Heavy Flavor Averaging Group

Ulrik Egede
On behalf of the HFLAV group

24 November 2021

@UlrikEgede

Who are we

- The Heavy Flavour Averaging Group was created in 2002 as follow-up on the LEP Heavy Flavor Steering Group
- Currently 40 members

The co-leaders of HFLAV are **Abner Soffer** (Tel Aviv University, ATLAS/BELLE II) asoffer@tau.ac.il and **Ulrik Egede** (Monash University, LHCb) ulrik.egede@monash.edu
The current members of the HFLAV groups are listed below with convenors in **bold**.

Oscillations

- Marcella Bona (Queen Mary, ATLAS)
- Veronika Chobanova (Santiago de Compostela, LHCb)
- Olivier Leroy (CPPM Marseille, LHCb)
- Martino Margoni (Padova, CMS)
- **Olivier Schneider** (EPFL Lausanne, BELLE/LHCb)

Unitarity Triangle

- **Tim Gershon** (Warwick, BABAR/LHCb)
- Matthew Kenzie (Cambridge, LHCb)
- Kenkichi Miyabayashi (Nara, BELLE)
- Diego Tonelli (Trieste, Belle II)

Semileptonic

- Concezio Bozzi (INFN Ferrara, BABAR/LHCb)
- **Marcello Rotondo** (INFN Frascati, BABAR/LHCb)
- **Christoph Schwanda** (Austrian Academy of Sciences, BELLE)
- Phillip Urquijo (University of Melbourne, BELLE)

Rare Decays

- **Eli Ben-Haim** (LPNHE-Paris, BABAR/LHCb)
- Arantza Oyanguren Campos (IFIC, University of Valencia/CSIC, BABAR, LHCb)
- Pablo Goldenzweig (Karlsruhe, BELLE II)
- Justine Serrano (CPPM Marseille, LHCb)

B To Charm

- Yasmine Amhis (LAL Orsay, LHCb)
- Andrzej Bozek (Kraków, BELLE)
- Daniel Johnson (CERN, LHCb)
- **Thomas Kuhr** (Ludwig-Maximilians-University, BELLE/CDF)
- Roman Mizuk (Lebedev, BELLE-II)
- Alexis Pompili (INFN Bari, CMS)
- Matteo Rama (INFN Pisa, BABAR)

Charm Decays

- **Hailong Ma** (IHEP, BES-III)
- **Paras Naik** (Bristol, LHCb)
- Tara Nanut (EPFL Lausanne, LHCb)
- John Yelton (Florida, BELLE)

Charm Oscillations and CV violation

- Jolanta Brodzicka (Polish Academy of Sciences, LHCb)
- **Marco Gersabeck** (Manchester, LHCb)
- **Alan Schwartz** (Cincinnati, BELLE)

Tau Physics

- Swagato Banerjee (University of Louisville, BABAR)
- Marcin Chrząszcz (CERN, LHCb)
- Kiyoshi Hayasaka (Niigata University, BELLE)
- Hisaki Hayashii (Nara Woman's University, BELLE)
- **Alberto Lusiani** (Scuola Normale Superiore and INFN Pisa, BABAR)
- Mike Roney (University of Victoria, BABAR/BELLE-II)
- Boris Shwartz (BINP, BELLE)

The mission

- The mission of HFLAV is to take published and preliminary results from all experiments involved in heavy flavour physics and form “informed” averages of the measurements
- Text, numbers and plots ...

7.2.2 Analysis in the kinetic scheme

We obtain $|V_{cb}|$ and the six non-perturbative parameters mentioned above with a fit that follows closely the procedure described in Ref. [553] and relies on the calculations of the lepton energy and hadronic mass moments in $\overline{B} \to X_c \ell^- \overline{\nu}_\ell$ decays described in Ref. [539, 540]. The detailed fit result and the matrix of the correlation coefficients is given in Table 80. Projections of the fit onto the lepton energy and hadronic mass moments are shown in Figs. 55 and 56, respectively. The result in terms of the main parameters is

$$|V_{cb}| = (42.19 \pm 0.78) \times 10^{-3} , \quad (199)$$
$$m_b^{\rm kin} = 4.554 \pm 0.018 \text{ GeV} , \quad (200)$$
$$\mu_\pi^2 = 0.464 \pm 0.076 \text{ GeV}^2 , \quad (201)$$

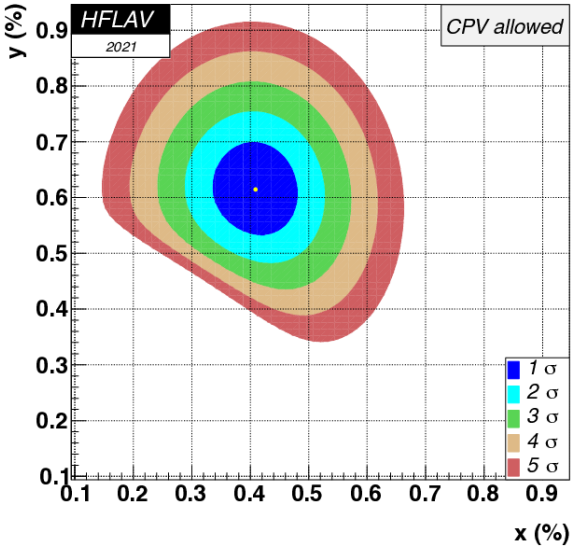
with a χ^2 of 15.6 for 43 degrees of freedom. The scale μ of the quantities in the kinetic scheme is 1 GeV.

