B to semitauonic decays at Belle/Belle II

Outline:

- Physics motivation & experimental situation
- Polarization measurements in $B \rightarrow D^* \tau \nu$ by Belle
- Prospects for Belle/Belle II

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Physics motivation

Observables

\[ R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau^+ \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} \ell^+ \nu_\ell)} \]

\[ F_{LD}^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_L^*) + \Gamma(D_T^*)} \]

\( F_{LD}^{D^*} \): fraction of longitudinal polarization of \( D^* \)

SM: \( F_{LD}^{D^*} = [0.44 - 0.46] \pm 10\% \)

\[ P_\tau = \frac{\Gamma(\lambda_\tau = +1/2) - \Gamma(\lambda_\tau = -1/2)}{\Gamma(\lambda_\tau = +1/2) + \Gamma(\lambda_\tau = -1/2)} \]

SM: \( P_\tau(D^*) \approx -0.5 \)

New Physics scenarios

CKM, September 19, 2019

September 18, 2018
The Belle Experiment

**KEKB**

**Belle detector - multipurpose large-solid-angle magnetic spectrometer**

**KEKB B-factory - asymmetric e\(^+\) e\(^-\) collider**

\[ e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \quad (772 \times 10^6 \; B\bar{B}) \]

- clean source of \(B\) meson pairs
- reconstruction of one \(B\) meson (\(B_{\text{tag}}\)) provides information on momentum vector and other quantum numbers of another \(B\) (\(B_{\text{sig}}\))

\[ E_B = E_{\text{beam}} = \frac{\sqrt{s}}{2} \]
Experimental techniques

Tagging techniques

- **Inclusive**
  \[ B \to \text{hadrons} \text{ (inclusive modes)} \]
  \[ \epsilon \approx O(1\%) \]

- **Semileptonic**
  \[ B \to D(\ast)\ell\nu_\ell \]
  \[ \epsilon \approx O(0.3\%) \]
  (Y. Sato: PRD 94, 072007, (2016).)

- **Hadronic**
  \[ B \to \text{hadrons} \text{ (exclusive modes)} \]
  \[ \epsilon \approx O(0.1\%) \]
Experimental situation

\[ R(D^{(*)}) = \frac{\mathcal{B}(B \to \bar{D}^{(*)} \tau^+ \nu_\tau)}{\mathcal{B}(B \to \bar{D}^{(*)} \ell^+ \nu_\ell)} \]

\[ \ell = e, \mu : \text{normalization} \]

SM predictions

\[ R(D^{*})^{SM} = \frac{\mathcal{B}(B \to \bar{D}^{*} \tau^+ \nu_\tau)}{\mathcal{B}(B \to \bar{D}^{*} \ell^+ \nu_\ell)} = 0.258 \pm 0.005 \]
\[ R(D)^{SM} = \frac{\mathcal{B}(B \to \bar{D} \tau^+ \nu_\tau)}{\mathcal{B}(B \to \bar{D} \ell^+ \nu_\ell)} = 0.299 \pm 0.003 \]

HFLAV

\[ R_D = 0.407 \pm 0.039_{stat} \pm 0.024_{syst} \]
\[ R_{D^*} = 0.306 \pm 0.013_{stat} \pm 0.007_{syst} \]

deviation from SM:
\[ \sim 2.3\sigma \text{ for } R(D) \]
\[ \sim 3.4\sigma \text{ for } R(D^*) \]
\[ \sim 4\sigma \text{ tension between SM and combined } R(D^{(*)}) \text{ by BaBar, Belle and LHCb} \]
Kinematic variables describing $B \to D^* \tau \nu$

$q^2 \equiv M_W^2$ - effective mass squared of the $\tau \nu$ system

$\theta_{\tau}$ - angle between $\tau$ & $B$ in $W^*$ rest frame

$\chi$ - angle between the $\tau \nu$ and $D^*$ decay planes

$\theta_{\text{hel}}(D^*)$ - angle between $D$ & $B$ in $D^*$ rest frame

$\theta_{\text{hel}}(\tau)$ - angle between $\pi$ & direction opposite to $W^*$ in $\tau$ rest frame

\[
\frac{d\Gamma}{d\cos\theta_{\text{hel}}(\tau)} = \frac{1}{2} \left( 1 + \alpha P_\tau \cos \theta_{\text{hel}}(\tau) \right)
\]
\[
\alpha = 1.0 \text{ for } \tau \to \pi \nu; \quad \alpha = 0.45 \text{ for } \tau \to \rho \nu
\]

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_{\text{hel}}(D^*)} = \frac{3}{4} \left[ 2 F_{L}^{D^*} \cos^2(\theta_{\text{hel}}(D^*)) + (1 - F_{L}^{D^*}) \sin^2(\theta_{\text{hel}}(D^*)) \right]
\]

