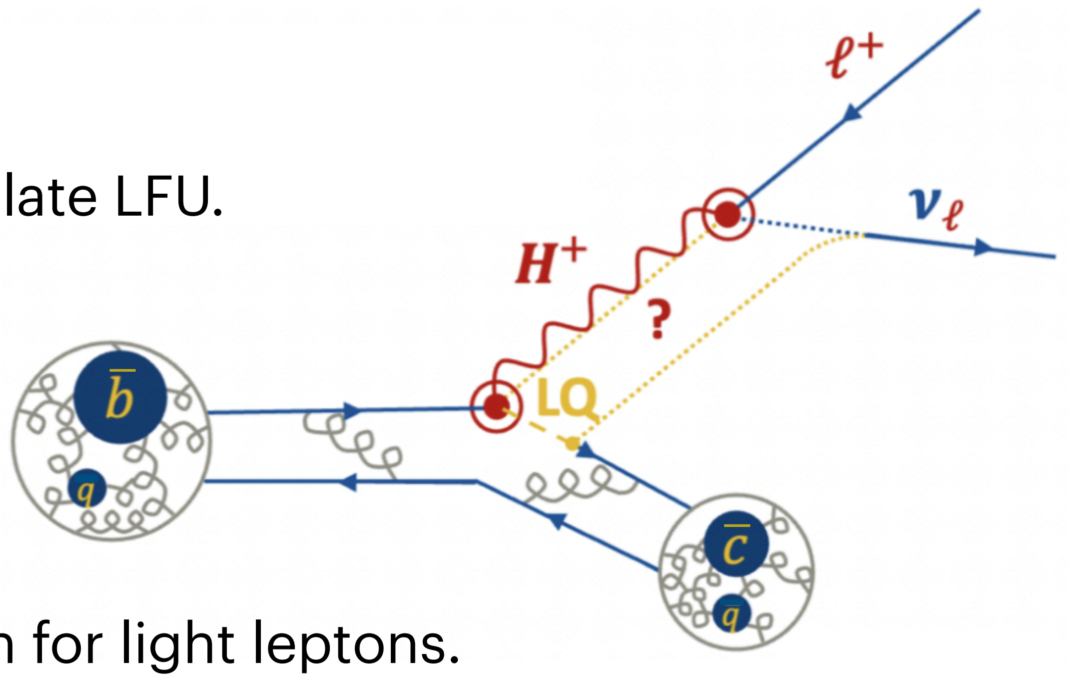
Measurements of lepton-flavour universality in semileptonic *B* decays at Belle and Belle II

Michele Mantovano (University and INFN Trieste)
on behalf of the Belle II Collaboration

FPCP 2024, Bangkok
Parallel Session
May 28, 2024

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

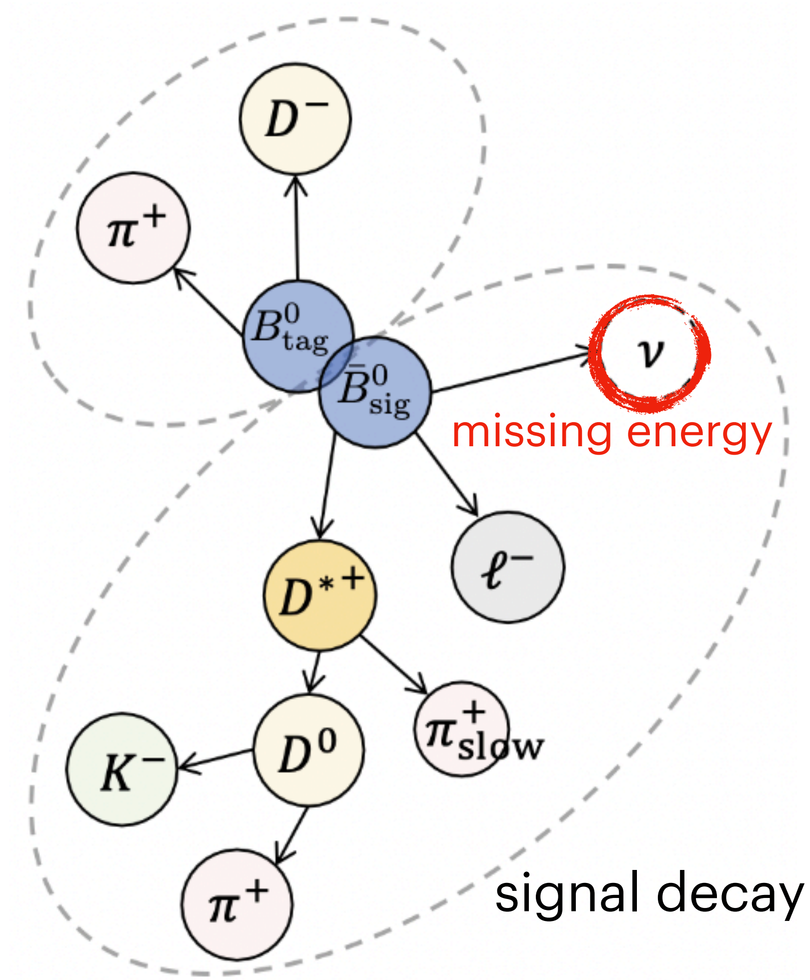
Belle (II) ideally suited to study decay with missing energy: hermetic detector, at-threshold $B\bar{B}$ production with precisely known energy.

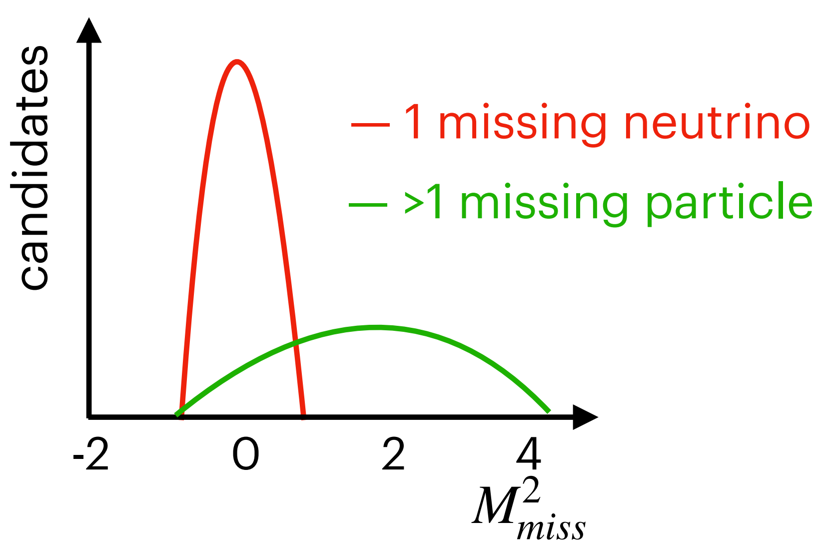
- Fully reconstruct the partner B meson in hadronic decay mode. (B_{tag} efficiency <1%, purity up to 90% [FEI]).
- Match remaining particles with signal decay.
- Identify invisible particles using:

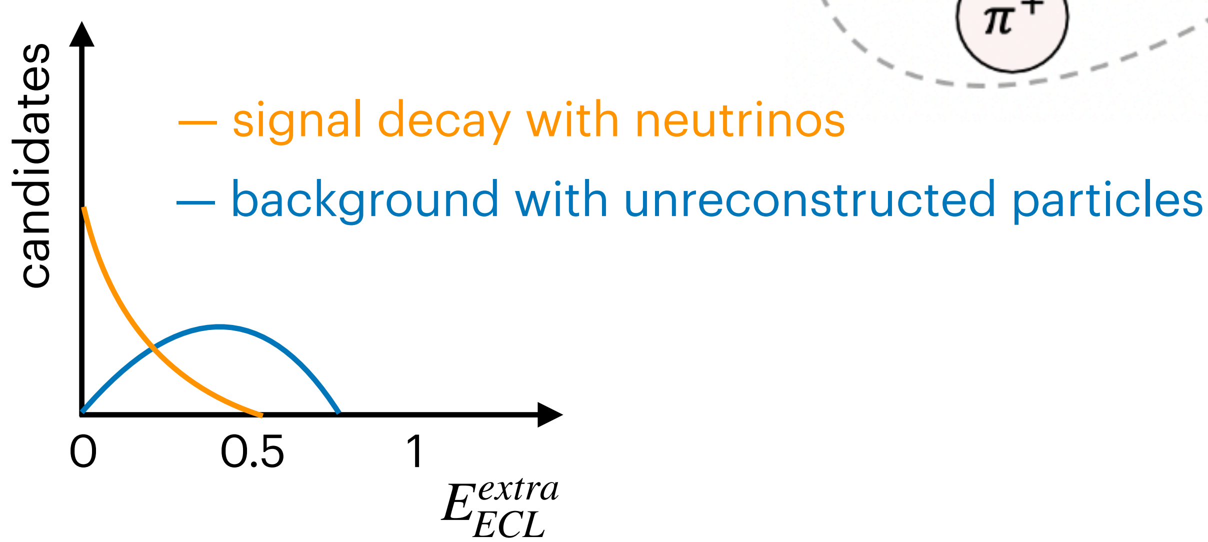
1. Missing mass of undetected particles $M^2_{miss} = (p_{e^+e^-} - p_{visible})^2$.

