CLEO Measurements of the CKM Elements $|V_{ub}|$ and $|V_{cb}|$

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Outline

- Current Situation
- How to Measure $|V_{q_1 q_2}|$
- B's at CLEO
- Getting $|V_{cb}|$ From $B \to D^* \ell \nu$
- Getting $|V_{ub}|$ From $B \to \pi/\rho/\omega/\eta\ \ell\nu$
- Summary and Outlook

Status of $|V_{ub}|$ and $|V_{cb}|$

Unitary CKM matrix describes mixing between quark mass eigenstates in (charged-current) weak interactions

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

- PDG 00 values:

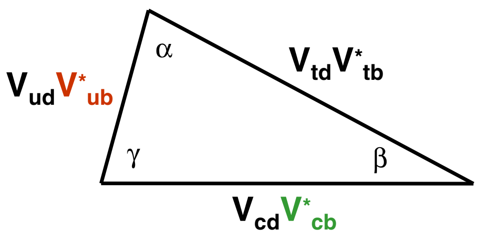
$$|V_{cb}| = 0.0402 \pm 0.0019 \quad \text{and} \quad |V_{ub}| = (3.6 \pm 1.0) \times 10^{-3}$$

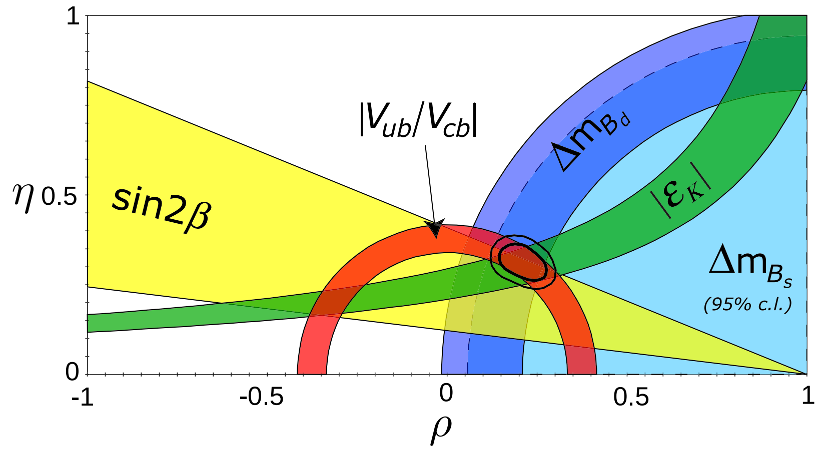
- Note **4.7**% error on $|V_{cb}|$
  - ▸ Third most accurately measured CKM element
    (After $|V_{ud}|$ and $|V_{us}|$)
  - ▸ From exclusive $B \to D^{(*)}\ell\nu$, inclusive $b \to c$
    (CLEO, LEP)
- And **28**% error on $|V_{ub}|$!
  - ▸ Based primarily on lepton endpoint measurements
  - ▸ Agrees with CLEO measurements of $B \to \pi/\rho\,\ell\nu$
    And values from LEP $b \to u\,\ell\nu$
- Branching fractions

$$\mathcal{B}(b \to c\,\ell\nu) \;=\; 10.5\% \quad ☺$$
$$\mathcal{B}(b \to u\,\ell\nu) \;\sim\; 2 \times 10^{-3} \quad ☹$$

Interest in $|V_{ub}|$ and $|V_{cb}|$

Unitarity property (constraint) leads to famous triangle in complex plane when applied to d and b columns





Only this combination produces triangle with all sides of same order $\mathcal{O}(\lambda^3)$

CKM elements *define* Standard Model (SM)

- $|V_{q_1 q_2}|$ simply sets scale for all $q_2 \to q_1$ transitions
- Area of triangle measures CP violation within SM

  $\Rightarrow$ Sides—and angles—probe $\not{C}$P

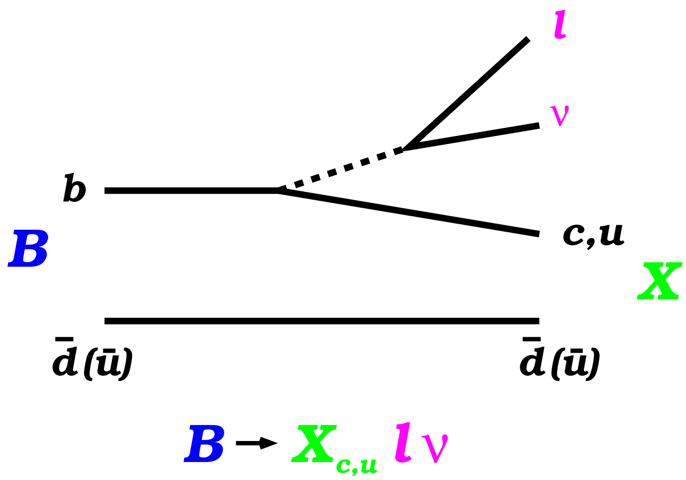
- $|V_{ub}|$ sets bound on apex $\rho^2 + \eta^2$, $|V_{cb}|$ sets scale of base

Also provide window for *testing* it

- *Over-constrain* triangle—stress-test the theory
- Tests of unitarity $\Leftrightarrow$ Sensitivity to new physics

Experimental measurement, however, is non-trivial . . .

SEMILEPTONIC B DECAY

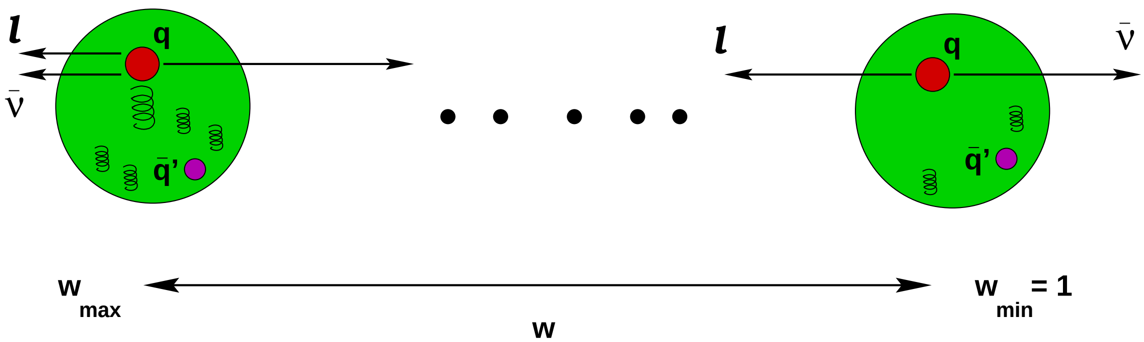


Good place to study $b \to c$, u transitions

- Leptonic physics understood and calculable
- Hadronic physics unknown—but can be parameterized with *form factors*
  - √ Constraints from HQET, other symmetries
  - √ Universal to some extent
  - × Model-dependent

