Status of CKM Paradigm

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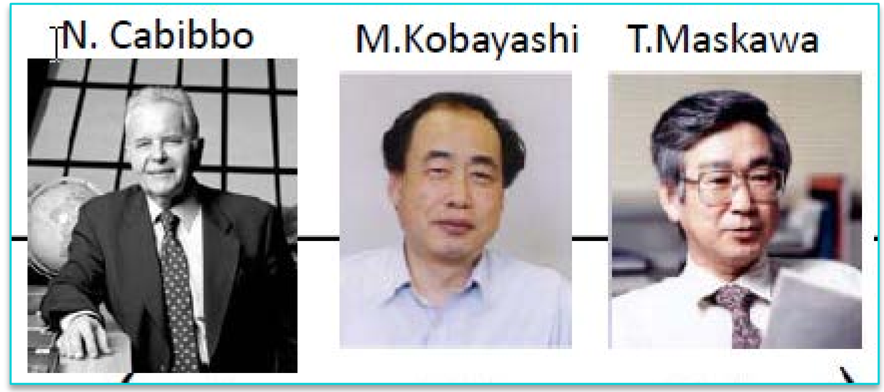
The landscape of Flavour Physics towards the high intensity era, SNS (Pisa) 9-10/12/2014

CKM MATRIX

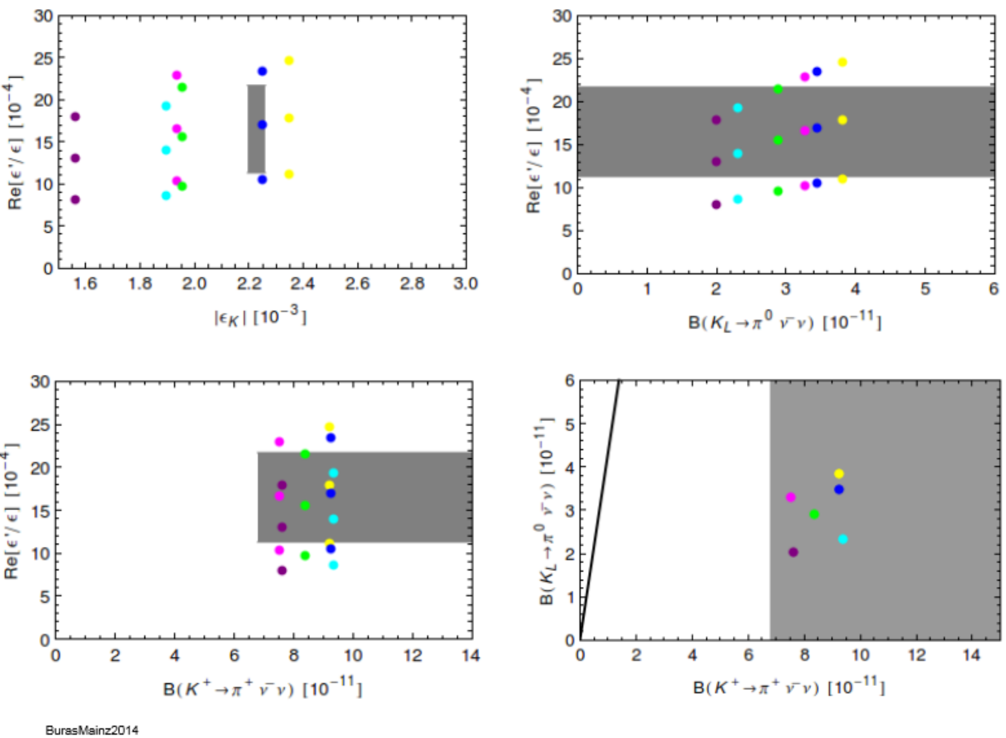


$\vert V_{ud}\vert$ $\frac{\Delta V}{V} \simeq 10^{\{-4\}}$	$\vert V_{us}\vert$ $\frac{\Delta V}{V} \simeq 10^{\{-3\}}$	$\vert V_{ub}\vert$ reaching 0.1
$\vert V_{cd}\vert$ $\frac{\Delta V}{V} \simeq 10^{\{-2\}}$	$\vert V_{cs}\vert$ $\frac{\Delta V}{V} \simeq 10^{\{-2\}}$	$\vert V_{cb}\vert$ $\frac{\Delta V}{V} \simeq 10^{\{-2\}}$
$\vert V_{td}\vert$ $\frac{\Delta V}{V} \simeq 10^{\{-2\}}$	$\vert V_{ts}\vert$ $\frac{\Delta V}{V} \simeq 10^{\{-2\}}$	$\vert V_{tb}\vert$ $\frac{\Delta V}{V} \simeq 10^{\{-2\}}$

