Exclusive Semileptonic B Decays and $|V_{ub}|$: Experimental

4th Flavor and CP Violation Conference
Vancouver, BC
9th - 12th April 2006

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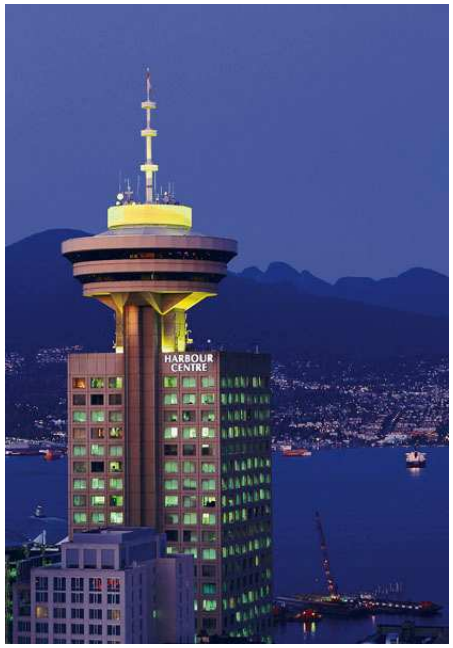
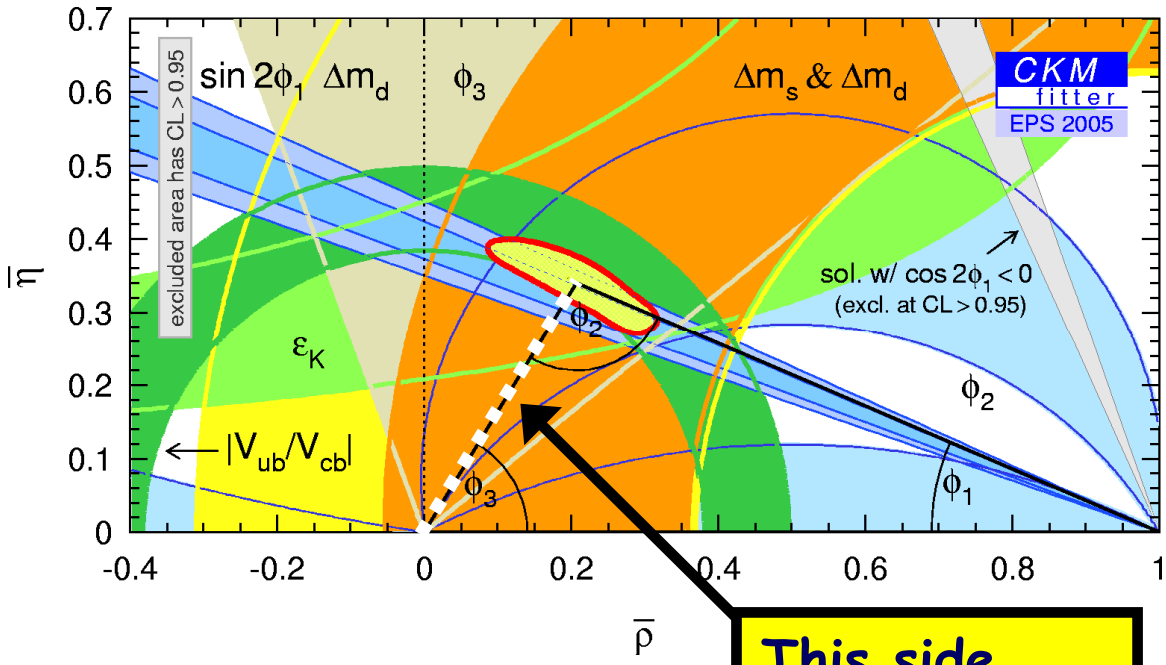
University of Sydney



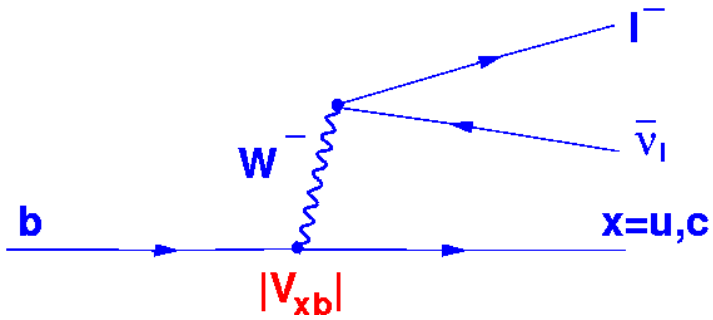
Significance of $|V_{ub}|$ Measurement

- Precision measurement of SM parameter, size not theoretically predicted
- Constrain one side of the Unitarity Triangle
- Test consistency of SM picture, particularly between $|V_{ub}|/|V_{cb}|$ and $\sin 2\phi_1$ ($\sin 2\beta$)
- Current precision
  - $\sin 2\phi_1$ ~ 4%
  - $|V_{cb}|$ ~ 2% (one recent update mentioned here)
  - $|V_{ub}|$ ~ 7% inclusive (talk this afternoon, E. Barberio)
    >10% exclusive (main subject of this talk)
  - Aim is for < 5% precision for $|V_{ub}|_{excl}$, compare with $|V_{ub}|_{incl}$

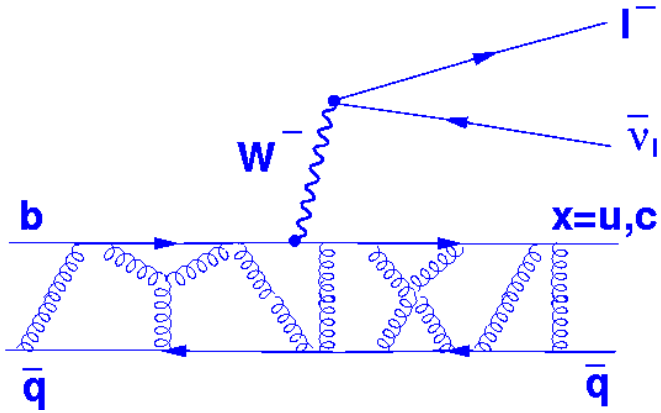


From Exclusive Semileptonic B decay to $|V_{ub}|$

- Measurements made in $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Ideally want to measure rate of tree level process $\Gamma(b \to x\, \ell\, \nu)$



- Complicated by strong interaction effects – form factors needed



- Channel $B \to \pi\, \ell\, \nu$ is the most promising for $|V_{ub}|$
  - one dominant form factor $f_+(q^2)$

  q^2 shape and normalization needed

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

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 > ~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 < ~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
  (R. Hill talk)

Approaches to Measuring B(B → π ℓ ν)

Untagged

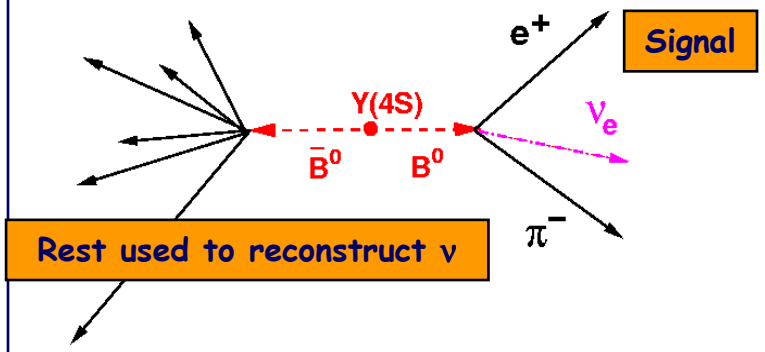
- initial 4-momentum known
- missing 4-momentum = ν
- Reconstruct B → π ℓ ν using m_B (beam-constrained) and $\Delta E = E_B - E_{beam}$

Pros

- High efficiency

Cons

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



Semileptonic (SL) Tag

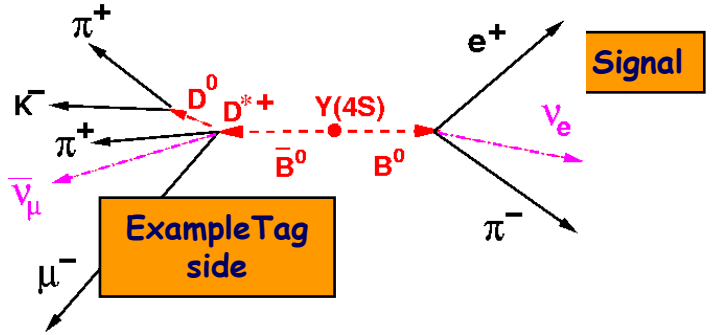
- One B reconstructed in a selection of $D^{(*)}$ ℓ ν modes
- Two missing ν in event Use kinematic constraints