Semileptonic B Decay—Kinematics

View as $b \to Wq$, $W \to \ell\nu$



Kinematic variables

- w: Lorentz boost γ of X in B rest frame

$$w = v_B \cdot v_X$$

- q^2: Mass of virtual W, 4-mom transfer to $\ell\,\nu$ pair

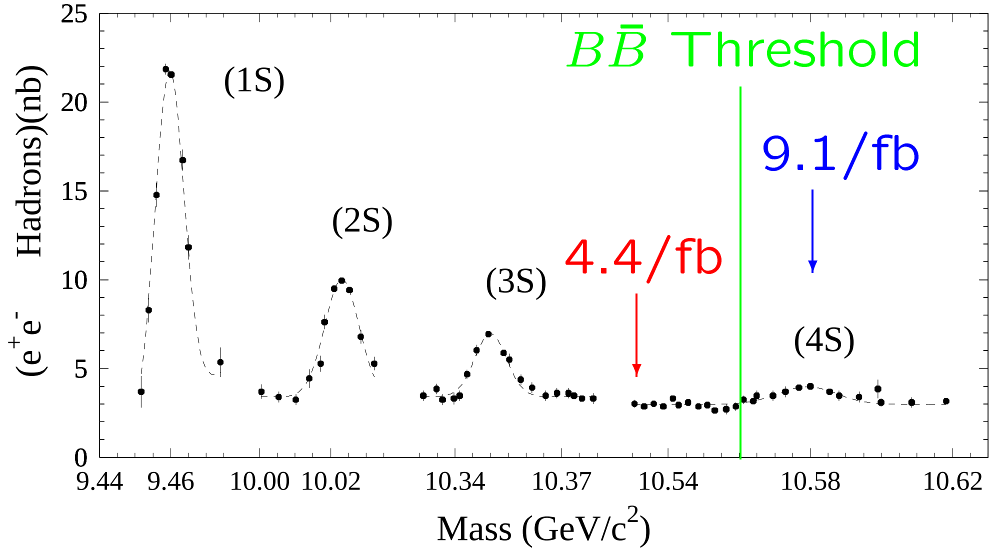
$$q^2 = (p_\nu + p_\ell)^2 = (p_B - p_X)^2$$

At $w = 1$ (q^2_{max}), daughter quark q *does not recoil*

For heavy q, light degrees of freedom (q' + gluons) unaware of $b \to q$ transition (Heavy Quark Symmetry)

$\Rightarrow$ Theoretical calculation on sound footing

B's at CLEO



- Symmetric $e^+ \, e^-$ machine
  - Operates on $\Upsilon(4S)$ resonance
  - $B\bar{B}$ pairs produced at threshold

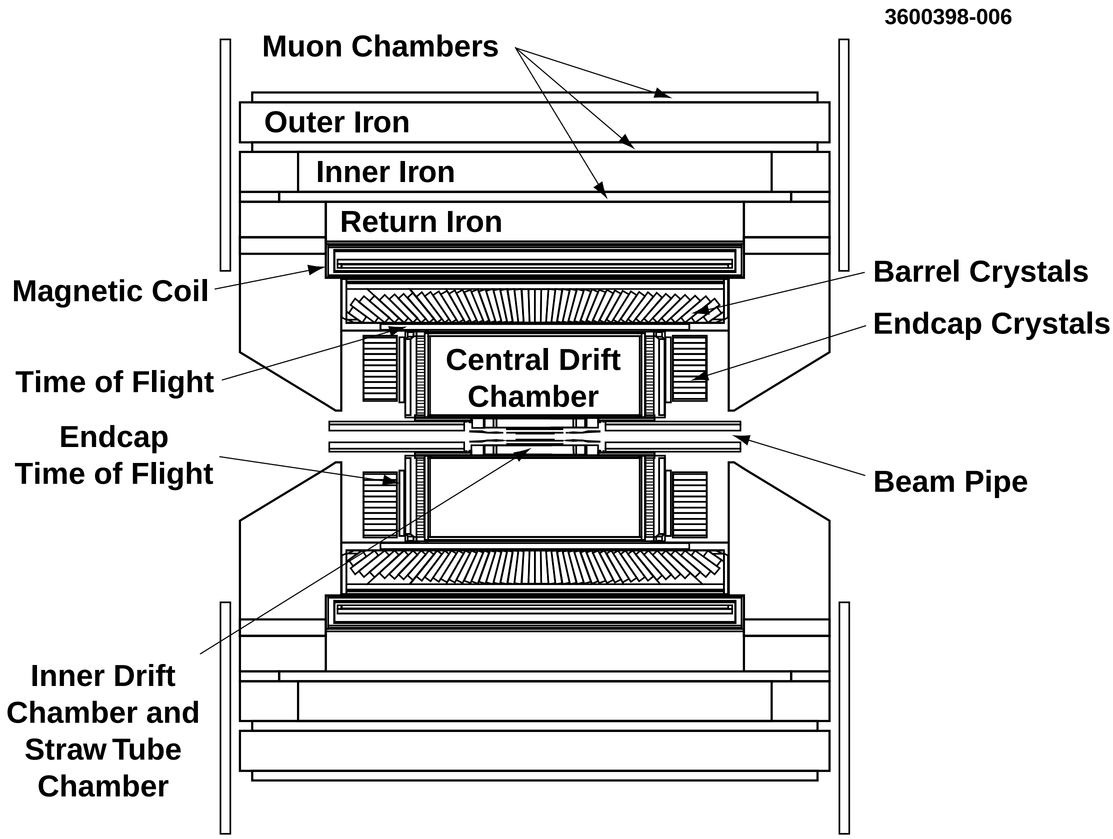
    Each B has only $|\vec{p}_B| \approx 300$ MeV/c
  - Cross-sections

    $\sigma(B\bar{B}) = 1.0$ nb

    $\sigma(q\bar{q}) = 3.1$ nb
- Off-resonance ("continuum") running 60 MeV below $\Upsilon(4S)$
  - Measure in *data* production of various "background" processes

    $q\bar{q}$ $(q = u, d, s, c)$, $\tau\bar{\tau}$, 2-photon, . . .
  - Simply *subtract* these from B-physics analyses

CLEO



- CLEO II (1989) [3.3×10^6 $B\bar{B}$ decays]

  Drift chambers, crystal calorimeter, muon counters

- CLEO II.V—Upgraded version (1996) [6.5×10^6 $B\bar{B}$ decays]
  - Silicon detector replaces inner wire chamber
- Nearly hermetic detector
  - Tracking coverage $\approx 95\%$ of 4π
  - Calorimeter coverage $\approx 98\%$

ANALYZING $B \to D^* \ell \nu$

Differential decay rate:

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

- $\mathcal{G}(w)$ contains kinematics and is *known*
- $\mathcal{F}(w)$ is form factor for $B \to D^*$
  - Parameterizes non-perturbative (*unknown*) physics
  - Absolutely normalized at zero recoil ($w = 1$) i.e. $\mathcal{F}(1)$ provided by theory
    - In $m_Q \to \infty$ limit: $\mathcal{F}(1) \to 1$
    - For $B \to D^* \ell \nu$, corrections only at order $1/m_c^2$ $\Rightarrow \mathcal{F}(1) = 0.913 \pm 0.042$ [a]

Basic analysis technique:

1. Fit for $B \to D^* \ell \nu$ signal in data, in (10) bins of w
2. Measure $d\Gamma/dw$ in each bin
3. Fit with functional form from phenomenology
4. Extrapolate to $w = 1$ and extract $\mathcal{F}(1)|V_{cb}|$

[a] (PL**B264**,455; **338**,84; PR**D47**,2965; **51**,2217; **53**,3149; PRL 76, 4124)

