Semileptonic $B$ Decays
— $B$ Physics Beyond CP Violation —

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SLAC Experimental Seminar
26 September 2006
Outline

- Introduction: Why semileptonic $B$ decays?
- $|V_{ub}/V_{cb}|$ from inclusive semileptonic decays
  - Measurements: Branching fractions and kinematic spectra
  - Theoretical challenge: Shape Function
    - Determining the SF from data: $B \rightarrow X_c \ell \nu$, $B \rightarrow X_s \gamma$
    - Avoiding the Shape Function
- $|V_{ub}/V_{cb}|$ from exclusive semileptonic decays
  - Measurements: $\Gamma(B \rightarrow D^* \ell \nu)$, $\Gamma(B \rightarrow \pi \ell \nu)$
  - Theoretical challenge: Form Factors
    - Determining the shape of the FF from data
- Summary
Semileptonic $B$ Decays

- $B \to X\ell\nu$ decays were seen as soon as the $Y(4S)$ resonance was discovered

CLEO measured in 1981

- $\mathcal{B}(B \to Xe\nu) = (13 \pm 3 \pm 3)\%$
- $\mathcal{B}(B \to X\mu\nu) = (9.4 \pm 3.6)\%$

- Weakly decaying “new” quark would give $BF = 1/9$ for each lepton

CLEO PRL 46:84 (1981)
Fast Forward 25 Years

- $B$ Factories have accumulated over 1 billion $B\bar{B}$ events
- Original goal: Use CP violation in $B^0$ decays to test if the Cabibbo-Kobayashi-Maskawa model is “correct”

$CP$ violation measures the angles of the Unitarity Triangle
New goal: Use every information to test if the Cabibbo-Kobayashi-Maskawa model is “complete”

- We need both precision and redundancy

- How many things can we measure “precisely”? 
Redundancy and Precision

- **Angle** $\beta$ and the right-side measured to better than 5%.
  - Orthogonal constraints $\Rightarrow$ Anchor the $(\rho, \eta)$ apex

- **Next:** the left side over-constrains the Triangle
  - Uncertainty dominated by $|V_{ub}|$
  - Precision is improving — was $\pm 15\%$ in 2003

**Goal:** Measure $|V_{ub}|$ with <5% precision

<table>
<thead>
<tr>
<th></th>
<th>WA</th>
<th>Prec.</th>
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<tbody>
<tr>
<td>$</td>
<td>V_{td}/V_{ts}</td>
<td>$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$(21.7 \pm 1.0)^\circ$</td>
<td>4.7%</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}/V_{cb}</td>
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</table>
Semileptonic $B$ Decays

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

**Parton level**

- Decay rate $\Gamma_x \equiv \Gamma(b \to x\ell\nu) \propto |V_{xb}|^2$
- $|V_{ub}/V_{cb}| \approx 0.1 \rightarrow \Gamma_c$ 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 $|V_{ub}|, |V_{cb}|$
Inclusive vs. Exclusive

**Inclusive** $\bar{B} \to X_c \ell \nu$

\[ \bar{B} \rightarrow W^- \ell^- \]
\[ V_{cb} 
\]
\[ \bar{B} \rightarrow W^- \ell^- \]
\[ V_{cb} \]

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

\[ \bar{B} \rightarrow W^- \ell^- \]
\[ V_{cb} \]
\[ D^* \]

**Inclusive** $\bar{B} \to X_u \ell \nu$

\[ \bar{B} \rightarrow W^- \ell^- \]
\[ V_{ub} \]
\[ X_u \]

**Exclusive** $\bar{B} \to \pi \ell \nu$

\[ \bar{B} \rightarrow W^- \ell^- \]
\[ V_{ub} \]
\[ \pi \]
Inclusive Measurements

- **Operator Product Expansion** predicts the total rate $\Gamma_u$ as

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

- Perturbative terms known to $\mathcal{O}(\alpha_s^2)$
- Non-perturb. terms suppressed by $1/m_b^2$

- **Dominant error from** $m_b^5$
  - $m_b$ measured to $\pm 1\%$
    $$\Rightarrow \pm 2.5\% \text{ on } |V_{ub}|$$

- **Total rate can’t be measured** due to $B \rightarrow X_c \ell \nu$ background.
  - Must enhance $S/B$ with cuts
Kinematical Cuts