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

hadronic tag decay





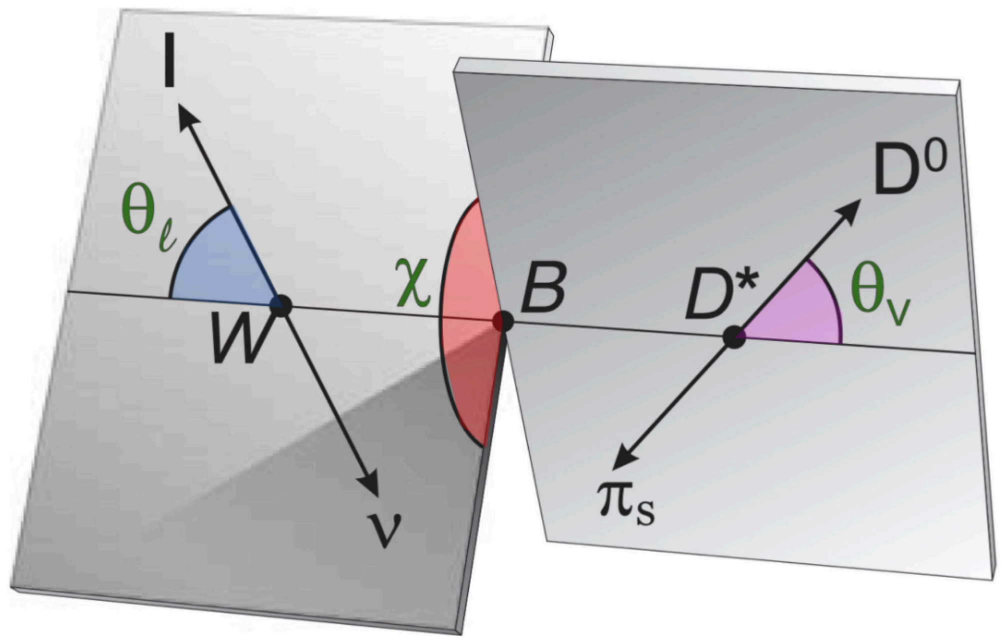


All the analyses shown in this talk are tagged.

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^*.



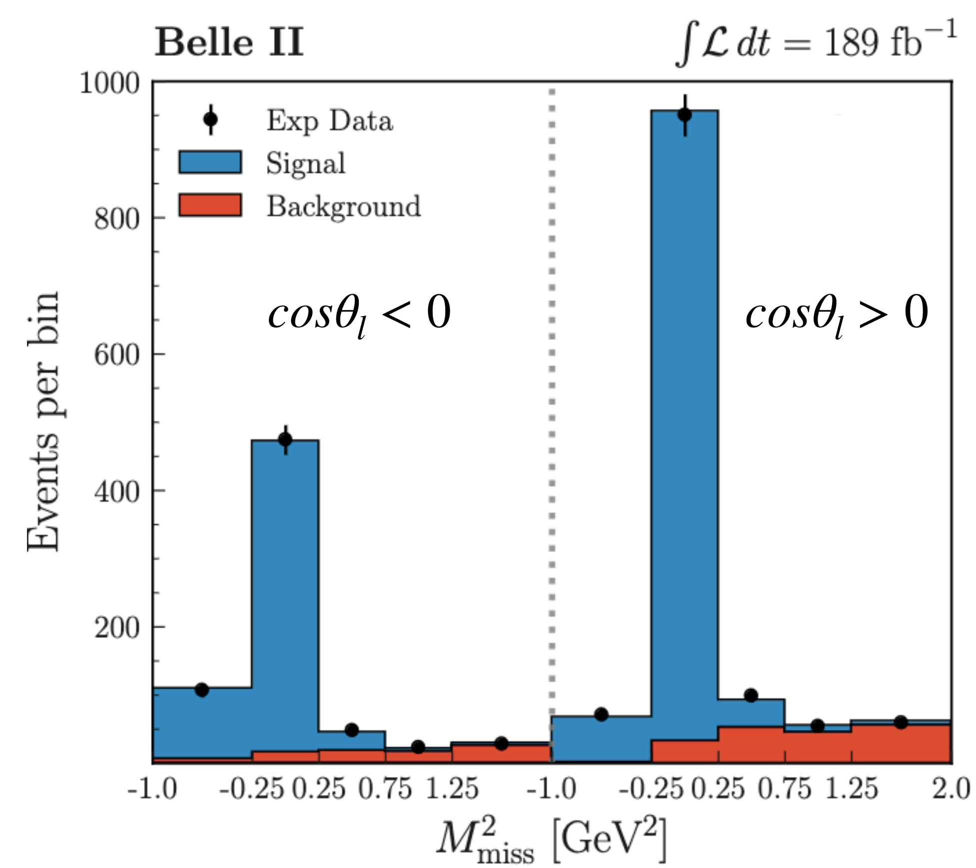
Comparing angular observables between muons and electrons gives powerful LFU tests.

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 $= 189 fb^{-1}$

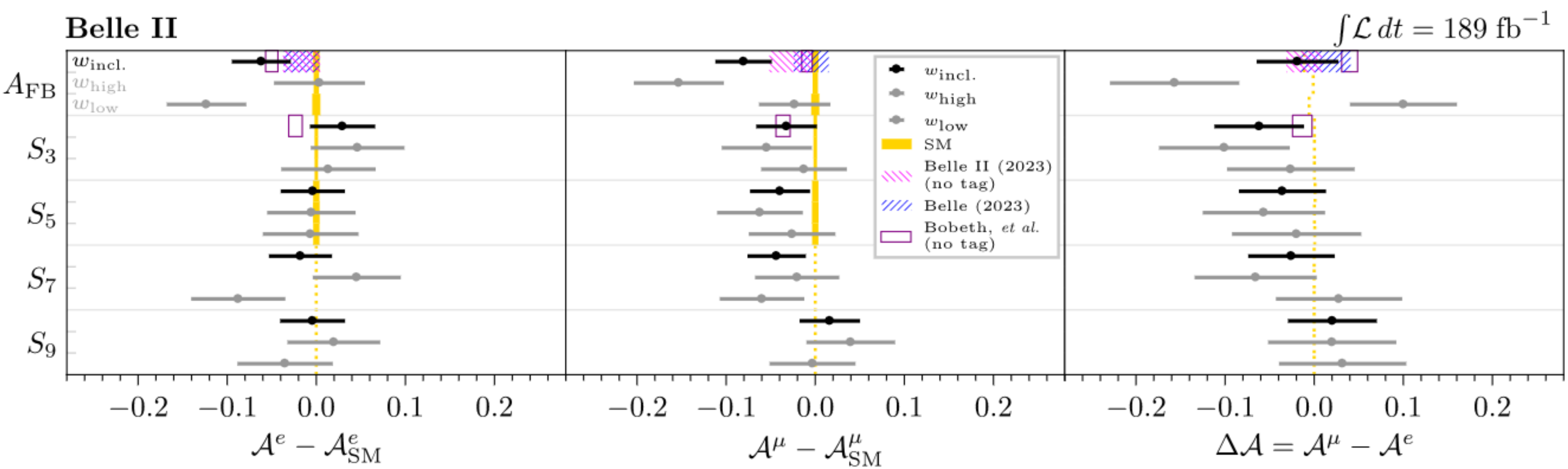
PRL 131, 181801 (2023)

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:

- 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 mesons 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

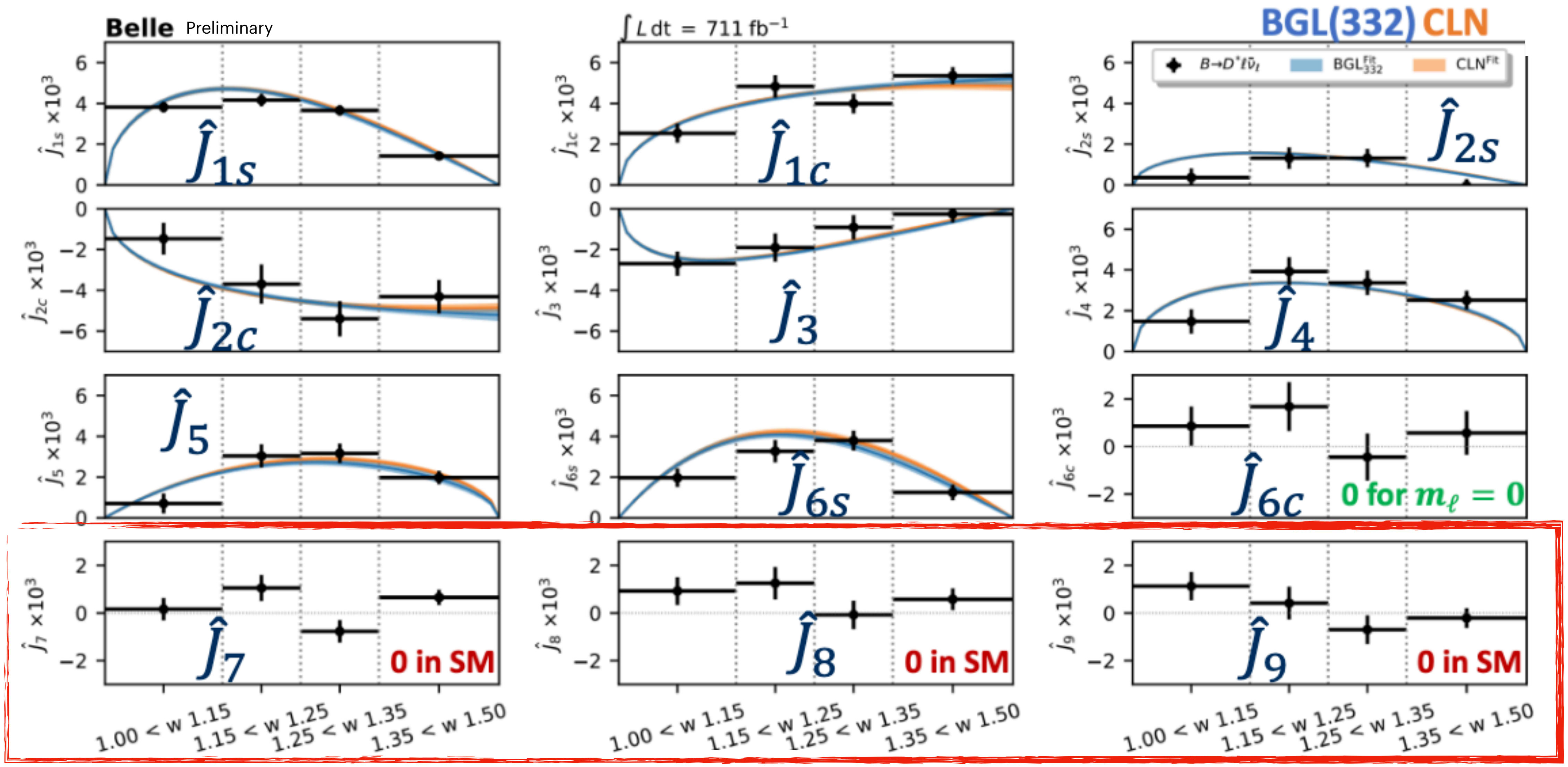
BELLE $= 711 fb^{-1}$

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 mesons 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.

