A proposal to solve some puzzles in charmed semileptonic B decays

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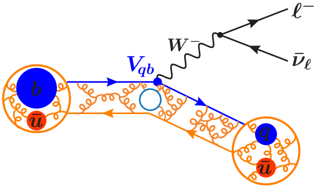
Outline



[Illustration by F. Tackmann]

I. Introduction: Summary of the exp. and theo. situation
   a Recap of incl. and excl. measurements
   b Recap of the '1/2' vs '3/2' problem

II. Discovery of potential 2*S* charmed state(s) by *BaBar*

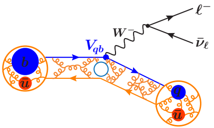
III. Our Proposal and its Viability

IV. Prediction of $\Gamma(B \to D'^{(*)}\,\ell\,\bar{\nu}_\ell)$ using *light-cone sum rules*

V. Summary

I.a Experimental situation for $B \to X_c \, \ell \, \bar{\nu}_\ell$

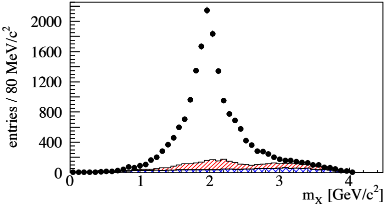
- *BaBar* and *Belle*: 1.1 ab^{-1} at $\Upsilon(4S)$
- $\approx$ 25% of all B decay semileptonic



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

- Most abundant $b \to c$: $\mathcal{B}(B^+ \to X_c \, \ell^+ \, \nu_\ell) = (10.92 \pm 0.16)\,\%$

X_c: charmed system; isospin averaged value from [HFAG]



- Major focus of experimental attention from B factories
- Inclusive X_c mass spectrum

  (not unfolded; $p_l^* > 0.8$) [PRD81:032003]
- Presence of charm decays up to $\approx$ 3 GeV (resolution 0.36 GeV)
- $D^{(*)}$, D^{**}, $D'^{(*)}$ $\leftrightarrow$ $1S$, $1P$, $2S$

I.a Experimental situation for $B \to X_c \, \ell \, \bar{\nu}_\ell$

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

broad states (D_0^*, D_1^*): $(0.86 \pm 0.12)\%$

narrow states (D_1, D_2^*): $(0.84 \pm 0.04)\%$

All values from [HFAG 2010]. For the values of $B \to D\,\pi\,\ell\,\bar{\nu}_\ell$ and $B \to D^*\,\pi\,\ell\,\bar{\nu}_\ell$ an uncertainty weighted average of both isospin modes was calculated assuming a 100% correlation between both values.

$\Rightarrow$ **'Gap'** of $(1.45 \pm 0.29)\,\%$ emerges which is not accounted for

Uses semi-inclusive $D^{(*)}\pi$ branching fractions; with measured $1P$ $D^{**} \to D^{(*)}\pi \Rightarrow (1.28 \pm 0.29)\,\%$

I.b Theoretical situation of $B \to X_c \ell \bar{\nu}_\ell$

- Comparable rates for the narrow and broad D^{**} states problematic:

$D_0^* \to D\,\pi$	$(0.41 \pm 0.08)\,\%$	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 $(0.84 \pm 0.04)\%$
$D_2^* \to D^{(*)}\,\pi$	$(0.41 \pm 0.03)\,\%$	

- Uraltsev's sum rule + covariant quark model estimate from [EPJ:C52975]

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

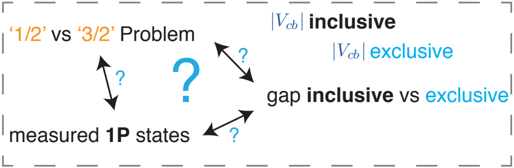
  i.e. clear dominance of narrow over broad.

- Experimental violation known as '1/2' vs '3/2' puzzle.
- Persistent $\backsim 2 - 3\sigma$ difference between $|V_{cb}|$ from **inclusive** vs exclusive

$$(\mathbf{41.9} \pm \mathbf{0.4}_{\text{exp.}} \pm \mathbf{0.6}_{\text{theo.}}) \times \mathbf{10}^{-3} \quad \text{vs} \quad (38.7 \pm 0.6_{\text{exp.}} \pm 0.5_{\text{theo.}}) \times 10^{-3}$$

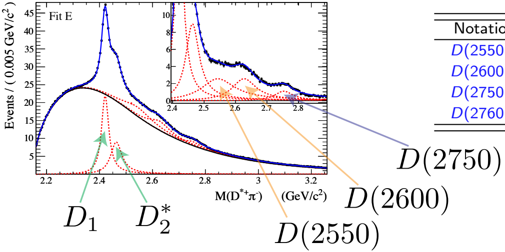
  [ARNPS:201161119]

- Any connections?



