Phenomenology from Effective Field Theory: The $1/m_b$ Expansion

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Some slides borrowed from P. Gambino and J. Flynn
One Slide Introduction

Semileptonic Decays
- $V_{cb}$ and the HQE parameters
- $V_{ub}$, shape functions and all that

Nonleptonic Decays
- Inclusive Decays: Lifetimes
- Exclusive Decays
Many Effective Field Theory Methods:
- Weak Interactions: Expansion in $1/M_W^2$
- Chiral Perturbation Theory: Expansion in $1/\Lambda_{\chi_{SB}}^2$
- Heavy Quark Expansion: Expansion in $1/m_Q^2$

Numerators of the expansion parameters are non-perturbative parameters

→ need to be obtained from other sources: Lattice, QCD-Sum Rules, Experiment ...

Here: A (personal) list of interesting topics
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$V_{cb}$ and the HQE parameters

Exclusive $V_{cb}$

- **Main ingredient: Form Factors**

\[
\frac{d\Gamma}{dw}(\bar{B} \to D^* \ell \bar{\nu}_\ell) = \frac{G_F^2}{48\pi^3} |V_{cb}|^2 m_D^3 (w^2 - 1)^{1/2} P(w) (\mathcal{F}(w))^2
\]

\[
\frac{d\Gamma}{dw}(\bar{B} \to D \ell \bar{\nu}_\ell) = \frac{G_F^2}{48\pi^3} |V_{cb}|^2 (m_B + m_D)^2 m_D^3 (w^2 - 1)^{3/2} (\mathcal{G}(w))^2
\]

\[
\omega = v \cdot v'
\]

$P(\omega) : \text{Phase Space Factor}$
Heavy Quark Symmetries


- **Absolute Normalization of the form factors is known at** $\omega = 1$

- **Corrections can be calculated / estimated**

$$F(\omega) = \eta_{\text{QED}} \eta_A \left[ 1 + \delta_1/\mu^2 + \cdots \right] + (\omega - 1)\rho^2 + \mathcal{O}((\omega - 1)^2)$$

$$G(1) = 1 + \mathcal{O}\left( \frac{m_B - m_D}{m_B + m_D} \frac{1}{\mu} \right)$$

$$\eta_{\text{QED}} = 1.007, \quad \eta_A = 0.960 \pm 0.007$$

$$\frac{1}{\mu} = \frac{1}{m_c} - \frac{1}{m_b} : \text{Parameter of HQS breaking}$$
b→c Form Factors from the Lattice

- Unquenched Calculations become available!
- Heavy mass limit is not used (Hashimoto, Kronfeld ...)
- Lattice calculations of the deviation from unity

\[ F(1) = 0.913^{+0.024}_{-0.017} \pm 0.016^{+0.003+0.000}_{-0.014-0.016-0.014} \]

\[ G(1) = 1.074 \pm 0.018 \pm 0.016 \]

(from the CKM05 talk by A. Kronfeld)
New: BaBar Form Factors (hep-ex/0602023)

- New measurement

\[
R_1 = 1.396 \pm 0.060 \pm 0.044 \\
R_2 = 0.885 \pm 0.040 \pm 0.026 \\
\rho^2 = 1.145 \pm 0.059 \pm 0.046
\]

- New Value will lower $V_{cb}$ exclusive!
Value from this measurement:

\[ V_{cb} = 3.76(3)_{\text{stat}}(13)_{\text{syst}}(18)_{\text{theo}} \times 10^{-2} \]

2\sigma away from previous measurements
\[ \Gamma = |V_{cb}|^2 \hat{\Gamma}_0 m_b^5(\mu)(1 + A_{ew}) A^{\text{pert}}(r, \mu) \times \]
\[ \left[ z_0(r) + z_2(r) \left( \frac{\mu_{\pi}^2}{m_b^2}, \frac{\mu_G^2}{m_b^2} \right) + z_3(r) \left( \frac{\rho_D^3}{m_b^3}, \frac{\rho_{LS}^3}{m_b^3} \right) + \ldots \right] \]

