$\mathcal{R}(D^{(*)})$at LHCb

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CERN

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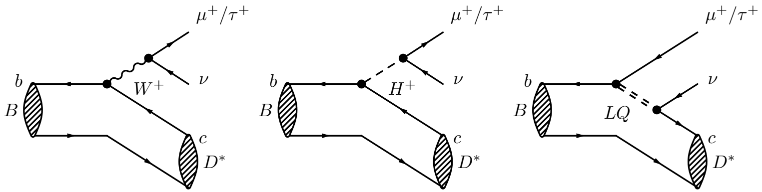
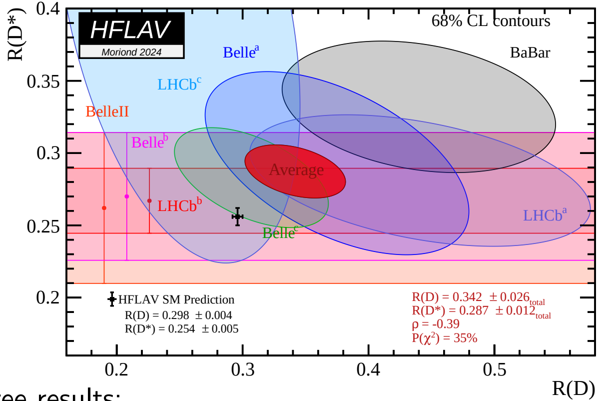
$\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$



- 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
- 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
  - Form factors mostly cancel (except helicity suppressed amplitude) $\to$ reduced dependence on theory
- D vs D^*: different meson spin, so different physics sensitivity

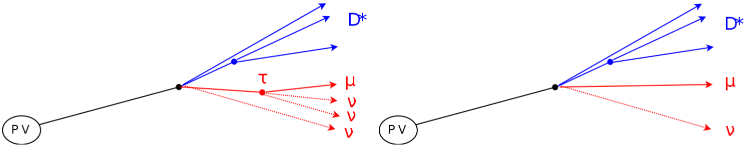
Overview



- Three results:
  - $R(D^*)$ and $R(D^0)$ with $\tau \to \mu\nu\nu$ (LHCb-PAPER-2022-039)
  - $R(D^{*+})$ with $\tau \to \pi\pi\pi\nu$ (LHCb-PAPER-2022-052)
  - $R(D^{*+})$ and $R(D^+)$ with $\tau \to \mu\nu\nu$ (LHCb-PAPER-2024-007)
- The two muonic analyses follow broadly the same strategy, will discuss together

Experimental challenge

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

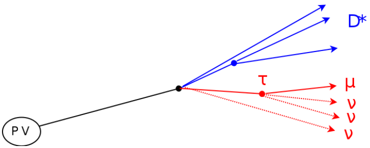


- Difficulty: multiple neutrinos
  - No narrow peak to fit (in any distribution)
- Main backgrounds: partially reconstructed B decays
  - $B \to D^*\mu\nu$, $B \to D^{**}\mu\nu$, $B \to D^*D(\to \mu X)X$ ...
  - Reject these with charged track isolation
- Also combinatorial, misidentified backgrounds

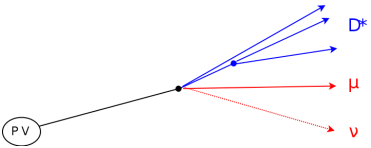
Fit strategy

Phys. Rev. Lett. 115 (2015) 111

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

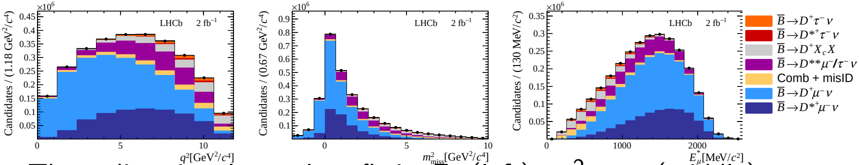


$\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$



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

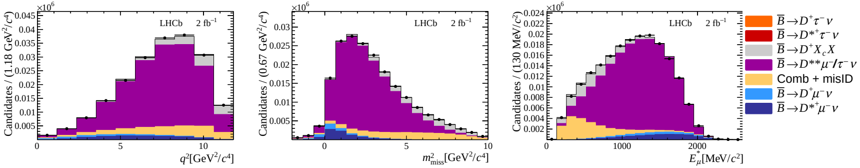
Fit strategy



- 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
- (Understanding agreement between simulation and data also essential)

