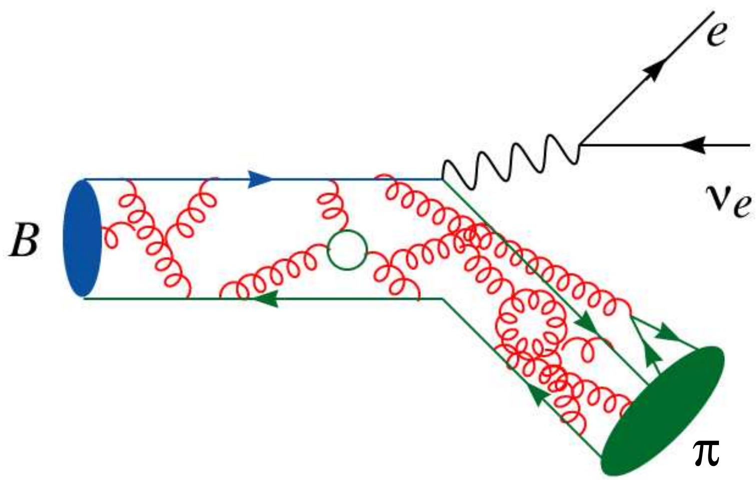
Measurement of Exclusive $b \to u\ell\nu$ Decays and $|V_{ub}|$ with CLEO



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

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CLEO Collaboration

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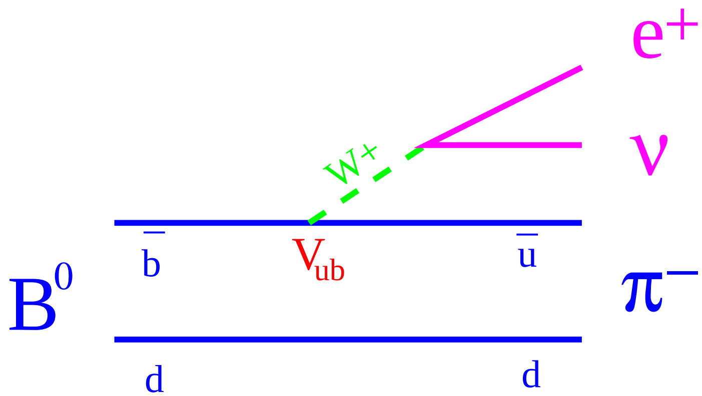
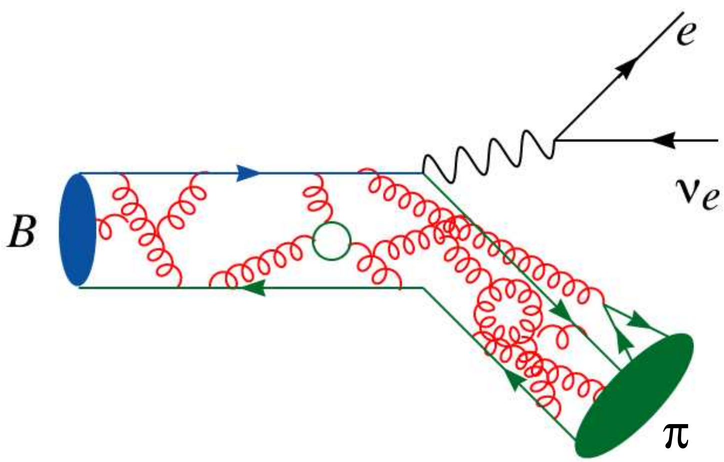
CKM Measurements in Semileptonic B Decays



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

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



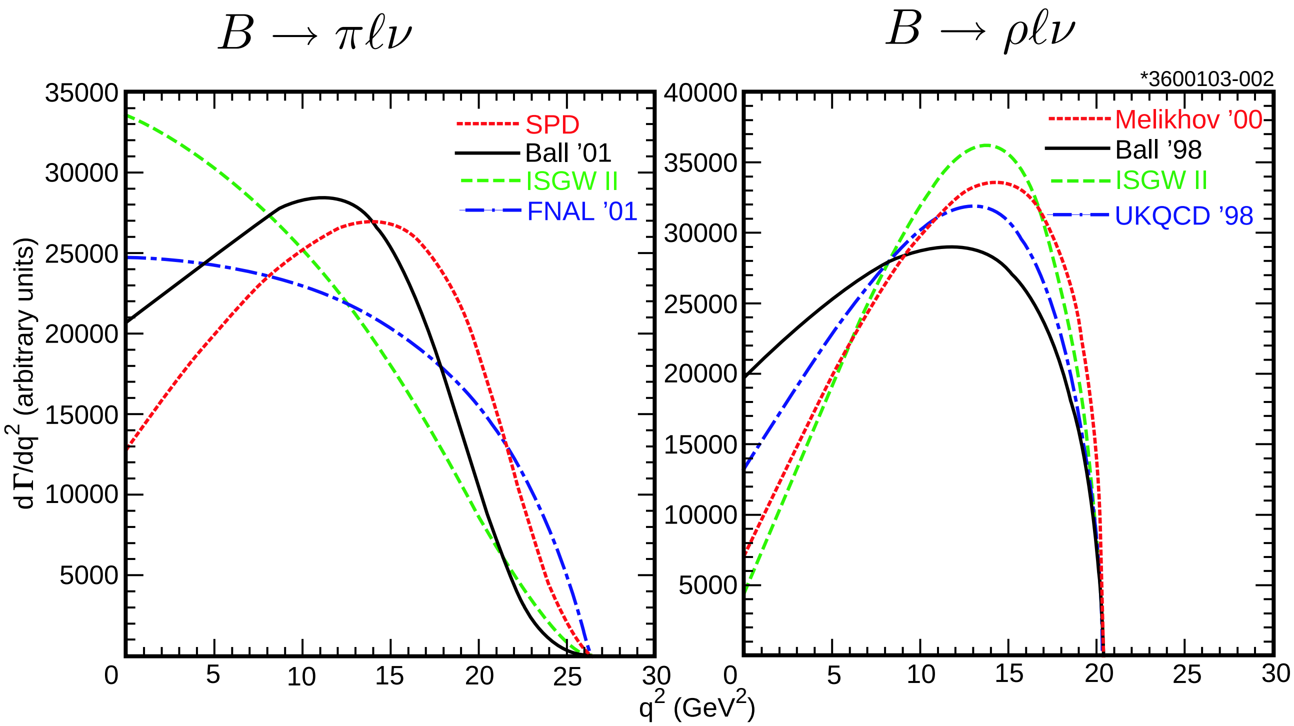
Complication!

