Leptonic and Semileptonic decays at BaBar

Fabio Ferrarotto

INFN Roma I

on behalf of BaBar

Fourth Workshop on Theory, Phenomenology and Experiments in Flavour Physics

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Outline

- Introduction
- Tagging
- Semileptonic Exclusive Measurements
  - $B \to D^{(*)}\tau\nu$
  - $B^+ \to X_u / \nu$
- Semileptonic Inclusive Measurements
- Leptonic B decays
  - $B^0 \to \text{invisible} (+\gamma)$
  - Search for FCNC
    - $B^+ \to h^+\tau\nu$
    - $D^0 \to l^+l^-$
- Tests of SM and NP
- Conclusions and Outlook

arXiv:1205.5442
arXiv:1112.0702v1

NEW

NEW

NEW
Introduction

Multipurpose, asymmetric $4\pi$ detector at $e^+e^-$ collider (PEP-II @SLAC)

$$\int d\mathcal{L} = 432 \text{ fb}^{-1} @ Y(4s)$$

BB threshold

$$\sigma(Y(4s)) \sim 1.05 \text{ nb}$$

- $472 \times 10^6 \, B\bar{B}$ pairs produced in $e^+e^-$ collisions at $Y(4S)$ \sim at rest in CM
- asymmetric CM energy (boost $\beta=0.55$) $\Rightarrow$ we can separate the B decay vertices
- exclusive B decays : kinematics variables
  $$\Delta E = E_B - E_{\text{beam}}$$
  centered at 0
  $$m_{ES} = \sqrt{E_{\text{beam}}^2 - P_B^2}$$
  centered at $m_B$
- low background : $\sigma(B\bar{B}) \sim 1/5 \, \sigma(\text{had})$
- Continuum contribution measured by off-resonance runs during data taking
- low-multiplicity ($\sim 11$ tracks /evt) $\Rightarrow$ "easy" to fully reconstruct B decay
- very good particle ID and separation
Tagging method

**Weak signal signature**
Decay with $p_{\text{mis}}$ (one or more $\nu$ in final state) $\rightarrow$ lack of kinematics constraints in final state
$\rightarrow$ background rejection improved identifying the companion B
$\rightarrow$ kinematics from the companion B

Look for signal in the rest of the event

**Semileptonic B decays**
Ex : $B \rightarrow D^* \ell \nu$
- PRO: Higher efficiency $\varepsilon_{\text{tag}} \sim O(10^{-2})$
- CON: more backgrounds, B momentum unmeasured

**Hadronic B decays (with charm)**
Ex : $B^+ \rightarrow D^{(*)0} X^+$ or $B^0 \rightarrow D^{(*)+} X^-$
- X charged system of hadrons : among ($\pi,K,\pi^0,K_s$) up to 5-6 charged and 2-3 neutrals
- PRO: cleaner events, B momentum reconstructed
- CON: smaller efficiency $\varepsilon_{\text{tag}} \sim O(10^{-3} - 10^{-2})$
Semileptonic decays to $\tau$ sensitive to charged Higgs at tree level → less model dependence
Have an additional helicity amplitude $H_t$

$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |p| q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2\right] \left(1 + \frac{m_\tau^2}{2q^2} \right) + \frac{3}{2} \frac{m_\tau^2}{q^2} |H_t|^2$$

Test of SM : measure of

$$R(D) = \frac{Y(B \to D\tau\nu)}{Y(B \to D\ell\nu)}$$
$$R(D^*) = \frac{Y(B \to D^*\tau\nu)}{Y(B \to D^*\ell\nu)}$$

- Fully reconstruct $B_{tag}$ in $B \to D^{(*)}X$, $D_s^{(*)}X$, $J/\Psi X$ ($X = \pi, K$ modes, $n_X < 6$)
- $B_{sig}$ : reco of $D^{(*)}$ and $e$ or $\mu$ + no additional charged particles
- Kinematic selection : $q^2 > 4$ GeV$^2$
- Background suppression by Boosted Decision Tree (combinatorial and $D^{**}\ell\nu$)
- $E_{Extra}$ : important variable but has large uncertainties

