Precision tests of the Standard Model with kaon decays

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FlaviaNet Kaon WG

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Outline

- Introduction
- V_{ud} from nuclear β decays

Hardy-Towner, Marciano-Sirlin

- V_{us}, V_{us}/V_{ud} from kaon (and pion) decays

FlaviaNet working group

- CKM unitarity and G_F universality

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

FlaviA net Kaon WG

Working Group on Precise SM Tests in K Decays

FlaviA net

Kaon WG home
FlaviaNet home

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Rare Decays

Contacts
Acknowledgements

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Talks
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CKM unitarity: G_F universality

SM coupling to *W*: $\frac{g}{\sqrt{2}} W_\alpha^+ \left(\bar{U}_L V_{CKM} \gamma^\alpha D_L + \bar{e}_L \gamma^\alpha \nu_{eL} + \bar{\mu}_L \gamma^\alpha \nu_{\mu_L} + \bar{\tau}_L \gamma^\alpha \nu_{\tau L} \right)$

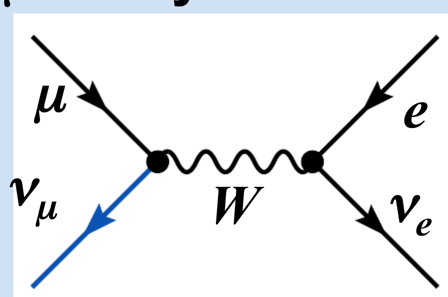
one gauge coupling (g) — ***unitary matrix*** (V_{CKM})

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \stackrel{?}{=} 1$$

negligible ($|V_{ub}|^2$)

Most precise test of CKM unitarity from 1st row

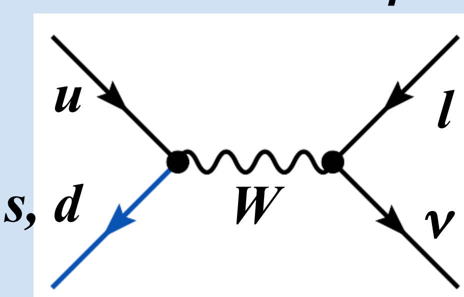
μ decay



$$\left(g_\mu g_e\right)^2 / M_W^4 = G_F^2$$

?
=

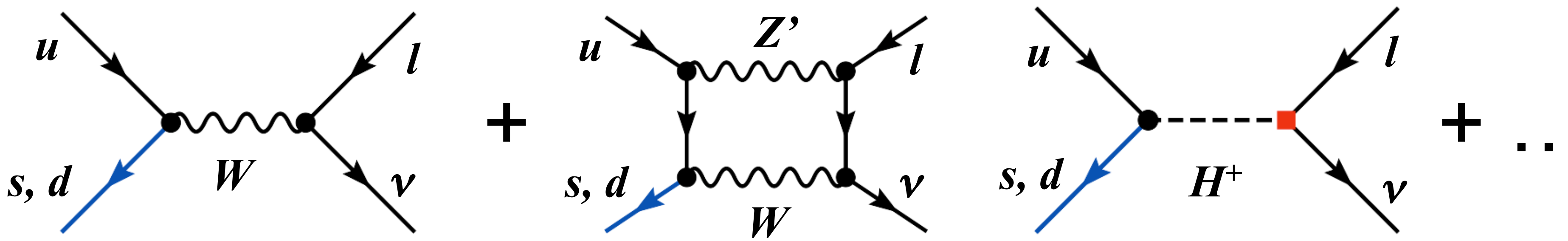
***K*, π and nuclear *β* decays**



$$\left(g_q g_\ell\right)^2 \left(|V_{ud}|^2 + |V_{us}|^2\right) / M_W^4 = G_{CKM}^2$$

CKM unitarity: G_F universality

New Physics extensions of the SM can break gauge universality



$$SM + NP \propto G_F^2 \left|V_{uq}\right|^2 \left(1 + a\left(M_W / M_X\right)^2\right)^2$$

naively $a_{tree} \approx 1$, $a_{loop} \approx g^2$

μ lifetime:	$G_F = 1.166371(6)\times10^{-5}$ GeV^{-2}	
τ decay:	$G_\tau = 1.1678(26)$	
ew precision test:	$G_{ew} = 1.1655(12)$	
V_{us} at 0.5%:	$G_{CKM} = 1.16xx(4)$	$\Rightarrow$ $M_{tree} \approx$ 10 TeV, $M_{loop} \approx$ 1 TeV

V_{ud} from nuclear β decays

Experimental survey + radiative corrections (nucleus-dep.)

Towner, Hardy arXiv:0812.1202

Radiative corrections (nucleus-indep.)

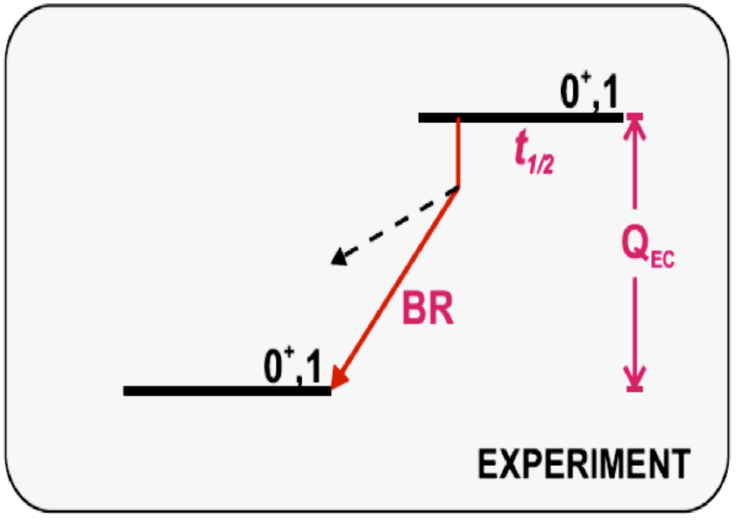
Marciano, Sirlin PRL 96 (2006)

V_{ud} from Fermi transitions ($0^+ \to 0^+$)

$$V_{ud}^2 = \frac{K}{2G_F^2 \overline{\mathcal{F}t}(1+\Delta_R)}$$

$$\mathcal{F}t = ft(1+\delta'_R)(1-(\delta_C - \delta_{NS}))$$

nucleus independent



- Measured on 13 nuclei:

  $t = t_{1/2}$/BR partial half life $\quad$ f = statistical rate function $f(Z,Q_{EC})$

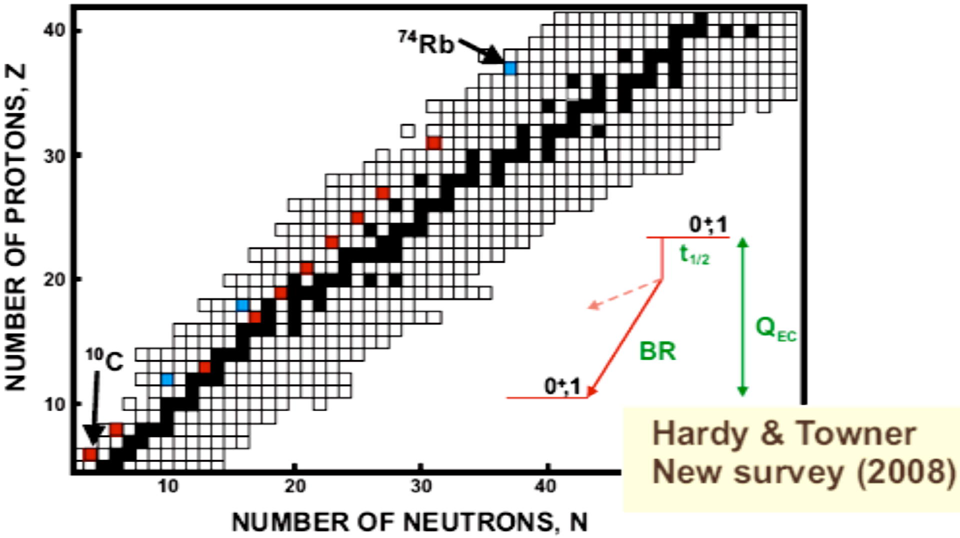
- Radiative corrections:

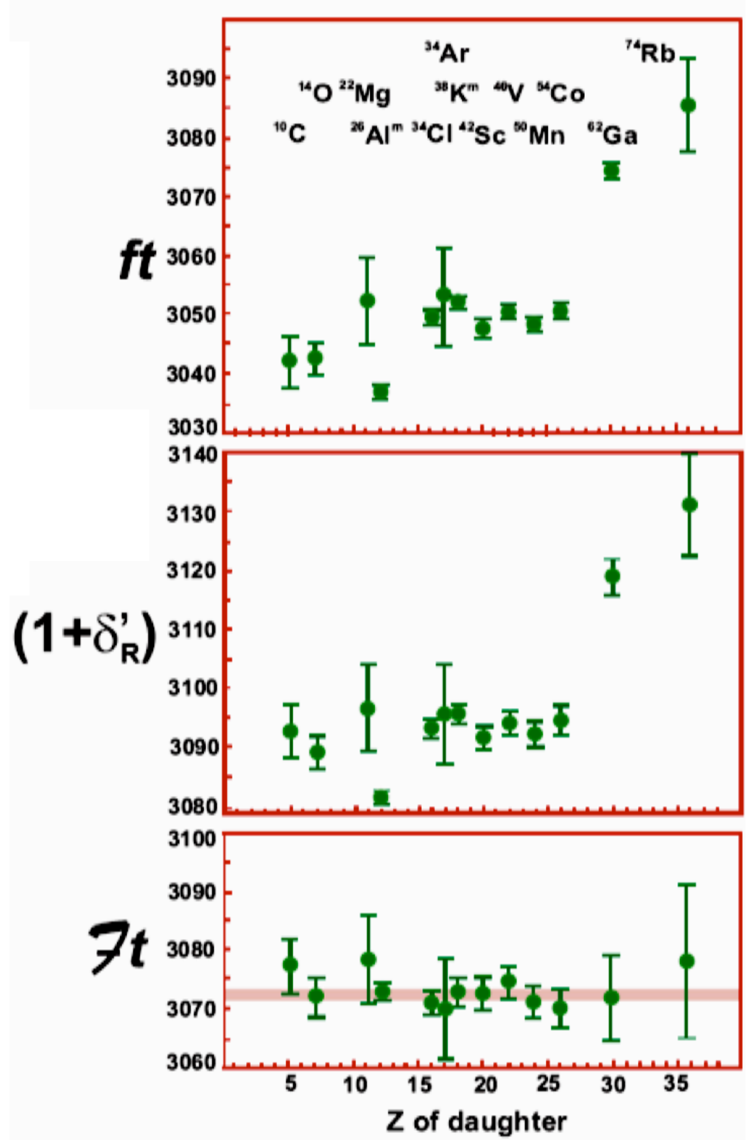
  Δ_R = 2.361(38)%, nucleus-independent (Marciano-Sirlin 2006)

  δ'_R , δ_{NS} nucleus-dependent

- δ_C nucleus dependent isospin breaking

World data for $0^+ \rightarrow 0^+$ decay, 2008





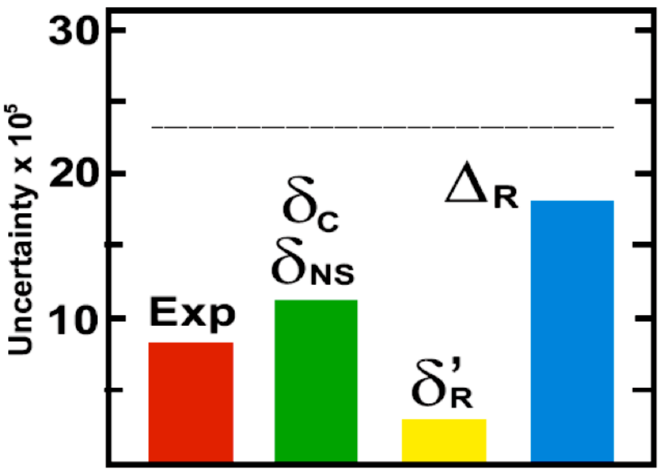
10 cases with *ft*-values measured to **~0.1% precision**; 3 more cases with **<0.3% precision**

$$\mathcal{F}t = ft(1+\delta'_R)(1-(\delta_C-\delta_{NS}))$$

V_{ud} from $0^+ \rightarrow 0^+$ decay in 2008

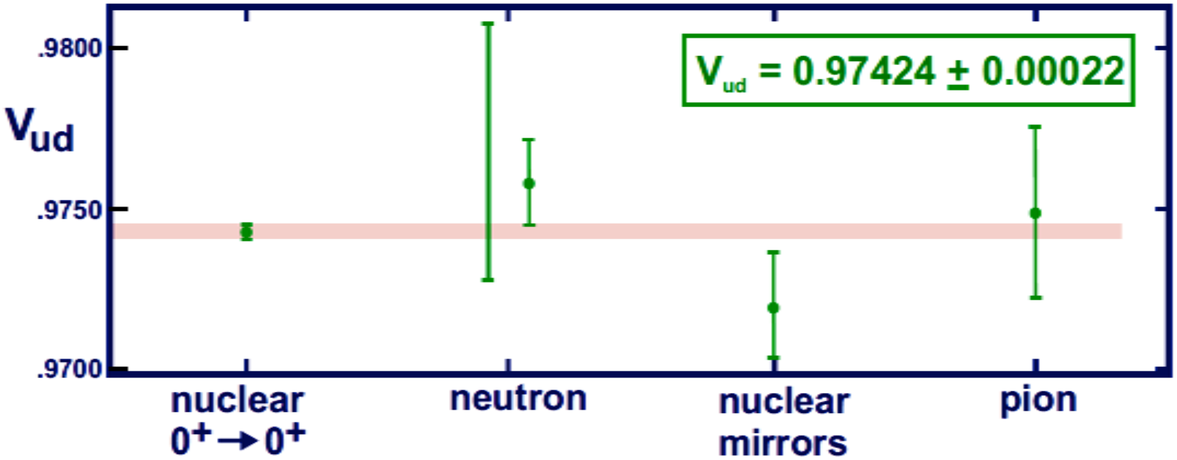
$V_{ud} = 0.97424 \pm 0.00022$

Hardy-Towner, CIPANP '09



- Nuclear-structure dependent corrections, δ_C and δ_{NS}, can be tested by experiment
- Add new transistions

nuclear $0^+ \rightarrow 0^+$ still the most precise (by a factor ~10)