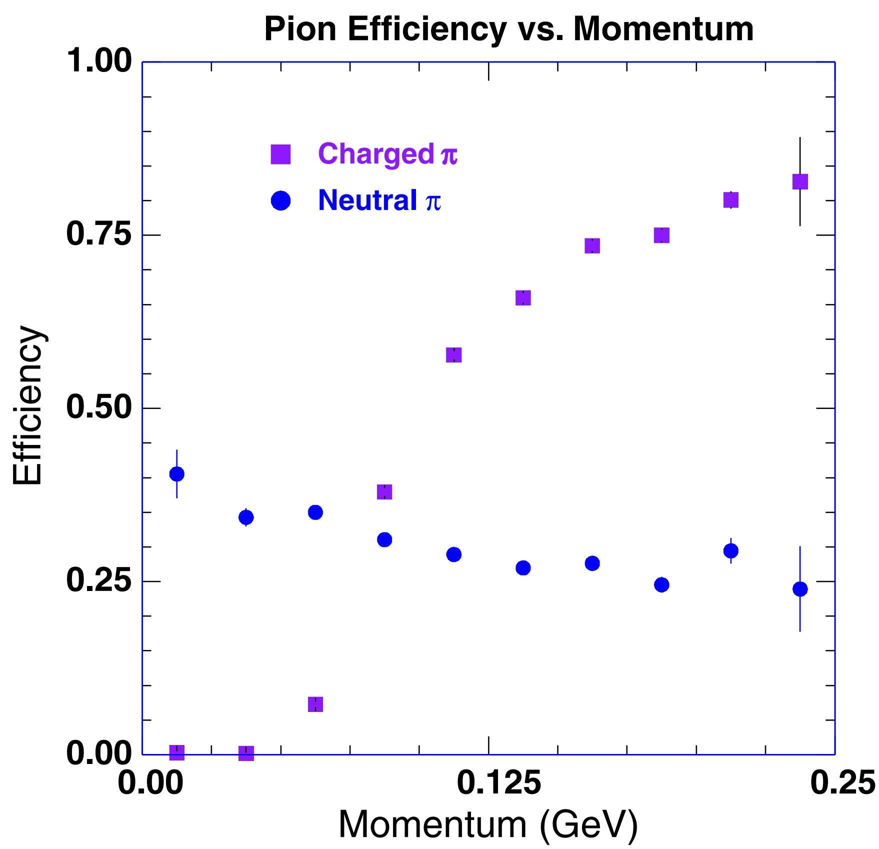
RECONSTRUCTING $B \to D^*\ell\nu$

Fully reconstruct D^* decay

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

Separate analyses for $\bar{B}^0 \to D^{*+}\ell\nu$, $B^- \to D^{*0}\ell\nu$

- Backgrounds, $\mathcal{B}(D^* \to D\pi)$, τ_B different
- Eff'y for charged $\pi^\pm$ different than for neutral π^0

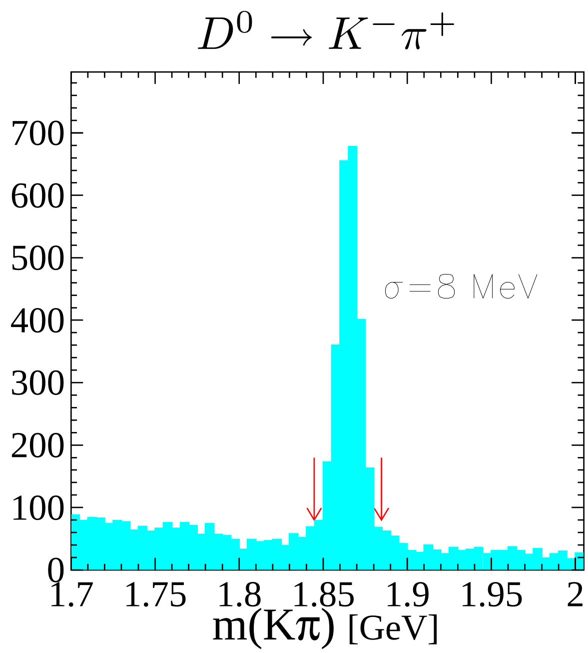


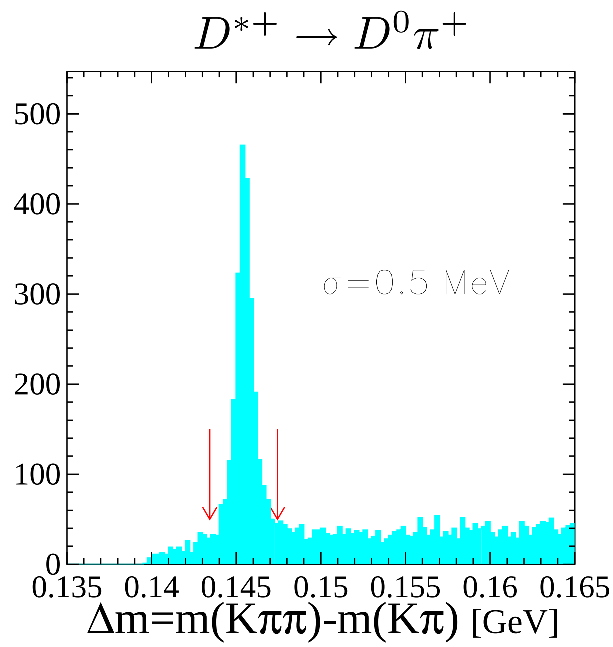
$\Rightarrow$ D^{*+} **analysis has preliminary results for $\mathcal{B}$ and $\mathcal{F}(1)|V_{cb}|$**

FINDING $D^* \ell$'S

D^* Finding

- D candidate from K and π tracks
- D^* from addition of slow π





$D^*\ell$ pairs can arise from more than just signal ⚠

- $B \to D^* X \ell \nu$
  - Non-resonant $B \to D^* \pi \ell \nu$ or higher resonant states, *e.g.* $D^{**} \to D^* \pi$
- Other backgrounds
  - Estimated *in data*, some input from Monte Carlo

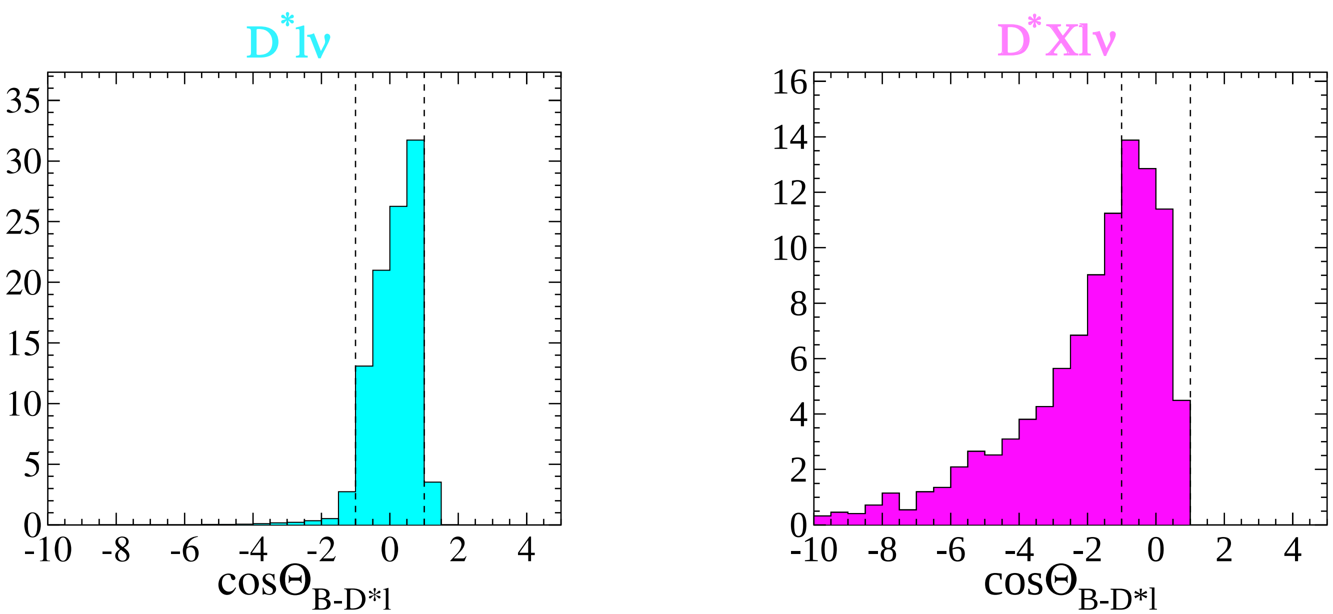
Fitting for the $B \to D^* \ell \nu$ Yield

Separate signal $B \to D^* \ell \nu$ from $B \to D^* X \ell \nu$ with kinematics:

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

Signal should have $\cos\theta \in [-1, 1]$

Background extends to unphysical values

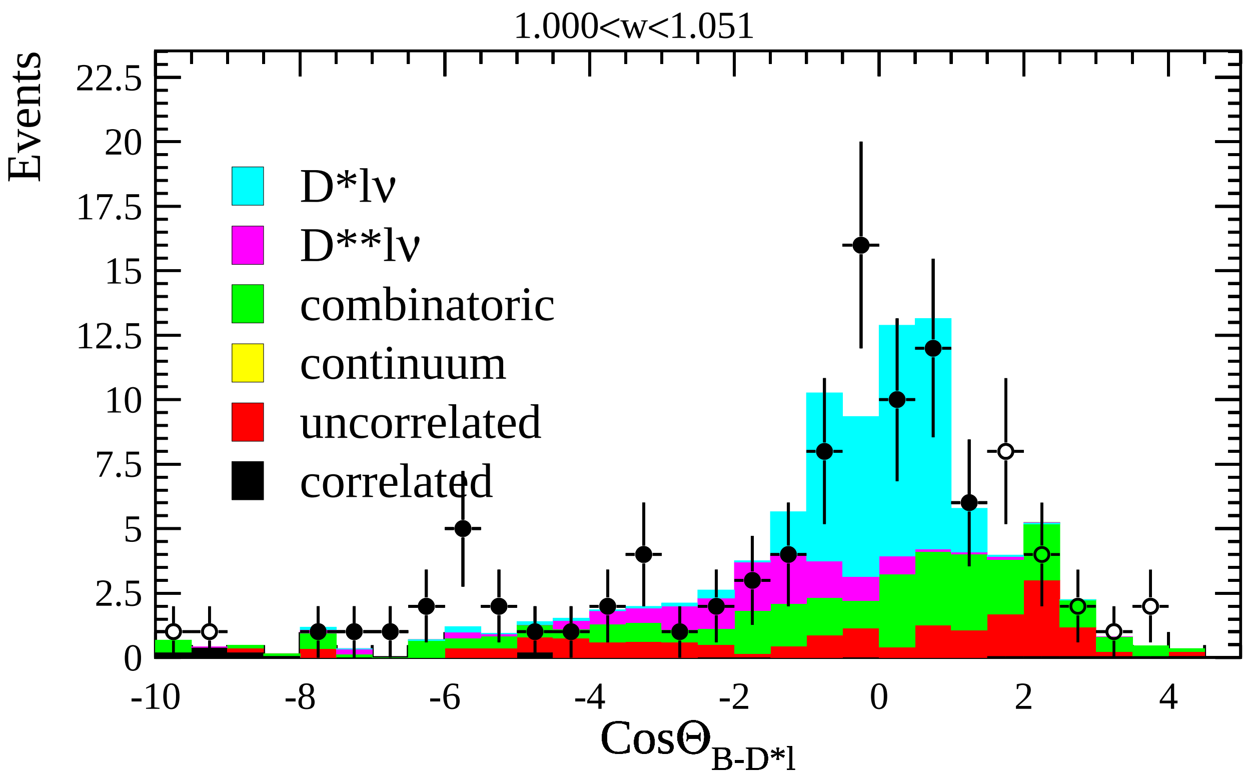


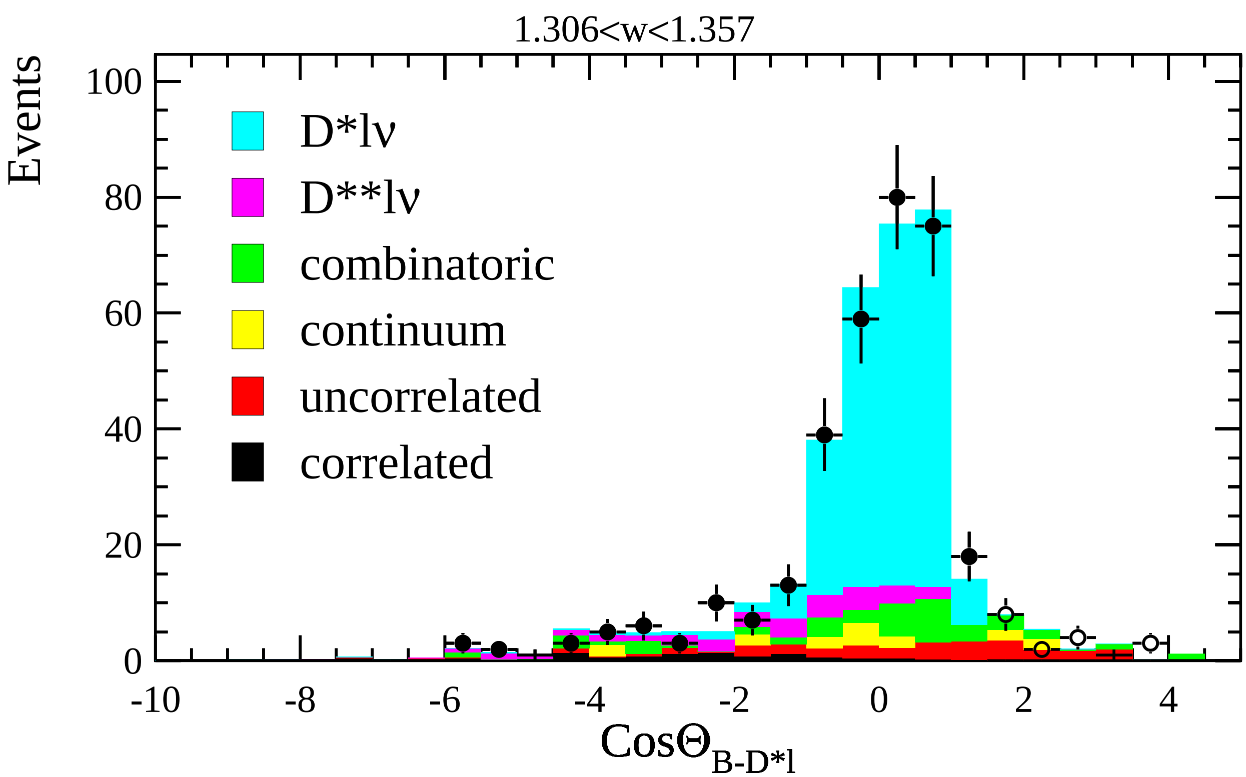
Binned maximum-likelihood fit to $\cos\theta_{B-D^*\ell}$ distribution in data

- Backgrounds subtracted
- Signal shape in $cos\theta_{B-D^*\ell}$ from Monte Carlo
- Normalizations (= yields) allowed to float

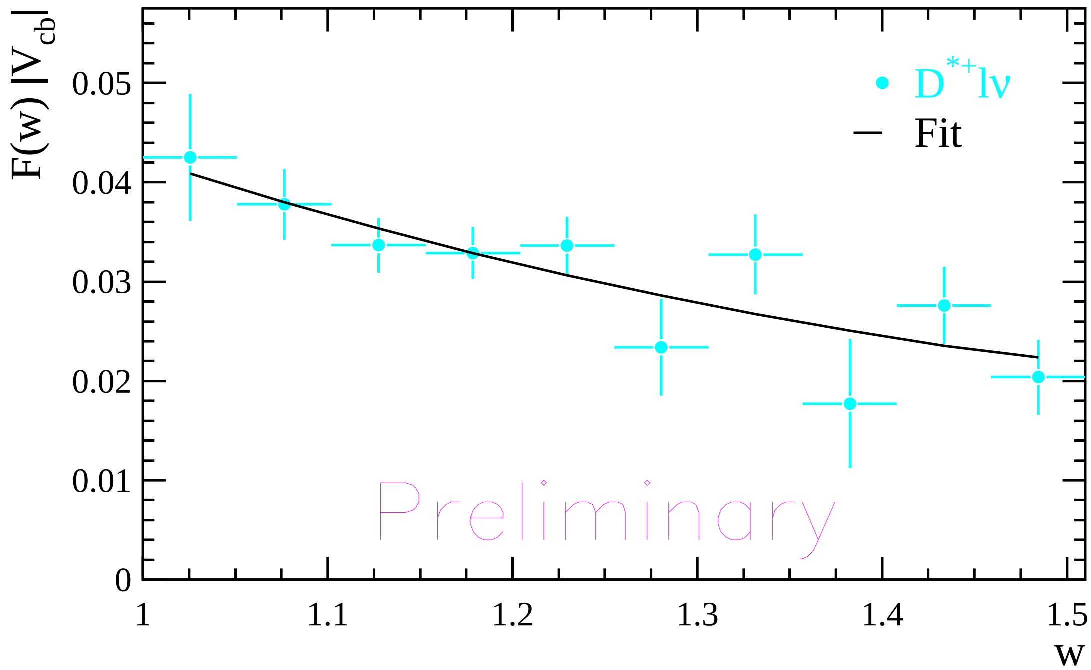
⇒Result: $B \to D^* \ell \nu$ and $B \to D^* X \ell \nu$ yield in each w-bin

