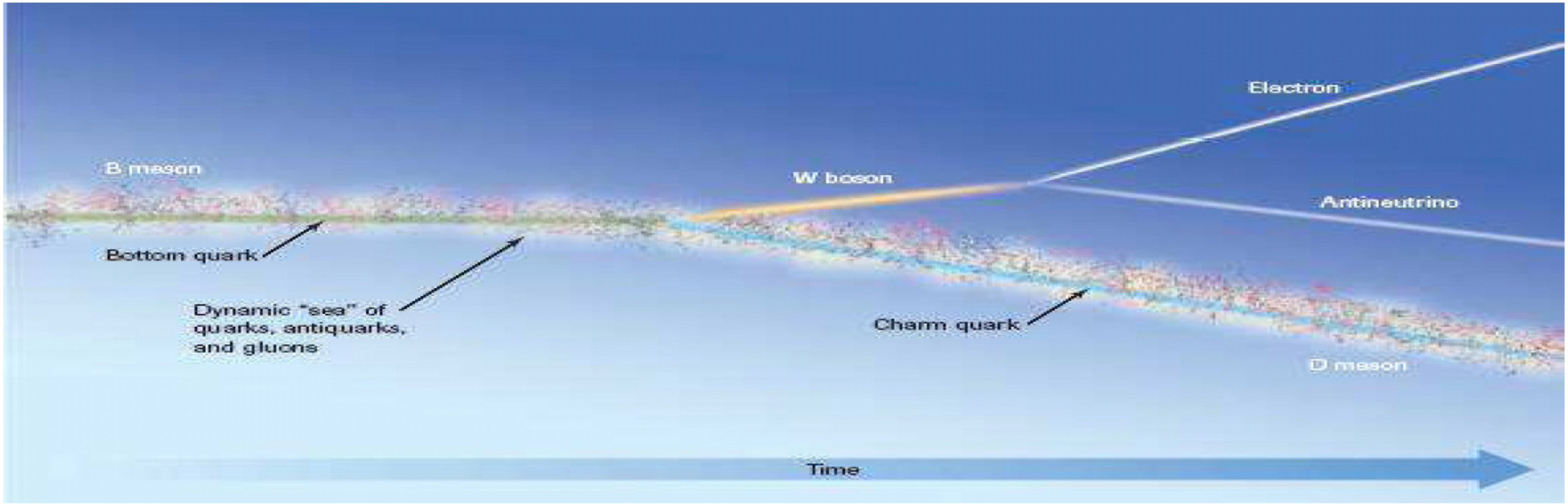
$B \to D^{(*,**)} l\nu$: $|V_{cb}|$ and Form-Factors

A. Snyder, SLAC

Heavy Quarks and Leptons (HQL)

München, October 16-20, 2006

... ...



$$\Gamma(b \to c) \propto |V_{cb}|^2 \otimes FF's$$

Organization

I'll follow order simple$\longrightarrow$complicated…therefore consider…

$\rightarrow$ $B \rightarrow Dl\nu$

$\rightarrow$ $B \rightarrow D^*l\nu$

$\rightarrow$ $B \rightarrow D^{**}l\nu$

$\rightarrow$ $B \rightarrow D^{(*)}n\pi l\nu$

I will not attempt a comprehensive review but will concentrate on reasonably fresh results…and a little self-indulgence…rather a lot on $D^*l\nu$ form-factors…

Issues that will come-up:

$\rightarrow$ Measuring form-factors

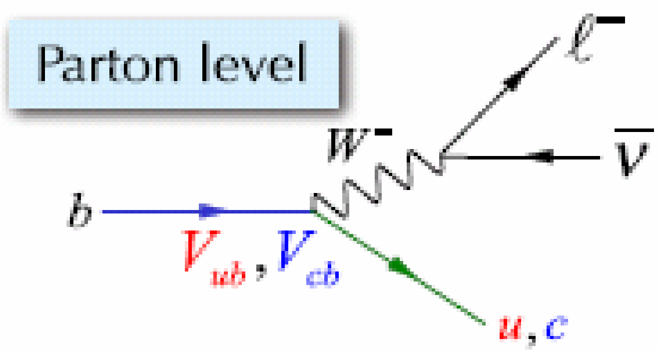
$\rightarrow$ Measuring branching fractions

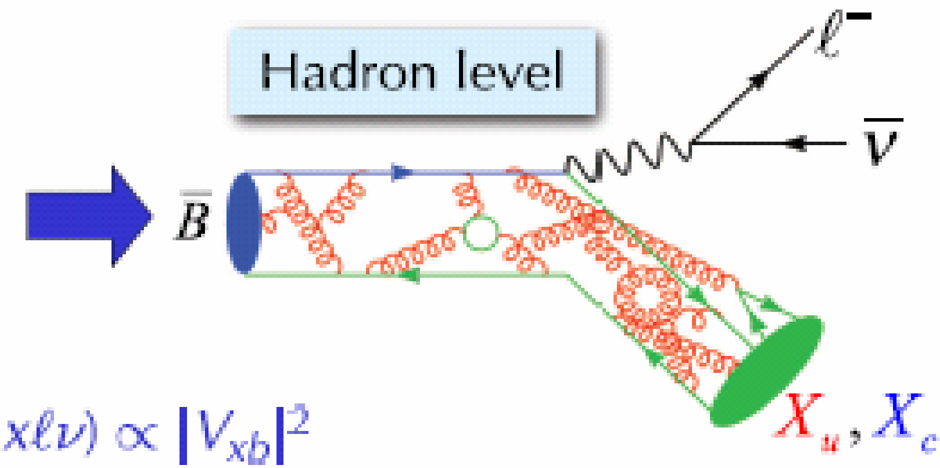
$\rightarrow$ Measuring $|V_{cb}|$

$\rightarrow$ Consistency of results

Form-Factors

⇓ Topic of this talk is on exclusive level





- Decay rate $\Gamma_x \equiv \Gamma(b \to x\ell\nu) \propto |V_{xb}|^2$

→ Parton level is – in principle – theoretically straight forwardly related to fully inclusive rate. However, the need to select signal complicates theoretical predictions and introduces model dependencies

→ Hadron level directly related to exclusive rates is straight forward (well. . . simpler anyway) experimentally but then we need form-factors!

→ There's a sort of no-win theorem

→ HQET and LQCD are the theoretical tools for coping with form-factors

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$B \to Dl\nu$

Phenomenology $B \to Dl\nu$ starts from general form-factor relation

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3}|V_{cb}|^2(m_B+m_D)^2 m_D^3 (w^2-1)^{\frac{3}{2}} \mathcal{F}_D^2(w) \tag{1}$$

where

$$w = v_B \cdot v_D = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D} = \frac{E_D^*}{m_D}. \tag{2}$$

Because this is $0^- \to 0^-$ transition there is only one form factor – $\mathcal{F}_D(w)$.

In heavy quark limit (HQS) $\mathcal{F}_D(w=1)=1$; lattice QCD calculations determine $\mathcal{F}_D(w=1) \approx 1.07$ [13]. Dispersion relations given $\mathcal{F}_D \approx 1$.

The $Dl\nu$ analyses uses the heavy quark effective theory (HQET) based parametrization of $\mathcal{F}_D$ developed by Caprini, Lellouch and Neubert (CLN) [1] which expands in the improved convergence variable $z \equiv (\sqrt{w+1}-\sqrt{2})/(\sqrt{w+1}+\sqrt{2})$:

$$\mathcal{F}_D(w) = \mathcal{F}_D(1) \times (1 - 8\rho^2 z + (51\rho^2 - 10)z^2 + (252\rho^2 - 84)z^3 \tag{3}$$

Thus we are left with only a single parameter – ρ^2 – to fit.

$D l \nu$ fit and results

CLEO $D^0 + D^+$ (1998) [3] and BELLE D^+ only (2001) [4]

→ The w-distribution extracted by BELLE (they call it $\tilde{y}$)

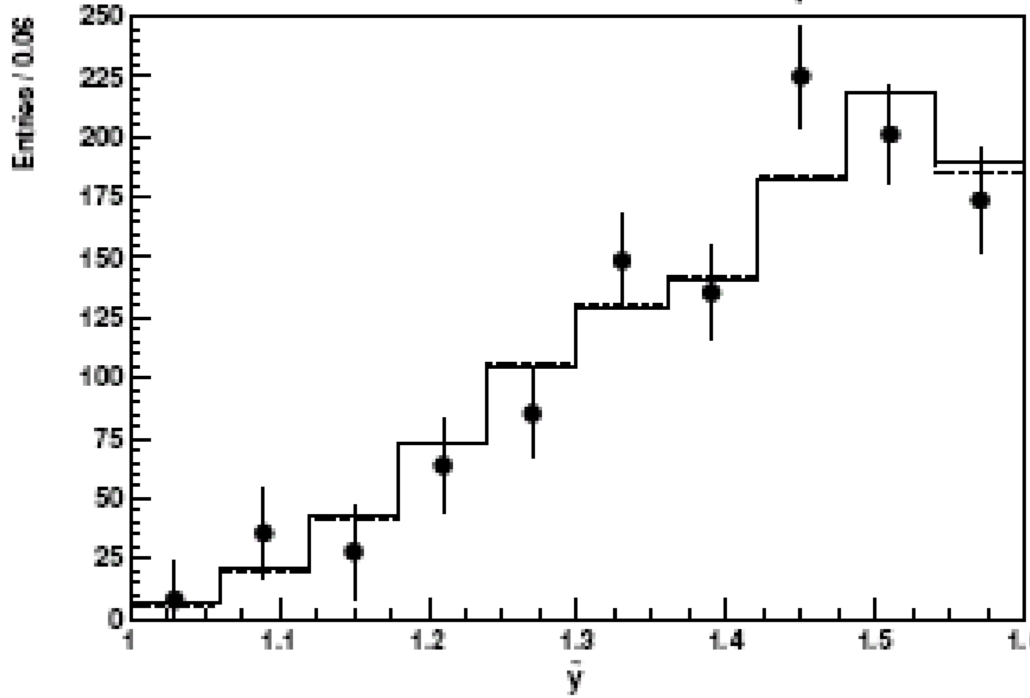
→ Note p-wave shape $\propto (w^2-1)^{3/2}$

Fit to something like:

$$\chi^2 = \sum_i \left(\frac{N_i^{obs} - \sum_j \varepsilon_{ij} N_j(N, \rho^2)}{\sigma_i} \right)^2$$

→ Dashed linear parametrization, solid CLN

BELLE -- from 10.8×10^6 $B\bar{B}$ pairs



Exp	$\mathcal{B}(B^- \to D^0 l^- \bar{\nu})$ (%)	ρ^2(CLN)	$\mathcal{F}(1) \times \lvert V_{cb}\rvert (10^{-3})$
CLEO	$2.21 \pm 0.13 \pm 0.19$	1.27 ± 0.25	$44.8 \pm 0.61 \pm 0.37$
BELLE	$2.13 \pm 0.12 \pm 0.39$	1.12 ± 0.22	$41.1 \pm 0.52 \pm 0.52$
HFAG	2.12 ± 0.20	1.17 ± 0.18	42.6 ± 4.5

