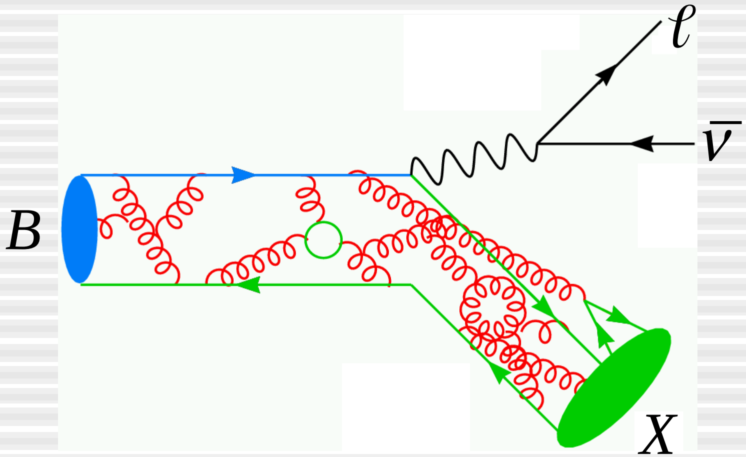


Experimental Particle Physics Seminar

Edinburgh, May 18th 2006

Semileptonic B decays

Francesca Di Lodovico

Queen Mary, University of London

What? Cracking the Triangle

Framework: the CKM Matrix

- B^+ and B^0 are the most accessible 3rd-generation particles
- Their decays allow detailed studies of the CKM matrix

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\left(\bar{u}_L \quad \bar{c}_L \quad \bar{t}_L\right)\gamma^\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W_\mu^+ + h.c.$$

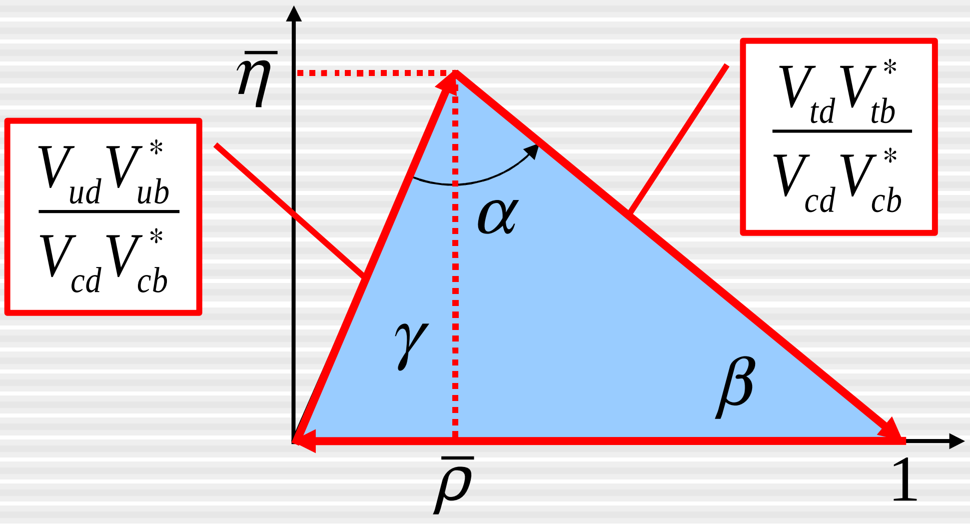
- Unitary matrix V_{CKM} translates mass and weak basis
- 3 real parameters + 1 complex phase

The only source of CPV in the Minimal SM

- Is this the complete description of the CP violation?
  - Is everything consistent with a single unitary matrix?

Representation: the Unitarity Triangle

- Unitarity of V_{CKM} ⇒ $V_{CKM}^{\dagger} V_{CKM} = 1$ ⇒ $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - This is neatly represented by the familiar Unitarity Triangle



$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

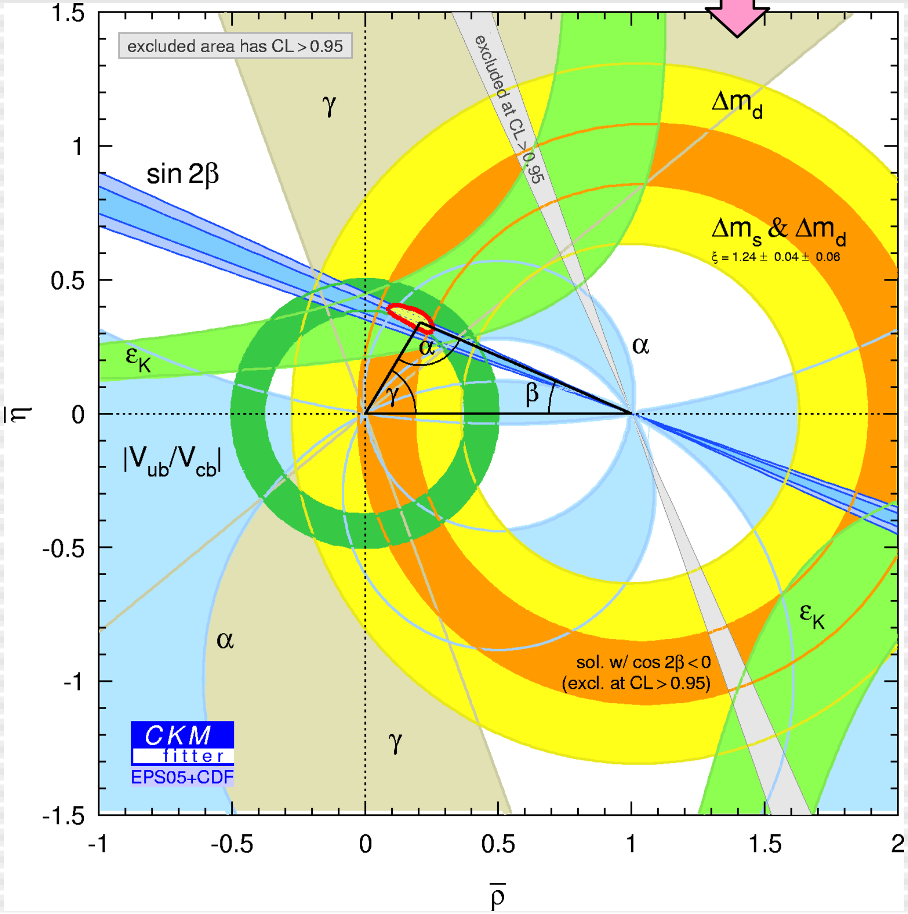
$$\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

  - Angles α, β, γ can be measured with CPV of B decays

Test: the Consistency

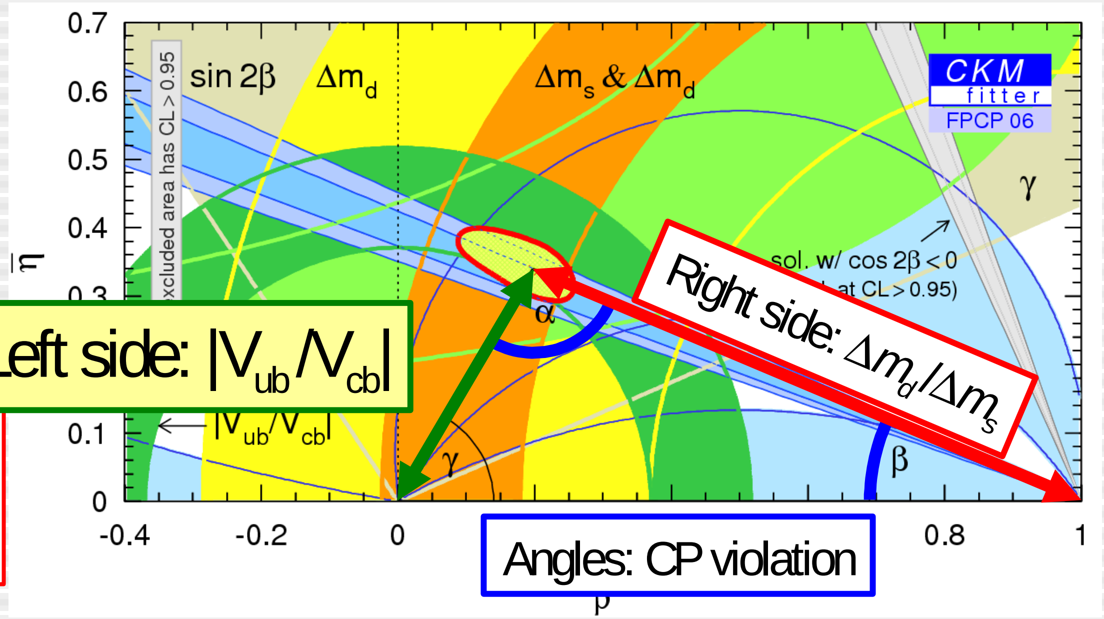
- Compare the measurements (contours) on the (ρ, η) plane
  - If the SM is the whole story, they must all overlap
- The  tells us this is true as of today
  - Still large enough for New Physics to hide
- Precision of $\sin 2\beta$ outstripped the other measurements
  - Must improve the others to make more stringent test



Next Step: $|V_{ub}/V_{cb}|$

- Zoom in to see the overlap of "the other contours
  - It's obvious: we must make the green ring thinner
- Left side of the Triangle is

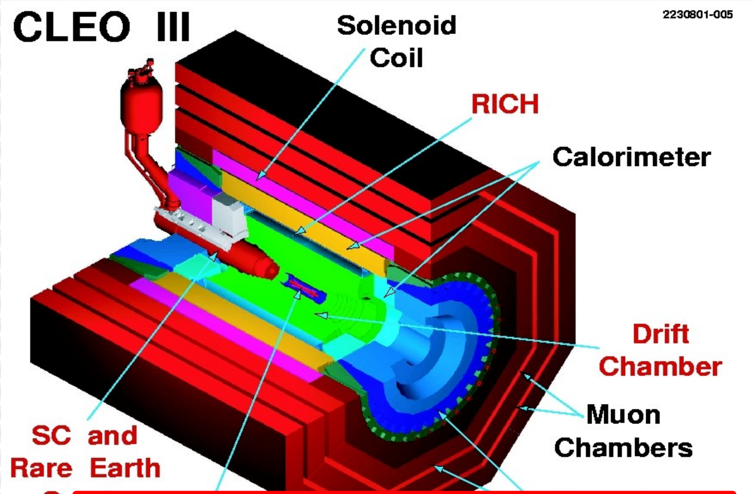
$$\left|\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right| = \left|\frac{V_{ub}}{V_{cb}}\right|\frac{1}{\tan\theta_C}$$



Measurement of $|V_{ub}/V_{cb}|$ is complementary to $\sin 2\beta$

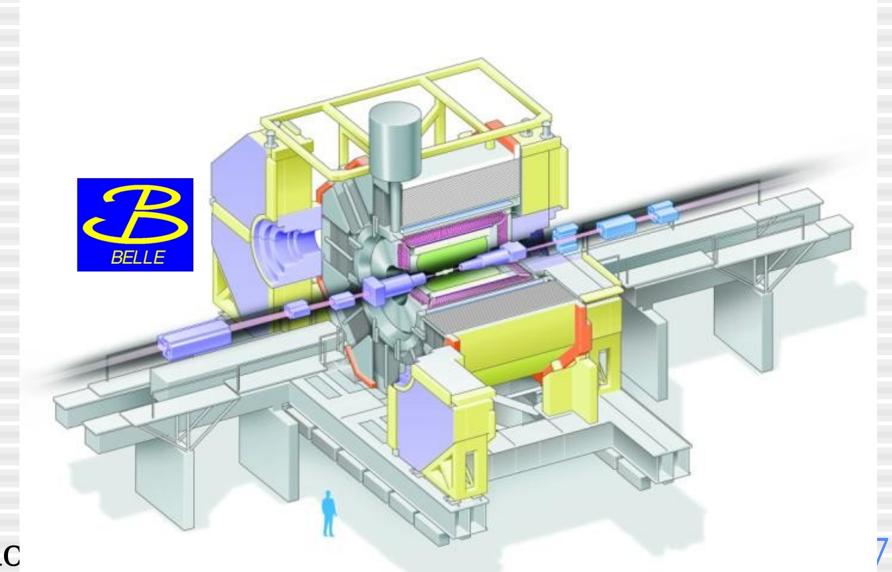
Goal: Accurate determination of both $|V_{ub}/V_{cb}|$ and $\sin 2\beta$

$\sin\beta$ (all charmonium) = 0.687 ± 0.032 ~ percentage error: 4.6% (HFAG)



CLEO, $e^+e^- \to \Upsilon(4S)$, no boost

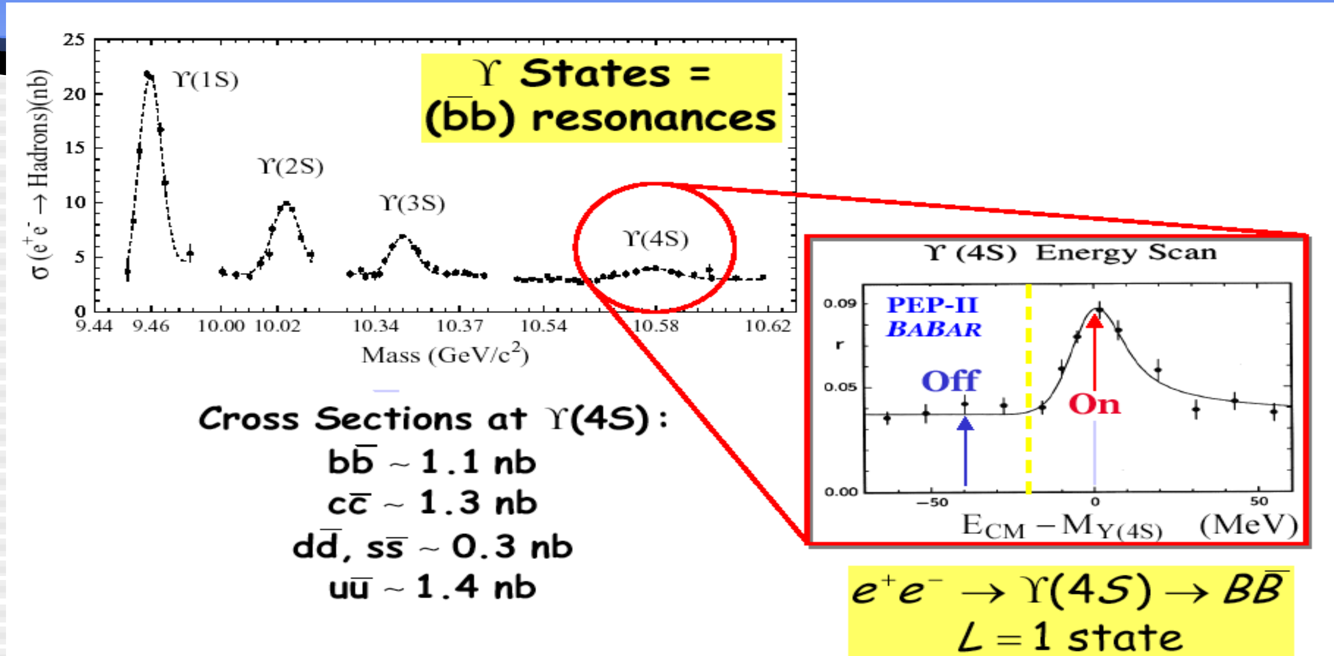
Where?@ the B-Factories

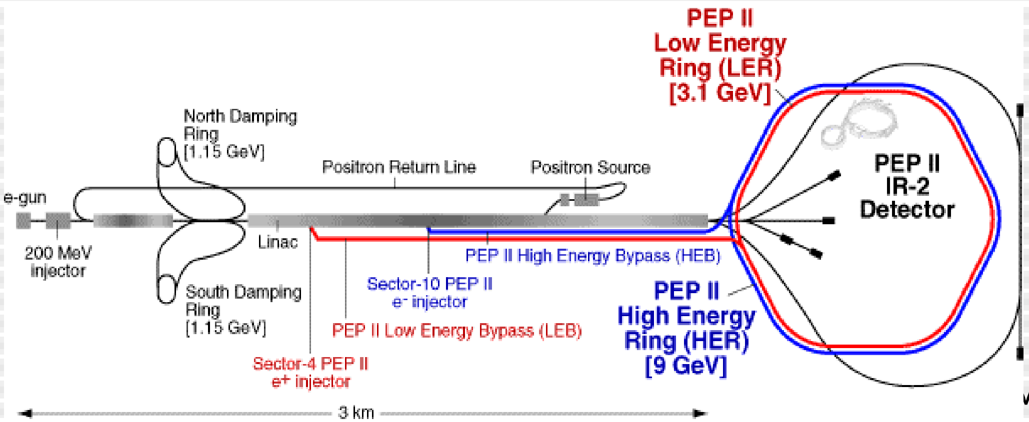


BaBar, $e^+e^- \to \Upsilon(4S)$, $\Upsilon(4S)$ boost ~ 0.56

BELLE, $e^+e^- \to \Upsilon(4S)$, $\Upsilon(4S)$ boost ~ 0.43

The B-Factory concept





- High luminosity B-factories @ Y(4S)
- CLEO: symmetric factory
- BaBar (BELLE) asymmetric factory
- 9 (8) GeV e^- on 3.1 (3.5) GeV e^+
- (4S) boost: $\beta\gamma$~0.56 (0.43l)

MUL

Luminosity: just spectacular!