II. Discovery of new charmed states at *BABAR*

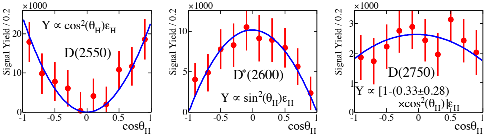
- *BABAR* observed four new charmed states [PRD82:111101]:



Notation	m (GeV)	Γ (GeV)	Sig.
$D(2550)^0$	2.54 ± 0.01	0.130 ± 0.018	3σ
$D(2600)^0$	2.61 ± 0.01	0.093 ± 0.014	7σ
$D(2750)^0$	2.75 ± 0.01	0.071 ± 0.013	4σ
$D(2760)^0$	2.76 ± 0.01	0.061 ± 0.006	9σ

The $m_{D^*\pi}$ mass distribution for $D(2550)$, $D(2600)$, $D(2750)$ is shown. $D(2760)$ reconstructed in $D\pi$ channel.

- Helicity angles of $D(2550)$ and $D(2600)$ helicity consistent with $2S$:



Helicity angle from $D^* \to D\pi$ is defined as the angle between the primary pion and $\pi_{\rm slow}$ from $D^* \to D\pi_{\rm slow}$ (in the D^* rest frame)

- $D(2750)$ candidate for $1D$ (Likely no relevant for semileptonic decays $\to$ cf. Backup)

II. Strong decays of $2S$ states D' & D'^{*}

- Strong D' and D'^{*} decays:

$$2S \to 1S$$

or

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

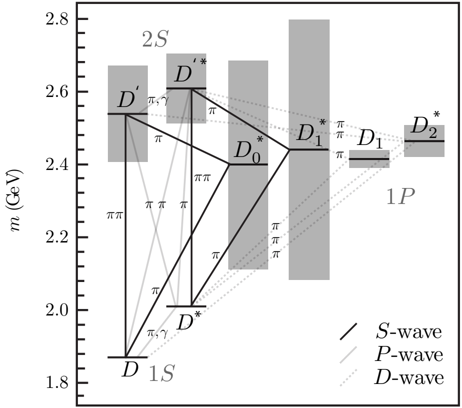
E.g. p-wave $+ \pi \quad \to 1S$
s-wave $+ \pi \quad \to 1P_{\text{broad}}$ $(\to 1S)$
Mom. of the emitted pion $p_\pi \backsim 0.01 - 0.5$ GeV
s-wave $+ \pi\pi \quad \to 1S$
d-wave $+ \pi \quad \to 1P_{\text{narrow}}$ $(\to 1S)$

Signature s-wave: $D'^{(*)} \to D^{(*)}\pi\pi$

Signature p-wave: $D'^{(*)} \to D^{(*)}\pi$

More decays involving ρ and η in principle allowed

- Significant $2S \to 1P_{\text{broad}}$ cross feed plausible [PRD:83014009]



A selection of the allowed strong decays involving single or two pion emissions are illustrated.

III. Our Proposal and its Viability

Proposal Explore possibility that the sum of $D'^{(*)}$ rate is substantial,

$$\mathcal{B}(B^+ \to D'^{(*)}\,\ell^+\,\nu_\ell) \backsim \mathcal{O}(1\%)$$

and show that this can help resolve the problems mentioned earlier without giving rise to new ones

1. This is a big enough contribution to the sum over exclusive states to close the gap between **inclusive** and exclusive without e.g. introducing **non-resonant** $B^+ \to D^{(*)}\,\pi\,\ell^+\,\nu_\ell$ contributions.

   A large non-resonant rate at high $D^*\pi$ invariant mass would disagree with the inclusive lepton spectrum and the measured semi-exclusive $B^+ \to D^{(*)}\,\pi\,\ell^+\,\nu_\ell$ rate

2. The $D'^{(*)}$ states can decay with one pion in an s-wave to members of the $s_l^\pi = \frac{1}{2}^+$ states, and could thus enhance the observed decay rate to the $\frac{1}{2}^+$, and thus give rise to the '1/2' vs '3/2' puzzle.

