Measurement of Form Factors in the Decay $B- > D^{*}l\nu$

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Outline

1. Introduction + Motivation – why is this useful?
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Motivations

- Semileptonic decay measurement in transitions of b to c quarks always yield a rate proportional to $|V_{cb}\mathcal{F}_{D^*}(1)|^2$, where the second factor is the modified form of the Isgur-Wise (IW) function evaluated at zero recoil of the D^*.

- This form factor must be determined from elsewhere in order to extract a value for V_{cb} (from this technique).

- The more accurately we can determine this form factor, the more we can reduce the errors in the V_{cb} extraction.

- V_{cb} is a fundamental parameter of the Standard Model (SM), being one of the entries in the CKM (quark-mixing) matrix:

$$V_{ij}^{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- The CKM matrix has three unique real parameters and one complex phase, and can be rewritten in the Wolfenstein parameterization:

$$V^{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \tag{1}$$

with the approximate values from experiment:

$$A = 1 \pm .2, \;\; \lambda = .22, \;\; \rho^2 + \eta^2 \leq .3$$

- Now the CKM matrix is a unitary matrix (in the SM), with one of the constraint equations being:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- Using the Wolfenstein form we write:

$$\begin{aligned} V_{ud}V_{ub}^* &= A\lambda^3(\rho + i\eta) \\ V_{cd}V_{cb}^* &= -A\lambda^3 \\ V_{td}V_{tb}^* &= A\lambda^3(1 - \rho - i\eta) \end{aligned}$$

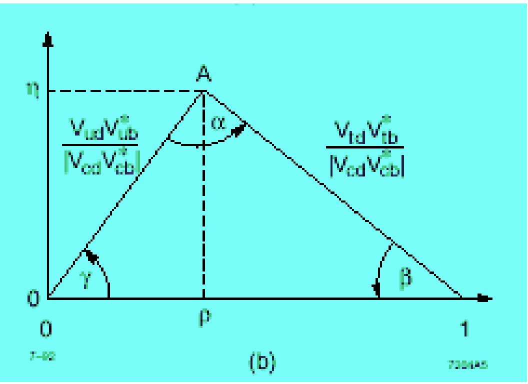
so defining:

$$R_u = \sqrt{\rho^2 + \eta^2}; \;\; R_t = \sqrt{(1-\rho^2) + \eta^2}$$

the above constraint eq. becomes:

$$R_u e^{i\gamma} + R_t e^{i\beta} - 1 = 0$$

which can be translated into the complex plane as:



- This is one of the unitarity triangles, and is the one being tested for closure (and thus consistency with the SM) at the B-factories currently through various B decay processes.

- We can in fact measure V_{cb} through doing this fit (by keeping the overall normalization as a free parameter), but the cut optimization for V_{cb} emphasizes precise knowledge of efficiency whereas the FF fit cuts are honed for purity.

- Another reason for measuring form factors is that different forms of heavy quark effective theory (HQET) predict different values for the form factors.

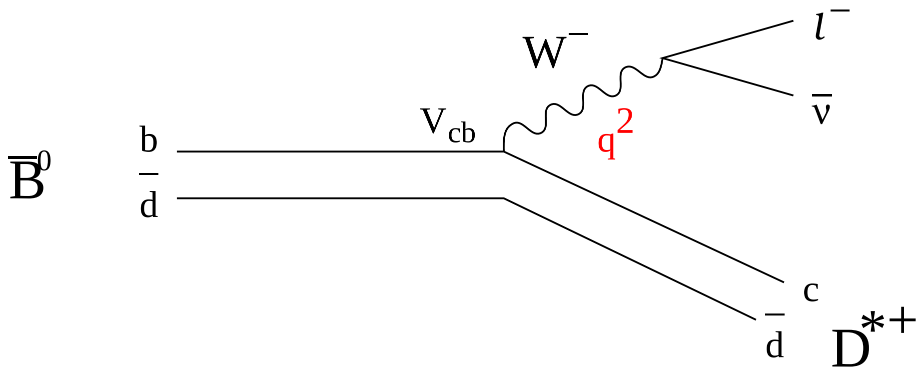
- Accurate determination may potentially rule out some of the proposed HQET models, for the first time ever.

