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

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on behalf of the Belle II Collaboration

FPCP 2024, Bangkok
Parallel Session
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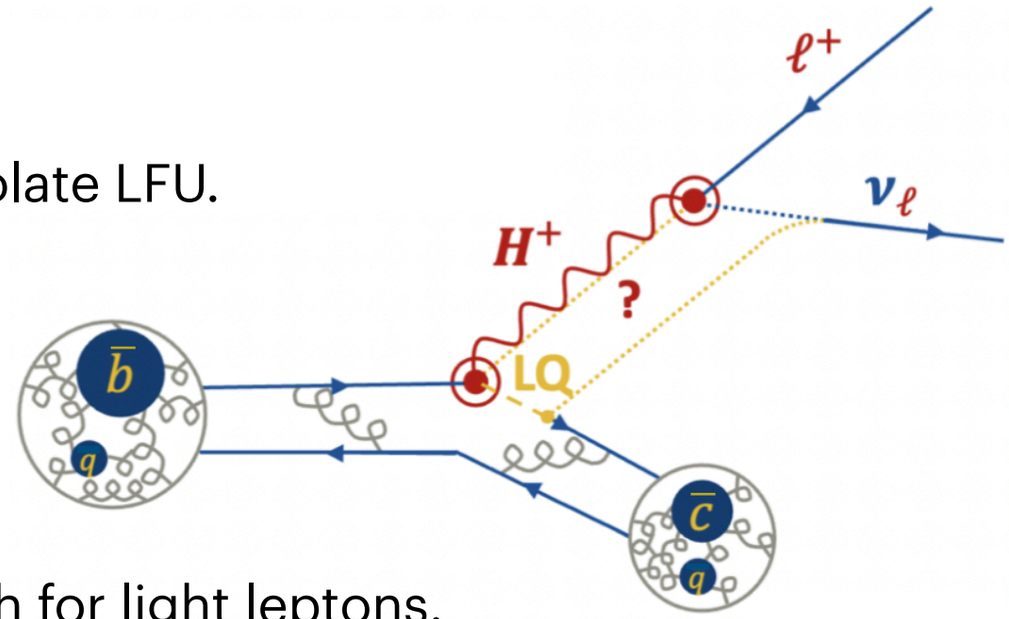
Lepton Flavour Universality in B decays

- W boson couples equally to e, μ, τ in the SM→ Lepton Flavour Universality (LFU).

- Accidental symmetries, not required by first principles.
  Non-SM contributions (H^+, LQ, SUSY...) can generally violate LFU.

- Tree-level semileptonic B decays offer a rich phenomenology for LFU tests:



  1. Asymmetries in angular distributions enhance the reach for light leptons.
     Exploit high rates of $B \to D^* \ell \nu$ decays.

  2. Ratio of rates suppress most theoretical and experimental uncertainties.
     Persistent anomaly observed between tau and light leptons, $R(D^{(*)}_{\tau/\ell}) = \dfrac{\mathcal{B}(B \to D^{(*)} \tau \nu)}{\mathcal{B}(B \to D^{(*)} \ell \nu)}$.

- Today: LFU tests from Belle and Belle II. Most are new since last FPCP.

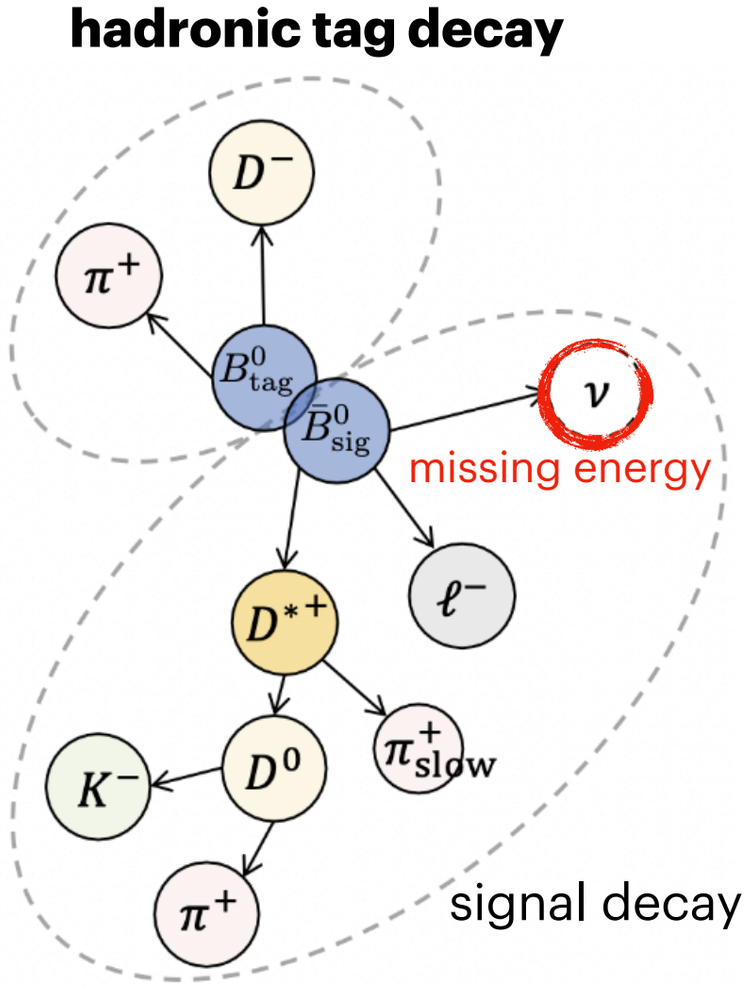
Dealing with missing energy

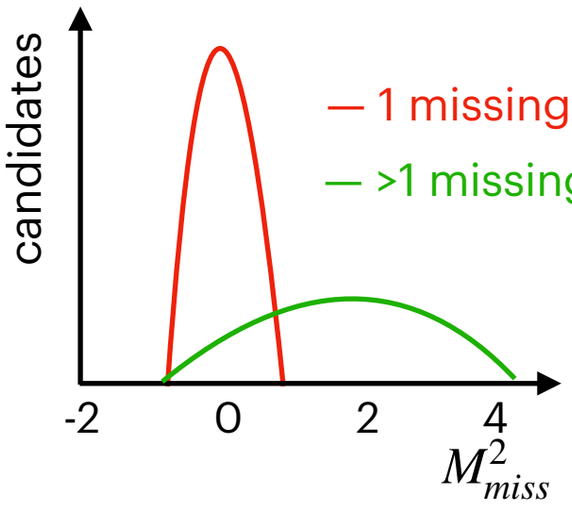
Belle (II) ideally suited to study decay with missing energy: hermetic detector, at-threshold $B\bar{B}$ production with precisely known energy.

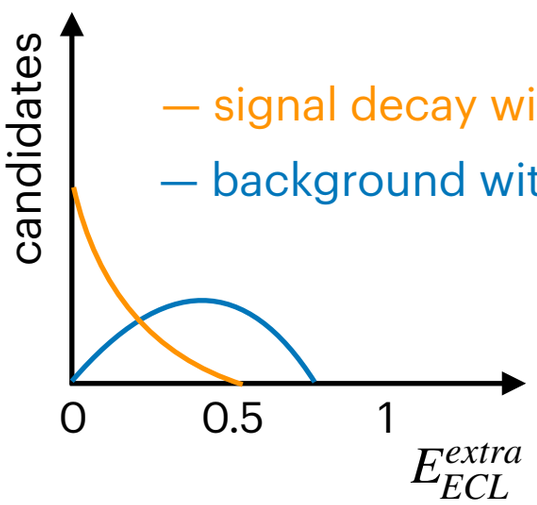
- Fully reconstruct the partner B meson in hadronic decay mode. (B_{tag} efficiency <1%, purity up to 90% [FEI]).
- Match remaining particles with signal decay.
- Identify invisible particles using:

  1. Missing mass of undetected particles $M^2_{miss} = (p_{e^+e^-} - p_{visible})^2$.

  2. Residual energy in the calorimeter E^{extra}_{ECL}.





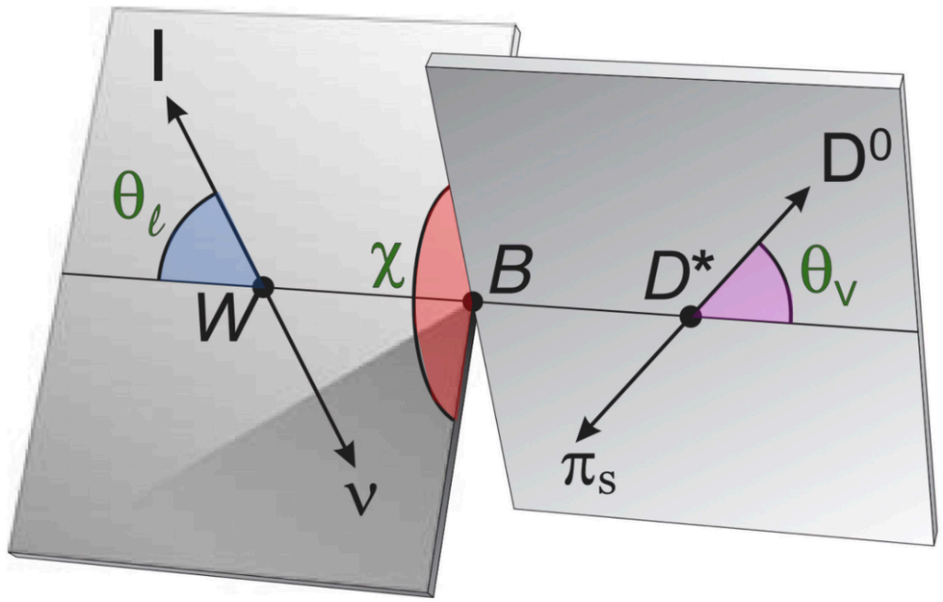


All the analyses shown in this talk are tagged.