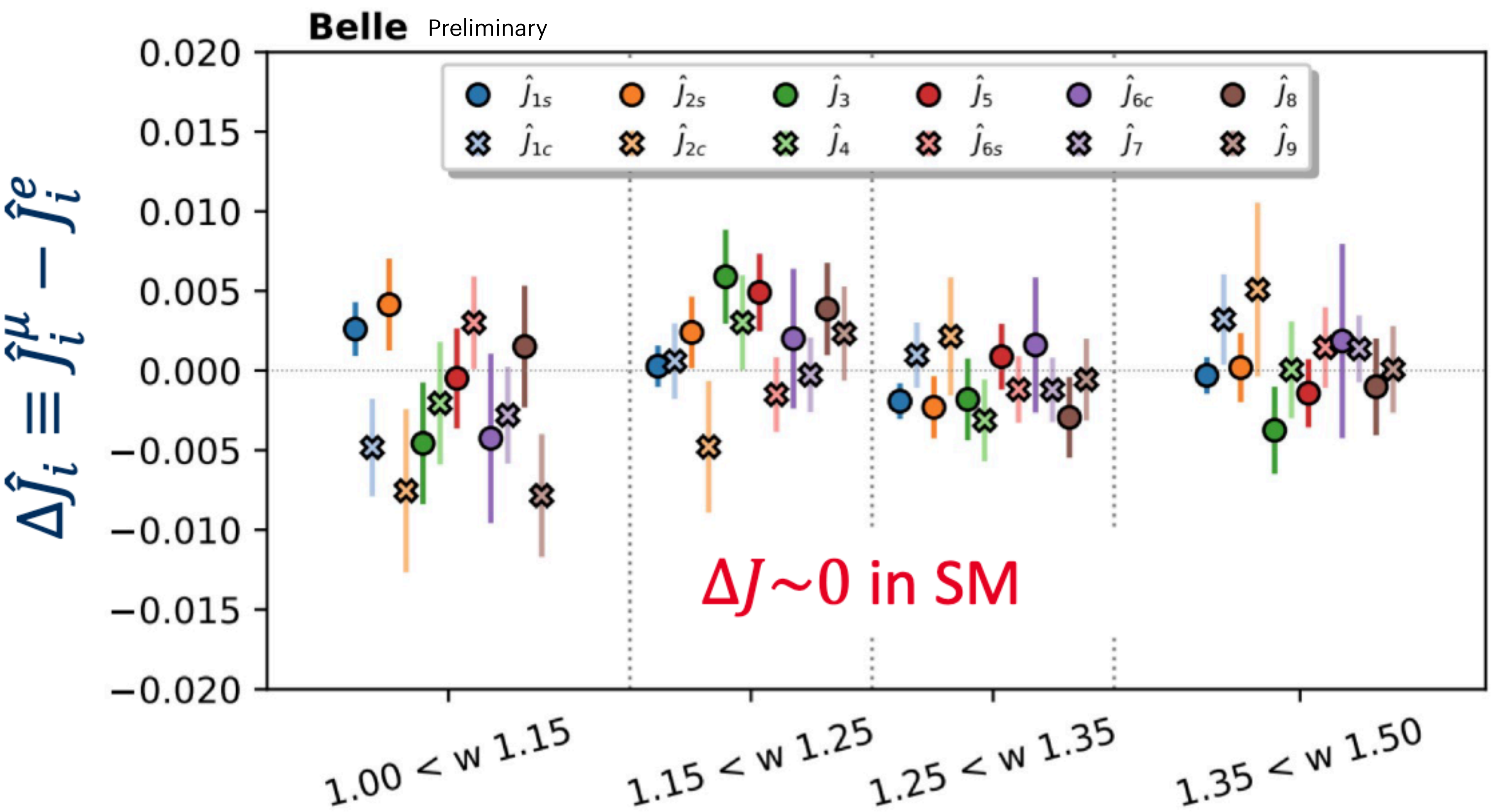
Coefficients consistent with the SM prediction.

$B \to D^* \ell \nu$ 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 $R(D^*_{\tau/\ell}) = \dfrac{\mathscr{B}(B \to D^* \tau \nu_\tau)}{\mathscr{B}(B \to D^* \ell \nu_\ell)}$

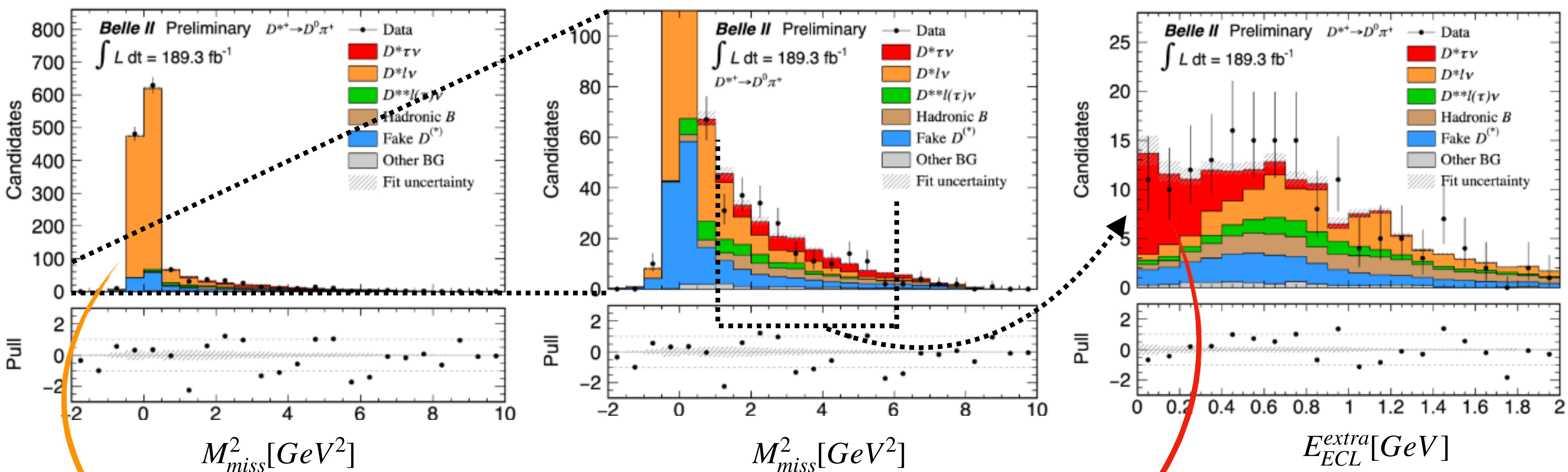
- Three signal modes: $D^{*+} \to D^0\pi^+, D^+\pi^0$ and $D^{*0} \to D^0\pi^0$. Identify lepton from $\tau \to \ell\nu\bar{\nu}$.

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 $= 189 fb^{-1}$

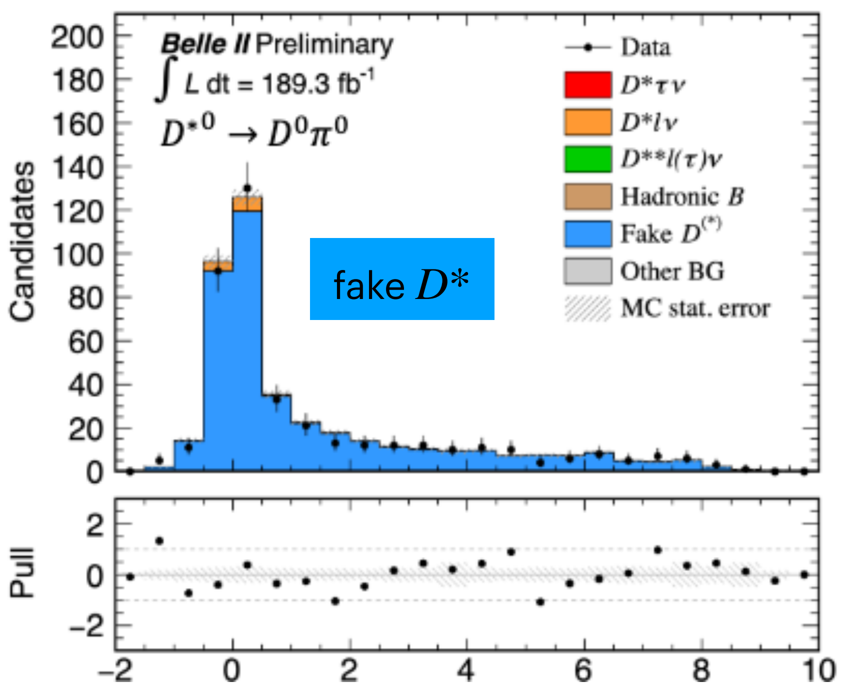
arXiv:2401.02840

Submitted to PRD

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

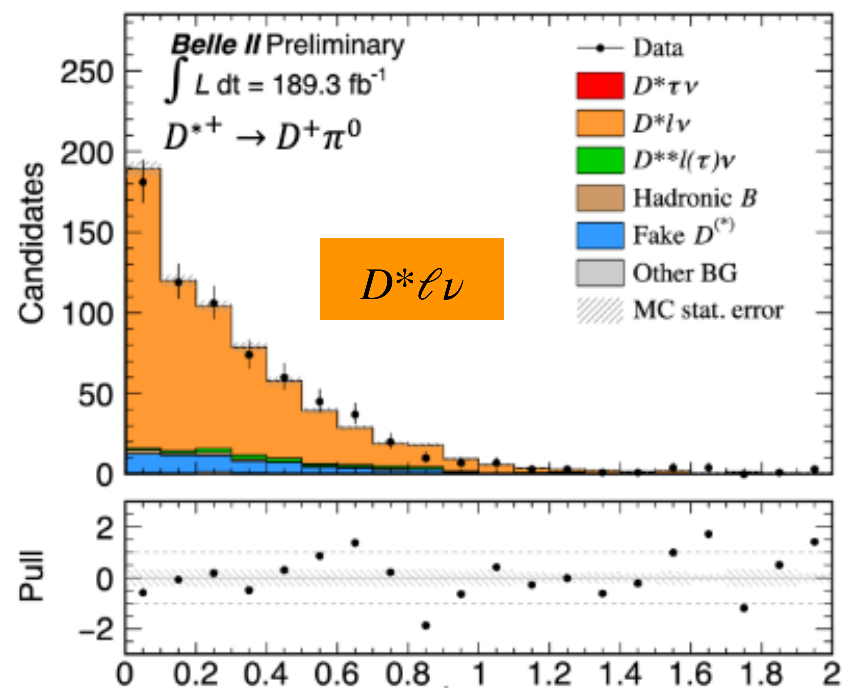
Data-driven validation of background and signal model based on studies of control regions.

