Semileptonic B Decays at BaBar

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Outline

Introduction
- Motivations
- BaBar
- Experimental approach

Inclusive decays
- Determination of $|V_{cb}|$
- Determination of $|V_{ub}|$

Exclusive Decays
- $D^{(*)}\ell\nu$
- $\pi(\eta^{(')})\ell\nu$

Conclusions
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  ➤ $D^{(*)}\ell\nu$
  ➤ $\pi(\eta')\ell\nu$
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Semileptonic Decays

Semileptonic decays are an important tool to study:

- CKM matrix elements
- Heavy quark parameters (e.g., $b$, $c$ quark masses)
- QCD Form Factors
- New Physics
Framework: the CKM Matrix

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

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

- Unitary matrix
- $V_{CKM}$ connects the weak to the mass eigenstates
- 3 real parameters + 1 complex phase

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

The only source of $CP$ in the Minimal SM
Representation: the Unitarity Triangle

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

\[ \alpha = \arg \left( -\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*} \right) \]
\[ (\phi_2) \]
\[ \beta = \arg \left( -\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right) \]
\[ (\phi_1) \]
\[ \gamma = \arg \left( -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right) \]
\[ (\phi_3) \]

- Angles $\alpha$, $\beta$, $\gamma$ can be measured with CP of $B$ decays
\[ |V_{ub}/V_{cb}| \]

- Compare the measurements on the \((\rho, \eta)\) plane
  - The \(\Delta m_d/\Delta m_s\) tells us this is true as of today: still large enough to hide new physics!
  - We need the green ring thinner
- Left side of the Triangle is
  \[
  \left| \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right| = \left| V_{ub} \right| \frac{1}{\tan \theta_C}
  \]

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

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

\[ \sin \beta \text{(all charmonium)} = 0.680 \pm 0.025 \sim \text{percentage error: 3.7\% (HFAG)} \]
Semileptonic B Decays

- Natural probe for $|V_{ub}|$ and $|V_{cb}|$
- Decay rate $\Gamma_{c(u)} \equiv \Gamma(b \to c(u)\ell\nu) \propto |V_{c(u)b}|^2$
- $\Gamma_c$ larger than $\Gamma_u$ by a factor $\sim 50$
- Extracting $b \to u\ell\nu$ signal challenging
- Sensitive to hadronic effects
- Must understand them to extract $|V_{ub}|, |V_{cb}|$

PDG 2006

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to l^+\nu_l + \text{anything}$</td>
<td>$10.9 \pm 0.4 %$</td>
</tr>
<tr>
<td>$B^+ \to \bar{D}^*(2007)^0 \ell^+\nu_\ell$</td>
<td>$(6.5 \pm 0.5) %$</td>
</tr>
<tr>
<td>$B^+ \to \bar{D}^0 \ell^+\nu_\ell$</td>
<td>$(2.15 \pm 0.22) %$</td>
</tr>
<tr>
<td>$B^+ \to \bar{D}<em>1(2420)^0 \ell^+\nu</em>\ell$</td>
<td>$(0.56 \pm 0.16) %$</td>
</tr>
<tr>
<td>$B^+ \to \bar{D}<em>2(2460)^0 \ell^+\nu</em>\ell$</td>
<td>$&lt; 0.8 % @90\text{CL}$</td>
</tr>
<tr>
<td>$B^+ \to D^-\pi^+\ell^+\nu_\ell$</td>
<td>$(0.53 \pm 0.10) %$</td>
</tr>
<tr>
<td>$B^+ \to D^*+\pi^+\ell^+\nu_\ell$</td>
<td>$(0.64 \pm 0.15) %$</td>
</tr>
<tr>
<td>$B^+ \to \bar{D}^*(\ast) n\pi\ell^+\nu_\ell$</td>
<td>??</td>
</tr>
</tbody>
</table>
Total $b \to c(u) \ell \nu$ Rate

Tree level, short distance (perturbative) + long distance (non perturbative):

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

\[
\Gamma(B \to X_{c(u)} \ell \nu) = G_F^2 m_b^5 / 192 \pi^3 |V_{c(u)b}|^2 [1 + A_{ew}] A_{pert} A_{nonpert}
\]

- Non-perturbative parameters need to be measured.
- They depend on the expansion, which depends on the $m_b$ definition
- Similar expression for $b \to s \gamma$. 