V_{us} and V_{us}/V_{ud} from kaon decays

by FlaviaNet working group

- "official" analysis: arXiv:0801.1817
- partial update presented today

V_{us} from K_{l3} decay rates

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

with $K = K^+, K^0$; $l = e, \mu$ and C_K^2 = 1/2 for K^+, 1 for K^0

Inputs from theory:

S_{EW} Universal short distance EW correction (1.0232)

$f_+^{K^0\pi^-}(0)$ Hadronic matrix element at zero momentum transfer (t=0)

$\Delta_K^{SU(2)}$ Form factor correction for SU(2) breaking

Δ_{Kl}^{EM} Long distance EM effects

Inputs from experiment:

$\Gamma(K_{l3(\gamma)})$ **Branching ratios** with well determined treatment of radiative decays; **lifetimes**

$I_{Kl}(\lambda)$ Phase space integral: λs parameterize form factor dependence on t :

K_{e3} : only λ_+ (or λ_+' λ_+'')

$K_{\mu 3}$: need λ_+ and λ_0

V_{us} from kaon decays: recent history

→ 2002
(2004 PDG)

Old Kl3 data give $1 - V_{ud}^2 - V_{us}^2 = 0.0035(15)$

A 2.3σ hint of unitarity violation?

2003

BNL 865 measures higher BR(K^+e3) = 5.13(10)%

V_{us} consistent with unitarity

2004-present

Many new measurements from KTeV, KLOE, ISTRA+, NA48

- **BRs, lifetimes, form-factor slopes**
- **Much higher statistics** than older measurements
- Importance of **radiative corrections**
- Proper reporting of correlations between measurements

2008-beyond

Value of V_{us} used in precision tests of Standard Model

Extraction of V_{us} from K_{l3} data

1) BR and lifetime averages: K_L and K_S

2) BR and lifetime averages: $K^{\pm}$

3) Form factor slopes and phase space

4) Extraction of $|V_{us}| f_+(0)$ (and V_{us})

Fit to K_L BR and lifetime measurements

21 input measurements:

- **5 KTeV** ratios
- **NA48** BR(K_{e3}/2 track)
- **4 KLOE** BRs
- **KLOE**, **NA48** BR($\pi^+\pi^-/K_{l3}$)
- **KLOE**, **NA48** BR($\gamma\gamma/3\pi^0$)
- **PDG** ETAFIT BR($2\pi^0/\pi^+\pi^-$)
- **KLOE** τ_L from $3\pi^0$
- **Vosburgh** '72 τ_L
- **KTeV** BR($\pi^+\pi^-\gamma/\pi^+\pi^-(\gamma)$)
- **E731**, **2KTeV** BR($\pi^+\pi^-\gamma_{DE}/\pi^+\pi^-\gamma$)

all published results

1 constraint: ΣBR=1

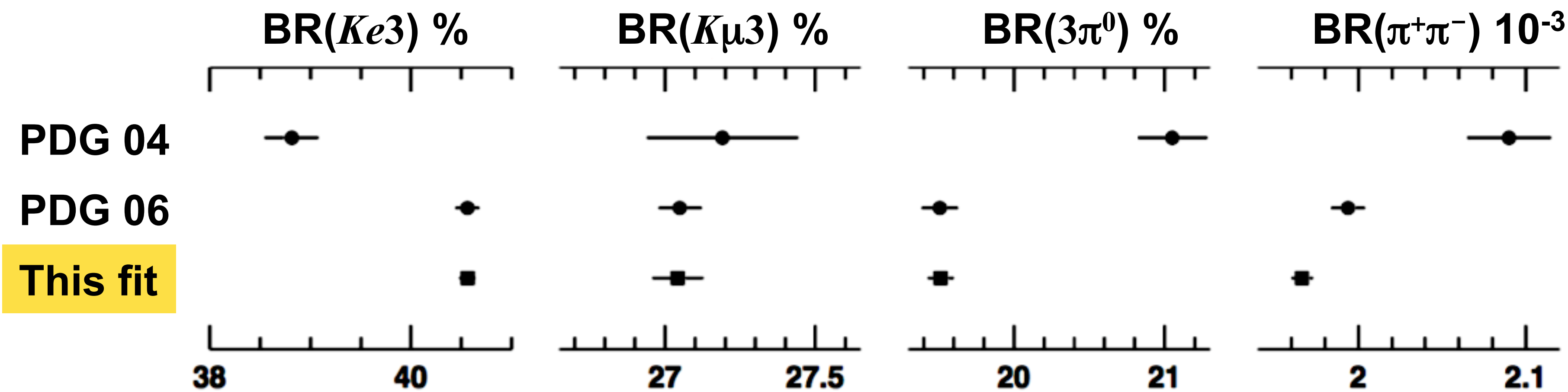
FlaviaNet fit

Parameter	Value	S
$Ke3$	0.4056(9)	1.3
$K\mu3$	0.2704(10)	1.5
$3\pi^0$	0.1952(9)	1.2
$\pi^+\pi^-\pi^0$	0.1254(6)	1.1
$\pi^+\pi^-(\gamma_{IB})$	1.967(7)×10^{-3}	1.6
$\pi^+\pi^-\gamma$	4.15(9)×10^{-5}	1.3
$\pi^+\pi^-\gamma_{DE}$	2.84(8)×10^{-5}	1.1
$2\pi^0$	8.65(4)×10^{-4}	1.4
$\gamma\gamma$	5.47(4)×10^{-4}	1.1
τ_L	51.16(21) ns	1.1

χ^2/ **ndf = 19.8/12** (Prob = 7.1%)

compare PDG'08: 35.7/17 (0.5%)

Evolution of K_L BRs



Differences between FlaviaNet and PDG are minor

Since PDG '04:

- Proper radiative corrections, especially for *Ke3*
- Exclusion of old measurements

from K_L BRs:	PDG '04	This fit	
$K_{\mu3}/K_{e3}$	0.701(9)	0.6666(29)	ok with lepton universality
$\lvert\eta_{+-}\rvert \times 10^3$	2.284(14)	2.223(6)	$>3\sigma$ difference

BR($K_S \to \pi e \nu$) and K_S lifetime

BRs from KLOE tagged K_S beam, 1.2×10[8] events

KLOE 2006

BR($K_S \to \pi e \nu$)/BR($K_S \to \pi^+\pi^-$) = 10.19(13) × 10^{-4} **σ~1.3%**

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

Add NA48 result (fit K_S and K_L components in decay-length distribution)

NA48 2007

$\Gamma(K_S \to \pi e \nu)$ /$\Gamma(K_L \to \pi e \nu)$ = 0.993(26)(22) **σ~3.4%**

we obtain **BR($K_S \to \pi e \nu$) = 7.05(8) × 10^{-4}**

PDG

τ_S = 0.08958(5) ns

From fit to *CP* parameters, does not assume *CPT*

Dominated by **NA48 '02** and **KTeV '03** values

Extraction of V_{us} from K_{l3} data

1) BR and lifetime averages: K_L and K_S

2) BR and lifetime averages: $K^{\pm}$

3) Form factor slopes and phase space

4) Extraction of $|V_{\rm us}|\, f_+(0)$ (and $V_{\rm us}$)

Recent results on $K^\pm$ BRs

BNL 865 2003

$BR(K^+ \to \pi^0_D e^+ \nu)/BR(K^+ \to \pi^0_D X^+) = 0.1962(8)(35)$

the start of the V_{us} revolution

NA48/2 2007

$BR(K^\pm_{e3})/BR(\pi^\pm \pi^0) = 0.2470(9)(4)$

$BR(K^\pm_{\mu3})/BR(\pi^\pm \pi^0) = 0.1637(6)(3)$

$K^+ K^-$ simultaneous beams

ISTRA+ 2007

$BR(K^-_{e3})/BR(\pi^- \pi^0) = 0.2449(4)(14)$

still preliminary, not used in the updated fit

KLOE 2004-2008

$BR(K^+ \to \mu^+ \nu) = 63.66(9)(15)\%$

$BR(K^+ \to \pi^+ \pi^0) = 20.65(5)(8)\%$

$BR(K^\pm_{e3}) = 4.965(53)(38)\%$

$BR(K^\pm_{\mu3}) = 3.233(29)(26)\%$

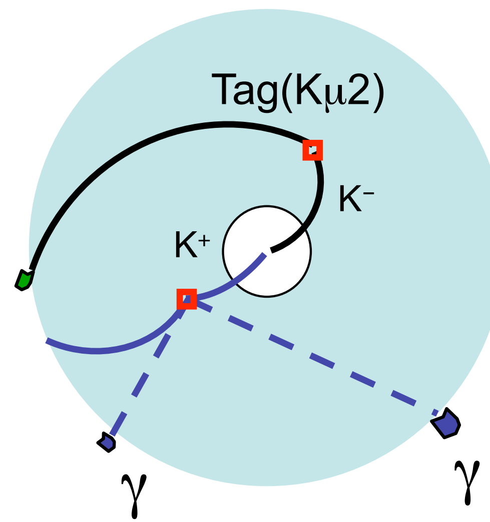
$BR(K^+ \to \pi^+ \pi^0 \pi^0) = 1.763(13)(22)\%$

absolute BR measurements with tagged $K^\pm$ beams

KLOE: measurement of $K^{\pm}$ lifetime

Poor consistency (CL=0.2%) between old meas., need confirmation

Tag events with $K^{\pm} \to \mu^{\pm} \nu$ decay
Identify a kaon decay vertex on the opposite side



- **1st method: obtain $\tau_{\pm}$ from the K decay length**
  take into account the energy loss: $\tau_K = \sum_i \Delta L_i/(\beta_i \gamma_i c)$

- **2nd method: obtain $\tau_{\pm}$ from the K decay time**
  use photons from $K^{\pm} \to \pi^{\pm}\pi^0$ decay

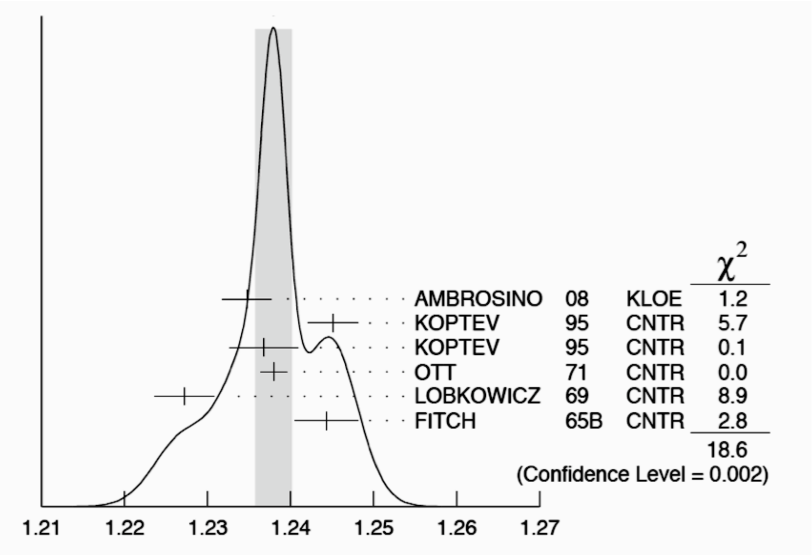
Compatible results, average with correlations:

$$\tau_{\pm} = 12.347(30) \text{ ns}$$

$$\tau_{+}/\tau_{-} = 1.004(4)$$

JHEP (01) 2008

$K^{\pm}$ lifetime: older data



PDG
2008 average

$\tau_{\pm}$= 12.379(21) ns
S = 1.9

Serious doubts about accuracy of error estimates for older experiments

Ott & Pritchard '71

Statistical errors incorrect by x2.3 (~0.56/√N)
Uncorrelated combination of systematic errors

Koptev *et al.* '95

~2σ difference begtween results for same experiment, different stoppers → **use average with scaled errors**

Lobkowicz *et al.* '69

Focused on τ_+/τ_- , precision absolute scale not emphasized, fit not compatible with exponential behaviour → **not used in our fit**

Fit to $K^{\pm}$ BR and lifetime measurements

Compared to PDG, our fit:

We exclude all six Chiang '72 measurements

- No radiative corrections
- 6 BRs constrained by ΣBR = 1, correlations unavailable

After a carefull review, we exclude also

- 2 Ke3/2-body (Ecshstruth '68, Cester '66)
- 2 Kμ3/Ke3 (Botterill '68, Heintze '77)
- $\Gamma(K^+ \to \pi^+\pi^+\pi^-)$ from Ford '67 ← ***new measurement needed!***

Lifetime measurements

- No Lobkowicz '69
- Koptev '95 measurements combined with scaled errors

Compared to previous Flavianet fit (KAON 07):

- Ke3/$\pi\pi^0$ from ISTRA+ excluded (never published)
- new KLOE BR($K^+ \to \pi^+\pi^0$), important as normalization channel

Fit results to $K^{\pm}$ BR and lifetime

17 input measurements:

- **3 older τ values in PDG**
- **1 KLOE τ**
- **KLOE BR($\mu\nu$), BR($\pi\pi^0$)**
- **KLOE $Ke3$, $K\mu3$ BRs**
- **NA48/2 $K_{e3}/\pi\pi^0$, $K_{\mu3}/\pi\pi^0$**
- **E865 K_{e3}/Kdal**
- **KEK246 $K\mu3/Ke3$**
- **3 old $\pi\pi^0/\mu\nu$**
- **1 old + 1 KLOE results on 3π**

all published results

1 constraint: ΣBR=1

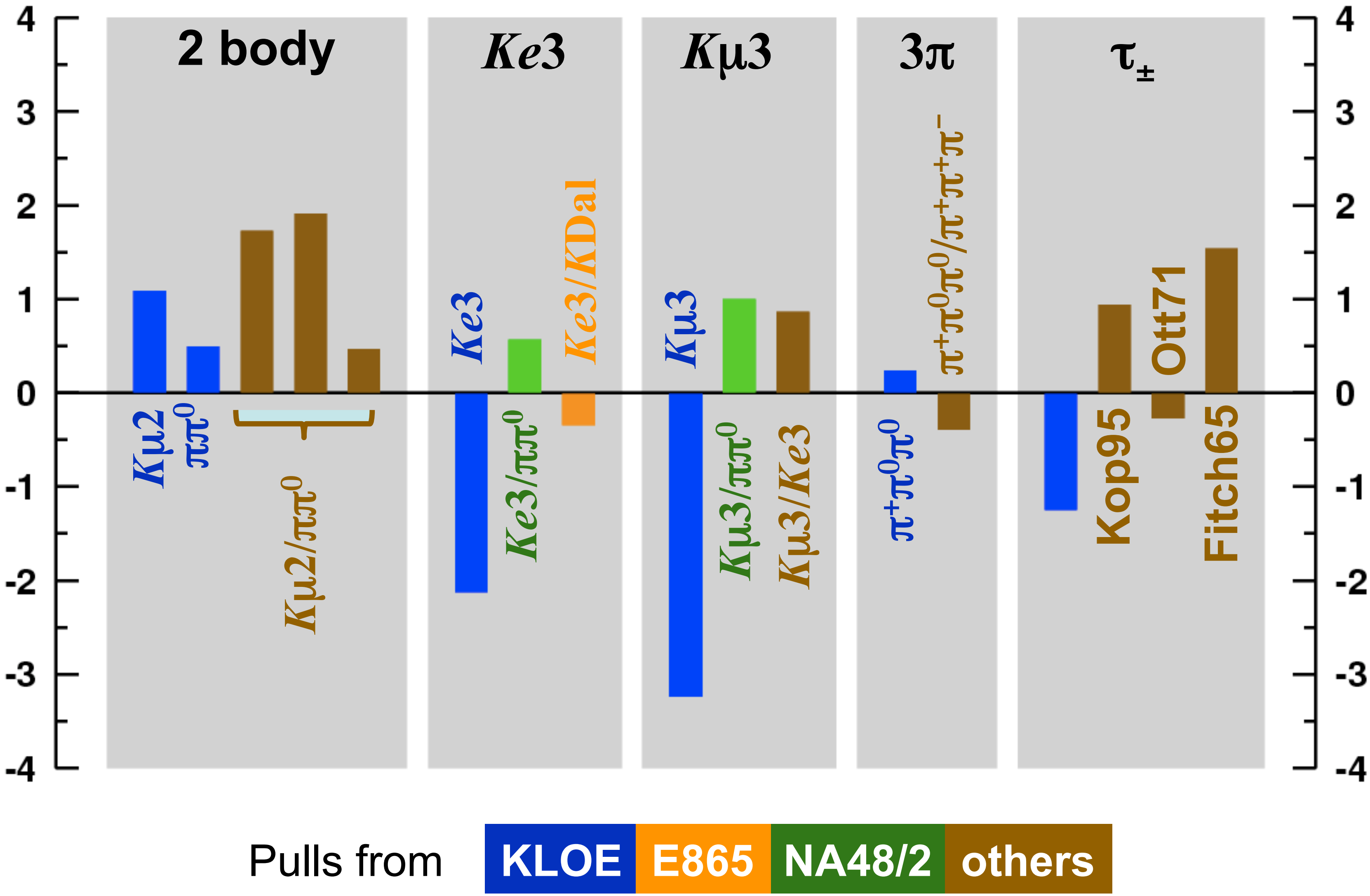
FlaviaNet fit

Parameter	Value	S
BR($\mu\nu$)	63.47(18)%	1.3
BR($\pi\pi^0$)	20.61(8)%	1.1
BR($\pi\pi\pi$)	5.73(16)%	1.2
BR($Ke3$)	5.078(31)%	1.3
BR($K\mu3$)	3.359(32)%	1.9
BR($\pi\pi^0\pi^0$)	1.757(24)%	1.0
$\tau_{\pm}$	12.384(15) ns	1.2

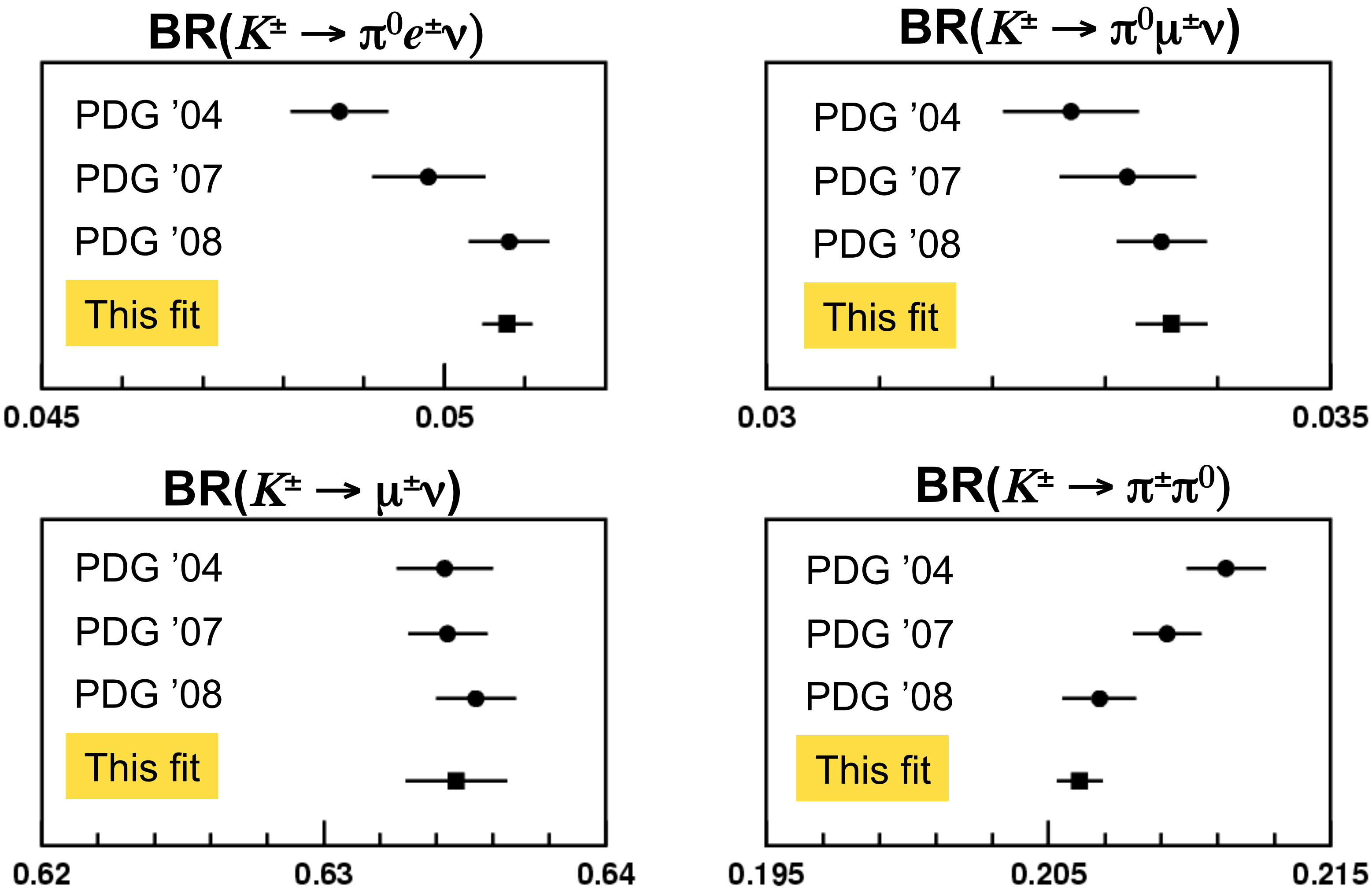
χ^2/ ndf = 25.8/11 (Prob = 0.7%)

compare PDG'08: 52/24 (0.1%)

$K^{\pm}$ BR fit vs. data



Evolution of $K^{\pm}$ BRs



Extraction of V_{us} from K_{l3} data

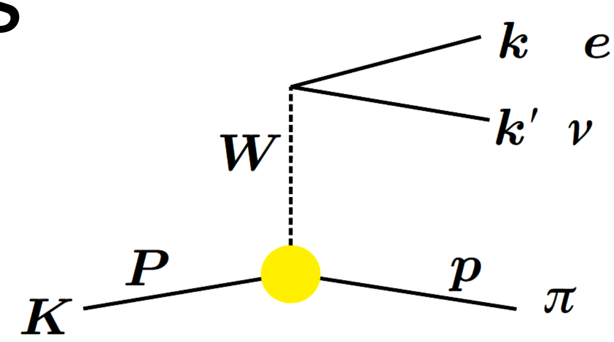
1) BR and lifetime averages: K_L and K_S

2) BR and lifetime averages: $K^{\pm}$

3) Form factor slopes and phase space

4) Extraction of $|V_{us}| f_+(0)$ (and V_{us})

K_{l3} form-factors



Hadronic matrix element:

$$\langle \pi | J_\alpha^V | K \rangle = f_+(0) \times \left(\tilde{f}_+(t)(P+p)_\alpha + \tilde{f}_-(t)(P-p)_\alpha \right)$$

$$t = (P-p)^2$$

$f_-(t)$* term only important for $K_{\mu3}$ → scalar *ff

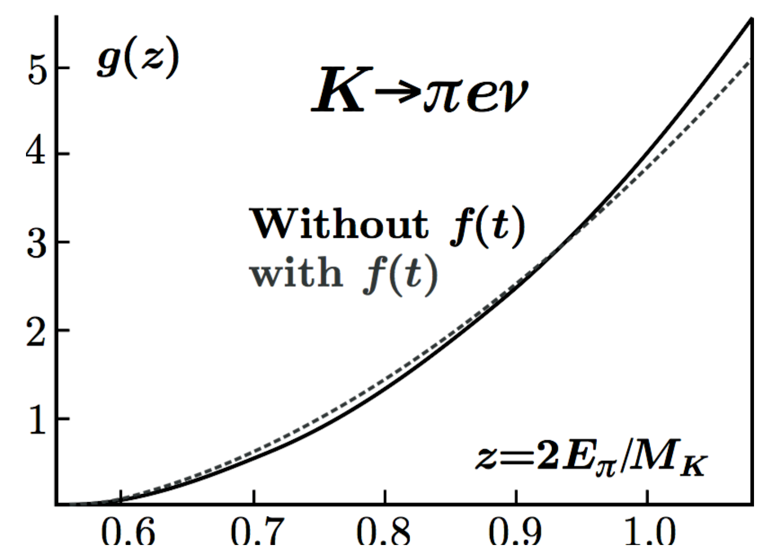
$$\tilde{f}_0(t) = \tilde{f}_+(t) + \tilde{f}_-(t)\frac{t}{m_K^2 - m_\pi^2}$$

To evaluate phase space integrals (for V_{us}) need to parameterize (and measure) *ff*-dependence on *t*

Quadratic: $\tilde{f}_{+,0}(t) = 1 + \lambda'_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right) + \lambda''_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right)^2$

Fits exhibit high correlation for λ', λ''

Polar: $\tilde{f}_{+,0}(t) = \frac{M_{V,S}^2}{M_{V,S}^2 - t}$
$$\begin{cases} \lambda' = \left(m_{\pi^+}/M\right)^2 \\ \lambda'' = 2(\lambda')^2 \end{cases}$$



