Test of lepton flavor universality at Belle and Belle II

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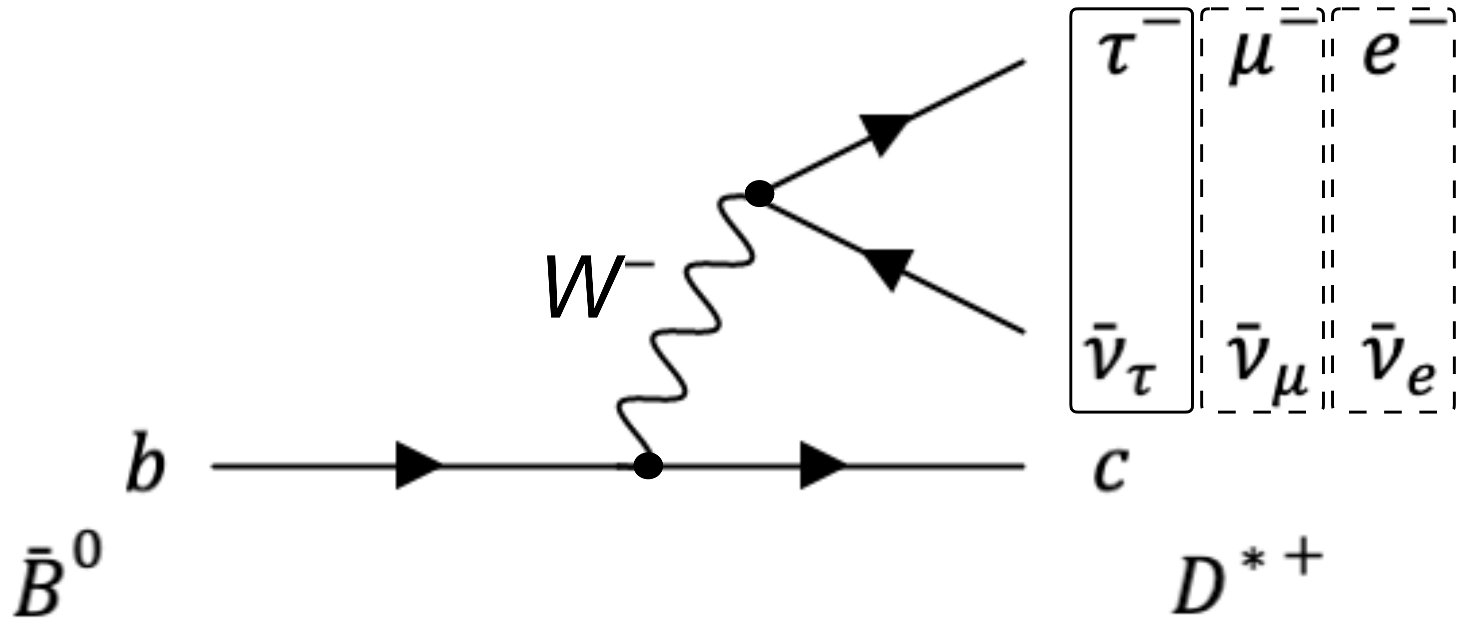
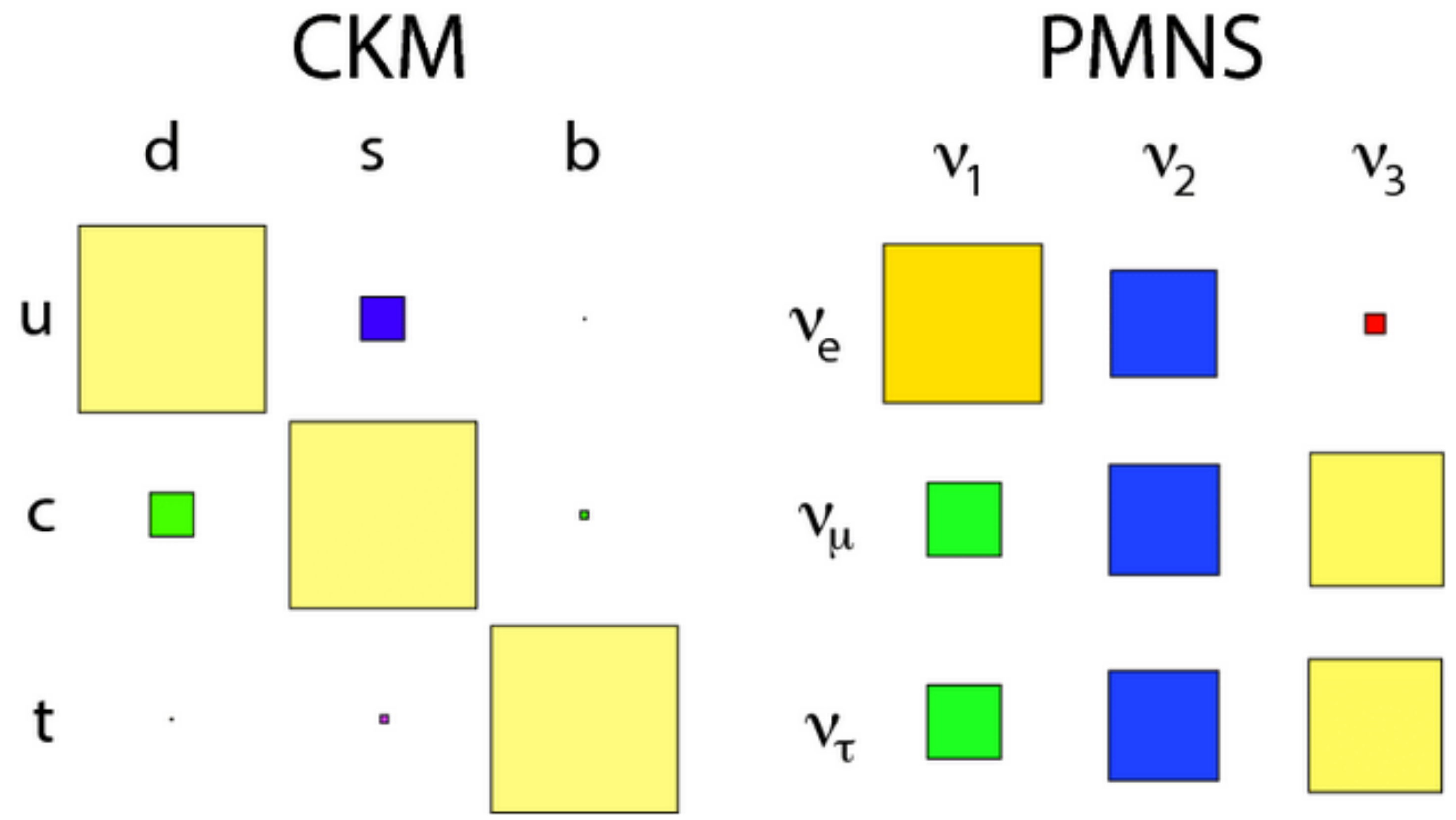
Motivation for studying LFUV

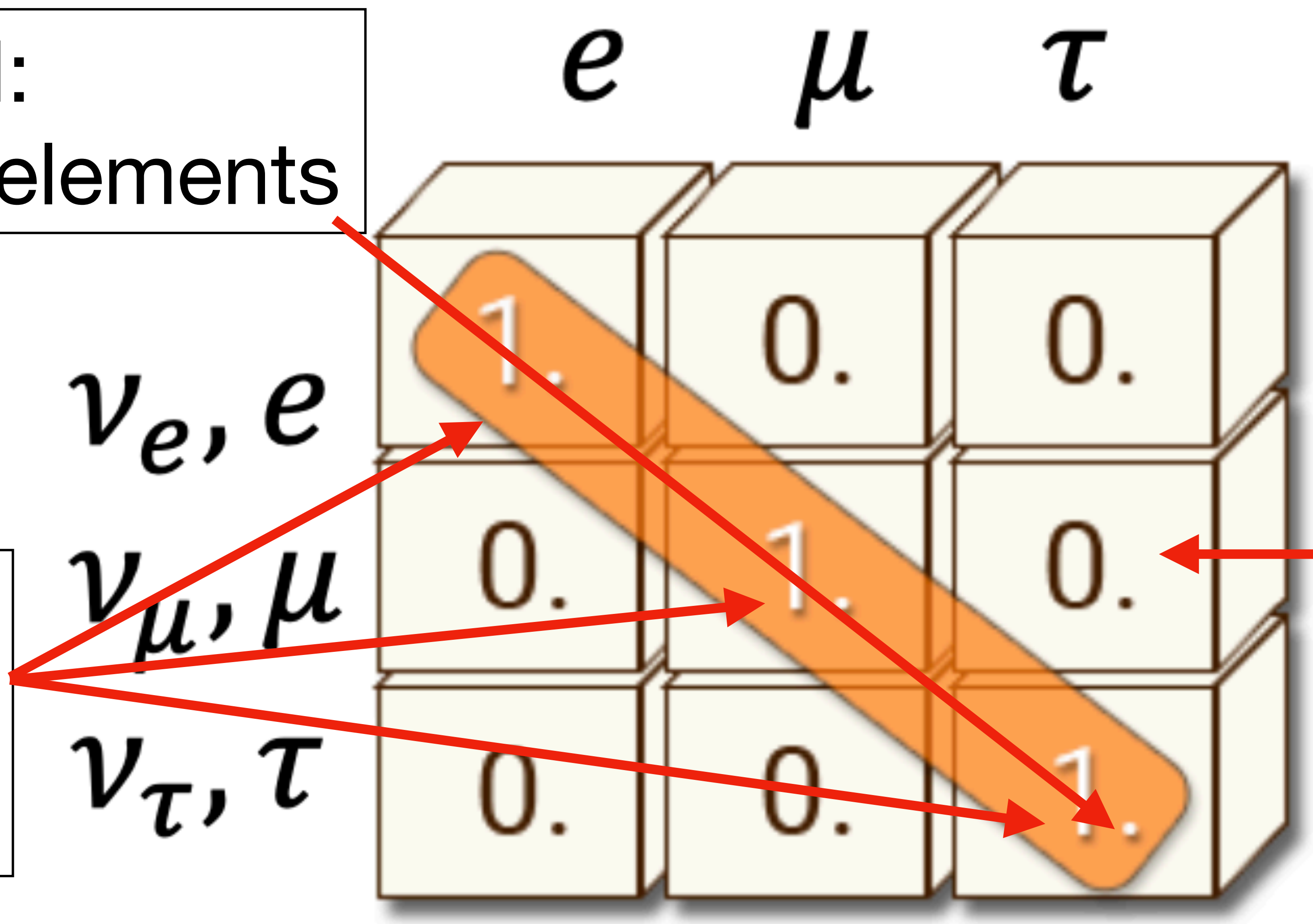
- Lepton Flavor Universality (LFU): *W* boson couples to leptons with equal strength
  - Difference in kinematics and Higgs coupling due to different lepton masses
- SM fields do mix:
  - Quarks sector -> CKM matrix
  - Neutrinos sector -> PMNS matrix
- Charged leptons -> the matrix purely diagonal?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





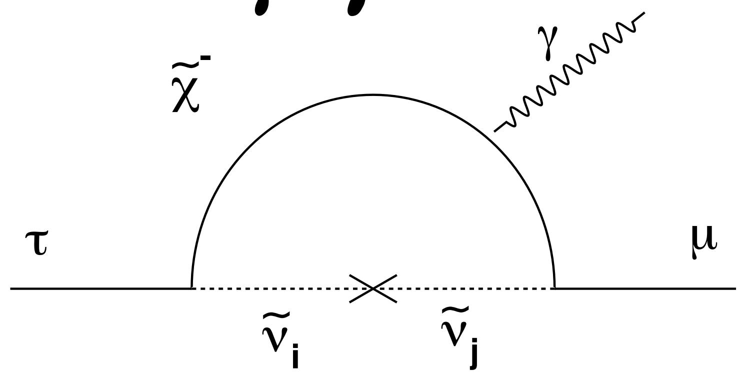
g-2, EDM:
diagonal elements

LFUV:
Relation among
diagonal elements



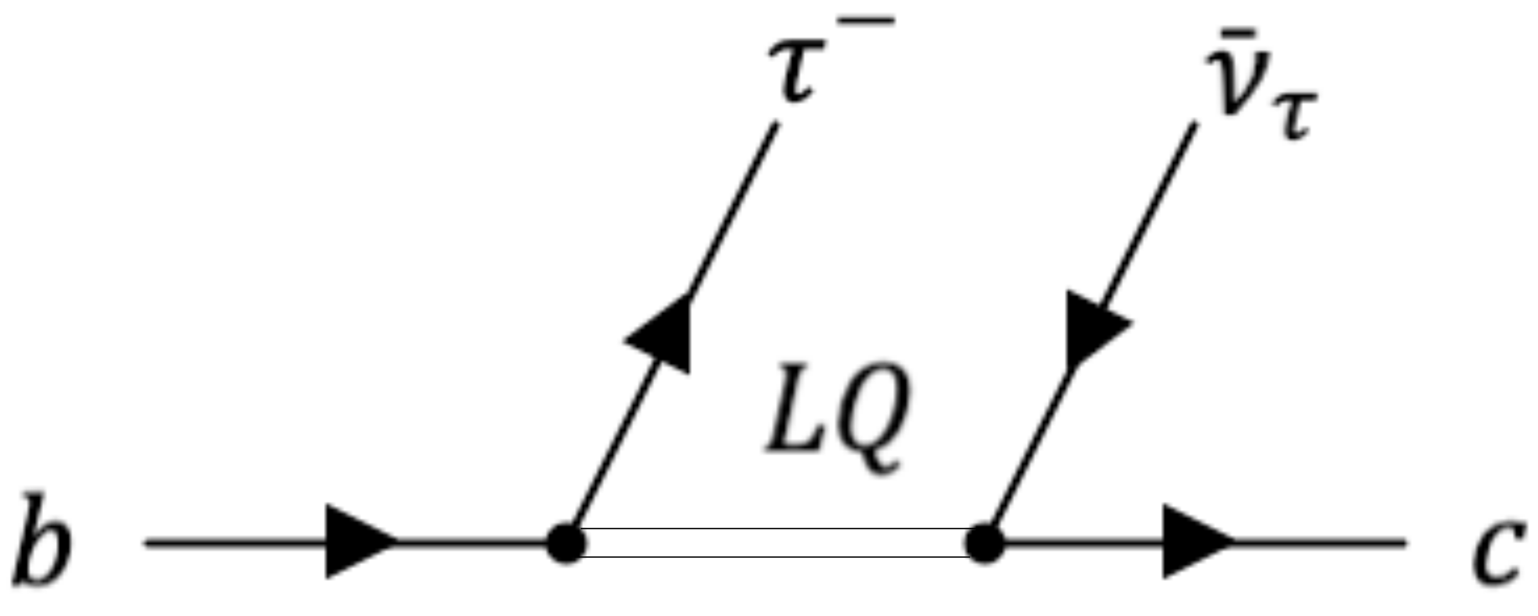
Lepton Flavor Violation (LFV):
off diagonal term

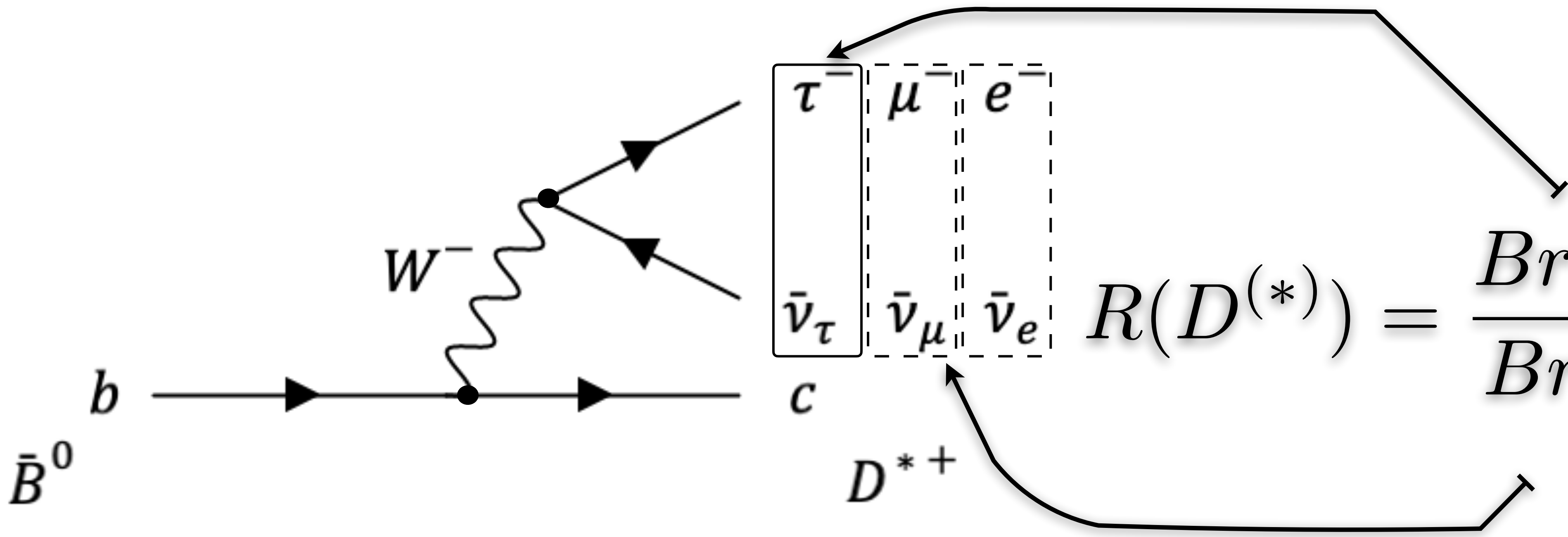
$\tau \to \mu\gamma$



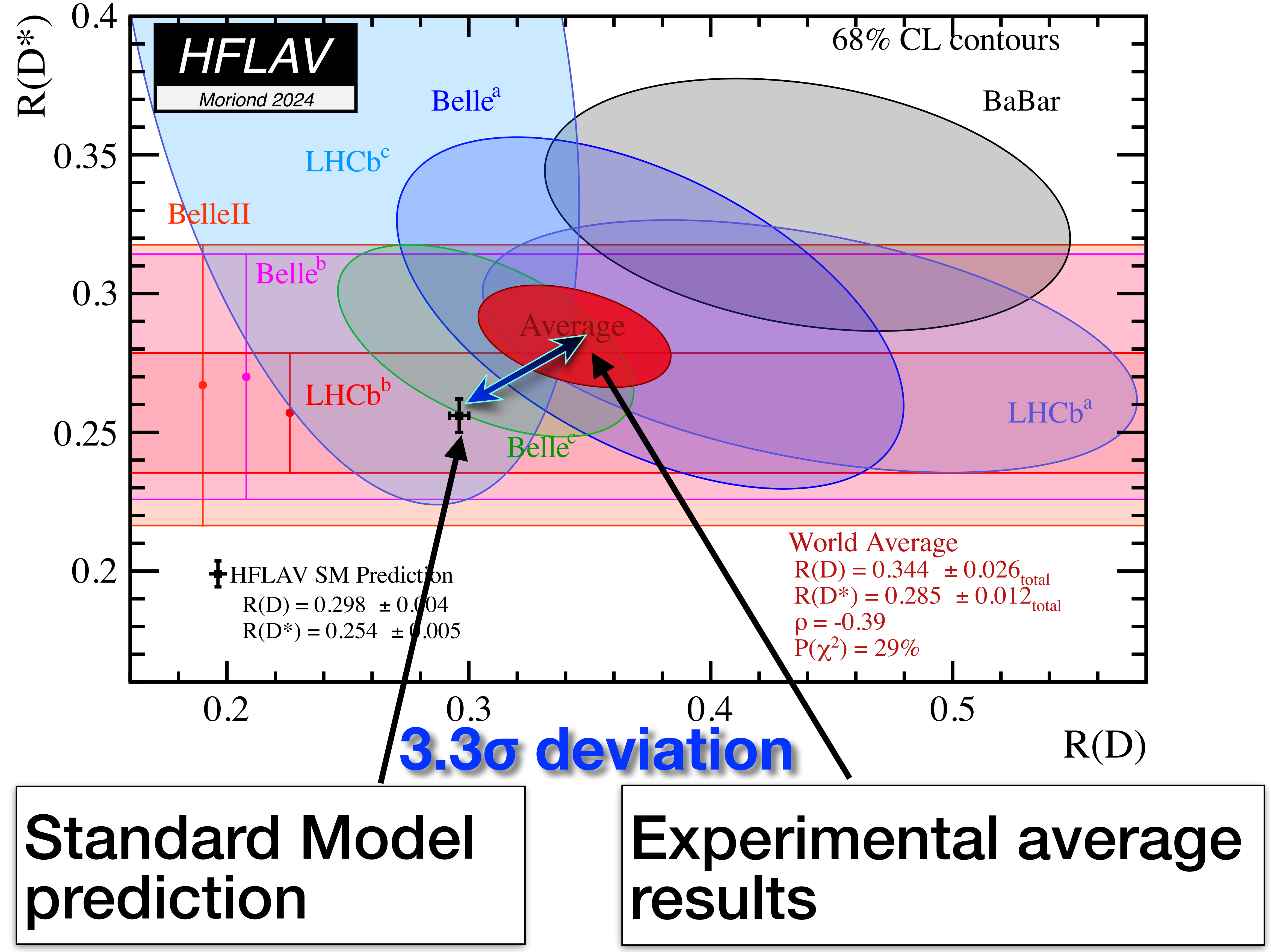
“*B* anomaly” in semileptonic decays

- 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]