Table 80: Fit result in the kinetic scheme, using a precise c-quark mass constraint. The error matrix of the fit contains experimental and theoretical contributions. In the lower part of the table, the correlation matrix of the parameters is given. The scale μ of the quantities in the kinematic scheme is 1 GeV.

Table 102: Branching fractions for decays to a $D^{(*)0}$ meson and a light meson.

Parameter $[10^{-4}]$	Measurements		Average HFLAV / PDG
$\mathcal{B}(B^0 \to \overline{D}^0 \rho^0(770))$	Belle [645]	$3.19 \pm 0.20 \pm 0.45$	3.07 ± 0.46
	Belle [658]	$4.1 \pm 2.0 \pm 0.2$ [1]	3.21 ± 0.21
	LHCb [659][2]		
$\mathcal{B}(B^0 \to \overline{D}^*(2007)^0 \rho^0(770))$	Belle [658]	< 5.1	< 5.1
$\mathcal{B}(B^0 \to \overline{D}^0 \eta)$	BaBar [652]	$2.53 \pm 0.09 \pm 0.11$	2.36 ± 0.13
	Belle [653]	$1.77 \pm 0.16 \pm 0.21$	2.36 ± 0.32
$\mathcal{B}(B^0 \to \overline{D}^*(2007)^0 \eta)$	BaBar [652]	$2.69 \pm 0.14 \pm 0.23$	2.26 ± 0.22 $_{p=5.8\%}$
	Belle [653]	$1.4 \pm 0.3 \pm 0.3$	2.26 ± 0.61
$\mathcal{B}(B^0 \to \overline{D}^0 \eta')$	BaBar [652]	$1.48 \pm 0.13 \pm 0.07$	1.38 ± 0.12
	Belle [660]	$1.14 \pm 0.20 ^{+0.10}_{-0.13}$	1.38 ± 0.16
$\mathcal{B}(B^0 \to \overline{D}^*(2007)^0 \eta')$	BaBar [652]	$1.48 \pm 0.22 \pm 0.13$	1.40 ± 0.22
	Belle [660]	$1.21 \pm 0.34 \pm 0.22$	
$\mathcal{B}(B^0 \to \overline{D}^0 \omega(782))$	BaBar [652]	$2.57 \pm 0.11 \pm 0.14$	2.54 ± 0.16
	Belle [653]	$2.37 \pm 0.23 \pm 0.28$	
	LHCb [654]	$2.81 \pm 0.72 \pm 0.18$	
	Belle [658][3]		
$\mathcal{B}(B^0 \to \overline{D}^*(2007)^0 \omega(782))$	BaBar [652]	$4.55 \pm 0.24 \pm 0.39$	3.64 ± 0.35 $_{p=1.8\%}$
	Belle [653]	$2.29 \pm 0.39 \pm 0.40$	3.64 ± 1.11
$\mathcal{B}(B^0 \to \overline{D}^0 f_2(1270))$	LHCb [654]	$1.61 \pm 0.11 \pm 0.17$	1.54 ± 0.18
	Belle [645]	$1.2 \pm 0.2 \pm 0.4$	1.56 ± 0.21

[1] Using $\mathcal{B}(B^0 \to \overline{D}^0 \omega(782))$.
[2] Measurement of $\mathcal{B}(B_s^0 \to \overline{D}^0 \overline{K}^*(892)^0)/\mathcal{B}(B^0 \to \overline{D}^0 \rho^0(770))$ used in our fit.
[3] Measurement of $\mathcal{B}(B^0 \to \overline{D}^0 \rho^0(770))/\mathcal{B}(B^0 \to \overline{D}^0 \omega(782))$ used in our fit.



Averaging process

- All measurements of a given quantity are collected
  - Measurements that are superseded are excluded
  - Preliminary measurements that are not after a reasonable period published are excluded
  - New preliminary results are included
- The optimal for averaging would be to combine likelihoods from all measurements, apply uniform external constraints and perform fit
  - This is essentially never an option!

