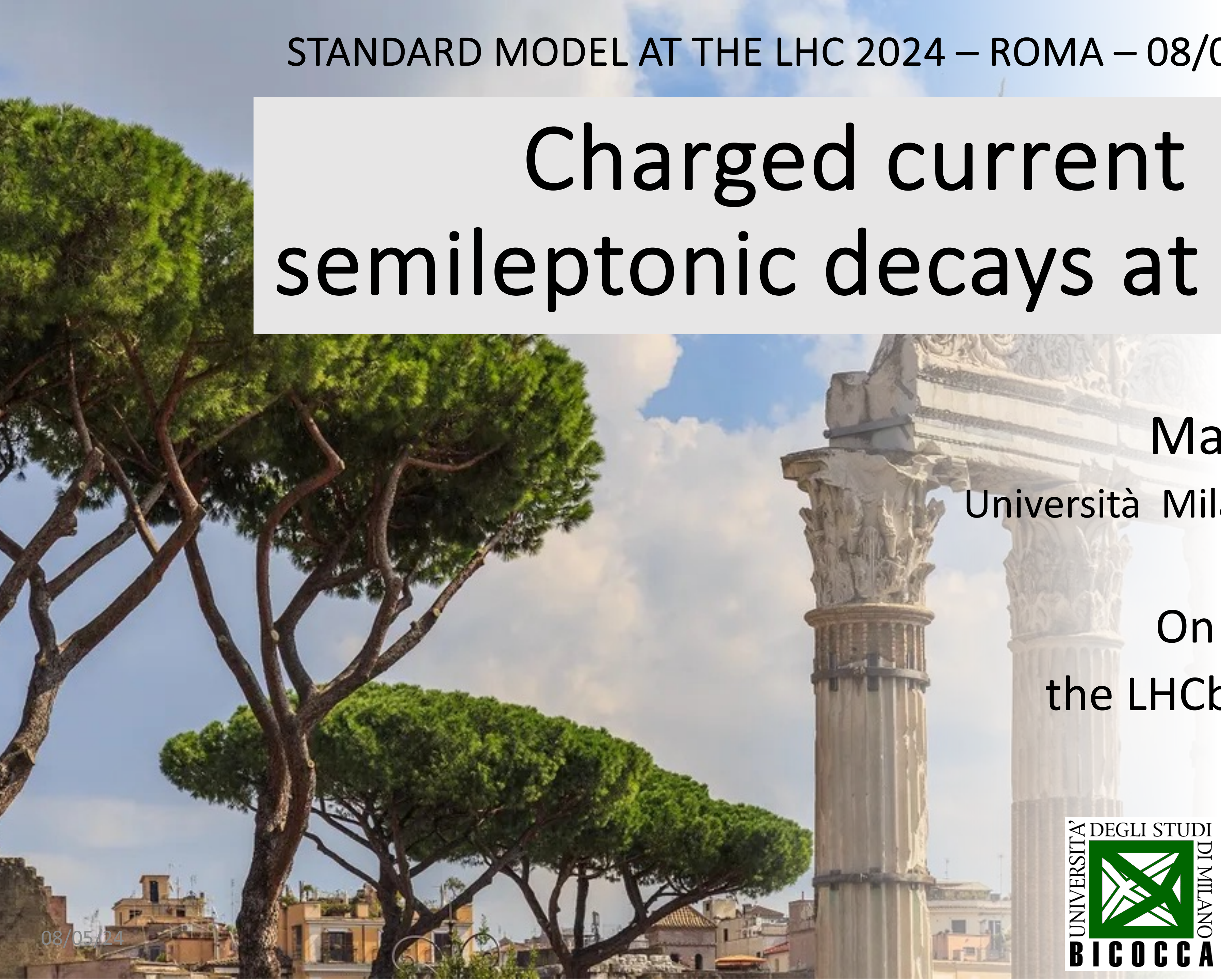
STANDARD MODEL AT THE LHC 2024 – ROMA – 08/05/2024

Charged current semileptonic decays at LHCb



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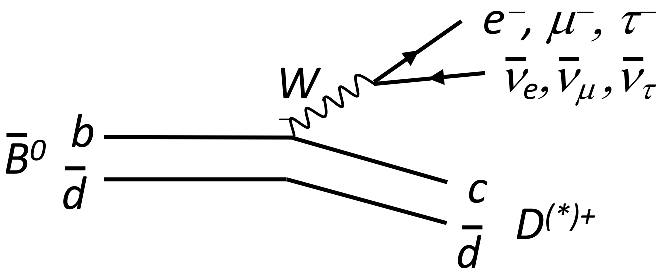
On behalf of
the LHCb Collaboration

Charged current semileptonic decays

Tree-level semileptonic decays due to weak charged current are an open portal for many studies

- Large semileptonic branching ratios
- Huge production of all b-hadrons at LHC



LHCb measurements done on

✓ CKM parameters, notably V_{cb} [PRD101(2020)072004] , V_{ub} [PRL126(2021)081804], [NP11(2015)743]

✓ Decay rate shapes: form factors [JHEP 12(2020)144],[PRD96(2017)112005]

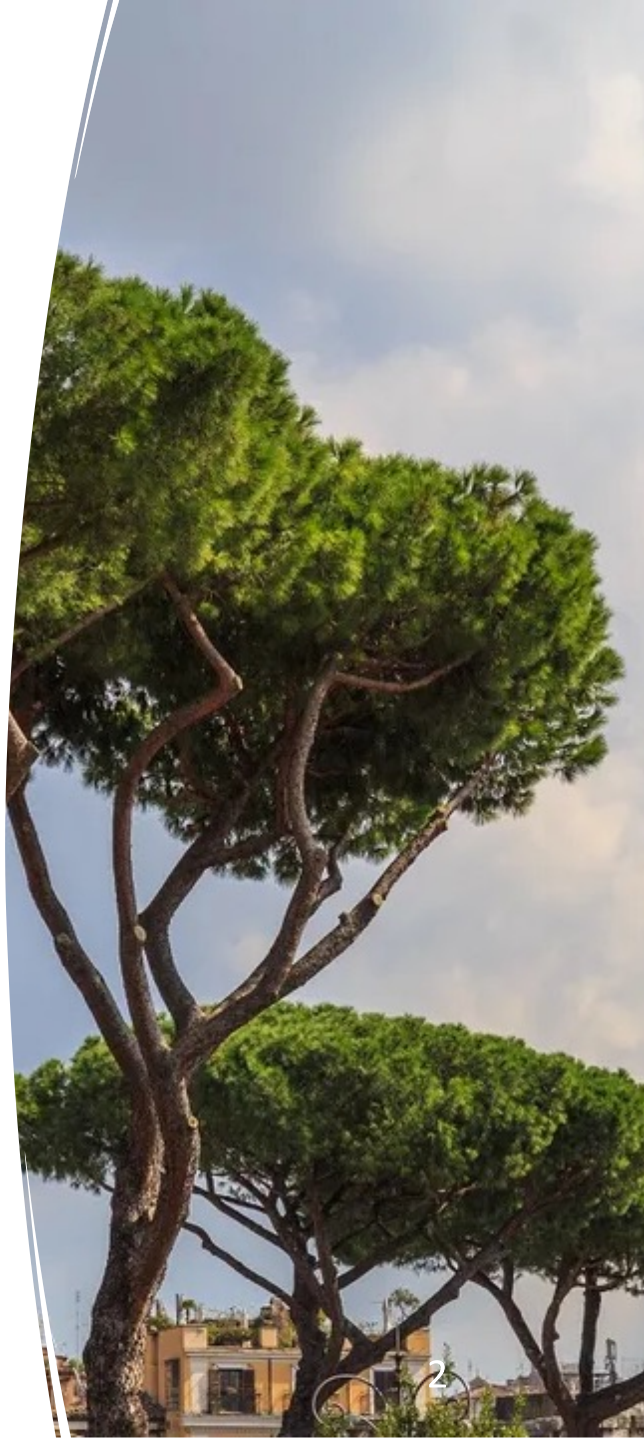
✓ B hadrons production fractions [PRD100(2019)0311022], lifetimes [PRL119(2017)101801]

Leaning on precise SM predictions

→ Test SM consistency and search for effects of possible Physics BSM

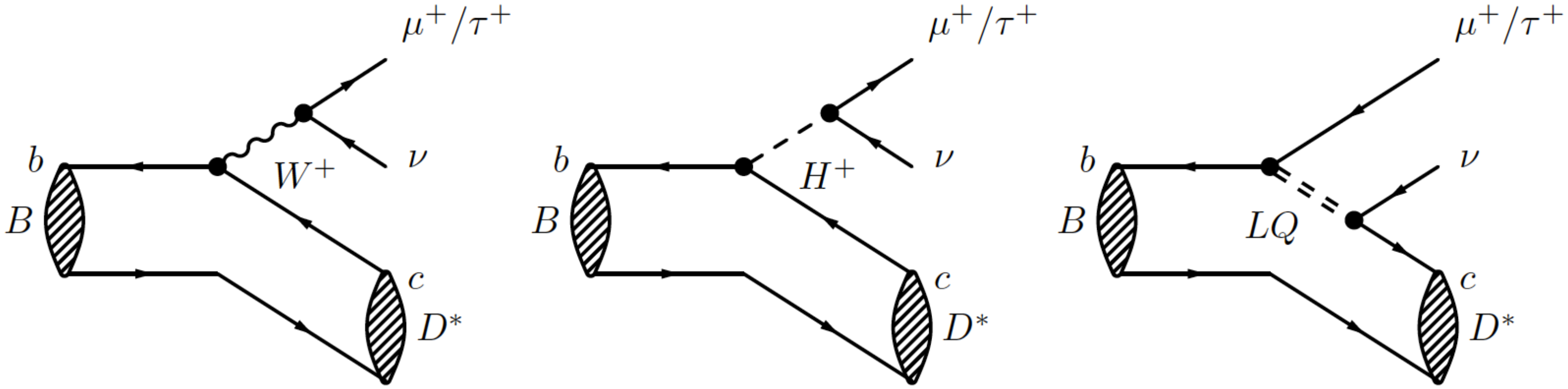
In this talk

- Test of Lepton Flavour Universality
- Angular analysis



LFU and semitauonic decays

- Lepton Flavour Universality
  - Electroweak couplings to all charged leptons are universal in the SM, differences between e, μ, and τ are driven only by masses
    - no known symmetry principle behind this
  - Any deviation from LFU is a key signature of physics processes beyond the SM.



