Semileptonic *B* Decays

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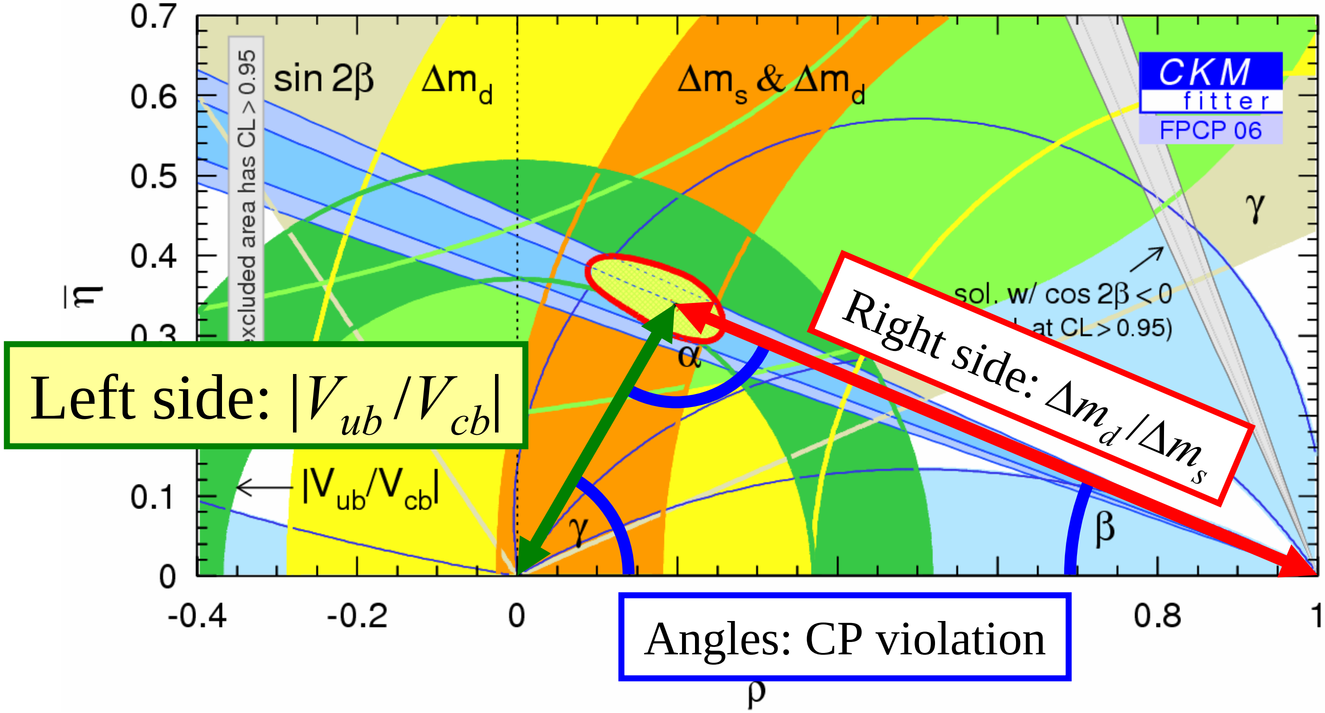
Determination of $|V_{ub}|$ and $|V_{cb}|$ with Inclusive and Exclusive $b \to u\ell\nu$ and $b \to c\ell\nu$ Decays

APS Meeting, April 22-25, 2006

The Unitary Triangle

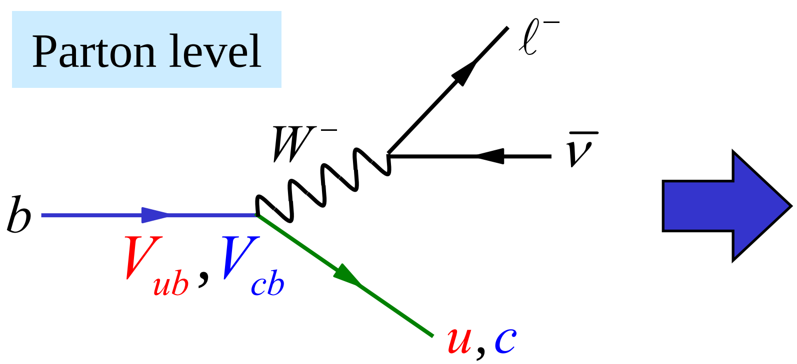
- The goal: Over-constrain the apex $(\bar{\rho}, \bar{\eta})$ to test the completeness of the Cabibbo-Kobayashi-Maskawa model

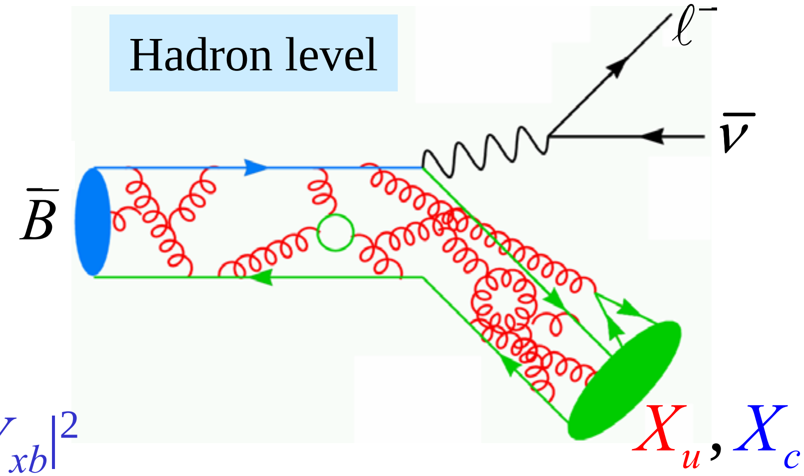


- $\beta = 21.7^{+1.3}_{-1.2}$ degrees → Let's measure the opposite side precisely!

Semileptonic *B* Decays

- Natural probe for $|V_{ub}|$ and $|V_{cb}|$

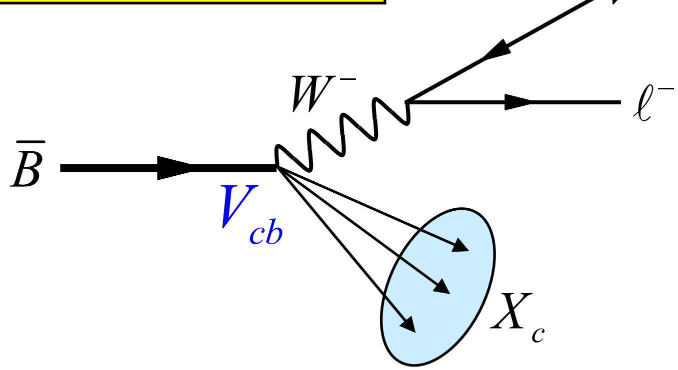




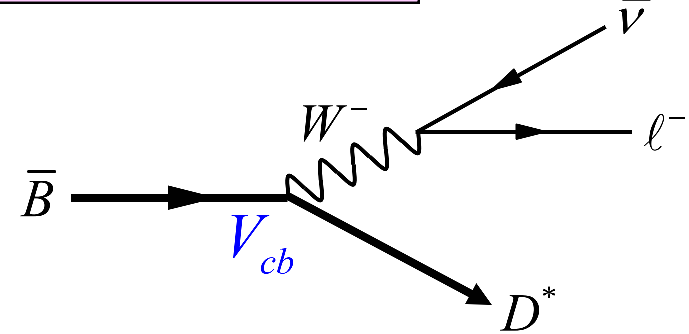
  - Decay rate $\Gamma_x \equiv \Gamma(b \to x\ell\nu) \propto |V_{xb}|^2$
- Γ_c larger than Γ_u by a factor ~50
  - Extracting $b \to u\ell\nu$ signal challenging
- Sensitive to hadronic effects
  - Must understand them to extract $|V_{ub}|$, $|V_{cb}|$
  - Use data to bolster theory