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

- Measure partial rates in favorable regions of the phase space

- Caveat: Spectra more sensitive to non-perturbative effects than the total rate $\mathcal{O}(1/m_b)$ instead of $\mathcal{O}(1/m_b^2)$

- Need to know the Shape Function (= what the $b$ quark is doing inside the $B$ meson)

- Solution: Determine the Shape Function from the data
Shape Function

- Two ways to determine the Shape Function from data:
  - Directly from the $E_\gamma$ spectrum of the $B \to X_s \gamma$ decay

Measurement limited by statistics and background
Two ways to determine the Shape Function from data:

- Indirectly from fitting the $B \rightarrow X_c\ell\nu$ and $B \rightarrow X_s\gamma$ decays

  - OPE predicts observables integrated over large phase space as functions of $m_b$, $m_c$, and non-perturbative parameters

- Global fit can determine the OPE parameters, which constrain the Shape Function
Inclusive $B \to X_c \ell \nu$

- Observables: $E_\ell$ (lepton energy) and $m_X$ (hadron mass)

<table>
<thead>
<tr>
<th></th>
<th>$\langle E_\ell^n \rangle$</th>
<th>$n$</th>
<th>$\langle m_X^n \rangle$</th>
<th>$n$</th>
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</thead>
<tbody>
<tr>
<td>$BABAR$</td>
<td>PRD 69:111103, 47 fb$^{-1}$</td>
<td>0, 1, 2, 3</td>
<td>PRD 69:111104, 81 fb$^{-1}$</td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td>Belle Prelim.</td>
<td>Belle-Conf-0667, 140 fb$^{-1}$</td>
<td>0, 1, 2, 3, 4</td>
<td>Belle-Conf-0668, 140 fb$^{-1}$</td>
<td>2, 4</td>
</tr>
</tbody>
</table>

Measure moments as functions of minimum-$E_\ell$ cut
Inclusive $B \rightarrow X_s \gamma$

- $E_\gamma$ spectrum in $B \rightarrow X_s \gamma$ decays connected directly to SF
- Small rate and high background makes it tough to measure

<table>
<thead>
<tr>
<th></th>
<th>$\langle E_\gamma^n \rangle$</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BABAR$</td>
<td>PRD 72:052004, 81 fb$^{-1}$</td>
<td>Sum of exclusive</td>
</tr>
<tr>
<td>$BABAR$</td>
<td>hep-ex/0607071, 81 fb$^{-1}$</td>
<td>Fully inclusive</td>
</tr>
<tr>
<td>Belle</td>
<td>PRL 93:061803, 140 fb$^{-1}$</td>
<td>Fully inclusive</td>
</tr>
</tbody>
</table>

Reconstruct exclusive $X_s$ decays and sum up
Measure inclusive photon spectrum

- Partial BF (10$^{-3}$/100 MeV)
- Events/100 (MeV)

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Global OPE Fit

- Buchmüller & Flächer (PRD73:073008) fit data from 10 measurements with an OPE calculation by Gambino & Uraltsev (EPJC34:181)

- Fit parameters: $|V_{cb}|, m_b, m_c, \mu_{\pi}^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, B(B \to X_c \ell \nu)$

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

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

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

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

- $|V_{cb}|$ error $\pm 2\%$, $m_b$ error $\pm 1\%$
- Consistency between $X_c \ell \nu$ and $X_s \gamma$ add confidence to the theory
Inclusive $B \rightarrow X_u \ell \nu$

- Measure partial BF $\Delta B(B \rightarrow X_u \ell \nu)$ 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

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

| Experiment  | $E_\ell$ (GeV) | $|V_{ub}|$ ($10^{-3}$) |
|-------------|----------------|------------------------|
| BABAR 80fb$^{-1}$ | 2.0–2.6 | $4.39 \pm 0.25_{\text{exp}} \pm 0.39_{\text{SF+theo}}$ |
| Belle 27fb$^{-1}$ | 1.9–2.6 | $4.82 \pm 0.45_{\text{exp}} \pm 0.30_{\text{SF+theo}}$ |
| CLEO 9fb$^{-1}$ | 2.2–2.6 | $4.09 \pm 0.48_{\text{exp}} \pm 0.36_{\text{SF+theo}}$ |

