Test of lepton flavor universality at Belle II

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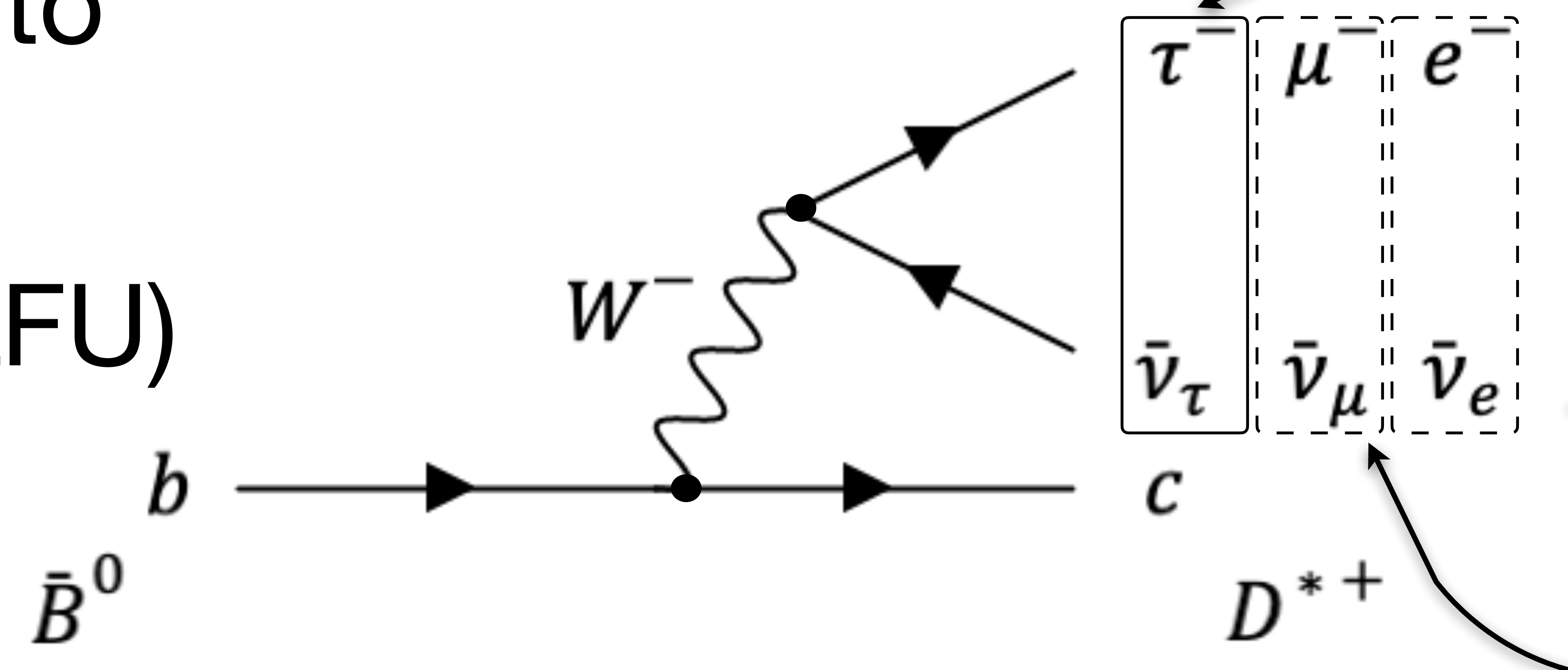
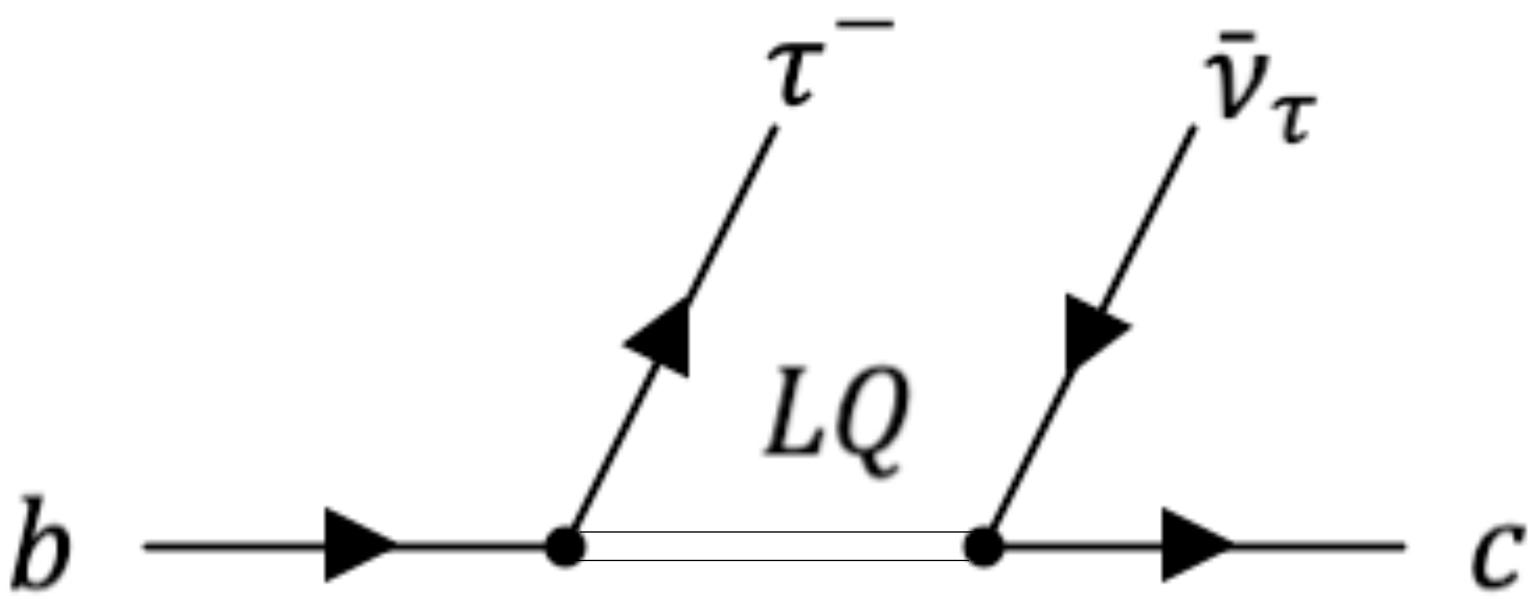
Motivation for studying LFU in B decays

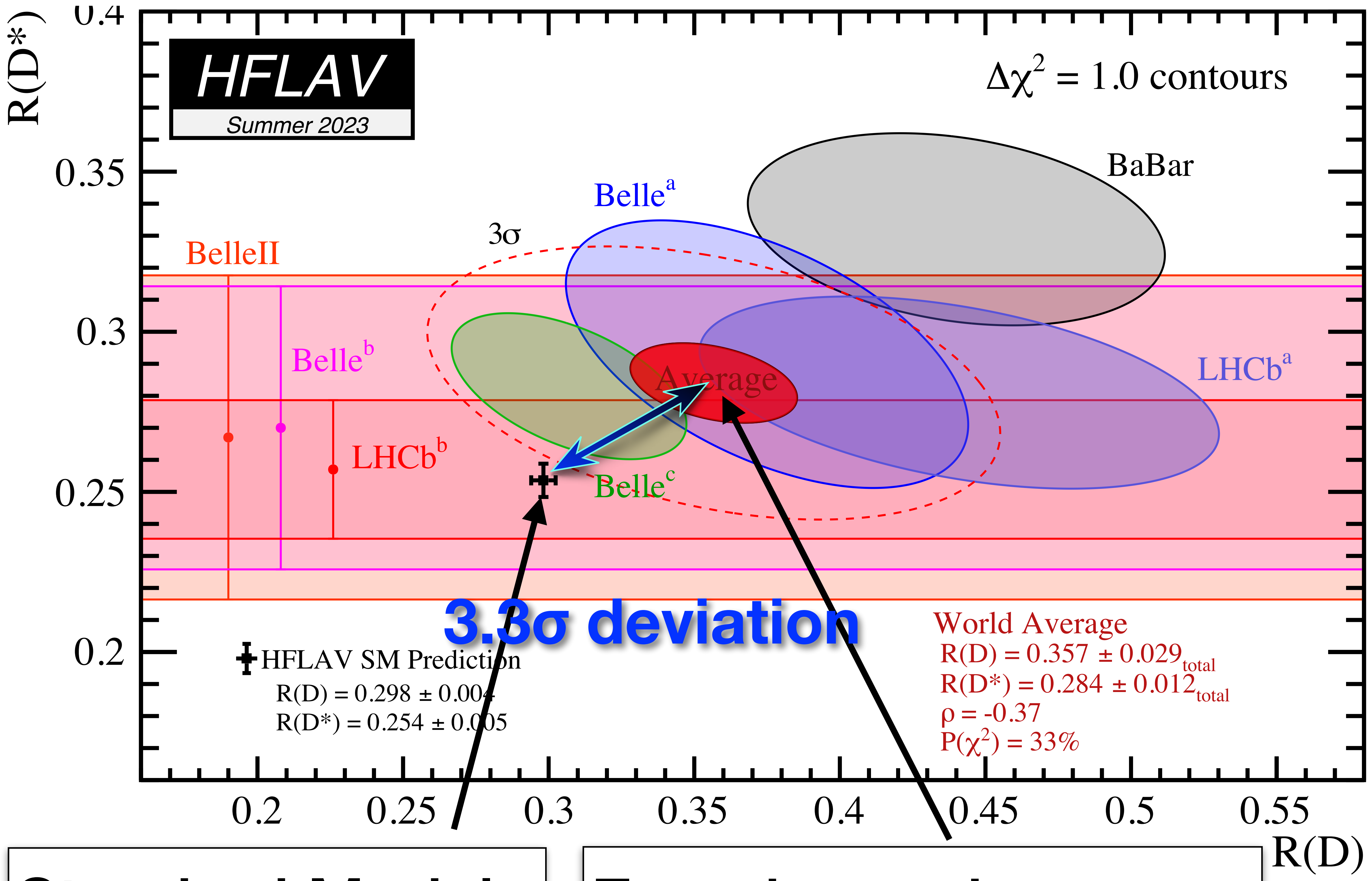
- Universality: *W* boson couples to leptons with equal strength
  - Lepton Flavor Universality (LFU) is fundamental axiom of Standard Model (SM)



$$R(D^{(*)}) = \frac{Br(\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)}{Br(\bar{B}^0 \to D^{(*)+}\ell^-\bar{\nu}_\ell)}$$

