Semileptonic B baryon decays and $B \to D^* \tau \nu$

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Semileptonic decays

- **Semileptonic $B$ decays**: $H_b \rightarrow X_{c,u} \ell \nu$
  - Neutrino goes unreconstructed $\rightarrow$ missing energy
  - Need external constraint to reconstruct full decay kinematics
  - Challenging measurements
- Used to measure CKM elements $|V_{ub}|$ and $|V_{cb}|$
  - In both cases $\sim 3\sigma$ tensions between exclusive and inclusive measurements
- Also used to search for new physics, e.g. with tauonic final states
This talk

- $|V_{ub}|$ from $\Lambda_b^0 \to p\mu\nu$ at LHCb
  - LHCB-PAPER-2015-013
- $B \to D^*\tau\nu$ at LHCb
  - Presented here for the first time
- Both channels include large physics backgrounds:
  - $B \to X_c\mu\nu$ decays more frequent than $\Lambda_b^0 \to p\mu\nu$
  - $B \to D^*\mu\nu \sim 20$ times larger than $B \to D^*\tau\nu$ (in $D^{*+}\mu$ final state)
- Neither channel believed to be possible to measure at LHCb
\[ \Lambda_b^0 \rightarrow p \mu \nu \]
**Λ^0_b → pμν strategy**

- Measure ratio of Λ^0_b → pμν and Λ_b → Λ_c(→ pKπ)μν → sensitive to |V_{ub}|/|V_{cb}|
- Direct calculation on lattice with high precision from W. Detmold, C. Lehner and S. Meinel: arxiv:1503.01421(hep-lat)
  - Close collaboration integral in development of the measurement
- Lattice calculation only precise at high q^2 → only perform measurement in this region
  - Measurement overlaps completely with lattice data points → no need for q^2 shape fit for precise |V_{ub}|
Corrected mass

- Measure $B$ decay, origin positions $\rightarrow B$ momentum vector should point back along this 'flight direction'
  - Can infer unreconstructed momentum transverse to flight direction ($p_\perp$)
- Use this information to construct “Corrected mass” variable
  $$M_{\text{corr}} = \sqrt{p_\perp^2 + M_{\text{reco}}^2 + p_\perp}$$
  - Dates back to SLD: hep-ex/0202031v1
  - Corresponds to minimum mass, assuming a missing single massless particle
- Distributions shown for $\Lambda^0_b \rightarrow p\mu\nu$ and $\Lambda^0_b \rightarrow \Lambda_c\mu\nu$ (only $p\mu$ reconstructed)
  - Cutting on estimated $M_{\text{corr}}$ resolution helps increase discrimination
\( q^2 \) reconstruction

- Reconstruct \( q^2 \) up to twofold ambiguity:
  - Measurement of \( p_\perp + B \) mass constraint + missing massless particle
- Reduce \( q^2 \) migration by requiring both solutions to be above cut value
Isolation MVA

- **Strategy**: use MVA to decide if each track is from the same B, or the rest of the event
  - Cut on most same-B-like track in event
  - Output based on properties of track, and $B + \text{track}$ combination
- $\sim 90\%$ charged background rejection with $\sim 80\%$ signal efficiency
Normalisation fit

- Fit to corrected mass for $\Lambda_b^0 \rightarrow \Lambda_c \mu \nu$ candidates used for normalisation, $q^2 > 7 \text{ GeV}/c^2$
  - $34255 \pm 571 \Lambda_b^0 \rightarrow \Lambda_c \mu \nu$ candidates
  - Small fraction of excited states (already suppressed by isolation)
  - Boxes indicate template statistical uncertainties
Signal fit

- Fit to corrected mass for $\Lambda_b^0 \rightarrow p\mu\nu$ candidates to determine signal yield, $q^2 > 15$ GeV/$c^2$
  - Signal clearly visible
  - $17687 \pm 733 \Lambda_b^0 \rightarrow p\mu\nu$ candidates (4.1% relative uncertainty)
- Most signal-like background: $\Lambda_b \rightarrow N^*\mu\nu$
  - Very loose constraint on yield, shape uncertainties determined by repeating fit with form-factors varied
## Systematics / efficiencies

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathcal{B}(\Lambda_c^+ \rightarrow pK^{+}\pi^-))</td>
<td>(\pm 4.7) (-5.3)</td>
</tr>
<tr>
<td>Trigger</td>
<td>3.2</td>
</tr>
<tr>
<td>Tracking</td>
<td>3.0</td>
</tr>
<tr>
<td>(\Lambda_c^+) selection efficiency</td>
<td>3.0</td>
</tr>
<tr>
<td>(\Lambda_b^0 \rightarrow N^*\mu^-\bar{\nu}_\mu) shapes</td>
<td>2.3</td>
</tr>
<tr>
<td>(\Lambda_b^0) lifetime</td>
<td>1.5</td>
</tr>
<tr>
<td>Isolation</td>
<td>1.4</td>
</tr>
<tr>
<td>Form factor</td>
<td>1.0</td>
</tr>
<tr>
<td>(\Lambda_b^0) kinematics</td>
<td>0.5</td>
</tr>
<tr>
<td>(q^2) migration</td>
<td>0.4</td>
</tr>
<tr>
<td>PID</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>(\pm 7.8) (-8.2)</td>
</tr>
</tbody>
</table>

