Semileptonic B and D decays

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Outline

- Motivations

- Semileptonic B decays

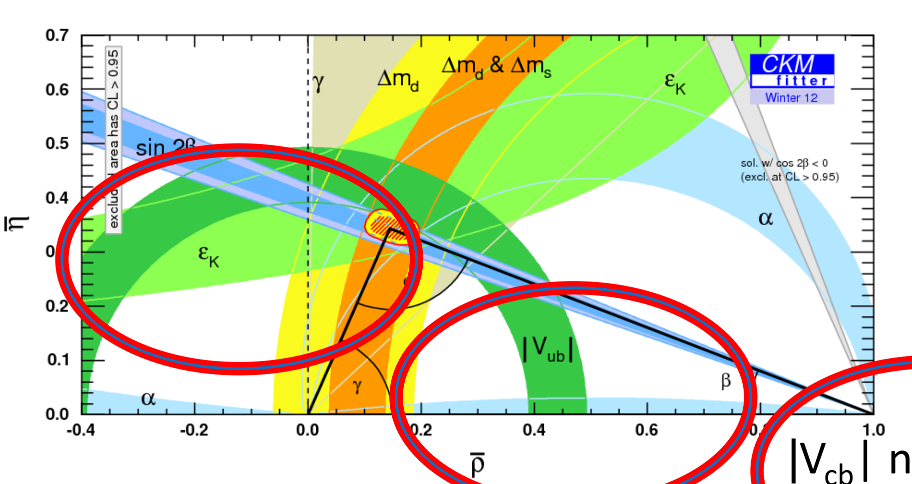
  - ♣ Exclusive measurement
    - ♣ $b \to c\ell\nu$ ($B \to D^{(*/**)} \ell\nu$) CKM favoured
    - ♣ $b \to u\ell\nu$ ($B \to \eta\ell\nu$, $B \to \pi\ell\nu$) CKM suppressed
    - ♣ $b \to s\ell^+\ell^-$ ($B \to K^*\ell^+\ell$) FCNC, rare decays
    - ♣ $b \to d\ell^+\ell^-$ ($B \to \pi\, \mu^+\mu^-$) FCNC, the rarest decay

  - ♣ Inclusive measurement $B \to X_{c(u)} \ell\nu$

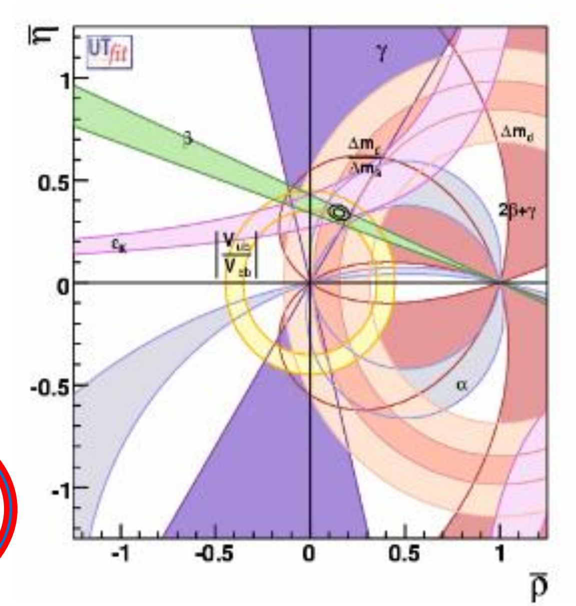
  - ♣ $|V_{ub}|$ $|V_{cb}|$ extraction

- Semileptonic D decays

Motivations I



$|V_{cb}|$ normalizes the whole UT



Precise determination:

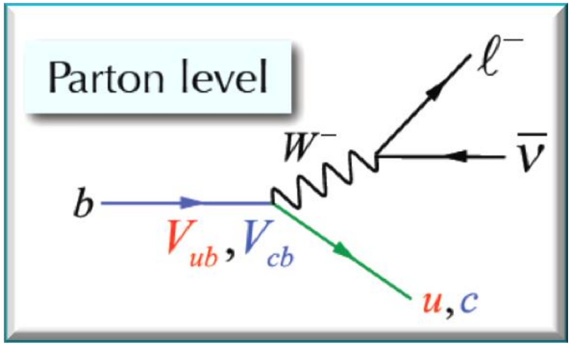
from semileptonic B decays: $|V_{ub}|$ $|V_{cb}|$

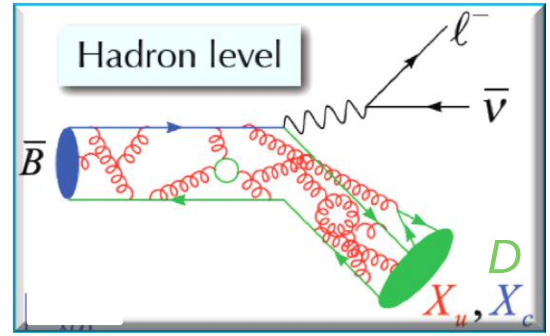
input for NP sensitive other estimates, e.g. $\boldsymbol{\varepsilon_K} = f(|V_{ub}|, A(|V_{cb}|))$

from semileptonic D decays: $|V_{cs}|$ $|V_{cd}|$

hadronic form factors

Motivation II (Because we can…)





