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

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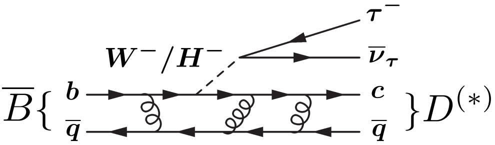
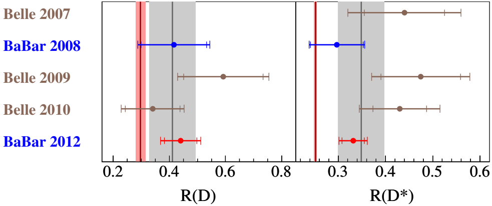
What we want to measure



- 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
- 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
- Theoretically clean?
  - $\sim 2\%$ uncertainty for D^* mode, $\sim 6\%$ for D
- Focus here more on $B \to D^*\tau\nu$ with $\tau \to \mu\nu\nu$
- Also introduce $B \to D^*\tau\nu$ with $\tau \to \pi\pi\pi\nu$

Existing measurements

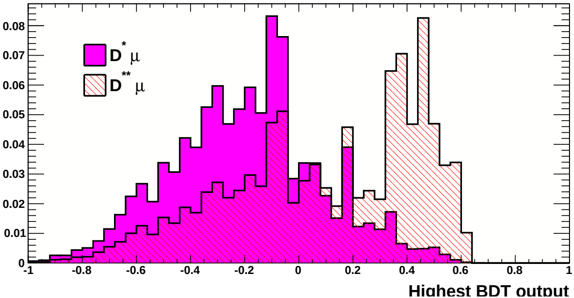


- Previous measurements from B factories in $\tau \rightarrow \ell\nu\nu$ channel
- Most recent measurement from BaBar claimed 3 σ excess over SM expectation
  - BaBar have used their final dataset, corresponding Belle measurement yet to come
- B factory measurements based on reconstructing missing mass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

Experimental challenge

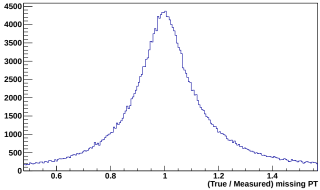
- Difficulty: neutrinos - 3 for $(\tau \to \mu\nu\nu)\nu$
  - No narrow peak to fit (in any distribution)
- Main backgrounds: partially reconstructed B decays
  - $B \to D^{*(*)}\mu\nu$, $B \to D^{*}\pi\pi\pi X$, $B \to D^{*}D$ ...
- Also combinatorial background
- Need to find fit distributions which differentiate signal and background $\to$ fit
- Additional information used to reduce backgrounds:
  - Isolation
  - τ flight (lifetime $= 87\mu m$)

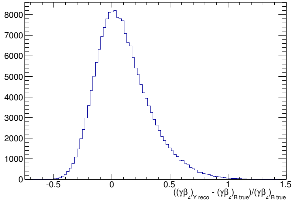
Isolation MVA



- 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
- Highest MVA output distribution for D^{**} and $B \to D^* \mu\nu$
- Inverting the cut gives a sample hugely enriched in physics backgrounds $\to$ use this to control shapes

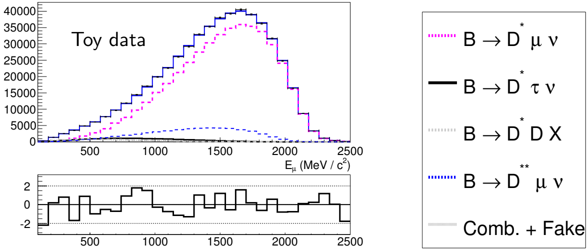
Fit strategy





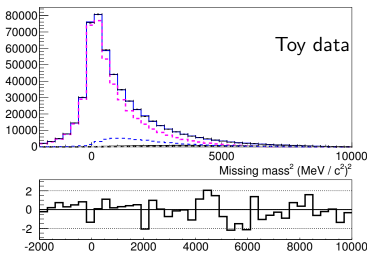
- Can use B flight direction to measure transverse component of missing momentum
- No way of measuring longitudinal component $\rightarrow$ use approximation to access rest frame kinematics
  - B boost $>>$ energy release in decay
  - Assume $\gamma\beta_{z,visible} = \gamma\beta_{z,total}$
  - $\sim$18%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

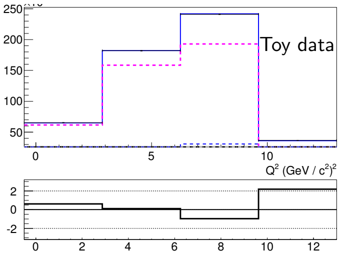
Toy data



- 3D template fit in lepton energy (B rest frame), missing mass squared and q^2
- Toy dataset show after isolation requirement
- Backgrounds described in detail later
- Signal not large...