$\Longrightarrow |V_{cb}| \approx 39.8 \pm 4.2 \pm 1.0$

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$\bar{B}^0 \to D^{*+} l^- \bar{\nu}$

BaBar [6, 7]:

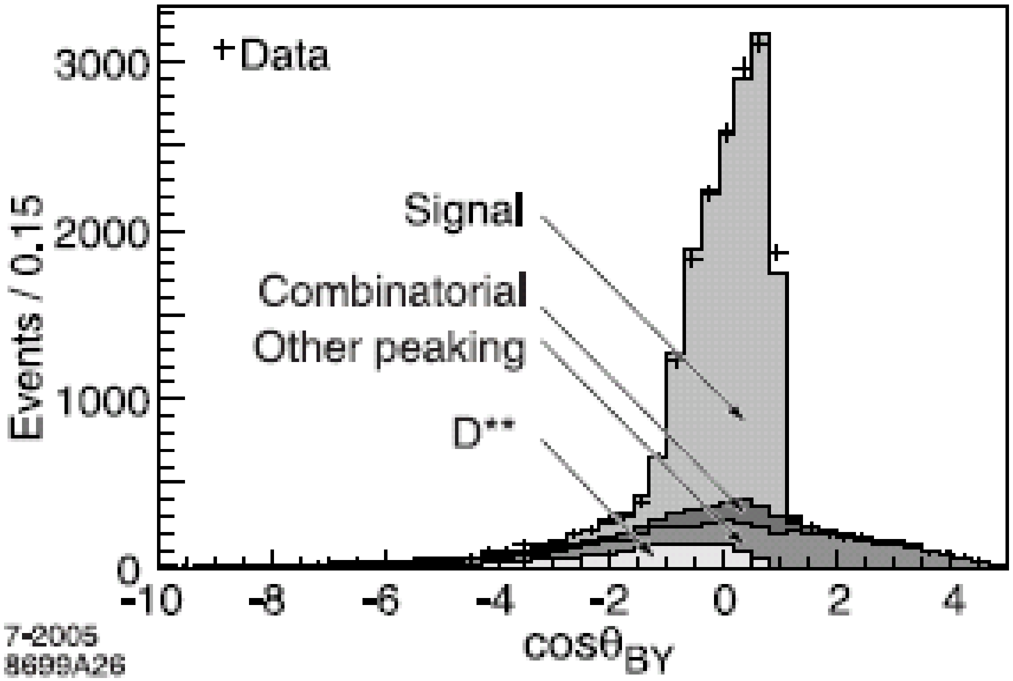
Signal extraction is similar to $Dl\nu$ except that it's much cleaner due to the narrow width $\Delta m = m_{D^*} - m_D$. The Δm and $cos\theta_{BY}$ distributions are used to fit for the signal and background. After Δm selection $|cos\theta_{BY}| \leq 1.2$ is used to select final sample.

→ Fit to background shapes taken from MC

→ Only signal and "D^{**}" are free in $cos\theta_{BY}$ fit

→ Other backgrounds are fixed from MC or Δm fit

→ Fits in bins of w or other variables ($cos\theta_l$, etc.) allows extraction of background subtracted distributions

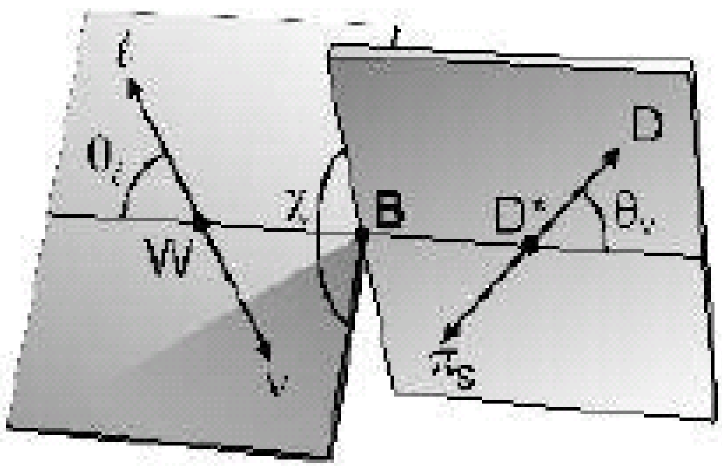


BaBar takes two approaches: a maximum likelihood fit to the full $q^2(w)$ and angular distribution and a fit to projection plots (simple moments). The first approach is statistically more powerful, but the second is less dependent on MC to model the background.

$D^* l\nu$ form-factor – A_1, A_2, V

- Three are three form-factors (A_1, A_2 and V) needed to describe $B \to D^* l\nu$ (pseudo-scalar→vector transition)
- There is, in principle, enough information in the angular distributions to extract them. In practice we need constraints from theory

$$\frac{d\Gamma}{dw\, d\cos_l\, d\cos_V\, d\chi} = K|V_{cb}|^2 q^2 p_{D^*} \times \quad (4)$$
$$\{H_+^2(1-\cos\theta_l)^2 \sin^2\theta_V + H_-^2(1+\cos\theta_l)^2 \sin^2\theta_V$$
$$+4H_0^2 \sin^2\theta_l \cos^2\theta_V - 2H_+H_- \sin^2\theta_l \sin^2\theta_V \cos 2\chi$$
$$-4H_0(H_+(1-\cos\theta_l) - H_-(1+\cos\theta_l)) \sin\theta_V \cos\theta_V \cos\chi\}$$

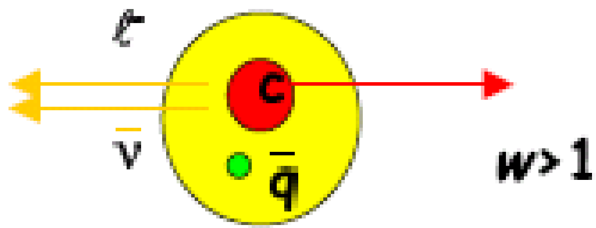


where the amplitudes H_i are related to the form-factors by

$$H_\pm = -(m_B + m_{D^*})A_1(w) \pm \frac{2p_{D^*}m_B}{m_B + m_{D^*}}V(w) \quad (5)$$
$$H_0 = -\frac{m_B + m_{D^*}}{m_{D^*}\sqrt{q^2}}(m_{D^*}(wm_B - m_{D^*})A_1(w) - \frac{4m_B^2 p_{D^*}^2}{(m_B + m_{D^*})^2})A_2(w)$$

All we've done is replace three real amplitudes with three real form-factors, but this will make it easier to implement needed theoretical constraints.

HQET constraints



→ HQET relates our three form-factors to a common form-factor called the Isgur-Wise function $\xi(w)$

→ In heavy quark limit $h_{A_1}(w) = \xi(w)$ and $\xi(1) = 1$ (c-quark just sits there)

$$A_2(w) = \frac{R_2(w)}{R_*^2}\frac{2}{w+1}A_1(w) \qquad (6)$$

$$V(w) = \frac{R_1(w)}{R_*^2}\frac{2}{w+1}A_1(w)$$

$$A_1(w) = R_*\frac{w+1}{2}h_{A_1}(w) \to R_*\frac{w+1}{2}\xi(w)$$

→ The functions $R_1(w)$ and $R_2(w)$ are constructed to be ≈ 1 and to have weak w-dependence

where $R_* = 2\sqrt{m_B m_{D*}}/(m_B + m_{D*})$.

→ Fits only needs to deal with the single function $h_{A_1}(w)$

From CLN [1], based on dispersive bounds, we take:

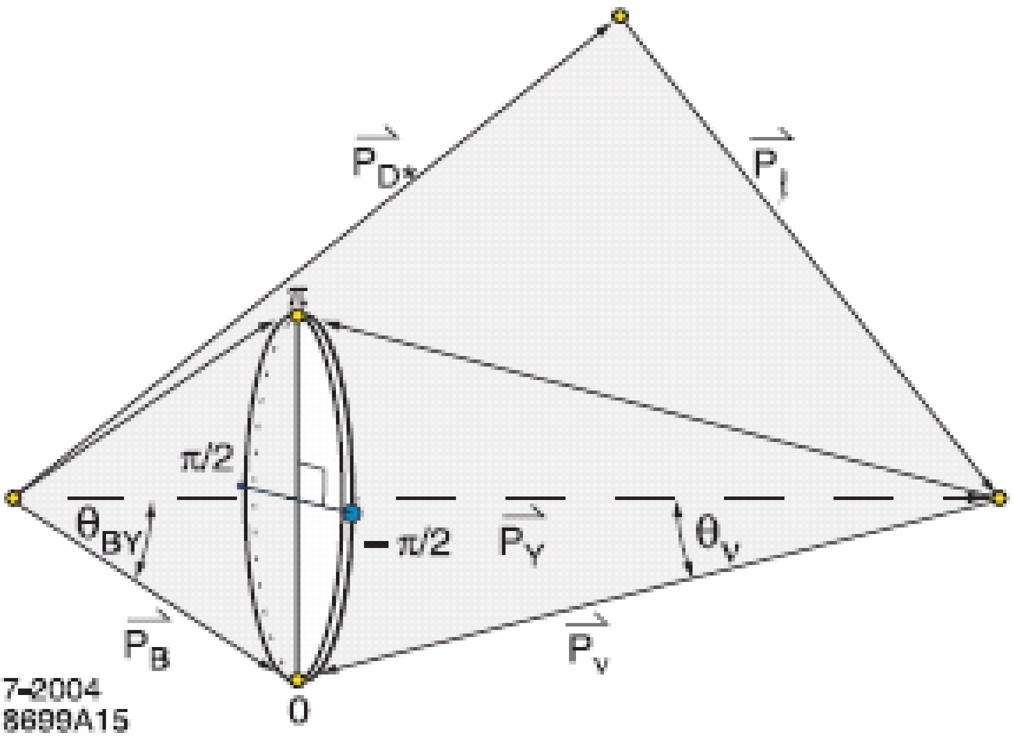
$$R_1(w) = 1.27 - 0.12(w-1) + 0.05(w-1)^2,\ R_2(w) = 0.79 + 0.15(w-1) - 0.04(w-1)^2$$

$$h_{A_1}(w) = h_{A_1}(1)(1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3 \qquad (7)$$

HQET constraints reduce the number of fit parameters to three – $R_1(1)$, $R_2(1)$ and ρ^2.

