A proposal to solve some puzzles in semileptonic B decays

Sascha Turczyk

Lawrence Berkeley National Laboratory
Work in collaboration with F. Bernlochner and Z. Ligeti

[Phys.Rev. D85 (2012) 094033, arXiv:1202.1834]

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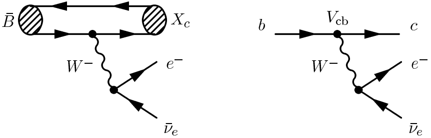
Outline

1. Introduction
   - Motivation
   - Current Situation
2. Proposal
   - Theoretical Considerations
   - Viability
3. Discussion

Experiments

- BaBar and Belle: 1.1 ab^{-1} at $\Upsilon(4s)$
- About 25% of all B decays are semi-leptonic



Semileptonic Charm Modes

- Access to V_{cb}
- Input for rare decay modes

⇒ Important concistency checks

⇒ Background understanding

- Several tensions with varying level of significance for over ten years

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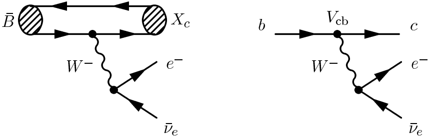

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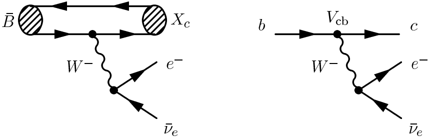

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Notation	$s_l^{\pi_l}$	J^P	m (GeV)	Γ (GeV)	
D	$\frac{1}{2}^-$	0^-	1.87		} 1s
D^*	$\frac{1}{2}^-$	1^-	2.01		
D_0^*	$\frac{1}{2}^+$	0^+	2.40	0.28	} 1p "broad"
D_1^*	$\frac{1}{2}^+$	1^+	2.44	0.38	
D_1	$\frac{3}{2}^+$	1^+	2.42	0.03	} 1p "narrow"
D_2^*	$\frac{3}{2}^+$	2^+	2.46	0.04	
D'	$\frac{1}{2}^-$	0^-	2.54	0.13	} 2s
D'^*	$\frac{1}{2}^-$	1^-	2.61	0.09	

- Isospin averaged masses and widths
- $s_l^{\pi_l}$ spin and parity of the light degrees of freedom
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Tension: Inclusive vs. Exclusive Measurement [HFAG 2010]

Charm state X_c	$\mathcal{B}(B^+ \to X_c\, \ell^+\, \nu)$	
D	$(2.31 \pm 0.09)\,\%$	
D^*	$(5.63 \pm 0.18)\,\%$	
$\sum D^{(*)}$	$(\mathbf{7.94 \pm 0.20})\,\%$	
$D_0^* \to D\,\pi$	$(0.41 \pm 0.08)\,\%$	broad states $(0.86 \pm 0.12)\%$
$D_1^* \to D^*\,\pi$	$(0.45 \pm 0.09)\,\%$	
$D_1 \to D^*\,\pi$	$(0.43 \pm 0.03)\,\%$	narrow states $(0.84 \pm 0.04)\%$
$D_2^* \to D^{(*)}\,\pi$	$(0.41 \pm 0.03)\,\%$	
$\sum D^{**} \to D^*\pi$	$(\mathbf{1.70 \pm 0.12})\,\%$	
$D\,\pi$	$(0.66 \pm 0.08)\,\%$	
$D^*\,\pi$	$(0.87 \pm 0.10)\,\%$	
$\sum D^*\pi$	$(\mathbf{1.53 \pm 0.13})\,\%$	
$\sum D^{(*)} + \sum D^*\pi$	$(\mathbf{9.47 \pm 0.24})\,\%$	
$\sum D^{(*)} + \sum D^{**} \to D^{(*)}\pi$	$(\mathbf{9.64 \pm 0.23})\,\%$	
Inclusive X_c	$(\mathbf{10.92 \pm 0.16})\,\%$	