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Moments in $B \rightarrow X_{c(u)} \ell \nu$ decays

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

Lepton moments:
$$\langle E_1^n \rangle = \frac{1}{\Gamma_{c(u)}} \int \left( E_1 - \langle E_1 \rangle \right)^n \frac{d\Gamma_{c(u)}^{\ell \nu}}{dE_1}$$

Hadronic mass moments:
$$\langle m_X^n \rangle = \frac{1}{\Gamma_{c(u)}} \int m_X^n \frac{d\Gamma_{c(u)}^{\ell \nu}}{dm_X}$$

Moments are related to non-perturbative parameters

For comparison with data, use low-order moments of inclusive distributions over large ranges on phase space to avoid problem with quark-hadron duality

Similarly, moments in the photon energy are calculated for $b \rightarrow s \gamma$


> 60 measured moments available form DELPHI, CLEO, BABAR, Belle, CDF
Exclusive Measurements

- Matrix element for semileptonic decays:
  \[ \mathcal{M}(M_{Q\bar{q}} \to X_{q'\bar{q}}\ell^-\bar{\nu}_\ell) = -i \frac{G_F}{\sqrt{2}} V_{q'Q} L^\mu H_\mu \]

- Leptonic current exactly known:
  \[ L^\mu = \bar{u}_\ell \gamma^\mu (1 - \gamma_5) \nu_\ell \]

- Hadronic current described by Form Factors (FF), functions of squared momentum transfer \( q^2 \):
  \[ \langle P'(p')|V^\mu|P(p)\rangle = f_+(q^2)(p + p')^\mu + f_-(q^2)(p - p')^\mu \]

- Exclusive rates determined by \( |V_{c(u)b}| \) and Form Factors (FF), which represent the probability that the heavy-quark combine to form the selected final state particle.
  - Theoretically calculable at kinematical limits
  - Lattice QCD works if \( D^* \) or \( \pi \) is \( \sim \) at rest relative to \( B \)
  - Empirical extrapolation is necessary to extract \( |V_{c(u)b}| \) from measurements
  - Measure differential rates to constrain the FF shape, then use FF normalization from the theory for \( |V_{c(u)b}| \)
New Physics, $B \rightarrow D^{(*)}\tau\nu$

• Same Feynman diagram as the light leptons ($e, \mu$), but the decays can also be mediated by a charged Higgs boson.

• Very clean probe of New Physics:
  – NP contributes at tree level
  – Measurements of FF's for light leptons allow for very precise prediction of the $\tau$-hadronic behaviour
  – Spin zero Higgs does not couple to all the helicity states, affect $D$ and $D^*$ differently, $\tau$ polarization.
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PEPII at SLAC and BaBar

- B-factories: run @ Y(4S)
- BaBar (BELLE) asymmetric factory: 9 GeV e⁻ on 3.1 GeV e⁺, Y(4S) boost: βγ~0.56

Cross Sections at Y(4S):
- b̅b ~ 1.1 nb
- c̅c ~ 1.3 nb
- d̅d, s̅s ~ 0.3 nb
- u̅u ~ 1.4 nb

Peak luminosity:
1.2×10^{34} cm^2 s^{-1}

Integrated luminosity:
482 fb⁻¹ (Jan 1, 2008)

Analyses presented here: 79-382 fb⁻¹

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The BaBar Detector

- \( B \rightarrow X_{c,u} \ell \nu \)
  - \( \rightarrow \pi^\pm \text{s, } K^\pm \text{s, } \gamma \text{s} \)
  - \( \ell = e, \mu, \tau \)

- Good e, \( \mu \) ID (\( p^*_\ell > 1 \text{GeV} \))
- Good hadron ID (e.g., \( \pi/K \) separation)
- Angular coverage \( \approx 91\% \) of 4\( \pi \) in CMS
  (challenge for \( \nu \) reconstruction)

- 5-layer SVT tracker
- 40-layer Drift Chamber \( \rightarrow \text{dE/dx} \)
- DIRC (RICH) for particle ID
- CsI(Tl) crystal calorimeter (\( e^\pm, \gamma \))
- Instrumented Flux Return for muon ID

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## Approaches to Measuring $B \to X\ell\nu$

### Untagged
- **Pros**
  - High efficiency
- **Cons**
  - $\nu$ resolution problematic
  - Rel. high backgrounds (relatively low purity)
- Initial 4-momentum known
- Missing 4-momentum = $\nu$
- Reconstruct $B \to X\ell\nu$ using $m_B$ (beam-constrained) and $\Delta E = E_B - E_{\text{beam}}$

### Semileptonic (SL) Tag
- **Pros**
  - Lower backgrounds (higher purity)
- **Cons**
  - Relatively low efficiency
- One $B$ reconstructed in a selection of $D^{(*)}\ell\nu$ modes
- Two missing $\nu$ in event
- Use kinematic constraints

### Full Recon Tag (Breco)
- **Pros**
  - Very good $\nu$ resolution
  - Very low backgrounds
- **Cons**
  - Very low efficiency
- One $B$ reconstructed completely in known $b \to c$ mode.
- Many modes used.

