HFAG tau lepton averages

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(on behalf of the **HFAG-Tau group**)

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Tau Lepton Physics

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HFAG-Tau sub-group

- since 2008, the Heavy Flavor Averaging Group (HFAG) includes a Tau sub-group
- mandate
  - compute tau world averages
  - more up-to-date and refined than PDG
  - make best use of often systematic-dominated B-factories' results
- members
  - Swagato Banerjee (Univ. of Victoria, BaBar)
  - Kiyoshi Hayasaka (Nagoya University, Belle)
  - Hisaki Hayashii (Nara Women's University, Belle)
  - Alberto Lusiani (Scuola Normale Superiore and INFN, Pisa, BaBar), convener
  - J. Michael Roney (Univ. of Victoria, BaBar)
  - Boris Shwartz (Budker Institute of Nuclear Physics, Belle)
- `http://www.slac.stanford.edu/xorg/hfag/org/index.html`

HFAG-Tau averages and derived elaborations

- tau branching fractions fit producing also a correlation matrix
  - lepton universality tests
  - universality improved $B(\tau \to e\nu\overline{\nu})$ and R^{τ}_{had}
  - $|V_{us}|$
- tau mass
- compilation of tau LFV upper limits

Averaging procedures

- use available published and recent preliminary results
  - preliminary results older than 2 years are typically dropped
- report on arXiv every ~ 2 years, last report: **Early 2012**
- intermediate yearly or conference based web updates
- goal: avoid PDG-style error scale factors taking better account of
  - statistical and systematic correlations between different results
  - dependencs on common external parameters (e.g. tau pair cross-section)
- quote a confidence level rather than an error scale factor

HFAG-Tau reports

- **Summer 2010** HFAG, arXiv:1010.1589v3 [hep-ex],
  D. Asner et al., "Averages of b-hadron, c-hadron, and tau-lepton Properties"
  - 12 *BABAR* and 10 Belle measurement added to 124 former measurements in PDG
  - 3 $|V_{us}|$ fits, lepton universality tests
- **Summer 2011** HFAG-tau, intermediate web-only,
  `http://www.slac.stanford.edu/xorg/hfag/tau/summer-2011/`
  - drop old ALEPH and CLEO $B(\tau^- \to K^-\eta\nu_\tau)$ measurements
  - add new *BABAR* $B(\tau^- \to K^-\eta\nu_\tau)$ measurement
  - implemented M.Davier comments to 1st report
    - added ALEPH: $B(\tau^- \to \pi^- K^0 \overline{K}^0 \nu_\tau)$ and $B(\tau^- \to \pi^- K^0 \overline{K}^0 \pi^0 \nu_\tau)$ N
    - added ALEPH estimate of $B(\tau^- \to a_1^-(\to \pi^-\gamma)\nu_\tau)$ N

HFAG-Tau reports (2)

- **Early 2012** HFAG, arXiv:1207.1158v1 [hep-ex],
  Y. Amhis et al., “Averages of b-hadron, c-hadron, and tau-lepton properties as of early 2012”
  http://www.slac.stanford.edu/xorg/hfag/tau/winter-2012/index.html
  - updated external parameters to PDG 2012
  - added Belle $B(\tau^- \to \pi^- \overline{K}^0 \pi^0 \nu_\tau)$ and $B(\tau^- \to K^- \pi^0 K^0 \nu_\tau)$ **new prelim. results**
  - published used measurements, constraints, results correlation
  - one global $|V_{us}|_\tau$ fit combining 3 fits

collaboration	measurements	collaboration	measurements	collaboration	measurements
ALEPH	39	ARGUS	2	BaBar	15
Belle	12	CELLO	1	CLEO	35
CLEO3	6	DELPHI	14	HRS	2
L3	11	OPAL	19	TPC	3

Tau Branching Fractions Fit

- 157 measurements, 46 constraint equations
- fit 85 quantities: 39 BRs, 46 ratios of linear combinations of BR
- χ^2/d.o.f. = 143.5/118, CL = 5.5%
- no unitarity constraint (reduce "pollution" from hadronic to leptonic modes)
- 5.44 error scale factor for inconsistent *BABAR* and Belle $B(\tau^- \to K^- K^- K^+ \nu_\tau)$
- consistent with unitarity, per mill precision, residual = (0.0704 ± 0.1060)%

