Testing Lepton Flavor Universality with the Belle and Belle II experiments

周启东(ZHOU Qi-Dong)
qzhou@sdu.edu.cn
Institute of Frontier and Interdisciplinary Science,
Shandong Univ. (Qingdao)

21 Nov. 2024, Online
70th Flavor Physics Lecture

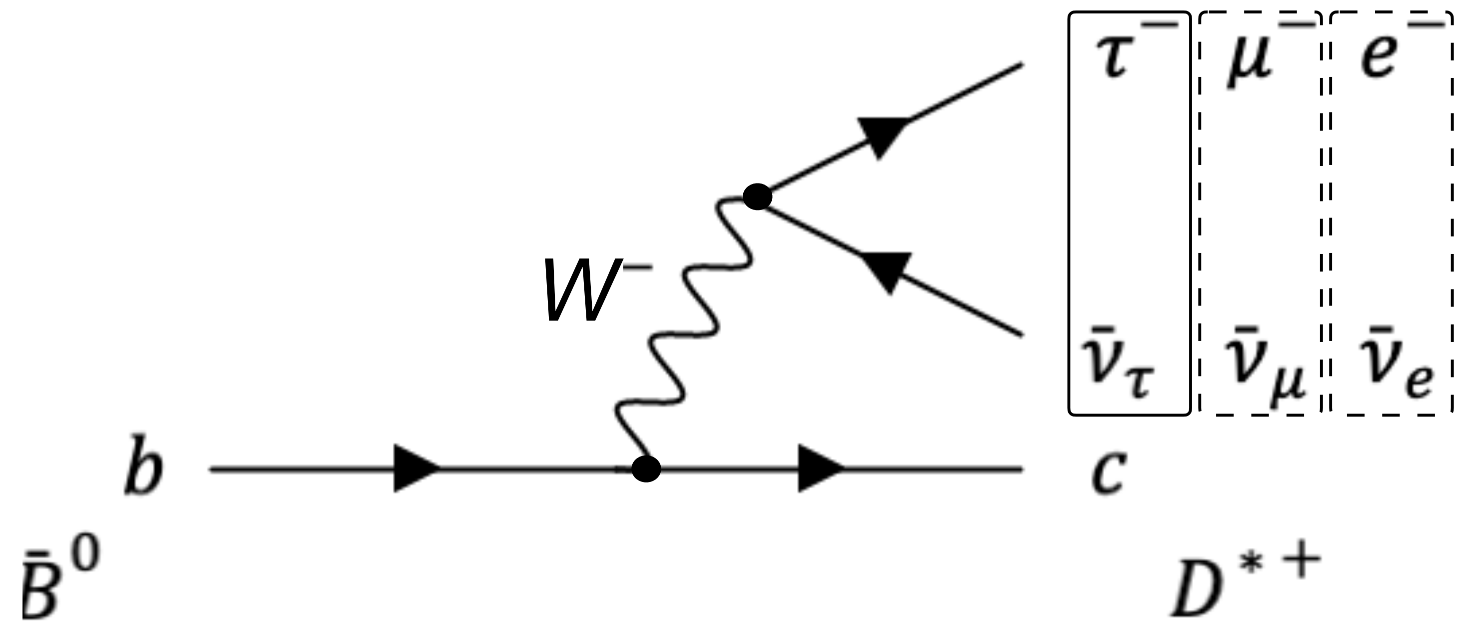
Lepton Flavor Universality

- Lepton Flavor Universality (LFU): A fundamental axiom of standard model is *W* boson couples, g_W, to **three generations** of leptons with **equal strength**
  - Description by matrix elements for leptonic and hadronic currents as a four Fermi interaction
  - Experiments confirmed LFU using W/Z boson decays, light meson decays, or lepton decays
- Difference in kinematics and Higgs coupling due to different lepton masses
  - Charged lepton mass changes kinematics and modifies form factors in the hadronization
  - QED corrections depend on lepton velocity (τ vs. ℓ (e, μ))

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left(\bar{c}\gamma_\mu P_L b\right)\left(\bar{l}\gamma_\mu P_L \nu_l\right) + \text{h.c.}, \; (l = e, \mu, \tau)$$

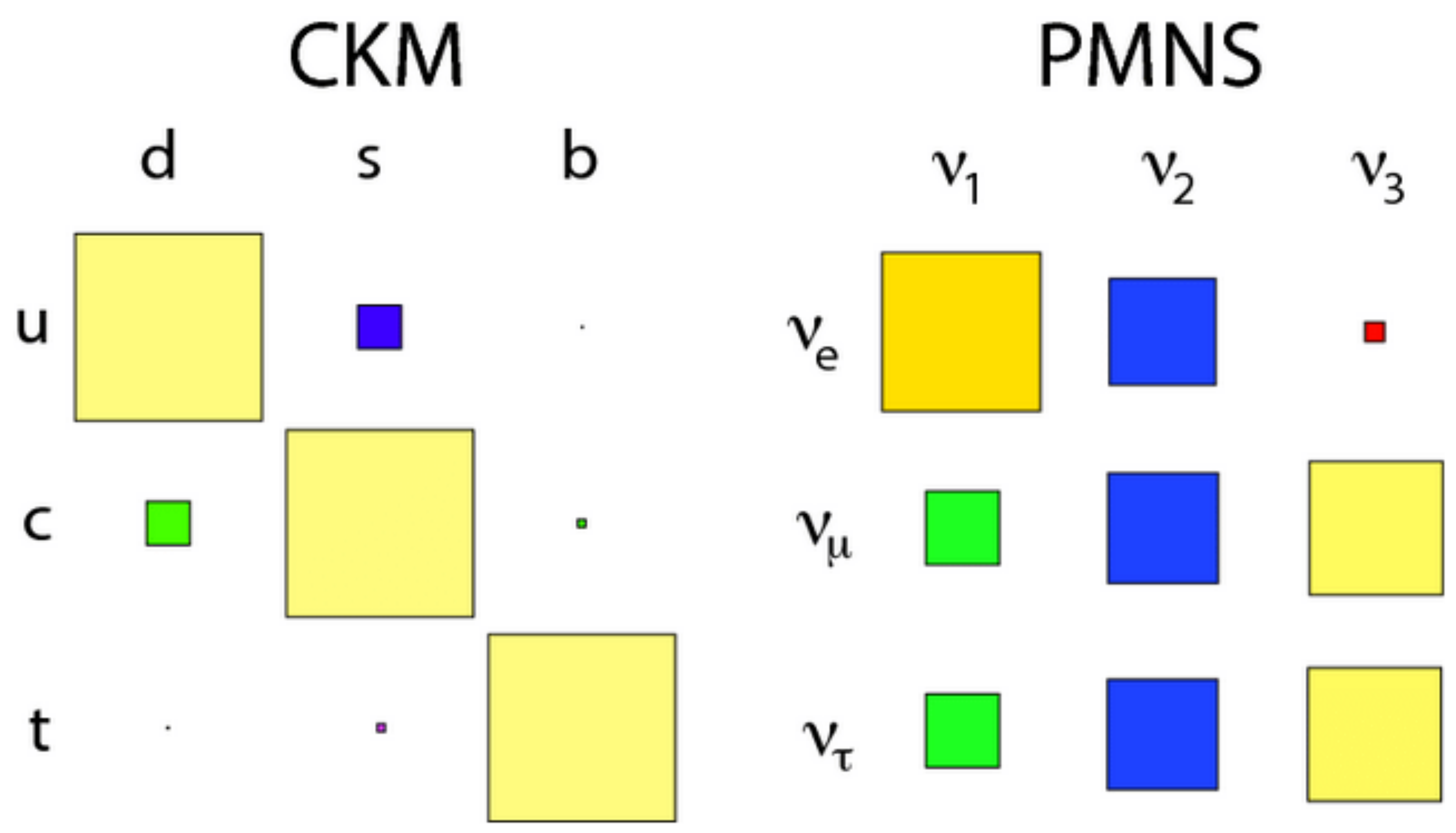
$$\frac{G_F}{\sqrt{2}} = \frac{g_W}{8M_W^2},$$

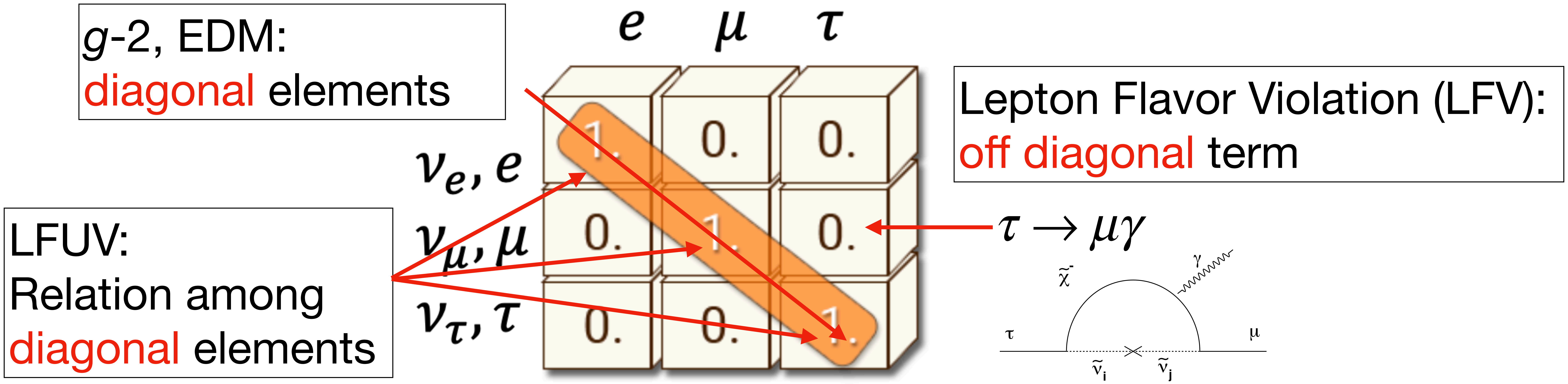
g_W: $SU(2)$ weak coupling constant



Motivation for studying LFUV

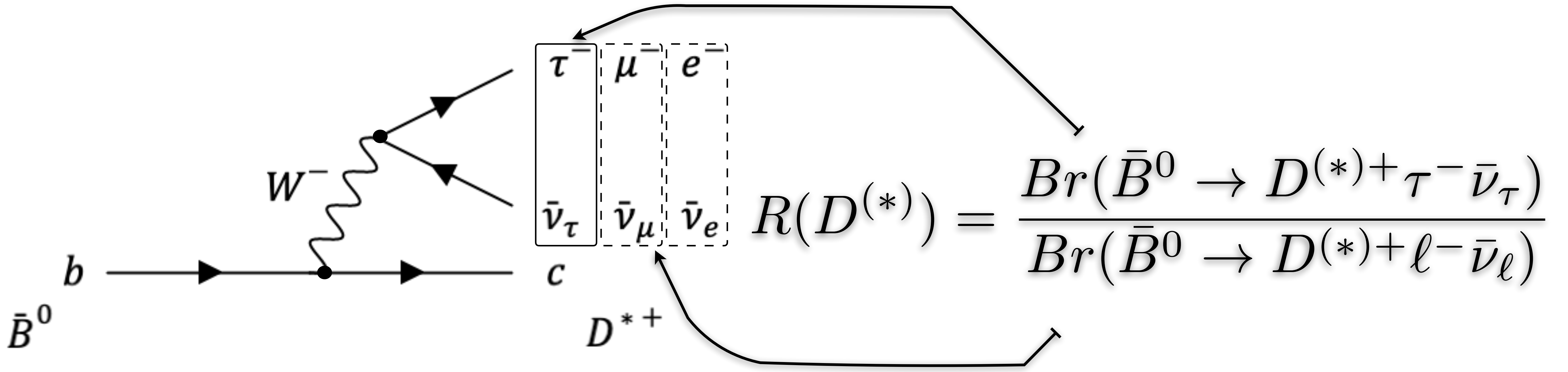
- SM fields do mix:
  - Quarks sector -> CKM matrix
  - Neutrinos sector -> PMNS matrix
- Charged leptons ->
  the matrix diagonal-like?(neutrino mass)
- LFUV: diagonal terms not all equal

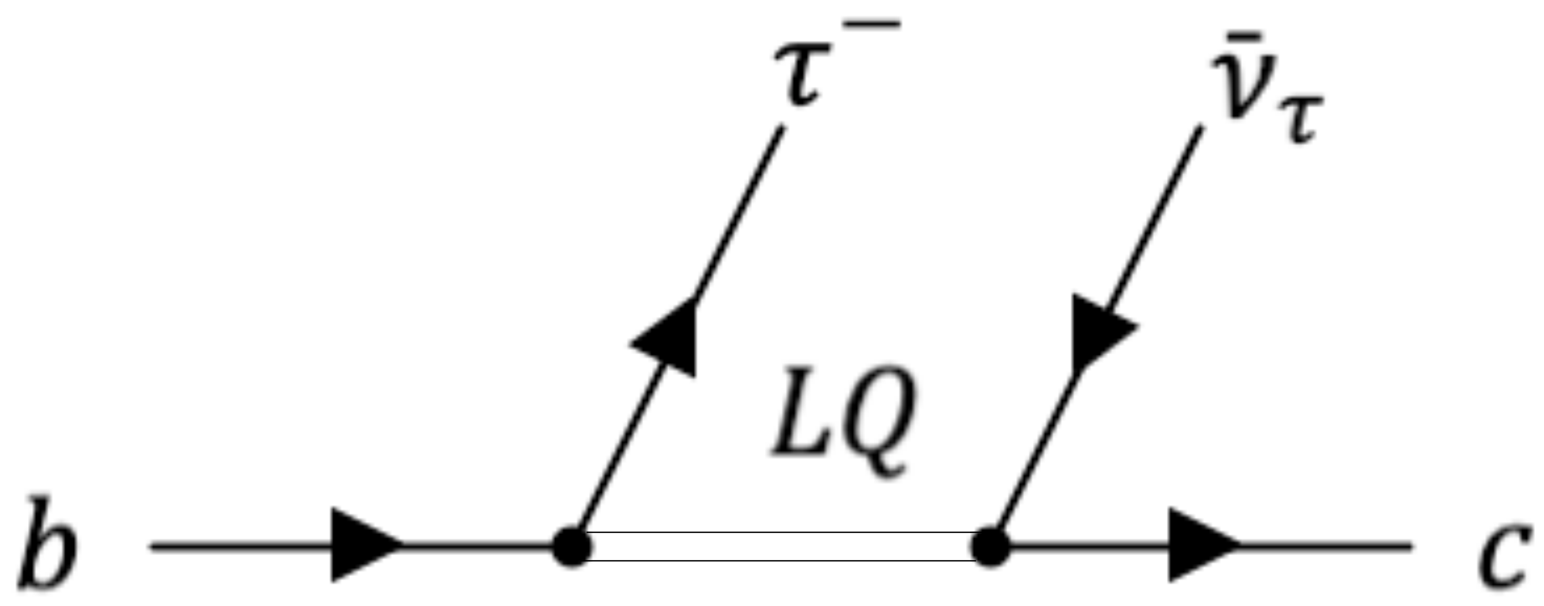




LFU test with semileptonic *B* decays

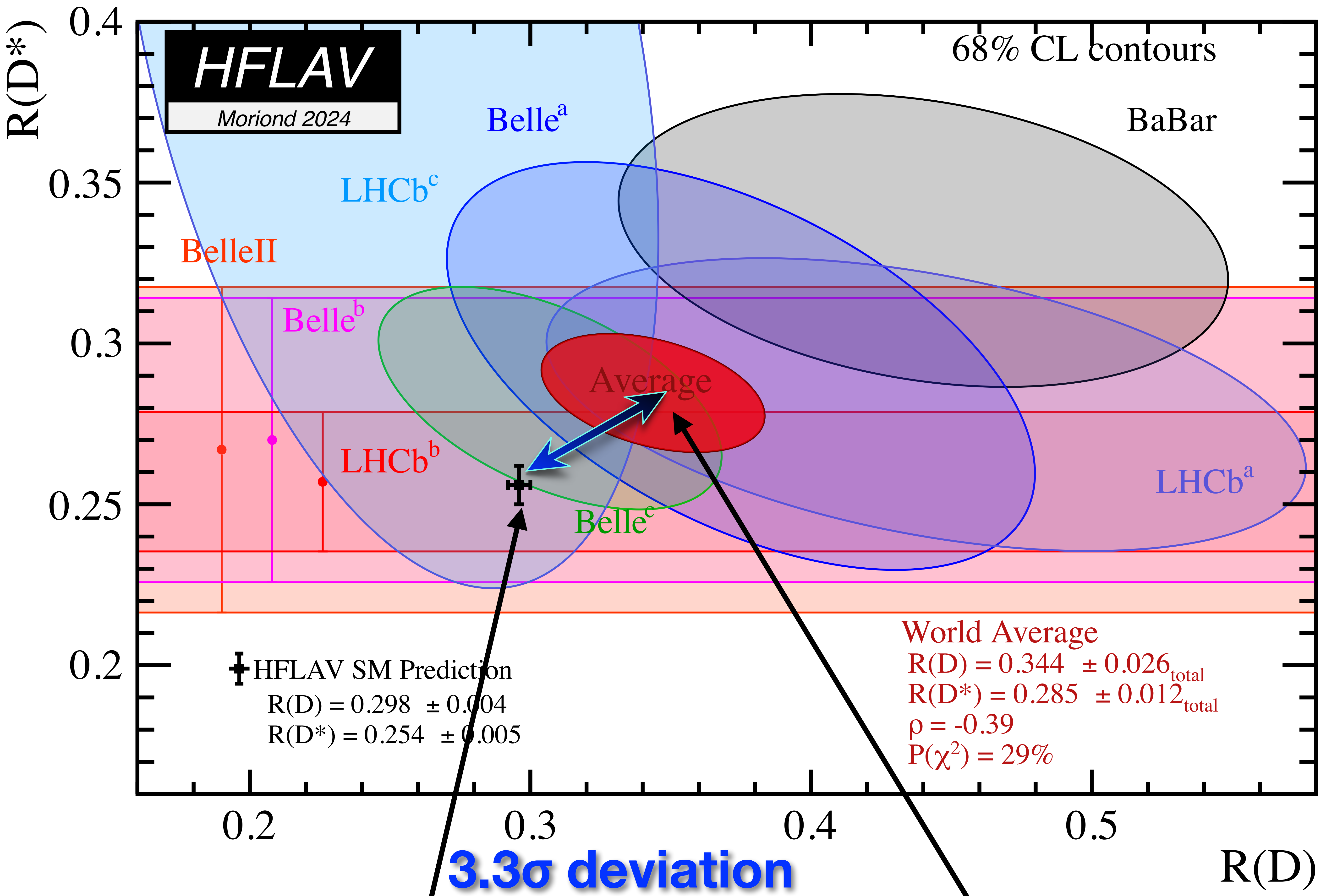
- Ratios of $b \to q\tau\nu / q\mu\nu / qe\nu$ branch fractions cancel out most of the uncertainties on $|V_{cb}|$, **form factors** and the **experimental systematics**
- $B \to D^{(*)}\tau\nu$ sensitive to New Physics (NP) because the massive 3rd generation *b* quark and τ lepton are involved
- Sensitivities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





		Branching fraction [%]	
		$\mathcal{B}(B^0)$	$\mathcal{B}(B^+)$
World average ($\ell = e$ or μ)	$\overline{B} \to X_c \ell^- \overline{\nu}_\ell$	10.1 ± 0.4	10.8 ± 0.4
	$\overline{B} \to D^* \ell^- \overline{\nu}_\ell$	5.41 ± 0.11	5.03 ± 0.11
SM	$\overline{B} \to D^* \tau^- \overline{\nu}_\tau$	~1.37	~1.28

"*B* anomaly" in semileptonic decays



3.3σ deviation

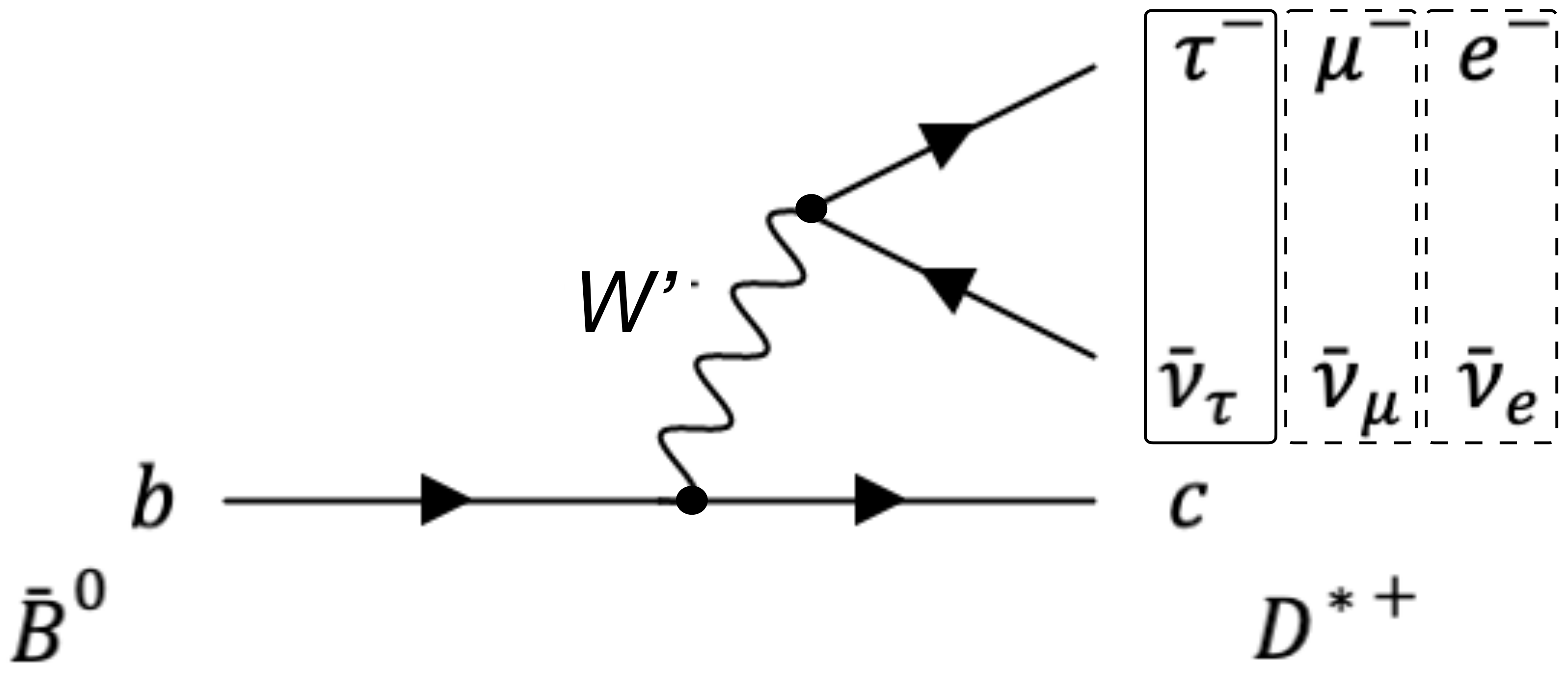
Standard Model prediction

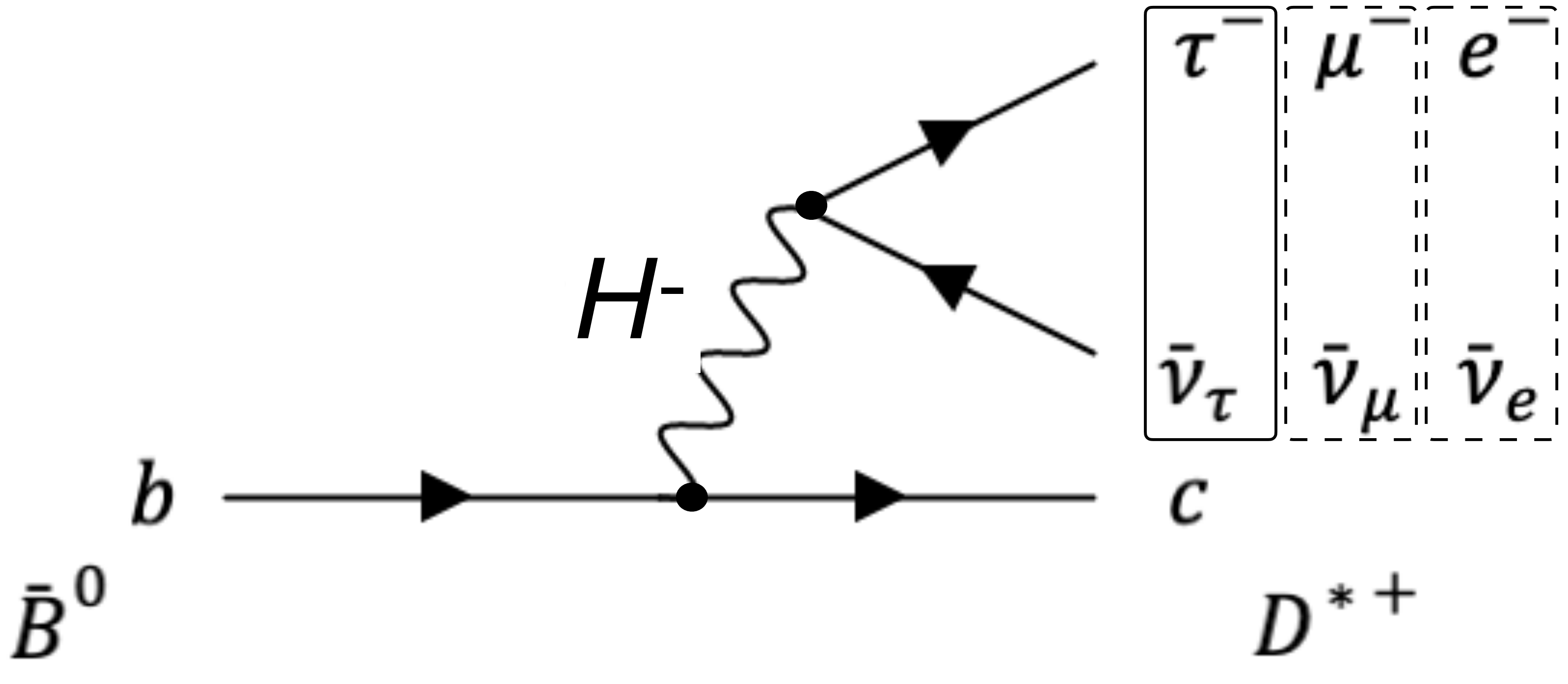
Experimental average results

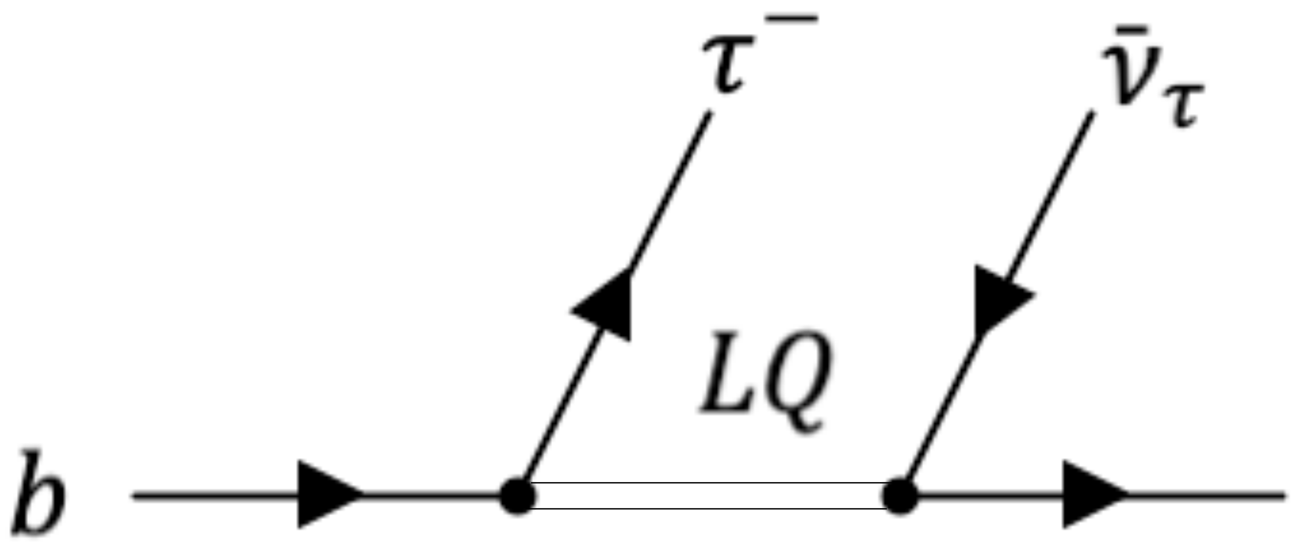
New physics scenarios for the $R(D^{(*)})$ anomaly