- We can also learn more about the structure of heavy mesons and QCD through discarding some of these models.

- An interesting possibility that has also recently been pointed out is constraining of the right handed coupling of b quarks to W's (i.e. V+A interactions) through the comparing V_{cb} extracted from exclusive $D^*l\nu$ decay and the inclusively measured value (see ref. Voloshin 1997)

Basic Formalism

- We begin with the basic quark-level diagram:



[Fig: draw a circle around the two quark lines making up the D*, showing complex gluon-quark interactions]

In this diagram, $q^2 \equiv (p_B - p_D^*)^2$ which is linearly related to another variable we will be using later,

$$w = \frac{M_B^2 + M_{D^*}^2 - q^2}{2M_B M_{D^*}} \tag{2}$$

- It can be shown that this is equivalent to the definition

$$w = v_B \cdot v_{D^*} = \frac{p_B \cdot p_{D^*}}{M_B M_{D^*}} \tag{3}$$

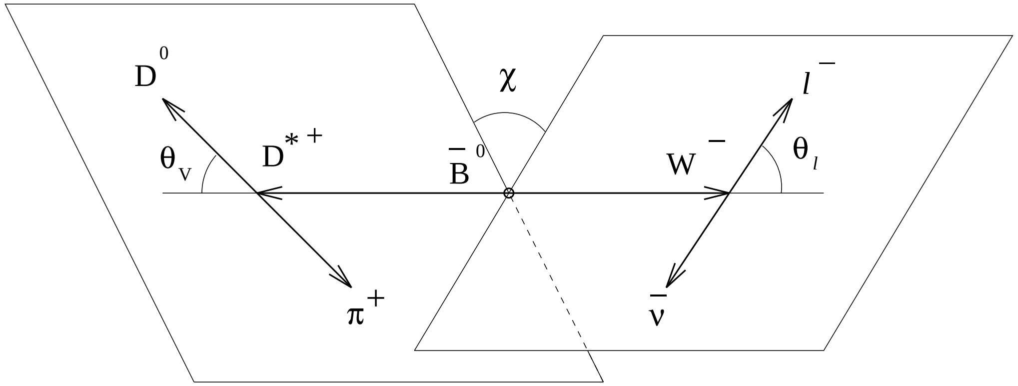
where p is the 4-momentum and v the 4-velocity $\left(\text{i.e.,} \frac{p}{m}\right)$ of the respective particles.

- w is in fact just the relativistic boost factor γ of the D^* in the B rest frame.
- Note that q^2 is equivalently $(p_l + p_\nu)^2$, the invariant mass of the virtual W, and higher q^2 corresponds to more kick to the W.
- q^2 and w take the following values in the extremal configurations:

Configuration	q^2	w
Stationary D^* :	$\sim 10.7\text{GeV}^2$	1.0
Max. boosted D^* :	$m_l^2 \sim 0$	1.5

[fig will be inserted here showing extremal configs]

- Upon hadronization of the quarks, we find:



- This figure defines three angles, which, along with q^2, form the four independent kinematic variables we use:
  - $\cos\theta_l$, the cosine of the included angle between the lepton in the virtual W rest frame, and the virtual W in the B rest frame
  - $\cos\theta_v$, the cosine of the included angle between the D^0 in the D^* rest frame, and the D^* in the B rest frame
  - χ, the angle between the plane formed by the $D^* - D^0 - \pi_s$ system and that formed by the $W - l - \nu$ system.

