b → clν decays at LHCb

Julián García Pardiñas[1]
on behalf of the LHCb Collaboration

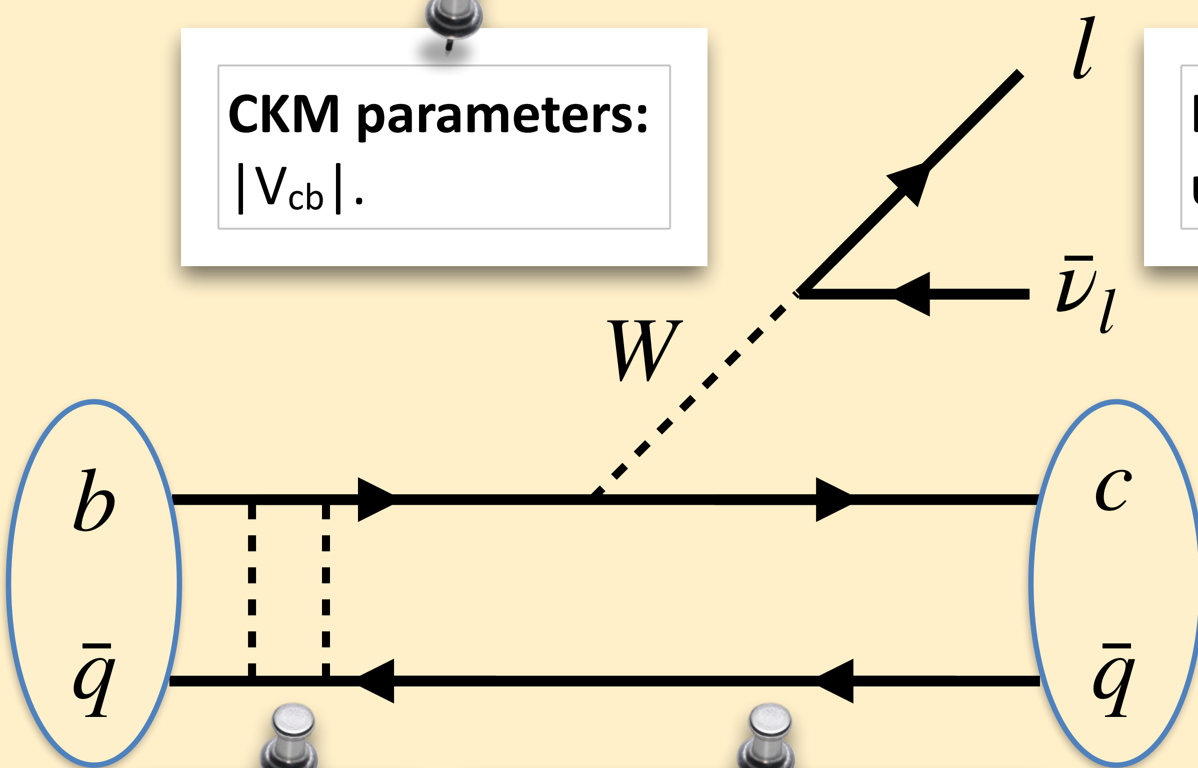
1 CERN (Switzerland)

Moriond EW 2024 **27th March 2024**

b-hadron properties: production fractions, lifetimes.

CKM parameters: $|V_{cb}|$.

Lepton-flavour universality (LFU) ratios.



c-hadron properties: production fractions, lifetimes.

Neutral meson mixing

Decay properties: BF, form factors, angular coefficients.

Advantages

- **Large data samples.**
- **Theoretically clean:** only b→c hadronic current.

Challenges

- All decays are **partially reconstructed** due to the neutrinos.
- **Large amounts of background.**

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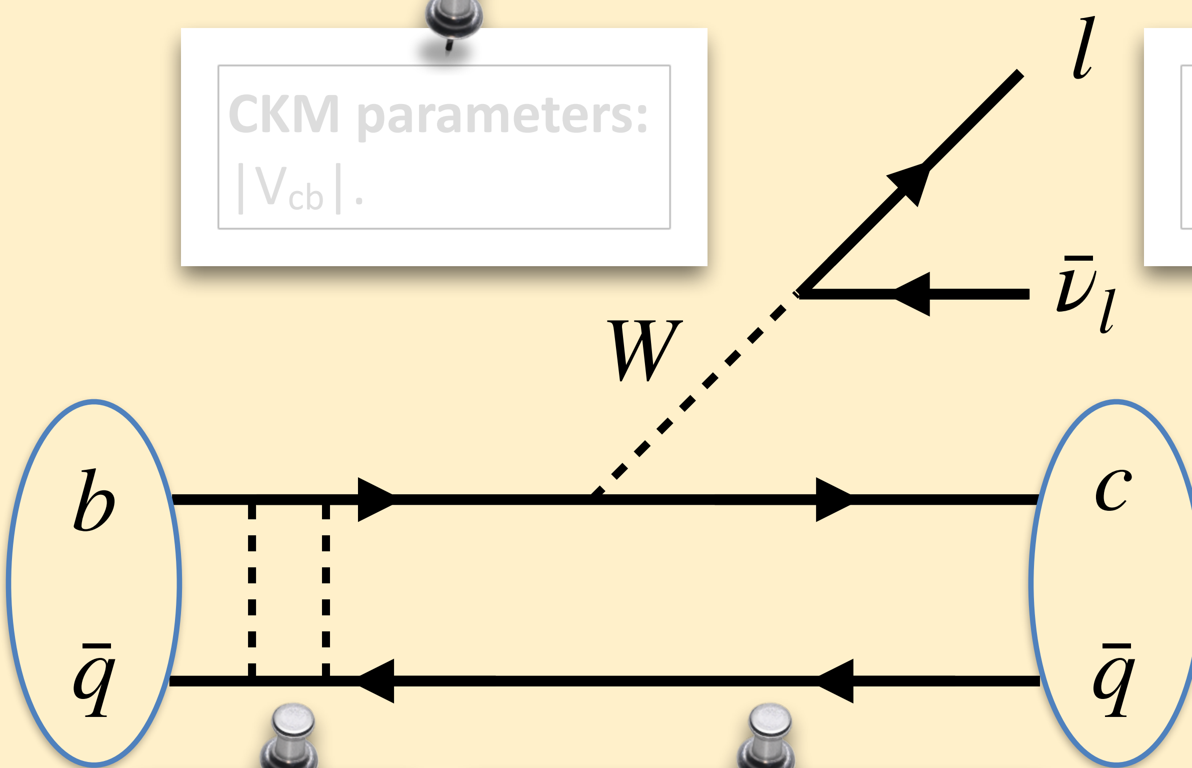

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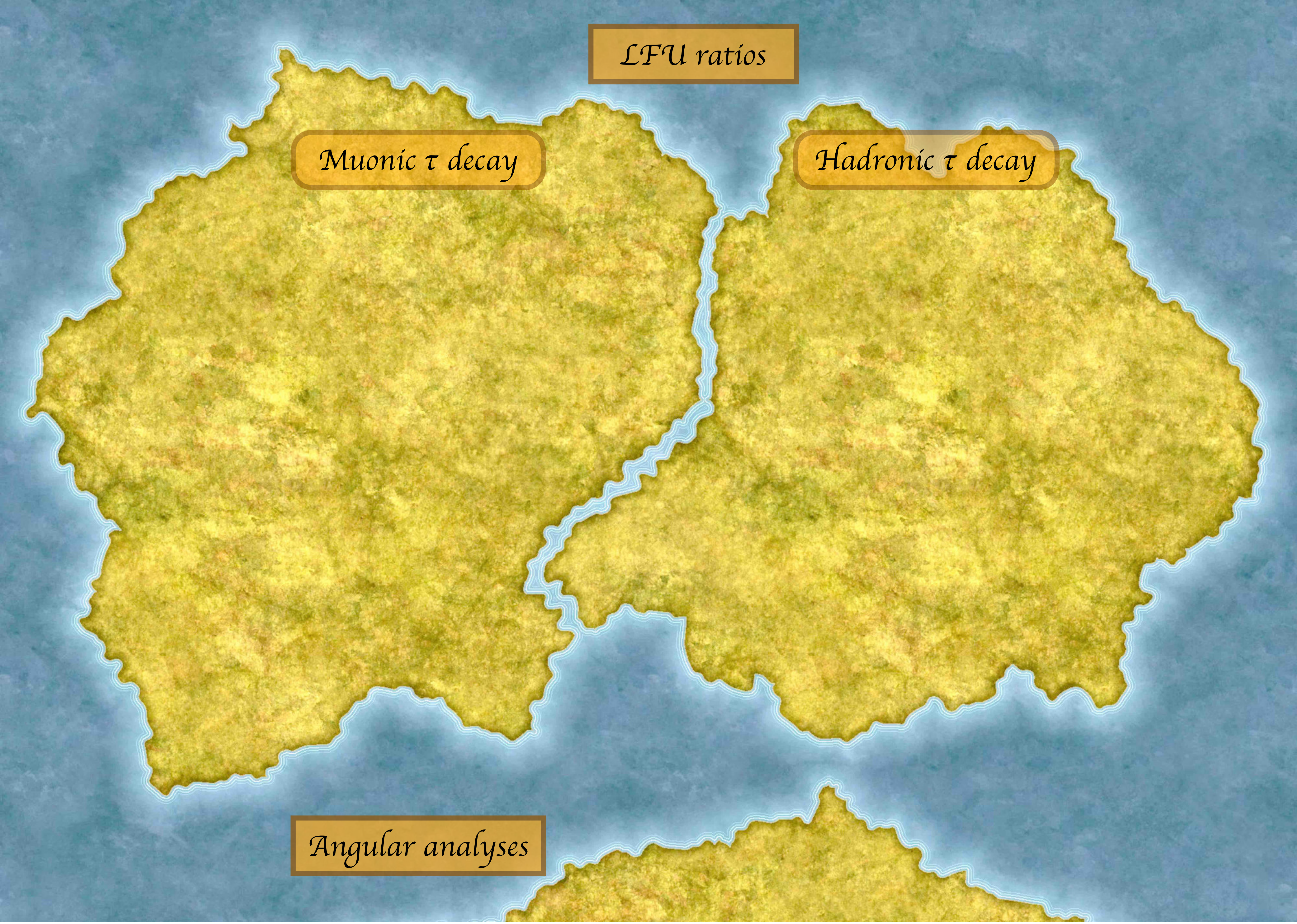

LFU ratios
Muonic τ decay
Hadronic τ decay
Angular analyses

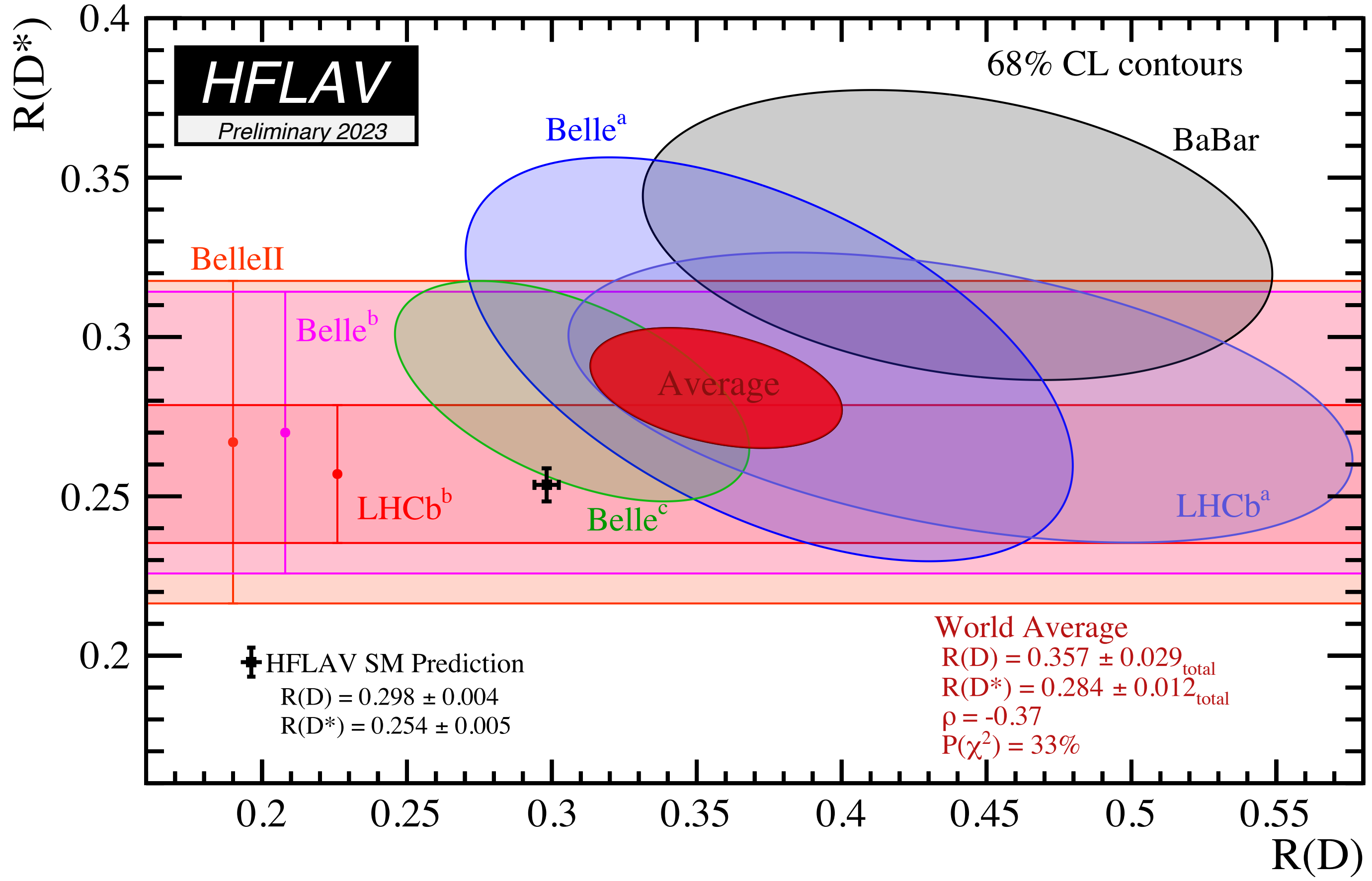
LFU ratios

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

$$\mathcal{H}_b = B^0, B^+_{(c)}, \Lambda^0_b, B^0_s ...$$
$$\mathcal{H}_c = D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi ...$$

