Improved study of $\bar{B} \rightarrow D^{(*)}\tau\bar{\nu}$ with vertexing at Belle II

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On behalf of the Belle II Collaboration

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Introduction

Largest cross section for $\tau$ production in $B$ decays

Sensitive to new physics that couples more strongly to heavy fermions (e.g., charged Higgs)

Important physics at LHCb and Belle II

$R(D^{(*)}) \equiv \frac{Br(\bar{B} \rightarrow D^{(*)}\tau\bar{\nu})}{Br(\bar{B} \rightarrow D^{(*)}\ell\bar{\nu})}$: currently $3.8\sigma$ from SM prediction[1]

An important background is $\bar{B} \rightarrow D^{**}\ell\bar{\nu}$

$D^{**}$(Excited charm state) $\rightarrow D^{(*)} +$ pions/eta (when unobserved)

In this talk, we will mostly focus $\bar{B} \rightarrow D^{**}\ell\bar{\nu}$ background at Belle II using precise vertexing.

[1]:arXiv:1709.00129:Belle
Belle IIOverview so far

- Belle II is an $e^+e^-$ collider experiment operating primarily at the Y(4S) resonance.
- Produces $B\bar{B}$ and $\tau^+\tau^-$ pairs, as well as $q\bar{q}$ background.
- Phase 2 is currently in progress:
  - All Belle II subdetectors except vertex detector.
  - D and B meson “rediscovery” in progress.

$$\cos\theta_{BY} = \frac{2E_B^*E_Y^*-M_B^2-m_Y^2}{2p_b^*p_Y^*}$$

Plot by Minakshi Nayak.
Full Event reconstruction is helpful in missing energy studies and reducing backgrounds.

These study uses Belle II’s improved reconstruction algorithm.

This Hadronic full reconstruction is expected to be used for:

- semi-leptonic and semi-tauonic modes for $R(D^{(*)})$
- $B \to \tau \nu$ decays

**Missing Energy**

\[ m^2_{\text{miss}} = (p_{ee} - p_{\text{tag}} - p_D - p_\ell)^2 \]

* This image is taken from Sophie Hollitt’s talk at ICHEP2018
$m_{miss}^2$ and $\bar{B} \to D^{**} \ell \bar{\nu}$ background

- Relative efficiencies
  - $R(D) = 5.0$, $R(D^*) = 2.0$

- Branching ratios
  - $Br(D^{**} \to D^{(*)} \pi^0/\pi^\pm) = 0.7$, $0.5$
  - $Br(D^{**} \to D^{(*)} \pi\pi) = 2.1$, $2.6$
  - $Br(\bar{B} \to D^{**} \ell \bar{\nu}) = 0.8$, $0.3$
  - $Br(\bar{B} \to D^{**} \tau \bar{\nu}) = 1.8$, $1.7$

- $\sim 1.3 - 3.3\%$ error in Belle [2] and LHCb [3] analyses with $\tau \to \ell \nu \bar{\nu}$

At Belle II ...

- $2\%$ will already be a large error with $5 \text{ ab}^{-1}$

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### Known $D^{**}$ states

<table>
<thead>
<tr>
<th>State</th>
<th>~Width (MeV)</th>
<th>$J^P$</th>
<th>Seen/allowed decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_0^*(2400)$</td>
<td>270</td>
<td>$0^+$</td>
<td>$D\pi, D\eta$</td>
</tr>
<tr>
<td>$D_1(2420)$</td>
<td>27</td>
<td>$1^+$</td>
<td>$D^<em>\pi, D\pi\pi, D^</em>\pi\pi$</td>
</tr>
<tr>
<td>$D_1'(2430)$</td>
<td>380</td>
<td>$1^+$</td>
<td>$D^<em>\pi, D^</em>\eta, D^{(*)}\pi\pi$</td>
</tr>
<tr>
<td>$D_2^*(2460)$</td>
<td>50</td>
<td>$2^+$</td>
<td>$D^{(<em>)}\pi, D^{(</em>)}\pi\pi, D^{(*)}\eta$</td>
</tr>
<tr>
<td>$D(2550)$</td>
<td>130</td>
<td>$0^-$</td>
<td>$D^*\pi$</td>
</tr>
<tr>
<td>$D(2600)$</td>
<td>90</td>
<td>??</td>
<td>$D^{(*)}\pi$</td>
</tr>
<tr>
<td>$D^*(2640)$</td>
<td>&lt; 15</td>
<td>??</td>
<td>$D^*\pi\pi$</td>
</tr>
<tr>
<td>$D(2750)$</td>
<td>65</td>
<td>??</td>
<td>$D^{(*)}\pi$</td>
</tr>
</tbody>
</table>

- Exclusive $\bar{B} \rightarrow D^{**} \ell\bar{\nu}$ decays observed only for the 4 lightest resonances
- Non-resonant $\bar{B} \rightarrow D^{**} \ell\bar{\nu}$ decays

