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

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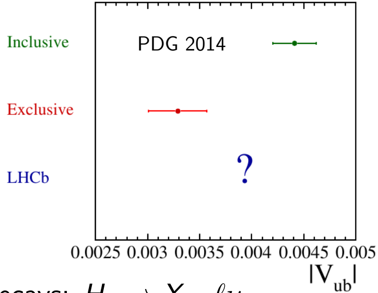
Semileptonic decays



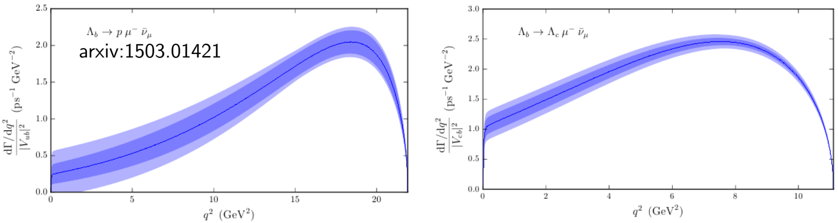
- Semileptonic B decays: $H_b \to X_{c,u} \ell \nu$
  - Neutrino goes unreconstructed $\to$ missing energy
  - Need external constraint to reconstruct full decay kinematics
  - Challenging measurements
- Used to measure CKM elements $|V_{\mathrm{ub}}|$ and $|V_{\mathrm{cb}}|$
  - In both cases $\sim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

This talk

- $|V_{\rm ub}|$ 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
  - LHCB-PAPER-2015-013, in preparation
- 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

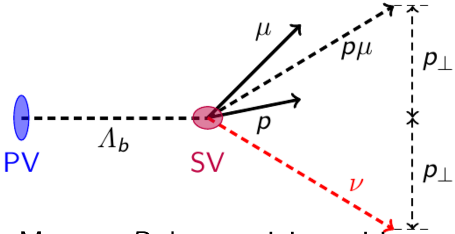
$\Lambda_b^0 \to p\mu\nu$

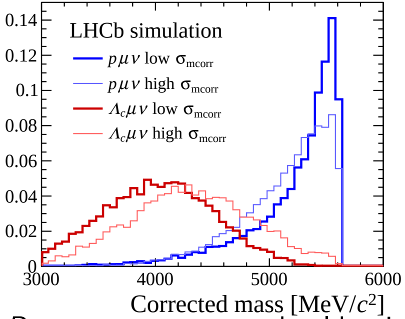
$\Lambda_b^0 \to p\mu\nu$ strategy



- Measure ratio of $\Lambda_b^0 \to p\mu\nu$ and $\Lambda_b \to \Lambda_c(\to pK\pi)\mu\nu$ $\to$ sensitive to $|V_{\rm ub}|/|V_{\rm cb}|$
- 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 $\to$ only perform measurement in this region
    - Measurement overlaps completely with lattice data points $\to$ no need for q^2 shape fit for precise $|V_{\rm ub}|$

Corrected mass



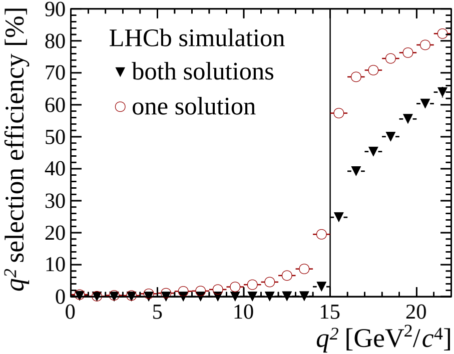


- Measure B decay, origin positions $\to$ B momentum vector should point back along this 'flight direction'
  - Can infer unreconstructed momentum transverse to flight direction ($p_\perp$)
- Use this information to construct "Corrected mass" variable