- Theory
  - ♣b → c (u) ℓν tree level processes: assumed NP free quantities
  - ♣Leptonic and hadronic contributions factorize
- Experiment
  - ♣Not helicity suppressed, as leptonic decays (τ not suppressed but exp challenging)

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

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

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

$$\omega = v_B \cdot v_{D^{(\star)}}$$

1) Data for $|V_{cb}||\mathcal{G}(\omega)|$ and $|V_{cb}||\mathcal{F}(\omega)|$ taken at ω≠1 due to kinematics

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

Constraints by HQEF

3) Nonperturbative th evaluation of $|\mathcal{G}(1)|$ and $|\mathcal{F}(1)|$

lattice, QCD sum rules

4) $|V_{cb}|$ extraction

lattice

Recent 2+1 evaluation

Fermilab/MILC 2010

$$\mathcal{F}(1) = 0.902 \pm 0.17$$

More precision than in general form factor evaluation since possible to connect to *ratio (or double ratios)* where most uncertainties cancel e.g.

$$\frac{< D^\star|\bar{c}\gamma_j\gamma_5 b|\bar{B} > < \bar{B}|\bar{b}\gamma_j\gamma_5 c|D^\star >}{< D^\star|\bar{c}\gamma_0 c|D^\star > < \bar{B}|\bar{b}\gamma_0 b|\bar{B} >}$$

Including ew corrections to the four-fermion operator and adding errors in quadrature

Data from HFAG (end of 2009) = PDG (fit 2012)

$$|V_{cb}||\mathcal{F}(1)| \times 10^3 = 36.0 \pm 0.5$$

$$|V_{cb}|_{B\to D^\star l\nu} = (39.6 \pm 0.6_{(\mathrm{exp})} \pm 0.8_{(\mathrm{th})}) \times 10^{-3}$$

Unquenched evaluation

Okamoto et al (Fermilab/MILC) 2005

Data from HFAG (end of 2011) (more recent Babar 2008/09)

$$\mathcal{G}(1) = 1.074 \pm 0.018_{\mathrm{stat}} \pm 0.016_{\mathrm{syst}}$$

$$|V_{cb}|\mathcal{G}(1) = (42.6 \pm 0.7 \pm 1.4) \times 10^{-3}$$

$$|V_{cb}|_{B\to Dl\nu} = (39.4 \pm 1.4_{\mathrm{exp}} \pm 1.3_{\mathrm{th}}) \times 10^{-3}$$

form factor normalization at values ω>1 may allow more precise determinations; currently available only in the quenched approximation

higher $|V_{cb}| \approx 41.6$

De Divitiis et al 2007

Non lattice estimates

One or two σ lower than lattice estimates → V_{cb} relatively higher

Zero recoil sum rules
Gambino et al 2010

$$\mathcal{F}(1) = 0.86 \pm 0.04$$

Including full α_s and up to $1/m_b^5$

$$|V_{cb}|_{B\to D^\star l\nu} = (41.6 \pm 0.6_{(\mathrm{exp})} \pm 1.9_{(\mathrm{th})}) \times 10^{-3}$$

"BPS" expansion: limit $\mu_\pi^2 = \mu_G^2$ HQE
Uraltsev 2004

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

Motivations: rather close values obtained from experiment in inclusive B decay

$$|V_{cb}|_{B\to Dl\nu} = (40.7 \pm 1.5_{\mathrm{exp}} \pm 0.8_{\mathrm{th}}) \times 10^{-3}$$

COMPARE AVERAGES

$$|V_{cb}|_{\mathrm{non-lattice}} = (41.0 \pm 1.5) \times 10^{-3}$$

Non lattice PDG 2012

$$|V_{cb}|_{\mathrm{lattice}} = (39.6 \pm 0.9) \times 10^{-3}$$

two unquenched MILC/Fermilab
PDG 2012

Routes to lattice improvement: examination of the extrapolation to zero recoil, unquenched lattice-QCD calculations at ω ≠ 1, larger lattice sizes….

