$|V_{cb}|$ and $|V_{ub}|$ from CLEO

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For the CLEO Collaboration

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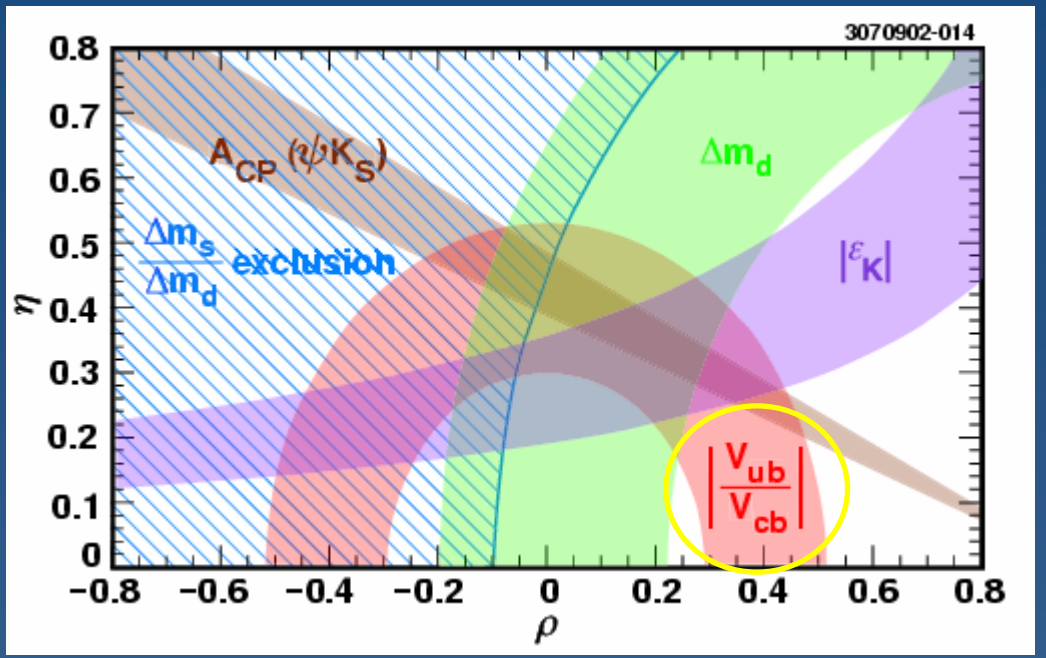
Motivation & Outline ~ Current ρ - η Plane, CKM Unitarity Triangle

Goal: overconstrain plane in many ways

sin 2β well-measured (BaBar/Belle)
and theoretically clean

$|V_{ub} / V_{cb}|$ side needs greater precision:

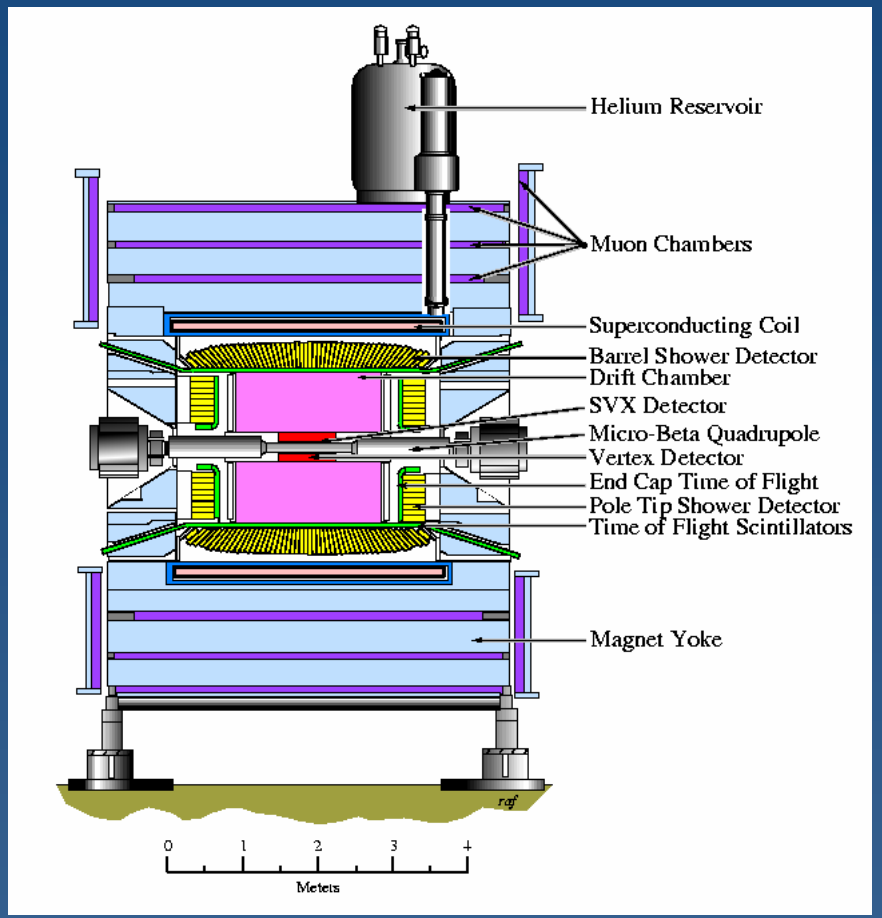
- CLEO is pioneering techniques
- Recent and ongoing theoretical advances



Recent CLEO results in semileptonic B-meson decays:

- Spectral moments to extract non-perturbative QCD parameters
- Improved inclusive $|V_{cb}|$ measurements
- Exclusive $|V_{cb}|$: $B \to D^* \ell \nu$
- Improved inclusive $|V_{ub}|$ from lepton energy endpoint

New!
- Exclusive $|V_{ub}|$ and reduced model dependence: $B \to [\pi, \rho, \omega, \eta] \ell \nu$
- Future of $|V_{cb}|$ and $|V_{ub}|$



CLEO II/II.V Detector and Datasets

CLEOII distinguished by:

- excellent CsI calorimeter
- ~95% hermeticity

← CLEOII.V distinguished by (in addition):

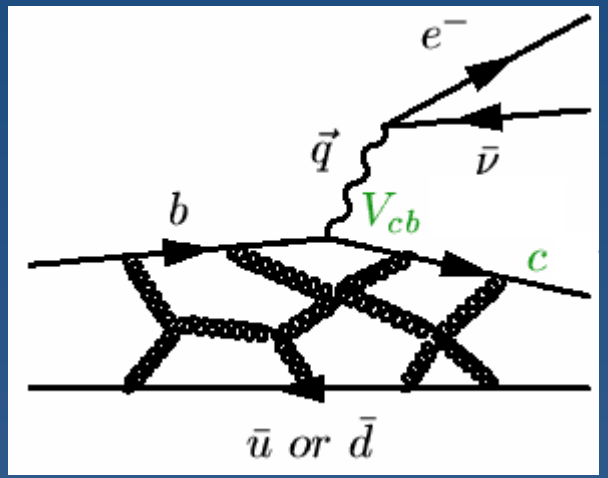
- first silicon vertex detector at $\Upsilon(4S)$
- first major use of He-based drift gas

