A Measurement of $|V_{cb}|$ with $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ at CLEO and a Search for CPV in B_d^0 Mixing

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Search for CP Violation in B_d^0 Mixing

Mass eigenstates for the B_d^0 meson:

$$|B_{H,L}\rangle = \frac{(1+\epsilon_B)|B^0\rangle \pm (1-\epsilon_B)|\bar{B}^0\rangle}{\sqrt{2(1+|\epsilon_B|^2)}}$$

by analogy with the K^0–$\bar{K}^0$ system where there is CP violation in mixing.

In the Standard Model $|\epsilon_B| \sim 10^{-3}$, while new physics may allow $|\epsilon_B| \sim 10^{-2}$.

$$B^0 \to \bar{B}^0 \neq \bar{B}^0 \to B^0$$

We search for CP violation using charge asymmetries in semileptonic decays of B_d^0 mesons at CLEO.

Our method takes advantage of

- coherently produced $B^0\bar{B}^0$ pairs from $\Upsilon(4S)$ decays
- high momentum leptons as a flavor tag at decay $(B^0 \to \ell^+ X)$
- high statistics – a factor of 10 over earlier analysis (1993)
- use of single lepton (a_ℓ) and dilepton asymmetries $(a_{\ell\ell})$ to reduce systematics

Experimental Method

Consider semileptonic decays:

A positively charged lepton is a flavor tag for a $B^0 \equiv (\bar{b}d)$ decay, $\bar{b} \to \bar{c}W^+$

In $\Upsilon(4S) \to B\bar{B}$ there are two B decays, so we define

Dilepton asymmetry:

$$a_{\ell\ell} \equiv \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} = \frac{4\Re e(\epsilon_B)(1+|\epsilon_B|^2)}{(1+|\epsilon_B|^2)^2 + 4\Re e(\epsilon_B)^2} \approx \frac{4\Re e(\epsilon_B)}{(1+|\epsilon_B|^2)}$$

Single lepton asymmetry:

$$a_{\ell} \equiv \frac{N(\ell^+) - N(\ell^-)}{N(\ell^+) + N(\ell^-)} = a_{\ell\ell}\chi_d \left[\frac{f_{00}\tau_0^2}{f_{00}\tau_0^2 + f_{+-}\tau_\pm^2}\right] \approx \frac{a_{\ell\ell}\chi_d}{2}$$

where the mixing parameter χ_d is

$$\chi_d \equiv \frac{N(B^0B^0) + N(\bar{B}^0\bar{B}^0)}{N(B^0B^0) + N(\bar{B}^0\bar{B}^0) + N(\bar{B}^0B^0)}$$

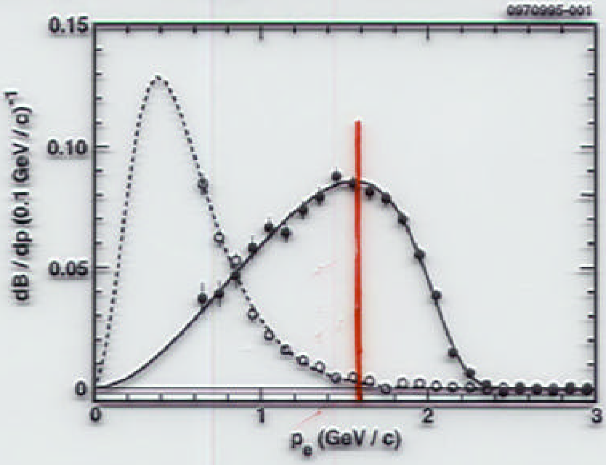
Of course the measured lepton asymmetry includes backgrounds from non-B^0 decays, resulting in dilution and a potential false asymmetry.

EVENT SAMPLE

We use CLEO II and CLEO II.V data samples: 9.1 fb^{-1} at $\Upsilon(4S)$ (10^7 $B\bar{B}$) and 4.4 fb^{-1} below $\Upsilon(4S)$

Lepton Selection:

- electron ID uses E/p, shower shape and dE/dx
- muon ID requires hits at $\geq 5\lambda_{int}$ in muon counters
- $1.6 < p_\ell < 2.4$ GeV/c to suppress ℓ from $b \to c \to \ell$



- J/ψ, ψ' veto and γ conversion veto
- In dilepton events $-0.8 < \cos\theta_{\ell\ell} < 0.9$

Background Subtraction:

- $e^+e^- \to q\bar{q}$ background using data taken below $\Upsilon(4S)$
- fake leptons measured using fake-rate scaled hadron sample

Left with single lepton and dilepton yields from $B\bar{B}$ events.

Measured Asymmetries

The measured asymmetries,

$$a_\ell^m \equiv \frac{N^m(\ell^+) - N^m(\ell^-)}{N^m(\ell^+) + N^m(\ell^-)}$$

$$a_{\ell\ell}^m \equiv \frac{N^m(\ell^+\ell^+) - N^m(\ell^-\ell^-)}{N^m(\ell^+\ell^+) + N^m(\ell^-\ell^-)}$$

include fake leptons and non-primary leptons.

Using

- the lepton identification and detection efficiency η
- the probability for a hadron to fake a lepton f

the number of measured leptons may be written

$$N^m(\ell^\pm) = \eta(\ell^\pm)N^0(\ell^\pm) + f(h^\pm)N^0(h^\pm).$$

Similarly for the dileptons:

$$N^m(\ell^\pm\ell^\pm) = \eta^2(\ell^\pm)N^0(\ell^\pm\ell^\pm) + \eta(\ell^\pm)f(h^\pm)N^0(h^\pm\ell^\pm) + f^2(h^\pm)N^0(h^\pm h^\pm)$$

The superscript 0 denotes the produced quantities.

Neglecting small terms we write the measured asymmetries as

$$a_\ell^m = \frac{d_\ell a_\ell^0 + a_\eta + r_0(a_h + a_f)}{1 + r_0}$$
$$a_{\ell\ell}^m = \frac{d_{\ell\ell}^{like} a_{\ell\ell}^0 + 2a_\eta + r_1(a_{\ell h} + a_f)}{1 + r_1}$$

where

- d_ℓ and $d_{\ell\ell}$ represent dilution from non-primary B decays.
  We determine these in MC & check by measuring χ_d.
  $d_\ell \approx 0.97$, $d_{\ell\ell}^{like} \approx 0.70$
- a_f is the charge asymmetry in the fake probabilities
  We measure this using well identified hadrons from our data
- $r_0/(1 + r_0)$ is the fraction of measured leptons which are fakes
- $r_1/(1 + r_1)$ is the fraction of measured dileptons with one fake
  $r_0 \approx 0.001(e)$, $0.02(\mu)$, $r_1 \approx 0.006(ee)$, $0.15(\mu\mu)$
- a_η is the charge asymmetry in lepton identification.
  Difficult to measure sufficiently well. Use a trick below.

Trick: We use the relationship

$$a_\ell^0 = \chi_d \left[f_{00}\tau_0^2 / (f_{00}\tau_0^2 + f_{+-}\tau_+^2) \right] a_{\ell\ell}^0$$

and the top equation to express a_η in terms of a_ℓ^m and $a_{\ell\ell}^0$.

We use this to eliminate a_η from the expression for $a_{\ell\ell}^m$, which we solve for $a_{\ell\ell}^0$.

$$a^0_{\ell\ell} = \frac{a^m_{\ell\ell}(1+r_1) - 2a^m_{\ell}(1+r_0) - (r_1 - 2r_0)a_f}{d^{like}_{\ell\ell} - 2d_\ell\chi_d\left[f_{00}\tau_0^2/(f_{00}\tau_0^2 + f_{+-}\tau_+^2)\right]}$$

The procedure is carried out separately for five types of dilepton pairs (ee, μe, $\mu\mu$, $\mu e'$ and ee').

e' denotes electron candidates in the endcap region, where fake rates and efficiency differ from the barrel region.

Sample	++ Yield	−− Yield	Like-sign Asymmetry
$\mu\mu$	286 ± 19	286 ± 19	$+0.000 \pm 0.046$
ee	205 ± 17	175 ± 16	$+0.079 \pm 0.062$
μe	500 ± 25	505 ± 25	-0.004 ± 0.035
$\mu e'$	163 ± 16	126 ± 15	$+0.128 \pm 0.078$
ee'	103 ± 19	112 ± 20	-0.042 ± 0.128
combined			$+0.013 \pm 0.050$

With a similar trick we can write an expression for χ_d.

We find $\chi_d = 0.175 \pm 0.008$ in good agreement with the PDG2000 average $\chi_d = 0.174 \pm 0.009$.

We do *not* claim a new measurement of B^0_d mixing with this data.

But we use this agreement to set the uncertainty on our dilution factor $d_{\ell\ell}$ at 7%.

