UNIÓN EUROPEA
FONDO EUROPEO DE DESENVOLVEMENTO REXIONAL
"Unha maneira de facer Europa"

LEPTON FLAVOUR UNIVERSALITY TESTS WITH SEMILEPTONIC $b \to c\ell\nu_\ell$ DECAYS

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LHCb
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Lepton Flavour Universality

- The SM predicts equal couplings between gauge bosons and the three lepton families. This is called **Lepton Flavour Universality (LFU)**
  - **Observation of LFU violation $\longrightarrow$ sign of new physics (NP)**
- Semileptonic decays show **tensions between SM expectation and experimental results** in $b \to c\ell\nu_\ell$ and $b \to s\ell\ell$ (Ricci's talk) transitions
- LFU can be probed by studying different observables:
  - Differential branching fractions
  - Angular analyses
  - **Ratio observables**

Ratio observables:
- Very well predicted
- Cancellation of theoretical and experimental uncertainties in the ratio

$$R_{D^*}(q^2) = \frac{\mathrm{d}\Gamma(B \to D^{*-}\tau^+\nu_\tau)}{\mathrm{d}q^2} \Big/ \frac{\mathrm{d}\Gamma(B \to D^{*-}\ell^+\nu_\ell)}{\mathrm{d}q^2}$$

$$q^2 = (p_B - p_{D^*})^2$$

Semileptonic $b \to c\ell\nu_\ell$ decays

- Test LFU by measuring $R(H_c) = \dfrac{BR(H_b \to H_c\tau^+\nu_\tau)}{BR(H_b \to H_c\mu^+\nu_\mu)}$

  where $H_b = B^0, B^+_{(c)}, \Lambda^0_b, B^0_s, \ldots$
  and $H_c = D^{(*)\pm}, D^0, D_s, \Lambda_c^+, J/\psi, \ldots$

- Clean theoretical prediction

- $R(H_c)$ **deviates from unity** due to different lepton masses

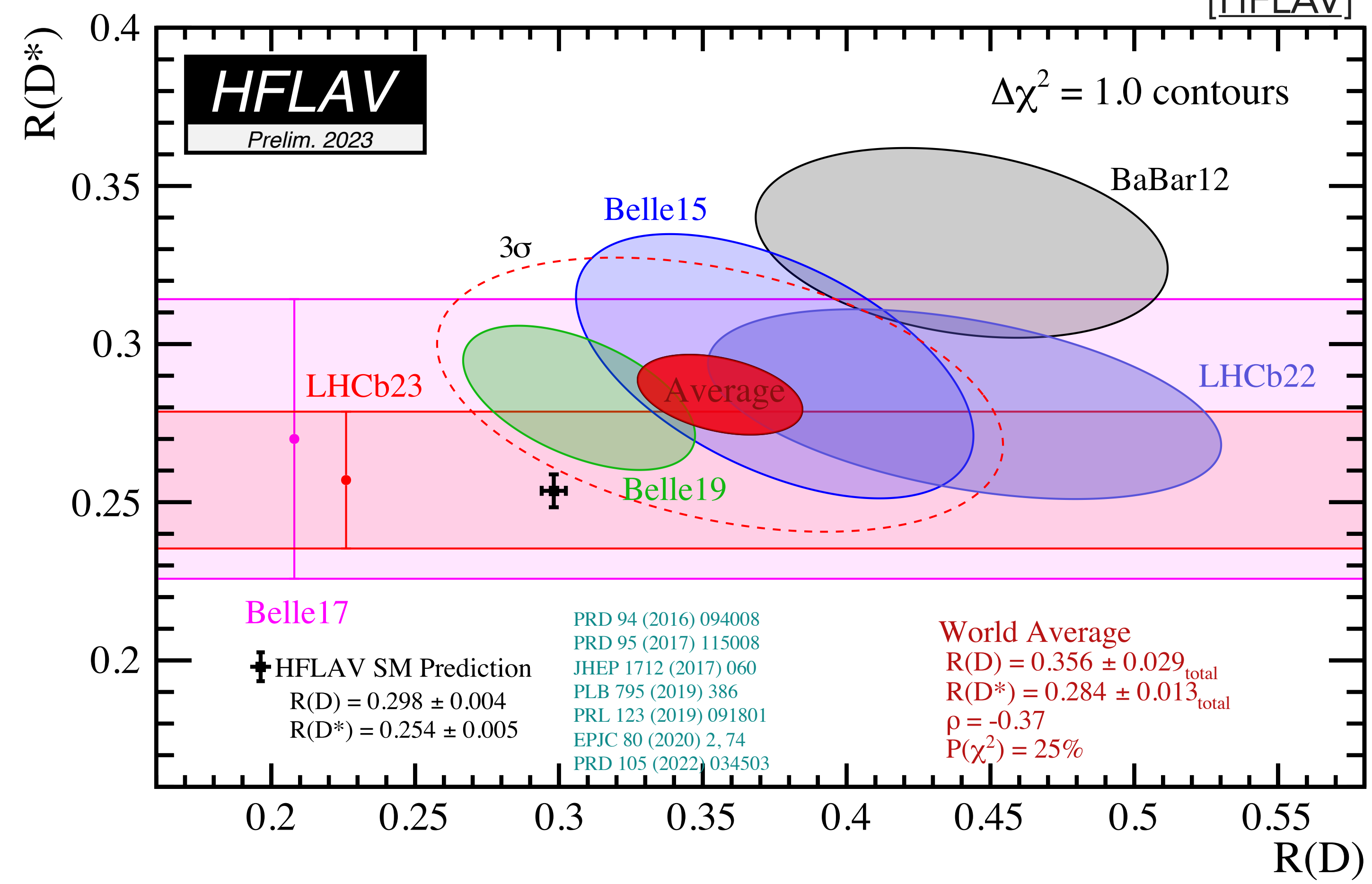
  $m_\tau \sim \begin{cases} 17 \cdot m_\mu \\ 3500 \cdot m_e \end{cases}$

- **Missing momentum of neutrinos**

- Different strategies:
  - **Muonic decay of the tau:** $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$
  - **3-prong decays:** $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

- Combined $R(D)$ and $R(D^*)$ measurement in **tensions with SM predictions by** 3.2σ

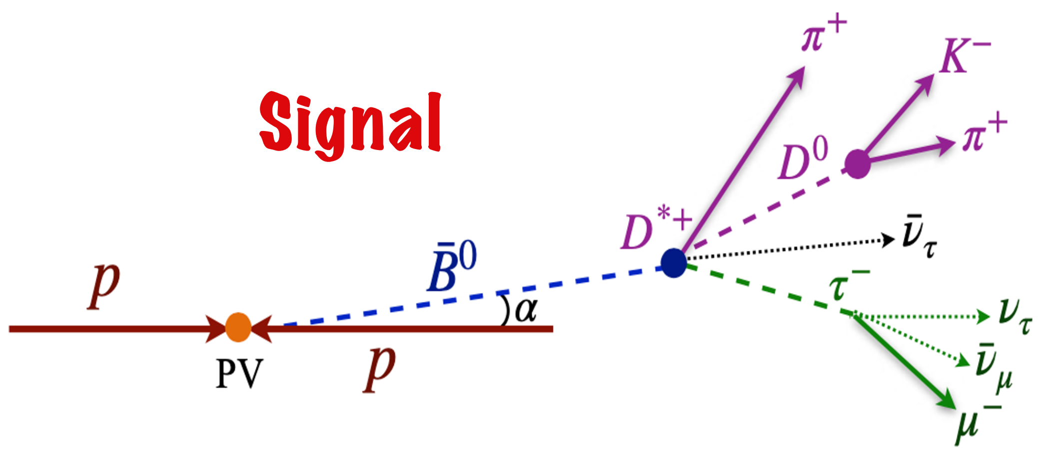
[HFLAV]

