Theory $|V_{xb}|$ determinations

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Outline:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$\delta V_{cb} / V_{cb} \sim 2$ %

- Semileptonic decays
  - Exclusive $B \to D^{(*)}\ell\nu$
    $\ell = e, \mu$
  - Inclusive $B \to X_c\, l\, \nu$

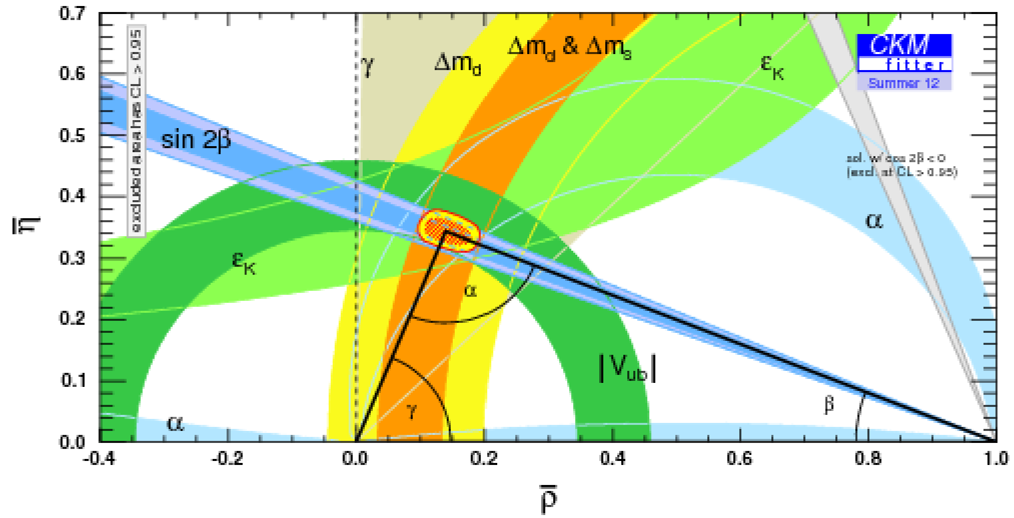
$\delta V_{ub} / V_{ub} \sim 6\text{-}15$ %

- Semileptonic decays
  - Exclusive $B \to \pi\ell\nu$
  - Inclusive $B \to X_u\, l\, \nu$,
- Leptonic decay $B \to \tau\, \nu$

$\delta V_{tb} / V_{tb} \sim 5\text{-}8$ %

- $\sigma_{t\bar{t}}$, single top

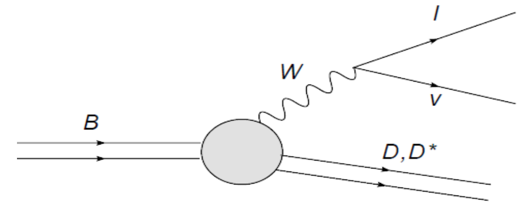
Vcb



❖normalizes the whole unitarity triangle

❖input for NP sensitive other estimates

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



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

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

1) Data for $|V_{cb}||\mathcal{G}(\omega)|$ and $|V_{cb}||\mathcal{F}(\omega)|$

taken at ω≠1 due to kinematics

Data from LEP, CLEO,
Babar and Belle reduction both syst (max ½) and stat errors (almost 1/10)

2) Results extrapolated at non-recoil point ω=1

$F(\omega = 1) = G(w = 1) = 1$ Heavy flavour limit

+

$+ \, c(\alpha) + C\left(\frac{1}{m}\right) + C\left(\frac{1}{m^2}\right) + \ldots$

3) Nonperturbative th evaluation of form factor at non-recoil point

4) $|V_{cb}|$ extraction

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

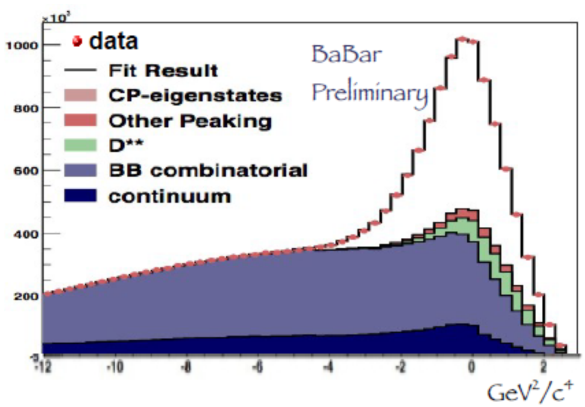
Preferred

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

- Experiment
  - ✓ cleaner signal $D^* \to D\,\pi$ (slow pion)

Dynamics decay $\omega \neq 1$ may be parameterized by normalization and shape parameters ρ, $R_1(1)$, $R_2(1)$ (HQET)

Data fit $|V_{cb}||\mathcal{F}(1)| = (35.90 \pm 0.45) \times 10^{-3}$ HFAG 12 (more recent Belle 10)