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



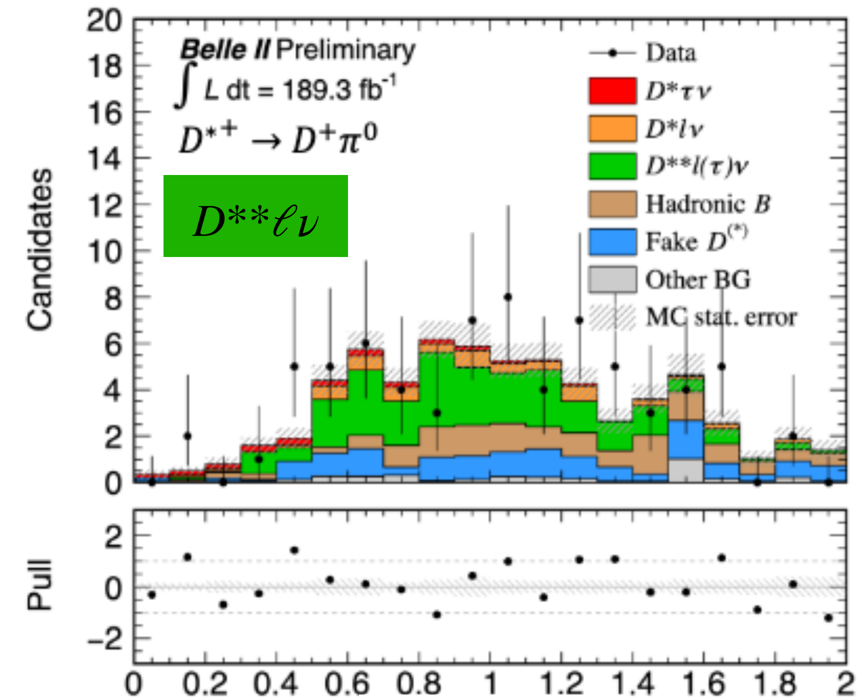
$M^2_{miss}[GeV^2]$

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



$E^{extra}_{ECL}[GeV]$

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



$E^{extra}_{ECL}[GeV]$

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: $^{+7.5\%}_{-7.5\%}$, $\mathscr{B}(B \to D^{**}\ell\nu)$: $^{+4.8\%}_{-3.5\%}$

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

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

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

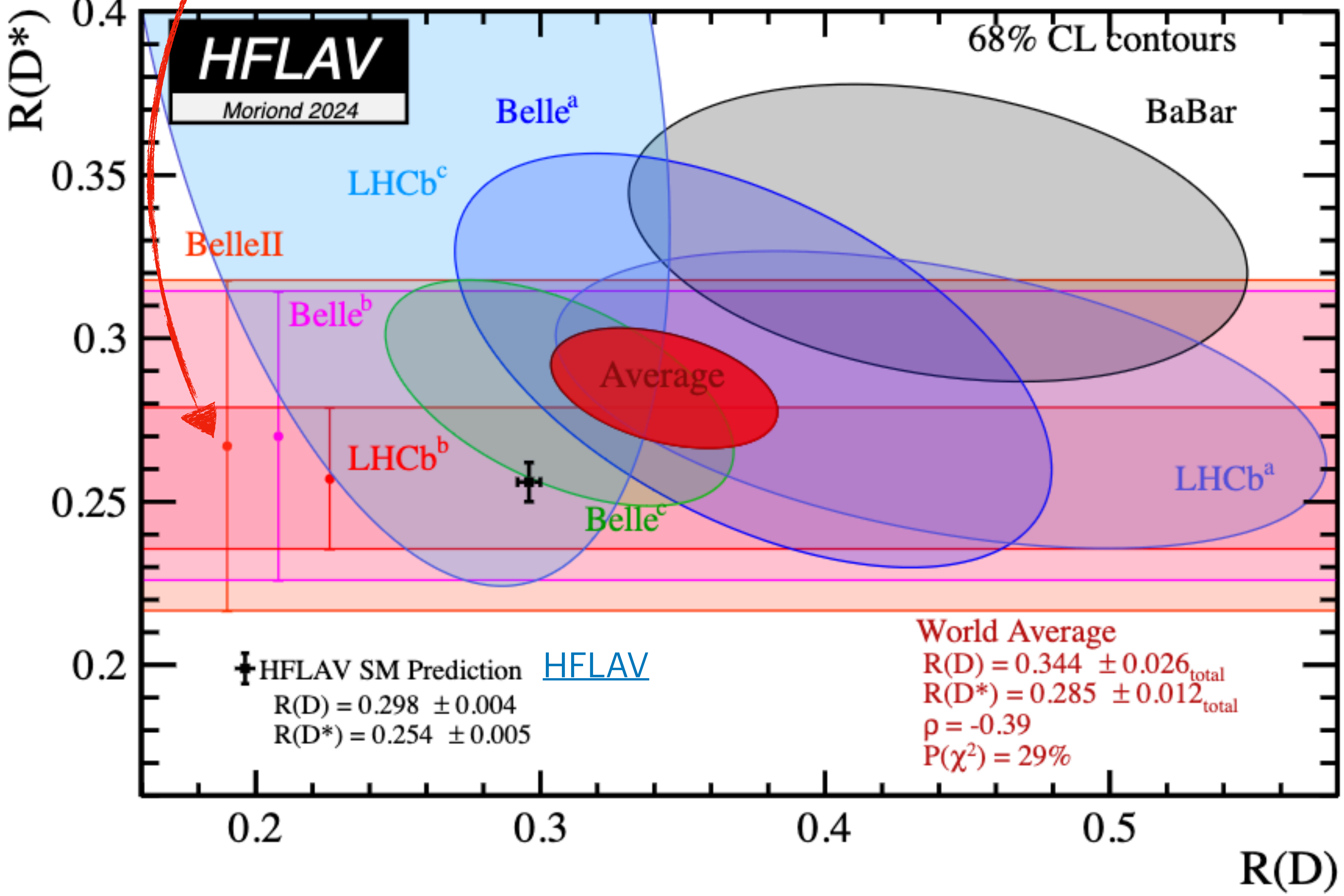
arXiv:2401.02840

Submitted to PRD

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

HFLAV 23: $R(D^*) = 0.285 \pm 0.012$

Consistent with the previous measurements.



