Recent results of Lepton Flavor Universality test at the Belle II experiment

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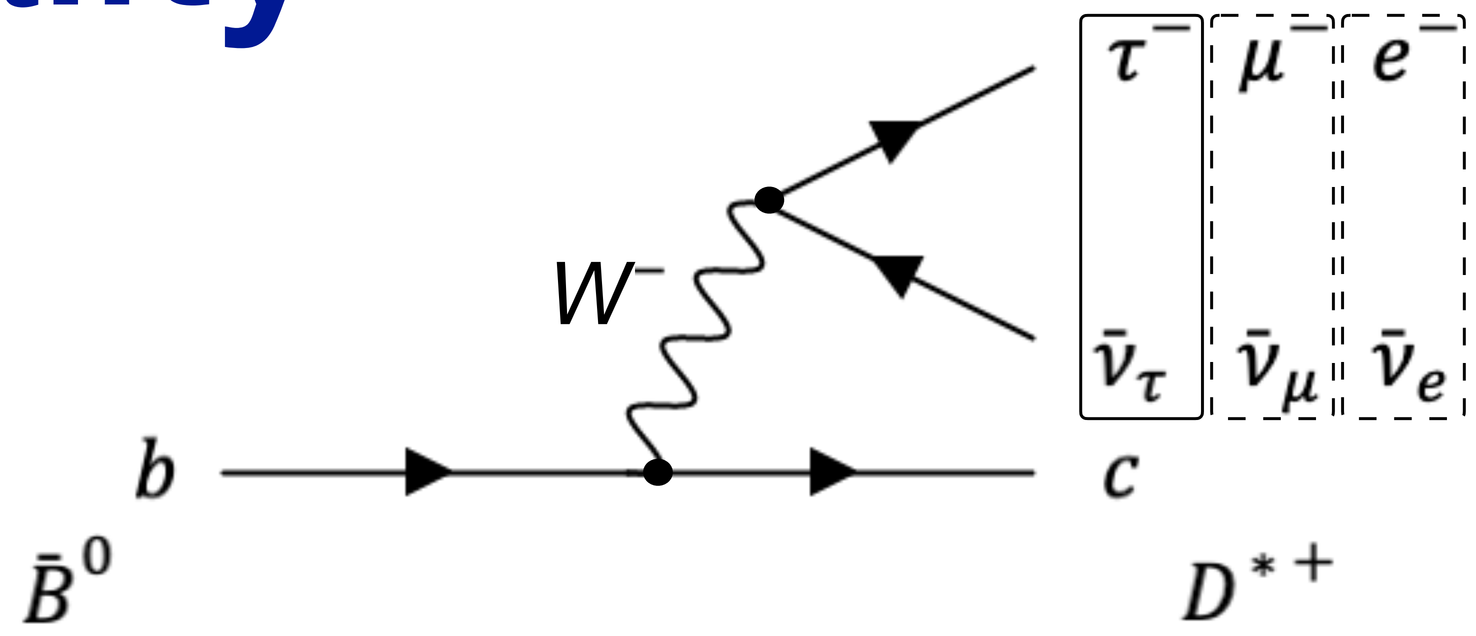
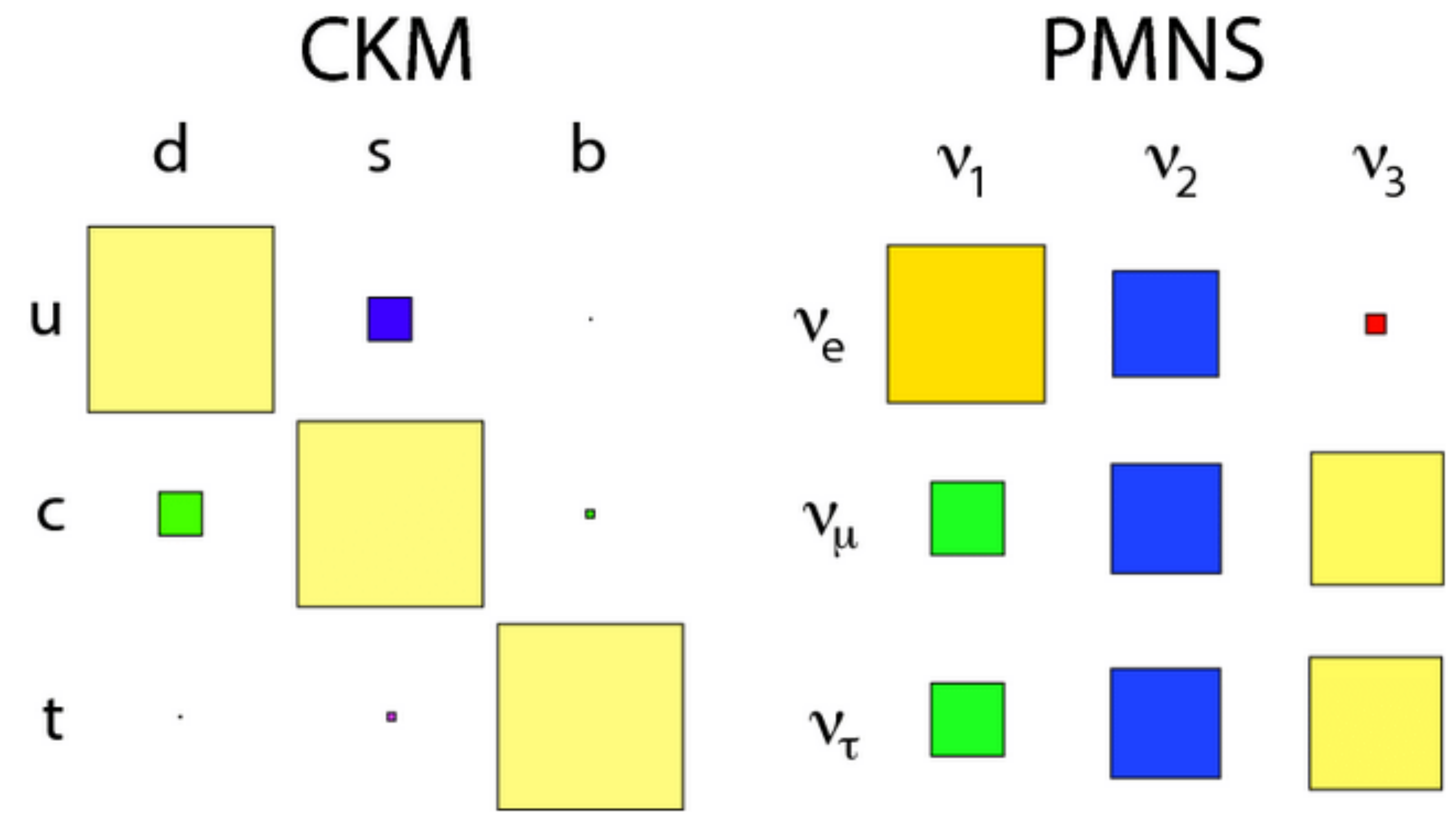
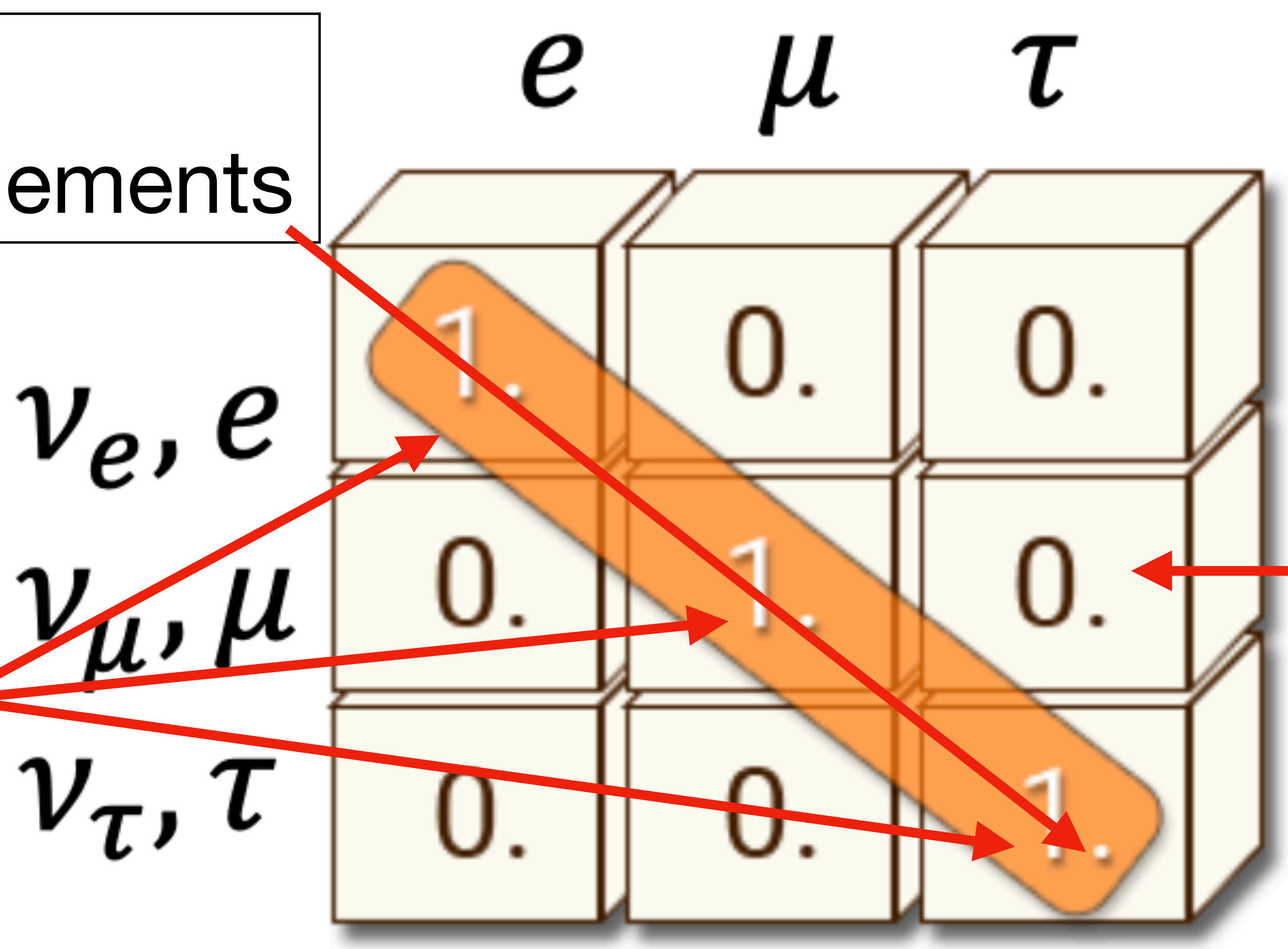
Lepton Flavor Universality

- Lepton Flavor Universality (LFU): *W* boson couples to leptons with equal strength ($m_e < m_\mu < m_\tau$)
- 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





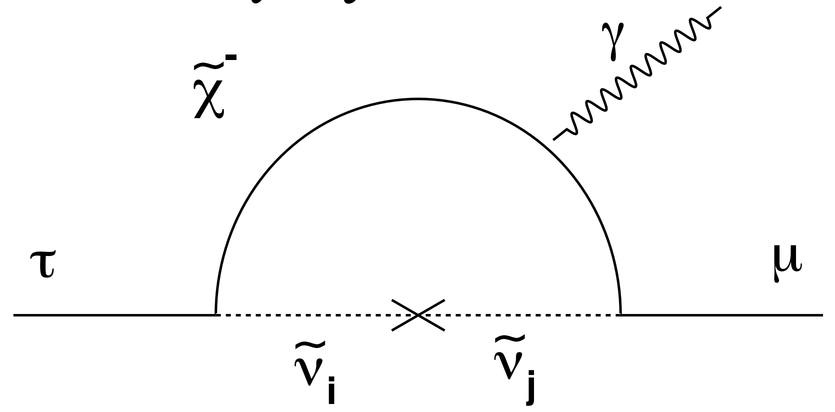
g-2, EDM: diagonal elements



LFUV:
Relation among diagonal elements

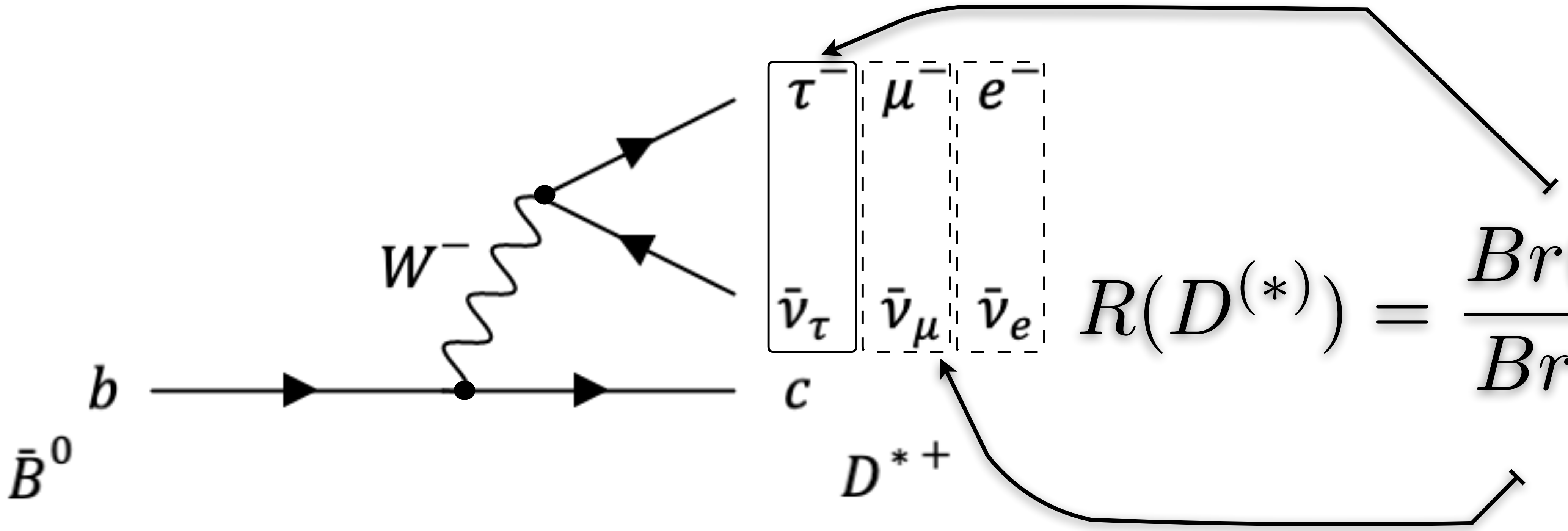
Lepton Flavor Violation (LFV):
off diagonal term

$\tau \to \mu\gamma$



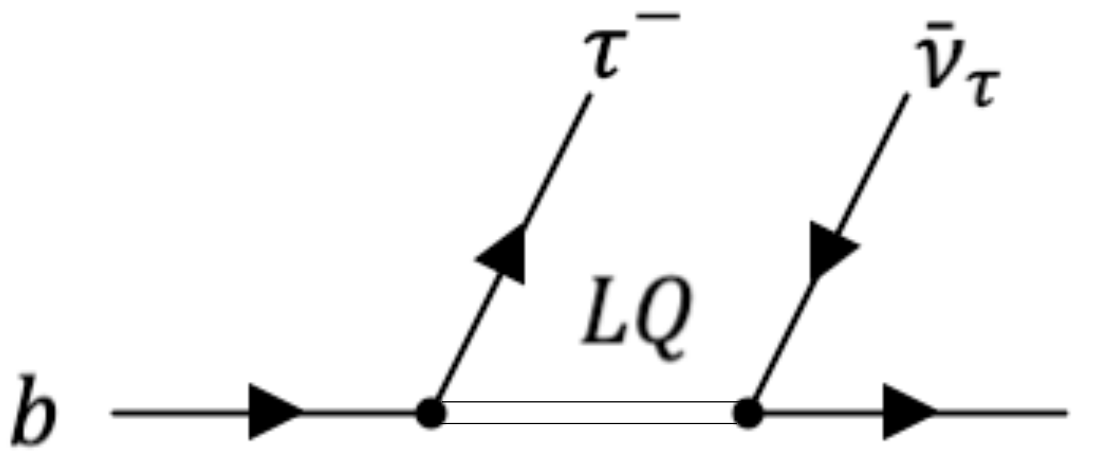
LFU test with semileptonic *B* decays

- Ratios of $b \to q\tau\nu/q\mu\nu/qe\nu$ branch fractions cancel out the uncertainties on **$|V_{cb}|$,** most uncertainties of **form factors** and the **experimental systematics**



