FPCP 2024

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LFU tests in semileptonic $b \to c$ decays at LHCb

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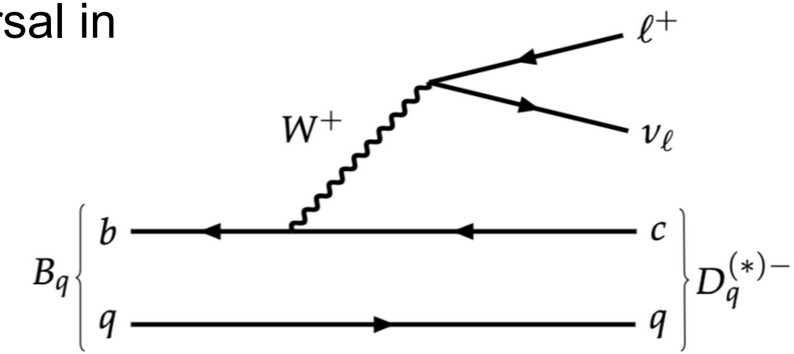
On behalf of LHCb Collaboration

INFN LNF Istituto Nazionale di Fisica Nucleare

LFU with b → c l ν

- Electroweak couplings to all charged leptons are universal in the SM
  - Differences only driven by lepton masses
- Any deviations from LFU is a key signature of physics beyond SM



$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau \nu_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu \nu_\mu)}$$

$$\mathcal{H}_b = B^0, B^+_{(c)}, \Lambda^0_b, B^0_s \ldots$$

$$\mathcal{H}_c = D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi \ldots$$

Powerful test of LFU from ratios of BF to different leptons
- Hadronic uncertainties mostly cancel in the ratio
- Reduced experimental systematic uncertainties

- Most precise measurements done with B → Dτν and B → D*τν
- Deviations from SM in R(D)-R(D*) seen in various measurements, and the World Average is in tension with the SM at ~3σ

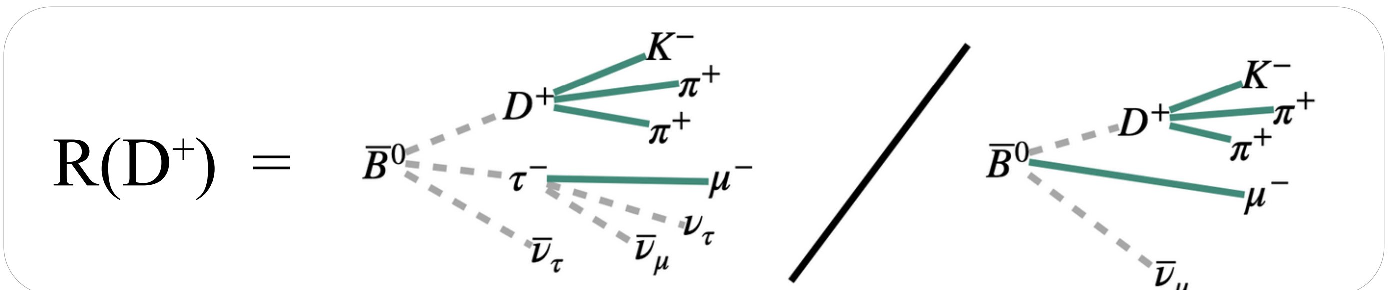
  – R(D)-R(D*) with muonic tau ($\tau \to \mu \nu \bar{\nu}$) PRL131,111802
  – R(D*) with hadronic tau ($\tau \to 3\pi(\pi^0)\nu$) PRD108, 012018

LHCb

Measurement of $R(D^+)$ and $R(D^{*+})$

$$R\left(D^{(*)+}\right) = \frac{\mathcal{B}(\bar{B}^0 \to D^{(*)+}\tau^-\nu_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)+}\mu^-\nu_\mu)}$$

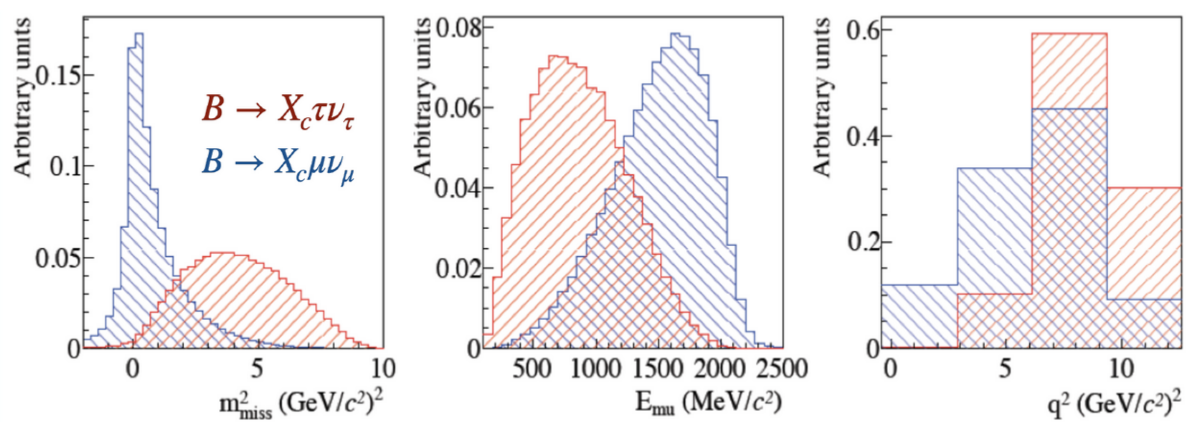
- First LHCb measurement using the D^+ ground state
  - Tau muonic decay mode $\tau \to \mu \nu \bar{\nu}$
  - $D^+ \to K^- \pi^+ \pi^+$
- Feed-down from from $D^{*+} \to D^+ \pi^0, D^+\gamma$ gives access to $R(D^{*-})$ with the same final state



- B momentum at LHC: exploit B flight direction and boost approximation

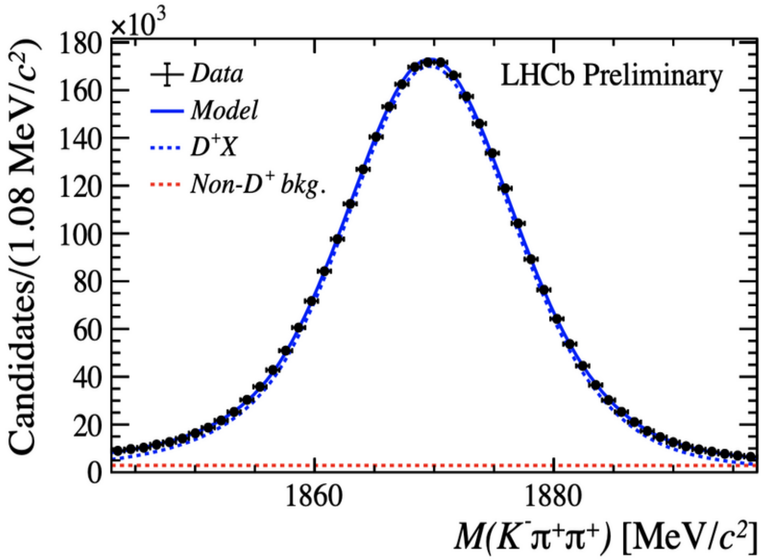
$$\gamma\beta_{z,total} = \gamma\beta_{z,visible}$$

m^2_{miss} $=(p_B - p_D - p_\mu)^2$
E_μ muon energy in B rest frame
q^2 $= (p_B - p_D)^2$



Data sample selection

- 2 fb^{-1} collected in 2015 and 2016
- **Candidate selection:**
  - Basic requirements on $(K^- \pi^+ \pi^+) \mu^-$ candidates: kinematic, particle-ID, topologic
  - Fake D^+ statistically subtracted by fitting $M(K^- \pi^+ \pi^+)$
  - Isolation against additional charged and neutral particles from the rest of the event



Sample composition

Signal

$B^0 \to D^+ \tau [\to \mu \nu \nu] \nu$
$B^0 \to D^{*+} \tau [\to \mu \nu \nu] \nu$

Normalization

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

Feed-down from 1P D states**

$B^0 \to D^{**} [D^+X] \mu \nu$
$B^0 \to D^{**} [D^+X] \tau \nu$

Feed-down from higher mass D states**

$B^0 \to D^{**} [D^+X] \mu/\tau \nu$

Double-charm decays

$B^0 \to D^+ H_c [\to \mu X] Y$

Muon mis-ID

Combinatorial bkg.

