Inclusive b → c experiment

Christoph Schwanda
Institute of High Energy Physics
Austrian Academy of Sciences

"Challenges in semileptonic B decays"

Mainz Institute of Theoretical Physics, April 9-13, 2018

Data used in b → c inclusive analyses

BaBar	$\langle E_l^n \rangle$: n=0,1,2,3 [PRD 69, 111104 (2004), PRD 81, 032003 (2010)] $\langle M_X^{2n} \rangle$: n=1,2, 3 [PRD 81, 032003 (2010)]
Belle	$\langle E_l^n \rangle$: n=0,1,2,3 [PRD 75, 032001 (2007)] $\langle M_X^{2n} \rangle$: n=1,2 [PRD 75, 032005 (2007)]
CDF	$\langle M_X^{2n} \rangle$: n=1,2 [PRD 71, 051103 (2005)]
CLEO	$\langle M_X^{2n} \rangle$: n=1,2 [PRD 70, 032002 (2004)] $\langle E_\gamma^n \rangle$: n=1 [PRL 87, 251807 (2001)]
DELPHI	$\langle E_l^n \rangle$: n=1,2,3 $\langle M_X^{2n} \rangle$: n=1,2 [EPJ C45, 35 (2006)]

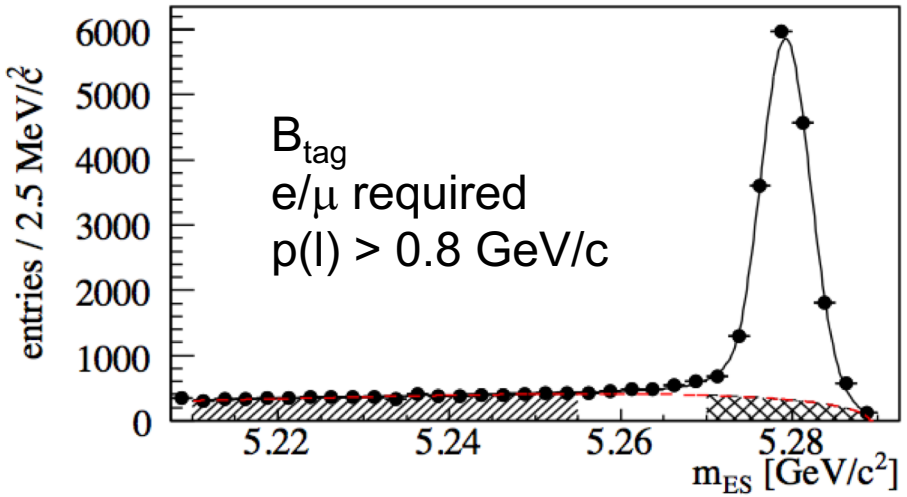
- Newest measurement is from the year 2010!

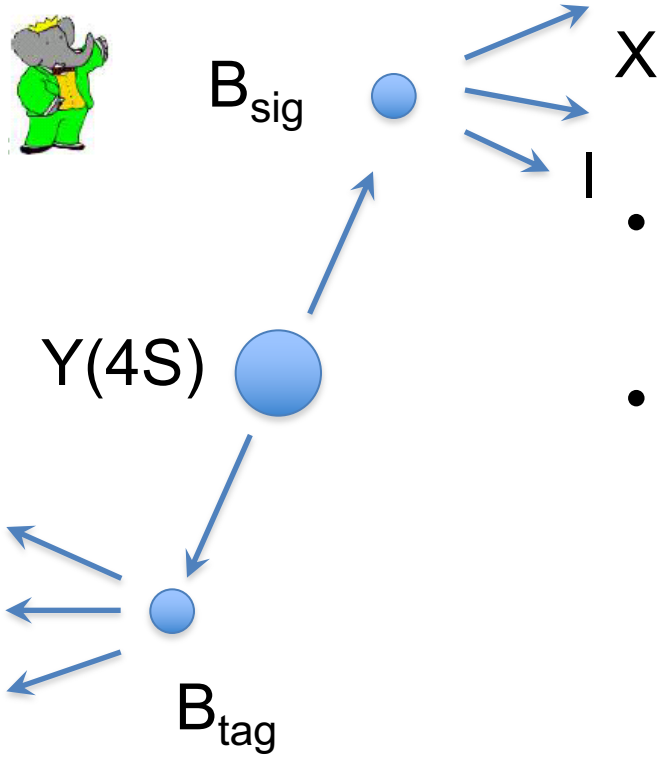
PRD 81, 032003 (2010)