Systematic Uncertainties

Uncertainties on $a^0_{\ell\ell}$

Additive Systematic	
Source	**Size**
a_η	± 0.0030
Hadron fake rate	± 0.0037
On-Off subtraction	± 0.0020
Charge dependent momentum scale	± 0.0006
Total additive systematic	± 0.0050

Multplicative Systematic	
Source	**Size**
Dilution $d^{\text{like}}_{\ell\ell}$	7.0%
χ_d	1.7%
On-Off subtraction	1.7%
Total multiplicative systematic	10.0%

RESULTS

Our dilepton analysis gives:

$$a^0_{\ell\ell} = (+0.013 \pm 0.050 \pm 0.005)(1.00 \pm 0.10)$$

Combining with our hadronic tag analysis which found (PLB **490**, 36 (2000)):

$$a^0_{\ell\ell} = +0.017 \pm 0.070 \pm 0.014$$

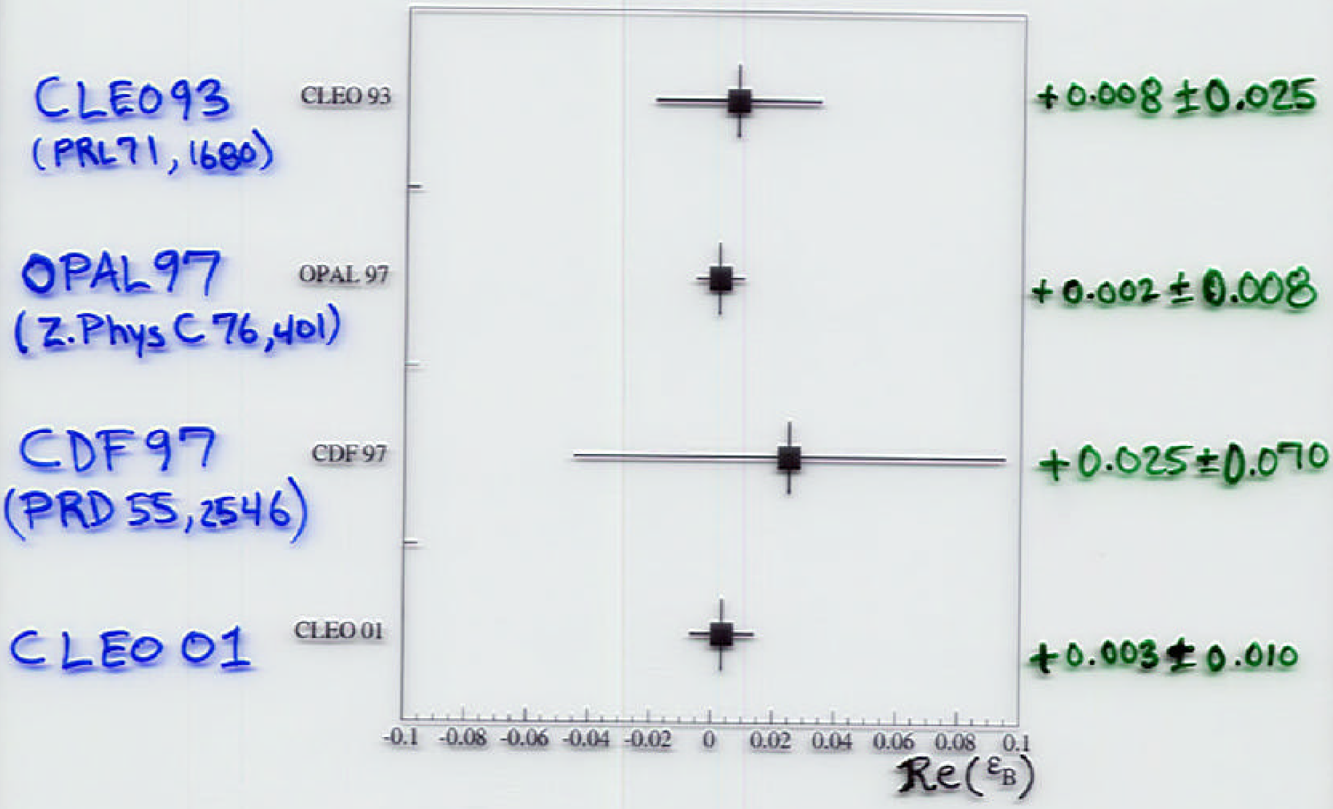
We measure:

$$\frac{\Re e(\epsilon_B)}{1 + |\epsilon_B|^2} = +0.0035 \pm 0.0103 \pm 0.0015$$

CLNS 01-1717, CLEO 01-01 (hep-ex/0101006), submitted to PRL

Status of ϵ_B

Comparison with other measurements from CDF and OPAL.



Conclusions

- Our new result is competitive without any assumption about CPV in B_s^0 mixing (ϵ_{B_s}), made by non-$\Upsilon(4S)$ experiments.
- Our technique is statistics limited and appropriate for use with much larger datasets.

EXTRACTING $|V_{cb}|$ FROM $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$

The partial width is proportional to $|V_{cb}|^2$:

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3}|V_{cb}|^2[\mathcal{F}(w)]^2\mathcal{G}(w)$$

$$w = v_B \cdot v_{D^*} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$$

For $D^*\ell\nu$, w runs from 1 to 1.5.

$$\mathcal{G}(w) = m_{D^*}^3(m_B - m_{D^*})^2\sqrt{w^2-1}(w+1)^2\left[1 + \frac{4w}{w+1}\frac{1-2wr+r^2}{(1-r)^2}\right]$$

with $r = m_{D^*}/m_B$

- $\mathcal{G}(w)$ contains kinematic factors and is *known*
- $\mathcal{F}(w)$ is the form factor describing $B \to D^*$ transition
  - HQET relations simplify the most general form factor V, A_i
  - absolutely normalized at zero recoil ($w = 1$)
  - As $m_Q \to \infty$, $\mathcal{F}(1) \to 1$; corrections of order $1/m_Q^2$

The plan is to measure $d\Gamma/dw$ and extrapolate to $w = 1$ to extract $\mathcal{F}(1)|V_{cb}|$. We divide the data into ten bins of w and measure the $D^{*+}\ell\nu$ yield.

$D^*\ell\nu$ Form Factor

The form factor is parameterized in HQET as

$$\mathcal{F}(w) = h_{A_1}(w)\sqrt{\frac{\tilde{H}_0^2+\tilde{H}_+^2+\tilde{H}_-^2}{1+4\frac{w}{w+1}\frac{1-2wr+r^2}{(1-r)^2}}}.$$

Helicity Form Factors:

$$\tilde{H}_0(w) = 1+\frac{w-1}{1-r}(1-R_2(w))$$
$$\tilde{H}_\pm(w) = \frac{\sqrt{1-2wr+r^2}}{1-r}\left(1\mp\sqrt{\frac{w-1}{w+1}}R_1(w)\right)$$

Form Factor Ratios: (measured by CLEO PRL **76**, 3898)
in agreement with HQET

$$R_1(w) \equiv h_V(w)/h_{A_1}(w) \approx 1.2$$
$$R_2(w) \equiv (h_{A_3}(w)+rh_{A_2}(w))/h_{A_1}(w) \approx 0.7$$

$h_{A_1}(w)$ may be expanded in a Taylor series around $w=1$:

$$h_{A_1}(w) = h_{A_1}(1)(1-\rho^2_{h_{A_1}}(w-1)+\ldots)$$

Alternatively dispersion relations may be used to constrain the functional form of $h_{A_1}(w)$. (Boyd *et al.*; Caprini *et al.*)

