Test of lepton flavor universality at Belle and Belle II

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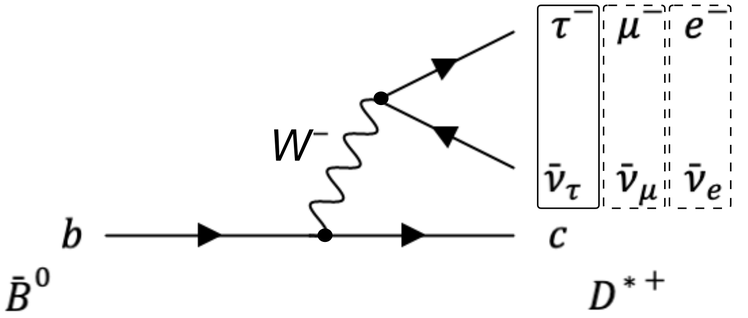
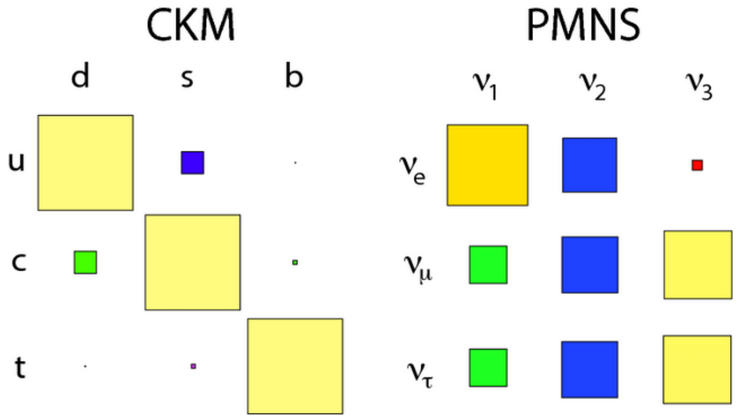
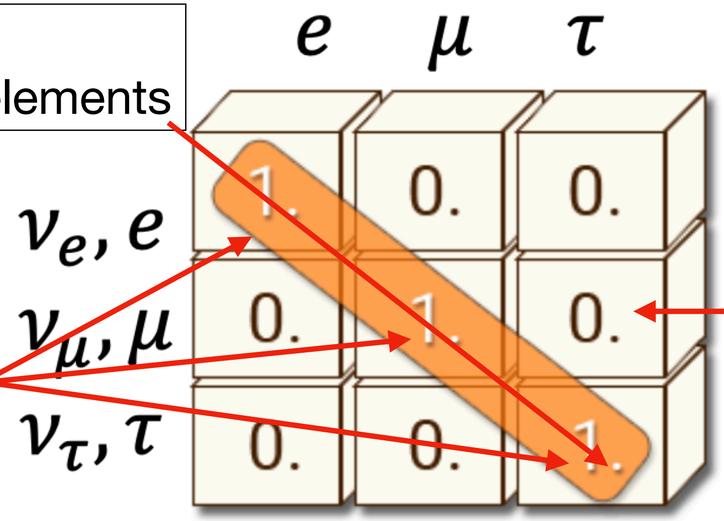
Motivation for studying LFUV

- Lepton Flavor Universality (LFU): *W* boson couples to leptons with equal strength
  - Difference in kinematics and Higgs coupling due to different lepton masses
- SM fields do mix:
  - Quarks sector -> CKM matrix
  - Neutrinos sector -> PMNS matrix
- Charged leptons -> the matrix purely diagonal?
- LFUV: diagonal terms not all equal





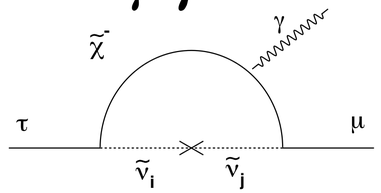
g-2, EDM:
diagonal elements



LFUV:
Relation among
diagonal elements

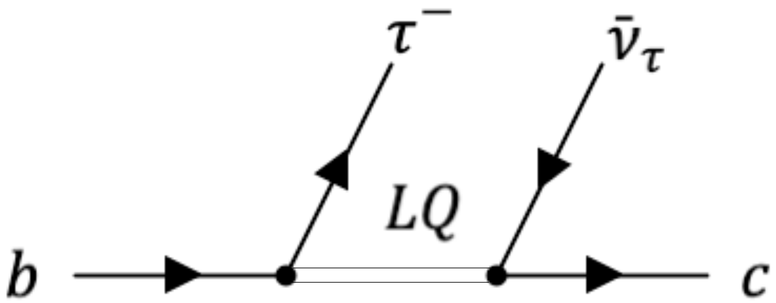
Lepton Flavor Violation (LFV):
off diagonal term