**Shape Function**

**Theory errors**
Hadronic $B$ Tag

- Fully reconstruct one $B$ in hadronic decays
- Recoiling $B$ with known charge and momentum
- Access to all kinematic variables

| Region | $|V_{ub}|$ ($10^{-3}$) |
|--------|----------------------|
| $m_X < 1.7$ GeV, $q^2 > 8$ GeV$^2$ | $4.70 \pm 0.37_{\text{exp}} \pm 0.31_{\text{SF+theo}}$ |
| $m_X < 1.7$ GeV | $4.06 \pm 0.27_{\text{exp}} \pm 0.24_{\text{SF+theo}}$ |
| $P_+ > 0.66$ GeV | $4.19 \pm 0.36_{\text{exp}} \pm 0.28_{\text{SF+theo}}$ |

Belle 253 fb$^{-1}$

| $m_X < 1.7$ GeV, $q^2 > 8$ GeV$^2$ | $4.75 \pm 0.35_{\text{exp}} \pm 0.32_{\text{SF+theo}}$ Prelim. |

BABAR 211 fb$^{-1}$
$|V_{ub}|$ from Inclusive $B \rightarrow X_u \ell \nu$

- CLEO (endpoint) $4.09 \pm 0.48 \pm 0.36$
- BELLE (endpoint) $4.82 \pm 0.45 \pm 0.30$
- BABAR (endpoint) $4.39 \pm 0.25 \pm 0.39$
- BABAR ($E_\ell$, $q^2$) $4.57 \pm 0.31 \pm 0.41$
- BELLE $m_X$ $4.06 \pm 0.27 \pm 0.24$
- BELLE sim. ann. ($m_X$, $q^2$) $4.37 \pm 0.46 \pm 0.29$
- BABAR ($m_X$, $q^2$) $4.75 \pm 0.35 \pm 0.32$

**World Average** $4.49 \pm 0.33$

$\chi^2$/dof = 6.1/6 (CL = 40.7%)

OPE-HQET-SCET (BLNP)


$m_b$ input from $b \rightarrow c \ell \nu$ and $b \rightarrow s \gamma$ moments

$|V_{ub}|$ determined to $\pm 7.3\%$

<table>
<thead>
<tr>
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<th>±2.2%</th>
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<tbody>
<tr>
<td>Statistical</td>
<td></td>
</tr>
<tr>
<td>Expt. syst.</td>
<td>±2.8%</td>
</tr>
<tr>
<td>$b \rightarrow c\ell\nu$ model</td>
<td>±1.9%</td>
</tr>
<tr>
<td>$b \rightarrow u\ell\nu$ model</td>
<td>±1.6%</td>
</tr>
<tr>
<td>SF params.</td>
<td>±4.2%</td>
</tr>
<tr>
<td>Theory</td>
<td>±4.2%</td>
</tr>
</tbody>
</table>

- Expt. and SF errors will improve with more data
- What’s the theory error?
Theory Errors

- **Subleading Shape Function** ⇒ ±3.8% error
  - Higher order non-perturbative corrections
  - Cannot be constrained with $b \to s \gamma$

- **Weak annihilation** ⇒ ±1.9% error
  - Measure $\Gamma(B^0 \to X_u \ell \nu)/\Gamma(B^+ \to X_u \ell \nu)$
    or $\Gamma(D^0 \to X\ell \nu)/\Gamma(D_s \to X\ell \nu)$ to constrain
  - Reduce the effect by rejecting the high-$q^2$ region

- **Quark-hadron duality** is believed to be negligible
  - $b \to c \ell \nu$ and $b \to s \gamma$ data fit well with the HQE predictions

- **Ultimate error on inclusive $|V_{ub}|$** may be ~5%
Avoiding the Shape Function

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

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

- Leibovich, Low, Rothstein, PLB 486:86
- Lange, Neubert, Paz, JHEP 0510:084, Lange, JHEP 0601:104

- No need to assume functional forms for the SF
- Need $b \rightarrow s\gamma$ spectrum in the $B$ rest frame
  - Only one measurement ($BABAR$ PRD 72:052004) available
  - Cannot take advantage of precise $b \rightarrow c\ell\nu$ data
- How well does this work? Only one way to find out…
SF-Free $|V_{ub}|$ Measurement