Inclusive vs. Exclusive

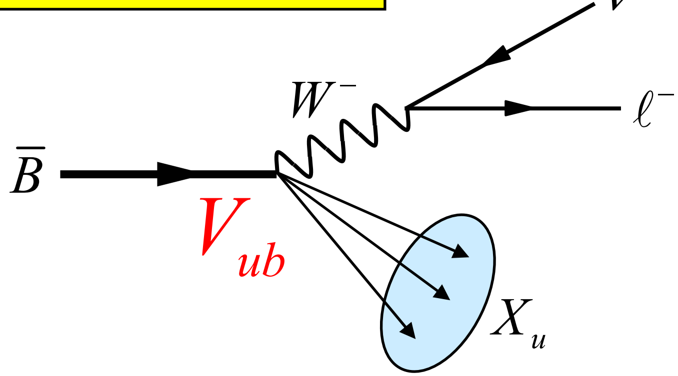
Inclusive $B \to X_c \ell \nu$



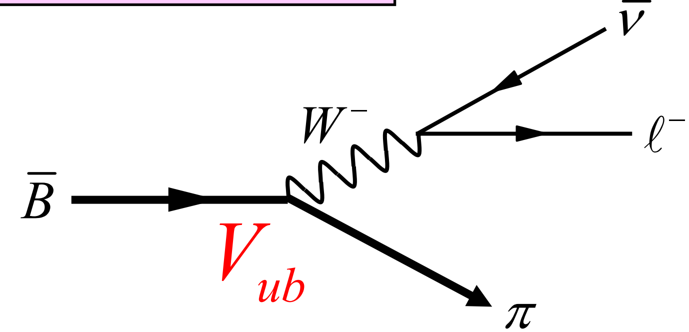
Exclusive $B \to D^* \ell \nu$



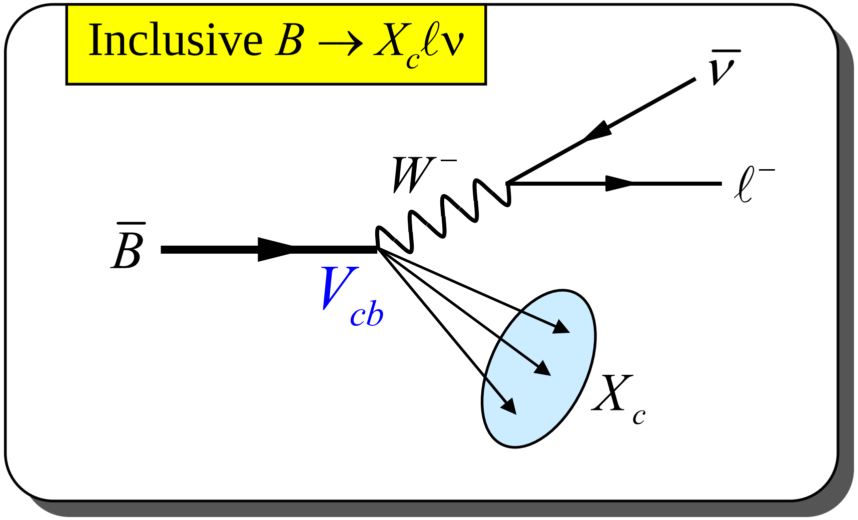
Inclusive $B \to X_u \ell \nu$

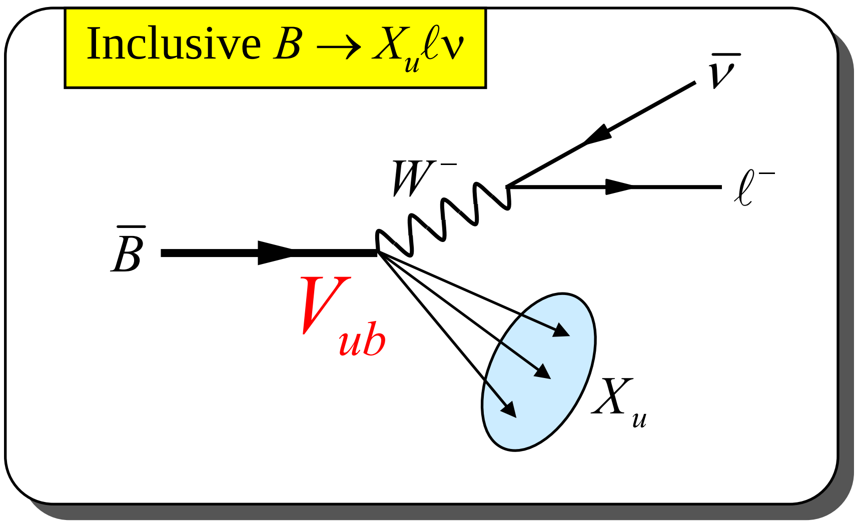


Exclusive $B \to \pi \ell \nu$



Inclusive Measurements





- Operator Product Expansion predicts total rate Γ_u as

$$\frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3}\left[1-\mathcal{O}\left(\frac{\alpha_s}{\pi}\right)-\mathcal{O}\left(\frac{1}{m_b^2}\right)+\cdots\right]$$

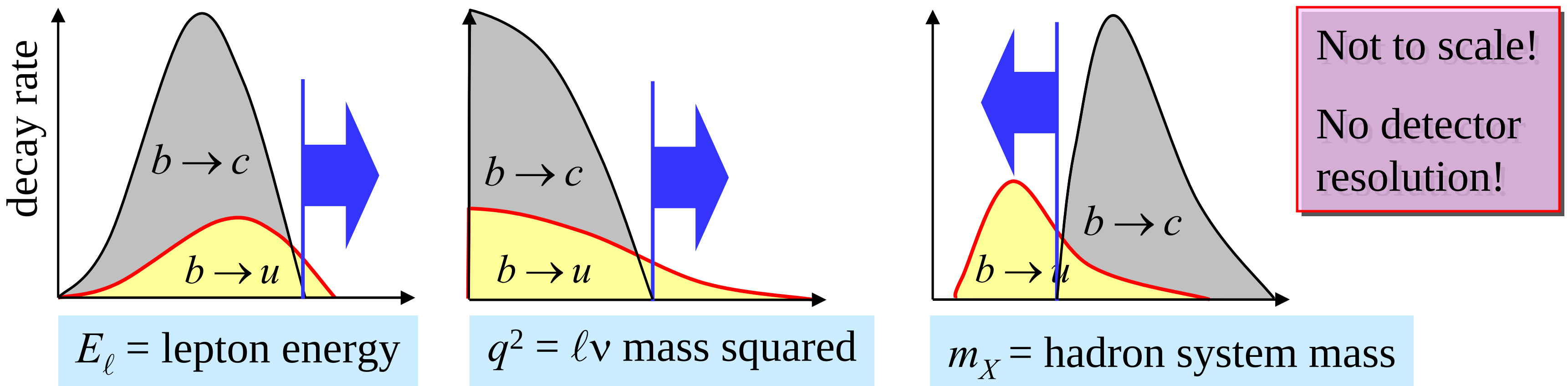
Perturbative terms known to $\mathcal{O}(\alpha_s^2)$

Non-perturb. terms suppressed by $1/m_b^2$

  - Dominant error from m_b^5
    - m_b measured to ±1% ➔ ±2.5% on $|V_{ub}|$
- Total rate can't be measured due to $B \to X_c \ell\nu$ background
  - Must enhance S/B with cuts

Kinematical Cuts

- Three independent kinematic variables in $B \to X\ell\nu$

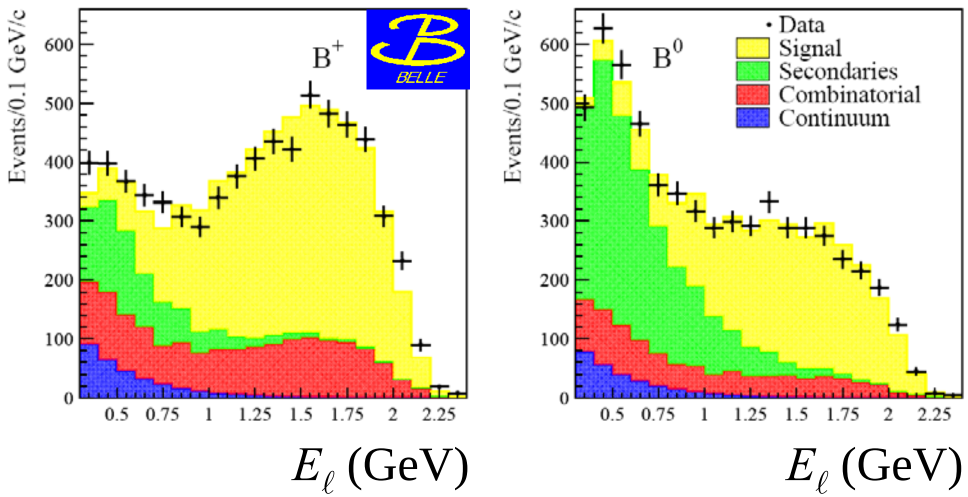


  - Measure partial rates in favorable regions of the phase space
- Caveat: Spectra more sensitive to non-perturbative effects than the total rate ➔ $\mathcal{O}(1/m_b)$ instead of $\mathcal{O}(1/m_b^2)$
  - Need to know the **Shape Function** (= what the *b*-quark is doing inside the *B* meson)
- Solution: Measure $B \to X_c\ell\nu$ spectra ➔ Non-perturb. effects