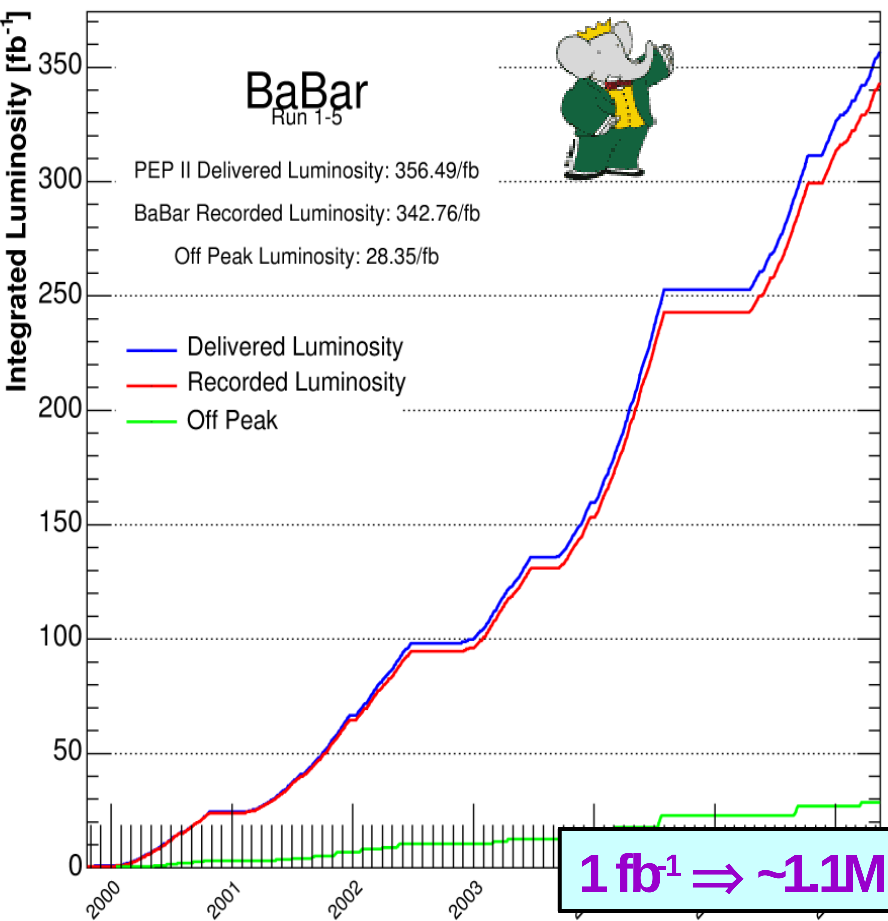
Peak luminosity 1.00×10^{34} cm^{2}s^{-1}

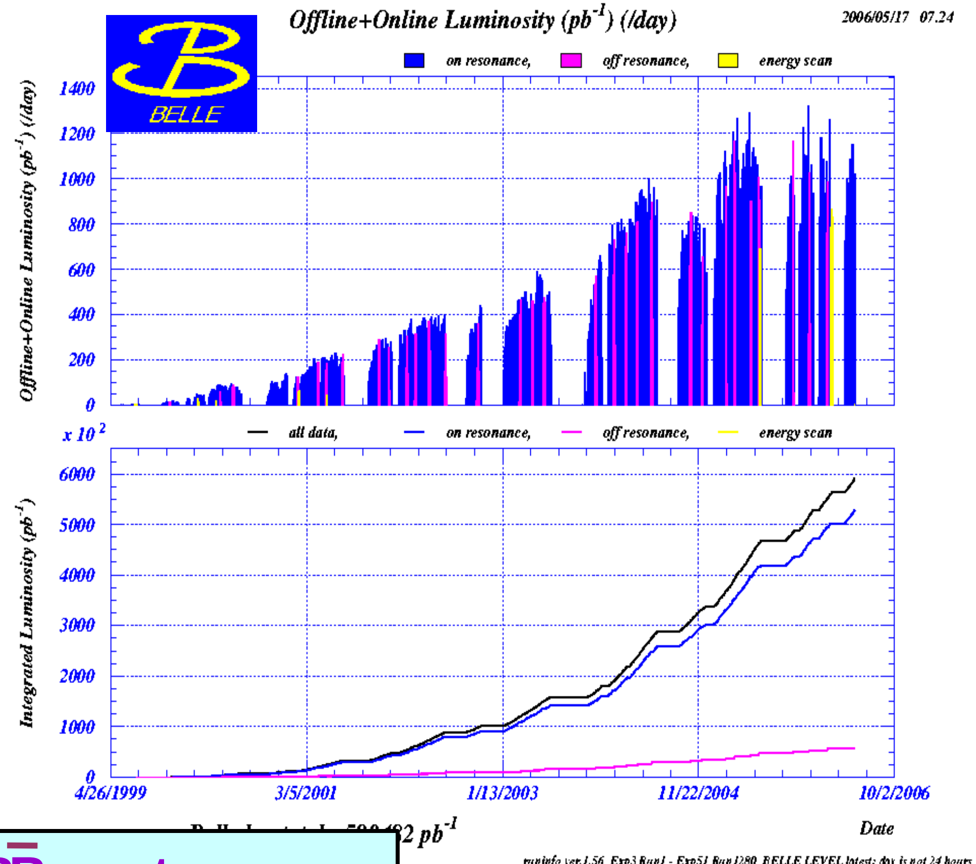
Integrated luminosity 343 fb^{-1} (May 17, 06)

21

Peak luminosity 1.63×10^{34} cm^{2}s^{-1}

Integrated luminosity 590 fb^{-1} (May 17, 06)



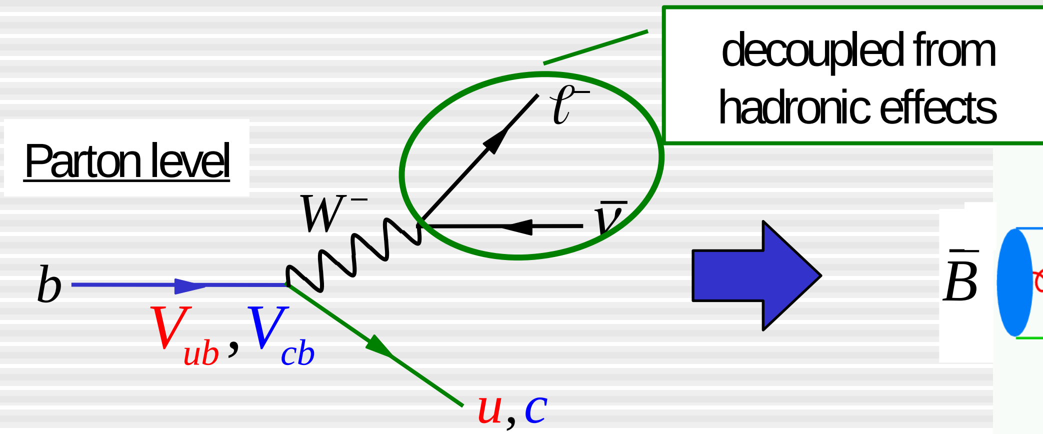


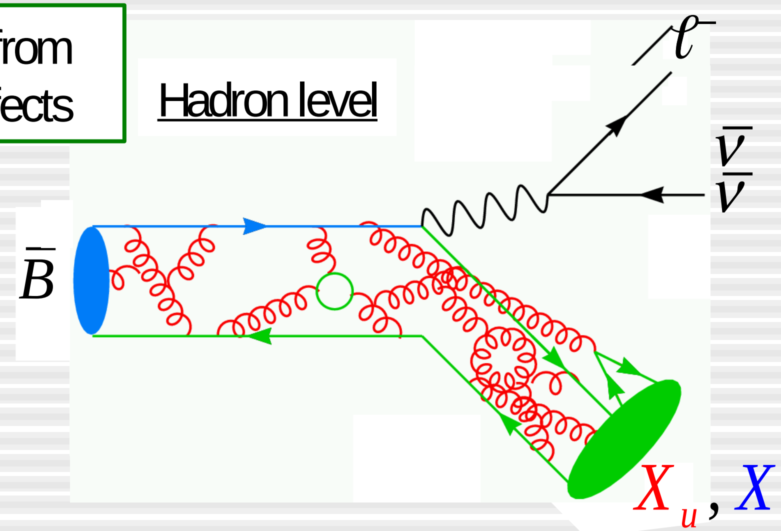
1 fb^{-1} ⇒ ~1.1M $B\bar{B}$ events

How? The Semileptonic Decays

Semileptonic B Decays

- Natural probe for $|V_{ub}|$ and $|V_{cb}|$: Decay rate $\Gamma_x \equiv \Gamma(b \to x\ell\nu) \propto |V_{xb}|^2$

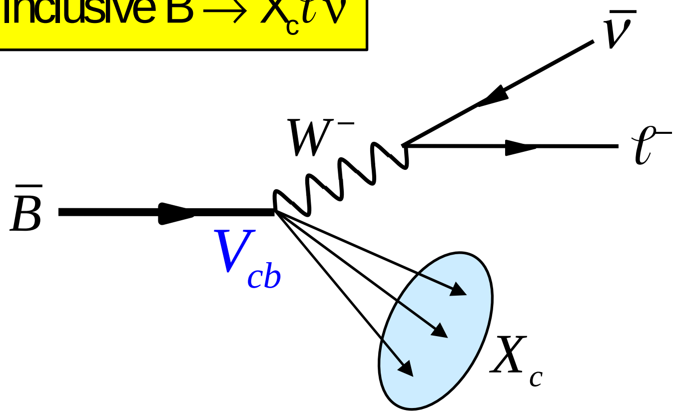




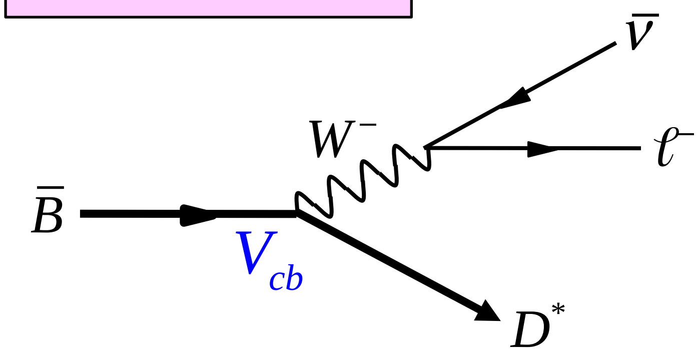
- Γ_c larger than Γ_u by a factor ~50
  - Extracting $b \to u\ell\nu$ signal challenging
- Sensitive to hadronic effects
  - Must understand them to extract $|V_{ub}|$, $|V_{cb}|$ (use data to bolster theory)

Inclusive vs. Exclusive

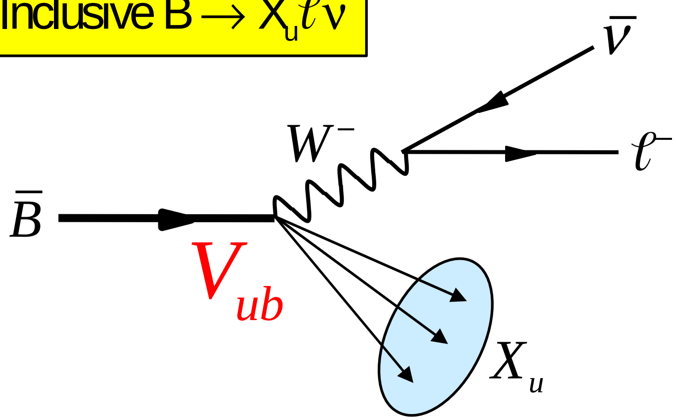
Inclusive $B \to X_c \ell \nu$



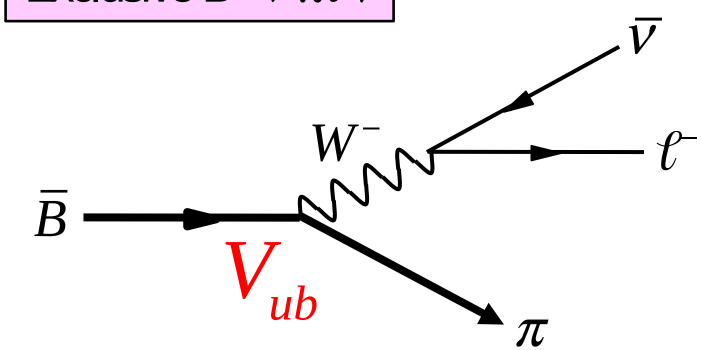
Exclusive $B \to D^* \ell \nu$



Inclusive $B \to X_u \ell \nu$



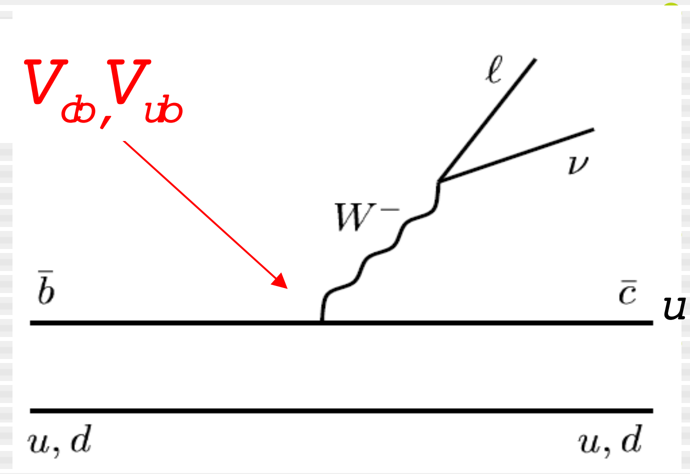
Exclusive $B \to \pi \ell \nu$



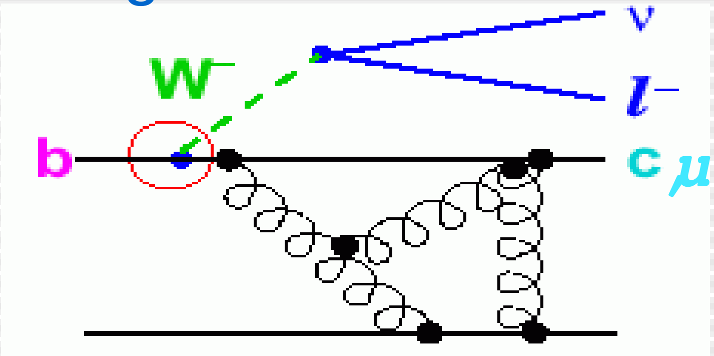
Inclusive Decays

Inclusive SL Decays

tree level, short distance:



+ long distance:



Decay properties depends directly on $|V_{cb}|$, $|V_{ub}|$, m_b, perturbative regime (α_s^n)

$\rightarrow$ short distance is calculable

But quarks are bound by soft gluons: non-perturbative long distance (Λ_{QCD}) interactions of b-quark with light quark

Long distance leading order and short distance contribution are cleanly separated and probability to hadronize is 1.

