$B$ Physics Beyond $CP$ Violation

— Semileptonic $B$ Decays —

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University of Illinois Urbana-Champaign HETEP Seminar
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Outline

- Introduction: Why semileptonic $B$ decays?
  - CKM matrix — Unitarity Triangle — $CP$ violation
  - $|V_{ub}|$ vs. $\sin 2\beta$
- $|V_{ub}|$ from inclusive $b \to u\ell\nu$ decays
  - Measurements: lepton energy, hadron mass, lepton-neutrino mass
  - Theoretical challenge: Shape Function
  - Latest from $BABAR$ – Avoiding the Shape Function
- $|V_{ub}|$ from exclusive $b \to u\ell\nu$ decays
  - Measurements: $\Gamma(B \to \pi\ell\nu)$
  - Theoretical challenge: Form Factors
- Summary
Mass and the Generations

- Fermions come in three generations
  - They differ only by the masses
  - The Standard Model has no explanation for the mass spectrum
- The masses come from the interaction with the Higgs field
  - ... whose nature is unknown
  - We are looking for the Higgs particle at the Tevatron, and at the LHC in the future

The origin of mass is one of the most urgent questions in particle physics today
If there were no masses

- Nothing would distinguish $u$ from $c$ from $t$
  - We could make a mixture of the wavefunctions and pretend it represents a physical particle

\[
\begin{align*}
  u & \quad u \\
  c & \quad = M \quad c \\
  t & \quad t \\
  d & \quad d \\
  s & \quad = N \quad s \\
  b & \quad b
\end{align*}
\]

$M$ and $N$ are arbitrary $3 \times 3$ unitary matrices

- Suppose $W^{\pm}$ connects $u' \leftrightarrow d'$, $c' \leftrightarrow s'$, $t' \leftrightarrow b'$

\[
\begin{align*}
  u & \quad u \\
  c & \quad = M^{-1} \quad c \\
  t & \quad t \\
  d & \quad d \\
  s & \quad = M^{-1} N \quad s \\
  b & \quad b
\end{align*}
\]

Weak interactions between $u$, $c$, $t$, and $d$, $s$, $b$ are “mixed” by matrix $V$

- That’s a poor choice of basis vectors
Turn the masses back on

Masses uniquely define the $u, c, t, d, s, b$ states

- We don’t know what creates masses
  - We don’t know how the eigenstates are chosen
  - $M$ and $N$ are arbitrary

- $V$ is an arbitrary $3 \times 3$ unitary matrix

$$
\begin{array}{cccc}
  u & W^\pm & d & V_{ud} & V_{us} & V_{ub} \\
  c & V & s & V_{cd} & V_{cs} & V_{cb} \\
  t & b & V_{td} & V_{ts} & V_{tb} & d & s & b
\end{array}
$$

**Cabibbo-Kobayashi-Maskawa matrix**

or **CKM** for short

- The Standard Model does not predict $V$
  - ... for the same reason it does not predict the particle masses
Structure of the CKM matrix

- The CKM matrix looks like this ➔
  - It’s not completely diagonal
  - Off-diagonal components are small
    - Transition across generations is allowed but suppressed
- The “hierarchy” can be best expressed in the Wolfenstein parameterization:

\[
V = \begin{pmatrix}
0.974 & 0.226 & 0.004 \\
0.226 & 0.973 & 0.042 \\
0.008 & 0.042 & 0.999
\end{pmatrix}
\]

- One irreducible complex phase ➔ CP violation
  - The only source of CP violation in the minimal Standard Model
The CKM mechanism fails to explain the *amount* of matter-antimatter imbalance in the Universe
- ... by several orders of magnitude

New Physics beyond the SM is expected at 1-10 TeV scale
- e.g. to keep the Higgs mass < 1 TeV/c²
- Almost all theories of New Physics introduce new sources of *CP* violation (e.g. 43 of them in supersymmetry)

New sources of *CP* violation almost certainly exist
- Precision studies of the CKM matrix may uncover them
The Unitarity Triangle