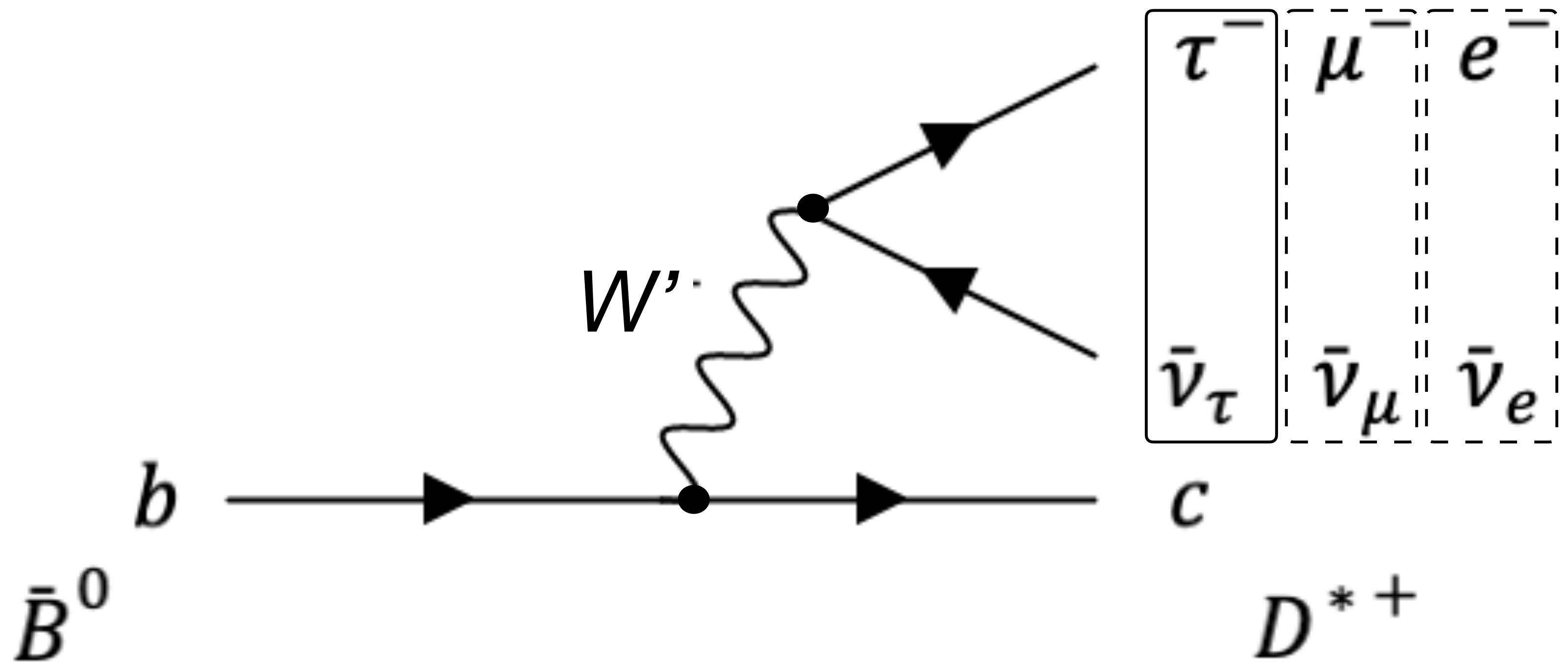
$$R(D^{(*)}) = \frac{Br(\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)}{Br(\bar{B}^0 \to D^{(*)+}\ell^-\bar{\nu}_\ell)}$$

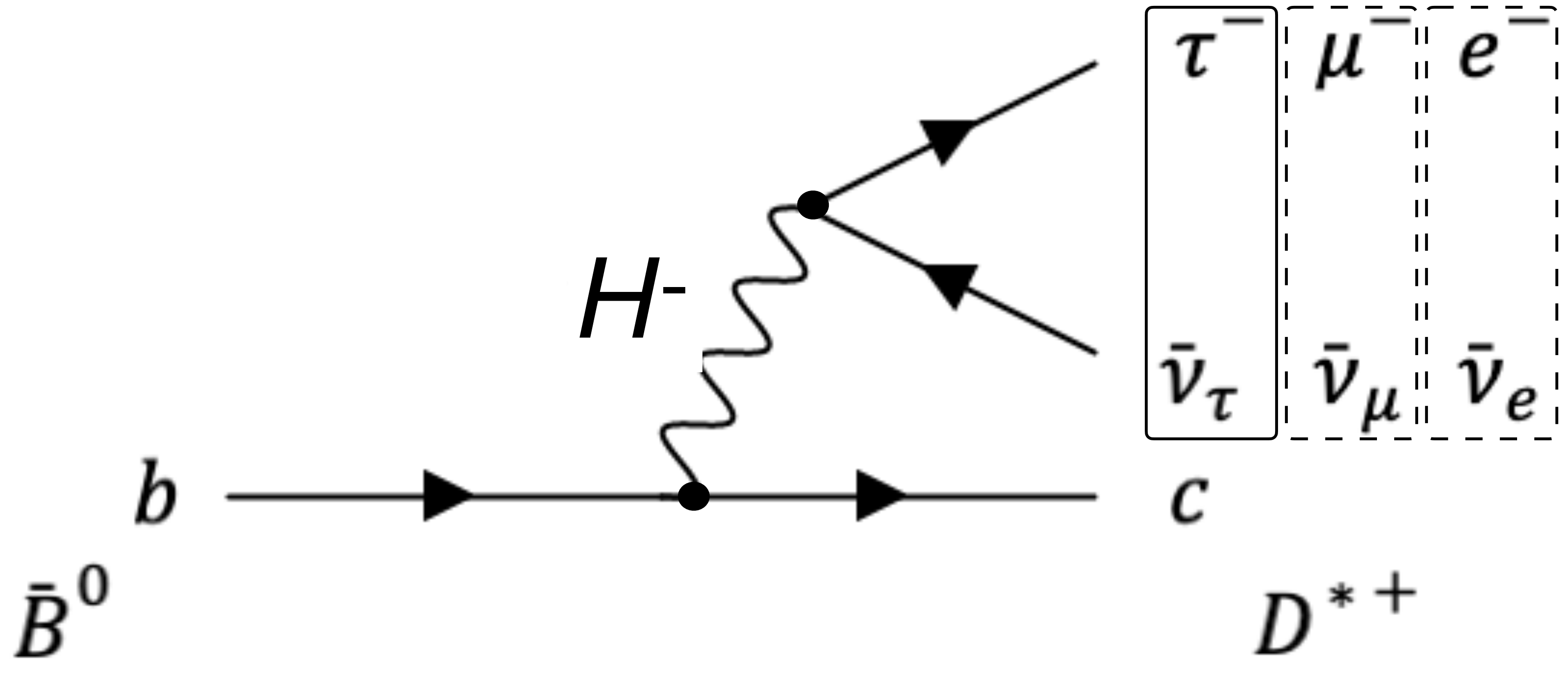


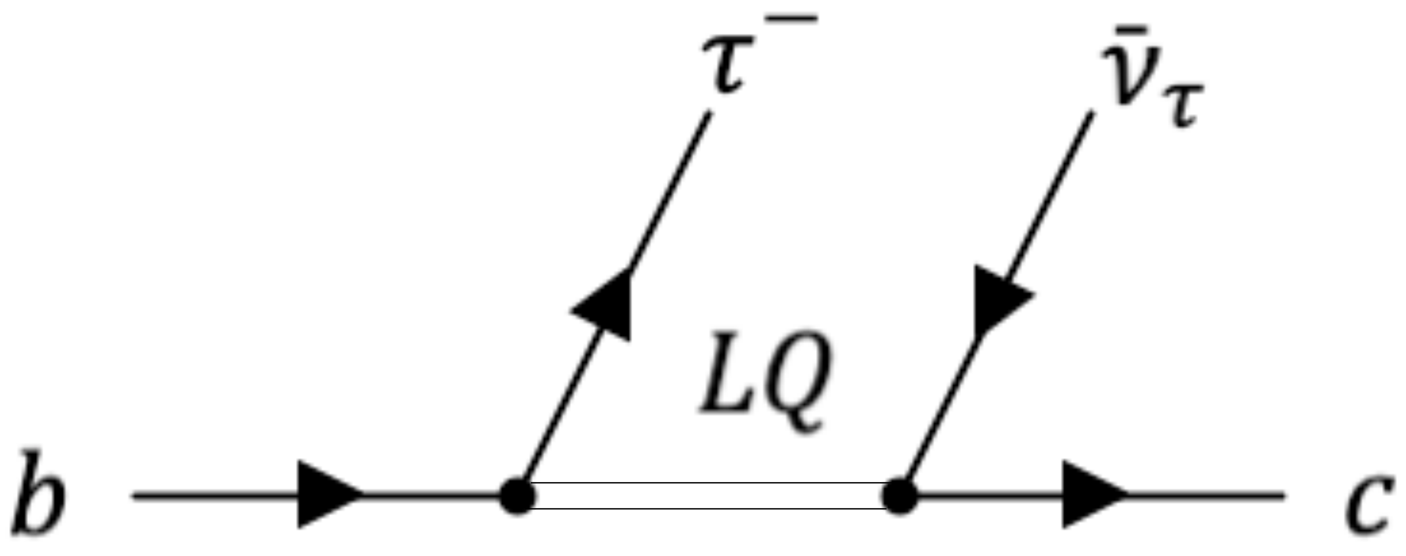
New physics scenarios for the $R(D^{(*)})$ anomaly

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.
    PRD 105 095011(2022)
- 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}), PRD 110 072020 (2024)
  - $R_{\tau/\ell}(X)$ at Belle II (189 fb^{-1}), PRL132, 211804 (2024)
  - $R_{e/\mu}(X)$ from Belle II (189 fb^{-1}), PRL 131, 051804 (2023)
  - $R_{e/\mu}(D^*)$ from Belle (711 fb^{-1}), PRD 108, 012002 (2023)
  - Test of LFU in angular asymmetries of $B \to D^* l\nu$ at Belle II (189 fb^{-1}), PRL 131, 181801 (2023)
  - Test of LFU in τ decays at Belle II (362 fb^{-1}) JHEP 08 (2024) 205

Luminosity frontier: SuperKEKB

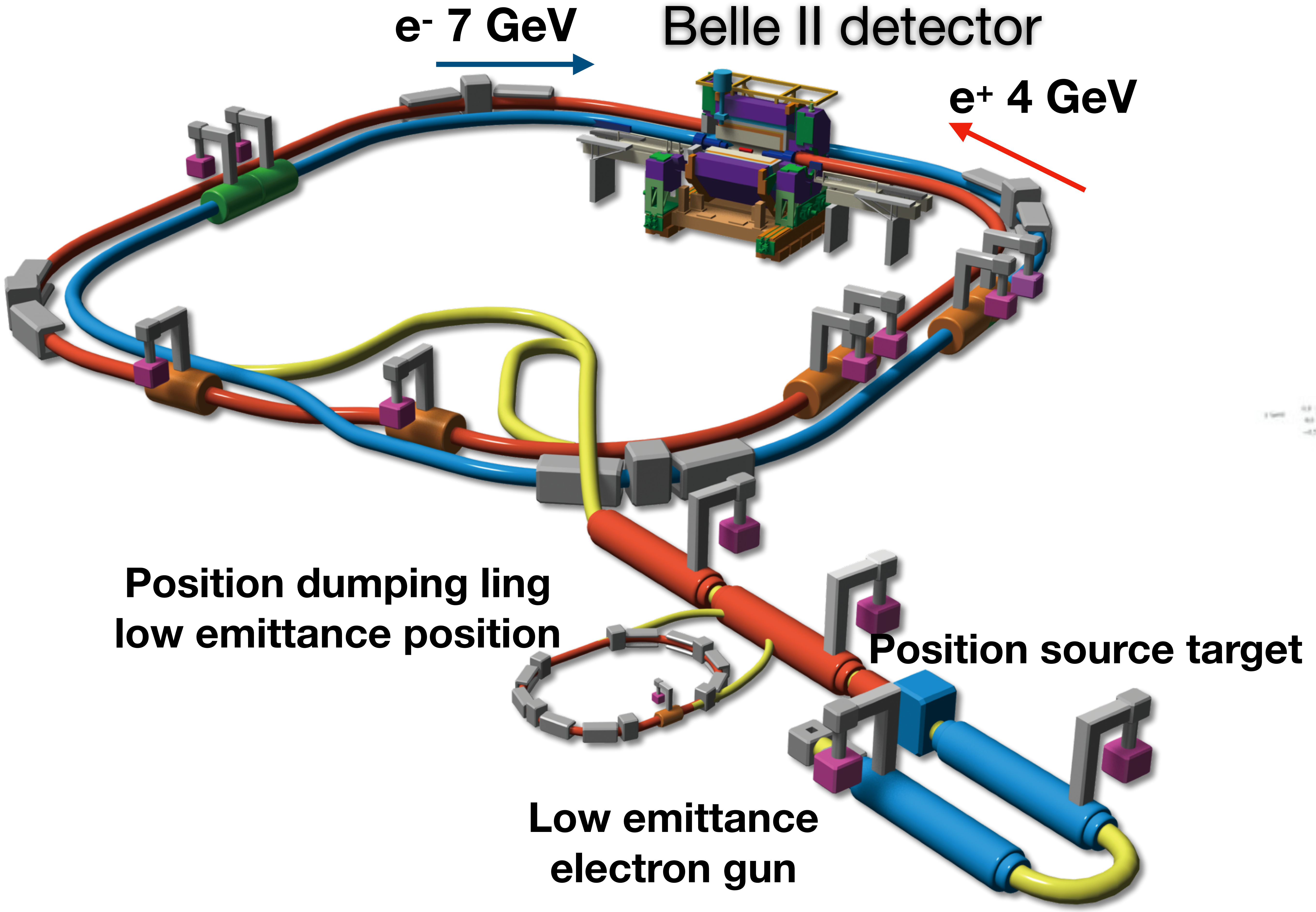
Luminosity frontier: SuperKEKB

- Asymmetric e^+e^- collider
  - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
  - very clean and well-known initial state

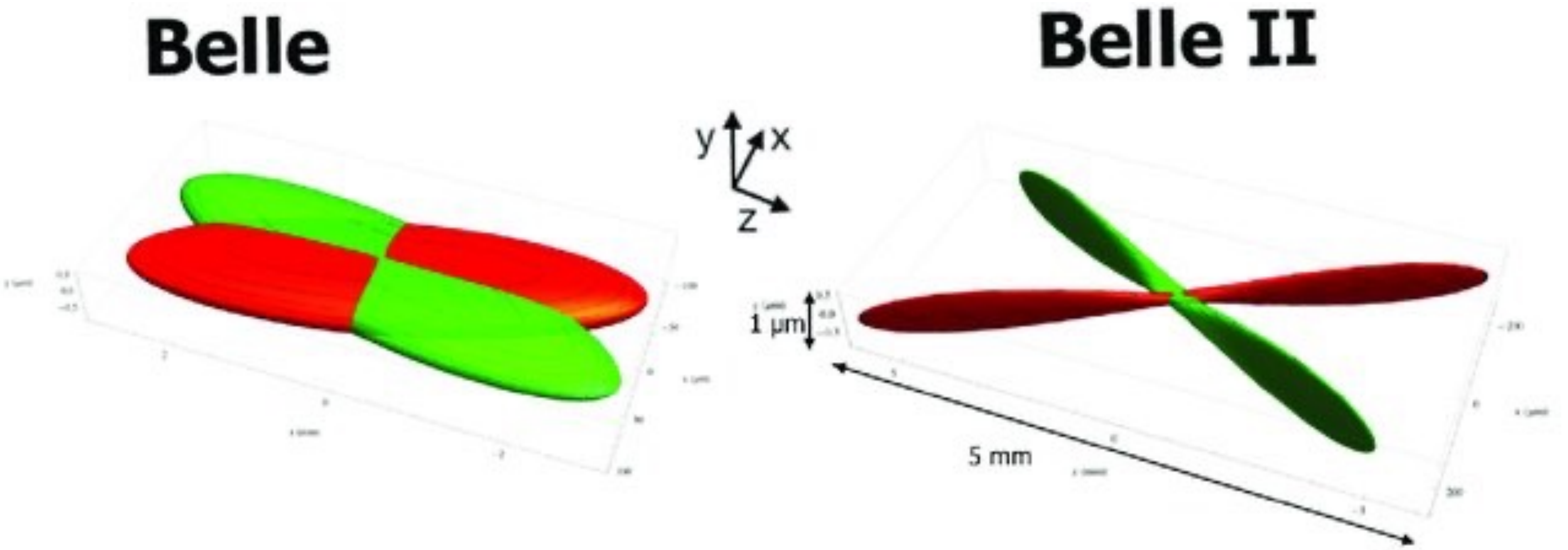
Beam current: KEKB x ~1.5

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

Beam squeeze: KEKB / ~20



Nano beam scheme



Target: L = 60 x 10^{34} cm^{-2} s^{-1}

Achieved : 4.7 x 10^{34} cm^{-2} s^{-1} (Record)

- Data:
  - **531** fb^{-1} (Belle II) <-> 980 fb^{-1} (Belle)

