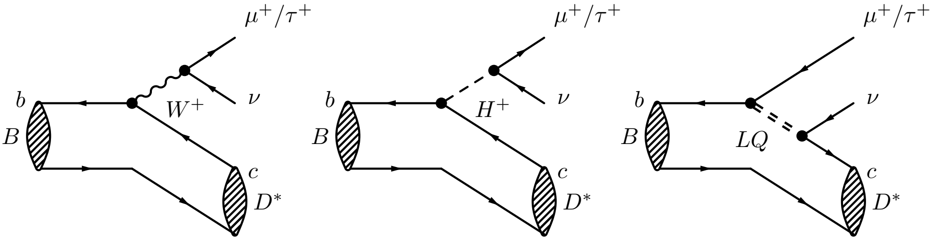
Overview of LHCb results on $B \to D^* \tau \nu$ and related topics

Greg Ciezarek,
on behalf of the LHCb collaboration

March 27, 2017

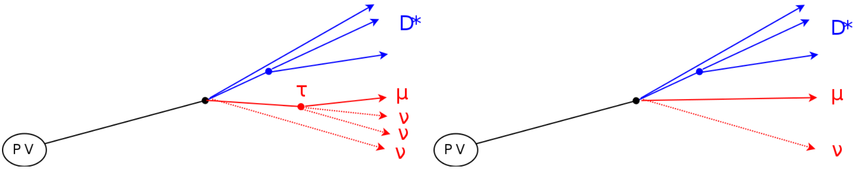
$B \to D^* \tau\nu$



- 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 e.g charged Higgs, leptoquark
- Current world average for $\mathcal{R}(D^{(*)})$in $\sim 4\sigma$ tension with Standard Model!

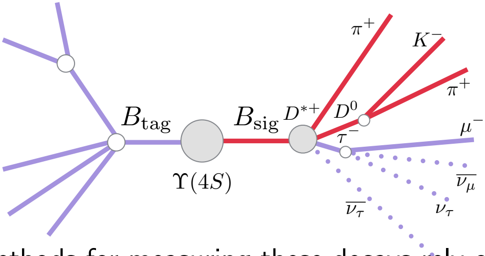
Experimental challenge

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



- 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

What you can't do at a hadron collider

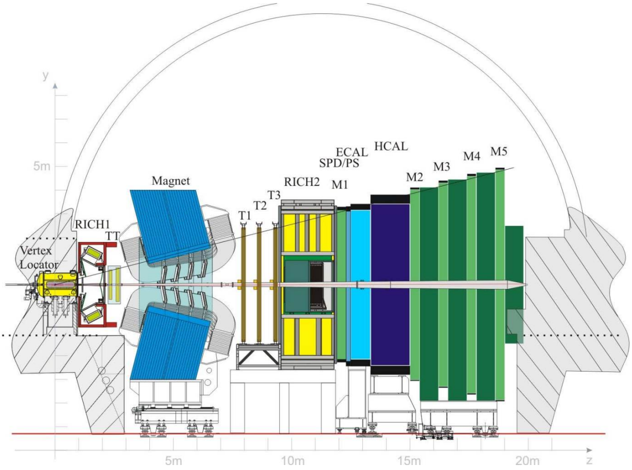


- Traditional methods for measuring these decays rely on $e^+e^- \to B\overline{B}$ event properties
  - Fully reconstruct other $B \to$ measurement of signal B kinematics
  - Signal B + other B should be entire event $\to$ strong rejection against other missing reconstructable particles
- In a hadron collider the $B\overline{B}$ centre of mass isn't fixed $\to$ rest of event provides little constraint on the signal B kinematics
  - Event also contains a lot of junk from the proton-proton interaction $\to$ reconstructing the whole event is meaningless
- Needed completely different methods

Overview

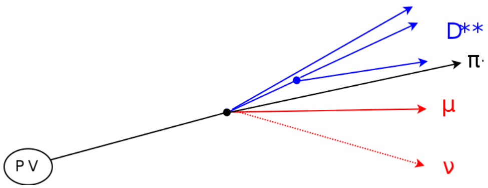
- Published $\mathcal{R}(D^*)$ measurement with $\tau \rightarrow \mu\nu\nu$
- $\tau \rightarrow \pi\pi\pi\nu$ measurements covered in Benedetto Siddi's talk next
- Ongoing measurements
- Future