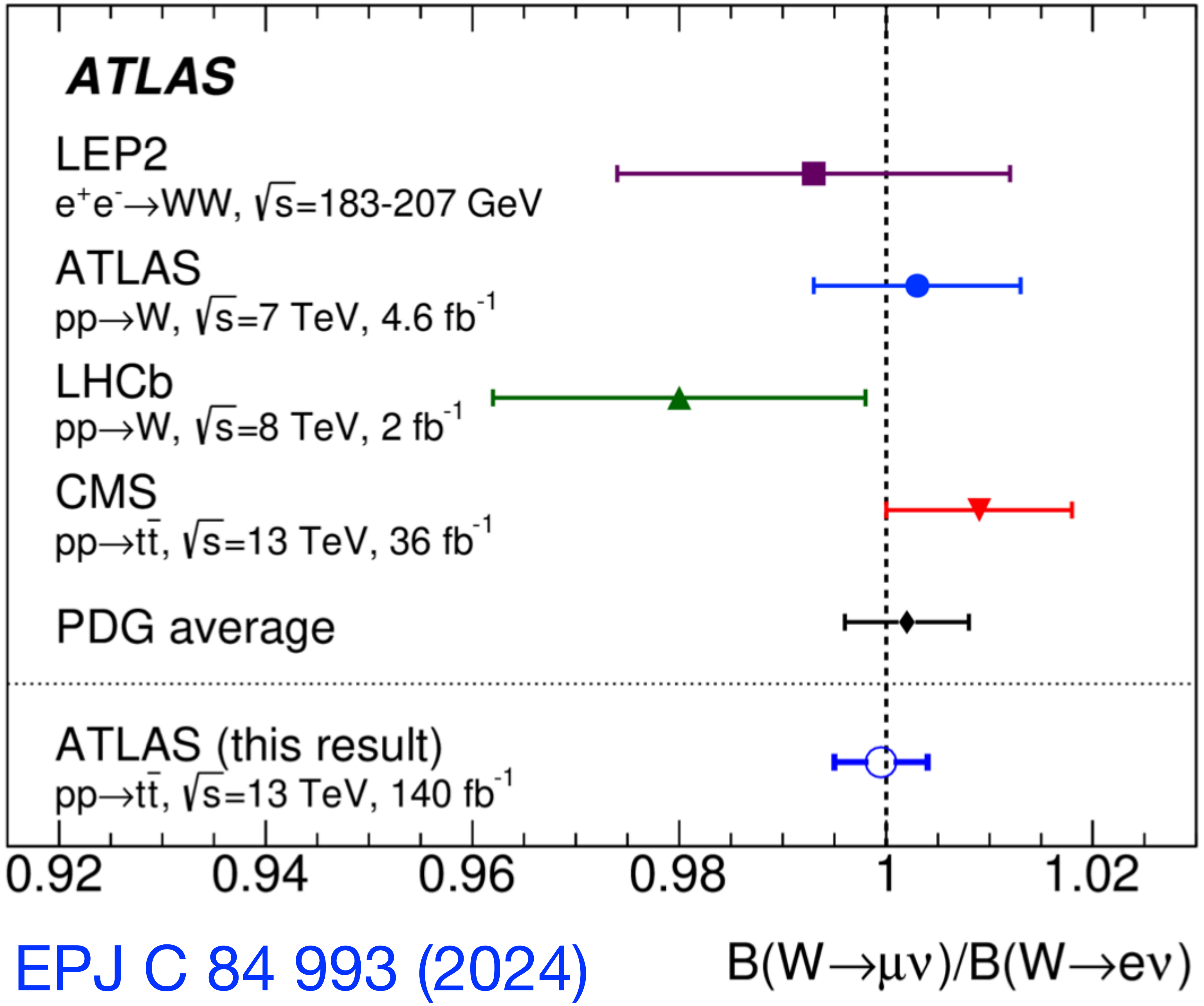
$$R(D^{(*)}) = \frac{Br(\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)}{Br(\bar{B}^0 \to D^{(*)+}\ell^-\bar{\nu}_\ell)}$$

- LFU is broken in Yukawa interaction
  - Charged lepton mass changes kinematics and modifies form factors in the hadronization
- Long-distance QED corrections depend on lepton velocity (τ vs. ℓ (*e*, *μ*))
- $B \to D^{(*)}\tau\nu$ 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]



LFU test with *W/Z* decays

- Used existing tension from LEP in $W \to \tau\nu / W \to (e, \mu)\nu$
- CMS and ATLAS can use ttbar events



EPJ C 84 993 (2024)

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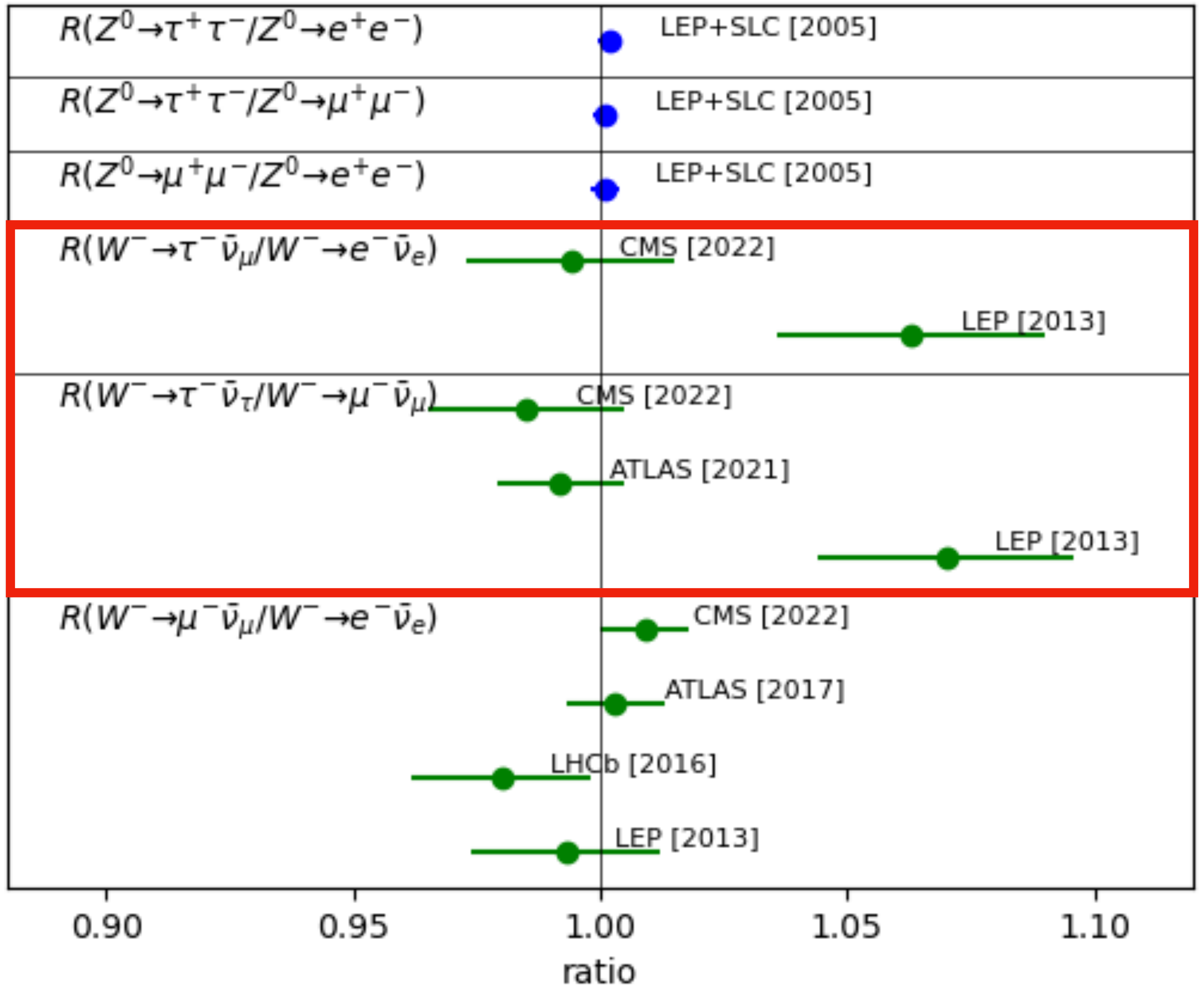


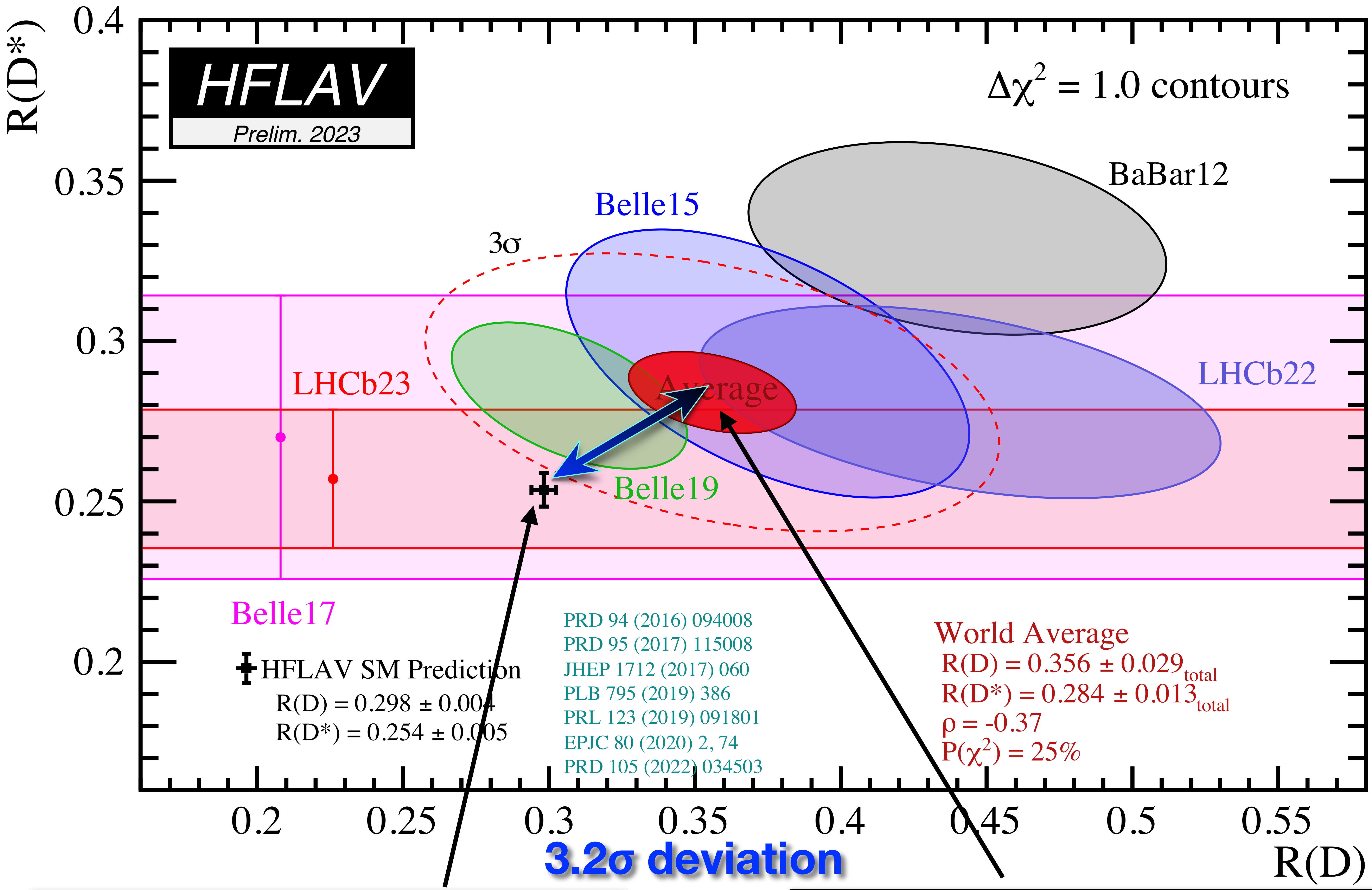
- LFU confirmed in Z/W decays with high precision, also for $W \to \tau\nu / W \to (e, \mu)\nu$

LFU test in D_s decays

BESIII **PRD108(2023)11200, $\mu\nu$** **$(5.29\pm0.11\pm0.09)\times10^{-3}$**

$$R_{\tau/\mu}=\frac{\mathcal{B}[D_s^+\to\tau^+\nu]}{\mathcal{B}[D_s^+\to\mu^+\nu]}=10.05\pm0.35$$ consistent with the SM prediction 9.75

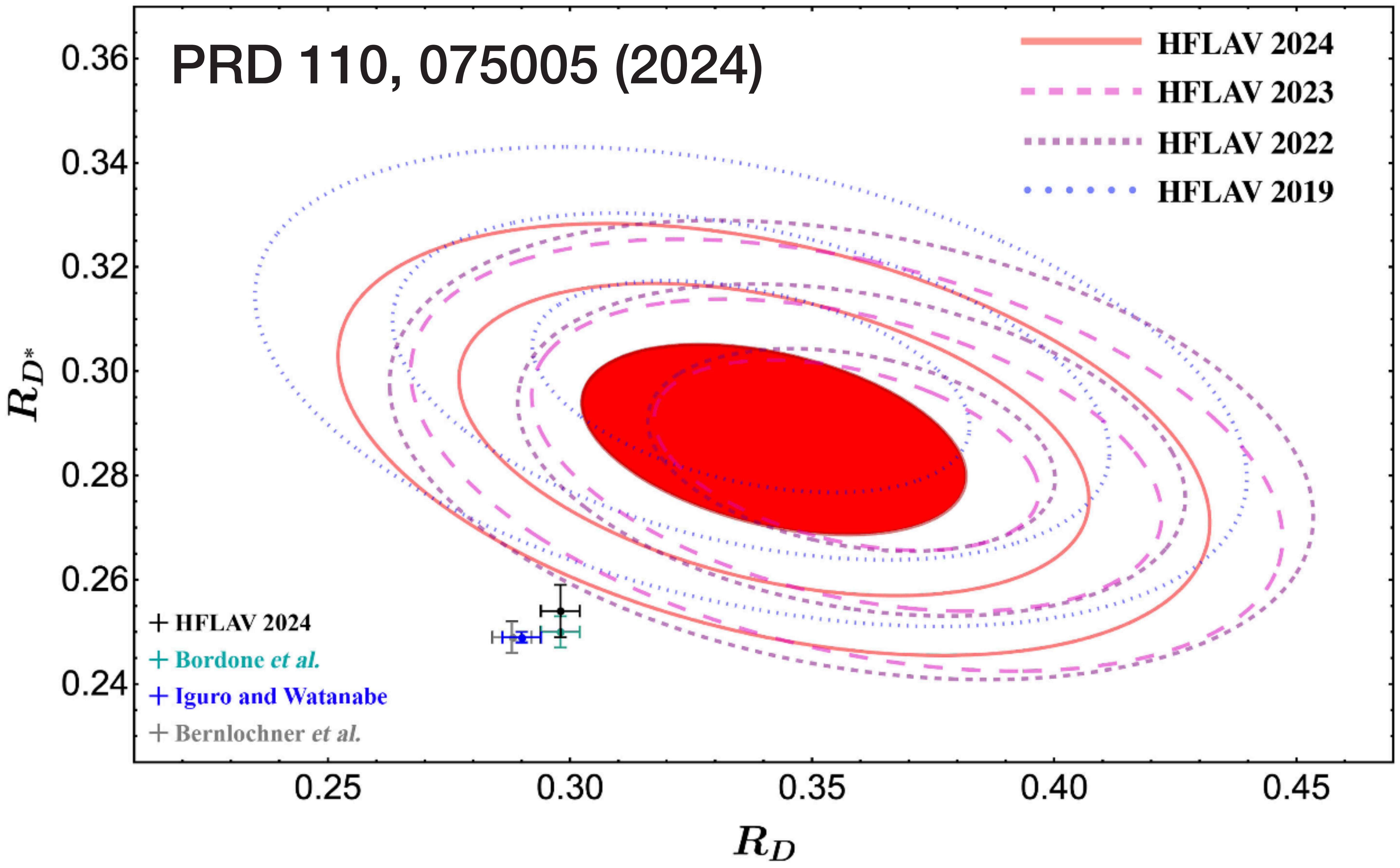
“*B* anomaly” in semileptonic *B* decays 2023