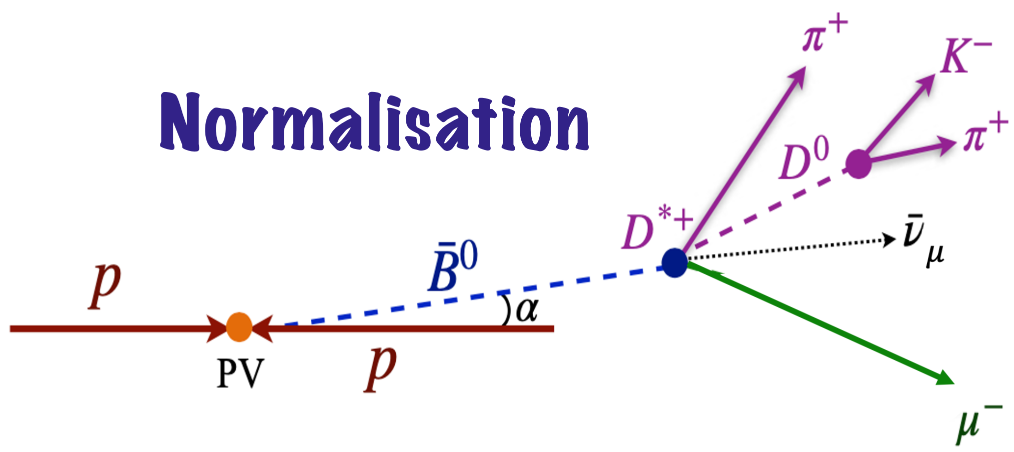


Muonic $R(D)$-$R(D^*)$ measurement

Run 1 3 fb^{-1}
arxiv:2302.02886

- Measurement of $R(D^{(*)}) = \dfrac{BR(B^0 \to D^{(*)}\tau^+\nu_\tau)}{BR(B^0 \to D^{(*)}\mu^+\nu_\mu)}$ with $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$

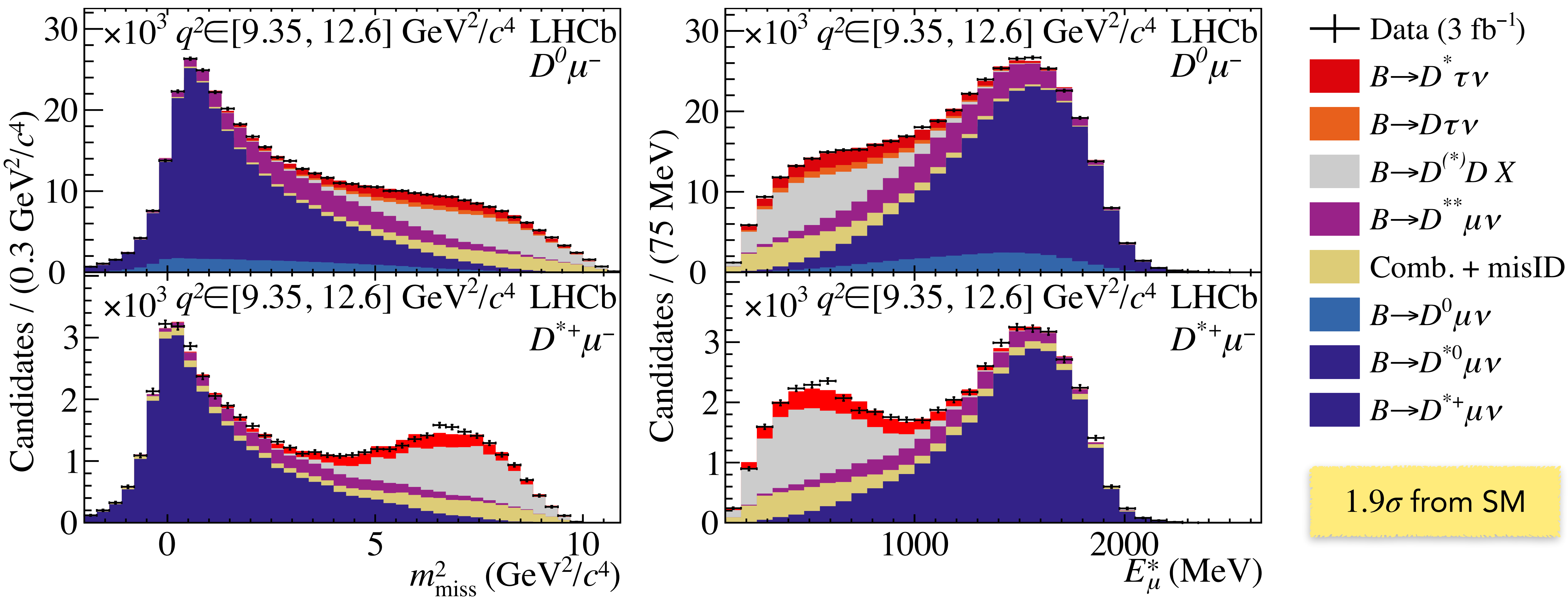




- **Same final states** for signal and normalisation
- B^0 boost along z axis $\gg$ boost of decay products in B^0 rest frame
- Momentum approximated as $(p_z)_B = \dfrac{m_B}{m_{D^*\mu}}(p_z)_{D^*\mu}$

Muonic $R(D)$-$R(D^*)$ measurement

- Separation of τ and μ channels via a 3D binned template fit to data:
  - $q^2 = (p_B - p_{D^*})^2$
  - $m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$
  - μ energy in the B rest frame, E^*_μ



1.9σ from SM

$$R(D^*) = 0.281 \pm 0.018 \pm 0.024$$

$$R(D) = 0.441 \pm 0.060 \pm 0.066$$

$\rho = -0.43$ correlation

Hadronic $R(D^*)$ measurement

Run 1, 3 fb^{-1}:[PRD 97 072013 (2018), PRL 120 171802 (2018)]

15+16, 2 fb^{-1}: [arxiv:2305.01463]

- τ reconstructed with 3-prong τ decays $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$
- Measure $BR(B^0 \to D^{*-}\tau^+\nu_\tau)$ w.r.t. the normalisation mode $B^0 \to D^{*-}\pi^+\pi^-\pi^+$:

$$K(D^*) = \frac{N_{sig}}{N_{norm}} \cdot \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \cdot \frac{1}{BR(\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau)}$$

$$R(D^*) = K(D^*) \cdot \frac{BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{BR(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

External inputs

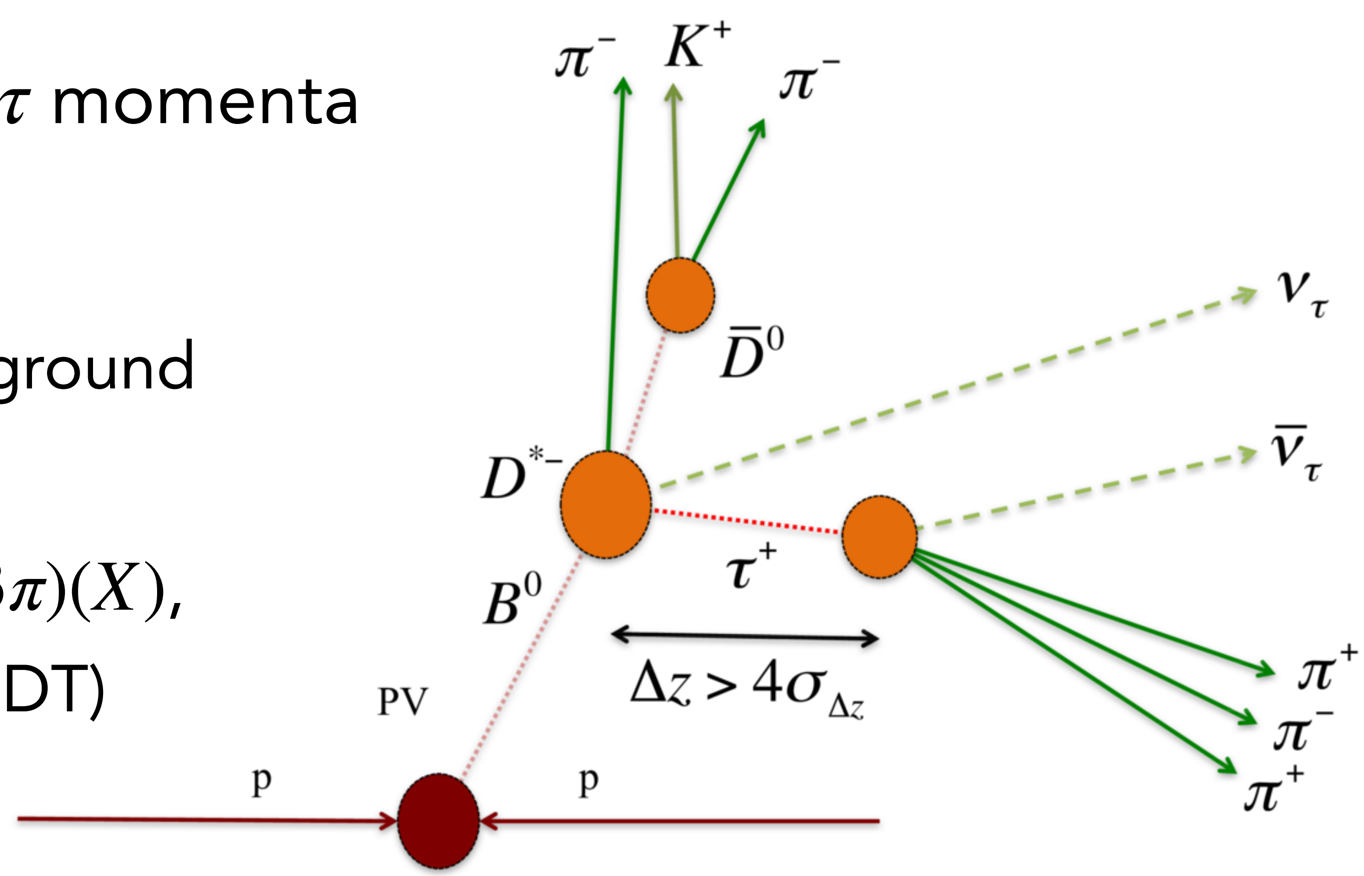
$BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+) = (7.21 \pm 0.29) \cdot 10^{-3}$