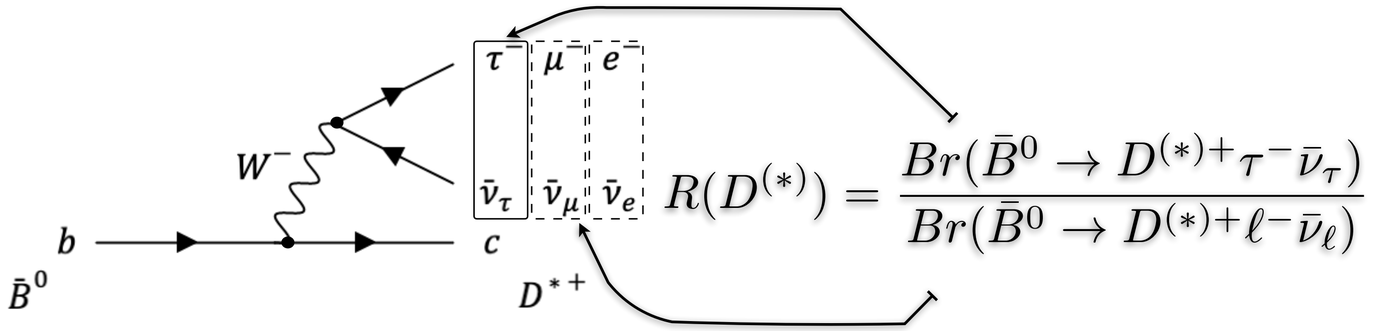
$\tau \rightarrow \mu\gamma$

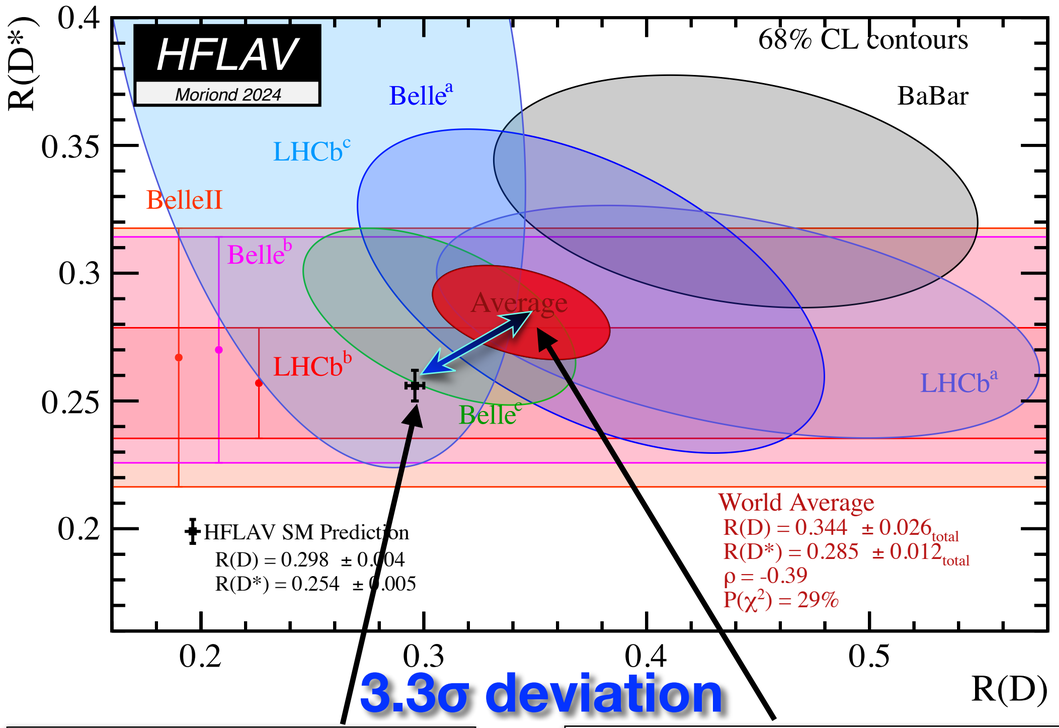


"*B* anomaly" in semileptonic decays

- Ratios of $b \to q\tau\nu/q\mu\nu/qe\nu$ branch fractions cancel out most of the uncertainties on $|V_{cb}|$, form factors and the experimental systematics
- $B \to D^{(*)}\tau\nu$ sensitive to New Physics (NP) because the massive 3rd generation *b* quark and τ lepton are involved
- Sensitivities to high energy scale; ~10 TeV [Belle II phys. book]







3.3σ deviation

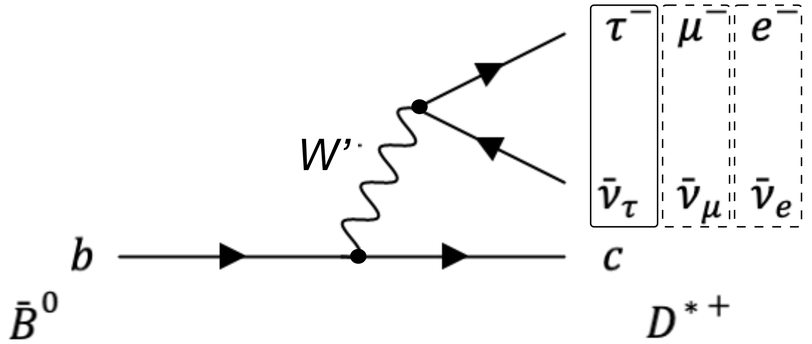
Standard Model prediction

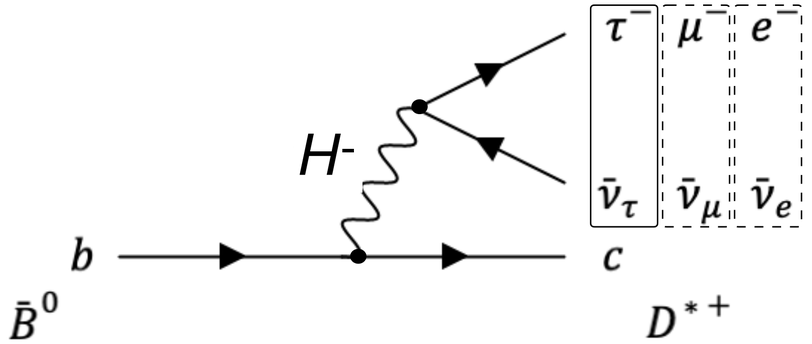
Experimental average results

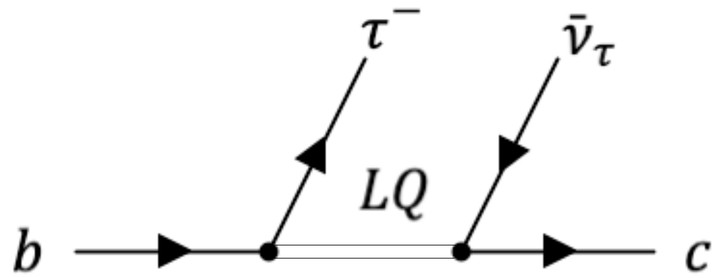
New physics scenarios for the $R(D^{(*)})$ anomaly

In general, there are three typical candidate scenarios to explain the anomaly observed in $R(D^{(*)})$

- Heavy vector bosons
  - Constrained from $W' \to \tau\nu$ and $Z' \to \tau\tau$ search
- Charged Higgs
  - Constrained from $B_c \to \tau\nu$ and $H^{\pm} \to \tau\nu$,still allowed
  - Previously, it was rejected by $B_c \to \tau\nu$ measurement, however, recovered by recalculating the B_c lifetime.
    arXiv:2201.06565
- Leptoquark
  - $gg \to LQ\ LQ^*$, still broad parameter regions are allowed







LFU test program at Belle II

- The analyses presented in this talk

  - $R_{\tau/\ell}(D^*)$ at Belle II (189 fb^{-1}), preliminary, arXiv:2401.02840
  - $R_{\tau/\ell}(X)$ at Belle II (189 fb^{-1}), PRL132, 211804
  - $R_{e/\mu}(X)$ from Belle II (189 fb^{-1}), PRL 131, 051804
  - $R_{e/\mu}(D^*)$ from Belle (711 fb^{-1}), PRD 108, 012002
  - Test of LFU in angular asymmetries of $B \to D^* l \nu$ at Belle II (189 fb^{-1}), PRL 131, 181801
  - Test of LFU in τ decays at Belle II (362 fb^{-1}), preliminary, arXiv:2405.14625

