Status and progress of the HFLAV-Tau group activities

Alberto Lusiani

Scuola Normale Superiore and INFN, sezione di Pisa

Outline

HFLAV Tau sub-group
(HFLAV = Heavy Heavy Flavour Averaging Group)
(new acronym since 2017)

- Tau sub-group established since 2008, http://www.slac.stanford.edu/xorg/hflav/tau/

membership

BABAR
- Swagato Banerjee (Victoria $\rightarrow$ Louisville)
- A. L. (convener)
- J. Michael Roney (Victoria)

Belle
- Kiyoshi Hayasaka (Nagoya $\rightarrow$ Niigata)
- Hisaki Hayashii (Nara)
- Boris Shwartz (Budker)

LHCb
- Marcin Chrząszcz (Zürich / Cracow) (since 2014)

Introduction

HFLAV-Tau goals

- provide up-to-date tau lepton properties world averages
  (especially when one can improve over PDG standard averages)
- exploit at best all relevant experimental information
- provide some useful elaborations of tau data
  (*e.g.*, charged weak current lepton universality, $|V_{us}|$ computed from tau data)

recent history

2014
- summer 2014 HFLAV report (arXiv preprint)

2016
- summer 2016 HFLAV report (arXiv preprint)
- PDG tau branching fraction fit provided by HFLAV-Tau group since 2016
- PDG tau BRs mini-review since 2016 co-authored by 2 HFLAV members

2017
- acronym changed from HFAG to HFLAV
- spring 2017 HFLAV report submitted for refereed publication
  - very minor refinements w.r.t. summer 2016 release

Tau Branching Fractions Fit

HFLAV Tau Branching Fraction Fit Features

- use published statistical and systematic correlations
- aim to avoid error scale factors as used by PDG, including relevant systematic effects
- global minimum χ^2 fit using constraint equations (see later)

systematic dependencies of results from external parameters

- experimental measurements typically depend on external parameters [*e.g.*, $\sigma(e^+e^- \to \tau^+\tau^-)$, η and ω branching fractions, other τ branching fractions]
- identify dependencies from external parameters, typically from systematics tables
- update results values and uncertainties according to updates of external parameters

common systematics across different experimental results

- two or more results may depend on the same external parameters (also across different publications and different experiments) *e.g.*: may depend on estimated integrated luminosity, $\sigma(e^+e^- \to \tau^+\tau^-)$
- account for statistical correlations induced by common systematics

HFLAV Tau Branching Fraction Fit Features (2)

example of constraint equations

- $\mathcal{B}(\tau \to h\nu) = \mathcal{B}(\tau \to \pi\nu) + \mathcal{B}(\tau \to K\nu) \qquad (h = \pi, K)$
- $\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-\nu) = \mathcal{B}[\tau^- \to \pi^-\pi^+\pi^-\nu \text{ (ex. } K_S \to \pi^+\pi^-)] + \mathcal{B}(\tau^- \to \pi^- K_S \nu) \cdot \mathcal{B}(K_S \to \pi^+\pi^-)$
- $\left[\dfrac{\mathcal{B}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{B}(\tau \to e\bar{\nu}\nu)}\right] = \dfrac{[\mathcal{B}(\tau \to \mu\bar{\nu}\nu)]}{[\mathcal{B}(\tau \to e\bar{\nu}\nu)]}$
- unitarity constraint (not used for HFLAV-Tau fit, used for PDG BR fits)

properties of PDG fit before 2016 that differ from HFLAV fit

- unitarity constraint
- does not usually consider effects of external parameters dependencies
- uses error scale factors (complex procedure used for scale factors in global fit)

Main Changes from 2014 to 2016-2017

- no new experimental input (there were several in the 2014 report)
- removed two old preliminary results
  - $\Gamma_{35} = \mathcal{B}(\tau \to \pi K^0_S \nu)$, *BABAR*, ICHEP 2008
  - $\Gamma_{40} = \mathcal{B}(\tau \to \pi K^0_S \pi^0 \nu)$, *BABAR*, DPF 2009
- removed result $\mathcal{B}[\tau \to K^0_S(\text{particles})^-]$, Belle, 2014
  - information in the paper does not allow computing consistent correlations with the other esclusive results in the same paper; the 2014 report included some inconsistent estimate, which made the results covariance matrix negative-definite
- ALEPH 1998 Γ_{46} $(\tau^- \to \pi^- K^0 \bar{K}^0 \nu_\tau)$ has been removed because 100% correlated with other esclusive results
- several minor constraint imperfections were fixed
- all fixes have negligible effects on $|V_{us}|$, lepton-universality tests, ...

Tau Branching Fractions Fit results

- 170 measurements, 88 constraint equations
- fit 135 quantities: 47 BRs, 88 derived quantities (ratios of linear combinations of BRs)
- χ^2/d.o.f. $= 137/123$, CL $= 17.79\%$ (was 16.45% in 2014)
- 5.44 error scale factor for inconsistent *BABAR* and Belle $\mathcal{B}(\tau^- \to K^- K^- K^+ \nu_\tau)$ as in 2014
- consistent with unitarity within 0.1% uncertainty, residual $= (0.03 \pm 0.10)\%$

2016 fit inputs results by experiment

experiment	number of results
ALEPH	39
CLEO	35
BaBar	23
OPAL	19
Belle	15
DELPHI	14
L3	11
CLEO3	6
TPC	3
ARGUS	2
HRS	2
CELLO	1