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)

$B \to X_u\ell\nu$ Form Factors



Form factor calculations are challenging (non-perturbative QCD)

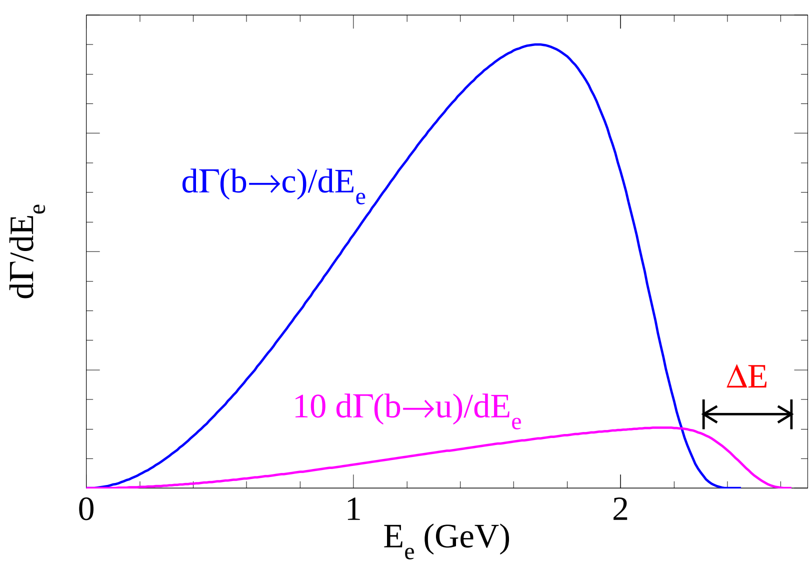
Shapes vary $\longrightarrow$ model dependence

New analysis which bins in q^2 to reduce model dependence

Normalization of form factors has a large uncertainty.

Experimental Challenges in $b \to u\ell\nu$

From Leibovich hep-ph/0011181



Large $b \to c\ell\nu$ backgrounds

- Signal is 1% of background!
- Suppress using kinematics

Approaches:

- Exclusive Reconstruction
  + Constraints from full recon
- Inclusive Reconstruction
  + Kinematic cuts (% of rate)
  - $E_\ell \gtrsim 2.2$ GeV (13%)
  - $q^2 \gtrsim 12$ GeV^2 (20%)
  - $M_X \lesssim M_D$ (70%)

Both approaches currently suffer from large uncertainties

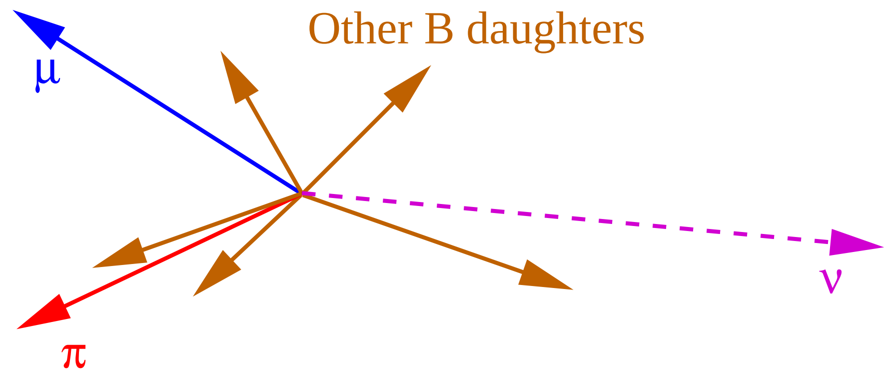
- Exc: Poorly known form factors
- Inc: Effect of kinematic cuts (...not very inclusive!)

⟶ Important to pursue both inclusive and exclusive measurements.

Neutrino Reconstruction

Uses hermeticity of detector (CLEO 93% of 4π):

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



Gives powerful kinematic constraints for full reconstruction:

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

where α is chosen event by event to force $\Delta E = 0$

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

Reject "ghost" tracks & shower fragments from hadronic interactions.