BR fit, leptonic branching fractions

$\Gamma_5 = B(\tau^- \to e^- \overline{\nu}_e \nu_\tau)$	$(17.818 \pm 0.041) \cdot 10^{-2}$	HFAG	Winter 2012 fit
	$(17.837 \pm 0.080 \pm 0.000) \cdot 10^{-2}$	ALEPH	Schael:2005am
	$(17.760 \pm 0.180 \pm 0.000) \cdot 10^{-2}$	CLEO	Anastassov:1996tc
	$(17.877 \pm 0.155 \pm 0.000) \cdot 10^{-2}$	DELPHI	Abreu:1999rb
	$(17.806 \pm 0.129 \pm 0.000) \cdot 10^{-2}$	L3	Acciarri:2001sg
	$(17.810 \pm 0.108 \pm 0.000) \cdot 10^{-2}$	OPAL	Abbiendi:1998cx
$\Gamma_3 = B(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)$	$(17.392 \pm 0.040) \cdot 10^{-2}$	HFAG	Winter 2012 fit
	$(17.319 \pm 0.077 \pm 0.000) \cdot 10^{-2}$	ALEPH	Schael:2005am
	$(17.325 \pm 0.122 \pm 0.000) \cdot 10^{-2}$	DELPHI	Abreu:1999rb
	$(17.342 \pm 0.129 \pm 0.000) \cdot 10^{-2}$	L3	Acciarri:2001sg
	$(17.340 \pm 0.108 \pm 0.000) \cdot 10^{-2}$	OPAL	Abbiendi:2002jw
$\frac{\Gamma_3}{\Gamma_5} = \frac{B(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \overline{\nu}_e \nu_\tau)}$	0.9761 ± 0.0028	HFAG	Winter 2012 fit
	$0.9970 \pm 0.0532 \pm 0.0000$	ARGUS	Albrecht:1991rh
	$0.9789 \pm 0.0039 \pm 0.0003$	*BaBar*	Aubert:2009qj
	$0.9777 \pm 0.0107 \pm 0.0000$	CLEO	Anastassov:1996tc
	0.972559 ± 0.000008	theory	

BR Fit: unitarity constraint branching fractions

BR	HFAG fit
$\mu^- \overline{\nu}_\mu \nu_\tau$	$(17.3916 \pm 0.0396)\%$
$e^- \overline{\nu}_e \nu_\tau$	$(17.8182 \pm 0.0409)\%$
$\pi^- \nu_\tau$	$(10.8112 \pm 0.0527)\%$
$K^- \nu_\tau$	$(0.6955 \pm 0.0096)\%$
$\pi^- \pi^0 \nu_\tau$	$(25.5040 \pm 0.0917)\%$
$K^- \pi^0 \nu_\tau$	$(0.4322 \pm 0.0149)\%$
$\pi^- 2\pi^0 \nu_\tau$ (ex. K^0)	$(9.2414 \pm 0.0997)\%$
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	$(0.0630 \pm 0.0222)\%$
$\pi^- 3\pi^0 \nu_\tau$ (ex. K^0)	$(1.0322 \pm 0.0749)\%$
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	$(0.0419 \pm 0.0218)\%$
$h^- 4\pi^0 \nu_\tau$ (ex. K^0, η)	$(0.1091 \pm 0.0391)\%$
$\pi^- \overline{K}^0 \nu_\tau$	$(0.8206 \pm 0.0182)\%$
$K^- K^0 \nu_\tau$	$(0.1591 \pm 0.0157)\%$
$\pi^- \overline{K}^0 \pi^0 \nu_\tau$	$(0.3649 \pm 0.0108)\%$
$K^- \pi^0 K^0 \nu_\tau$	$(0.1450 \pm 0.0071)\%$
$\pi^- \overline{K}^0 \pi^0 \pi^0 \nu_\tau$	$(0.0269 \pm 0.0230)\%$
$\pi^- K^0_S K^0_S \nu_\tau$	$(0.0240 \pm 0.0050)\%$
$\pi^- K^0_S K^0_L \nu_\tau$	$(0.1082 \pm 0.0203)\%$
$\pi^- K^0 \overline{K}^0 \pi^0 \nu_\tau$	$(0.0310 \pm 0.0230)\%$
$\overline{K}^0 h^- h^- h^+ \nu_\tau$	$(0.0222 \pm 0.0202)\%$

