Recent Belle II results on tests of lepton flavor universality in semileptonic B meson decays

Karol Adamczyk
on behalf of the Belle II Collaboration

THE 17th INTERNATIONAL CONFERENCE ON HEAVY QUARKS AND LEPTONS
Sept. 15-19, 2025 · Beijing, China

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

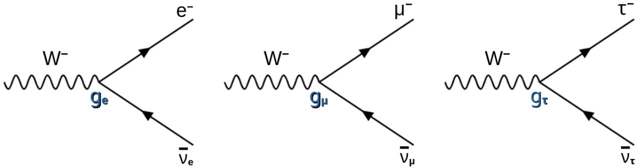
Belle II

Outline

1. Introduction
   - Motivation
   - Belle II experiment overview
   - Experimental techniques
2. first tests of LFU via **inclusive and exclusive semileptonic B decays** at Belle II
   - $\mathcal{R}(X)$ with exclusive hadronic B tagging using 189 fb^{-1}
   - $\mathcal{R}(D^*)$ with exclusive hadronic B tagging using 189 fb^{-1}
   - $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with exclusive semileptonic B tagging using 365 fb^{-1}
3. Prospects and summary

Lepton Flavor Universality

one of the assumption in SM

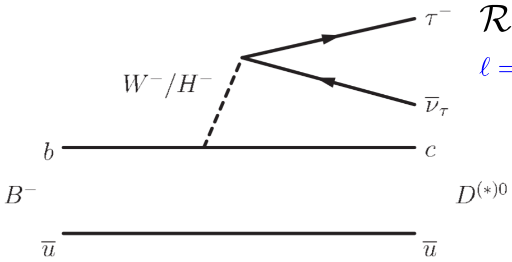


- in the SM all leptons share the same electroweak coupling, a symmetry known as Lepton Flavor Universality: $g_e = g_\mu = g_\tau$
- branching fractions differ due to phase space availability ($m_e < m_\mu < m_\tau$)
- Is this symmetry of SM fully preserved? any deviation would be a clear sign of BSM physics

test "laboratories": on shell W decays in ATLAS/CMS/...; off shell in B & τ decays at Babar/Belle/Belle II/LHCb/...

Semitauonic B decays

A Lepton Flavor Universality laboratory [1]



$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to \overline{D}^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to \overline{D}^{(*)}\ell^+\nu_\ell)}$$

$\ell = e, \mu$

- cancellation of V_{cb} and partially FF
- (partial) cancellation of experimental effects (luminosity and $\sigma_{b\bar{b}}$, reconstruction efficiencies, particle identification, . . .)

Motivation:

- theoretically clean (small hadronic effects)
- sensitive to New Physics at tree level (i.a. extended Higgs sector)

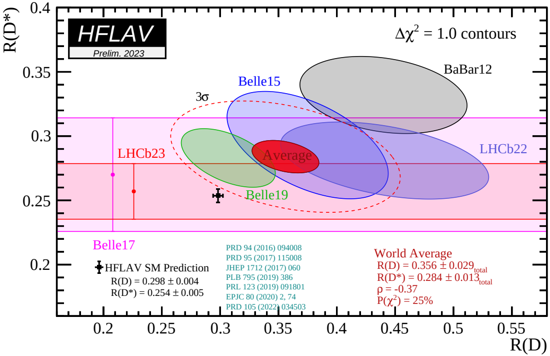
Arithmetic average of SM predictions from HFLAV (2025):

$$R(D)^{\mathrm{SM}} = 0.296 \pm 0.004$$
$$R(D^*)^{\mathrm{SM}} = 0.254 \pm 0.005$$

[1] "Semitauonic b -hadron decays: A lepton flavor universality laboratory", Rev. Mod. Phys. **94**, 015003 (2022)

LFU in B decays

tension with SM



difference with the SM predictions:

3.2σ for $\mathcal{R}(D)$&$\mathcal{R}(D^*)$

1.98σ for $\mathcal{R}(D)$, 2.15σ for $\mathcal{R}(D^*)$

$\mathcal{R}(D) - \mathcal{R}(D^*)$ correlation: -0.37

(winter 2023) // before presented Belle II

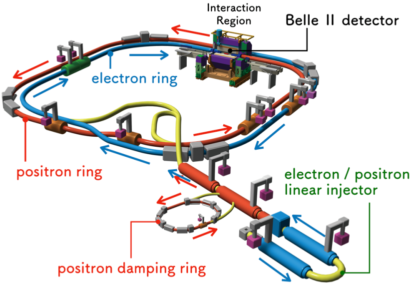
measurements, and new result from LHCb)

Present and future experimental efforts @ Belle II:

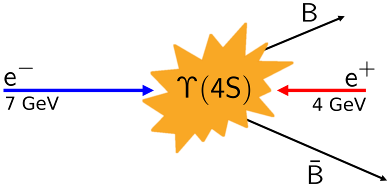
- ongoing updates on $\mathcal{R}(D)$ and $\mathcal{R}(D^{(*)})$
- measure other complementary ratios in inclusive ($R(X_{\tau/\ell})$) and exclusive ($R(\pi)$) B decays
- utilize additional observables sensitive to interaction structures
  $\Rightarrow$ angular observables (D^*, τ polarizations), kinematic spectra (q^2)

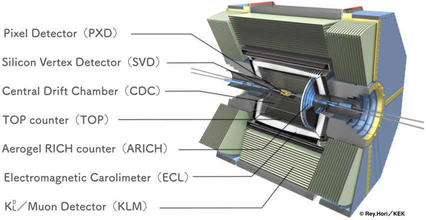
Belle II experiment

SuperKEKB: Intensity Frontier machine



- asymmetric e^+ e^- collider operating **mainly** at energy of $\Upsilon(4S)$ (10.58 GeV)
- **Dec 2024: World record of instantaneous L: 5.1 $\times$ 10^{34} cm^{-2}s^{-1}**
- **SuperKEKB + Belle II detector** $\equiv$ 2$^{\text{nd}}$ generation **super B-factory**

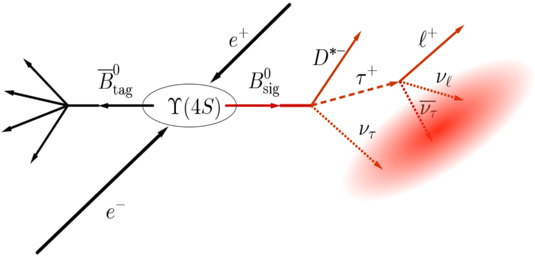


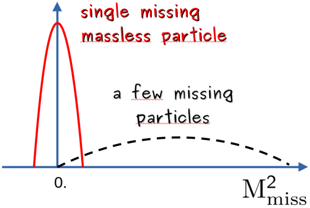


- hermetic detector: **full event reconstruction to exploit kinematic constraints**
- excellent tracking, PID, and vertex performance
- **total collected data:** $\sim$ **600 fb^{-1} (2019-2024)**