One pion sample

LHCb-PAPER-2024-007



- 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

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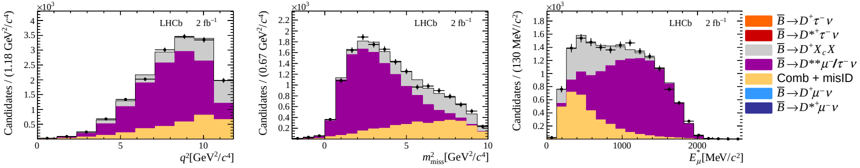

- Sample with exactly two additional pions: heavier D^{**} backgrounds (including any non-resonant)
- No theory model: cocktail sample, variation in q^2 slope

Kaon sample

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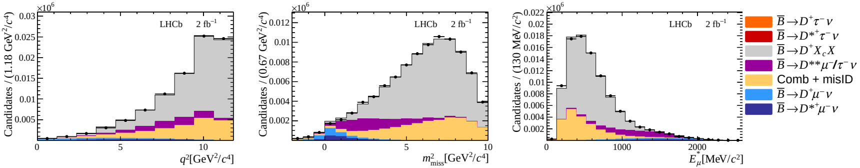
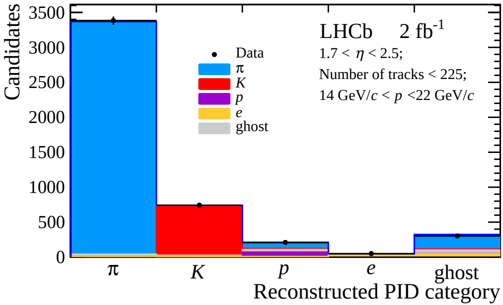


- Sample with at least one additional kaon: $B\to D^0DX$ backgrounds
  - Also strongly constrained by the previous two samples

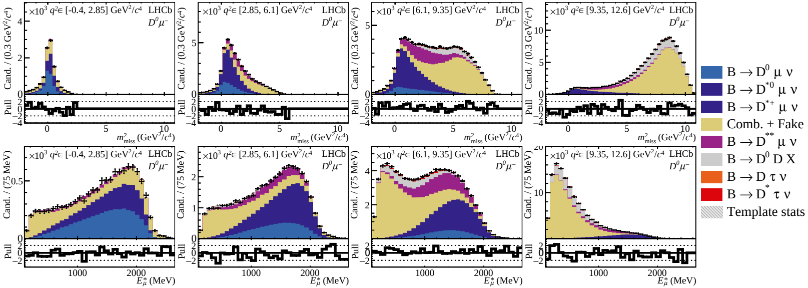
Misidentified backgrounds



- Misidentified hadron component derived from data
- Use RICH PID to decompose pions,kaons etc
- Put them back together with different weights, momentum smearing

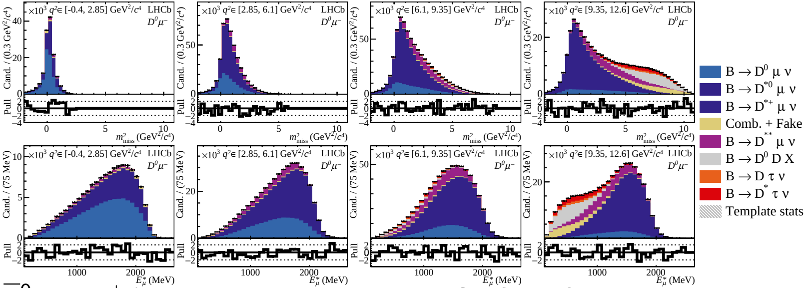
LHCb-PAPER-2022-039

Misidentified backgrounds



- Inverted muon ID: select misidentified muons
  - We have these backgrounds under good control
  - Systematic uncertainty $\sim$ 4 times smaller than original muonic $R(D^*)$