### Signal example: $B \to \pi \ell \nu$
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Moments in $B \rightarrow X_c \ell \nu$ decays

- **B-reco.** Subtract background with $m_{ES}$
- 1 lepton (e, $\mu$) in recoil with energy $P_\ell > 0.8$ GeV in B-rest frame
- Remaining charged and neutral particles form inclusive $X_c$ system
- Measure moments of hadronic mass $m_x$ and mixed mass-and-energy moments for several lower cuts on $P_\ell$
- Improve resolution with kinematic fit
  - energy-momentum conservation
  - $E_{miss}$, $p_{miss}$ consistent with $\nu$
- Correct $X_c$ system for bias due to unmeasured particles
- Dominant systematic uncertainty: efficiency on inclusive event reconstruction
Measured Moments

- Moments integrated over data for various lepton cuts over the same mass or lepton energy distribution (all points highly correlated)
- Each observable has a different dependence on $|V_{cb}|$, $m_b$, $m_c$, and several non-perturbative params
- Parameters determined by a global fit over ● points
- The ○ points, not used in the fit, agree well with the fit results

$$n_x = m_x^2c^4 - 2\Lambda \bar{E}_x + \Lambda$$

$(\Lambda = 0.65 \text{ GeV})$
Global OPE Fit – Kinetic Scheme

- **27 input moments:**
  - 8 mass moments (this analysis)
  - 13 $E_i$ moments
    (Phys. Rev. D69 111104 (2004))
  - 6 $E_\gamma$ moments

- **Further input:** $\tau_B$

- **8 fit parameters:**
  - $|V_{cb}|$, $m_b$, $m_c$, $B_{SL}$
  - 4 HQE parameters

- **Fit results:**
  
  \[
  |V_{cb}| = (41.88 \pm 0.44_{\text{exp}} \pm 0.35_{\text{theo}} \pm 0.59_{\text{LS}}) \times 10^{-3} \quad (1.9\% \text{ total error})
  
  m_b = (4.55 \pm 0.038_{\text{exp}} \pm 0.040_{\text{theo}}) \text{ GeV} \quad (1.2\% \text{ total error})
  
  m_c = (1.070 \pm 0.038_{\text{exp}} \pm 0.040_{\text{theo}}) \text{ GeV}
  
  B_{SL} = (10.597 \pm 0.171_{\text{exp}} \pm 0.053_{\text{theo}}) \%
  
  \begin{align*}
  m^2_\pi &= (0.471 \pm 0.034_{\text{exp}} \pm 0.062_{\text{theo}}) \text{ GeV}^2 \\
  m^2_G &= (0.330 \pm 0.042_{\text{exp}} \pm 0.043_{\text{theo}}) \text{ GeV}^2 \\
  \rho^3_D &= (0.220 \pm 0.021_{\text{exp}} \pm 0.042_{\text{theo}}) \text{ GeV}^3 \\
  \rho^3_{LS} &= -(0.159 \pm 0.081_{\text{exp}} \pm 0.050_{\text{theo}}) \text{ GeV}^3
  \end{align*}
  \]
OPE Global Fits

- More results from global fits in the kinetic and 1S schemes are available. Recent averages performed by the HFAG.
- A pattern is present: results with $b \to c \ell \nu$ and $b \to s \gamma$ moments differ from results with $b \to c \ell \nu$ moments only (except in hep-ex/0611047, but larger errors).
- HFAG results for Lepton Photon:

  \[
  \begin{array}{cc}
  m_b \text{ (GeV)} & m_b \text{ (GeV)} \\
  b \to c \ell \nu, b \to s \gamma & b \to c \ell \nu \\
  \text{Kinetic scheme} & 4.613 \pm 0.035 \quad 4.677 \pm 0.053 \\
  \text{1S scheme} & 4.701 \pm 0.030 \quad 4.751 \pm 0.058 \\
  \end{array}
  \]

- Large uncertainties due to the ansatz and missing terms.
- Different values of $m_b$ impact the determination of $|V_{ub}|$ from inclusive decays.
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Conclusions
B$\rightarrow$X$_{u}$$\ell$$\nu$ rate

- B$\rightarrow$X$_{c}$$\ell$$\nu$ background is about 50 times larger than B$\rightarrow$X$_{u}$$\ell$$\nu$
- Major experimental challenge is to separate B$\rightarrow$X$_{c}$$\ell$$\nu$ background from signal
- This is achieved in region of phase space where the B$\rightarrow$X$_{c}$$\ell$$\nu$ background is suppressed → partial decay rate

