$B \rightarrow \tau \nu$ AND RELATED RESULTS

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on behalf of the Belle collaboration

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**KEKB**

- **Asymmetric-energy** $e^+e^-$ collider: 3.5GeV × 8GeV
- **Record luminosity** $L = 2.1 \times 10^{34} cm^{-2}s^{-1}$

**Belle**

- Designed for $CP$ violation study in $B$ decays
- Suitable for many other studies: charm, $\tau$ etc.
- Data was taken in 1999 – 2010
- World largest accumulated luminosity > 1 ab\(^{-1}\)
- 711 fb\(^{-1}\) on \(\Upsilon(4S')\) resonance correspond to \(772 \times 10^6\) \(B\bar{B}\) pairs

\[
\begin{align*}
\text{KEKB} & \quad \text{PEP-II} \\
1998/1 & \quad 2000/1 \quad 2002/1 \quad 2004/1 \quad 2006/1 \quad 2008/1 \quad 2010/1 \quad 2012/1
\end{align*}
\]
The Standard Model describes known processes very well;
However, there are indications, that the Standard Model is not complete:
- neutrino oscillations, baryon asymmetry, dark matter;
- too many parameters, hierarchy problem;

There should be something beyond the Standard Model — New Physics.
New Physics effects are expected to be small, therefore the best way to look is to study rare decays.
**New Physics and** $B \to \ell\nu$

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

- Leptonic $B$ decays are clean since there are no hadronic uncertainties.
- Leptonic decays are helicity-suppressed:
  \[ \mathcal{B}(B^- \to e^- \bar{\nu}_e) \ll \mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) \ll \mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau). \]
- Good place to look for New Physics, e.g. charged Higgs exchange:
  \[ \mathcal{B}_{NP}(B^- \to \ell^- \bar{\nu}_\ell) = \mathcal{B}_{SM}(B^- \to \ell^- \bar{\nu}_\ell) \times r_H, \]
  where $r_H$ depends on the Higgs model, but not on the mode.
  In Type II 2HDM (W. S. Hou, PRD 48, 2342 (1993))
  \[ r_H = (1 - \frac{m_H^2}{m_H^2} \tan^2 \beta)^2. \]
Full reconstruction tagging

- At $B$ factory events are clearly separated;
- $\Upsilon(4S)$ decays into two $B$ mesons;
- All particles (but neutrinos) are detected;
- Initial energy is known.

We can reconstruct one $B$ meson in hadronic or semileptonic mode ($B_{\text{tag}}$), reconstruct some particles from the other $B$ meson ($B_{\text{sig}}$), and restrict unreconstructed part from the information about the whole event.
Hadronic tagging

- Exclusive tagging:
  - $B_{\text{tag}}$ is reconstructed as $D(\ast)X$ combination;
  - $B_{\text{sig}}$ is reconstructed;

- Inclusive tagging:
  - $B_{\text{sig}}$ is reconstructed;
  - The rest of the event is combined into $B_{\text{tag}}$ and checked if it is consistent with $B$ meson hypothesis;

- Efficiency $\sim 0.2\%$;

Semileptonic tagging

- $B$ meson is reconstructed as $D(\ast)\ell$;
- Efficiency $\sim 0.7\%$, but more background;

\[
\Delta E = E_B - E_{\text{beam}}, \quad M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^2}
\]
Existing experimental results

- **Belle**
  - Hadronic tagging, 449M
    \[ B = [1.79^{+0.56}_{-0.49} +0.46] \times 10^{-4} \]
  - Semileptonic tagging, 657M
    \[ B = [1.54^{+0.38}_{-0.37} +0.29] \times 10^{-4} \]

- **BaBar**
  - Hadronic tagging, 468M
    \[ B = [1.80^{+0.57}_{-0.54} \pm 0.24] \times 10^{-4} \]
  - Semileptonic tagging, 459M
    \[ B = [1.7 \pm 0.8 \pm 0.2] \times 10^{-4} \]

2.8σ deviation

“Tension” in CKM global fit?
Analysis of $B \to \tau \nu_\tau$ with hadronic tag was already made by Belle at smaller data sample (PRL 97, 251802 (2006)).

What is new in this analysis?

- All data reprocessed; better efficiency of low $p_T$ tracks and neutrals reconstruction;
- Increased data sample $449M \Rightarrow 772M$ (factor of 1.7);
- Improved hadronic tagging efficiency due to new algorithm (factor of 2.2);
- Improved signal efficiency due to less restrictive requirements (factor of 1.8);
- 2D fit (residual calorimeter energy $E_{ECL}$ vs missing mass $M_{miss}$) instead of 1D fit (residual energy only);
- Background rejection with reconstructed $K_L$.

