HFLAV-Tau group report

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Outline

HFLAV Tau sub-group - (HFLAV = Heavy Flavour AVeraging Group)

- global fit of tau BRs
  - elaborations: lepton universality tests, universality-improved $\mathcal{B}_e$, R_{had}, $|V_{us}|$
- list of limits on lepton flavour violation searches and combinations of limits per decay mode

recent history

2008
- formation of HFLAV-Tau sub-group
- ...

2016
- summer 2016 HFLAV report (arXiv preprint)
- HFLAV-Tau contributes to the PDG tau branching fractions fit and review

2017
- acronym changed from HFAG to HFLAV
- spring 2017 HFLAV report on refereed magazine: Eur. Phys. J. C77 (2017) 895
- web site moved from SLAC to CERN: `https://hflav.web.cern.ch/content/tau`

membership

BaBar
- Swagato Banerjee (Louisville)
- A. L. (convener)
- J. Michael Roney (Victoria)

LHCb
- Marcin Chrząszcz (CERN / Cracow)

Belle
- Kiyoshi Hayasaka (Niigata)
- Hisaki Hayashii (Nara)
- Boris Shwartz (Budker)

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

- $\mathcal{B}(\tau \to h\nu) = \mathcal{B}(\tau \to \pi\nu) + \mathcal{B}(\tau \to K\nu) \qquad (h = \pi, K)$
- $\mathcal{B}(\tau{\to}3\pi\nu) \;=\; \mathcal{B}[\tau{\to}3\pi\nu\ (ex.\ K_S{\to}2\pi)] \;+\; \mathcal{B}(\tau{\to}\pi K_S\nu)\cdot\mathcal{B}(K_S{\to}2\pi)$
- $\Gamma_{5by3} = \Gamma_5/\Gamma_3$, where $\Gamma_3 = \mathcal{B}(\tau \to \mu\bar{\nu}\nu)$, $\Gamma_5 = \mathcal{B}(\tau \to e\bar{\nu}\nu)$, $\Gamma_{5by3} = \dfrac{\mathcal{B}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{B}(\tau \to e\bar{\nu}\nu)}$
- 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)

HFLAV Tau Branching Fraction Fit Features (3)

re-elaboration of ALEPH measurements

- ALEPH provides the most precise and complete set of tau BR data
- ALEPH $\mathcal{B}(\tau \to \pi\ n\pi^0\ \nu)$ results are actually coming from measurements of $\mathcal{B}(\tau \to h\ n\pi^0\ \nu)$ by subtracting measured $\mathcal{B}(\tau \to K\ n\pi^0\ \nu)$
  - the same happens for $\mathcal{B}(\tau \to 3\pi\ n\pi^0\ \nu)$
- HFLAV uses ALEPH $\mathcal{B}(\tau \to h\ n\pi^0\ \nu)$ rather than $\mathcal{B}(\tau \to \pi\ n\pi^0\ \nu)$ this is more accurate and recovers otherwise lost crrelations

inclusion of more especially recent results

- over the time the HFLAV fit has included an ever increasing amount of modes and constraints than the PDG

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 $\mathcal{B}(\tau^- \rightarrow K^- K^- K^+ \nu_\tau)$ 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

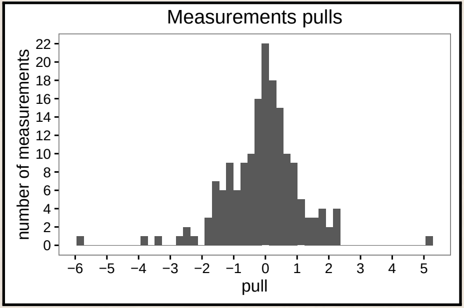
HFLAV spring 2017 basis modes

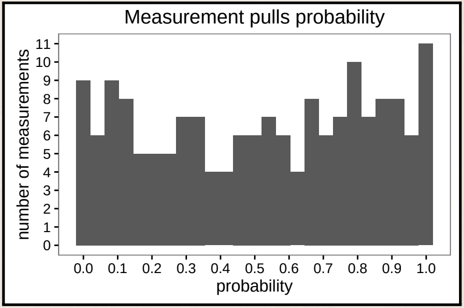
B ($\tau \to \ldots$)	HFLAV spring 2017
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.3917 ± 0.0396
$e^- \bar{\nu}_e \nu_\tau$	17.8162 ± 0.0410
$\pi^- \nu_\tau$	10.8103 ± 0.0526
$K^- \nu_\tau$	0.6960 ± 0.0096
$\pi^- \pi^0 \nu_\tau$	25.5023 ± 0.0918
$K^- \pi^0 \nu_\tau$	0.4327 ± 0.0149
$\pi^- 2\pi^0 \nu_\tau$ (ex. 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 (HFLAV Spring 2017, no scaling)