Experimental techniques

Modes with large missing energy (i.e. multiple neutrinos) in the final state $\Rightarrow$ experimentally difficult! (no clear mass peak)





Missing Mass

$$M^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{Y})^2$$

Y represents the system of visible decay products on signal side (i.e. $Y = D^{(*)}\ell$)

- $M^2_{\text{miss}} \approx 0$ 0 for one missing particle
- $M^2_{\text{miss}} > 0$ for a few missing particles

- exclusive production of $B\overline{B}$ pairs at B factories $\Rightarrow$ reconstruction of second B
- kinematical constrains from beam energy $\Rightarrow$ B_{tag} flavor, charge, momentum $\vec{p^*}_{B_{\text{tag}}}$

Efficiency

Experimental techniques

second B reconstruction $\Rightarrow$ B tagging

- Untagged
  $\epsilon_{\text{tag}} \approx O(100\%)$
  - \+ large statistics
  - – large background; no kinematic and flavor/charge constraints

- Inclusive Hadronic Tagging
  $B_{\text{tag}} \to \sum$ of inclusive hadronic modes; $\epsilon_{\text{tag}} \approx O(10\%)$
  - \+ quite large statistics
  - – partially reduced background

- Inclusive or Exclusive Semileptonic Tagging
  $B_{\text{tag}} \to \sum D^{(*)}(n\pi)\ell\nu_\ell$; $\epsilon_{\text{tag}} \approx O(5\%)$
  - \+ efficient reconstruction
  - – less information about B_{tag} due to ν_ℓ

- Exclusive Hadronic Tagging
  $B_{\text{tag}} \to \sum$ of exclusive hadronic modes; $\epsilon_{\text{tag}} \approx O(0.5\%)$
  - \+ high purity
  - – low tagging efficiency

Purity

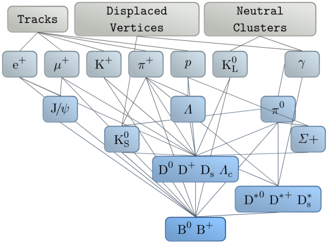
Remarks:

$\Rightarrow$ optimal technique depends on signature of signal side

$\Rightarrow$ total efficiency and purity depends on final selection

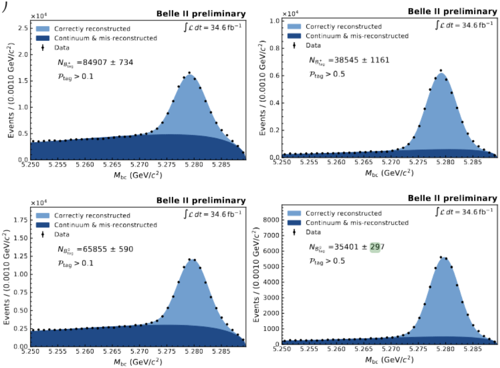
Experimental techniques

exclusive B_{tag} reconstruction algorithm



Full Event Interpretation (FEI)

- improved algorithm based on BDTs
- hierarchical approach to reconstruct $O(10^4)$ decay chains
- for hadronic tag: dominant tag-side decay mode categories: $D\pi$, $D^*\pi$, $Dn\pi$, $D^*n\pi$
- for semileptonic tag: $D^{(*)}\ell\nu$, $D^{(*)}\pi\ell\nu$
- $\epsilon_{SL} \approx 2\%$, $\epsilon_{had} \approx 0.5\%$

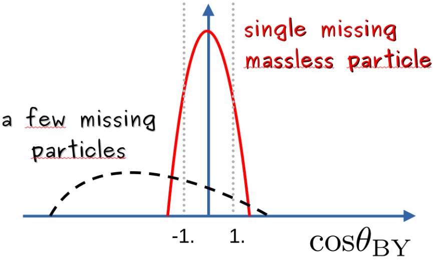


$$M_{bc} = \sqrt{E_{\text{beam}}^2 - (\vec{p}_{B_{tag}}^{\,CM})^2}$$

- E_{beam} is the beam energy in the CMS of $\Upsilon(4S)$
- $\vec{p}_B$ is the momentum of the reconstructed B_{tag}

Experimental techniques

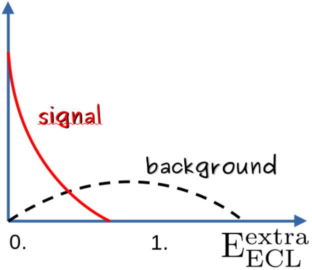
@ B-factories: key variables



- cosine of the angle between B momentum and Y (momenta of visible decay products of signal side) in the $\Upsilon(4S)$ rest frame

$$\cos\theta_{BY} = \frac{2E_{beam}E^*_Y - m_B^2 - m_Y^2}{2|\vec{p}^*_B||\vec{p}^*_Y|}$$

- $-1 \leq \cos\theta_{BY} \leq 1$ for single missing massless particle
- $\cos\theta_{BY} << -1$ for a few missing particles
- it doesn't depend on the reconstruction of the tag side, unlike M^2_{miss}



- sum of energies of all neutral clusters in the ECL, not used in $\Upsilon(4S)$ reconstruction
- $E^{\mathrm{extra}}_{\mathrm{ECL}} \approx 0$ for correctly reconstructed signal
- $E^{\mathrm{extra}}_{\mathrm{ECL}} > 0$ for misreconstructed signal or bkg; extra energy due to additional energy deposition

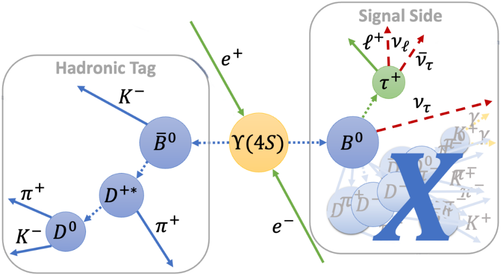
$$\mathcal{R}(X_{\tau/\ell}) = \frac{\mathcal{B}(B \to X \tau^+ \nu_\tau)}{\mathcal{B}(B \to X \ell^+ \nu_\ell)}$$

the first test of LFU via **inclusive** semileptonic B decays
at Belle II with hadronic tagging

