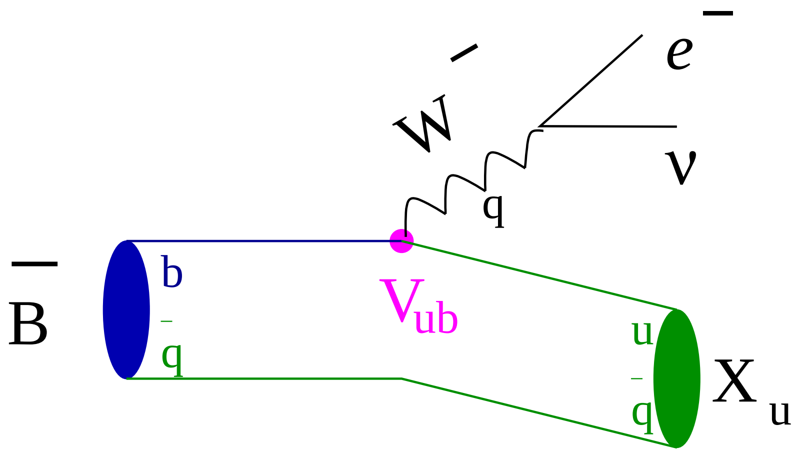
# $|V_{cb}|$, $|V_{ub}|$ and HQET at CLEO




**Karl Ecklund, Cornell University**

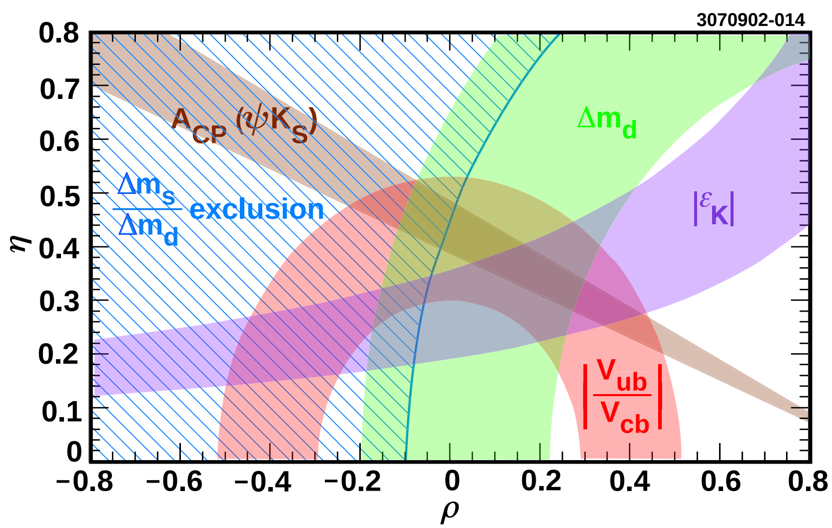
**July 17, 2003**

# $|V_{cb}|$ and $|V_{ub}|$ in the Unitarity Triangle

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

Precision measurements of $|V_{ub}|$ and $|V_{cb}|$ needed to test CKM paradigm for flavor mixing and $CP$ violation

Status of test: Unitarity Triangle; apex at $(\rho, \eta)$

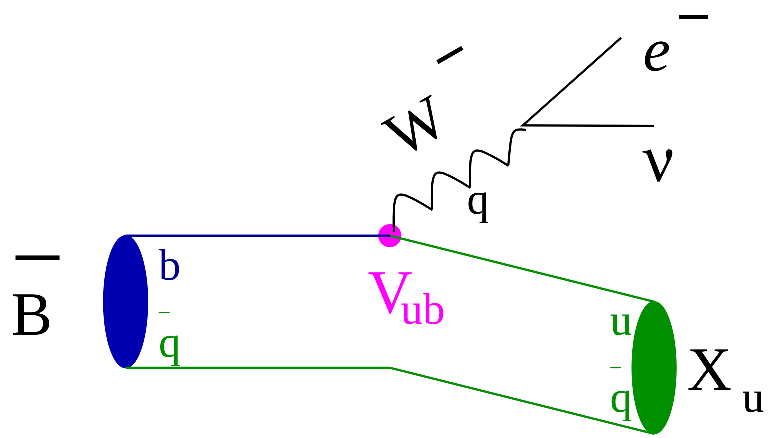



- Need sides and angles
- $|V_{cb}|$ is base of UT
- $|V_{ub}|$ is height of UT
- Tree level $b \to c\ell\nu$, $b \to u\ell\nu$:
  - New physics unlikely
  - No Final State Interactions
  - QCD corrections from theory

Non-perturbative QCD is hard: largest uncertainties

Must test predictions of theory and make multiple measurements!

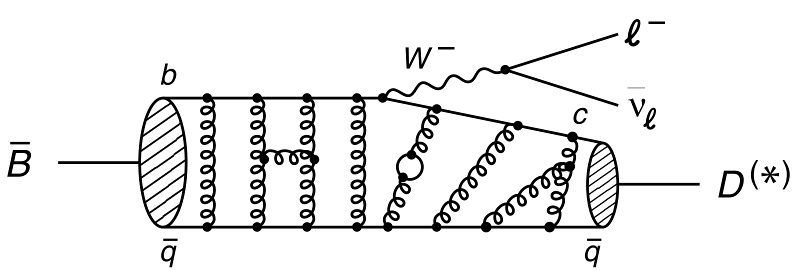
# CKM Measurements in Semileptonic $B$ Decays




In naive spectator picture the process is analogous to $\mu$ decay

$$\Gamma(b \to u\ell\nu) \approx \frac{G_F^2 m_b^5}{192\pi^3}|V_{ub}|^2$$

Rate gives $|V_{ub}|^2$




Complication!

QCD corrections are needed to extract weak decay physics

Both perturbative and non-perturbative QCD Corrections:

Directly calculate (e.g.,LQCD) or measure via symmetry-related processes

Use many techniques and compare results to gain confidence in QCD corr.

Two approaches: Exclusive and inclusive measurements

# Inclusive $b \to c\ell\bar{\nu}$

Rather than focusing on one hadronic final state,

Sum over all states and compare to quark-level calculation

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

Sum over hadronic states: $X_c^{(i)} = D, D^*, D^{**}, D\pi$ non-resonant, ...

Relies on assumption of quark-hadron duality

Hard to quantify; must be tested!

Fortunately there are other observables besides $\Gamma$

- lepton energy spectrum $d\Gamma/dE_\ell$
- hadronic recoil mass spectrum $d\Gamma/dM_X^2$

Measure these to constrain theory parameters and test consistency

## Theoretical Tools for Inclusive $b \to c\ell\bar{\nu}$

Heavy Quark Expansion in powers of $\Lambda_{QCD}/M_B$ and $\alpha_s$

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

At order $\Lambda_{QCD}/M$:

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

At order $\Lambda^2_{QCD}/M^2$:

$\lambda_1 = \frac{1}{2m_B}\left\langle B|\bar{h}(iD)^2 h|B\right\rangle$ - kinetic energy of $b$ quark in $B$ meson

$\lambda_2 = \frac{1}{6m_B}\left\langle B|\bar{h}\frac{g}{2}\sigma_{\mu\nu}G^{\mu\nu}h|B\right\rangle$ - hyperfine interaction of $b$ spin & light d.o.f.
(determine $\lambda_2 = 0.128 \pm 0.010$ GeV$^2$ from $B$–$B^*$ mass splitting)

At order $\Lambda^3_{QCD}/M^3$:

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

and so on ... [*c.f.* Manohar and Wise, *Heavy Quark Physics*]

Use HQE/OPE tools to calculate 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 $\bar B \to X_c \ell \bar\nu$:

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

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

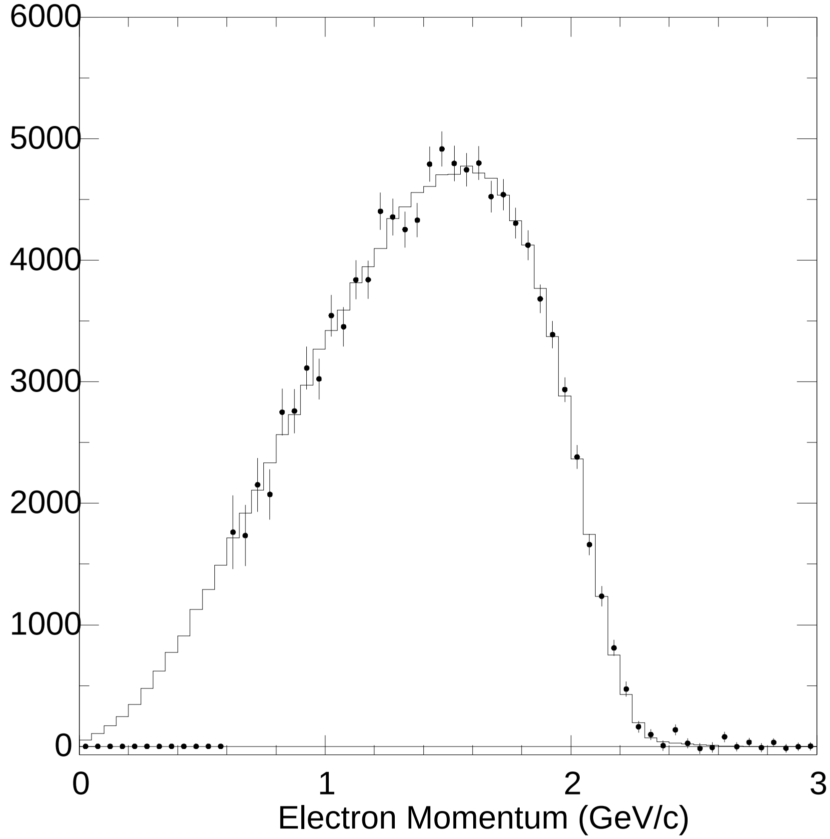
Example:

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

Measure $\langle M_X^2\rangle$, $\langle E_\gamma\rangle$, $\langle E_\ell\rangle$ to overdetermine $\lambda_1$, $\bar\Lambda$

Add $\Gamma_{\rm SL}$ to make a model-independent measurement of $|V_{cb}|$

# Measurement of Semileptonic Branching Fraction




- Update of PRL 76, 1570 (1996)
- 10 $\mathrm{fb}^{-1}$ of $B\bar{B}$ data
- $p > 1.4$ GeV/$c$ lepton tag
  98% $B \to X\ell\nu$; $Q_\ell$ =flavor tag
- Additional electron (un)like sign
- Remove backgrounds
- Unfold primary and secondary leptons using charge, kinematic correlations
- Correct for $B^0$–$\bar{B}^0$ mixing

$\mathcal{B}(B \to Xe^+\nu) = (10.88 \pm 0.08 \pm 0.33)\%$ PRELIMINARY

Coming soon: Spectral moments for $E_\ell^{\mathrm{min}} = 0.6$ GeV

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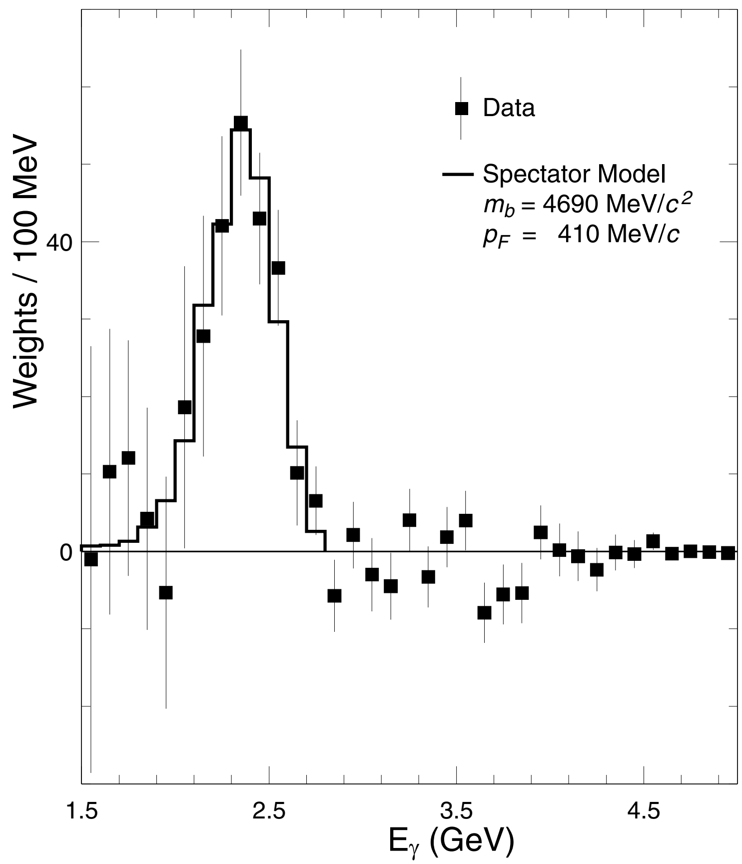
# $B \to X_s\gamma$: $E_\gamma$ Moments




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 $\bar{\Lambda}$

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

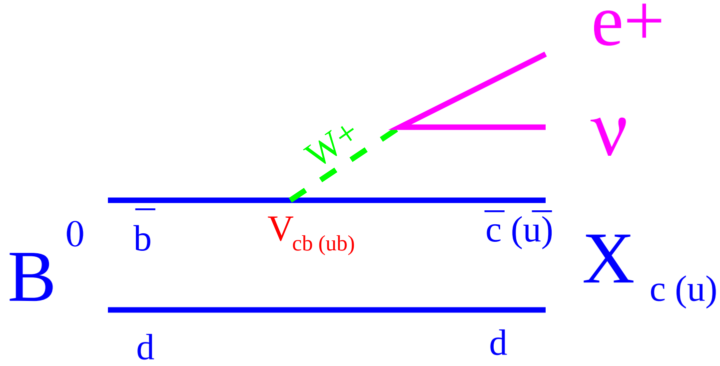
Theory: Bauer PRD57, 5611 (1998)

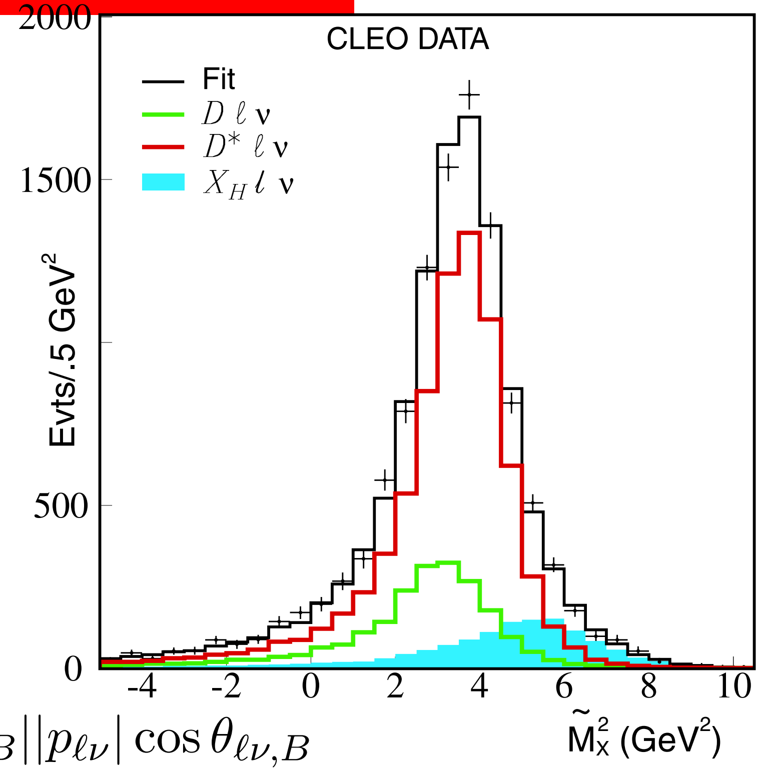
Ligeti *et al.*, PRD60, 034019 (1999)

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

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

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




CLEO PRL 88, 251808 (2001)

Require $E_\ell > 1.5$ GeV

$(P_\nu, E_\nu)$ from hermetic detector

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

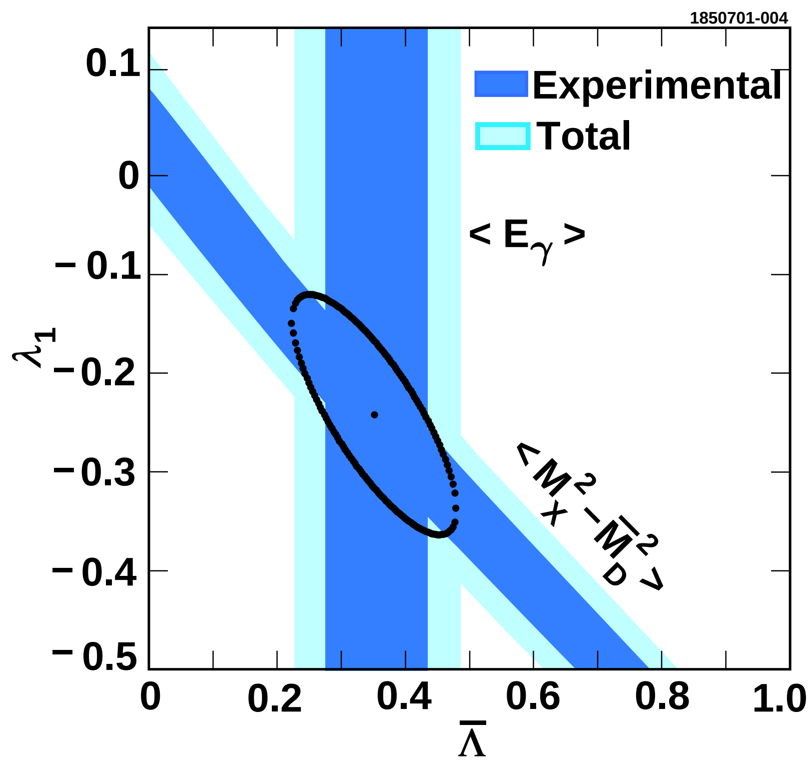
$$\approx \widetilde{M_X^2} = M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu}$$

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

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

Spin-averaged $D$ mass:
$\overline{M_D} = (M_D + 3M_{D^*})/4$
BaBar agrees on $\langle M_X^2 \rangle$ for $E_\ell > 1.5$ GeV