Both detectors well-understood with mature Monte Carlo

Hadronic and leptonic moments of $B \to X_c \ell \nu$, and $B \to D^* \ell \nu$ use CLEOII:
(3.2 + 1.6) fb^{-1} (on + off res.) containing 3.4M $B\bar{B}$ pairs

$b \to s\gamma$, $b \to u \ell \nu$ endpoint and $B \to [\pi, \rho, \omega, \eta] \ell \nu$ use CLEOII+II.V:
(9.2 + 4.5) fb^{-1} (on + off res.) containing 9.7M $B\bar{B}$ pairs

Inclusive $|V_{cb}|$: QCD Tools Required



HQET: Power-series expansions in $1/M_B$ and α_s

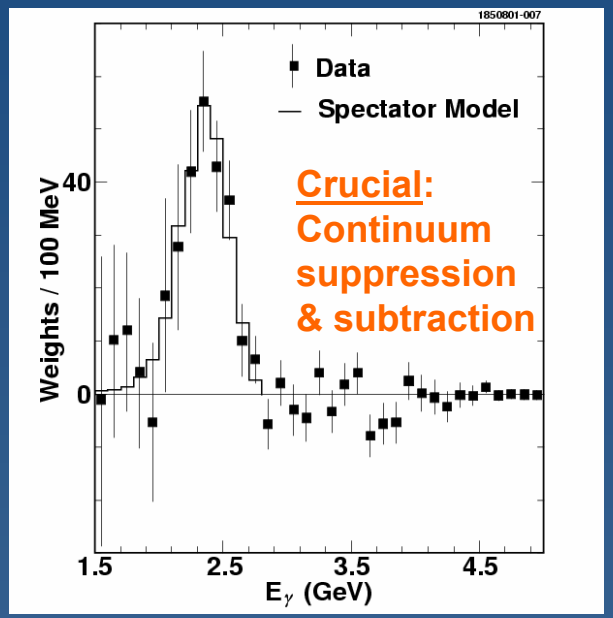
- Calculable inclusive observables in OPE, *e.g.*
  - **Spectral moments:**
    E_γ in $b \to s\gamma$; M_X^2 and p_ℓ in $B \to X \ell \nu$
  - **Semileptonic decay widths:** $\Gamma_{sl} \propto |V_{cb}|^2$
- 3 universal parameters encode non-perturbative QCD to order $1/M^2$
  - $\overline{\Lambda}$: **energy of light d.o.f. (b-quark pole mass)**
  - λ_1: **Fermi motion energy of b quark inside meson**
  - λ_2: **chromomagnetic interaction; known from *B*–B* mass difference**
- (Potential) issues
  - **Expansion convergence in some observables**
  - **Control of non-perturbative parameters at higher orders**
  - **Assumption of parton-hadron duality**

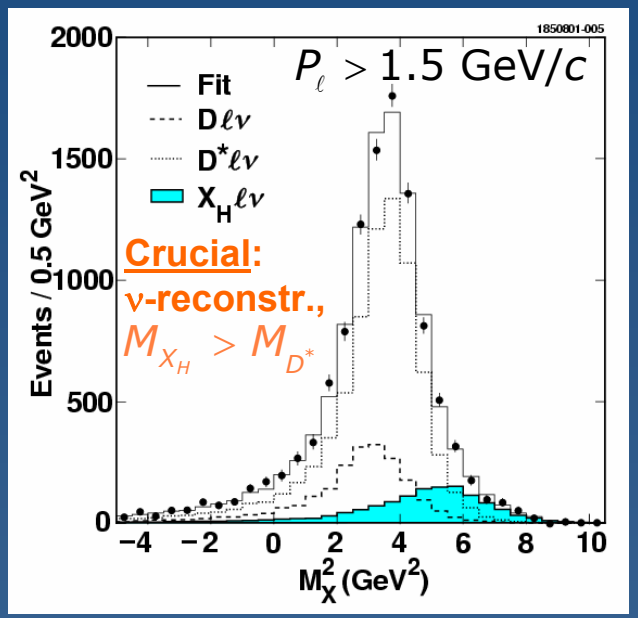
CLEO: Inclusive Measurements

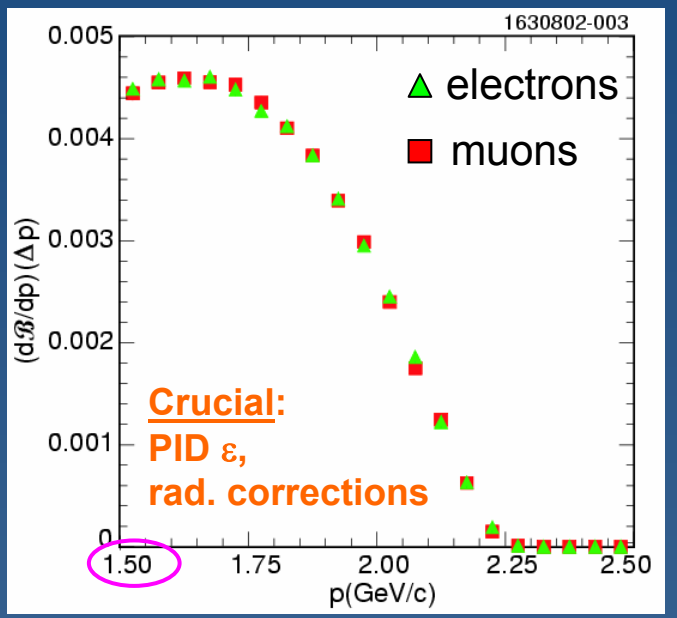
- Test theoretical consistency of non-pQCD parameters across
  - **Observables**
  - **Processes**
- Enable extraction of CKM matrix element $|V_{cb}|$
- Help to test assumption of parton-hadron duality

Spectral Moments leading to Non-pQCD HQET Parameters

E_γ from Inclusive $b \to s\gamma$ M_X^2 from Inclusive $B \to X\ell\nu$ p_ℓ from Inclusive $B \to X\ell\nu$







PRL 87, 251807 (2001)

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

$$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 = (2.26 \pm 0.66 \pm 0.20) \times 10^{-2} \quad \text{(GeV}^2\text{)}$$

PRL 87, 251808 (2001)

$$\langle M_X^2 - \bar{M}_D^2 \rangle = 0.251 \pm 0.023 \pm 0.062 \quad \text{(GeV}^2\text{)}$$