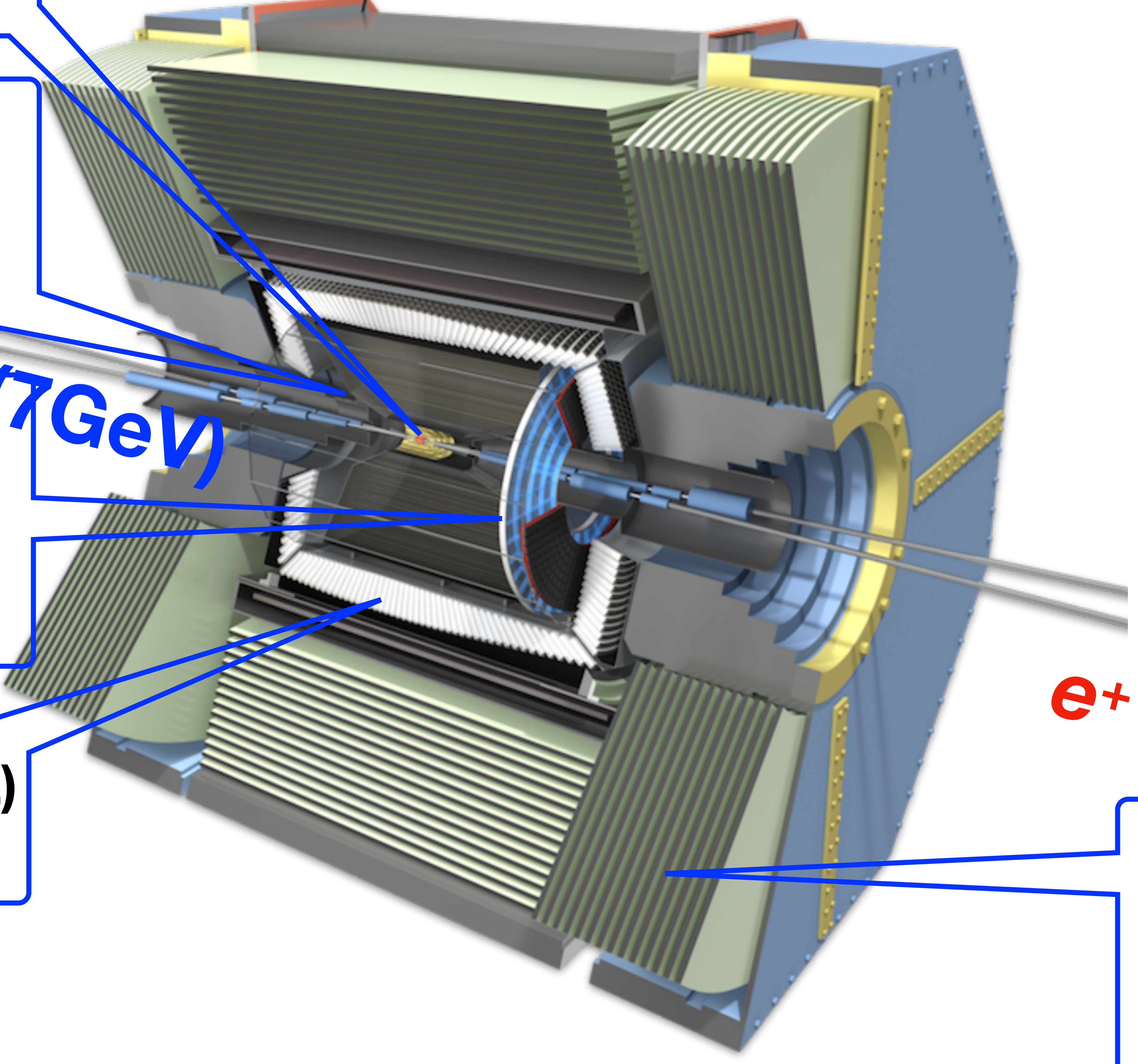
Belle II detector and dataset

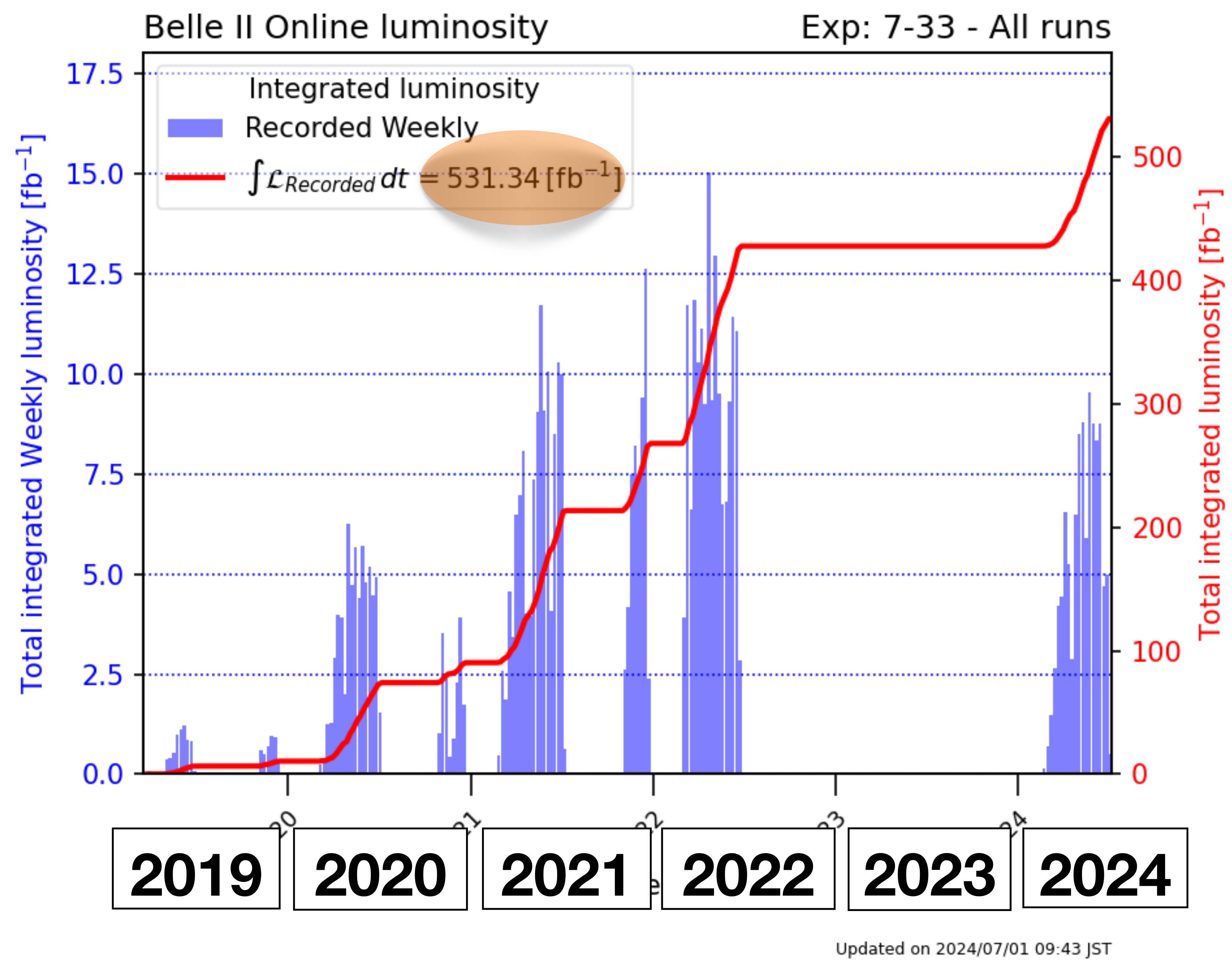
Vertex detector (VXD)
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)

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



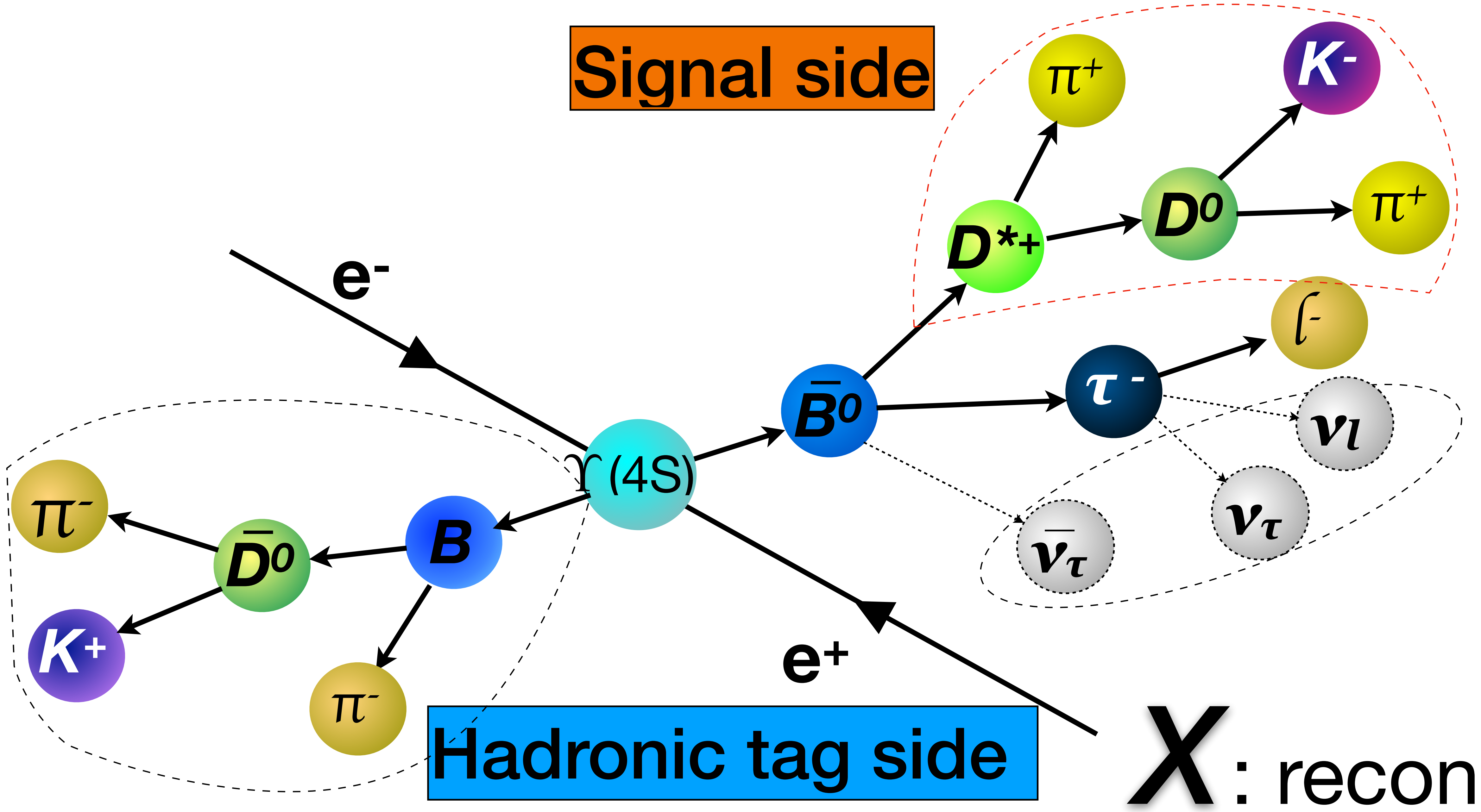


K_L/μ detector (KLM)
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator

- 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

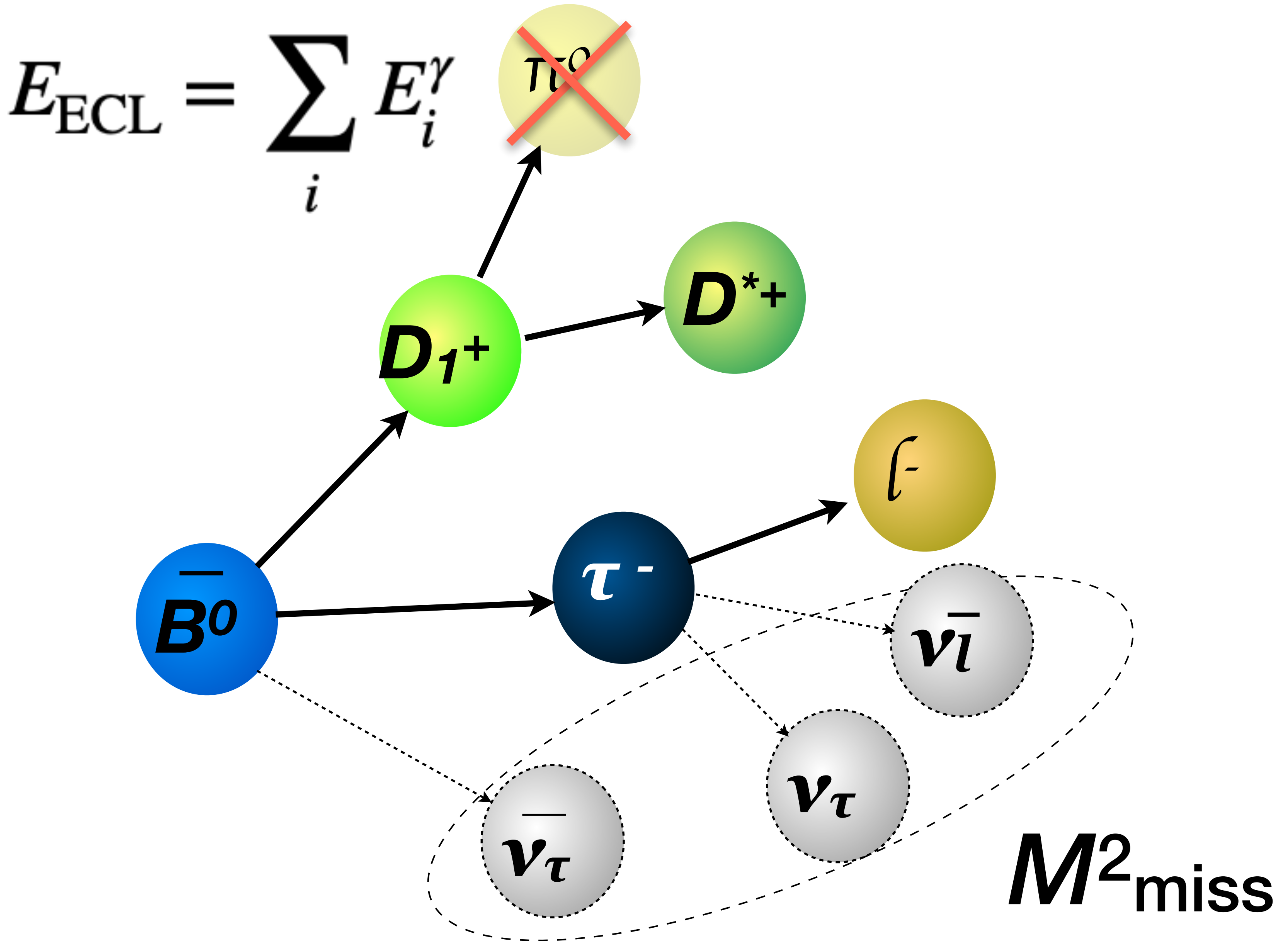


X: reconstruct other particles than a lepton as X on signal side

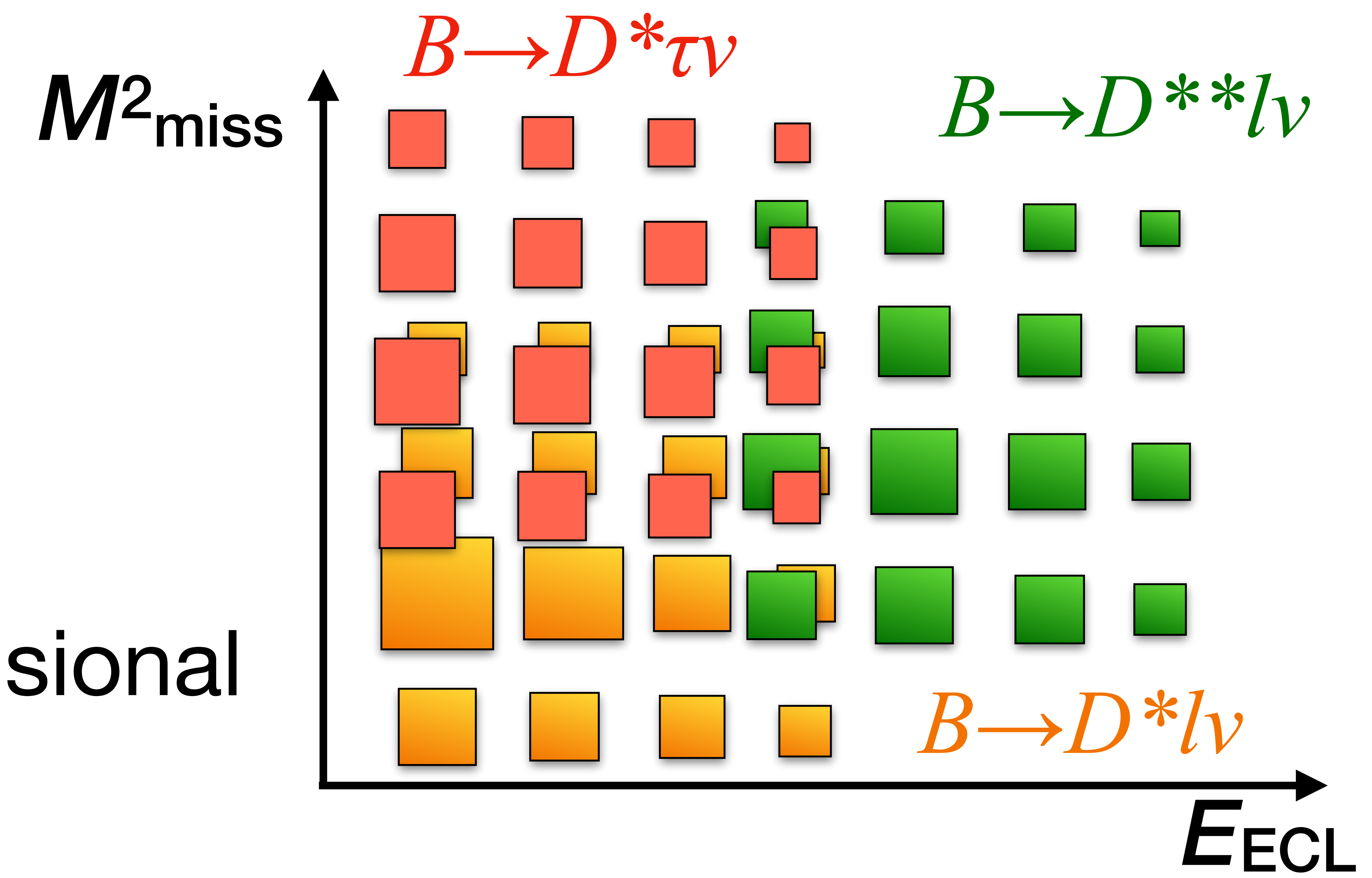
- Fully reconstruct one of the B mesons (B tag), possible to measure momentum of other B meson (B signal)
- Indirectly measure missing momentum of neutrinos in signal B decays
- $M^2_{\mathrm{miss}} = (p_{\mathrm{beam}} - p_{\mathrm{Btag}} - p_{D^{(*)}} - p_l)^2$
- E_{ECL} unassigned neutral energy in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

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)



- $M^2_{miss} = (p_{beam} - p_{Btag} - p_{D(*)} - p_\ell)^2$
- 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