$$M_{corr} = \sqrt{p_\perp^2 + M_{reco}^2} + p_\perp$$

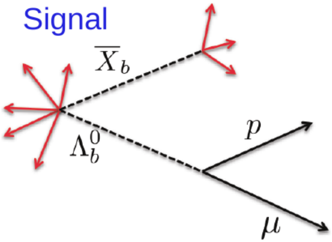
  - Dates back to SLD: hep-ex/0202031v1
  - Corresponds to minimum mass, assuming a missing single massless particle
- Distributions shown for $\Lambda_b^0 \to p\mu\nu$ and $\Lambda_b^0 \to \Lambda_c\mu\nu$ (only $p\mu$ reconstructed)
  - Cutting on estimated M_{corr} resolution helps increase discrimination

q^2 reconstruction



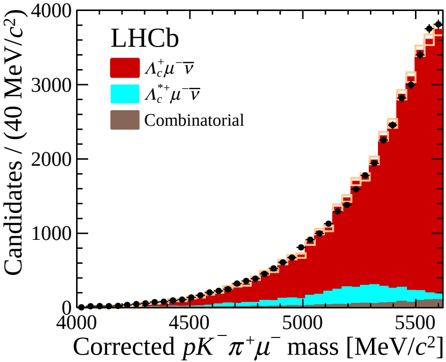
- Reconstruct q^2 up to twofold ambiguity:
  - Measurement of $p_\perp$ + B mass constraint + missing massless particle
- Reduce q^2 migration by requiring both solutions to be above cut value

Isolation MVA



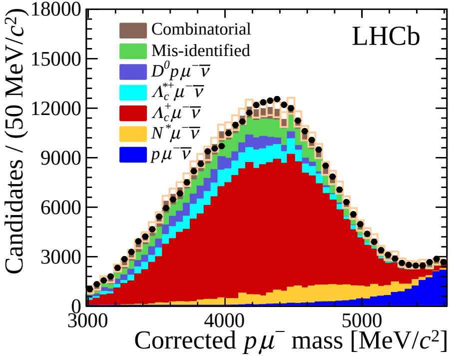
- Strategy: use MVA to decide if each track is from the same B, or the rest of the event
    - Cut on most same-B-like track in event
    - Output based on properties of track, and $B + track$ combination
- $\sim 90\%$ charged background rejection with $\sim 80\%$ signal efficiency

Normalisation fit



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

Signal fit



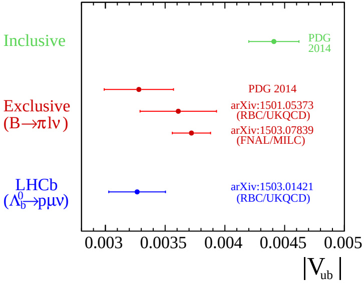
- Fit to corrected mass for $\Lambda_b^0 \to p\mu\nu$ candidates to determine signal yield, $q^2 > 15\,\mathrm{GeV}/c^{2\,2}$
  - Signal clearly visible
  - 17687 ± 733 $\Lambda_b^0 \to p\mu\nu$ candidates (4.1% relative uncertainty)
- Most signal-like background: $\Lambda_b \to N^* \mu\nu$
  - Very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

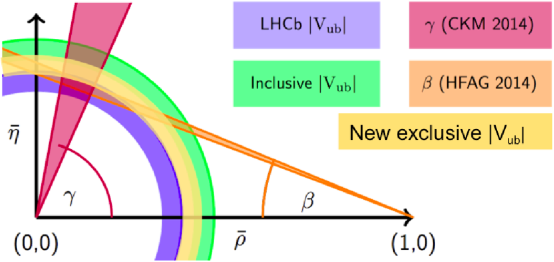
Systematics / efficiencies

Source	Relative uncertainty (%)
→ $\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

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

Result

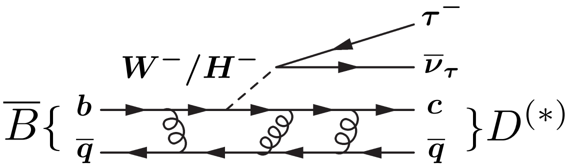




- $|V_{\rm ub}| = 3.27 \pm 0.15(exp) \pm 0.17(theory) \pm 0.06(|V_{\rm cb}|)$
- Result in good agreement with past exclusive $|V_{\rm ub}|$ measurements
- 3.5σ below inclusive measurements
- Implications for CKM fit shown
- LHCB-PAPER-2015-013