Toy data





- 3D template fit in lepton energy (B rest frame), missing mass squared and q^2
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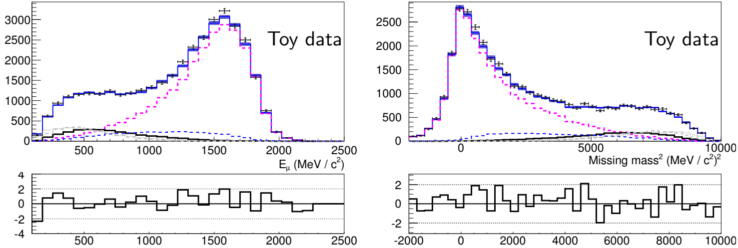
Toy data (high q^2)

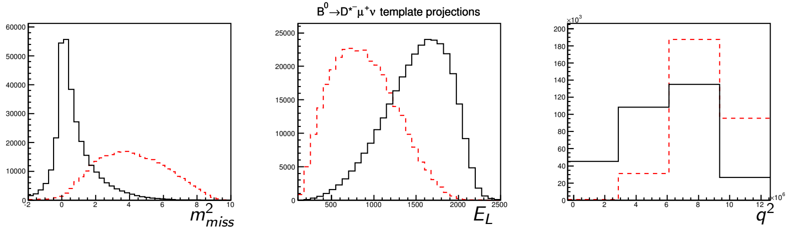


- Fit projections for highest q^2 bin
- A bit more promising at least
- The key to the analysis is the background modelling

Background shape uncertainties

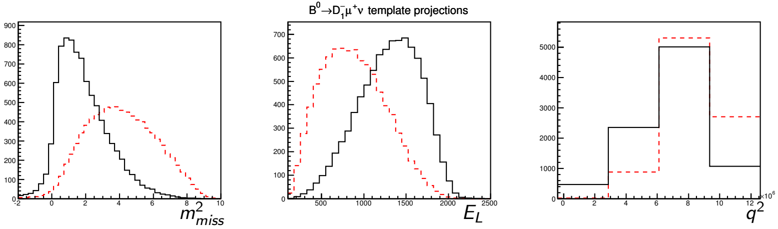
- Uncertainties on template shapes incorporated in fit:
    - Reweight MC samples reflecting e.g different form factor parameters
    - Two implementations: interpolate or regenerate histograns at each minimisation step
    - Parameterisation for each background discussed later
- Allows background shape parameters to be varied continuously
    - All major backgrounds controlled using data
    - Rely only on parameterisations, not parameters

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



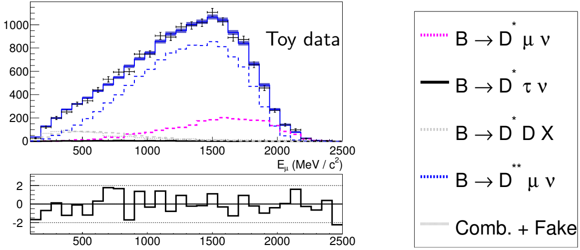
- $B \to D^* \mu\nu$ (black) vs $B \to D^* \tau\nu$ (red)
- $B \to D^* \mu\nu$ is both the normalisation mode, and the highest rate background ($\sim 20 \times B \to D^* \tau\nu$)
  - Use CLN parameterisation for form factors
  - Float form factors parameters in fit $\to$ uncertainty taken into account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

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



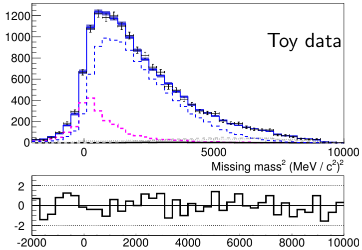
- $B \to D^{**}\mu^+\nu$ refers to any higher charm resonances (or non resonant hadronic modes)
- Not so well measured
  - Set of states comprising D^{**} known to be incomplete
  - Decay models not well measured
- For the established states (shown in black):
  - Separate components for each resonance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

