Measurements of lepton-flavour universality in semileptonic B decays at Belle II

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HELMHOLTZ

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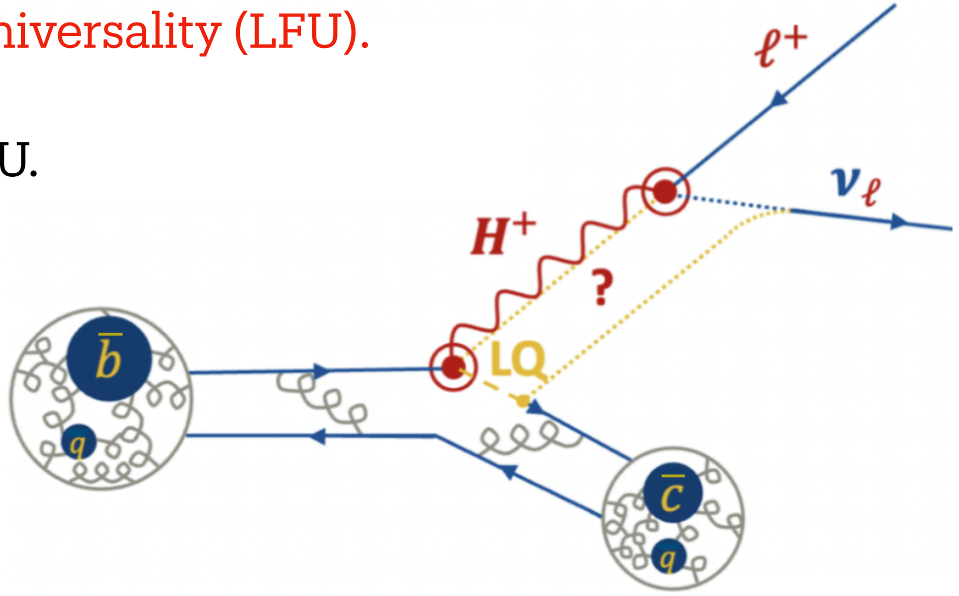
Lepton-flavour universality in semileptonic B decays

Motivation

- W boson couples equally to e, μ, τ in the SM→ Lepton Flavour Universality (LFU).
- Non-SM contributions (H^+, LQ, SUSY...) can generally violate LFU.
- Different ways to investigate LFU with semileptonic B decays:



1. Asymmetries in $B \to D^* \ell \nu$ angular distributions.

2. Ratio of rates suppress most theoretical and experimental uncertainties.

   Persistent anomaly observed between τ and light lepton ratios, e.g. $R(D^{(*)}_{\tau/\ell}) = \dfrac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$.

- In this talk, I will focus only on the latter.

$R(D^{(*)}_{\tau/\ell})$ and $R(X_{\tau/\ell})$ measurements at Belle II

Overview

Various Belle II measurements of the ratio between τ and ℓ BRs in both exclusive and inclusive B decay:

- $R(D^*_{\tau/\ell})$ with hadronic B tagging using 189 fb^{-1} [PRD 110, 072020]

- $R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ measurements using 365 fb^{-1} [arXiv.2504.11220, **submitted to PRD**]

  First result using semileptonic B tagging.

  First combined $R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ Belle II measurement.

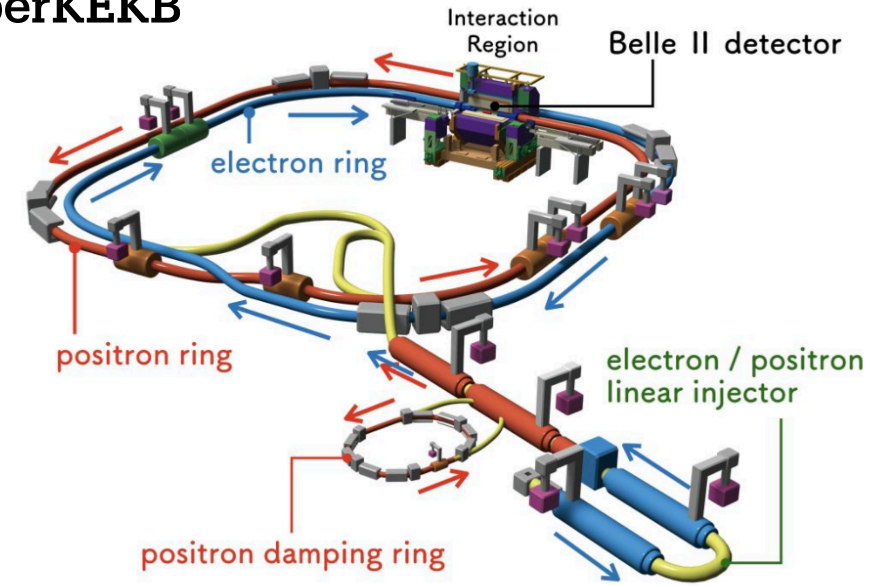
- $R(X_{\tau/\ell})$ with hadronic B tagging using 189 fb^{-1} [PRL 132, 211804]

Belle II experiment

Experimental setup

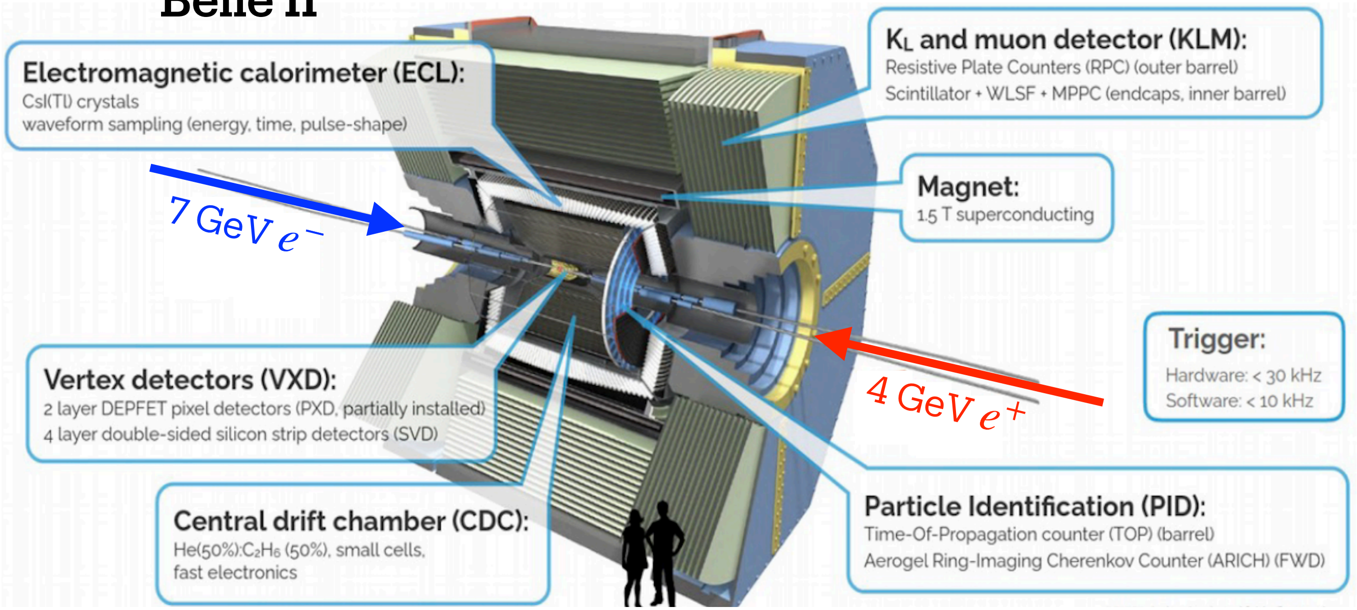
Belle (II) ideally suited to study decay with missing energy: hermetic detector, at-threshold $B\bar{B}$ production with precisely known energy.

SuperKEKB



Asymmetric-energy $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
Centre-of-mass energy= 10.58 GeV
World record inst. luminosity= $5.1 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Belle II



Run 1 luminosity: $(365.37 \pm 1.70)\ \mathrm{fb}^{-1}$
First Run 2 collision: 20 Feb 2024, 22:12 JST
Between 2019-2024, ~$575\ \mathrm{fb}^{-1}$ collected.