# Determination of $\bar{\Lambda}$ and $\lambda_1$




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

$\mathcal{B}(B \to X_c\ell\nu) = (10.77 \pm 0.34)\%$

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

and $\tau_B$ (PDG2003) to find

$\Gamma_{\rm SL} = (0.442 \pm 0.014) \times 10^{-10}$ MeV

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

$|V_{cb}| = (41.1 \pm 0.5 \pm 0.7 \pm 0.8) \times 10^{-3}$

(M) (Γ) (T)

2.9% determination of $|V_{cb}|$

Largest uncertainty from unknown theory parameters at $\mathcal{O}(1/M^3)$

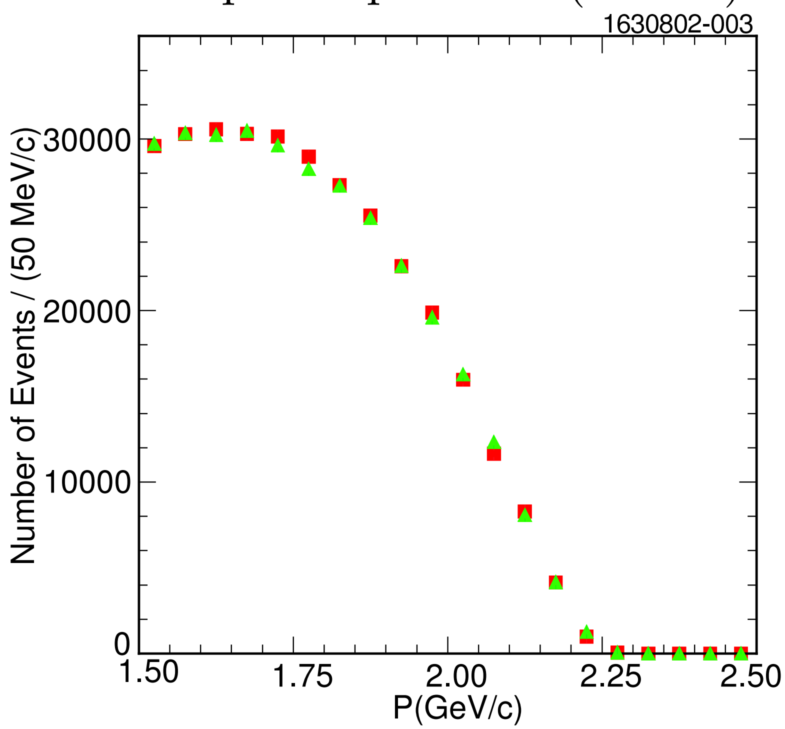
$E_\ell$ moments also sensitive to $\bar{\Lambda}, \lambda_1$

How consistent?

# $B \to X_c \ell \nu$: $E_\ell$ Moments

PRD 67,072001(2003) EPS Abstract 124

CLEO Lepton Spectrum (3 fb$^{-1}$)



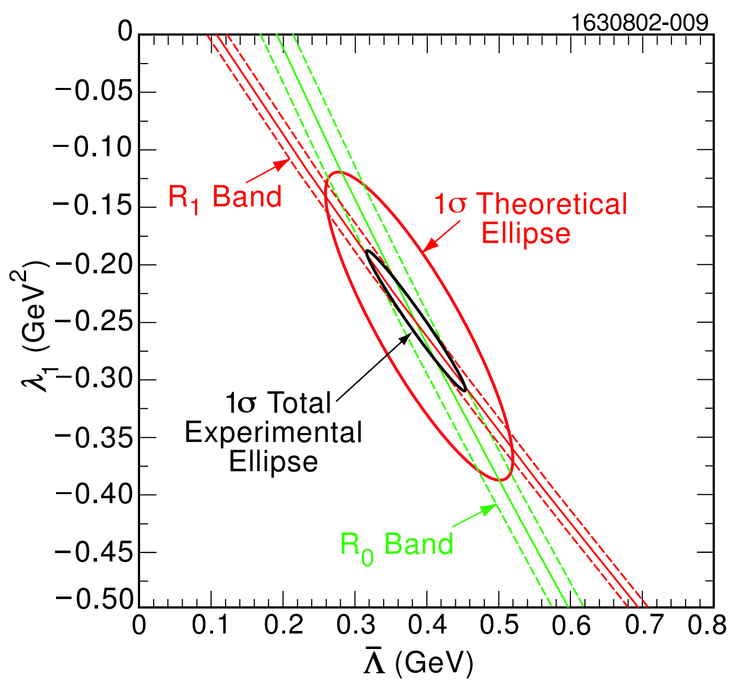

| | $R_0$ | $R_1$ (GeV) |
|---|---|---|
| Electrons | 0.6184(16)(17) | 1.7817(08)(10) |
| Muons | 0.6189(23)(20) | 1.7802(11)(11) |
| Combined | 0.6187(14)(16) | 1.7810(07)(09) |

Generalized Energy Moments:

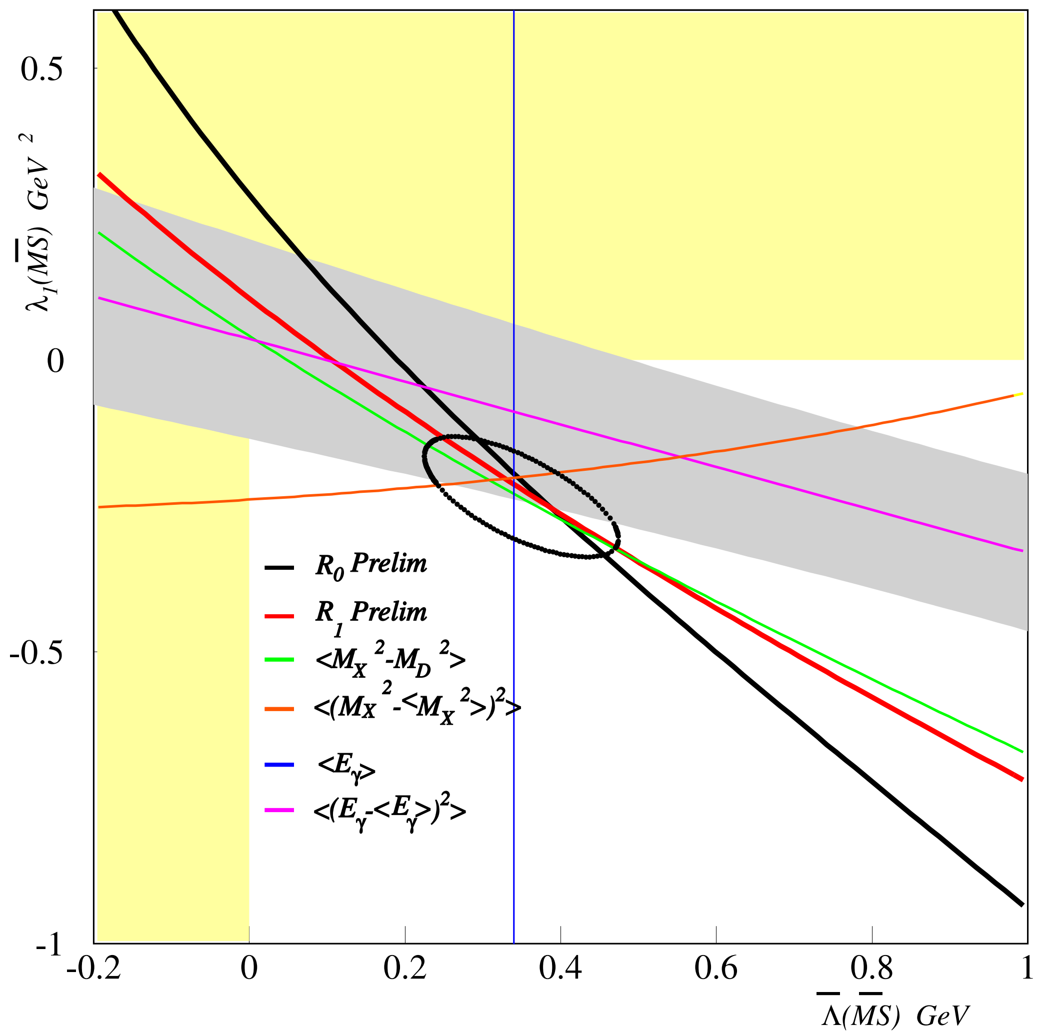
Gremm *et al.* PRL**77**,20 (1996)

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

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



# Comparing Constraints on $\bar{\Lambda}, \lambda_1$




Moment Measurements from CLEO

All in agreement!
Worst within 1 $\sigma$ (E+T)
$\langle(E_\gamma - \langle E_\gamma\rangle)^2\rangle$

Ellipse shows E+T from $\langle E_\gamma\rangle$ and $\langle M_X^2\rangle$

So far inclusive method looks good, but ...

