$B \to X\tau\nu$ measurements at LHCb

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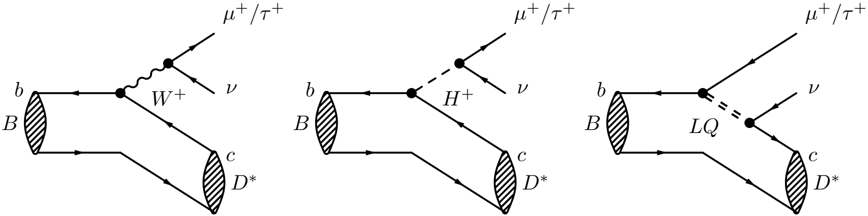
on behalf of the LHCb collaboration

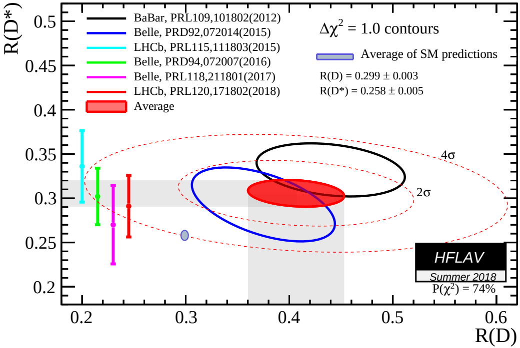
April 20, 2022

$B \rightarrow D^{(*)}\tau\nu$



- 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
  - Form factors mostly cancel in the ratio of rates (except helicity suppressed amplitude)
- 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

Where do we stand?



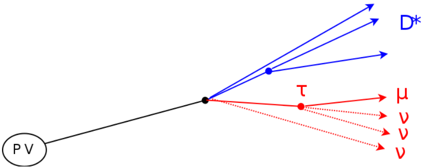
- Plus $R_{J/\psi}$
- Plus R_{Λ_b} - see talk from Patrick later
- Updates long overdue...

What are we working on?

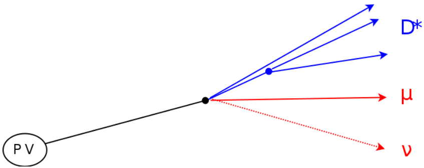
- Update for muonic $\mathcal{R}(D^*)$: $D^0\ell\nu$ vs $D^{*+}\ell\nu$
  - Backgrounds not so much worse than in $D^{*+}\mu X$
  - Significant improvement in precision
- Similar measurement with $D^+\ell\nu X$
- Update hadronic $\mathcal{R}(D^*)$ (before $D\tau\nu$)
  - Also, a D^{*+} polarisation measurement
- $B_s \to D_s^{(*)}\tau\nu$
  - Main difference to $B \to D^{(*)}\tau\nu$: feed-down mostly via neutrals
- $B \to D^{**}\tau\nu$ (narrow states)
- $\Lambda_b \to \Lambda_c^{(**)}\tau\nu$
  - Different spin structure to meson modes $\to$ different physics sensitivity
- Update $R_{J/\psi}$

Experimental challenge

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



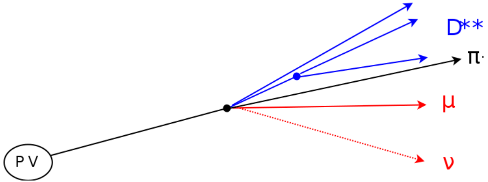
$B \to D^* \mu \nu$

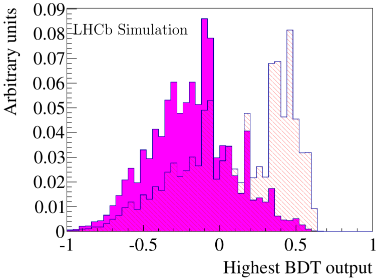


- Difficulty: neutrinos - 2 for $(\tau \to \pi\pi\pi\nu)\nu$, 3 for $(\tau \to \mu\nu\nu)\nu$
  - No narrow peak to fit (in any distribution)
- Main backgrounds: partially reconstructed B decays
  - $B \to D^* \mu\nu$,$B \to D^{**} \mu\nu$, $B \to D^* D(\to \mu X)X$ ...
  - $B \to D^* \pi\pi\pi X$, $B \to D^* D(\to \pi\pi\pi X)X$ ...
- Also combinatorial, misidentified background