Tensions Inclusive-Exclusive determinations

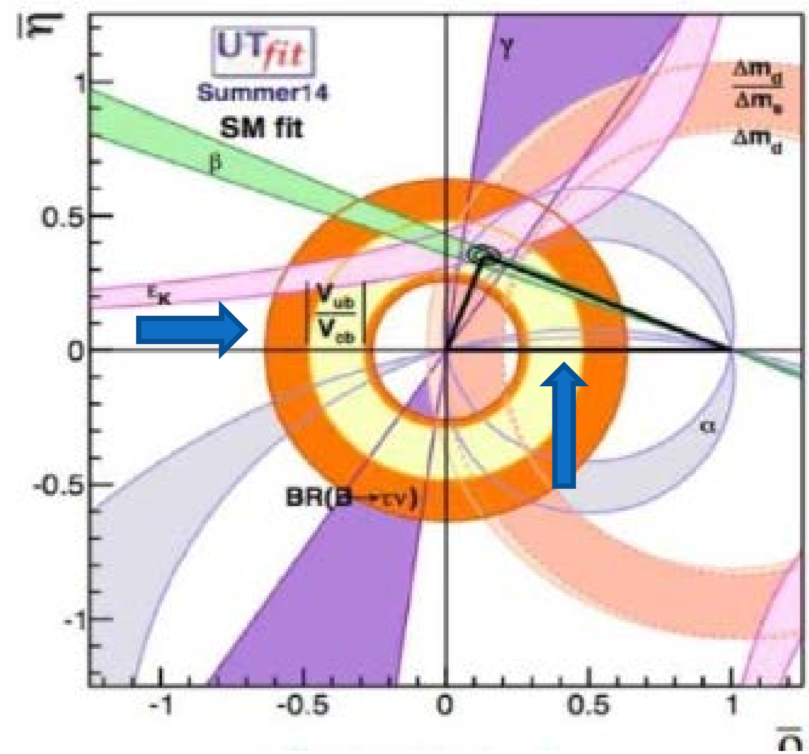
$|V_{ub}|$, $|V_{cb}|$ crucial parameters

SM Predictions for different $|V_{ub}|$, $|V_{cb}|$



$\lvert V_{ub}\rvert \cdot 10^{-3}$	$\lvert V_{cb}\rvert \cdot 10^{-3}$
3.2	39.0
3.2	42.0
4.1	39.0
4.1	42.0
3.7	40.5
3.9	42.0

Unitarity triangle



NP scenarios

$|V_{cb}|$ determination

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

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

Massless leptons limit

$$\frac{d\Gamma}{d\omega}(B \to D\, l\nu) = \frac{G_F^2}{48\pi^3}(m_B + m_D)^2 m_D^3 (\omega^2 - 1)^{\frac{3}{2}} |V_{cb}|^2 |\eta_{EW}|^2 |\mathscr{G}(\omega)|^2$$

$$\frac{d\Gamma}{d\omega}(B \to D^*\, l\nu) = \frac{G_F^2}{48\pi^3}(m_B - m_{D^*})^2 m_{D^*}^3 \chi(\omega)(\omega^2 - 1)^{\frac{1}{2}} |V_{cb}|^2 |\eta_{EW}|^2 |\mathscr{F}(\omega)|^2$$

$\mathscr{F}(\omega) = \mathscr{G}(\omega)$ $\quad$ $\xi(\omega = 1) = 1$ $\quad$ heavy mass limit at zero recoil

NP corrections beyond HM limit ($m = m_b, m_c$)

$$\mathscr{F}(\omega = 1) = 1 + O\left(\frac{1}{m^2}\right) \qquad \mathscr{G}(\omega = 1) = 1 + O\left(\frac{1}{m}\right)$$

