Semileptonic B decays

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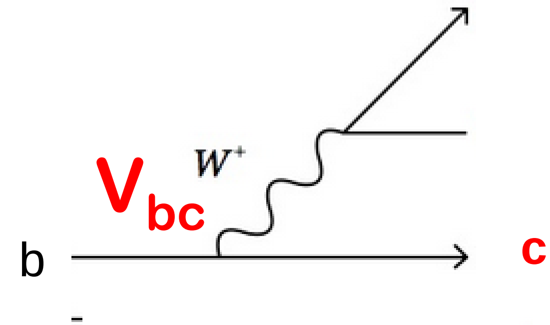
Quark Confinement and the Hadron Spectrum XI

7-12 September 2014
St. Petersburg

Overview

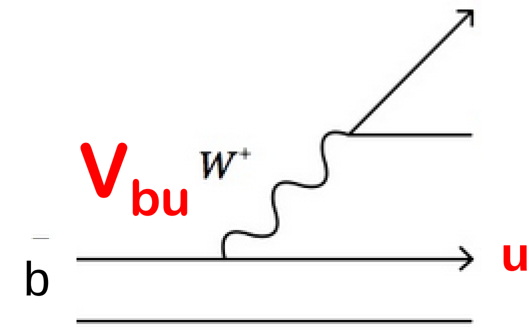
$b \to c\, l\, \nu$

- Exclusive $B \to D^{(*)} \ell \nu$,
- Inclusive $B \to X_c\, \ell \nu$



$b \to u\, l\, \nu$

- Exclusive $B \to \pi\, (\ldots) \ell \nu$,
- Inclusive $B \to X_u\, \ell \nu$



Most precise determination of $|V_{ub}|$ $|V_{cb}|$

- **Tension between inclusive and exclusive determinations**
- **Low mass open charm spectrum**
- **BSM when $\ell \to \tau$**

Exclusive decays $B \to D^{(*)} \ell \nu$

$$\frac{d\Gamma}{d\omega}(B \to D^* (D)) \propto |V_{cb}|^2 (\omega^2 - 1)^{1/2\ (3/2)} \mathcal{F}(\omega)^2 (G(\omega)^2)$$

$$\omega = \frac{p_{D(*)} \cdot p_B}{m_B\, m_{D(*)}}$$

Standard Step by Step

Comparison with data at a kinematically not suppressed point $\mathcal{F}(\omega)^2 |V_{cb}|^2$

Extrapolation at zero-recoil point ω=1

↑ dependence on parameterization

Perturbative and non-perturbative $1/m^n_{c,b}$ corrections to unity form factors (in HF limit)

↑ pertubative order: complete α_s^2 at zero recoil

Czarnecki, Melnikov 1996-99

$|V_{cb}|$ extraction

$B \to D^* \ell \nu$

Generally Preferred

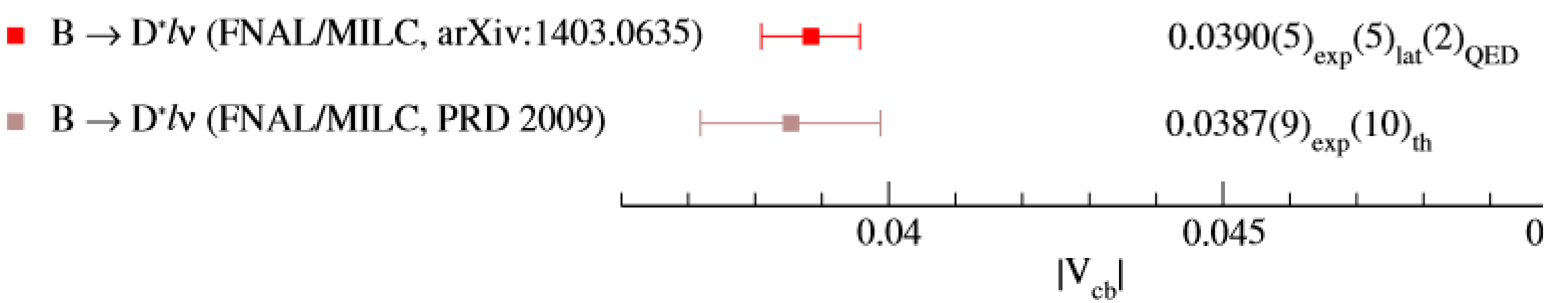
- ✓ less suppressed at zero recoil: $(\omega^2\text{-}1)^{1/2}$ (rather than $(\omega^2\text{-}1)^{3/2}$)
- ✓ vanishing corrections order 1/m (Luke's theorem)