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

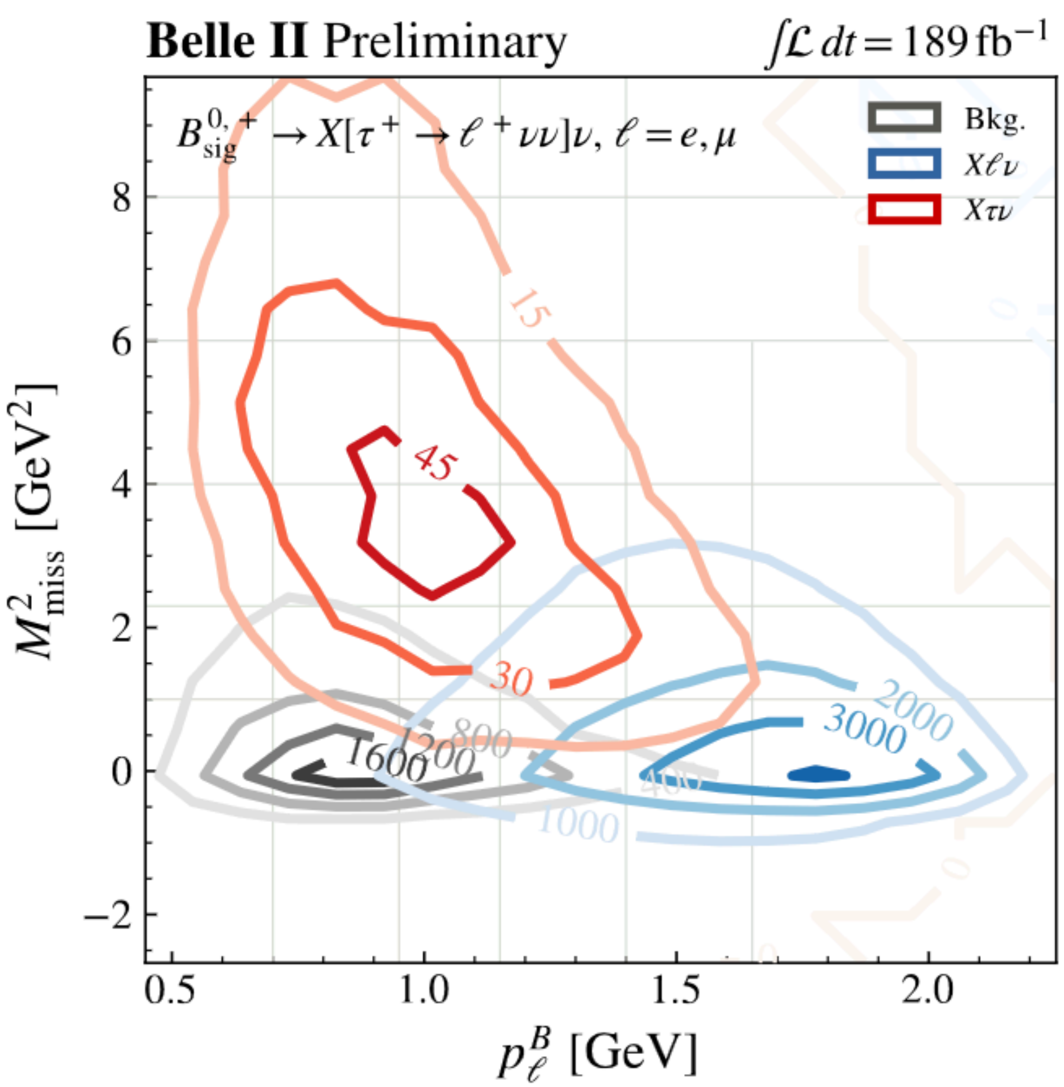
Measurement of $R(X_{\tau/\ell})$

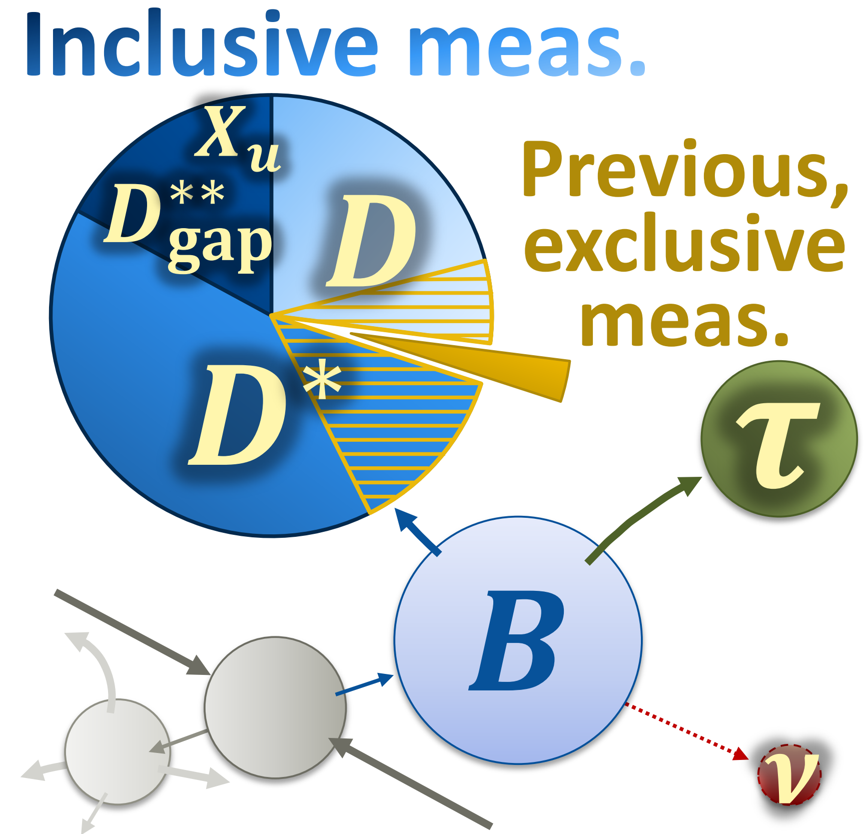
Belle II $= 189 fb^{-1}$
arXiv: 2311.07248
Accepted by PRL

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

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.





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 $= 189 fb^{-1}$

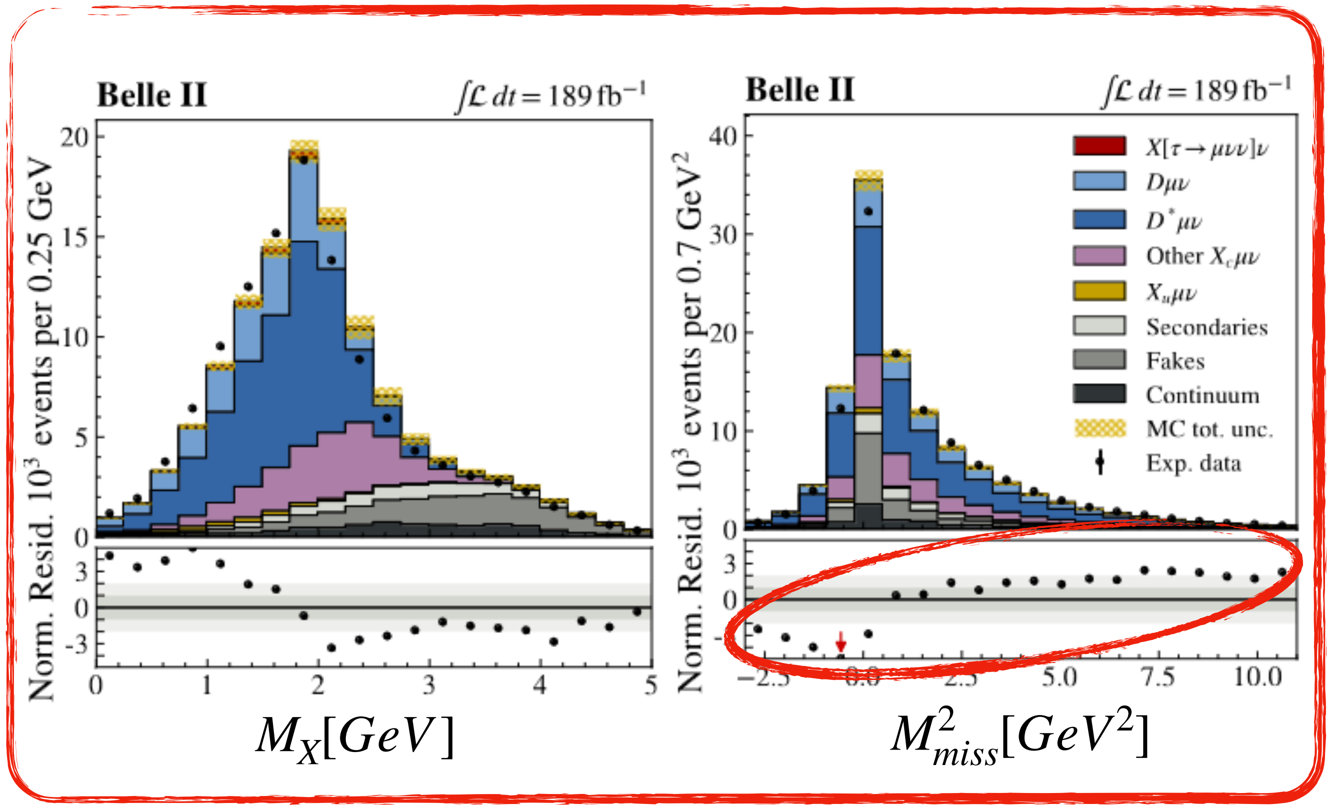
arXiv: 2311.07248
Accepted by PRL

Main challenge: modelling the X system.

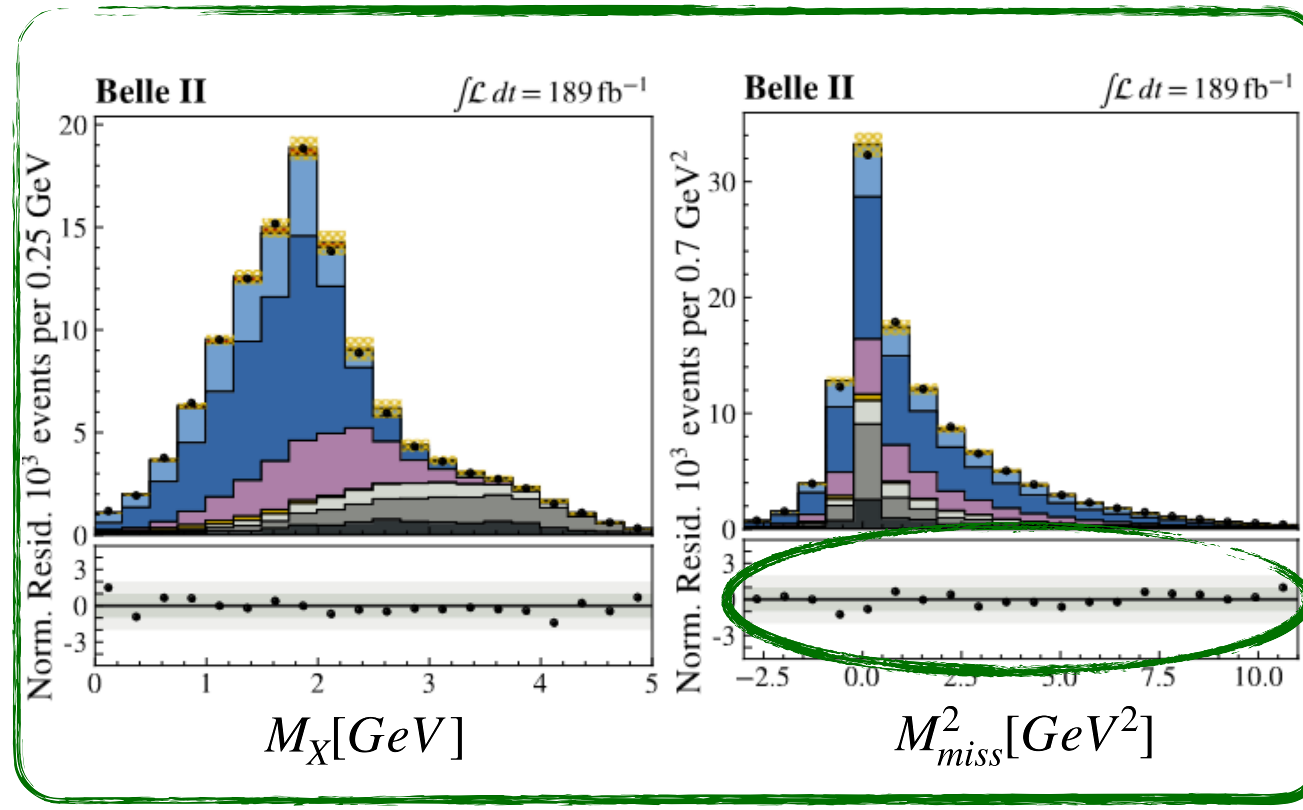
Detailed adjustments to simulation: form factors, B and D branching fractions.
Corrections based on comparison of simulation with control regions.

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}.