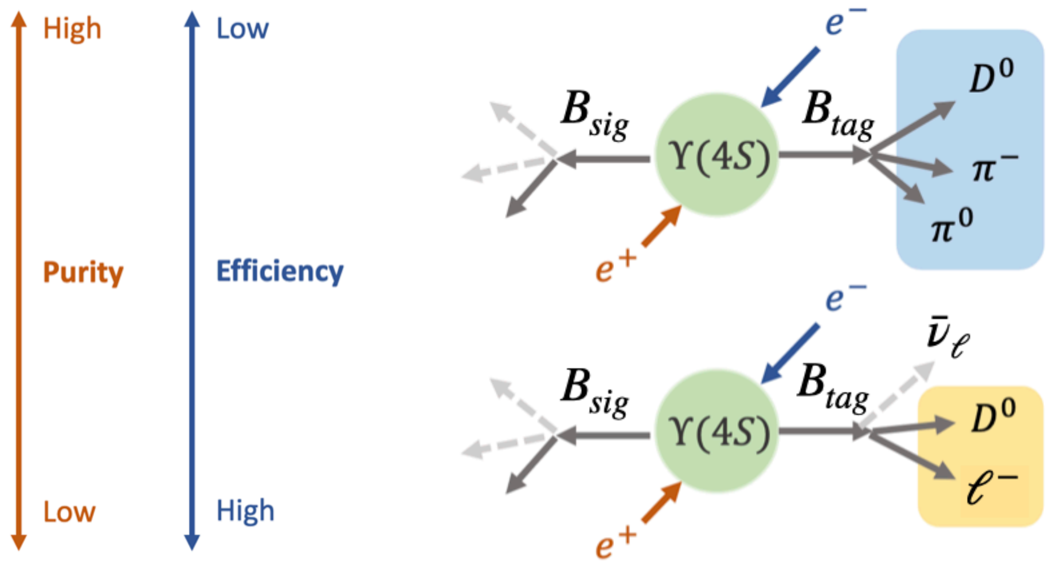
Dealing with missing energy

Reconstruction techniques

The measurements discussed in this talk are based on two different methods to deal with non-signal side B meson (B_{tag}):

1. Hadronic tagging:
   reconstruct B_{tag} by hadronic decay modes.

2. Semileptonic tagging:
   reconstruct B_{tag} by semileptonic decay modes.



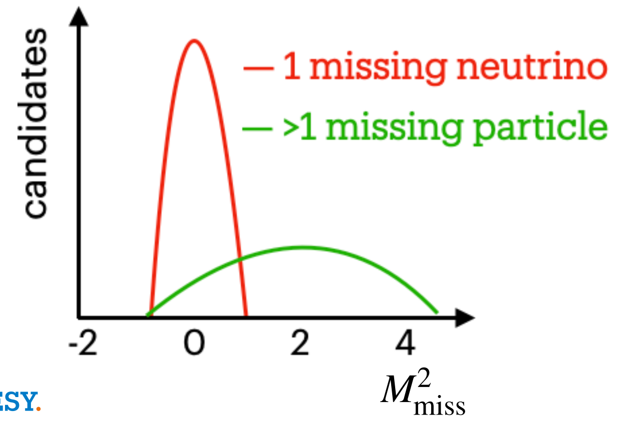
Reconstruction efficiency is $\mathcal{O}(0.1\%)$ and $\mathcal{O}(1\%)$ for the hadronic and semileptonic tagging, respectively.

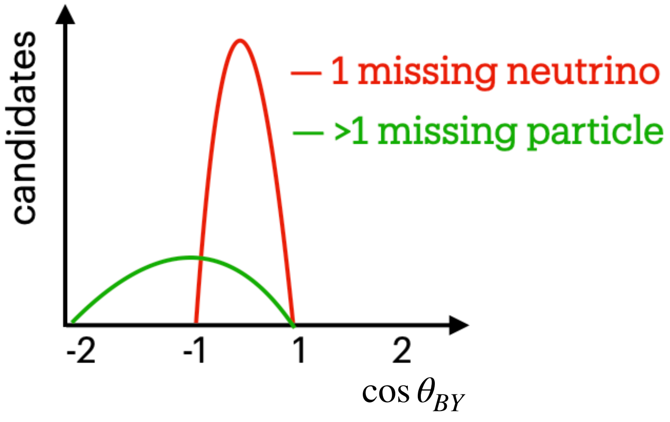
Dealing with missing energy

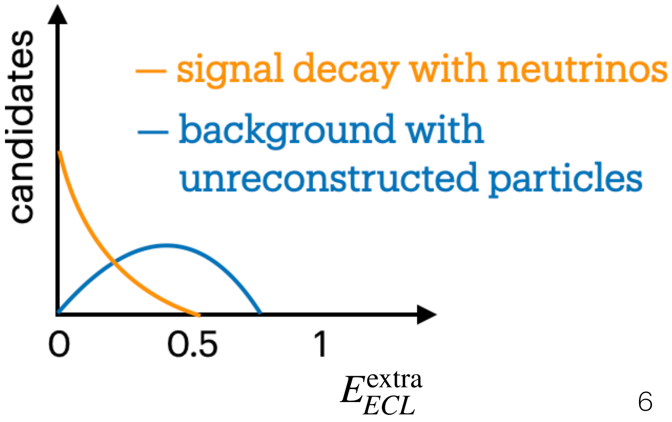
Fit variables

Fully reconstruct the partner B meson in hadronic/semileptonic decay modes. Match remaining particles with signal decay. Identify invisible particles using:

1. Missing mass of undetected particles $M^2_{miss} = (p_{e^+e^-} - p_{visible})^2$.
2. Use available kinematic constraint $\cos\theta_{BY} = \dfrac{2E^*_B E^*_Y - m^2_B - m^2_Y}{2|p^*_B||p_Y|^*}$ with $Y = D\ell$ system.
3. Residual energy in the calorimeter E^{extra}_{ECL}.