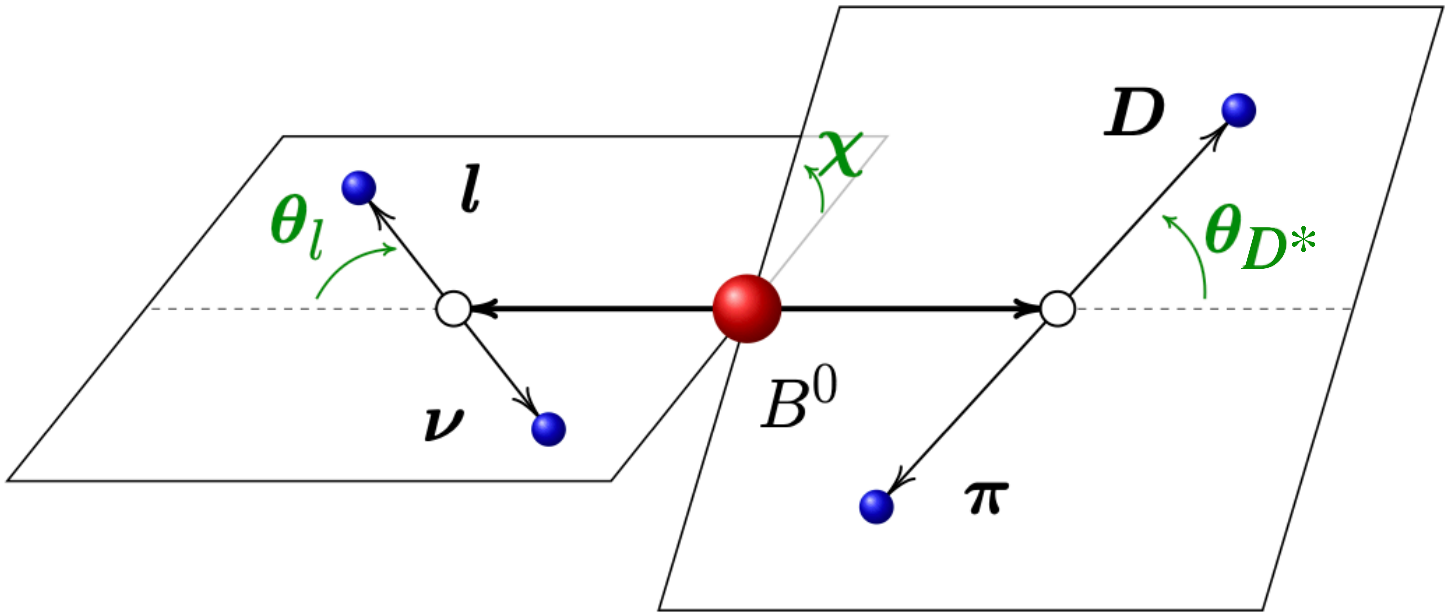
- **Precise measurements** both theoretically and experimentally.
- Deviations seen by several experiments.
  ➥Current combined tension at the level of **3.34 σ**.
- Potential physics beyond the Standard Model (BSM) affecting **semi-tauonic decays**.

[HFLAV]



Angular analyses

From integrated BFs to differential measurements: angular analyses of semi-tauonic decays to **probe the spin structure** of possible BSM physics.



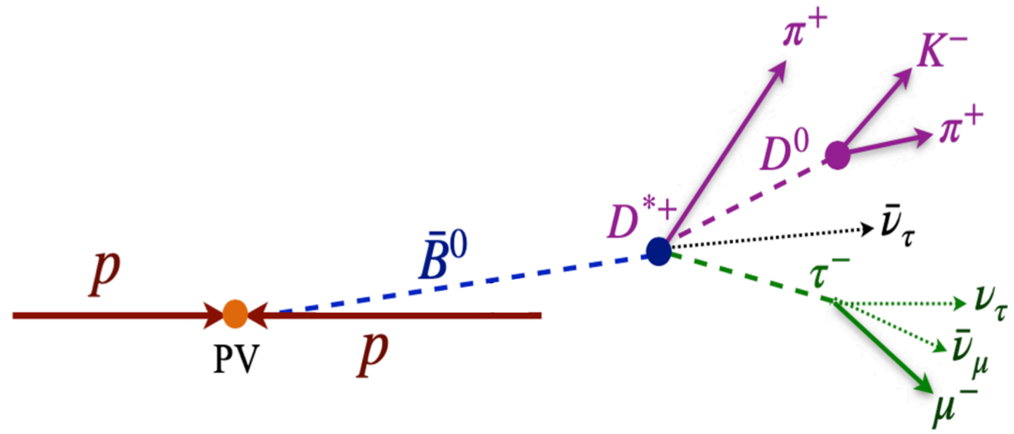
$$\frac{d^4(B^0 \to D^* \ell^+ \nu_\ell)}{dq^2 d\cos^2\theta_\ell d\cos\theta_{D^*} d\chi} \propto |V_{cb}|^2 \sum_i \mathcal{H}_i(q^2) f_i(\theta_\ell, \theta_{D^*}, \chi)$$

Sensitivity to BSM physics.

Angular analyses

LFU ratios

Muonic τ decay



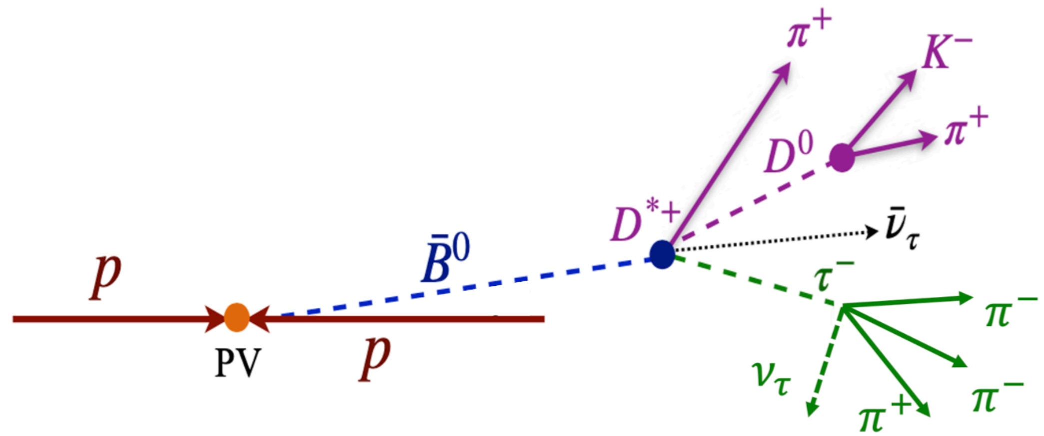
Pros:

- **Direct measurement of R(D$^{(*)}$)**, as normalisation channel shares the same visible final state.
- **Large signal and normalisation yields**.

Cons:

- **Multiple missing neutrinos**: use boost approximation ($p_B^{\|} \propto p_{vis}^{\|}$) to estimate B momentum.
- **Large background contributions** that need to be controlled very accurately.

Hadronic τ decay

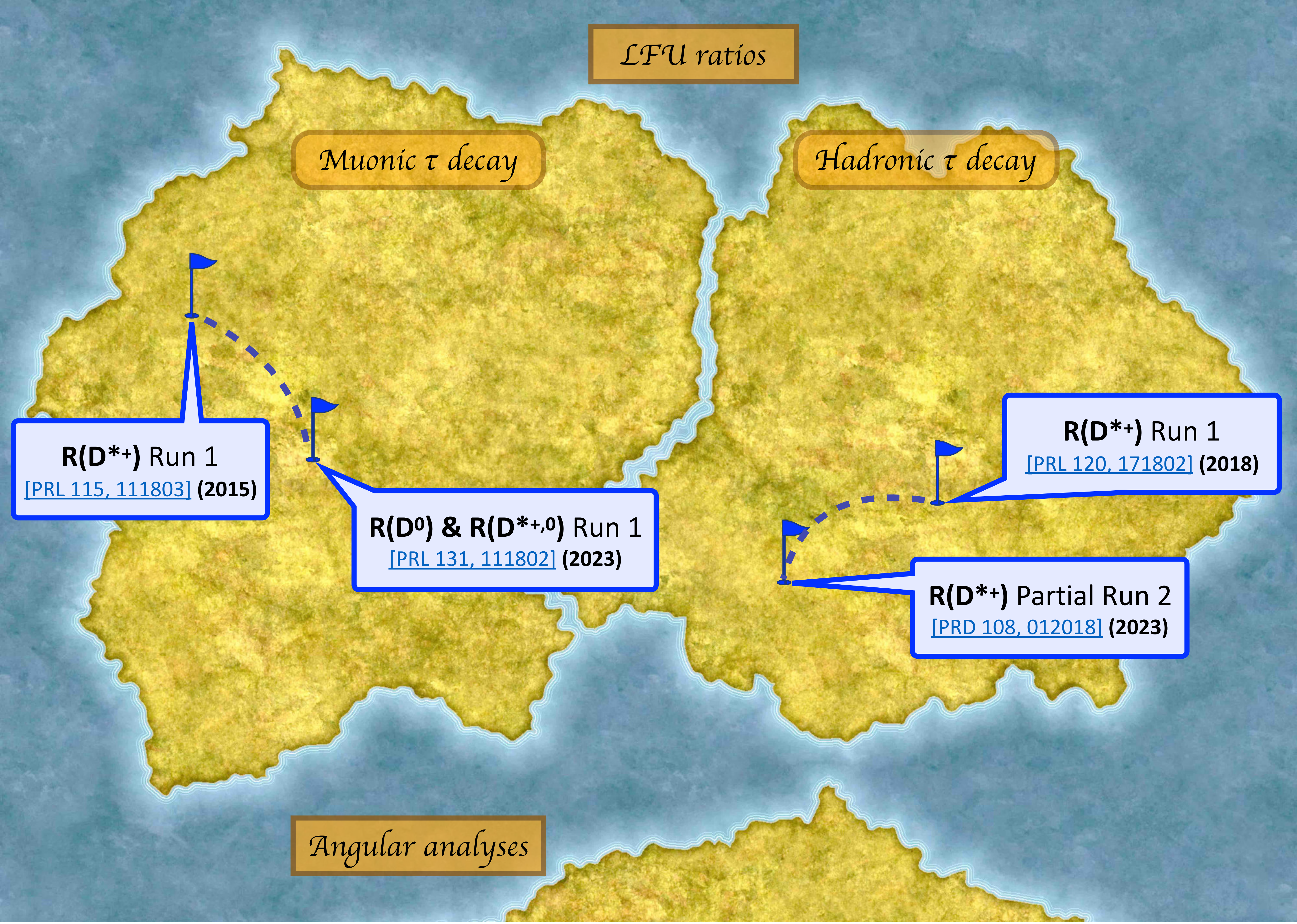


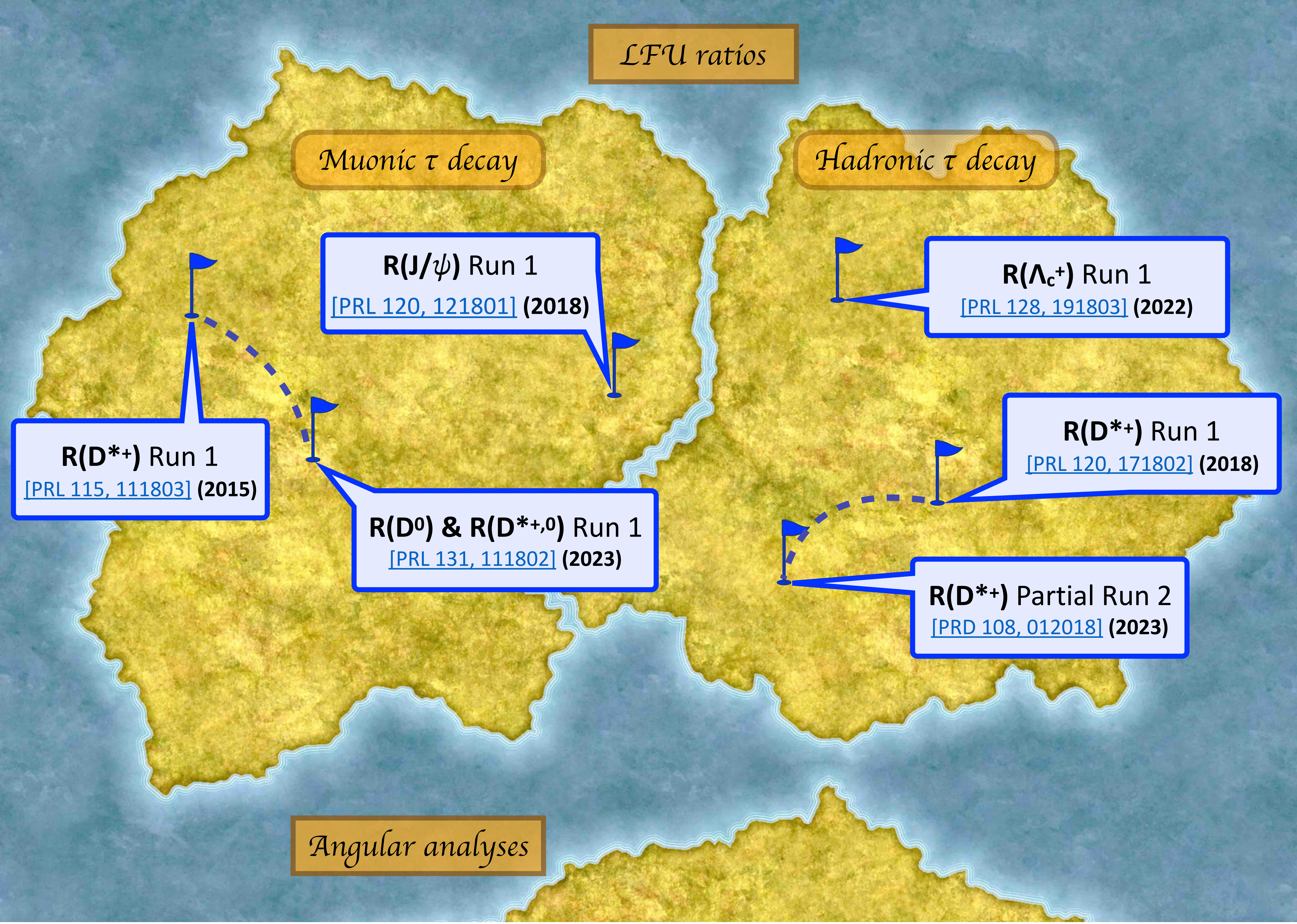
Pros:

- Tau vertex measurement and 3π kinematics allow for strong. background rejection and **high purity**.
- **Better resolution**, as B momentum can be determined up to a 2-fold ambiguity.

Cons:

- **Lower yields** due to smaller BF.
- **Requirement of external BF** to measure R(D$^{(*)}$).