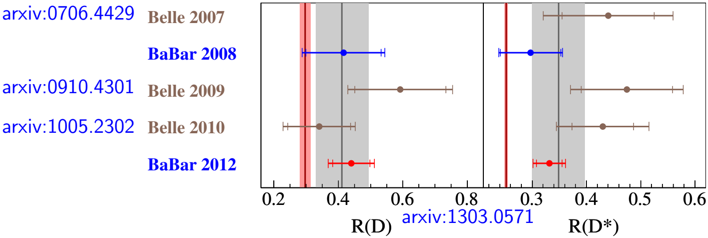
$B \to D^* \tau \nu$

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



- In the Standard model, the only difference between $B \to D^{(*)}\tau\nu$ and $B \to D^{(*)}\mu\nu$ is the mass of the lepton
  - Theoretically clean - $\sim 2\%$ uncertainty for D^* mode
- Ratio R($D^{(*)} = \mathcal{B}(B \to D^{(*)}\tau\nu)$ / $\mathcal{B}(B \to D^{(*)}\mu\nu)$ is sensitive to charged Higgs
  - Or non-MFV couplings favouring τ
- New measurement $B \to D^*\tau\nu$ with $\tau \to \mu\nu\nu$ presented here for the first time

Existing measurements

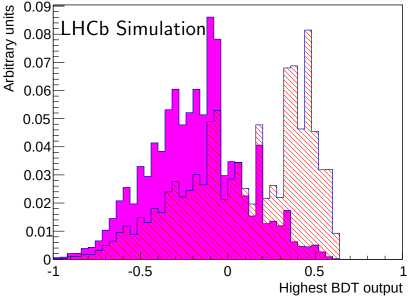


- Previous measurements from B factories in $\tau \to \ell\nu\nu$ channel
- Most recent measurement from BaBar (arxiv:1303.0571) claimed 3 σ excess over SM expectation
  - BaBar have used their final dataset, corresponding Belle measurement yet to come
- B factory measurements based on reconstructing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

Experimental challenge

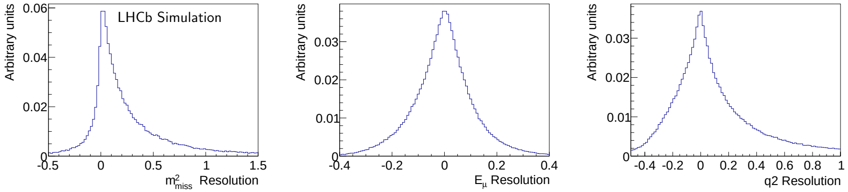
- Difficulty: neutrinos - 3 for $(\tau \to \mu\nu\nu)\nu$
  - No narrow peak to fit (in any distribution)
- Main backgrounds: partially reconstructed B decays
  - $B \to D^{*(*)}\mu\nu$, $B \to D^* D$ ...
- Also combinatorial background

Isolation MVA



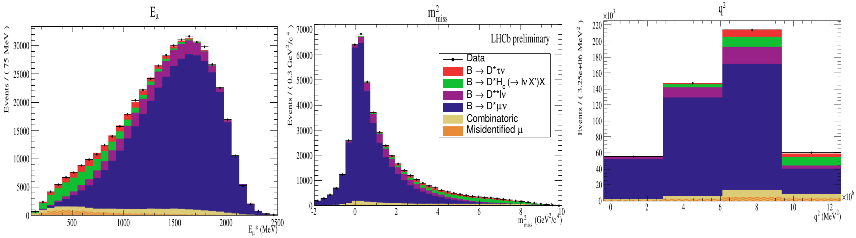
- Strategy: use MVA to decide if each track is from the same B, or the rest of the event
  - As shown before for $\Lambda_b^0 \to p\mu\nu$
- Highest MVA output distribution for $B \to D^{**}\mu^+\nu$ (hatched) and $B \to D^*\mu\nu$ (solid)
- Inverting the cut gives a sample hugely enriched in physics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