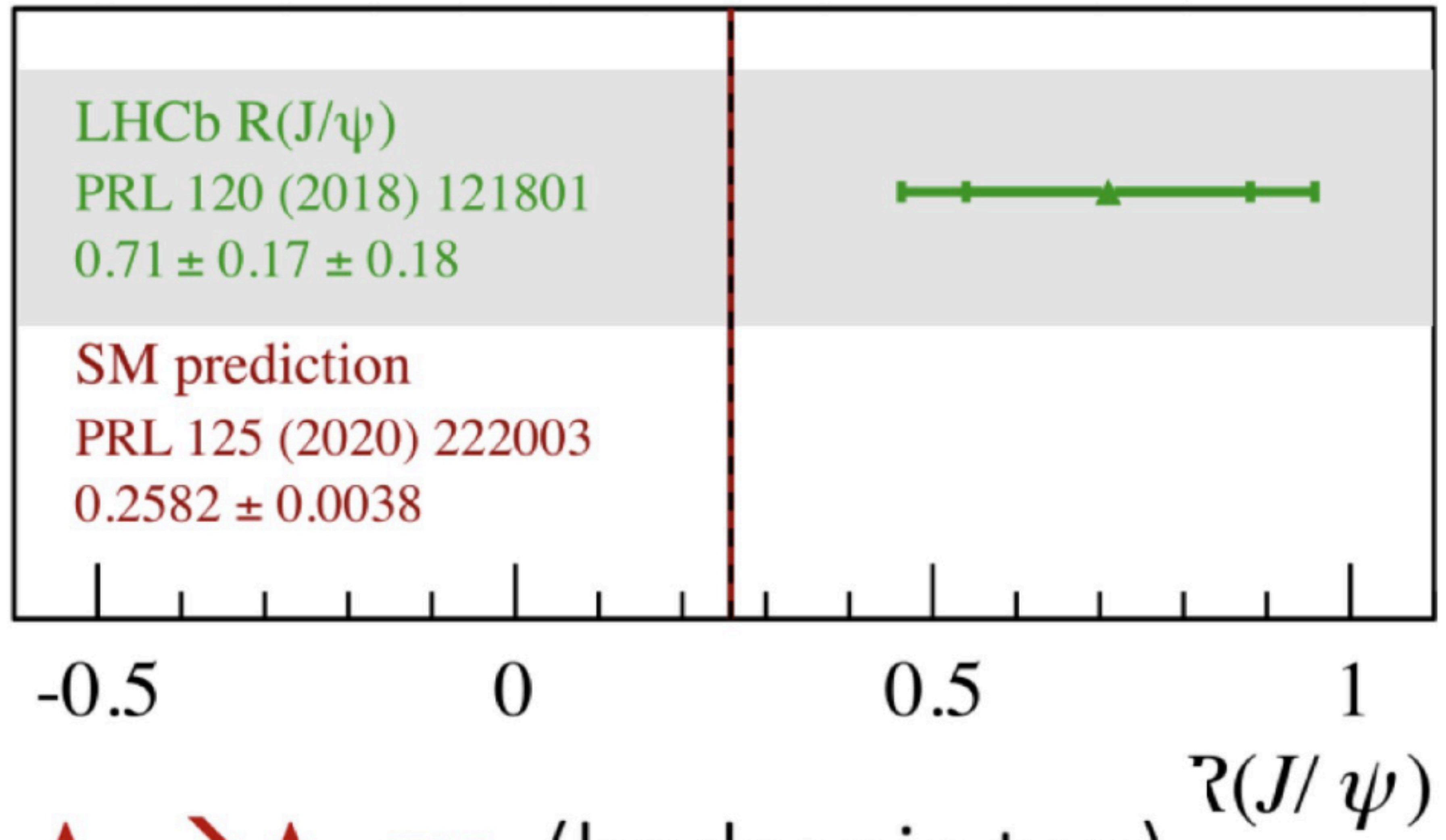
Standard Model prediction

Experimental average results

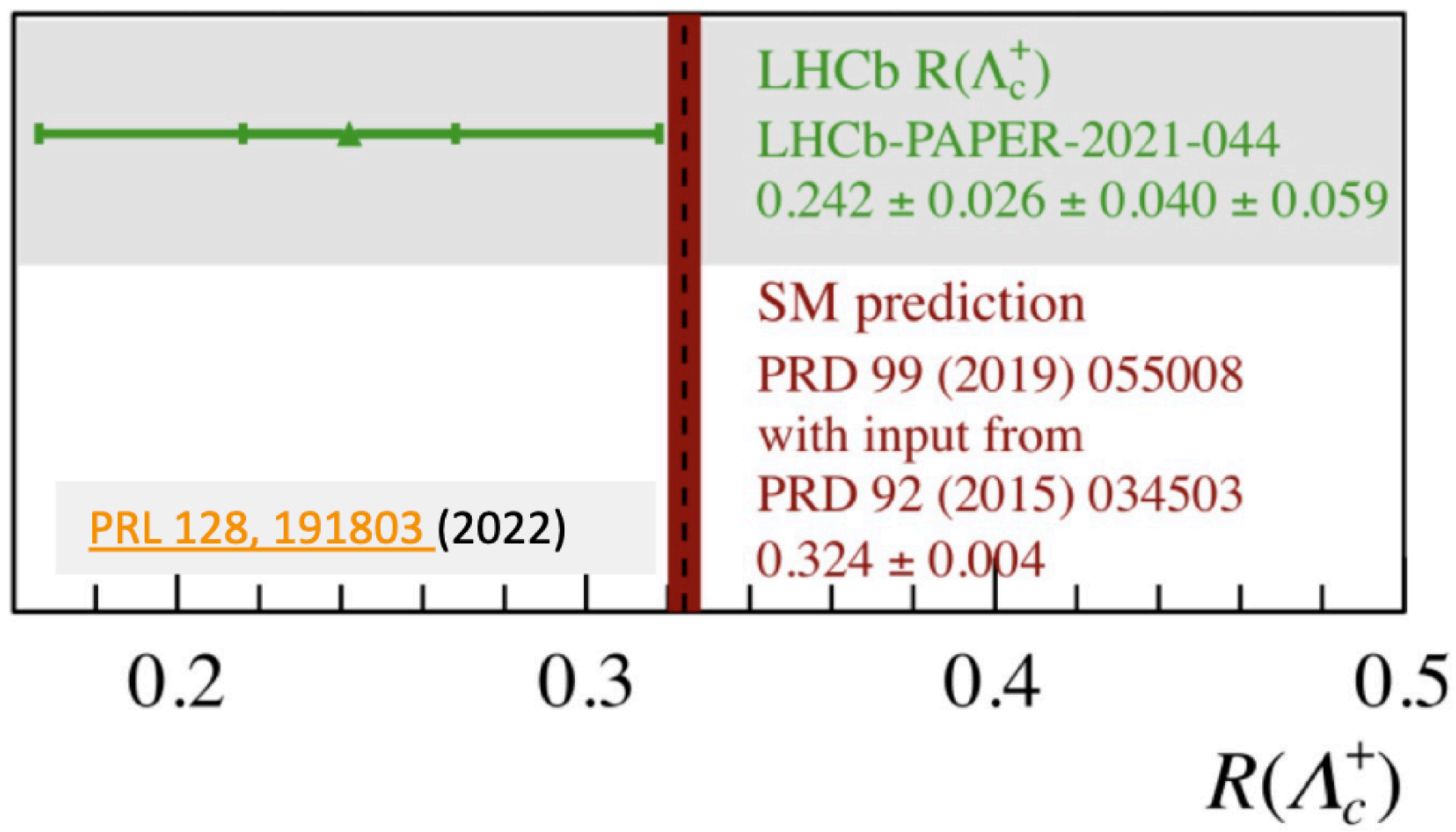
“B anomaly” validations



$B_c \to J/\psi\, \tau\nu$ (muonic tau)



$\Lambda_b \to \Lambda_c\, \tau\nu$ (hadronic tau)



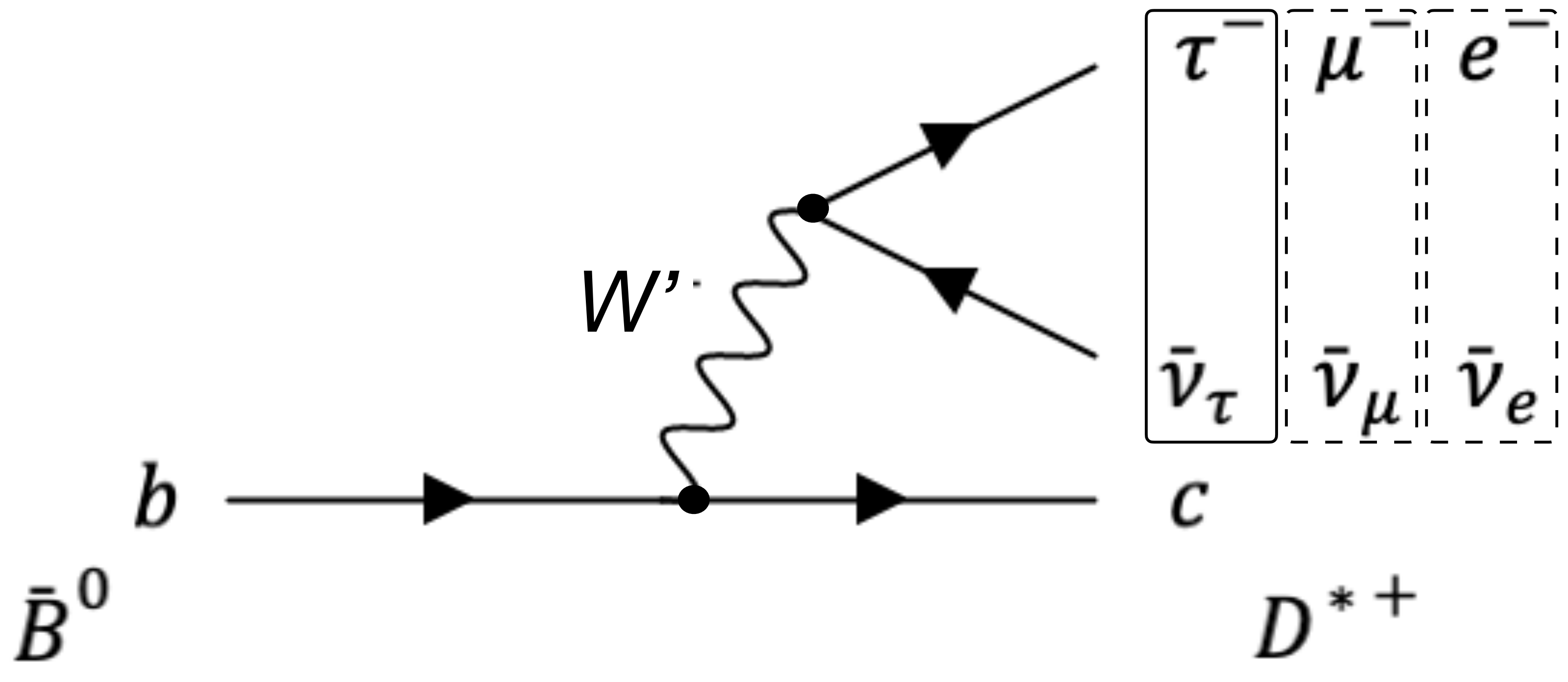
- Model independent sum rule, possible cross check

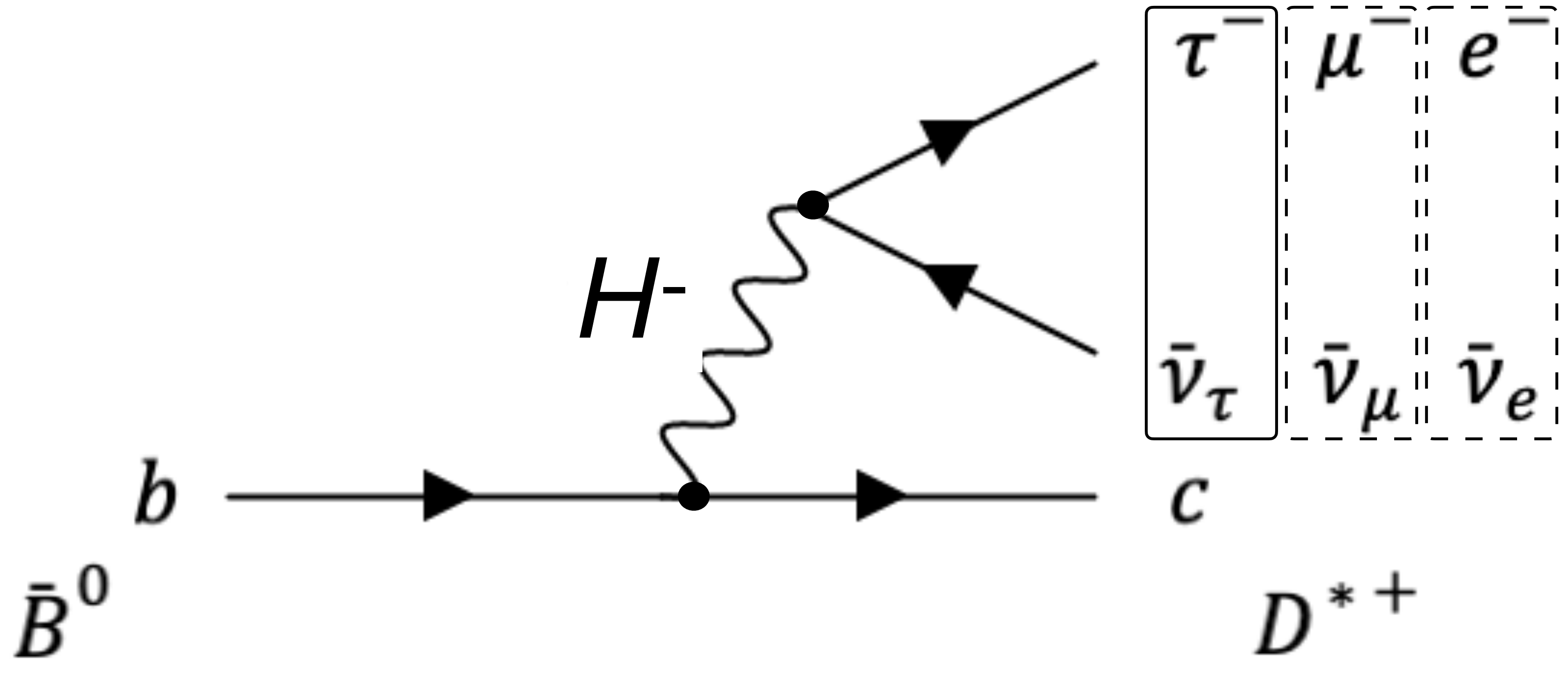
$$\frac{R(\Lambda_c)}{R(\Lambda_c)_{\rm SM}} \simeq 0.26\frac{R(D)}{R(D)_{\rm SM}} + 0.74\frac{R(D^*)}{R(D^*)_{\rm SM}}$$

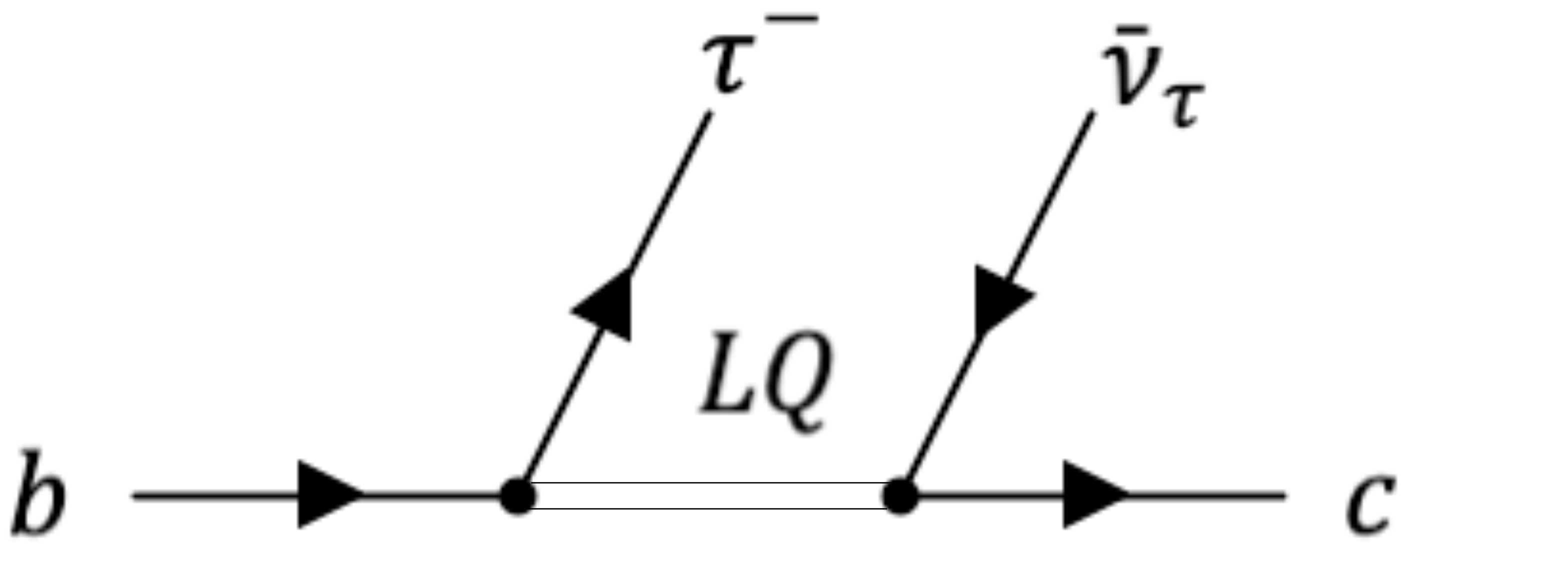
New physics scenarios for the $R(D^{(*)})$ anomaly