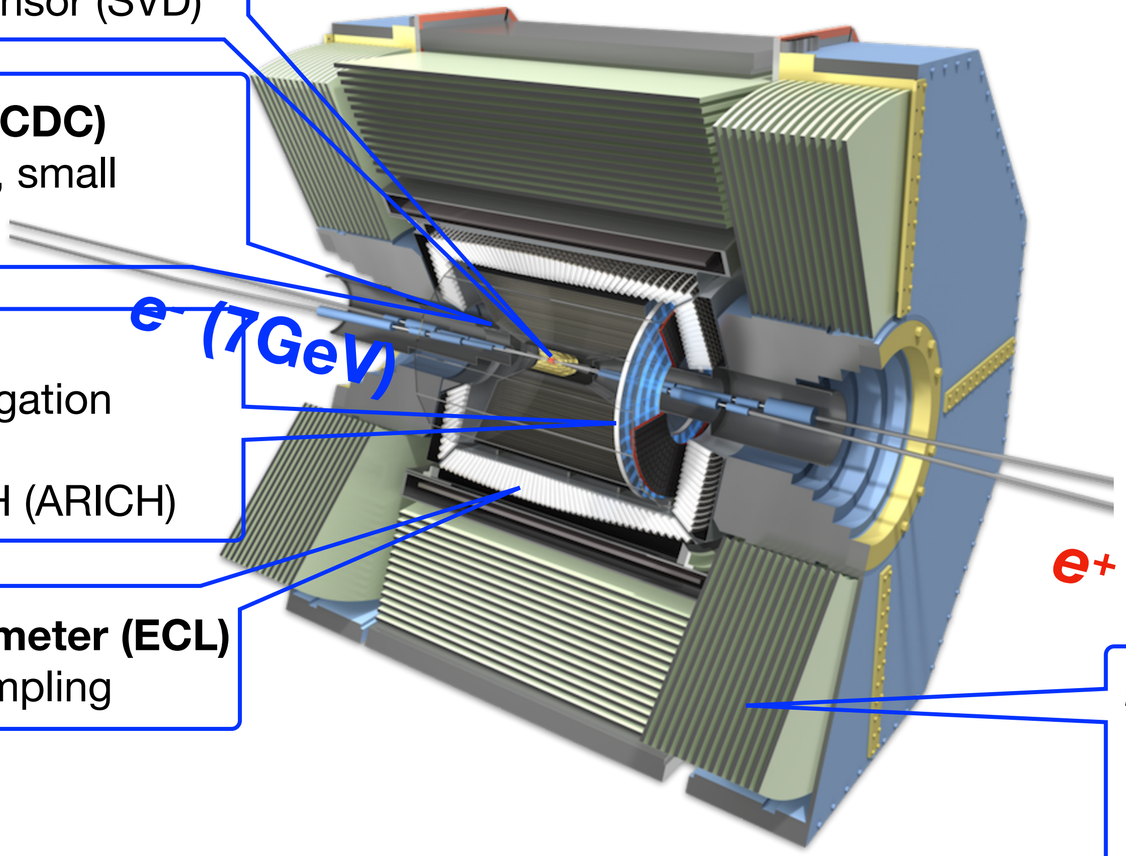
Belle II detector and dataset

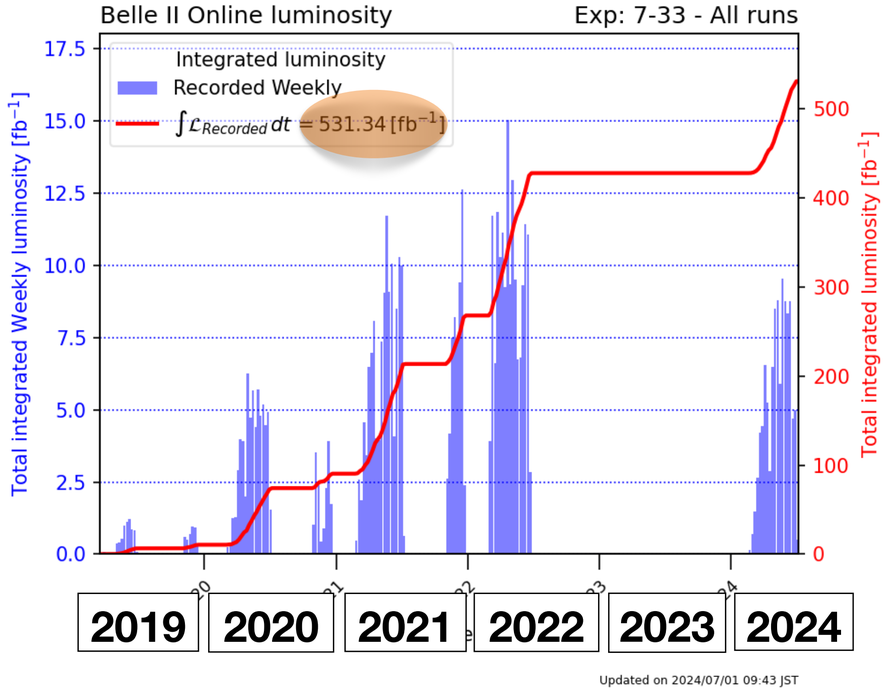
Vertex detector (VXD)
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)

Central Drift Chamber (CDC)
He (50%), C_2H_6 (50%), small cells, long lever arm

Particle Identification
Barrel: Time-Of-Propagation counters (TOP)
Forward: Aerogel RICH (ARICH)

ElectroMagnetic Calorimeter (ECL)
CsI(Tl) + waveform sampling



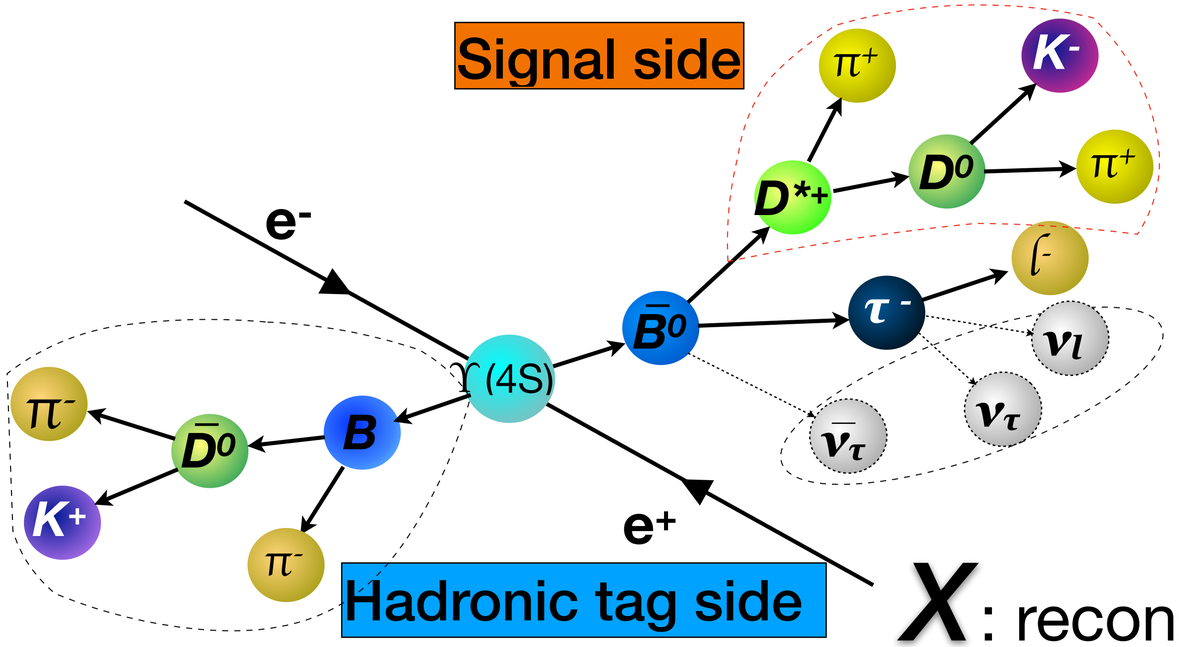


K_L/μ detector (KLM)
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator

- Features:
  - Near-hermetic detector
  - Vertexing and tracking: σ vertex ~ 15μm, CDC spatial res. 100μm $\sigma(P_T)/P_T$ ~ 0.4%
  - Good at measuring neutrals, π^0, γ, K_L… $\sigma(E)/E$ ~ 2-4%

Tagging methods

- The $B\bar{B}$ pairs are produced near threshold
- B tagging is necessary to measure $B\to X\,/\,D^{*}\tau\nu$, $B\to X\,/\,D^{*}l\nu$ ($\nu\geq 2$) simultaneously
- Hadronic tag
  - Fully reconstruct $B\to D^{(*)}(/J/\psi/\Lambda)X$
  - Tagging efficiency 0.2~0.4%
  - less background