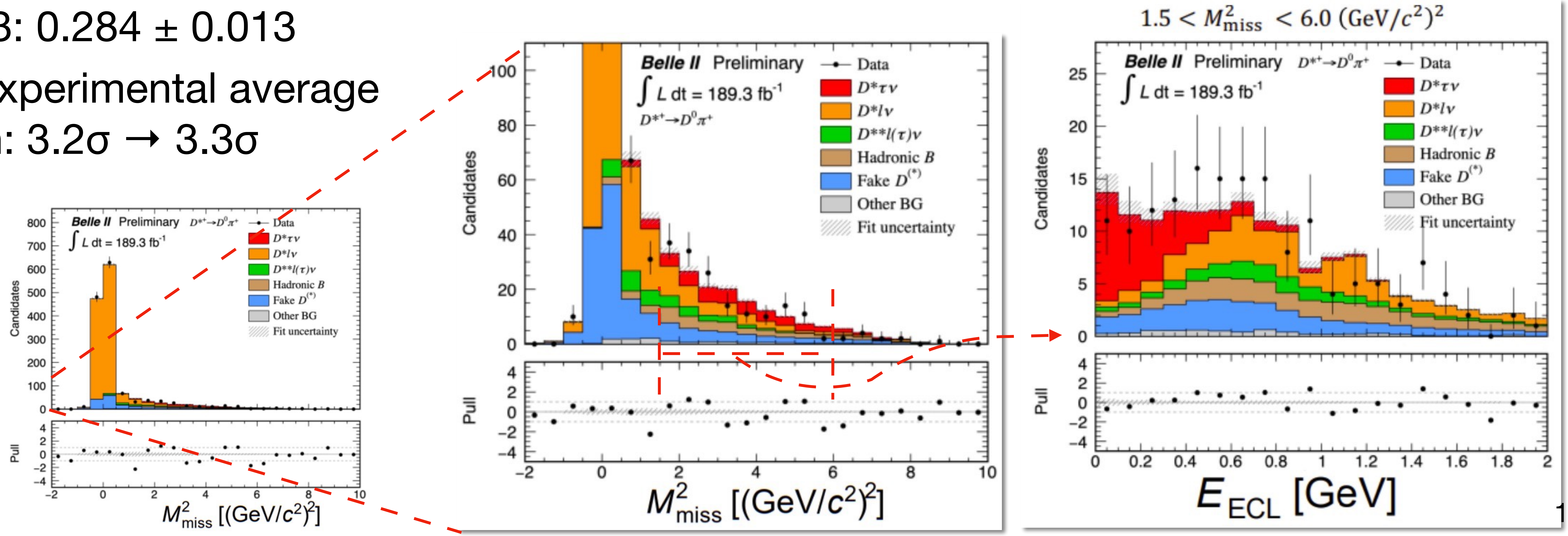
$R_{\tau/\ell}(D^*)$ results

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

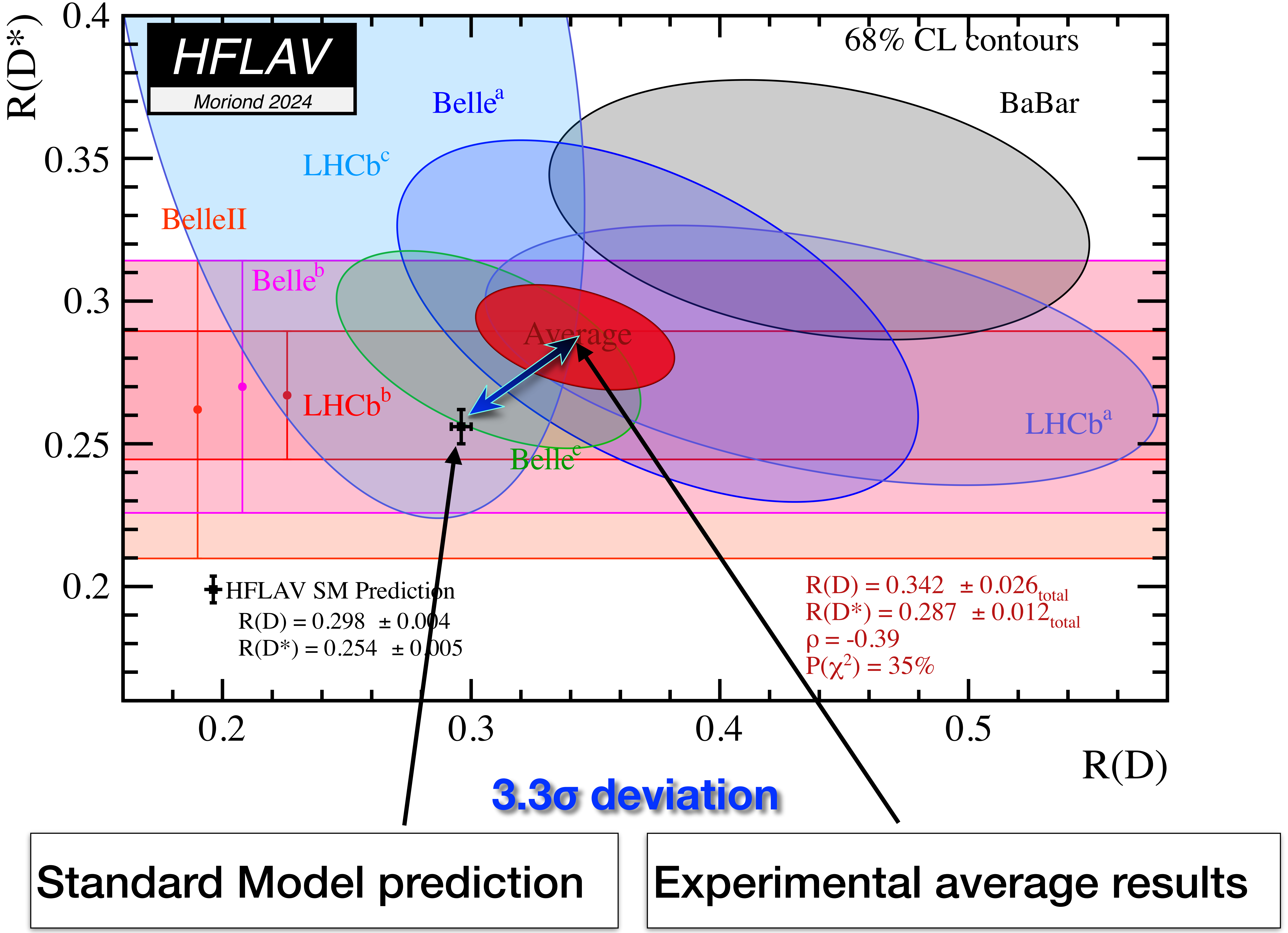
$R(D^*_{\tau/\ell}) = 0.262\ ^{+0.041}_{-0.039}\ (\text{stat})\ ^{+0.035}_{-0.032}\ (\text{syst})$

Source	Uncertainty
Statistical uncertainty	+15.4% -14.6%
E_{ECL} PDF shape	+9.1% -8.3%
MC statistics	±7.5%
$B \to D^{**} l \nu$ modeling	+4.8% -3.5%

- Consistent with
  SM: 0.254 ± 0.005,
  HFLAV23: 0.284 ± 0.013
- SM vs. experimental average deviation: 3.2σ → 3.3σ



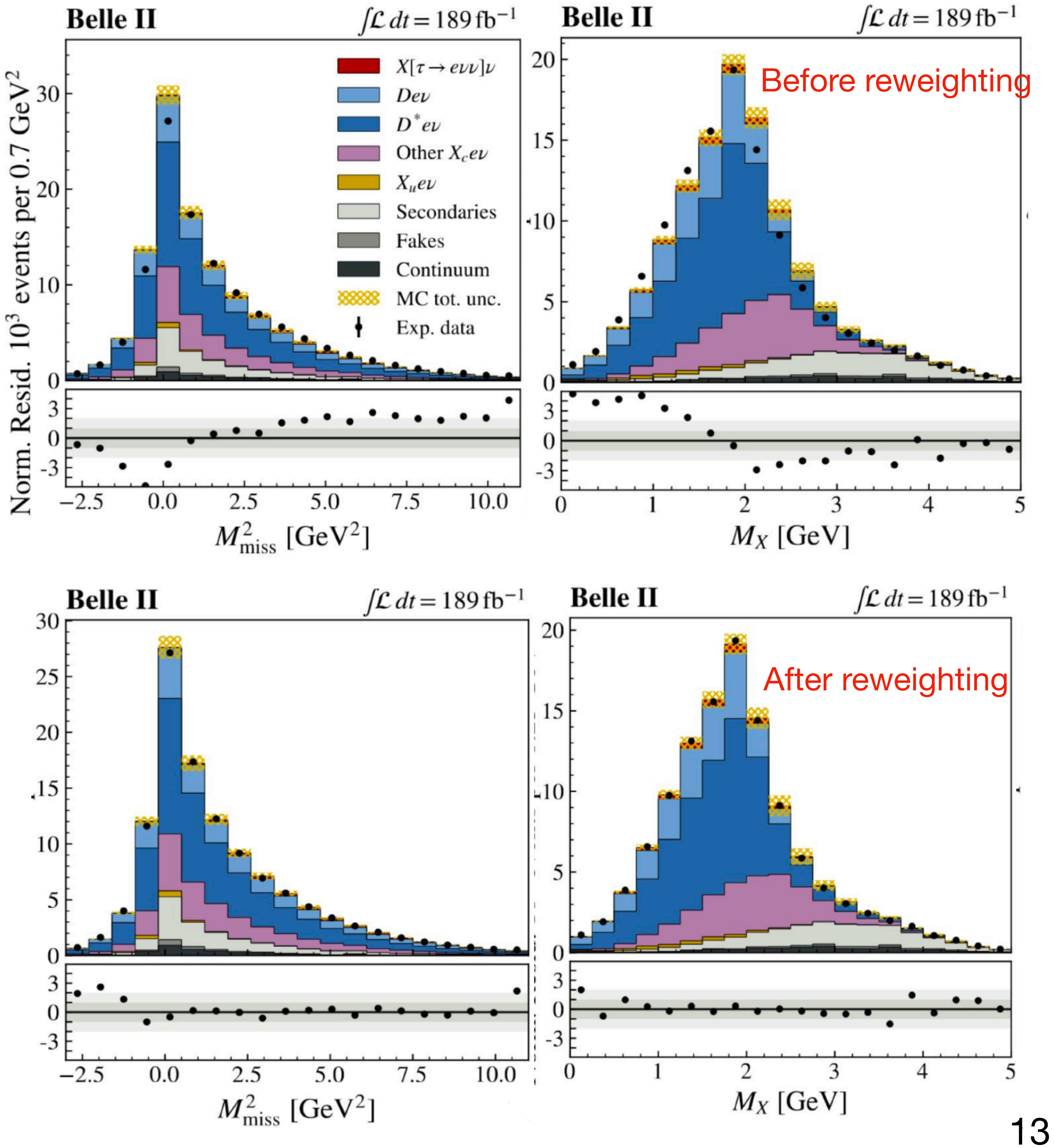
“*B* anomaly” in semileptonic decays



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

- 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

PRL132, 211804



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

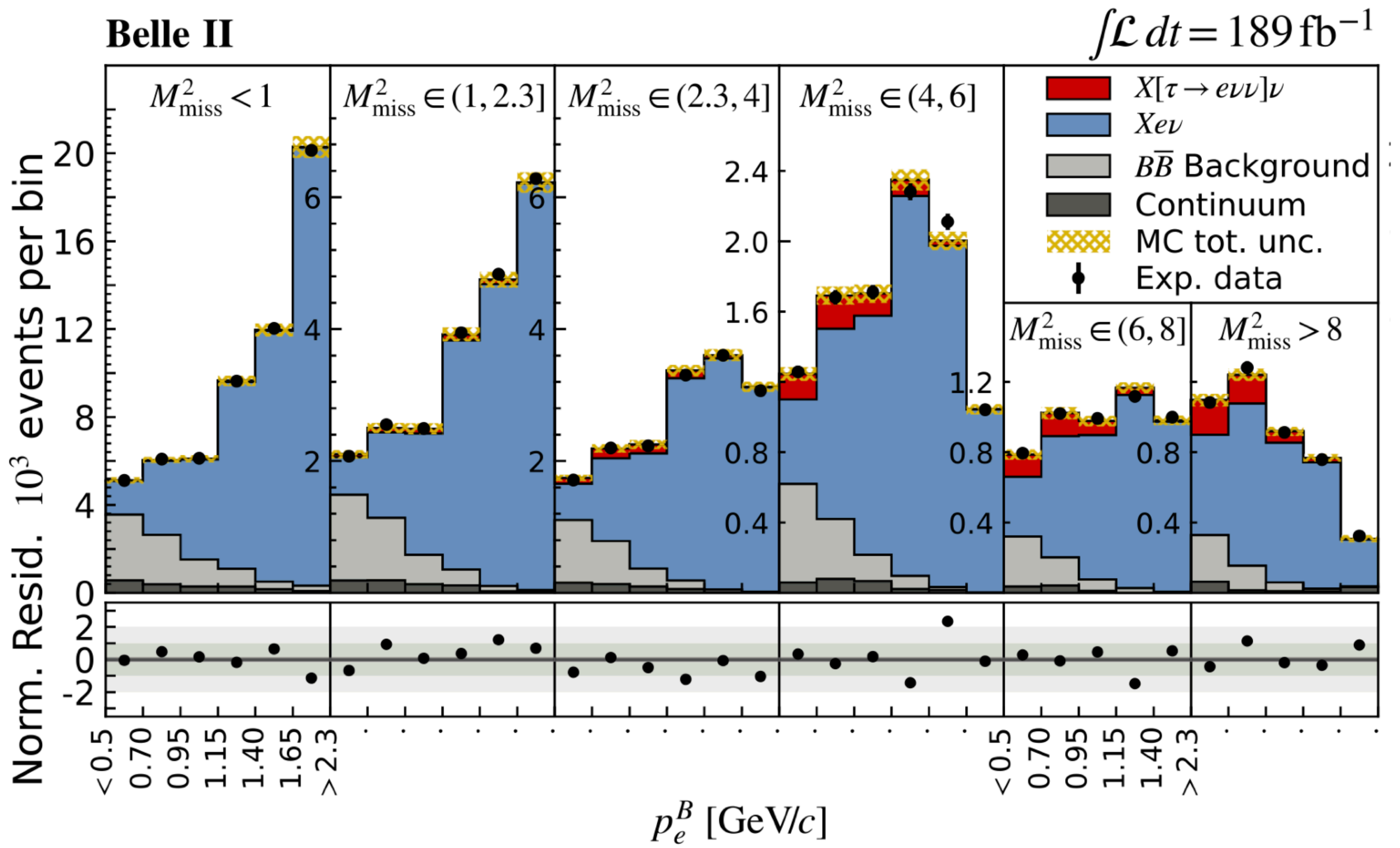
$R_{\tau/\ell}(X) = 0.228 \pm 0.016\ (\text{stat}) \pm 0.036\ (\text{syst})$

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

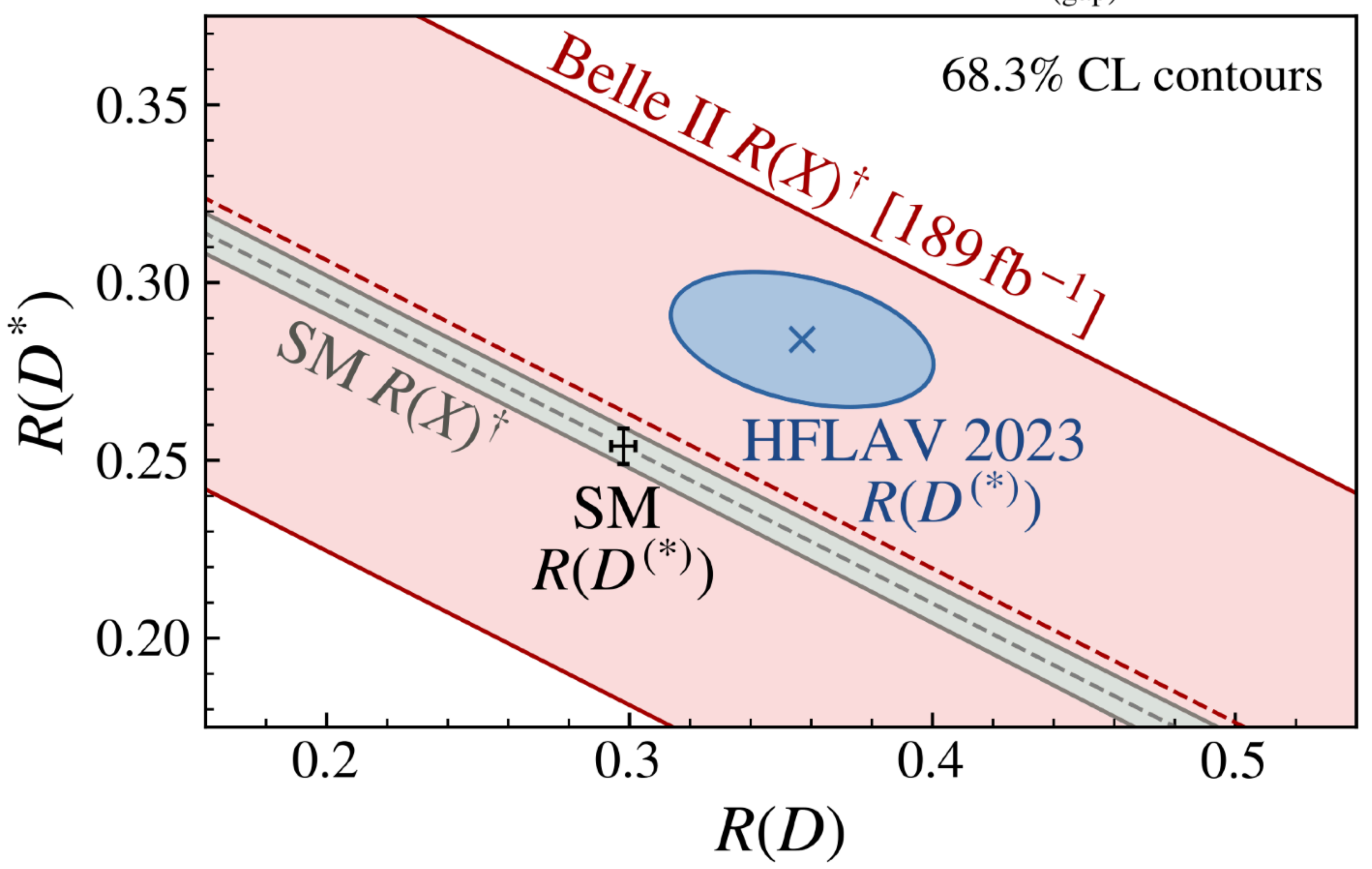
$R_{\tau/\mu}(X) = 0.222 \pm 0.027\ (\text{stat}) \pm 0.050\ (\text{syst})$

- Consistent with rough SM expectation

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



† = with expected SM contributions of $D^{**}_{(gap)}, X_u$ removed



Light-lepton universality test

PRL 131, 051804

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

  $R(X_{e/\mu})$ = 1.007 ± 0.009 (stat) ± 0.019 (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 ± 0.001 JHEP 11 (2022) 007

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

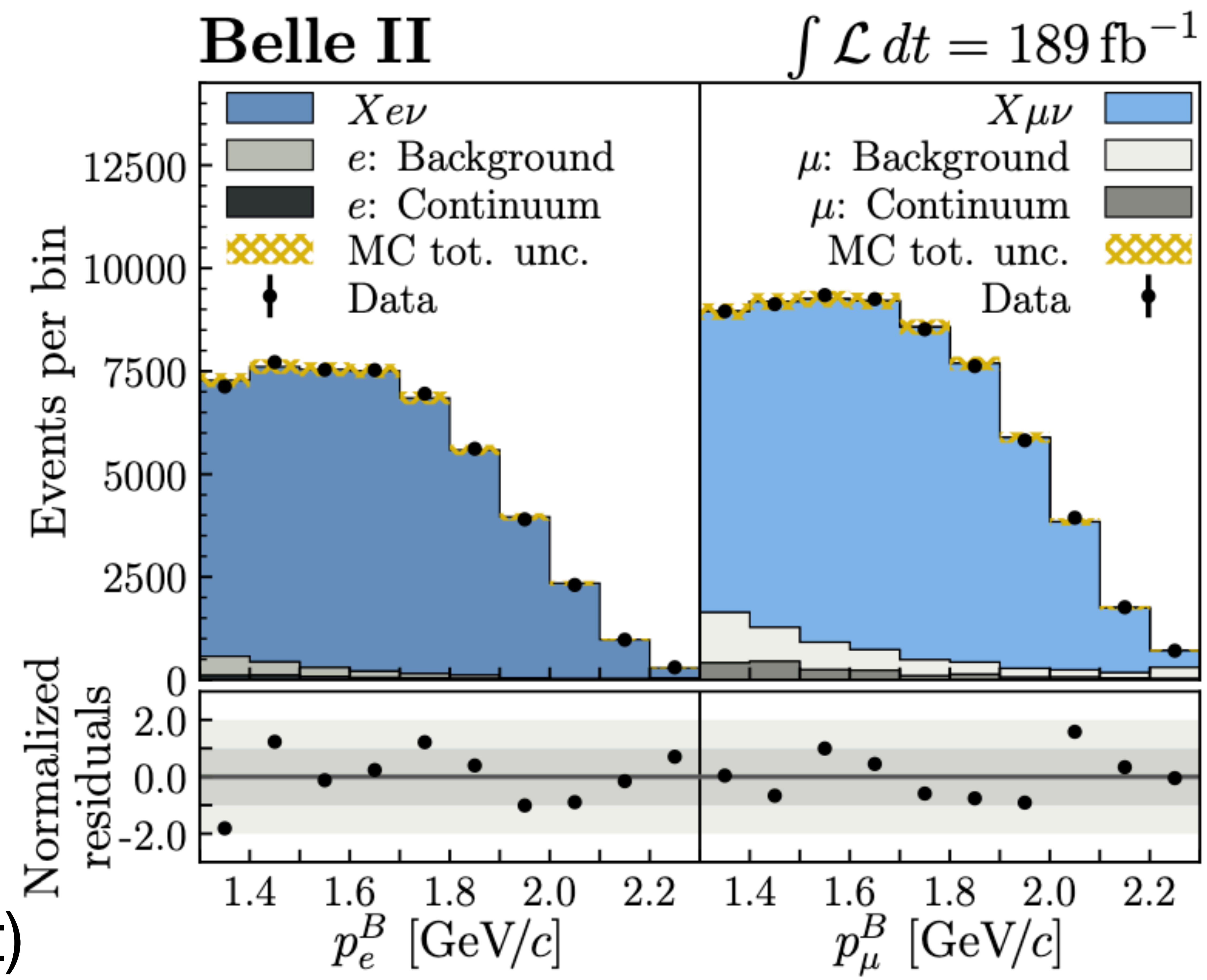
  PRD 100, 052007 (2019)