- We may write the matrix element for this process as:

$$\mathcal{M} = -i\frac{G_F}{\sqrt{2}}V_{cb}L_\mu H^\mu \quad (4)$$

Where the lepton tensor is simply $L_\mu = \bar{l}\gamma_\mu(1-\gamma_5)\nu$

- Hadronic tensor is formed by writing all possible Lorentz invariants of the available four vectors: the D^* spin polarization vector ϵ_μ, and the B^0 and D^* 4-momenta: p_μ, k_ν

- The tensor can then be parameterized most generally in terms of four form factors, which can only be functions of q^2 (V and A indicate that the term arises from underlying Vector or Axial vector couplings):

$$H^\mu = \langle D^{*+}(k,\varepsilon)|\bar{c}\gamma^\mu(1-\gamma_5)b|\bar{B}^0(p)\rangle =$$
$$\frac{2i\epsilon^{\mu\nu\alpha\beta}}{M_B+M_{D^*}}\varepsilon^*_\nu k_\alpha p_\beta V(q^2) - (M_B+M_{D^*})\varepsilon^{*\mu}A_1(q^2) +$$
$$\frac{\varepsilon^*\cdot p}{M_B+M_{D^*}}(p+k)^\mu A_2(q^2) - \frac{\varepsilon^*\cdot p}{M_B+M_{D^*}}(p-k)^\mu A_3(q^2).$$

- A_3 can be neglected in the limit of small lepton mass relative to the meson masses in the process (as can be easily seen by just contracting the lepton and hadron tensors; this case holds for both the e and μ, but not the τ), thus we drop it henceforth.

- To arrive at a physically measurable quantity, first reparameterize the three remaining form factors into helicity form factors for the D^* as so:

$$H_+ \equiv -(M_B + M_{D^*})A_1(q^2) + 2\frac{\wp_{D^*} M_B}{M_B + M_{D^*}} V(q^2),$$

$$H_- \equiv -(M_B + M_{D^*})A_1(q^2) - 2\frac{\wp_{D^*} M_B}{M_B + M_{D^*}} V(q^2),$$

$$H_0 \equiv -\frac{1}{2M_{D^*}\sqrt{q^2}}(A_1(q^2)(M_B + M_{D^*})(M_B^2 - M_{D^*}^2 - q^2) - 4\frac{M_B^2 \wp_{D^*}^2}{M_B + M_{D^*}} A_2(q^2))$$

- Integrating over phase space, this finally leads to the differential decay rate with respect to the four relevant kinematic variables:

$$\frac{d\Gamma(B\to D^* l\nu)}{dq^2 d\cos\theta_l d\cos\theta_v d\chi} = \frac{3G_F^2|V_{cb}|^2 P_{D^*} q^2}{8(4\pi)^4 M_B^2}$$

$$(|H_+|^2(1-\cos\theta_l)^2\sin^2\theta_V + |H_-|^2(1+\cos\theta_l)^2\sin^2\theta_V$$

$$+4|H_0|^2\sin^2\theta_\ell\cos^2\theta_V - 2H_+H_-\sin^2\theta_\ell\sin^2\theta_V\cos(2\chi)$$

$$-4H_+H_0\sin\theta_l(1-\cos\theta_l)\sin\theta_v\cos\theta_v\cos\chi$$

$$+4H_-H_0\sin\theta_l(1+\cos\theta_l)\sin\theta_v\cos\theta_v\cos\chi)$$

This is the final form of the differential decay rate with respect to the 4 kinematic variables we take as a complete set of independent parameters.

- Connect to theoretical predictions by defining two ratios in which uncertainties drop out:

$$R_1(w) \equiv \left[1 - \frac{q^2}{(M_B + M_{D^*})^2}\right] \frac{V(q^2)}{A_1(q^2)},$$
$$R_2(w) \equiv \left[1 - \frac{q^2}{(M_B + M_{D^*})^2}\right] \frac{A_2(q^2)}{A_1(q^2)}.$$

- To keep the number of degrees of freedom (three) conserved, make another definition based on HQET models: 50

$$h_{A_1}(w) = R^* \left[1 - \frac{q^2}{(M_B + M_{D^*})^2}\right]^{-1} A_1(q^2). \qquad (5)$$

(where we have introduced $R^* = \frac{2\sqrt{M_B M_{D^*}}}{(M_B + M_{D^*})}$.