Mangoni CKM 12

background events also involving higher mass charm states (via $B \to D^{**}\ l\ \nu$)

✓ BR for inclusive $B \to X_c\ l\ \nu$ not saturated by sum of exclusive BR

✓ $\Gamma(B \to D^{**}\left(j_l = \frac{3}{2}\right) l\,\nu) \gg \Gamma(B \to D^{**}\left(j_l = \frac{1}{2}\right) l\,\nu)$ th prediction not confirmed by data

LATTICE STUDIES HAVE STARTED (Atoui, Becirevic, …12)

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

- pertubative order: complete α_s^2 at zero recoil — Czarnecki 96

- Power suppressions $O(1/m_c^2)$

✓ Lattice

unquenched calculations — FNAL/MILC (from 2008)

$$\mathscr{F}(1) = 0.908 \pm 0.017$$

$$|V_{cb}| = (39.54 \pm 0.50_{\text{exp}} \pm 0.74_{\text{th}}) \times 10^{-3}$$

2010 update + HFAG 2012

full MILC data set , reduced discretization effects, $\delta|V_{cb}|$ down to 1.6%

Lahio 2012

✓ Non-lattice

zero recoil sum rules. Lattice budget error questioned (HQ masses, matching)

Gambino et al 2012

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

$$|V_{cb}| = (41.6 \pm 0.6_{\text{exp}} \pm 1.9_{\text{th}}) \times 10^{-3}$$

+HFAG 2012

$B \to D \ell \nu$

- Power suppression corrections to the unity limit at zero recoil

✓ Lattice

unquenched calculations $\mathcal{G}(1) = 1.074 \pm 0.024$ FNAL/MILC 05

Data fit: normalization and slope ρ^2 $|V_{cb}||\mathcal{G}(1)| = (42.64 \pm 1.53) \times 10^{-3}$

$$|V_{cb}| = (39.70 \pm 1.42_{\text{exp}} \pm 0.89_{\text{th}}) \times 10^{-3}$$

HFAG 12

✓ Non-lattice

heavy quark expansion (BPS limit) $\mathcal{G}(1) = 1.04 \pm 0.02$ Uraltsev 04

$$|V_{cb}| = (40.7 \pm 1.5_{\text{exp}} \pm 0.8_{\text{th}}) \times 10^{-3}$$

PDG 12

- form factor directly at non-zero recoil, avoiding extrapolation and reducing model dependence (**quenched**)

$$|V_{cb}| = (41.6 \pm 1.8 \pm 1.4 \pm 0.7_{FF}) \times 10^{-3}$$

Roma-TorVer 07
+ Babar 09

- non-recoil unquenched FNAL/MILC **in progress**

Quio et al 12

Inclusive decays $B \to X_c l \nu$

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

sum over all possible final states X_q (single and multi-particle)

no dependence on details of final state, quark-hadron duality generally assumed

OPE factorization of short and long distance dynamics

- ✓ Short distance: coefficients, perturbative
- ✓ Long distance: matrix elements, non-perturbative, HQET parameterization

- ❑ Common hadronic parameters in OPE to different inclusive B meson observables (spectra, moments): can be measured in experiments ⟹ global fit
- ❑ quark masses defined in a scheme (1S, kinetic, etc.); other hadronic parameters in consistent framework

double series in α_s and Λ/m_b

kinetic scheme

- $O(\alpha_s{}^2)$ corrections to leading term (parton model)+BLM terms $\alpha_s{}^{n+1}\beta_0{}^n$
  [Melnikov , Czarnecki, Pak , Biswas , Gambino ,...]
- $O(\Lambda/m_b{}^{2,3})$ known, $O(\Lambda/m_b{}^{4,5})$ estimated
  [Gremm, Kapustin, Dassinger, Turczyk, Mannel , Gambino, Bigi, Uraltsev, Zwicky ...]
- $\alpha_s \frac{\mu_\pi{}^2}{mb}$ modest corrections to width and moments (2012 new analytical computation)
  [Becher, Boos, Lunghi, Alberti , Ewerth, Gambino, Nandi ,...]
- $\alpha_s \frac{\mu_G{}^2}{mb}$ **in progress** (known for inclusive radiative decays, about 20% in the rate)
  [Alberti, Ewerth, P. Gambino, S. Nandi,...]
- $\log m_c, 1/m_c{}^2$ ... intrinsic charm estimates
  [Breidenbach, Feldmann, Mannel, Turczyk, Bigi, Mannel, Uraltsev, ...]

non trivial translation to other schemes $\rightarrow$ e.g. 1S $\mu_\pi^2 = -\lambda_1 + O(\alpha_s)$, ...
[Hoang, Bauer, Ligeti, Luke, Manohar, Trott, ...]