Exclusive $B \to [\pi, \rho, \omega, \eta]\ell^+\nu$ Reconstruction

Mesons (7 modes)

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

Leptons (2 flavors)

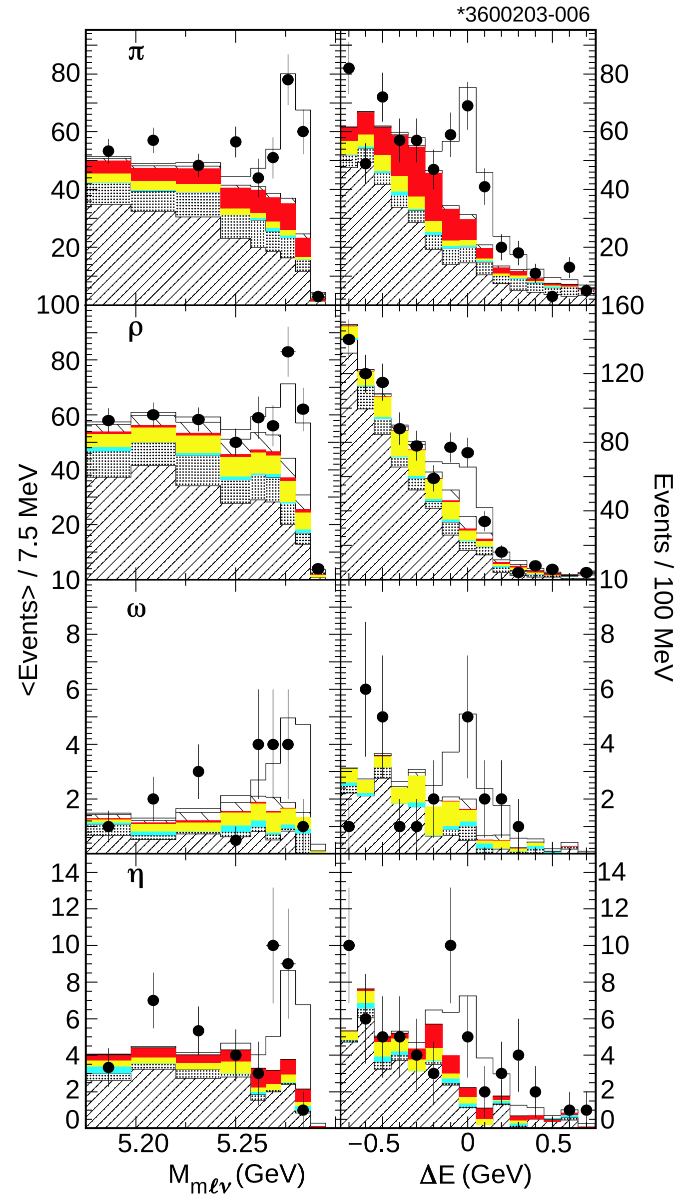
- Electrons or muons ($\epsilon \geq 90\%$; fake rates $e \approx$0.1%, $\mu \approx 1\%$)
- Require $p_\ell \geq 1.0(1.5)$ GeV/c in P(V) modes
- Veto additional identified leptons (imply additional ν!)