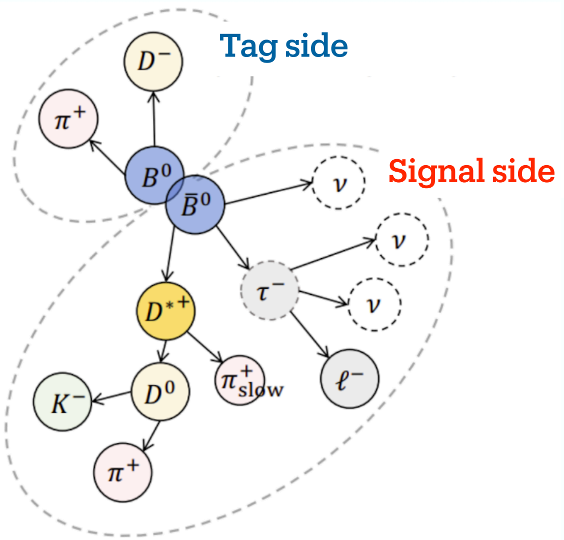




$R(D^*_{\tau/\ell})$ with hadronic B tagging

$R(D^*_{\tau/\ell})$ with hadronic B tagging

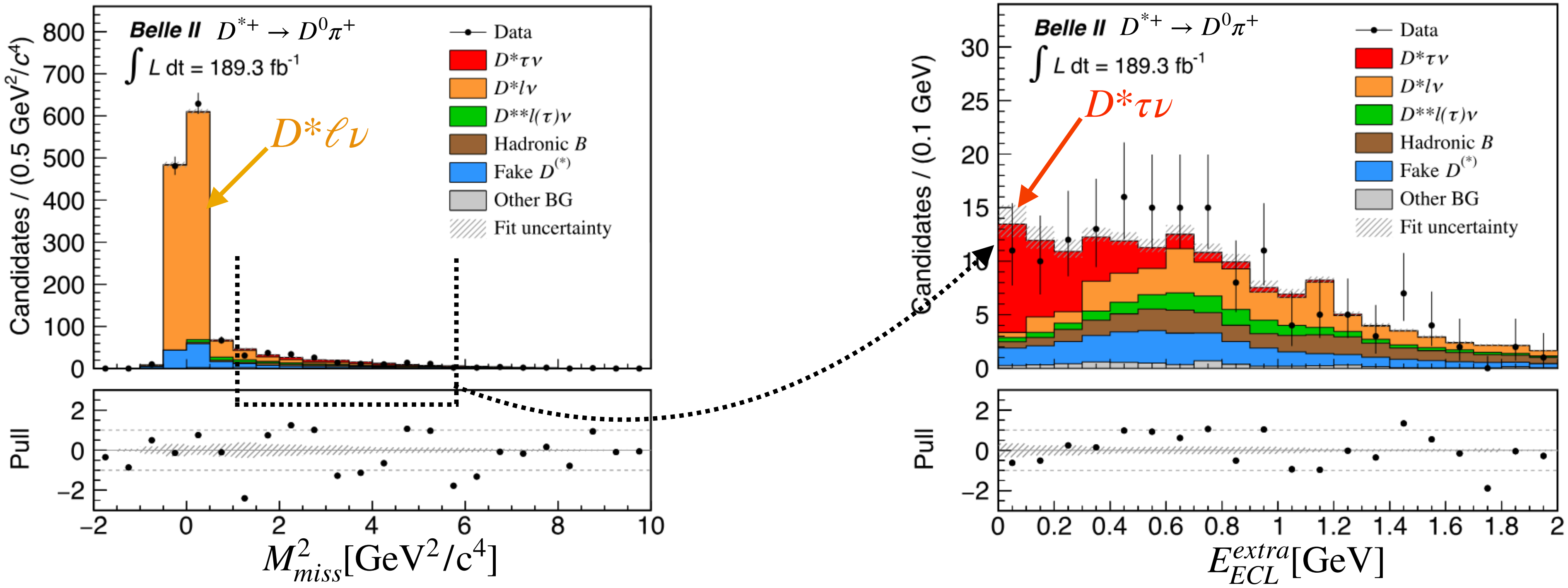
Strategy



- Measure $R(D^*_{\tau/\ell})$ by reconstructing $D^{*+} \to D^0\pi^+, D^+\pi^0$ and $D^{*0} \to D^0\pi^0$. Identify lepton from $\tau \to \ell\bar{\nu}\nu$.
- Extract signal/normalisation yields using a 2D likelihood fit to E_{ECL}^{extra} and M_{miss}^2.

M_{miss}^2 projection for $D^{*+} \to D^0\pi^+$ mode

Signal-enhanced projection for $D^{*+} \to D^0\pi^+$ mode



$R(D^*_{\tau/\ell})$ with hadronic B tagging

Results

- Main challenge: validate modelling of background fit templates.

  Data-driven validation of background and signal model based on studies of control regions.

- Main sources of systematic unc.: PDF shapes: ${}^{+9.1\%}_{-8.3\%}$, MC statistics: ${}^{+7.5\%}_{-7.5\%}$,$\mathscr{B}(B \to D^{**}\ell\nu)$: ${}^{+4.8\%}_{-3.5\%}$

- Statistical uncertainty: experimental sample size: ${}^{+15.7\%}_{-14.7\%}$

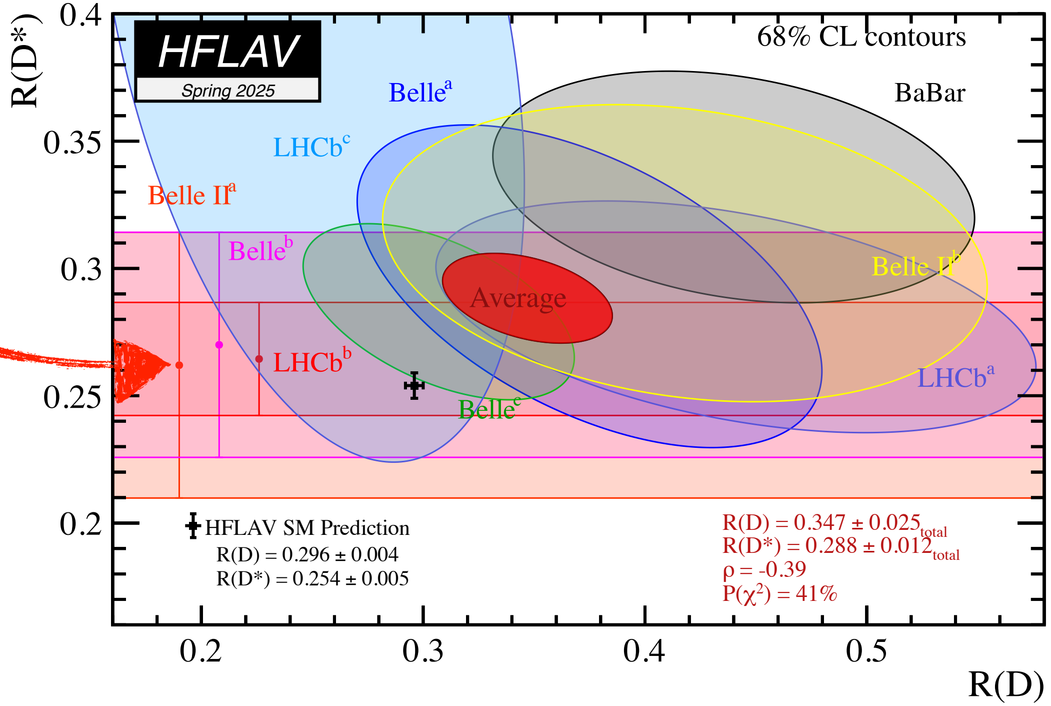
$$R(D^*_{\tau/\ell}) = 0.262^{+0.041}_{-0.039}(stat)^{+0.035}_{-0.032}(syst)$$

Compatible with the previous measurements.

HFLAV 25: $R(D^*) = 0.288 \pm 0.012$

Overall mean of all $R(D^*_{\tau/\ell})$ measurements indicates a tension of 2.7σ with SM prediction.

HFLAV



$R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ semileptonic B tagging

arXiv.2504.11220
submitted to PRD

$R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ semileptonic B tagging

Reconstruction

- First $R(D^{(*)})$ Belle II measurement using semileptonic B tagging.

  Reconstruct $B_{\text{tag}} \to D\ell\nu_\ell$ and $B_{\text{tag}} \to D^*\ell\nu_\ell$.

- Reconstruct B_{sig} candidates in $D^+\ell^-$ and $D^{*+}\ell^-$ final states not associated with the B_{tag} candidate.

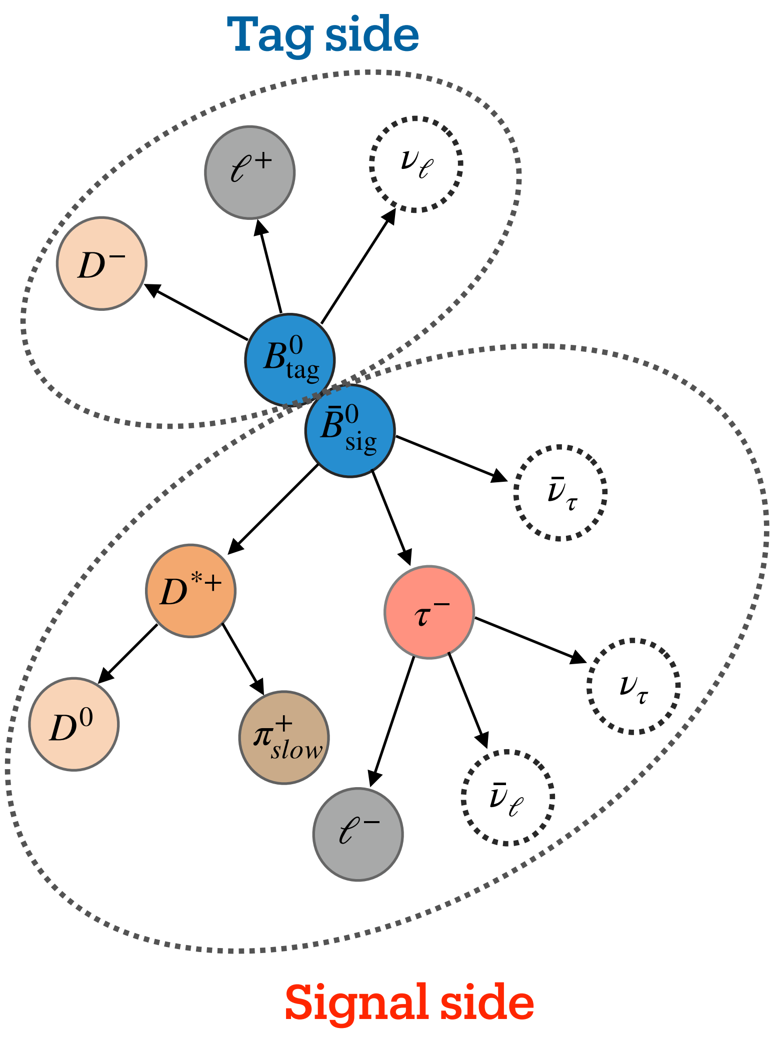
- Identify signal τ decays from $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$.