$BR(B^0 \to D^{*-}\mu^+\nu_\mu) = (5.05 \pm 0.14)\,\%$

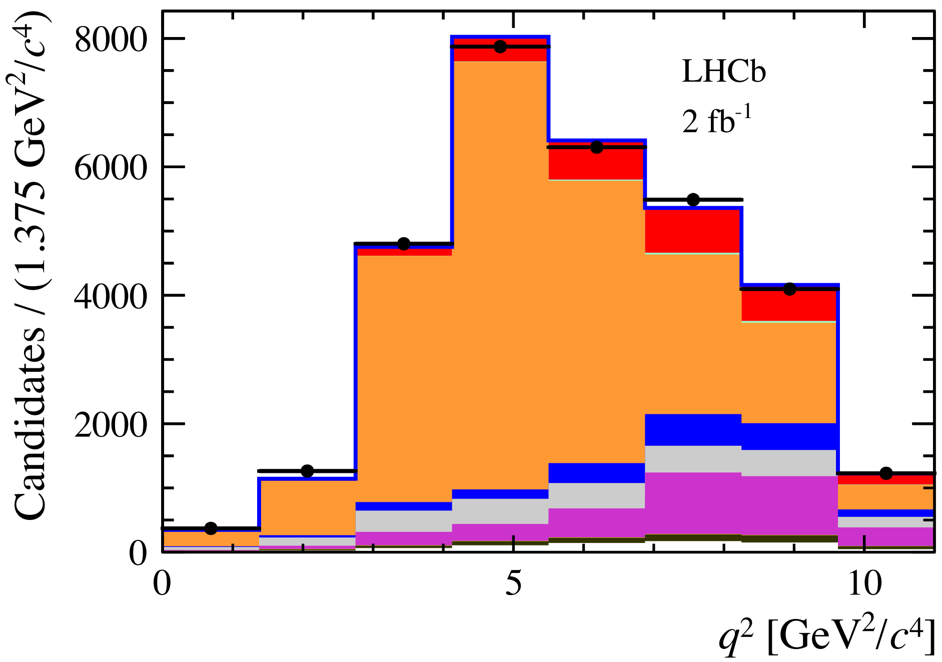
$BR(\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau) = (9.02 \pm 0.05)\,\%$

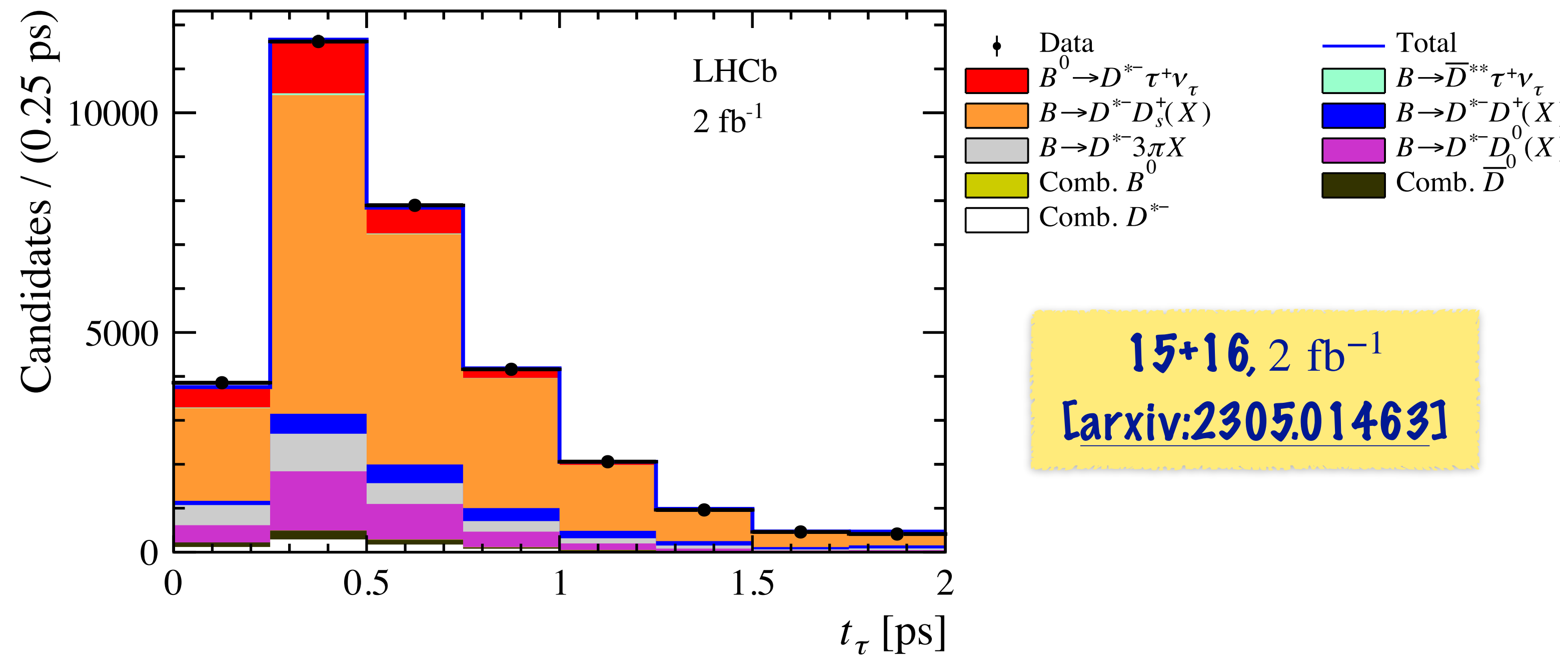
$BR(\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau) = (4.49 \pm 0.05)\,\%$

- Approximations to estimate B and τ momenta
- Largest background channels:
  - **Prompt** $B^0 \to D^{*-}\pi^+\pi^-\pi^+(X)$ background suppressed by $\Delta z > 4\sigma_{\Delta z}$
  - **Doubly charmed** $B \to D^{*-}D_s^+(\to 3\pi)(X)$, treated with multivariate analysis (BDT)

