New physics in $B \to D^*\tau\nu$?

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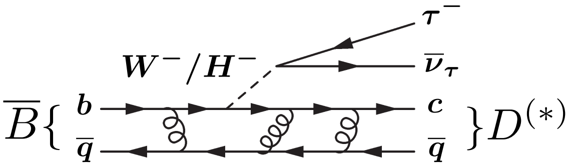
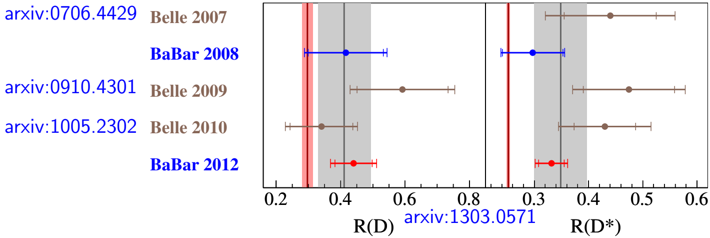
$B \to D^*\tau\nu$



- 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
- New measurement $B \to D^*\tau\nu$ with $\tau \to \mu\nu\nu$ published in PRL last month

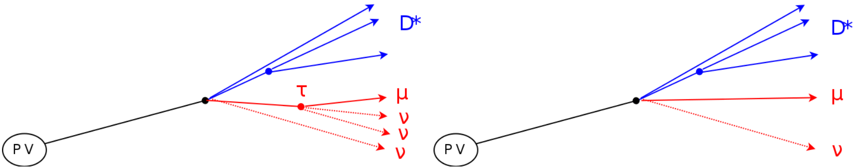
Existing measurements



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

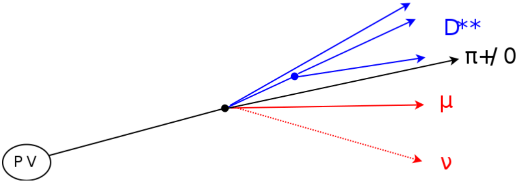
Experimental challenge

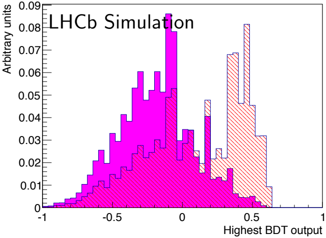
$B \to D^* \tau \nu$ $\qquad\qquad$ $B \to D^* \mu \nu$



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

Isolation MVA

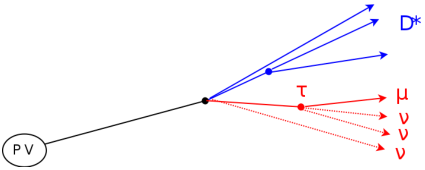




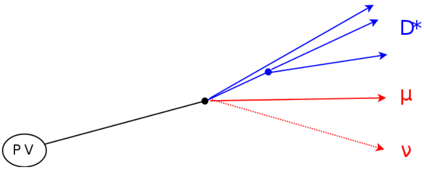
- Reject physics backgrounds with additional charged tracks
- MVA output distribution for (one) background (hatched) and signal (solid)
- Inverting the cut gives a sample hugely enriched in background $\rightarrow$ control samples

Fit strategy

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

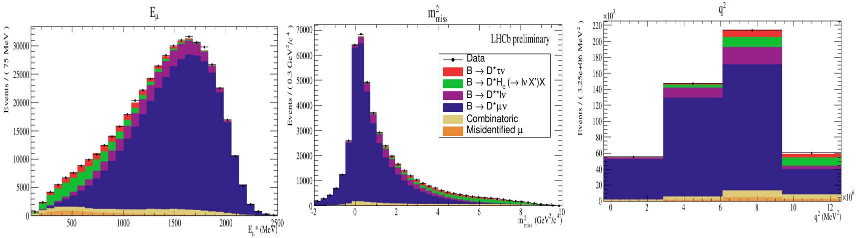


$B \to D^* \mu \nu$



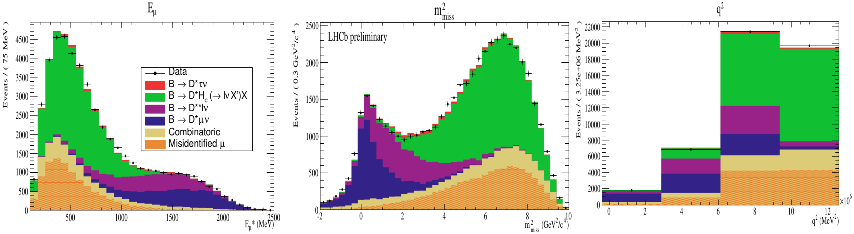
- Can use B flight direction to measure transverse component of missing momentum
- No way of measuring longitudinal component $\to$ use approximation to access rest frame kinematics
  - B boost >> energy release in decay
  - Assume $\gamma\beta_{z,visible} = \gamma\beta_{z,total}$
  - $\sim$18% resolution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