Inclusive semileptonic decays

$|V_{cb}|$ versus $|V_{ub}|$

$|V_{cb}|$:

- most accurate determination from the inclusive decays
- 2% precision limited by theory error
- precise Heavy Quarks parameters, tests of OPE

$|V_{ub}|$:

- 7.5% precision shared between experimental and theoretical errors
- small rate and large $b \to c\ell\nu$ background
- space cuts to remove $b \to c\ell\nu$ background which introduce dependence on non-perturbative b-quark distribution function

$|V_{cb}|$ from Inclusive Decays

$|V_{cb}|$ from inclusive semileptonic decays

$\Gamma(b\to c\ell\nu)$ described by Heavy Quark Expansion in $(1/m_b)^n$ and α_s^k

$$\Gamma(B\to X_c l\nu)=G_F^2 m_b^5/192\pi^3|V_{cb}|^2[[1+A_{ew}]A_{nonpert}A_{pert}]$$

non-perturbative parameters need to be measured

The expansion depends on the m_b definition: non-perturbative terms are expansion dependent

Theory error was dominated by $1/m_b^3$ terms and above

Moments in $B \to X_c \ell \nu$ decays

Moments are related to non-perturbative parameters

Moments evaluated on the full lepton/mass spectrum or part of it: $p_\ell > p_{min}$ in the B rest frame

$$\langle E_\ell^n \rangle = \frac{1}{\Gamma_c} \int \left(E_\ell - \langle E_\ell \rangle \right)^n \frac{d\Gamma_c}{dE_\ell} dE_\ell \qquad \langle m_X^n \rangle = \frac{1}{\Gamma_c} \int m_X^n \frac{d\Gamma_c}{dm_X} dm_X$$

Higher moments are sensitive to $1/m_b^3$ terms $\rightarrow$ reduce theory error on $|V_{cb}|$ and HQ parameters

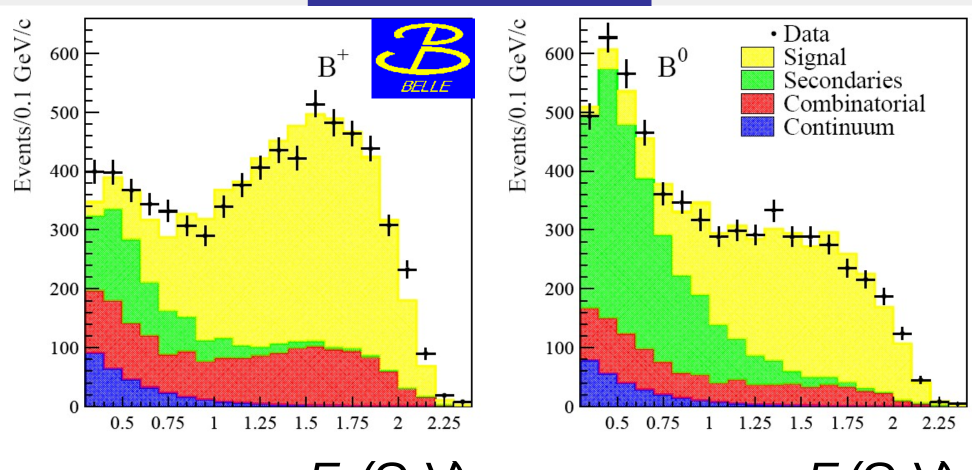
Moments in $B \to X_c \ell \nu$ decays

E_ℓ : lepton energy spectrum in $B \to X_c \ell \nu$ (BaBar Belle CLEO Delphi)

M_X^2: hadronic mass spectrum in $B \to X_c \ell \nu$ (BaBar CDF CLEO Delphi)

Recent example for lepton and hadron mass moments from Belle:

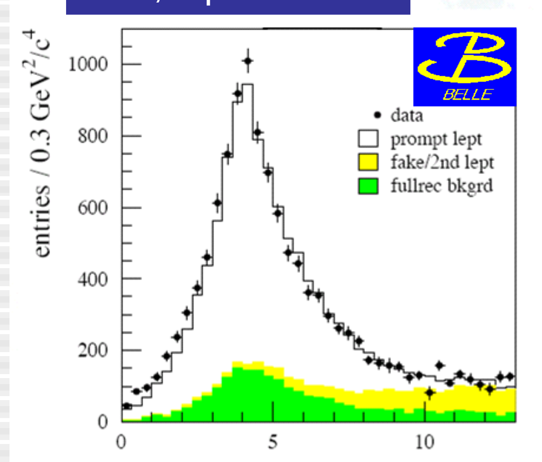
Belle, hep-ex/0508056



E_ℓ (GeV) E_ℓ(GeV)

P^{*B}_{min} =0.4 GeV

Belle, hep-ex/0509013



m_X^2 (GeV²/c⁴)

P^{*B}_{min} =0.7 GeV

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-perturbative 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 Shape Function (= what the b-quark is doing inside the B meson) so it is used in the global fit

OPE Fit Results

- 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, $BR(B \to X_c \ell \nu)$

Needed for $|V_{ub}|$

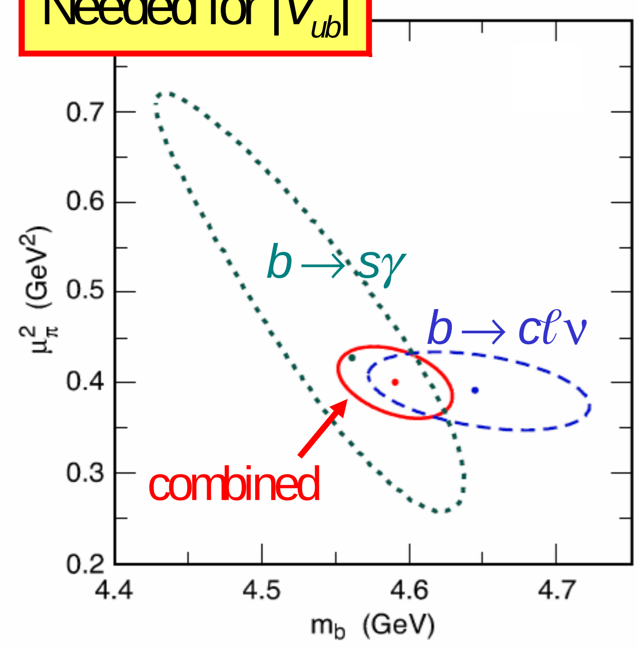
±2% $\Rightarrow$ $$|V_{cb}| = (41.96 \pm 0.23_{\text{exp}} \pm 0.35_{\text{OPE}} \pm 0.59_{\Gamma_{sl}})\ 10^{-3}$$

±1% $\Rightarrow$ $$m_b = 4.590 \pm 0.025_{\text{exp}} \pm 0.030_{\text{OPE}}\ \text{GeV}$$

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

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

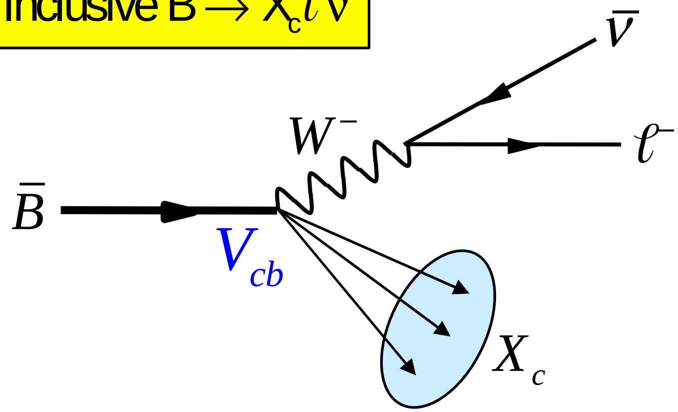
$$BR = 10.71 \pm 0.10_{\text{exp}} \pm 0.08_{\text{OPE}}\ \%$$



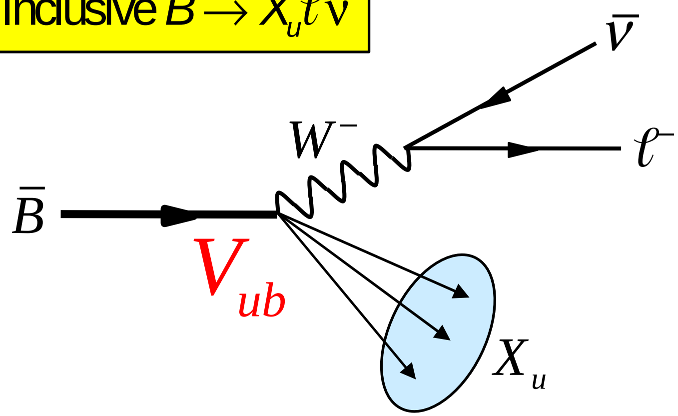
$|V_{ub}|$ from Inclusive Decays

$B \to X_u \ell \nu$ rate

Inclusive $B \to X_c \ell \nu$



Inclusive $B \to X_u \ell \nu$



- Operator Product Expansion predicts total
- rate Γ_u as:

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

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

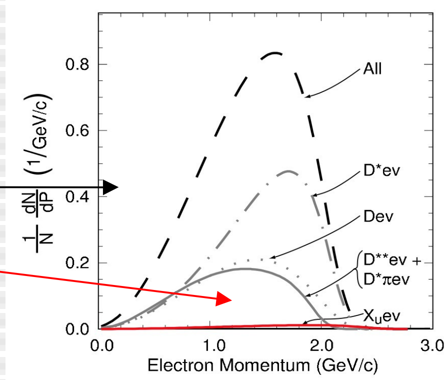
Non-perturb. terms suppressed by $1/m_b^2$

- Dominant error from m_b^5

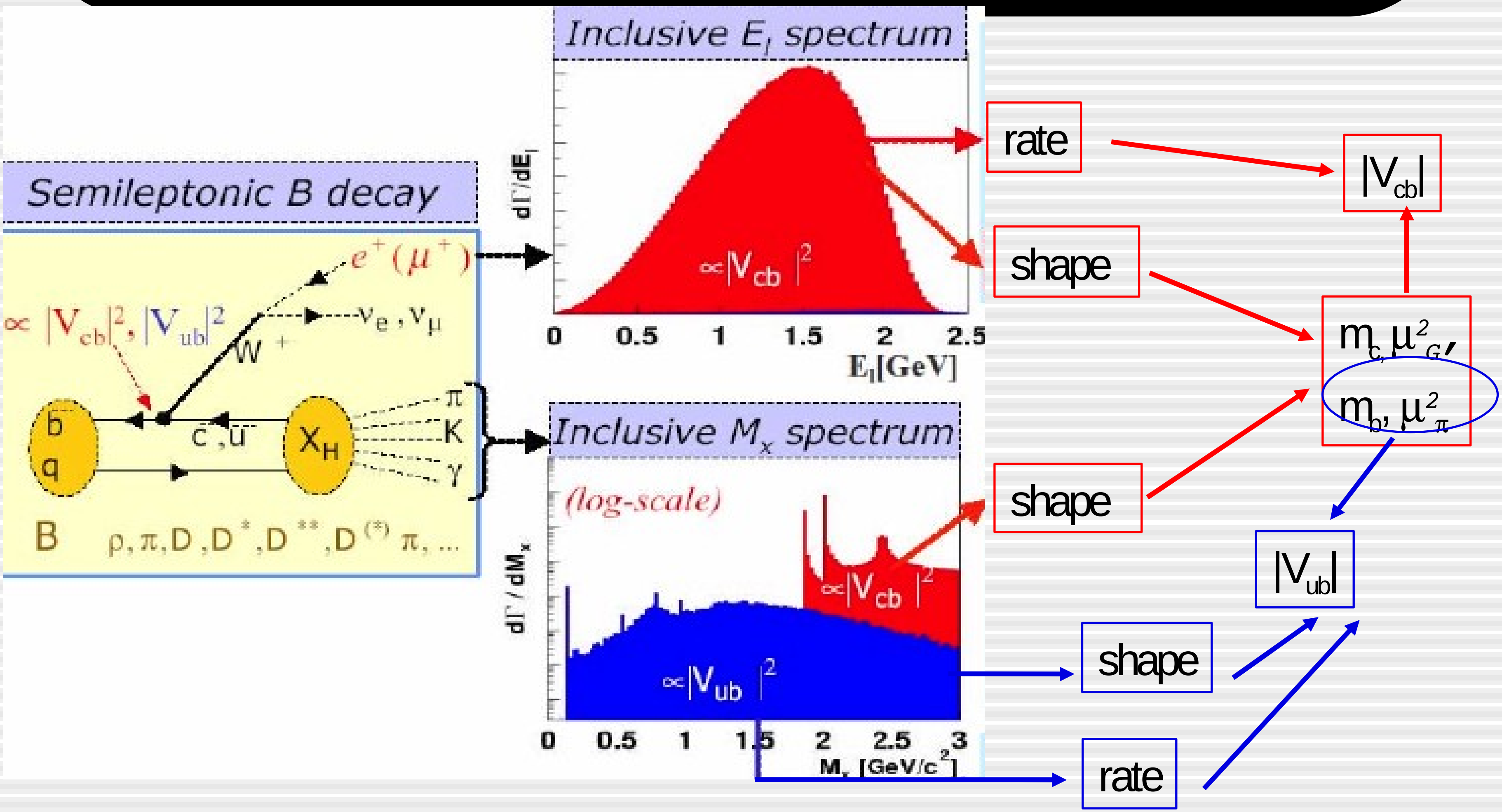
m_b measured to ±1% ➔ ±2.5% on $|V_{ub}|$

Total rate can't be measured due to $B \to X_c \ell \nu$ background

signal

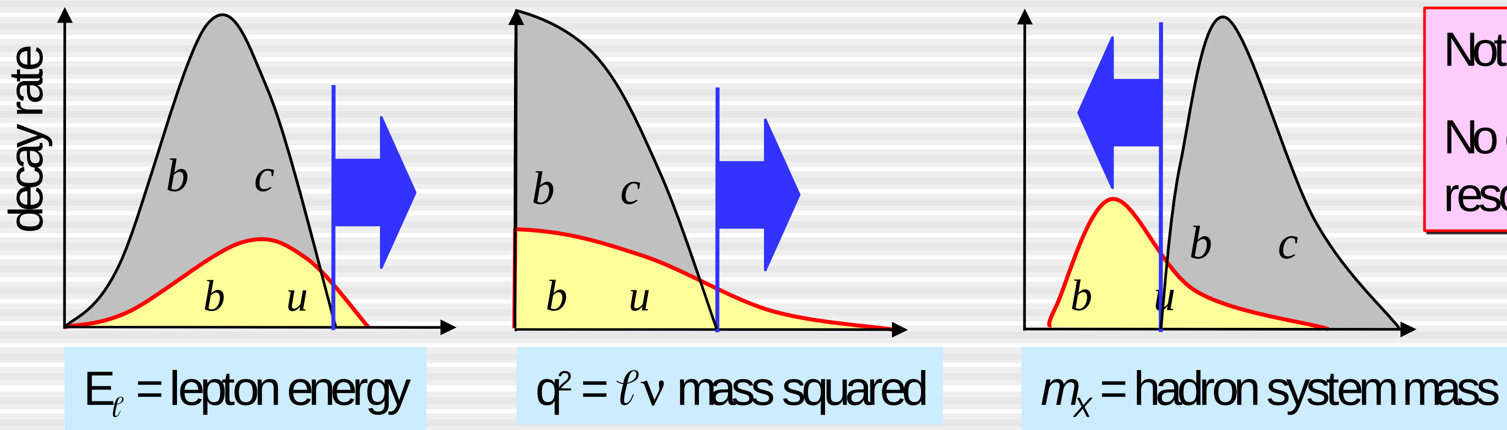


$|V_{ub}|$ from inclusive SL decays



Kinematical Cuts

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



Not to scale!

No detector resolution!