- \( V^\dagger V = 1 \) gives us
  
  \[
  V_{ud}V_{us} + V_{cd}V_{cs} + V_{td}V_{ts} = 0
  \]
  
  \[
  V_{ud}V_{ub} V_{cd}V_{cb} + V_{td}V_{tb} V_{cd}V_{cb} = 0
  \]
  
  \[
  V_{us}V_{ub} V_{cs}V_{cb} + V_{ts}V_{tb} V_{cs}V_{cb} = 0
  \]

A triangle on the complex plane

- Measurements of angles and sides constrain the apex \((\rho, \eta)\)

This one has the 3 terms in the same order of magnitude

\[
= \arg \left( \frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right)
\]

\[
= \arg \left( \frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right)
\]

\[
= \arg \left( \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)
\]
Consistency Test

- Compare the measurements (contours) on the $(\rho, \eta)$ plane
  - If the SM is the whole story, they must all overlap
  - The tells us this is true as of summer 2004
    - 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: $|V_{ub}|$

- 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
  $$\frac{|V_{ud}V_{ub}|}{|V_{cd}V_{cb}|}$$
  - Uncertainty dominated by $\pm 15\%$ on $|V_{ub}|$

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

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

- Best probe: semileptonic $b \rightarrow u$ decay

- The problem: $b \rightarrow c \ell v$ decay

$$\frac{(b \quad ul \quad \bar{\nu})}{(b \quad cl \quad \bar{\nu})} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \frac{1}{50}$$

- How can we suppress $50 \times$ larger background?
Detecting $b \rightarrow u \ell \nu$

**Inclusive:** Use $m_u << m_c \rightarrow$ difference in kinematics
- Maximum lepton energy 2.64 vs. 2.31 GeV
- First observations (CLEO, ARGUS, 1990) used this technique
- Only 6% of signal accessible
  - How accurately do we know this fraction?

**Exclusive:** Reconstruct final-state hadrons
- $B \rightarrow \pi \ell \nu, B \rightarrow \rho \ell \nu, B \rightarrow \omega \ell \nu, B \rightarrow \eta \ell \nu, \ldots$
- Example: the rate for $B \rightarrow \pi \ell \nu$ is

$$
\frac{d}{dq^2} \frac{B}{\ell} = \frac{G_F^2}{24} \left| V_{ub} \right|^2 \frac{F_{+}(q^2)}{p^3}.
$$

- How accurately do we know the FFs?
Inclusive $b \rightarrow u\ell\nu$

- There are 3 independent variables in $B \rightarrow X\ell\nu$

  - $E_\ell = \text{lepton energy}$
  - $q^2 = \text{lepton-neutrino mass squared}$
  - $m_X = \text{hadron system mass}$

- Signal events have smaller $m_X \rightarrow \text{Larger } E_\ell$ and $q^2$

Not to scale!
Lepton Endpoint

- Select electrons in $2.0 < E_\ell < 2.6$ GeV
  - Push below the charm threshold
    - Larger signal acceptance
    - Smaller theoretical error
- Accurate subtraction of background is crucial!
- Measure the partial BF

<table>
<thead>
<tr>
<th></th>
<th>$E_\ell$ (GeV)</th>
<th>$\Delta B$ ($10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BABAR\ 80fb^{-1}$</td>
<td>2.0–2.6</td>
<td>$5.72 \pm 0.41_{\text{stat}} \pm 0.65_{\text{sys}}$</td>
</tr>
<tr>
<td>Belle $27fb^{-1}$</td>
<td>1.9–2.6</td>
<td>$8.47 \pm 0.37_{\text{stat}} \pm 1.53_{\text{sys}}$ (cf. Total BF is $\sim 2 \times 10^{-3}$)</td>
</tr>
<tr>
<td>CLEO $9fb^{-1}$</td>
<td>2.2–2.6</td>
<td>$2.30 \pm 0.15_{\text{stat}} \pm 0.35_{\text{sys}}$</td>
</tr>
</tbody>
</table>
Use $p_\nu = p_{\text{miss}}$ in addition to $p_e \rightarrow$ Calculate $q^2$

- Define $s_h^{\text{max}}$ = the maximum $m_X$ squared
  - Cutting at $s_h^{\text{max}} < m_D^2$ removes $b \rightarrow c\ell\nu$ while keeping most of the signal