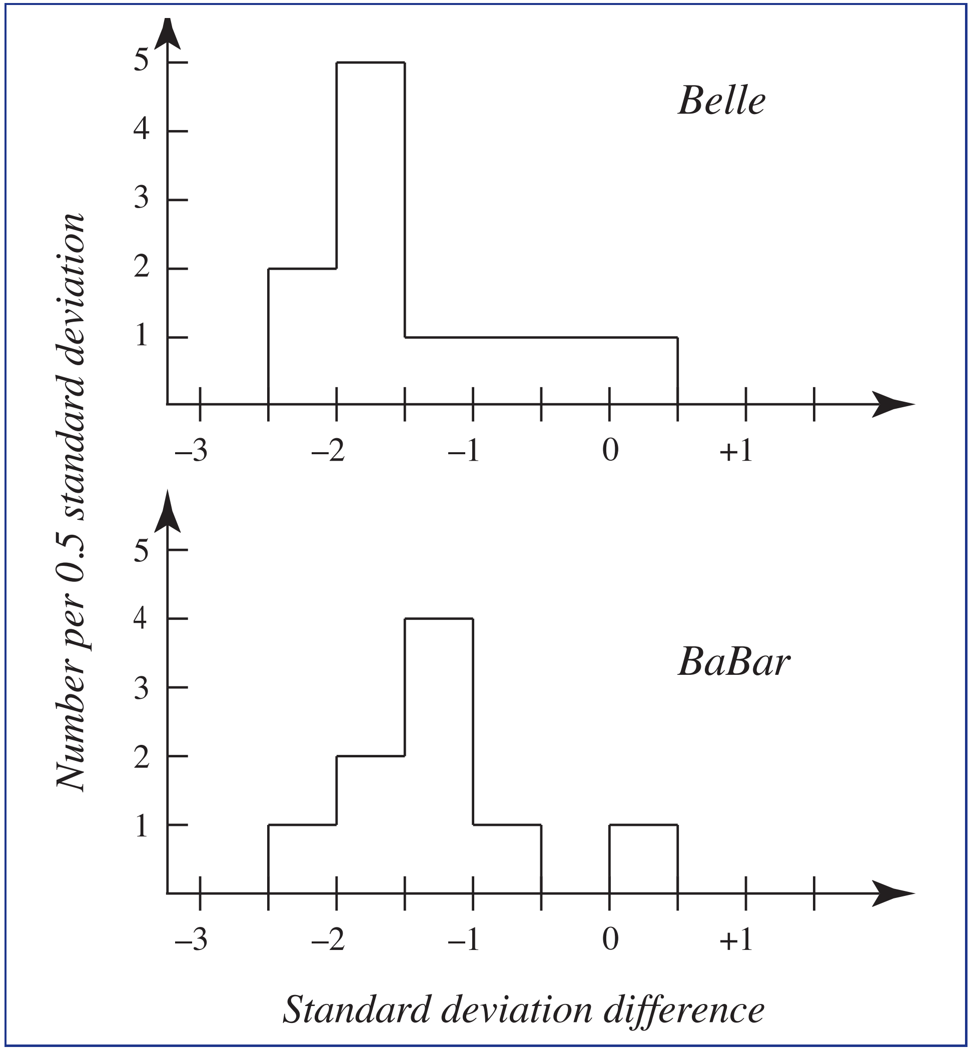
BR	HFAG fit
$\pi^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	$(8.9719 \pm 0.0511)\%$
$\pi^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω)	$(2.7659 \pm 0.0710)\%$
$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex. K^0, ω, η)	$(0.0973 \pm 0.0354)\%$
$h^- h^- h^+ 3\pi^0 \nu_\tau$	$(0.0320 \pm 0.0031)\%$
$\pi^- K^- K^+ \nu_\tau$	$(0.1435 \pm 0.0027)\%$
$\pi^- K^- K^+ \pi^0 \nu_\tau$	$(0.0061 \pm 0.0018)\%$
$3h^- 2h^+ \nu_\tau$ (ex. K^0)	$(0.0823 \pm 0.0031)\%$
$3h^- 2h^+ \pi^0 \nu_\tau$ (ex. K^0)	$(0.0198 \pm 0.0024)\%$
$\pi^- \pi^0 \eta \nu_\tau$	$(0.1386 \pm 0.0072)\%$
$K^- \eta \nu_\tau$	$(0.0153 \pm 0.0008)\%$
$K^- \pi^0 \eta \nu_\tau$	$(0.0048 \pm 0.0012)\%$
$\pi^- \overline{K}^0 \eta \nu_\tau$	$(0.0094 \pm 0.0015)\%$
$K^- \omega \nu_\tau$	$(0.0410 \pm 0.0092)\%$
$h^- \pi^0 \omega \nu_\tau$	$(0.4049 \pm 0.0418)\%$
$\pi^- \omega \nu_\tau$	$(1.9535 \pm 0.0647)\%$
$K^- \phi \nu_\tau (\phi \to KK)$	$(0.0037 \pm 0.0014)\%$
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	$(0.2923 \pm 0.0068)\%$
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	$(0.0411 \pm 0.0143)\%$
$\pi^- K^0_L K^0_L \nu_\tau$	$(0.0240 \pm 0.0050)\%$
$a_1^- (\to \pi^- \gamma) \nu_\tau$	$(0.0400 \pm 0.0200)\%$
Unitarity residual	$(0.0704 \pm 0.1060)\%$