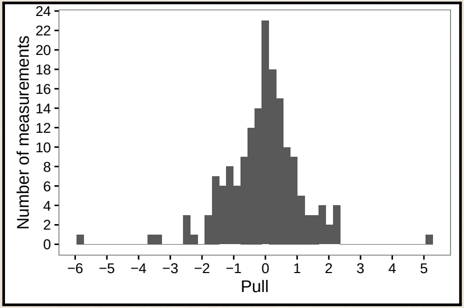
HFLAV spring 2017 basis modes

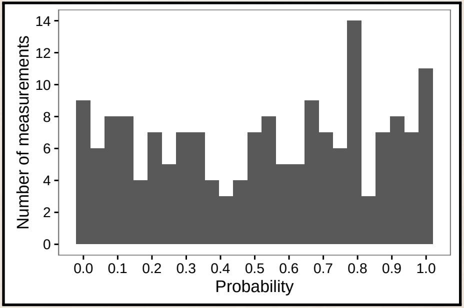
B $(\tau \to \ldots)$	HFLAV spring 2017
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.3917 ± 0.0396
$e^- \bar{\nu}_e \nu_\tau$	17.8162 ± 0.0410
$\pi^- \nu_\tau$	10.8103 ± 0.0526
$K^- \nu_\tau$	0.6960 ± 0.0096
$\pi^- \pi^0 \nu_\tau$	25.5023 ± 0.0918
$K^- \pi^0 \nu_\tau$	0.4327 ± 0.0149
$\pi^- 2\pi^0 \nu_\tau$ (ex. K^0)	9.2424 ± 0.0997
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.0640 ± 0.0220
$\pi^- 3\pi^0 \nu_\tau$ (ex. K^0)	1.0287 ± 0.0749
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.0428 ± 0.0216
$h^- 4\pi^0 \nu_\tau$ (ex. K^0, η)	0.1099 ± 0.0391
$\pi^- \bar{K}^0 \nu_\tau$	0.8386 ± 0.0141
$K^- K^0 \nu_\tau$	0.1479 ± 0.0053
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.3812 ± 0.0129
$K^- \pi^0 K^0 \nu_\tau$	0.1502 ± 0.0071
$\pi^- \bar{K}^0 \pi^0 \pi^0 \nu_\tau$ (ex. K^0)	0.0234 ± 0.0231
$\pi^- K^0_S K^0_S \nu_\tau$	0.0233 ± 0.0007
$\pi^- K^0_S K^0_L \nu_\tau$	0.1047 ± 0.0247
$\pi^- \pi^0 K^0_S K^0_S \nu_\tau$	0.0018 ± 0.0002
$\pi^- \pi^0 K^0_S K^0_L \nu_\tau$	0.0318 ± 0.0119
$\bar{K}^0 h^- h^- h^+ \nu_\tau$	0.0222 ± 0.0202
$\pi^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	8.9704 ± 0.0515
$\pi^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω)	2.7694 ± 0.0711
$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.0976 ± 0.0355

B $(\tau \to \ldots)$	HFLAV spring 2017
$\pi^- K^- K^+ \nu_\tau$	0.1434 ± 0.0027
$\pi^- K^- K^+ \pi^0 \nu_\tau$	0.0061 ± 0.0018
$\pi^- \pi^0 \eta \nu_\tau$	0.1386 ± 0.0072
$K^- \eta \nu_\tau$	0.0155 ± 0.0008
$K^- \pi^0 \eta \nu_\tau$	0.0048 ± 0.0012
$\pi^- \bar{K}^0 \eta \nu_\tau$	0.0094 ± 0.0015
$\pi^- \pi^+ \pi^- \eta \nu_\tau$ (ex. K^0)	0.0218 ± 0.0013
$K^- \omega \nu_\tau$	0.0410 ± 0.0092
$h^- \pi^0 \omega \nu_\tau$	0.4058 ± 0.0419
$K^- \phi \nu_\tau$	0.0044 ± 0.0016
$\pi^- \omega \nu_\tau$	1.9544 ± 0.0647
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	0.2923 ± 0.0067
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.0410 ± 0.0143
$a_1^- (\to \pi^- \gamma) \nu_\tau$	0.0400 ± 0.0200
$\pi^- 2\pi^0 \omega \nu_\tau$ (ex. K^0)	0.0071 ± 0.0016
$2\pi^- \pi^+ 3\pi^0 \nu_\tau$ (ex. K^0, η, ω, f_1)	0.0013 ± 0.0027
$3\pi^- 2\pi^+ \nu_\tau$ (ex. K^0, ω, f_1)	0.0768 ± 0.0030
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. K^0)	0.0001 ± 0.0001
$2\pi^- \pi^+ \omega \nu_\tau$ (ex. K^0)	0.0084 ± 0.0006
$3\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0, η, ω, f_1)	0.0038 ± 0.0009
$K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0)	0.0001 ± 0.0001
$\pi^- f_1 \nu_\tau$ $(f_1 \to 2\pi^- 2\pi^+)$	0.0052 ± 0.0004
$\pi^- 2\pi^0 \eta \nu_\tau$	0.0193 ± 0.0038
$1 - \Gamma_{\text{All}}$	0.0355 ± 0.1031

note: a linear combination sums up to 1

Measurement pulls, pulls probability - HFLAV spring 2017, no scaling



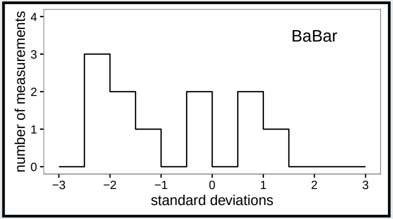


- two outliers: *BABAR* and Belle $\mathcal{B}(\tau \to K^- K^- K^+ \nu_\tau)$ results
- (pull probabilities expressed as n. of Gaussian sigma's)

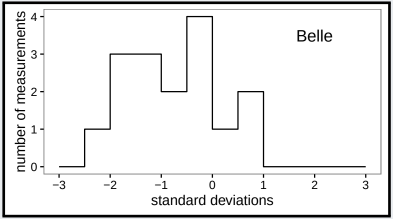
B-factories tend to measure lower BFs

- first noted in PDG tau branching fraction review
- compared fit results in the same fit framework with and without *B*-factories results

BABAR results vs. non-BF fit results



Belle results vs. non-BF fit results



Lepton Universality

Lepton universality - HFLAV spring 2017

Standard Model for leptons λ, $\rho = e, \mu, \tau$ (Marciano 1988)

$$\Gamma[\lambda \to \nu_\lambda \rho \bar{\nu}_\rho(\gamma)] = \Gamma_{\lambda\rho} = \Gamma_\lambda \mathcal{B}_{\lambda\rho} = \frac{\mathcal{B}_{\lambda\rho}}{\tau_\lambda} = \frac{G_\lambda G_\rho m_\lambda^5}{192\pi^3} f\left(m_\rho^2/m_\lambda^2\right) R_W^\lambda R_\gamma^\lambda \,,$$

$$G_\lambda = \frac{g_\lambda^2}{4\sqrt{2}M_W^2} \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \qquad f_{\lambda\rho} = f\left(m_\rho^2/m_\lambda^2\right)$$

where

$$R_W^\lambda = 1 + \frac{3}{5}\frac{m_\lambda^2}{M_W^2} + \frac{9}{5}\frac{m_\rho^2}{M_W^2} \qquad R_\gamma^\lambda = 1 + \frac{\alpha(m_\lambda)}{2\pi}\left(\frac{25}{4} - \pi^2\right)$$

