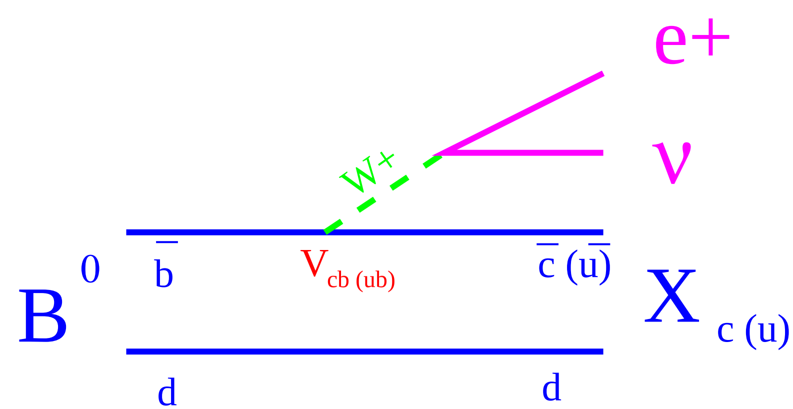
$|V_{cb}|$ from Semileptonic B decays at CLEO



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CLEO Collaboration
June 18, 2002

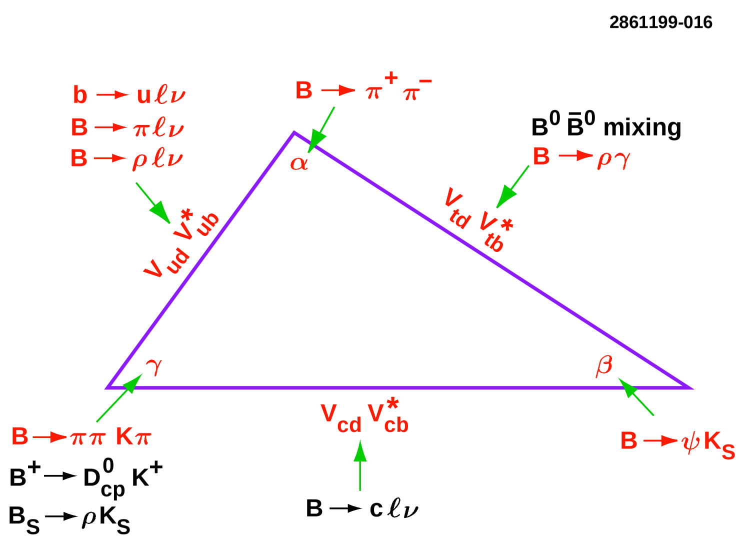
Outline

- Introduction: $|V_{cb}|$ and Heavy Flavor Physics
- Exclusive decays:
  - $\bar{B} \to D^* \ell \bar{\nu}$
- Inclusive decays: $\bar{B} \to X_c \ell \bar{\nu}$
  - Branching fraction
  - Hadronic mass spectrum
  - Lepton energy spectrum
- Summary and Outlook

$|V_{cb}|$ in the Unitarity Triangle

Program of heavy flavor physics - test flavor sector of Standard Model

Precision measurements of $|V_{cb}|$ are needed to test CKM paradigm



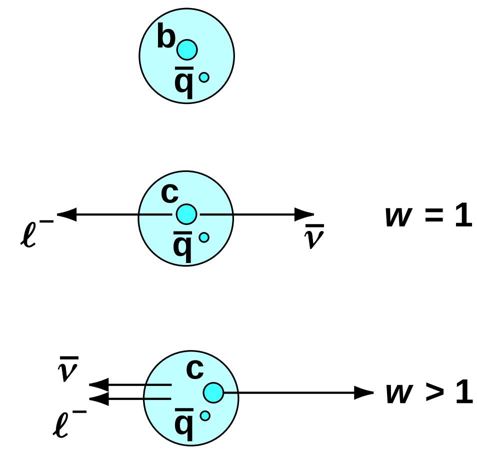
- $|V_{cb}|$ is base of UT
- Need sides and angles
- ϵ_K ellipse scales as $|V_{cb}|^4$
- Tree level $b \to c\ell\nu$:
  - New physics unlikely
  - No Final State Interactions
  - QCD corrections from HQET

Non-perturbative QCD is hard: largest uncertainties

Must test predictions of HQET and make multiple measurements!

Two approaches: Exclusive $\bar{B} \to D^*\ell\bar{\nu}$ and Inclusive $\bar{B} \to X_c\ell\bar{\nu}$

$|V_{cb}|$ from $\bar{B} \to D^* \ell \bar{\nu}$



Extracting $|V_{cb}|$ from exclusive decays:

The decay rate is given by

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

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

- $\mathcal{K}(w)$ contains kinematic factors and is *known*
- $\mathcal{F}(w)$ is the form factor describing $B \to D^*$ transition
- HQET relations simplify the form factor
- HQS normalizes at zero recoil ($w = 1$): As $M_Q \to \infty$, $\mathcal{F}(1) \to 1$
- Corrections to HQS limit at $\mathcal{O}(1/M_Q^2)$: $\mathcal{F}(1) = 0.91 \pm 0.04$

Plan: Measure $d\Gamma/dw$ and Extrapolate to $w = 1$ to extract $\mathcal{F}(1)|V_{cb}|$.

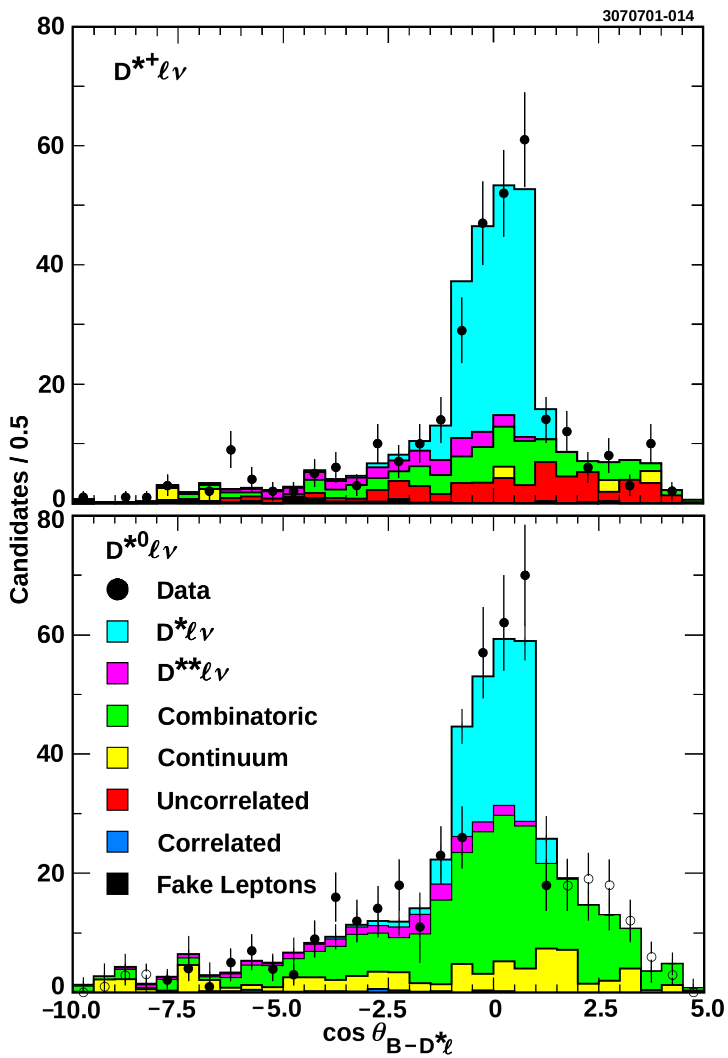
$B \to D^*$ Form Factor

- Must know form factor shape to extrapolate
- Must know $\mathcal{F}(1)$ to extract $|V_{cb}|$