- Decay modes with taus are particularly interesting for new mediators coupling to 3-rd generation, e.g charged Higgs, leptoquarks …

$R(H_c)$

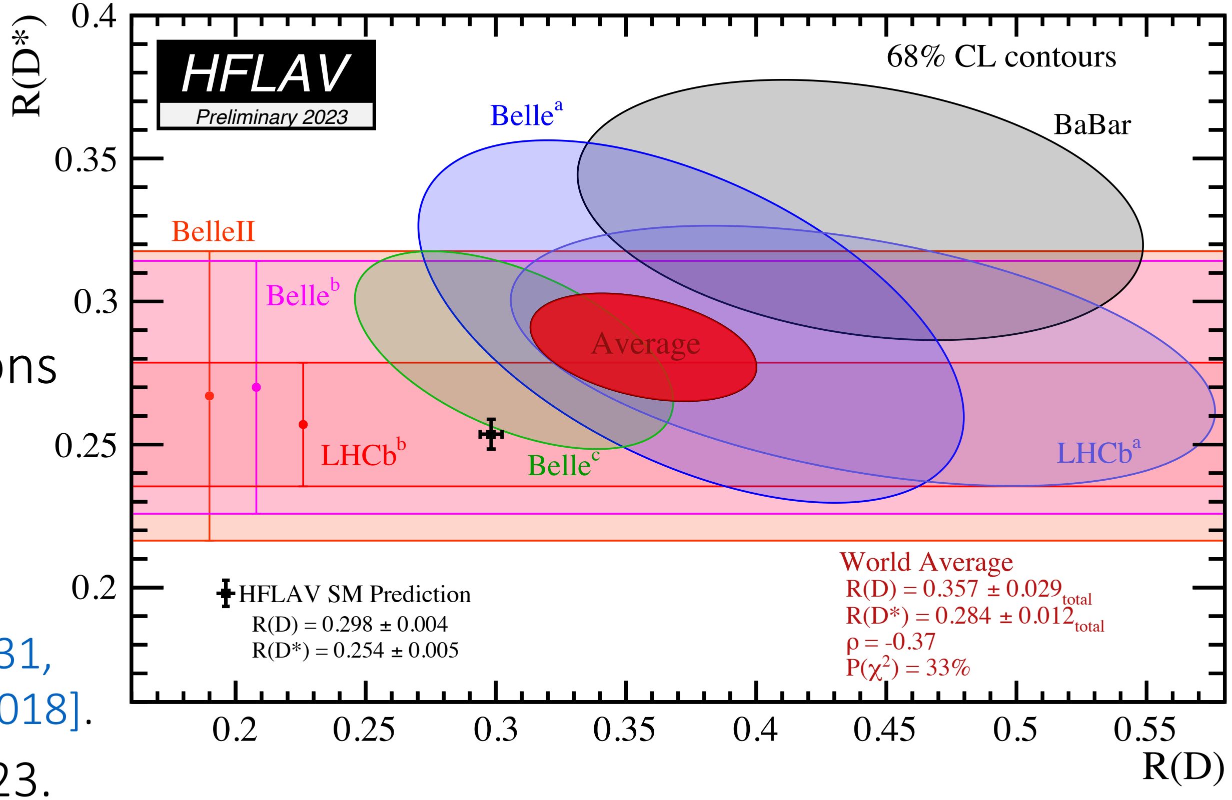
- Powerful tests of LFU from ratios of branching fractions of B decays to different leptons
  - Hadronic uncertainties mostly cancel in the ratio →precise theory predictions
  - Reduced experimental systematic uncertainties in ratios of efficiencies

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

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

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

- Measurements done for several b and c hadrons
  - Most precise for $B \to D^{(*)} l\nu$
- Deviations from SM in R(D)-R(D*) seen by several experiments
  - LHCb measurements done with muonic [PRL 131, 111802] and hadronic tau decays [PRD 108, 012018].
  - World average in 3.3 σ tension from SM in 2023.



HFLAV SM Prediction
$R(D) = 0.298 \pm 0.004$
$R(D^*) = 0.254 \pm 0.005$

World Average
$R(D) = 0.357 \pm 0.029_{\text{total}}$
$R(D^*) = 0.284 \pm 0.012_{\text{total}}$
$\rho = -0.37$
$P(\chi^2) = 33\%$

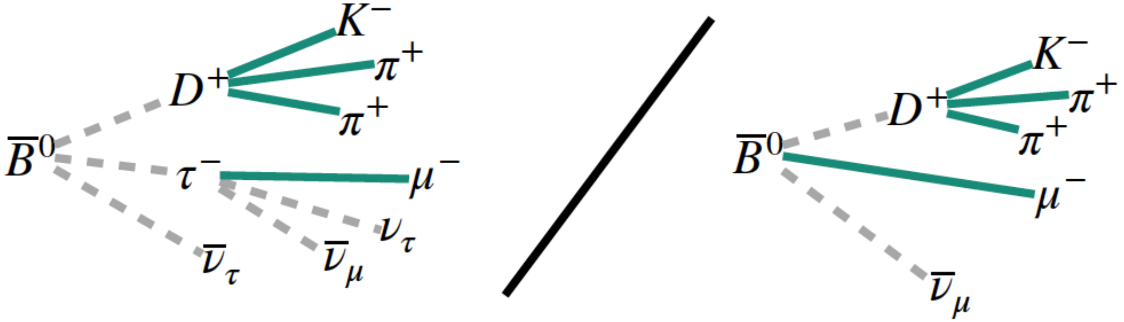
New: R($D^{(*)+}$) from $\bar{B}^0 \rightarrow D^{(*)+}\tau^-\bar{\nu}_\tau$

LHCb-PAPER-2024-007 in preparation

First presented at Moriond EW

- First LHCb measurement using $D^+ \rightarrow K^-\pi^+\pi^+$
- Feed-down from unreconstructed $D^{*+} \rightarrow D^+\pi^0/\gamma$ gives access to R(D^*) in the same visible $K^-\pi^+\pi^+\mu^-$ final state.
- Using muonic $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$ decays have same final state for signal and normalization modes

R(D^+) =



- No direct knowledge on B momentum at LHC, rest frame kinematics determined using B flight direction and boost approximation: $\gamma\,\beta_{z,\mathrm{total}} = \gamma\,\beta_{z,\mathrm{visible}}$
  - Provides good separation between signal and normalization modes in kinematic distributions

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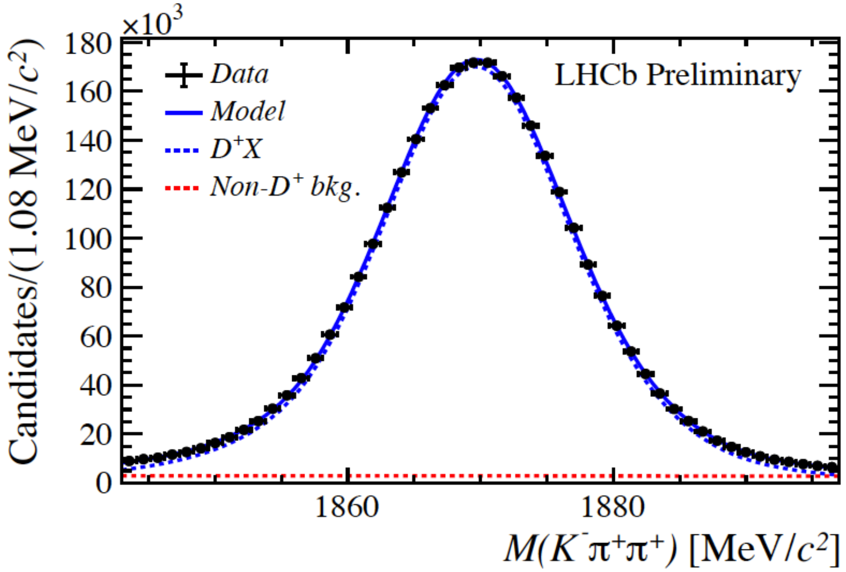
Data sample selection