Tests of lepton universality from ratios of above partial widths:

$$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^\mu}{\tau_\tau m_\tau^5 f_{\tau e} R_\gamma^\tau R_W^\tau}} = 1.0010 \pm 0.0015 = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\tau e}^{\text{SM}}}}$$

$$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^\mu}{\tau_\tau m_\tau^5 f_{\tau \mu} R_\gamma^\tau R_W^\tau}} = 1.0029 \pm 0.0015 = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau \mu}^{\text{SM}}}}$$

$$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau e}} \frac{f_{\tau e}}{f_{\tau \mu}}} = 1.0019 \pm 0.0014$$

fashionable $\sim 2\sigma$ lepton universality violation

- precision: **0.20–0.23%** pre-B-Factories $\Rightarrow$ **0.14–0.15%** today
  thanks essentially to the Belle tau lifetime measurement, PRL 112 (2014) 031801
- $R_\gamma^\tau = 1 - 43.2 \cdot 10^{-4}$ and $R_\gamma^\mu = 1 - 42.4 \cdot 10^{-4}$ (Marciano 1988), M_W from PDG 2015

Lepton Universality tests with hadron decays - HFLAV spring 2017

Standard Model:

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

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

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = \mathbf{0.9961 \pm 0.0027}\,, \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = \mathbf{0.9860 \pm 0.0070}\,.$$

fashionable $\sim 2\sigma$ lepton universality violations

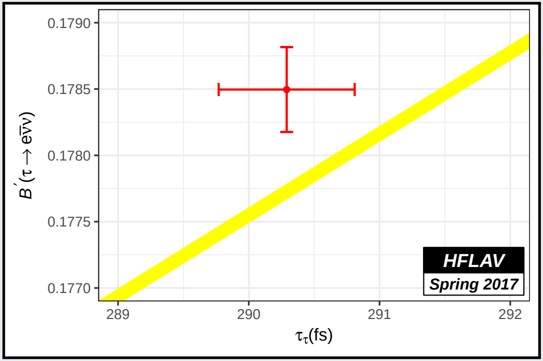
(electron tests less precise because $h \to e\nu$ decays are helicity-suppressed)

Averaging the three g_τ/g_μ ratios:

$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = \mathbf{1.0000 \pm 0.0014}\,, \qquad \text{(accounting for statistical correlations)}$$

Lepton universality - HFLAV spring 2017 (2)

Canonical tau lepton universality test plot



- $\dfrac{\Gamma(\tau \to e\bar{\nu}\nu)}{\Gamma(\mu \to e\bar{\nu}\nu)} = \dfrac{B'(\tau \to e\bar{\nu}\nu)}{B(\mu \to e\bar{\nu}\nu)} = \dfrac{\tau_\tau}{\tau_\mu} \dfrac{m_\tau^5}{m_\mu^5} \dfrac{f_{\tau e} R_\gamma^\tau R_W^\tau}{f_{\mu e} R_\gamma^\mu R_W^\mu}$
- $B'(\tau \to e\bar{\nu}\nu)$ computed averaging:
  - $\mathcal{B}_e(e) = \mathcal{B}(\tau \to e\bar{\nu}\nu)$
  - $\mathcal{B}_e(\mu) = \mathcal{B}(\tau \to \mu\bar{\nu}\nu) \cdot f_{\tau e}/f_{\tau\mu}$

inputs

PDG 2015 and HFLAV-Tau spring 2017, other details listed in HFLAV 2016 report

Universality test uncertainty now limited by leptonic BRs

input	Δinput	Δtest
τ_τ	0.090%	0.18%
$\mathcal{B}_{\tau\to\mu,e}$	0.115%	0.23%
m_τ	0.022%	0.009%

Universality improved $\mathcal{B}(\tau \to e\nu\bar{\nu})$ and R_{had} - HFLAV spring 2017

Universality improved $\mathcal{B}(\tau \to e\nu\bar{\nu})$

- (M. Davier, 2005): assume SM to improve $\mathcal{B}_e = \mathcal{B}(\tau \to e\bar{\nu}_e\nu_\tau)$ averaging:

$$\mathcal{B}_e(e) = \mathcal{B}_e, \qquad \mathcal{B}_e(\mu) = \mathcal{B}_\mu \cdot f_{\tau e}/f_{\tau\mu} \qquad \mathcal{B}_e(\tau_\tau) = \frac{\tau_\tau}{\tau_\mu}\frac{m_\tau^5}{m_\mu^5}\frac{f_{\tau e}R_\gamma^\tau R_W^\tau}{f_{\mu e}R_\gamma^\mu R_W^\mu}$$

- $\mathcal{B}_e^{\text{univ}} = (17.815 \pm 0.023)\%$ HFLAV spring 2017 fit

$R_{\text{had}} = \Gamma(\tau \to \text{hadrons})/\Gamma_{\text{univ}}(\tau \to e\nu\bar{\nu}) = \mathcal{B}(\tau \to \text{hadrons})/\mathcal{B}_{\text{univ}}(\tau \to e\nu\bar{\nu})$

- $R_{\text{had}} = \dfrac{\mathcal{B}_{\text{hadrons}}}{\mathcal{B}_e^{\text{univ}}} = 3.6349 \pm 0.0082$ HFLAV spring 2017 fit
- $R_{\text{had}}(\text{lepton univ.}) = \dfrac{1 - \mathcal{B}_e^{\text{univ}} - f_{\tau\mu}/f_{\tau e} \cdot \mathcal{B}_e^{\text{univ}}}{\mathcal{B}_e^{\text{univ}}} = 3.6406 \pm 0.0072$ HFLAV spring 2017 fit
- $R_{\text{had}}(\text{lepton only}) = \dfrac{1 - \mathcal{B}_e - \mathcal{B}_\mu}{\mathcal{B}_e^{\text{univ}}} = 3.637 \pm 0.011$ HFLAV spring 2017 fit