NIM A654, 432 (2011)
Analysis procedure

- $\tau^-$ is identified in the $e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$, $\pi^-\nu_\tau$, and $\pi^-\pi^0\nu_\tau$ decay channels;
- No tracks, $\pi^0, K_L$ left in the event after $B_{\text{tag}}, B_{\text{sig}}$ reconstruction;
  - $K_L$ efficiency checked in $D^0 \to \phi K_S, \phi \to K_L K_S$ vs $\phi \to K^+ K^-$;
- Backgrounds were simulated by MC;
- $E_{ECL}, M_{\text{miss}}^2$ distributions were validated in number of samples: sidebands, $B^0$ sample, $B^-_{\text{sig}} \to D^{*0} \ell^- \bar{\nu}_\ell$. 

$E_{ECL}$ and $M_{\text{miss}}^2$ for $B^-_{\text{sig}} \to D^{*0} \ell^- \bar{\nu}_\ell$

Dots with error bars — data

Rectangles — normalized MC
New $B \to \tau\nu_\tau$ study results

- Simultaneous fit to different $\tau$ decay modes.
- Signal yield $N = 62^{+23}_{-22} \pm 6$
- $\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$
- Significance = $3.0\sigma$ including systematic error
- Results for individual decay modes are consistent.
- Result at the data sample used earlier is consistent with the previous result.
Comparison of the $B \to \tau \nu_\tau$ results

Latest Belle result
$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.72^{+0.27}_{-0.25} \pm 0.11] \times 10^{-4}$

Latest Belle average
$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.96 \pm 0.26] \times 10^{-4}$

Measured world average
$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [1.15 \pm 0.23] \times 10^{-4}$

CKM global fit
$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.73^{+0.12}_{-0.07}] \times 10^{-4}$
**Comparison of the $B \to \tau \nu_\tau$ results**

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CKM global fit

\[ \mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = [0.73^{+0.12}_{-0.07}] \times 10^{-4} \]

“Tension” in CKM global fit is reduced (1.6\(\sigma\)).
$B \to \ell \nu$ with hadronic tagging

- SM expectation:
  $\mathcal{B}(B \to e\nu_e) \sim 1 \times 10^{-11}$
  $\mathcal{B}(B \to \mu\nu_\mu) \sim 5 \times 10^{-7}$

- Exclusive hadronic tagging
- Zero events observed
- $\mathcal{B}(B \to e\nu_e) < 3.5 \times 10^{-6}$
  $\mathcal{B}(B \to \mu\nu_\mu) < 2.5 \times 10^{-6}$

- Inclusive tag with 772M $B\bar{B}$
  (PLB 647, 67 (2007))
  $\mathcal{B}(B \to e\nu_e) < 1.7 \times 10^{-6}$
  $\mathcal{B}(B \to \mu\nu_\mu) < 0.98 \times 10^{-6}$
Semileptonic $B \to \bar{D}^{(*)} \tau \nu_\tau$ decays are sensitive to charged Higgs and are complementary to leptonic $B \to \tau \nu$ decay.

To reduce experimental and theoretical uncertainties we use ratio

$$R(D) \equiv \frac{\mathcal{B}(B \to \bar{D} \tau \nu_\tau)}{\mathcal{B}(B \to \bar{D} \ell \nu_\ell)}$$

SM expected values:

$$\mathcal{B}(B \to \bar{D} \tau \nu_\tau) \sim 0.7\%$$

$$\mathcal{B}(B \to \bar{D}^{(*)} \tau \nu_\tau) \sim 1.4\%$$
$B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$ with inclusive tagging

Inclusive tagging is a variant of “full reconstruction” tagging:

- $B_{\text{sig}}$ is reconstructed as $D^{*-} \tau^+$;
- The rest of the event is checked to be consistent with $B$ hypothesis.

The first observation of exclusive $B$ decay due to $b \rightarrow c \tau \nu_\tau$ transition.

$\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau) = (2.02^{+0.40}_{-0.37} \pm 0.37)\%$, $5.2\sigma$ significance
$B^+ \rightarrow \bar{D}(^*)^0 \tau^+ \nu_\tau$ with inclusive tagging

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

- 2D fit to $M_{\text{tag}}$ and $P_D$.

$\mathcal{B}(B^+ \rightarrow \bar{D}^*\tau^+ \nu_\tau) = (2.12^{+0.28}_{-0.27} \pm 0.29)\%,$

8.1$\sigma$ significance

$\mathcal{B}(B^+ \rightarrow \bar{D}^0\tau^+ \nu_\tau) = (0.77 \pm 0.22 \pm 0.12)\%,$

3.5$\sigma$ significance

a), b) $D^*\tau\nu$

c), d) $D^0\tau\nu$

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Dmitri Liventsev – $B \rightarrow \tau\nu$ and related results – 16 / 23
$B^0 \to D^{(*)-} \tau^+ \nu_\tau$ with exclusive tagging

- Exclusive hadronic tagging method;
- Simultaneous extraction of $D$ and $D^*$ yields;
- 2D fit to $M_{miss}^2$ and $E_{ECL}$.