Averaging process

- Form a χ^2

Measurements in papers

$$\chi^2(\boldsymbol{x}) = \sum_i^N (\boldsymbol{x}_i - \boldsymbol{x})^{\mathrm{T}} \boldsymbol{V}_i^{-1} (\boldsymbol{x}_i - \boldsymbol{x})$$

Sum over papers

Correlation between measurements

The HFLAV averages

and minimise for the average parameters *x*

$$\chi^2(\boldsymbol{p}) = \sum_i^N (\boldsymbol{f}_i(\boldsymbol{p}) - \boldsymbol{x}_i)^{\mathrm{T}} \boldsymbol{V}_i^{-1} (\boldsymbol{f}_i(\boldsymbol{p}) - \boldsymbol{x}_i)$$

Averaging process

- In more complex examples, the parameters measured in papers are not the parameters that we are interested in

Measurements in papers
e.g. a branching fraction ratio

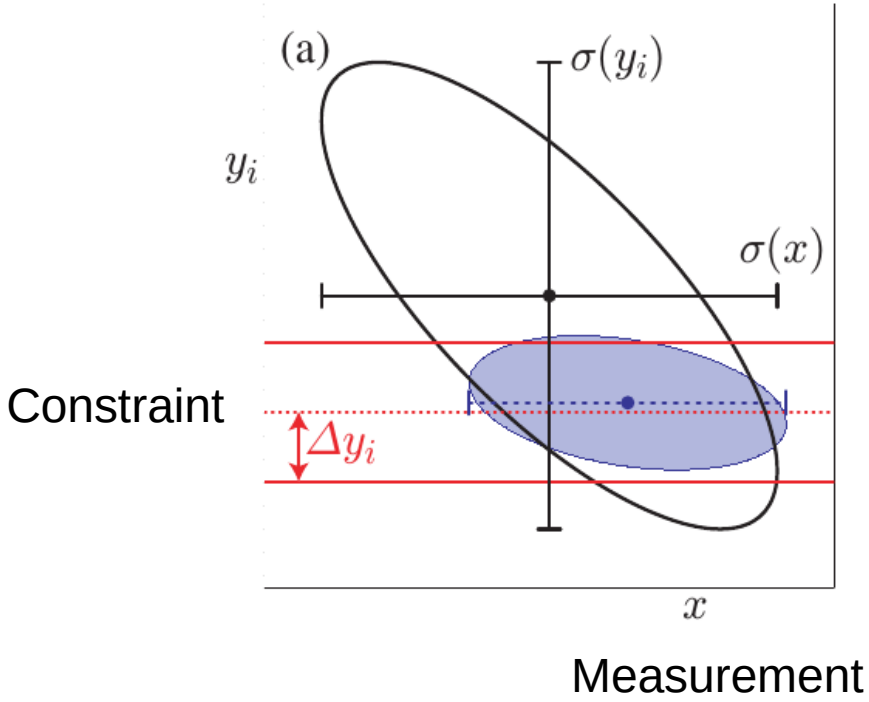
$$\chi^2(\boldsymbol{p}) = \sum_i^N \left(\boldsymbol{f}_i(\boldsymbol{p}) - \boldsymbol{x}_i\right)^{\mathrm{T}} \boldsymbol{V}_i^{-1} \left(\boldsymbol{f}_i(\boldsymbol{p}) - \boldsymbol{x}_i\right)$$

The HFLAV averages
e.g the branching fractions

How to get from HFLAV parameters
to parameters in papers

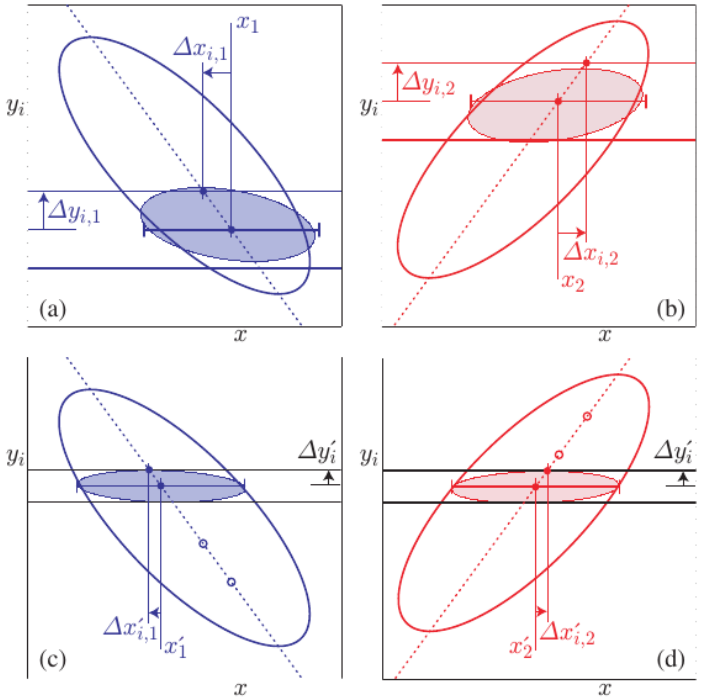
Averaging process

- Often measurements use external parameters to make measurement
  - As an example, a measurement might use Δm_s as an external constraint



Averaging process

- When Δm_s gets an updated value, we wish to correct the old measurements



Published measurements

Corrected measurements

- This is only possible when we know measurements without the constraint!