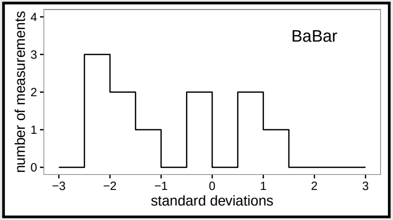


- two outliers: *BABAR* and Belle $\mathcal{B}(\tau \to K^- K^- K^+ \nu_\tau)$ results
  $\Rightarrow$ use scale uncertainties up by 5.44 for the two above experimental inputs

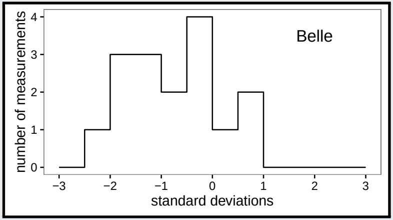
B-factories tend to measure lower BFs (HFLAV Spring 2017)

- 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



PDG tau branching fraction fit since 2016

- since 2016, PDG fit is a variant of the HFLAV tau BFs fit
- unitarity constrained (traditional PDG BFs fits' feature)
- does not use yet re-elaboration of ALEPH results

Elaborations of tau BFs

Lepton universality - HFLAV spring 2017

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

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

where

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

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

Tests of lepton universality from ratios of above partial widths:

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

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

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

$\sim 2\sigma$

- 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)

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

$\sim 2\sigma$

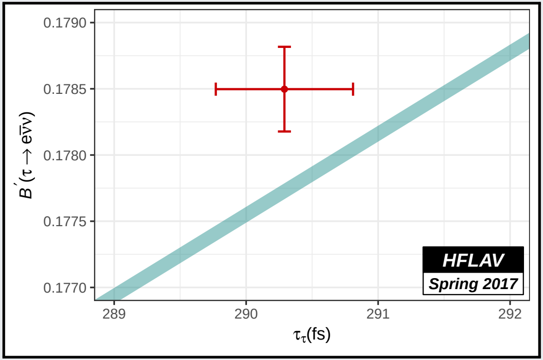
(electron tests less precise because $h \to e\nu$ decays are helicity-suppressed)

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



- $$\frac{\Gamma(\tau \to e\bar{\nu}\nu)}{\Gamma(\mu \to e\bar{\nu}\nu)} = \frac{B'(\tau \to e\bar{\nu}\nu)}{B(\mu \to e\bar{\nu}\nu)} = \frac{\tau_\tau}{\tau_\mu} \frac{m_\tau^5}{m_\mu^5} \frac{f_{\tau e} R_\gamma^\tau R_W^\tau}{f_{\mu e} R_\gamma^\mu R_W^\mu}$$
- $B'(\tau \to e\bar{\nu}\nu)$ 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%

R_{had} from tau branching ratios fit results

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

- $R_{\text{had}} = \dfrac{\mathcal{B}_{\text{hadrons}}}{\mathcal{B}_e^{\text{univ}}} = 3.6350 \pm 0.0082$ 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
- $R_{\text{had}}(\text{lepton only}) = \dfrac{1 - \mathcal{B}_e - \mathcal{B}_\mu}{\mathcal{B}_e^{\text{univ}}} = 3.6369 \pm 0.0076$ HFLAV spring 2017 fit

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

Main ways to measure $|V_{us}|$

from kaon decays

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

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**

  $[R(\tau \to X) = \Gamma(\tau \to X)/\Gamma(\tau \to e\nu\bar{\nu})]$
- $\frac{\Gamma(\tau^- \to K^- \nu_\tau)}{\Gamma(\tau^- \to \pi^- \nu_\tau)} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{\left(1 - m_K^2/m_\tau^2\right)^2}{\left(1 - m_\pi^2/m_\tau^2\right)^2} \frac{r_{\textbf{LD}}(\tau^- \to K^- \nu_\tau)}{r_{\textbf{LD}}(\tau^- \to \pi^- \nu_\tau)}$ **$\tau \to K/\tau \to \pi$ method**

