LEPTON FLAVOR UNIVERSALITY STUDIES AT BELLE AND BELLE II

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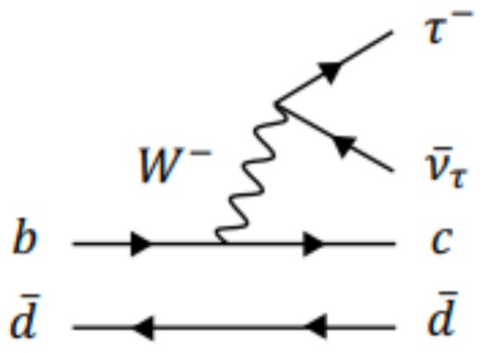
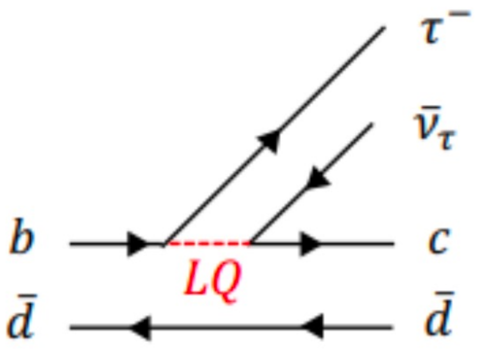
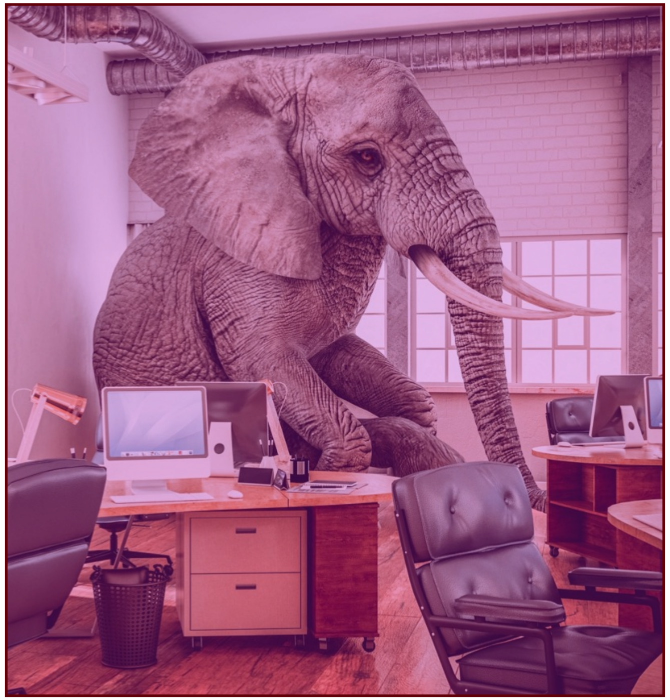
representing the Belle II collaboration

Motivation for studying LFU in B decays

- Universality: W boson couples to weak isospin → isodoublets couple with equal strength
- Non-SM contributions (e.g. LQ, H^+, SUSY) are not in general universal
- Semileptonic decays are ≈ clean; FFs and experimental uncertainties partially cancel in ratios R of $b \to q\tau\nu/q\mu\nu/qe\nu$ decay rates
- Differences in angular asymmetries for different lepton flavors are also sensitive to BSM physics and have small systematic uncertainties







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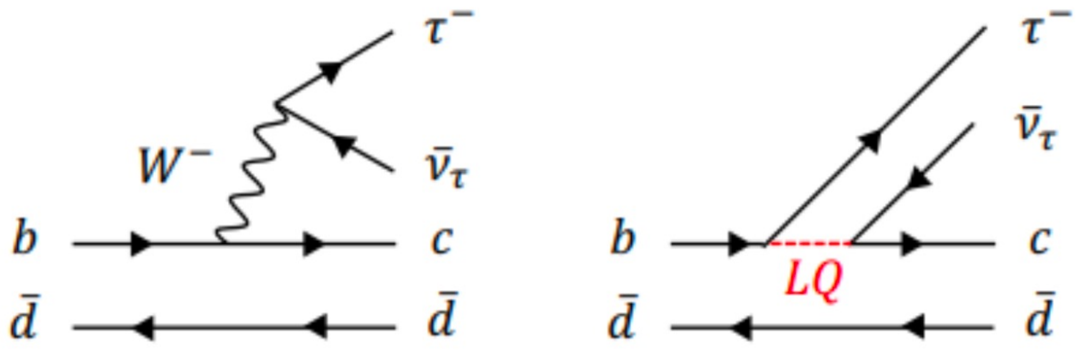
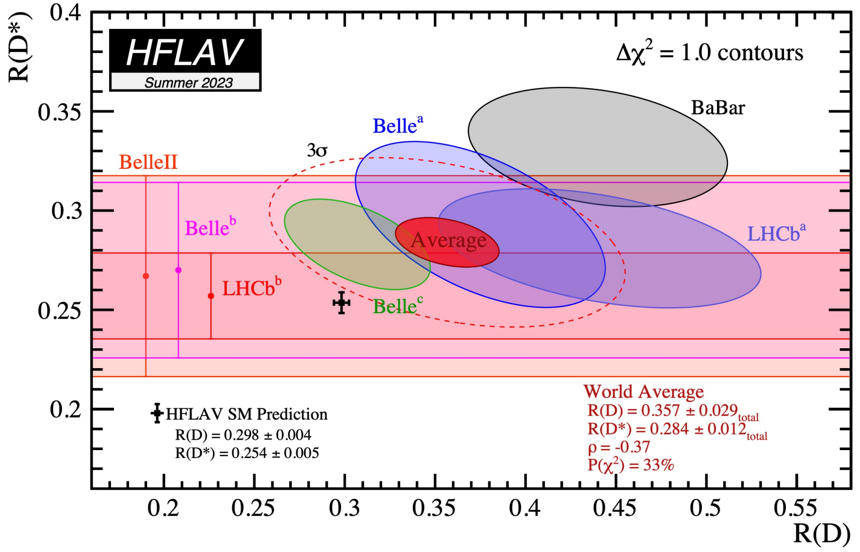


And… there is a long-standing tension between the LFU-sensitive quantities $R(D)$ and $R(D^*)$ and SM predictions:



3.3σ tension as of summer 2023

Analyses presented in this talk

Notation: $R_{\ell_2/\ell_1}(h) \equiv \frac{\mathcal{B}(B \to h \ell_2 \nu)}{\mathcal{B}(B \to h \ell_1 \nu)}$ and $X \equiv \sum_i h_i$

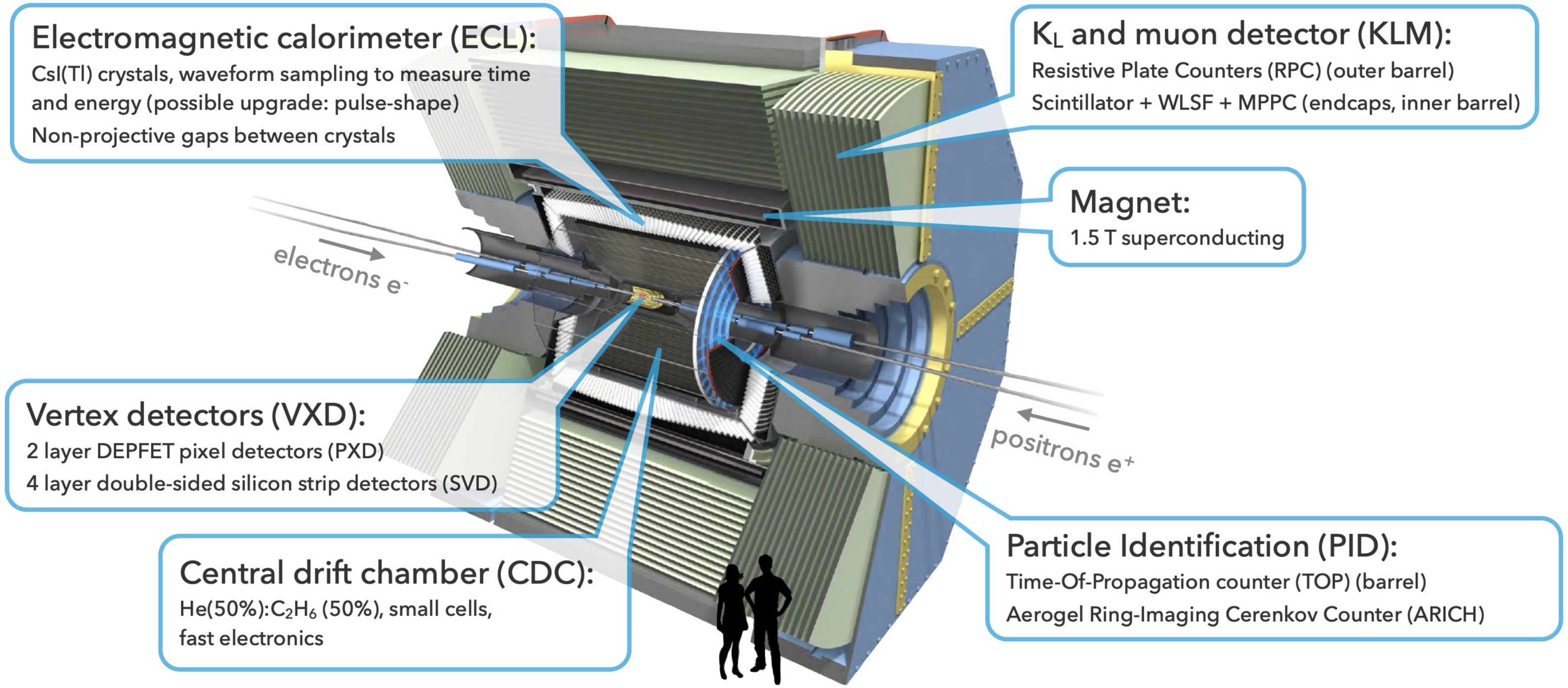
- $R_{\tau/\ell}(D^*)$ from Belle II ($189\ \mathrm{fb}^{-1}$), preliminary (Lepton-Photon 2023)
- $R_{\tau/\ell}(X)$ from Belle II ($189\ \mathrm{fb}^{-1}$), preliminary (EPS-HEP 2023)

