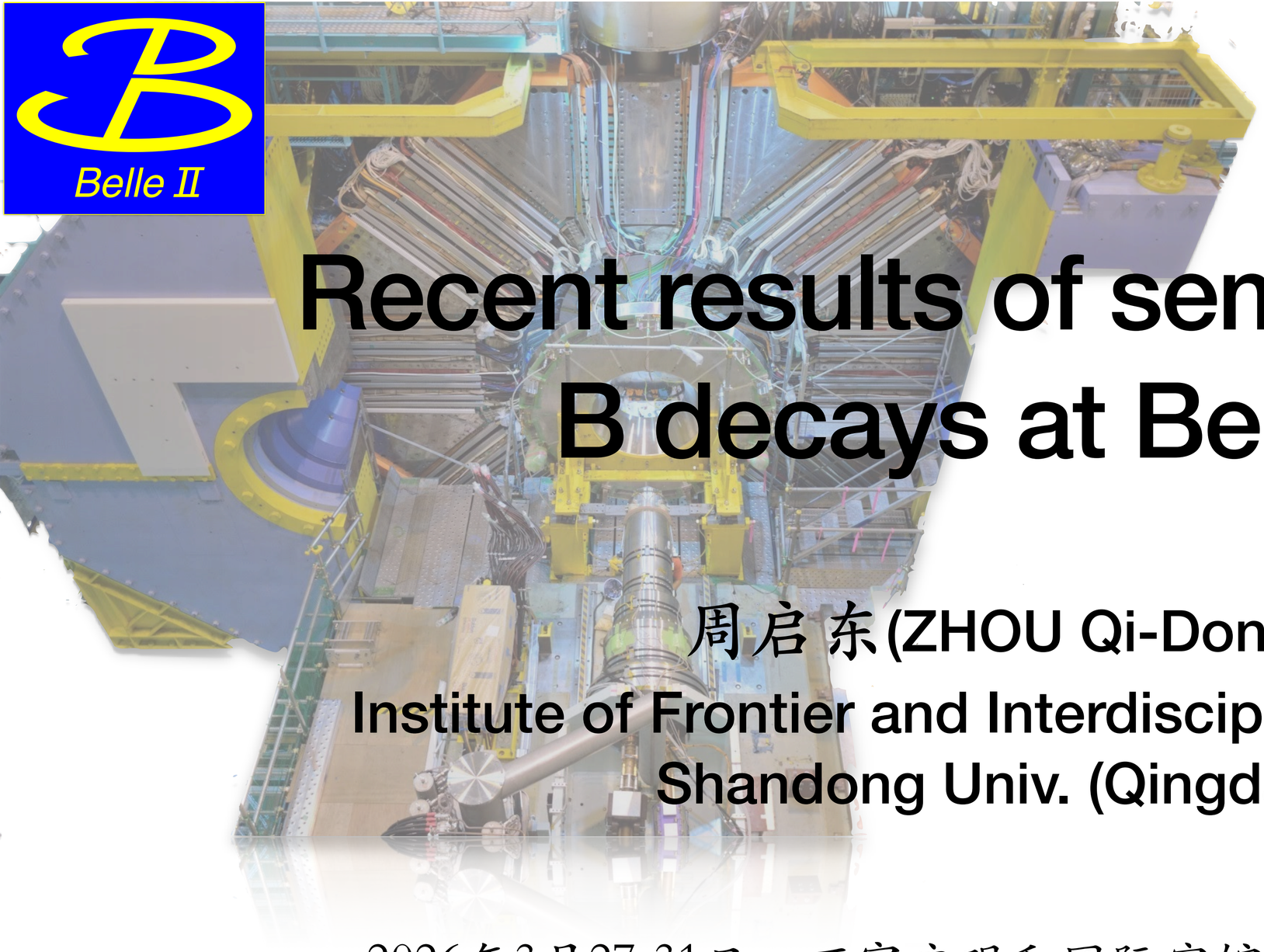

Recent results of semileptonic B decays at Belle II

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2026年3月27-31日，石家庄观和国际宾馆， 河北师范大学