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.
    [PRD 105 095011(2022)]
- Leptoquark
  - $gg \to LQ\ LQ^*$, still broad parameter regions are allowed







LFU test program at Belle and Belle II

- The analyses presented in this talk

  - **$R_{\tau/l}$ (D^*) at Belle II (189 fb^{-1}), PRD 110 072020 (2024)**
  - **$R_{\tau/l}$ (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)

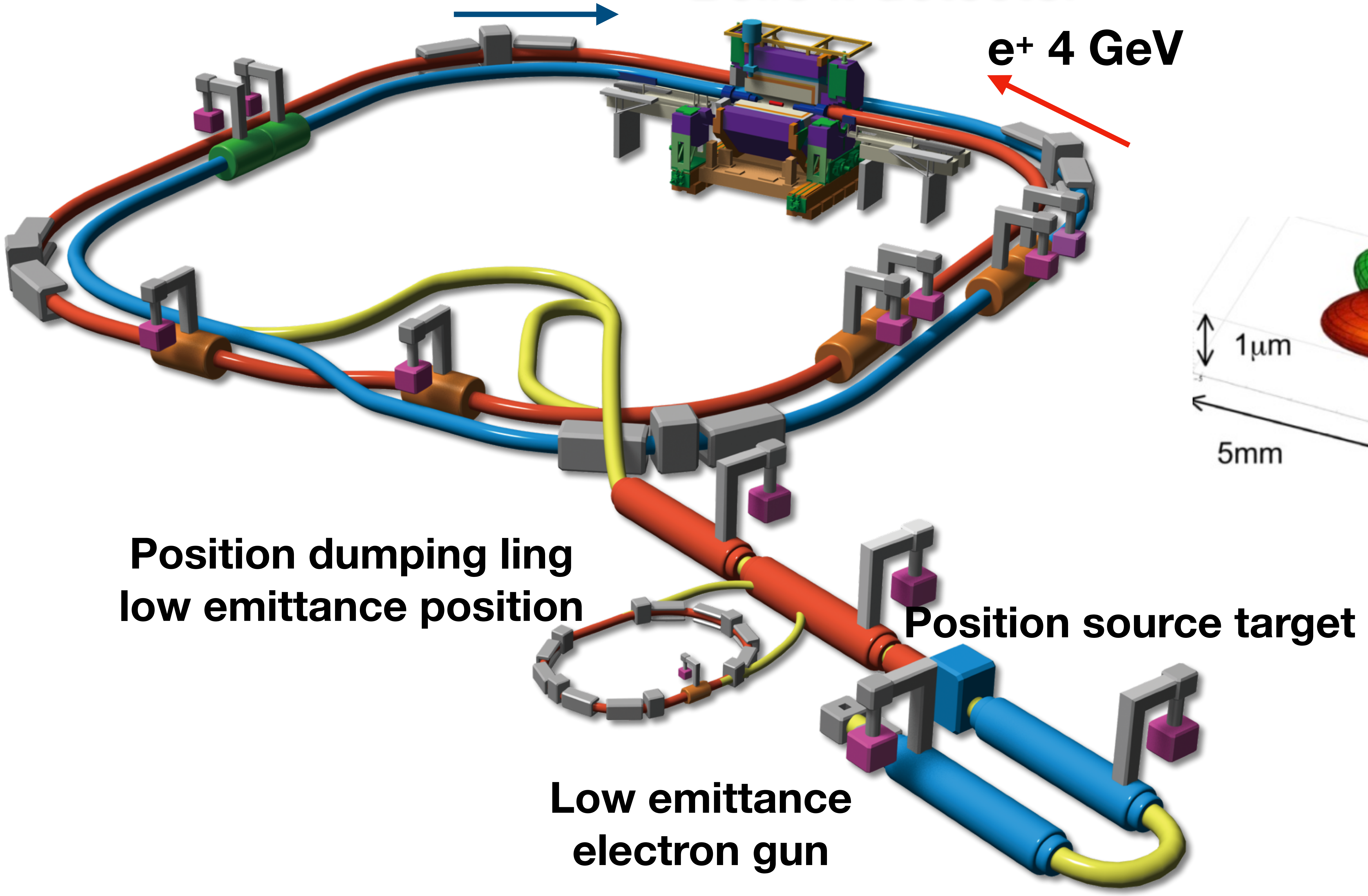
Luminosity frontier: SuperKEKB

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

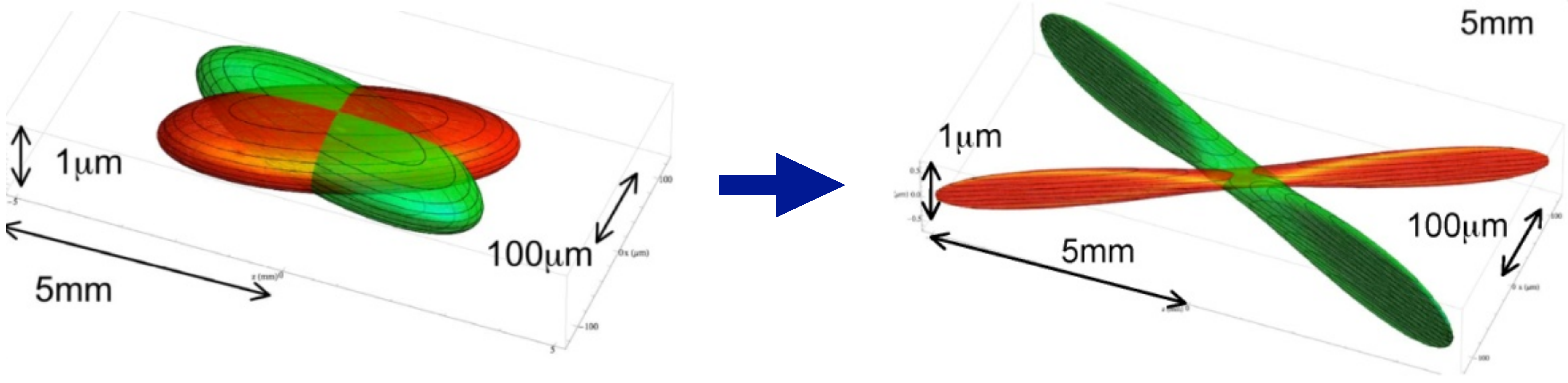
Beam current: KEKB x ~1.5

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

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:
  - 548 fb^{-1} (Belle II) <-> 980 fb^{-1} (Belle)

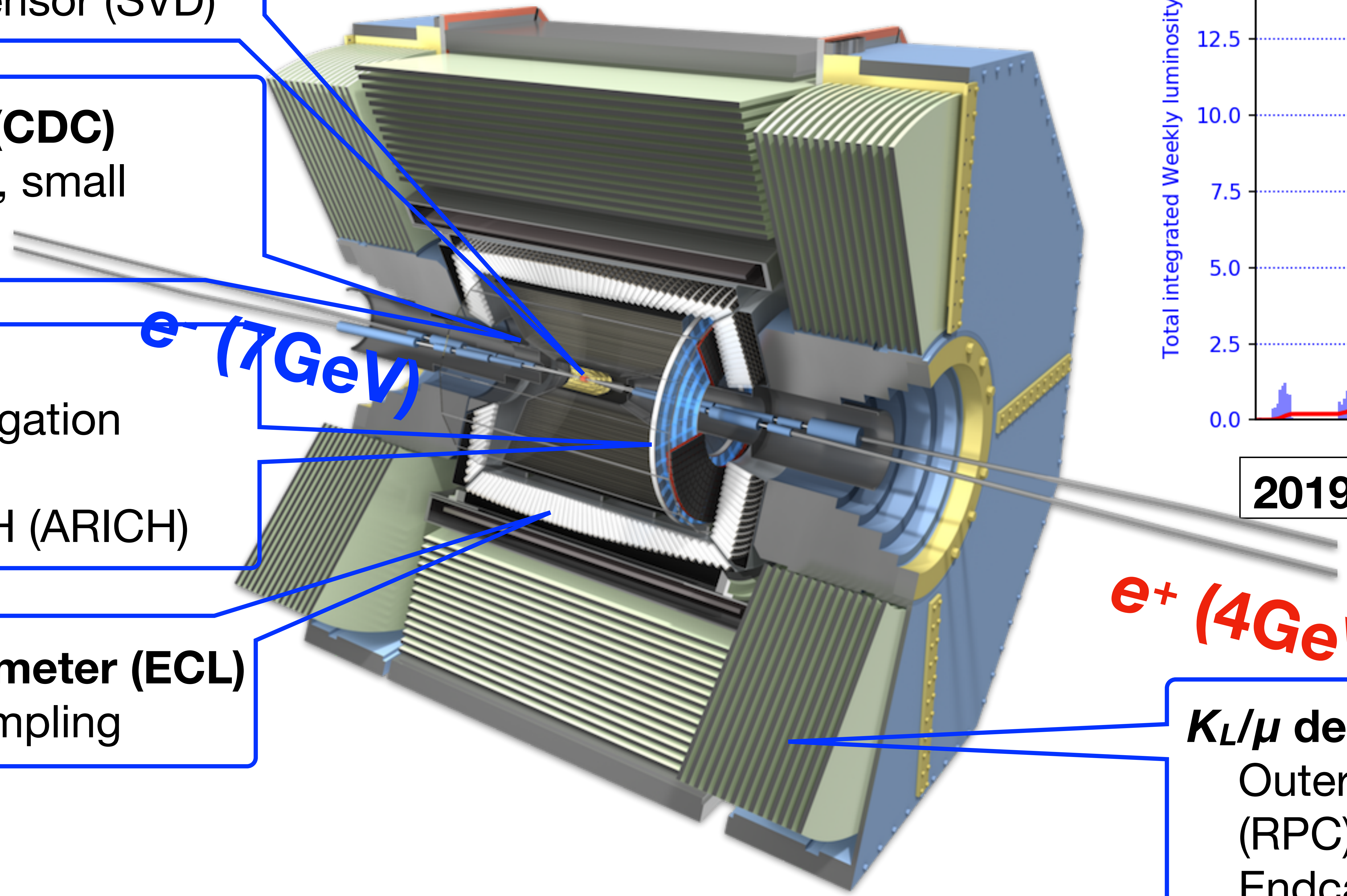
Belle II detector and dataset

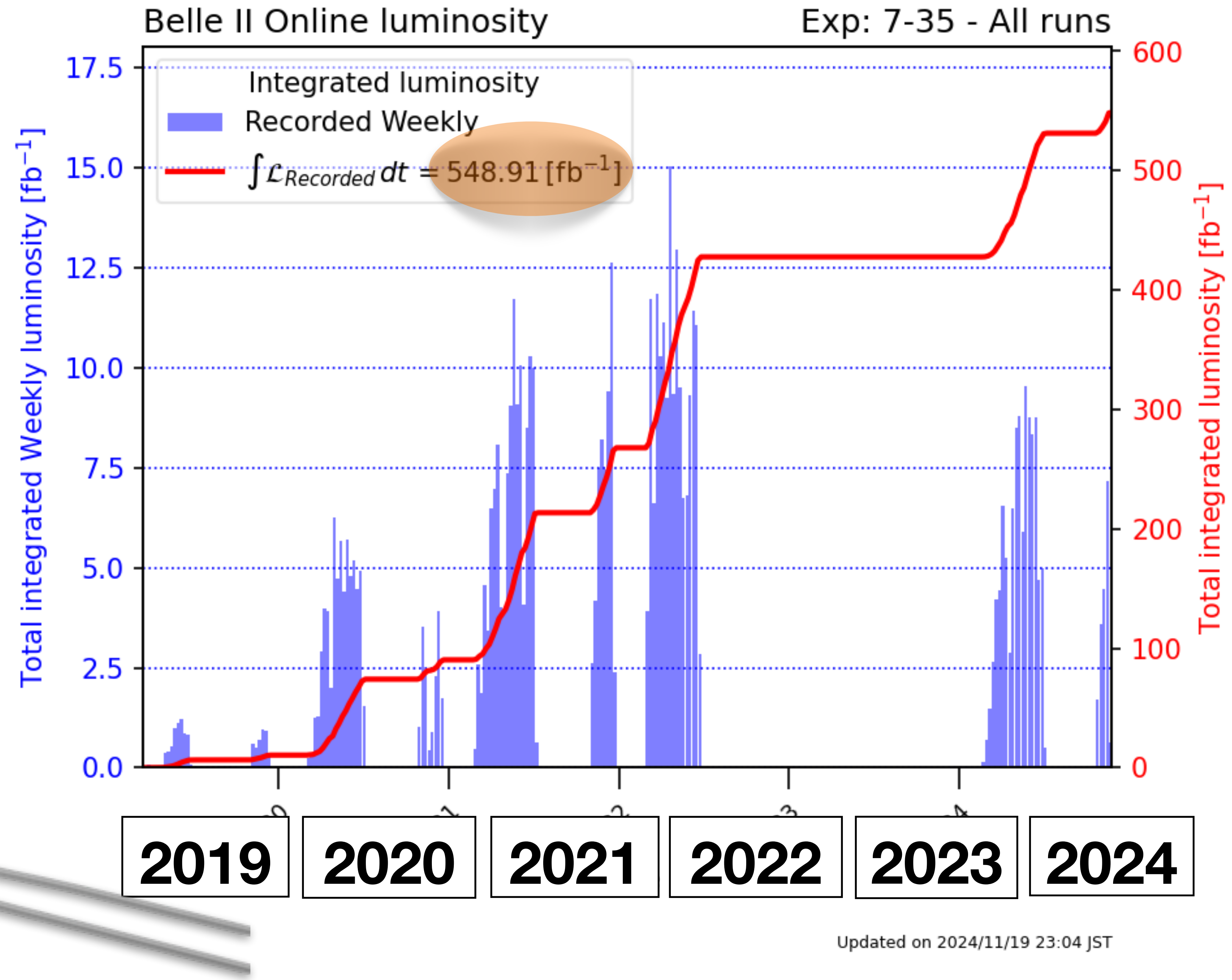
Vertex detector (VXD)
Inner 2 layers: pixel detector (PXD)
Outer 4 layers: strip sensor (SVD)

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



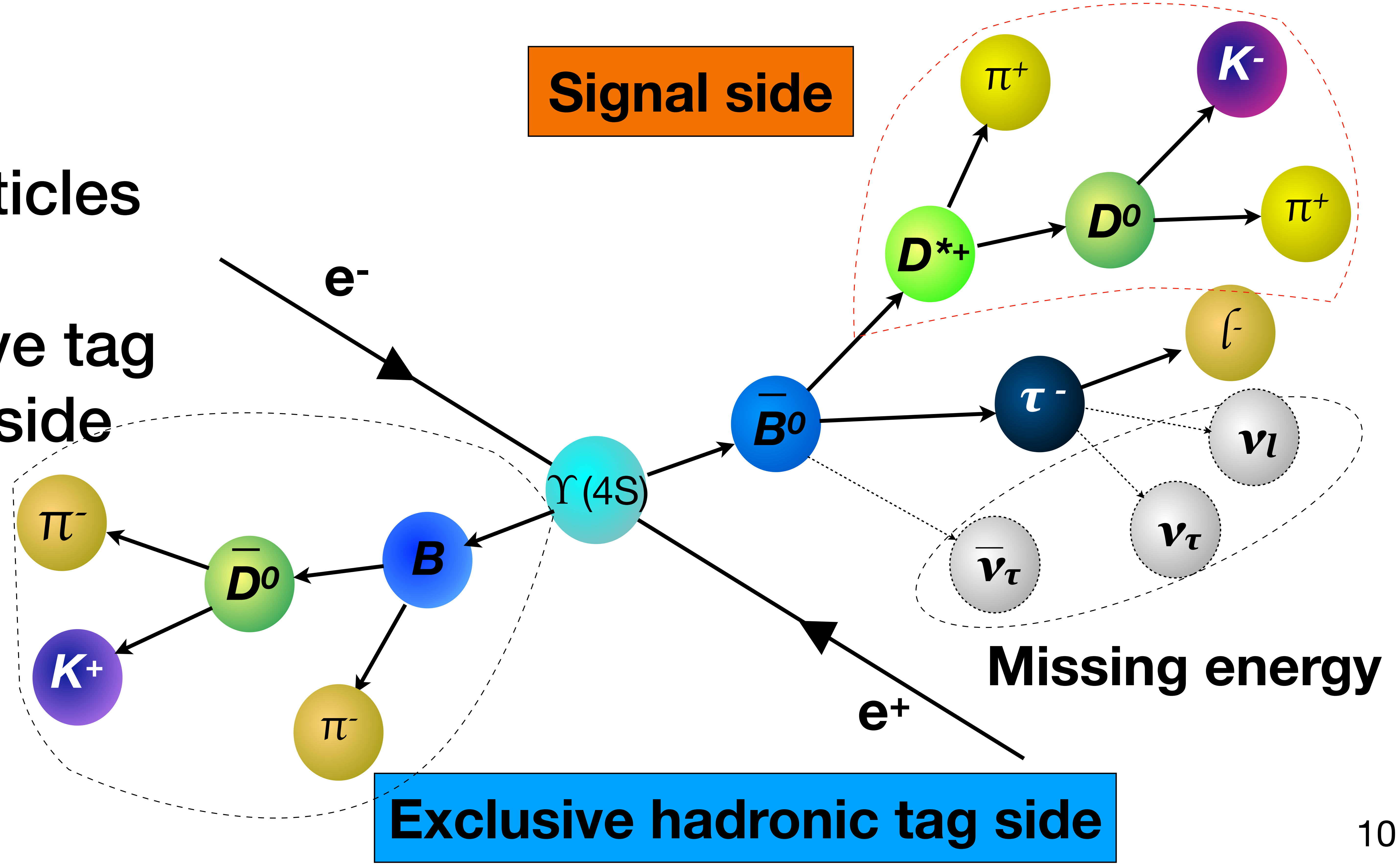


K_L/μ detector (KLM)
Outer barrel: Resistive Plate Counter (RPC)
Endcap/inner barrel: Scintillator

- 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%

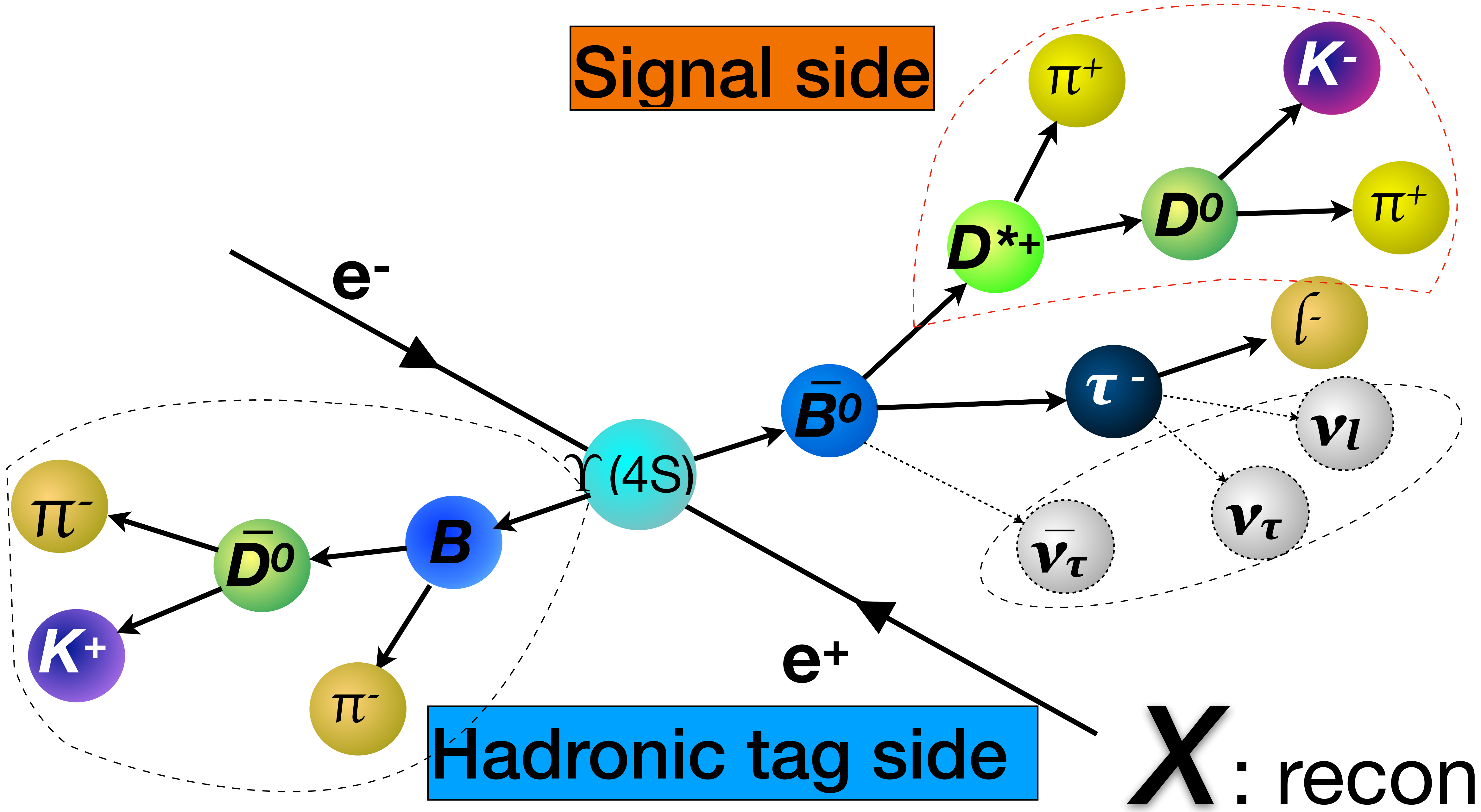
Tagging methods

- B tagging is necessary to measure $B \to D^* \tau \nu$, $B \to D^* l \nu$ ($\nu \geq 2$) simultaneously
- <u>Hadronic tag</u>
  - <u>Exclusive tag</u>
    - Fully reconstruct $B \to D^{(*)}(/J/\psi/\Lambda)X$
    - Tagging efficiency 0.2~0.4%
    - less background
  - <u>Inclusive tag</u>
    - Reconstruct tag *B* with all particles except signal *B*
    - Higher efficiency than exclusive tag
    - Low purity, need clean signal-side final state
- <u>Semileptonic tag</u>
  - Reconstruct $B \to D^{(*)} l \nu$
  - Tagging efficiency ~0.5%
  - More background