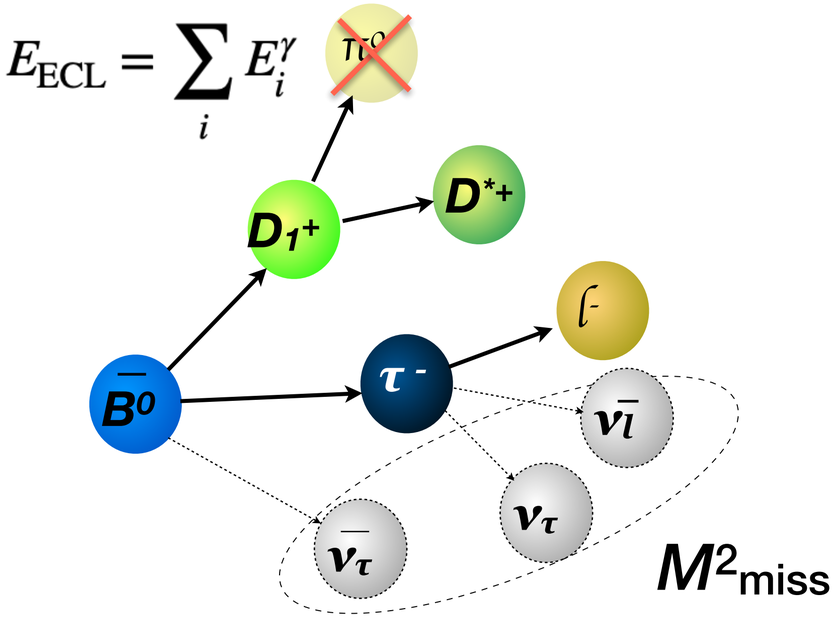


- Fully reconstruct one of the B mesons (B tag), possible to measure momentum of other B meson (B signal)
- Indirectly measure missing momentum of neutrinos in signal B decays
- $M^2_{\text{miss}} = (p_{\text{beam}} - p_{\text{Btag}} - p_{D(*)} - p_{\ell})^2$
- E_{ECL} unassigned neutral energy in the calorimeter $E_{\text{ECL}} = \sum_i E_i^{\gamma}$

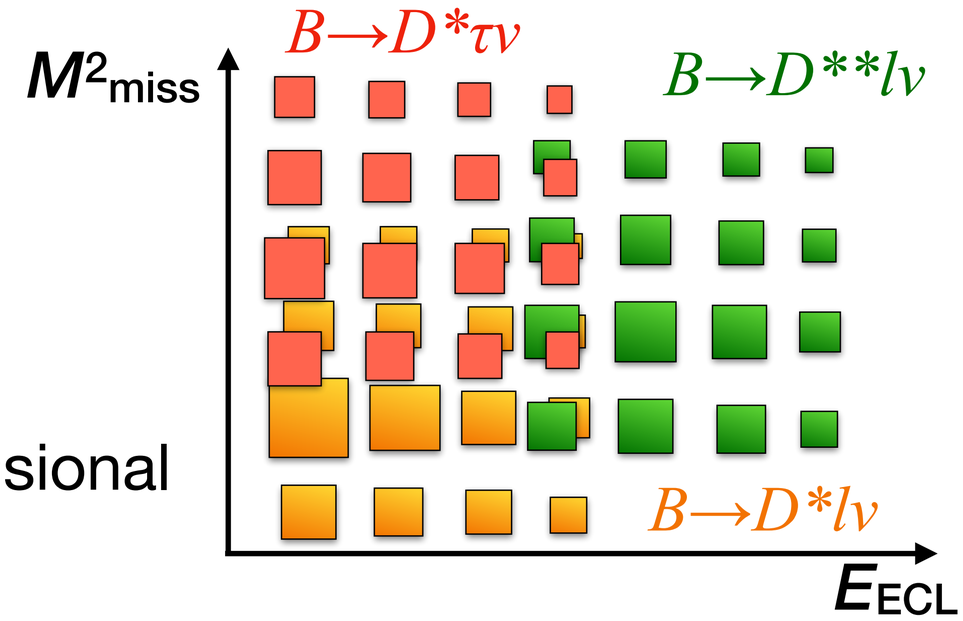
X: reconstruct other particles than a lepton as X on signal side

Analysis strategy

- Reconstruct $B \to D^* \tau \nu$ and $B \to D^* l \nu$ with same selections
- τ lepton reconstruct with ℓ (e, μ)$\nu\nu$
- D/D^* meson reconstruct with $K^{\pm}$, $\pi^{\pm}$,K_s, π^0
  - 8 D^0 modes (Br ~36%), 4 D^+ modes (Br ~12.3%)
  - $D^{*+} \to D^0\pi^+/D^+\pi^0$(Br ~98%), $D^{*0} \to D^0\pi^0$(Br ~65%)
- Both neutral and charged $B^{\pm}/B^0$ mesons reconstruct with D^{*+}/D^{*0} and τ/ℓ = (e, μ)



- $M^2_{\rm miss} = (p_{\rm beam} - p_{B\rm tag} - p_{D(*)} - p_\ell)^2$
- $E_{\rm ECL}$: **extra** neutral energy in the calorimeter **NOT** associate with signal



- Extracting $B \to D^* \tau \nu$, $B \to D^* l \nu$ yields by a two-dimensional simultaneously fit

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

- Similarly sensitivity as Belle 15' result @ 711 fb^{-1} with only 189 fb^{-1}
- Belle II first preliminary result for $R(D^*)$

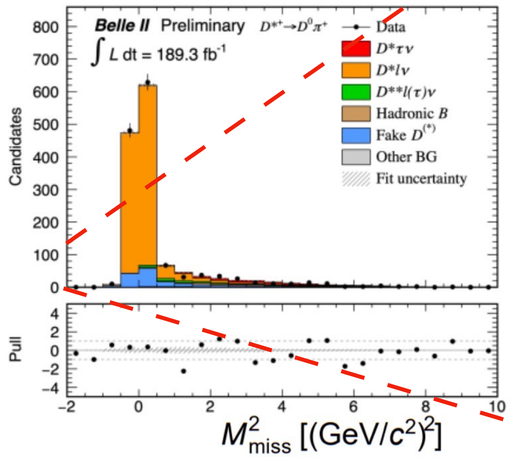
$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat})\ ^{+0.028}_{-0.033}(\text{sys})$$

