$B \rightarrow D^{*}\tau\nu$ at LHCb

Greg Ciezarek,

on behalf of the LHCb collaboration

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\[ B \rightarrow D^{*} \tau \nu \]

- In the Standard model, the only difference between \( B \rightarrow D^{(*)} \tau \nu \) and \( B \rightarrow D^{(*)} \mu \nu \) is the mass of the lepton.
  - Theoretically clean: \( \sim 2\% \) uncertainty for \( D^* \) mode.
- Ratio \( R(D^{(*)}) = \mathcal{B}(B \rightarrow D^{(*)} \tau \nu) / \mathcal{B}(B \rightarrow D^{(*)} \mu \nu) \) is sensitive to e.g., charged Higgs, leptoquark.
• Before 2015: measurements from B factories in $\tau \rightarrow \ell \nu \nu$ channel
• Final measurement from BaBar (Phys. Rev. D. 88 072012) claimed 3 $\sigma$ excess over SM expectation
  • More recent measurements from Belle not shown here → presentation after next
• This talk: recent LHCb measurement of $B \rightarrow D^* \tau \nu$ with $\tau \rightarrow \mu \nu \nu$ published in Phys. Rev. Lett. 115 (2015) 111803
• B factory measurements based on reconstructing missing mass using opposite side reconstruction
  • This method not possible at LHCb → develop new techniques
### Experimental challenge

- **$B \to D^* \tau \nu$**
  - $B \to D^* \mu \nu$

- **$B \to D^* \tau \nu$**
  - Difficulty: neutrinos - 3 for $(\tau \to \mu \nu \nu)\nu$
    - No narrow peak to fit (in any distribution)
  - Main backgrounds: partially reconstructed B decays
    - $B \to D^* \mu \nu, B \to D^{**} \mu \nu, B \to D^* D(\to \mu X) X ...$
  - Also combinatorial background
Isolation MVA

- Reject physics backgrounds with additional charged tracks
- MVA output distribution for (one) background (hatched) and signal (solid)
- Inverting the cut gives a sample hugely enriched in background $\rightarrow$ control samples
Fit strategy

\[ B \rightarrow D^* \tau \nu \]

- Can use \( B \) flight direction to measure transverse component of missing momentum
- No way of measuring longitudinal component \( \rightarrow \) use approximation to access rest frame kinematics
  - \( B \) boost \( \gg \) energy release in decay
  - Assume \( \gamma \beta_z, \text{visible} = \gamma \beta_z, \text{total} \)
  - \( \sim 18\% \) resolution on \( B \) momentum, long tail on high side
- Can then calculate rest frame quantities - \( m^2_{\text{missing}}, E_\mu, q^2 \)
2. Fit

Fit strategy

- Three dimensional template fit in $E_\mu$ (left), $m_{\text{missing}}^2$ (middle), and $q^2$
  - Projections of fit to isolated data shown
- All uncertainties on template shapes incorporated in fit:
  - Continuous variation in e.g. different form factor parameters
Background strategy

- Three main physics backgrounds:
  \[ B \rightarrow D^{**}(\rightarrow D^*\pi)\mu\nu, B \rightarrow D^{**}(\rightarrow D^*\pi\pi)\mu\nu, B \rightarrow D^*DX \]
- Three control samples used to model shapes:
  - Isolation MVA selects a single pion, two pions, or one kaon
  - Each sample fitted using full model
  - Data-driven systematic uncertainties
  - Quality of fit used to justify modelling
- All combinatorial or misidentified backgrounds taken from data
- More details on everything in backups
2. Fit

**Signal fit**

- Fit to isolated data, used to determine ratio of $B \rightarrow D^* \tau \nu$ and $B \rightarrow D^* \mu \nu$
- Model fits data well
Signal fit

- Fit to isolated data, used to determine ratio of $B \rightarrow D^* \tau \nu$ and $B \rightarrow D^* \mu \nu$
- Model fits data well
  - Fit model uncertainties listed on next slide
2. Fit

Systematics / efficiencies

### Model uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>2.0</td>
</tr>
<tr>
<td>Misidentified $\mu$ template shape</td>
<td>1.6</td>
</tr>
<tr>
<td>$D^*$ form factors</td>
<td>0.6</td>
</tr>
<tr>
<td>$B \to D^* D X$ shape</td>
<td>0.5</td>
</tr>
<tr>
<td>$B(B \to D^{<strong>}\tau\nu)/B(B \to D^{</strong>}\mu\nu)$</td>
<td>0.5</td>
</tr>
<tr>
<td>$B \to [D^*\pi\pi] \mu\nu$ shape</td>
<td>0.4</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td>0.4</td>
</tr>
<tr>
<td>Combinatoric background shape</td>
<td>0.3</td>
</tr>
<tr>
<td>$D^{**}$ form factors</td>
<td>0.3</td>
</tr>
<tr>
<td>$B \to D^*(D_s \to \tau\nu) X$ fraction</td>
<td>0.1</td>
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<tr>
<td>Total model uncertainty</td>
<td>2.8</td>
</tr>
</tbody>
</table>

### Multiplicative uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>0.6</td>
</tr>
<tr>
<td>Hardware trigger efficiency</td>
<td>0.6</td>
</tr>
<tr>
<td>Particle identification efficiencies</td>
<td>0.3</td>
</tr>
<tr>
<td>Form-factors</td>
<td>0.2</td>
</tr>
<tr>
<td>$B(\tau \to \mu\nu)$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>Total multiplicative uncertainty</td>
<td>0.9</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>3.0</td>
</tr>
</tbody>
</table>

- Statistical uncertainty on $R(D^*)$ (fixing all templates to nominal shapes): 2.7% (absolute)
- Largest systematic from simulation statistics $\to$ reducible in future
- Next largest systematic from choice of method used to construct fake muon template
- Other systematic from background modelling depend on control samples in data
  - No uncertainties limited by external inputs
- Systematics from ratio of $B \to D^*\mu\nu$ and $B \to D^*\tau\nu$ efficiencies small
• We measure $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
  • In good agreement with other measurements
  • Agreement with SM at 2.1σ level

• HFAG average July 2015: 3.9σ from SM(!)