- $S/B = 1/2$ achieved for $E_\ell > 2.0$ GeV and $s_h^{\text{max}} < 3.5$ GeV
  - cf. ~1/15 for the endpoint $E_\ell > 2.0$ GeV

- Measured partial BF

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<tr>
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<td>$3.54 \pm 0.33^{\text{stat}} \pm 0.34^{\text{sys}}$</td>
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Small systematic errors

$E_\ell$ vs. $q^2$

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Measuring $m_X$ and $q^2$

- Must reconstruct all decay products to measure $m_X$ or $q^2$
- Select events with a **fully-reconstructed** $B$ meson
  - Rest of the event contains one “recoil” $B$
    - Flavor and momentum known
- Find a lepton in the **recoil** $B$
  - Neutrino = missing momentum
    - Make sure $m_{\text{miss}} \sim 0$
- All left-over particles belong to $X$
  - We can now calculate $m_X$ and $q^2$
- Suppress $b \to c \ell \nu$ by vetoing against $D^{(*)}$ decays
  - Reject events with $K$
  - Reject events with $B^0 \to D^{*+} (\to D^0 \pi^+) \ell^- \nu$
Measuring Partial BF

- Measure the partial BF in regions of \((m_X, q^2)\)

For example: 
\(m_X < 1.7\) GeV and \(q^2 > 8\) GeV^2

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<tr>
<th>Phase Space</th>
<th>(\Delta B) ((10^{-4}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BABAR</strong> 211fb(^{-1})</td>
<td>(m_X &lt; 1.7, q^2 &gt; 8)</td>
</tr>
<tr>
<td>(m_X &lt; 1.7)</td>
<td></td>
</tr>
<tr>
<td><strong>Belle</strong> 253fb(^{-1})</td>
<td>(m_X &lt; 1.7, q^2 &gt; 8)</td>
</tr>
</tbody>
</table>

Large \(\Delta B\) thanks to the high efficiency of the \(m_X\) cut
Theoretical Issues

- Tree level rate must be corrected for QCD
- Operator Product Expansion gives us the inclusive rate
  - Expansion in $\alpha_s(m_b)$ (perturbative) and $1/m_b$ (non-perturbative)
  
  \[
  (B \to X_u) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192} \left( 1 + \frac{9}{2m_b^2} + L \right)
  \]
  - known to $O(\alpha_s^2)$
  - Suppressed by $1/m_b^2$

- Main uncertainty ($\pm 5\%$) from $m_b^5 \to \pm 2.5\%$ on $|V_{ub}|$
- But we need the accessible fraction (e.g., $E_\ell > 2$ GeV) of the rate

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Shape Function

- OPE doesn’t work everywhere in the phase space
  - OK once integrated
  - Doesn’t converge, e.g., near the $E_\ell$ end point
- Resumming turns non-perturb. terms into a Shape Function
  - $\approx b$ quark Fermi motion parallel to the $u$ quark velocity
  - Cannot be calculated by theory
  - Leading term is $O(1/m_b)$ instead of $O(1/m_b^2)$

We must determine the Shape Function from experimental data
$b \rightarrow s\gamma$ Decays

- **Measure**: Same SF affects (to the first order) $b \rightarrow s\gamma$ decays

  - Measure $E_\gamma$ spectrum in $b \rightarrow s\gamma$
  - Extract $f(k_+)$
  - Predict partial BFs in $b \rightarrow u\ell\nu$

**Inclusive** measurement. Photon energy in the Y(4S) rest frame

**Exclusive** $X_s + \gamma$ measurement. Photon energy determined from the $X_s$ mass

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*BABAR PRD 72:052004, hep-ex/0507001*

*Belle hep-ex/0407052*

*CLEO hep-ex/0402009*
Predicting $b \rightarrow u\ell\nu$ Spectra

- Fit the $b \rightarrow s\gamma$ spectrum to extract the SF
  - Must assume functional forms, e.g. $f(k_+) = N(1 - x)^a e^{(1+a)x}; \quad x = k_+ / \bar{m}_{b}$

