$\mathcal{R}(D^*)$ and $\mathcal{R}(D)$ with $\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$

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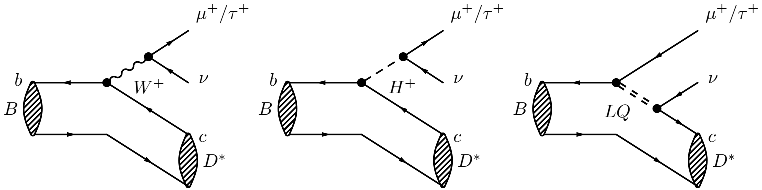
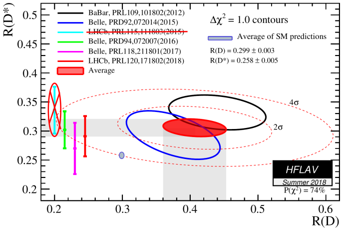
$\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$



- In the SM, the only difference between $\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$ and $\overline{B} \to D^{(*)}\mu^-\overline{\nu}_\mu$ is the mass of the lepton
  - Form factors mostly cancel in the ratio of rates (except helicity suppressed amplitude)
- Ratio $\mathrm{R}(D^{(*)}) = \mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau) \;/\; \mathcal{B}(\overline{B} \to D^{(*)}\mu^-\overline{\nu}_\mu)$ is sensitive to e.g charged Higgs, leptoquarks
- D vs D^*: different meson spin, so different physics sensitivity

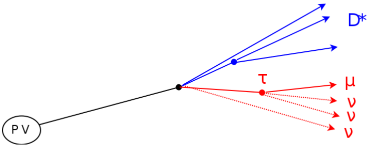
Previous status



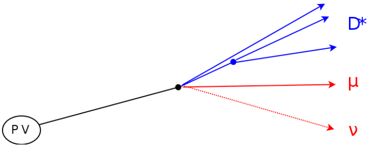
- Before: measure $\mathcal{R}(D^*)$ with Run 1 $D^{*+}\mu^-$ data
- Now: simultaneously measure $\mathcal{R}(D)$and $\mathcal{R}(D^*)$ with Run 1 $[D^0\mu^-]$ and $[D^{*+}\mu^-]$ data
  - Higher branching fractions and higher efficiency - $[D^0\mu^-]$ sample $\sim 5\times$ bigger than $[D^{*+}\mu^-]$
  - Largest contribution from $B \to D^{*0}(\to D^0\pi^0)\ell\nu$
- LHCb-PAPER-2022-039 in preparation

Experimental challenge

$$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$$



$$\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$$



- Difficulty: neutrinos - 3 for $(\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu)\nu$
    - 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, misidentified backgrounds

Fit strategy

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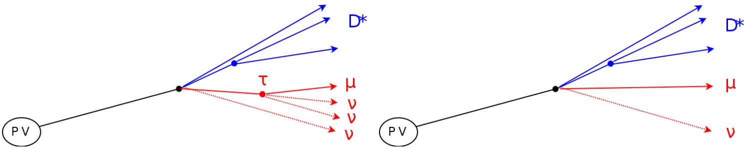
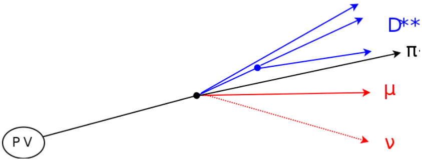
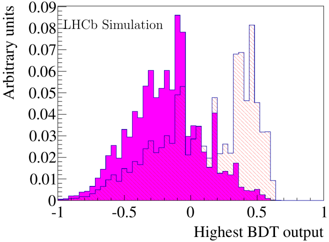
$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$



- 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
  - 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, $q^2 \equiv M(\ell\nu)$

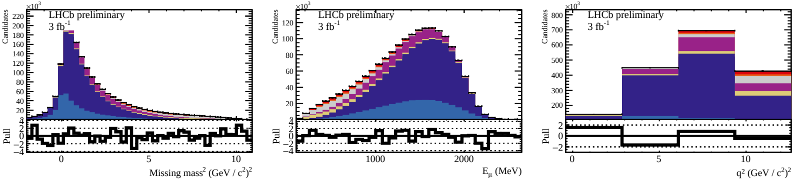
Isolation





- 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

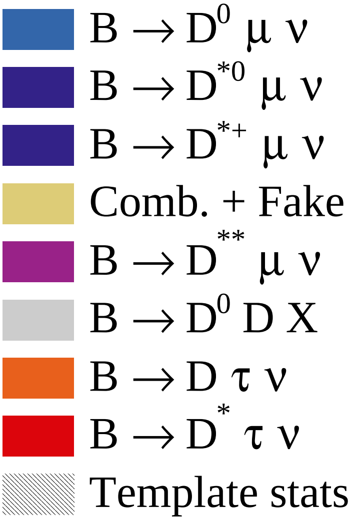


- Three dimesional template fit in E_μ (left), $m^2_{missing}$ (middle), and q^2
  - Projections of fit to isolated data shown
- All uncertainties on template shapes incorporated in fit:
  - Continuous variation in e.g different form factor parameters
  - Shape variations for all major backgrounds controlled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