Global fit results

global fit of $|V_{cb}|, m_b$ and hadron parameters

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

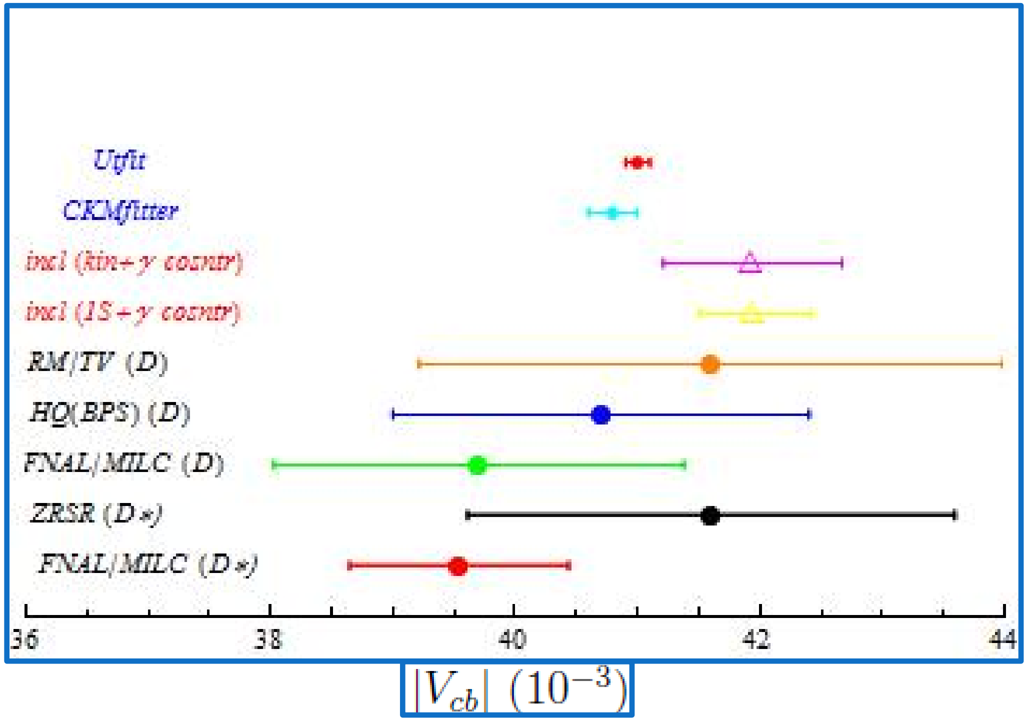
Constraint	$\lvert V_{cb}\rvert$ (10^{-3})
$B \to X_s\gamma$	41.96 ± 0.45
None	42.37 ± 0.65

1S scheme
(no m_c dependence) HFAG 12

$$\frac{\delta V_{cb}}{V_{cb}} < 2\%$$

to compare with excl ~2%

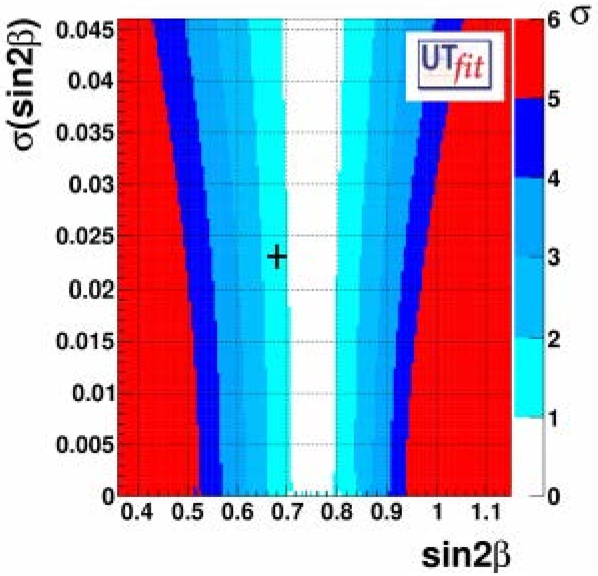
Vcb results: Pick your one



Future:

- CLEO →≈50-70 more stat B factories →≈50 more stat Belle II
- LHCb: about 1.2 million $B \to D^* \mu \nu$ decay reconstructed in 1 fb^{-1}; promising prospects for $|V_{cb}|$ measurement

$|V_{ub}|$



❖ least known, but most studied CKM matrix element
both theoretically and experimentally

❖ Connected to CP violation: $\sin\ 2\beta$ from $B \rightarrow J/\psi$ K
compatibility strongly depends on input for $|V_{ub}|$

(see Silvestrini's talk)