→ Not used in the fit
- MC correction based on data distributions
- Fit unbinned M.L. fit on 2-D distributions:

$$m_{miss}^2 = (P_{e+e-} - P_{Btag} - P_{D(*)} - P_{l})^2 \quad , \quad P_{l}^{*} \quad \text{in B rest frame}$$

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$B \rightarrow D^* \tau \nu$

Full BABAR dataset: 472 million BB pairs

4 signal samples: $D^0/l$, $D^{*0}/l$, $D^+/l$, $D^{*+}/l$ ($l = e$ or $\mu$)

PDFs from MC

Fitted Yields: 4 $D^{(*)}\tau \nu$ Signal + 4 $D^{(*)}/\nu$ Normalization + 4 $D^{*\nu}/\nu$ Background

Fixed Backgrounds: $B^0$–$B^+$ cross feed + BB combinatorial BG + Continuum $e^+e^- \rightarrow f\bar{f}(\gamma)$

<table>
<thead>
<tr>
<th></th>
<th>$D^{*0}\tau \nu$</th>
<th>$D^{*+}\tau \nu$</th>
<th>$D^{*\nu}\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{sig}}$</td>
<td>$639 \pm 62$</td>
<td>$245 \pm 27$</td>
<td>$888 \pm 63$</td>
</tr>
<tr>
<td>Significance ($\sigma$)</td>
<td>$11.3$</td>
<td>$11.6$</td>
<td>$16.4$</td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>$0.322 \pm 0.032$</td>
<td>$0.355 \pm 0.039$</td>
<td>$0.332 \pm 0.024$</td>
</tr>
</tbody>
</table>

Stat error only

Good consistency between charged and neutral modes

Isospin constrained fit
B → Dτν

Full BABAR dataset: 472 million BB pairs

4 signal samples: D^0 \ell, D^{*0} \ell, D^{+} \ell, D^{*+} \ell (\ell = e or \mu)

PDF's from MC

Fitted Yields: 4 D^{(*)}\tau\nu Signal + 4 D^{(*)}\ell\nu Normalization + 4 D^{**}\ell\nu Background

Fixed Backgrounds: B^{0}−B^{+} cross feed + B\bar{B} combinatorial BG + Continuum e^{+}e^{-} → ff(\gamma)

<table>
<thead>
<tr>
<th>N_{\text{sig}}</th>
<th>D^{0}\tau\nu</th>
<th>D^{+}\tau\nu</th>
<th>D_{\tau\nu}</th>
</tr>
</thead>
<tbody>
<tr>
<td>314 ± 60</td>
<td>177 ± 31</td>
<td>489 ± 63</td>
<td></td>
</tr>
<tr>
<td>Significance (\sigma)</td>
<td>5.5</td>
<td>6.1</td>
<td>8.4</td>
</tr>
<tr>
<td>R(D)</td>
<td>0.429 ± 0.082</td>
<td>0.469 ± 0.084</td>
<td>0.440 ± 0.058</td>
</tr>
</tbody>
</table>

good consistency between charged and neutral modes

First > 5 \sigma observation

Isospin constrained fit

Stat error only
Summary of $R(D)$ and $R(D^*)$ Measurement

**R(D) and R(D*) correlated (-0.27)**

Combination yields $\chi^2/NDF=14.6/2$

i.e. Prob = $6.9 \times 10^{-4}$ !

**Data exclude SM by 3.4 $\sigma$ !!**

Including syst errors

$B \rightarrow D\tau\nu : 6.8 \sigma$ significance

**Comparison with previous measurements**

<table>
<thead>
<tr>
<th></th>
<th>$R(D)$</th>
<th>$R(D^*)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR</td>
<td>$0.440 \pm 0.072$</td>
<td>$0.332 \pm 0.029$</td>
</tr>
<tr>
<td>SM*</td>
<td>$0.297 \pm 0.017$</td>
<td>$0.252 \pm 0.003$</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>$2.0 \sigma$</td>
<td>$2.7 \sigma$</td>
</tr>
</tbody>
</table>

* Z. Phys. C46, 93 (1990)  
  PRD 82, 0340276 (2010)  
  PhD 85, 094025 (2012)  
  and recent updates
Implications for the Higgs sector