- 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





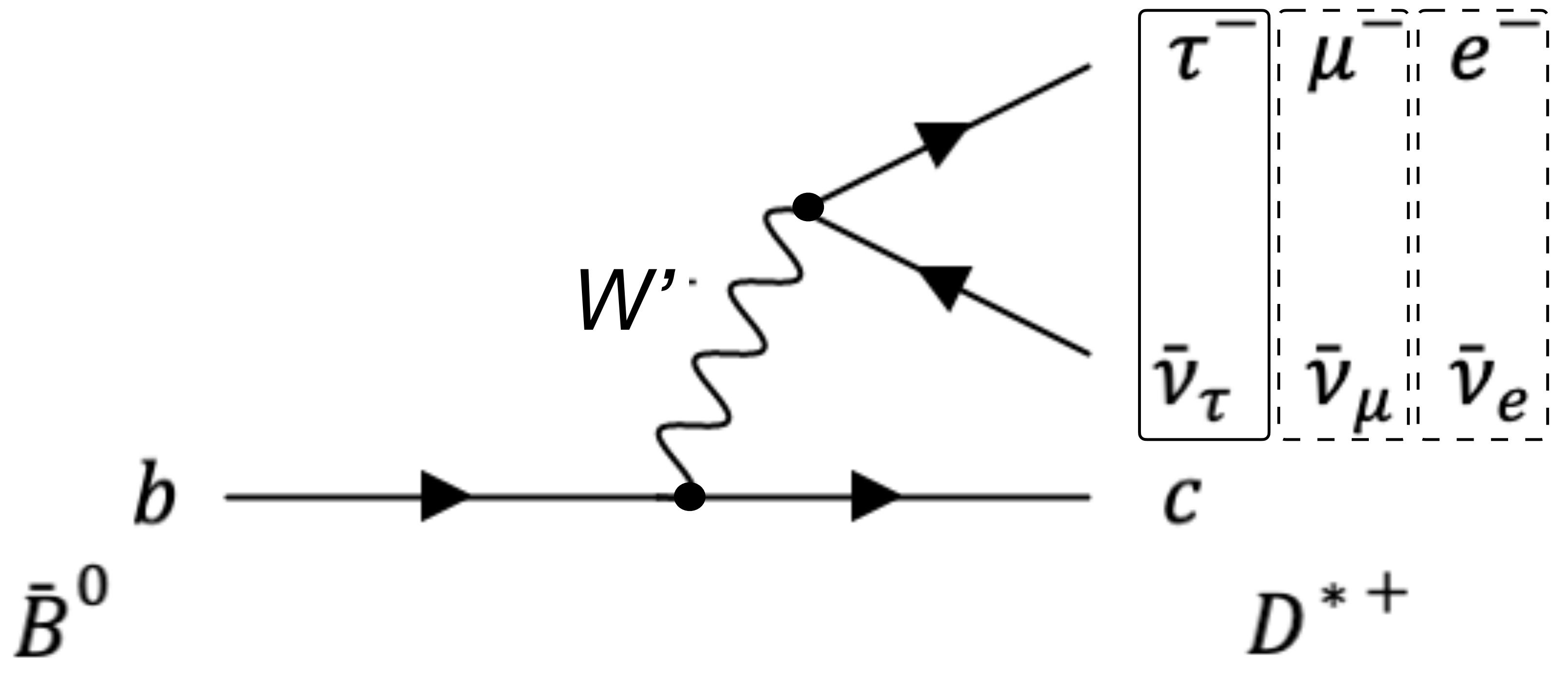
Standard Model prediction

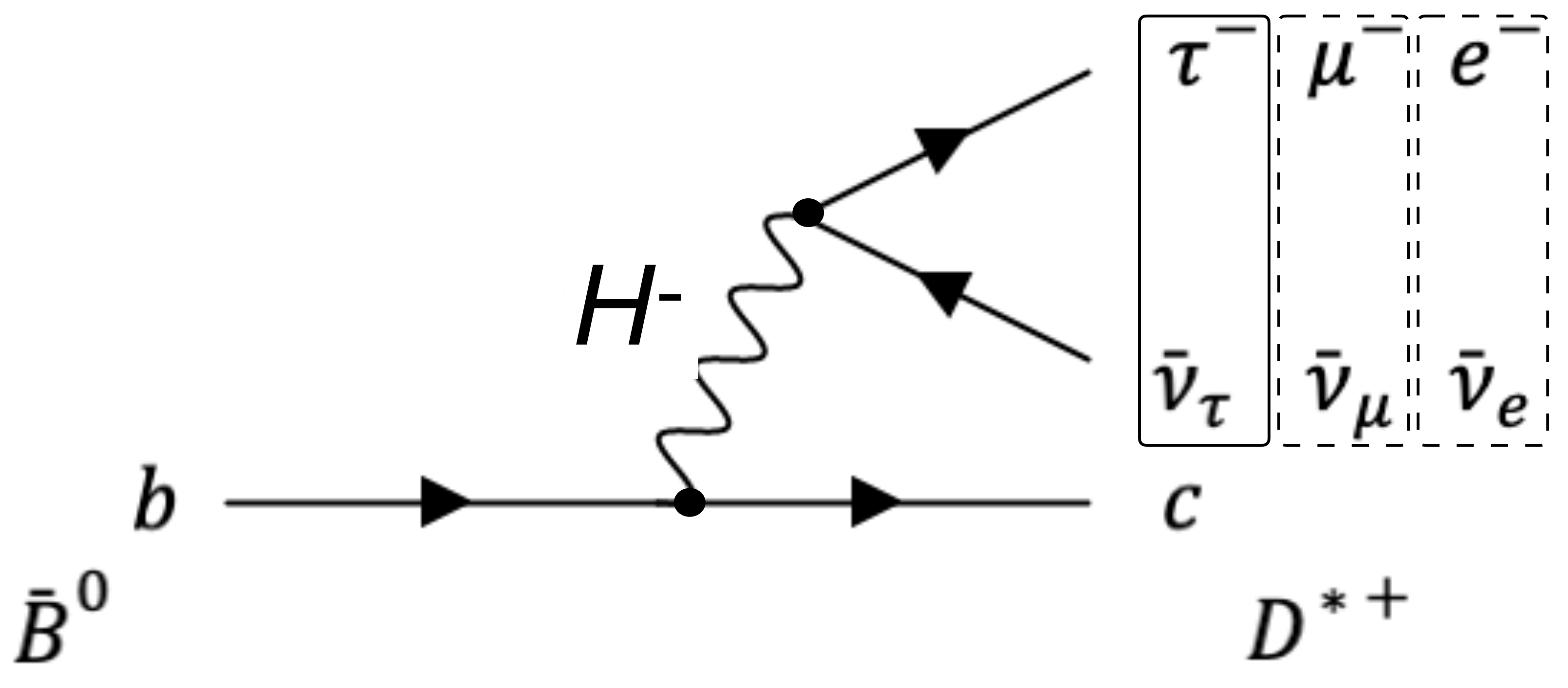
Experimental average results

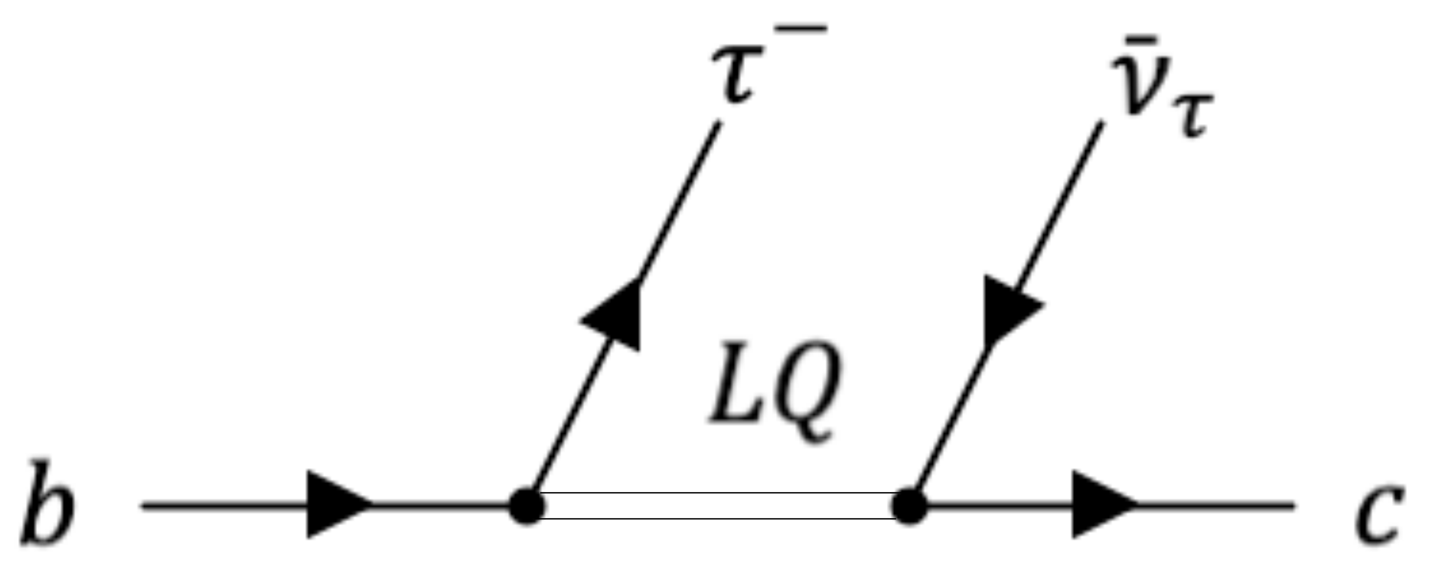
New physics scenarios for the $R(D^{(*)})$ anomaly

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

- $R_{\tau/\ell}(D^*)$ from Belle II (189 fb^{-1}), preliminary
- $R_{\tau/\ell}(X)$ from Belle II (189 fb^{-1}), preliminary, arXiv:2311.07248

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

- Tests of LFU in angular asymmetries of $B \to D^* l\nu$ from

  Belle II (189 fb^{-1}), PRL 131, 181801

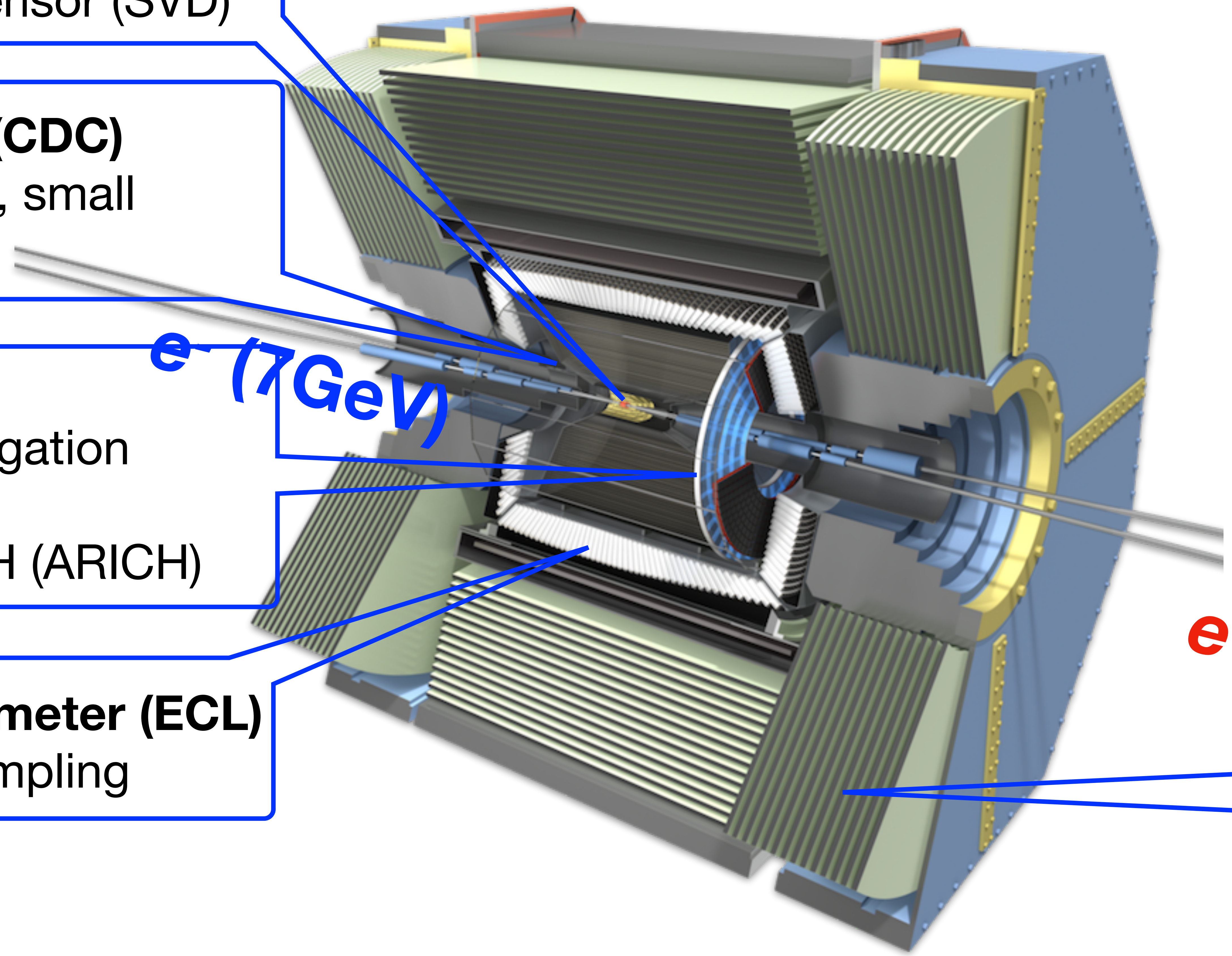
Belle II detector and dataset

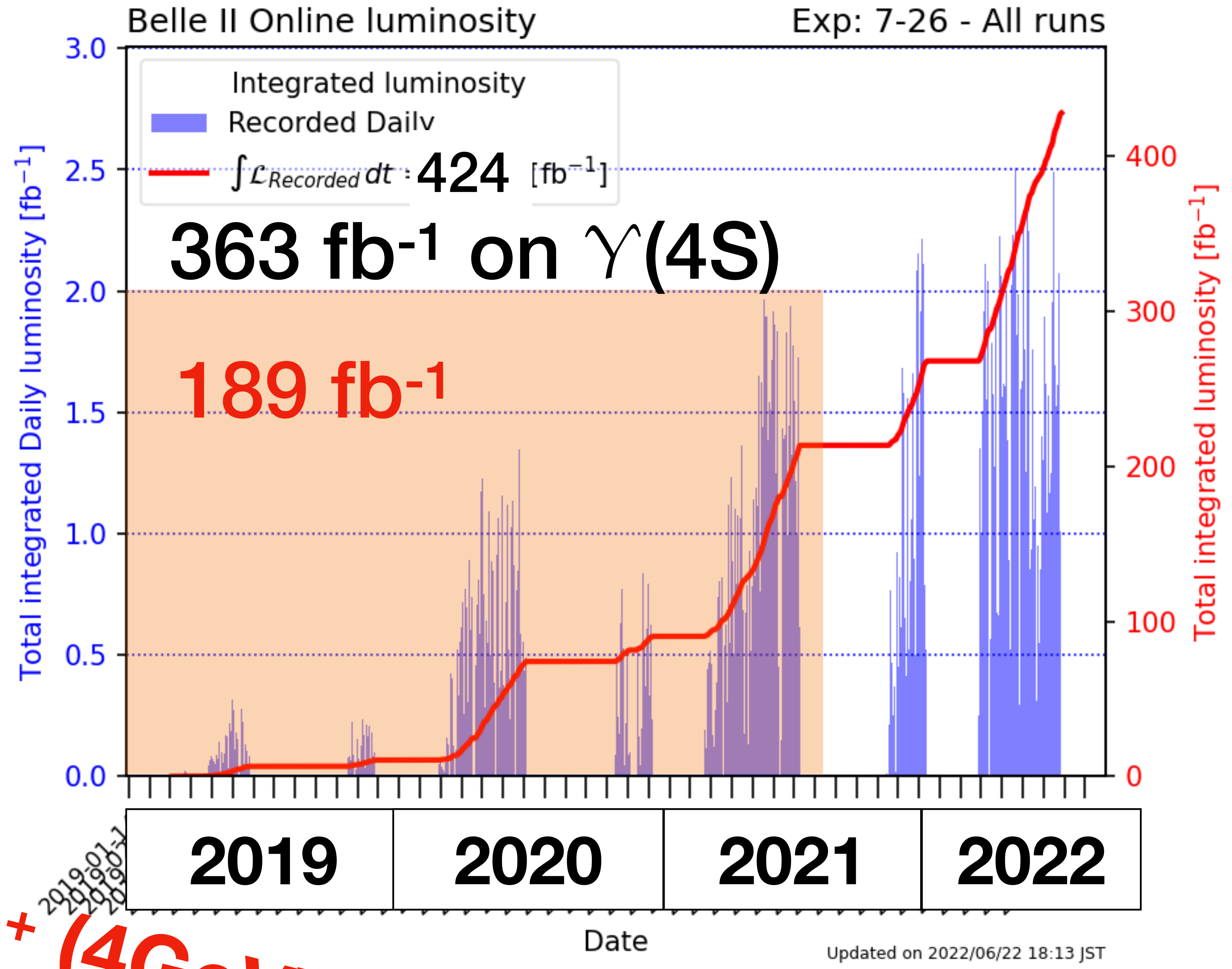
Vertex detector (VXD)
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)

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



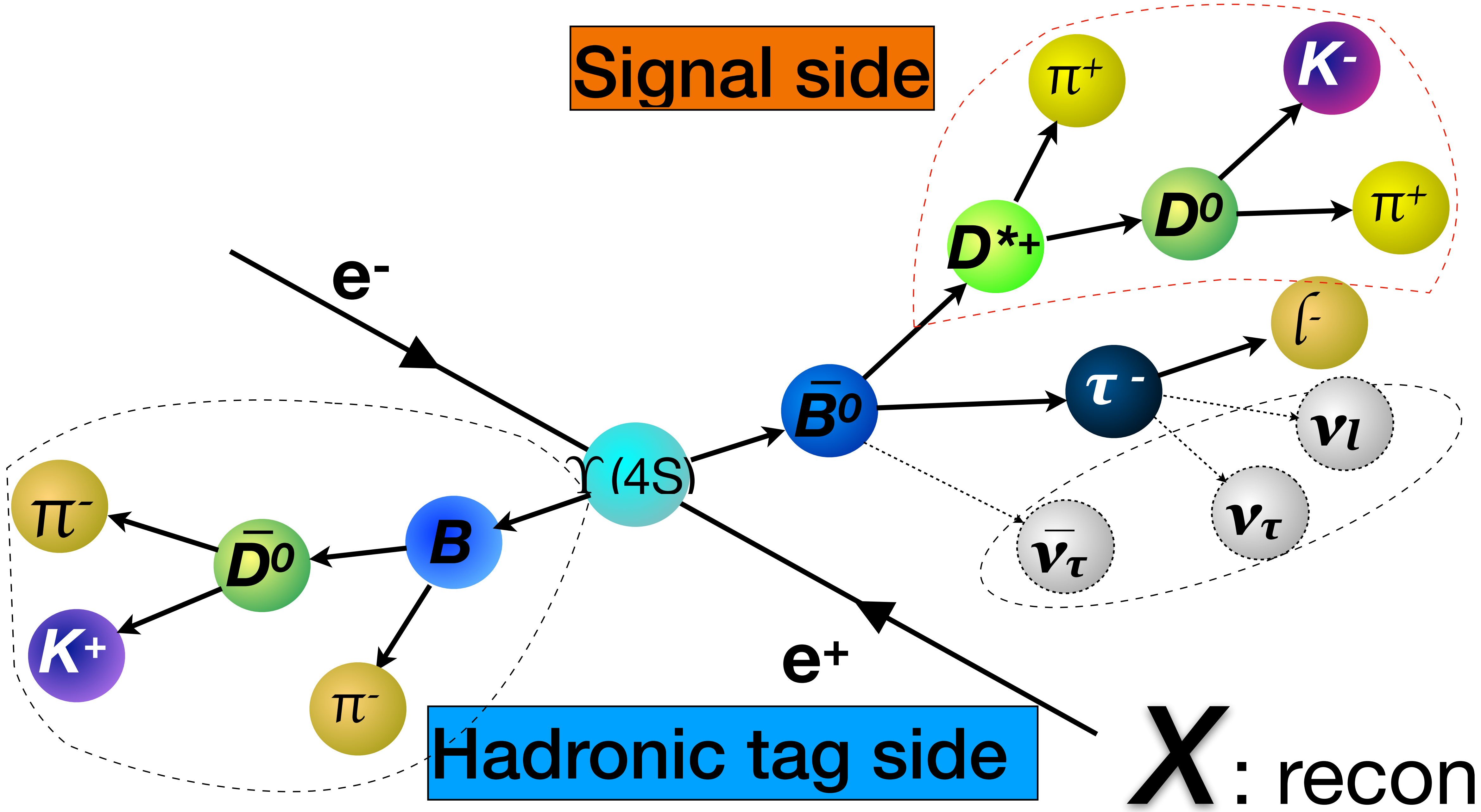


K_L/μ detector (KLM)
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator

- 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



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

- 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 $E_{\text{ECL}} = \sum_i E_i^{\gamma}$