PRL. **132**, 211804 (2024)

$\mathcal{R}(X_{\tau/\ell})$ with **hadronic** tagging

based on Data sample: 189 fb^{-1} (2019-2021 run period)



Selection

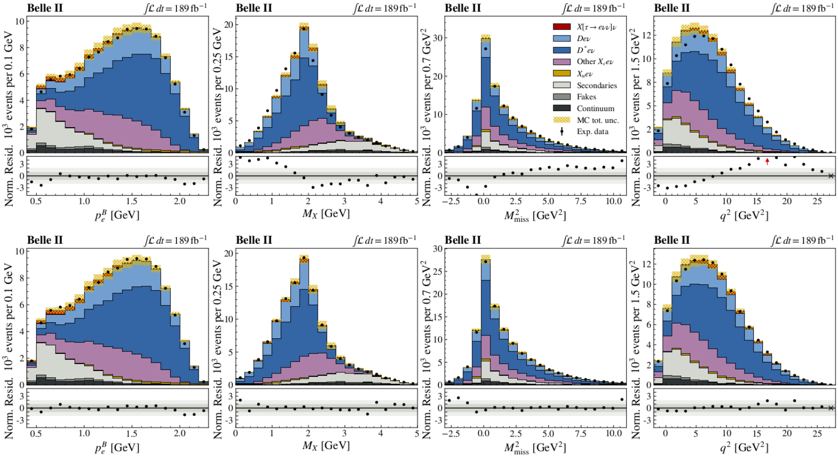
- hadronic tagging with FEI ($\epsilon_{had} \approx 0.1\%$) $+\ell$
- optimized lepton ID requirements and quality of tracks+clusters from X
- continuum suppressed by BDT

Challenges

- large background from less constrained X (significant systematic uncertainties associated with background composition)
- difficult MC modeling of the $X = D, D^*, D^{**}$ (source of cross-feeds), non resonant hadronic decays ("gap") ≈ 1 %
  $\Rightarrow$ probe inclusive $B \to X\ell\nu$ modeling in data-driven way

$\mathcal{R}(X_{\tau/\ell})$ with **hadronic** tagging

simulation samples reweighted based on p_ℓ^{lab} and M_X



- electron channel before (top) and after (bottom) template shape calibration
- mismodeling in M_X due to significant deficit/excess for low/high region due to relative abundance of D decays with K_L^0 in DATA

$\mathcal{R}(X_{\tau/\ell})$ with **hadronic** tagging

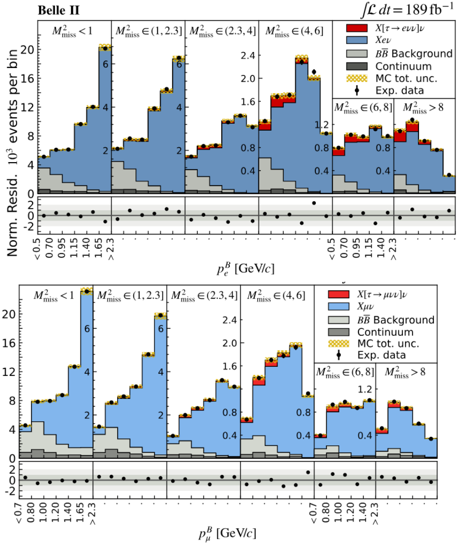
Signal extraction

Strategy

- 2D binned likelihood template fit in the **lepton momentum $p_\ell^{B_{\text{sig}}}$ in signal B rest frame and squared missing mass**
- 4 components: signal, normalization, $B\overline{B}$ bkg, continuum
- continuum with constraint on yield derived from off-resonance data

Signal yields

- $X\tau\nu$: $N_e^{\text{meas}} = 2590 \pm 450$
  $N_\mu^{\text{meas}} = 1810 \pm 460$
- $X\ell\nu$: $N_e^{\text{meas}} = 95690 \pm 770$
  $N_\mu^{\text{meas}} = 89970 \pm 810$
- $\mathcal{R}(X_{\tau/\ell}) = \frac{N_\tau^{\text{meas}}}{N_\ell^{\text{meas}}} \times \frac{N_\tau^{\text{sel}}}{N_\ell^{\text{sel}}} \times \frac{N_\tau^{\text{gen}}}{N_\ell^{\text{gen}}}$ where **meas**ured, **sel**ected, **gen**erated



1D template fit projections of lepton momenta in M^2_{miss} bins

$\mathcal{R}(X_{\tau/\ell})$ with **hadronic** tagging

Results based on Data sample: 189 fb^{-1} (2019-2021 run period)

- specific modes:

$$\mathcal{R}(X_{\tau/e}) = 0.232 \pm 0.020(\textit{stat}) \pm 0.037(\textit{syst})$$
$$\mathcal{R}(X_{\tau/\mu}) = 0.222 \pm 0.027(\textit{stat}) \pm 0.050(\textit{syst})$$

- Average of combined modes:

$$\mathcal{R}(X_{\tau/\ell}) = 0.228 \pm 0.016 \pm 0.036$$

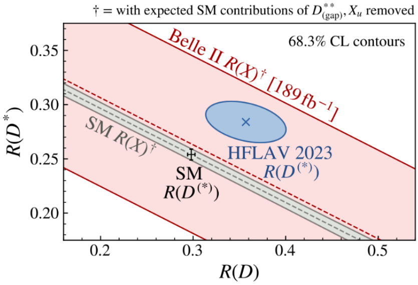
- SM prediction:
  $\mathcal{R}(X_{\tau/\ell})_{\text{SM}} = 0.223 \pm 0.005$
- agreement with SM at 1.7σ
- systematically limited measurement (17.5%)

- additionally LFU tests of electrons vs. muons:

$$\mathcal{R}(X_{e/\mu}) = 1.07 \pm 0.05(\text{stat}) \pm 0.02(\text{syst})$$

Leading systematics

- $X_c\tau(\ell)\nu$ form factors: (7.8%)
- $B \to X\ell\nu$ branching fractions: (7.7%)
- $X_c\ell\nu$ reweighting: (7.1%)
- experimental sample size: (7.1%)



small statistical overlap between $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(X)$ $\Rightarrow$

largely independent probe of $b \to c\tau\nu$ anomaly

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \to D^* \tau^+ \nu_\tau)}{\mathcal{B}(B \to D^* \ell^+ \nu_\ell)}$$

the first test of LFU via **exclusive** semileptonic B decays at Belle II with hadronic tagging

PRD **110** 072020 (2024)