第五届强子与重味物理理论与实验联合研讨会

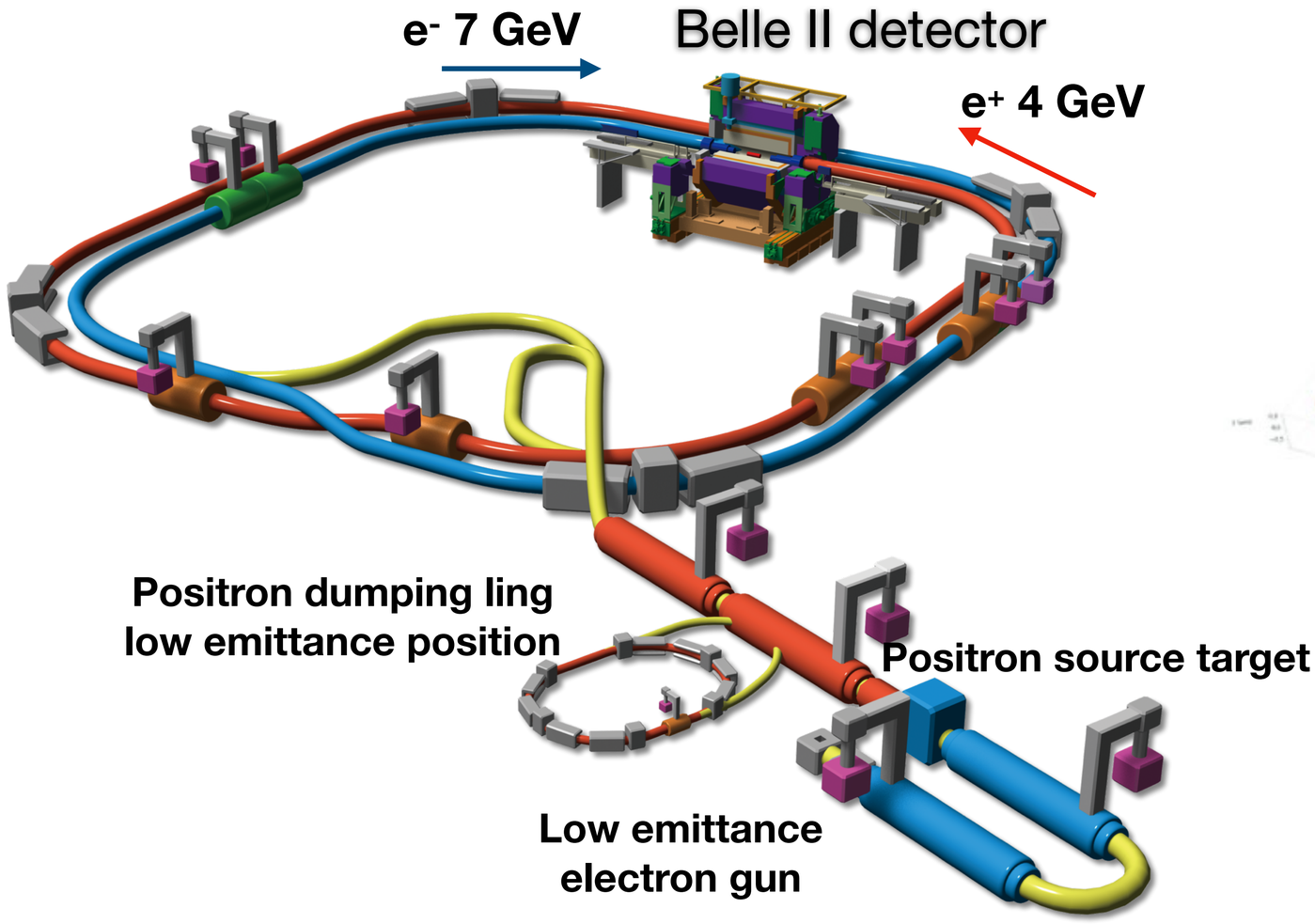
Luminosity frontier: SuperKEKB

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

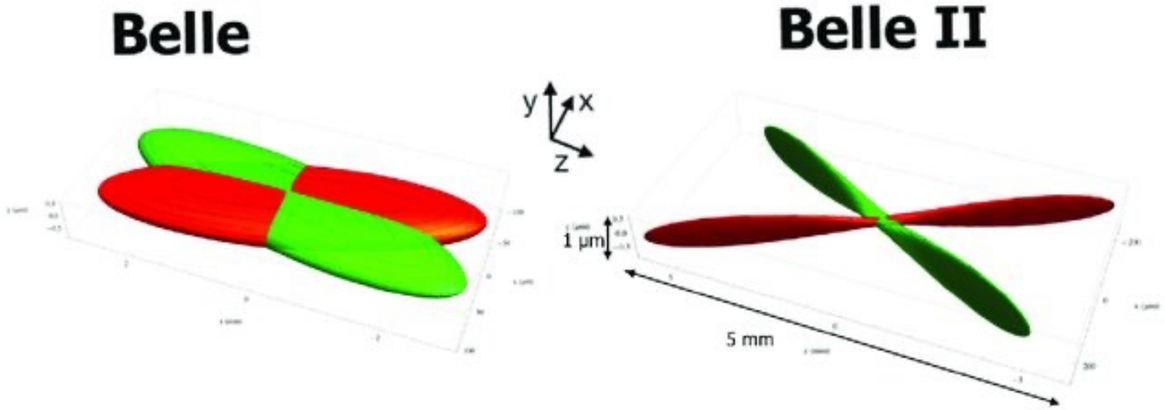
Beam current: KEKB x ~1.5

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

Beam squeeze: KEKB / ~20



Nano beam scheme



Achieved : 5.1 x 10^{34} cm^{-2} s^{-1} (Record)