- Uncertainties still large
- Hints of trouble for $\langle M_X^2\rangle$ as $E_\ell^{\min}$ is lowered (BaBar@ICHEP02)

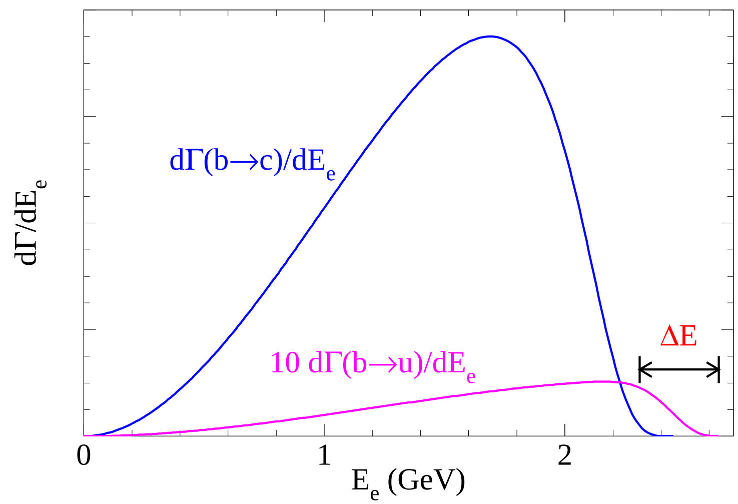
# $|V_{cb}|$ Summary

| Measurement | $\lvert V_{cb}\rvert \times 10^3$ | $\delta\lvert V_{cb}\rvert/\lvert V_{cb}\rvert$ |
|---|---|---|
| CLEO $\bar{B} \to X_c \ell \bar{\nu}$ | $(41.1 \pm 0.9 \pm 0.8)$ | 2.9% |
| HFAG Average $\bar{B} \to D^* \ell \bar{\nu}$ | $(42.4 \pm 1.2 \pm 1.9)$ | 5.2% |

- Inclusive techniques more precise but rely on theoretical framework
- Spectral Moments probe HQ expansion for non-perturbative physics
  - two moments determine two parameters at $\mathcal{O}(1/M^2)$
  - additional moments now overconstrain and test consistency
- Exclusive/Inclusive agreement tests quark-hadron duality
- Hints of a discrepancy for $\bar{B} \to D^* \ell \bar{\nu}$
  - HFAG Average 2.9% C.L. — CLEO finds larger $|V_{cb}|$
- Expect to hear more from CLEO on inclusive analyses soon:
  - $\langle E_\ell \rangle$ from spectrum above 0.6 GeV – $\langle M_X^2 \rangle$ for $E_\ell > 1.0$ GeV

# $|V_{ub}|$ from lepton spectrum and $b \to s\gamma$

From Leibovich hep-ph/0011181




To measure $b \to u\ell\nu$

Must suppress $b \to c\ell\nu$

Cutting on $E_\ell$ introduces problems:

- Large model dependence (What fraction above cut?)
- At edge of spectrum sensitive to $b$ quark motion

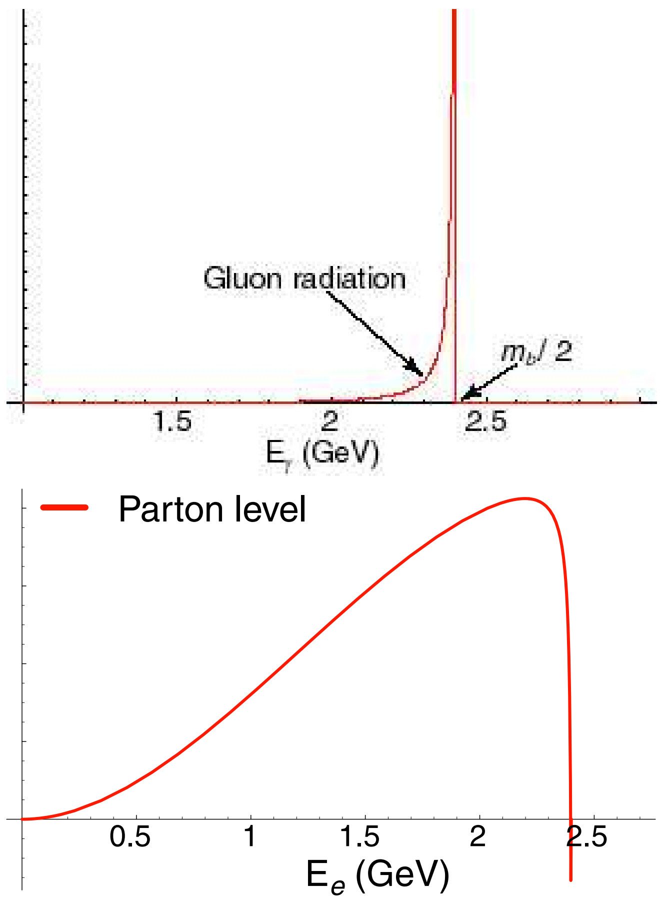
Idea: Reduce problems by using $b \to s\gamma$ photon spectrum

To first order same non-perturbative QCD effects smear the spectra

Both are heavy→light decays $(m_s, m_u, m_\ell, m_\nu \approx 0)$

Neubert; Bigi, Shifman, Uraltsev, Vainshtein; Leibovich, Low, Rothstein

# How $B \to X_s\gamma$ helps $|V_{ub}|$




Parton Level

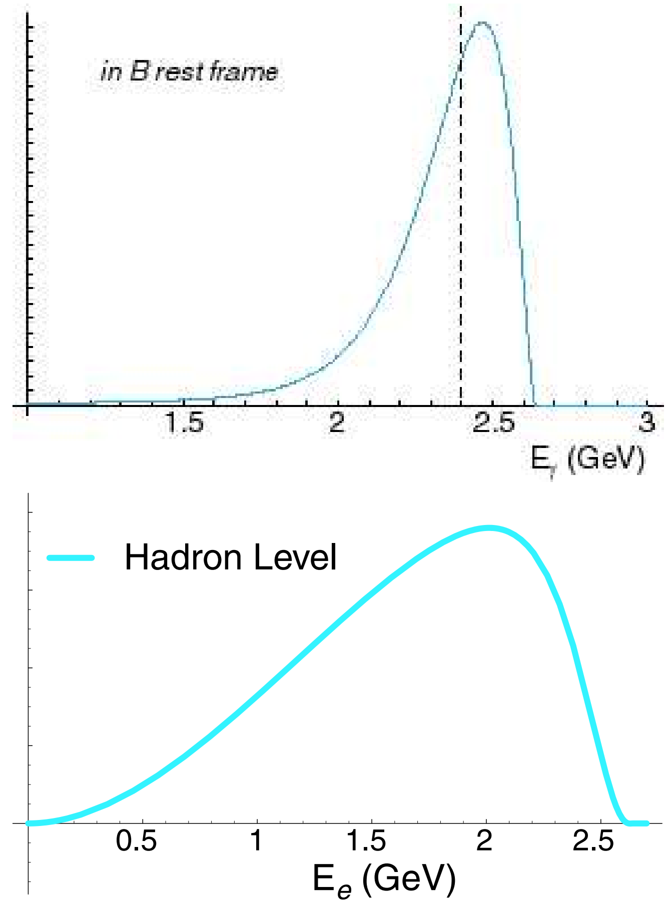
$B \to X_s\gamma$

$\Longrightarrow$

Smearing from b-quark motion in $B$

$\Longrightarrow$

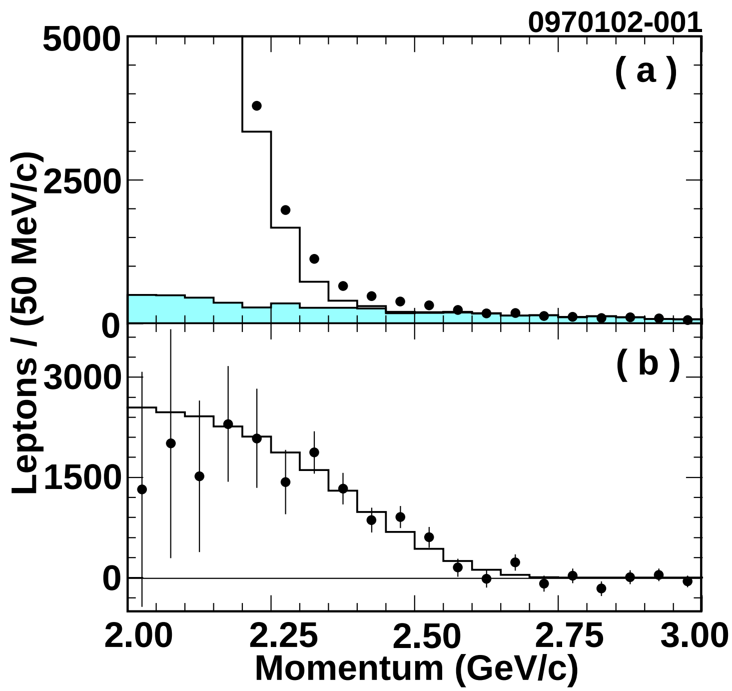
$B \to X_u\ell\nu$




Hadron Level

$b \to s\gamma$ is sort of a Green's function for smearing

# $|V_{ub}|$ from lepton spectrum and $b \to s\gamma$




In $(2.2 < p_\ell < 2.6)$ GeV/$c$

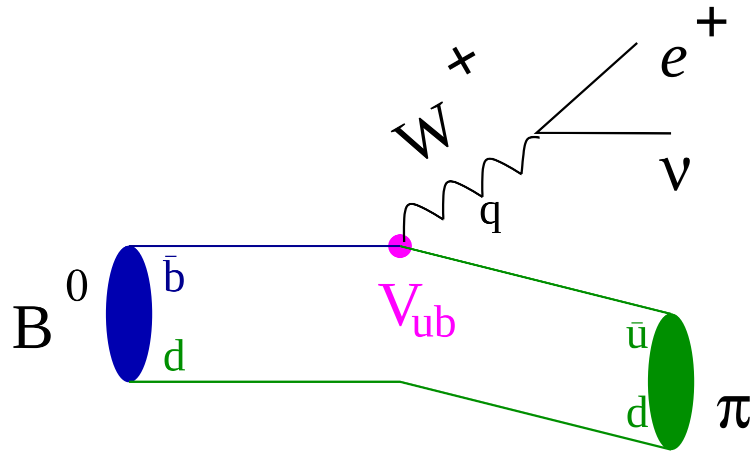
- suppress and subtract $q\bar{q}$ (cyan)
- subtract $B \to X_c \ell\nu$ yield (hist)
- $N_{ub} = 1901 \pm 122 \pm 256$ $B \to X_u \ell\nu$ events
- $\Delta\mathcal{B}_u = (2.30 \pm 0.15 \pm 0.35) \times 10^{-4}$
- From the $b \to s\gamma$ spectrum $f_u = 0.130 \pm 0.024 \pm 0.015$