LFU tests with angular asymmetries for light leptons

Angular analysis: basics

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



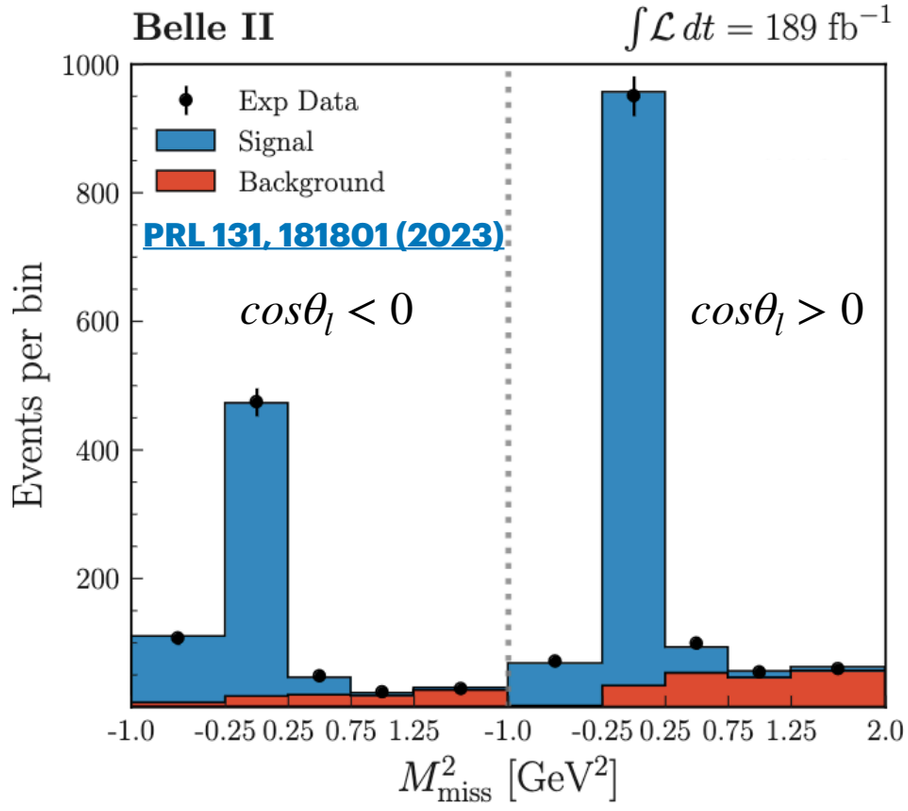
Comparing angular observables between muons and electrons gives powerful LFU tests.

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

Belle II $= 189 fb^{-1}$

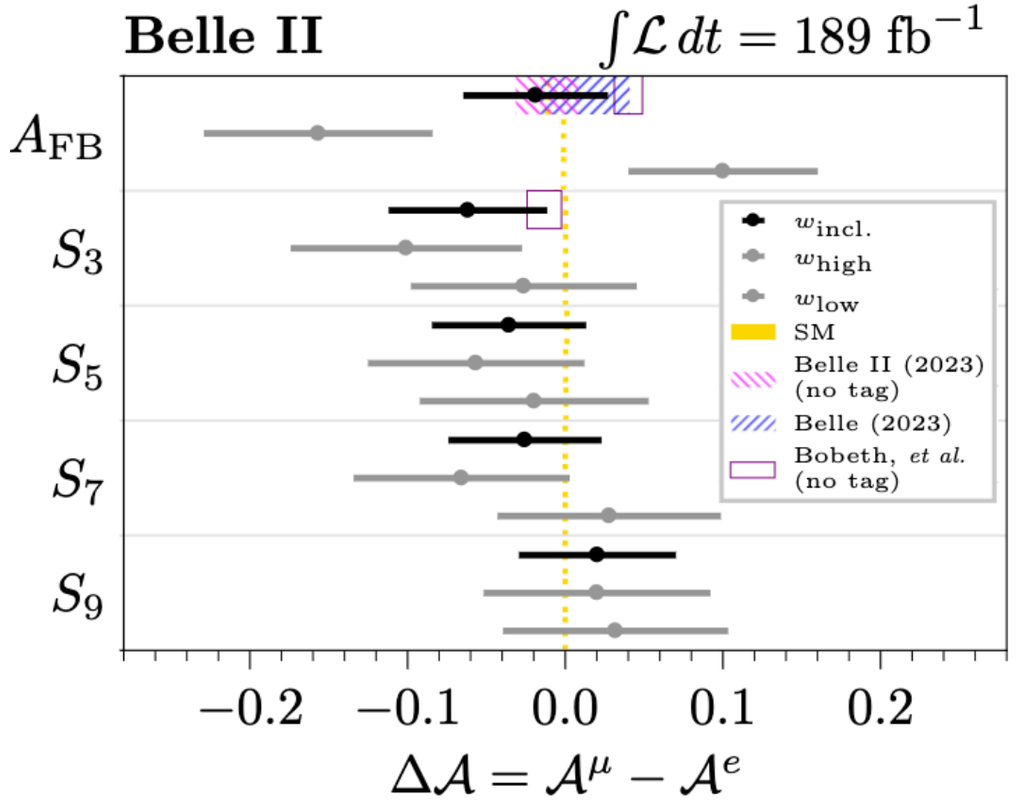
PRL 131, 181801 (2023)

Pheno analysis of Belle data [Bobeth et al.] pointed to possible LFU violation. Need a verification.

Goal: measure 5 angular asymmetries and compare them for muons and electrons in 2 bins of 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.

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

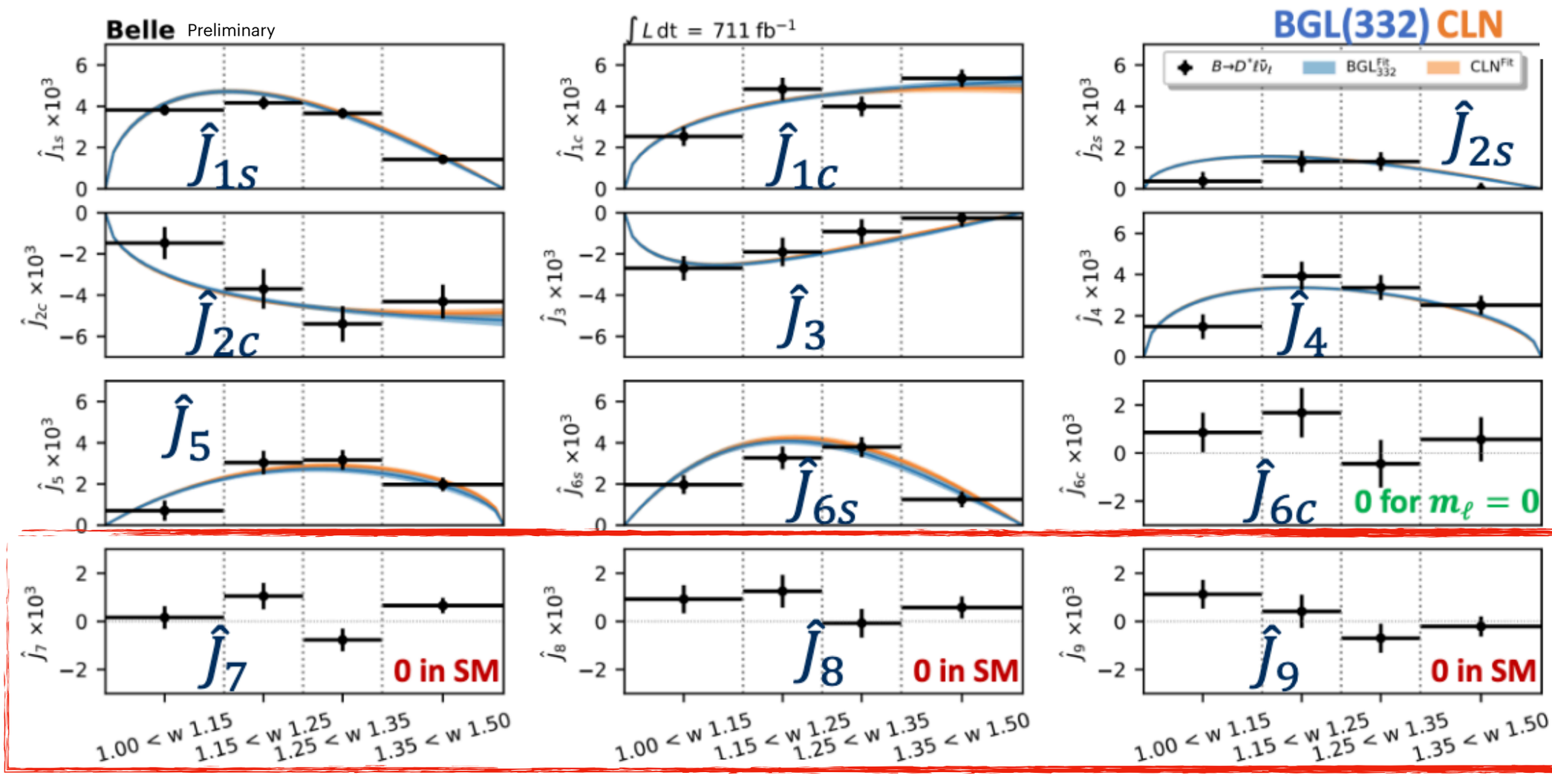
BELLE $= 711 fb^{-1}$

arXiv: 2310.20286

- The differential decay rate can be decomposed in a basis of angular functions with 12 coefficients J_i, all dependent on w.

Goal: measuring of J_i in 4 bins of w. Provide information on form-factors and test SM expectations.

- Reconstruct D meson in different modes: $D \to KK$, $D \to KK(n)\pi$ and $D \to K(n)\pi$.



Coefficients are in good agreement with the fit using BGL(332) and CLN form-factor parametrizations.