✓ Latest from Lattice

-first unquenched calculation
includes loops of sea quarks, up, down, strange Nf=2+1

$$\mathcal{F}(1) = 0.906 \pm 0.004 \pm 0.012$$

Bailey et al. Fermilab/MILC 1403.0635



Bailey, lattice 14

Central value unchanged, total uncertainty on |Vcb| reduced to 1.9%;
lattice and exp errors commensurate

$B \to D^* \ell \nu$

✓ Important to have additional LQCD calculations

-Preliminary results ETM Nf=2 ensembles (“ratio method” to reduce errors) in agreement

Atoui 1305.0462

-only quenched results at the non-recoil point («step scaling» method, alternative to HQET)

de Divitiis et al 0707.0582

✓ Comparison with most recent zero recoil sum rules

$$\mathscr{F}(1) = 0.86 \pm 0.02$$

Gambino, Mannel, Uraltsev, 1206.2296+HFAG 12
Gambino Schwanda 1307.4551

-Slightly lower average than LQCD ($\to$ higher $|V_{cb}|$)

-Much larger th error (More than twice on $|V_{cb}|$)

$B \to D \ell\nu$

✓ Latest from Lattice

unquenched calculations at non-zero recoil full kinematic range

Qiu et al Fermilab/MILC 1312.0155

-same valence-quark actions and ensembles than B -> D*
consistent $|V_{cb}|$ (less precise :total uncertainty of about 5%)

-Heavy-quark discretization errors largest source of uncertainty
work in progress to reduce it

Jang et al SWME, MILC, and Fermilab 1311.5029

✓ Non-lattice

heavy quark expansion (+ BPS limit)

Uraltsev 04
+PDG 0312001

$$\mathcal{G}(1) = 1.04 \pm 0.02$$

-Consistently lower than unquenched
-Exp+th on $|V_{cb}|$ uncertainty comparable with LQCD

Prospects

✓ Experimental progress

- high statistics at LHCb for $B \to D^{(*)} l \nu$; however, at B factories fully reconstruction of B (or conjugate) helps measurements in presence of missing neutral particle (ν)

-Belle II estimated error on $|V_{cb}|$ at 75 ab^{-1} is about 1%

✓ Lattice attacking $B_s \to D_s l \nu$

-More affordable on lattice: light spectator fixed to its known mass (m_s) and no extrapolation in the light quark mass needed

-Modification of step scaling method — Blossier et al(ETM Collab). 0909.3187

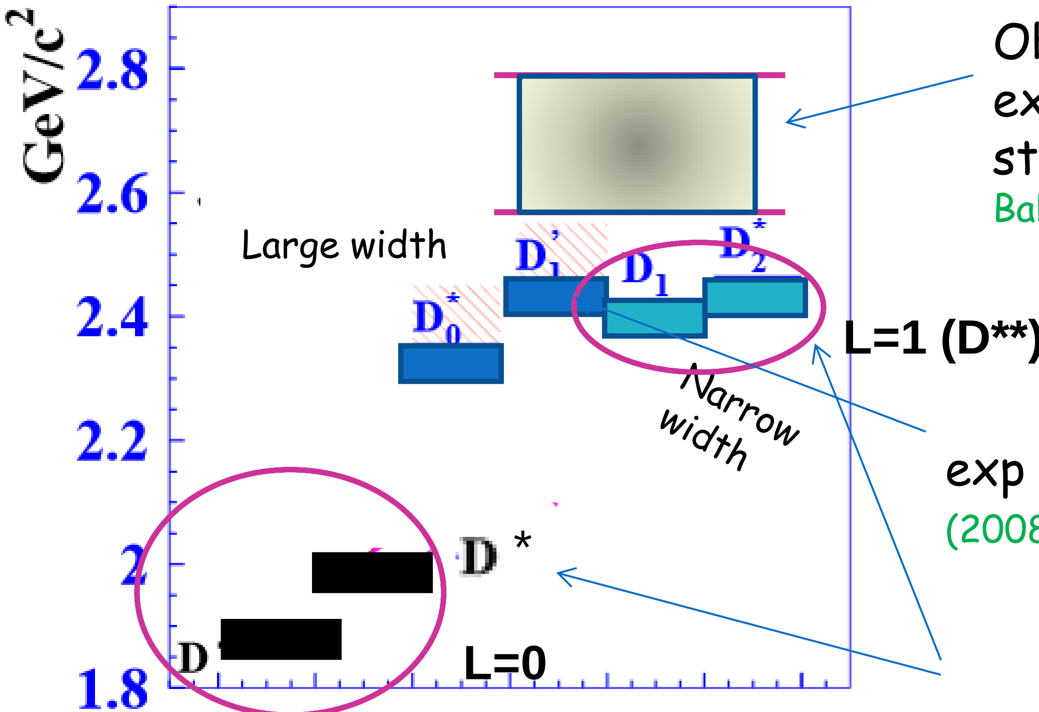
-Agreement with SR data $\mathcal{G}(1) = 1.052(46)$ — Atoui et al 1310.5238