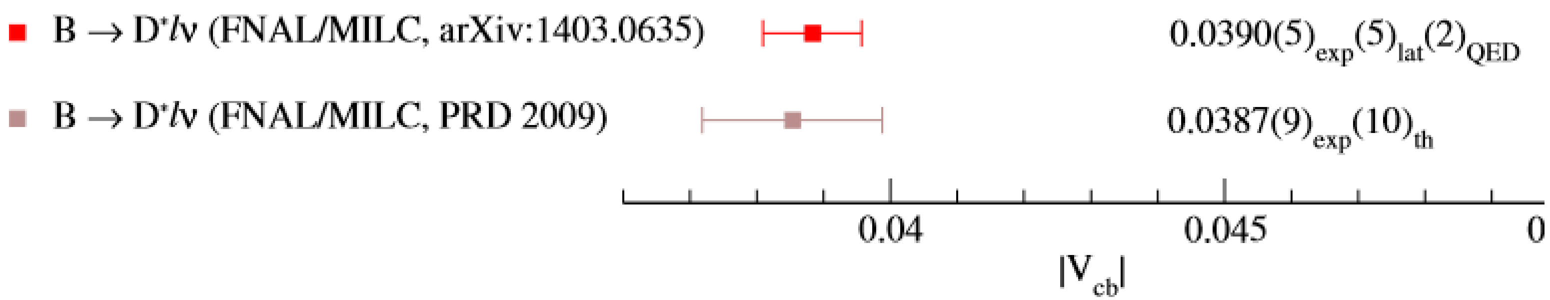
Luke's theorem

✓ $B \to D^{*}\ell\nu$ Lattice Nf=2+1 calculation

Bailey et al. Fermilab/MILC 1403.0635

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

Bailey, lattice 14



Uncertainty	$\lvert V_{cb} \rvert$
QCD	1.4%
QED	0.5%
Expt	1.3%

Kronfeld 2014

Largest error from discretization, Estimated taking the difference between HQET description of LGT and QCD

✓ Preliminary results ETM Nf=2 (realistic charm finite mass) in agreement

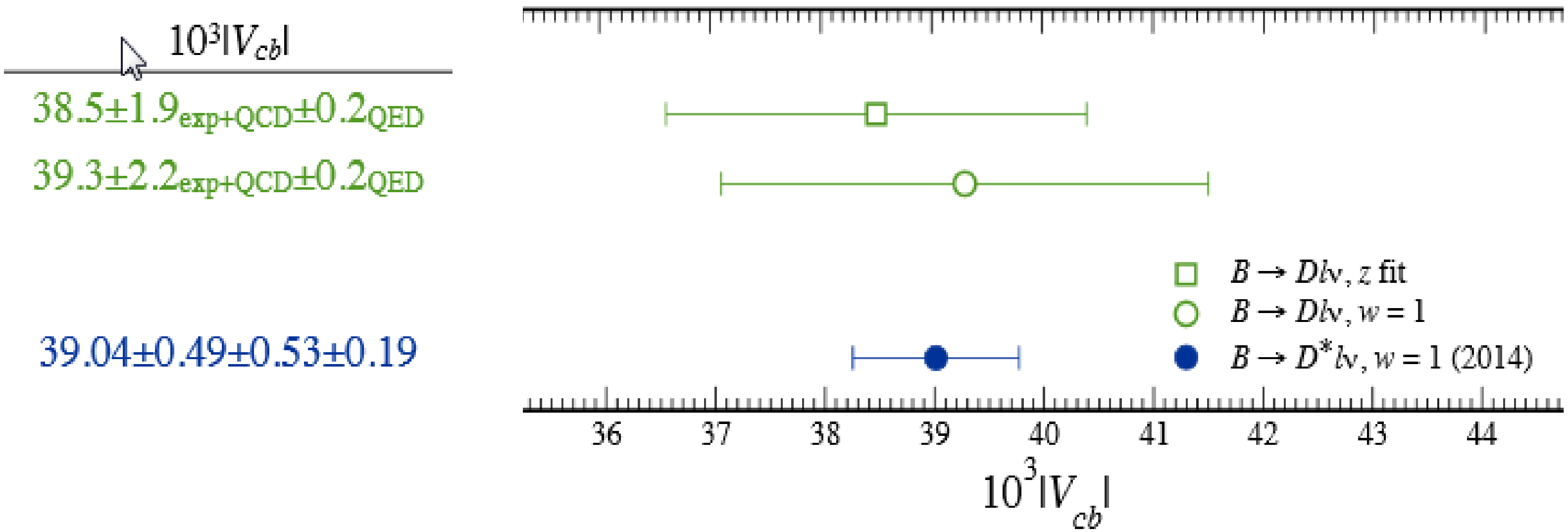
Atoui 1305.0462

✓ only quenched results at the non-recoil point («step scaling» method)

de Divitiis et al 0707.0582

✓ B → D ℓν unquenched calculations at non-zero recoil full kinematic range

Qiu et al Fermilab/MILC 1312.0155



Kronfeld 14

-Reducing errors by using world average of exp data (large syst at large ω)

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

Jang et al SWME, MILC, and Fermilab 1311.5029

LCSR

❑ $B \to D^* \ell \nu$

✓ Recent calculations incorporates higher order effects and estimates inelastic corrections

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

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

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

-OPE power corrections $1/m^{4,5}$ matrix elements estimated by ground state saturation