Individual measurement exceeds SM by $> 2\sigma$ : 2Higgs Doublet Model may explain excesses individually.
A charged Higgs (2HDM type II) of spin 0 coupling to $\tau$ will affect $H_t$

\[ H_t^{2\text{HDM}} = H_t^{\text{SM}} \times \left(1 - \frac{\tan^2\beta}{m_H^2} \frac{q^2}{1 \mp m_c/m_b} \right) \]

+ $D\tau\nu$
- $D^*\tau\nu$

Combination of $R(D)$ and $R(D^*)$ inconsistent and excludes type II 2HDM with a probability $> 99.8\%$ in the full $\tan 2\beta$-$m_H$ parameter space !!
(provided $m_H > 10$ GeV)

2HDM changes kinematic distributions as a fct of $\tan \beta/m_H$, hence the efficiencies change
Inclusive $|V_{ub}|$ with hadronic tag

**Experimental challenges:**
- Large $B \rightarrow X_c \ell \nu$ background ($\sim 50$ times larger)
- Variables like $M_X$ and $q^2$ require full event reconstruction
- Background BF, bkg and signal distributions not that well understood

**Theoretical challenges:**
- OPE convergence destroyed in limited phase space
- Rates are sensitive to b-quark dynamics inside B meson.
- Uncertainties in input parameters

**Fully reconstruct $B_{\text{tag}}$ in $B \rightarrow D^{(*)}X$ ($X = \pi, K$ modes, $n_X < 6$ charged $+ < 3$ neutrals)**
- $\rightarrow$ kinematics and flavour of $B_{\text{sig}}$ known (high purity, low efficiency $O(10^{-3})$)

**Look for a lepton ($p^*_l > 1$ GeV/c) and neutrino (missing momentum) in $B_{\text{sig}}$**
Inclusive $|V_{ub}|$ with hadronic tag

Full BABAR dataset: 472 million BB pairs

Precision of $V_{ub}$ limited by theory uncertainties due to phase space cuts

- Performed a $(M_X, q^2)$ 2-dim unbinned ML fit without phase space cuts (except $p^*_l > 1.0$ GeV → 88-90% of phase space where theo uncertainties are smaller)

$\Delta B (B \to X_u l \bar{\nu}) (10^{-3}) = 1.80 \pm 0.13 \text{ stat} \pm 0.15 \text{ syst} \pm 0.02 \text{ theo}$

$|V_{ub}| = (4.31 \pm 0.25 \text{ exp} \pm 0.16 \text{ theo}) \times 10^{-3}$ [avg 4 QCD predictions *]

Systematic error mostly from $B \to X_u l \bar{\nu}$ and BG simulation

- BaBar measurement in different kinematic regions agree!

$|V_{ub}| = \sqrt{\frac{\Delta B(\bar{B} \to X_u l \bar{\nu})}{\tau_B \Delta \Gamma_{\text{theory}}}}$

- BLNP: multi-scale OPE based on SCET
- DGE: resummed perturbations theory
- GGOU: large range of distributions function
- ADFR: partial BF in terms of $|V_{cb}|^2/|V_{ub}|^2$

- NP B699, 335 (2004)
- JHEP 0601, 096 (2006)
- JHEP 0710, 058 (2007)
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B → invisible

SM : $B^0 \rightarrow \nu\nu$ decay suppressed by a factor $(m_\nu/m_{B^0})^2$

$BF(B^0 \rightarrow \nu\nu\gamma)$ is of the order of $10^{-9}$

In SUSY model $BR(B^0 \rightarrow \text{Invisible})$ can be enhanced up to $10^{-7}$-$10^{-6}$ due to neutrino+neutralino production in the final state


Semileptonic tag: $B_{\text{tag}}^0 \rightarrow D^{(*)-}/^{+}\nu$

Look for consistency with an invisible(+γ) decay of the other neutral $B_{\text{sig}}$
Most discriminating variable: **total residual energy** - unassociated clusters in the calo ($E_{\text{extra}}$)

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{\text{sig}}$</th>
<th>$N_{\text{bkg}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to \text{invisible}$</td>
<td>$-22 \pm 9$</td>
<td>$334 \pm 21$</td>
</tr>
<tr>
<td>$B^0 \to \text{invisible} + \gamma$</td>
<td>$-3.1 \pm 5.2$</td>
<td>$113 \pm 12$</td>
</tr>
</tbody>
</table>