LFU ratios
Muonic τ decay
Hadronic τ decay
R(D*+) Run 1
[PRL 115, 111803] (2015)
R(D0) & R(D*+,0) Run 1
[PRL 131, 111802] (2023)
R(D*+) Run 1
[PRL 120, 171802] (2018)
R(D*+) Partial Run 2
[PRD 108, 012018] (2023)
Angular analyses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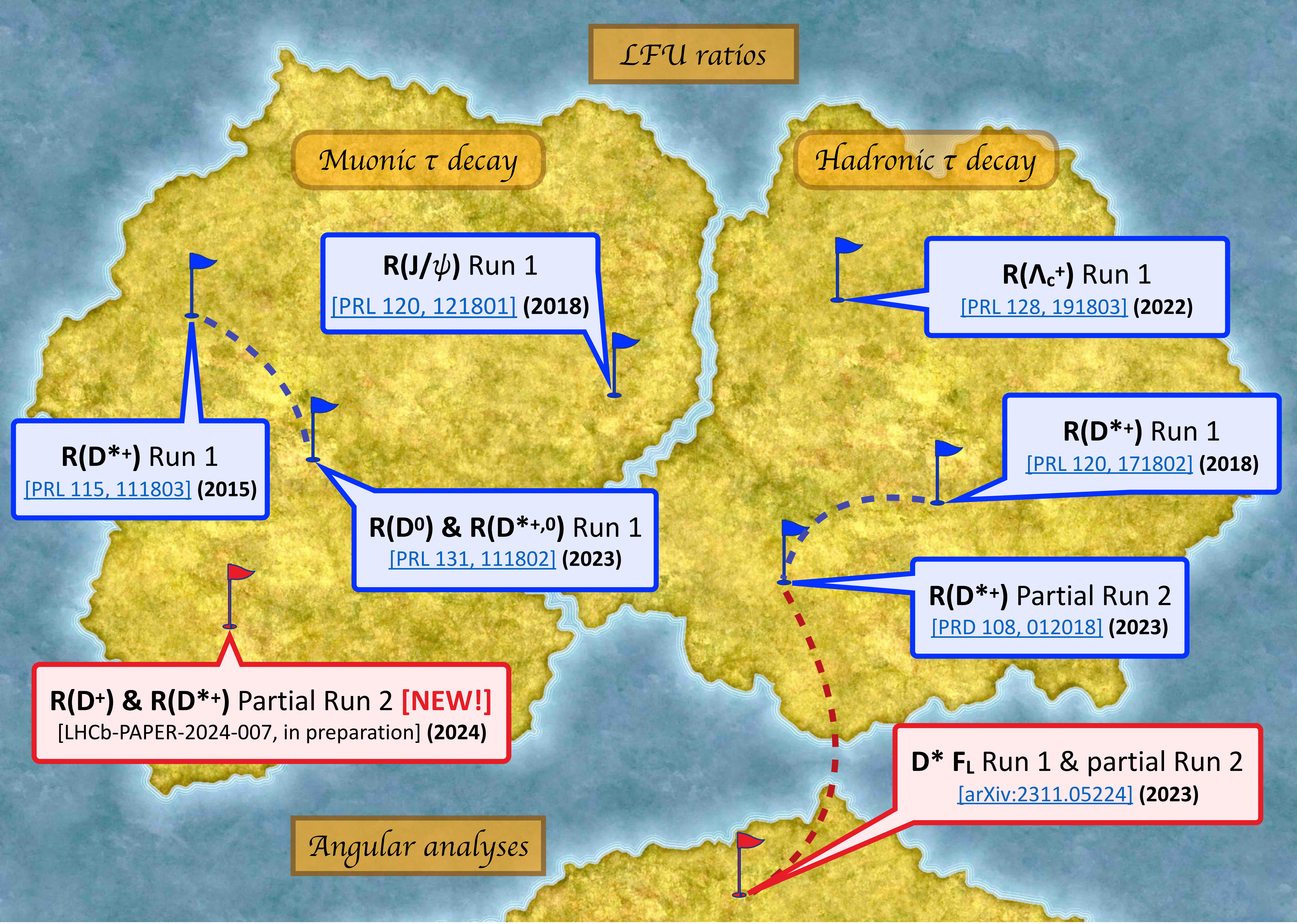
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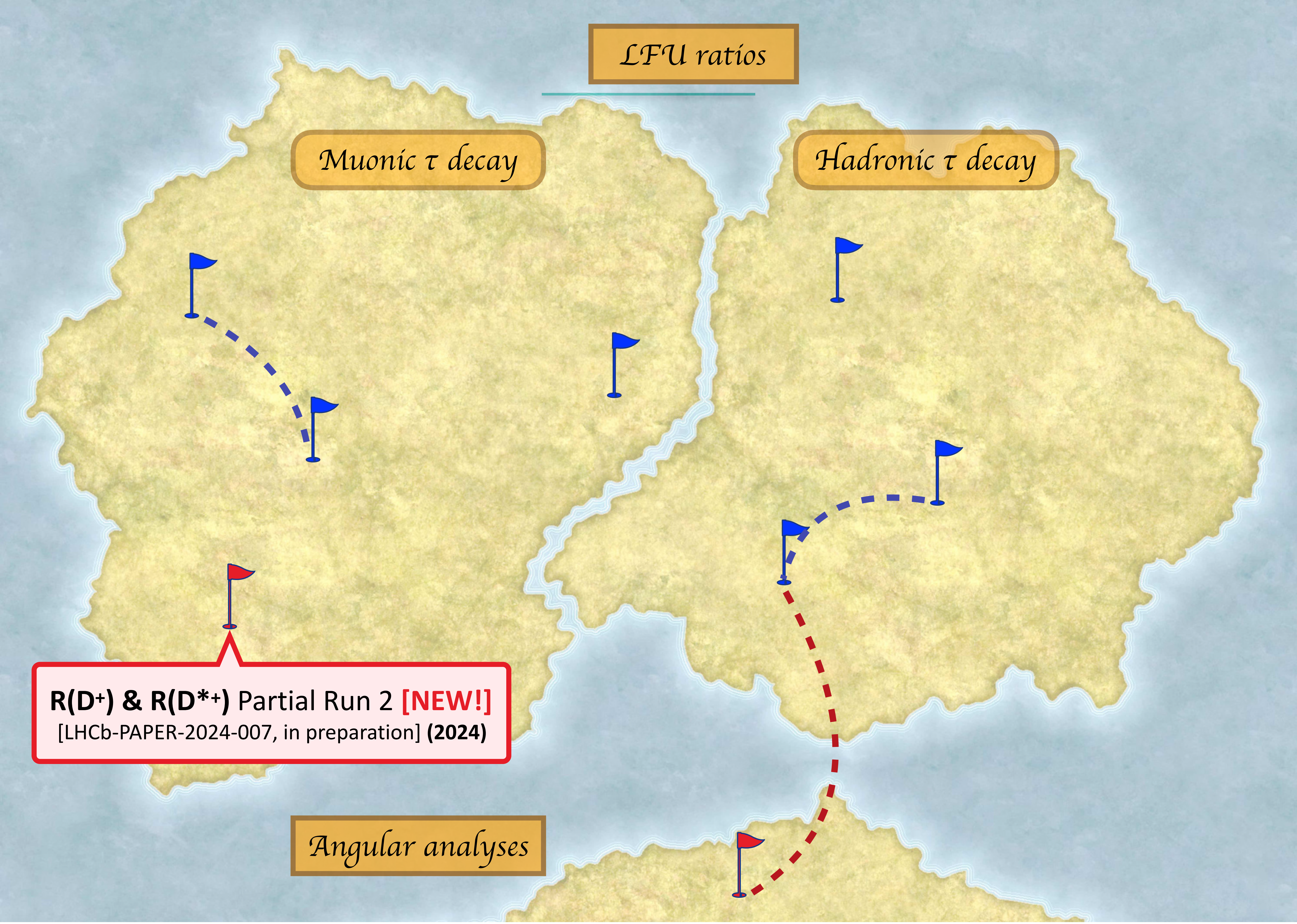
R(D+) & R(D*+) Partial Run 2 [NEW!]
[LHCb-PAPER-2024-007, in preparation] (2024)
D* FL Run 1 & partial Run 2
[arXiv:2311.05224] (2023)
Angular analyses


LFU ratios
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R(D+) & R(D*+) Partial Run 2 [NEW!]
[LHCb-PAPER-2024-007, in preparation] (2024)
Angular analyses

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

[NEW!]

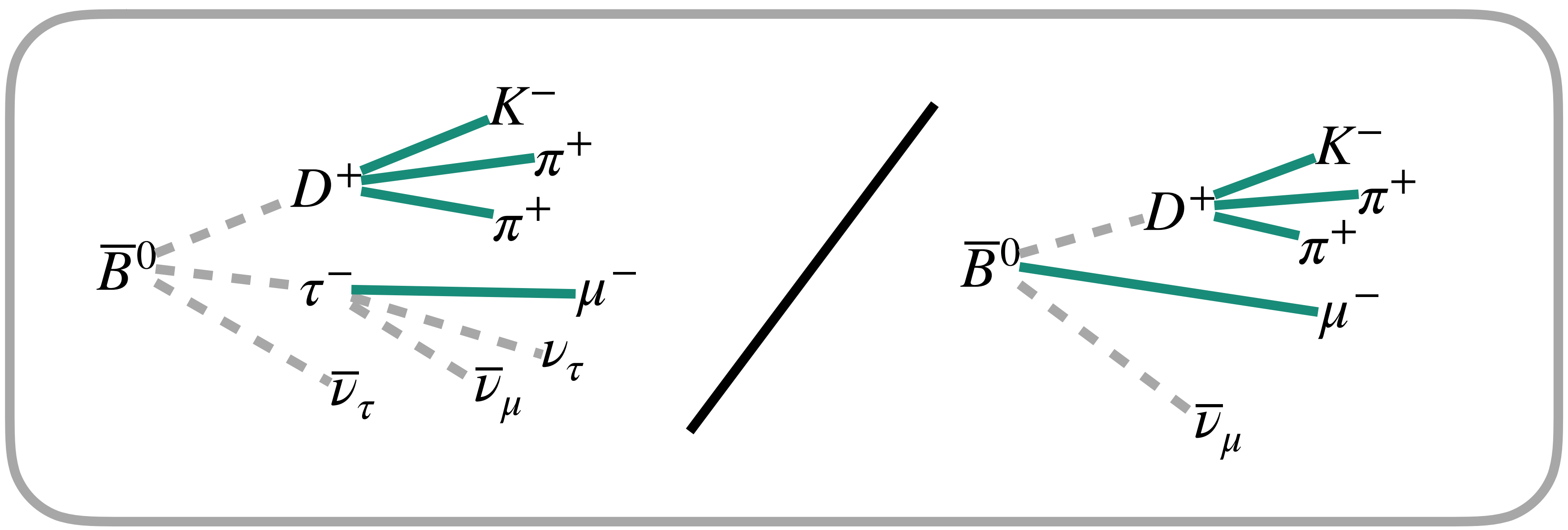
LHCb-PAPER-2024-007

First LHCb measurement using the D^+ ground state, with $D^+ \to K^- \pi^+ \pi^+$, **muonic-tau decay**.

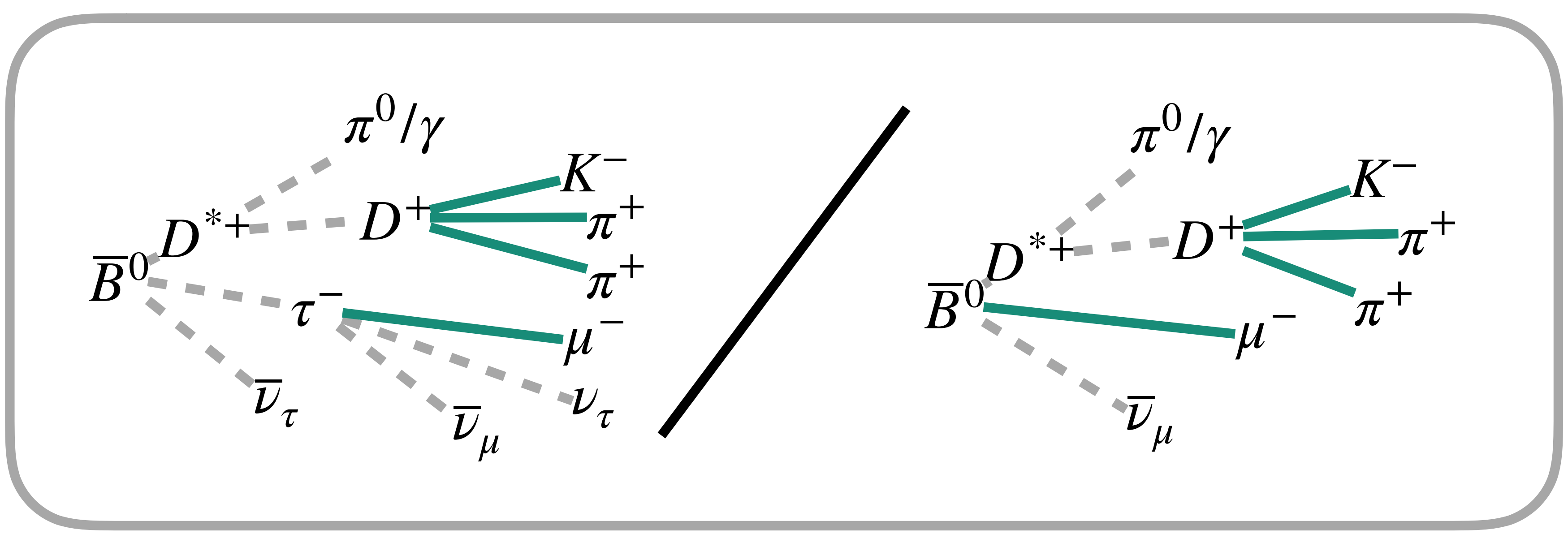
➥ Primary goal is to measure $R(D^+)$.

➥ Feed down from $D^{*+} \to D^+ \pi^0/\gamma$ with not reconstructed π^0/γ gives also access to $R(D^{*+})$ in the same visible final state $K^- \pi^+ \pi^+ \mu^-$.

$R(D^+)$ =



$R(D^{*+})$ =



Background reduction

[NEW!]