Representative Fits for $\bar{B}^0 \to D^{*+}\ell\nu$





Fitting the Decay Rate



- Unfolds phase space, kinematic factors, and form factor $\mathcal{F}(w)$
- Takes into account reconstruction eff'y, smearing in w
- w-dependence of $\mathcal{F}(w)$ from dispersion relations [a]
- Fit parameters essentially $\mathcal{F}(1)|V_{cb}|$ and $\rho^2_{h_{A_1}}$ (slope at $w = 1$)

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

- Integrating over w,

$$\mathcal{B}(\bar{B}^0 \to D^{*+} \ell \nu) = (5.66 \pm 0.29 \pm 0.33)\%$$

[a] NP**B530**,153

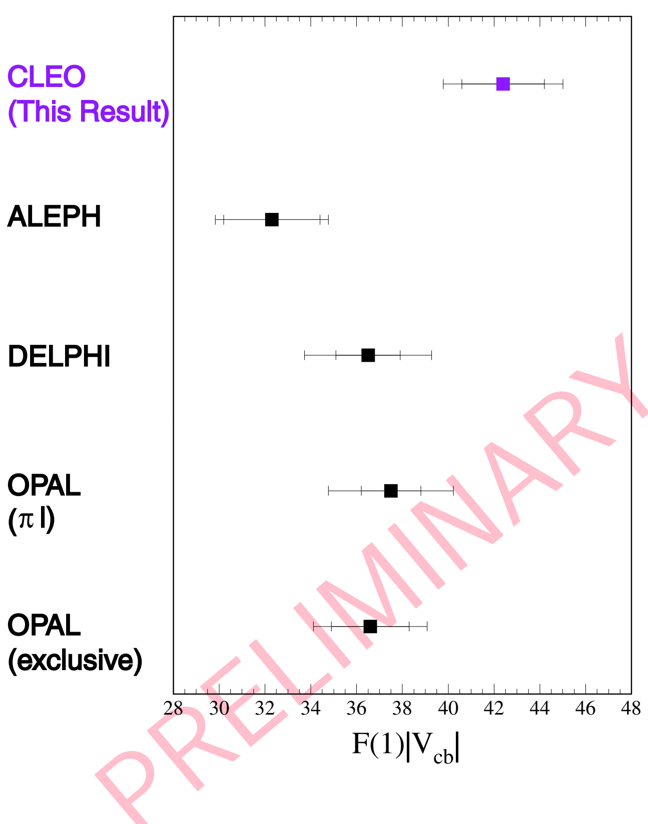
EXTRACTING $|V_{cb}|$

Form factor at zero recoil known: $\mathcal{F}(1) = 0.913 \pm 0.042$

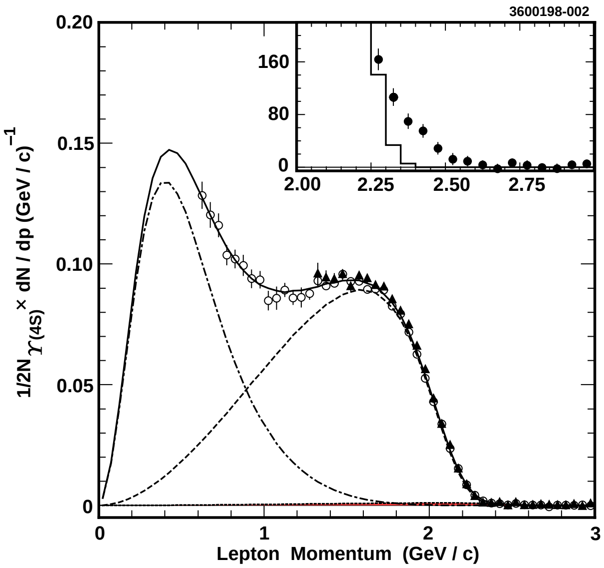
$$\Rightarrow \boxed{|V_{cb}| = 0.0464 \pm 0.0020 \pm 0.0021 \pm 0.0021} \quad \text{[CLEO]}$$

- Consistent with previous CLEO, LEP measurements—but slightly higher

Compare this result to previous ones



CHALLENGE OF $|V_{ub}|$



Swamped by Cabibbo-favored $b \to c\ell\nu$

- $|V_{ub}| > 0$ first verified only in 1990
- Hard cuts required experimentally to control $b \to c$ backgrounds—makes theoretical interpretation difficult
- Inclusive theoretical calculations only reliable when *large* part of phase space is sampled—experimental measurement hard!

Tradeoff

Exclusive analysis incurs large model dependence

but

Inclusive analysis suffers from large backgrounds

$B \to X_u \ell\nu$ Analysis

Analysis Goals—In progress

- Extract $|V_{ub}|$
- Measure $\mathcal{B}_i$ and kinematics (q^2) of π, ρ modes
- Consider/Evaluate range of models
- Reconstruct $B \to X_u \ell\nu$ candidates in seven channels

$\pi^\pm$	$\rho^\pm \to \pi^\pm\pi^0$
π^0	$\rho^0 \to \pi^+\pi^-$
$\eta \to \pi^+\pi^-\pi^0$	
$\eta \to \gamma\gamma$	$\omega \to \pi^+\pi^-\pi^0$