Strategy to measure signal yields

- Signal and normalization extracted from 3D binned template fit to data
  - Variables m^2_{miss}, E_μ, q^2
  - Templates constructed from MC or data control samples
- Invert isolation requirement to select control samples with enhanced sensitivity to background contributions

Signal sample	**1π sample**	**2π sample**	**1K sample**
$D^+\mu^-$	$D^+\mu^-\pi^-$	$D^+\mu^-\pi^+\pi^-$	$D^+\mu^-K^\pm$

- Simultaneous fit to the 4 data samples, with enhanced sensitivity to specific components

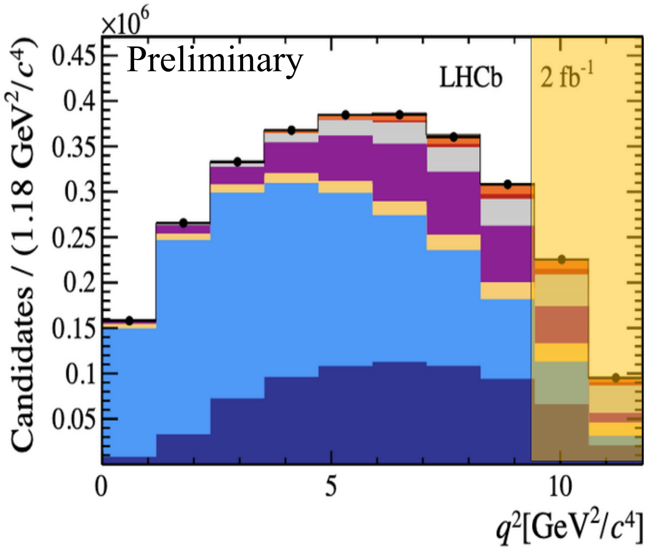
- Feed-down from B→D**μν
  - Fractions of 1P states varied in the fit
  - Higher mass states: shape also varied
- Double-charm
  - Fractions and shapes varied in the fit

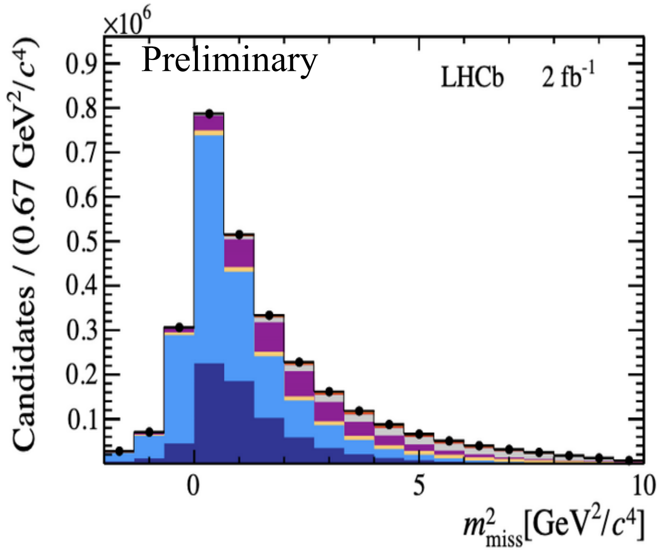
HAMMER (EPJC80(2020)883) and RooHammerModel (JINST17(2022) T04006) to vary the form factor parameters in the fit (applied as external constraint)