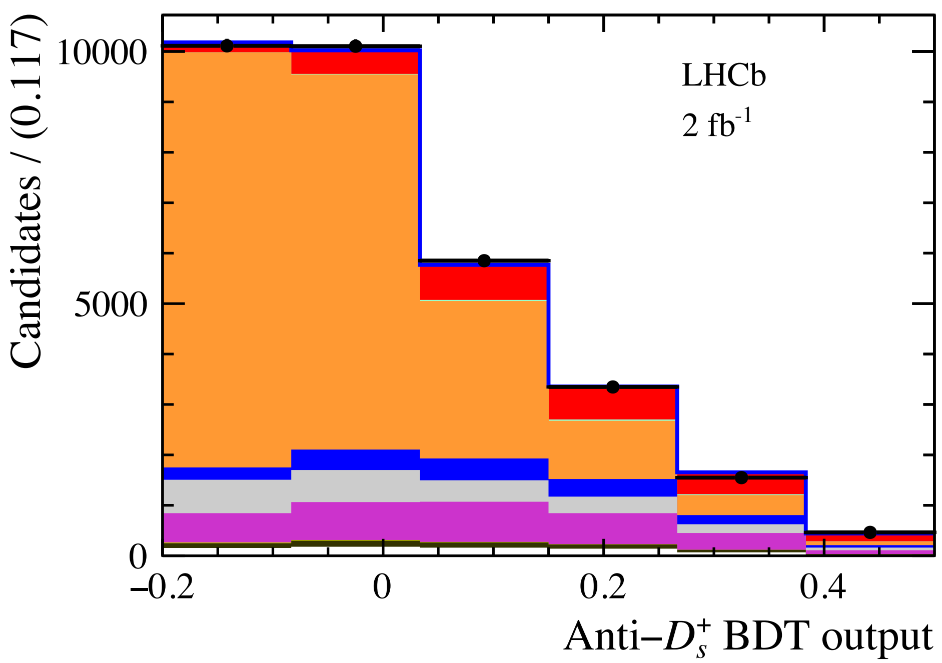


Hadronic $R(D^*)$ measurement





15+16, 2 fb^{-1}
[arxiv:2305.01463]



- **Normalisation yield** → invariant mass fit to $m(D^{*-}3\pi)$
- **Signal yield** → 3D template fit in τ decay time, q^2 and BDT

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

- Agreement with $R(D^*)_{\text{SM}} = 0.254 \pm 0.005$

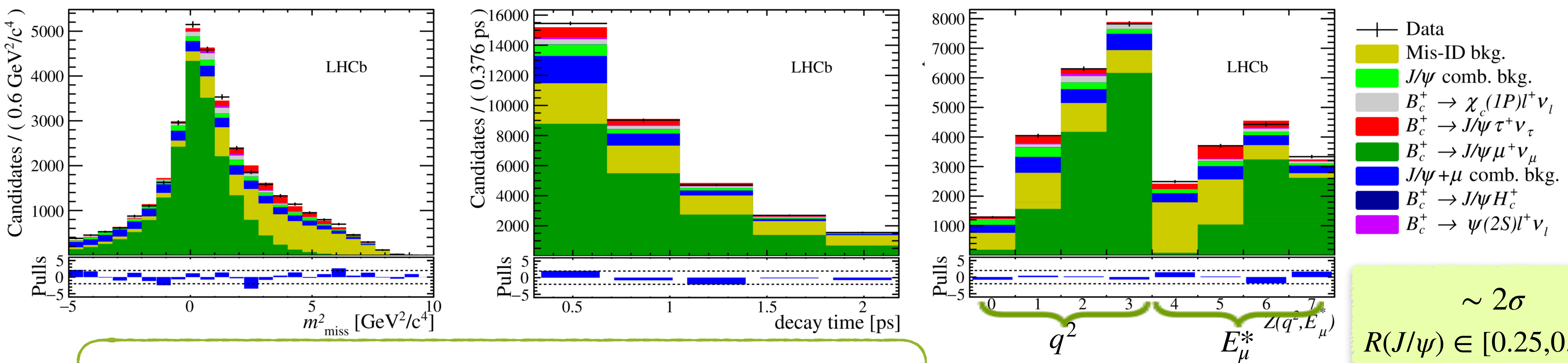
- Including Run 1 result:

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

$R(J/\psi)$ and $R(\Lambda_c^+)$ measurements

$$R(J/\psi) = \frac{BR(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{BR(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$ with $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$ decays

Run 1
3 fb^{-1}



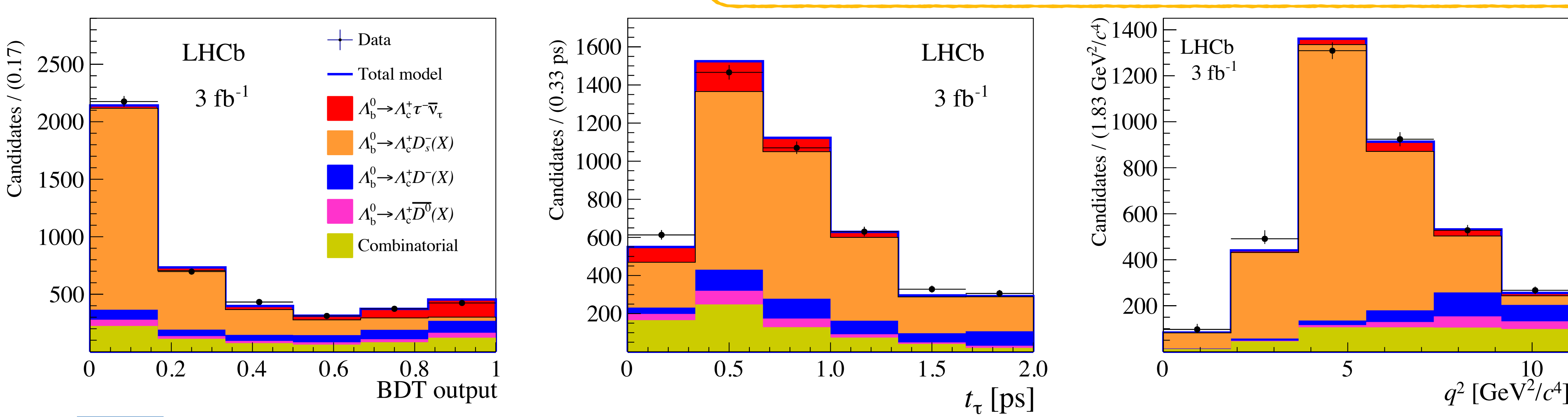
$\sim 2\sigma$
$R(J/\psi) \in [0.25, 0.28]$

$$R(J/\psi) = 0.71 \pm 0.17\ (\text{stat}) \pm 0.18\ (\text{syst})$$

[PLB 452 129 (1999)]
[arXiv:hep-ph/0211021]
[PRD 73 054024 (2006)]
[PRD 74 074008 (2006)]
[PRL 115 111803 (2015)]
[HFLAV]

$$R(\Lambda_c^+) = \frac{BR(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{BR(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$ with **3-prong τ decays**

$$R(\Lambda_c^+) = 0.242 \pm 0.026\ (\text{stat}) \pm 0.040\ (\text{syst}) \pm 0.0597\ (\text{ext})$$



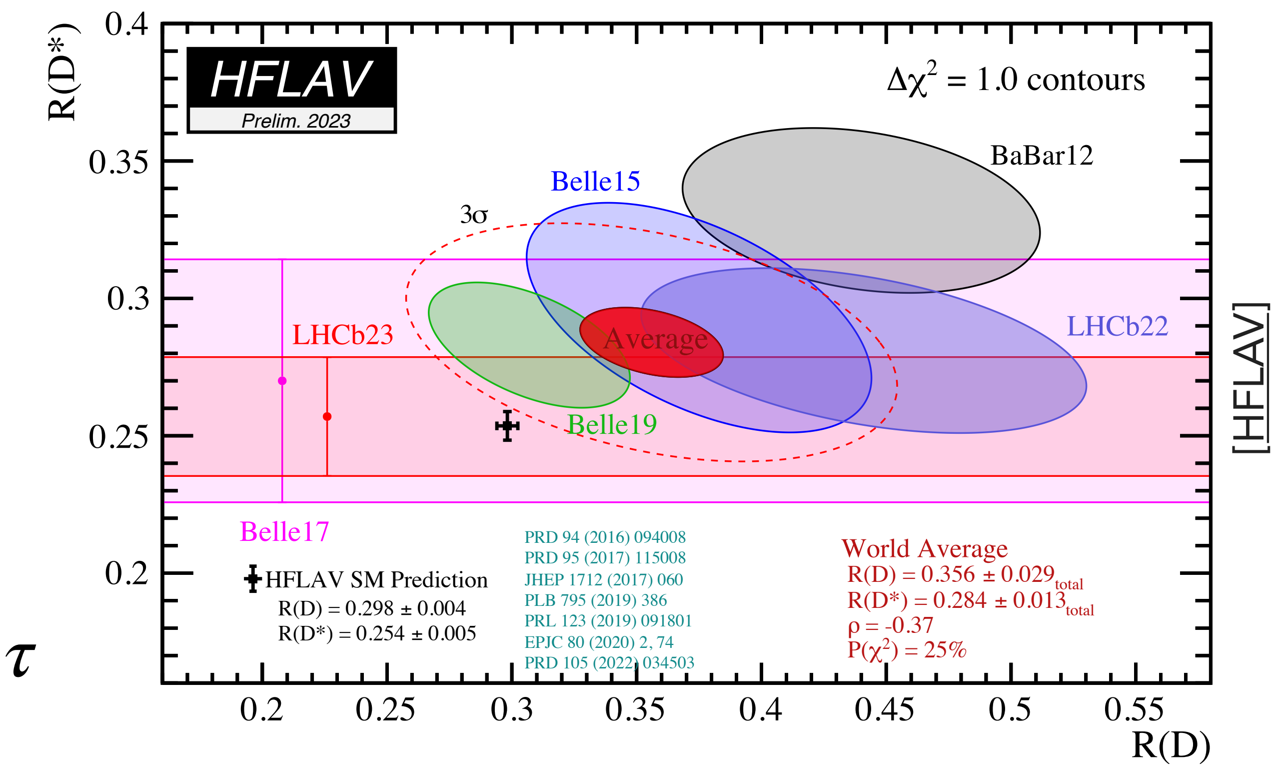
[arXiv:2201.03497]