- Data sample: 2 fb^{-1} collected in 2015-16
- Candidate selection:

  topologic, kinematic and particle ID requirements on $(K\pi\pi)_D\mu$, and fake-D^+ subtraction
- Isolation BDT against additional charged and neutral particles from the rest of the event



- 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 of the 4 samples using the rest-frame quantities: m^2_{miss}, E_μ^*, $q^2=(p_B-p_D)^2$

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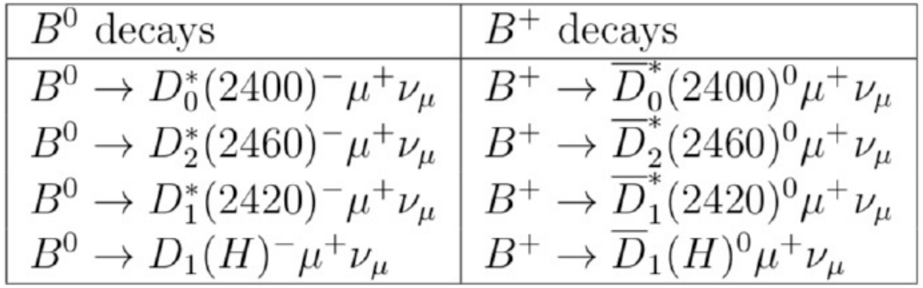
Fit components (I)

- Signal, normalization and physic backgrounds templates constructed from MC

- Main background
  - Feed-down from B→D**[D$^+$ X]$\mu\nu$ and B→D**[D$^+$ X]$\tau\nu$
    - Fractions of 1P states varied in the fit.
    - Higher mass states varied also in shape.
  - Double-charm B→ D$^+$ H$_c$[$\mu\nu$X] X'
    - Fractions and shapes of different components varied in the fit.



B^0 decays	B^+ decays
$B^0 \to D_0^*(2400)^-\mu^+\nu_\mu$	$B^+ \to \overline{D}_0^*(2400)^0\mu^+\nu_\mu$
$B^0 \to D_2^*(2460)^-\mu^+\nu_\mu$	$B^+ \to \overline{D}_2^*(2460)^0\mu^+\nu_\mu$
$B^0 \to D_1^*(2420)^-\mu^+\nu_\mu$	$B^+ \to \overline{D}_1^*(2420)^0\mu^+\nu_\mu$
$B^0 \to D_1(H)^-\mu^+\nu_\mu$	$B^+ \to \overline{D}_1(H)^0\mu^+\nu_\mu$

- Form factor parameterisation:

  B → D$^+$: BGL [PRD 94 (2016) 094008]

  B → D*: BGL [Eur. Phys. J. C 82, 1141 (2022)]

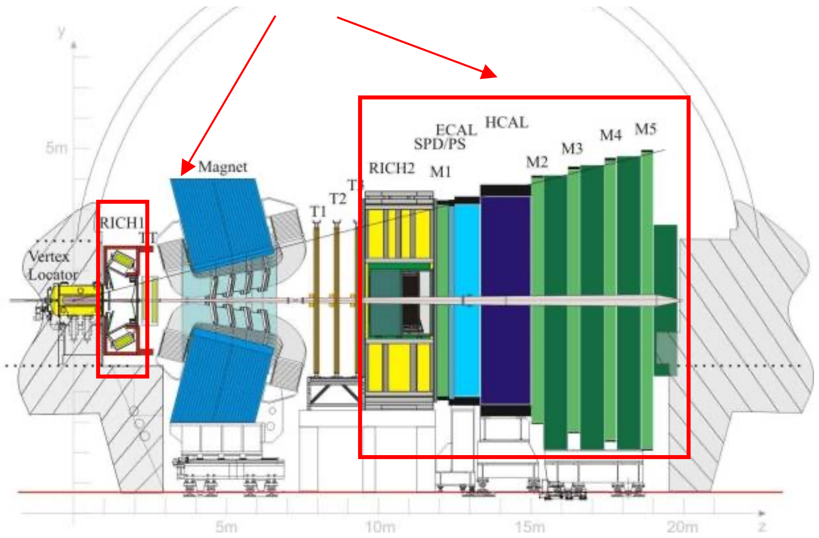
  B → D**: BLR [PRD 95 (2017) 014022]

Use HAMMER [Eur. Phys. J. C. 80(2020) 883] and RooHammerModel [JINST 17 (2022) T04006] to vary the form factor parameters in the fit (with external constraints applied).

Fit components (II)

- Size of simulated sample can limit the final precision
- This analysis uses a «tracker-only» ultra-fast simulation to generate large samples
  - Emulate missing features of some detectors response
  - PID efficiencies determined from data calibration samples

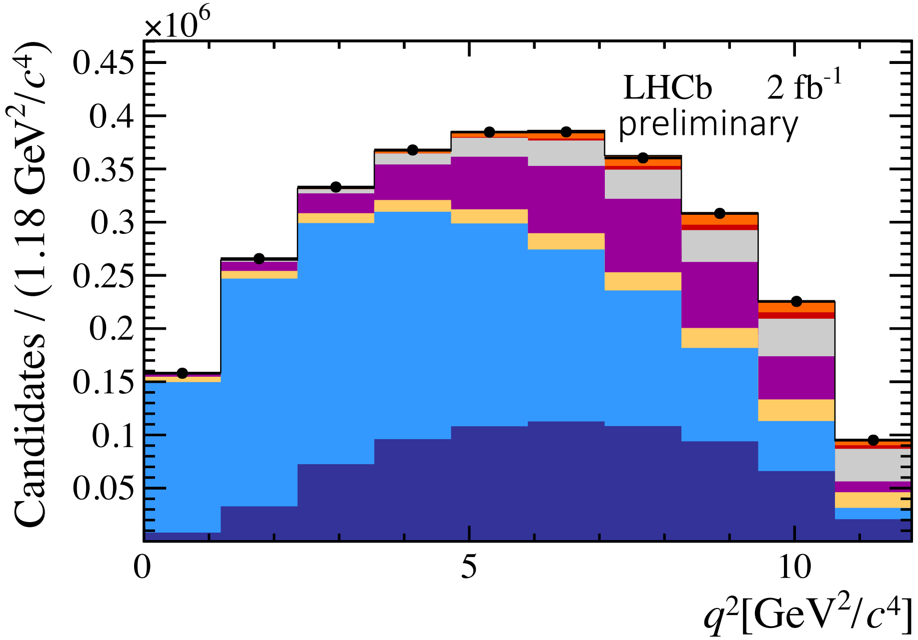
sub-detectors response turned-off



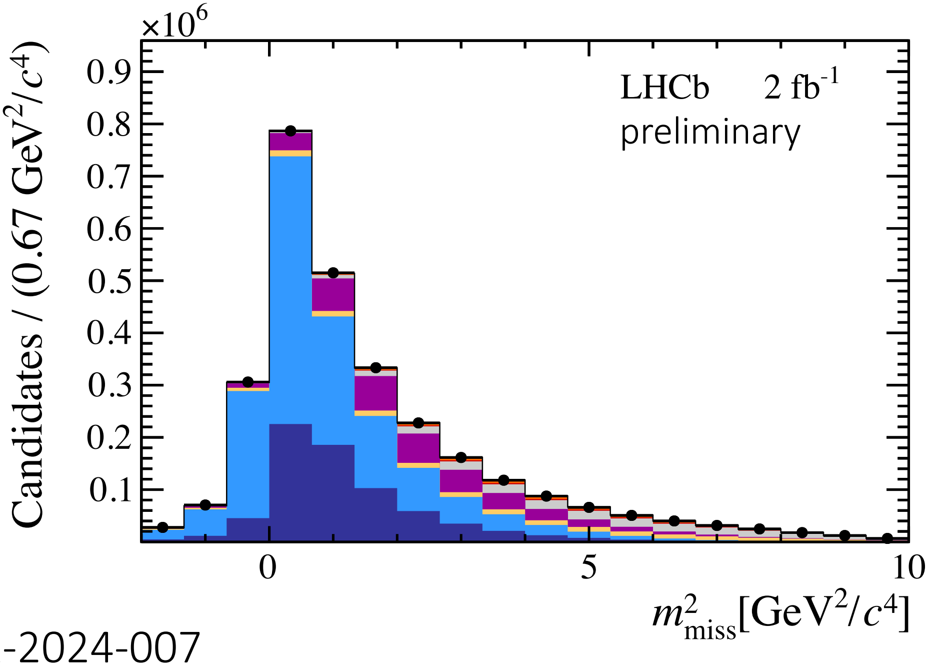
- Two templates from data
  - μ mis-identified component extracted from non-muon control sample
  - combinatorial background from same charge $D^{\pm}\mu^{\pm}$ data sample