The most general Lorentz-invariant form factor is simplified by

- Massless leptons
  - For $B \to D\ell\nu$ only vector current one FF: V_1
  - For $B \to D^*\ell\nu$ three FFs: A_1, A_2, V but ...
- Heavy Quark Symmetry
  - $M_Q \to \infty$: one form factor, the famous Isgur-Wise Function
  - Form Factor Ratios $R_1 \propto V/A_1$ and $R_2 \propto A_2/A_1 \approx$ constant in w
- QCD dispersion relations constrain the shape (Boyd *et al.*)
  - Parameterization of FF: Caprini *et al.* NPB530 (1998) 153
  - Includes curvature but one shape parameter: ρ^2, slope at $w = 1$

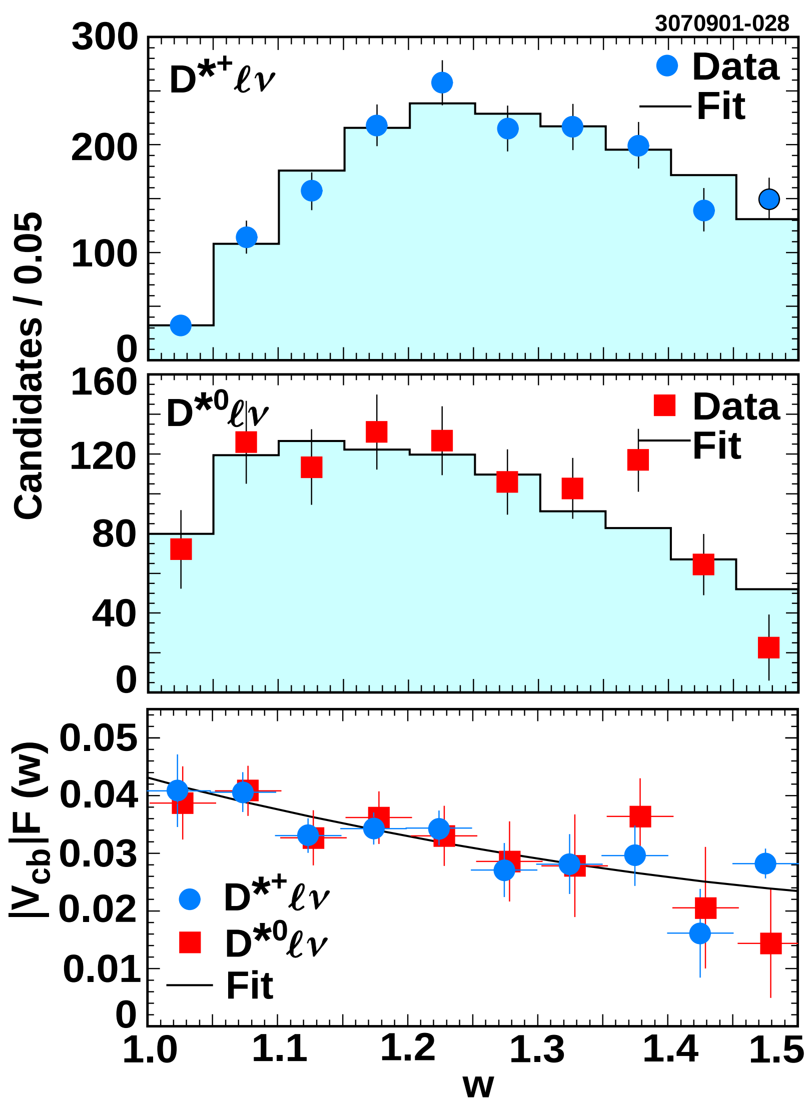
$|V_{cb}|$ from $\bar{B} \to D^* \ell \bar{\nu}$



CLEO hep-ex/0203032

- Reconstruct $D^0 \to K^- \pi^+$, $D^{*+} \to D^0 \pi^+$& $D^{*0} \to D^0 \pi^0$
- Pair D^* with a lepton
  - $e : 0.8 < p_e < 2.4$ GeV/c
  - $\mu : 1.4 < p_\mu < 2.4$ GeV/c
- Assume $\bar{B} \to D^* \ell^- \bar{\nu}$ decay compute $\cos\theta_{B-D^*\ell}$
- Estimate Bkgds from data/MC fake D^*, $q\bar{q}$, (un)correlated
- Fit $\cos\theta_{B-D^*\ell}$ for signal and backgrounds in 10 bins of w
- $D^*\ell\nu$ and $D^*X\ell\nu$ float in fit

CLEO $\bar{B} \to D^* \ell \bar{\nu}$ hep-ex/0203032 to appear in PRL



(3.1 fb^{-1} 3.3 M $B\bar{B}$)

Given yields in 10 w bins

Fit using Caprini form factor

Parameters:

- $\mathcal{F}(1)|V_{cb}|$ (intercept)
- ρ^2 (slope)

$\mathcal{F}(1)|V_{cb}| = (43.1 \pm 1.3 \pm 1.8) \times 10^{-3}$

$\rho^2 = 1.61 \pm 0.09 \pm 0.21$

Theory: $\mathcal{F}(1) = 0.91 \pm 0.04$

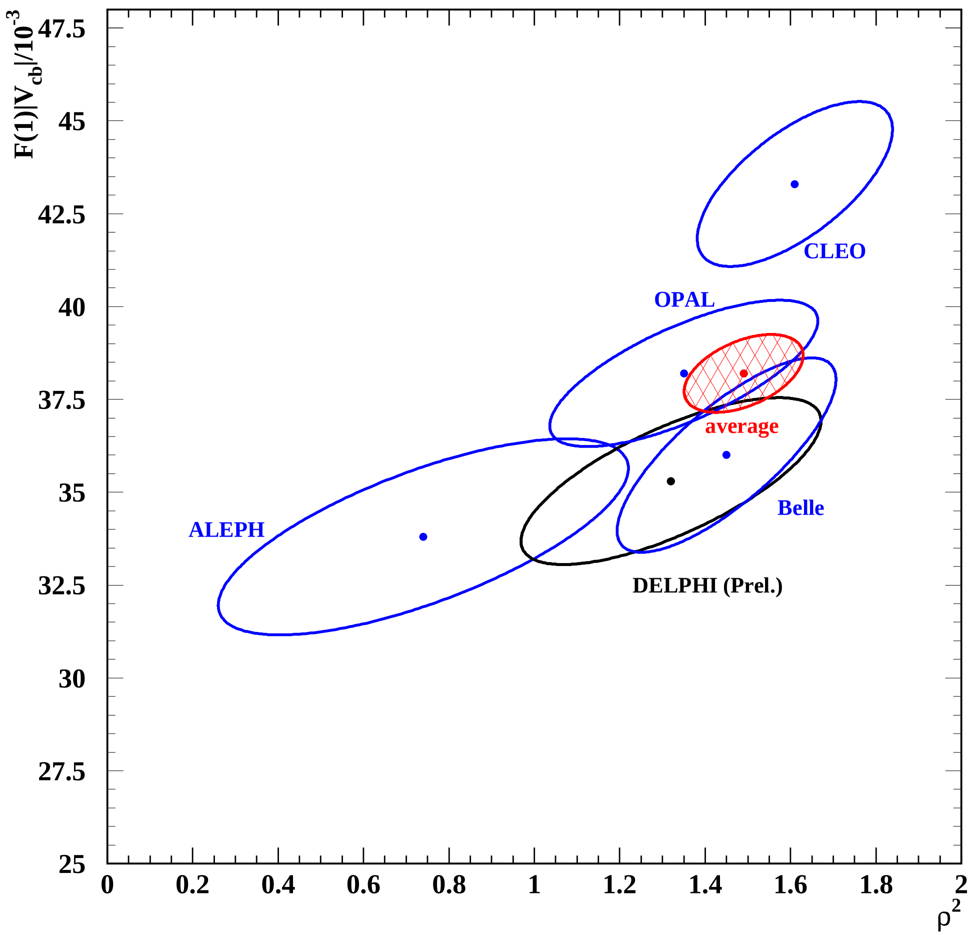
$|V_{cb}| = (47.4 \pm 1.4 \pm 2.0 \pm 2.1) \times 10^{-3}$