- Additional information from $b \rightarrow c\ell\nu$ decays
  - $E_\ell$ and $m_X$ moments $\Rightarrow$ $b$-quark mass and kinetic energy
    $$m_b = (4.60 \pm 0.04) \text{ GeV, } \quad m_b^2 = (0.20 \pm 0.04) \text{ GeV}^2$$
    - NB: $m_b$ is determined to better than 1%

  $\Rightarrow$ First two moments of the SF

- Plug in the SF into the $b \rightarrow u\ell\nu$ spectrum calculations
  - Bosch, Lange, Neubert, Paz, NPB 699:335
  - Lange, Neubert, Paz, PRD 72:073006

- Ready to extract $|V_{ub}|$

Buchmüller & Flächer
hep-ph/0507253

Lepton-energy spectrum by BLNP
# Turning $\Delta B$ into $|V_{ub}|$

- Using BLNP + the SF parameters from $b \rightarrow s\gamma$, $b \rightarrow c\ell\nu$

| Phase Space | $|V_{ub}|$ (10^{-3}) | Reference |
|-------------|---------------------|-----------|
| **BABAR 80fb^{-1}** | $E_\ell > 2.0$ | $4.41 \pm 0.29^{\text{exp}} \pm 0.31_{\text{SF,theo}}$ | PRD 73:012006 |
| **Belle 27fb^{-1}** | $E_\ell > 1.9$ | $4.82 \pm 0.45^{\text{exp}} \pm 0.30_{\text{SF,theo}}$ | PLB 621:28 |
| **CLEO 9fb^{-1}** | $E_\ell > 2.2$ | $4.09 \pm 0.48^{\text{exp}} \pm 0.36_{\text{SF,theo}}$ | PRL 88:231803 |
| **BABAR 80fb^{-1}** | $E_\ell > 2.0$, $s_h^{\text{max}} < 3.5$ | $4.10 \pm 0.27^{\text{exp}} \pm 0.36_{\text{SF,theo}}$ | PRL 95:111801 |
| **BABAR Adjusted to $m_{X}\leq (1.7, q^2 \geq 8.04)$** | $4.75 \pm 0.35^{\text{exp}} \pm 0.32_{\text{SF,theo}}$ | hep-ex/0507017 |
| **Theory errors from Lange, Neubert** | | |
| **Last Belle result** | | |
| **Belle 253fb^{-1}** | $m_X < 1.7$, $q^2 > 8\text{ GeV}^2$ | $4.06 \pm 0.27^{\text{exp}} \pm 0.24_{\text{SF,theo}}$ | PRL 95:241801 |
| **Belle 87fb^{-1}** | $m_X < 1.7$, $q^2 > 8\text{ GeV}^2$ | $4.37 \pm 0.46^{\text{exp}}$ | PRL 92:101802 |
Inclusive $|V_{ub}|$ as of 2005

$|V_{ub}|$ world average, Winter 2006

- |$V_{ub}$| determined to ±7.4%

| $|V_{ub}|$ determined to ±7.4% |
|-----------------|------|
| Statistical     | ±2.2%|
| Expt. syst.     | ±2.7%|
| $b \to c\ell\nu$ model | ±1.9%|
| $b \to u\ell\nu$ model | ±2.1%|
| SF params.      | ±4.1%|
| Theory          | ±4.2%|

- The SF parameters can be improved with $b \to s\gamma$, $b \to c\ell\nu$ measurements
- What’s the theory error?

CLEO (endpoint)  
4.09 ± 0.48 ± 0.36

BELLE (endpoint)  
4.82 ± 0.45 ± 0.30

BABAR (endpoint)  
4.41 ± 0.29 ± 0.31

BABAR ($E_e$, $q^2$)  
4.10 ± 0.27 ± 0.36

BELLE $m_X$  
4.06 ± 0.27 ± 0.24

BELLE sim. ann. ($m_X$, $q^2$)  
4.37 ± 0.46 ± 0.29

BABAR ($m_{X^*}$, $q^2$)  
4.75 ± 0.35 ± 0.32

Average +/- exp +/- (mb, theory)  
4.45 ± 0.20 ± 0.26

$\chi^2$/dof = 5.5/6 (CL = 48.7)