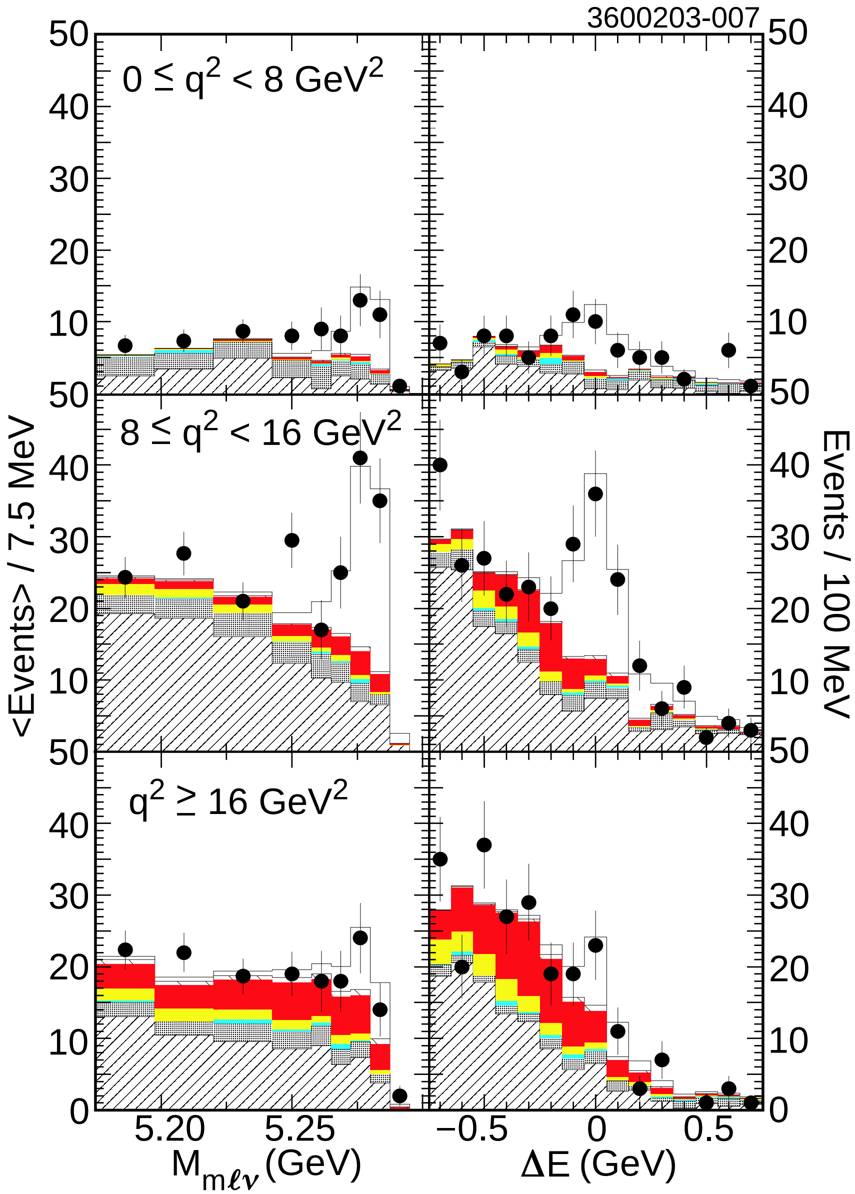
Neutrinos

- From neutrino reconstruction; $M_\nu^2 = E_{\rm miss}^2 - p_{\rm miss}^2$ consistent with 0

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 π and ρ
- Net event charge $|\Delta Q| = 0, 1$
- Accounts for crossfeed



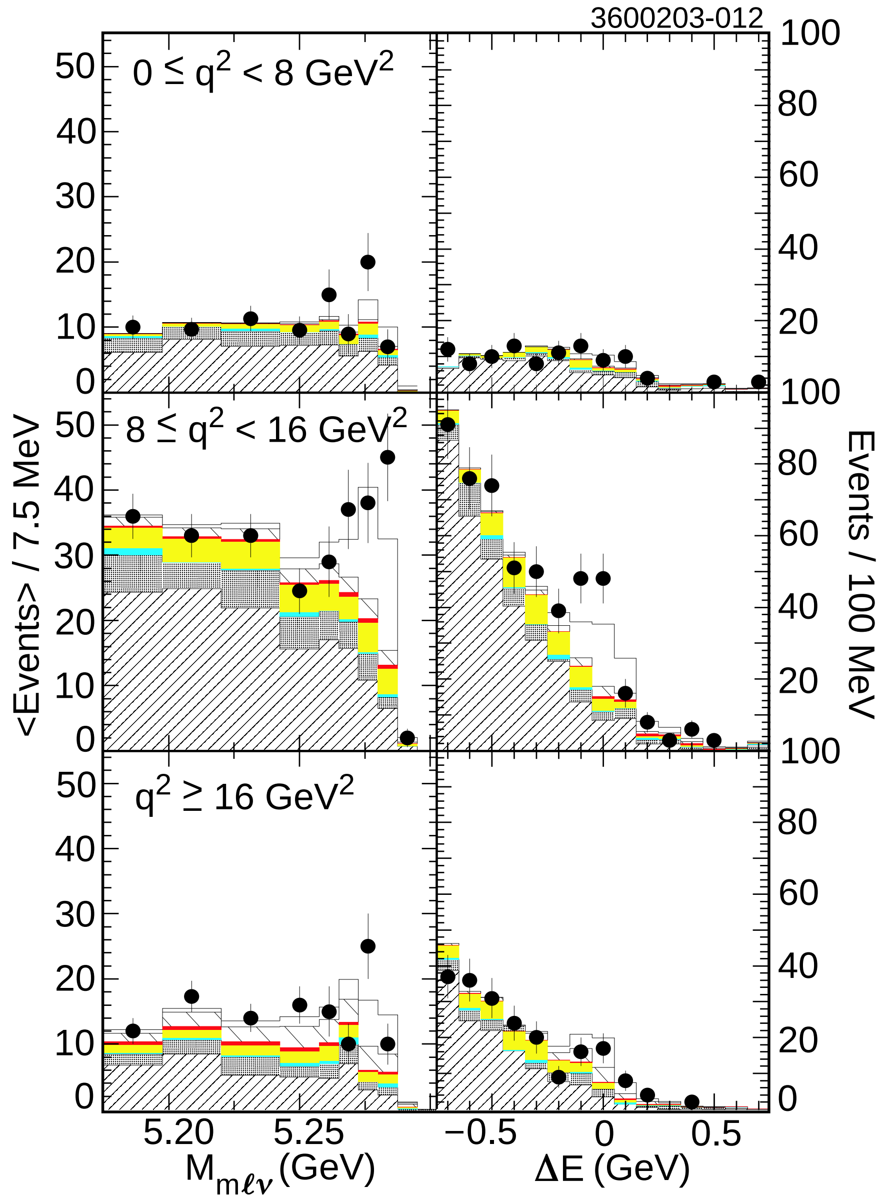


$B \to \pi\ell^+\nu$ q^2 binning

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

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

Clear signals in all 3 q^2 bins



$B \to \rho\ell^+\nu$ q^2 binning

Central $M_{\pi\pi}$ bin (95 MeV)

$p_\ell > 1.5$ GeV$/c$

- points on-resonance data
- open histogram signal
- coarse hatched crossfeed from other V modes
- red histogram crossfeed from π or η modes
- yellow $B \to X_u\ell\nu$ other
- cyan fakes
- dotted continuum
- fine hatched $b \to c$