Restriction of the phase-space is a challenge to theory!
B→X_u ℓν theory: OPE approach

Restrict kinematics to suppress background from B→X_c ℓν: OPE convergence is compromised! Need light-cone distribution (shape) function of b quark:

Detailed shape not constrained, in particular the low tail.
Needs to be determined by data

Four approaches:

- 3-scale OPE based on HQET, SCET: Bosch, Lange, Neubert, Paz (BLNP) [PRD 72:073006 (2005)]
- Relate b→uℓν directly to b→sγ: Lange, Neubert, Paz (LNP) [JHEP 0510:084, 2005], Leibovich, Low, Rothstein (LLR) [PLB 486:86]
- Select phase space in m_X-q^2 with reduced SF dependence: Bauer, Ligeti, Luke (BLL) [PRD 64:113004 (2001)]
- Kinetic scheme: P.Gambino, P.Giordano, G.Ossola, N.Uraltsev (GGOU) [JHEP10(2007)058] (very recent!)
B→X_u ℓν theory: parton-level approach

• **On-shell** calculation framework

• Use **perturbation QCD**, with inclusive hadron final states coming from gluon radiation, as $m_b \gg \Lambda$ (hadronic scale)

• The perturbative expansion of spectra in the threshold region is affected by large logarithms, to be resummed

• No **Shape Function** is introduced, but a modelling of non-perturbative QCD effects is adopted.

• Two approaches:
  - **Dressed Gluon Exponentiation**: J.R. Andersen and E. Gardi (DGE)  
    [JHEP 0601:097 (2006)]
  - **Analytic Coupling**: U. Aglietti, G. Ferrera, G. Ricciardi (AC)  
B → X_u ℓν: fully tagged B

- Fully reconstructed B
- Events identified fitting the m_{ES} distribution
- Normalize to semileptonic events to be independent of tagging efficiency
- Use 3 kinematic variables to distinguish b → c ℓ ν from b → u ℓ ν: M_x, P^+, M_x-q^2
- Major systematic errors from: detector, m_{ES} fits, MC stat.

Variables | X_u ℓν events | ΔB(10^{-3})
--- | --- | ---
M_x | 803 ± 60 | 1.18 ± 0.09_{stat} ± 0.07_{syst} ± 0.01_{theo}
P^+ | 633 ± 63 | 0.95 ± 0.10_{stat} ± 0.08_{syst} ± 0.01_{theo}
M_x,q^2 | 562 ± 55 | 0.76 ± 0.08_{stat} ± 0.07_{syst} ± 0.02_{theo}
B → X_u ℓν m_X moments

- Analysis approach similar to arXiv:0708.3702 [hep-ex]
- Unfold the m_X spectrum for detector acceptance, efficiency and resolution.
- Extract mass moments with upper cut m_X^2 < 6.2 GeV^2

- M_1 = (1.96 ± 0.34^{stat} ± 0.53^{syst}) GeV^2
- U_2 = (1.92 ± 0.59^{stat} ± 0.87^{syst}) GeV^4
- U_3 = (1.79 ± 0.62^{stat} ± 0.78^{syst}) GeV^6

First measurement of m_b in X_u ℓν (but large errors):
m_b = 4.604 ± 0.025^{stat} ± 0.193^{mom. syst} ± 0.097^{syst} GeV
Weak Annihilation

Small contribution to $B \rightarrow X_u \ell \nu$ decay (<3% of total rate)

- Compare $B^0 \rightarrow X_u \ell \nu$ partial rate to charge-averaged $B \rightarrow X_u \ell \nu$ rate in WA-enhanced region (large $p_\ell$ and large $q^2$)

- Tagging: $B^0 \rightarrow D^* \ell \nu X$ with partial $D^*$ reconstruction

- Neutrino mass derived from kinematics $m_\nu^2 = (P_B - P_{D^*} - P_\ell)^2$

- Measure $\bar{B}$ for $P_\ell > 2.2-2.4$ GeV

<table>
<thead>
<tr>
<th>$\Delta P_\ell$</th>
<th>$\Delta B(B^0) \cdot 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 - 2.6 GeV/c</td>
<td>2.62±0.33±0.16</td>
</tr>
<tr>
<td>2.3 - 2.6 GeV/c</td>
<td>1.30±0.21±0.07</td>
</tr>
<tr>
<td>2.4 - 2.6 GeV/c</td>
<td>0.76±0.15±0.05</td>
</tr>
</tbody>
</table>