- **$\tau \to s$ 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

Determine $|V_{us}|$ and/or m_s from $\mathcal{B}(\tau \to s)$ inclusive

Gamiz, Jamin, Pich, Prades, Schwab, JHEP 01 (2003) 06, PRL 94 (2005) 011803

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

- $\delta R_{\tau,\text{SU3 breaking}}$ computed with OPE techniques using also
  - finite-energy sum rules (FESR)
  - either fixed-order (FOPT) or contour-improved (CIPT) perturbation theory

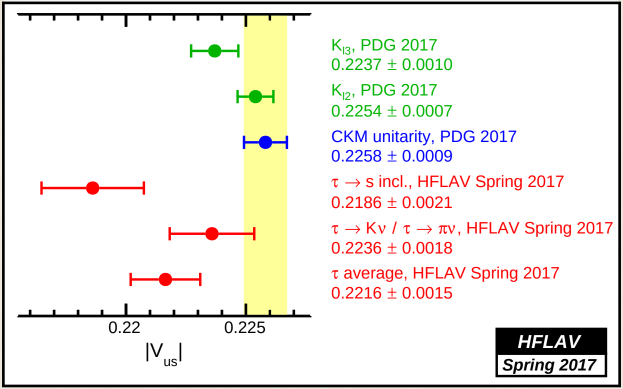
Determine $|V_{us}|$ relying on the world average for m_s

- E. Gamiz *et al.*, JHEP 01 (2003) 060, PRL 94 (2005) 011803, Nucl. Phys .Proc. Suppl. 169 (2007) 85, PoS KAON (2008) 008

$\mathcal{B}(\tau \to X_s \nu)$ from HFLAV Spring 2017 fit

Tau decay mode	Branching fraction (%)
$K^- \nu_\tau$	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

$|V_{us}|$ from tau BRs using the HFLAV Spring 2017 fit



- $\tau \to s$ inclusive vs. CKM unitarity discrepancy: $-3.1\,\sigma$
  - no significant change since the first HFLAV fit in 2010
- $m_s = 95.00 \pm 5.00\,\text{MeV}$ (PDG 2015), form factors from FLAG 2016
- $\delta R_\tau = 0.242 \pm 0.032$ (E. Gamiz *et al.*, arXiv:hep-ph/0612154v1)
- details in HFLAV Spring 2017 report, Eur. Phys. J. C77 (2017) 895 , arXiv:1612.07233

ICHEP 2018 *BaBar* tau BRs measurements

BABAR preliminary tau BRs measurements, T. Lueck, ICHEP 2018

- simultaneous measurement of 6 modes:

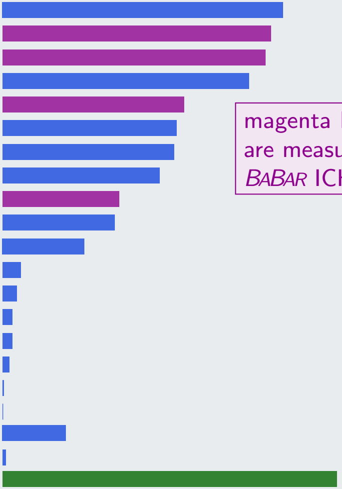
  $\tau \to K\ n\pi^0\ \nu \quad (\text{ex. } K^0 \to 2\pi^0, \text{ ex. } \eta \to 3\pi^0) \quad n = 0, 1, 2, 3$

  $\tau \to \pi\ n\pi^0\ \nu \quad (\text{ex. } K^0 \to 2\pi^0, \text{ ex. } \eta \to 3\pi^0) \quad n = 3, 4$

  to best account for cross-feeds between signal modes
- will be presented later by T. Lueck

HFLAV $|V_{us}|$ from $\tau \to s$ inclusive uncertainties budget (%) for the HFLAV Spring 2017 determination

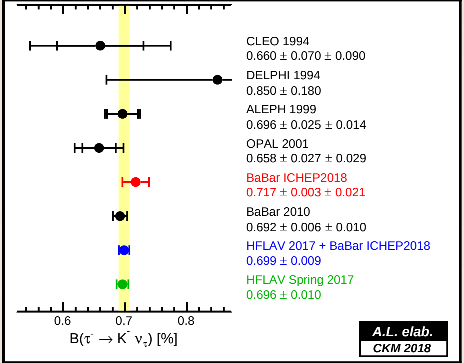
$\pi^- \bar{K}^0 \pi^0 \pi^0 \nu_\tau$ (ex. K^0)	0.3963
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.3789
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.3715
$\bar{K}^0 h^- h^- h^+ \nu_\tau$	0.3478
$K^- \pi^0 \nu_\tau$	0.2561
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.2456
$\pi^- \bar{K}^0 \nu_\tau$	0.2424
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	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