Determination of $|V_{us}|$ from Tau Decays

Determination of $|V_{us}|$ from experimental data

from kaon decays

- $\Gamma(K \to \pi \ell \bar{\nu}_\ell[\gamma]) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{EW}^K \left(|V_{us}| f_+^{K\pi}(0)\right)^2 I_K^\ell \left(1 + \delta_{EM}^{K\ell} + \delta_{SU(2)}^{K\pi}\right)^2$
- $\frac{\Gamma(K^\pm \to \ell^\pm \nu)}{\Gamma(\pi^\pm \to \ell^\pm \nu)} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{m_K(1 - m_\ell^2/m_K^2)^2}{m_\pi(1 - m_\ell^2/m_\pi^2)^2} (1 + \delta_{EM})$

from tau decays

- $\frac{R(\tau \to X_{\textbf{strange}})}{|V_{us}|^2} - \frac{R(\tau \to X_{\textbf{non-strange}})}{|V_{ud}|^2} = \delta R_{\tau,\textbf{SU3 breaking}}$, "$\tau \to s$ inclusive" method
  $[R(\tau \to X) = \Gamma(\tau \to X)/\Gamma(\tau \to e\nu\bar{\nu})]$
- $\frac{\mathcal{B}(\tau^- \to K^- \nu_\tau)}{\mathcal{B}(\tau^- \to \pi^- \nu_\tau)} = \frac{f_K^2 |V_{us}|^2}{f_\pi^2 |V_{ud}|^2} \frac{\left(1 - m_K^2/m_\tau^2\right)^2}{\left(1 - m_\pi^2/m_\tau^2\right)^2} \frac{r_{\textbf{LD}}(\tau^- \to K^- \nu_\tau)}{r_{\textbf{LD}}(\tau^- \to \pi^- \nu_\tau)}$
- $\Gamma(\tau \to \bar{K}\pi\nu_\tau[\gamma]) = \frac{G_F^2 m_\tau^5}{96\pi^3} C_K^2 S_{\textbf{EW}}^{\tau K\pi} \left(|V_{us}| f_+^{K\pi}(0)\right)^2 I_K^\tau \left(1 + \delta_{EM}^{K\tau} + \tilde{\delta}_{SU(2)}^{K\pi}\right)^2$

- only $\tau \to s$ inclusive method does not require form factors from lattice QCD and therefore has theory systematics uncorrelated to lattice QCD form factors

"$\tau \to s$ inclusive" $|V_{us}|$ determination

$$\frac{R(\tau \to X_{\text{strange}})}{|V_{us}|^2} - \frac{R(\tau \to X_{\text{non-strange}})}{|V_{ud}|^2} = \delta R_{\tau,\text{SU3 breaking}}$$

$\delta R_{\tau,\text{SU3 breaking}}$ can be computed with OPE techniques

- finite-energy sum rules (FESR) with either fixed-order (FOPT) or contour-improved (CIPT) prescriptions
- strong dependence from m_s
- problematic convergence requires special treatment
- non-pert. terms fitted and/or estimated using tau spectral functions moments
- assumptions on $D>4$ OPE contributions

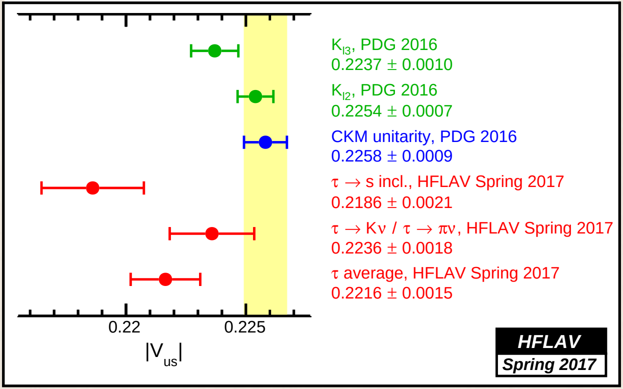
get m_s from world average and compute $|V_{us}|$

- Gamiz, Jamin, Pich, Prades, Schwab, JHEP 01 (2003) 06, PRL 94 (2005) 011803,
- Maltman, 1011.6391 [hep-ph]
- Maltman, Lattice 2015, 1510.06954 [hep-ph] (uses tau spectral functions)

Tau branching fractions to strange final states, HFLAV spring 2017

Branching fraction	HFLAV spring 2017 fit
$K^- \nu_\tau$	0.6960 ± 0.0096
$K^- \pi^0 \nu_\tau$	0.4327 ± 0.0149
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.0640 ± 0.0220
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.0428 ± 0.0216
$\pi^- \bar{K}^0 \nu_\tau$	0.8386 ± 0.0141
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.3812 ± 0.0129
$\pi^- \bar{K}^0 \pi^0 \pi^0 \nu_\tau$ (ex. K^0)	0.0234 ± 0.0231
$\bar{K}^0 h^- h^- h^+ \nu_\tau$	0.0222 ± 0.0202
$K^- \eta \nu_\tau$	0.0155 ± 0.0008
$K^- \pi^0 \eta \nu_\tau$	0.0048 ± 0.0012
$\pi^- \bar{K}^0 \eta \nu_\tau$	0.0094 ± 0.0015
$K^- \omega \nu_\tau$	0.0410 ± 0.0092
$K^- \phi \nu_\tau$ ($\phi \to K^+ K^-$)	0.0022 ± 0.0008
$K^- \phi \nu_\tau$ ($\phi \to K^0_S K^0_L$)	0.0015 ± 0.0006
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	0.2923 ± 0.0067
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.0410 ± 0.0143
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. K^0)	0.0001 ± 0.0001
$K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0)	0.0001 ± 0.0001
$X_s^- \nu_\tau$	2.9087 ± 0.0482

