Strong Interaction Effects in Semileptonic B Decays

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July 25, 2002

ICHEP 2002
Amsterdam

Extracting V_{cb} and V_{ub} requires control over nonperturbative effects

$B \to D^* \ell\nu$ near zero recoil $d\Gamma \propto |F_{D^*}(0)|^2 \, |V_{cb}|^2$

At $m_b, m_c \to \infty$ $F_{D^*}(0)$ would be unity

Actual $F_{D^*}(0)$? $F_{D^*}(0) \simeq 0.9$ to order $1/m_Q^2$

SUV 1994

$\frac{\delta F_{D^*}(0)}{F_{D^*}(0)} \approx 5\%$ – expansion in $1/m_c \ldots$

$\delta_{1/m^3} \approx 3\%$ N.U. 1996

Lattice (FNAL 2001): $F(0) \simeq 0.88$ order $1/m_Q^2$

$F(0) \simeq 0.91$ order $1/m_Q^3$

higher orders in $1/m_c$?

Significant part of the correction is added `theoretically` rather than emerged from the lattice simulation

Total width $\Gamma(B \to X\,\ell\nu)$ is well measured

Strong interactions are controlled by

QCD theorem (1992)

Bigi, Shifman, Uraltsev, Vainshtein

No $\Lambda_{\rm QCD}/m_b$ corrections to inclusive widths of heavy flavor hadrons

Applies to all types: semileptonic, nonleptonic, $b \to s+\gamma$, $b \to s\,\ell^+\ell^-$, ...

$\Gamma(B)$ is expressed in terms of quark masses and local heavy quark expectation values

expansion runs in $E_r = m_b - m_c \simeq 3.5\,\mathrm{GeV}$

$$\delta^{\Gamma}_{\rm np} \sim \frac{0.5\,\mathrm{GeV}^2}{(3.5\,\mathrm{GeV})^2}\left(1+\mathcal{O}\left(\frac{0.7\,\mathrm{GeV}}{3.5\,\mathrm{GeV}}\right)\right) \approx 4\%$$

$$\Gamma \propto (m_b,\, m_b - m_c)^5$$

m_b, m_c, μ_π^2, ... can be determined from the decay distributions themselves BSUV, 1993-1994

Today is implemented in a number of experiments

NEW

Experiment:

accurate measurement of various moments
implementing proper theoretical formalism

Theory:

Constraints from exact HQ sum rules
"BPS" approximation at $\mu_\pi^2 - \mu_G^2 \ll \mu_\pi^2$

Theoretical status

Can go down to 1% in $|V_{cb}|$ if relevant parameters are determined:

- $m_{b,c}(\mu)$, $\mu_\pi^2(\mu)$, $\mu_G^2(\mu)$, ... are completely defined and can (in principle) be determined from experiment with an unlimited accuracy
- Duality violation is very small in $\Gamma_{\rm sl}(B)$ BU 2001
- α_s corrections to Wilson coefficients are feasible
- We know how to analyze higher power corrections

Comprehensive approach: measure many observables to extract the 'theoretical' input parameters

Extreme opposite – B experiment provides only $\Gamma_{\rm sl}$ the rest must theory

Until recently relied on charm mass expansion

$$m_b - m_c = \overline{M}_B - \overline{M}_D - \frac{\mu_\pi^2}{2}\left(\frac{1}{m_c} - \frac{1}{m_b}\right) - \frac{\rho_D^3 - (\rho_{\pi\pi}^3 + \rho_S^3)}{4}\left(\frac{1}{m_c^2} - \frac{1}{m_b^2}\right) + \ldots$$

Expansion in $1/m_c$ is questionable: $\frac{1}{m_c^2} > 14\,\frac{1}{m_b^2},\quad 8\,\frac{1}{(m_b - m_c)^2}$

Non-local correlators $(\rho_{\pi\pi}^3,\ \rho_S^3)$ are probably quite large

	N.U.	2001
't Hooft model	Lebed, N.U.	2000
Lattice	Kronfeld, Simone	2000

Non-local correlators are not measured in B decays

Expansion for $M_B - M_D$ enjoys much smaller power corrections compared to $\overline{M}_B - \overline{M}_D$ 'BPS' limit

We can do without relying on $1/m_c$ expansion at all

rather check it

$\Gamma(B) \propto m_Q^5$ $\qquad\qquad$ $\langle E_\ell \rangle \propto m_b$

need $\langle E_\ell \rangle$ with a sub-% accuracy

DELPHI

$$\langle E_\ell \rangle = 1.383 \pm 0.015\,\text{GeV}$$
$$\langle (E_\ell - \langle E_\ell \rangle)^2 \rangle = 0.192 \pm 0.009\,\text{GeV}^2$$
$$\langle (E_\ell - \langle E_\ell \rangle)^3 \rangle = -0.029 \pm 0.008\,\text{GeV}^3$$

