Measurements of Partial Branching Fractions for $\bar{B} \to X_u \ell \bar{\nu}$ and the Determination of $|V_{ub}|$

Michael Sigamani
(on behalf of the *BABAR* collaboration)

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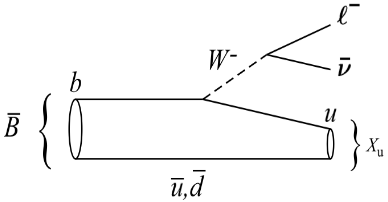
Introduction

1. **CKM matrix element $|V_{ub}|$ is a fundamental parameter of the SM**
   - The measurement uses semileptonic decays, tree-level processes largely free of new physics which can be used to test SM predictions of CP violation

2. **Make an exclusive or inclusive $\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$ measurement**
   - Sensitive to different selection criteria, different backgrounds, different QCD calculations to extract $|V_{ub}|$
   - Well known tension between measurements of $|V_{ub}|$ from exclusive and inclusive methods

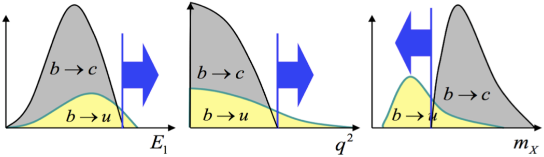


3. **For inclusive measurements the main experimental challenge is separating the rare $\bar{B} \to X_u \ell \bar{\nu}$ signal from the dominant $\bar{B} \to X_c \ell \bar{\nu}$ background ($\mathcal{B}_{b\to c}/\mathcal{B}_{b\to u} \simeq 50$)**

4. **Forced to select regions of phase space where charm background is suppressed and** measure a partial branching fraction, $\Delta\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$

5. **This technique leaves us sensitive to model dependent uncertainties when calculating $|V_{ub}|$** increasing the theoretical uncertainty

6. **Can use the lepton momentum (p_ℓ^*), the hadronic invariant mass (M_X), the leptonic invariant mass squared (q^2), $P_+ = E_X - |\vec{P}_X|$ [1] as discriminating variables (or various 2-d combinations)**



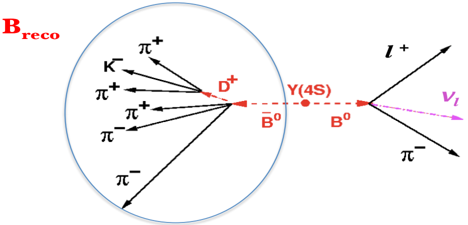
***Idealized spectra**

Measured spectra on slide 9*

[1] E_X and $\vec{P}_X$ are the energy and momentum of the hadronic system X in the B-meson rest frame

The $B_{\rm reco}$ selection

1. **This analysis is an update of** *Phys. Rev. Lett. 100 (2008) 171802*
   - Use same $B_{\rm reco}$ selection, more kinematic cuts etc.
   - Use full *BABAR* data set of 467 million $\Upsilon(4S) \to B\bar{B}$ events
2. **Tag $B\bar{B}$ event using a full reconstruction one of the B mesons ($B_{\rm reco}$)**
   - Use hadronic modes of the type $B_{\rm reco} \to \bar{D}^{(*)} Y^{\pm}$ ($Y^{\pm} = \pi/K$) - Over 1000 modes used



Pros: Low backgrounds, good ν_ℓ resolution. Momentum, charge, and flavour for $B_{\rm recoil}$ well determined

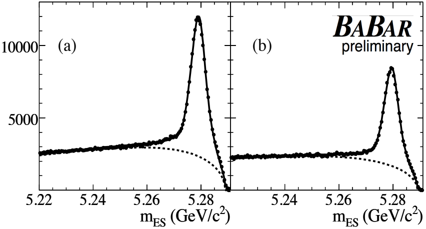
Cons: Low statistics (reconstruction efficiency: 0.3% for $B^0\bar{B}^0$, and 0.5% for B^+B^-)

3. **The signal and background for the $B_{\rm reco}$ selection is determined from a fit to data of the $m_{\rm ES}$ distribution**

$$m_{\rm ES} = \sqrt{s/4 - \vec{p}_B^{\,2}} \quad (1)$$

$\sqrt{s}$ is the total energy of the $\Upsilon(4S)$, and p_B is the momentum of the $B_{\rm reco}$ candidate. Both in the $\Upsilon(4S)$ rest-frame.