- Extract charge asymmetry, using info from untagged $B \rightarrow u \ell \nu$ from endpoint analysis (Phys.Rev.D73:012006,2006)

$$A^{+/-0} = \frac{\Delta \Gamma^+ - \Delta \Gamma^0}{\Delta \Gamma^+ + \Delta \Gamma^0}$$

- Limit on contribution from WA tor interval 2.3 < $E_\ell$ < 2.6 GeV:

$$\frac{|\Gamma_{WA}|}{\Gamma_u} = \frac{2 \cdot f_u(\Delta P_\ell)}{f_{WA}(\Delta P_\ell)} \cdot A^{+/-0} \lesssim \frac{3.8 \%}{f_{WA}(2.3 - 2.6)}, \text{ at 90\% C.L.}$$

$$\Gamma_{WA} = \Gamma^+ - \Gamma^0$$

$$f_{WA}(\Delta P_\ell) = \text{fraction of WA in interval } \Delta P_\ell$$

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B → X_u ℓ ν E_ℓ analyses

- The E_ℓ (endpoint) analysis is the original method to study B → X_u ℓ ν
- Two untagged analyses so far
- Identify high energy lepton (electron, plenty of statistics)
- Very high background from B → X_c ℓ ν!
- Accurate subtraction of the background is crucial
- Missing momentum used for determining q^2

Suppress background using:

\[ s_h^{\text{max}} = m_B^2 + q^2 - 2 m_B \left( E_e + \frac{q^2}{4E_e} \right) \]

\[ S/B \sim 1/15 \ (E_\ell > 2 \text{ GeV}) \]

### Graph
- **Background-subtracted E_ℓ spectrum**
- **Data (B̄B)**
- **Signal MC**
- **Background MC**

**References**
- Phys.Rev.Lett.95:111801,2005
SF independent analyses

- Assumption that QCD interactions affecting $b \rightarrow s \gamma$ and $b \rightarrow u \ell \nu$ are the same
- Take ratio of weighted $b \rightarrow s \gamma$ and $b \rightarrow u \ell \nu$ decay rates
- $b \rightarrow s \gamma$ spectrum from Phys. Rev. D72 (2005) 052004
- Two BaBar analyses:

  - Using the endpoint spectrum, $|V_{ub}|$ is calculated as a function of $E_\ell$
  - Consistent results except at high $E_\ell$

- ArXiv:hep-ph/0702072v1 accepted by PRD
  - Select Breco events and measure $m_X$
  - Statistic limited analysis

- Using the endpoint spectrum, $|V_{ub}|$ is calculated as a function of $E_\ell$
- Consistent results except at high $E_\ell$

- Full rate
- Expt. error

- Theory(LLR)
Plethora of theoretical approaches → plethora of $|V_{ub}|$ values for each analysis

Current approach is either to quote all the values or just BLNP (OPE)

**BLNP:** $m_b$ from $b \rightarrow c l \nu$ moments:

\[
|V_{ub}| = (3.98 \pm 0.15 \pm 0.30) \times 10^{-4}
\]

**BLNP:** $m_b$ from $b \rightarrow c l \nu$ and $b \rightarrow s \gamma$ moments can't be used because of uncontrolled theoretical errors for the $b \rightarrow s \gamma$ moments. $|V_{ub}|$ value using $b \rightarrow c l \nu$ and $b \rightarrow s \gamma$ was:

\[
|V_{ub}| = (4.31 \pm 0.17 \pm 0.35) \times 10^{-3}
\]

Use only the partial $B$ from $m_X$ for the Breco analyses as experimental correlation among the variables are not published
More $|V_{ub}|$ results

Compilation of the other calculations

- HFAG Ave. (BLNP) $3.98 \pm 0.15 \pm 0.30$
- HFAG Ave. (DGE) $4.34 \pm 0.16 \pm 0.25$
- HFAG Ave. (BLL) $4.83 \pm 0.21 \pm 0.37$
- BABAR (LLR) $4.43 \pm 0.45 \pm 0.29$
- BABAR endpoint (LLR) $4.28 \pm 0.29 \pm 0.25$
- BABAR endpoint (Neubert) $4.01 \pm 0.27 \pm 0.51$
- BABAR endpoint (LNP) $4.40 \pm 0.30 \pm 0.47$

Analytic Coupling

- BaBar ($E_l$) $3.44 \pm 0.14 \pm 0.28$
- Belle ($E_l$) $3.18 \pm 0.16 \pm 0.26$
- CLEO ($E_l$) $3.47 \pm 0.20 \pm 0.29$
- BaBar ($m_X$) $3.87 \pm 0.19 \pm 0.30$
- Belle ($m_X$) $3.73 \pm 0.25 \pm 0.28$
- Belle ($m_X$, $q^2$) $3.93 \pm 0.41 \pm 0.29$
- BaBar ($E_l$, $s_h^{\text{max}}$) $3.87 \pm 0.26 \pm 0.29$