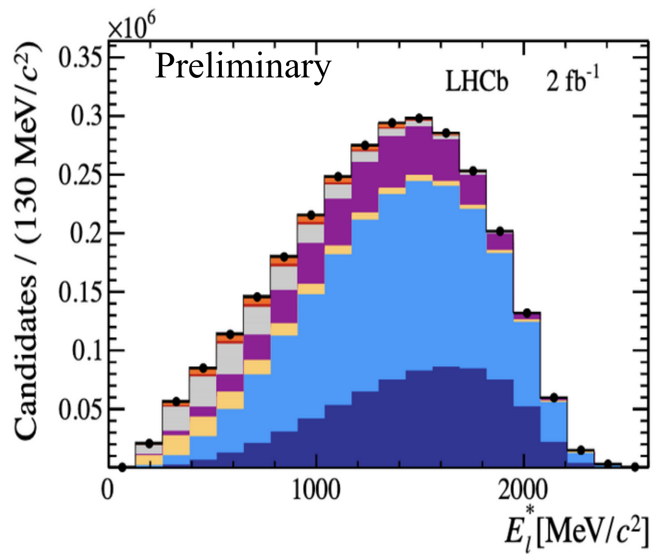
“Tracker-Only” ultra fast simulation

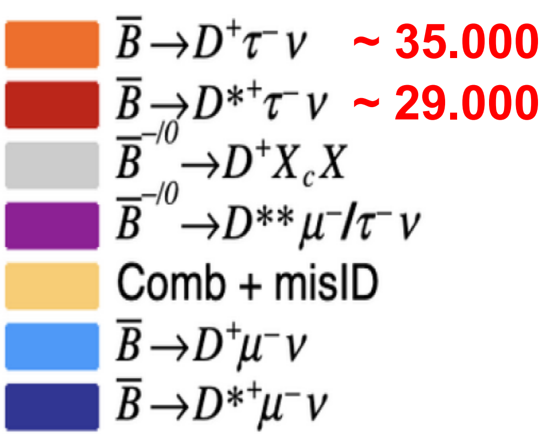
Fit results: projections

LHCb-PAPER-2024-007
In preparation

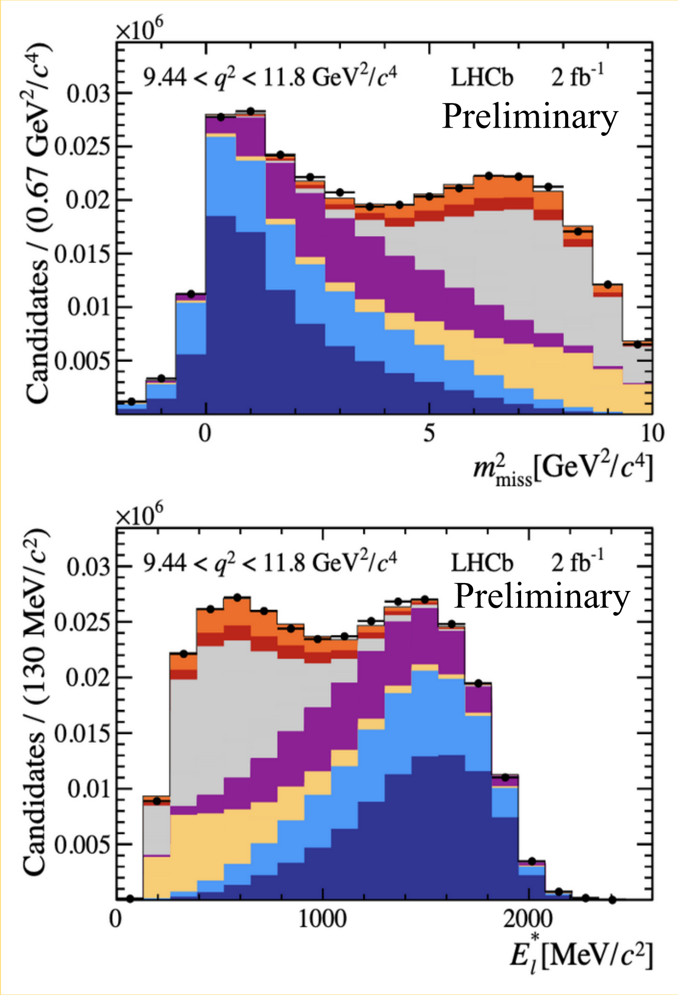






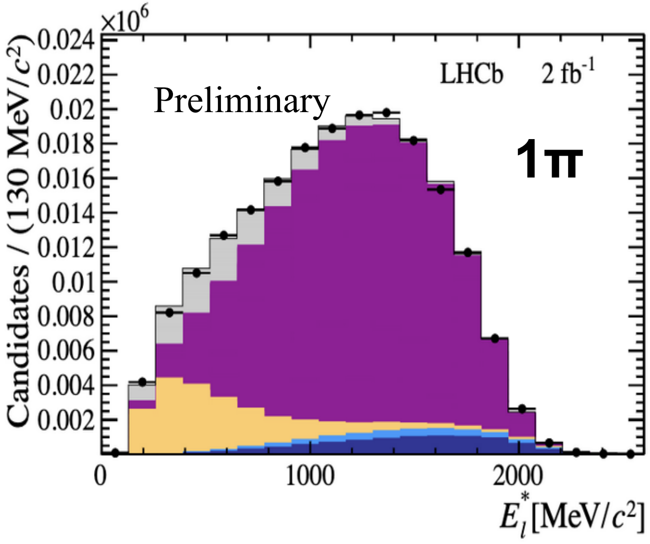


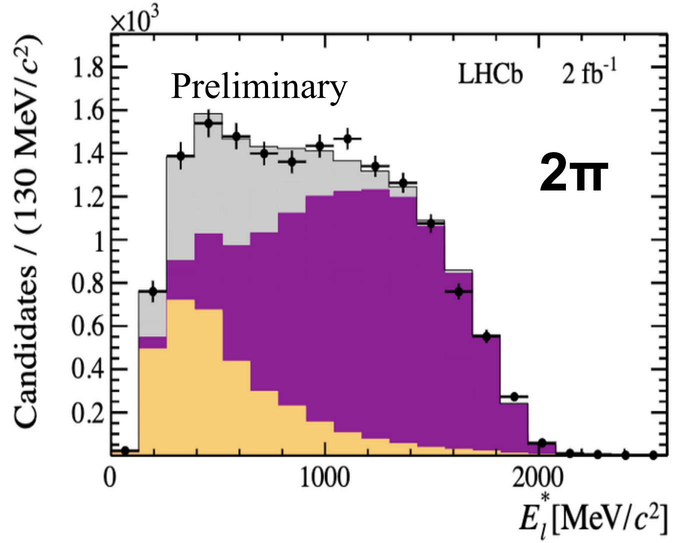
Zoom in high q^2 region



Fit results: projections on control samples

LHCb-PAPER-2024-007
In preparation





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

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

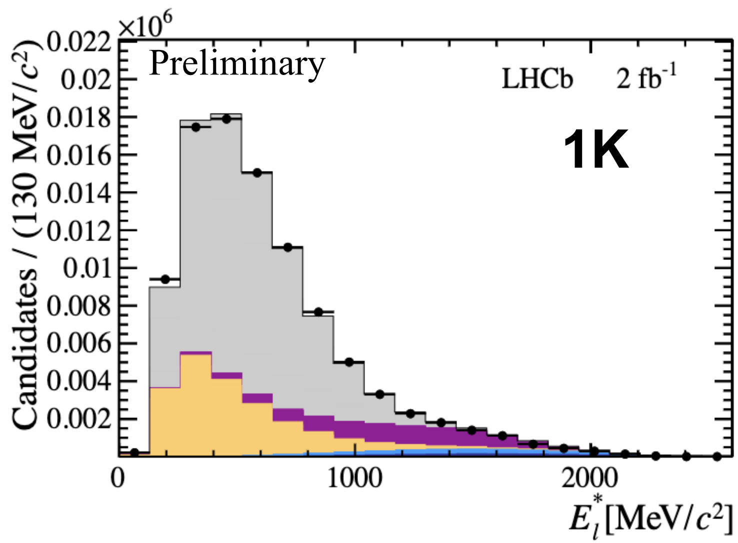
$\overline{B}^{-/0} \to D^+ X_c X$

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

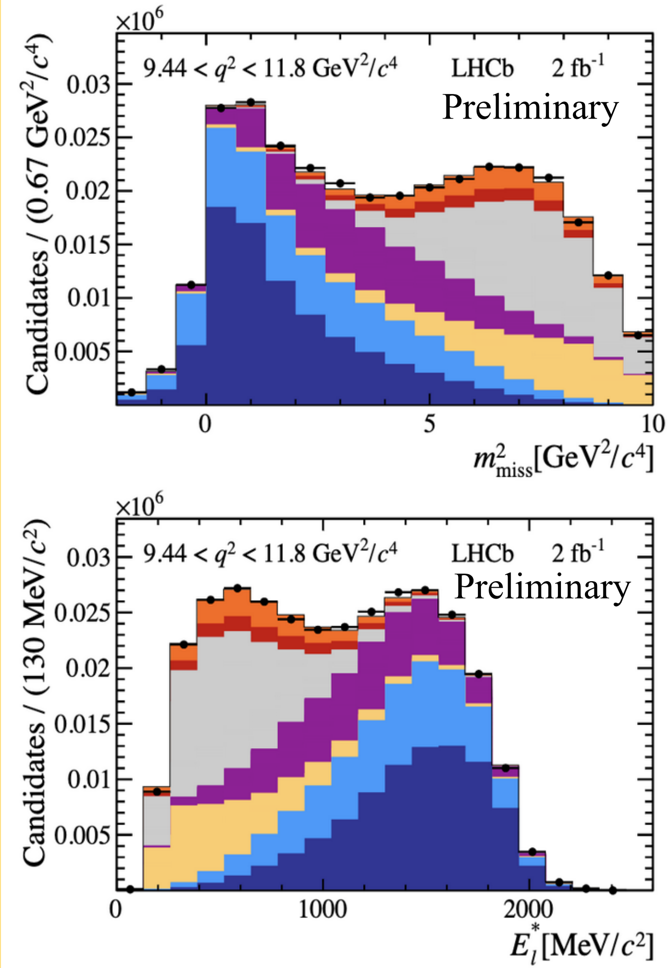
Comb + misID

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

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



Zoom in high q^2 region



Results

$$R(D^{+(*)}) = \frac{\mathcal{B}(\bar{B}^0 \to D^{+(*)}\tau^-\nu_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{+(*)}\mu^-\nu_\mu)} = \frac{\epsilon_\mu^{D^{+(*)}}}{\epsilon_\tau^{D^{+(*)}}} \frac{N_\tau^{D^{+(*)}}}{N_\mu^{D^{+(*)}}} \frac{1}{\mathcal{B}(\tau^- \to \mu^-\nu_\tau\nu_\mu)}$$

$$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$
$$\rho = \text{-}0.39$$

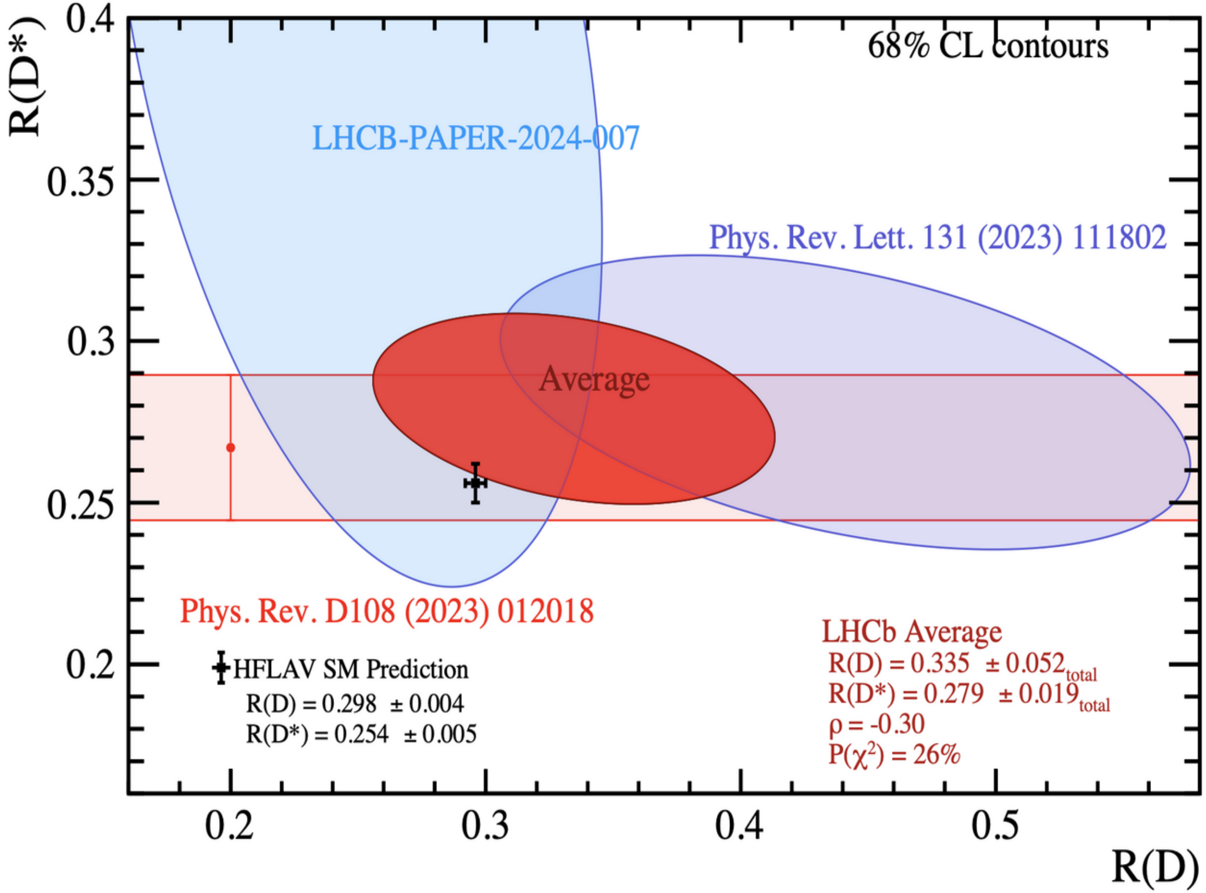
Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$
Form factors	0.023	0.035
$\bar{B} \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\bar{B}^{+/0} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.086

Compatible with SM at 0.8σ
and with World Average at ~1σ

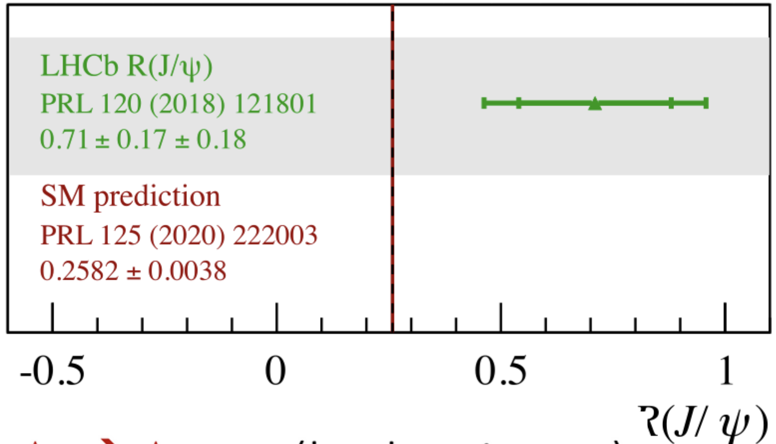
Main systematic uncertainties from form factor parameters and background modeling

Uncertainty on ratio of efficiencies are sub-dominant

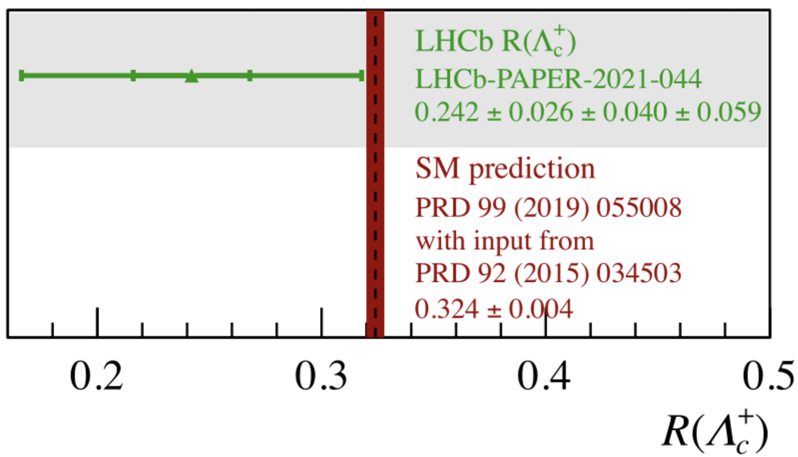
LHCb measurements



$B_c \to J/\psi\, \tau\nu$ (muonic tau)