Courtesy of Florian Bernlochner

- $B \to D^{(*)}\,\pi\,\ell\,\bar{\nu}_\ell$: Weighted average of both isospin modes, assuming a 100% correlation between both values.
- “ Inclusive X_c - $[\sum D^{(*)} + \sum D^*\pi]$ ”:Gap of $(1.45 \pm 0.29)\%$ emerges
- Uses semi-inclusive $D^{(*)}\pi$ branching fractions; Instead use measured $1P$ decay $D^{**} \to D^{(*)}\pi \Rightarrow (1.28 \pm 0.28)\,\%$

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- Use only B^0 modes and relate to B^+ with isospin
- Add $B \to D_1 \ell \bar{\nu}_\ell \to [D\pi\pi]\ell\bar{\nu}_\ell$ recently observed by LHCb and Belle

$$X_c - \left[\sum D^{(*)} + \sum D^*\pi\right] = 1.74 \pm 0.24$$

$$X_c - \left[\sum D^{(*)} + \left(\sum D^{**} \to D^{(*)}\pi\right) + (D_1 \to D\pi\pi)\right] = 1.80 \pm 0.25$$

- No longer exclude Belle lower limit on D_1' (neg. yields)

$$X_c - \left[(D^{(*)}) + D(*)\pi + D_1 \to D\pi\pi\right] = 1.61 \pm 0.25$$

Comments

- Analysis often fill up 'gap'
- Differences between Isopsin related modes
- Even with conservative uncertainties and rejecting incompatible measurements gap stays
- Difference in 'obtaining' gap strengthens argument to investigate
- **The discussion here is independent of the actual gap**

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Some more Tensions

Exclusive vs inclusive Determination of V_{cb} [PDG 2012]

$$|V_{cb}| = (41.9 \pm 0.7) \times 10^{-3} \quad \text{(inclusive)}$$
$$|V_{cb}| = (39.9 \pm 0.9) \times 10^{-3} \quad \text{(exclusive)}$$

- Inclusive: Based on HQE and inclusive measurement
- Exclusive: Theory input form factor; Measurement extrapolates to $q^2 = 0$

"1/2 vs 3/2 puzzle“

- Uraltsev sum rule prediction + quark model [Bigi et. al., arXiv:0708.1621]

$$\mathcal{B}(B^+ \to D^{**}_{1/2=\text{broad}}\, \ell^+ \nu)/\mathcal{B}(B^+ \to D^{**}_{3/2=\text{narrow}}\, \ell^+ \nu) \sim 0.1 - 0.2$$

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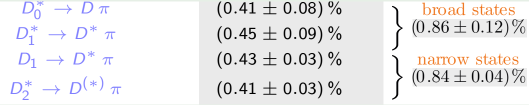

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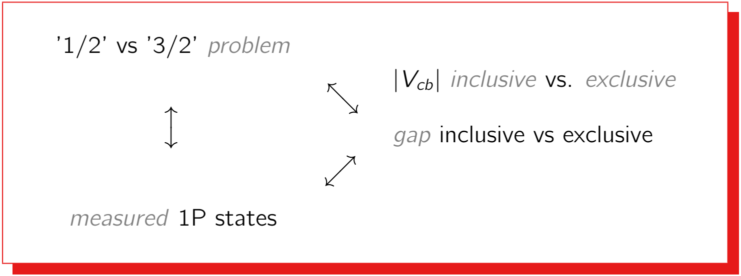
Natural Question



'1/2' vs '3/2' *problem*

$|V_{cb}|$ *inclusive* vs. *exclusive*

gap inclusive vs exclusive

measured 1P states

Is there any connection?

Possible Decay Chains

- Strong decay chain of $D'^{(*)}$

$$2S \to 1S$$

$$2S \to 1P \to 1S$$

- Particle spectrum in decay

$$p\text{−wave} + \pi \to 1S$$

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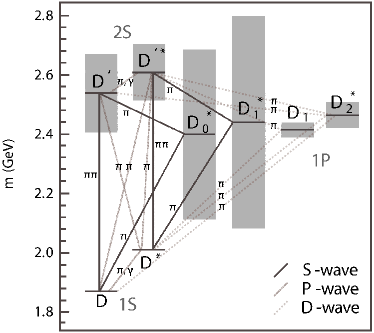
$$p_\pi \sim 0.01 - 0.5\ \text{GeV}$$



