$|V_{us}|$ from hadronic τ decays

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1. Introduction

Cabibbo-Kobayashi-Maskawa matrix element $|V_{us}|$

Fundamental parameter of the Standard Model

* Check unitarity in the first row of CKM matrix.

$$\Delta_{CKM} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0.9999(6)$$ **PDG2012**

fits to K_{l3}, K_{l2} exper. data and lattice results for $f_+(0)^{K\to\pi}$ and f_K/f_π

$\to \mathcal{O}(10\ \mathrm{TeV})$ bound on the scale of new physics **M. Antonelli** *et al*, 1005.2323.

* Input in UT analysis.

Look for new physics effects in the comparison of $|V_{us}|$ extracted from different processes: helicity suppressed $K_{\mu 2}$, helicity allowed K_{l3}, hadronic τ decays.

1. Introduction

The τ is the only lepton massive enough to decay into hadrons

→ **ideal ground to investigate hadronic weak currents.**

Using high precision experimental measurements of **ALEPH, OPAL, Belle, BaBar** (see **I. Nugent's** talk)

$$R_\tau \equiv \frac{\Gamma[\tau^- \to \text{ hadrons}(\gamma)]}{\Gamma[\tau^- \to e^- \overline{\nu_e} \nu_\tau (\gamma)]}$$

(and related observables dR_τ/ds)

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(and related observables dR_τ/ds)

* Determination of the strong coupling α_s: **A. Pich**, summary talk TAU12:

$$\alpha_s(m_\tau^2)_{\tau,av} = 0.334 \pm 0.014 \qquad \to \qquad \boxed{\alpha_s(m_Z^2)_{\tau,av} = 0.1204 \pm 0.0016}$$

in perfect agreement with the value obtained from hadronic decays at the Z: $\alpha_s(m_Z^2)_{\mathrm{Z\,width}} = 0.1190 \pm 0.0027$

→ **the most precise test of Asymptotic Freedom**

$$\boxed{\alpha_s^\tau(M_Z^2) - \alpha_s^Z(M_Z^2) = 0.0014 \pm 0.0016_\tau \pm 0.0027_Z}$$

1. Introduction

Sizeable corrections in the semi-inclusive τ-decay width into Cabbibo-suppressed modes due to $SU(3)$ breaking.

$$\delta R_\tau \equiv \frac{R_{\tau,V+A}}{|V_{ud}|^2} - \frac{R_{\tau,s}}{|V_{us}|^2}$$

Dominated by m_s (flavour indep. uncertainties drop out in the difference)

$\rightarrow$ extraction of the strange quark mass **Pich and Prades**, hep-ph/9909244

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* Strong dependence of m_s on $|V_{us}|$

$\Longrightarrow$ **Determination of $|V_{us}|$ from a fixed m_s**

E.G., Jamin, Pich, Prades, Schwab, hep-ph/0212230,0408044

$$|V_{us}|^2 = \frac{R_{\tau,S}^{exp}}{\frac{R_{\tau,V+A}^{exp}}{|V_{ud}|^2} - \delta R_\tau^{theor}}$$

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$$|V_{us}|^2 = \frac{R_{\tau,S}^{exp}}{\frac{R_{\tau,V+A}^{exp}}{|V_{ud}|^2} - \delta R_\tau^{theor}}$$

Advantage: Final error dominated by experimental uncertainty

→ potential to be competitive with best determinations

2. $|V_{us}|$ from inclusive Cabibbo-supressed hadronic τ decays

E.G., Jamin, Pich, Prades, Schwab

2.1. Theoretical Framework

The hadronic decay rate of the τ is related to QCD correlators

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$$R_\tau \;=\; 12\pi \int_0^{M_\tau^2} \frac{ds}{M_\tau^2} \left(1 - \frac{s}{M_\tau^2}\right)^2 \left[\left(1 + 2\frac{s}{M_\tau^2}\right) \mathrm{Im}\,\Pi^T(s) + \mathrm{Im}\,\Pi^L(s) \right]$$

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basic objects: Two-point correlation functions for vector and axial-vector two-quark currents ($i, j = u, d, s$).