HQET also provides a robust prediction for the normalization at $w=1$: (PLB**264**,455; **338**,84; PRD**47**,2965; **51**,2217; **52**, 3149; PRL **76**, 4124)

$$\mathcal{F}(1) = h_{A_1}(1) = 0.913 \pm 0.042$$

BaBar Book

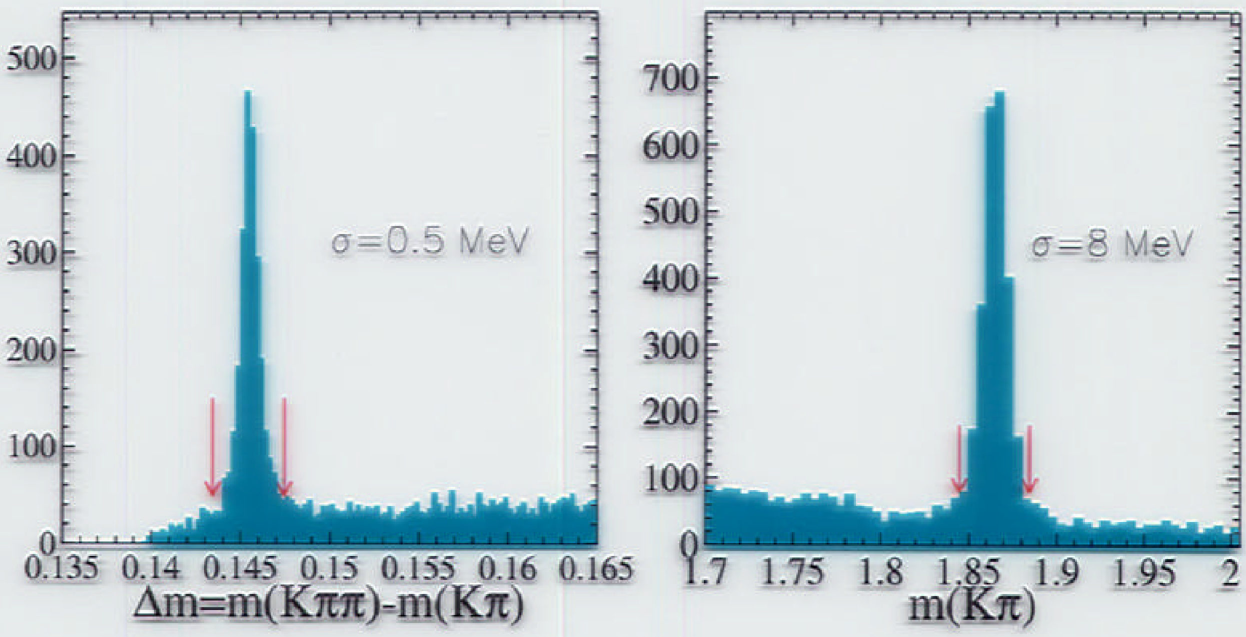
c.f. Lattice 0.935 ± 0.035
Simone et al.

EXPERIMENT

We begin with 3.3 Million $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ events collected using the CLEO II detector at the symmetric collider CESR.

We fully reconstruct D^{*+} candidates in the decay chain

$D^{*+} \to D^0\pi^+$ $\quad$ $D^0 \to K^-\pi^+$



We reconstruct and identify lepton (e or μ) candidates using cylindrical drift chambers and a crystal calorimeter and muon counters.

We require p_e=0.8–2.4 GeV/c and p_μ=1.4–2.4 GeV/c.

Signal and Backgrounds

The D^* ℓ pairs may come from different sources:

- $D^*\ell\nu$ events
- $D^*X\ell\nu$ events including $D^{**}\ell\nu$ and $D^*\pi\ell\nu$
- combinatoric background ($\sim 6\%$)
  - fake D^{*+} candidates
  - estimated from events in the Δm sideband.
- continuum background ($\sim 4\%$)
  - from $e^+e^- \to q\bar{q}$
  - subtracted using data below the $B\bar{B}$ threshold
- uncorrelated background ($\sim 4\%$)
  - real D^{*+} and ℓ from different B's
  - estimated using MC normalized by inclusive D^{*+} and ℓ yields
- correlated background ($\sim 0.5\%$)
  - real D^{*+} and ℓ from same B
  - *e.g.* $B \to D^*D_s$ with $D_s \to \ell X$
  - estimated using MC

We fit for $D^*\ell\nu$ and $D^*X\ell\nu$ after subtracting other sources of D^{*+} ℓ pairs.

We separate $D^*\ell\nu$ and backgrounds from $D^*X\ell\nu$ using kinematics.

$$\cos\theta_{B-D^*\ell} = \frac{2E_B E_{D^*\ell} - M_B^2 - M_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}$$

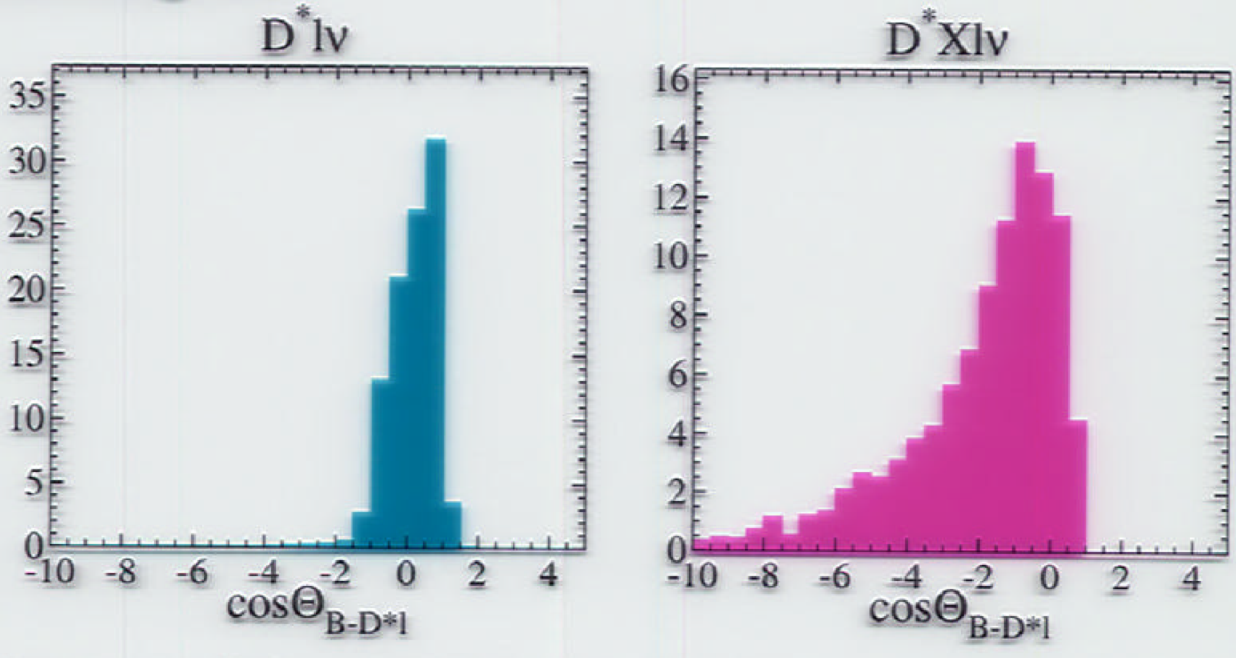
$\cos\theta_{B-D^*\ell}$ can be determined using 4-momentum conservation,

$$p_B = (p_{D^*} + p_\ell) + p_\nu,$$

and the constraints

$$p_\nu^2 = m_\nu^2 = 0 \quad \text{and} \quad E_B = \sqrt{p_B^2 + m_B^2} = E_{\text{beam}}.$$

For signal events, $\cos\theta_{B-D^*\ell} \in (-1, 1)$, allowing separation of $D^*\ell\nu$ from background.



We separate $D^*\ell\nu$ and $D^*X\ell\nu$ events by fitting $\cos\theta_{B-D^*\ell}$.

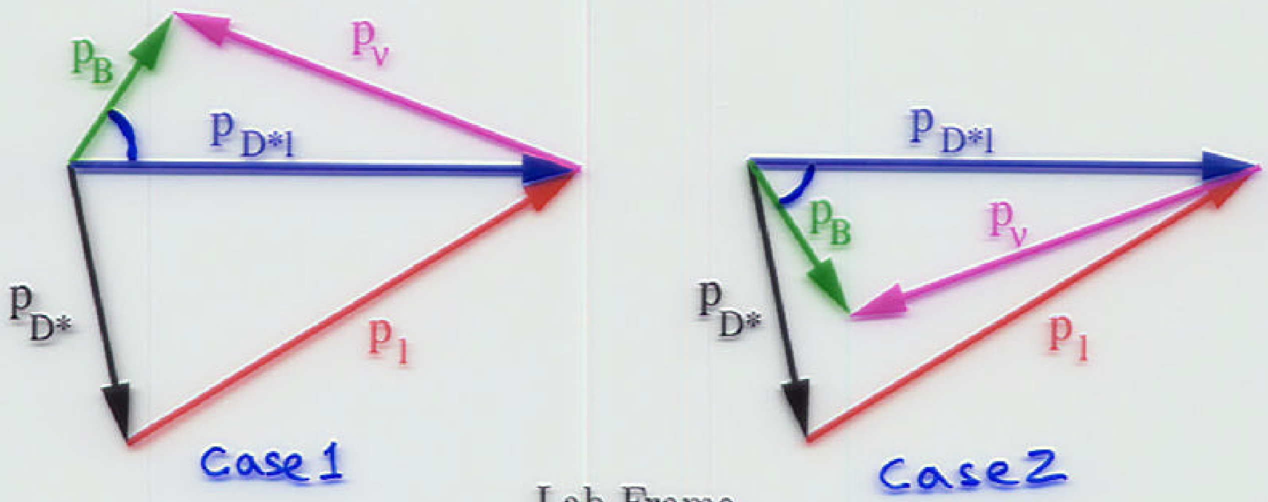
MEASURING w

$w \in (1, 1.51)$ is the Lorentz boost of the D^* in the B rest frame.