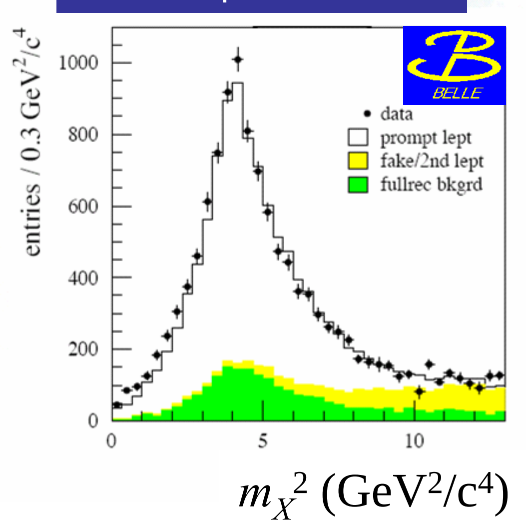
Inclusive $B \to X_c \ell \nu$ Spectra

- Observables: E_ℓ (lepton energy) and m_X (hadron system mass)
  - Measurements by *BABAR*, Belle, CDF, CLEO, DELPHI

Belle, hep-ex/0508056



Belle, hep-ex/0509013

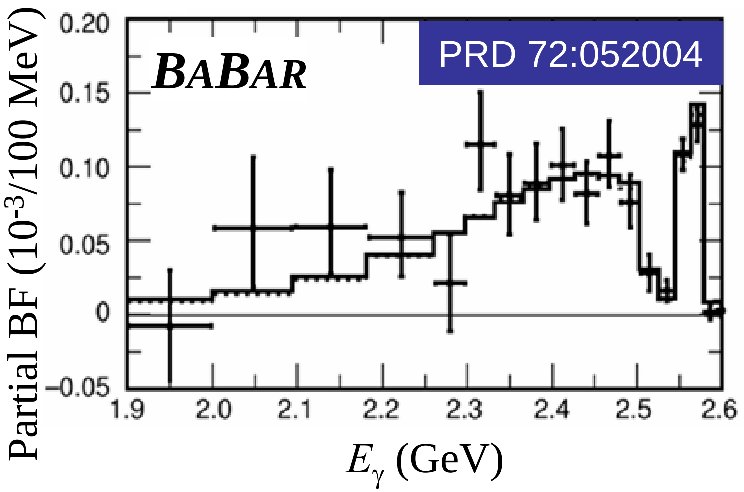


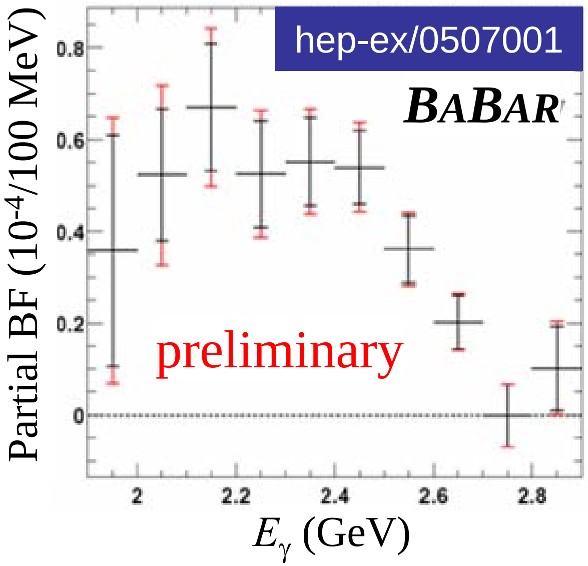
- OPE predicts observables integrated over large phase space

➔ Moments: $\langle E_\ell^n \rangle = \dfrac{1}{\Gamma_c} \int \left(E_\ell - \langle E_\ell \rangle\right)^n \dfrac{d\Gamma_c}{dE_\ell} dE_\ell$ $\quad \langle m_X^n \rangle = \dfrac{1}{\Gamma_c} \int m_X^n \dfrac{d\Gamma_c}{dm_X} dm_X$

Global OPE Fit

- OPE predicts total rate Γ_c and moments $\langle E_\ell^n \rangle$, $\langle m_X^n \rangle$ as functions of $|V_{cb}|$, m_b, m_c, and several non-perturb. params
  - Each observable has different dependence
    ➔ Can determine all parameters from a global fit
- E_γ spectrum in $B \to X_s\gamma$ decays connected directly to the SF
  - Small rate and high background makes it tough to measure
  - Measured by *BABAR*, Belle, CLEO





OPE Fit Results

BaBar	PRD69:111103 PRD69:111104 PRD72:052004 hep-ex/0507001
Belle	PRL93:061803 hep-ex/0508005
CLEO	PRD70:031002 PRL87:251807
CDF	PRD71:051103
DELPHI	EPJ C45:35

- Buchmüller & Flächer (hep-ph/0507253) fit data from 10 measurements with an OPE calculation by Gambino & Uraltsev (Eur. Phys. J. C34 (2004) 181)
  - Fit parameters: $|V_{cb}|$, m_b, m_c, μ_π^2, μ_G^2, ρ_D^3, ρ_{LS}^3, $BR(B \to X_c \ell\nu)$

±2%

±1%

$$|V_{cb}| = (41.96 \pm 0.23_{\text{exp}} \pm 0.35_{\text{OPE}} \pm 0.59_{\Gamma_{sl}}) \times 10^{-3}$$

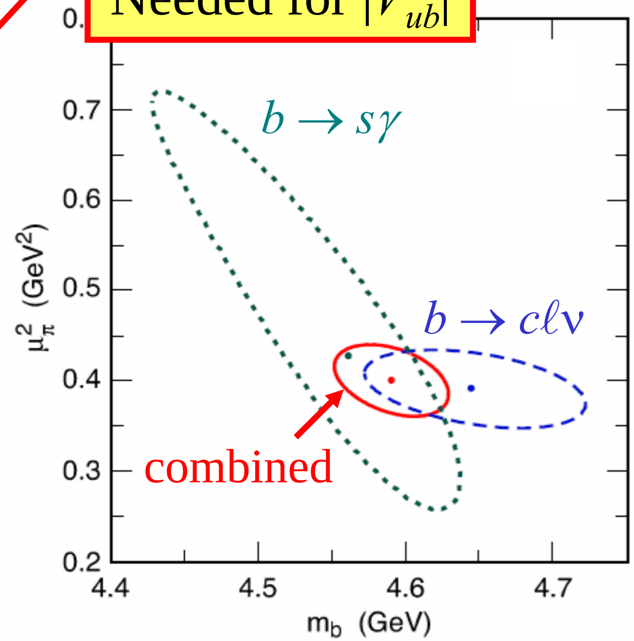
$$m_b = 4.590 \pm 0.025_{\text{exp}} \pm 0.030_{\text{OPE}}\ \text{GeV}$$

$$m_c = 1.142 \pm 0.037_{\text{exp}} \pm 0.045_{\text{OPE}}\ \text{GeV}$$

$$\mu_\pi^2 = 0.401 \pm 0.019_{\text{exp}} \pm 0.035_{\text{OPE}}\ \text{GeV}^2$$

$$BR = 10.71 \pm 0.10_{\text{exp}} \pm 0.08_{\text{OPE}}\,\%$$

Needed for $|V_{ub}|$



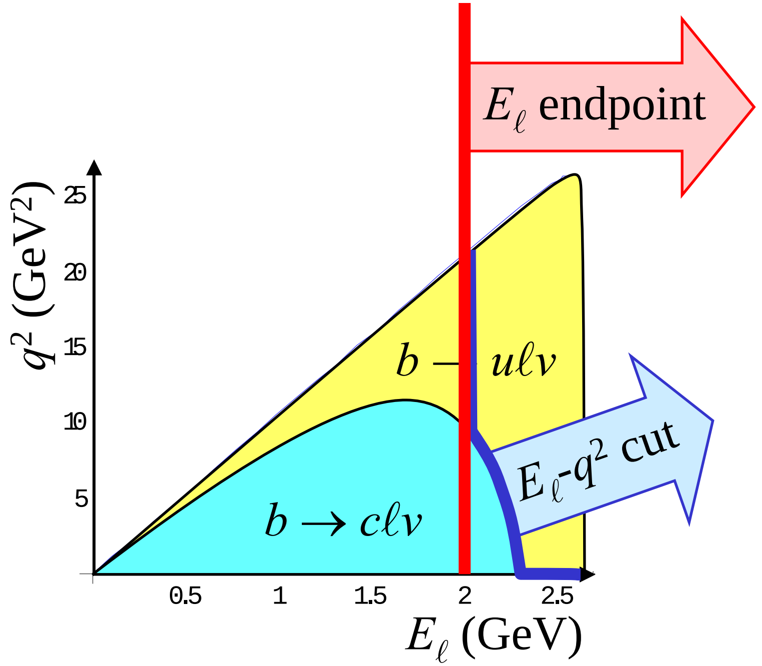
  - Goodness of the fit and the consistency between $X_c\ell\nu$ and $X_s\gamma$ add confidence to the theory