- $BABAR$ applied Leibovich-Low-Rothstein to 80 fb$^{-1}$ data
  - $\Delta \Gamma(B \to X_u \ell \nu)$ with varying $m_X$ cut
  - $d\Gamma(B \to X_s \gamma)/dE_{\gamma}$ from PRD 72:052004
- With $m_X < 1.67$ GeV
  
  \[ |V_{ub}| = (4.43 \pm 0.38 \pm 0.25 \pm 0.29) \times 10^{-3} \]

  - SF error $\rightarrow$ Statistical error

- Also measured $m_X < 2.5$ GeV
  - Almost (96%) fully inclusive $\rightarrow$ No SF necessary

  \[ |V_{ub}| = (3.84 \pm 0.70 \pm 0.30 \pm 0.10) \times 10^{-3} \]

- Attractive new approaches with increasing statistics
Inclusive vs. Exclusive

Inclusive $B \rightarrow X_c \ell \nu$

$\bar{B} \rightarrow W^- \ell^-$

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

$\bar{B} \rightarrow W^- \ell^- D^*$

Inclusive $B \rightarrow X_u \ell \nu$

$\bar{B} \rightarrow W^- \ell^-$

Exclusive $B \rightarrow \pi \ell \nu$

$\bar{B} \rightarrow W^- \ell^- \pi$
Exclusive Measurements

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

- Decay rate is
  \[ \frac{d\Gamma(B \to D^{*}\ell\nu)}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} \left| \mathcal{F}(w) \right|^2 \mathcal{G}(w) \]

- Form factor
- Phase space

- $\mathcal{F}(1) = 1$ in the heavy-quark limit
  - Quenched lattice QCD gives $\mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$ [Hashimoto et al, PRD 66:014503]

- $\mathcal{F}(w)$ shape expressed by $\rho^2$ (slope at $w = 1$) and $R_1, R_2$ (form factor ratios)
  - Analyticity constrains curvature [Caprini, Lellouch, Neubert, NPB 530:153]

- Measure decay angles $\theta_\ell, \theta_\nu, \chi$

- Fit 3-D distribution in bins of $w$ to extract $\rho^2, R_1, R_2$
**B → D*ℓν Measurements**

- **BABAR** measured |V<sub>cb</sub>| and FFs using \( D^{*+} \rightarrow D^{0}\pi^+ \)
- Two nearly-independent analyses on the same (79 fb<sup>-1</sup>) data

<table>
<thead>
<tr>
<th></th>
<th>hep-ex/0602023</th>
<th>hep-ex/0607076</th>
<th>Prelim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^0 ) decay modes</td>
<td>( K^-\pi^+ )</td>
<td>( K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+ )</td>
<td></td>
</tr>
<tr>
<td># of candidates</td>
<td>16,000</td>
<td>69,000</td>
<td></td>
</tr>
<tr>
<td>Purity</td>
<td>85%</td>
<td>77%</td>
<td></td>
</tr>
</tbody>
</table>

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**BABAR prelim.**

- Data
- Signal
- Combinatorial
- Other peaking
- \( D^{**} \)

**BABAR prelim.**

- \( D^{*}\ell\nu \)
- \( D^{*}X\ell\nu \)
- Fake lepton
- Uncorrelated \( D^{*}\ell \)
- Correlated \( D^{*}\ell \)
- Continuum
- Combinatoric

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B → D*ℓν Results

- Determine the FFs combining two measurements

\[ R_1 = 1.417 \pm 0.061 \pm 0.044 \]
\[ R_2 = 0.836 \pm 0.037 \pm 0.022 \]
\[ \rho^2 = 1.179 \pm 0.048 \pm 0.028 \]

- R₁ and R₂ improved by a factor 5 over previous CLEO measurement PRL 76:3898 (1996)

- Large impact on other measurements of B → D*ℓν

- Extrapolating the partial rate to \( w = 1 \), we find

\[ \mathcal{F}(1) |V_{cb}| = (34.68 \pm 0.32 \pm 1.15) \times 10^{-3} \]

\[ |V_{cb}| = (37.7 \pm 0.3 \pm 1.3) \times 10^{-3} \]

- We also measure the total rate

\[ \mathcal{B}(B^0 \rightarrow D^-\ell^+\nu) = (4.77 \pm 0.04 \pm 0.39)\% \]
$|V_{cb}|$ from $B \to D^* \ell \nu$