- D mesons reconstructed in multiple hadronic decays on both sides:

  Tag side: 26 decay modes

  Signal side: 13 decay modes

- Require $\cos\theta_{BY}^{\text{tag}} \in$ [-1.75, 1.1] and $\cos\theta_{BY}^{\text{sig}} \in [-15, 1.1]$.



arXiv.2504.11220
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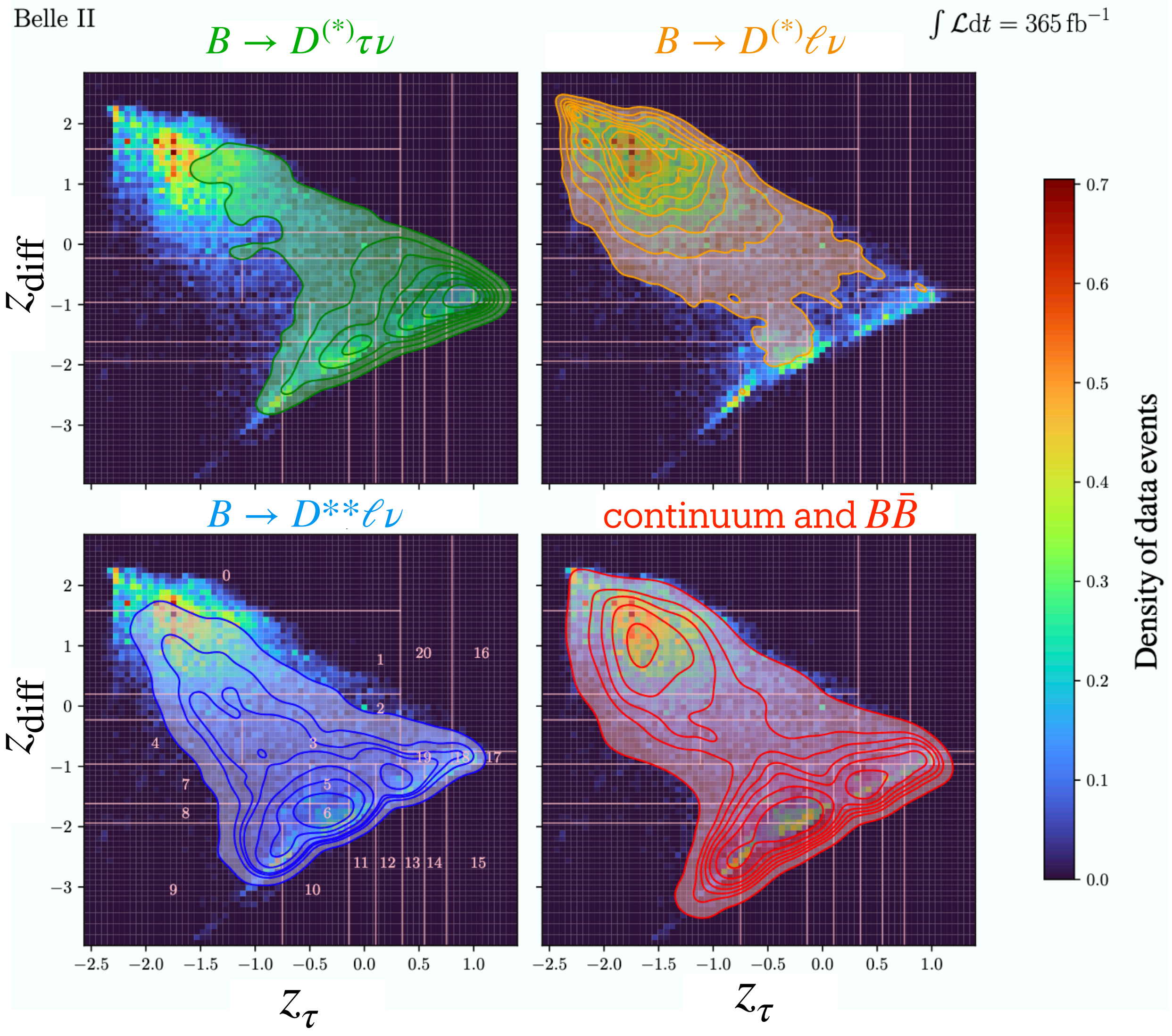
$R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ semileptonic B tagging

Strategy

- BDT used to separate the events in 3 different types:
  1. Semitauonic signal events: $B \to D^{(*)}\tau\nu$.
  2. Semileptonic events: $B \to D^{(*)}\ell\nu$ and $B \to D^{**}\ell\nu$.
  3. Background events: continuum and $B\bar{B}$.
- BDT trained on five input variables: the most discriminating variables are $\cos\theta_{BY}$ and E_{ECL}^{extra}.
- Each event is assigned a BDT score: $z_\tau, z_\ell, z_{\rm bkg}$. Define $z_{\rm diff} = z_\ell - z_{\rm bkg}$.

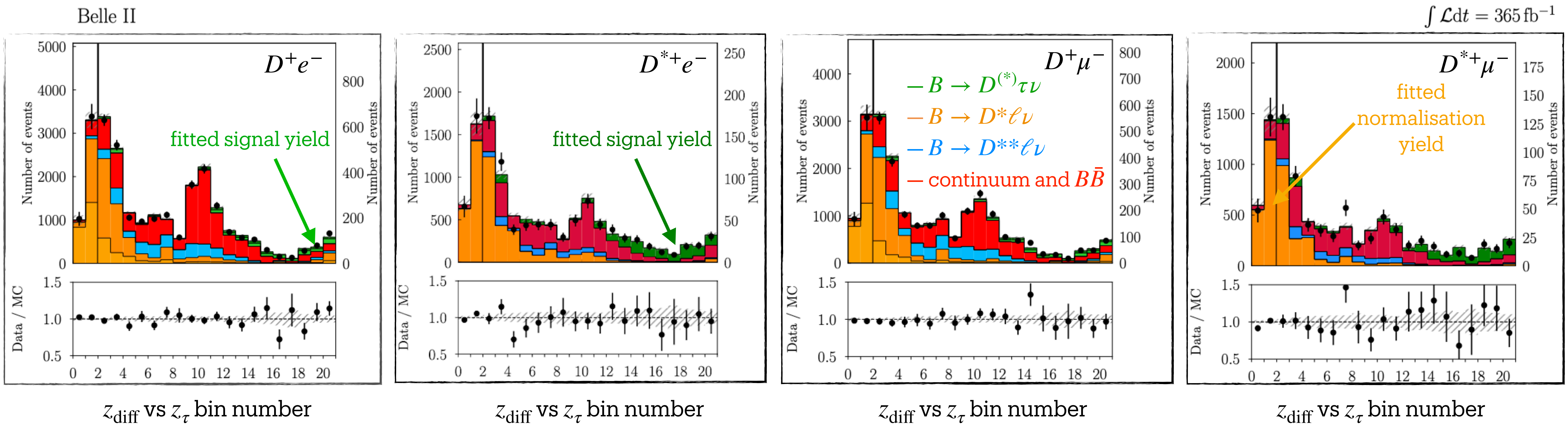


Good separation of all three event types.

$R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ semileptonic B tagging

Fit extraction

- Extract signal and normalisation yields using a 2D binned likelihood fit of z_τ and z_{diff}.
- The fit is performed over 4 separate channels: $D^+e^-, D^+\mu^-, D^{*+}e^-, D^{*+}\mu^-$.
- 10 fit parameters: 2 for the signal, 2 for the normalisation and 6 for the background.



arXiv.2504.11220
submitted to PRD

$R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ semileptonic B tagging

Results

- Main sources of syst. unc. $\frac{R(D^*_{\tau/\ell})}{R(D_{\tau/\ell})}$: MC statistics: $\frac{4.7\%}{8.0\%}$, $\mathscr{B}(B \to D^{**}\ell\nu) : \frac{0.1\%}{6.4\%}$, Muon eff. [misID]: $\frac{0.1\%}{5.1\%}\left[\frac{0.9\%}{2.9\%}\right]$.

- Statistical uncertainty $\frac{R(D^*_{\tau/\ell})}{R(D_{\tau/\ell})}$: experimental sample size: $\frac{11.0\%}{18.0\%}$.