At symmetric colliders, the B's are nearly at rest: $p_B \approx 300$ MeV/c.

We know the magnitude but not the direction of the B momentum. It is determined up to an azimuthal ambiguity.

We compute w using the two extreme possibilities for the B direction in the lab frame and boost the D^* to the B rest frame.



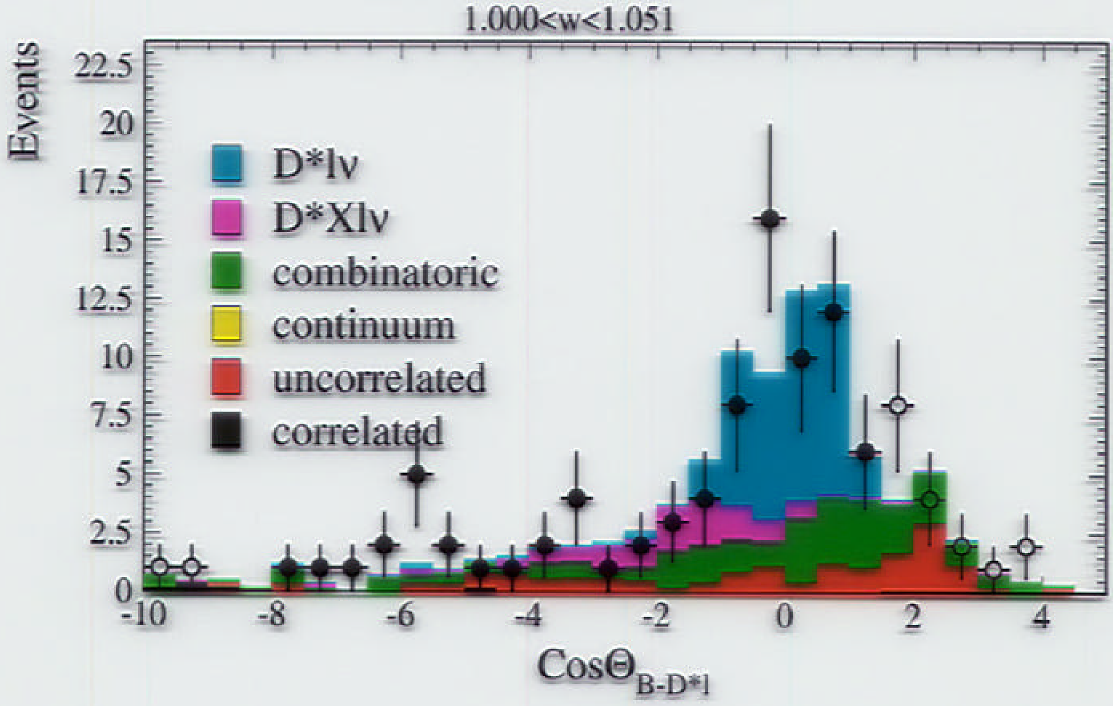
Lab Frame

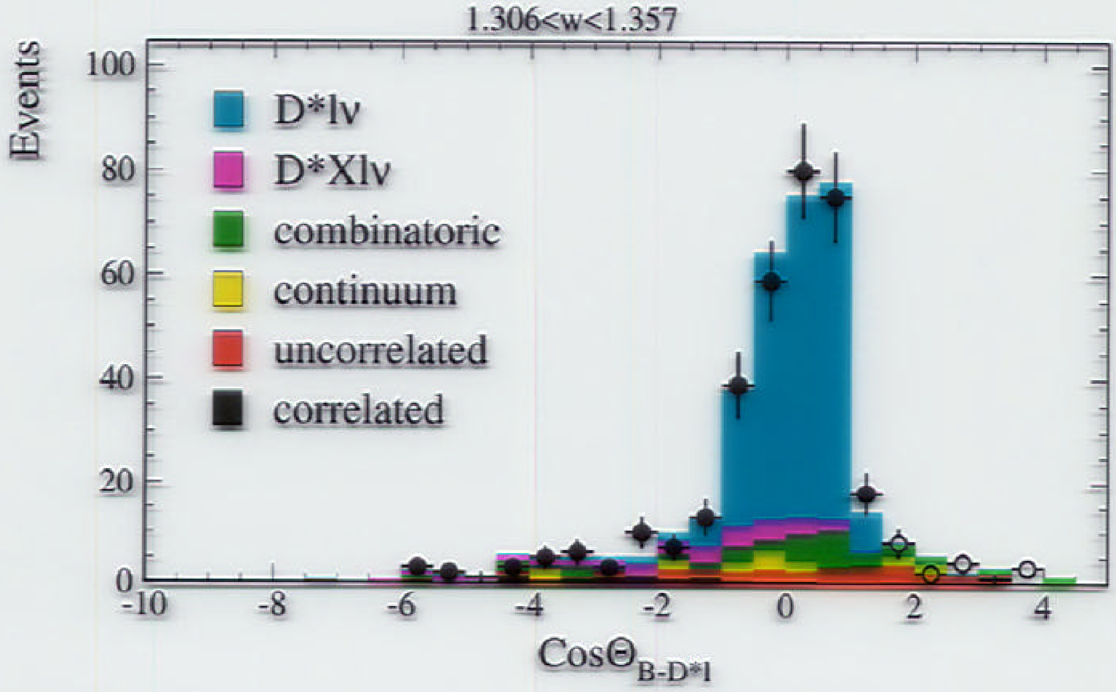
Take the mean w of the two cases

The resolution with this method is $\sigma_w \approx 0.03$

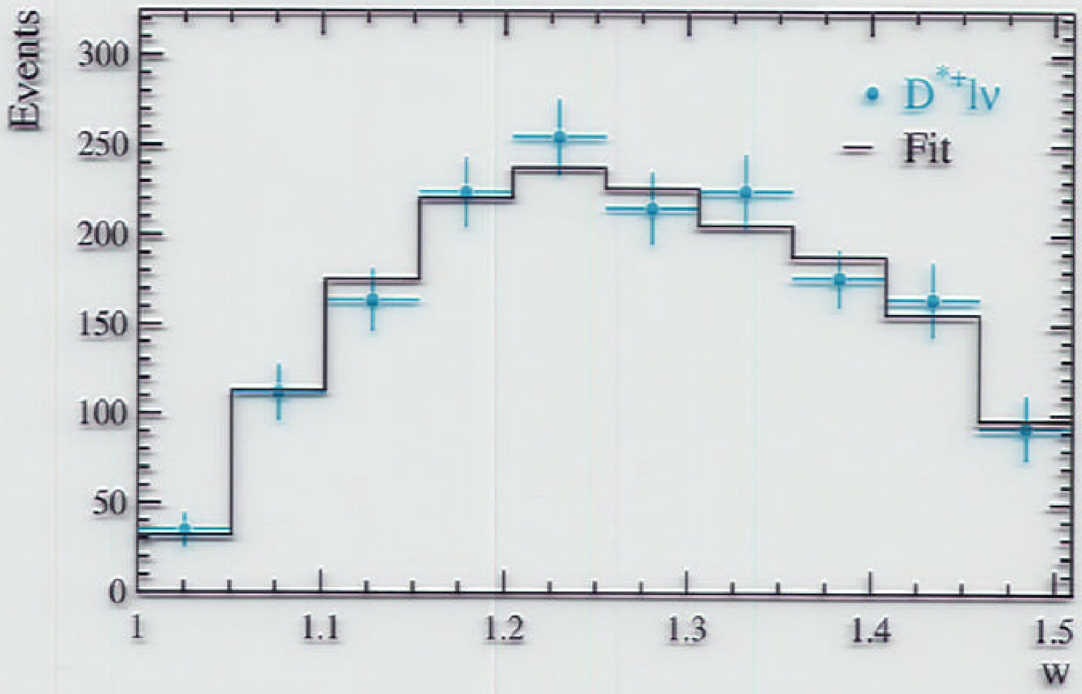
We measure $d\Gamma/dw$ by fitting $\cos\theta_{B-D^*\ell}$ for the yield of $D^*\ell\nu$ events in ten bins of w.

