

# Measurement of $R(D^*)$ with hadronic $\tau^+$ decays at $\sqrt{s} = 13$ TeV by the LHCb collaboration

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(on behalf of the LHCb collaboration)

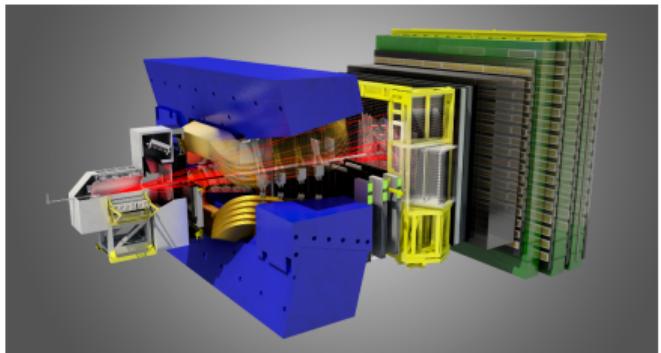
CERN Seminar  
March 21, 2023

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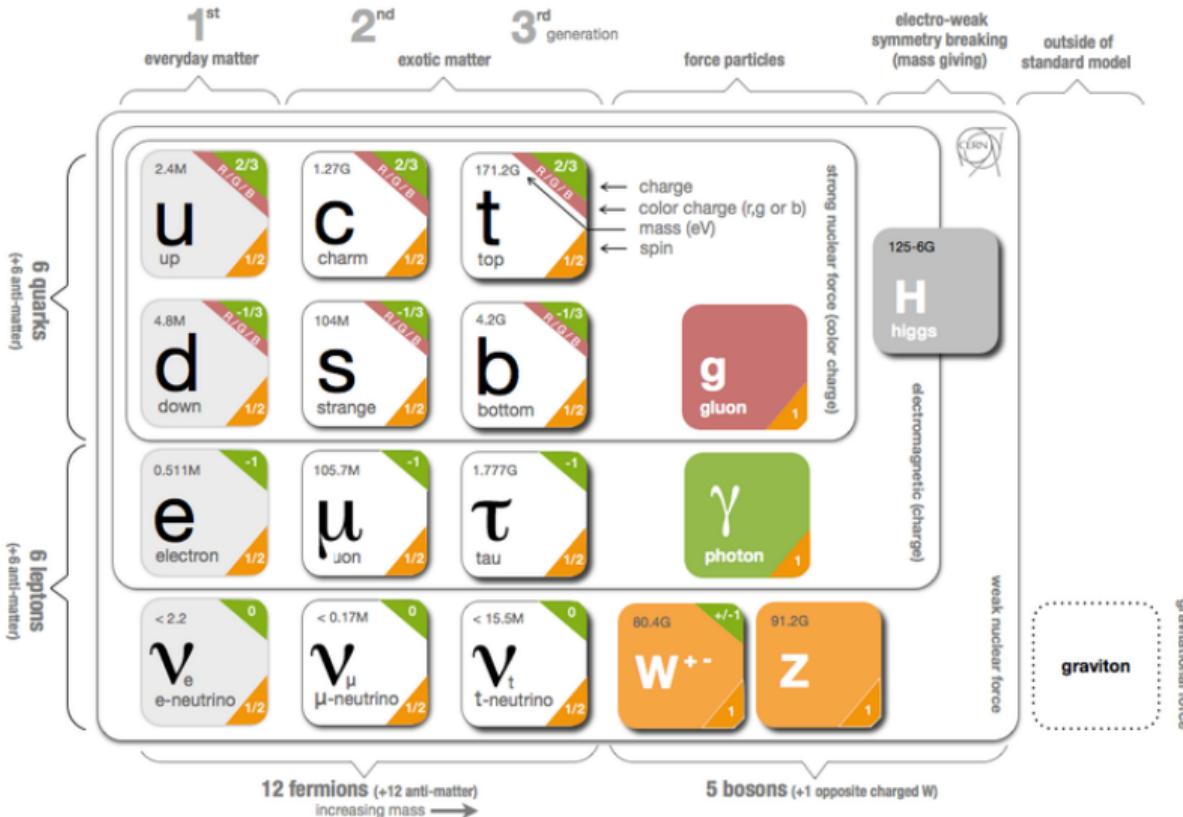


# Outline

- Introduction
- Selection and simulation samples
- Understanding the backgrounds
- Signal and normalisation yields
- $R(D^*)$  results
- Outlook & Conclusions



# Standard Model of elementary particles



# Lepton Flavour Universality

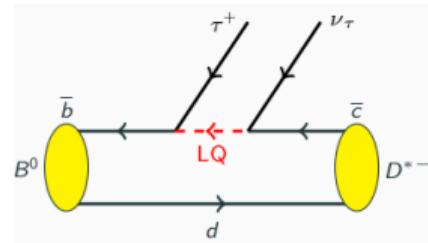
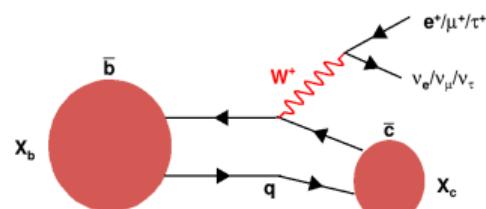
- In the Standard Model (SM), electroweak couplings to all charged leptons are universal; difference between  $e, \mu$  and  $\tau$  driven only by mass
- LFU tests with ratios of branching fractions of decays involving different  $\ell = e, \mu, \tau$
- In  $b \rightarrow c\ell^\pm \bar{\nu}_\ell$  transitions (tree-level semileptonic decays):

$$R(X_c) = \frac{\mathcal{B}(X_b \rightarrow X_c \tau^+ \bar{\nu}_\tau)}{\mathcal{B}(X_b \rightarrow X_c \ell^+ \bar{\nu}_\ell)}$$

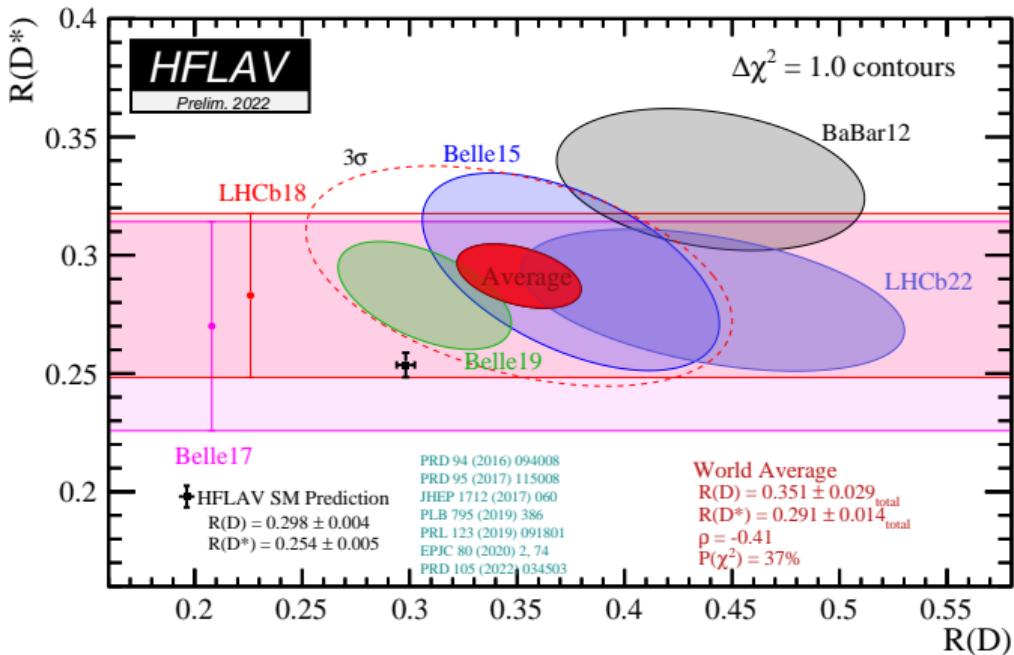
$$X_b = B^0, B_{(c)}^+, B_s^0, \Lambda_b, \dots \quad X_c = D, D^*, D_s, \Lambda_c, \dots$$

- Hadronic uncertainties *mostly* cancel
- Ratios sensitive to possible enhanced coupling to the 3<sup>rd</sup> generation (e.g. Leptoquarks) predicted by some models involving physics beyond SM

[PRD 85, 094025 (2012), PLB 755, 270 (2016), ...]



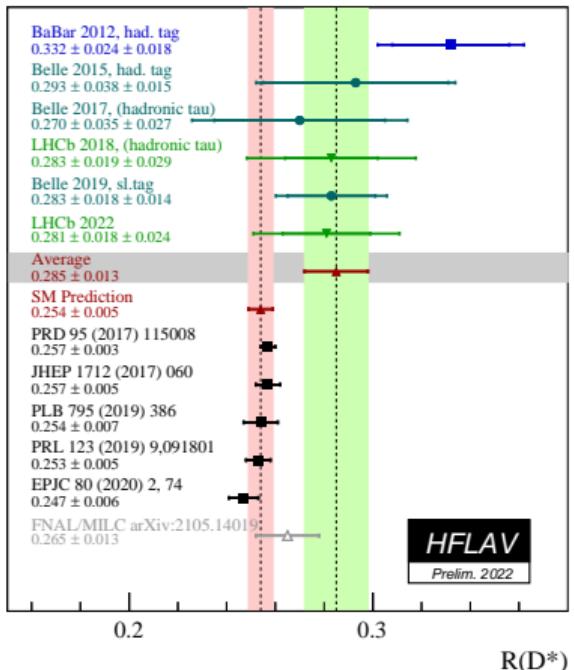
# Lepton Flavour Universality - current status



- $R(X_c)$  measurements show deviations from SM expectation
- Combination of  $R(D)$  and  $R(D^*)$  is  $3.5\sigma$  away from SM

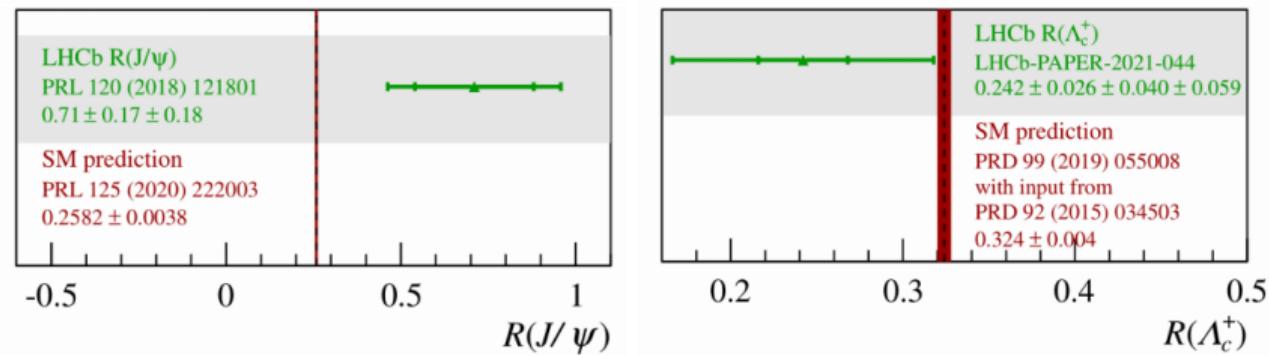
# $R(X_c)$ measurements at LHCb

- LFU tests in  $b \rightarrow c \ell \nu_\ell$  decays
- LHCb Run 1 data :  $3 \text{ fb}^{-1}$ , 2011-12
- Measurements with **muonic**  $\tau$  decays
  - $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$
  - $R(D^*)$  and  $R(J/\psi)$  measurements  
[PRL 115, 111803 (2015), PRL 120, 121801 (2018)]
  - Latest  $R(D)$ - $R(D^*)$  measurement  
[arXiv:2302.02886] (Submitted to PRL)
- Measurements with **hadronic**  $\tau$  decays
  - $\tau^+ \rightarrow \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau$
  - $R(D^*)$  and  $R(\Lambda_c)$  measurements  
[PRL 120, 171802 (2018), PRD 97, 072013 (2018),  
PRL 128, 191803 (2022)]