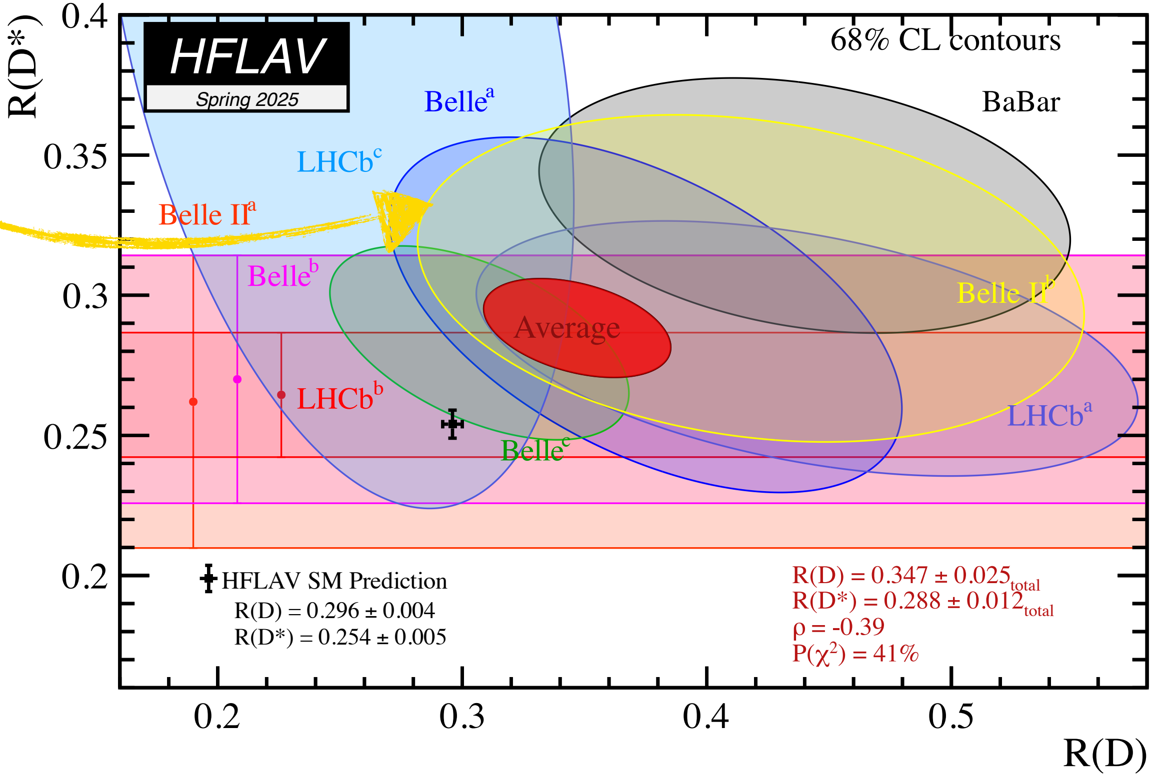
$$R(D^{*+}_{\tau/\ell}) = 0.306 \pm 0.034(stat) \pm 0.018(syst)$$
$$R(D^{+}_{\tau/\ell}) = 0.418 \pm 0.074(stat) \pm 0.051(syst)$$

The tension between the LFU-sensitive quantities $R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ and SM predictions increases to 3.8σ.

$$R(D^{*+}_{e/\mu}) = 1.08 \pm 0.04(stat) \pm 0.02(syst)$$
$$R(D^{*+}_{e/\mu}) = 1.07 \pm 0.05(stat) \pm 0.02(syst)$$

Consistent with the SM within 1.6σ—1.2σ respectively.

HFLAV



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

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

Strategy

- Measure $R(X_{\tau/\ell})$ by combining events with $B_{tag} + \ell$.

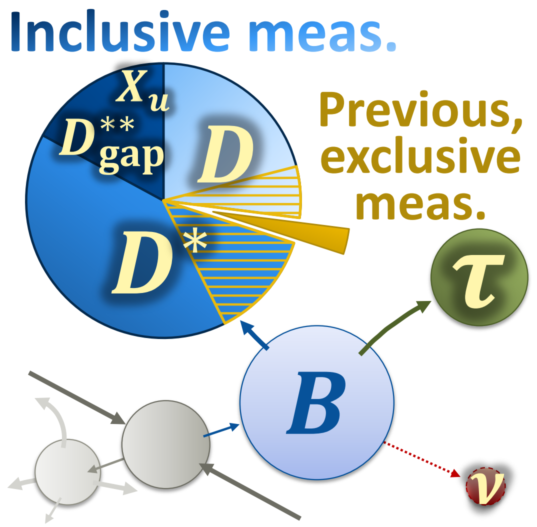
  Remaining particles attributed to X.

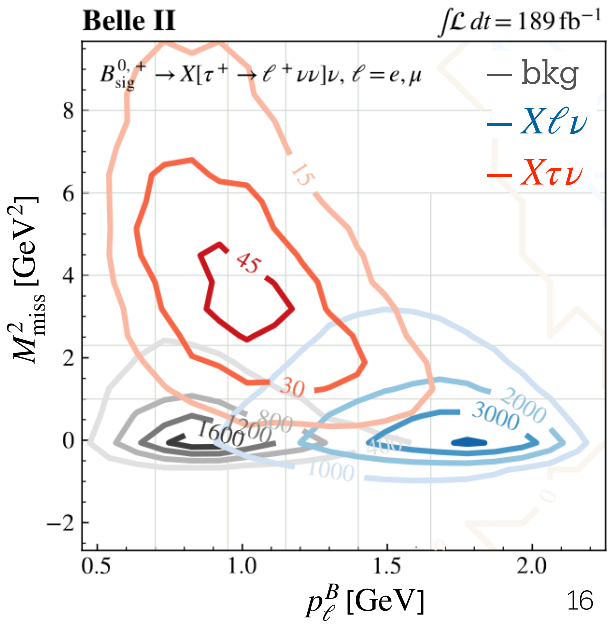
- Innovative and complementary measurement w.r.t. $R(D^{(*)})$ potentially more precise with different sources of systematics.

- Extract signal and normalisation yields using a simultaneous 2D likelihood fit to lepton momentum p_l^B (B rest frame) and M_{miss}^2.

  $B \to X\tau\nu$ and $B \to X\ell\nu$ well separated in the 2D plane.

- Main challenge: modelling the X system. Corrections based on comparison of simulation with control regions.