Pros

- Lower backgrounds (higher purity)

Cons

- Rel. low efficiency



Full Recon Tag

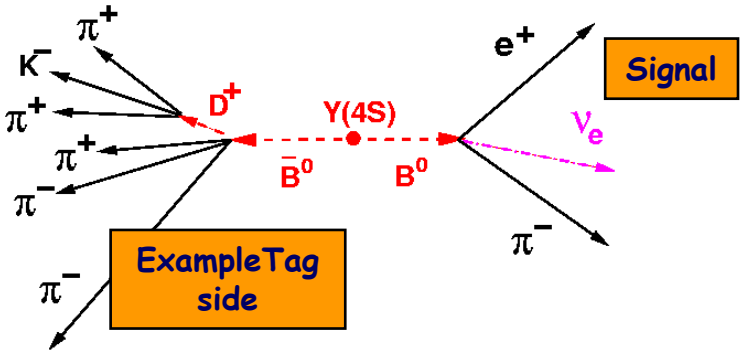
- One B reconstructed completely in known b → c mode. Many modes used.

Pros

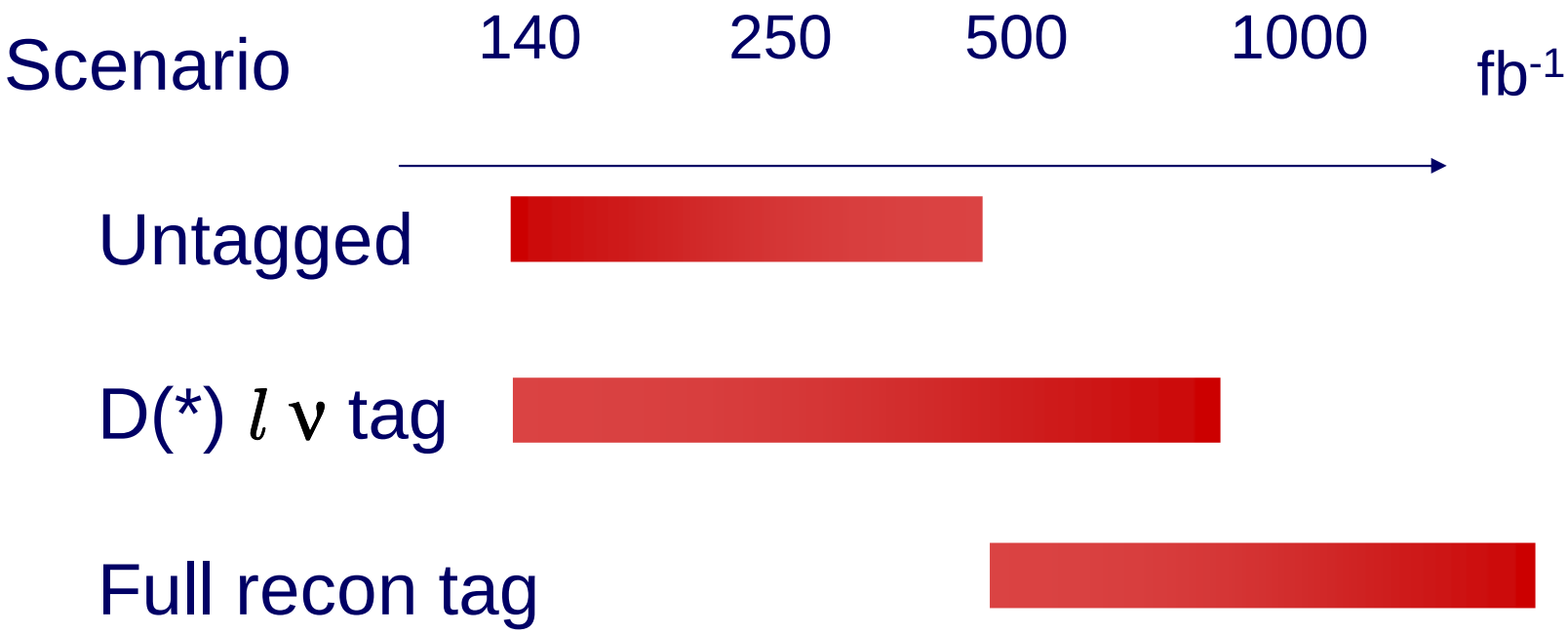
- Very good ν resolution
- Very low backgrounds

Cons

- Very low efficiency



Range of Applicability of Methods



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

Currently

Belle $\mathcal{L}_{int}$ ~ 500 fb^{-1}

BaBar $\mathcal{L}_{int}$ ~ 300 fb^{-1}

CLEO Untagged B → π ℓ ν

Phys. Rev. D 68 (2003) 072003

(9.7M $B\bar{B}$)

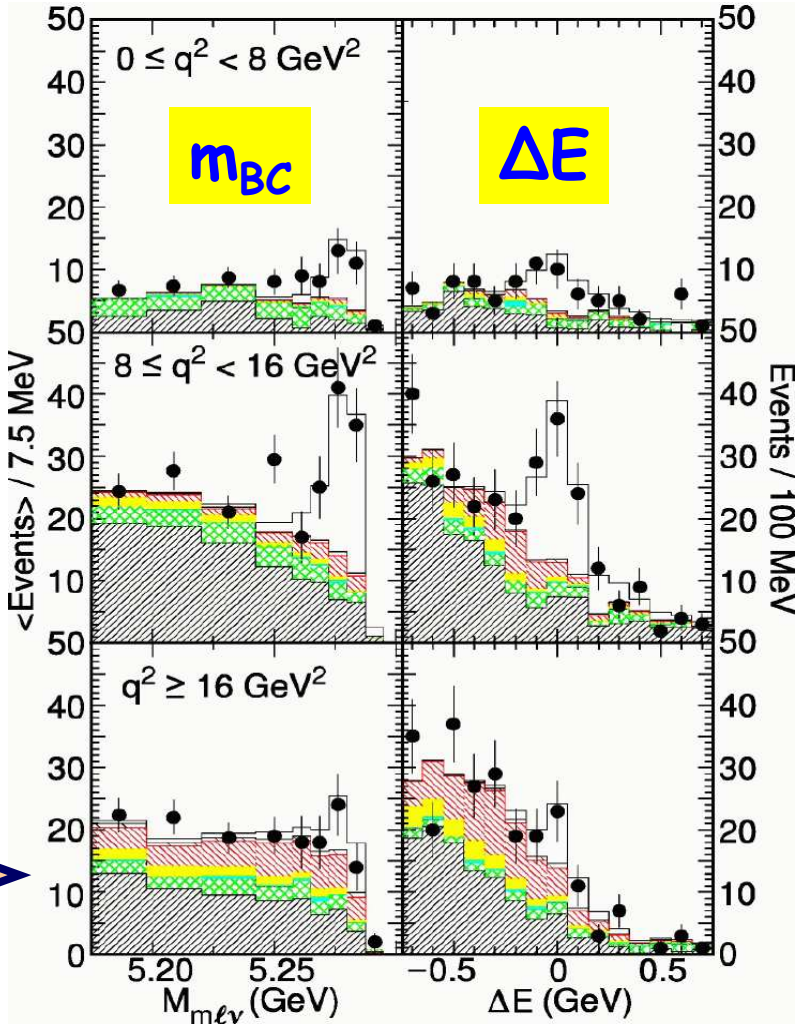
- Search (and fit for yields) across a number of exclusive X_u ℓ ν modes