$\mathcal{B}(B \to X_u \ell\nu) = \Delta\mathcal{B}/f_u = (1.77 \pm 0.29_{\Delta\mathcal{B}} \pm 0.38_{f_u}) \times 10^{-3}$ implies

$|V_{ub}| = (4.08 \pm 0.34_{\text{exp}} \pm 0.44_{f_u} \pm 0.16_\Gamma \pm 0.24_{\Lambda/M_B}) \times 10^{-3}$

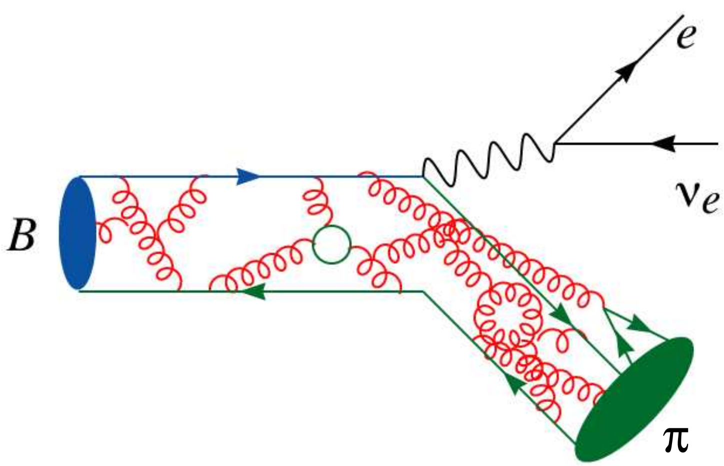
Improved 15% uncertainty CLEO, Phys. Rev. Lett. **88**, 231803 (2002)

# $|V_{ub}|$ from Exclusive Semileptonic $B$ Decays




$$\Gamma(b \to u\ell\nu) \approx \frac{G_F^2 m_b^5}{192\pi^3}|V_{ub}|^2$$

Rate gives $|V_{ub}|^2$




Once again,

QCD Corrections are needed to extract weak decay physics

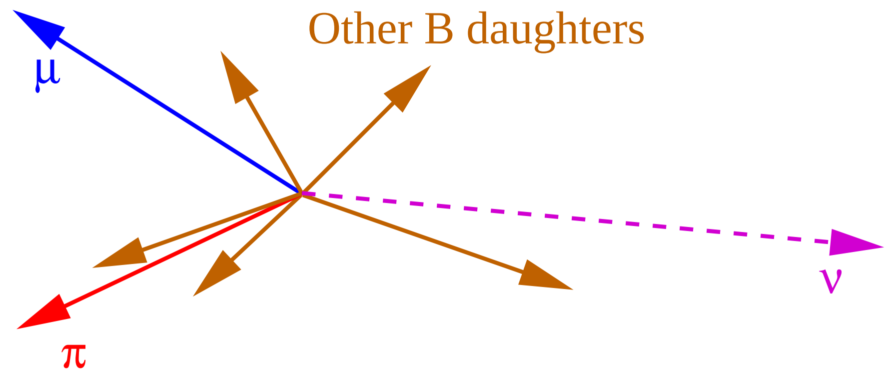
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 p_\pi^3}{24\pi^3}|f_1(q^2)|^2|V_{ub}|^2$$

Form factors needed from theory (LQCD, LCSR, quark models)

# Neutrino Reconstruction

Uses hermeticity of detector (CLEO 95% of $4\pi$):

- $E_{\text{miss}} = 2E_{\text{beam}} - \sum_i E_i$
- $\vec{p}_{\text{miss}} = -\sum_i \vec{p}_i$
- $\vec{p}_\nu \equiv \vec{p}_{\text{miss}};\ E_\nu \equiv |\vec{p}_{\text{miss}}|$ (better resolution than $E_{\text{miss}}$)
- $\sigma(\vec{p}_\nu) \approx 110$ MeV$/c$




Reject suprious tracks & shower fragments from hadronic interactions.

Gives powerful kinematic constraints for full reconstruction:

$$M_{m\ell\nu} = \sqrt{E_{\text{beam}}^2 - |\alpha\vec{p}_\nu + \vec{p}_\ell + \vec{p}_m|^2}$$
$$\Delta E = (E_\nu + E_\ell + E_m) - E_{\text{beam}}$$

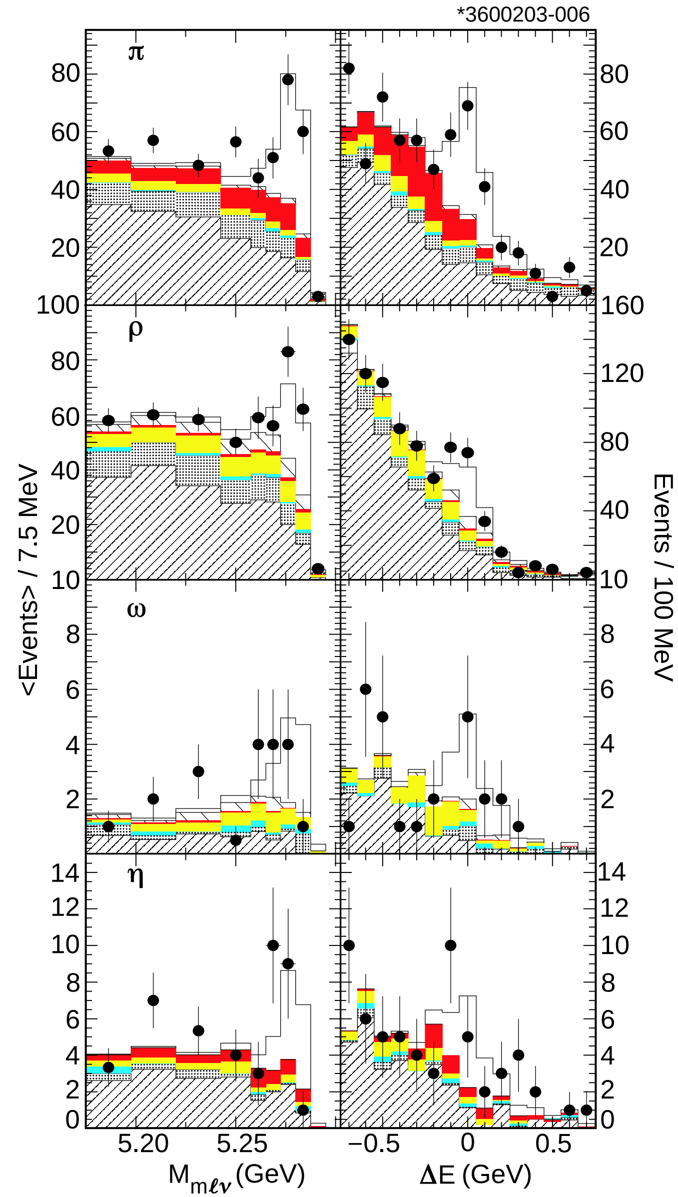
($\alpha$ rescales magnitude of $\vec{p}_\nu$ for slightly improved mass resolution)