**Non-Perturbative Parameters:**

\[
\begin{align*}
\tilde{\Lambda} & = M_B - m_b \\
\mu_{\pi}^2 & = - \langle B|\bar{b}(iD_\perp)^2b|B\rangle \\
\mu_G^2 & = \langle B|\bar{b}(iD_\perp^\mu)(iD_\perp^\nu)\sigma_{\mu\nu}b|B\rangle \\
\rho_D^3 & = \langle B|\bar{b}(iD_\perp^\mu)(ivD)(iD_\perp^\nu)b|B\rangle \\
\rho_{LS}^3 & = \langle B|\bar{b}(iD_\perp^\mu)(ivD)(iD_\perp^\nu)\sigma_{\mu\nu}b|B\rangle
\end{align*}
\]
Global Fit for the HQE Parameters

Result of fit to all moment measurements:

- $|V_{cb}| @ 2\%$
- $m_b < 1\%$
- $m_c @ 5\%$

\[ \text{In MS scheme:} \]
\[ \frac{m_b(m_b)}{\bar{m}_b(\bar{m}_b)} = 4.20 \pm 0.04 \text{ GeV} \]
\[ \frac{m_c(m_c)}{\bar{m}_c(\bar{m}_c)} = 1.24 \pm 0.07 \text{ GeV} \]
\[ \frac{m_c(\mu)}{\bar{m}_b(\mu)} = 0.235 \pm 0.012 \]

Based on Gambino & Uraltsev, Benson et al

Good agreement with other similar analyses:
- Bauer et al. hep-ph/0408002
- DELPHI hep-ex/0510024

$V_{cb}$ and the HQE parameters $V_{ub}$, shape functions and all that

- $m_b = 4.590 \pm 0.025 \pm 0.030 \text{ GeV}$
- $m_c = 1.142 \pm 0.037 \pm 0.045 \text{ GeV}$
- $\mu_{\pi}^2 = 0.401 \pm 0.019 \pm 0.035 \text{ GeV}^2$
- $\mu_{G}^2 = 0.297 \pm 0.024 \pm 0.046 \text{ GeV}^2$
- $\rho_{D}^3 = 0.174 \pm 0.009 \pm 0.022 \text{ GeV}^3$
- $\rho_{LS}^3 = -0.183 \pm 0.054 \pm 0.071 \text{ GeV}^3$
- $\Gamma_{SL}^{2} = 10.71 \pm 0.10 \pm 0.08 \%$

$B \rightarrow s \gamma$
$B \rightarrow c l \nu$
combined

$B \rightarrow c l \nu$
combined

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Phenomenology from Effective Field Theory
Main ingredient: Form Factors

\[ \langle \pi(p_\pi) | V^\mu | B(p_B) \rangle = \]

\[ f_+(q^2) \left[ p_B^\mu + p_\pi^\mu - \frac{m_B^2 - m_\pi^2}{q^2} q^\mu \right] + f_0(q^2) \frac{m_B^2 - m_\pi^2}{q^2} q^\mu \]

Rate (vanishing lepton masses):

\[ \frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2 \]
Results from Lattice QCD

- Unquenched estimates are available
- Results for large $q^2$
- Extrapolation using Becirevic Kaidalov parametrization

\[ f_+(q^2) = \frac{c_B (1 - \alpha_B)}{(1 - \tilde{q}^2)(1 - \alpha_B \tilde{q}^2)} \]

Rate for $q^2 > 16 \text{ GeV}^2$

\[ |V_{ub}|^2 \times (1.31 \pm 0.33) \text{ ps}^{-1} \]
\[ |V_{ub}|^2 \times (1.80 \pm 0.48) \text{ ps}^{-1} \]
Inclusive $V_{ub}$, Shape functions