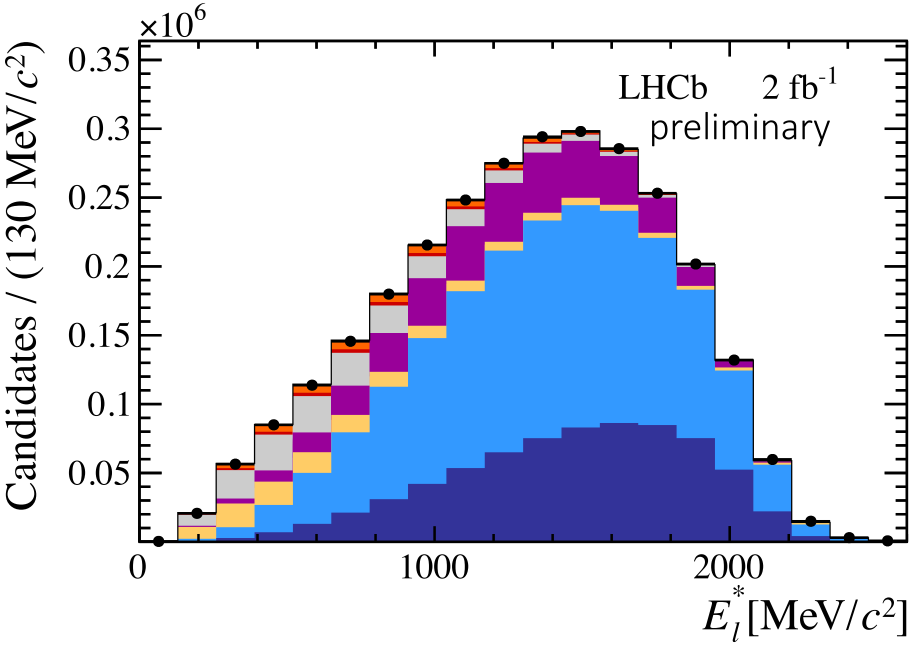
- Final tuning with multi-dimensional reweighting: excellent data/simulation agreement

Fit results - signal region



🟧 $\overline{B} \to D^+ \tau^- \nu$
🟥 $\overline{B} \to D^{*+} \tau^- \nu$
⬜ $\overline{B}^{-/0} \to D^+ X_c X$
🟪 $\overline{B}^{-/0} \to D^{**} \mu^- / \tau^- \nu$
🟨 Comb + misID
🟦 $\overline{B} \to D^+ \mu^- \nu$
🟦 $\overline{B} \to D^{*+} \mu^- \nu$





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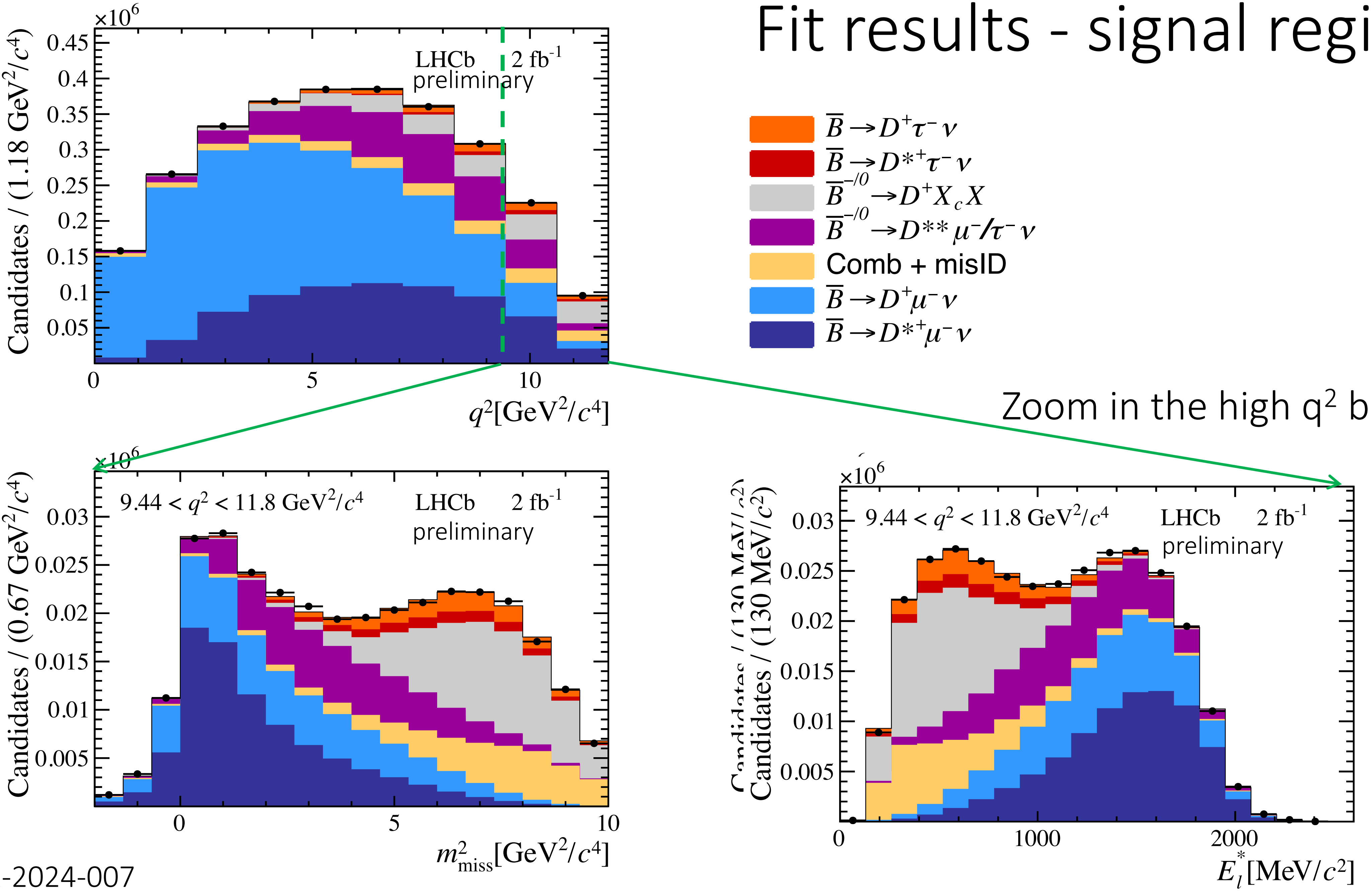
Fit results - signal region



Zoom in the high q^2 bins

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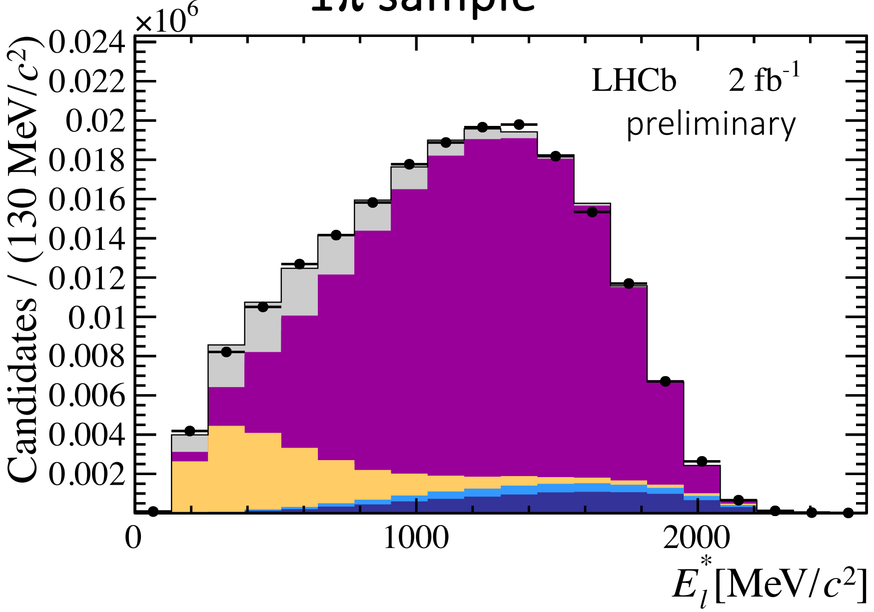
Fit results - control regions