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

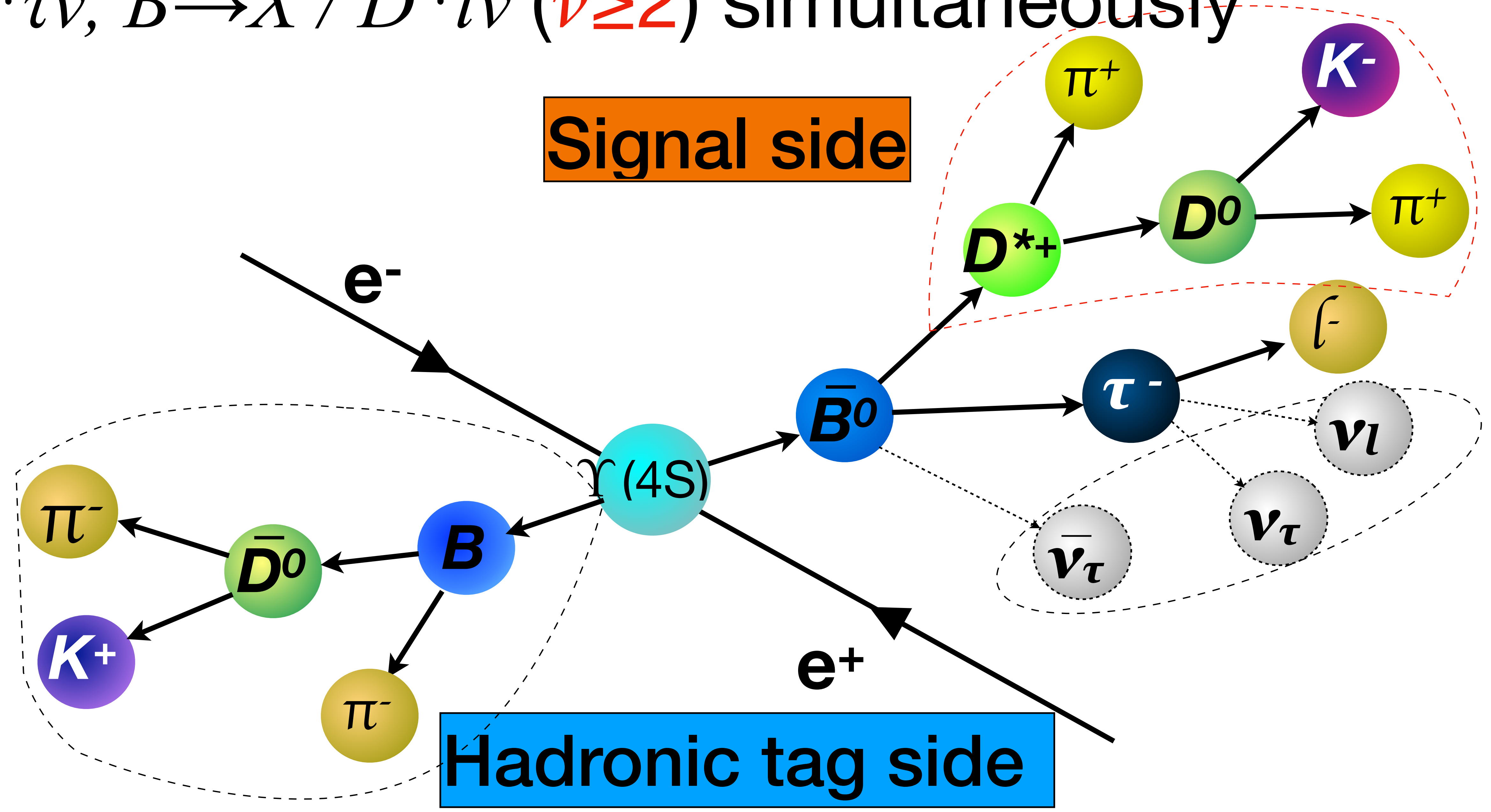




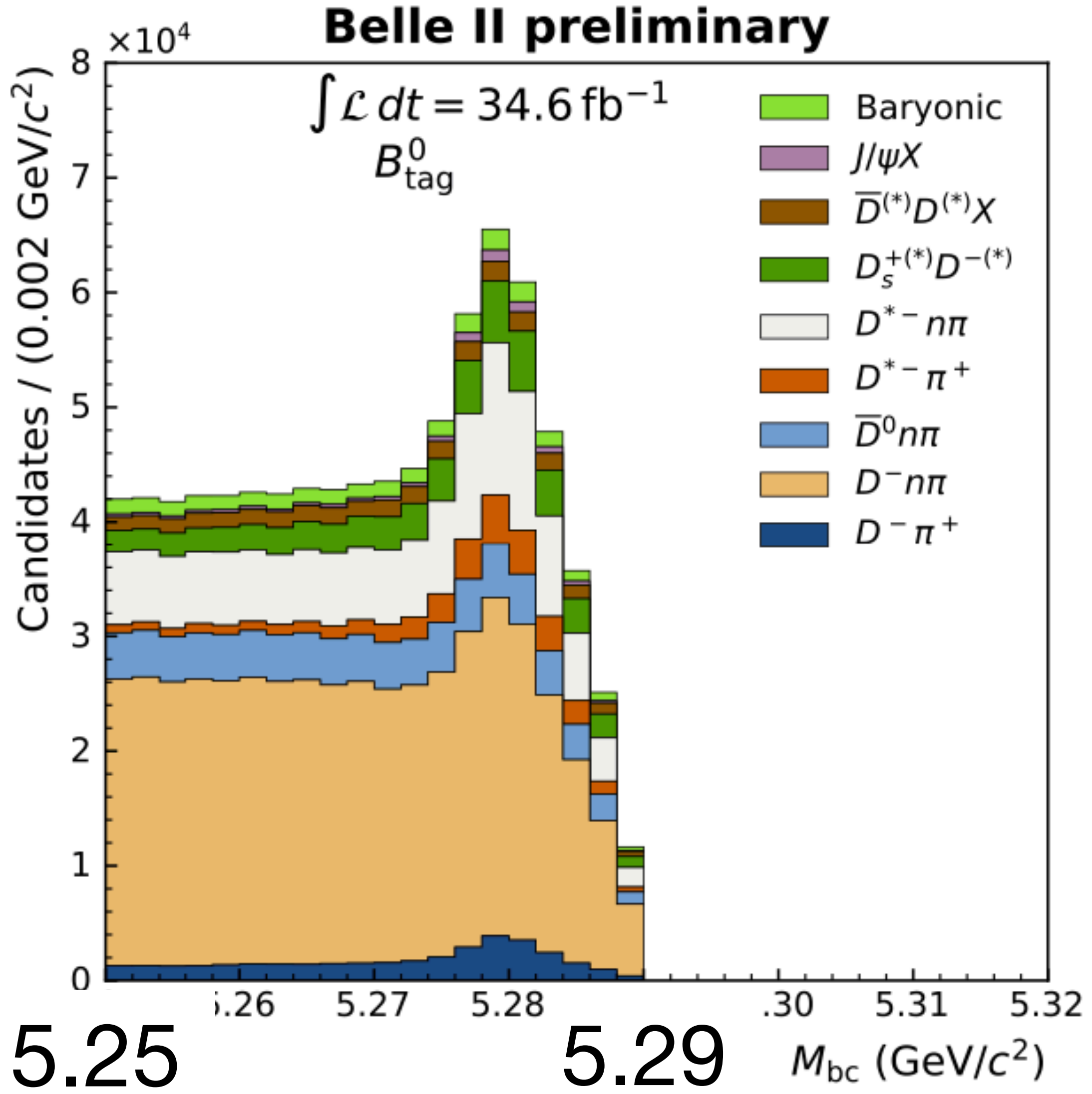


Tagging methods

- 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
- <u>Hadronic tag</u>
  - Fully reconstruct $B \to D^{(*)}(/J/\psi/\Lambda)X$
  - Tagging efficiency 0.2~0.4%
  - less background
- <u>Semileptonic tag</u>
  - Reconstruct $B \to D^{(*)}l\nu$
  - Tagging efficiency ~1%
  - More background



- 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



<u>arXiv:2008.06096</u>

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

First $R(D^*)$ result from Belle II PRD 110 072020 (2024)

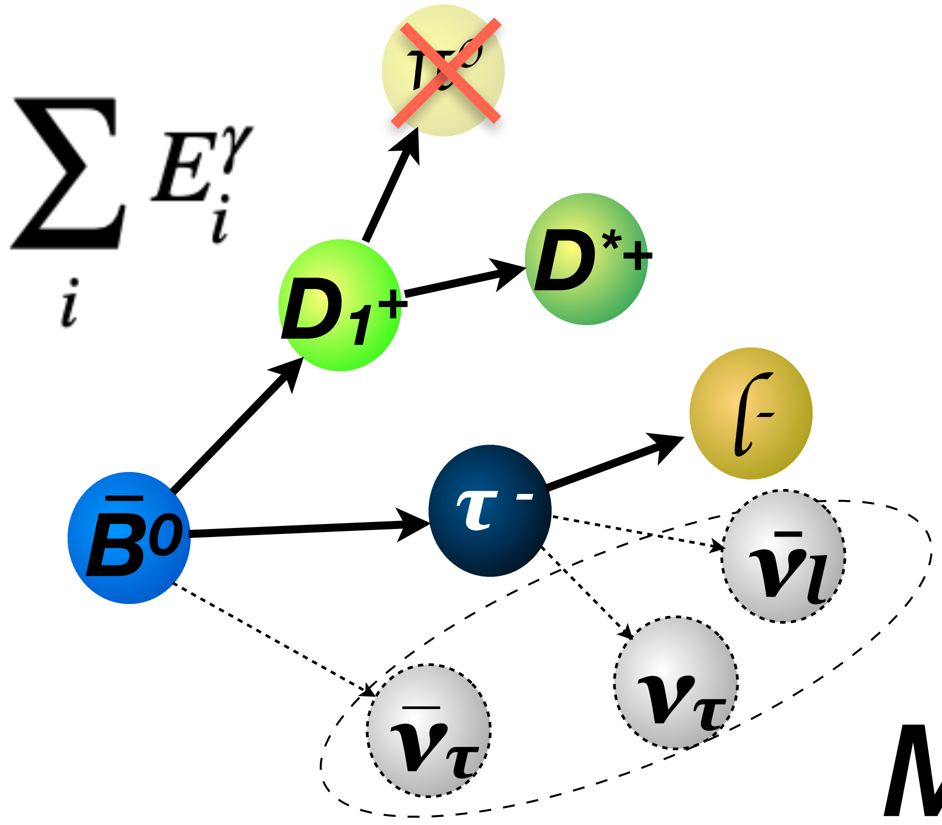
- Belle II first result for $R(D^*)$ @ 189 fb^{-1}
  - Hadronic tag with FEI
  - Leptonic τ decays

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

- Consistent with
  SM: 0.254 ± 0.005,
  HFLAV24: 0.287 ± 0.012
- SM vs. experimental average deviation: 3.2σ → 3.3σ

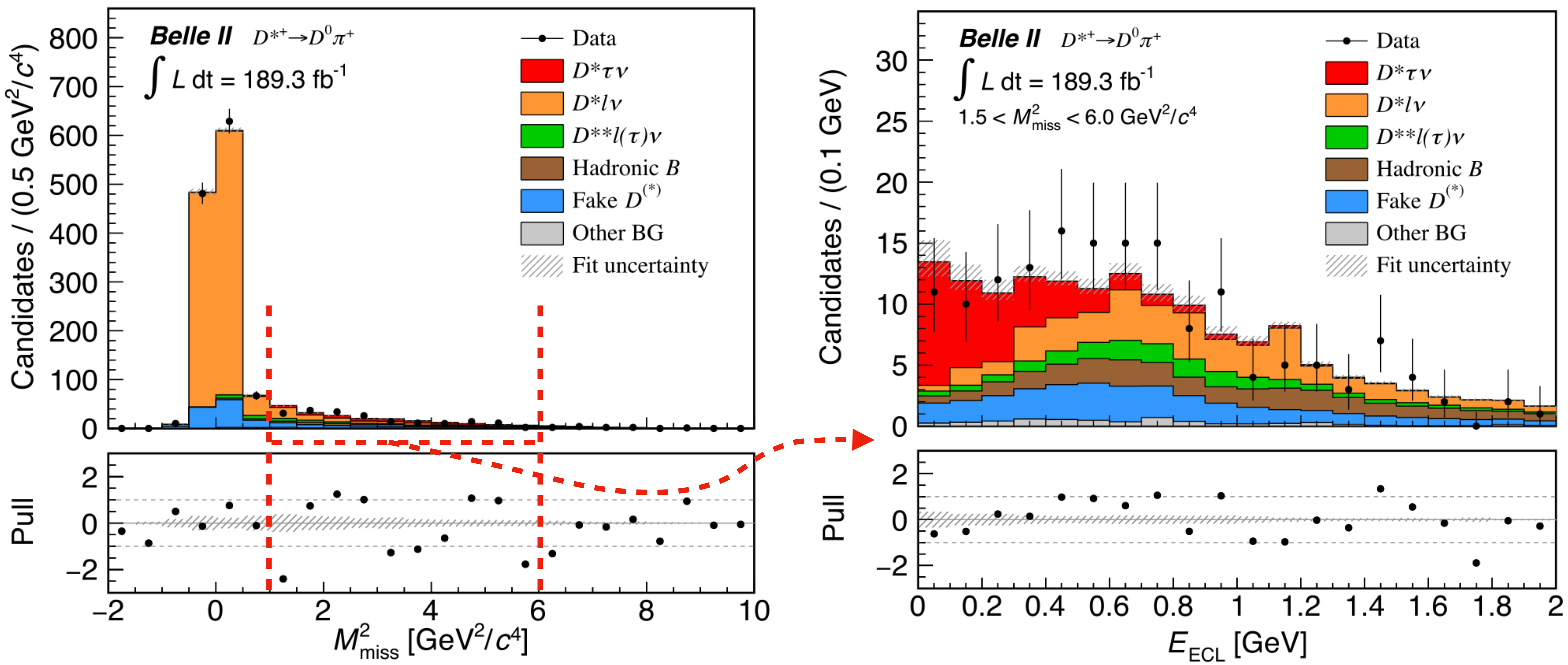
Source	Uncertainty
Statistical uncertainty	+15.4% -14.6%
$E_{\rm ECL}$ PDF shape	+9.1% -8.3%
MC statistics	±7.5%
$B \to D^{**} l \nu$ modeling	+4.8% -3.5%

$$E_{\rm ECL} = \sum_i E_i^\gamma$$



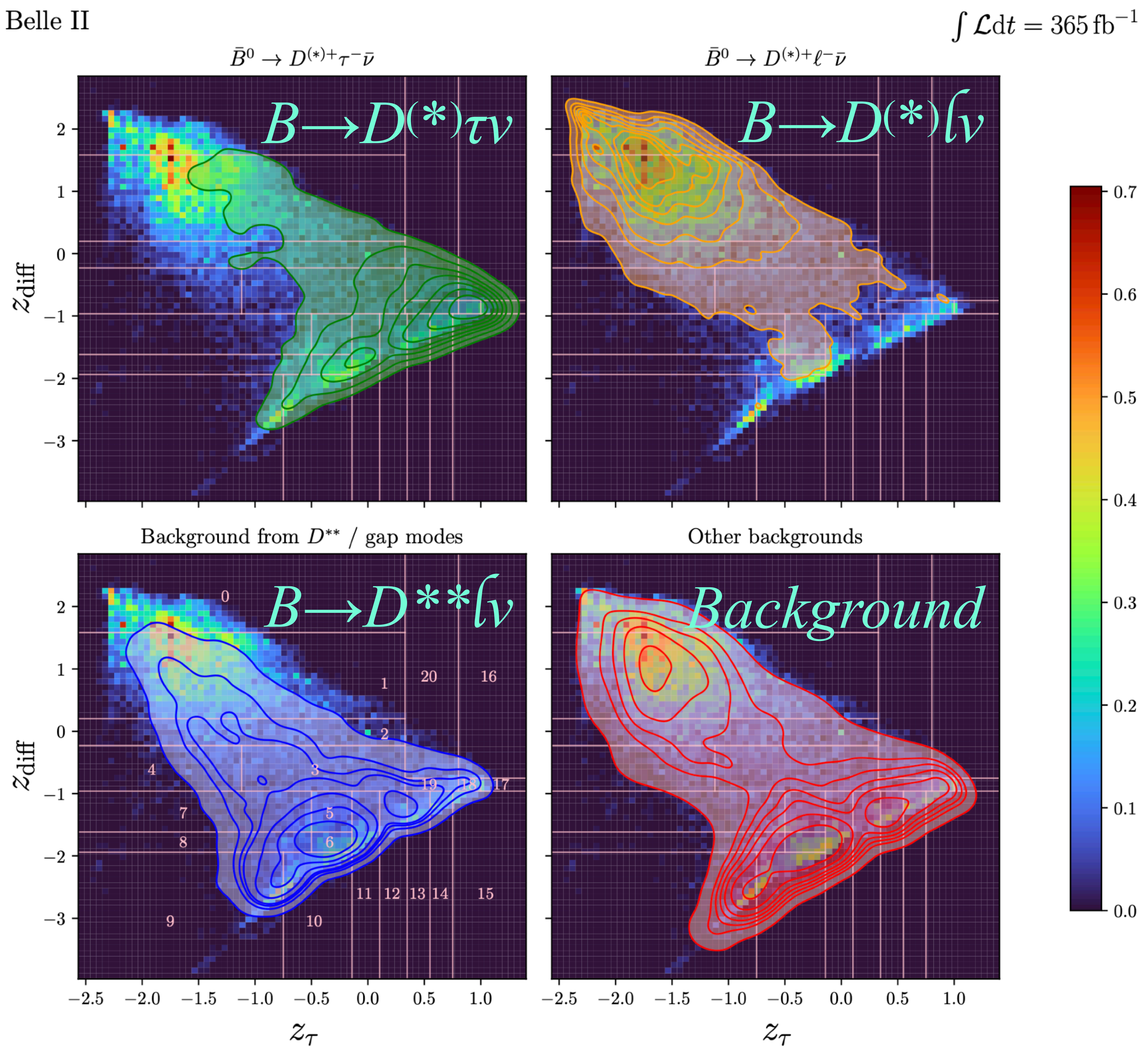
$M^2_{\rm miss}$

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



$R(D^{(*)+})$ w/ semileptonic tag

- Belle II data @ 365 fb^{-1}
- Semileptonic tag: $B \to D^{(*)} l \nu$
  - 26 D decays
- Signal reconstruction: only B^0, leptonic tau decays
  - 13 D decays



- A BDT trained to separate events in 3 classes
  - Semitauonic signal events z_τ
  - Semileptonic normalization evnets z_ℓ
  - Background z_{bkg}
- Extract signal in a 2D binned template fit
  - z_τ vs. $z_{\mathrm{diff}}(z_\ell - z_{bkg})$

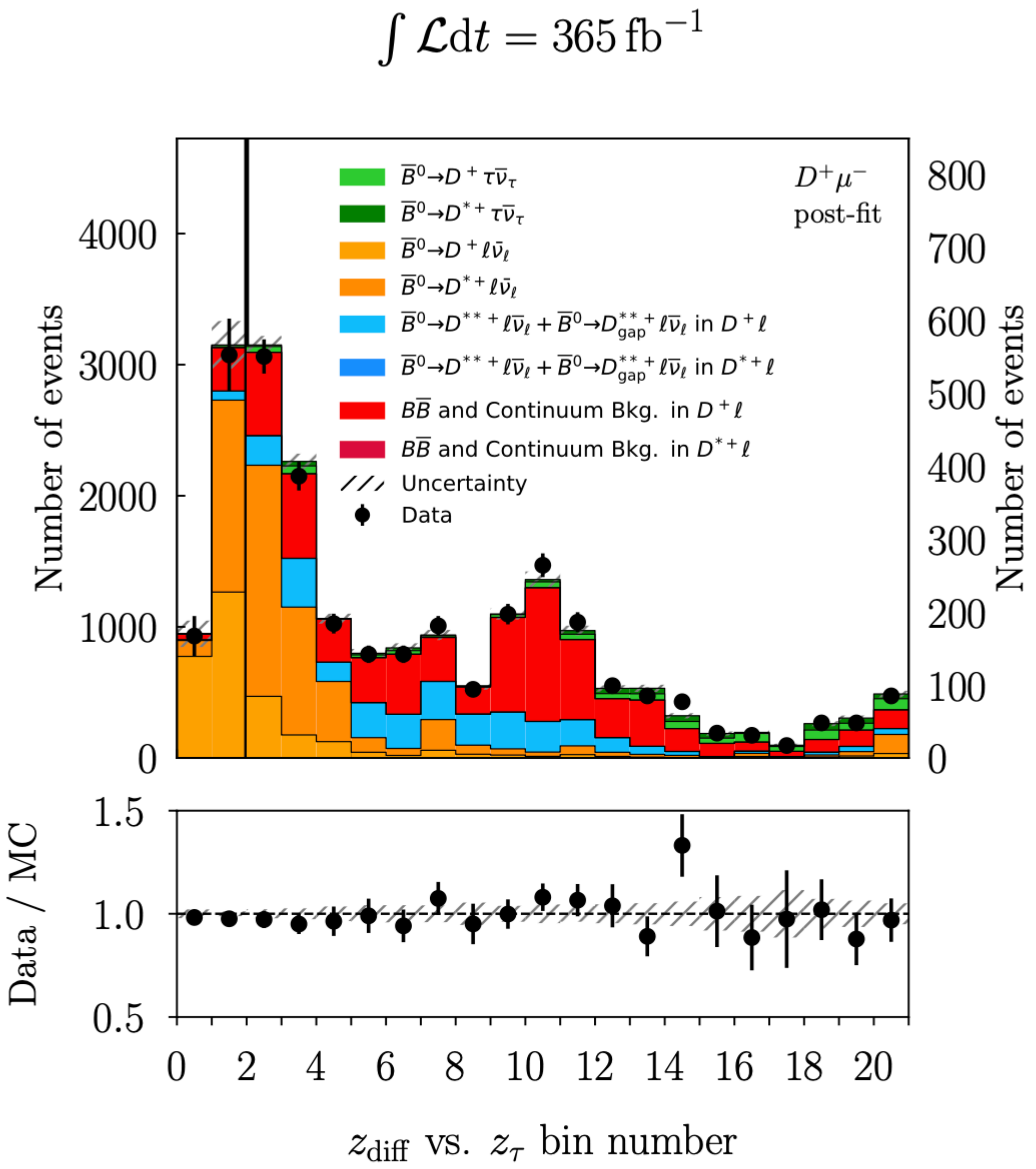
Results of $R_{\tau/\ell}(D^{(*)+})$ w/ semilep. tag PRD 112 032010 (2025)