$|V_{us}|$ results



- $\tau \to s$ inclusive vs. CKM unitarity discrepancy: $-3.1\,\sigma$
- no significant change since beginning of HFLAV-Tau (2010)
- $m_s = 95.00 \pm 5.00$ MeV (PDG 2015) and $\delta R_\tau = 0.242 \pm 0.032$ (arXiv:hep-ph/0612154) (chosen estimate of δR_τ with intermediate uncertainty)

Further investigations on $|V_{us}|$ from $\tau \to s$ inclusive

$|V_{us}|$ from $\tau \to s$ inclusive by K. Maltman *et al.* (2015→)

- arXiv:1510.06954 [hep-ph], arXiv:1511.08514 [hep-ph], arXiv:1702.01767 [hep-ph]

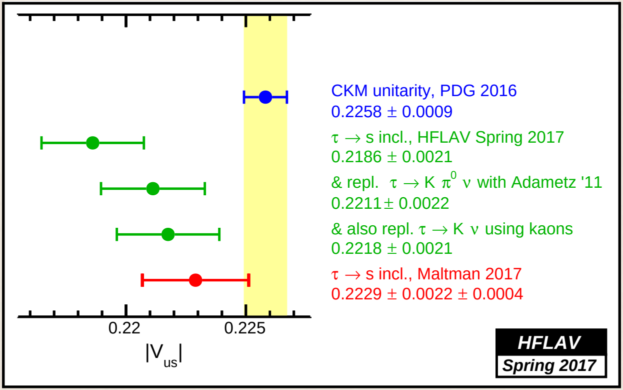
modifications of method

- uses spectral functions of $\tau \to X_s \nu$ decays
  $\Rightarrow$ improves reliability of estimated theory uncertainty

modifications of inputs

- replaces HFLAV $\mathcal{B}(\tau \to K\pi^0\nu)$ with value from A. Adametz PHD thesis (2011) (inspirehep.net/record/946707), *BABAR* work-in-progress, never made public by *BABAR*
- replaces HFLAV $\mathcal{B}(\tau \to K\nu)$ with indirect calculation using $\mathcal{B}(K \to \ell\nu)$

$|V_{us}|$ from $\tau \to s$ inclusive by K. Maltman *et al.* (2015→)



- using traditional $\tau \to s$ inclusive method, reproduce $|V_{us}|$ shifts due to change of inputs
  $\Rightarrow$ reduction of discrepancy mostly due to change of inputs

Tau BRs measurements in A. Adametz PHD thesis (2011)

- based on full BABAR dataset, but for BABAR they are still "work in progress", never released
- authors became essentially unavailable before completing internal BABAR review
- now plan to bring to publication (thanks also to funds from Scuola Normale)
- use data for reconstruction efficiencies, more refined than BABAR 2007 $\mathcal{B}(\tau \to K\pi^0\nu)$

Simultaneous measurement of

$\tau \to K\ n\pi^0\ \nu \qquad n = 0, 1, 2, 3$

$\tau \to \pi\ n\pi^0\ \nu \qquad n = 3, 4$

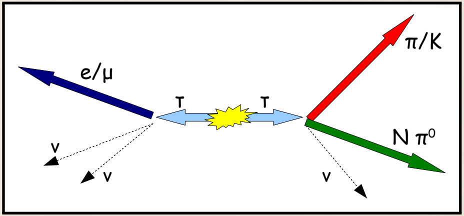
π^0 efficiency & cross-check from

$\tau \to \pi\ n\pi^0\ \nu \qquad n = 0, 1, 2$

π & K PID efficiency from

$\tau^- \to \pi^-\pi^-\pi^+\nu \qquad$ pure π^+

$\tau^- \to \pi^- K^+ K^-\nu \qquad$ pure K^-

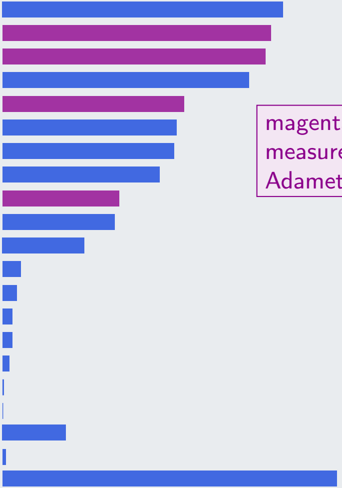


Dataset

$\sim$full BABAR data sample, $\sim$430fb^{-1}

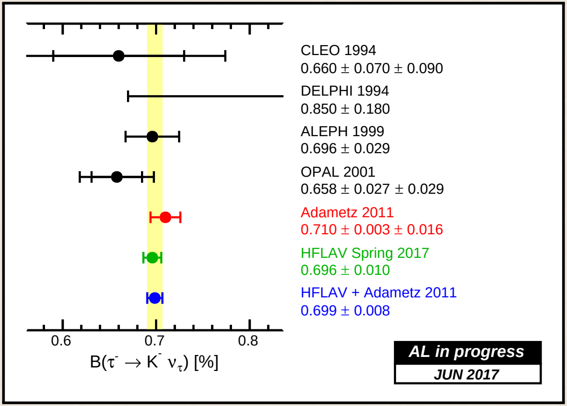
HFLAV $|V_{us}|$ from $\tau \to s$ inclusive uncertainties budget (%)

$\pi^- \bar{K}^0 \pi^0 \pi^0 \nu_\tau$ (ex. K^0)	0.3963	
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.3789	
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.3715	
$\bar{K}^0 h^- h^- h^+ \nu_\tau$	0.3478	
$K^- \pi^0 \nu_\tau$	0.2561	
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.2456	
$\pi^- \bar{K}^0 \nu_\tau$	0.2424	
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.2219	
$K^- \nu_\tau$	0.1646	
$K^- \omega \nu_\tau$	0.1585	
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	0.1157	
$\pi^- \bar{K}^0 \eta \nu_\tau$	0.0256	
$K^- \pi^0 \eta \nu_\tau$	0.0200	
$K^- \eta \nu_\tau$	0.0138	
$K^- \phi \nu_\tau$ ($\phi \to K^+ K^-$)	0.0138	
$K^- \phi \nu_\tau$ ($\phi \to K^0_S K^0_L$)	0.0096	
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. K^0)	0.0021	
$K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0)	0.0010	
$\tau \to$ non-strange	0.0896	
$\mathcal{B}_e^{\text{univ}}$	0.0045	
theory	0.4722	