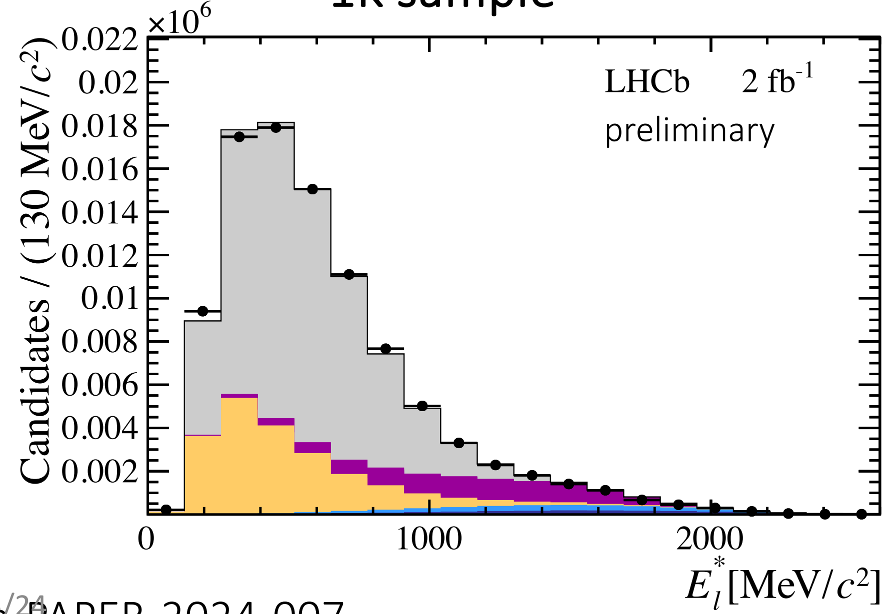
1π sample



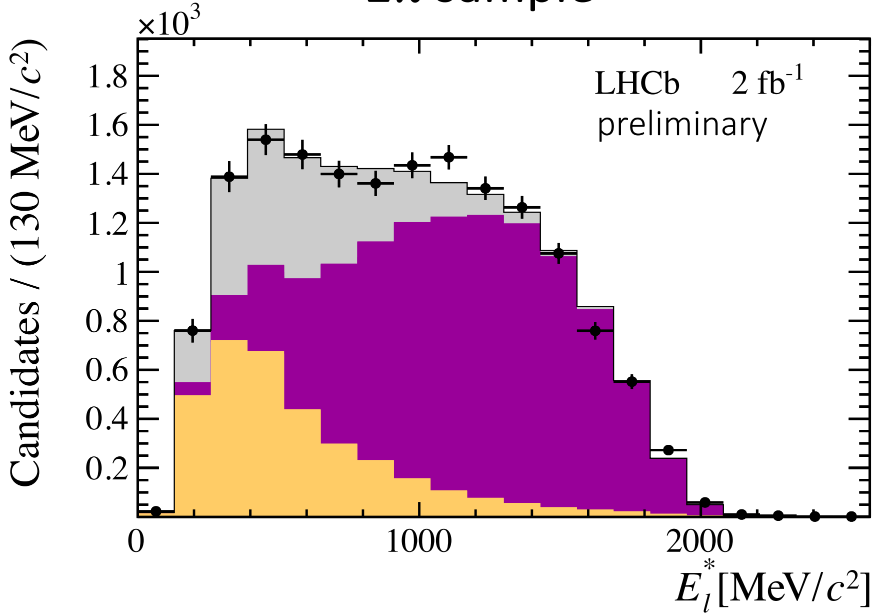
- 🟧 $\overline{B} \to D^+\tau^-\nu$
- 🟥 $\overline{B} \to D^{*+}\tau^-\nu$
- ⬜ $\overline{B}^{-/0} \to D^+X_cX$
- 🟪 $\overline{B}^{-/0} \to D^{**}\mu^-/\tau^-\nu$
- 🟨 Comb + misID
- 🟦 $\overline{B} \to D^+\mu^-\nu$
- 🟦 $\overline{B} \to D^{*+}\mu^-\nu$

- Excellent agreement also in the sub-samples that control the background modelling

1K sample



2π sample



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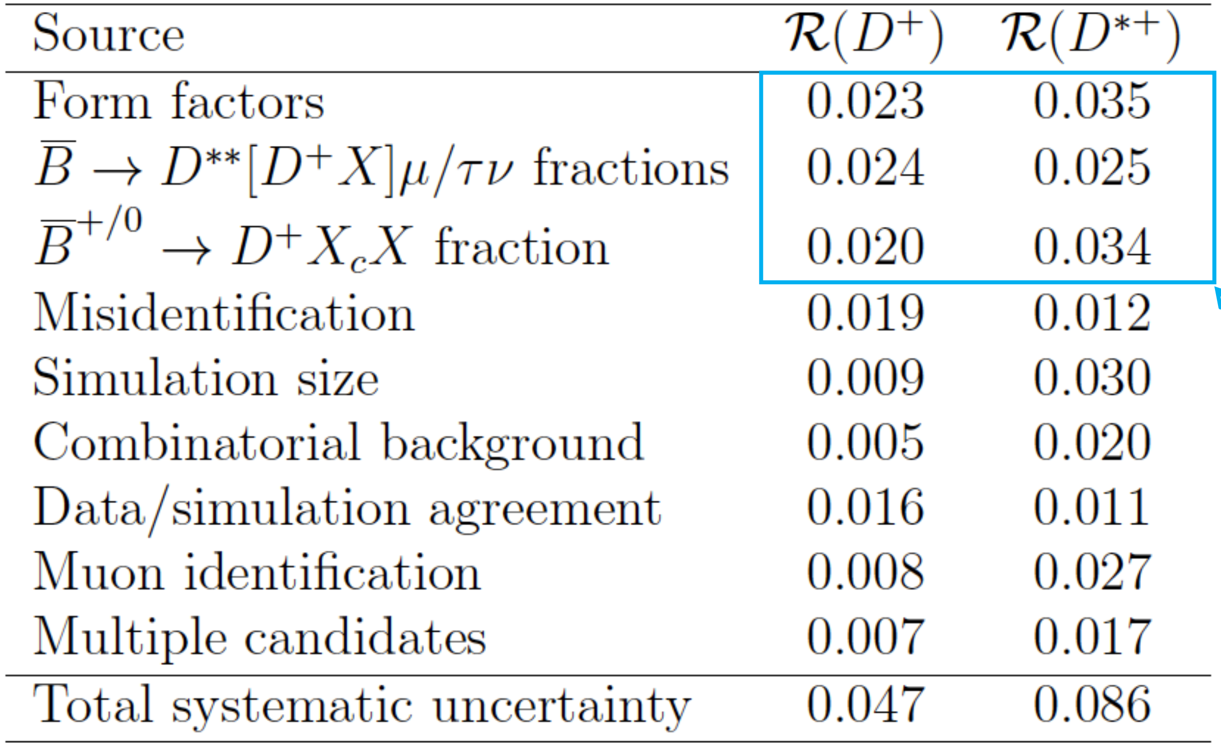
Results

$$\boxed{\begin{aligned} R(D^+) &= 0.249 \pm 0.043 \pm 0.047 \\ R(D^{*+}) &= 0.402 \pm 0.081 \pm 0.085 \end{aligned}}$$

ρ = – 0.39

Systematic uncertainties



Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$
Form factors	0.023	0.035
$\overline{B} \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\overline{B}^{+/0} \to D^+X_cX$ 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

Signal yields: N_τ^D ~35.000, $N_\tau^{D^*}$ ~29.000

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

Uncertainty on ratio of efficiencies very subdominant.

Main systematic uncertainties from form-factor parameterisation and background modelling.

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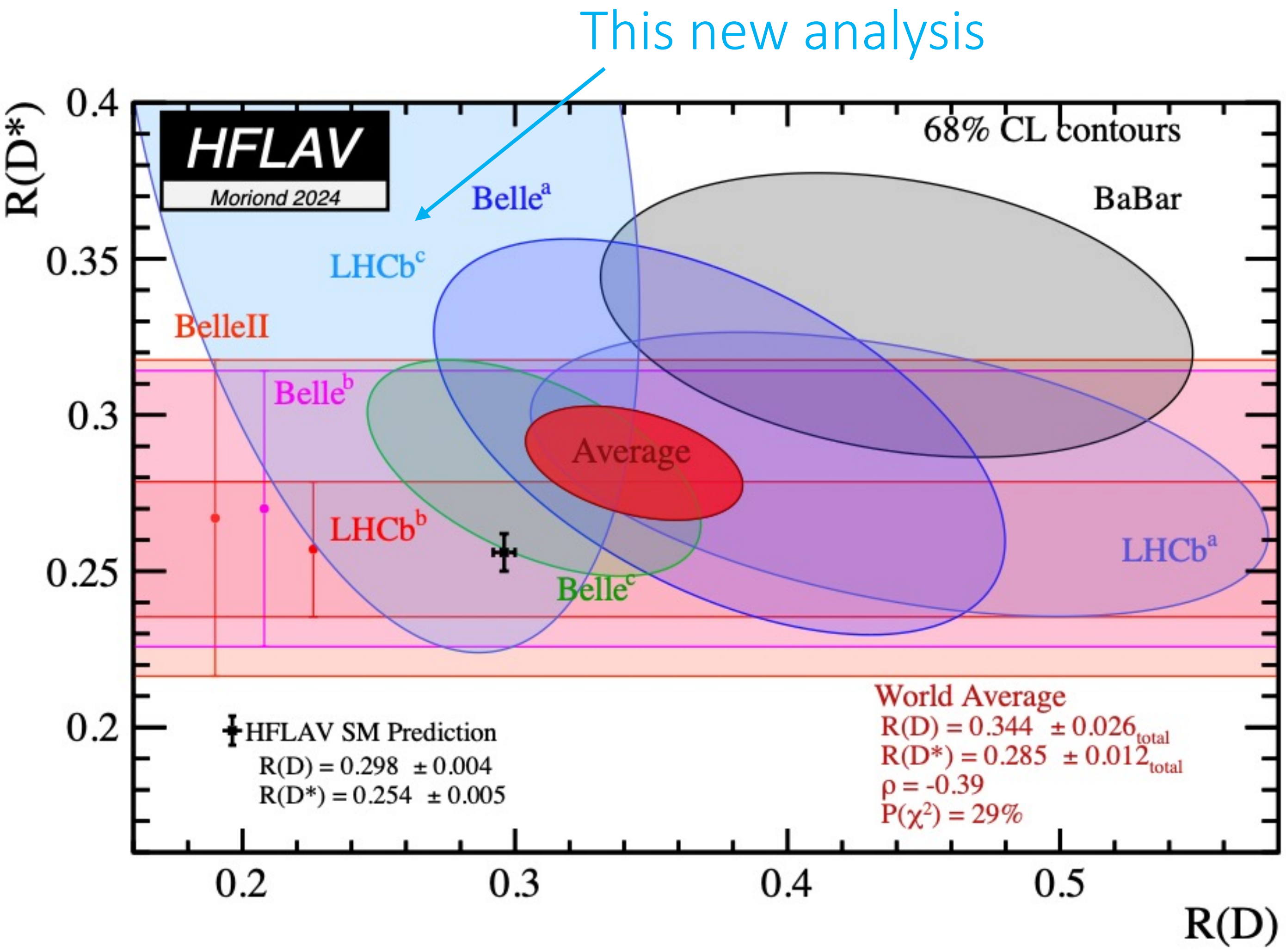
New R(D)-R(D*) world average