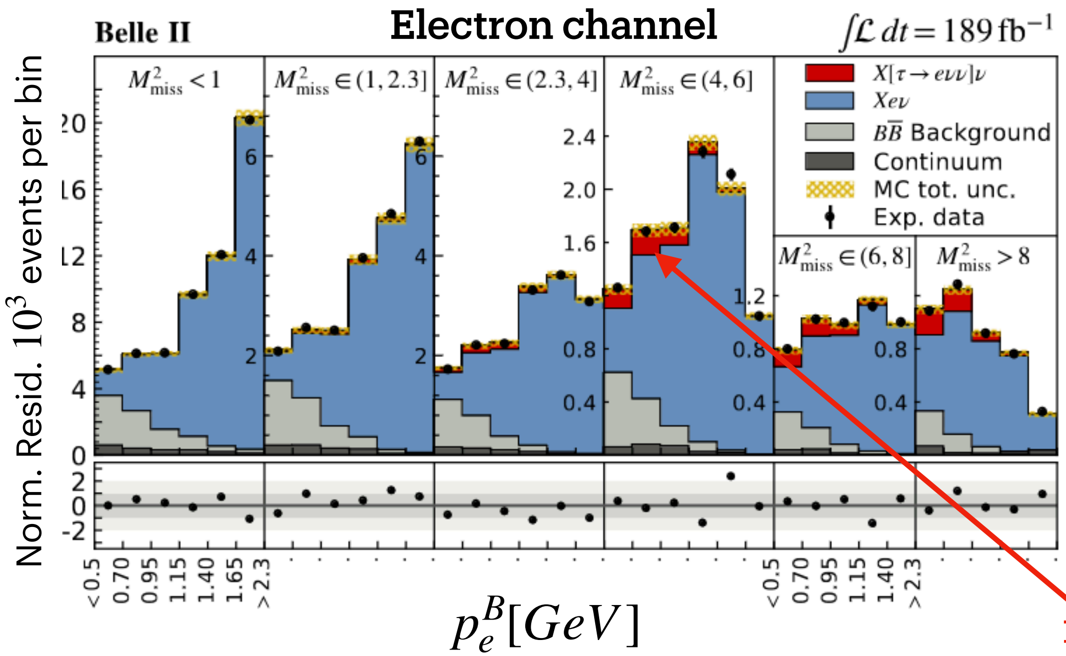


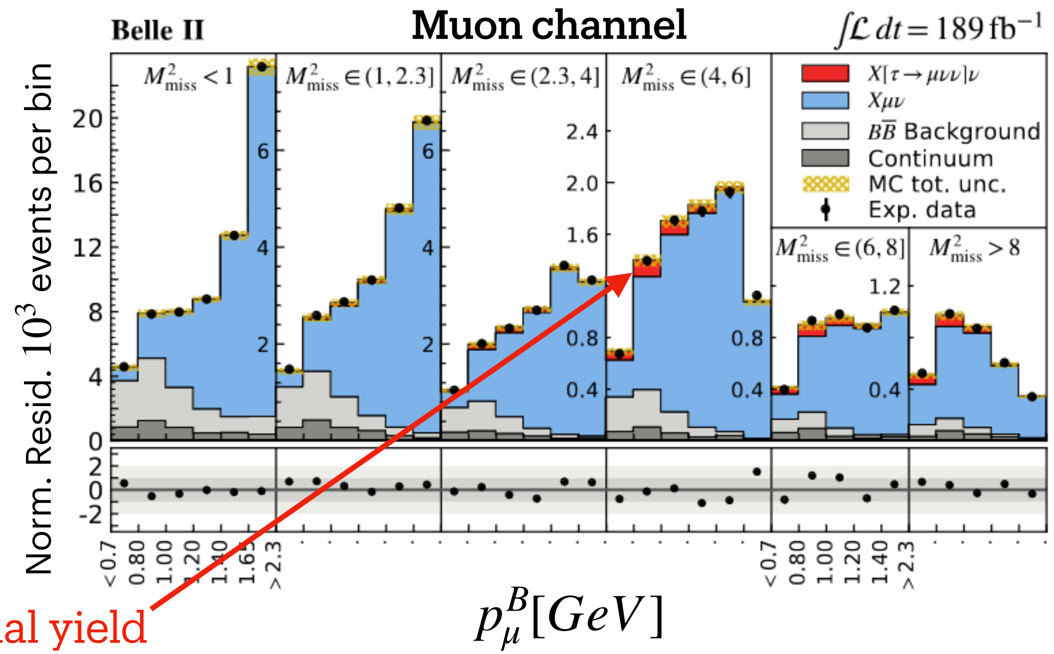


$R(X_{\tau/\ell})$ with hadronic B tagging

Results

- Main sources of systematic unc.: $X_c \ell \nu$ M_X shape: 7.1%, $\mathscr{B}(B \to X \ell \nu)$:7.7%, $X_c \tau(\ell)\nu$ form factors: 7.8%
- Statistical uncertainty: experimental sample size: 7.1%





fitted signal yield

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

SM prediction: $R(X_{\tau/\ell}) = 0.223 \pm 0.005$

Compatible with SM and $R(D^{(*)}_{\tau/\ell})$ measurements.

Summary

- Various Belle II measurements of the ratio between τ and ℓ BRs in both exclusive and inclusive semileptonic B decay were presented in this talk: the results are compatible with the previous measurements and consistent with SM predictions.

- Including the new combined $R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ result from Belle II using semileptonic B tagging, the tension between the LFU-sensitive observables $R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ and SM predictions increases to 3.8σ.

- Many other $R(D^{(*)}_{\tau/\ell})$ measurements from Belle II are on the way: expected higher precision using the full collected data set. Some systematic uncertainties could also be reduced with improved modelling.

Backup

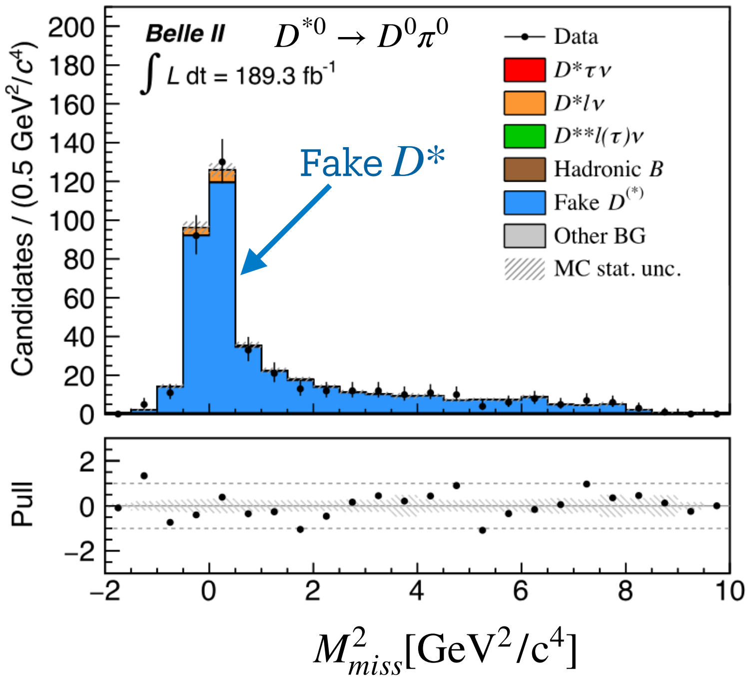
$R(D^*_{\tau/\ell})$ with hadronic B tagging

Modelling validation

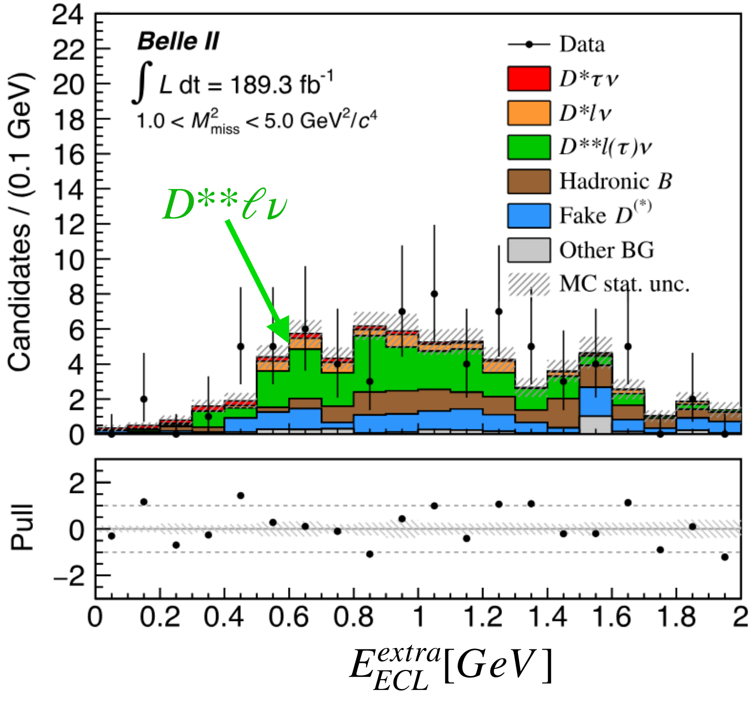
- Main challenge: validate modelling of background fit templates.

  Data-driven validation of background and signal model based on studies of control regions.

ΔM_{D^*} sideband:
validate fake D^* modelling



Reconstruct $D^*\pi^0\ell\nu$:
validate D^{**} modelling



All the major sources of background are well described in the sideband regions.

$R(D^*_{\tau/\ell})$ with hadronic B tagging

Systematic uncertainties

Fractional contributions to the total uncertainty of $R(D^*_{\tau/\ell})$.

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	$^{+13.5\%}_{-12.3\%}$

$R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$ semileptonic B tagging

Systematics uncertainties

Fractional contributions to the total uncertainty of $R(D_{\tau/\ell}) - R(D^*_{\tau/\ell})$.