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

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

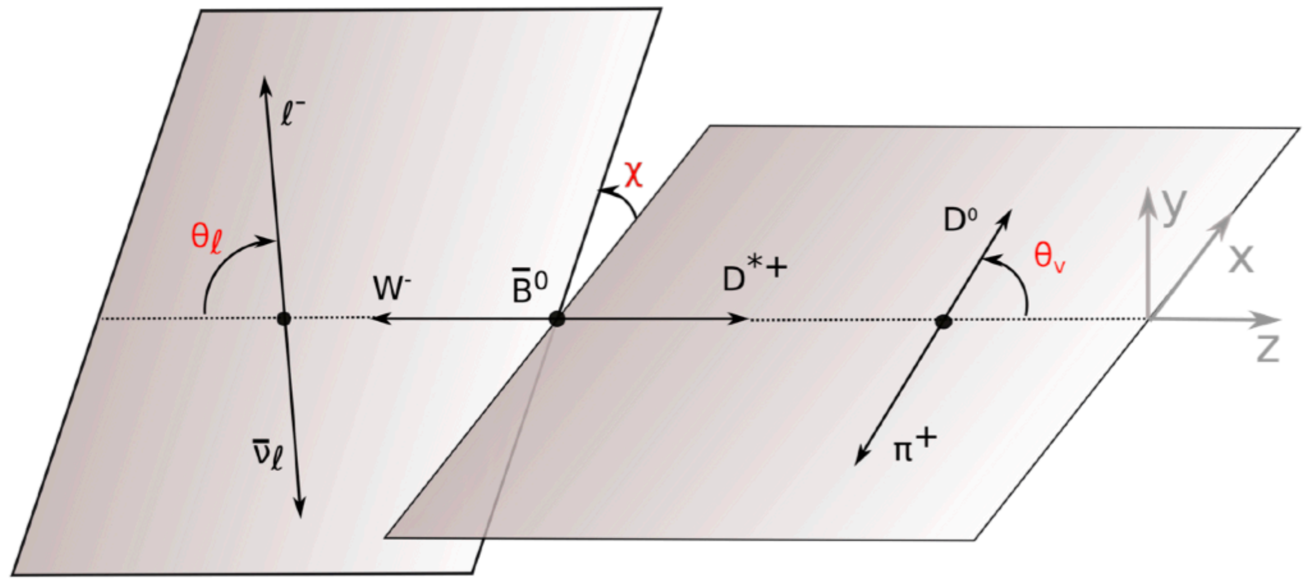
  PRD 108, 012002

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

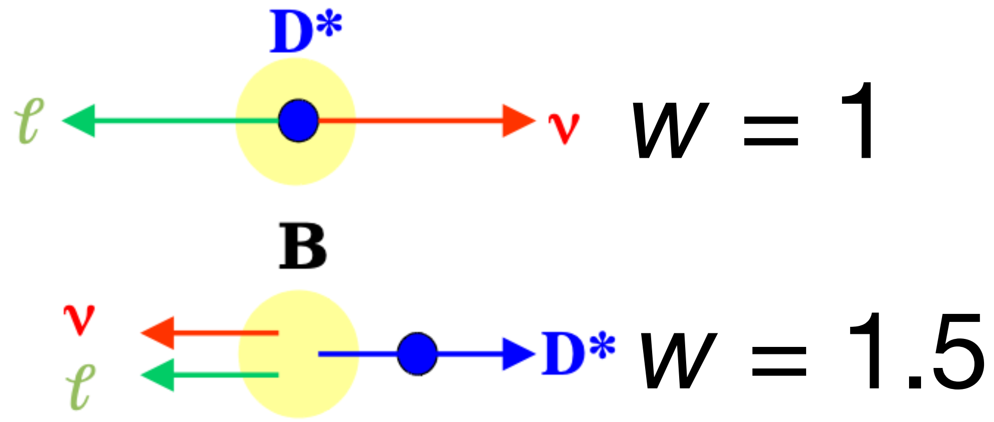


$$\mathcal{A}_x(w) \equiv \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dx \frac{d^2\Gamma}{dw dx} \qquad \mathcal{A}_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}$$

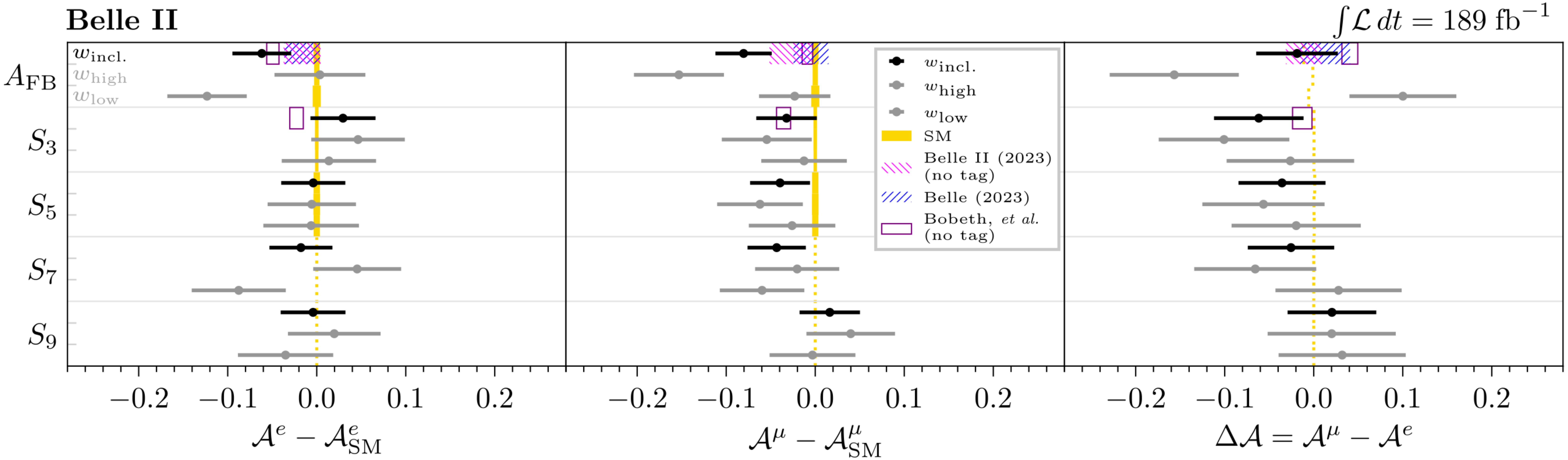
$$w \equiv \frac{m_{B^0}^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

- The differences are expected to be small in SM

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

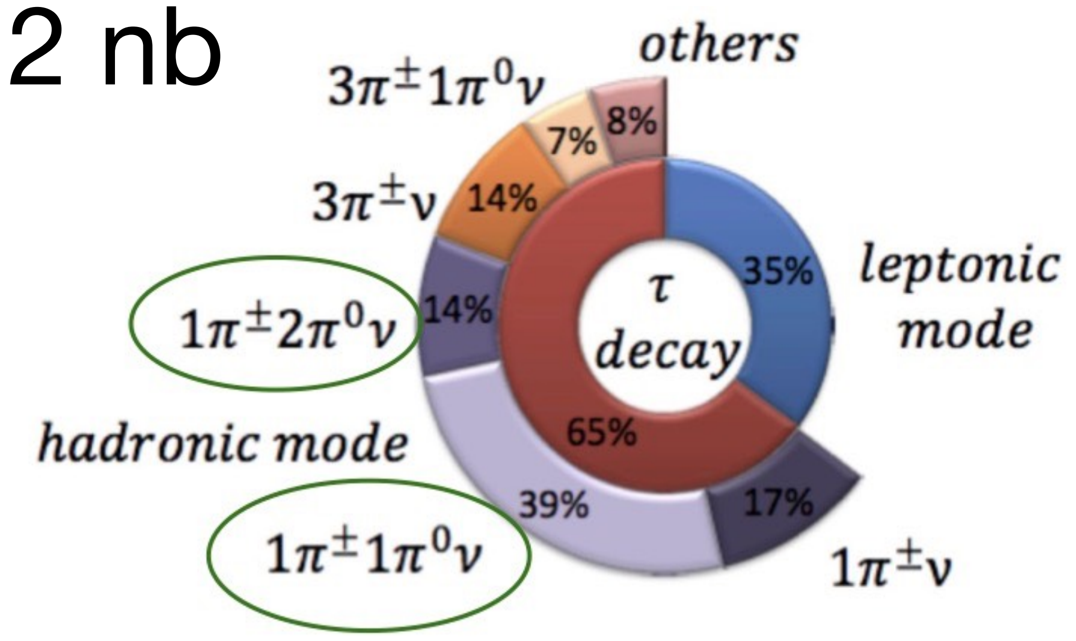


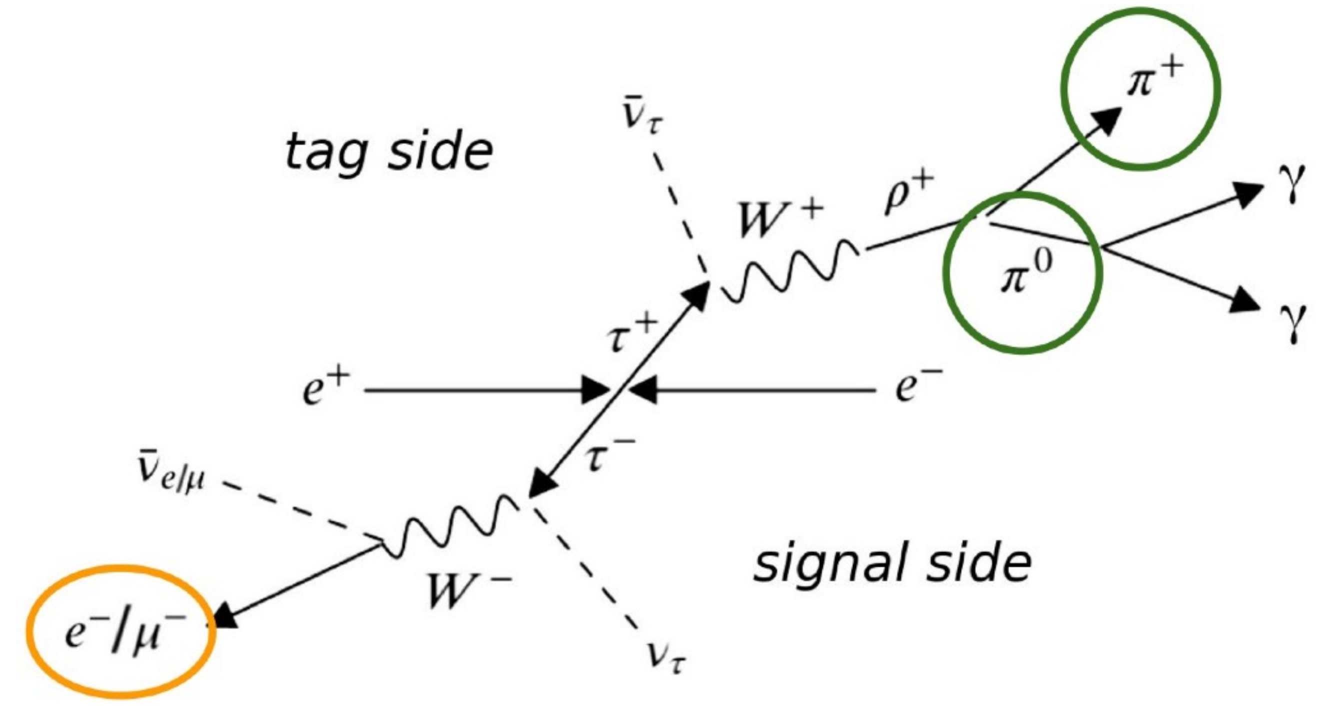
- All asymmetry consistent with SM, the measurements are statistics limited



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





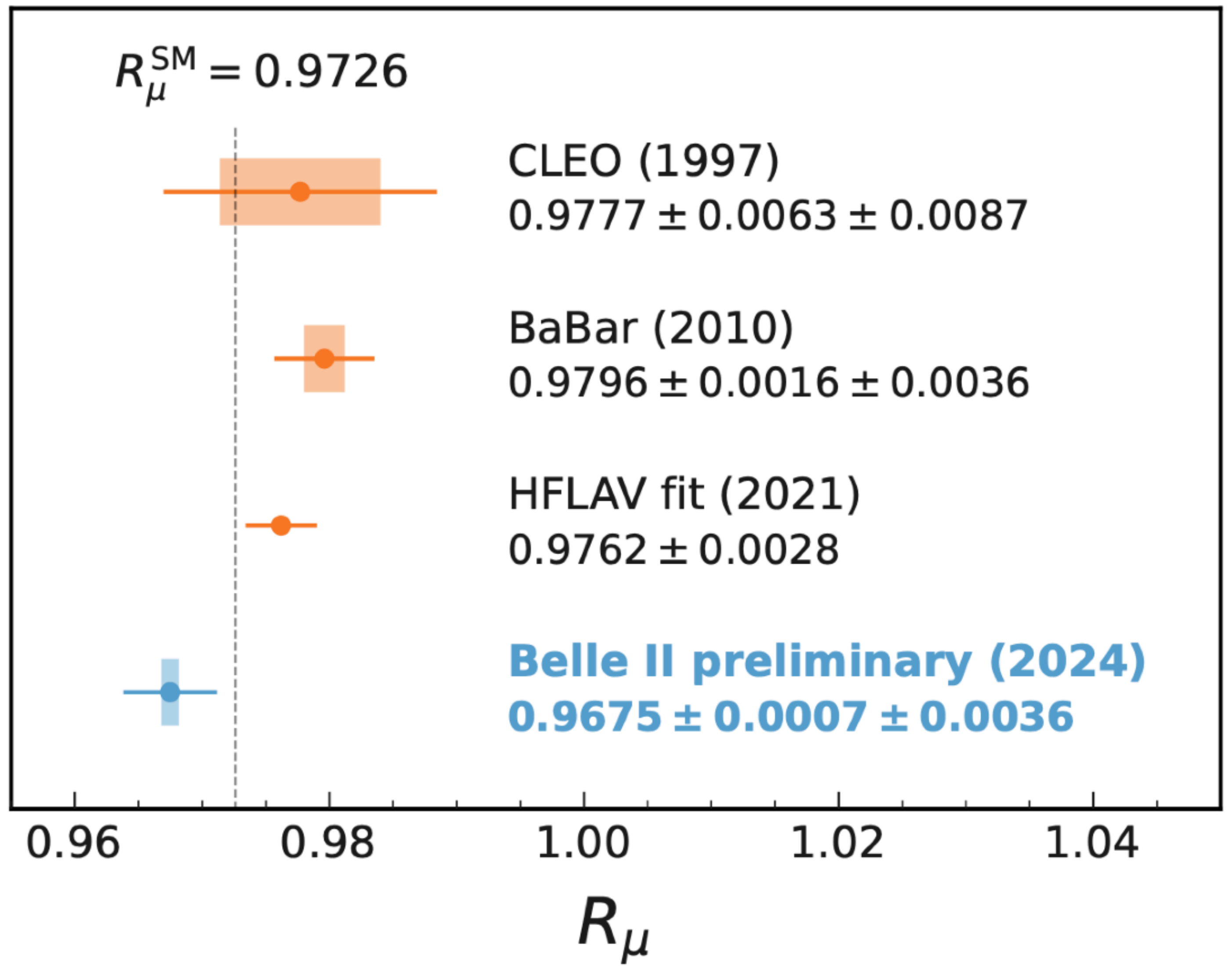
$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

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



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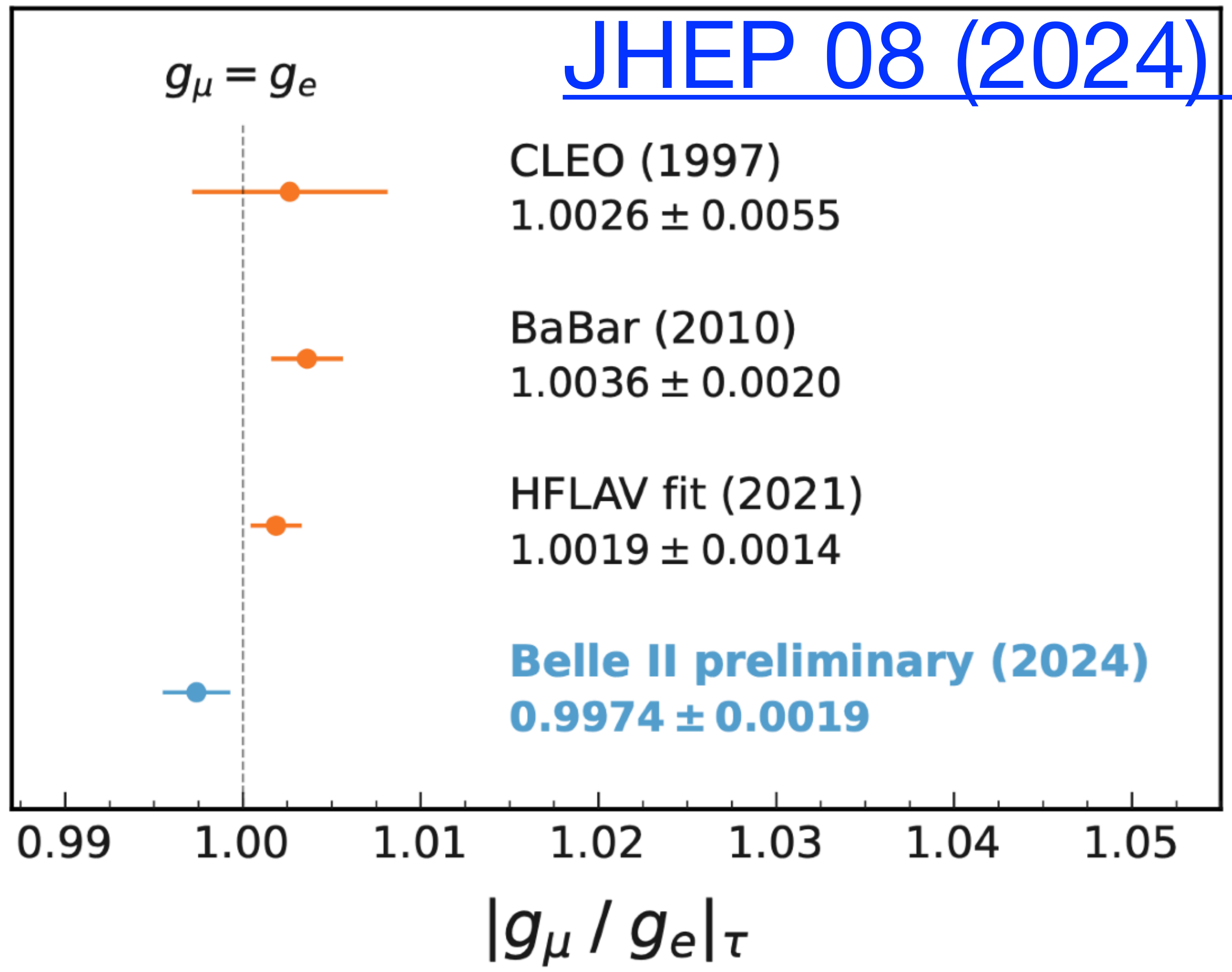