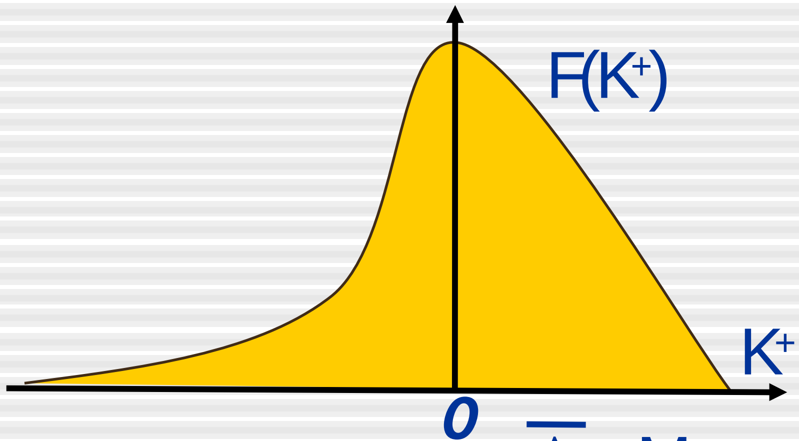
- Measure partial rates in favorable regions of the phase space minimizing the effect of the Shape Function
- Caveat: Spectra more sensitive to non-perturbative effects than the total rate ➔ $O(1/m_b)$ instead of $O(1/m_b^2)$

Shape Function

Limited phase space to reduce the $B \rightarrow X_c \ell \nu$ background:

OPE doesn't work everywhere in the phase space $\rightarrow$ non-perturbative Shape Function $F(K^+)$ to extrapolate to the full phase space

Detailed shape not constrained, in particular the low tail



$\bar{\Lambda} = M_B - m_b$

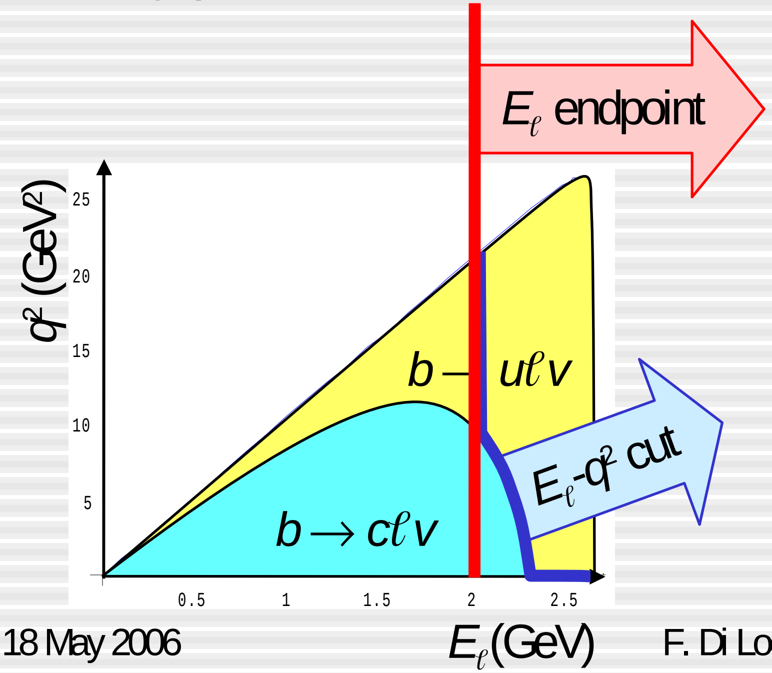
Mean and r.m.s. are known

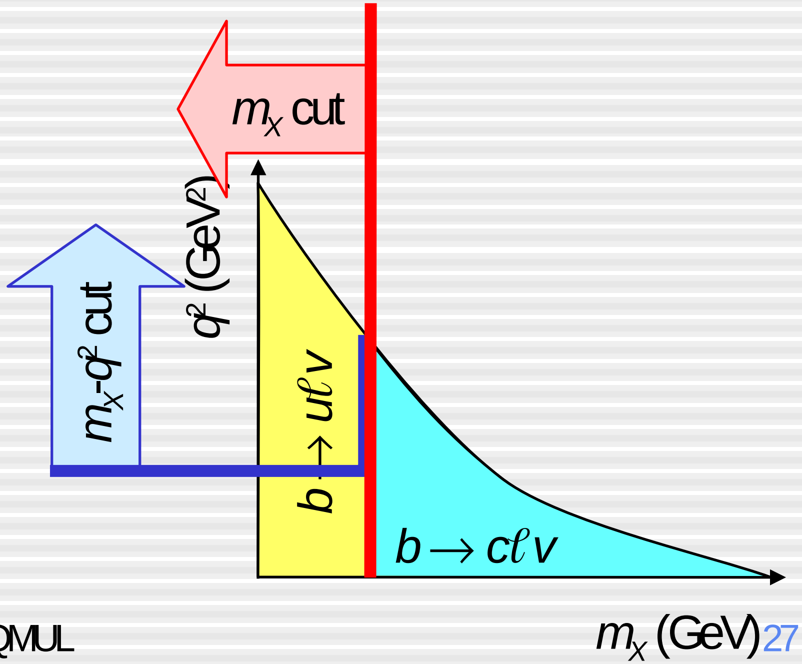
Shape Function need to be determined from experimental data

Inclusive $B \to X_u \ell \nu$

- Measure partial BF $\Delta B(B \to X_u \ell \nu)$ in a region where ...
  - the signal/background is good, and
  - the partial rate $\Delta\Gamma_u$ is reliably calculable
- Many possibilities – Review a few recent results

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





Lepton Endpoint

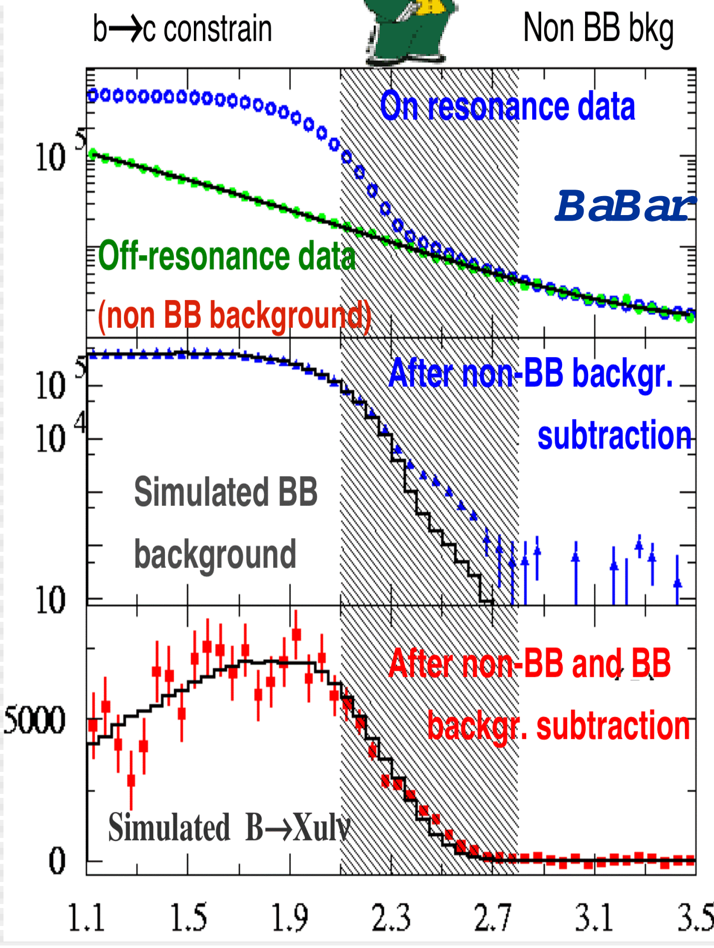
BABAR PRD 73:012006
Belle PLB 621:28
CLEO PRL 88:231803

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

	E_ℓ (GeV)	$\lvert V_{ub}\rvert$ (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 Function: determined from the OPE fit

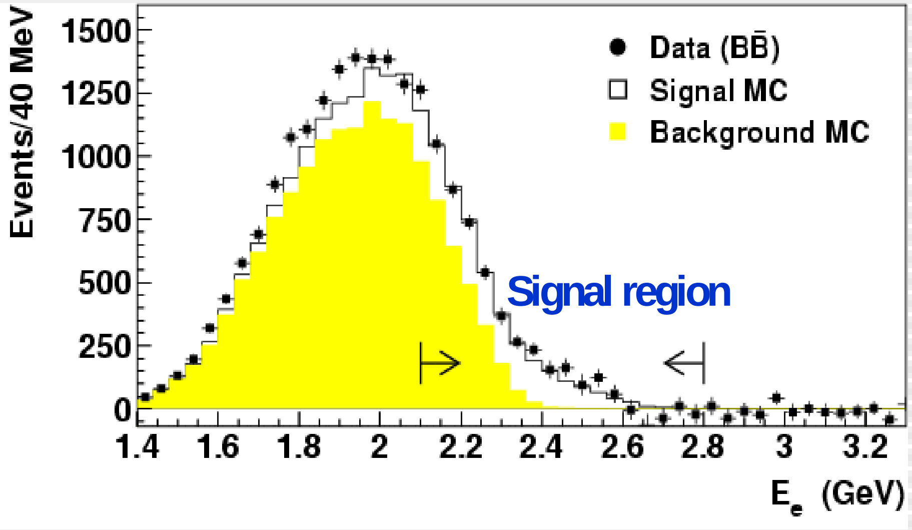
Theory errors: Lange *et al.* PRD72:073006



q^2 E_ℓ analysis with ν reconstruction

hep-ex/0506036

- High energy electron E_e > 2.1 GeV
- Missing momentum used for neutrino parameters estimation
- Cuts on missing momentum magnitude and direction and event shape
- Suppress background using: $s_h^{max} = m_B^2 + q^2 - 2m_B(E_e + \frac{q^2}{4E_e})$



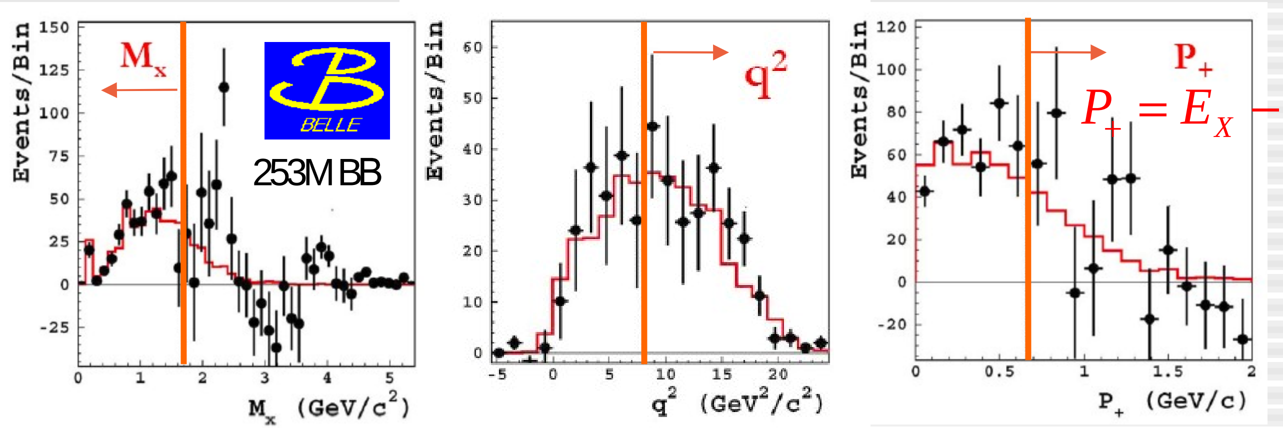
$\Delta\mathcal{B}$ (2.0,3.5) = (3.54 ± 0.33 ± 0.34) x 10^{-4}

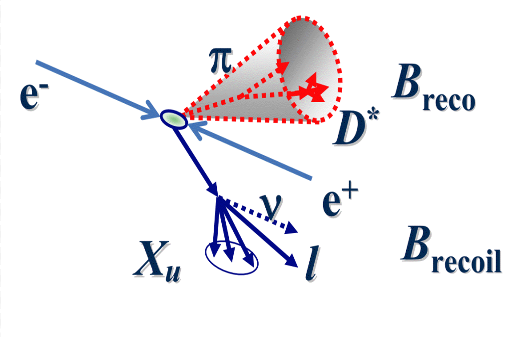
$|V_{ub}|$ = (4.10 ± 0.27$_{exp}$ ± 0.36$_{SF+theo}$) x 10^{-3}

Hadronic B Tag

BABAR hep-ex/0507017
Belle PRL 95:241801

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



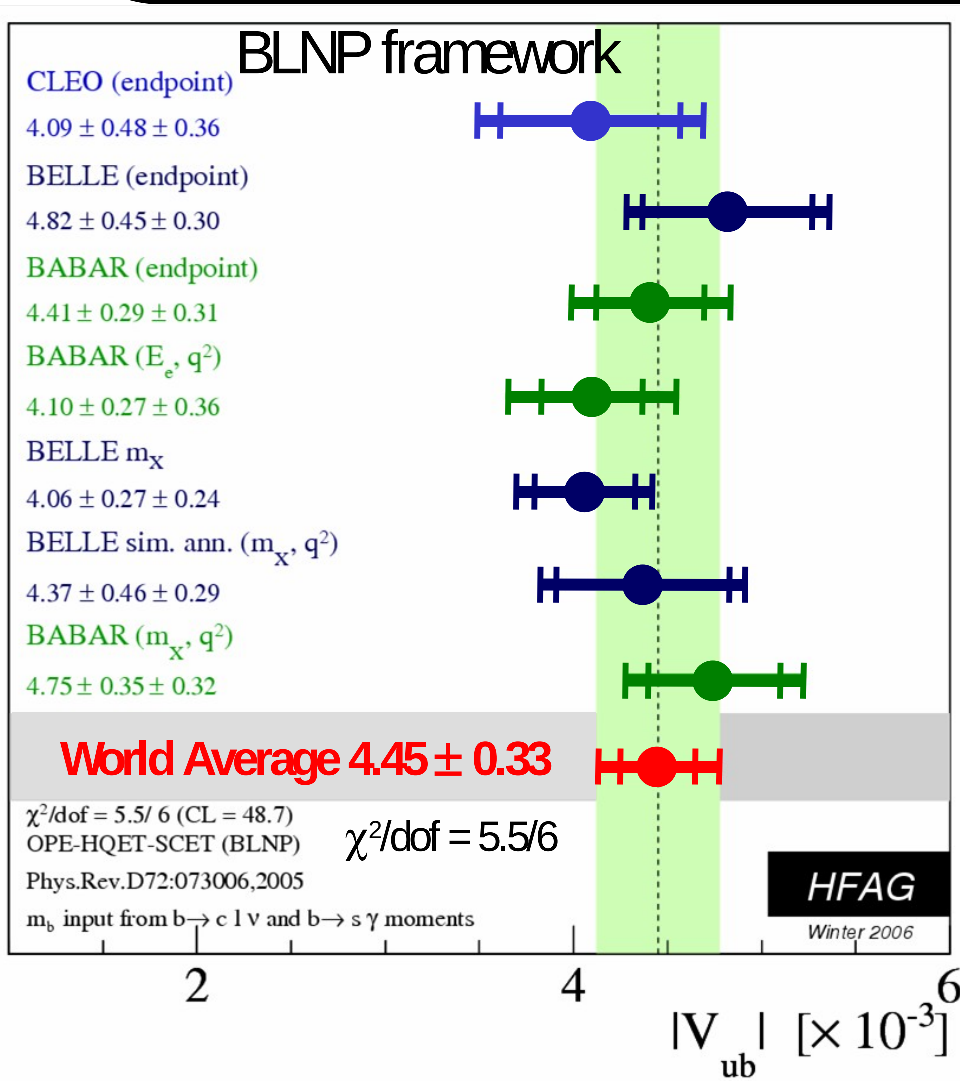


S/B ~ 2 Eff~ 0.1%

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

Prelim.