- As w only varies from $1 \to 1.5$ expanding this FF in a Taylor series around the point $w = 1$ as so:

$$h_{A_1}(w) = h_{A_1}(1)[1 - \rho^2_{A_1}(w-1)], \qquad (6)$$

where $\rho^2_{A_1}$ is called the 'slope' of the FF, is a good approximation over the whole allowed w range.

- The three parameters we will fit for later will be exactly these: R_1, R_2, ρ_{A_1}, (equivalent to a determination of the three FF's, V, A_1, A_2, or the three helicity amplitudes H_0, H_+, H_-).

- From the above definitions, it is easily seen that:

$$
\begin{aligned}
V(q^2) &= R_1(w) h_{A_1}(w)/R^*, \\
A_2(q^2) &= R_2(w) h_{A_1}(w)/R^*.
\end{aligned}
$$

- Thus, given any theoretical prediction for $R1, R2, h_{A_1}$, we can invert to get V, A_1, A_2, and then substituting these into the helicity amplitudes, fill in the prediction for the differential decay rate, eq. for dΓ.

[Fig: insert a flowchart here showing the procedure]

- Different HQET theories make different predictions for R_1 and R_2, (the slope is determined from sum rules or lattice calculations), as examples, Neubert (based on an effective Lagrangian with corrections due to non-infinite heavy quark mass) predicts:

$$\begin{aligned} R_1(w) &= 1.35 - 0.22(w-1) + 0.09(w-1)^2, \\ R_2(w) &= 0.79 + 0.15(w-1) - 0.04(w-1)^2. \end{aligned}$$

and Close & Wambach (based on VMD models) predict:

$$\begin{aligned} R_1(w) &= 1.15 - 0.07(w-1), \\ R_2(w) &= 0.91 + 0.04(w-1). \end{aligned}$$

so that with a good enough measurement of the FF's, we will be able to distinguish between these various theories.

2. Previous Results at CLEO (A. Ryd, J. Richman)

- CLEO is a detector at the CESR (Cornell Electron Synchotron Ring) accelerator; both the ring and the detector are fully symmetric.

- The last CLEO measurement of these FF's was done on 3fb^{-1} of data (2.4 on peak, 0.6 off peak) in about 1996, and was in fact the same one reported at Osaka this year. That data was collected from Nov 90 to Feb 94 (despite more data, no current work on this is happening).

  [Fig: pic of Cleo detector]

- This yielded a sample of 2.6 million collected $B\overline{B}$ (neutral+charged) pairs, out of which they reconstructed 940 events in the decay chain $B^0 \to D^* l \nu$ with $D^* \to D^0 \pi$ and the D^0 decaying to the two modes $K\pi, K\pi\pi^0$ (where 'π' denotes a charged pion).

- Structure of CLEO detector:
  - Tracking detectors - from the inside out:
    - Innermost: Precision Tracking Layer – 6 layers of straw-tube chambers.
    - Middle: Vertex Detector – 10-layered drift chamber.
    - Outermost: DR, inner radius of 25 cm, outer radius of 90cm.
  - Next, the Electromagnetic Calorimeter, for detecting energy deposition of charged particles.
  - Finally, the muon system: required a minimum p_μ of about 1.3 GeV to identify μ's, had a fake rate from pions and kaons of about 2.5%.

Method of Fitting at CLEO

- Create MC points according to the 4-dim PDF, and filled the allowed phase space with this MC distribution.

- A global maximum likelihood fit to the data for the 4 kinematic variables was done, by calculating the likelihood for a given set of data points with the generated MC distribution.
  - In more detail: 4 dim'l box was formed around each data point and the density of MC points in each box calculated.