Isolation

Phys. Rev. Lett. 115 (2015) 111803



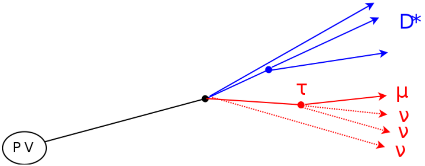


- Reject physics backgrounds with additional charged tracks
- MVA output distribution for $B \to D^{**}\mu^+\nu$ background (hatched) and signal (solid)
- Inverting the cut gives a sample hugely enriched in background $\to$ control samples

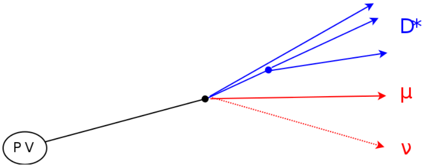
Fit strategy

Phys. Rev. Lett. 115 (2015) 111803

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



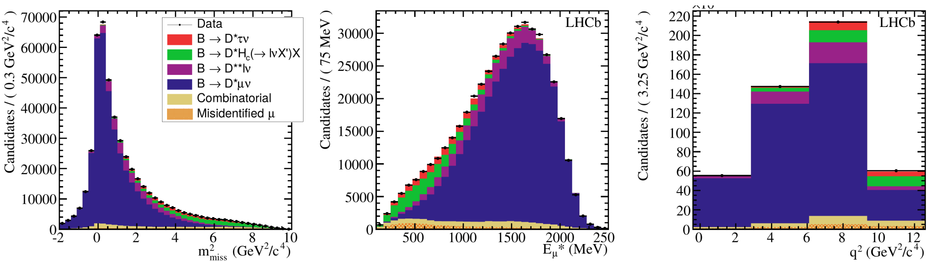
$B \to D^* \mu \nu$



- 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
  - Assume $\gamma\beta_{z,visible} = \gamma\beta_{z,total}$
  - $\sim$20% resolution on B momentum, long tail on high side
- Can then calculate rest frame quantities - $m^2_{missing}$, E_μ, q^2

Fit strategy

Phys. Rev. Lett. 115 (2015) 111803

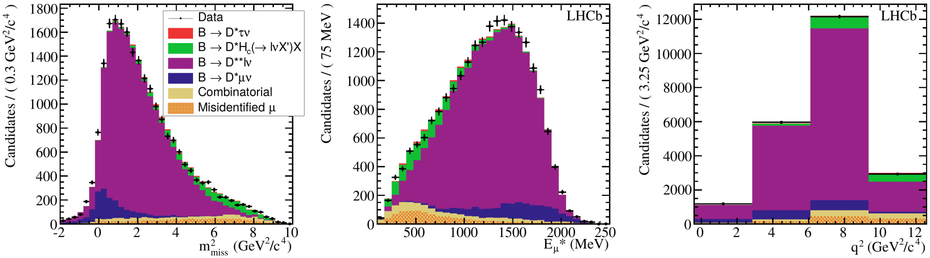


- Three dimesional template fit in E_μ (left), $m^2_{missing}$ (middle), and q^2
  - Projections of fit to isolated data shown
- All uncertainties on template shapes incorporated in fit:
  - Continuous variation in e.g different form factor parameters
- (Understanding agreement between simulation and data also essential)

Background strategy

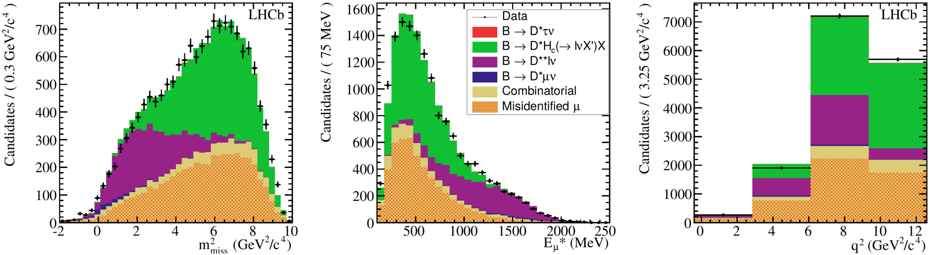
- All major backgrounds modelled using control samples in data
  - Dedicated samples for different backgrounds ($D^*\pi$, $D^*\pi\pi$, D^*DX
  - Quality of fit used to justify modelling
  - Data-driven systematic uncertainties
- All combinatorial or misidentified backgrounds taken from data

