Introduction - Physics motivations

Experimental methodology

The $B \to \tau\nu$ measurements

The $B \to D^{(*)}\tau\nu$ measurements
Physics motivations

- Decays $B^+ \to \tau^+ \nu$ and $B \to \bar{D}^{(*)} \tau^+ \nu$ sensitive to new scalar fields (e.g. charged Higgs boson): New Physics at the level of tree diagrams.
Physics motivations

- Decays $B^+ \rightarrow \tau^+ \nu$ and $B \rightarrow \bar{D}(*) \tau^+ \nu$ sensitive to new scalar fields (e.g. charged Higgs boson): New Physics at the level of tree diagrams.

\begin{equation}
\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 f_B^2}{8\pi} |V_{ub}|^2 \tau_{B^+} M_{B^+} m_\ell^2 (1 - \frac{m_\ell^2}{M_{B^+}^2})^2.
\end{equation}

- Depends on: $B$ meson decay constant $f_B$ from lattice and $|V_{ub}|$ from measurement.
- helicity suppressed.

$B^+ \rightarrow \tau^+ \nu$ - New Physics effect

- Potentially sensitive to New Physics effects

\begin{equation}
\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell)_{2HDM} = \mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell)_{SM} \times r_H
\end{equation}

- $r_H = (1 - m_B^2 \frac{\tan^2 \beta}{m_{H^+}^2})^2$. 
Physics motivations

- Decays $B^+ \rightarrow \tau^+ \nu$ and $B \rightarrow \bar{D}^{(*)} \tau^+ \nu$ sensitive to new scalar fields (e.g. charged Higgs boson): New Physics at the level of tree diagrams.

![Tree diagram for $B \rightarrow D^{(*)} \tau^+ \nu$]

$B \rightarrow \bar{D}^{(*)} \tau^+ \nu$

- larger numbers of observable in respect to $B^+ \rightarrow \tau^+ \nu$
- new observable: $\tau$ and $D^*$ polarization, $q^2$ distributions, lepton momentum.
- relatively small hadronic uncertainties (few % in SM frame)

$R$ - BF ratios

$$R(D^{(*)}) \equiv \frac{B(B \rightarrow \bar{D}^{(*)} \tau^+ \bar{\nu}_\tau)}{B(B \rightarrow \bar{D}^{(*)} \ell^+ \bar{\nu}_\ell)}$$
$B^+ \rightarrow \tau^+ \nu$ and $B \rightarrow \bar{D}^{(*)} \tau^+ \nu$ decays in 2HDM-II

$$B = B_{SM} \times r_H$$

$$r_H^{B \rightarrow \tau \nu} = \left( 1 - \frac{m_H^2}{m_{H^\pm}^2} \tan^2 \beta \right)^2$$

$$r_H^{B \rightarrow \bar{D}^{(*)} \tau \nu} = \frac{R}{R_{SM}} = 1 + 1.5 Re(C_{NP}^{\tau}) + 1.1 |C_{NP}^{\tau}|^2$$

$$C_{NP}^{\tau} = -\frac{m_b m_{\tau}}{m_{H^\pm}^2} \frac{\tan^2 \beta}{1 + \varepsilon_0 \tan \beta}$$

The $B \rightarrow \tau \nu$ and $B \rightarrow \bar{D}^{(*)} \tau^{+} \nu$ are sensitive to different range of $\tan \beta / m_{H^\pm}$

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Experimentally challenging

B factories: \( e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B \bar{B} \)

- The reconstruction of \( B_{\text{tag}} \rightarrow \) tags a \( B \bar{B} \) events → reduce combinatorial and continuum(\( q \bar{q}, q = u, d, s, c \)) backgrounds.
- The reconstructed \( B_{\text{tag}} \) allows us to obtain kinematics constraints on \( B_{\text{sig}} (B \rightarrow D^{(*)} \tau \nu) \) momentum:
  \[ \vec{p}_{\text{sig}} = -\vec{p}_{\text{tag}} \Rightarrow p_B \]
- Small reconstruction efficiency (below \( 10^{-2} \))