- Cuts against the $b \rightarrow c$ backgrounds ruin the $1/m_b$ expansion
- Switch to a twist expansion:
- Non-perturbative object: Universal shape function

$$2M_B f(\omega) = \langle B | \bar{Q}_v \delta(\omega + n \cdot (iD)) Q_v | B \rangle$$

- Several shape functions at subleading order
- Universal: the same function for $b \rightarrow u$ as well as for $b \rightarrow s$ transitions
- Moments are related to local operators: $\mu_\pi^2$ etc.
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$$2M_B f(\omega) = \langle B|\tilde{Q}_v \delta(\omega + n \cdot (iD))Q_v|B\rangle$$

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Switch to a twist expansion:

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$$2M_B f(\omega) = \langle B | \bar{Q}_\nu \delta(\omega + n \cdot (iD)) Q_\nu | B \rangle$$

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## Pros and Cons of the various strategies

<table>
<thead>
<tr>
<th>cut</th>
<th>% of rate</th>
<th>good</th>
<th>bad</th>
</tr>
</thead>
</table>
| $E_\ell > \frac{m_B^2 - m_D^2}{2m_B}$ | $\sim 10\%$ | don’t need neutrino | - depends on $f(k^+)$ (and subleading corrections)  
- WA effects largest  
- reduced phase space - duality issues? |
| $s_H < m_D^2$ | $\sim 80\%$ | lots of rate | - depends on $f(k^+)$ (and subleading corrections)  
- need shape function over large region |
| $q^2 > (m_B - m_D)^2$ | $\sim 20\%$ | insensitive to $f(k^+)$ | - very sensitive to $m_b$  
- WA corrections may be substantial  
- effective expansion parameter is $1/m_c$ |
| “Optimized cut” | $\sim 45\%$ | - insensitive to $f(k^+)$  
- lots of rate  
- can move cuts away from kinematic limits and still get small uncertainties | - sensitive to $m_b$ (need +/- 60 MeV for 5% error in best case) |
| $P_+ > m_D^2/m_B$ | $\sim 70\%$ | - lots of rate  
- theoretically simplest relation to $b\to s\gamma$ | depends on $f(k^+)$ (and subleading corrections) |
### BLNP $|V_{ub}|$ (B → $X_c\ell\nu$ & B → $X_s\gamma$ moments)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value [10^{-3}]</th>
<th>References</th>
<th>Phase Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO (9fb(^{-1}))</td>
<td>4.09 ± 0.48 ± 0.36</td>
<td>PRL88:231803,2002</td>
<td>$2.1 &lt; E_\ell &lt; 2.6$</td>
</tr>
<tr>
<td>BELLE (27fb(^{-1}))</td>
<td>4.82 ± 0.45 ± 0.30</td>
<td>PLB621:28,2005</td>
<td>$1.9 &lt; E_\ell &lt; 2.6$</td>
</tr>
<tr>
<td>BABAR (80fb(^{-1}))</td>
<td>4.41 ± 0.29 ± 0.31</td>
<td>PRD73:012006,2006</td>
<td>$2.0 &lt; E_\ell &lt; 2.6$</td>
</tr>
<tr>
<td>BABAR (80fb(^{-1}))</td>
<td>4.10 ± 0.27 ± 0.36</td>
<td>PRL95:111801,2005</td>
<td>$E_\ell &gt; 2.0$, $s_h^{max} &lt; 3.5$</td>
</tr>
<tr>
<td>BELLE (253fb(^{-1}))</td>
<td>4.06 ± 0.27 ± 0.24</td>
<td>PRL95:241801,2005</td>
<td>$m_X &lt; 1.7$, BRECO tag</td>
</tr>
<tr>
<td>BELLE (87fb(^{-1}))</td>
<td>4.37 ± 0.46 ± 0.29</td>
<td>PRL92:101801,2004</td>
<td>$m_X &lt; 1.7$, $q^2 &gt; 8$, annealing</td>
</tr>
<tr>
<td>BABAR (211fb(^{-1}))</td>
<td>4.75 ± 0.35 ± 0.32</td>
<td>hep-ex/0507017</td>
<td>$m_X &lt; 1.7$, $q^2 &gt; 8$, BRECO tag</td>
</tr>
<tr>
<td><strong>Average ± exp ± (mb, theory)</strong></td>
<td><strong>4.45 ± 0.20 ± 0.26</strong></td>
<td><strong>chi2/dof = 5.5/6 (CL = 0.49)</strong></td>
<td><strong>HQ parameter input from b → c l \nu and b → s \gamma moments</strong></td>
</tr>
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</table>