Most precise test of LFU in τ decays

Summary and prospects

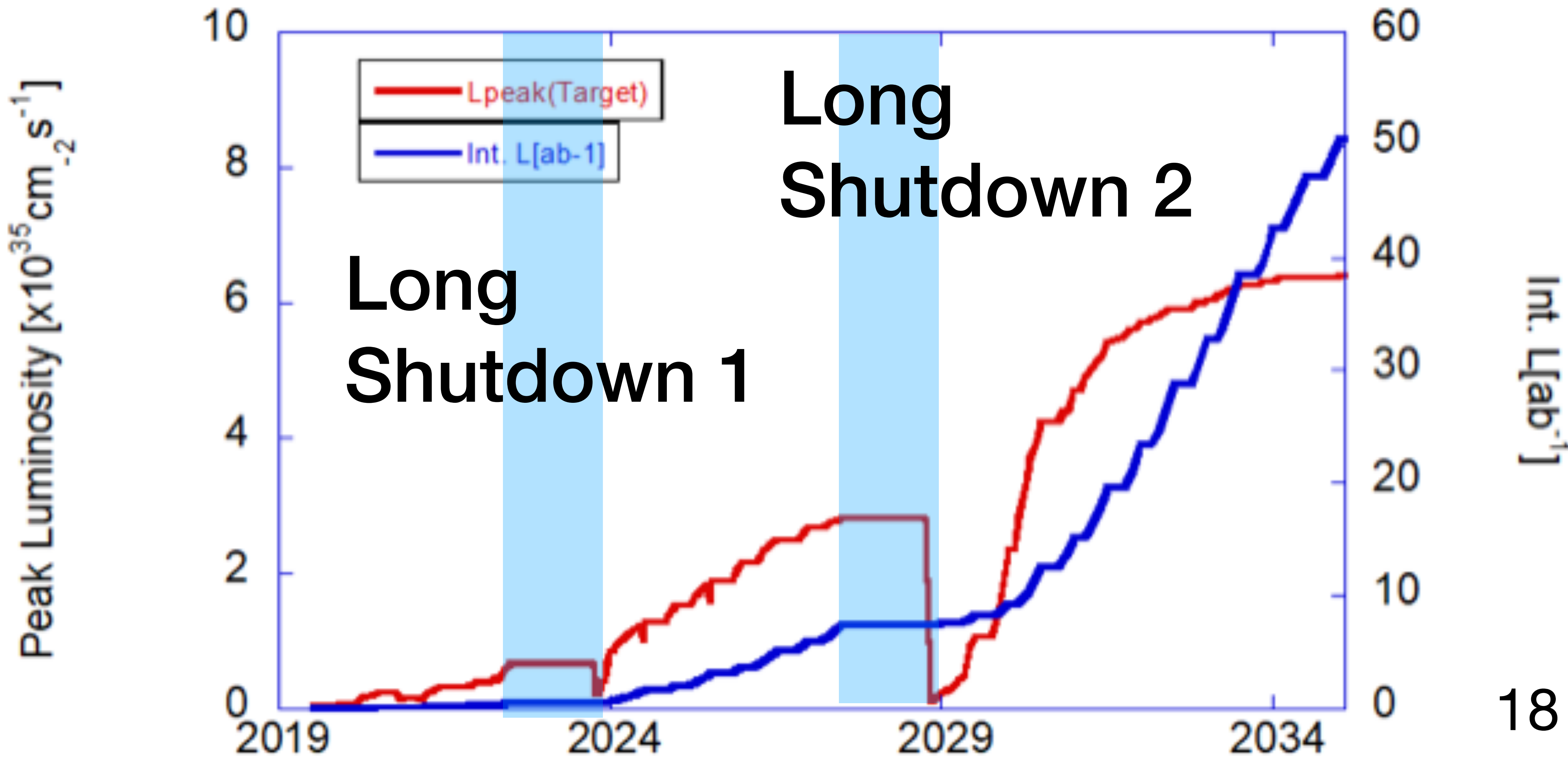
- $R(D^{(*)})$ shows 3.3σ deviation between experimental average value and standard model prediction
  - Hint of Lepton Flavor Universality Violation

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

$$R_{\tau/\ell}(D^*) = 0.262\ ^{+0.041}_{-0.039}\ \text{(stat)}\ ^{+0.035}_{-0.032}\ \text{(syst)}$$

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

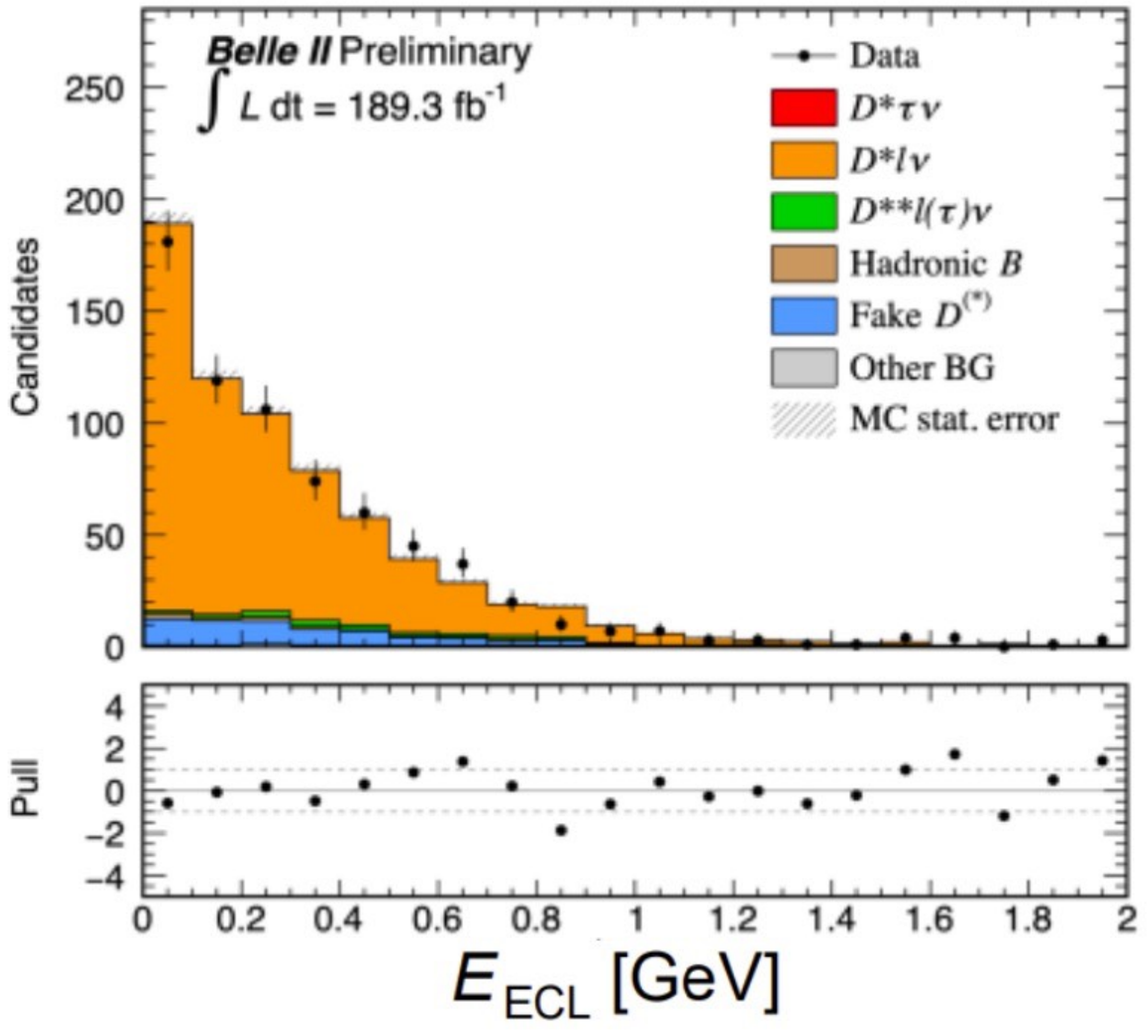
- Light lepton universality, angular asymmetry differences ΔA_x also measured, statistics limited
- Most precise test of LFU in τ decays 362 fb^{-1} data
- SuperKEKB/Belle II accumulated 531 fb^{-1} data, just resumed operation of this run period.

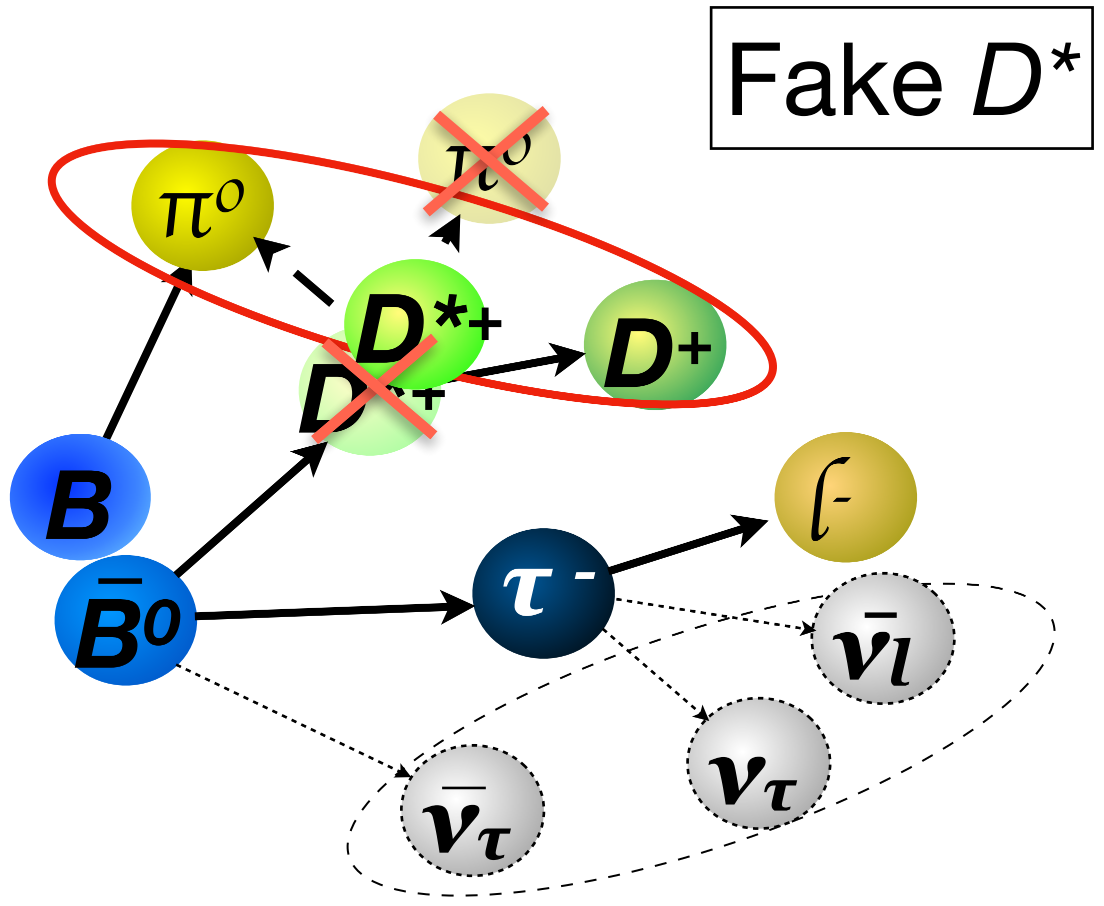


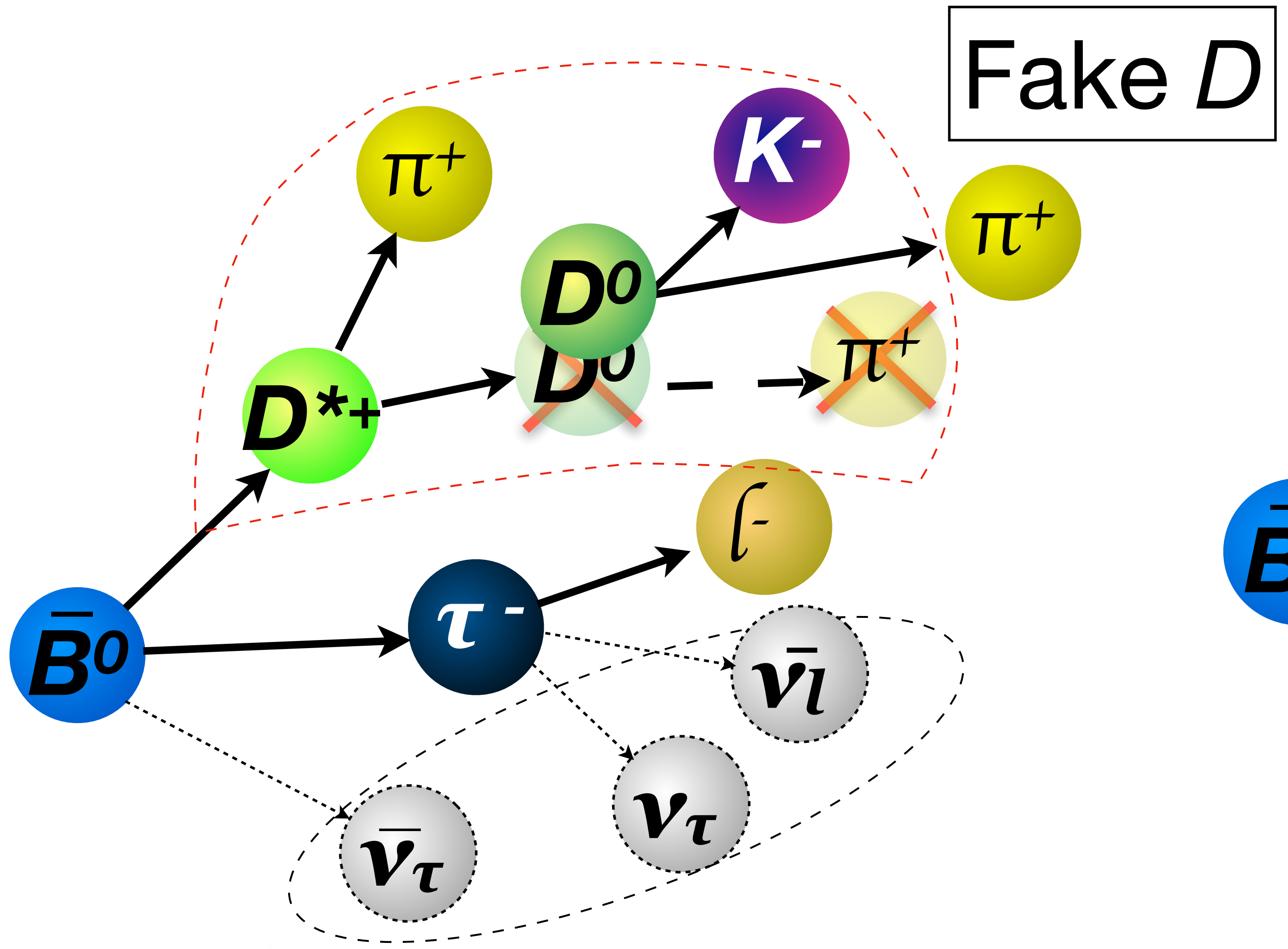
Backup

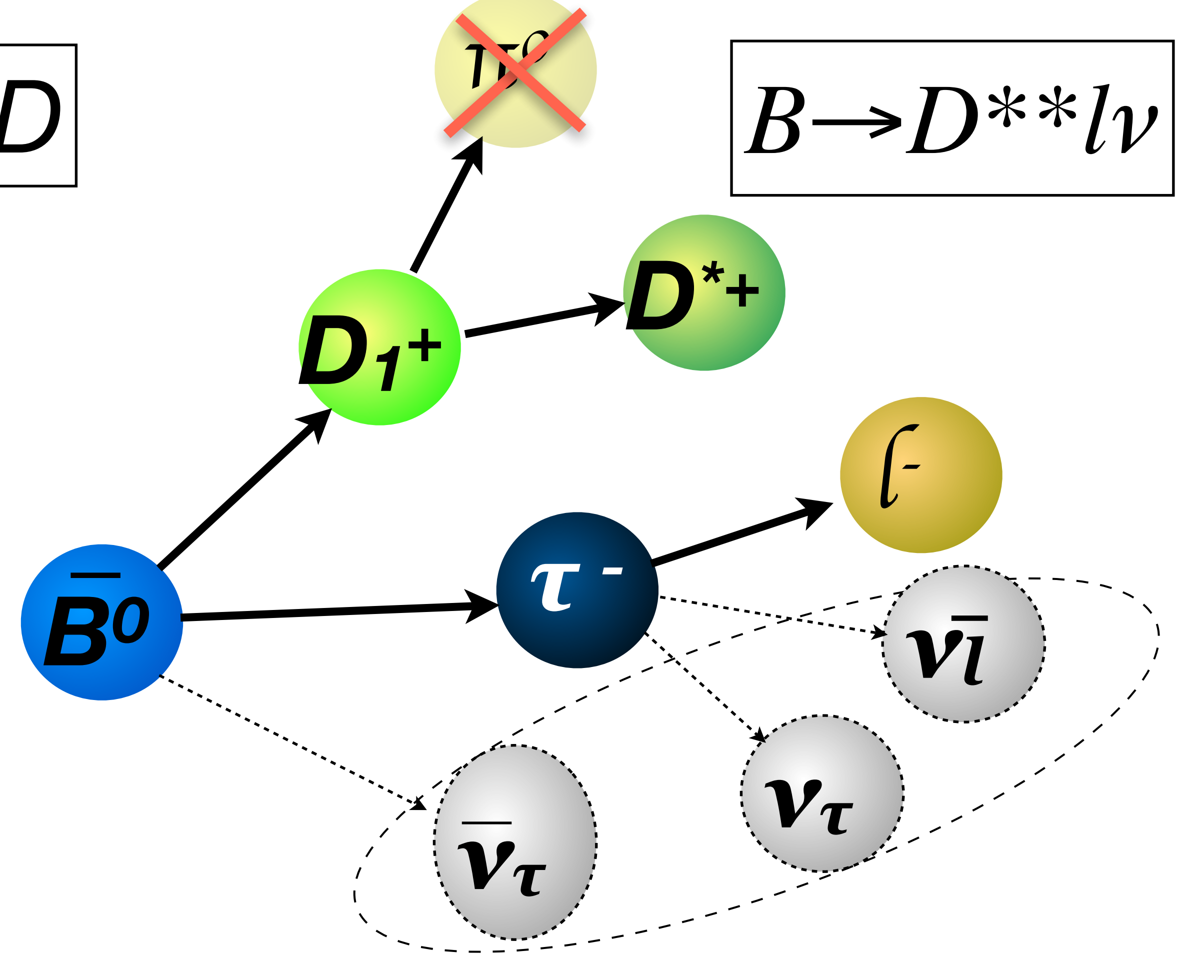
Dominant backgrounds and control samples