$\mathcal{R}(D^*)$ with **hadronic** tagging

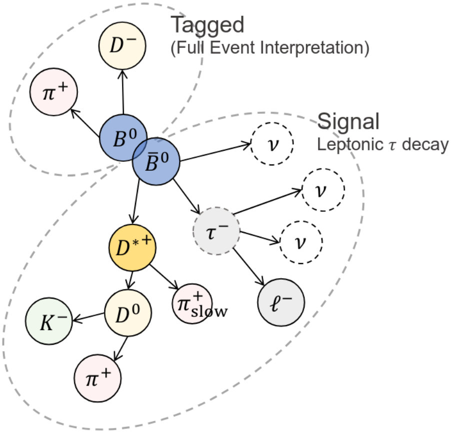
based on dataset: 189 fb^{-1} (2019-2021 run period)

Selection

- tag side reconstructed with hadronic FEI
- signal side by both decay chains:
  $B^0 \to \overline{D}^{*-}\tau^+/\ell^+\nu_\tau$,
  $B^+ \to \overline{D}^{*0}\tau^+(\ell^+)\nu_\tau$
  with leptonic τ decays
- charmed meson in three D^* decay channels: $D^{*+} \to D^0\pi^+, D^+\pi^0$; $D^{*0} \to D^0\pi^0$

Challenges

- modeling of bkg fit templates
  $\Rightarrow$ data-driven validation of background and signal model based on studies of control regions



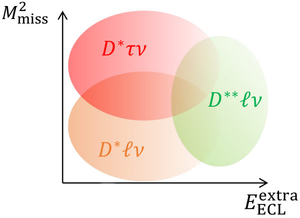
$\mathcal{R}(D^*)$ with **hadronic** tagging

signal extraction

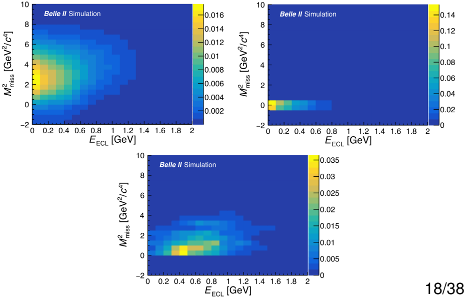
- signal region: $q^2 > 4.0$ GeV
  $q^2 = (p_{\tau/\ell} + p_{\nu_{\tau/\ell}})^2 = (p_{B_{\mathrm{sig}}} - p_{D^*})^2$
- extract signal and normalization yields from 2D likelihood fit to M^2_{miss} and $E^{\mathrm{extra}}_{\mathrm{ECL}}$
- fit performed over 6 separate modes:
  $D^{*+}e^-$, $D^{*+}\mu^-$
  D^* decay channels:
  $D^{*+} \to D^0\pi^+, D^+\pi^0$; $D^{*0} \to D^0\pi^0$
- main components: signal, normalization, bkg with true D^*, bkg with fake D^* (fixed)
- $N^i_{D^*\tau\nu} + N^i_{D^*\tau\nu,\ell\text{-misID}} = 108 \pm 16$
  $N^i_{D^*\ell\nu} = 2164 \pm 80$

$$\mathcal{R}(D^*) = \frac{N_{\bar{B}\to D^*\tau^-\bar{\nu}_\tau}}{N_{\bar{B}\to D^*\ell^-\bar{\nu}_\ell}/2} \cdot \frac{\varepsilon_{\bar{B}\to D^*\ell^-\bar{\nu}_\ell}}{\varepsilon_{\bar{B}\to D^*\tau^-\bar{\nu}_\tau}}$$

ε : reconstruction efficiency



templates for signal, normalization and peaking bkg $\bar{B} \to D^{**}\ell^-\bar{\nu}$



$\mathcal{R}(D^*)$ with **hadronic** tagging

Results based on dataset: 189 fb^{-1}

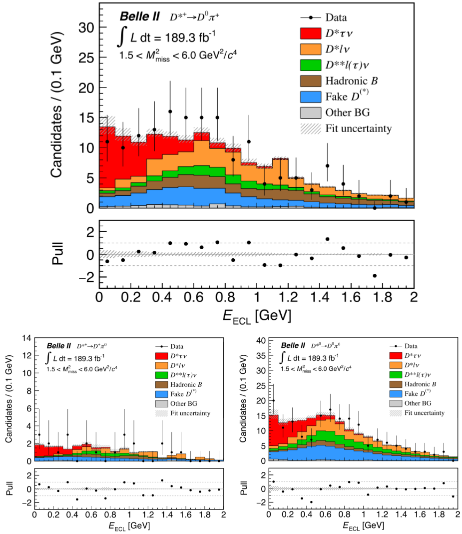
$$\mathcal{R}(D^*) = 0.262^{+0.041}_{-0.039}(\mathrm{stat})^{+0.035}_{-0.032}(\mathrm{syst})$$

- **consistent with the current HFLAV average (0.288$\pm$0.012) and with SM prediction**
- statistically limited measurement ($^{+15.7\%}_{-14.7\%}$)
- ongoing update on full sample and with a few improvements (better bkg suppression, more D modes, ...)

Leading systematics

- PDF shapes: $^{+9.1\%}_{-8.3\%}$
- simulation sample size: $\pm 7.5\%$
- $\mathcal{B}(\overline{B} \to D^{**}\ell^- \overline{\nu})$: $^{+4.8\%}_{-3.5\%}$

total systematics: $^{+13.5\%}_{-12.3\%}$



$$\mathcal{R}(D^{(*)+}) = \frac{\mathcal{B}(B \to D^{(*)+} \tau^+ \nu_\tau)}{\mathcal{B}(B \to D^{(*)+} \ell^+ \nu_\ell)}$$

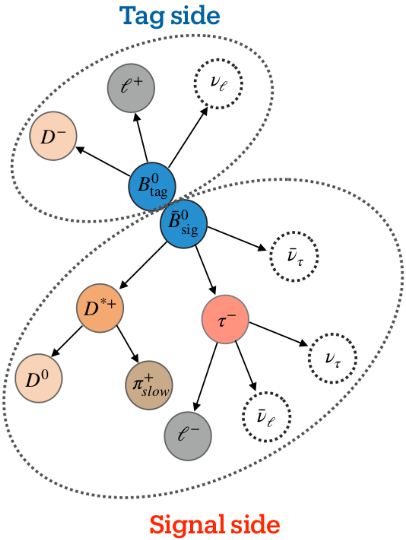
the first test of LFU via **exclusive** semileptonic B decays at Belle II with semileptonic tagging

Phys. Rev. D **112**, 032010 (2025)