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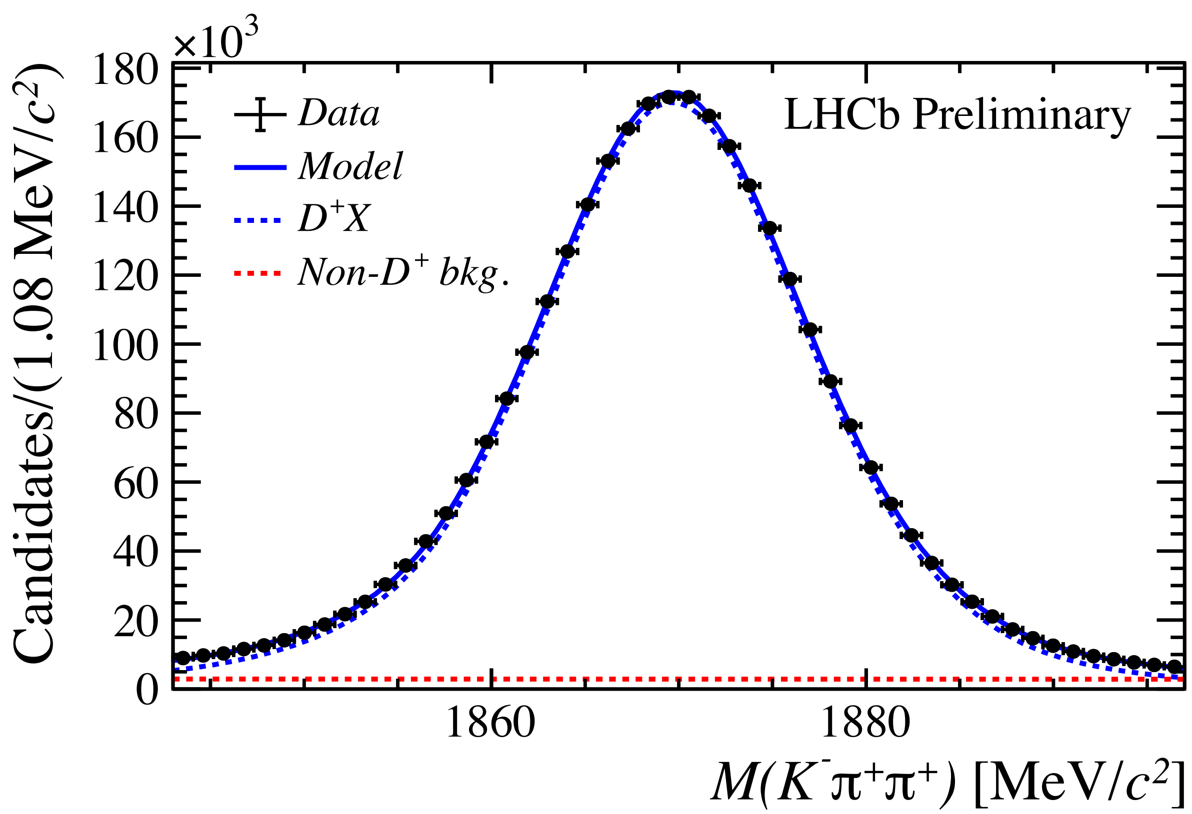
Data sample: $2fb^{-1}$. collected in **2015 and 2016**.

Candidate selection:

- **Basic requirements on $K^-\pi^+\pi^+\mu^-$ candidates** (topologic, kinematic and particle-identification).
- **Isolation against both charged and neutral particles** from the rest of the event.
  ➥ Inverse requirements on the charged isolation are combined with particle-identification requirements on extra particles to define **complementary control samples** (see next slide).
- **Fake-D^+ bkg. statistically subtracted with *sPlot* technique**, by fitting the $M(K^-\pi^+\pi^+)$ distribution.



Strategy to measure signal and norm. yields

[NEW!]

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3D binned template fit to data, using the rest-frame quantities m^2_{miss}, E_l^* and $q^2=(p_B-p_{D+})^2$.

Signal modes

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

$\overline{B}^0 \to D^{*+}[D^+\pi^0/\gamma]\tau^-[\mu^-\nu_\tau\overline{\nu}_\mu]\overline{\nu}_\tau$

Normalisation modes

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

$\overline{B}^0 \to D^{*+}[D^+\pi^0/\gamma]\mu^-\overline{\nu}_\mu$

Feed-down bkg. from 1P D states**

$B \to D^{**}[D^+X]\mu^-\overline{\nu}_\mu$

$B \to D^{**}[D^+X]\tau^-[\mu^-\nu_\tau\overline{\nu}_\mu]\overline{\nu}_\tau$

Double-charm bkg.

$B \to D^+H_c[\mu^-\overline{\nu}_\mu X]X'$

Muon Mis-ID bkg.

D^+h^-

Feed-down bkg. from higher-mass D states**

$B \to D^{**}[D^+X]\mu^-\overline{\nu}_\mu$

Neutronic bkg.

$\Lambda_b^0 \to nD^+\mu^-\overline{\nu}_\mu$

Combinatorial bkg.

D^+, μ^-

Simultaneous fit to four data samples, with enhanced sensitivity to specific components:

Signal sample

$D^+\mu^-$

1π sample

$D^+\mu^-\pi^-$

2π sample

$D^+\mu^-\pi^+\pi^-$

1K sample

$D^+\mu^-K^\pm$

Strategy to measure signal and norm. yields

[NEW!]

LHCb-PAPER-2024-007

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Combinatorial bkg.

D^+, μ^-

Simultaneous fit to four data samples, with enhanced sensitivity to specific components:

Signal sample $D^+\mu^-$ → Signal modes

1π sample $D^+\mu^-\pi^-$ → Feed-down bkg. from 1P D** states

2π sample $D^+\mu^-\pi^+\pi^-$ → Feed-down bkg. from higher-mass D** states

1K sample $D^+\mu^-K^\pm$ → Double-charm bkg.

Data-based templates

[NEW!]

LHCb-PAPER-2024-007

ation modes

$\mu^-\overline{\nu}_\mu$

$^+[D^+\pi^0/\gamma]\mu^-\overline{\nu}_\mu$

Feed-

$B \rightarrow$

$B \rightarrow$

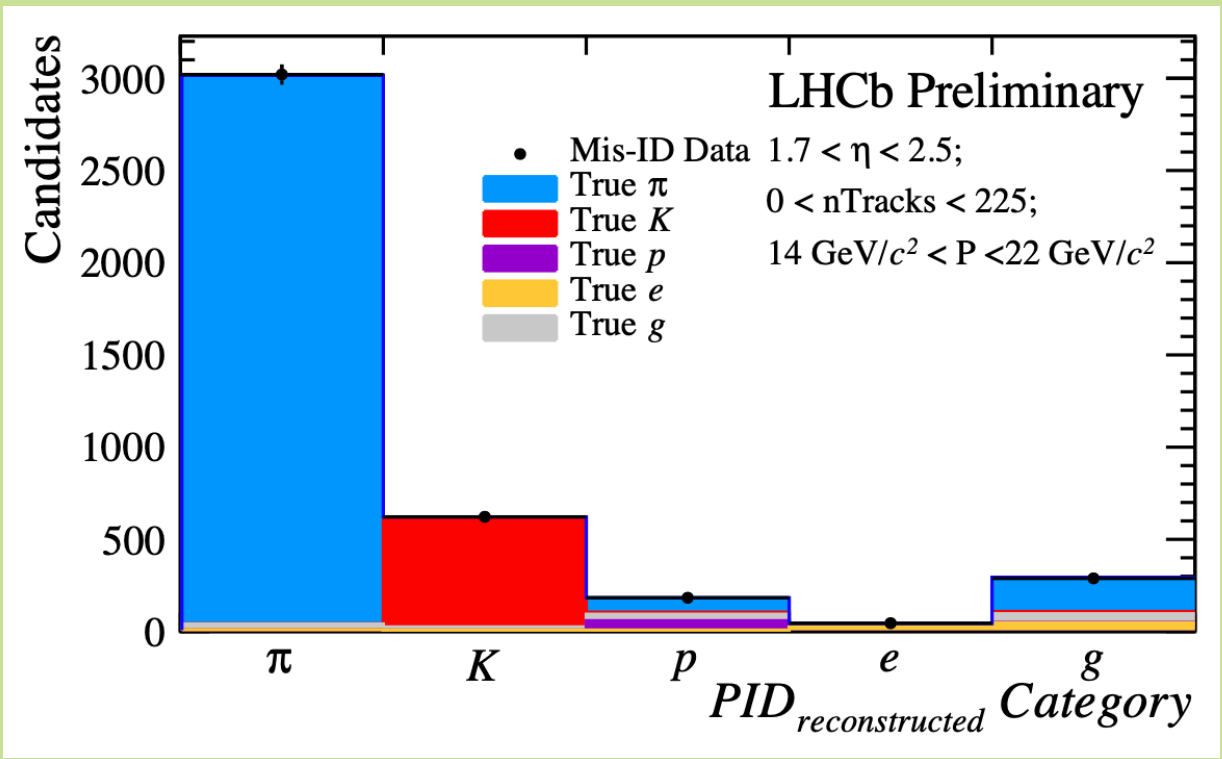
Feed-c

$B \rightarrow D$

bkg.

$\mu^-\overline{\nu}_\mu$

Obtained from **non-muon control sample**. **True-particle-type composition unfolded** by fitting the reconstructed-particle-type category.



(g (“ghost”) = fake tracks)

Muon Mis-ID bkg.
D^+h^-

Combinatorial bkg.
D^+, μ^-

Obtained from **wrong-sign ($D^+\mu^+$) control sample**.

Simulation-based templates: form factors

[NEW!]

LHCb-PAPER-2024-007

Signal modes

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

$\overline{B}^0 \to D^{*+}[D^+\pi^0/\gamma]\tau^-[\mu^-\nu_\tau\overline{\nu}_\mu]\overline{\nu}_\tau$

Normalisation modes

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

$\overline{B}^0 \to D^{*+}[D^+\pi^0/\gamma]\mu^-\overline{\nu}_\mu$

Feed-down bkg. from 1P D states**

$B \to D^{**}[D^+X]\mu^-\overline{\nu}_\mu$

$B \to D^{**}[D^+X]\tau^-[\mu^-\nu_\tau\overline{\nu}_\mu]\overline{\nu}_\tau$

Feed-down bkg. from higher-mass D st**

$B \to D^{**}[D^+X]\mu^-\overline{\nu}_\mu$

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 parameterisations:

- B → D$^+$: **BGL** [PRD 94 (2016) 094008]
- B → D*: **BGL** [Eur. Phys. J. C 82, 1141 (2022)]
- B → D**: **BLR** [PRD 95 (2017) 014022]

First analysis that uses 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).

Simulation-based templates: decay composition

[NEW!]

LHCb-PAPER-2024-007

Signal modes

$\ldots]\overline{\nu}_\tau$

$\ldots]\tau^-[\mu^-\nu_\tau\overline{\nu}_\mu]\overline{\nu}_\tau$

Normalisation modes

Component fractions varied.

Component fractions varied + shape corrections.

Feed-down bkg. from 1P D states**

$B \to D^{**}[D^+X]\mu^-\overline{\nu}_\mu$

$B \to D^{**}[D^+X]\tau^-[\mu^-\nu_\tau\overline{\nu}_\mu]\overline{\nu}_\tau$

Double-charm bkg.

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Feed-down bkg. from higher-mass D states**

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Neutronic bkg.

$\Lambda_b^0 \to nD^+\mu^-\overline{\nu}_\mu$

Shape correction.

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

Shape correction.

Modelling of detector effects in simulation

[NEW!]

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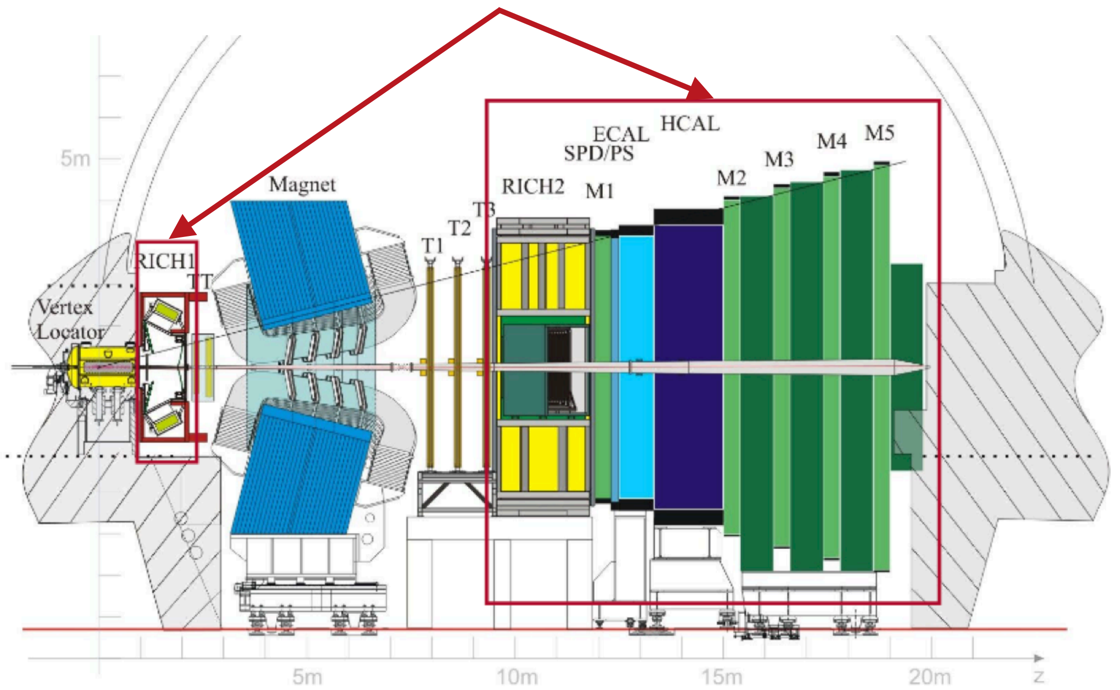
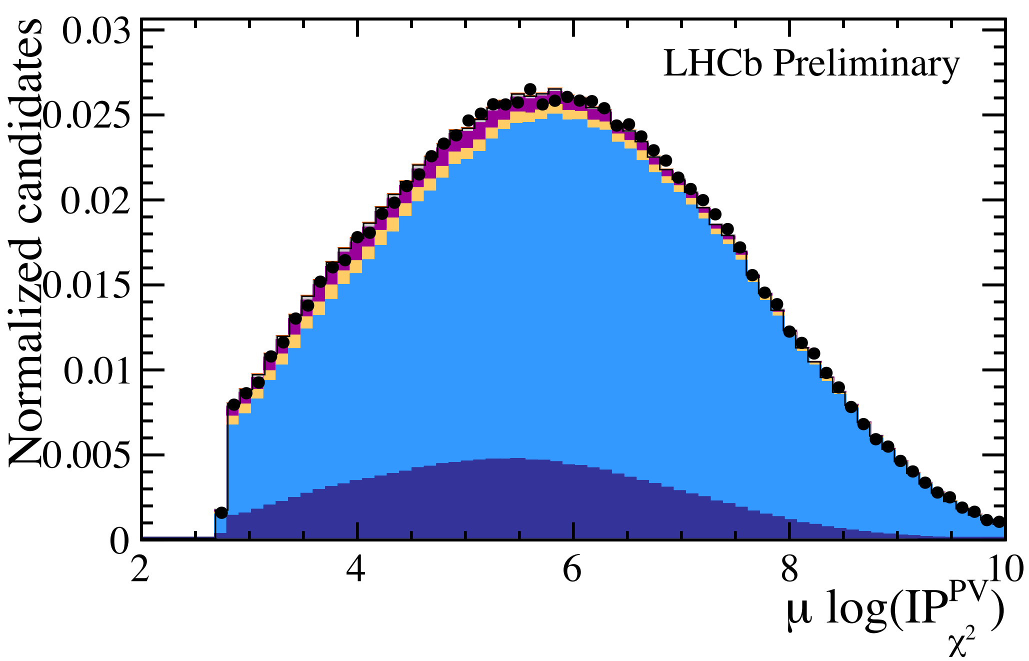
Tracker-Only ultra-fast simulation
➡ **First analysis that uses this method.**
➡ **Reduce syst. uncertainty on simulation sample size**.
➡ Emulation of missing features at analysis level.