This new analysis

- New LHCb result is compatible with previous LHCb measurements that used muonic and hadronic tau decays and with SM.

New word average

- R(D) and R(D*) exceed the SM predictions by 1.7σ and 2.3σ respectively.
- R(D)-R(D*) combined average in 3.17 σ tension from SM

Semitauonic decays - Angular analysis

- Angular analyses provide sensitivity to NP beyond integrated rates
  - Can test presence of new mediators and different spin structures

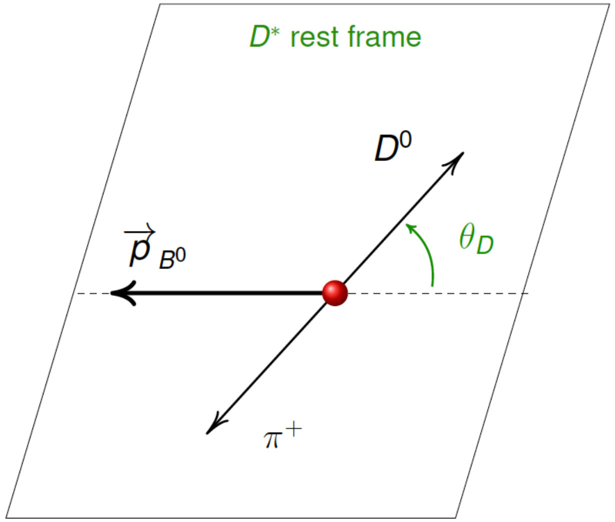
- First LHCb angular analysis on B→D$^*\tau\nu$ decays measures the D* polarization fraction

- The differential decay rate

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

unpolarized signal fraction

polarized signal fraction



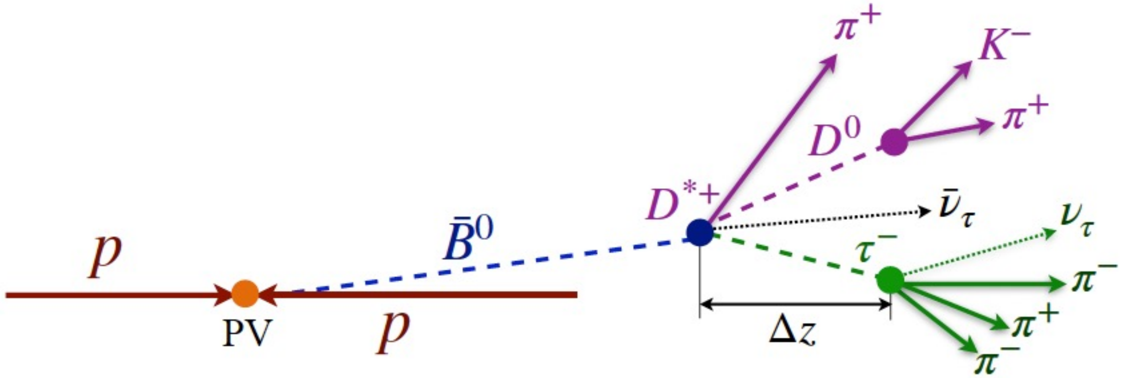
Longitudinal D*
polarization fraction

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

[arXiv:2311.05224]

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

- Use $\tau^- \to 3\pi(\pi^0)\nu_\tau$ decays.
- Run1 and part of Run2 data (5 fb^{-1}), same samples as for $R(D^*)$ hadronic tau analyses [PRL 120, 171802], [PRD 108, 012018]



- Three pions vertex provides tau decay position that suppress dominant background $B^0 \to D^{*-} 3\pi$
- D^0, τ^- and B^0 decay vertices allow to estimate B momentum with good precision
  - Additional background suppression from specific dynamics of $\tau^- \to 3\pi\nu_\tau$ decay
- Lower hadronic tau BR, but higher purity sample than in muonic analysis
- 4D-binned template fit, simultaneous on two q^2 bins ($\lesseqgtr 7$ GeV^2/c^4), τ^- decay time, anti-D_s BDT output and $\cos\theta_D$

[arXiv:2311.05224]

$F_L^{D^*}$ results

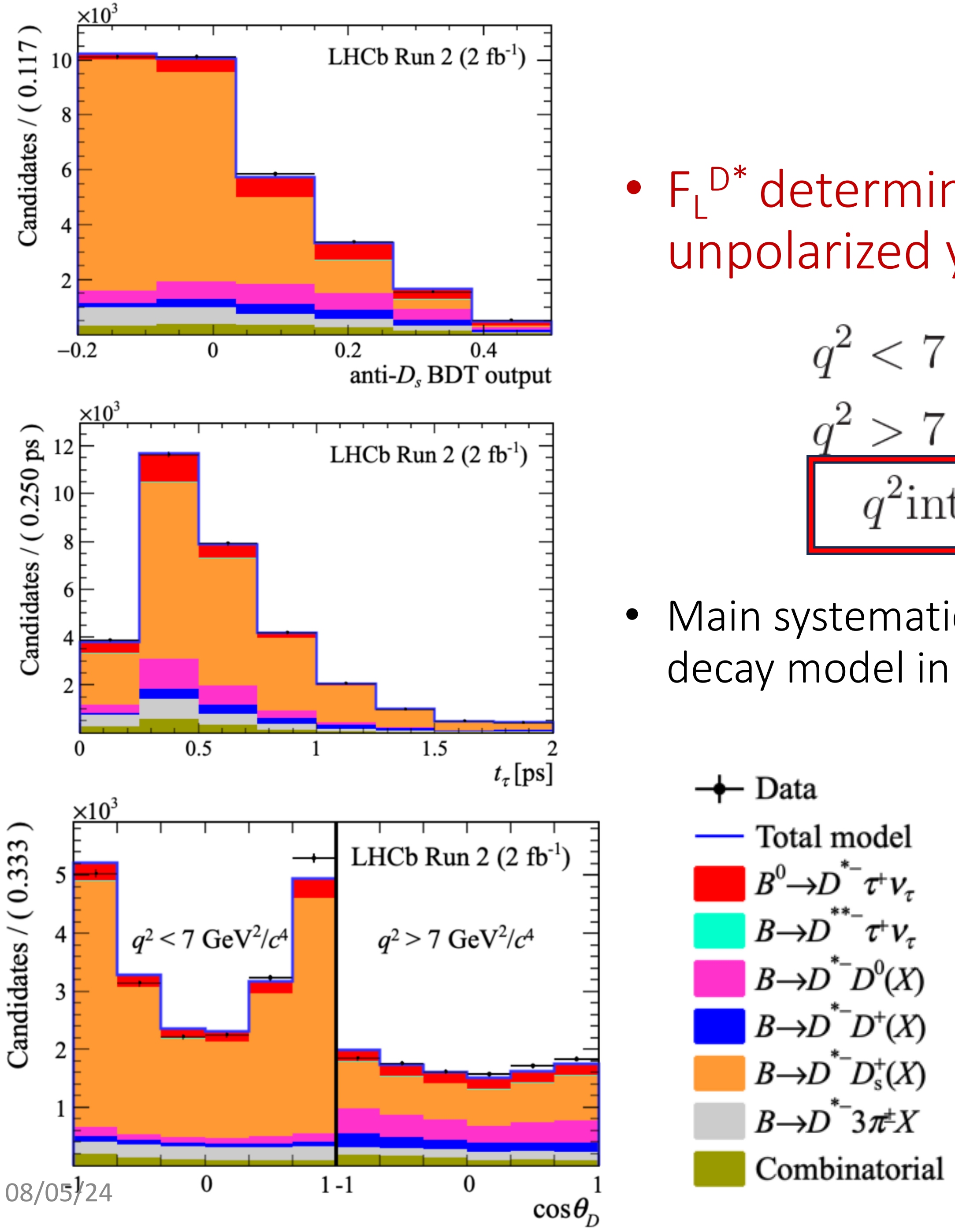
- $F_L^{D^*}$ determined from the observed signal polarized and unpolarized yields

$$q^2 < 7\,\mathrm{GeV}^2/c^4 : \quad 0.51 \pm 0.07(stat) \pm 0.03(syst)$$

$$q^2 > 7\,\mathrm{GeV}^2/c^4 : \quad 0.35 \pm 0.08(stat) \pm 0.02(syst)$$

$$\boxed{q^2\text{integrated} : \quad 0.43 \pm 0.06(stat) \pm 0.03(syst)}$$

- Main systematic from simulated templates statistics, FF parametrization, D_s decay model in background.