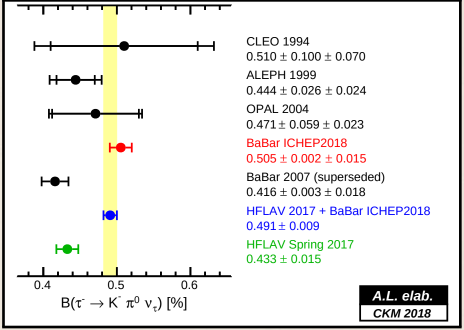
magenta BRs are measured in *BABAR* ICHEP 2018

Preliminary global HFLAV fit with BABAR ICHEP 2018 results

$\mathcal{B}(\tau \to K\nu)$ measurements and fits



$\mathcal{B}(\tau \to K\pi^0\nu)$ measurements and fits



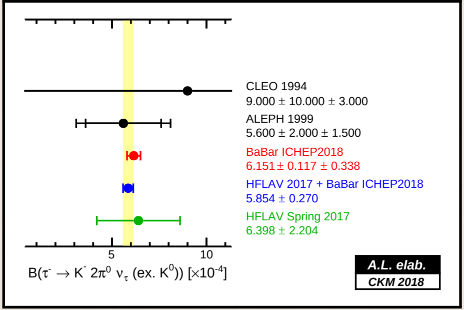
- BABAR 2010 $\mathcal{B}(\tau^- \to K^- \nu_\tau)$ (more precise) statistically independent because measured on 3–1 prongs tau pairs

- new result supersedes BABAR 2007 $\mathcal{B}(\tau^- \to K^- \pi^0 \nu_\tau)$

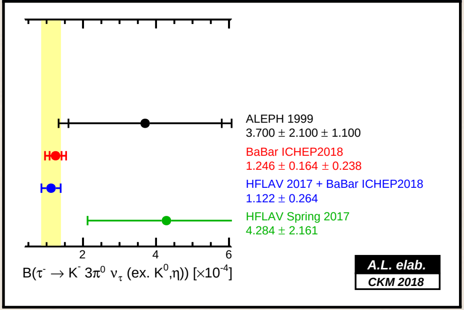
- the plots report a branching fraction and its existing measurements, but note that in the HFLAV global fit also other indirect measurements (ratios of branching fractions, or more inclusive branching fractions) can contribute in a significant way to determine the fit result for the plotted quantities.

Preliminary global HFLAV fit with *BaBar* ICHEP 2018 results

$\mathcal{B}(\tau \to K 2\pi^0 \nu)$ measurements and fits



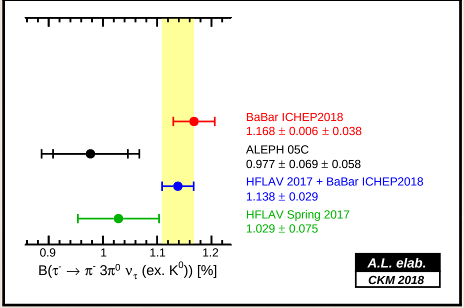
$\mathcal{B}(\tau \to K 3\pi^0 \nu)$ measurements and fits



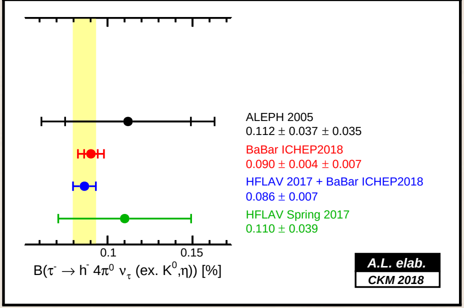
- the plots report a branching fraction and its existing measurements, but note that in the HFLAV global fit also other indirect measurements (ratios of branching fractions, or more inclusive branching fractions) can contribute in a significant way to determine the fit result for the plotted quantities.