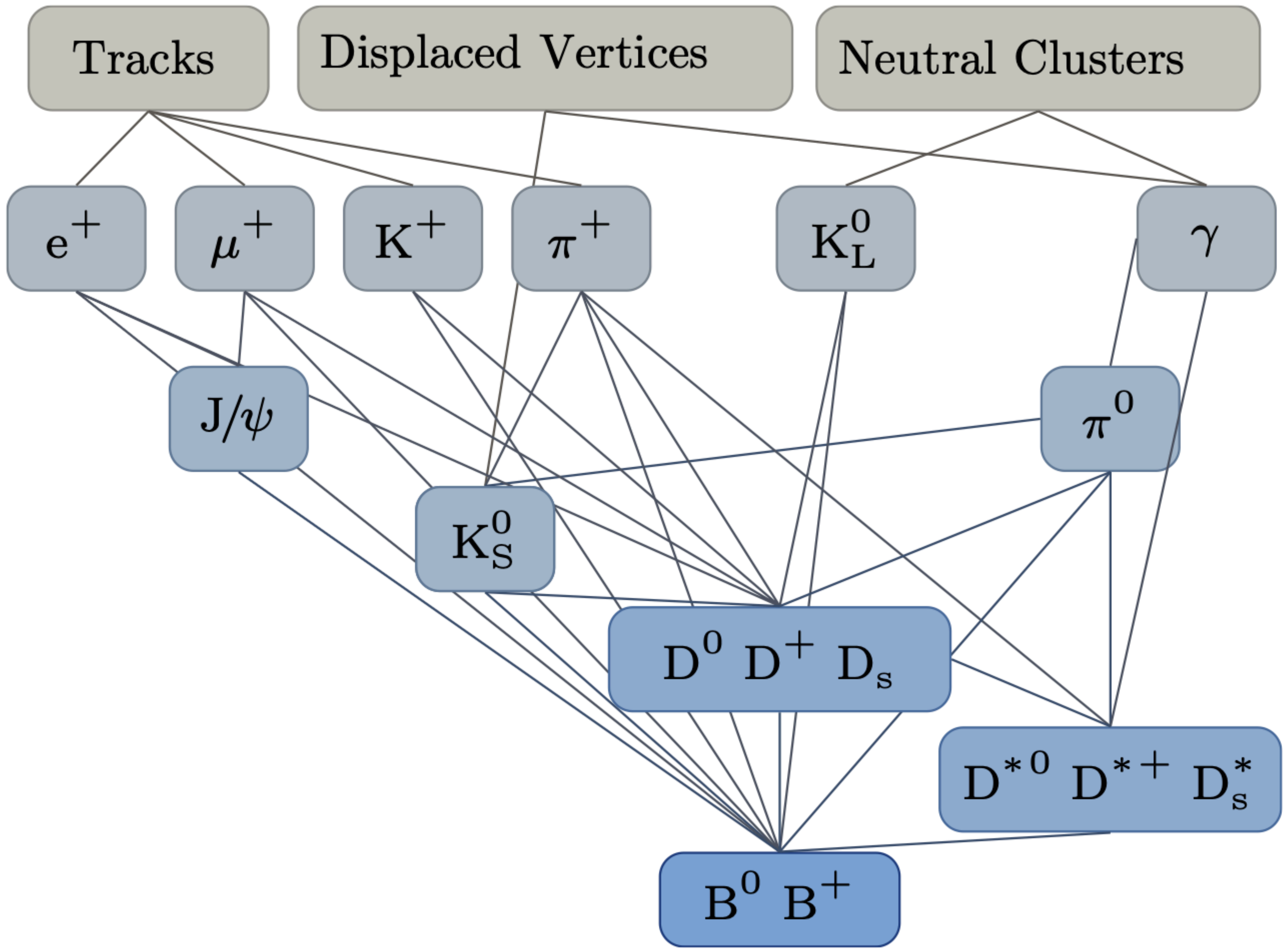
Hadronic tag reconstruction at Belle II

- Hadronic tagging reconstruction: Full Event Interpretation (FEI) trained 200 Boost Decision Tree (BDT) to reconstruct ~100 decay channels, ~10,000 *B* decay chains
  - ε=0.30% for $B^{\pm}$
  - ε=0.23% for B^0

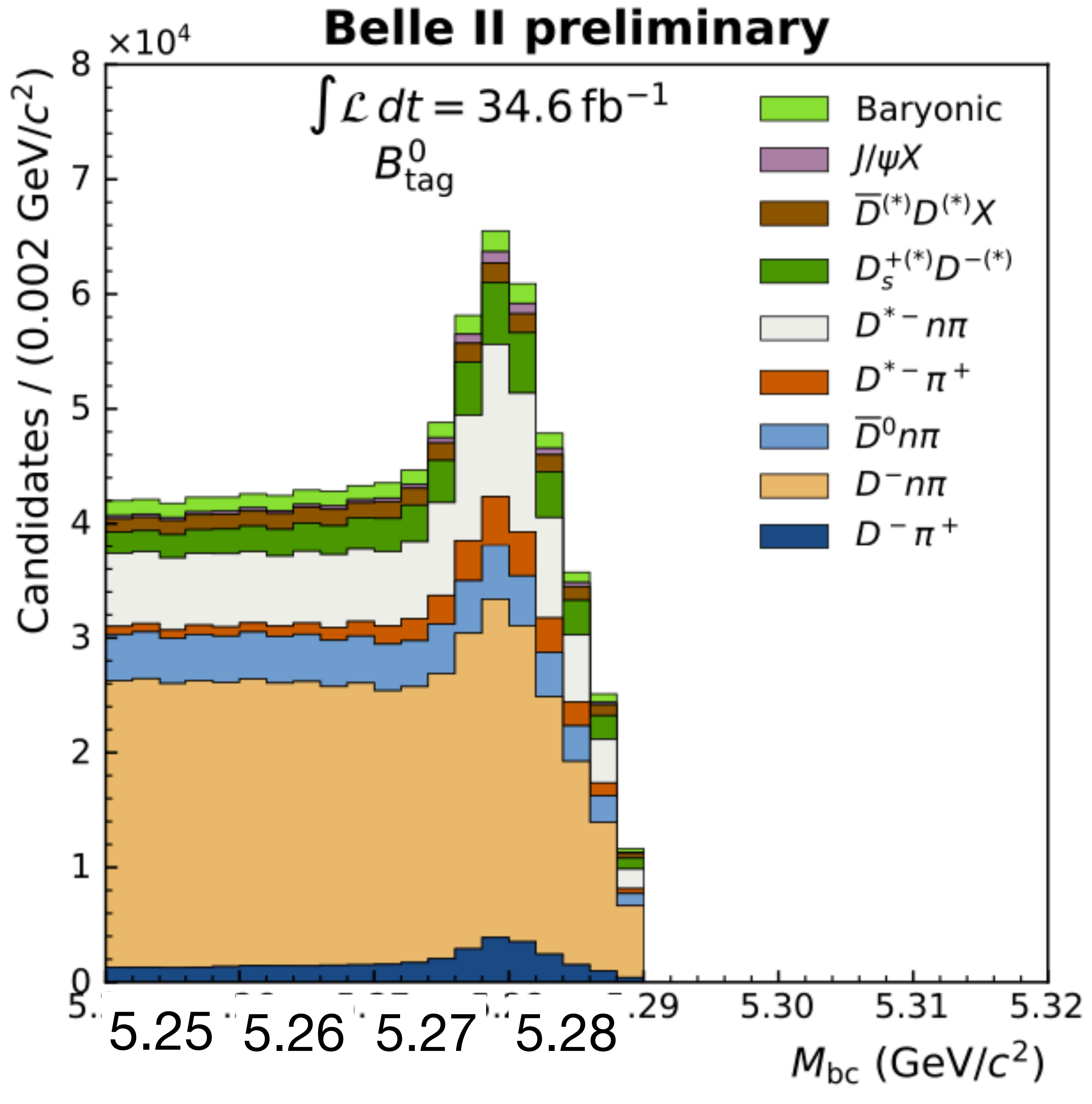
10-30% increased

  - ε=0.28% for $B^{\pm}$ @Belle
  - ε=0.18% for B^0 @Belle

Comp. and Soft. For Big Sci. 3, 6 (2019)



arXiv:2008.06096

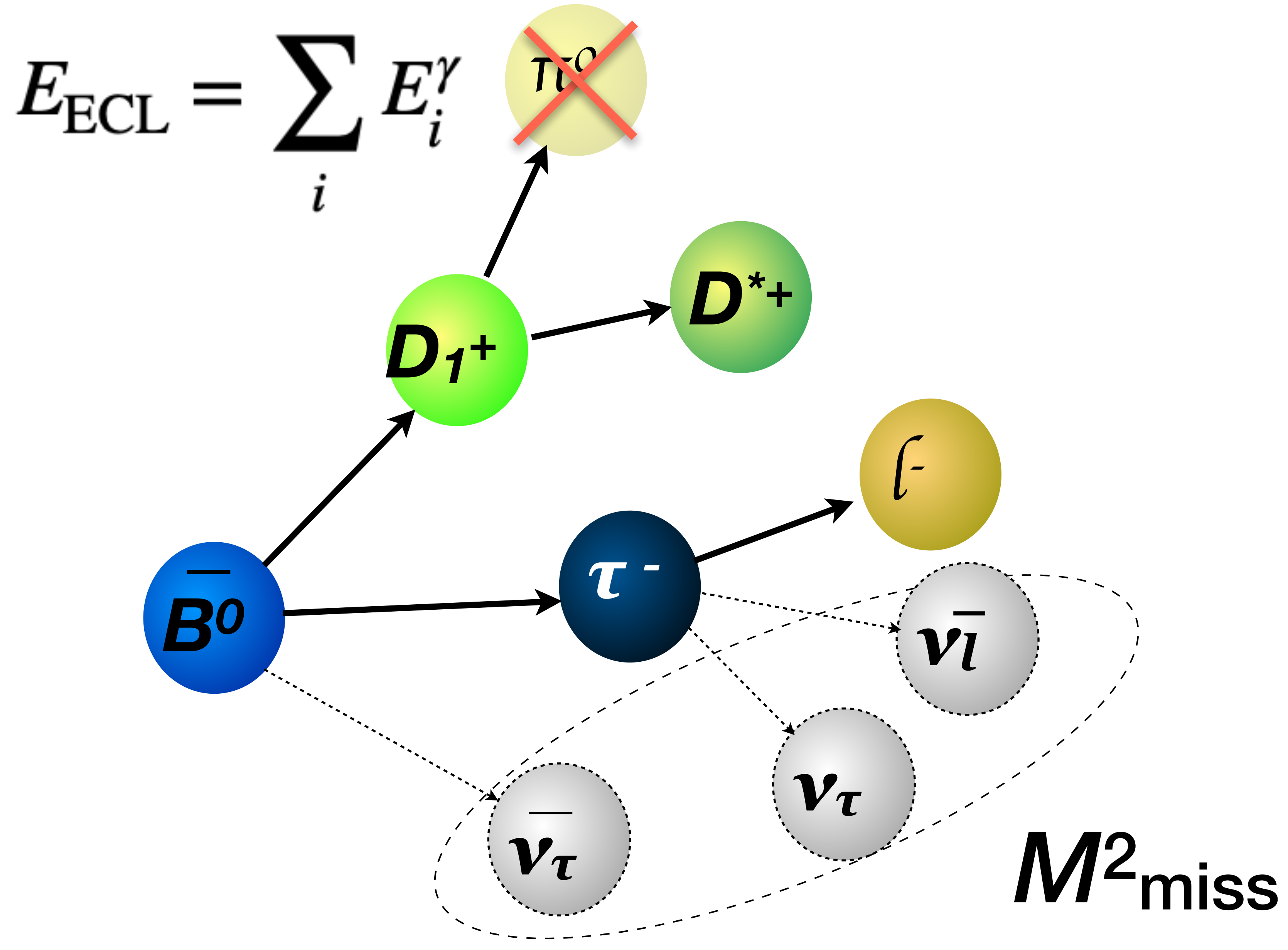


$$m_{\rm bc} = \sqrt{(E^*_{\rm beam})^2 - (p^*_B)^2}$$

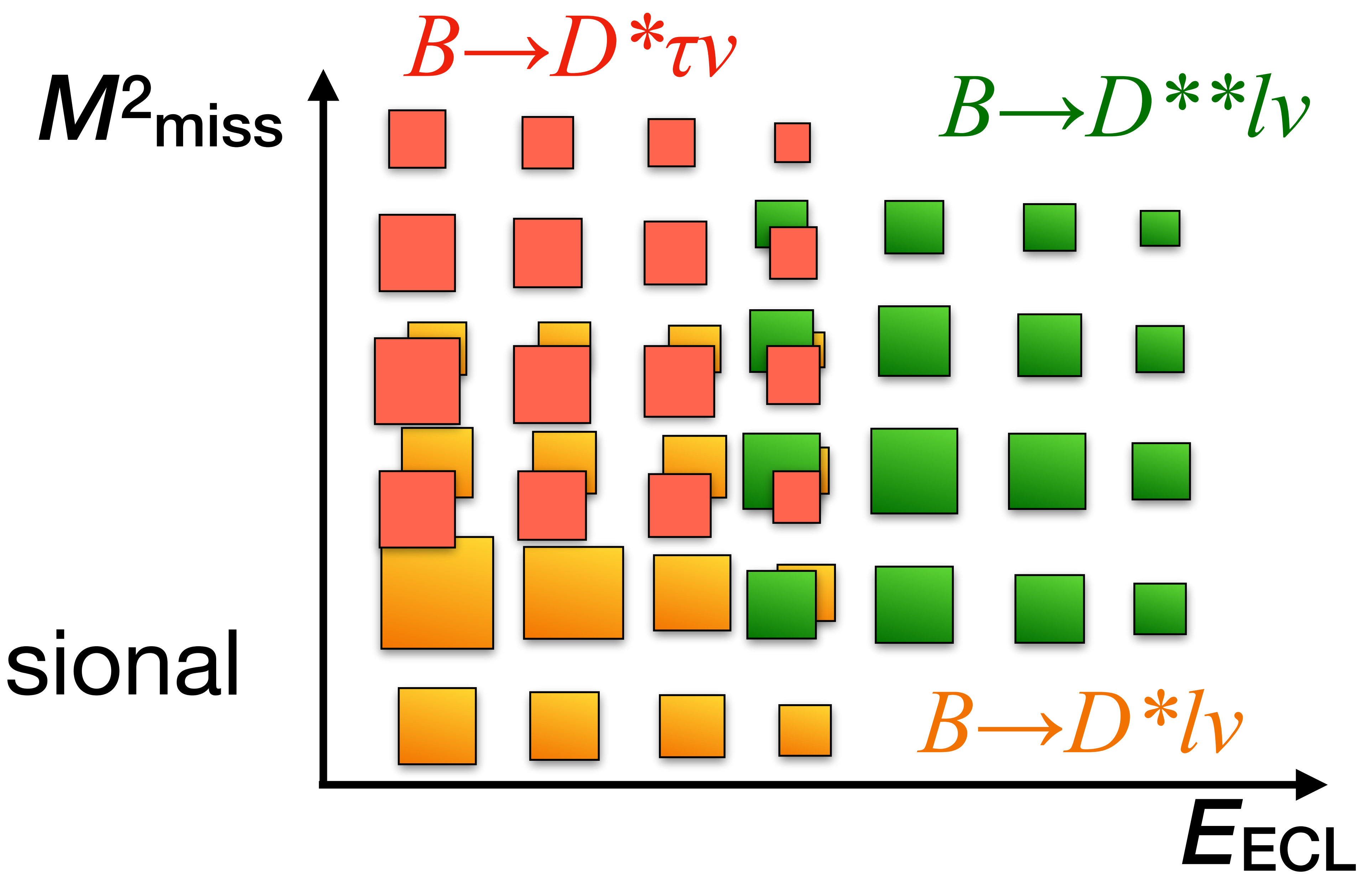
$R_{\tau/\ell}(D^*)$

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)