## $R(X_c)$ measurements at LHCb

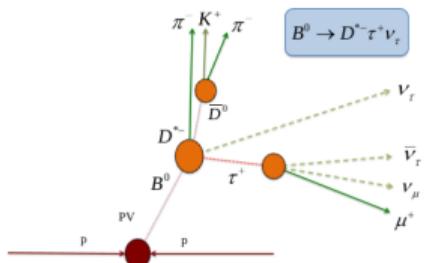
- These semileptonic measurements are complicated
  - Presence of neutrinos
  - No narrow signal peaks to fit to
  - A number of different background sources
- Nevertheless, we have been extremely successful at LHCb!
  - Many  $R(X_c)$  measurements; some are exclusive to LHCb



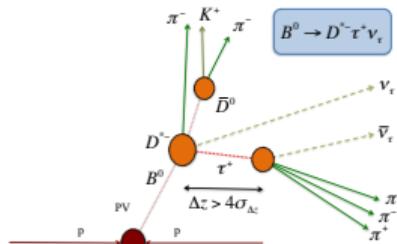
[PRL 120, 121801 (2018), PRL 128, 191803 (2022)]

# $R(X_c)$ measurements at LHCb - two complementary $\tau$ decay channels

$$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$$



$$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau$$



- Direct measurement of  $R(X_c)$
- High statistics
- Backgrounds from  $D^+$  must be controlled well
- Sensitive to  $D^{**} \mu^- \nu_\mu$

- Measuring  $\tau^+$  decay position key to reject dominant backgrounds
- High purity sample
- $\tau^+ \rightarrow 3\pi^\pm$  dynamics is very specific  
⇒ more control over backgrounds
- $R(X_c)$  requires external inputs
- Lower statistics

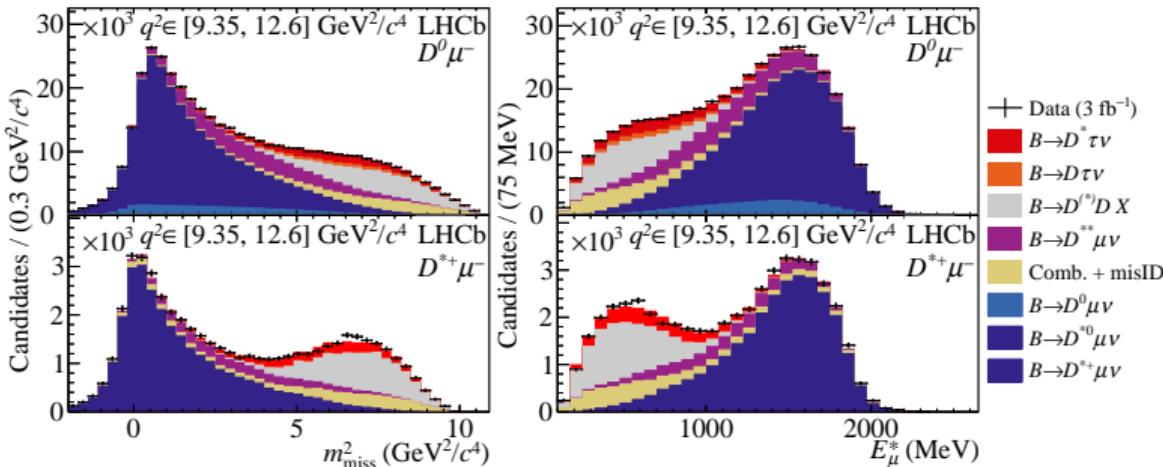
# $R(D^{(*)})$ with muonic $\tau$ decays

[arXiv:2302.02886] (Submitted to PRL)

- Simultaneous measurement of  $R(D)$  and  $R(D^*)$  with Run 1 data using muonic  $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$

3D template fit to

- $q^2 \equiv (p_B - p_{D^{(*)}})^2$
- $m_{\text{miss}}^2 \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$
- $E_\mu^*$  energy of  $\mu$



$$\begin{aligned} R(D) &= 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst}) \\ R(D^*) &= 0.281 \pm 0.018(\text{stat}) \pm 0.023(\text{syst}) \end{aligned}$$

Agreement with SM at  $1.9\sigma$

[CERN Seminar 18/10/22]

# $R(\Lambda_c)$ with hadronic $\tau$ decays

[PRL 128, 191803 (2022)]

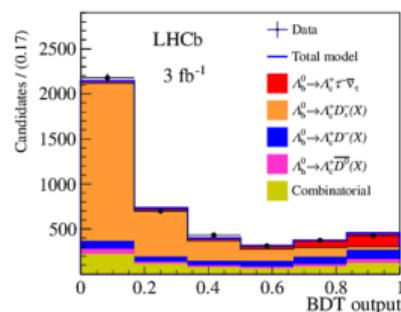
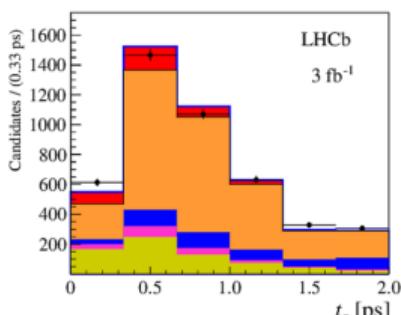
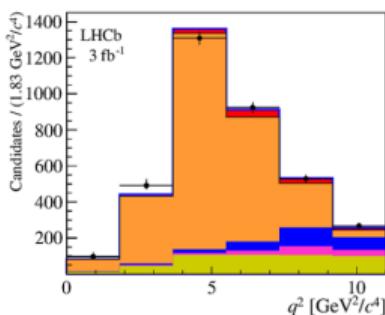
- First LFU test in a baryonic  $b \rightarrow c\ell\nu_\ell$  decay with Run 1 data using hadronic  $\tau^+ \rightarrow \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

- Normalisation channel  $\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$

$$\mathcal{K}(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi)}$$

- 3D template fit to extract signal yield

$$R(\Lambda_c^+) = \mathcal{K}(\Lambda_c^+) \left\{ \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu)} \right\}_{\text{ext. input}}$$



$$\mathcal{K}(\Lambda_c^+) = 2.46 \pm 0.27(\text{stat}) \pm 0.40(\text{syst})$$

$$R(\Lambda_c^+) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext})$$

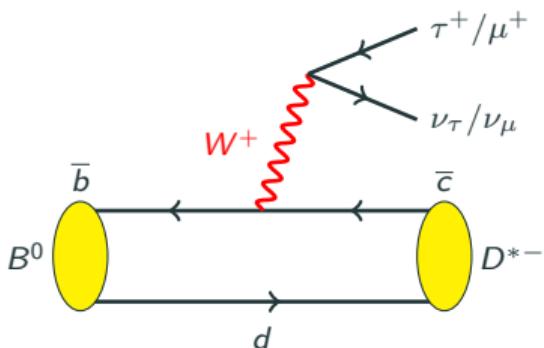
Agreement within  $1.0\sigma$  to SM

# New Physics scenarios

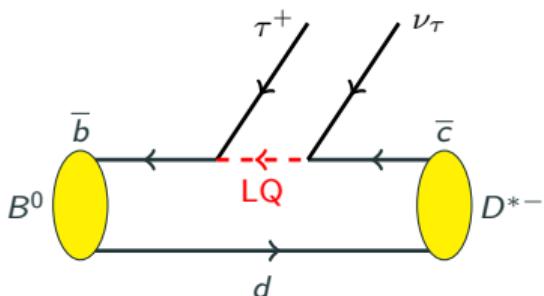
There are three typical candidates to account for the deviations seen in  $R(D^*)$  and  $R(D)$  observables:

- Leptoquarks  
[PRD 85, 094025 (2012), PLB 755, 270 (2016),...]
- Two-Higgs-doublet models  
[PRL 116, 081801 (2016),...]
- Heavy vector bosons, e.g.  $W'$   
[JHEP 2015, 142 (2015),...]

SM diagram:

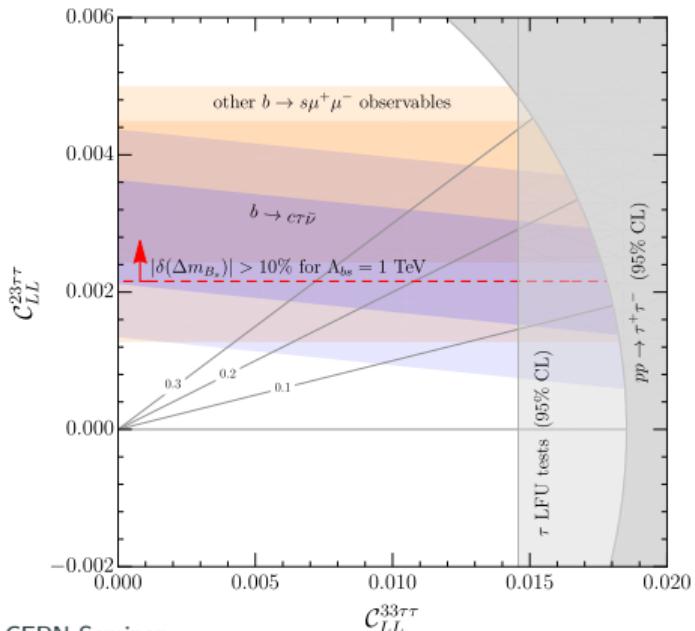
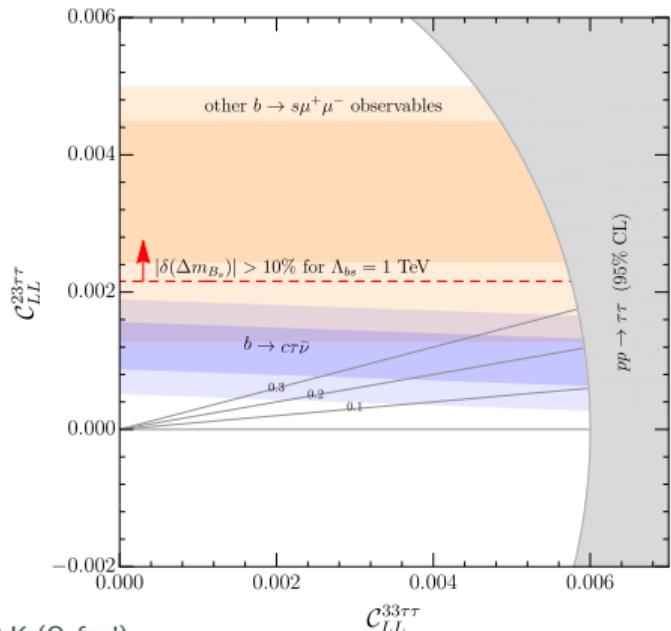


Leptoquark diagram:



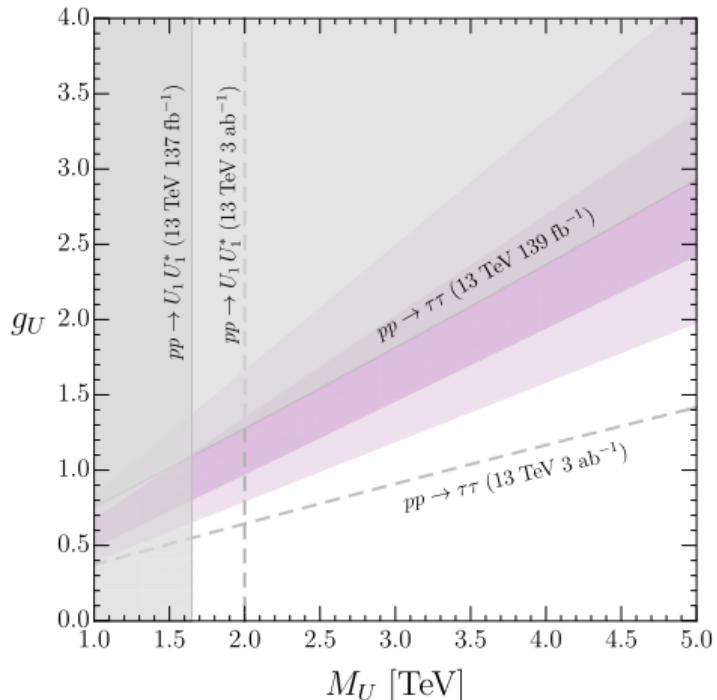
# Global fits

- Many phenomenological interpretations of LFU ratio results in charged and neutral current sectors
- Combined analyses using Effective Field Theory approaches for various New Physics scenarios
  - A TeV scale vector leptoquark model (U1) [JHEP 08, 050 (2021)]



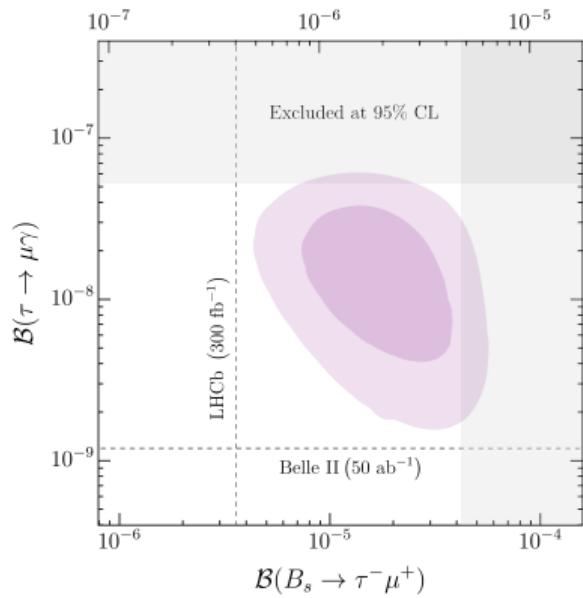
## Global fits

- Dominant LQ decay channels involving pairs of third-generation fermions
- Constraints from high  $p_T$  direct searches at LHC [JHEP 08, 050 (2021)]



## Global fits

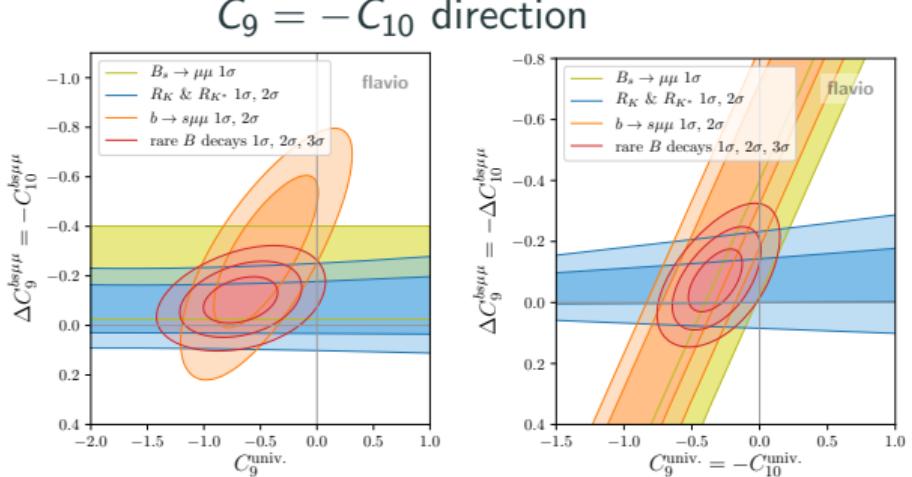
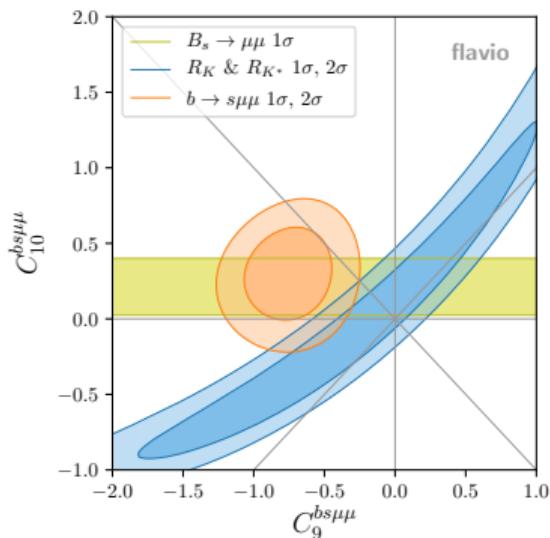
- Predictions for Lepton Flavour Violating decays [JHEP 08, 050 (2021)]



- Limits on  $\mathcal{B}(B \rightarrow K\tau\mu)$  approaching interesting zone of sensitivity!

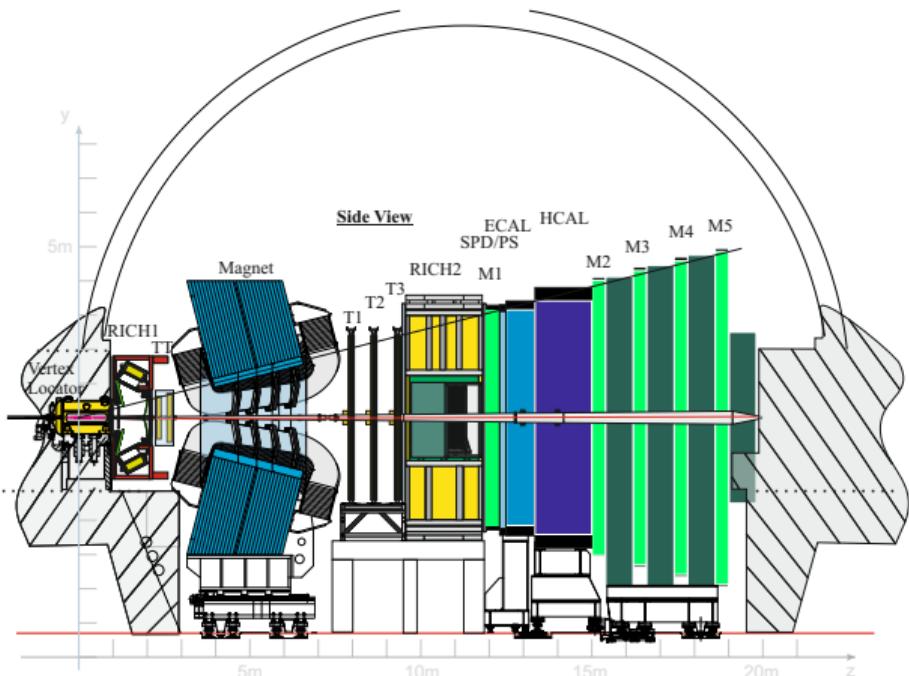
# Global fits

- Fits including the latest  $R_K$ - $R_{K^*}$  results from LHCb [arXiv:2212.09152, arXiv:2212.09153]
- Tension between LFU ratios and  $b \rightarrow s\mu^+\mu^-$  data [arXiv:2212.10497]
  - Solvable with LFU NP, either in  $C_9$  or



- $C_9^{\text{univ.}}$  central value slightly increased
- Implications in  $b \rightarrow c$ ?

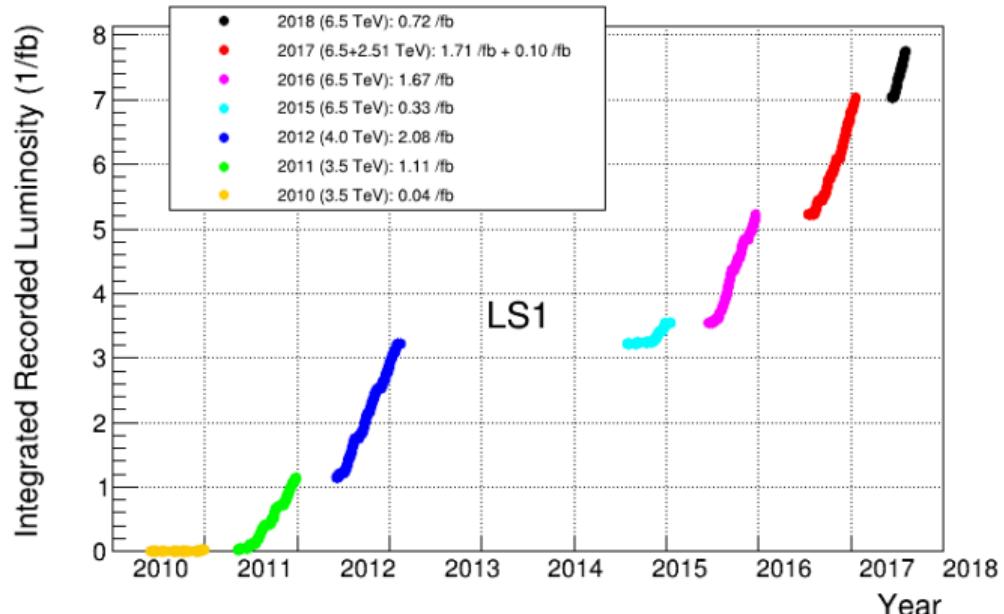
# LHCb experiment



- Excellent vertex resolution ( $10 - 40 \mu m$  in  $xy$ -plane and  $50 - 300 \mu m$  in  $z$ -axis)  
 $\tau^+$  lifetime resolution  $0.4 ps$
- Particle identification efficiencies  $\sim 97\%$  for  $\mu, e$  and  $\sim 3\%$  pion misidentification, good separation between  $\pi, K, p$

[JINST 3 (2008) S08005, Int. J. Mod. Phys. A30, 1530022 (2015)]

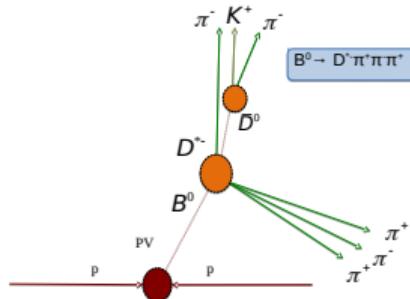
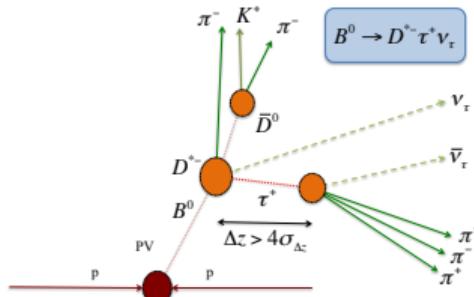
LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018



Period	Integrated luminosity	$\sqrt{s}$	Number of $b\bar{b}$
Run1 2011-2012	$3.2 \text{ fb}^{-1}$	7-8 TeV	$2.5 \times 10^{11}$
Run2 2015-2016	$2.0 \text{ fb}^{-1}$	13 TeV	$2.9 \times 10^{11}$
Run2 2017-2018	$3.9 \text{ fb}^{-1}$	13 TeV	$5.7 \times 10^{11}$

# $R(D^*)$ with hadronic $\tau$ decays

[LHCb-PAPER-2022-052] (In preparation)