$$\Pi^{\mu\nu}_{V,ij}(q) \equiv i\int \mathrm{d}^4x\, e^{iq\cdot x}\langle 0|T\left([V^\mu_{ij}]^\dagger(x)V^\nu_{ij}(0)\right)|0\rangle; \qquad V^\mu_{ij} \equiv \overline{q}_i\gamma^\mu q_j$$

$$\Pi^{\mu\nu}_{A,ij}(q) \equiv i\int \mathrm{d}^4x\, e^{iq\cdot x}\langle 0|T\left([A^\mu_{ij}]^\dagger(x)A^\nu_{ij}(0)\right)|0\rangle; \qquad A^\mu_{ij} \equiv \overline{q}_i\gamma^\mu\gamma_5 q_j$$

Lorentz decomposition

$$\Pi^{\mu\nu}_{ij,V/A}(q) \;=\; \left(-g_{\mu\nu}q^2 + q^\mu q^\nu\right)\,\Pi^T_{ij,V/A}(q^2) + q^\mu q^\nu\,\Pi^L_{ij,V/A}(q^2)$$

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proportional to $\searrow$ $\swarrow$

ALEPH,OPAL BaBar,Belle	$\Longrightarrow$	**spectral functions** τ decay data

2.1. Theoretical Framework

We can decompose R_τ (`experimentally` and `theoretically`) into

$$R_\tau = R_{\tau,V} + R_{\tau,A} + R_{\tau,S}$$

according to the quark content

$$\Pi^J(s) \equiv |V_{ud}|^2 \left\{ \Pi^J_{V,ud}(s) + \Pi^J_{A,ud}(s) \right\} + |V_{us}|^2 \left\{ \Pi^J_{V,us}(s) + \Pi^J_{A,us}(s) \right\}$$

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Sensitivity to the **strange** quark mass enhanced by considering the $SU(3)$-breaking quantity

$$\delta R_\tau = \frac{R_{\tau,V+A}}{|V_{ud}|^2} - \frac{R_{\tau,S}}{|V_{us}|^2}$$

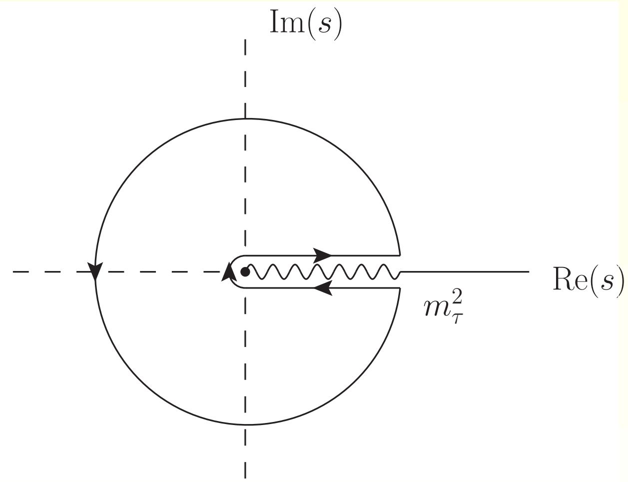
- ⋆ Dominated by the **strange quark mass**
- ⋆ **Flavour independent** uncertainties **drop out in the difference**

2.1. Theoretical Framework

Using the analytic properties of $\Pi^J(s)$

$$R_\tau = -i\pi \oint_{|s|=M_\tau^2} \frac{\mathrm{d}s}{s} \left[1 - \frac{s}{M_\tau^2}\right]^3 \left\{ 3 \left[1 + \frac{s}{M_\tau^2}\right] D^{L+T}(s) + 4\, D^L(s) \right\}$$

$$D^{L+T}(s) \equiv -s \frac{\mathrm{d}}{\mathrm{d}s} [\Pi^{L+T}(s)] \,; \qquad D^L(s) \equiv \frac{s}{M_\tau^2} \frac{\mathrm{d}}{\mathrm{d}s} [s\Pi^L(s)]$$



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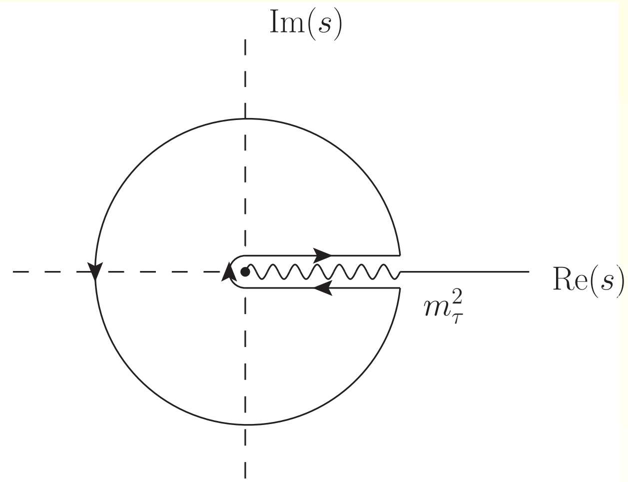