    [Fig of box with MC and data points in it]
  - Eventually, just as in a 1-dim fit, the values of the parameters $R_1, R_2, \rho^2_{A_1}$ that led to a 4-dim'l hypersurface that most closely approximated the data points was found, and a best fit of for them was achieved.
  - Because 4-dim'l fits are difficult to visualize, they made one-dim'l projections of each of their kinematic variables so one can get a feeling for what these distributions look like:

    [Fig: the page with the 4 1-dim'l kin var dists]

- Numerically, they found the values in the following table:

Measurement	R_1	R_2	$\rho^2_{A_1}$
CLEO '96	$1.18 \pm .30 \pm .12$	$.71 \pm .22 \pm .07$	$.91 \pm .16 \pm .06$

Table 1: Values for the measurements of R_1, R_2, and $\rho^2_{A_1}$ at CLEO. These are all clearly heavily statistics dominated!

- They found this to be consistent with all the major theories on the market, as in the table below:

Prediction	R_1	R_2
Neubert	1.35	.79
Close & Wambach	1.15	.92
ISGW2	1.0	1.0

Table 2 : Central values for the predictions of R_1, R_2, and $\rho^2_{A_1}$ in various HQET models.

PEP II and Babar

- In contrast to CESR and CLEO, PEP II (Positron Electron Producer) at SLAC is an asymmetric ring, designed this way for the primary reason of giving boost to the produced B mesons. [Fig: find a decent picture of PEP II]

- This boost will be helpful in allowing us to more easily measure one of the most difficult particles to detect in this decay process, called the slow pion.

- This leads naturally to an asymmetric detector, called Babar.

- The subdetectors from the inside out at Babar are:
  - The Silicon Vertex Tracker (SVT), for very precise vertexing and angular resolution information.
  - The Drift Chamber (DCH), for measuring the direction of charged particles.
  - The Detector of Internally Reflected Cerenkov radiation (DIRC), for particle identification (PID).
  - The Electromagnetic Calorimeter (EMC), for measuring energy deposition by (almost) all particles.
  - The Instrumented Flux Return (IFR), for detecting any muons or K_L particles that range out to it.
- Several of these subdetectors should allow us to ultimately control systematics better than CLEO: e.g. the SVT will give us more precise vertex information, the DIRC allows us to discriminate better between e.g. pions and kaons

- The primary functions of the detector we are concerned about are these:
  - The SVT and DCH contribute to PID through $\frac{dE}{dx}$ measurements and through tracking and vertexing, give us the topology of all charged tracks in the event.
  - The DIRC is important for distinguishing kaons from pions, especially in high multiplicity modes like $K\pi\pi\pi$.
  - The EMC is critical for an $\frac{E}{p}$ measurement, very important for electron ID. Also, it is how we measure direction and energy of photons, which we trace back to be reconstructed as π^0ś.
  - The IFR is useful for further checking muon ID (we use both electrons and muons, which contribute nearly equally, in this analysis.)

Overview of Experimental Method

Overall structure:

- We will reconstruct events in the decay chain:
  - $B^0 \to D^{*-} e^+ \nu$
  - $D^{*-} \to \overline{D^0} \pi^-$
  - $\overline{D^0} \to K^- \pi^+$
- Next we estimate the various backgrounds we have, amount and type.
- We then estimate from MC the efficiency we have in finding each of the four variables.
- Finally we will do a 4-dim'l global fit to extract the predicted quantities.
- Ultimately we will find the contribution of the backgrounds, MC, and fitting method to the systematic error.

Method of Event Selection

- To suppress backgrounds from non-$B\overline{B}$ events, we first make an event level cut on the Fox-Wolfram moment R_2 – higher R_2 corresponds to more “jetty” events, like continuum quark and Bhabha events.

  [Fig: effect of R2 cut, and picture of what it does]

- We split up the reconstruction of the event into several subsections: D^0, D^* ,and B^0 .

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