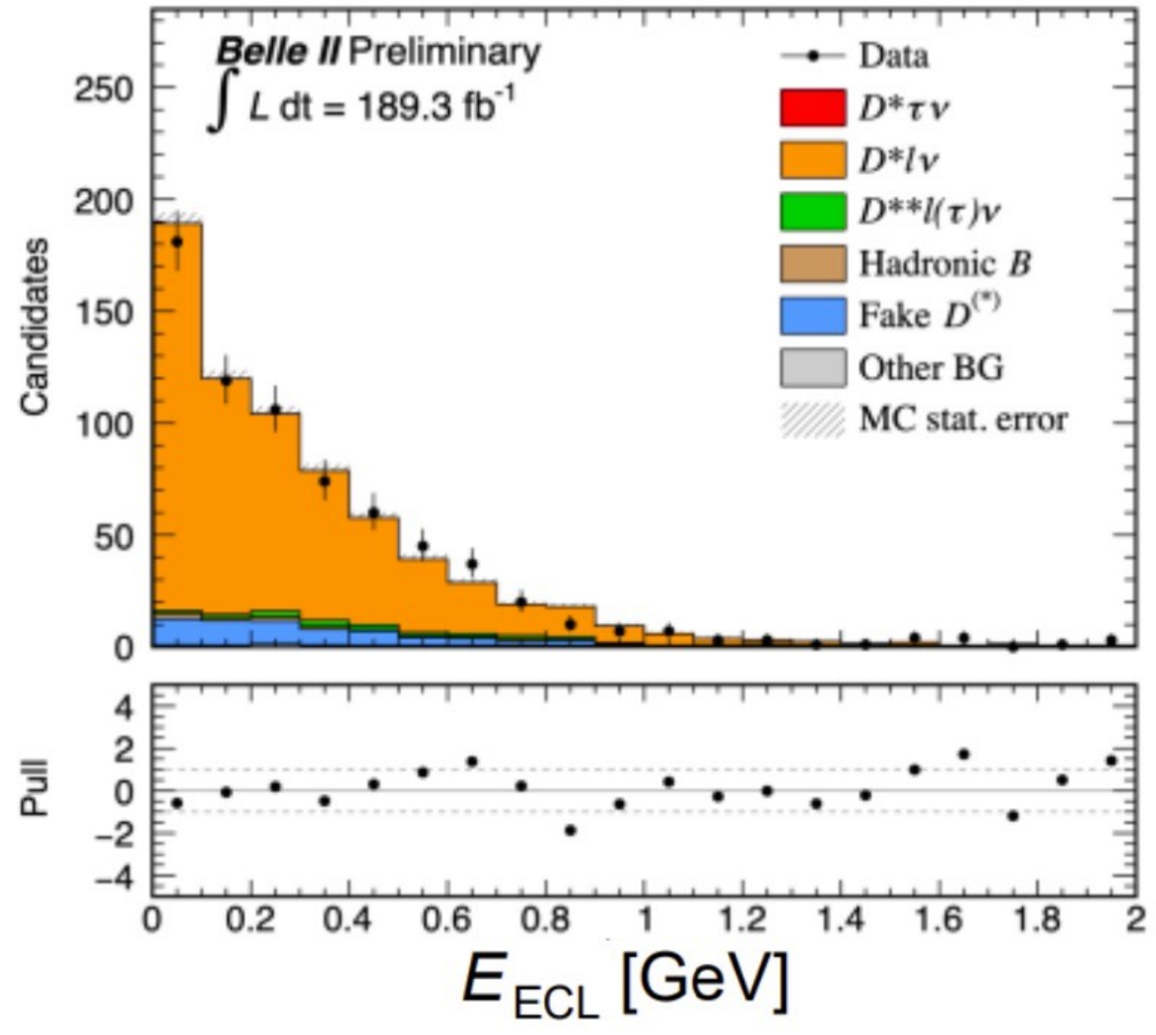
- $M^2_{\mathrm{miss}} = (p_{\mathrm{beam}} - p_{\mathrm{Btag}} - p_{D(*)} - p_{\ell})^2$
- E_{ECL}: **extra** neutral energy in the calorimeter **NOT** associate with signal



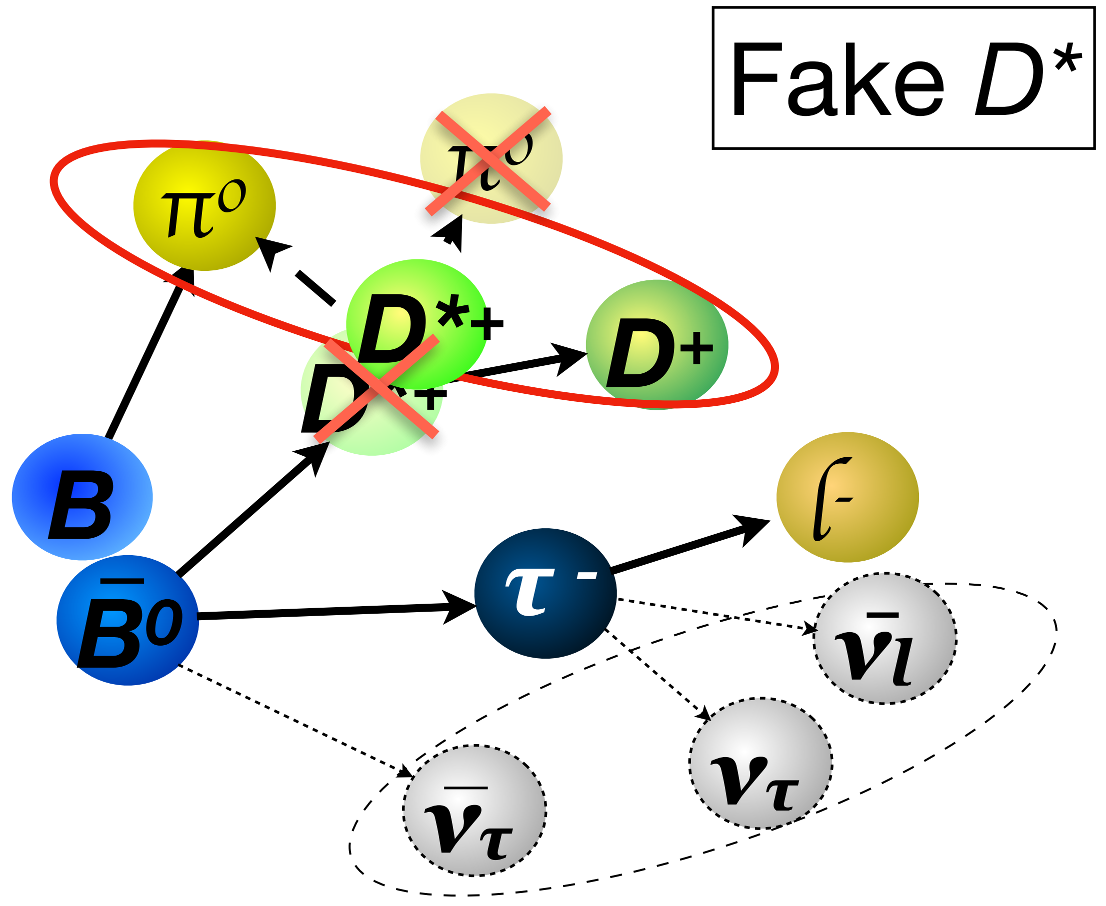
- Extracting $B \to D^* \tau \nu$, $B \to D^* l \nu$ yields by a two-dimensional simultaneously fit

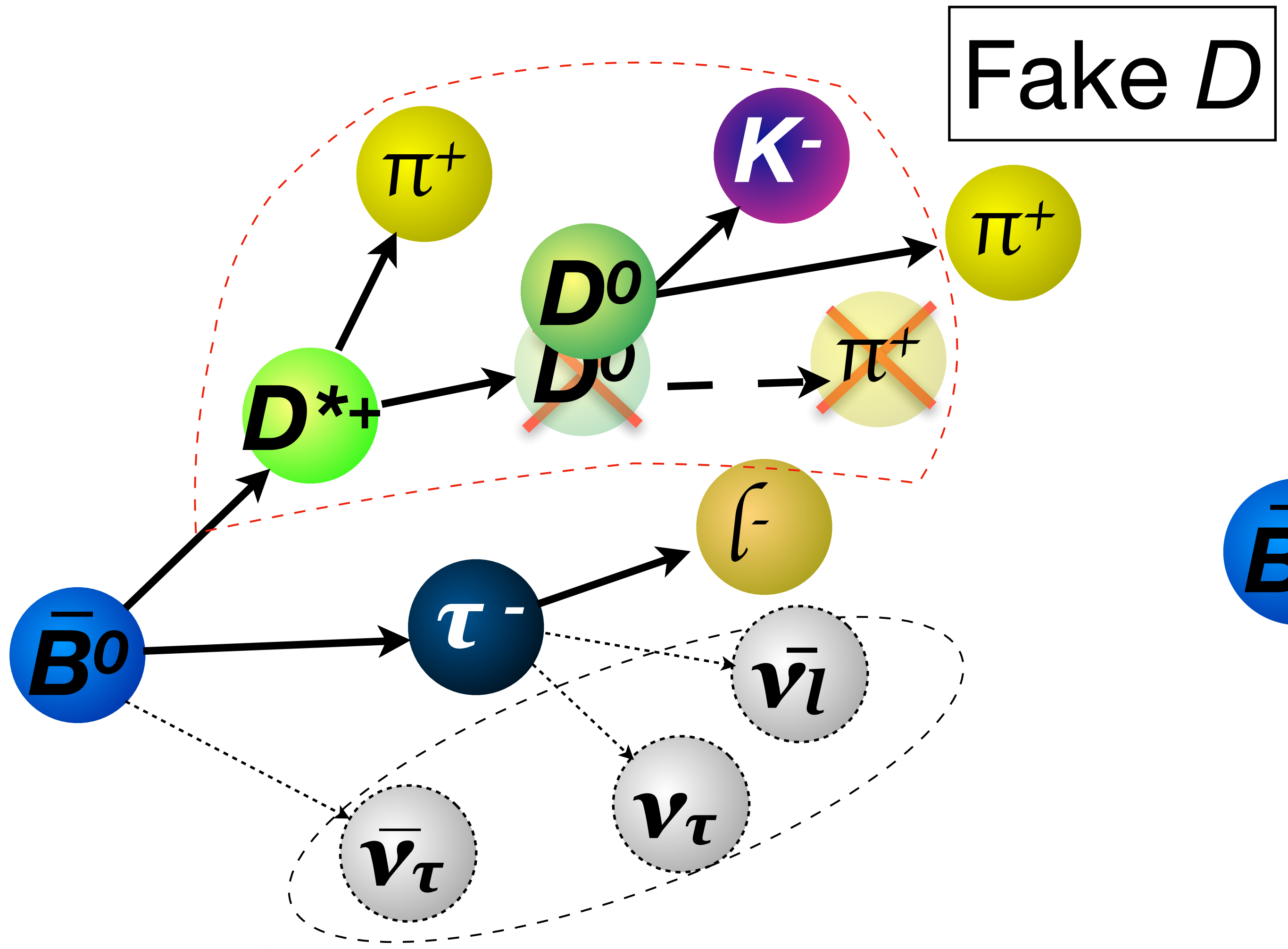
Dominant backgrounds and control samples

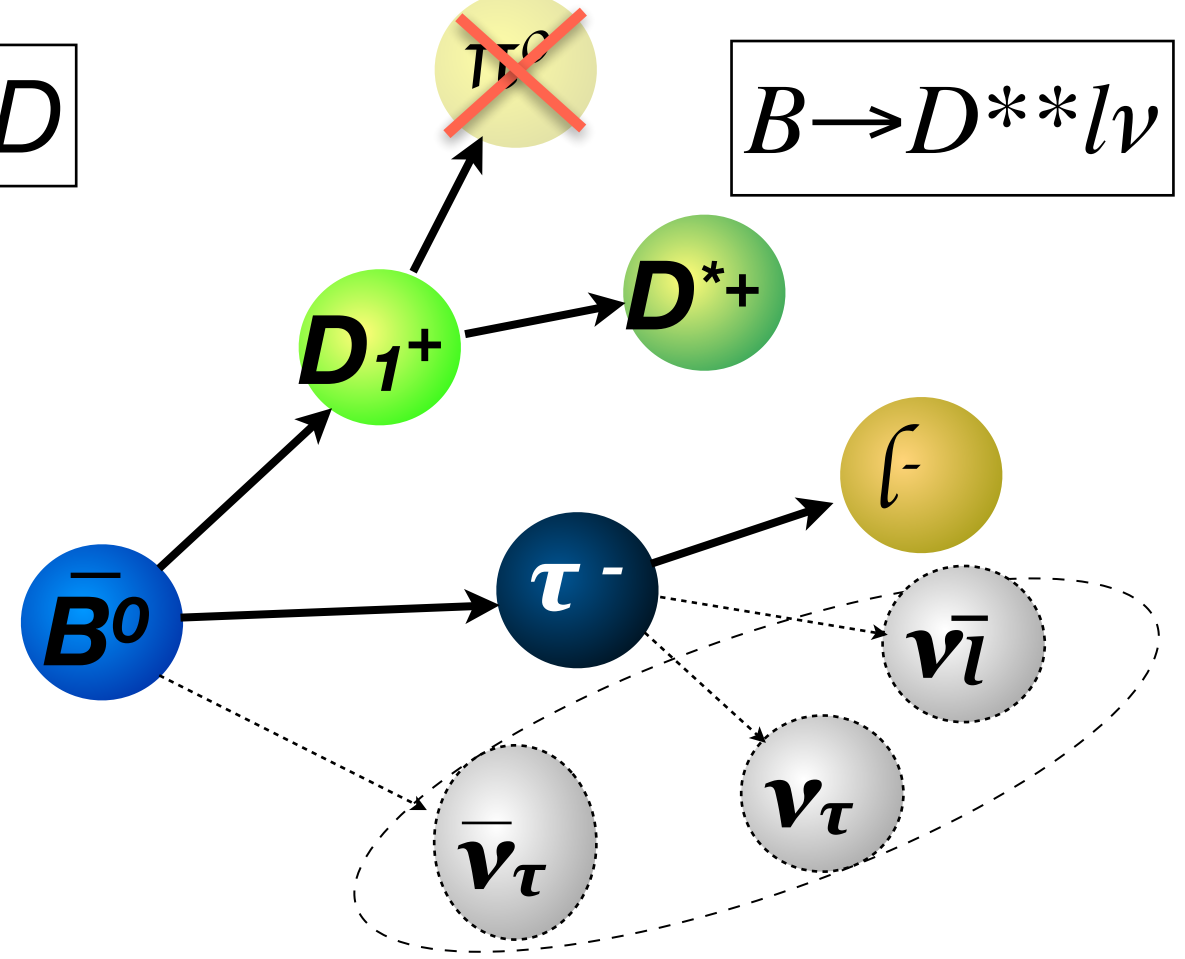
B condidates	$B \to D^* \tau \nu$	$B \to D^* l \nu$	Background truth $D^{(*)}$	Background Fake $D^{(*)}$
			$B \to D^{**} l \nu$, $B \to D^{(*)} X$, $B^0 <-> B^{\pm}$, …	
B^0	2.7%	65.5%	12.5%	19.2%
$B^{\pm}$	1.7%	34.7%	5.9%	57.8%