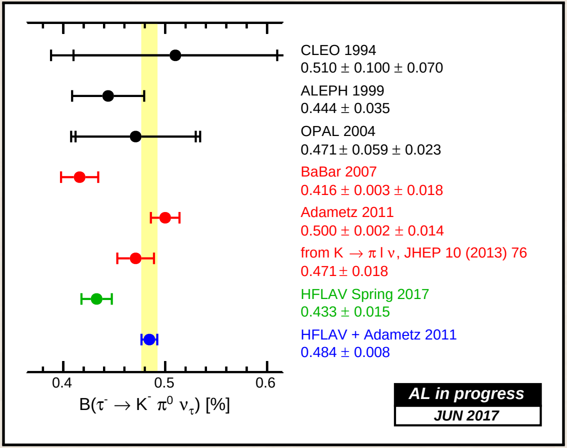
magenta BRs measured in Adametz thesis

A. Adametz 2011 thesis $\mathcal{B}(\tau \to K\nu)$



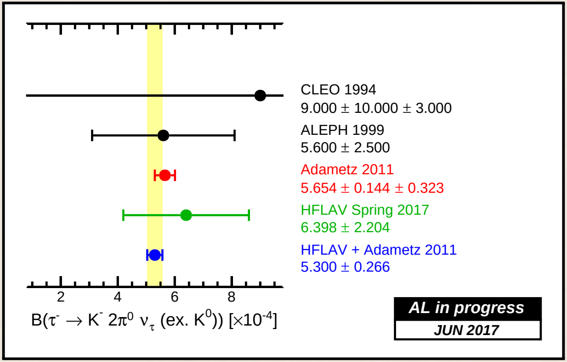
- HFLAV average dominated by *BABAR* measurement of $\mathcal{B}(\tau \to K\nu)/\mathcal{B}(\tau \to e\bar{\nu}\nu)$ (not reported in the plot)

A. Adametz 2011 thesis $\mathcal{B}(\tau \to K\pi^0\nu)$

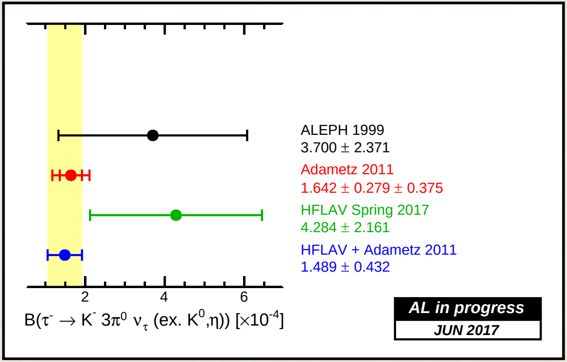


- in "HFLAV + Adametz 2011", BABAR 2007 result is superseded by Adametz 2011 result
- for comparison, show also $\mathcal{B}(\tau \to K\pi^0\nu)$ indirect determination from $\mathcal{B}(K \to \ell\pi^0\bar{\nu})$

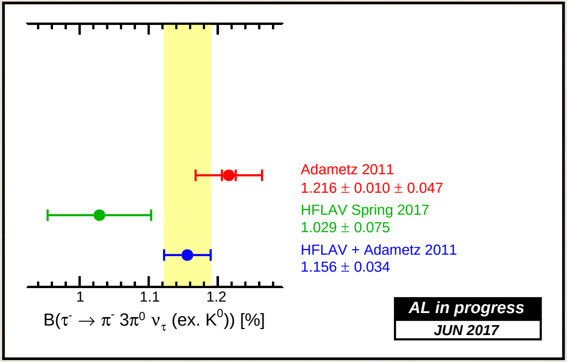
A. Adametz 2011 thesis $\mathcal{B}(\tau \to K 2\pi^0 \nu)$



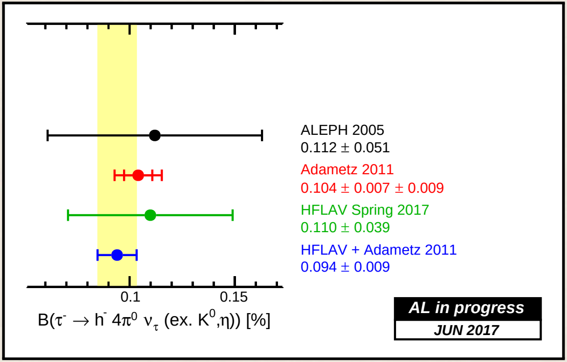
A. Adametz 2011 thesis $\mathcal{B}(\tau \to K 3\pi^0 \nu)$



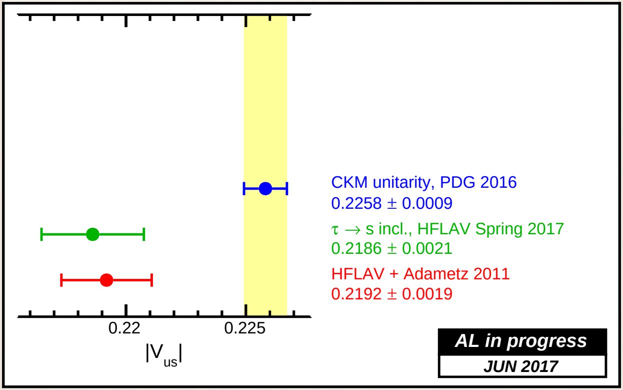
A. Adametz 2011 thesis $\mathcal{B}(\tau \to \pi 3\pi^0 \nu)$



A. Adametz 2011 thesis $\mathcal{B}(\tau \to \pi 4\pi^0 \nu)$



$|V_{us}|$ $\tau \to s$ inclusive, HFLAV 2017 + Adametz 2011 thesis



- using all Adametz 2011 results, no significant modification of $|V_{us}|$
- Adametz 2011 $\mathcal{B}(\tau \to K\pi^0\nu)$ increases $|V_{us}|$ significantly
- other Adametz 2011 results and correlations decrease $|V_{us}|$ by a similar amount