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]

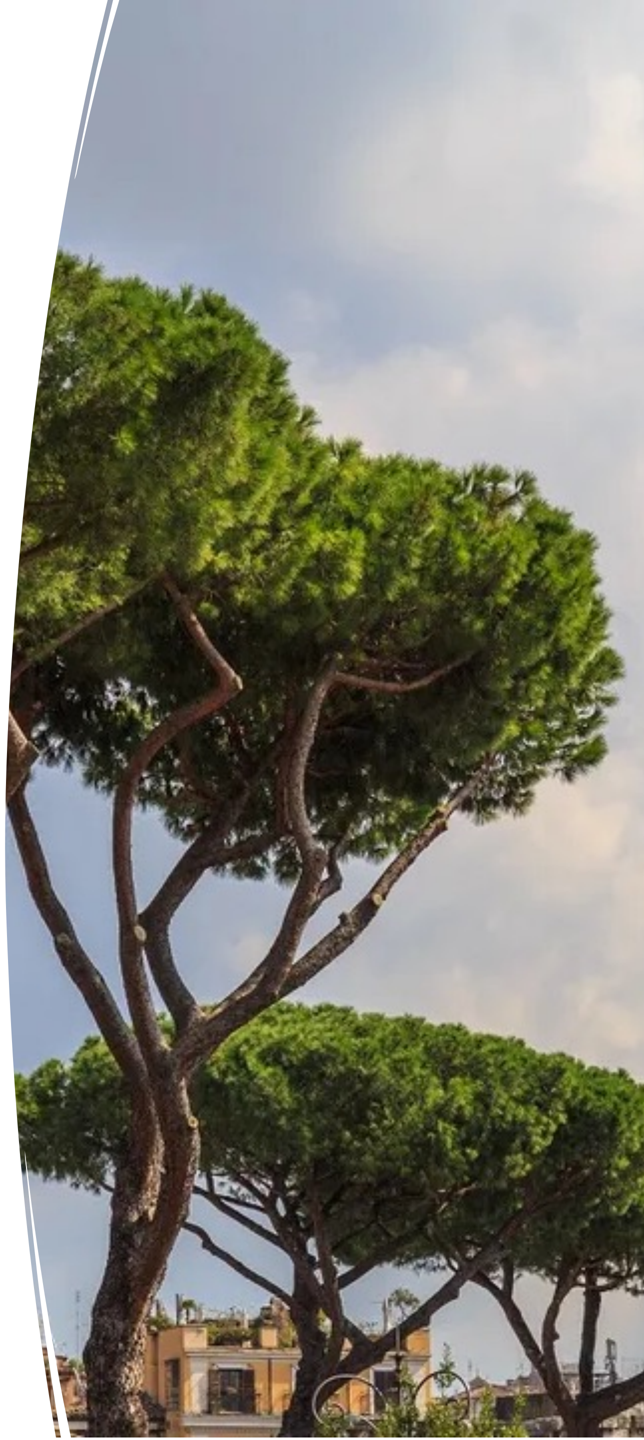
$F_L^{D^*}[q^2 < 7GeV^2/c^4] = 0.495 \pm 0.017$ [arXiv:2310.03680]

$F_L^{D^*}[q^2 > 7GeV^2/c^4] = 0.383 \pm 0.006$ [arXiv:2310.03680]

Conclusion and Outlook (I)

- First LHCb measurement of $R(D^+)$ & $R(D^{*+})$, with a muonic decay of the tau lepton.
  - Compatible with the World Average and with the SM.
  - New HFLAV average: overall tension with SM at the level of 3.17 σ.

- LFU can be tested in many more modes
  - $B_c \rightarrow J/\psi\ \tau\nu$ (muonic tau) [PRL 120, 121801] and $\Lambda_b \rightarrow \Lambda_c\ \tau\nu$ (hadronic tau) [PRL 128, 191803] already pioneered by LHCB with Run1 data. Updates on Run2 data are ongoing.
  - New modes under study
    - $B_s \rightarrow D_s^{(*)}\ l\nu$ decays
    - B^0 decays to other charm mesons and other D decay modes
      - $B^0 \rightarrow D^{**-}\tau^+\nu_\tau$
      - $D^{*+} \rightarrow D^0\pi^+$ $(D^0 \rightarrow K^-3\pi)$; $D^{*0} \rightarrow D^0\ \gamma/\pi^0$



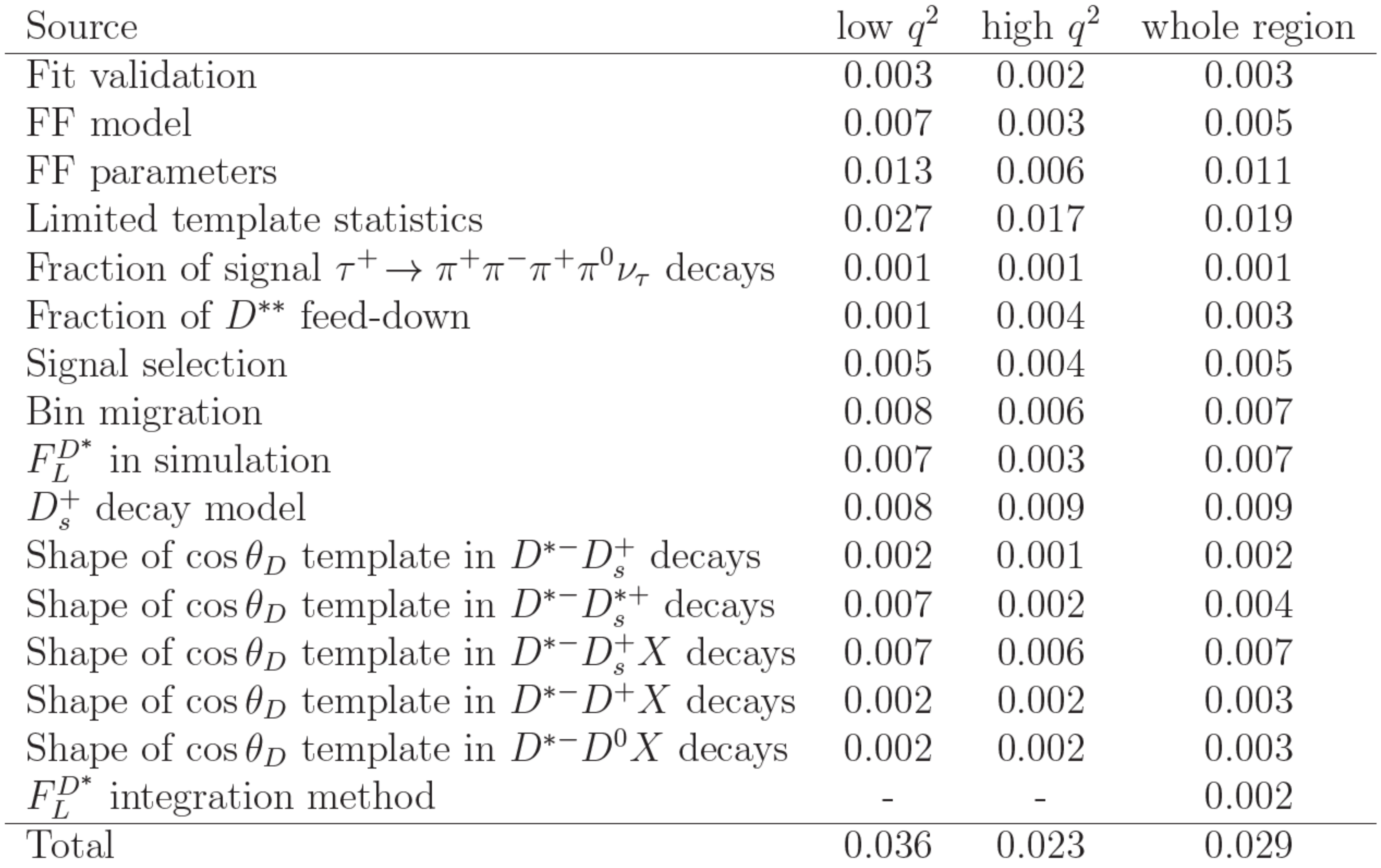
Conclusion and Outlook (II)