BaBar hadronic moments

232M BB

- Fully reconstruct the hadronic decay of one B in Y(4S) → BB (efficiency ~0.4%, purity ~80%)





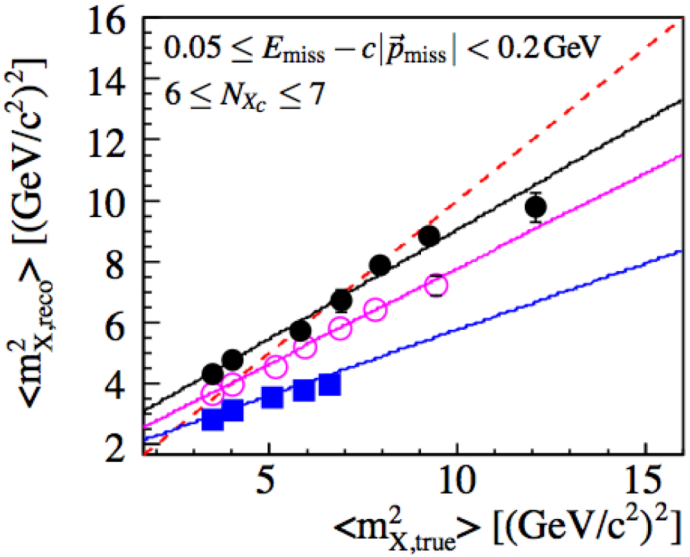
- Require one identified lepton amongst the signal-side particles (p > 0.8 GeV/c)
- Combine all remaining particles to the X system and do a kinematic fit
  - 4-momentum conservation
  - Missing mass consistent with zero mass neutrino

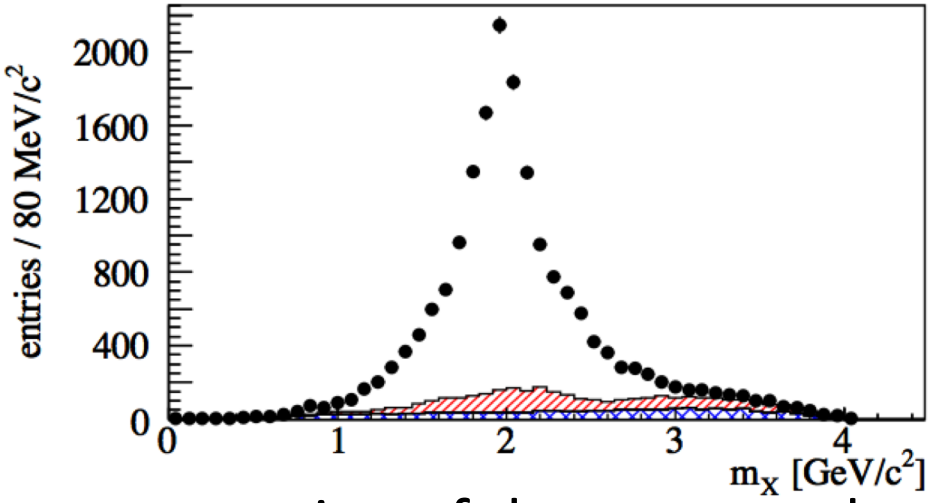
Moment measurement

PRD 81, 032003 (2010)

232M BB

- Hadronic mass spectrum after kinematic fit





- Linear correction of the measured moments in bins of X multiplicity, E_{miss}-cp_{miss} and lepton momentum

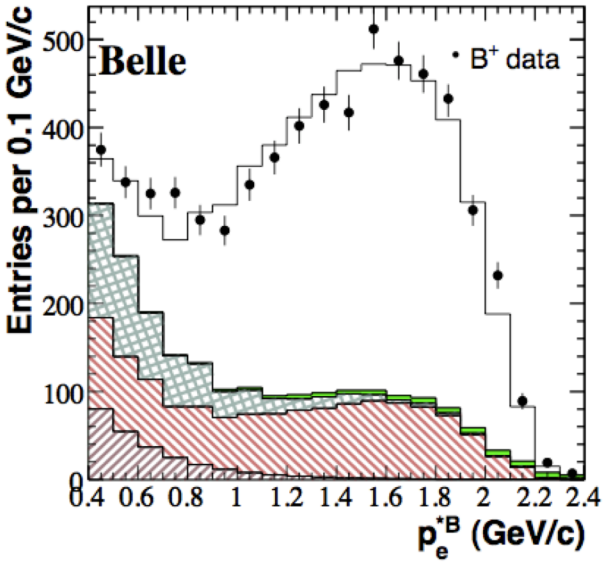
- Moments of the hadronic mass spectrum up to M^6_X for E_{cut} between 0.8 and 1.9 GeV are measured
- Also mixed mass-energy moments are determined and the electron energy moments from [PRD69, 111104] are re-evaluated