- Main systematics
  - The finite size of the simulated samples
  - The lepton ID efficiency and fake rate corrections

- Belle II $R(D^{(*)+})$ result with semilep. tag

$R_{\tau/\ell}(D) = 0.418 \pm 0.074\ (\text{stat}) \pm 0.051\ (\text{syst})$

$R_{\tau/\ell}(D^*) = 0.316 \pm 0.034\ (\text{stat}) \pm 0.018\ (\text{syst})$

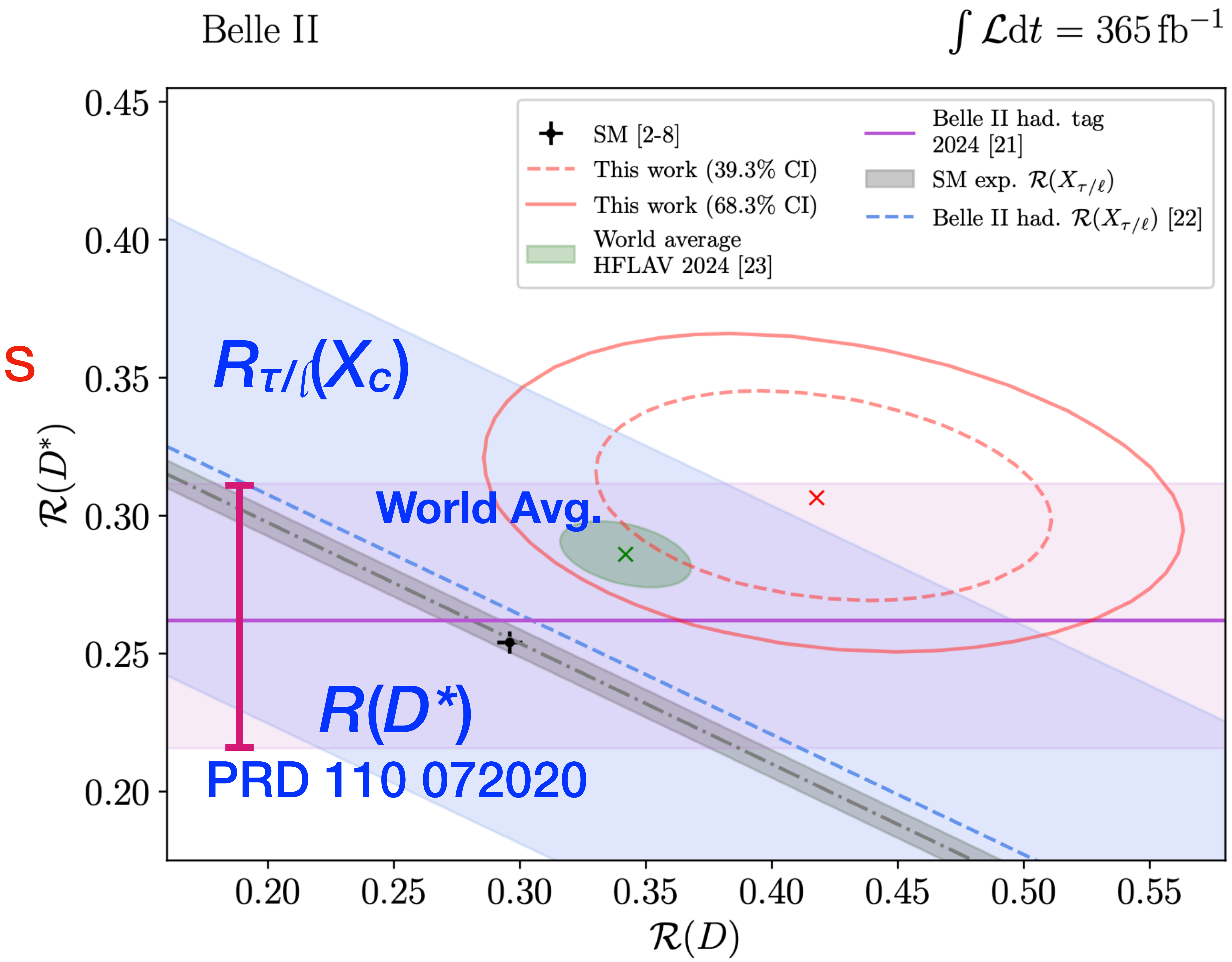


$D^{(*)}\tau\nu$

$D^{(*)}l\nu$

$D^{**}l\nu$

Backgrounds

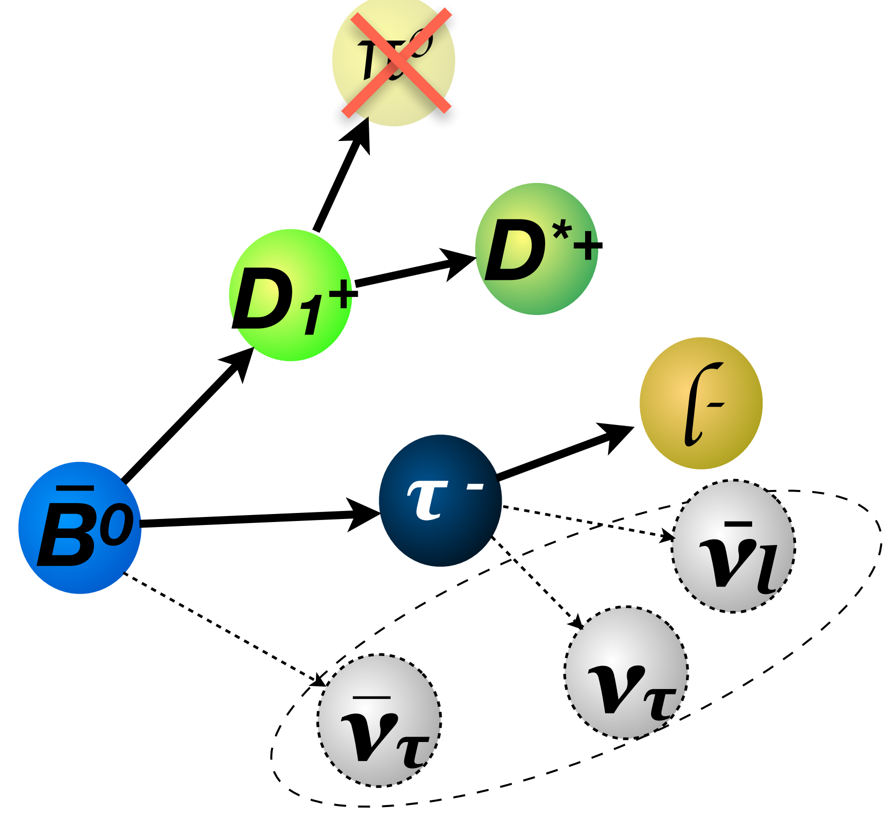


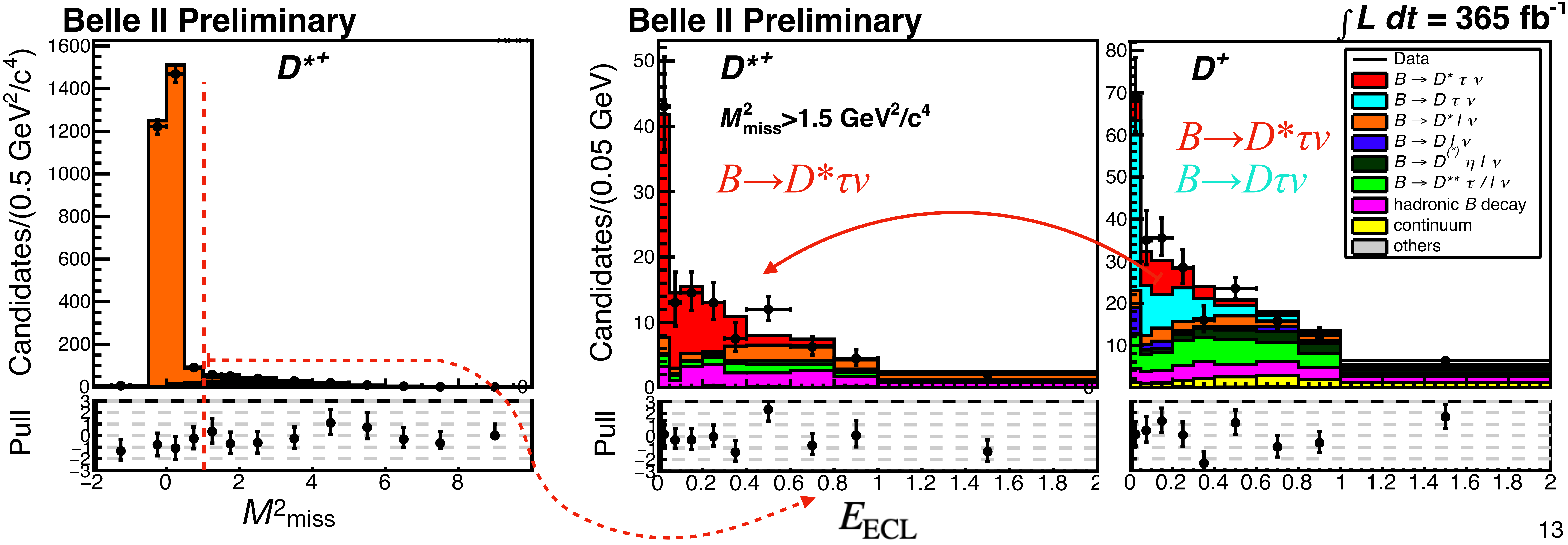
$R_{\tau/\ell}(D^{(*)})$ with hadronic tag

- Belle II UPDATED result for $R(D^{(*)})$ @ 365 fb^{-1}
  - Hadronic tag with FEI
  - Leptonic τ decays
  - $B \to D^{*+}$, $D^{*0}(\pi^0)$, $D^{*0}(\gamma)$, $D^+, D^0, \tau/\ell\nu$

$$E_{\mathrm{ECL}} = \sum_i E_i^{\gamma}$$

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





Results of $R_{\tau/\ell}(D^{(*)})$ w/ had. tag *Preliminary*

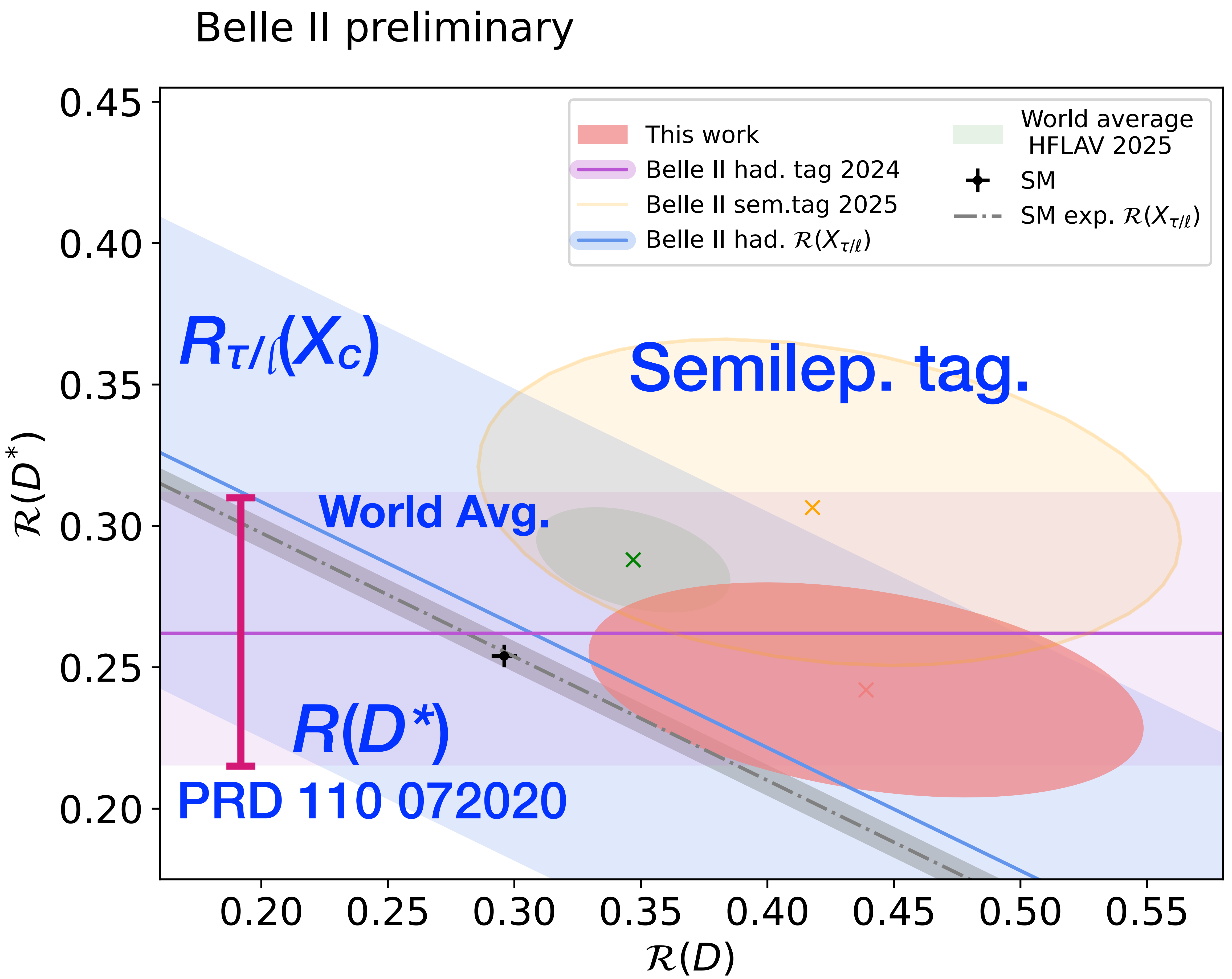
- Main systematics
  - The finite size of the simulated samples
  - Branch fraction of $B \to D^{(*)}\eta\ell\nu$

Source	Uncertainty R(D*)	Uncertainty R(D)
Statistical uncertainty	±8.3%	±16.3%
Simulation sample size	±4.8%	±8.4%
$B \to D^{(*)}\eta l\nu$ branch fraction	±2.8%	±3.6%
$B \to D^{**}l\nu$ branch fraction	±0.3%	±1.3%
…	…	…

- Belle II $R(D^{(*)})$ result with had. tag

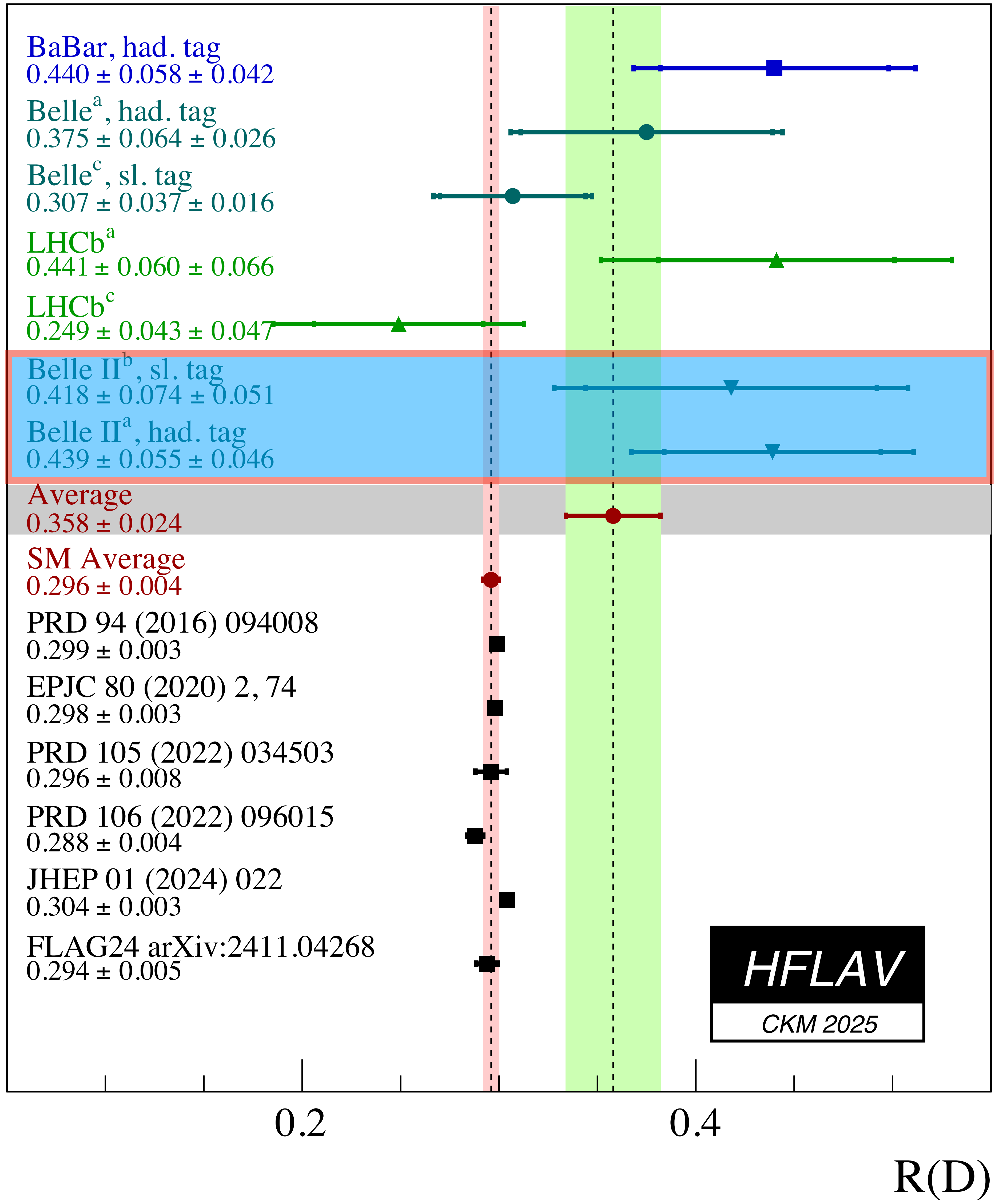
$R_{\tau/\ell}(D) = 0.439 \pm 0.055\,(\text{stat}) \pm 0.045\,(\text{syst})$

