Soft photon emission in $B \to D$ meson decays

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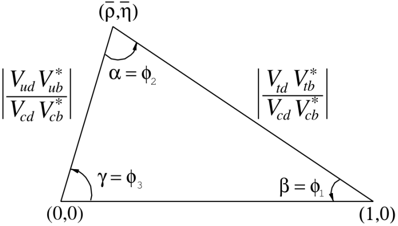
Outline

- Extracting $|V_{cb}|$ in $B \to D\ell\nu$ decays
  - Shape of semileptonic form factor
  - Heavy-quark symmetry
  - Nonperturbative methods
- Fake events due to undetected photons
  - Bremsstrahlung - known
  - Structure dependent terms - unknown
  - Dominated by nearby resonances
  - Effects on systematics

V_{cb}



$$|V_{cb}|_{incl} = (41.6 \pm 0.6) \times 10^{-3}$$
$$|V_{cb}|_{excl} = (38.6 \pm 1.3) \times 10^{-3}$$

- Apex of unitarity triangle determined by V_{ub}/V_{cb}
- Consistency test against precise $\sin 2\beta$ measurement
- Measurement of V_{ub} requires precise knowledge of $b \to c\ell\nu$ background in some kinematic regions
- Current precision from inclusive analyses $< 2\%$, expected to reach 1% at superB

V_{cb} in $B \to D\ell\nu$

- Independent method to pin down $|V_{cb}|$, different systematics
- Measure shape of spectrum at $q^2 < q^2_{max}$

$$\frac{d\Gamma}{dq^2} \sim G_f^2 |V_{cb}|^2 f_+(q^2)^2 + \mathcal{O}(m_\ell) f_0(q^2)$$

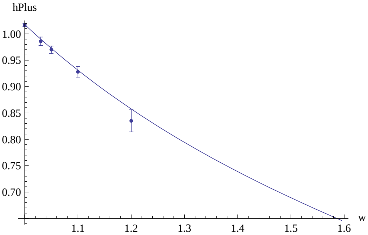
- Use HQ symmetry and analyticity/unitarity to extrapolate to q^2_{max}, where all FFs reduce to Isgur-Wise function $(\xi(1) = 1) \Rightarrow |V_{cb}| f_+(q^2_{max})$
- At q^2_{max} calculate HQ symmetry breaking corrections to form factors
- Luke's theorem: power corrections to h_+ vanish in NLO power corrections

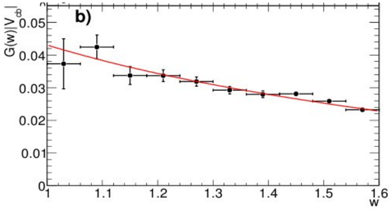
$$\frac{m_B + m_D}{2\sqrt{m_B m_D}} f_+(q^2) = h_+(w) - \frac{m_B - m_D}{m_B + m_D} h_-(w)$$

- short distance QCD corrections
- extract $|V_{cb}|$

V_{cb}, $B \to D\ell\nu$ and nonpert. methods

- alternatively $\to$ use nonperturbative method to determine of *FFs*
- Nowadays, form factors from quenched simulation are calculated at several points below q^2_{max} (de Divitiis et al)



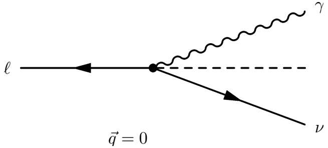


(BaBar (0904.4063))

- Unquenched calculations are underway
- At low q^2 sum rules results available
- With improved nonperturbative results we can avoid extrapolation to q^2_{max} and drop assumptions on shape of the form factor.