- Largest experimental systematic: external measurement of \(\mathcal{B}(\Lambda_c \rightarrow pK\pi)\)
- Efficiency ratio \(\frac{\epsilon_{\Lambda_b^0 \rightarrow p\mu\nu}}{\epsilon_{\Lambda_b^0 \rightarrow \Lambda_c \mu\nu}}\) calculated from simulation
  - Many small sources of systematic uncertainty (listed)
### Result

- $|V_{ub}| = 3.27 \pm 0.15(expt) \pm 0.17(theory) \pm 0.06(|V_{cb}|)$
- Result in good agreement with past exclusive $|V_{ub}|$ measurements
- $3.5\sigma$ below inclusive measurements
- Implications for CKM fit shown
- LHCB-PAPER-2015-013
$B \rightarrow D^* \tau \nu$
\( B \rightarrow D^{*} \tau \nu \)

- 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 charged Higgs
  - Or non-MFV couplings favouring \( \tau \)
- New measurement \( B \rightarrow D^{*} \tau \nu \) with \( \tau \rightarrow \mu \nu \nu \) presented here for the first time
Existing measurements

- Previous measurements from B factories in $\tau \rightarrow \ell \nu \nu$ channel
- Most recent measurement from BaBar (arxiv:1303.0571) claimed 3 $\sigma$ excess over SM expectation
  - BaBar have used their final dataset, corresponding Belle measurement yet to come
- B factory measurements based on reconstructing missing mass using full event reconstruction
  - This method not possible at LHCb $\rightarrow$ develop new techniques
Experimental challenge

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

- Strategy: use MVA to decide if each track is from the same B, or the rest of the event
  - As shown before for $\Lambda_b^0 \rightarrow p\mu\nu$
- Highest MVA output distribution for $B \rightarrow D^{**}\mu^+\nu$ (hatched) and $B \rightarrow D^*\mu\nu$ (solid)
- Inverting the cut gives a sample hugely enriched in physics backgrounds → use this to control shapes
Fit strategy

• 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 - $m^2_{\text{missing}}, E_\mu, q^2$
Fit strategy

- Three dimensional template fit in $E_\mu$ (left), $m^2_{\text{missing}}$ (middle), and $q^2$
  - Projections of fit to isolated data shown
- Uncertainties on template shapes incorporated in fit:
  - Continuous variation in e.g. different form factor parameters
  - Shape variations for all major backgrounds controlled using data samples
  - Histogram statistics included via Barlow-Beeston “lite”
$B \to D^* \mu \nu$

- $B \to D^* \mu \nu$ (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 $\rightarrow$ uncertainty taken into account
  - Values from fit more precise than HFAG averages
$B \to D^{**}\mu^+\nu$

- $B \to D^{**}\mu^+\nu$ 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 ($D_1, D_2^*, D_1'$)
  - Use LLSW model, float slope of Isgur-wise function
$B \rightarrow D^{**}(\rightarrow D^{*+}\pi)\mu\nu$ 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 → D** (→ D*⁺ππ)µν control sample

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

- $B \to D^* DX$ 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
$B \to D^* DX$ control sample

- Isolation MVA selects a track with loose kaon ID $\to$ select a sample enhanced in $B \to D^* DX$
- Use this to constrain, justify $B \to D^* DX$ 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: \(B \to D^{**} \tau^+ \nu\) (shown) and \(B \to D^* (D_s \to \tau \nu) X\)

- Both too small to measure

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

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

- Fit to isolated data, used to determine ratio of $B \to D^* \tau \nu$ and $B \to D^* \mu \nu$
- Model fits data well
- Statistical uncertainty on $\mathcal{R}(D^*)$ (fixing all templates to nominal shapes): 0.027
Signal fit

- Fit to isolated data, used to determine ratio of $B \to D^* \tau\nu$ and $B \to D^* \mu\nu$
- Model fits data well
- Statistical uncertainty on $\mathcal{R}(D^*)$ (fixing all templates to nominal shapes): 0.027
  - Fit model uncertainties listed on next slide
Systematics / efficiencies

<table>
<thead>
<tr>
<th>Model uncertainties</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>$B \to D^*DX$ 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>
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<tr>
<td>Corrections to simulation</td>
<td>0.4</td>
</tr>
<tr>
<td>Combinatorial background shape</td>
<td>0.3</td>
</tr>
<tr>
<td>$D^{**}$ form factors</td>
<td>0.3</td>
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<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>
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<table>
<thead>
<tr>
<th>Multiplicative uncertainties</th>
<th>Size ($\times 10^{-2}$)</th>
</tr>
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<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>
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<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>

- Largest systematic from simulation statistics $\rightarrow$ 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 $\mathcal{R}(D^*) = 0.336 \pm 0.027 \pm 0.030$

- In good agreement with past measurements
- Agreement with SM at 2.1\sigma level

Measurement will improve with more data: largest systematic uncertainties depend on control samples (or simulation size)

Paper (LHCB-PAPER-2015-025) to come in a few weeks
Conclusion

• $\Lambda^0_b \rightarrow p\mu\nu$: First measurement of $|V_{ub}|$ at a hadron collider
  • Consistent with past exclusive measurements, competitive precision
  • $3.5\sigma$ tension with inclusive measurements

• $B \rightarrow D^*\tau\nu$: First measurement of any $B \rightarrow \tau X$ decay at a hadron collider
  • Consistent with past measurements, competitive precision
  • Agreement with SM at $2.1\sigma$ level

• Neither of these measurements were supposed to be possible at LHCb
  • They are
  • Many other semileptonic measurements also are
  • Rich program underway