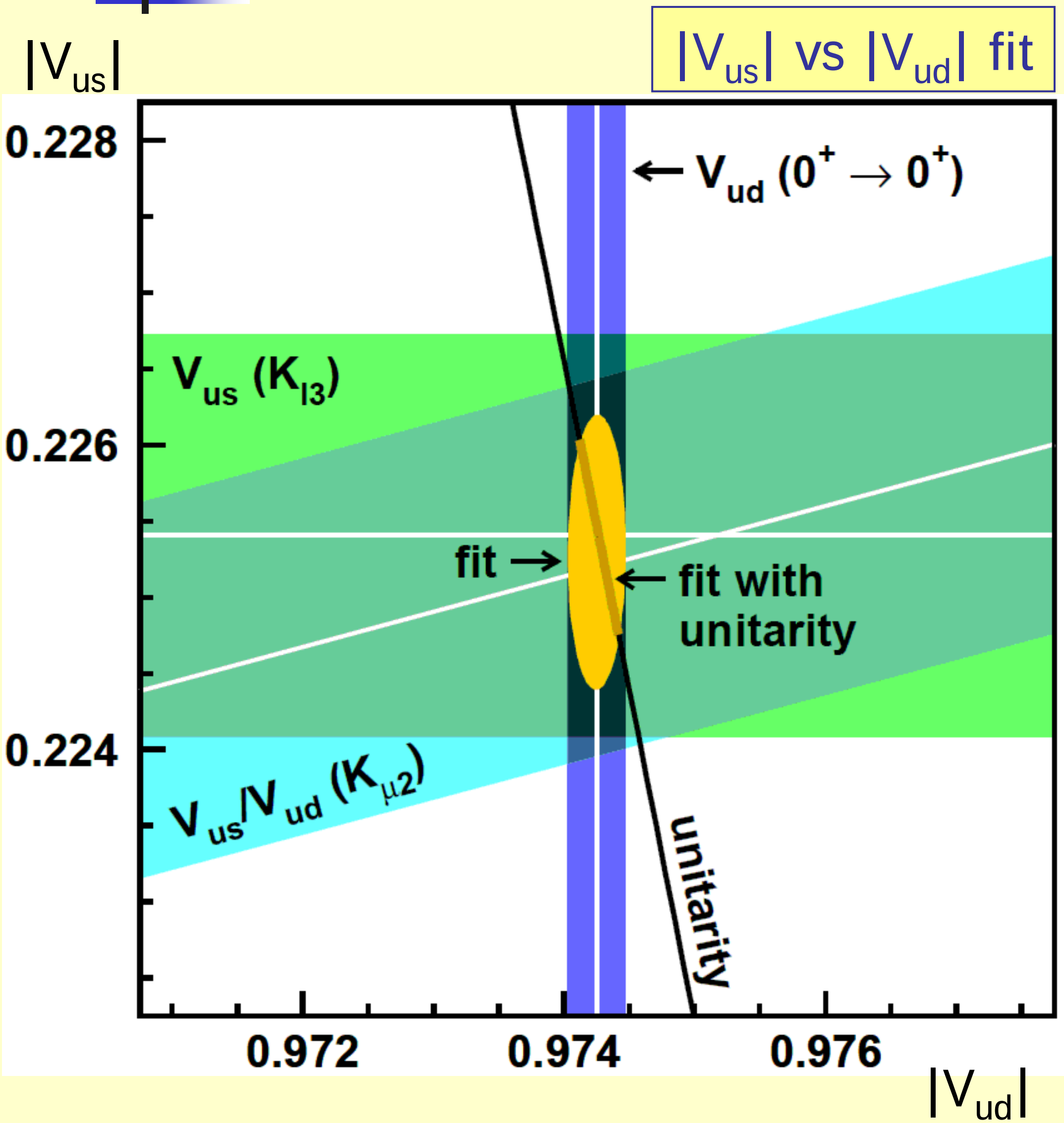
$\Gamma(\pi^\pm\to\mu^\pm\nu)$ = 38.408(7) μs^{-1}

<u>Experimental result:</u>

$|V_{us}/V_{ud}|\ f_K/f_\pi$ = 0.2758(5) ← **0.18%**

CKM unitarity and SM tests

CKM unitarity



<u>Experimental input:</u> **~0.2%**

$|V_{us}|f_+(0)$ = 0.2163(5)

$|V_{us}/V_{ud}|\ f_K/f_\pi$ = 0.2758(5)

$|V_{ud}|$ = 0.97425(22)

(average from 20 nuclear beta decays, Hardy & Towner, PRC79 (2009) 055502)

<u>Lattice input:</u> **0.6%**

$f_+(0)$ = 0.959(6)

f_K/f_π = 1.193(6)

Fit result: **0.4%**

$|V_{us}|$ = 0.2253(9)

Fit imposing unitarity:

$|V_{us}|$ = 0.2254(6)