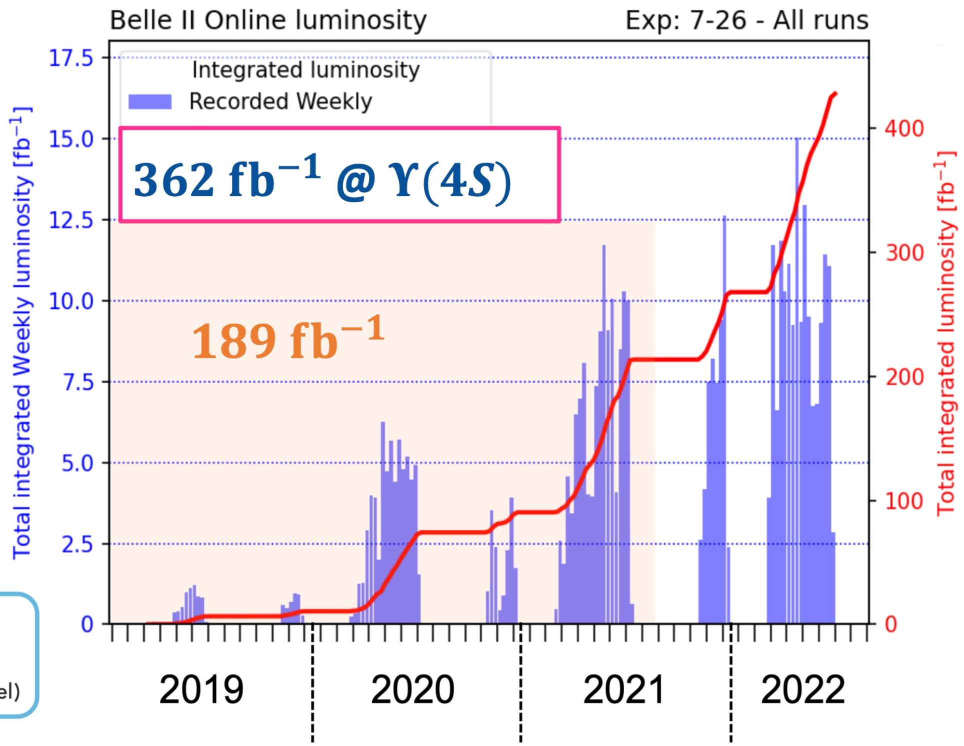
- $R_{e/\mu}(X)$ from Belle II ($189\ \mathrm{fb}^{-1}$), PRL **131**, 051804
- $R_{e/\mu}(D^*)$ from Belle ($711\ \mathrm{fb}^{-1}$), PRD 108, 012002

- Tests of light-lepton universality in angular asymmetries of $(B \to D^* \ell \nu)$ from Belle II ($189\ \mathrm{fb}^{-1}$), arXiv:2308.02023, submitted to PRL
- Measurement of differential distributions in $B \to D^* \ell \nu$ from Belle ($711\ \mathrm{fb}^{-1}$), PRD 108.012002
- New test of LFU using angular coefficients from Belle ($711\ \mathrm{fb}^{-1}$), preliminary

Belle II detector and dataset

- Asymmetric collisions, $E_{e^-} = 7\ \mathrm{GeV}$, $E_{e^+} = 4\ \mathrm{GeV}$
- Large solid angle coverage
- Better tracking/vertexing than Belle



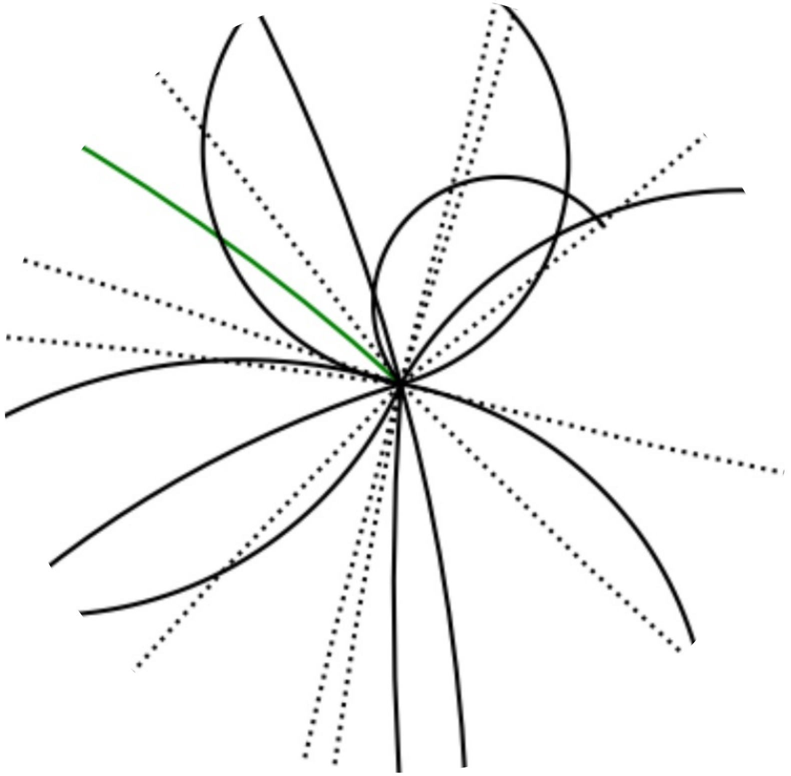


- Belle CsI(Tl) crystals, new electronics
- Excellent particle ID (dE/dx, TOP, Cherenkov)
- Initial state 4-vector known → kinematic constraints available

Experimental environment at $\Upsilon(4S)$

The $B\bar{B}$ pairs are produced near threshold: B and $\bar{B}$ decay products are ≈isotropic and overlap