$|V_{ub}|$ 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

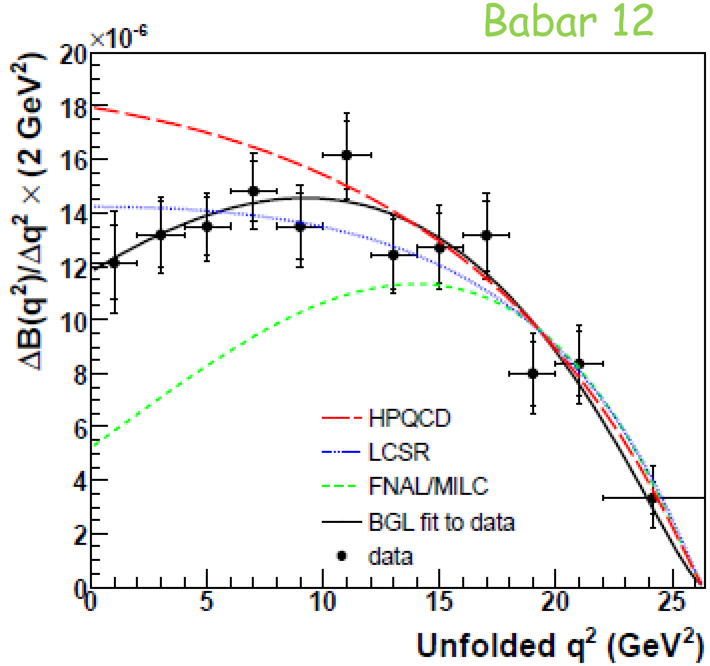
(OPE near the light-cone)

✓ Lattice large $q^2 \sim > 16$ GeV

(to avoid large discretization errors)

Better fit with data

Babar 12



[Unquenched HPQCD 07, FNAL/MILC 09, LCSR Khodjamirian et al 11, BGL: Boyd, Grinstein, Lebed, (2 par)]

Other exclusive semileptonic players

Babar 12 BF x 10^{-4}

$B \to \pi \ell^+ \nu$	$1.45 \pm 0.04 \pm 0.06$
$B^0 \to \pi^- \ell^+ \nu$	$1.47 \pm 0.05 \pm 0.06$
$B^+ \to \pi^0 \ell^+ \nu$	$0.77 \pm 0.04 \pm 0.03$
$B^+ \to \omega \ell^+ \nu$	$1.19 \pm 0.16 \pm 0.09$
$B^+ \to \eta \ell^+ \nu$	$0.38 \pm 0.05 \pm 0.05$
$B^+ \to \eta' \ell^+ \nu$	$0.24 \pm 0.08 \pm 0.03$

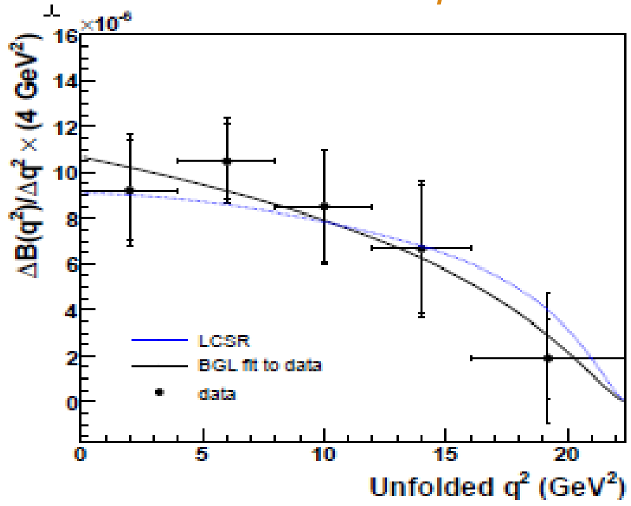
$$\mathcal{B}(B^0 \to \rho^- \ell^+ \nu) = (1.75 \pm 0.15 \pm 0.27) \times 10^{-4}$$

Babar 11

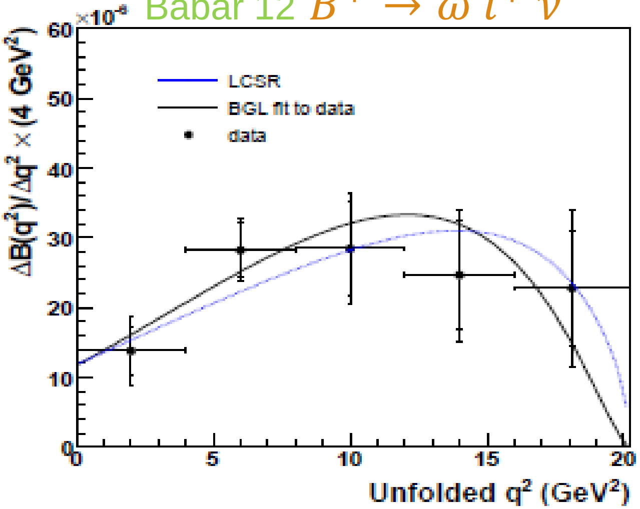
$B^0 \to \pi^+ \ell \nu$	$1.49 \pm 0.09 \pm 0.08$
$B^+ \to \pi^0 \ell \nu$	$0.80 \pm 0.08 \pm 0.04$
$B^0 \to \rho^+ \ell \nu$	$3.17 \pm 0.27 \pm 0.18$
$B^+ \to \rho^0 \ell \nu$	$1.86 \pm 0.10 \pm 0.09$
$B^+ \to \omega \ell \nu$	$1.09 \pm 0.16 \pm 0.08$
$B^+ \to \eta \ell \nu$	$0.42 \pm 0.12 \pm 0.05$
$B^+ \to \eta' \ell \nu$	< 0.57 at 90% CL