6.7% precision

Systematics! efficiency, bkgds, BFs

Larger $|V_{cb}|$ than previous results

Status of $\mathcal{F}(1)|V_{cb}|$



Correlated $\mathcal{F}(1)|V_{cb}|$ & ρ^2

$|V_{cb}|$ WG Combined 2d-fit accounts for correlations Currently 5% C.L.

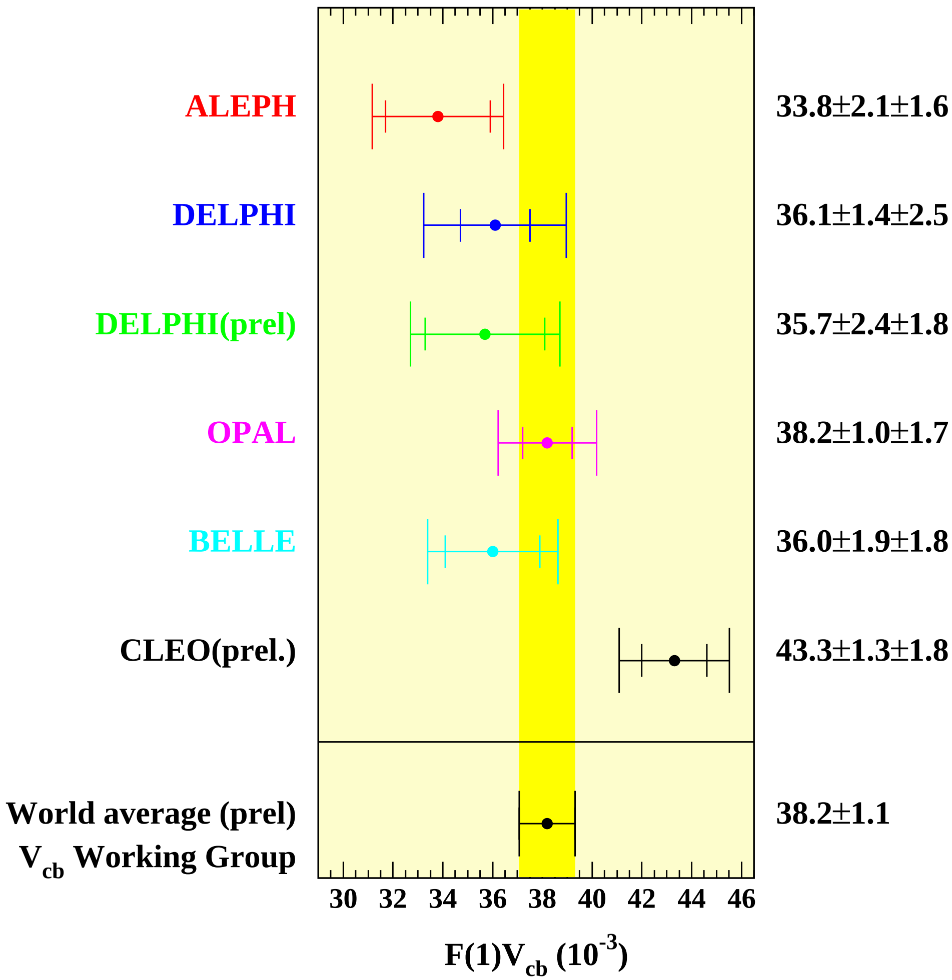
N.B. Only CLEO

- Includes D^{*0}
- Fits data simultaneously for $D^*X\ell\nu$ background

Others share $D^*X\ell\nu$ estimate & model

Ellipses are $\Delta\chi^2 = 1$ for each measurement (stat+syst)

LEPWG $\mathcal{F}(1)|V_{cb}|$



$$\mathcal{F}(1)|V_{cb}| = (38.2 \pm 1.1) \times 10^{-3}$$

With $\mathcal{F}(1) = 0.91 \pm 0.04$ $|V_{cb}| = (42.0 \pm 1.2_{\rm exp} \pm 1.8_{\rm thr}) \times 10^{-3}$

Inclusive $b \to c\ell\nu$

Rather than focusing on one hadronic final state where corrections may be calculated reliably,

Sum over all states and compare to quark-level calculation

$$\sum_i \Gamma(B \to X_c^{(i)} \ell\nu) = \Gamma(b \to c\ell\nu)$$

Relies on assumption of quark-hadron duality

Hard to quantify; must be tested!

Fortunately there are other observables besides Γ

- lepton energy spectrum
- hadronic recoil mass

Use these to constrain theory parameters and test consistency

Theoretical Tools for Inclusive $b \to c\ell\nu$

Heavy Quark Expansion in powers of $1/M_B$ and α_s

Operator Product Expansion - introduce parameters as matrix elements of non-perturbative operators:

At order $1/M$:

$\bar{\Lambda}$ - $\approx M_B - m_b$ energy of light degrees of freedom

At order $1/M^2$:

λ_1 - kinetic energy of b quark in B meson

λ_2 - hyperfine interaction of b spin with light d.o.f.
(determine $\lambda_2 = 0.128 \pm 0.010$ GeV^2 from B–B^* mass splitting)

At order $1/M^3$:

$\rho, \mathcal{T}$ - six more parameters with less-intuitive interpretations

and so on ...