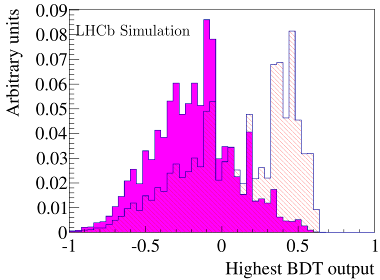
What you can do at a hadron collider



- Single arm forward spectrometer covering $2 < \eta < 5$
- Precision vertex measurement
- Muon and Hadron PID

Isolation

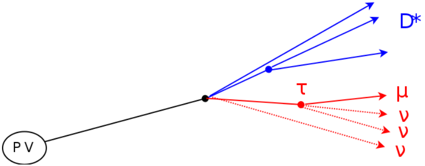




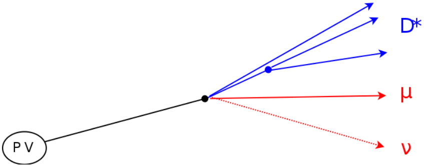
- Reject physics backgrounds with additional charged tracks
- MVA output distribution for $B \to D^{**}\mu^+\nu$ background (hatched) and signal (solid)
- Inverting the cut gives a sample hugely enriched in background $\to$ control samples

Fit strategy

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

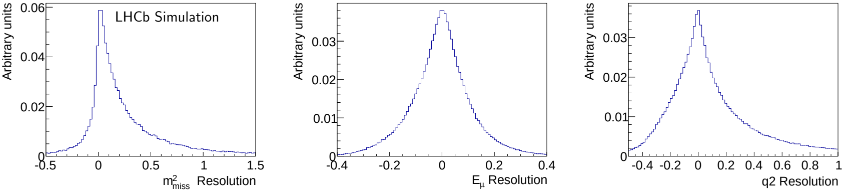


$B \rightarrow D^* \mu \nu$



- 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$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



- Can use *B* flight direction to measure transverse component of missing momentum
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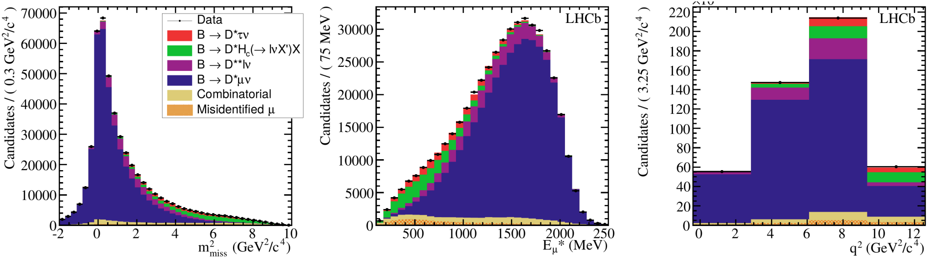
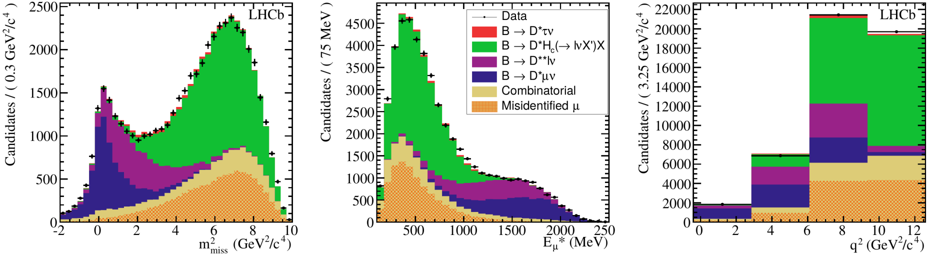
Fit strategy



