Measurement of V_{cb}

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Inclusive approaches

Exclusive approaches ($B \rightarrow D^* l \nu$, $B \rightarrow D l \nu$)

Moments and Form factors (if time permits)

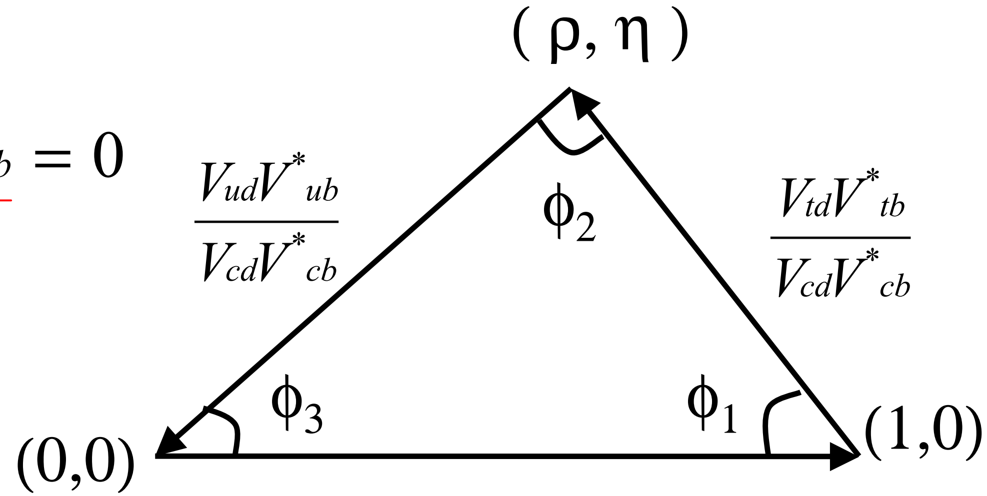
Conclusion

The V_{cb} element of the CKM matrix

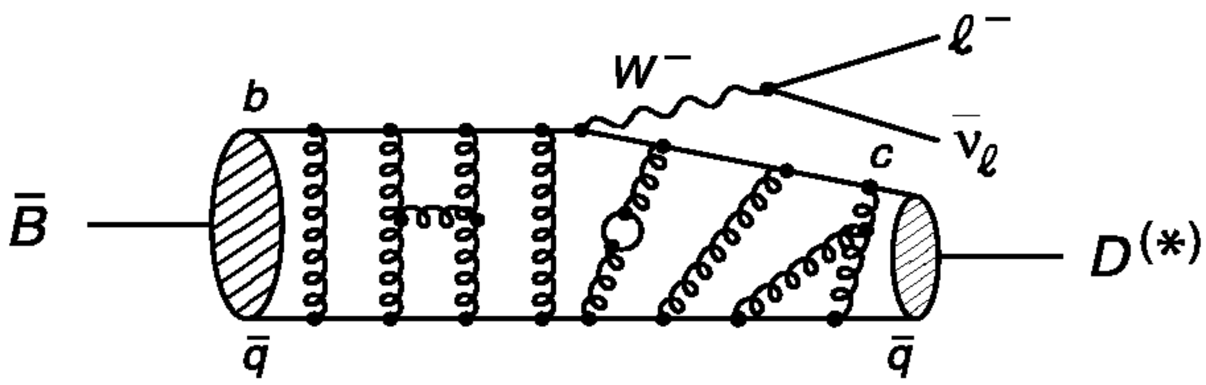
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Determination of V_{cb} allows the determination of A, which is important for indirect constraints on the CKM triangle. For example, the CPV parameter ϵ_K is proportional to A^4.

$$V_{td}V^*_{tb} + V_{cd}\underline{V^*_{cb}} + V_{ud}\underline{V^*_{ub}} = 0$$



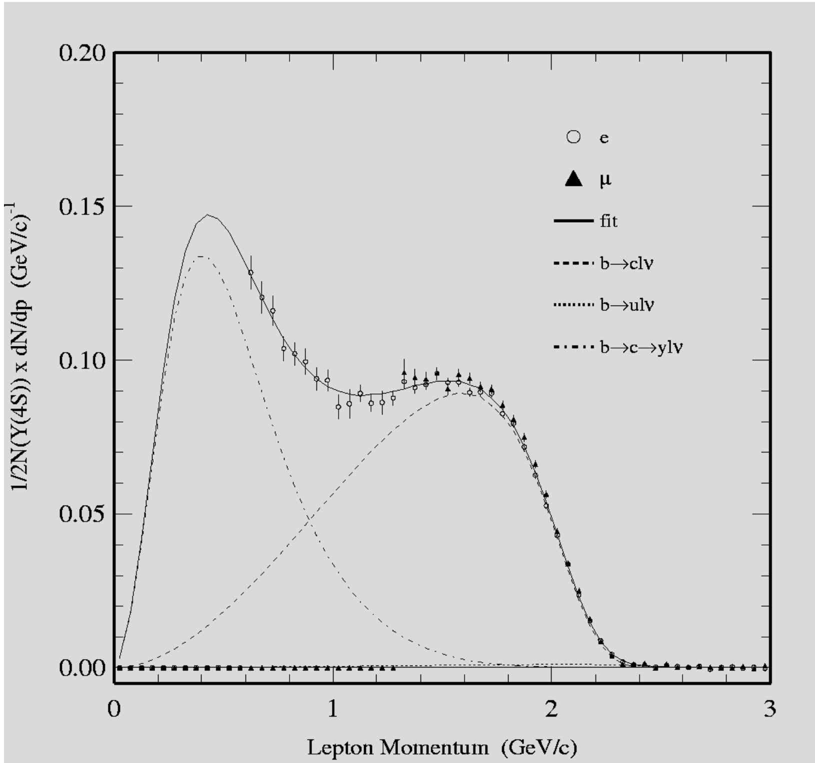
Inclusive Approach to b→c

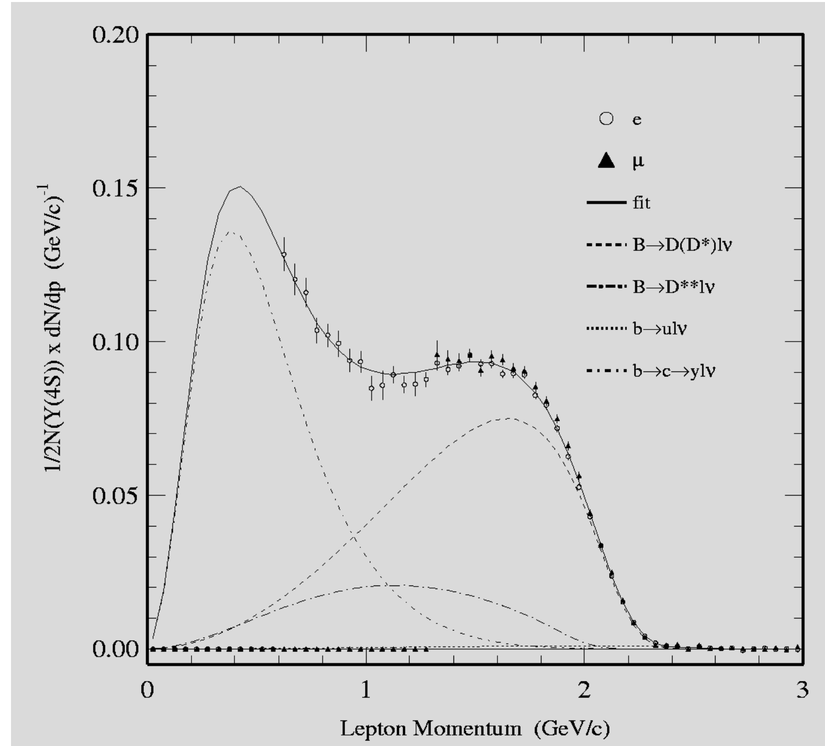


Hadronic effects are restricted to the lower part of the graph.

Sum over all final states: *only detect the final state lepton.*

Inclusive Approach to b→c (single leptons)





ACCM model (inclusive)

ISGW** model (exclusive)

Either cut at p^*_L >1.4 GeV and accept large model dependence or fit: the correlation between b→c (direct) and b->c→s l ν (cascade) component leads to model dependence e.g. BF: 10.42% to 10.98%

Inclusive Approach to b→c l υ (dileptons)

To overcome this problem, ARGUS introduced a new approach using dileptons.

Idea: tag with one high momentum lepton $p^*>1.4$ GeV (to guarantee that it is from a primary b→c decay). Then examine a second lepton with $p^*>0.6$ GeV.

The charge correlation (**opposite for direct leptons** and same for cascade leptons) eliminates correlation problem. The angular correlation between the two leptons removes the background due to leptons from the same B meson.

Application of the dilepton method to b→c l υ

Example from Belle

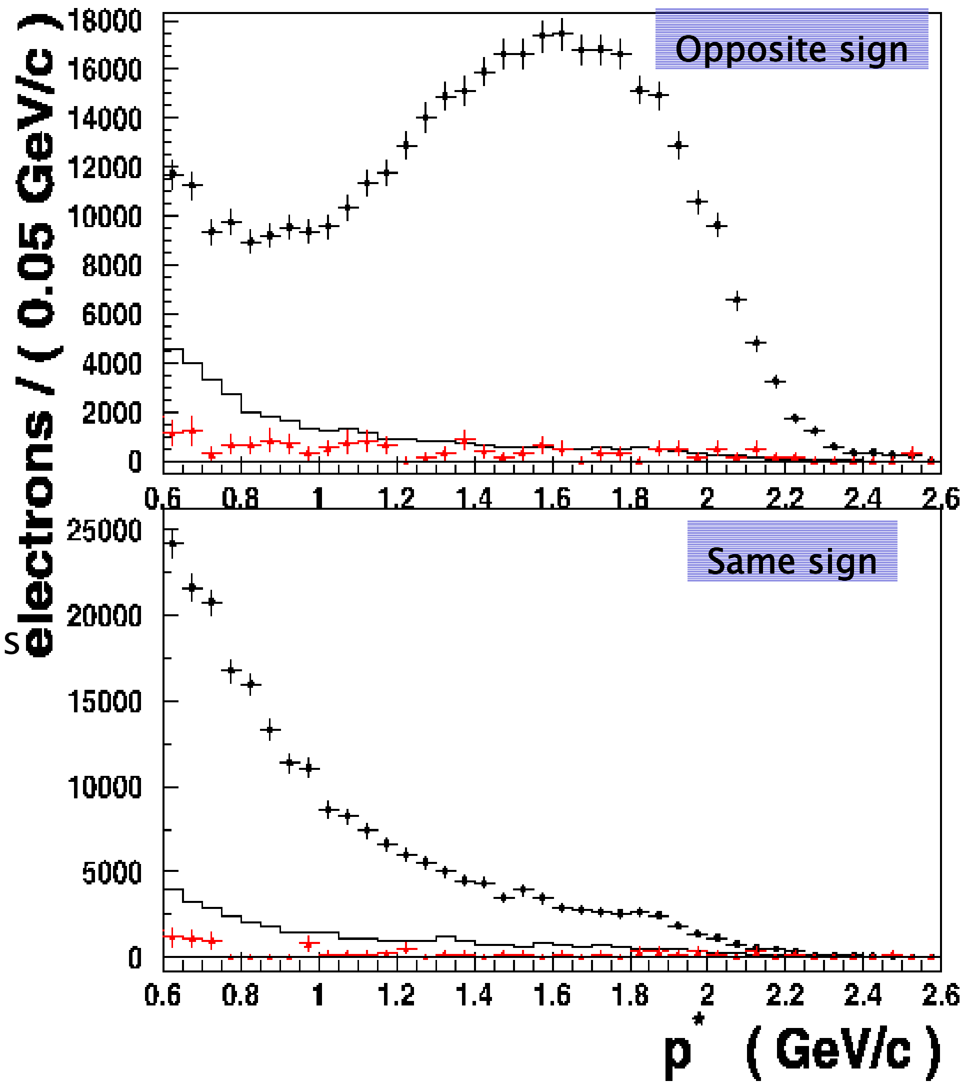
High momentum lepton tag:
$1.4 < p_l < 2.2$ GeV

Require an additional electron
(p_e down to 0.6 GeV)

Divide the sample into opposite/ same sign events.

Suppress secondary opposite sign leptons
with $p_e + \cos le > 1.2$
(cos le = opening angle btn leptons)

Estimate # of electrons by fitting E/p in momentum bins.