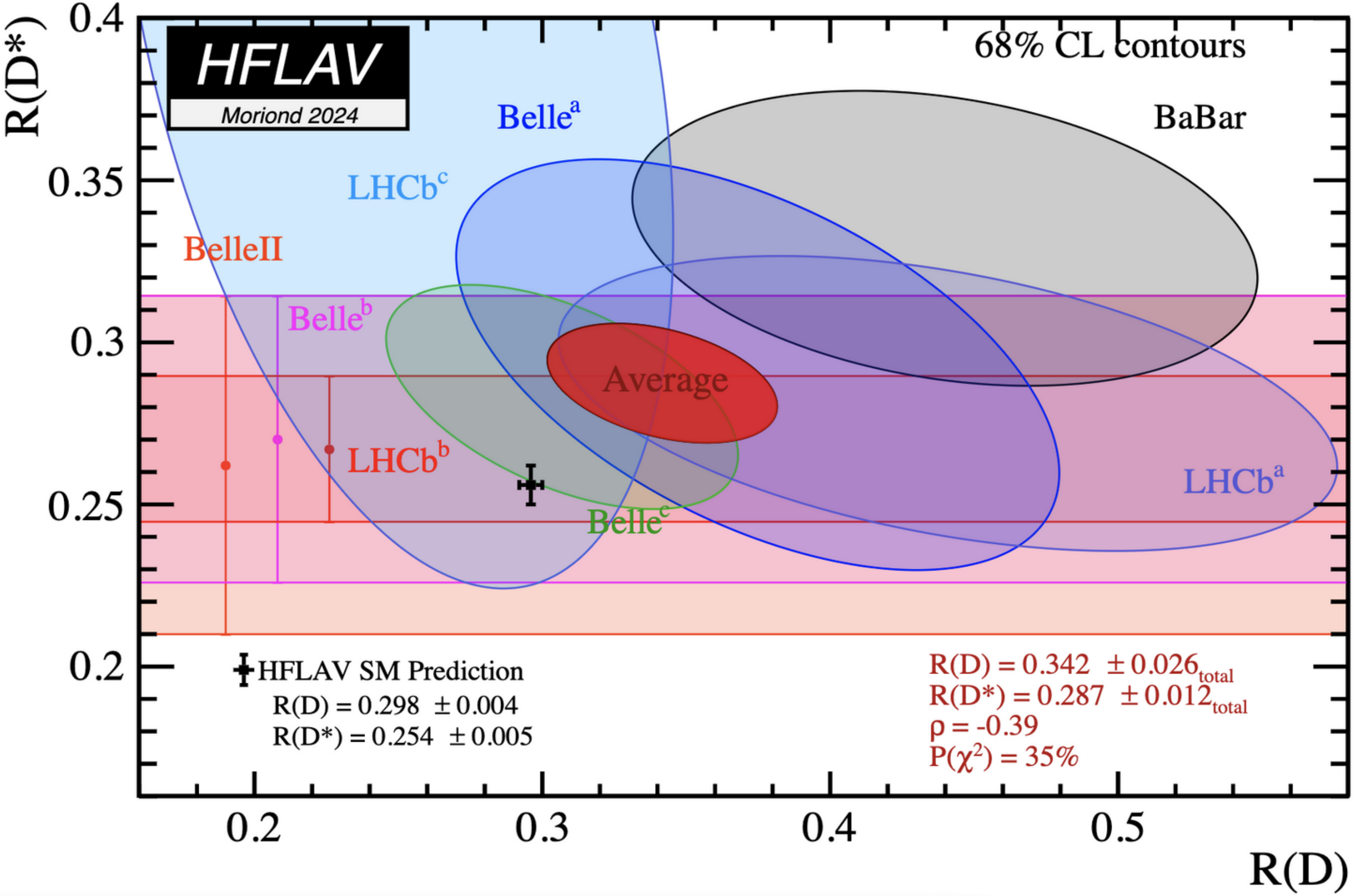


$\Lambda_b \to \Lambda_c\, \tau\nu$ (hadronic tau)



R(D)-R(D*) world average

HFLAV



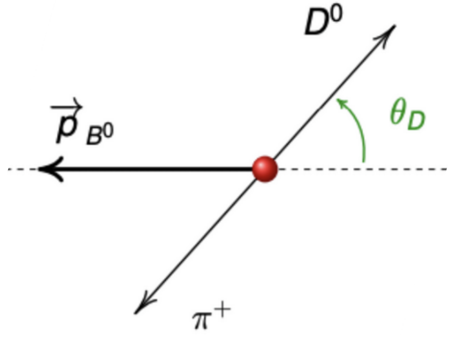
- R(D) and R(D*) combined average in 3.3σ tension with the SM prediction

- What is the SM prediction ?
- R(D): predictions consistent
- R(D*): tensions between some of the predictions

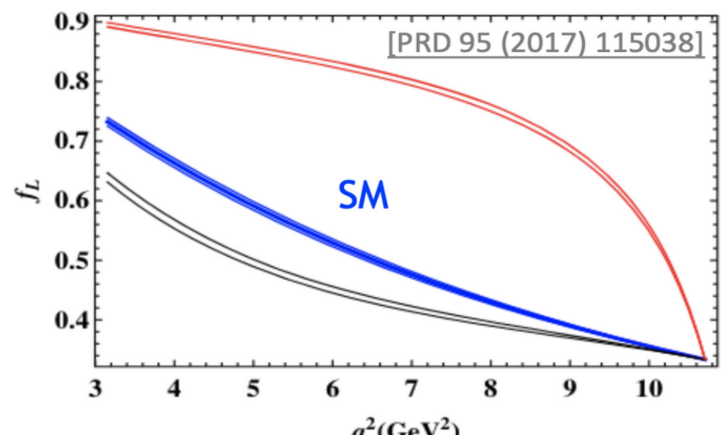
Beyond ratios R(H$_c$): angular analyses

- Angular analyses provide sensitivity to NP: can test presence of new mediators and different spin structures
- D* polarization fraction in $B^0 \to D^{*-}\tau\nu$

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$



Example assuming contribution from scalar New Physics



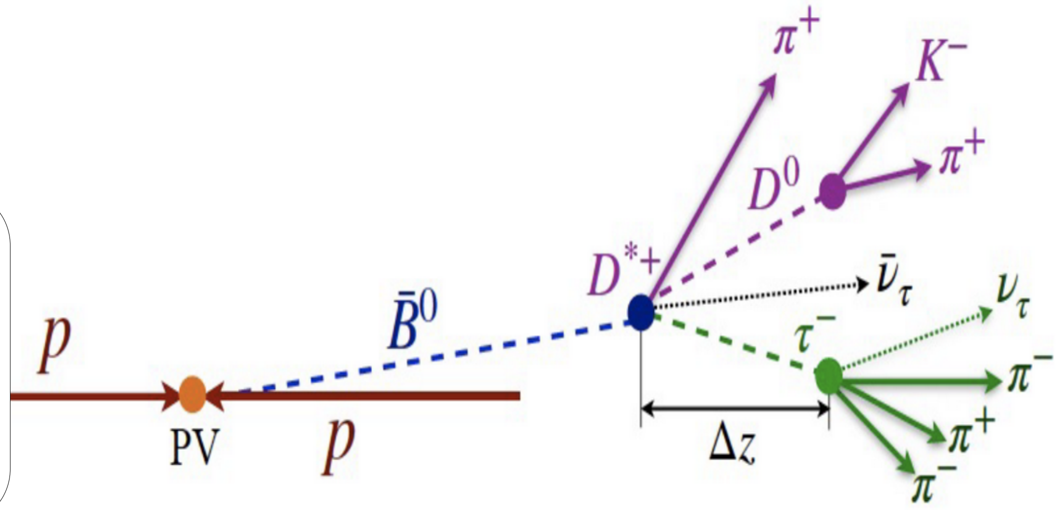
Longitudinal D* polarization fraction

$$F_L^{D^*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$

D* longitudinal polarization fraction in $B^0 \to D^{*-} \tau \nu$

- Same sample and analysis technique used for R(D*) with hadronic tau
  - Use $\tau \to 3\pi(\pi^0)\nu$
  - Run1 (3 fb-1) and part of Run2 (2fb-1)

- The 3π vertex provides the tau decay position: suppress dominant background from $B \to D^{*-} 3\pi$
- The B vertex and the secondary D and τ vertices, allow a good estimation of the B momentum



- Additional background suppression from secondary $D_s \to 3\pi X$ exploiting specific dynamics of $\tau \to 3\pi(\pi^0)\nu$ in a BDT

- Signal yields extacted from a binned template fit in q^2, τ decay time, anti-D_s BDT output, $\cos\theta_D$
  - Simultaneous in two q^2 bins: $q^2 < 7$ GeV^2 and $q^2 > 7$ GeV^2
  - Background shapes adjusted with control samples

[arXiv:2311.05224]

Fit results [arXiv:2311.05224]