The HFAG fit includes more BRs than PDG in the unitarity constraint

BR	PDG 2012	HFAG 2012	HFAG planned
$\pi^- K^0 \overline{K}^0 \pi^0 \nu_\tau$	no	yes	new measurements
$K^- K^- K^+ \nu_\tau$	no	yes	yes
$K^- \pi^0 \eta \nu_\tau$	no	yes	yes
$\pi^- \overline{K}^0 \eta \nu_\tau$	no	yes	yes

- several other measurements, especially involving resonances, cannot be used but are represented by inclusive measurements (see PDG 2012 review on tau BRs)
- a recently submitted *BABAR* paper, `http://arxiv.org/abs/1209.2734`, measuring several high multiplicity BR on both the resonant and non-resonant contributions will permit adding several such measurements

B-factories measure on average lower BRs



PDG 2012 review

- -1.30σ *BABAR* (9 measurements)
- -1.41σ Belle (11 measurements)

BABAR vs. Belle discrepancies from PDG 2012 review

mode	*BABAR* – Belle in σ
$\pi^-\pi^-\pi^+\nu_\tau$ (ex.K^0)	+1.4
$K^-\pi^-\pi^+\nu_\tau$ (ex.K^0)	–2.9
$\pi^-K^-K^+\nu_\tau$	–2.9
$K^-K^-K^+\nu_\tau$	–5.4
$K^-\eta\nu_\tau$	–1.0
$\tau \to \phi K \nu$	–1.3

Lepton Universality tests

Standard Model (Marciano 1988):

$$\Gamma(L \to \nu_L \ell \overline{\nu}_\ell(\gamma)) = \frac{B(L \to \nu_L \ell \overline{\nu}_\ell)}{\tau_L} = \frac{G_L G_\ell m_L^5}{192\pi^3} f\left(\frac{m_\ell^2}{m_L^2}\right) r_W^L r_\gamma^L ,$$

where

$$G_\ell = \frac{g_\ell^2}{4\sqrt{2}M_W^2} \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

$$r_W^L = 1 + \frac{3}{5}\frac{m_L^2}{M_W^2} \qquad r_\gamma^L = 1 + \frac{\alpha(m_L)}{2\pi}\left(\frac{25}{4} - \pi^2\right)$$

Using: $r_\gamma^\tau = 1 - 43.2 \cdot 10^{-4}$ and $r_\gamma^\mu = 1 - 42.4 \cdot 10^{-4}$ (Marciano 1988), M_W from PDG 2011

Proper ratios of the above partial widths:

$$\left(\frac{g_\tau}{g_\mu}\right) = 1.0006 \pm 0.0021 , \qquad \left(\frac{g_\tau}{g_e}\right) = 1.0024 \pm 0.0021 , \qquad \left(\frac{g_\mu}{g_e}\right) = 1.0018 \pm 0.0014 .$$

- no significant change with respect to the Summer 2010 report (no significant new measurement)

Lepton Universality tests (2)

Standard Model:

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{B(\tau \to h\nu_\tau)}{B(h \to \mu\overline{\nu}_\mu)} \frac{2m_h m_\mu^2 \tau_h}{(1+\delta_h) m_\tau^3 \tau_\tau} \left(\frac{1 - m_\mu^2/m_h^2}{1 - m_h^2/m_\tau^2}\right)^2 \qquad (h = \pi \text{ or } K)$$

rad. corr. $\delta_\pi = (0.16 \pm 0.14)\%$, $\delta_K = (0.90 \pm 0.22)\%$ (Decker 1994)

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9956 \pm 0.0031 , \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9852 \pm 0.0072 .$$

electron tests less precise because hadron two body decays to electrons are helicity-suppressed

Averaging the three g_τ/g_μ ratios:

$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 0.9996 \pm 0.0020 ,$$

accounting for statistical correlations.

♦ no significant change with respect to the Summer 2010 report (no significant new measurement)

Universality improved $B(\tau \to e\nu\bar{\nu})$ and R_{had}

- (Davier 2005): assume lepton universality to improve $B_e = B(\tau \to e\bar{\nu}_e\nu_\tau)$
  - $B_e = B_\mu \cdot f(m_e^2/m_\tau^2)/f(m_\mu^2/m_\tau^2)$
  - $B_e = B(\mu \to e\bar{\nu}_e\nu_\mu) \cdot (\tau_\tau/\tau_\mu) \cdot (m_\tau/m_\mu)^5 \cdot f(m_e^2/m_\tau^2)/f(m_e^2/m_\mu^2) \cdot (\delta_\gamma^\tau\delta_W^\tau)/(\delta_\gamma^\mu\delta_W^\mu)$
    $(B(\mu \to e\bar{\nu}_e\nu_\mu) = 1)$
- HGAG-Tau early 2012 report:
  - $B_e^{\text{univ}} = (17.839 \pm 0.028)\%$
  - $R_{\text{had}} = \frac{\Gamma(\tau\to\text{hadrons})}{\Gamma(\tau\to e\nu\bar{\nu})} = 3.6280 \pm 0.0094$

$|V_{us}|$ from inclusive tau partial width to strange

$$|V_{us}| = \sqrt{R_s / \left[\frac{R_{VA}}{|V_{ud}|^2} - \delta R_{\text{theory}} \right]}; \quad R_i = \frac{\Gamma_i}{\Gamma_e^{\text{univ}}} = \frac{B_i}{B_e^{\text{univ}}}; \quad R_{\text{had}} = R_s + R_{VA};$$

- $\delta R_{\text{theory}} = 0.240 \pm 0.032$ (Gamiz et al 2006) QCD sum rules & scattering data
  - uncertainty between two more recent estimates (Gamiz 2007, Maltman 2010)
- $|V_{ud}| = 0.97425 \pm 0.00022$ (Hardy & Towner 2008)
- often $\boldsymbol{B_{\text{had}} = 1 - B_e - B_\mu}$ (or similar expressions based on B_e^{univ})
- HGAG-Tau 2012: B_{had}, B_{VA} directly from hadronic tau BRs (new)
  - no statistical loss (other expr. more correlated to B_e^{univ})
  - R_{VA} will not absorb effect of unobserved hadronic decay modes
- $|V_{us}|_{\tau s} = 0.2173 \pm 0.0022$ (3.4σ lower than $|V_{us}|_{\text{uni}} = \sqrt{1 - |V_{ud}|^2} = 0.2255 \pm 0.0010$)
  - $B_s = (2.875 \pm 0.050)\%$; $B_{VA} = (61.85 \pm 0.11)\%$)
  - discrepancy 3.4σ if rather using $B_{\text{had}} = 1 - B_e - B_\mu$
  - discrepancy 3.6σ HFAG Summer 2010 and HFAG Summer 2011
  - discrepancy 3.3σ Tau10 proceedings (constrained fit)