  $\pi^+, \pi^0, \rho^+, \rho^0, \omega, \eta$

- Isospin constraints imposed in fit

- Extract partial BF in 3 q^2 bins for π^+ and ρ^+

π^- result



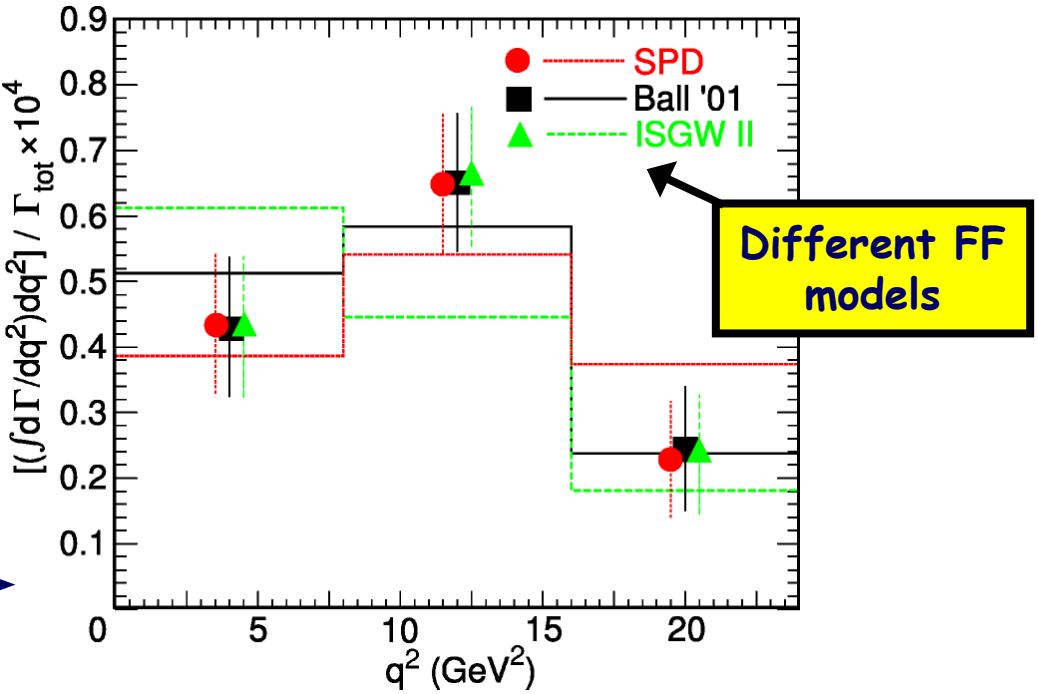
CLEO Untagged B → π ℓ ν (cont.)

Phys. Rev. D 68 (2003) 072003

(9.7M $B\bar{B}$)

- FF models enter extraction of BF through
  - Signal efficiency from MC
  - b → u crossfeed and b → c background modelling in MC

π^- result



$$B(B^0 \to \pi^- \ell^+ \nu) = (1.33 \pm 0.18_{\text{stat}} \pm 0.11_{\text{syst}} \pm 0.01_{\text{FF sig}} \pm 0.07_{\text{FF crossfeed}}) \times 10^{-4}$$

$$|V_{ub}| = (3.17 \pm 0.17_{\text{stat}}\ {}^{+0.16}_{-0.17}{}_{\text{syst}}\ {}^{+0.53}_{-0.39}{}_{\text{theo}} \pm 0.03_{\text{FF shape }\rho}) \times 10^{-3}$$

(π and ρ mode combined)
LCSR + LQCD (unq)

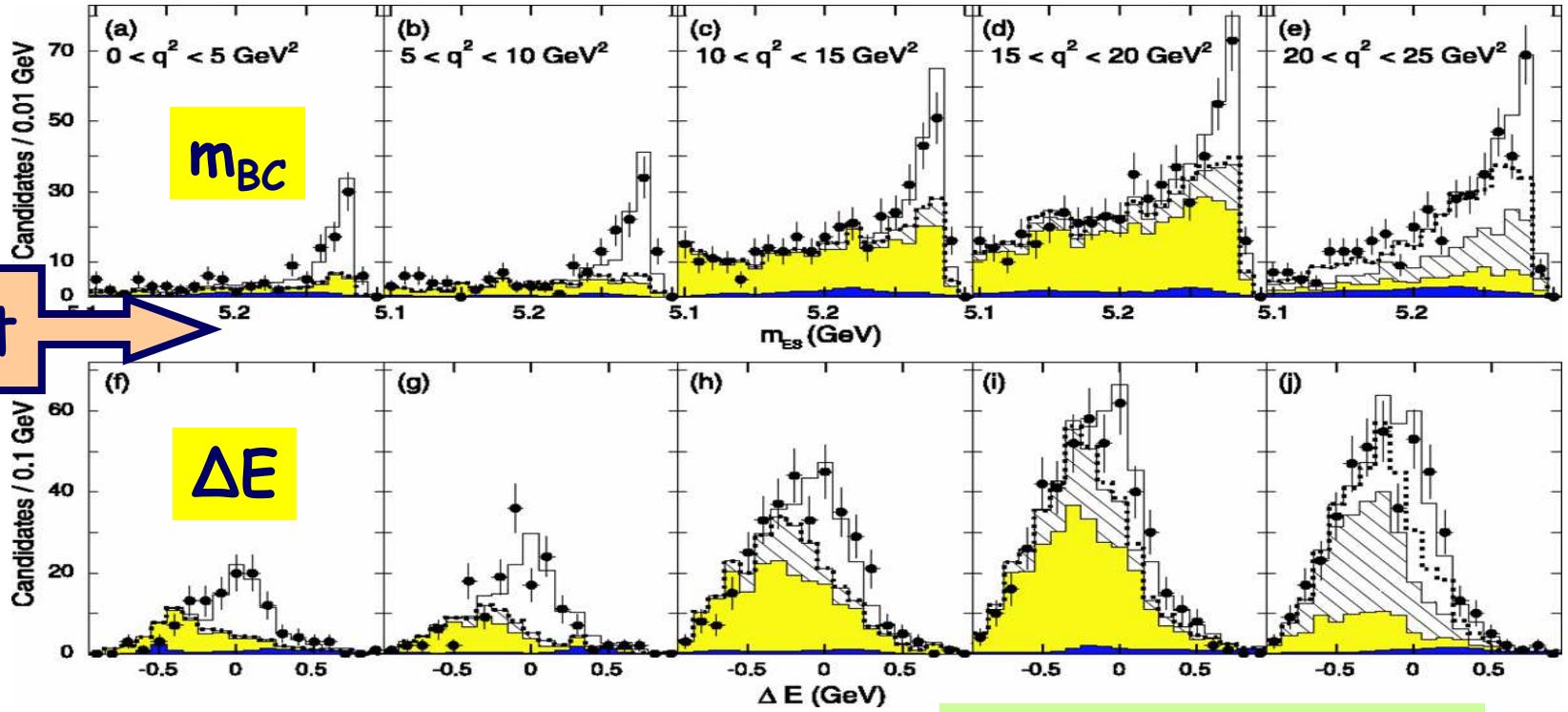
BaBar Untagged $B^0 \to \pi^- \ell^+ \nu$

Phys .Rev. D72 (2005) 051102

79fb^{-1} (86M $B\bar{B}$)

§ Simultaneous extraction of modes $\pi^+, \pi^0, \rho^+, \rho^0$

π^- result



Yield 396 $\pi^-\ell\nu$, 137 $\pi^0\ell\nu$

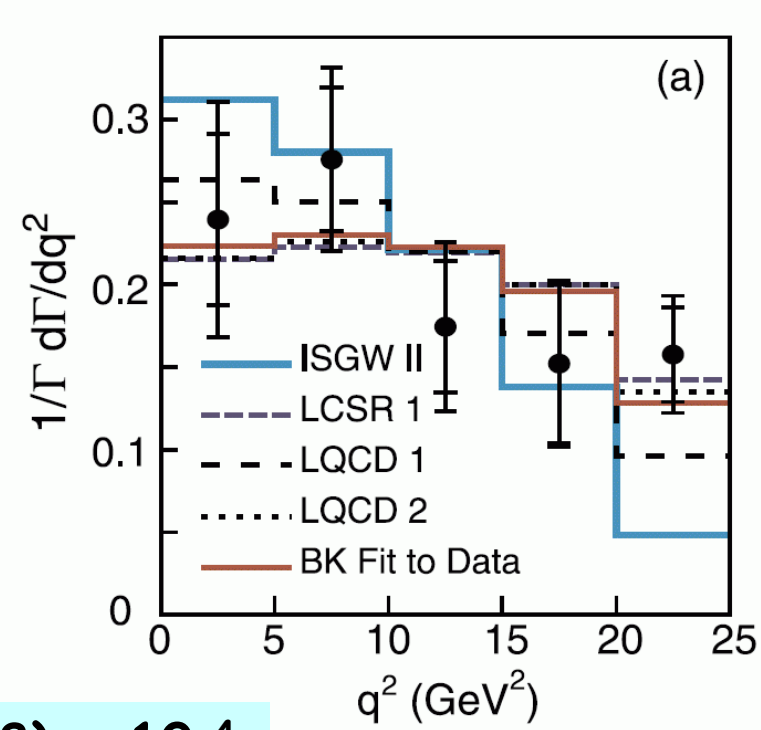
BaBar Untagged $B^0 \to \pi^- \ell^+ \nu$ (cont)