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



Inputs:

$m_b(SF) = 4.60 \pm 0.04$ GeV

$\mu_\pi^2(SF) = 0.20 \pm 0.04$ GeV^2

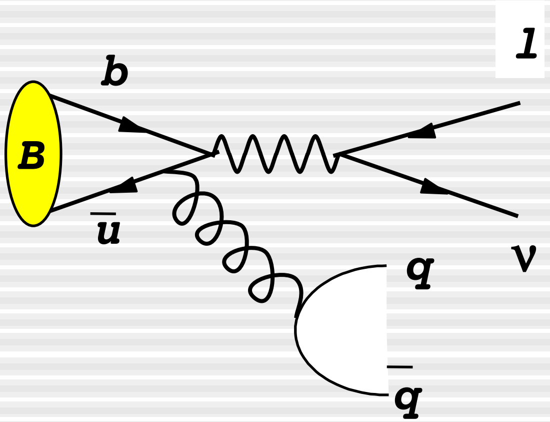
$\delta|V_{ub}| = \pm 7.3\%$

Statistical	±2.2%
Expt. syst.	±2.7%
$B \to X_c \ell \nu$ model	±1.9%
$B \to X_u \ell \nu$ model	±2.1%
Subleading SF	±3.8%
other theory error	±4.5%

Theory Errors (BLNP)

Quark-hadron duality is not considered (cut dependent)

- $b \to c l \nu$ and $b \to s\gamma$ data fit well HQ predictions



Weak annihilation ➔ ± 1.9% error

- Expected to be <2% of the total rate
- $\Gamma_{w.a.}/\Gamma(b \to u) < 7.4$ % from CLEO

HQ parameters ➔ ± 4.1% mainly m_b; kinematics cuts depend on m_b!

Sub-leading shape function ➔ ± 3.8% dominated by the lepton endpoint measurements

Inclusive $|V_{ub}|$ (DGE framework)

Dressed Gluon Exponentiation (DGE)

on-shell b-quark calculation converted into hadronic variables

used as approximation to the meson decay spectrum

$$|V_{ub}|^{DGE} = (4.41 \pm 0.20 \pm 0.20)\, 10^{-3}$$

DGE theory → ±2.9% matching scheme method and scale

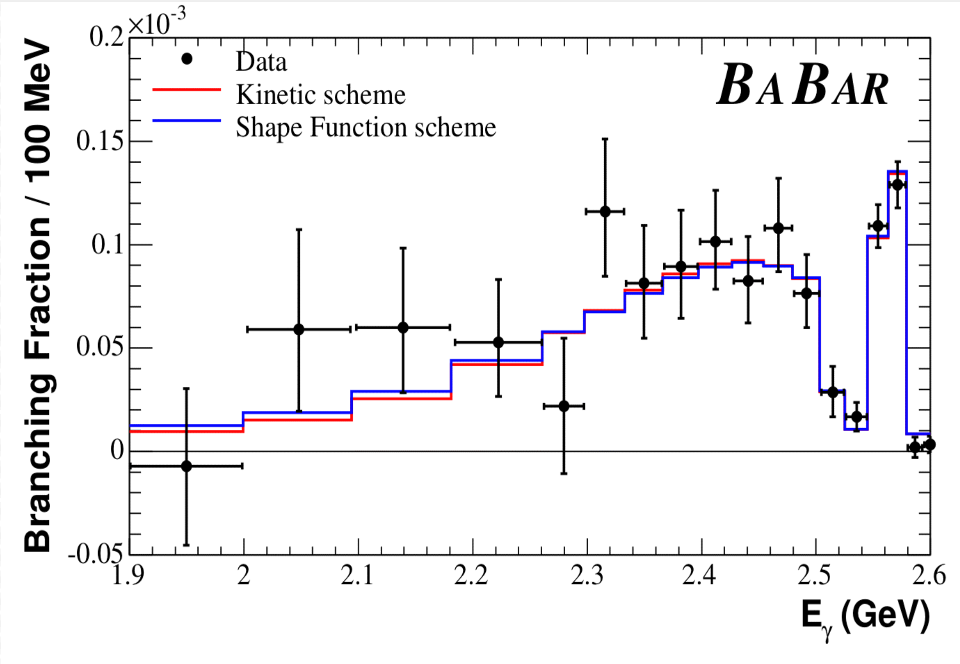
$m_b(MS)$ → ± 1.3% on event fraction $m_b(MS)=4.20\pm0.04$ GeV

α_s → ± 1.0% on event fraction

total Γ_{SL} → ± 3.0 %

Dealing with Shape Function

Solution → use directly the b→sγ spectrum:



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

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

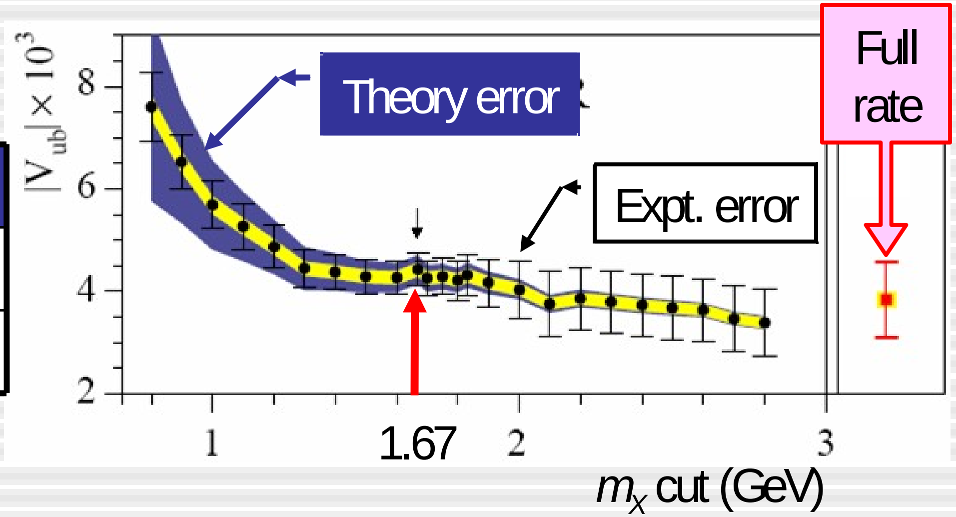
Weight function

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

BABAR hep-ex/0601046

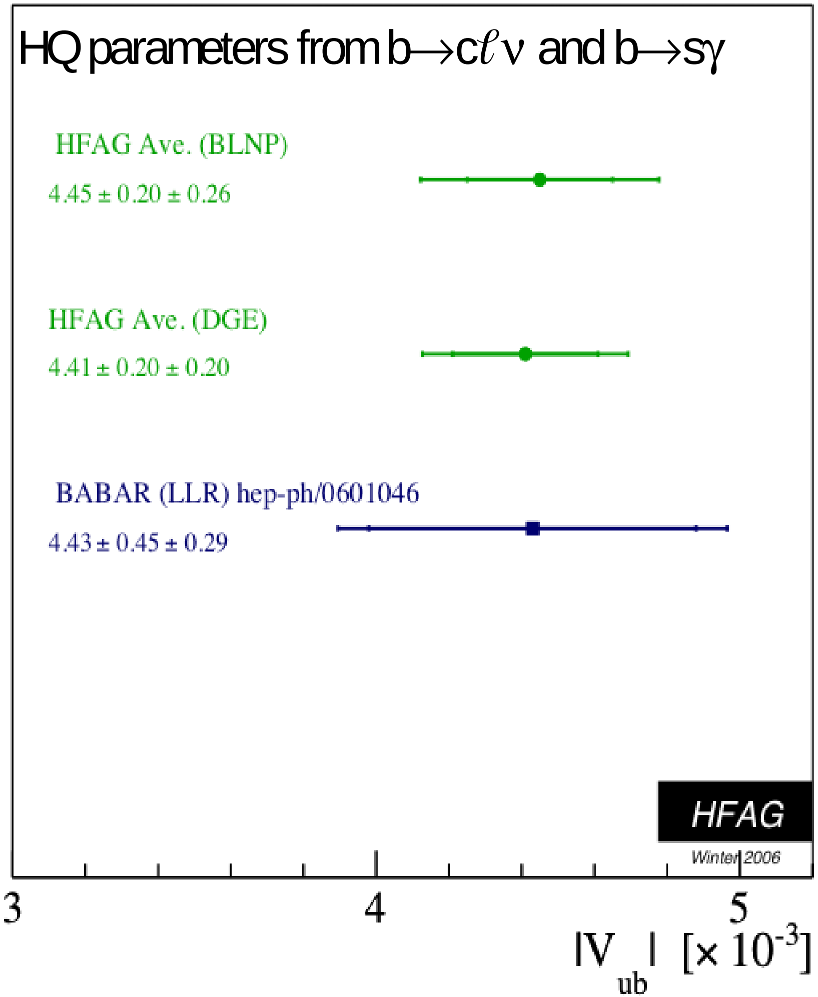
- BABAR applied Leibovich, Low, Rothstein (PLB 486:86) to 80 fb^{-1} data

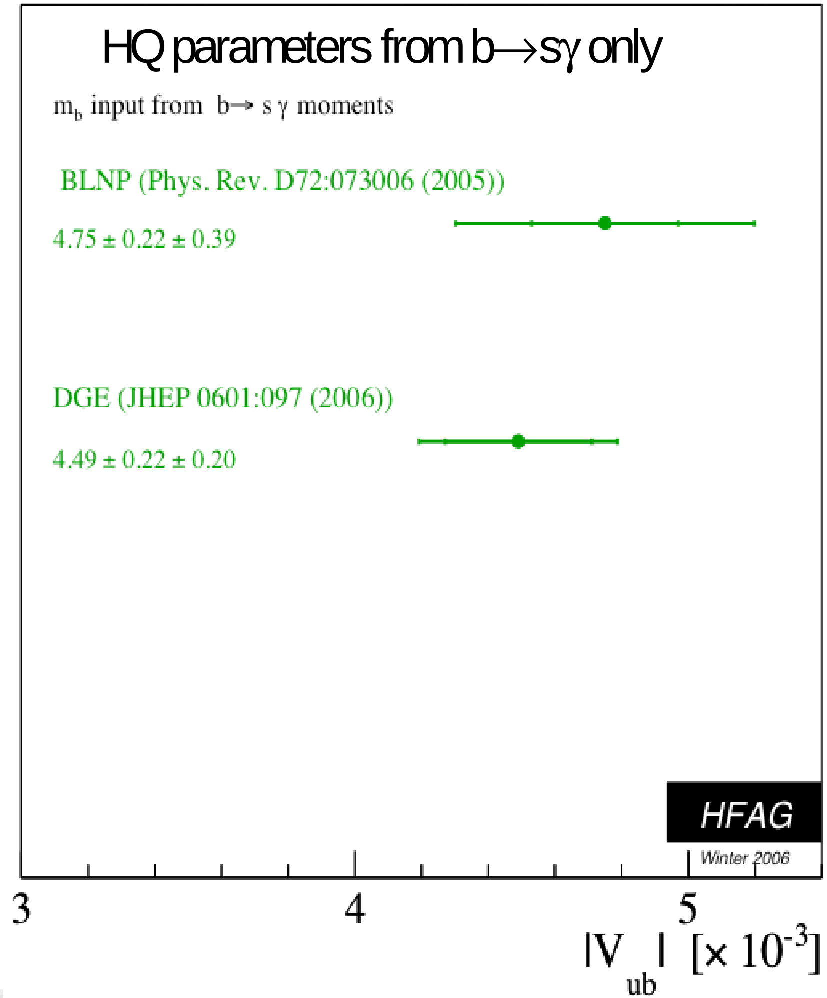
m_X cut	$\|V_{ub}\|$ (10^{-3})
1.67 GeV	$4.43 \pm 0.45_{exp} \pm 0.29_{theo}$
2.5 GeV	$3.84 \pm 0.76_{exp} \pm 0.10_{theo}$



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

Inclusive $|V_{ub}|$: comparisons



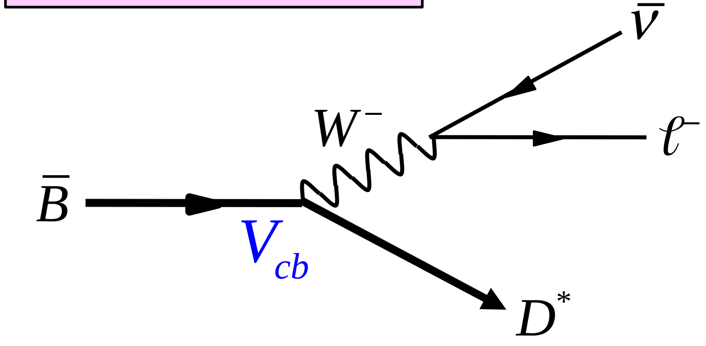


Exclusive Decays

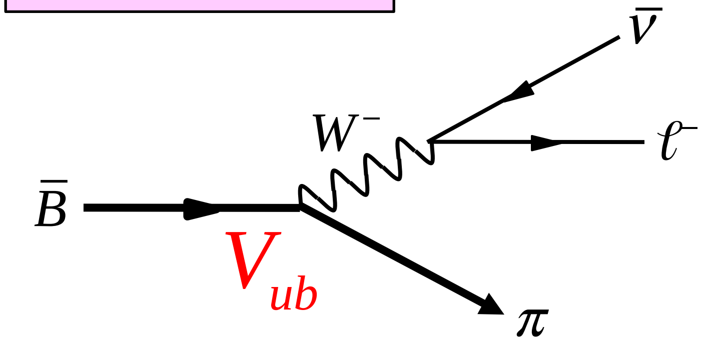
Exclusive Measurements

- Exclusive rates determined by $|V_{xb}|$ and Form Factors (FF)
  - 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 for $|V_{ub}|$

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

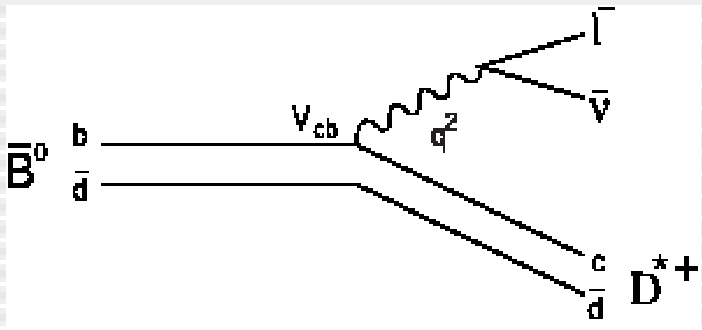


Exclusive $B \to \pi \ell \nu$



$|V_{cb}|$ from Exclusive Decays

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



- Decay rate is

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

form factor

phase space

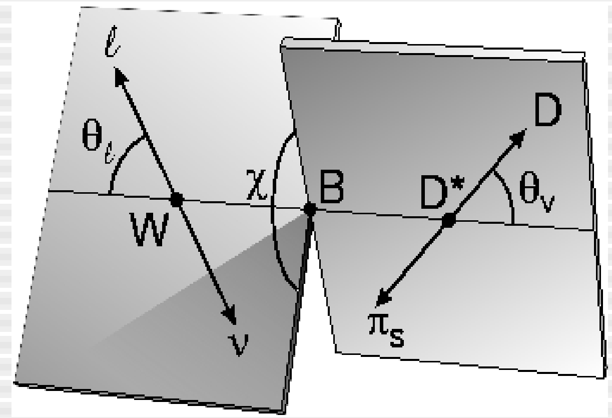
D^* boost in the B rest frame

  - $\mathcal{F}(1) = 1$ 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

BaBar Exclusive $|V_{cb}|$ Measurement

hep-ex/0602023

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



$w = v_B \cdot v_{D^*}$

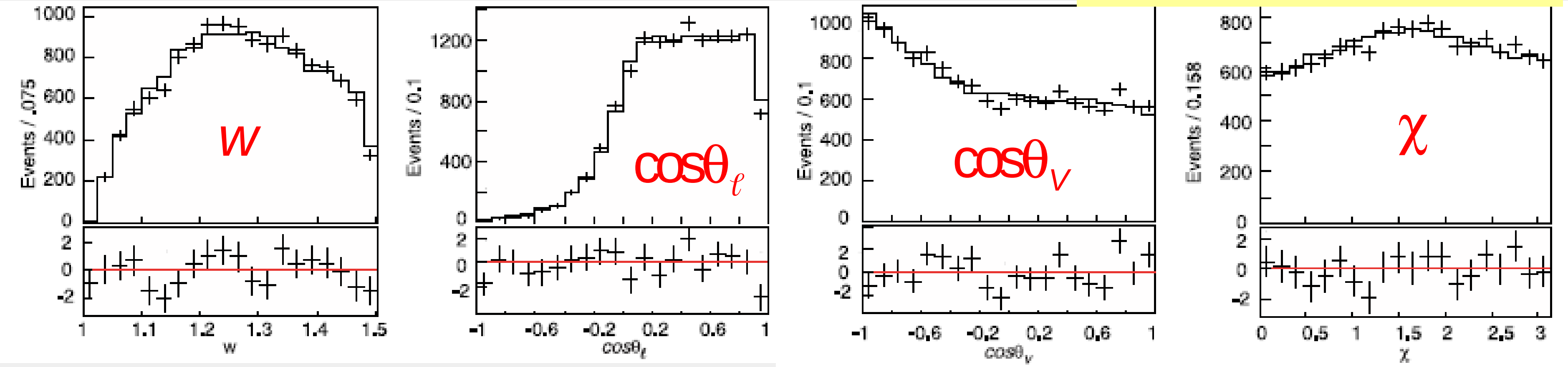
- Multi-Dimensional fit to helicity amplitudes for ρ^2 (slope parameter) and R_1, R_2 (FF ratios), all functions
- of $H_{+,-,0}(w)$.