Reconstructing of the kinematic variables

The data needed for fitting consists of the kinematic variables w, $cos\theta_l$, $cos\theta_V$ and χ for each event. They are estimated by a partial reconstruction technique based on kinematic constraints from B mass and missing neutrino as drawn below:



Angle θ_{BY} of B w.r.t. $\mathbf{P}_Y = \mathbf{P}_{D*} + \mathbf{P}_l$ direction is determined by

$$cos\theta_{BY} = \frac{2E_B E_{D^*+l} - m_B^2 - m_{D+l}^2}{2|\mathbf{p}_{D^*}||\mathbf{p}_Y|}$$

→ The azimuthal angle ϕ_{BY} around the Y direction is undetermined

→ We estimate w, $cos\theta_l$, $cos\theta_V$ and χ by averaging the values obtained at $\phi_{BY} = 0$, π and $\pm\frac{\pi}{2}$

→ Resolution is reasonable

Here we use this construction not just for event selection, but to estimate kinematic variables as well.

Likelihood Fit

Since a $D*l\nu$ decay is described by four variables – $\Omega =(w,\ cos\theta_l,\ cos\theta_V,\ \chi)$ – and the efficiency and resolutions are correlated, it is hard (near impossible) to obtain enough MC statistics to full characterize the full four dimensional distribution needed for a likelihood fit.

$\Longrightarrow$ We employ a "trick" – call it the "integral method" – to evade this problem.

$$F(\tilde{\Omega}|\mu) \approx F(\Omega|\mu) \times \frac{\tilde{F}(\tilde{\Omega}|\mu_{mc})}{F(\tilde{\Omega}|\mu_{mc})}$$

$$log\mathcal{L} = \sum log\tilde{F}(\tilde{\Omega}_i|\mu) - \int d\tilde{\Omega}F(\tilde{\Omega}|\mu)$$

$$\approx \sum logF(\tilde{\Omega}_i|\mu) - \tilde{I}(\mu,\mu_{mc})$$

where

$\tilde{I}(\mu,\mu_{mc}) \approx \frac{1}{N_{mc}}\sum \frac{F(\tilde{\Omega}_{imc}|\mu)}{F(\tilde{\Omega}_{imc}|\mu_{mc})}$ (MC integral)

→ If the parameter value used in MC is close enough to "truth" you can approximate the PDF $\tilde{F}$ for the measured variables in terms of the theoretical PDF F

→ Dropping terms that don't depend on the parameters μ, this approximation allows the efficiency and resolution dependence to be factored out of the likelihood

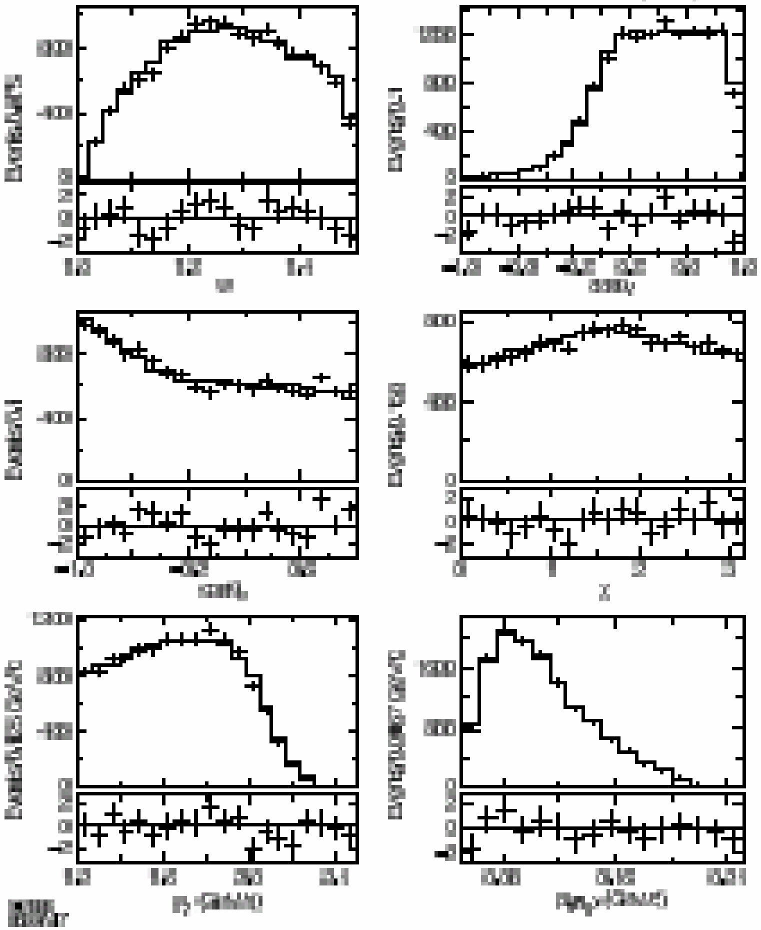
→ Efficiency and resolution only enter through the integral which can be evaluated with the MC.

$\Longrightarrow$No need to explicitly **know** the 4D efficiency function $\varepsilon(\Omega)$!

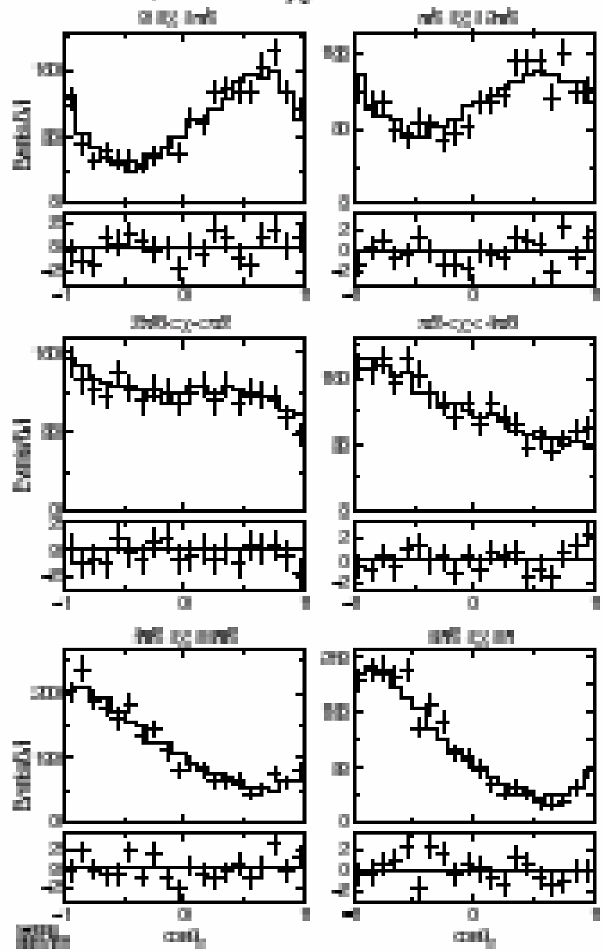
Likelihood fit comparisons

As there's no explicit PDF $\tilde{F}$ constructed, we re-weight the MC to fitted values of $R_1(1)$, $R_2(1)$ and ρ^2 (histogram) and compare it to the data (points) to see if fit is good.

w, $cos\theta_l$, $cos\theta_V$, χ, p_l and $p_t(\pi_s)$



$cos\theta_V$ for 6 χ-intervals



BABAR: Based on 86×10^6 $B\bar{B}$-pairs

$\longrightarrow$ Fit reproduces even details of interference ($cos\theta_V$ vs. χ)

$\longrightarrow$ $6 \times 6 \times 6 \times 6$ binned $\chi^2/dof = 1336.66/1291$, $P = 19\%$.

A. Snyder, HQL2006

$B \to D^*$ Form-Factor Results

BABAR result [6] using $\bar{B}^0 \to D^{*+} e^- \bar{\nu}_e$
Uses only the cleanest mode $D^{*+} \to \pi^+ D^0$, $D^0 \to K^- \pi^+$

Baseline, R_1 and R_2 constant
$R_1(1) = 1.396 \pm 0.046 \pm 0.027$
$R_2(1) = 0.885 \pm 0.046 \pm 0.013$
$\rho^2 = 1.145 \pm 0.066 \pm 0.035$

CLN $R_1$and R_2 w-dependence
$\Delta R_1 = R_1(expt) - R_1(CLN)$
$\Delta R_1(1) = 1.42 - 1.27 = 0.15$ $(\approx 2\sigma)$
$\Delta R_2 = 0.887 - 0.80 = 0.07$ $(\approx 1.5\sigma)$

$\longrightarrow$ This only second $B \to D^*$ form-factor measurement ever done. It is consistent with pioneering CLEO result of $R_1 = 1.18 \pm 0.30 \pm 0.12$, $R_2 = 0.71 \pm 0.22 \pm 0.07$. The slope parameters ρ^2 also agree when equivalent parametrization of $h_{A_1}(w)$ are used.

$\longrightarrow$ $|V_{cb}|$ is highly sensitive to $R_1$and R_2, so this measurement leads to a substantial reduction in error achievable

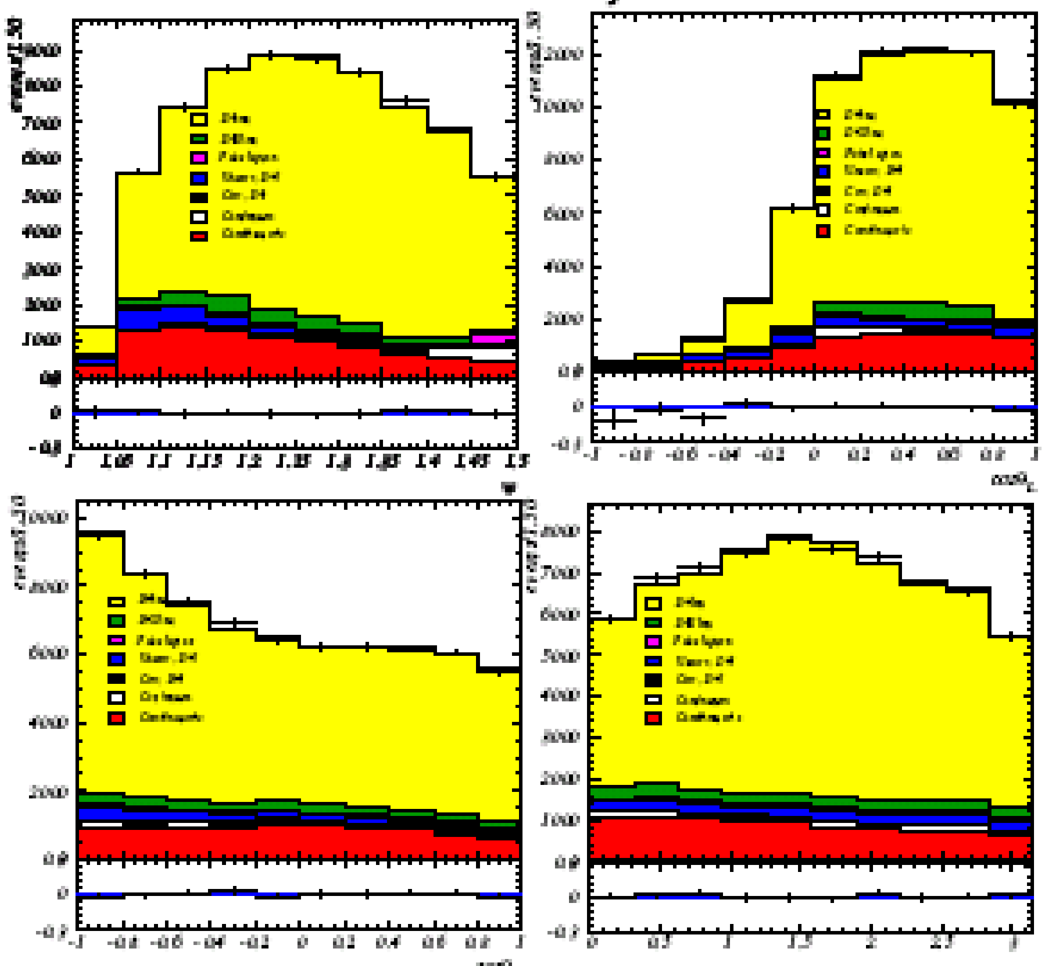
$\longrightarrow$ It is consistent with theoretical expectations

Prospects: BaBar and Belle have a lot more (less clean) data that could be used in form-factor analysis. In principle a model-independent measurement could be made by performing angular analysis (eq. 4) in bins of w (q^2). This would allow for a direct confrontation with HQET. . .