Application of the dilepton method to b→c l υ

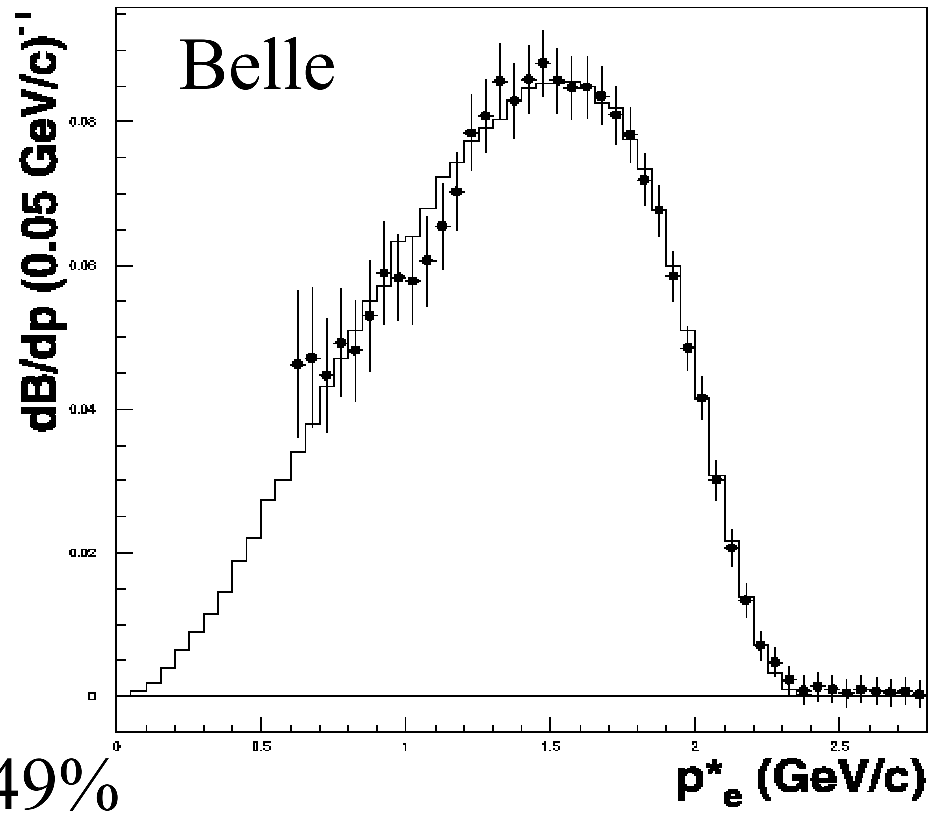
$$\begin{pmatrix} N_{+-}(p^*) \\ N_{\pm\pm}(p^*) \end{pmatrix} = N_{tag} \begin{pmatrix} \varepsilon_1(1-\chi) & \varepsilon_1\chi \\ \varepsilon_2\chi & \varepsilon_2(1-\chi) \end{pmatrix} \begin{pmatrix} \dfrac{dBr(b \to e\nu X)}{dp^*} \\ \dfrac{dBr(b \to c \to e\nu X)}{dp^*} \end{pmatrix}$$

$\chi = \chi_0 f_{00} = 0.0843 \pm 0.0060$
mixing parameter(PDG)

ε_1 : eff. for opposite sign

ε_2 : eff. for same sign

Correct for B-Bbar mixing and the small fraction of signal (6.1%) below 0.6 GeV.



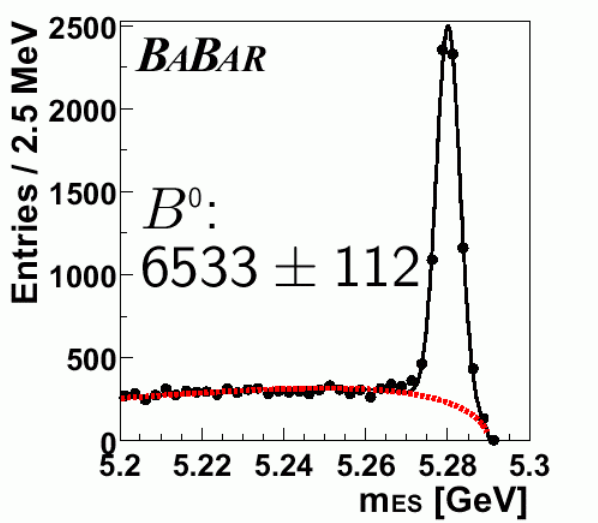
BF(b→c l ν) =10.90± 0.12±0.49%

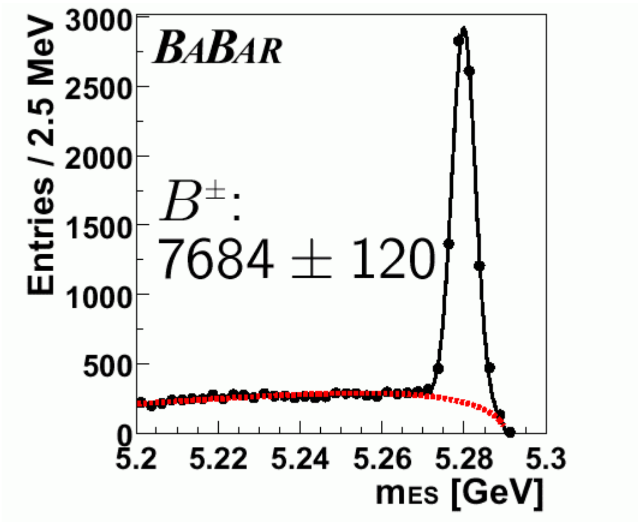
B→c l ν with Fully Reconstructed B Tags

- Fully reconstructed hadronic B decays:

  $B \to D^{(*)}\pi$, $D^{(*)}\rho$, $D^{*}a_1$
  $\to J/\psi\, K^{(*)}$, $\psi(2S)\, K^{(*)}$

Check whether spectator quark effects are important – compare B_{SL} for B+ and B^0 decays.

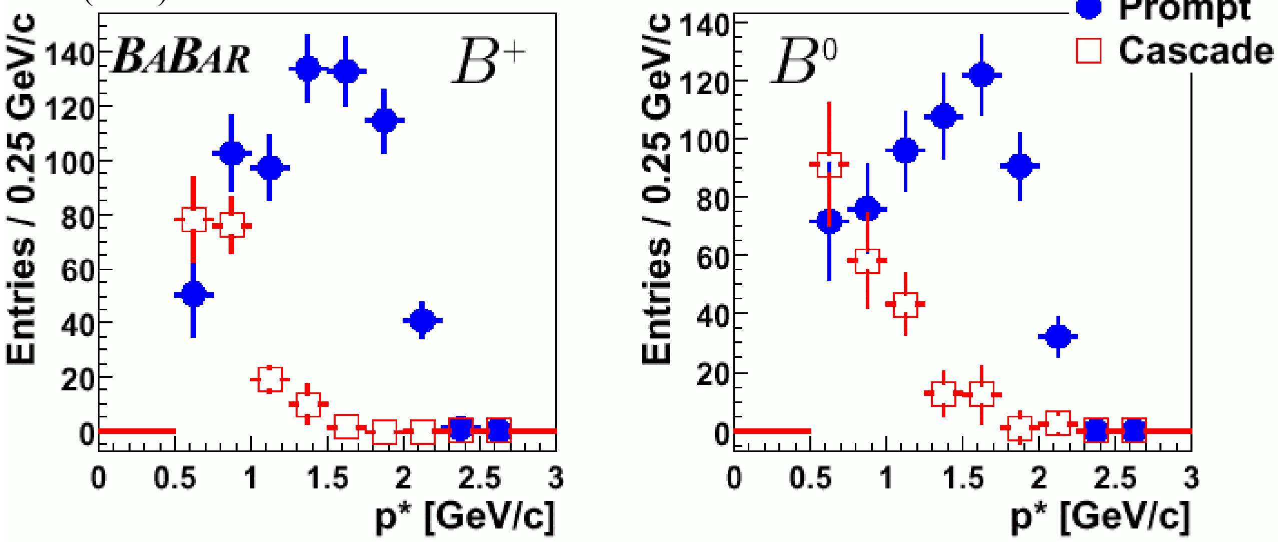




BaBar: semileptonics from B tags

$N^{+}_{prompt} = 597 \pm 38_{(stat)}$

$N^{0}_{prompt} = 674 \pm 34_{(stat)}$



- Branching fractions (preliminary) :
  - $BF(B^+ \to X\, e\, \nu) = (10.3 \pm 0.6_{stat} \pm 0.5_{sys})\%$
  - $BF(B^0 \to X\, e\, \nu) = (10.4 \pm 0.8_{stat} \pm 0.5_{sys})\%$

$BF(B \to X\, e\, \nu) = (10.4 \pm 0.5_{stat} \pm 0.5_{sys})\%$

$BF(B^+ \to X\, e\, \nu)\, /\, BF(B^0 \to X\, e\, \nu) = 0.99 \pm 0.10_{stat} \pm 0.04_{sys}$

Determinations of BF($b \rightarrow c\ l\ \upsilon$)

Expt.	BR	stat	syst
CLEO	10.49	±0.17	±0.43
BELLE (ℓ Tag)	10.90	±0.12	±0.49
BABAR (e Tag)	10.87	±0.18	±0.30
AVERAGE	10.63	±0.19	±0.16

Eid, tracking, and low p background subtractions

Expt.	BR	stat	syst	model
ALEPH	10.70	±0.10	±0.23	±0.26
DELPHI	10.70	±0.08	±0.21	$^{+0.44}_{-0.30}$
L3	10.85	±0.12	±0.38	±0.26
L3 (double tag)	10.16	±0.13	±0.20	±0.22
OPAL	10.83	±0.10	±0.20	$^{+0.20}_{-0.13}$
AVERAGE	10.63	±0.09	±0.15	±0.18

Good agreement between Upsilon(4S) and LEP results.

Conversion of BF($b \rightarrow c\ l\ \upsilon$) to V_{cb}

$$\gamma_c |Vcb|^2 \cong Br(B \rightarrow Xl\nu) / \tau_B$$

Using the Belle result

Model	$\lvert Vcb \rvert \times 10^{-2}$
ACCMM	$4.10 \pm 0.10 \pm 0.40$
ISGW2	$4.00 \pm 0.10 \pm 0.40$
M.Shifman	$4.04 \pm 0.10 \pm 0.20$
P.Ball	$3.95 \pm 0.09 \pm 0.19$

This type of determination also assumes quark-hadron duality i.e. that the inclusive quark-level rate reproduces the sum of a few exclusive states ($B \rightarrow D\ l\ \nu$, $B \rightarrow D^{*}\ l\ \nu$, $B \rightarrow D^{**}\ l\ \nu$)

OPE Expansion and Moments

$$\Gamma_{sl} = \frac{G_F^2 |V_{cb}|^2}{192\pi^3} m_B^5 c_1 \left\{ 1 - c_2 \frac{\alpha_s}{\pi} + \frac{c_3}{m_B} \overline{\Lambda} (1 - c_4 \frac{\alpha_s}{\pi}) + \frac{c_5}{m_B^2} (\overline{\Lambda}^2 + c_6 \lambda_1 + c_7 \lambda_2) + O(\frac{1}{m_B^3}) + O(\frac{\alpha_s^2}{\pi}) \cdots \right\}$$

Λ, λ_1, λ_2 are non-perturbative parameters.

λ_1 (-) kinetic energy of the b-quark (a.k.a μ_π^2)

λ_2 hyperfine splitting from B*-B mass difference, $\lambda_2 = 0.12 GeV^2$ (a.k.a μ_C^2)

$\Lambda = m_B - m_b + (\lambda_1 - 3\lambda_2)/2m_B$ … (energy of "light DOF")

–Additional parameters enter at higher orders (ρ_1,ρ_2, τ_1, τ_2, τ_3, τ_4); use theoretical estimates

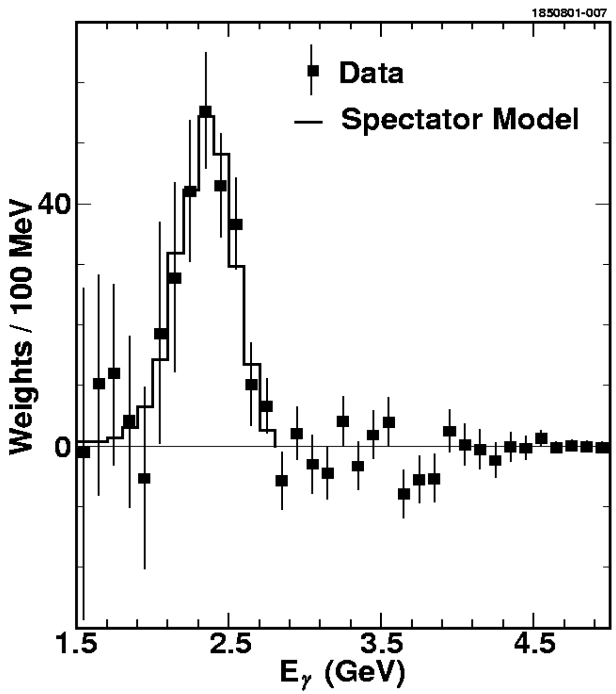
Λ, λ_1, λ_2 are the main sources of theoretical uncertainty in inclusive V_{cb} (calibrate γ_c).