$$\frac{d\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} = \frac{3G_F^2|V_{cb}|^2 p_{D^*} q^2}{8(4\pi)^4 M_B^2}\mathcal{B}_{D^*D} \times \Big[H_+^2(1-\cos\theta_\ell)^2\sin^2\theta_V + H_-^2(1+\cos\theta_\ell)^2\sin^2\theta_V + 4H_0^2\sin^2\theta_\ell\cos^2\theta_V - 2H_+H_-\sin^2\theta_\ell\sin^2\theta_V\cos 2\chi - 4H_+H_0\sin\theta_\ell(1-\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi + 4H_-H_0\sin\theta_\ell(1+\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi\Big]$$

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

hep-ex/0602023

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



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

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

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

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

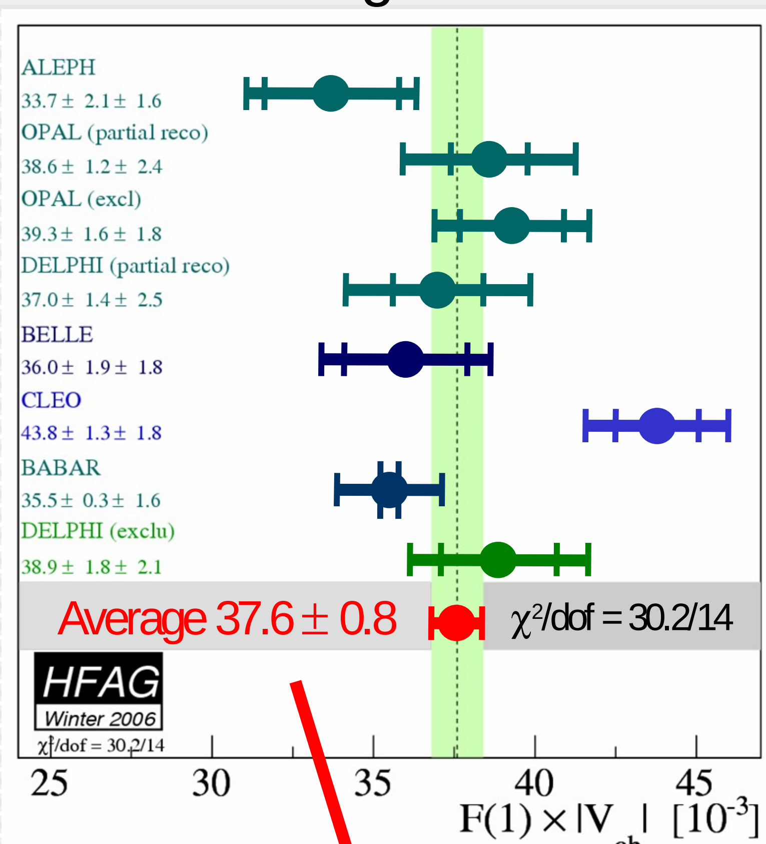
Using *BABAR* measurements only

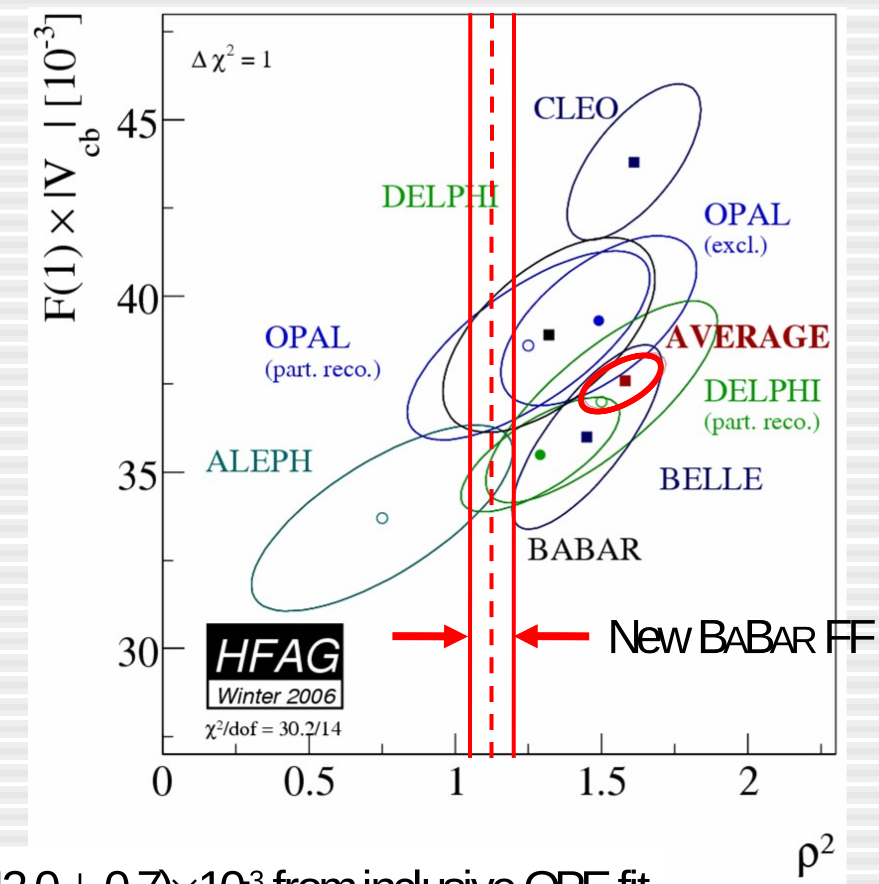
$$|V_{cb}| = 37.6 \pm 0.3(stat) \pm 1.3(syst) \; {}^{+1.5}_{-1.3}(theory) \times 10^{-3}$$

Syst error from 1.7% to 1.3%

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

- HFAG average still uses FF from CLEO





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

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

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

$|V_{ub}|$ from Exclusive Decays

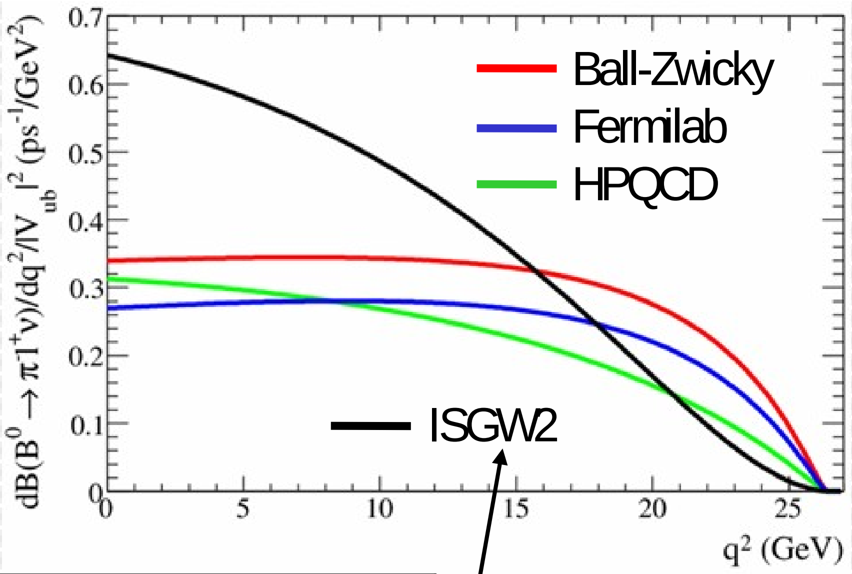
Exclusive $B \to \pi \ell \nu$

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

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

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

Approaches to Measuring $B \to \pi \ell \nu$

Untagged

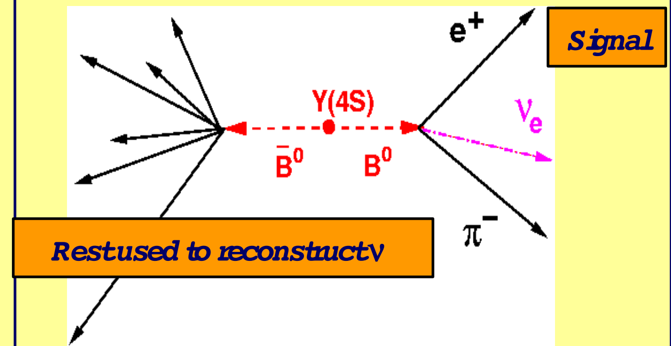
- initial 4-momentum known
- missing 4-momentum = ν
- Reconstruct $B \to \pi \ell \nu$ using m_B (beam-constrained) and $\Delta E = E_B - E_{beam}$

Pros

- High efficiency

Cons

- ν resolution problematic
- Rel. high backgrounds (rel. low purity)



Semileptonic (SL) Tag

- One B reconstructed in a selection of $D^{(*)} \ell \nu$ modes
- Two missing ν in event

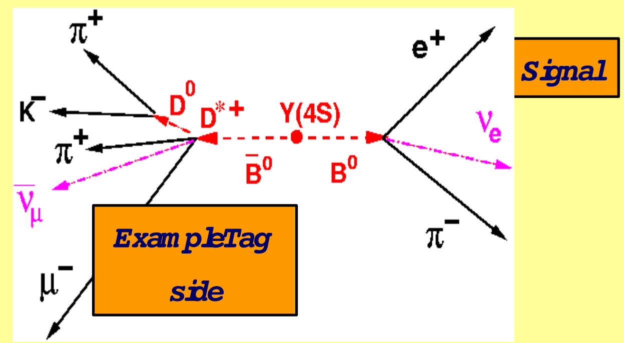
Use kinematic constraints

Pros

- Lower backgrounds (higher purity)

Cons

- Rel. low efficiency



Full Recon Tag

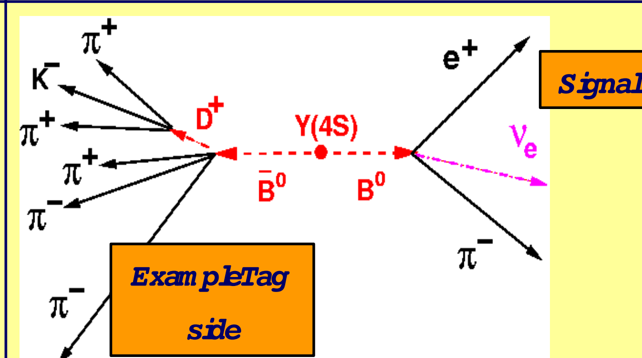
- One B reconstructed completely in known $b \to c$ mode. Many modes used.

Pros

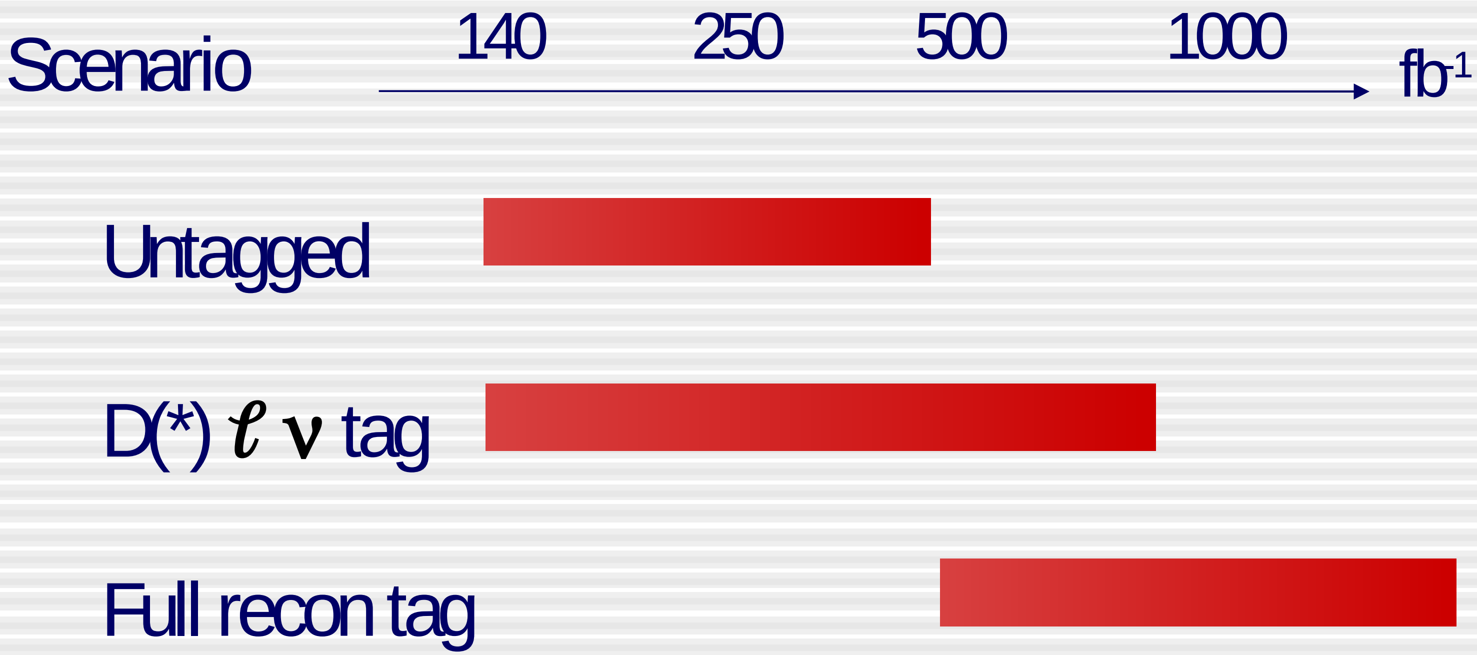
- Very good ν resolution
- Very low backgrounds

Cons

- Very low efficiency



Range of Applicability of Methods

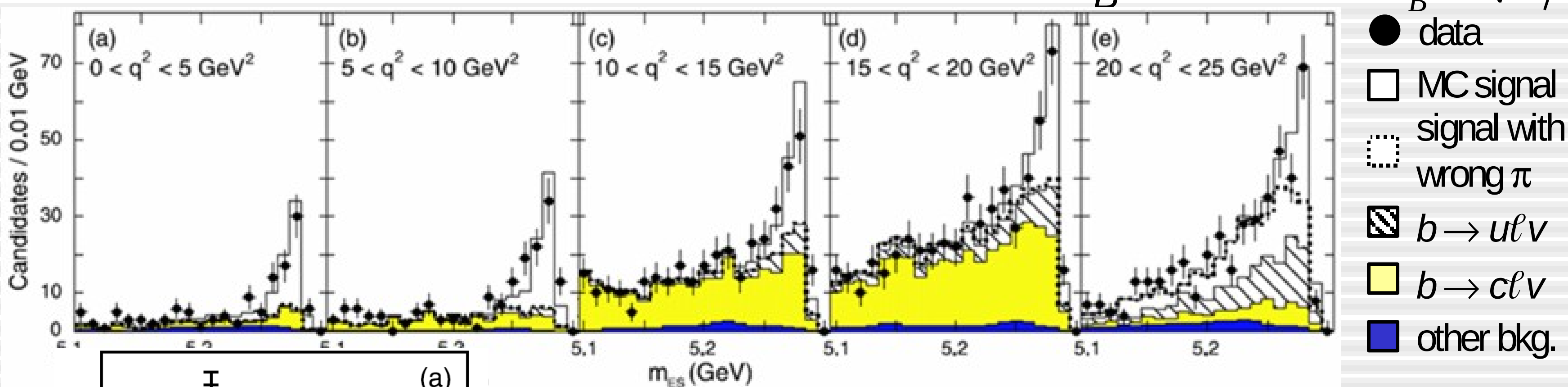


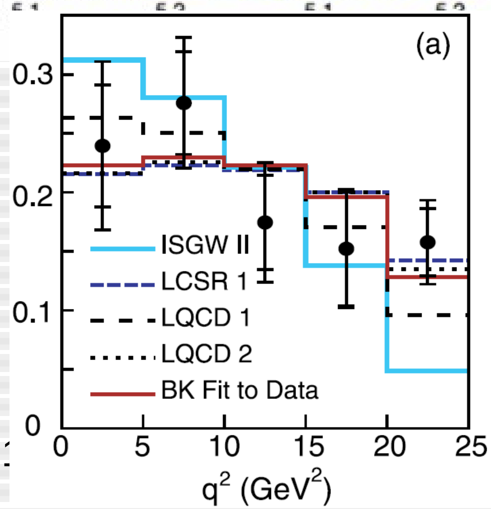
- Boundaries indicative only
- Full recon tag will ultimately become method of choice