Different approach for \( B_{\text{tag}} \) reconstructions

\( B_{\text{tag}} \) fully reconstructed in hadronic decays – many exclusive modes used

\( B_{\text{tag}} \) reconstructed in semileptonic \( D^{(*)} \nu \) modes

\( B_{\text{tag}} \) reconstructed inclusively/partially in hadronic or semileptonic modes

→ \( B_{\text{tag}} \) momentum resolution
$B_{\text{sig}}$ reconstruction

\[ B^- \rightarrow \tau^- \bar{\nu}_\tau \]
\[ B' \rightarrow \bar{D}^0 \pi^+ \]
\[ B' \rightarrow K^+ \pi^- \pi^- \]

$E_{\text{ECL}}$ - Extra energy in the calorimeter (Energy left over after $B_{\text{sig}}$ and $B_{\text{tag}}$ reconstruction)

$M^{2}_{\text{mis}}$ - missing mass square

**Exclusive analysis** → **Signal extraction from signal side variable.** - historic nomenclature used in that talk.

Exclusive $B_{tag}$ reconstruction

First we find an event with reconstructed $B_{tag}$ then we check if the rest of the tracks are consistent with signal hypothesis.

**Hadronic decay tags:**

$B_{tag} \rightarrow D(\ast) X (X = \pi, \rho, D_s, \ldots)$

$M_{bc} = \sqrt{E_{beam}^2 - p^2}$

$\Delta E = E - E_{beam}$

**Semileptonic decay tags:**

$B_{tag} \rightarrow D(\ast) \ell \nu \ell$

$\cos \theta_{B,D(\ast) \ell} = \frac{2E_{beam}E_{D(\ast) \ell}^\text{cms} - m_B^2 - M_D^2}{2P_B^\text{cms}P_{D(\ast) \ell}^\text{cms}}$

$
\cos \theta_{B,D(\ast) \ell} = \frac{2E_{beam}E_{D(\ast) \ell}^\text{cms} - m_B^2 - M_D^2}{2P_B^\text{cms}P_{D(\ast) \ell}^\text{cms}}$

$449M$ BBbar

new freq

old freq
$B^+ \rightarrow \tau^+ \nu$ measurements
$B^+ \rightarrow \tau^+ \nu$ by semileptonic tag

**Belle**
- based on 657 M $B\bar{B}$
- $B = (1.54^{+0.38}_{-0.37} +0.29_{-0.31}) \times 10^{-4}$

**BABAR**
- based on 459 M $B\bar{B}$,
- counting method used,
- $B = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$.

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Belle PRD 82, 071101(R) (2010)
BABAR PRD 81, 051101(R) (2010)
Belle

- based on 772 M $B\bar{B}$ (full data sample),
- four $\tau$ decay channels: $e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, $\rho\nu$;
- improved tracking,
- improved tagging (NeuroBayes),
- $K_L$ veto added,
- better understanding of the peaking background,
- signal extracted from 2D fit in $(E_{ECL}, M_{miss}^2)$,
- $B = (0.72^{+0.27}_{−0.25} \pm 0.11) \times 10^{-4}$.
Belle

- based on 468 M $B\bar{B}$ (full data sample),
- four $\tau$ decay channels: $e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, $\rho\nu$;
- improved tagging efficiency - larger set of hadronic tag modes
  - $\times 2$ in respect to previous tagging method
- $B = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$. 