OPE-HQET-SCET (BLNP)

$|V_{ub}|$ [× 10$^{-3}$]

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Theory Errors

- **Subleading Shape Function** $\Rightarrow \pm 3.8\%$ error
  - Higher order non-perturbative corrections
  - Cannot be constrained with $b \rightarrow s\gamma$

- **Weak annihilation** $\Rightarrow \pm 1.9\%$ error
  - Measure $\Gamma(B^0 \rightarrow X_u\ell\nu)/\Gamma(B^+ \rightarrow X_u\ell\nu)$ or $\Gamma(D^0 \rightarrow X\ell\nu)/\Gamma(D_s \rightarrow X\ell\nu)$ to improve the constraint
  - Also: study $q^2$ spectrum near endpoint (CLEO hep-ex/0601027)
  - Reduce the effect by rejecting the high-$q^2$ region

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

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

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

\[
(B \mid X_u) = \frac{|V_{ub}|^2}{|V_{ts}|^2} \cdot W(E) \cdot \frac{d}{dE} \left( B \frac{X_s}{dE} \right) dE
\]

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

- No need to assume functional forms for the Shape Function
- Need $b \to s\gamma$ spectrum in the $B$ rest frame
  - Only one measurement ($B_{ABAR}$ PRD 72:052004) available
  - Cannot take advantage of precise $b \to c\ell\nu$ data

- How well does this work? Only one way to find out…
SF-Free $|V_{ub}|$ Measurement

- $BABAR$ applied LLR (PLB 486:86) to 80 fb$^{-1}$ data
  - $\Gamma(B \to X_u \ell\nu)$ with varying $m_X$ cut
  - $d\Gamma(B \to X_s \gamma)/dE_\gamma$ from PRD 72:052004

- With $m_X < 1.67$ GeV
  $$|V_{ub}| = (4.43 \pm 0.38 \pm 0.25 \pm 0.29) \cdot 10^3$$
  - SF error $\Rightarrow$ Statistical error

- Also measured $m_X < 2.5$ GeV
  - Almost (96%) fully inclusive $\Rightarrow$ No SF necessary
  $$|V_{ub}| = (3.84 \pm 0.70 \pm 0.30 \pm 0.10) \cdot 10^3$$
  - Theory error $\pm 2.6$

- Attractive new approaches with increasing statistics
Exclusive $B \to \pi \ell \nu$

- Measure specific final states, e.g., $B \to \pi \ell \nu$
  - Can achieve good signal-to-background ratio
  - Branching fractions in $O(10^{-4}) \Rightarrow$ Statistics limited

- Need Form Factors to extract $|V_{ub}|$

\[
\frac{d}{dq^2} \frac{d}{d(1/|V_{ub}|^2)} = \frac{G_F^2}{24} |V_{ub}|^2 \quad \text{with massless lepton}
\]

- $f_+(q^2)$ has been calculated using
  - Lattice QCD ($q^2 > 15 \text{ GeV}^2$)
    - Existing calculations are “quenched” $\Rightarrow$ $\sim 15\%$ uncertainty
  - Light Cone Sum Rules ($q^2 < 14 \text{ GeV}^2$)
    - Assumes local quark-hadron duality $\Rightarrow$ $\sim 10\%$ uncertainty
  - ... and other approaches
Form Factor Calculations

- **Unquenched LQCD** calculations started to appear in 2004

  - Fermilab (hep-lat/0409116) and HPQCD (hep-lat/0601021)
  - Uncertainties are ~11%

- Measure $d\Gamma(B \to \pi \ell v)/dq^2$ as a function of $q^2$
  - Compare with different calculations

*Ball-Zwicky PRD71:014015*
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>
</thead>
<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

$(1.35 \pm 0.08_{\text{stat}} \pm 0.08_{\text{syst}}) \cdot 10^{-4}$

±8.4% precision
Untagged $B \rightarrow \pi \ell \nu$

- Missing 4-momentum = neutrino
- Reconstruct $B \rightarrow \pi \ell \nu$ and calculate $m_B$ and $\Delta E = E_B - E_{\text{beam}}/2$

![BABAR data](image1)