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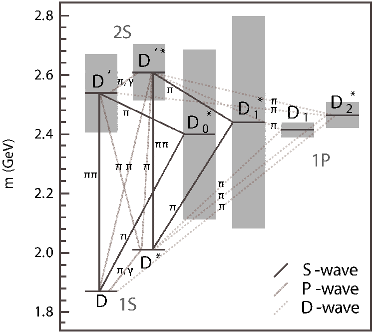

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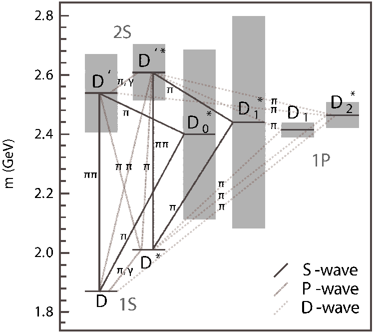

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One Solution to Ease All Tensions?

Postulate: Substantial Branching Fraction to radially excited $D'^{(*)}$

$$\mathcal{B}\big(B \to D'^{(*)}\ell\bar{\nu}\big) \sim \mathcal{O}(1\,\%)$$

Ways of Easing Tensions

1. Sufficient to saturate inclusive rate
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Decay Rate

- Same quantum numbers as $1S$ ground state ($\Rightarrow$ 6 form factors)
- $1 \leq w \equiv v \cdot v' \lesssim 1.3$

$$\frac{\mathrm{d}\Gamma_{D'^*}}{\mathrm{d}w} = \frac{G_F^2 |V_{cb}|^2\, m_B^5}{48\pi^3}\, r^3 (1-r)^2 \sqrt{w^2-1}\, (w+1)^2 \left[1 + \frac{4w}{w+1}\, \frac{1-2rw+r^2}{(1-r)^2}\right] \left[F(w)\right]^2$$

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What we know and expect about the FF

- $m_{b,c} \gg \Lambda_{\mathrm{QCD}}$: Single universal Isgur-Wise function $\xi_{(}w)$
- $\xi_2(1) = 0 \Rightarrow$ FF at $w = 1$ entirely determined by power corrections

$\Rightarrow$ For $w > 1$ no power suppression, but low kinematical range

  $\Rightarrow$ Potentially large $\Lambda_{\mathrm{QCD}}/m_{b,c}$ corrections

- Naive expectation in quark model
  - Expectation value of wave function increases for 1S $\rightarrow$ 2S

  $\Rightarrow \left.\frac{\mathrm{d}\xi_2}{\mathrm{d}w}\right|_{w=1} > 0$

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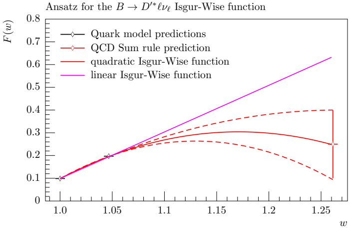
Quark Model Estimate at $w = 1$

[Ebert et. al., hep-ph/9912357]

Remarks

- Model for lightest excitation for given set of quantum numbers
- Calculates slope and value
- Rough estimate (no uncertainty quoted)
- Consistent with expectations from HQET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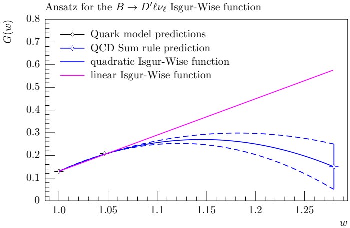
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$$F(1.0) = 0.10 \qquad G(1.0) = 0.13$$

$$F(1.05) = 0.20 \qquad G(1.05) = 0.21$$

Sum Rule Estimate at w_{max}

Ansatz

- Model for lightest excitation for given set of quantum numbers
- 2S is first excitation with same quantum numbers as 1s
- QCD light-cone sum rules shown to work for 1s with non-perturbative input functions from *initial*-state

Sketch of Calculation

- Modify existing calculation to project out ground-state

$$\frac{m_D^4 f_D^2}{m_c^2(m_D^2-q^2)} + \frac{m_{D'}^4 f_{D'}^2}{m_c^2(m_{D'}^2-q^2)} + \int_{s_0^{D'}}^{\infty} \mathrm{d}s \, \frac{\rho(s)}{s-q^2}$$