$m_{miss}^2$ shape in the fit depends on our assumption. We need a model-independent handle on $\bar{B} \rightarrow D^{**} \ell\bar{\nu}$ background in $\bar{B} \rightarrow D^{(*)}\tau\bar{\nu}$
Distance between B vertex and lepton

Signal:

\[ \bar{\nu}_\tau \rightarrow \bar{B} \rightarrow \tau \rightarrow \nu_\tau \bar{\nu}_\ell \]

Background:

\[ \bar{\nu}_\tau \rightarrow \bar{B} \rightarrow \bar{\nu}_\ell \rightarrow D^{*} \rightarrow D^{(*)} \pi \]
Distance between B vertex and lepton

Signal:

\[ \bar{v}_\tau \rightarrow D^{(*)} \]
\[ \bar{B} \rightarrow \tau \nu_\tau \bar{\nu}_\ell \]
\[ \bar{\nu}_\ell \]

Background:

\[ \bar{v}_\tau \rightarrow D^{**} \rightarrow D^{(*)}\pi \]
\[ \bar{B} \rightarrow \bar{\nu}_\ell \]
\[ \ell \]

- Belle II spatial resolution is twice as good as @ BABAR/Belle.
- Pixels @ \( r = 14 \)mm:
- Nanobeam collision scheme:

- Average \( \tau \) flies only \( 45 \) \( \mu \)m, less than the Belle II spatial resolution,
- S-B separation weaker than for \( m_{\text{miss}}^2 \) etc.
- But exploit model independence to check \( \bar{B} \rightarrow D^{**} \ell \bar{\nu} \) yield in the analysis fit
Distance between B vertex and lepton

Signal:
\[ \bar{\nu}_\tau \rightarrow D^{(*)} \]

Exploit:
- Reconstruction of recoil B
- Very small beamspot
- Detector spatial resolution

Background:
\[ \bar{\nu}_\tau \rightarrow D^{**} \rightarrow D^{(*)}\pi \]
- Not a complete analysis
- Studies only the separation between signal and $\bar{B} \rightarrow D^{**}\ell\bar{\nu}$
- Study only $B^- \rightarrow D^0\tau^-\bar{\nu}$ (signal) $B^- \rightarrow D^{**0}\ell^-\bar{\nu}$ (background)
- Assume correct tag-B and signal-B reconstruction
- Misreconstruction background is already handled with other analysis variables
- Results reflect a current snapshot of the reconstruction and analysis software
Signal-B position resolution

\[ \sigma_x = 27 \, \mu m \]

Belle II Simulation

\[ x_{reco} - x_{true} \, (\mu m) \]

Arbitrary units

\[ \sigma_x = 24 \, \mu m \]

Belle II Simulation

\[ y_{reco} - y_{true} \, (\mu m) \]

Arbitrary units

\[ \sigma_x = 37 \, \mu m \]

Belle II Simulation

\[ z_{reco} - z_{true} \, (\mu m) \]

Arbitrary units

- \( D\tau\bar{\nu} \)
- \( D^{**}\ell\bar{\nu} \)
The distance $d$ in $\tau \rightarrow \ell \nu \bar{\nu}$

- Signal-Background separation is partly due to larger signal $\sigma_d$, which is due mostly to the softer lepton.
- We focus on $p_\ell$ and see the correlation with $\sigma_d$. 

sourav dey (TAU, Israel)
The distance $d$ in $\tau \rightarrow \ell \nu \bar{\nu}$

After reweighting background events by lepton momentum:

- The S-B separation is small
- But sufficient for verifying that the kinematic-variable fit gives the correct fraction of non-$\tau$ events.

- Approximating signal and background yields from the BABAR analysis scaled to Belle II luminosity ($\times 100$), we find that a fit to the $d$ distribution gives the prompt-lepton background yield with a $\sim 10\%$ error per mode $(D^0, D^+, D^{*0}, D^{*+})$
The distance \( d \) in \( \tau \rightarrow 3\pi \nu \)

Simulated background chosen just to test the capability to “see” the \( \tau \) displacement:
\( B \rightarrow D3\pi2\nu \) with same kinematic distributions as signal

3-track vertex has much better resolution than single lepton:

Also measure the angle \( \theta \) b/w \( \vec{d} \) and \( \vec{p}_{3\pi} \)

in background, \( \tau \) is replaced by \( \rho(3s)^- \)
Summary

- $\bar{B} \to D^{(*)}\tau\bar{\nu}$ is an important part of the the physics programs of Belle II and LHCb.
- In the $\tau \to \ell\nu\bar{\nu}$ mode, $\bar{B} \to D^{**}\ell\bar{\nu}$ background presents a systematic challenge.
- Exploit Belle II’s spatial resolution and small beamspot to obtain a new, model-independent handle on this background: distance, between the signal-$B$ decay position and the lepton.
- In the $\tau \to 3\pi\nu$ mode, 3 pions give improved precision on d and additional background suppression from the angle $\theta$ between d and the 3-pion momentum vector.
- Even better resolution expected for $\bar{B} \to \tau\bar{\nu}$. Currently under study.