$B^+ \rightarrow \tau^+\nu$ by hadronic tag - BABAR
**$B^+ \rightarrow \tau^+ \nu$ measurements summary**

<table>
<thead>
<tr>
<th>Tag</th>
<th>Measurement 1</th>
<th>Measurement 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic</td>
<td>$B = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$</td>
<td>$B = [1.83^{+0.53}_{-0.49}(\text{stat}) \pm 0.24(\text{syst})] \times 10^{-4}$</td>
</tr>
<tr>
<td>Semileptonic</td>
<td>$B = [1.54^{+0.38}<em>{-0.37}(\text{stat})^{+0.29}</em>{-0.31}(\text{syst})] \times 10^{-4}$</td>
<td>$B = [1.7 \pm 0.8(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Belle combined: $B = (0.96 \pm 0.26) \times 10^{-4}$  
BaBar combined: $B = (1.79 \pm 0.48) \times 10^{-4}$

**Naive world average** $B = (1.15 \pm 0.23) \times 10^{-4}$. 

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$B^+ \rightarrow \tau^+ \nu$ measurements summary

Hadronic tag

Semileptonic tag

Belle combined: $B = (0.96 \pm 0.26) \times 10^{-4}$  
BaBar combined: $B = (1.79 \pm 0.48) \times 10^{-4}$

Naive world average $B = (1.15 \pm 0.23) \times 10^{-4}$. 

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$B \to D^{(*)}_{\tau \nu}$ measurements
**Inclusive $B_{\text{tag}}$ reconstruction**

First we reconstruct $B_{\text{sig}}$ then the left over tracks and clusters in calorimeter are used to $B_{\text{tag}}$ reconstructions.

**Signal extraction based on tag side variables:**

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

Belle $B^- \rightarrow \bar{D}^{*0}\tau^-\nu$:

![Graph showing $M_{\text{tag}}$ distribution](image)

- Of course signal should be also visible on signal side variables ($MM^2$, $D^{(*)}$, $h$ and $\ell$ momentum)

**In Principe less constraints on signal side:**

- less model dependent constraints on signal side distributions or,
- kinematic distributions from fits in $M_{\text{tag}}$ bins

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Inclusive vs Exclusive analysis

**Exclusive**

- lower $B_{\text{tag}}$ efficiency,
- large number the $D(\ast)$ decays channels,
- the $\tau$ decays limited to leptonic decays $\rightarrow \ell \nu \nu$,
- the signal extraction based on $B_{\text{sig}}$ variables.

The latest BABAR analysis is called *inclusive → higher tagging efficiency*, $\rightarrow$ reconstruction starts from $B_{\text{sig}}$.

**Inclusive**

- higher $B_{\text{tag}}$ efficiency,
- only the cleanest $D(\ast)$ decays are used,
- the $\tau^+ \rightarrow \ell^+ \nu \nu$, $\pi^+ \nu$ and $\rho \nu$ decay channels are included,
- the signal extraction based mostly on $B_{\text{tag}}$ variables.

Unfortunately Belle has not yet shown data based on full data set.

All the Belle data below comes from published or presented earlier results.
Signal extraction in the $B \rightarrow \bar{D} \tau^- \nu$ and $B \rightarrow \bar{D}^* \tau^- \nu$ channels.

- large feed-across to $B \rightarrow \bar{D} \tau^+ \nu$ channels from $B \rightarrow \bar{D}^* \tau^- \nu$,
- especially important for $B^+ \rightarrow \bar{D}^0 \tau^+ \nu$ sample.
- $B \rightarrow \bar{D}^* \tau^+ \nu$ channels are clean

Existing studies were oriented to maximize sensitivities not S/N
Branching fraction measurement

PRL 99 (2007) (535 × 10^6)
PRD 82 (2010) (657 × 10^6)
hep-ex/0910.4301 (657 × 10^6)
PRL 109 (2012) (471 × 10^6)

SM expectation
(S. Fajfer, J. Kamenik, I. Nisandzic, PRD 85, 094025 (2012))

private average of Belle results
SM expectations: (S. Fajfer, J. Kamenik, I. Nisandzic, PRD 85, 094025 (2012))

\[ R(D) = 0.297 \pm 0.017, \quad R(D^*) = 0.252 \pm 0.003 \]

private average of Belle results
SM expectations: (S. Fajfer, J. Kamenik, I. Nisandzic, PRD 85, 094025 (2012))

\[ R(D) = 0.297 \pm 0.017, \quad R(D^*) = 0.252 \pm 0.003 \]

**BABAR SM deviations**

- \( R(D^*) \) is 2.7σ
- \( R(D) \) is 2.0σ
- \( R(D^{(*)}) \) is 3.4σ

Observed deviations between observable and SM expectations for \( R(D^*) \) are not only due to improvement of experimental results but also reduction in theoretical uncertainties.