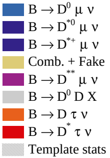
Fit strategy

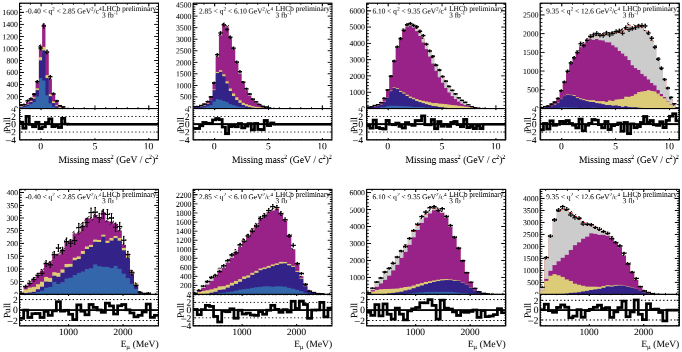
- Signal region + 3 control samples, for both D^0 and D^{*+} samples - 8 regions
- Two fully independent fitters, independent implementations
- Nominal result: simultaneous fit of all 8 samples
- Agreement between fitters established

Fit overview



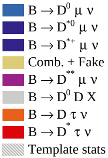
One pion sample

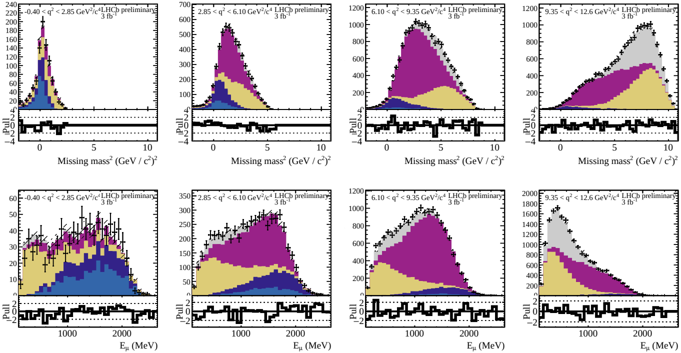




- Sample with exactly one additional pion: D^{**} backgrounds
  - Include the four known resonances, individually floating yields
  - Updated model from Bernlochner, Ligeti: all parameters unconstrained

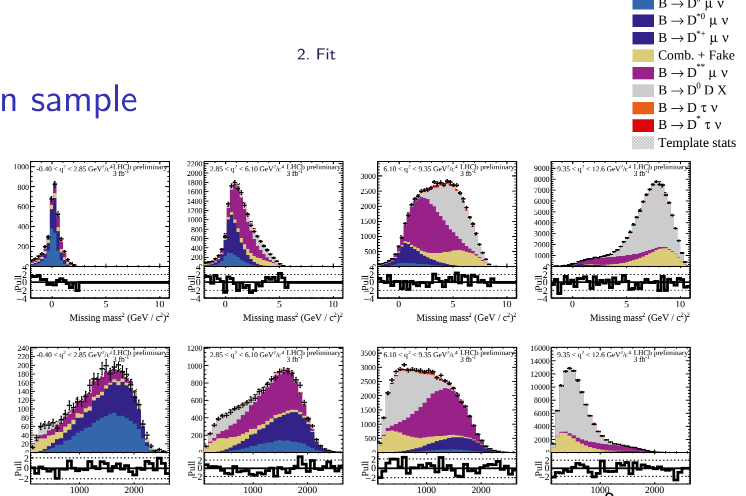
Two pion sample





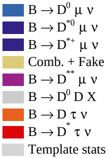
- Sample with exactly two additional pions: heavier D^{**} backgrounds (including any non-resonant)
- No theory model: cocktail sample, variation in q^2 slope

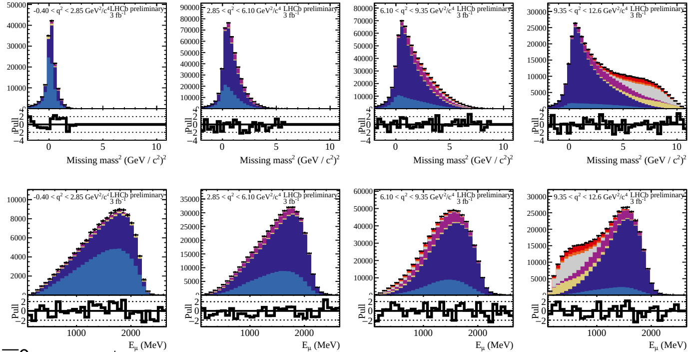
Kaon sample



- Sample with at least one additional kaon: $B \to D^0 DX$ backgrounds
    - Also strongly constrained by the previous two samples
- Degrees of freedom: $B \to DDKX$ mass combinations, fraction of $B \to DDK*$
- Spread from an ensemble of alternative models taken as an additional systematic uncertainty