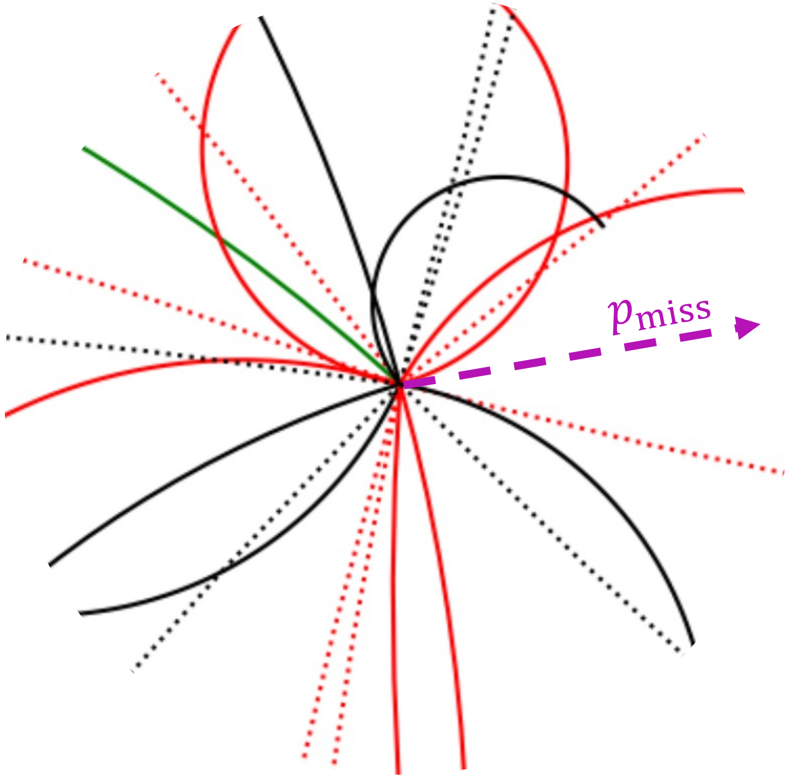
- Leptons and kaons can be reliably selected, but overall multiplicity of pions and photons is large: $\mathcal{O}(10)$ each
- combinatorial challenge for reconstruction of short-lived hadrons (e.g. D^*, D)
- hard to cleanly isolate decays involving multiple missing particles, where few kinematic constraints are available



Background reduction: B tagging

Hadronic FEI (full event interpretation) used in the analyses shown here

- Fully reconstruct one B in a hadronic decay mode, e.g. $B \to D^{(*)} n(\pi^{\pm}) m(\pi^0)$; require $n \leq 3$ and $m \leq 1$ in most modes (trade-off between efficiency and purity)
- Demand remaining particles match desired signal decay up to soft neutral activity (*completeness*)
- Reduces $e^+e^- \to q\bar{q}$ continuum background, $B \leftrightarrow \bar{B}$ feed-across background
- Initial state known, can determine p_{miss}, $M^2_{\text{miss}} = p^2_{\text{miss}}$



Cost: B_{tag} efficiency $\lesssim$ 1%

$$R_{\tau/\ell}(D^*)$$

Measuring $R_{\tau/\ell}(D^*)$ – analysis strategy

- reconstruct tau and light-lepton decays into the *same final state particles* to cancel many systematic uncertainties

$$R_{\tau/\ell}(D^*) \propto \frac{N(B \to D^*[\tau \to \ell\bar{\nu}\nu]\nu)}{N(B \to D^*\ell\nu)}$$

- Tag the other B to greatly reduce background and obtain *kinematic* and *completeness* ($\Upsilon(4S) \to B_{\text{tag}}B_{\text{sig}}$ + **“nothing”**) constraints
- Balance efficiency/purity through selection of B_{tag} and B_{sig} decay modes

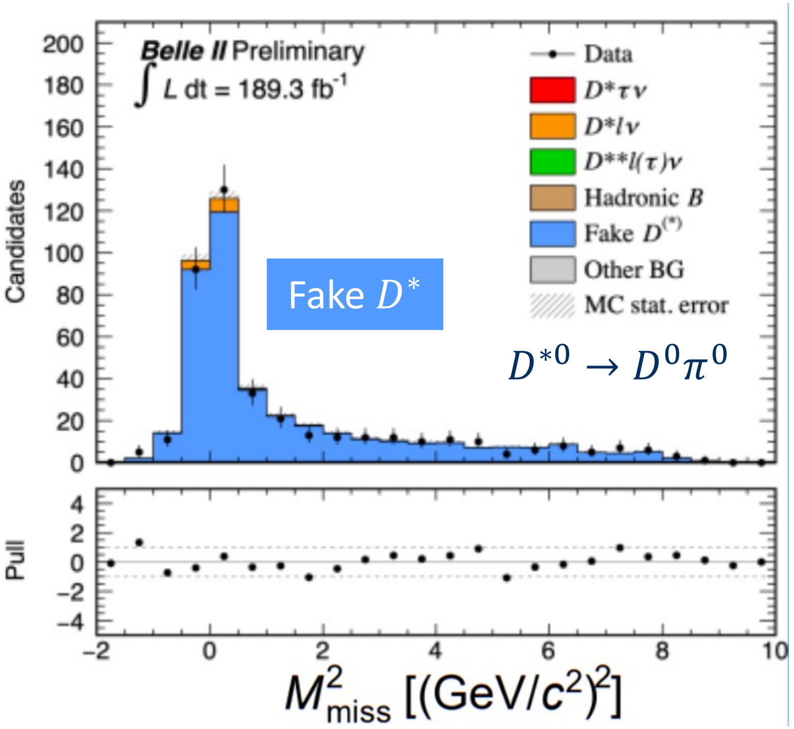
$D^{*+} \to D^0\pi^+$, $D^{*+} \to D^+\pi^0$ or $D^{*0} \to D^0\pi^0$
$D^0 \to K^-\pi^+(\pi^0), K^-\pi^+\pi^-\pi^+, K_S^0\pi^+\pi^-(\pi^0), K_S^0\pi^0, h^+h^-$
$D^+ \to K_S^0\pi^+, K^-h^+\pi^+$ where $h^+ = K^+$ or π^+

- Distinguish $\bar{B} \to D^*\tau^-\nu$ from $\bar{B} \to D^*\ell^-\nu$ and background using M_{miss}^2, require no unused charged particles and small *unassigned neutral ECL energy* (E_{ECL})
- Determine yields with a 2D binned template likelihood fit

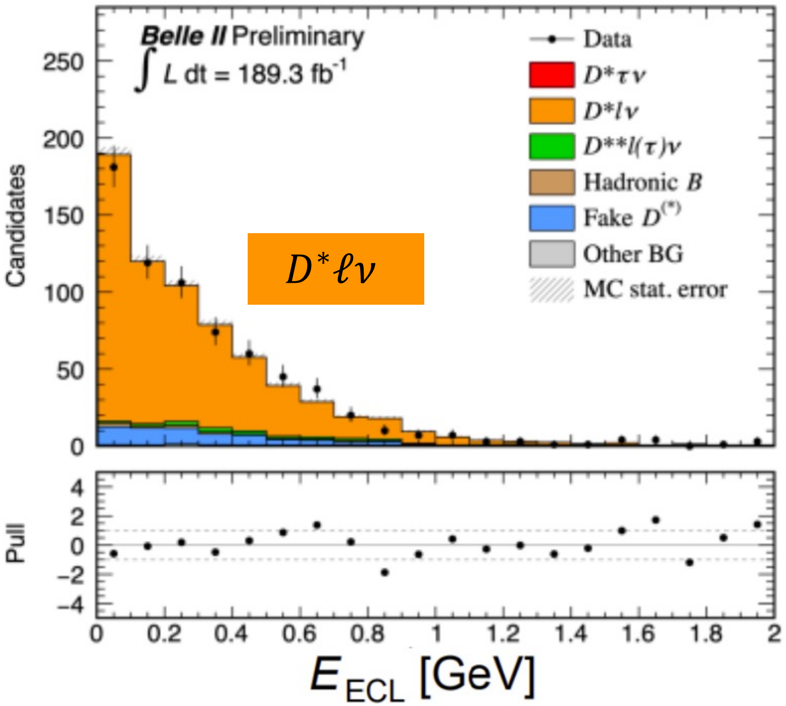
$R_{\tau/\ell}(D^*)$ – control samples

Validate / correct modeling of fit template variables using control samples; e.g.