Average $3.69 \pm 0.13 \pm 0.31$

- Results vary from $4.83 \times 10^{-3}$ (BLL) to $3.69 \times 10^{-3}$ (AC)
- $b$-quark masses approaches and dependences different.
- Aim for the near future: to quote one value of $|V_{ub}|$
- $|V_{ub}|$ average using the Kinetic scheme (P.Gambino, P.Giordano, G.Ossola, N.Uraltsev, [JHEP10(2007)058]) is being computed.
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Conclusions
|V_{cb}| and Form Factors from B→D^*\ell\nu

- Differential decay rate:
  \[
  \frac{d\Gamma(B^0 \rightarrow D^* - \ell^+\nu_\ell)}{dw \, d\cos \theta_\ell \, d\cos \theta_\nu \, d\chi} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} F(w, \theta_\ell, \theta_\nu, \chi) G(w)
  \]

- HQ symmetry (b and c mass infinite) predicts a unique universal FF, normalized to 1.0 at zero recoil.
- QCD (and QED) correction to F(1) needed!
- F(w,\theta_\ell,\theta_\nu,\chi) incorporates 3 non-trivial form factors, A_1(w), A_2(w), V(w)
- HQET relates the 3 FF's to each other through HQS, but leaves 3 free parameters to be determined experimentally. They are:
  - Amplitude ratios: \( R_1(w) = V/A_1 \)
  - \( R_2(w) = A_2/A_1 \)
  - Curvature: \( \rho^2 = -\frac{dF/dw}{|_{w=1}} \)
- Using a parametrization by CLN (Caprini, Lellouch, Neubert, NPB530, (1998) 153): three parameters need to be extracted from data \( R_1(1), R_2(1) \) and \( \rho^2 \).
- Goal is to determine \( R_1(w), R_2(w), \rho^2 \)
- There are 4 observables: \( w \) and 3 angles \( (\theta_\ell, \chi, \theta_\nu) \)
B^0 \rightarrow D^{*+} \ell \nu Selection

Select B^0 \rightarrow D^{*+} \ell \nu (D^{*+} \rightarrow D^0\pi^+) events with p^*_\ell > 1.2 GeV

Estimate backgrounds (comb., D^{**}) from \Delta M = M(D^*)-M(D) and \cos\theta_{BY}

Two BABAR analyses:

(1) Three D modes: D^0 \rightarrow K\pi, K\pi\pi^0, K\pi\pi\pi, \chi^2 fit to 1D projections

(2) One D mode: D^0 \rightarrow K\pi, 4D maximum Likelihood fit

10 January 2008
B \rightarrow D^* Form Factors: 1D Projections

- Simultaneous $\chi^2$ fit of 1D projections in three variables $w$, $\cos\theta_l$, $\cos\theta_V$ (integrated over angle $\chi$)
- First simultaneous measurement of form factors and $|V_{cb}|$, fully accounting for all correlations

- Final results combined with Phys.Rev. D74 (2006) 092004 (which uses a full 4D fit) to give a combined value of the form factors:

\[ \rho^2 = 1.179 \pm 0.048 \pm 0.028 \quad R_1(1) = 1.417 \pm 0.061 \pm 0.044 \]
\[ R_2(1) = 0.836 \pm 0.037 \pm 0.022 \quad F(1)|V_{cb}| = (34.7 \pm 0.3 \pm 1.1) \times 10^{-3} \]

New BaBar FF are \~5 times better than the old ones from CLEO (with \~3 fb^{-1})
$|V_{cb}|$ and Form Factors from $B^- \rightarrow D^{*0} e^- \nu$

- Look at decay chain: $D^{*0} \rightarrow \pi^0 D^0$ and $D^0 \rightarrow K^- \pi^+$
- Discriminating variables: $\Delta m$, $\cos \theta_{BY}$
- Binned maximum likelihood fit in $\Delta m$, $\cos \theta_{YB}$ and $\omega$
- $23500 \pm 330$ signal events from the fit
- Main background: mis-reconstructed $B^{0\pm} \rightarrow D^{*0\pm} e^- \nu$
- Main systematic uncertainties:
  - $\pi^0$ reconstruction efficiency
  - $\mathcal{B}(D^{*0} \rightarrow \pi^0 D^0)$
  - $R_1(1)$ and $R_2(1)$ for $\rho^2$
- Results:
  - $F(1)|V_{cb}| = (35.9 \pm 0.6 \pm 1.4) \times 10^{-3}$
  - $\rho^2 = 1.16 \pm 0.06 \pm 0.08$
  - $\mathcal{B}(B^- \rightarrow D^{*0} e^- \nu) = (5.56 \pm 0.08 \pm 0.41)\%$
- in agreement with PDG values of $\mathcal{B}(B^0 \rightarrow D^* e^+ \nu)$