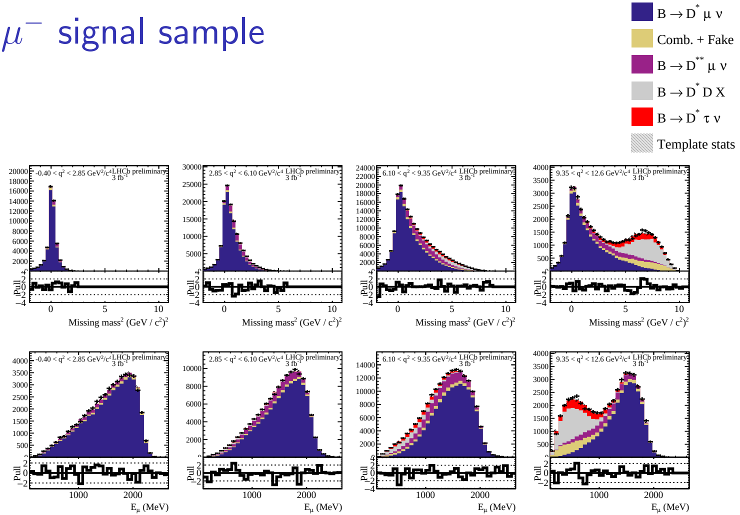
$D^0\mu^+$ signal sample





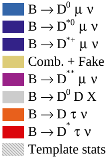
- $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ now modelled using BGL form-factors, $B^- \to D^0\ell^-\overline{\nu}_\ell$ with BCL
  - Helicty-suppressed terms constrained by theory, other parameters float freely
  - $B^- \to D^0\ell^-\overline{\nu}_\ell$ form factors from HPQCD
  - $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ form factors from: Bigi, Gambino, Schacht

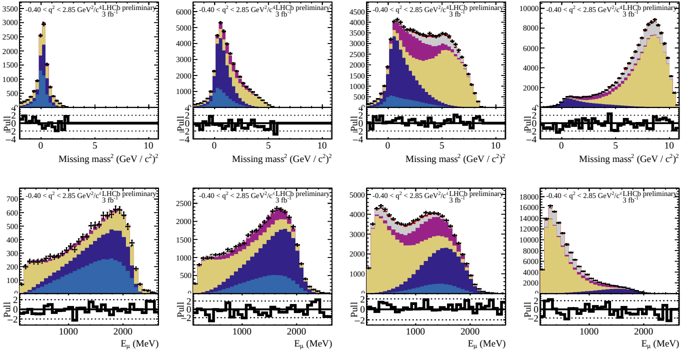
$D^{*+}\mu^{-}$ signal sample



- Excellent fit quality throughout

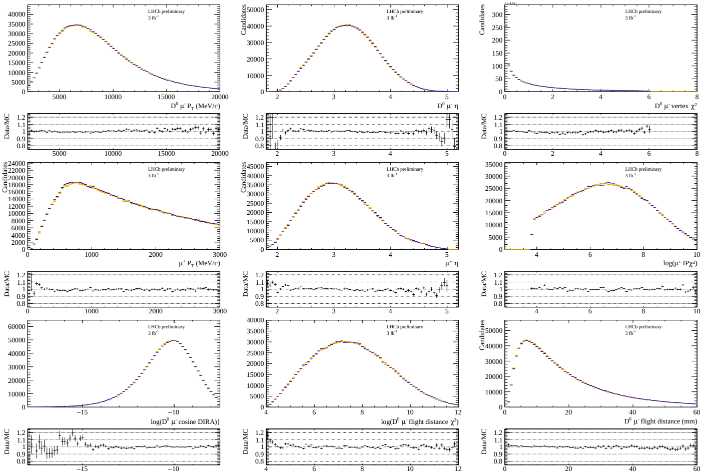
Misidentified backgrounds





- Misidentified hadron component derived from data
- Inverted muon ID: select misidentified muons
  - We have these backgrounds under good control
  - Systematic uncertainty $\sim$ 4 times smaller than previous analysis

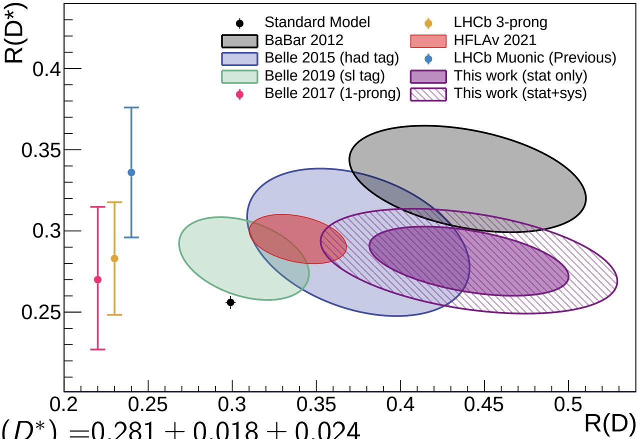
Data/MC agreement



- Generally percent level agreement, some localised discrepancies $\rightarrow$ systematic