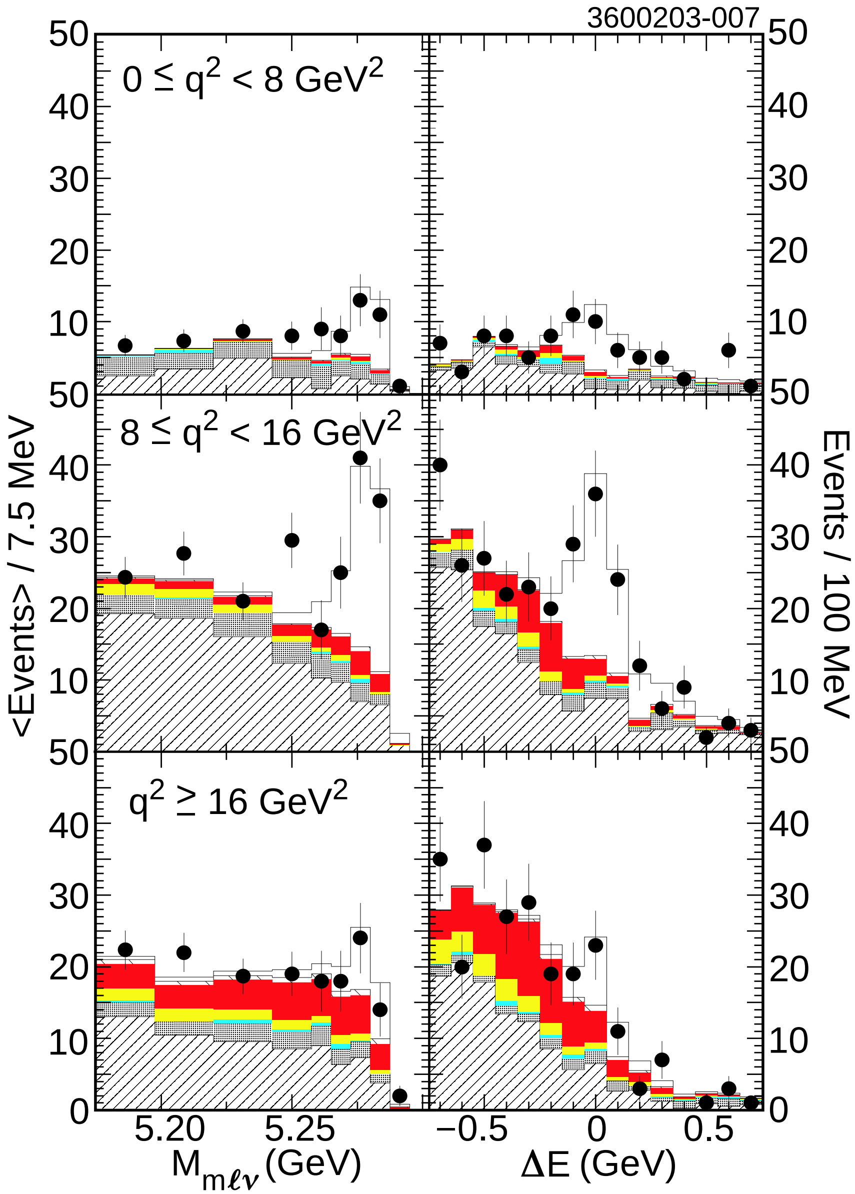
Energy and momentum conservation: $\Delta E \approx 0$, $M_{m\ell\nu} = M_B$ for signal

# Simultaneous Maximum Likelihood Fit

- $\Delta E, M_{m\ell\nu}$ variables
- 7 signal mode topologies $[\pi, \rho, \omega, \eta]\ell\nu$
- Isospin & quark symmetry constraints:
  - $\Gamma(\pi^-) = 2\Gamma(\pi^0)$
  - $\Gamma(\rho^-) = 2\Gamma(\rho^0) = 2\Gamma(\omega)$
- 3 $q^2$ bins for $\pi$ and $\rho$
- Net event charge $|\Delta Q| = 0, 1$
- Accounts for crossfeed

  $\pi \rightarrow \rho$, $\rho \rightarrow \pi$ etc



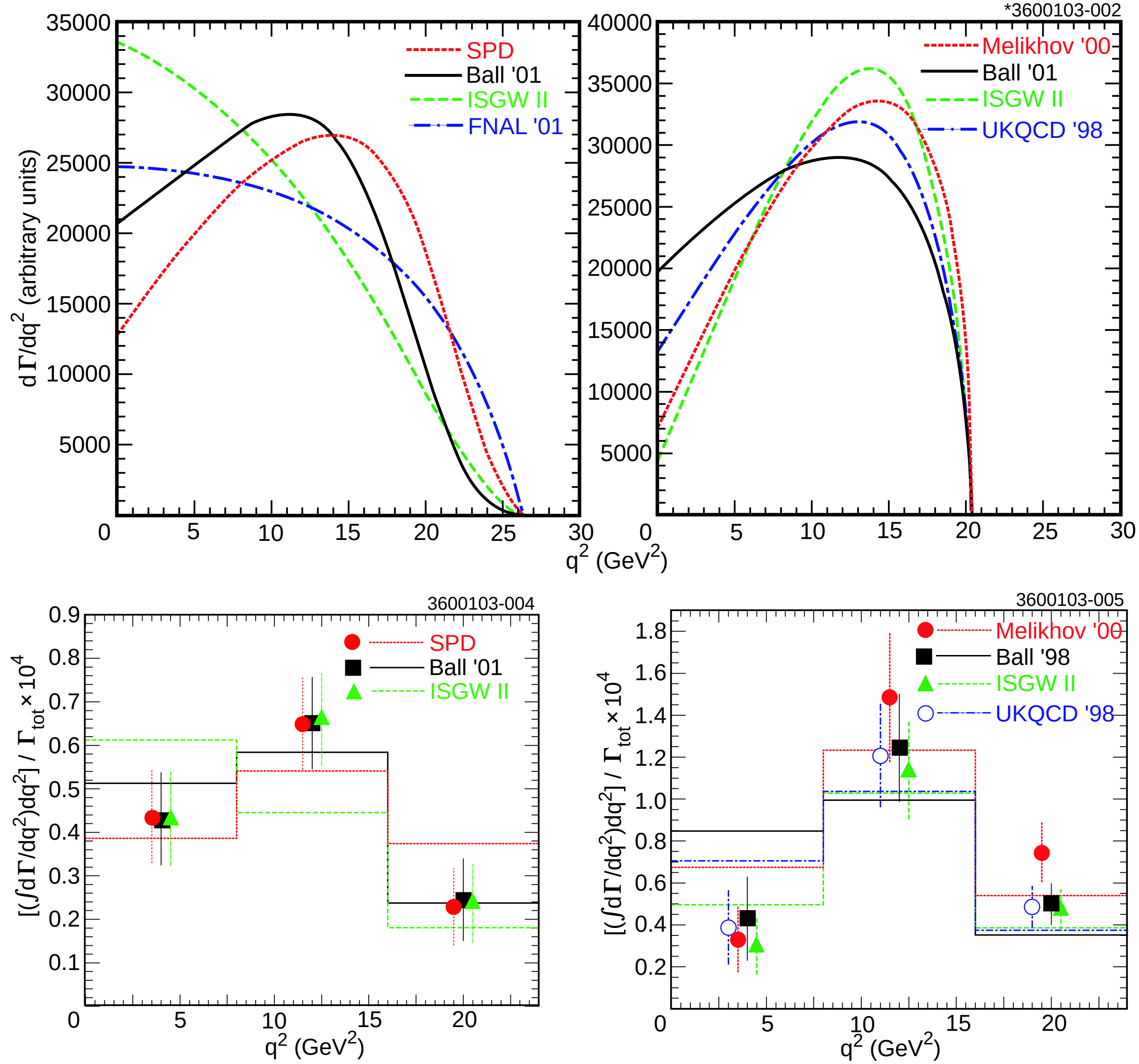



## $B \to \pi\ell^+\nu$ $q^2$ binning

Projections show $\Delta Q = 0$ ($|\Delta Q| = 1$ also in fit)

- points on-resonance data
- open histogram signal
- red histogram cross-feed from $V$ or $\eta$ modes
- yellow $B \to X_u \ell\nu$ other
- cyan fakes
- black continuum
- hatched $b \to c$