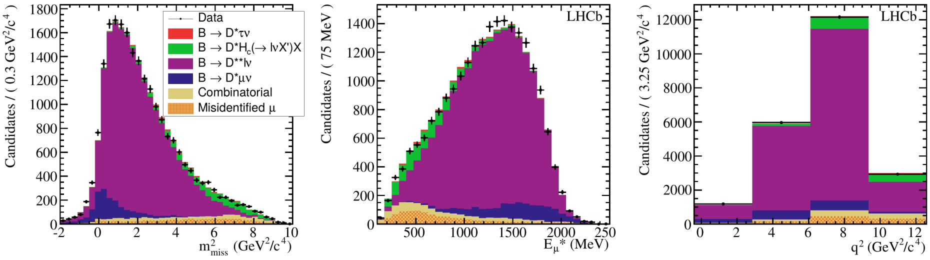
- Three dimesional template fit in E_{μ} (left), $m^2_{missing}$ (middle), and q^2
    - Projections of fit to isolated data shown
- All uncertainties on template shapes incorporated in fit:
    - Continuous variation in e.g different form factor parameters

Background strategy



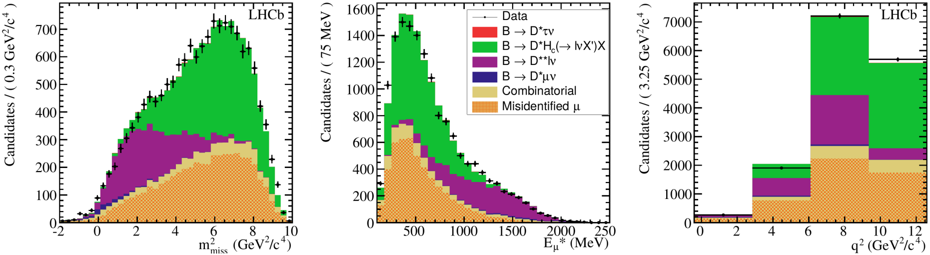
- All major backgrounds modelled using control samples in data
  - Dedicated samples for different backgrounds
  - Quality of fit used to justify modelling
  - Data-driven systematic uncertainties
- All combinatorial or misidentified backgrounds taken from data
- More details on everything in backups

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



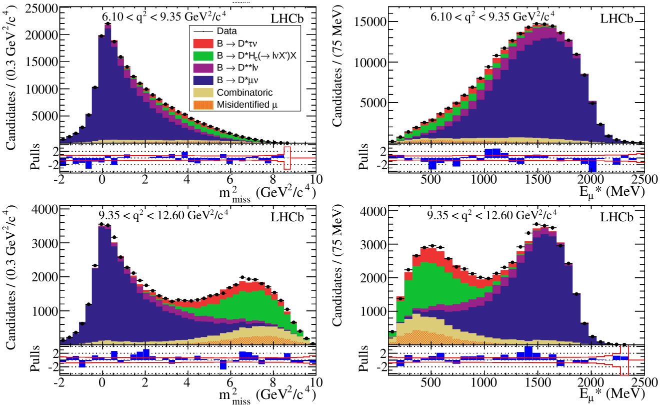
- Isolation MVA selects one track, $M_{D^{*+}\pi}$ around narrow D^{**} peak $\to$ select a sample enhanced in $B \to D^{**}\mu^+\nu$
  - Use this to constrain, justify $B \to D^{**}\mu^+\nu$ shape for light D^{**} states
  - Also fit above, below narrow D^{**} peak region to check all regions of $M_{D^{*+}\pi}$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

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



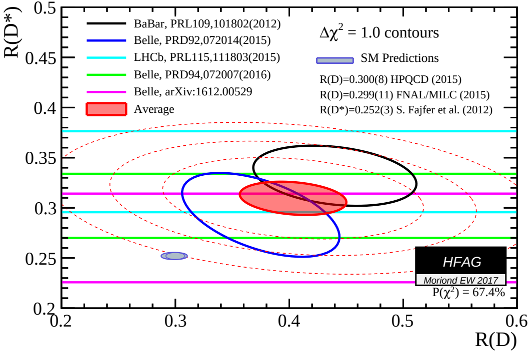
- Also look for two tracks with isolation MVA → study $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ in data
- Can control shape of this background