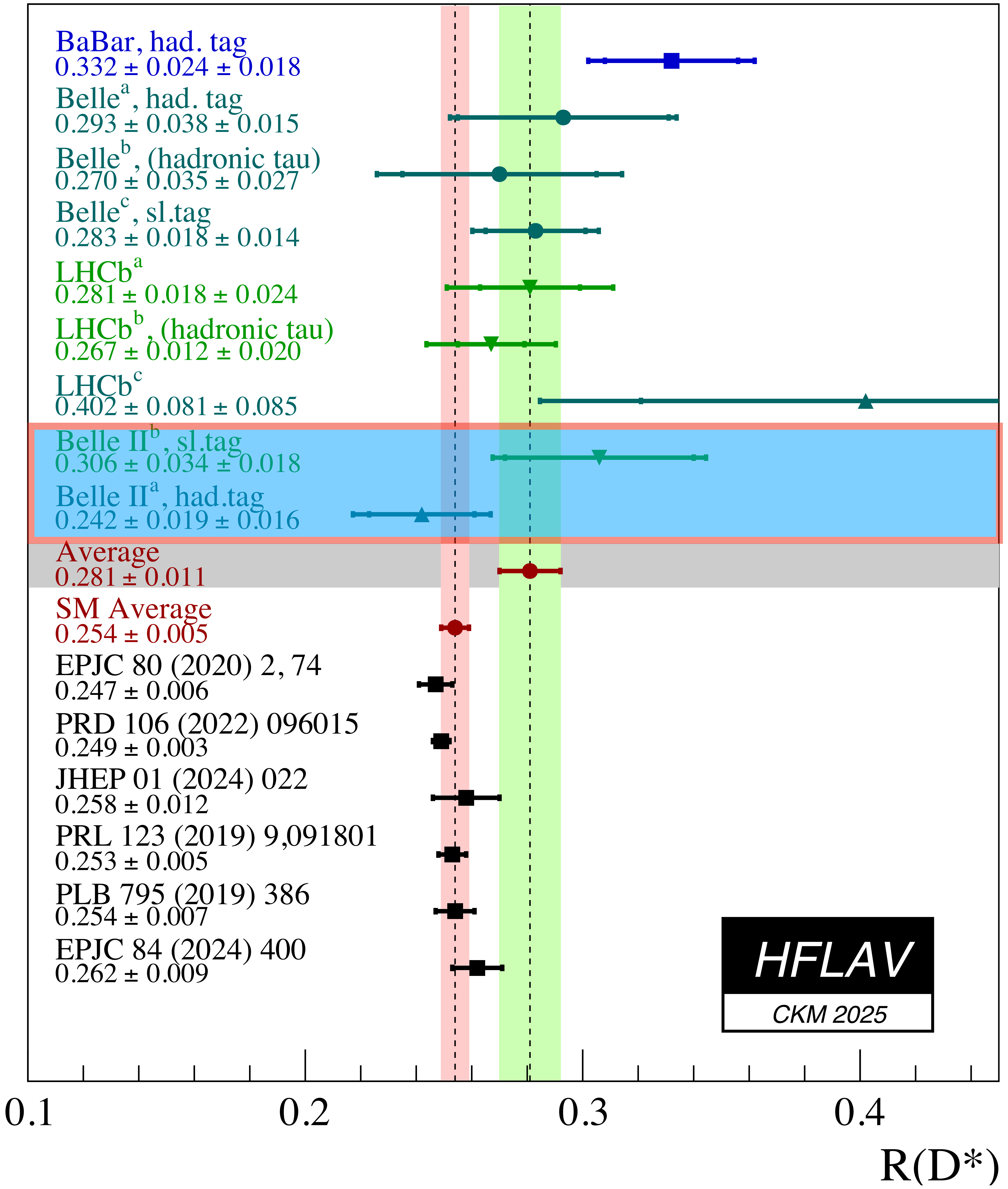
$R_{\tau/\ell}(D^*) = 0.242 \pm 0.019\,(\text{stat}) \pm 0.016\,(\text{syst})$



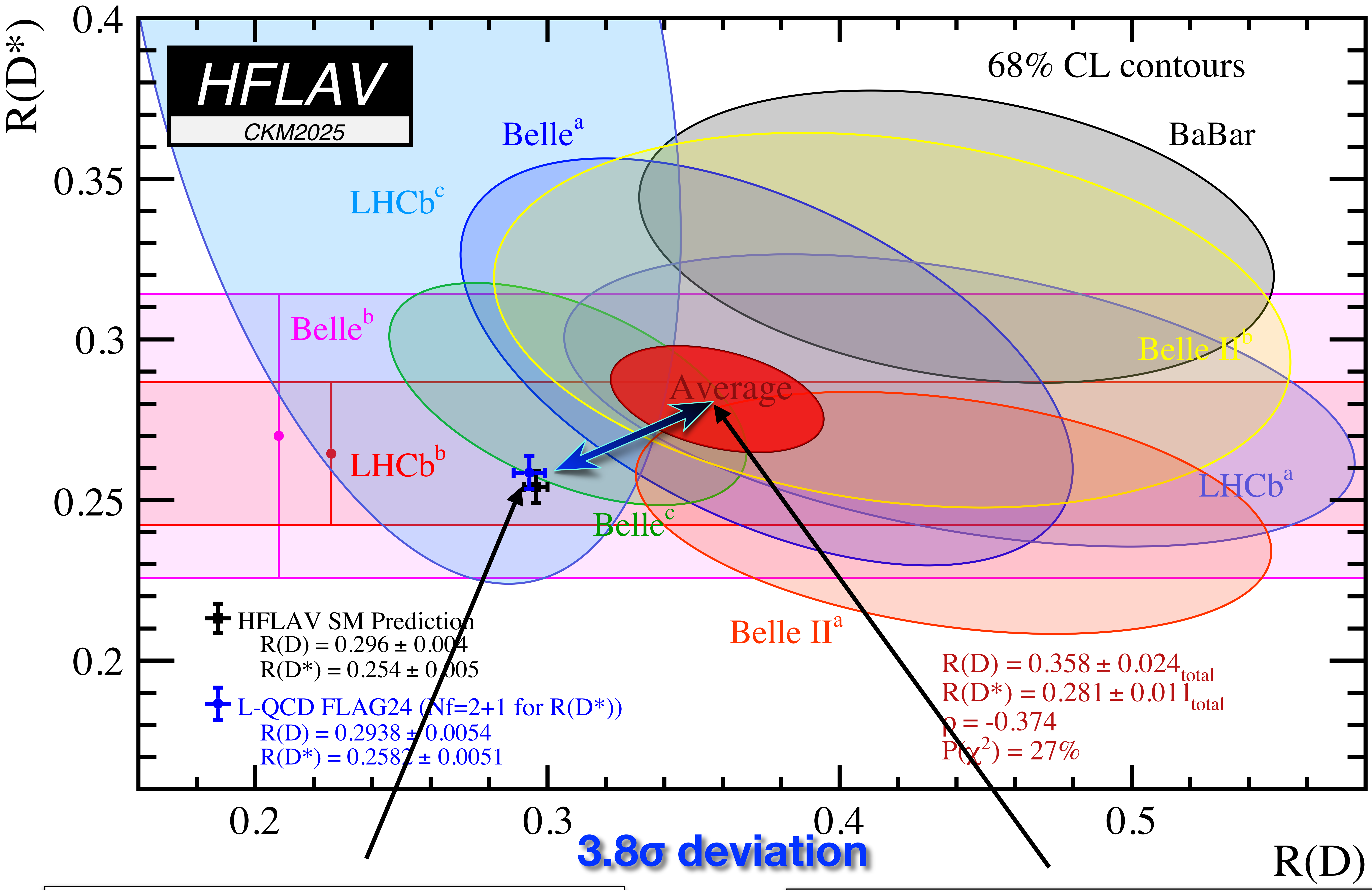
“*B* anomaly” in semileptonic decays

- Similarly sensitivity as Belle 15’ result @ 711 fb^{-1} with only 365 fb^{-1}





"*B* anomaly" in semileptonic decays 2025

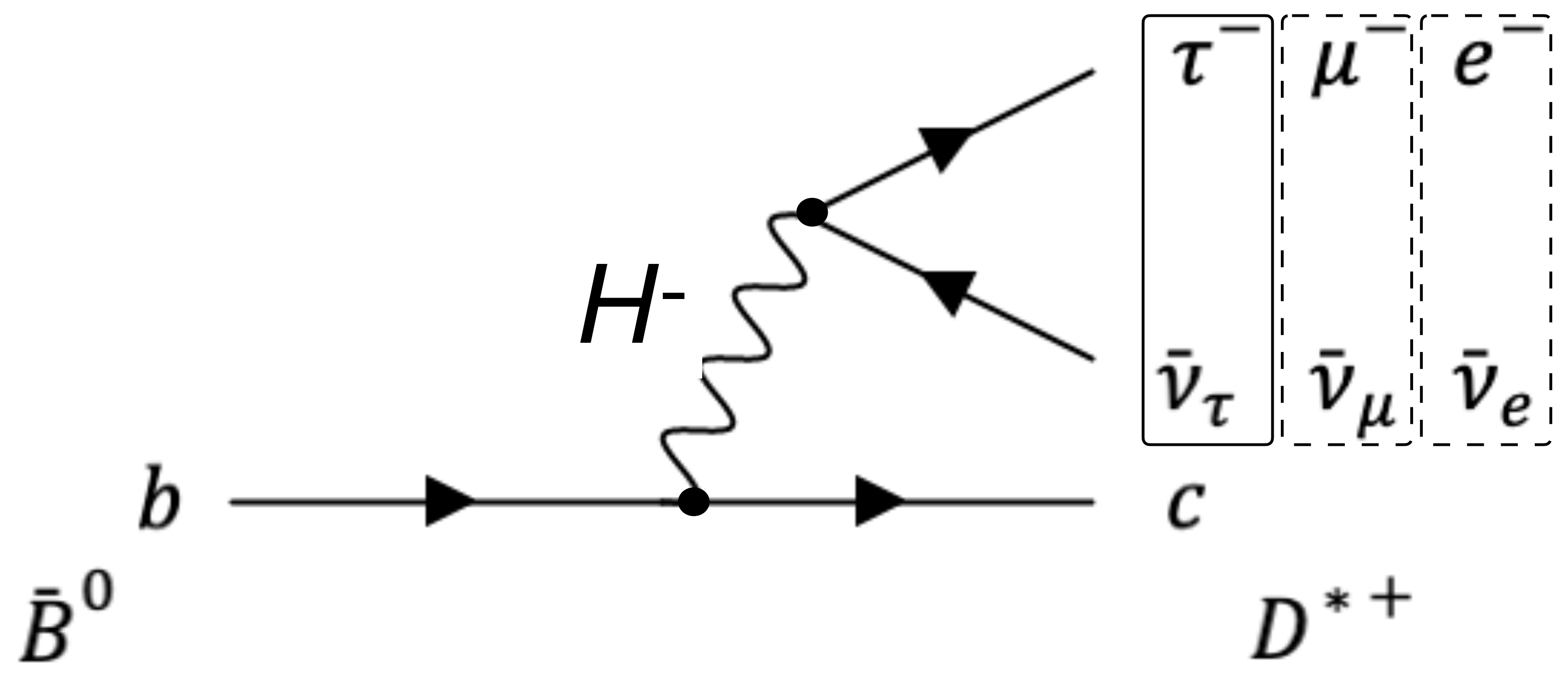


Standard Model prediction

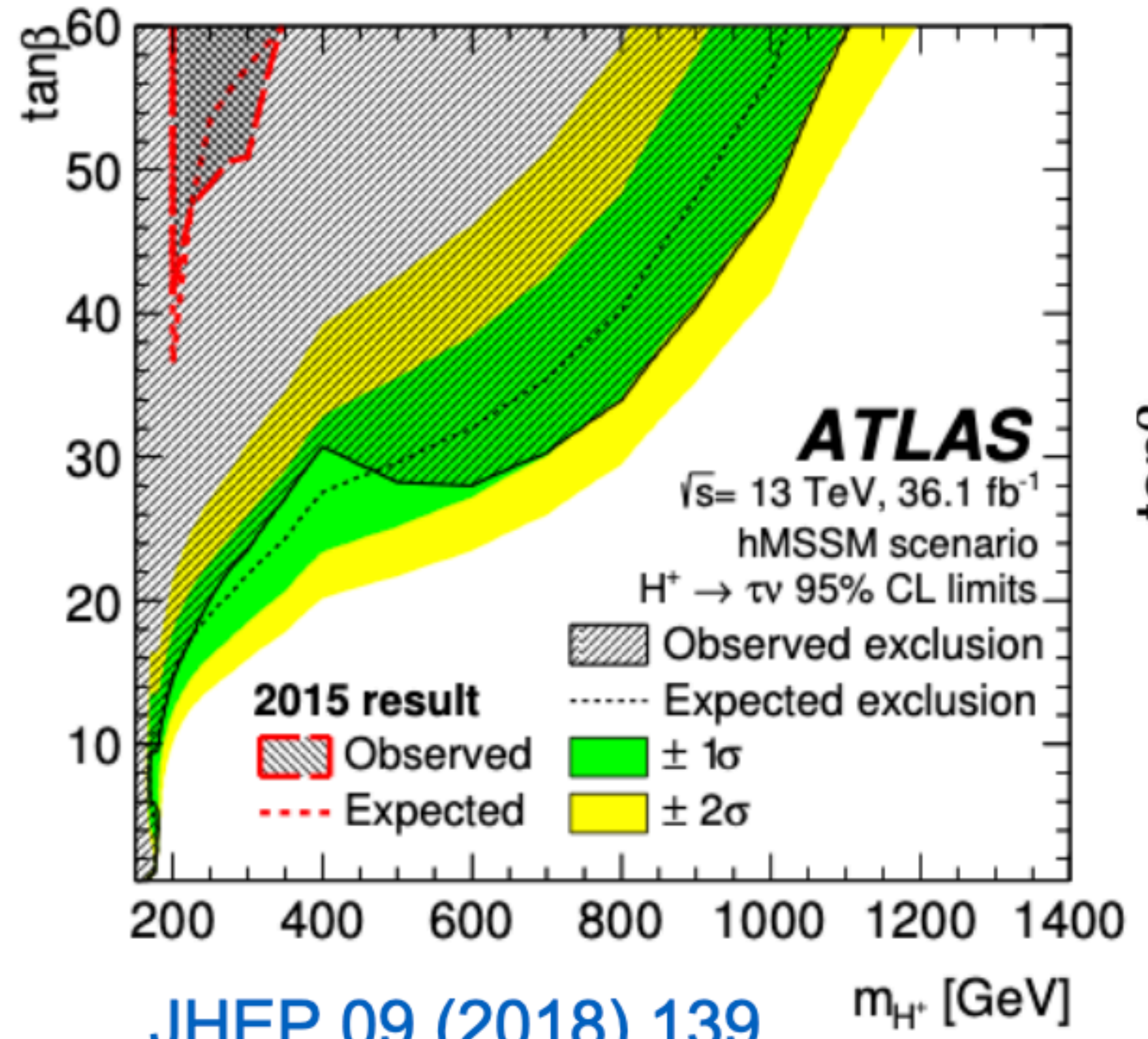
Experimental average results

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}



2HDM (type II)