Hadronic 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
- $M^2_{miss} = (p_{beam} - p_{Btag} - p_{D(*)} - p_l)^2$
- E_{ECL} unassigned neutral energy in the calorimeter $E_{ECL} = \sum_i E_i^{\gamma}$

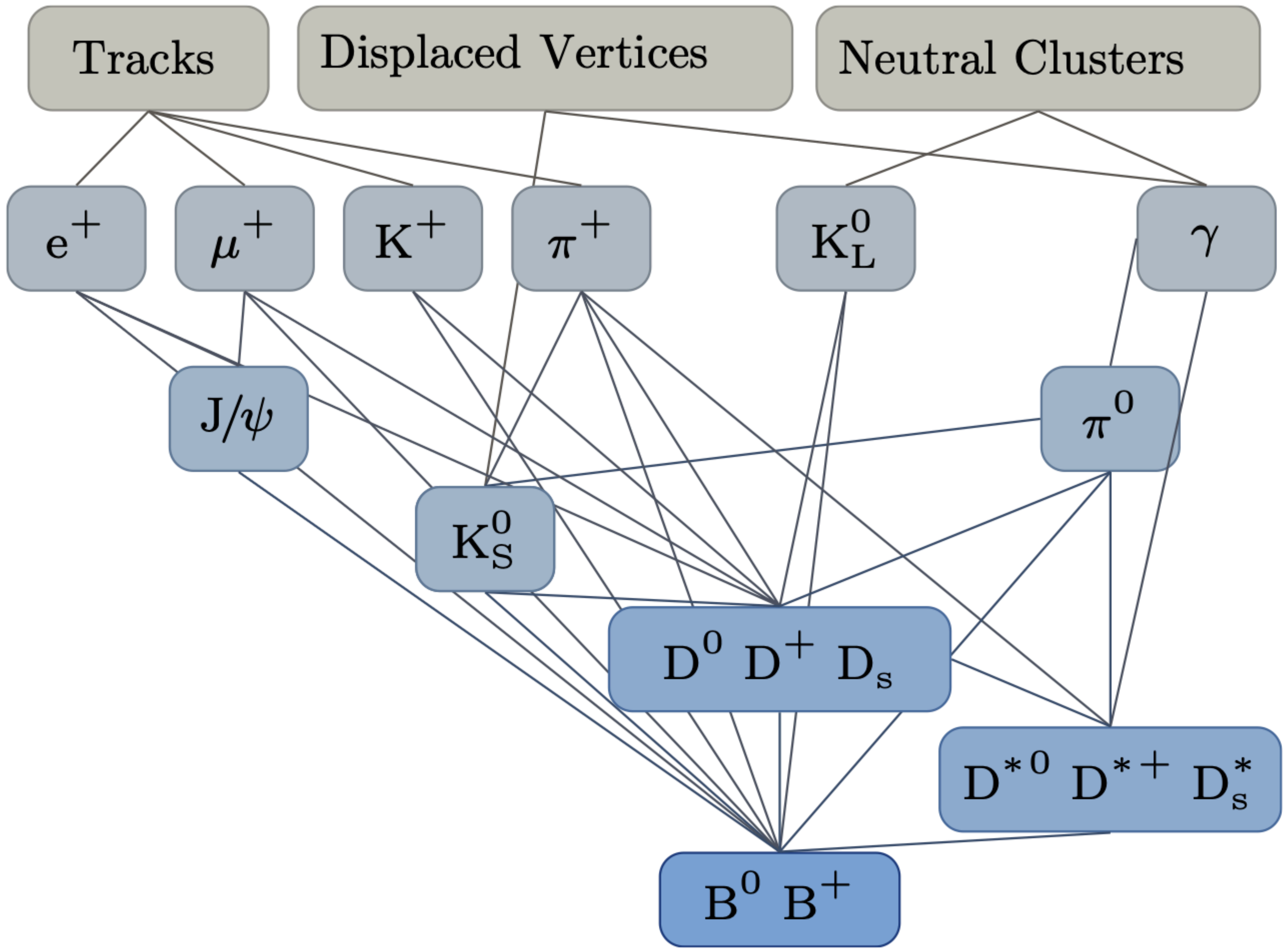
Hadronic tag reconstruction at Belle II

- 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}

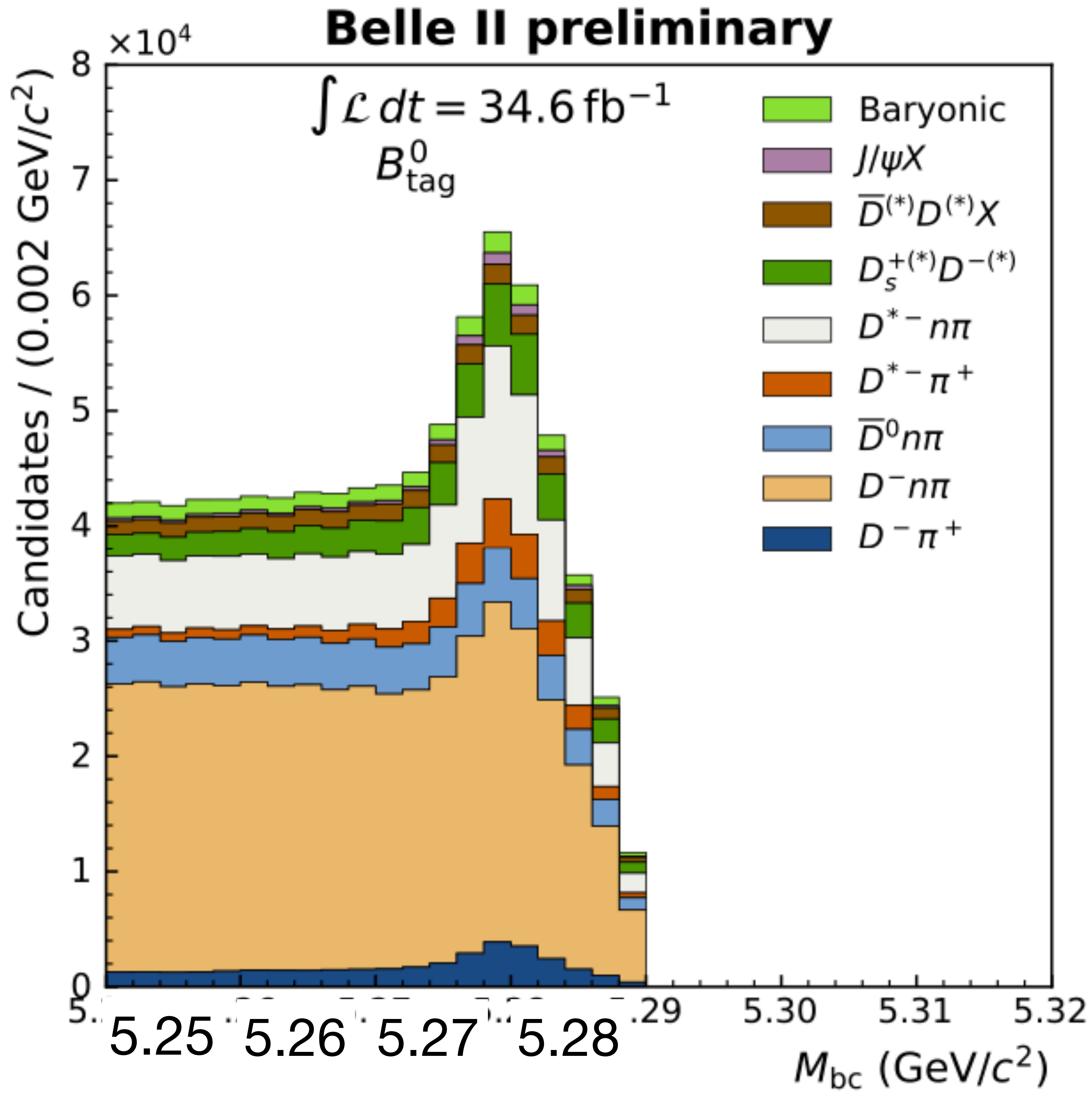
10-30% increased

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

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



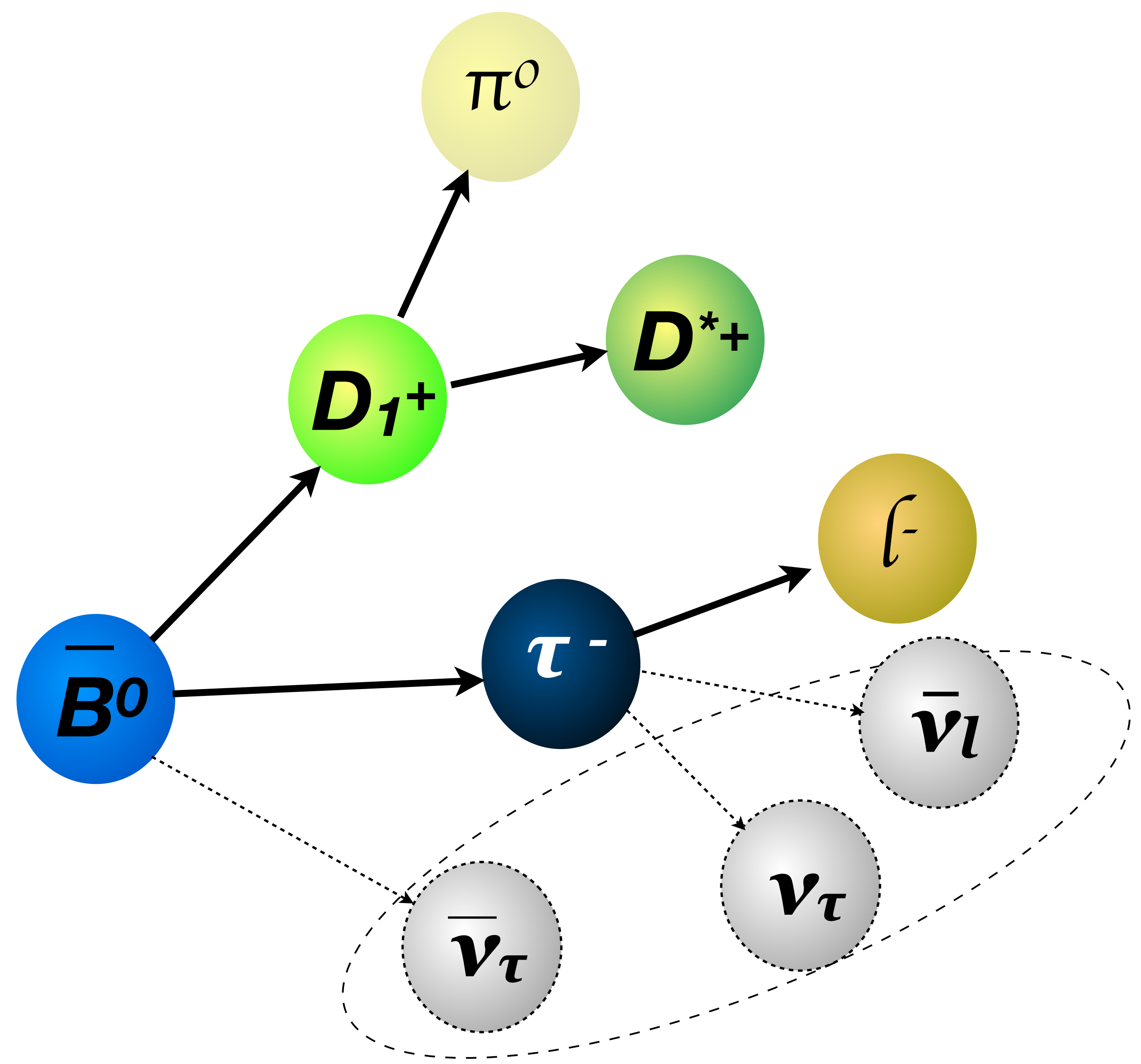
arXiv:2008.06096



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

Signal B reconstruction

- Reconstruct $B \to D^* \tau \nu$ and $B \to D^* l \nu$ with same selections
- τ lepton reconstruct with $\ell(e, \mu)\nu\nu$
- D/D^* meson reconstruct with $K^{\pm}$, $\pi^{\pm}$, K_S, π^0
- Both neutral and charged $B^{\pm}/B^0$ mesons reconstruct with D^{*+}/D^{*0} and $\tau/\ell = (e, \mu)$



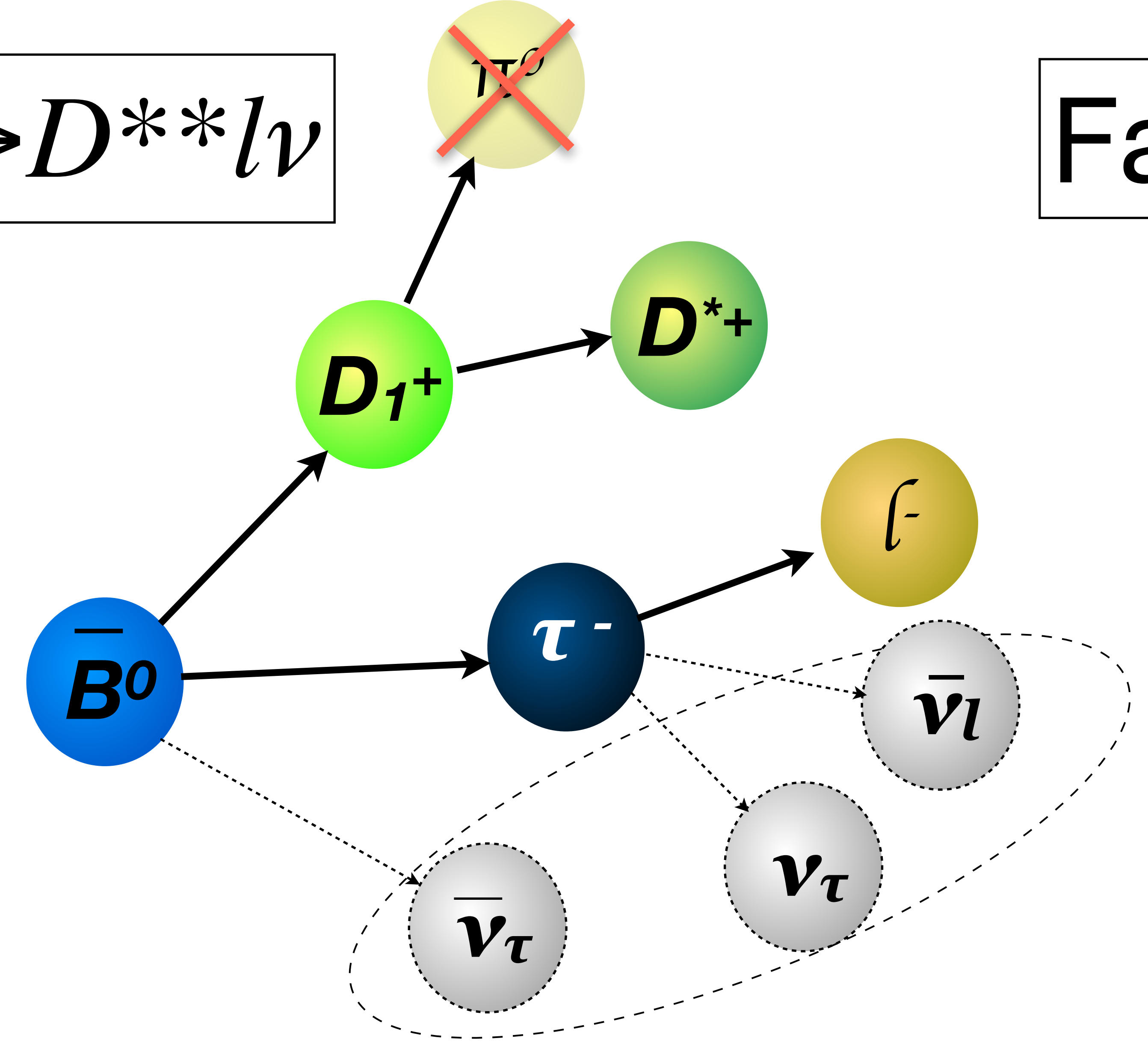
$D^{*+} \to D^0\pi^+/D^+\pi^0$	$\mathcal{B}$~98%
$D^{*0} \to D^0\pi^0$	$\mathcal{B}$~65%
Eight D^0 modes	$\mathcal{B}$~36%
Three D^+ modes	$\mathcal{B}$~12%

Dominant backgrounds

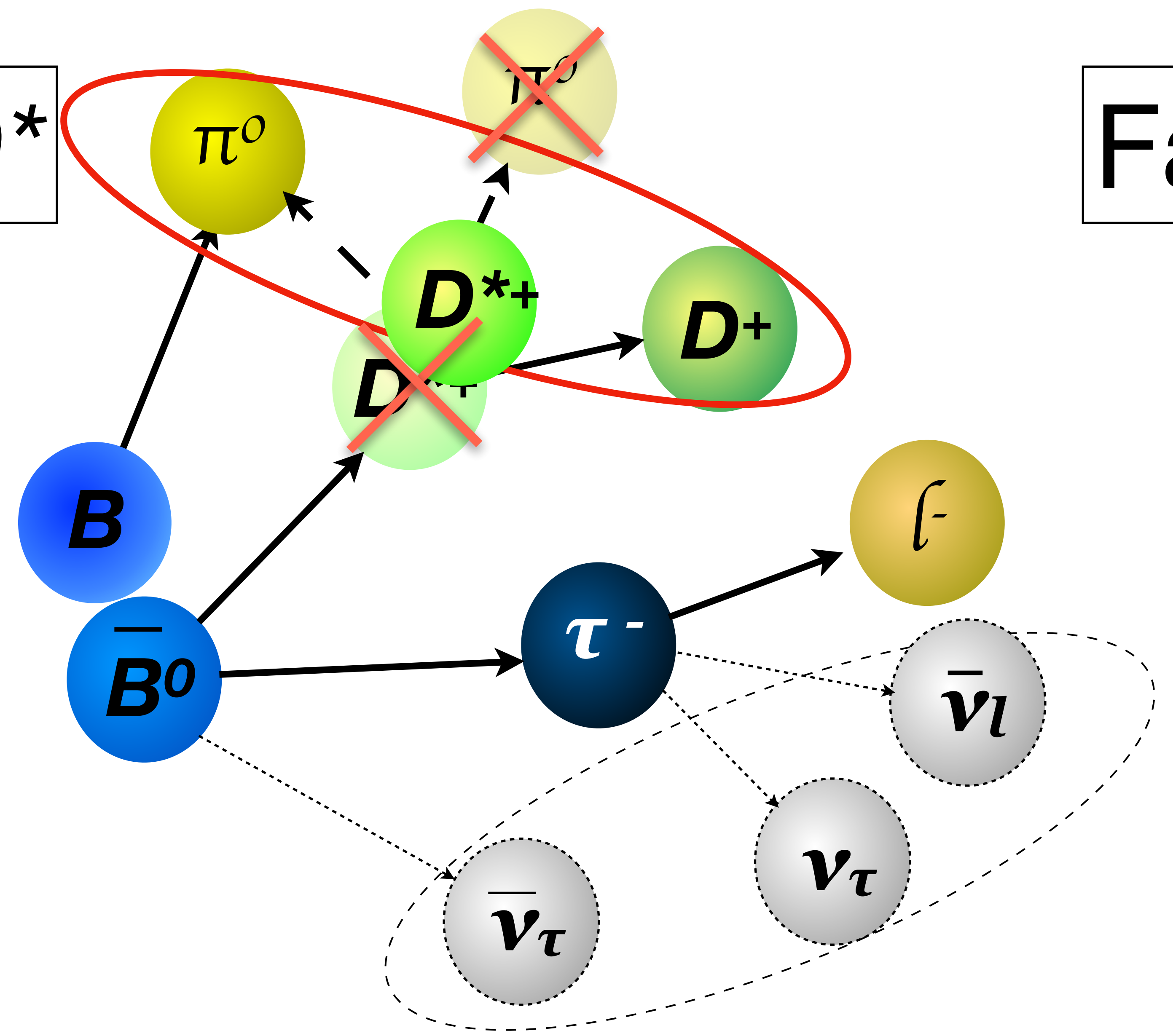
- Fraction of survived *B* candidates in each category after event selections are estimated based on Belle II MC simulation