10 January 2008

F. Di Lodovico, QMUL
BABAR Results vs. World Average

- Global multidimensional fit (arXiv:0712.3493, B→D*0ev not yet included)

\[ F(1)|V_{cb}| = (35.89 \pm 0.56) \times 10^{-3} \]
\[ \rho^2 = 1.23 \pm 0.05 \]

- Improved precision: 2.1% (Winter 2006) → 1.6% (now) on F(1)|V_{cb}|
- Using F(1)=0.919+0.033 (Hashimoto et al PRD66 104503): \[ |V_{cb}| = (39.1+0.6+1) \times 10^{-3} \]
- While from inclusive decays (kin. scheme) \[ |V_{cb}| = (41.68+0.39+0.58) \times 10^{-3} \]
- Discrepancy between inclusive and exclusive |V_{cb}|

\[ B(B^0 \rightarrow D^- l^+ \nu) = (5.11 \pm 0.12) \% \]
Branching Fractions for $B \rightarrow D/D^*/D\pi/D^*\pi\ell\nu$

- Breco sample
- reconstruct $e, \mu$ in the recoil
- reconstruct $D^{(*)0}(0)(\pm)$ in the recoil
- extract signal by fitting missing mass squared
- dominant syst due to Breco, $\mathcal{B}(D^{(*)0}(0)(\pm))$ and track reconstr.

$$\mathcal{B}(B^- \rightarrow D^{(*)} \pi^- \ell^- \bar{\nu}_\ell) = (1.52 \pm 0.12_{\text{stat.}} \pm 0.10_{\text{syst.}})\%$$
$$\mathcal{B}(B^0 \rightarrow D^{(*)} \pi^- \ell^- \bar{\nu}_\ell) = (1.37 \pm 0.17_{\text{stat.}} \pm 0.10_{\text{syst.}})\%,$$

Results consistent with isospin symmetry, but
$\Delta_{\text{excl-incl.}} = (1.2 \pm 0.4)\%$!
Observation of $B \to D^{(*)}\tau\nu$

- Large $\tau$ mass gives sensitivity to new physics at tree level. Eg charged Higgs boson.
- Very challenging: $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$ produce two additional neutrinos.
- Select Breco events. Identify $D^{(*)}$ plus lepton in the recoil.
- Maximum likelihood fit with:
  - two discriminating variables missing mass squared squared and lepton energy
  - 8 channels: 4 signal ($D^0\tau\nu$, $D^{*0}\tau\nu$, $D^+\tau\nu$, $D^{*+}\tau\nu$), 4 background $B \to D^{**}\ell\nu$.  

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$D(*)\tau\nu$ – fit results

Normalization region (low invariant mass squared)

Signal region (high invariant mass squared)

**BaBar** Preliminary

$D^0\ell$

$D^*0\ell$

$D^{*+}\ell$

$D^{*}\tau\nu$

$D\tau\nu$

$D^*\ell\nu$

$D\ell\nu$

$D^{**}\ell\nu$

Comb.
Observation of $B \rightarrow D^{(*)}\tau \bar{\nu}_\tau$

Confirmation of Belle observation in $D^{*+}$, first observation of $D^0$ and first evidence for the $D$ modes.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$R \ [%]$</th>
<th>$B \ [%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow D^{\tau-}\bar{\nu}_\tau$</td>
<td>41.6 ± 11.7 ± 5.2</td>
<td>0.86 ± 0.24 ± 0.11 ± 0.06</td>
</tr>
<tr>
<td>$B \rightarrow D^{*\tau-}\bar{\nu}_\tau$</td>
<td>29.7 ± 5.6 ± 1.8</td>
<td>1.62 ± 0.31 ± 0.10 ± 0.05</td>
</tr>
</tbody>
</table>

Main systematic errors from PDF parametrization, combinatoric background parametrization

$3.6 \sigma$

$6.2 \sigma$

Outline

Introduction
- Motivations
- BaBar
- Experimental approach

Inclusive decays
- Determination of $|V_{cb}|$
- Determination of $|V_{ub}|$

Exclusive Decays
- $D^{(*)}\ell\nu$
- $\pi(\eta')(\ell\nu)$

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

- $B \to \pi \ell \nu$ rate is given by
  \[ \frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2 \]