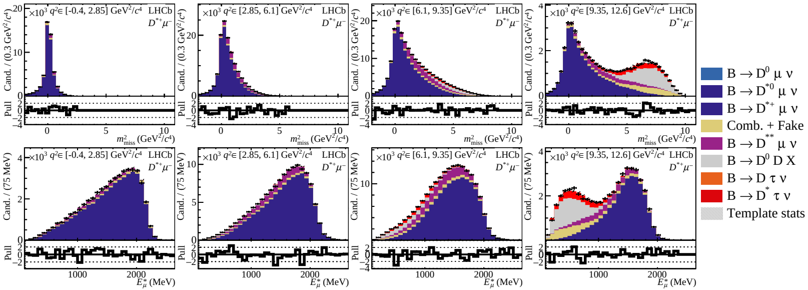
$D^0\mu^+$ signal sample



- $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ 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 (D^0)

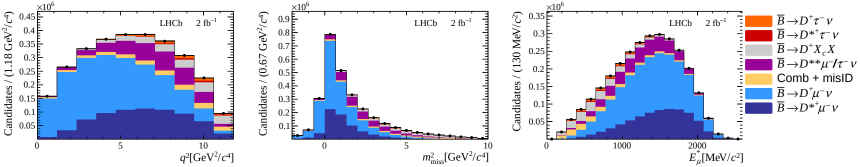
LHCb-PAPER-2022-039



- Excellent fit quality throughout

$D^+\mu^+$ signal sample

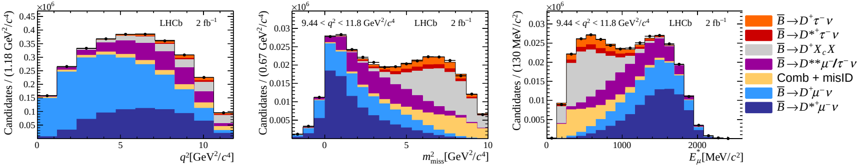
LHCb-PAPER-2024-007



- Neutral isolation rejects $D^{*+}\to D^+\pi^0$, reduces cross feed $\to$ use the D^{*+} as a signal sample, next slide

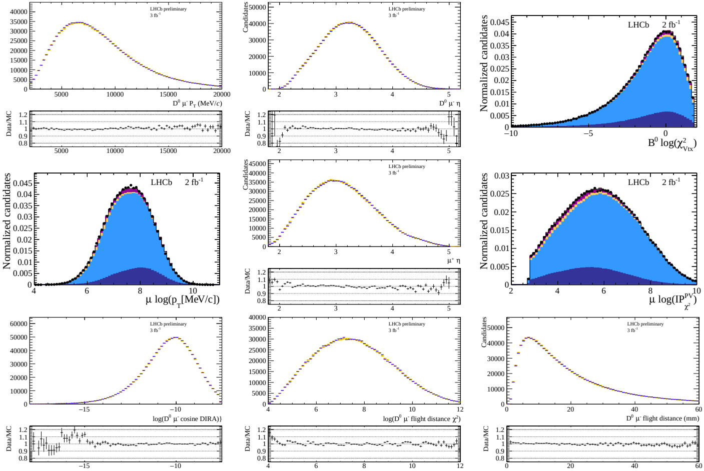
$D^{*+}\mu^+$ signal sample (D^+)

LHCb-PAPER-2024-007



- Very nice additional sample reconstructed with neutral! $D^{*+}\to D^+\pi^0$

Data/MC agreement



- Generally percent level agreement, some localised discrepancies → systematic

Full uncertainties

D^0

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	**Correlation**
Statistical uncertainty	1.8	6.0	−0.49
Simulated sample size	1.5	4.5	
$B \to D^{(*)}DX$ template shape	0.8	3.2	
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ form-factors	0.7	2.1	
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\ (\overline{B} \to D^* D_s^-(\to \tau^-\overline{\nu}_\tau)X)$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\ (\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	0.5	0.5	
Combinatorial	< 0.1	0.1	
Resolution	< 0.1	0.1	
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7	
$\overline{B}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Baryonic backgrounds	0.7	1.2	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
Data/simulation corrections	0.4	0.8	
MisID template unfolding	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
Data/simulation corrections	$0.4\times\mathcal{R}(D^*)$	$0.6\times\mathcal{R}(D^0)$	
$\tau^- \to \mu^-\nu\overline{\nu}$ branching fraction	$0.2\times\mathcal{R}(D^*)$	$0.2\times\mathcal{R}(D^0)$	
Total systematic uncertainty	2.4	6.6	−0.39
Total uncertainty	3.0	8.9	−0.43