- $F_L^{D^*}$ determined from the observed signal and unpolarized yields

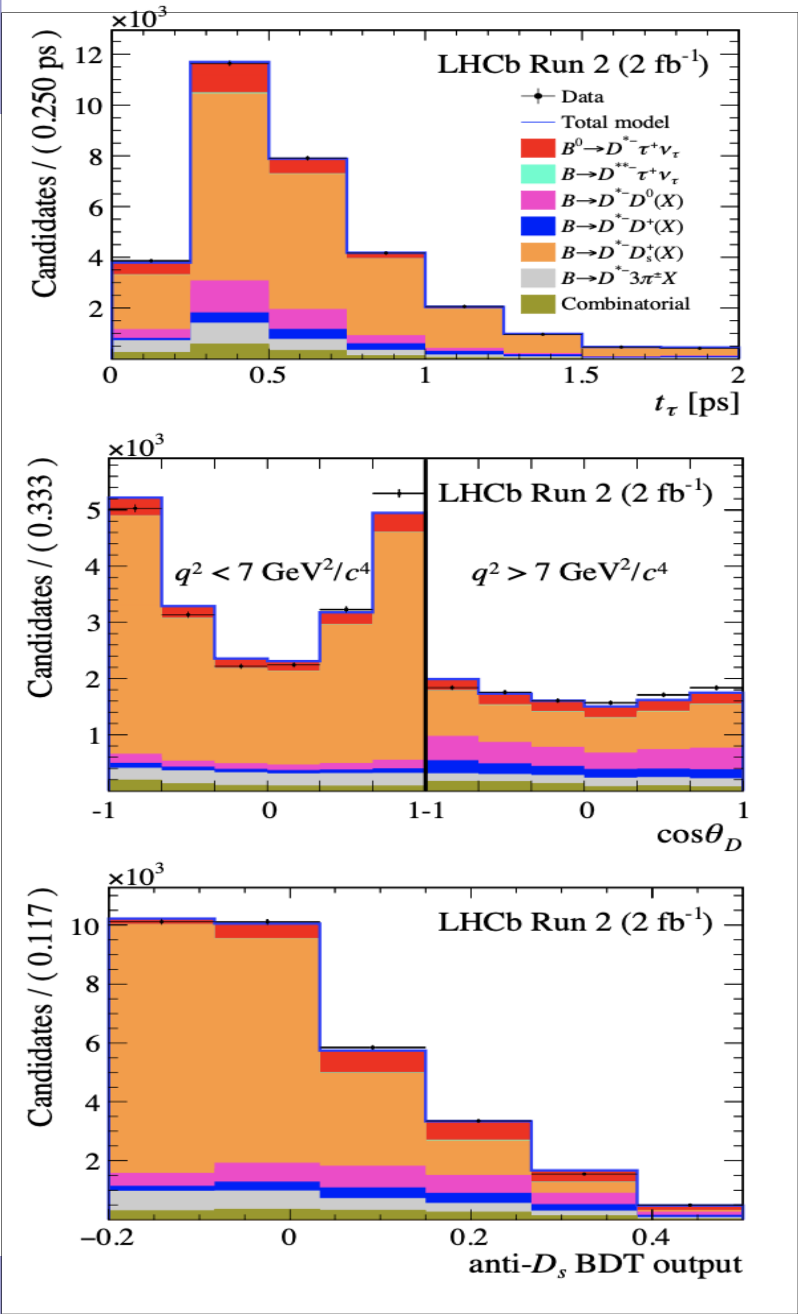
$$q^2 < 7\,\text{GeV}^2/c^4 : \quad 0.51 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst})$$
$$q^2 > 7\,\text{GeV}^2/c^4 : \quad 0.35 \pm 0.08\,(\text{stat}) \pm 0.02\,(\text{syst})$$
$$q^2 \text{ whole range} : \quad 0.43 \pm 0.06\,(\text{stat}) \pm 0.03\,(\text{syst}).$$

Compatible with previous Belle measurement:

$F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$ [arXiv:1903.03102]

Compatible with SM:

$F_L^{D^*} = 0.441 \pm 0.006$ [PRD 98 (2018) 095018]
$F_L^{D^*} = 0.457 \pm 0.010$ [Eur. Phys. J. C 79, 268 (2019)]
$F_L^{D^*} = 0.467 \pm 0.009$ [Eur. Phys. J. C 80, 347 (2020)]
$F_L^{D^*} = 0.422 \pm 0.010$ [arXiv:2310.03680]
$F_L^{D^*}[q^2 < 7GeV^2/c^4] = 0.495 \pm 0.017$ [arXiv:2310.03680]
$F_L^{D^*}[q^2 > 7GeV^2/c^4] = 0.383 \pm 0.006$ [arXiv:2310.03680]



Summary and prospects

- First LHCb measurement of $R(D^+)$ and $R(D^{*+})$ with muonic tau lepton
  - Compatible with the World Average and with the SM predictions
- First LHCb angular analysis of charged-current semitauonic decays
  - D^* polarization fraction in $B^0 \to D^{*-}\tau\nu$
  - Compatible with Belle and with SM predictions

- Outlook
  - Update measurements with full Run2
  - Add other $R(H_c)$: $B_c \to J/\psi\ \tau\nu$ and $\Lambda_b \to \Lambda_c\ \tau\nu$ already pioneered by LHCb
    - Update to Run2 ongoing
  - Full angular analysis of $B \to D^{*-}\mu\nu$ and $B^0 \to D^{*-}\tau\nu$ will provide tests and constraints to physics beyond SM
  - Run3 data taking at 5x instantaneous luminosity is underway

Backup

- $R(D^{*+})$ Run1 (2015)
  - [PRL 115, 111803]
- $R(D^0)\&R(D^*)$ Run1 (2023)
  - [PRL 131, 111802]
- $\boldsymbol{R(D^+)}$ **&** $\boldsymbol{R(D^{*+})}$ **part. Run2 (2024)**
  - [LHCb-PAPER-2024-007, in preparation]

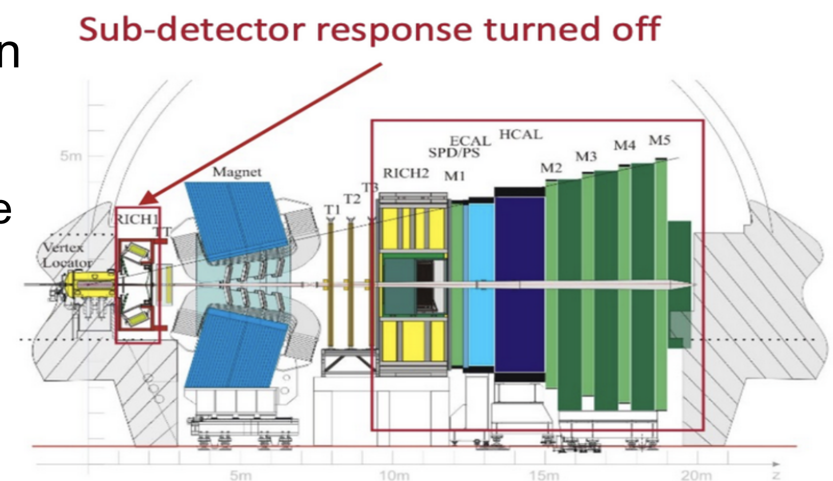
New!

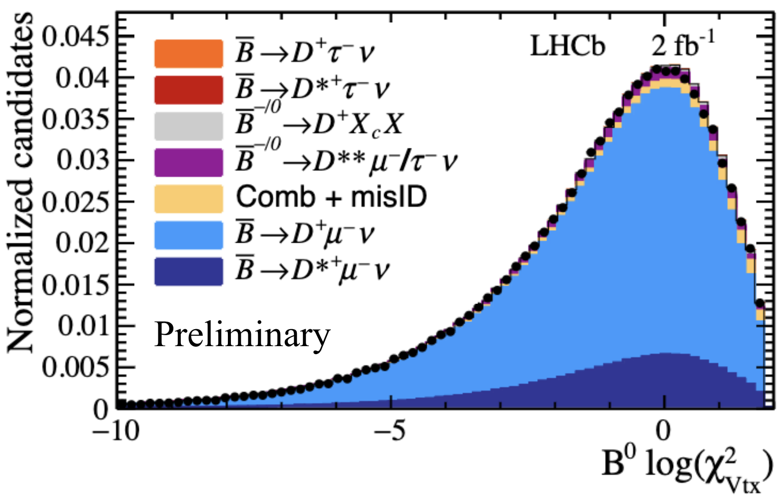
- $R(J/\psi)$ Run1 (2018)
  - [PRL 120, 121801]

- $R(D^{*+})$ Run1 (2018)
  - [PRL 120, 171802]
- $R(D^{*+})$ part. Run2 (2023)
  - [PRD 108, 012018]
- $R(\Lambda_c^+)$ Run1 (2022)
  - [PRL 128, 191803]
- $\boldsymbol{D^{*+}\ F_L}$ **Run1 & part. Run2 (2023)**
  - [arXiv:2311.05224]

Fit components from Simulation and Data

- This analysis uses a "Tracker-Only" ultra fast simulation
  - Require emulation of some detector response
  - PID efficiencies determined from data calibration sample
  - ➔ Enable producing large amount of simulation samples





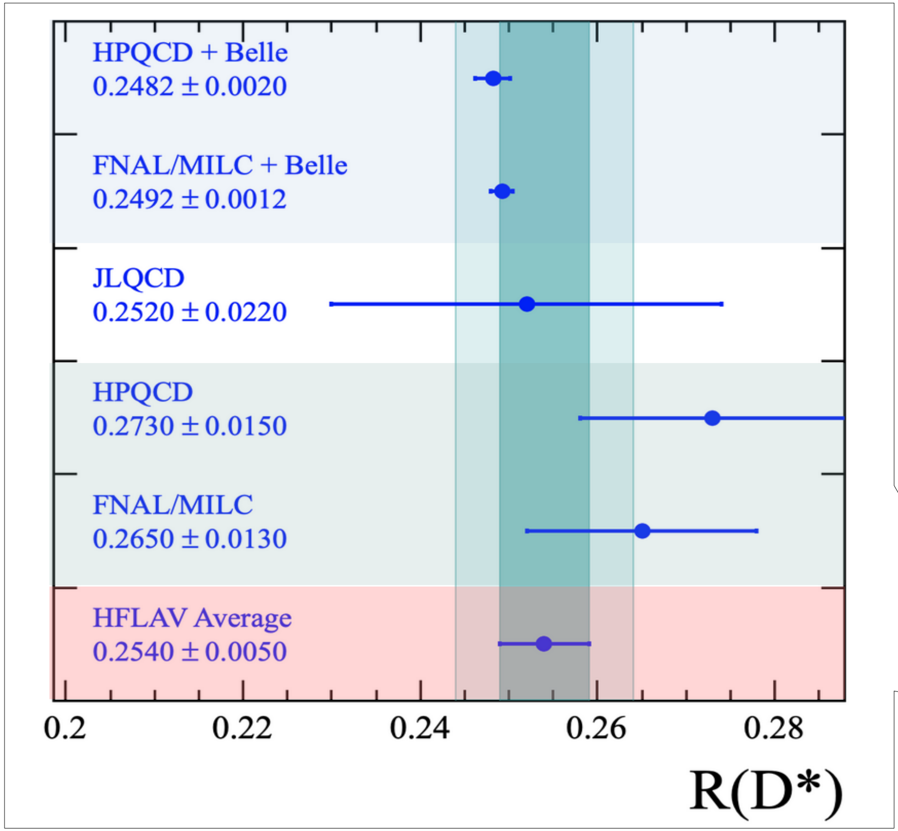
Tuning of templates from MC with Data/Simulation corrections