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



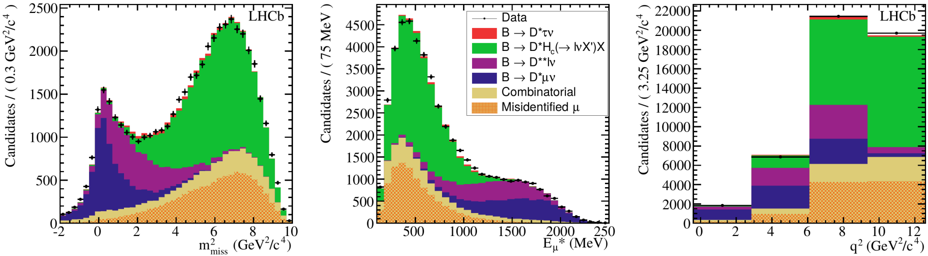
- Isolation MVA selects one track, $M_{D^{*+}\pi}$ around narrow D^{**} peak $\to$ select a sample enhanced in $B \to D^{**}\mu^+\nu$
  - Use this to constrain form factors, justify $B \to D^{**}\mu^+\nu$ shape for light D^{**} states
  - Also fit above, below narrow D^{**} peak region to check all regions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

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



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

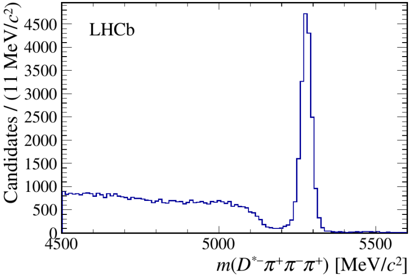
$B \to D^* D X$ control sample



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

$\mathcal{R}(D^*)$ with $\tau \to \pi\pi\pi\nu$

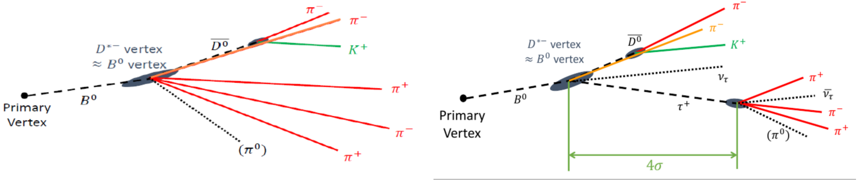
LHCb-PAPER-2017-017, LHCb-PAPER-2017-027



- Compared to muonic $\mathcal{R}(D^*)$:
  - Large $B \to D^*\mu\nu$, $B \to D^{**}\mu^+\nu$ backgrounds absent
  - Additional $B \to D^*\pi\pi\pi X$ backgrounds
  - $B \to D^* DX$ with $D \to \pi\pi\pi X$
- Control experimental efficiencies by measuring rate relative to $B \to D^*\pi\pi\pi$

Removing $B \to D^*\pi\pi\pi X$

LHCb-PAPER-2017-017, LHCb-PAPER-2017-027



- Can use decay topology to remove direct $B \to D^*\pi\pi\pi X$ decays:
- If the $\pi\pi\pi$ vertex is displaced from the B vertex, cannot be direct $B \to D^*\pi\pi\pi X$
- Can remove a large, poorly measured background
  - And control the remainder
- $B \to D^*DX$ major physics background remaining

Dealing with $B \to D^* D X$

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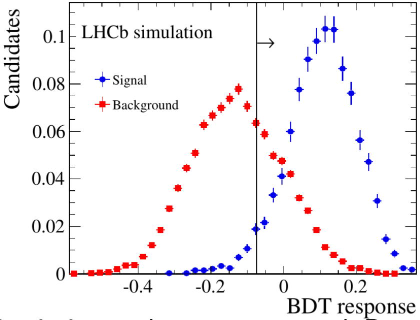
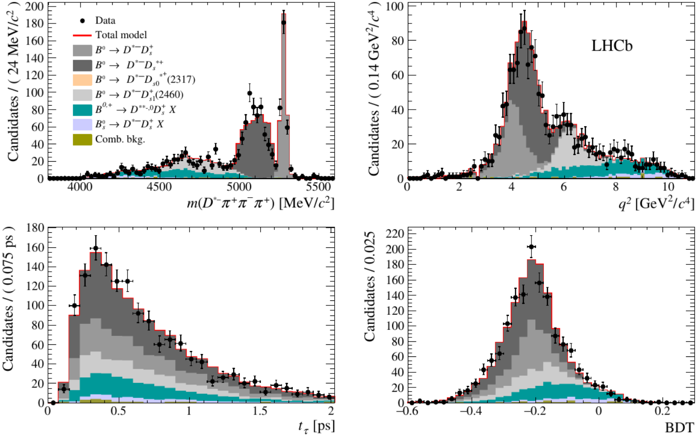