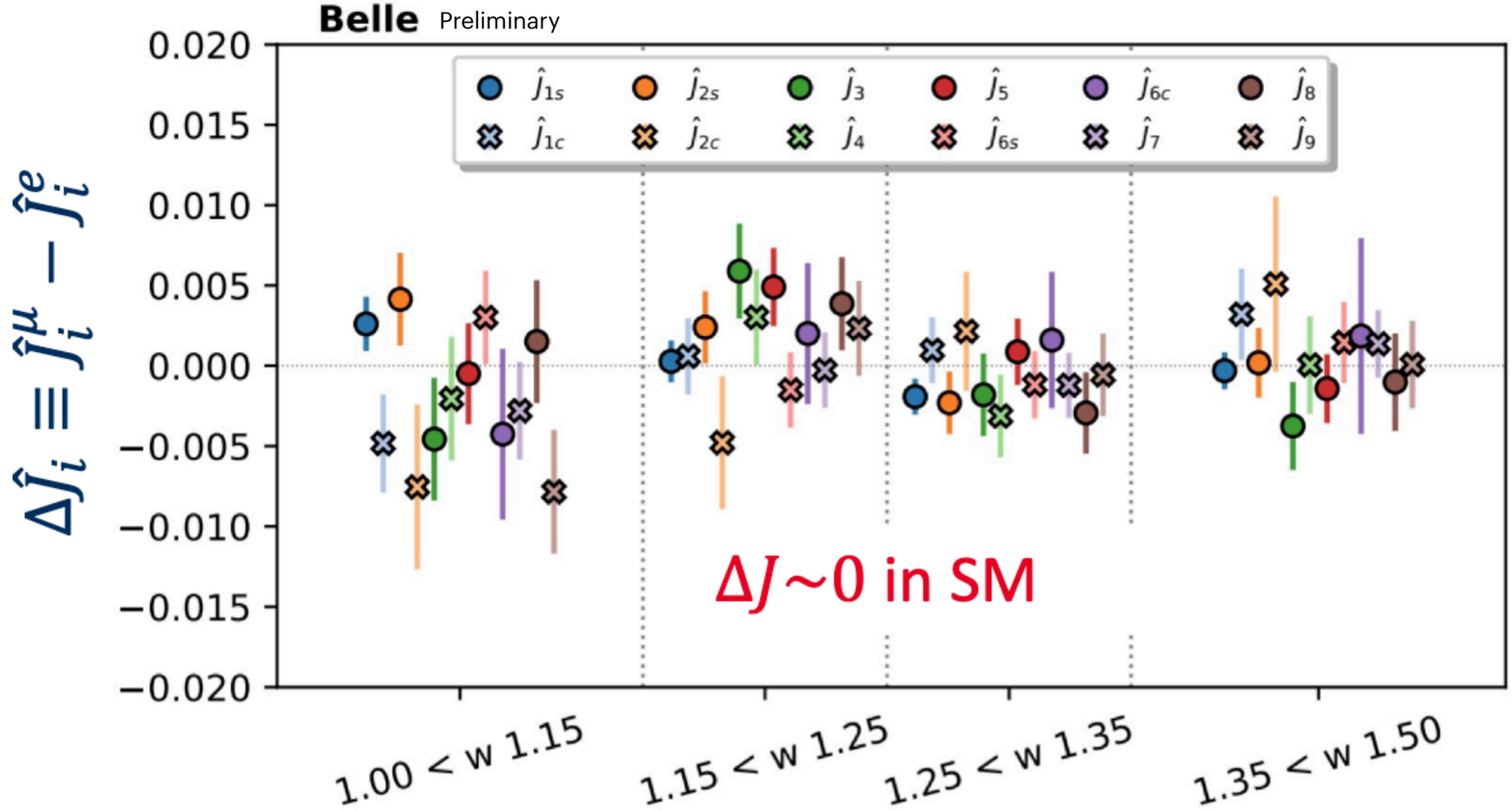
Coefficients consistent with the SM prediction.

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

BELLE $= 711 fb^{-1}$

arXiv: 2310.20286

Difference between electron and muon sensitive to LFU: $\Delta J_i = J_i^\mu - J_i^e$.



No significant deviations observed from the SM.

Aside: determination of $|V_{cb}|$ using CLN and BGL parametrizations and lattice data from [1-2-3]:

$$|V_{cb}|_{BGL} = (41.0 \pm 0.7) \cdot 10^{-3}$$

$$|V_{cb}|_{CLN} = (40.9 \pm 0.6) \cdot 10^{-3}$$

Similar values, closing the gap with the inclusive $|V_{cb}|$ measurement.

LFU tests with the third generation: $R(D^*)$ and $R(X)$ measurements

Measurement of $R(D^*)$

Belle II $= 189 fb^{-1}$

arXiv:2401.02840

Submitted to PRD

Goal: measure $R(D^*_{\tau/\ell}) = \dfrac{\mathcal{B}(B \to D^* \tau \nu_\tau)}{\mathcal{B}(B \to D^* \ell \nu_\ell)}$

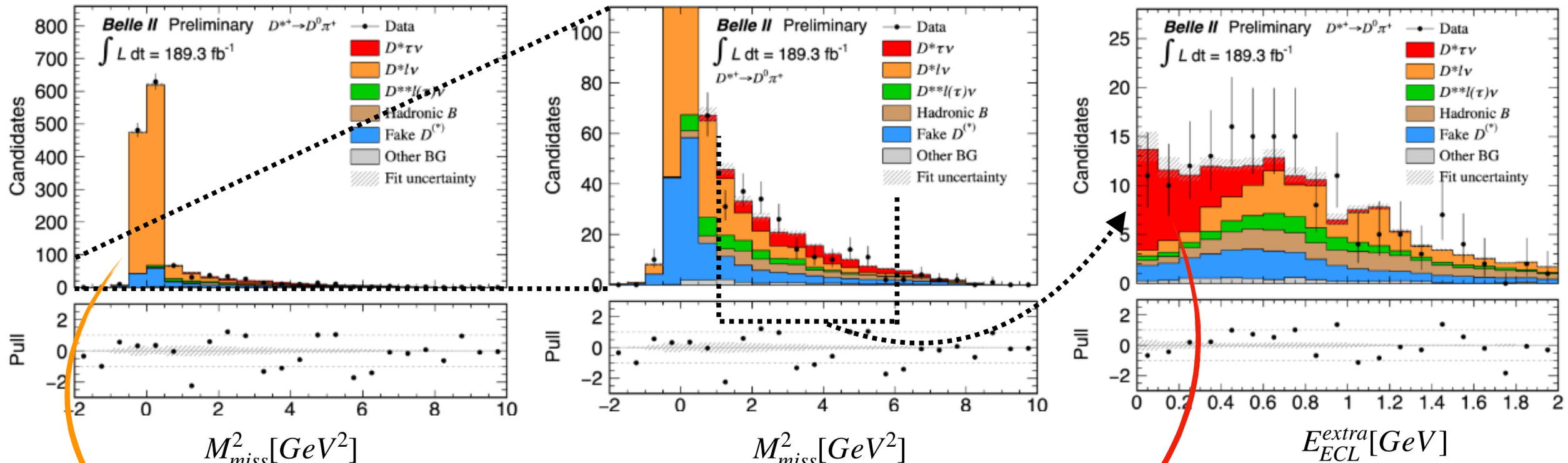
Three signal modes: $D^{*+} \to D^0\pi^+, D^+\pi^0$ and $D^{*0} \to D^0\pi^0$. Identify lepton from $\tau \to \ell \nu \bar{\nu}$.

Extract signal and normalisation yields using a simultaneous 2D likelihood fit to E^{extra}_{ECL} and M^2_{miss}.

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

Zoom of M^2_{miss} projection for $D^{*+} \to D^0\pi^+$ mode

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



normalisation yield: 2163 ± 79

signal yield: 108 ± 16

Measurement of $R(D^*)$

Belle II $= 189 fb^{-1}$

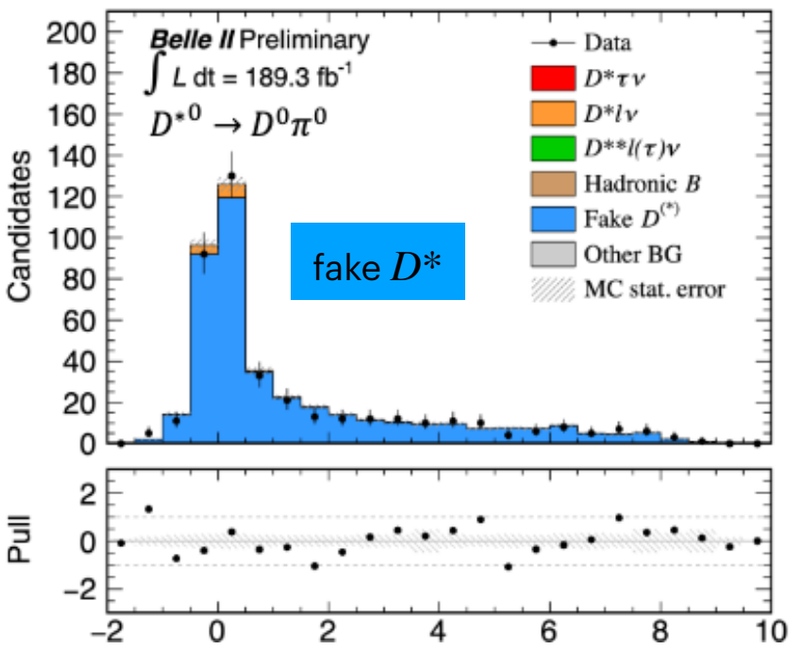
arXiv:2401.02840

Submitted to PRD

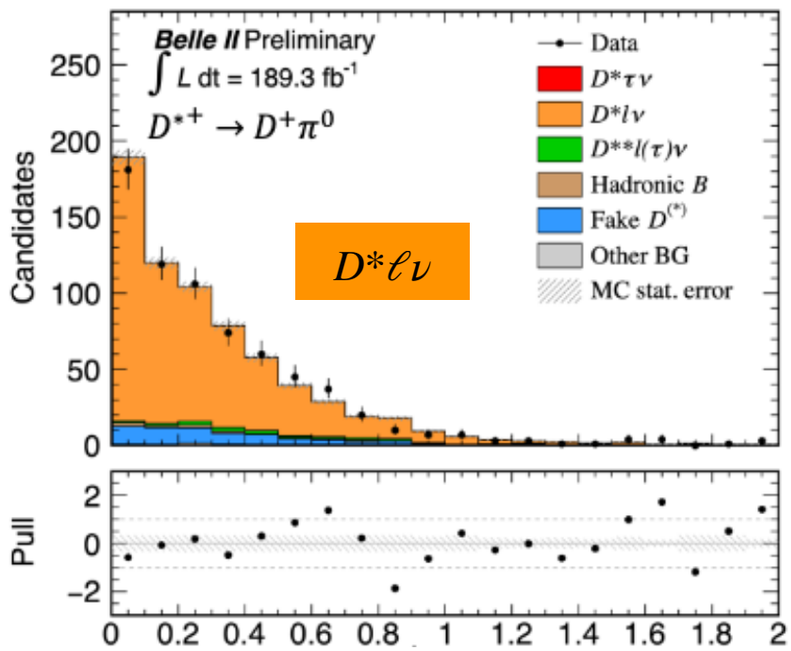
Main challenge: validate modelling of background/normalization fit templates.