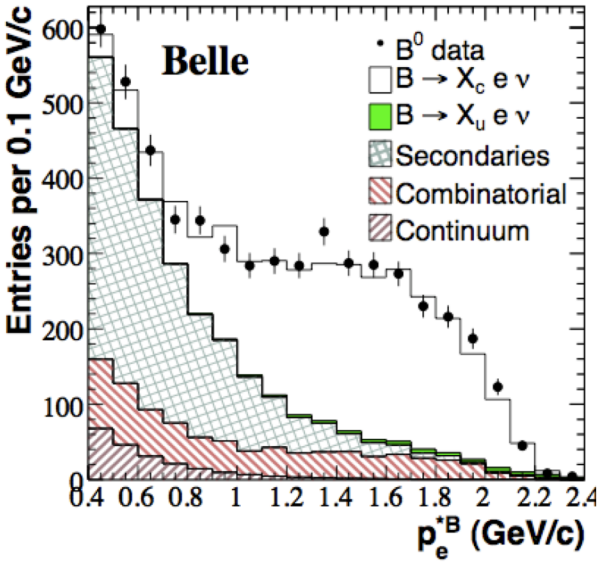
Belle E_l and M^2_X moments

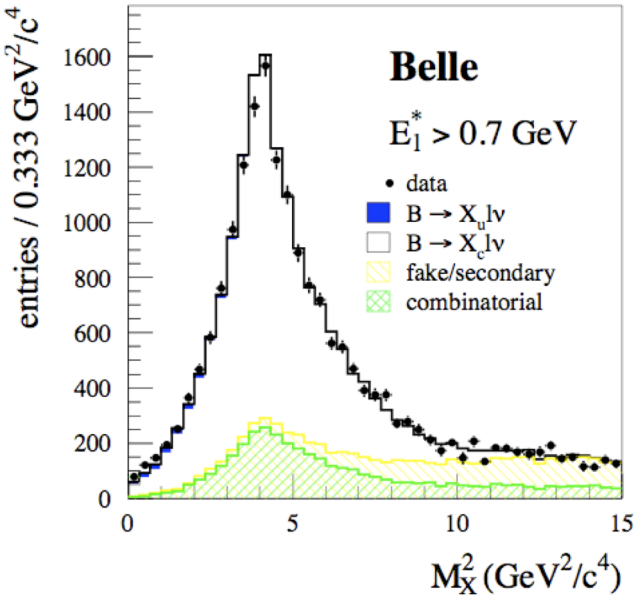
PRD 75, 032001 (2007)
PRD 75, 032005 (2007)

152M BB

- For both the E_l and M^2_X measurements, similar experimental method using fully reconstructed events
- The finite detector resolution is unfolded with SVD algorithm [NIM A372, 469 (1996)]
- $\langle E^n_e \rangle$ measured for n=0,…,4 and E_{cut}=0.4-2.0 GeV
- $\langle M^{2n}_X \rangle$ measured for n=1,2 and E_{cut}=0.7-1.9 GeV







$|V_{cb}|$ from inclusive decays

$B \to X l \nu$ $$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2\left(1+\frac{c_5(\mu)\langle O_5\rangle(\mu)}{m_b^2}+\frac{c_6(\mu)\langle O_6\rangle(\mu)}{m_b^3}+\mathcal{O}(\frac{1}{m_b^4})\right)$$

- Based on the Operator Product Expansion (OPE)
- $\langle O_i \rangle$: hadronic matrix elements (non-perturbative)
  c_i: coefficients (perturbative)
- Parton-hadron duality $\rightarrow$ the hadronic ME depend only on the initial state