4. **Maximum likelihood fit with 2 PDFs:**
   - Modified Crystal Ball function for the signal
   - Argus function for the sum of the combinatorial and continuum background ($e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$)

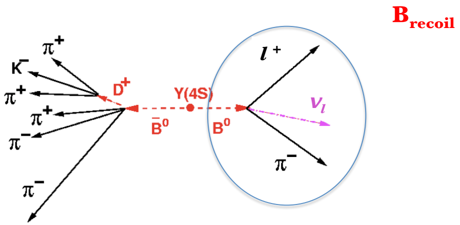


Fit of $m_{\rm ES}$ distribution to $\bar{B} \to X \ell \bar{\nu}$ data events for (a) $B^{\pm}$, and (b) B^0

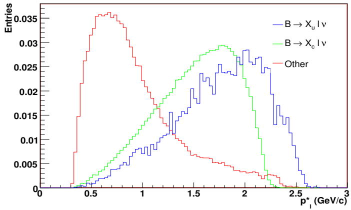
The B_{recoil} selection

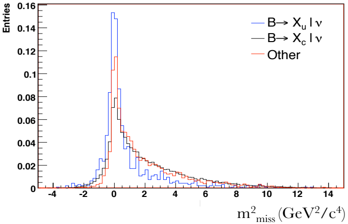
1. **Select a lepton (e or μ) from the other B with momentum greater than 1.0 GeV/c in the B_{recoil} rest frame**
   - Reconstruct the neutrino from the missing momentum in the event
   - Remaining particles in the event associated to the hadronic X system

2. **Select 3 samples of semileptonic decay:**
   - Inclusive $\overline{B} \to X \ell \bar{\nu}$ (for normalization)
   - $\overline{B} \to X_u \ell \bar{\nu}$ signal enhanced selection
   - $\overline{B} \to X_u \ell \bar{\nu}$ signal depleted selection (for data/MC studies)



(1) Semileptonic selection	At least one lepton $p^*_\ell > 1.0\,\mathrm{GeV}/c$
(2) $\bar{B} \to X_u \ell \bar{\nu}$ signal enhanced selection	Only one lepton $m^2_{miss} < 0.5\,\mathrm{GeV}^2/c^4$ (Charge) $Q_{\rm B_{reco}} + Q_{\rm B_{recoil}} = 0$ $Q_{B_{\rm recoil}} Q_\ell > 0$ (only for $B^\pm$) Veto events with partially reconstructed $D^* \ell^\mp \bar{\nu}$ Veto events with kaons in the $B_{\rm recoil}$
(3) $\bar{B} \to X_u \ell \bar{\nu}$ signal depleted selection	Selection (2) without kaon veto, and partial $D^* \ell^\mp \bar{\nu}$ veto