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* phase space factor: order three zero in real axis

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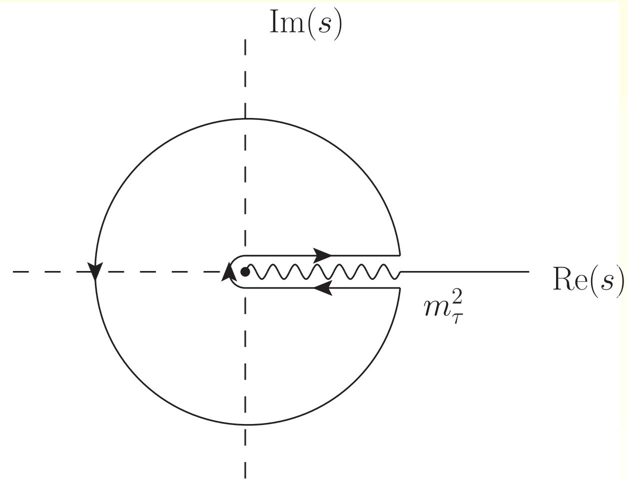

* Eliminate renormalization scheme dependent subtraction constants

* phase space factor: order three zero in real axis

* large enough Euclidean $Q^2 = -s \Longrightarrow D^{L+T}(Q^2)$ and $D^L(Q^2)$ organized in series of operators of increasing dimension using OPE

2.1. Theoretical Framework

Theoretically, performing an OPE of the correlators, R_τ can be expressed

$$R_\tau = N_c S_{\mathrm{EW}} \Big\{ (|V_{ud}|^2 + |V_{us}|^2) \left[1 + \delta^{(0)} \right] + \sum_{D \geq 2} \left[|V_{ud}|^2 \delta_{ud}^{(D)} + |V_{us}|^2 \delta_{us}^{(D)} \right] \Big\}$$

* $\delta_{ud}^{(D)}$ and $\delta_{us}^{(D)}$ are corrections in the OPE

2.2. Theoretical Framework: OPE

$$\delta R_\tau = \frac{R_{\tau,V+A}}{|V_{ud}|^2} - \frac{R_{\tau,S}}{|V_{us}|^2} = N_c\, S_{EW} \sum_{D\geq 2} \left[\delta_{ud}^{(D)} - \delta_{us}^{(D)}\right]$$

* $\delta_{ij}^{(2)}$ are known to $\mathcal{O}(\alpha_s^3)$ for both $J = L$ and $J = L + T$

  Chetyrkin;Gorishny, Kataev, Larin, Sugurladze; Baikov, Chetyrkin, Kühn; Becchi, Narison, de Rafael; Bernreuther, Wetzel.

* $\delta_{ij}^{(4)}$ fully included (m_q^4/M_τ^4, $m_q\langle\bar{q}q\rangle/M_\tau^4$)
* $\delta_{ij}^{(6)}$ estimated (VSA) to be of order or smaller than error of $D = 4$
* we disregard **OPE** corrections of $D \geq 8$

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Perturbative L series behave very badly ! $\rightarrow$

replace scalar/pseudoscalar QCD correlators with phenomenology

2.3. Theoretical Framework: Longitudinal contribution

⋆ Scalar spectral functions from s-wave $K\pi$ scatt. data **Jamin,Oller,Pich**, 0605095

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⋆ Dominant contribution: pseudoscalar us spectral function

$$s^2 \frac{1}{\pi} \mathrm{Im}\Pi^L_{us,A} = 2 f_K^2 m_K^4 \delta(s - m_K^2) + 2 f_{K(1460)} M^4_{K(1460)} BW(s)$$

$BW(s)$: Normalized Breit-Wigner **Kambor,Maltman**

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Comparison of these spectral functions with QCD

	$R^{00,L}_{us,A}$	$R^{00,L}_{us,V}$	$R^{00,L}_{ud,A}$
Theory:	-0.144 ± 0.024	-0.028 ± 0.021	$-(7.79 \pm 0.14) \cdot 10^{-3}$
Phenom:	-0.135 ± 0.003	-0.028 ± 0.004	$-(7.77 \pm 0.08) \cdot 10^{-3}$