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

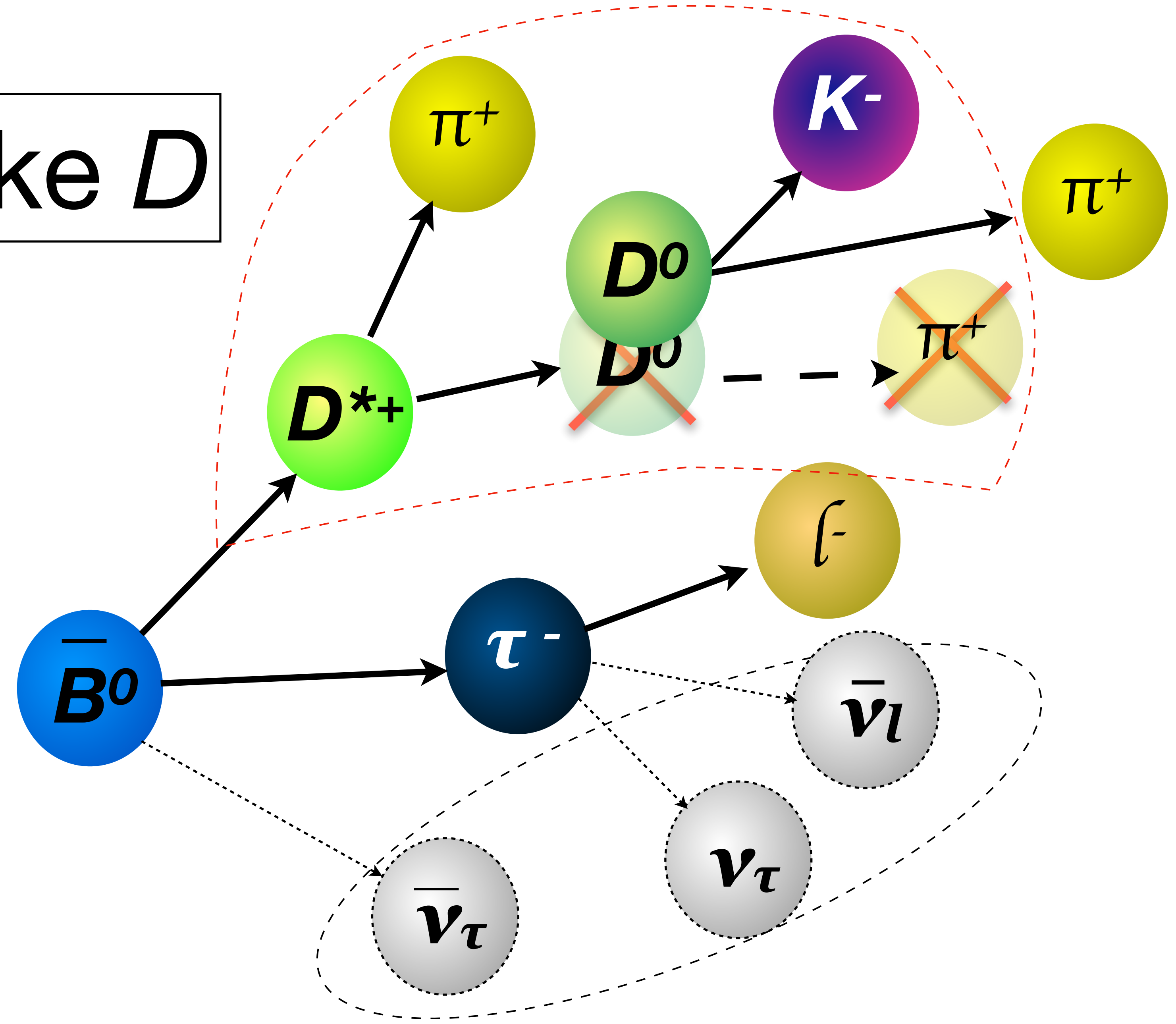
$B \to D^{**} l \nu$



Fake D^*

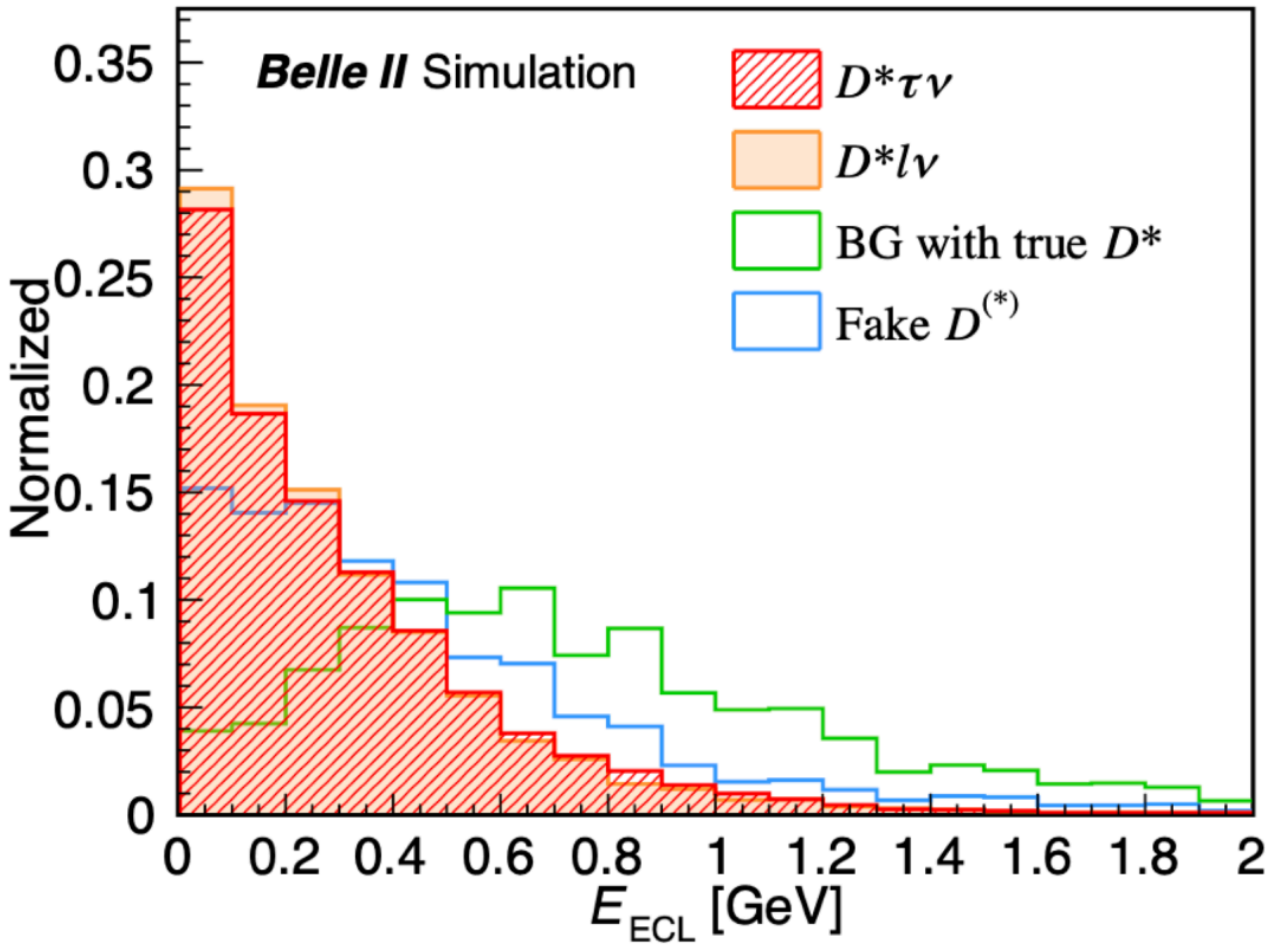


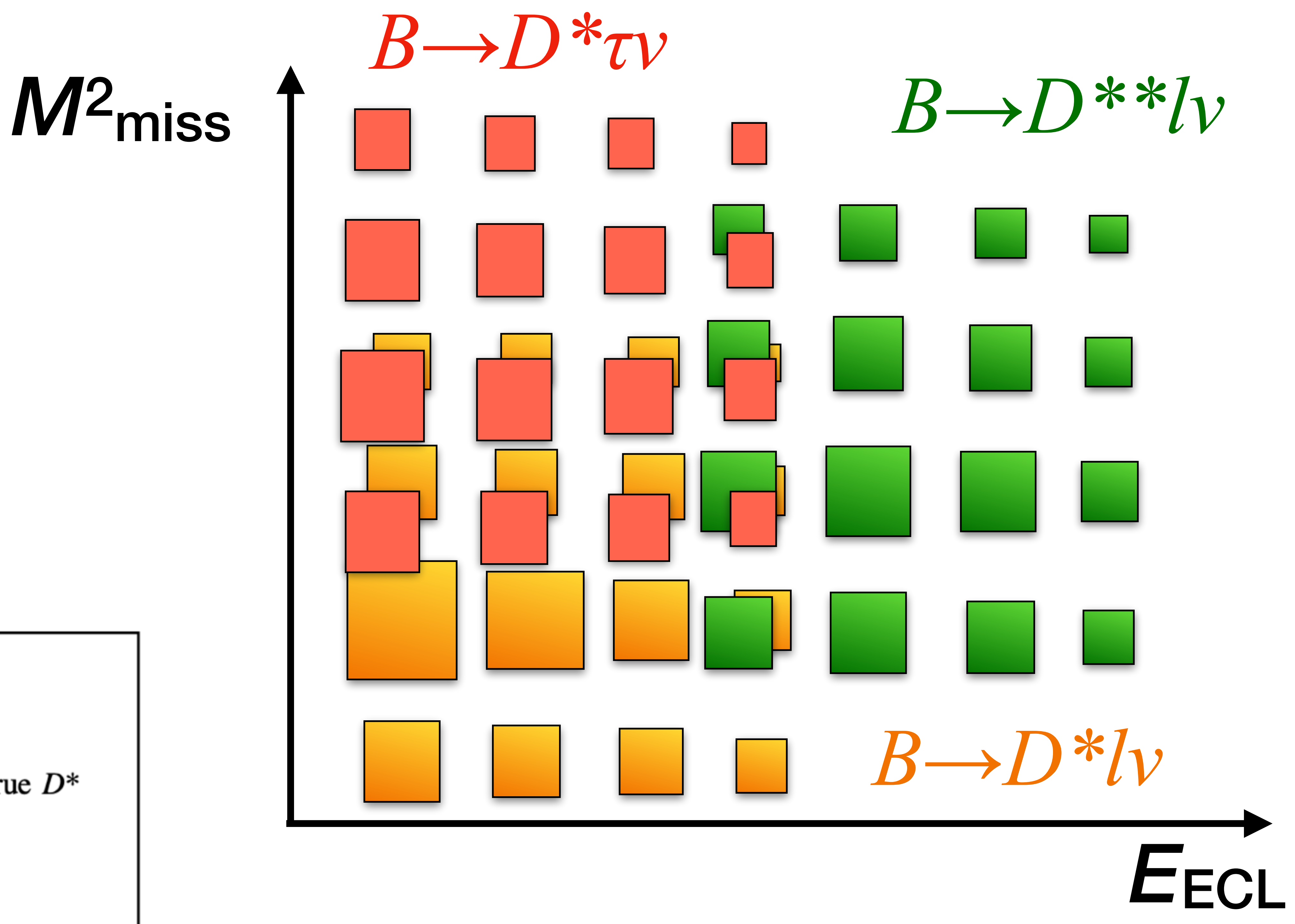
Fake D

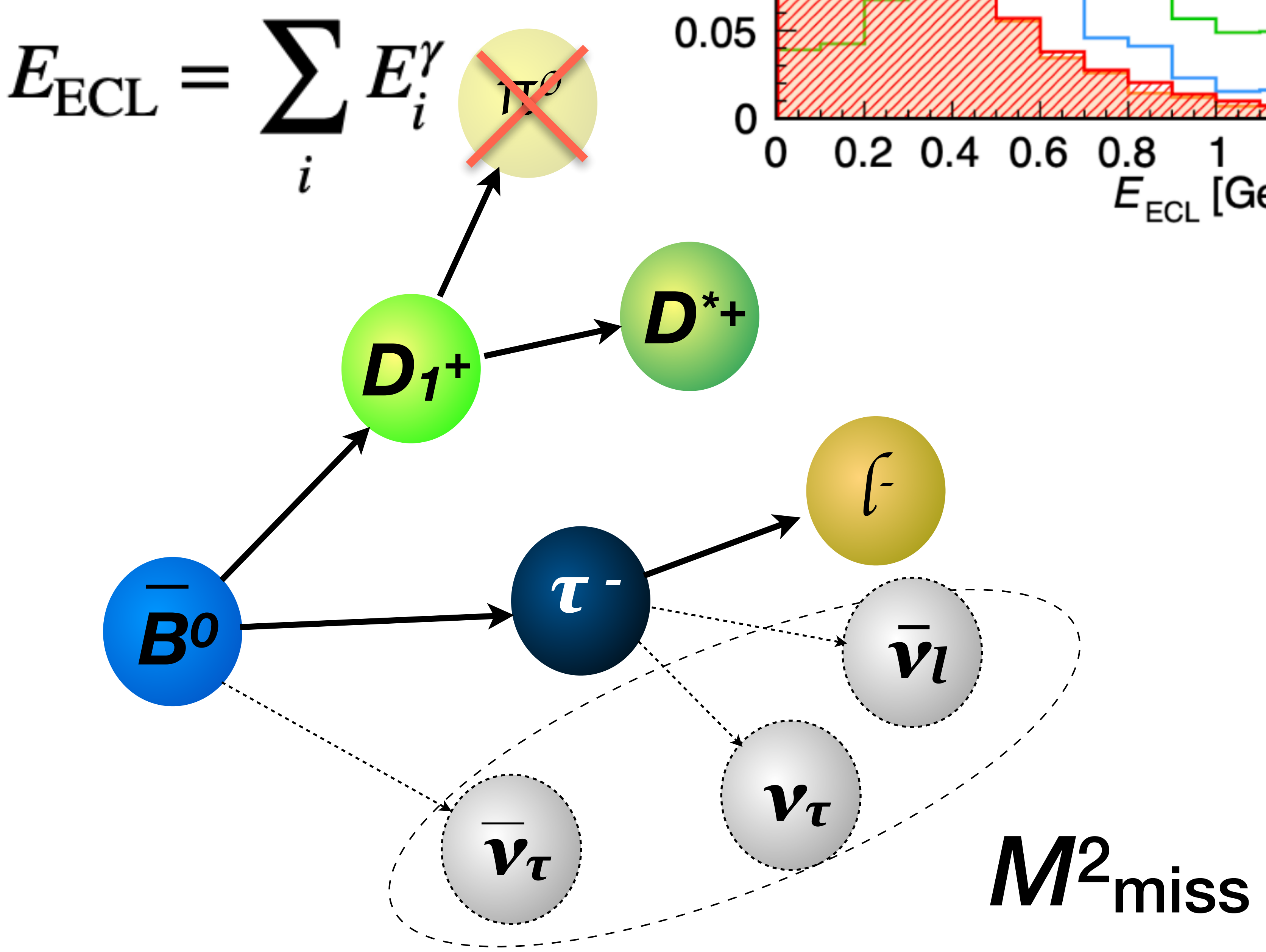


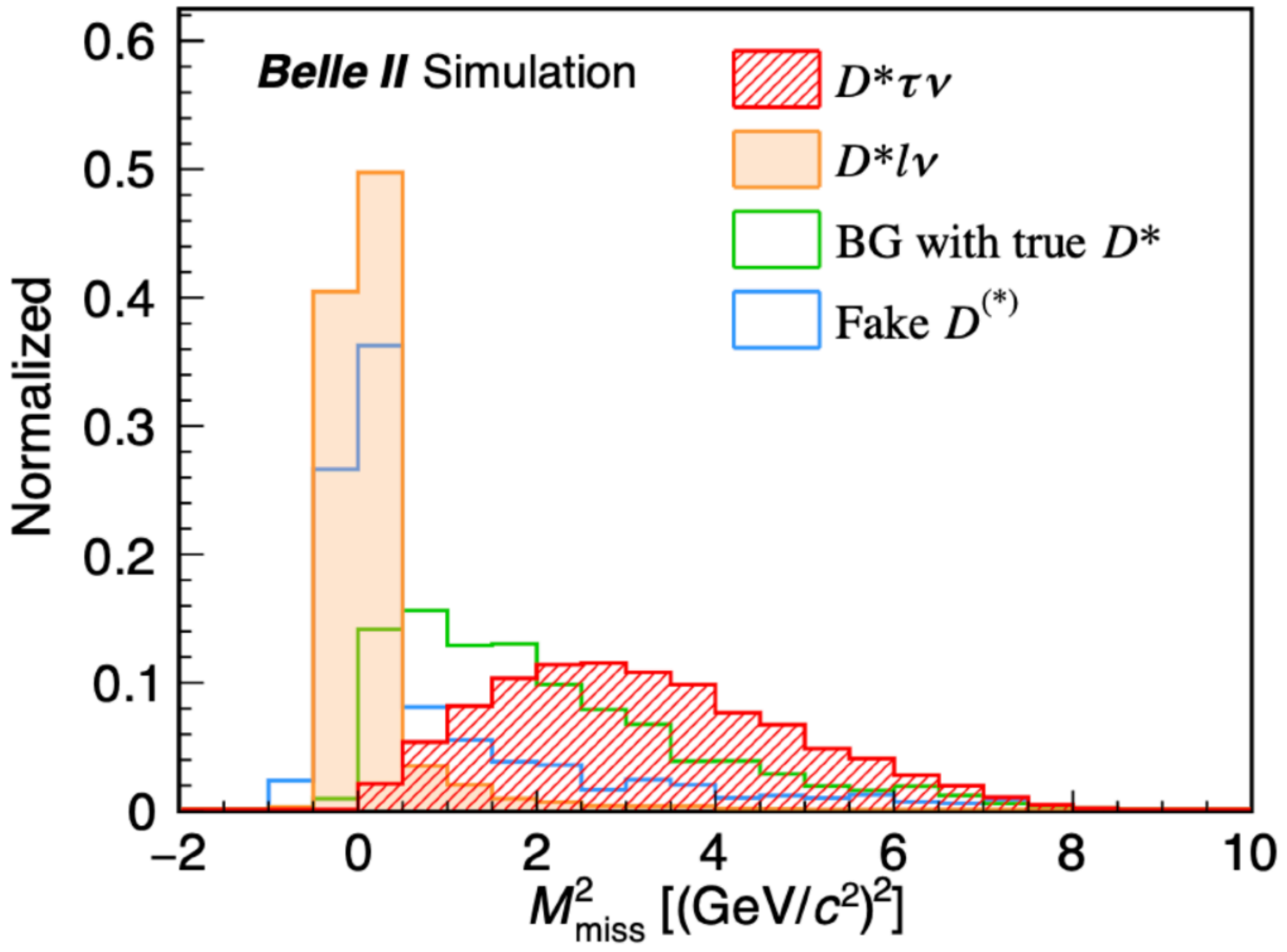
Fitting methodology and variables

- Extracting $B \to D^* \tau \nu$, $B \to D^* l \nu$ yields by a two-dimensional simultaneously fit
  - $M^2_{\text{miss}} = (p_{\text{beam}} - p_{B\text{tag}} - p_{D^{(*)}} - p_{l})^2$
  - E_{ECL} unassigned neutral energy in the calorimeter $E_{\text{ECL}} = \sum_i E_i^{\gamma}$

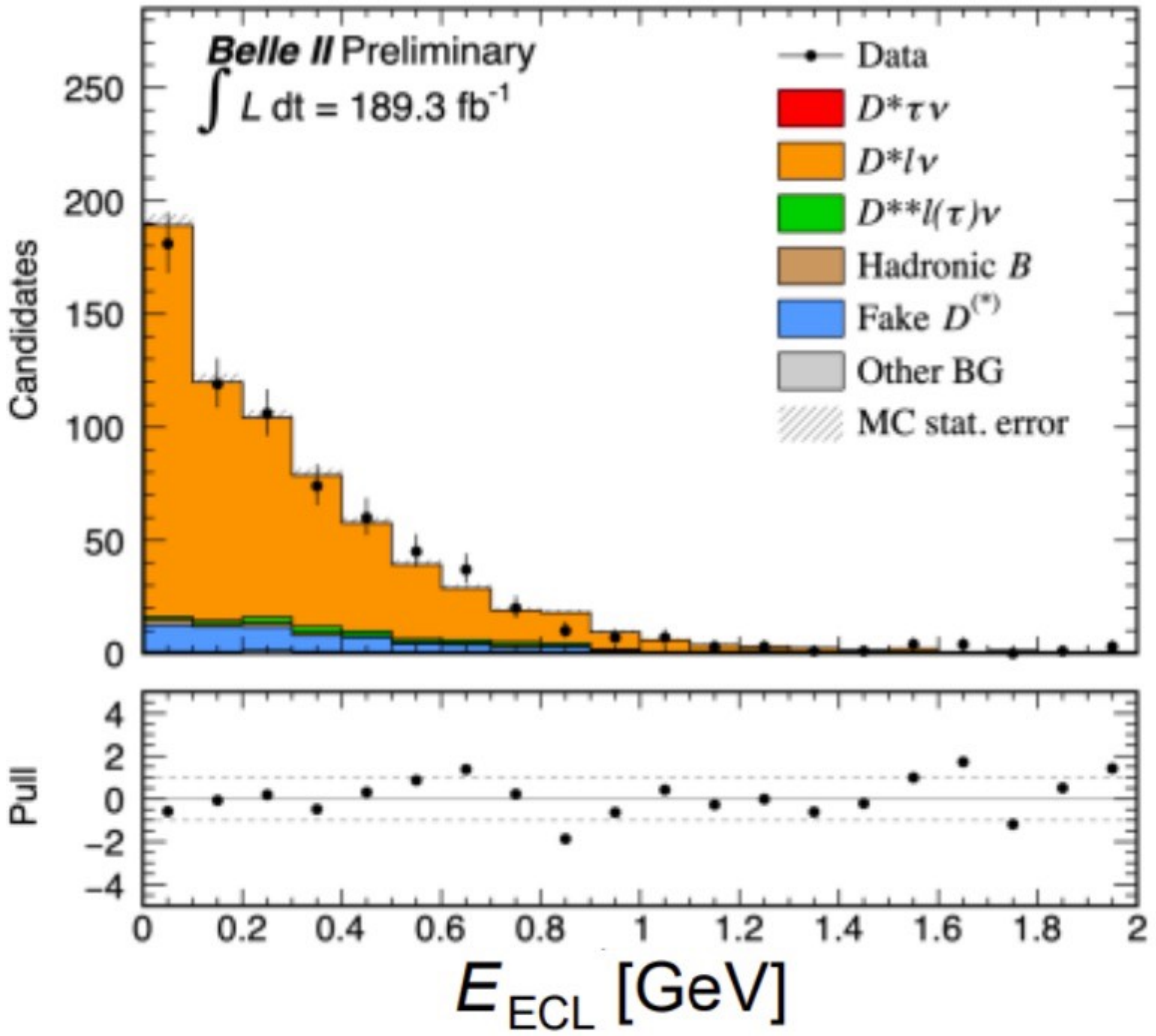






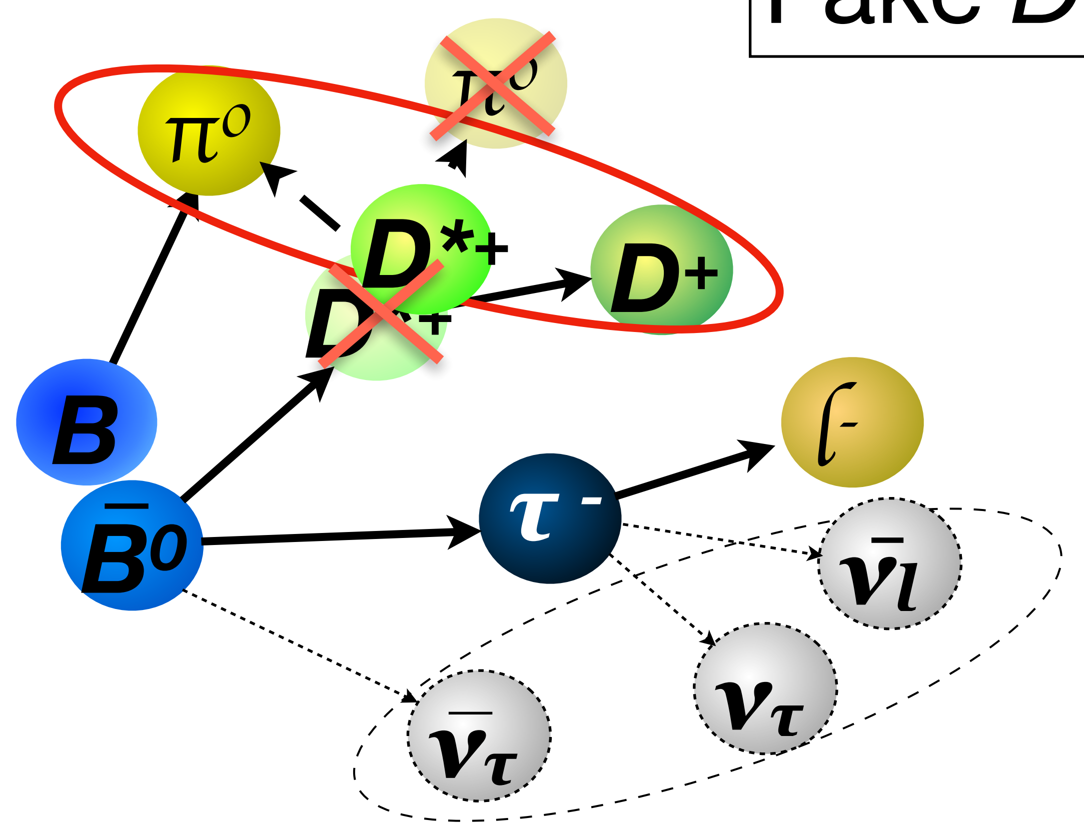


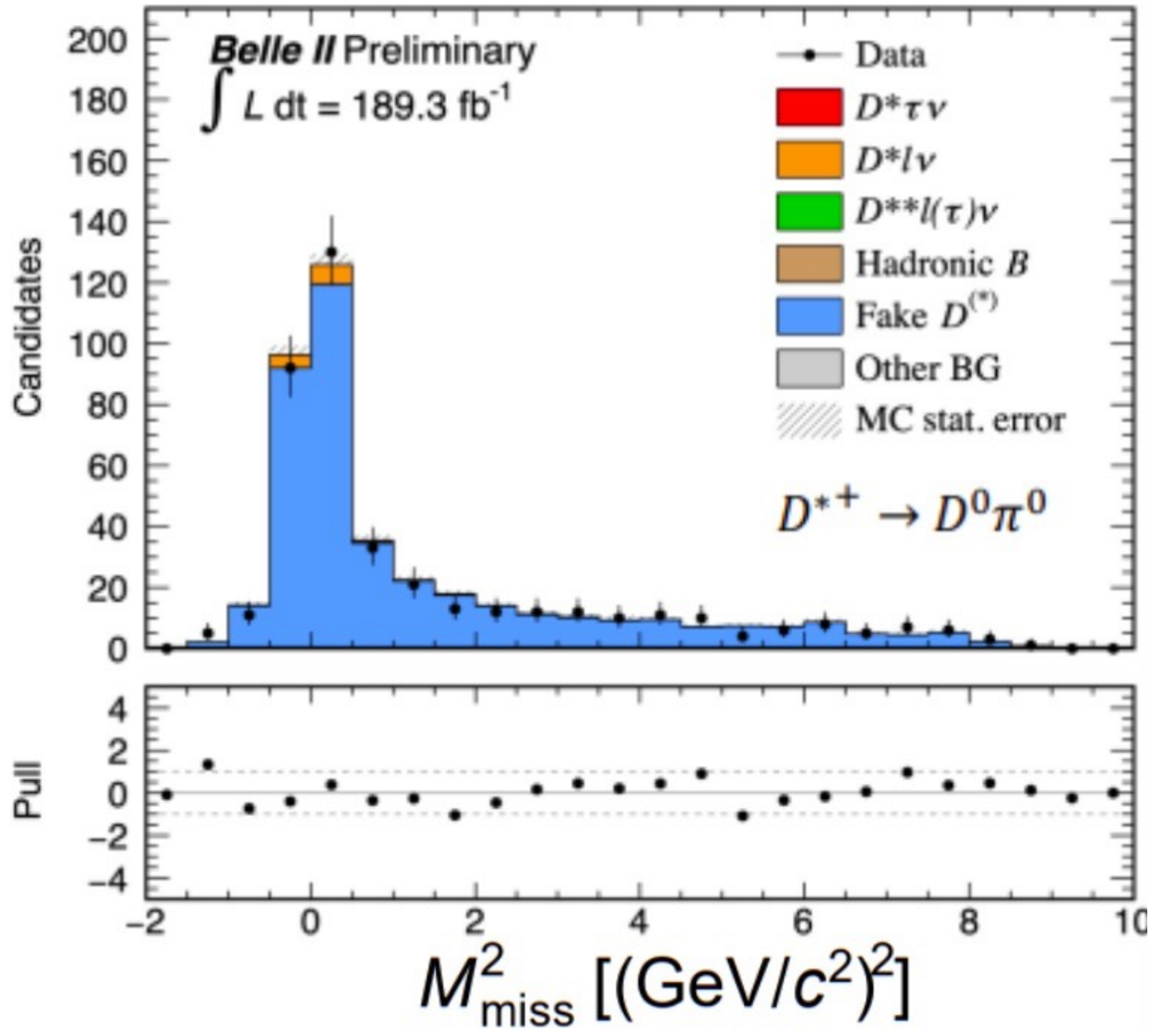
Dominant backgrounds and control samples