Phys .Rev. D72 (2005) 051102

79fb^{-1} (86M $B\bar{B}$)

- Isospin constraints imposed
- Extract partial BF in
  - 5 q^2 bins π
  - 3 q^2 bins ρ

π^- result



- "Marginal" agreement with ISGW2

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.38 \pm 0.10_{\text{stat}} \pm 0.16_{\text{syst}} \pm 0.08_{\text{FF shape}}) \times 10^{-4}$$

$$|V_{ub}| = (3.82 \pm 0.14_{\text{stat}} \pm 0.22_{\text{syst}} \pm 0.11_{\text{FF shape}} {}^{+0.88}_{-0.52}{}_{\text{FF norm}}) \times 10^{-3}$$

FNAL LQCD

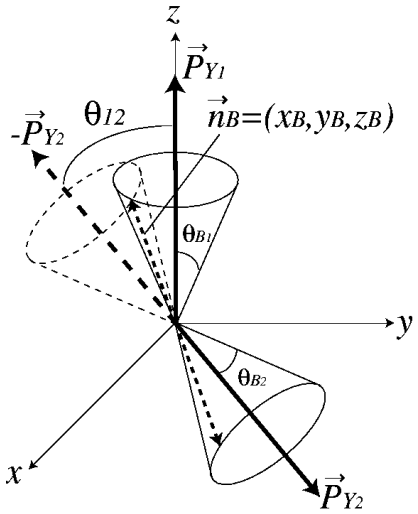
Belle SL Tag $B \to \pi \ell^+ \nu$

hep-ex/0604024

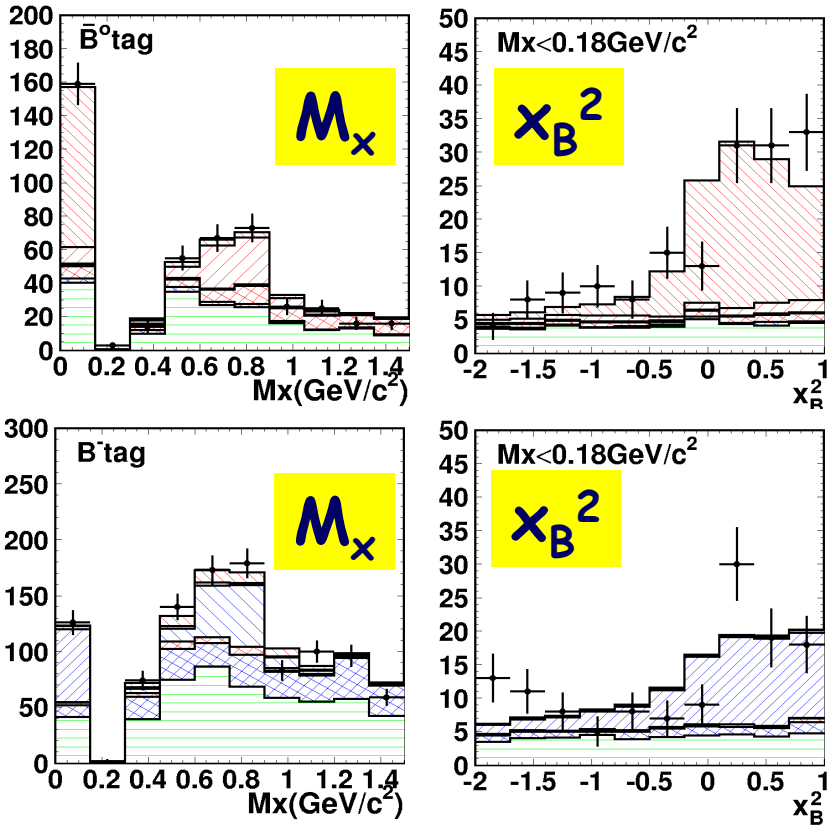
Submitted to PLB

253fb^{-1} (275M $B\bar{B}$)

- Simultaneous extraction of modes $\pi^+, \pi^0, \rho^+, \rho^0$



$$x_B^2 = 1 - \frac{1}{\sin^2\theta_{12}} \cdot \left(\cos^2\theta_{B_1} + \cos^2\theta_{B_2} - 2\cos\theta_{B_1}\cos\theta_{B_2}\cos\theta_{12}\right)$$



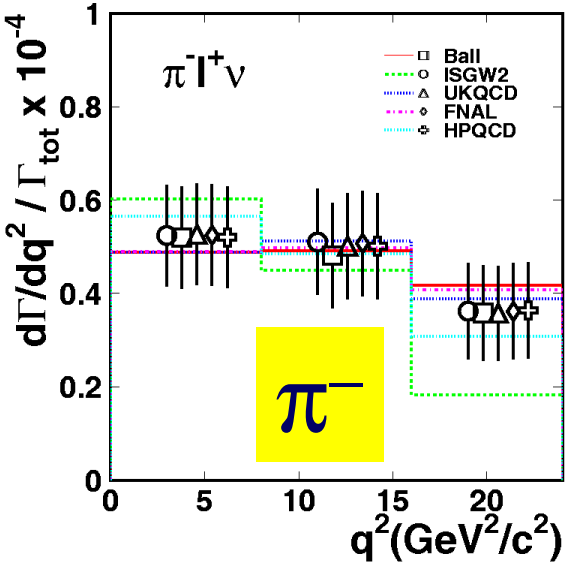
- x_B^2 must lie in range [0,1] for signal events

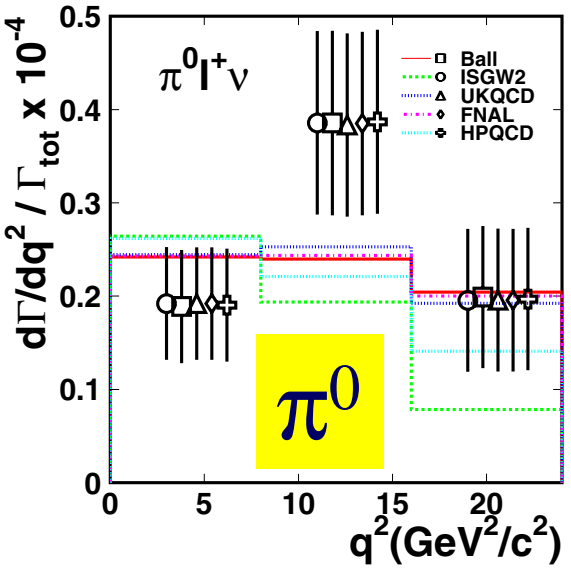
Yield 156 $\pi^-\ell\nu$, 69 $\pi^0\ell\nu$

Belle SL Tag $B \to \pi \ell^+ \nu$ (cont)

hep-ex/0604024

- Extract partial BF in 3 q^2 bins





$$B(B^0 \to \pi^- \ell^+ \nu) = (1.38 \pm 0.19_{stat} \pm 0.14_{syst} \pm 0.03_{FF\ shape}) \times 10^{-4}$$

$$B(B^+ \to \pi^0 \ell^+ \nu) = (0.77 \pm 0.14_{stat} \pm 0.09_{syst} \pm 0.00_{FF\ shape}) \times 10^{-4}$$

$$|V_{ub}| = (3.60 \pm 0.41_{stat} \pm 0.20_{syst} {}^{+0.62}_{-0.41}{}_{theo}) \times 10^{-3}$$

$\pi^+ + \pi^0$, $q^2 \geq 16\ GeV^2$, FNAL

$$|V_{ub}| = (4.03 \pm 0.46_{stat} \pm 0.22_{syst} {}^{+0.59}_{-0.41}{}_{theo}) \times 10^{-3}$$