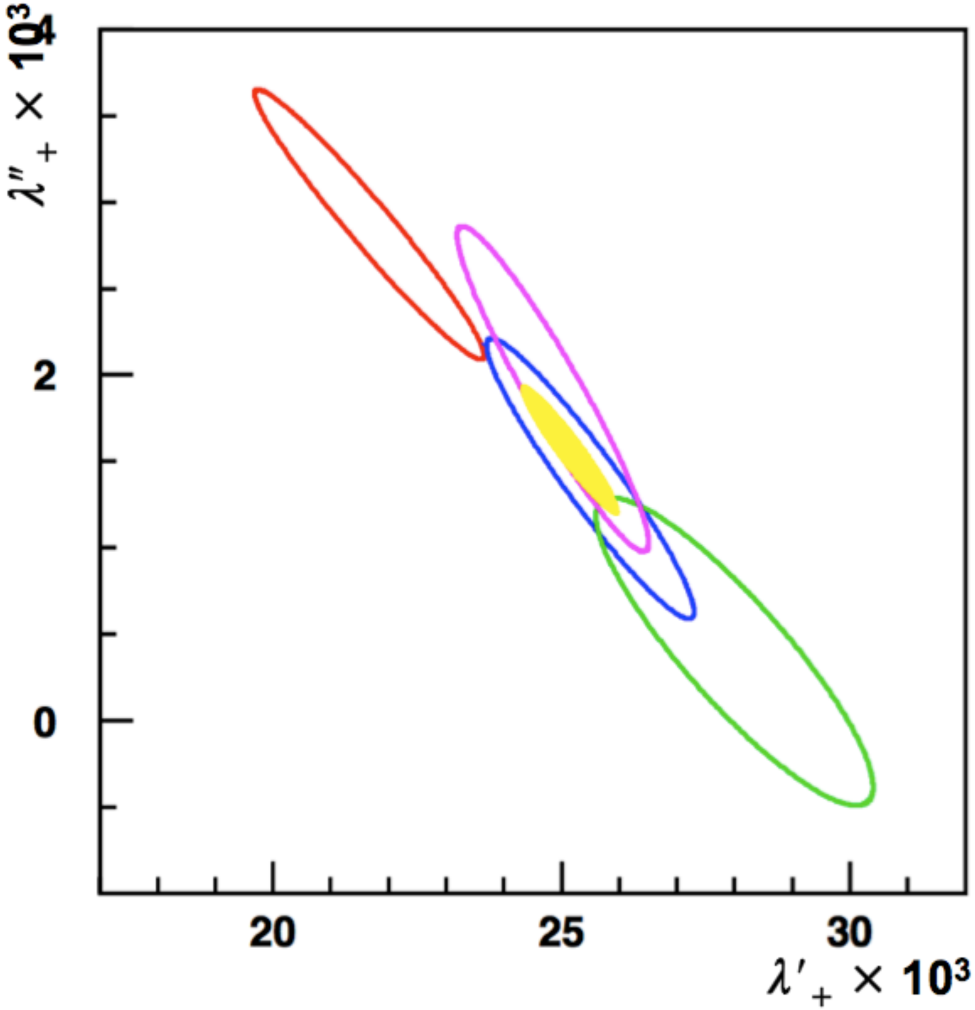
Current data on *Ke3* form-factor slopes

	$\lambda'_+ \times 10^3$	$\lambda''_+ \times 10^3$	analysis
ISTRA+ **PLB 589 (2004)**	24.9 ± 1.7	1.9 ± 0.9	0.9×10^6 K^-e3 $\rho(E_e,E_\pi)$
KTeV **PRD 70 (2004)**	21.7 ± 2.0	2.9 ± 0.8	1.9×10^6 K_Le3 $t^\pi_\perp$
NA48 **PLB 604 (2004)**	28.0 ± 2.4	0.4 ± 0.9	5.6×10^6 K_Le3 $\rho(t_{low}, t_{high})$
KLOE **PLB 632 (2006)**	25.5 ± 1.8	1.4 ± 0.8	2.0×10^6 K_Le3 t from K_S

* ISTRA+ results are rescaled by $(m_{\pi+}/m_{\pi0})^2$

Ke3 slopes: quadratic fits

Slopes from KTeV | KLOE | ISTRA+ | NA48 | *FlaviaNet* fit



Slope parameters $\times 10^3$

$\lambda'_+ = 25.15 \pm 0.87$

$\lambda''_+ = 1.57 \pm 0.38$

$\rho(\lambda'_+, \lambda''_+) = -0.941$

$\chi^2/\text{ndf} = 5.3/6$ (51%)

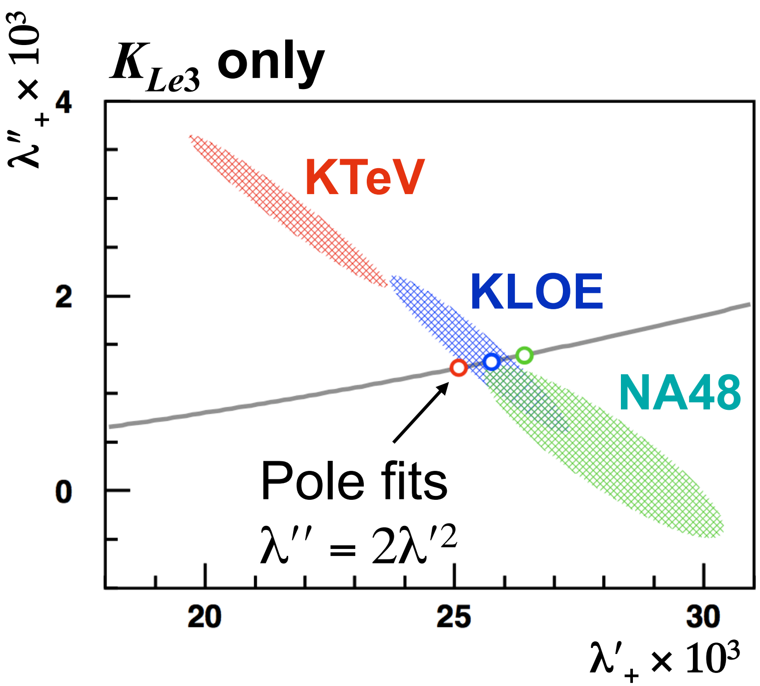
Excellent compatibility

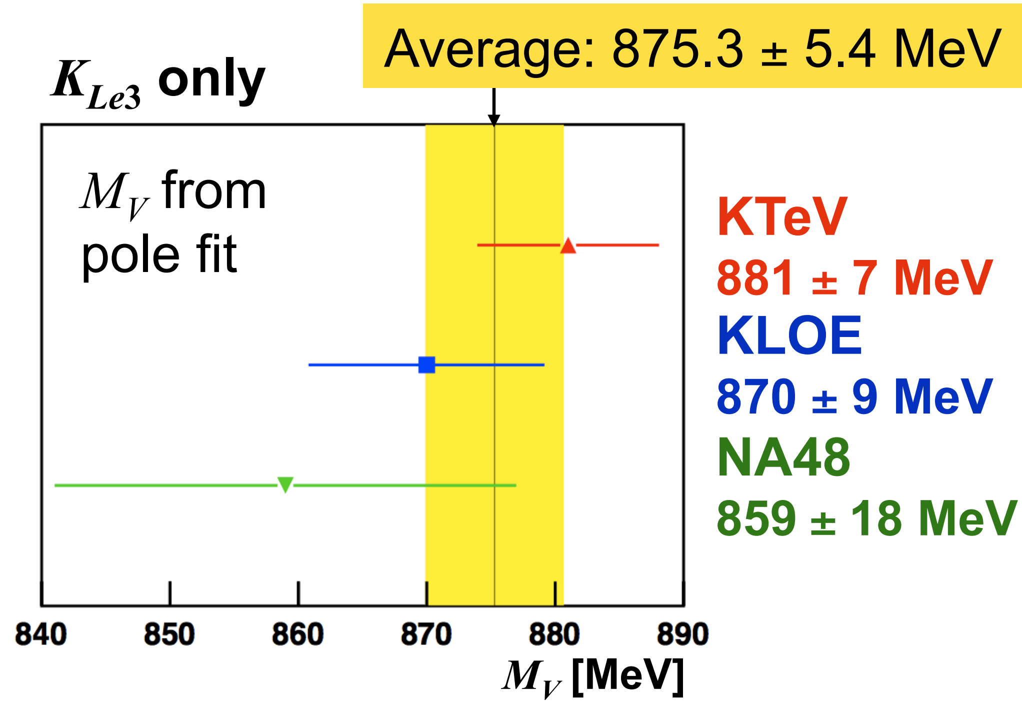
Significance of $\lambda''_+ \sim 4\sigma$

$I(K^0e3)$= 0.15463(21)

$I(K^+e3)$= 0.15900(22)

K_{e3} slopes: Quadratic vs. pole fits





K_{Le3} data	$P(\chi^2)$ fit Quad	K_{Le3} integral Quad	$P(\chi^2)$ fit Pole	K_{Le3} integral Pole	Difference
KTeV	54%	0.15378(51)	43%	0.15449(25)	+0.46%
KLOE	92%	0.15472(42)	92%	0.15489(33)	+0.11%
K_{Le3} avg		0.15463(21)		0.15481(18)	+0.12%

Current data on $K\mu 3$ form-factor slopes

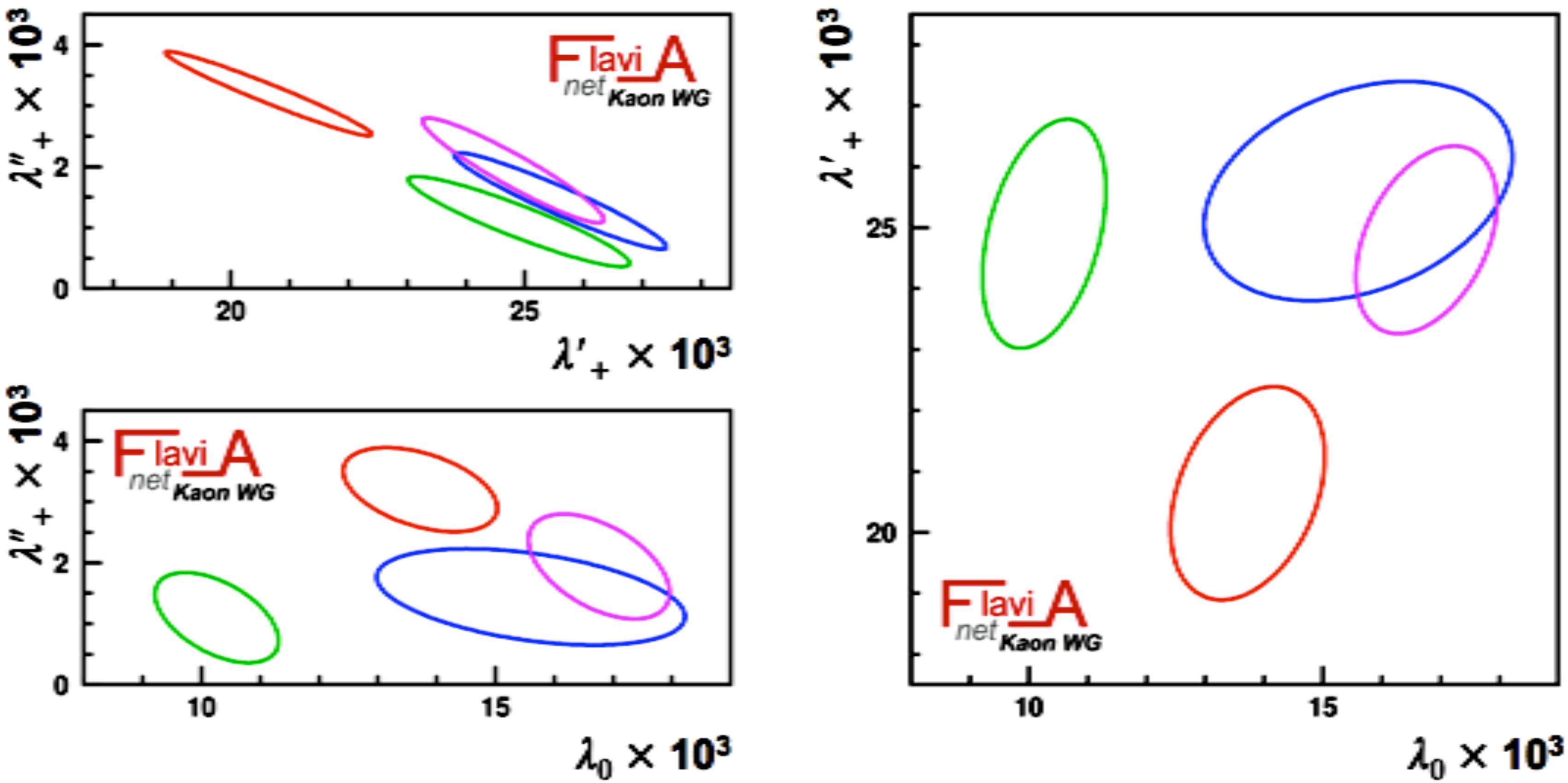
	$\lambda'_+ \times 10^3$	$\lambda''_+ \times 10^3$	$\lambda_0 \times 10^3$	analysis
ISTRA+ **PLB 581 (2004)**	**23.0 ± 6.4**	**2.3 ± 2.3**	**17.1 ± 2.2**	0.9×10^6 $K^-\mu 3$ $\rho(E_\mu,E_\pi)$
KTeV **PRD 70 (2004)**	**17.0 ± 3.7**	**4.4 ± 1.5**	**12.8 ± 1.8**	1.5×10^6 $K_L\mu 3$ $\rho(t^\mu_\perp,M_{\pi\mu})$
NA48 **PLB 647 (2007)**	**20.5 ± 3.3**	**2.6 ± 1.4**	**9.5 ± 1.4**	2.3×10^6 $K_L\mu 3$ $\rho(E_\mu,E_\pi)_{low}$
KLOE **JHEP 12 (2007)**	**25.6 ± 1.8**	**1.5 ± 0.8**	**15.4± 2.2**	1.8×10^6 $K_L\mu 3$ E_ν spectrum + $K_L e3$