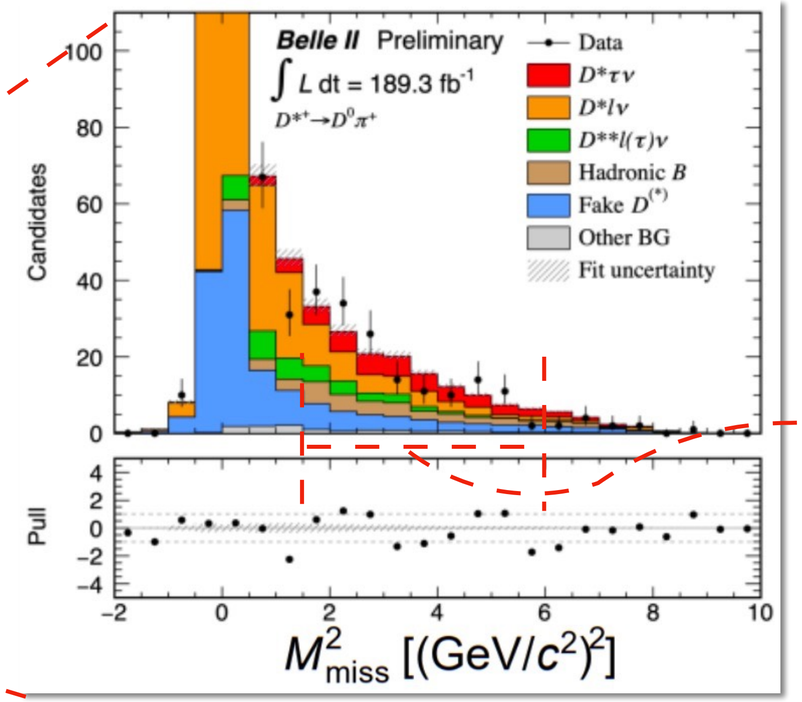
- Consistent with

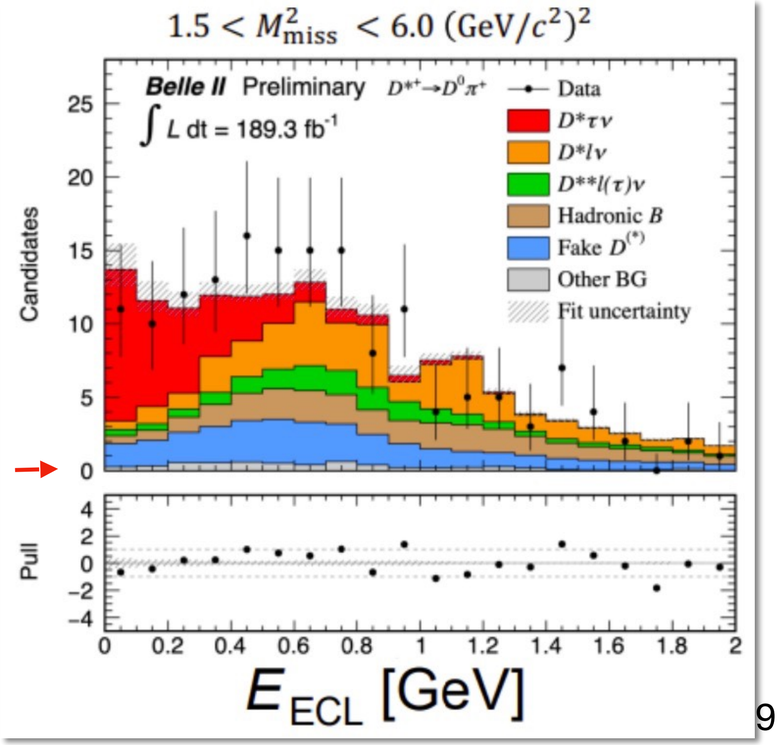
  SM: 0.254 ± 0.005,

  HFLAV23: 0.284 ± 0.013
- SM vs. experimental average deviation: 3.2σ → 3.3σ

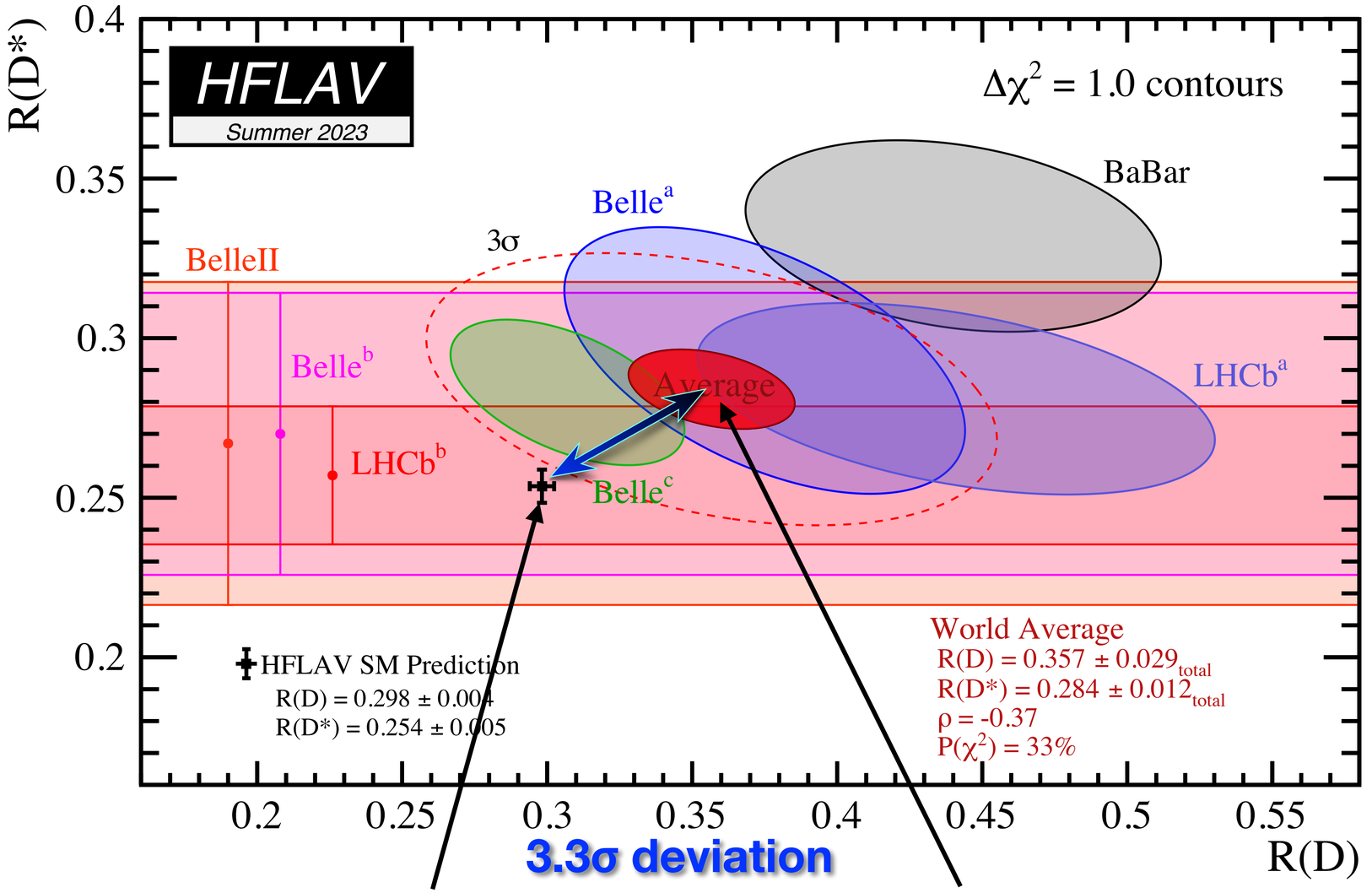
Source	Uncertainty
Statistical uncertainty	+15.4% -14.6%
E_{ECL} PDF shape	+5.5% -9.3%
MC statistics	±7.0%
$B \to D^{**} l\nu$ modeling	+4.7% -2.7%