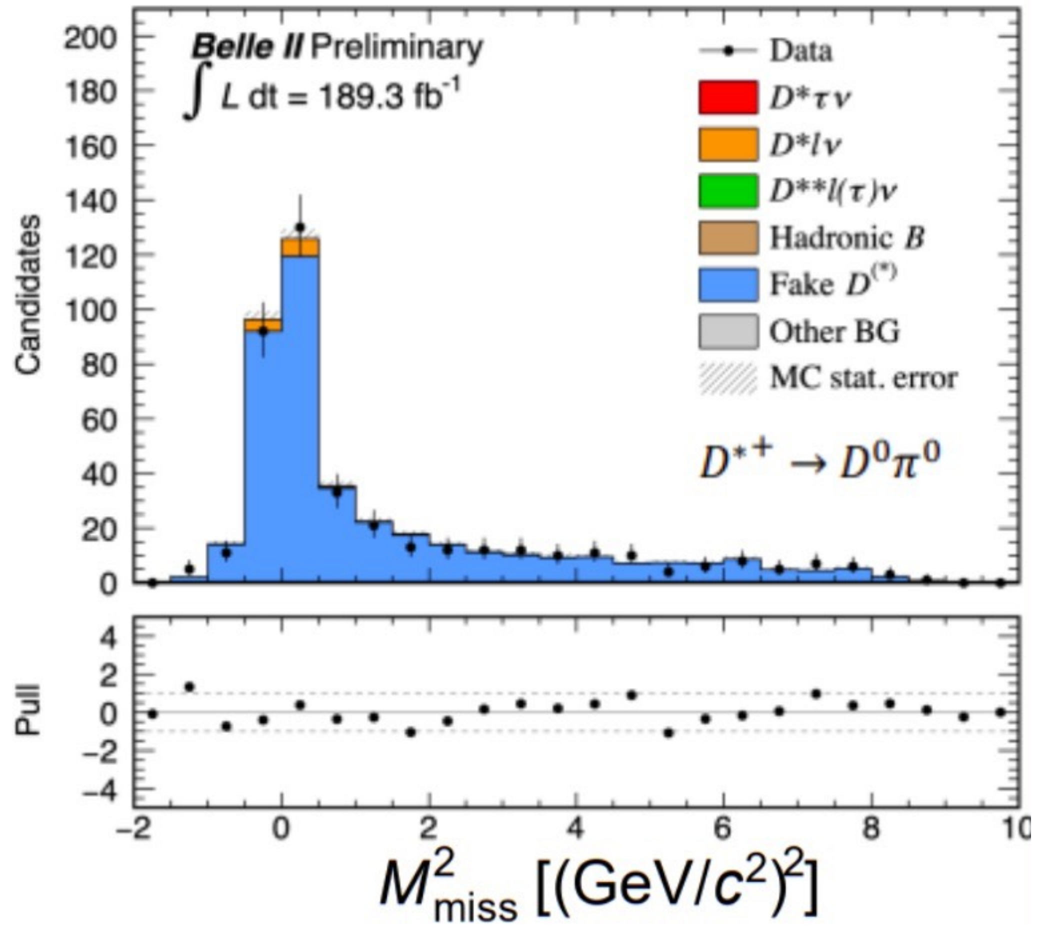


$q^2 < 3.5$ GeV sideband: validate E_{ECL} modeling



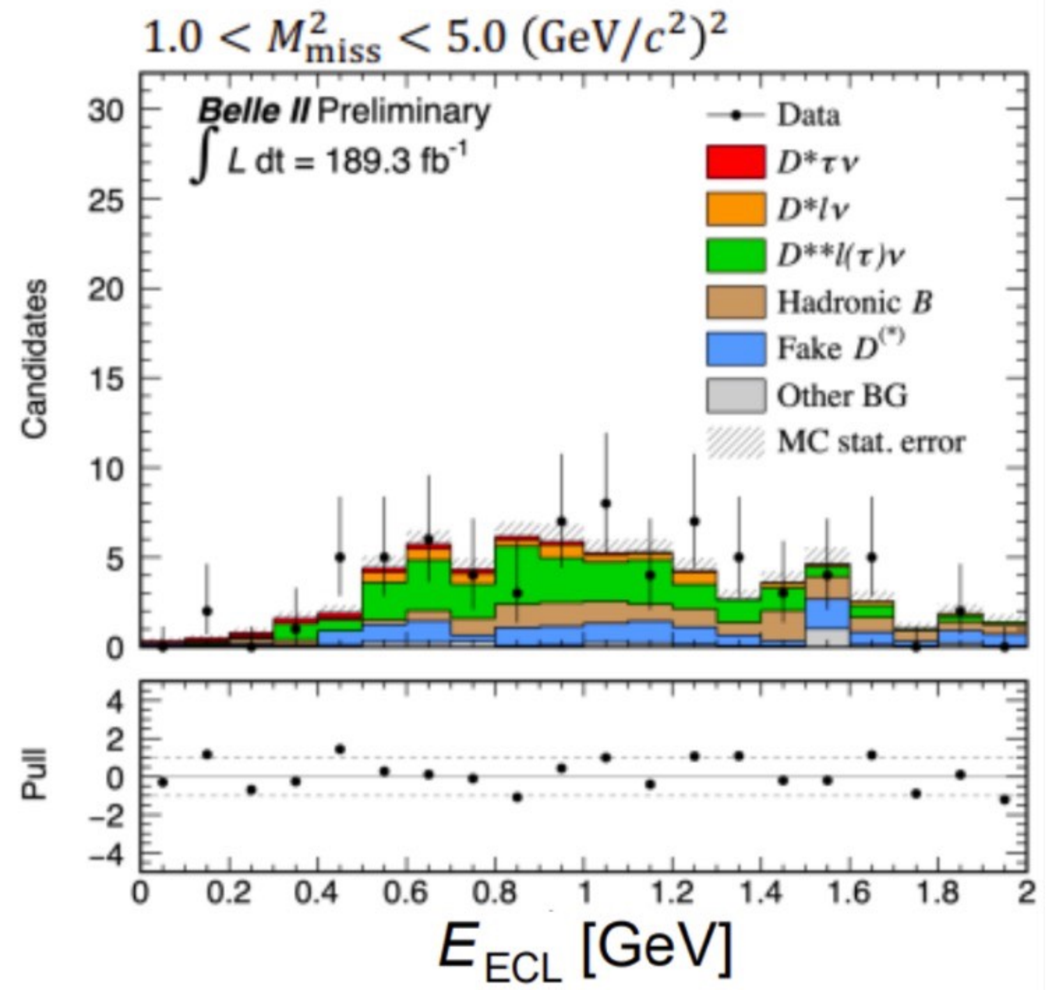






$m(D\pi)$ - $m(D^*)$ sideband: validate fake D^* modeling

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



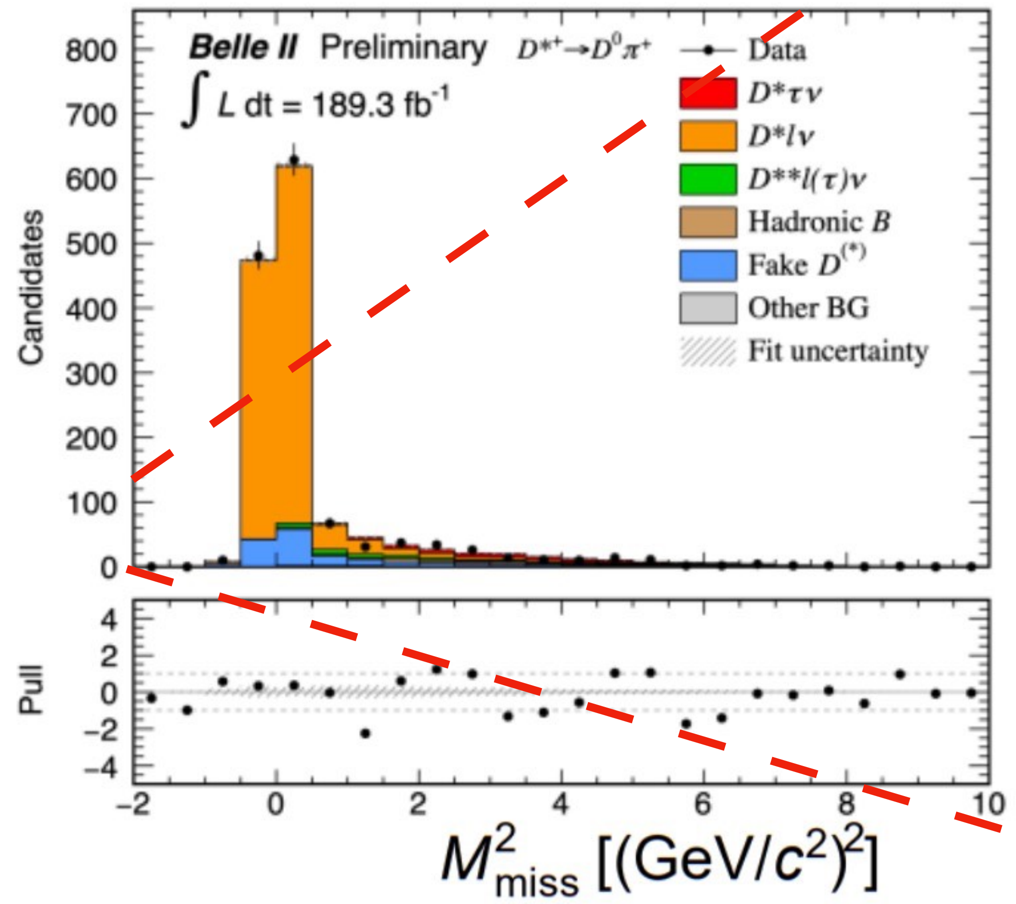
$R_{\tau/\ell}(D^*)$ results

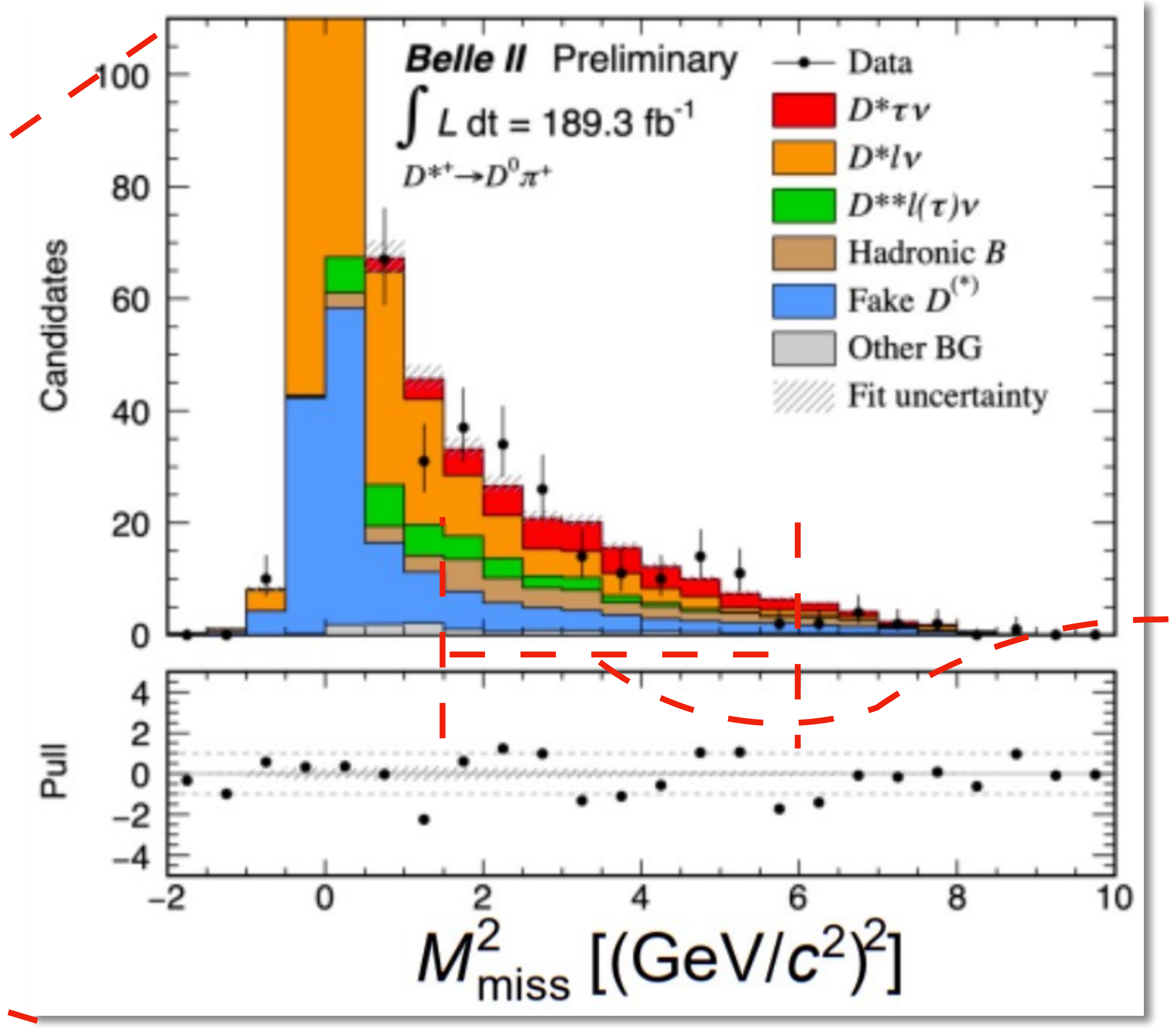
- Similarly sensitivity as Belle 15' result @ 711 fb^{-1} with only 189 fb^{-1}
- Belle II first preliminary result for $R(D^*)$

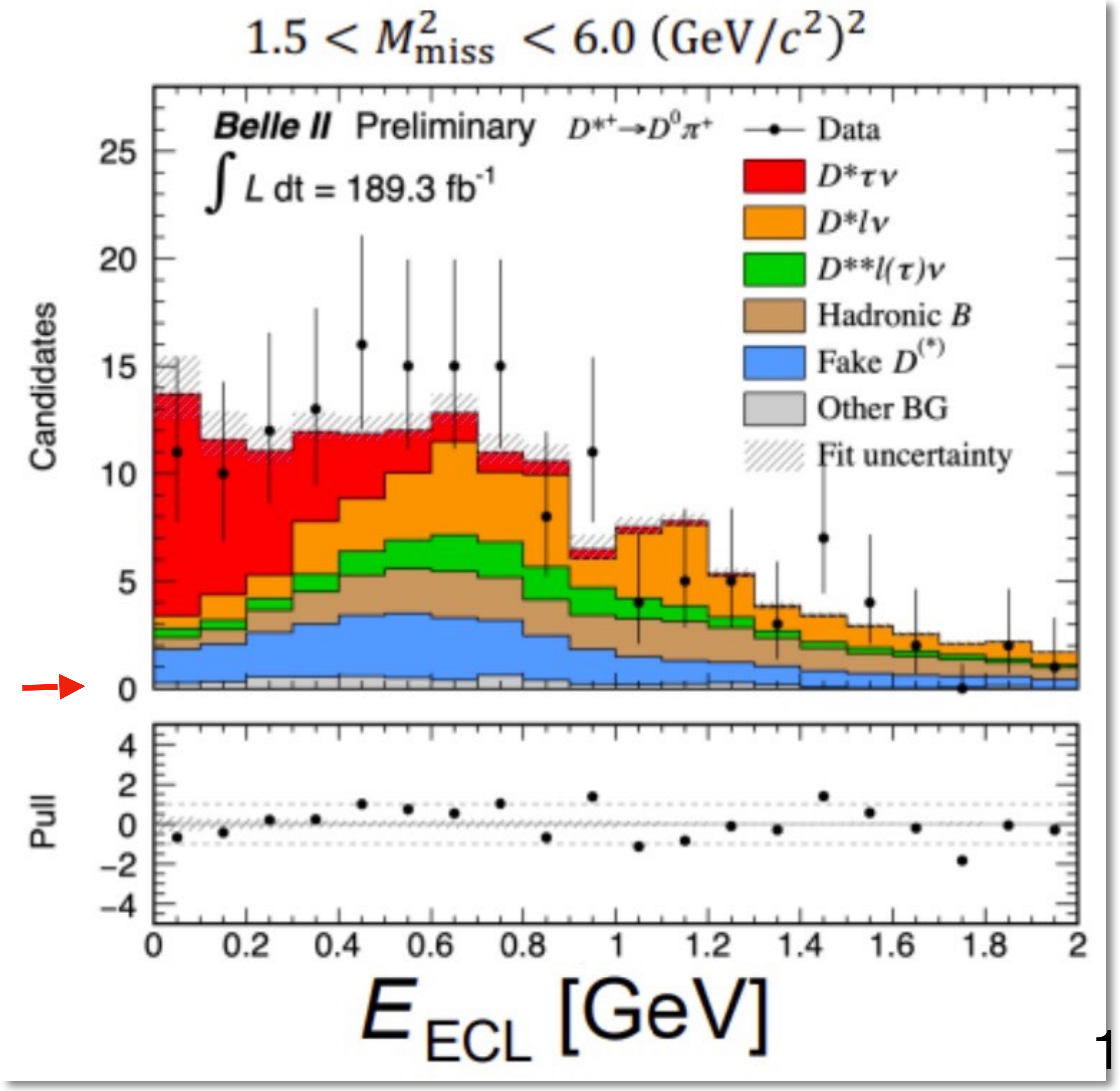
$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat})\ ^{+0.028}_{-0.033}(\text{sys})$$