$M_W^2$, $M_M^2$ and $\cos \theta_{\text{hel}}(\tau)$, $\cos \theta_{\text{hel}}(D^*)$ can be reconstructed at B-factories with hadronic decays of $B_{\text{tag}}$
Measurement of $\tau$ polarization in B decays


- both $\bar{B}^0$ and $B^-$ decays are used;
- only 2 body $\tau$ decays: $\tau \to \pi \nu, \rho \nu$
- sample divided into two bins of $\cos \theta_{\text{hel}}$:
  I: $-1 < \cos \theta_{\text{hel}} < 0$;
  II: $0 < \cos \theta_{\text{hel}} < 0.8$ (for $\tau \to \pi \nu$)

Experimental challenges

- Distribution of $\cos \theta_{\text{hel}}(\tau)$ is modified by:
  - cross-feeds from other $\tau$ decays (contribute mainly in the region of $\cos \theta_{\text{hel}}(\tau) < 0$)
  - peaking background (concentrated around $\cos \theta_{\text{hel}}(\tau) \approx 1$)
- corrections for detector effects: acceptance, asymmetric $\cos \theta_{\text{hel}}$ bins, crosstalks between different $\tau$ decays
- for $\tau \to \pi(\rho)\nu$ modes combinatorial background from poorly known hadronic B decays

\[
P_{\tau} = \frac{2}{\alpha} \frac{\Gamma_{\cos \theta_{\text{hel}}>0} - \Gamma_{\cos \theta_{\text{hel}}<0}}{\Gamma_{\cos \theta_{\text{hel}}<0} + \Gamma_{\cos \theta_{\text{hel}}>0}}
\]
Result on $P_\tau(D^*)$


$P_\tau(D^*) = -0.38 \pm 0.51 \text{(stat.)}^{+0.21}_{-0.16} \text{(syst.)}$

$R(D^*) = 0.270 \pm 0.035 \text{(stat.)}^{+0.028}_{-0.025} \text{(syst.)}$

- first measurement of $P_\tau(D^*)$; the result excludes $P_\tau(D^*) > +0.5$ at 90% C.L.
- combined $R(D^*)$ and $P_\tau(D^*)$ result is consistent with the SM within 0.6$\sigma$

dominant systematics:
- hadronic B decays composition $(+0.13, +7.6\%)^{-0.10, -6.8\%}$
- MC stat. for PDF shapes
**D**\(^*\) polarization studies

\(R(D^{(*)})\) systematically above the SM expectations, surprisingly large effect for \(R(D^*) \rightarrow D^*\) polarization measurement

Measure \(F_{L}^{D^*}\) from fit to \(\cos \theta_{\text{hel}}(D^*)\) distribution:

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{\text{hel}}(D^*)} = \frac{3}{4} \left[ 2F_{L}^{D^*} \cos^2(\theta_{\text{hel}}(D^*)) + (1 - F_{L}^{D^*}) \sin^2(\theta_{\text{hel}}(D^*)) \right]
\]

In comparison to \(\tau\) polarization:

- all \(\tau\) decays are useful \(\rightarrow\) larger statistic
- not affected by cross-feeds between different \(\tau\) decays

Theoretical papers (\(D^*\) polarization studies):

Challenges for $D^*$ polarization measurement

Main experimental problem: strong acceptance effects for $\cos \theta_{hel}(D^*) \geq 0.0$

Efficiency distribution of slow $\pi^\pm$ from $D^*$

Effectively only $\cos \theta_{hel}(D^*) < 0$ is useful for $F_L^{D^*}$ measurement
$D^*$ polarization - analysis method

- Extract signal yield in bins of $\cos \theta_{hel}(\tau)$ in the range of $-1 < \cos \theta_{hel}(\tau) < 0$
- Extract $F_L$ from fit to $\cos \theta_{hel}(D^*)$ distribution

- Employ **inclusive** $B_{tag}$ reconstruction method
- Select clean decay chains:
  - $B^0 \rightarrow D^{*-}(\rightarrow D^0 \pi^-)\tau^+\nu$;
  - $D^0 \rightarrow K\pi, K\pi\pi^0, K\pi\pi\pi$;
  - $\tau \rightarrow e\nu\nu; \mu\nu\nu; \pi\nu$
Method of **inclusive** reconstruction of $B_{\text{tag}}$