Fit strategy



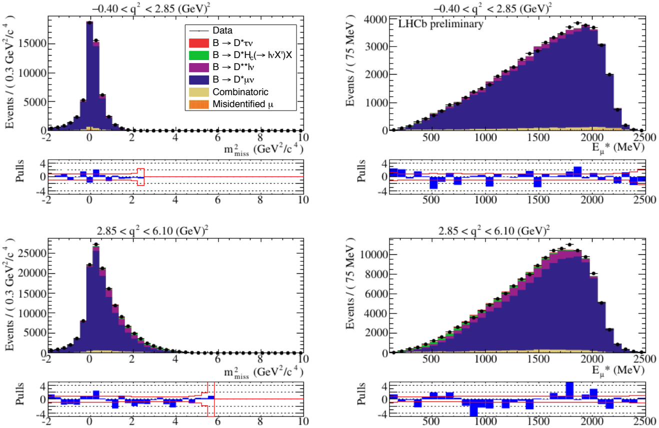
- Three dimesional template fit in E_μ (left), $m^2_{missing}$ (middle), and q^2
  - Projections of fit to isolated data shown
- All uncertainties on template shapes incorporated in fit:
  - Continuous variation in e.g different form factor parameters

Background strategy



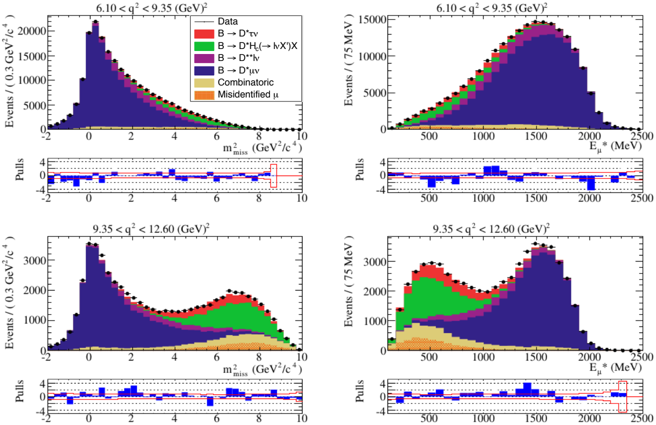
- All major background controlled using data
  - Data-driven uncertainties
  - Justification of modelling
- More details on everything in backups

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

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

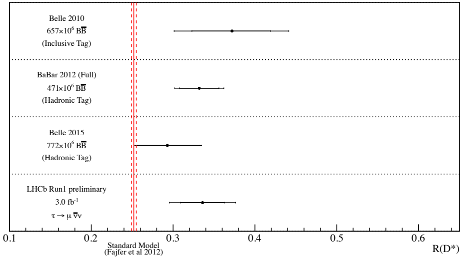
Uncertainties

Model uncertainties	Size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
D^* form factors	0.6
$B \to D^* D X$ 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**

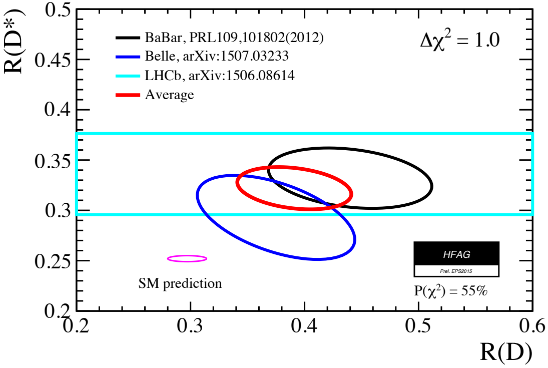
- Statistical uncertainty 2.7%
- All major systematics reducible with more data / MC