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

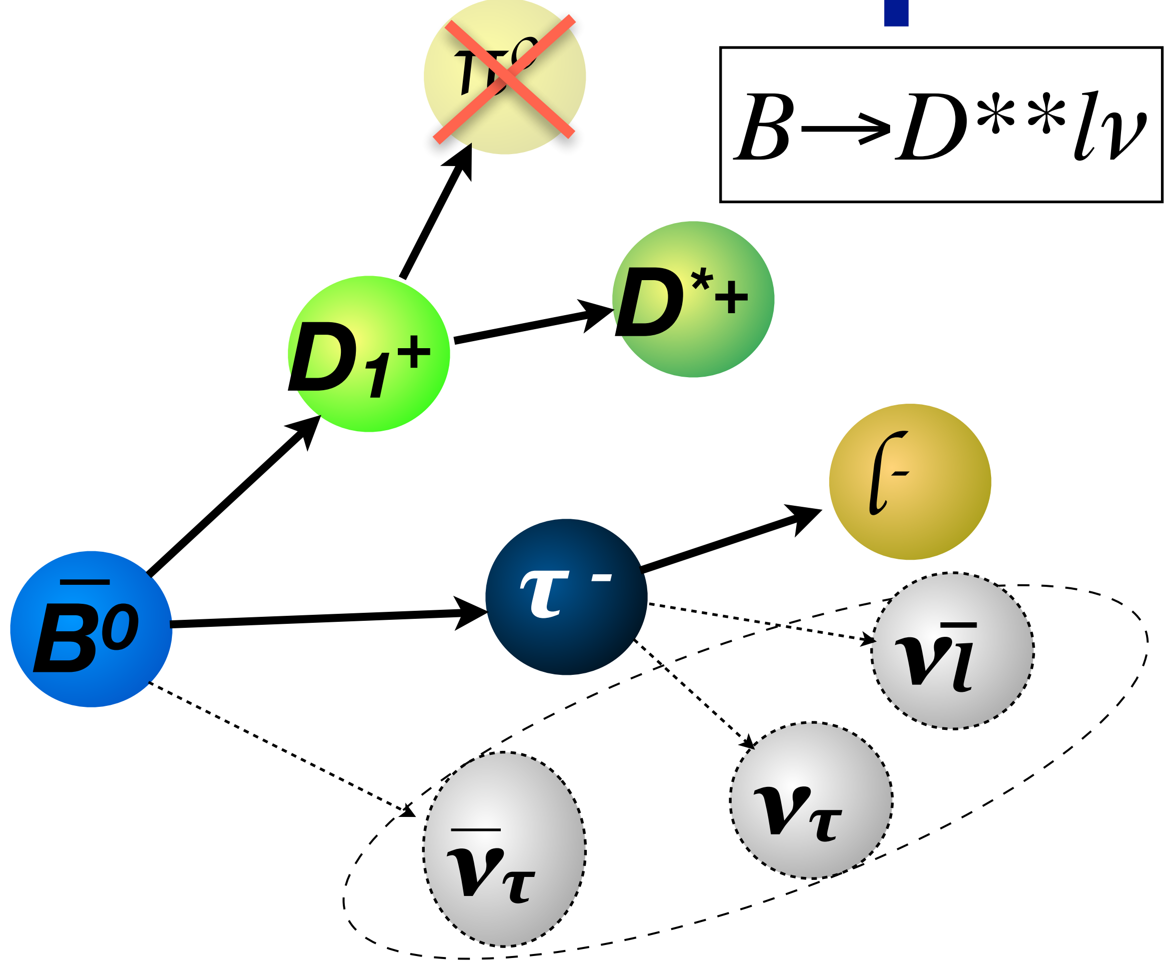
Fake D^*

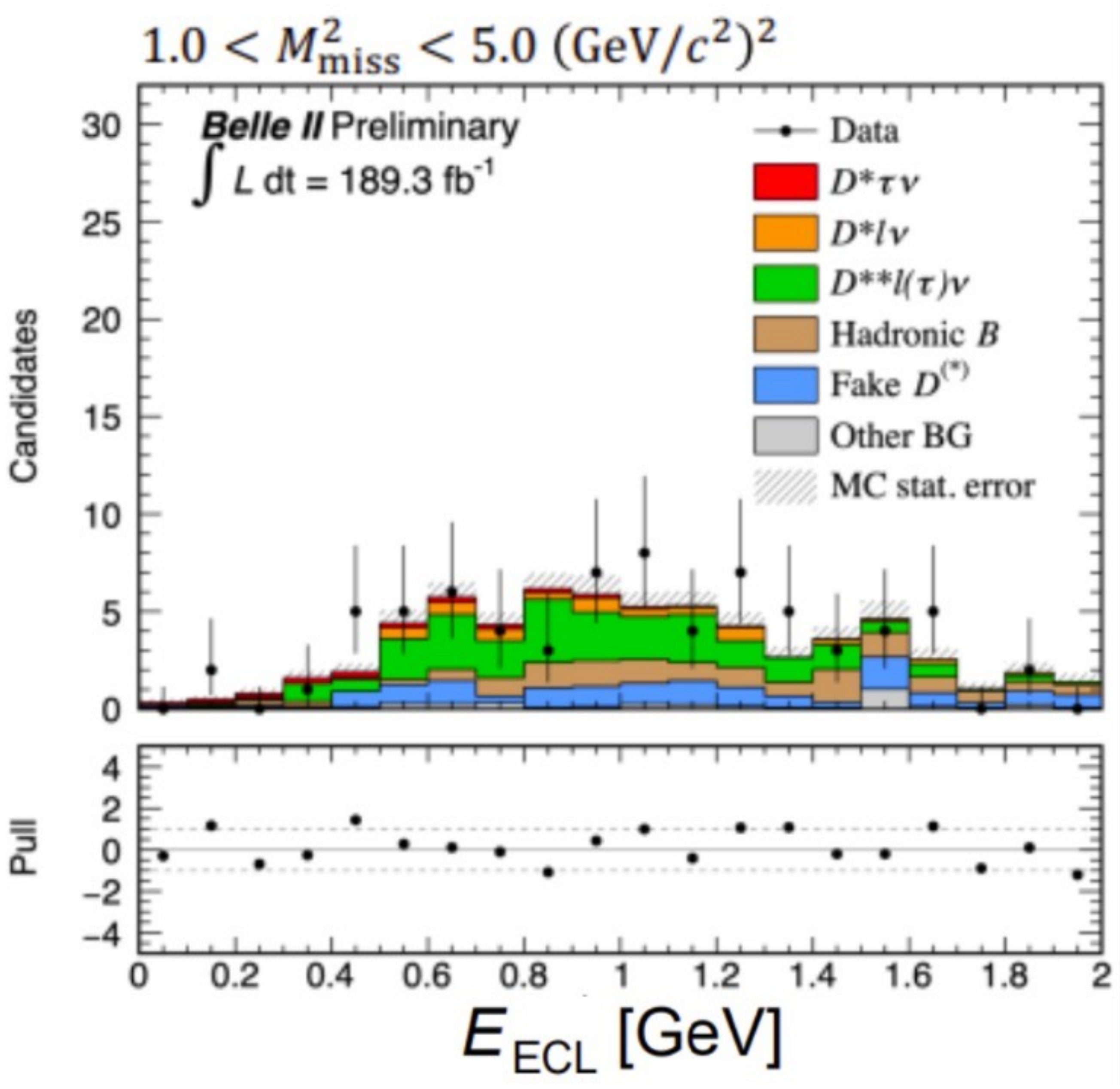




$m(D\pi)$ - $m(D^*)$ sideband: validate fake D^* modeling

$B \to D^{**} l \nu$





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 result for $R(D^*)$

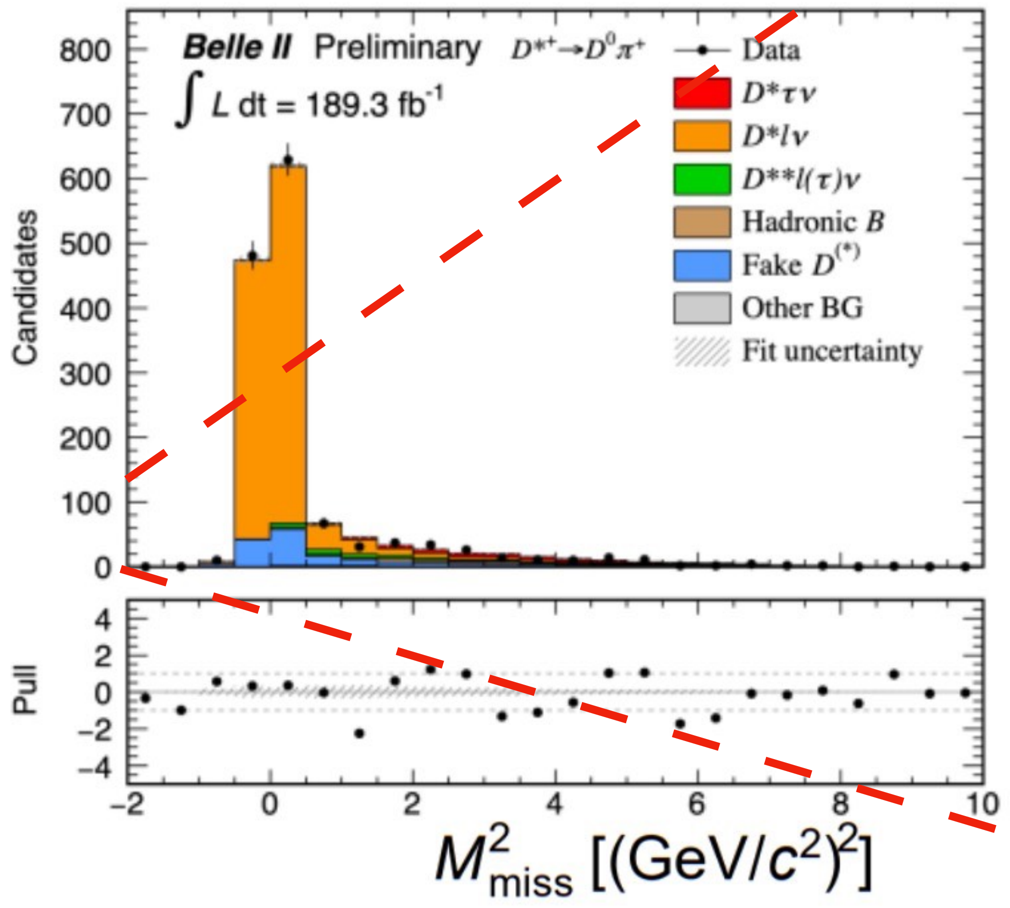
$R(D^*_{\tau/\ell}) = 0.262\ ^{+0.041}_{-0.039}\ \text{(stat)}\ ^{+0.035}_{-0.032}\ \text{(syst)}$

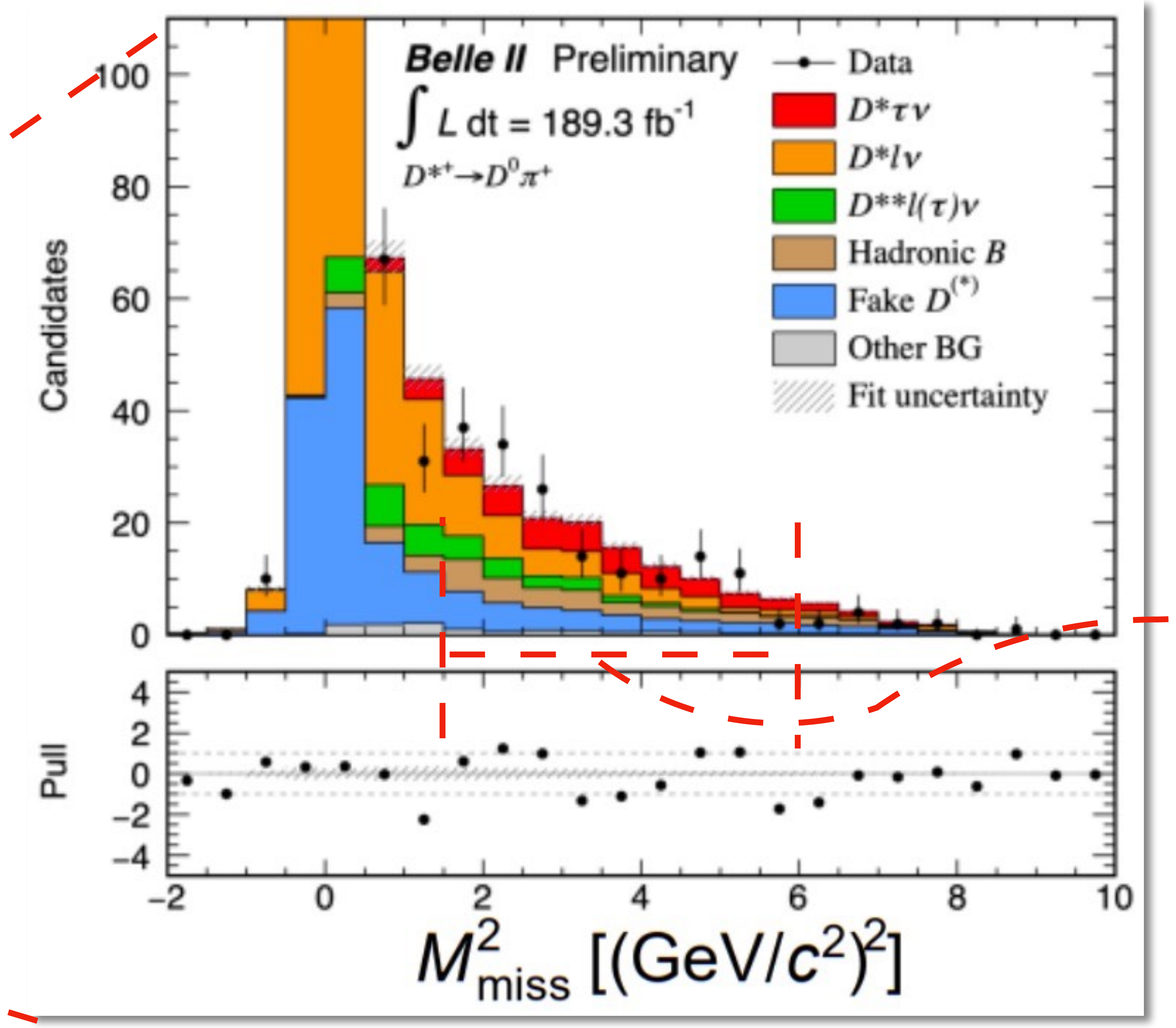
- Consistent with

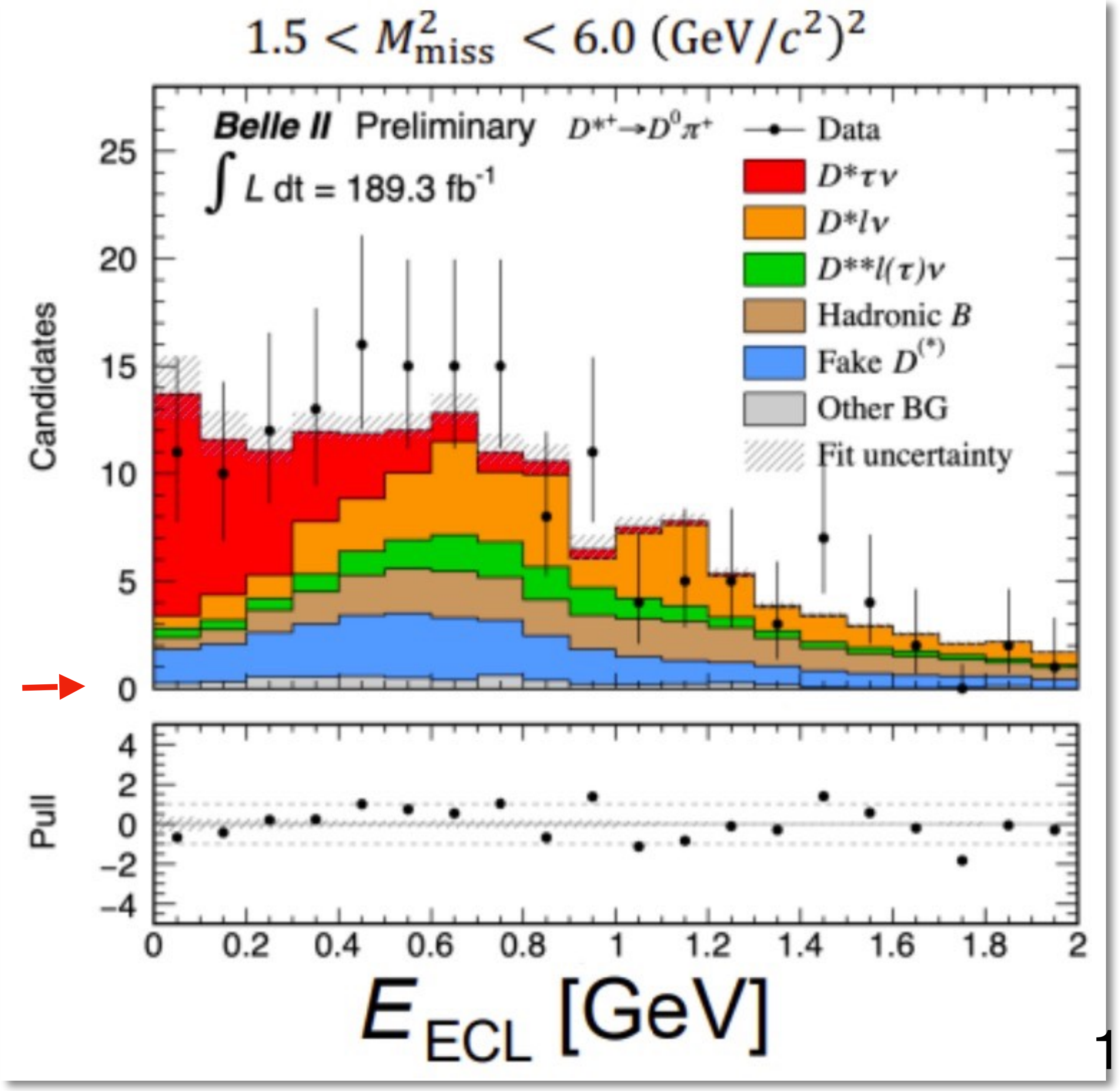
  SM: 0.254 ± 0.005,

  HFLAV24: 0.287 ± 0.012
- SM vs. experimental average deviation: 3.2σ → 3.3σ

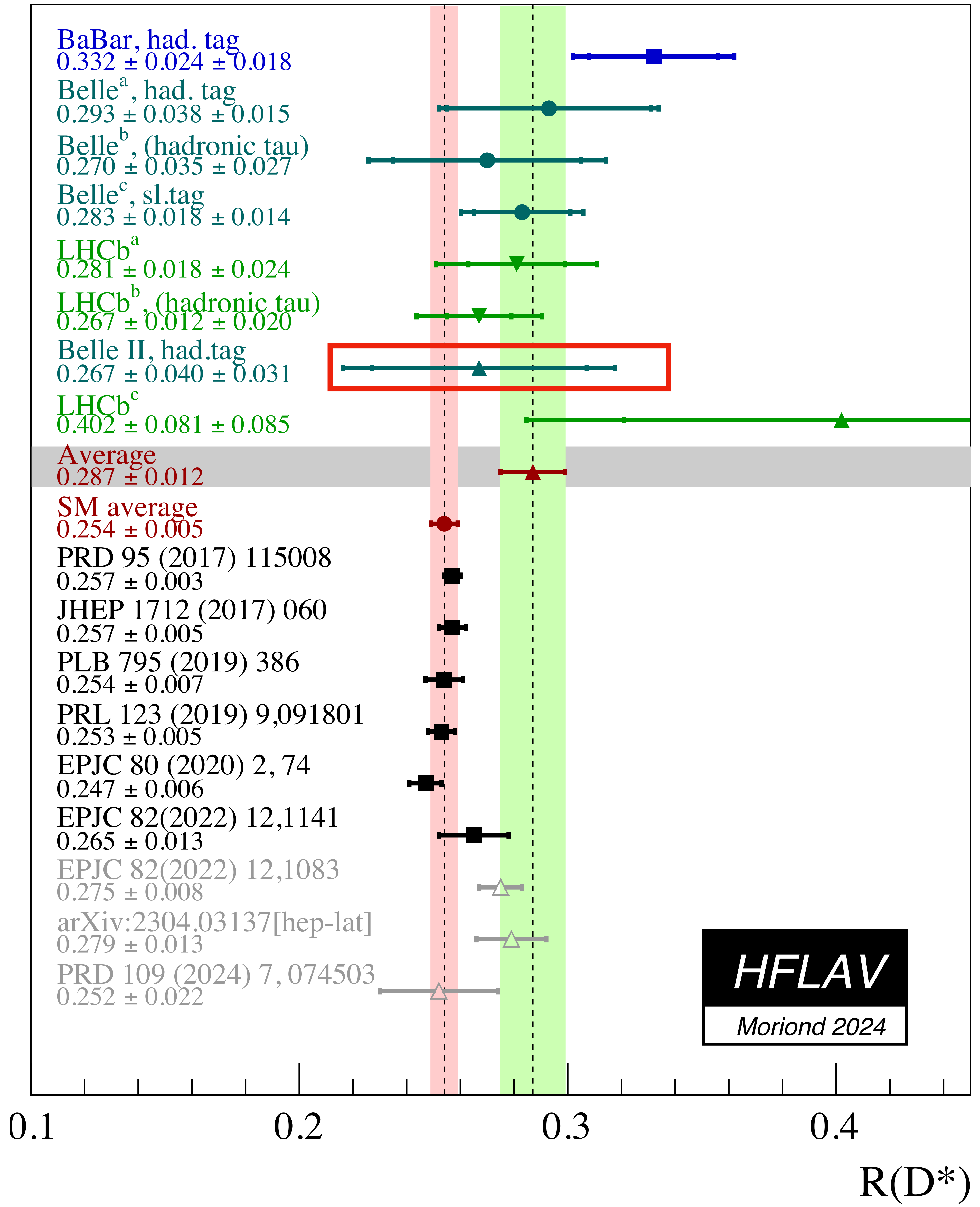
Source	Uncertainty
Statistical uncertainty	+15.4% -14.6%
E_{ECL} PDF shape	+9.1% -8.3%
MC statistics	±7.5%
$B \to D^{**} l \nu$ modeling	+4.8% -3.5%

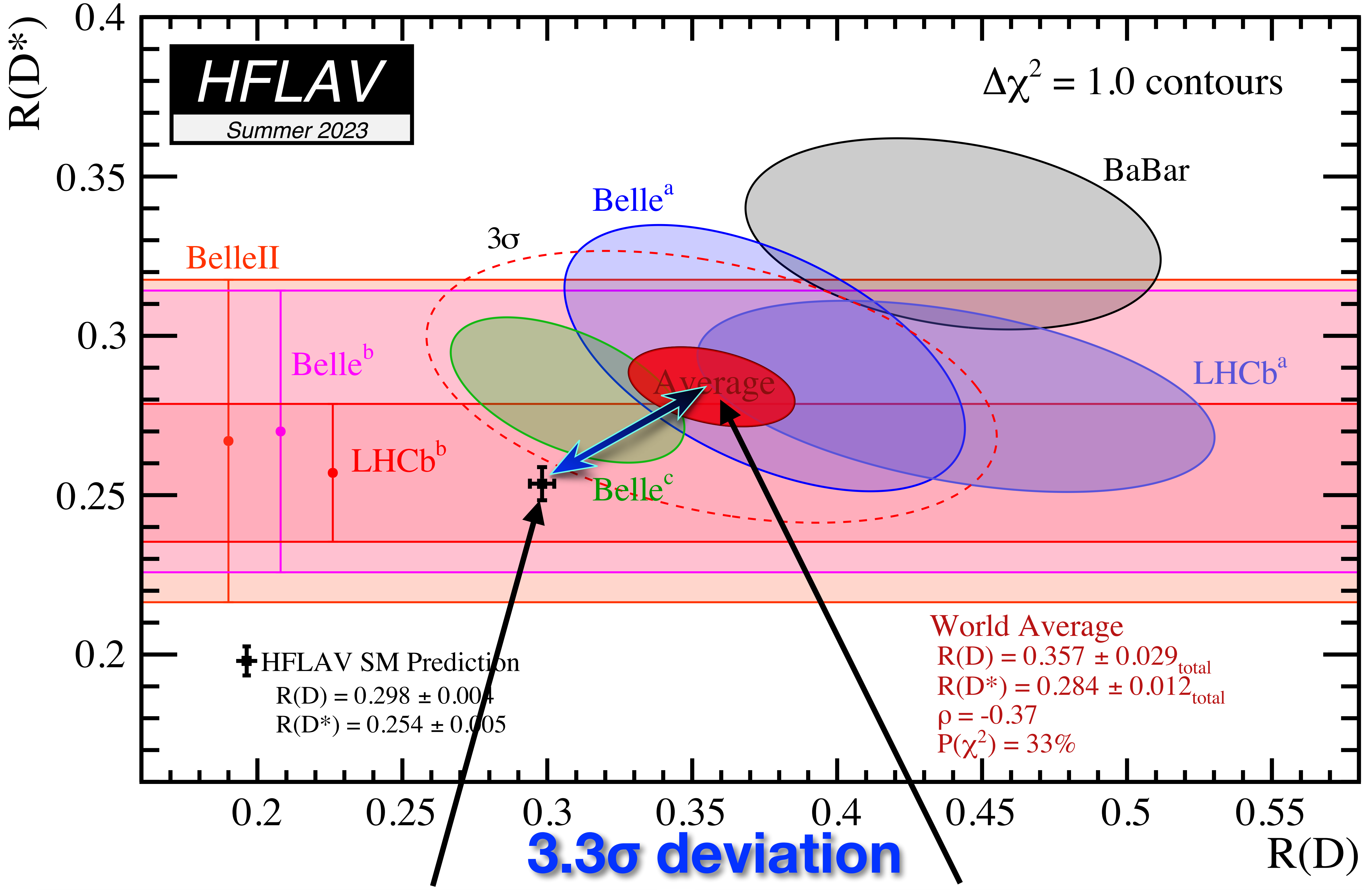






“*B* anomaly” in semileptonic decays





Standard Model prediction

Experimental average results

New Physics Scenarios with Effective Field Theory

- New physics contribution to $R(D^{(*)})$ are tested with Wilson operators

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} [(1 + C_{V_L})\mathcal{O}_{V_L} + C_{V_R}\mathcal{O}_{V_R} + C_{S_L}\mathcal{O}_{S_L} + C_{S_R}\mathcal{O}_{S_R} + C_T\mathcal{O}_T]$$