Unbinned Maximum Likelihood fit to $E_{\text{extra}}$

Full BABAR dataset: 472 million BB pairs

$B^{+} \to \text{invisible}(+\gamma)$ control sample

NO signal

1 order of magnitude improvement over previous limits:

$B(B^0 \to \text{invisible}) < 2.4 \times 10^{-5}$

$B(B^0 \to \text{invisible} + \gamma) < 1.7 \times 10^{-5}$
Search for Lepton-Flavor Violation:
\[ B^+ \to K^+\tau e, \ B^+ \to K^+\tau\mu \ , B^+ \to \pi^+\tau e, \ \ B^+ \to \pi^+\tau\mu \]

Tree-level Flavor-Changing Neutral-Currents (FCNC) **forbidden** in SM

Well-motivated extensions of the SM include LFV in FCNCs:
\[ \rightarrow \text{NP may enhance interactions coupling to 2nd and 3rd generations} \]

Experimental constraints involving \( \tau \) in B meson decays weak
\[ \rightarrow \text{difficulty: reconstruct } \tau \text{ daughters (involving neutrinos)} \]

From Black et al.* on \( \tau-\mu \) flavor violation, using full BABAR data and expected sensitivity on \( B(B^\pm \to K^\pm\tau\mu) \) the NP energy scale in FC operators can be pushed to \( \Lambda > 15 \text{ TeV} \)


8 final states looked

Fully reconstruct hadronic \( B_{\text{tag}} \to D^{(*)0}X^- \) decays

Determine \( B_{\text{tag}} \) momentum \( \to \) known \( B_{\text{sig}} \) momentum

Combinatoric background rejection performed with likelihood ratio

Studied 3 single prong \( \tau \) decays \( (e,\mu,\pi [\geq 0\ \pi^0]) \) channels

Fully reconstruct \( \tau \) invariant mass using \( E_{\text{beam}} \) in \( \Upsilon(4S) \) CM frame

Submitted to PRD
arXiv:1204.2852
Search for Lepton-Flavor Violation:
$B^+ \rightarrow K^+ \tau e$, $B^+ \rightarrow K^+ \tau \mu$, $B^+ \rightarrow \pi^+ \tau e$, $B^+ \rightarrow \pi^+ \tau \mu$

Full BABAR dataset: 472 million BB pairs

Results for all modes: **first time measurement** for these 3 decay modes

Signal region: $m_\tau \pm 60$ MeV

Count events in $\tau$ regions: **No evidence** for signals
Search for Lepton-Flavor Violation:

\[ \mathcal{B}(B^+ \to K^+\tau\ell) \times 10^{-5} \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>( \mathcal{B} (B \to h\tau l) )</th>
<th>Central Value</th>
<th>90% CL UL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ \to K^+\tau^+\mu^- )</td>
<td>-0.4</td>
<td>+1.4</td>
<td>&lt; 2.8</td>
</tr>
<tr>
<td>( B^+ \to K^+\tau^-\mu^+ )</td>
<td>+0.2</td>
<td>+2.1</td>
<td>&lt; 4.3</td>
</tr>
<tr>
<td>( B^+ \to K^+\tau^-e^+ )</td>
<td>-1.3</td>
<td>+1.5</td>
<td>&lt; 1.5</td>
</tr>
<tr>
<td>( B^+ \to K^+\tau^+e^- )</td>
<td>-0.4</td>
<td>+3.1</td>
<td>&lt; 6.2</td>
</tr>
<tr>
<td>( B^+ \to \pi^+\tau^-\mu^+ )</td>
<td>0.0</td>
<td>+2.6</td>
<td>&lt; 4.5</td>
</tr>
<tr>
<td>( B^+ \to \pi^+\tau^-\mu^- )</td>
<td>-3.1</td>
<td>+2.4</td>
<td>&lt; 2.0</td>
</tr>
</tbody>
</table>

