Leptonic and semileptonic B decays at the B-factories

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Blois 2010
New physics?

Exploit the unitarity constraint to look for new physics

Precision era where new physics may appear as a few percent disagreement:

- Large new physics contributions to penguins would have been seen
- New physics contributions to decays such as $B \rightarrow \tau \nu$ are still open
Integrated luminosity

KEKB for Belle

PEP-II for BaBar

~770M BB

~470M BB

> 1.0 ab⁻¹
On-resonance samples:
4S: 711 fb⁻¹
5S: 121 fb⁻¹
3S: 3.0 fb⁻¹
2S: 24 fb⁻¹
1S: 5.7 fb⁻¹
Off-resonance: 87 fb⁻¹

~553 fb⁻¹
On-resonance samples:
4S: 433 fb⁻¹
3S: 30 fb⁻¹
2S: 14 fb⁻¹
Off-resonance: 54 fb⁻¹
leptonic and semileptonic decays

I. Leptonic decays
  \( B \rightarrow \tau \nu \)
  \( B \rightarrow \mu \nu \)
  \( B \rightarrow e \nu \)

II. Semileptonic decays
  \( B \rightarrow D^{(*)}\tau \nu \)

III. Radiative leptonic decays
  \( B \rightarrow \gamma l \nu \)

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leptonic decays

- **Standard Model:**
  - Helicity suppressed
  - $B \to \tau \bar{\nu} \approx 10^{-4}
  - $B \to \mu \bar{\nu} \approx 10^{-7}
  - $B \to e \bar{\nu} \approx 10^{-12}$

Theoretically clean:
small hadronic effects

$\mathcal{B}(B \to \ell \nu) = \frac{G_F^2 m_B}{8\pi} \cdot m_\ell^2 \cdot (1 - \frac{m_\ell^2}{m_B^2})^2 \cdot f_B^2 \cdot |V_{ub}|^2 \cdot \tau_B$

From measurements + theory
$|V_{ub}| = (3.53 \pm 0.15) \times 10^{-3}$ [HFAG summer 2010]

From lattice $f_B = 190 \pm 13$ MeV [HPQCD, arXiv:0902.1815]
Tauonic decays

New Physics: charge Higgs mediation is NOT helicity suppressed

Model dependent predictions:

\[ B(B \to \ell \nu)_{2HDM} = B(B \to \ell \nu) \times \left(1 - \frac{\tan^2 \beta}{m^2_H} \right)^2 \]

\[ B(B \to \ell \nu)_{SUSY} = B(B \to \ell \nu) \times \left(1 - \frac{\tan^2 \beta}{1 + \eta_0 \tan \beta} \frac{m^2_B}{m^2_H} \right)^2 \]


Amplitude of charged Higgs diagram proportional to \( m_b \, m_\tau \, \tan^2 \beta \)

Enhancement for large \( \tan \beta \) or small \( m_{H^+} \)

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Tagging methods

Fully reconstruct a $B$ ($B_{tag}$):
Remove the corresponding particles from the event to reduce combinatorial background.

I. Hadronic tag
More pure, less efficient $\sim 0.2\%$
No "missing" energy

II. Semileptonic tag
Less pure, more efficient $\sim 1.5\%$
$\nu$ gives "missing" energy

B decay of interest ($B_{sig}$):
signal from remaining energy distribution
Challenge: neutrinos in $\tau$ and $l$ decays

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$B \rightarrow \tau \nu$ hadronic tag

Decay modes: $e\nu\nu, \mu\nu\nu, 1,2$ and 3 prongs

Signal: $e\mu\pi^{-/+} +$ nothing

Sum of neutral energy not associated to $B_{\text{tag}}$ or $\pi^0$ from $\tau$ decays

17.2$^{+5.3}_{-4.7}$ signal events

$\text{Br}(B \rightarrow \tau \nu) = (1.79^{+0.56}_{-0.49(\text{stat})}^{+0.46}_{-0.51(\text{syst})}) \times 10^{-4}$

3.5 $\sigma$ significance including systematics

PRL 97, 251802 (2006)
B → τν semileptonic tag

Tag-side
\( B^+ → D^{*0}l^+ \nu \), \( B^+ → D^0l^+ \nu \) with fully reconstructed \( D^{*0} \) and \( D^0 \)

Signal-side:
\( \tau^+ → e^+ \nu \nu, \mu^+ \nu \nu, \pi^+ \nu \)

EM calorimeter (\( E_{ECL} \)) signal shape calibrated with double semileptonic events

\( 143^{+36}_{-35} \) signal events

\( \text{Br}(B → τν) = (1.54^{+0.38}_{-0.37(\text{stat})}^{+0.29}_{-0.31(\text{syst})}) \times 10^{-4} \)