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



- Isolation MVA selects one track, $M_{D^{*+}\pi}$ around narrow D^{**} peak $\to$ select a sample enhanced in $B \to D^{**}\mu^+\nu$
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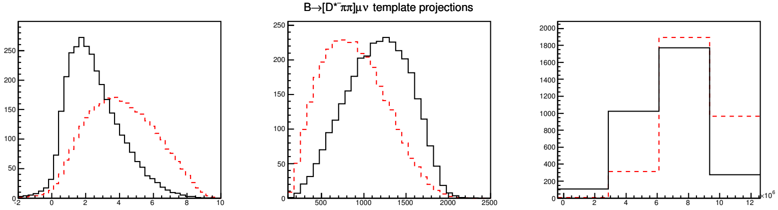
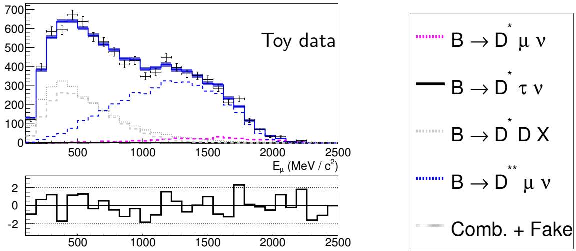
Higher $B \to D^{**}\mu^+\nu$ states



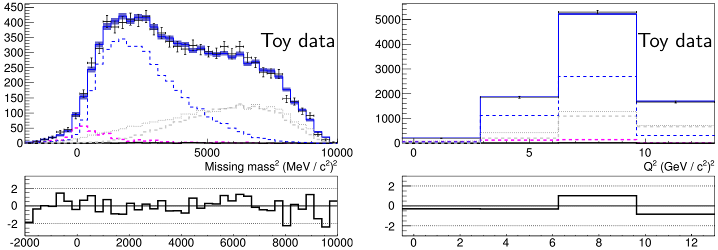
- Previously unmeasured $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ contributions recently measured by BaBar
  - Too little data to separate individual (non)resonant components
  - Single fit component, empirical treatment
- Constrain based on a control sample in data
  - Degrees of freedom considered: D^{**}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

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



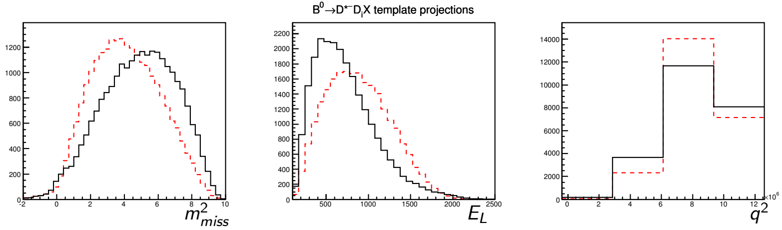
- Look for two tracks with isolation MVA $\to$ study $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ in data
  - Toy dataset shown
- Can control shape of this background

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



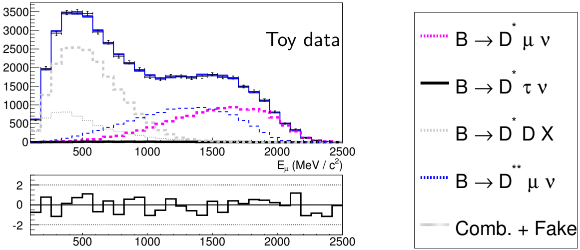
- Also look for two tracks with isolation MVA $\to$ study $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ in data
  - Toy dataset shown
- Can control shape of this background

$B \to D^* DX$



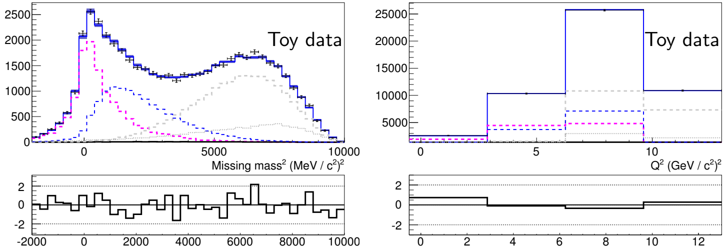
- $B \to D^* DX$ consists of a very large number of decay modes
  - Physics models for many modes not well established
- Constrain based on a control sample in data
- Single component, empirical treatment
  - Consider variations in: M_{DD}, M_X and $M_{\mu\nu}$
  - Multiply simulated distributions by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

$B \to D^* DX$ control sample



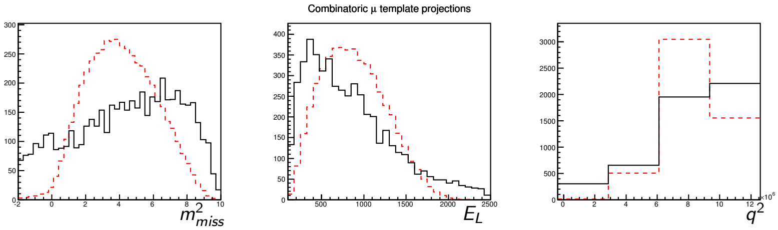
- Isolation MVA selects a track with loose kaon ID $\to$ select a sample enhanced in $B \to D^* DX$
- Use this to constrain, justify $B \to D^* DX$ shape