Decays to excited D Meson States

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

$$\mathcal{B}(B^+ \to X_c l^+ \nu) - \mathcal{B}(B^+ \to D l^+ \nu) - \mathcal{B}(B^+ \to D^{(\star)} l^+ \nu) - \mathcal{B}(B^+ \to D^{(\star)} \pi l^+ \nu) = (1.45 \pm 0.67)\%$$

Bernlochner et al 2012

2) "1/2 vs 3/2" puzzle

- j_ℓ total angular momentum of the light degrees of freedom in HQ limit
- D^{**} generically denotes two pairs (j_ℓ=1/2 and j_ℓ=3/2) of 1P (L=1) positive parity states in the non-relativistic constituent quarkmodel

Theory expected (Leibovich et al 98, Uraltsev 01…) **not confirmed** by exp

$$\Gamma(B \to D^{\star\star}(j_l = 3/2) l \bar{\nu}) \gg \Gamma(B \to D^{\star\star}(j_l = 1/2) l \bar{\nu})$$

- Exp situation (Babar, Belle 08) not clear
- non resonant additions (D* nπ, D nπ, D* * nπ)
- cross-feed between the different 1P states, due to strong interaction
- decays to radially excited charm mesons (2S) (Babar 2010)

Bernlochner et al 2012

Semileptonic Bs

Independent determination of $|V_{cb}|$ and $|V_{ub}|$

1. Inclusive:

$B_s \to X \, l \, \nu$

Comparing with semileptonic B: check of quark-hadron duality, evauation of heavy quark expansion parameters…

Gronau, Rosner 10
Bigi, Mannel, Uraltsev 12, …

2. Exclusive:

$B_s \to D^{(*)} \, l \, \nu$, $B_s \to K^{(*)} \, l \, \nu$, $B_s \to B \, e \, \nu$ (b spectator)

check (expected sizable) SU(3) breaking
Inclusive vs sum of exclusive
form factors evaluation

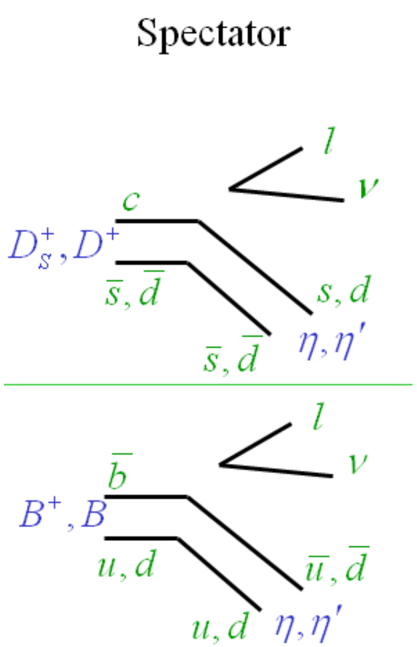
Melic, Duplancic 08

Light Flavour Spectroscopy in Semileptonic Decays

$D_s^+ \to \eta^{(\prime)} l^+ \nu$ $D^+ \to \eta^{(\prime)} l^+ \nu$ $B^+ \to \eta^{(\prime)} l^+ \nu$

- **Spectator diagram dominance**

- Cabibbo allowed c →s, suppressed c →d and CKM suppressed b →u



Gives information on mixing angle and gluonic content of η-η´ system Di Donato, Bigi, GR 2012,...

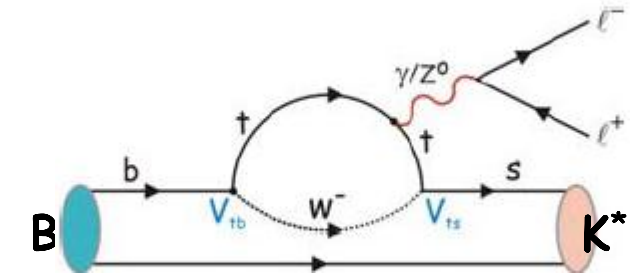
e.g. CLEO09

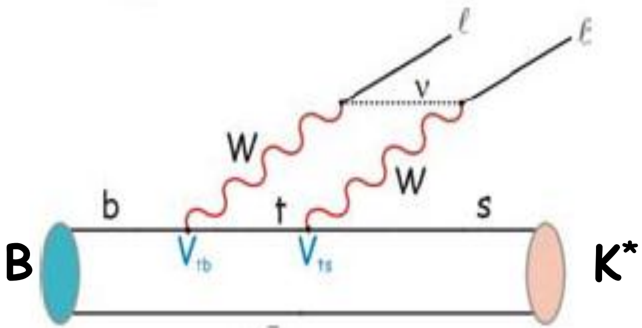
$$\phi_P \approx \frac{\Gamma(D_s^+ \to \eta' l^+ \nu)/\Gamma(D_s^+ \to \eta l^+ \nu)}{\Gamma(D^+ \to \eta' l^+ \nu)/\Gamma(D^+ \to \eta l^+ \nu)} \simeq \cot^4 \phi_P$$

BESIII expects errors on ϕ_P going down to 2%

lattice FF calculation QCDSF Ds (in progress)

FCNC decays $B \to K^{(*)} l l$





transition form factors: leading source of th uncertainty: may be as large as ~ 30% on some branching ratios Ali et al 2000/02,…

Large energy of the emitted meson in the B meson rest frame (low q^2) ⟹ light cone QCD sum rules

Ball,Braun 1998,…

small energy (high q^2) ⟹ lattice preliminary unquenched results

Liu et al 2011

Long list of interesting observables:

1. branching ratio
2. lepton forward-backward asymmetry A_{FB}
3. longitudinal K*-polarization fraction F_L
4. Transverse asymmetry S_3
5. T-odd CP asymmetry A_{im}…

Investigated by ($l = \mu$) by Belle 09, CDF 2011, Babar (see talk by L. Sun) & LHCb (see talk by N. Serra) 2012
Some tension with SM in some observables

Stay tuned!