Use HQE/OPE tools to predict semileptonic decay rate

$$\Gamma_{\rm SL} = \frac{G_F^2 |V_{cb}|^2 M_B^5}{192\pi^3}\left[\mathcal{G}_0 + \frac{1}{M_B}\mathcal{G}_1(\bar\Lambda) + \frac{1}{M_B^2}\mathcal{G}_2(\bar\Lambda,\lambda_1,\lambda_2) + \frac{1}{M_B^3}\mathcal{G}_3(\bar\Lambda,\lambda_1,\lambda_2|\rho_1,\rho_2,\mathcal{T}_1,\mathcal{T}_2,\mathcal{T}_3,\mathcal{T}_4) + \mathcal{O}\left(\frac{1}{M_B^4}\right)\right]$$

and moments of decay spectra in $B \to X_c \ell \nu$:

$\langle E_\ell \rangle$,$\langle E_\ell^2 \rangle$,$\langle M_X^2 \rangle$ [Falk,Luke,Savage,Gremm,Kapustin,Bauer,Trott]

and $B \to X_s \gamma$: $\langle E_\gamma \rangle$,$\left\langle E_\gamma^2 \right\rangle$ [Bauer, Z.Ligeti *et al.*]

Example:

$$\langle E_\gamma \rangle = \frac{M_B}{2}\Big[1 - .385\frac{\alpha_s}{\pi} - .620\beta_0\left(\frac{\alpha_s}{\pi}\right)^2 - \frac{\bar\Lambda}{M_B}\left(1 - .954\frac{\alpha_s}{\pi} - 1.175\beta_0\left(\frac{\alpha_s}{\pi}\right)^2\right) - \frac{13\rho_1 - 33\rho_2}{12M_B^3} - \frac{\mathcal{T}_1 + 3\mathcal{T}_2 + \mathcal{T}_3 + 3\mathcal{T}_4}{4M_B^3} - \frac{\rho_2 C_2}{9M_B M_D^2 C_7} + \mathcal{O}(1/M_B^4)\Big]$$

Road map for Inclusive $|V_{cb}|$

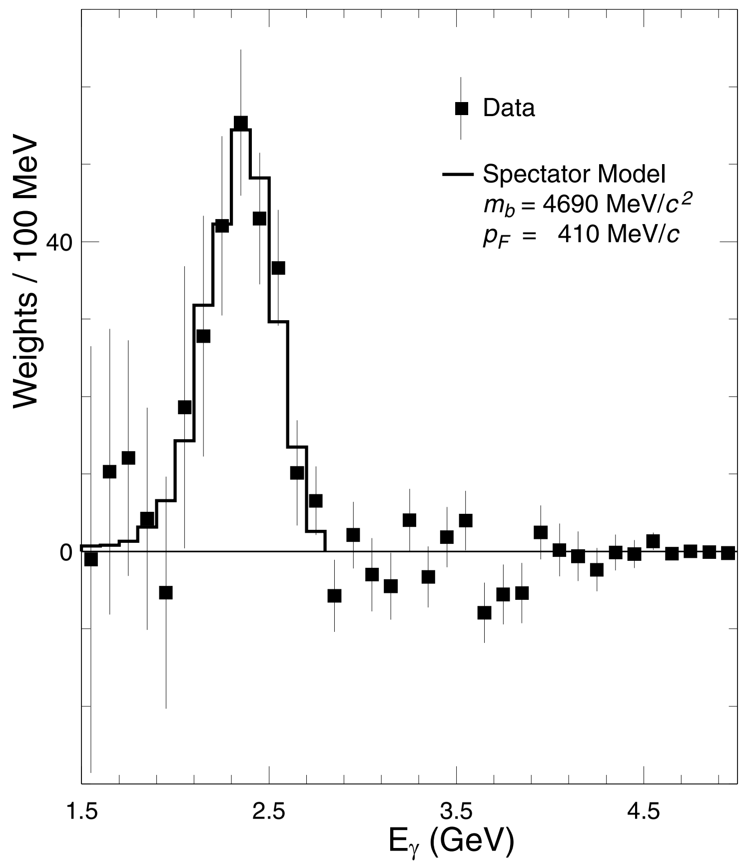
Milestones:

- Theory
  - Expressions for Γ and moments
- Experiment
  - Inclusive branching fraction $\mathcal{B}(B \to X\ell\nu)$
  - Lifetimes τ_{B^0}, τ_{B^+}
  - Moments: $\langle E_\gamma \rangle$ in $b \to s\gamma$ and $\langle M_X^2 \rangle$ and dN/dE_ℓ in $B \to X_c\ell\nu$

In what follows I will tell you about:

- Recent improvement on $|V_{cb}|$ using experimental measurements of $\langle E_\gamma \rangle$ and $\langle M_X^2 \rangle$ to bound the HQET parameters $\bar{\Lambda}, \lambda_1$
- New preliminary results: redundant bounds on $\bar{\Lambda}, \lambda_1$ from lepton spectrum above 1.5 GeV

$B \to X_s\gamma$: E_γ Moments



CLEO $b \to s\gamma$ spectrum

PRL **87**, 251807 (2001) $\langle E_\gamma \rangle \approx m_b/2$

Broadened by

- Fermi motion
- gluon bremsstrahlung
- B boost in lab

Use first moment to determine $\bar{\Lambda}$

$$\bar{\Lambda} = 0.35 \pm 0.08 \pm 0.10 \text{ GeV}$$

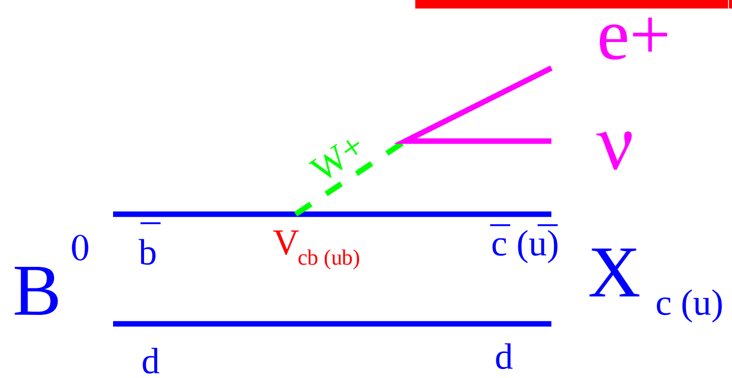
Theory: Bauer PRD57, 5611 (1998)

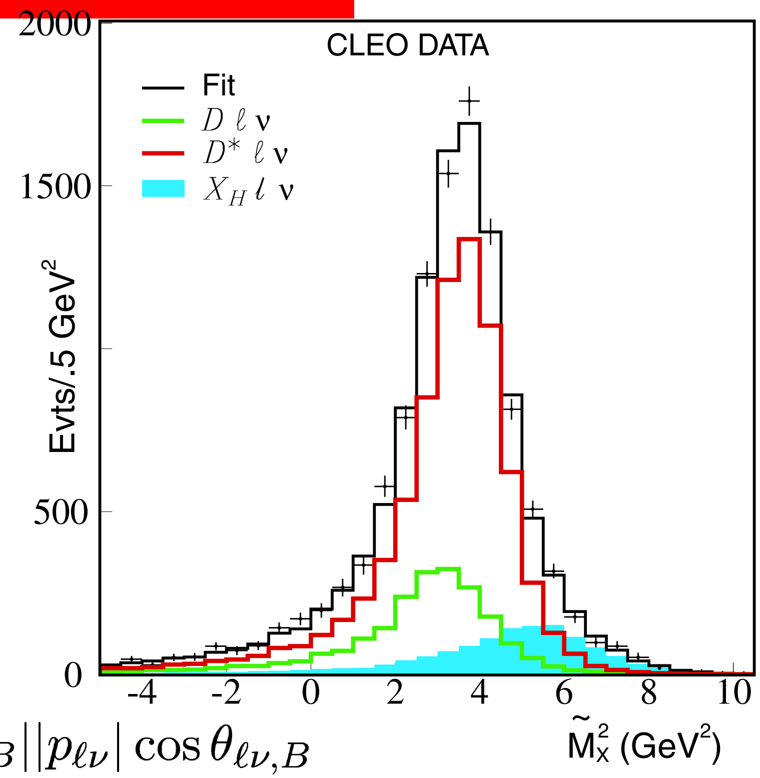
Ligeti *et al.*, PRD60, 034019 (1999)

$$\langle E_\gamma \rangle = 2.346 \pm 0.032 \pm 0.011 \text{ GeV}$$

$$\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle = 0.0231 \pm 0.0066 \pm 0.0022 \text{ GeV}^2$$