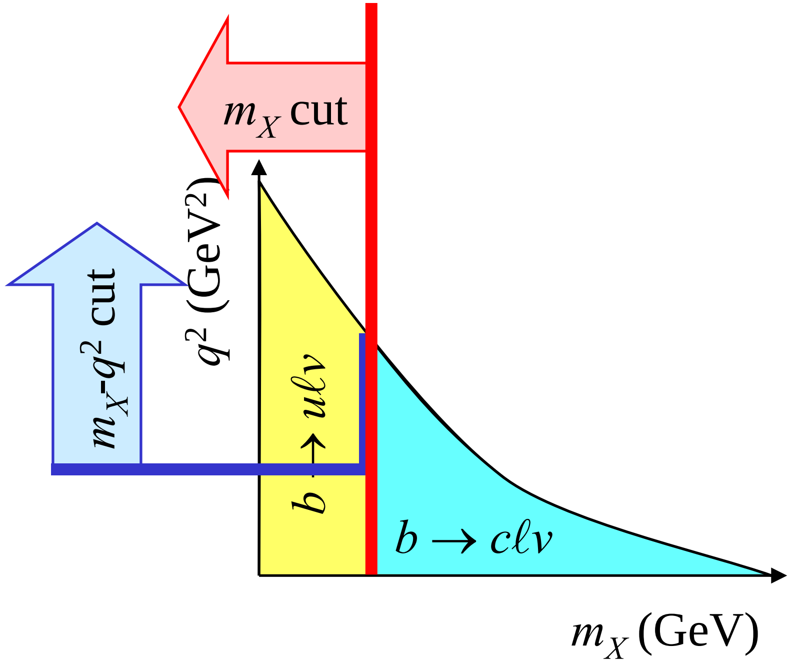
Inclusive $B \to X_u \ell \nu$

- Measure partial BF $\Delta\mathcal{B}(B \to X_u \ell \nu)$ in a region where ...
  - the signal/background is good, and
  - the partial rate $\Delta\Gamma_u$ is reliably calculable

Large $\Delta\Gamma_u$ generally good, but not always

- Many possibilities – Review a few recent results





Lepton Endpoint

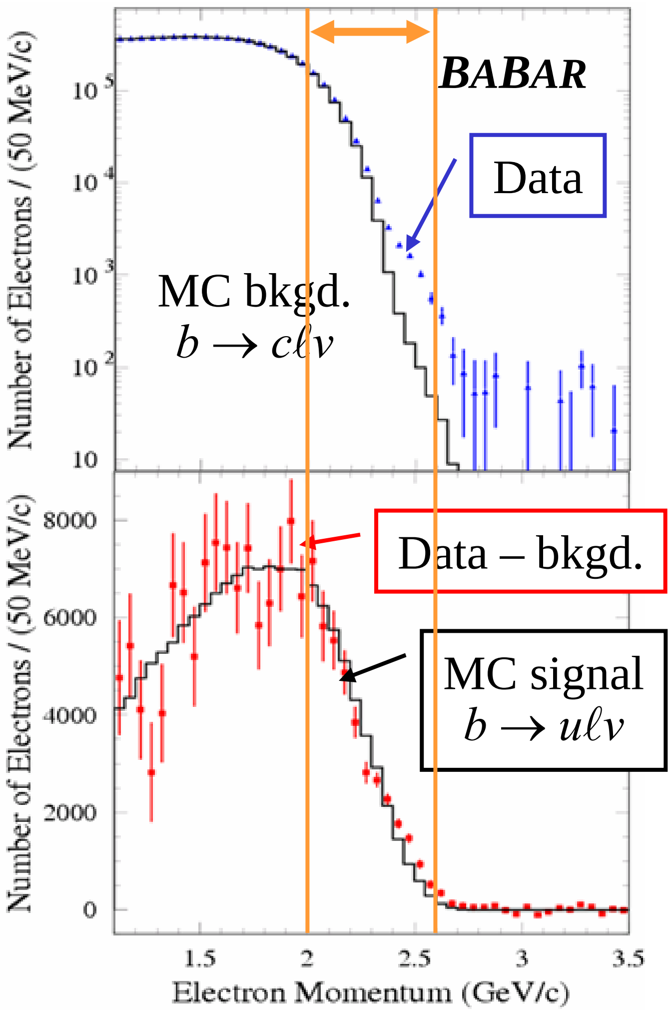
BABAR PRD 73:012006
Belle PLB 621:28
CLEO PRL 88:231803

- Find leptons with large E_ℓ
  - Push below the charm threshold
    ➔ Larger signal acceptance
    ➔ Smaller theoretical error
  - $S/B \sim 1/15$ ($E_\ell > 2$ GeV) ➔ Accurate subtraction of background is crucial!

	E_ℓ (GeV)	$\|V_{ub}\|$ (10^{-3})
BABAR 80fb^{-1}	2.0–2.6	$4.41 \pm 0.29_{exp} \pm 0.31_{SF+theo}$
Belle 27fb^{-1}	1.9–2.6	$4.82 \pm 0.45_{exp} \pm 0.30_{SF+theo}$
CLEO 9fb^{-1}	2.2–2.6	$4.09 \pm 0.48_{exp} \pm 0.36_{SF+theo}$

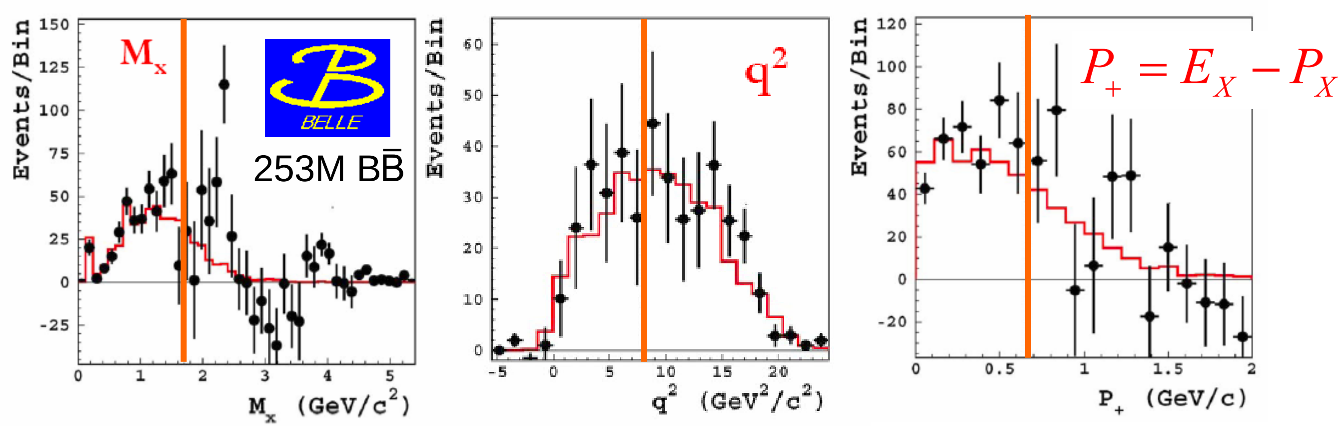
Shape **F**unction: determined from the OPE fit

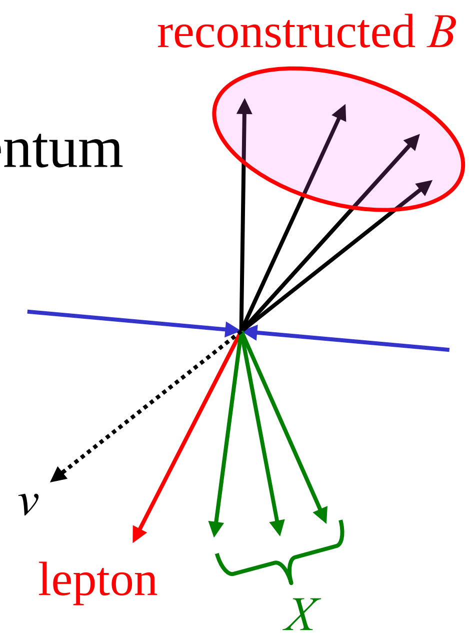
Theory errors: Lange *et al.* PRD72:073006