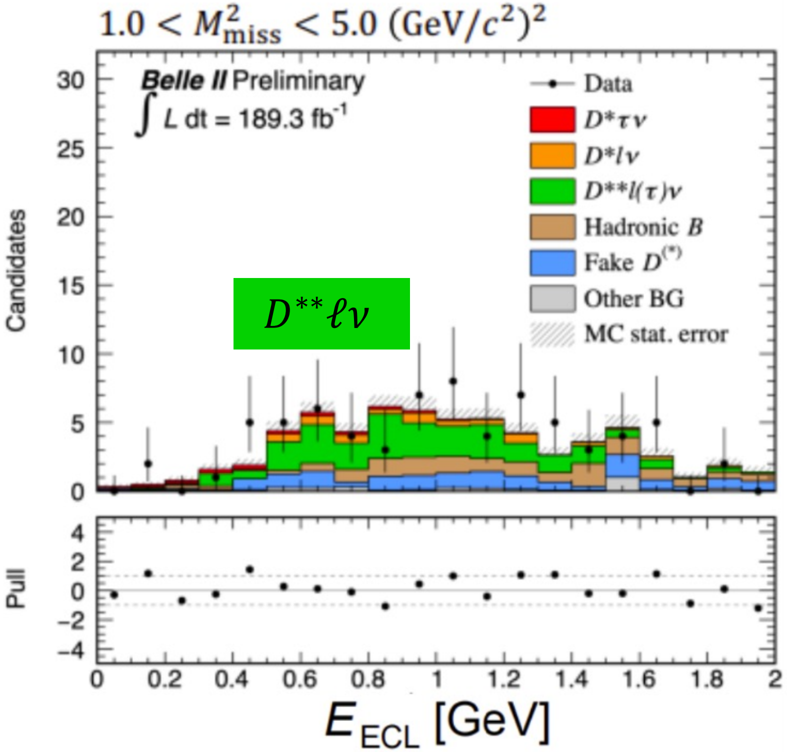
$m(D\pi) > \mathrm{m}(D^*)$ sideband:
validate fake D^* modeling



$q^2 < 3.5\ \mathrm{GeV}^2$ sideband:
validate E_{ECL} (modeling of beam background, detector response)



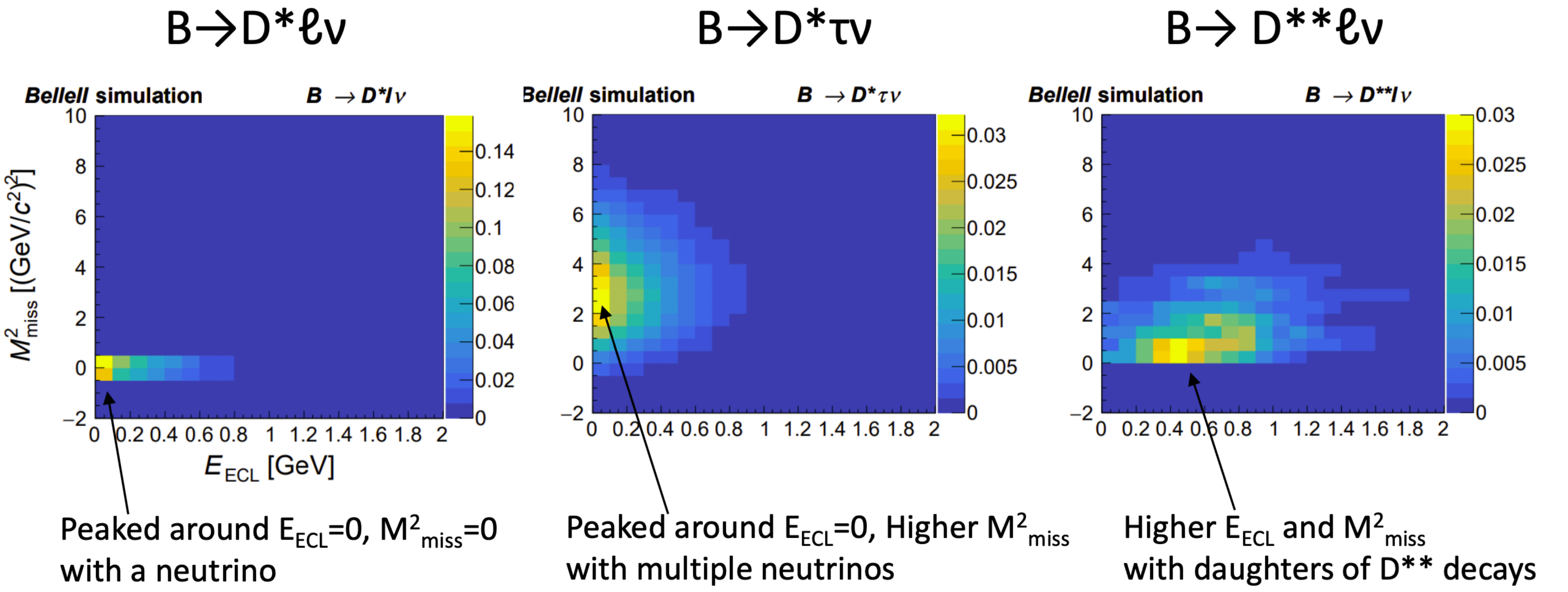
Reconstruct $D^*\pi^0\ell\nu$:
validate D^{**} modeling



$R_{\tau/\ell}(D^*)$ templates and fit

- Sources separated in $M^2_{\text{miss}}, E_{ECL}$ space
- other sources (e.g. $\bar{B} \to D^{(*)}D_s^-$) not shown; shapes similar to $B \to D^{**}\ell\nu$
- Use template PDFs based on smoothed histograms
- Comparable sensitivities from B^+ and B^0

Category	Yield determination
Signal $D^*\tau\nu$	Floated
Normalization $D^*\ell\nu$	Floated
Background from $D^{**}\ell\nu$	Floated
Other Background with true D^*	Fixed from MC
Background with fake D^*	Floated with sideband constraint



$R_{\tau/\ell}(D^*)$ – Results

Main sources of systematic uncertainty:

- MC statistics $\pm 7.0\ \%$
- E_{ECL} PDF shapes $^{+5.5}_{-9.3}\ \%$
- D^{**} modeling $^{+4.7}_{-2.7}\ \%$

Belle II preliminary: first result on this channel

$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat})\ ^{+0.028}_{-0.033}(\text{sys})$$