3.6σ significance including systematics

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$\text{Br}(B \rightarrow \tau \nu) = (1.8^{+0.9}_{-0.8}\text{(stat)} \pm 0.4_{\text{bck}} \pm 0.2_{\text{syst}}) \times 10^{-4}$

2.2 $\sigma$ excess
**B → τν constraints on new physics**

Naïve world average: \( \text{Br}(B \to \tau \nu) = (1.73 \pm 0.35) \times 10^{-4} \)

CKM Fitter 2010: \( \text{Br}(B \to \tau \nu) = (0.845^{+0.103}_{-0.096}) \times 10^{-4} \)

2.6\( \sigma \) between measured BR and CKM fit without \( B \to \tau \nu \) and \( V_{ub} \)

\[
\Delta m_s = \frac{3\pi}{4} m^2_{\tau} \left( 1 - \sin^2 2\beta \right) \left| V_{ud} \right|^2 \]

\[
B \to \tau \nu \text{ without } B \to \tau \nu \text{ and } V_{ub}
\]
$B \rightarrow e/\mu \nu$

Very rare → inclusive measurement
High efficiency but high background

Signal: single monochromatic $e/\mu$ in $B$ rest frame

signal extracted from a simultaneous fit to the momentum in the CM frame ($p_\text{l}^*$) and 4-momentum of everything else in the event ($m_{\text{ES}}$).

- $B \rightarrow e\bar{\nu}$
  - $B$ at 90% CL $< 1.9 \times 10^{-6}$
  - $B$ at 90% CL $< 0.98 \times 10^{-6}$

- $B \rightarrow \mu\bar{\nu}$
  - $B$ at 90% CL $< 1.0 \times 10^{-6}$
  - $B$ at 90% CL $< 1.7 \times 10^{-6}$

B → D(\(\ast\))\(\tau\)\(\nu\) and new Physics

Theory uncertainties
- Dependence from form factors but no dependence on \(f_B\)
- \(|V_{cb}|\) cancels in the ratio \(\text{Br}(B \to D(\ast)\tau\nu)/\text{Br}(B \to D(\ast)l\nu)\)

- 3 body decays hence more observables:
  - \(q^2\)-distribution, \(\tau\) polarization, \(D^*\) polarization
First observation: $B^0 \rightarrow D^{*-} \tau + \nu$

**Signal**

$D^{*-} \rightarrow D^0 \pi^+ \text{ with } D^0 \rightarrow K^- \pi^+, K^- \pi^0$ and $\tau^+ \rightarrow e^+ \nu \nu, \pi^+ \nu$

**Tag side**

$P_{\text{tag}} = \sum P_i$, $E_{\text{tag}} = \sum E_i$

$M_{\text{tag}}^2 = E_{\text{beam}}^2 - P_{\text{tag}}^2$

60$^{+12}_{-11}$ signal events

5.2 $\sigma$ significance

$\text{Br}(B^0 \rightarrow D^{*-} \tau + \nu) = (2.02^{+0.40}_{-0.37(\text{stat})} \pm 0.37(\text{syst}))%$

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PRL 99, 191807 (2007)
B^+ \rightarrow D^{*0} \tau^+ \nu \tau

Extension of the previous analysis to B^+

Large D^{*0}/D^0 cross feed: simultaneous extraction of D^{*0} and D^0 form fit to $M_{\text{tag}}$ and $P_{D^0}$

$$\text{Br}(B^+ \rightarrow D^{*0}\tau^+\nu) = (2.12^{+0.28}_{-0.27}\text{(stat)} \pm 0.29\text{(syst)})\%$$

446^{+58}_{-56} events (8.1σ significance)

$$\text{Br}(B^+ \rightarrow D^0\tau^+\nu) = (0.77 \pm 0.22\text{(stat)} \pm 0.12\text{(syst)})\%$$

146^{+42}_{-41} events (3.5σ significance)

First evidence

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arXiv:1005.2302v1 [hep-ex]
$B^+ \rightarrow D^{*-} \tau^+ \nu / D^{*0} \tau^+ \nu$

Hadronic tag

Signal has large missing mass ($m_{\text{miss}}$)