**BABAR** dominates the world average

- **ALEPH**
  - $32.6 \pm 2.0 \pm 1.3$
- **OPAL** (partial reco)
  - $37.8 \pm 1.2 \pm 2.3$
- **OPAL** (excl)
  - $37.9 \pm 1.6 \pm 1.6$
- **DELPHI** (partial reco)
  - $36.0 \pm 1.4 \pm 2.3$
- **BELLE**
  - $34.9 \pm 1.8 \pm 1.7$
- **CLEO**
  - $42.5 \pm 1.3 \pm 1.6$
- **BABAR**
  - $34.4 \pm 0.3 \pm 1.2$
- **DELPHI** (exclu)
  - $37.6 \pm 1.7 \pm 1.9$

**Average** $36.2 \pm 0.8$

$\chi^2$/dof = 38.7/14

$|V_{cb}| = (39.4 \pm 0.9 \, \text{exp} -1.2 \, F(1)) \times 10^{-3}$

c.f. $(42.0 \pm 0.7) \times 10^{-3}$ from inclusive OPE fit
Exclusive $B \rightarrow \pi \ell \nu$

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

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

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

- Form factor 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 $q^2 < 16\text{ GeV}^2$
Measuring $B \rightarrow \pi \ell \nu$

Measurements differ in what you do with the “other” $B$

<table>
<thead>
<tr>
<th>Technique</th>
<th>Efficiency</th>
<th>Purity</th>
</tr>
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<tbody>
<tr>
<td>Untagged</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Tagged by $B \rightarrow D(*)\ell \nu$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tagged by $B \rightarrow$ hadrons</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Total BF is

$$(1.37 \pm 0.06_{\text{stat}} \pm 0.06_{\text{syst}}) \times 10^{-4}$$

±6.2% precision
Untagged $B \rightarrow \pi \ell \nu$

- Missing 4-momentum $= \rho_\nu \rightarrow$ Reconstruct $B \rightarrow \pi \ell \nu$
  - Calculate $m_B$ and $\Delta E$, and perform 2-D fit for signal yields
- $BABAR$'s new result ($206 \text{ fb}^{-1}$, preliminary) uses 12 $q^2$ bins

$\Delta E = E_B - \sqrt{s}/2$ (GeV)

- High signal efficiency: 6.5 to 10%
- Total BF: $\mathcal{B}(B \rightarrow \pi \ell \nu) = (1.44 \pm 0.08_{\text{stat}} \pm 0.10_{\text{syst}}) \times 10^{-4}$
  - Best single measurement to date

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Untagged \( B \to \pi \ell \nu \)

**Measured \( q^2 \) spectrum constrains the FF shape**

<table>
<thead>
<tr>
<th>Form Factor</th>
<th>( \chi^2 )</th>
<th>Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball-Zwicky</td>
<td>13.0</td>
<td>37.2%</td>
</tr>
<tr>
<td>HPQCD</td>
<td>10.2</td>
<td>60.2%</td>
</tr>
<tr>
<td>FNAL</td>
<td>12.5</td>
<td>41.0%</td>
</tr>
<tr>
<td>ISGW2</td>
<td>34.1</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Becirevic-Kaidalov parameterization

\[
f_+(q^2) = \frac{1}{\left(1 - q^2/m_{B^*}^2\right)\left(1 - \alpha q^2/m_{B^*}^2\right)}
\]

\( \alpha = 0.53 \pm 0.05_{\text{stat}} \pm 0.04_{\text{syst}} \)
**$D^{(*)}\ell\nu$-tagged $B \rightarrow \pi \ell\nu$**

- Tag one $B$ in $D^{(*)}\ell\nu$ and look for $B \rightarrow \pi \ell\nu$ in the recoil
  - **Pro:** $B \rightarrow D^*\ell\nu$ BF large
  - **Con:** Two neutrinos in the event
- Event kinematics determined assuming known $m_B$ and $m_\nu$

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**Pro:** $B \rightarrow D^*\ell\nu$ BF large

**Con:** Two neutrinos in the event

---

**Event kinematics determined assuming known $m_B$ and $m_\nu$**

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**BABAR**

- **Signal**
- **Background**

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**Belle**

- **Signal**
- **Background**

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<table>
<thead>
<tr>
<th>Mode</th>
<th>BF (10^-4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^-\ell\nu$</td>
<td>$1.12 \pm 0.27$</td>
</tr>
<tr>
<td>$\pi^0\ell\nu$</td>
<td>$0.73 \pm 0.21$</td>
</tr>
<tr>
<td>$\pi^-\ell\nu$</td>
<td>$1.38 \pm 0.24$</td>
</tr>
<tr>
<td>$\pi^0\ell\nu$</td>
<td>$0.77 \pm 0.16$</td>
</tr>
</tbody>
</table>
Hadronic-tagged $B \rightarrow \pi \ell \nu$