Hadronic *B* Tag

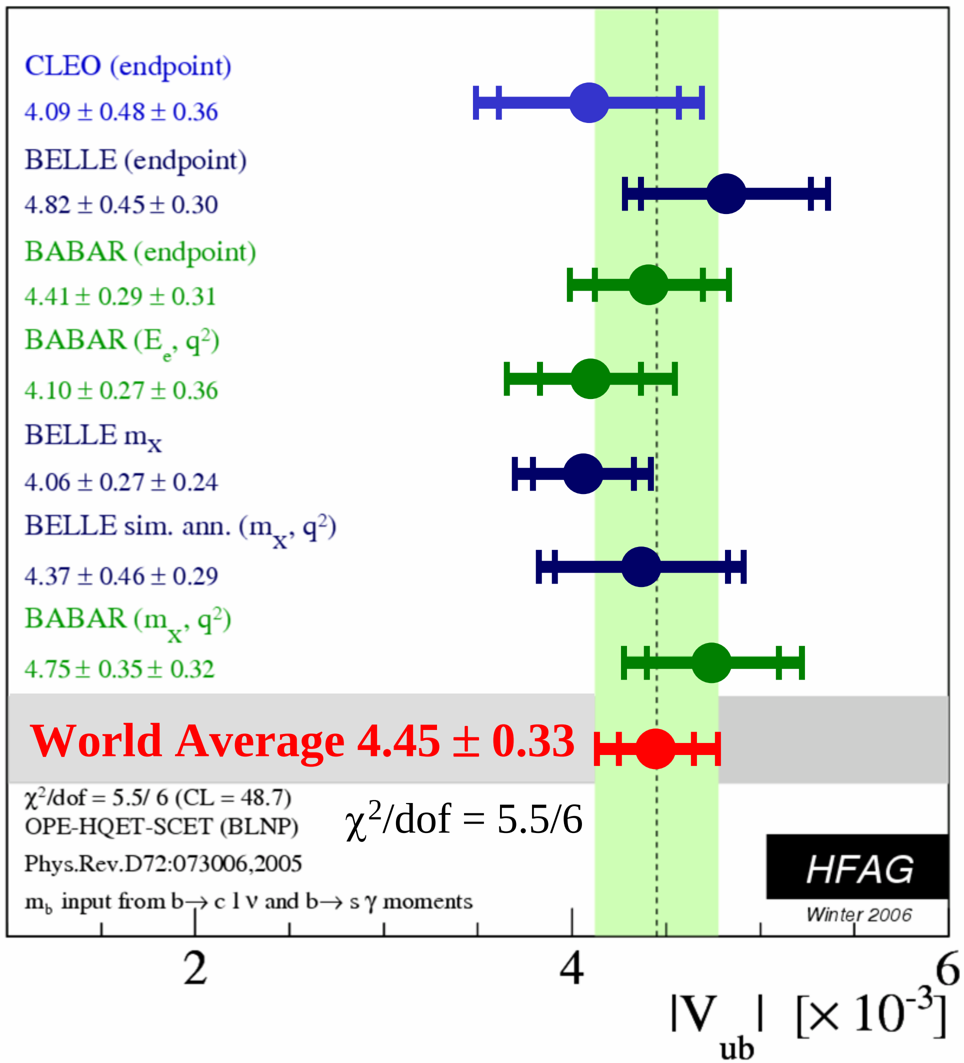
- Fully reconstruct one *B* in hadronic decays
  - Use the recoiling *B* with known charge and momentum
  - Access to all kinematic variables





	Region	$\lvert V_{ub}\rvert$ (10^{-3})
Belle 253M *BB*	$m_X < 1.7$ GeV, $q^2 > 8$ GeV^2	$4.70 \pm 0.37_{\text{exp}} \pm 0.31_{\text{SF+theo}}$
	$m_X < 1.7$ GeV	$4.09 \pm 0.28_{\text{exp}} \pm 0.24_{\text{SF+theo}}$
	$P_+ > 0.66$ GeV	$4.19 \pm 0.36_{\text{exp}} \pm 0.28_{\text{SF+theo}}$
BABAR 210M *BB*	$m_X < 1.7$ GeV, $q^2 > 8$ GeV^2	$4.75 \pm 0.35_{\text{exp}} \pm 0.32_{\text{SF+theo}}$ Prelim.

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



- $|V_{ub}|$ determined to ±7.4%

Experimental	±4.5%
SF params.	±4.1%
Theory	±4.2%

  - Expt. and SF errors will improve with more data
- Theory errors from
  - Sub-leading SF (3.8%)
    - Higher-order non-perturbative corrections
  - Weak annihilation (1.9%)
    - Can be constrained with future measurements

SF-Free $|V_{ub}|$ Measurement

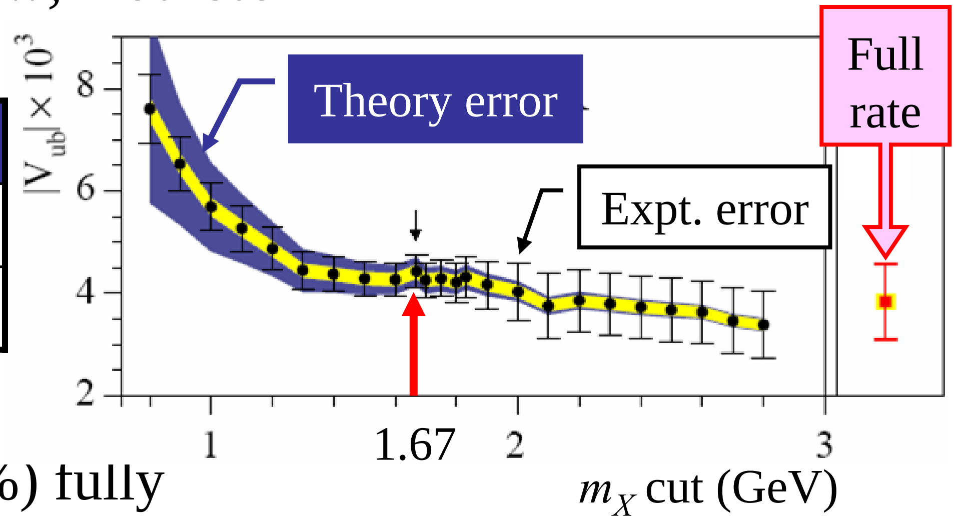
- Possible to combine $b \to u\ell\nu$ and $b \to s\gamma$ so that the SF cancels

$$\Gamma(B \to X_u \ell \nu) = \frac{|V_{ub}|^2}{|V_{ts}|^2} \int W(E_\gamma) \frac{d\Gamma(B \to X_s \gamma)}{dE_\gamma} dE_\gamma$$

Weight function

- *BABAR* applied Leibovich, Low, Rothstein (PLB 486:86) to 80 fb^{-1} data

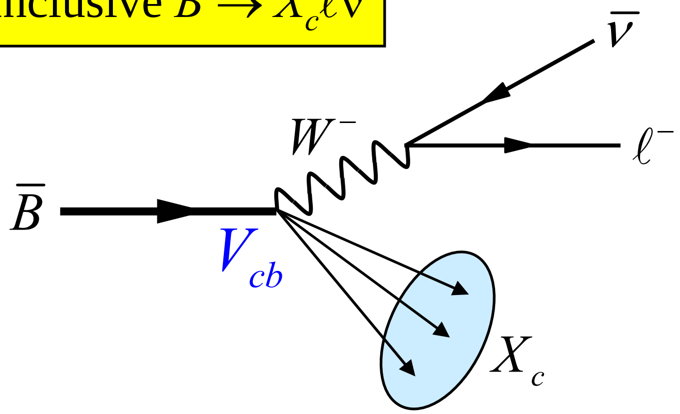
m_X cut	$\lvert V_{ub}\rvert$ (10^{-3})
1.67 GeV	$4.43 \pm 0.45_{\text{exp}} \pm 0.29_{\text{theo}}$
2.5 GeV	$3.84 \pm 0.76_{\text{exp}} \pm 0.10_{\text{theo}}$



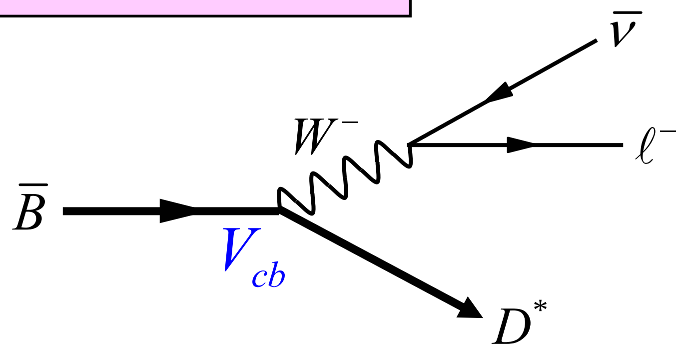
  - Trade SF error ➔ Stat. error
  - $m_X < 2.5$ GeV is almost (96%) fully inclusive ➔ Theory error reduces to ±2.6%