Mannel, Turczyk, Uraltsev 2010, Heinonen, Mannel 2014

❑ $B \to D \ell \nu$

✓ heavy quark expansion (+ BPS limit, where HF symmetries hold all orders)
Uraltsev 04
✓ +PDG 0312001

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

-Exp+th on $|V_{cb}|$ uncertainty comparable with LQCD

Consistently lower than LQCD (higher $|V_{cb}|$)

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%

✓ $B_s \to D_s l \nu$

-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

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

HQE for sufficiently inclusive quantities (total width, moments of kinematical distributions) away from perturbative singularities

Double series in α_s and 1/m

$$\Gamma(B \to X_q l \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{qb}|^2 \left[c_3 \langle O_3 \rangle + c_5 \frac{\langle O_5 \rangle}{m_b^2} + c_6 \frac{\langle O_6 \rangle}{m_b^3} + O\left(\frac{\Lambda_{QCD}}{m_b^4}, \frac{\Lambda_{QCD}}{m_b^3 m_c^2} + \ldots \right) \right.$$

$$m_c^2 \sim \Lambda_{\{\mathrm{QCD}\}} m_b$$

STATUS

✓ Completed $O(\alpha_s{}^2)$ corrections

to leading term (parton model) — Aquila et al 05, Pak et al 08, Biswas et al 10

to power suppressed coefficients $0(\alpha_s{}^2 \frac{\Lambda^2}{mb^2})$ — Becher et al 07, Alberti et al 12-13, Mannel et al 14

✓ Neglecting perturbative corrections, i.e. working at tree level

computed and estimated up order $O(\frac{1}{m_b^5})$ — Gremm et al 96, Dassinger et al 06, Mannel et al 10, Heinonen et al 14

Global fit results

simultaneous fit to HQE parameters, quark masses and $|V_{cb}|$ by measuring width + all available hadron, lepton moments

about 70 measurements available (Delphi, CLEO, CDF, Belle, Babar)

Latest fits: in the kinetic scheme, incorporating 6 non perturbative parameters $m_c,\ m_b,\ \mu_\pi^2,\ \mu_G^2,\ \rho_D^3,\ \rho_{LS}^3$

Including NNLO $O(\alpha_s^2)$ corrections

$$|V_{cb}| = (42.46 \pm 0.88) \times 10^{-3}$$

HFAG 14

Including recently calculated corrections to power corrected terms $O\left(\frac{\alpha_s^2 \Lambda_{QCD}}{m_b^2}\right)$