- 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%





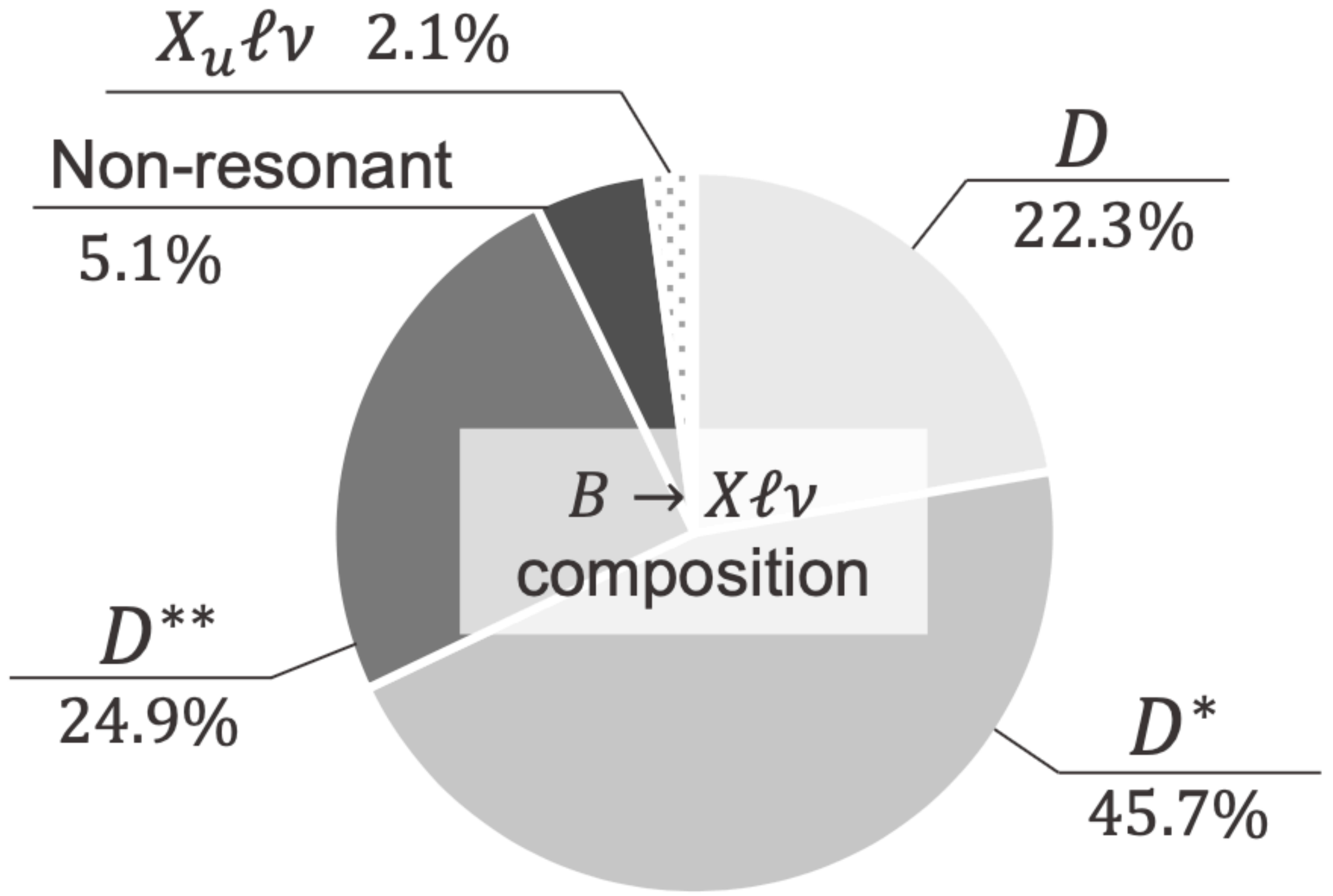


$$R_{\tau/\zeta}(X)$$

LFU test by $R_{\tau/\ell}(X)$ measurement

- Breakdown of $B \to Xl\nu$ branching fractions
  - ~ 2/3 overlap with D and D^*
    - ~ 3/4 D decay to ν, K_L^0, $n\pi$ …
  - ~ 1/3 contribution from D^{**} and nonresonant X_c
- Multiple LEP experiments measured Br($B \to X\tau\nu$)
  - Br($B \to X\tau\nu$) are completely saturated by D/D^* BFs

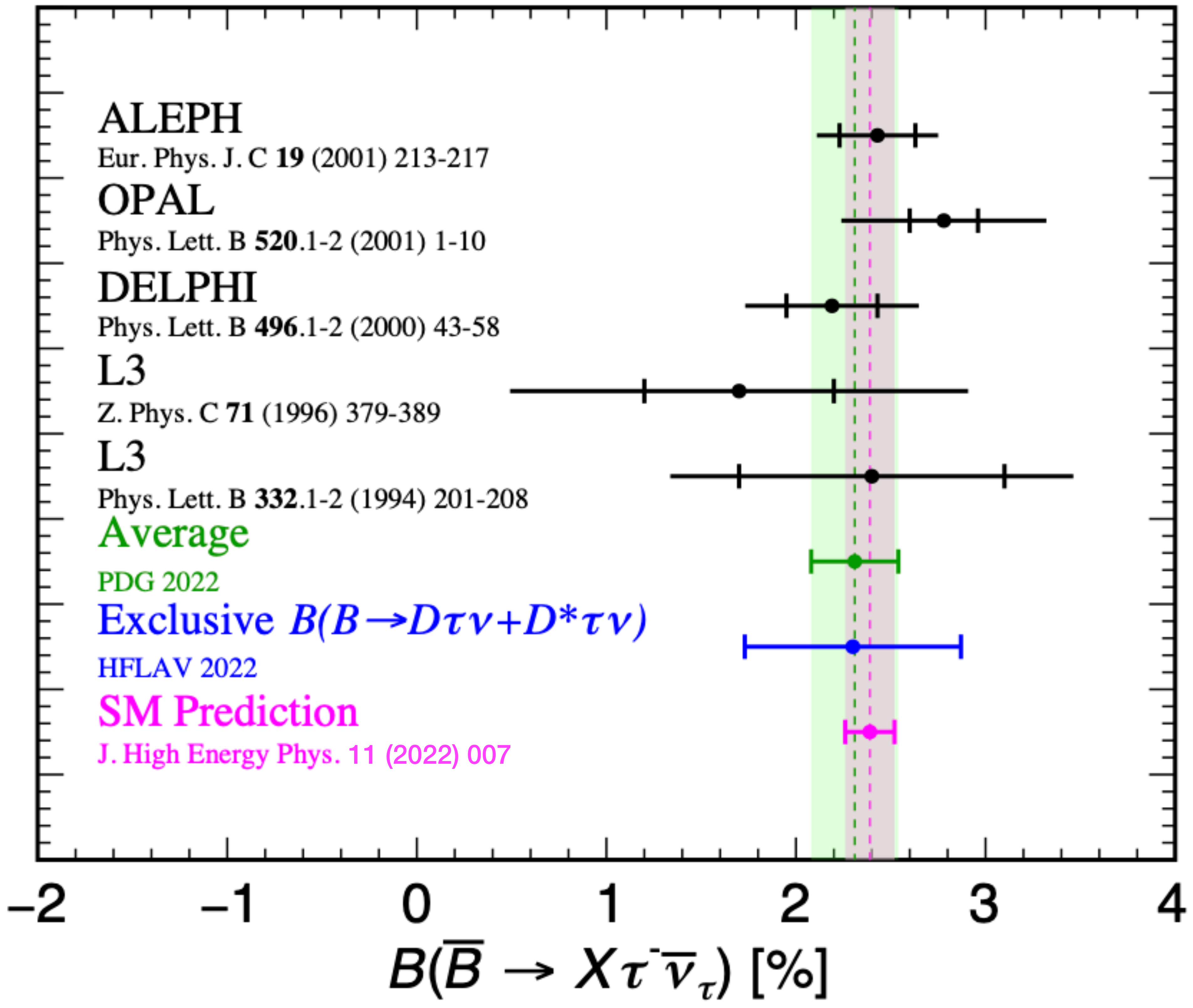
  ➡ An update measurement is needed



- $R(X)$ is critical cross-check of $R(D^{(*)})$, largest contribution from $R(D^{(*)})$, a partially complementary test of LFU

$$R(X_{\tau/\ell}) = \frac{Br(\bar{B} \to X\tau^- \bar{\nu}_\tau)}{Br(\bar{B} \to X\ell^- \bar{\nu}_\ell)}$$

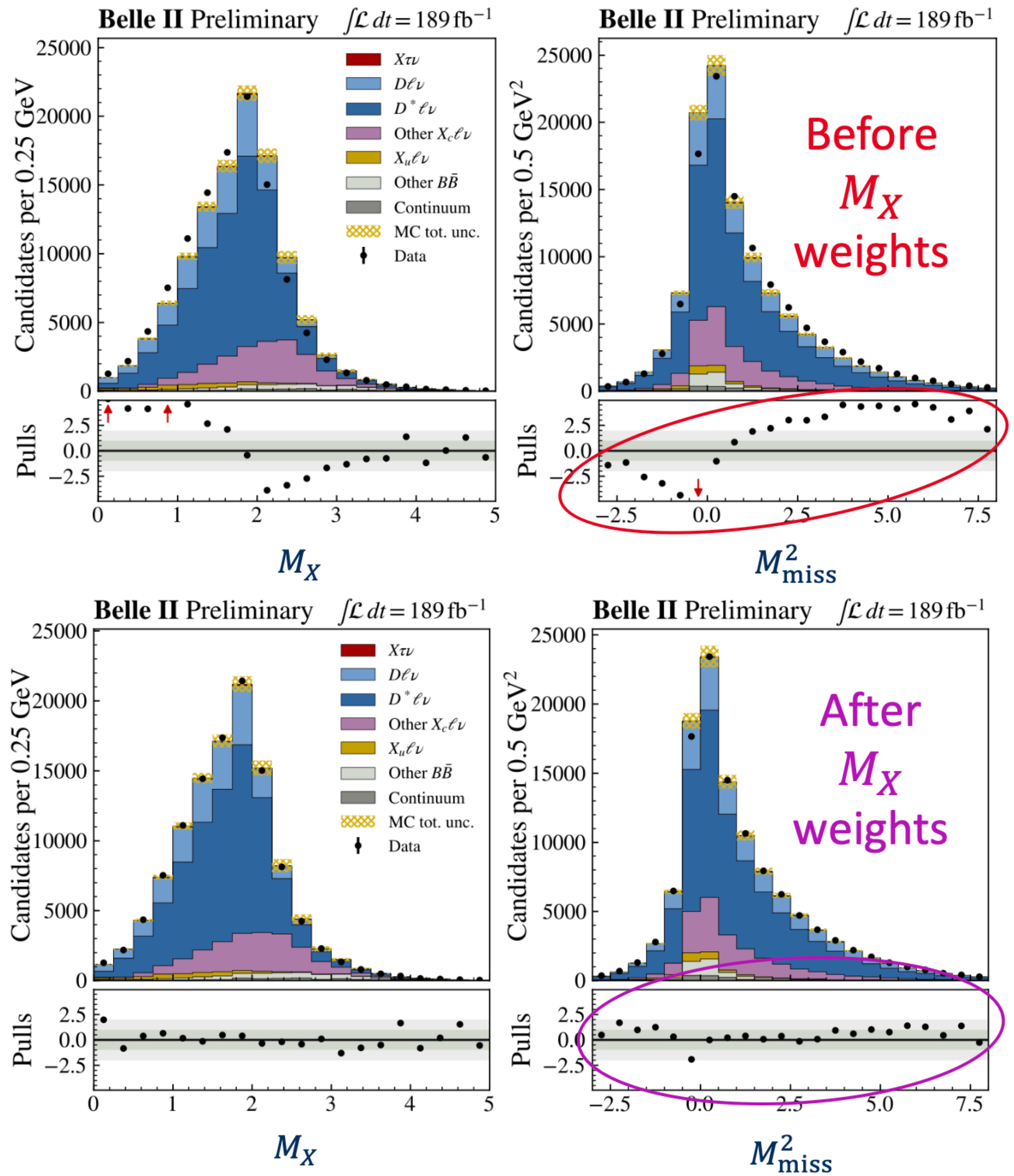
- $R(X)$ has never been measured



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

arXiv:2311.07248

- 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

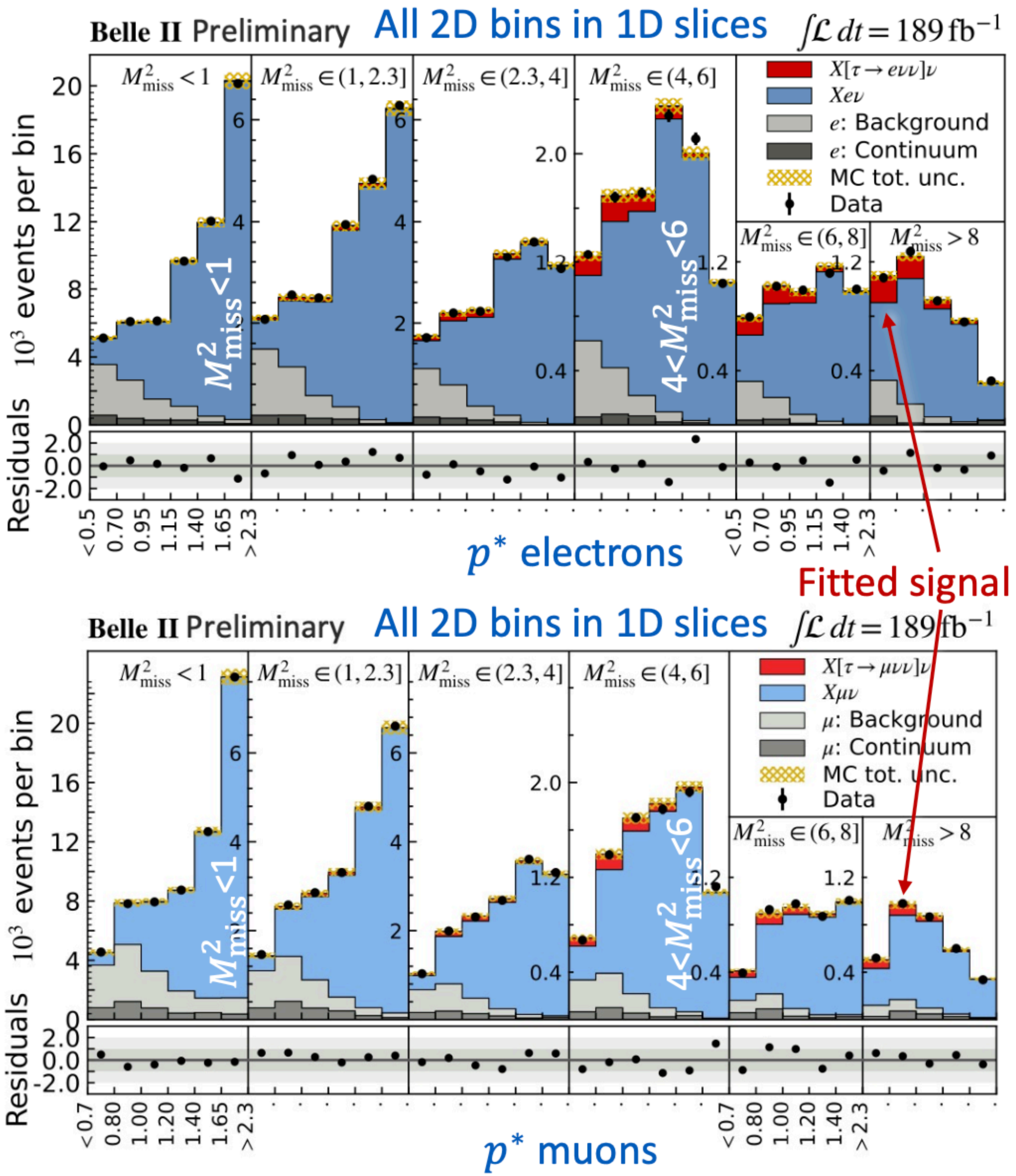
  $R_{\tau/\ell}(X) = 0.228 \pm 0.016\ (\text{stat}) \pm 0.036\ (\text{syst})$