$\mathcal{O}_{V_L}$, $\mathcal{O}_{V_R}$: Left-, right-handed vector operators
$\mathcal{O}_{S_L}$, $\mathcal{O}_{S_R}$: Left-, right-handed scalar operators
$\mathcal{O}_T$: Tensor vector operators

C_X: Willson coefficient for a X operator

PRD 110, 075005 (2024)

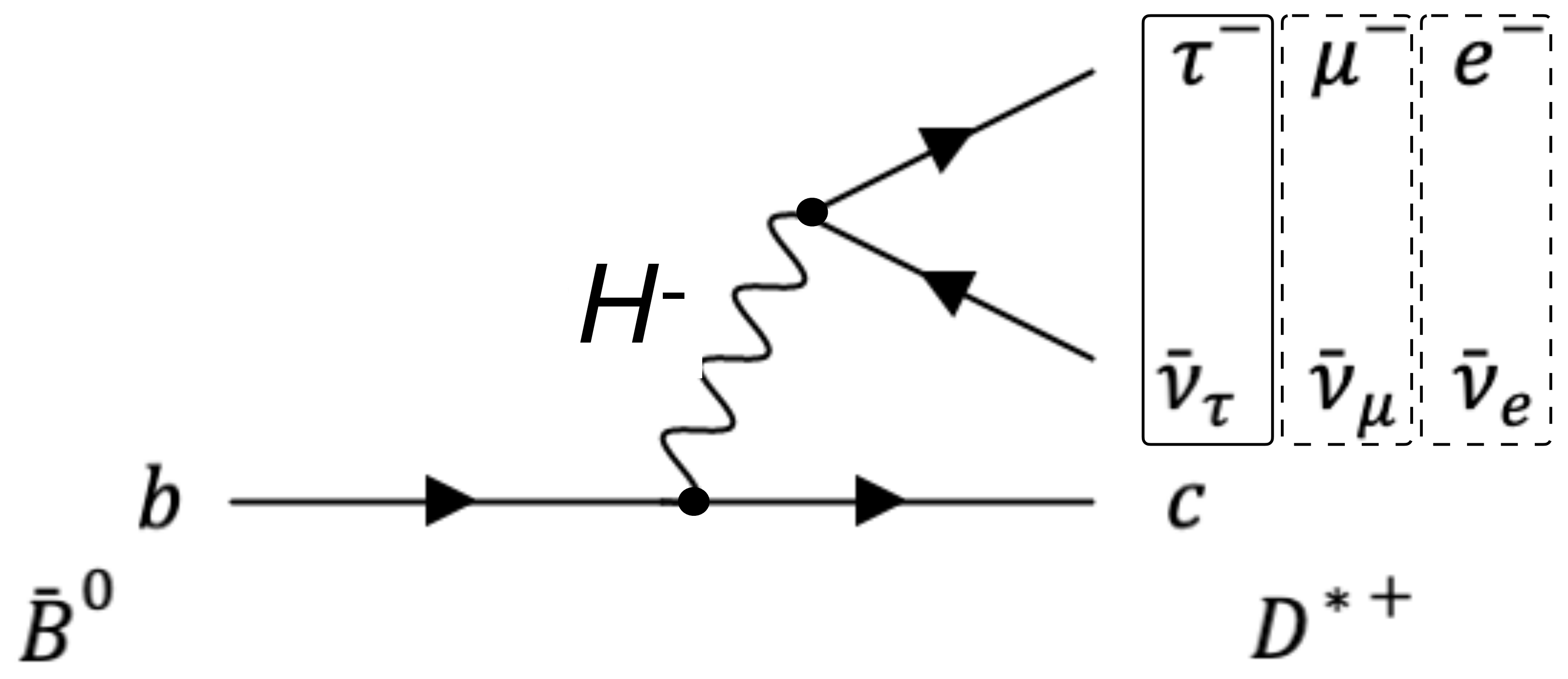
$$\frac{R_{D^*}}{R_{D^*}^{\text{SM}}} = |1 + C_{V_L}|^2 + |C_{V_R}|^2 + 0.04|C_{S_L} - C_{S_R}|^2 + 16.0|C_T|^2$$
$$- 1.83\text{Re}[(1 + C_{V_L})C^*_{V_R}] - 0.11\text{Re}[(1 + C_{V_L} - C_{V_R})(C^*_{S_L} - C^*_{S_R})]$$
$$- 5.17\text{Re}[(1 + C_{V_L})C^*_T] + 6.60\text{Re}[C_{V_R}C^*_T],$$

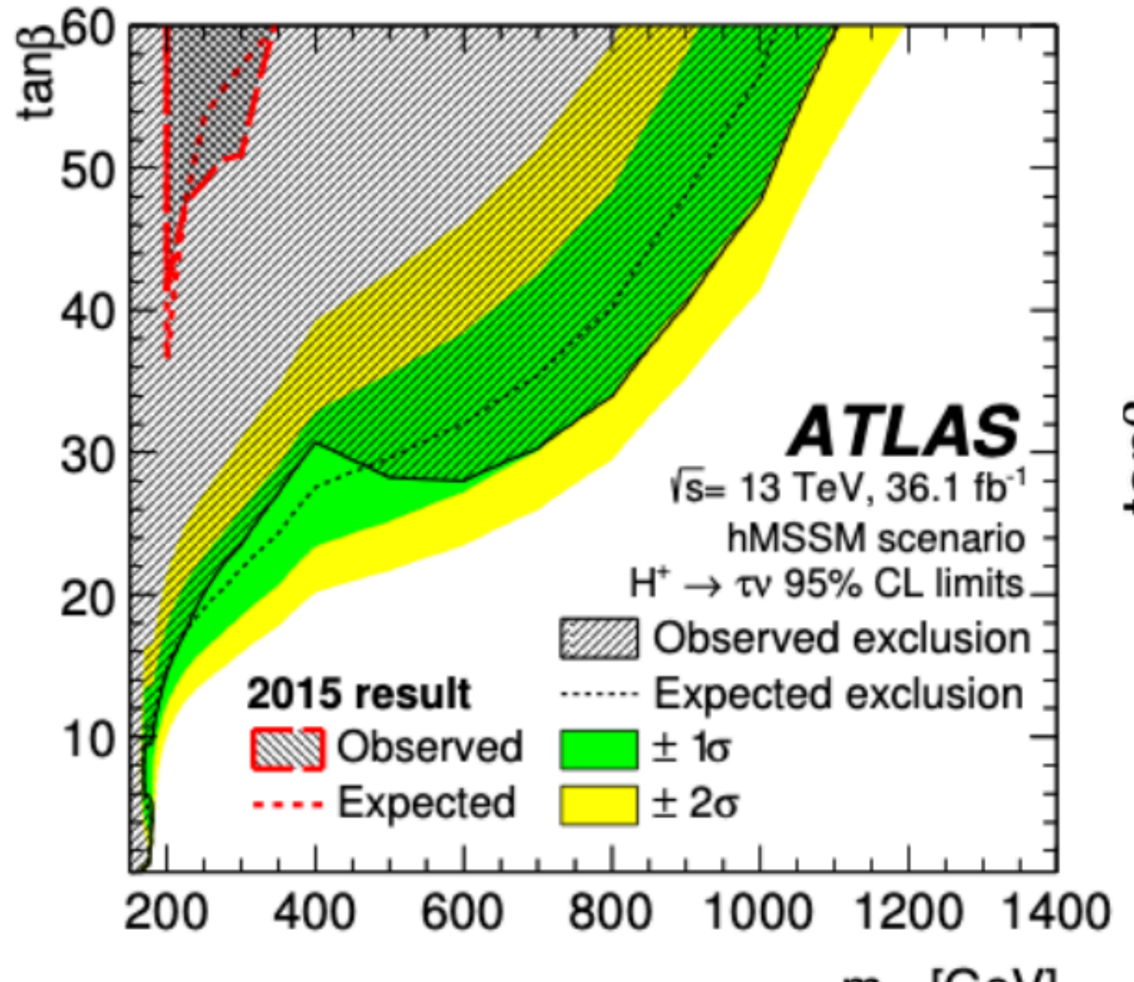
- Exp. average to constrain Wilson coefficients

	$R(D)$	$R(D^*)$
Exp. average	0.356 ± 0.029	0.284 ± 0.013
SM	0.298 ± 0.004	0.254 ± 0.005

Constraint on Charged Higgs scenario

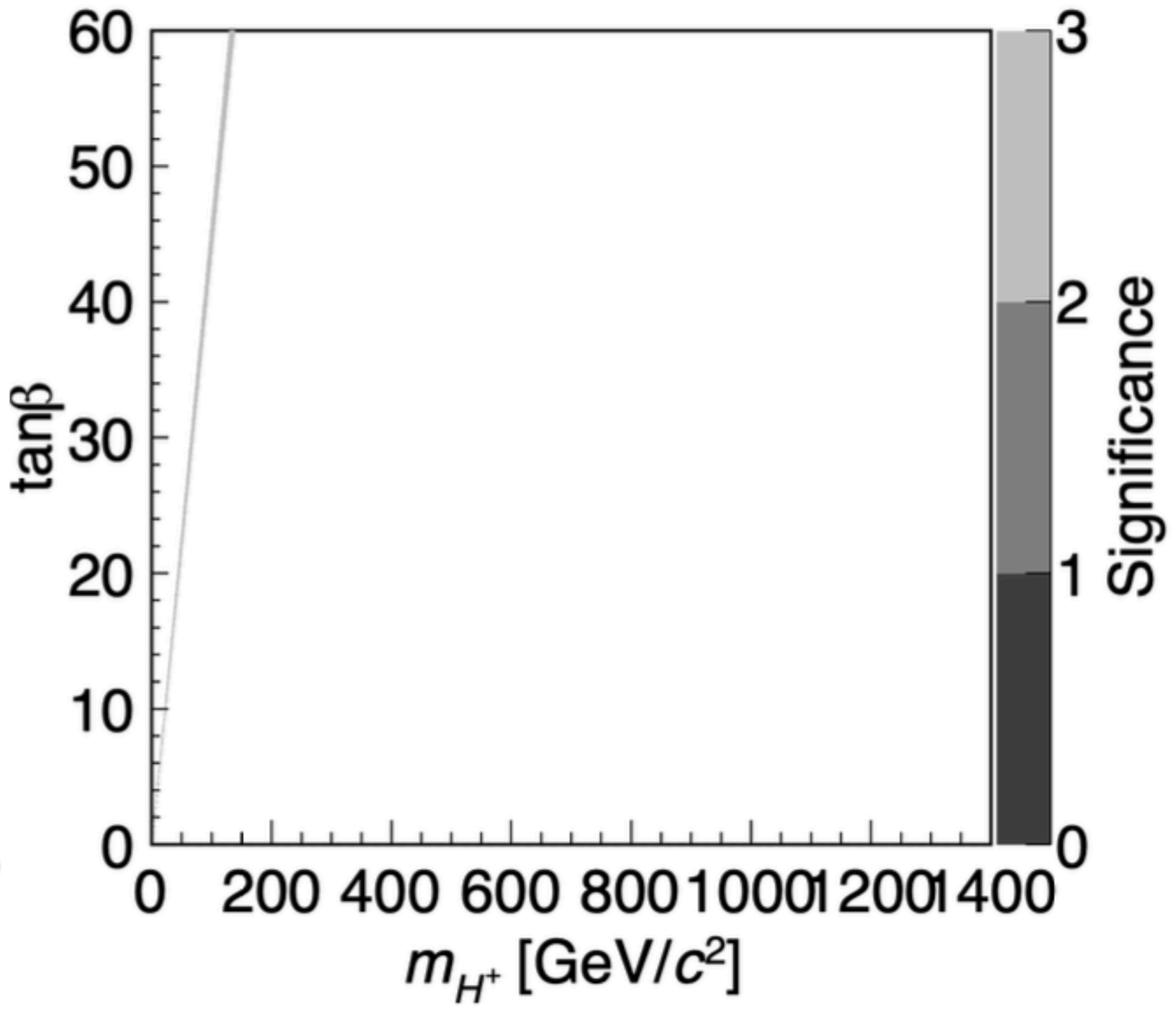
Model	Coefficients
2HDM (type-II) [Phys. Rev. D 87, 034028](#)	$\begin{cases} C_{S_L} = -m_b m_\tau(\mu_b)\dfrac{\tan^2\beta}{m_{H^+}^2} \\ C_{S_R} = -m_c(\mu_b) m_\tau(\mu_b)\dfrac{1}{m_{H^+}^2} \end{cases}$
General 2HDM	C_{S_L}



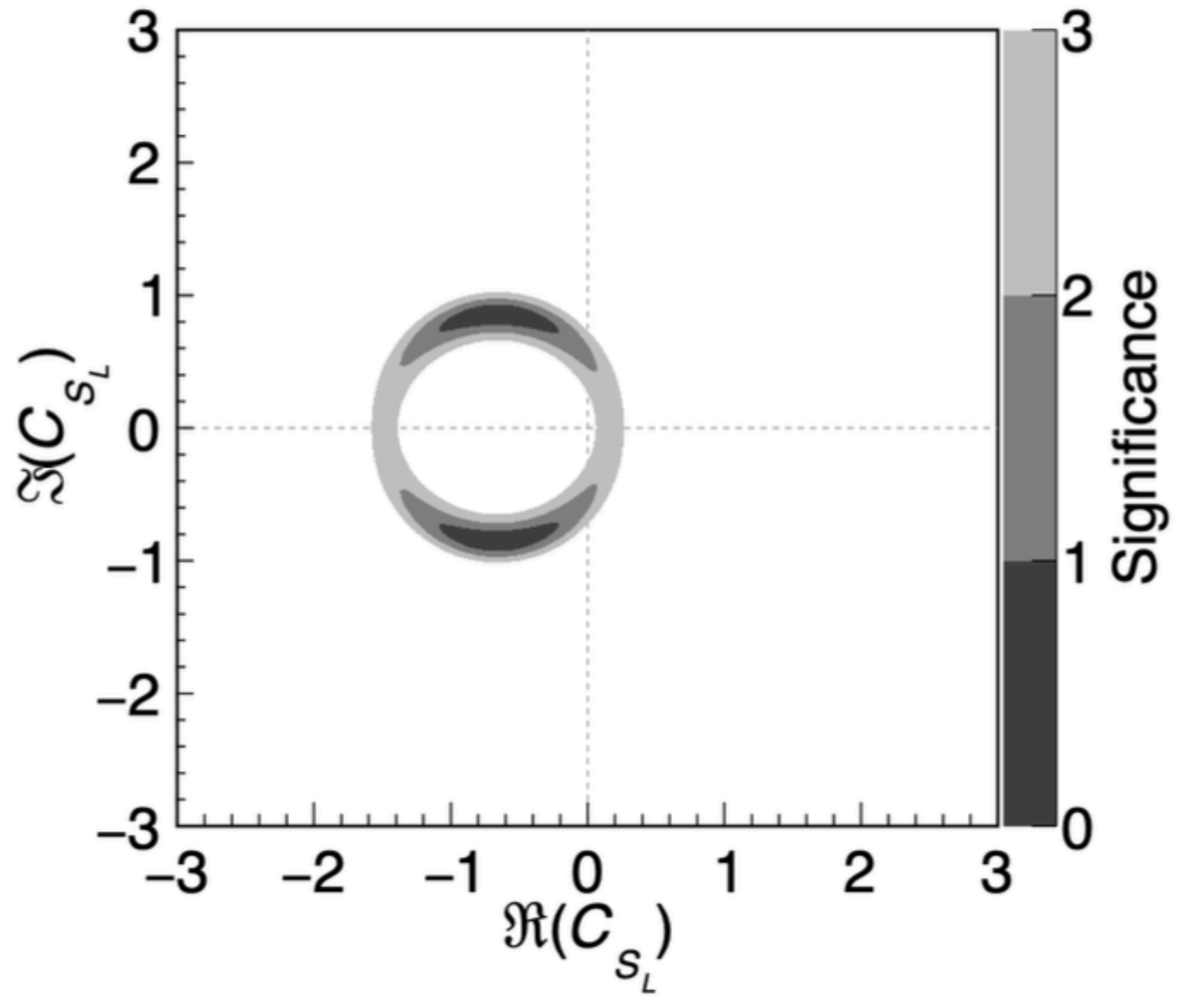


JHEP 09 (2018) 139

2HDM (type II)



General 2HDM



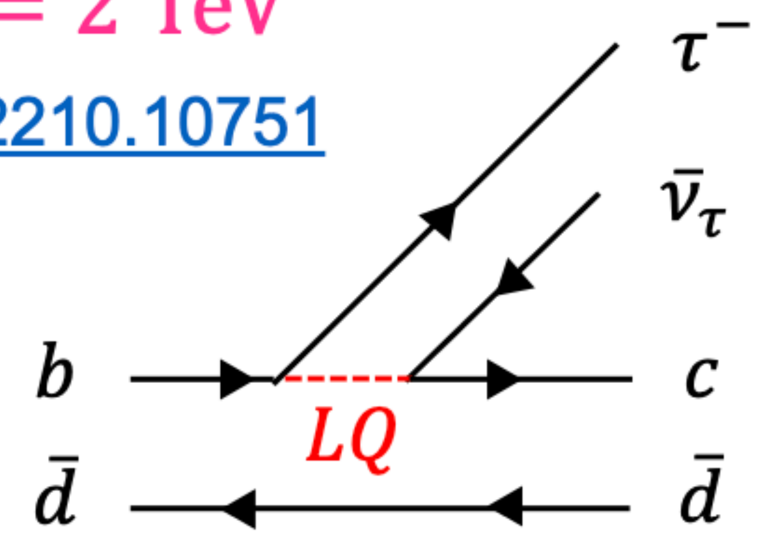
- Charged Higgs in 2HDM (type II) is disfavored
- General 2HDM still survives

Constraint on Charged Higgs scenario

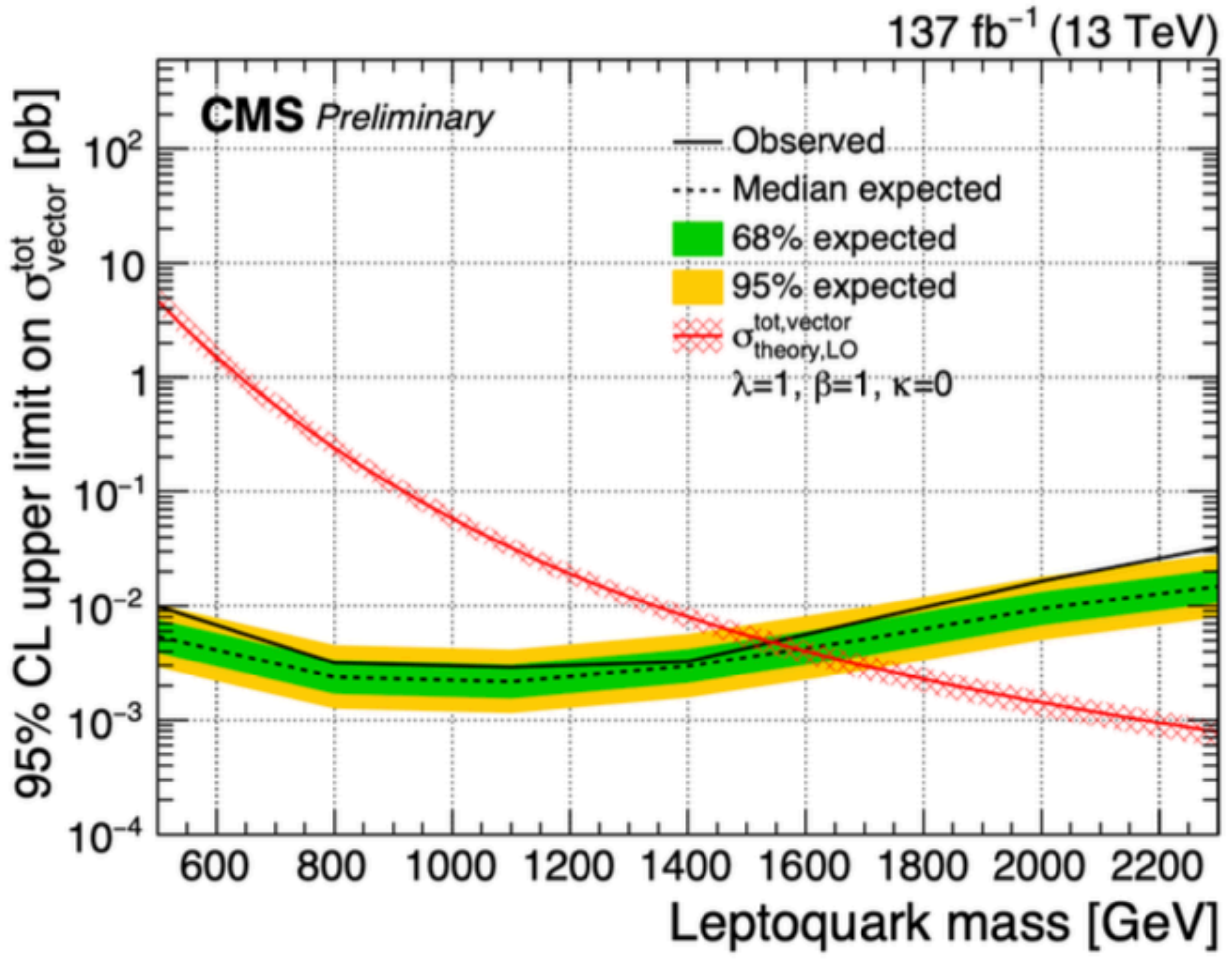
Model	Coefficients	
	$\Lambda_{LQ} = M_{LQ}$	$\mu_b = m_b$
$SU(2)_L$-singlet vector U_1^{μ}	C_{V_L}, C_{S_R}	C_{V_L}, C_{S_R}
$SU(2)_L$-singlet scalar S_1	C_{V_L}, $C_{S_L} = -4C_T$	C_{V_L}, $C_{S_L} = -8.7C_T$
$SU(2)_L$-doublet vector R_2	C_{V_R}, $C_{S_L} = +4C_T$	C_{V_R}, $C_{S_L} = +8.2C_T$