✓ Extraction from baryonic decays at hadronic machines,(exp hard) $\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}$ — Stone and Zhang 1402.4205

Exclusive summary

Exclusive decay	$\mathbf{|V_{cb}| \times 10^3}$
$\bar{B} \to D^* \, l \, \bar{\nu}$	
FNAL/MILC (Lattice unquenched 2014)	$39.04 \pm 0.49_{\rm exp} \pm 0.53_{\rm QCD} \pm 0.19_{\rm QED}$
HFAG (Lattice unquenched 2012)	$39.54 \pm 0.50_{\rm exp} \pm 0.74_{\rm th}$
Rome (Lattice quenched $\omega \neq 1$ 2008)	$37.4 \pm 0.5_{\rm exp} \pm 0.8_{\rm th}$
HFAG (Sum Rules 2012)	$41.6 \pm 0.6_{\rm exp} \pm 1.9_{\rm th}$
$\bar{B} \to D \, l \, \bar{\nu}$	
FNAL/MILC (Lattice unquenched $\omega \neq 1$ 2013)	$38.50 \pm 1.9_{\rm exp+lat} \pm 0.2_{\rm QED}$
PDG (HQE + BPS 2012)	$40.6 \pm 1.5_{\rm exp} \pm 0.8_{\rm th}$
Rome (Lattice quenched $\omega \neq 1$ 2009)	$41.6 \pm 1.8 \pm 1.4 \pm 0.7_{FF}$

Low mass open charm spectrum



Observed candidates for radial excitations and L=2 excited states
Babar (2010) , LHCb (2013)

exp tension $B \to D'_1$ l ν Babar (2008) , Belle (2004)

Well established (PDG)

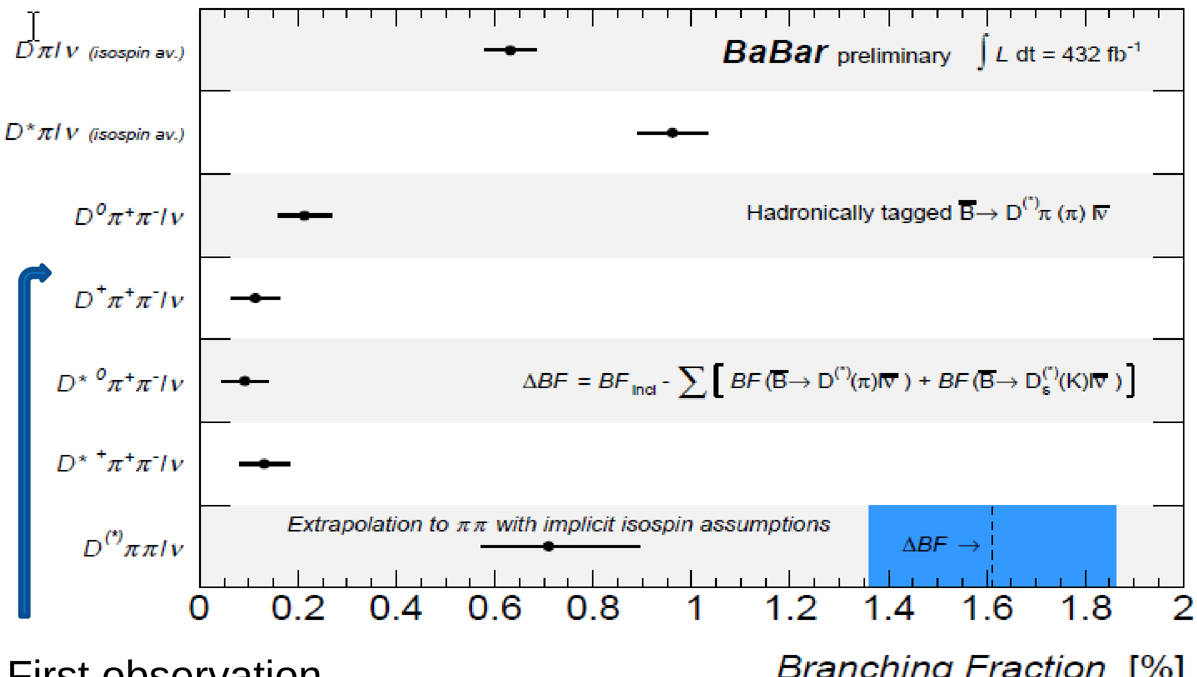
higher mass charm states background events to $B \to D^{(*)}$ l ν
(e.g. via $B \to D^{**}$ l ν)