The \( B \to \tau\nu \) and \( B \to D^{(*)}\tau\bar{\nu} \) measurements

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The \( B \to \tau\nu \) and \( B \to D^{(*)}\tau\bar{\nu} \) measurements
**R measurement**

**SM expectations:** (S.Fajfer, J.Kamenik, I.Nisandzic, PRD 85, 094025 (2012))

\[
R(D) = 0.297 \pm 0.017, \quad R(D^*) = 0.252 \pm 0.003
\]

**BABAR SM deviations**
- \(R(\bar{D}^*)\) 2.7\(\sigma\)
- \(R(\bar{D})\) 2.0\(\sigma\)
- \(R(\bar{D}(*)\) 3.4\(\sigma\)

**Belle average SM deviations**
- \(R(\bar{D}^*)\) 3.0\(\sigma\)
- \(R(\bar{D})\) 1.4\(\sigma\)
- \(R(\bar{D}(*)\) 3.3\(\sigma\)

**Belle and BABAR average deviation from SM**
- \(R(\bar{D}^*)\) 3.8\(\sigma\)
- \(R(\bar{D})\) 2.4\(\sigma\)
- \(R(\bar{D}(*)\) 4.8\(\sigma\)

Observed deviations between observable and SM expectations for \(R_{D(*)}\) are not only due to improvement of experimental results but also reduction theoretical uncertainties.


\[
R(D) = 0.316 \pm 0.012 \pm 0.007
\]
Comparison with 2HDM-II

The $B \to \tau \nu$ and $B \to \bar{D}^{(*)} \tau + \nu$ measurements

experimental band $\rightarrow$ acceptance variation with $\tan \beta / m_H^+$
Comparison with 2HDM-II

Experimental band $\rightarrow$ acceptance variation with $\tan \beta/m_H^+$

Acceptance variation with $\tan \beta/m_H^+$ was not included in that plot. Small for exclusive analysis.
Comparison with 2HDM-II

**BABAR**

experimental band $\rightarrow$ acceptance variation with $\tan \beta / m_H^+$

**Belle results**

Acceptance variation with $\tan \beta / m_H^+$ was not included in that plot. Small for exclusive analysis.

- $R(r_H)$ in $B^+ \rightarrow \tau^+ \nu$, $B \rightarrow \bar{D} \tau^+ \nu$ and $B \rightarrow \bar{D}^* \tau^+ \nu$ suggest different values of $\tan \beta / m_H^+$
  - $r_H \rightarrow \approx 0 − 0.1$ or $\approx 0.25$ GeV$^{-1}$
  - $R_D \rightarrow \approx 0.4 − 0.5$ GeV$^{-1}$
  - $R_{D^*} \rightarrow \approx 0.7 − 0.9$ GeV$^{-1}$

- The BABAR collaborations excludes 2HDM-II charged Higgs at 99.8% confidence level for any value of $\tan \beta / m_H^+$ and points on 2HDM-III.
Can we measure kinematic distributions?

The $B \rightarrow \tau \nu$ and $B \rightarrow D^{(*)} \tau + \nu$ measurements...
$q^2$ distributions

\[
\begin{align*}
\text{SM} & \quad \tan \beta / m_{H}^\pm = 0.30 \text{GeV}^{-1} \quad \tan \beta / m_{H}^\pm = 0.45 \text{GeV}^{-1} \\
\end{align*}
\]

- large acceptance correction $\rightarrow$ see BABAR PRD paper:
  - contribution from $B \rightarrow \bar{D}^{*\ast} (\tau^+ / \ell^+) \nu$