	Kinetic scheme [JHEP 1109 (2011) 055]	1S scheme [PRD70, 094017 (2004)]
O(1)	m_b, m_c	m_b
$O(1/m_b^2)$	μ^2_π, μ^2_G	λ_1, λ_2
$O(1/m_b^3)$	ρ^3_D, ρ^3_{LS}	ρ_1, $\tau_{1\text{-}3}$

Moments of the E_l and M^2_X spectrum

Also other observables in B → Xlν can be expanded into an OPE with the same heavy quark parameters, e.g.,

- The n[th] moment of the (truncated) lepton energy spectrum

$$R_n(E_{\rm cut},\mu) = \int_{E_{\rm cut}} (E_\ell - \mu)^n \, \frac{{\rm d}\Gamma}{{\rm d}E_\ell} \, {\rm d}E_\ell \,, \quad \langle E_\ell^n \rangle_{E_{\rm cut}} = \frac{R_n(E_{\rm cut},0)}{R_0(E_{\rm cut},0)}$$

- The n[th] moment of the (truncated) M^2_X spectrum

$$\langle m_X^{2n} \rangle_{E_{\rm cut}} = \frac{\displaystyle\int_{E_{\rm cut}} (m_X^2)^n \, \frac{{\rm d}\Gamma}{{\rm d}m_X^2} \, {\rm d}m_X^2}{\displaystyle\int_{E_{\rm cut}} \frac{{\rm d}\Gamma}{{\rm d}m_X^2} \, {\rm d}m_X^2}$$

Master plan:

- Measure the quark masses and heavy quark parameters using moments
- Substitute them in the formula of the semileptonic width
- Determine $|V_{cb}|$ from the semileptonic branching fraction

Two sets of theoretical calculations

- Kinetic running mass
  - P. Gambino, N. Uraltsev, Eur. Phys. J. C34, 181 (2004)
  - P. Gambino, JHEP 1109 (2011) 055
  - A. Alberti, P. Gambino, K.J. Healey, S. Nandi, Phys. Rev. Lett. 114, 061802 (2015)
- 1S mass
  - C. Bauer, Z. Ligeti, M. Luke, A. Manohar, M. Trott, Phys. Rev. D70, 094017 (2004)
- Non-perturbative parameters in the $1/m_b$ expansion

	Kinetic scheme	1S scheme
O(1)	m_b, m_c	m_b
$O(1/m^2_b)$	μ^2_π, μ^2_G	λ_1, λ_2
$O(1/m^3_b)$	ρ^3_D, ρ^3_{LS}	ρ_1, $\tau_{1\text{-}3}$

Moments used in the HFLAV analysis

HFLAV

Summer 2016

Experiment	Hadron moments $\langle M_X^n \rangle$	Lepton moments $\langle E_\ell^n \rangle$
BABAR	$n = 2,\ c = 0.9, 1.1, 1.3, 1.5$ $n = 4,\ c = 0.8, 1.0, 1.2, 1.4$ $n = 6,\ c = 0.9, 1.3$ [495]	$n = 0,\ c = 0.6, 1.2, 1.5$ $n = 1,\ c = 0.6, 0.8, 1.0, 1.2, 1.5$ $n = 2,\ c = 0.6, 1.0, 1.5$ $n = 3,\ c = 0.8, 1.2$ [495, 496]
Belle	$n = 2,\ c = 0.7, 1.1, 1.3, 1.5$ $n = 4,\ c = 0.7, 0.9, 1.3$ [497]	$n = 0,\ c = 0.6, 1.4$ $n = 1,\ c = 1.0, 1.4$ $n = 2,\ c = 0.6, 1.4$ $n = 3,\ c = 0.8, 1.2$ [498]
CDF	$n = 2,\ c = 0.7$ $n = 4,\ c = 0.7$ [499]	
CLEO	$n = 2,\ c = 1.0, 1.5$ $n = 4,\ c = 1.0, 1.5$ [500]	
DELPHI	$n = 2,\ c = 0.0$ $n = 4,\ c = 0.0$ $n = 6,\ c = 0.0$ [489]	$n = 1,\ c = 0.0$ $n = 2,\ c = 0.0$ $n = 3,\ c = 0.0$ [489]

- 23 measurements from BaBar, 15 measurements from Belle, 12 from other experiments