• Average subsequently updated to include new Belle measurement
  • No spoilers here
Future

• Expect new measurements soon!
  • Evolution of muonic $\mathcal{R}(D^*)$: simultaneous measurement of $R_D$
  • Measurement of $\mathcal{R}(D^*)$ using $\tau \rightarrow \pi\pi\pi\nu$

• Work underway with other $B$ hadrons: $B_s \rightarrow D_s^{(*)}\tau\nu$, $\Lambda_B \rightarrow \Lambda_c^{(*)}\tau\nu$
Conclusion

- LHCb measurement of $B \rightarrow D^* \tau \nu$ ($\tau \rightarrow \mu \nu \nu$) consistent with SM at 2.1$\sigma$ level
  - First ever measurement of a $b \rightarrow \tau$ decay at a hadron collider
  - Will continue to improve with more data
- World average for $R(D^{(*)})$ in 3.9$\sigma$ tension with SM
- LHCb will have much more to say on this in the near future
- And beyond - program is expanding
Backups
\[ B \to D^* \mu \nu \]

- \( B \to D^* \mu \nu \) (black) vs \( B \to D^* \tau \nu \) (red)
- \( B \to D^* \mu \nu \) is both the normalisation mode, and the highest rate background (\( \sim 20 \times B \to D^* \tau \nu \))
  - Use CLN parameterisation for form factors
  - Float form factors parameters in fit \( \to \) uncertainty taken into account
$B \rightarrow D^{**} \mu^+ \nu$

- $B \rightarrow D^{**} \mu^+ \nu$ refers to any higher charm resonances (or non resonant hadronic modes)
- Not so well measured
  - Set of states comprising $D^{**}$ known to be incomplete
  - Decay models not well measured
- For the established states (shown in black):
  - Separate components for each resonance ($D_1, D_{2*}, D_{1}'$)
5. Backup

\[ B \rightarrow D^{**}(\rightarrow D^{*+}\pi)\mu\nu \] control sample

- Isolation MVA selects one track, \( M_{D^{*+}\pi} \) around narrow \( D^{**} \) peak \( \rightarrow \) select a sample enhanced in \( B \rightarrow D^{**}\mu^+\nu \)
  - Use this to constrain, justify \( B \rightarrow D^{**}\mu^+\nu \) shape for light \( D^{**} \) states
  - Also fit above, below narrow \( D^{**} \) peak region to check all regions of \( M_{D^{*+}\pi} \) are modelled correctly in data
Higher $B \rightarrow D^{**} \mu^+ \nu$ states

- Previously unmeasured $B \rightarrow D^{**}(\rightarrow D^{*+} \pi \pi)\mu\nu$ contributions recently measured by BaBar
  - Too little data to separate individual (non)resonant components
  - Single fit component, empirical treatment
- Constrain based on a control sample in data
  - Degrees of freedom considered: $D^{**}$ mass spectrum, $q^2$ distribution
  - Effect of $D^{**}$ mass spectrum negligible
$B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ control sample

- Also look for two tracks with isolation MVA $\to$ study $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ in data
- Can control shape of this background
**B → D^*DX**

- **B → D^*DX** consists of a very large number of decay modes
  - Physics models for many modes not well established
- Constrain based on a control sample in data
- Single component, empirical treatment
  - Consider variations in \( M_{DD} \)
  - Multiply simulated distributions by second order polynomials
  - Parameters determined from data
• Isolation MVA selects a track with loose kaon ID \( \rightarrow \) select a sample enhanced in \( B \rightarrow D^*DX \)
• Use this to constrain, justify \( B \rightarrow D^*DX \) shape
Combinatorial backgrounds

- Combinatorial background modelled using same-sign $D^{*+} \mu^+$ data
- Two sources of combinatorial background are treated separately (shown on next slide)
Combinatorial backgrounds

- Non $D^{*+}$ backgrounds (fake $D^*$) template modelled using $D^0\pi^-$ data (shown)
  - Yield determined from sideband extrapolation beneath $D^{*+}$ mass peak
- Hadrons misidentified as muons (fake muons)
  - Controlled using $D^{*+}h^\pm$ sample
  - Both template and expected yield can be determined
- Both of these are subtracted from $D^{*+}\mu^+$ template to avoid double counting
Two small backgrounds containing taus, each $< \sim 10\%$ of the signal yield: $B \rightarrow D^{**} \tau^+ \nu$ (shown) and $B \rightarrow D^*(D_s \rightarrow \tau \nu)X$

- Both too small to measure

$B \rightarrow D^{**} \tau^+ \nu$ constrained based on measured $B \rightarrow D^{**} \mu^+ \nu$ yield, theoretical expectations ($\sim 50\%$ uncertainty)

$B \rightarrow D^*(D_s \rightarrow \tau \nu)X$ constrained based on $B \rightarrow D^* DX$ yield, and measured branching fractions ($\sim 30\%$ uncertainty)