3. With the relatively low mass of the $D'^{(*)}$ the lepton spectrum can stay quite hard, in agreement with the observations

4. The $\mathcal{B}(B^+ \to D^*\pi\,\ell^+\,\nu_\ell)$ semi inclusive measurement is not in conflict with our hypothesis, since the decay of the $D'^{(*)}$ would yield two or more pions most of the time.

$\Rightarrow$ full details in Phys.Rev. D85 (2012) 094033 or arXiv:1202.1834

IV. Prediction for $\Gamma(B^+ \to D'^{(*)}\,\ell^+\,\nu_\ell)$

- $D'^{(*)}$ and $D^{(*)}$: identical quantum numbers

  i.e. same formulae for decay rate and definitions of form factors

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

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

where $r = m_{D'^{(*)}}/m_B$ and $w = v \cdot v'$ denotes the recoil parameter, where v denotes the velocity of the B meson, and v' of the $D'^{(*)}$.

- In $m_{b,c} \gg \Lambda_{\rm QCD}$ limit: 6 form factors $\to$ single universal Isgur-Wise function $\zeta_2(w)$

  i.e. $F(w) = G(w) = \zeta_2(w)$

- Heavy quark symmetry: $\zeta_2(w=1) = 0$

  $\to$ Non-zero rate at zero recoil entirely due to $\Lambda_{\rm QCD}/m_{b,c}$ corrections

- For $w > 1$ no power suppression, but low kinematic range of $1 < w < 1.3$ role of $\Lambda_{\rm QCD}/m_{b,c}$ corrections can be very large.

- Naive expectation: $\left.\frac{\mathrm{d}\zeta_2}{\mathrm{d}w}\right|_{w=1} > 0$ In quark model main effect of wave function of the brown muck is to increase the expectation value of the distance from the heavy quark of a spherically symmetric wave function. Overlap of initial and final state wave functions should increase as w increases.

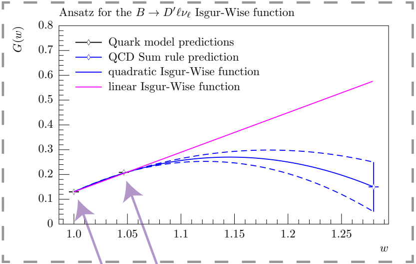
IV. The $B^+ \to D'^{(*)}\,\ell^+\,\nu_\ell$ form factors

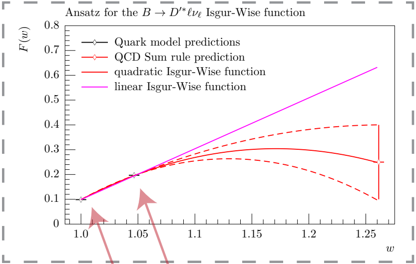
Not easy to calculate the $B^+ \to D'^{(*)}\,\ell^+\,\nu_\ell$ form factors:

- a Quark model [PRD:62:014032]
  hoped to be trustable near $w = 1$,
- b Modify QCD light-cone sum rule calculation [PJC:60603]
  hoped to be reasonable near max. recoil

But *Both models were developed, tuned, and tested for states that are the lightest within a given set of quantum numbers, thus take prediction with truck load of salt.* But even rough estimates can be helpful!

Quark Model form factors at $w = 1$ and linear extrapolation to $w = 1.05$:





Linear extrapolation to G(w=1.05)

G(w=1) from [PRD:62:014032]

Linear extrapolation to F(w=1.05)

F(w=1) from [PRD:62:014032]

IV. The $B^+ \to D'^{(*)} \ell^+ \nu_\ell$ form factors

Modify QCD light-cone sum rules so that the $2S$ state can be projected out

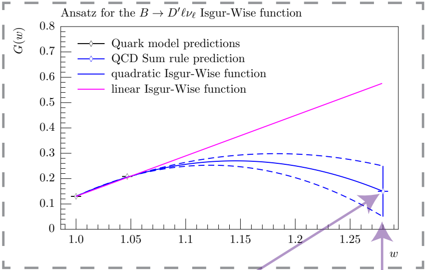
e.g. schematically for the decay constant

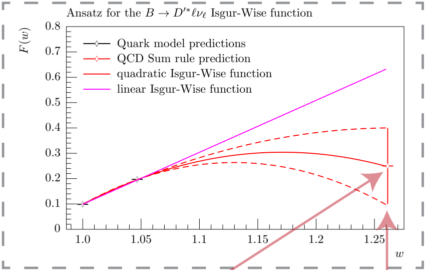
$$\frac{m_D^4 f_D^2}{m_c^2(m_D^2 - q^2)} + \frac{m_{D'}^4 f_{D'}^2}{m_c^2(m_{D'}^2 - q^2)} + \int_{s_0^{D'}}^{\infty} \mathrm{d}s \, \frac{\rho(s)}{s - q^2} \, .$$

where ρ is the spectral density function, and f_D and $f_{D'}$ denote the $1S$ and $2S$ decay constant, respectively.