FCNC $B \to \pi \mu^+ \mu^-$ the rarest

Same lowest order penguin and box diagrams as $B \to K\, l^+ l^-$, but $b \to d$

Suppressed by a factor $|V_{td}|^2/|V_{ts}|^2 \approx 0.04$

First observation at LHCb (1.0 fb^{-1})

$BR(B^+ \to \pi^+ \mu \mu) = (2.4 \pm 0.6 \pm 0.2) \times 10^{-8}$ LHCb-CONF-2012-006

Agrees with Standard Model,
within the large errors possible enhancement due to new physics
Aliev, Savci 1999, Hai-Zhen, Lin-Xia, Gong-Ru 08, Wang et al 2008…

FCNC Bs as well: $B_s \to \phi \mu^+ \mu^-$

$BR(B_s \to \phi \mu^+ \mu^-) = (0.78 \pm 0.10_{(stat)} \pm 0.06_{(syst)} \pm 0.28(B)) \times 10^{-8}$ LHCb-CONF-2012

|Vub| Exclusive determination

- The decay B → π ℓ ν is the simplest to interpret, as it is affected by a single form factor (FF)

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

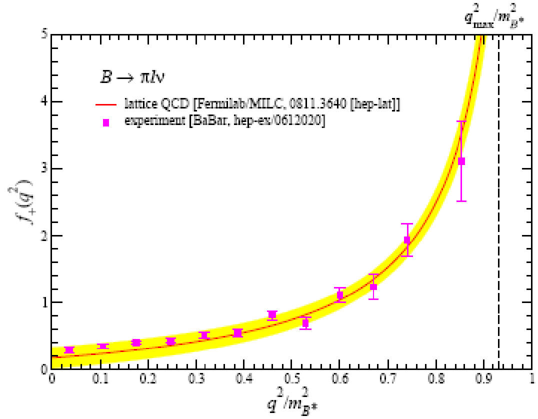
- theoretical predictions for the FF $f_+(q^2)$ split into two parts: form factor normalization $f_+(0)$ & functional form of the **q^2** dependence.
  - quark models, QCD sum rules, Lattice

- Progress in enlarging the region of accessible momentum transfers

- LCSR generally access low q^2 regions (≤16 GeV^2)

  → analitycally continue to higher values

- Complementary information from lattice: lattice simulations are restricted to large q^2 (≥16 GeV^2) to avoid large discretization errors

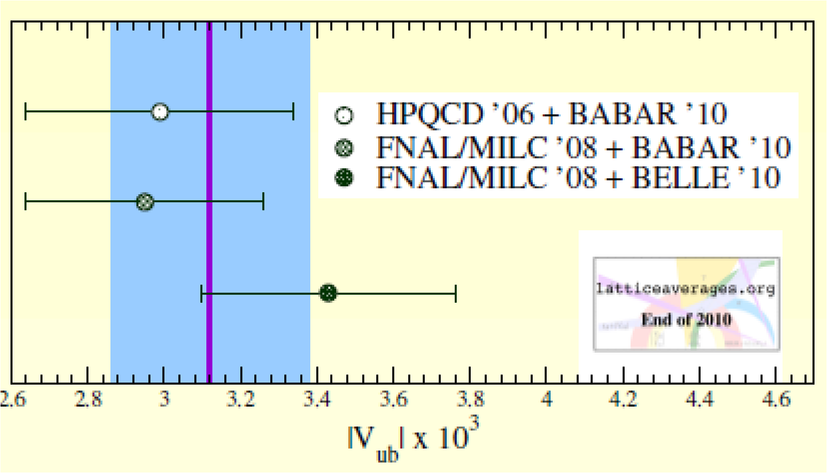


Fermilab/MILC 09

Lattice

Two parameterizations for FF shape in q^2:

- z-expansion (Arnesen et al., Boyd, Grinstein, Lebed), based on analyticity, unitarity, and HQ symmetry (used with FNAL/MILC data)
- Becirevic Kaidalov (BK) parameterization, 3-parameters description given by the M_{B*} pole (used with **HPQCD** data)



$$|V_{ub}^{exc.}|^{\mathbf{LLV}} = (3.12 \pm 0.26) \times 10^{-3}$$

Laiho, Lunghi, Van de Water (LLV) 2010

www.latticeaverages.org

include only Nf=2+1

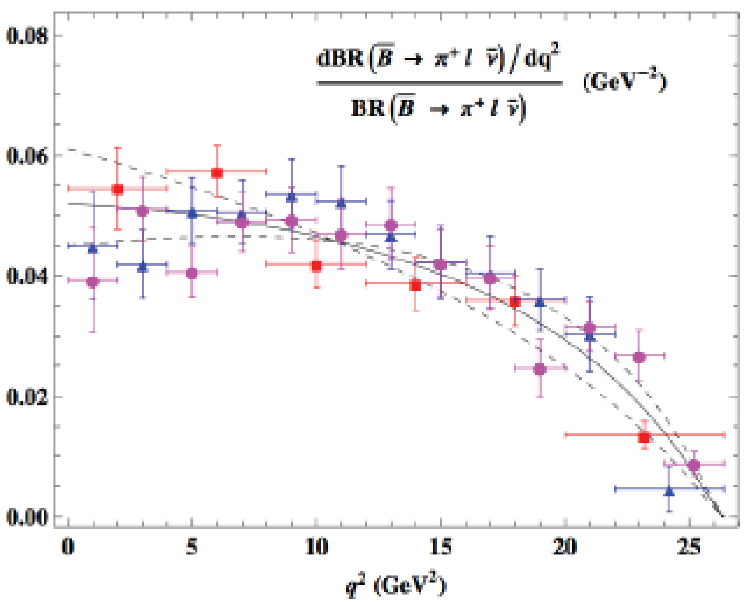
100% correlation is taken for the

theory/experimental errors in calculations using the same lattice/exp. data.

QCD Light Cone Sum Rules

latest update of estimates in the full kinematic regions (z-parameterization): error down to 10%

Khodjamirian, Mannell, Offen, Wang 2011



(colour online) The normalized q^2-distribution in $B \to \pi l \nu$ obtained from LCSR and extrapolated with the z-series parameterization (central input- solid, uncertainties -dashed). The experimental data points are from BABAR: (red) squares [1], (blue) triangles [2] and Belle [3]: (magenta) full circles.

$$|V_{ub}| = (3.40 \pm 0.07_{\rm exp}{}^{+0.37}_{-0.32}{}_{\rm theo}) \times 10^{-3}$$

PDG12 from HFAG11

$q^2 < 12$ GeV^2

agreement with lattice

still lower than

inclusive determination

$$|V_{ub}| = (3.23 \pm 0.31\,) \times 10^{-3}$$

PDG12 **exclusive** average

Inclusive decays

- OPE factorization of short and long distance dynamics
  - Nonperturbative input given by matrix elements of local operators
  - Coefficients of the operators perturbatively calculated
- parameterization of heavy quark dynamics by means of HQET
  - double series in αs and Λ/mb
  - dependence on quark masses and HQET expansions parameters (2 parameters at $O(1/m_b^2)$, 2 more at $O(1/m_b^3)$...)
  - quark masses defined in a chosen scheme (1S, kinetic, etc.)

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

$$\Gamma(B \to X_c l \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \left[f(\rho) + k(\rho)\frac{\mu_\pi^2}{m_b^2} + g(\rho)\frac{\mu_G^2}{m_b^2} + O\left(\frac{1}{m_b^3}\right)\right]$$

$$f(\rho) = f^0(\rho) + f1(\rho)\frac{\alpha_s(\mu)}{\pi} + \ldots \qquad \rho = \frac{m_c^2}{m_b^2}$$

f, k, g differ for different observables, e.g. total rate, moments…

- $O(\alpha_s^2)$ corrections to leading term (parton model)+BLM terms $\alpha_s^{n+1} \beta_0^n$ [Melnikov 08; Czarnecki, Pak 08, Biswas and K. Melnikov, 10, Gambino 11..
- $O(\Lambda_{QCD}/m_b^5)$ at leading term for total rate [Dassinger, Turczyk, Mannel 07, Bigi, Uraltsev, Zwicky 07, Mannel, Turczyk, Uraltsev 10…]
- SD μ_π^2 at order $O(\alpha_s)$ (μ_G^2 still at tree level) [Becher, Boos, Lunghi07,…]
- Intrinsic charm estimates (log m_c, $1/m_c^2$ $1/m_b^3$…) [Breidenbach, Feldmann, Mannel, Turczyk08, Bigi, Mannel, Turczyk Uraltsev 10,…]