Fit strategy



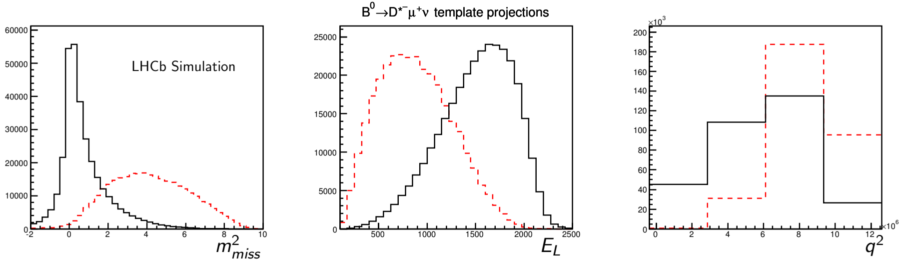
- Can use B flight direction to measure transverse component of missing momentum
- No way of measuring longitudinal component $\to$ use approximation to access rest frame kinematics
  - B boost $>>$ energy release in decay
  - Assume $\gamma\beta_{z,visible} = \gamma\beta_{z,total}$
  - $\sim$18% resolution on B momentum, long tail on high side
- Can then calculate rest frame quantities - $m^2_{missing}$, E_μ, q^2

Fit strategy



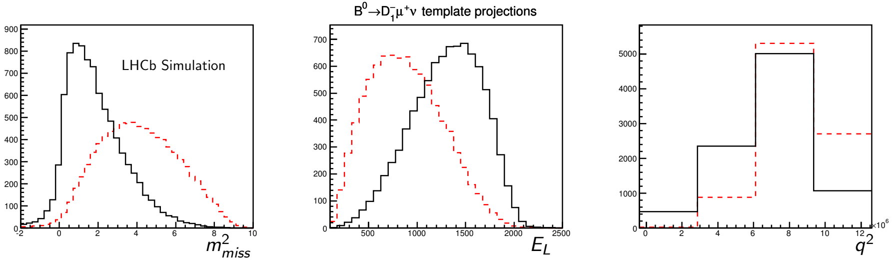
- Three dimesional template fit in E_μ (left), $m^2_{missing}$ (middle), and q^2
  - Projections of fit to isolated data shown
- Uncertainties on template shapes incorporated in fit:
  - Continuous variation in e.g different form factor parameters
  - Shape variations for all major backgrounds controlled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

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



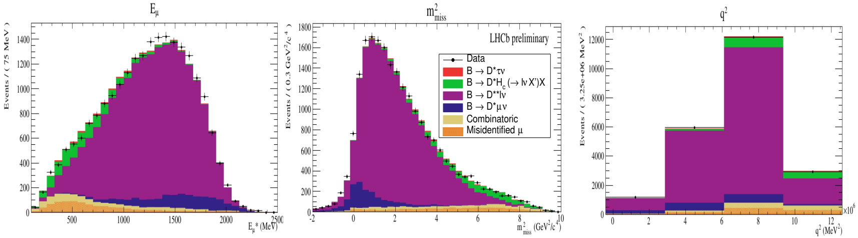
- $B\to D^*\mu\nu$ (black) vs $B\to D^*\tau\nu$ (red)
- $B\to D^*\mu\nu$ is both the normalisation mode, and the highest rate background ($\sim 20\times B\to D^*\tau\nu$)
  - Use CLN parameterisation for form factors
  - Float form factors parameters in fit $\to$ uncertainty taken into account
  - Values from fit more precise than HFAG averages