$\rightarrow$ Theory uncertainty much reduced using phenomenology for the $J = L$ component in δR_τ

2.4. Results

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

Theoretically determined: **OPE** $(L+T)$+ **phenomenology** (L)

E.G., Jamin, Pich, Prades, Schwab (between two more recent estimates, **E.G., Jamin, Pich, Prades, Schwab**, 0709.0282, **Maltman**, 1011.6391)

$$\delta R_{\tau,th} = (\underbrace{0.1544 \pm 0.0037}_{\text{L}}) + \underbrace{(9.3 \pm 3.4) m_s^2(\overline{MS}, 2\ \text{GeV})}_{\text{L+T, D=2}} + (0.0034 \pm 0.0028)$$

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Experimental data **HFAG 2012**:

$$R_{\tau,V+A} = 3.4671 \pm 0.0084 \qquad R_{\tau,S} = 0.1612 \pm 0.0028$$

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Other inputs:

* $|V_{ud}| = 0.97425 \pm 0.0022$ **Hardy and Towner** 2008

* $m_s(2\ \text{GeV}) = 93.4 \pm 1.1$ (lattice average from **Laiho, Lunghi, Van de Water**)

2.4. Results

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$$\Longrightarrow \qquad \boxed{|V_{us}| = 0.2173 \pm 0.0020_{\mathrm{exp}} \pm 0.0010_{\mathrm{th}}}$$

3. $|V_{us}|$ from $\tau \to K\pi\nu$

Alternative way of extracting $|V_{us}|$ using $\Gamma(\tau \to K\pi\nu)$ **E. Passemar**, talk at TAU12, work in progress, **Antonelli, Banerjee, Cirigliano, Lusiani, Passemar**

$$\Gamma(\tau \to K\pi\nu) = N\,|f_+(0)V_{us}|^2\, I_K^\tau \quad \text{with} \quad I_K^\tau = \int ds\, F(s, \bar{f}_+(s), \bar{f}_0(s))$$

where the form factors $f_+(s)$ and $f_0(s)$ are the same as in $K \to \pi l\nu$.

* Parametrize $f_{+,0}$ using dispersion relations **Bernard, Boito, Passemar** (in progress) and fit to K_{l3} and $\tau \to K\pi\nu$ data $\to$ constraints from different energy regions

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* Using new Belle data for $B(\tau \to K\pi\nu)$ (**S. Ryu's**, talk at TAU12)

$$|f_+(0)V_{us}| = 0.2140 \pm 0.0041_{I_k^\tau} \pm 0.0031_{exp}$$

and the lattice average $f_+(0)^{lattice} = 0.9584 \pm 0.0044$, **Laiho, Lunghi, Van de Water**, see **A. Juettner's** talk

$$\boxed{|V_{us}| = 0.2233 \pm 0.0055}$$

Not competitive with other methods yet but it can be an interesting check to the extraction from $Kl3$ and inclusive τ decays

3. $|V_{us}|$ from $\tau \to K\pi\nu$

A sizeable fraction of the strange branching ratio is due to the decay $\tau \to K\nu_\tau$, which can be predicted theoretically with smaller errors than the direct experimental measurements

* From $B(K \to \mu\nu_\mu(\gamma))$ **Decker and Finkemeier**, NPB438, PLB334 $\to$
  $B(\tau \to K\nu_\tau) = (0.715 \pm 0.004) \cdot 10^{-2}$ **Davier, Höcker, Zhang**, 0507078

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Several branching fractions can be predicted using form factors obtained by fitting to K_{l3} and $\tau \to K\pi\nu$ data and Kaon BR's very precisely measured **E. Passemar** TAU12

Branching fraction	HFAG Winter 2012 fit	Theory prediction **Preliminary**
$\Gamma_{10} = K^-\nu_\tau$	$(0.6955 \pm 0.0096) \cdot 10^{-2}$	$(0.713 \pm 0.003) \cdot 10^{-2}$
$\Gamma_{16} = K^-\pi^0\nu_\tau$	$(0.4322 \pm 0.0149) \cdot 10^{-2}$	$(0.4473 \pm 0.0244) \cdot 10^{-2}$
$\Gamma_{35} = \pi^-\bar{K}^0\nu_\tau$	$(0.8206 \pm 0.0182) \cdot 10^{-2}$	$(0.8627 \pm 0.0353) \cdot 10^{-2}$
$\Gamma_{110} = X_s^-\nu_\tau$	$(2.8746 \pm 0.0498) \cdot 10^{-2}$	$(2.9496 \pm 0.0571) \cdot 10^{-2}$

Preliminary, using only Belle $\tau \to K\pi\nu$ data in the form factors fits.