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



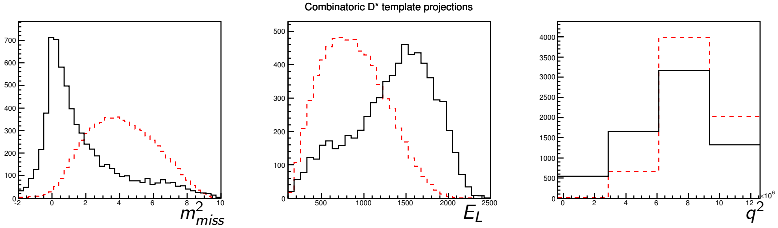
- Isolation MVA selects a track with loose kaon ID $\to$ select a sample enhanced in $B \to D^* D X$
- Use this to constrain, justify $B \to D^* D X$ shape

Combinatorial backgrounds



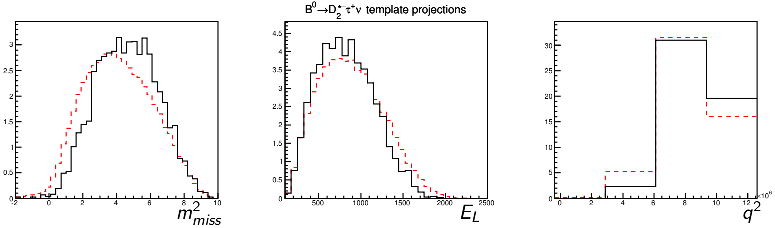
- Combinatorial background modelled using same-sign $D^{*+}\mu^{+}$ data
- Two sources of combinatorial background are treated separately (shown on next slide)

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 expected to be $<\sim$ 10% of the signal yield: $B \to D^{**}\tau^+\nu$ (shown) and $B \to D^*(D_s \to \tau\nu)X$
- $B \to D^{**}\tau^+\nu$ 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)
- Both too small to measure

Sensitivity

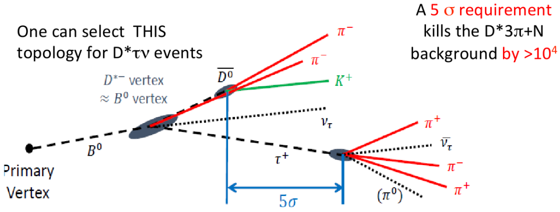
- Overall uncertainty competitive with BaBar
- Largest systematic uncertainties from background modelling
    - Controlled by background samples in data → will scale with statistics
    - Largest single systematic uncertainty from MC template statistics → can be reduced
- Uncertainties from selectionefficiency etc not significant

Measurement with $\tau \rightarrow \pi\pi\pi\nu$

Introduction

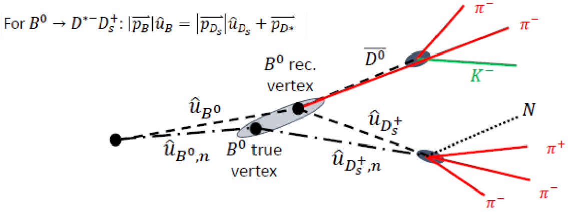
- Measurement of $\mathcal{B}(B \to D^*\tau\nu)$ also underway using $\tau \to \pi\pi\pi\nu$
- Different sets of backgrounds:
  - Large $B \to D^*\mu\nu$ component absent
  - $B \to D^{**}\mu^+\nu$ also not present
  - Additional $B \to D^*\pi\pi\pi X$ backgrounds
  - $B \to D^*DX$ with $D \to \pi\pi\pi X$

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



- Can use decay topology to remove direct $B \to D^*\pi\pi\pi X$ decays:
- If the $[\pi\pi\pi]$ vertex is downstream of the $[D]$ vertex, the $[\pi\pi\pi]$ must have flown $\to \tau$ or D decay
- Can remove a large, poorly measured background
  - Negligible with sufficiently tight cut
- $B \to D^* DX$ major physics background remaining

Dealing with $B \to D^* DX$



- Can use partial reconstruction techniques to reconstruct D peak in $B \to D^{*+} D$ (not $B \to D^* DX$)
  - Use this to control $D \to \pi\pi\pi X$ modelling
- $\tau \to \pi\pi\pi\nu$ 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 $B \to D^* DX$
- Measurement underway

Conclusion

- LHCb can measure $B \to D^* \tau \nu$
- Measurement of $\mathcal{R}(D^*)$ using $\tau \to \mu \nu \nu$ coming soon
  - All major backgrounds controlled with data
- Measurement using $\tau \to \pi \pi \pi \nu$ also in progress
- $B \to D^0 \tau \nu$ and $\Lambda_b^0 \to \Lambda_c \tau \nu$ next on agenda