Signal fit



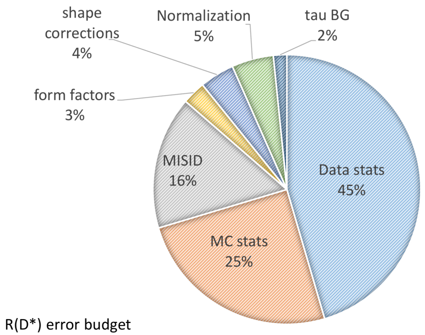
- Fit to isolated data, used to determine ratio of $B \rightarrow D^{*}\tau\nu$ and $B \rightarrow D^{*}\mu\nu$
- Model fits data well
- We measure $\mathcal{R}(D^{*}) = 0.336 \pm 0.027 \pm 0.030$, consistent with SM at 2.1σ level
  - LHCB-PAPER-2015-025

Next step: $D^0\mu X$ vs $D^{*+}\mu X$



- Final states closely entwined: D^* decays to D^0
    - Always a large correlation between $\mathcal{R}(D)$and $\mathcal{R}(D^*)$ measurements $\rightarrow$ this is second round of $\mathcal{R}(D^*)$ measurement
- $B \rightarrow D^{(*)}\tau\nu$ signal $\sim 5\times$ larger than in reconstructed $D^{*+}\mu X$ sample
    - $\sim 75\% D^*$ feed-down $\rightarrow$ significant update to $\mathcal{R}(D^*)$
- Backgrounds not so much worse than in $D^{*+}\mu X$

Sources of $\mathcal{R}(D^*)$ uncertainty

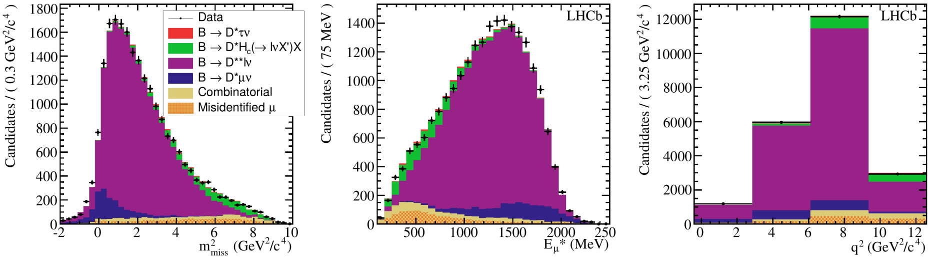


- Last year: measured $\mathcal{R}(D^*)$ using $B \to D^* \tau \nu$, $\tau \to \mu \nu \nu$,
  - Relative contributions to total [error squared] shown
  - Largest systematics from MC statistics and non-muon component
- All uncertainties improved
  - MC statistics increased
  - Misid (hadrons $\to$ muons) component uncertainty will be reduced by improved methods, smarter use of PID

Ongoing analyses

- Ongoing: $B_s \to D_s^{(*)} \tau\nu$
  - Similar situation to $\mathcal{R}(D^{(*)})$
  - Main difference to $B \to D^{(*)}\tau\nu$: feed-down mostly via neutrals
- Expected soon: $B_c \to J/\psi\,\tau\nu$
  - Production rate low, but $J/\psi \to \mu\mu$ is a nice final state $\to$ high efficiencies
  - Charmonium feed-down not so high, spectrum relatively well studied
  - Large background from $B \to J/\psi + (\text{hadron misidentified as muon X})$

Ongoing analyses

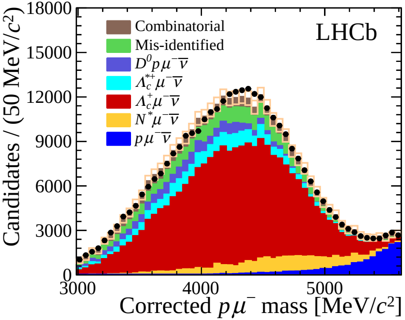


- Ongoing: $\Lambda_b \to \Lambda_c^{(*)} \tau\nu$
  - Different spin structure to meson modes → different physics sensitivity
  - In particular, would help discriminate tensor contributions
- Potential: $B \to D^{**}\tau\nu$
  - Samples of $D^{**}\mu X$ not so small: control sample for $\mathcal{R}(D^*)$ measurement shown
  - To interpret results, need to split measurements between different D^{**} states
  - More work needed first on $B \to D^{**}\mu\nu$ modes