Kinetic scheme analysis

HFLAV

Summer 2016

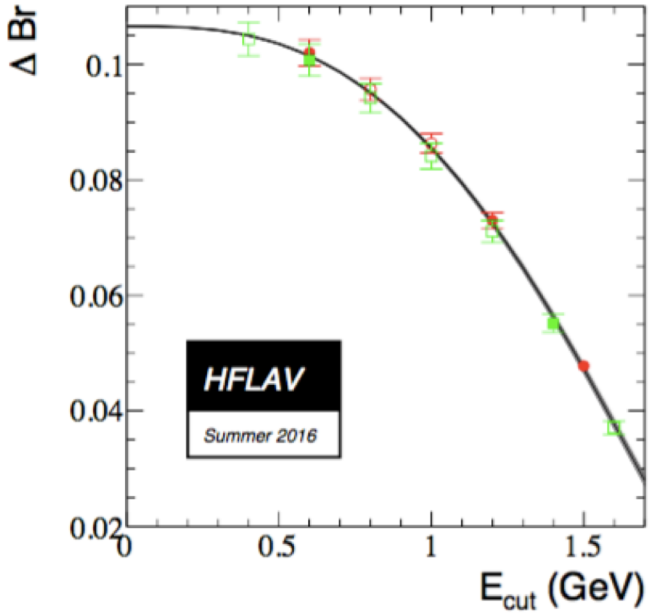
	$\lvert V_{cb}\rvert$ $[10^{-3}]$	$m_b^{\rm kin}$ [GeV]	$m_c^{\overline{\rm MS}}$ [GeV]	μ_π^2 [GeV^2]	ρ_D^3 [GeV^3]	μ_G^2 [GeV^2]	ρ_{LS}^3 [GeV^3]
value	42.19	4.554	0.987	0.464	0.169	0.333	−0.153
error	0.78	0.018	0.015	0.076	0.043	0.053	0.096
$\lvert V_{cb}\rvert$	1.000	−0.257	−0.078	0.354	0.289	−0.080	−0.051
$m_b^{\rm kin}$		1.000	0.769	−0.054	0.097	0.360	−0.087
$m_c^{\overline{\rm MS}}$			1.000	−0.021	0.027	0.059	−0.013
μ_π^2				1.000	0.732	0.012	0.020
ρ_D^3					1.000	−0.173	−0.123
μ_G^2						1.000	0.066
ρ_{LS}^3							1.000

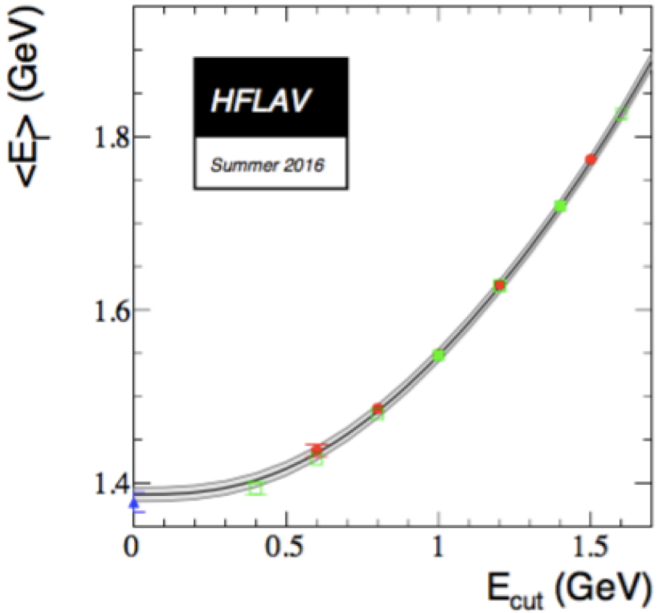
$$\mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.65 \pm 0.16)\%$$

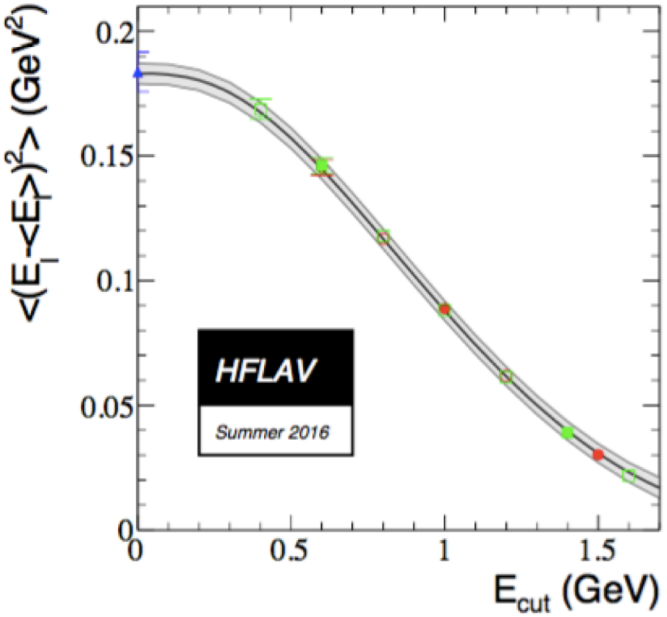
χ^2 of 15.6 for 43 degrees of freedom.