Using tau BRs predictions from kaon BRs

M. Antonelli *et al.*, JHEP 10 (2013) 76

- $|V_{us}|$ calculation using 3 tau BRs from kaons to replace the HFLAV averages
- $\mathcal{B}(\tau \to K\nu) = (0.713 \pm 0.003)\%$
- $\mathcal{B}(\tau \to K\pi^0\nu) = (0.857 \pm 0.030)\%$
- $\mathcal{B}(\tau \to K^0\pi\nu) = (0.471 \pm 0.018)\%$
- (the latter two uncertainties are 100% correlated)

$$\mathcal{B}(\tau \to K\nu_\tau) = \frac{m_\tau^3}{2 m_K m_\mu^2} \frac{S_{\mathbf{EW}}^\tau}{S_{\mathbf{EW}}^K} \left(\frac{1 - m_K^2/m_\tau^2}{1 - m_\mu^2/m_K^2} \right)^2 \frac{\tau_\tau}{\tau_K} R_{\mathbf{EM}}^{\tau/K} \mathcal{B}(K_{\mu 2})$$

$$\mathcal{B}(\tau \to \bar{K}\pi\nu_\tau) = \frac{2 m_\tau^5}{m_K^5} \frac{S_{\mathbf{EW}}^\tau}{S_{\mathbf{EW}}^K} \frac{I_K^\tau}{I_K^\ell} \frac{\left(1 + \delta_{\mathrm{EM}}^{K\tau} + \tilde{\delta}_{\mathrm{SU(2)}}^{K\pi}\right)^2}{\left(1 + \delta_{\mathrm{EM}}^{K\ell} + \delta_{\mathrm{SU(2)}}^{K\pi}\right)^2} \frac{\tau_\tau}{\tau_K} \mathcal{B}(K \to \pi e \bar{\nu}_e)$$

[and similar formula for $\mathcal{B}(\tau \to K\pi^0\nu)$]

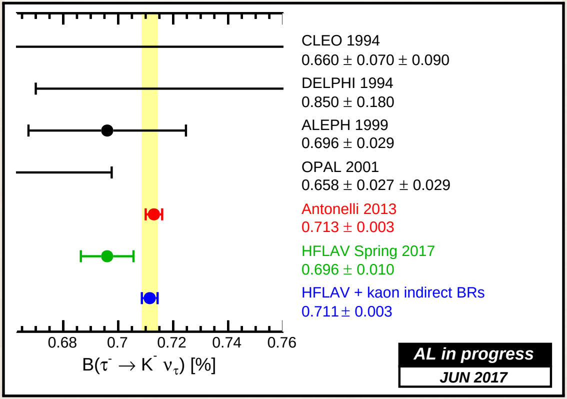
phase space integrals, require tau spectral functions

$$I_K^\tau = \frac{1}{m_\tau^2} \int_{s_{K\pi}}^{m_\tau^2} \frac{ds}{s\sqrt{s}} \left(1 - \frac{s}{m_\tau^2}\right)^2 \left[\left(1 + \frac{2s}{m_\tau^2}\right) q_{K\pi}^3(s) |\bar{f}_+(s)|^2 + \frac{3\Delta_{K\pi}^2}{4s} q_{K\pi}(s) \, |\bar{f}_0(s)|^2 \right]$$

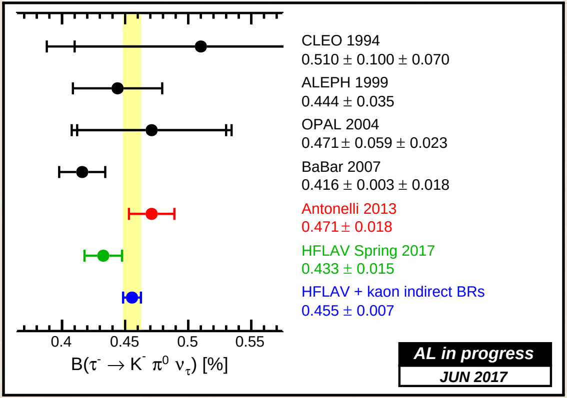
Vus from HFLAV spring 2017 and kaon indirect BRs

- compute $|V_{us}|$ with $\tau \to s$ inclusive method using both tau and kaon data (assuming Standard Model holds) (different from JHEP 10 (2013) 76, where tau BRs from kaon data replace tau BRs)
- in the following, tau BRs from kaons contribute to fit according to their uncertainties

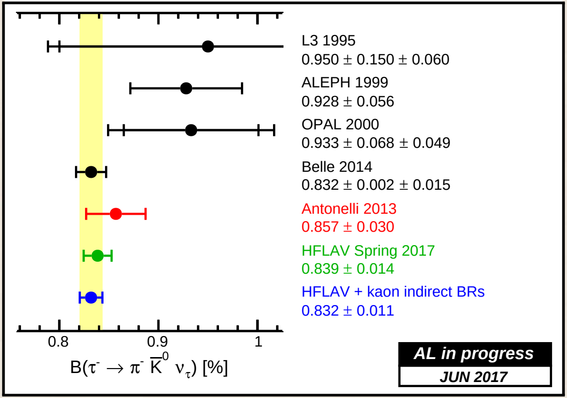
$\mathcal{B}(\tau \to K\nu)$ HFLAV 2017 + indirect kaon BRs



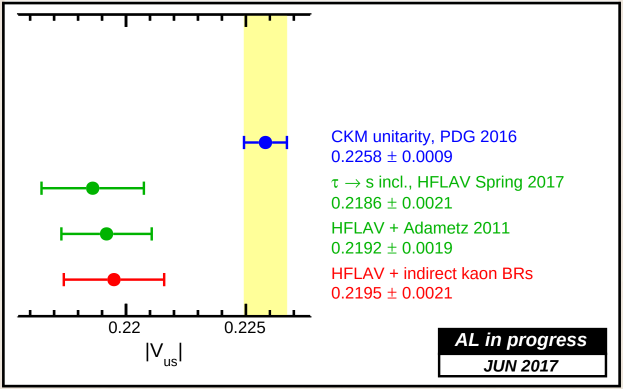
$\mathcal{B}(\tau \to K\pi^0\nu)$ HFLAV 2017 + indirect kaon BRs