V_{cb} from $D^* l \nu$

BABAR's new *preliminary* $|V_{cb}|$ measurement [7] is obtained along with an alternative determination of the form-factors. This method (fitting projections in stead of full $4D$ distribution) is statistically less powerful than the likelihood approach, but depends less on MC to model the background and it uses all the D^0 decay modes not just $K\pi$.

Preliminary



→ Fits to Δm and $cos\theta_{BY}$ (*e.g.*, see page 6) are used to extract projection plots with signal (**yellow**) and backgrounds separately for w, $cos\theta_l$, $cos\theta_V$ and χ (assorted colors)

→ The w, $cos\theta_l$ and $cos\theta_V$ projections are fit for R_1, R_2, ρ^2 and $\mathcal{F}(1)|V_{cb}|$ taking into account the correlations between different projections.

→ Figure shows good fit is obtained. The χ-distribution was not fit.

$|V_{cb}|$ Results

For final result we combine the form-factor only likelihood measurement with the simultaneous $|V_{cb}|$/form-factor fit result taking into account the correlation due to the overlap of the event samples.

We obtain (using CLN parametrization):

$$\mathcal{F}(1)|V_{cb}| = (34.68 \pm 0.31 \pm 1.15) \times 10^{-3}$$

$$R_1 = 1.417 \pm 0.061 \pm 0.044$$

$$R_2 = 0.836 \pm 0.037 \pm 0.022$$

$$\rho^2 = 1.179 \pm 0.048 \pm 0.028$$

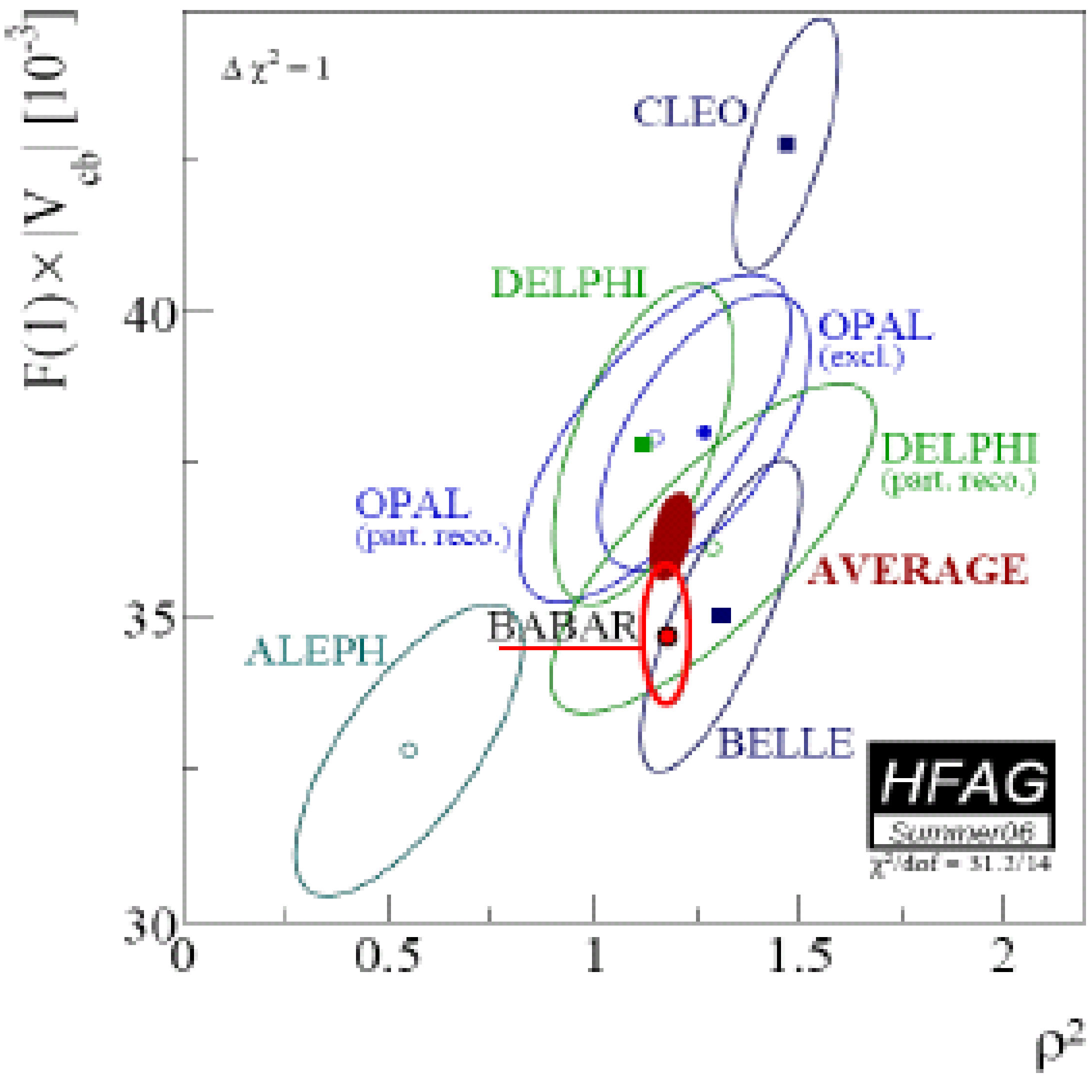
Using $\mathcal{F}(1)$ from the lattice [8] we obtain:

$$|V_{cb}| = (37.74 \pm 0.35 \pm 1.25^{+1.23}_{-1.44}) \times 10^{-3}.$$

The corresponding $D^{*+} l^- \bar{\nu}$ branching fraction is $4.84 \pm 0.05 \pm 0.39\%$.

Note: R_1,R_2 contribution to error has been moved from systematic to statistical

$B \to D^* l \nu$ comparisons



- $\rightarrow$ R_1,R_2 from BABAR
- $\rightarrow$ Comparison $|V_{cb}|$ and ρ^2 measurements from HFAG
- $\rightarrow$ BABAR is the best and dominates
- $\rightarrow$ $\chi^2/dof = 39/14$ (not good!)
- $\rightarrow$ CLEO, ALEPH are "outliers"
- $\rightarrow$ Is HFAG incorporating R_1 and R_2 correctly? *I.e.*, including correlations

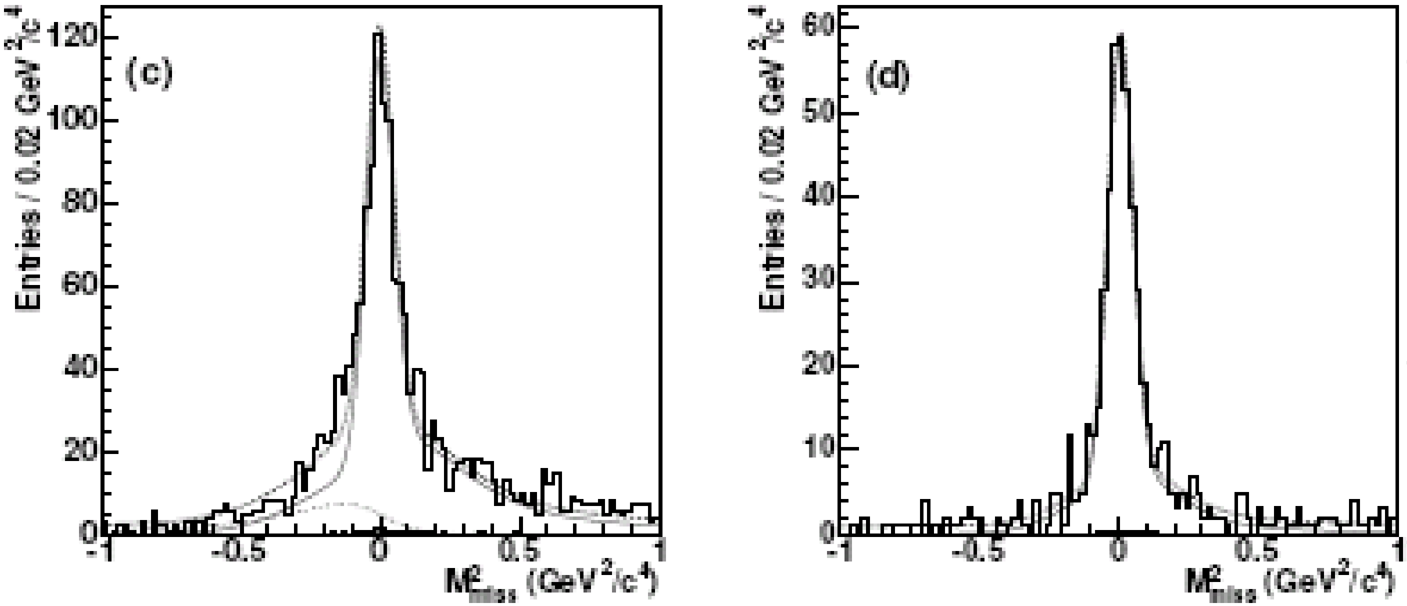
A. Snyder, HQL2006

Branching fraction conflict

$B^0$and $B^\pm$?