CLEO $R_1,\ R_2,\ R_0$

$$\langle E_\ell \rangle_{E_\ell > 1.5\,\text{GeV}} = 1.5 + 0.2295 \pm 0.0007 \pm 0.0007\,\text{GeV}$$
$$\langle E_\ell^2 \rangle_{E_\ell > 1.5\,\text{GeV}} = 1.5^2 + 0.9482 \pm 0.0025 \pm 0.0025\,\text{GeV}^2$$
$$\frac{\Gamma(E_\ell > 1.7\,\text{GeV})}{\Gamma(E_\ell > 1.5\,\text{GeV})} = 0.6173 \pm 0.0016 \pm 0.0014$$

$b \to s + \gamma$ CLEO: $\langle E_\gamma \rangle = 2.346 \pm .034\,\text{GeV}$

at $E_\gamma > 2\,\text{GeV}$

Hadronic moments: if m_c were large enough first would yield $\overline{\Lambda}$, second μ_π^2, third ρ_D^3 more or less directly BSUV 1993-94

CLEO 2001

$$\langle M_X^2 \rangle_{E_\ell > 1.5\,\text{GeV}} - M_{\bar{D}}^2 = 0.251 \pm 0.066\,\text{GeV}^2$$
$$\langle (M_X^2 - M_{\bar{D}}^2)^2 \rangle_{E_\ell > 1.5\,\text{GeV}} = 0.576 \pm 0.170\,\text{GeV}^4$$

DELPHI

$$\langle M_X^2 \rangle - M_{\bar{D}}^2 = 0.534 \pm 0.085\,\text{GeV}^2$$
$$\langle \left(M_X^2 - \langle M_X^2 \rangle\right)^2 \rangle = 1.226 \pm 0.22\ \text{GeV}^4$$
$$\langle \left(M_X^2 - \langle M_X^2 \rangle\right)^3 \rangle = 2.97 \pm 0.83\ \text{GeV}^6$$

BaBar

$$\langle M_X^2 \rangle_{E_\ell > 1\,\text{GeV}} - M_{\bar{D}}^2 = 0. \pm 0.0\ \text{GeV}^2$$

details in the original experimental talks

A word of caution: $-\lambda_1$, $\overline{\Lambda}$ ("HQET parameters", viz. at $\mu = 0$) are not well defined and depend on the context – rather can be viewed as intermediate entries

We can translate them into the 'running' parameters

$$\overline{\Lambda}_{\rm HQET} \simeq \overline{\Lambda}(1\,{\rm GeV}) - 0.255\,{\rm GeV}, \qquad -\lambda_1 \simeq \mu_\pi^2(1\,{\rm GeV}) - 0.18\,{\rm GeV}^2$$

for the *canonical* approximation

$$m_b(1\,{\rm GeV}) = 4.57 \pm 0.06\,{\rm GeV} \qquad \text{from } \sigma\left(e^+e^- \to \Upsilon(nS)\right)$$

1998-1999

corresponds to $\overline{\Lambda} \simeq 700\,{\rm MeV}$

$$\mu_\pi^2(\mu) > \mu_G^2(\mu)$$

BSUV, Voloshin 1993-94

$$\mu_\pi^2(1\,{\rm GeV}) = 0.45 \pm 0.1\,{\rm GeV}^2$$

Quite consistent with results from B decays

I think (exact HQ sum rules and inequalities) $m_b = 4.57\,{\rm GeV}$ is on the lower side, more probably m_b centers around $4.63\,{\rm GeV}$

Many analyses rely on strong assumptions about six $D=6$ parameters

Uncertainties (say, in V_{cb}) are dominated by theory ? depends on perspective!

'eclectic' option – $\Gamma_{\rm sl}$, $\overline{\Lambda}$, μ_π^2 from experiment the rest for theory

Theory says the mass relation in charm is the weakest point ...

With the comprehensive studies can do without this

- width is affected only by ρ_D^3 to order $1/m_b^3$
  moments also depend (weakly) on ρ_{LS}^3
- No non-local correlators ever enter
- Deviations from the HQ limit are driven by $1/m_b$
  actually, $\propto \mu_\pi^2 - \mu_G^2 \ll \mu_\pi^2$ in B BPS limit
- Exact sum rules and inequalities for properly defined parameters

$$\frac{R_1}{1.78} = 0.986 + 0.15[(m_b - 4.6\,\mathrm{GeV}) - 0.63\,(m_c - 1.15\,\mathrm{GeV}) + 0.27\,(\mu_\pi^2 - 0.4\,\mathrm{GeV}^2) - 0.36\,(\tilde\rho_D^3 - 0.12\,\mathrm{GeV}^3)]$$

$$\frac{R_2}{3.20} = 0.975 + 0.31[(m_b - 4.6\,\mathrm{GeV}) - ...] + 0.004\,(m_c - 1.15\,\mathrm{GeV}) + 0.007\,(\mu_\pi^2 - 0.4\,\mathrm{GeV}^2) - 0.013\,(\tilde\rho_D^3 - 0.12\,\mathrm{GeV}^3)$$

$$\frac{R_0}{.617} = 0.953 + 0.76[(m_b - 4.6\,\mathrm{GeV}) - ...] - 0.03\,(m_c - 1.15\,\mathrm{GeV}) - 0.17\,(\mu_\pi^2 - 0.4\,\mathrm{GeV}^2) + 0.18\,(\tilde\rho_D^3 - 0.12\,\mathrm{GeV}^3)$$