Other hadronic analyses

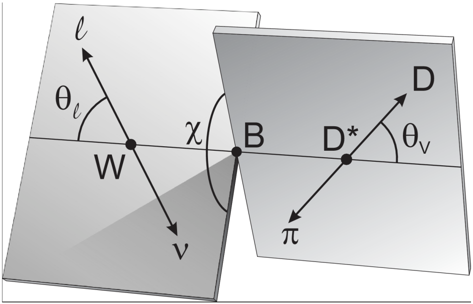
- After $\mathcal{R}(D^*)$, expect full program of measurements with hadronic tau
- $\mathcal{R}(\Lambda_c)$already underway
- Key issue: normalisation channels
    - Hadronic $\mathcal{R}(D^*)$ measurement relies on precise external measurement of $B \rightarrow D^{*+}\pi^-\pi^+\pi^-$
    - These do not exist for e.g $\Lambda_b \rightarrow \Lambda_c\pi^-\pi^+\pi^-$
    - Plan to use theory calculation for $\mathcal{B}(\Lambda_b \rightarrow \Lambda_c\mu\nu)/\mathcal{B}(B \rightarrow D^*\mu\nu)$ to avoid dependence on Λ_b production fraction

$b \to u\tau\nu$



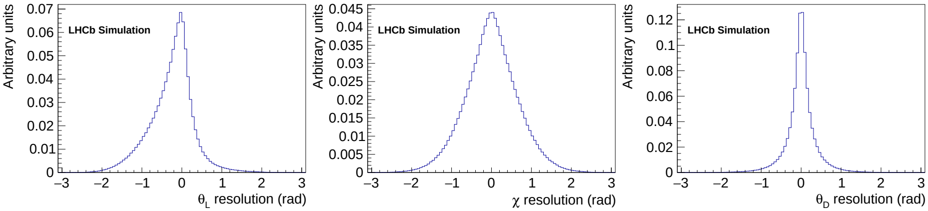
- If we establish a new physics signal in $b \to c\tau\nu$, would really want to test the flavour structure: $b \to u\tau\nu$
  - $b \to c\tau\nu$ hard enough to measure, before extra suppression $\to$ background levels challenging
  - Requires very careful choice of channel to give us any hope
- See Mark Smith's talk tomorrow

Beyond Rs



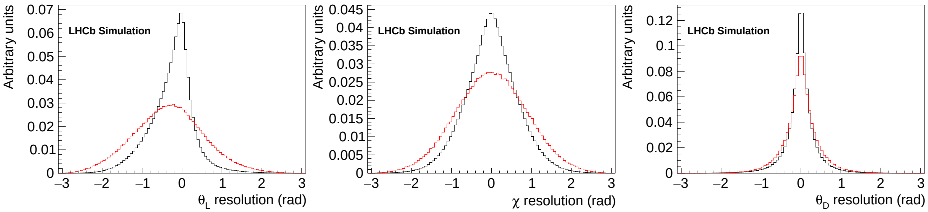
- Ratios of branching fractions are only the first observable
  - q^2, angles, τ/D^* polarisation have different sensitivity to new physics
- Variables fitted in $\tau \to \mu\nu\nu$ analyses already have some sensitivity to this
  - For now, measurements assume SM distributions (+ uncertainties)

Angular resolutions for $B \to D^* \mu\nu$



- Before taus, first look at angular resolution for $B \to D^* \mu\nu$ simulated events
- Pretty wide, but have something to work with
  - Interesting mesurements possible in muonic modes

Angular resolutions for $B \to D^{*}\tau\nu$ ($\tau \to \mu\nu\nu$)



- Angular resolution for $B \to D^{*}\tau\nu$
- Tau decay results in loss of information
  - θ_ℓ and χ degraded
  - θ_D about the same $\to$ $D^{*+}(\Lambda_c)$ polarisation related observables maybe a good first target
  - Ideas for how to proceed, some tools already exist
  - Possible first step: measure scalar form-factor directly from $B \to D^{(*)}\tau\nu$ data, eliminate dependence on calculations
- Sensitivity not yet known, may need larger samples to really pin things down..