$B \to X_c \ell \nu$: M_X^2 Moments





CLEO PRL 88, 251808 (2001)

Require $E_\ell > 1.5$ GeV

(P_ν, E_ν) from hermetic detector

$$M_X^2 = M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu} + 2|p_B||p_{\ell\nu}|\cos\theta_{\ell\nu,B}$$

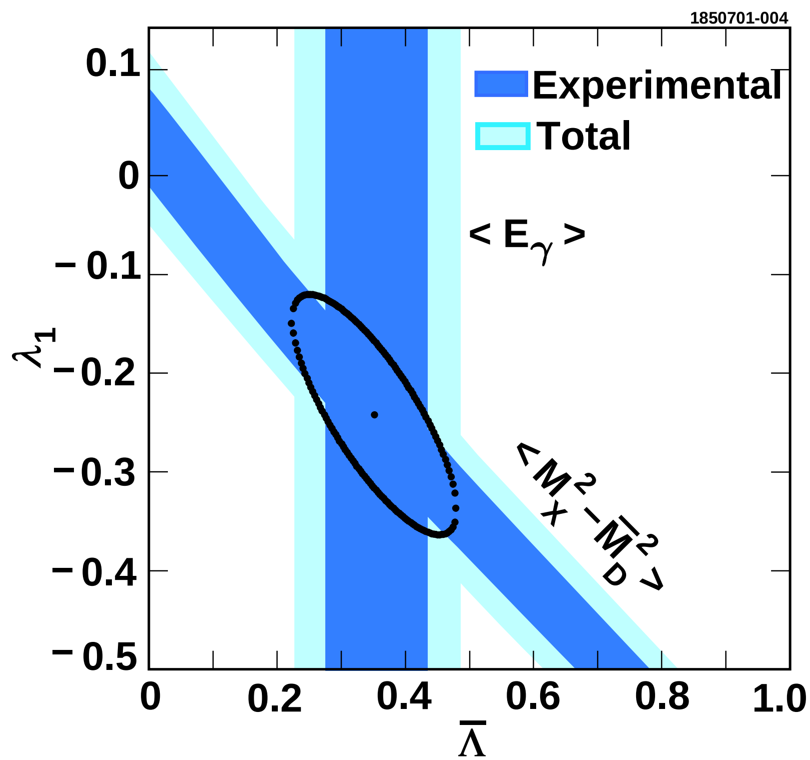
$$\approx \widetilde{M_X^2} = M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu}$$

$$\langle M_X^2 - \overline{M_D}^2 \rangle = 0.251 \pm 0.023 \pm 0.062\ \mathrm{GeV}^2$$

$$\langle (M_X^2 - \overline{M_D}^2)^2 \rangle = 0.639 \pm 0.056 \pm 0.178\ \mathrm{GeV}^4$$

Spin-averaged D mass: $\overline{M_D} = (M_D + 3M_{D^*})/4$

Determination of $\bar{\Lambda}$ and λ_1



$\bar{\Lambda} = 0.35 \pm 0.07 \pm 0.10$ GeV

$\lambda_1 = -0.238 \pm 0.071 \pm 0.078$ GeV^2

Warning: scheme dependence

$\overline{MS}$ to order $1/M^3$, $\beta_0 \alpha_s^2$

Combine

$\mathcal{B}(B \to X_c \ell \nu) = (10.39 \pm 0.46)\%$

(CLEO, $B \to X_u \ell \nu$ removed)

and τ_B (PDG2000) to find

$\Gamma_{SL} = (0.427 \pm 0.020) \times 10^{-10}$ MeV

Add $\bar{\Lambda}, \lambda_1$ to determine

$|V_{cb}| = (40.4 \pm 0.5 \pm 0.9 \pm 0.8) \times 10^{-3}$

(M) (Γ) (T)

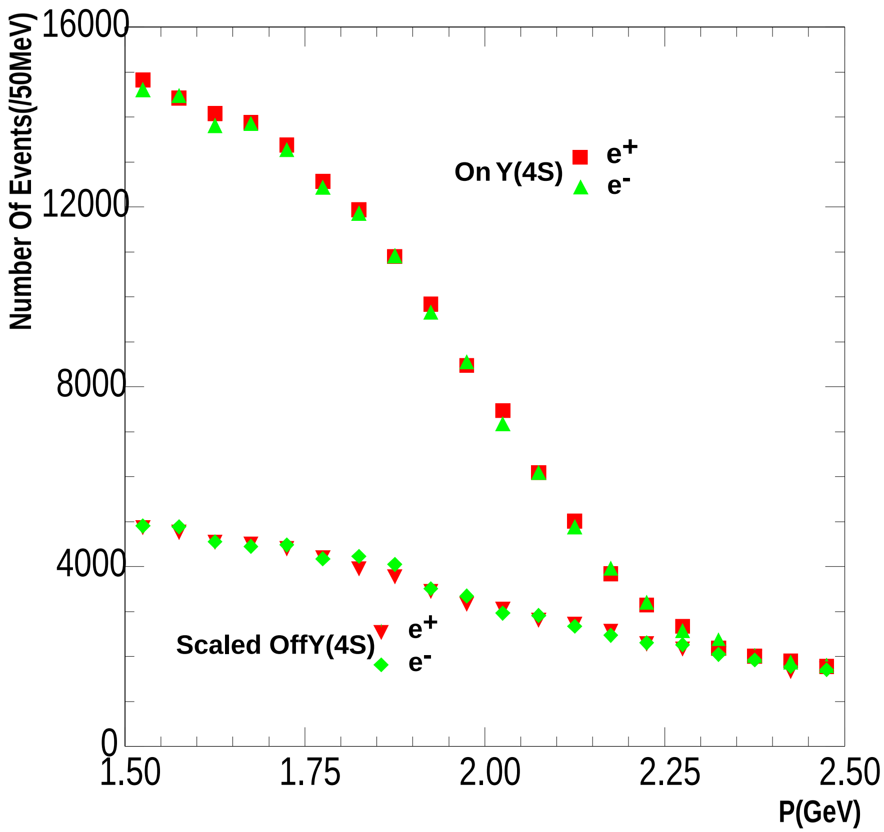
3.2% determination of $|V_{cb}|$

implicit q-H duality assumption

E_ℓ moments also sensitive to $\bar{\Lambda}, \lambda_1$

How consistent?