$M_{LQ} = 2$ TeV

arXiv:2210.10751

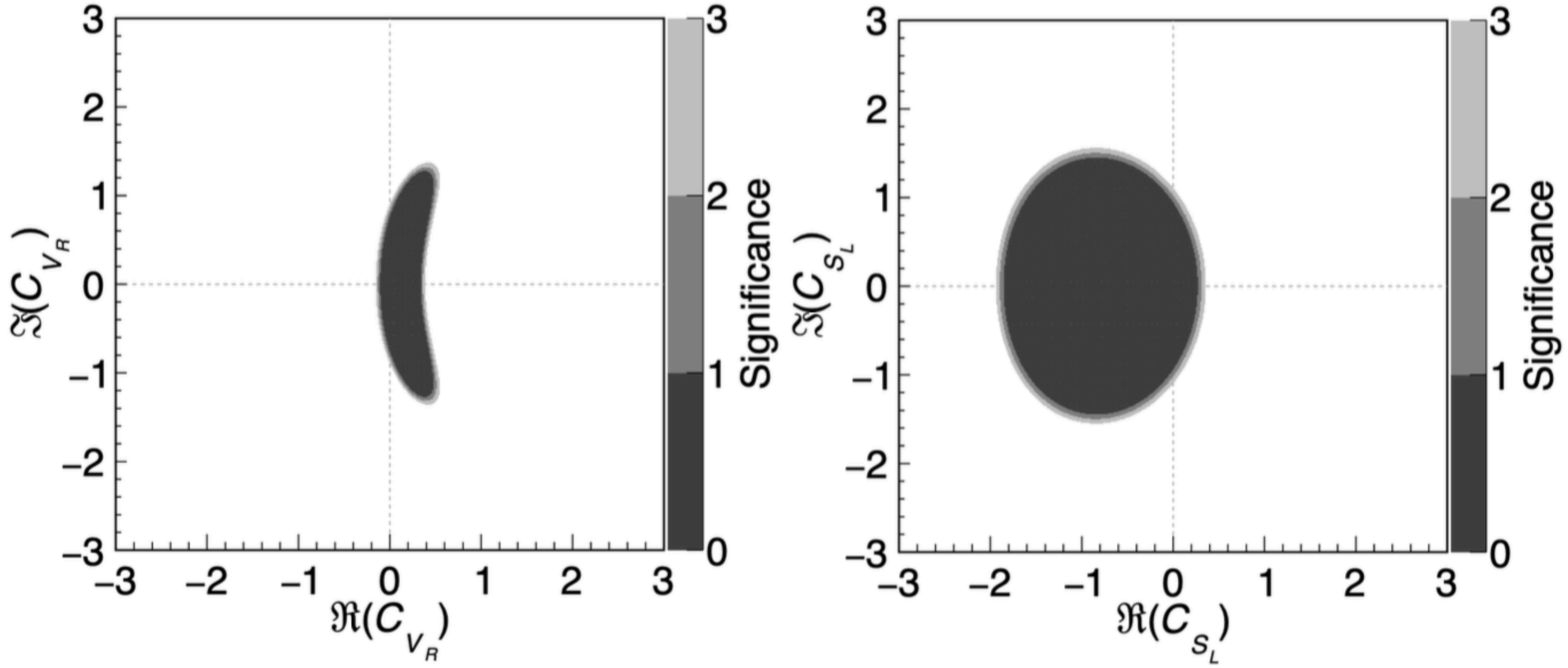


Vector leptoquark model



JHEP 05 (2024) 311

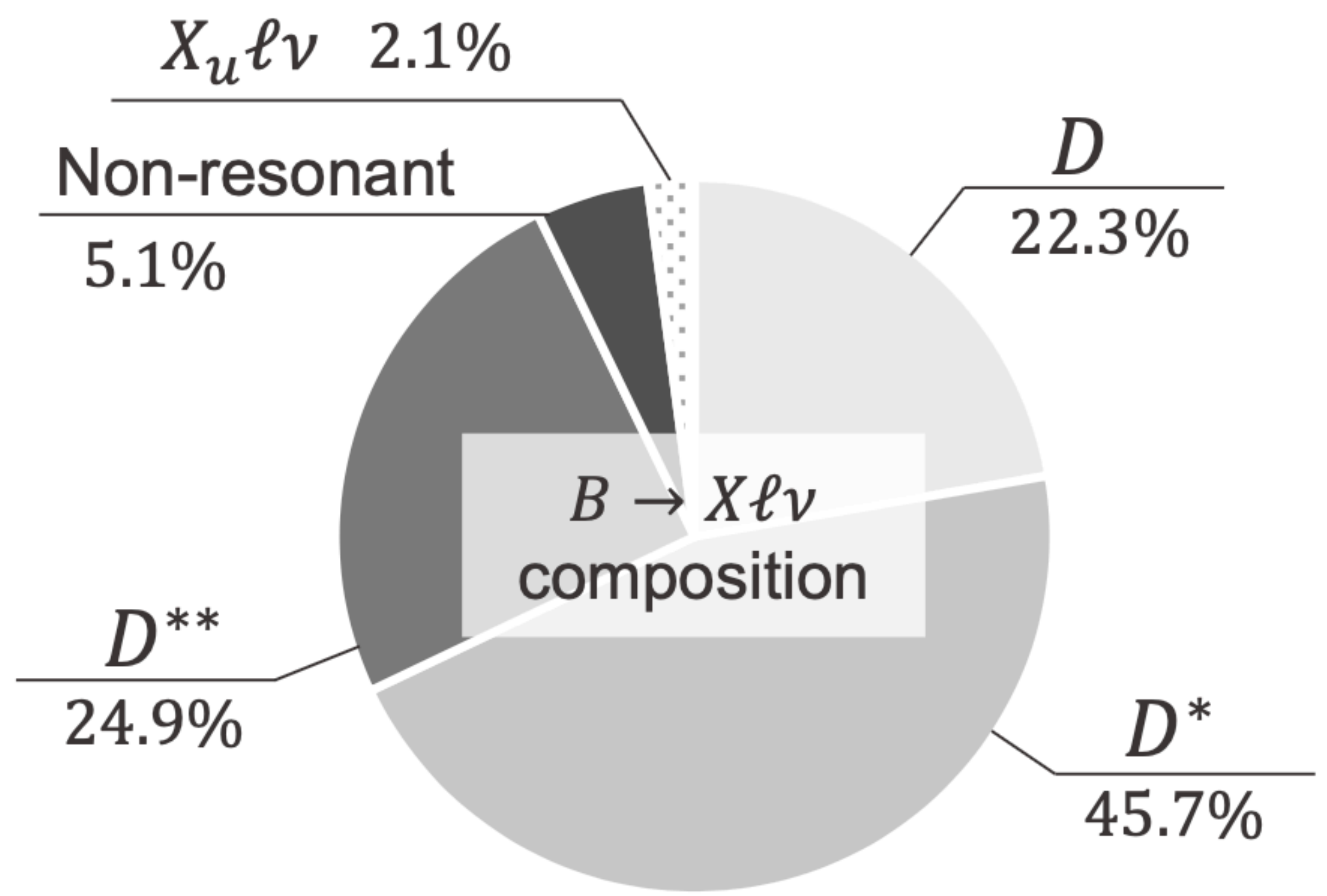
Leptoquark model (R_2 type)



- All three models have favored regions within 1σ $R(D^{(*)})$ exp. average
- $R(D^{(*)})$ can be explained with three leptoquark models of 2 TeV

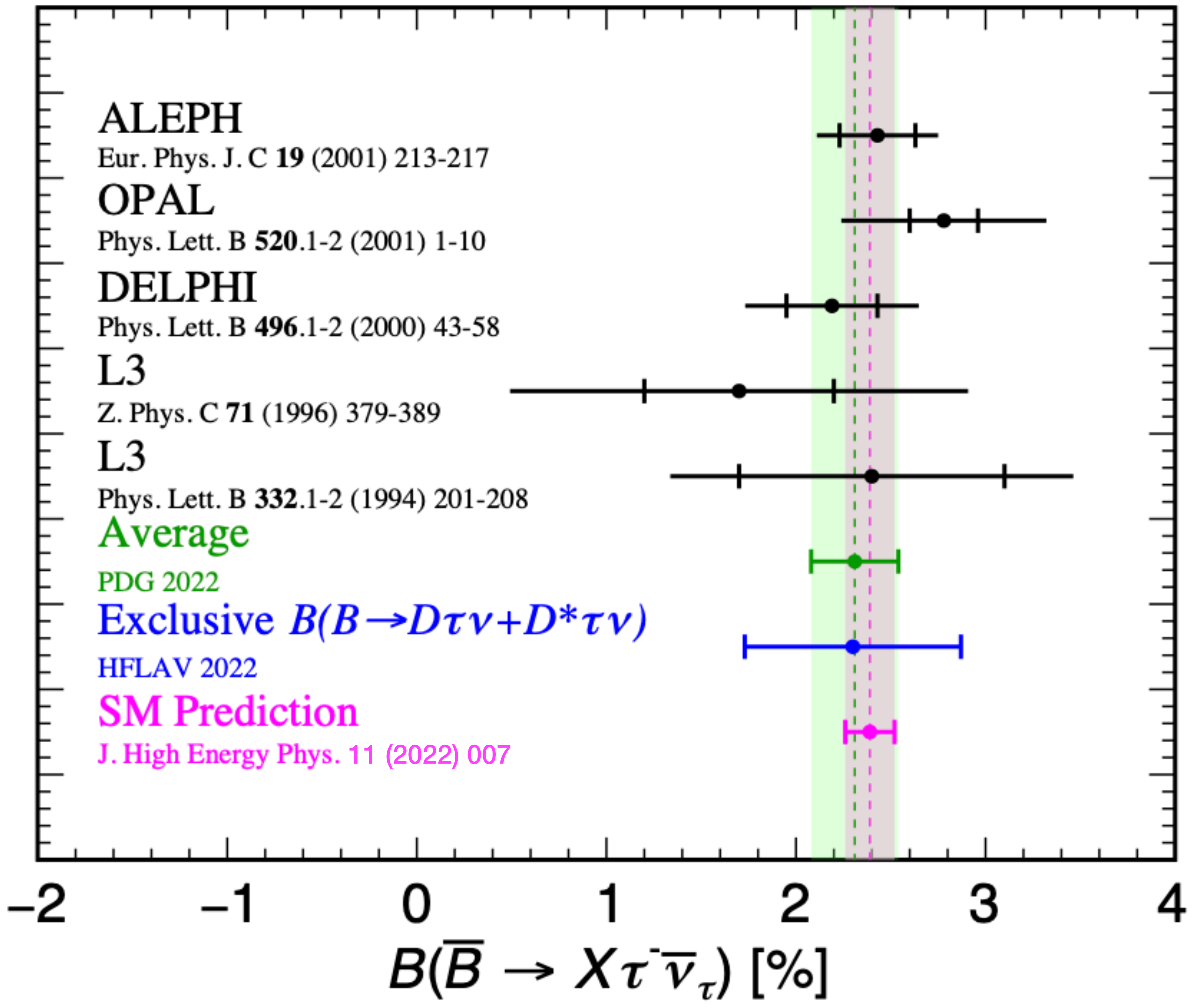
LFU test by $R_{\tau/\ell}(X)$ measurement

- 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

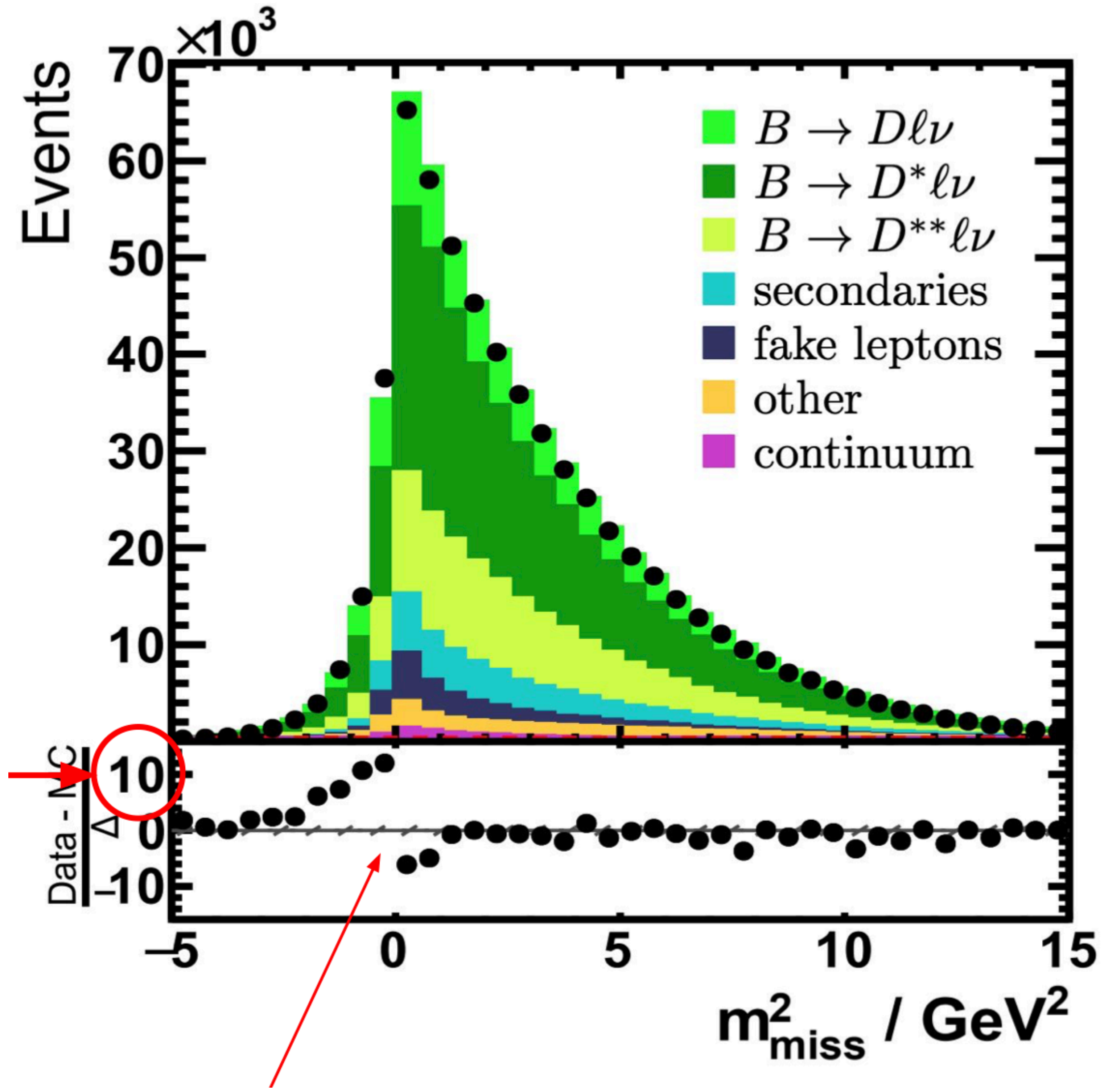
$$R(X_{\tau/\ell}) = \frac{Br(\bar{B} \to X\tau^-\bar{\nu}_\tau)}{Br(\bar{B} \to X\ell^-\bar{\nu}_\ell)}$$



- *R*(*X*) has never been measured

$R_{\tau/\ell}(X)$ measurement is difficult

- Belle attempt to understand the Data/MC disagreement
  - Detector effects are far too small
  - Beam backgrounds are far too small
  - The original appears to be somewhere in the physics simulation
- The main issues are:
  - Branching fractions are a big piece of the puzzle (particularly $D\to K_L X$) but cannot solve it entirely
  - The phase-space modeling using in ~40% of D decays is significant/unfixable
  - The PDG inclusive and exclusive BFs cannot be reconciled



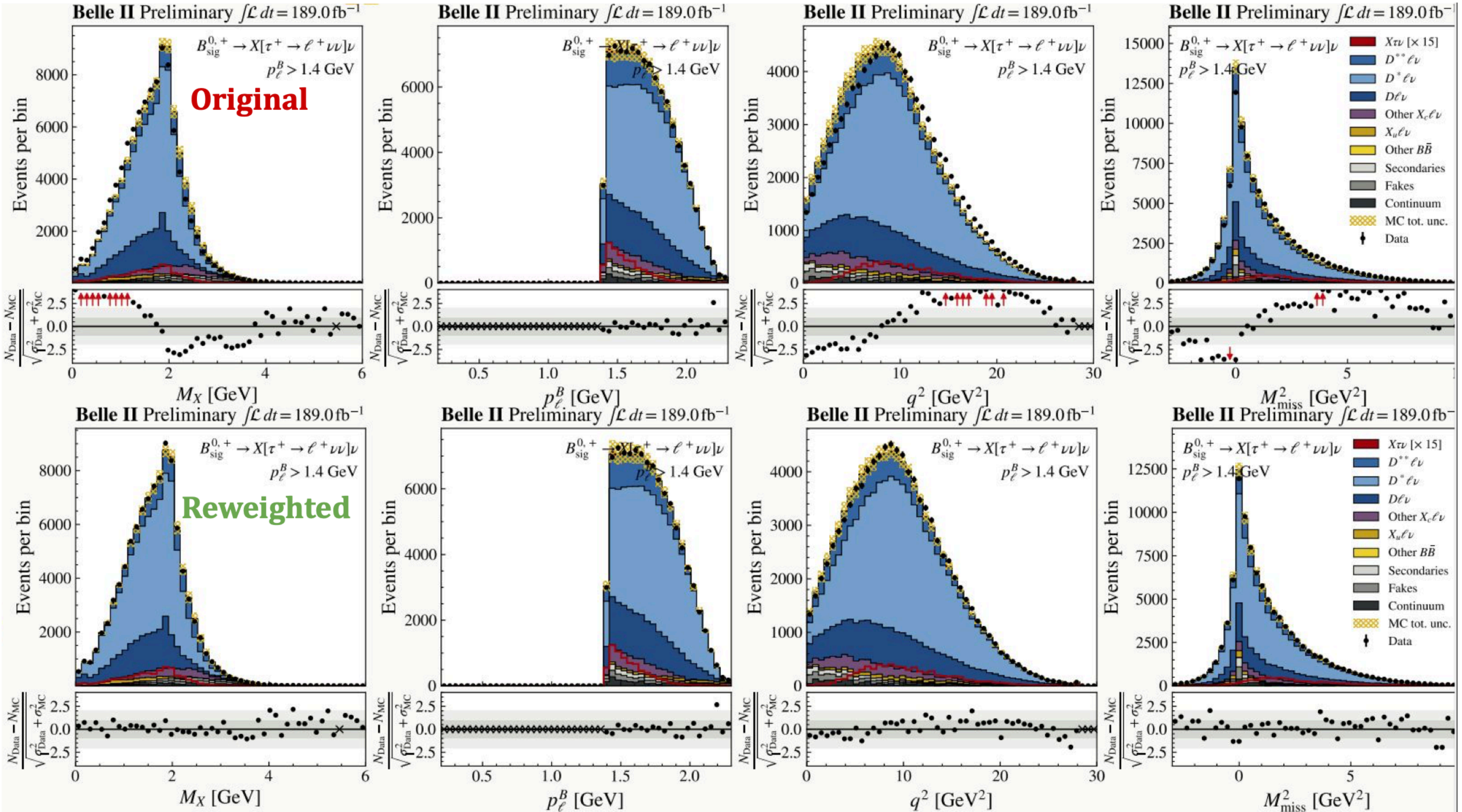
- Fixing the issue at generator level is not feasible
  - Instead, use M_X to reweight our MC

M_X reweighting

Reliable

Henrik Junkerkalefeld

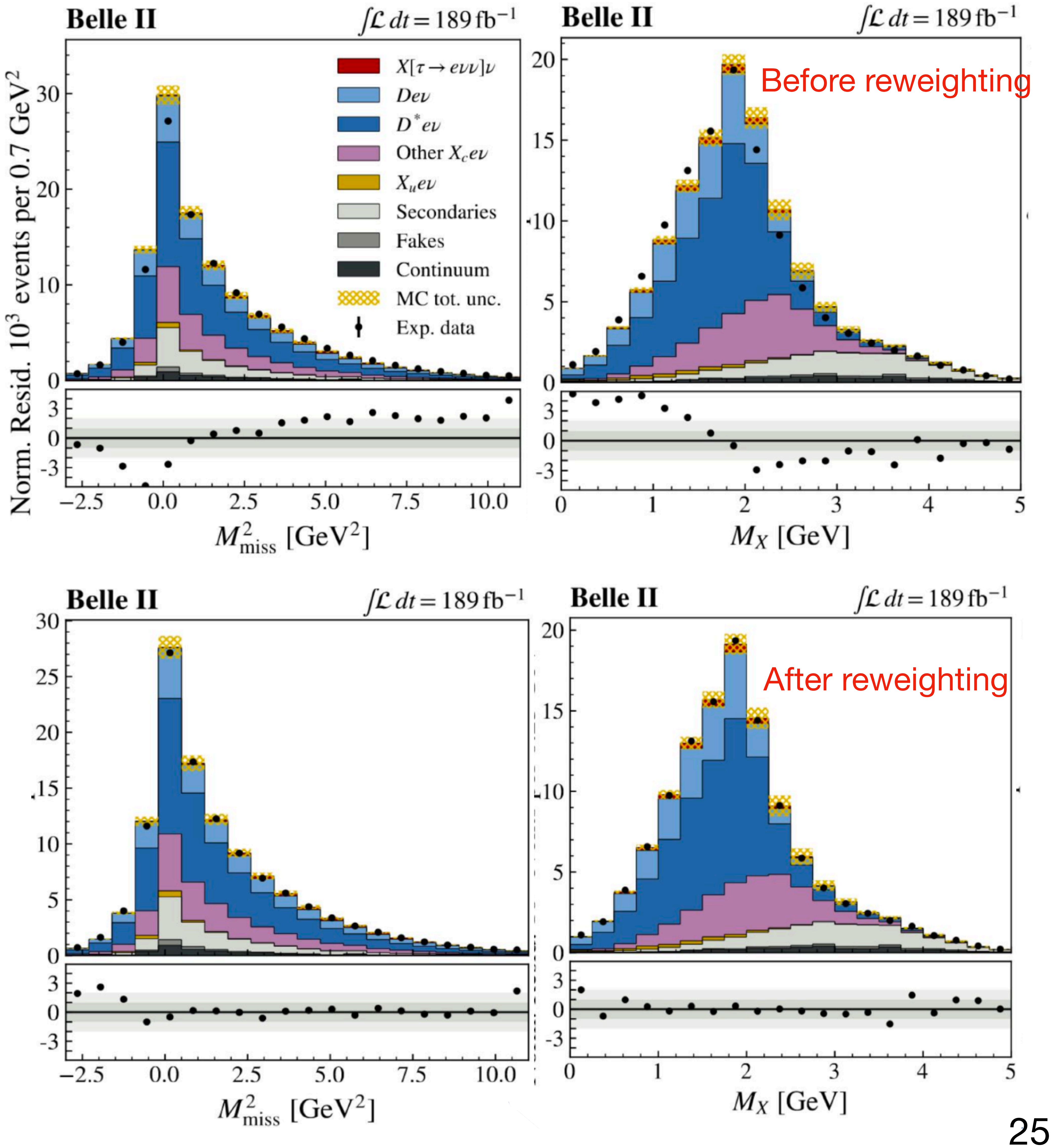
$$M_X{}^2 = \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}^2 \qquad q^2 = \left[\begin{pmatrix} E_{\mathrm{CMS}}/2 \\ -\vec{p}_{B_{\mathrm{tag}}} \end{pmatrix} - \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}\right]^2 \qquad m_{\mathrm{miss}}^2 = \left[\begin{pmatrix} E_{\mathrm{CMS}} \\ \vec{p}_{\mathrm{CMS}} \end{pmatrix} - \begin{pmatrix} E_{\mathrm{CMS}}/2 \\ -\vec{p}_{B_{\mathrm{tag}}} \end{pmatrix} - \begin{pmatrix} E_\ell \\ \vec{p}_\ell \end{pmatrix} - \begin{pmatrix} E_X \\ \vec{p}_X \end{pmatrix}\right]^2$$



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

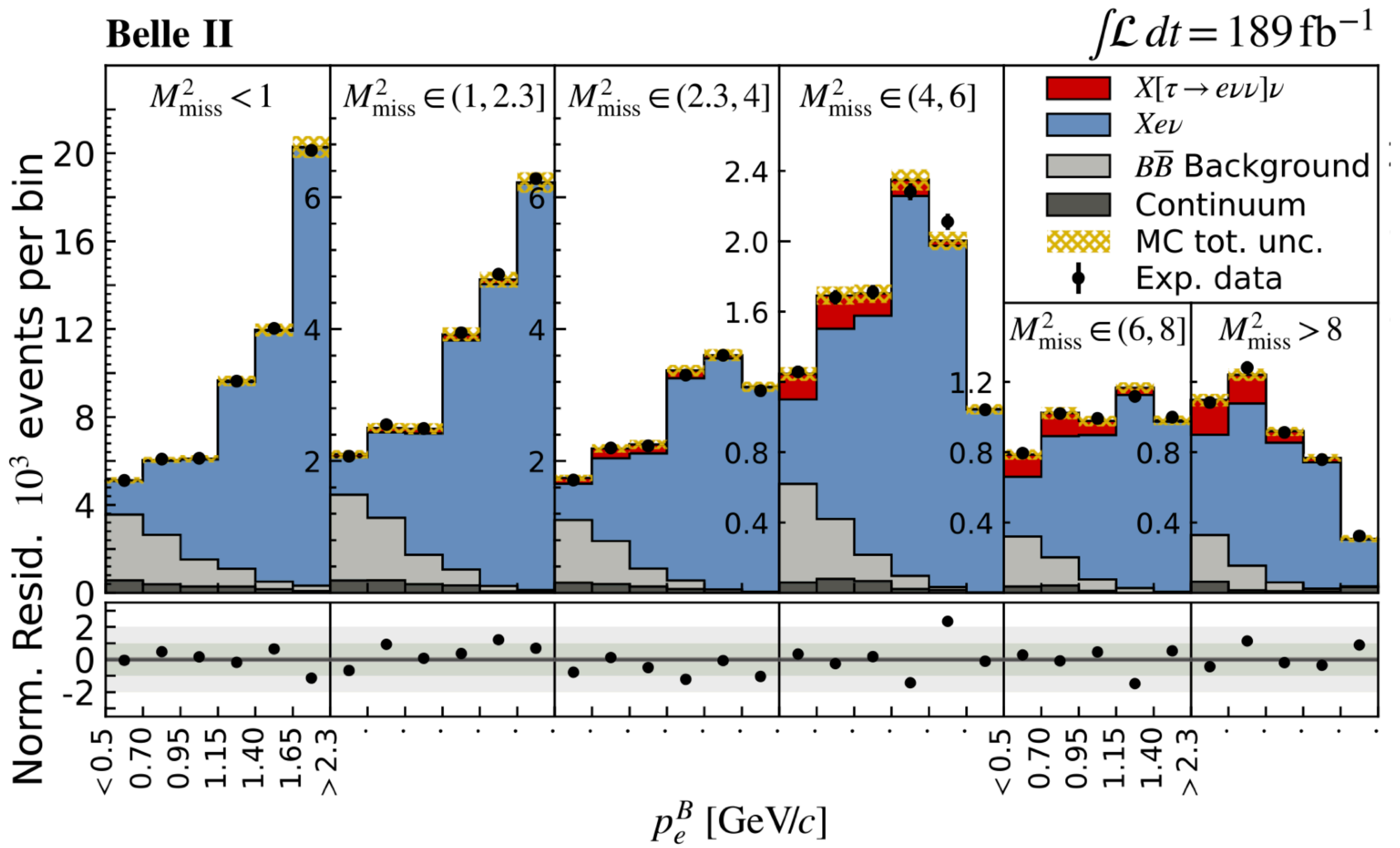
- First Belle II preliminary $R_{\tau/\ell}(X)$ result