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

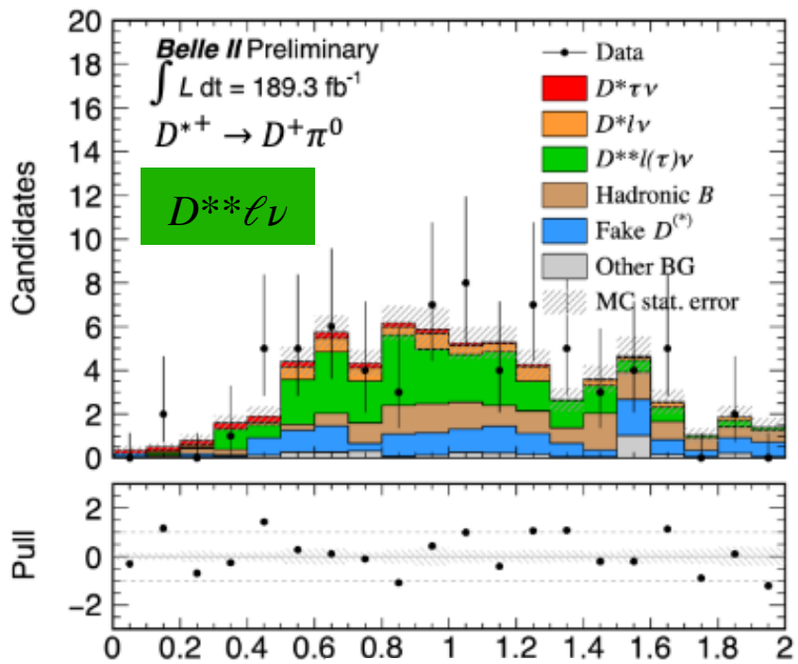
$m(D\pi) > m(D^*)$ sideband:
validate fake D^* modelling



$q^2 < 3.5 GeV^2$ sideband:
validate E_{ECL}



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



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

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

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

Measurement of $R(D^*)$: results

Belle II $= 189 fb^{-1}$

arXiv:2401.02840
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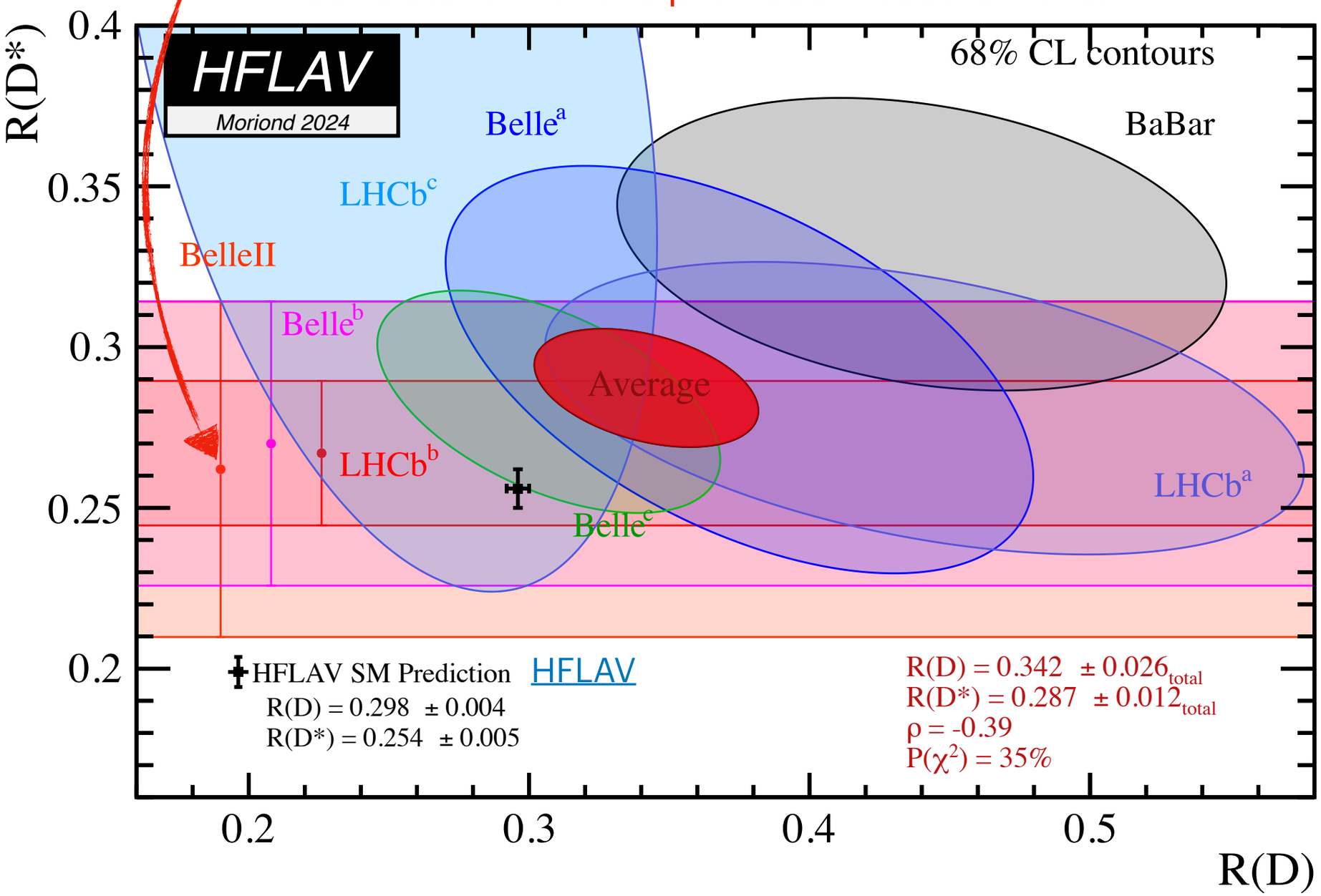
$$R(D^*) = 0.262^{+0.041}_{-0.039}(stat)^{+0.035}_{-0.032}(syst)$$

HFLAV 23: $R(D^*) = 0.287 \pm 0.012$

Consistent with the previous measurements.



3.3σ tension between the LFU-sensitive quantities $R(D)$ and $R(D^*)$ and SM predictions.

Measurement of $R(X_{\tau/\ell})$

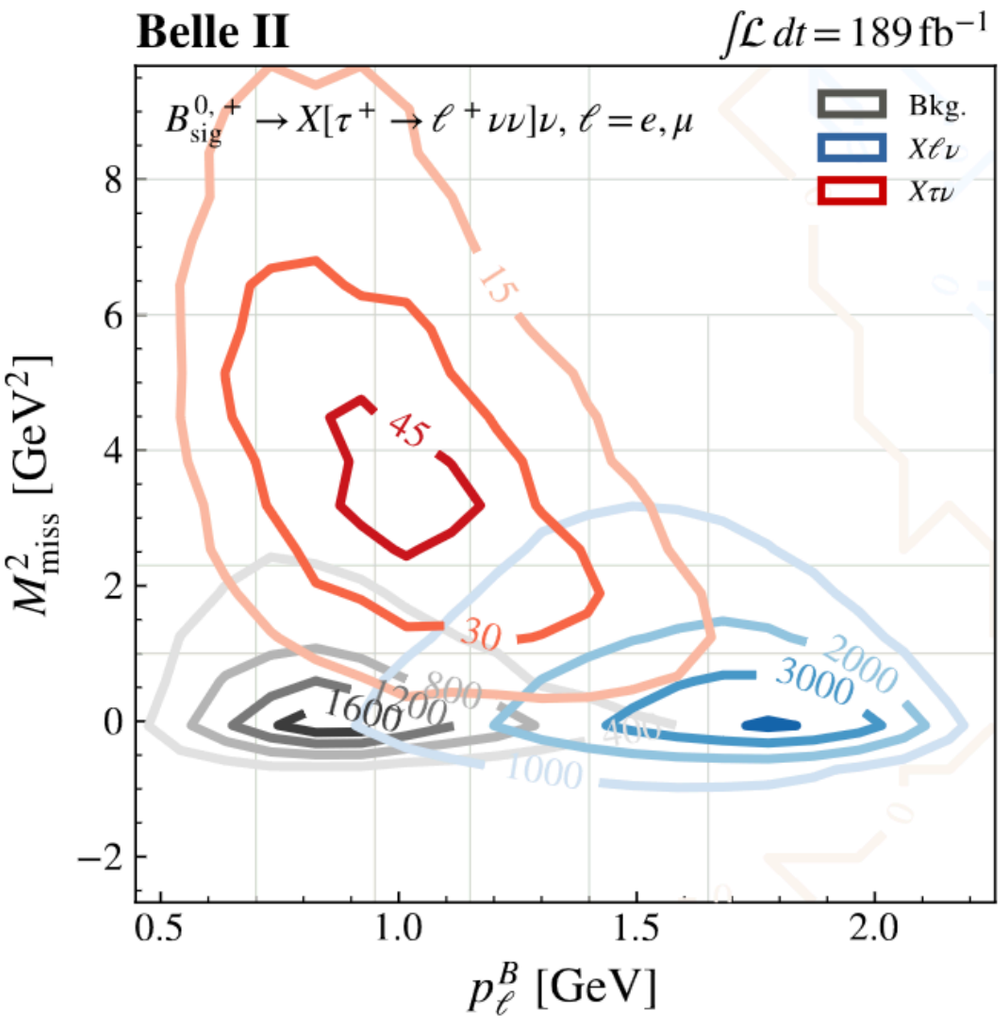
Belle II $= 189 fb^{-1}$

PRL 132, 211804

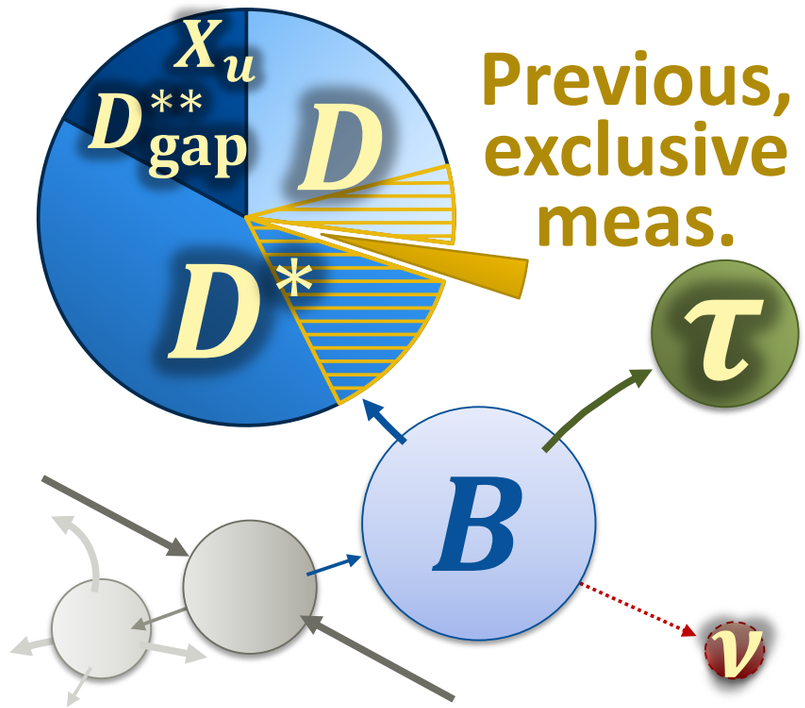
Goal: measure $R(X_{\tau/\ell}) = \dfrac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$

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

Select events with $B_{tag} + \ell$, remaining particles attributed to X.