What is required from publications

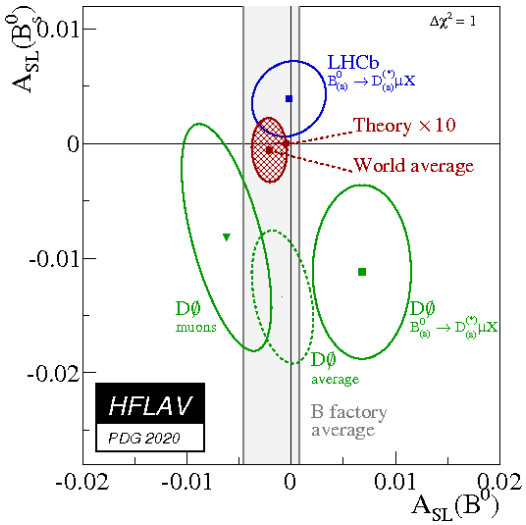
- Full likelihood in a reusable format if at all possible
- Full results and correlation matrix for all fit parameters that may reappear in other results
- As much information as possible should be provided on any external constraints used to provide final numbers. Fit results without the external constraint even better
- Exact quotation of all numbers used – not just “we use the HFLAV average”
- When setting limits, give fit results as well (even if negative BF or not significant)

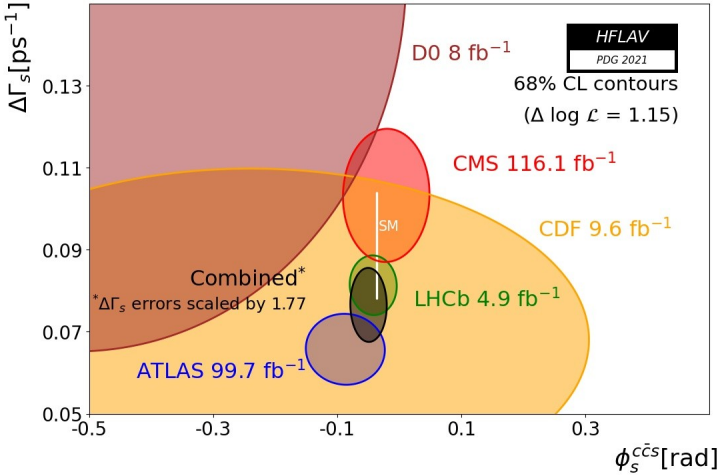
Correlations

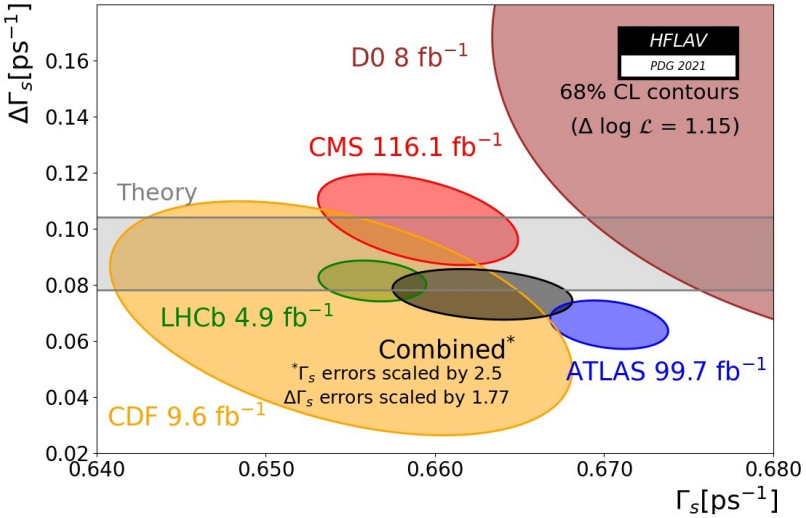
- When combining results, we treat the systematic uncertainties as statistical effects
- Important to understand the correlations of systematics
  - Tracking efficiencies might be correlated for different measurements from same experiment
  - Systematics related to production fractions might be correlated across experiments
  - Systematics from simulation statistics most likely not correlated
- Split up systematics as much as possible and discuss this

The details - B lifetimes and oscillation parameters

- Group covers b hadron lifetimes, Δm_d, $\Delta\Gamma_d$, Δm_s, $\Delta\Gamma_s$, CPV in mixing.
  - Production fractions from hadron colliders will be dropped in the future
- This is the group with the largest impact of results from ATLAS and CMS