Representative Fits





FITTING $d\Gamma/dw$



$$\chi^2 = \sum_{i=1}^{10} \frac{[N_i^{obs} - \sum_{j=1}^{10} \epsilon_{ij} N_j]^2}{\sigma^2_{N_i^{obs}}}$$

N_i^{obs} = yield in the i^{th} w bin

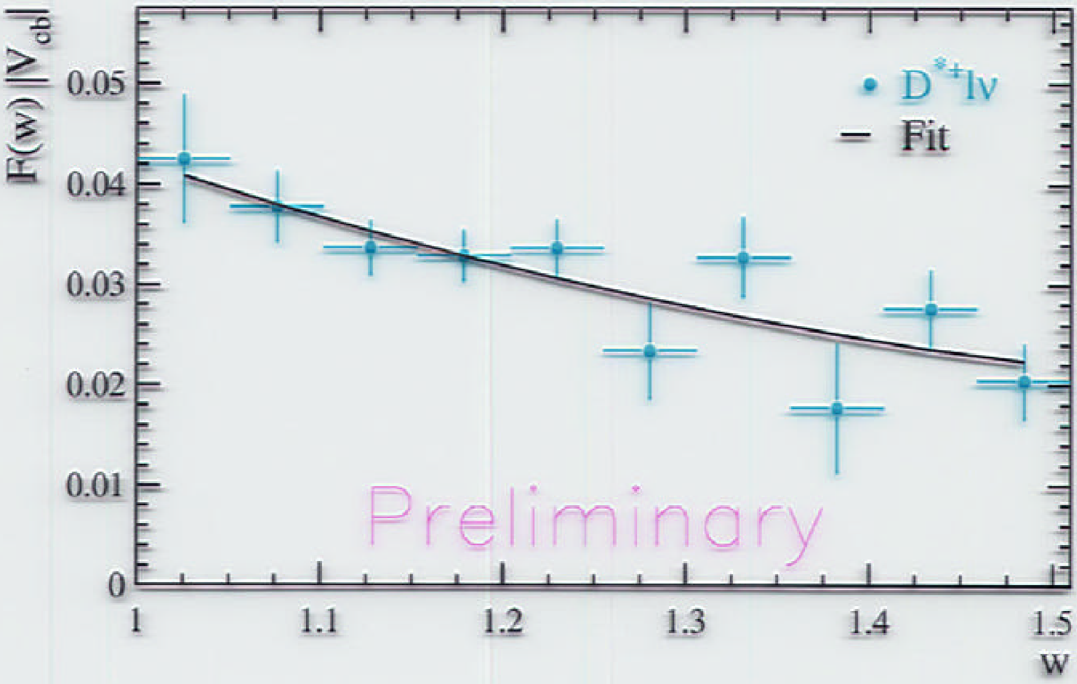
N_j = number of decays in the j^{th} w bin

ϵ_{ij} accounts for the reconstruction efficiency and the smearing in w.

$$N_j \;= 4 f N_{\Upsilon(4S)} \mathcal{B}(D^* \to D\pi) \mathcal{B}(D \to K\pi) \tau_B \int_{w_j} dw \; (d\Gamma/dw)$$

We use the form factor of Caprini, Lellouch, Neubert (NP**B**530, 153) and fit for $\mathcal{F}(1)|V_{cb}|$ and $\rho^2_{h_{A_1}}(w=1)$.

FIT RESULTS



The fit gives

$$\mathcal{F}(1)|V_{cb}| = (42.4 \pm 1.8 \pm 1.9) \times 10^{-3}$$
$$\rho^2_{h_{A_1}} = (1.67 \pm 0.11 \pm 0.22),$$

with correlation coefficient $C(\mathcal{F}(1)|V_{cb}|, \rho^2) = 0.90$.

Integrating $d\Gamma/dw$ we find

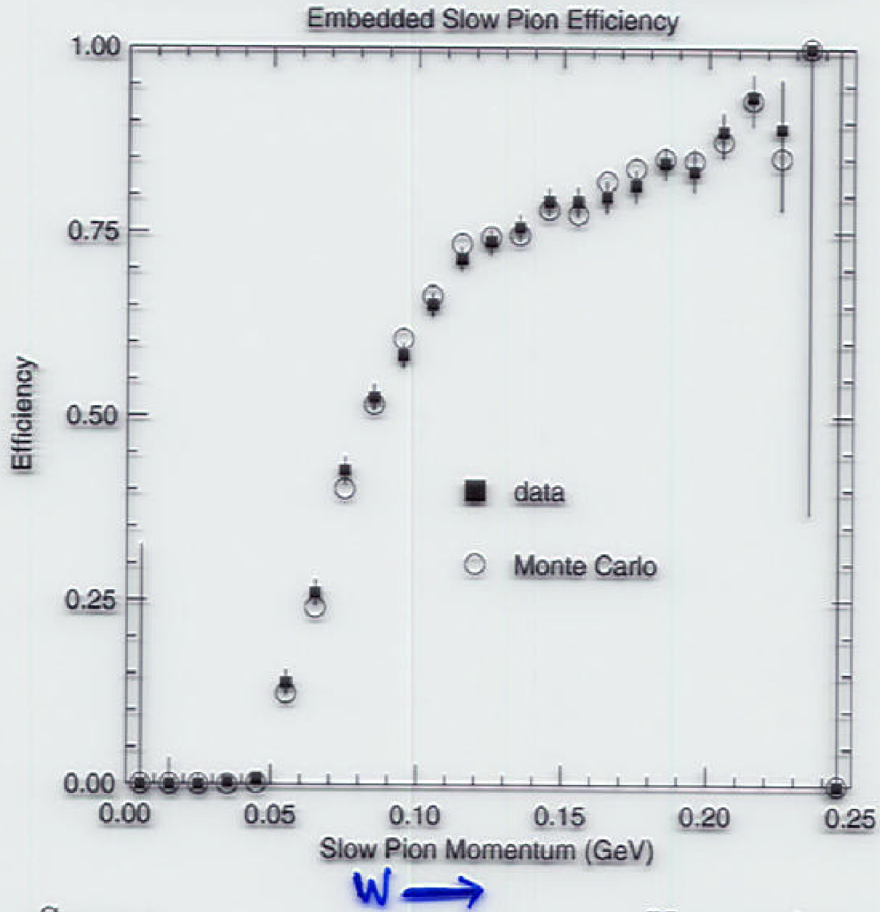
$$\Gamma(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}) = (0.0366 \pm 0.0018 \pm 0.0023)\ \mathrm{ps}^{-1}$$
$$\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}) = (5.66 \pm 0.29 \pm 0.33)\%$$

Preliminary

Systematic Errors

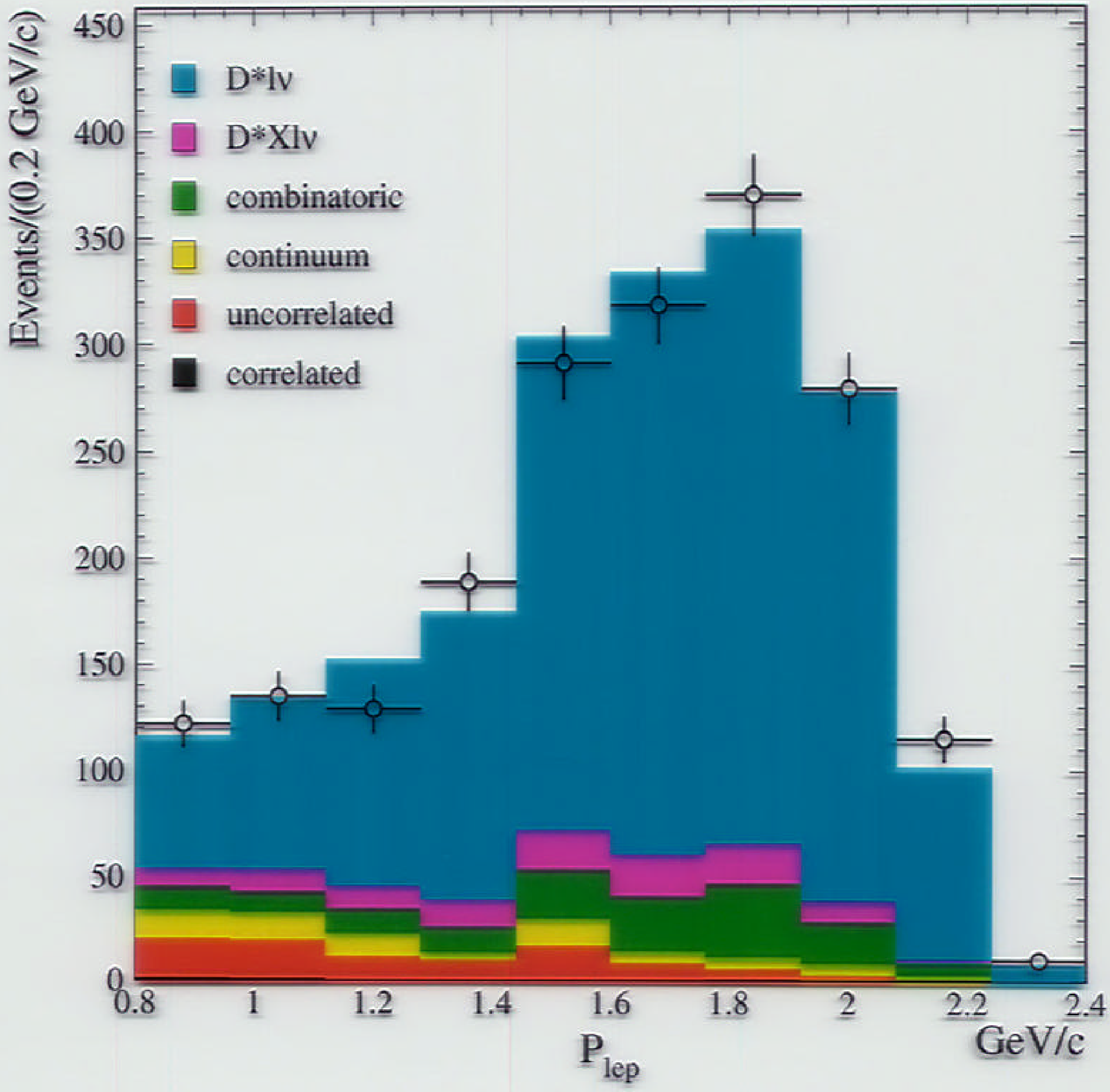
Source	$\lvert V_{cb}\rvert \mathcal{F}(1)(\%)$	$\rho^2(\%)$	$\Gamma(B \to D^*\ell\nu)(\%)$
Slow π finding	3.1	3.7	2.9
Combinatoric Bkgd	1.4	1.8	1.2
Lepton ID	1.1	0.0	2.1
K, π &ℓ finding	1.0	0.0	1.9
Number of $B\bar{B}$ events	0.9	0.0	1.8
Uncorrelated Bkgd	0.7	0.9	0.7
Correlated Bkgd	0.4	0.3	0.5
B momentum & mass	0.3	0.5	0.4
$D^*X\ell\nu$ model	0.2	1.9	1.9
Subtotal	3.8	4.7	5.0
$R_1(1)$ and $R_2(1)$	1.4	12.0	1.8
$B(D \to K\pi)$	1.2	0.0	2.3
τ_B	1.0	0.0	2.1
$B(D^* \to D\pi)$	0.4	0.0	0.7
Subtotal	2.2	12.0	3.7
Total	**4.4**	**13**	**6.2**