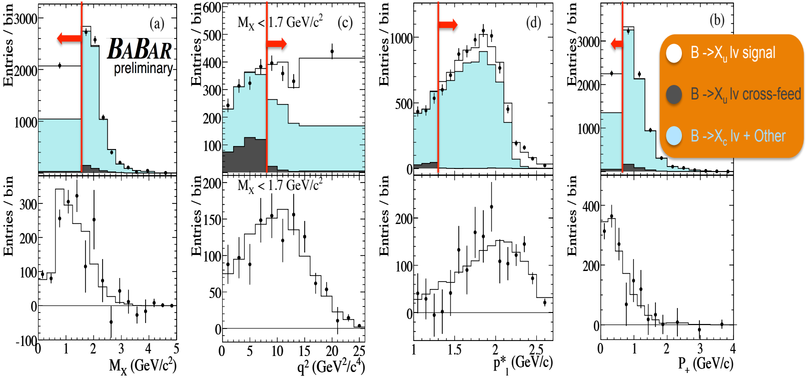


Extraction of signal yields

1. **We study the distributions in the following regions of phase space:**
   - $M_X < 1.55\,\mathrm{GeV}/c^2$,
   - (M_X, q^2), $p^*_\ell > 1.0\ \mathrm{GeV}/c$ - 2-d full phase space fit,
   - $M_X < 1.70\,\mathrm{GeV}/c^2$ (a) [reference to plots on slide 9],
   - $P_+ < 0.66\,\mathrm{GeV}/c$ (b),
   - $M_X < 1.70\,\mathrm{GeV}/c^2$, $q^2 > 8.0\mathrm{Gev}^2/\mathrm{c}^4$ - 2-d fit (c),
   - $p^*_\ell > 1.0 - 2.4\ \mathrm{GeV}/c$ (d) - Choose optimal cut value at 1.3 GeV

2. **The distribution for each kinematic variable is fitted with a χ^2 minimization technique to extract the signal yield (perform $m_{\rm ES}$ fits in each bin of the kinematic variable)**

3. **For regions dominated by $\bar{B} \to X_c \ell \bar{\nu}$ (high M_X, low p^*_ℓ) we re-weight the relative contribution from $X_c = D^*_0, D^*_2, D_1, D^{'}_1$**
   - Fit quality improves in these regions
   - Small effect on extracted signal yield



4. 'Other' bkg includes: Secondary leptonic decays from D^*, or τ. Leptons from $J/\psi \to \ell\ell$ decays. Fake leptons (mis-identified hadrons).
5. **Upper row:** Measured M_X, q^2 with $M_X < 1.7\ \mathrm{GeV}/c^2$, P_+, and p^*_ℓ
6. **Lower row:** Final $\bar{B} \to X_u \ell \bar{\nu}$ sample after background subtraction (re-binned to show shape of the distribution)

Results for $\Delta\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$

	Signal yield	$\Delta\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$ (10^{-3})
$M_X < 1.55$	$1033 \pm 73_{stat}$	$1.08 \pm 0.08_{stat} \pm 0.06_{sys}$
$M_X < 1.70$	$1089 \pm 82_{stat}$	$1.15 \pm 0.10_{stat} \pm 0.08_{sys}$
$P_+ < 0.66$	$902 \pm 80_{stat}$	$0.98 \pm 0.09_{stat} \pm 0.08_{sys}$
$M_X < 1.70$ and $q^2 > 8$	$665 \pm 53_{stat}$	$0.68 \pm 0.06_{stat} \pm 0.04_{sys}$
(M_X, q^2), $p^*_\ell > 1.0$	$1441 \pm 102_{stat}$	$1.80 \pm 0.13_{stat} \pm 0.15_{sys}$
$p^*_\ell > 1.0$	$1462 \pm 137_{stat}$	$1.76 \pm 0.16_{stat} \pm 0.18_{sys}$
$p^*_\ell > 1.3$	$1326 \pm 118_{stat}$	$1.50 \pm 0.13_{stat} \pm 0.14_{sys}$

7. **We measure the ratio** $\Delta R_{\mathrm{u/sl}} = \frac{\Delta\mathcal{B}(\bar{B}\to X\ell\bar{\nu})}{\mathcal{B}(\bar{B}\to X\ell\bar{\nu})}$ **to reduce systematics**
   - Multiply $R_{\mathrm{u/sl}}$ by $(10.66 \pm 0.15)\%$ to obtain $\Delta\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$
8. $M_X < 1.55\ \mathrm{GeV}/c^2$ **gives the lowest experimental error at** 9%
9. **Good agreement between the two results for** $p^*_\ell > 1\,\mathrm{GeV}/c$ **and full phase space** (M_X, q^2) **fits.**

Systematic uncertainties

1. **Since we measure a ratio of BFs many systematics are reduced (lepton ID etc)**
2. **The statistical and systematic errors are comparable in size, and differ for different selected samples (see slide 24 for percentage breakdown of experimental errors)**
3. **We evaluate systematics concerning:** tracking, neutrals, particle ID/ mis-ID, fitting technique, $\bar{B} \to X_c \ell \bar{\nu}$ knowledge, $\bar{B} \to X_u \ell \bar{\nu}$ knowledge...