"*B* anomaly" in semileptonic decays



3.3σ deviation

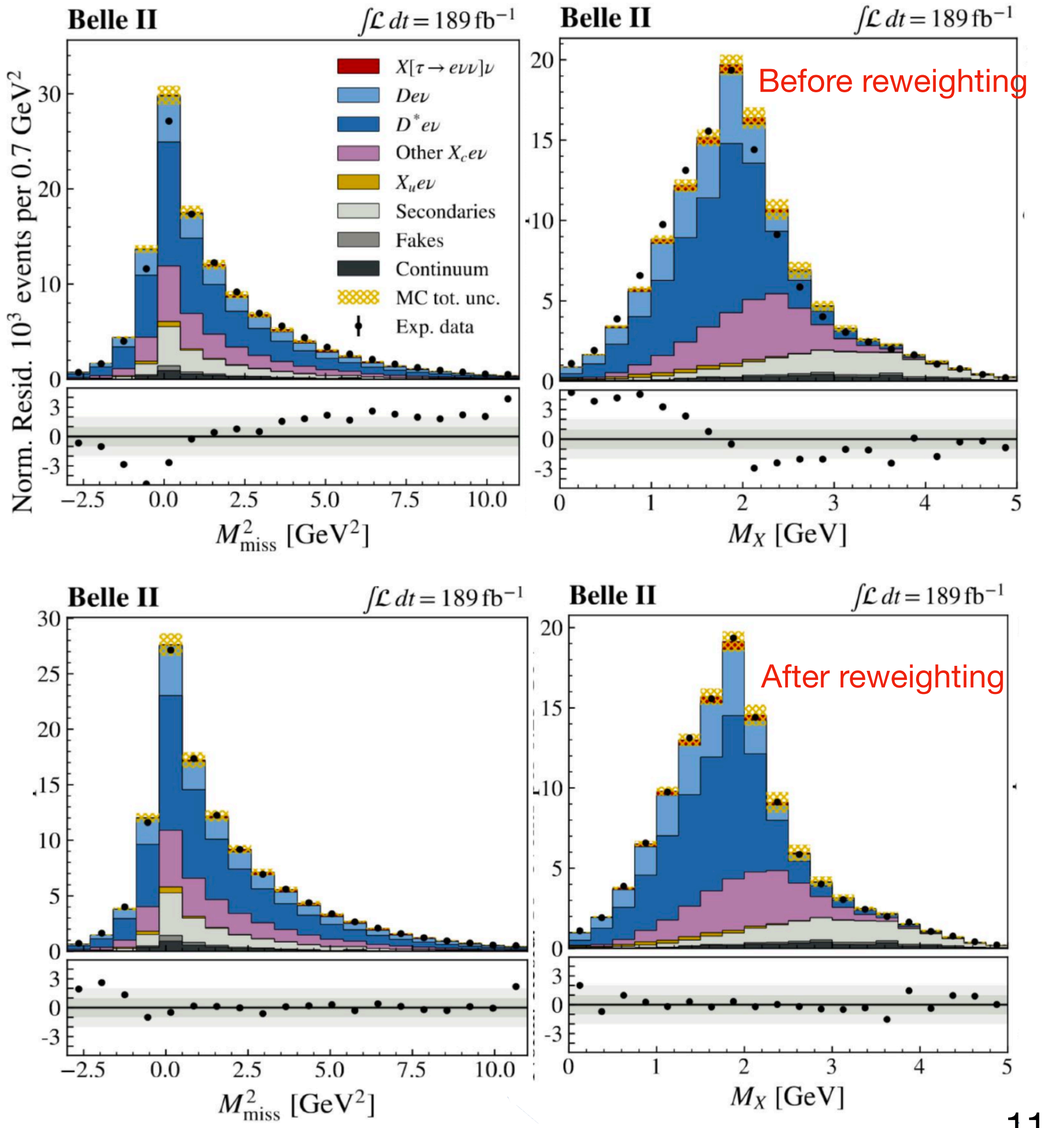
Standard Model prediction

Experimental average results

Update the modeling for $R_{\tau/\ell}(X)$ measurement

PRL132, 211804

- Approach employed at Belle II: M_X reweighting
  - Events weights from data/MC ratio in M_X distribution, applied to all events
  - q^2, M^2_{miss} can be expressed by reliable parts and M_X part
- Detailed adjustments to MC (FFs, B and D BFs)
- Signal yields are extracted by a binned maximum-likelihood simultaneous fit to lepton momentum at different M^2_{miss} bins



Results of $R_{\tau/\ell}(X)$ for LFU test

- Main systematics
  - Adjustment to MC (form factor, D and B branching factions)
  - Sample size in sideband for reweighting

- First Belle II preliminary $R_{\tau/\ell}(X)$ result

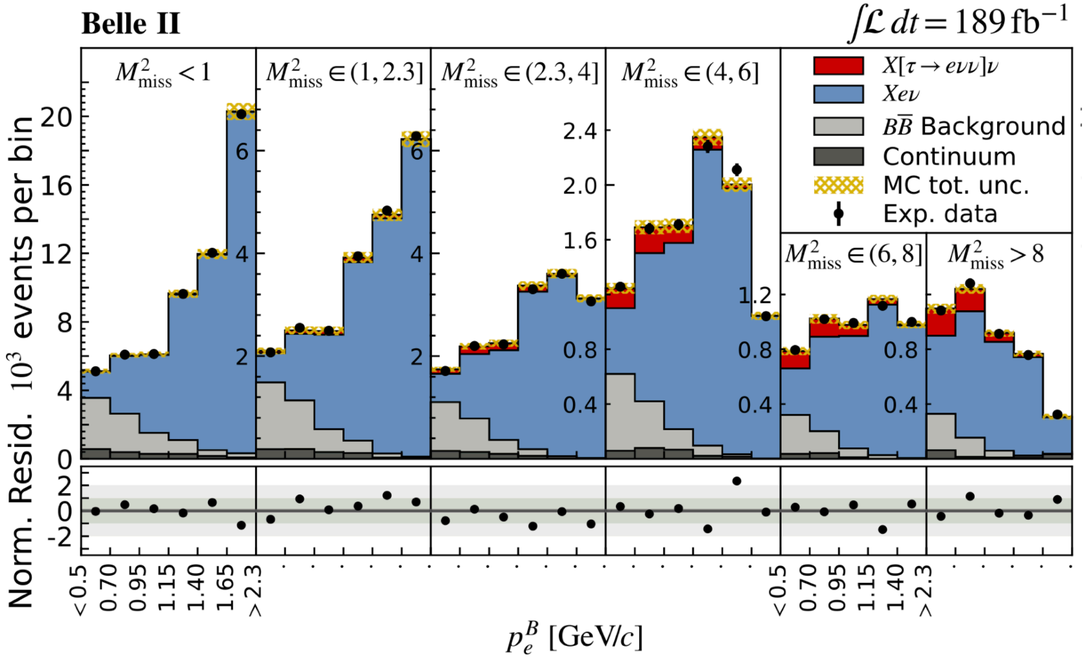
$R_{\tau/\ell}(X) = 0.228 \pm 0.016\ (\text{stat}) \pm 0.036\ (\text{syst})$