Conversion of BF($b \rightarrow c\, l\, \upsilon$) to $|V_{cb}|$

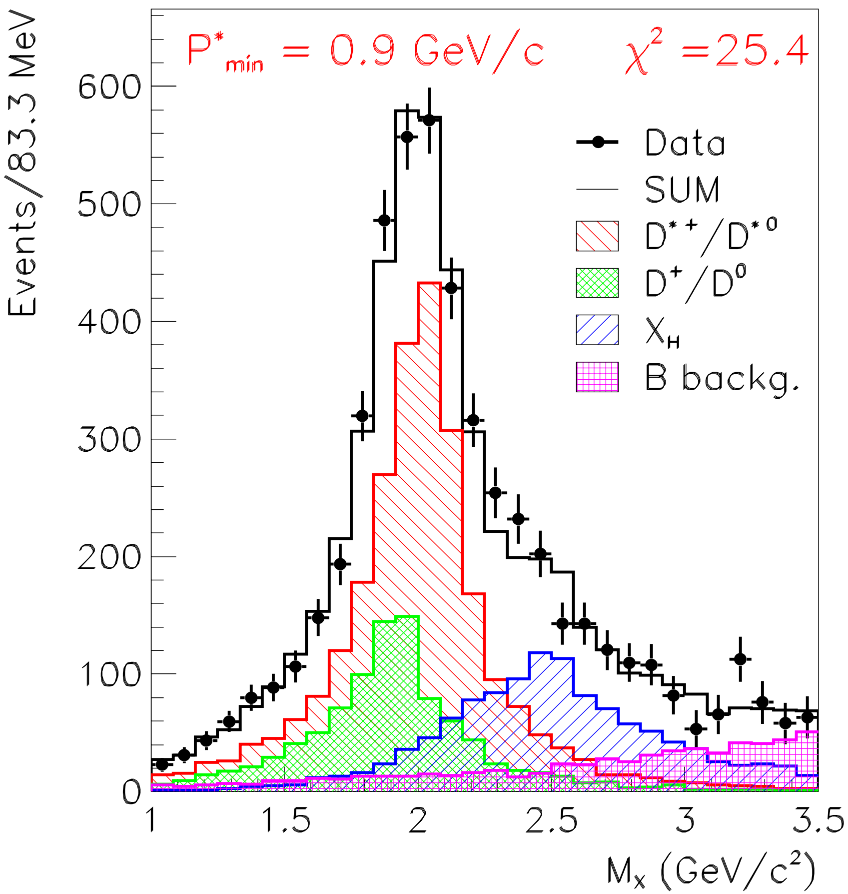
Idea: The non-perturbative parameters Λ, λ_1, λ_2 can be determined from other experimental measurements.

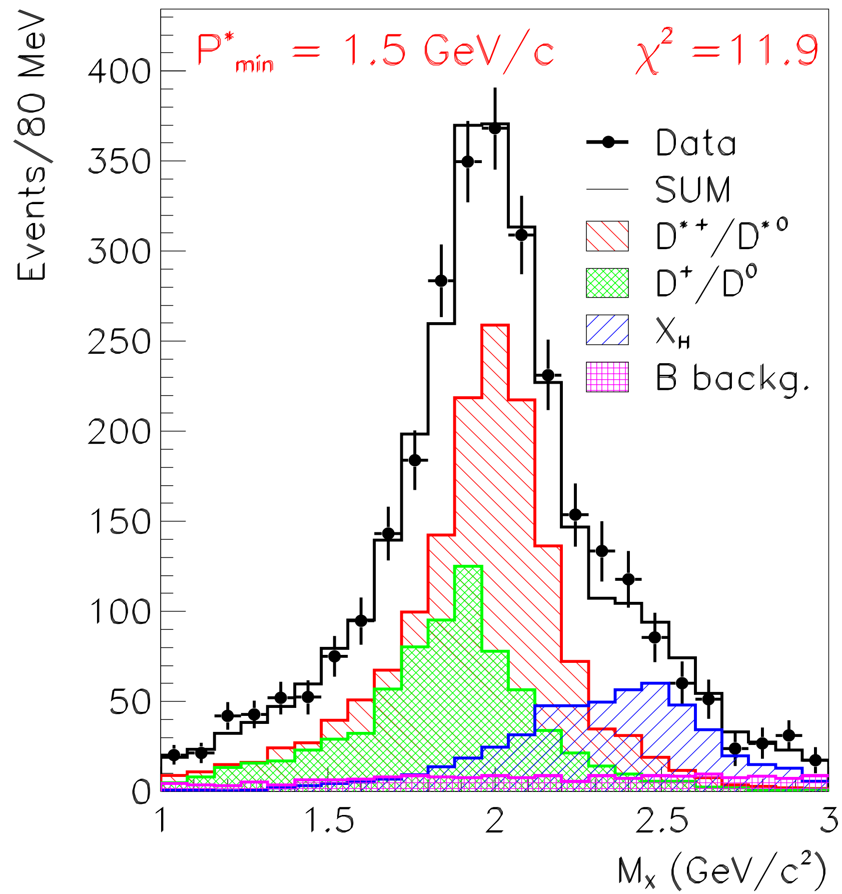
$b \rightarrow s\, \gamma$ photon energy moments, $b \rightarrow c\, l\, \upsilon$ lepton energy moments, and $b \rightarrow c\, l\, \upsilon$ hadronic mass moments.

For example: $\langle E_\gamma \rangle$ and $\langle E_\gamma \rangle^2 - \langle E_\gamma^2 \rangle$ in $b \rightarrow s\, \gamma$



BaBar: Moments of the M_x Distribution



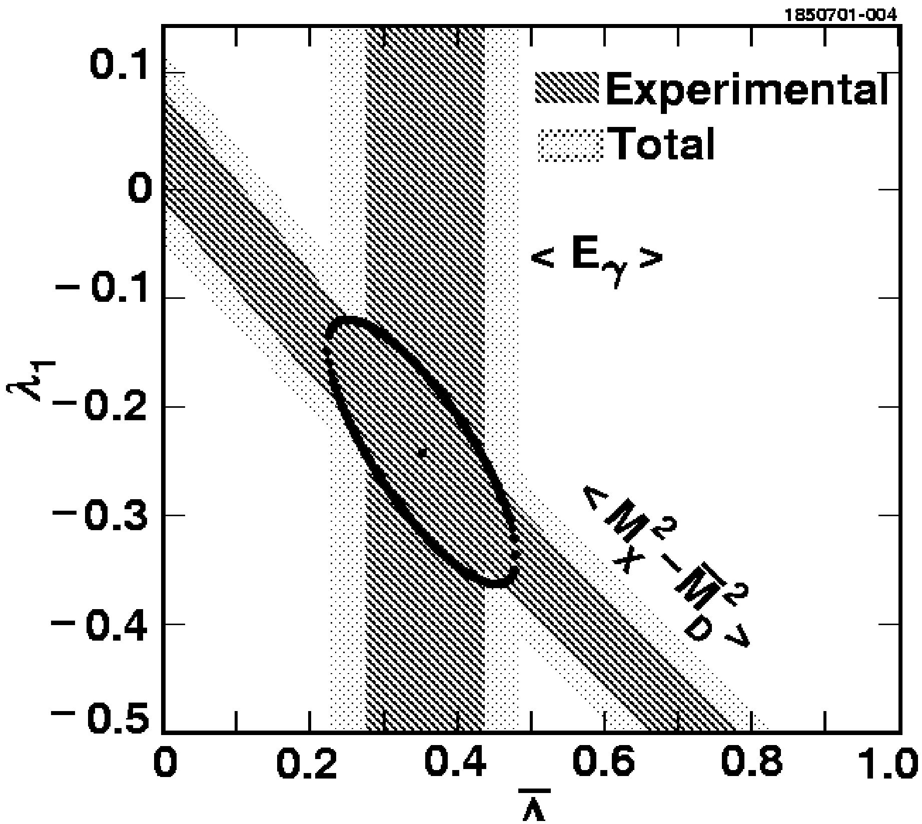


Binned χ^2 fit to M_X Distribution: 4 Contributions

$D = f_D P_D + f_{D*} P_{D*} + f_{HX} P_{HX} + f_{BG}(\text{fixed}) P_{BG}$

OPE parameters determined from two sets of moments:

CLEO

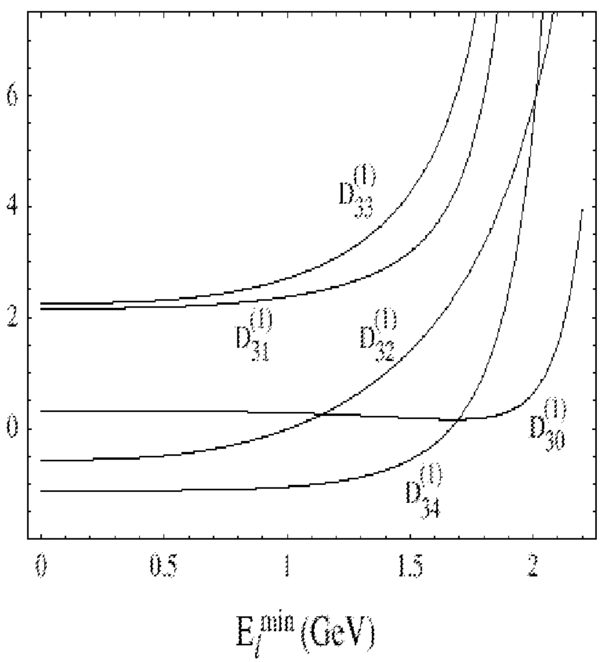


Λ=0.35 ±0.07 ± 0.10 GeV , λ_1 = 0.236± 0.071± 0.078GeV^2

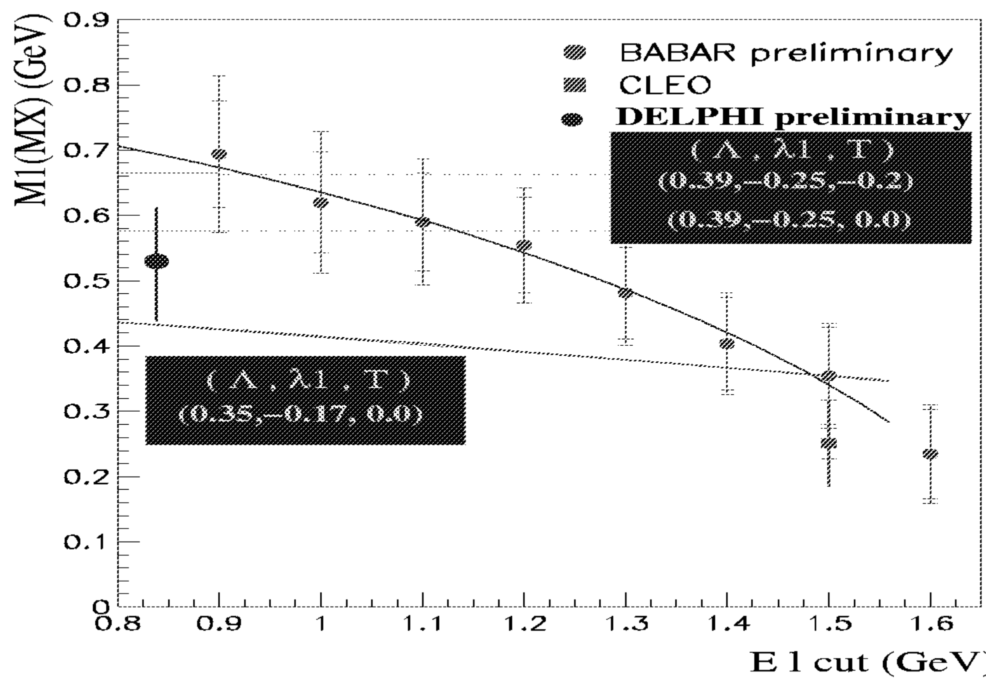
BaBar: Problem with E_L cut dependence of moments.

CLEO $E_\ell > 1.5$ GeV DELPHI $E_\ell \geq 0.5$ GeV
BABAR $0.8 \text{ GeV} < E_\ell < 1.6$ GeV

$1/m_b^3$ Coefficients vs. E_ℓ^{cut}
Falk and Luke



$M_1(M_X)$ vs. E_ℓ^{cut}
CLEO + BABAR + DELPHI PRELIMINARY



Using the measured OPE parameters, can determine a more precise V_{cb} value.

$$V_{cb} = (40.4 \pm 0.5(\text{exp}) \pm 0.5(\lambda_1, \Lambda) \pm 0.8(\text{theo})) \times 10^{-3}$$

V_{cb} from B → $D^{(*)}$ l ν at zero recoil

The differential rate for B → $D^{(*)}$ l ν at zero recoil is related to Vcb:

$$\frac{d\Gamma}{d\omega} \propto |Vcb|^2 F_{D^{(*)}}{}^2(\omega)$$

ω: relativistic γ factor of the D^* in the B rest frame ($\omega = E_{D*}/m_{D*}$)

$\omega = v \cdot v'$, the dot product of B and $D^{(*)}$ 4-velocities.

Other notations are used including: w, y

$$\omega = (m_B^2 + m_{D*}^2 - q^2)\frac{1}{2m_B m_{D*}}$$

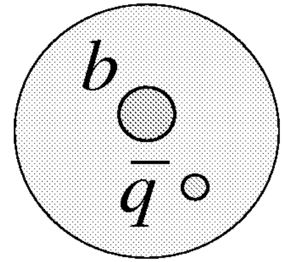
V_{cb} from B →$D^{(*)}$ l ν at zero recoil

$$\frac{d\Gamma}{d\omega} \propto \left|V_{cb}\right|^2 F_{D^{(*)}}{}^2(\omega)$$

In the zero-recoil configuration, HQET symmetry implies F(ω =1)=1 with small theoretical corrections.