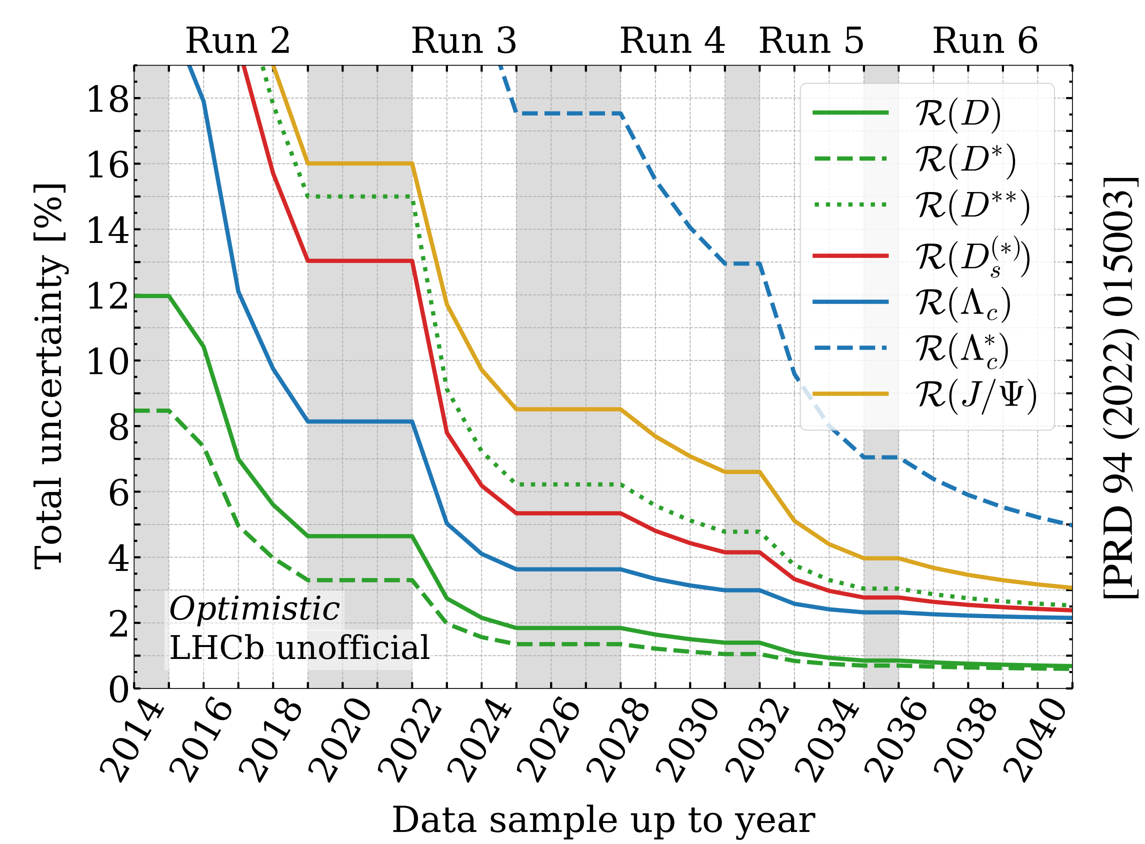
$\sim 1\sigma$
$R(\Lambda_c^+) = 0.324 \pm 0.004$

[PRD99 (2019) 055008]

Prospects and conclusions

- Perform **LFU tests to probe the SM**
- In the last months new results from LHCb
  - $R(D)$-$R(D^*)$ **combination** with $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$
  - $R(D^{*-})$ measurement with **3-prong τ decays**
- **Several measurements ongoing** with larger data samples
  - Reduce data-driven systematics and statistical uncertainties
  - Angular analyses
- New results from LHCb and Belle II
  - ➡ new answers on LFU problem