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%

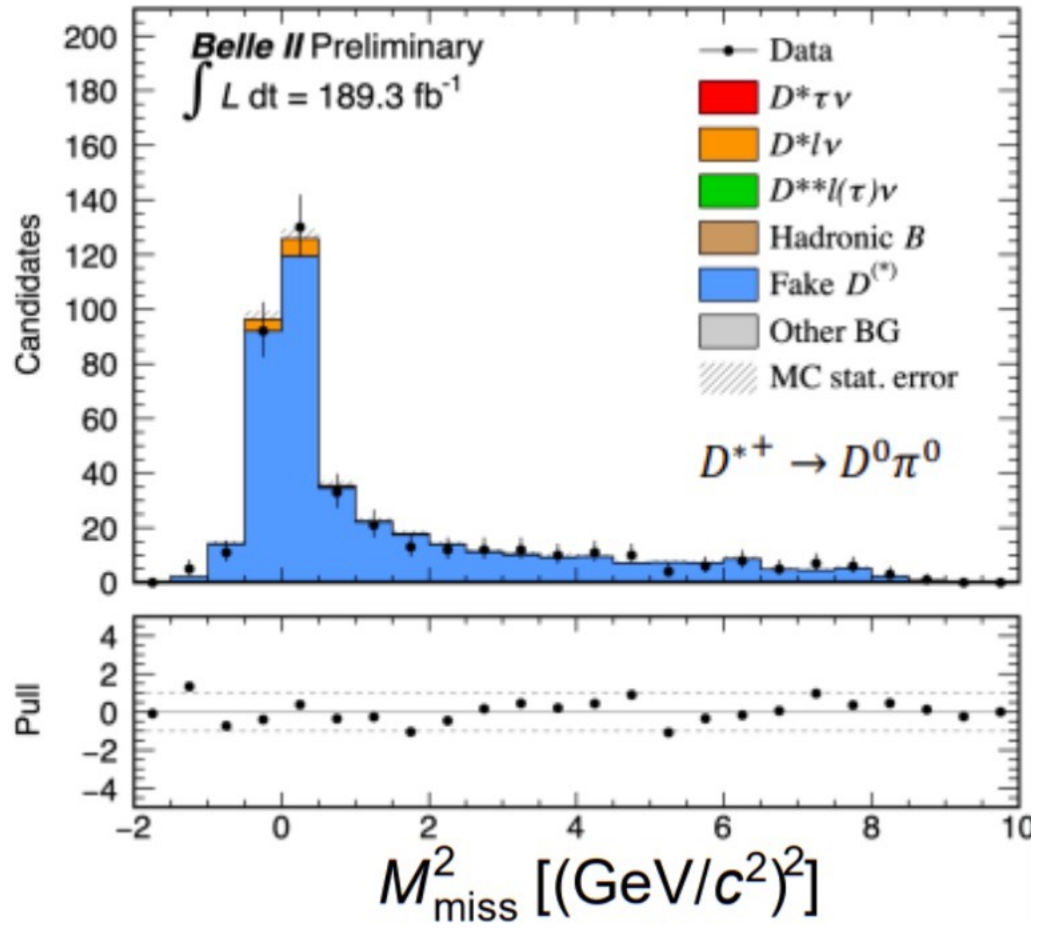




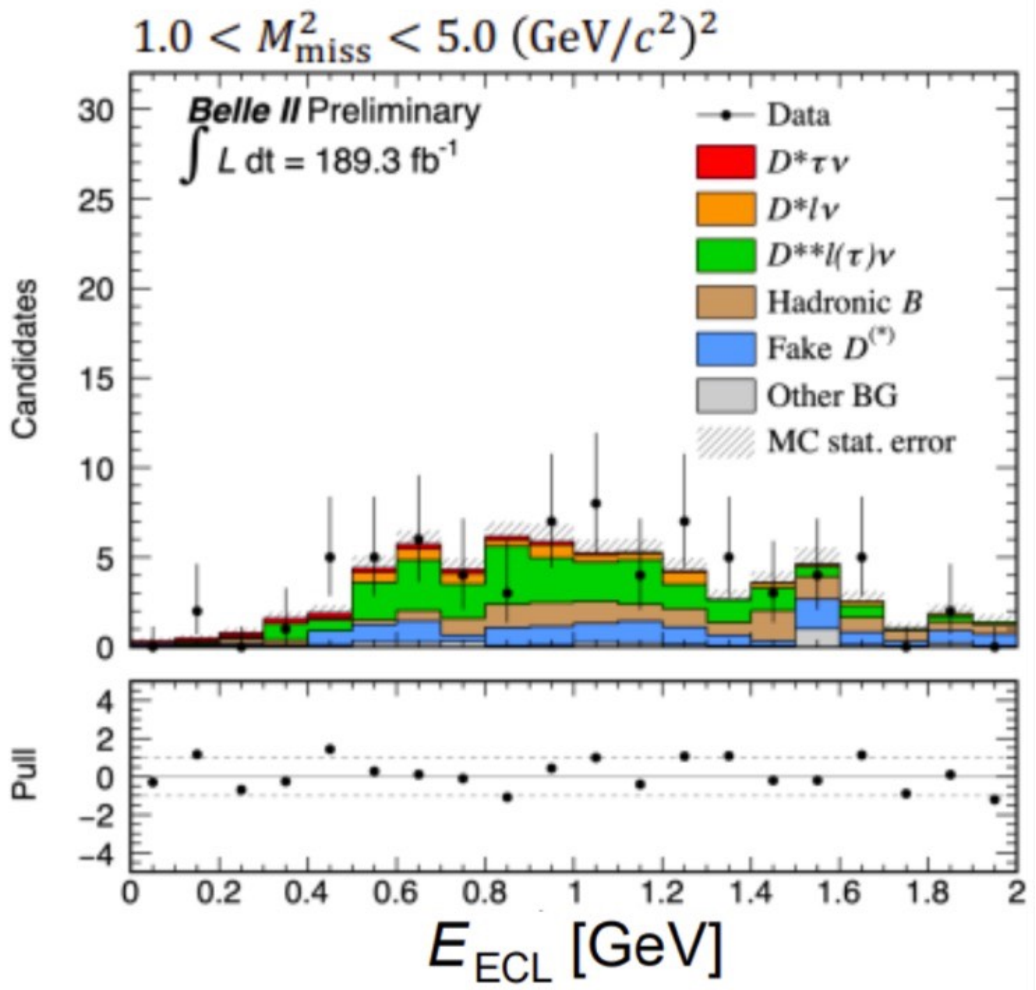




$q^2 < 3.5$ GeV sideband: validate E_{ECL} modeling



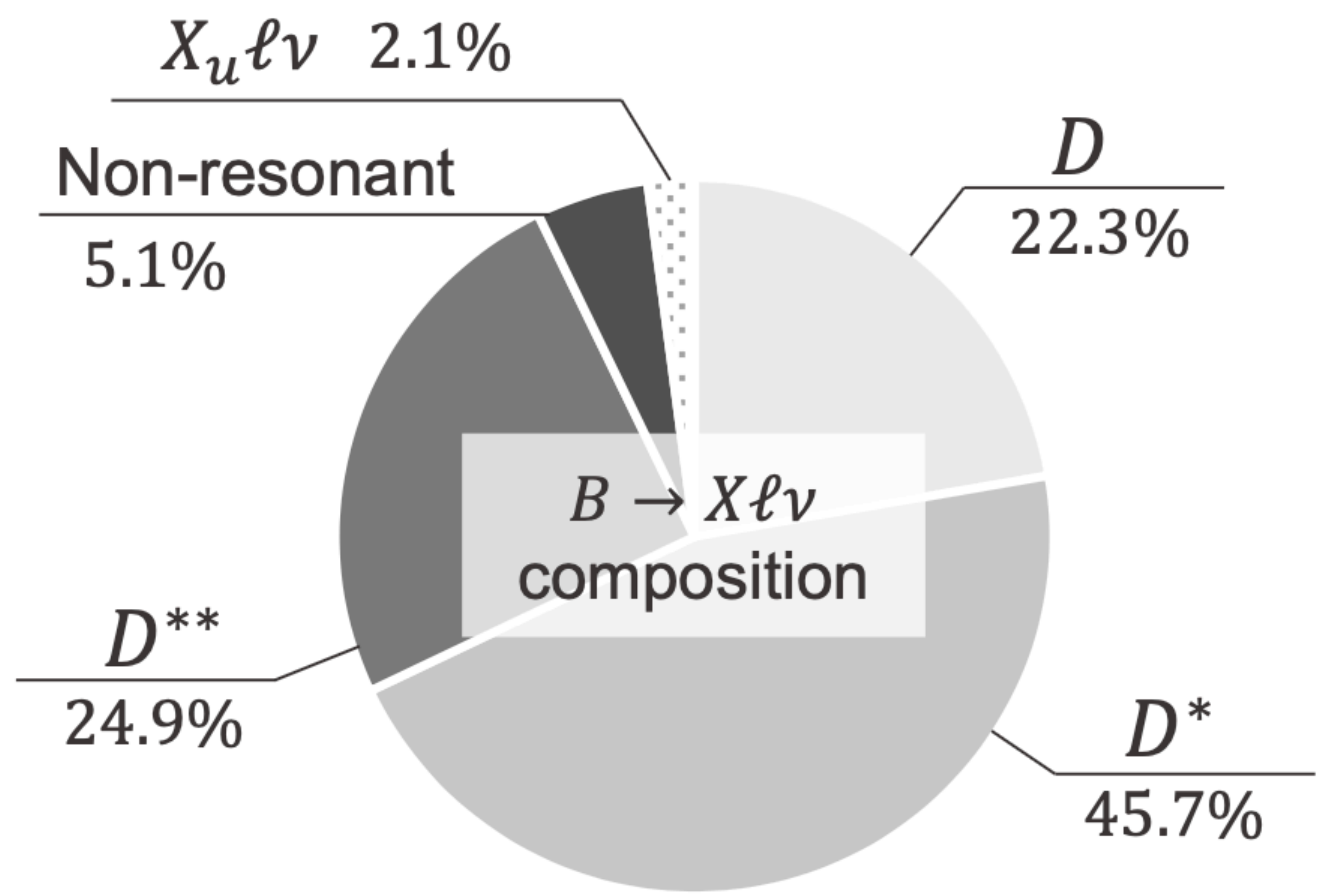
$m(D\pi)$ - $m(D^*)$ sideband: validate fake D^* modeling



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

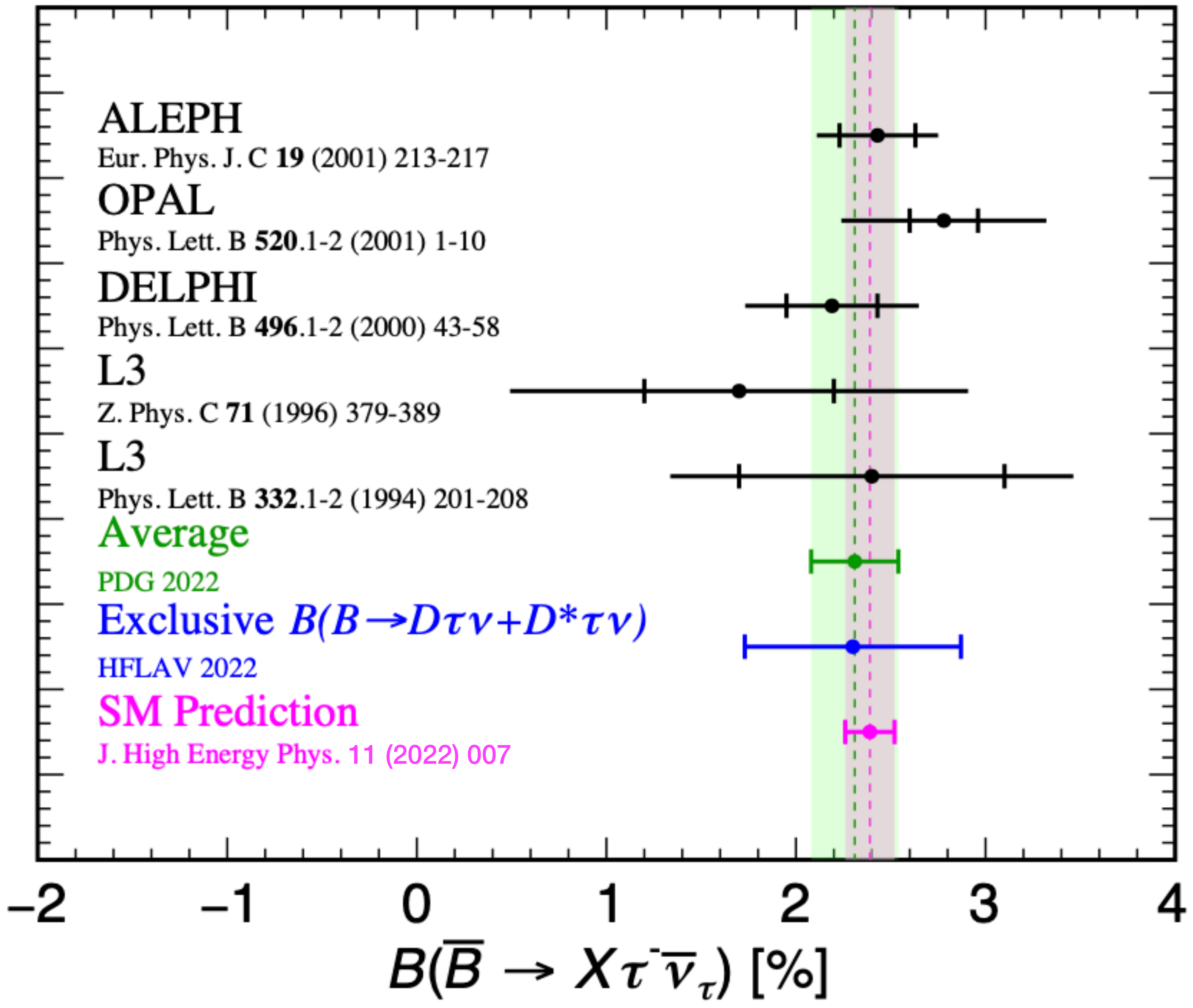
LFU test by $R_{\tau/\ell}(X)$ measurement

- 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

Hadronic tag reconstruction at Belle II

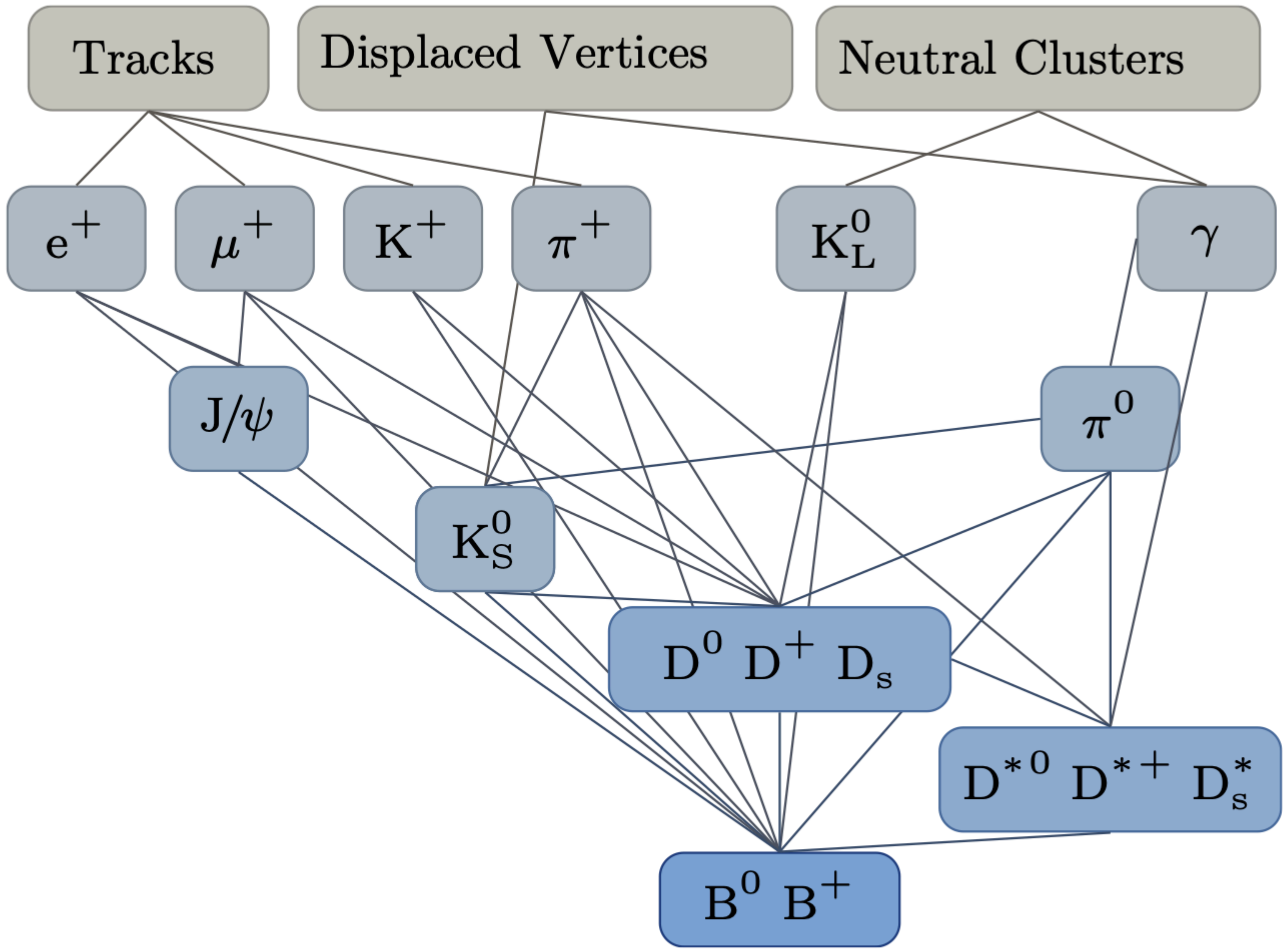
- Hadronic tagging reconstruction: Full Event Interpretation (FEI) trained 200 Boost Decision Tree (BDT) to reconstruct ~100 decay channels, ~10,000 B decay chains
  - ε=0.30% for $B^{\pm}$
  - ε=0.23% for B^{0}