3. $|V_{us}|$ from $\tau \to K\pi\nu$

Shift in $R_{\tau,S}$, and then in $|V_{us}|$ from inclusive τ decays.

$$|V_{us}| = 0.2173 \pm 0.0022 \qquad \to \qquad |V_{us}| = 0.2203 \pm 0.0025$$

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$$|V_{us}| = 0.2173 \pm 0.0022 \qquad \to \qquad |V_{us}| = 0.2203 \pm 0.0025$$

PDG2012: "Eighteen of the 20 B-factory branching fraction measurements are smaller than the non-B-factory values. The average normalized difference between the two sets of measurements is -1.30(-1.41 for the 11 Belle measurements and -1.24 for the 9 BaBar measurements)"

Missing modes?

4. $|V_{us}|$ from exclusive $B(\tau \to K\nu)/B(\tau \to \pi\nu)$ and $B(\tau \to K\nu)$

$|V_{us}|$ can be extracted from the ratio:

$$\frac{B(\tau \to K\nu)}{B(\tau \to \pi\nu)} = \frac{f_K^2 |V_{us}|^2 (1 - m_K^2/m_\tau^2)^2}{f_\pi^2 |V_{ud}|^2 (1 - m_\pi^2/m_\tau^2)^2} \frac{r_{LD}(\tau^- \to K^- \nu_\tau)}{r_{LD}(\tau^- \to \pi^- \nu_\tau)}$$

where r_{LD} corresponds to the long-distance EW radiative correction, see **HFAG2012**, 1207.1158.

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* Using **HFAG2012**: $r_{LD}(\tau^- \to K^- \nu_\tau)/r_{LD}(\tau^- \to \pi^- \nu_\tau) = 1.0003 \pm 0.0044$, $B(\tau \to K\nu)/B(\tau \to \pi\nu) = 0.0643 \pm 0.0009$

* $|V_{ud}| = 0.97425 \pm 0.0022$ from **Hardy and Towner** 2008

* and the lattice average $f_K/f_\pi = 1.1936 \pm 0.0053$, see **J. Laiho's** talk

$$\boxed{|V_{us}|_{\tau K\pi} = 0.2229 \pm 0.0021}$$

4. $|V_{us}|$ from exclusive $B(\tau \to K\nu)/B(\tau \to \pi\nu)$ and $B(\tau \to K\nu)$

$|V_{us}|$ can also be extracted from:

$$B(\tau \to K\nu) = \frac{G_F^2 f_K^2 |V_{us}|^2 m_\tau^3 \tau_\tau}{16\pi\hbar} \left(1 - \frac{m_K^2}{m_\tau^2}\right) S_{EW}$$

* Using again HFAG2012 averages for exp. quantities
* and the lattice average $f_K = (156.1 \pm 1.1)\ \mathrm{MeV}$, see **Laiho, Lunghi, Van de Water**

$$\boxed{|V_{us}|_{\tau K} = 0.2214 \pm 0.0022}$$

4. $|V_{us}|$ from exclusive $B(\tau \to K\nu)/B(\tau \to \pi\nu)$ and $B(\tau \to K\nu)$

$|V_{us}|$ can also be extracted from:

$$B(\tau \to K\nu) = \frac{G_F^2 f_K^2 |V_{us}|^2 m_\tau^3 \tau_\tau}{16\pi\hbar}\left(1 - \frac{m_K^2}{m_\tau^2}\right) S_{EW}$$