Inclusive meas.



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

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

Measurement of $R(X_{\tau/\ell})$

Belle II $= 189 fb^{-1}$

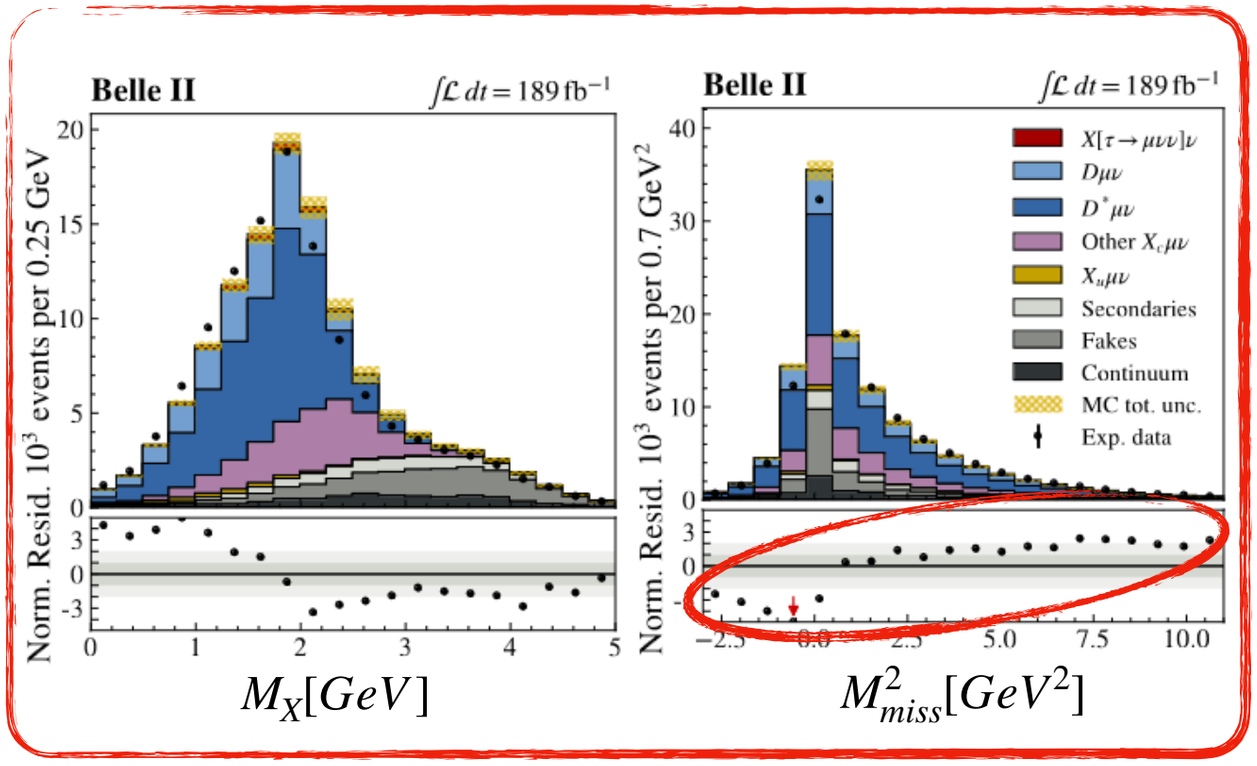
PRL 132, 211804

Main challenge: modelling the X system.

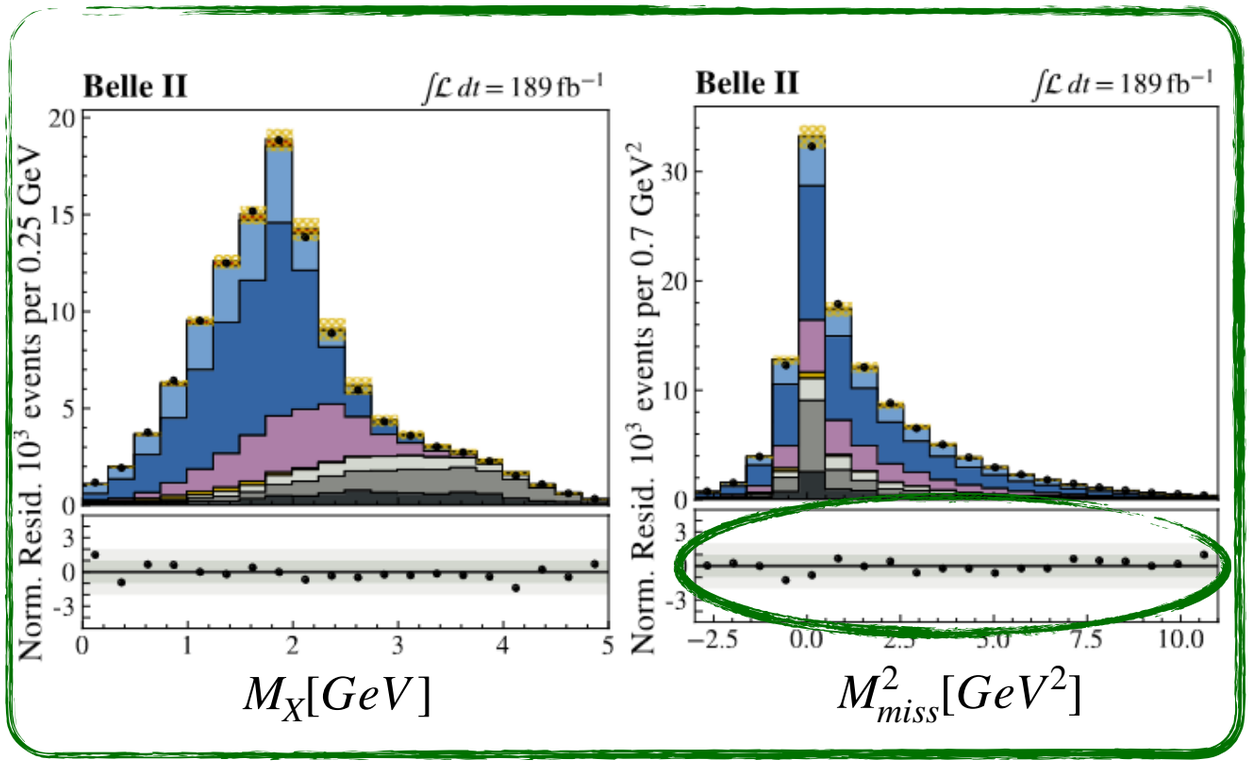
Detailed adjustments to simulation: form factors, B and D branching fractions.
Corrections based on comparison of simulation with control regions.

Example:

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}.

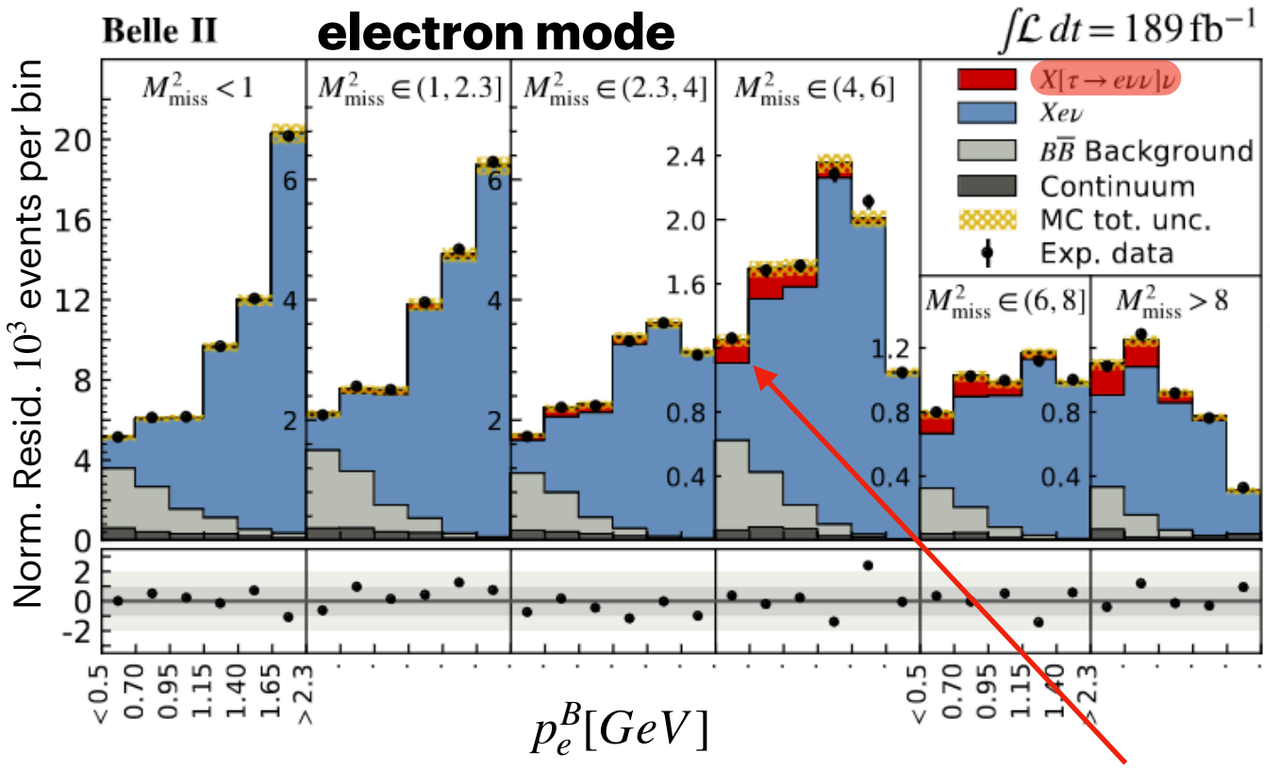
Main sources of syst. uncertainties: $X_c \ell \nu$ M_X shape: 7.1%, $\mathcal{B}(B \to X \ell \nu)$:7.7 %, $X_c \tau(\ell)\nu$ form factors: 7.8%

