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

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\( \bar{B} \to D(*)\tau\bar{\nu} \) 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
- In addition, \( R(D(*)) \equiv \frac{Br(B\to D(*)\tau\nu)}{Br(B\to D(*)\ell\nu)} \) are currently 3.8\( \sigma \) from SM prediction
  
- An important background is \( \bar{B} \to D^{**}\ell\bar{\nu} \)
  
- Most of this talk focuses on addressing the \( \bar{B} \to D^{**}\ell\bar{\nu} \) background at Belle II using precise vertexing.
Hadronic recoil-B reconstruction in $e^+e^- \rightarrow \bar{B}B$ events

- Reconstructing the event in full is very useful in missing energy studies to constrain the event and reduce backgrounds
- Multiple channels for tag-side B are used to increase efficiency
- Hadronic full reconstruction expected to be used for:
  - Semi-leptonic and semi-tauonic modes for $R(D^{(*)})$
  - $B \rightarrow \tau \nu$ decays
- These studies will use Belle II's new algorithm

$$m_{miss}^2 = \left( p_{ee} - p_{tag} - p_D - p_{\ell} \right)^2$$

is the main signal-background discriminator
\( m_{miss}^2 \) and \( \bar{B} \rightarrow D^{**} \ell \bar{\nu} \) background

E.g., 1 mode in BABAR analysis[1]:

Simultaneous fit to \( \bar{B} \rightarrow D^{**} \ell \bar{\nu} + \pi^0 \) candidate:

\[ \rightarrow \text{D}^{**} \text{ systematic (\%)} \]

- Relative efficiencies: 5.0 \( R(D) \) 2.0 \( R(D^*) \)
- \( Br(D^{**} \rightarrow D(\ast)\pi^0/\pi^\pm) \): 0.7 \( Br(D^{**} \rightarrow D(\ast)\pi\pi) \): 2.1
- \( Br(\bar{B} \rightarrow D^{**} \ell \bar{\nu}) \): 0.8 \( Br(\bar{B} \rightarrow D^{**} \tau \bar{\nu}) \): 1.8

\[ \sim 1.3 \sim 3.3\% \text{ error in Belle [2] & LHCb [3] analyses with } \tau \rightarrow \ell \nu \bar{\nu} \]

- At Belle II, 2\% will already be a large error with 5 ab\(^{-1}\)

What we know about $D^{**}$ states

<table>
<thead>
<tr>
<th>State</th>
<th>$\sim$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 $\bar{B} \to D^{**}\ell\bar{\nu}$ decays observed only for the 4 lightest resonances
- Additional resonances?
- Nonresonant $\bar{B} \to D^{**}\ell\bar{\nu}$ decays
- Additional $D^{(*)}(n\pi)$ decays?

Assumptions affect the $m_{miss}^2$ shape in the fit

Need a model-independent handle on $\bar{B} \to D^{**}\ell\bar{\nu}$ background in $\bar{B} \to D^{(*)}\tau\bar{\nu}$
Distance between B vertex & lepton

Signal:

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

\[ \bar{B} \rightarrow D^{(*)} \]

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

Background:

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

\[ \bar{B} \rightarrow D^{**} \rightarrow D^{(*)} \pi \]

\[ \ell \]
Distance between B vertex & lepton

- Belle II spatial resolution is twice as good as @ BABAR/Belle.
- Pixels @ $r = 14\text{mm}$:
- Nanobeam collision scheme:
- Average $\tau$ flies only 45 $\mu$m, less than the Belle II spatial resolution,
- S-B separation weaker than for $m_{miss}^2$ etc.
- But exploit model independence to check $\bar{B} \rightarrow D^{**} \ell\bar{\nu}$ yield in the analysis fit
Distance between B vertex & lepton

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

**Background:**
\[ \bar{\nu}_\tau \rightarrow \bar{B} \rightarrow \bar{\nu}_\ell \]

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

Drawn to approximate scale
Study with Belle II GEANT4 simulation

- 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)
  - $K^- \pi^+$
  - $D^0 \pi^+$
- 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 & analysis software
Signal-B position resolution

\[ \sigma_x = 27 \, \mu m \]
\[ \sigma_x = 24 \, \mu m \]
\[ \sigma_x = 37 \, \mu m \]
The distance $d$ in $\tau \rightarrow \ell \nu \bar{\nu}$

S-B separation is partly due to larger signal $\sigma_d$, which is due mostly to the softer lepton.

But $p_\ell$ is already among the analysis kinematic variables, so it isn’t new.
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 $\tau \to 3\pi\nu$

Simulated background chosen just to test the capability to “see” the $\tau$ displacement:
$\bar{B} \to D3\pi2\nu$ 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 $\vec{p}_{3\pi}$
Summary

- $\bar{B} \to D(\ast)\tau\bar{\nu}$ is an important part of the physics programs of Belle II and LHCb.

- In the $\tau \to \ell\nu\bar{\nu}$ mode, $\bar{B} \to D^{\ast\ast}\ell\bar{\nu}$ 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 $d$ 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 $\vec{d}$ and the 3-pion momentum vector.

- Even better resolution expected for $\bar{B} \to \tau\bar{\nu}$. Currently under study.