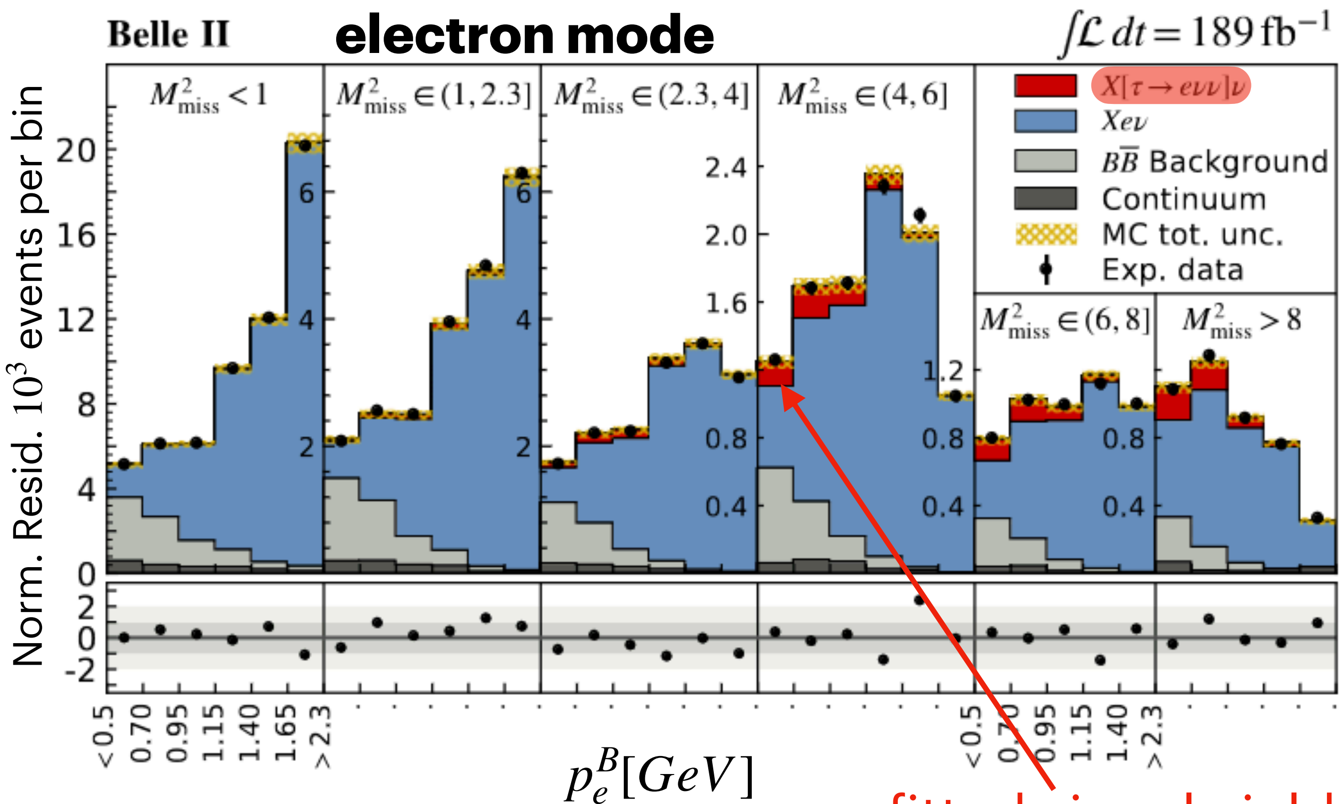
Main sources of syst. uncertainties: $X_c \ell \nu$ M_X shape: 7.1%, $\mathscr{B}(B \to X\ell\nu)$:7.7%, $X_c\tau(\ell)\nu$ form factors: 7.8%

Statistical uncertainty: experimental sample size: 7.1%

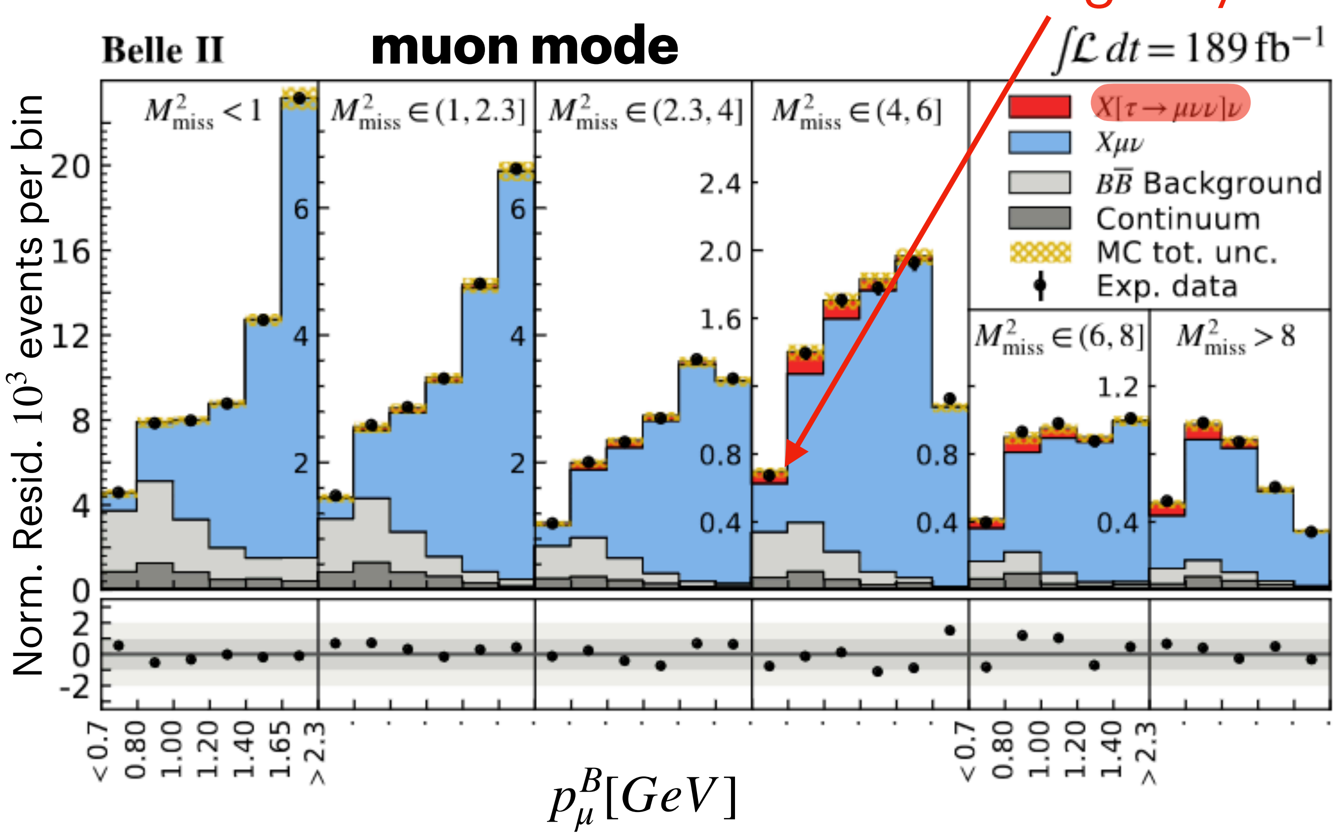
Measurement of $R(X_{\tau/\ell})$: results

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

arXiv: 2311.07248
Accepted by PRL



fitted signal yield

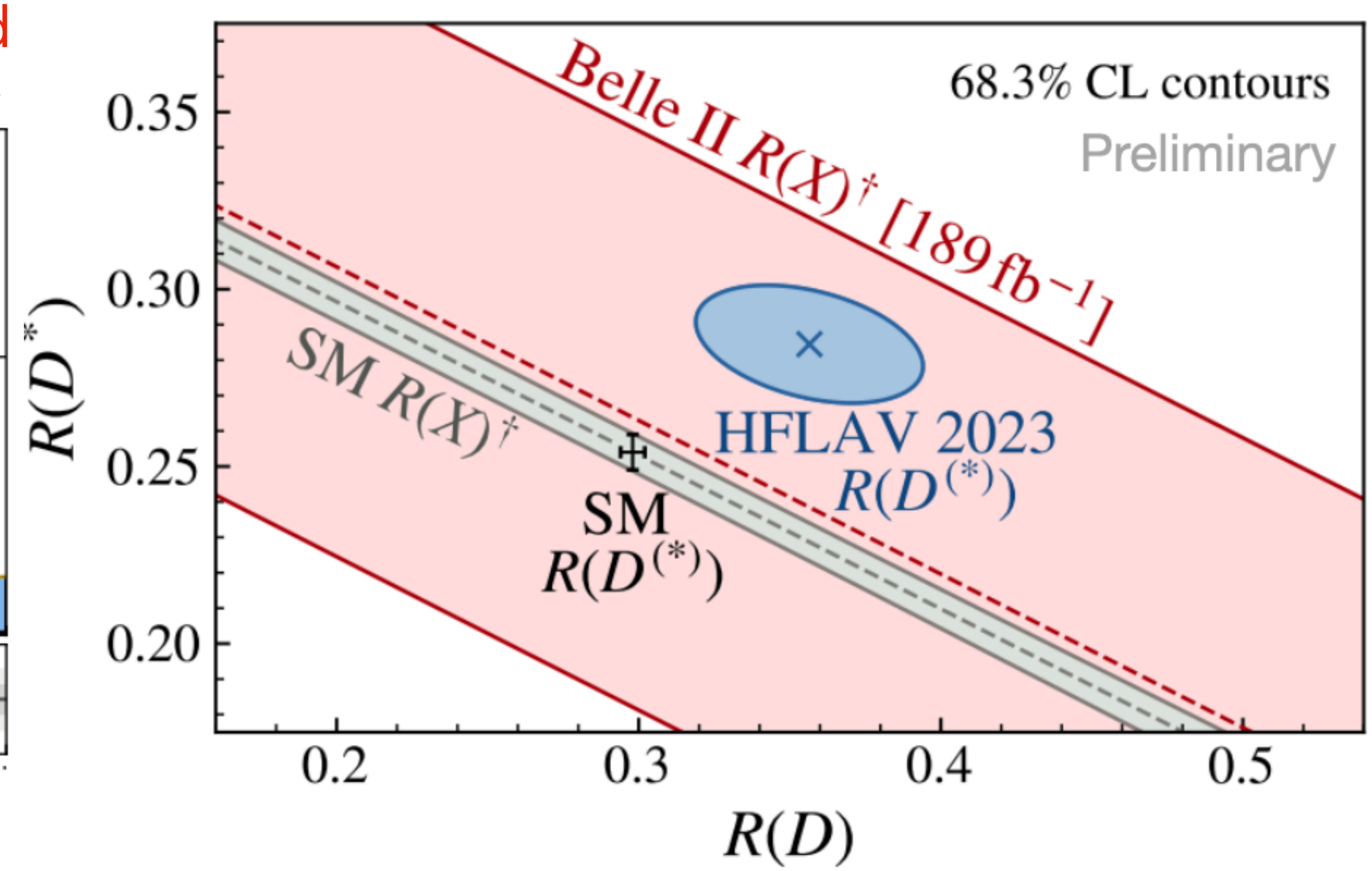


$$R(X_{\tau/\ell}) = 0.228 \pm 0.016(stat) \pm 0.036(syst)$$

(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:

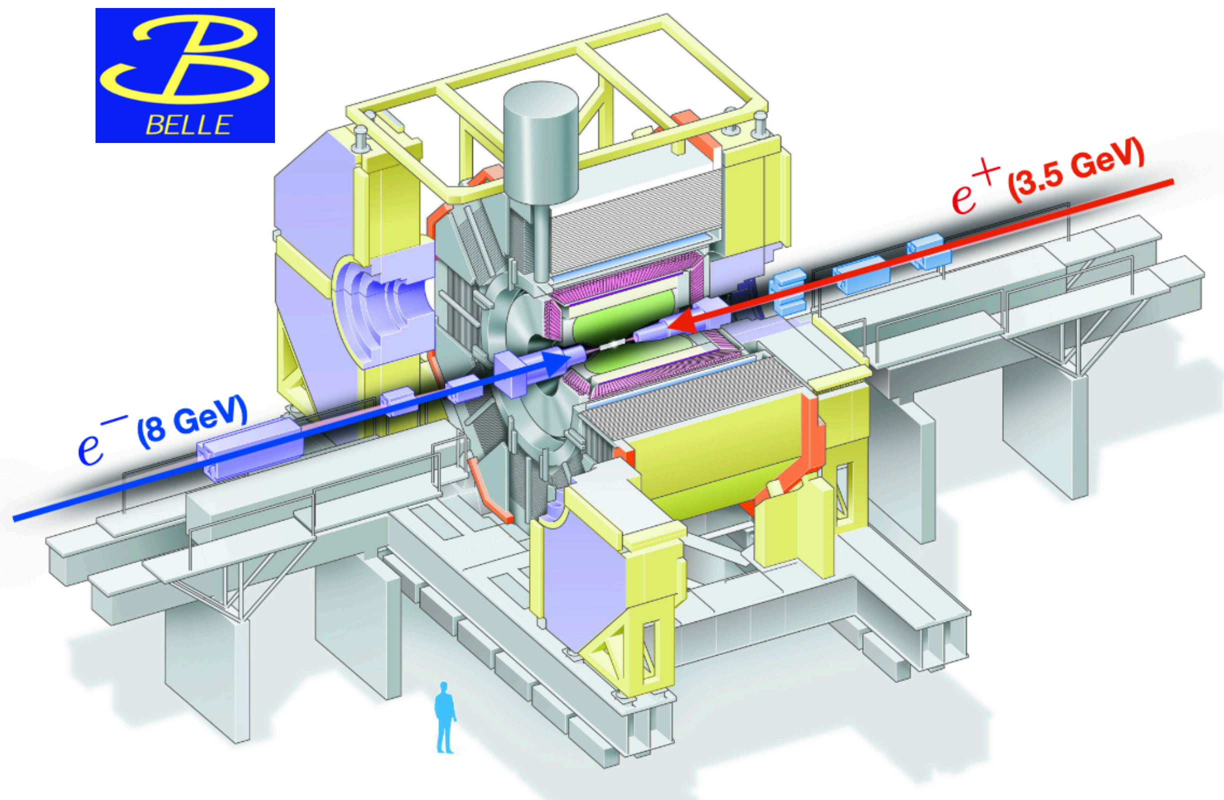
  - Higher precision expected at Belle II for the next $R(X)$ and $R(D^*)$ results using the full collected data set.
  - Some systematic uncertainties could be reduced with improved modelling.

Backup

From Belle...to Belle II

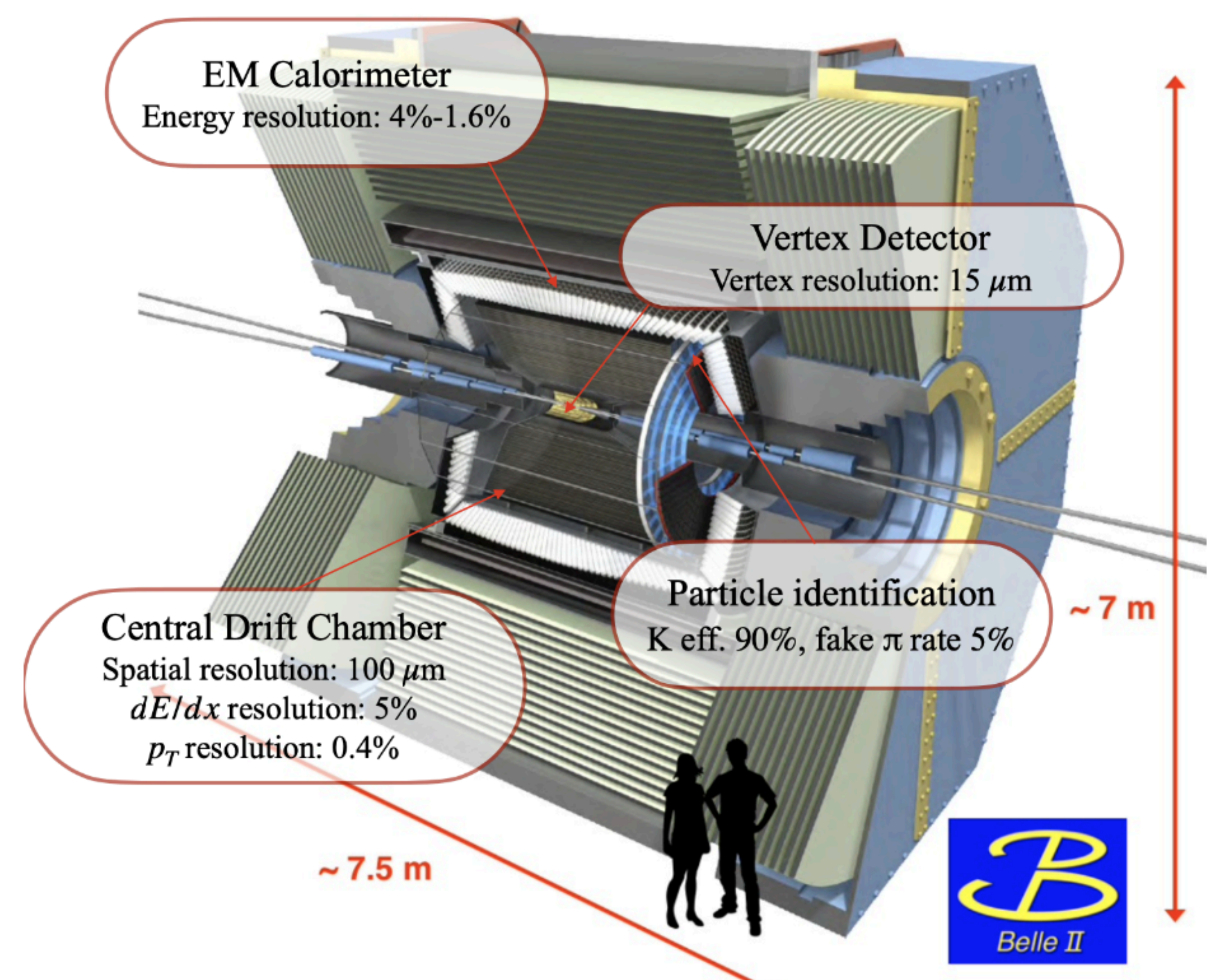
Belle

- 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.

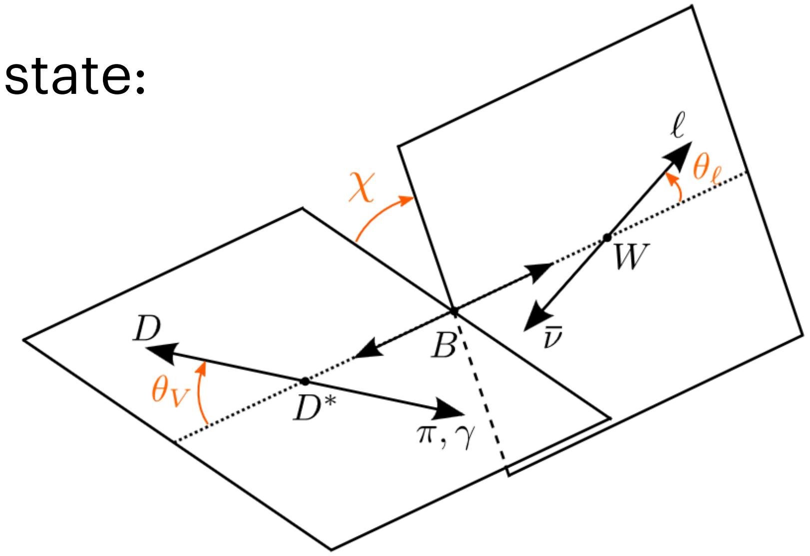
Topology of $B \to D^* \ell \nu$ decays

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:

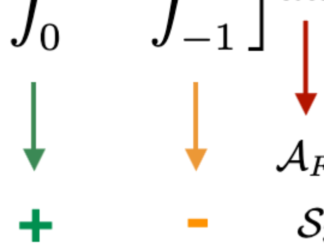
$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

- 3 angles: θ_V, θ_ℓ and χ.