Inclusive vs. Exclusive

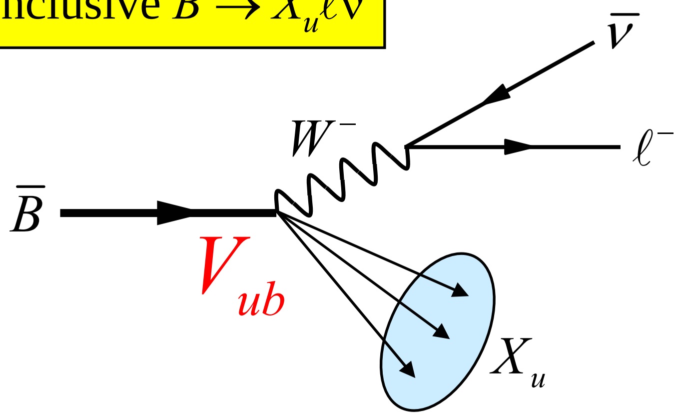
Inclusive $B \to X_c \ell \nu$



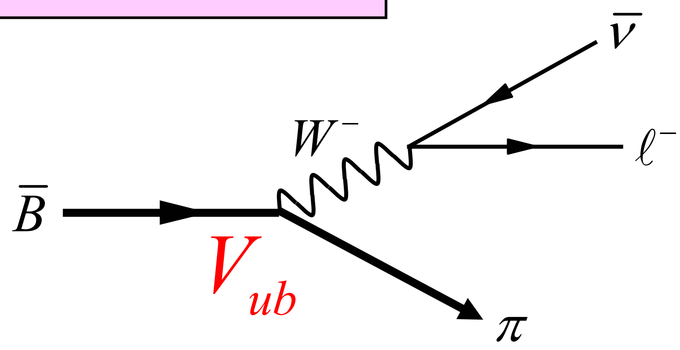
Exclusive $B \to D^* \ell \nu$



Inclusive $B \to X_u \ell \nu$



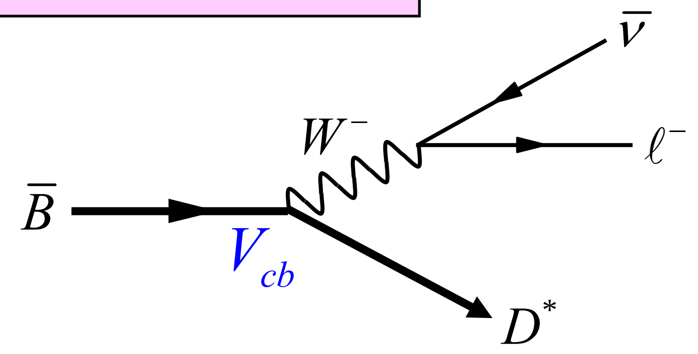
Exclusive $B \to \pi \ell \nu$



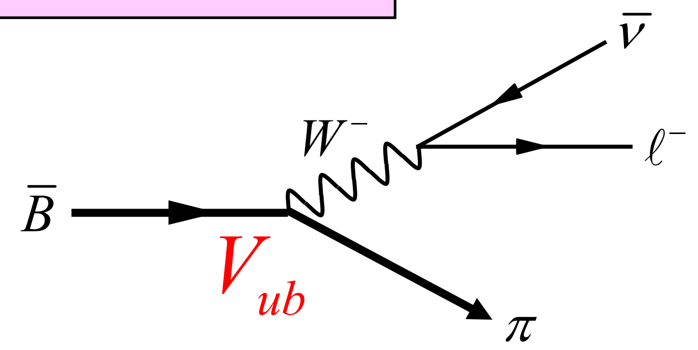
Exclusive Measurements

- Exclusive rates determined by $|V_{xb}|$ and Form Factors
  - Theoretically calculable at kinematical limits
    - Lattice QCD works if D^* or π is ~ at rest relative to B
  - Empirical extrapolation is necessary to extract $|V_{xb}|$ from measurements
- Measure differential rates to constrain the FF shape
  - Then use FF normalization from the theory

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



Exclusive $B \to \pi \ell \nu$



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

- Decay rate is

form factor

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

phase space

D^* boost in the B rest frame

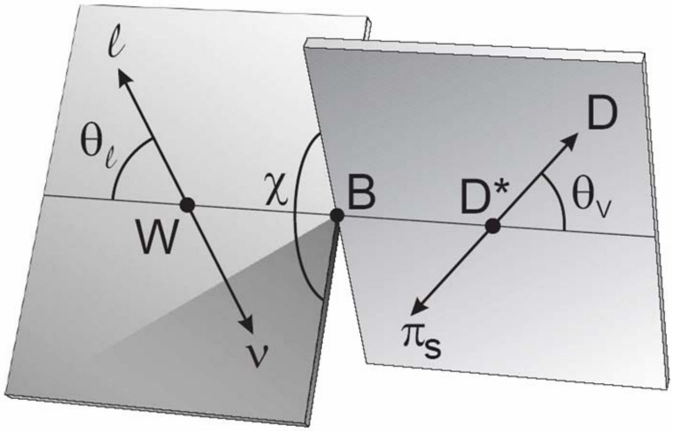
  - $\mathcal{F}(1) = 1$ in the heavy-quark limit; lattice QCD: $\mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$

Hashimoto et al, PRD 66 (2002) 014503

  - $\mathcal{F}(w)$ shape expressed by ρ^2 (slope at $w = 1$) and R_1, R_2 (form factor ratios)
    - Curvature constrained by analyticity

Caprini, Lellouch, Neubert NPB530 (1998) 153

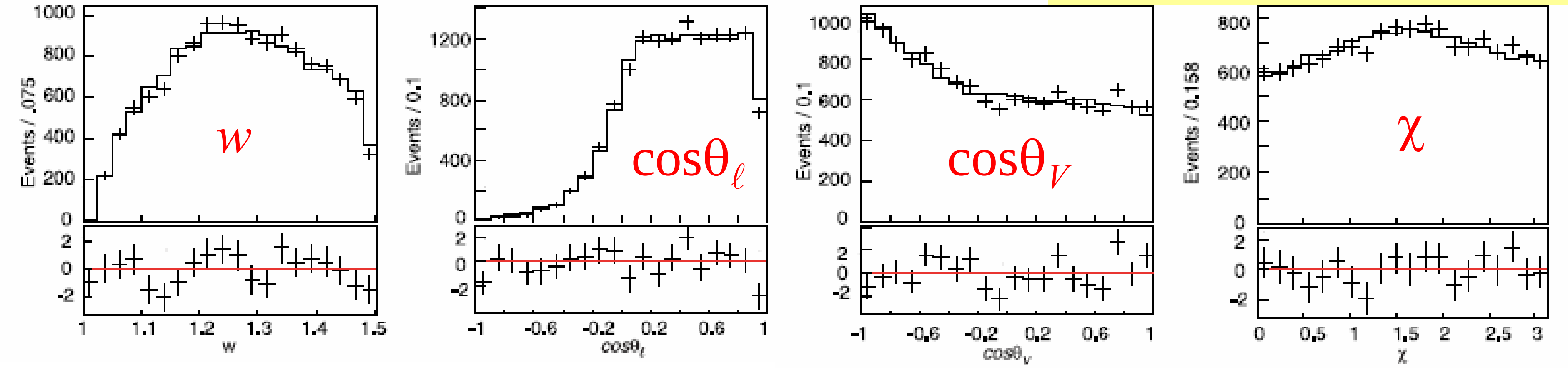
- Measure decay angles θ_ℓ, θ_V, χ
  - Fit 3-D distribution in bins of w to extract ρ^2, R_1, R_2



$B \to D^* \ell \nu$ Form Factors

- *BABAR* measured FF params. with 79 fb^{-1}

Signal MC vs. bkgd.-subtracted data, 1D projections



$$R_1 = 1.396 \pm 0.060_{\text{stat}} \pm 0.044_{\text{syst}}$$

$$R_2 = 0.885 \pm 0.040_{\text{stat}} \pm 0.026_{\text{syst}}$$

$$\rho^2 = 1.145 \pm 0.059_{\text{stat}} \pm 0.046_{\text{syst}}$$

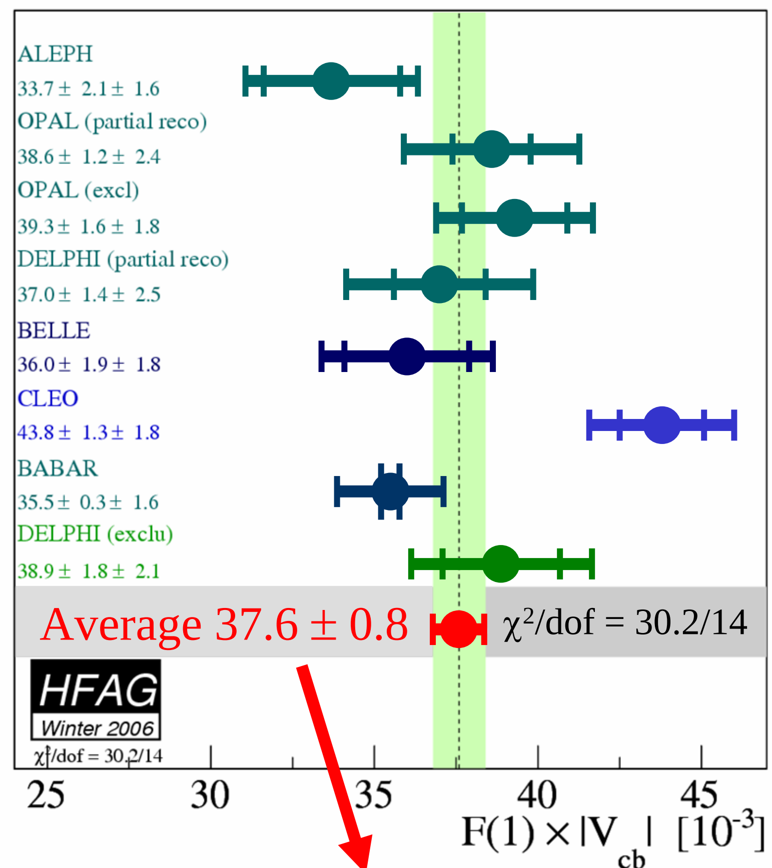
- R_1 and R_2 improved by a factor 5 over previous CLEO measurement PRL 76 (1996) 3898
- Will improve all measurements of $B \to D^* \ell \nu$