Belle prelim results (ICHEP 12) BF x 10^{-4}

Babar 12 $B^+ \to \eta\, l^+ \nu$



Babar 12 $B^+ \to \omega\, l^+ \nu$



Lattice

Unquenched results form factors for $B \to \pi \ell \nu$

Fermilab/MILC and HPQCD collabs. ➡ substantial agreement

Theory	q^2 (GeV$^2/c^4$)	$\lvert V_{ub}\rvert$ ($\times 10^{-3}$)
HPQCD 06	> 16	$3.55 \pm 0.13^{+0.62}_{-0.41}$
FNAL 05	> 16	$3.78 \pm 0.14^{+0.65}_{-0.43}$
FNAL/MILC 09	all regions	3.43 ± 0.33

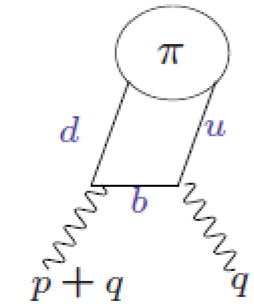
Belle 12

(see Gamiz's talk)

Theory	q^2 (GeV$^2/c^4$)	$\lvert V_{ub}\rvert$ ($\times 10^{-3}$)
HPQCD 06	16-24.6	$3.47 \pm 0.10 \pm 0.08^{+0.60}_{-0.39}$
FNAL/MILC 09	16-24.6	$3.31 \pm 0.09 \pm 0.07^{+0.37}_{-0.30}$
FNAL/MILC 09	all regions	3.43 ± 0.33

Babar 12

Light Cone Sum Rules



- Correlation functions
- OPE near the light-cone

Recent progress in pion distribution amplitudes

- NLO leading and LO high order twists

[Duplancic, Khodjamirian, Mannel, Melic, Offen, Wang, Ball, Jones…]

- latest update: leading-twist $O(\alpha_s^2\, \beta_0)$ corrections to $f_+(q^2)$

$$|V_{ub}| = (3.34 \pm 0.10 \pm 0.05 +^{+0.29}_{-0.26})10^{-3}$$

Babar 12+
Bharucha 12

- From $B^+ \to \omega\, l^+\, \nu$

$$|V_{ub}| = (3.20 \pm 0.21 \pm 0.12^{+0.45}_{-0.32})10^{-3}$$

Babar 12+
Ball Zwicky 05

- From $B^+ \to \rho\, l^+\, \nu$

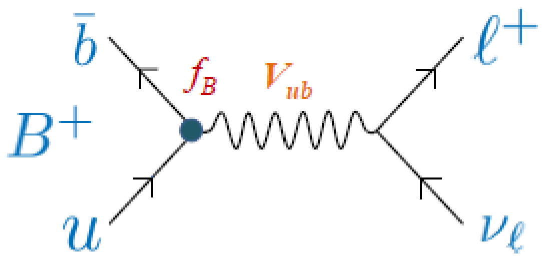
$$|V_{ub}| = (2.75 \pm 0.24)10^{-3}$$

Babar 11+
Ball Zwicky 05

- Future and in progress: extraction via $\Lambda_b \to p\, l\, \nu$, via $B_s \to K\, l\, \nu$