- Hadronic tags have high purity, but low efficiency
  - Event kinematics is known by a 2-C fit
  - Use $m_B$ and $m_{\text{miss}}$ distributions to extract the signal yield

<table>
<thead>
<tr>
<th>Mode</th>
<th>BF ($10^{-4}$)</th>
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</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \pi^- \ell^+ \nu$</td>
<td>1.07 ± 0.33</td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^0 \ell^+ \nu$</td>
<td>0.82 ± 0.25</td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^- \ell^+ \nu$</td>
<td>1.49 ± 0.27</td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^0 \ell^+ \nu$</td>
<td>0.86 ± 0.18</td>
</tr>
</tbody>
</table>

Belle

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

- Average BF measurements and apply FF calculations

<table>
<thead>
<tr>
<th>$\Delta B(q^2 &lt; 16)$ $(10^{-4})$</th>
<th>$\Delta B(q^2 &gt; 16)$ $(10^{-4})$</th>
<th>Total $B$ $(10^{-4})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.95 \pm 0.05_{\text{stat}} \pm 0.05_{\text{syst}}$</td>
<td>$0.35 \pm 0.03_{\text{stat}} \pm 0.03_{\text{syst}}$</td>
<td>$1.37 \pm 0.06_{\text{stat}} \pm 0.06_{\text{syst}}$</td>
</tr>
</tbody>
</table>

| Form Factor | $q^2$ (GeV$^2$) | $|V_{ub}|$ $(10^{-3})$ |
|------------|----------------|-----------------|
| Ball-Zwicky | $< 16$ | $3.38 \pm 0.12_{\text{exp}}^{+0.56}_{-0.37_{\text{theo}}}$ |
| HPQCD      | $> 16$ | $3.93 \pm 0.26_{\text{exp}}^{+0.59}_{-0.41_{\text{theo}}}$ |
| FNAL       | $> 16$ | $3.51 \pm 0.23_{\text{exp}}^{+0.61}_{-0.40_{\text{theo}}}$ |

- Errors dominated by the FF normalizations

Inclusive: $4.49 \pm 0.19_{\text{exp}}^{+0.27}_{-\text{SF+theo}}$

LCSR

Unquenched LQCD

HFAG

M. Morii, Harvard
Form Factor Tests

- Measured $q^2$ dependence of $B \to \pi\ell\nu$ can constrain input parameters to LCSR
  - Ball, Zwicky PLB 625:225
- Ultimate test: $D \to \pi\ell\nu, Kl\nu$
  - We know $|V_{cd}|$ and $|V_{cs}| \rightarrow$ Measure the FF
- Preliminary measurements are coming out

<table>
<thead>
<tr>
<th></th>
<th>$m_{\text{pole}}(D \to \pi)$ [GeV]</th>
<th>$m_{\text{pole}}(D \to K)$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BABAR 75 fb$^{-1}$</strong></td>
<td>In progress</td>
<td>$1.85 \pm 0.02_{\text{stat}} \pm 0.02_{\text{syst}}$</td>
</tr>
<tr>
<td><strong>Belle 282 fb$^{-1}$</strong></td>
<td>$1.97 \pm 0.08_{\text{stat}} \pm 0.04_{\text{syst}}$</td>
<td>$1.82 \pm 0.04_{\text{stat}} \pm 0.03_{\text{syst}}$</td>
</tr>
<tr>
<td><strong>CLEO-c 281 pb$^{-1}$</strong> at $\psi(3770)$</td>
<td>$1.95 \pm 0.04_{\text{stat}} \pm 0.02_{\text{syst}}$</td>
<td>$1.96 \pm 0.03_{\text{stat}} \pm 0.01_{\text{syst}}$</td>
</tr>
<tr>
<td><strong>Lattice QCD</strong></td>
<td>$1.99 \pm 0.04$</td>
<td>$1.72 \pm 0.05$</td>
</tr>
</tbody>
</table>