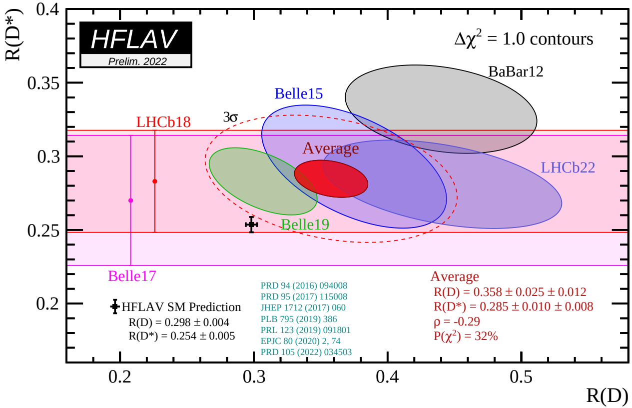
Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$
Statistical uncertainty	1.8	6.0
Simulated sample size	1.5	4.5
$B \to D^* DX$ template shape	0.8	3.2
$\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ form-factors	0.7	2.1
$B \to D^{**}\mu^+\nu$ form-factors	0.8	1.2
$\mathcal{B}(B \to D^*(D_s \to \tau\nu)X)$	0.3	1.2
MisID template	0.1	0.8
$\mathcal{B}(B \to D^{**}\tau^+\nu)$	0.5	0.5
Combinatorial	< 0.1	0.1
Resolution	< 0.1	0.1
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7
$\overline{B}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4
Data/simulation corrections	0.4	0.75
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3
misID template unfolding	0.7	1.2
Baryonic backgrounds	0.7	1.2
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$
Data/simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D)$
$\tau^- \to \mu^-\nu_\tau\overline{\nu}_\mu$ branching fraction	$0.2 \times \mathcal{R}(D^*)$	$0.2 \times \mathcal{R}(D)$
Total uncertainty	3.0	8.9

Result



- $\mathcal{R}(D^*)$ $=0.281 \pm 0.018 \pm 0.024$
- $\mathcal{R}(D)$$=0.441 \pm 0.060 \pm 0.066$
- $\rho = -0.43$
- 1.9σ agreement with SM

Result



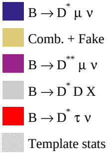
- New preliminary average: slightly lower $\mathcal{R}(D^*)$, slightly higher $\mathcal{R}(D)$, reduced correlation
  - $3.3\sigma \to 3.2\sigma$ agreement with SM
  - Excellent overall agreement between measurements

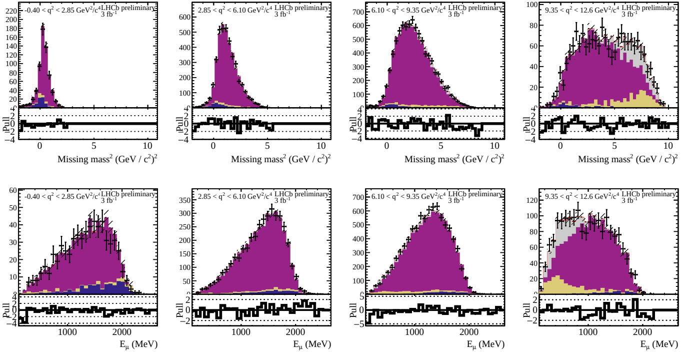
Conclusion

- First joint measurement of $\mathcal{R}(D)$and $\mathcal{R}(D^*)$ at a hadron collider: a step up in complexity, a step up in sample size, still only Run 1
  - LHCb-PAPER-2022-039 in preparation
- Important caveat: assumes SM shape+uncertainties for $\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$
  - Fine for a SM null test
  - If there is non lefthanded vector new physics, measurements of $\mathcal{R}(D^{(*)})$no longer valid
- Much more to come!
- Run 2 measurements ongoing in this and other channels
- Very small change in world average $\rightarrow$ this remains intriguing

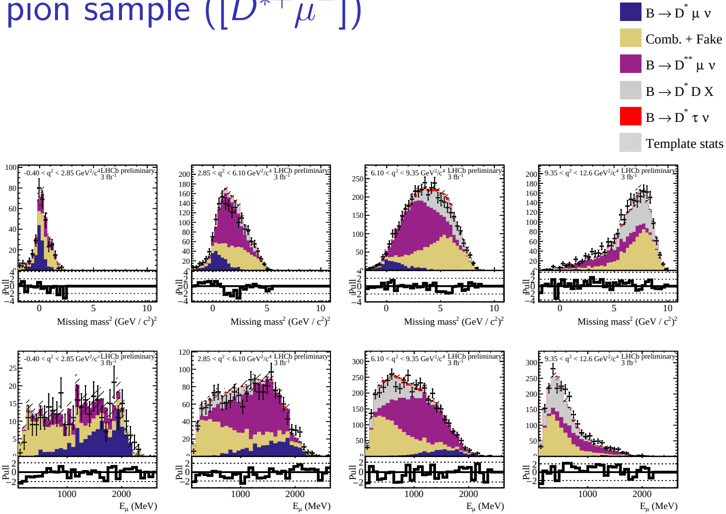
Backups

One pion sample ($[D^{*+}\mu^-]$)

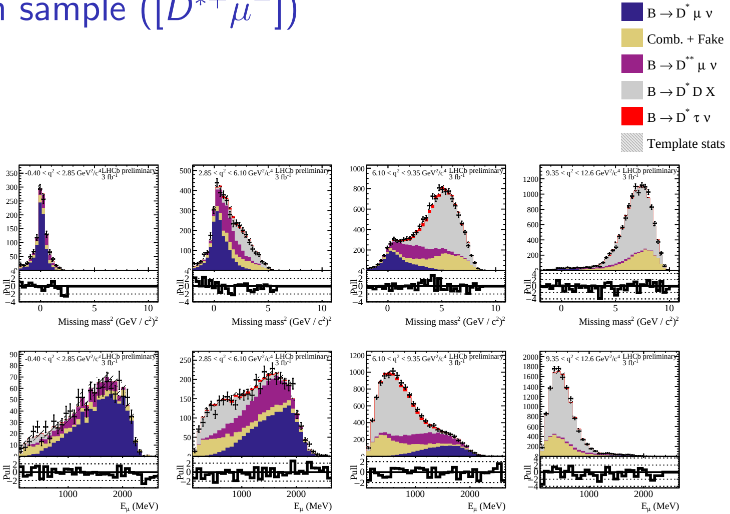




Two pion sample ($[D^{*+}\mu^-]$)