* KLOE quotes Ke3+Kμ3 average

* ISTRA+ don't quote systematic error for quadratic fit: *we exclude from global fit*

Fit to *Kl3* form factor slopes

*e*3-μ3 averages from KTeV KLOE ISTRA+ NA48



Kl3 form factor slopes: fit results

Compatibility poor, inconsistency parameterized by scale factors for fit results

Slopes × 10^3:

λ'_+ = 24.54 ± 0.87 S = 1.1

λ''_+ = 1.81 ± 0.41 S = 1.2

λ_0 = 11.67 ± 1.38 S = 1.9

χ^2/ ndf = 29/8 (3×10^{-4})

Phase space integrals	
$I(K^0e3)$	0.15449(20)
$I(K^+e3)$	0.15885(21)
$I(K^0\mu3)$	0.10171(32)
$I(K^+\mu3)$	0.10467(33)

Correlation coefficients:

	λ'_+	λ_0
λ''_+	−0.94	−0.52
λ'_+		+0.44

Without NA48 Kμ3:

- χ^2/ ndf = 9.5/7 (22%)
- *I*(Kμ3): +0.7%
- **e3-μ3 average for $|V_{us}|f_+(0)$: −0.09%**

Extraction of V_{us} from K_{l3} data

1) BR and lifetime averages: K_L and K_S

2) BR and lifetime averages: $K^{\pm}$

3) Form factor slopes and phase space

4) Extraction of $|V_{us}| f_+(0)$ (and V_{us})

$SU(2)$ correction

$$\Delta^{SU(2)} = \frac{f_+(0)^{K^+\pi^0}}{f_+(0)^{K^0\pi^-}} - 1$$

Strong isospin breaking
Quark mass differences
$\eta - \pi^0$ mixing in $K^+\pi^0$ channel

+2.36(22)%	Cirigliano ’07 (updating Cirigiliano et al. ’02) O(p^4) chiral correction Quark mass-ratio analysis based on Leutwyler ‘96
⇨ **+2.9(4)%**	Kastner & Neufeld ’08 Quark mass-ratio from Ananthanarayan, Moussallam ’04
+2.31%	Bijnens, Ghorbani ‘07 O(p^6) chiral correction

Long-distance EM corrections

Δ^{EM} = mode-dependent integrated correction to the decay rate from Dalitz plot modifications from EM effects; values depend on acceptance for events with additional real photon(s)

All recent measurements assumed fully inclusive

Δ^{EM}	**Cirigliano et al. '04** ChPT	**Andre '04** Had. model	**Cirigliano et al. '08** ChPT
K^0_{e3}	+0.52(10)%	+0.65(15)%	**+0.50(11)%**
K^+_{e3}	+0.03(10)%		**+0.05(13)%**
$K^0_{\mu3}$		+0.95(15)%	**+0.70(11)%**
$K^+_{\mu3}$			**+0.01(13)%**

Cirigliano et al. '08 perform comprehensive analysis at fixed order e^2p^2

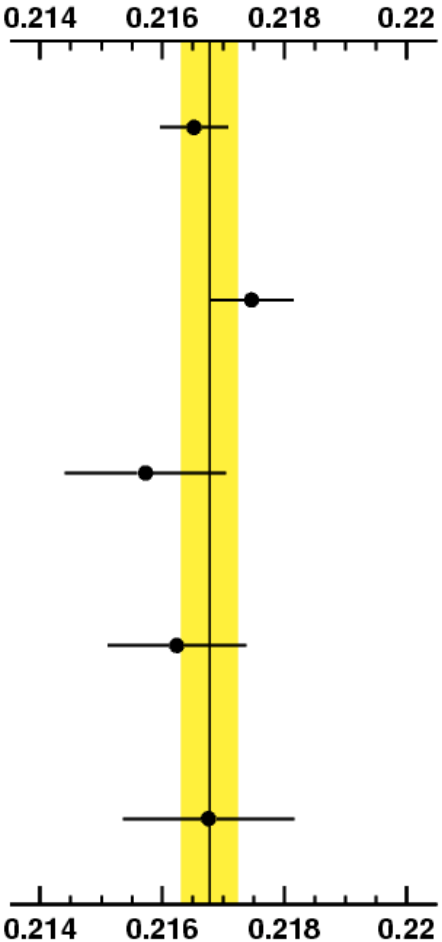
Fully inclusive prescription to treat real photon emission

Updated values of LECs for structure-dependent terms

Correlations evaluated, e.g.: $\rho(K^0e3, K^0\mu3) = +0.69$, $\rho(K^0e3, K^+e3) = +0.08$

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

$|V_{us}|\,f_+(0)$



Approx. contrib. to % err from:

		% err	BR	τ	Δ	Int
K_Le3	**0.21652(56)**	**0.25**	0.11	**0.20**	0.11	0.10
$K_L\mu3$	**0.21746(69)**	**0.32**	0.17	**0.19**	0.11	0.15
K_Se3	**0.21572(132)**	**0.61**	**0.60**	0.03	0.11	0.10
$K^{\pm}e3$	**0.21624(113)**	**0.52**	**0.31**	0.06	**0.41**	0.09
$K^{\pm}\mu3$	**0.21676(141)**	**0.65**	**0.48**	0.06	**0.41**	0.15

Average: $|V_{us}|\,f_+(0)$ = 0.21660(47) χ^2/ndf = 3.03/4 (55%)

$|V_{us}| f_+(0)$: $K^\pm$ vs $K_{L,S}$

Fit 5 modes with separate values of $|V_{us}|\, f_+(0)$ for $K^\pm$ and $K_{L,S}$ modes

- Using results of overall fit to form-factor slopes
- With $SU(2)$ corrections for $K^\pm$ modes **[$\Delta^{SU(2)}_{\text{theory}}$ = 2.9(4)%]**

$K^\pm$ modes		$K_{L,S}$ modes
$\|V_{us}\|\, f_+(0)$ = 0.2163(11)	⟷	$\|V_{us}\|\, f_+(0)$ = 0.2167(5)

0.3σ difference

χ^2/ndf = 2.9/3 (41%) ρ = 0.04

When fit performed without $SU(2)$ corrections for $K^\pm$ modes, obtain an experimental value for $\Delta^{SU(2)}$

$K^\pm$ modes, no $SU(2)$	$\Delta^{SU(2)}_{\text{exp}}$ = 2.7(4)%
$\|V_{us}\|\, f_+(0)$ = 0.2226(7)	

$K_{\ell 3}$ data and lepton universality

For each state of kaon charge, we evaluate:

$$r_{\mu e} = \frac{(R_{\mu e})_{\rm obs}}{(R_{\mu e})_{\rm SM}} = \frac{\Gamma_{\mu 3}}{\Gamma_{e3}} \cdot \frac{I_{e3}\,(1+\delta_{e3})}{I_{\mu 3}\,(1+\delta_{\mu 3})} = \frac{[|V_{us}|\, f_+(0)]^2_{\mu 3,\,\rm obs}}{[|V_{us}|\, f_+(0)]^2_{e3,\,\rm obs}} = \frac{g_\mu^2}{g_e^2}$$

Modes	2004 BRs*	This fit
$K^\pm$	1.016(12)	1.005(9)
$K_{L,S}$	1.056(15)	1.009(6)

*Assuming current values for form-factor parameters and Δ^{EM}; K_S not included

Average *Kl3*

$r_{\mu e}$ **= 1.008(5)**

Without NA48 Kμ3: $r_{\mu e}$ = 1.002(5)

Compare with:

$\pi \rightarrow \ell\nu$ $(r_{\mu e})$ = 1.0042(33)

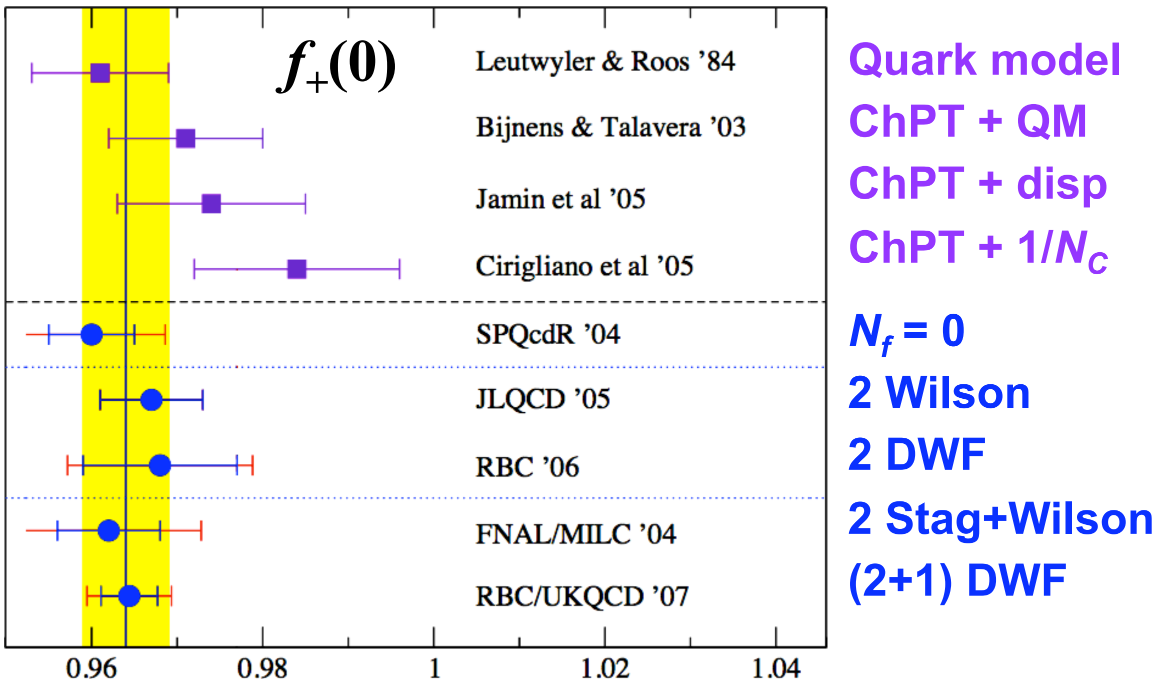
Ramsey-Musolf, Su, Tulin ’07

$\tau \rightarrow \ell\nu\nu$ $(r_{\mu e})$ = 1.000(4)

Davier, Hoecker, Zhang ’06

Evaluations of $f_+(0)$

Compilations: L. Lellouch, Lattice '08



Provisional coding (Lellouch), similar to FLAG scheme

ref.	publication	N_f, action, etc	mass extrap	$a \to 0$	finite volume
JLQCD '05	🔴	🟠	🔴	🔴	🔴
RBC '06	🟢	🟠	🔴	🔴	🔴
FNAL/MILC '04	🔴	🟠	🔴	🔴	🔴
RBC/UKQCD '08	🟢	🟢	🟠	🔴	🟠

Many evaluations available, analytic and lattice-based

ChPT results tend to give higher values for $f_+(0)$

Trend is to use lattice results, but which ones?