Preliminary global HFLAV fit with *BABAR* ICHEP 2018 results

$\mathcal{B}(\tau\to\pi 3\pi^0\nu)$ measurements and fits



$\mathcal{B}(\tau\to\pi 4\pi^0\nu)$ measurements and fits



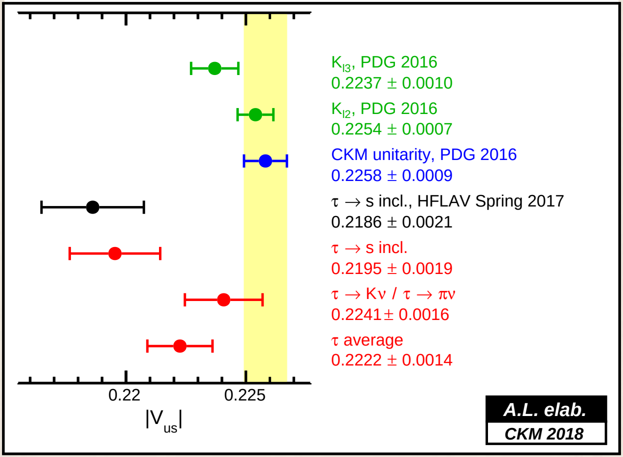
- $\mathcal{B}(\tau^-\to\pi^- 4\pi^0\nu_\tau) = \mathcal{B}(\tau^-\to h^- 4\pi^0\nu_\tau)$, where $h = \pi, K$, since $\mathcal{B}(\tau^-\to K^- 4\pi^0\nu_\tau)$ has not yet been measured and is considered to be negligible

- the plots report a branching fraction and its existing measurements, but note that in the HFLAV global fit also other indirect measurements (ratios of branching fractions, or more inclusive branching fractions) can contribute in a significant way to determine the fit result for the plotted quantities.

HFLAV Spring 2017 + *BaBar* ICHEP 2018 fit

Tau decay mode	Branching fraction (%)
$K^- \nu_\tau$	0.6986 ± 0.0086
$K^- \pi^0 \nu_\tau$	0.4910 ± 0.0091
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.0585 ± 0.0027
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.0112 ± 0.0026
$\pi^- \bar{K}^0 \nu_\tau$	0.8388 ± 0.0141
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.3811 ± 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
$K^- \eta \nu_\tau$	0.0154 ± 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
$X_s^- \nu_\tau$	2.9327 ± 0.0413

$|V_{us}|$ from tau, HFLAV 2017 + *BaBar* ICHEP 2018



- $\tau \to s$ inclusive vs. CKM unitarity discrepancy: $-3.0\,\sigma$
  - no significant change, $|V_{us}|$ increased a bit, uncertainty reduced

Using kaon BRs to predict tau BRs

Use precisely measured kaon BRs to predict tau BRs

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

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

new:

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

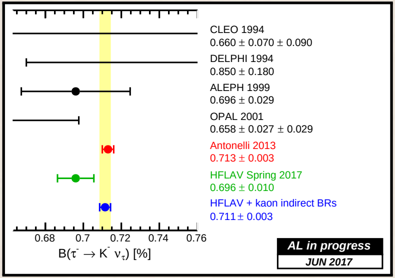
[and similar formula for $\mathcal{B}(\tau \to K\pi^0\nu)$]

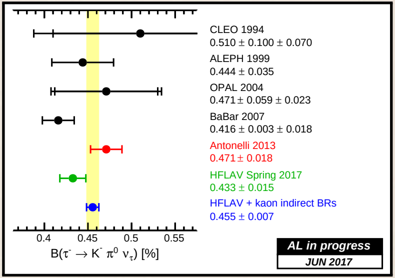
phase space integrals I_K^τ require tau spectral functions

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

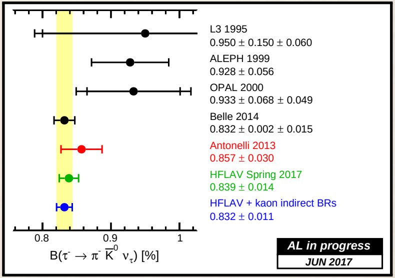
- results:
  - $\mathcal{B}(\tau \to K\nu) = (0.713 \pm 0.003)\%$
  - $\mathcal{B}(\tau \to K\pi^0\nu) = (0.471 \pm 0.018)\%$
  - $\mathcal{B}(\tau \to K^0\pi\nu) = (0.857 \pm 0.030)\%$
- note: the latter two uncertainties are 100% correlated