$\mathcal{R}(D^{(*)+})$ with **semileptonic** tagging

Reconstruction

- tag side B mesons with semileptonic exclusive modes ($B^0 \to D^{(*)}\ell\nu$) (w/ FEI)
- on signal side: $B^0 \to D^{(*)-}\tau^+\nu$ and τ in leptonic decay channels
- D mesons reconstructed in **6** $D^\pm$ ($D^+ \to K^-\pi^+\pi^+$, $K_s^0\pi^+\pi^0$, $K_s^0\pi^+\pi^+\pi^-$, $K_s^0\pi^+$, $K^-K^+\pi^+$, $K_s^0 K^+$) and **7** D^0 ($D^0 \to K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K_s^0 K^+ K^-$, K^+K^-, $K^-\pi^+$, $K_s^0\pi^+\pi^-$, $\pi^-\pi^+$)
- preselection: $\cos\theta_{\mathrm{BY}}^{\mathrm{tag}}[-1.75, 1.1]$, $\cos\theta_{\mathrm{BY}}^{\mathrm{sig}}[-15, 1.1]$, $E_{\mathrm{ECL}}^{\mathrm{extra}} < 1.2$ GeV



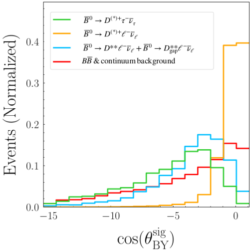
$\mathcal{R}(D^{(*)+})$ with **semileptonic** tagging

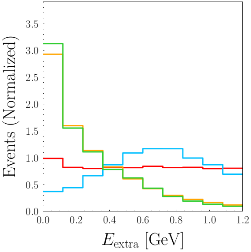
components and their classification

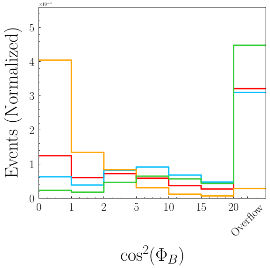
- 4 components: signal, normalization, $B \to D^{**}\ell\nu$, $B\bar{B}$ + continuum
- BDT trained on 5 features (according to importance)

  1. $\cos\theta_{\mathrm{BY}}$ on signal side
  2. $\mathrm{E}_{\mathrm{extra}}$
  3. $\cos^2(\Phi_B)$
  4. p^*_D
  5. p^*_ℓ

  where,
  $\cos^2(\Phi_B)$ combines $\cos\theta_{\mathrm{BY}}$ from both the signal and tag candidates with the angle γ between their visible momenta (p_{Y})
  p^*_D, p^*_ℓ are momenta of D meson and lepton form signal side in the $\Upsilon(4S)$ rest frame





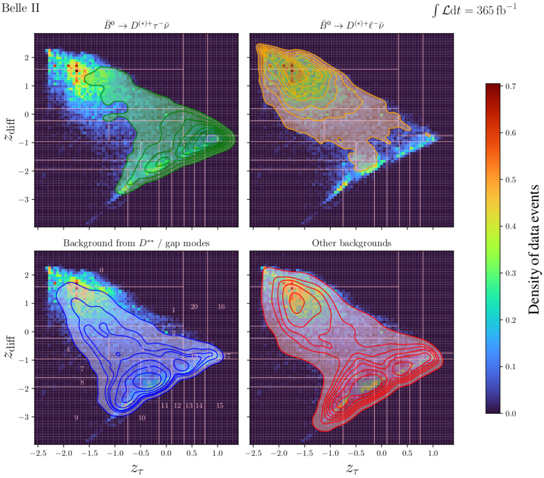


$\mathcal{R}(D^{(*)+})$ with **semileptonic** tagging

Multivariate classification + fitting procedure

- BDT separates events in 3 classes:
  - $B^0 \to D^{(*)-}\tau^+\nu_\tau$
  - $B^0 \to D^{(*)-}\ell^+\nu_\ell$
  - bkg ($B \to D^{**}\ell\nu$, other $B\overline{B}$)
- each event is assigned BDT scores: z_τ, z_ℓ, $z_{\rm bkg}$
- signal extracted in a 2D binned template fit of z_τ and $z_{\rm diff}$ = z_ℓ - $z_{\rm bkg}$
- 10 fit parameters: 2 for signal, 2 for normalization, 6 for background
- non-uniform binning $\Rightarrow$ increase granularity in regions with semitauonic and poorly known semileptonic bkg

Sample	D^+e	$D^+\mu$	$D^{*+}e$	$D^{*+}\mu$
$\overline{B}^0 \to D^+\ell\bar{\nu}_\ell$	2519 ± 68	2233 ± 61		
$\overline{B}^0 \to D^{*+}\ell\bar{\nu}_\ell$	2486 ± 63	2323 ± 58	2344 ± 51	1961 ± 44
$\overline{B}^0 \to D^+\tau\bar{\nu}_\tau$	191 ± 41	155 ± 65		
$\overline{B}^0 \to D^{*+}\tau\nu$	106 ± 14	84 ± 11	155 ± 19	111 ± 14
$\overline{B} \to D^{**}\ell\bar{\nu}_\ell/\overline{B} \to D^{**}_{\rm gap}\ell\bar{\nu}_\ell$	653 ± 112	586 ± 102	87 ± 55	75 ± 46
$B\overline{B}$ and Continuum Bkg.	2177 ± 145	1582 ± 149	611 ± 95	497 ± 83
Data	8219	6854	3241	2621



$\mathcal{R}(D^{(*)+})$ with **semileptonic** tagging

Results based on full Run 1 dataset: 365 fb^{-1}

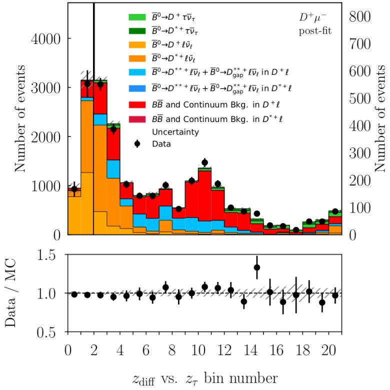
- fit performed over 4 separate modes: $D^0 e^-$, $D^0 \mu^-$, $D^+ e^-$, $D^+ \mu^-$

$\mathcal{R}(D^+)$ = 0.418±0.074(stat)±0.051(syst)

$\mathcal{R}(D^{*+})$ = 0.306±0.034(stat)±0.018(syst)

with correlation of $\rho = -0.24$

- **agreement with SM at** 1.7σ
- statistically limited measurement ($\mathcal{R}(D)$: 18.0%, $\mathcal{R}(D^*)$: 11.0%)
- lower uncertainty expected when including B^+ modes