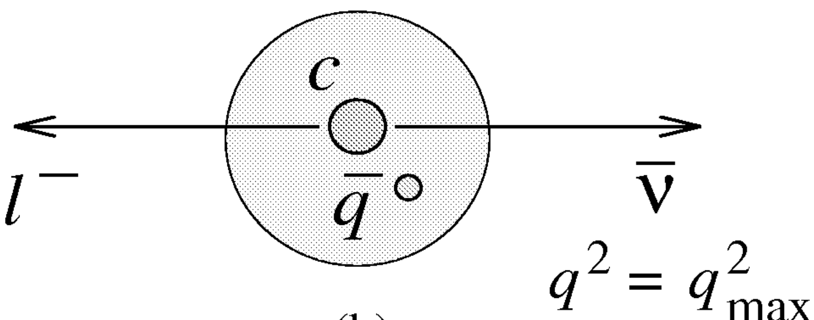
Luke's theorem: the corrections to 1 are $O(1/m_b^2)$ for B→D* l ν in HQET. From models and lattice, F(1)=0.91±0.04 (PDG)

Initial B meson



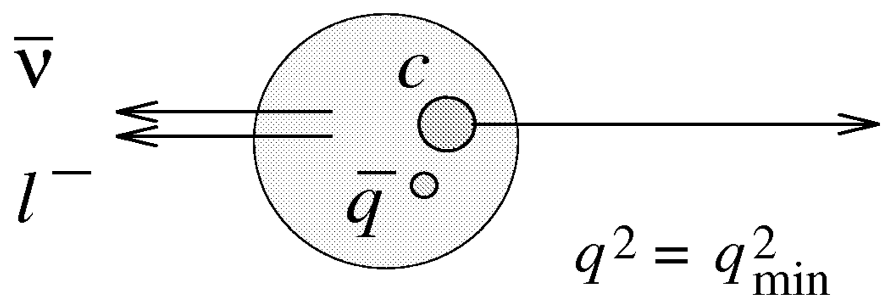
(a)

Light degrees of freedom are not disturbed ➔F(1)=1



(b)

ω=1



(c)

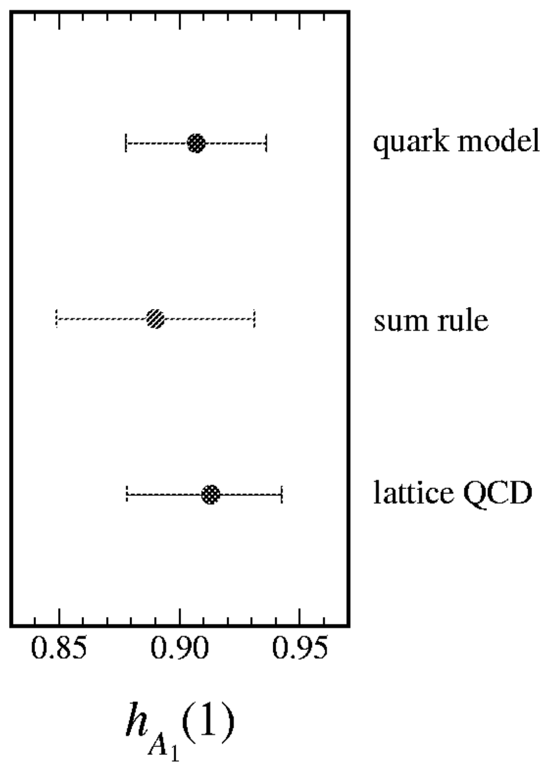
ω =1.5

V_{cb} from $B \rightarrow D^{(*)}\, l\, \nu$ at zero recoil (theory)

$$\mathcal{F}_{B\to D^*}(1) = 0.913 \underbrace{{}^{+0.024}_{-0.017}}_{\text{stat}} \underbrace{\pm 0.016}_{\text{match}} \underbrace{{}^{+0.003}_{-0.014}}_{a} \underbrace{{}^{+0.000}_{-0.016}}_{m_q} \underbrace{{}^{+0.006}_{-0.014}}_{\text{quench}}$$

State of the art
Lattice calculation
from Kronfeld et al.

See Lepage's talk

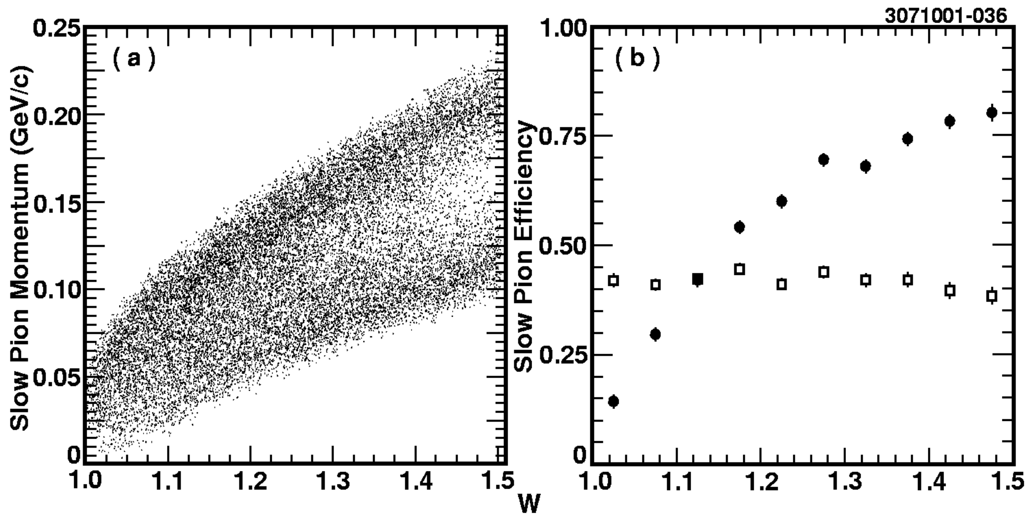


(Still quenched)

Theory uncertainties still at the 3-4% level

Experimental issues for zero recoil:

The D^* is nearly at rest i.e. slow pion from $D^* \rightarrow D\,\pi$ has a very low momentum.



But at LEP eff is flat.

Rate is proportional to p_{D*}. (At zero recoil there is no rate). *Measure the rate near zero recoil, then assume a functional form for $F(\omega)$ and extrapolate.*

CLEO 2002: B →D$^{(*)}$ l ν signals

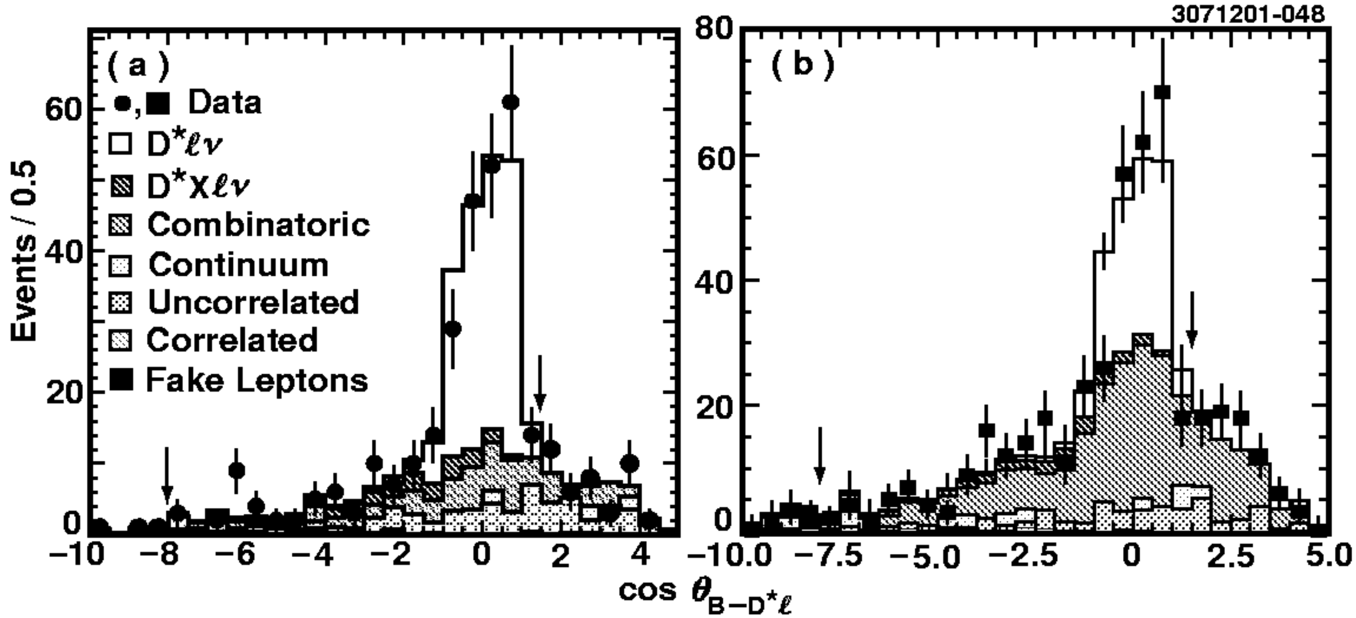


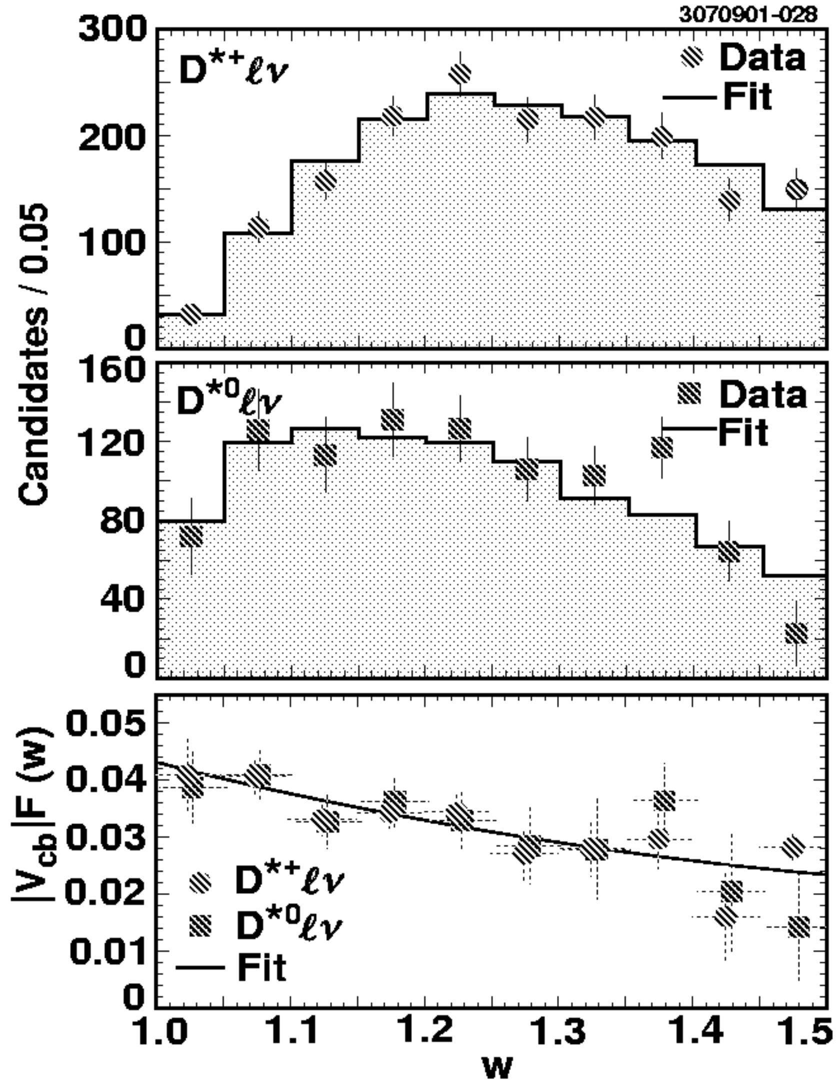
FIG. 1. The candidate yields for $1.10 < w < 1.15$ bin with the results of the fit superimposed for (a) $D^{*+}\ell^-\bar{\nu}$ and for (b) $D^{*0}\ell^-\bar{\nu}$. The fit uses the region between the arrows.

$$\cos\theta_{B-Xl} \equiv \frac{2E_B E_{Xl} - M^2{}_B - M^2{}_{Xl}}{2|\vec{p}_B||\vec{p}_{Xl}|}$$