Measuring $B \to D\ell\nu$ - soft photon emission

Misidentified $B \to D\ell\nu\gamma$ decays for soft enough γ



Photon inclusive width

$$\Gamma(B \to D\ell\nu) + \Gamma(B \to D\ell\nu + \gamma)_{E_\gamma < E_{cut}} + \cdots$$

- Use hadronic final states for momentum tagging
- $m^2_{miss} = (p_{\Upsilon(4S)} - p_{tag} - p_D - p_\ell)^2$
- $m_{ES} = \sqrt{s/4 - \mathbf{p}^{*2}_{tag}}$ required to be in small range around m_B
- $E_{cut} \sim (\mathrm{one-to-few})\,100\ \mathrm{MeV}$

Measuring $B \to D\ell\nu$ - bremsstrahlung

- Inner bremsstrahlung (IB) contribution has a pole at $E_\gamma \to 0$ which is cancelled by $\mathcal{O}(\alpha_{em})$ virtual correction.
- IB contributions are structure independent, i.e., only depend on charges of initial and final state particles, and universal (Low's theorem)
- Resummations known for any number of radiated γ's
- Systematic error due to bremsstrahlung photons usually estimated by employing Monte-Carlo algorithm (e.g. PHOTOS)

Structure dependent $B \to D\ell\nu\gamma$

- Structure dependent (SD) part is finite at $E_\gamma = 0$, and generally believed to be unimportant due to α_{em} suppression.
- Nonperturbative in origin
- Studied in K_{l3} decays, where found to be smaller than bremsstrahlung (Gasser et al, Bijnens et al,...)
- Effects estimated to be sizable in $B \to \mu\nu$, where α_{em} is compensated by helicity enhancement and nearby resonances (Bećirević et al, 2009)

- Is per-cent precision of V_{cb} from this process allowed by systematics introduced by SD contribution?
- Our goal is to estimate the structure dependent contribution in $B \to D\ell\nu\gamma$
- $B^- \to D^0$ expected to be enhanced with respect to $B^0 \to D^+$.

$B^- \to D^0 \ell \nu \gamma$ amplitude decomposition

$$\mathcal{A} = \frac{eG_F V_{cb}}{\sqrt{2}} \epsilon^{*\mu} \, \bar{u}(p_l) \left(-\frac{F_\nu(t)}{2p_l \cdot q} \gamma_\mu (\not{p}_l + \not{p}_\gamma + m_l) + V_{\mu\nu} - A_{\mu\nu} \right) \gamma^\nu (1-\gamma_5) v(k)$$

Correlators of currents:

$$F_\nu(t) = i \langle D \,|\, H_\nu(0) \,|\, B \rangle \,, \qquad t = (p-p')^2$$

$$V_{\mu\nu} - A_{\mu\nu} = \int d^4y \, e^{iq\cdot y} \langle D \,|\, T\left[J_\mu(y) H_\nu(0)\right] |\, B \rangle \,, \qquad H^\nu = (\bar{c}b)^\nu_{V-A}$$

Ward identities:

$$q^\mu V_{\mu\nu} = (Q_D - Q_B) F_\nu(t) = F_\nu(t)$$

$$q^\mu A_{\mu\nu} = 0$$

$B^- \to D^0 \ell \nu \gamma$ polology

Inserting 1-particle intermediate states in $V_{\mu\nu} - A_{\mu\nu}$:

$$\frac{i\,\langle D\,|\,J_\mu\,|\,D_n(\mathbf{p}'+\mathbf{q})\rangle\,\langle D_n(\mathbf{p}'+\mathbf{q})\,|\,V_\nu - A_\nu\,|\,B\rangle}{(p'+q)^2 - m_{D_n}^2 + i\epsilon},$$

$$\frac{i\,\langle D\,|\,V_\nu - A_\nu\,|\,B_n(\mathbf{p}-\mathbf{q})\rangle\,\langle B_n(\mathbf{p}-\mathbf{q})\,|\,J_\mu\,|\,B\rangle}{(p-q)^2 - m_{B_n}^2 + i\epsilon}.$$

- Contributing states:

$$D_n = D^{*0}, D_1, \ldots, \qquad B_n = B^-, B^{*-}, B_1, \ldots$$

- Poles at $E_\gamma \to 0$:

$$\frac{1}{m_D^2 - m_{D_n}^2}, \quad \frac{1}{m_B^2 - m_{B_n}^2}, \text{ where } 1 - m_{B^*}^2/m_B^2 = -0.017$$

- For D_n resonances pole is in physical region - possibly dominant on-shell intermediate states (in SL $K \to \pi$, K^* and ρ are too heavy)

$B^- \to D^0 \ell\nu\gamma$ polology

The B^- pole is IR divergent and structure independent.