- Hadronic  $\tau^+ \rightarrow \pi^+ \pi^- \pi^+(\pi^0) \bar{\nu}_\tau$
- Normalisation mode with same visible final state :  $B^0 \rightarrow D^{*-} 3\pi^\pm$
- $R(D^*)$  hadronic result from Run 1 analysis

$$0.283 \pm \underbrace{0.019(\text{stat})}_{6.8\%} \pm \underbrace{0.026(\text{syst})}_{9.3\%} \pm \underbrace{0.013(\text{ext})}_{4.6\%}$$

[PRL 120, 171802 (2018), PRD 97, 072013 (2018)]

- Systematically limited (size of simulation sample)
- We present the **updated analysis** including the **2015-16** dataset

## $R(D^*)$ with hadronic $\tau$ decays

- Hadronic  $\tau^+ \rightarrow \pi^+ \pi^- \pi^+(\pi^0) \bar{\nu}_\tau$
- LHCb **partial Run 2** data :  $2 \text{ fb}^{-1}$  at  $\sqrt{s} = 13 \text{ TeV}$ , 2015-16  
 $(\sim 1.5 \times \text{Run 1 sample})$
- We determine the ratio of BFs for the signal and normalisation decays as

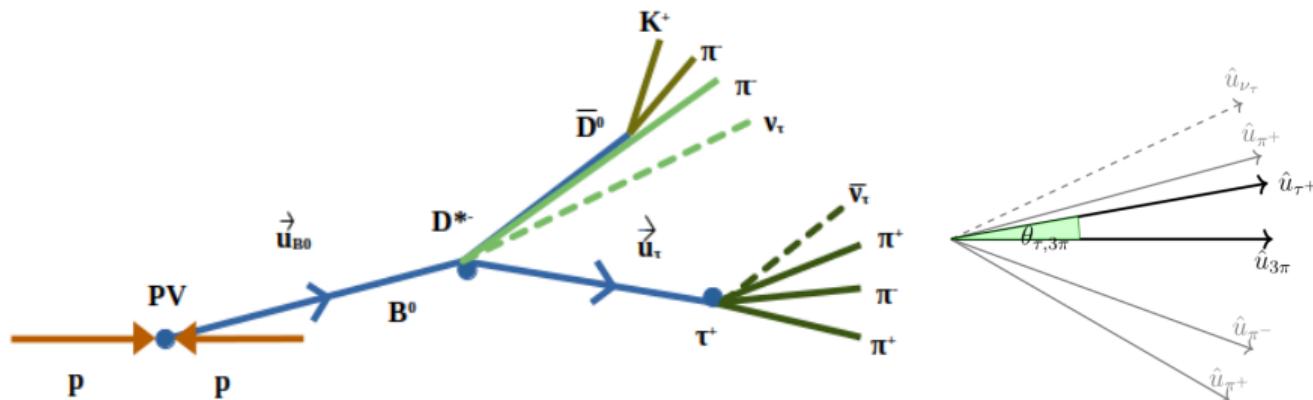
$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{1}{\mathcal{B}(\tau^+ \rightarrow 3\pi^\pm (\pi^0) \bar{\nu}_\tau)}$$

- This is converted to  $R(D^*)$  with external inputs as

$$R(D^*) = \mathcal{K}(D^*) \left\{ \frac{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)} \right\}_{\text{ext. input}}$$

# Signal decay kinematics

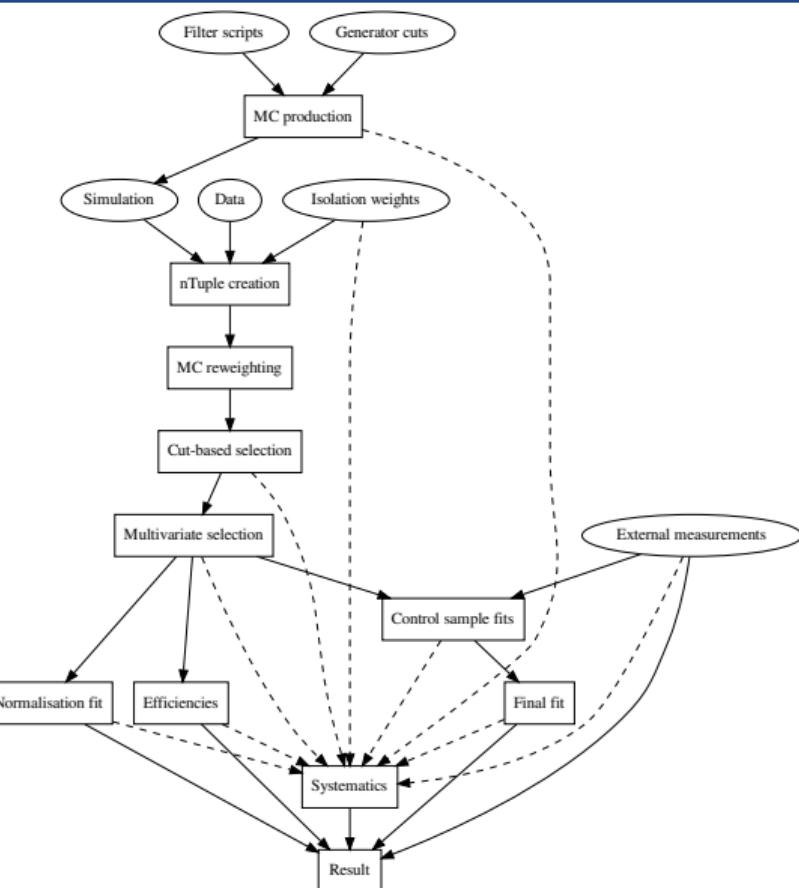
- Neutrinos not detected; approximation needed for  $B$  reconstruction
- Well measured  $B^0$  and  $\tau^+$  vertices allow reconstruction of flight directions
- Momentum as a function of angle between the systems



- Maximum allowed values for the angles  $\Rightarrow$  unambiguous estimate of momentum

# Analysis strategy

- No narrow peaks to fit to for signal extraction!
- $N_{\text{sig}}$  from 3D binned template fit:
  - $q^2 \equiv (p_{B^0} - p_{D^*})^2$ ,
  - $\tau^+$  decay time,
  - Output of BDT trained to discriminate  $\tau$  from  $D_s^+$ .
- $N_{\text{norm}}$  from unbinned ML fit to  $m(D^*3\pi^\pm)$ .
- Efficiencies  $\varepsilon$  from simulation samples

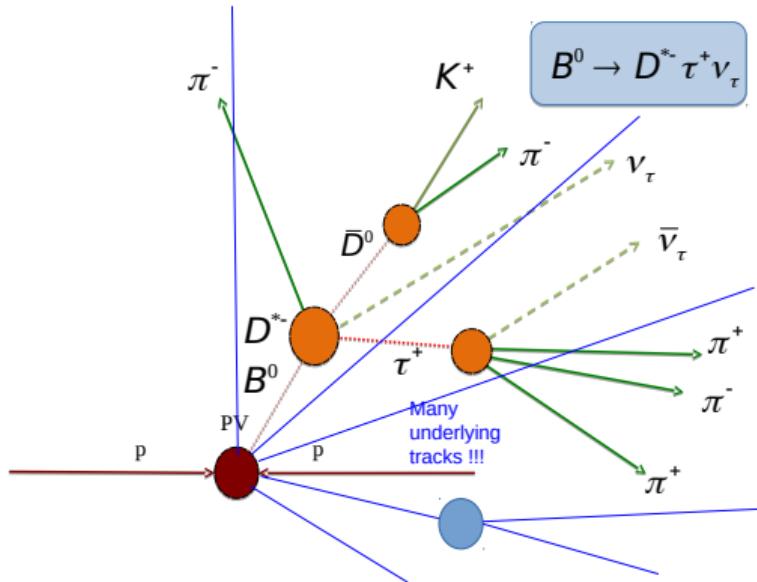


## Simulation samples

- Simulation samples are important in two fronts
  - Estimating efficiencies
  - Building templates for the signal extraction fit
- The dominant systematic uncertainty in the Run 1 analysis - limited size of the simulation sample
- Simulation technique of *ReDecay* to mitigate this  $\Rightarrow$  over 3 billion events generated and around 194 million events saved

[EPJC 78, 1009 (2018)]

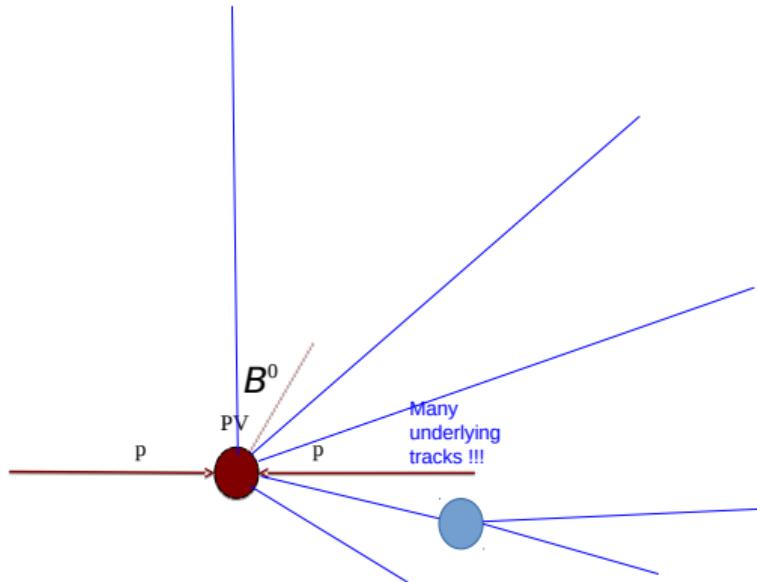
# Simulation with ReDecay



[EPJC 78, 1009 (2018)]

- ① Generate 1 complete event: signal + underlying event

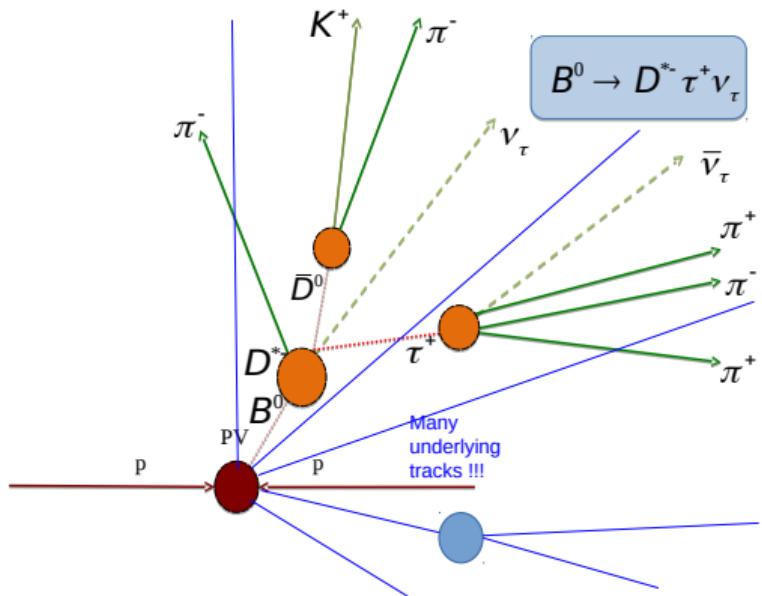
# Simulation with ReDecay



[EPJC 78, 1009 (2018)]

- ① Generate 1 complete event: signal + underlying event
- ② Re-generate the  $B$  decay 100 times and merge each with the underlying event