Future

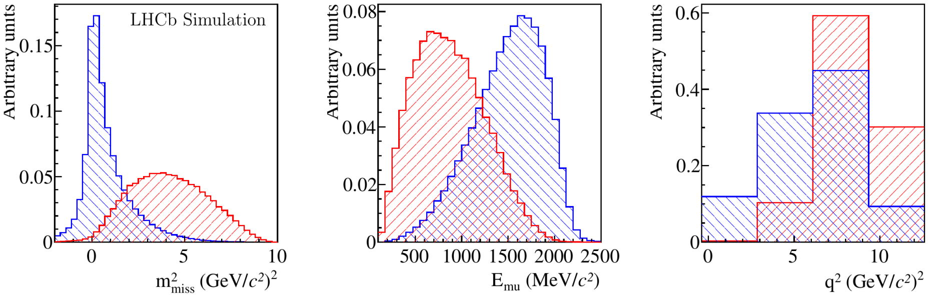
- What we have analysed now is a tiny fraction of the sample we will eventually collect
  - With 50 fb^{-1} (2021-2030), samples will grow by a factor ~ 30
  - With 300 fb^{-1}, (2034) samples will grow by a factor ~ 200
  - No sign that we hit a systematic limit
  - O(10 million) $B \to D^{*}\tau\nu$ ($\tau \to \mu\nu\nu$) events $\to$ huge power for angular analysis
  - Need to work together with theory to understand all contributions to the needed precision $\to$ continuous process
  - Even more suppressed signals ($B_c \to J/\psi\,\tau\nu X$, $B \to D^{**}\tau\nu$, $b \to u\tau\nu$ modes?) can have high statistical precision

Conclusion

- First LHCb measurement of $B \to D^{*}\tau\nu$ ($\tau \to \mu\nu\nu$) consistent with SM at 2.1σ level
  - First ever measurement of a $b \to \tau$ decay at a hadron collider
  - Phys. Rev. Lett. 115 (2015) 111803
- Coming soon: $\mathcal{R}(D^{*})$ measurement with $\tau \to \pi\pi\pi\nu$, $\mathcal{R}(J/\psi)$, $\mathcal{R}(D^{(*)})$(both $\tau \to \mu\nu\nu$)
  - Exciting times
- Program of measurements in other channels underway, will continue to expand
- Will also start measuring observables beyond branching fractions
- All these measurements are still limited by sample sizes, will continue to improve

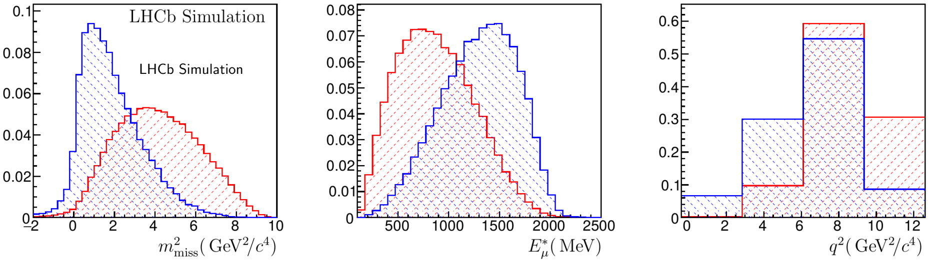
Backups

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



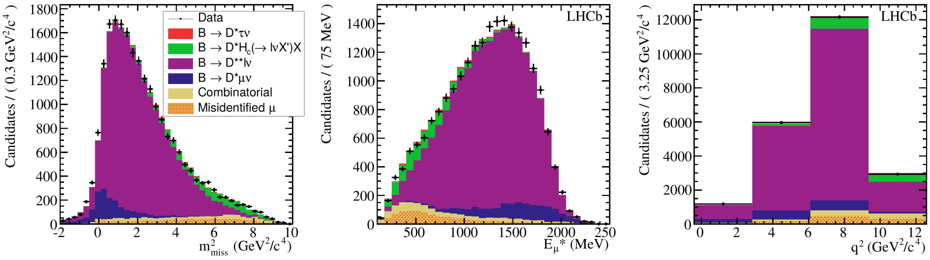
- $B \to D^* \mu\nu$ (black) vs $B \to D^* \tau\nu$ (red)
- $B \to D^* \mu\nu$ is both the normalisation mode, and the highest rate background ($\sim 20 \times B \to D^* \tau\nu$)
  - Use CLN parameterisation for form factors
  - Float form factors parameters in fit $\to$ uncertainty taken into account