D^+

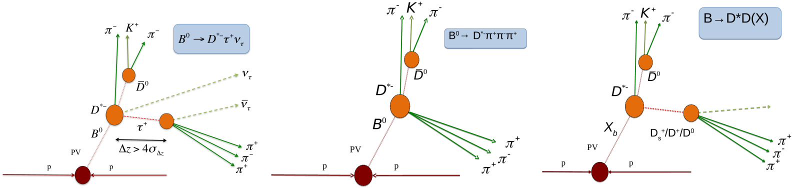
Source	$R(D^+)$	$R(D^{*+})$
Form factors	0.023	0.035
$\overline{B} \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\overline{B} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.085
Statistical uncertainty	0.043	0.081

$\tau \to \pi\pi\pi(\pi^0)$

LHCb-PAPER-2022-052

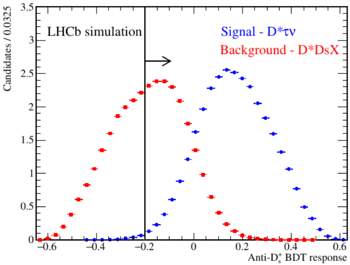
- Compared to muonic $\mathcal{R}(D^*)$:
    - Large $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$, $B \to D^{**}\mu^+\nu$ backgrounds absent
    - Additional $B \to D^*\pi\pi\pi X$ backgrounds
    - $B \to D^* DX$ with $D \to \pi\pi\pi X$
- Need external input: measure rate relative to $B \to D^*\pi\pi\pi$
- Now updated with 2015+2016 data

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



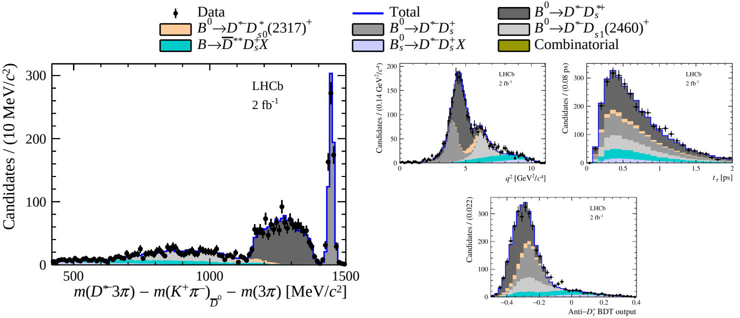
- Can use decay topology to remove direct $B \to D^{*}\pi\pi\pi X$ decays:
- If the $\pi\pi\pi$ vertex is displaced from the B vertex, cannot be direct $B \to D^{*}\pi\pi\pi X$
- Can remove a large, poorly measured background
  - And control the remainder
- $B \to D^{*}DX$ major physics background remaining

D_s BDT



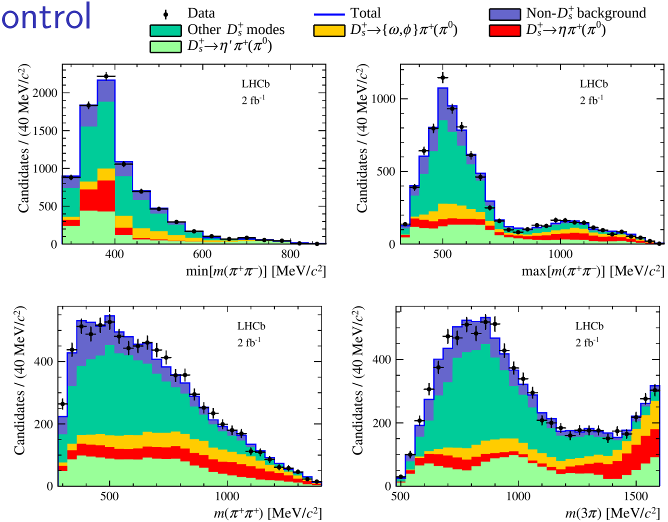
- $[\pi\pi\pi]$ lifetime discriminates between tau and $B \to D^* DX$
- Can use partial reconstruction techniques to reconstruct D peak in $B \to D^{*+} D$ (not $B \to D^* DX$)
- $\tau \to \pi\pi\pi\nu$ is mostly $a1(1260)$, $D \to \pi\pi\pi X$ mostly isn't
  - Use the $\pi\pi\pi$ (sub) structure to separate $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ from $B \to D^{*+} D_s^- X$
- Put everything in an MVA: kinematics, Dalitz, partial reconstruction, neutral isolation