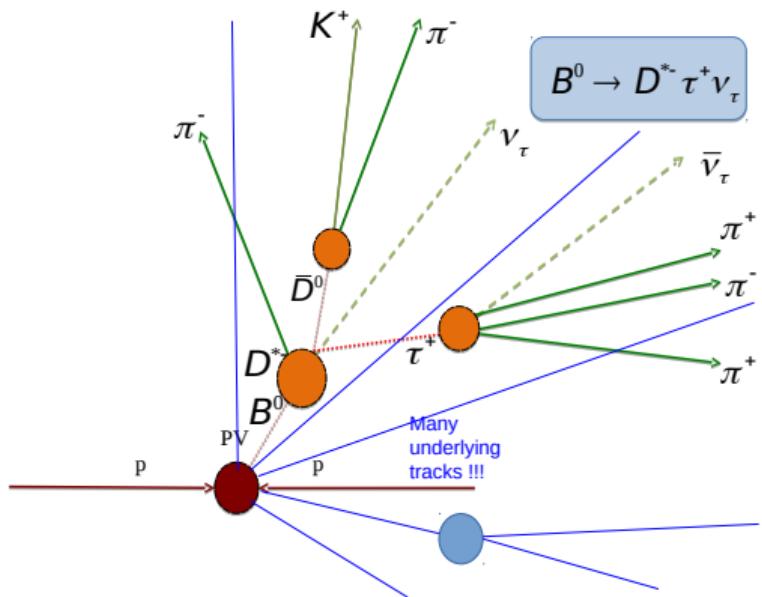
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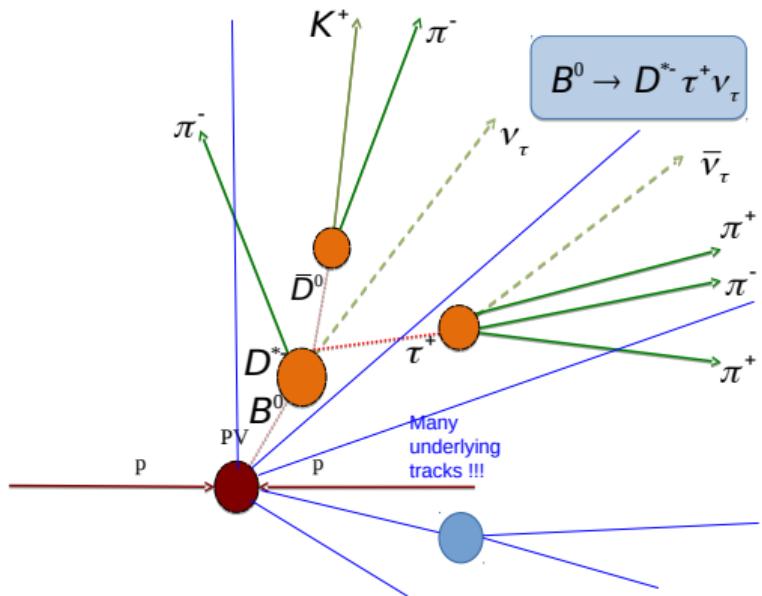
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[EPJC 78, 1009 (2018)]

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- ③ Repeat ① and ②  $N$  times

# Simulation with ReDecay



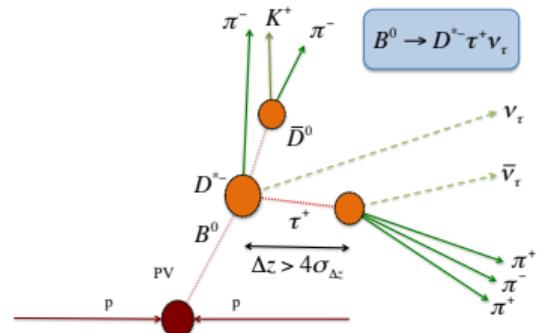
[EPJC 78, 1009 (2018)]

- ① Generate 1 complete event: signal + underlying event
- ② Re-generate the  $B$  decay 100 times and merge each with the underlying event
- ③ Repeat ① and ②  $N$  times  
 → Factor  $\mathcal{O}(10)$  faster simulation

## Corrections to simulation

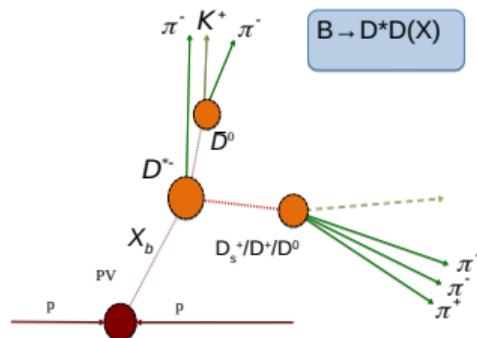
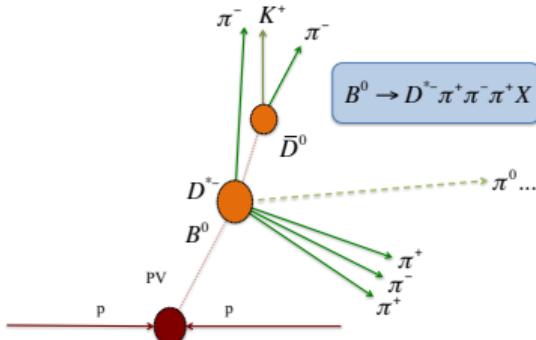
- Important to have simulation mimic the properties of data
- Corrections applied in case of disagreements
- The kinematic properties of simulation are corrected by a two dimensional reweighting using the transverse momentum and pseudo-rapidity of  $B$  candidates
- The uncertainty on the z-component of the  $3\pi^\pm$  vertex position is rescaled to match that of data
- The simulated  $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$  decays are reweighted with CLN form-factor parametrisation [Nucl. Phys. B 50, 153 (1998)]
- More corrections for the background simulation samples with inputs from data control samples  $\Rightarrow$  discussed later

- Signal candidates are built based on the **6 final-state charged tracks** with dedicated “online selection”
- Matching criteria include track/vertex quality, particle identification and mass constraints for composite particles
- Transverse distance of  $3\pi^\pm$  vertex from primary vertex in the range [0.2, 5.0] mm  
⇒ reduces spurious pions from secondary interactions
- A BDT classifier is used to suppress combinatorial events originating from random combinations of the final state particles



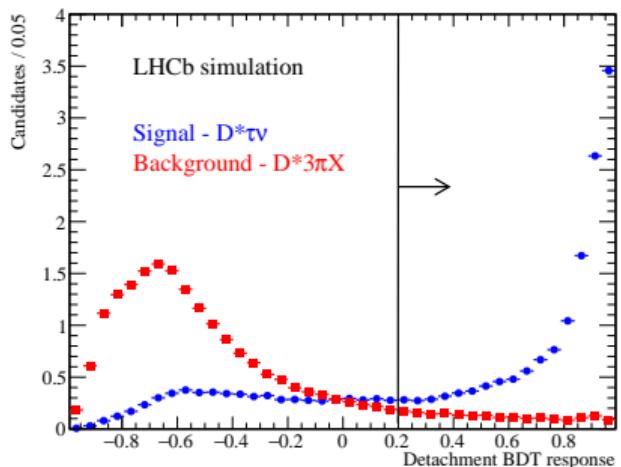
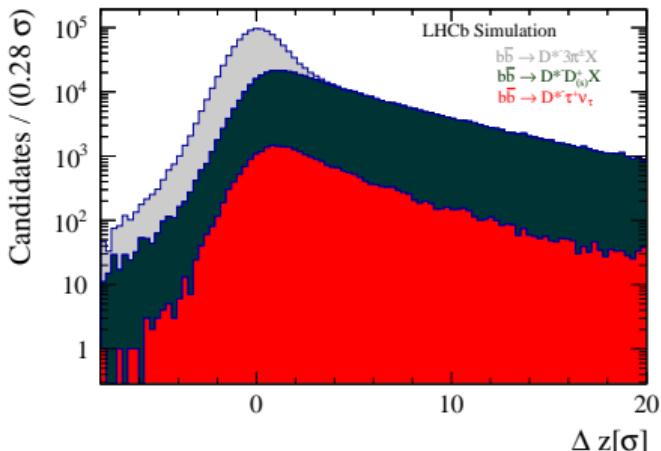
# Background contributions

- The most dominant background is  $B \rightarrow D^{*-} 3\pi^\pm X$ 
  - The  $3\pi^\pm$  directly from  $B$  meson
  - Around  $\sim 100\times$  signal decays
- The second largest contribution from  $B \rightarrow D^{*-} DX$  decays - termed as “double charm” decays
  - $D = D_s^+, D^+, D^0$
  - Signal like topology with a detached vertex due to non-negligible lifetime
  - $B \rightarrow D^{*-} D_s^+ X \sim 10\times$  signal decays



$B \rightarrow D^{*-} 3\pi^\pm X$  backgrounds

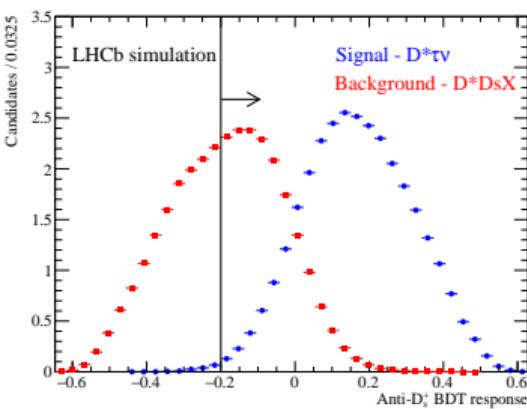
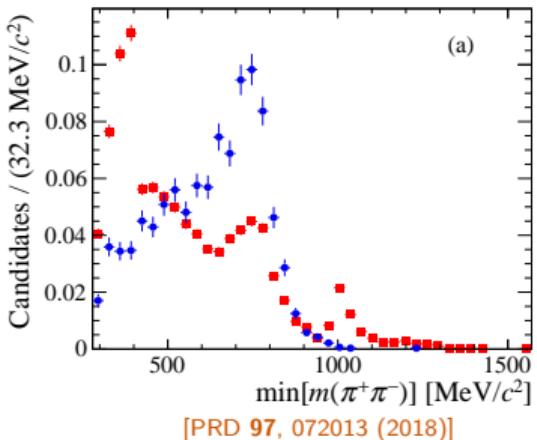
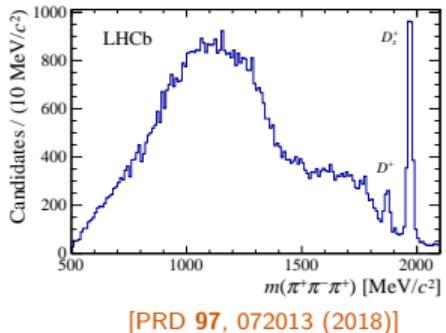
- Suppressed by requiring the  $\tau$  vertex to be downstream w.r.t. the  $B$  vertex along the beam direction - detachment criteria
- A BDT classifier is used along with the vertex separation variables



- More than 99% of  $B \rightarrow D^{*-} 3\pi^\pm X$  backgrounds rejected with this selection

# Double-charm backgrounds

- $B \rightarrow D^{*-}(D_s^+, D^+, D^0)X$  backgrounds
- $B \rightarrow D^{*-}D_s^+X$  the largest contributor
- A BDT classifier based on dynamics and resonant structure to separate signal from  $B \rightarrow D^{*-}D_s^+X$

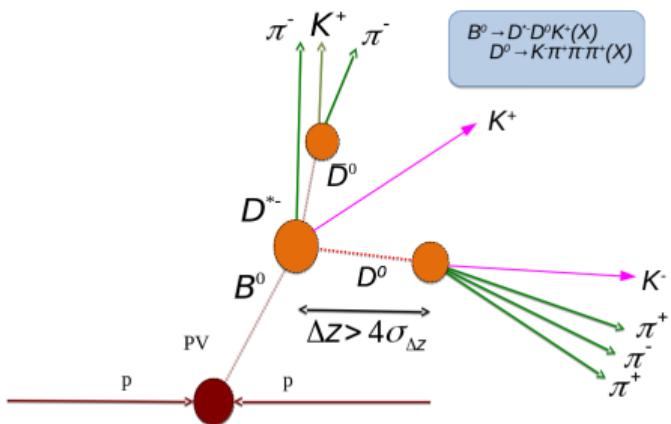


- This BDT output is one of the fit variables for signal extraction

## Double-charm backgrounds

- $B \rightarrow D^{*-}(D^+, D^0)X$  decays are sub-leading contributors
- $D^+ \rightarrow K^-\pi^+\pi^+(\pi^0)$  contributes to the  $B \rightarrow D^{*-}D^+X$  backgrounds
  - Significant when  $\pi^-$  is misidentified as  $K^-$
  - Tight particle identification requirements