Tau branching fractions to strange final states

Branching fraction	HFAG Winter 2012 fit
$\Gamma_{10} = K^- \nu_\tau$	$(0.6955 \pm 0.0096) \cdot 10^{-2}$
$\Gamma_{16} = K^- \pi^0 \nu_\tau$	$(0.4322 \pm 0.0149) \cdot 10^{-2}$
$\Gamma_{23} = K^- 2\pi^0 \nu_\tau$ (ex. K^0)	$(0.0630 \pm 0.0222) \cdot 10^{-2}$
$\Gamma_{28} = K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	$(0.0419 \pm 0.0218) \cdot 10^{-2}$
$\Gamma_{35} = \pi^- \overline{K}^0 \nu_\tau$	$(0.8206 \pm 0.0182) \cdot 10^{-2}$
$\Gamma_{40} = \pi^- \overline{K}^0 \pi^0 \nu_\tau$	$(0.3649 \pm 0.0108) \cdot 10^{-2}$
$\Gamma_{44} = \pi^- \overline{K}^0 \pi^0 \pi^0 \nu_\tau$	$(0.0269 \pm 0.0230) \cdot 10^{-2}$
$\Gamma_{53} = \overline{K}^0 h^- h^- h^+ \nu_\tau$	$(0.0222 \pm 0.0202) \cdot 10^{-2}$
$\Gamma_{128} = K^- \eta \nu_\tau$	$(0.0153 \pm 0.0008) \cdot 10^{-2}$
$\Gamma_{130} = K^- \pi^0 \eta \nu_\tau$	$(0.0048 \pm 0.0012) \cdot 10^{-2}$
$\Gamma_{132} = \pi^- \overline{K}^0 \eta \nu_\tau$	$(0.0094 \pm 0.0015) \cdot 10^{-2}$
$\Gamma_{151} = K^- \omega \nu_\tau$	$(0.0410 \pm 0.0092) \cdot 10^{-2}$
$\Gamma_{801} = K^- \phi \nu_\tau (\phi \to KK)$	$(0.0037 \pm 0.0014) \cdot 10^{-2}$
$\Gamma_{802} = K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	$(0.2923 \pm 0.0068) \cdot 10^{-2}$
$\Gamma_{803} = K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	$(0.0411 \pm 0.0143) \cdot 10^{-2}$
$\Gamma_{110} = X_s^- \nu_\tau$	$(2.8746 \pm 0.0498) \cdot 10^{-2}$

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

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

- $|V_{us}|_{\tau K/\pi} = 0.2229 \pm 0.0021$ 1.1σ below CKM unitarity prediction
- details on rad. corrections in the report
- $f_K/f_\pi = 1.1936 \pm 0.0053$ Laiho, Lunghi, & Van de Water 2010, `http://www.latticeaverages.org`
  - lattice uncertainty significantly improved

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

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

- $|V_{us}|_{\tau K} = 0.2214 \pm 0.0022$ 1.7σ below CKM unitarity prediction
- details on rad. corrections in the report
- $f_K = 156.1 \pm 1.1$ MeV Laiho, Lunghi, & Van de Water 2010, `http://www.latticeaverages.org`
  - lattice uncertainty significantly improved
- using CODATA 2006