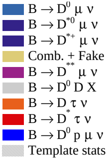
Kaon sample ($[D^{*+}\mu^-]$)

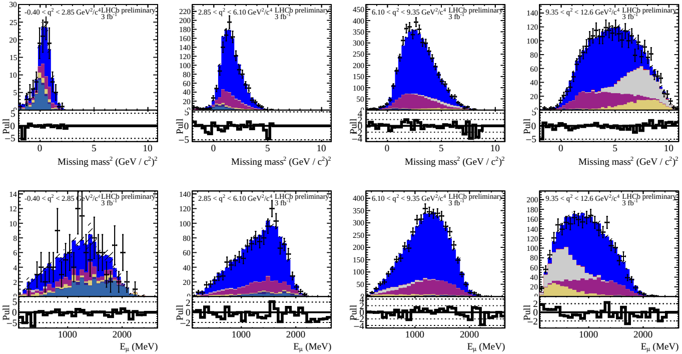


Extra fit validation

- Validation fits: fix all shape parameters to nominal best fit values, try fitting alternative control sample selections
    - (exceptions in the next two slides for specific parameters)
- Check that we really understand the backgrounds in detail

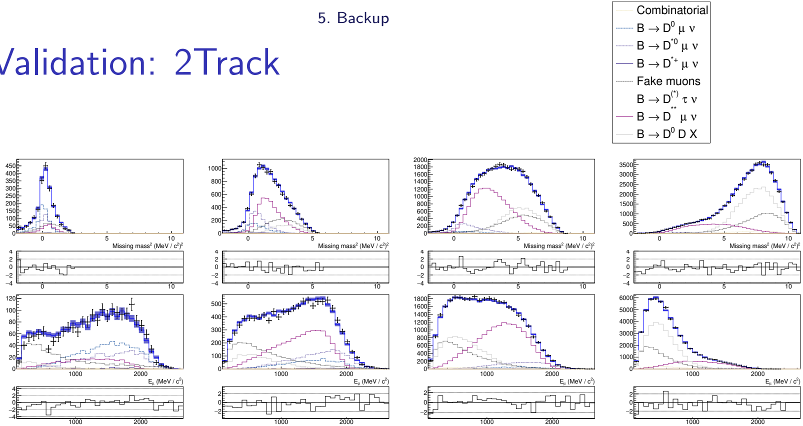
Backgrounds with baryons?





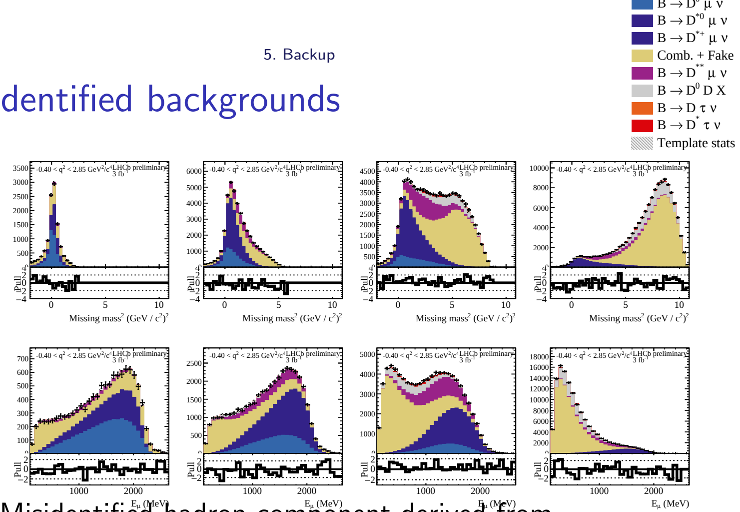
- No baryonic backgrounds included in the nominal model
- Look at a $D^0\mu$+p sample
  - Reuse existing $B \to D^{**}\mu^+\nu$ samples to fit $\Lambda_b \to D^0\mu p X$
  - Shift from including this in the full fit taken as a systematic uncertainty

Validation: 2Track



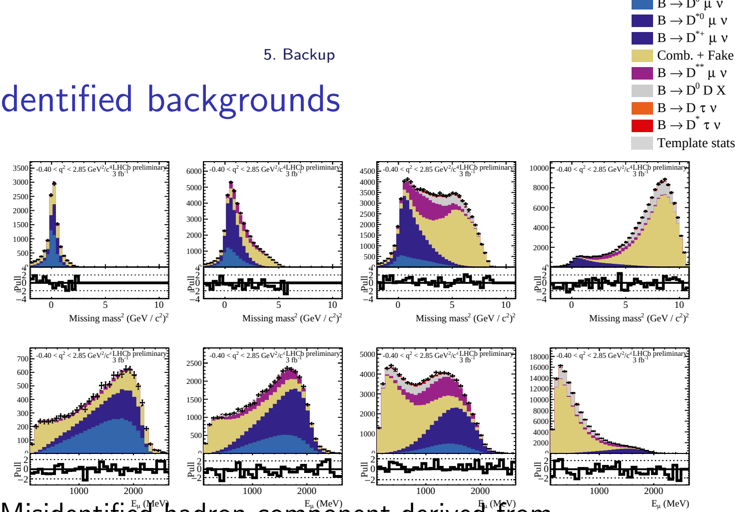
- Select three pions - check for missing high-multiplicity backgrounds
- Also selects a lot of muon misID: yield here similar to signal sample