<table>
<thead>
<tr>
<th></th>
<th>$B \rightarrow D\tau^+\nu$</th>
<th>$B \rightarrow D^{\ast}\tau^+\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>83.1%</td>
<td>98.8%</td>
</tr>
<tr>
<td>$\tan \beta / m_{H}^\pm = 0.30 \text{GeV}^{-1}$</td>
<td>95.7%</td>
<td>98.9%</td>
</tr>
<tr>
<td>$\tan \beta / m_{H}^\pm = 0.45 \text{GeV}^{-1}$</td>
<td>0.4%</td>
<td>97.9%</td>
</tr>
</tbody>
</table>

Differential distributions for $\ell/h$ and $D^{(*)}$ momentum

Belle PRD 82 (2010)  
BABAR PRL 109 (2012)

- Currently used for signal extraction
Summary

- $B \rightarrow \tau \nu$ and $B \rightarrow D^{(*)} \tau \nu$ are sensitive tool for search NF,
- Recent $B \rightarrow \tau \nu$ results have weakened the tension with other measurements (CKM fits) $B \rightarrow \tau \nu$,
- The $R^{(*)}/BF$ measurement shows discrepancies from SM expectations (especially for $B \rightarrow D^{*} \tau \nu$ decays) \rightarrow result improvement but also theory errors reduced.
- Current measurement are inconsistent with 2HDM-II models, complementary channels are pointing for different $\tan \beta / m_{H^\pm}$ values (problem for MSSM ?)
- We can measure some kinematic distributions for $B \rightarrow D^{(*)} \tau \nu$ based on B- factory data sets, $q^2$, $|p_\ell|$, $|p_D^{(*)}|$.

The new results from Belle, based on full statistic, is due soon.

Belle II - run starts in 2016

- It is important to improve the measurement of $B \rightarrow \tau \nu$ and $B \rightarrow D^{(*)} \tau \nu$ up to the level of few %.
- Improved measurement of kinematic distributions for $B \rightarrow D^{(*)} \tau \nu$ would allow to probe New Physics scenarios by looking to the correlations between different observables,
The $B \to \tau \nu$ and $B \to \bar{D}(\ast) \tau + \nu$ measurements
Tau polarization measurement

The $B \to \tau \nu$ and $B \to \bar{D}(*) \tau + \nu$ measurements

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### $B \rightarrow D^{(*)\tau\nu}$ results