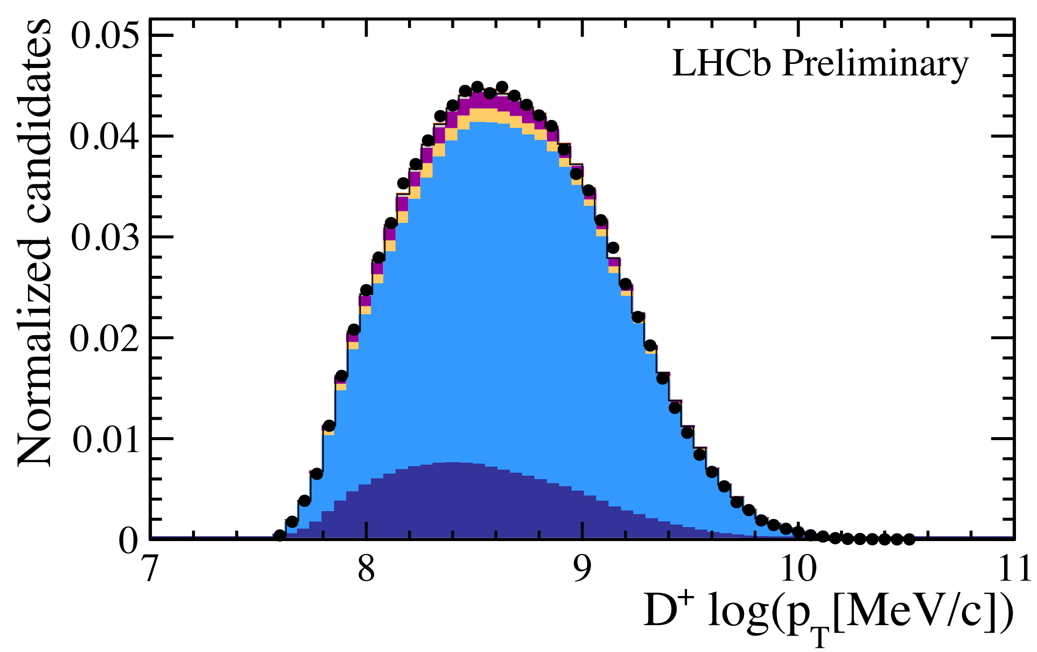
Sub-detector response turned off



Data/simulation corrections
➡ Multi-dimensional reweightings.
➡ Correction of QED effects [PRL 120, 261804 (2018)].

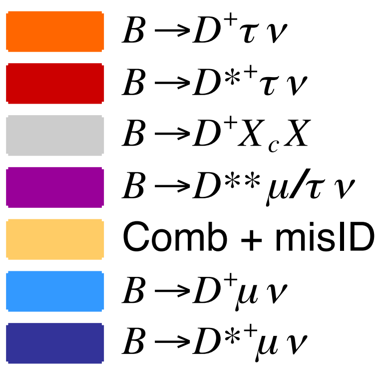
Excellent agreement achieved (see below for a normalisation-enriched control region).

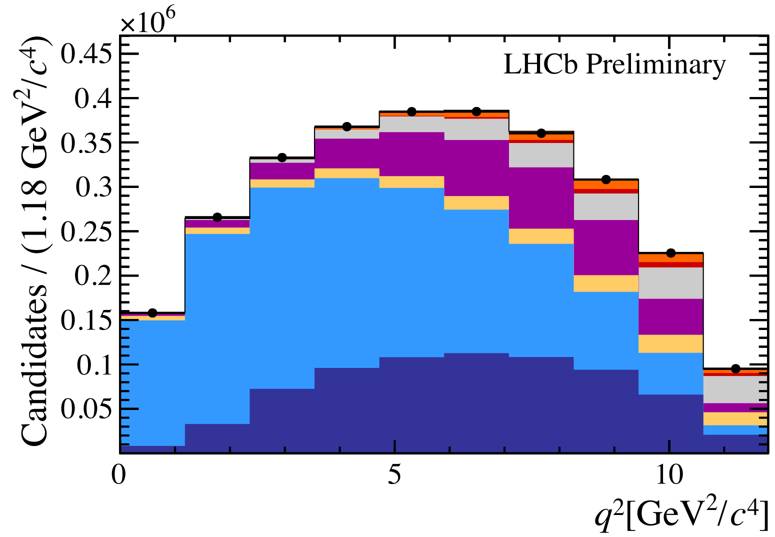


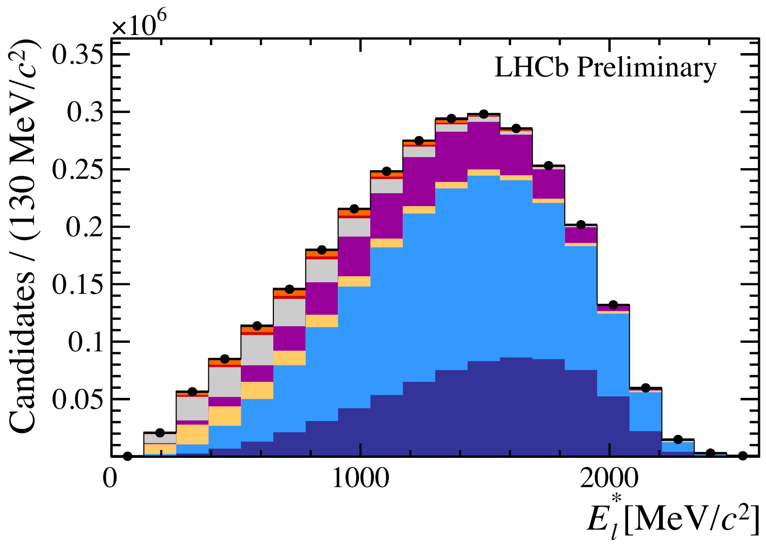


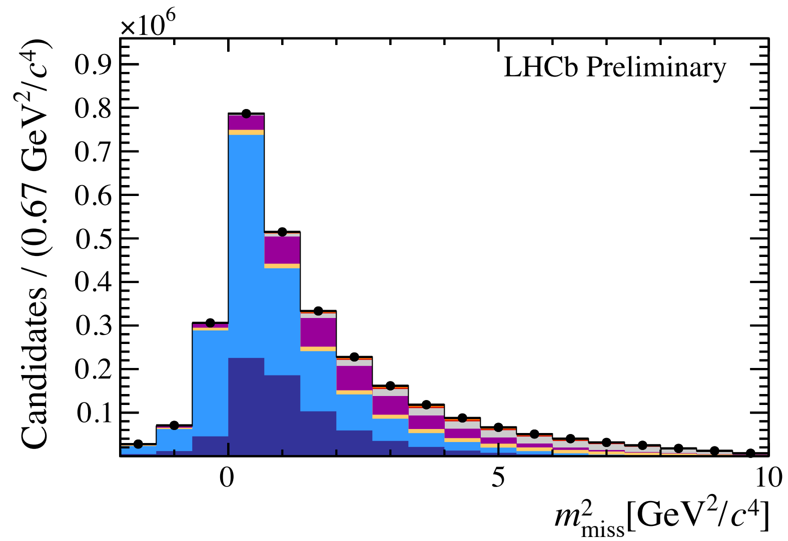
Results

Signal sample

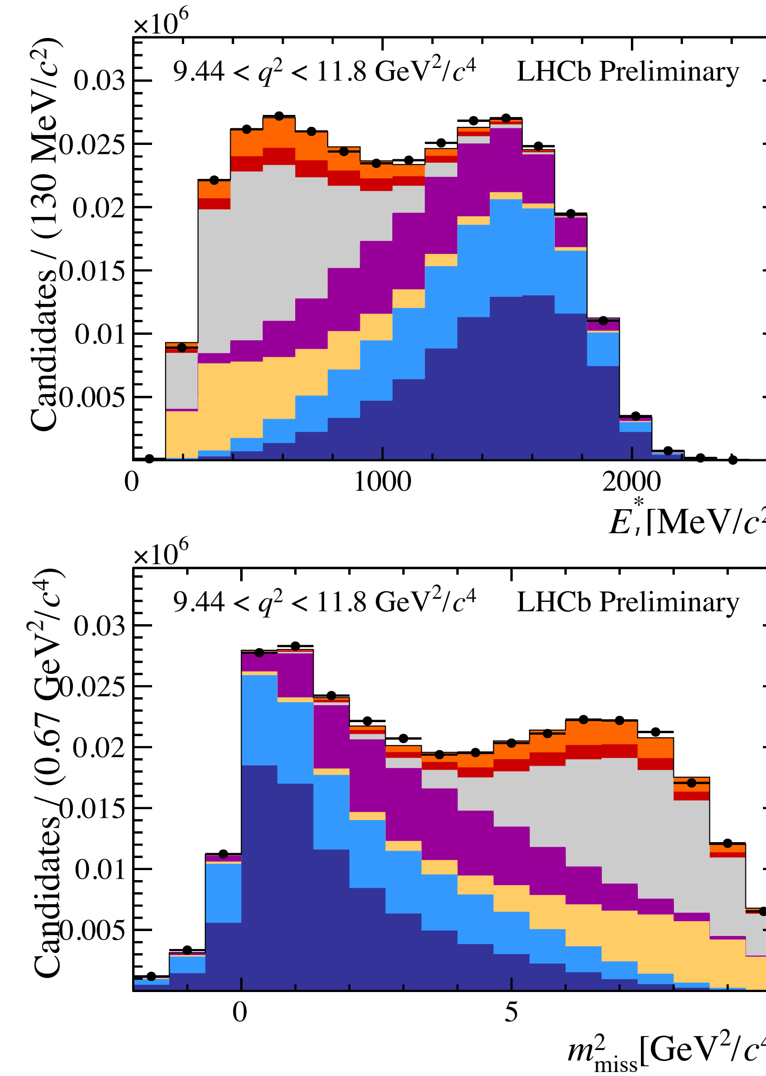




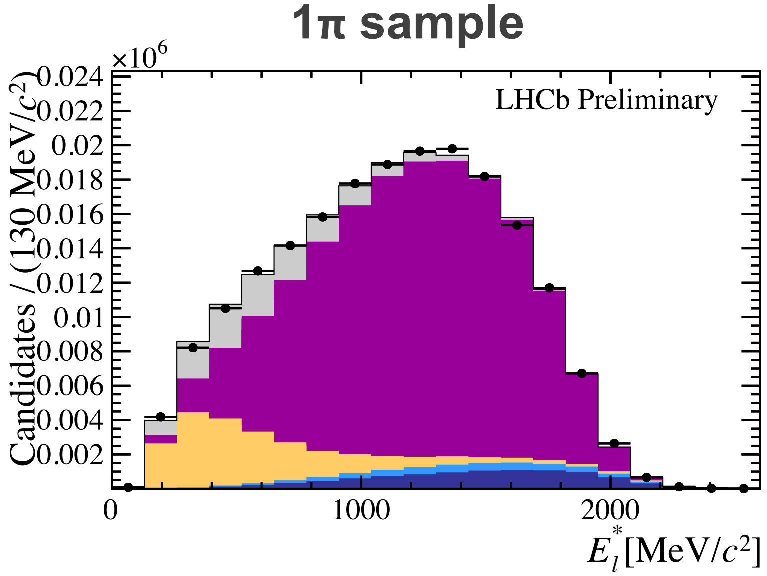




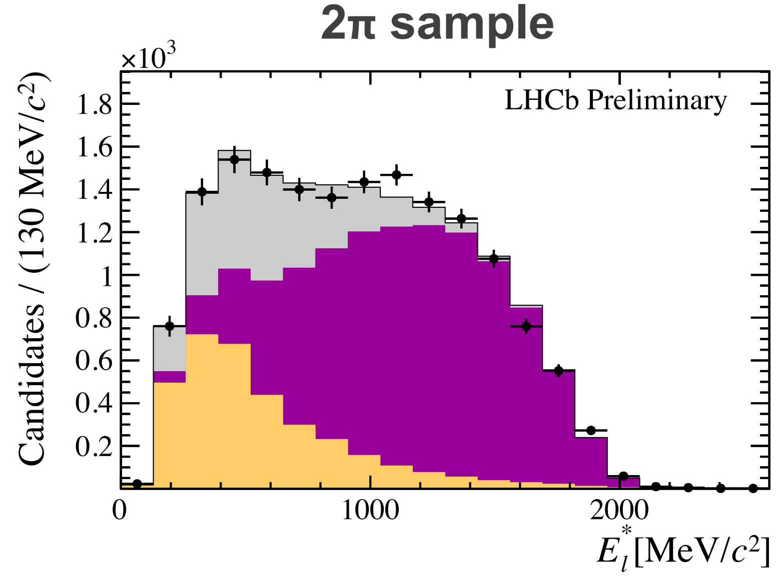
Zoom in high q² region



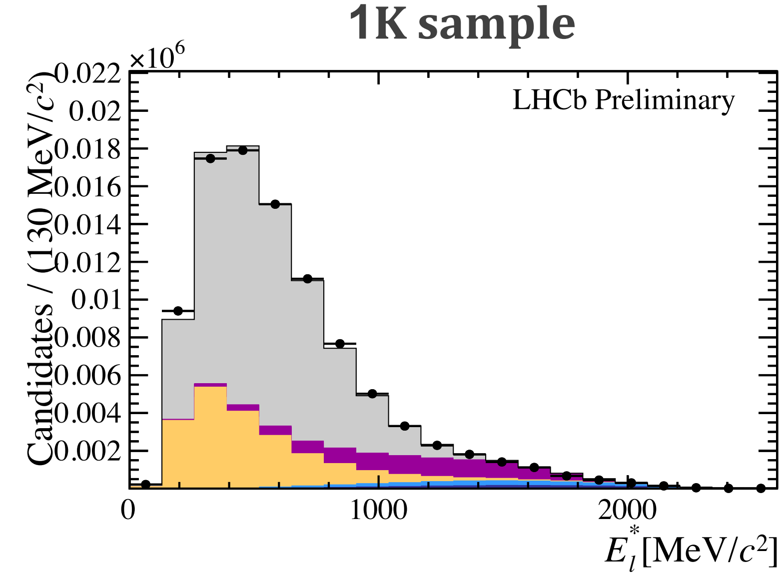
1π sample



2π sample



1K sample



Results

LHCb-PAPER-2024-007

From simulation.