FlaviaNet Lattice Averaging Group (FLAG) has promised to make a recommendation

For now use:

$$f_+(0) = 0.9644(49)$$

RBC/UKQCD '07

V_{us} from K_{l3} data and CKM unitarity

K_{l3} average: $|V_{us}|\, f_+(0)$ = 0.21660(47)

was 0.2167 at Kaon'07

With $f_+(0)$ **= 0.9644(49)** from lattice QCD:

K_{l3} average: $|V_{us}|$ = 0.2246(12)

Using $|V_{ud}|$ **= 0.97424(22)** from average $0^+ \rightarrow 0^+$ β decays (Towner-Hardy '09)

$V_{ud}^2 + V_{us}^2 - 1$ = -0.0004(7)

Compatibility with unitarity -0.6σ

was 0031(15) in PDG04

$\sigma(V_{ud}^2)$~0.0004 $\sigma(V_{us}^2)$~0.0005

V_{us}/V_{ud} from $K, \pi \to \mu\nu$ decays

$$\frac{\Gamma(K_{\mu2(\gamma)})}{\Gamma(\pi_{\mu2(\gamma)})} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{m_K(1-m_\mu^2/m_K^2)^2}{m_\pi(1-m_\mu^2/m_\pi^2)^2} [1+\alpha(C_K - C_\pi)]$$

Inputs from theory:

f_K/f_π **= 1.189(7)** from lattice QCD

(HPQCD/UKQCD '07)

Cancellation of lattice-scale uncertainties

1 + $\alpha(C_K - C_\pi)$ **= 0.9930(35)**

(Marciano '04)

Uncertainty from SD virtual corrections (Finkemeier '96)

Inputs from experiment:

$K^\pm$ **BR fit:**

BR($K^\pm_{\mu2(\gamma)}$**) = 0.6347(18)**

$\tau_{K\pm}$ **= 12.384(15) ns**

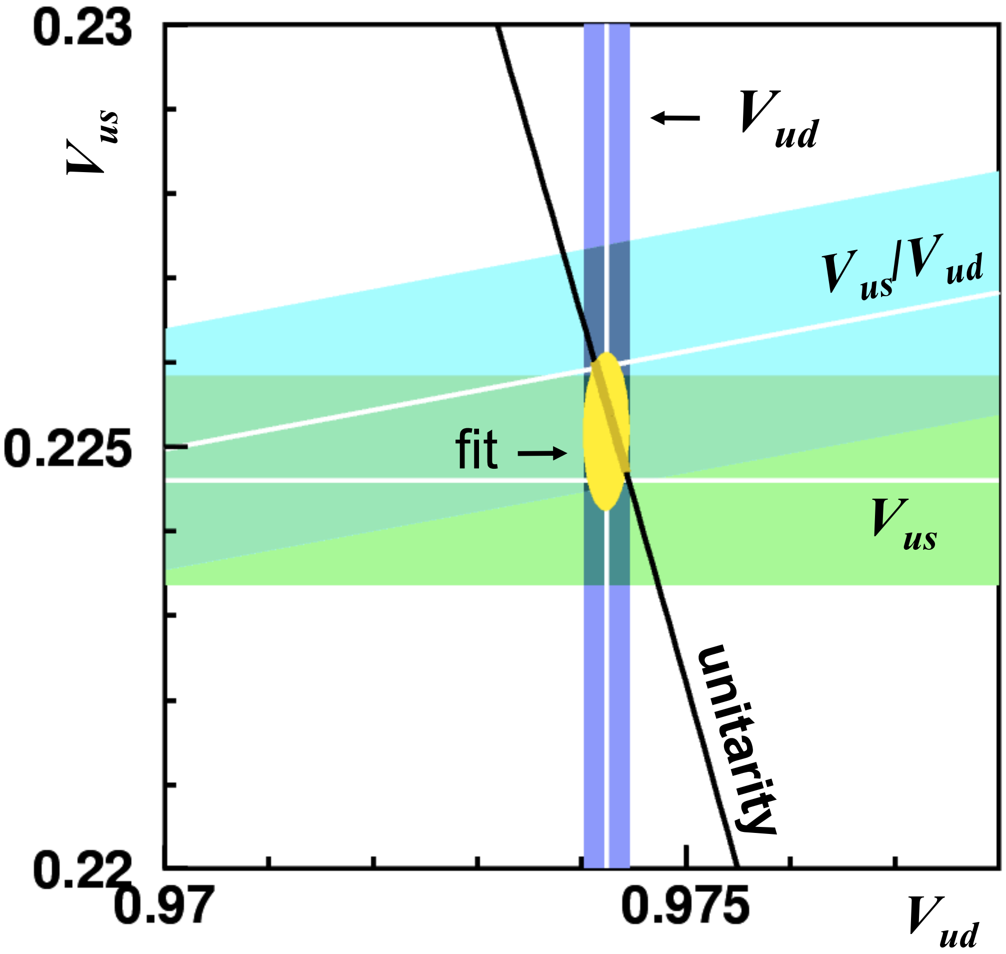
PDG:

BR($\pi^\pm_{\mu2(\gamma)}$**) = 0.9999**

$\tau_{\pi\pm}$ **= 26.033(5) ns**

$|V_{us}|/|V_{ud}|$ = 0.2319(15)

CKM unitarity



Now can fit:

- V_{us} from $Kl3$
- V_{us}/V_{ud} from $K_{\mu 2}/\pi_{\mu 2}$
- V_{ud} from β decay

V_{ud} = **0.97424(22)**
V_{us} = **0.2252(9)**
χ^2/ndf = 0.52/1 (47%)

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

We use $f_+(0)$ = **0.9644(49)**, f_K/f_π = **1.189(7)**

1st-row unitarity and gauge universality

MuLan '07	G_μ = 1.166371(6) × 10^{-5} GeV^{-2}
CKM 1st row	**1.16626(30) × 10^{-5} GeV^{-2}**
Precision EW tests	1.1655(12) × 10^{-5} GeV^{-2}
τ decay	1.1678(26) × 10^{-5} GeV^{-2}

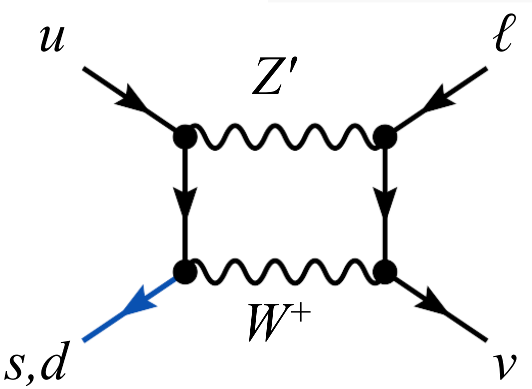
From new physics:
$G_F \to G_F\,[1 + a(M_W/\Lambda_{NP})^2]$

Probe mass scales
$a_{loop} \sim g^2/16\pi^2 \sim 1$ TeV
$a_{tree} \sim 1$ ~ 10 TeV

Example: *Z′* bosons

$$G_\mu = G_{CKM}\left[1 - 0.007 Q_{eL}(Q_{\mu L} - Q_{dL})\frac{2\ln(m_{Z'}/m_W)}{m_{Z'}^2/m_W^2 - 1}\right]$$

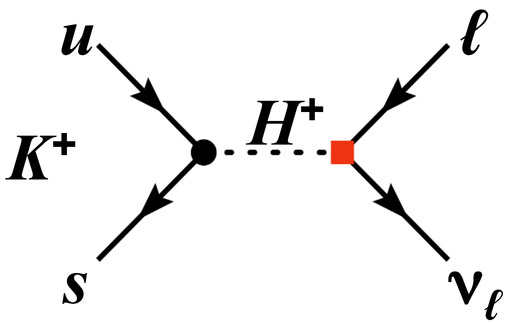
(Marciano)



Z′ boson from *SO*(10) GUT:
$Q_{eL} = Q_{uL} = -3Q_{dL} = 1$

$m_{Z'}$ > 700 GeV 95% CL
About same sensitivity as direct searches

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



Scalar currents, e.g. due to Higgs exchange, could affect $K \to \mu\nu$ width

$$\frac{\Gamma(K^+ \to \ell\nu)}{\Gamma_{SM}(K^+ \to \ell\nu)} = \left[1 - \left(\frac{m^2_{K^+}}{m^2_{H^+}}\right) \frac{\tan^2\beta}{1+\varepsilon_0 \tan\beta}\right]^2$$

The observable:

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

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

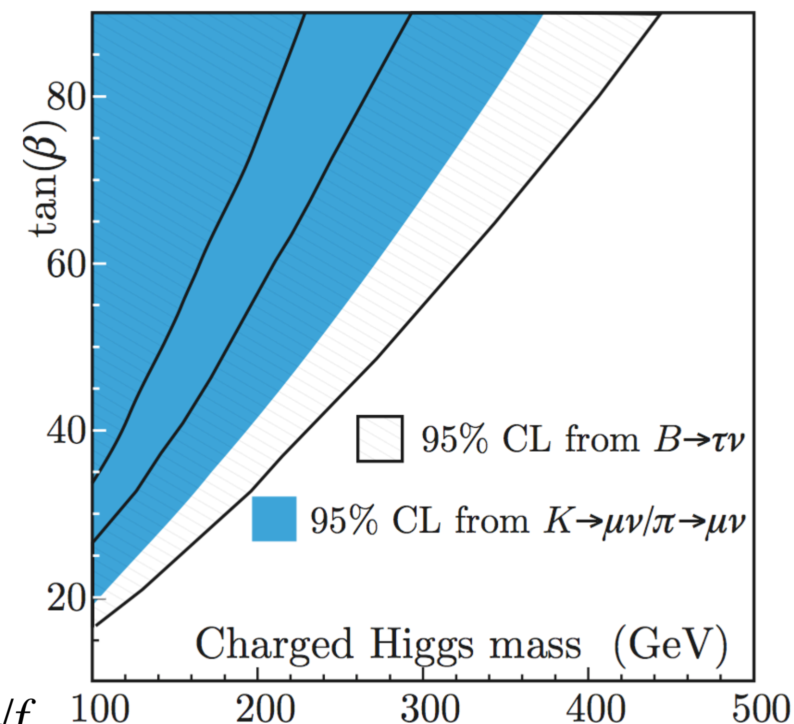
(Hou, Isidori-Paradisi)

we find

R_{l23} = 1.008 ± 0.008

(KLOE only)

limited by lattice uncertainty on $f_+(0)$ and f_K/f_π



Fit to determine $f_+(0)$ and f_K/f_π

Assuming the SM, we can extract the decay costants

Start from $K_{\ell 2}$ rate expression:

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

Rewrite as:

$$Q_{K\ell 2} = \frac{|V_{us}\, f_+(0)|^2_{K\ell 3}}{|V_{ud}|^2_{0^+\rightarrow 0^+}} \times \frac{1}{f_+(0)^2} \times \frac{f_K^2}{f_\pi^2}$$

Experimental inputs

up to IB and radiative corrections

V_{ud} from $0^+ \rightarrow 0^+$

$V_{us} f_+(0)$ from $K_{\ell 3}$

$Q_{K\ell 2}$ rate ratio

Parameters from theory

$f_+(0)$

f_K/f_π

Constraints from: $Q_{K\ell 2}$ rate expression and 1st row CKM unitarity

Fit to determine $f_+(0)$ and f_K/f_π

5 parameters:

$V_{ud}, V_{us}, Q_{K\ell 2}, f_+(0), f_K/f_\pi$

3 inputs:

$V_{ud},\ V_{us} f_+(0),\ Q_{K\ell 2}$

2 constraints:

$Q_{K\ell 2}$ rate relation

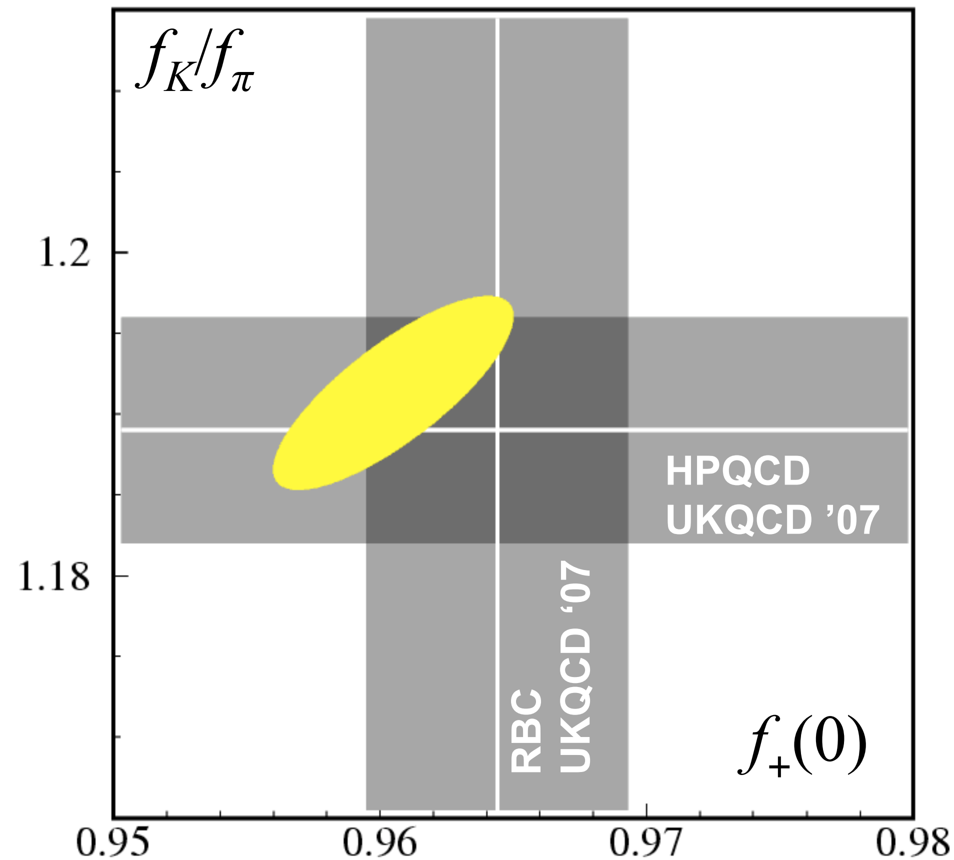
1st row unitarity

$f_+(0)$ = 0.9605(45)

f_K/f_π = 1.1913(60)

ρ = +0.79

$$Q_{K\ell 2} = \frac{|V_{us} f_+(0)|^2_{K\ell 3}}{|V_{ud}|^2_{0+\to 0+}} \times \frac{1}{f_+(0)^2} \times \frac{f_K^2}{f_\pi^2}$$



Summary

$K_{\ell 3}$ average: $|V_{us}| f_+(0)$ = 0.21660(47)

With V_{ud} from $0^+ \to 0^+ \beta$ decays and hadronic parameters from lattice QCD, first-row CKM unitarity is verified:

$V_{ud}^2 + V_{us}^2 - 1 = -0.0004(7)$
Compatibility with unitarity -0.6σ

This allows precision tests of the SM and places important limits on universality-breaking new physics

FlaviA net Kaon WG

Very rich new kaon data set; expect to improve on $K^{\pm}$ BRs and semileptonic slopes
Impressive results from lattice QCD: very interesting prospects for precision test of the SM

Additional information

WHAT'S NEW SINCE CIPANP 2006?