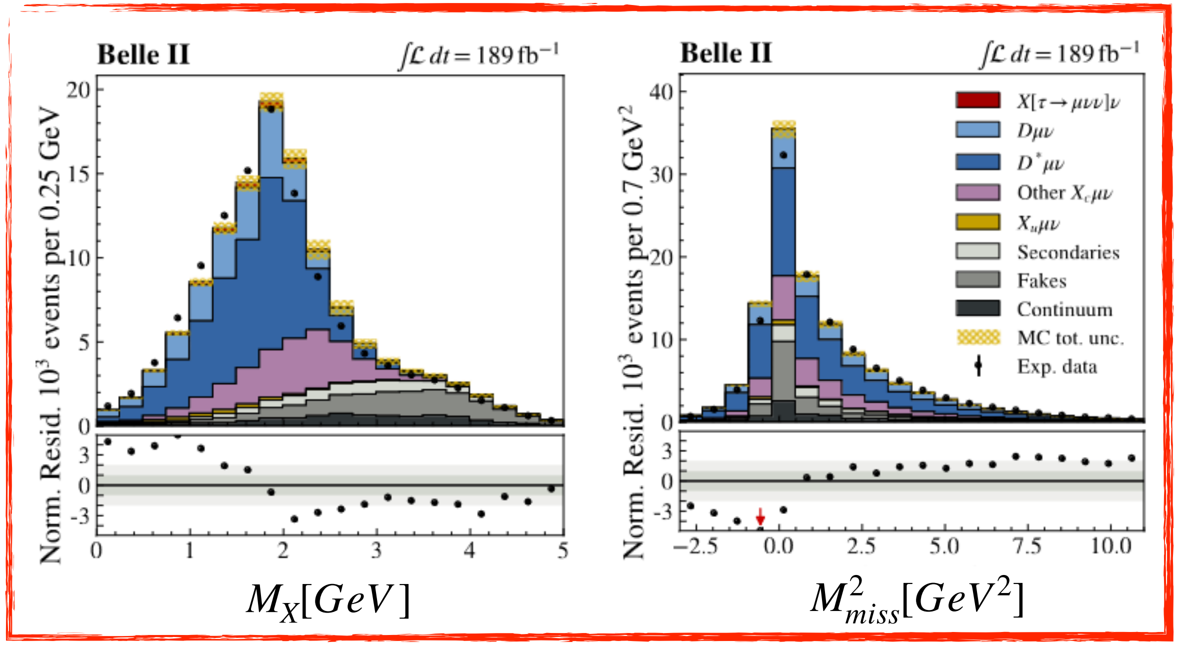
Systematic Uncertainty	$\Delta\mathcal{R}(D^{+})$	$\Delta\mathcal{R}(D^{*+})$
Additive		
MC sample size	0.033 (8.0%)	0.014 (4.7%)
Gap $\mathcal{B}$	0.027 (6.4%)	0.001 (0.1%)
LID efficiency (μ)	0.022 (5.1%)	0.001 (0.1%)
Fake rates (e)	0.012 (2.9%)	0.003 (0.9%)
$\pi^{\pm}$ from $D^* \to D\pi$	0.003 (0.7%)	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%)

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

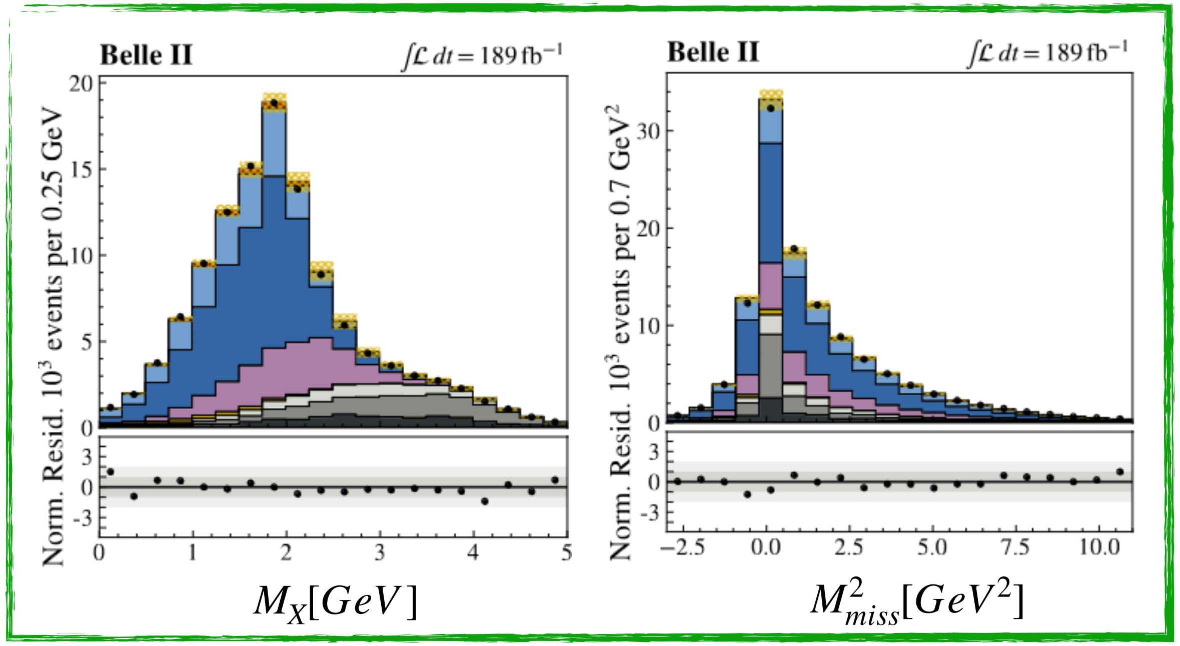
Modelling validation

- Main challenge: modelling the X system. Detailed adjustments to simulation: form factors, B and D branching fractions. Corrections based on comparison of simulation with control regions.

before M_X reweighting



after M_X reweighting



Adjusting M_X distribution in high p_l^B sideband also improves modelling in M^2_{miss}.

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

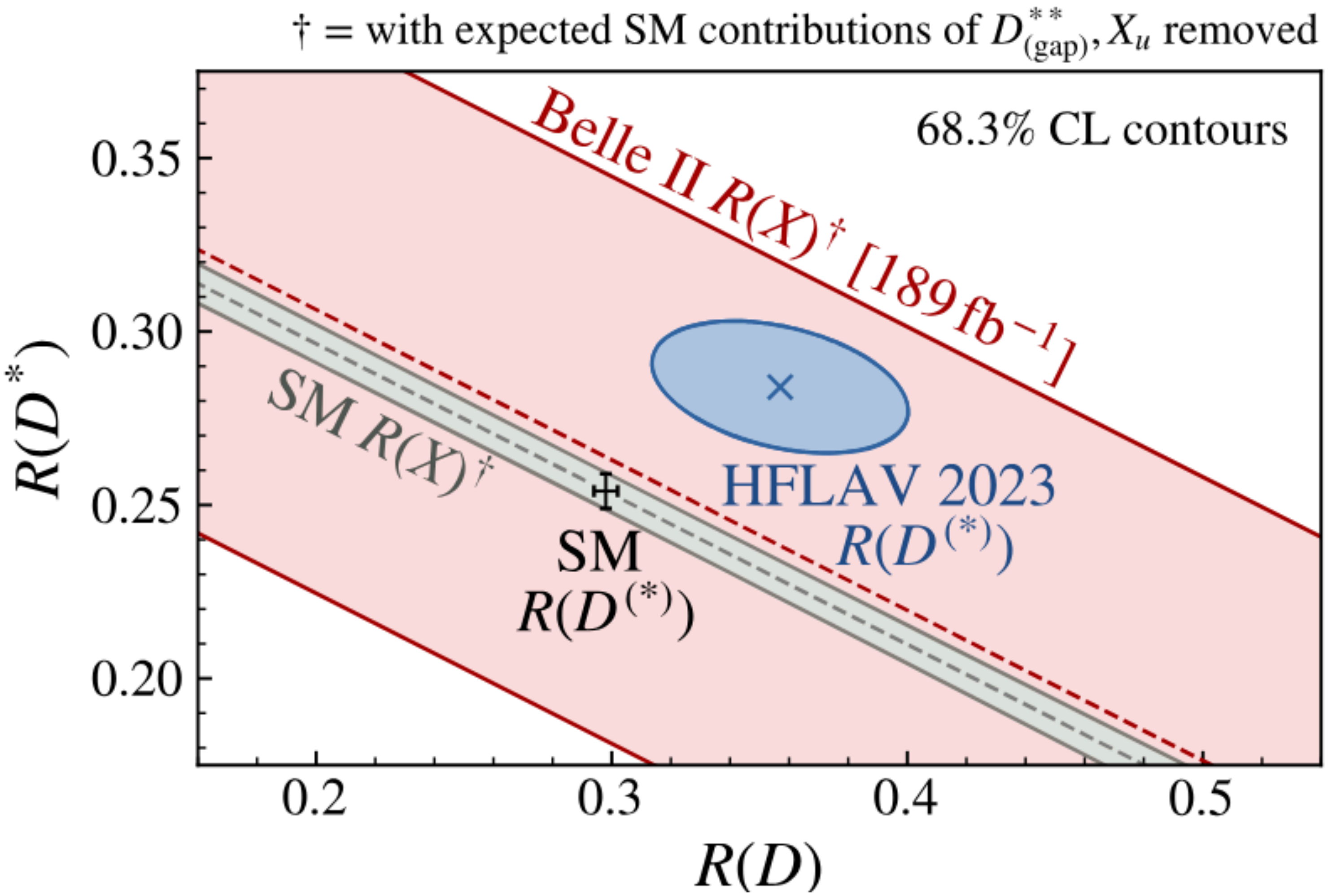
Systematics uncertainties

Relative uncertainties on the value of $R(X_{\tau/\ell})$ for electrons, muons and their combination (ℓ).