|Vcb| determination

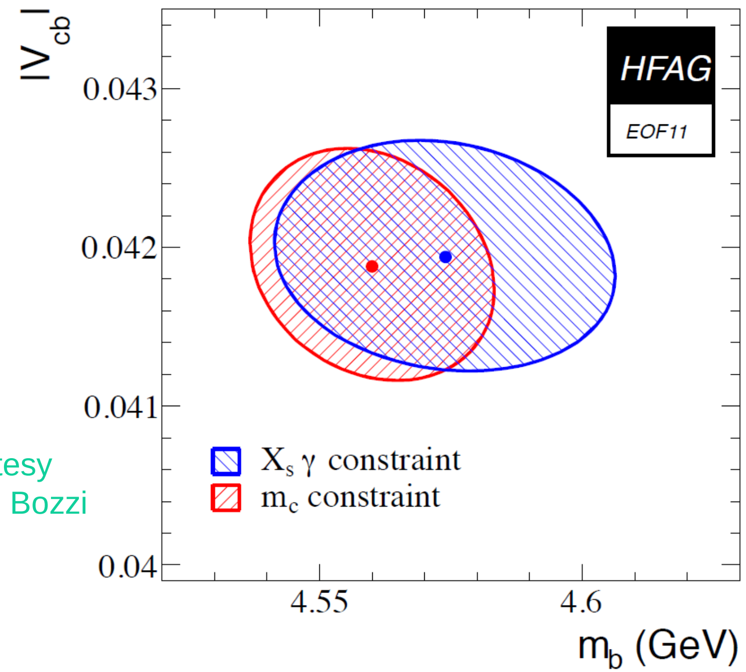
- measure spectrum + as many moments as possible (Babar, Belle, CDF, CLEO, Delphi)
- Fit to HQE parameters, quark masses and $|V_{cb}|$

- Mass and HQE parameters depend on the renormalization scale and schemes:
  - Pole scheme: calculationally most convenient, but plagued by large misbehaved
  - MSbar: Setting the scale: order of the b quark mass unnaturally high, due to the presence of typical scales signicantly below
  - low subtracted mass schemes: non perturbative contribution to the heavy quark pole mass can be subtracted by making contact to some physical observable , e.g**. kinetic scheme or the 1S scheme** [Bigi et al.95, Hoang et al 99]
- OPE-treatable HF decays in two separate steps: heavy quark decay + final hadron composition second step not determine gross characteristic like total rates, etc. (duality)
  - Duality violation effects are hard to classify; in practice they would appear as unnaturally large coefficients of higher order terms in the expansion.

    duality assumed
- Threshold resummation (vs **fixed order**) of large scale [Aglietti et al 07, Di Giustino et al 2011]

|Vcb| results

global fit to lepton energy and hadronic mass moments in the kinetic mass scheme (full order α_s^2)



Courtesy of C. Bozzi

The fit constrains only a linear combination of m_b and m_c.
To precisely determine m_b, two (alternative) constraints

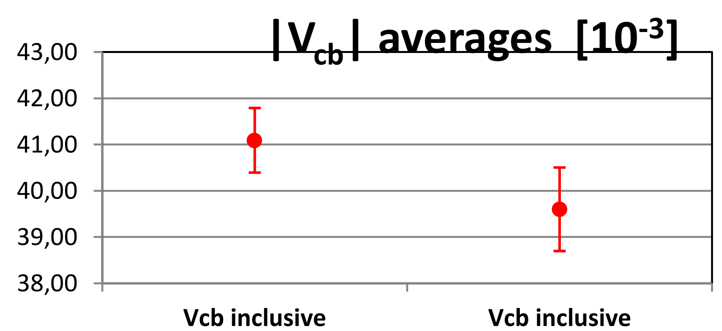
1) photon energy moments in B -> $X_s\,\gamma$ [Benson, Bigi, Uraltsev 05]
2) precise c-quark mass in the MSbar scheme, m_c(3 GeV) = 0.998(29) GeV [Dehnadi et al 2011]

$$|V_{cb}|_{\rm incl} = (41.9 \pm 0.7) \times 10^{-3}$$

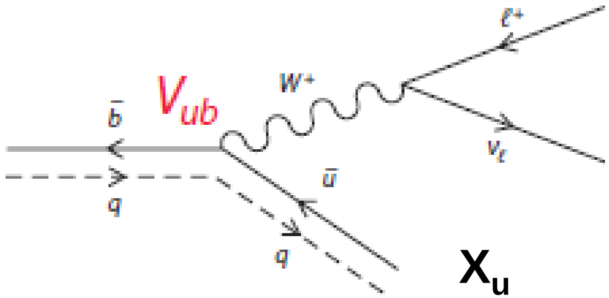
COMPARE AVERAGES

$$|V_{cb}| = (40.0 \pm 1.1) \times 10^{-3}$$

scaled incl-excl average (PDG 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 at $m_X^2 \approx \Lambda_{QCD} E_X$