Conservative constraints on NP parameters from “clean” modes

Used Feldman-Cousins UL

Black et al.*: estimate NP energy scales for 3rd generation flavor changing couplings

\[ \mathcal{B}(B^+ \to \pi^+\tau\mu^+) < 6.2 \times 10^{-5} \quad \rightarrow \quad \Lambda_{bd} > 12 \text{ TeV} \]

\[ \mathcal{B}(B^+ \to K^+\tau\mu^+) < 4.5 \times 10^{-5} \quad \rightarrow \quad \Lambda_{bs} > 15 \text{ TeV} \]


1 order of magnitude improvement over old limits
Preliminary

\[ \int d\mathcal{L} = 468 \text{ fb}^{-1} \]

FCNC decay highly GIM suppressed in SM.
Long-distance corrections raise \( D^0 \to \mu^+\mu^- \) BF to as high as \( 10^{-13} \) within SM

BF could be enhanced by many orders of magnitude by NP.

Sensitivity with full dataset and improved analysis expected to be \( \sim 10^{-7} \)

- \( D^0 \) candidates from \( D^{*+} \to D^0 \pi^+ \) to reduce combinatoric BG.
  - \( p^*(D^0) > 2.4 \text{ GeV} \) to remove \( D^0 \) from B decay
- Lepton particle ID to help BG separation
- Combinatoric background mostly has real leptons in it
  - BB background: Fisher discriminant, continuum BG: helicity angle cut
- Peaking background from \( D^0 \to h^+h^- \)
  - \( D^0 \to K\pi^+ \) and \( D^0 \to K^+K^- \) modes are far away in \( m(D^0) \) (not a problem).
  - \( D^0 \to \pi^+\pi^- \) is a dominant BG for the \( D^0 \to \mu^+\mu^- \) mode.
D⁰ → l⁺l⁻

Very few events survive all cuts -- use cut-and-count approach

Normalize signal BF relative to D⁰ → π⁺π⁻.

\[ \Delta m = m(D^*) - m(D) \]

\[ D^0 \rightarrow e^+e^- \]
\[ D^0 \rightarrow \mu^+\mu^- \]
\[ D^0 \rightarrow e^±\mu^∓ \]

Combinatoric BG in signal window from upper SB

Peaking D⁰ → π⁺π⁻ in µµ signal window from misid rates measured in data

<table>
<thead>
<tr>
<th>Mode</th>
<th>N_{BG}</th>
<th>N_{obs}</th>
<th>B_{ll}, 90% CL</th>
<th>B_{ll}</th>
</tr>
</thead>
<tbody>
<tr>
<td>D⁰ → e⁺e⁻</td>
<td>1.0 ± 0.4 ± 0.4</td>
<td>1</td>
<td>&lt; 1.7 \times 10⁻⁷</td>
<td>(0.1 ± 0.7) \times 10⁻⁷</td>
</tr>
<tr>
<td>D⁰ → μ⁺μ⁻</td>
<td>3.9 ± 0.4 ± 0.5</td>
<td>8</td>
<td>[0.6, 8.1] \times 10⁻⁷</td>
<td>(3.3 ± 2.6) \times 10⁻⁷</td>
</tr>
<tr>
<td>D⁰ → e±μ∓</td>
<td>1.4 ± 0.3 ± 0.2</td>
<td>2</td>
<td>&lt; 3.3 \times 10⁻⁷</td>
<td>(0.5 ± 1.3) \times 10⁻⁷</td>
</tr>
</tbody>
</table>

For µµ channel

Feldman-Cousins UL procedure results in a 2-sided 90% CL interval

Superseeds PRL 93, 191801 (2004)
Tests of SM and NP

General striking overall consistency of UT constraints

However ..... some measurements show “tensions”

$$|V_{cb}| \text{ exclusive (D*/ν)} \quad |V_{cb}| = (39.04 \pm 0.55 \pm 0.73) \cdot 10^{-3}$$

$$|V_{cb}| \text{ inclusive} \quad |V_{cb}| = (41.88 \pm 0.44 \pm 0.59) \cdot 10^{-3}$$

$$|V_{ub}| \text{ exclusive (π/ν)} \quad |V_{ub}| = (3.28 \pm 0.18 \pm 0.24) \cdot 10^{-3}$$

$$|V_{ub}| \text{ inclusive} \quad |V_{ub}| = (4.41 \pm 0.15 \pm 0.17) \cdot 10^{-3}$$

Another problem : $B \rightarrow \tau \nu \quad |V_{ub}| = (5.0 \pm 0.6) \cdot 10^{-3}$

... and now also the rates for $B \rightarrow D^{(*)}\tau \nu$ exceed the SM by 3.4 $\sigma$

Caveat: based on BF average of 4 low statistics measurements.
Conclusions and outlook - I

Study of leptonic and semileptonic decays continues to be a very active area for both theory and experiment and has recently greatly improved.