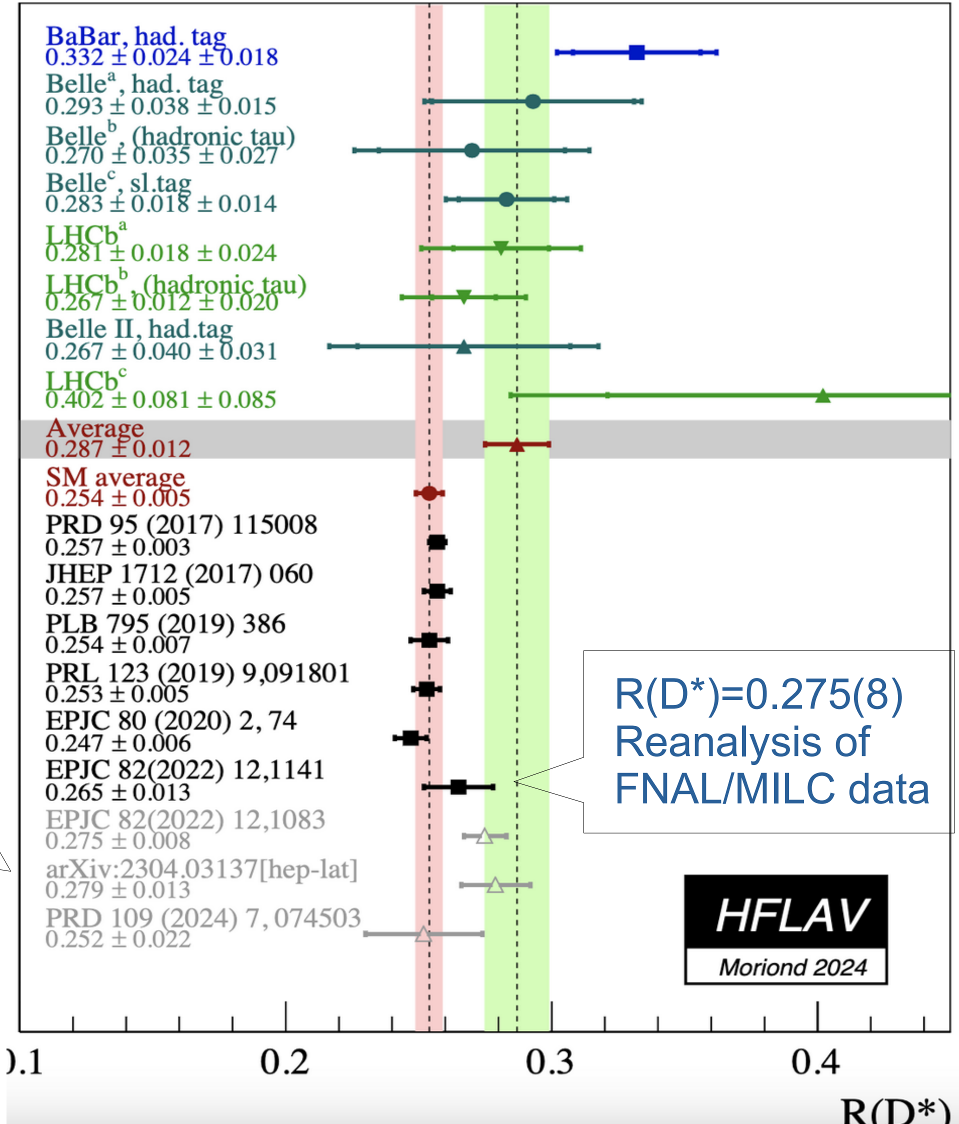
- B kinematic, multiplicity, …
- QED effects PRL120,261804(2018)

- Templates from data control sample:
  - Muons from mis-identified pions, extracted from non-muon control sample
  - Combinatorial background from Same-Charge D^{+}-muon data sample

Status of R(D*) predictions

Most of the SM predictions use fit of theory inputs (mostly LQCD) and experimental data of $B \to D/D^* \ell \nu$ with light leptons

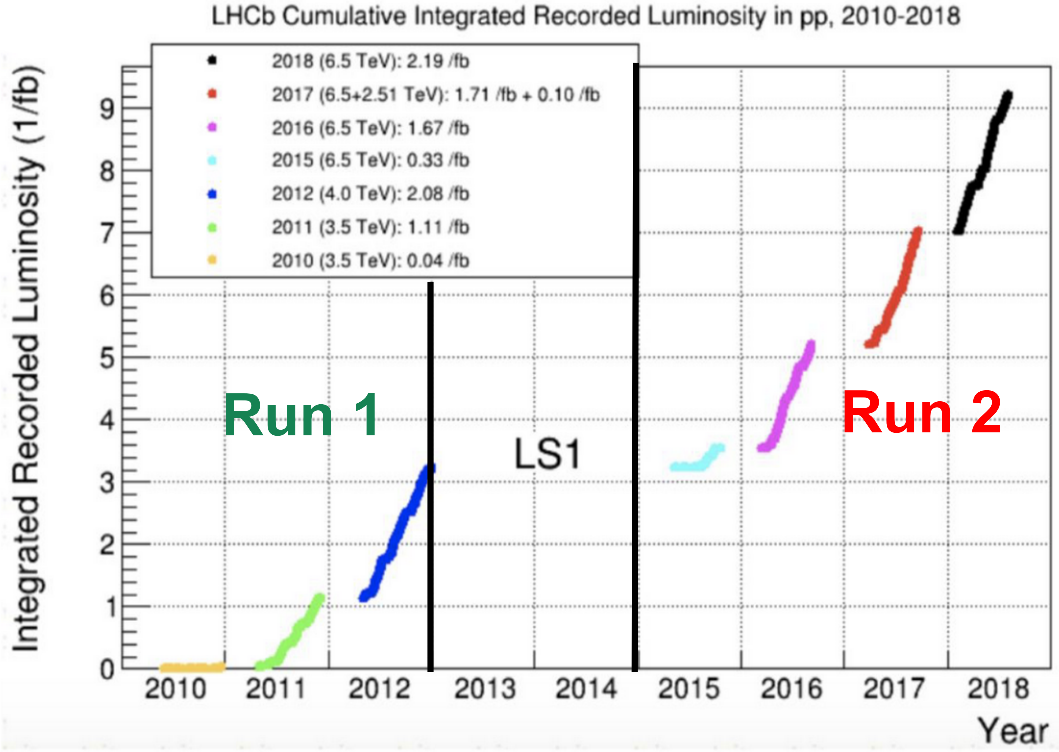




Impact of including $B \to D^* \ell \nu$ data from Belle
[PRD 100, 052007 (2019)]

LHCb SL measurements

- LFU test
  - R(D)-R(D*), R(J/ψ), R(Λ_c), **Run1**
  - R(D*), **Run1** + **Run2**(2015-16)
  - D* F_L, **Run1** + **Run2**(2015-16)
- CKM
  - $|V_{ub}/V_{cb}|$, $\Lambda_b \to p$, $B_b \to K$, **Run1**(2012)
  - $|V_{cb}|$, $B_s \to D_s/D_s^*$, **Run1**
- Exclusive $b \to c$
  - $\Lambda_b \to \Lambda_c \mu\nu$ differential rate, **Run1**
  - $B_s \to D_s^* \mu\nu$ differential rate, **Run2**(2016)
  - $D/D^*/D^{**}\mu\nu$ production rate, **Run1**
- Exclusive $b \to u$
  - $B \to p\bar{p}\mu\nu$, search for $B \to 3\mu\nu$, **Run1**
- H_b production: B_s, Λ_c, B_c at 7 and 13 TeV

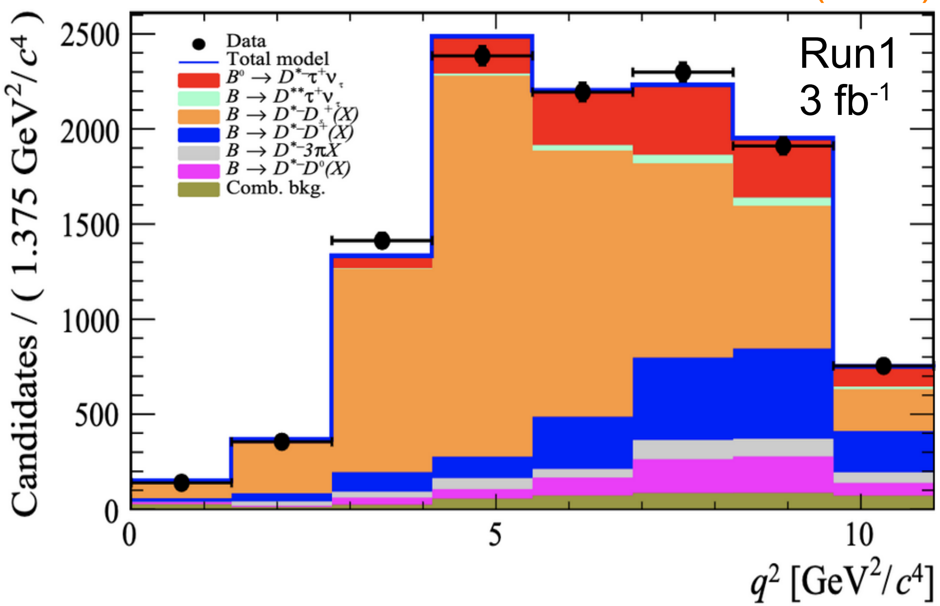


- Run2: larger dataset
  - 1.9 x Luminosity, 1.8 x σ(bb)
- Systematics usually non-negligible
- More data requires larger data controls samples (scale with L) and larger MC
  - <u>Fast MC crucial to exploit the data</u>