Results for Branching Fractions

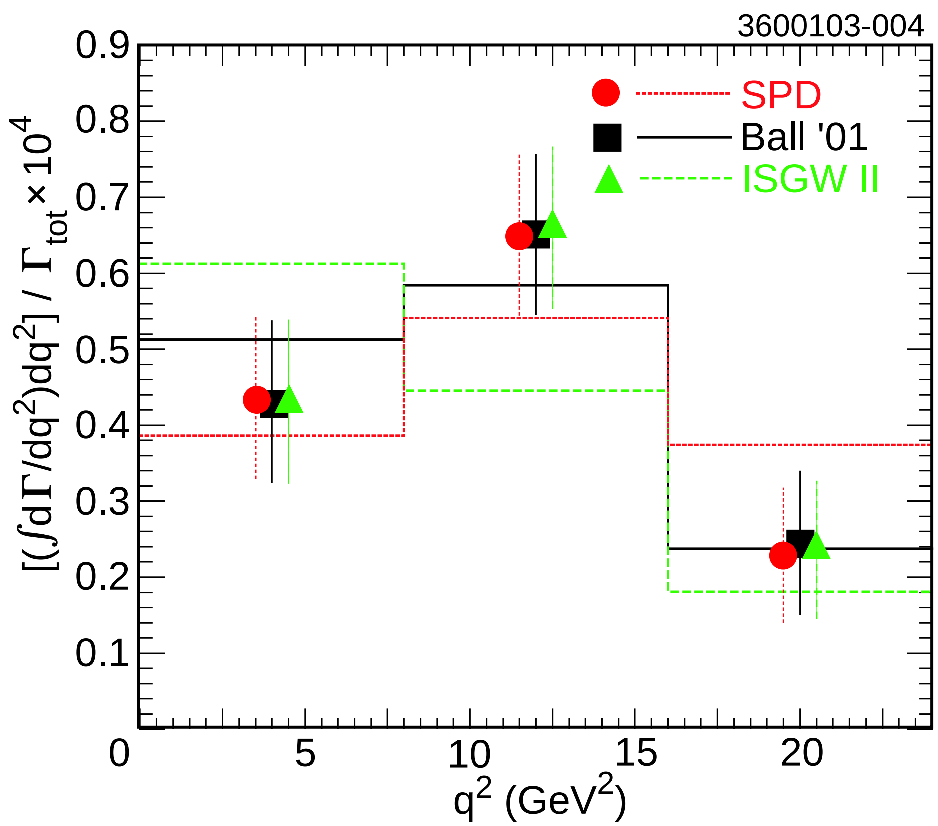
Mode	$\mathcal{B}_{q^2 \text{ interval}}$	$\times 10^{-4}$
$B^0 \to \pi^- \ell^+ \nu$	$\mathcal{B}_{\text{total}}$	$1.33 \pm 0.18 \pm 0.11 \pm 0.01 \pm 0.07$
	$\mathcal{B}_{<8}$	$0.43 \pm 0.11 \pm 0.05 \pm 0.004 \pm 0.01$
	$\mathcal{B}_{8-16}$	$0.65 \pm 0.11 \pm 0.07 \pm 0.01 \pm 0.03$
	$\mathcal{B}_{\geq 16}$	$0.25 \pm 0.09 \pm 0.04 \pm 0.01 \pm 0.03$
$B^0 \to \rho^- \ell^+ \nu$	$\mathcal{B}_{\text{total}}$	$2.17 \pm 0.34 \,^{+0.47}_{-0.54} \pm 0.41 \pm 0.01$
	$\mathcal{B}_{<8}$	$0.43 \pm 0.20 \pm 0.23 \pm 0.09 \pm 0.01$
	$\mathcal{B}_{8-16}$	$1.24 \pm 0.26 \,^{+0.27}_{-0.33} \pm 0.22 \pm 0.004$
	$\mathcal{B}_{\geq 16}$	$0.50 \pm 0.10 \,^{+0.08}_{-0.11} \pm 0.19 \pm 0.004$
$B^+ \to \eta \ell^+ \nu$	$\mathcal{B}_{\text{total}}$	$0.84 \pm 0.31 \pm 0.16 \pm 0.09$