- $D^0 \rightarrow K^-3\pi^\pm$  contributes to the  $B \rightarrow D^{*-}D^0X$  backgrounds
  - When there is an extra charged track
  - A BDT classifier is used to reject such events



# Double-charm backgrounds

- Double-charm decays being the largest fraction in the final sample, need to be modelled well in the final signal extraction fit
  - Templates used in the signal fit are derived from simulation and corrections need to be applied wherever necessary
- Specific control samples derived using the peculiarities of these decays for further studies

Decay	Sample selection
$B \rightarrow D^{*-} D_s^+ X$	reversing the anti- $D_s^+$ BDT selection
$B \rightarrow D^{*-} D_s^+ (\rightarrow 3\pi^\pm) X$	$m(3\pi^\pm)$ around $D_s^+$ mass
$B \rightarrow D^{*-} D^+ X$	kaon mass hypothesis given to $\pi^-$ among the $3\pi^\pm$ candidates
$B \rightarrow D^{*-} D^0 X$	additional charged track (kaon) selected in an event

## $B \rightarrow D^{*-} D_s^+ X$ decays

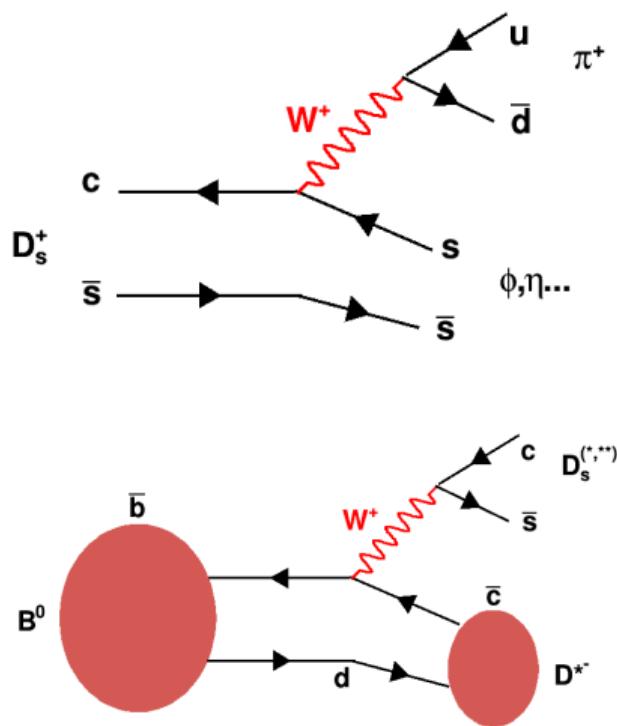
- Important to understand the **decay** and **production** of  $D_s^+$  in  $B \rightarrow D^{*-} D_s^+ X$  events

### Decay

- $D_s^+ \rightarrow 3\pi^\pm X$  branching fractions not all well known and/or correctly simulated
- The fractions obtained from control sample fits and simulation reweighted

### Production

- $B \rightarrow D^{*-} D_s^+ X$  decays produced in a spectrum of  $B \rightarrow D^{*-} D_s^{+(*,**)} X$  processes
- Fractions estimated from control sample fits of  $B \rightarrow D^{*-} D_s^+(\rightarrow 3\pi^\pm) X$  decays
- Constraints in the signal extraction fit



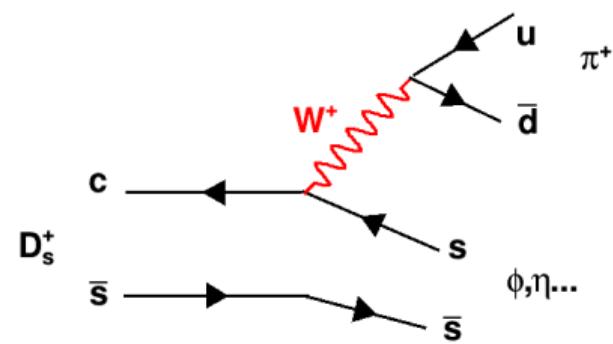
$D_s^+$  decay

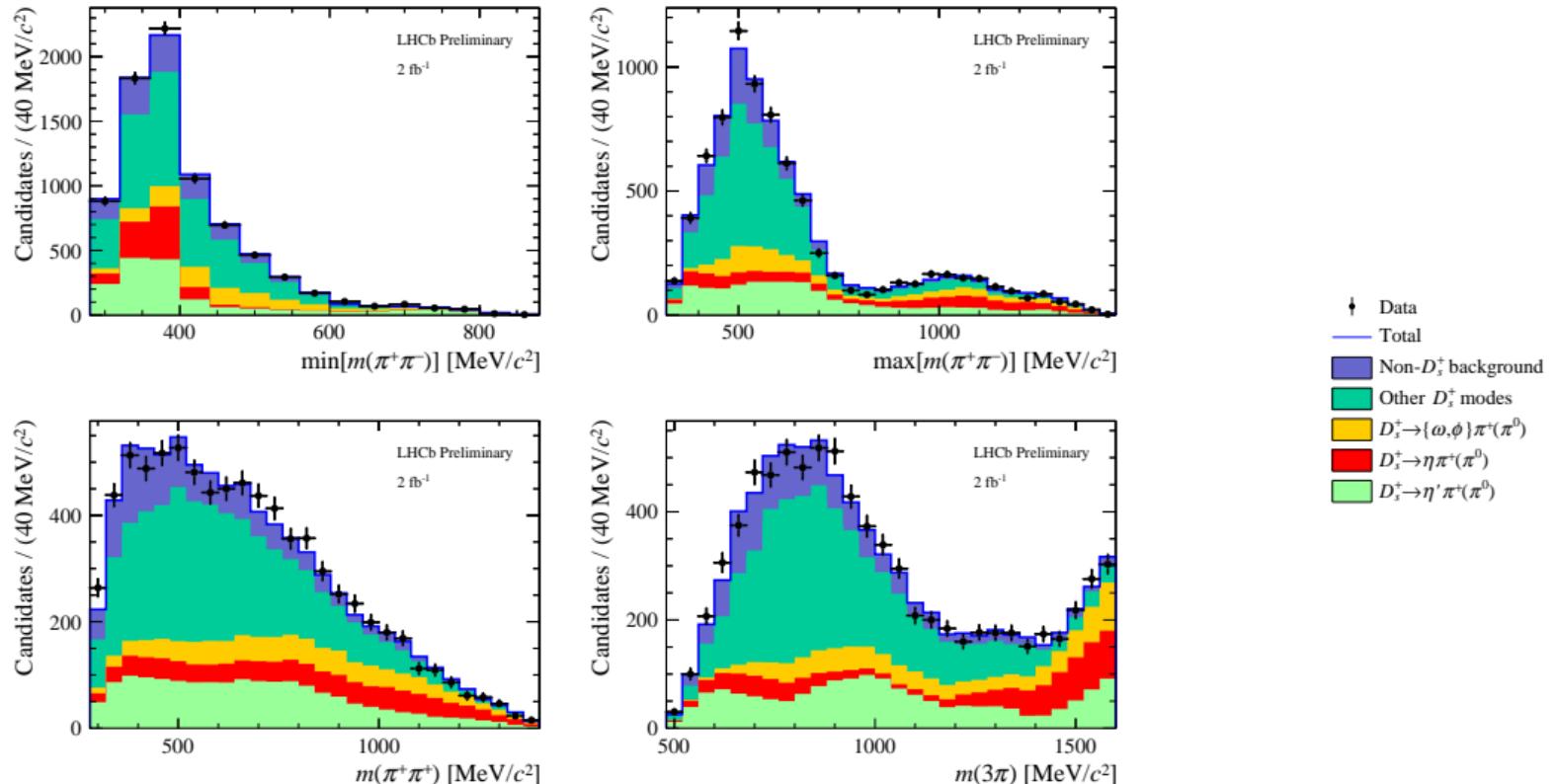
- Data sample selected with low anti- $D_s^+$  BDT score
- Simultaneous fit to  $m(\pi^+\pi^-)_{\min}$ ,  $m(\pi^+\pi^-)_{\max}$ ,  $m(\pi^+\pi^+)$  and  $m(3\pi^\pm)$
- The fit model PDF is constructed as

$$\mathcal{P}_{\text{total}} = N_{D_s^+} \sum_i f_i \mathcal{P}_i(D_s^+) + N_{\text{non}-D_s^+} \mathcal{P}_{\text{non}-D_s^+}$$

where  $i$  represents different  $D_s^+$  decay modes

- The different  $D_s^+$  modes can be broadly divided into
  - $\eta\pi^+/\eta\rho^+$
  - $\eta'\pi^+/\eta'\rho^+$
  - $(\omega + \phi)\pi^+ / (\omega + \phi)\rho^+$
  - rest of the modes -  $\eta 3\pi$ ,  $\eta a_1$ ,  $\eta' 3\pi$ ,  $\eta' a_1$ ,  $\omega 3\pi$ ,  $\omega a_1$ ,  $\phi 3\pi$ ,  $\phi a_1$ ,  $K^0 3\pi$ ,  $K^0 a_1$ ,  $\tau\nu$  and non-resonant  $3\pi$



$D_s^+$  decay

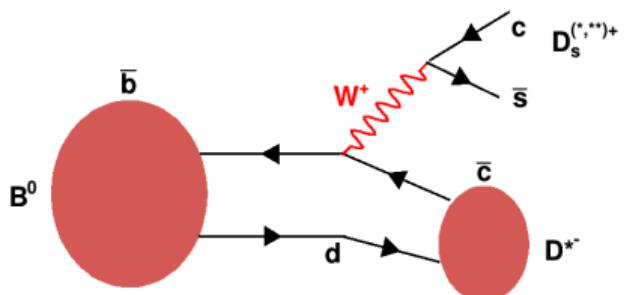
- The fractions of various modes extracted and simulation corrected accordingly