- LFU tests of electrons vs. muons:

$\mathcal{R}(D^+_{e/\mu})$ = 1.07±0.05(stat)±0.02(syst)

$\mathcal{R}(D^{*+}_{e/\mu})$ = 1.08±0.04(stat)±0.02(syst)

consistent with SM within 1.2σ and 1.6σ respectively

Main systematics [$\mathcal{R}(D)$, $\mathcal{R}(D^*)$]

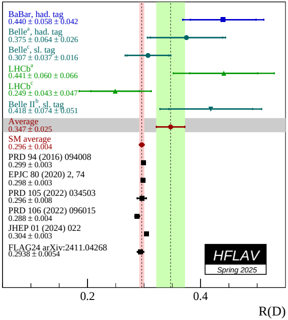
- finite size of simulated samples (8.0%, 4.7%)
- $\mathcal{B}(B \to D^{**} \ell \nu)$: (6.4%, 0.1%)
- muon eff. : (2.9%, 0.9%)

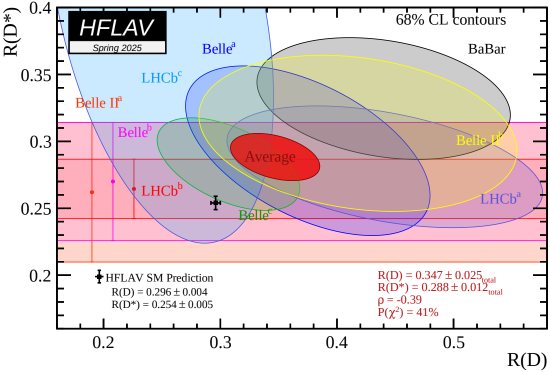
total systematics: 12.0%, 6.2%

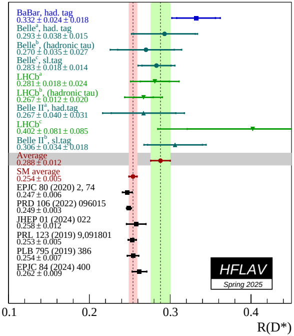
Summary and outlook

Current experimental status

$\mathcal{R}(D) - \mathcal{R}(D^*)$ (**Spring 2025**)







deviations from SM:

$\sim 2.0\sigma$ for $\mathcal{R}(D)$, $\sim 2.7\sigma$ for $\mathcal{R}(D^*)$

$\mathcal{R}(D) - \mathcal{R}(D^*)$ correlation: -0.39

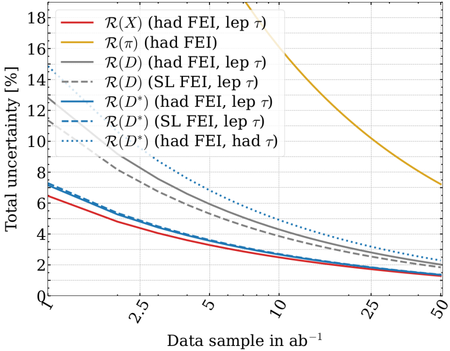
$\sim$ **3.8σ** $\mathcal{R}(D)\&\mathcal{R}(D^*)$

before new Belle II and LHCb measurements: 3.2σ

Prospects

expected Belle II sensitivity as function of $\mathcal{L}_{\text{int}}$

$$\mathcal{R}(Y) = \frac{\mathcal{B}(B \to Y \tau^+ \nu_\tau)}{\mathcal{B}(B \to Y \ell^+ \nu_\ell)};\ Y = \pi, D, D^*, X_{\text{c,u}};\ \ell = e, \mu$$



- extrapolation from Snowmass report: arXiv:2207.06307

Target for 10 ab^{-1} (Run2): [a]

- **accurate tagged measurement of** $B \to D^{**}\ell\nu$, the most significant and poorly known background, whose feed-down may bias results
- **exclude SM prediction on $\mathcal{R}(D^{(*)})$ if the current central value persist**
- **expected relative precisions: 1.8% for $\mathcal{R}(D^*)$, 3.0% for $\mathcal{R}(D)$**

---

[a] The Belle II Experiment at SuperKEKB – Input to the European Particle Physics Strategy, ArXiv: 2503.24155

Summary

main results based on Run1 dataset

- Belle II provides many precise tests of Lepton Flavor Universality in semileptonic B decays with missing energy
- Presented results:
  - new measurements of $\mathcal{R}(D^*)$ with **hadronic tagging** and combined $\mathcal{R}(D) + \mathcal{R}(D^*)$ with **semileptonic tagging** via sum of exclusive B decays
  - the first measurement of $R(X_{\tau/\ell})$ via **inclusive** B decays
- ongoing efforts are focused on updating measurements with the full Run 1 dataset and preparing for the follow-up of Run 2, starting in November 2025

BACKUP

Belle II detector

+ performance

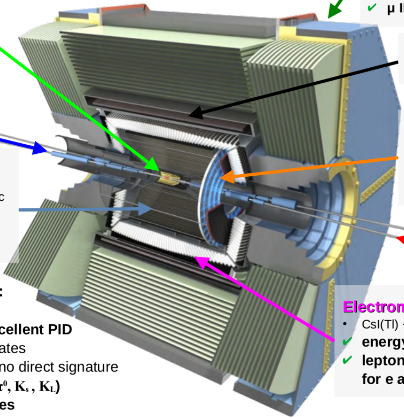
K_L and μ detector
- Resistive Plate Counter (barrel outer layers)
- Scintillator + WLS fiber + MPPC (end-caps & inner 2 barrel layers)

✔ **μ ID efficiency: 90 %**

Silicon vertex detectors
- 2 layers DEPFET (pixel)
- 4 outer layers DSSD

✔ **vertexing resolution ~ 15 μm**

Magnetic field
- **1.5 T superconducting magnet**



electrons (7 GeV)

Particle ID detectors
- Time-of-Propagation counter (barrel)
- Aerogel RICH (forward end-cap)

✔ **hadron ID efficiency ~90% at 10% fakes**

Tracking detector
- central drift chamber (He + C_2H_6)
- small cells, long lever arm, fast electronic

✔ **spatial resolution: 100 μm**
✔ **p_T resolution ~ 0.4%/p_T**
✔ **dE/dx resolution: 5%**

positrons (4 GeV)

Electromagnetic Calorimeter
- CsI(Tl) + waveform sampling (barrel + end-caps)

✔ **energy resolution ~1.6-4%**
✔ **lepton ID efficiency 90% at fakes: 0.5% for e and 7% for μ**