$B(\bar{B}^0 \to D^{*-} l^+ \bar{n}) \sim 5\%$ vs. $B(B^+ \to \bar{D}^{*0} l^+ \bar{\nu}) \sim 6.5\%$

Isospin violation? Hard to swallow…



→ *E.g.*, BELLE 2005 $D * l\nu$ from paper on $D^{(*)}\pi l\nu$ (discussed later)

→ Uses missing mass in fully reco'd tags

→ (c) is B^0, (d) is $B^\pm$

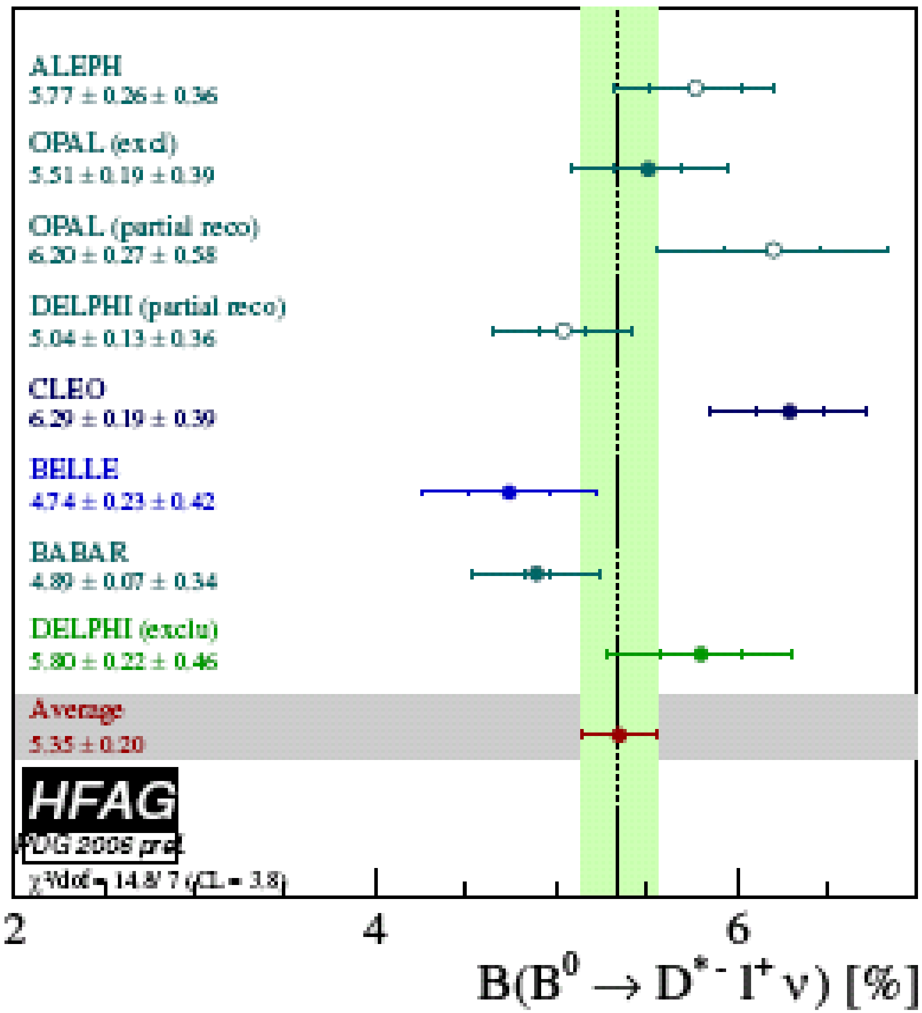
$B(\bar{B}^0 \to D^* l\nu) = 4.7 \pm 0.24\%$, $B(B^+ \to D^* l\nu) = 6.06 \pm 0.25\%$ $(\sim 4\sigma?)$

No systematic error given ("raw branching fractions"), but it's a persistent pattern… across experiments…

…but the method has a lot of potential…

PDG 2006: $5.36 \pm 0.2\%$ vs. $6.5 \pm 0.5\%$ $(\sim 2\sigma)$

Partial reco vs. exclusive BF Methods?



→ I don't see any systematic difference between exclusive vs. inclusive methods in branching fraction. . .

→ Within errors there's not that much conflict

→ CLEO is a bit high, but it's not that bad

→ ALEPH gives a low $|V_{cb}|$ but branching fraction is unexceptional

→ $|V_{cb}|$ conflicts follows more from form-factors (ρ^2) than from branching fractions

→ Indeed it's refreshing to see a "strip chart" for which the agreement is not too good

The only real conflict is between these neutral B branching fractions and the charged – not between different methods of neutral B reconstruction.

A. Snyder, HQL2006

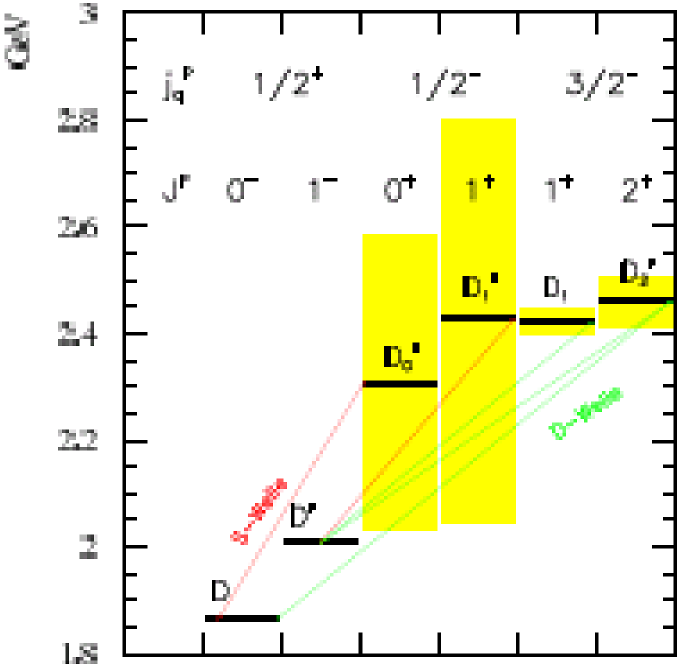
D^{**} and friends

Why bother? Just be cause they're there?

→ Engineering: D^{**}, $D^{(*)}n\pi$ are backgrounds for $D^{*}l\nu$ in both inclusive and exclusive analysis. To understand these modes we need to better understand the high mass sector

→ HQET can make predictions about form-factors of excited D-mesons. Perhaps lattice can contribute as well. Measurements in the high mass sector can provide test of the theory that underlies extraction of V_{cb} and are of some interest in themselves

To see what he could see?



→ What could be there? Resonance wide/and narrow predicted by HQET based models (see figure)

→ Narrow ones easy... $D_1(2420)$ and $D_2^*(2460)$ already seen...

→ Wide will be very hard... partial waves... *superB*...

→ Other stuff... $D^{(*,**)}n\pi$...

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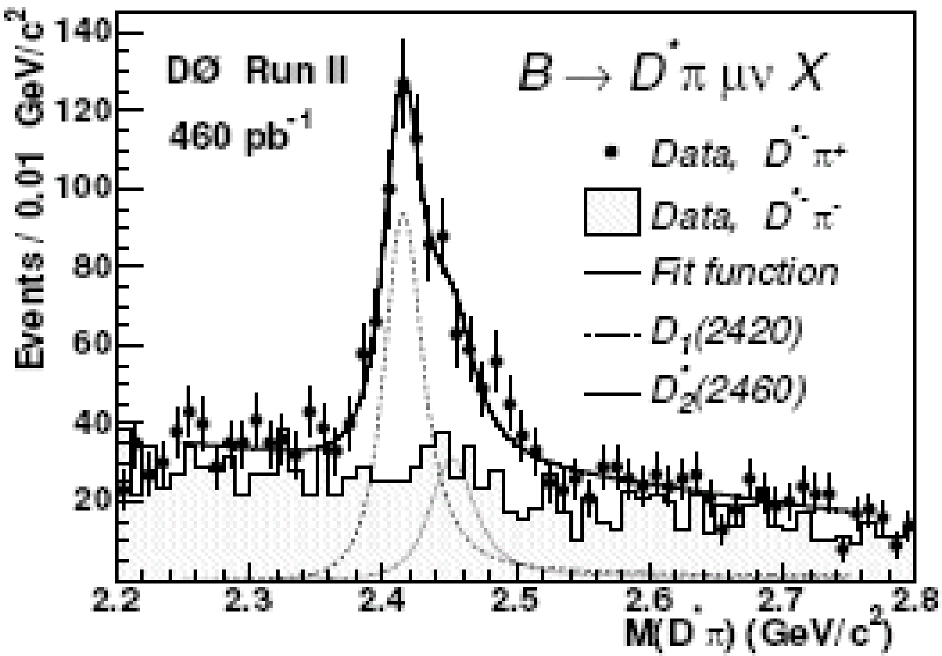
Narrow states

D0 [12]: $D_1^0(2420)$ and $D_2^{*0}(2460)$

Production/decay channel is $b \to B \to D^{**} l \nu$, $D^{**} \to D^{*-}\pi^+$ in $p\bar{p}$ collisions.



> Only products of production × branching fractions are directly measured:

$D_1^0 \to D^{*-}\pi^+ = 0.087 \pm 0.007 \pm 0.014$

$\bar{D}_2^{*0} \to D^{*-}\pi^+ = 0.035 \pm 0.007 \pm 0.008$

$\bar{D}_2^{*0}/\bar{D}_1^0 = 0.39 \pm 0.09 \pm 0.12$

> Using $b \to B = 39\%$ and isospin the branching fractions can be estimated:

$\mathcal{B}(B \to \bar{D}_1^0 l^+ \nu X) = 0.33 \pm 0.06\%$

(PDG $= 0.74 \pm 0.16\%$)

$\mathcal{B}(B \to \bar{D}_2^{*0} l^+ \nu X) = 0.44 \pm 0.16\%$

Note: "X", *i.e.*, not strictly exclusive.

Useful, but we need exclusive measurements too!