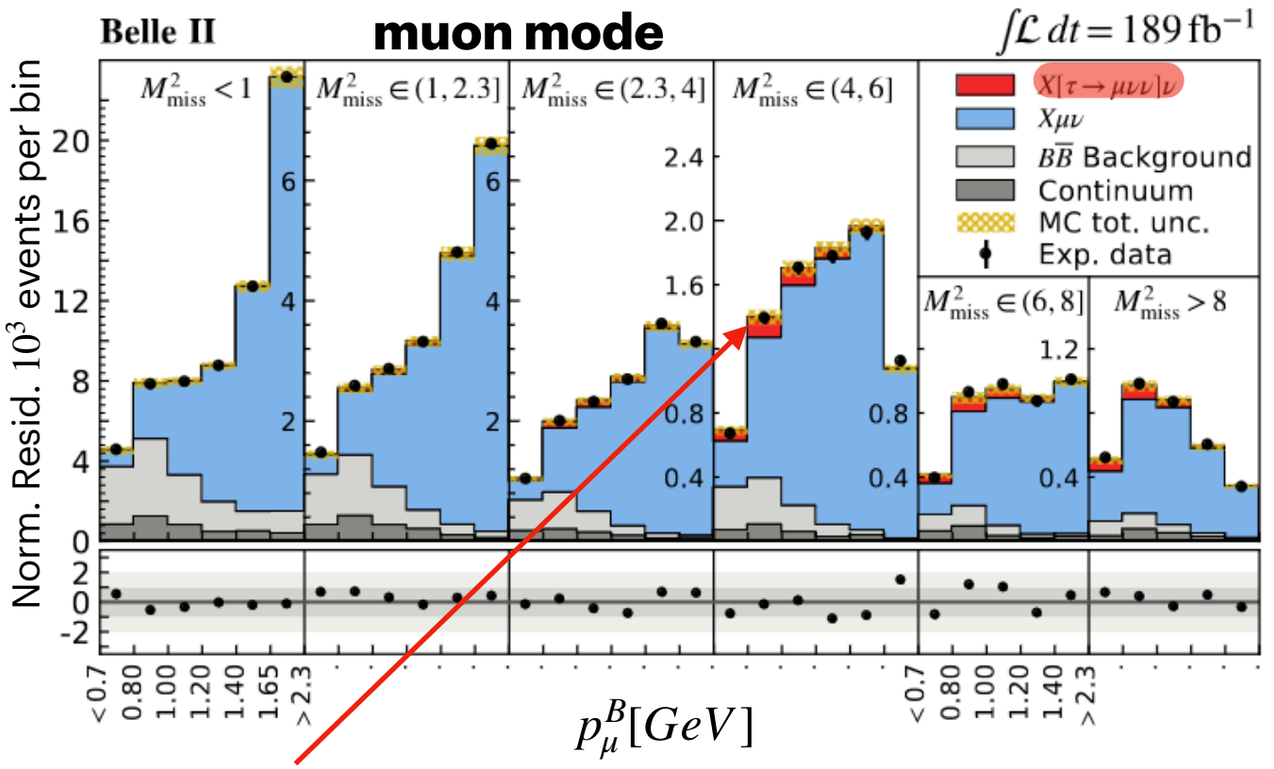
Statistical uncertainty: experimental sample size: 7.1%

Measurement of $R(X_{\tau/\ell})$: results

Belle II $= 189 fb^{-1}$

PRL 132, 211804





fitted signal yield

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

(average of electron and muon channels)

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

Compatible with SM and $R(D^{(*)})$measurements.

Summary

- Many new exciting measurements from both Belle and Belle II.

  The results are in good agreement with LFU and SM.

- With half of collected data set ($189 fb^{-1}$), Belle II already produces world-leading and unique results.

- Belle data still fruitful after >10 years.

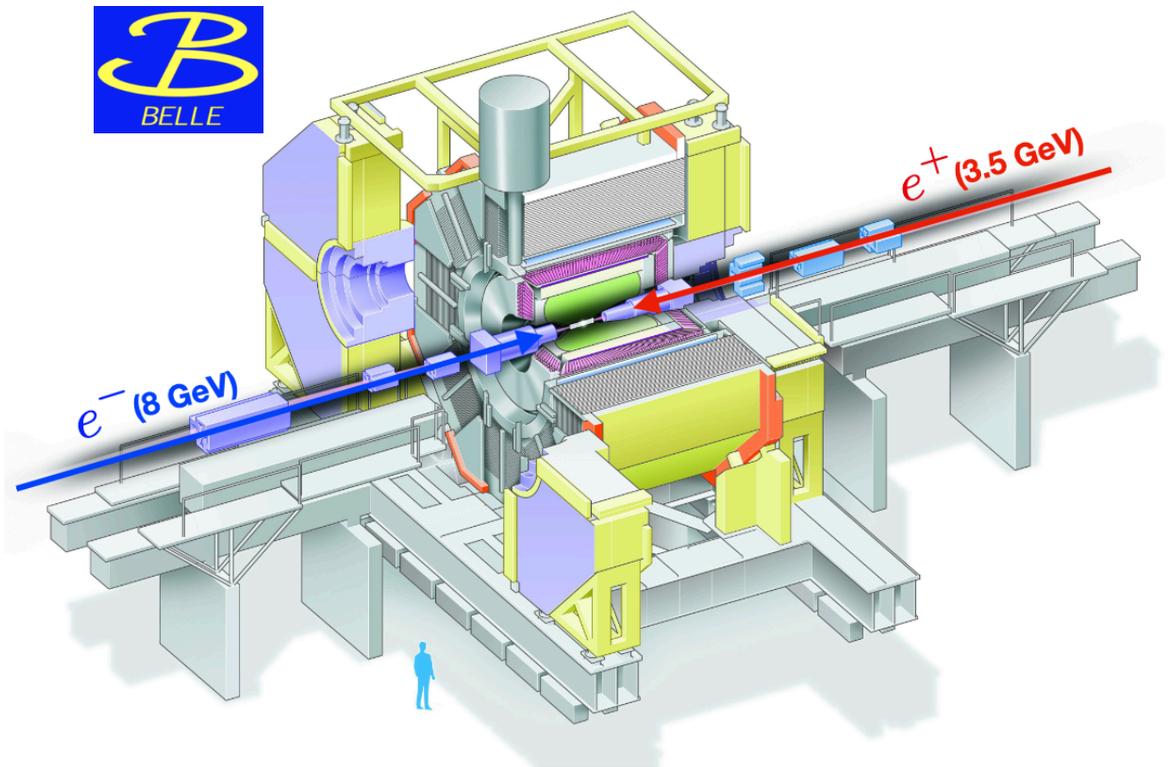
- Continuous effort from experiment and theory needed:
  - Higher precision expected at Belle II for the next $R(X)$ and $R(D^*)$ results using the full collected data set.
  - Some systematic uncertainties could be reduced with improved modelling.

Backup

From Belle...to Belle II

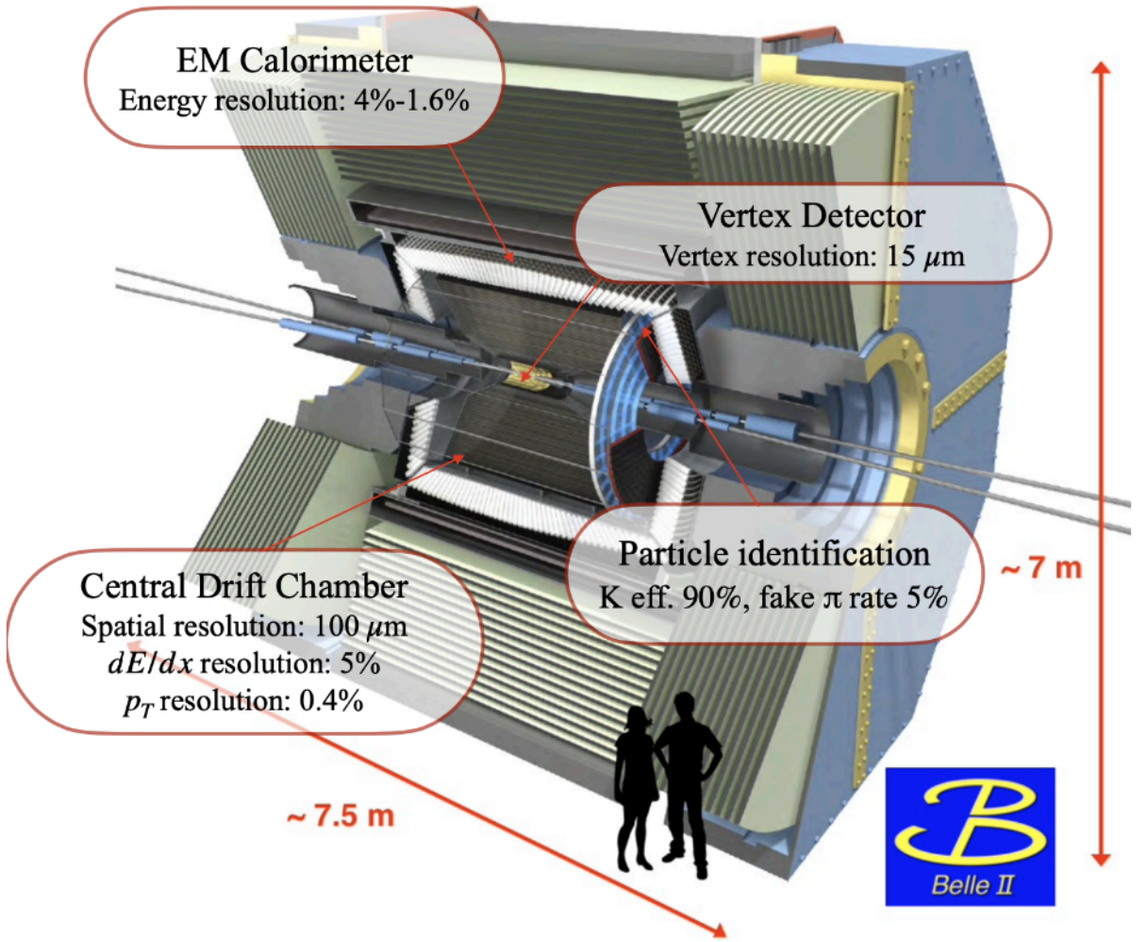
Belle

- From 1999 to 2010 at KEK (Japan).
- 3.5-on-8 GeV e^+e^- collider at $\Upsilon(4S)$ resonance.
- Collected $772 \cdot 10^6$ $B\bar{B}$ pairs.