$$V_{\mu\nu}^{IB} = \frac{p_\mu}{p \cdot q} F_\nu(t)$$
$$V_{\mu\nu} = V_{\mu\nu}^{IB} + V_{\mu\nu}^{SD}, \quad q^\mu V_{\mu\nu}^{SD} = 0$$

Gauge invariant only together with the lepton bremsstrahlung piece.

$$\mathcal{A}_\mu \sim \bar{u}(p_l) \left(-\frac{F_\nu(t)}{2p_l \cdot q} \gamma_\mu (\not{p}_l + \not{q} + m_l) + \frac{p_\mu}{p \cdot q} F_\nu(t) \right) \gamma^\nu (1 - \gamma_5) v(k)$$

Remaining piece is also gauge invariant (and structure dependent)

$$q^\mu V_{\mu\nu}^{SD} = 0, \qquad q^\mu A_{\mu\nu} = 0,$$

... which determines the minimal parameterization.

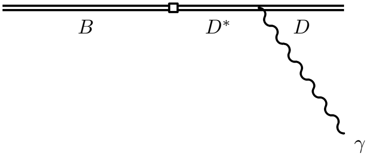
Lorentz decomposition of the SD amplitude

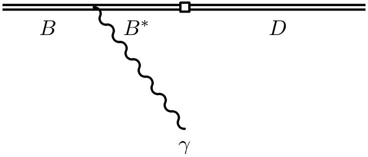
In terms of 4 vector and 4 axial functions:

$$
\begin{aligned}
V^{SD}_{\mu\nu} &= V_1(p'_\mu q_\nu - p' \cdot q\, g_{\mu\nu}) \\
&+ V_2\,(p_\mu q_\nu - p \cdot q\, g_{\mu\nu}) \\
&+ (V_3\, p_\nu + V_4\, p'_\nu)(p \cdot q\, p'_\mu - p' \cdot q\, p_\mu)
\end{aligned}
$$

$$
\begin{aligned}
A_{\mu\nu} &= A_1 \epsilon_{\mu\nu\alpha\beta}\, p^\alpha q^\beta \\
&+ A_2 \epsilon_{\mu\nu\alpha\beta}\, p'^\alpha q^\beta \\
&+ (A_3 p_\nu + A_4 p'_\nu)\, \epsilon_{\mu\alpha\beta\gamma}\, p^\alpha q^\beta p'^\gamma
\end{aligned}
$$

- These will be expressed as products $(B \to D^*\ \text{form factors}) \times g_{D^* D\gamma} \times \text{pole}(D^*)$ and $(B^* \to D\ \text{form factors}) \times g_{B^* B\gamma} \times \text{pole}(B^*)$, for the D^* and B^* resonances, respectively.
- In this preliminary study we only keep nearest resonances B^{*-} and D^{*0}.





Nonperturbative parameters

- EM current probes hadronic structure and defined for real photon as

$$\langle B^*(p^*,\eta)\,|\,J_\mu\,|\,B(p)\rangle \equiv g_{B^*B\gamma}\epsilon_{\mu\nu\rho\sigma}\eta^{*\nu}p^\rho p^{*\sigma}$$

$g_{B^*B\gamma} = 1.1$ from $\Gamma(B^{*-} \to B^-\gamma)$, $g_{D^*D\gamma} = 2.5$ from lattice (Bećirević et al)

- Vector and 3 axial weak current form factors:

$$\langle D^*\,|\,V_\nu\,|\,B\rangle \to V^{BD^*}(W^2), \qquad W^2 \equiv (p_l + k)^2$$
$$\langle D^*\,|\,A_\nu\,|\,B\rangle \to A^{BD^*}_{0,1,2}(W^2)$$

Also fitted to lattice points using quenched results (de Divitiis et al)