Key factors:

✔ **known initial state + nearly hermetic detector with excellent PID**
► reconstruct fully-inclusive final states
► broadly search for particles with no direct signature

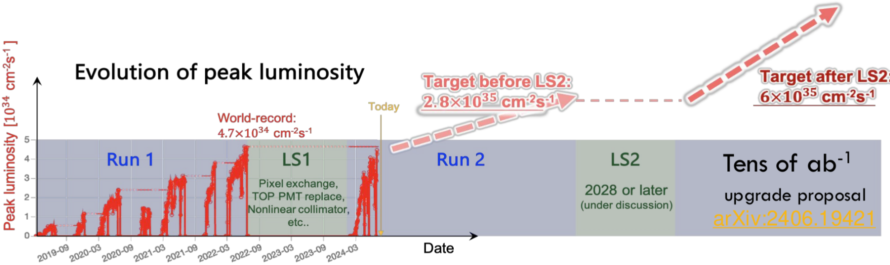
✔ **reconstruct neutral particles (γ, π^0, K_s, K_L) nearly as well as charged particles**

Current DATA status

+ luminosity projections

- Run 1 (2019-2022): $L_{\text{integrated}} = 365\ \text{fb}^{-1}$ ($\approx$ Babar dataset) at $\Upsilon(4S)$
- Run 2 (2024-2032): $\approx 150\ \text{fb}^{-1}$ so far; **goal: 10 ab^{-1}**

- **Dec 2024: World record of instantaneous L: 5.1 $\times$ 10^{34} cm^{-2}s^{-1}**
- **ultimate targets**:
  - peak luminosity: $6 \times 10^{35}\ \text{cm}^{-2}\ \text{s}^{-1}$ (30x KEKB)
  - integrate up to 50 ab^{-1} (50x Belle dataset) in next decade



$\mathcal{R}(X_{\tau/\ell})$ with **hadronic** tagging

Systematics

TABLE I. Relative statistical and systematic uncertainties on the value of $R(X_{\tau/\ell})$ for electrons, muons, and their combination (ℓ). Detailed descriptions of each source are provided in the text.

	Uncertainty [%]		
Source	e	μ	ℓ
Experimental sample size	8.8	12.0	7.1
Simulation sample size	6.7	10.6	5.7
Tracking efficiency	2.9	3.3	3.0
Lepton identification	2.8	5.2	2.4
$X_c\ell\nu$ reweighting	7.3	6.8	7.1
$B\bar{B}$ background reweighting	5.8	11.5	5.7
$X\ell\nu$ branching fractions	7.0	10.0	7.7
$X\tau\nu$ branching fractions	1.0	1.0	1.0
$X_c\tau(\ell)\nu$ form factors	7.4	8.9	7.8
Total	18.1	25.6	17.3

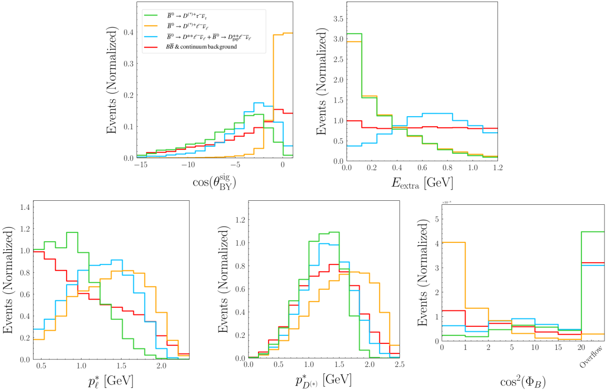
$\mathcal{R}(D^*)$ with **hadronic** tagging

Systematics

Source	Uncertainty
PDF shapes	$^{+9.1\%}_{-8.3\%}$
Simulation sample size	$^{+7.5\%}_{-7.5\%}$
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$ branching fractions	$^{+4.8\%}_{-3.5\%}$
Fixed backgrounds	$^{+2.7\%}_{-2.3\%}$
Hadronic B decay branching fractions	$^{+2.1\%}_{-2.1\%}$
Reconstruction efficiency	$^{+2.0\%}_{-2.0\%}$
Kernel density estimation	$^{+2.0\%}_{-0.8\%}$
Form factors	$^{+0.5\%}_{-0.1\%}$
Peaking background in ΔM_{D^*}	$^{+0.4\%}_{-0.4\%}$
$\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell$ branching fractions	$^{+0.2\%}_{-0.2\%}$
$R(D^*)$ fit method	$^{+0.1\%}_{-0.1\%}$
Total systematic uncertainty	$^{+13.5\%}_{-12.3\%}$

$\mathcal{R}(D^{(*)})$ with **semileptonic** tagging

Multivariate classification

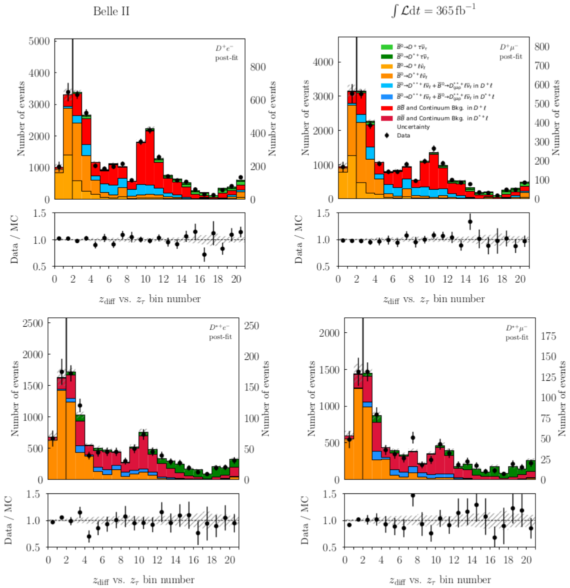


- BDT trained on 5 features: $\cos\theta_{\text{BY}}$, E_{extra}, $\cos^2(\Phi^2)$, p^*_D, p^*_ℓ
- $\cos(\theta^{\text{sig}}_{\text{BY}})$ - cosine of the angle between B momentum and Y (momenta of visible decay products) in the c.m. frame
- $\cos^2(\Phi_{\text{B}}) = \dfrac{\cos^2\theta^{\text{sig}}_{\text{BY}} + \cos^2\theta^{\text{tag}}_{\text{BY}} + 2\cos\theta^{\text{sig}}_{\text{BY}}\cos\theta^{\text{tag}}_{\text{BY}}\cos\gamma}{\sin^2\gamma}$