Important new experimental data:

Total of 27 new published experiments (most significant are precise Penning-trap Q-value measurements). New survey in:

Hardy & Towner, PRC in press (2009)

Inner radiative correction, Δ_R:

Theoretical uncertainty reduced by a factor of 2.

Marciano & Sirlin, PRL 96, 032002 (2006)

Isospin symmetry-breaking correction, δ_C:

Improved by addition of core states.

Towner & Hardy, PRC 77, 025501 (2008)

New calculations with Hartree-Fock radial wave functions as test of uncertainty.

Hardy & Towner, PRC in press (2009)

Statistical rate function, *f* :

Small correction added for atomic excitation of daughter atom

Hardy & Towner, PRC in press (2009)

EXPERIMENTS PUBLISHED SINCE 2005

Q_{EC} values:

Argonne (Canadian Penning trap)
- ^{46}V Savard *et al.*, PRL 95, 102501 (2005)

Jyvaskyla (JYFLTRAP)
- ^{62}Ga Eronen *et al.* PLB 636, 191 (2006)
- ^{26}Al^m, ^{42}Sc, ^{46}V Eronen *et al.*, PRL 97, 232501 (2006)
- ^{50}Mn, ^{54}Co Eronen *et al.*, PRL 100, 132502 (2008)

NSCL (LEBIT)
- ^{38}Ca Bollen *et al.*, PRL 96, 152501 (2006)
- ^{66}As Schury *et al.*, PRC 75, 055801 (2007)

Munich Tandem
- ^{46}V Faestermann *et al.*, Progress Report

ISOLTRAP
- ^{38}Ca George *et al.*, PRL 98, 162501 (2007)
- ^{26}Al^m George *et al.*, EPL 82, 50005 (2008)

Half-lives:

Auckland/Canberra
- ^{50}Mn Barker & Byrne, PRC 73, 064306 (2006)

LBNL
- ^{14}O Burke *et al.*, PRC 74, 025501 (2006)

Texas A&M
- ^{34}Cl, ^{34}Ar Iacob *et al.*, PRC 74, 055502 (2006)
- ^{10}C Iacob *et al.*, PRC 77, 045501 (2008)

TRIUMF
- ^{18}Ne Grinyer *et al.*, PRC 76, 025503 (2007)
- ^{62}Ga Grinyer *et al.*, PRC 77, 015501 (2008)

Jyvaskyla
- ^{26}Si Matea *et al.*, EPJA to be pub. (2008)

Melbourne
- ^{26}Al^m Scott *et al.*, NIMPRA 539, 191 (2005)

Branching ratios:

TRIUMF
- ^{62}Ga Finlay *et al.*, PRC 78, 025502 (2008)
- ^{38}K^m Leach *et al.*, PRL 100, 192504 (2008)

Jyvaskyla
- ^{26}Si Matea *et al.*, EPJA to be pub. (2008)
- ^{62}Ga Bey *et al.*, EPJA 36, 121 (2008)

Texas A&M
- ^{14}O Towner & Hardy, PRC 72, 055501 (2005)

T=1/2 SUPERALLOWED BETA DECAY

BASIC WEAK-DECAY EQUATION

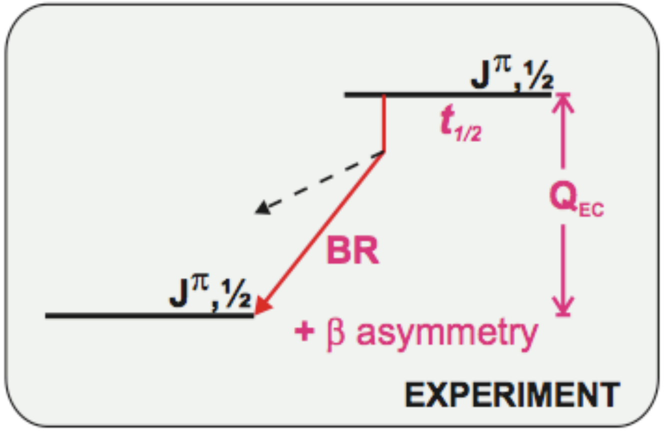
$$ft = \frac{K}{G_V^2 <\tau>^2 + G_A^2 <\sigma\tau>^2}$$

f = statistical rate function: $f(Z, Q_{EC})$

t = partial half-life: $f(t_{1/2}, BR)$

$G_{V,A}$ = coupling constants

< > = Fermi, Gamow-Teller matrix elements



INCLUDING RADIATIVE CORRECTIONS

$$\mathcal{F}t = ft\,(1 + \delta_R')[1 - (\delta_C - \delta_{NS})] = \frac{K}{G_V^2\,(1 + \Delta_R)(1 + \lambda^2 <\sigma\tau>^2)}$$

$\lambda = G_A/G_V$

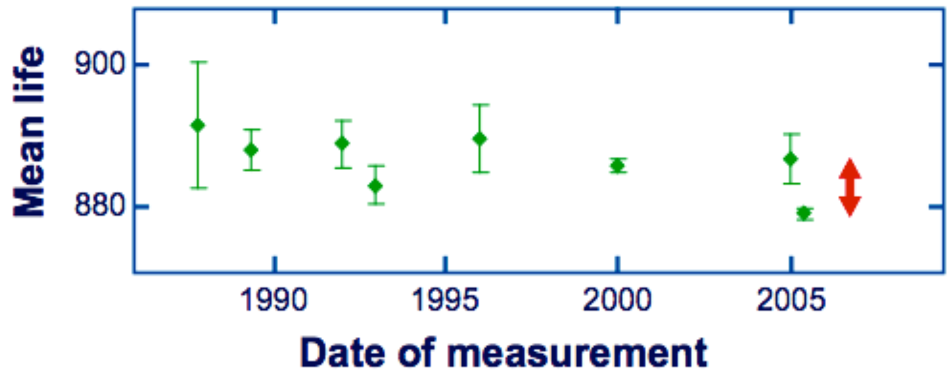
NEUTRON DECAY

Requires additional experiment: for example, β asymmetry

NEUTRON DECAY DATA 2009

Mean life:

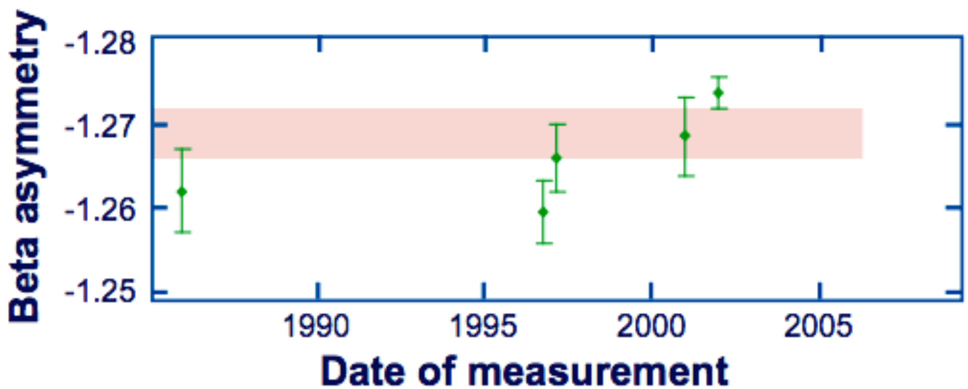
$878 < \tau < 886$ s



β asymmetry:

$\lambda = -1.269 \pm 0.003$

$\chi^2/N = 3.9$



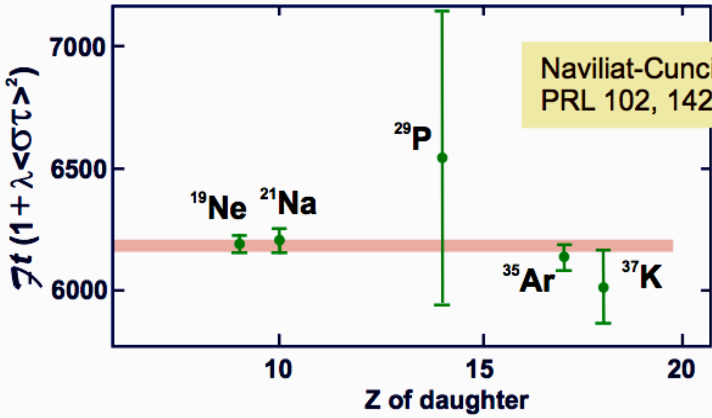
$0.9727 < V_{ud} < 0.9807$

most recent values only: $V_{ud} = 0.9758 \pm 0.0013$

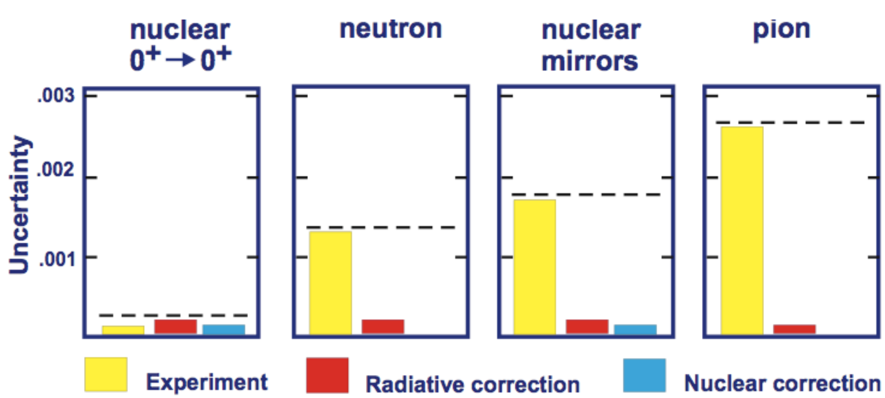
J.C. Hardy at CIPANP '09

NUCLEAR T=1/2 MIRROR DECAY DATA 2009

$$\mathcal{F}t = ft\,(1 + \delta_R')[1 - (\delta_C - \delta_{NS})] = \frac{K}{G_V^2\,(1 + \Delta_R)(1+\lambda^2\langle\sigma\tau\rangle^2)}$$



$V_{ud} = 0.9719 \pm 0.0017$



PION BETA DECAY

Decay process:

$$\pi^+ \longrightarrow \pi^0\, e^+\, \nu_e$$

$$0^-,1 \longrightarrow 0^-,1$$

Experimental data:

τ = 2.6033 ± 0.0005 x 10^{-8} s (PDG 2009)

BR = 1.036 ± 0.007 x 10^{-8}

Pocanic *et al*, PRL 93, 181803 (2004)

Result:

$V_{ud} = 0.9749 \pm 0.0026$

K_L branching ratios from KTeV

5 ratios of main BRs from independent samples of 10^5-10^6 events collected with a single trigger

KTeV, PRD 70 (2004)

2-track ratios

$BR(K_{\mu3})$/ $BR(K_{e3})$ = 0.6640(26)

$BR(\pi^+\pi^-\pi^0)$/ $BR(K_{e3})$ = 0.3078(18)

$BR(\pi^+\pi^-)$/ $BR(K_{e3})$ = 0.004856(28)

Neutral ratio

$BR(2\pi^0)/BR(3\pi^0)$ = 0.004446(25)

Mixed ratio

$BR(3\pi^0)$/ $BR(K_{e3})$ = 0.4782(55)

- 6 decays = 99.93% of K_L width, KTeV combines ratios to extract BRs
- Fit to BRs uses the 5 ratios (correlations available)

K_L branching ratios from NA48

1) K_L beam, 2-track sample, 80×10^6 events (6×10^6 signal)

NA48, PLB 602 (2004)

BR(K_{e3})/ BR(2 track) = 0.4978(35)

- NA48 evaluates BR(K_{e3}) from BR(2 track) = 1.0048-BR$(3\pi^0)_{\mathrm{KTeV}}$
- The measured ratio used in fit to BRs

2) Measurement of $\Gamma(K_L \to 3\pi^0)/\,\Gamma(K_S \to 2\pi^0)$ with same number of K_L and K_S produced on target, 2-6×10^5 signal events; use $\Gamma(K_S \to 2\pi^0)$ to extract $\Gamma(K_L \to 3\pi^0)$

NA48, 2004 preliminary

$\mathrm{BR}(K_L \to 3\pi^0)/\,\tau_L$ = 3.795(58) MHz

K_L branching ratios and lifetime from KLOE

1) Absolute BRs: K_L decays tagged by $K_S \to \pi^+\pi^-$

13×10^6 tagged, 10^5 -10^6 signal

KLOE, PLB 632 (2006)

$BR^{(0)}(K_{e3}) = 0.4049(21)$

$BR^{(0)}(K_{\mu 3}) = 0.2726(16)$

$BR^{(0)}(3\pi^0) = 0.2018(24)$

$BR^{(0)}(\pi^+\pi^-\pi^0) = 0.1276(15)$

at $\tau_L^{(0)} = 51.54$ ns, with
$d\mathrm{BR}/\mathrm{BR} = 0.67\ d\tau_L/\tau_L$
(geometrical acceptance)

Correlations available

KLOE results: set ΣBR(i)=1 and solve for τ_L
Fit to BRs: use unconstrained BRs with dependence on τ_L

2) Lifetime: measurement from an independent sample of
15×10^6 $K_L \to \pi^0\pi^0\pi^0$ events

uniform reconstruction eff. over $0.4\tau_L$

KLOE, PLB 626 (2005)

$\tau_L = 50.92(30)$ ns

$K_L \to \pi^+\pi^-$

New measurements of $K_L \to \pi^+\pi^-(\gamma)$ also useful in global fit

KTeV
PRD 70 (2004)

BR($\pi^+\pi^-/Ke3$) = 4.856(29) × 10^{-3}
1 of 5 ratios in K_L BR analysis
Contribution from direct emission (DE) negligible

KLOE
PLB 638 (2006)

BR($\pi^+\pi^-/K\mu3$) = 7.275(68) × 10^{-3}
Fully inclusive of DE component

NA48
PLB 645 (2007)

BR($\pi^+\pi^-/Ke3$) = 4.826(27) × 10^{-3}
Residual DE contribution of 0.19% subtracted

For consistency and to better satisfy S BR = 1 in global fit,
DE contribution of **1.52(7)%*** added to **KTeV** and **NA48** results

* From E731 ’93, KTeV ’01 and KTeV ’06 $K_L \to \pi^+\pi^-\gamma$ results

Can we observe λ_0''?