1. Create candidates for $B_{\text{sig}}$ daughters: $D^* + (d_\tau = h$ or $\ell)$
2. Reconstruct $B_{\text{tag}}$ inclusively form all remaining particles

$$E_{\text{tag}} = \sum_i E_i \quad p_{\text{tag}} = \sum_i p_i$$

consistency of $B_{\text{tag}}$ candidates checked using $M_{\text{tag}} = \sqrt{E_{\text{beam}}^2 - p_{\text{tag}}^2}$,

$$\Delta E_{\text{tag}} = E_{\text{beam}} - E_{\text{tag}}$$

3. Suppres bkg using observables sensitive to multiple neutrion final states (e.g. visible energy, missing mass, ...)

4. Extract number of signal events by fitting $M_{\text{tag}}$ distribution

This approach allows for signal extraction using **known** PDF's (CrystalBall and Argus) parametrizations;
Signal extraction

- the signal yields are extracted from a simultaneous, extended UML-fit to all 9 sub-channels in the $M_{\text{tag}}$ distributions
- procedure is performed in 3 bins of $\cos \theta_{\text{hel}}(D^*)$ in the range [-1,0];
  I : $-1.0 < \cos \theta_{\text{hel}}(D^*) < -0.67$
  II : $-0.67 < \cos \theta_{\text{hel}}(D^*) < -0.33$
  III : $-0.33 < \cos \theta_{\text{hel}}(D^*) < 0.0$
- example fit projection to $M_{\text{tag}}$ distribution in the range $-1.0 < \cos \theta_{\text{hel}}(D^*) < -0.67$
Result on $F_{L}^{D^*}$ for $B^0 \rightarrow D^* \tau \nu$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{\text{hel}}(D^*)} = \frac{3}{4} \left[ 2F_{L}^{D^*} \cos^2(\theta_{\text{hel}}(D^*)) + (1 - F_{L}^{D^*}) \sin^2(\theta_{\text{hel}}(D^*)) \right]$$

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<tbody>
<tr>
<td>Entries</td>
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<td>Mean</td>
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<tr>
<td>RMS</td>
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<td>$\chi^2$/ndf</td>
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<td>p0</td>
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Number of events in:
I bin: 151±21
II bin: 125±19
III bin: 55±15
- signal yields corrected for acceptance variations

Dominant systematics:
- MC statistics (AR shape and peaking background) = ±0.03

$$F_{L}^{D^*} = 0.60 \pm 0.08(\text{stat.}) \pm 0.035(\text{syst.})$$

SM: $F_{L}^{D^*} = 0.46 \pm 0.03$ (Phys. Rev. D 95, 115038 (2017), A.K. Alok, et al) (1.5 $\sigma$)
SM: $F_{L}^{D^*} = 0.441 \pm 0.006$ (arXiv:1808.03565, Z-R. Huang, et al) (1.8 $\sigma$)

$\Rightarrow$ consistent with the SM within 2$\sigma$
Prospects @ Belle

- $F_{L}^{D^*}$ also for $B^{\pm}$

- simultaneous measurement of $R(D)$ and $R(D^*)$ with semileptonic tag
  - in the previous analysis only: $B^0\overline{B}^0 \rightarrow (D^*\ell^+)(D^{*+}\ell^-)$
  - add B decays modes: $B^0\overline{B}^0 \rightarrow (D^-\ell^+)(D^{+}\ell^-))$
    $B^+B^- \rightarrow (\overline{D}^{(*)0}\ell^+)(D^{(*)0}\ell^-))$

\[
R(D^{(*)}) = \frac{B(B \rightarrow D^{(*)}\tau^+\nu_\tau)}{B(B \rightarrow D^{(*)}\ell^+\nu_\ell)} = \frac{\text{signal}}{\text{normalization}}
\]

analysis made in BASF2 (Belle II software framework) using FEI (Full Event Interpretation - a new exclusive tagging algorithm for multivariate analysis with BDT classifier)

more details about FEI
in Moritz Gelb talk on "B to l nu gamma at Belle"
Prospects @ Belle II


- **Belle**: $0.772 \times 10^9 \, |B\bar{B}|$
- **Belle II**: $\sim 50 \times 10^9 \, |B\bar{B}| \times (50^{-1} \, \text{ab})$

- **expected number of events for** $P_\tau(D^*)$ **measurement**:
  - $\sim 4000$ in $B^0(\bar{B}^0)$ mode (hadronic $B_{\text{tag}}$ reconstruction)
  - $\sim 10000$ in $B^+(\bar{B}^-)$ mode (hadronic $B_{\text{tag}}$ reconstruction)

- **expected number of events for** $F_L^{D^*}$ **measurement**:
  - $\sim 15000$ in $B^0(\bar{B}^0)$ mode (inclusive $B_{\text{tag}}$ reconstruction)

- **expected precision** (the statistical and systematic errors respectively)