Tau BRs from kaon BRs, compared to measurements of tau BRs

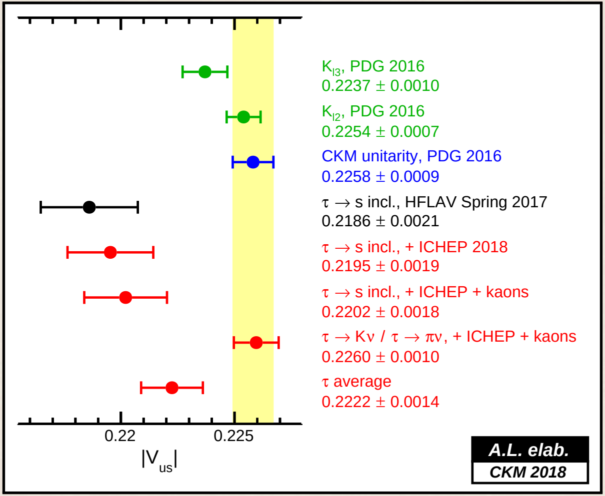




- red: tau BR predicted using kaon BR
- green: HFLAV average using only tau BRs inputs
- blue: HFLAV average combining tau BRs inputs and predictions from kaon BRs



$|V_{us}|$ from tau using HFLAV, *BABAR* ICHEP 2018, kaon predictions



- $\tau \to s$ inclusive vs. CKM unitarity discrepancy: $-2.7\,\sigma$
- most complete unbiased usage of exp. data for $|V_{us}|$ with $\tau \to s$ inclusive

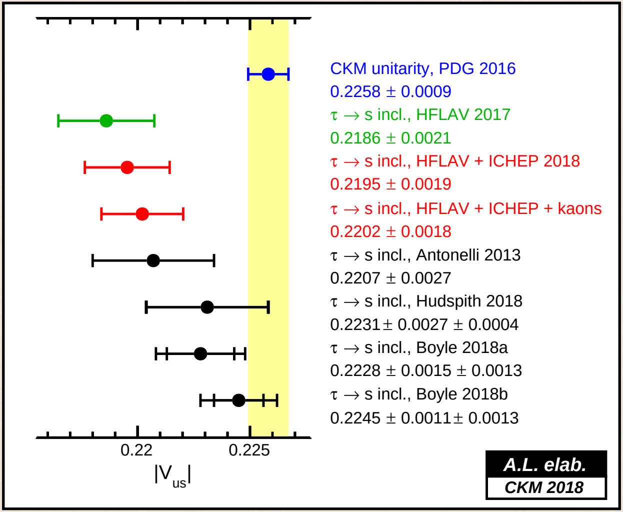
Other $|V_{us}|$ from $\tau \to s$ inclusive determinations

Other $|V_{us}|$ from $\tau \to s$ inclusive determinations (non exhaustive)

- M. Antonelli *et al.*, JHEP 10 (2013) 76
  predict $K, K\pi^0, K_s^0\pi$ tau BRs from kaon decays to replace tau results and compute $|V_{us}|$
  - predict $K, K\pi^0, K_s^0\pi$ tau BRs from kaon decays to replace tau results
  - compute $|V_{us}|$ with the standard technique
- J. Hudspith *et al.*, PLB 781 (2018) 206
  - compute $|V_{us}|$ from tau inclusive using also the tau spectral functions
  - presented later
- P. Boyle *et al.*, arXiv:1803.07228 [hep-lat]
  compute $|V_{us}|$ from tau inclusive using lattice QCD
  - Boyle 2018a: uses HFLAV tau BRs + tau spectral functions
  - Boyle 2018b: like 2018a but replaces $\mathcal{B}(\tau \to K\nu)$ with prediction from kaon BRs
  - presented later