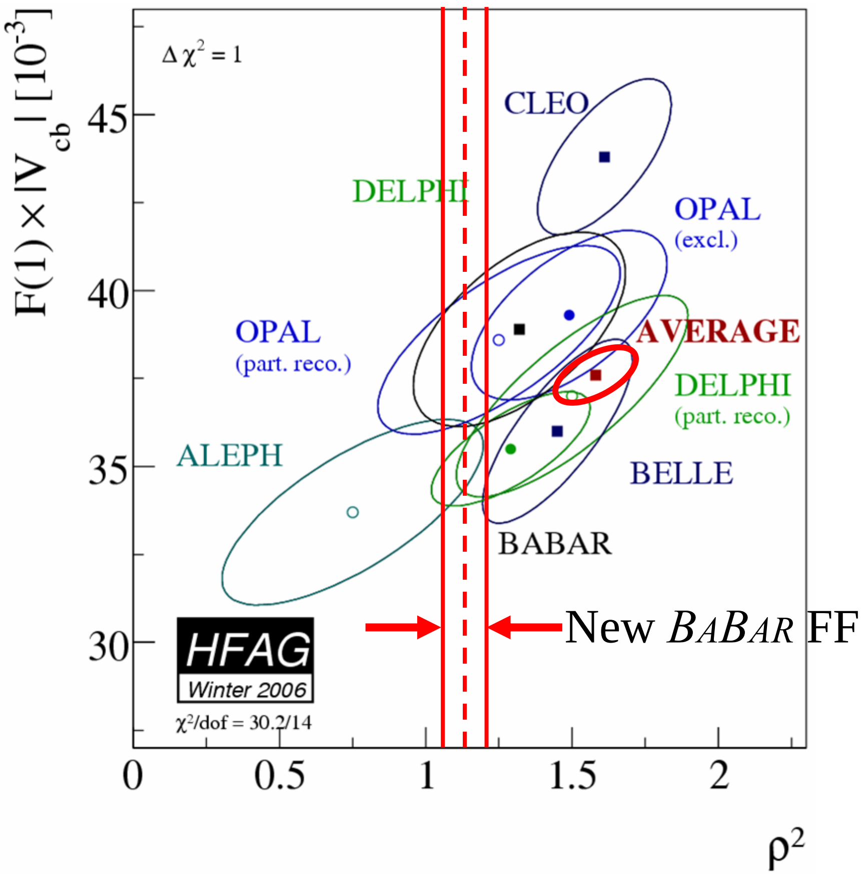
Using *BABAR* measurements only

$$|V_{cb}| = 37.6 \pm 0.3(stat) \pm 1.3(syst)\ {}^{+1.5}_{-1.3}(theory) \times 10^{-3}$$

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

- HFAG average still uses FF from CLEO





$$|V_{cb}| = (40.9 \pm 0.9 \pm 1.5_{\mathcal{F}(1)}) \times 10^{-3}$$

c.f. $(42.0 \pm 0.7)\times 10^{-3}$ from inclusive OPE fit

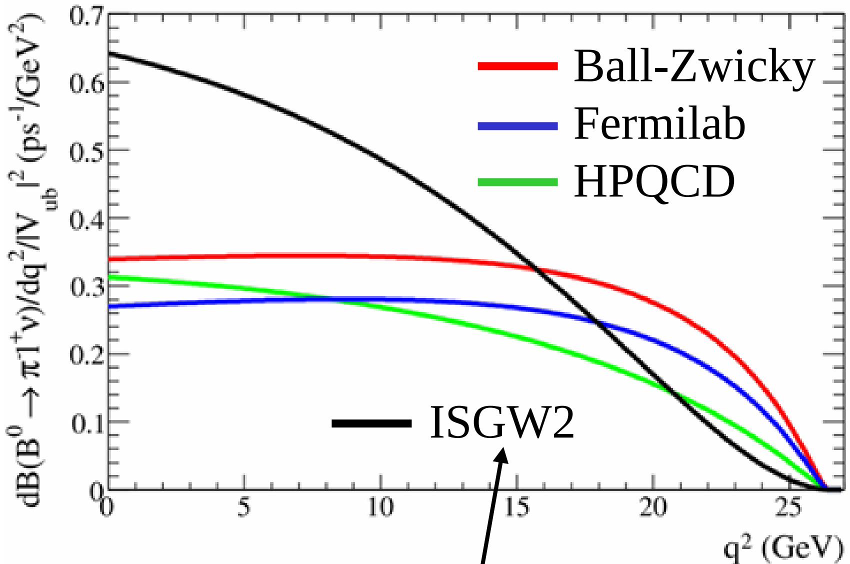
Exclusive $B \to \pi\ell\nu$

- $B \to \pi\ell\nu$ rate is given by

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

One FF for $B \to \pi\ell\nu$ with massless lepton

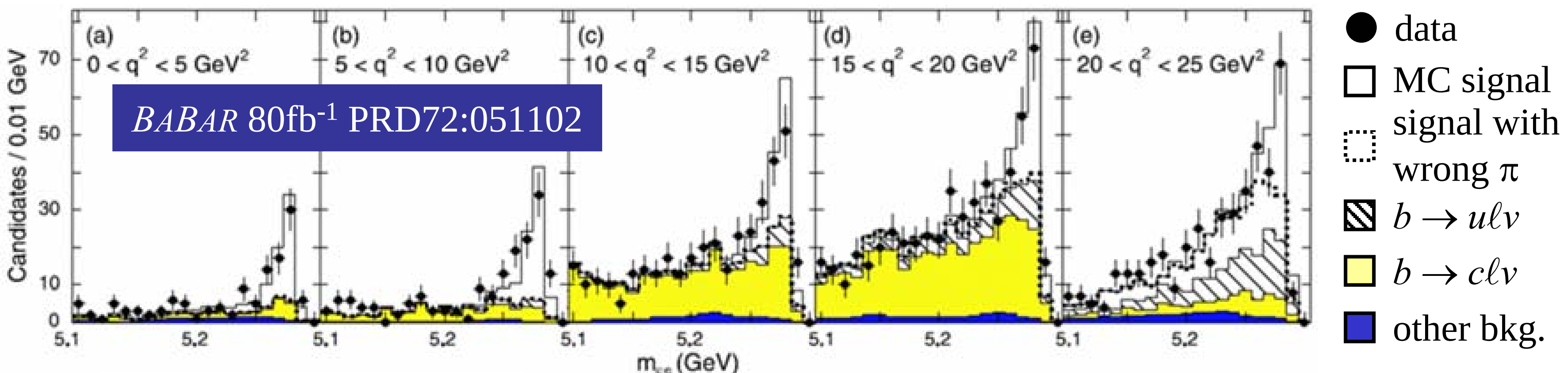
- Form factor $f_+(q^2)$ has been calculated using
  - Lattice QCD
    - Unquenched calculations by Fermilab (hep-lat/0409116) and HPQCD (PRD73:074502)
    - ±12% for $q^2 > 16$ GeV^2
  - Light Cone Sum Rules
    - Ball & Zwicky (PRD71:014015)
    - ±13% for $q^2 < 16$ GeV^2