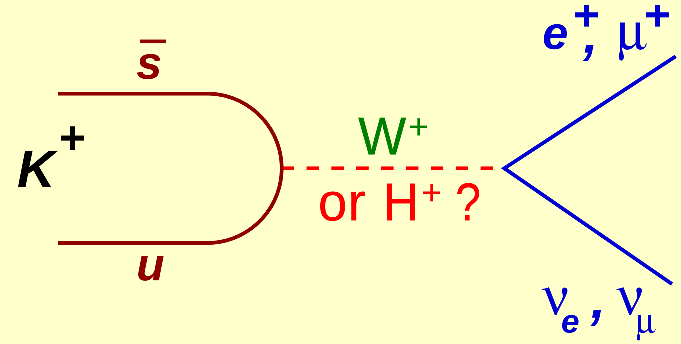
CKM unitarity test:

$|V_{us}|^2 + |V_{ud}|^2 - 1$ = –0.0001(6)

Other (less precise) $|V_{us}|$ evaluations have been made with hyperon and tau decays

$K_{\mu 2}$: sensitivity to new physics

Comparison of $|V_{us}|$ determined from helicity-suppressed $K_{\mu 2}$ decays vs helicity allowed K_{l3} decays

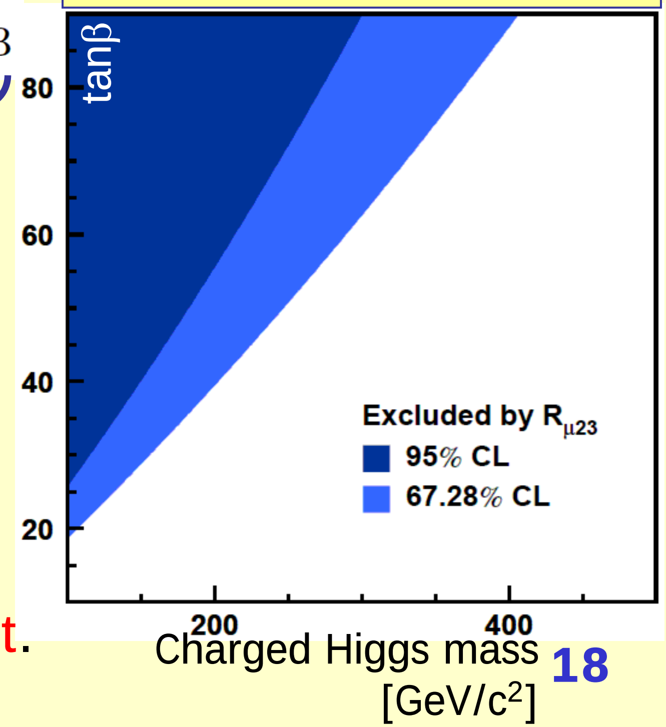


To reduce uncertainties of hadronic and EM corrections to $K_{\mu 2}$,

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

Lattice QCD input | Measured with $K_{\mu 2}/\pi_{\mu 2}$ | Measured with K_{l3}

tanβ vs H^+ mass exclusion



SM expectation: $R_{\mu 23} = 1$.

Charged Higgs mediated currents lead to

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

Experiment: $R_{\mu 23} = 0.999(7)$, limited by lattice input.

K_{l3}: lepton universality test

Comparison of $|V_{us}|$ determined from K_{e3} vs $K_{\mu3}$ decays

$$r_{\mu e} = \frac{[|V_{us}|f_+(0)]^2_{\mu3,\,\mathrm{exp}}}{[|V_{us}|f_+(0)]^2_{e3,\,\mathrm{exp}}} = \frac{\Gamma_{K\mu3}}{\Gamma_{Ke3}}\,\frac{I_{e3}\,(1+2\delta^{Ke}_{\mathrm{EM}})}{I_{\mu3}\,(1+2\delta^{K\mu}_{\mathrm{EM}})} = (g_\mu/g_e)^2 = 1$$

SM

lepton coupling at the $W \to l\nu$ vertex

Experimental results

$K^\pm$: $r_{\mu e} = 0.998(9)$

K^0: $r_{\mu e} = 1.003(5)$

→ $r_{\mu e} = 1.002(4)$

Non-kaon measurements:

$\pi \to l\nu$: $r_{\mu e} = 1.0042(33)$ (PRD 76 (2007) 095017)

$\tau \to l\nu\nu$: $r_{\mu e} = 1.000(4)$ (Rev.Mod.Phys. 78 (2006) 1043)

The sensitivity in kaon sector approaches those obtained in the other fields.