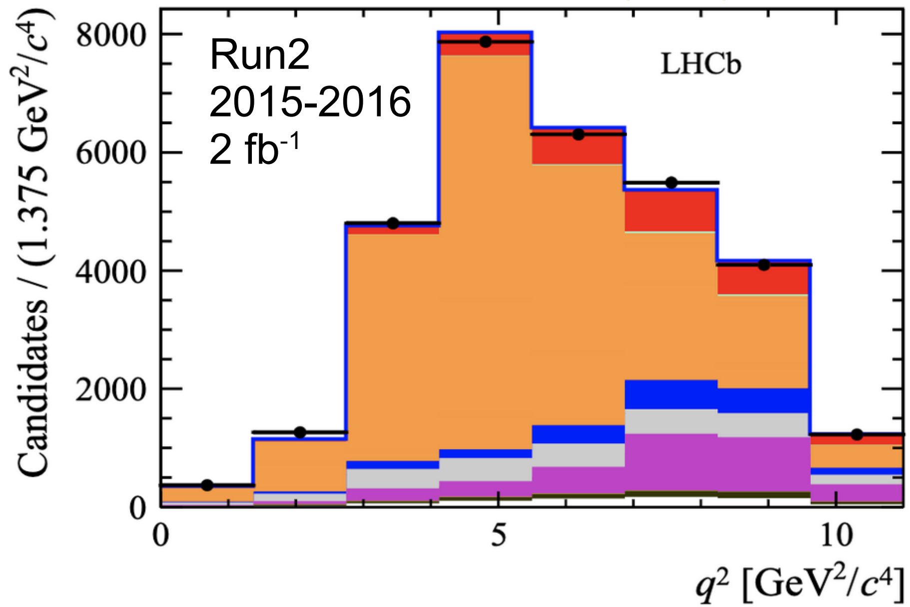
R(D*) with $\tau \rightarrow 3\pi(\pi^0)\nu$

$$\mathcal{K}(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}$$

PRL 120, 171802 (2018)



PRD 108(2023)1,012018



N_{sig}=1296 ± 86

N_{sig}=2469 ± 154

$$\mathcal{K}(D^{*-}) = 1.97 \pm 0.13\,(\text{stat}) \pm 0.18\,(\text{syst})$$

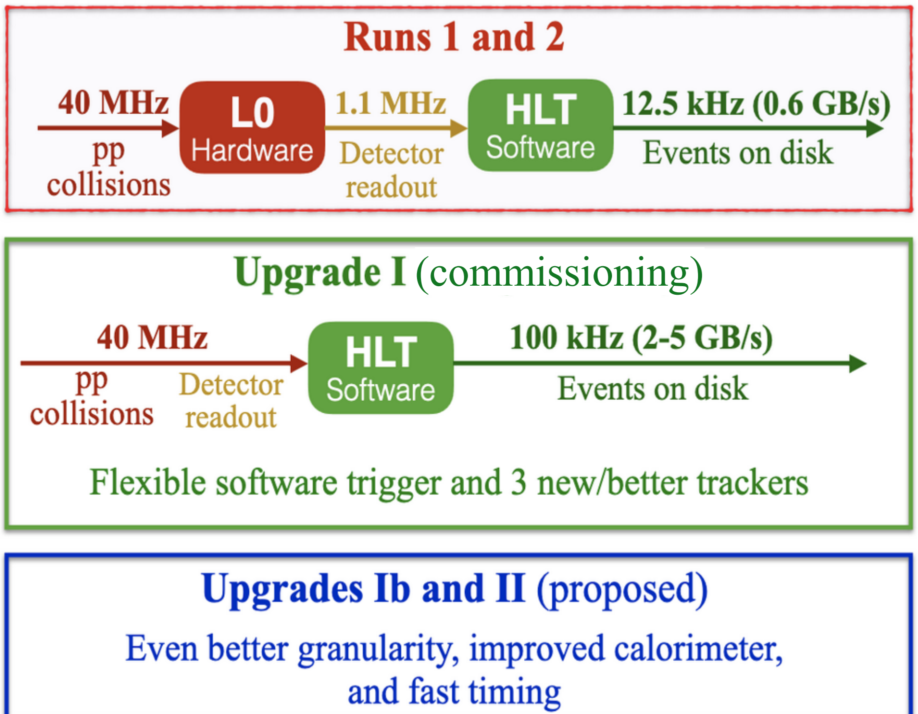
10%

$$\mathcal{K}(D^{*-}) = 1.70 \pm 0.10(\text{stat})^{+0.11}_{-0.10}(\text{syst})$$

6%

MC size is the single dominant systematic (4.1%) → Reduced to 2% using fast MC ReDecay, EPJC 78, 1009 (2018)

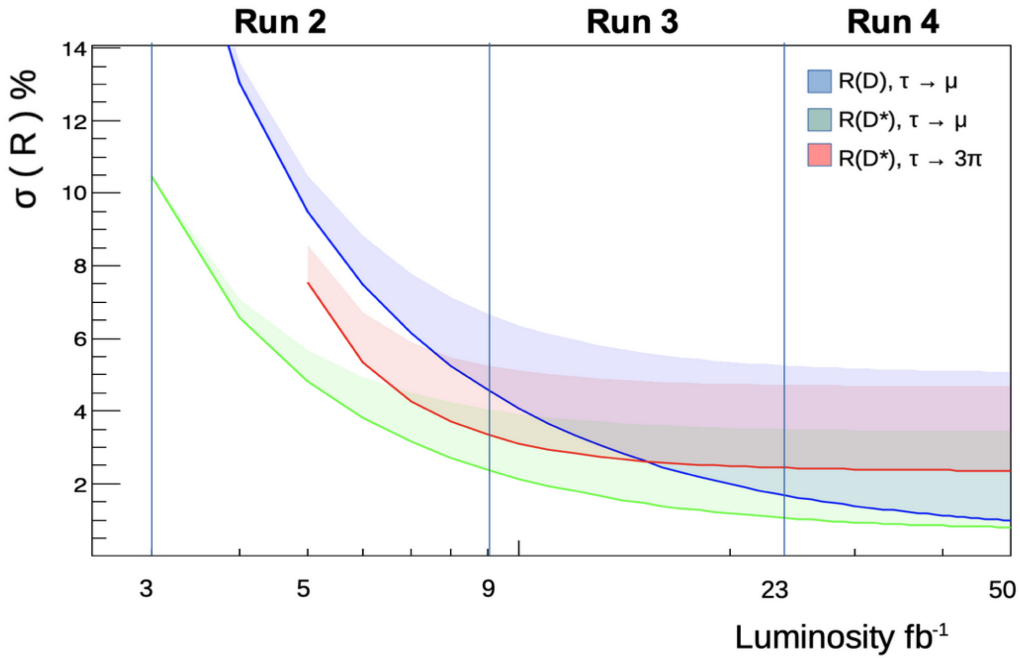
Run3 and beyond



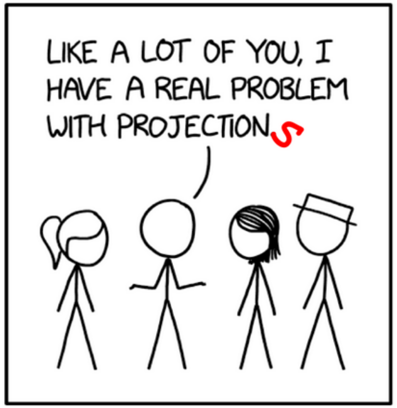
LHCb Physics with Upgrade II
arXiv:1808.08865

- Run3: currently taking data with Upgrade I detector
  - Completely new software-only trigger
  - No more required pT cut on the muon in L0
  - Exploit this to improve purity for tau decays
  - Improve analyses with electrons in final state
- Run4: maintenance and some upgrades (ECAL)
  - Steady data taking
- Run5-6: Upgrade II detector
  - Fully exploit the HL-LHC
  - Very challenging: average of ~50 PVs
  - Timing in sub-detectors is needed to fully exploit the higher luminosity

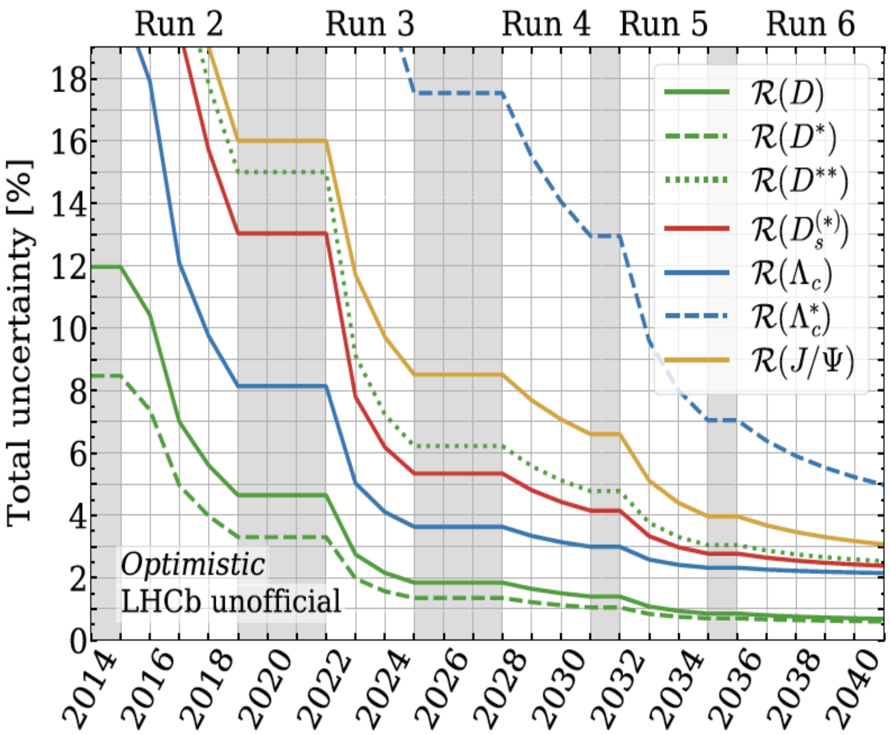
Projections on R(Hc) measurements



the bands represent the degree of optimism (pessimism) in our ability to reduce systematics