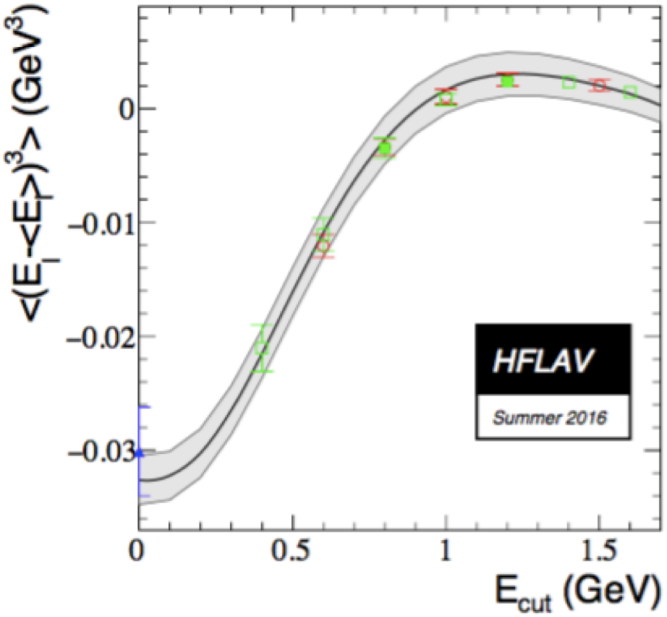
- c quark mass constraints $m_c^{\overline{\rm MS}}(3\ {\rm GeV}) = 0.986 \pm 0.013\ {\rm GeV}$
- Average B lifetime: (1.579 +/- 0.004) ps