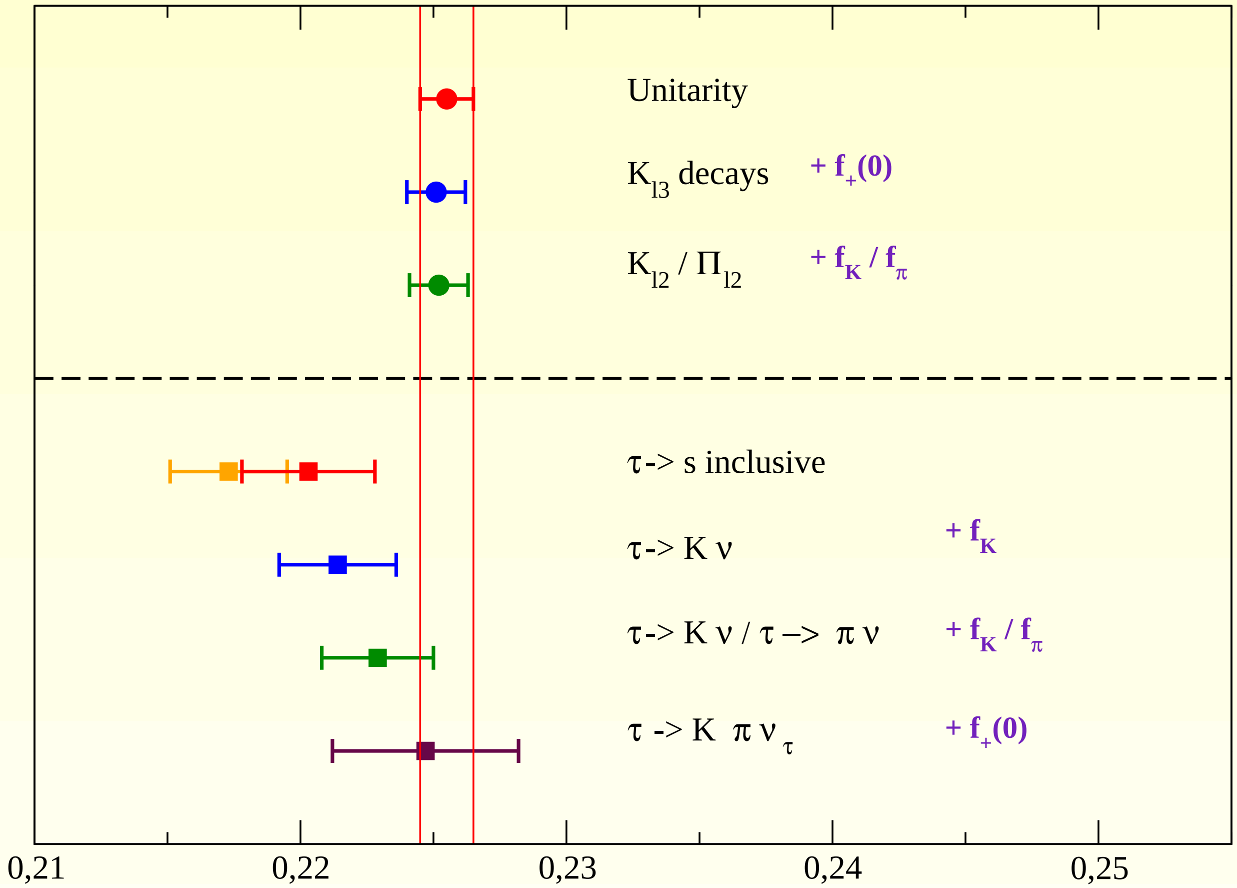
* Using again **HFAG2012** averages for exp. quantities
* and the lattice average $f_K = (156.1 \pm 1.1)\ \mathrm{MeV}$, see **Laiho, Lunghi, Van de Water**

$$\boxed{|V_{us}|_{\tau K} = 0.2214 \pm 0.0022}$$

(Using instead the theory prediction from
Antonelli, Banerjee, Cirigliano, Luisiani, Passemar for $B(\tau \to K\nu_\tau)$)

($|V_{us}|_{\tau K} = 0.2242 \pm 0.0016$ **Preliminary**)

5. Summary of results and conclusions



From inclusive Cabibbo-suppressed hadronic τ decays:

$|V_{us}| = 0.2173 \pm 0.0020_{exp} \pm 0.0010_{th}$

Error is dominated by experiment $\rightarrow$ potential to be the most precise determination of $|V_{us}|$

5. Summary of results and conclusions

Need experimental improvement: BaBar, Belle, Belle II, SuperB,
see I. Nugent's talk

* Systematic uncertainties now greatly exceed the statistical uncertainties.

Some questions that remain to be studied.

* Branching fractions from B-factories systematically smaller than previous measurements.