$B \to D^{**} \mu^+ \nu$



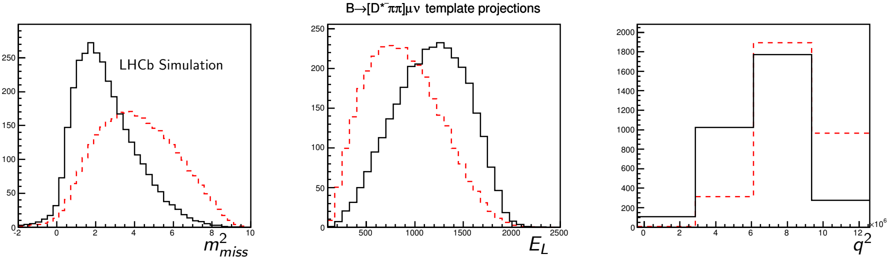
- $B \to D^{**} \mu^+ \nu$ refers to any higher charm resonances (or non resonant hadronic modes)
- Not so well measured
  - Set of states comprising D^{**} known to be incomplete
  - Decay models not well measured
- For the established states (shown in black):
  - Separate components for each resonance (D_1, D_2^*, D_1')
  - Use LLSW model, float slope of Isgur-wise function

$B \to D^{**}(\to D^{*+}\pi)\mu\nu$ control sample



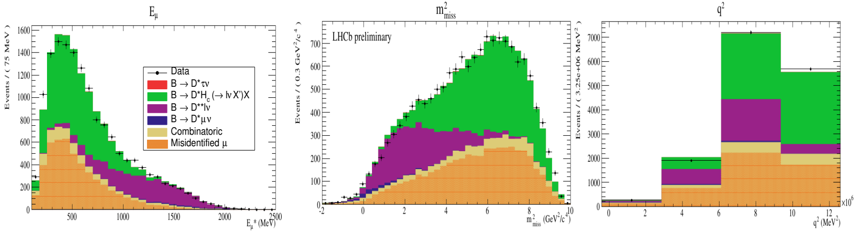
- Isolation MVA selects one track, $M_{D^{*+}\pi}$ around narrow D^{**} peak $\to$ select a sample enhanced in $B \to D^{**}\mu^+\nu$
  - Use this to constrain, justify $B \to D^{**}\mu^+\nu$ shape for light D^{**} states
  - Also fit above, below narrow D^{**} peak region to check all regions of $M_{D^{*+}\pi}$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

Higher $B \to D^{**} \mu^+ \nu$ states



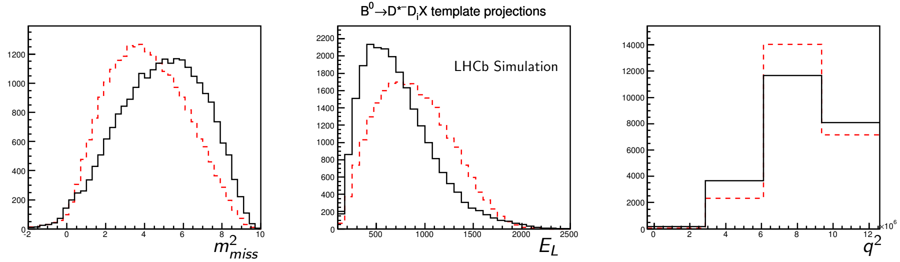
- Previously unmeasured $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ contributions recently measured by BaBar
  - Too little data to separate individual (non)resonant components
  - Single fit component, empirical treatment
- Constrain based on a control sample in data
  - Degrees of freedom considered: D^{**}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

$B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ control sample



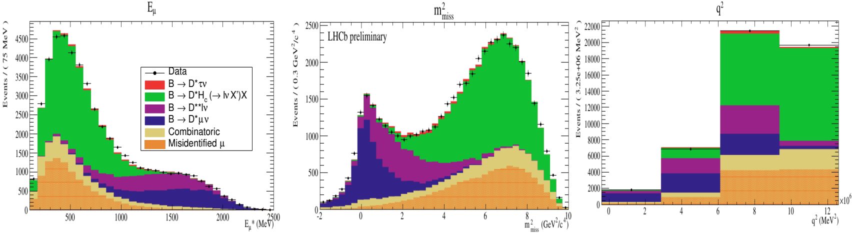
- Also look for two tracks with isolation MVA $\to$ study $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ in data
- Can control shape of this background