$B \longrightarrow \pi\ell\nu$ $B \longrightarrow \rho\ell\nu$




Fit $\frac{d\Gamma}{dq^2}$

- discriminate amongst FFs
- extract $|V_{ub}|$

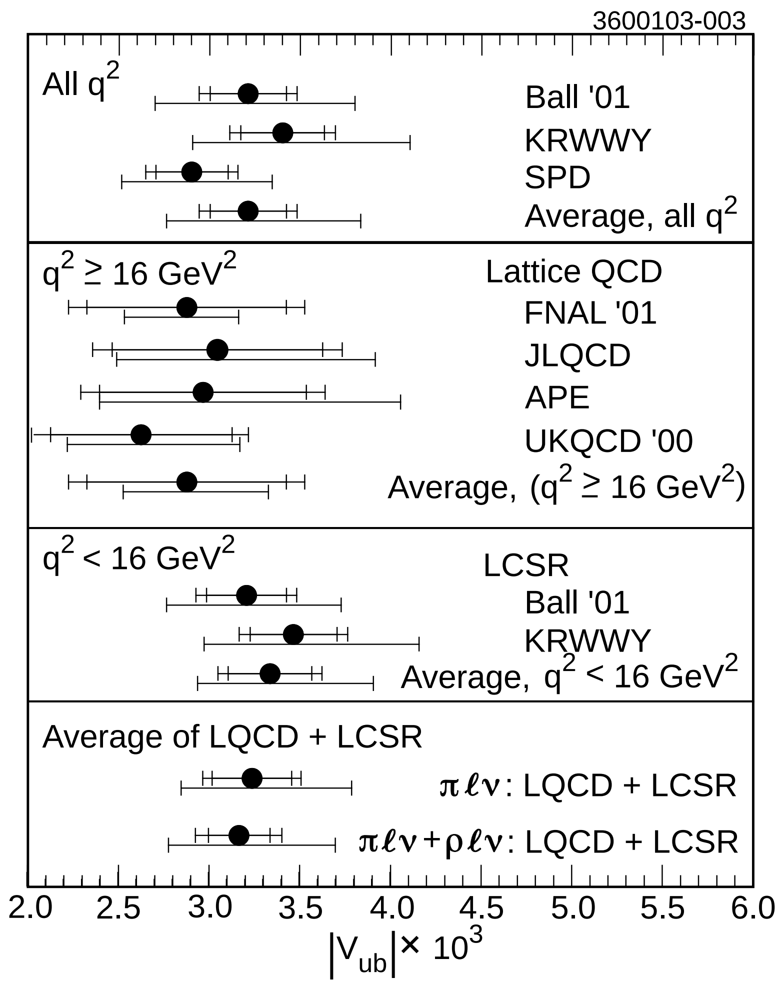
$B \rightarrow \pi\ell\nu$

- small FF dependence
- ISGW II is disfavored

$B \rightarrow \rho\ell\nu$

- larger FF dependence

# Extractions of $|V_{ub}|$ from $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$




hep-ex/0304019, to appear in PRD

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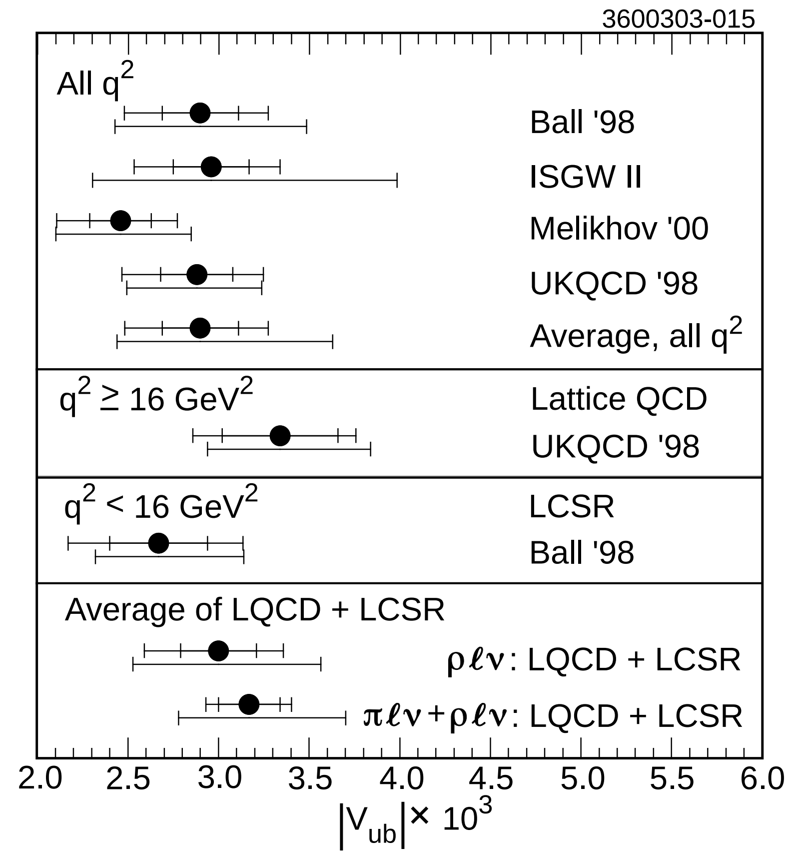



$|V_{ub}| = (3.17 \pm 0.17 \; ^{+0.16}_{-0.17} \; ^{+0.53}_{-0.39} \pm 0.03) \times 10^{-3}$ ($\pi + \rho$ LQCD+LCSR)

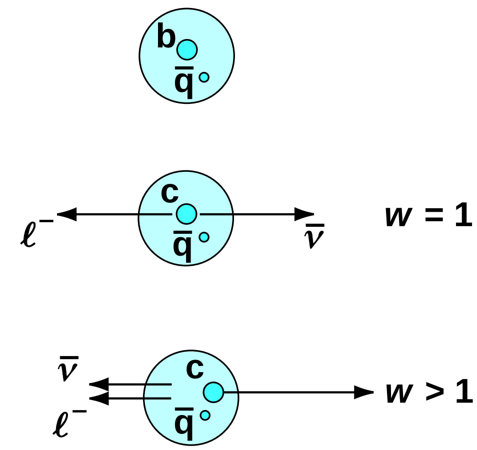
+18% -14% measurement of $|V_{ub}|$, dominated by theory uncertainty

# Summary and Outlook

- CLEO continues to contribute to $|V_{ub}|$ and $|V_{cb}|$ determination
- Most results are limited by systematic and theory uncertainties
- Analyses using mature data and MC samples
  - Inclusive and Exclusive techniques
  - Moments and Rates in inclusive semileptonic $B$ decays
  - Obtain $|V_{cb}|(\sigma \approx 3\%)$ and $|V_{ub}|(\sigma \approx 15\%)$
  - Insight into CKM electroweak and QCD physics
- Techniques to reduce non-perturbative QCD uncertainties
  - Use of $b \to s\gamma$ photon spectrum
  - Measurement of partial rates, testing form factors
- Future progress on CKM physics from CLEO
  - New CLEO $B$ analyses – CLEO-c: CKM, QCD in charm decays

# Backup Slides

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




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

The decay rate is given by

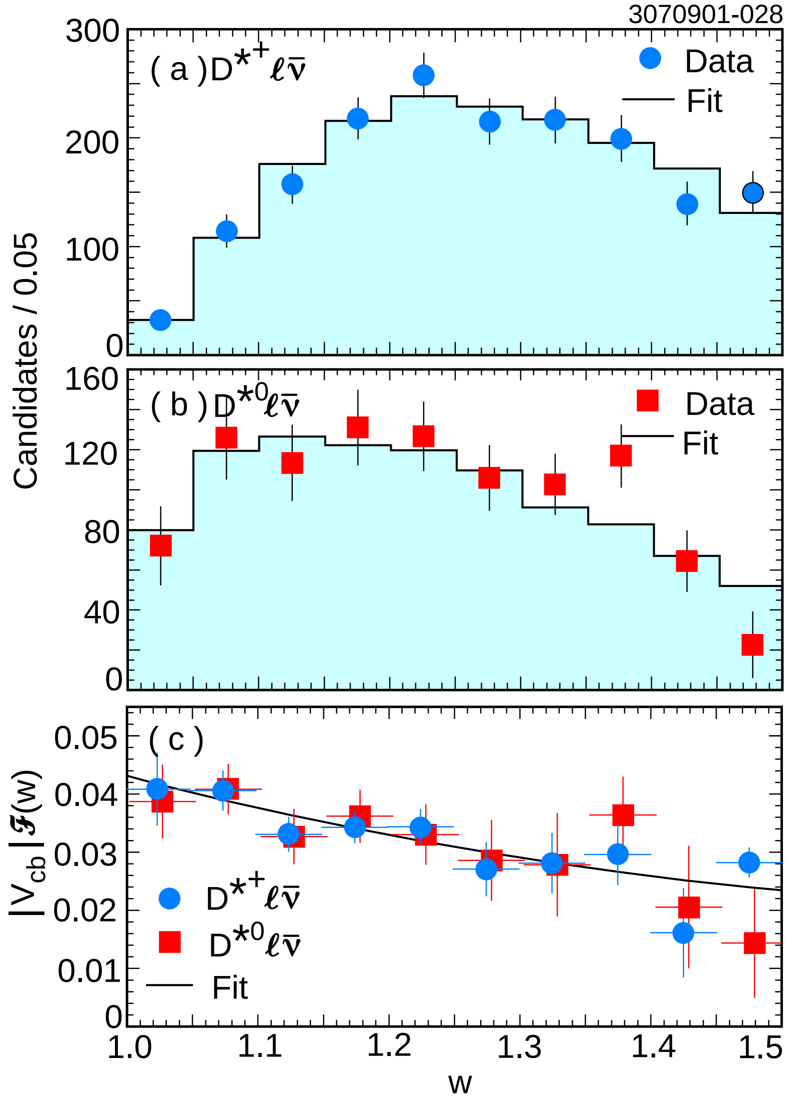
$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3}|V_{cb}|^2[\mathcal{F}(w)]^2\mathcal{K}(w)$$

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

- $\mathcal{K}(w)$ 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 $\mathcal{F}(1)|V_{cb}|$.

## CLEO $\bar{B} \to D^*\ell\bar{\nu}$ PRL **89**, 081803 (2002) & PRD **67**, 032001 (2003)




(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)
- $\rho^2_{A_1}$ (slope)