	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

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

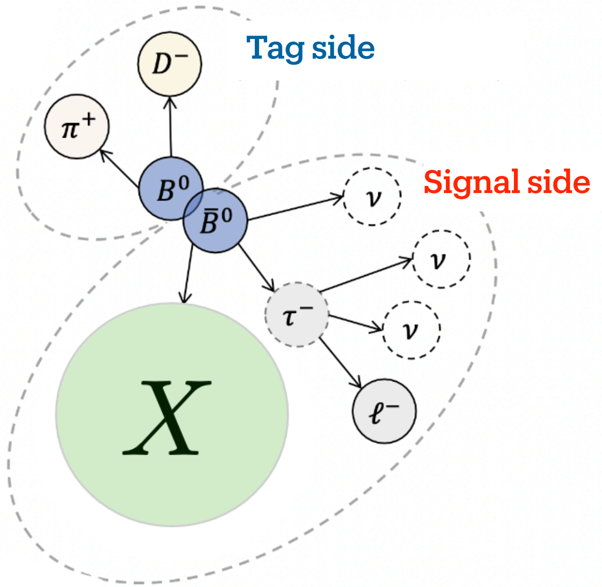
Results



Compatible with SM and $R(D^{(*)}_{\tau/\ell})$ measurements.

$R(X_{e/\mu})$ with hadronic B tagging

Results



- Goal: measure $R(X_{e/\mu}) = \dfrac{\mathscr{B}(B \to Xe\nu_e)}{\mathscr{B}(B \to X\mu\nu_\mu)}$.

The most precise test of $e - \mu$ universality in semileptonic B decays.

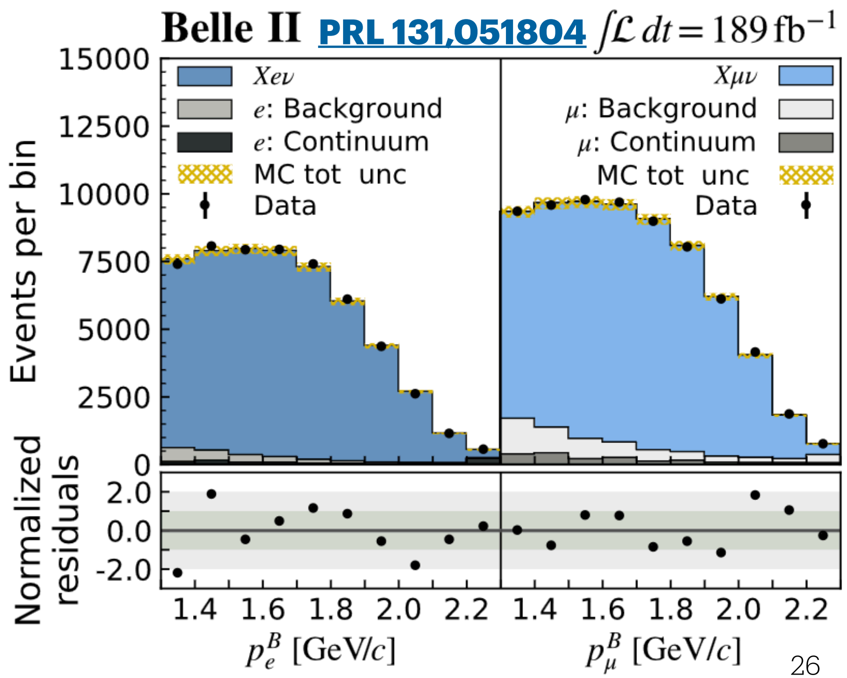
- Extract signal with simultaneous maximum-likelihood templates fits to p_e^B and p_μ^B spectra.

- Main challenge: modelling $X\ell\nu$, fake leptons and secondaries. Use a sideband to validate these components.

- Main source of systematic unc.: lepton e/μ identification (1.9%)

$$R_{e/\mu}(X) = 1.007 \pm 0.009(stat) \pm 0.019(syst)$$

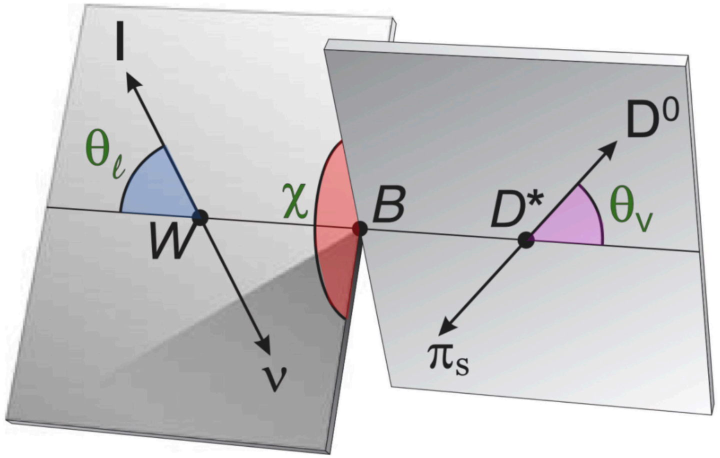
Compatible with SM and previous measurements.



Angular analysis

Basics

$B \to D^*\ell\nu$ decay: rich phenomenology due to different decay amplitudes. Encoded in angular distributions as a function of the recoil energy w of the D^*.



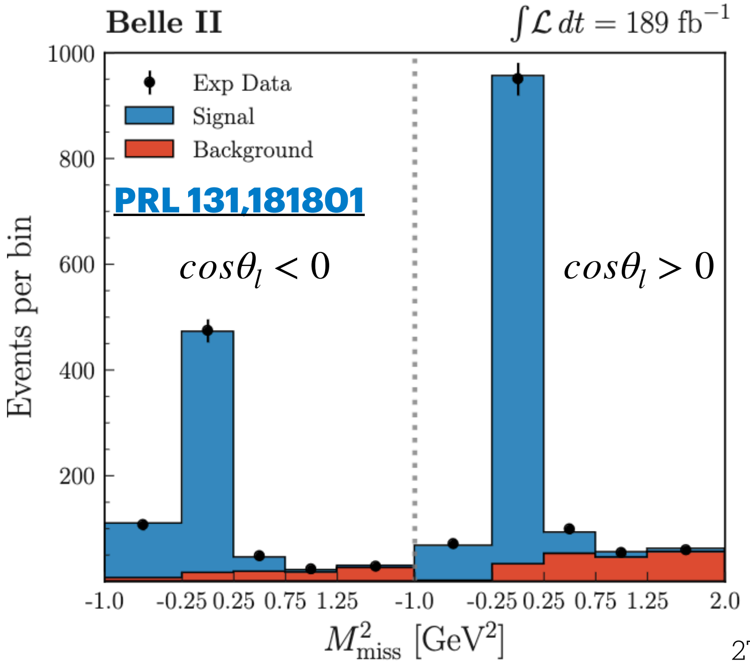
Comparing angular observables between muons and electrons gives powerful LFU tests.

Experimentally:

1. Reconstruct the distributions by measuring signal yields in bins of (combinations of) angular variables.

2. Signal/background separation by fitting M^2_{miss}.

3. Correct for detector acceptance, reconstruction efficiencies and resolution effects using simulation.



$B \to D^* \ell \nu$ angular asymmetries

Results

Measure 5 angular asymmetries and compare them for e and μ in 2 bins of the recoil energy w:

- A_{FB} : tendency of the lepton to travel along the W direction.
- S_3, S_9 : sensitive to alignment of lepton and D^* direction.
- S_5, S_7 : measure coupled alignments in the orientation of the D with respect to the D^*.

Reconstruct D meson in different modes:

$D \to K(n)\pi$ and $D \to KK$.

All asymmetry measurements are statistics limited.

Compatible with SM, no evidence for LFU violation.