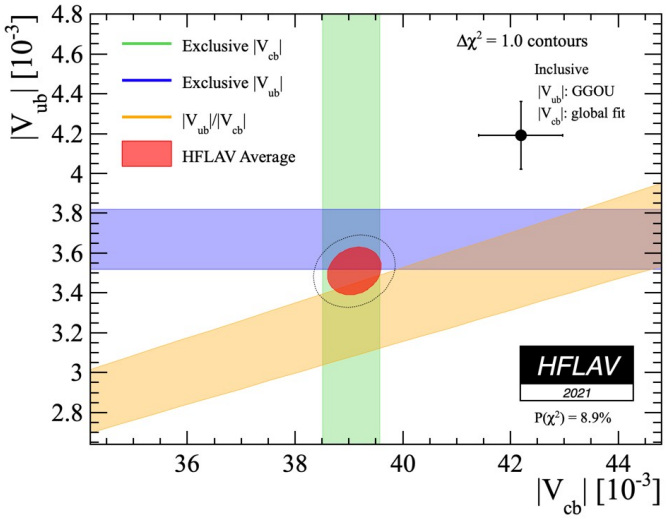


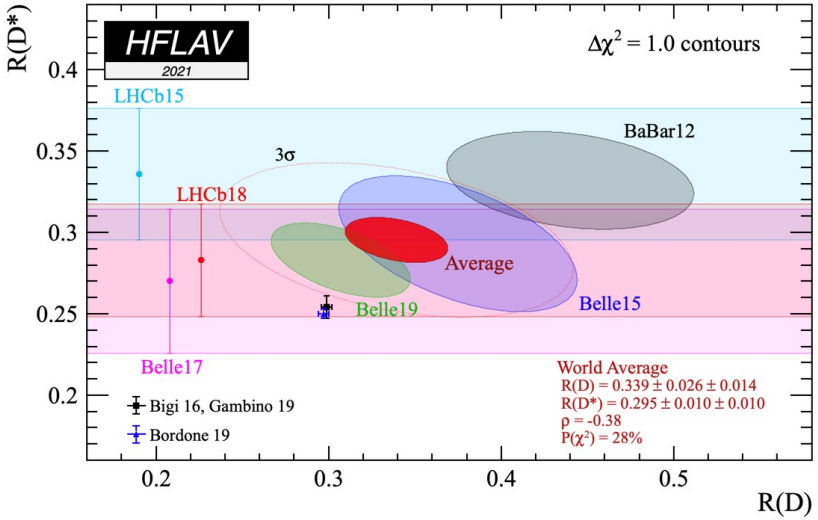




The details – Semileptonic B decays

- Semileptonic branching fractions, CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ as well as semileptonic lepton universality measurements
- Significant input from Lattice QCD for the work in this group





The details – B decays to charm final states

- The process for obtaining averages has been completely revised
  - Now fit all measurements that are related together, to take all correlations into account
  - Automatic comparison to PDG numbers – very useful in identifying omitted results and encoding errors for both HFLAV and PDG

Parameter $[10^{-4}]$	Measurements		Average HFLAV / PDG
$\mathcal{B}(B^+ \to \overline{D}^0 K^+)$	LHCb [457]	$3.604 \pm 0.028 \pm 0.140$ [1]	
	Belle [767]	$3.132 \pm 0.106 \pm 0.168$ [1]	
	BaBar [766]	$3.845 \pm 0.162 \pm 0.148$ [2,1]	3.56 ± 0.13
	Belle [768]	$3.56 \pm 0.23 \pm 0.30$ [1]	3.63 ± 0.12
	Belle [768]	$3.83 \pm 0.25 \pm 0.37$	
	Belle [767] [4]		
$\mathcal{B}(B^+ \to \overline{D}^0 K^*(892)^+)$	BaBar [774]	$5.29 \pm 0.30 \pm 0.34$	5.29 ± 0.45
			5.32 ± 0.45

The details – charmless b-hadron decays

- This group covers both charmless decays and penguin decays
  - Covers branching fractions, direct CPV measurements, polarisation measurement
- Ongoing discussions if fits to Wilson coefficients to penguin decay results should be included

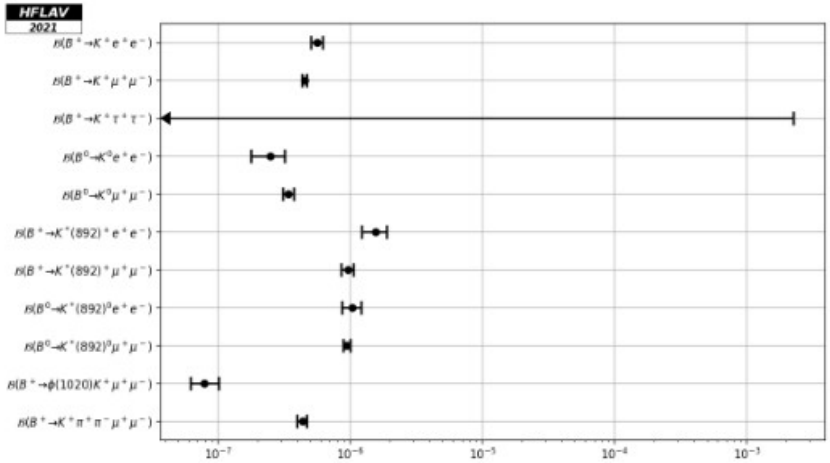
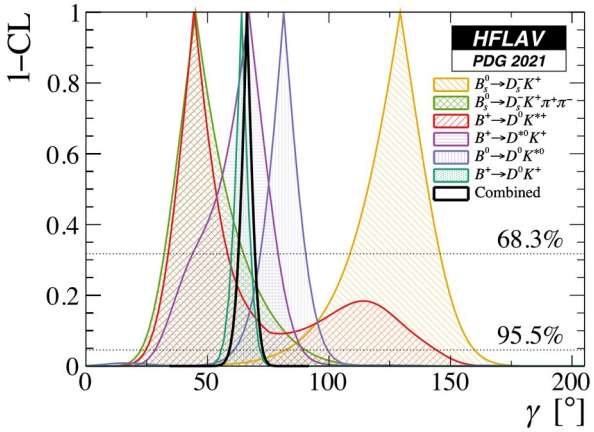