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$B$ [%]</th>
<th>$R$</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B^+ \rightarrow D^{*0\tau+\nu\tau}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belle incl.</td>
<td>$2.12^{+0.28}_{-0.27} \pm 0.29$</td>
<td>$0.372^{+0.049}_{-0.047} \pm 0.057$ (*)</td>
<td></td>
</tr>
<tr>
<td>Belle excl.</td>
<td>$2.68^{+0.63}<em>{-0.57}^{+0.34}</em>{-0.40} \pm 0.09$ (*)</td>
<td>$0.47^{+0.11}<em>{-0.10}^{+0.06}</em>{-0.07}$</td>
<td></td>
</tr>
<tr>
<td>Belle average</td>
<td>$2.24 \pm 0.29 \pm 0.15$</td>
<td>$0.393 \pm 0.051 \pm 0.027$</td>
<td></td>
</tr>
<tr>
<td>$BABAR$</td>
<td>$1.71 \pm 0.17 \pm 0.13$</td>
<td>$0.322 \pm 0.032 \pm 0.022$</td>
<td></td>
</tr>
<tr>
<td>WA</td>
<td>-</td>
<td>$0.344 \pm 0.036$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$B^0 \rightarrow D^{*\tau+\nu\tau}$</td>
<td></td>
<td></td>
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<tr>
<td>Belle incl.</td>
<td>$2.02^{+0.40}_{-0.37} \pm 0.37$</td>
<td>$0.408^{+0.081}_{-0.075} \pm 0.077$ (*)</td>
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<tr>
<td>Belle excl.</td>
<td>$2.38^{+0.69}<em>{-0.59}^{+0.30}</em>{-0.20} \pm 0.05$ (*)</td>
<td>$0.48^{+0.14}<em>{-0.12}^{+0.06}</em>{-0.04}$</td>
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<tr>
<td>Belle average</td>
<td>$2.24 \pm 0.29 \pm 0.15$</td>
<td>$0.393 \pm 0.051 \pm 0.027$</td>
<td></td>
</tr>
<tr>
<td>$BABAR$</td>
<td>$1.74 \pm 0.19 \pm 0.12$</td>
<td>$0.355 \pm 0.039 \pm 0.021$</td>
<td></td>
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<tr>
<td>WA</td>
<td>-</td>
<td>$0.372 \pm 0.039$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$B^+ \rightarrow D^0\tau+\nu\tau$</td>
<td></td>
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<tr>
<td>Belle incl.</td>
<td>$0.77 \pm 0.22 \pm 0.12$</td>
<td>$0.341^{+0.097}_{-0.097} \pm 0.063$ (*)</td>
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<tr>
<td>Belle excl.</td>
<td>$1.58^{+0.43}<em>{-0.41}^{+0.25}</em>{-0.20} \pm 0.08$ (*)</td>
<td>$0.70^{+0.19}<em>{-0.18}^{+0.11}</em>{-0.09}$</td>
<td></td>
</tr>
<tr>
<td>Belle average</td>
<td>$0.95 \pm 0.21 \pm 0.08$</td>
<td>$0.420 \pm 0.091 \pm 0.034$</td>
<td></td>
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<tr>
<td>$BABAR$</td>
<td>$0.99 \pm 0.19 \pm 0.13$</td>
<td>$0.429 \pm 0.082 \pm 0.052$</td>
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<tr>
<td>WA</td>
<td>-</td>
<td>$0.425 \pm 0.069$</td>
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<tr>
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<td>$B^0 \rightarrow D^-\tau+\nu\tau$</td>
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<tr>
<td>Belle excl.</td>
<td>$1.04^{+0.48}<em>{-0.41}^{+0.13}</em>{-0.11} \pm 0.06$</td>
<td>$0.48^{+0.22}<em>{-0.19}^{+0.06}</em>{-0.05}$ (*)</td>
<td></td>
</tr>
<tr>
<td>$BABAR$</td>
<td>$1.01 \pm 0.18 \pm 0.12$ (*)</td>
<td>$0.469 \pm 0.084 \pm 0.053$</td>
<td></td>
</tr>
<tr>
<td>WA</td>
<td>-</td>
<td>$0.471 \pm 0.090$</td>
<td></td>
</tr>
</tbody>
</table>
The $B \rightarrow \tau \nu$ and $B \rightarrow D^{(*)} \tau + \nu$ measurements

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Accumulate Luminosity

> 1 ab$^{-1}$

On resonance:
$\Upsilon(5S)$: 121 fb$^{-1}$
$\Upsilon(4S)$: 711 fb$^{-1}$
$\Upsilon(3S)$: 3 fb$^{-1}$
$\Upsilon(2S)$: 24 fb$^{-1}$
$\Upsilon(1S)$: 6 fb$^{-1}$

Off resonance/scan:
$\sim 100$ fb$^{-1}$

$\sim 550$ fb$^{-1}$

On resonance:
$\Upsilon(4S)$: 433 fb$^{-1}$
$\Upsilon(3S)$: 30 fb$^{-1}$
$\Upsilon(2S)$: 14 fb$^{-1}$

Off resonance:
$\sim 54$ fb$^{-1}$

The $B \to \tau\nu$ and $B \to D^{(*)}\tau^{+}\nu$ measurements
Charged Higgs search

The extended Higgs sector models contain charged $H^\pm$ bosons.

In the simplest extension of the SM, New Physics is coming from new scalar fields → 2HDM

The so called 2HDM of type II - One of the Higgs doublets is coupled with upper quarks, second to lower quarks. Same structure is the base of MSSM.

$tan\beta \equiv \frac{v_2}{v_1}$
$v_1, v_2$ - vacuum expectation

Belle II exclusion region from $B^+ \rightarrow \tau^+ \nu$ decays.