$$|V_{cb}| = (42.21 \pm 0.78) \times 10^{-3}$$

Alberti et al. 14

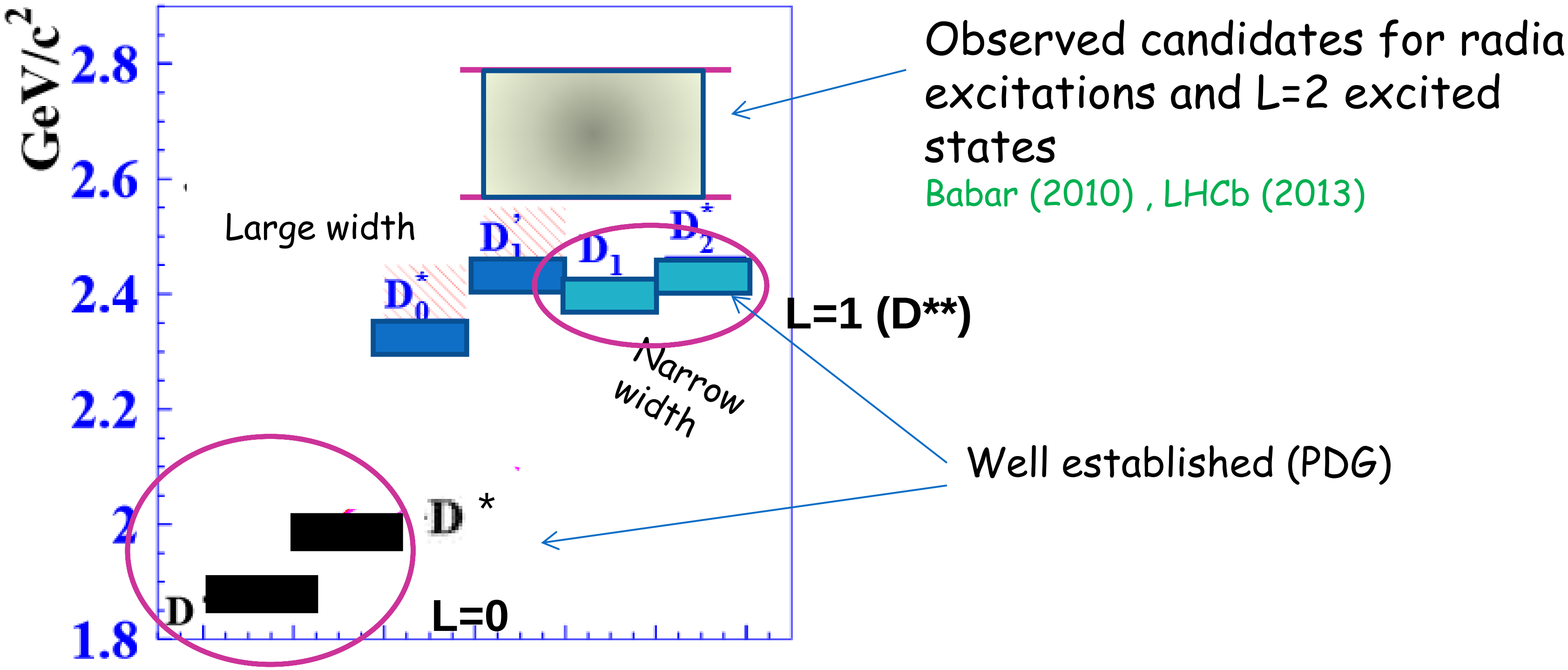
Error below 2%

$|V_{cb}|$ summary

Exclusive decays	$\|V_{cb}\| \times 10^3$
$\bar{B} \to D^* l \bar{\nu}$	
FNAL/MILC (Lattice unquenched) [11]	$39.04 \pm 0.49_{\rm exp} \pm 0.53_{\rm latt} \pm 0.19_{\rm QED}$
HFAG (Lattice unquenched) [39, 9, 10]	$39.54 \pm 0.50_{\rm exp} \pm 0.74_{\rm th}$
Rome (Lattice quenched $\omega \neq 1$) [13, 14]	$37.4 \pm 0.5_{\rm exp} \pm 0.8_{\rm th}$
HFAG (Sum Rules) [15, 16, 39]	$41.6 \pm 0.6_{\rm exp} \pm 1.9_{\rm th}$
$\bar{B} \to D l \bar{\nu}$	
FNAL/MILC (Lattice unquenched $\omega \neq 1$) [18]	$38.5 \pm 1.9_{\rm exp+lat} \pm 0.2_{\rm QED}$
PDG (HQE + BPS) [24, 23]	$40.6 \pm 1.5_{\rm exp} \pm 0.8_{\rm th}$
Rome (Lattice quenched $\omega \neq 1$) [22, 20]	$41.6 \pm 1.8_{\rm stat} \pm 1.4_{\rm syst} \pm 0.7_{\rm FF}$
Inclusive decays	
kin scheme (HFAG) [39]	42.46 ± 0.88
kin scheme [40]	42.21 ± 0.78
Indirect fits	
UTfit [41]	41.7 ± 0.6
CKMfitter (3σ) [42]	$41.4^{+1.4}_{-1.8}$

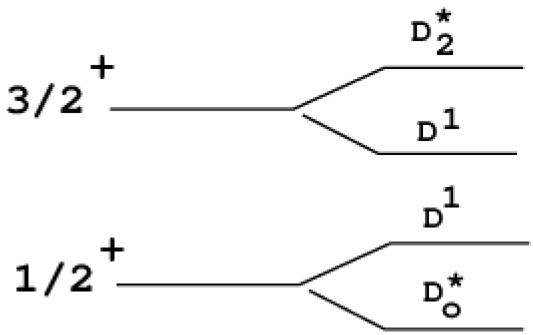
2.9σ disagreement (2014 results)

Low mass open charm spectrum



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

In the HQ limit heavy and light degrees of freedom decouple
P-wave mesons can be grouped into two doublets: $j_l = L \otimes s_l$



narrow width ~ 20-30 MeV

large width ~ 200-400 MeV

1) 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....)