$|V_{us}|$ summary

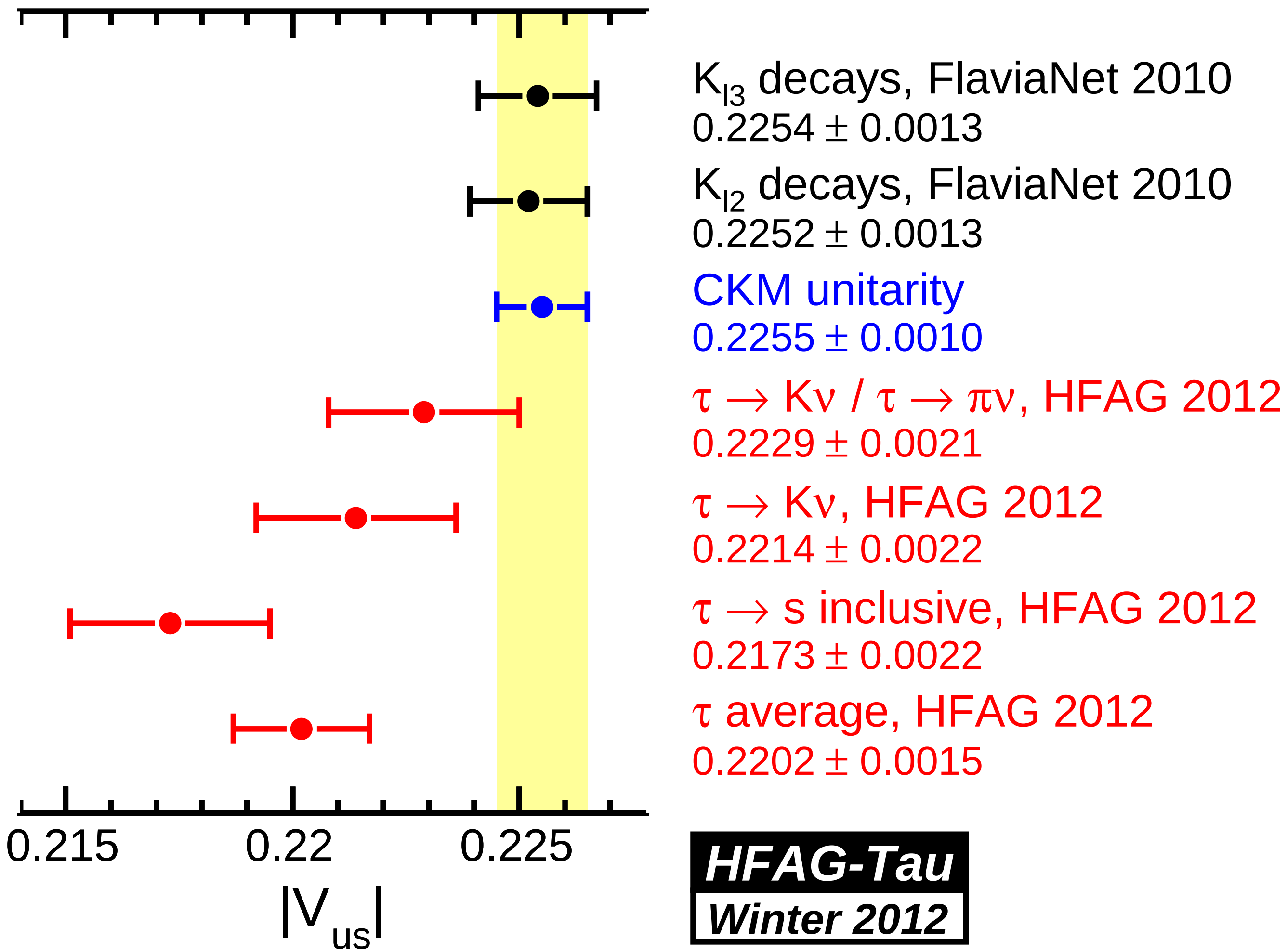
Summary of $|V_{us}|$ measurements, with discrepancies w.r.t. CKM unitarity

$$
\begin{aligned}
|V_{us}|_{\rm uni} &= 0.2255 \pm 0.0010 & & \text{from } \sqrt{1-|V_{ud}|^2} \ \text{(CKM unitarity)}\,, \\
|V_{us}|_{\tau s} &= 0.2173 \pm 0.0022 & -3.4\sigma & \text{ from } \Gamma(\tau^- \to X_s^- \nu_\tau)\,, \\
|V_{us}|_{\tau K/\pi} &= 0.2229 \pm 0.0021 & -1.1\sigma & \text{ from } \Gamma(\tau^- \to K^- \nu_\tau)/\Gamma(\tau^- \to \pi^- \nu_\tau)\,, \\
|V_{us}|_{\tau K} &= 0.2214 \pm 0.0022 & -1.7\sigma & \text{ from } \Gamma(\tau^- \to K^- \nu_\tau)\,.
\end{aligned}
$$

averaging the three $|V_{us}|$ tau determinations

- $|V_{us}|_\tau = 0.2202 \pm 0.0015$ -2.9σ below CKM unitarity new
- all significant correlations included
- there is some uncertainty on the correlations of the lattice results (see report for details)
- **no significant change with respect to previous HFAG reports**

$|V_{us}|$ summary (2)



Prospects

- include several *BABAR* results submitted just before Tau 2012
  - arXiv:1208.0376 [hep-ex], The branching fraction of $\tau \to \pi^- K^0_S K^0_S (\pi^0) \nu$ decays
  - arXiv:1209.2734 [hep-ex], Study of high-multiplicity 3-prong and 5-prong tau decays at *BABAR*
- include any other new result from Tau 2012 and later (also mass and lifetime)
- *BABAR* will eventually release complex study of $\tau \to K n\pi^0 \nu$, $n = 0–3$ → report to update $|V_{us}|$