- Result sensitive to decay constant, Borel and duality parameters
- Check: Form factor vanishes for parameter set of ground-state

$$F(w_{\text{max}}) = 0.25 \pm 0.15 \qquad G(w_{\text{max}}) = 0.15 \pm 0.1$$

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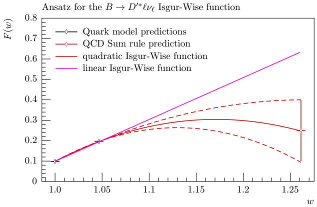
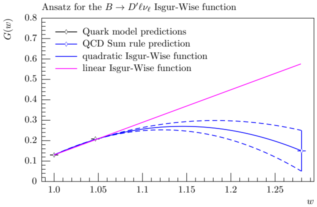
Combining Estimate of Form Factor





Linear and Quadratic Interpolation

$$F(w) = \beta_0^* + (w-1)\beta_1^* + (w-1)^2\beta_2^*$$

$$G(w) = \beta_0 + (w-1)\beta_1 + (w-1)^2\beta_2 \,.$$

- Linear interpolation (quark model only)

$$\beta_0^* = 0.10\,, \qquad \beta_1^* = 2.1$$

$$\beta_0 = 0.13\,, \qquad \beta_1 = 1.6$$

- Quadratic interpolation

$$\beta_0^* = 0.10\,, \quad \beta_1^* = 2.3 - 2.5\,, \quad \beta_2^* = -(4.2 - 9.8)$$

$$\beta_0 = 0.13\,, \quad \beta_1 = 1.9 - 2.0\,, \quad \beta_2 = -(5.1 - 8.2)$$

Estimated Branching Fraction

Linear Interpolation

$$\mathcal{B}\big(B \to (D' + D'^{*})\ell\nu_\ell\big) \sim 1.4\,\%$$

Quadratic Interpolation

$$\mathcal{B}\big(B \to (D' + D'^{*})\ell\nu_\ell\big) \sim (0.3 - 0.7)\,\%$$

Comment

- *Indication* that a large radial contribution is plausible
- Decays to radially excited $D'^{(*)}$ may account for a substantial part of the observed '*Gap*' between *inclusive* and *exclusive* decays
- Rough estimate, no precision prediction

⇒ Needs to be verified experimentally

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Possible Way to Constraint Form Factors

Factorization in Non-Leptonic Decays

$$\Gamma(B \to D'^{(*)}\pi) = \frac{3\pi^2 C^2 \, |V_{ud}|^2 f_\pi^2}{m_B \, m_{D'^{(*)}}} \left. \frac{\mathrm{d}\Gamma(B \to D'^{(*)}\ell\bar{\nu})}{\mathrm{d}w} \right|_{w_{\max}}$$

Analysis

- Proven to leading order in heavy mass limit [Bauer et. al.,hep-ph/0107002]
- Constrain form factors $F(w)$ and $G(w)$ at LCSR kinematical point
- Involves Dalitz plot analysis of $\bar{B} \to D'^{(*)}\pi \to [D^{(*)}\pi^+\pi^-]\pi^-$

⇒ Valuable in understanding decay rates of $D'^{(*)}$ states

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If $\mathcal{B}(B \to D'^{(*)}\ell\bar{\nu}) \sim \mathcal{O}(1\,\%)$ is experimentally verified, it can be tested:

1. Precise prediction of branching fraction
2. Shape of form factors
3. Data on non-leptonic two-body decays with a pion

May yield a better understanding of

1. The $b \to c$ background in
   - Inclusive $b \to u \Rightarrow$ more precise determination of $|V_{ub}|$
   - Exclusive $B \to D^{(*)}\ell\bar{\nu} \Rightarrow$ improve $|V_{cb}|$ measurements
2. Missing exclusive contributions to the inclusive rate
3. Better measurement of semileptonic BF to the $s_l^{\pi_l} = \frac{1}{2}^+$ and $\frac{3}{2}^+$ states

   $\Rightarrow$ May help to resolve the "1/2 vs. 3/2 puzzle"
4. Measured $B \to D^{(*)}\tau\bar{\nu}$ and tension w.r.t. to the SM [BaBar,arXiv:1205.5442]
5. Stronger sum rule bound on the $B \to D^{*}\ell\bar{\nu}$ form factor $\mathcal{F}(1)$

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