	$M_X < 1.55$	$M_X < 1.7$	$P_+ < 0.66$	$M_X < 1.7$ $q^2 > 8$	(M_X, q^2) $p^*_\ell > 1$	$p^*_\ell > 1.3$
Stat. (%)	7.1	8.9	8.9	8.0	7.1	8.9
Syst. (%)	5.2	6.3	8.1	6.2	8.1	9.1
Tot. (%)	8.9	11.0	12.1	10.3	10.8	12.7

Experimental uncertainties on $\Delta\mathcal{B}(\bar{B} \to X \ell \bar{\nu})$ (lowest for $M_X < 1.55$)

Extraction of $|V_{ub}|$ for different samples

1. **No preferred method to extract $|V_{ub}|$ - Use all calculations and compare final results**

   BLNP: http://arxiv.org/pdf/hep-ph/0504071v3 **GGOU:** http://arxiv.org/pdf/0707.2493v2
   DGE: http://arxiv.org/pdf/hep-ph/0509360v2 **ADFR:** http://arxiv.org/pdf/0809.4860v1

2. **With BLNP, DGE, and GGOU we have the following relation:**

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(\overline{B} \to X_u \ell \bar{\nu})}{\tau_B \cdot \Delta_{theory}}} \qquad (2)$$

   $\tau_B = 1.573 \times 10^{-12}$ s, and Δ_{theory} (ps^{-1}) is provided by authors of the particular calculation

3. **Propagate the theoretical uncertainty from Δ_{theory} onto $|V_{ub}|$ (as assessed by the authors)**

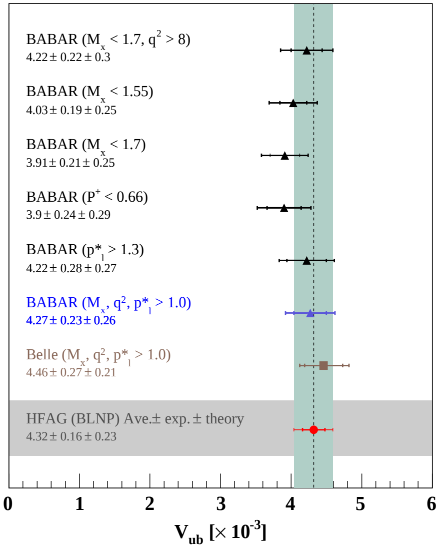
4. **Final results compared with HFAG (end of 09) average**

   http://www.slac.stanford.edu/xorg/hfag2/semi/EndOfYear09

   and Belle multivariate

5. **HFAG Average does not take into account these preliminary results from BABAR**

6. **Results for BLNP, GGOU, DGE, ADFR**



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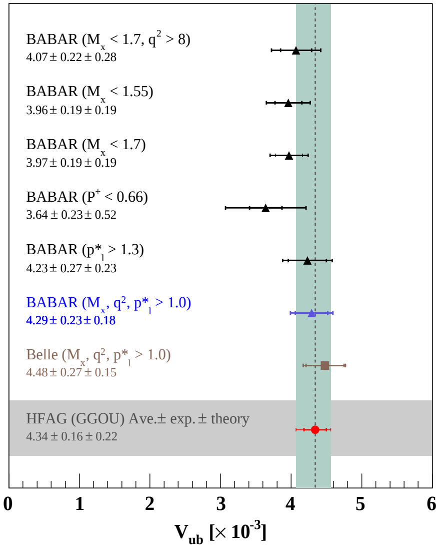

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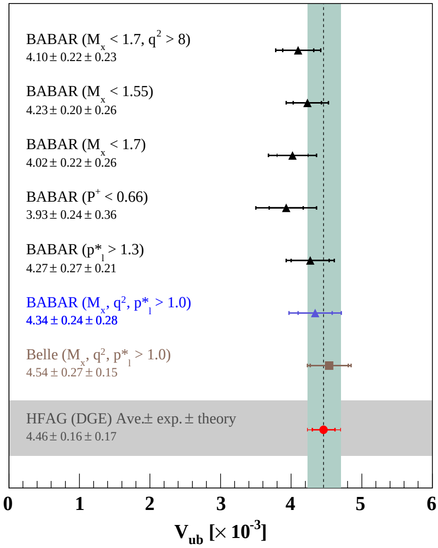