Bharucha, Melic, Duplancic, …

Leptonic $B^+ \to \ell^+ \nu$

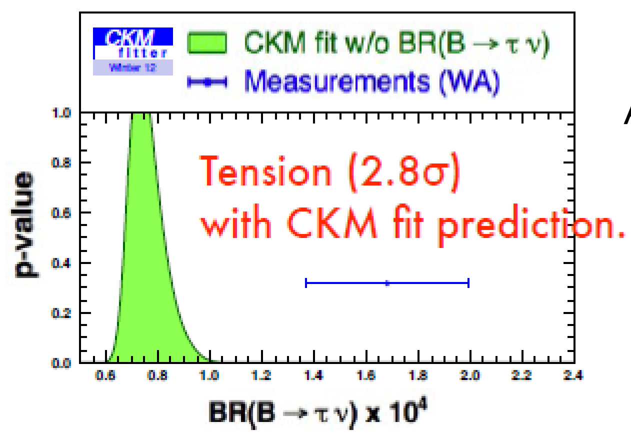


$$B(B^+ \to \ell^+ \nu_l) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

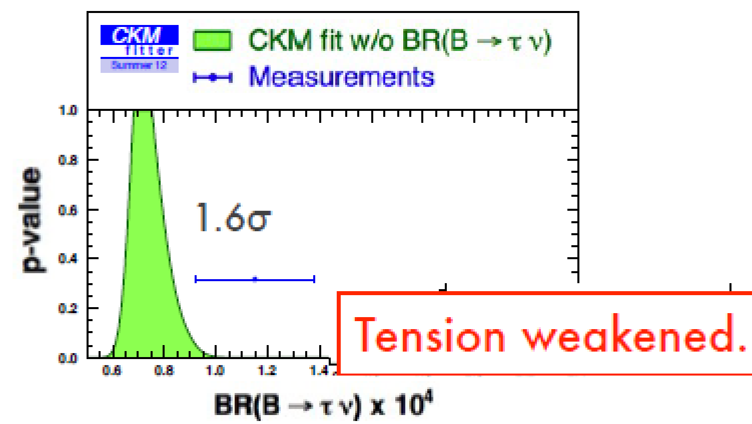
Helicity suppressed
(l=e, μ)

✓ th clean process
but depends on f_B
(lattice precisely det: see Gamiz talk)

$$\mathcal{B}(B \to e\nu)_{SM} \sim 10^{-11}$$
$$\mathcal{B}(B \to \mu\nu)_{SM} \sim 3.5 \times 10^{-7}$$
$$\mathcal{B}(B \to \tau\nu)_{SM} \sim 10^{-4}$$



After ICHEP 2012



Horii talk

If there were NP….

Difficult to assess; a tree process
exchange of a new particle *without* NP effects in other observables

- A charged scalar particle which couples proportionally to the masses of the fermions involved: a charged Higgs boson

  - ✓ Consider also other constraints

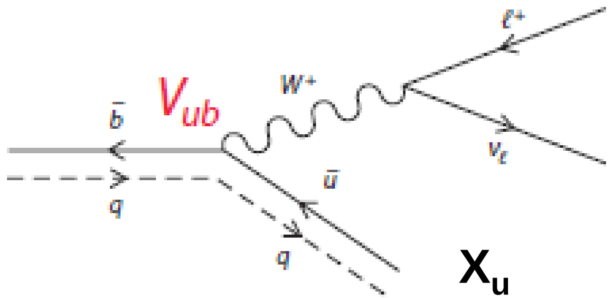
    e.g. Type II 2HDM disfavoured by recent data on $B \to D^{(*)} \tau \nu$

    Compatible with Type III 2HDM

- Other possibilities: (essentially changing $|V_{ub}|$…)
  right-handed currents, NP in B mixings

Crivellin, Greub, Kokulu, 12 Lenz et al, 12 ….

Inclusive $|V_{ub}|$



large $b \to c$ 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 $b \to c$):

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

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

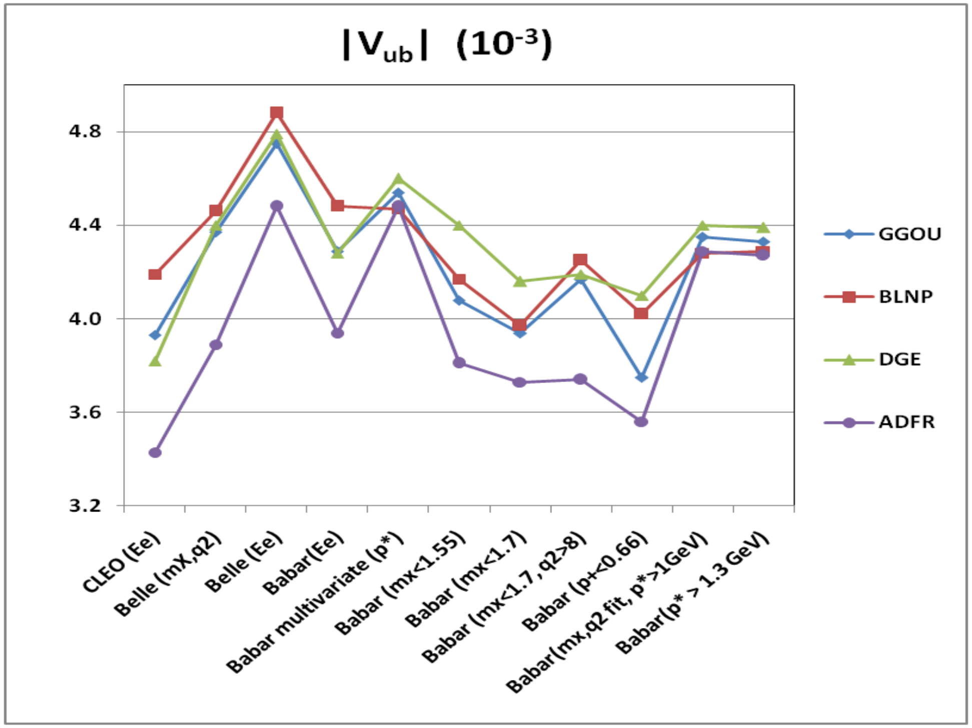
  to be resummed at all orders in PT

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

- Experimental progress
  - Belle results 09 access 90% data, claimed overall uncertainty of 7% on $|V_{ub}|$
  - More recent Babar similar data range