- Use of B tagging technique: substantially reduces backgrounds + improves systematic uncertainties
- Major improvements in analysis + larger data sets: reduced uncertainties on BF, $|V_{ub}|$ and $|V_{cb}|$
- Stringent new limits on rare and forbidden B decays and New Physics

Yet found no evidence for New Physics: overall consistency of UT constraints

**BUT**

some "tensions" are visible:

- values of inclusive and exclusive $|V_{ub}|$ and $|V_{cb}|$ differ by more than 2 sigma
- $B (B \to \tau \nu)$ [vs $\sin 2\beta$ and $V_{ub}$] do not agree with SM expectations
- A significant excess of events has been observed in $B \to D\tau\nu$ and $B \to D^*\tau\nu$
  - cannot be explained in terms of a 2DHM of type II

Statistical fluctuations, unknown systematic uncertainties or hints of NP around the corner?
Conclusions and outlook - II

Impressive number of new results from BaBar [and Belle] still produced

BaBar still well and alive long after end of data-taking (2008)

Physics Book of B-Factories in preparation by BaBar and Belle jointly

SM very well verified by UT constraints

BUT

"tensions" present : NP could be near

We need more data and better precision
Major advances are expected from LHCb and future B Factories!
Backup slides
The BaBar detector

Exclusive reconstruction of B decay; kinematic constraint from beam energies

- $m_{ES} = \sqrt{E_{beam}^* - P_B^*}$
- $\Delta E = E_B^* - E_{beam}^*$

Continuum (q\bar{q}) bkg suppression

- Topology:
  - $e^+e^- \rightarrow \pi(4S) \rightarrow BB$
  - $e^+e^- \rightarrow q\bar{q}$

- Angular distribution:
  - $p_B^* \sim 300 \text{ MeV} / c$

- Multivariate analysis (NN, Fisher)

K/\pi separation: Cherenkov angle + dE/dx

Excellent separation between 1.5 and 4 GeV/c

Flavor tagging

Coherent $B^0\bar{B}^0$ production

Boost $\beta_\gamma \approx 0.55$ allows $\Delta t$ measurement

Leptons and kaons tag flavor of other $B$
Search for Lepton-Flavor Violation:
$B^+ \to K^+ \tau e$, $B^+ \to K^+ \tau \mu$, $B^+ \to \pi^+ \tau e$, $B^+ \to \pi^+ \tau \mu$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mathcal{B}(B \to h\tau l)$ ($\times 10^{-5}$)</th>
<th>90% CL UL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to K^+ \tau^+ \mu^+$</td>
<td>+0.8 $^{+1.9}_{-1.4}$</td>
<td>&lt; 4.5</td>
</tr>
<tr>
<td>$B^+ \to K^+ \tau^\mp \mu^\mp$</td>
<td>$-0.4$ $^{+1.4}_{-0.9}$</td>
<td>&lt; 2.8</td>
</tr>
<tr>
<td>$B^+ \to K^+ \tau^\mp e^\pm$</td>
<td>+0.2 $^{+2.1}_{-1.0}$</td>
<td>&lt; 4.3</td>
</tr>
<tr>
<td>$B^+ \to K^+ \tau^\pm e^\mp$</td>
<td>$-1.3$ $^{+1.5}_{-1.8}$</td>
<td>&lt; 1.5</td>
</tr>
<tr>
<td>$B^+ \to \pi^+ \tau^\mp \mu^\pm$</td>
<td>+0.4 $^{+3.1}_{-2.0}$</td>
<td>&lt; 6.2</td>
</tr>
<tr>
<td>$B^+ \to \pi^+ \tau^\pm \mu^\mp$</td>
<td>0.0 $^{+2.6}_{-2.0}$</td>
<td>&lt; 4.5</td>
</tr>
<tr>
<td>$B^+ \to \pi^+ \tau^\mp e^\pm$</td>
<td>2.8 $^{+2.4}_{-1.9}$</td>
<td>&lt; 7.4</td>
</tr>
<tr>
<td>$B^+ \to \pi^+ \tau^\pm e^\mp$</td>
<td>$-3.1$ $^{+2.4}_{-2.1}$</td>
<td>&lt; 2.0</td>
</tr>
</tbody>
</table>