- MC signal
- Signal with wrong $\pi$
- $b \rightarrow u \ell \nu$
- $b \rightarrow c \ell \nu$
- Other bkg.
$D^{(*)}\ell\nu$-tagged $B \to \pi\ell\nu$

- Reconstruct one $B$ and look for $B \to \pi\ell\nu$ in the recoil
  - Tag with either $B \to D^{(*)}\ell\nu$ or $B \to$ hadrons
- Semileptonic ($B \to D^{(*)}\ell\nu$) tags are efficient but less pure
  - Two neutrinos in the event
- Event kinematics determined assuming known $m_B$ and $m_{\nu}$

![Graphs showing distribution of $q^2$ for different $B$ decay channels]

- $\cos^2\phi_B \leq 1$ for signal
  - data
  - MC signal
  - MC background

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Hadronic-tagged $B \to \pi \ell \nu$

- 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

![Graphs showing $B^0$ and $B^0$ distributions with BABAR preliminary data.](image)

- data
- MC signal
- $b \to u \ell \nu$
- $b \to c \ell \nu$
- other bkg.
\[ dB(B \rightarrow \pi \ell \nu)/dq^2 \]

- Measurements start to constrain the \( q^2 \) dependence
- ISGW2 rejected
- Partial BF measured to be

\[
\begin{array}{|c|c|}
\hline
q^2 \text{ range} & \Delta B [10^{-4}] \\
\hline
< 16 \text{ GeV}^2 & 0.94 \pm 0.06 \pm 0.06 \\
> 16 \text{ GeV}^2 & \pm 0.04 \pm 0.04 \\
\hline
\end{array}
\]

Errors on \(|V_{ub}|\) dominated by the FF normalization

\[
|V_{ub}| = (3.36 \pm 0.15 \text{ expt} \pm 0.55^{+0.37}_{-0.37} \text{ FF}) \times 10^3 \quad \text{Ball-Zwicky } q^2 < 16
\]

\[
(4.20 \pm 0.29 \text{ expt} \pm 0.63^{+0.43}_{-0.43} \text{ FF}) \times 10^3 \quad \text{HPQCD } q^2 > 16
\]

\[
(3.75 \pm 0.26 \text{ expt} \pm 0.65^{+0.43}_{-0.43} \text{ FF}) \times 10^3 \quad \text{Fermilab } q^2 > 16
\]
Future of $B \rightarrow \pi \ell \nu$

- Form factor normalization dominates the error on $|V_{ub}|$
  - Experimental error will soon reach ±5%
- Significant efforts in both LQCD and LCSR needed
  - Spread among the calculations still large
  - Reducing errors below ±10% will be a challenge
- Combination of LQCD/LCSR with the measured $q^2$ spectrum and dispersive bounds may improve the precision
  - Fukunaga, Onogi, PRD 71:034506
  - Arnesen, Grinstein, Rothstein, Stewart, PRL 95:071802
  - Ball, Zwicky, PLB 625:225
  - Becher, Hill, PLB 633:61-69
How Things Mesh Together

$b \rightarrow s\gamma$

$E_\gamma$

$b \rightarrow u\ell\nu$

$E_\ell$

$q^2$

$m_X$

$|V_{ub}|$

HQE Fit

Shape Function

SSFs

$duality$

WA

Inclusive $b \rightarrow c\ell\nu$

$E_\ell$

$m_X$

$m_b$

Exclusive $b \rightarrow u\ell\nu$

$LCSR$

$LQCD$

FF

$duality$

unquenching

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The UT 2004 → 2005

- Dramatic improvement in $|V_{ub}|$
- $\sin 2\beta$ went down slightly ⇒ Overlap with $|V_{ub}/V_{cb}|$ smaller
Summary

- Precise determination of $|V_{ub}|$ complements $\sin 2\beta$ to test the (in)completeness of the Standard Model
  - $\pm 7.4\%$ accuracy achieved so far $\Rightarrow 5\%$ possible?

- Close collaboration between theory and experiment is crucial
  - Rapid progress in inclusive $|V_{ub}|$ in the last 2 years
  - Improvement in $B \rightarrow \pi \ell \nu$ form factor is needed