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

BABAR PRD 72:051102

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





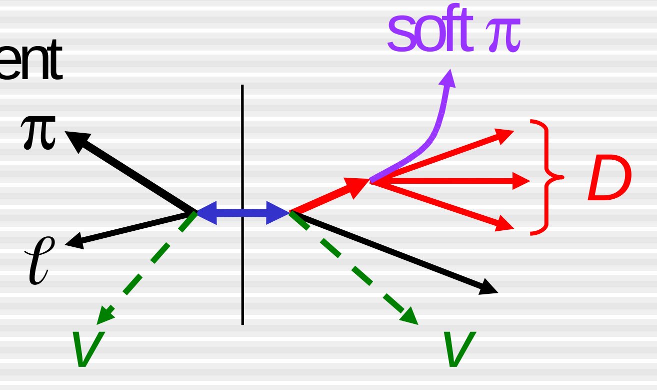
$$\mathcal{B}(B^0 \Rightarrow \pi^- l^+ \nu) \quad (1.38 \pm 0.10_{stat} \pm 0.18_{syst}) \quad 10^{-4}$$

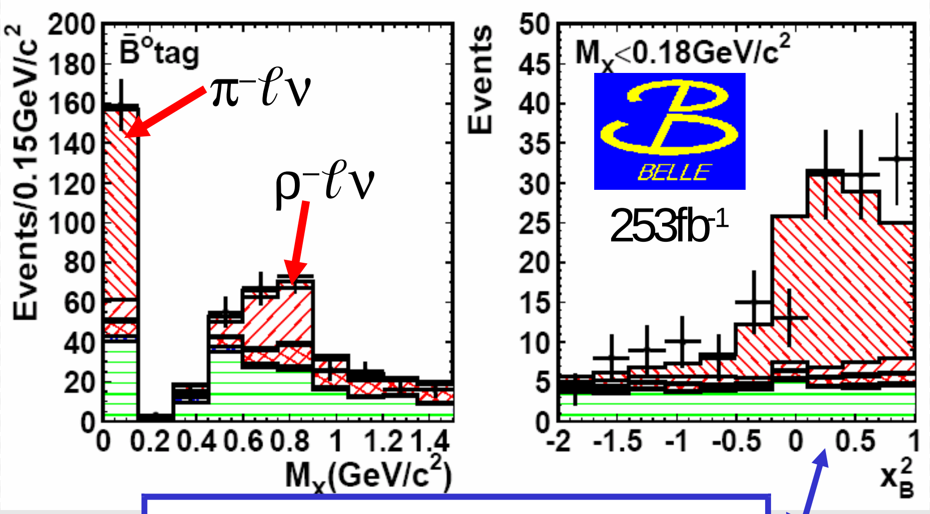
- Measured q^2 spectrum starts to constrain the FF shape
  - LQCD/LCSR favored over ISGW2

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

BABAR hep-ex/0506064
BABAR hep-0506065
Belle hep-ex/0508018

- 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 $m_\nu = 0$





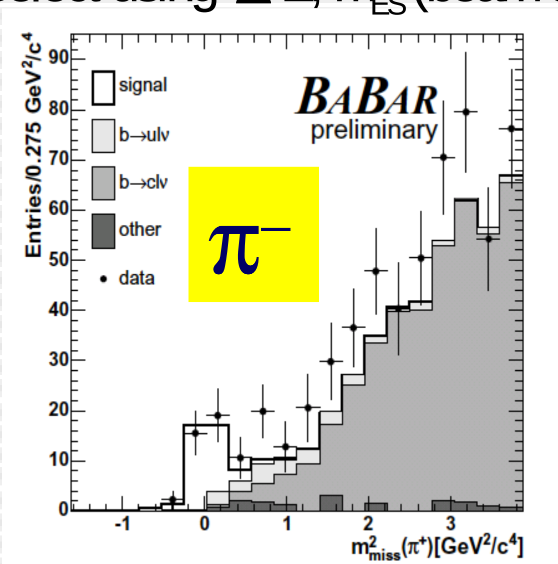
Signal appears in $0 < x_B^2 < 1$

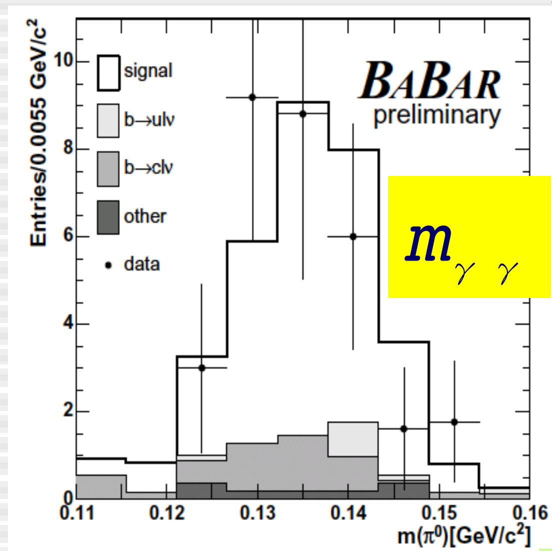
	Mode	BF (10^{-4})
Belle	$B^0 \to \pi^-\ell\nu$	1.38 ± 0.24
	$B^+ \to \pi^0\ell\nu$	0.77 ± 0.16
BABAR Prelim.	$B^0 \to \pi^-\ell\nu$	1.02 ± 0.28
	$B^+ \to \pi^0\ell\nu$	1.86 ± 0.44

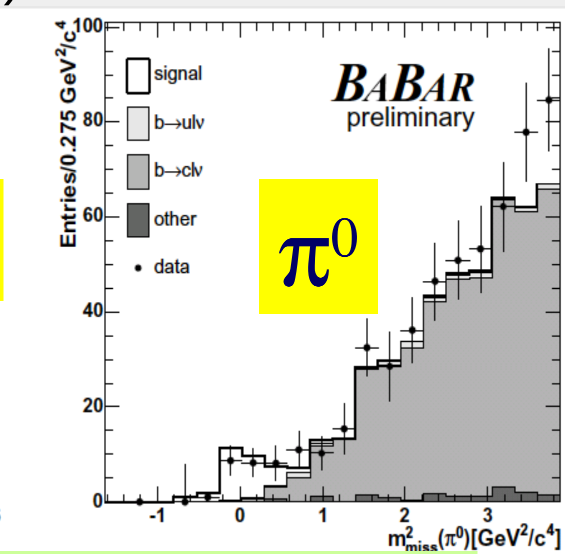
hep-ex/0507085

BaBar Full Recon Tag $B \to \pi \ell^+ \nu$

- Tag : Fully reconstructed $B \to D$ decays (Breco tag)
  Select using ΔE, m_{ES} (beam constrained B candidate mass)







Yield 36 $\pi \ell \nu$, 34 $\pi^0 \ell \nu$

$$B(B^0 \to \pi^- l^+ \nu) = (1.14 \pm 0.27_{stat} \pm 0.17_{syst}) \times 10^{4}$$

$$B(B^+ \to \pi^0 l^+ \nu) = (0.86 \pm 0.22_{stat} \pm 0.11_{syst}) \times 10^{4}$$

$$B(B \to \pi l^+ \nu) = (1.28 \pm 0.23_{stat} \pm 0.16_{syst}) \times 10^{4}$$

Combined $\pi^+ + \pi^0$

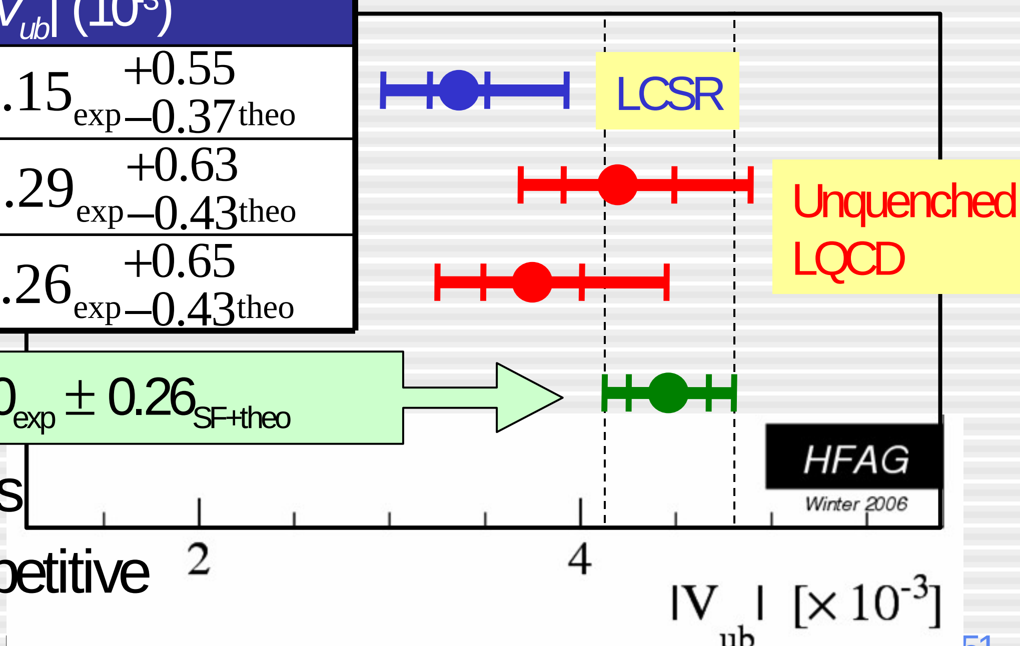
$|V_{ub}|$ from $B \to \pi \ell \nu$

- 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})
$0.94 \pm 0.06_{stat} \pm 0.06_{syst}$	$0.39 \pm 0.04_{stat} \pm 0.04_{syst}$	$1.34 \pm 0.08_{stat} \pm 0.08_{syst}$

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

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



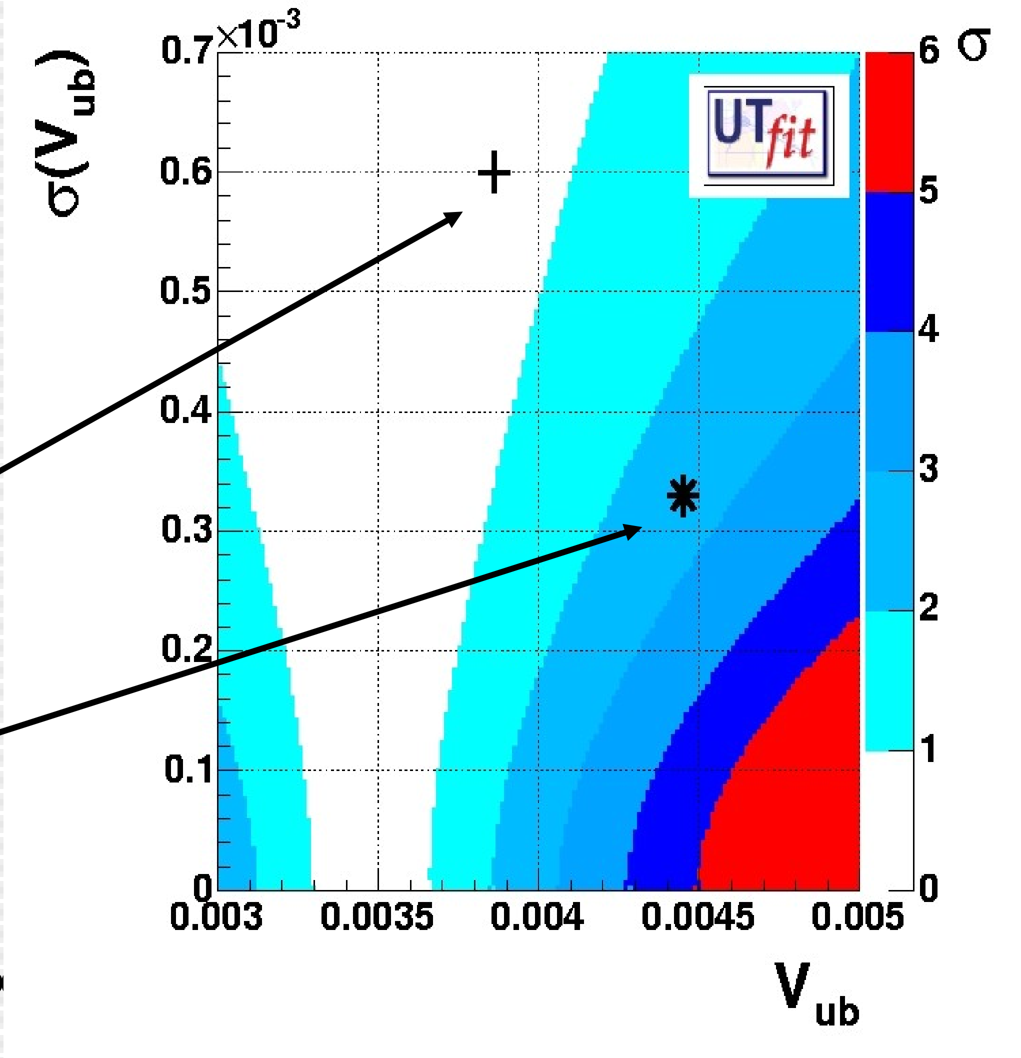
- Consistent within (large) FF errors
- Experimental errors already competitive

$|V_{ub}|$: CKM consistency

Most probable value of $|V_{ub}|$ from measurements of other CKM parameters Standard Model

$|V_{ub}|$ from exclusive measurements

$|V_{ub}|$ from inclusive measurements



Other $B \to X_u \ell \nu$ Exclusive Modes

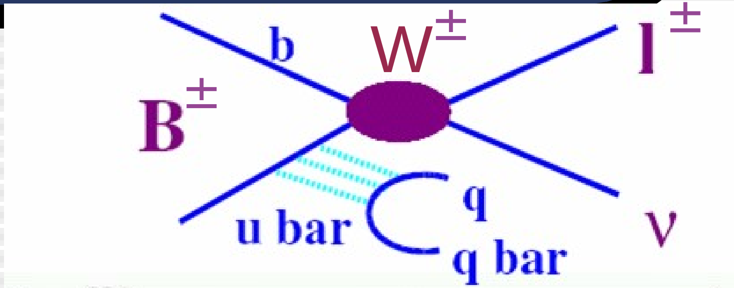
Expt	Mode	Tag	BF [10^{-4}]	Reference
CLEO	$B^0 \to \rho^- \ell \nu$	Untagged	$2.17 \pm 0.34^{+0.47}_{-0.54} \pm 0.41$	PRD 68 (2003) 072003
CLEO	$B^0 \to \rho^- \ell \nu$	Untagged	$2.69 \pm 0.41^{+0.35}_{-0.47} \pm 0.50$	PRD 61 (2000) 052001
BaBar	$B^0 \to \rho^- \ell \nu$	Full	$2.57 \pm 0.52 \pm 0.59$	hep-ex/0408068
BaBar	$B^0 \to \rho^- \ell \nu$	Untagged	$3.29 \pm 0.42 \pm 0.47 \pm 0.60$	PRL 90 (2003) 181801
BaBar	$B^0 \to \rho^- \ell \nu$	Untagged	$2.14 \pm 0.21 \pm 0.51 \pm 0.28$	PRD 72 (2005) 051102
Belle	$B^0 \to \rho^- \ell \nu$	SL	$2.17 \pm 0.54 \pm 0.31 \pm 0.08$	hep-ex/0604024
CLEO	$B^+ \to \eta \ell \nu$	Untagged	$0.84 \pm 0.31 \pm 0.16 \pm 0.09$	PRD 68 (2003) 072003
Belle	$B^+ \to \rho^0 \ell \nu$	SL	$1.33 \pm 0.23 \pm 0.17 \pm 0.05$	hep-ex/06xxxxx
Belle	$B^+ \to \omega \ell \nu$	Untagged	$1.3 \pm 0.4 \pm 0.2 \pm 0.3$	PRL 93 (2004) 131803