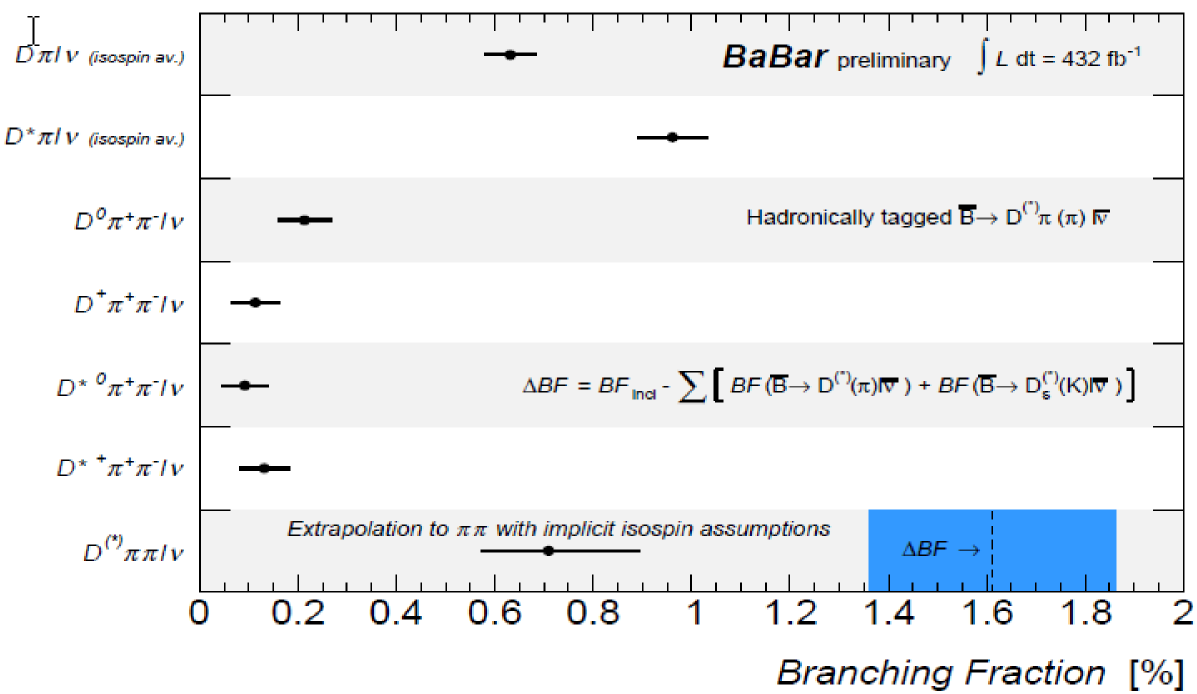
not confirmed by data (1/2 vs 3/2 puzzle) Belle, Babar 06

- ✓ Potentially large $B \to D'[\to D_{\frac{1}{2}} \gg \to D_{\frac{3}{2}}]\, l\, \nu$ Bernlocher et al 12
- ✓ Relevance of the infinite mass limit approach in b → c decay
- ✓ Lattice studies with realistic charm mass are in progress Atoui et al 13-14

2) BR for inclusive $B \to X_c\, l\, \nu$ not saturated by sum of exclusive BR (gap puzzle)

-Decays into $D^{(*)}$ make up ~ 70% of total inclusive $B \to X_c\, l\, \nu$ rate
-Decays into $D^{(*)}\, \pi$ make up ~ 15% of total inclusive $B \to X_c\, l\, \nu$ rate

Leaves a gap of about 15%



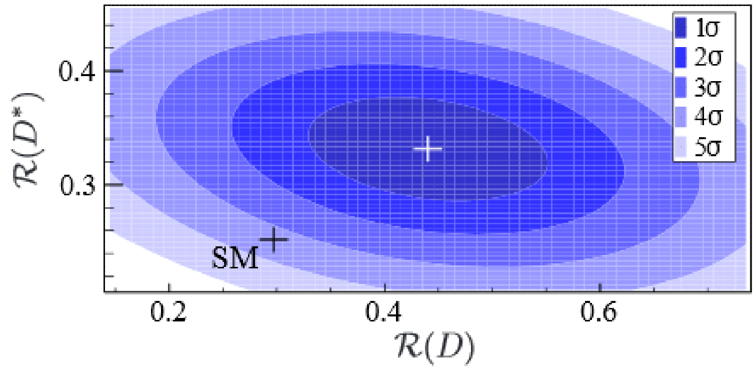
Closing the gap experimentally?

assigning about 0.7% to $B \to D^{(*)}\, \pi\, \pi\, l\, \nu$ production, significance reduced from 7σ to 3σ.