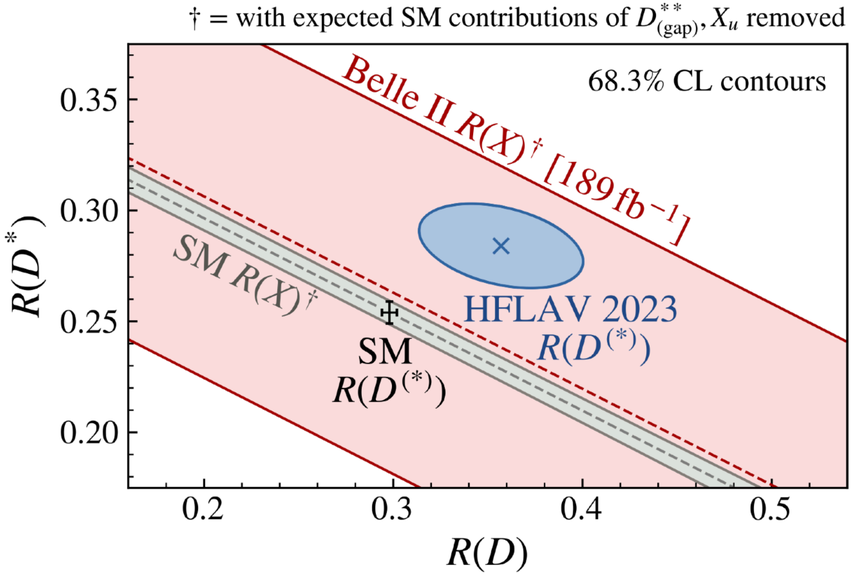
$R_{\tau/e}(X) = 0.232 \pm 0.020\ (\text{stat}) \pm 0.037\ (\text{syst})$

$R_{\tau/\mu}(X) = 0.222 \pm 0.027\ (\text{stat}) \pm 0.050\ (\text{syst})$

- Consistent with rough SM expectation

$R_{\tau/l}(X)_{\text{SM}} \approx 0.222$





Light-lepton universality test

PRL 131, 051804

- First $R(X_{e/\mu})$ measurement

  $R(X_{e/\mu}) = 1.007 \pm 0.009\ (\text{stat}) \pm 0.019\ (\text{syst})$

- Most precise BF based LFU test of e-μ universality with semileptonic B decays to date
- Consistent with SM value by 1.2σ

  $R(X_{e/\mu})_{\text{SM}} = 1.006 \pm 0.001$ JHEP 11 (2022) 007
- Compatible with exclusive Belle (711 fb^{-1}) measurements

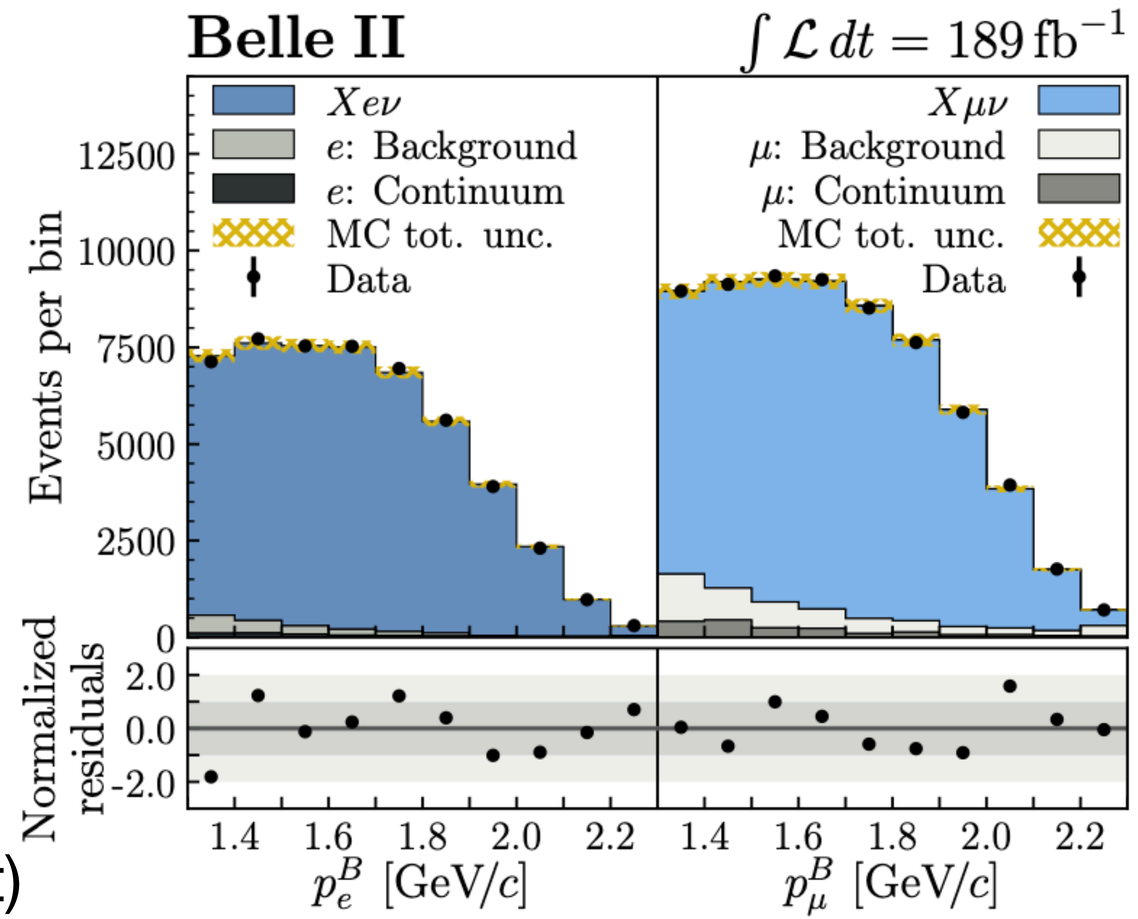
  PRD 100, 052007 (2019)

  $R(D^*_{e/\mu}) = 1.01 \pm 0.01\ (\text{stat}) \pm 0.03\ (\text{syst})$

  $R(D^*_{e/\mu}) = 0.993 \pm 0.023\ (\text{stat}) \pm 0.023\ (\text{syst})$

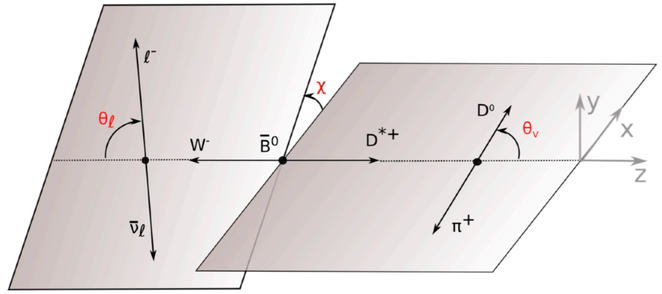
  PRD 108, 012002

Signal channel ($B^0\bar{B}^0/B^+B^-$)



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

- Measure angular asymmetries separately for $D^*e\nu$ and $D^*\mu\nu$ final states; their differences are sensitive to LFU violation
- Belle II measures A_{FB}, S_3, S_5, S_7, S_9 (defined in PRD 107,015011) as a function of w, with $x = \cos\theta_l$ for $A_x(w)$, other choices for S_3-S_9

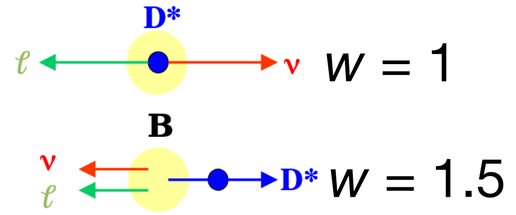


$$\mathcal{A}_x(w) \equiv \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dx \frac{d^2\Gamma}{dw dx} \qquad \mathcal{A}_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}$$