Avg of $\mathcal{B}(B \to h\tau l)$ assuming $\mathcal{B}(B \to h\tau^+ l) = \mathcal{B}(B \to h\tau^- l)$

Conservative constraints on NP parameters from “clean” modes
Used Feldman-Cousins UL

Black et al.*: estimate NP energy scales for 3rd generation flavor changing couplings

$\mathcal{B}(B^+ \to \pi^+ \tau^\mp \mu^\pm) < 6.2 \times 10^{-5}$ → bound on $\Lambda_{bd} > 12$ TeV

$\mathcal{B}(B^+ \to K^+ \tau^\mp \mu^\pm) < 4.5 \times 10^{-5}$ → bound on $\Lambda_{bs} > 15$ TeV

Inclusive $|V_{ub}|$ with hadronic tag

Theoretical challenges:
- OPE convergence destroyed in limited phase space
- Rates become sensitive to $b$-quark dynamics inside $B$ meson.
  - Unknown higher orders terms in $\alpha_s$ and $1/m_b$ expansions
- Shape functions (SF) – to be extracted from data
  - Leading order in $1/m_b$: universal SF
  - Order $\Lambda_{QCD}/m_b$: several subleading SF
- Uncertainties in input parameters
  - $m_b$: total rate $\Gamma \sim |V_{ub}|^2 m_b^5$, partial rates $\Delta\Gamma \sim |V_{ub}|^2 m_b^{10}$
Systematics of $R(D)$ and $R(D^*)$ Measurement

### Systematic errors

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty ($%$)</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{*\pm}\nu$ background</td>
<td>5.8</td>
<td>0.62</td>
</tr>
<tr>
<td>MC statistics</td>
<td>5.0</td>
<td>-0.48</td>
</tr>
<tr>
<td>Cont. and $B\bar{B}$ bkg.</td>
<td>4.9</td>
<td>-0.30</td>
</tr>
<tr>
<td>$\epsilon_{\text{sig}}/\epsilon_{\text{norm}}$</td>
<td>2.6</td>
<td>0.22</td>
</tr>
<tr>
<td>Systematic uncertainty</td>
<td>9.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>13.1</td>
<td>-0.45</td>
</tr>
<tr>
<td><strong>Total uncertainty</strong></td>
<td><strong>16.2</strong></td>
<td><strong>-0.27</strong></td>
</tr>
</tbody>
</table>

- $D^{*\pm}\nu$: conservative 15% constraints + fit to $D\pi$ sample
- Limited MC signal samples 2-dim PDFs ~2000 events

Largest errors are Gaussian distributed!

### Decay and $R(D^{(*)})$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\mathcal{R}(D^{(*)})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \to D^0\tau^-\bar{\nu}_\tau$</td>
<td>$0.429 \pm 0.082 \pm 0.052$</td>
</tr>
<tr>
<td>$B^- \to D^{*0}\tau^-\bar{\nu}_\tau$</td>
<td>$0.322 \pm 0.032 \pm 0.022$</td>
</tr>
<tr>
<td>$B^0 \to D^+\tau^-\bar{\nu}_\tau$</td>
<td>$0.469 \pm 0.084 \pm 0.053$</td>
</tr>
<tr>
<td>$ar{B}^0 \to D^{*-}\tau^-\bar{\nu}_\tau$</td>
<td>$0.355 \pm 0.039 \pm 0.021$</td>
</tr>
<tr>
<td>$\bar{B} \to D\tau^-\bar{\nu}_\tau$</td>
<td>$0.440 \pm 0.058 \pm 0.042$</td>
</tr>
<tr>
<td>$\bar{B} \to D^{*-}\tau^-\bar{\nu}_\tau$</td>
<td>$0.332 \pm 0.024 \pm 0.018$</td>
</tr>
</tbody>
</table>