Theoretical puzzles

1) BR for inclusive B → X_c l ν not saturated by sum of exclusive BR (gap puzzle)

-Decays into $D^{(*)}$ make up ~ 70% of total inclusive B → X_c l ν rate
-Decays into D^{**} make up ~ 15% of total inclusive B → X_c l ν rate

Leaves a gap of about 15%



First observation

Closing the gap experimentally?

assigning about 0.7% to B → D(*) π π l ν production, significance reduced from 7σ to 3σ.

Luck (Babar) ICHEP 2014

In the HQ limit $j_l = L \otimes s_l$

P-wave mesons can be grouped into two doublets:

j_l=1/2

strongly decays only though S-waves-> broad states

j_l=3/2

strongly decays only though D-waves-> narrow states

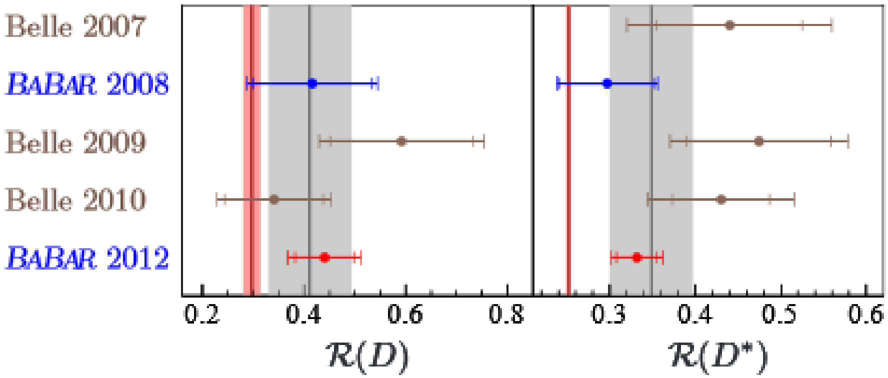
2) narrow width dominates over large width states (sum rules + HQ, quark models) Le Yaouanc et al 96, Uraltsev 2001, Morenas et al. 1997, Ebert et al. 1998, Leibovich et al. 2007, Bigi et al. 2007....)

not confirmed by data (1/2 vs 3/2 puzzle) Belle, Babar 06

- ✓ Relevance of the infinite mass limit approach in $b \to c$ decay
- ✓ Background for $|V_{ub}|$

$B \to D^{(*)} \tau \nu_\tau$

B factories



$$\mathcal{R}^*_{\tau/l} \equiv \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* l \nu)} = 0.332 \pm 0.024 \pm 0.018$$

$$\mathcal{R}_{\tau/l} \equiv \frac{\mathcal{B}(B \to D \tau \nu)}{\mathcal{B}(B \to D l \nu)} = 0.440 \pm 0.058 \pm 0.018$$

Babar 2012 1205.5442

$\mathcal{R}_{\tau/l}(SM) = 0.297 \pm 0.017$ **2.7σ**

Combined **3.4σ**

$\mathcal{R}^*_{\tau/l}(SM) = 0.252 \pm 0.003$ **2.0σ**

✓ Agreement with Belle sample 657 x 10^6 B pair events — Belle 0910.4301.

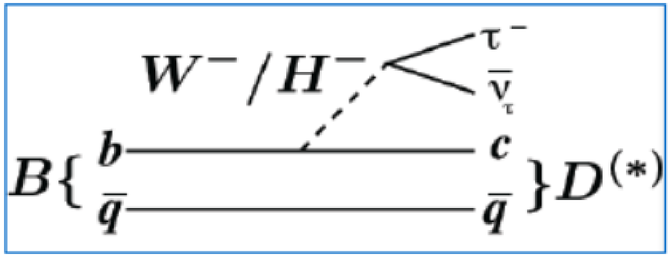
✓ NP breaking of lepton-flavour universality?