# $D_s^+$ production

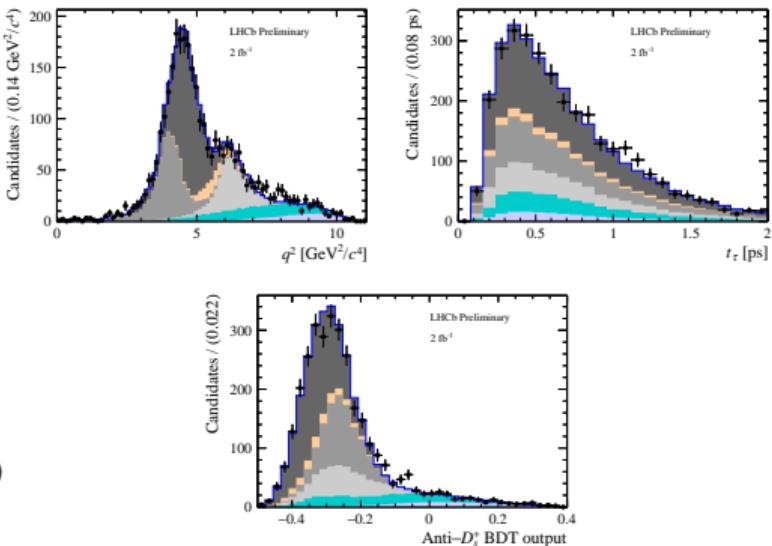
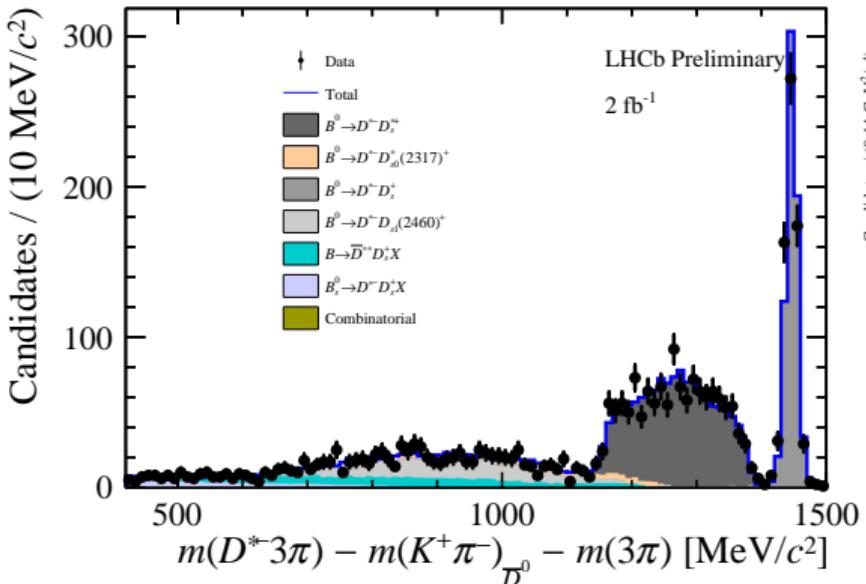
- Data sample selected with  $m(3\pi^\pm)$  around  $D_s^+$  mass
- Fit to  $m(D^{*-}3\pi) - m(D^0) - m(3\pi^\pm)$

Components:

- $B^0 \rightarrow D^{*-} D_s^+$
- $B^0 \rightarrow D^{*-} D_s^{*+}$
- $B^0 \rightarrow D^{*-} D_{s0}^*(2317)^+$
- $B^0 \rightarrow D^{*-} D_{s1}^*(2460)^+$
- $B \rightarrow D^{**-} D_s^+ X$
- $B_s^0 \rightarrow D^{*-} D_s^+ X$



# $D_s^+$ production

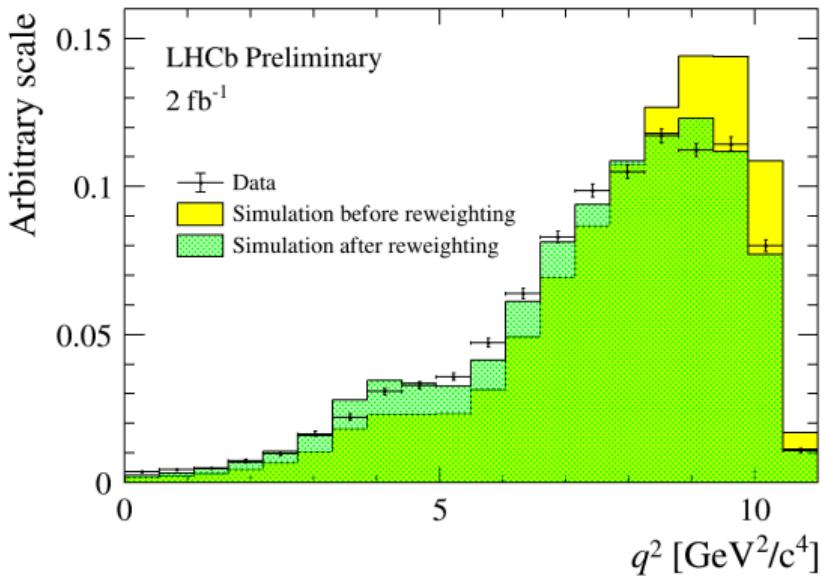


- Fractions of each component determined and used as constraints in the signal extraction fit

- Good agreement between model and data for the fit variables

# $B \rightarrow D^{*-}(D^+, D^0)X$ decays

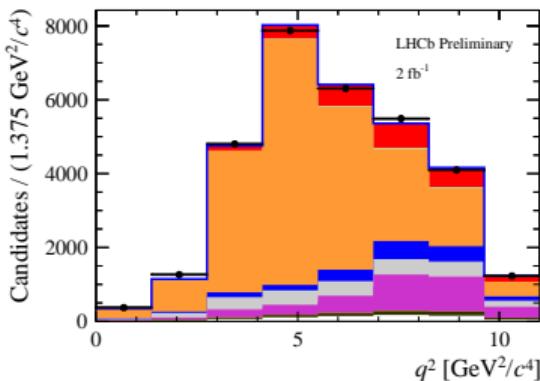
- Data control samples for  $B \rightarrow D^{*-}(D^+, D^0)X$  decays compared with simulation
- $q^2$  distribution in simulation is corrected for the observed differences



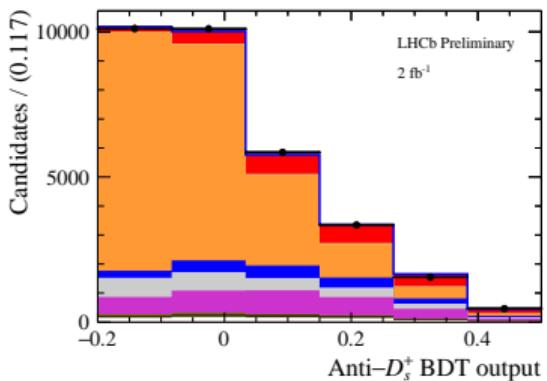
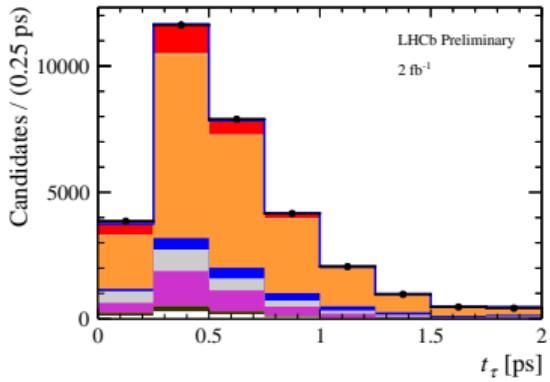
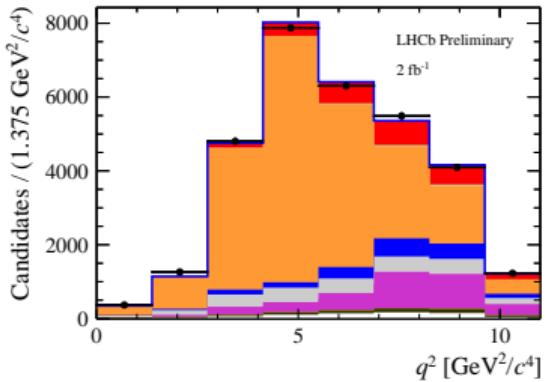
- $\tau^+$  decay time and anti- $D_s^+$  BDT output distributions in good agreement

# Signal extraction

- 3D binned template fit to:
  - $q^2 \equiv (p_{B^0} - p_{D_s^+})^2$
  - $\tau^+$  decay time
  - Anti- $D_s^+$  BDT output
- $8 \times 8 \times 6$  bins
- Total 16 components in the fit
  - Templates for 13 of them derived from simulation samples
  - Rest of them (combinatorial backgrounds) derived from data
- Contribution from excited  $D^{**}$  states estimated from simulation and corrected with weights calculated using theoretical inputs [Rev. Mod. Phys. 94, 015003 (2022)]



# Signal extraction



- † Data
- Total
- $B^0 \rightarrow D^- \tau^+ \nu_\tau$
- $B \rightarrow \bar{D}^{**} \tau^+ \nu_\tau$
- $B \rightarrow D^+ D_s^+(X)$
- $B \rightarrow D^+ D^+(X)$
- $B \rightarrow D^+ 3\pi X$
- $B \rightarrow D^+ D^0(X)$
- $\text{Comb. } B^0$
- $\text{Comb. } \bar{D}^0$
- $\text{Comb. } D^+$

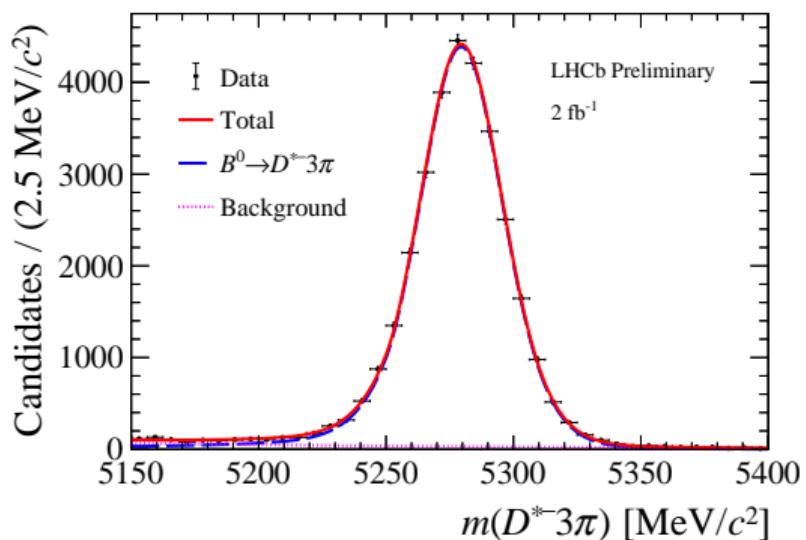
$$N(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau) = 2469 \pm 154$$

Run 1 yield =  $1296 \pm 86$

- Larger dataset
- Improved selection

Normalisation mode  $B^0 \rightarrow D^{*-} 3\pi^\pm$ 

- Data sample with similar selection as that for signal decays
  - No detachment criteria on  $3\pi^\pm$  vertex



- $N(B^0 \rightarrow D^{*-} 3\pi^\pm) = 30540 \pm 182$

## Systematic uncertainties

Major sources are

- Signal and background modelling
- Selection criteria on  $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$  and  $B^0 \rightarrow D^{*-} 3\pi^\pm$  decay modes
- Limited size of the simulation samples
  - The largest contribution in Run 1 from limited simulation samples (4%)
  - This is reduced to half its value in this analysis
  - Simulation technique *ReDecay* has allowed for the production of large simulation samples
- Empty bins in the templates

# Systematic uncertainties

Source	Systematic uncertainty on $\mathcal{K}(D^*)$ (%)
PDF shapes uncertainty (size of simulation sample)	2.0
Fixing $B \rightarrow D^* - D_s^+(X)$ bkg model parameters	1.1
Fixing $B \rightarrow D^* - D_s^0(X)$ bkg model parameters	1.5
Fractions of signal $\tau^+$ decays	0.3
Fixing the $\bar{D}^{**} \tau^+ \nu_\tau$ and $D_s^{***} \tau^+ \nu_\tau$ fractions	$+1.8$ $-1.9$
Knowledge of the $D_s^+ \rightarrow 3\pi X$ decay model	1.0
Specifically the $D_s^+ \rightarrow a_1 X$ fraction	1.5
Empty bins in templates	1.3
Signal decay template shape	1.8
Signal decay efficiency	0.9
Possible contributions from other $\tau^+$ decays	1.0
$B \rightarrow D^* - D^+(X)$ template shapes	$+2.2$ $-0.8$
$B \rightarrow D^* - D^0(X)$ template shapes	1.2
$B \rightarrow D^* - D_s^+(X)$ template shapes	0.3
$B \rightarrow D^* - 3\pi X$ 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

## $R(D^*)$ with hadronic $\tau$ decays

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)} = 1.700 \pm 0.101(\text{stat})^{+0.105}_{-0.100}(\text{syst})$$