D_s control



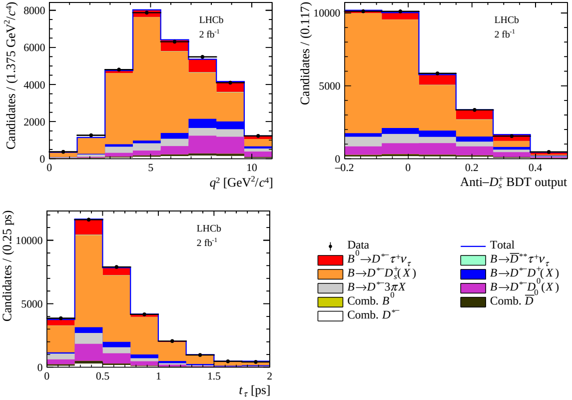
- Use data to control $B \to D^* D X$ modelling
- Can use $D_{(s)} \to \pi\pi\pi$ mass peak to select a pure $B \to D^* D X$ sample
- This controls the $B \to D^* D X$ modelling, but not the $D \to \pi\pi\pi X$

D_s control



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

Fit



- 3D template fit in BDT,q^2, tau lifetime to determine signal yield
- Control fit input implemented via constraints

Uncertainties (relative)

Source	Systematic uncertainty on $\mathcal{K}(D^*)$ (%)
PDF shapes uncertainty (size of simulation sample)	2.0
Fixing $B \to D^{*-} D_s^+(X)$ bkg model parameters	1.1
Fixing $B \to D^{*-} D^0(X)$ bkg model parameters	1.5
Fractions of signal τ^+ decays	0.3
Fixing the $\overline{D}^{**}\tau^+\nu_\tau$ and $D_s^{**+}\tau^+\nu_\tau$ fractions	$^{+1.8}_{-1.9}$
Knowledge of the $D_s^+ \to 3\pi X$ decay model	1.0
Specifically the $D_s^+ \to a_1 X$ fraction	1.5
Empty bins in templates	1.3
Signal decay template shape	1.8
Signal decay efficiency	0.9
Possible contributions from other τ^+ decays	1.0
$B \to D^{*-} D^+(X)$ template shapes	$^{+2.2}_{-0.8}$
$B \to D^{*-} D^0(X)$ template shapes	1.2
$B \to D^{*-} D_s^+(X)$ template shapes	0.3
$B \to D^{*-} 3\pi X$ template shapes	1.2
Combinatorial background normalisation	$^{+0.5}_{-0.6}$
Preselection efficiency	2.0
Kinematic reweighting	0.7
Vertex error correction	0.9
PID efficiency	0.5
Signal efficiency (size of simulation sample)	1.1
Normalisation mode efficiency (modelling of $m(3\pi)$)	1.0
Normalisation efficiency (size of simulation sample)	1.1
Normalisation mode PDF choice	1.0
Total systematic uncertainty	$^{+6.2}_{-5.9}$
Total statistical uncertainty	5.9

Conclusion

- Joint measurements of $\mathcal{R}(D)$and $\mathcal{R}(D^*)$ with D^0 and D^+: LHCb-PAPER-2022-039 and LHCb-PAPER-2024-007
- D^0 update with Run 2 data ongoing
- Hadronic $\mathcal{R}(D^*)$ updated with partial run 2 data
  - LHCb-PAPER-2022-052
- Important caveat: measurements assume 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!