compare with $B \to \tau \nu_\tau$

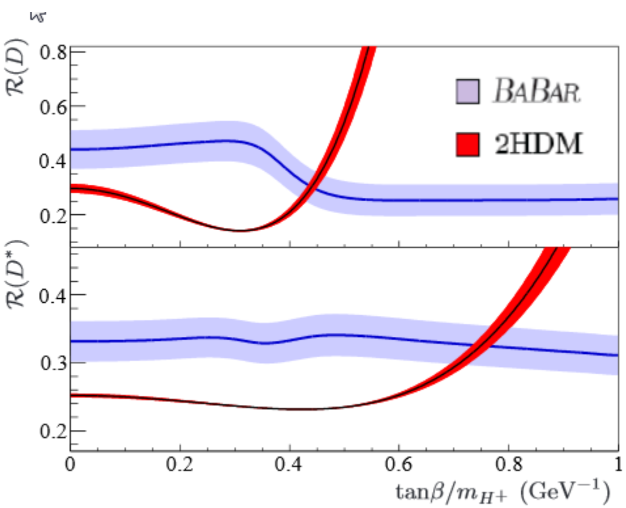
Previous disagreement with SM; **now** (with full Belle data set) consistency
Belle 1208.4678

Awaiting for Belle update with full data set (772 x 10^6 B pairs)

New charged Higgs?



2HDM:
Type I: only one Higgs doublet couples to fermions
Type II: one Higgs couples to up-type fermions and the other to down-type quarks (MSSM)



SM

- ✓ Excludes type II 2HDM charged Higgs boson with 99.8% CL ($m_{H+} > 10$ GeV)
  (Region with $m_{H+} < 10$ GeV already excluded by $B \to X_s \gamma$ measurements)

Misiak 0609232

Babar 2012 1205.5442

Inclusive decays $B \rightarrow X_c\, l\, \nu$

$$\Gamma(B \to X_q l \nu) = \frac{G_F^2 m_b^5}{192\pi^3}|V_{qb}|^2 \left[c_3 < O_3 > + c_5 \frac{< O_5 >}{m_b^2} + c_6 \frac{< O_6 >}{m_b^3} + O\left(\frac{1}{m_b^4}\right)\right]$$

OPE factorization of short and long distance dynamics

✓ Scheme dependence (quark mass definition:1S, kinetic, etc.)

✓ Kinetic scheme

- Complete $O(a_s{}^2)$ corrections to leading term (parton model)+BLM terms $a_s{}^{n+1}\,\beta_0{}^n$
  [Melnikov , Czarnecki, Pak , Biswas , Gambino ,...]
- Complete $\alpha_s \frac{\Lambda^2}{mb^2}$ [Becher, Boos, Lunghi, Alberti , Ewerth, Gambino, Nandi ,...]
- $O(1/mb^{2,3})$ known, $O(\Lambda/m_b{}^{4,5})$ estimated
  [Gremm, Kapustin, Dassinger, Turczyk, Mannel , Gambino, Bigi, Uraltsev, Zwicky ...]
- $\log mc, 1/mc^2$ ... intrinsic charm estimates
  [Breidenbach, Feldmann, Mannel, Turczyk, Bigi, Mannel, Uraltsev, ...]
- Threshold resumming (double Sudakov-like logs) not relevant (cut off by the mc mass)
  Di Giustino, GR, Trentadue 11, ..

Global fit results

width + hadron, lepton momenta: about 70 measurements available (80% from B factories)

Additional constraint to increase precision estimate in m_b
photon energy moments in $B \to X_s \gamma$, or a precise constraint on m_c

Constraint	$\lvert V_{cb}\rvert$ (10^{-3})
$B \to X_s\gamma$	$41.94 \pm 0.43_{\rm fit} \pm 0.59_{\rm th}$
$m_c^{\overline{\rm MS}}(3\ {\rm GeV})$	$41.88 \pm 0.44_{\rm fit} \pm 0.59_{\rm th}$

kinetic scheme HFAG 12 $\frac{\delta V_{cb}}{V_{cb}} < 2\%$

to compare with excl $\sim 2\%$

Latest global fits in kinetic scheme (mc constraint)

$$|V_{cb}| = (42.42 \pm 0.86) \times 10^{-3}$$

Gambino Schwanda 2014

Including α_s/m_b^2 : error decreases

$$|V_{cb}|_{inc} = (42.42 \pm 0.81) \times 10^{-3}$$

Healey ICHEP 2014

Incorporating α_s/m_b^3 in progress

$|V_{cb}|$ summary

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$\bar{B} \to D^* l \bar{\nu}$	
FNAL/MILC (Lattice unquenched 2014)	$39.04 \pm 0.49_{exp} \pm 0.53_{QCD} \pm 0.19_{QED}$
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Inclusive decays	
HFAG ($B_s \to X_s \gamma$ constraint)	$41.94 \pm 0.43_{fit} \pm 0.59_{th}$
HFAG (m_c constraint)	$41.88 \pm 0.44_{fit} \pm 0.59_{th}$
Gambino, Schwanda 2014	42.42 ± 0.86

3σ disagreement

Future:

- CLEO →≈50-70 more stat B factories →≈50 more stat Belle II
- LHCb: about 5 million $B \to D^* \mu \nu$ decay no prospects for $|V_{cb}|$ measurement

| V_{ub} | exclusive detemination

❑ Traditionally extracted by the decay $B \to \pi \ell \nu$ (only a single form factor in massless limit)

$$\frac{d\Gamma(\overline{B}^0 \to \pi^+ \ell \bar{\nu})}{dq^2} = \frac{G_F^2 |\vec{p}_\pi|^3}{24\pi^3} |V_{ub}|^2 \, |f_+(q^2)|^2$$

$$\langle \pi^+(p) | \bar{u}\gamma_\mu b | \bar{B}^0(p+q) \rangle = f_+(q^2)\,(2p_\mu + q_\mu)$$

Non-pert th predictions for f_+ usually confined to regions of q^2

Complementarity

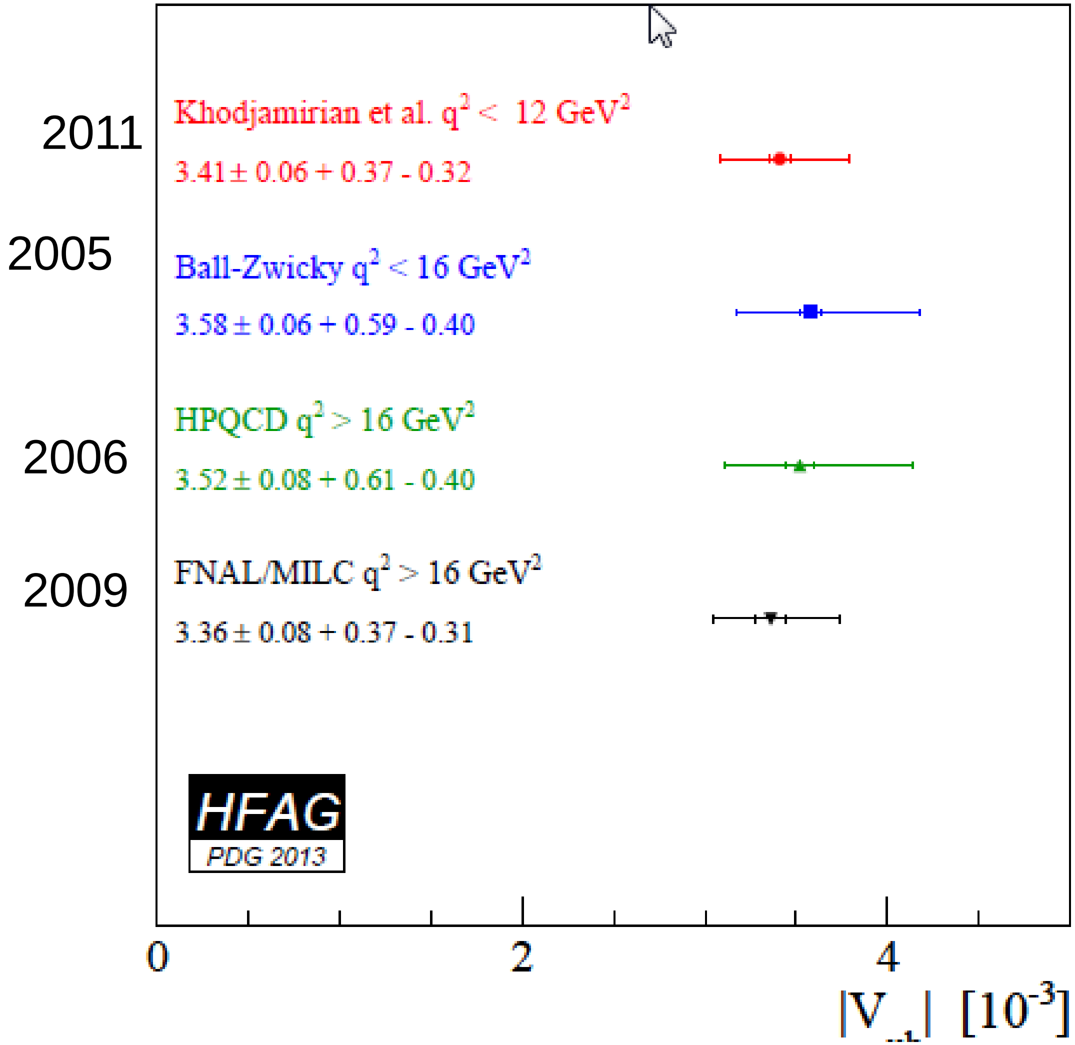
✓ Light Cone Sum Rules LCSR low q^2 regions $\sim < 16$ GeV
(OPE near the light-cone)