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

[LHCb preliminary]

$R(D^+) = 0.249 \pm 0.043(stat) \pm 0.047(syst)$

$R(D^{*+}) = 0.402 \pm 0.081(stat) \pm 0.085(syst)$

$\rho = -0.39$

Results compatible with the SM at the **0.78 σ** level.
Results compatible with the (previous) World Average at the **1.09 σ** level.

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

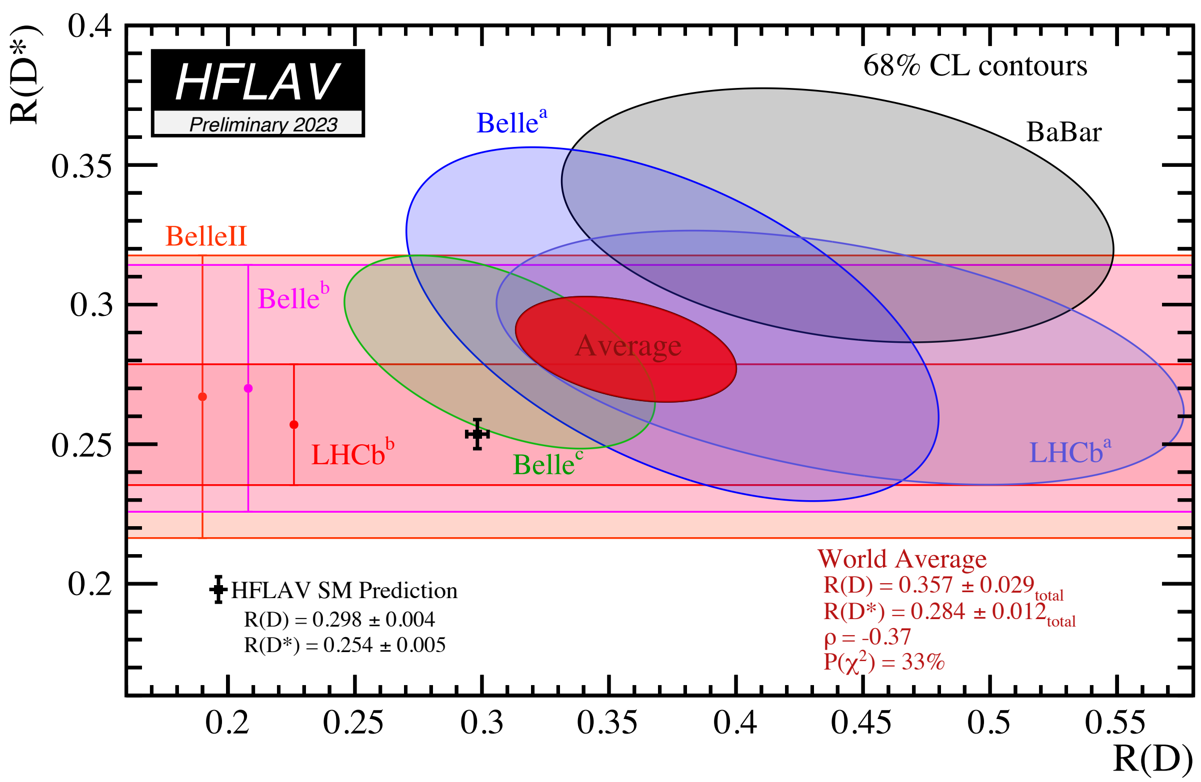
Main systematic uncertainties from form-factor parameterisation and background modelling.

New World Average

[NEW!]

LHCb-PAPER-2024-007

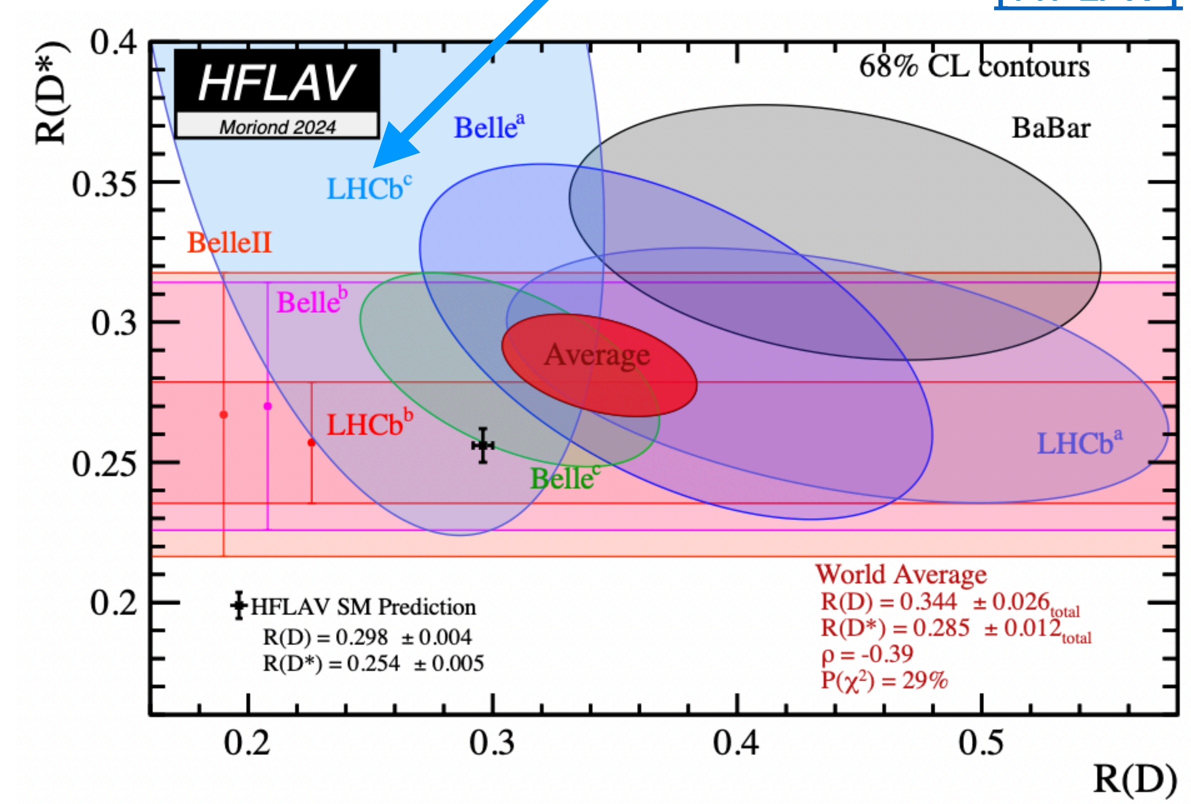
[HFLAV]



This result [LHCb preliminary]

[NEW!]

[HFLAV]



Previous World Average.
Tension with SM at the level of **3.34 σ**.

New World Average.
Tension with SM at the level of **3.17 σ**.

LHCb combination

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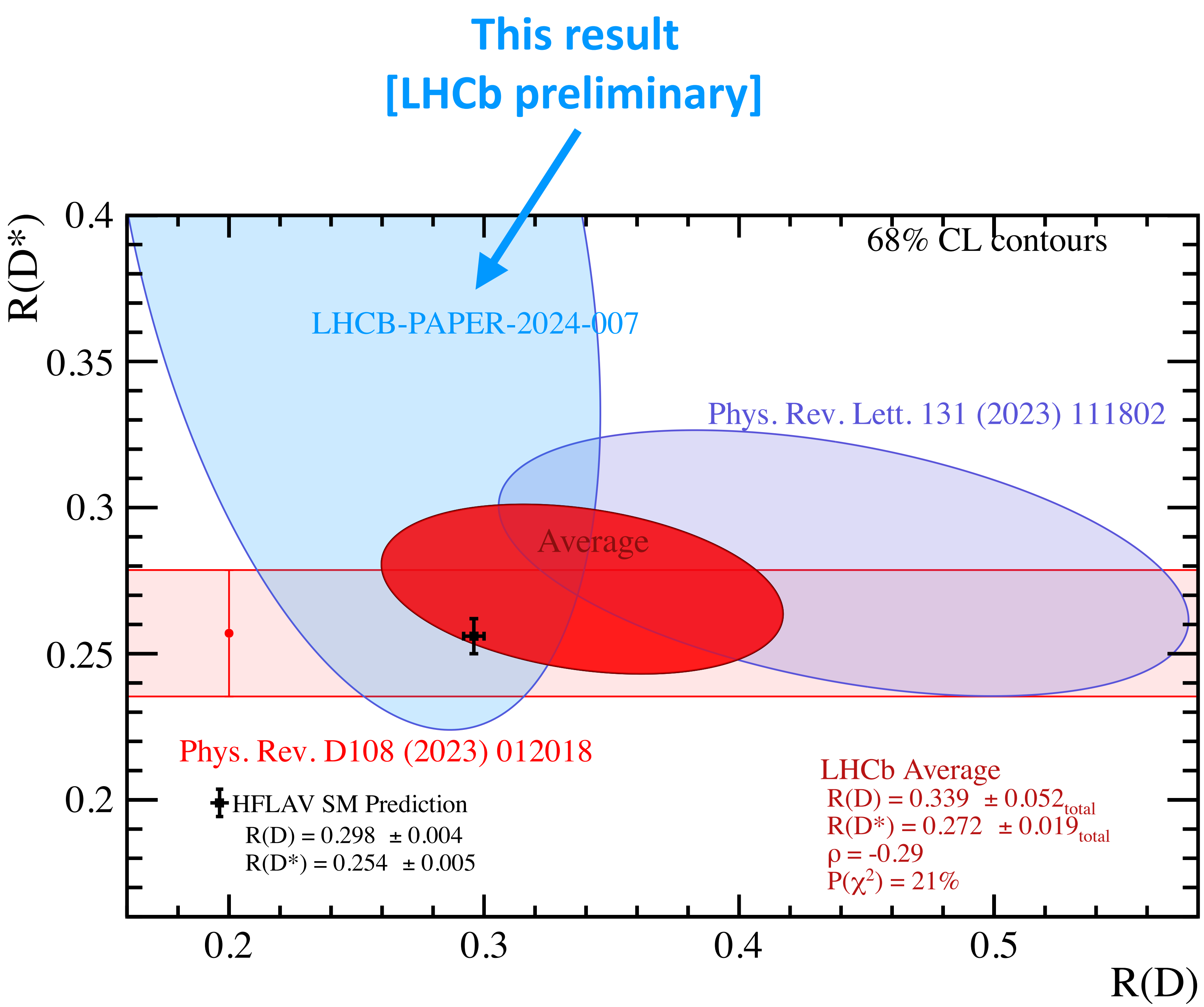

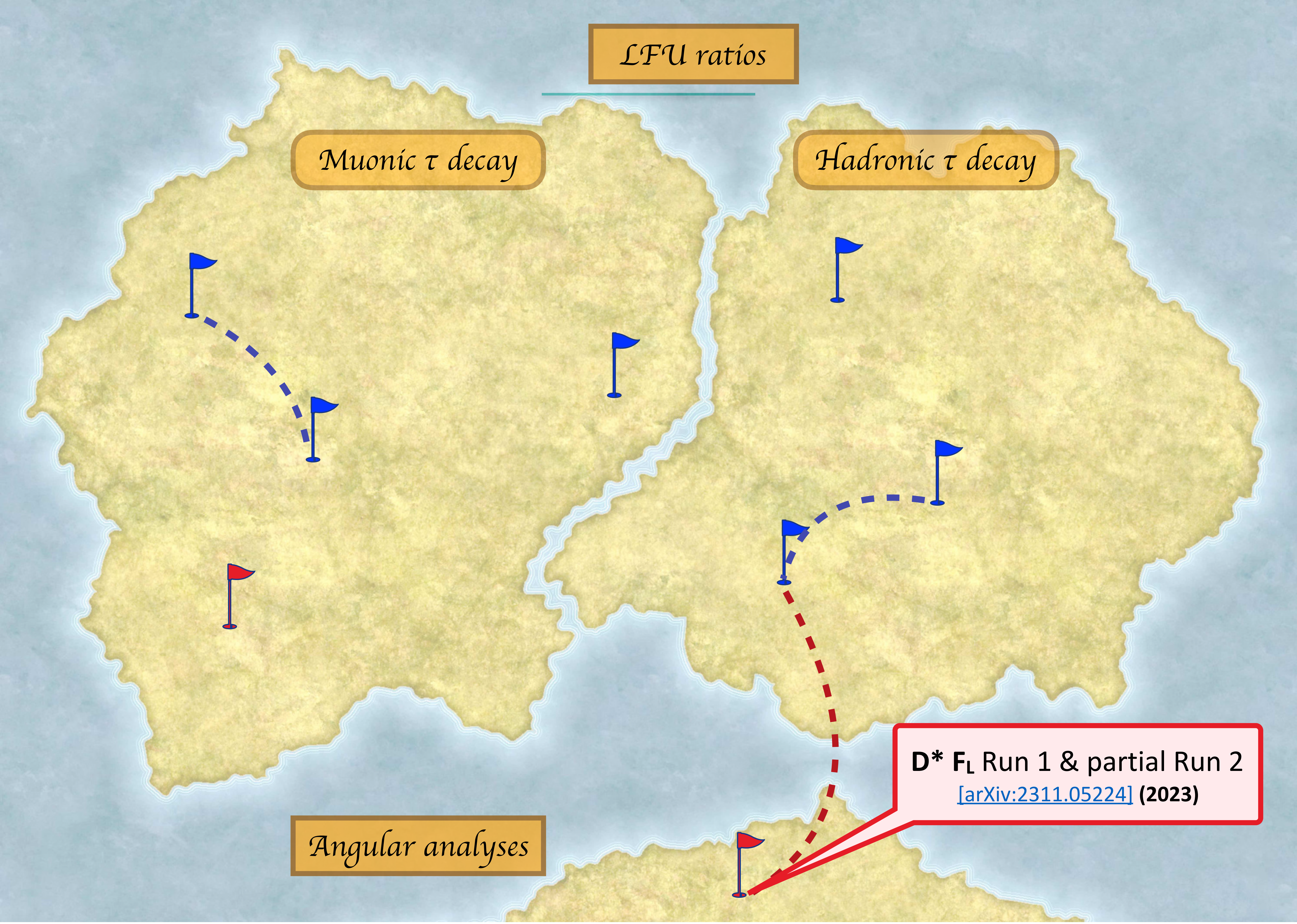
LFU ratios
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D* F_L Run 1 & partial Run 2
[arXiv:2311.05224] (2023)