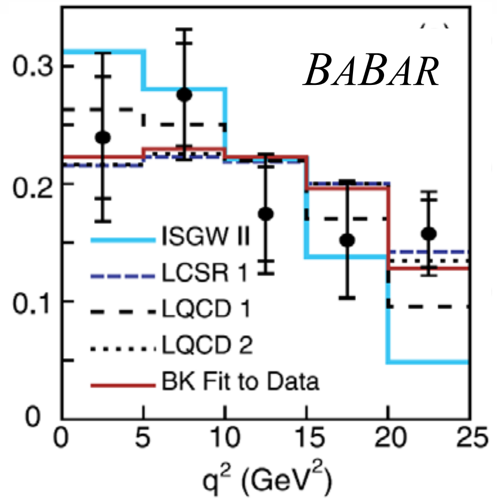


Quark model, PRD52 (1995) 2783

Untagged $B \to \pi\ell\nu$

- Missing 4-momentum = neutrino
  - Reconstruct $B \to \pi\ell\nu$ and calculate m_B and $\Delta E = E_B - \sqrt{s}/2$



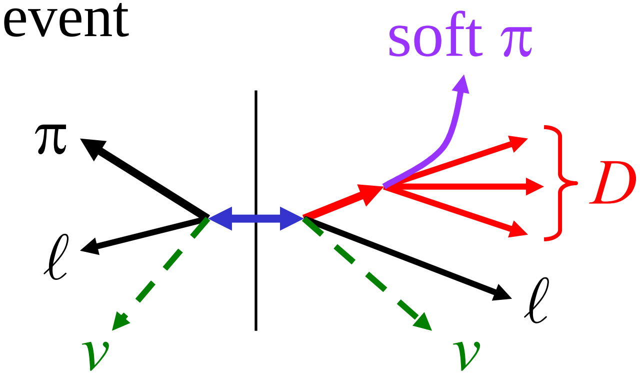


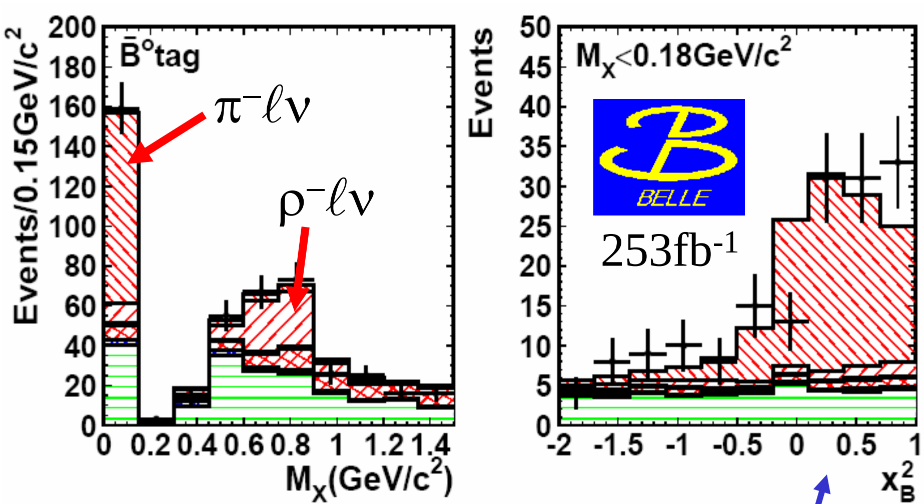
$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.38 \pm 0.10_{\text{stat}} \pm 0.18_{\text{syst}}) \times 10^{-4}$$

- Measured q^2 spectrum starts to constrain the FF shape
  - LQCD/LCSR favored over ISGW2

$D^{(*)}\ell\nu$-tagged $B \to \pi\ell\nu$

- Reconstruct one B in $D^{(*)}\ell\nu$ and look for $B \to \pi\ell\nu$ in the recoil
  - $B \to D^*\ell\nu$ BF large; two neutrinos in the event
- Event kinematics determined assuming known m_B and $m_\nu = 0$





Signal appears in $0 < x_B^2 < 1$

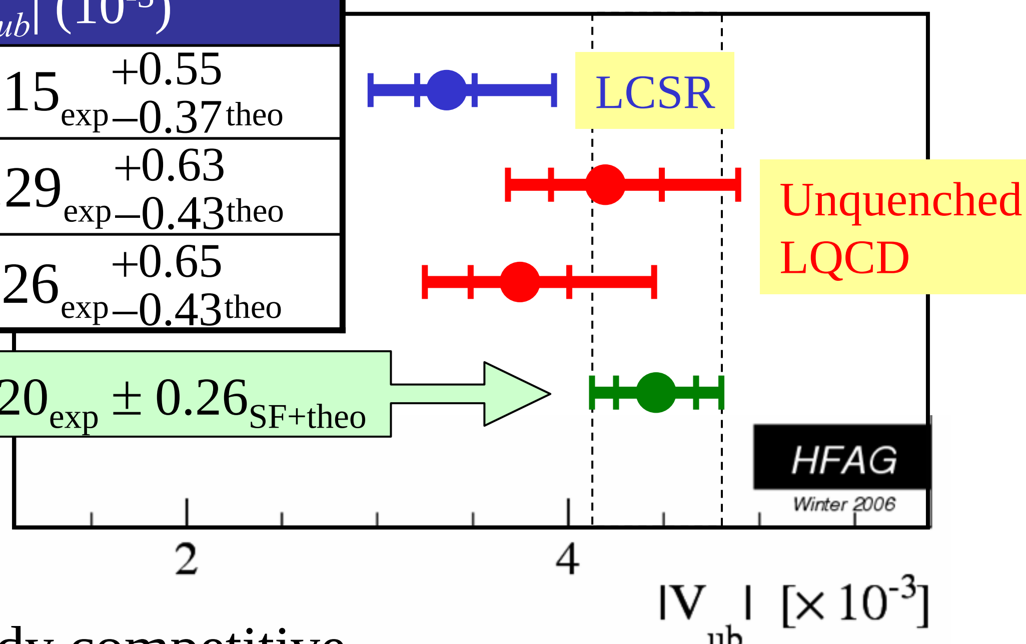
	Mode	BF (10^{-4})
Belle	$B^0 \to \pi^-\ell\nu$	1.38 ± 0.24
	$B^+ \to \pi^0\ell\nu$	0.77 ± 0.16
BABAR Prelim.	$B^0 \to \pi^-\ell\nu$	1.02 ± 0.28
	$B^+ \to \pi^0\ell\nu$	1.86 ± 0.44

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

- Average BF measurements and apply FF calculations

$\Delta\mathcal{B}(q^2 < 16)$ (10^{-4})	$\Delta\mathcal{B}(q^2 > 16)$ (10^{-4})	Total $\mathcal{B}$ (10^{-4})
$0.94 \pm 0.06_{\text{stat}} \pm 0.06_{\text{syst}}$	$0.39 \pm 0.04_{\text{stat}} \pm 0.04_{\text{syst}}$	$1.34 \pm 0.08_{\text{stat}} \pm 0.08_{\text{syst}}$

Form Factor	q^2 (GeV^2)	$\|V_{ub}\|$ (10^{-3})
Ball-Zwicky	< 16	$3.36 \pm 0.15_{\text{exp}}\,{}^{+0.55}_{-0.37}{}_{\text{theo}}$
HPQCD	> 16	$4.20 \pm 0.29_{\text{exp}}\,{}^{+0.63}_{-0.43}{}_{\text{theo}}$
FNAL	> 16	$3.75 \pm 0.26_{\text{exp}}\,{}^{+0.65}_{-0.43}{}_{\text{theo}}$



Inclusive: $4.45 \pm 0.20_{\text{exp}} \pm 0.26_{\text{SF+theo}}$

- Consistent within (large) FF errors
- Experimental errors already competitive

Summary

- Semileptonic B decays offer exciting physics opportunities
  - $|V_{ub}/V_{cb}|$ complements $\sin 2\beta$ to test (in)completeness of the SM
- Challenge of hadronic physics met by close collaboration between theory and experiment
  - Inclusive $B \to X_c \ell\nu$ & $X_s\gamma$ fit precisely determines $|V_{cb}|$, m_b, etc.
  - Dramatic progress in both measurement and interpretation of inclusive $B \to X_u \ell\nu$ in the last 2 years
- Inclusive $|V_{ub}|$ achieved ±7.4% accuracy
  - Room for improvements with additional data statistics
- $B \to D^* \ell\nu$ form factors have improved by a factor 5
- Measurements of $B \to \pi\ell\nu$ becoming precise
  - Improved form factor calculation needed

Backup Slides

Weak Annihilation

- WA turns B^+ into $\ell\nu$ + soft hadrons
- Size and shape of WA poorly known
- Minimize the impact
  - Measure $X_u\ell\nu$ with v. loose cuts
  - Cut away large q^2 region
- Measure WA contribution
  - $\Gamma_{sl}(D^+)$ vs. $\Gamma_{sl}(D_s)$
    - CLEO-c
  - Distortion in q^2
    - CLEO hep-ex/0601027
  - $\Gamma(B^+ \to X_u\ell\nu)$ vs. $\Gamma(B^0 \to X_u\ell\nu)$
    - Work in progress