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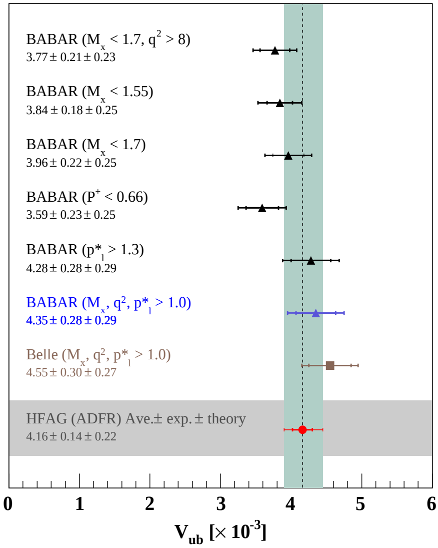
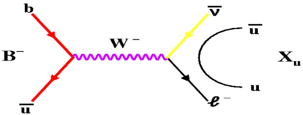


Limits on Weak Annihilation effects

1. **Contributions from non-tree level processes affect the extraction of $|V_{ub}|$**



2. **Use BFs for B^0 and B^+ to set a limit on the size of the Weak Annihilation (WA) in B^+ decays**

$$R^{+/0} = \frac{\Delta\Gamma^+}{\Delta\Gamma^0} = \frac{\tau^0}{\tau^+}\frac{\Delta\mathcal{B}(B^+ \to X_u \ell\nu)}{\Delta\mathcal{B}(B^0 \to X_u \ell\nu)} \quad (3)$$

where $\tau^+/\tau^0 = 1.071 \pm 0.009$ (the ratio of the lifetimes for B^+ and B^0)

	$R^{+/0} - 1$	C.L. (90%)
$M_X \leq 1.70$, $q^2 \geq 8$	$0.042 \pm 0.066 \pm 0.009$	$-0.07 \leq \gamma_{WA}/\Gamma \leq 0.15$
$M_X \leq 1.55$	$-0.020 \pm 0.066 \pm 0.003$	$-0.13 \leq \gamma_{WA}/\Gamma \leq 0.09$
$M_X \leq 1.70$	$0.071 \pm 0.117 \pm 0.011$	$-0.12 \leq \gamma_{WA}/\Gamma \leq 0.26$
(M_X, q^2) $p^*_\ell > 1.0$	$0.109 \pm 0.157 \pm 0.019$	$-0.15 \leq \gamma_{WA}/\Gamma \leq 0.37$

Summary

1. **We present preliminary results of $\Delta\mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$ using different phase space regions and different kinematic variables based on the B_{reco} sample (including p^*_ℓ)**

2. **Use partial branching ratios of B^0 and $B^\pm$ to set a limit on the size of the WA at $< 9\%$ at 90% C.L.**

3. **Quote the $|V_{ub}|$ value using the most inclusive measurement (M_X-q^2 with $p^*_\ell > 1.0$) - Has the smallest overall uncertainty on $|V_{ub}|$**
   - The arithmetic average over the different theoretical calculations gives $|V_{ub}| = (4.31 \pm 0.35) \times 10^{-3}$ (8% uncertainty)
   - Result consistent with earlier *BABAR* measurement, and in good agreement with Belle multivariate analysis