Capri, May 30th 2006
C. Bozzi - |V_{ub}| @ B Factories
Inclusive Decays: Lifetimes

- Standard Description via OPE
- Total rates are written as

\[ \Gamma(H_b) = \frac{1}{m_{H_b}} \text{Im}\langle H_b | \mathcal{T} | H_b \rangle \]

where

\[ \mathcal{T} = i \int d^4x \, \mathcal{T} \left[ \mathcal{H}^{\Delta B=1}(x) \mathcal{H}^{\Delta B=1}(0) \right] \]

- Expansion in \( 1/m_b \)

\[ \Gamma(H_b) = \sum_k \frac{c_k(\mu) \langle H_b | O_k(\mu) | H_b \rangle}{m_b^k} \]
Systematics of the Expansion

Neubert–Sachrajda, 1996

- $O(1)$: $\bar{b}b$ free quark decay
  \[ \langle \bar{b}b \rangle_{\text{HQET}} = 1 - \frac{\mu_\pi^2 - \mu_G^2}{2m_b^2} + O(m_b^{-3}) \]

- $O(1/m_b)$: no contribution

- $O(1/m_b^2)$: $\bar{b}g_s\sigma\cdot G b$
  chromomagnetic operator
  \[ \langle \bar{b}g_s\sigma\cdot G b \rangle_{\text{HQET}} = 2\mu_G^2 + O(m_b^{-1}) \]

- $O(1/m_b^3)$: $\bar{b}\Gamma q \bar{q}\Gamma b$
  spectator effects (1-loop $\rightarrow 16\pi^2$ factor):
  four $\Delta B=0$ 4-quark operators
# Results for the Lifetimes

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<th>Expt</th>
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<th>GOP</th>
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<td>$\frac{\tau(B^+)}{\tau(B^0)}$</td>
<td>$1.076 \pm 0.008$</td>
<td>$1.06 \pm 0.02$</td>
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<td>$\frac{\tau(B_s)}{\tau(B^0)}$</td>
<td>$0.957 \pm 0.020$</td>
<td>$1.00 \pm 0.01$</td>
<td>$1.00 \pm 0.01$</td>
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<tr>
<td>$\frac{\tau(\Lambda_b)}{\tau(B^0)}$</td>
<td>$0.844 \pm 0.043$</td>
<td>$0.88 \pm 0.05$</td>
<td>$0.86 \pm 0.05$</td>
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- Expt is [HFAG with van Kooten, FPCP2006](http://example.com) for $\tau(B_s)$
- T05 is [Tarantino CKM2005, updating analysis of Franco et al, 2002](http://example.com)
- GOP is [Gabbiani–Onishchenko–Petrov, 2004](http://example.com)
Recent development:
Factorization Formulae in the infinite mass limit

Variety of approaches:
- Soft Collinear Effective Theory (SCET)
- QCD Factorization
- Perturbative QCD

Many common features, the differences lie in the details

Subleading terms are hard to control:
\[ 1/\ln m_Q, 1/\sqrt{m_Q} \]
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QCD Factorization, PQCD and SCET

- Starts from the limit \( m_b \rightarrow \infty \)

- Perturbative calculation, systematic expansion (?)
- Strong phases are small (\( \mathcal{O}(\alpha_s(m_b)) \) or \( \mathcal{O}(\Lambda/m_b) \))
- Sizable uncertainties, subleading terms ?