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



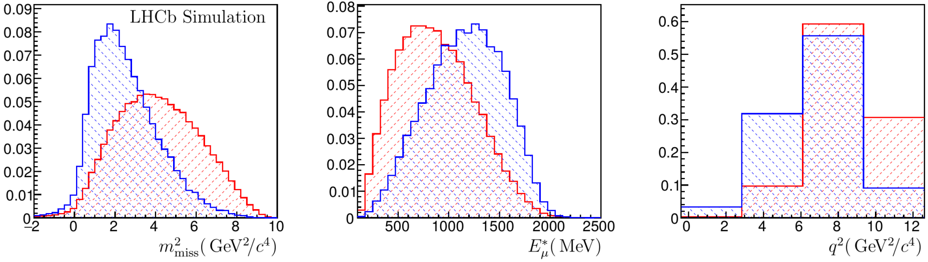
- $B \to D^{**}\mu^+\nu$ refers to any higher charm resonances (or non resonant hadronic modes)
- Not so well measured
  - Set of states comprising D^{**} known to be incomplete
  - Decay models not well measured
- For the established states (shown in black):
  - Separate components for each resonance (D_1,D_2^*,D_1')
  - Use LLSW model (Phys. Rev. D. (1997) 57 307), float slope of Isgur-wise function

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



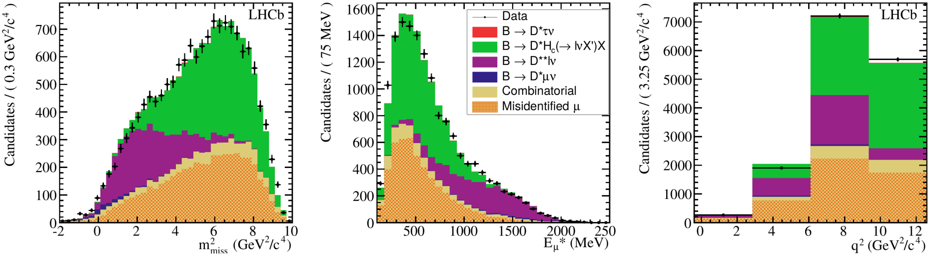
- Isolation MVA selects one track, $M_{D^{*+}\pi}$ around narrow D^{**} peak $\to$ select a sample enhanced in $B \to D^{**}\mu^+\nu$
  - Use this to constrain, justify $B \to D^{**}\mu^+\nu$ shape for light D^{**} states
  - Also fit above, below narrow D^{**} peak region to check all regions of $M_{D^{*+}\pi}$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

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



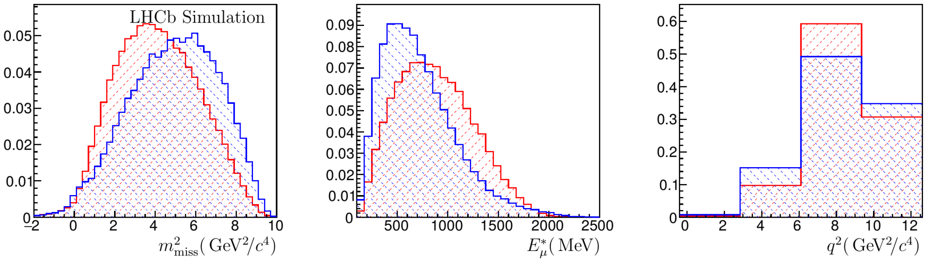
- Previously unmeasured $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ contributions recently measured by BaBar
  - Too little data to separate individual (non)resonant components
  - Single fit component, empirical treatment
- Constrain based on a control sample in data
  - Degrees of freedom considered: D^{**}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