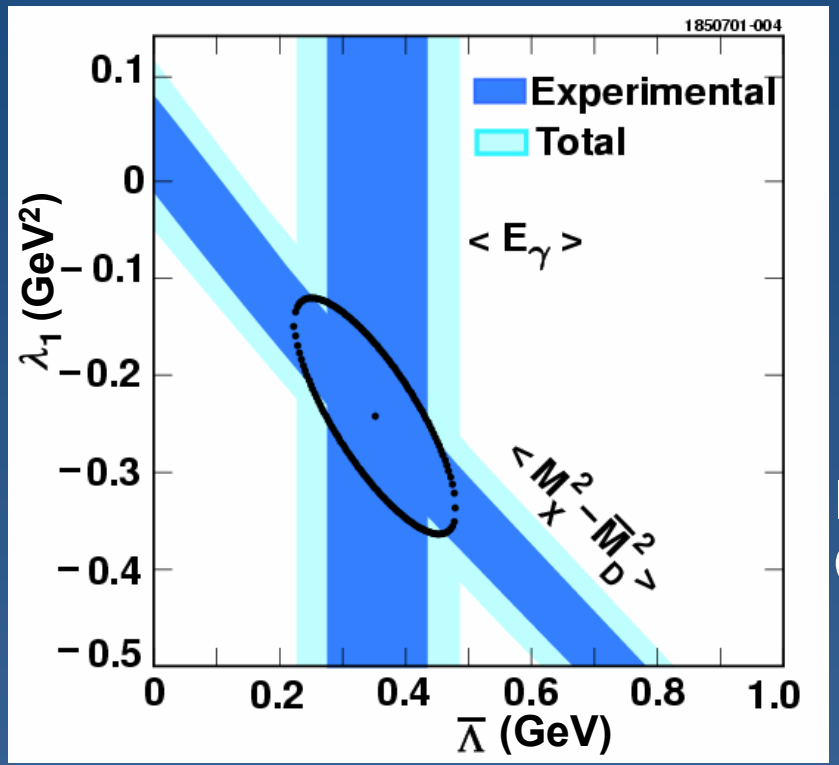
$$\langle (M_X^2 - \bar{M}_D^2)^2 \rangle = 0.639 \pm 0.056 \pm 0.178 \quad \text{(GeV}^4\text{)}$$

hep-ex/0212051; accepted by PRD

$$\frac{\int_{1.7} (d\Gamma_{sl}/dE_\ell)\,dE_\ell}{\int_{1.5} (d\Gamma_{sl}/dE_\ell)\,dE_\ell} = 0.6187 \pm 0.0014 \pm 0.0016$$

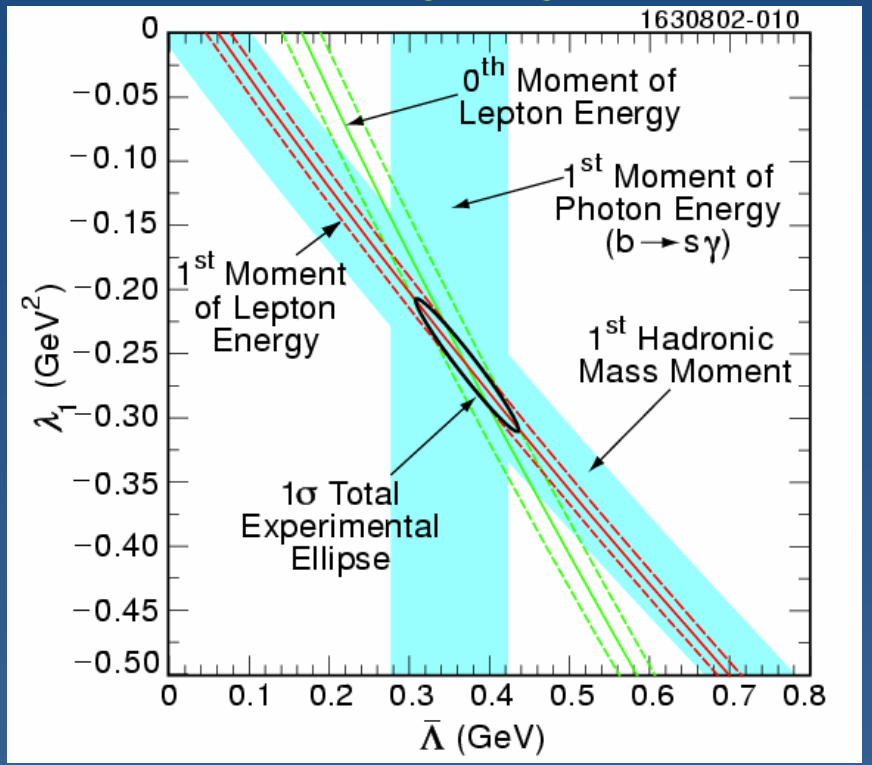
$$\frac{\int_{1.5} E_\ell\,(d\Gamma_{sl}/dE_\ell)\,dE_\ell}{\int_{1.5} (d\Gamma_{sl}/dE_\ell)\,dE_\ell} = 1.7810 \pm 0.0007 \pm 0.0009 \quad \text{(GeV)}$$

CLEO Constrains the λ_1 $\bar{\Lambda}$ Plane: Four Moments in Two Different Decay Types



$\overline{\text{MS}}$ Scheme
Order $1/M_B^3$
Order $\beta_0\alpha_s^2$

Independent
Consistency



γ-Energy & Hadronic-Mass 1st Moments

Lepton-Energy 0th and 1st Moments

$\bar{\Lambda} = 0.35 \pm 0.07 \pm 0.10$ GeV ↔ $\bar{\Lambda} = 0.39 \pm 0.03 \pm 0.06 \pm 0.12$ GeV

$\lambda_1 = -0.236 \pm 0.071 \pm 0.078$ GeV^2 ↔ $\lambda_1 = -0.25 \pm 0.02 \pm 0.05 \pm 0.14$ GeV^2

$|V_{cb}| = \left[40.4 \pm 0.9|^{\text{CLEO}}_{\Gamma_{sl}} \pm 0.5|^{\text{expt}}_{\bar{\Lambda},\lambda_1} \pm 0.8|^{\text{theo}}_{\alpha_s,M_B^{-3}} \right] \times 10^{-3}$ ↔ $|V_{cb}| = \left[40.8 \pm 0.5|^{\text{PDG}}_{\Gamma_{sl}} \pm 0.4|^{\text{expt}}_{\bar{\Lambda},\lambda_1} \pm 0.9|^{\text{theo}}_{\alpha_s,M_B^{-3}} \right] \times 10^{-3}$

(±3.2%) (±2.7%)

Exclusive $|V_{cb}|$

PRL 89, 081803 (2002); PRD 67, 032001 (2003)

Study $\bar{B} \to D^{*+}\ell\bar{\nu}$ and $\bar{B} \to D^{*0}\ell\bar{\nu}$ rates

HQET: predicts rate at negligible recoil

- w = 1
- $q^2 = q^2_{max}$

Fit Parameters

Intercept at w=1	Slope at w=1	$Br[\Upsilon(4S) \to B^+B^-]$
$\mathcal{F}(1)\lvert V_{cb}\rvert$	ρ^2	f_{+-}
$(4.31 \pm 0.13 \pm 0.18)\%$	$1.61 \pm 0.09 \pm 0.21$	0.521 ± 0.012