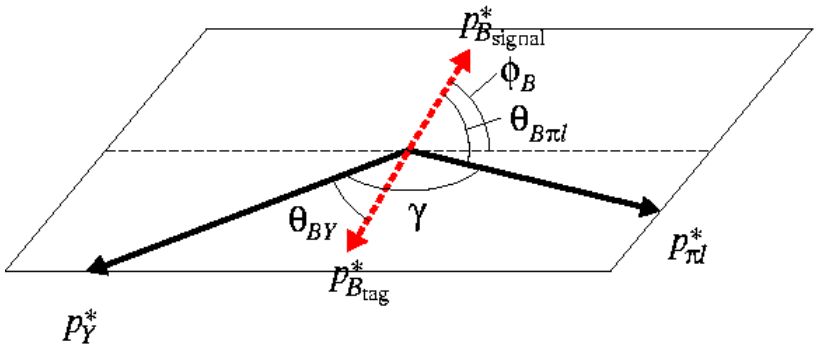
$\pi^+ + \pi^0$, $q^2 \geq 16\ GeV^2$, HPQCD

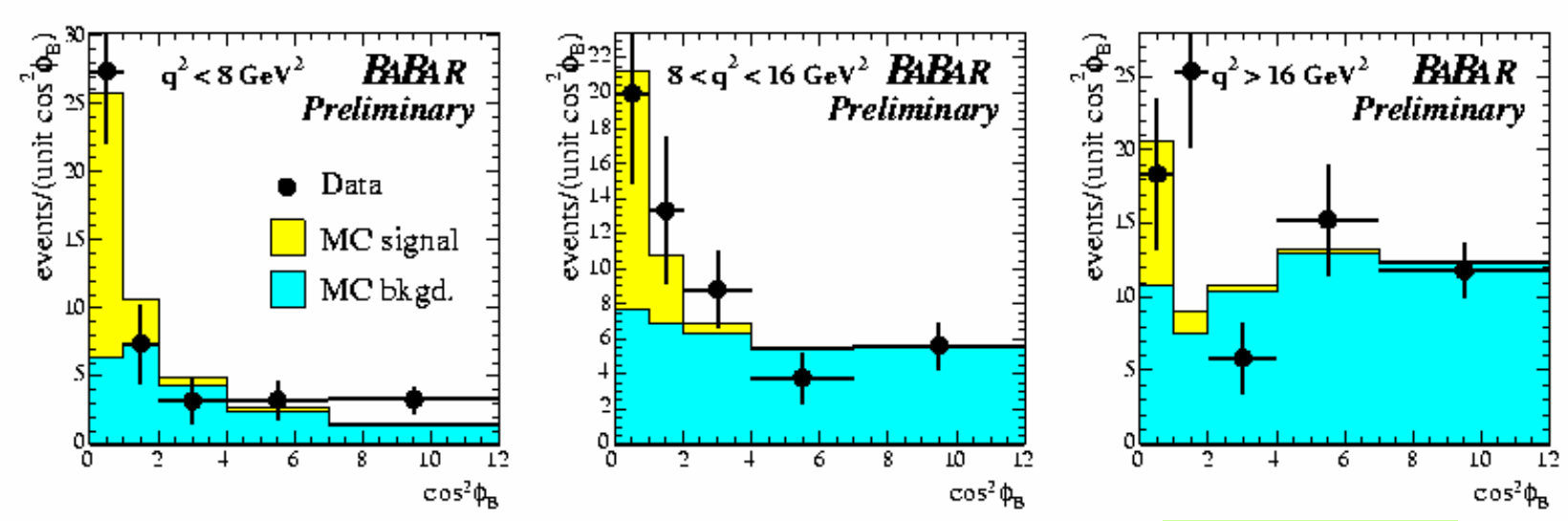
BaBar SL Tag $B^0 \to \pi^- \ell^+ \nu$

hep-ex/0506064

211fb^{-1} (232M $B\bar{B}$)

- Single mode π^- studied
- $\cos^2\phi_B \in [0,1]$ for signal events





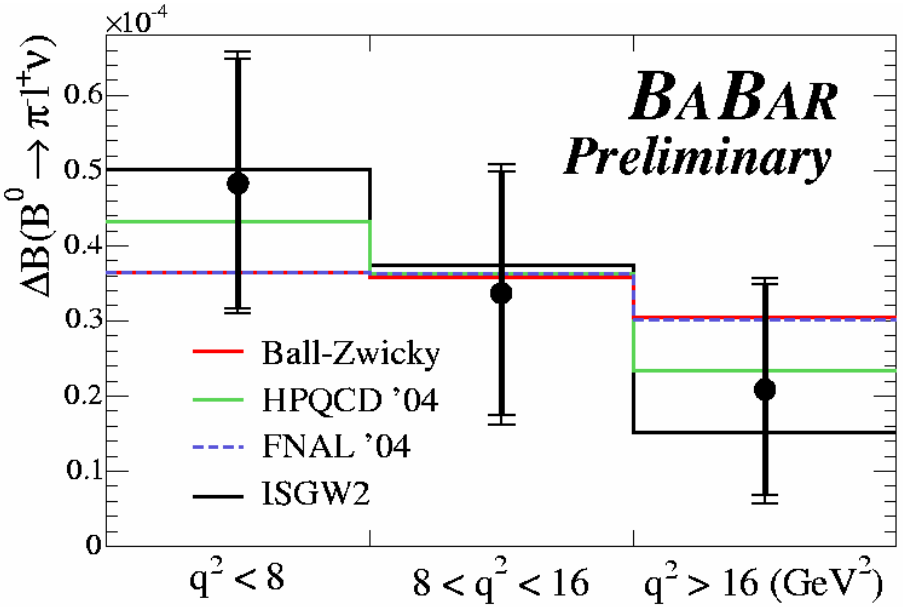
Yield 61 $\pi^-\ell\nu$

BaBar SL Tag $B^0 \to \pi^- \ell^+ \nu$ (cont)

hep-ex/0506064

211fb^{-1} (232M $B\bar{B}$)

- Extract partial BF in 3 q^2 bins



$$B(B^0 \to \pi^- \ell^+ \nu) = (1.03 \pm 0.25_{\text{stat}} \pm 0.13_{\text{syst}}) \times 10^{-4}$$

$$|V_{ub}| = (3.3 \pm 0.4_{\text{stat}} \pm 0.2_{\text{syst}} {}^{+0.8}_{-0.4}{}_{\text{FF norm}}) \times 10^{-3}$$

HPQCD04

BaBar SL Tag $B^+ \to \pi^0 \ell^+ \nu$

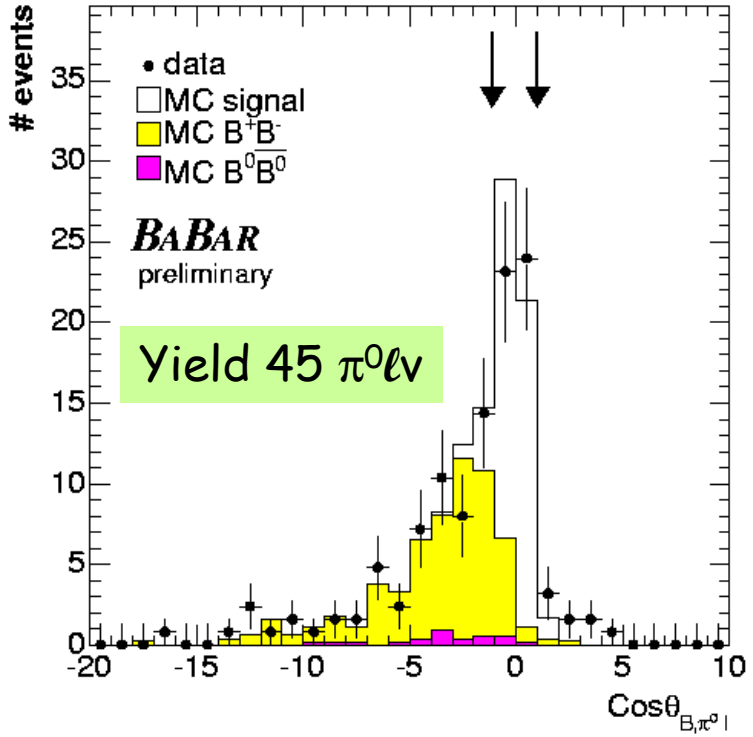
hep-ex/0506065

81fb^{-1} (88M $B\bar{B}$)