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

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

- Consistent with rough SM expectation

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



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

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

  $R(X_{e/\mu})_{SM} = 1.006 \pm 0.001$ JHEP 11 (2022) 007

- Compatible with exclusive Belle (711 fb^{-1}) measurements

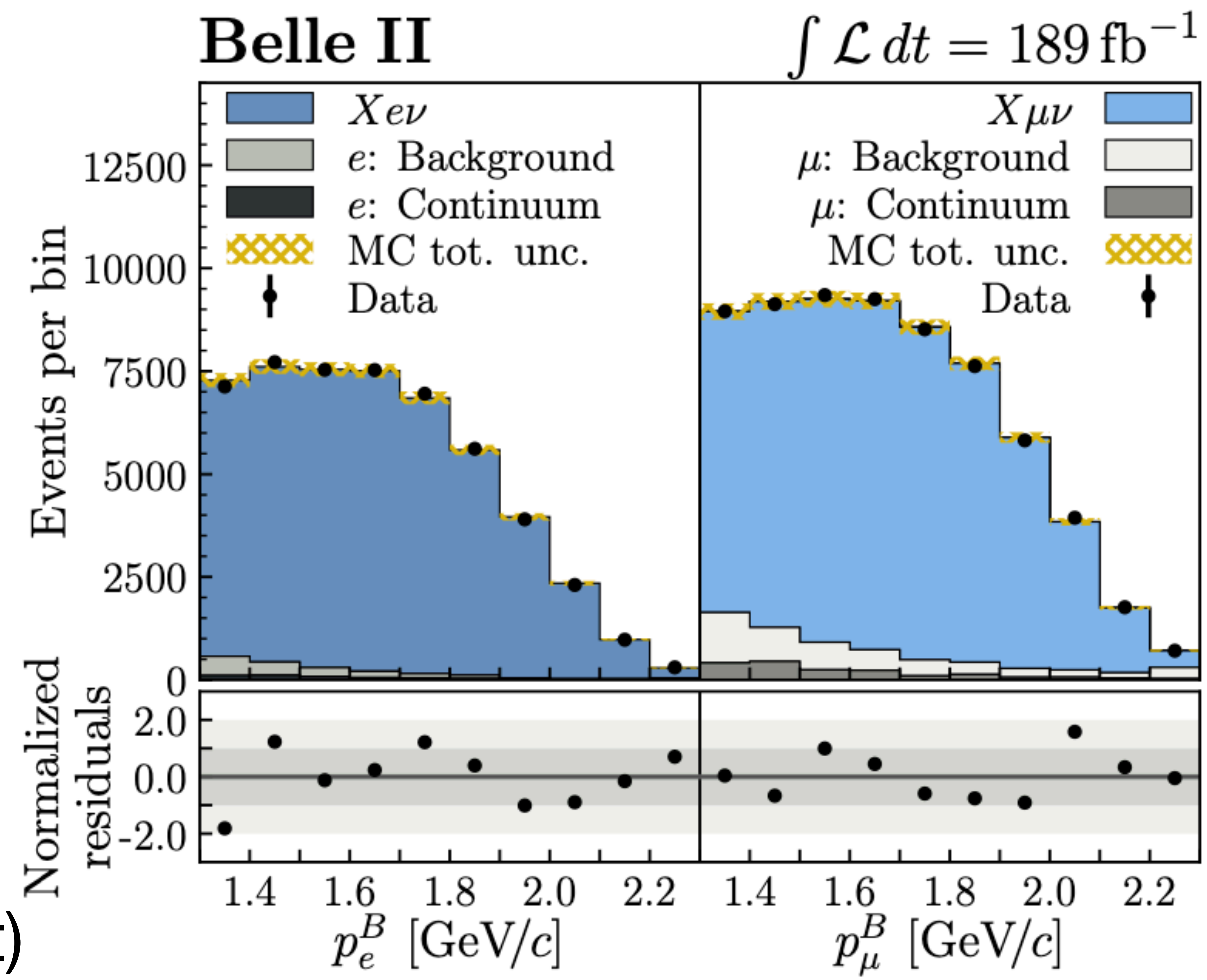
  PRD 100, 052007 (2019)

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

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

  PRD 108, 012002

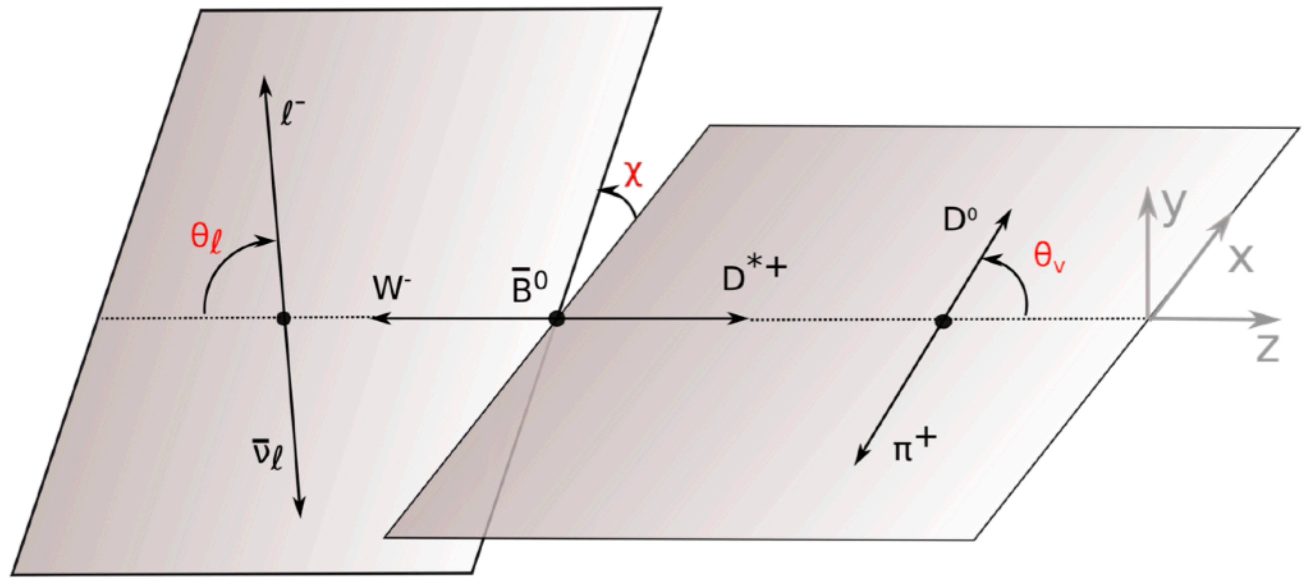
Signal channel ($B^0\bar{B}^0/B^+B^-$)



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

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

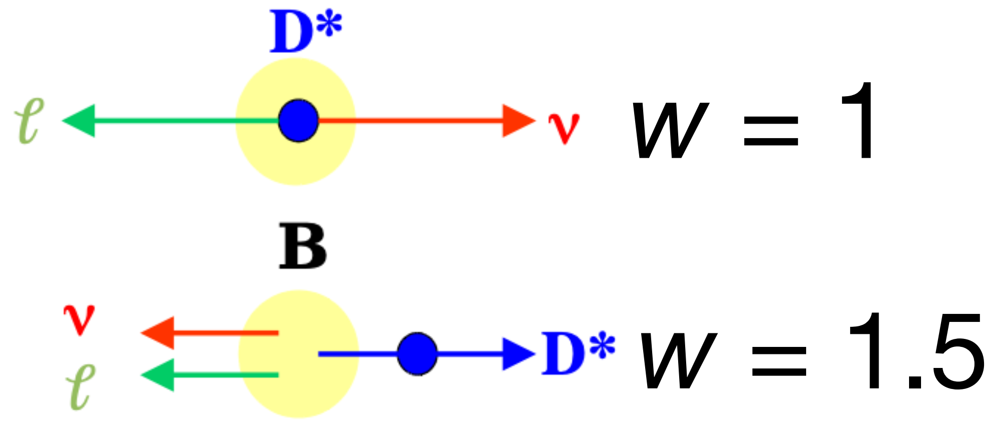


$$\mathcal{A}_x(w) \equiv \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}w}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right]\mathrm{d}x\,\frac{\mathrm{d}^2\Gamma}{\mathrm{d}w\,\mathrm{d}x} \qquad \mathcal{A}_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}$$

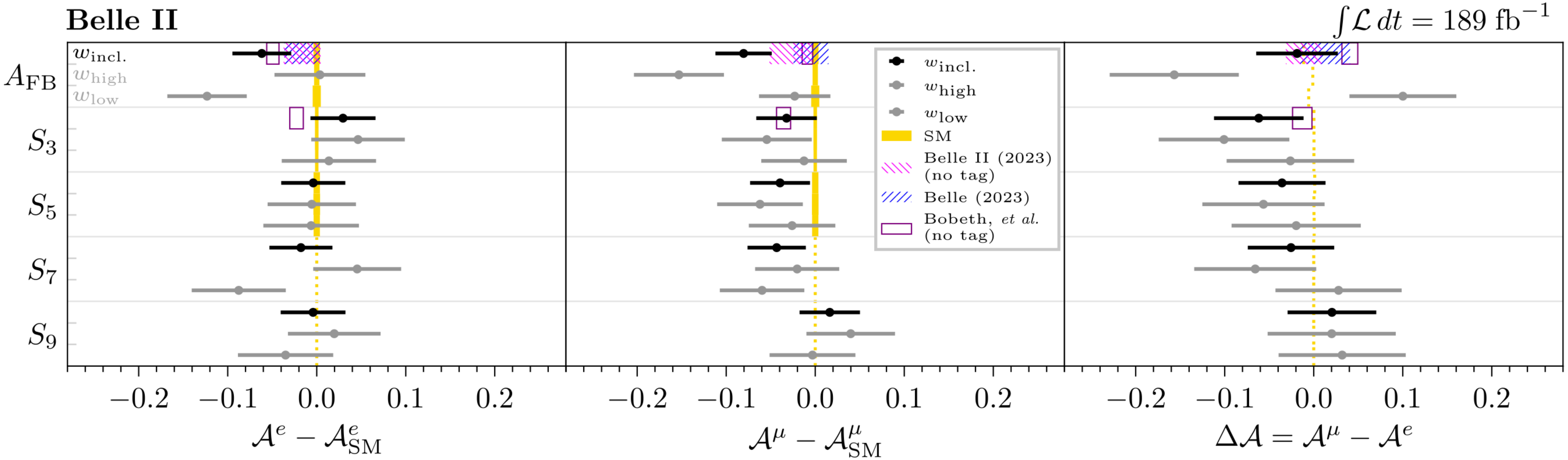
$$w \equiv \frac{m_{B^0}^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$$