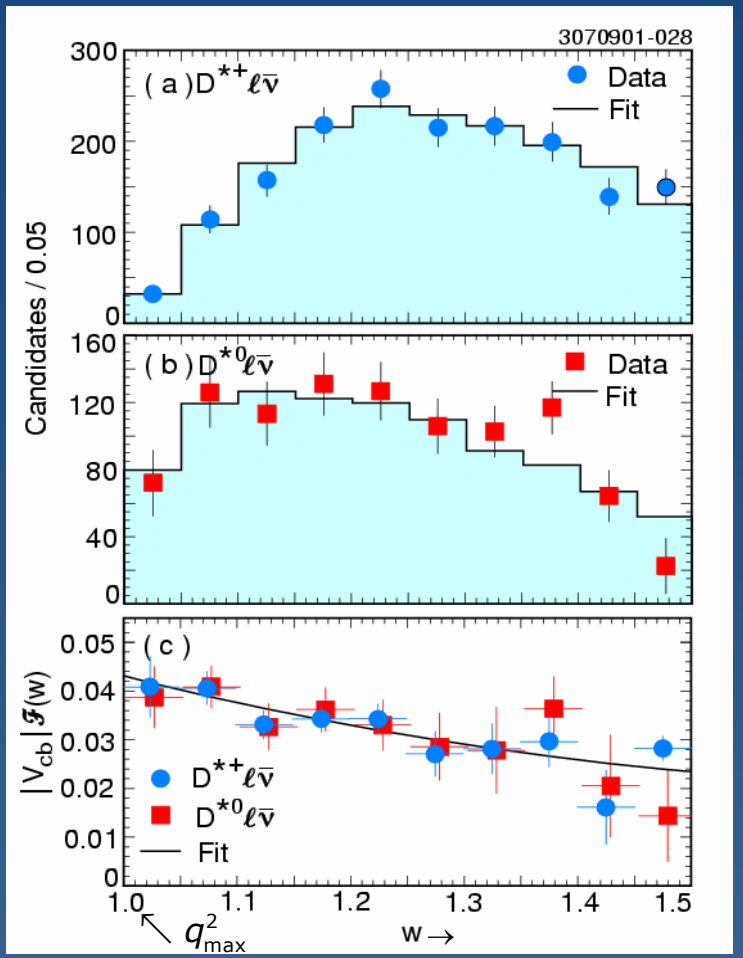
QED-Corrected FNAL Lattice Calculation

$\mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$

S. Hashimoto *et al.*, PRD 66, 014503 (2002)

Dominant Systematics

- Efficiency (*e.g.*, slow-pion tracking)
- Charm branching fractions
- Backgrounds
- Form factors (mostly for ρ^2)



$$|V_{cb}| = \left(\begin{array}{lll} 46.9 & \pm 1.4 & [stat] \\ & \pm 2.0 & [syst] \\ & \pm 1.8 & [theo] \end{array} \right) \times 10^{-3}$$

(±7% total)

Exclusive $|V_{cb}|$ Summary

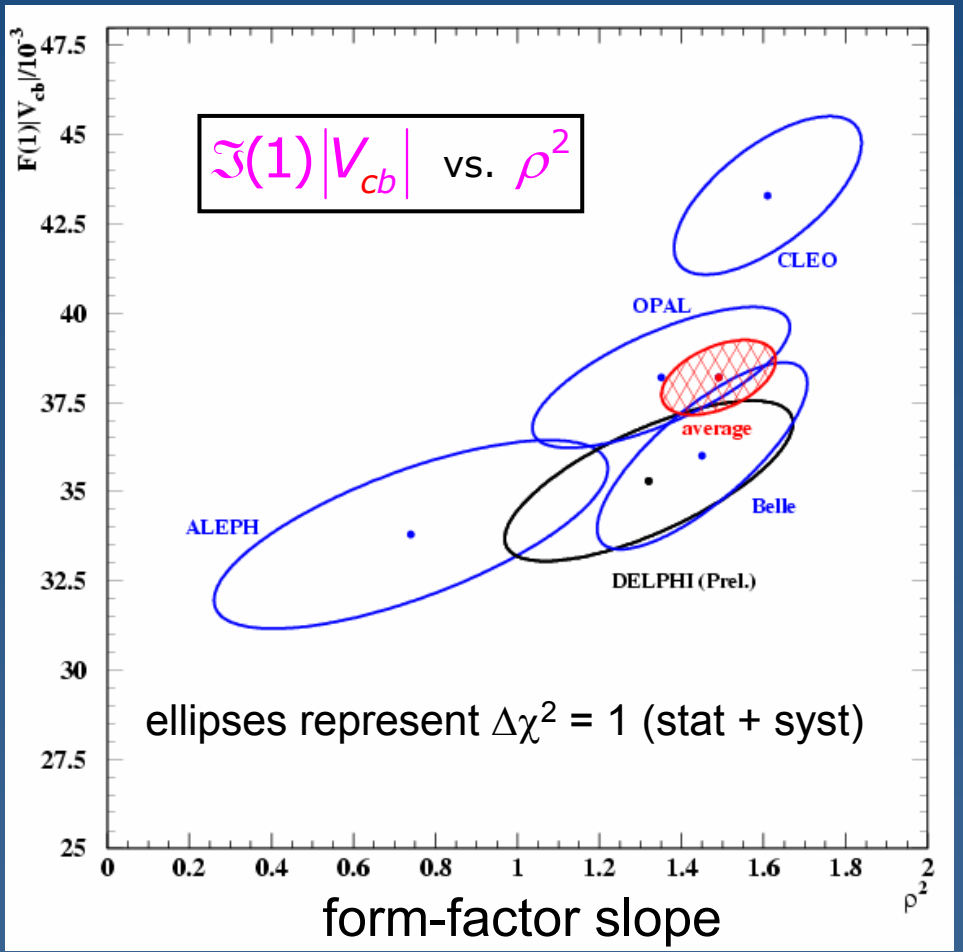
ρ^2 and $\mathcal{F}(1)|V_{cb}|$ are correlated

$D^* X \ell \nu$ Component

- LEP: model (based on external BFs)
- CLEO: simultaneously fitted in data
- CLEO: better rejection due to missing-mass resolution

Slow-Pion Efficiency

- LEP: flat
- CLEO: ~0% – 80% for 1.0 < w < 1.5
- CLEO: includes D^{*0} (π^0 flat)



Consistent at 5% level

Inclusive $|V_{ub}|$ from $B \to X_u \ell \nu$ Lepton Endpoint

Analysis

- To avoid b $\to$ c bkg., $2.2 < p_\ell < 2.6$ GeV/c
- Neural-net continuum suppression
- Remaining continuum subtracted using off-res.
- Measure partial branching fraction
- Sensitive to b-quark Fermi motion in B meson

Assumptions

- Common non-perturbative structure function for $b \to u \ell \nu$ and $b \to s\gamma$
- Parton-Hadron duality