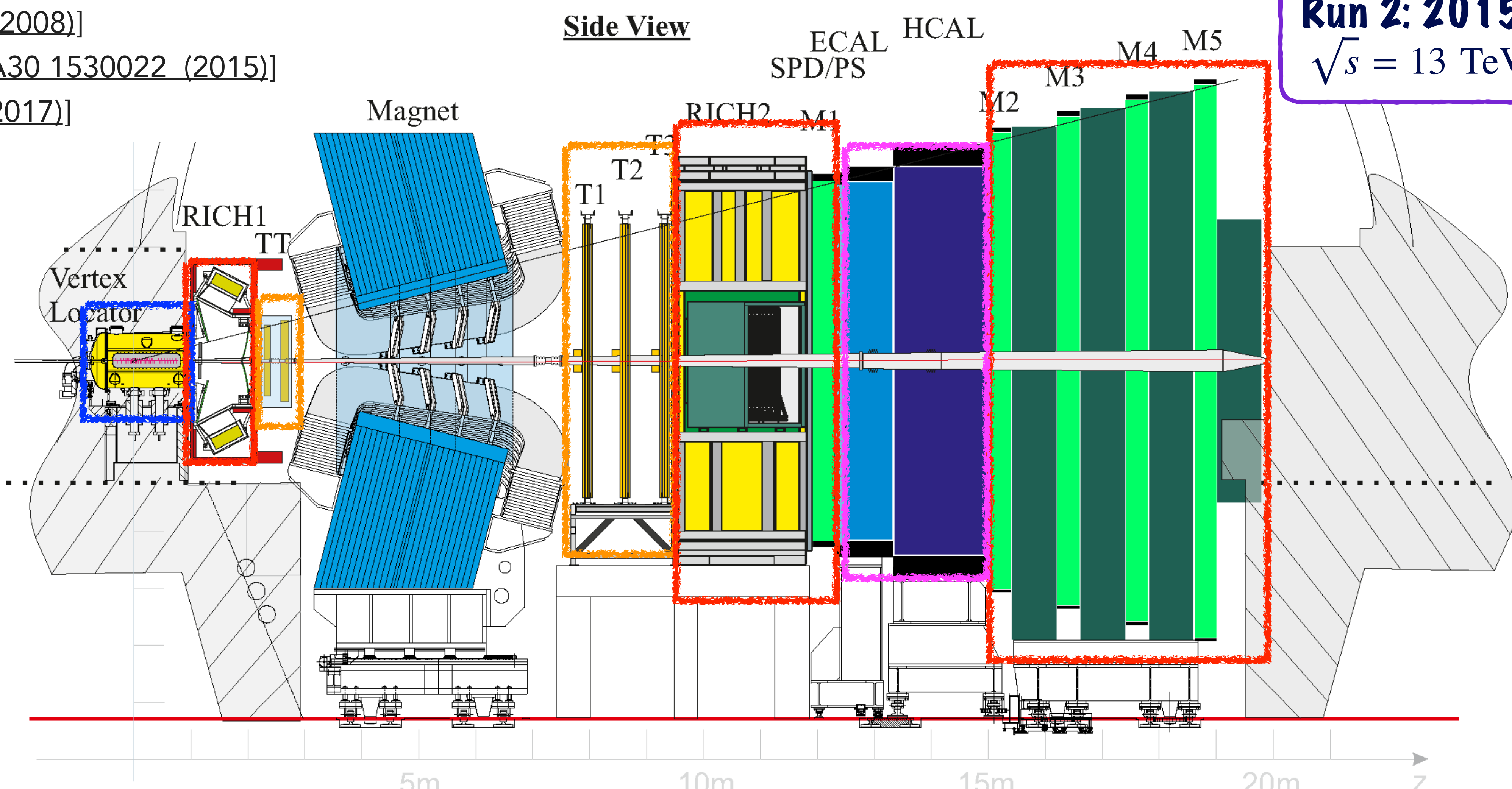


BACKUP

The LHCb detector

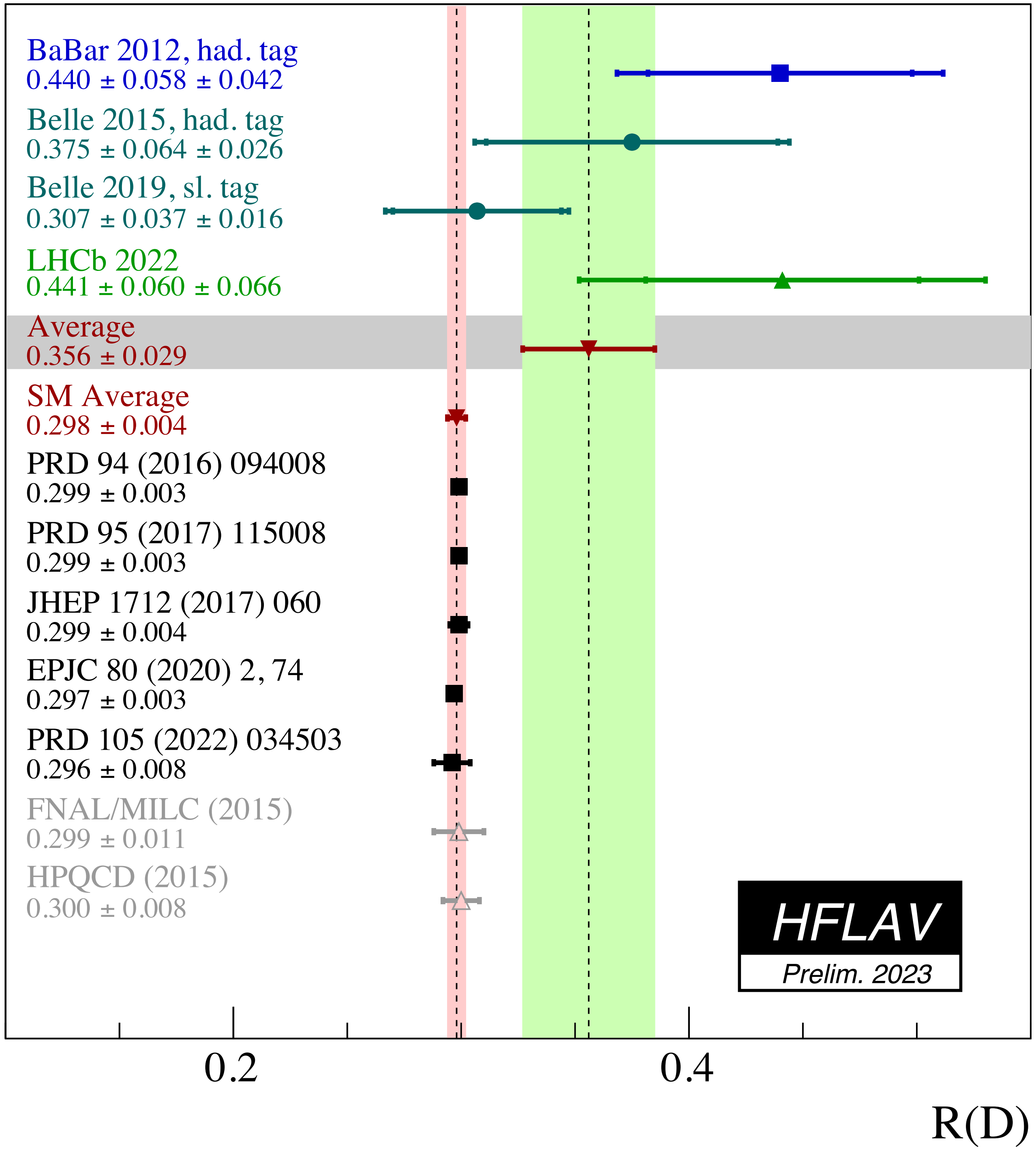
Run 1: 2010-2012
$\sqrt{s} = 7,\ 8$ TeV $\mathscr{L}_{int} = 3\ \text{fb}^{-1}$
Run 2: 2015-2018
$\sqrt{s} = 13$ TeV $\mathscr{L}_{int} = 6\ \text{fb}^{-1}$

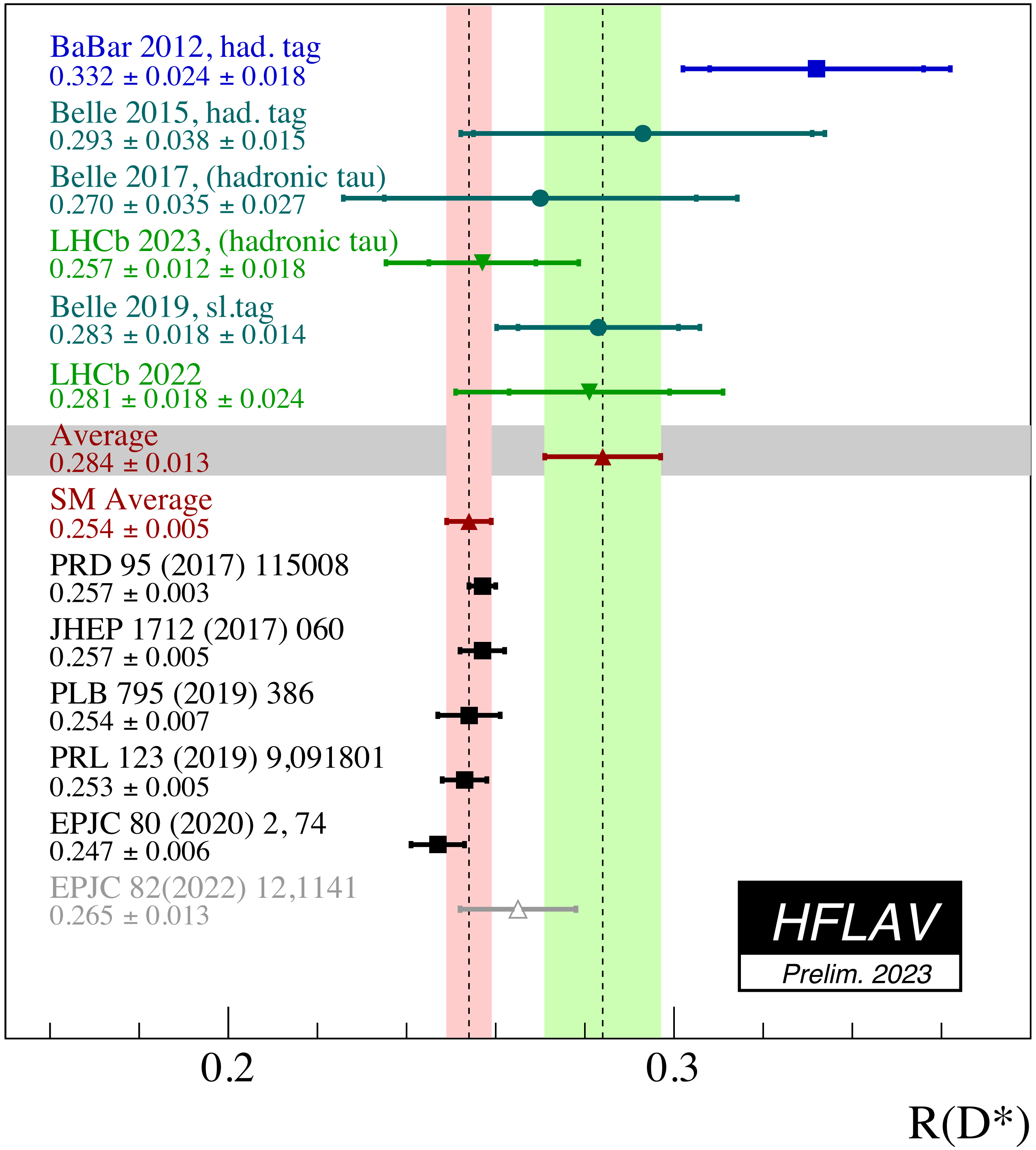
[JINST 3 S080005 (2008)]
[Int. J. Mod Phys. A30 1530022 (2015)]
[PRL 118 052002 (2017)]