Simultaneous extraction of $D$ and $D^*$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Branching Ratio</th>
<th>Events</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow D^0 \tau^+ \nu$</td>
<td>$(0.67 \pm 0.37 \text{(stat)} \pm 0.11 \text{(syst)} \pm 0.07 \text{(norm)})%$</td>
<td>$35.6 \pm 19.4$</td>
<td>$1.8\sigma$</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^{*0} \tau^+ \nu$</td>
<td>$(2.25 \pm 0.48 \text{(stat)} \pm 0.22 \text{(syst)} \pm 0.17 \text{(norm)})%$</td>
<td>$92.2 \pm 19.6$</td>
<td>$5.3\sigma$</td>
</tr>
<tr>
<td>$B^0 \rightarrow D \tau^+ \nu$</td>
<td>$(1.04 \pm 0.35 \text{(stat)} \pm 0.15 \text{(syst)} \pm 0.10 \text{(norm)})%$</td>
<td>$23.3 \pm 7.8$</td>
<td>$3.3\sigma$</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^* \tau^+ \nu$</td>
<td>$(1.11 \pm 0.51 \text{(stat)} \pm 0.04 \text{(syst)} \pm 0.04 \text{(norm)})%$</td>
<td>$15.5 \pm 7.2$</td>
<td>$2.7\sigma$</td>
</tr>
</tbody>
</table>

First evidence

Signal shown in light green resp. magenta

PRL 100, 021801 (2008)
PRD 79, 092002 (2009)
$B^{+/0} \rightarrow D^{*-} \tau + \nu / D^{*0} \tau + \nu$

Lepton momentum and $q^2$ distributions

First measurement of decay distribution

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Overlap between „inclusive” and „exclusive” $B_{\text{tag}}$ reconstruction Belle analysis is negligible (~.2%)

**syst. stat.**

- „inclusive” $B_{\text{tag}}$ reconstruction
- „exclusive” $B_{\text{tag}}$ reconstruction

1005.2302[hep-ex] $B^+ \rightarrow D^*\tau^+\nu_\tau$ and PRL 99,191807(2007) $B^0 \rightarrow D^*\tau^+\nu_\tau$

Belle preliminary 0910.4301[hep-ex] $B^+ \rightarrow D^*\tau^+\nu_\tau$

Babar PRL 100,02180(2008)


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Global constraints on $m_{H^+}$ and $\tan\beta$ from all observables

$m_{H^+} > 316$ GeV @ 95% CL

$m_{H^+} > 78.6$ GeV @ 95% CL

EXCLUDED BY LEP

http://arxiv.org/pdf/0907.5135
Summary

- Tauonic and semitauonic decays
  Well established but tension with $\sin(2\beta)$

- $B \rightarrow \mu \nu$ Upper limit ...but at the edge of SM
- $B \rightarrow e \nu$ Upper limit
- $B \rightarrow \gamma l \nu$ Upper limit ...but at the edge of SM

All contribute to a stringent limit on $m_{H^+}$
**B → τν** constraints on new Physics

Naïve world average: \( \text{Br}(B \rightarrow \tau \nu) = (1.73 \pm 0.35) \times 10^{-4} \)

SM value: \( \text{Br}(B \rightarrow \tau \nu) = (1.20 \pm 0.25) \times 10^{-4} \)

**Effective scalar coupling** \( g_s \)

\[
\frac{B(B \rightarrow \tau \nu)}{B(B \rightarrow \tau \nu)|_{SM}} = |1 - g_s|^2
\]

**Diagram**

- **Excluded area** has CL > 0.95
- **CKM** line
- **2HDM** line

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**Abstract**

Standard Model in future experiments. If such physics is found, it will be a signal for the existence of standard model inputs.

Repulsion with leptonic and semileptonic decays is given, and the di-function of HDM [195] based on supersymmetric extensions of the Standard Model, the ratio \( s \) which constrains ended technicolor scenarios [196].

The shaded region and explained in the text.

\( \text{Br}(B \rightarrow \tau \nu) = (1.73 \pm 0.35) \times 10^{-4} \)

The range of theoretical predictions is obtained by assuming the knowledge of leptonic and semileptonic decays involving a muon in the final state is very important.

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Lepton Flavour Universality

Large violations of LF universality within the MSSM.

For large $\tan\beta$

\[
\Gamma(B \to \mu^+ \nu_{\mu})_{\text{exp}} = \Gamma(B \to \mu^+ \nu_{\mu}) + \Gamma(B \to \mu^+ \nu_e) + \Gamma(B \to \mu^+ \nu_{\tau})
\]

\[
\Gamma(B \to \mu^+ \nu_{\mu}) = \text{SM}
\]

\[
\Gamma(B \to \mu^+ \nu_e) \approx 0
\]

\[
\Gamma(B \to \mu^+ \nu_{\tau}) \propto \text{scalar LFV amplitude}
\]

Experimental probe out of reach of current $B$-factories:

\[
\tau \mu = \frac{\Gamma(B \to \mu \nu)}{\Gamma(B \to \tau \nu)} \sim 10\% R_{\tau \mu}, \text{SM}
\]

\[
R_{\tau e} = \frac{\Gamma(B \to e \nu)}{\Gamma(B \to \tau \nu)} \sim 10^3 R_{\tau e}, \text{SM}
\]


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