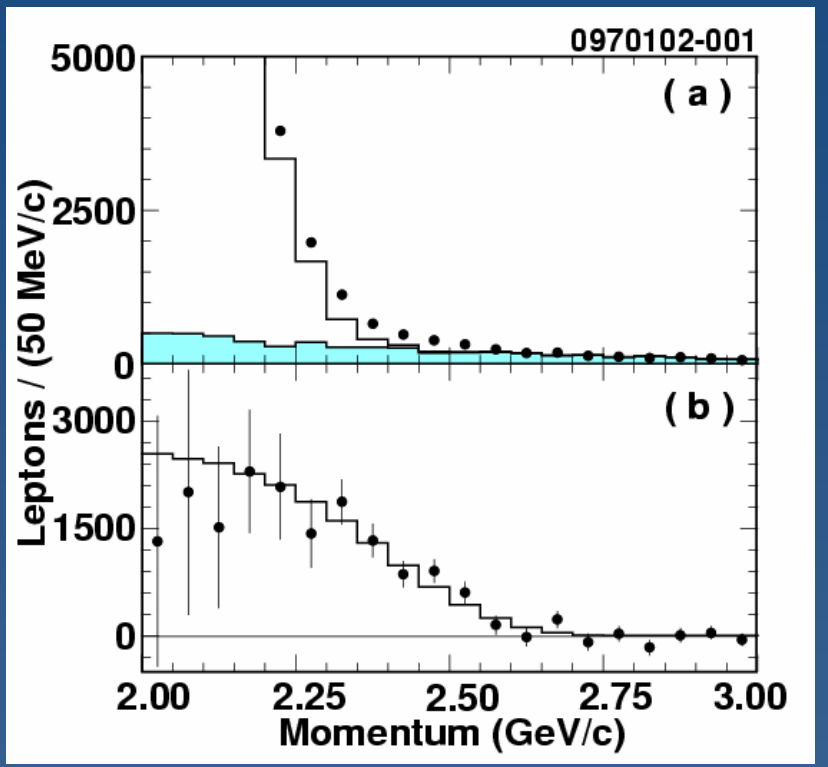
Endpoint Acceptance Fraction

- Convolve E_γ spectrum with $b \to u \ell \nu$ calculation
- $f_u(2.2 - 2.6\ \text{GeV}/c) = (13.0 \pm 2.4 \pm 1.5)\%$

Systematics

- Fraction of full spectrum above 2.2 GeV/c
- b $\to$ c bkg. simulation (D* FFs, D**, non-resonant)

PRL 88, 231803 (2002)



$$|V_{ub}| = \left[\begin{array}{ll} \pm 3.4 & \Delta \mathrm{Br}(p) \\ \pm 4.4 & f_u \\ \pm 1.6 & \Gamma_{sl} \to V_{ub} \\ \pm 2.4 & b \to s\gamma \end{array} \right] \times 10^{-4}$$

$(\pm 15\%)$

New CLEO Exclusive $|V_{ub}|$

$$B \to [\pi, \rho, \omega, \eta]\, \ell \nu$$

Neutrino Reconstruction Technique

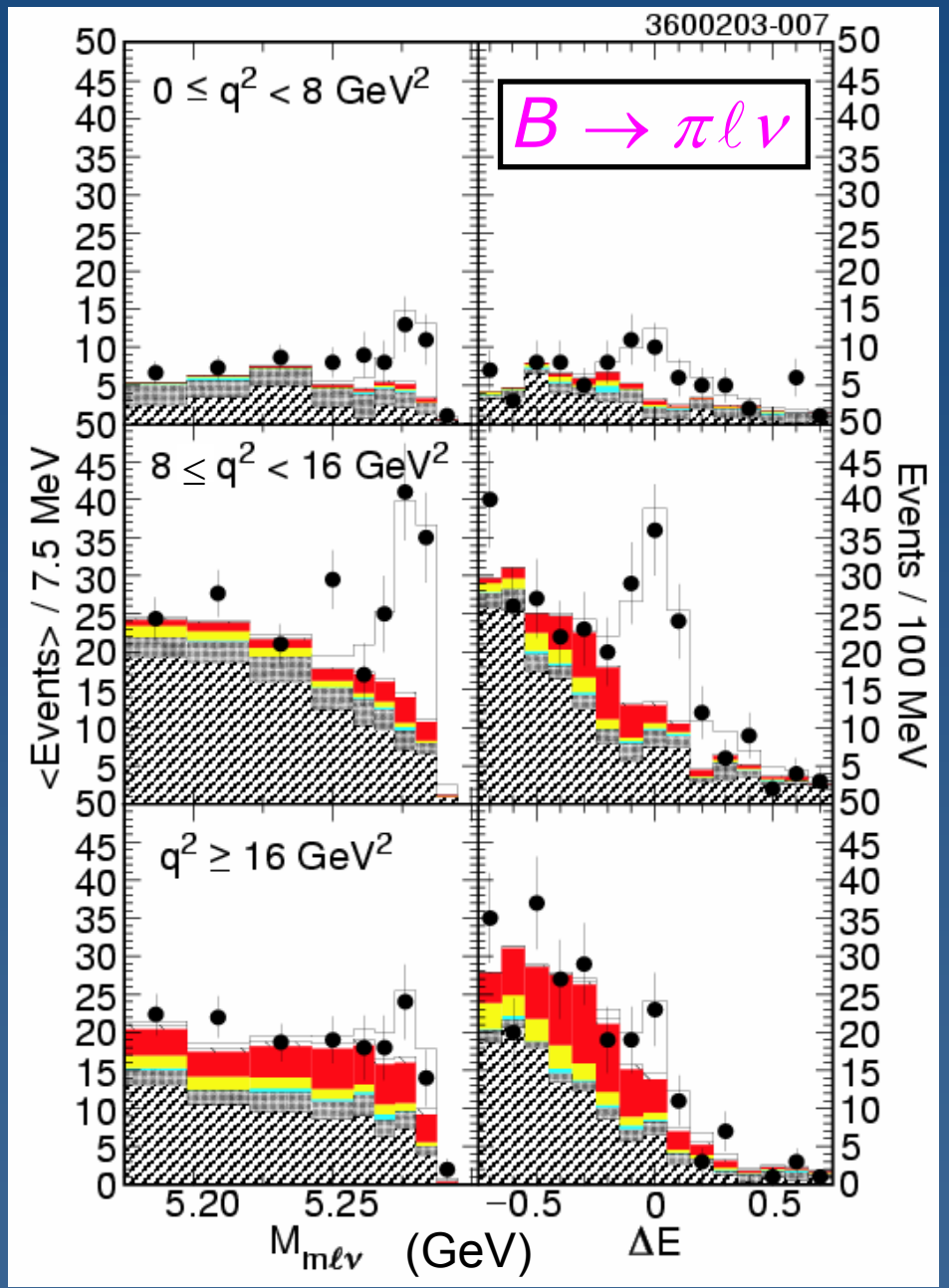
- $\vec{p}_\nu \equiv \vec{P}_{\text{miss}} \quad E_\nu \equiv |\vec{P}_{\text{miss}}|$ **Detector Hermeticity**
- $\sigma(\vec{p}_\nu) \sim 110$ MeV