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\begin{align*}
\Phi_{M_2} & \quad \Phi_{M_2} \\
F_j & \quad T_{i,j}^I \\
B & \quad M_2
\end{align*}
\]

\[
\begin{align*}
\Phi_B & \quad T_{i}^{II} \\
B & \quad M_2
\end{align*}
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Phenomenology from Effective Field Theory
Partial Calculations of the hard scattering kernels to NNLO available

Small strong phases due to power suppression / perturbation theory

Data indicate sizable power corrections

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Results agree quantitatively with the ones from QCD LC Sum rules (Khodjamirian, Melic, Melcher, M.)
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$B \rightarrow \pi\pi$, $B \rightarrow K\pi$ in QCD Factorization

(Beneke, Buchalla, Neubert, Sachrajda)

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Recent NNLO calculation (Beneke Jaeger)

Variation of the inverse moment $\lambda_B$:
Is a small value of $\lambda_B$ realistic?
Update on the BR's by Neubert (CKM 2005, San Diego)
Update on the CP Asymmetries by Neubert (CKM 2005)

HFAG
AUGUST 25th 2004

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Phenomenology from Effective Field Theory
Summary

- There has been enormous progress through effective field theory methods
  - Semi-leptonic decays become very precise tools
  - \( \rightarrow 1/m_b \) expansion seems to work quite well
  - Inclusive non-leptonic decays: \( \Lambda_b \) lifetime problem has dissappeared!
  - Exclusive non-leptonic decays: Theory is still a construction area!
  - There are some tensions:
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- Inclusive non-leptonic decays:
  - $\Lambda_b$ lifetime problem has disappeared!
- Exclusive non-leptonic decays:
  - Theory is still a construction area!
- There are some tensions:
There has been enormous progress through effective field theory methods

Semi-leptonic decays become very precise tools

$\rightarrow \frac{1}{m_b}$ expansion seems to work quite well

Inclusive non-leptonic decays:
$\Lambda_b$ lifetime problem has disappeared!

Exclusive non-leptonic decays:
Theory is still a construction area!

There are some tensions:
If we take it seriously, we need to go beyond the SM

\[
\sin 2\beta = 0.687 \pm 0.032 \pm 0.013
\]

From direct measurement

\[
\sin 2\beta = 0.790 \pm 0.031
\]

From indirect determination
**sin 2\(\beta\) from \(b \rightarrow s\bar{s}s\) penguin modes**

<table>
<thead>
<tr>
<th>Charmonium</th>
<th>(0.726 \pm 0.037)</th>
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- \(\eta_f \times S_f\)

Thomas Mannel, University of Siegen

Phenomenology from Effective Field Theory
**B → K\pi Puzzle**

(Buras, Fleischer, Recksiegel, Schwab...)

- Use Isospin and full SU(3) to relate ππ and Kπ
- Assume that deviations form QCD factorization in ππ can be explained by large rescattering
- \( B \rightarrow K\pi \) puzzle:
  Abnormalities in the electroweak penguin sector?

\[
R_c = \frac{2Br(B^+ \rightarrow K^+\pi^0) + Br(B^- \rightarrow K^-\pi^0)}{Br(B^+ \rightarrow \pi^+K^0) + Br(B^- \rightarrow \pi^+\bar{K}^0)} = 1.01 \pm 0.09
\]

\[
R_n = \frac{1Br(B_d \rightarrow \pi^-K^+) + Br(\bar{B}_d \rightarrow \pi^+K^-)}{2Br(B_d \rightarrow \pi^0K^0) + Br(\bar{B}_d \rightarrow \pi^0\bar{K}^0)} = 0.83 \pm 0.08
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$B \rightarrow K\pi$ Puzzle

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\]
WE SHALL SEE ...