Misidentified backgrounds



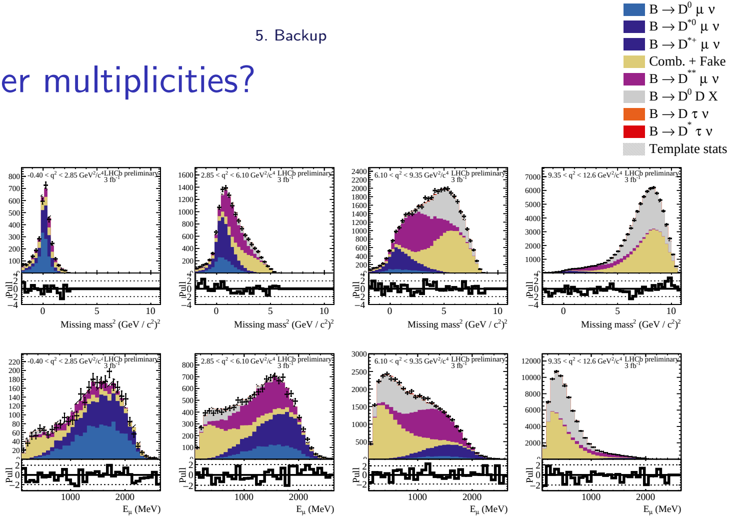
- Misidentified hadron component derived from $D^{(*)}$+non-muon track data sample
- We model these very well
- Two different methods, improved since last time
- Last time: two methods for misid template shape (systematic uncertainty assigned from difference)
- Now: two better methods

Misidentified backgrounds



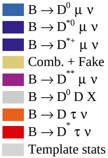
- Misidentified hadron component derived from $D^{(*)}$+non-muon track data sample
- Two different methods, improved since last time
  - Likelihood + sWeight based method
  - Iterative bayesian unfolding, as for $R_{J/\psi}$
- Include a momentum smearing to include the effect of muon decay-in-flight in the templates

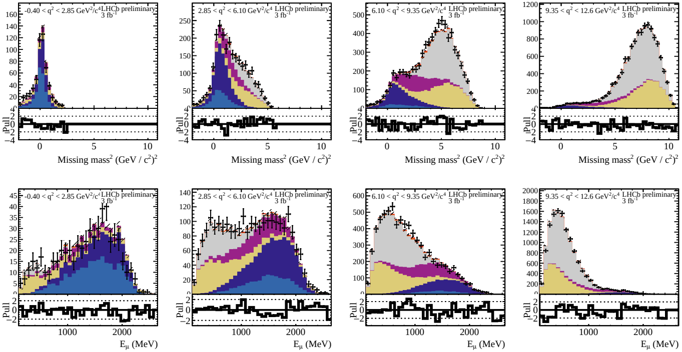
Higher multiplicities?



- Select three pions - check for missing high-multiplicity backgrounds
- Also selects a lot of muon misID: yield here similar to signal sample

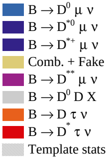
DD - right sign kaon

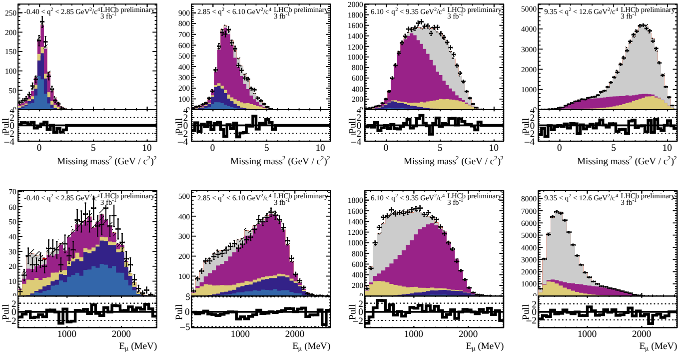




- Split DD sample by relative charge of kaon: right sign sample contains both $D \to K^+ \mu X$ and $B \to DDK^+$ decay chains

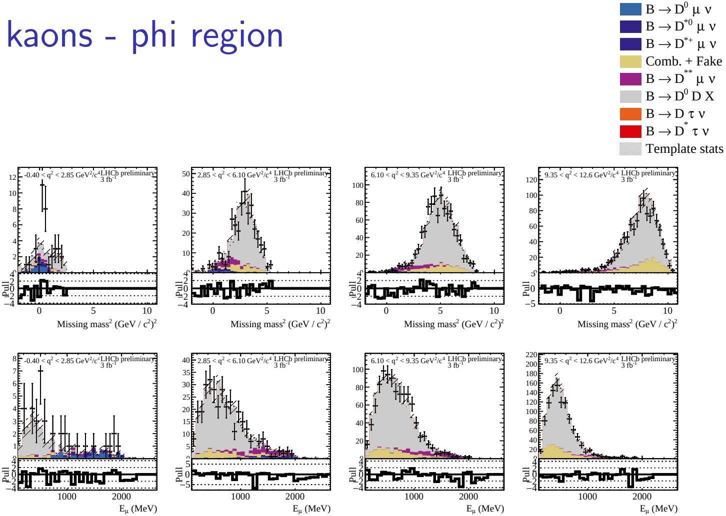
DD - wrong sign kaon





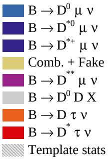
- Split DD sample by relative charge of kaon: wrong sign sample contains only a subset of $B \to DDK^-$ decay chains