- First LHCb angular analysis of charged-current semitauonic decays, measuring $F_L^{D^*}$ in $B^0 \rightarrow D^* \tau\nu$
  - Better precision than previous result, compatible with it and with the SM
- Full angular analysis of $B^0 \rightarrow D^* \mu\nu$ and $B^0 \rightarrow D^* \tau\nu$ will provide new tests of possible physics beyond SM
- Full Run2 data sample to be fully exploited (total of 9 fb^{-1}) and Run3 data taking at x5 instantaneous luminosity underway. Future LHCb upgrade could provide up to 300 fb^{-1} .
  - Larger control samples and improved model descriptions will help to control systematic uncertainties

Backup

$F_L^{D^*}$ IN $B \rightarrow D^* \tau \nu$ DECAYS –Systematics

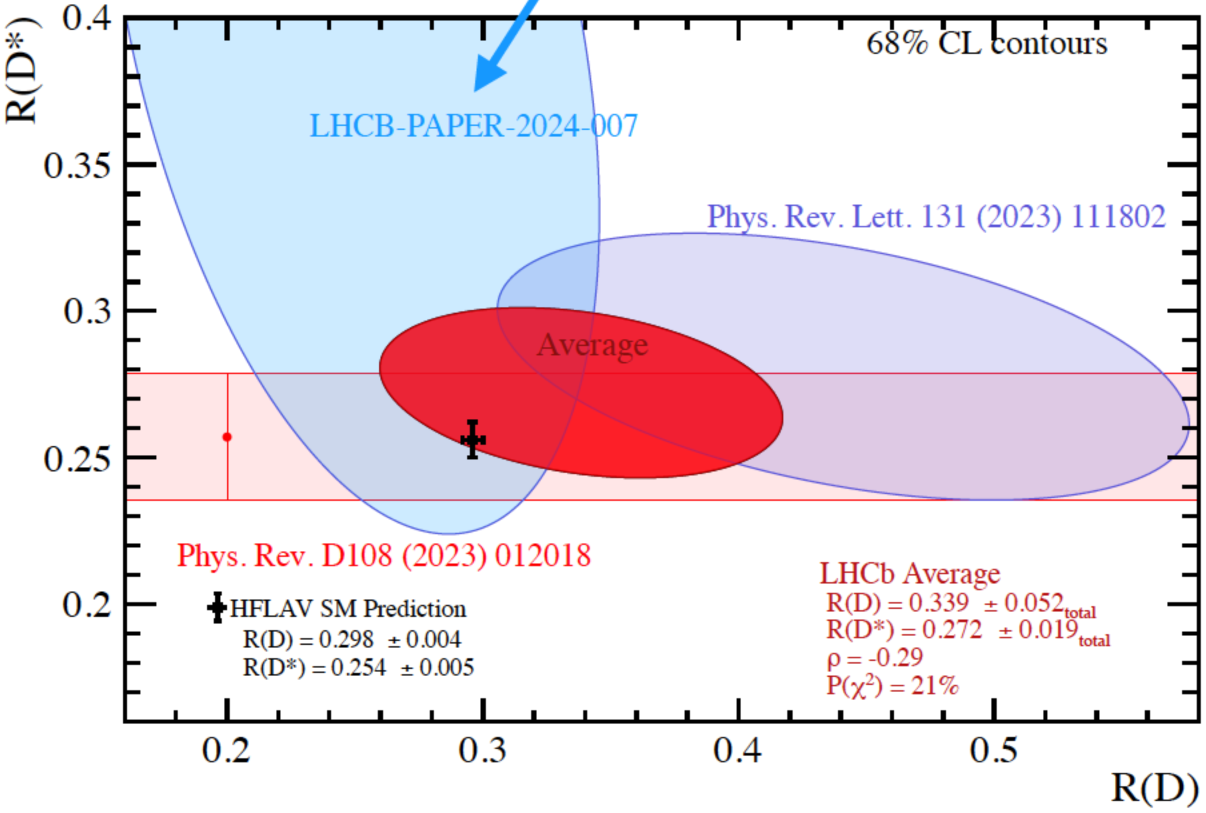
LHCb-PAPER-2023-020



Source	low q^2	high q^2	whole region
Fit validation	0.003	0.002	0.003
FF model	0.007	0.003	0.005
FF parameters	0.013	0.006	0.011
Limited template statistics	0.027	0.017	0.019
Fraction of signal $\tau^+ \rightarrow \pi^+\pi^-\pi^+\pi^0\nu_\tau$ decays	0.001	0.001	0.001
Fraction of D^{**} feed-down	0.001	0.004	0.003
Signal selection	0.005	0.004	0.005
Bin migration	0.008	0.006	0.007
$F_L^{D^*}$ in simulation	0.007	0.003	0.007
D_s^+ decay model	0.008	0.009	0.009
Shape of $\cos\theta_D$ template in $D^{*-}D_s^+$ decays	0.002	0.001	0.002
Shape of $\cos\theta_D$ template in $D^{*-}D_s^{*+}$ decays	0.007	0.002	0.004
Shape of $\cos\theta_D$ template in $D^{*-}D_s^+X$ decays	0.007	0.006	0.007
Shape of $\cos\theta_D$ template in $D^{*-}D^+X$ decays	0.002	0.002	0.003
Shape of $\cos\theta_D$ template in $D^{*-}D^0X$ decays	0.002	0.002	0.003
$F_L^{D^*}$ integration method	-	-	0.002
Total	0.036	0.023	0.029

LHCb combination

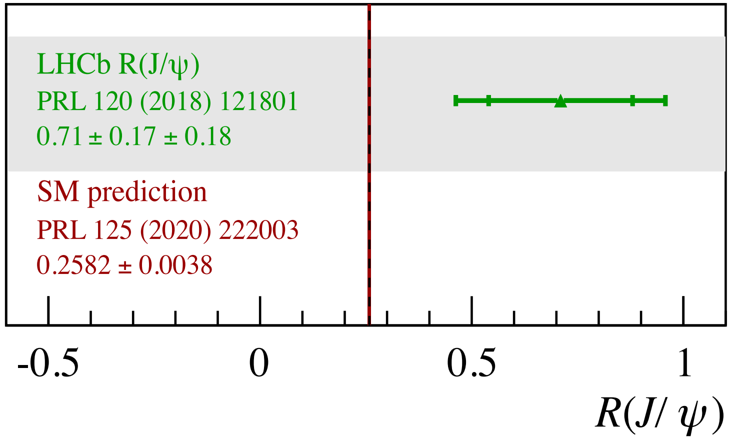
This result
[LHCb preliminary]



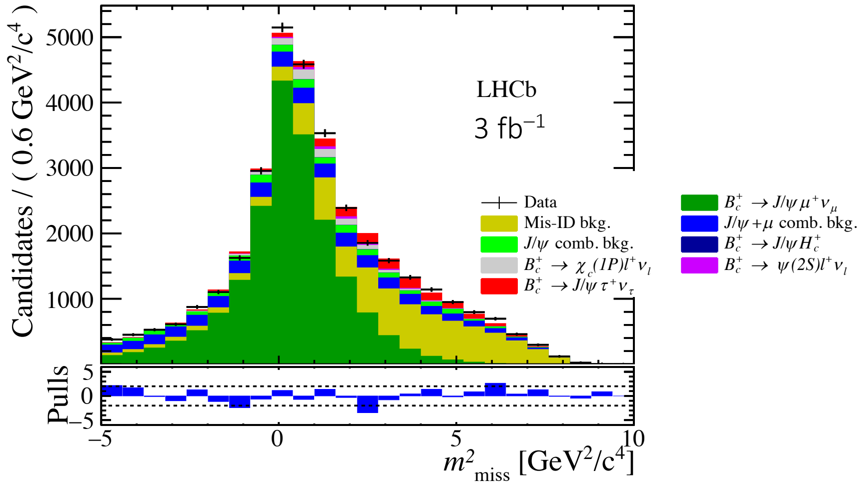
Other R(H_c) at LHCb

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

Phys. Rev. Lett. 120, 121801

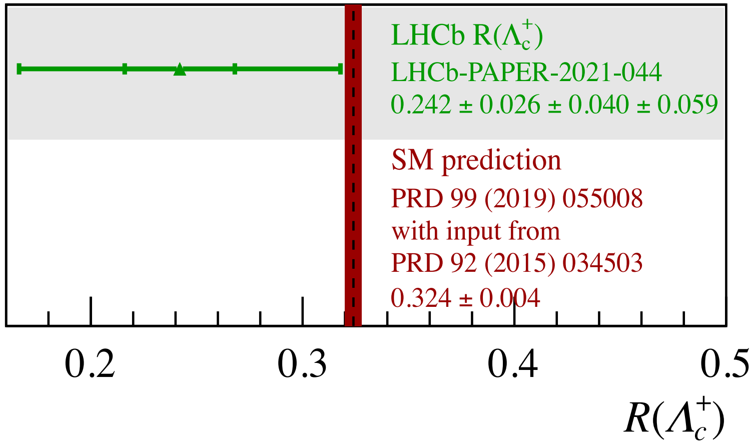


$B_c \rightarrow J/\psi\tau\nu$



- $\Lambda_b \rightarrow \Lambda_c\, \tau\nu$ (hadronic tau)

Phys. Rev. Lett. 128, 191803



$\Lambda_b \rightarrow \Lambda_c\tau\nu$