$|\cos_{B-Xl}|<1$ if X and lepton come from signal

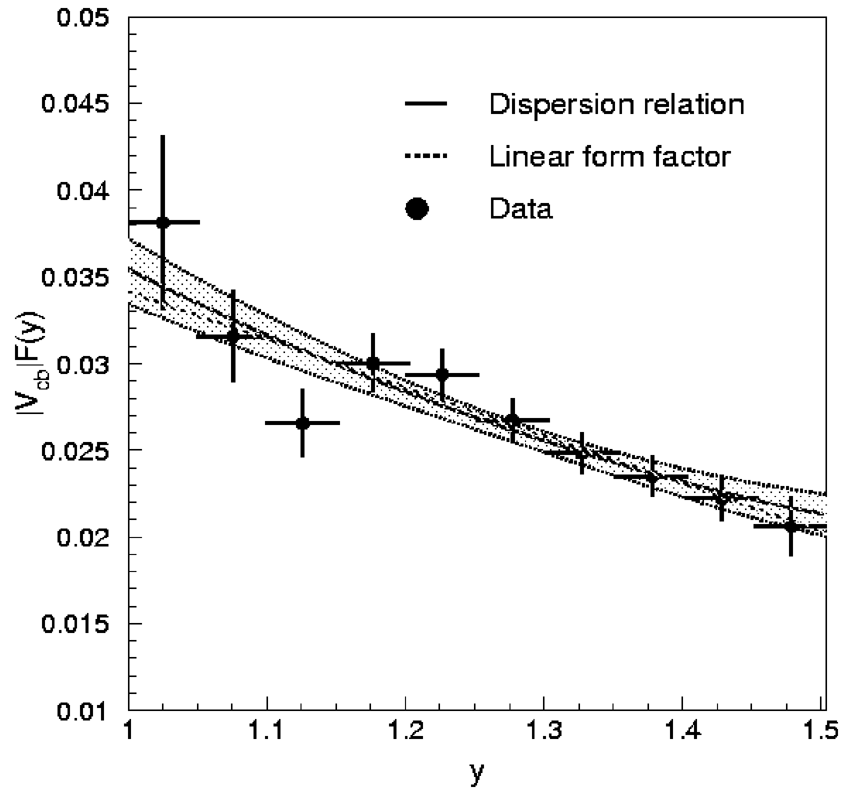
CLEO 2002: V_{cb} from B →$D^{(*)}$ l ν at zero recoil

Note higher efficiency near w ~1



Use both D^{*+} →$D^0\,\pi^+$ and D^{*0} →$D^0\,\pi^0$

Belle: Sensitivity of $|V_{cb}|$ to FF parameterization.



$|V_{cb}|F(1)$ 0.0342-0.0358
➔ V_{cb} range 5%

Summary of fit results according to different form factor (FF) parameterizations, where the errors are statistical only. Our main analysis uses values of $R_1(1)$, $R_2(1)$ from QCD sum rules.

FF shape & $R_1(1)$, $R_2(1)$	$\|V_{cb}\|F(1)\cdot 10^2$	$\rho^2_{A_1}$	ρ^2_F	$\mathcal{B}(\bar{B}^0 \to D^{*+}e^-\bar{\nu})$	χ^2/ndf
Dispersive & QCD sum rules	3.54±0.19	1.35±0.17	·	(4.59±0.23)%	3.38/8
Dispersive & CLEO value	3.58±0.19	1.45±0.16	·	(4.60±0.23)%	3.79/8
Linear & Heavy quark limit	3.42±0.17	·	0.81±0.12	(4.57±0.24)%	2.23/8

B→D*l ν Form Factor Parametrization Issues I

$$\frac{d\Gamma(B \to D^* l \nu)}{dw} = \frac{G_F^2}{48\pi^3} M_{D^*}^3 (M_B - M_{D^*})^2 \sqrt{w^2 - 1}(w+1)^2 g(w) |V_{cb}|^2 F_{D^*}^2(w)$$

where $g(w) = \left[1 + \frac{4w}{(1+w)} \frac{1 - 2wr + r^2}{(1-r)^2}\right], r = M_{D^*} / M_B$

First round of measurements assumed a linear functional form for F(y).

$$F(\omega) = F(1)\,[\,1 - \rho^2\ (\omega - 1) + O(\omega^2)]$$

B→D*l ν Form Factor Parametrization Issues II

$$\frac{d\Gamma(B \to D^* l \nu)}{dw} = \frac{G_F^2}{48\pi^3} M_{D^*}^3 (M_B - M_{D^*})^2 \sqrt{w^2-1}(w+1)^2 g(w) |V_{cb}|^2 F_{D^*}^2(w)$$

Using the axial vector form factor $A_1(y)$, form factor ratios $R_1(y)$ and $R_2(y)$

$$g(w)F_{D^*}^2(w) = \left[2\left(\frac{1-2wr+r^2}{(1-r)^2}\right)\left(1+R_1^2(w)\frac{w-1}{w+1}\right) + \left(1+\left(1-R_2(w)\right)\frac{w-1}{1-r}\right)^2 \right] A_1^2(w)$$

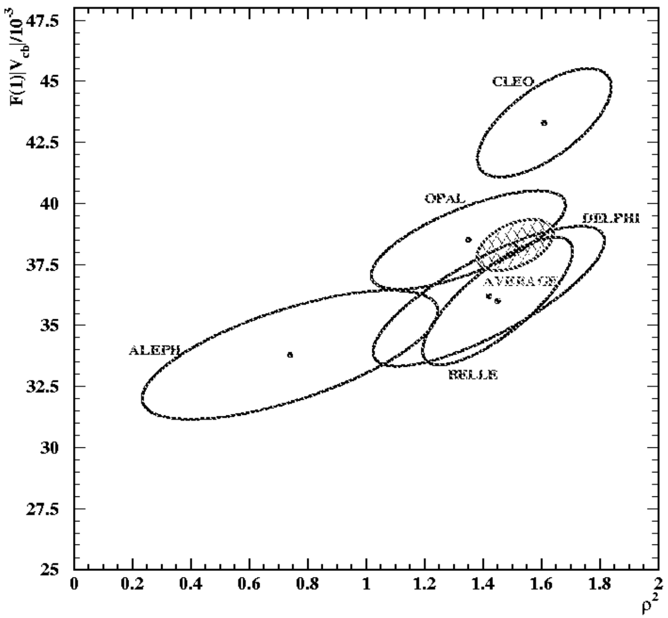
Dispersion relations give model-independent bounds on form factors
(Caprini, NP B530 (1998))

$$z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$

$R_1(w) \sim R_1(1) - 0.12(w-1) + 0.05(w-1)^2$
$R_2(w) \sim R_2(1) - 0.11(w-1) - 0.06(w-1)^2$
$A_1(w) \sim A_1(1)[1-8r^2z+(53r^2-15)z^2-(231r^2-91)z^3]$

V_{cb} from the end point of B ->$D^{(*)}$ l ν

Note strong V_{cb}, ρ^2 correlation

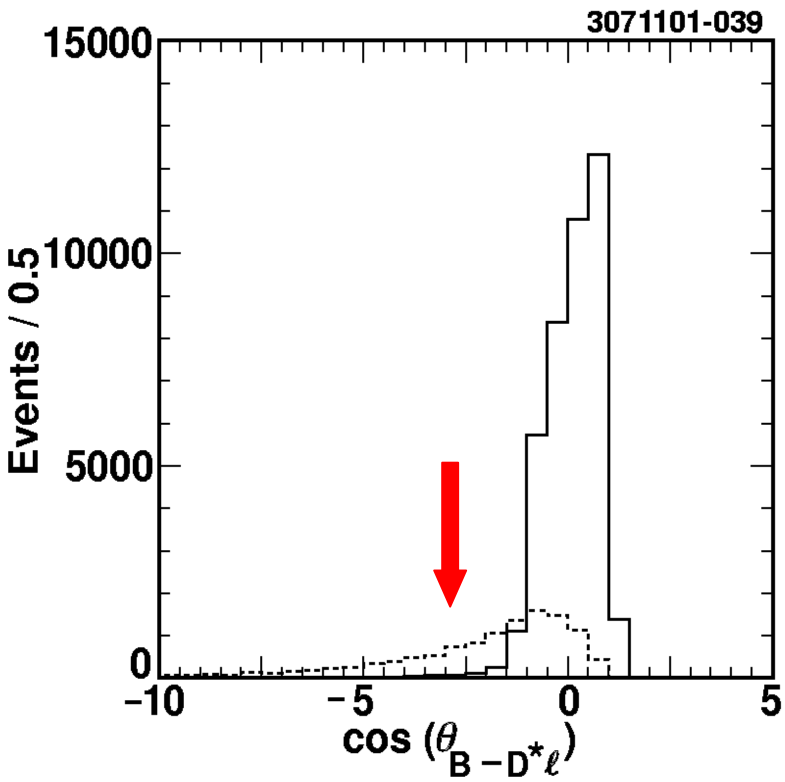


experiment	$\mathcal{F}(1)\lvert V_{cb}\rvert$ $(\times 10^3)$	ρ^2	$\mathrm{Corr}_{\mathrm{stat}}$
ALEPH	33.8± 2.1± 1.6	0.74± 0.25± 0.41	94%
DELPHI	36.1± 1.4± 2.5	1.42± 0.14± 0.37	94%
OPAL	38.5± 0.9± 1.8	1.35± 0.12± 0.31	89%
Belle	36.0± 1.9± 1.8	1.45± 0.16± 0.20	90%
CLEO	43.3± 1.3± 1.8	1.61± 0.09± 0.21	86%
World average	38.3 ± 0.5± 0.9	1.51± 0.05± 0.12	86%

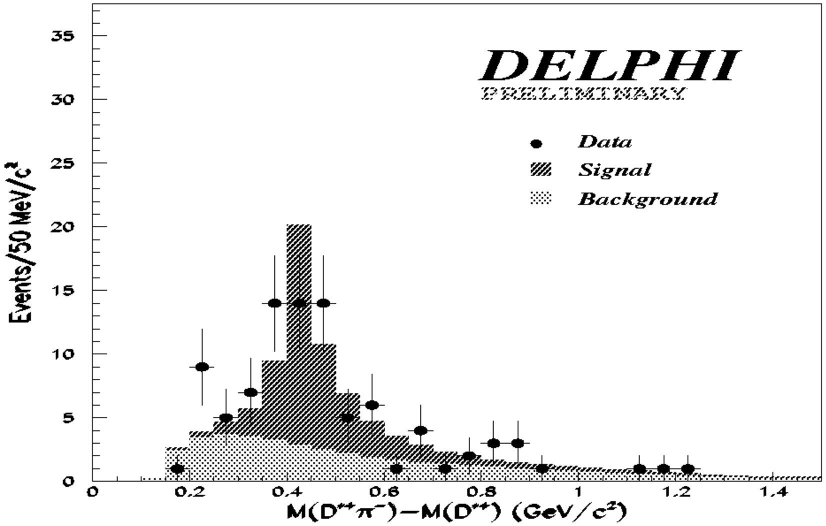
Artuso and Barbieri.

Exp error is only 2.7% , limited by theory

Uncertainty in B ->D^{**} l ν background



Explains the difference between CLEO and other results.



BF(B →D^* π l ν)= (0.64±0.08±0.09) %

B→D l ν versus B→D* l ν for V_{cb}

(+)Detection efficiency for B→D is higher than B→D* (no slow π).

(-)Background is worse for B→D (no D* mass constraint) .

(-)B→D l ν has a p_D^3 suppression while B→D* l ν has only a p_{D*} suppression

(-)Luke's theorem does not apply to B→D l ν. There are O(1/m_b) corrections. (See Ligeti's talk).