Since 1996 (CLEO first observation)

- Full CLEOII dataset
- Lowered lepton momentum criteria
- Improved background characterization
- Partial rates in q^2 bins
- Theory progress: LQCD, LCSR

Simultaneous Binned ML Fit

- $M_{m\ell\nu} \equiv \left[E_{\text{beam}}^2 - |\alpha \vec{p}_\nu + \vec{p}_\ell + \vec{p}_m|^2 \right]^{\frac{1}{2}}$
- $\Delta E \equiv (E_\nu + E_\ell + E_m) - E_{\text{beam}}$
- 7 signal-mode topologies $[\pi, \rho, \omega, \eta]\, \ell \nu$
- Momentum transfer q^2, 3 bins
- 2 event net-charge states ($|\Delta Q| = 0,1$)



$|V_{ub}|$: Exclusive Reconstruction of $B \to [\pi, \rho, \omega, \eta]\, \ell\, \nu$ Decays

Points: On-resonance data

Open: Signal MC simulation

Coarsely Hatched: crossfeed among P (V) modes and q^2 bins

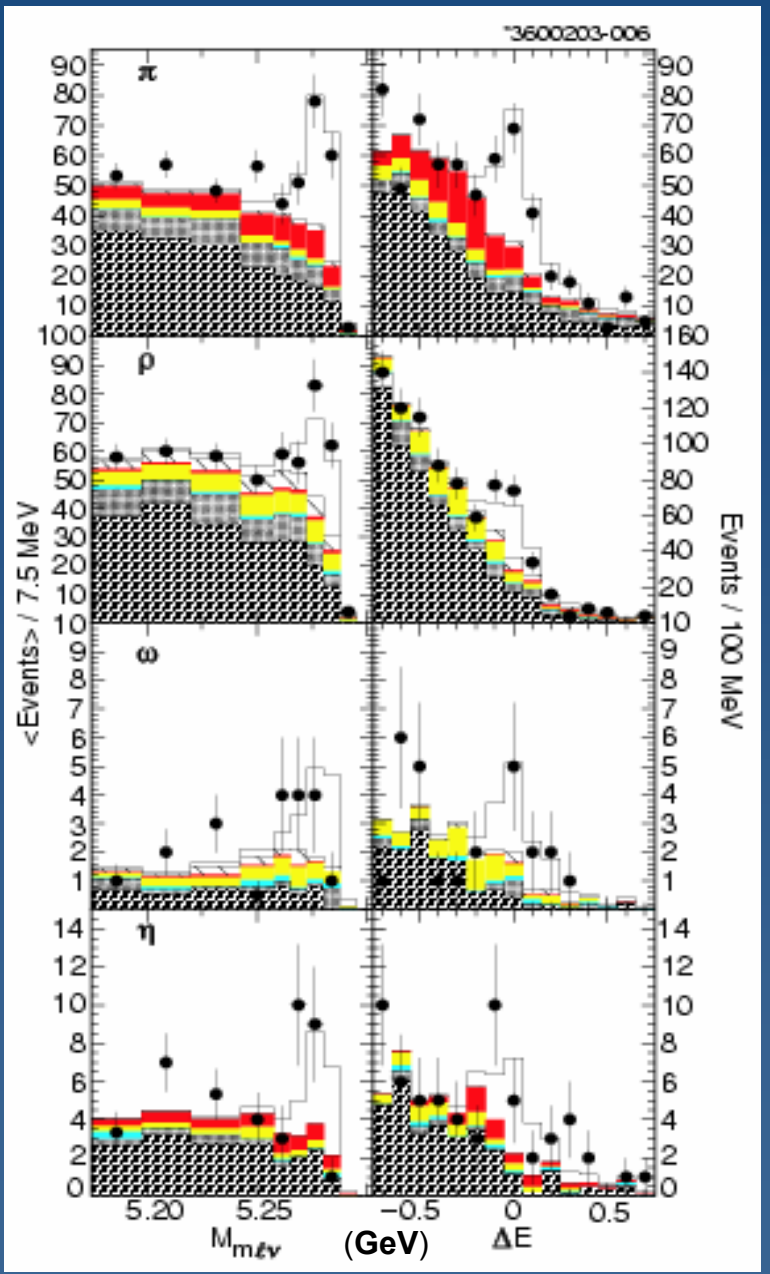
Red: Crossfeed from V (P) modes into P (V) modes

Yellow: $B \to X_u \ell\, \nu$ non-signal feeddown; floated in fit, subject to constraint from CLEO endpoint analysis

Cyan: Fake leptons

Dotted: Continuum

Finely Hatched: b → c



Reduction of Model Dependence: q^2 Binning

Branching Fraction Fit Results

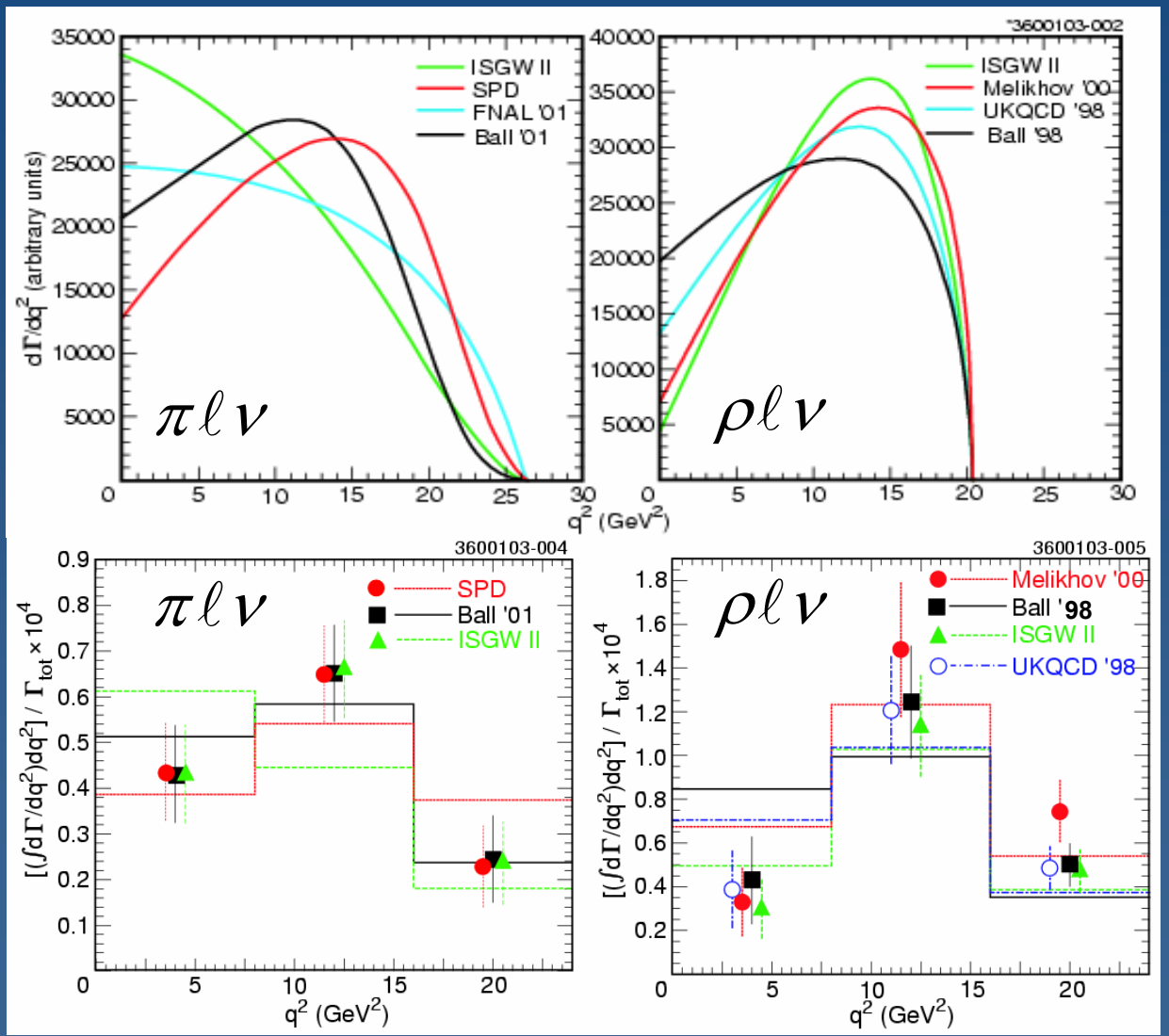
only sensitive to FF shape within a given q^2 bin