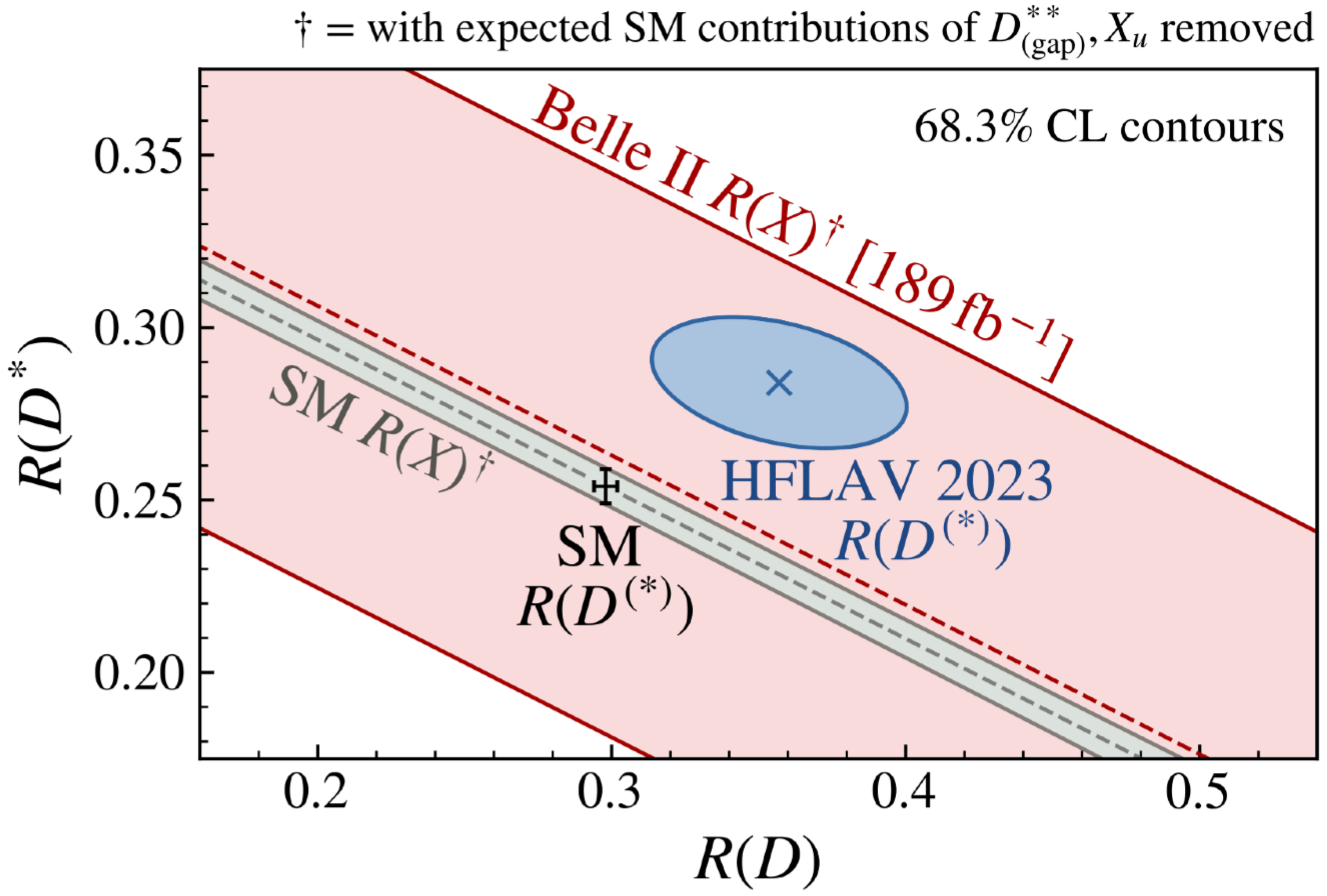
  $R_{\tau/\ell}(X) = 0.228 \pm 0.016\,(\text{stat}) \pm 0.036\,(\text{syst})$

  $R_{\tau/e}(X) = 0.232 \pm 0.020\,(\text{stat}) \pm 0.037\,(\text{syst})$
  $R_{\tau/\mu}(X) = 0.222 \pm 0.027\,(\text{stat}) \pm 0.050\,(\text{syst})$

- Consistent with rough SM expectation

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



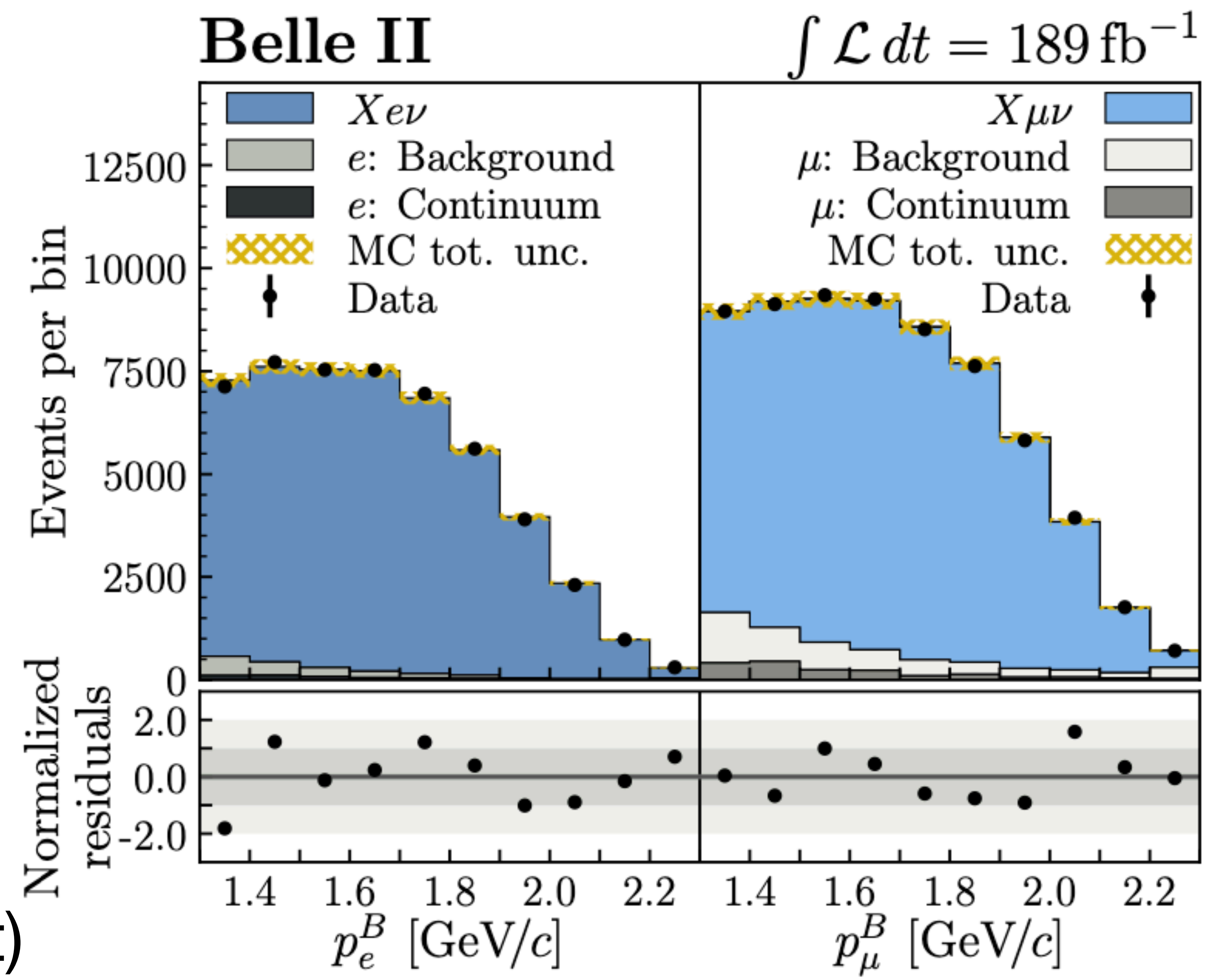


Light-lepton universality test

PRL 131, 051804

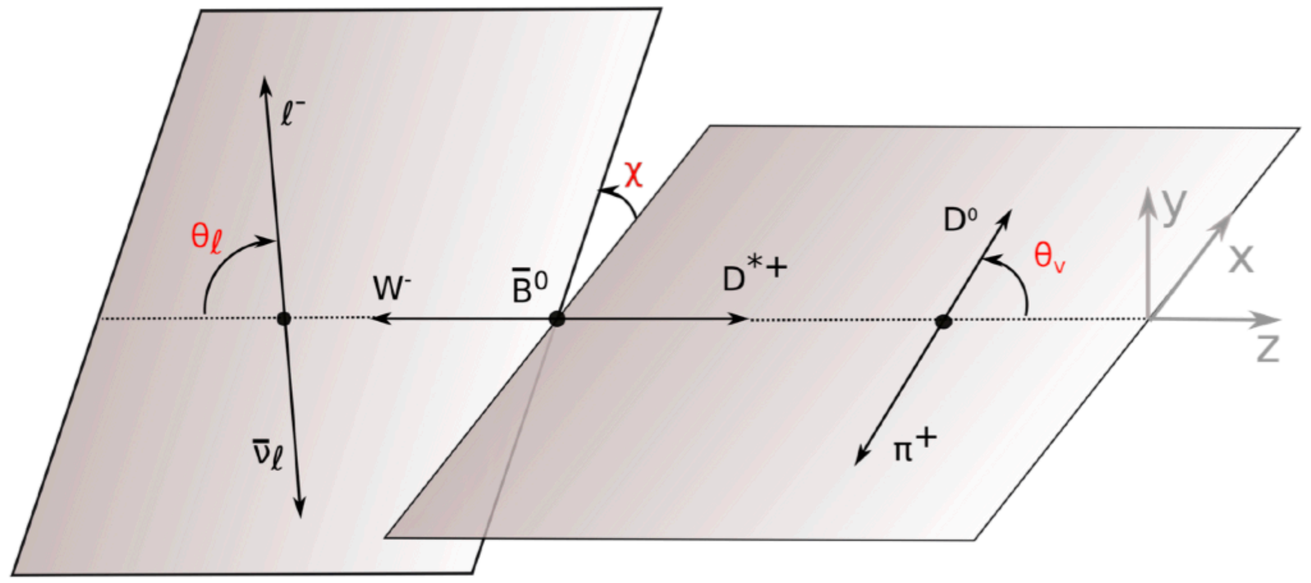
- First $R(X_{e/\mu})$ measurement
  $R(X_{e/\mu})$ = 1.007 ± 0.009 (stat) ± 0.019 (syst)
- Most precise BF based LFU test of e-μ universality with semileptonic B decays to date
- Consistent with SM value by 1.2σ
  $R(X_{e/\mu})_{SM}$ = 1.006 ± 0.001 JHEP 11 (2022) 007
- Compatible with exclusive Belle (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

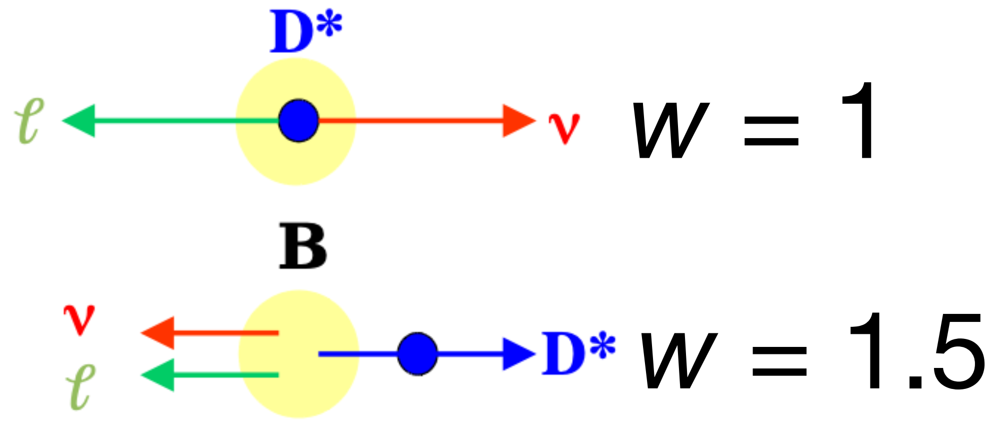


$$\mathcal{A}_x(w) \equiv \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}w}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right]\mathrm{d}x\,\frac{\mathrm{d}^2\Gamma}{\mathrm{d}w\,\mathrm{d}x} \qquad \mathcal{A}_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}$$

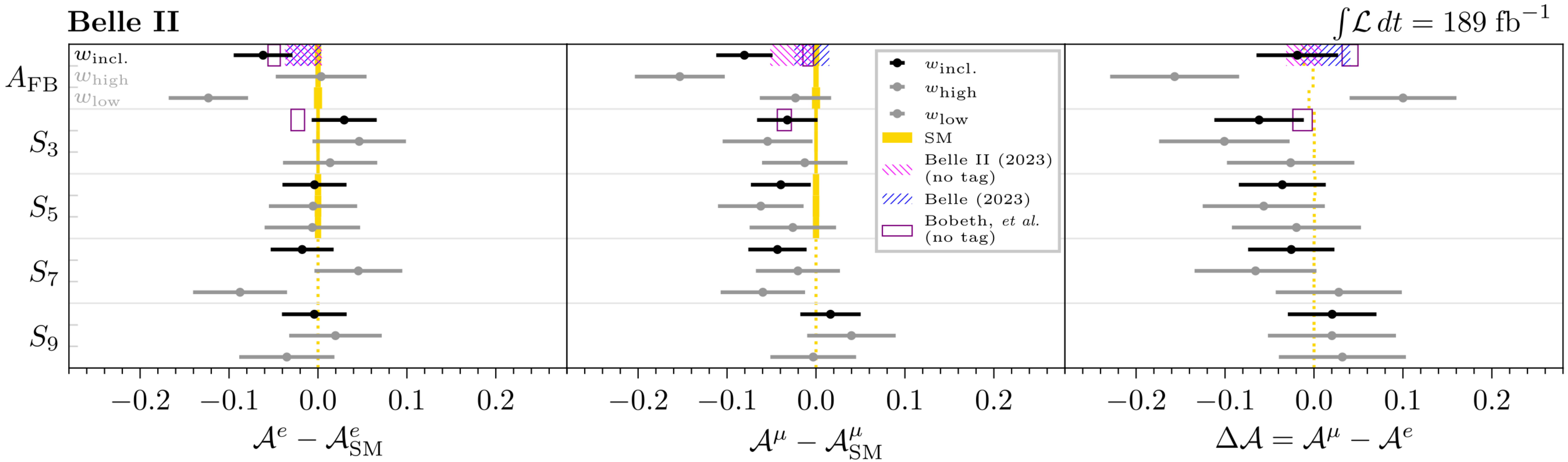
$$w \equiv \frac{m_{B^0}^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

- The differences are expected to be small in SM

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

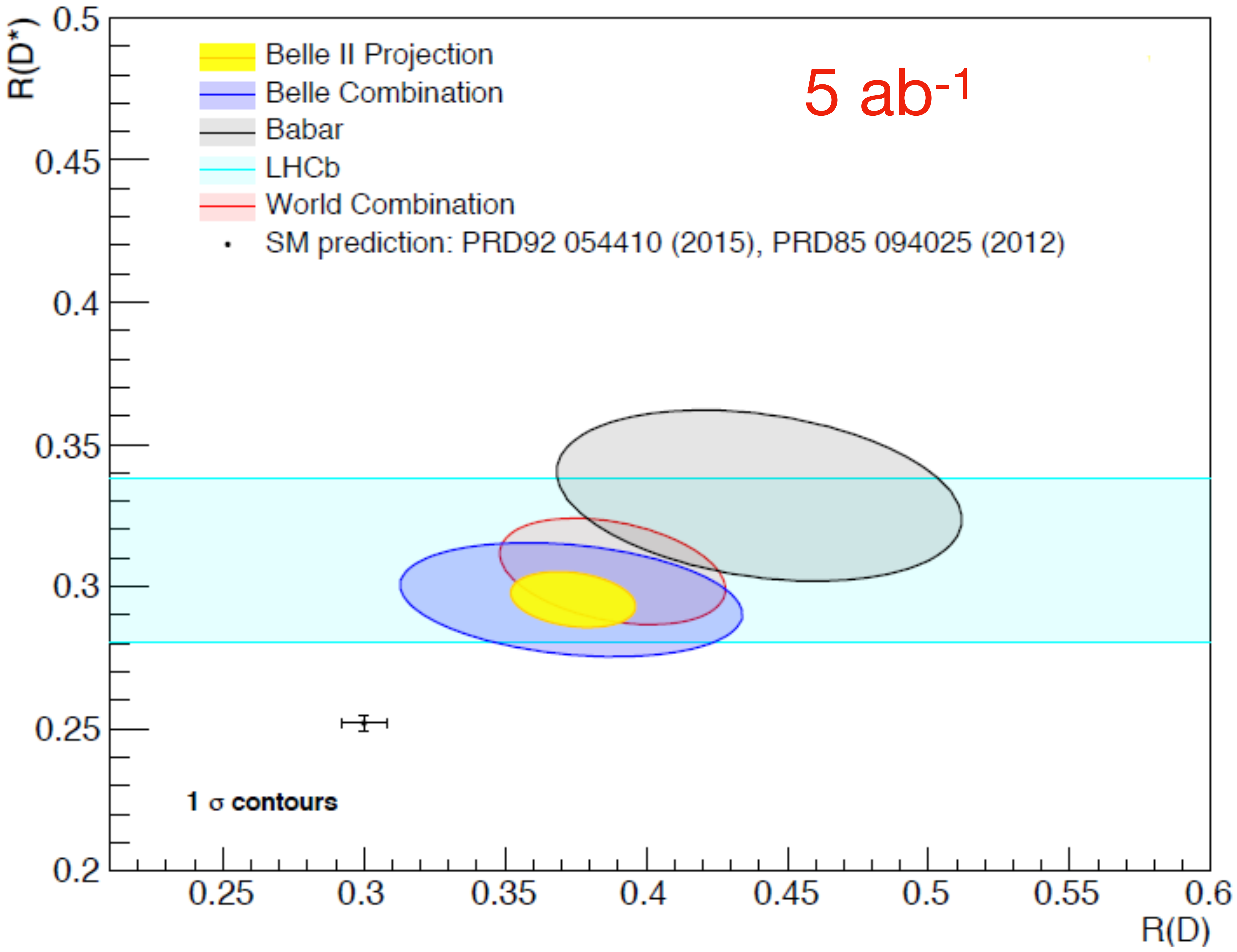


- All asymmetry consistent with SM, the measurements are statistics limited

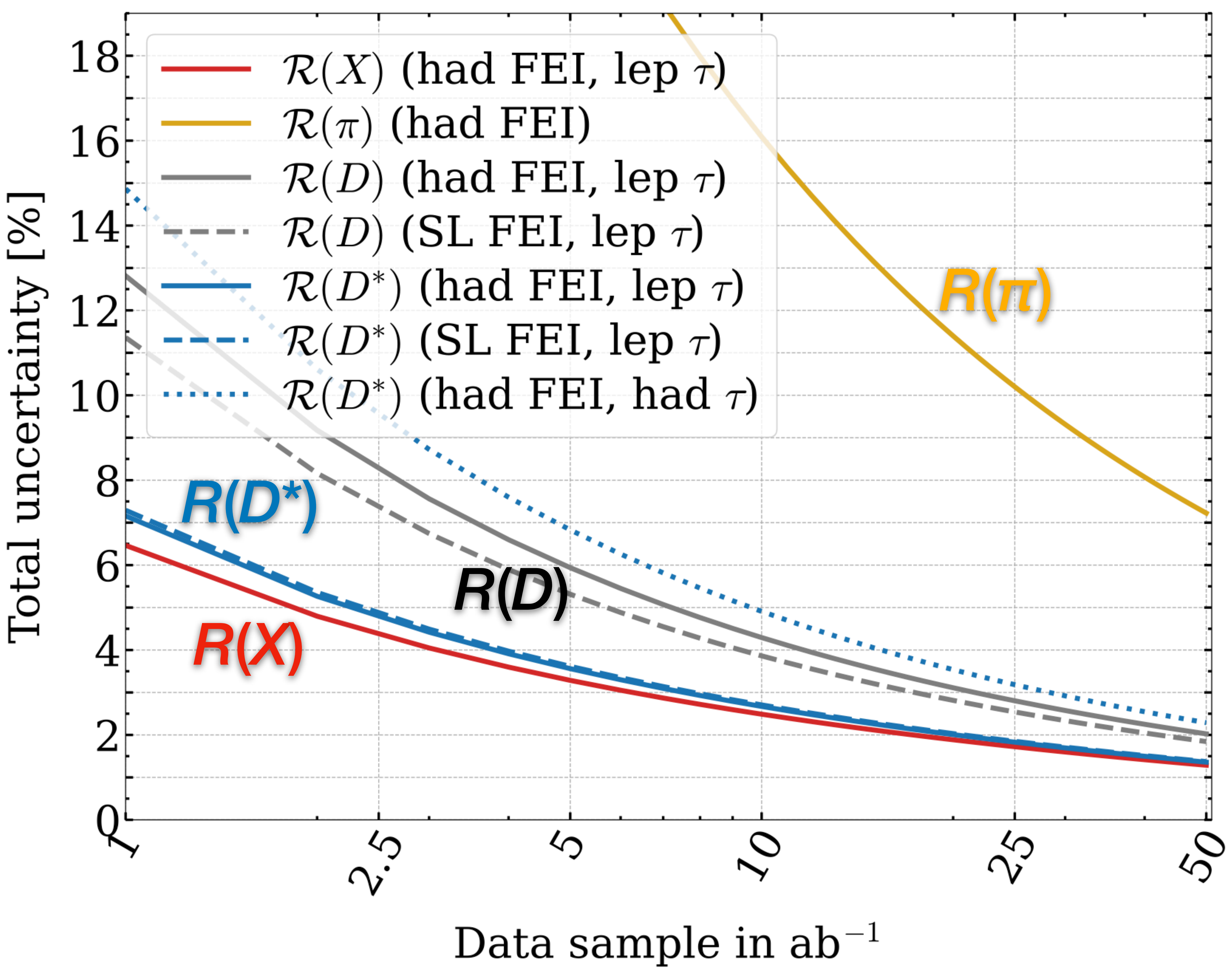


Expected sensitivity of LFU test at Belle II

The Belle II Physics Book, PTEP 2019, 123C01



arXiv:2207.06307

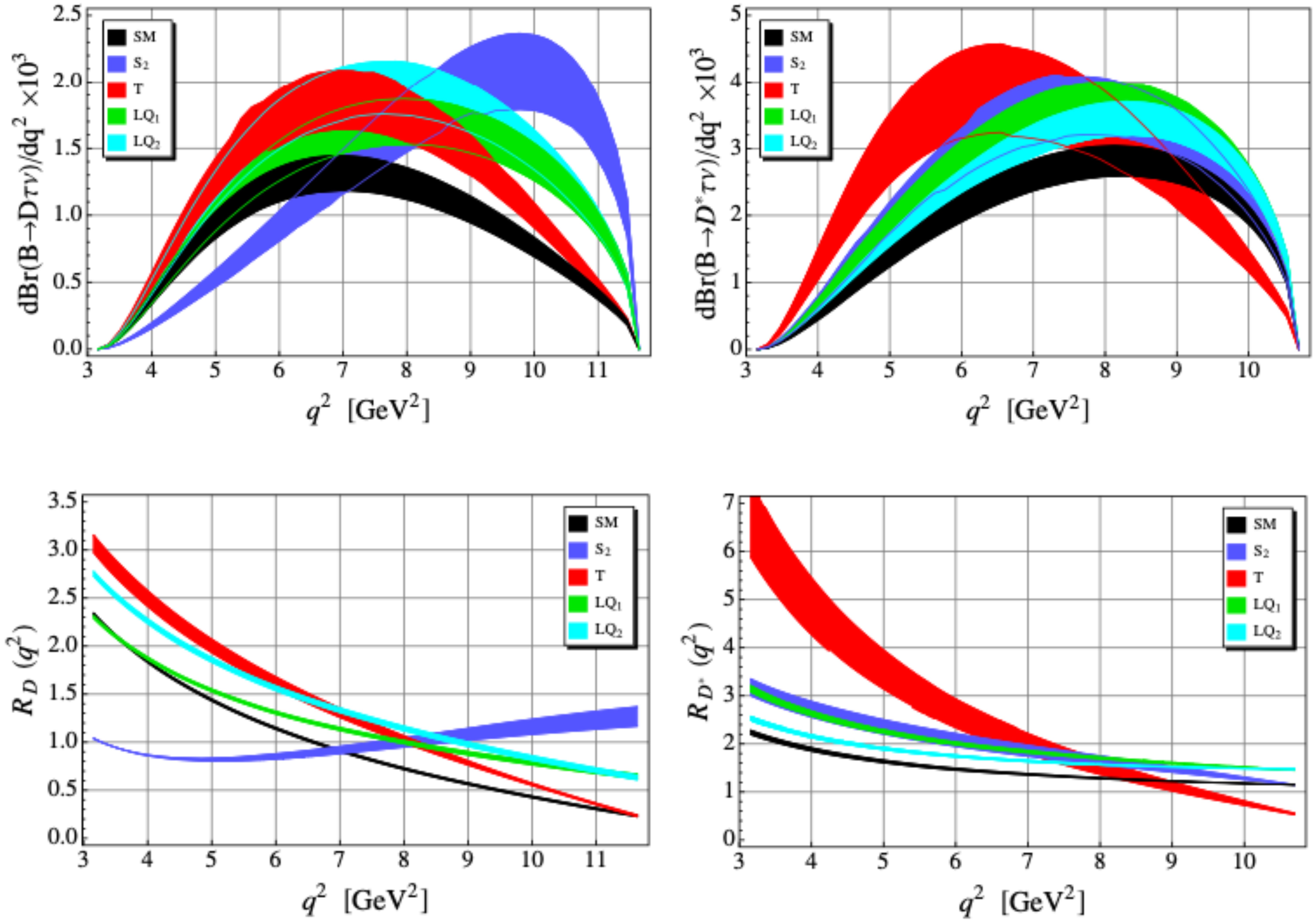


Measurement of $R_{D^{(*)}}(q^2)$

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

- 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)



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
- SuperKEKB/Belle II will resumed operation at the beginning of 2024 after LS1