Determination of $f_+(0)$ with ChPT calculations at O(p^6), would benefit from the measurement of scalar form factor curvature (Bijnens and Talavera, 2003):

$$2C_{12}^r + C_{34}^r \sim \lambda_0' \qquad C_{12}^r \sim \lambda_0''$$

[C_{ij}^r = LEC's at order O(p^6)]

Unfortunately, for $K\mu3$ there are two FF and 4 parameters → high correlations → big errors. If we compute errors on λ_0'' from the (no experimental resolution) we get:

$$\rho(\lambda_0', \lambda_0'') = -0.999$$

$d\lambda_0'' \sim 20/\sqrt{N}$	$d\lambda_0'' \sim 2.5/\sqrt{N}$
Fit to λ_+', λ_+'', λ_0', λ_0''	Fit to λ_0', λ_0'' (λ_+', λ_+'' fixed)
impossible	**25M** events for $d\lambda_0'' = 0.5\times10^{-3}$

Dispersive treatment of form factors

Ignoring λ_0'' changes $K_{\mu3}$ phase space by –0.1% (0.2σ KLOE)

Better parameterization allows tests of ChPT & low-energy dynamics

Use parameterizations of f_+, f_0 from twice-subtracted dispersion relations constrained by fits to $K\pi$ scattering data

Bernard et al. '06

Expansion gives:

$$\tilde{f}_{+,0}(t) = 1 + \lambda^C_{+,0}\left(\frac{t}{m^2_{\pi^+}}\right) + \frac{(\lambda^C_{+,0})^2 + p_2}{2}\left(\frac{t}{m^2_{\pi^+}}\right)^2 + \frac{(\lambda^C_{+,0})^3 + 3\,\lambda^C_{+,0}\,p_2 + p_3}{6}\left(\frac{t}{m^2_{\pi^+}}\right)^3$$

	Fit results:	$I(K_{L\mu3})$ phase-space integrals		
KLOE $e3$-$\mu3$ **JHEP 12(2007)**	$\lambda_+^C = (25.7 \pm 0.6) \times 10^{-3}$ $\lambda_0^C = (14.0 \pm 2.1) \times 10^{-3}$ $\rho = -0.26$	Quad-lin: Disp:	0.10271(52) 0.10262(47)	} 0.1%
NA48 $\mu3$ only **PLB 647 (2007)**	$\lambda_+^C = (23.3 \pm 0.9) \times 10^{-3}$ $\lambda_0^C = (8.8 \pm 1.2) \times 10^{-3}$ $\rho = -0.44$	Quad-lin: Disp:	0.10039(58) 0.10063(31)	} 0.1%

NB: NA48 value for λ_+^C converted from ln C = 0.1438(138)

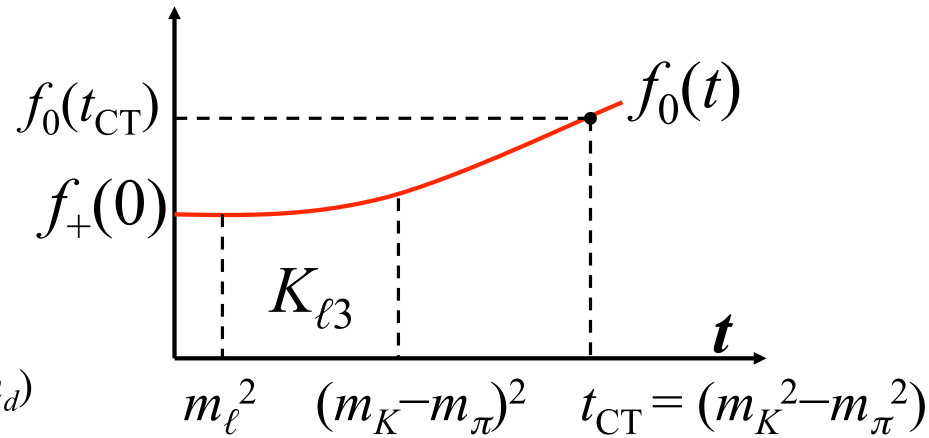
Form factors and the Callan-Treiman relation

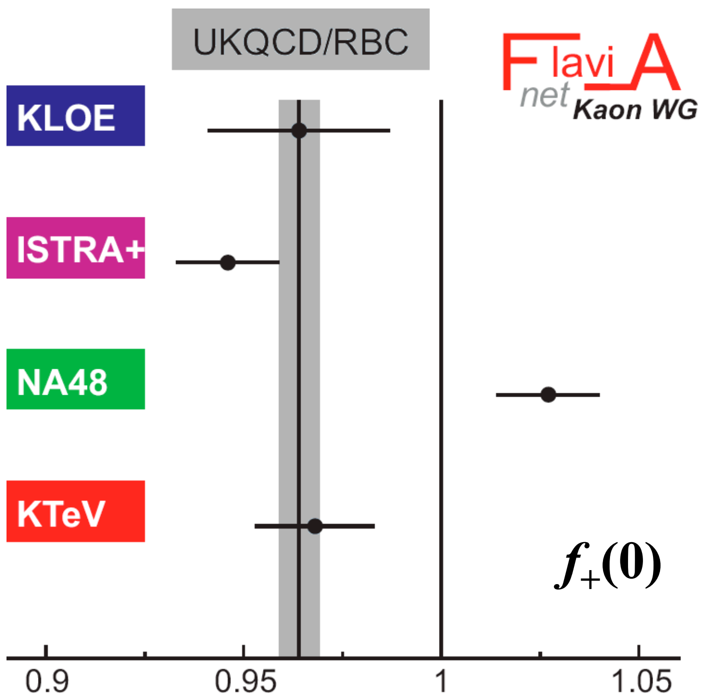
Callan-Treiman relation:

$$\tilde{f}_0(t_{CT}) = \frac{f_K}{f_\pi}\frac{1}{f_+(0)} + \Delta_{CT}$$

$t_{CT} = m_K^2 - m_\pi^2$

Δ_{CT} = $SU(2)$-breaking correction
= −(3.5 ± 8.0) × 10^{-3} in NLO ChPT ($m_u = m_d$)





Use dispersive parameterization of $f_0(t)$ and statistical considerations to extrapolate to t_{CT}

Lattice QCD f_K/f_π = 1.190(15)

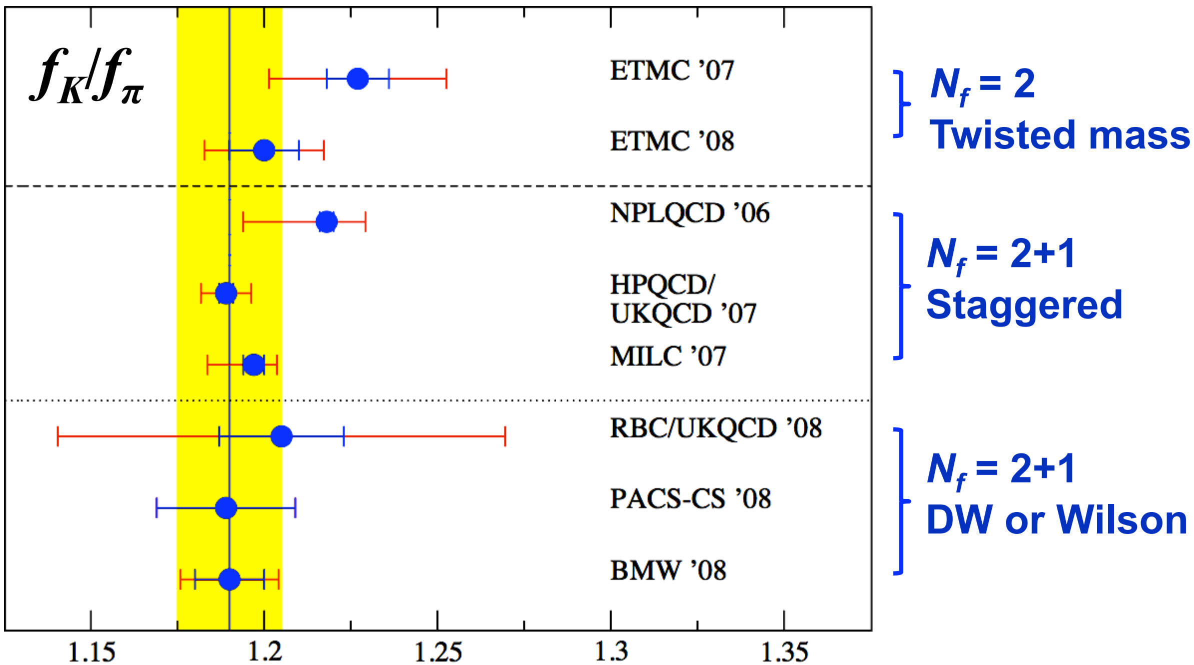
KLOE $K_{e3\text{-}\mu3}$ data:
λ_0^C = (14.0 ± 2.1) × 10^{-3} → $f_+(0)$ = 0.968(28)

NA48 $K_{\mu3}$ data:
ln C = 0.1438(138) → $f_+(0)$ = 1.027(20)

Lattice QCD $f_+(0)$ = 0.964(5)

Lattice evaluations of f_K/f_π

Compilations: L. Lellouch, Lattice '08



Only *published* result with full evaluation of systematic errors is

HPQCD/UKQCD '07

$N_f = 2+1_{\mathrm{HISQ}}$

$f_K/f_\pi = 1.189(7)$

Results without staggered quarks have large errors (PACS '08 has stat errs only) or are preliminary (BMW '08)

For now use HPQCD/UKQCD'07

V_{us} from τ

V_{us} from inclusive $\tau \to \nu X_{us}$ involves PQCD

$$|V_{us}|^2 = \frac{R^{00}_{\tau,S}}{\frac{R^{00}_{\tau,V+A}}{|V_{ud}|^2} - \delta R^{00}_{\tau,\mathrm{th}}}$$

Gámiz-Jamin-Pich-Prades-Schwab

$V_{us} = 0.2159\ (30_{exp})(5_{th})$

~3 σ lower wrt kaons (same fitting m_s, V_{us})

Theory? Exp.?

S. Banerjee arXiv:0811.1429

X^-_{us}	$\mathcal{B}_{\text{World Averages}}$ (%)
K^- [τ decay]	0.690 ± 0.010
($[K_{\mu 2}]$)	(0.715 ± 0.004)
$K^-\pi^0$	0.426 ± 0.016
$\bar{K}^0\pi^-$	0.835 ± 0.022 ($S = 1.4$)
$K^-\pi^0\pi^0$	0.058 ± 0.024
$\bar{K}^0\pi^0\pi^-$	0.360 ± 0.040
$K^-\pi^-\pi^+$	0.290 ± 0.018 ($S = 2.3$)
$K^-\eta$	0.016 ± 0.001
$(\bar{K}3\pi)^-$ (est'd)	0.074 ± 0.030
$K_1(1270) \to K^-\omega$	0.067 ± 0.021
$(\bar{K}4\pi)^-$ (est'd)	0.011 ± 0.007
$K^{*-}\eta$	0.014 ± 0.001
$K^-\phi$	0.0037 ± 0.0003 ($S = 1.3$)
TOTAL	2.8447 ± 0.0688
	(2.8697 ± 0.0680)

check with kaons on exclusive modes(~70% of R_S):

(24% of R_S) BR(Kν) = 0.69(1) vs 0.715(4) from Kμ2

but BR(Kν)/BR(πν) ok