Projections on other ongoing analyses in LHCb. If the anomaly persists, it is crucial cross check with other decay modes



arXiv:2101.08326

Beyond R(H$_c$): going differential

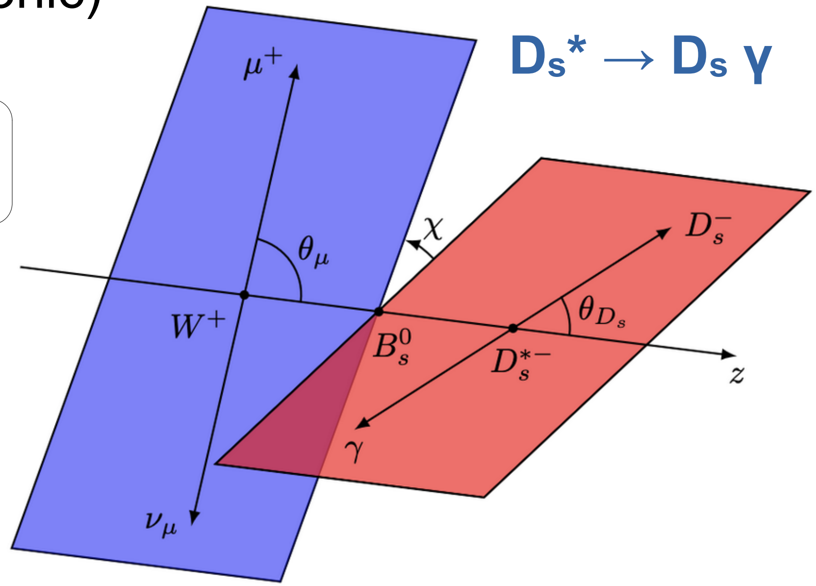
- Angular analyses with semitauonic (and semimuonic) to probe spin structure of physics beyond SM
  - Even in case R(H$_c$) is SM-like, it will put strong constraints on NP models

$$\frac{d^4(B^0 \to D^* \ell^+ \nu_\ell)}{dq^2 d\cos^2\theta_\ell d\cos\theta_{D^*} d\chi} \propto |V_{cb}|^2 \sum_i \mathcal{H}_i(q^2) f_i(\theta_\ell, \theta_{D^*}, \chi)$$

H_i sensitive to New Physic and Form Factors
Many observables can be derived by H_i

$B_s \to D_s^* \mu\nu$

$D_s^* \to D_s \gamma$



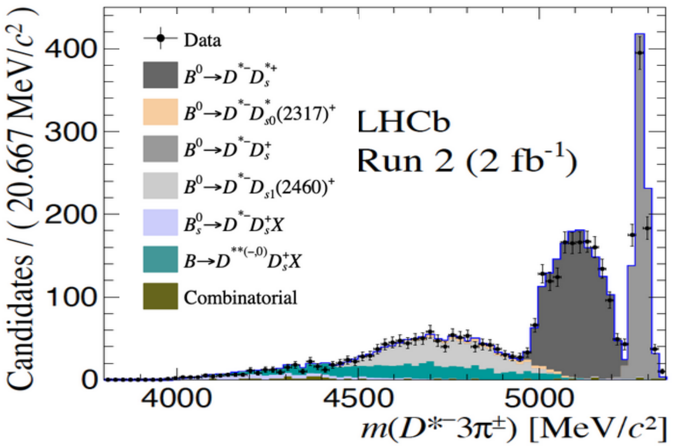
Recent literature (non-exhaustive list):

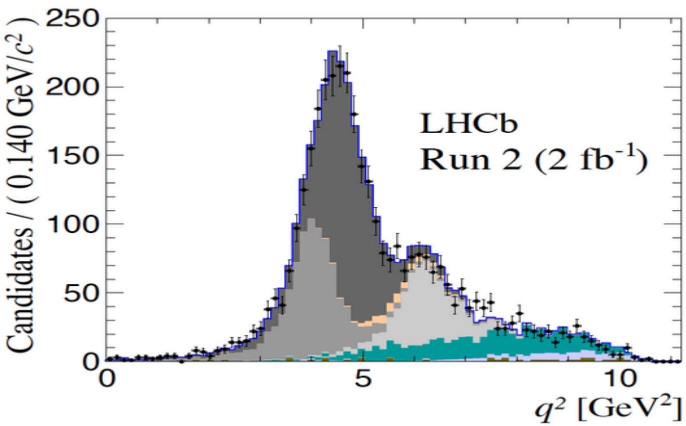
D.Hill et al. JHEP 11 (2019) 133
V. Dedu, A.Poluektov JHEP 07 (2023) 063
B. Bhattacharya et al. JHEP 05 (2019) 191
C.Bobeth et al. EPJ.C 81 (2021) 11, 984
M. Fedele et al. ArXiv;2305.15457
Z. Huang et al. PRD 105 (2022) 1, 013010
B. Bhattacharya et al. JHEP 07 (2020) 07, 194
M. Ivanov et al. PRD 95 (2017) 3, 036021
D. Becirevic et al. NPB 946 (2019) 114707
O. Colangelo, F.DeFazio, JHEP 06 (2018) 082

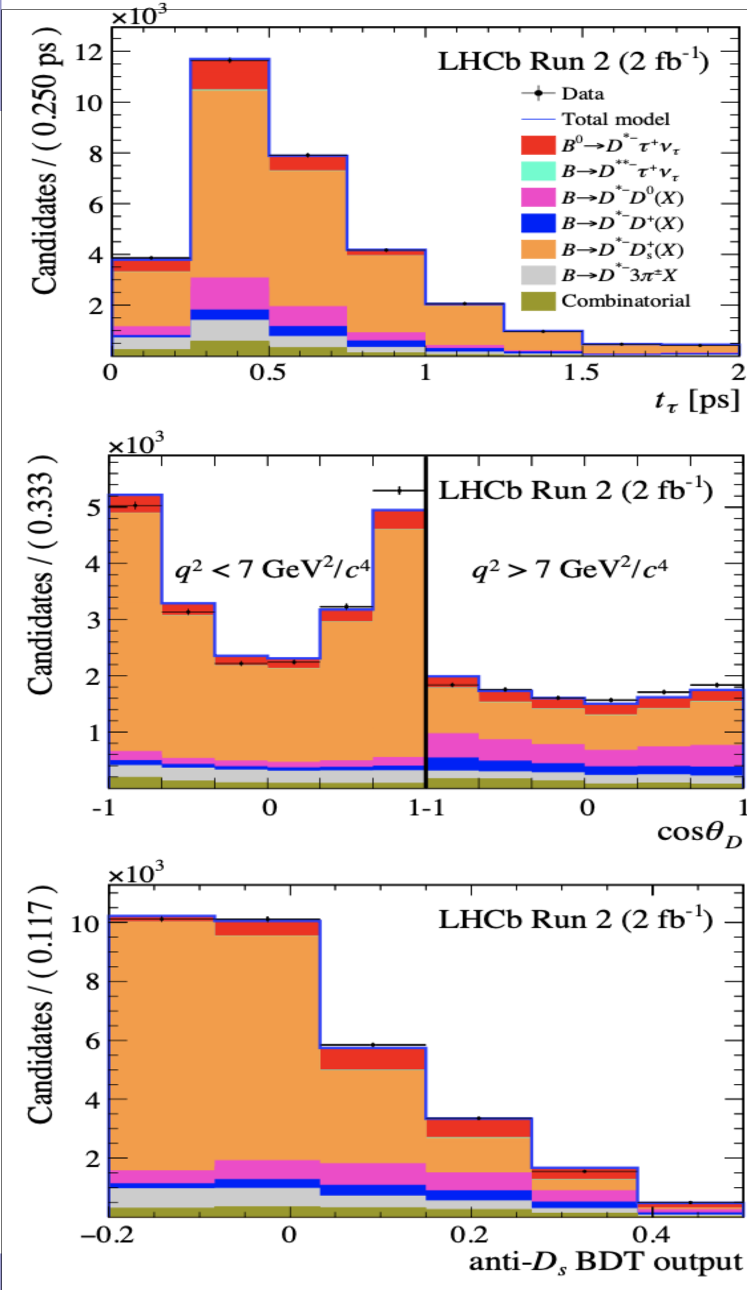
Fit results

[arXiv:2311.05224]

- Background shapes adjusted with control samples
- $B \to D^{*-} D_s (X)$ with $D_s \to 3\pi$ control sample:







Conclusions

- Many ongoing analysis on full dataset
  - Major focus: $R(H_c)$ and full angular analysis of many different channels
- Statistics and detector performances foreseen in Run3-Run4 with Upgrade I is very promising
  - huge statistics, higher signal efficiency, interesting opportunities with electrons
  - Often systematics are limited by external inputs
    - Crucial inputs from other experiments (BES III, Belle, Belle II)
    - Crucial a close collaboration with theorists (both Continuum and Lattice)
- The motivation for a Upgrade II for SL decays is strong
  - Very high precision on measurement of differential shapes for many b-hadrons
  - Significant contribution to ultimate precision on $|V_{ub}|$, $|V_{cb}|$
  - Unique program to study semitauonic decays