- Theoretical approaches (HAFG averages)
  - predictions based on parameterizations of shape function, and OPE constraints
  - BLNP — Bosch, Lange, Neubert , Paz
  - GGOU — Gambino, Giordano, Ossola, Uraltsev
  - predictions based on resummed pQCD
  - DGE Dressed Gluon Exponentiation — Andersen, Gardi
  - ADFR — Aglietti, Di Lodovico, Ferrera , GR
  - global fit of shape function, $|V_{ub}|$ and m_b (also data on $B \to Xs\,\gamma$)
  - SIMBA — Tackmann, Lacker, Ligeti, Stewart…

Data fit experiment by experiment

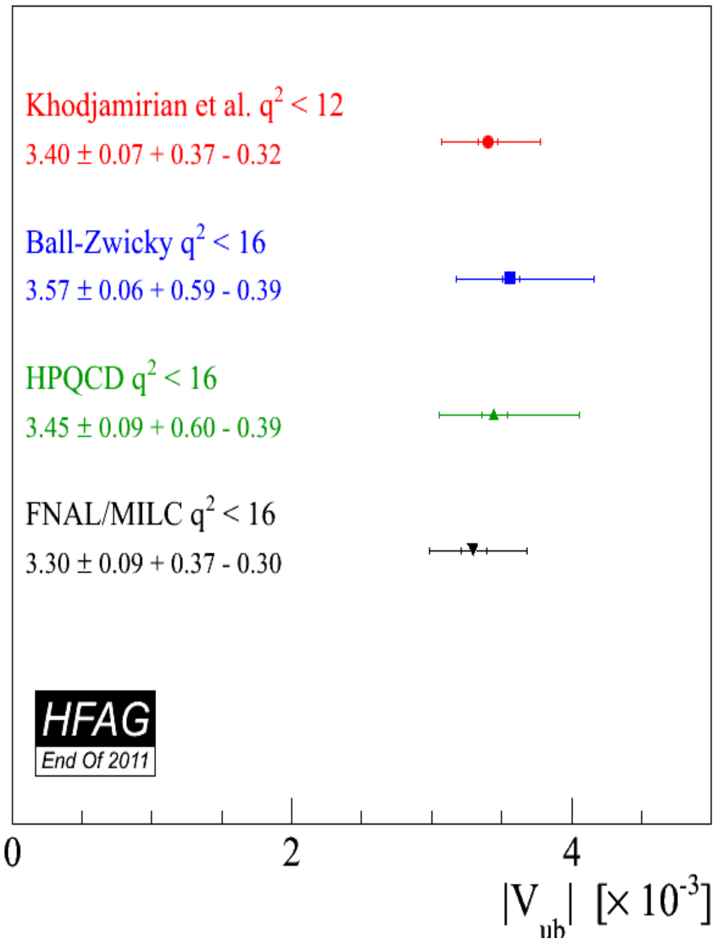


Data from HFAG (end of 2011)

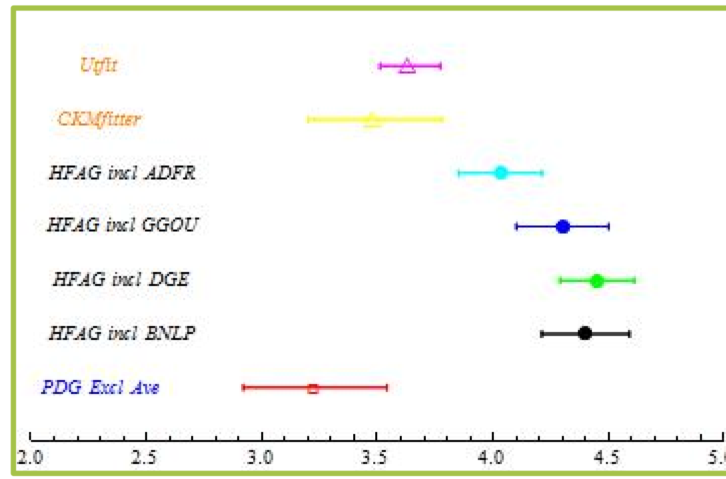
- Spread among calculations comparable to quoted theoretical (non-parametric) errors