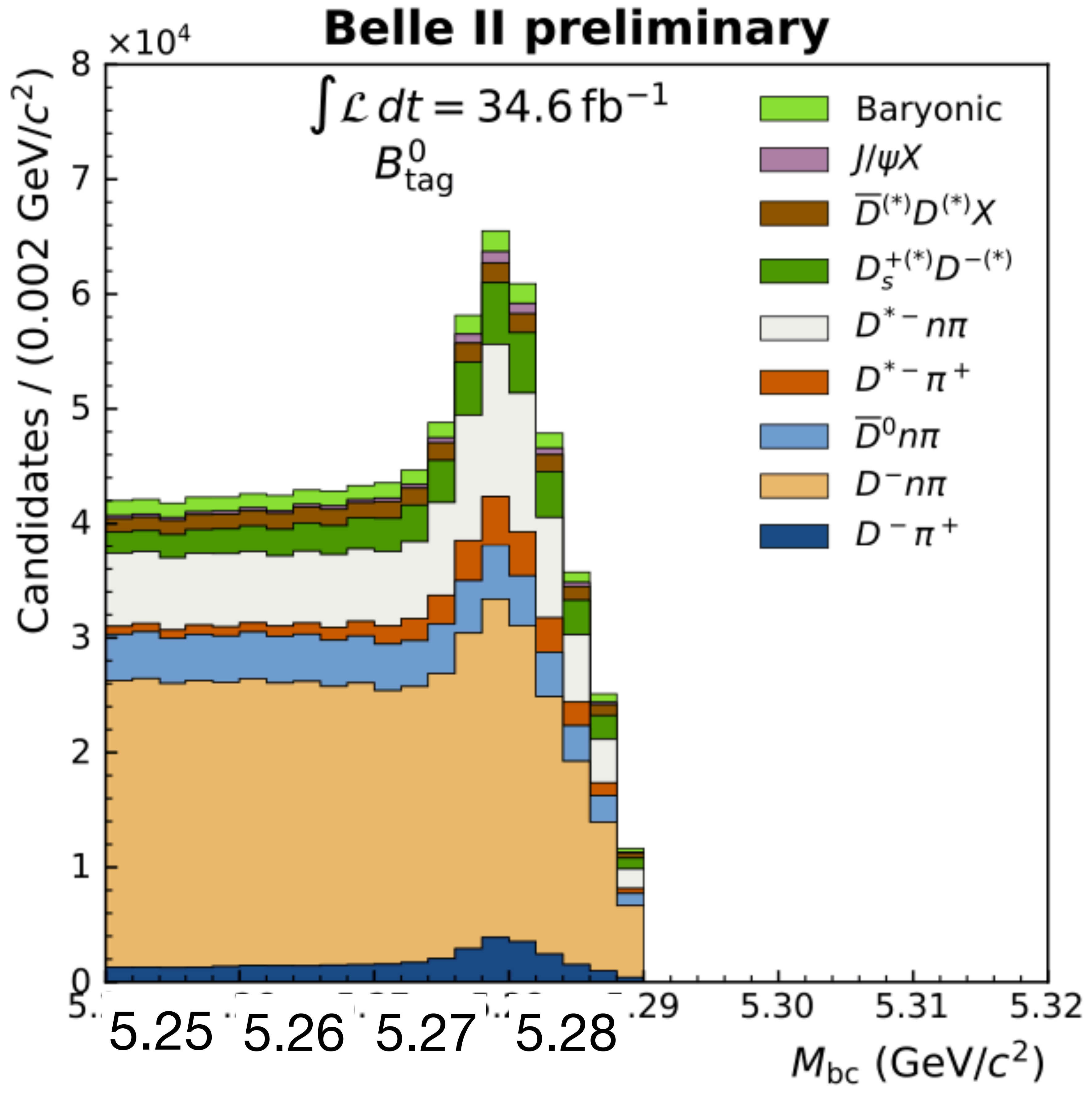
10-30% increased

- 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





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

Obtained parameters from fit

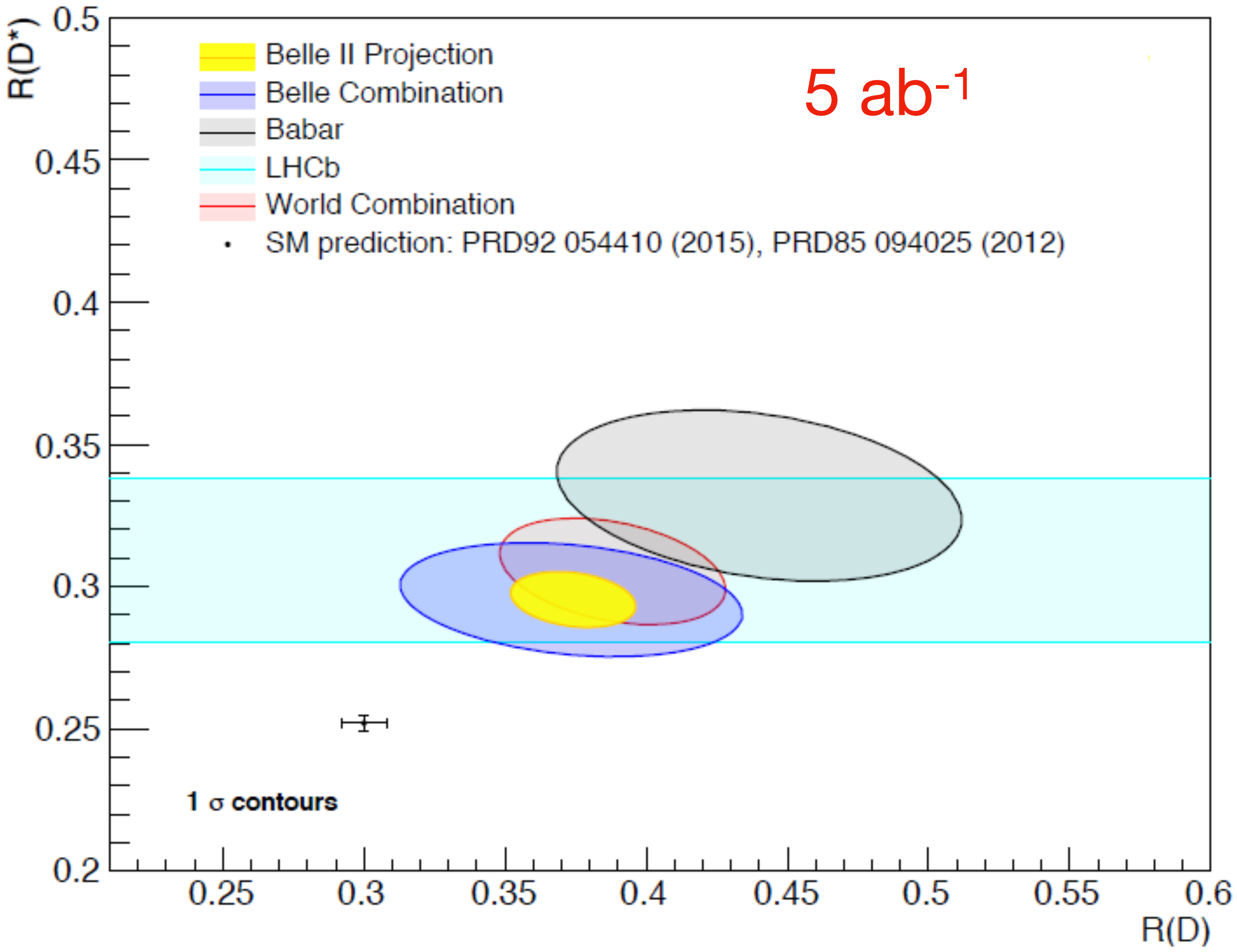
Parameter	Observed (expected) value		
$R(D^*)$	$0.262\ ^{+0.041}_{-0.039}$		
$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell)$ [%]	$5.27\ ^{+0.25}_{-0.24}\ (5.03 \pm 0.11)$		
$\mathcal{B}(B^- \to D^{*0}\ell^-\bar{\nu}_\ell)$ [%]	$5.50\ ^{+0.28}_{-0.27}\ (5.41 \pm 0.11)$		
	$D^{*+} \to D^0\pi^+$	$D^{*+} \to D^+\pi^0$	$D^{*0} \to D^0\pi^0$
$N_{D^{**}\ell\nu}$	$34.7^{+19.2}_{-18.2}$ (61.6 ± 2.2)	$5.8^{+5.6}_{-4.7}$ (9.0 ± 0.9)	$64.5^{+19.3}_{-18.3}$ (46.0 ± 2.0)

- ✓ Consistent with the world averages.
- ✓ Consistent within $2\sigma_{\text{stat}}$.

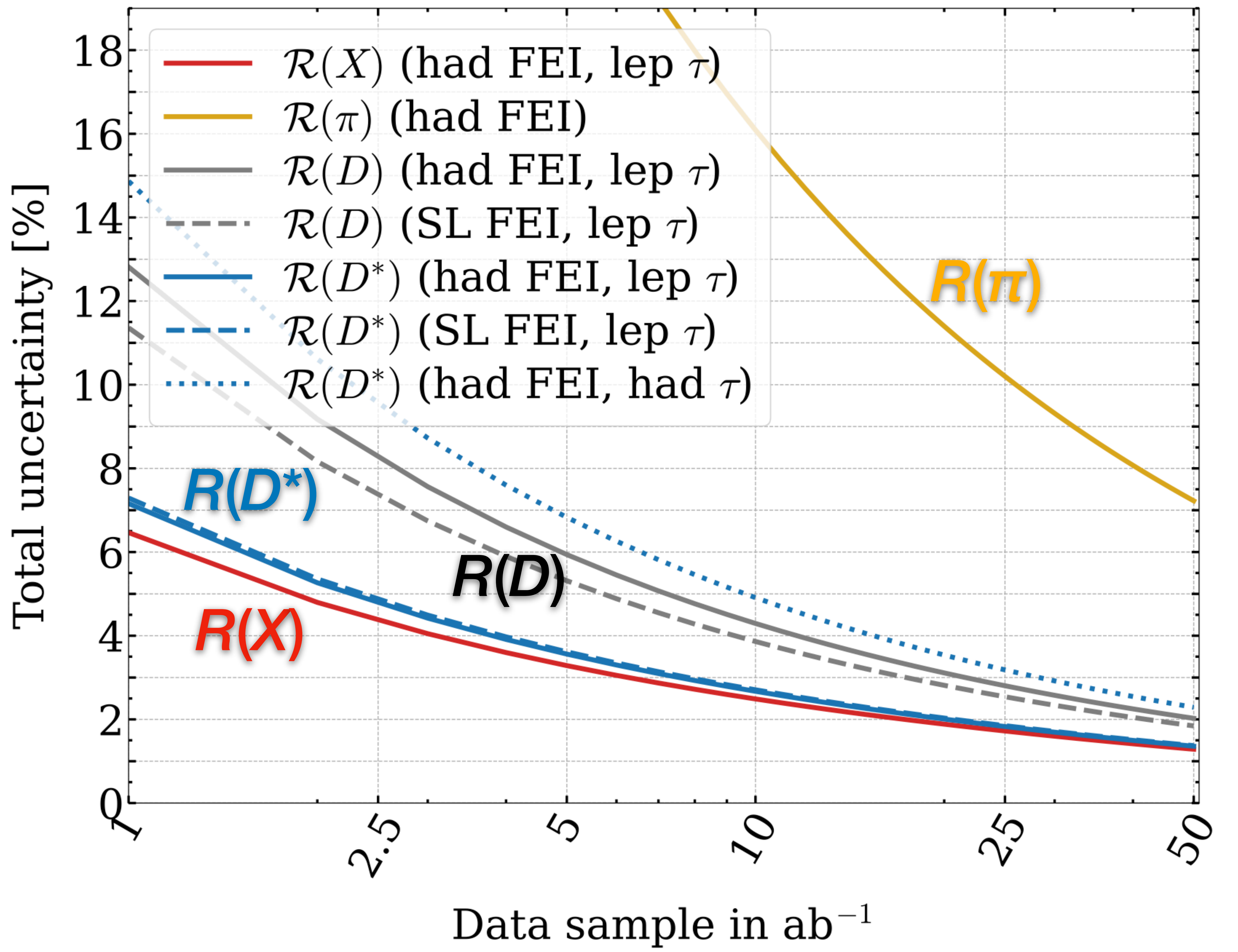
Taking into account systematic uncertainties from branching fractions of $\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell$ decays, the deviations from simulation are reduced to $0.5 - 0.9\sigma$.

Expected sensitivity of LFU test at Belle II

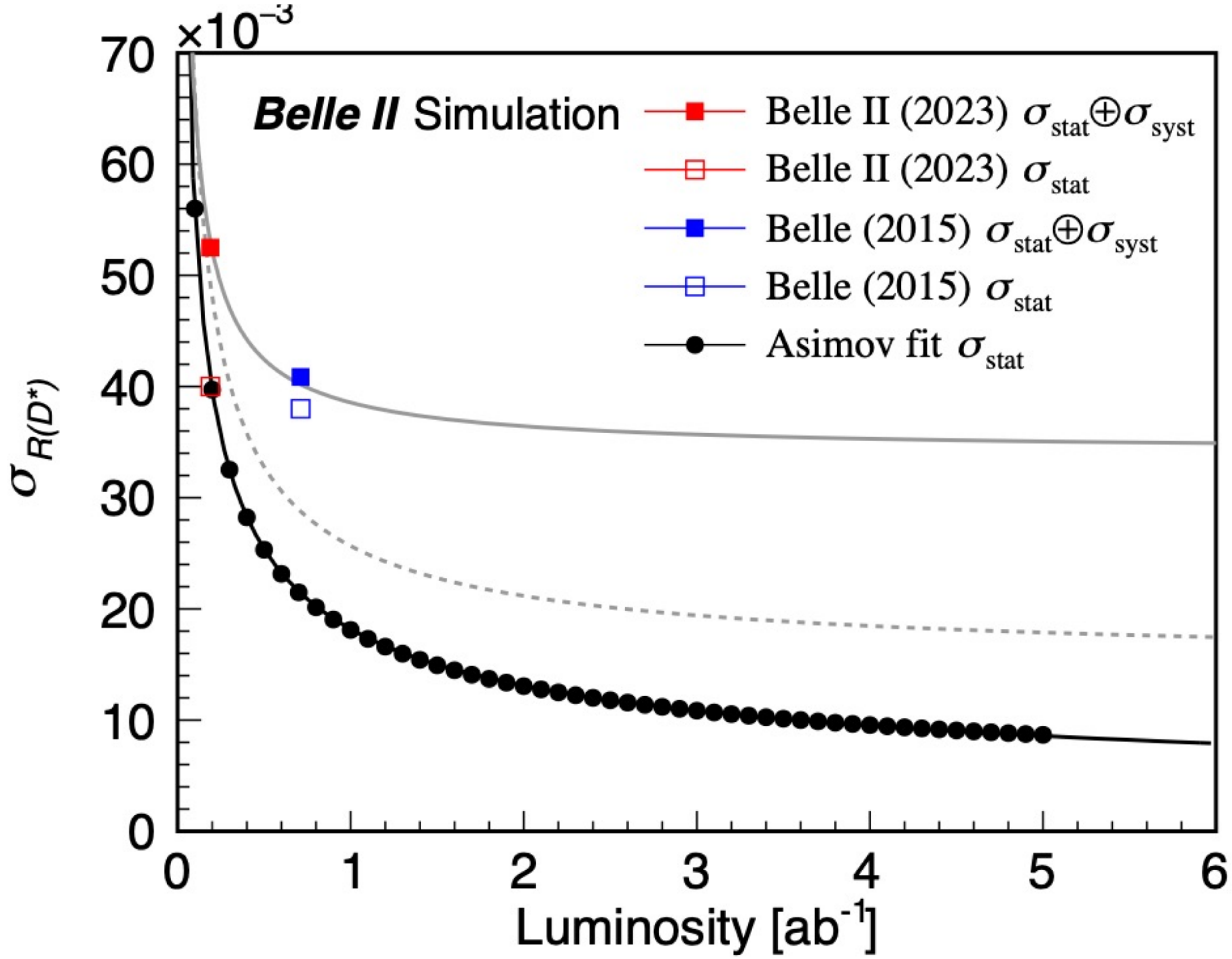
The Belle II Physics Book, PTEP 2019, 123C01



arXiv:2207.06307



Expected sensitivity of LFU test at Belle II



R(D)*

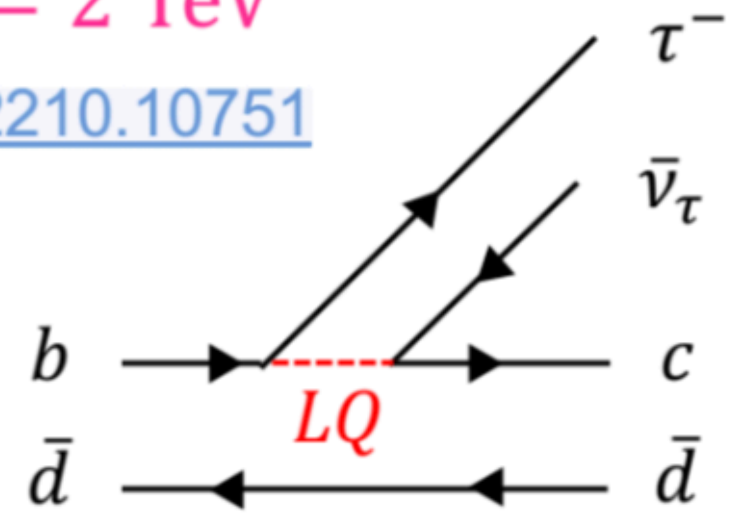
R(D*) as the single measurement with 3.6% statistical and 13.5% (6.9%) total uncertainties in the conservative (aggressive) scenarios using data of 4.0 ab^{-1} collected by April 2026

Leptoquark model to explain R(D(*))

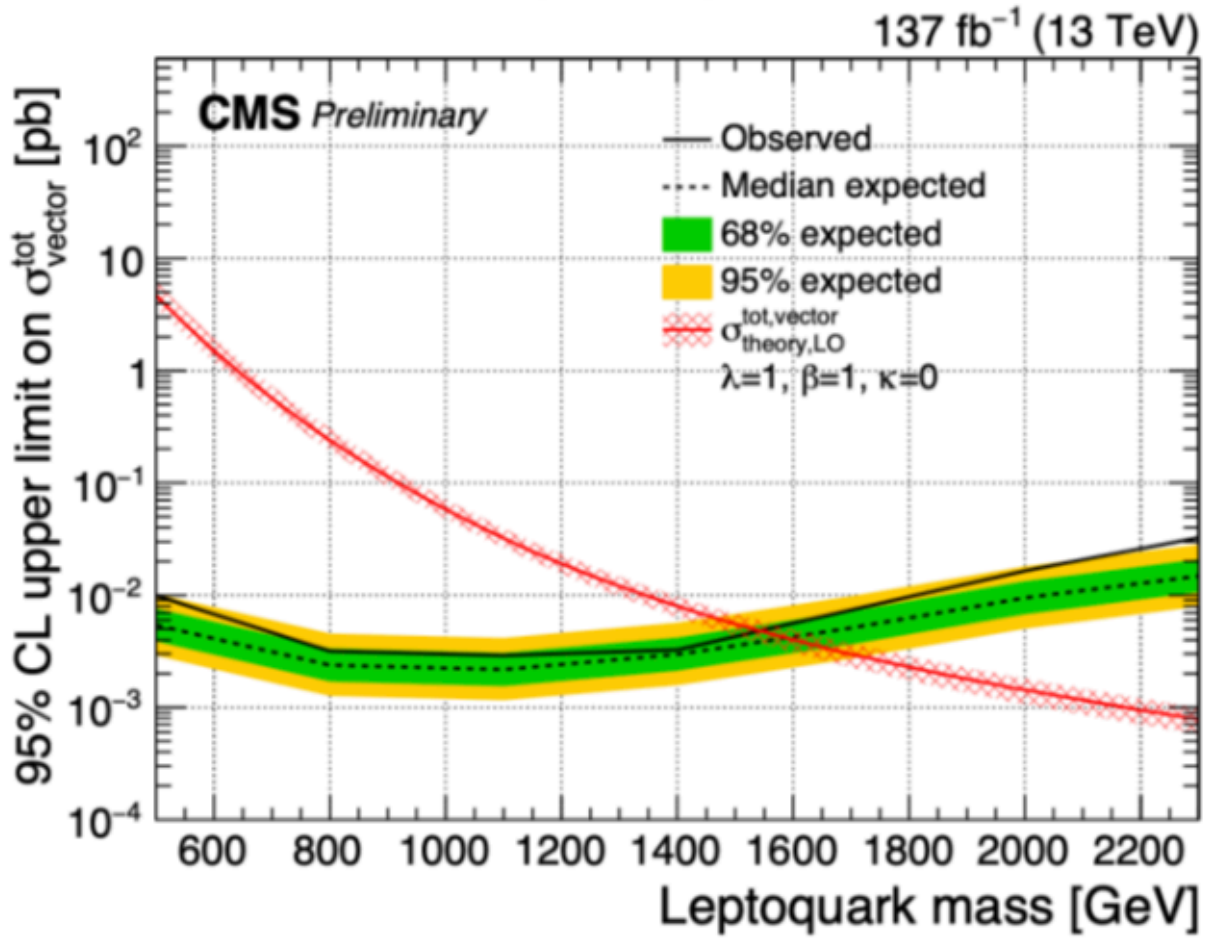
Model	Coefficients	
	$\Lambda_{LQ} = M_{LQ}$	$\mu_b = m_b$
$SU(2)_L$-singlet vector U_1^{μ}	C_{V_L}, C_{S_R}	C_{V_L}, C_{S_R}
$SU(2)_L$-singlet scalar S_1	C_{V_L}, $C_{S_L} = -4C_T$	C_{V_L}, $C_{S_L} = -8.7C_T$
$SU(2)_L$-doublet vector R_2	C_{V_R}, $C_{S_L} = +4C_T$	C_{V_R}, $C_{S_L} = +8.2C_T$

$M_{LQ} = 2$ TeV

arXiv:2210.10751

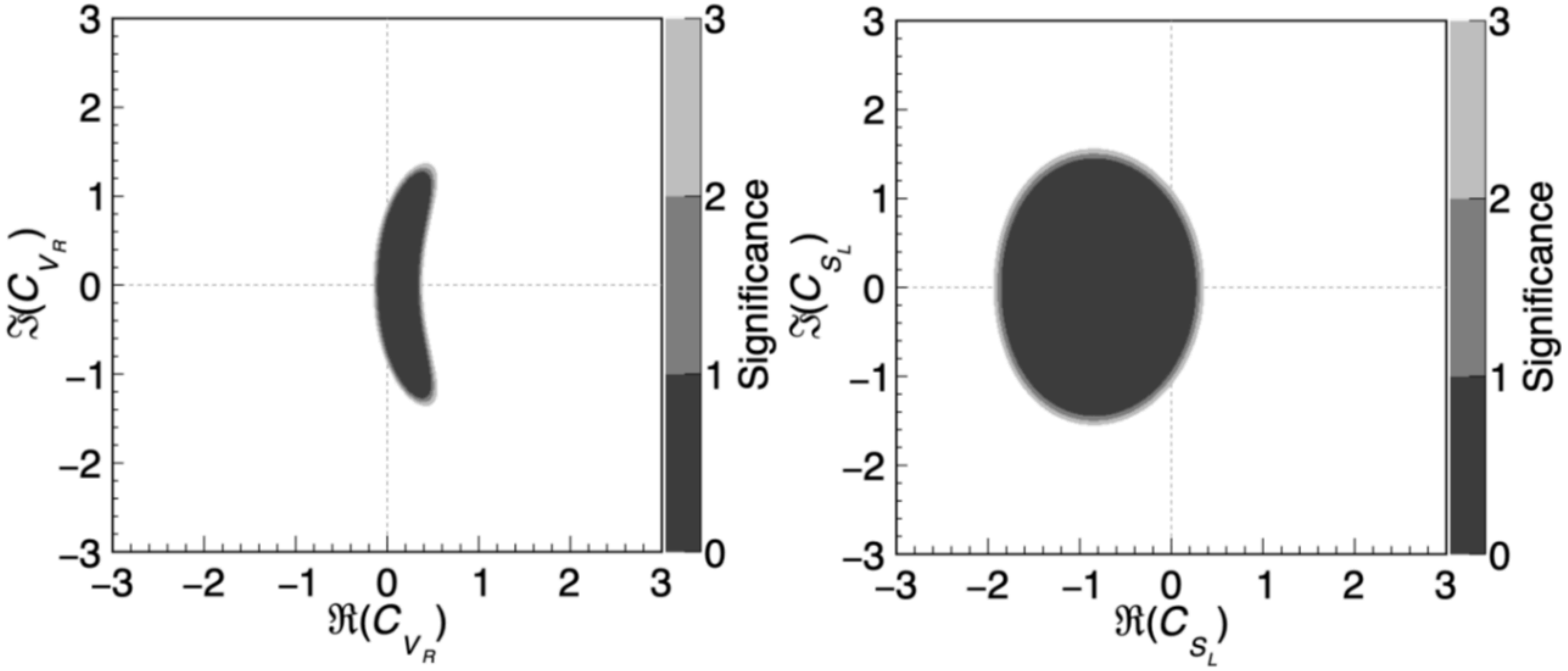


Vector leptoquark model



CMS-PAS-EXO-19-016

Leptoquark model (R_2 type)



All three leptoquark models have favored regions within 1σ of the $R(D^{(*)})$ world average.

The excess in $R(D^{(*)})$ can be explained with three leptoquark models of 2 TeV/c^2.