Measurement of Lepton Spectrum

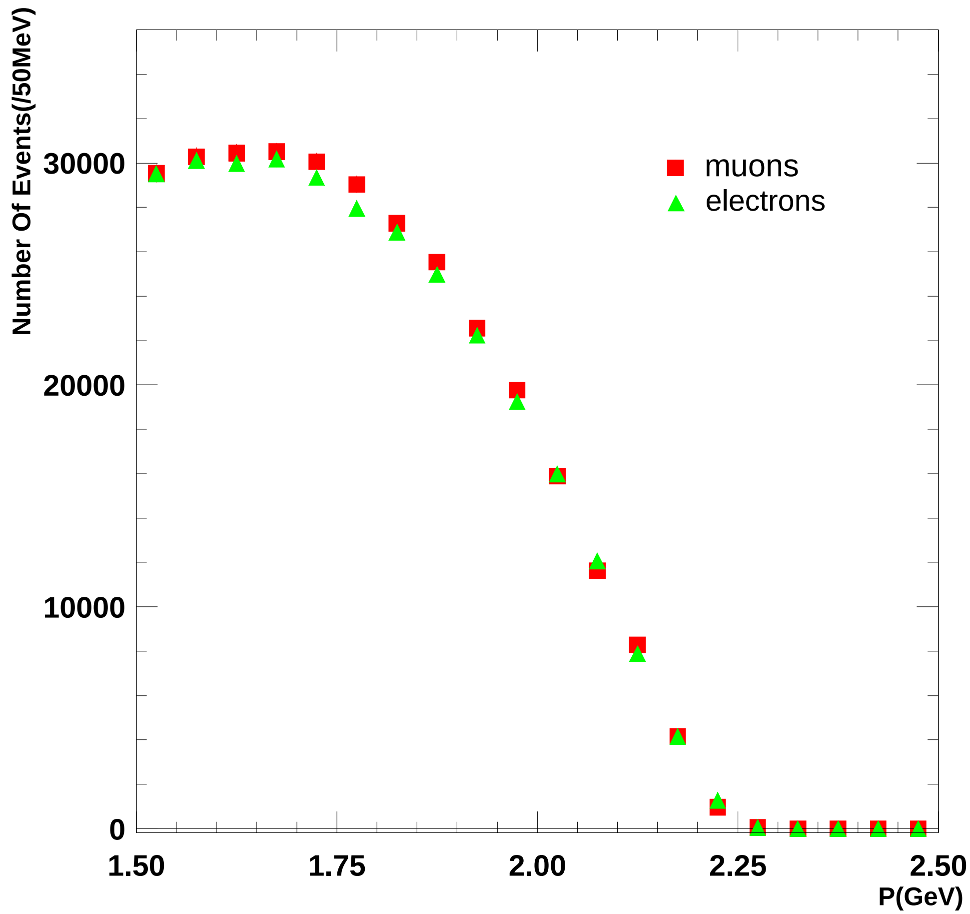


Raw spectrum includes backgrounds from

- non-$B\bar{B}$ decays (use off-$\Upsilon(4S)$ data)
- fake leptons (estimate from data)
- $\psi^{(\prime)} \to \ell^+\ell^-$
  $\pi^0 \to ee\gamma$, γ-conv.
  (data and MC)
- $b \to c \to s\ell\nu$
  $\tau \to \ell\nu\bar{\nu}$
  (MC estimate)

CLEO Preliminary using 3 fb^{-1} on-$\Upsilon(4S)$, 1.6 fb^{-1} off-$\Upsilon(4S)$ data

Correct raw spectrum for efficiency, EW and detector radiation, B boost



	Electrons	Muons
R_0	0.6173(16)(14)	0.6182(17)(17)
R_1 (GeV)	1.7797(7)(7)	1.7789(7)(9)

Generalized Moments:

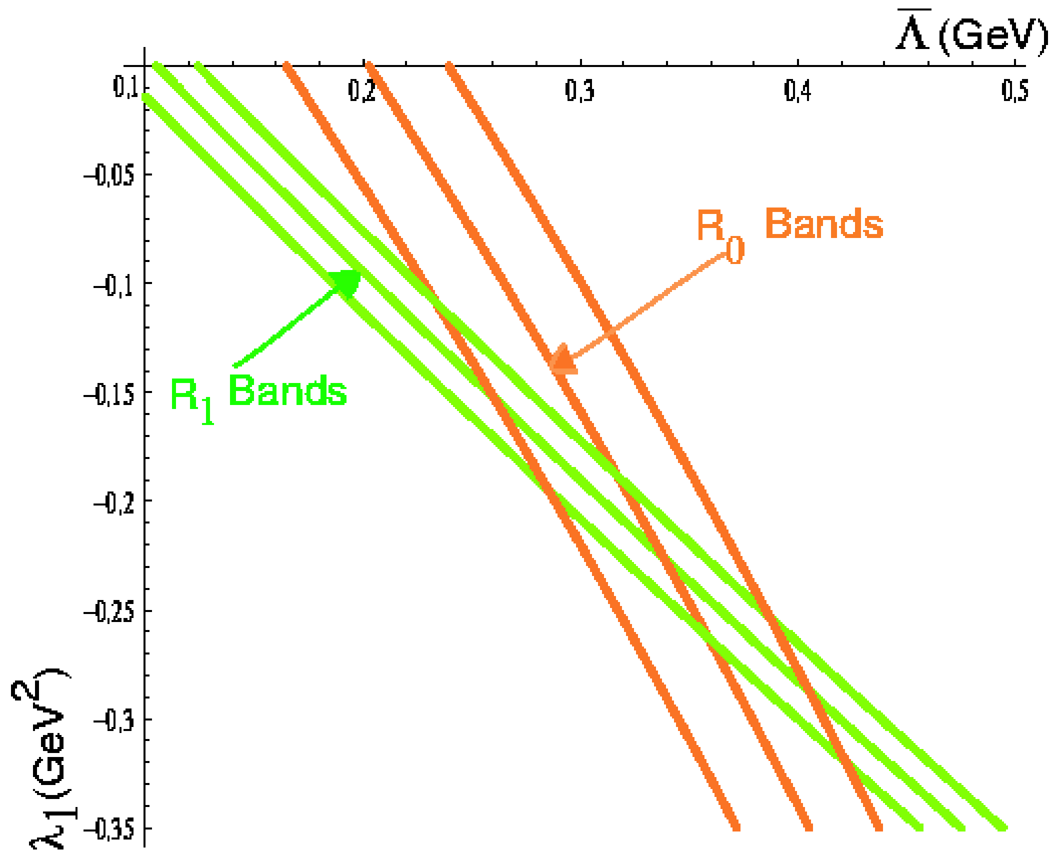
$$R_0 = \frac{\int_{1.7\ \mathrm{GeV}} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\ \mathrm{GeV}} \frac{d\Gamma}{dE_\ell} dE_\ell}$$

$$R_1 = \frac{\int_{1.5\ \mathrm{GeV}} E_\ell \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\ \mathrm{GeV}} \frac{d\Gamma}{dE_\ell} dE_\ell}$$

Computed in OPE in terms of $\lambda_1, \bar{\Lambda}$

Theory: PRL**77**,20 (1996) Gremm, Kapustin, Ligeti, Wise

CLEO Preliminary at APS/DPF



Electrons:

$\bar{\Lambda} = +0.35 \pm 0.06 \pm 0.12$

$\lambda_1 = -0.23 \pm 0.07 \pm 0.15$

Muons:

$\bar{\Lambda} = +0.31 \pm 0.08 \pm 0.12$

$\lambda_1 = -0.19 \pm 0.08 \pm 0.15$

$1/M^3$ dominant theory uncertainty

1 σ error bands (total expt.) from lepton spectrum $E_e > 1.5$ GeV

Similar bands for $E_\mu > 1.5$ GeV

Compare to $\bar{\Lambda}, \lambda_1$ from $\langle E_\gamma \rangle$ and $\langle M_X^2 \rangle$