LCSR Khodjamirian et al 11, BGL: Boyd, Grinstein, Lebed, …

✓ Lattice large $q^2 \sim > 16$ GeV (to avoid large discretization errors)
Better fit with data

[Unquenched HPQCD 07, FNAL/MILC 09, ma preliminary from ALPHA, HPQCD, FNAL/MILC, RBC/UKQCD 2012

$|V_{ub}|$ HFAG exclusive detemination



also
simultaneous fit of the BCL parameterization to data and LQCD calculations (all q^2 range)

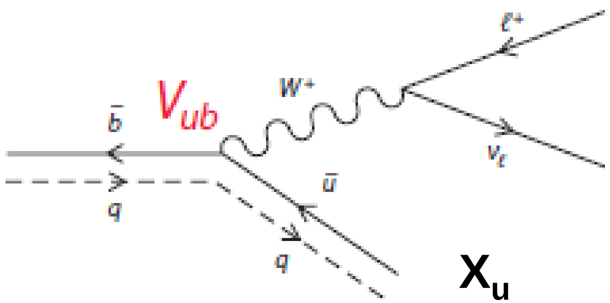
$|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$

new players

X_u	Theory	q^2 GeV/c^2	$\lvert V_{ub}\rvert$ 10^{-3}
π^0	LCSR [33]	< 12	$3.35 \pm 0.23 \pm 0.09^{+0.38}_{-0.31}$
	LCSR [34]	< 16	$3.63 \pm 0.20 \pm 0.10^{+0.60}_{-0.40}$
	HPQCD [35]	> 16	$3.44 \pm 0.31 \pm 0.09^{+0.59}_{-0.39}$
	FNAL [36]		$3.29 \pm 0.30 \pm 0.09^{+0.37}_{-0.30}$
π^+	LCSR [33]	< 12	$3.40 \pm 0.13 \pm 0.09^{+0.37}_{-0.32}$
	LCSR [34]	< 16	$3.58 \pm 0.12 \pm 0.09^{+0.59}_{-0.39}$
	HPQCD [35]	> 16	$3.81 \pm 0.22 \pm 0.10^{+0.66}_{-0.43}$
	FNAL [36]		$3.64 \pm 0.21 \pm 0.09^{+0.40}_{-0.33}$
ρ^0	LCSR [24]	< 16	$3.56 \pm 0.11 \pm 0.09^{+0.54}_{-0.37}$
	BM [37]	full range	$3.76 \pm 0.11 \pm 0.10^{+0.31}_{-0.25}$
	UKQCD [38]		$3.68 \pm 0.10 \pm 0.10^{+0.29}_{-0.34}$
	ISGW2 [25]		$3.98 \pm 0.11 \pm 0.10$
ρ^+	LCSR [24]	< 16	$3.51 \pm 0.16 \pm 0.13^{+0.53}_{-0.38}$
	BM [37]	full range	$3.66 \pm 0.15 \pm 0.14^{+0.30}_{-0.24}$
	UKQCD [38]		$3.59 \pm 0.15 \pm 0.13^{+0.28}_{-0.33}$
	ISGW2 [25]		$3.87 \pm 0.16 \pm 0.15$
ω	LCSR [24]	< 12	$3.08 \pm 0.29 \pm 0.11^{+0.44}_{-0.31}$
	ISGW2 [25]	full range	$3.03 \pm 0.23 \pm 0.11$

Babar PRD88 (2013) 032005

Inclusive $|V_{ub}|$



large $b \rightarrow c$ background $(|V_{cb}/V_{ub}|^2 \approx 100)$

Need experimental phase space cuts to reduce background; in general

$$m_X \ll E_X$$

Phase space regions where OPE fails become dominant; new unwelcome effects (with respect to semileptonic $b \rightarrow c$):

- Final gluon radiation strongly inhibited: soft and collinear singularities
- perturbative expansion of spectra affected by large logarithms

$$\alpha_s^n \ \log^{2n}(2\,E_X/m_X)$$

  to be resummed at all orders in PT

- non-perturbative effects related to a small vibration of the b quark in the B meson (Fermi motion) enhanced

- Experimental progress
  - Belle & Babar results access 90% data

- Theoretical approaches (HAFG averages)
  - predictions based on parameterizations of shape function, and OPE constraints