- Single mode π^0 studied

$$\cos\theta_{B\pi^0\ell} = \frac{2E_B^* E_{\pi^0\ell}^* - m_B^2 - m_{\pi^0\ell}^2}{2p_B^* p_{\pi^0\ell}^*}$$

- $\cos\theta_{B\pi^0\ell} \in [-1, 1]$ for signal events



$B(B^+ \to \pi^0 \ell^+ \nu) = (1.80 \pm 0.37_{stat} \pm 0.23_{syst}) \times 10^{-4}$

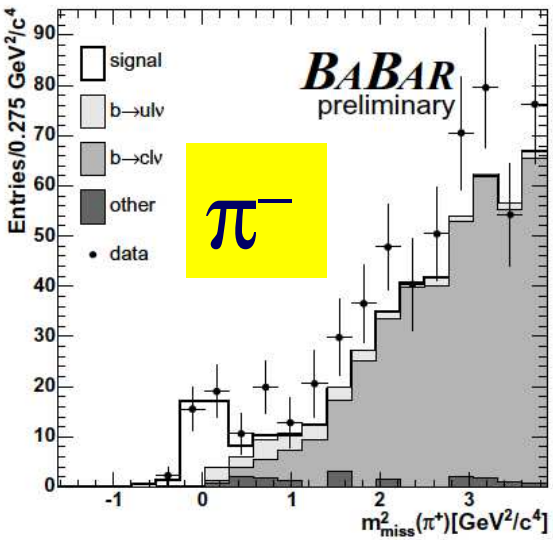
BaBar Full Recon Tag $B \to \pi \ell^+ \nu$

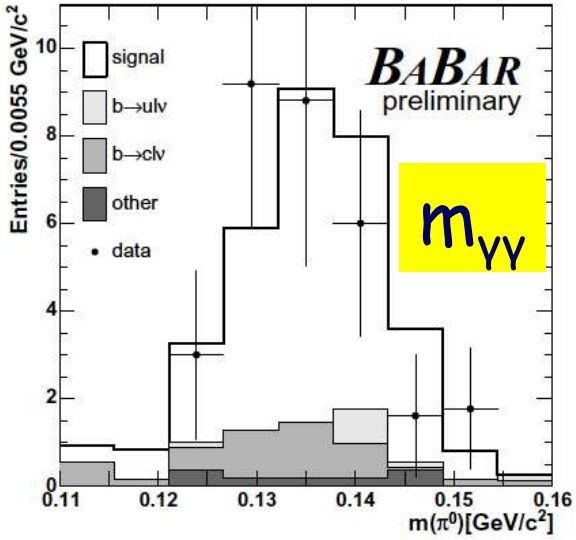
hep-ex/0507085

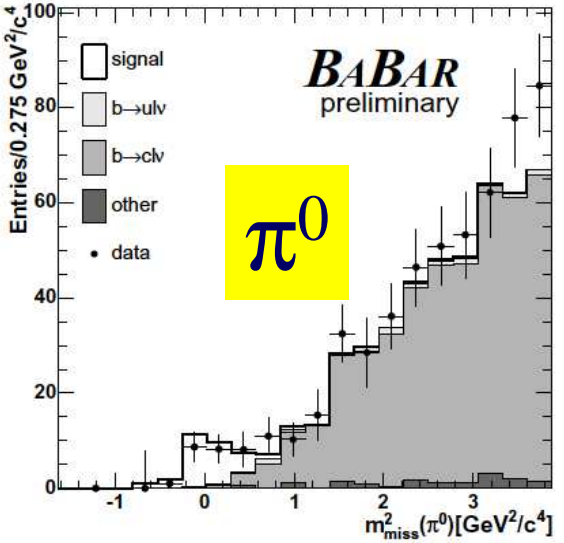
211fb^{-1} (233M $B\bar{B}$)

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

- m_{miss}^2 distribution : peaks at zero for signal (single missing neutrino)





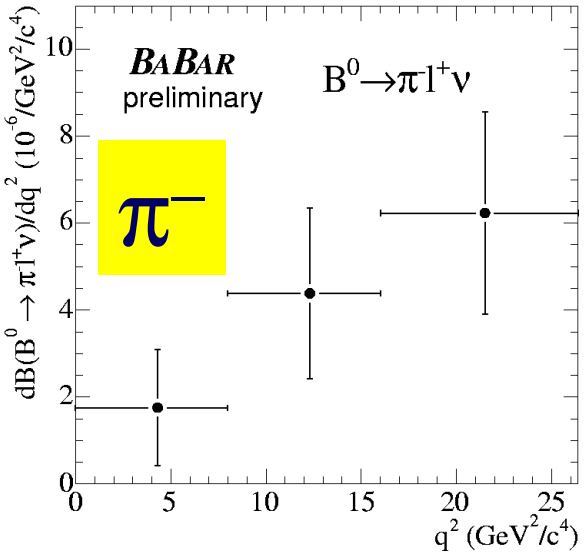


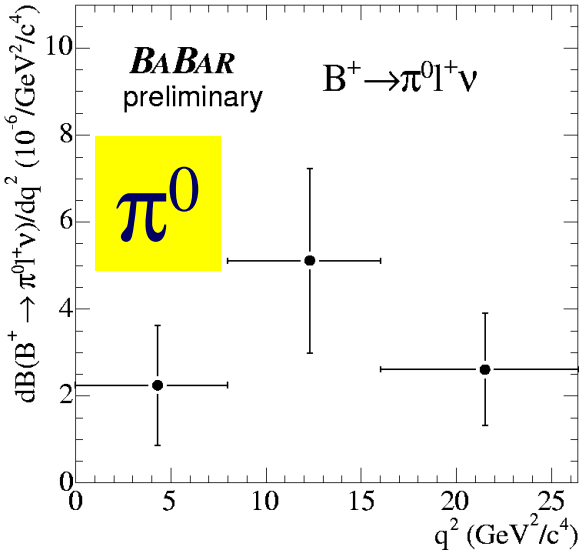
Yield 36 $\pi^-\ell\nu$, 34 $\pi^0\ell\nu$

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

hep-ex/0507085

§ Extract partial BF in 3 q^2 bins





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

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

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

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

$$|V_{ub}| = (3.7 \pm 0.3_{stat} \pm 0.2_{syst} {}^{+0.8}_{-0.5}{}_{\text{FF norm}}) \times 10^{-3}$$