SLOW π EFFICIENCY



Source	Uncertainty
event environment	1.7%
amount of material in detector	2.3%
hit resolution	0.3%
charge division	0.8%
hit efficiency	0.8%
Total	3.1%

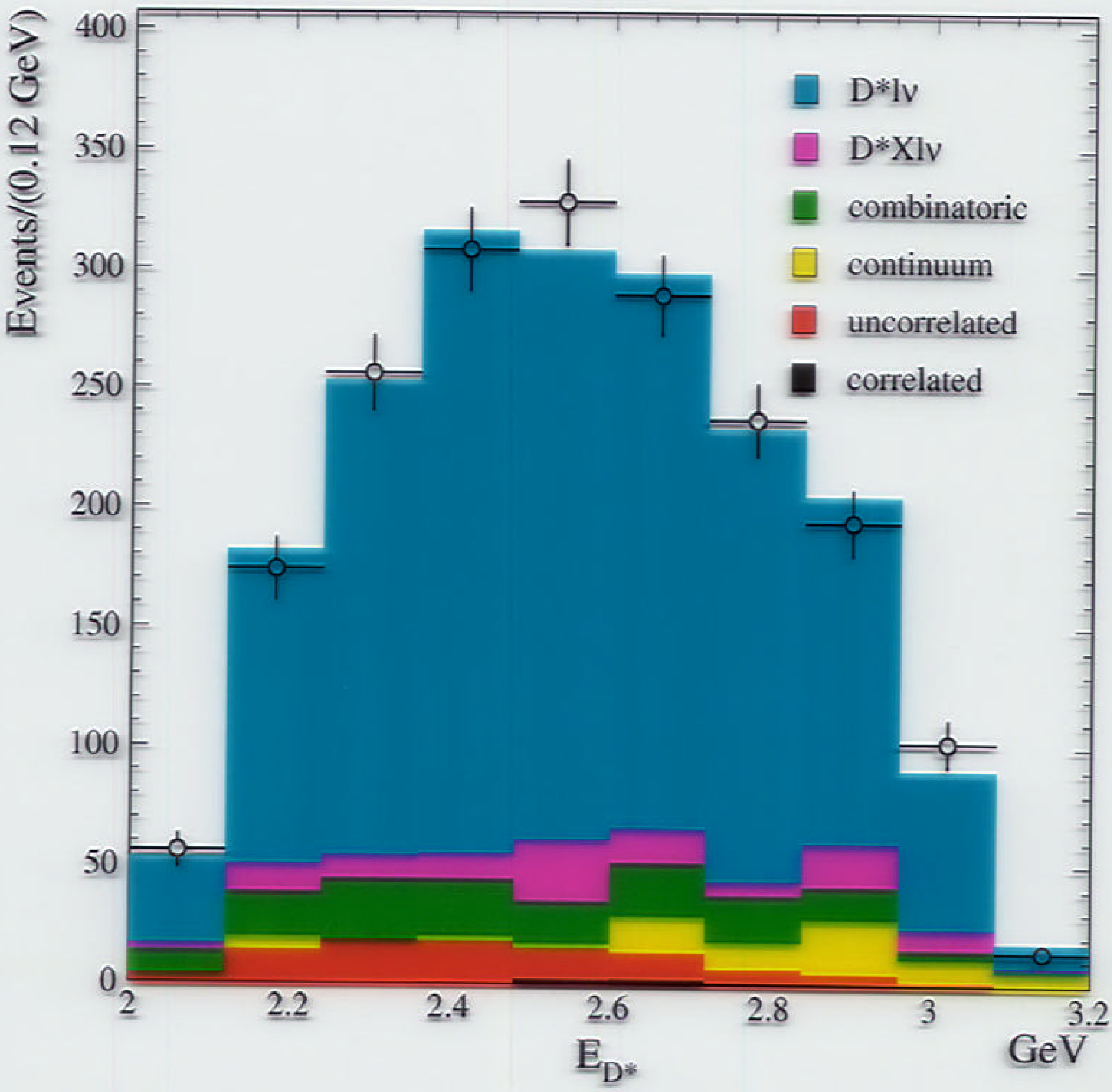
Lepton Spectrum



Comparison of lepton spectrum in fit and data for $|\cos\theta_{B-D^*\ell}| < 1$.

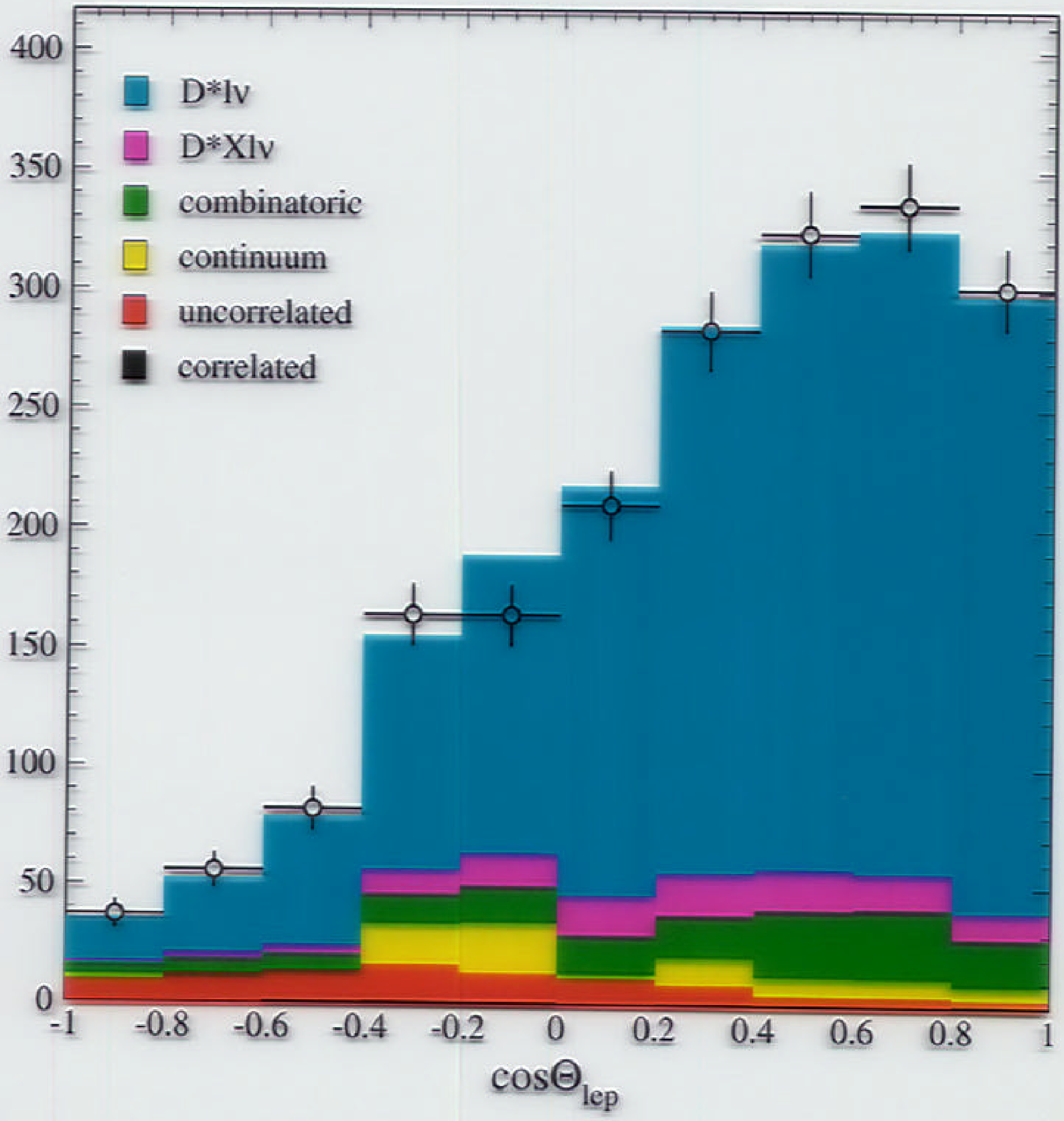
Note p_ℓ is *not* used in fit.