Belle II

- From Belle: structure, magnets, calorimeter crystals, K_L & μ detector.
- Run 1: collected $387 \cdot 10^6$ $B\bar{B}$ pairs.
- Starting Run 2 after improving vertex detector.
- First Run 2 collision: 20 Feb 2024, 22:12 JST.



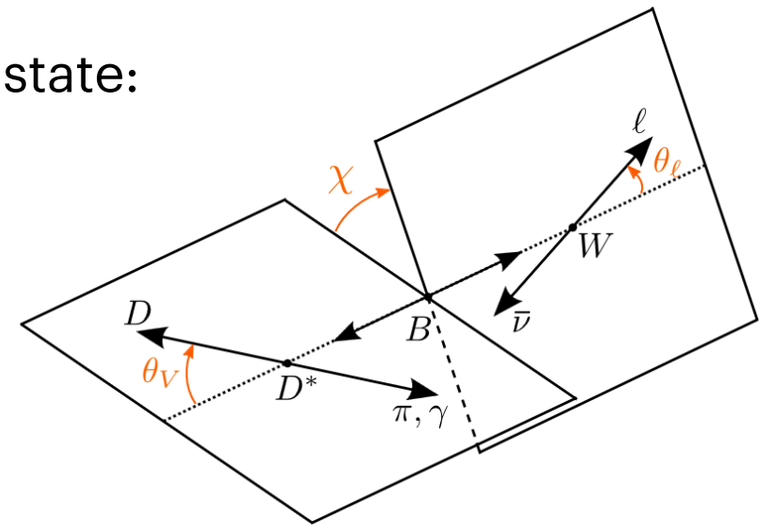
Promising with multiple neutral particles and neutrinos in the final states.

Topology of $B \to D^* \ell \nu$ decays

To theoretically describe $B \to D^* \ell \nu$ four kinematic variables are needed:

- w is related to the velocity transfer from the initial to the final state:

$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$



- 3 angles: θ_V, θ_ℓ and χ.

Asymmetries between electron and muon in the angular distributions sensitive to LFU:

$$A_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1} \left[\int_0^1 - \int_{-1}^0\right] dx \frac{d^2\Gamma}{dw dx}$$

+	-	$\mathcal{A}_{FB}(w) \quad dx \to d(\cos\theta_\ell)$
+	-	$\mathcal{S}_3(w) \quad dx \to d(\cos 2\chi)$
		$\dots$

Experimentally:

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

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

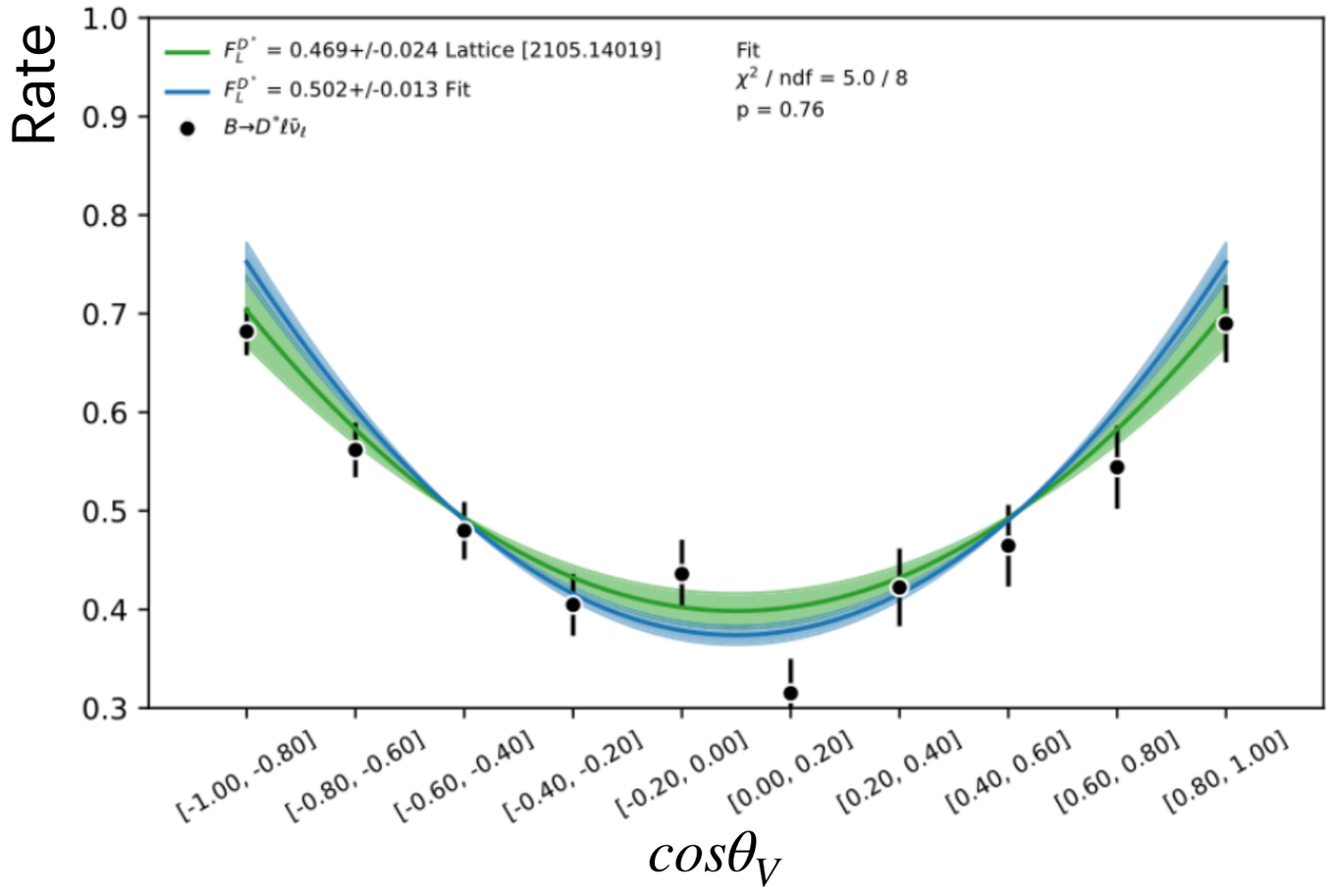
3. Correct for detector acceptance, reconstruction efficiencies and resolution effects using simulation.

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

BELLE $= 711 fb^{-1}$

PRD 108, 012002 (2023)

Goal: measure LFU sensitive observables using $B \to D^* \ell \nu$ final states.



Measure difference of electron and muon D^* longitudinal polarization fraction:

$$\Delta F_L^{D^*} = 0.030 \pm 0.025 \pm 0.007$$

Measure difference of electron and muon FB asymmetry:

$$\Delta A_{FB} = 0.028 \pm 0.028 \pm 0.008$$

Light lepton universality test :

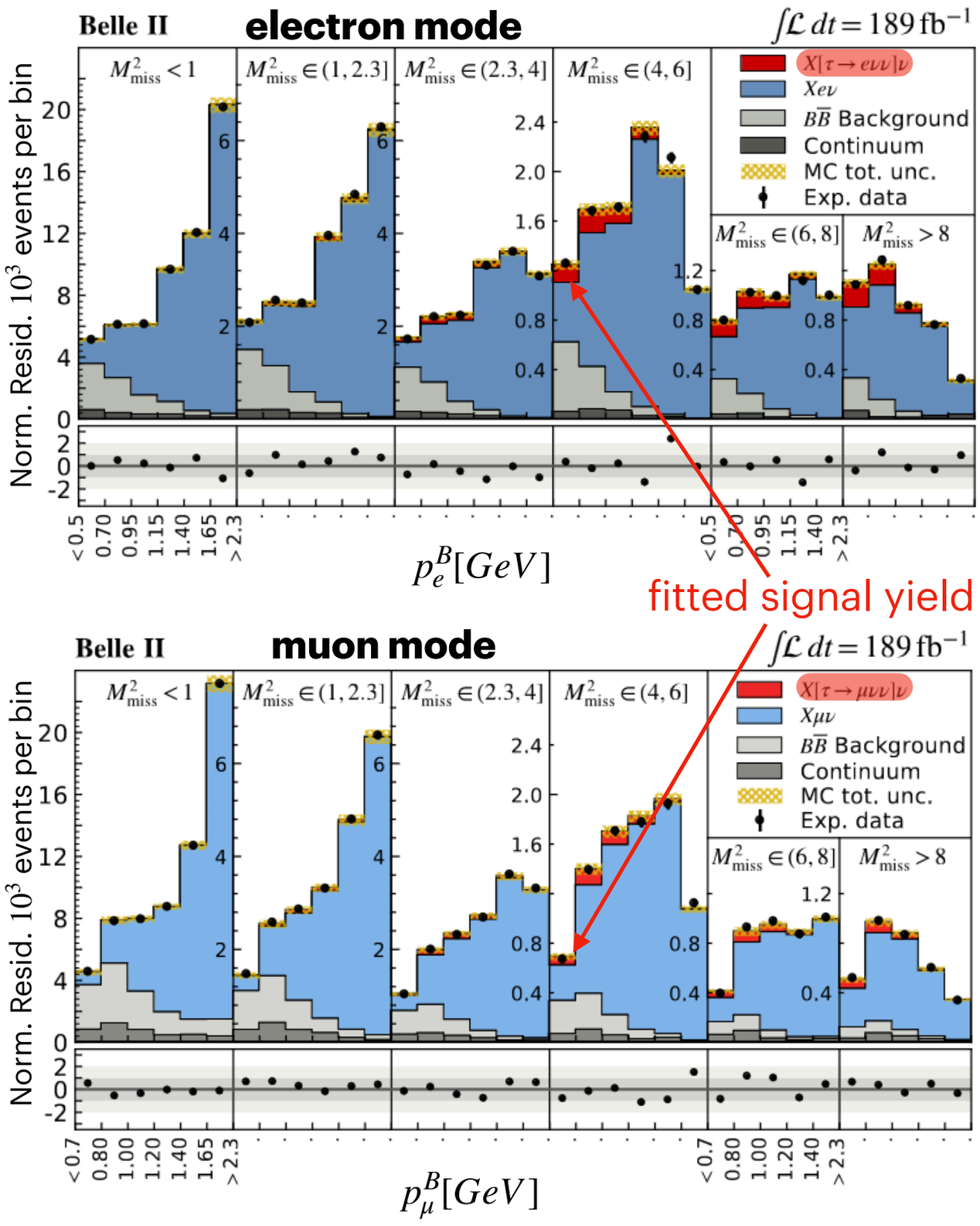
$$R_{e/\mu}(D^*) = \mathcal{B}(B \to D^* e \nu_e)/\mathcal{B}(B \to D^* \mu \nu_\mu) = 0.993 \pm 0.023(stat) \pm 0.023(syst)$$

Consistent with SM and previous measurements.