Thank you

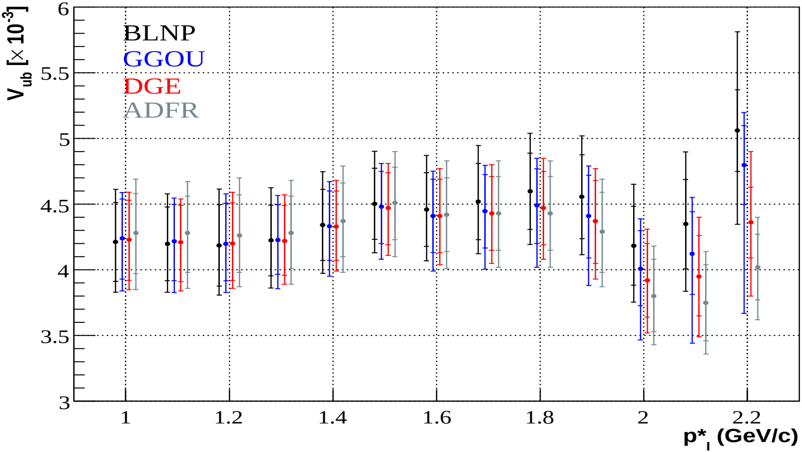
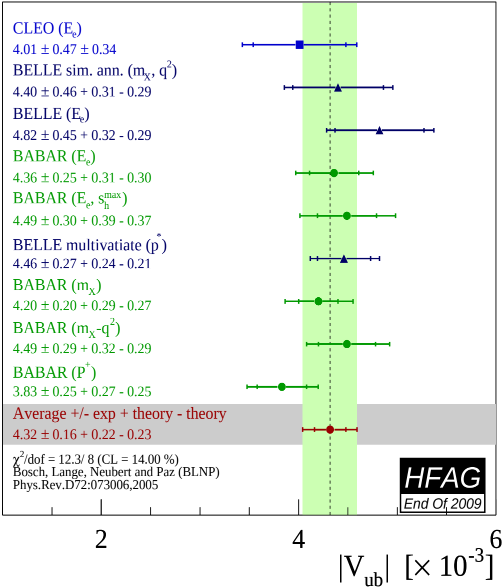


Figure: Results of $|V_{ub}|$ from all theoretical schemes for p^*_ℓ. Inner error bar corresponds to the experimental error, Outer error bar corresponds to the total error.


CLEO (E_e)
4.01 ± 0.47 ± 0.34
BELLE sim. ann. (m_X, q^2)
4.40 ± 0.46 + 0.31 - 0.29
BELLE (E_e)
4.82 ± 0.45 + 0.32 - 0.29
BABAR (E_e)
4.36 ± 0.25 + 0.31 - 0.30
BABAR (E_e, s_h^max)
4.49 ± 0.30 + 0.39 - 0.37
BELLE multivatiate (p*)
4.46 ± 0.27 + 0.24 - 0.21
BABAR (m_X)
4.20 ± 0.20 + 0.29 - 0.27
BABAR (m_X-q^2)
4.49 ± 0.29 + 0.32 - 0.29
BABAR (P^+)
3.83 ± 0.25 + 0.27 - 0.25
Average +/- exp + theory - theory
4.32 ± 0.16 + 0.22 - 0.23
χ^2/dof = 12.3/ 8 (CL = 14.00 %)
Bosch, Lange, Neubert and Paz (BLNP)
Phys.Rev.D72:073006,2005
HFAG
End Of 2009
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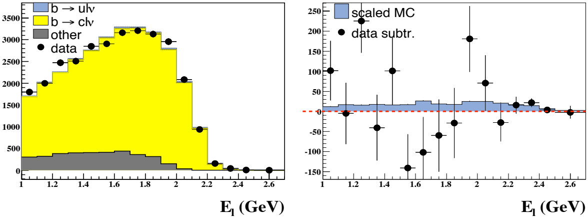
4
6
|V_ub| [× 10^-3]

$B \to D^{**}\ell\nu$ re-weighting



1. **Perform a three-parameter fit on the signal depleted sample**
2. **Calculate ratio ($R^{D^{**}}$) of scaling factors for:**
   - $B \to D^{**}\ell\nu/(\overline{B} \to X_c\ell\bar{\nu}$ **+Other) GREY/YELLOW**
3. **Fix the $B \to D^{**}\ell\nu$ component to this ratio in all subsequent fits**

Table: Table of statistical and theoretical correlations. Boldface refers to correlations on $|V_{ub}|$ measurements. Non-boldface refers to correlations of partial branching fractions. In the latter case, theoretical correlations have been included.