Extraction of $|V_{ub}|$: routes to progress

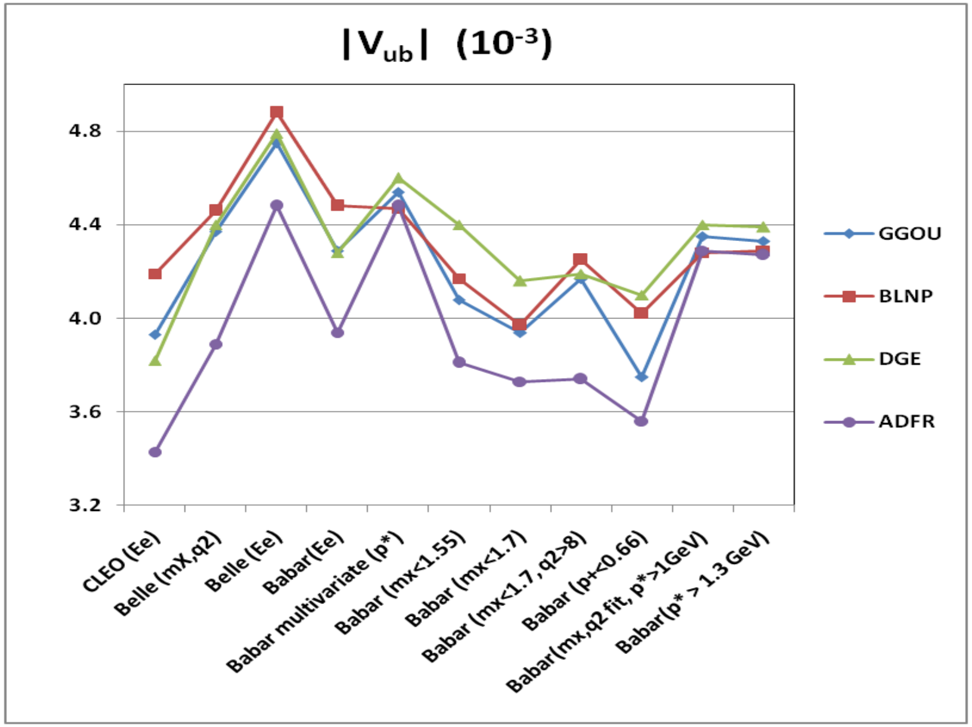
- Enlarge experimental range
  - Belle results 09 access 90% data, claimed overall uncertainty of 7% on $|V_{ub}|$ (actually low (<1/10) signal-to-background ratio in the threshold region)

- Enlarge theoretical prospective

from HFAG

- 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 $B \to X_s \gamma$)
- SIMBA — Tackmann, Lacker, Ligeti, Stewart…