Correlators

$$V_1^{B^*} = \frac{g_{B^* B\gamma}\, V^{B^* D}(W^2)\,(m_{B^*}^2 + m_B^2)}{(m_{B^*} + m_D)\left((p-q)^2 - m_{B^*}^2\right)}, \qquad V_2^{B^*} = \frac{-2 g_{B^* B\gamma}\, V^{B^* D}(W^2)\, m_B E_D}{(m_{B^*} + m_D)\left((p-q)^2 - m_{B^*}^2\right)},$$

$$V_3^{B^*} = \frac{-2 g_{B^* B\gamma}\, V^{B^* D}(W^2)}{(m_{B^*} + m_D)\left((p-q)^2 - m_{B^*}^2\right)}, \qquad V_4^{B^*} = 0$$

$$A_1^{B^*} = \frac{g_{B^* B\gamma}}{\left((p-q)^2 - m_{B^*}^2\right) W^2} \Big[-2 m_{B^*}\, p' \cdot q\, a_0^{B^* D}(W^2) + (m_{B^*} + m_D)(p' \cdot q - W^2) a_1^{B^* D}(W^2) + \frac{p' \cdot q\, (W^2 - m_{B^*}^2 + m_D^2)}{m_{B^*} + m_D}\, a_2^{B^* D}(W^2) \Big]$$

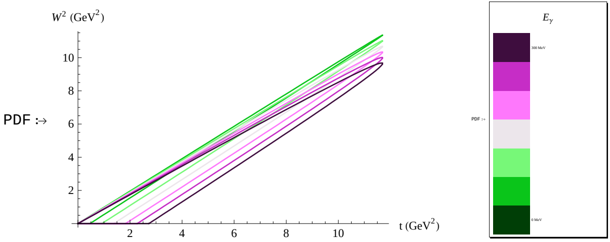
$$\vdots$$

Kinematics

- Variables

$$E_\gamma, \qquad t = (p - p')^2, \qquad W^2 = (p_l + k)^2, \qquad E_\ell, \qquad (p' + p_l)^2$$

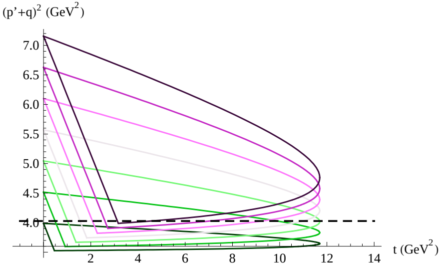
(in non-radiative, $E_\gamma \to 0$ limit, we have $W^2 \to t$)

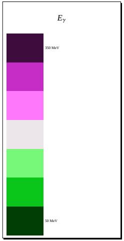


- Prescription for on-shell D^*

$\frac{1}{(p'+q)^2 - m_{D^*}^2 + i m_{D^*} \Gamma_{D^*}}$, and cut out the resonant peak region inside $(p' + q)^2 = m_{D^*}(m_{D^*} \pm \Gamma_{D^*})$

Kinematics



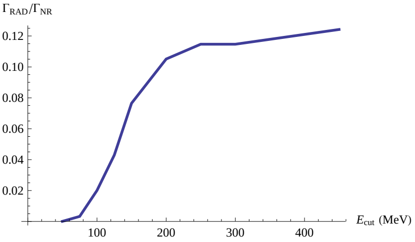


D^* on-shell only reachable for $E_\gamma \approx 50 - 350\ \mathrm{MeV}$ $(m_l = 0)$

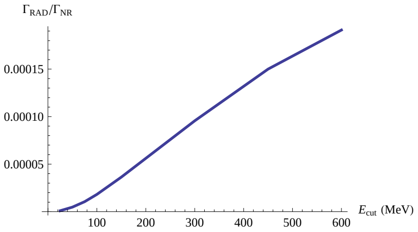
Fake events due to SD γ's

Preliminary estimate of fake events fraction in total semileptonic width

D^*



B^*



- In $100 - 200\ \mathrm{MeV}$ picking up the main contribution of D^*
- E_{cut} should be on the lower end of resonance region
- For a $\sim 1\%$ error (only due to fake γ events), need to resolve photons $100\ \mathrm{MeV}$.

Conclusions

- V_{cb} from exclusive $B \to D^{(*)}\ell\nu$
- Cross check inclusive analyses
- Nonperturbative input uncertainty: form factors.

EM corrections

- Lowering the error on V_{cb} towards 1% requires their knowledge
- Short distance under control.
- Acompanying soft photons?
- Structure dependent emission usually neglected.
- Kinematical conspiracy in semileptonic $B \to D$ for on-shell contributions