$B \to D^* DX$



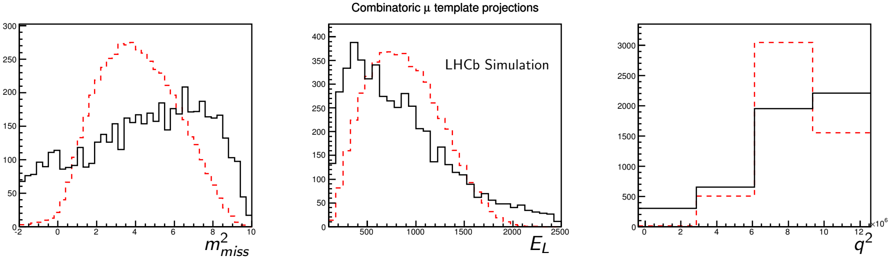
- $B \to D^* DX$ consists of a very large number of decay modes
  - Physics models for many modes not well established
- Constrain based on a control sample in data
- Single component, empirical treatment
  - Consider variations in M_{DD}
  - Multiply simulated distributions by second order polynomials
  - Parameters determined from data

$B \to D^* DX$ control sample



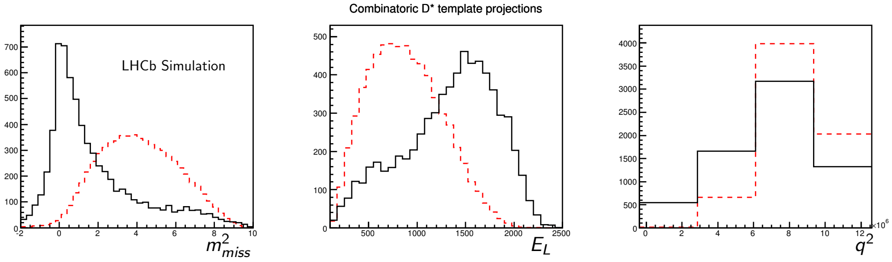
- Isolation MVA selects a track with loose kaon ID $\to$ select a sample enhanced in $B \to D^* DX$
- Use this to constrain, justify $B \to D^* DX$ shape

Combinatorial backgrounds



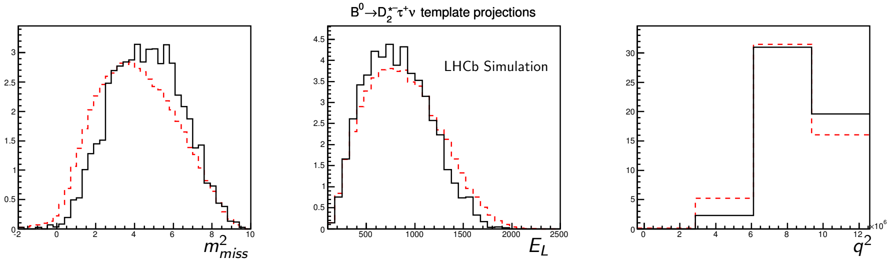
- Combinatorial background modelled using same-sign $D^{*+}\mu^+$ data
- Two sources of combinatorial background are treated separately (shown on next slide)

Combinatorial backgrounds



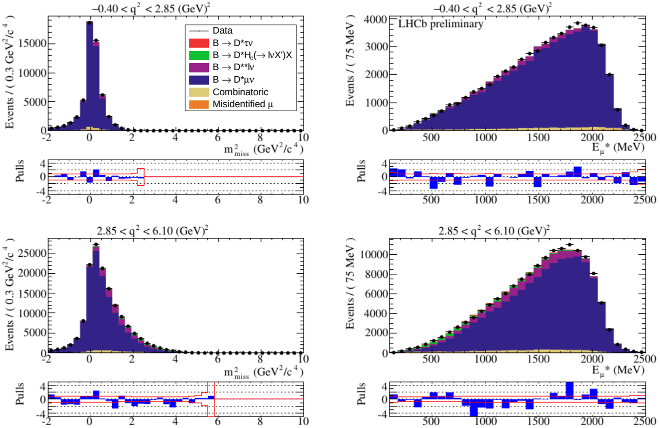
- Non D^{*+} backgrounds (fake D^*) template modelled using $D^0\pi^-$ data (shown)
  - Yield determined from sideband extrapolation beneath D^{*+} mass peak
- Hadrons misidentified as muons (fake muons)
  - Controlled using $D^{*+}h^{\pm}$ sample
  - Both template and expected yield can be determined
- Both of these are subtracted from $D^{*+}\mu^+$ template to avoid double counting