Variables for exclusive semileptonic analysis via ν reconstruction (used for B→D l ν)

$$p_{miss} = -\sum p_i$$

$$E_{miss} = 2E_{beam} - \sum E_i$$

$$M^2_{miss} = E^2_{miss} - P^2_{miss}$$

$$p_\nu = (p_{miss}, |p_{miss}|)$$

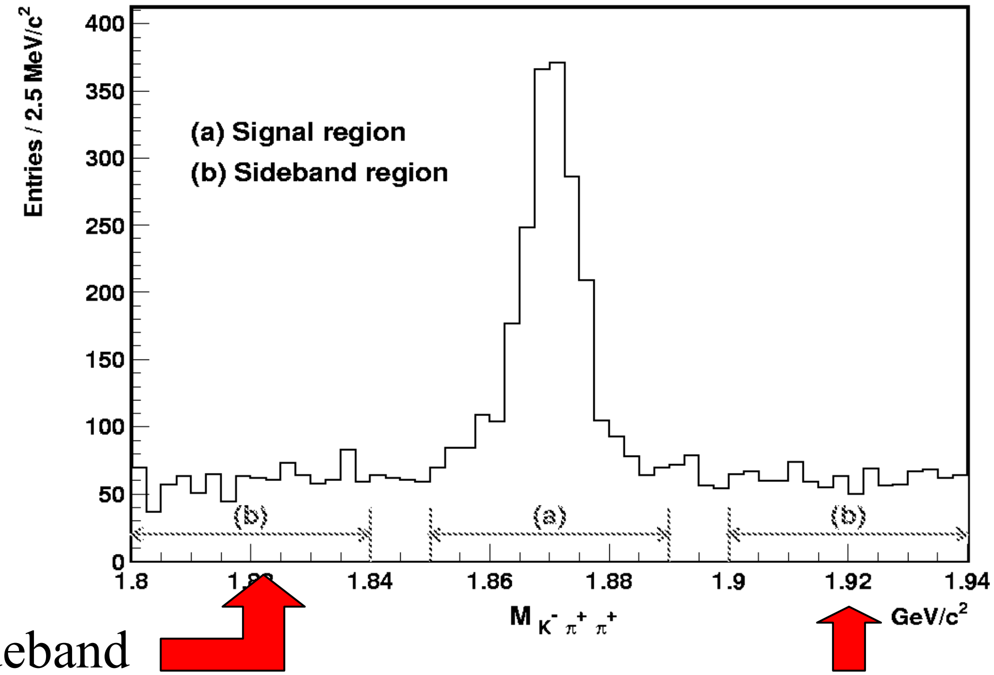
Can then form ΔE and M_B

$$\Delta E \equiv E_{beam} - (E_\pi + E_l + E_\nu)$$

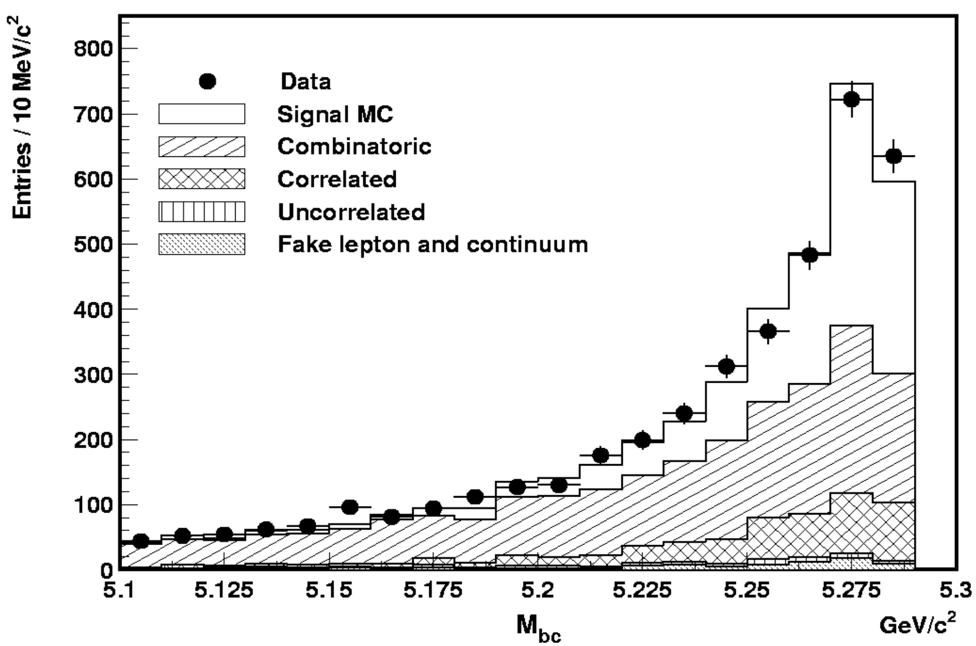
$$M_B \equiv \sqrt{E^2{}_{beam} - |p_\pi + p_l + p_\nu|^2}$$

where Ebeam = 5.29GeV

Belle: B→D l ν



sideband



Signal :1099±57

Corr: 983 ± 22

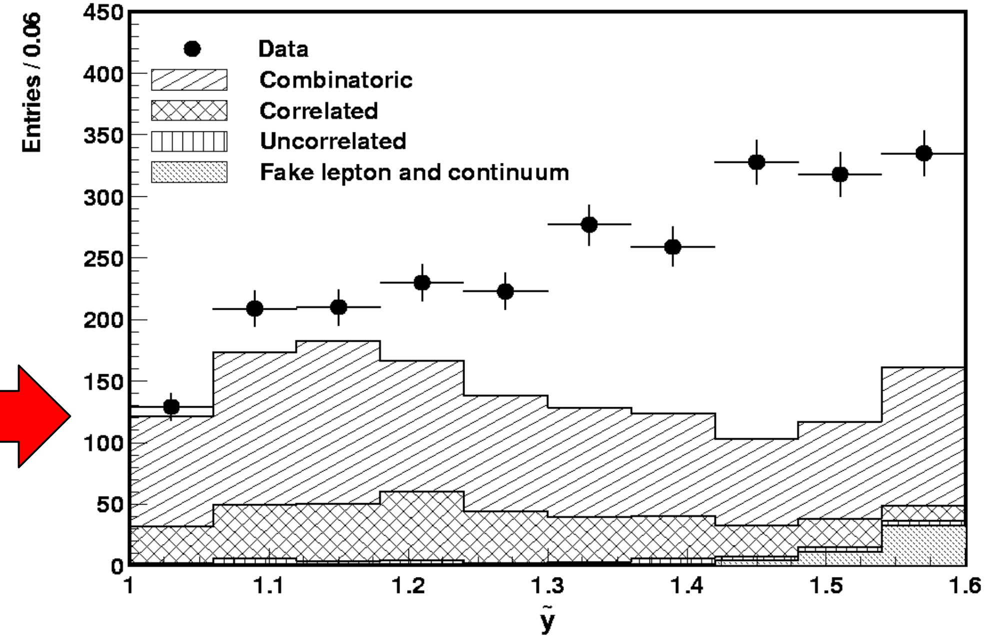
Uncorr: 35 ±4

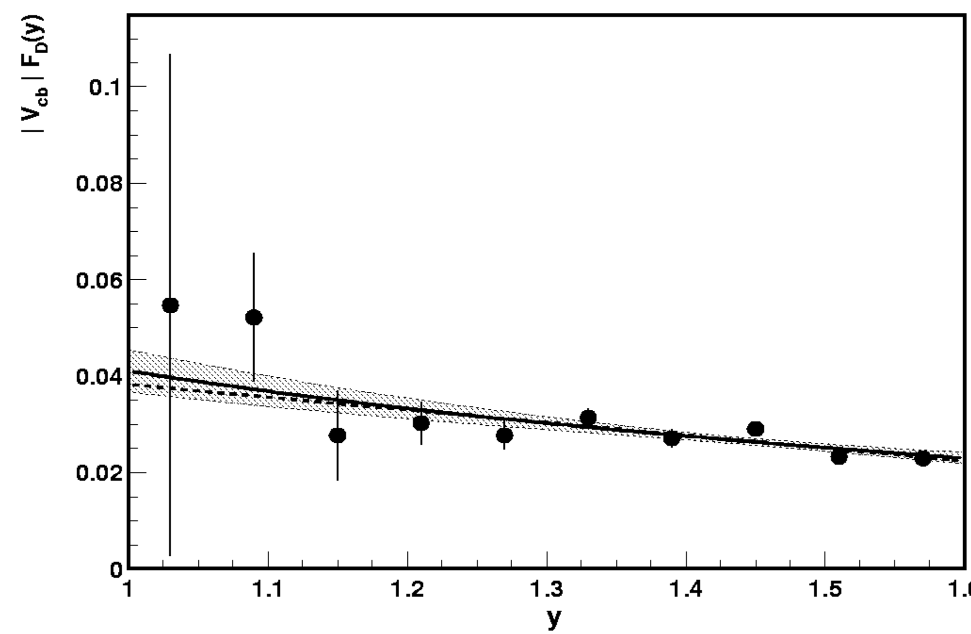
Fakes: 9 ±1

Cont: 43 ±7

Belle: B→D l ν

Note high efficiency but large backgrounds.



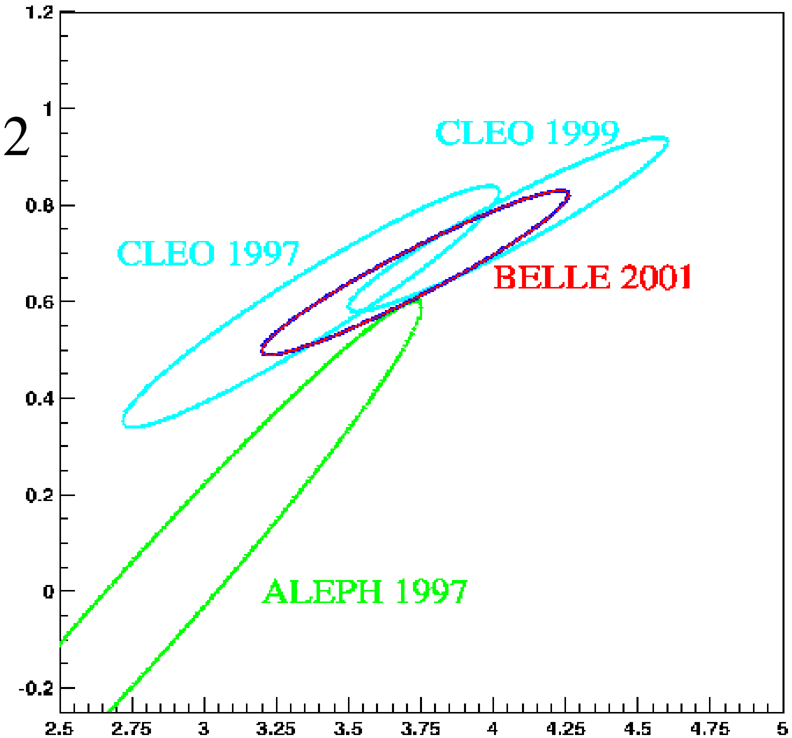


Results on V_{cb} and ρ^2 from $B \rightarrow D^{(*)} l \nu$

$B^0 \to D^- l^+ \nu$

All using a linear model

ρ^2

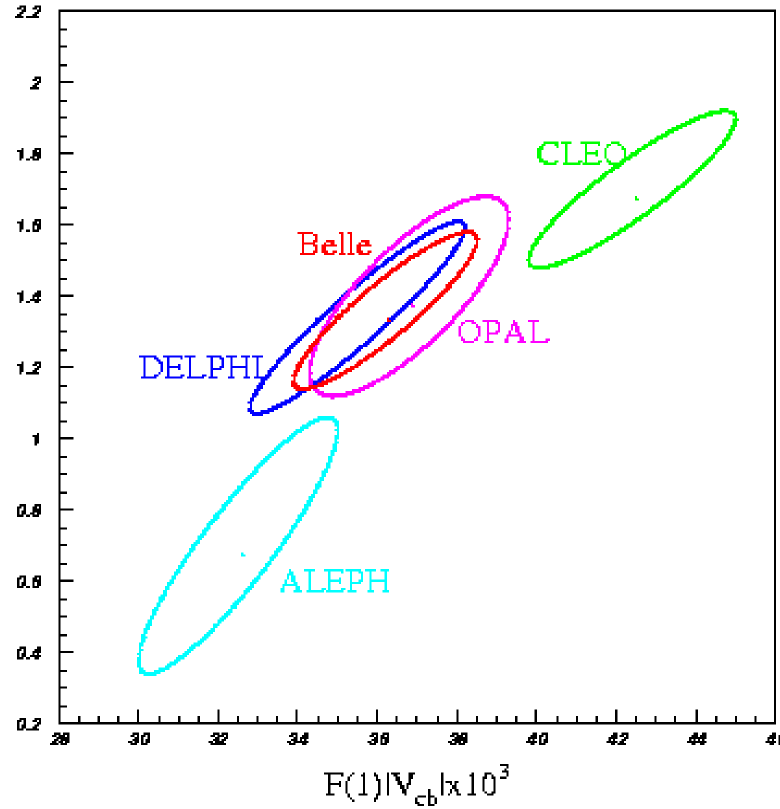


$F(1)|Vcb| \times 10^2$

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

All using a dispersion relation

ρ^2



$F(1)|Vcb| \times 10^2$

Test HQET: B→D l ν versus B→D* l ν

From the results of $\bar{B}^0 \to D^{*+} e^- \bar{\nu}$ analysis at Belle, the ratio of $F_D(1)$ and $F_{D^*}(1)$ and the difference between $\hat{\rho}_D^2$ and $\hat{\rho}_{D^*}^2$ are measured to be

$$\frac{F_D(1)}{F_{D^*}(1)} = \begin{cases} 1.12 \pm 0.12 \pm 0.12 \text{ (Linear form factor)} \\ 1.16 \pm 0.14 \pm 0.12 \text{ (Caprini } et\ al. \text{ form factor)}, \end{cases}$$

$$\hat{\rho}_D^2 - \hat{\rho}_{D^*}^2 = \begin{cases} -0.12 \pm 0.18 \pm 0.13 \text{ (Linear form factor)} \\ -0.23 \pm 0.29 \pm 0.20 \text{ (Caprini } et\ al. \text{ form factor)}, \end{cases}$$

The size of $O(1/m_Q)$ corrections is not large.

With more data, we will start to observe these corrections to HQET.

Motivation for $B \rightarrow D^{(*)} l \nu$ form factor analysis

HQET which is used to extract V_{cb} also predicts ratios of form factors.

Form factors are a major source of uncertainty in $|V_{ub}|$ analysis.