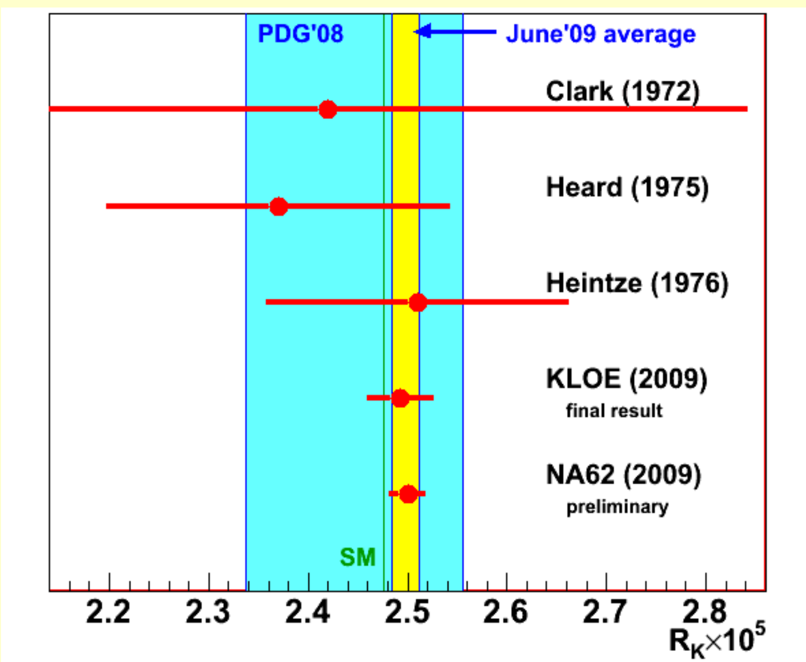
K_{l2}: lepton universality test

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

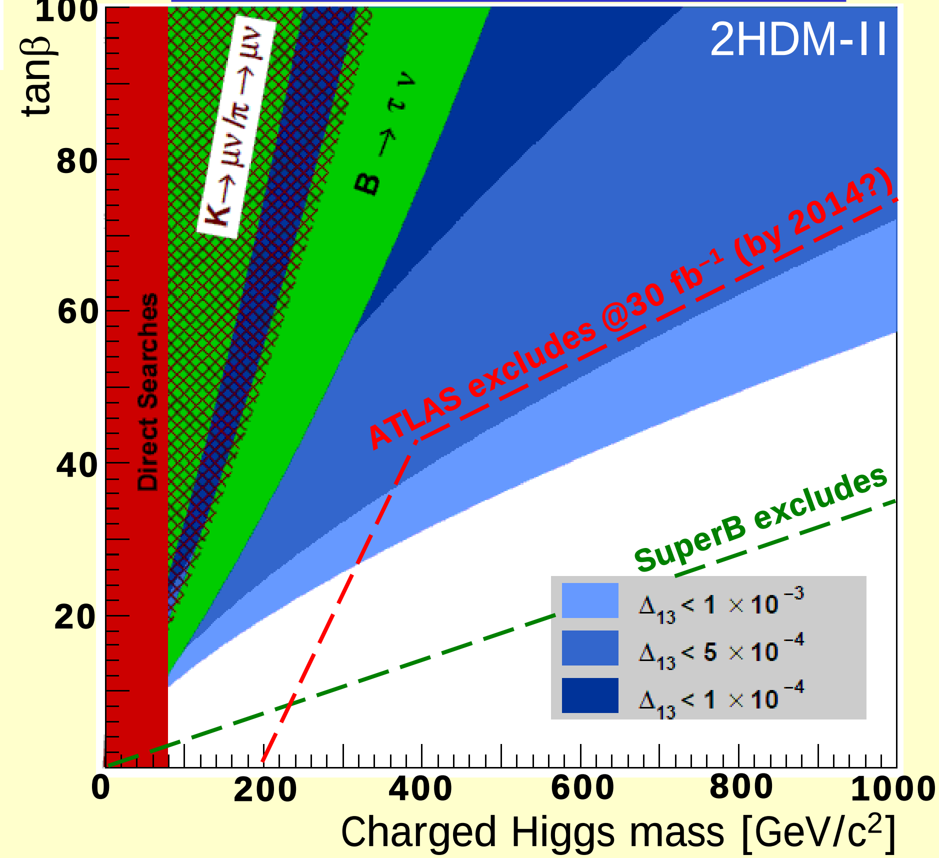
LFV $H^\pm$ exchange contribution:

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

can reach ~1% without contradicting any known experimental limits



(M_H, tanβ) 95% exclusion limits



Experiment: $R_K = 2.498(14) \times 10^{-5}$; SM: $R_K = 2.477(1) \times 10^{-5}$

Summary

- Tremendous progress in measurements and interpretation of (semi)leptonic kaon decays during the last decade!
- Thanks to advances of both experiment and theory, $|V_{us}|f_+(0)$ has been measured to 0.23% precision, and $|V_{us}|$ has been evaluated to 0.4% precision with kaon decays.
- CKM unitary with $|V_{ud}|^2+|V_{us}|^2$ tested at 0.06% precision:
  → O(10 TeV) bound on the scale of new physics.
- $K_{\mu2}/\pi_{\mu2}$ and $K_{e2}/K_{\mu2}$ put non-trivial constraints of 2HDM.
- Experimental precision on $|V_{us}|f_+(0)$ is expected to be improved to the level of ~0.1% in mid-term: a similar precision on $f_+(0)$ and an improvement on radiative corrections for $|V_{ud}|$ would allow for a CKM unitarity test at ~0.02% level.

Interpretation of K_{e3} data is currently limited by lattice QCD input