  where γ is angle between Y_{sig} and Y_{tag}

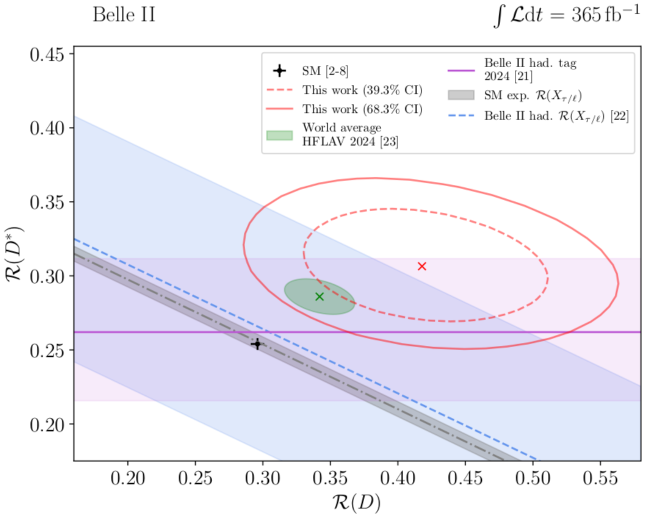
$\mathcal{R}(D^*)$ with **semileptonic** tagging

fitted classifier distributions



$\mathcal{R}(D^*)$ with **semileptonic** tagging

Measured $\mathcal{R}(D), \mathcal{R}(D^*), \mathcal{R}(X_{\tau/\ell})$ vs. HFLAV averages



- agreement with SM prediction: $\sim 1.7\sigma$
- consistent with experimental average: $\sim 0.6\sigma$

$\mathcal{R}(D^{(*)})$ with **semileptonic** tagging

Systematics + consistency checks

TABLE I. Systematic uncertainties on $\mathcal{R}(D^+)$ and $\mathcal{R}(D^{*+})$ ranked by the magnitude of the uncertainty on $\mathcal{R}(D^+)$. The percentage values in brackets indicate the relative uncertainty.

Systematic Uncertainty	$\Delta\mathcal{R}(D^+)$	$\Delta\mathcal{R}(D^{*+})$
Additive		
MC sample size	0.033 (8.0%)	0.014 (4.7%)
Gap $\mathcal{B}$	0.027 (6.4%)	0.001 (0.1%)
LID efficiency (μ)	0.022 (5.1%)	0.001 (0.1%)
Fake rates (e)	0.012 (2.9%)	0.003 (0.9%)
$\pi^\pm$ from $D^* \to D\pi$	0.003 (0.7%)	0.001 (0.1%)
Continuum fraction	0.002 (0.6%)	0.001 (0.2%)
$\overline{B} \to D^{(*)}\ell\bar{\nu}_\ell$ / $\tau\bar{\nu}_\tau$ FFs	0.002 (0.5%)	0.002 (0.7%)
Gap FFs	0.002 (0.5%)	0.001 (0.2%)
$\mathcal{B}(\overline{B} \to D^{**}\ell\bar{\nu}_\ell)$	0.002 (0.5%)	0.001 (0.1%)
$\overline{B} \to D^{**}\ell\bar{\nu}_\ell$ FFs	0.001 (0.3%)	0.001 (0.2%)
BDT modeling	0.001 (0.3%)	0.001 (0.2%)
LID efficiency (e)	0.001 (0.1%)	0.001 (0.2%)
Fake rates (μ)	0.001 (0.1%)	0.001 (0.1%)
Total Additive Uncertainty	0.050 (12%)	0.015 (4.8%)
Multiplicative		
$\overline{B} \to D^{(*)}\ell\bar{\nu}_\ell$ / $\tau\bar{\nu}_\tau$ FFs	0.009 (2.1%)	0.011 (3.5%)
MC sample size	0.007 (1.7%)	0.004 (1.2%)
LID efficiency (e)	0.001 (0.2%)	0.001 (0.2%)
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.001 (0.2%)	0.001 (0.2%)
LID efficiency (μ)	0.001 (0.1%)	0.001 (0.1%)
Tracking efficiency	0.001 (0.1%)	0.001 (0.1%)
$\pi^\pm$ from $D^* \to D\pi$	– (–)	0.001 (0.2%)
Total Multiplicative Uncertainty	0.012 (2.8%)	0.011 (3.7%)
Total Syst. Uncertainty	0.051 (12%)	0.018 (6.2%)
Total Stat. Uncertainty	0.074 (18%)	0.034 (11%)
Total Uncertainty	0.090 (22%)	0.039 (13%)

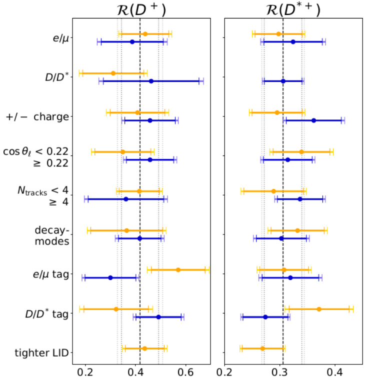
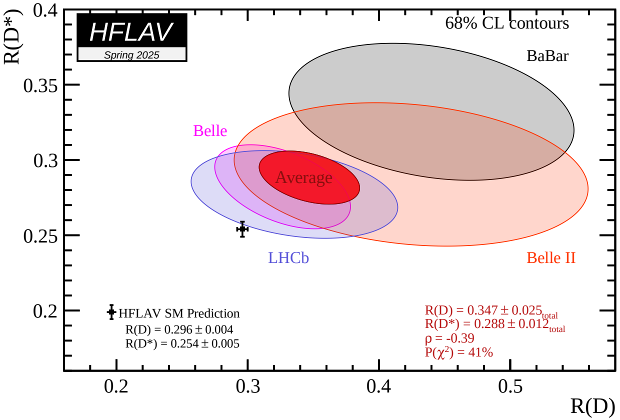


FIG. 6. Summary of the various consisitency checks. The central values of each sample split fit (blue and orange error bars), along with the sizes of the statistical and total uncertainties are shown (inner and outer ticks). The nominal results Eqs. 8 and 9 are also shown (dashed black line) with statistical and total uncertainty (inner and outer gray line).

Current experimental status

$\mathcal{R}(D) - \mathcal{R}(D^*)$ ((**Spring 2025**))



- averaged over each experiment (4)
- $\mathcal{R}(D)$: Babar (1), Belle (2), Belle II (1), LHCb (2)
- $\mathcal{R}(D^*)$: Babar (1), Belle (3), Belle II (2), LHCb (3)