Neutrino Reconstruction

- Conservation laws dictate that what goes in must come out

$$p^\mu_{\text{miss}} = p^\mu_0 - \sum_{\text{particles } i} p^\mu_i$$

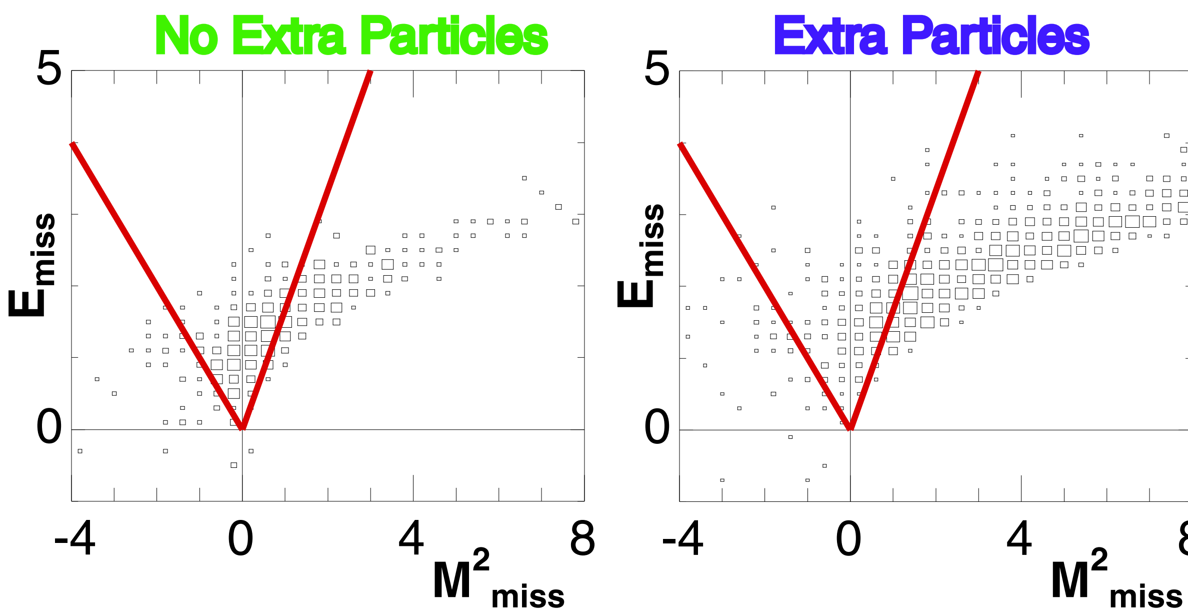
- Hermetic detector "captures" all particles
  1. Charged particles—tracks + PID $\Rightarrow p^\mu_i$
  2. π^0, γ—unmatched showers + beamspot $\Rightarrow p^\mu_i$
- Neutrino must carry away any momentum-energy missing in final state

$$\Rightarrow p^\mu_\nu \equiv p^\mu_{\text{miss}}$$

NEUTRINO RECONSTRUCTION

Must **veto** events with more than one missing particle

- *e.g.* Add'l ν, K_L^0, neutrons
- Lepton counting: $N_\ell > 1 \rightsquigarrow N_\nu > 1$
- *Test* neutrino hypothesis: $M^2_{\rm miss} \stackrel{?}{=} 0$
  Cuts out $b \to c\,\ell\nu$ that misreconstructs as signal



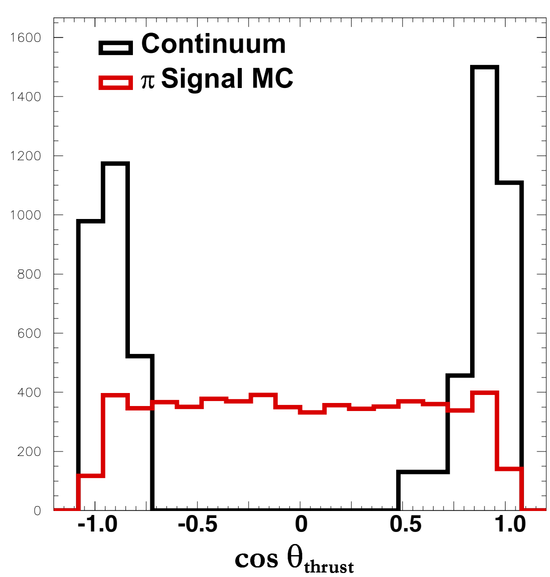
Measure tracks and showers, *not* particles

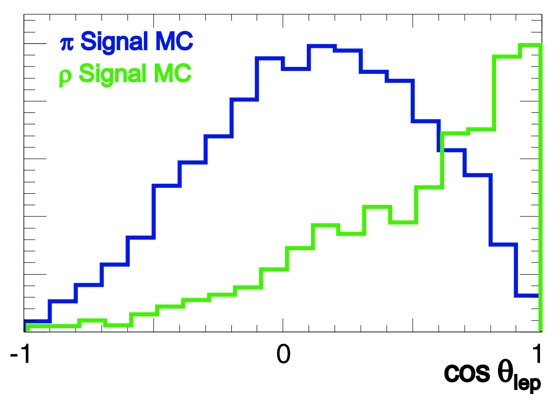
- Must be sure to account for each particle exactly once
- Examine net charge ΔQ of event
  - Easy way to detect missing tracks: $|\Delta Q| = 0$
  - Include $|\Delta Q| = 1$, increases signal eff'y more than bkgrd
    Ex: Slow π missed, but little impact on $(E_{\rm miss}, \vec{p}_{\rm miss})$

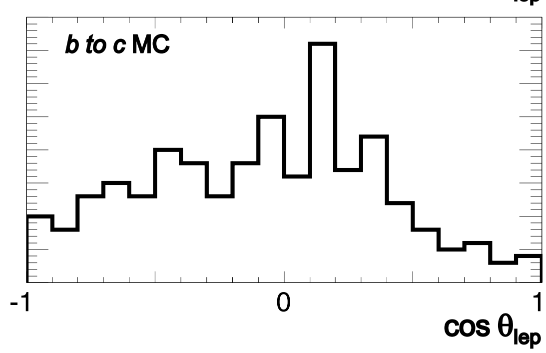
ANALYSIS TECHNIQUE

- Continuum suppression
  - Need to avoid cuts that bias q^2 distribution
  - θ_{thrust}: angle between X_u-ℓ and *thrust* of rest of event
  - Off-resonance data subtraction
- $b \to c\,\ell\nu$ suppression
  - Angle between ℓ in W rest frame and W in B frame

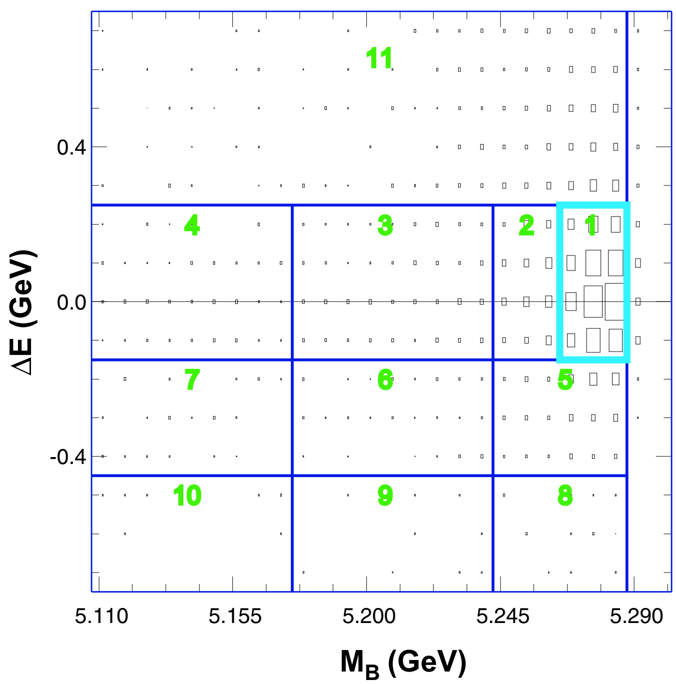
    Reflects $V - A$ nature of charged current
    - Apply cut on $\cos\theta_{\text{lep}}$ in vector modes only
  - $|p_\ell| > 1.5$ GeV/c (vector), 1.0 GeV/c (pseudoscalar)
    - Softer ℓ from $b \to c\,\ell\nu$ than $b \to u\,\ell\nu$







FITTING TECHNIQUE



- Define variables for each B-candidate

$$\Delta E \equiv (E_\nu + E_\ell + E_{\text{had}}) - E_{\text{beam}}$$
$$\tilde{M}_B \equiv \sqrt{E_{\text{beam}}^2 - |\alpha\vec{p}_\nu + \vec{p}_\ell + \vec{p}_{\text{had}}|^2}$$
$$\alpha = 1 - \frac{\Delta E}{E_\nu}$$