Aubin et al., PRL 94:011601

BABAR Prelim.
How Things Mesh Together

$\mathbf{b \rightarrow s \gamma}$

$E_\gamma$

Shape Function

OPE Fit

$\mathbf{m_b}$

Inclusive $\mathbf{b \rightarrow u \ell \nu}$

$E_\ell$

$q^2$

$m_\chi$

ExCLUSIVE $\mathbf{b \rightarrow c \ell \nu}$

$E_\ell$

$m_\chi$

Inclusive $\mathbf{b \rightarrow u \ell \nu}$

$E_\ell$

$q^2$

$m_\chi$

$\mathbf{|V_{ub}|}$

Exclusive $\mathbf{D \rightarrow \pi \ell \nu, K \ell \nu}$

Form Factor

LQCD

LCSR

Exclusive $\mathbf{B \rightarrow \pi \ell \nu}$
Where We Stand Now

- Marginal consistency across different determination methods
  - Inclusive measurements prefer higher values than exclusive measurements and fits to the Triangle
- What gives?
  - Unknown theory error in inclusive $B \rightarrow X_u \ell \nu$?
  - Form factor in $B \rightarrow \pi \ell \nu$?
  - Something more exciting?
**Things to Come**

- **BABAR** has analysed only a fraction of its data

- 390 fb\(^{-1}\) recorded. Expect \(\sim 1000\) fb\(^{-1}\) by the end of 2008

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Published?</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive (X_\ell\ell\nu)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(E_\ell) spectrum</td>
<td>PRD (2004)</td>
<td>47 fb(^{-1})</td>
</tr>
<tr>
<td>(m_X) spectrum</td>
<td>PRD (2004)</td>
<td>81 fb(^{-1})</td>
</tr>
<tr>
<td>Inclusive (X_u\ell\nu)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(E_\ell) endpoint</td>
<td>PRD (2006)</td>
<td>81 fb(^{-1})</td>
</tr>
<tr>
<td>(E_\ell) vs (q^2)</td>
<td>PRL (2005+2006)</td>
<td>81 fb(^{-1})</td>
</tr>
<tr>
<td>Hadronic tag</td>
<td>Preliminary</td>
<td>211 fb(^{-1})</td>
</tr>
<tr>
<td>Exclusive (D^*\ell\nu)</td>
<td>Submitted to PRD</td>
<td>79 fb(^{-1})</td>
</tr>
<tr>
<td>Untagged</td>
<td>Preliminary</td>
<td>206 fb(^{-1})</td>
</tr>
<tr>
<td>Tagged</td>
<td>Submitted to PRL</td>
<td>211 fb(^{-1})</td>
</tr>
</tbody>
</table>

Expect large gains with additional statistics.
Summary

- **Semileptonic B decays** continue to offer exciting physics opportunities
  - Determination of $|V_{ub}/V_{cb}|$ complements $\sin^2\beta \cap |V_{td}/V_{ts}|$ to test the (in)completeness of the Standard Model
- **Challenge of hadronic physics** is met by close collaboration between theory and experiment
  - Inclusive $B \to X_c \ell \nu$ & $X_s \gamma$ precisely determines $|V_{cb}|$, $m_b$, etc.
  - Inclusive $B \to X_u \ell \nu$ achieved $\pm 7.3\%$ accuracy on $|V_{ub}|$
    - Room for improvements with additional data statistics
  - **Exclusive $B \to \pi \ell \nu$ measurements** becoming precise
    - Improved form factor calculation needed
Future Experiments

Future $B$-physics programs will pursue New Physics through CP violation and rare decays

- e.g. $b \rightarrow s\bar{s}s$, $b \rightarrow s\gamma$, $b \rightarrow s\ell^+\ell^-$, $B \rightarrow \tau\nu$, $B \rightarrow D\tau\nu$, $B_s \rightarrow \mu^+\mu^-$
- $|V_{ub}/V_{cb}|$ provides a crucial New-Physics-free constraint

Will they improve $|V_{ub}|$ to $<< 5\%$?

- A Super $B$ Factory can produce high-statistics, high-purity, hadronic-tag sample to measure $b \rightarrow u\ell\nu$
- LHCb’s primary strength lies in $B_s$ physics

NB: the real challenge lies in theory

- Precision data can inspire and validate theoretical advances
- Lattice QCD holds the key
  - We need to see inclusive and exclusive $|V_{ub}|$ converge!