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
- New Belle measurement in between other measurements, SM
  - Consistent with both

Result

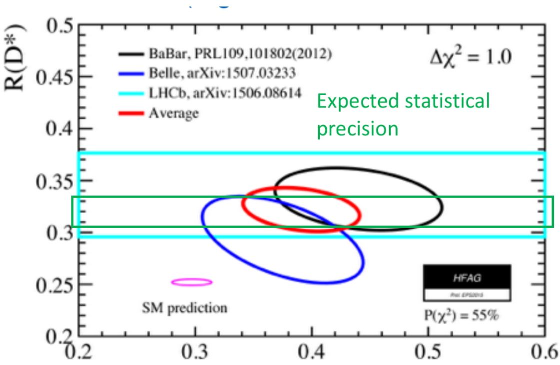


- HFAG average of $\mathcal{R}(D^{(*)})3.9\sigma$ from SM
- Intriguing enough to consider new physics implications $\rightarrow$ see next talk from Niels

Future plans

- Next step: measure $B \to D^0 \tau \nu$ (well underway)
  - Then $\Lambda_b^0 \to \Lambda_c \tau \nu$
- Measure q^2, angular distributions
- $\mathcal{R}(D^*)$ measurement using $\tau \to \pi\pi\pi\nu$ also underway
- Also working on $B \to D^{(*)} e\nu$ vs $B \to D^{(*)} \mu\nu$ → all other measurements of lepton universality in B decays in tension with expectations...

Future plans



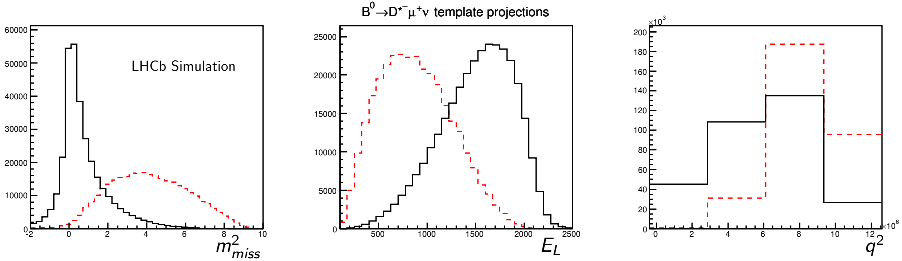
- Current expected statistical precision with $\tau \to \pi\pi\pi\nu$ mode looks very promising

Conclusion

- LHCb measurement of $B \rightarrow D^{*}\tau\nu$ consistent with SM at 2.1σ level
  - First ever measurement of a $b \rightarrow \tau$ decay at a hadron collider
  - LHCB-PAPER-2015-025
- World average for $\mathcal{R}(D^{(*)})$in 3.9σ tension with SM
  - Arguably the strongest current hint of new physics
- LHCb will have much more to say on this

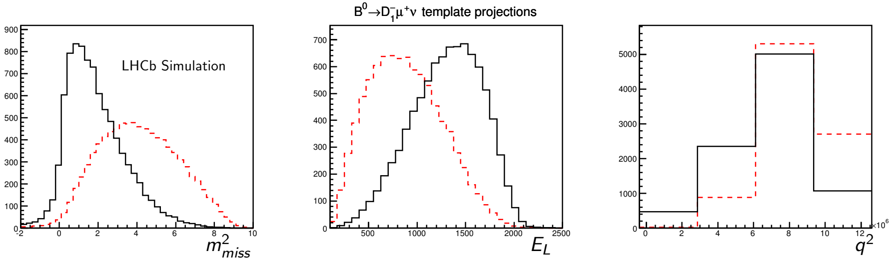
Backups

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



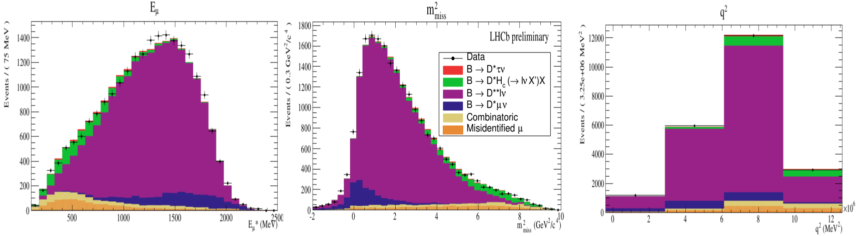
- $B \to D^* \mu\nu$ (black) vs $B \to D^* \tau\nu$ (red)
- $B \to D^* \mu\nu$ is both the normalisation mode, and the highest rate background ($\sim 20 \times B \to D^* \tau\nu$)
  - Use CLN parameterisation for form factors
  - Float form factors parameters in fit $\to$ uncertainty taken into account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