Lück (Babar) ICHEP 2014

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

Babar 2012 1205.5442, 1303.0571



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

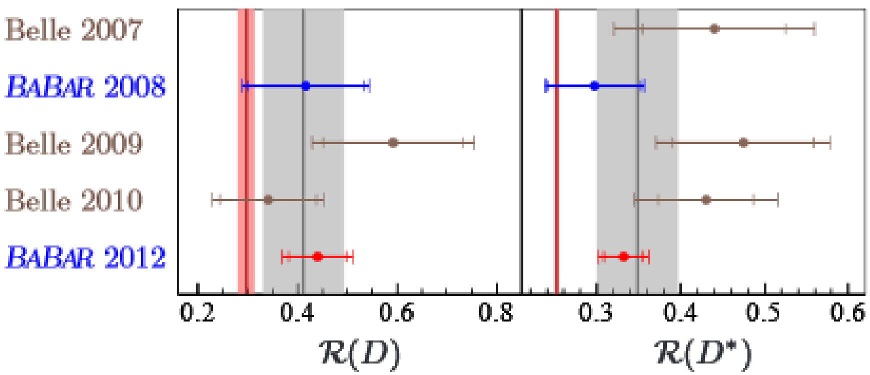
$$\mathcal{R}_{\tau/l} \equiv \frac{\mathcal{B}(B \to D \tau \nu)}{\mathcal{B}(B \to D l \nu)} = 0.440 \pm 0.058 \pm 0.018$$

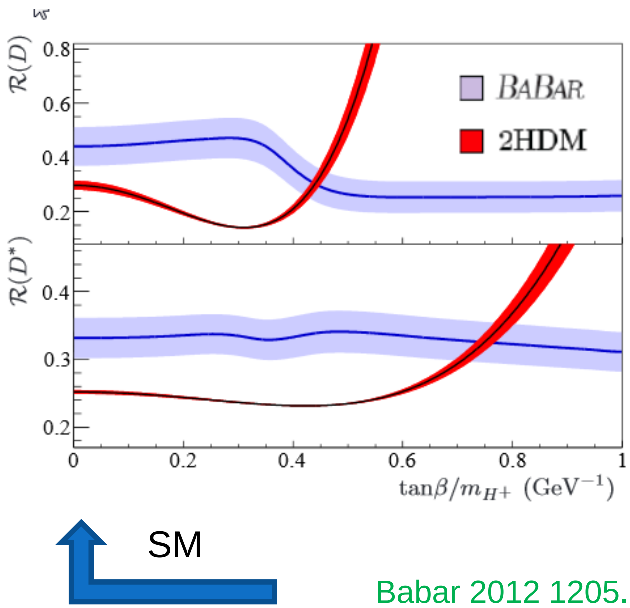
$$\mathcal{R}^*_{\tau/l}(SM) = 0.252 \pm 0.003$$ **2.0σ**

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

Combined **3.4σ**

agreement with past Belle results





Babar 2012 1205.5442

✓ 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 →Xs γ measurements) Misiak 0609232

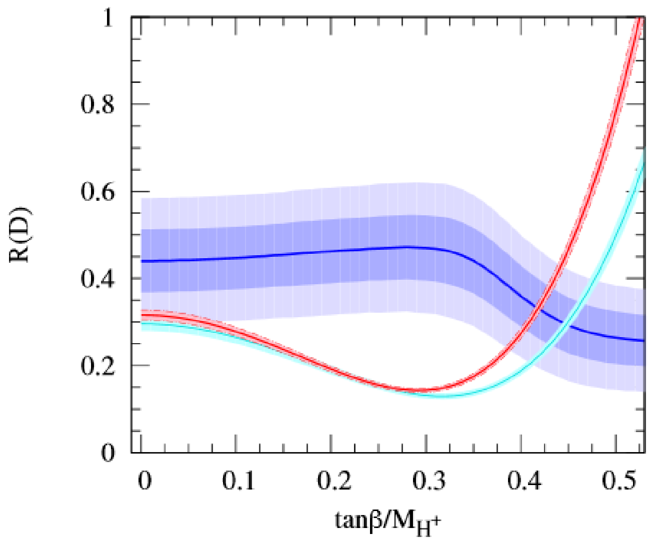
Using estimates of FF from HQET and quenched QCD

Large (order ~ 30%) NP breaking of lepton-flavour universality?

Several th framework tested:
effective Lagrangians, leptoquarks, additional tensor operators…

A2HDB not able to accommodate present data on R Celis 14

Fermilab/MILC 1206.4992



using unquenched lattice for R
tension lessens a bit 1.7σ

different SM R evaluations reduce tension as well

Fermilab/MILC 1206.4992
Becirevic et al 1206.4977

- ✓ Fermilab/MILC analysys for R* yet to be carried out

- ✓ Reanalysis of $B \rightarrow \tau\nu$ at Belle semileptonic tag new tracking and new hadronic tag full data set (20% more) (772 x 10^6 B pairs) has basically eliminated the tensions between the UT fit and this BR