Modification of Borel transformation in [PJC:60603] non-trivial endeavor.

Form factors sensitive fo chosen decay constants, Borel, and duality parameters





Our estimate for $G(w_{max})$

Our estimate for $F(w_{max})$

Effect of variation on duality and Borel parameters in calculation

IV. Prediction for $\Gamma(B^+ \to D'^{(*)}\, \ell^+\, \nu_\ell)$

Parametrize $F(w)$ and $G(w)$ which determine the $D'^{(*)}$ as quad. polynom. i.e.

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

$\Rightarrow$ Rough estimate for sum of two semileptonic $B^+ \to D'^{(*)}\, \ell^+\, \nu_\ell$ decays:

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

Earlier quark models without accounting for $\Lambda_{\rm QCD}/m_{b,c}$ effects obtained smaller rates, c.f. [PRD:39799],[PTP:91757]. Including $\Lambda_{\rm QCD}/m_{b,c}$ effects a value of 0.4% was obtained by [PRD:62:014032].

With a linear parametrization and the quark model result only:

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

We take this as an indication that a large radial contribution is plausible, and that $B^+ \to D'^{(*)}\, \ell^+\, \nu_\ell$ may account for a substantial part of the observed **'Gap'** between **inclusive** and exclusive decays.

V. Summary and Ideas

- Indication that hypothesis plausible and that $B \to D'^{(*)} \ell \bar{\nu}_\ell$ may account for a substantial part of the observed **'gap'**.

- Interesting measurement for LHCb (or B-factories): $B \to D'^{(*)} \pi = [D^{(*)} \pi^+ \pi^-] \pi^-$
  Factorization [PRL:87201806] implies relation between these channels and semileptonic decay rate at $w_{\max}$:

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

  C combination of Wilson coefficients with $C\,|V_{ud}| \approx 1$, and $w_{\max}$ corresponds to $q^2 = 0 \backsimeq m_\pi^2$

- If future measurement find a $B \to D'^{(*)} \ell \bar{\nu}_\ell$ decay rate ...
  the precise determination of the branching fraction and form factors would impact other measurements and the theory of semileptonic decays, e.g. it may yield a better understanding . . .

  i. . . . of $b \to c$ backgrounds and improve $|V_{ub}|$ and $|V_{cb}|$
  ii. . . . missing exclusive contributions to **inclusive** $B \to X_c \ell \bar{\nu}_\ell$
  iii. . . . of the measured $B \to D^{(*)} \tau \bar{\nu}_\tau$ and its tension with the SM

Further

  iv. Help improve the measurements of the semileptonic branching fractions of the $s_l^\pi = \frac{1}{2}$ and $\frac{3}{2}$ states, thus maybe help resolving the '1/2' vs '3/2' puzzle
  v. Help improve the sum rule bound on the $B \to D^* \ell \bar{\nu}_\ell$ form factor.

Thank you for your attention!

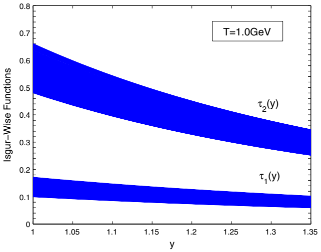
Backup

A. Prediction for $1D$ from QCD sum rules

- QCD sum rule result of [PRD:79034025] suggests that $1D$ contributions to the **inclusive** semileptonic decay rate are small

Decay	PRD:79034025	PLB:478408
$B \to D_1^* \, \ell \, \bar{\nu}_\ell$	6×10^{-6}	
$B \to D_2' \, \ell \, \bar{\nu}_\ell$	6×10^{-6}	
$B \to D_2 \, \ell \, \bar{\nu}_\ell$	1.5×10^{-4}	1×10^{-5}
$B \to D_3^* \, \ell \, \bar{\nu}_\ell$	2.1×10^{-4}	1×10^{-5}

The branching fractions for the four $1D$ states are quoted. Note that the D_1^* is not identical with the $1P$ state with the same name (which is sometimes denoted as D_1' to avoid this confusion)



The Isgur-Wise functions for the $\frac{3}{2}$ and the $\frac{5}{2}$ $1D$ doublets as a function of the recoil param. y $(= w)$ are shown.