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

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



$\mathcal{A}_{FB}(w)$ $\quad dx \to d(\cos\theta_\ell)$

$\mathcal{S}_3(w)$ $\quad dx \to d(\cos 2\chi)$

$\dots$

Experimental strategy:

1. Reconstruct the angular distributions.

2. Signal extraction by fitting M^2_{miss}.

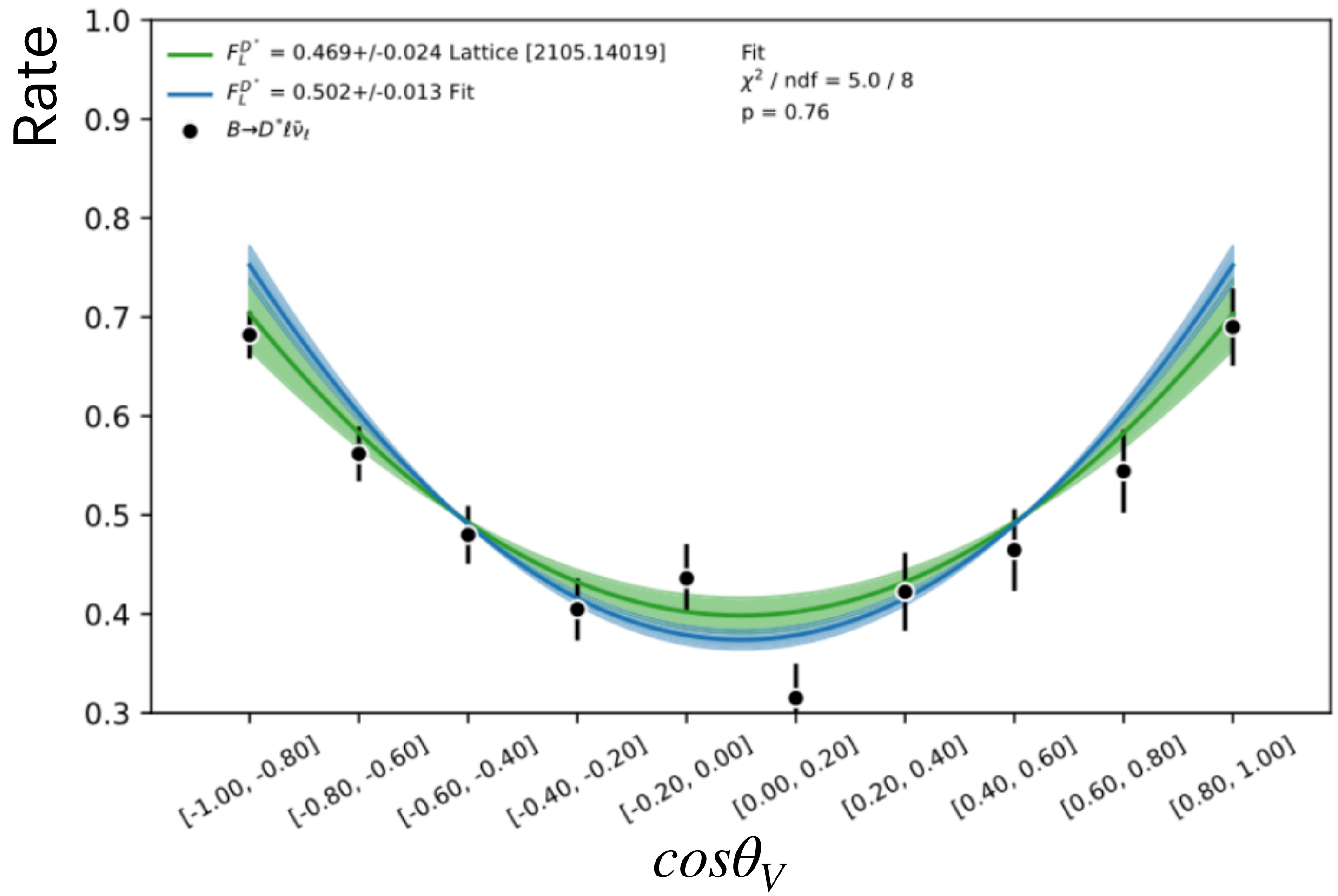
3. Increase the sensitivity of LFU tests by measure asymmetries in bins of w.

$B \to D^* \ell \nu$ 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 :

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

Consistent with SM and previous measurements.

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

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

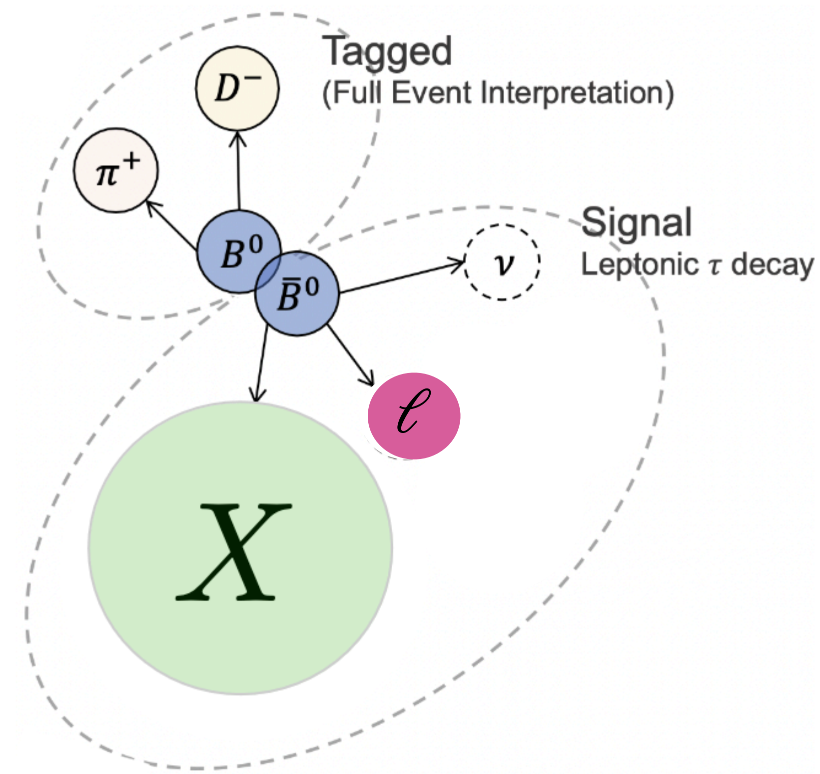
PRL 131, 051804

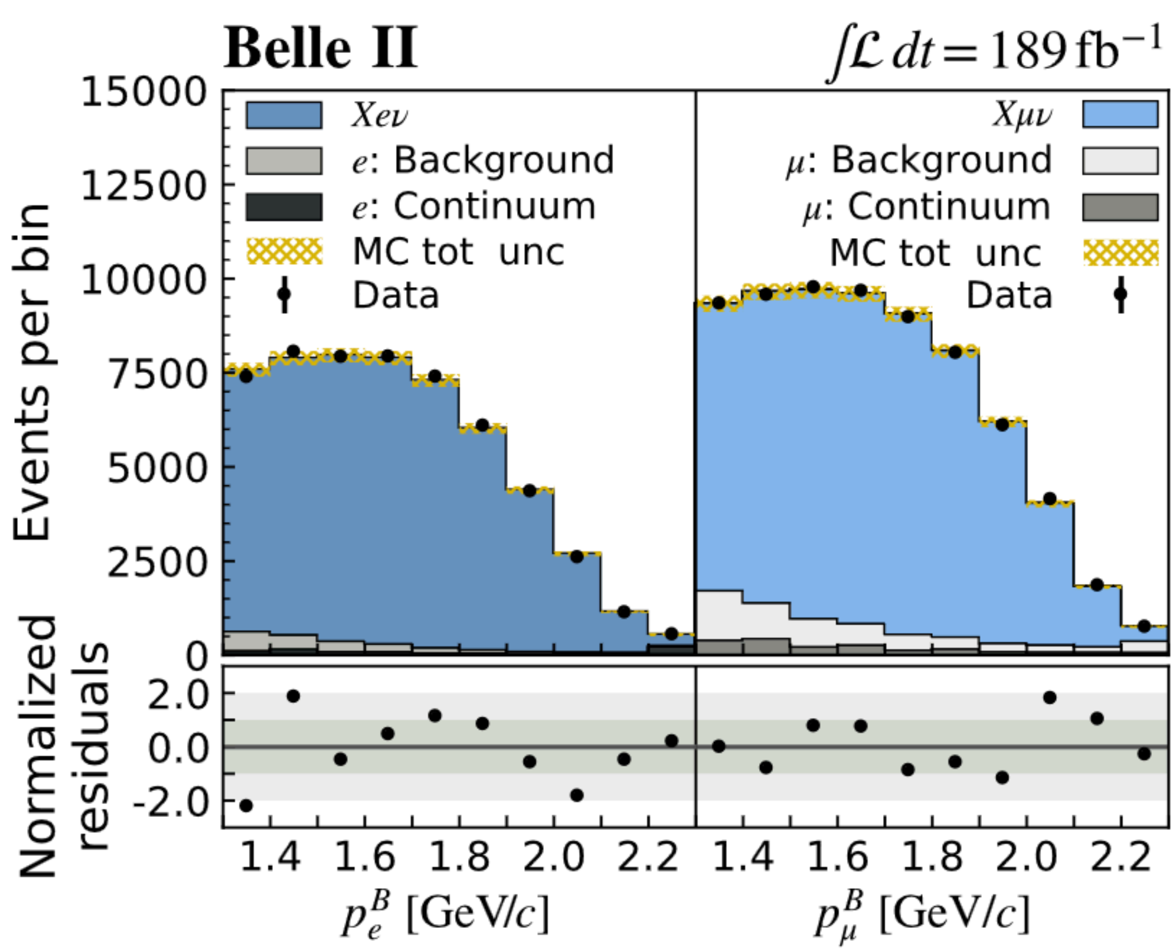
Goal: measure $R(X_{e/\mu}) = \frac{\mathcal{B}(B \to X e \nu_e)}{\mathcal{B}(B \to X \mu \nu_\mu)}$

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%)

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

Compatible with SM and previous measurements.