    Bosch, Lange, Neubert , Paz, Gambino, Giordano, Ossola, Uraltsev , …

  - predictions based on resummed pQCD

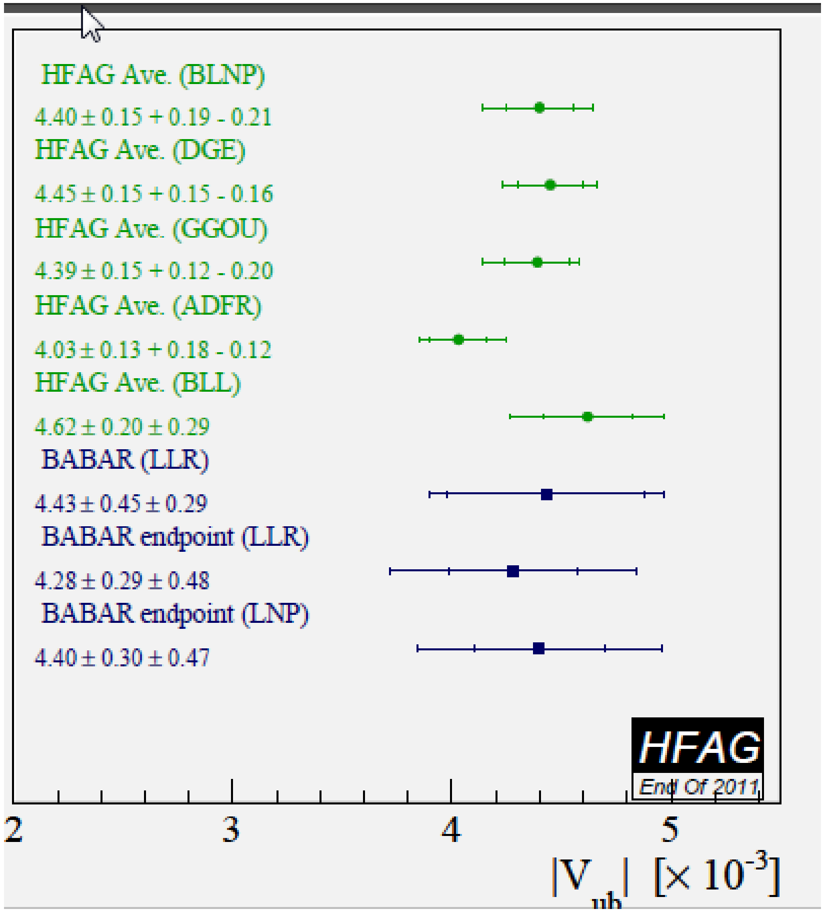
    Andersen, Gardi, Aglietti, Di Lodovico, Ferrera , GR

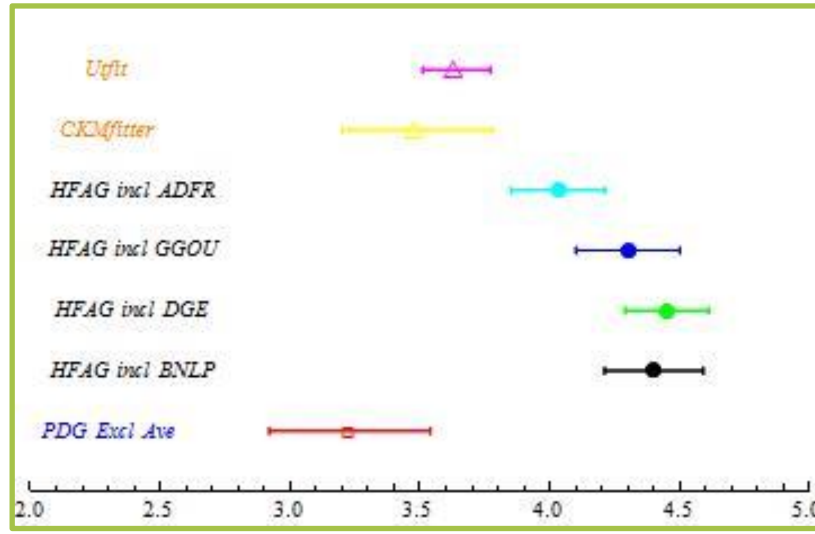
  - global fit of shape function, $|V_{ub}|$ and m_b

    Tackmann, Lacker, Ligeti, Stewart…

Results averages: Long lasting puzzle

Inclusive





Space for NP reducing (?)
Pokorski Crivellin 1407.1320

At SuperFlavour factories (75 ab^{-1}) errors expected to reduce to 3 % (excl) 2% (incl)

Conclusions

Semileptonic B decays on a well deserved podium to extract CKM matrix elements and to validate theoretical tools

Long standing $|V_{ub}|$ $|V_{cb}|$ discrepancy between exclusive, inclusive

Encouraging and impressive recent experimental progresses (LHCb now and Belle II from 2016 joining the arena)

---- We need th updates (Lattice , inclusive $b \rightarrow u$)