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

$\rho^2_{A_1} = 1.61 \pm 0.09 \pm 0.21$

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

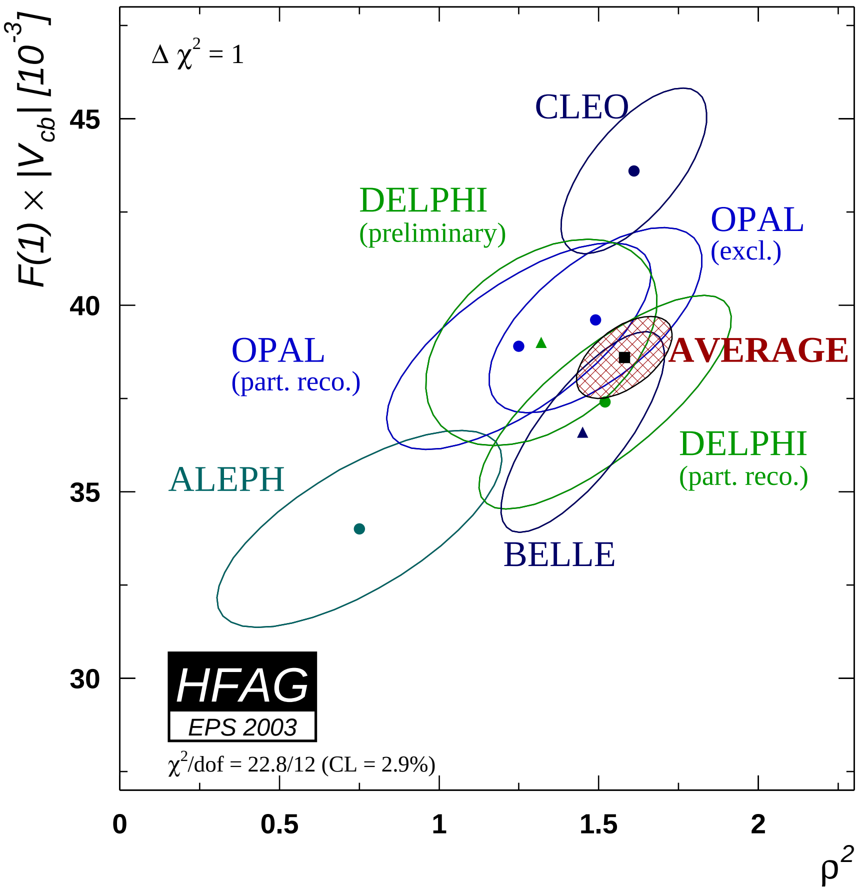
$|V_{cb}| = (47.4 \pm 1.4 \pm 2.0 \pm 2.1) \times 10^{-3}$

6.7% precision

Systematics! efficiency, bkgds, BFs

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

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




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

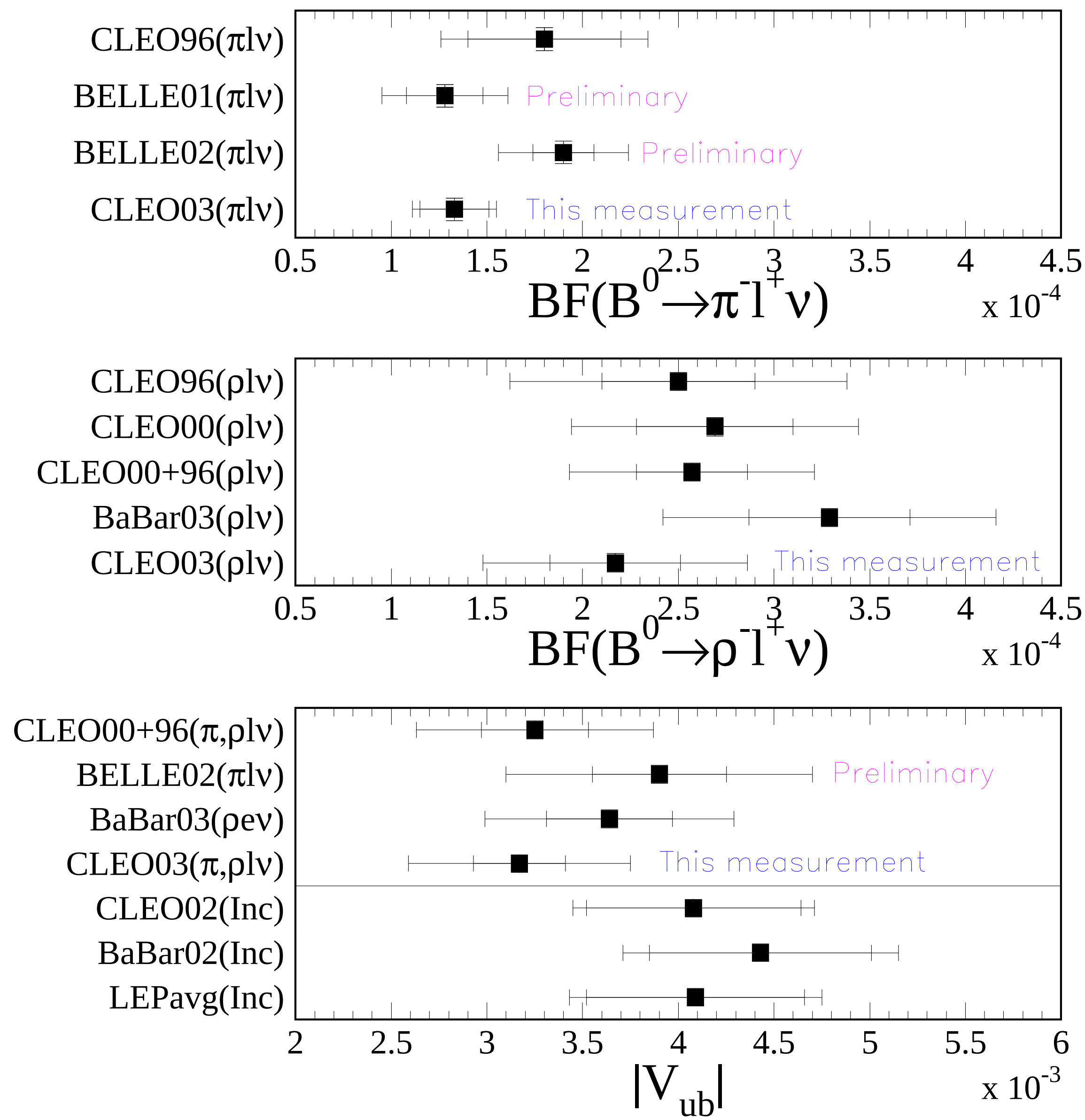
HFAG Combined 2d-fit accounts for correlations (stat&syst) among expts. Currently 3% C.L.

N.B. CLEO

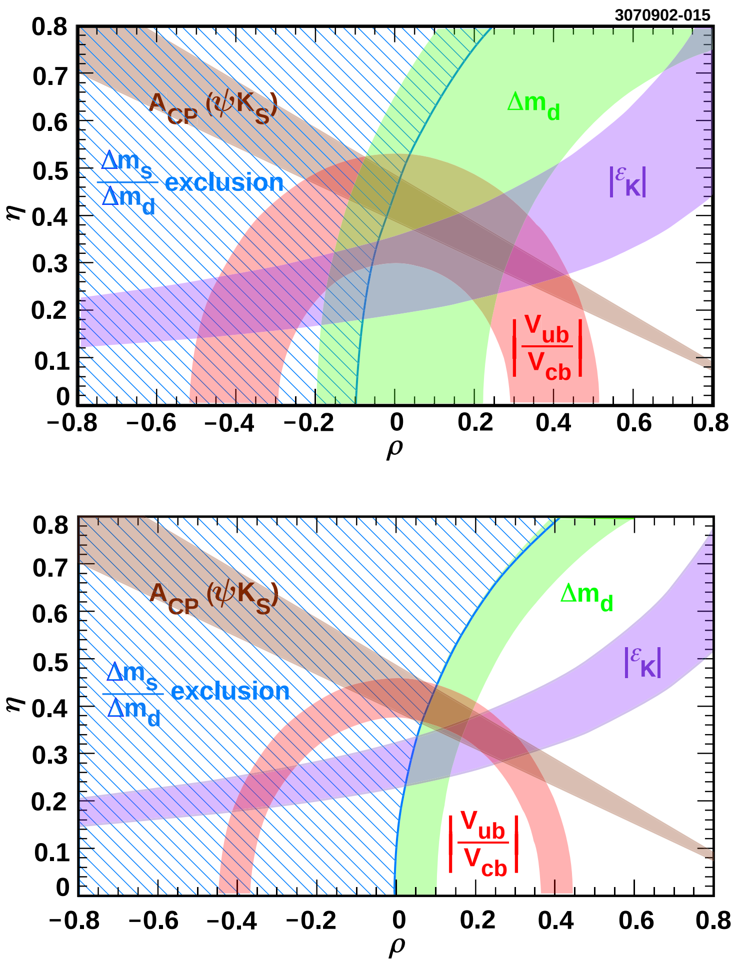
- Includes $D^{*0}$
- Fits data simultaneously for $D^* X \ell \nu$ background

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

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


CLEO96(πlv)
BELLE01(πlv)
Preliminary
BELLE02(πlv)
Preliminary
CLEO03(πlv)
This measurement
0.5 1 1.5 2 2.5 3 3.5 4 4.5
BF(B0→π-l+ν)
x 10-4
CLEO96(ρlv)
CLEO00(ρlv)
CLEO00+96(ρlv)
BaBar03(ρlv)
CLEO03(ρlv)
This measurement
0.5 1 1.5 2 2.5 3 3.5 4 4.5
BF(B0→ρ-l+ν)
x 10-4
CLEO00+96(π,ρlv)
BELLE02(πlv)
Preliminary
BaBar03(ρeν)
CLEO03(π,ρlv)
This measurement
CLEO02(Inc)
BaBar02(Inc)
LEPavg(Inc)
2 2.5 3 3.5 4 4.5 5 5.5 6
|Vub|
x 10-3

# CLEO's Future in CKM Physics




Apart from $\sin 2\beta$, CKM constraints are limited by QCD corrections. CLEO-c program of weak decay physics at charm threshold can help validate those QCD calculations.

- $D^+$ and $D_s^+$ decay constants help limits from $B$ oscillations
- semileptonic $D$ decay form factors help in $B$ decays, $|V_{ub}|$
- charm branching fractions $(D^0 \to K^-\pi^+)$ help $|V_{cb}|$

Impact of shrinking theory uncertainties only shown on bottom.