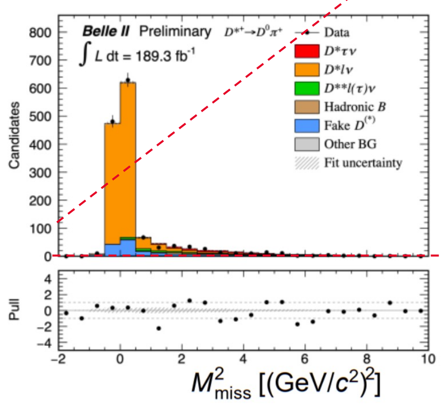
Consistent with SM,

$$R(D^*) = 0.254 \pm 0.005$$

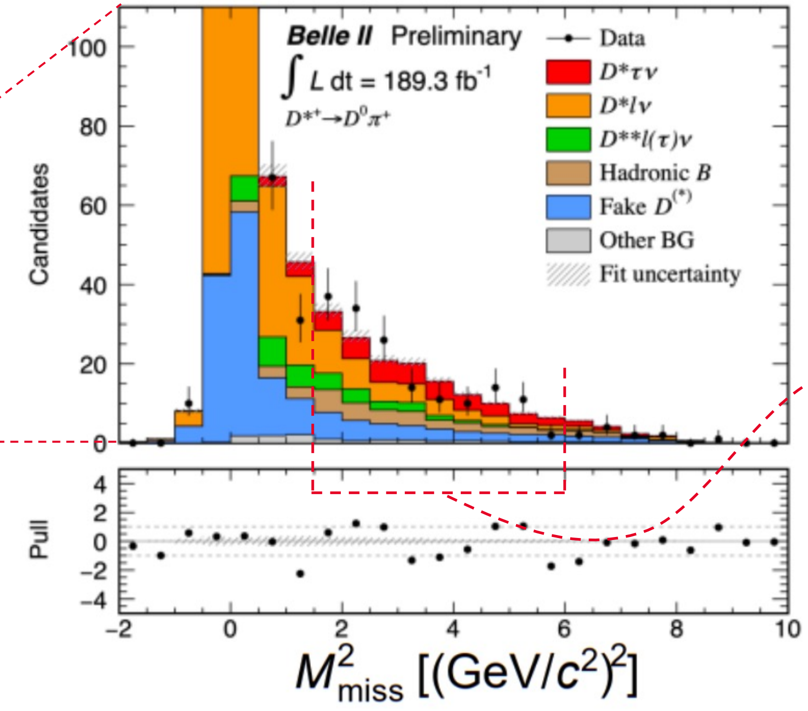
and with HFLAV 23,

$$R(D^*) = 0.284 \pm 0.013$$

Analysis of 363 fb^{-1} sample is underway

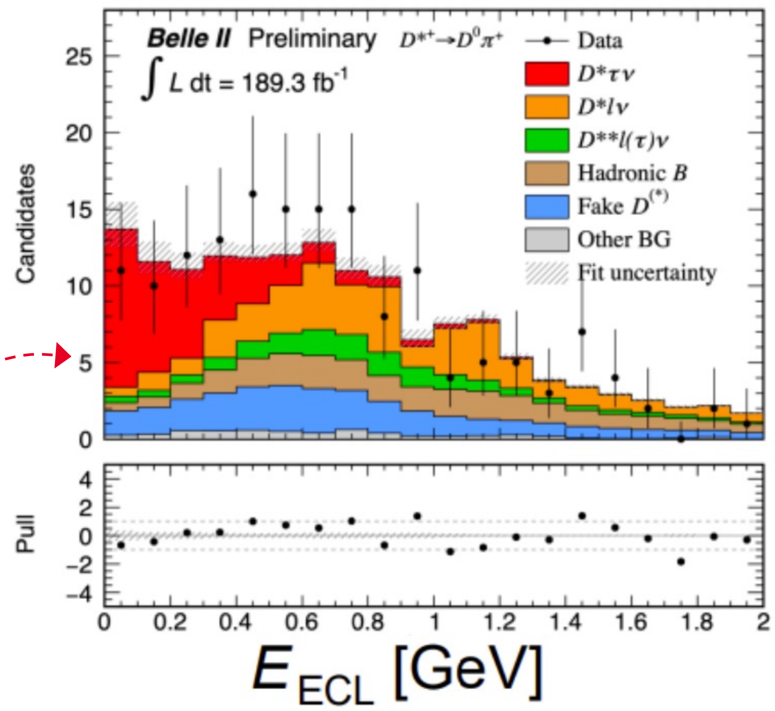


Zoom of M^2_{miss} projection for $D^{*+} \to D^0\pi^+$ mode



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

$1.5 < M^2_{\text{miss}} < 6.0\ (\text{GeV}/c^2)^2$



$R_{\tau/\ell}(X)$

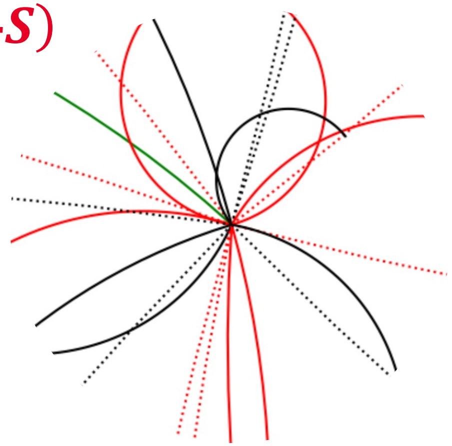
Why measure $R_{\tau/\ell}(X)$?

- Experimental uncertainties differ for $R_{\tau/\ell}(X)$ and $R_{\tau/\ell}(D^{(*)})$
- Largest contributions to $R_{\tau/\ell}(X)$ come from $B \to D^{(*)}\tau\nu$
- In SM expect $R_{\tau/\ell}(D) > R_{\tau/\ell}(D^{*}) > R_{\tau/\ell}(X) \cong 0.222$

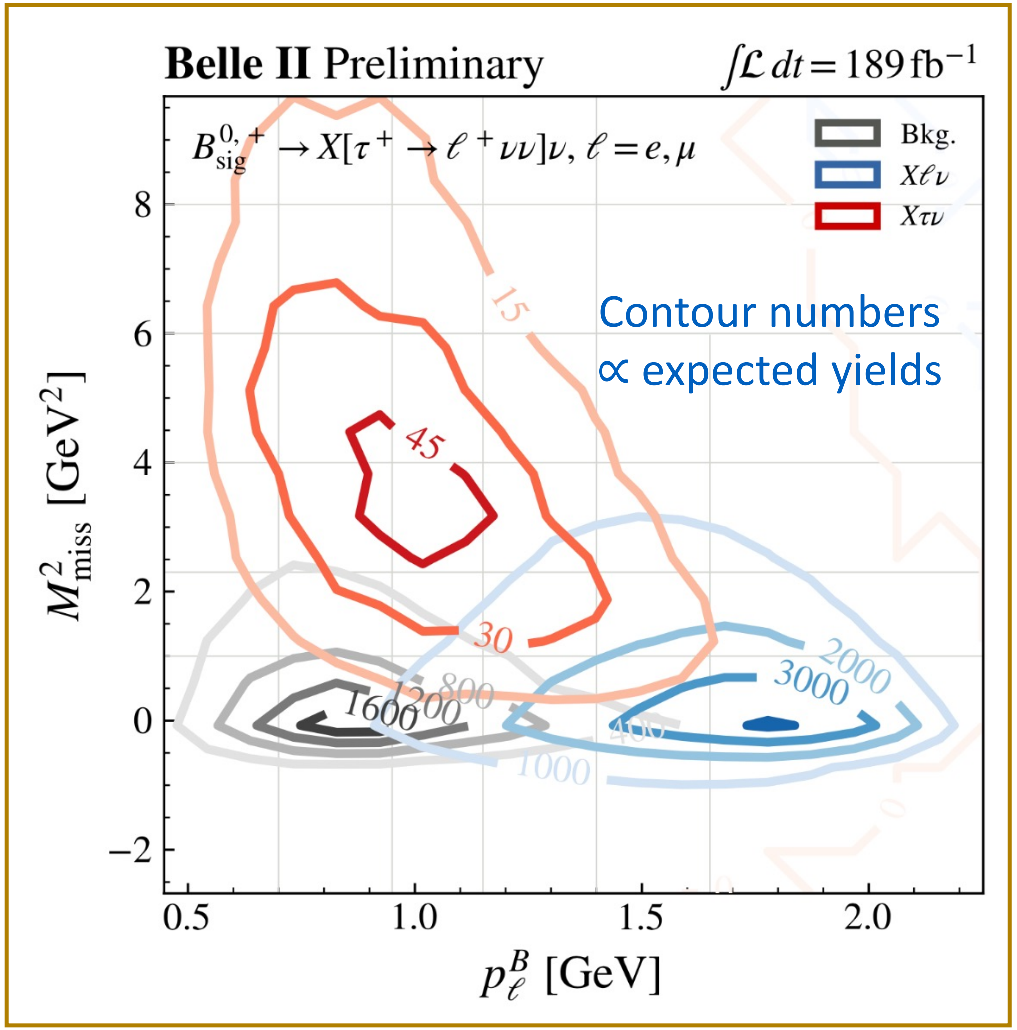
$R_{\tau/\ell}(X)$ at $\Upsilon(4S)$ – strategy

$$R_{\tau/\ell}(X) \propto \frac{N(B \to X[\tau \to \ell\bar{\nu}\nu]\nu)}{N(B \to X\ell\nu)}$$

In 1990s LEP experiments measured $\mathcal{B}(b \to q\ell\nu)$ in $Z^0 \to b\bar{b}$ decays; *not previously measured at $\Upsilon(4S)$*

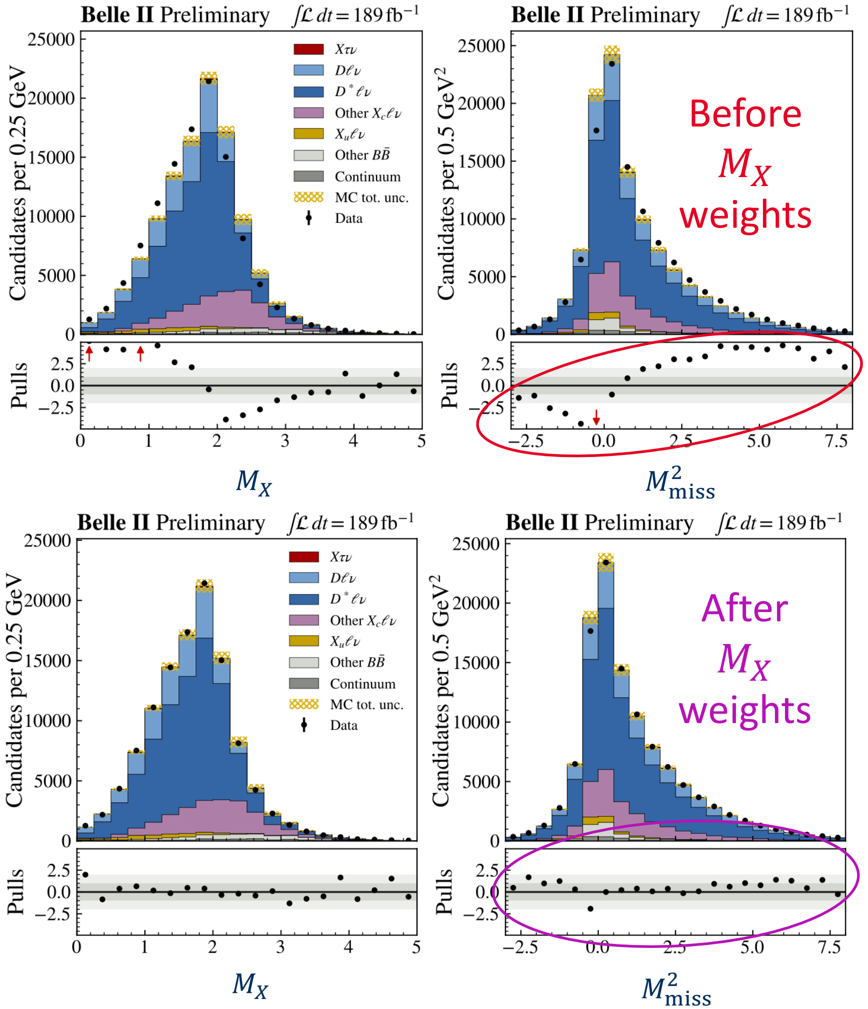


- Select events with $B_{tag} + \ell$, *remaining particles attributed to X*
- Distinguish $\bar{B} \to X\tau^- \nu$ from $\bar{B} \to X\ell^- \nu$ and background using $M^2_{\rm miss}$ and *kinematics* (p^*_ℓ) (but *not* E_{ECL})
- Background mostly from $b \to c \to \ell$; some continuum, fakes
- $p_e > 0.3$ (0.5) and $p_\mu > 0.4$ (0.7) in CMS (lab)