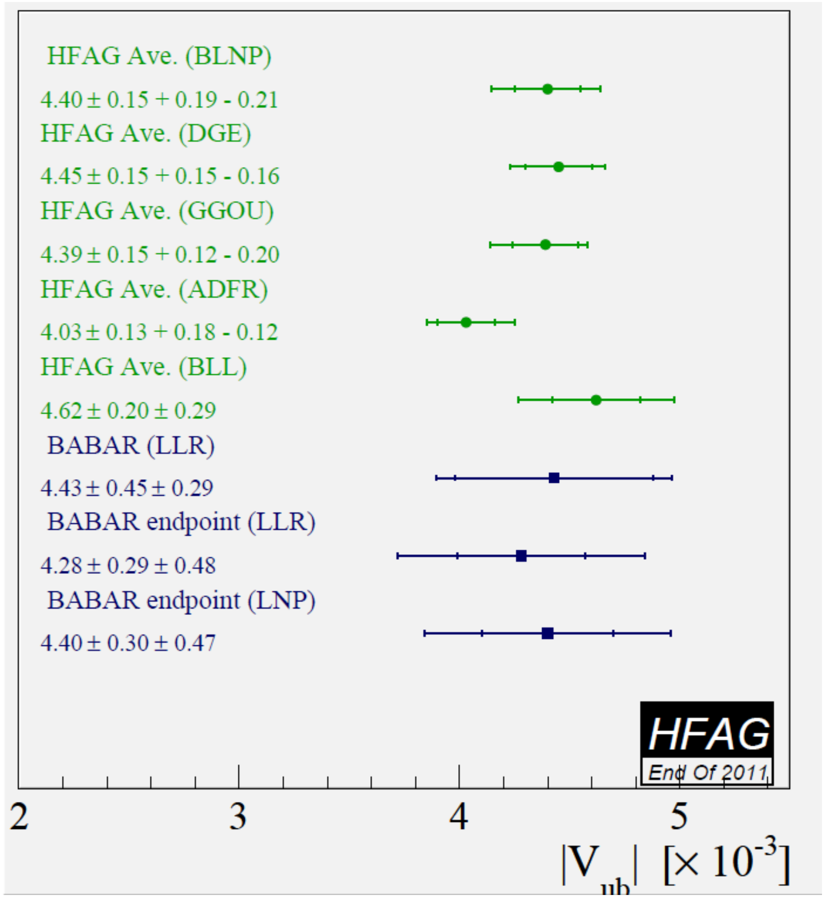
Fits to updated data

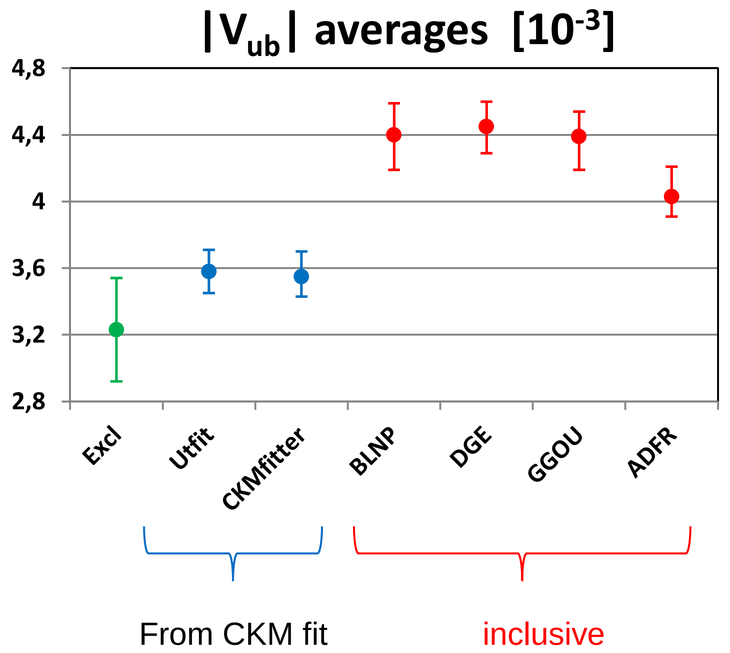


Data from HFAG (end of 2011)

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

Resulting averages





BLL= Bauer, Ligeti, Luke,
LLR= Leibovich, Low, Rothstein
LNP= Lange, Neubert, Paz

SF Model independent extraction (only Babar data)

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

Semileptonic D meson decays: (the same, only different)

$b \to c(u)\, l\, \nu$ ⟶ $c \to s(d)\, l\, \nu$

Extraction of $|V_{cd}|$ $|V_{cs}|$

More precise measurements using leptonic decays which depends on $f_{D(s)}$ (see talk of Bozek) :

$D^+_{(s)} \to l^+ \nu$

$$\Gamma(D^+_{(s)} \to \ell^+\nu) = \frac{G_F^2}{8\pi} f^2_{D_{(s)}} m_\ell^2 M_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{M^2_{D^+_{(s)}}}\right)^2 |V_{cq}|^2$$

present lattice and exp uncertainties reflect on $|V_{cd}|$ $|V_{cs}|$ up to ≈ 6%

PDG12

(recent QCD sum rules for form factor general agreement, larger errors)

(Lucha et al 11….)

Complementary role of semileptonic decays

$D \to (K,\pi)\, \ell^+ \nu$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\, p_h^3}{24\pi^3} |V_{cs,cd}|^2 \left|f_+(q^2)\right|^2$$

Only one form factor neglecting lepton masses

Uncertainty not too different than leptonic (≈ 10%)

By using unquenched lattice+ average recent exp results

PDG12

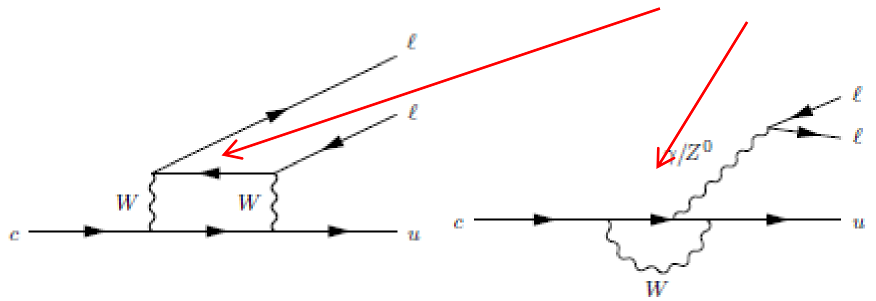
$|V_{cs}|$= 0.98 ±0.01±0.10 $|V_{cd}|$=0.229 ±0.006±0.024

First error is exp and the second from th uncertainty on form factors

Improvements to be expected:
lattice FNAL/MILC & ETMC calculation in progress

Rare Decays

FCNC in charm sector more suppressed than in the B sector, due to more efficient GIM mechanism (internal down-type quarks-not so different masses)



SM contribution is dominated by long distance effects

$D \to X_u \ell^+ \ell^-$ order (10^{-8})
(can be reached at SuperFlavour machines)

Fajfer 01, Burdman 02...
Asner 07...

Intermediate resonances (of larger branching ratios) separated from those due to short-range processes by applying selection criteria on the invariant mass of the leptonic pair

New physics enhancements not completely ruled out

Paul et al 11, ...

Conclusions

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

Long standing $|V_{ub}|$ discrepancy between exclusive, inclusive and UT fits determinations; tensions with SM in some observables (e.g. isospin asymmetry in $B \to K \mu^+ \mu^-$ at LHCb…)

CKM determinations in charm sectors consequential for other processes as well

Encouraging and impressive recent experimental progresses (notably LHCb and BES III joining the arena)

SO…

Stay tuned for progress in 2012, year of the dragon!

Thank you