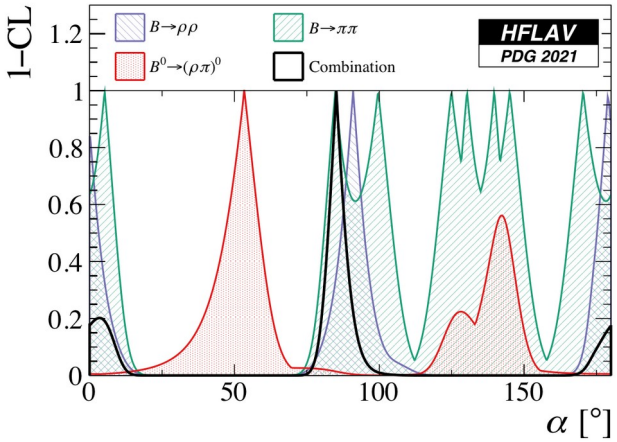
Table 245: Branching fractions of charmless semileptonic B^0 decays to LFV and LNV final states.

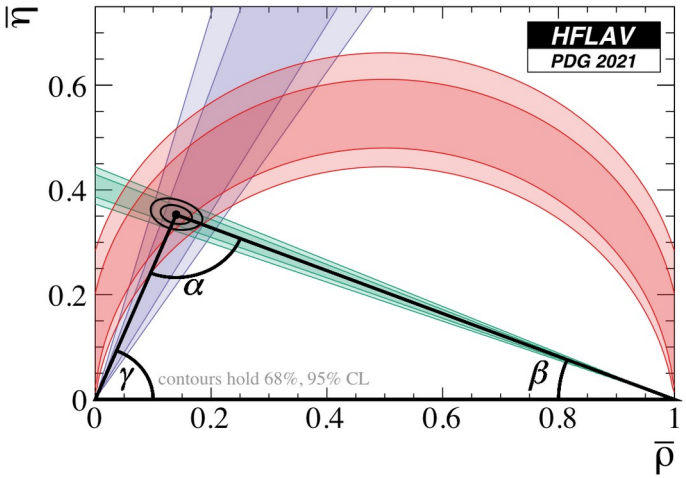
Parameter $[10^{-6}]$	Measurements		Average HFLAV PDG
$\mathcal{B}(B^0 \to K^*(892)^0 e^- \mu^+)$	Belle [1093]	< 0.12	< 0.12
	BaBar [1092]	< 0.34	
$\mathcal{B}(B^0 \to K^*(892)^0 e^+ \mu^-)$	Belle [1093]	< 0.16	< 0.16
	BaBar [1092]	< 0.53	
$\mathcal{B}(B^0 \to K^0 e^+ \mu^- + \text{c.c.})$	Belle [1076]	< 0.038	< 0.038
	BaBar [1092]	< 0.27	
$\mathcal{B}(B^0 \to \pi^0 e^+ \mu^- + \text{c.c.})$	BaBar [1091]	< 0.14	< 0.14
$\mathcal{B}(B^0 \to e^+ \mu^- + \text{c.c.})$	LHCb [1049]	< 0.001	< 0.0010
	CDF [1043]	< 0.064	
	BaBar [1117]	< 0.092	
	Belle [1118]	< 0.17	
$\mathcal{B}(B^0 \to e^+ \tau^- + \text{c.c.})$	BaBar [1141]	< 28.0	< 28
$\mathcal{B}(B^0 \to \mu^+ \tau^- + \text{c.c.})$	LHCb [1050]	< 14.0	< 14
	BaBar [1141]	< 22.0	

The details – Unitarity triangle angles

- Fits to the many different channels that provide information on the CKM angles
  - Includes combined fits to direct CPV and CPV in interference