$\mathcal{B}(\tau \to K^0 \pi \nu)$ HFLAV 2017 + indirect kaon BRs



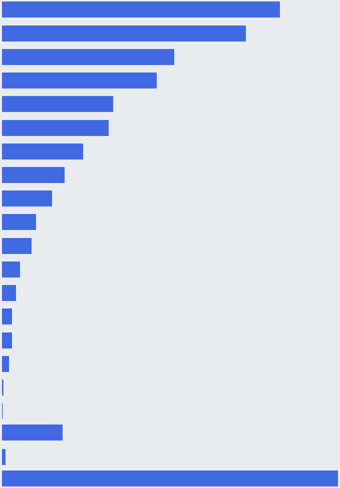
Vus from HFLAV spring 2017 and kaon indirect BRs



- tau BRs from kaons cause small shift and no visible improvement in $|V_{us}|$ precision

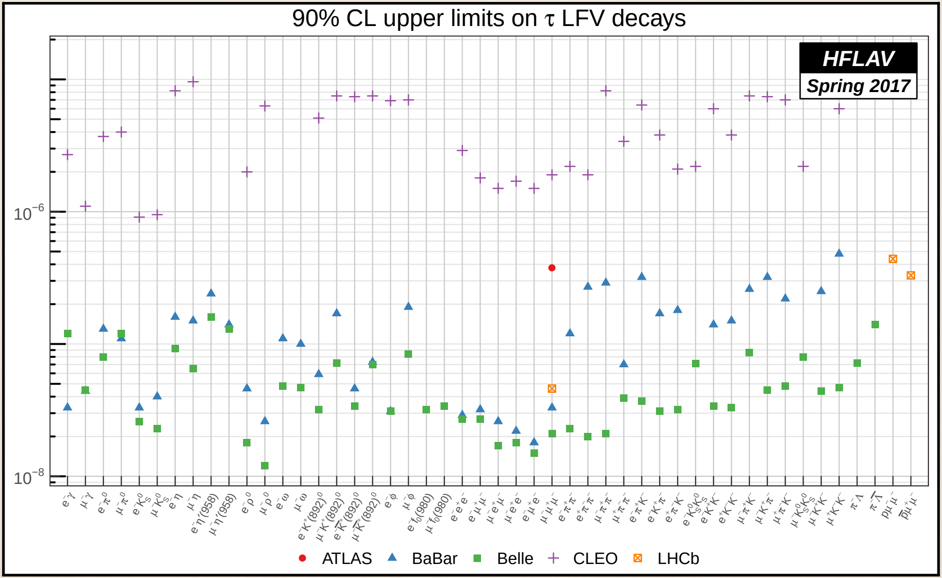
$|V_{us}|$ inclusive uncertainties budget (%)
after adding both Adametz 2011 and kaon indirect results

$\pi^- \bar{K}^0 \pi^0 \pi^0 \nu_\tau$ (ex. K^0)	0.3908
$\bar{K}^0 h^- h^- h^+ \nu_\tau$	0.3430
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.2422
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.2178
$K^- \omega \nu_\tau$	0.1563
$\pi^- \bar{K}^0 \nu_\tau$	0.1501
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	0.1140
$K^- \pi^0 \nu_\tau$	0.0881
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.0703
$K^- \nu_\tau$	0.0473
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.0414
$\pi^- \bar{K}^0 \eta \nu_\tau$	0.0253
$K^- \pi^0 \eta \nu_\tau$	0.0197
$K^- \eta \nu_\tau$	0.0136
$K^- \phi \nu_\tau$ ($\phi \to K^+ K^-$)	0.0136
$K^- \phi \nu_\tau$ ($\phi \to K^0_S K^0_L$)	0.0095
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. K^0)	0.0020
$K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0)	0.0010
$\tau \to$ non-strange	0.0853
$\mathcal{B}_e^{\text{univ}}$	0.0045
theory	0.4724

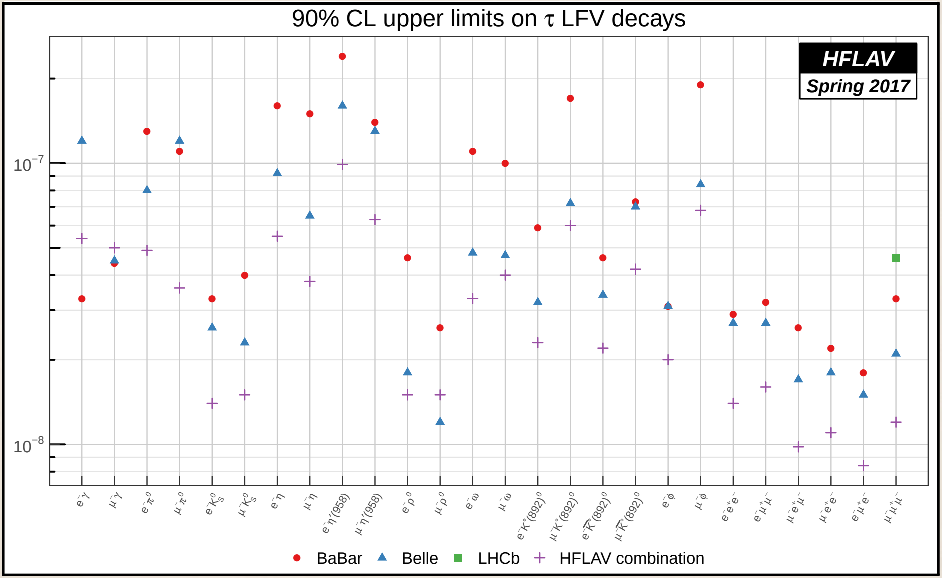


HFLAV Tau LVF combinations

HFLAV tau LFV limits



HFLAV tau LFV limits combinations



Summary

- HFLAV report including tau averages submitted for publication in 2017
- HFLAV-Tau group provides PDG with BR fit results since 2016
- charged weak current lepton universality verified at better than 0.2%
- $|V_{us}|$ from $\tau \to s$ inclusive shows discrepancy of $\sim 3\,\sigma$ w.r.t. $|V_{us}|$ from CKM unitarity
- calculated $|V_{us}|$ with the $\tau \to s$ inclusive method using, in addition to HFLAV inputs,
  - Adametz thesis results
  - tau BRs computed from kaon BRs
- in both cases, no significant change on $|V_{us}|$ discrepancy