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



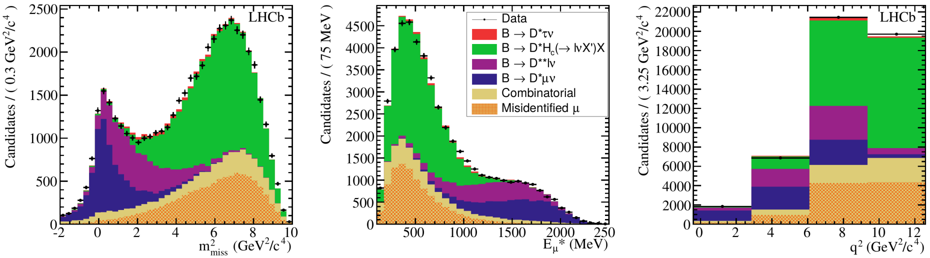
- Also look for two tracks with isolation MVA → study $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ in data
- Can control shape of this background

$B \to D^* D X$



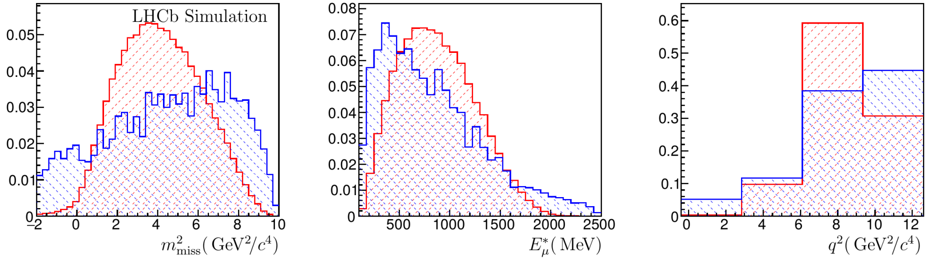
- $B \to D^* D X$ consists of a very large number of decay modes
  - Physics models for many modes not well established
- Constrain based on a control sample in data
- Single component, empirical treatment
  - Consider variations in M_{DD}
  - Multiply simulated distributions by second order polynomials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

$B \to D^* DX$ control sample



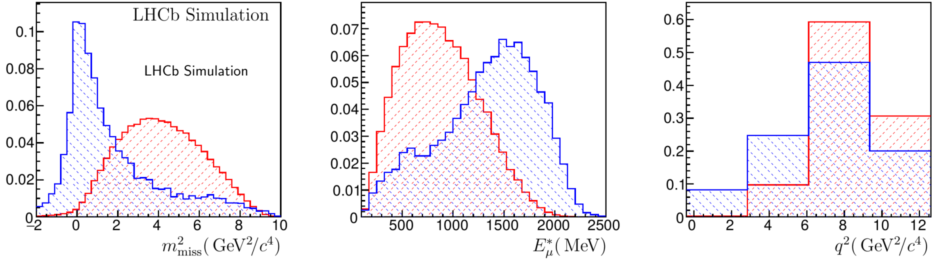
- Isolation MVA selects a track with loose kaon ID $\to$ select a sample enhanced in $B \to D^* DX$
- Use this to constrain, justify $B \to D^* DX$ shape

Combinatorial backgrounds



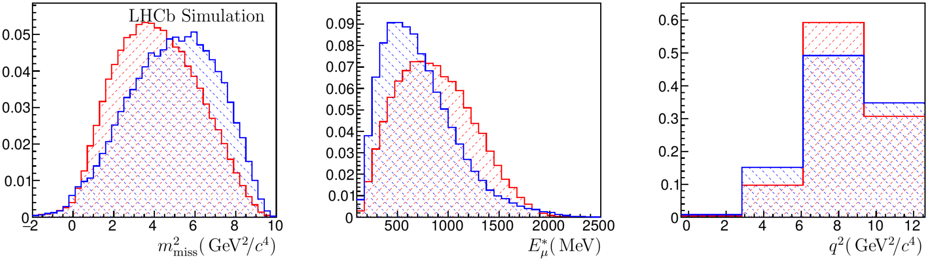
- Combinatorial background modelled using same-sign $D^{*+}\mu^+$ data
- Two sources of combinatorial background are treated separately (shown on next slide)

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)