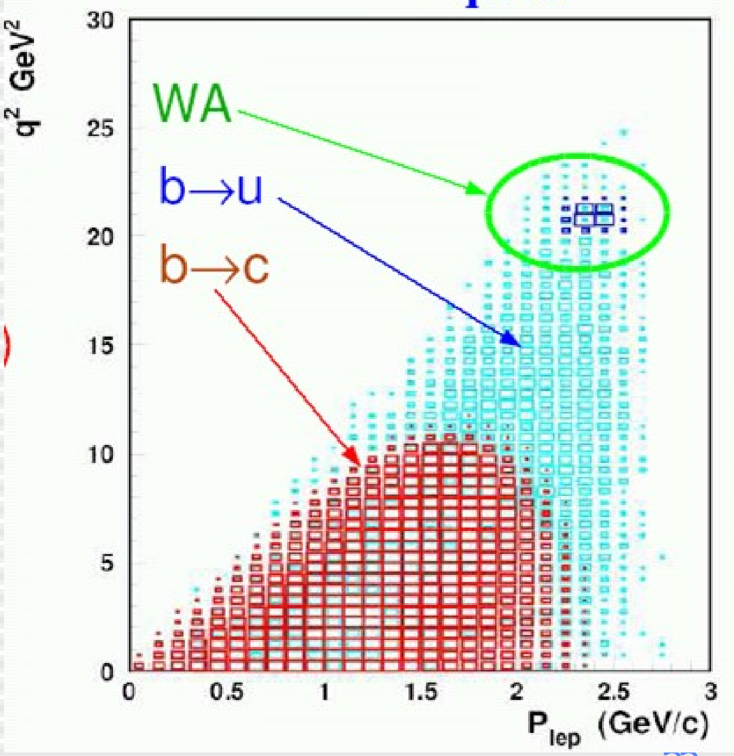
HFAG Compilation, except with updated Belle SL result included

Weak Annihilation

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 in BaBar/BELLE





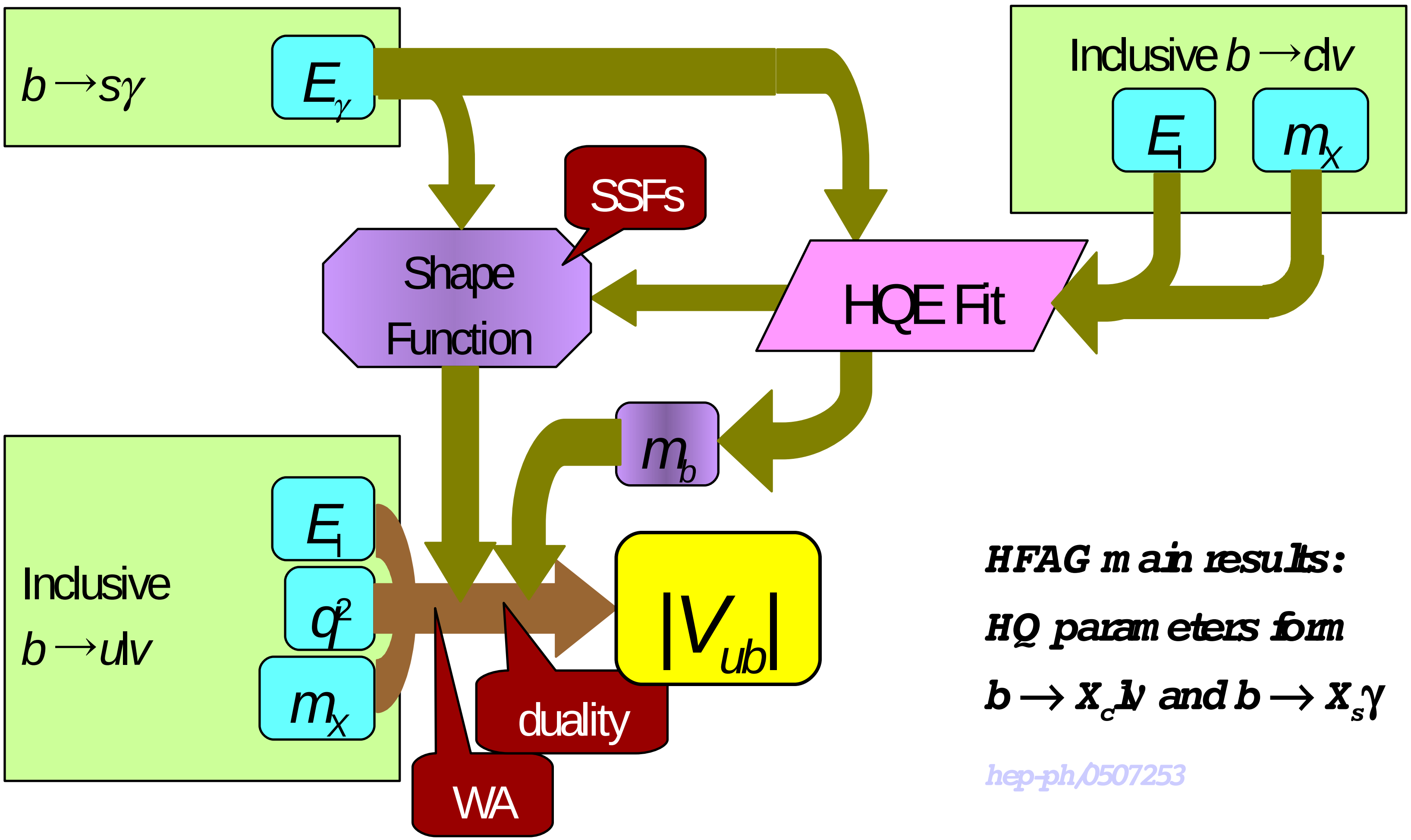
Conclusions

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 $\pm 7.4\%$ 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 (better FF needed!)

Backup Slides

Turning Δ into $|V_{ub}|$



HFAG main results:

HQ parameters form

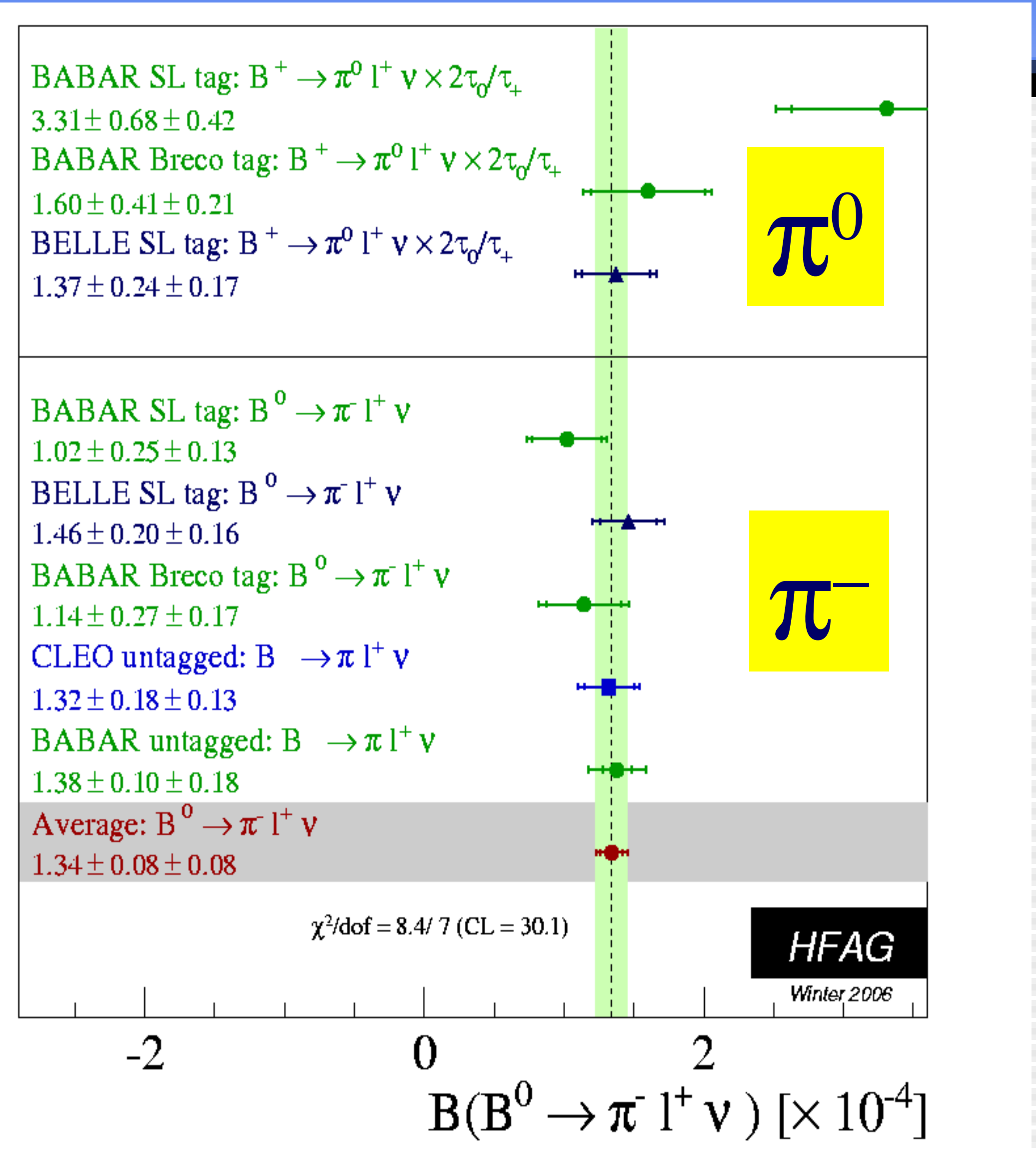
$b \to X_c l\nu$ and $b \to X_s\gamma$

hep-ph/0507253

Determining the Form Factor $f_+(q^2)$

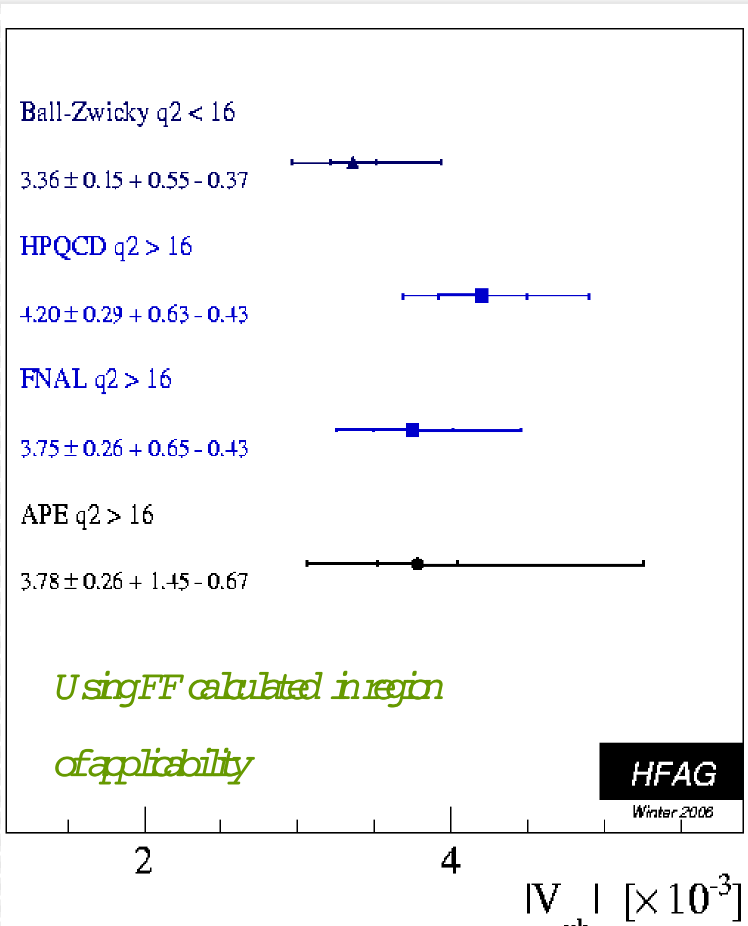
- Earlier predictions made with quark models, e.g. ISGW2
- Lattice QCD
  - makes predictions at high q^2 ($q^2 > \sim 16$ GeV^2)
  - unquenched calculations have become available in recent times
  - e.g. HPQCD *hep-lat-0601201*
    FNAL *hep-lat-0409116*
- Light Cone Sum Rules
  - makes predictions at low q^2 ($q^2 < \sim 14$ GeV^2)
  - e.g. Ball & Zwicky *PRD 71 (2005) 014015*
- Parametrization has traditionally been used to extend LQCD or LCSR to full q^2 range
- FF normalization main issue when extracting $|V_{ub}|$
- How much theory input needed for $|V_{ub}|$ measurement? *hep-ph/0509090*

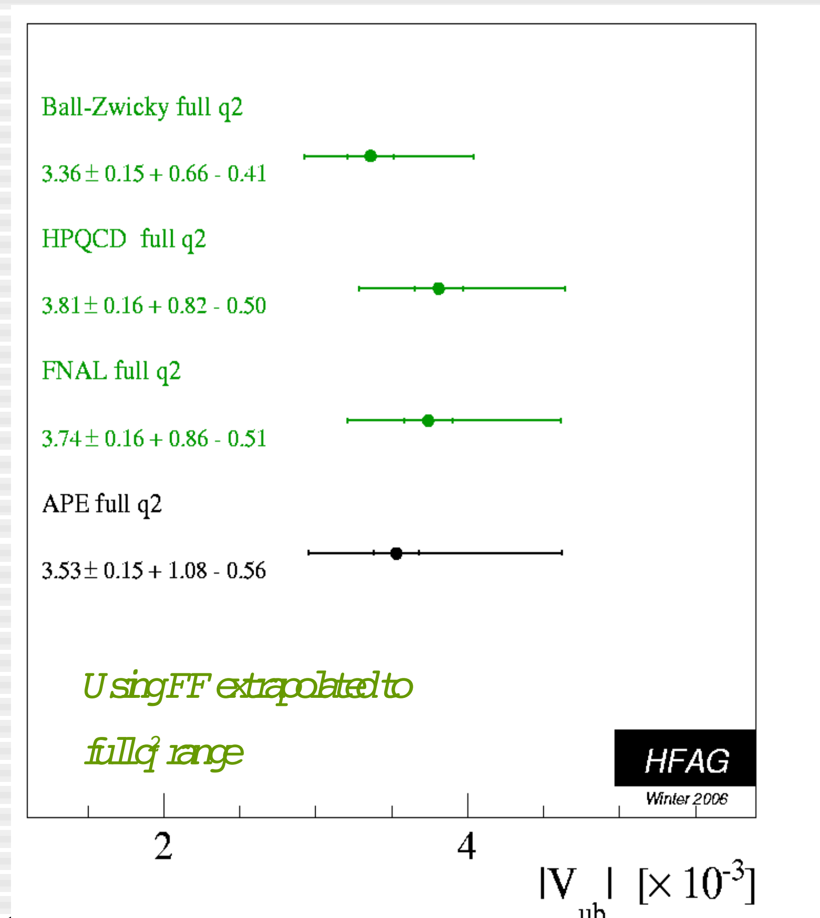
Summary of $B \to \pi \ell \nu$



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

Experimental q^2 shape input not used (yet)





$|V_{ub}|$: inclusive vs exclusive