Practically the same combination $m_b - 0.6m_c + 0.3\mu_\pi^2$ in R_1 and R_2; slightly different dependence on μ_π^2, ρ_D^3 in R_0

Similarly with $\langle E_\ell \rangle$, $\langle E_\ell^2 \rangle$; $\langle E_\ell^3 \rangle$ DELPHI

$$\frac{|V_{cb}|}{0.042} = 1 - 0.65\,[(m_b - 4.6\,\mathrm{GeV}) - ...] + 0.02\,(m_c - 1.15\,\mathrm{GeV}) + 0.19\,(\mu_\pi^2 - 0.4\,\mathrm{GeV}^2) + 0.13\,(\tilde\rho_D^3 - 0.12\,\mathrm{GeV}^3)$$

Precise value of m_c is irrelevant !

Need to know accurately μ_π^2 and ρ_D^3

no hidden assumptions

Hadronic moments

$$\langle M_X^2\rangle \simeq \text{const} - 5\,[(m_b-4.6\,\text{GeV}) - 0.63\,(m_c-1.15\,\text{GeV}) + \ldots] + 0.07\,(m_c-1.15\,\text{GeV}) + 0.7(\mu_\pi^2-0.4\,\text{GeV}^2) - 0.7(\tilde\rho_D^3-0.12\,)$$

Basically the same combination $m_b-0.6m_c$, a weaker dependence on μ_π^2, ρ_D^3

Not very constraining ... – instead can check that HQ expansion works

$$\langle (M_X^2-\langle M_X^2\rangle)^2\rangle \simeq \text{const} + 0.02(m_b-4.6\,\text{GeV}) - 0.7\,(m_c-1.15) + 4.5\,(\mu_\pi^2-0.4\,\text{GeV}^2) - 5.3\,(\tilde\rho_D^3-0.12\,\text{GeV}^3)$$

$$\langle (M_X^2-\langle M_X^2\rangle)^3\rangle \simeq \text{const} - (m_b-4.6\,\text{GeV}) - 3\,(m_c-1.15\,\text{GeV}) + 5\,(\mu_\pi^2-0.4\,\text{GeV}^2) + 12\,(\tilde\rho_D^3-0.12\,\text{GeV}^3)$$

Ideally, these measure kinetic and Darwin expectation values. In practice, for ρ_D^3 only approximate evaluation and an informative upper bound

Current sensitivity to μ_π^2 is about $0.1\,\text{GeV}^2$, $0.1\,\text{GeV}^3$ to ρ_D^3

Measurement of $\langle M_X^4\rangle$ and $\langle M_X^6\rangle$ is the real step in implementing the `comprehensive` program of extracting $|V_{cb}|$

`more work is required`

Bottle neck: 'Hardness' too low with the cut on E_ℓ

extraordinary accuracy cannot be even nearly used

For total width $\mathcal{Q} \simeq m_b - m_c$ with the cut ?

Generally $\mathcal{Q} \lesssim \omega_{\rm max}$ $\omega_{\rm max}$ is the threshold energy at which the process disappears if $m_b \to m_b - \omega$

In semileptonic decays

$$\mathcal{Q} \simeq m_b - E_{\rm min} - \sqrt{E_{\rm min}{}^2 + m_c^2}$$

This is only about $1.25\,{\rm GeV}$ for cut at $E_\ell = 1.5\,{\rm GeV}$

and below $1\,{\rm GeV}$ for $E_\ell > 1.7\,{\rm GeV}$

marginal $\mathcal{Q} \simeq 2\,{\rm GeV}$ for $E_\ell > 1\,{\rm GeV}$

In $b \to s + \gamma$ $\mathcal{Q} \simeq M_B - 2E_{\rm min} \simeq 1.2\,{\rm GeV}$

if the cut is at $E_\gamma = 2\,{\rm GeV}$

Reliability of theory is questionable ...

Hardness deteriorates for higher moments

Experiment must strive to lower the cuts ! Bigi, N.U. 2002

Conclusions

New level of exploring the HQ parameter space – and $|V_{cb}|$

`Comprehensive` approach would allow lowering $\delta V_{cb}/V_{cb}$ down to a percent of reliable accuracy

Recent experiments set solid grounds for future extensive studies at B factories

Nontrivial consistency between quite different measurements and with theory

- High premium should be placed to weaken the cuts for extracting $|V_{cb}|$
- Close attention to higher moments or their special combinations

In my opinion the presented analyses give convincing motivation for refinement in theory to fully realize future potential:

- perturbative corrections to Wilson coefficients
- attention to higher-order power corrections
- look at the alternative kinematic variables

Analyses should implement all theoretical constraints on HQ parameters in the quest for the ultimate precision

Saturation of the HQ sum rules yields nontrivial limitations

'BPS' expansion can guide us through higher-order power corrections