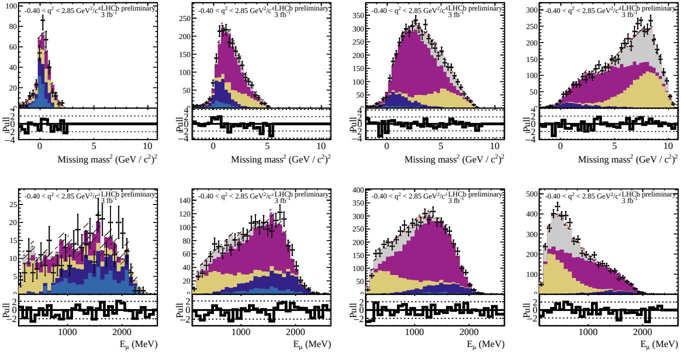
Two kaons - phi region



- $\phi \to K^+K^-$ picks out decay chains with $D_s \to \phi\mu^+\nu_\mu$

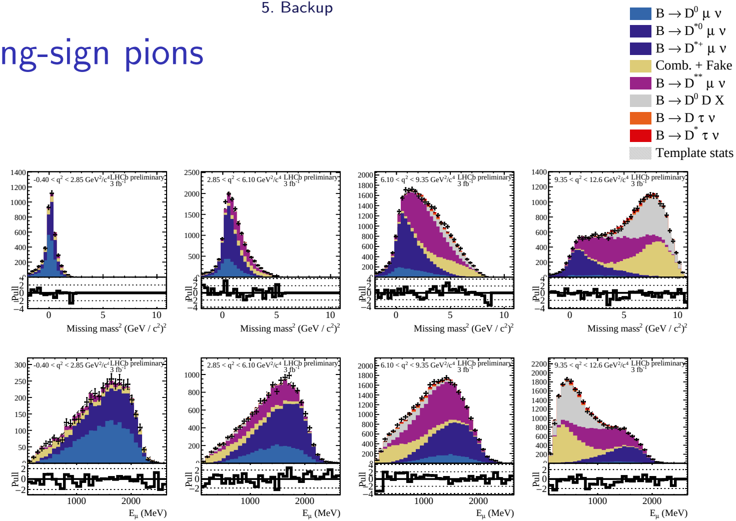
Two pions - eta region





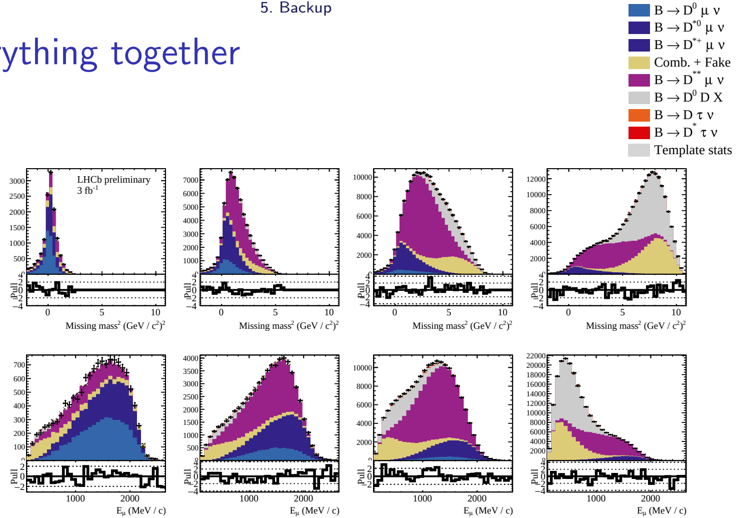
- Look in the region of $M_{\pi\pi}$ populated by $\eta \to \pi^+\pi^-\pi^0$: no evidence for a component with different shape

Wrong-sign pions



- Wrong-sign pions: alternative selection for modes with 2+ pions

Everything together

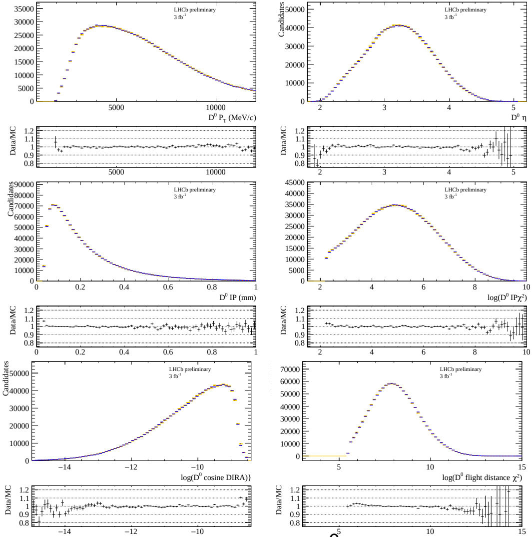


- Invert isolation cut (keep D^{*+} veto) - no other requirements
- Background yields larger than in the signal samples