Solution from R_0 & R_1 constraints: Preliminary

$\bar{\Lambda} = 0.35 \pm 0.06 \pm 0.12 \quad \lambda_1 = -0.23 \pm 0.07 \pm 0.15$ Electrons

$\bar{\Lambda} = 0.31 \pm 0.08 \pm 0.12 \quad \lambda_1 = -0.19 \pm 0.08 \pm 0.15$ Muons

Compare to solution from $\langle E_\gamma \rangle$ in $B \to X_s\gamma$ and $\langle M_X^2 \rangle$ in $B \to X_c\ell\nu$

$\bar{\Lambda} = 0.35 \pm 0.07 \pm 0.10 \quad \lambda_1 = -0.24 \pm 0.07 \pm 0.08$

- We now have a redundant determination of HQET parameters $\bar{\Lambda}, \lambda_1$
- The good agreement validates inclusive $|V_{cb}|$ (total uncertainty 3.2%)
- Work in progress: combine all constraints to extract $\bar{\Lambda}, \lambda_1$

$|V_{cb}|$ Summary and Outlook

Measurement	$\lvert V_{cb}\rvert \times 10^3$	$\delta_{V_{cb}}/V_{cb}$
CLEO $\bar{B} \to D^* \ell \bar{\nu}$	$(47.4 \pm 2.4 \pm 2.1)$	6.7%
$\lvert V_{cb}\rvert$ WG Average $\bar{B} \to D^* \ell \bar{\nu}$	$(42.0 \pm 1.2 \pm 1.8)$	5.2%
CLEO $\bar{B} \to X_c \ell \bar{\nu}$	$(40.4 \pm 1.0 \pm 0.8)$	3.2%

- Inclusive techniques are currently more precise but with reliance on theoretical framework to determine non-perturbative parameters
- Hints of a discrepancy (2σ) for $\bar{B} \to D^* \ell \bar{\nu}$
- Exclusive/Inclusive agreement tests quark-hadron duality
  - CLEO Exclusive and Inclusive differ by 2σ
  - WG Average Exc. and Inc. are in excellent agreement
- Data in hand at B factories to put our understanding to the test

Exclusive Future

- Improvements expected from new data (Babar and Belle)
  - form factor shape and R_1, R_2 (fit simultaneously)
  - better knowledge of $B \to D^* X \ell \nu$ backgrounds
- Unquenched lattice QCD $\mathcal{F}(1)$ will improve limiting uncertainty

Inclusive Future

- Extraction of theory parameters from inclusive distributions looks promising but needs confirmation with more moments
- More inclusive energy moments and new $\mathcal{B}$ in the summer from CLEO
- Contributions from Belle and Babar including $\mathcal{B}$, τ, moments

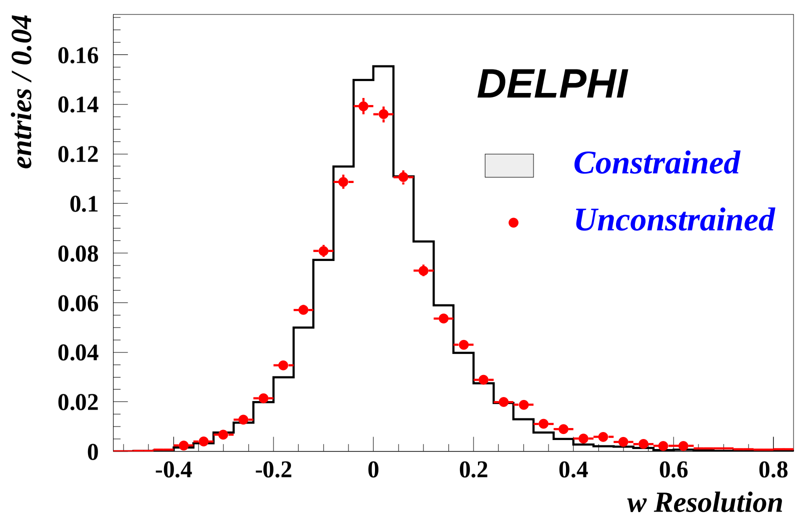
Comparison of measurements across experiments and techniques is essential for understanding $|V_{cb}|$ determination

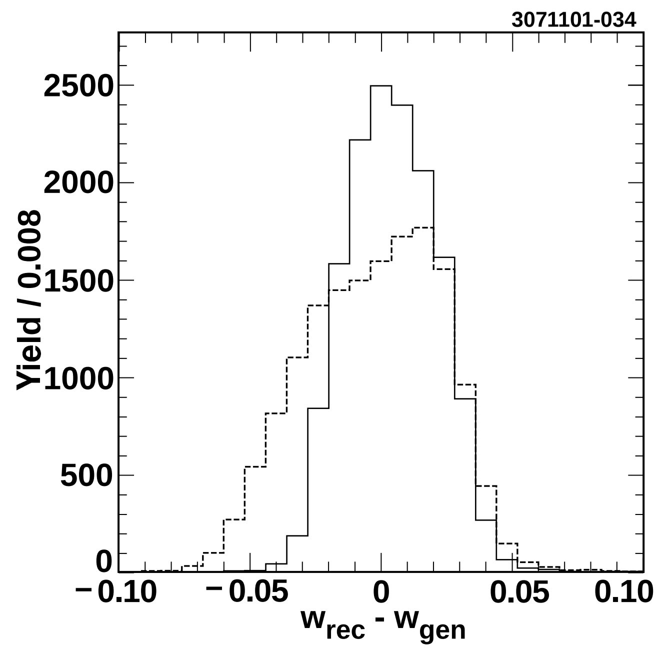
Backup Slides

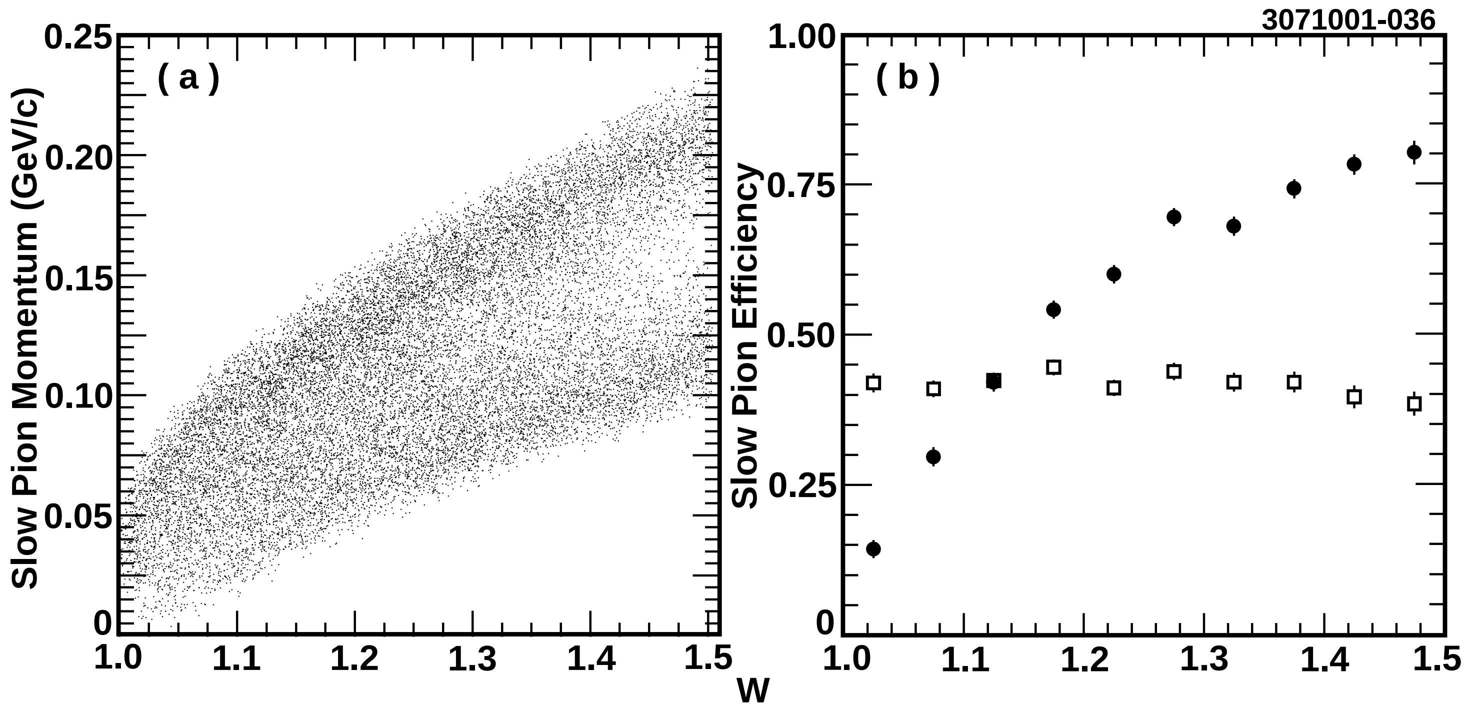
$D^*\ell\nu$ at $\Upsilon(4S)$ and Z Experiments