$B^0 \to D\tau \nu$

$M_{miss}^2$:
$E_{ECL} < 0.2\text{GeV}$

$E_{ECL}$:
$M_{miss}^2 > 2.0\text{GeV}^2/c^4$

$B^0 \to D^*\tau \nu$

$B(B^0 \to D^- \tau^+ \nu_\tau) = (1.01_{-0.41}^{+0.46} +0.13 \pm 0.10)\%$, $2.6\sigma$ significance

$B(B^0 \to D^{*-} \tau^+ \nu_\tau) = (2.56_{-0.66}^{+0.75} +0.31 \pm 0.10)\%$, $4.7\sigma$ significance

$R(D^0) = 0.70_{-0.18}^{+0.19} +0.11 \pm 0.09$

$R(D^{*0}) = 0.47_{-0.10}^{+0.11} +0.06$
\[ B^+ \rightarrow \bar{D}^{(*)0}\tau^+\nu_\tau \] with exclusive tagging

- Exclusive hadronic tagging method;
- Simultaneous extraction of \( D \) and \( D^* \) yields;
- 2D fit to \( M_{\text{miss}}^2 \) and \( E_{\text{ECL}} \).

\[
\mathcal{B}(B^+ \rightarrow \bar{D}^{0}\tau^+\nu_\tau) = (1.51^{+0.41}_{-0.39} - 0.19 \pm 0.15)\%, \quad 3.8\sigma \text{ significance}
\]

\[
\mathcal{B}(B^+ \rightarrow \bar{D}^{*0}\tau^+\nu_\tau) = (3.04^{+0.69}_{-0.66} - 0.47 \pm 0.22)\%, \quad 3.9\sigma \text{ significance}
\]

\[
\mathcal{R}(D^-) = 0.48^{+0.22}_{-0.19} + 0.06 - 0.05
\]

\[
\mathcal{R}(D^{*-}) = 0.48^{+0.14}_{-0.12} + 0.06 - 0.04
\]
Combining results from $B \to \tau \nu_\tau$ and $B \to \bar{D}^{(*)}\tau \nu_\tau$ we can constrain charged Higgs model 2HDM type II.

On all figures preferred regions are different.

2HDM type II is excluded?
$B \to \bar{D}^{(*)}\tau\nu_{\tau}$ and SM

**SM**

\[
\mathcal{R}(D) = 0.297 \pm 0.017 \\
\mathcal{R}(D^*) = 0.252 \pm 0.003
\]

**Belle**

\[
\mathcal{R}(D) = 0.430 \pm 0.091 \\
\mathcal{R}(D^*) = 0.405 \pm 0.047
\]

**Deviation**

\[
1.4\sigma \\
3.0\sigma
\]

**Combined**

\[
3.3\sigma
\]

**PRD 85, 094025 (2012)**

**BaBar**

\[
\mathcal{R}(D) = 0.440 \pm 0.058 \pm 0.042 \\
\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018
\]

**Deviation**

\[
2.0\sigma \\
2.7\sigma
\]

**Combined**

\[
3.4\sigma
\]

**PRL 109, 101802 (2012)**

**Belle & BaBar**

\[
\mathcal{R}(D) \\
\mathcal{R}(D^*)
\]

**Deviation**

\[
2.4\sigma \\
3.8\sigma
\]

**Combined**

\[
4.8\sigma
\]
Summary

- $B \rightarrow \tau \nu_\tau$ decay was studied at Belle with different tagging. Results are consistent with each other and BaBar result;
- Recent result is much closer to SM prediction, “tension” in CKM global fit is reduced;
- Results for $B \rightarrow \bar{D}(*)\tau \nu_\tau$ are consistent between tagging types and experiments;
- 2HDM type II seems to be excluded by combination of $B \rightarrow \tau \nu_\tau$ and $B \rightarrow \bar{D}\tau \nu_\tau$ results;
- Results for $R(D(*))$ are different from SM at 4.8$\sigma$ for combination of Belle and BaBar results.
Stay tuned for updated results and upcoming Belle II results.

Thank you!
Comparison of the $B \rightarrow \bar{D}^{(*)}\tau\nu_\tau$ results

- Good agreement between different tagging;
- Good agreement with BaBar:
  $\mathcal{B}(B \rightarrow \bar{D}^*\tau\nu_\tau) = [1.76 \pm 0.13 \pm 0.12]\%$
  $\mathcal{B}(B \rightarrow \bar{D}\tau\nu_\tau) = [1.02 \pm 0.13 \pm 0.11]\%$;
- All results are slightly larger than SM predictions.