Measurement of $R(X_{\tau/\ell})$: results

Belle II $= 189 fb^{-1}$

PRL 132, 211804

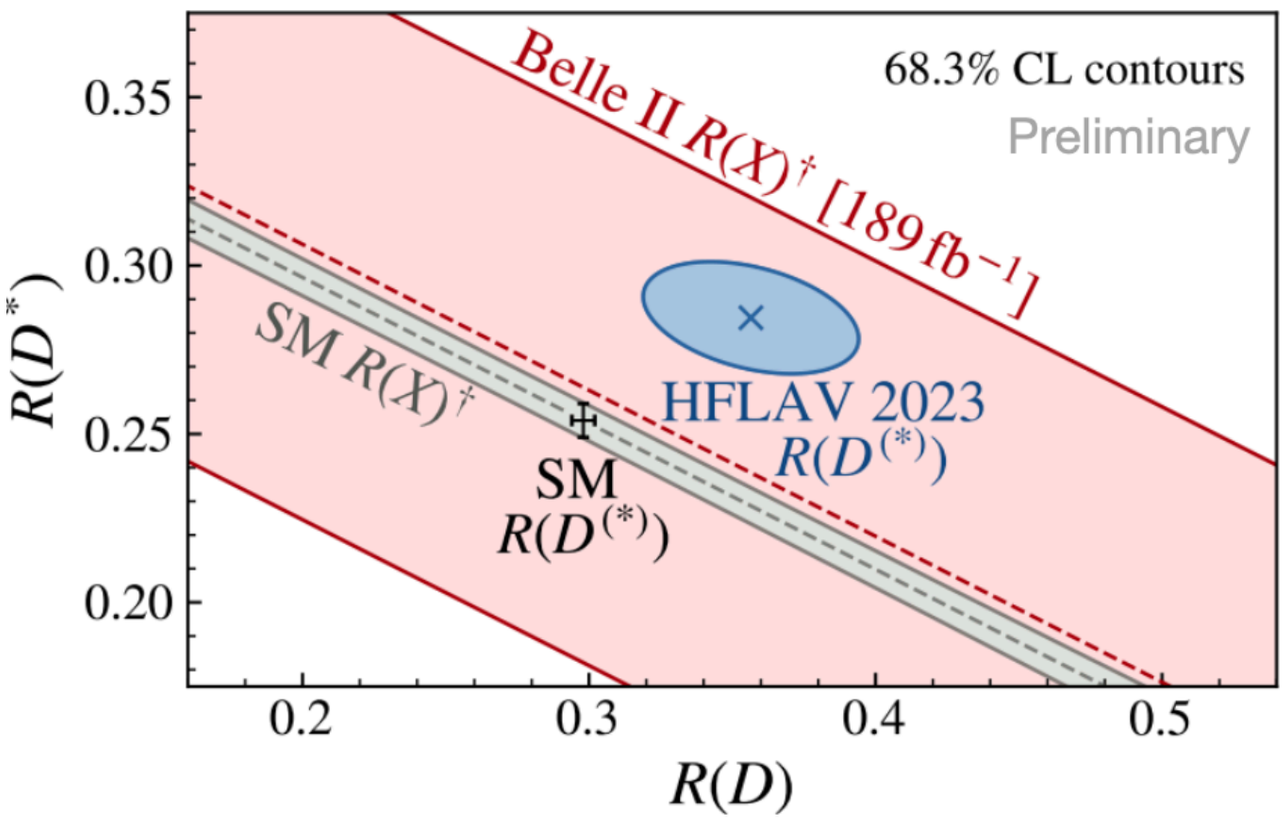


$$R(X_{\tau/\ell}) = 0.228 \pm 0.016(stat) \pm 0.036(syst)$$

(average of electron and muon channels)

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

Compatible with SM and $R(D^{(*)})$measurements.



Measurement of $R(X_{e/\mu})$

Belle II $= 189 fb^{-1}$

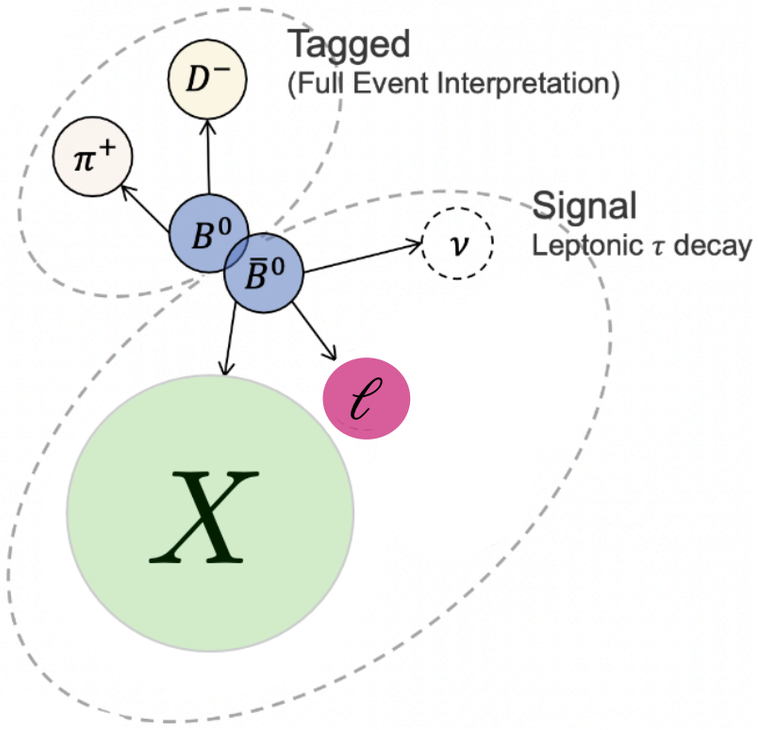
PRL 131, 051804

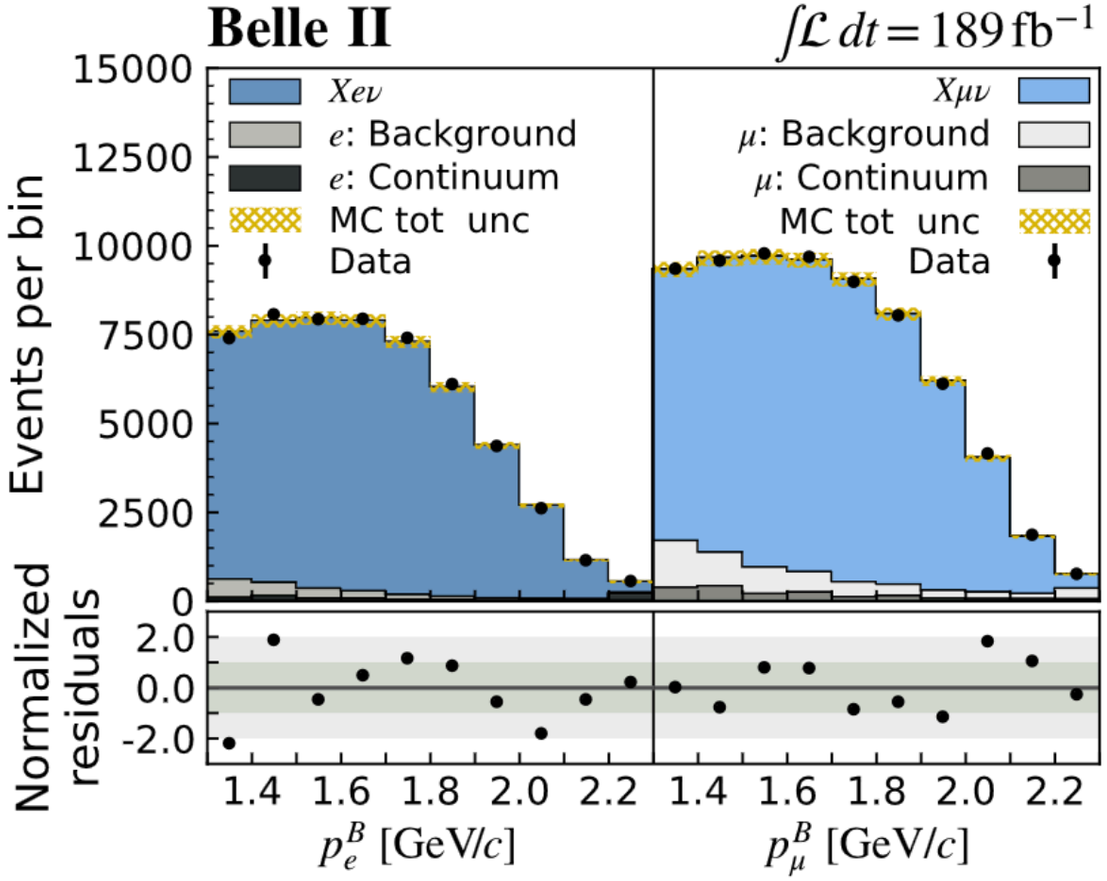
Goal: measure $R(X_{e/\mu}) = \dfrac{\mathcal{B}(B \to Xe\nu_e)}{\mathcal{B}(B \to X\mu\nu_\mu)}$

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 systematic: lepton e/μ identification (1.9%)

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

$R_{e/\mu}(D^*) = 0.993 \pm 0.023(stat) \pm 0.023(syst)$ PRD 108, 012002

Compatible with SM and previous measurements.