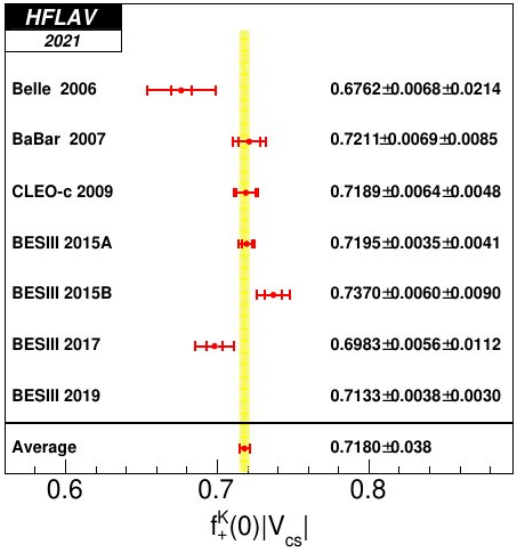


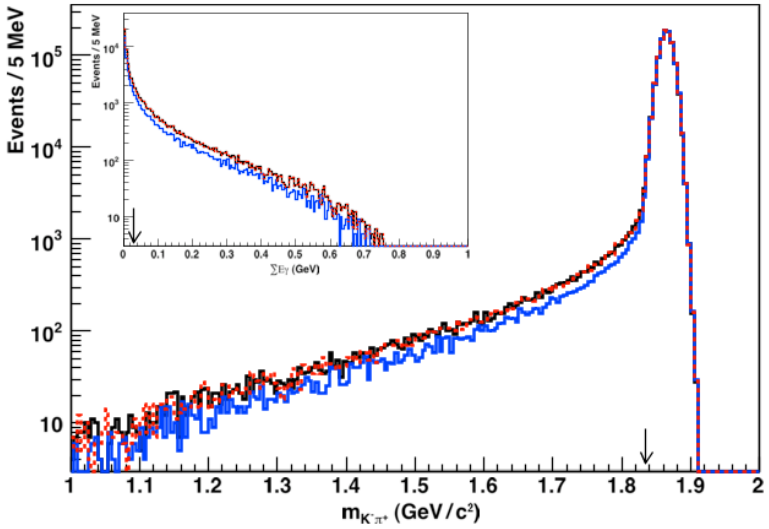




The details – Charm decays

- The groups both semileptonic and hadronic decays of charm hadrons
  - BES III has a significant impact on results in this group
  - The understanding of how FSR is treated in measurements of importance for precision BFs



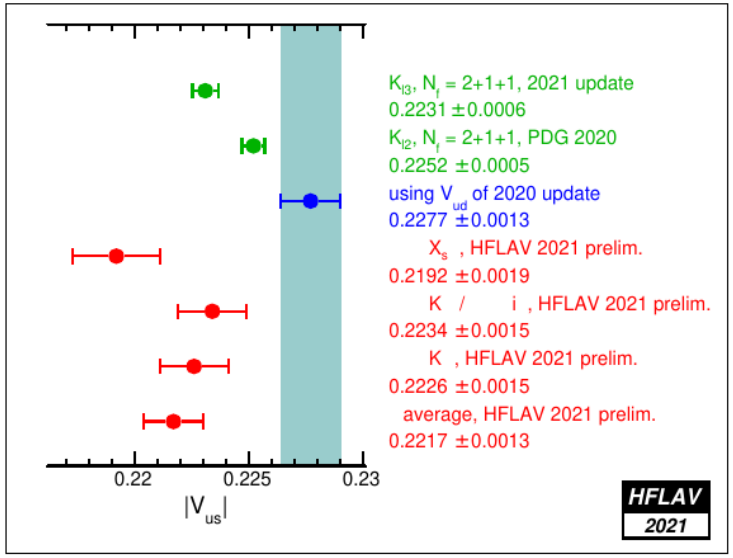


The details – Charm CPV and oscillations

- See separate presentation from Alan Schwartz in WG7

The details – Tau physics

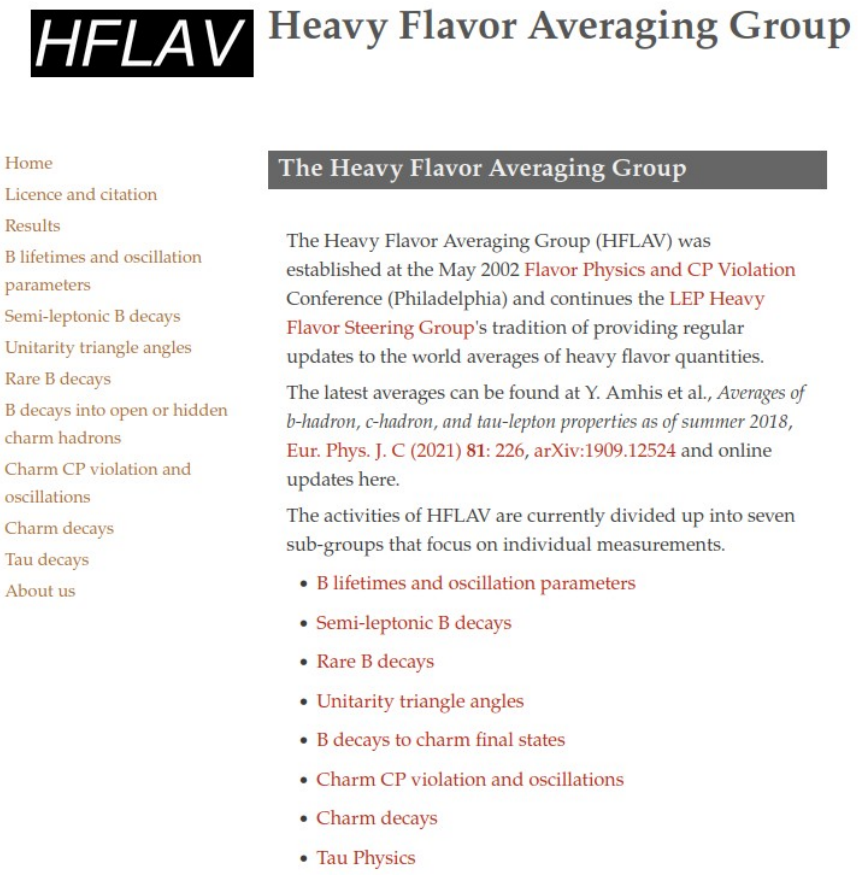
- Main part of tau group is a combined fit to all tau decay modes
- Also combination to produce $|V_{us}|$ and limits on rare decay modes