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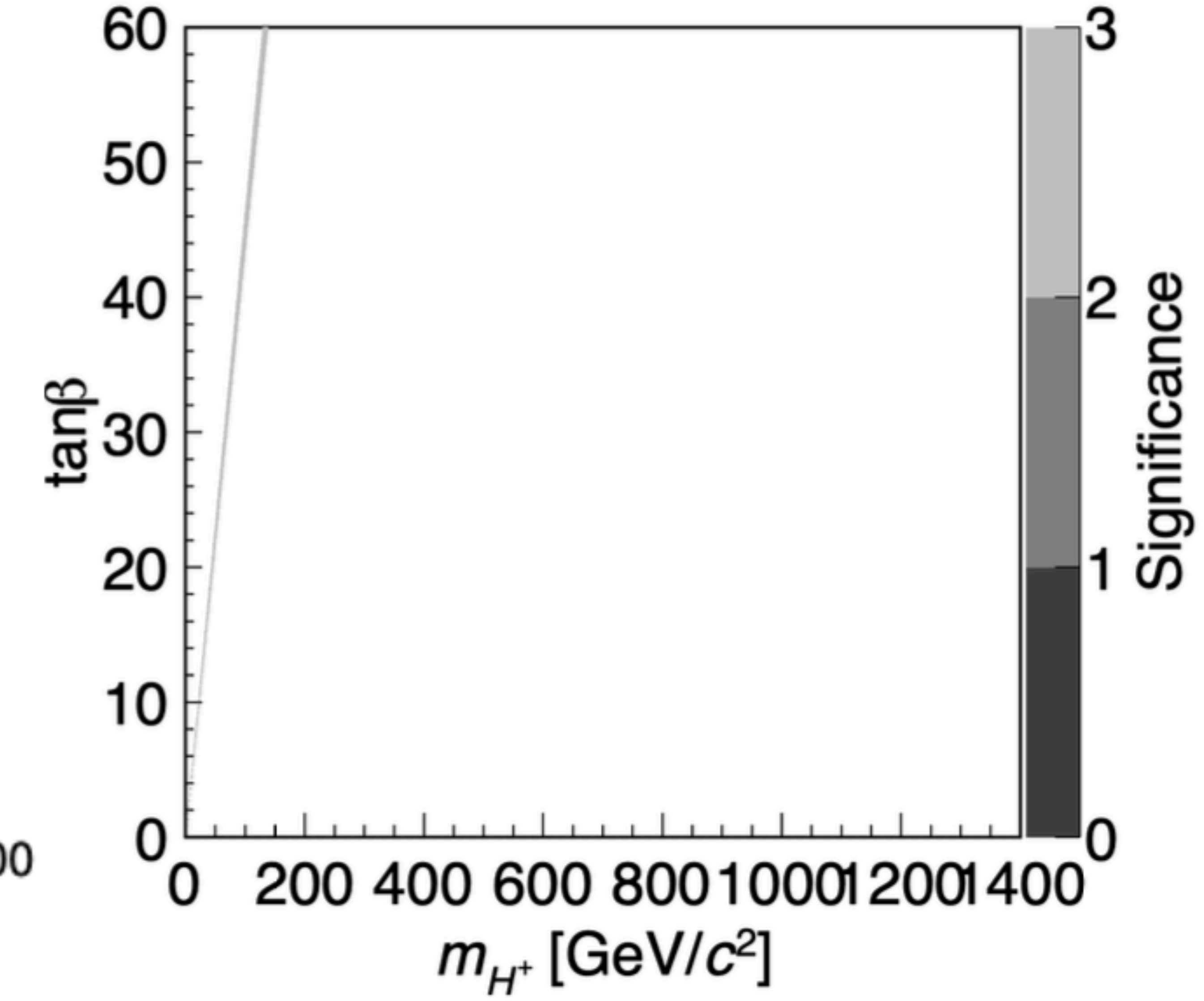
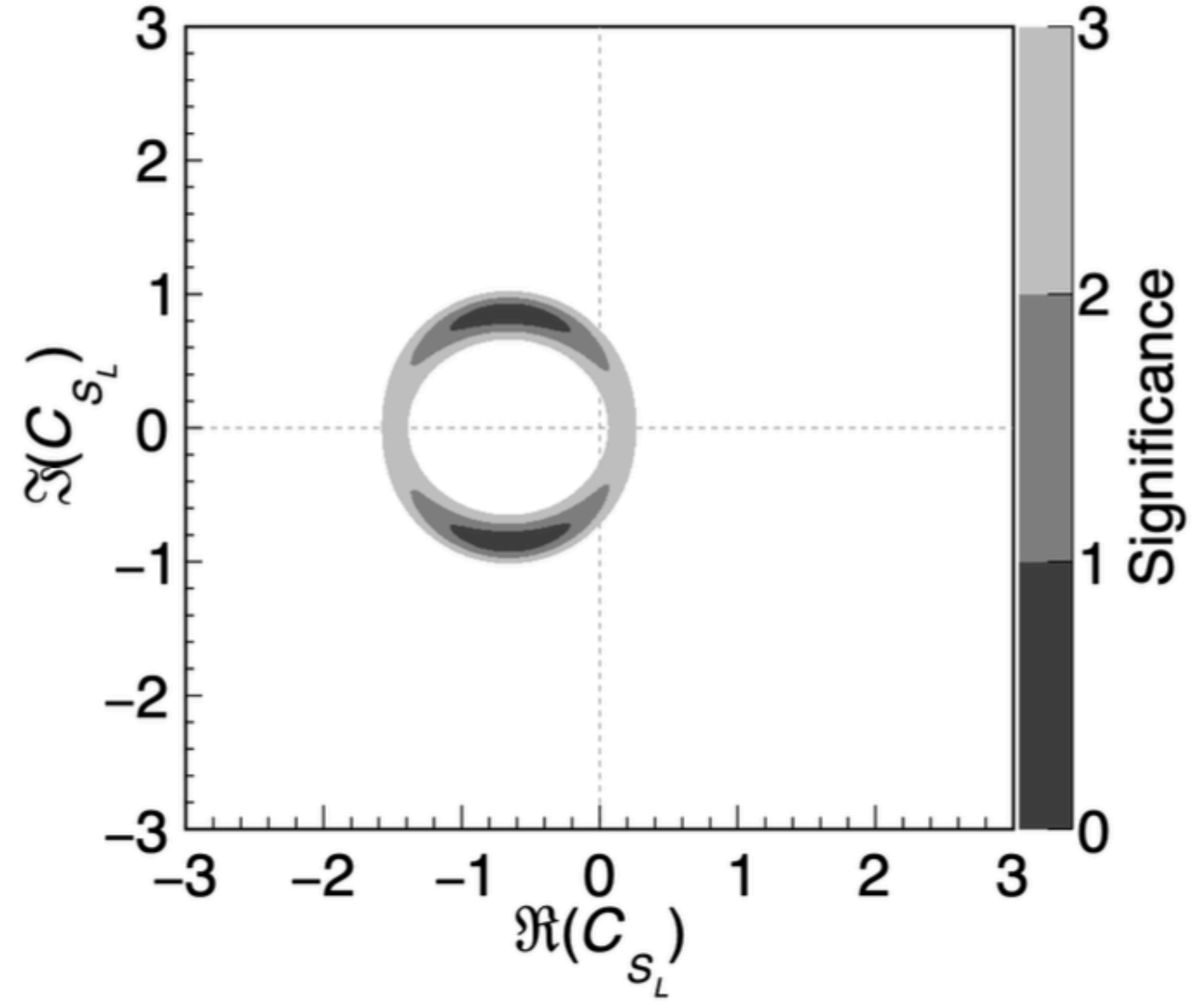


General 2HDM



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

Br($B\to\tau\nu$) result with had. tag

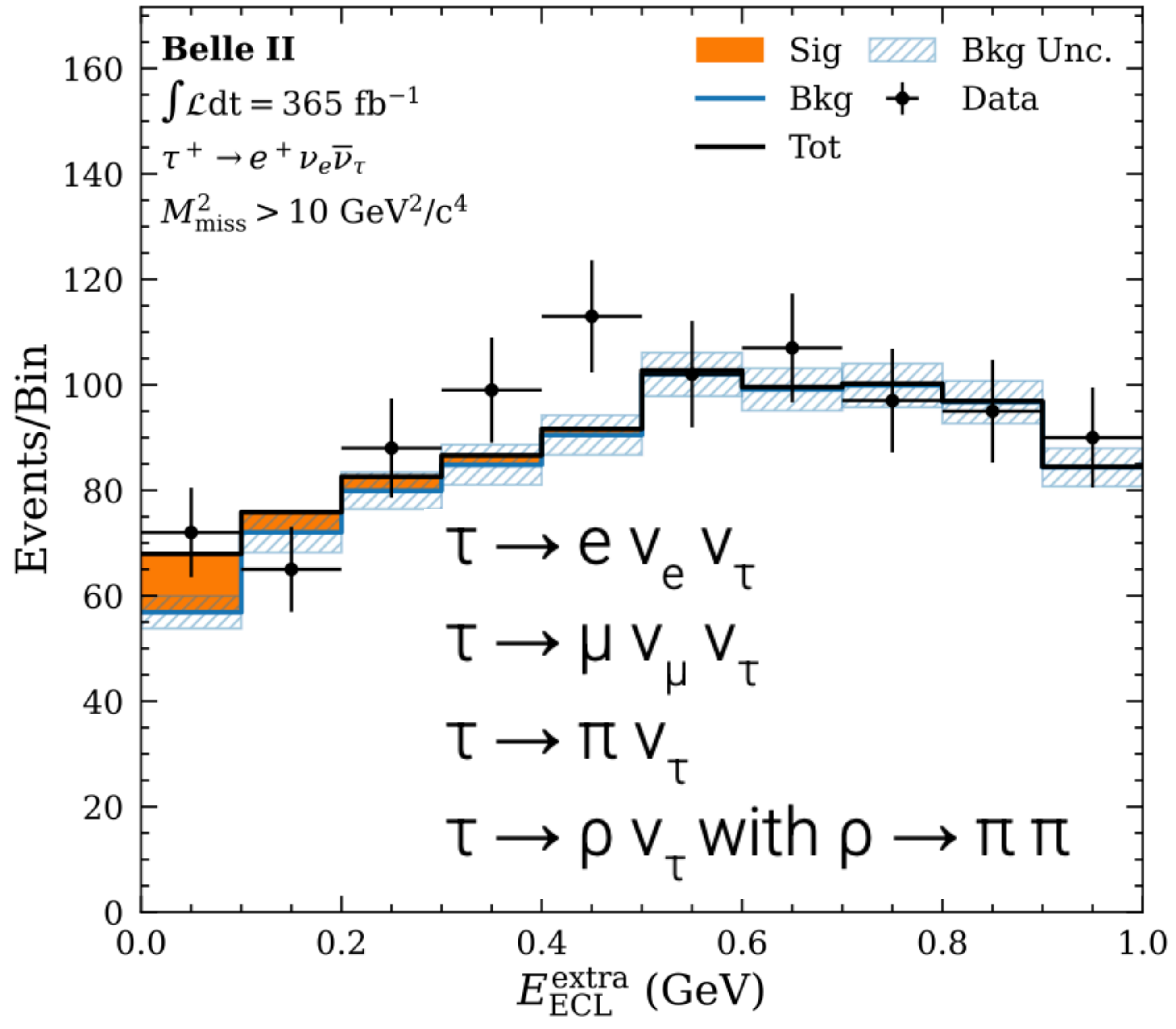
PRD 112 032010 (2025)

- Belle II *Br*($B\to\tau\nu$) measurement @ 365 fb^{-1}
  - Theoretical clean
  - Rare decay
  - Sensitive to new physics, e.g. charged higgs

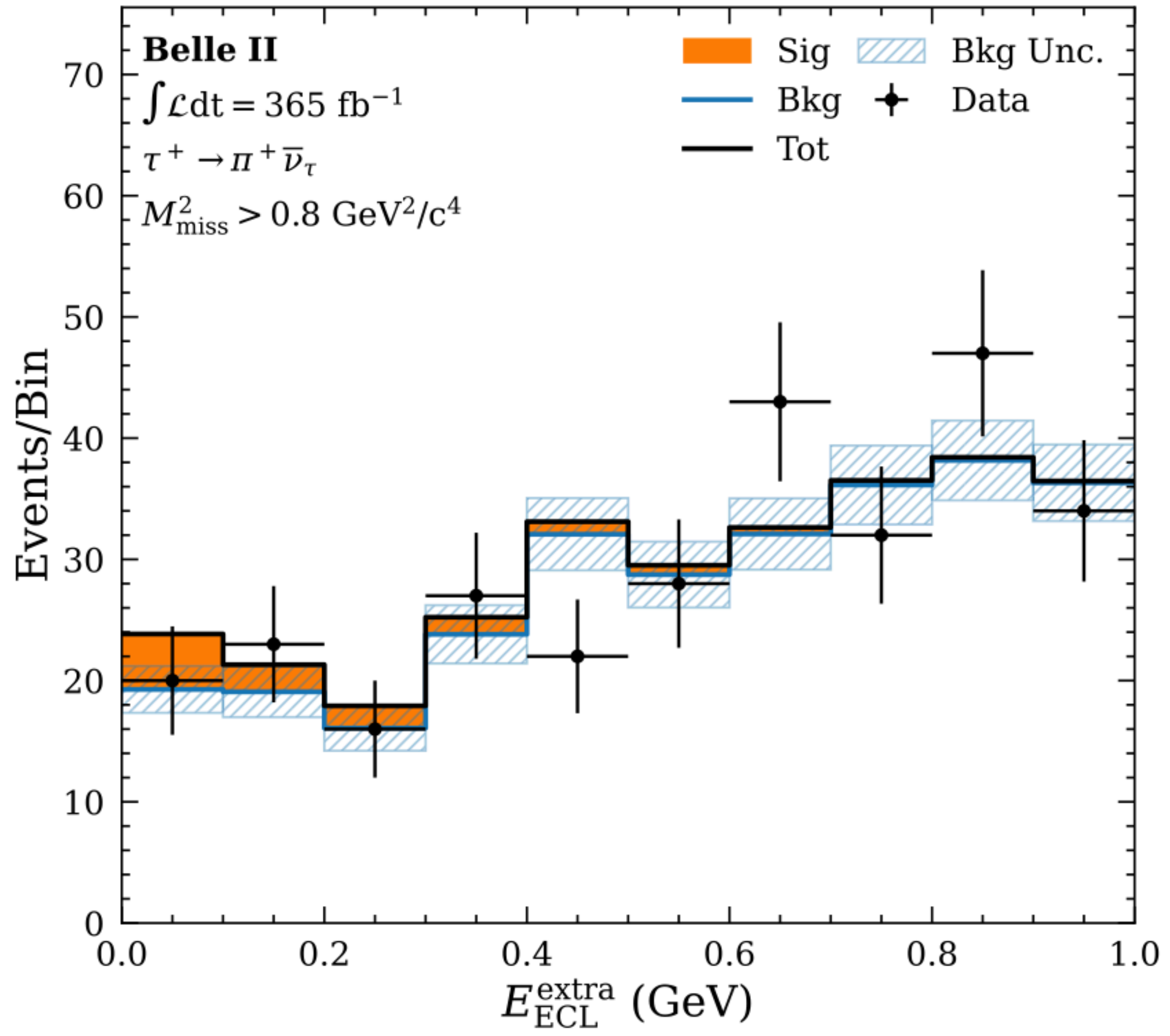
Leptonic Decay	SM Values	PDG Values
$\mathcal{B}(B^+\to e^+\nu_e)$	$(9.78\pm1.03)\times10^{-12}$	$<9.8\times10^{-7}$
$\mathcal{B}(B^+\to \mu^+\nu_\mu)$	$(4.18\pm0.44)\times10^{-7}$	$<8.6\times10^{-7}$
$\mathcal{B}(B^+\to \tau^+\nu_\tau)$	$(9.30\pm0.98)\times10^{-5}$	$(1.09\pm0.24)\times10^{-4}$

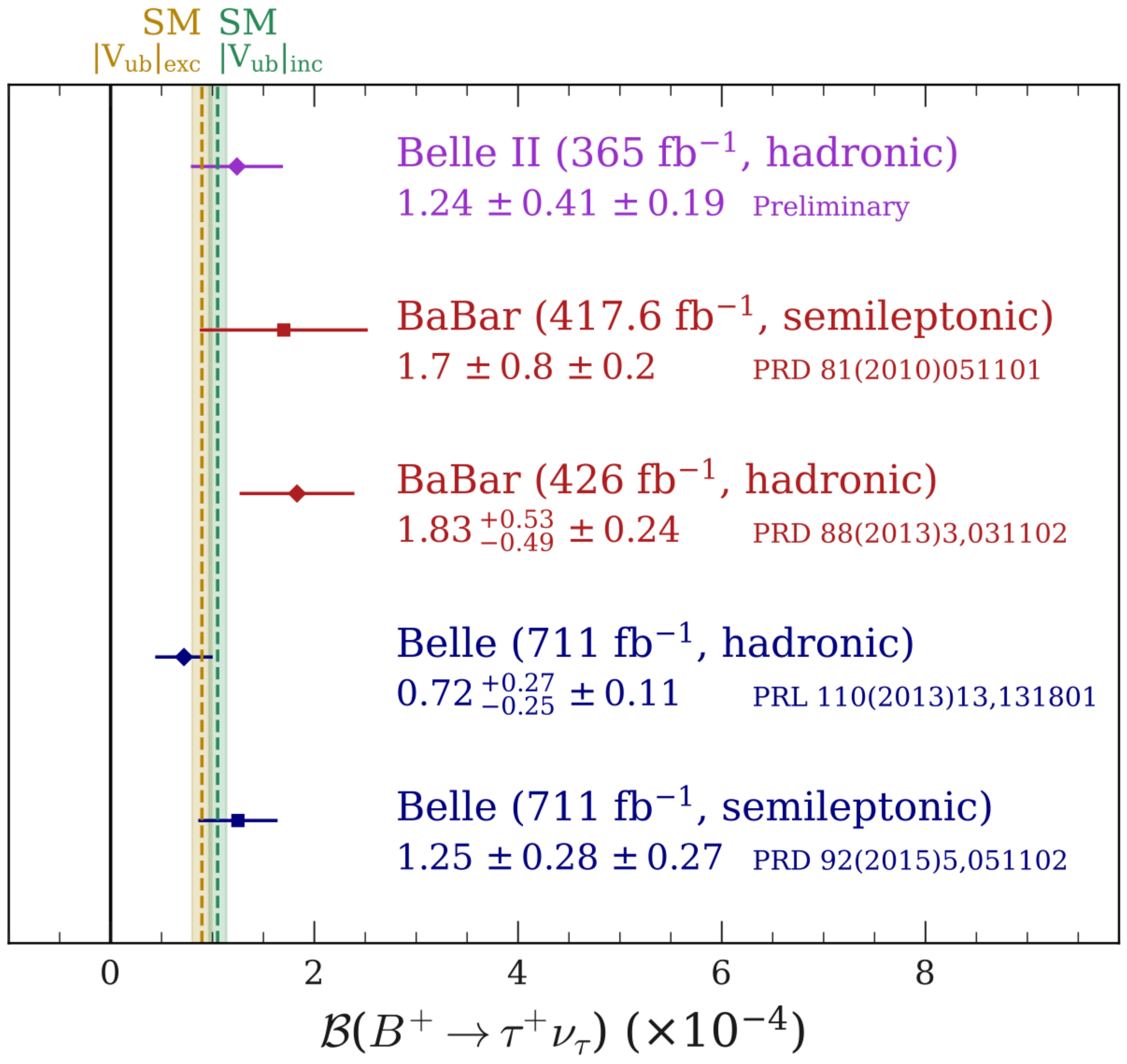
$$\mathcal{B}(B^+\to\ell^+\nu)=\frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1-\frac{m_\ell^2}{m_B^2}\right)^2 f_B^2|V_{ub}|^2\tau_B$$