Errors are statistical, systematic, and theory from π & ρ Form Factors

Evidence for $B \to \eta\ell\nu$ at 3.2σ statistical significance

Rate consistent with expectations from $B \to \pi\ell\nu$ & quark model

$B \to \pi\ell\nu$ $\frac{d\Gamma}{dq^2}$ Fit



Measured Rates in q^2 bins fit to theory $d\Gamma/dq^2$

Normalization gives $|V_{ub}|$

Shape tests FF models

3 different FFs used

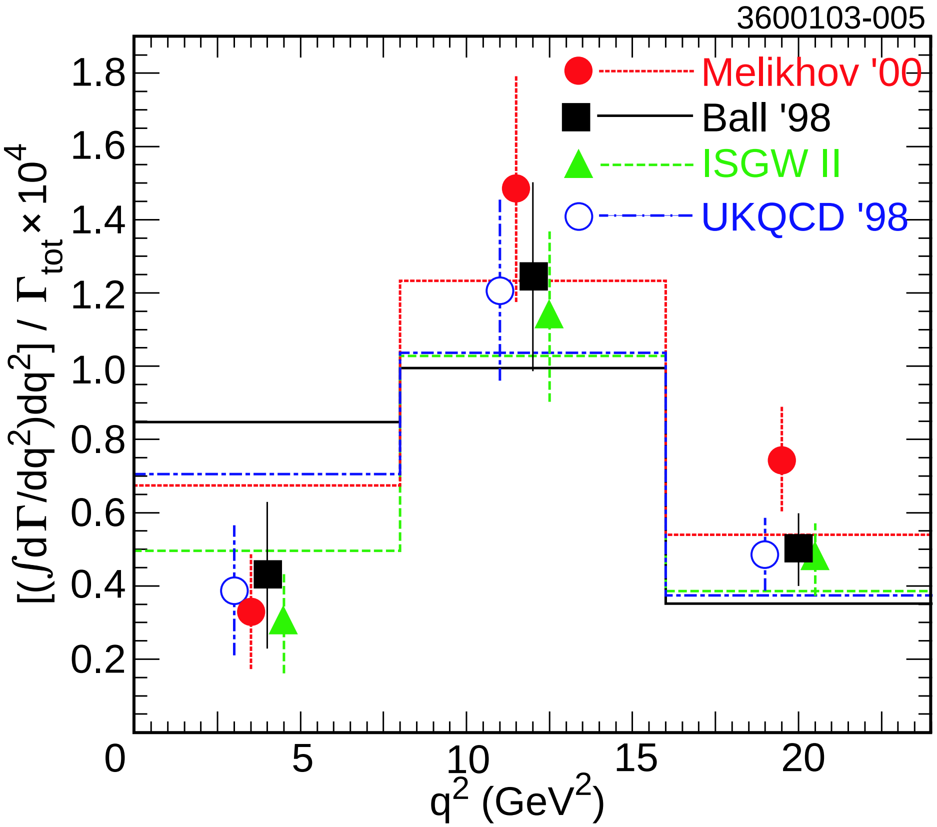
- Ball01 LCSR
- ISGW II
- Skewed Parton Dist.

ISGW II not favored (CL=3%)

For $\pi\ell\nu$ very little model dependence from FF shape.

All models have large uncertainty for FF normalization.

3 FFs give 3 values for $|V_{ub}|$.



$B \to \rho\ell\nu$ $\frac{d\Gamma}{dq^2}$ Fit

4 different FFs used

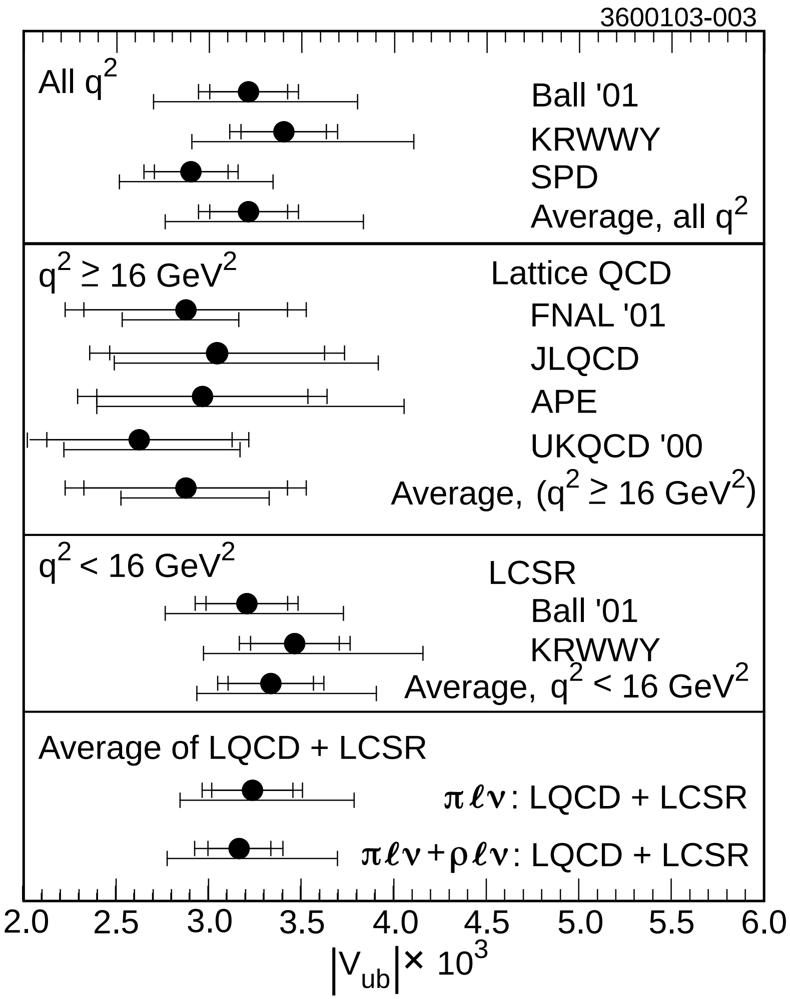
- Ball98
- ISGW II
- Melikhov00
- UKQCD98