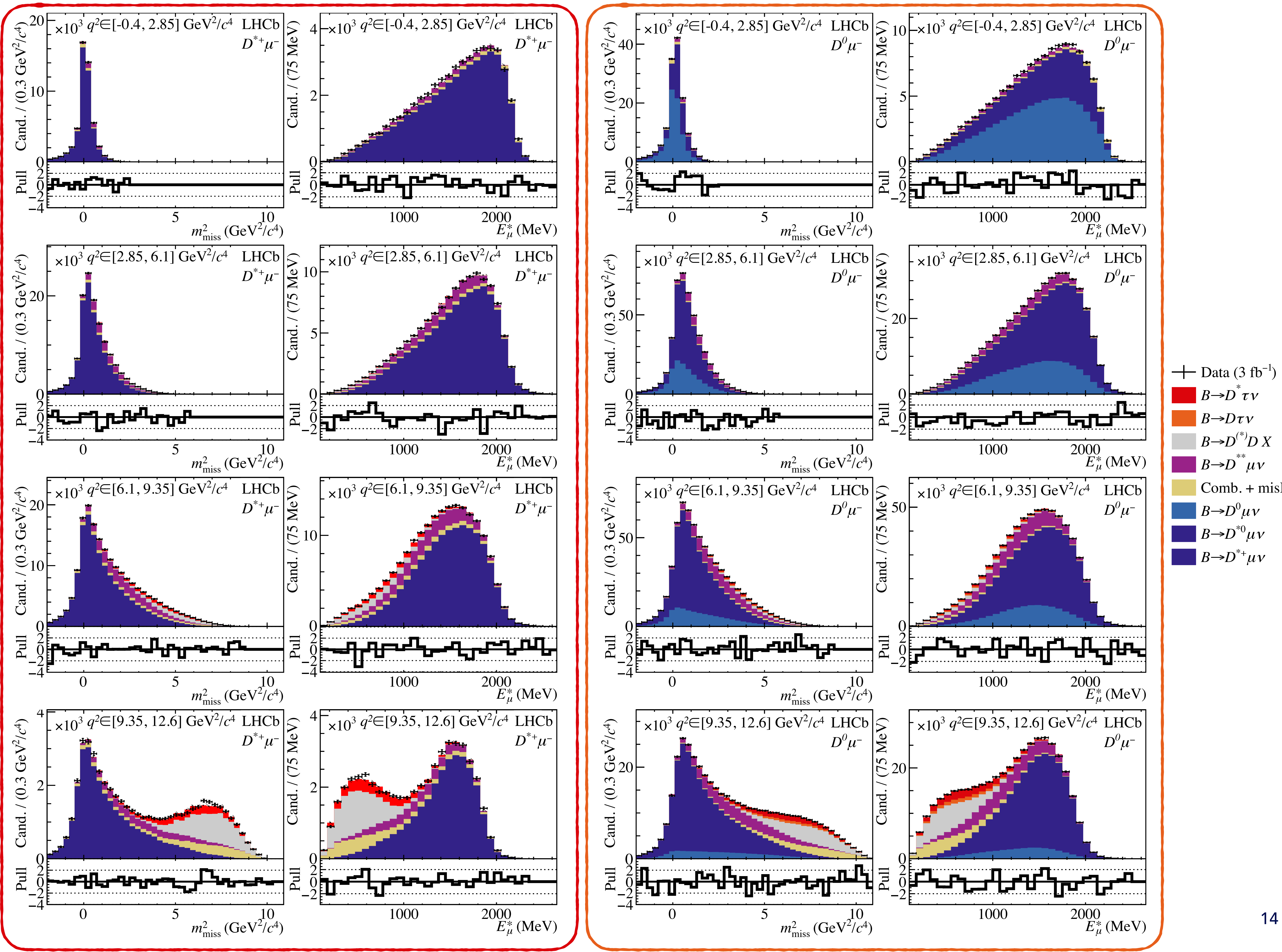
- Large amount of b and c hadrons produced, $\sigma_b = (144 \pm 1 \pm 21)\ \mu$b at $13\ $ TeV
- Forward spectrometer for $b-$ and $c-$hadron decays $(2 < \eta < 5)$
  - Good vertex and impact parameter resolution ($\sigma(\text{IP}) \sim 20\ \mu\text{m}$)
  - Excellent momentum resolution ($\delta p/p = [0.5 - 1]\,\%\ \ p < 200$ GeV)
  - Excellent charged particle identification (μ ID 97% for ($\mu \to \pi$) misID of 1-3%)
  - Capability for neutral identification

$R(D)$ and $R(D^*)$ status





$R(D) - R(D^*)$ COMBINATION WITH MUONIC τ



Data (3 fb^{-1})
$B\to D^{*}\tau\nu$
$B\to D\tau\nu$
$B\to D^{(*)}D\,X$
$B\to D^{**}\mu\nu$
Comb. + misID
$B\to D^{0}\mu\nu$
$B\to D^{*0}\mu\nu$
$B\to D^{*+}\mu\nu$
LHCb
$D^{*+}\mu^{-}$
$D^{0}\mu^{-}$
$q^2\in[-0.4, 2.85]$ GeV$^2/c^4$
$q^2\in[2.85, 6.1]$ GeV$^2/c^4$
$q^2\in[6.1, 9.35]$ GeV$^2/c^4$
$q^2\in[9.35, 12.6]$ GeV$^2/c^4$
Cand. / (0.3 GeV$^2/c^4$)
Cand. / (75 MeV)
Pull
$m^2_{\rm miss}$ (GeV$^2/c^4$)
E^*_μ (MeV)