Results averages: Long lasting puzzle

Exclusive



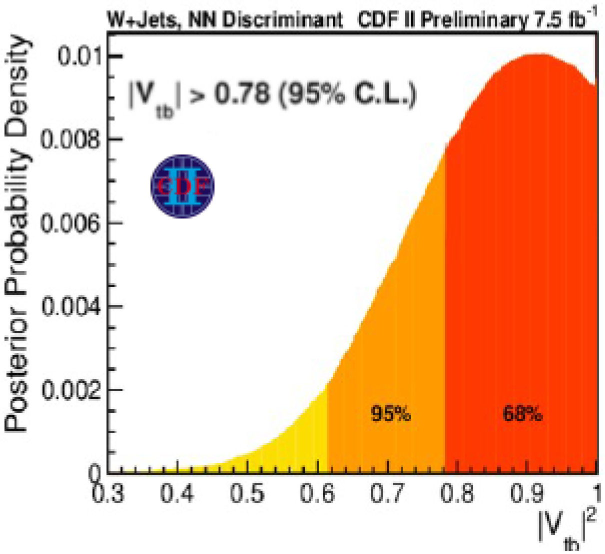
Incl vs Excl vs indirect fit



$|V_{ub}|$ [x 10^{-3}]

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

Vtb



❖Known by unitarity with great precision

❖Let us meet directly: Beyond SM, beyond unitarity

- In the standard model with 3 quark generations, the top quark is expected to decay to a W boson and a b quark roughly 99.8% of the time

- The magnitude of $|V_{tb}|$ is expected to be close to unity as a consequence of unitarity and of the measured values for the other CKM elements

indirect fit $|V_{tb}| = 0.999106 \pm 0.000024$ Utfit 2013

Very recent CDF simultaneous measurement of ratio

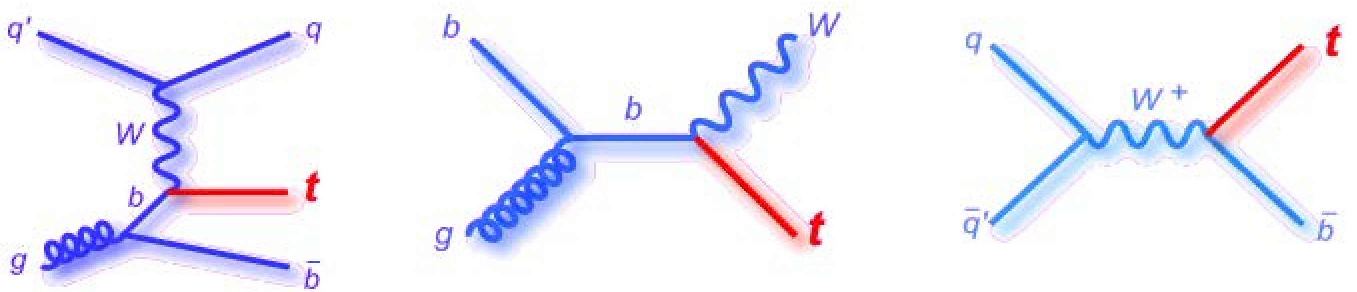
$$\frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

and top-quark-pair-production cross section $\sigma_{t\bar{t}}$ (integrated luminosity of $8.7\ fb^{-1}$), assuming $|V_{tb}| > 0.89$ CDF 2013

$$|V_{tb}| = 0.97 \pm 0.05$$

Agreement with SM, and previous CDF, D0, CMS measurements
$|V_{tb}| = 0.89 \pm 0.07$ (PDG 2012 average (includes single top))

Single top quark production cross section



possible to determine $|V_{tb}|$ directly without assuming unitarity

First observation by CDF and D0 in 2009;

With no assumptions on number of families or unitarity,
but SM vertex + $|V_{tb}|^2 \gg |V_{ts}|^2 + |V_{td}|^2$

$|V_{tb}| = 0.92_{-0.08}{}^{+0.10} \pm 0.05$ (th) CDF Moriond 13

LHC takes Tevatron legacy

limits **(unconstrained/constrained 95% C.L.):**

- **CMS** **(8 TeV)** $0.96 \pm 0.08_{(exp)} \pm 0.02_{(th)}$ / $81 < |V_{tb}| \leq 1$
- **ATLAS** **(8 TeV)** $1.04^{+0.10}_{-0.11}(th + \exp)$ / $80 < |V_{tb}| \leq 1$

Moriond 13

If there were NP….

Relaxing unitarity (see also PMNS neutrino mixing matrix in Antush talk):

❑ Here simplest way: adding fermions

✓ vector-like quarks (in many models, e.g. Randall-Sundrum or E6 GUTS)

Botella,Branco, Nebota 2012, Buras, Duling, Gori, 2009…

✓ more fermion generations Lacker et al 2012,…

✓ Generally coupling affected at order 5%

✓ Actual measurements about 8% precision: should nail it

Conclusions