Larger model dependence on rates

Agreement not as good: note 1st bin

Efficiency corrected yields in q^2 bins fit to $d\Gamma/dq^2$

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

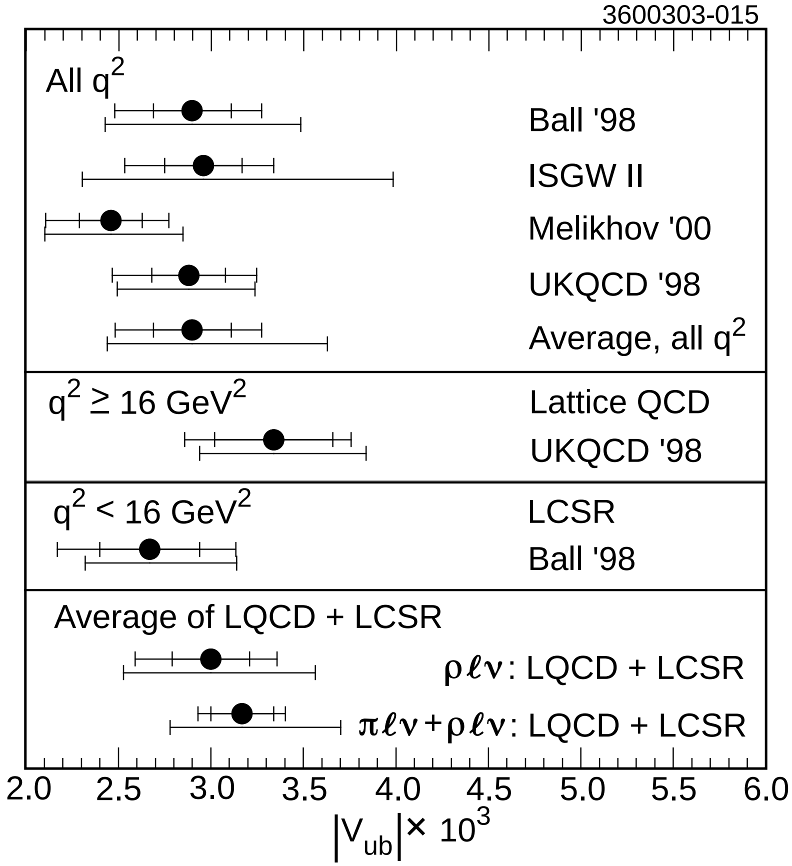


Alternatives:

- From fits to rates in q^2 bins
- From large q^2 using LQCD
- From small q^2 using LCSR
- Theory uncertainties taken as 70% of spread except … Lattice QCD, as cited plus 15% quenching uncertainty

We suggest the average of LQCD and LCSR as our central result.

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



Again as $B \to \pi\ell\nu$:

- From fits to rates in q^2 bins
- From large q^2 using LQCD
- From small q^2 using LCSR
- Theory uncertainties taken as 70% of spread except . . . Lattice QCD, as cited plus 20% quenching uncertainty— Broad ρ is more difficult than π on the lattice.

We suggest the average of LQCD and LCSR as our central result.

Results: Reporting average of LQCD and LCSR results as most reliable

$$B \to \pi\ell\nu: \ |V_{ub}| = (3.24 \pm 0.22 \ \pm 0.13^{+0.55}_{-0.39} \pm 0.09) \times 10^{-3}$$

$$B \to \rho\ell\nu: \ |V_{ub}| = (3.00 \pm 0.21 \ ^{+0.29}_{-0.35} \ ^{+0.49}_{-0.38} \pm 0.28) \times 10^{-3}$$

$$\text{Combined: } |V_{ub}| = (3.17 \pm 0.17 \ ^{+0.16}_{-0.17} \ ^{+0.53}_{-0.39} \pm 0.03) \times 10^{-3}$$

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

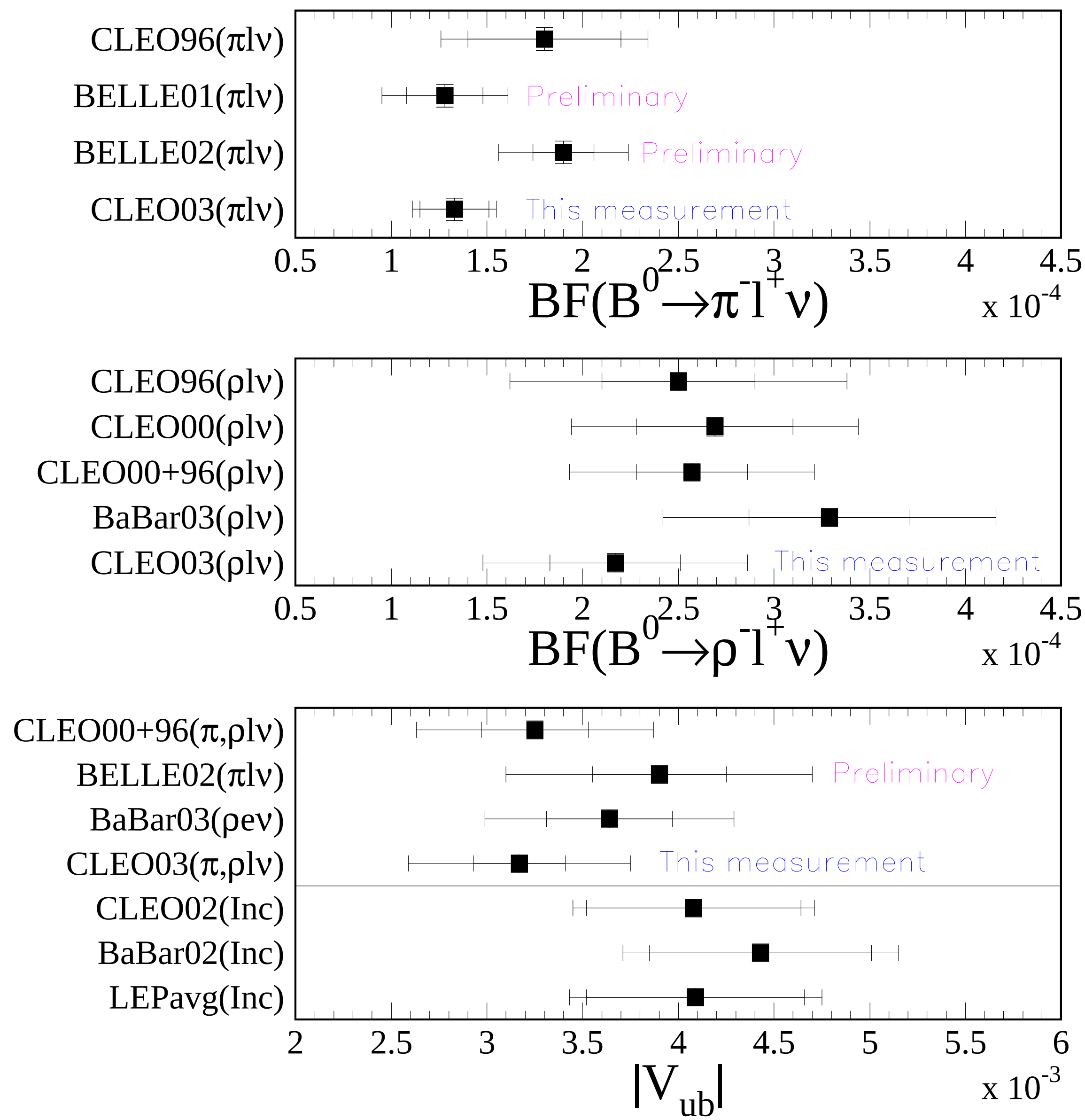
Differences compared to 1996 CLEO analysis (superseded):