OPAL [14]:

$\mathcal{B}(b \to \bar{B}) \times \mathcal{B}(D_1^0 l^- \bar{\nu}) \times \mathcal{B}(D^{*+}\pi^-) = (2.64 \pm 0.79 \pm 0.39) \times 10^{-3}$

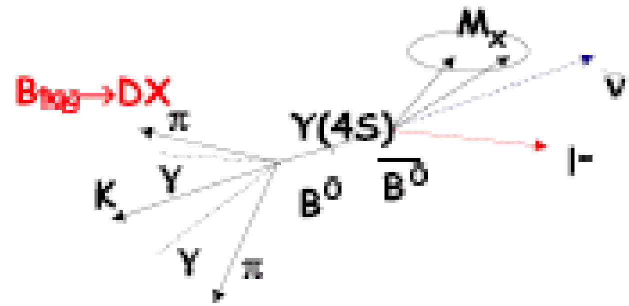
For D_2^{*0} they get $(0.26 \pm 0.59 \pm 0.35) \times 10^{-3}$ ($\leq 1.39 \times 10^{-3}$ F-C limit)

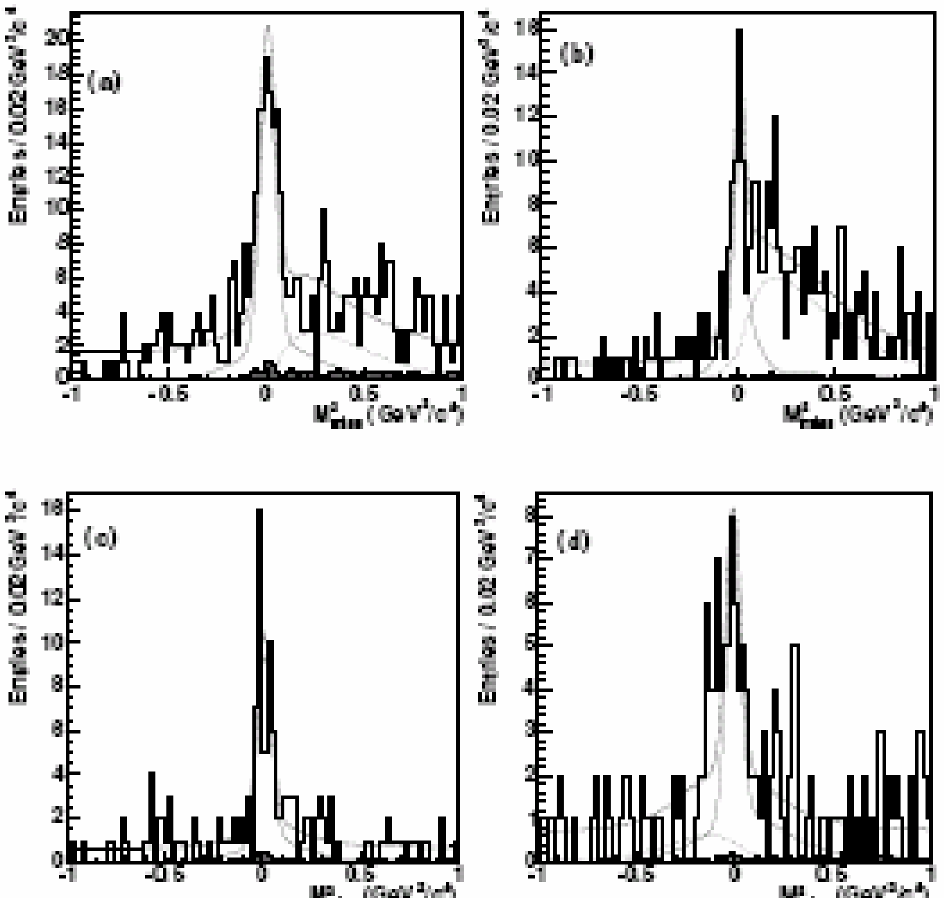
How do we compare these?

Exclusive $D\pi$ and $D^*\pi$

BELLE [9]: $B^- \to D^{(*)+}\pi^- l^- \bar{\nu}$ and $\bar{B}^0 \to D^{(*)0}\pi^+ l^- \bar{\nu}$ (the real topic of BELLE's paper).

In events with fully reco'd B plot missing mass squared (M^2_{miss}) against (a) $D^+\pi^- l^-$, (b) $D^0\pi^+ l^-$, (c) $D^{*+}\pi^0 l^-$ and $D^{*0}\pi^+ l^-$





- Signals appear at $M^2_{miss} \approx 0$ (nothing missing), *i.e.*, really exclusive

Branching factions $\times 10^{-2}$ obtained:

$B(D^+\pi^- l^- \bar{\nu}) = 0.54 \pm 0.07 \pm 0.07 \pm 0.06$

$B(D^0\pi^+ l^- \bar{\nu}) = 0.33 \pm 0.06 \pm 0.06 \pm 0.03$

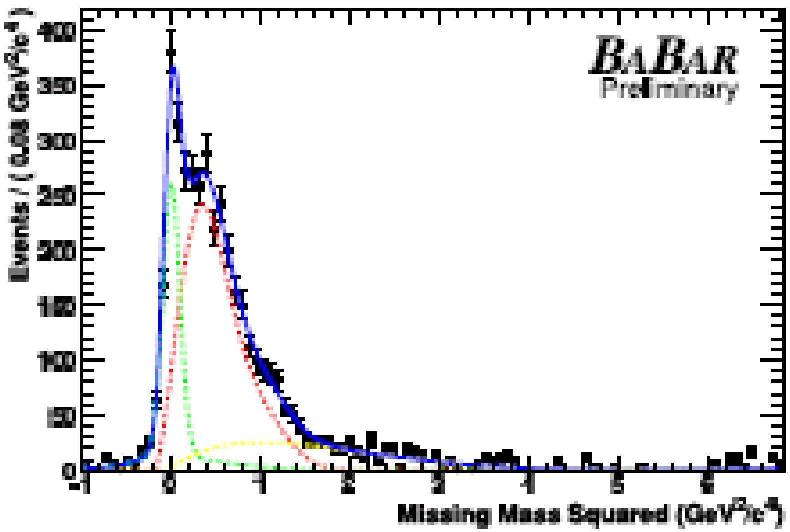
$B(D^{*+}\pi^- l^- \bar{\nu}) = 0.67 \pm 0.11 \pm 0.09 \pm 0.03$

$B(D^{*0}\pi^+ l^- \bar{\nu}) = 0.65 \pm 0.12 \pm 0.08 \pm 0.05$

- B^0 sum: $\approx 0.98 \pm 0.13\%$ – only $\sim 30\%$ of what's missing: $\mathcal{B}_{lvX} - \mathcal{B}_{Dl\nu} - \mathcal{B}_{D^*l\nu} \sim 10.7 - 2.1 - 5.3 = 3.3\%$
- There's no information about contributions from wide, narrow and non-resonant states.

$D/D^*/D^{(*)}\pi$

BABAR [10]: D, D^* and higher mass stuff by an "inclusive" method (previously mention on page 20).



- This analysis gives not only D^* discussed before but D and the high mass D "states" too
- The method is to look at the missing mass squared recoiling against $D^0 l^-$ in a sample in which the other B has been fully reconstructed.
- $D^0 l^- \bar{\nu}$ peaks at 0 (green), $D^{*0} l^- \nu$peaks some what higher ($\sim 0.8 GeV$) and the excited states have long tail to high missing mass (yellow)
- The shapes of these components (PDFs) are obtained from "enhanced" data samples

The results are the ratio to the $D^0 l$ Semileptonic rate:

$D^0 l^- \bar{\nu}/Dl = 0.210 \pm 0.017 \pm 0.021 \Longrightarrow \mathcal{B}(Dl\nu) \sim 2.1\%$

$D^{*0} l^- \bar{\nu}/Dl = 0.611 \pm 0.022 \pm 0.027 \Longrightarrow \mathcal{B}(D^* l\nu) \sim 6.1\% \ldots$ high?

$D^{(*)}\pi l \bar{\nu}/Dl = 0.173 \pm 0.017 \pm 0.021 \Longrightarrow \mathcal{B}(D^{(*)}\pi l\nu) \sim 1.7\%$

Another case where $B^{\pm}$ branching fraction to $D^* l\nu$ seems high

Only 1.7% in high higher mass stuff while we expect $\sim 3\%$ …if multiple π contribution is small…

What's wrong?

→ What's wrong with $B^- \to D^{*0} l^- \bar{\nu} \,/\, \bar{B}^0 \to D^{*+} l \bar{\nu}$?

- ⇝ Surely not isospin violation!
- ⇝ ⟹must be an experimental problem!
- ⇝ Slow pion efficiency badly wrong⟹charged branching fraction correct
- ⇝ Backgrounds in neutral modes not understood⟹neutral branching fractions correct?
  - ⇝ Fake π^0's not understood?

→ What's wrong with "inclusive" measurements of $D^* l \nu$?

- ⇝ Nothing?
- ⇝ Related to $B^- / \bar{B}^0$ with some methods?
- ⇝ Slow pion efficiency badly wrong⟹Inclusive correct? Seems unlikely…

→ Something wrong with modeling of higher mass states?

- ⇝ Certainly, but how much?
- ⇝ Multiple pions are not in MC though there's clear evidence one π is not enough
- ⇝ Can some of D^{**} states mimic $D^* l \nu$?

What to do?

→ We need to resolve the discrepancy between $D^{*0}l\nu$ and $D^{*+}l\nu$. It seems most unlikely that isospin violation is the culprit

⇝ Measure $\bar{B}^0 \rightarrow D^{*+}l^-\bar{\nu}$ in the $D^{*+} \rightarrow D^+\pi^0$ mode to probe whether the difference is in our understanding of slow pion (charged or neutral) efficiencies and backgrounds

⇝ Repeat BELLE style $D^*l\nu$ measurements in full reco tags (page 18) with careful attention to systematics and backgrounds.

→ We need to understand the higher mass states – D^{**}, etc.

⇝ Measure inclusive properties – branching factions of $D^{(*)}lX$. $D^{(*)}\pi$ is not the whole story.

⇝ As many exclusive branching fractions as possible – probably just the narrow states until the advent of really large full reco tag samples.

⇝ Specific final states like $D^{(*)}\pi$ or $D^{(*)}\pi\pi$ even if resonant structured can not be observed would also be useful.

→ Investigate theoretical constraints on behavior of high mass states. Can some of them mimic $D^*l\nu$ inclusive distributions or contribute more background to $D^{*0}\pi^0l\nu$ than we currently think?

→ Test HQET. In particular attempt model independent extraction of $D^*l\nu$ amplitudes or failing that try to reduce the theoretical constraints used

– Summary –

→ We know quite a bit already!