Data/MC strategy

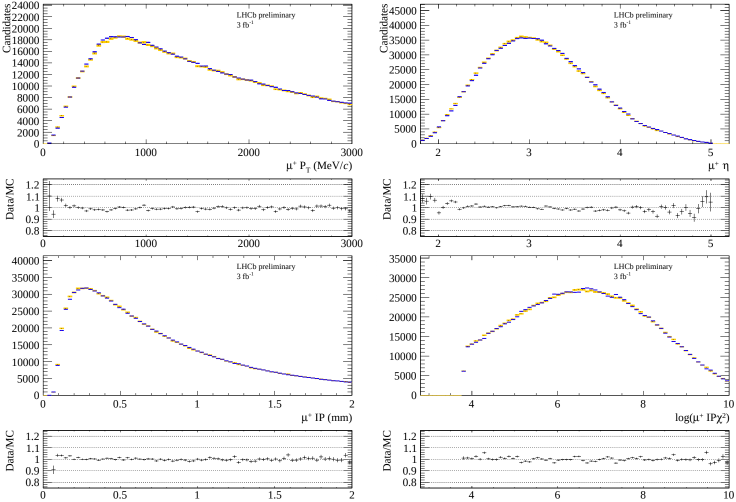
- Huge amount work dedicated to understanding the calibration of simulation to match data
  - Two stages of corrections
  - Reweight occupancy and B kinematics from $B^+ \to J/\psi K^+$
- Reweight simulation to match data in $\bar{B} \to D^{(*)} \mu^- \bar{\nu}_\mu$ control region ($m^2_{\rm miss} < 0.4(\,{\rm GeV}^2/c^4)$)
- Weights from $D^0\mu$ sample cover majority of effects in $D^{*+}\mu$ sample - small additional reweighting for slow pion kinematics
- Iterative procedure, once as nominal
  - Run a preliminary fit, generate weights, final fit

We understand charm



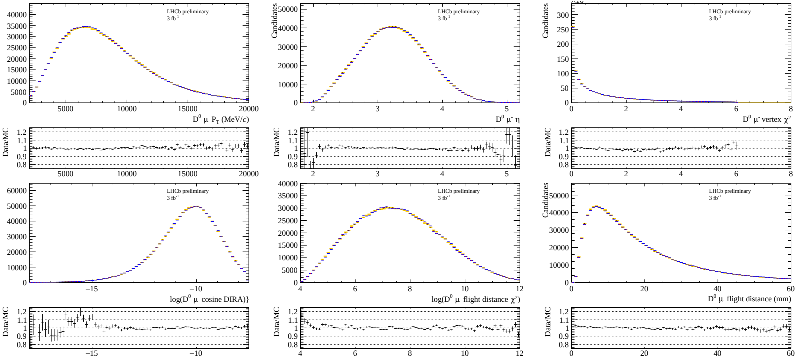
- Geometry: how much does the D^0 point back to the PV, how displaced is it?

We understand muons



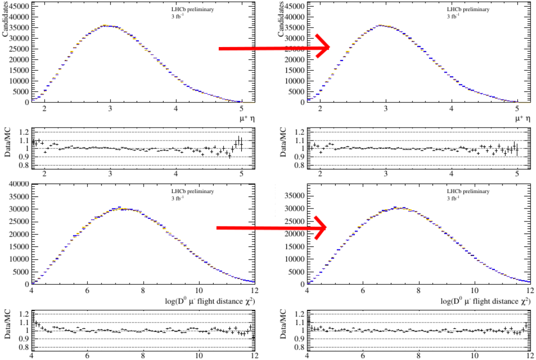
- Very large sample of muons, test our understanding

We understand charm+muon combinations



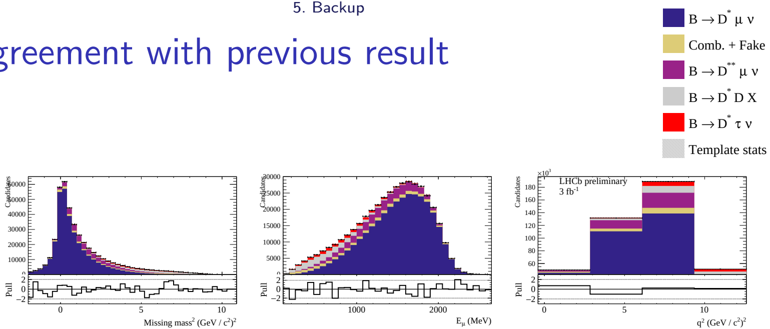
- Generally percent level agreement, some localised discrepancies

Data/MC systematic



- Overall agreement is excellent - small residual disagreements absorbed as a systematic via a second reweighting
  - Consider multiple schemes - finer binning, extra variables
  - Half the maximum taken as a systematic uncertainty

Agreement with previous result



- We refit the same $[D^{*+}\mu^-]$ data sample as the previous result, with improved knowledge
- How to quantify the agreement we expect? Difference in uncertainties
  - Uncorrelated uncertainty: 0.026 on $\mathcal{R}(D^*)$
- New $D^{*+}\mu^-$ sample $\mathcal{R}(D^*) = 0.293$, 1.6σ agreement with our previous result