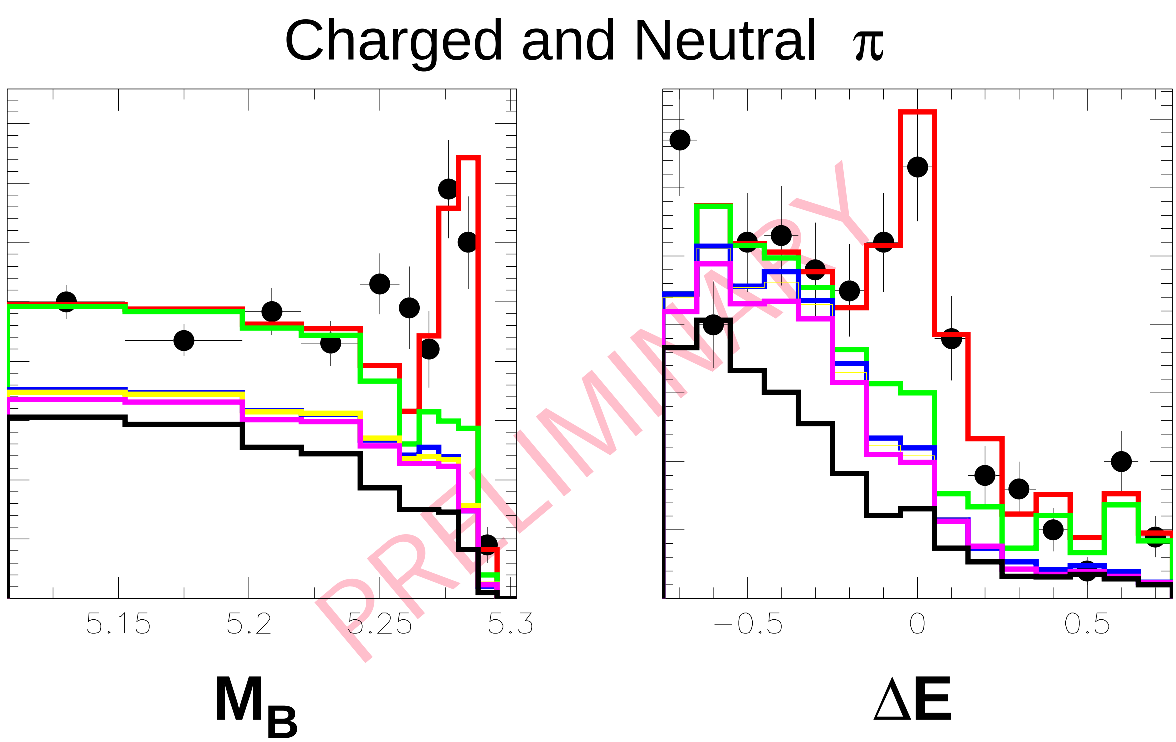
- Carve up $\Delta E - M_B$ plane into signal box (#1) and sidebands
  - Backgrounds, cross-feeds constrained by data *outside* signal box, too
- Perform binned χ^2 fit in $\Delta E - M_B$ to extract signal yields, background amounts in each box for each mode

SAMPLE π-MODE FITS

- Simultaneous fit for all X_u modes accounts for cross-feed and common backgrounds

  1. $b \to c\,\ell\nu$ backgrounds from Monte Carlo
  2. $b \to u\,\ell\nu$ "other", i.e. not in signal modes
  3. Cross-feed from *other* signal modes into this one, from MC
  4. Fakes ($h \mapsto \ell$), from non-leptonic data
  5. Continuum backgrounds, as measured in OFF data
  6. Signal from Monte Carlo

- Use ISGW2 model here for signal and background shapes



($\Delta Q = 0$ only)

Summary

- CKM elements offer special opportunity to investigate and test Standard Model
- CLEO has preliminary measurement of $|V_{cb}|$ from $\bar{B}^0 \to D^{*+}\ell\nu$
  - $|V_{cb}| = 0.0464 \pm 0.0020 \pm 0.0021 \pm 0.0021$
  - Charged and neutral D^* modes to be combined
  - Systematics understood; analyses nearing completion
  - Promises world's most precise measurement from $B \to D^*\ell\nu$
  - New analyses using CLEO II.V dataset underway as well
- CLEO has analyses in progress on $|V_{ub}|$ using *full* dataset
  - Exclusive $B \to \pi/\rho/\omega/\eta\, \ell\nu$
    - Promises $\mathcal{B}_i$ and q^2 information
    - Model discrimination
  - Lepton-energy endpoint
    - Window into essential non-perturbative physics
  - $|V_{ub}|$ from $b \to s\gamma$ + E_ℓ-endpoint
  - Several inclusive $b \to X\, \ell\nu$ analyses in the works

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Will the Standard Model hold up . . . ?

$B \to D^* \ell \nu$ Backgrounds

$D^* \ell$ pairs can arise from more than just signal ⚠

- $B \to D^* X \ell \nu$
  - Non-resonant $D^* \pi \ell \nu$ production
  - Higher resonant states, generically called $D^{**} \ell \nu$
  - Model with latest phenomenology
- Combinatoric—Events with D^* resulting from mis-reconstruction (fakes) — 6%[a]
  - Estimate magnitude from events in $\Delta m = M_{D^*} - M_D$ sideband
  - Shape from Monte Carlo
- Continuum—$e^+ e^- \to q\bar{q}$ with real D^* and ℓ — 4%
  - Subtracted using data taken slightly below $B\bar{B}$ threshold
- Uncorrelated—D^* and ℓ come from different B's — 4%
  - Estimate from inclusive D^* and ℓ yields
- Correlated—Real D^* and ℓ from same B, but not signal mode — 0.5%
  - Ex: $B \to D^* D_s$, with $D_s \to X \ell$
  - Estimated from Monte Carlo
- Fake lepton—Mis-ID hadrons as ℓ, combine with real D^* — 0.1%
  - Small enough to neglect

[a] Estimate for D^{*+} modes only

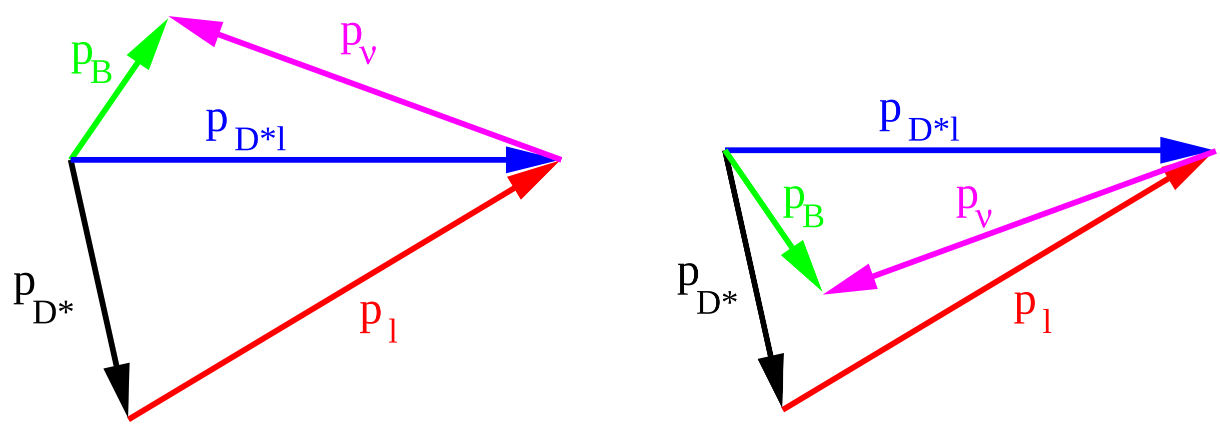
–RESERVE–

Estimating w

- $w \in (1, 1.51)$ is Lorentz boost of the D^* in the B rest frame
- At CESR/CLEO, B's nearly at rest: $|\vec{p}_B| \approx 300$ MeV/c
- Know the magnitude but not the *direction* of B momentum

  Determined only up to azimuthal ambiguity
- Compute estimate for w using two extreme possibilities for B direction