- The absolute branching fraction of  $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$  decays

$$\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau) = (1.23 \pm 0.07 \text{ (stat)} \pm 0.08 \text{ (syst)} \pm 0.05 \text{ (ext)}) \times 10^{-2}$$

$$R(D^*) = \mathcal{K}(D^*) \frac{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)}$$

- The BFs of  $B^0 \rightarrow D^{*-} 3\pi^\pm$  and  $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$  - external inputs

$$R(D^*) = 0.247 \pm 0.015 \text{ (stat)} \pm 0.015 \text{ (syst)} \pm 0.012 \text{ (ext)}$$

In agreement with Run 1 result

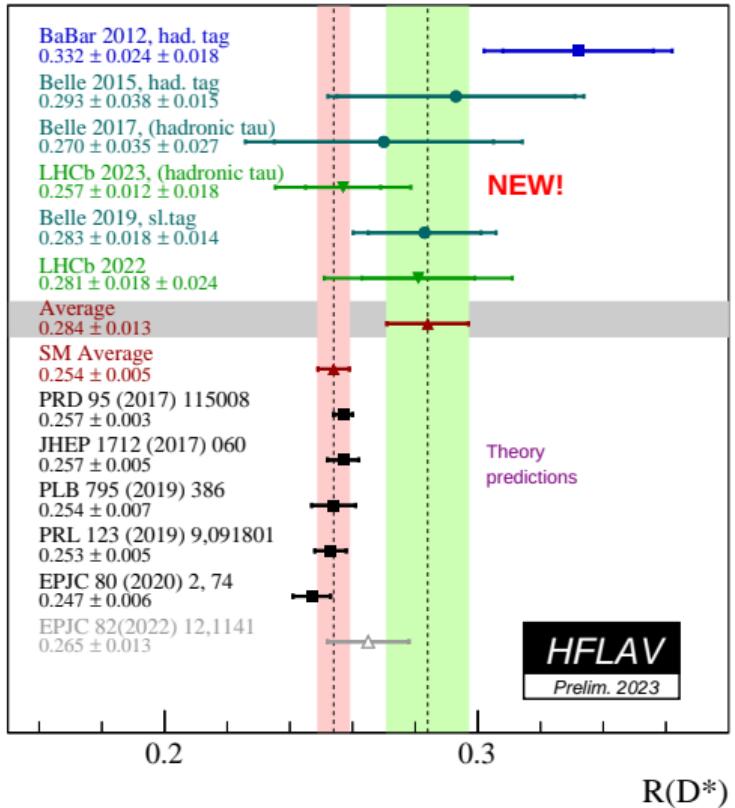
- Combining with the Run 1 result

$$R(D^*)_{2011-2016} = 0.257 \pm 0.012 \text{ (stat)} \pm 0.014 \text{ (syst)} \pm 0.012 \text{ (ext)}$$

Agreement within  $1\sigma$  to SM

$$R(D^*)_{\text{SM}} = 0.254 \pm 0.005 \text{ [HFLAV]}$$

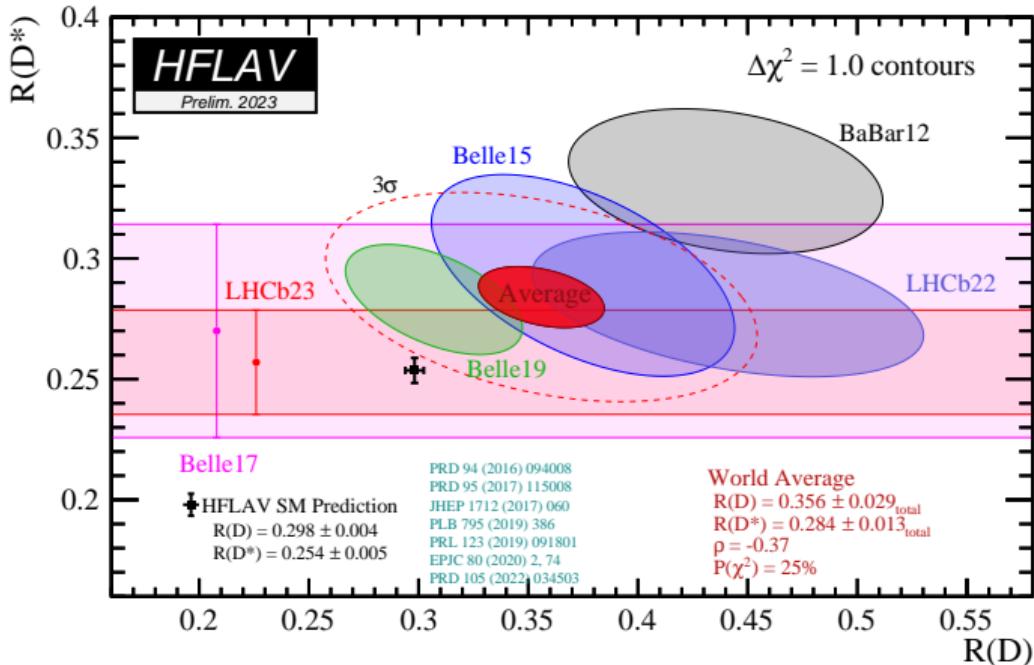
# $R(D^*)$ with hadronic $\tau$ decays



- One of the most precise measurements of  $R(D^*)$

[HFLAV]

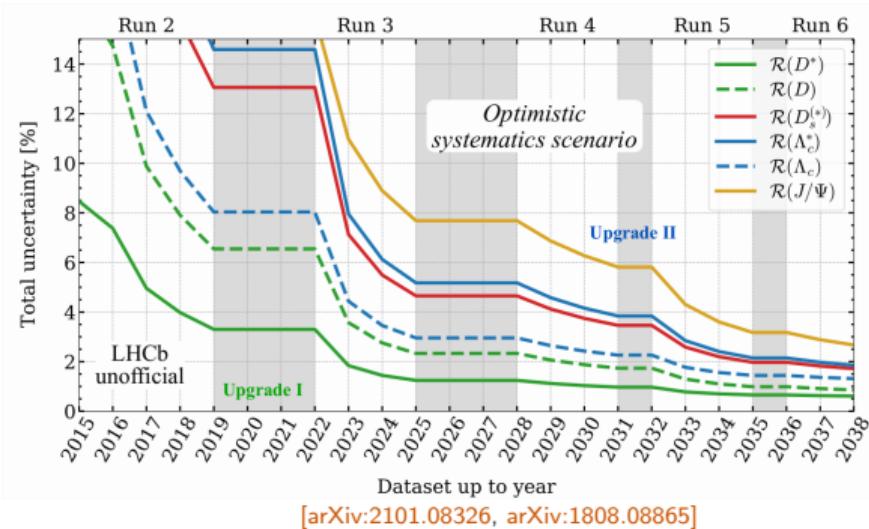
# $R(D^*)$ with hadronic $\tau$ decays



- Including this result, the world average becomes  
 $R(D^*) = 0.284 \pm 0.013; R(D) = 0.356 \pm 0.029$  [HFLAV]
- The deviation w.r.t. the SM is at  **$3.2\sigma$**  for the combination of  $R(D)$ - $R(D^*)$

# Outlook

- Adding full Run 2 dataset
- Many new measurements underway for a variety of  $R(X_c)$  ratios
  - $R(\Lambda_c)$  [PRL 128, 191803 (2022)],  $R(D_s)$ ,  $R(D^+)$ ...
- Exploring new observables beyond these ratios
  - Made possible by the good signal to noise level in the sample
  - Excellent prospects for polarisation and angular observables
- The recent BESIII results on inclusive  $D \rightarrow 3\pi^\pm X$  rates for  $D = D^0, D^+, D_s^+$  will significantly lower the systematic uncertainties in the legacy measurement to come [PRD 107, 032002 (2023), arXiv:2212.13072]

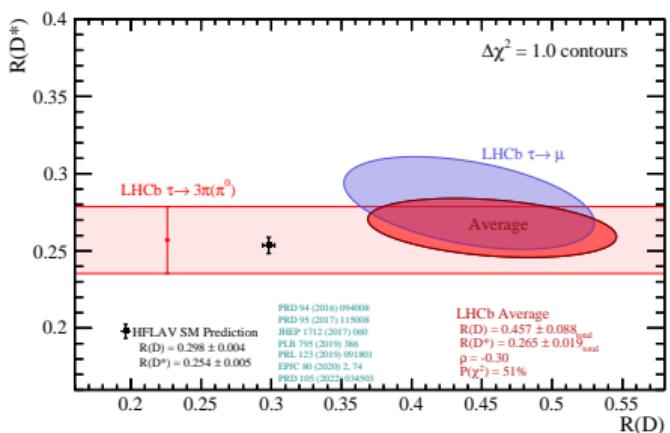


# Conclusions

- $R(D^*)$  measurement using hadronic  $\tau^- \rightarrow \pi^+ \pi^- \pi^- (\pi^0) \nu_\tau$  [LHCb-PAPER-2022-052]
- Used partial Run 2 dataset of  $2 \text{ fb}^{-1}$  at  $\sqrt{s} = 13 \text{ TeV}$  (In preparation)

$$R(D^*)_{2011-2016} = 0.257 \pm 0.012 \text{ (stat)} \pm 0.014 \text{ (syst)} \pm 0.012 \text{ (ext)}$$

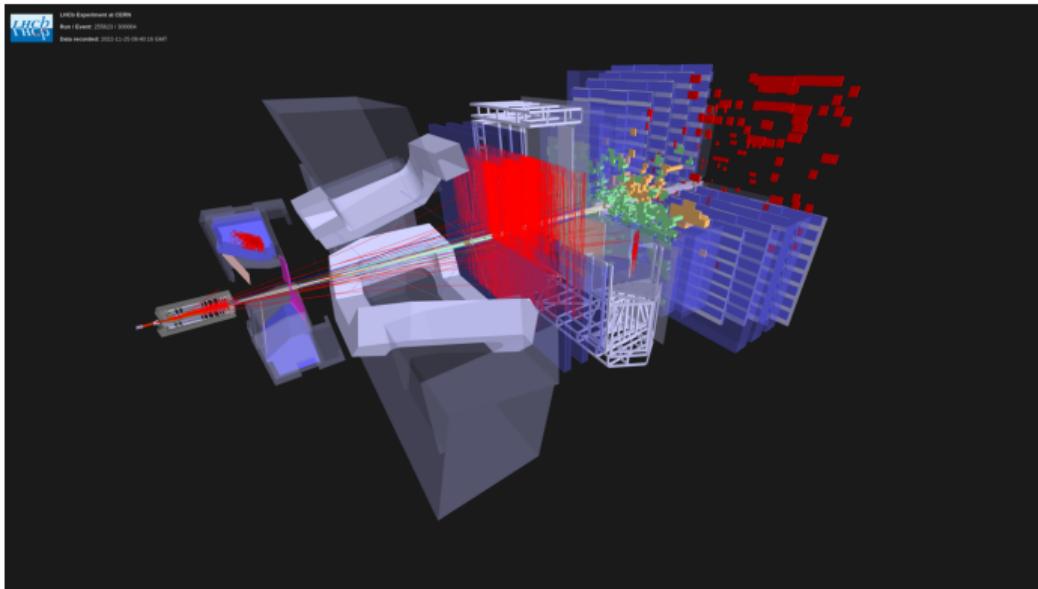
- Agreement within  $1\sigma$  to SM
- Global picture unchanged for  $R(D)$ - $R(D^*)$  combination with tension with SM at the level of  $3\sigma$



- Semileptonic decays are challenging at hadron colliders
- Yet,  $R(D^*)$  precision at LHCb similar to Belle
- LHCb a major player!

# Conclusions

- We have started taking data with first upgrade of LHCb, exciting times ahead!



thank you!