$\tau\to e\nu\nu$



$\tau\to\pi\nu$



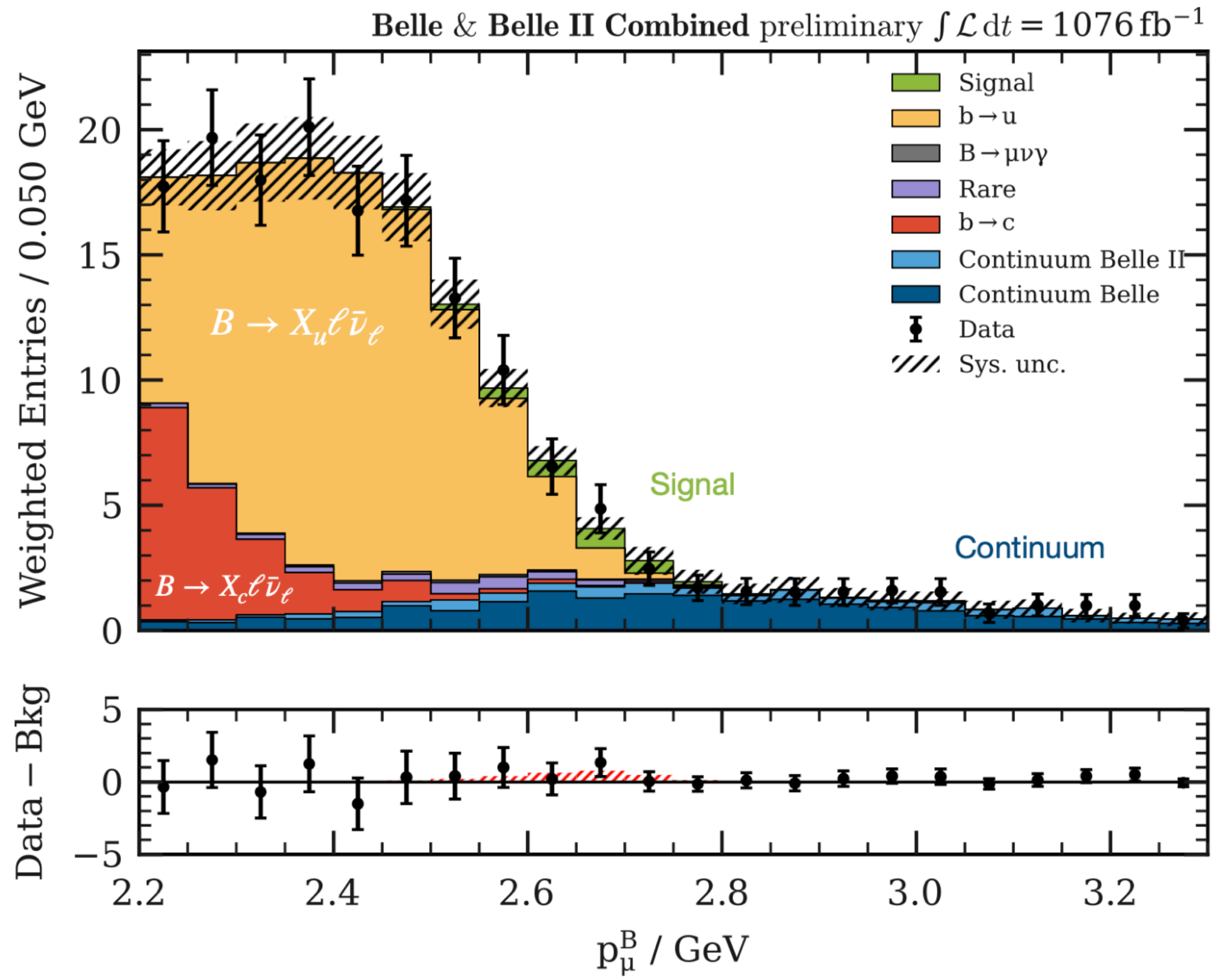


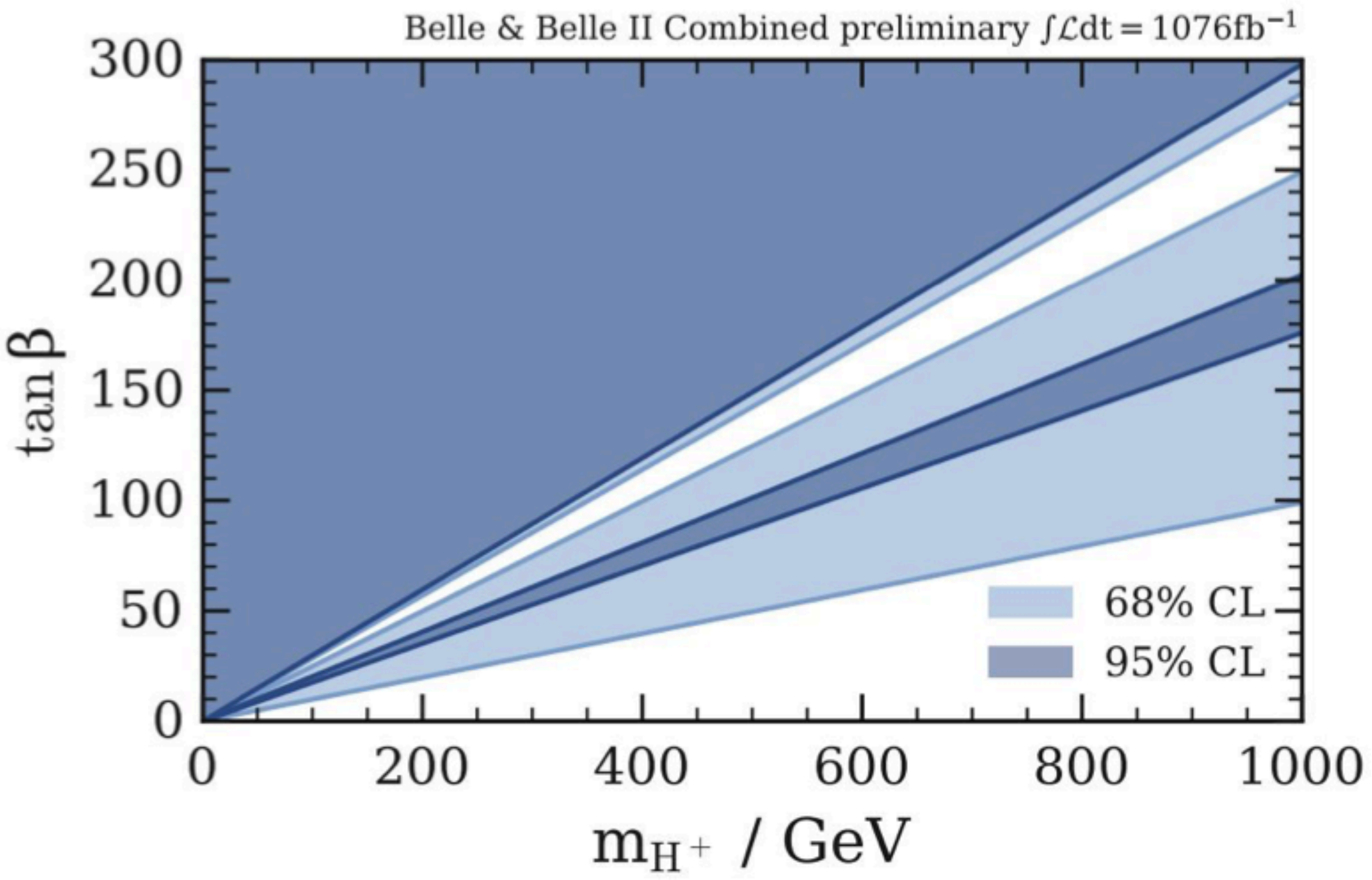
Br($B\to\tau\nu$) = $(1.24\pm0.41(\text{stat})\pm0.29(\text{syst}))\times10^{-4}$ 3σ wrt background-only hypothesis

Br($B\to\mu\nu$) result with inclusive tag

- Belle&Belle II *Br*($B\to\mu\nu$) measurement w/ inclusive tagging @ 1076 fb^{-1}
  - Theoretical clean
  - Rare decay
  - Sensitive to new physics, e.g. charged Higgs

$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) = \mathcal{B}_{SM} \times \left(1 - \frac{m_B^2 \tan^2\beta}{m_{H^+}^2}\right)^2$$



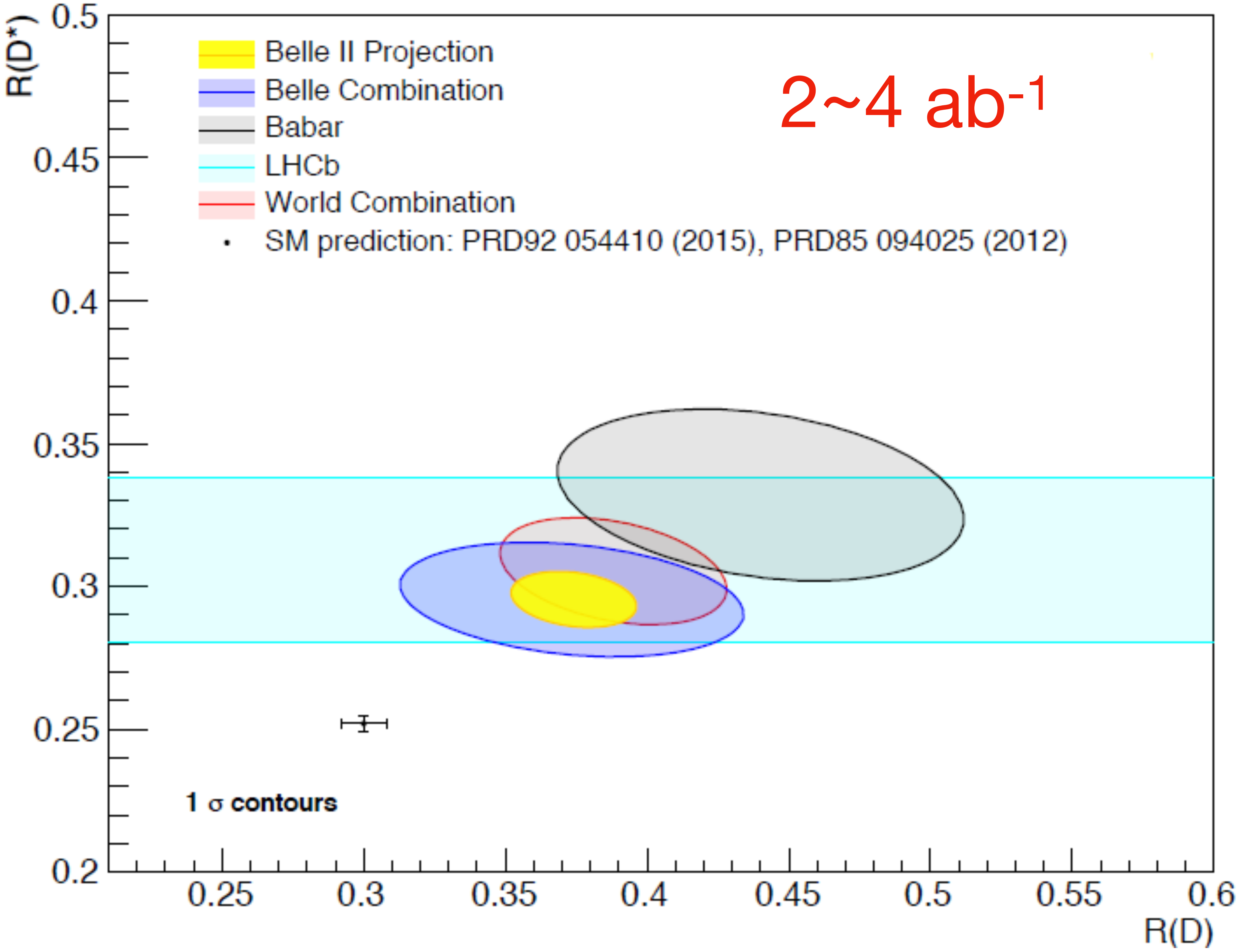


Br($B\to\mu\nu$) = (4.36 ± 1.89(stat) ± 1.02(syst)) x 10^{-7}

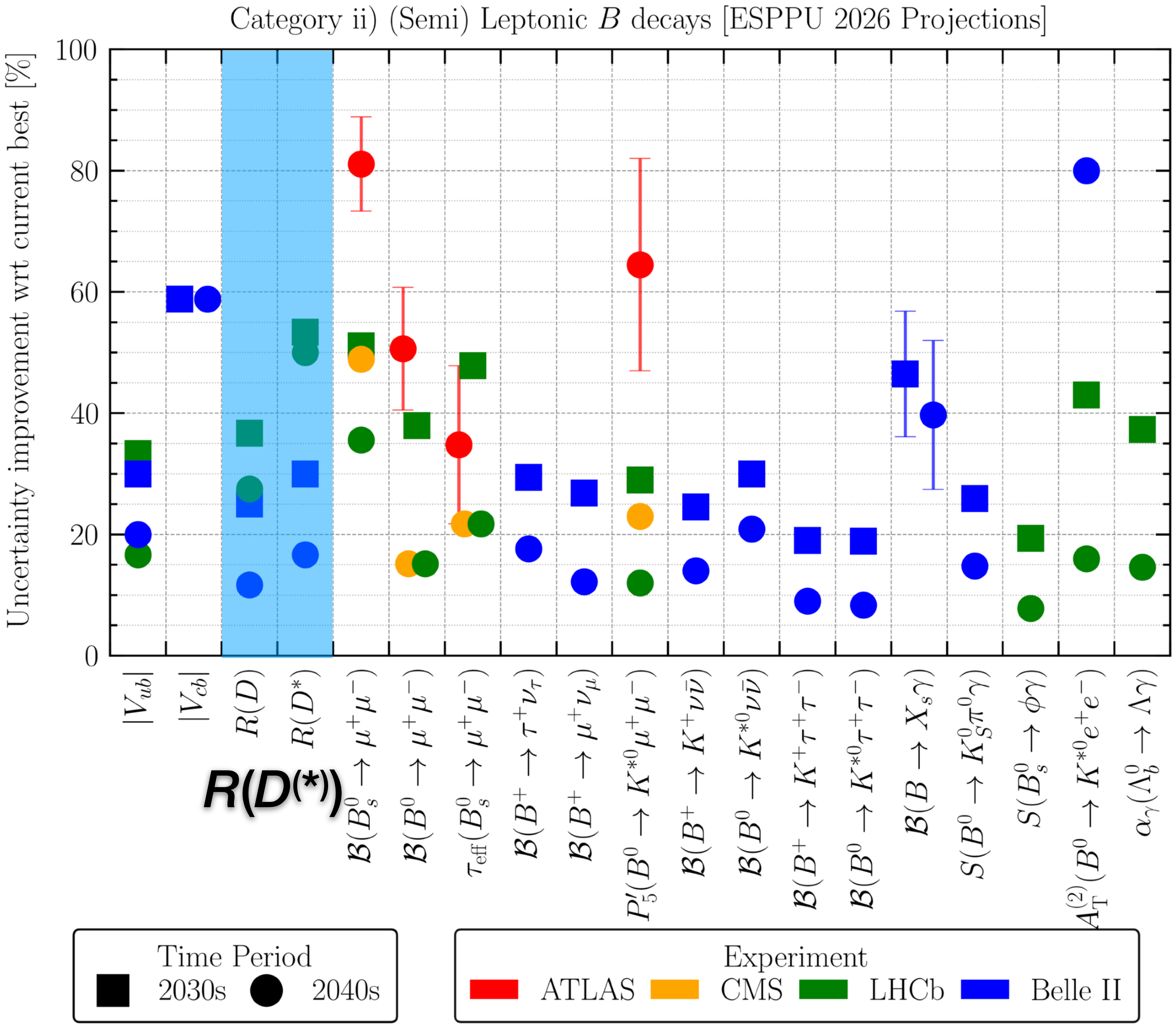
2.35σ over background-only hypothesis

Expected sensitivity of LFU test at Belle II

The Belle II Physics Book, PTEP 2019, 123C01



2~4 ab^{-1}



$R(D^{(*)})$

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
  - 189 fb^{-1} data

    $R_{\tau/\ell}(D^*) = 0.267\ ^{+0.041}_{-0.039}\ (\text{stat})\ ^{+0.028}_{-0.033}\ (\text{syst})$
  - 365 fb^{-1} data
    - Semileptonic tag

      $R_{\tau/\ell}(D^+) = 0.418 \pm 0.074\ (\text{stat}) \pm 0.051\ (\text{syst})$

      $R_{\tau/\ell}(D^{*+}) = 0.316 \pm 0.034\ (\text{stat}) \pm 0.018\ (\text{syst})$
    - Hadronic tag

      $R_{\tau/\ell}(D) = 0.439 \pm 0.055\ (\text{stat}) \pm 0.045\ (\text{syst})$

      $R_{\tau/\ell}(D^*) = 0.242 \pm 0.019\ (\text{stat}) \pm 0.016\ (\text{syst})$
- $R(D^*)$ vs. $P_\tau(D^*)$ result with hadronic tag @ 365 fb^{-1} coming soon, stay tuned !!!