D^* SPECTRUM



Comparison of D^* energy spectrum in fit and data for $|\cos\theta_{B-D^*\ell}| < 1$.

$\cos\theta_\ell$ DISTRIBUTION



Angular distribution of lepton in W rest frame from fit and data for $|\cos\theta_{B-D^*\ell}| < 1$.

Conclusion and Summary

We measure

$$\mathcal{F}(1)|V_{cb}| = (42.4 \pm 1.8 \pm 1.9) \times 10^{-3}$$
$$\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}) = (5.66 \pm 0.29 \pm 0.33)\%$$

From theory

$$\mathcal{F}(1) = 0.913 \pm 0.042,$$

which gives

$$|V_{cb}| = (46.4 \pm 2.0 \pm 2.1 \pm 2.1) \times 10^{-3}$$

Preliminary

I have presented a measurement of $\mathcal{F}(1)|V_{cb}|$ with a

- statistical error 4.2%
- systematic error 4.4%

STATUS OF $|V_{cb}|$

These results are

- consistent with CLEO's 1995 measurement
  - take into account difference in form factor
  - additional data prefers larger $\mathcal{F}(1)|V_{cb}|$
- comparable to LEP exclusive measurements but larger

OUTLOOK

CLEO II:

Since ICHEP in Osaka

- working to include $D^{*0}\ell\nu$
- validating systematic uncertainties - increased confidence in analysis
- no significant changes to results

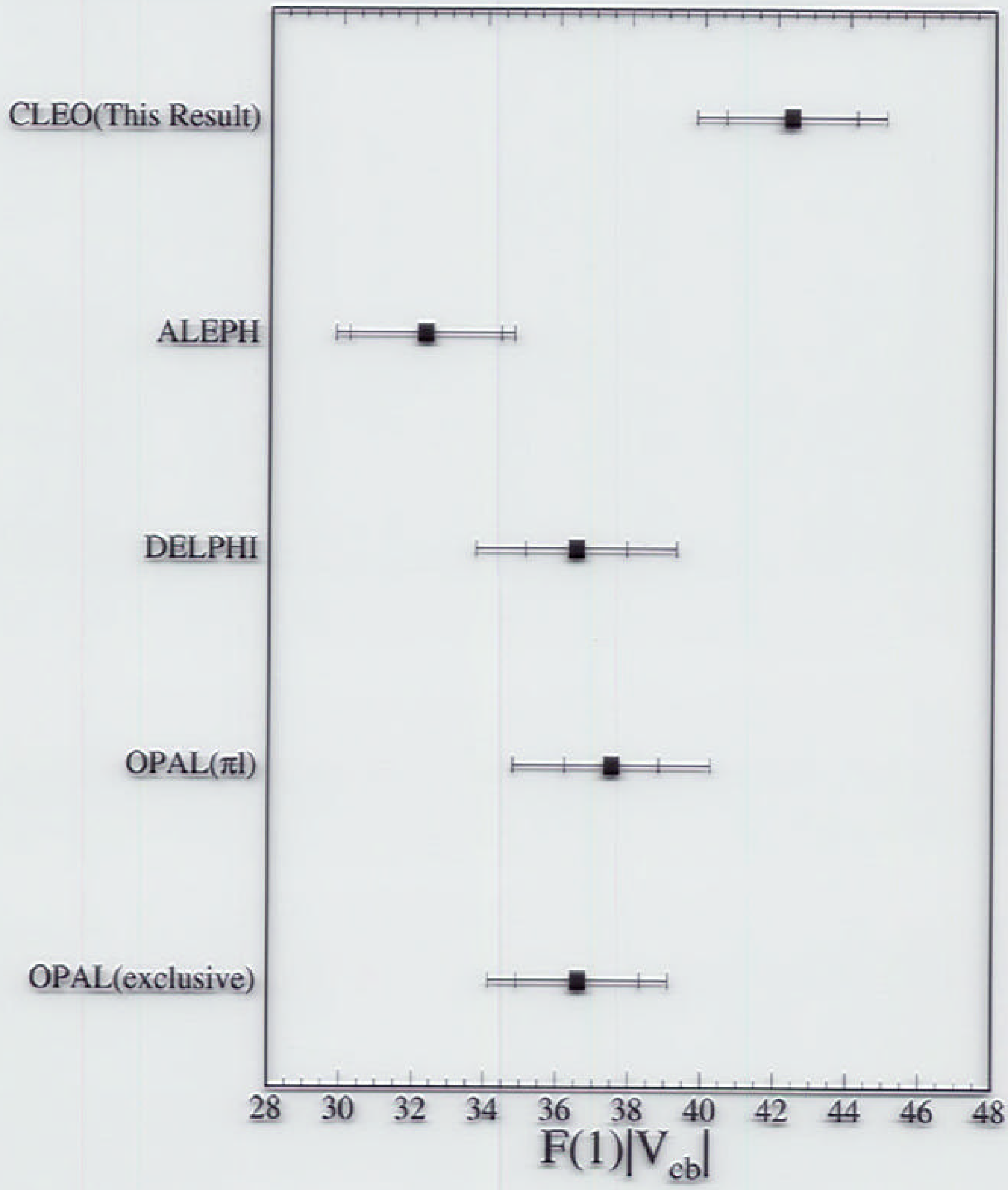
Combined results expected soon

Future:

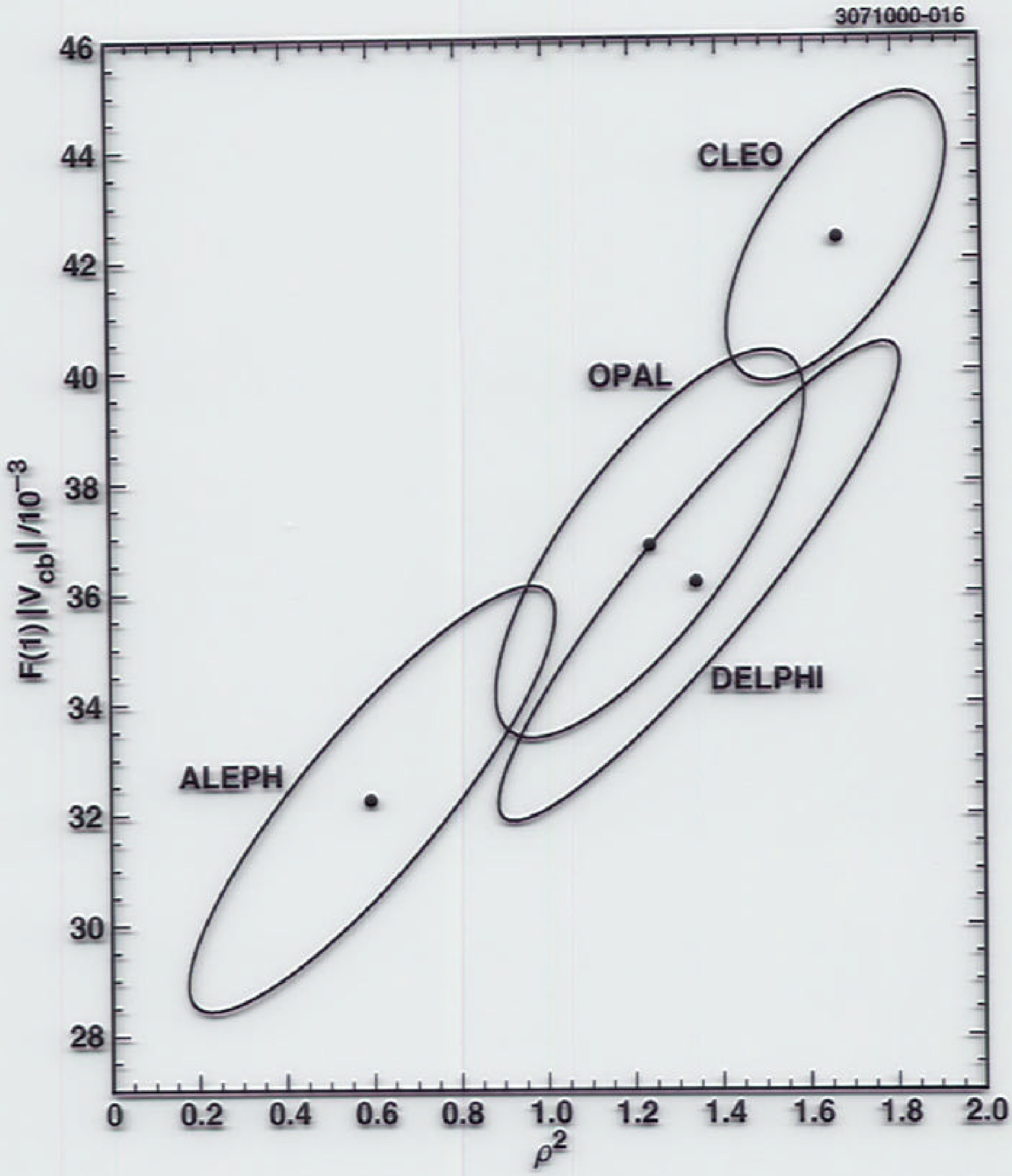
- CLEO II.V factor of 2 more data: 6.7 million $B\bar{B}$
- B factories even more data