$\mathcal{B}_{103} = 3h^-2h^+\nu_\tau$ (ex. K^0)		
$(8.260 \pm 0.314) \cdot 10^{-4}$	average	
$(7.200 \pm 0.900 \pm 1.200) \cdot 10^{-4}$	ALEPH	1562
$(6.400 \pm 2.300 \pm 1.000) \cdot 10^{-4}$	ARGUS	1612
$(7.700 \pm 0.500 \pm 0.900) \cdot 10^{-4}$	CLEO	1610
$(9.700 \pm 1.500 \pm 0.500) \cdot 10^{-4}$	DELPHI	1573
$(5.100 \pm 2.000 \pm 0.000) \cdot 10^{-4}$	HRS	1611
$(9.100 \pm 1.400 \pm 0.600) \cdot 10^{-4}$	OPAL	1613

Where to find us

- The HFLAV website is the main starting point, https://hflav.web.cern.ch/
  - Here the latest averages formed and figures can be found
- Every two to three years, a long write-up is created with all information
  - Latest published version: arXiv:1909.12524, Eur. Phys. J. C (2021) 81: 226



Why not just use the PDG?

- Some differences in how averages are made
  - HFLAV takes shared systematics into account between measurements
  - Preliminary measurements can be included
  - Scaling factors of uncertainties are (in general) not used
  - External constraints (theory, other measurements, …) are added
  - FSR treatment made consistent

Modes fit	Description	$\mathcal{B}(D^0 \to K^-\pi^+)$ (%)	χ^2/(deg. of freedom)
$K^-\pi^+$	PDG 2018 [21] equivalent	$3.931 \pm 0.017 \pm 0.041$	$4.5/(8-1) = 0.64$
$K^-\pi^+$	drop Ref. [1337]	$3.937 \pm 0.017 \pm 0.041$	$4.4/(7-1) = 0.73$
$K^-\pi^+$	add Ref. [1329]	$3.913 \pm 0.006 \pm 0.033$	$5.1/(8-1) = 0.73$
$K^-\pi^+$	add FSR updates	$3.948 \pm 0.006 \pm 0.032 \pm 0.019$	$3.5/(8-1) = 0.50$
$K^-\pi^+$	add FSR correlations	$3.949 \pm 0.006 \pm 0.032 \pm 0.033$	$3.7/(8-1) = 0.53$
all	add CLEO-c, CDF, and FOCUS h^+h^-	$3.956 \pm 0.006 \pm 0.032 \pm 0.033$	$11.1/(14-3) = 1.01$
all	add BES III h^+h^-	$3.999 \pm 0.006 \pm 0.031 \pm 0.032$	$36.0/(16-3) = 2.77$

What we do not do

- While there are no official rules, we try not to duplicate effort done elsewhere
- We also limit ourselves to the “heavy” flavours
- So no
  - Top quark physics
  - Production cross sections
  - Spectroscopy
  - Strange and light hadron decays
  - Exotics

The software

- The software that HFLAV is using in general has a long history
  - Some challenges in keeping everything running on modern software stacks
    - Part of code is from 1995
  - Use Google Summer of Coding project to deal with some of the pure software aspects
  - Slowly moving towards having everything in Gitlab with continuous integration and automatic creation of web pages
  - Licensing and copyright of software is slowly formalised
    - GPLv3 for software and CC-BY-4 for text and plots

Organisation

- The individual working groups of HFLAV are relatively stand-alone
- We meet a few times a year to discuss overall strategy and to look at the overlap between different groups
  - Charm group has been split into two to reflect the increasing number of measurements
  - b-quark hadronisation averages (f_d,f_s, ...) will be dropped as they are not universal
  - Y(4S) and Y(5S) decays moved from Oscillations group to B to Charm group to reflect where numbers are used

How do I become a member of HFLAV?

- The HFLAV conveners and the working group conveners identify a need for a new member
- Looking at what task we need more activity in, we identify experiment that we seek person from
- Experiment management asked for suitable candidates that are then discussed with HFLAV
- If candidate accepts, they are part of HFLAV
- No fixed tenure at the moment. With a 5+ year cycle of updating software, create preprint, get published we look for relatively long term involvement
- Non-active members are requested to withdraw from HFLAV

Summary

- HFLAV provides an important service to the community by forming averages of complex quantities
- It is a slow but nevertheless continuously evolving group in terms of both membership and the areas covered
- We are very open to receive input on way we work, activities that should be included, typos or outright errors in reports
  - In the first instance contact Abi Soffer or myself
- Many thanks to the full HFLAV collaboration as well as the experiments for providing all the results