Imagine $B \rightarrow D l \nu$ and $B \rightarrow D^{*} l \nu$ as two body $B \rightarrow D W$ and $D^{*} W$ decays. The first is a p-wave while the latter can be either a s, p or d-wave

Definition of angles for B→D* l ν FF analysis

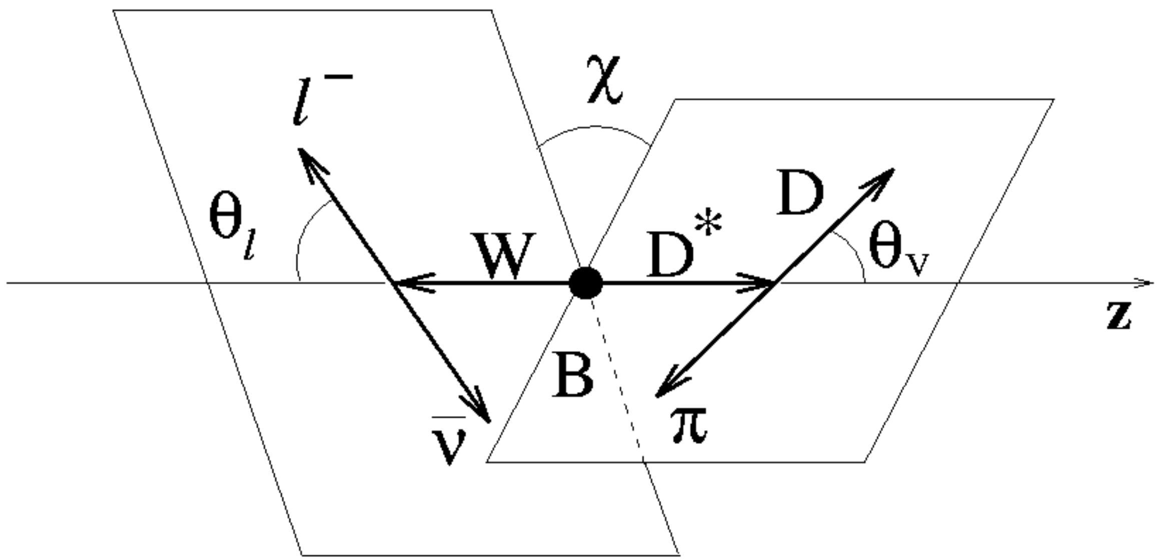


Fig. 34. Definition of the angles θ_V, θ_ℓ, and χ in the decay $\bar{B} \to D^* \ell^- \bar{\nu}$. (These angles are used for any $P \to V \ell \nu$ in which the vector meson decays into two pseudoscalars.) The lepton and neutrino are drawn back to back because they are shown in the W^* rest frame. Similarly, the D and the π are shown in the D^* rest frame. The angle θ_ℓ is thus measured in the W rest frame, while θ_V is measured in the D^* rest frame. The azimuthal angle χ is measured between the W and D^* decay planes. In the literature, the angle θ_ℓ is sometimes defined as the direction between the charged lepton and the recoiling vector meson, measured in the $\ell\nu$ rest frame.

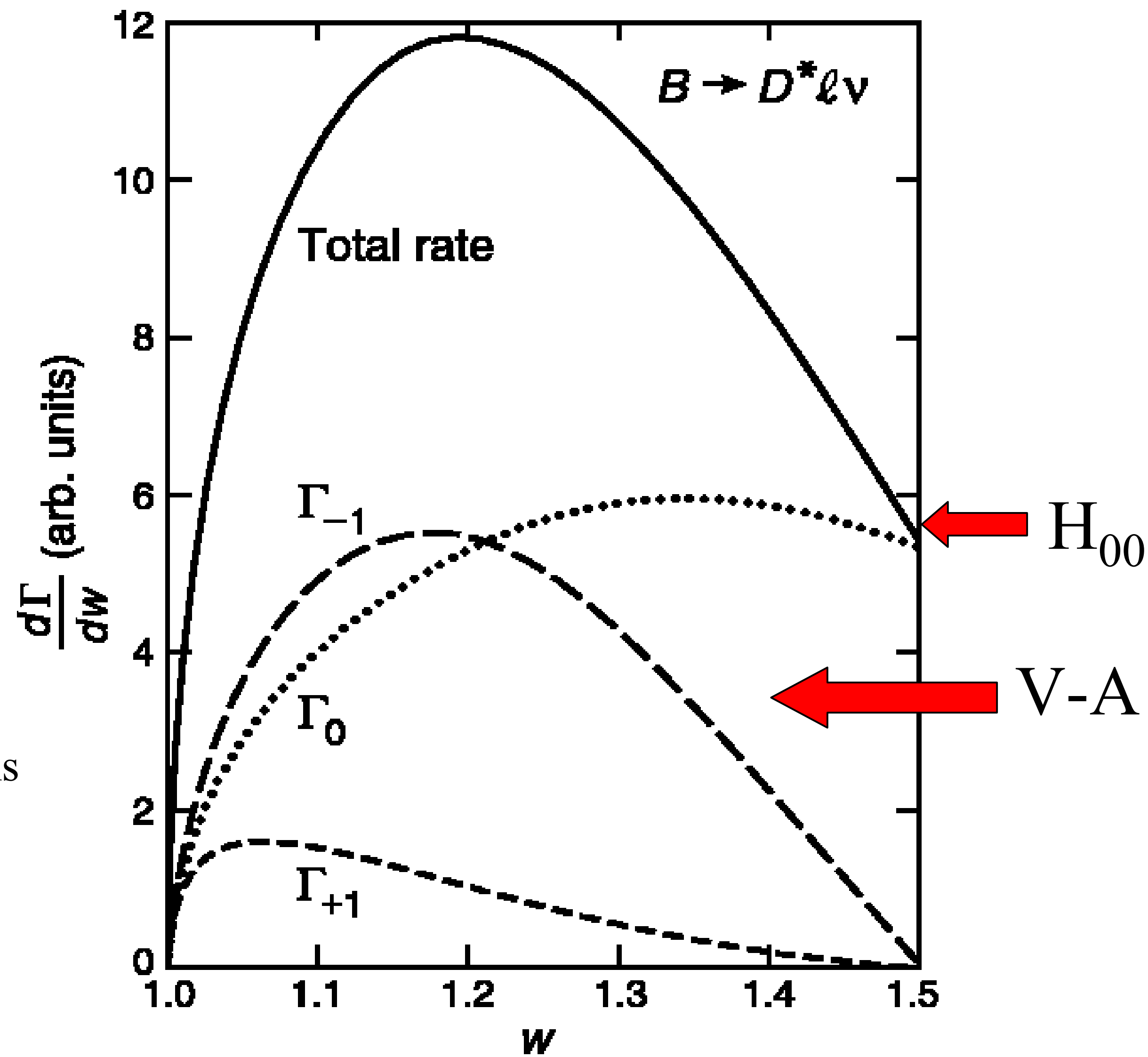
Differential rate for B→D* l ν

The differential decay rate for $P(Q\overline{q}) \rightarrow V(q'\overline{q})\ell^-\overline{\nu}$, $V \rightarrow P_1P_2$ can be expressed in terms of these four kinematic variables q^2, θ_ℓ, θ_V and χ (Gilm90, Korn90b):

$$\begin{aligned}
\frac{d\Gamma(P\rightarrow V\ell\nu,\ V\rightarrow P_1P_2)}{dq^2\,d\cos\theta_V\,d\cos\theta_\ell\,d\chi} &= \frac{3}{8(4\pi)^4}G_F^2|V_{q'Q}|^2\frac{p_V q^2}{M^2}\mathcal{B}(V\rightarrow P_1P_2) \\
&\times \{(1-\eta\cos\theta_\ell)^2\sin^2\theta_V|H_+(q^2)|^2 \\
&+ (1+\eta\cos\theta_\ell)^2\sin^2\theta_V|H_-(q^2)|^2 \\
&+ 4\sin^2\theta_\ell\cos^2\theta_V|H_0(q^2)|^2 \\
&- 4\eta\sin\theta_\ell(1-\eta\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi\,H_+(q^2)H_0(q^2) \\
&+ 4\eta\sin\theta_\ell(1+\eta\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi\,H_-(q^2)H_0(q^2) \\
&- 2\sin^2\theta_\ell\sin^2\theta_V\cos 2\chi\,H_+(q^2)H_-(q^2)\}, \qquad (113)
\end{aligned}$$

Involves three form factors $H_+(q^2)$, $H_-(q^2)$, $H_0(q^2)$ corresponding to the three possible W helicities.

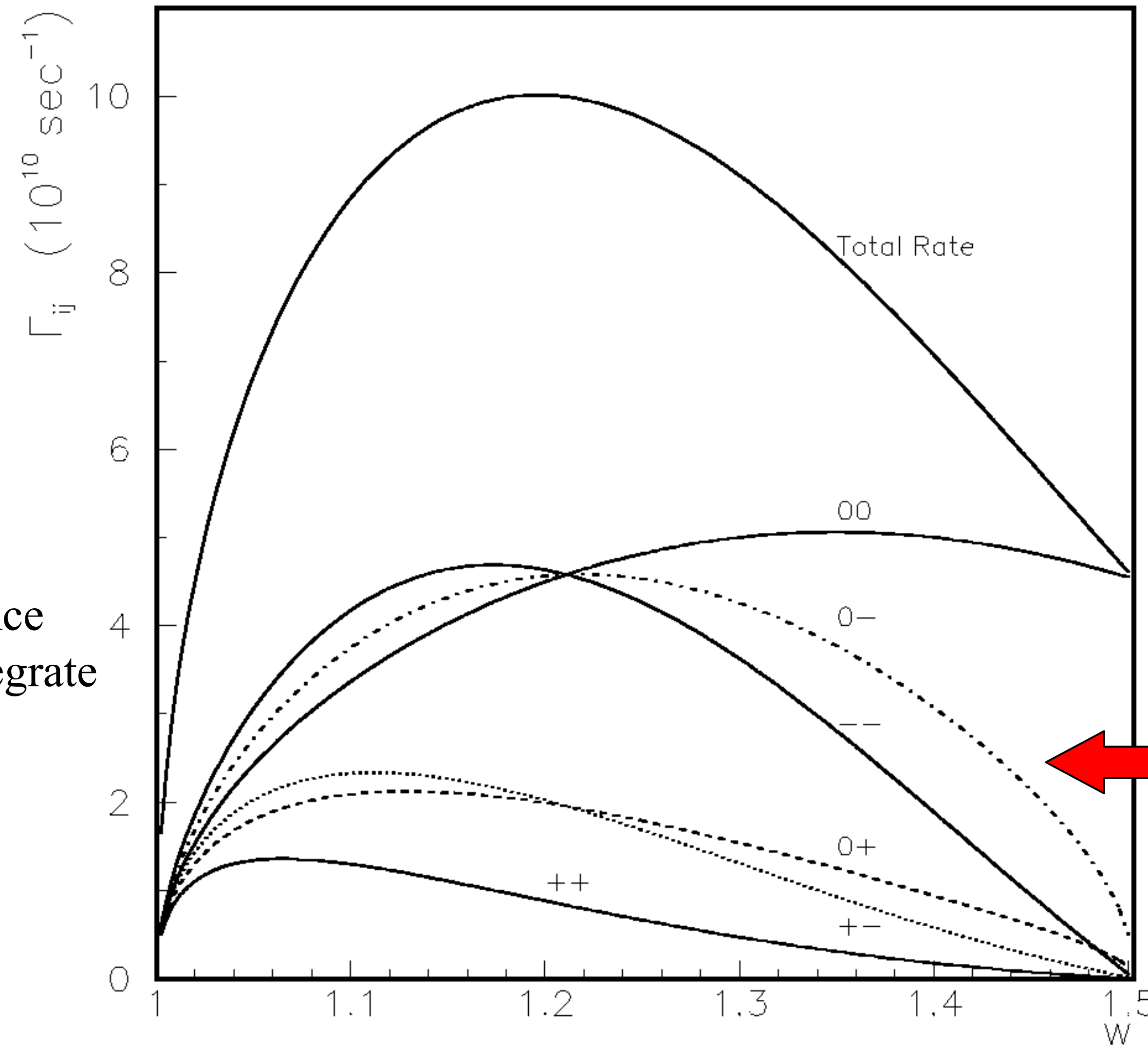
The w dependence of B→D* l ν FFs.



Interference terms integrate to zero

The w dependence of $B \rightarrow D^* l \nu$ FFs including interference.