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<tr>
<th></th>
<th>5 ab$^{-1}$</th>
<th>50 ab$^{-1}$</th>
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<tbody>
<tr>
<td>$R_D$</td>
<td>$(\pm 6.0 \pm 3.9)%$</td>
<td>$(\pm 2.0 \pm 2.5)%$</td>
</tr>
<tr>
<td>$R_{D^-}$</td>
<td>$(\pm 3.0 \pm 2.5)%$</td>
<td>$(\pm 1.0 \pm 2.0)%$</td>
</tr>
<tr>
<td>$P_\tau(D^*)$</td>
<td>$\pm 0.18 \pm 0.08$</td>
<td>$\pm 0.06 \pm 0.04$</td>
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Prospects @ Belle II


- expected constraints on $R_D$ vs. $R_{D^*}$; $R_{D^*}$ vs. $P_T^{D^*}$ compared to existing experimental constraints from Belle

- higher statistics and better reconstruction efficiencies should allow for precise measurements of kinematic distributions, e.g. $q^2$ and polarizations
Summary

- $R(D)$, $R(D^*)$, $P_\tau(D^{(*)})$ and $F_{L}^{D^*}$ in $\bar{B} \rightarrow D^{(*)}\tau\nu$ are good probes for NP

- Measurement of $\tau$ polarization:

  $$P_\tau(D^*) = -0.38 \pm 0.51 (\text{stat.})^{+0.21}_{-0.16} (\text{syst.})$$

- First measurement of $D^*$ polarization in $B^0(\bar{B}^0) \rightarrow D^{*}\tau\nu$

  $$F_{L}^{D^*} = 0.60 \pm 0.08 (\text{stat.}) \pm 0.035 (\text{syst.})$$

- Measurements sensitivity limited by the statistics

- Measurements of characteristics of semitauonic B decays will be important topic @ Belle II
BACKUP
$D^*$ polarization - NP scenarios

- SM: $F_L^{D^*} = 0.46 \pm 0.03$ (Phys. Rev. D 95, 115038 (2017), A.K. Alok, et al)
SM: $F_L^{D^*} = 0.441 \pm 0.006$ (arXiv:1808.03565, Z-R. Huang, et al)

- $F_L^{D^*}$ can be significantly modified in the presence of NP contributions; in particular $F_L^{D^*}$ is enhanced (decreased) by the scalar(tensor) operators

Phys. Rev. D 95, 115038
Momentum spectra to examine NP scenarios

Phys. Rev. D 94, 072007 (2016); semileptonic $B_{\text{tag}}$

- Measured distributions of $p_{D^*}$ and $p_l$ consistent with SM but statistically limited
- More observables with more data needed to clarify the situation
Background calibration

Sources of peaking background: $D^* \ell \nu$, $D^{**} \ell \nu$

Phase space divided in four regions:

<table>
<thead>
<tr>
<th>Region</th>
<th>Conditions</th>
<th>Description</th>
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<tbody>
<tr>
<td>I</td>
<td>$X_{\text{mis}} &lt; 0.5$</td>
<td>$M_{\text{tag}} &gt; 5.26 \text{ GeV}$ background from semileptonic B decays</td>
</tr>
<tr>
<td>II</td>
<td>$X_{\text{mis}} &gt; 0.5$</td>
<td>$M_{\text{tag}} &gt; 5.26 \text{ GeV}$ (blinded)</td>
</tr>
<tr>
<td>III</td>
<td>$X_{\text{mis}} &lt; 0.5$</td>
<td>$M_{\text{tag}} &lt; 5.26 \text{ GeV}$ background from hadronic B decays</td>
</tr>
<tr>
<td>IV</td>
<td>$X_{\text{mis}} &gt; 0.5$</td>
<td>$M_{\text{tag}} &lt; 5.26 \text{ GeV}$</td>
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$X_{\text{mis}} = \frac{E_{\text{mis}} - |\vec{p}_{D^*} + \vec{p}_h|}{\sqrt{E_{\text{beam}}^2 - M_B^2}}$ (similar to $M_M^2$)

$E_{\text{mis}} = E_{\text{beam}} - E_{D^*} - E_h$

Simultaneous fit to the following variables: $M_{\text{tag}}, X_{\text{mis}}, \Delta E, M_W^2, \pi$ energy, $D^*$ energy, $R_2$, $m_{D^*\pm} - m_{D^0}$

→ find scale factors for bkg components

CKM, September 19, 2019
Example distributions for final selection criteria
(e.g. $D^* \mu$ sample in $-0.67 < \cos \theta_{\text{hel}}(D^*) < -0.33$)
Signal box opening - extraction of signal yield

DATA: number of events in I bin: 151±21