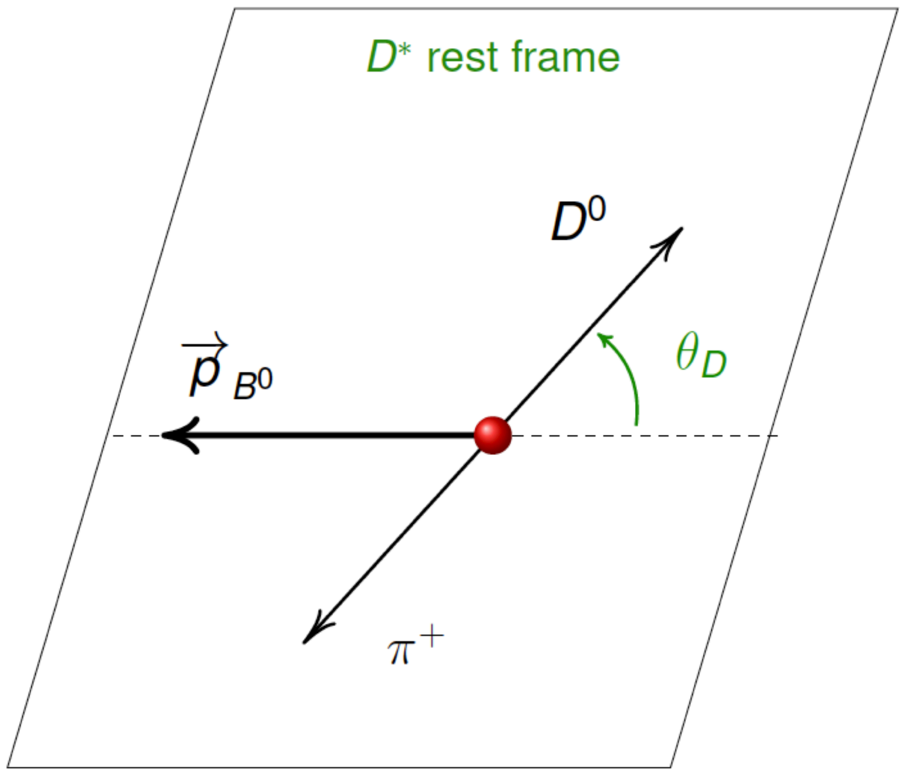
D* polarisation fraction in $\overline{B}^0 \to D^{*+}[D^0\pi^+]\tau^-\overline{\nu}_\tau$ decays

[arXiv:2311.05224]

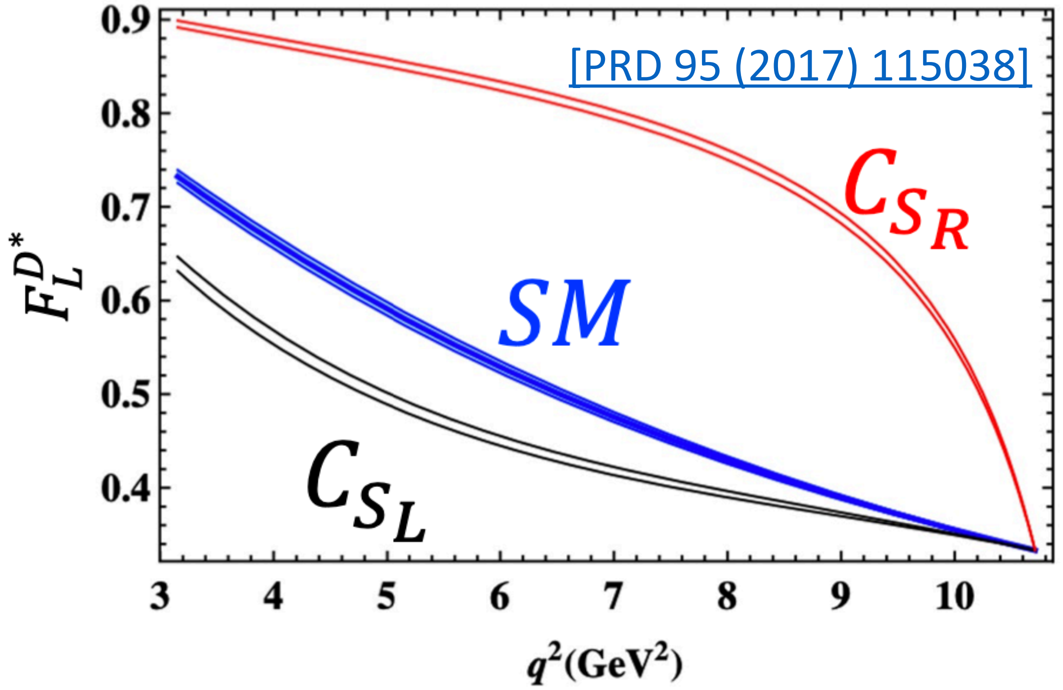
$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D \qquad F_L^{D^*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$

unpolarised signal fraction

polarised signal fraction



The presence of new mediators impacts the polarisation fraction.



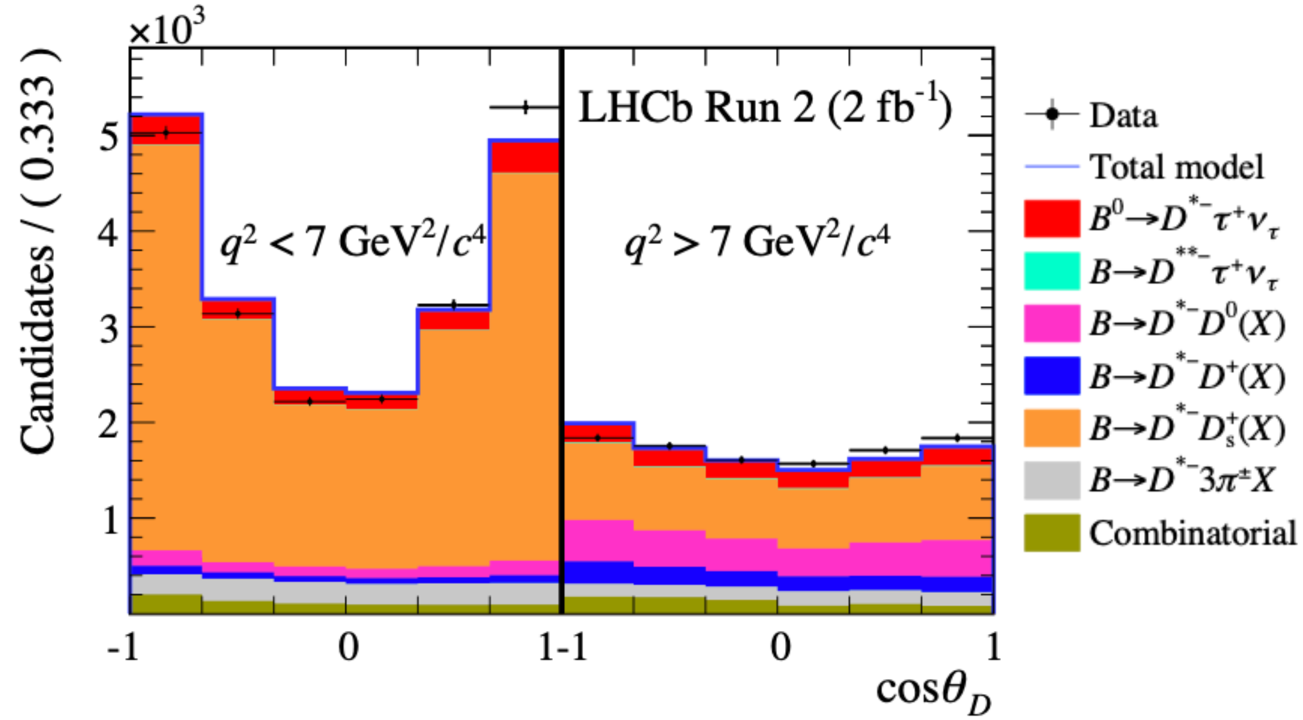
Analysis and results

[arXiv:2311.05224]

Run 1 + partial Run 2 ($5fb^{-1}$), **hadronic τ decay**.
➡Background suppression and control **similar to Run 2 R(D*) analysis** [PRD 108, 012018].

Measurement of F_L^{D*}:

- **4D-binned template fit** on: τ decay time, anti-D_s BDT output, **cos θ_D** and q^2 (**$q^2 \lesssim 7\ GeV^2/c^4$**).
- Two signal components: **polarised** & **unpolarised**.



Measured values of F_L^{D*}:

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

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]

Main systematic uncertainties from size of simulated samples, FF parameterisation and double-charm background modelling.

LFU ratios

Summary and outlook

Review of recent LHCb measurements of charged-current semileptonic decays, focused on $b \to c \tau \nu$ transitions.

First LHCb measurement of $R(D^+)$ & $R(D^{*+})$ **[NEW!]**, with a muonic decay of the tau lepton.

➥ **Compatible with the World Average and with the SM.**

➥ **New HFLAV average: overall tension at the level of 3.17 σ.**

First LHCb angular analysis of charged-current semitauonic decays, measuring the D^* polarisation fraction in $B^0 \to D^* \tau \nu$ with a hadronic decay of the tau lepton.

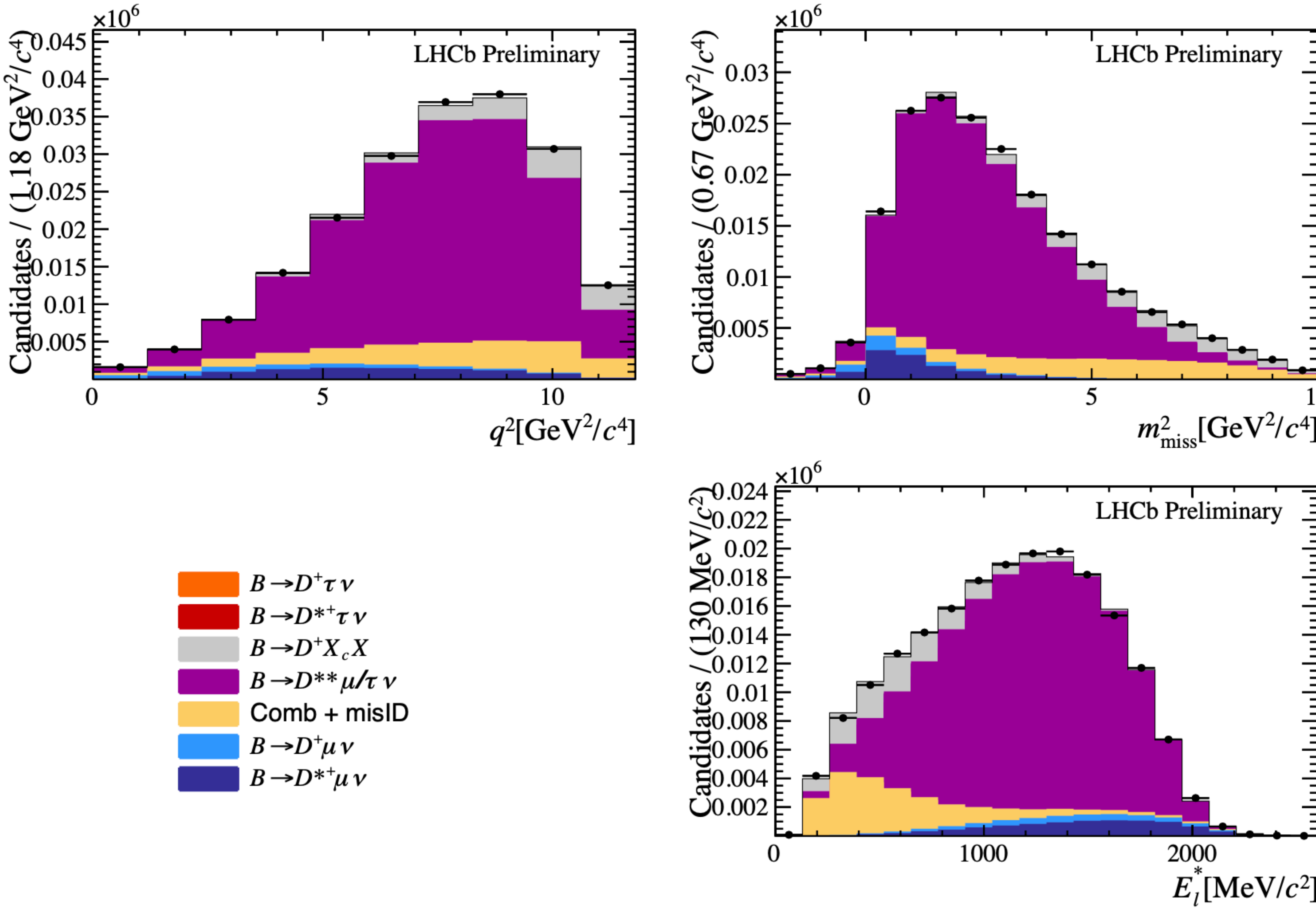
➥ **Better precision than previous result, compatible with it and with the SM**.

Outlook:

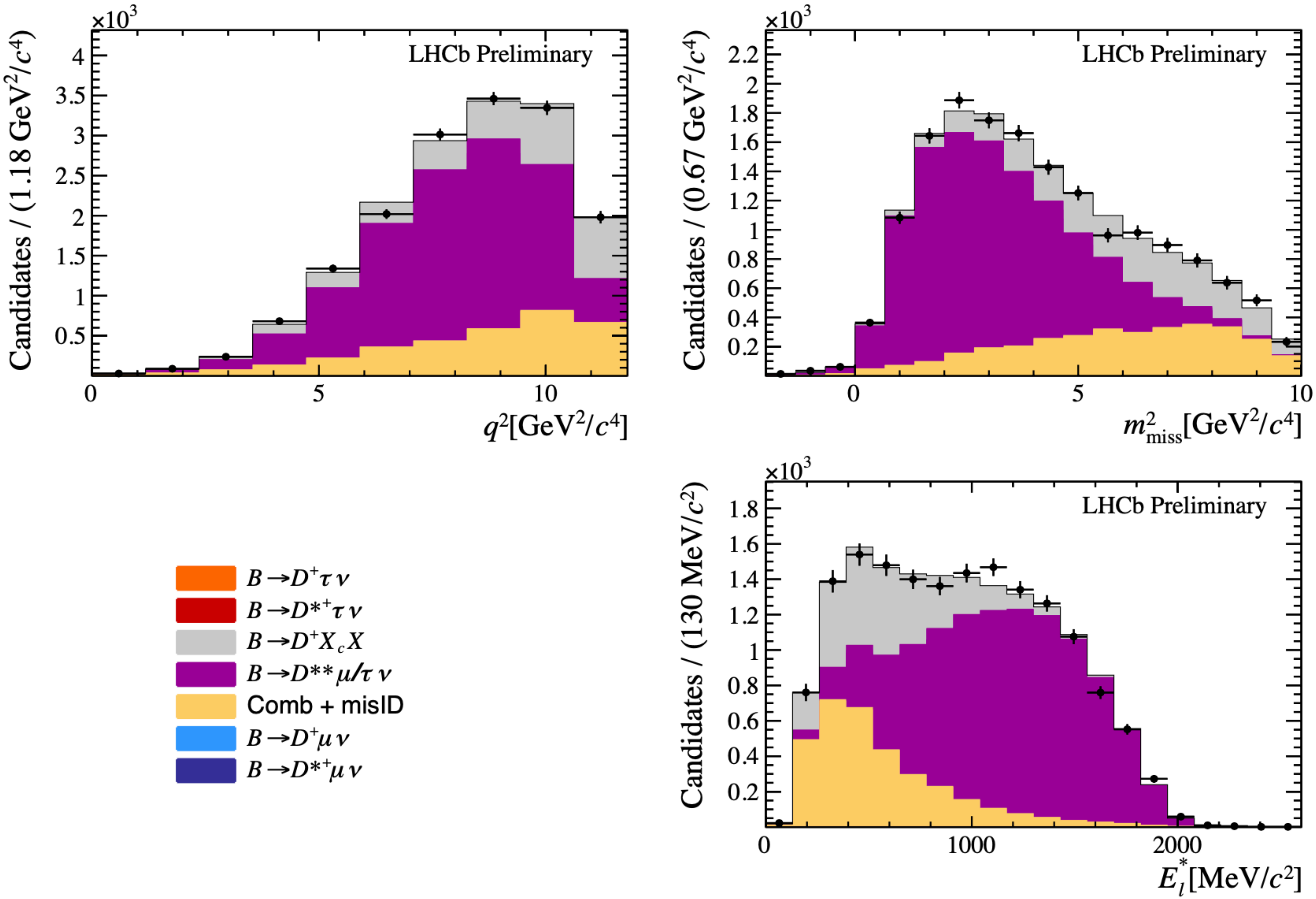
- Improve the precision of the current measurements: updates with full Run 2, Runs 3 and 4, Upgrade II (aiming to collect 300 fb^{-1}).
- Measure new observables: other $R(H_c)$ ratios, other angular observables.