$R_{\tau/\ell}(X)$ – updates to modeling

- Use separate e and μ templates for each of $X\tau\nu$, $X\ell\nu$, $B\bar{B}$ bkg and continuum $q\bar{q}$ (constrained using off-peak data)
- Main challenge is to produce reliable template shapes
  - Detailed adjustments to MC (FFs, B and D BFs)
  - Detailed corrections based on comparisons of simulation with control regions: low q^2 ($X_c\ell\nu$), low $M^2_{\rm miss}(X_c\ell\nu)$, high M_X (background)
  - Example: adjust M_X in $p_\ell > 1.4$ GeV sideband; using these weights also improves modeling in $M^2_{\rm miss}$ (shown) and q^2



Main sources of systematic uncertainty:

- MC stat ±5.7 %
- Bkg shape ±5.5 %
- M_X modeling ±7.1 %
- $B \to X_c\ell\nu$ BFs ±7.7 %
- $B \to X_c\ell\nu$ FFs ±7.9 %

$R_{\tau/\ell}(X)$ – results

Extensive data splits performed:

$e\,/\,\mu,\ \ell^+/\,\ell^-,\ B^+/\,B^0,\ \theta_\ell$ high/low, run periods

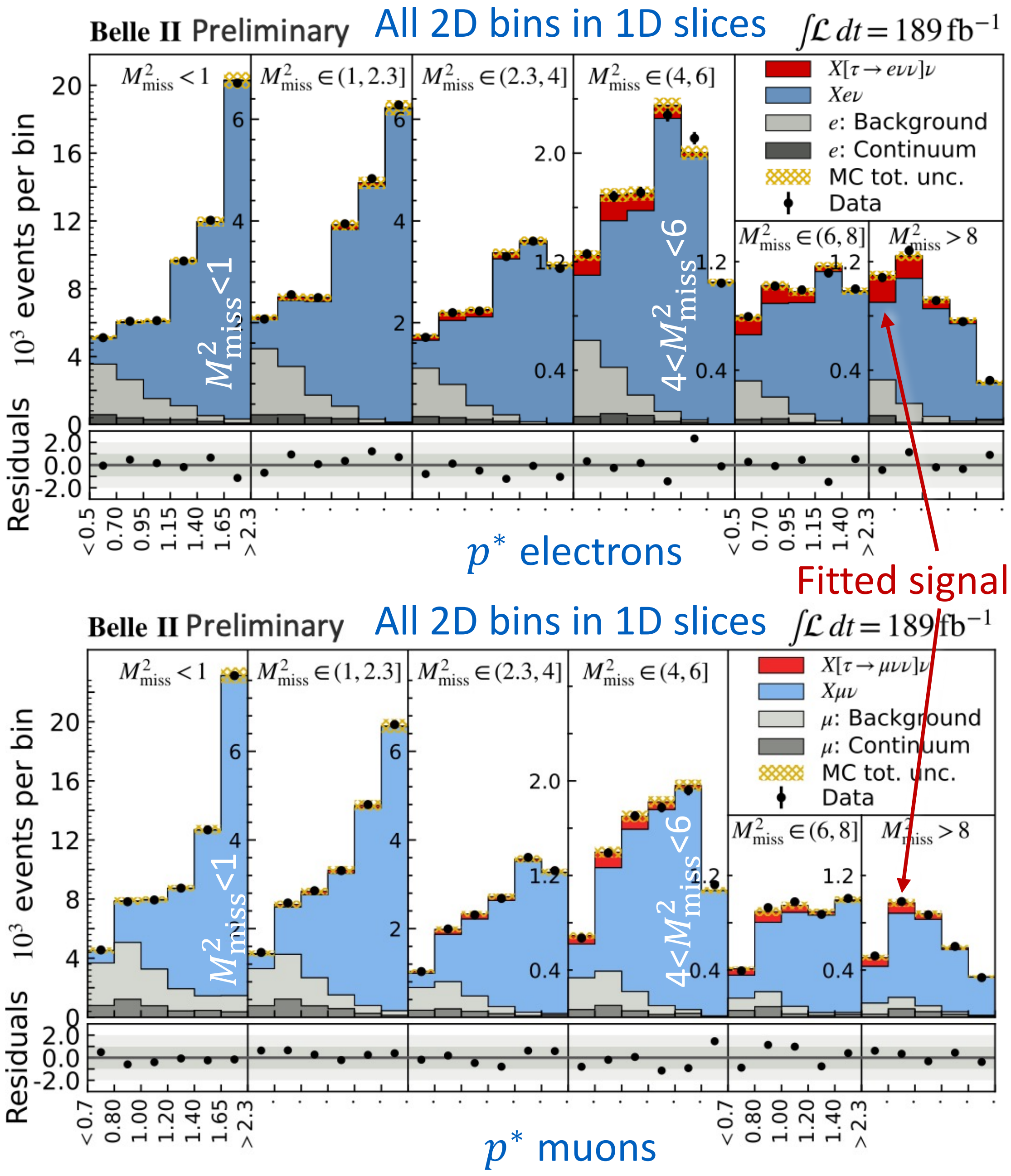
First $R_{\tau/\ell}(X)$ result at $\Upsilon(4S)$ (Belle II preliminary)

$$R_{\tau/\ell}\,(X) = 0.228 \pm 0.016(\text{stat}) \pm 0.036\,(\text{sys})$$
$$R_{\tau/e}\,(X) = 0.232 \pm 0.020(\text{stat}) \pm 0.037\,(\text{sys})$$
$$R_{\tau/\mu}\,(X) = 0.222 \pm 0.027(\text{stat}) \pm 0.050\,(\text{sys})$$

Consistent with SM and related $R(D^{(*)})$ measurements (HFLAV 23)

$$R(D^*) = 0.284 \pm 0.013$$
$$R(D) = 0.356 \pm 0.029$$

Rough SM expectation: $R_{\tau/\ell}\,(X) \approx 0.222$



$$R_{e/\mu}(X) \text{ and } R_{e/\mu}(D^*)$$

$R_{e/\mu}(X)$ – light lepton universality test

Semileptonic B decays to e/μ can be compared in inclusive or exclusive decays.