HFAG 2006 (so far):

→ $\mathcal{F}(1)|V_{cb}| = (36.2 \pm 0.8) \times 10^{-3}$

→ $\rho^2 = 1.19 \pm 0.06$

BaBar ($D^* l\nu$) [6, 7]:

→ $\mathcal{F}(1)|V_{cb}| = (34.7 \pm 1.2) \times 10^{-3}$

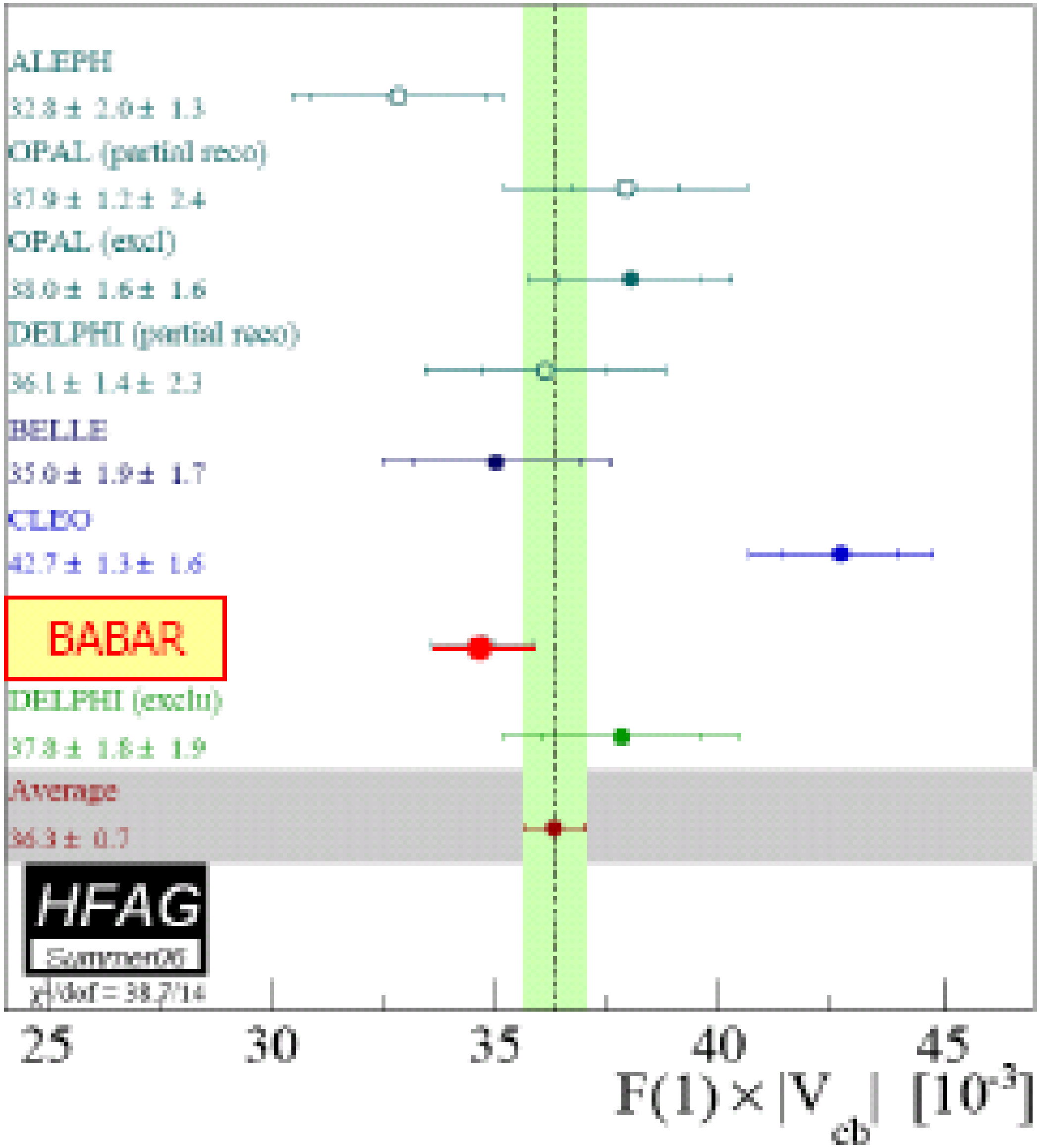
→ $R_1 = 1.42 \pm 0.075$

→ $R_2 = 0.84 \pm 0.043$

BELLE ($D^* l\nu$) [15]:

→ $\mathcal{F}(1)|V_{cb}| = (34.9 \pm 1.8) \times 10^{-3}$

→ $\rho^2 = 1.25 \pm 0.16$



A. Snyder, HQL2006

Exclusive vs. Inclusive $|V_{cb}|$?

From PRD73:073008: OPE fit in kinetic scheme gives

$$|V_{cb}| \times 10^3 = 41.96 \pm 0.23 \pm 0.35 \pm 0.59 = 42.0 \pm 0.7$$

HFAG for exclusive:

$$|V_{cb}| \times 10^3 = 39.6 \pm 0.9(exp)^{+1.5}_{-1.3}(lat)$$

the theoretical errors are uncorrelated, the experimental errors can also be considered uncorrelated, so

$$\Delta|V_{cb}| \times 10^3 = 2.4 \pm 1.8, \textit{i.e.}, \sim 1.3\sigma$$

Need improvement in lattice calculations, but there's no conflict at this point!

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[3] CLEO, CLNS 98/1594

[4] BELLE, hep-ex/0111082

[5] Isgure and Wise, "Weak Transition Form-Factors Between Heavy Mesons," Phys.Lett.B237:527,1990

[6] BABAR, $B \to D^*$ form-factors, hep-ex/0602023

[7] BABAR, $B \to D^*$ form-factors with simultaneous V_{cb}, hep-ex/0607076 (preliminary)

[8] Hashimoto et al., $\mathcal{F}(1)$ Lattice Computation, PRD 66,14503 (2002)

[9] BELLE, $D^{(*)}\pi l \nu$ with $D^{(*)} l \nu$, hep-ex/0507060

[10] BABAR, $B \to D/D^*/D^{**}(D^{(*)}\pi)l\nu$, Babar-CONF-06/024

[11] CDF, Orbitally excited D-mesons (preliminary), hep-ex/0412061 (2004)

[12] D0, Narrow D^{**} states, hep-ex/0507046 (2005)

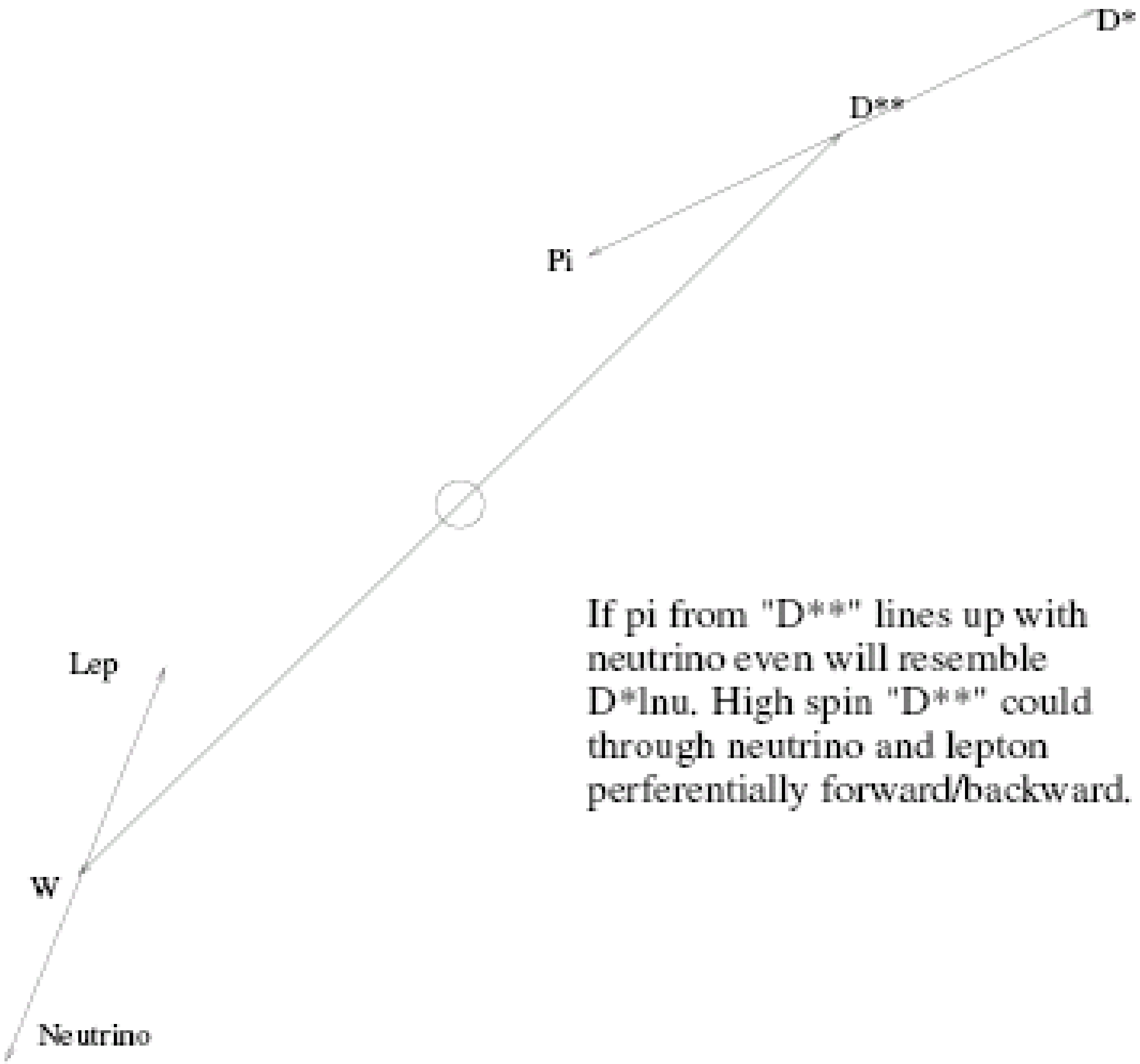
[13] Okamoto, Lattice 2005; Hashimoto, $Dl\nu$ form-factors, hep-lat/9810056

[14] OPAL, $D^{**}l\nu X$, hep-ex/0301018

[15] BELLE, $|V_{cb}|$ from $B^0 \to D^{*+}l\bar{\nu}$, hep-ex/0111060

[16] Falaecher and Buchmueller, Inclusive $|V_{cb}|$fits, PRD73:073008.

Possible fake out



If pi from "D**" lines up with neutrino even will resemble D*lnu. High spin "D**" could through neutrino and lepton perferentially forward/backward.

Resolutions

Kinematic variables: The data consists of the kinematic variables w, $cos\theta_l$, $cos\theta_V$ and χ.

We estimate them using a partial reconstruction technique based on momentum conservation constraints (depicted in figure on page 4). The constraints determine the angle $cos\theta_{BY}$ (angle between the B the $D^* + l$ direction, but leave the azimuthal angle ϕ_{BY} undetermined. We estimate the kinematic variables by averaging them over $\phi_{BY} = 0, \pi, \pm\pi/2$. The resolution obtained is not great, but it is adequate as can be seen below.

Kinematic variables: The data consists of the kinematic variables w, $cos\theta_l$, $cos\theta_V$ and χ.