Main differences arise from B momentum in lab frame:
At LEP $p_B \sim 30$ GeV/c; At $B\bar{B}$ threshold $p_B \sim 0.3$ GeV/c

- w is boost of D^* in B rest frame
- LEP resolution on σ_w ~0.07–0.14 compared to $\sigma_w \sim 0.03$ at 4S



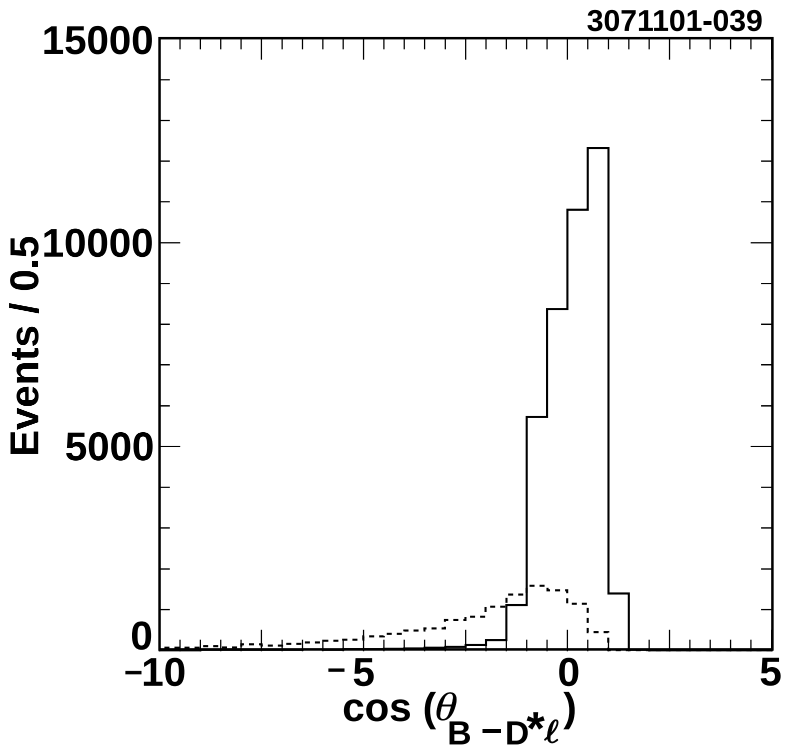




- 4S experiments suffer from π efficiency turn on

  At LEP Efficiency is flat
  - In $D^{*+} \to D^0\pi^+$ the π momentum comes from the boost of the D^*
  - Low efficiency below 50 MeV/c - precisely most interesting events for extrapolation to w=1.
  - Does not apply to $D^{*0} \to D^0\pi^0$; π^0 efficiency is flat.

- LEP expts. have more exposure to $B \to D^* X \ell \nu$
  - poorer missing mass resolution – 4S can separate sig/bkgd
  - larger systematic from poorly known $B \to D^{**} \ell \nu$ and non-resonant $B \to D^* \pi \ell \nu$ modes



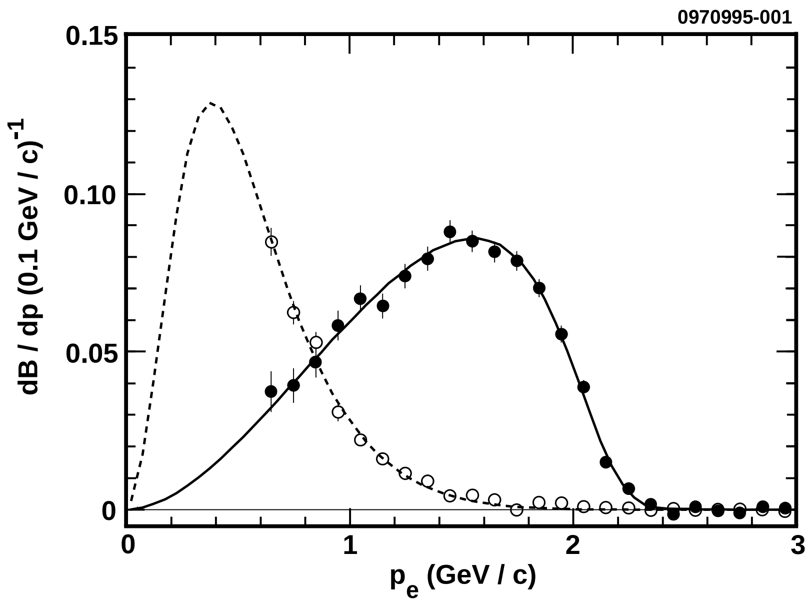
CLEO fits $D^* X \ell \nu$ systematic=0.3%

BELLE cuts systematic=1.2%

LEP systematic=1.2–5%

Inclusive Semileptonic Branching Fraction

Analyses by CLEO, BABAR, BELLE (ARGUS)



Use high p lepton to tag B

Measure second lepton

Separate primary • $b \to \ell X$

and secondary ∘ $b \to c \to \ell Y$

using charge and

angular correlations

CLEO PRL76 (1996)1570 (2 fb^{-1}) $\mathcal{B}(B \to Xe\nu) = (10.49 \pm 0.17 \pm 0.43)\%$

BELLE CONF-0123 (5 fb^{-1}) $\mathcal{B}(B \to Xe\nu) = (10.86 \pm 0.14 \pm 0.47)\%$

BABAR PRELIMINARY (5 fb^{-1}) $\mathcal{B}(B \to Xe\nu) = (10.82 \pm 0.21 \pm 0.38)\%$

Compare to

LEP Avg Working Group $\mathcal{B}(b \to X\ell\nu) = (10.59 \pm 0.09 \pm 0.15 \pm 0.26)\%$