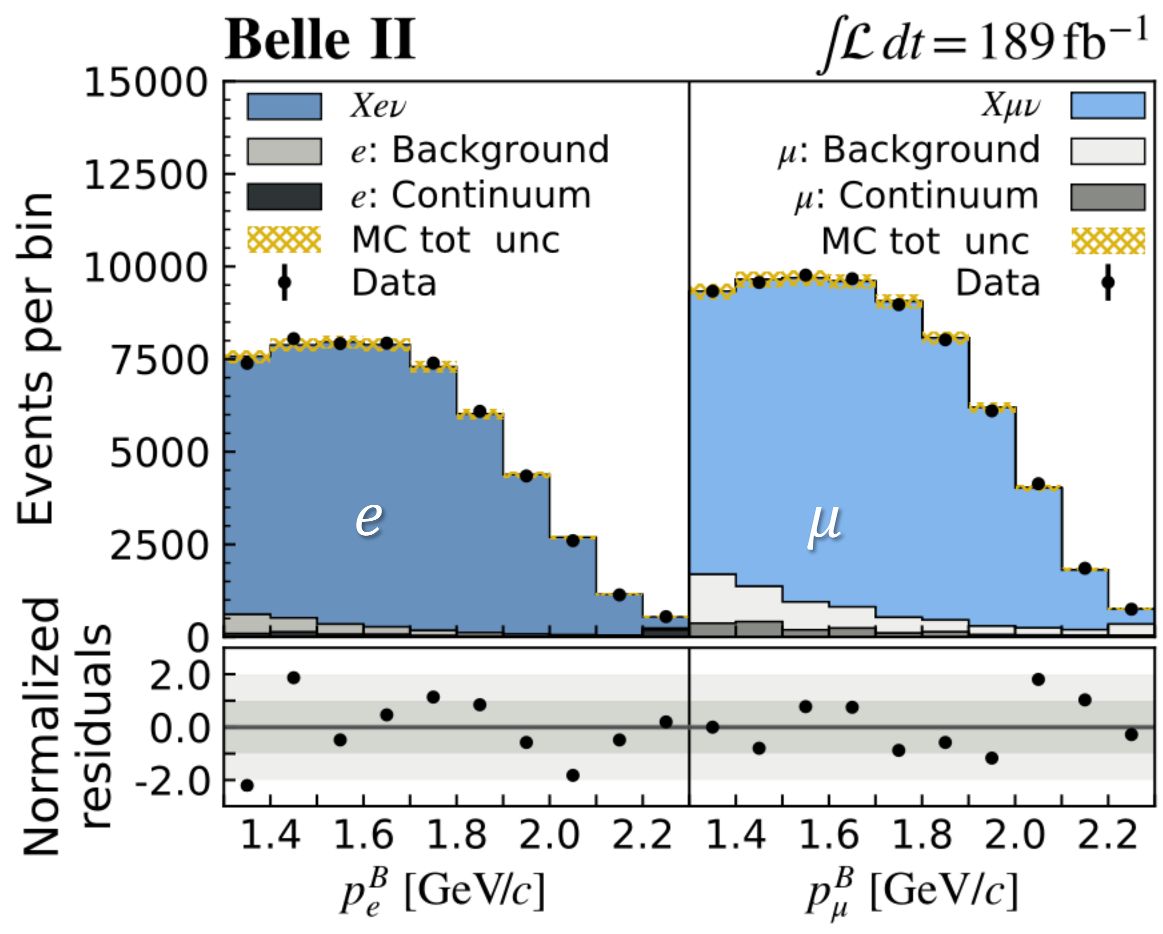
- Inclusive measurement from Belle II ($189\ \mathrm{fb}^{-1}$) :

  $R_{e/\mu}(X) = 1.007 \pm 0.009 \pm 0.019$ PRL 131, 051804

- Exclusive measurement in $B \to D^* \ell\nu$ from Belle ($711\ \mathrm{fb}^{-1}$):

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

Leading uncertainty comes from e/μ identification



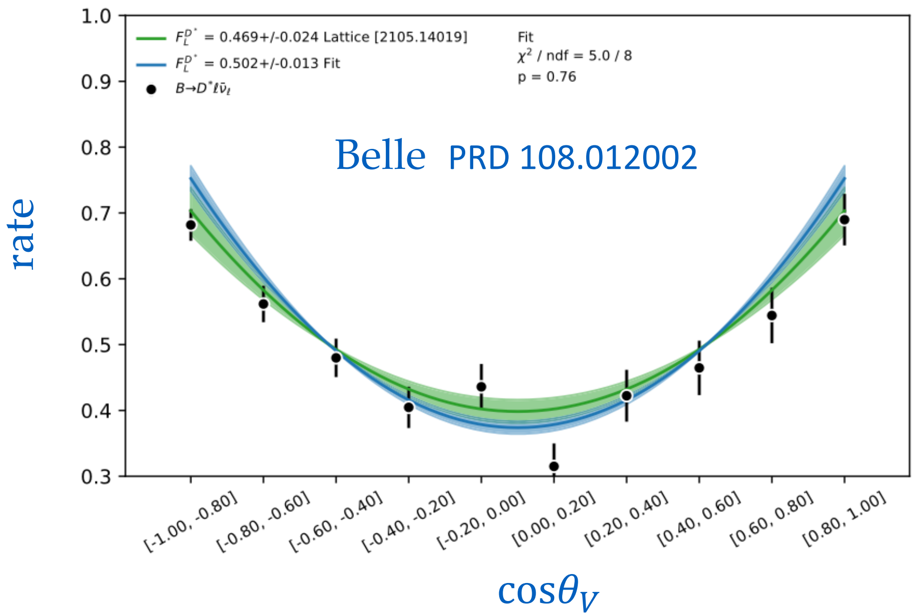
LFU tests in $B \to D^* \ell \nu$ angular asymmetries

Motivated by reanalysis of Belle data (*Bobeth et al.*, EPJC **81**, 984 (2021))
Now extended to use fully differential measurement input

LFU tests in $B \to D^*\ell\nu$ angular asymmetries – strategy

Measure angular asymmetries separately for $D^*e\nu$ and $D^*\mu\nu$ final states; their differences are sensitive to LFU violation

Belle measures A_{FB} and the longitudinal polarization fraction $F_L^{D^*}$

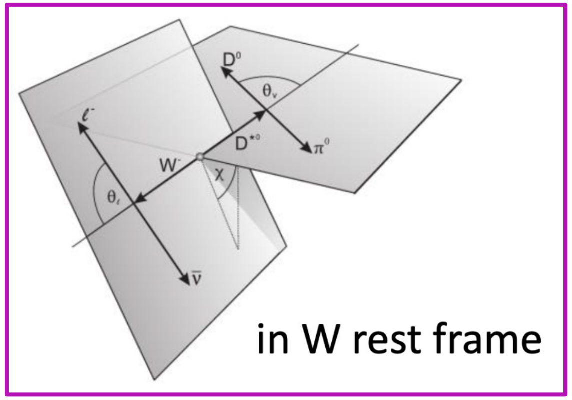


Belle II measures $A_{FB}, S_3, S_5, S_7, S_9$ (defined in PRD 107, 015011) as a function of $(w = v \cdot v)$:

$$A_x(w) \equiv \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dx \frac{d^2\Gamma}{dwdx}; \quad A^{\text{meas}} = \frac{N_F - N_B}{N_F + N_B}$$

With $x = \cos\theta_\ell$, $A_x(w) = A_{FB}(w)$; other x choices give $S_3 - S_9$

Angles : θ_ℓ, θ_V and χ

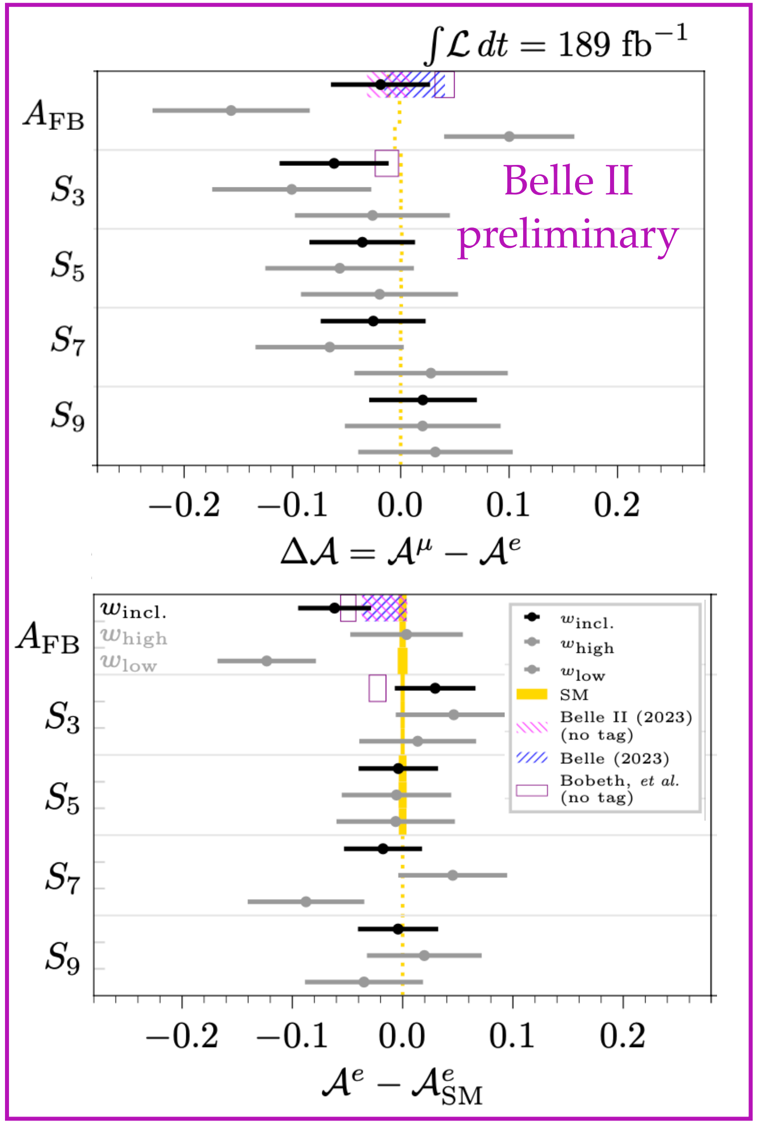


The differences $\Delta A_x \equiv A_x^\mu - A_x^e$ are expected to be small in SM, e.g.