–RESERVE–

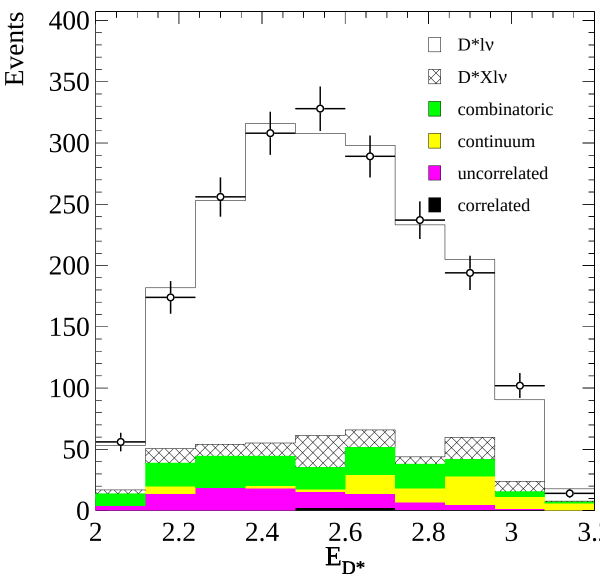


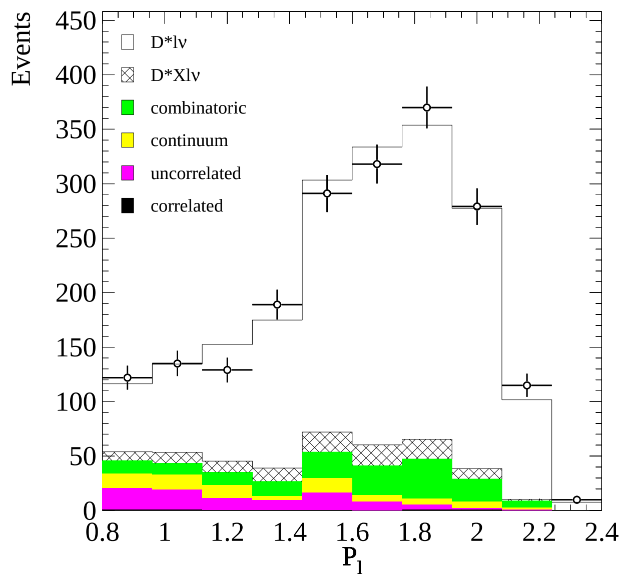
- Resolution good: $\sigma_w \approx 0.03$

Checking the Fit

Projections of fit results into signal region, all w-bins combined
Cut on $\cos\theta_{B-D^*\ell}$ applied

D^{*+} Energy E_{D^*} Lepton Energy E_ℓ





–RESERVE–

(Error bars on data are for data sample, and do not include statistical errors on combinatoric and continuum bkgrds)

FITTING $d\Gamma/dw$

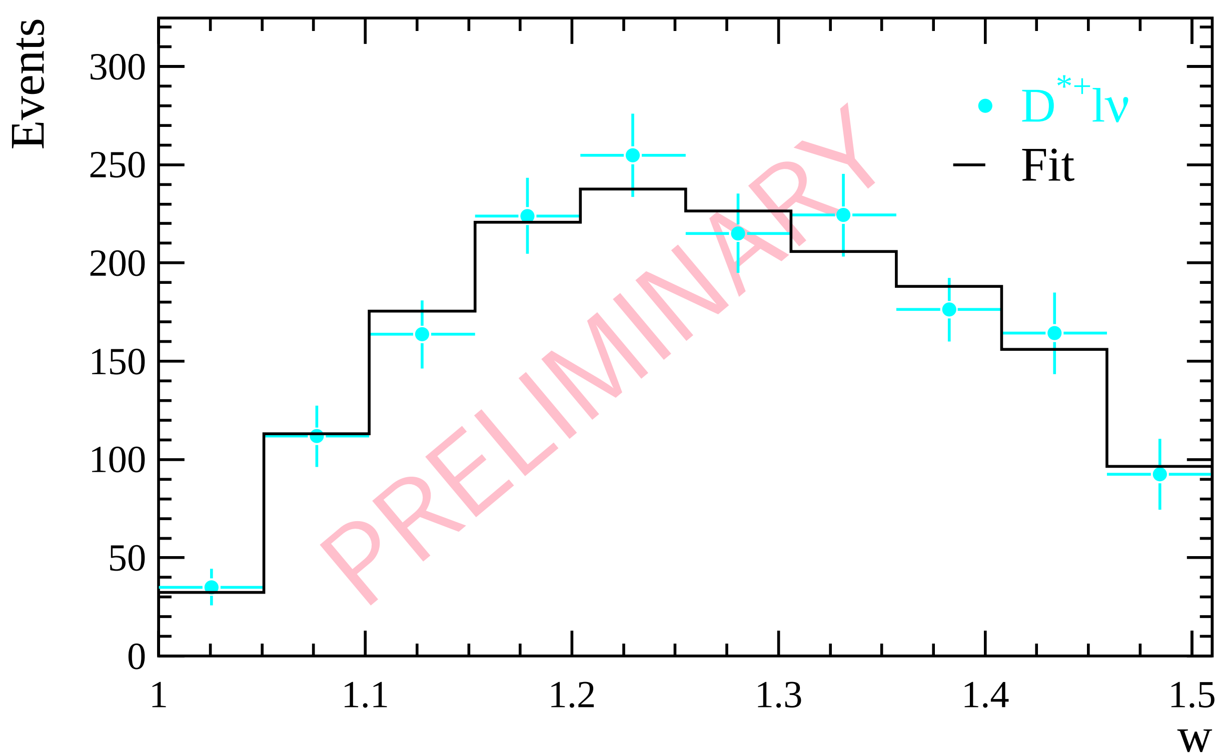
Binned χ^2 fit: $(B \to D^* \ell\nu \text{ yield})_i \mapsto (d\Gamma/dw)_i$

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

- N_i^{obs} : Yield in ith w-bin
- ϵ_{ij} : Accounts for reconstruction eff'y, w-smearing
- N_j : number of signal decays in jth w-bin

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

–RESERVE–



$\bar{B}^0 \to D^{*+}\ell\nu$ Systematics

Source	$\lvert V_{cb}\rvert\mathcal{F}(1)(\%)$	$\rho^2(\%)$	$\Gamma(\%)$
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**

–RESERVE–

$|V_{ub}|$ at CLEO

History

- First observation of $|V_{ub}| > 0$ made in 1990
  Found $B \to X\ell\nu$ beyond kinematic endpoint for charm
- Measurement of $\mathcal{B}(B \to \pi/\rho\,\ell\nu)$ and $|V_{ub}|$ published early 1996
  - Successful debut of ν–reconstruction
  - Data sample of 4 fb^{-1}
  - 20% error on $|V_{ub}|$—model-dependence of form factors

$$|V_{ub}| = (3.3 \pm 0.2^{+0.3}_{-0.4} \pm 0.7) \times 10^{-3}$$

–RESERVE–

- Update of $\mathcal{B}(B \to \rho\,\ell\nu)$ in 1999

$$|V_{ub}| = (3.25 \pm 0.14^{+0.21}_{-0.29} \pm 0.55) \times 10^{-3}$$

First examination of partial rate in (3) bins of q^2
High $|p_\ell|$ cut selects region where most models agree

OUTLOOK

Another round at CLEO continues . . .

- $|V_{cb}|$ from $B \to D^* \ell \nu$ with CLEO II.V dataset

  SVX improves slow π efficiency

- $|V_{ub}|$ from endpoint of lepton energy spectrum with full CLEO dataset

- $|V_{ub}|$ from measurements of non-perturbative physics from $b \to s\,\gamma$ combined with endpoint spectrum

- Inclusive $b \to u\,\ell \nu$ analysis
  - Use other kinematic variables to cut out charm

    Hadronic mass, q^2
  - But retain larger fraction of phase space

–RESERVE–