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



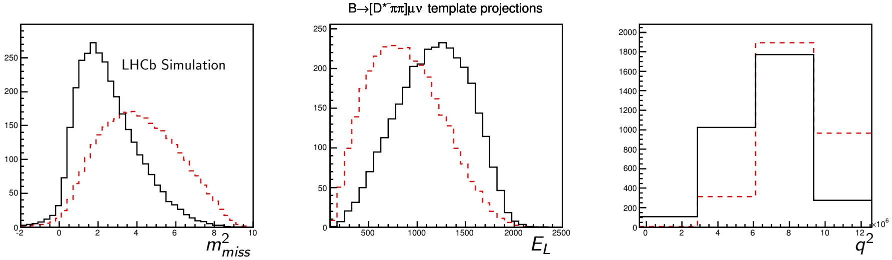
- $B \to D^{**}\mu^+\nu$ refers to any higher charm resonances (or non resonant hadronic modes)
- Not so well measured
  - Set of states comprising D^{**} known to be incomplete
  - Decay models not well measured
- For the established states (shown in black):
  - Separate components for each resonance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



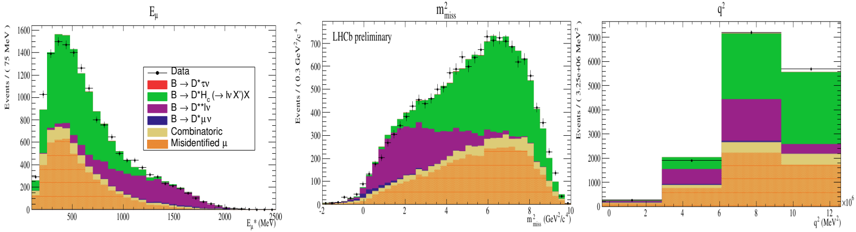
- Isolation MVA selects one track, $M_{D^{*+}\pi}$ around narrow D^{**} peak $\to$ select a sample enhanced in $B \to D^{**}\mu^+\nu$
  - Use this to constrain, justify $B \to D^{**}\mu^+\nu$ shape for light D^{**} states
  - Also fit above, below narrow D^{**} peak region to check all regions of $M_{D^{*+}\pi}$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

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



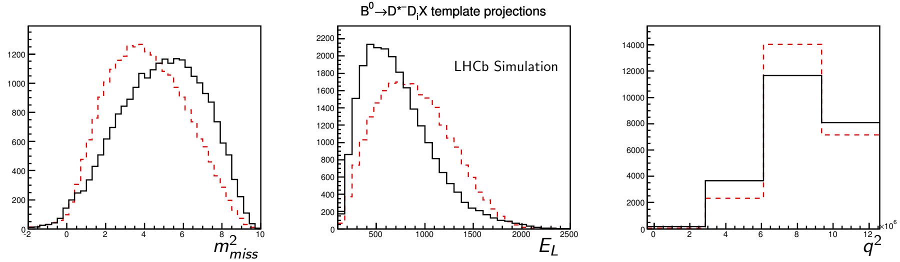
- Previously unmeasured $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ contributions recently measured by BaBar
  - Too little data to separate individual (non)resonant components
  - Single fit component, empirical treatment
- Constrain based on a control sample in data
  - Degrees of freedom considered: D^{**}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

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



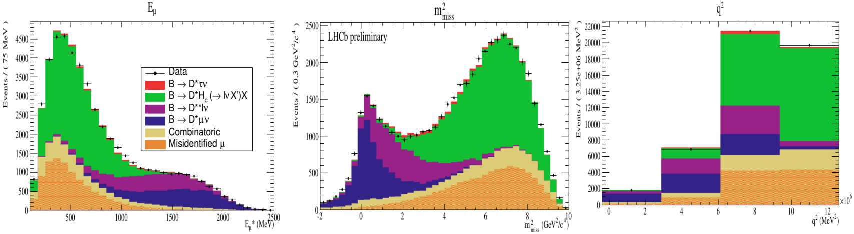
- Also look for two tracks with isolation MVA $\to$ study $B \to D^{**}(\to D^{*+}\pi\pi)\mu\nu$ in data
- Can control shape of this background