  Belle update with full data set expected soon

$|V_{ub}|$ exclusive determination

- 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

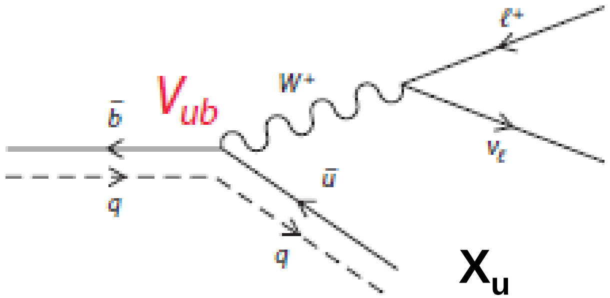
Unquenched HPQCD 07, FNAL/MILC 09, ma preliminary from ALPHA, HPQCD, FNAL/MILC, RBC/UKQCD 12

new players

X_u	Theory	q^2 GeV/c^2	$\lvert V_{ub}\rvert$ 10^{-3}
π^0	LCSR [33]	< 12	$3.35 \pm 0.23 \pm 0.09^{+0.36}_{-0.31}$
	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	$3.51 \pm 0.16 \pm 0.13^{+0.53}_{-0.36}$
	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	$3.03 \pm 0.23 \pm 0.11$

Belle PRD88 (2013) 032005

Inclusive $|V_{ub}|$



large b → 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 → c):

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

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

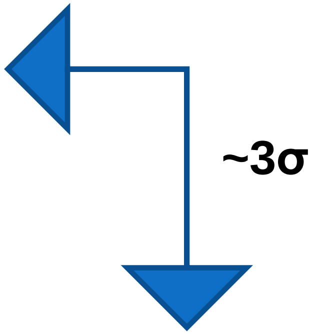
  to be resummed at all orders in PT

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

$|V_{ub}|$ determination status

Exclusive decays	$\lvert V_{ub}\rvert \times 10^3$
$\bar{B} \to \pi l \bar{\nu}_l$	
HPQCD ($q^2 > 16$) (HFAG) [68, 39]	$3.52 \pm 0.08^{0.61}_{0.40}$
Fermilab/MILC ($q^2 > 16$) (HFAG) [69, 39]	$3.36 \pm 0.08^{0.37}_{0.31}$
lattice, full q^2 range (HFAG) [39]	3.28 ± 0.29
LCSR ($q^2 < 12$) (HFAG) [77, 39]	$3.41 \pm 0.06^{+0.37}_{-0.32}$
LCSR ($q^2 < 16$) (HFAG) [80, 39]	$3.58 \pm 0.06^{+0.59}_{-0.40}$
lattice+ LCSR (Belle) [83]	3.52 ± 0.29
LCSR ($q^2 < 12$) Bayes. an. [82]	$3.32^{+0.26}_{-0.22}$
Indirect fits	
UTfit [41]	3.63 ± 0.12
CKMfitter (at 3σ) [42]	$3.57^{+0.41}_{-0.31}$

Long standing tension



Babar inclusive average

$$|V_{ub}| = 4.33 \pm 0.24_{\text{exp}} \pm 0.15_{\text{th}}$$

Inclusive decays ($|V_{ub}| \times 10^3$)

	BNLP [106, 107, 108]	GGOU [113]	ADFR [110, 111, 112]	DGE [109]
BaBar [105]	$4.28 \pm 0.24^{+0.18}_{-0.20}$	$4.35 \pm 0.24^{+0.09}_{-0.10}$	$4.29 \pm 0.24^{+0.18}_{-0.19}$	$4.40 \pm 0.24^{+0.12}_{-0.13}$
Belle [104]	$4.47 \pm 0.27^{+0.19}_{-0.21}$	$4.54 \pm 0.27^{+0.10}_{-0.11}$	$4.48 \pm 0.30^{+0.19}_{-0.19}$	$4.60 \pm 0.27^{+0.11}_{-0.13}$
HFAG [39]	$4.40 \pm 0.15^{+0.19}_{-0.21}$	$4.39 \pm 0.15^{+0.12}_{-0.20}$	$4.03 \pm 0.13^{+0.18}_{-0.12}$	$4.45 \pm 0.15^{+0.15}_{-0.16}$

Conclusions

- Significant advances in experiment (phase space in inclusive decays, $B \to D^{(*)} \pi \pi l \nu$ decays, $B \to \rho/\omega l\nu$, decays into τ…)
  more expected: LHCb now and Belle II from 2016
- Significant reduction of LQCD errors (& new non recoil calculations) and LCSR errors
- NP always more constrained
- $|V_{ub}|$ $|V_{cb}|$ discrepancy still confirmed