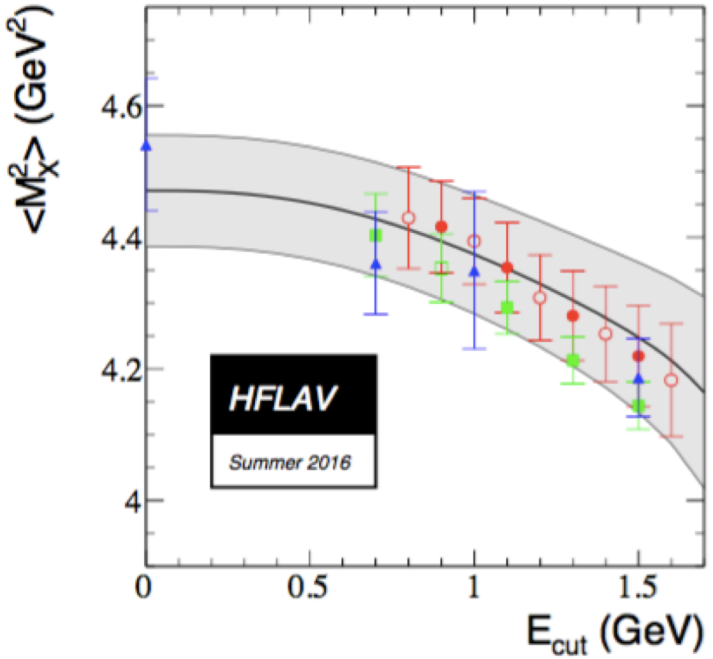
- BaBar
- Belle
- Other

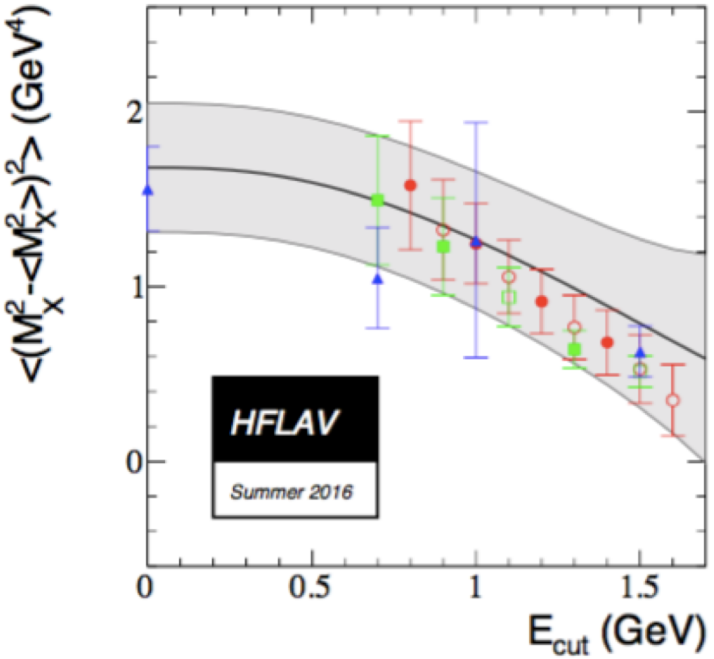




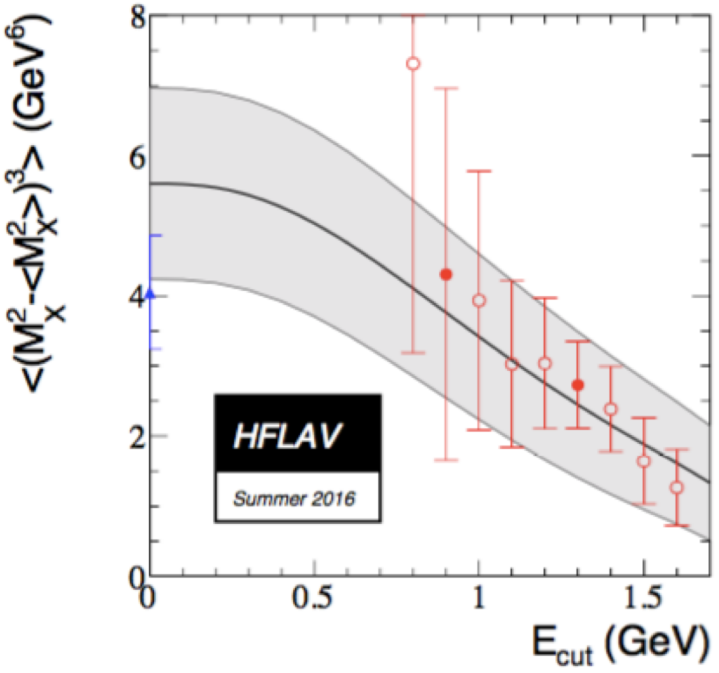








- BaBar
- Belle
- Other



1S scheme analysis

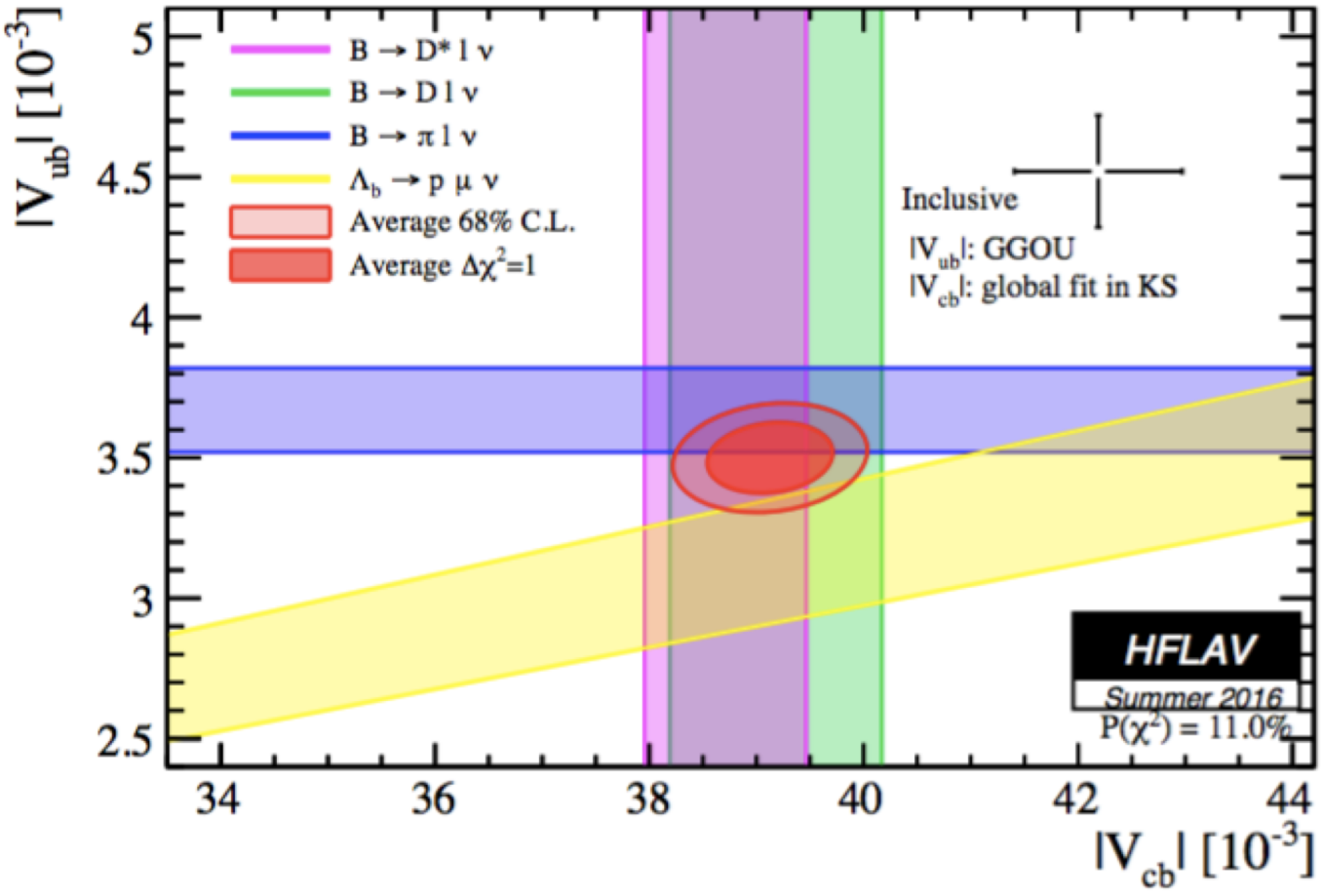
HFLAV

Summer 2016

	m_b^{1S} [GeV]	λ_1 [GeV^2]	ρ_1 [GeV^3]	τ_1 [GeV^3]	τ_2 [GeV^3]	τ_3 [GeV^3]	$\lvert V_{cb}\rvert$ [10^{-3}]
value	4.691	−0.362	0.043	0.161	−0.017	0.213	41.98
error	0.037	0.067	0.048	0.122	0.062	0.102	0.45
m_b^{1S}	1.000	0.434	0.213	−0.058	−0.629	−0.019	−0.215
λ_1		1.000	−0.467	−0.602	−0.239	−0.547	−0.403
ρ_1			1.000	0.129	−0.624	0.494	0.286
τ_1				1.000	0.062	−0.148	0.194
τ_2					1.000	−0.009	−0.145
τ_3						1.000	0.376
$\lvert V_{cb}\rvert$							1.000

χ^2 of 23.0 for 59 degrees of freedom

- B quark mass constrained with B $\rightarrow$ X_s γ data
- Average B lifetime: (1.579 +/- 0.004) ps


$|V_{ub}|$ $[10^{-3}]$
$|V_{cb}|$ $[10^{-3}]$
5
4.5
4
3.5
3
2.5
34
36
38
40
42
44
$B \to D^* l \nu$
$B \to D l \nu$
$B \to \pi l \nu$
$\Lambda_b \to p \mu \nu$
Average 68% C.L.
Average $\Delta\chi^2$=1
Inclusive
$|V_{ub}|$: GGOU
$|V_{cb}|$: global fit in KS
HFLAV
Summer 2016
$P(\chi^2)$ = 11.0%

Summary

- HFLAV analysis
  - While we see a good agreement between data and theory and between theory frameworks, there is a ~3σ disagreement between $|V_{cb}|$ inclusive/exclusive (3.2σ for D*, 2.4σ for D)
- Prospects for experiments
  - Measurements are old and should be updated to the full data sets
  - Experimental correlations are not fully available and thus not accounted in the present analysis
  - LHCb can and should also work on this measurement