- $[\pi\pi\pi]$ lifetime discriminates between tau and $B \to D^* D X$
- Can use partial reconstruction techniques to reconstruct D peak in $B \to D^{*+} D$ (not $B \to D^* D X$)
- $\tau \to \pi\pi\pi\nu$ is mostly $a1(1260)$, $D \to \pi\pi\pi X$ mostly isn't
  - Use the $\pi\pi\pi$ (sub) structure to separate $B \to D^* \tau\nu$ from $B \to D^* D X$
  - Shown: control region for $D_s \to \pi\pi\pi X$
- Put everything in an MVA: kinematics, Dalitz, partial reconstruction, neutral isolation

Dealing with $B \to D^* D X$



- Use data to control $B \to D^* D X$ modelling
- Can use $D_{(s)} \to \pi\pi\pi$ mass peak to select a pure $B \to D^* D X$ sample
- This controls the $B \to D^* D X$ modelling, but not the $D \to \pi\pi\pi X$

$D \to \pi\pi\pi X$

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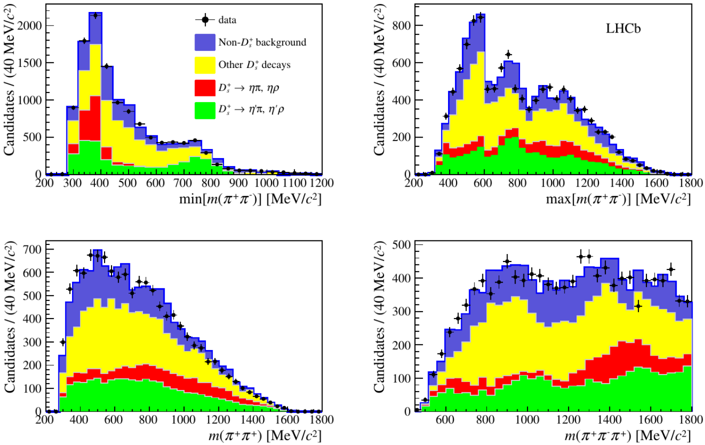

- Again, use data to control background modelling
- Use low BDT region to control $D_s \to \pi\pi\pi X$ substructure

Fit

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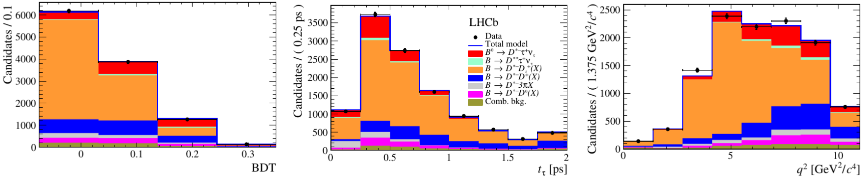
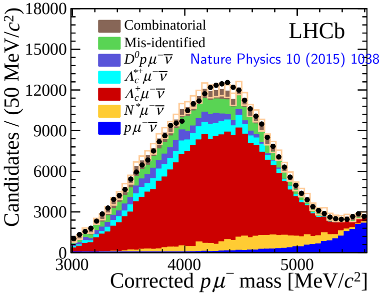


- 3D template fit in BDT,q^2, tau lifetime to determine signal yield

$b \to u\tau\nu$



- If we establish a new physics signal in $b \to c\tau\nu$, would really want to test the flavour structure: $b \to u\tau\nu$
  - $b \to c\tau\nu$ hard enough to measure, before extra suppression $\to$ background levels challenging
  - Requires very careful choice of channel to give us any hope
- $B \to p\overline{p}\tau\nu$ with $\tau \to \mu\nu\nu$
  - Experimentally the cleanest, Theoretically not so good...
  - Will make detailed measurements of corresponding $B \to p\overline{p}\mu\nu$ mode
- $\Lambda_b \to p\tau\nu$ with $\tau \to \pi\pi\pi\nu$?
  - Lattice calculations used to measure $|V_{\mathrm{ub}}|$ with equivalent $\Lambda_b \to p\mu\nu$ mode $\to$ already have a good theory prediction

Conclusion

- Measuring $B \to X\tau\nu$ is hard, takes time and care to do properly
- Updates will come
- Will transition into angular analyses
- Lots to look forward to