Analysis	$M_X < 1.55$	$M_X < 1.70$	$P_+ < 0.66$	$M_X < 1.70$, $q^2 > 8$	(M_X, q^2) $p_\ell^* > 1.0$	$p_\ell^* > 1.3$
$M_X < 1.55$	1	0.77	0.74	0.50	0.72	0.57
$M_X < 1.70$	**0.81**	1	0.86	0.55	0.94	0.73
$P_+ < 0.66$	**0.69**	**0.81**	1	0.46	0.78	0.61
$M_X < 1.70, q^2 > 8$	**0.40**	**0.46**	**0.38**	1	0.52	0.46
(M_X, q^2), $p_\ell^* > 1$	**0.58**	**0.88**	**0.67**	**0.34**	1	0.74
$p_\ell^* > 1.3$	**0.53**	**0.72**	**0.58**	**0.40**	**0.72**	1

Source $\sigma(\Delta\mathcal{B}(B \to X_u \ell \nu))$	$M_X < 1.55$ GeV/c^2	$M_X < 1.70$ GeV/c^2	$P_+ < 0.66$ GeV	$M_X < 1.70$ GeV/c, $q^2 > 8$GeV^2/c^4	(M_X, q^2) $p^*_\ell > 1.0$ GeV/c	$p^*_\ell > 1.0$ GeV/c	$p^*_\ell > 1.3$ GeV/c
Statistical error	7.1	8.9	8.9	8.0	7.1	9.4	8.9
MC statistics	1.3	1.3	1.3	1.6	1.1	1.1	1.2
Detector-related:							
Tracking efficiency	0.4	1.0	1.1	1.7	0.7	1.2	0.1
Neutral efficiency	1.3	2.1	4.0	0.7	1.0	0.9	0.9
π^0 efficiency	1.2	0.9	1.1	0.9	0.9	2.9	1.1
PID eff. & misID	1.9	2.4	3.3	2.9	2.3	2.9	2.2
K_L	0.9	1.3	1.1	2.1	1.6	1.3	0.6
Fit related: (tbu)							
m_{ES} fit parameters	2.0	2.7	1.9	2.6	1.9	2.0	2.5
combinatorial backg.	1.8	1.8	2.6	1.8	1.0	2.1	0.5
Signal knowledge:							
SF parameters	$^{2.4}_{-1.6}$	$^{1.8}_{-0.9}$	$^{0.6}_{-1.8}$	$^{0.6}_{-0.9}$	$^{6.0}_{-4.9}$	$^{5.8}_{-7.1}$	$^{7.1}_{-6.1}$
SF form	1.2	1.6	2.6	1.2	1.5	1.1	1.1
Exclusive $B \to X_u \ell \nu$	0.6	1.3	1.6	0.7	1.9	5.3	3.4
Gluon splitting	1.2	1.6	1.1	1.0	2.7	3.1	2.4
Background knowledge:							
K_S veto	0.8	1.4	1.7	2.1	1.2	1.3	0.3
B SL branching ratio	0.9	1.4	1.5	1.4	1.0	0.8	0.7
D decays	1.1	0.6	1.1	0.6	1.1	1.6	1.5
$B \to D \ell \nu$ form factor	0.5	0.5	1.3	0.4	0.4	0.1	0.2
$B \to D^* \ell \nu$ form factor	0.7	0.7	0.9	0.7	0.7	0.7	0.7
$B \to D^{**} \ell \nu$ form factor	0.8	0.9	1.3	0.4	0.9	1.0	0.3
$B \to D^{**}$ reweight	0.4	1.0	1.1	0.7	1.6	0.1	1.2
Total systematics:	$^{5.3}_{-5.0}$	$^{6.4}_{-6.2}$	$^{8.0}_{-8.1}$	$^{6.2}_{-6.2}$	$^{8.5}_{-7.7}$	$^{10.5}_{-11.2}$	$^{9.4}_{-8.7}$
Total error:	$^{9.0}_{-8.8}$	$^{11.0}_{-10.9}$	$^{12.0}_{-12.1}$	$^{10.2}_{-10.3}$	$^{11.1}_{-10.5}$	$^{14.1}_{-14.6}$	$^{12.9}_{-12.4}$