Systematics limited analysis, progress will come, but with much effort.

Status of $\mathcal{F}(1)|V_{cb}|$ from exclusive $B \to D^*\ell\nu$



(LEP results courtesy of the LEP $|V_{cb}|$ working group, July 2000)



Note the correlation between $\mathcal{F}(1)|V_{cb}|$ and ρ^2.

Consistency among all four at 7% C.L.

Status as of Summer 2000

COMMENTS ON LEP/CLEO $D^*\ell\nu$

Differences in experiments:

- CLEO has better w resolution $\sigma_w \sim 0.03$
  ALEPH (best at LEP) ~ 0.07
- LEP is more efficient at low w (better slow π efficiency)

$B \rightarrow D^* X \ell\nu$ is not well known

- CLEO fits for $D^* X \ell\nu$ modes
- LEP uses model of Leibovich *et al.* (PRD **57**,308 (1997)), also constrained by measurements
- CLEOs yield of $D^* X \ell\nu$ is lower than expected from other measurements, but consistent
- If $D^* X \ell\nu \downarrow$ then $D^*\ell\nu$ and $|V_{cb}| \uparrow$

Final comments:

- Final CLEO results will include $D^{*0}\ell\nu$
- Data from B factories will be very helpful

The first moments of the hadronic mass-squared distribution in $B \to X_c \ell \nu$ and the photon energy spectrum in $b \to s\gamma$ give:

To order $(\alpha_s)^2 \beta_0$ — Thanks to Adam Falk

0.38

$$\bar{\Lambda} = 0.469 \pm 0.060 \pm 0.015 \,,$$

$$\lambda_1 = -0.302 \pm 0.059 \pm 0.056 \,.$$

-0.23 — moments — $1/M^3$

These in turn give:

$$|V_{cb}| = 0.0401 \pm 0.0009 \pm 0.0006 \pm 0.0004 \,.$$

0.0413 — Γ_{sl} — $\bar{\Lambda}, \lambda_1$ — $1/M^3$

$|V_{cb}|$ STATUS

CLEO Inclusive $|V_{cb}|$: (New syst. from α_s added)

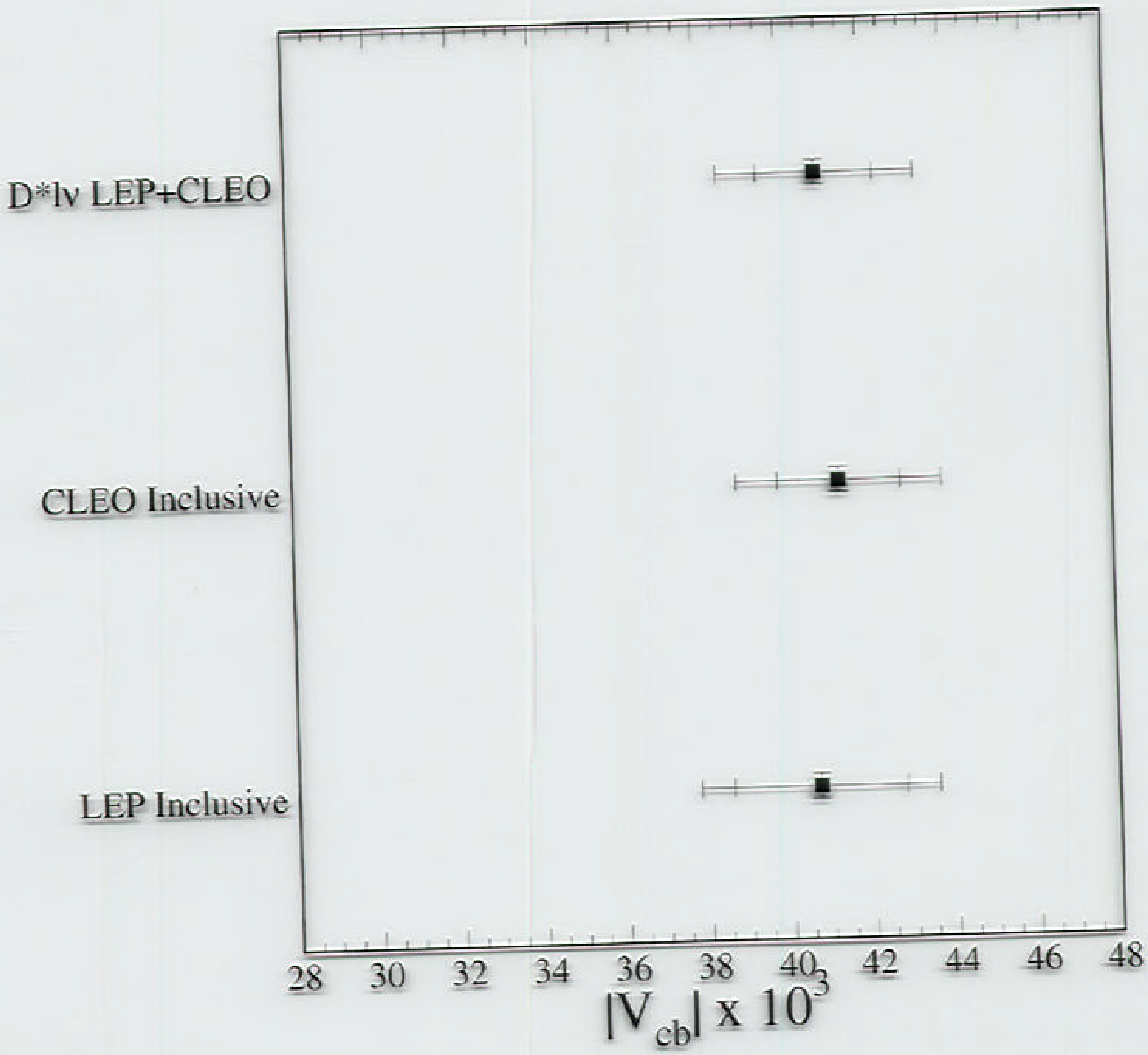
$$|V_{cb}| = (41.3 \pm 0.9 \pm 0.6 \pm 0.4 \pm 1.0) \times 10^{-3}$$
$$= (41.3 \pm 0.9 \pm 1.2) \times 10^{-3}$$

The above does not include theory uncertainty for quark-hadron duality assumption.

Estimate at 5% giving

$|V_{cb}| = (41.3 \pm 1.5$ expt. ± 2.0 theory$) \times 10^{-3}$

CLEO + LEP $D^*\ell\nu$	$\lvert V_{cb}\rvert = (40.9 \pm 1.4 \pm 1.9) \times 10^{-3}$
CLEO Inclusive	$\lvert V_{cb}\rvert = (41.3 \pm 1.5 \pm 2.0) \times 10^{-3}$
LEP Inclusive	$\lvert V_{cb}\rvert = (40.7 \pm 2.1 \pm 2.0) \times 10^{-3}$



- Good consistency, but
- Too soon to average inclusive and exclusive
- Must understand theory correlations