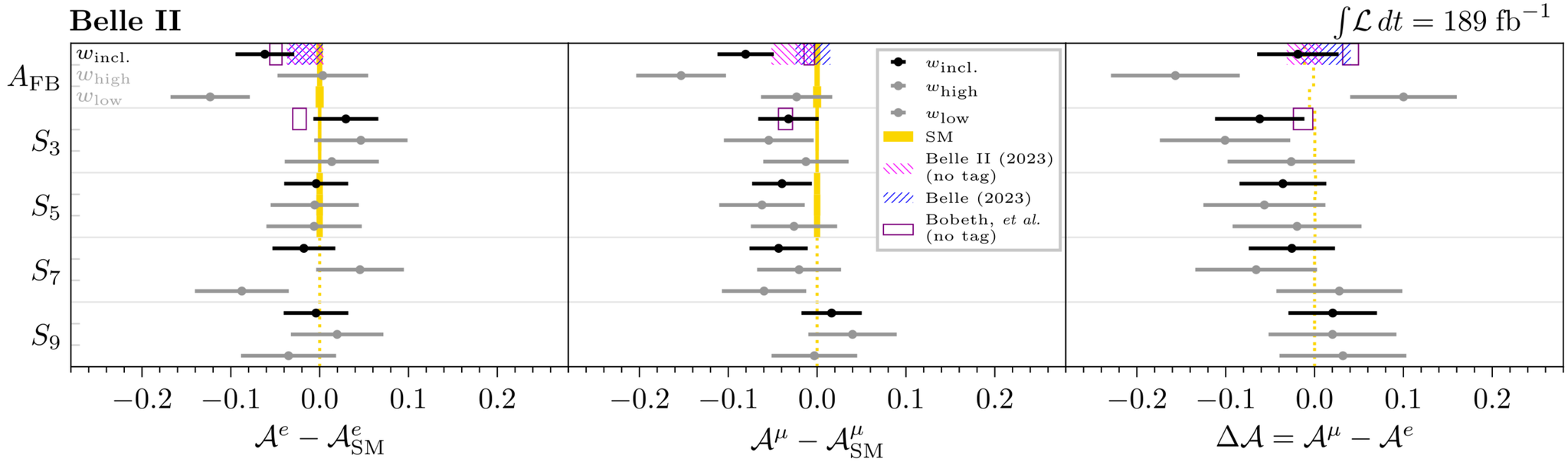
$$w \equiv \frac{m_{B^0}^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

- The differences are expected to be small in SM

$$\Delta\mathcal{A}_x(w) \equiv \mathcal{A}_x^\mu(w) - \mathcal{A}_x^e(w)$$

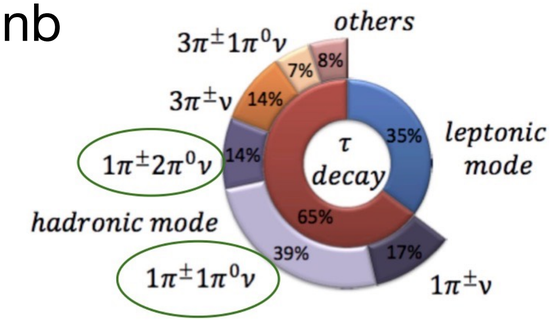


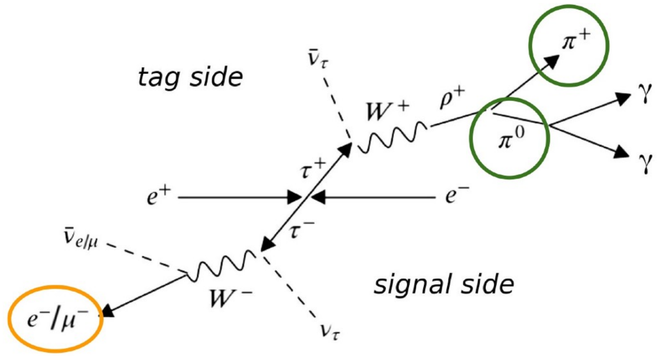
- All asymmetry consistent with SM, the measurements are statistics limited



LFU test: τ decays

- Belle II is also a τ factory, σ_τ =0.92 nb <-> σ_B=1.12 nb
  - Produced as τ pairs; tag τ and signal τ
- New analysis: 362 fb^{-1}
  - 1x1 event topology
- Main systematics
  - Particle identification (0.32%)
  - Trigger (0.10%)
- Consistent with the SM at 1.4 σ





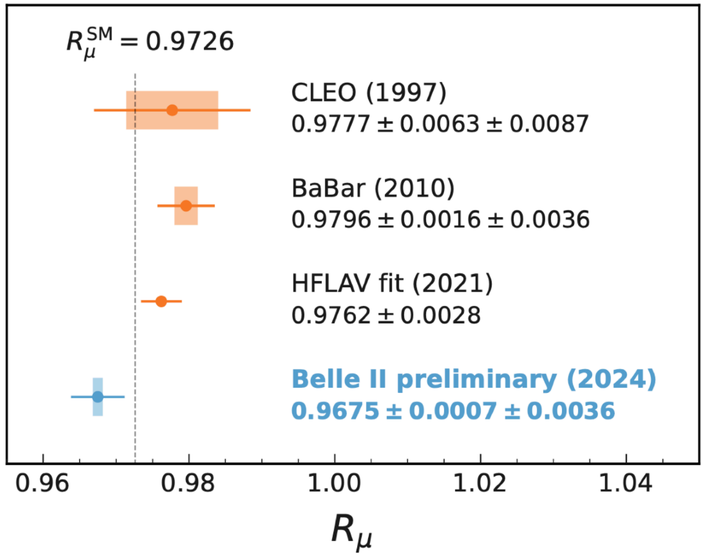
$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

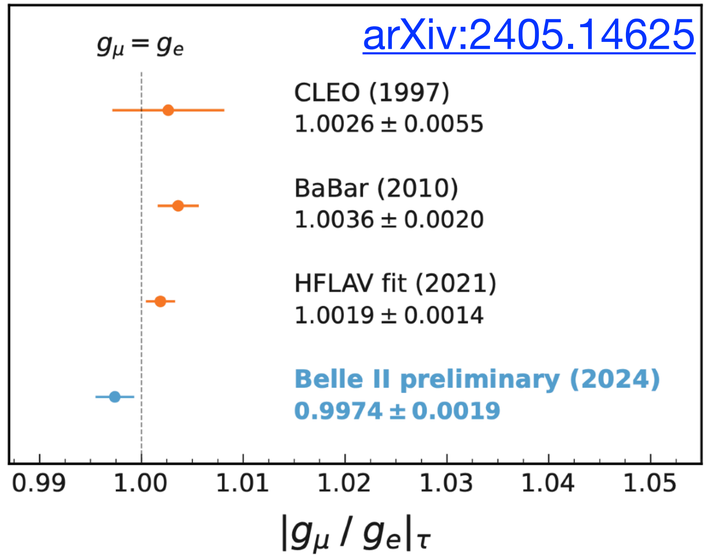
Slightly smaller than 1 in the SM due to e-u mass difference (R_μ^{SM} = 0.9726)

$$\left|\frac{g_\mu}{g_e}\right|_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

1 in the SM





Most precise test of LFU in τ decays

Summary and prospects

- $R(D^{(*)})$ shows 3.3σ deviation between experimental average value and standard model prediction
  - Hint of Lepton Flavor Universality Violation

- Belle II performed new tests of LFU based on 189 fb^{-1} data

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

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

- Light lepton universality, angular asymmetry differences ΔAx also measured, statistics limited
- Most precise test of LFU in τ decays 362 fb^{-1} data
- SuperKEKB/Belle II will resumed operation at the beginning of 2024 after LS1