$|V_{ub}|$ Fits

can discriminate between FF models

$$\mathrm{Br}(B^0 \to \pi^- \ell^+ \nu) = \left[\begin{array}{lll} \pm 1.8 & \text{stat} & \\ \pm 1.1 & \text{syst} & \\ \pm 0.1 & B \to \pi & \text{FF} \\ \pm 0.7 & B \to \rho & \text{FF} \end{array} \right] \times 10^{-5}$$

$$\mathrm{Br}(B^0 \to \rho^- \ell^+ \nu) = \left[\begin{array}{lll} \pm 3.4 & \text{stat} & \\ {}^{+4.7}_{-5.4} & \text{syst} & \\ \pm 4.1 & B \to \rho & \text{FF} \\ \pm 0.1 & B \to \pi & \text{FF} \end{array} \right] \times 10^{-5}$$



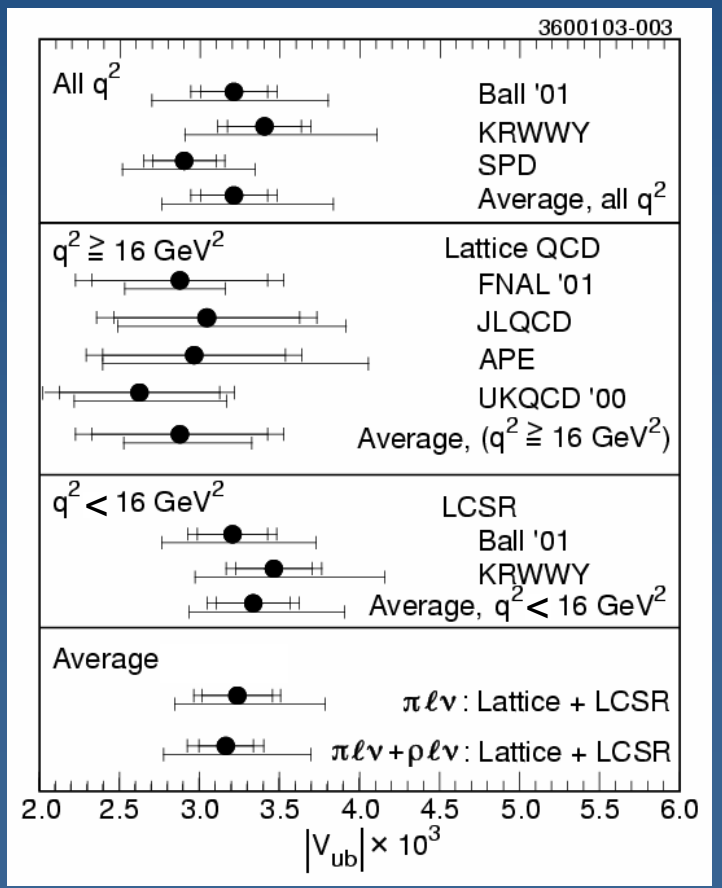
Newly Final! CLEO Exclusive $|V_{ub}|$ Result

Optimally Combining π, ρ, LQCD, LCSR:

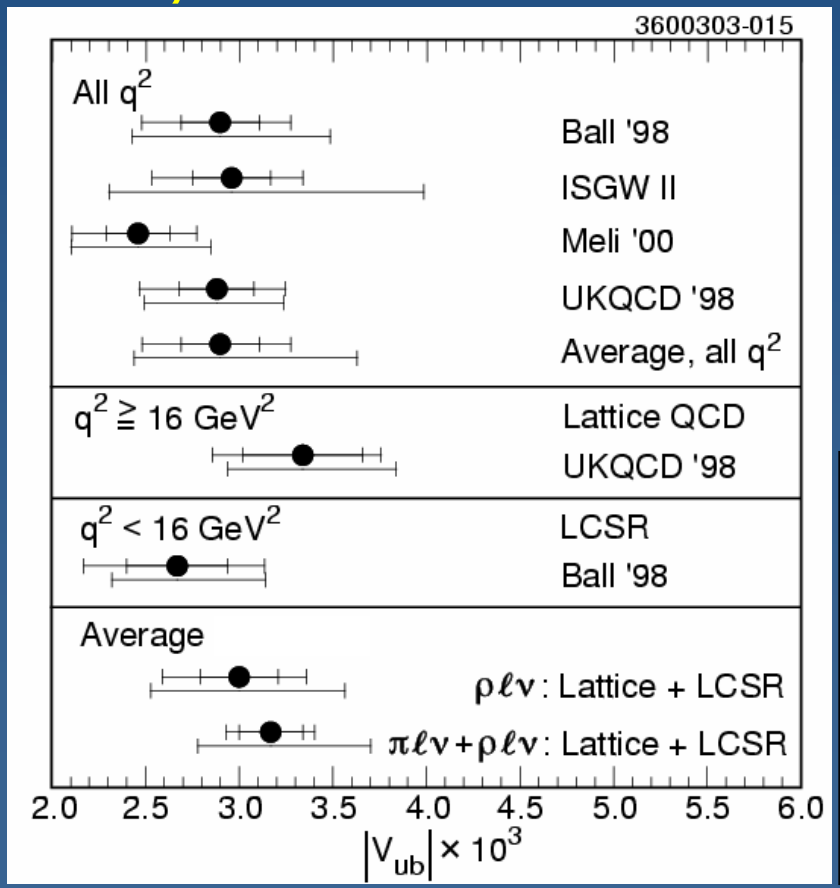
$$|V_{ub}| = \left[31.7 \pm 1.7|_{stat} \; {}^{+1.6}_{-1.7}|_{syst}^{expt} \; {}^{+5.3}_{-3.9}|_{LQCD/LCSR}^{theor} \pm 0.3|_{\rho\ell\nu\ FF}^{theor} \right] \times 10^{-4}$$