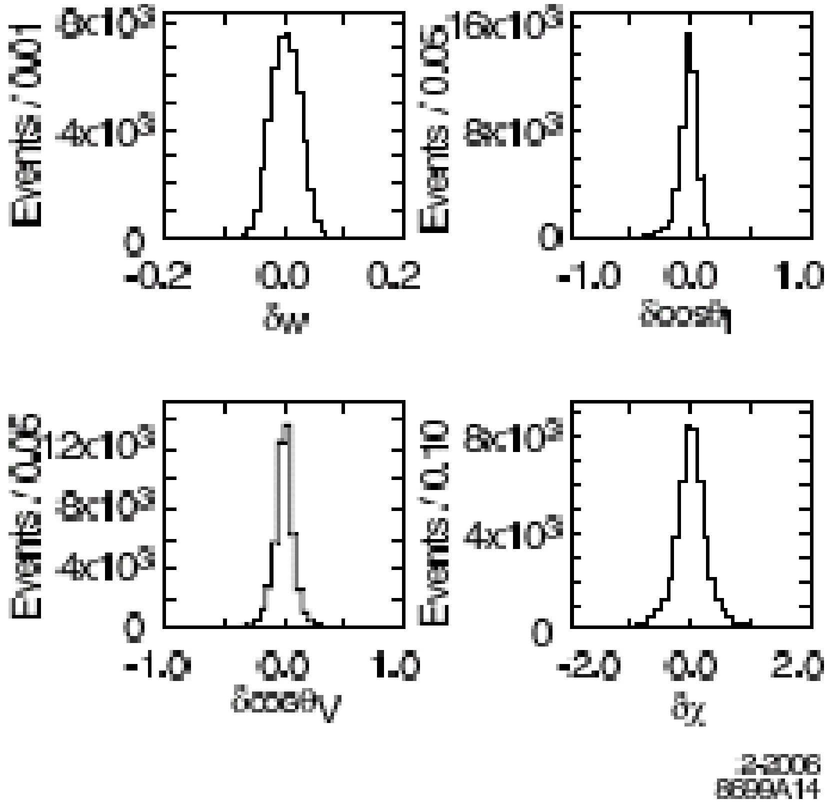
Monte Carlo Plots of

$\Delta w = w_{reco} - w_{true}$,

$\Delta cos\theta_l = cos\theta_l^{(reco)} - cos\theta_l^{(true)}$,

$\Delta cos\theta_V = cos\theta_V^{(reco)} - cos\theta_V^{(true)}$,

$\Delta\chi = \chi_{reco} - \chi_{true}$.



Likelihood II (efficiency and resolution correction)

Since $D^*l\nu$ is described in a four variables – $\Omega = (w,\ cos\theta_l,\ cos\theta_V,\ \chi)$ – and the efficiency and resolutions are correlated it is hard (near impossible) to obtain enough MC statistics to full characterize the full four dimensional distribution needed for a likelihood fit. We employ a "trick" – call it the integral method – to avoid this problem.

$$\tilde{F}(\tilde{\Omega}|\mu) = \int d\Omega G(\tilde{\Omega}, \Omega)\varepsilon(\Omega)F(\Omega|\mu) \quad (8)$$

$$= \int d\Omega G(\tilde{\Omega}, \Omega)\varepsilon(\Omega)F(\Omega|\mu_0) \times \frac{F(\Omega|\mu)}{F(\Omega|\mu_0)}$$

$$\approx F(\tilde{\Omega}|\mu) \times \frac{\tilde{F}(\tilde{\Omega}|\mu_0)}{F(\tilde{\Omega}|\mu_0)} \quad (9)$$

Note the parameter dependence occurs only in the know theoretical PDF $F(\tilde{\Omega}|\mu)$. The second factor is not need – only it's integral will enter.

Likelihood III

$$logL = \sum logF(\tilde{\Omega}_i|\mu) - \int d\tilde{\Omega}\tilde{F}(\tilde{\Omega}|\mu) \quad (10)$$

$$\approx \sum logF(\tilde{\Omega}_i|\mu) - \tilde{I}(\mu,\mu_0) \quad (11)$$

where $\tilde{I}(i)$ is the integral of the approximate PDF (eq. 9). It can be estimated using the MC:

$$\tilde{I}(\mu) \approx \frac{1}{N_{mc}} \sum \frac{F(\tilde{\Omega}_{imc}|\mu)}{F(\tilde{\Omega}_{imc}|\mu_0)} \quad (12)$$

Note that nowhere do we need to know the form of $\tilde{F}$; it is implicit in the MC integral. It can be shown that this procedure corrects for both acceptance and resolution if $\mu_0 \sim \mu$. We iterate to achieve this condition.

Backgrounds

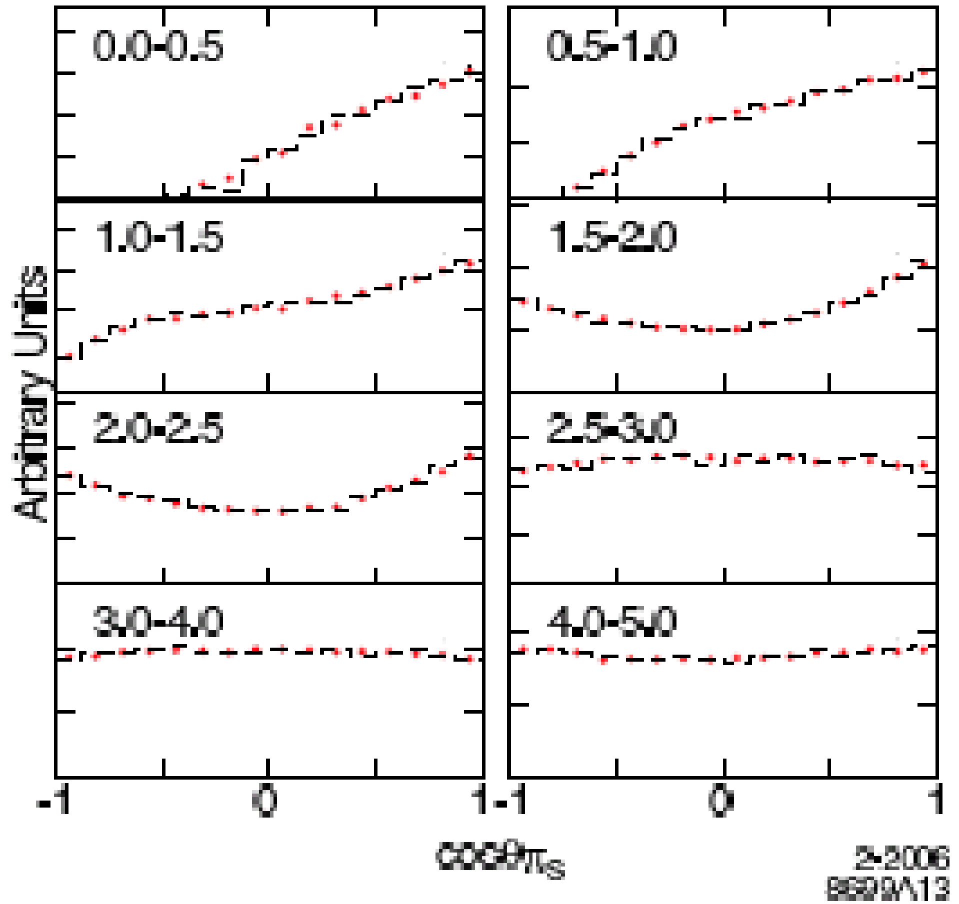
Backgrounds are normalized use $\Delta m = m_{D^*} - m_D$ and $cos\theta_{BY}$ fits and appropriately weighted MC events subtracted from the likely.

This is called direct unbinned background subtraction (DUBS) and used to avoid break the factorization of the PDF that allowed us to avoid needing to know $F(\tilde{\Omega})$. MC/data discrepancies are approximated by a linear dependence of background on the four kinematic variables.

The likelihood is replaced by pseudo likelihood

$$logL \Longrightarrow logL - \sum_{back} logF(\tilde{\Omega}_{ibk}|\mu). \quad (13)$$

Slow π



Inclusive $D^* \to \pi D^0$ fit to constant+linear+quadratic

due to physics – polarization of D^* quadratic terms are significant

linear terms due only to detector/reconstruction effects are not significant. . . 1st three bins $0.037 \pm 0.160,\ -0.023 \pm 0.024,\ -0.016 \pm 0.009$

Experimental extraction

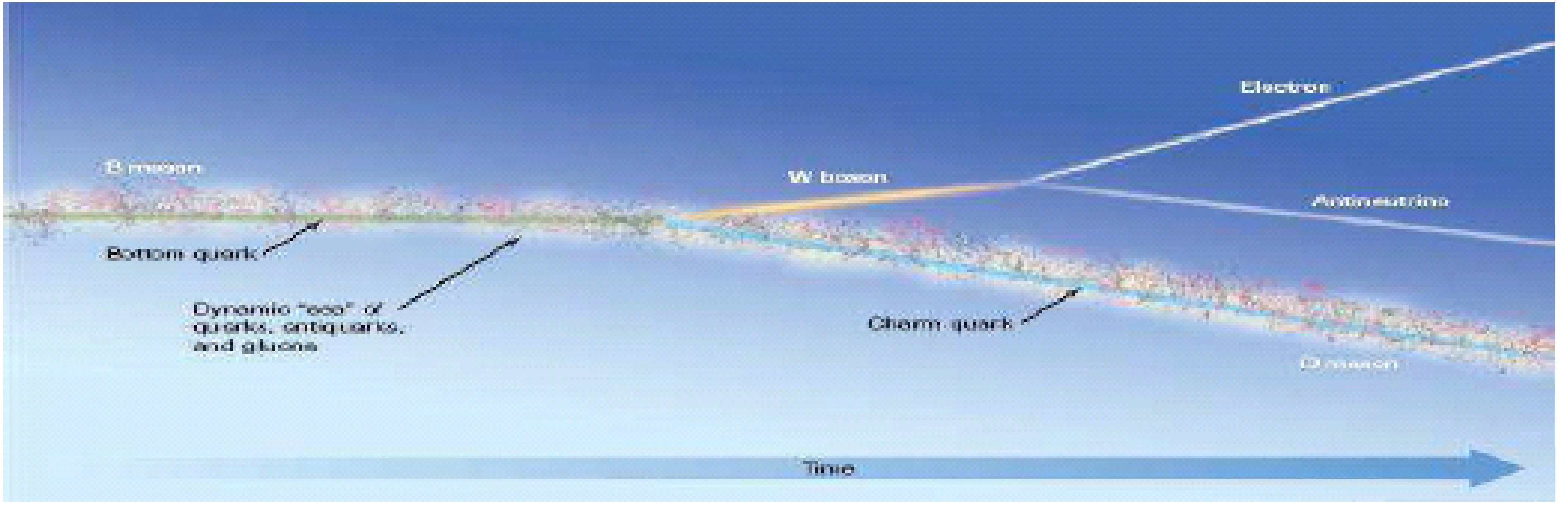
$B \to D^{(*,**)} l\nu$: $|V_{cb}|$ and Form-Factors

A. Snyder, SLAC

Heavy Quarks and Leptons (HQL)

München, October 16-20, 2006

... ...



$$\Gamma(b \to c) \propto |V_{cb}|^2 \otimes FF's$$