$$\Delta A_{FB} = -0.0057(1), \ \ \Delta F_L^{D^*} = 0.00012(1)$$ arXiv:2206.1128

LFU tests in $B \to D^* \ell \nu$ angular asymmetries – results

Belle II ($189\ \mathrm{fb}^{-1}$) measurements (arXiv:2308.02023) of $A_{FB}, S_3, S_5, S_7, S_9$ and ΔA_x at high/low w are consistent with zero



Belle ($711\ \mathrm{fb}^{-1}$) measures (PRD 108.012002) A_{FB} and $F_L^{D^*}$ separately for e and μ and for B^+ and B^0

	$\Delta F_L^{D^*}$		ΔA_{FB}
$\bar{B}^0 \to D^{*+}\ell\bar{\nu}_\ell$	$0.033 \pm 0.033 \pm 0.010$	$\bar{B}^0 \to D^{*+}\ell\bar{\nu}_\ell$	$0.063 \pm 0.044 \pm 0.012$
$B^- \to D^{*0}\ell\bar{\nu}_\ell$	$0.017 \pm 0.037 \pm 0.009$	$B^- \to D^{*0}\ell\bar{\nu}_\ell$	$0.008 \pm 0.037 \pm 0.009$
$B \to D^*\ell\bar{\nu}_\ell$	$0.030 \pm 0.025 \pm 0.007$	$B \to D^*\ell\bar{\nu}_\ell$	$0.028 \pm 0.028 \pm 0.008$

All asymmetry measurements are statistics limited

Consistent with SM expectations, which are close to zero in all cases

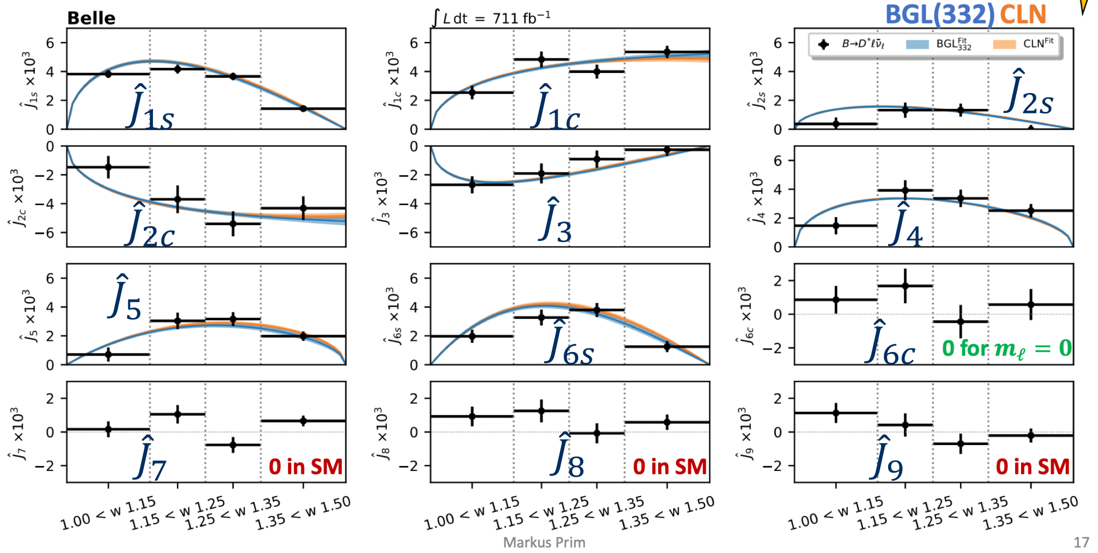
New - angular asymmetries from Belle (preliminary)

- Measure 12 angular coefficients J_i in bins of w
- Look for LFU violation using $\Delta J_i \equiv J_i^{\mu} - J_i^{e}$
- Normalized $\hat{J}_i$ are proportional to S_i

Preliminary

Angular Coefficients of $B \to D^* \ell \bar{\nu}_\ell$ vs. w

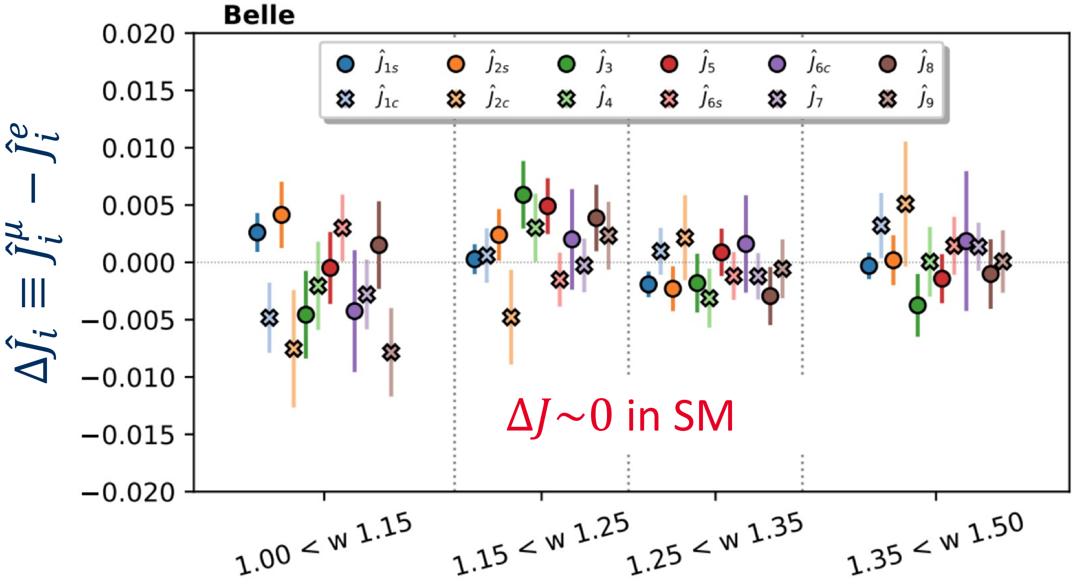
New!



$$\frac{d\Gamma}{dq^2 d\cos\theta_V d\cos\theta_\ell d\chi} = \frac{G_F^2 |V_{ub}^L|^2 m_B^3}{2\pi^4} \{J_{1s}\sin^2\theta_V + J_{1c}\cos^2\theta_V + (J_{2s}\sin^2\theta_V + J_{2c}\cos^2\theta_V)\cos 2\theta_\ell + J_3\sin^2\theta_V\sin^2\theta_\ell\cos 2\chi + J_4\sin 2\theta_V\sin 2\theta_\ell\cos\chi + J_5\sin 2\theta_V\sin\theta_\ell\cos\chi + (J_{6s}\sin^2\theta_V + J_{6c}\cos^2\theta_V)\cos\theta_\ell + J_7\sin 2\theta_V\sin\theta_\ell\sin\chi + J_8\sin 2\theta_V\sin 2\theta_\ell\sin\chi + J_9\sin^2\theta_V\sin^2\theta_\ell\sin 2\chi\}.$$

Phys.Rev.D 90 (2014) 9, 094003

No departures from LFU observed



Summary of recent LFU tests at Belle and Belle II

New tests of LFU in measured ratios of decay rates at **Belle II** $(189\ \mathrm{fb}^{-1})$:

$$R_{\tau/\ell}(D^*) = 0.267\,^{+\,0.041}_{-\,0.039}\,^{+\,0.028}_{-\,0.033}$$

$$R_{\tau/\ell}(X) = 0.228 \pm 0.016 \pm 0.036$$

Preliminary

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

and **Belle** $(711\ \mathrm{fb}^{-1})$:

$$R_{e/\mu}(D^*) = 0.993 \pm 0.023 \pm 0.023$$

All measurements presented here are consistent with SM and with previous measurements where available

Angular asymmetry differences $\Delta A_x \equiv A_x^{\mu} - A_x^{e}$ and $\Delta\hat{J}_i$ also measured; statistics limited

Belle II has collected twice the data sample analyzed here; more data to come, with improved pixel detector

Backup slides