Submission to PRD is imminent

$B \to \pi \ell \nu$



$B \to \rho \ell \nu$



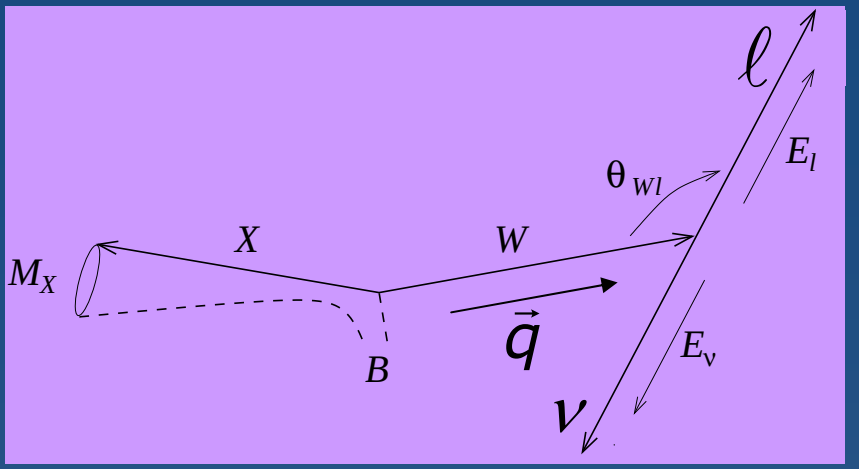
Error Bars

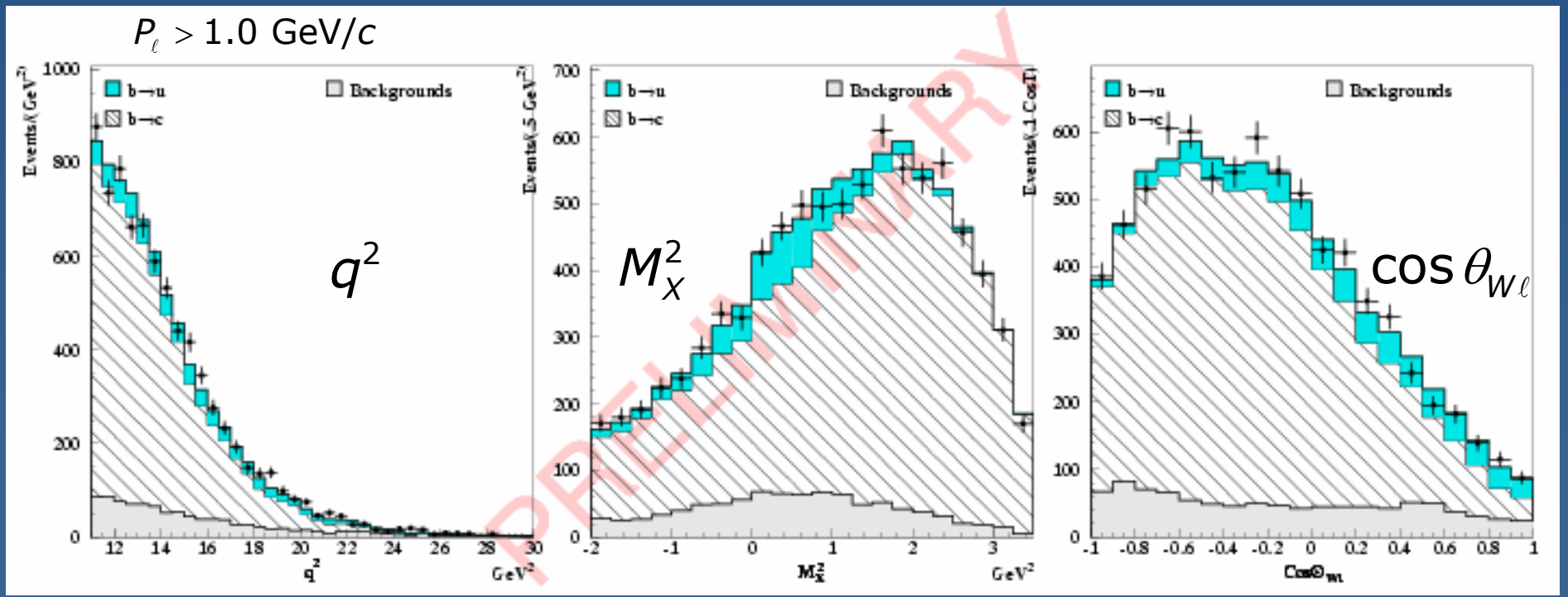
Upper: Experimental stat ⊕ syst

Lower: Theoretical

CLEO Future of $|V_{cb}|$ and $|V_{ub}|$

- Use 3 kinematic variables: M_X^2, q^2, $\cos\theta_{W\ell}$
- ML Fit for b $\rightarrow$ c and b $\rightarrow$ u components
- Measure rates, moments
- Preliminary $|V_{ub}|$ seen to be consistent
- <u>New method</u>: suppress $b \rightarrow c \rightarrow s\ell\nu$ by tagging the other B's lepton (P_e > 600 MeV/c)





Summary & Outlook

- New and recent CLEO analyses, using mature data & MC samples:
  - Measure Moments and Rates in semileptonic B decays
  - Use Inclusive and Exclusive techniques
  - Obtain $|V_{cb}|$ (σ~3%) and $|V_{ub}|$ (σ ~15%)
  - Help provide insight into CKM electroweak and QCD physics
- Most results are limited by systematic and theory uncertainties
- Techniques to reduce model dependence:
  - $b \to s\gamma$ shape function
  - q^2 binning, partial rates
  - Increased kinematic acceptance
- Future progress on CKM physics:
  - Still new CLEO analyses underway
  - HQET and LQCD theoretical tools attacking non-pQCD
  - CLEO-c! Stay tuned.

Slides removed for lack of time

$|V_{ub}|$ Challenges: Theory and Experiment

- Cabibbo Suppression: Rates are small from the outset, ~$\Gamma(b \to c)/100$
- Interpretation: Requires both Theory and Experiment
- Mutual Reliability of Theory and Experiment: Only in limited kinematic regions

Fraction of Full $b \to u$ Decay Rate:	**Inclusive**	**Exclusive**
Theory	**LARGE** (OPE; Duality)	**SMALL** (LCSR: non-pQCD; LQCD: discretization)
Experiment	**SMALL** ($b \to c$ background)	**LARGE** (Kinematic Constraints)