- Form factor $f_+(q^2)$ has been calculated using
  - Lattice QCD
    - Unquenched calculations by Fermilab (hep-lat/0409116) and HPQCD (PRD73:074502)
    - $\pm 12\%$ for $q^2 > 16 \text{ GeV}^2$
  - Light Cone Sum Rules
    - Ball & Zwicky (PRD71:014015)
    - $\pm 13\%$ for $q^2 < 16 \text{ GeV}^2$
Loose untagged $B \to \pi^+ \ell \nu$

- No Tag
- No *neutrino tight quality* cuts (increase signal efficiency)
- 12 $q^2$ bins
- Smallest statistical and systematic uncertainties of all individual published $B \to \pi \ell \nu$ measurements
- Larger systematic error due to fit

$$B(B \to \pi^+ \ell \nu) = (1.46 \pm 0.07_{\text{stat}} \pm 0.08_{\text{syst}}) \times 10^{-4}$$

→ ISGW2 incompatible (Prob<0.06%)
Tagged $B \to \pi^{0,+} \ell \nu$  

- Fully (hadronic) and semileptonic tags  
- Neutral and charged pion  
- 3 $q^2$ bins  
- Dominated by statistical error for the moment  
- Main syst errors: signal MC stat., signal PDF, photon and $\pi^0$ reconstruction.

$\phi_B$ is the angle between the directions of the two $B$ mesons.

Total $B$ comparable with untagged analysis  

$\mathcal{B}(B \to \pi^{\pm} \ell \nu) = (1.33 \pm 0.17_{\text{stat}} \pm 0.11_{\text{syst}}) \times 10^{-4}$
Exclusive $|V_{ub}|$: Summary

**HFAG branching fraction average:**

$B(B^0 \rightarrow \pi^+ \nu) \times 10^{-4}$

$B(B \rightarrow \pi^+ l \nu) = (1.39 \pm 0.06_{\text{stat}} \pm 0.06_{\text{syst}}) \times 10^{-4}$

**Dominant:**

- Small experimental errors
- Large theoretical error on FF
- Theory error needs to improve!
$|V_{ub}|$: CKM consistency

- Most probable value of $|V_{ub}|$ from measurements of other CKM parameters, Standard Model and from the exclusive final states favours a value $\sim 3.5 \times 10^{-3}$.

- Steady work in the inclusive decays to improve current calculations of $|V_{ub}|$.

- "Tension" with exclusive decays not there anymore for some calculations.

- Still work on the experimental and theoretical side needed to understand current results.

$V_{ub}$ values obtained with other methods have larger errors than $0.5 \times 10^{-3}$. 
Other Modes: $B \rightarrow \eta \ell \nu$ and $B \rightarrow \eta' \ell \nu$

Independent measurements of various $B \rightarrow X_u \ell \nu$ decay modes important to further constraint theoretical models

- Hadronic tag
- Reconstruction of signal $B$:
  - Lepton momentum $p^* > 0.5 \text{ GeV}$ for electrons $p^* > 0.8 \text{ GeV}$ for muons
  - Meson reconstructed in $\eta \rightarrow \pi^+ \pi^- \pi^0$
    $\eta \rightarrow \pi^0 \pi^0 \pi^0$
    $\eta' \rightarrow \rho \gamma$
    $\eta' \rightarrow \eta \pi^+ \pi^-$

- fit to $m_B$ distributions to extract signal yields

$\mathcal{B}(B^+ \rightarrow \eta \ell^+ \nu) < 1.4 \times 10^{-4} \ (90\% \ CL)$

$\mathcal{B}(B^+ \rightarrow \eta \ell^+ \nu) = (0.84 \pm 0.27_{\text{stat}} \pm 0.21_{\text{syst}}) \times 10^{-4}$

$\mathcal{B}(B^+ \rightarrow \eta' \ell^+ \nu) < 1.3 \times 10^{-4} \ (90\% \ CL)$

Need more data!
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Exclusive Decays
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- $\pi(\eta) \ell \nu$

Conclusions
Summary

- Very significant improvements of understanding semileptonic B decays in the past 5 years!
- Challenge of QCD corrections is being addressed.
- High order terms in OPE calculations are needed. Special treatment for $B \to X_s \gamma$ required.
- Experimentally, $B \to X_u \ell \nu$ measurements can be improved with higher statistics and reduced systematics.
- Exclusive measurements: needed improved normalization of FF by theory
- Current differences between exclusive and inclusive measurements may be of both theory and experimental nature.
- Tight scrutiny needed to arrive at a more stringent test of the CKM matrix in the future!
- First evidence of $B \to D \tau \nu$!