- lower lepton momentum cut π at 1.0 ρ at 1.5 GeV/c
- more statistics allowing q^2 binning giving less model dependence
- theory form factors LQCD and LCSR

Compatible with other measurements:

- CLEO inclusive $|V_{ub}| = (4.08 \pm 0.34 \pm 0.44 \pm 0.29) \times 10^{-3}$
- Other exclusive measurements: (CLEO, Belle, BaBar)

(to be submitted to PRD)


CLEO96(πlν)
BELLE01(πlν)
Preliminary
BELLE02(πlν)
Preliminary
CLEO03(πlν)
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(ρlν)
CLEO00(ρlν)
CLEO00+96(ρlν)
BaBar03(ρlν)
CLEO03(ρlν)
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,ρlν)
BELLE02(πlν)
Preliminary
BaBar03(ρeν)
CLEO03(π,ρlν)
This measurement
CLEO02(Inc)
BaBar02(Inc)
LEPavg(Inc)
2 2.5 3 3.5 4 4.5 5 5.5 6
|V_ub|
x 10⁻³

Systematic errors (%) on branching fractions

	$\pi\ell\nu$				$\rho(\omega)\ell\nu$				
		q^2 interval (GeV^2)				q^2 interval (GeV^2)			
Systematic	$\mathcal{B}_{total}$	< 8	$8 - 16$	≥ 16	$\mathcal{B}_{total}$	< 8	$8 - 16$	≥ 16	η
ν simulation	6.8	10.5	9.2	17.2	18.7	41.7	19.4	13.5	17.3
$b \to c\ell\nu$	1.7	2.5	1.9	3.2	2.0	21.4	4.7	4.2	5.5
$b \to u\ell\nu$ feeddown	0.5	3.0	1.8	1.9	8.3	23.8	6.1	5.6	1.6
Cont. smoothing	1.0	2.0	0.2	2.0	3.0	10.0	1.0	2.0	2.0
Fakes	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
f_{+-}/f_{00}	2.4	2.6	2.3	2.2	0.0	2.5	1.0	0.1	4.1
τ_{B^+}/τ_{B^0}	0.2	0.1	0.3	0.5	2.1	4.2	1.4	2.1	1.4
Isospin	0.0	0.0	0.0	0.2	2.4	1.9	2.7	2.3	0.1
Lepton ID	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Luminosity	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Upper	**8.6**	12.4	10.7	18.3	**21.4**	53.9	21.5	16.2	**19.3**
Non Resonant	–	–	–	–	-13	-9	-15	-14	
Lower	**8.6**	12.4	10.7	18.3	**25.1**	54.7	26.2	21.4	**19.3**

Dominant uncertainty: neutrino reconstruction/simulation

Dominant systematics (in %) from ν reconstruction

variation	$\pi^-\ell^+\nu$				$\rho^-\ell^+\nu$				$\eta\ell\nu$
	total	$q^2_{<8}$	q^2_{8-16}	$q^2_{>16}$	total	$q^2_{<8}$	q^2_{8-16}	$q^2_{>16}$	total
γ eff.	2.60	6.98	2.66	9.09	11.11	11.85	11.14	10.60	5.66
γ resol.	4.07	2.87	5.36	2.33	2.91	3.68	2.34	4.24	9.62
K_L shower	1.25	1.04	1.35	1.44	6.00	8.38	7.21	1.55	2.74
Particle ID	1.85	2.50	3.04	6.25	8.16	27.45	6.93	1.06	0.18
Splitoff rejection	1.52	2.92	3.05	5.03	1.23	9.44	1.80	2.54	5.50
track eff.	3.69	4.45	4.19	2.56	8.64	13.27	9.53	3.39	9.46
track resol.	1.01	1.77	2.44	11.19	6.22	12.74	6.01	2.66	0.92
splitoff sim.	0.40	1.35	0.53	2.31	1.03	10.37	0.97	4.67	6.02
K_L production	0.18	0.11	0.21	0.39	0.11	0.84	0.09	0.32	0.12
ν production	0.52	3.46	2.18	1.95	0.59	15.06	4.12	0.88	2.93
Total	6.76	10.46	9.20	17.19	18.73	41.72	19.43	13.53	17.25