$D^{*+}\tau X$ backgrounds



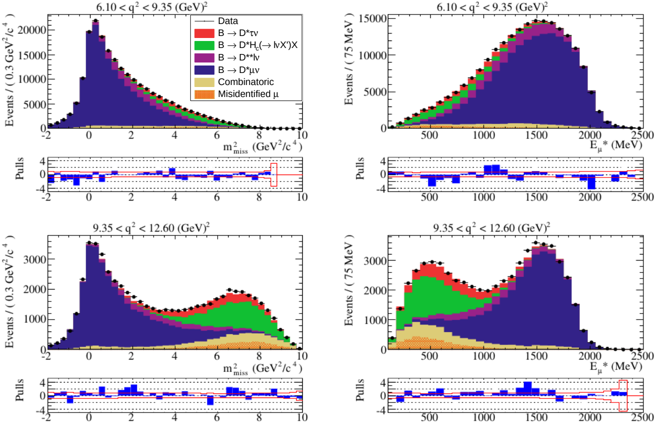
- Two small backgrounds containing taus, each $<\sim$ 10% of the signal yield: $B \to D^{**}\tau^+\nu$ (shown) and $B \to D^*(D_s \to \tau\nu)X$
  - Both too small to measure
- $B \to D^{**}\tau^+\nu$ constrained based on measured $B \to D^{**}\mu^+\nu$ yield, theoretical expectations ($\sim$50% uncertainty)
- $B \to D^*(D_s \to \tau\nu)X$ 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

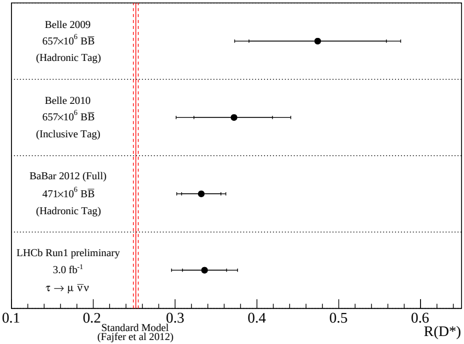
Systematics / efficiencies

Model uncertainties	Size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
D^* form factors	0.6
$B \to D^* DX$ shape	0.5
$\mathcal{B}(B \to D^{**}\tau\nu)/\mathcal{B}(B \to D^{**}\mu\nu)$	0.5
$B \to [D^*\pi\pi]\mu\nu$ shape	0.4
Corrections to simulation	0.4
Combinatoric background shape	0.3
D^{**} form factors	0.3
$B \to D^*(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**

Multiplicative uncertainties	Size ($\times 10^{-2}$)
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau \to \mu\nu\nu)$	< 0.1
Total multiplicative uncertainty	**0.9**
Total systematic uncertainty	**3.0**

- 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

Result



- We measure $\mathcal{R}(D^*) = 0.336 \pm 0.027 \pm 0.030$
  - In good agreement with past measurements
  - Agreement with SM at 2.1σ 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

- $\Lambda_b^0 \to p\mu\nu$: First measurement of $|V_{\mathrm{ub}}|$ at a hadron collider
    - Consistent with past exclusive measurements, competitive precision
    - 3.5σ tension with inclusive measurements
- $B \to D^*\tau\nu$: First measurement of any $B \to \tau X$ decay at a hadron collider
    - Consistent with past measurements, competitive precision
    - Agreement with SM at 2.1σ level
- Neither of these measurements were supposed to be possible at LHCb
    - They are
    - Many other semileptonic measurements also are
    - Rich program underway