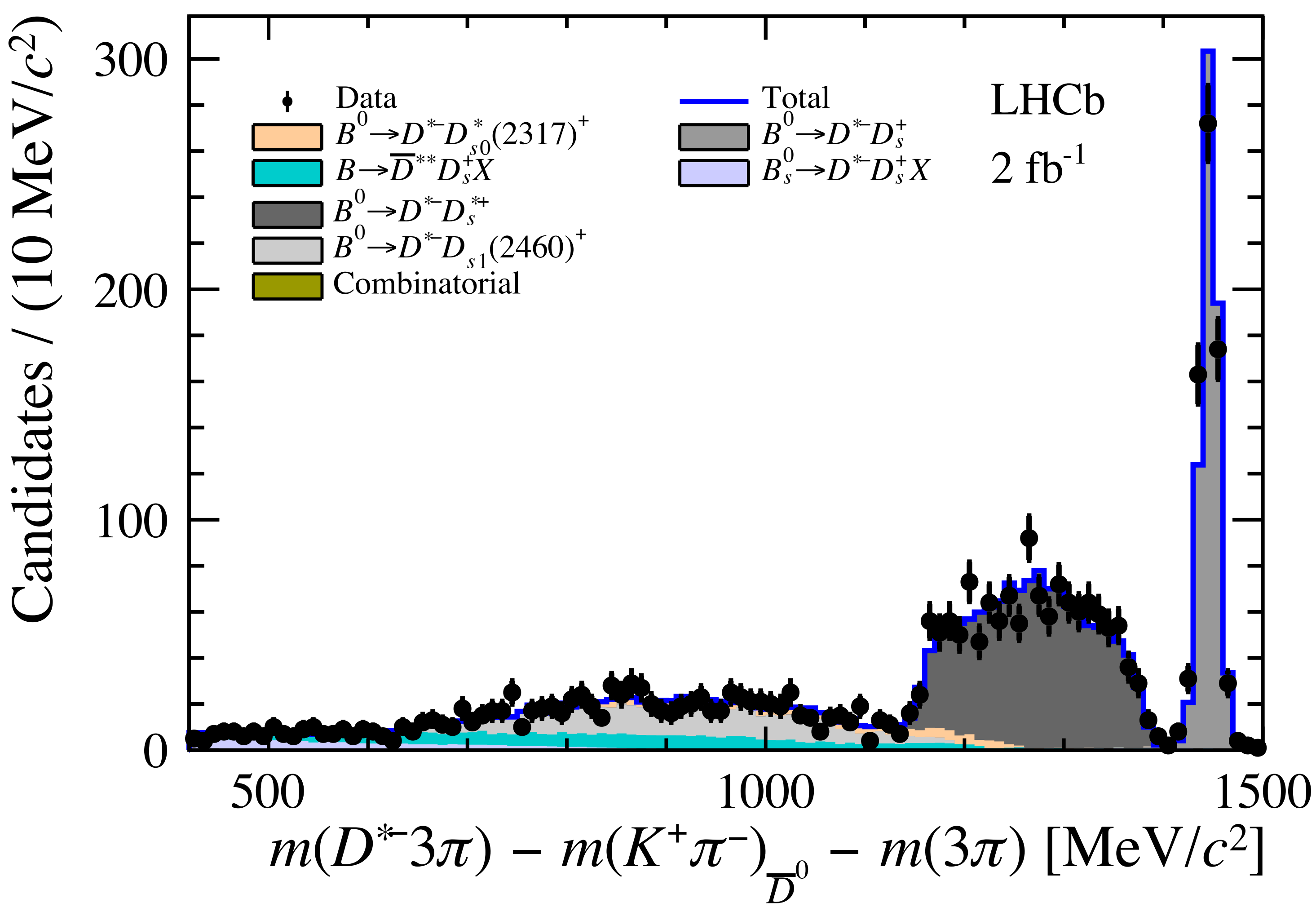
Systematic uncertainties

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	
Data/simulation corrections	0.4	0.8	
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	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
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

HADRONIC $R(D^*)$ MEASUREMENT

$R(D^{*-})_{\text{had}}$: $B \to D^* D_s X$ background

- Double charm decays are one of the most important source of background
- Select $D^{*-}D_s^+$ sample with exclusive $D_s^+ \to 3\pi$

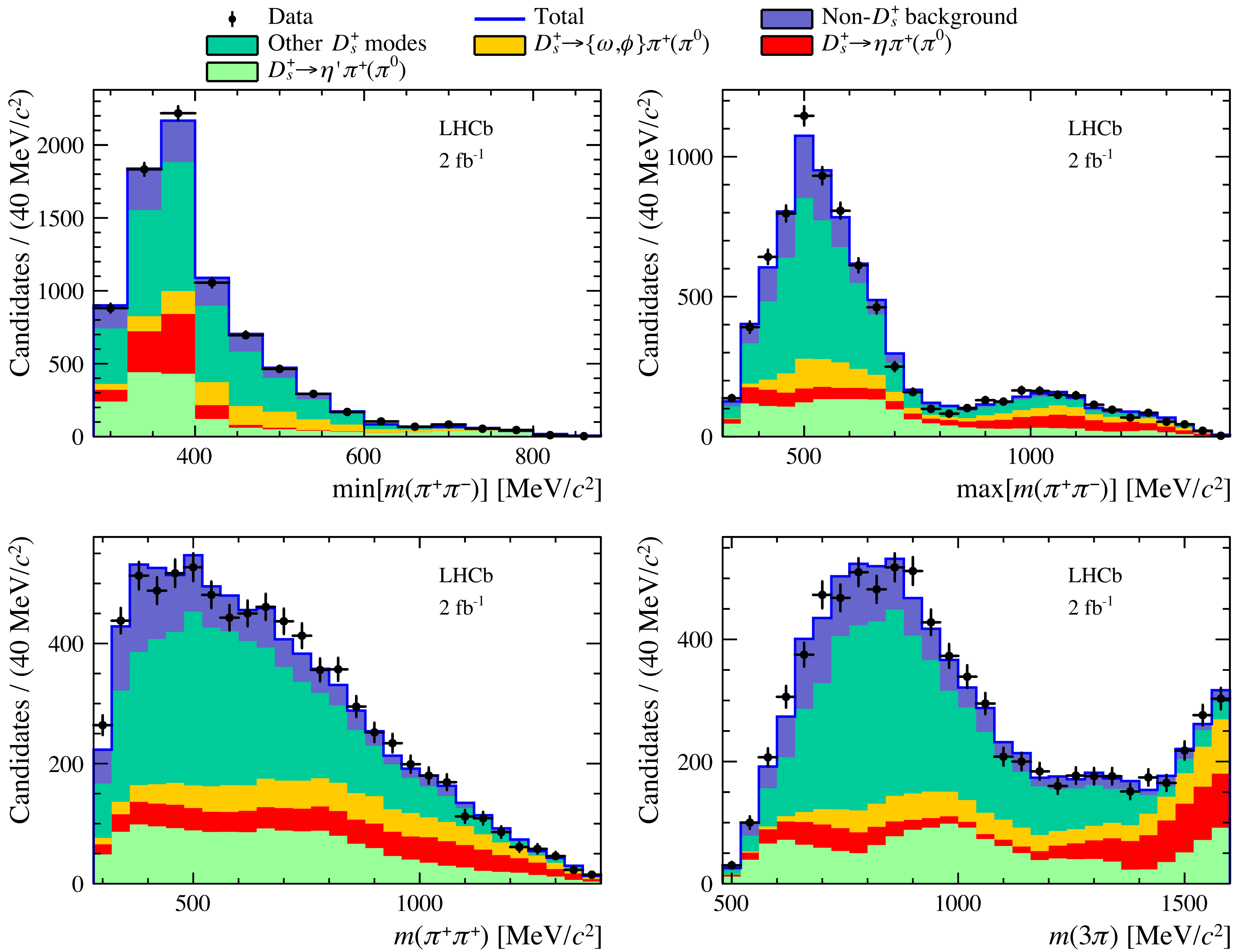


- Perform a mass fit to $D^{*-}D_s^+$ distribution
- Obtain relative yields to **correct MC** and **constrain** the respective parameters in the signal fit

Parameter	Fit result	$\left(\frac{\epsilon_{\text{sig}}}{\epsilon_{\text{control}}}\right)$	Corrected fraction
$f_{D_s^+}$	0.55 ± 0.03	0.992	0.55 ± 0.03
$f_{D_{s0}^{*+}}$	0.10 ± 0.04	1.077	0.11 ± 0.04
$f_{D_{s1}^+}$	0.37 ± 0.07	1.051	0.39 ± 0.07
$f_{\overline{D}^{**}D_s^+(X)}$	0.28 ± 0.10	1.208	0.34 ± 0.12
$f_{B_s^0 \to D^{*-}D_s^+(X)}$	0.12 ± 0.04	0.904	0.11 ± 0.04

$R(D^{*-})_{\text{had}}$: Inclusive $D_s^+ \to 3\pi(X)$ decays

- Strategy similar to Run 1 analysis → systematic $\sigma_{D_s^+} \sim 0.4\,\%$
- Data sample enriched in D_s^+ by requiring BDT below a threshold
- Simultaneous fit to data $\min(m(\pi^+\pi^-))$, $\max(m(\pi^+\pi^-))$, $m(\pi^+\pi^+)$ and $m(3\pi)$
- $D_s^+ \to 3\pi(X)$ mode fractions as fit parameters
- Contribution to systematics of $1.0\,\%$



$R(D^{*-})_{\mathrm{had}}$: fit results

Parameter	Fit result	Constraint
Free		
N_{sig}	2469 ± 154	
$N_{D_s^+}$	20446 ± 509	
f_{D^+}	0.08 ± 0.01	
$f_{D^0}^{v_1 v_2}$	2.10 ± 0.30	
Constrained		
$N_{B \to D^{*-} 3\pi X}$	2279 ± 177	2051 ± 200
$f_{B_s^0 \to D^{*-} D_s^+ (X)}$	0.13 ± 0.03	0.11 ± 0.04
$f_{D_{s1}^+}$	0.36 ± 0.03	0.40 ± 0.07
$f_{D_s^+}$	0.60 ± 0.02	0.55 ± 0.03
$f_{D_{s0}^{*+}}$	0.06 ± 0.03	0.11 ± 0.04
$f_{\overline{D}^{**} D_s^+ (X)}$	0.61 ± 0.06	0.34 ± 0.12
Fixed		
$N_{B_1 B_2}$	46	
$N_{D^0}^{\mathrm{same}}$	1051	
$N_{\mathrm{fake}\ \overline{D}^0}$	468	
$N_{\mathrm{fake}\ D^{*-}}$	714	
$f_{\overline{D}^{**} \tau^+ \nu}$	0.035	
$f_{\tau^+ \to 3\pi \overline{\nu}_\tau}$	0.780	