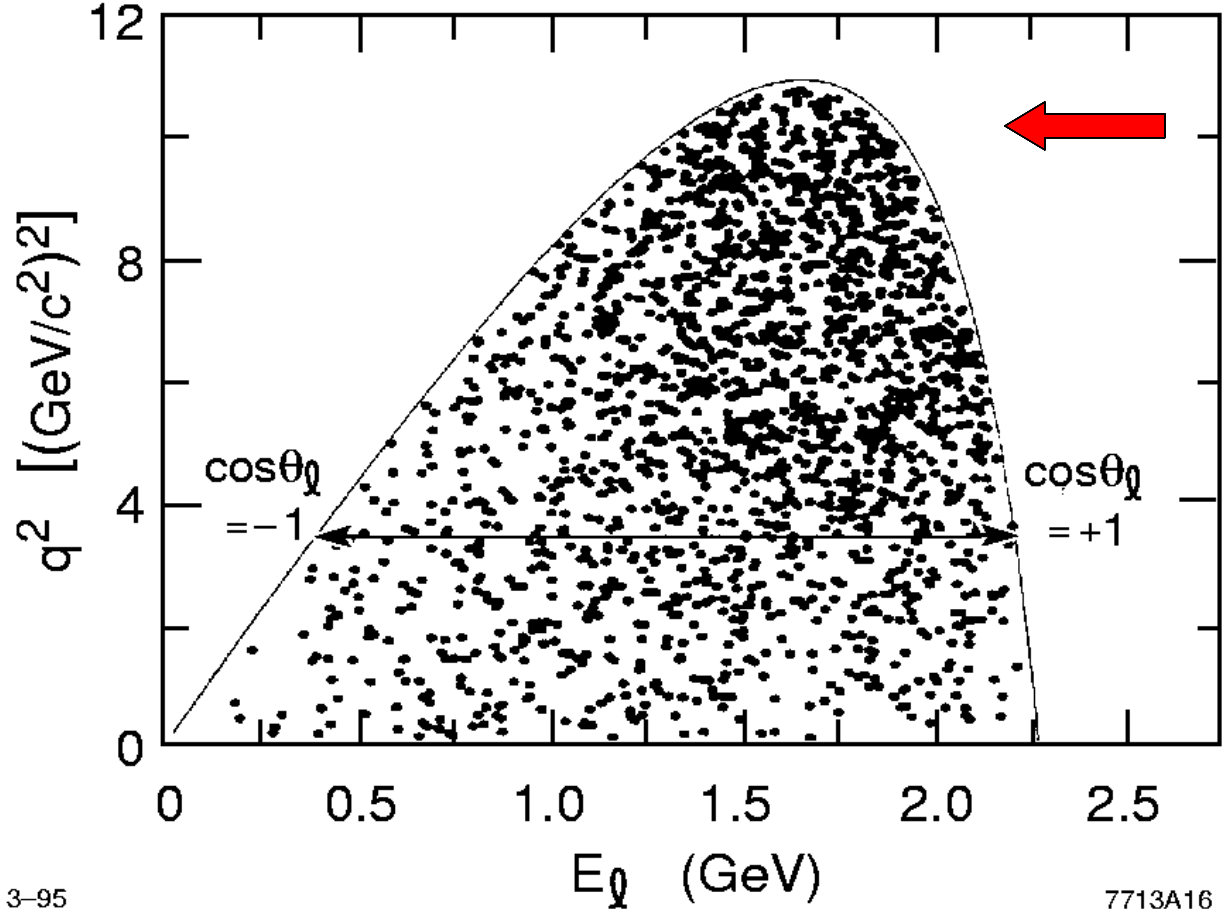
Interference terms integrate to zero



H_{00}

V-A

MC simulation of B→D* l ν Dalitz plot



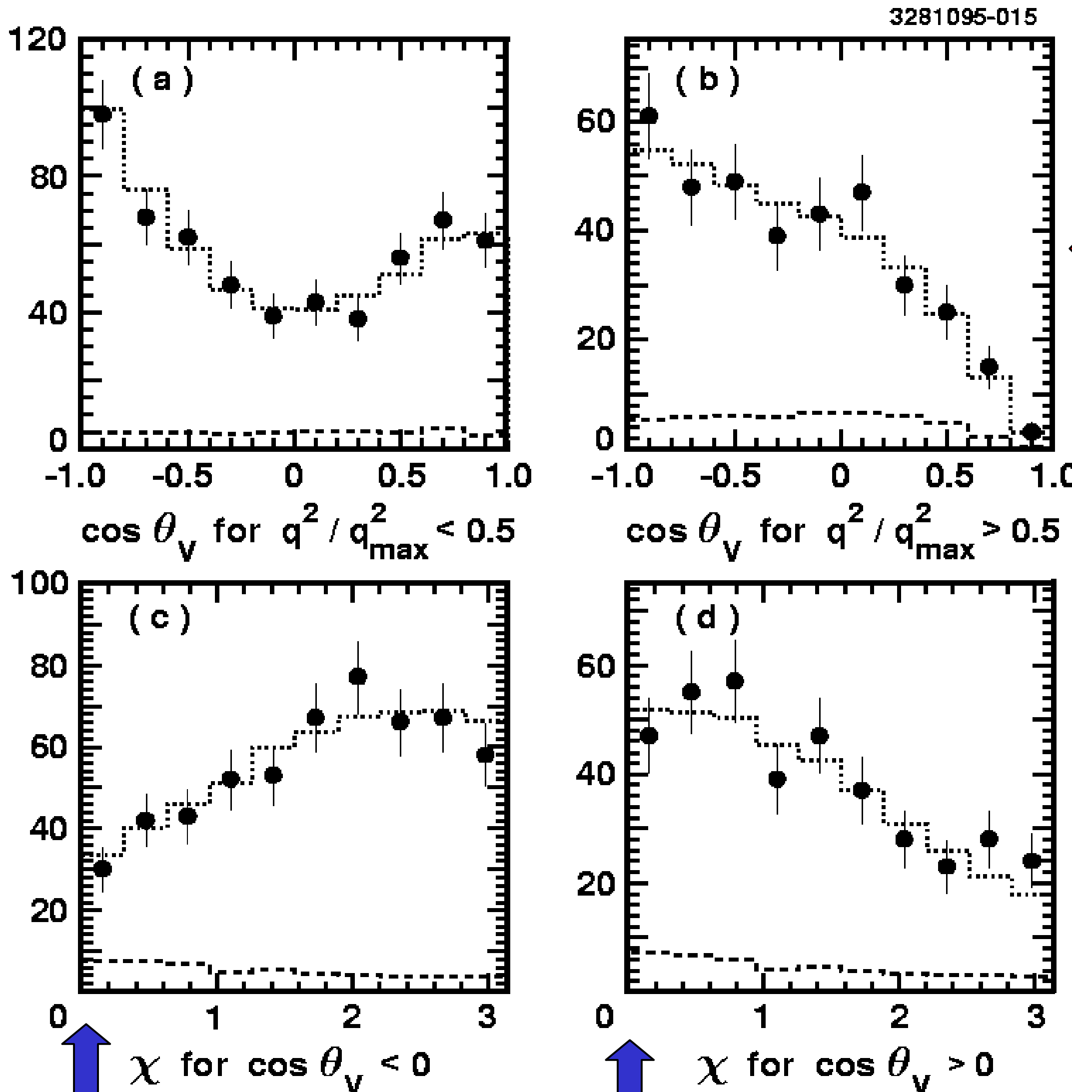
Unpolarized

V-A

density change from left to right.

CLEO: $B \rightarrow D^* l \nu$ FF analysis

H_{00} →



← H_{oo}, $H_{\pm1,\pm1}$

Interference term $H_{-1,-1}H_{00}$

Helicity amplitudes and HQET $B \to D^* l \nu$ FF

$$H_0(w) = (m_B - m_{D^*})\sqrt{\frac{m_B m_{D^*}}{q^2(w)}}(w+1)\, h_{A_1}(w) \times \left[1 + \left(\frac{w-1}{1-r}\right)(1 - R_2(w))\right]$$

$$H_\pm(w) = (m_B - m_{D^*})\sqrt{\frac{m_B m_{D^*}}{q^2(w)}}(w+1)\, h_{A_1}(w) \times \frac{\sqrt{1-2wr+r^2}}{1-r}\left[1 \mp \sqrt{\frac{w-1}{w+1}} R_1(w)\right],$$

Measure

$$R_1(w) \equiv \frac{h_V(w)}{h_{A_1}(w)} = \left[1 - \frac{q^2}{(M+m_V)^2}\right]\frac{V(q^2)}{A_1(q^2)}$$

$$R_2(w) \equiv \frac{h_{A_3}(w) + (m_V/M) h_{A_2}(w)}{h_{A_1}(w)} = \left[1 - \frac{q^2}{(M+m_V)^2}\right]\frac{A_2(q^2)}{A_1(q^2)}.$$

$R_1 = R_2 = 1$ in the infinite mass limit

Measure ratios, since h_{A1} determines overall norm.

Helicity amplitudes and usual B→D* l ν FF

The helicity amplitudes can, in turn, be related to the two axial-vector form factors, $A_1(q^2)$ and $A_2(q^2)$, and the vector form factor, $V(q^2)$, which appear in the hadronic current (Eq. 7.47):

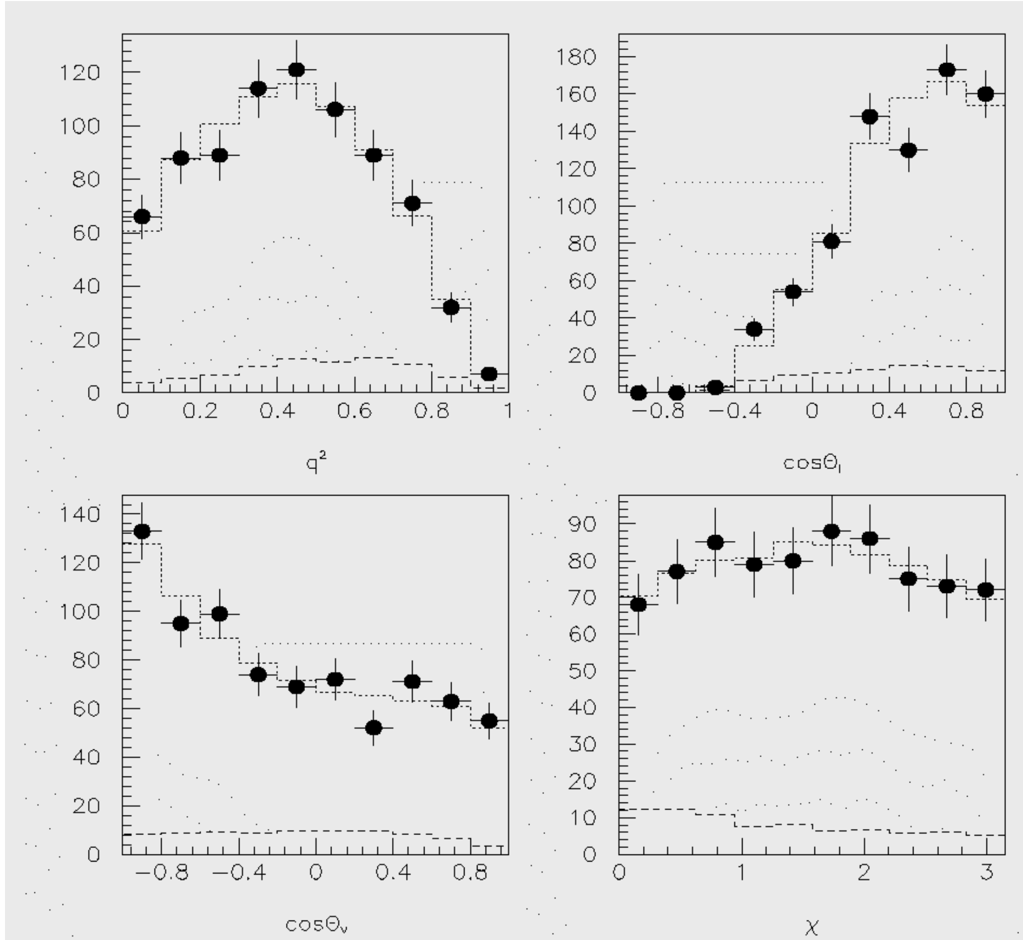
$$H_0(q^2) = \frac{1}{2m_V\sqrt{q^2}}[(M^2 - m_V^2 - q^2)(M + m_V)A_1(q^2) - 4\frac{M^2 p_V^2}{M + m_V}A_2(q^2)] \quad (7.59)$$

and

$$H_\pm(q^2) = (M + m_V)A_1(q^2) \mp \frac{2Mp_V}{M + m_V}V(q^2). \quad (7.60)$$

CLEO

R_2 → ← R_1



R_2 → ← R_1

A 4-dimensional fit is used to find the ratios R_1, R_2

	$R_1(w=1)$	$R_2(w=1)$
CLEO II	$1.18 \pm 0.30 \pm 0.12$	$0.71 \pm 0.22 \pm 0.07$
Neubert	1.3 ± 0.1	0.8 ± 0.2
Close & Wambach	1.15	0.91
ISGW2	1.27	1.01

← Test corrections to HQET

Conclusions on V_{cb}

Inclusive approaches give high precision results (1.2% exp) limited by errors on OPE parameters, theory and quark-hadron duality.

$$V_{cb} = (40.4 \pm 0.5(\text{exp}) \pm 0.5(\lambda_1, \Lambda) \pm 0.8(\text{theo})) \times 10^{-3}$$

HQET based approach to $B \to D^* l \nu$ gives increasingly precise measurements (2.7% exp) also limited by theory errors.

$$V_{cb} = (38.3 \pm 0.5(\text{exp}) \pm 0.9(\text{theo})) \times 10^{-3}$$

Check with complementary measmts (FFs, $B \to D\, l\, \nu$,..*.)*