$\pi^+ + \pi^0$, HPQCD

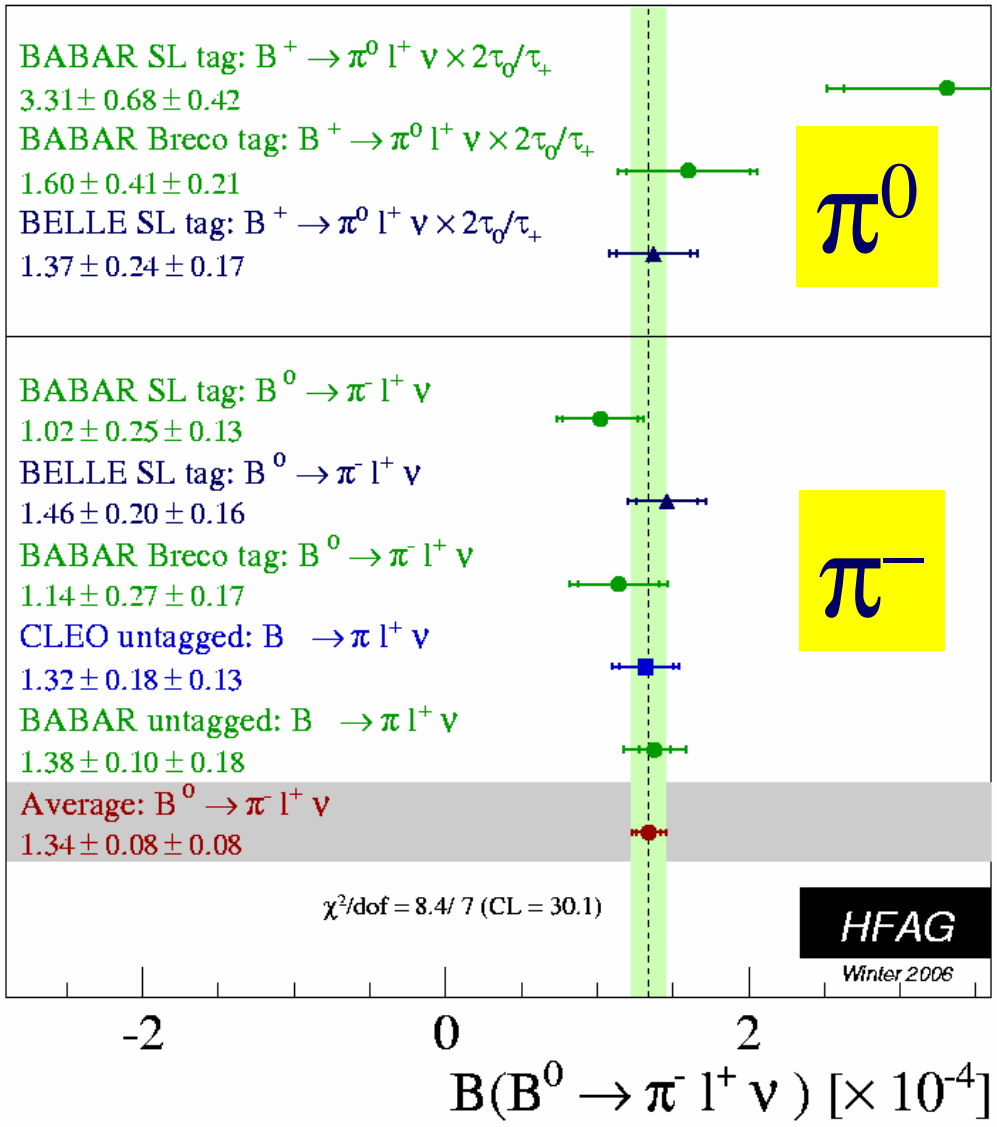
Summary of B(B → π ℓ ν) Exclusive

HFAG Winter 2006

Average B(B^0 → π$^-$ l^+ ν): (1.34 ± 0.08 ± 0.08) × 10^{-4}

Note: Updated Belle SL tag result not yet incorporated in plot

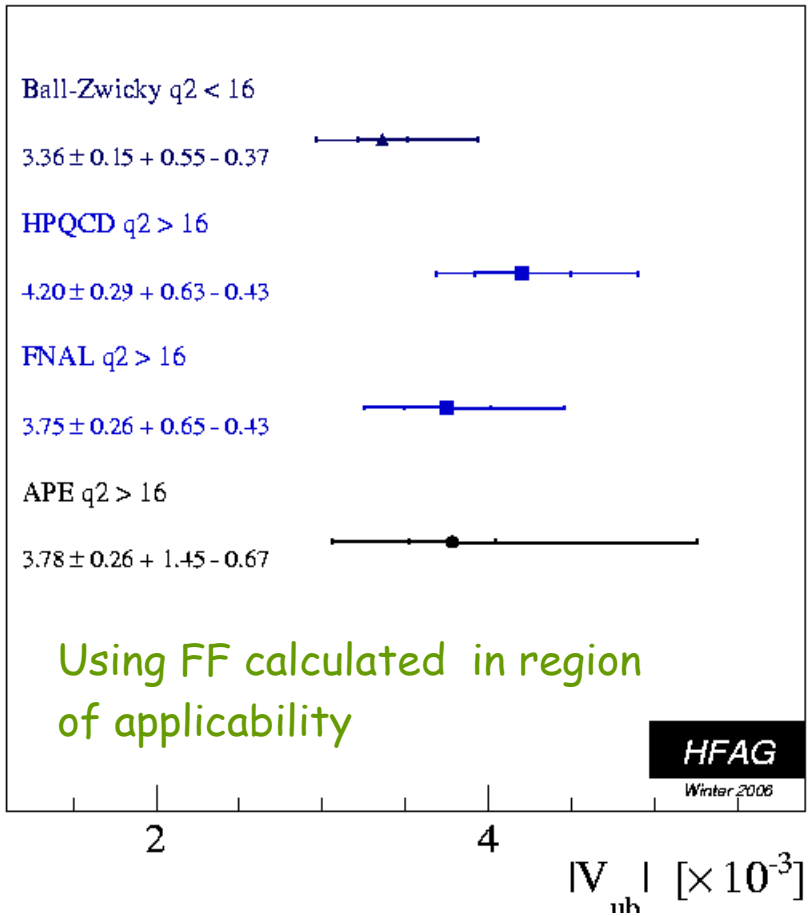
Untagged analyses currently the most precise

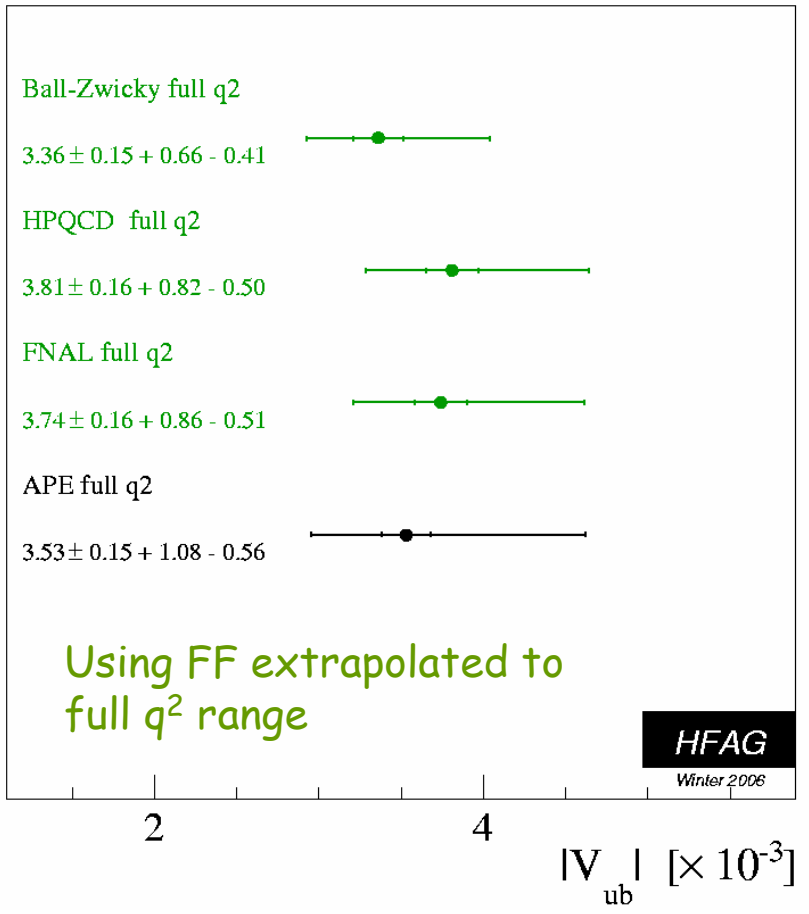


Summary of $|V_{ub}|$ from Exclusive $B \to \pi \ell \nu$

HFAG Winter 2006

Experimental q^2 shape input not used (yet)





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

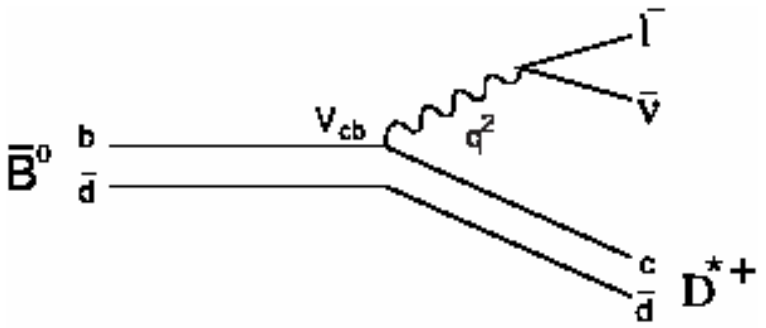
Expt	Mode	Tag	BF [10^{-4}]	Reference
CLEO	$B^0 \to \rho^- \ell \nu$	Untagged	$2.17 \pm 0.34 \,^{+0.47}_{-0.54} \pm 0.41$	PRD 68 (2003) 072003
CLEO	$B^0 \to \rho^- \ell \nu$	Untagged	$2.69 \pm 0.41 \,^{+0.35}_{-0.47} \pm 0.50$	PRD 61 (2000) 052001
BaBar	$B^0 \to \rho^- \ell \nu$	Full	$2.57 \pm 0.52 \pm 0.59$	hep-ex/0408068
BaBar	$B^0 \to \rho^- e \nu$	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