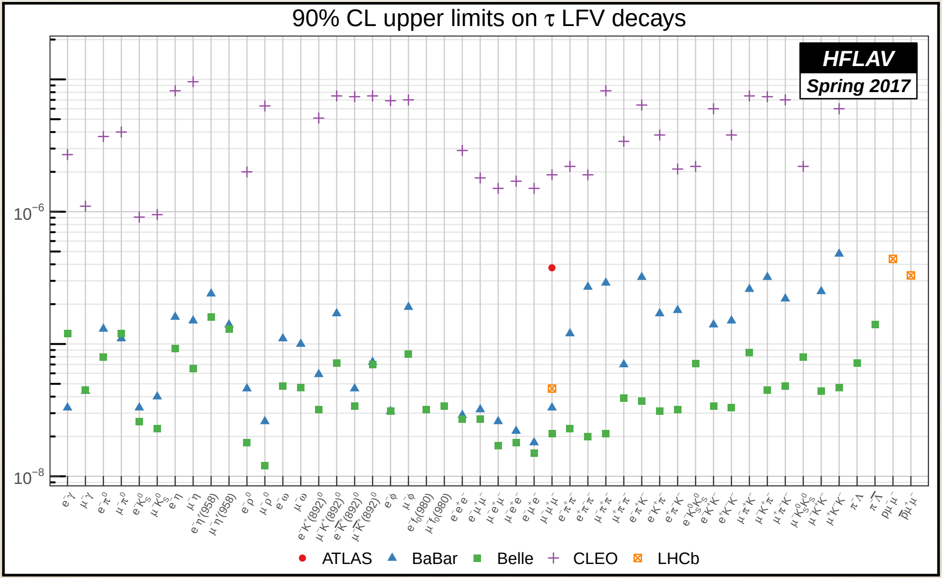
- there are differences in the set of experimental inputs that are used

Comparison of $|V_{us}|$ from tau inclusive determinations

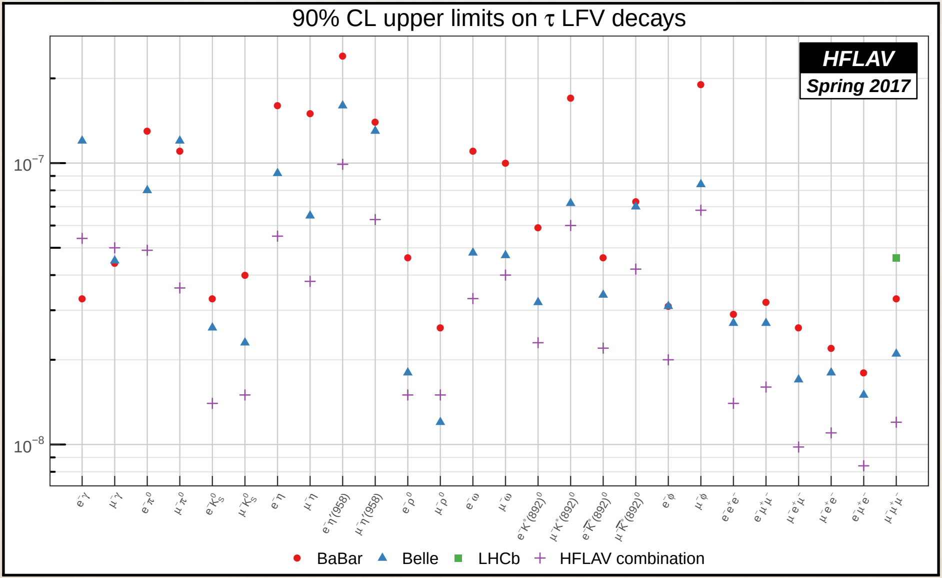


HFLAV Tau LVF combinations

HFLAV tau LFV limits



HFLAV tau LFV limits combinations



Conclusions

$|V_{us}|$ inclusive uncertainties budget (%)
after adding both BABAR ICHEP 2018 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

Very recent news I could not include

- new radiative corrections computed for $|V_{ud}|$
  - not clear how they would affect the nuclear transitions, which determine $|V_{ud}|$ today
  - would decrease $|V_{ud}|$, widening tau incl. (and Kl3) discrepancies with CKM unitarity
- LQCD form factors ofr kaon $|V_{us}|$ determinations remarkably improved
  - now LQCD uncertainties comparable with experimental ones
  - tau inclusive $|V_{us}|$ will remain less precise, and will serves as consistency check
- other $|V_{us}|$ from tau incl. determinations will be updated with most recent HFLAV results

Conclusions

- some experimental progress on measurements for the global fit on tau BRs
  - to be included in the HFLAV-Tau 2018 report
- using today's most complete set of experimental inputs in an unbiased way gives $|V_{us}|$ from tau inclusive determination $2.7\,\sigma$ away from CKM unitarity
- alternative more complex tau-inclusive $|V_{us}|$ determinations give $|V_{us}|$ values compatible with kaon results and CKM unitarity