Backup slides

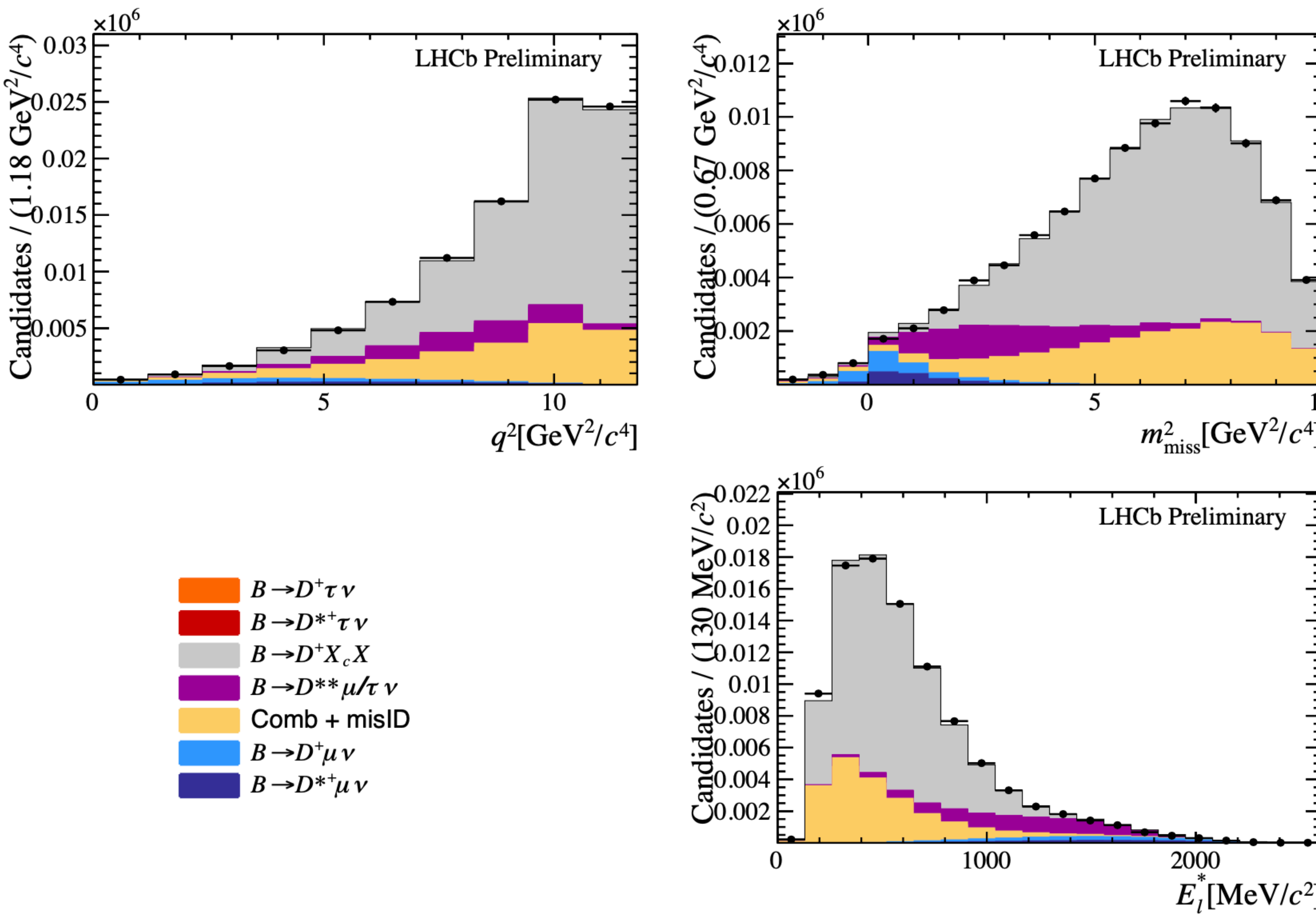
Measurement of $R(D^{(*)+})$: fit projections in 1π sample



Measurement of $R(D^{(*)+})$: fit projections in 2π sample



Measurement of $R(D^{(*)+})$: fit projections in 1K sample



Measurement of R(D$^{(*)+}$): analysis strategy

[arXiv:2311.05224]

Dataset: **Run 1 + partial Run 2** (5fb^{-1} in total), **hadronic τ decay**.

Background suppression and control similar to the Run 2 R(D*) analysis [PRD 108, 012018].

Measurement of $F_L^{D^*}$:

- 4D-binned template fit simultaneous on Run1 and Run2 data on: cos θ_D, q^2 (split in two regions $q^2 \lessgtr 7$ GeV^2/c^4), τ decay time and anti-D_s BDT output.
- Split the signal model into polarised and unpolarised components, whose relative fraction can be used to determine $F_L^{D^*}$.

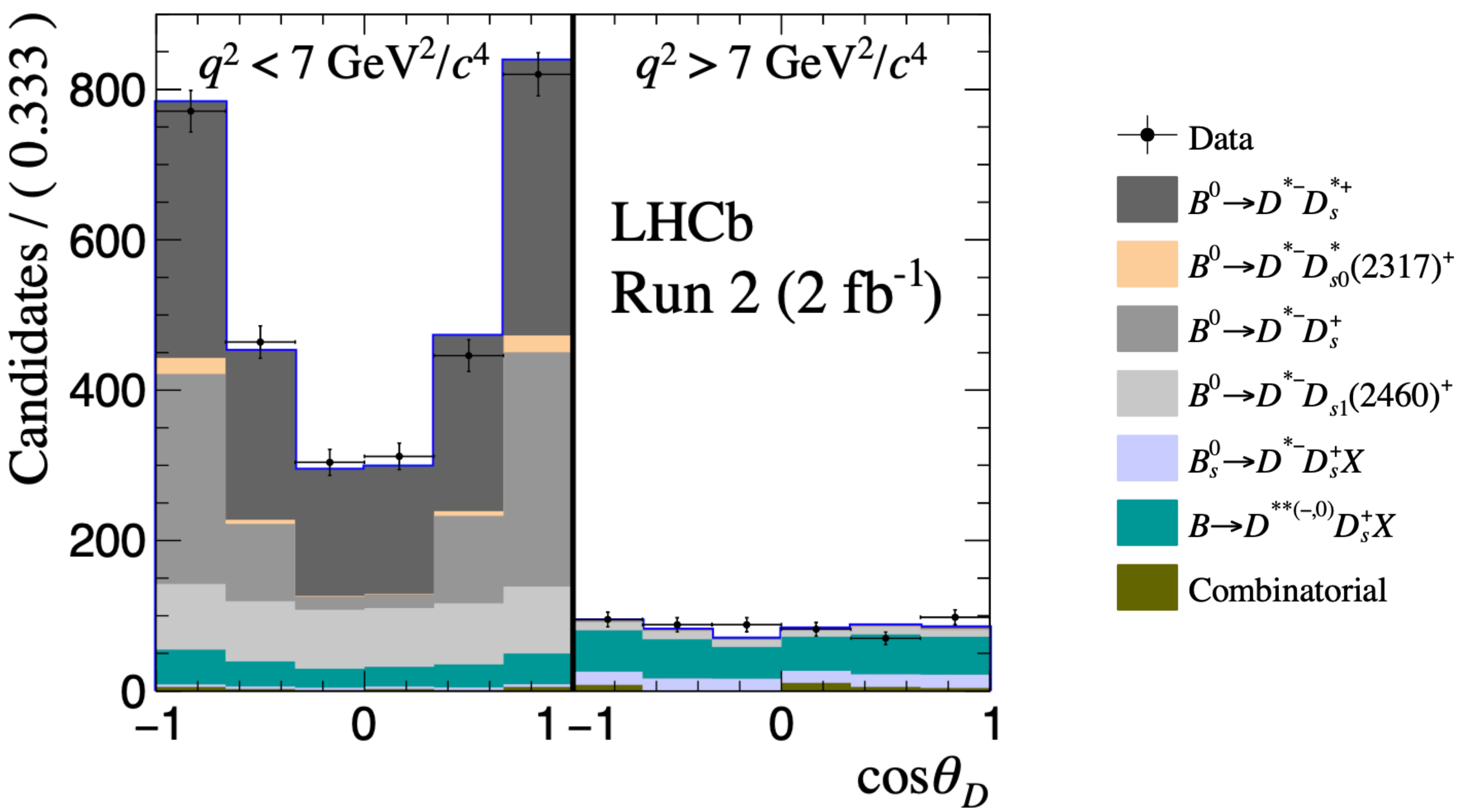
Background suppression:

- **"Prompt-decay" bkg., B→D*3πX (BF ~ 100x signal)**: require **displacement** between τ and B vertices + BDT in Run 2.
- **Double charm bkg., B→D*$D^{+,0}_{(s)}$ X (BF ~ 10x signal)**: **isolation** from extra charged particles + anti-D_s BDT (including isolation from extra neutral particles and **3π kinematics**).

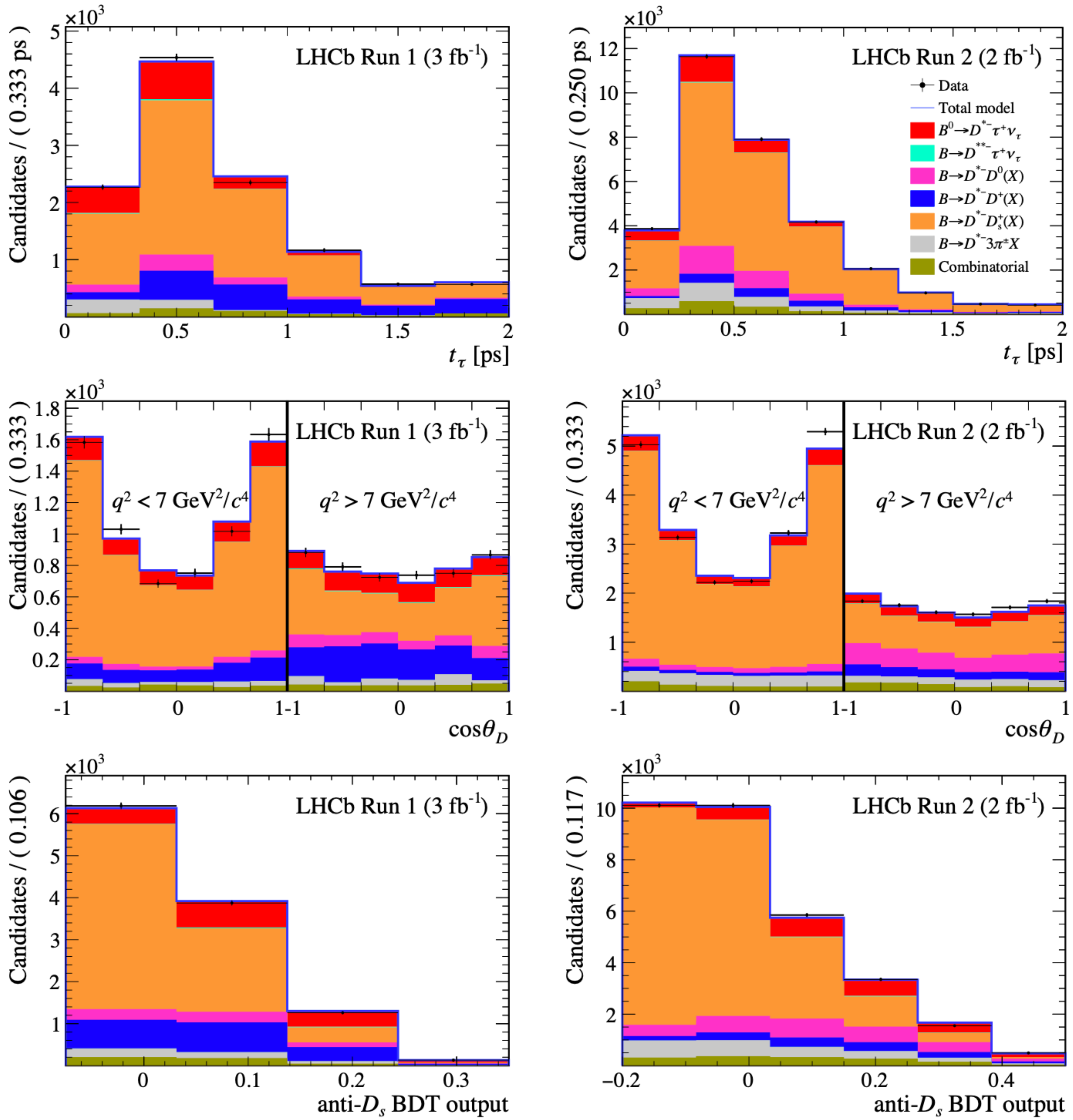
Data-driven correction of simulation samples:

- $D_s^{(*,**)}$ production fractions and D_s decay models in **B→D*$D^{+,0}_s$ X**.
- **B→D*$^-$$D^{0,+}$(X)** templates.

Measurement of D* F_L: control sample for $B \to D^* D^{+,0}_s X$



Measurement of D* F_L: fit projections



Measurement of D* F$_L$: systematic uncertainties

[arXiv:2311.05224]

Source	low-q^2	high-q^2	whole q^2 range
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 $\tau^+ \to \pi^+\pi^-\pi^+\pi^0\nu_\tau$ 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