$B \to D^* DX$



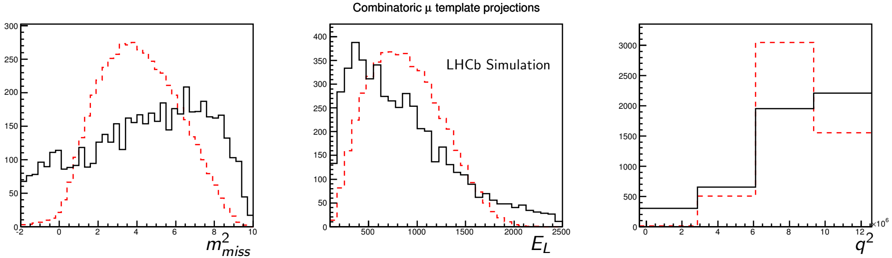
- $B \to D^* DX$ consists of a very large number of decay modes
  - Physics models for many modes not well established
- Constrain based on a control sample in data
- Single component, empirical treatment
  - Consider variations in M_{DD}
  - Multiply simulated distributions by second order polynomials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

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



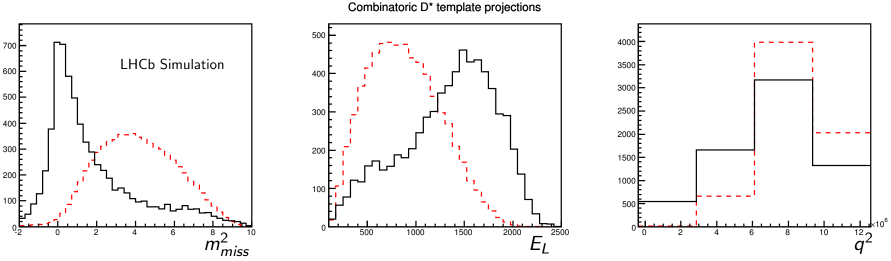
- Isolation MVA selects a track with loose kaon ID $\to$ select a sample enhanced in $B \to D^* D X$
- Use this to constrain, justify $B \to D^* D X$ shape

Combinatorial backgrounds



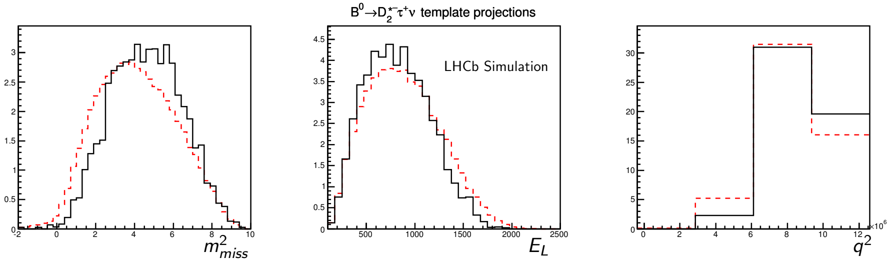
- Combinatorial background modelled using same-sign $D^{*+}\mu^+$ data
- Two sources of combinatorial background are treated separately (shown on next slide)

Combinatorial backgrounds



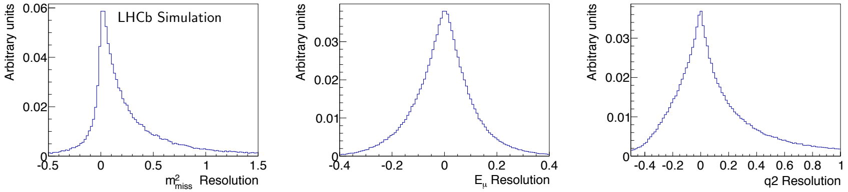
- Non D^{*+} backgrounds (fake D^*) template modelled using $D^0\pi^-$ data (shown)
  - Yield determined from sideband extrapolation beneath D^{*+} mass peak
- Hadrons misidentified as muons (fake muons)
  - Controlled using $D^{*+}h^{\pm}$ sample
  - Both template and expected yield can be determined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

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



- Two small backgrounds containing taus, each $<\sim$ 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)

Fit strategy



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