- The differences are expected to be small in SM

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

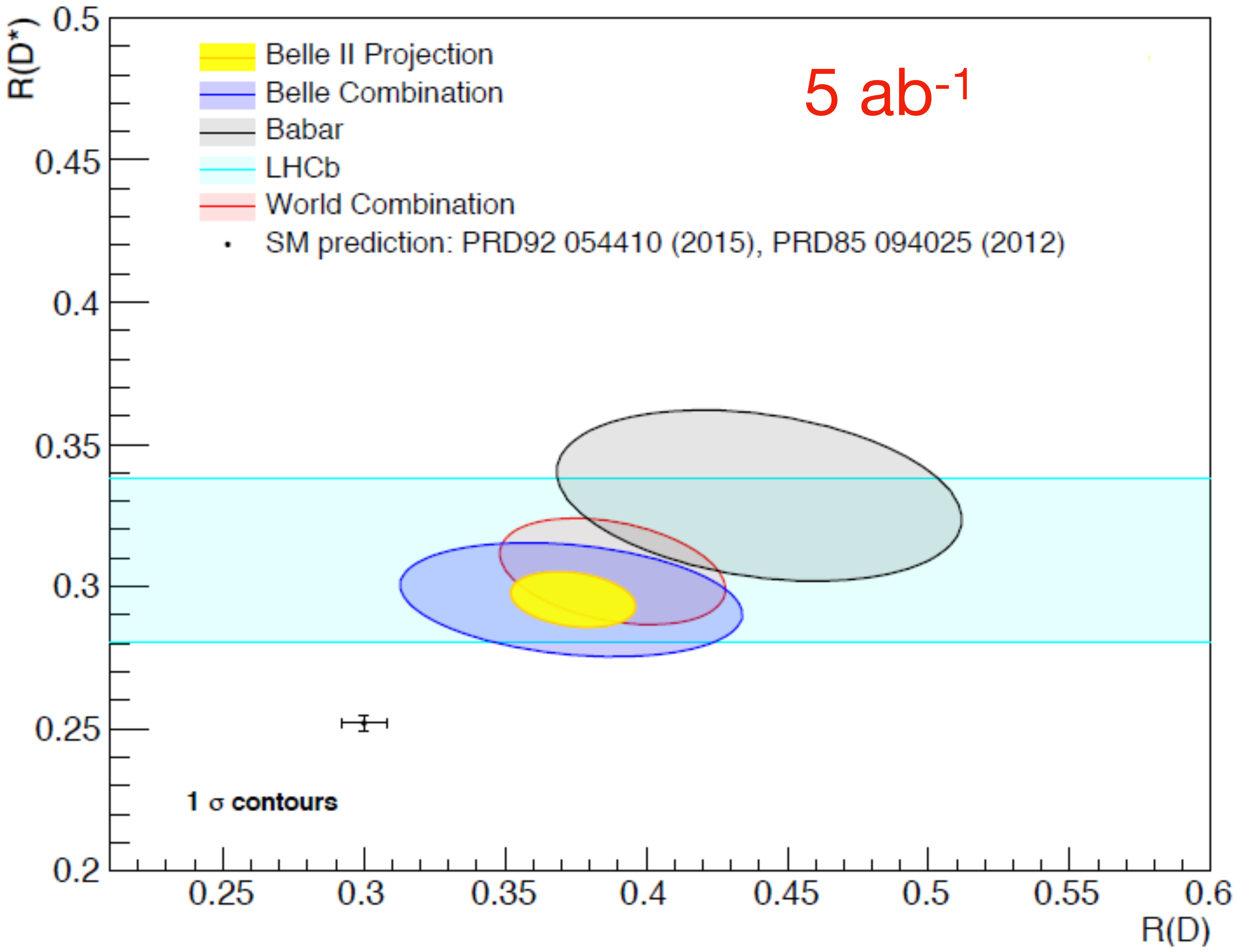


- All asymmetry consistent with SM, the measurements are statistics limited

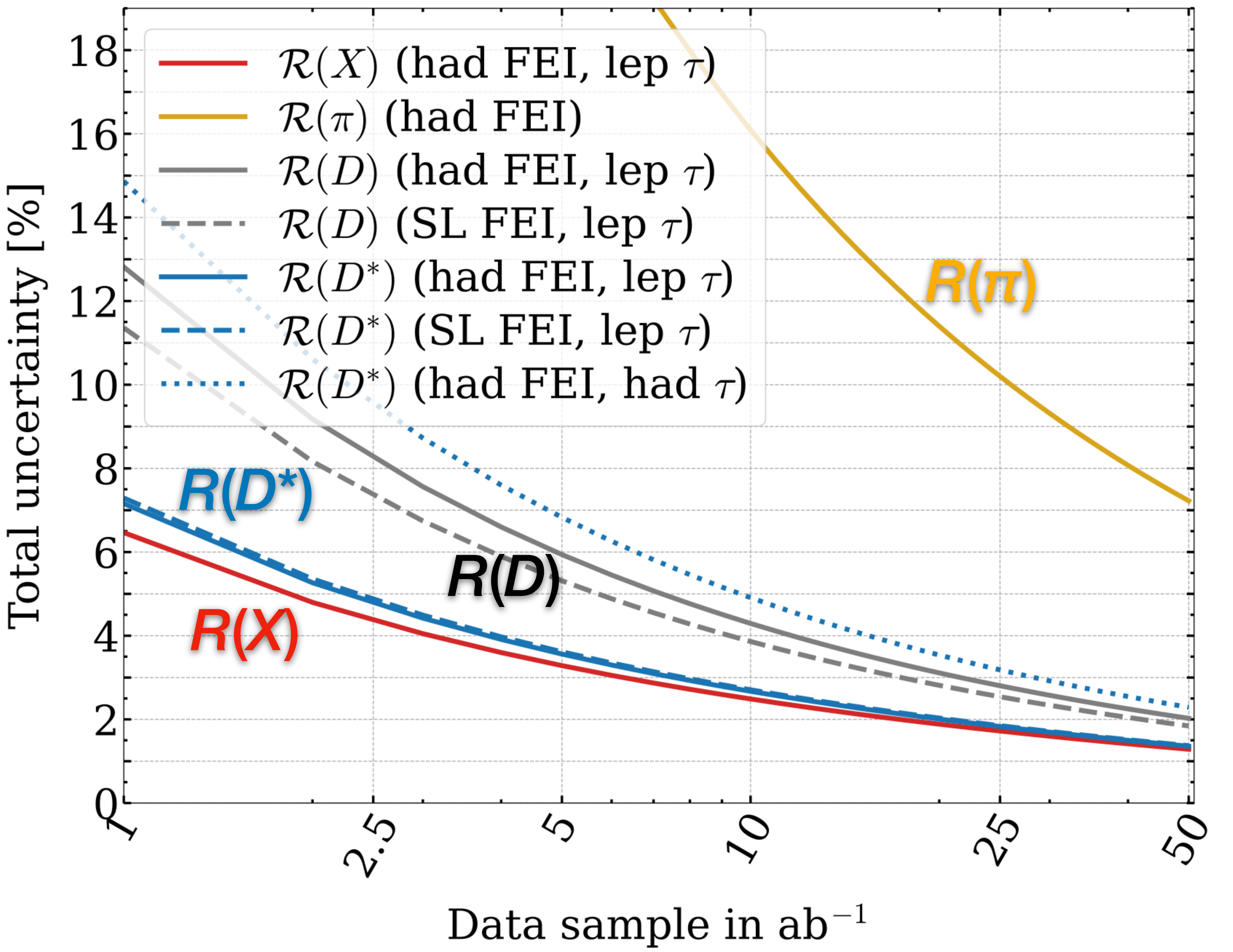


Expected sensitivity of LFU test at Belle II

The Belle II Physics Book, PTEP 2019, 123C01



arXiv:2207.06307



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

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

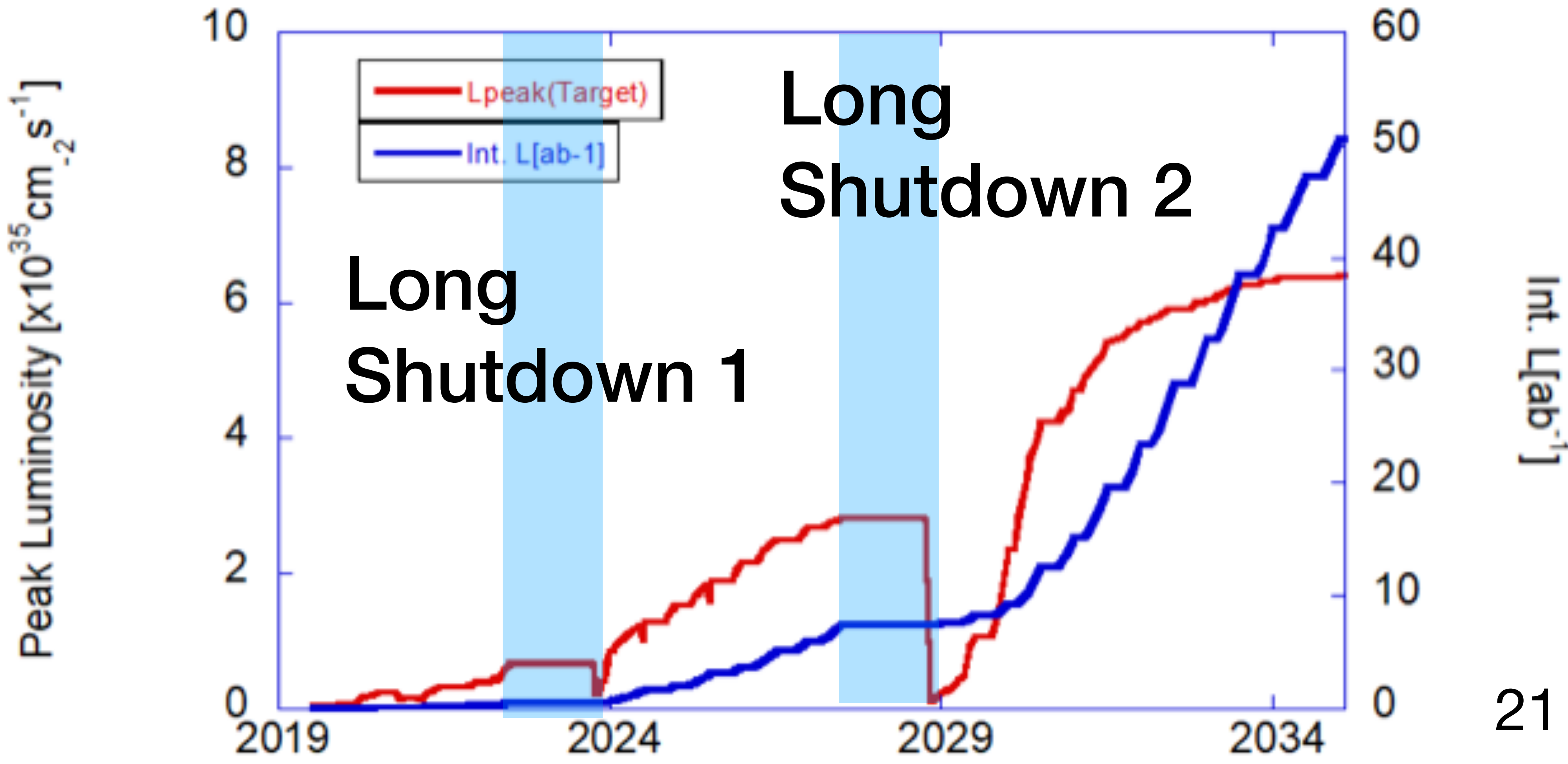
$$R_{\tau/\ell}(X) = 0.228 \pm 0.016\ \text{(stat)} \pm 0.036\ \text{(syst)}$$

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

and Belle 711 fb^{-1} data

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

- Angular asymmetry differences ΔAx also measured, statistics limited
- SuperKEKB/Belle II will resume operation at the beginning of 2024

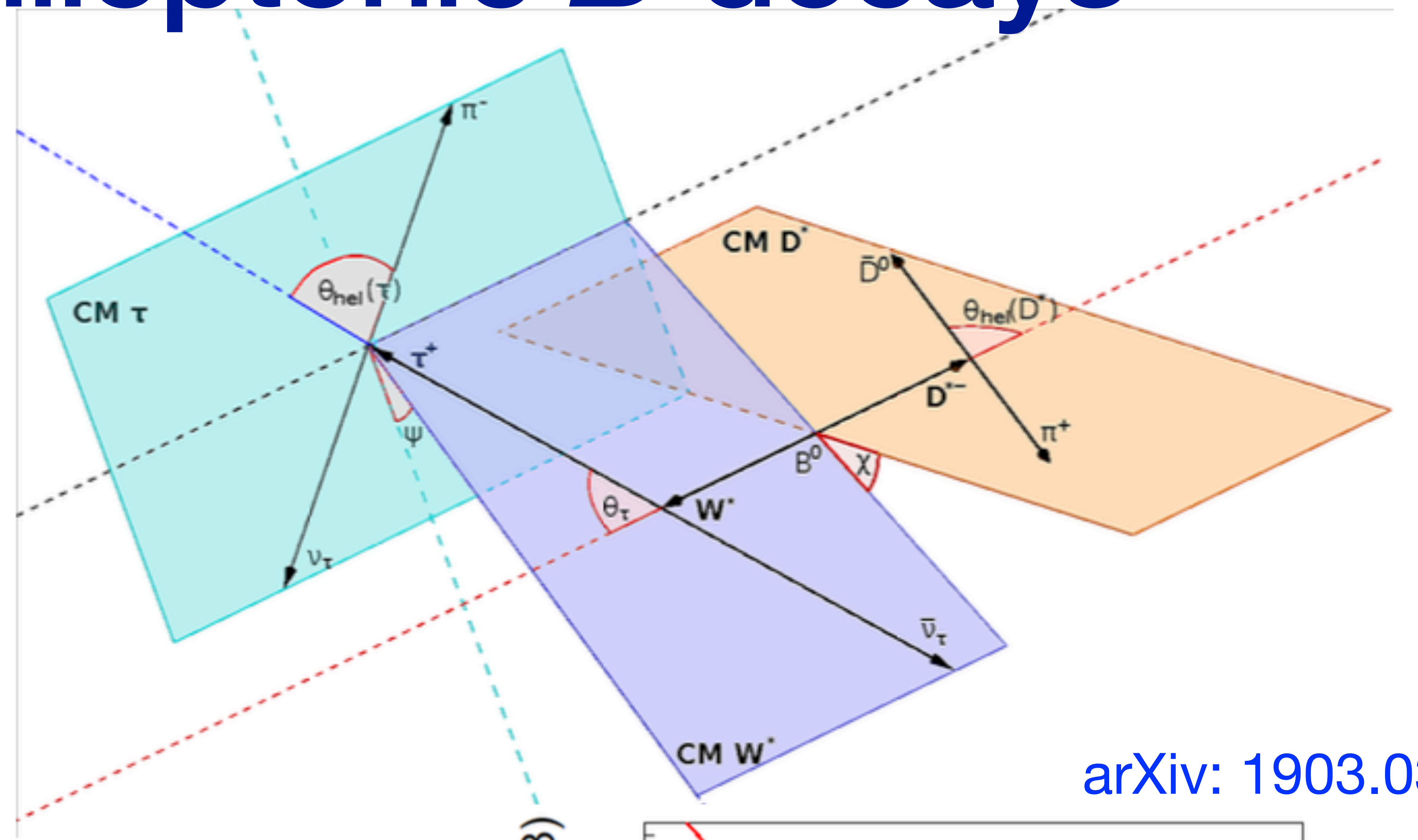


Backup

D^{*-} polarization in semileptonic B decays

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{3}{4}(2F_L^{D^*}\cos^2\theta_{\rm hel} + (1-F_L^{D^*})\sin^2\theta_{\rm hel})$$

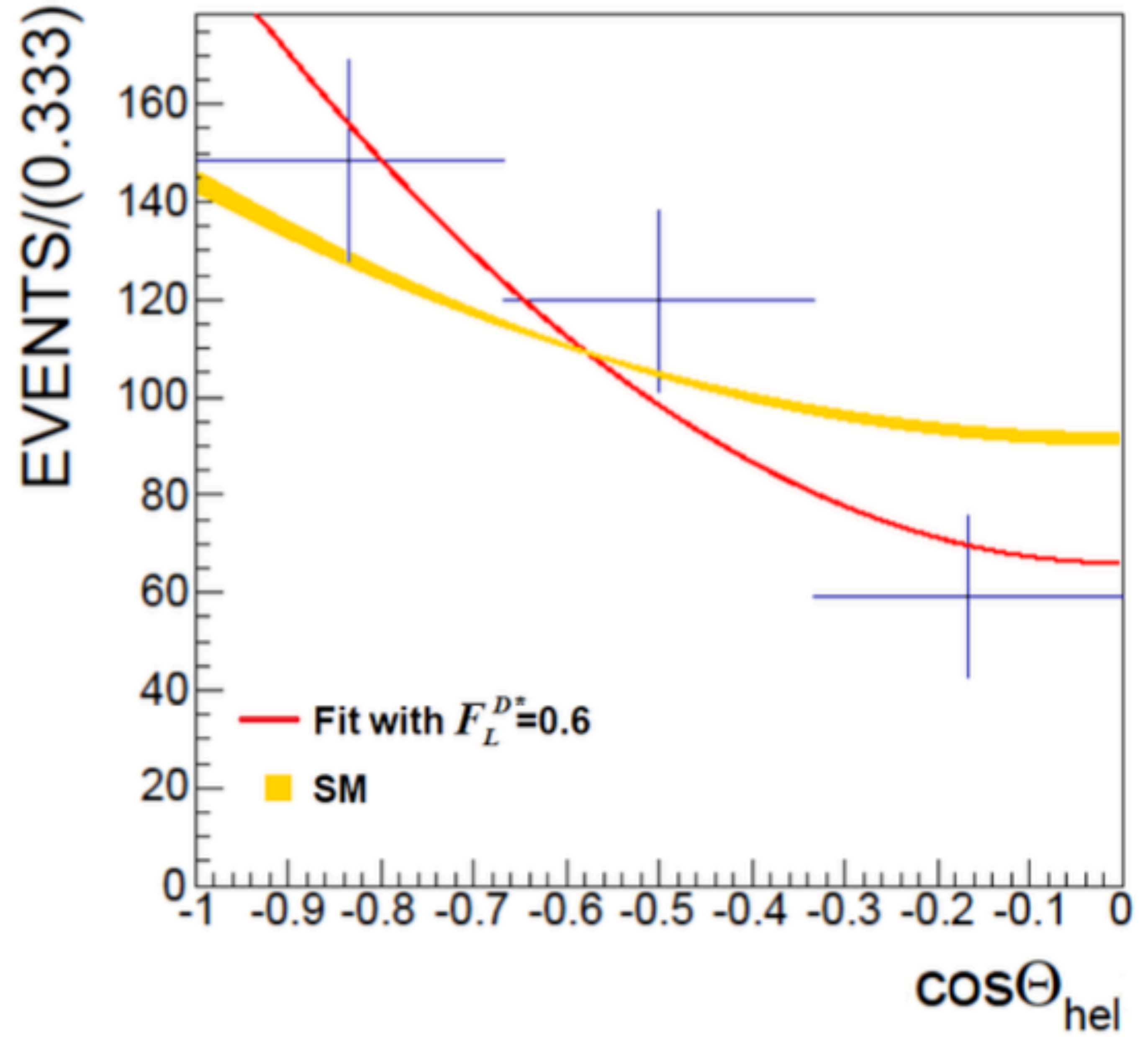
$$F_L^{D^*} = \frac{\Gamma(D_L^*)}{\Gamma(D_L^*)+\Gamma(D_T^*)}$$



- Belle measured the D^{*-} polarization in the decay of $B \to D^*\tau\nu$, with inclusive tagging based on full Belle data-set (772 M BBbar)
- Result only published on arXiv, NOT to a journal paper

$$F_L^{D^*} = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{sys})$$

arXiv: 1903.03



- Belle II 363 fb-1 data, will have sensitivity for measurement of $F_L{}^{D^*}$
- Low momentum of charged pion efficiency on forward and backward side is a challenge point.

Measurement of $R_{D^{(*)}}(q^2)$

$$R_{D^*}(q^2) \equiv \frac{d\mathcal{B}(\bar{B} \to D^*\tau\bar{\nu})/dq^2}{d\mathcal{B}(\bar{B} \to D^*\ell\bar{\nu})/dq^2}\left(1 - \frac{m_\tau^2}{q^2}\right)^{-2}$$

- q^2 specific systematic analysis
  - Cancel the uncertainties both from experimental and theoretical side.
- Has not been measured yet
- Already have sensitivity to rejecting some of the NP, with 363 fb^{-1}

PHYSICAL REVIEW D 91, 114028 (2015)