BaBar Exclusive $|V_{cb}|$ Measurement

hep-ex/0602023

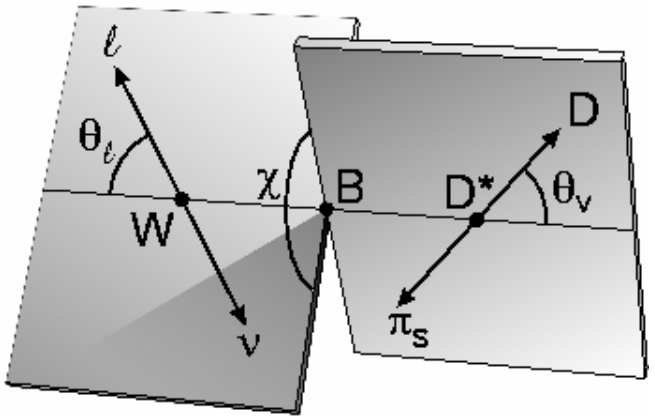
Update to
PRD **71** (2005) 051502
submitted to PRD



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

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

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



79fb^{-1} (86M B$\bar{B}$)

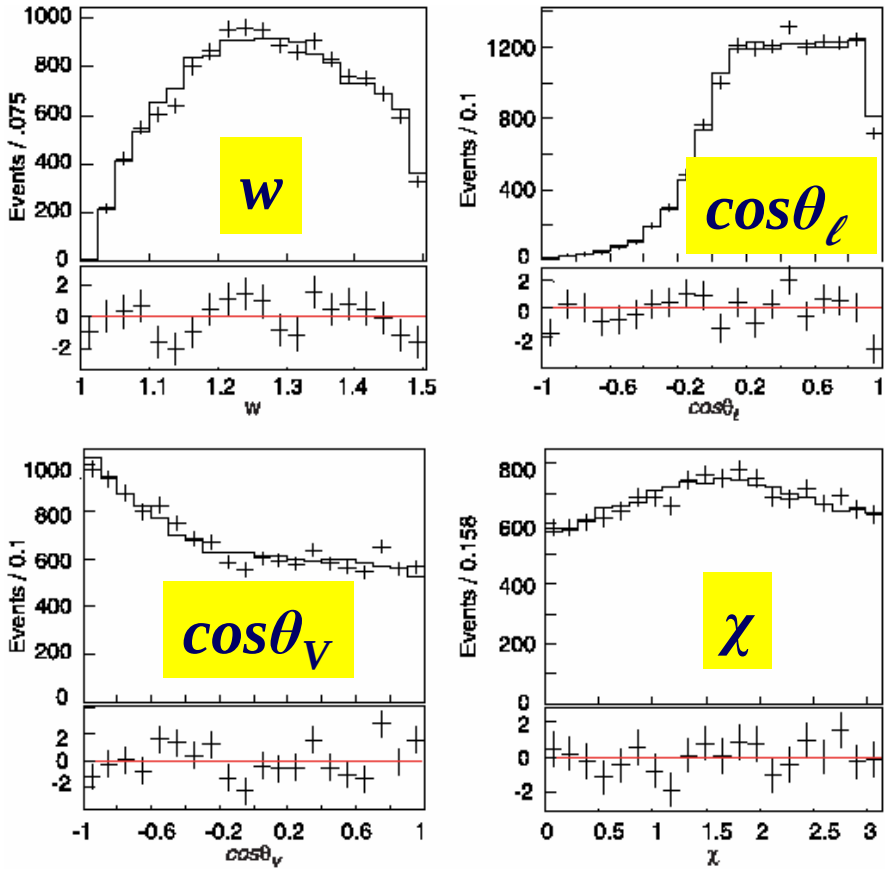
BaBar Exclusive $|V_{cb}|$ Measurement (cont)

hep-ex/0602023

$R_1 = 1.396 \pm 0.060 \pm 0.035 \pm 0.027$

$R_2 = 0.885 \pm 0.040 \pm 0.022 \pm 0.013$

$\rho^2 = 1.145 \pm 0.059 \pm 0.030 \pm 0.035$



- Improvement in FF uncertainty
- Reduces $|V_{cb}|$ systematic error
- Useful for understanding $b \to c$ background in $b \to u$

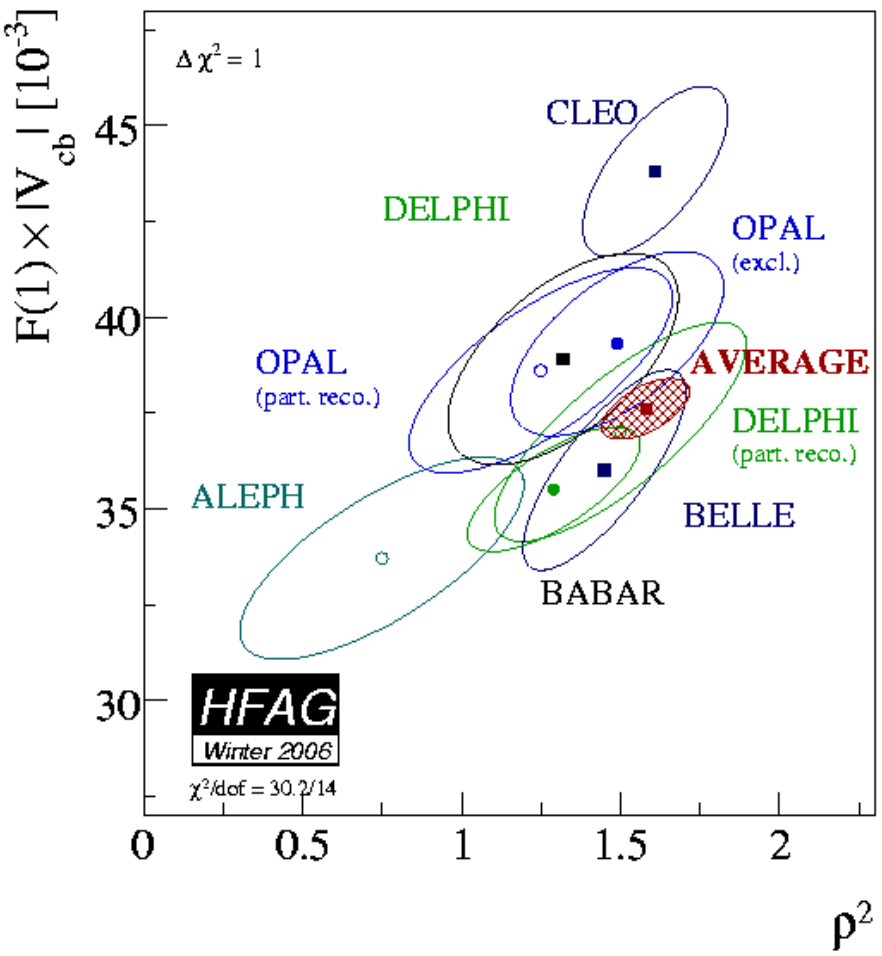
$$|V_{cb}| = (37.6 \pm 0.3_{stat} \pm 1.3_{syst} {}^{+1.5}_{-1.3}{}_{theo}) \times 10^{-3}$$

Summary of Exclusive $|V_{cb}|$ Measurements

HFAG Winter 2006

Note:

- Does not include latest BaBar result from hep-ex/0602023



Summary and Future : Exclusive $|V_{ub}|$ Measurements

- **CLEO, BaBar and Belle**
  - ⇒ X_u BF measurements using several channels and several techniques
    X_u : $\pi^+, \pi^0, \rho^+, \rho^0, \omega, \eta$
  - ⇒ $|V_{ub}|$ extracted using π^+, π^0 modes – Exptl error approaches **5%**
    - FF normalization error dominates
  - ⇒ X_c BF measurements and $|V_{cb}|$ continue to be important
  - ⇒ future precision X_u measurements using Full Recon tagging
  - ⇒ FF shape measurements from experiment now possible

- **Theory progress important (and happening) as well** (R. Hill talk) (P. Mackenzie talk)
- **$|V_{ub}|$ to better than 5% precision overall from exclusive semileptonic B-factory measurements?** ⇒ **Feasible.**