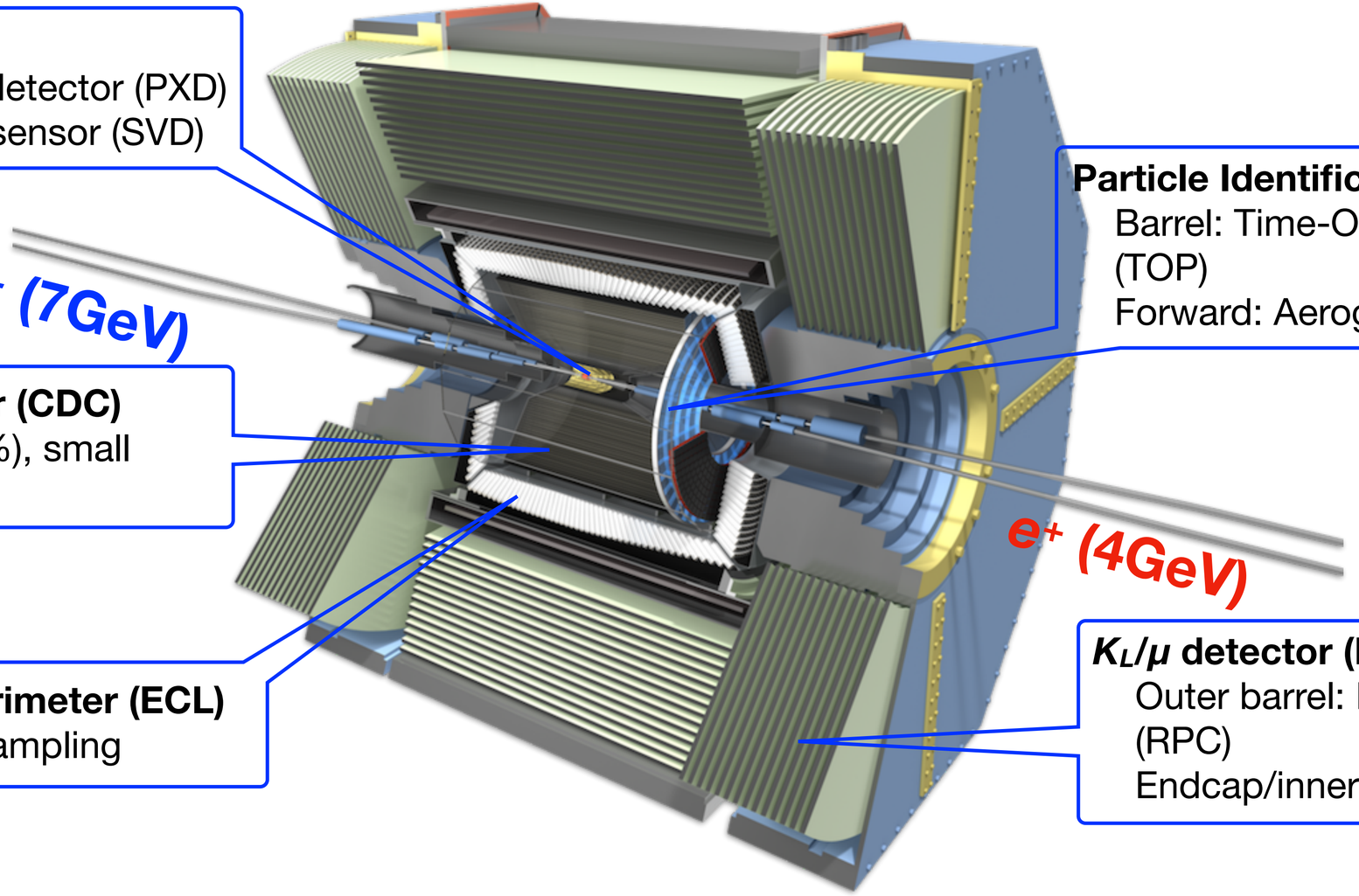
- Data at $\Upsilon(4S)$:
  - **~520** fb^{-1} (Belle II) <-> 711 fb^{-1} (Belle)

The Belle II detector

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

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

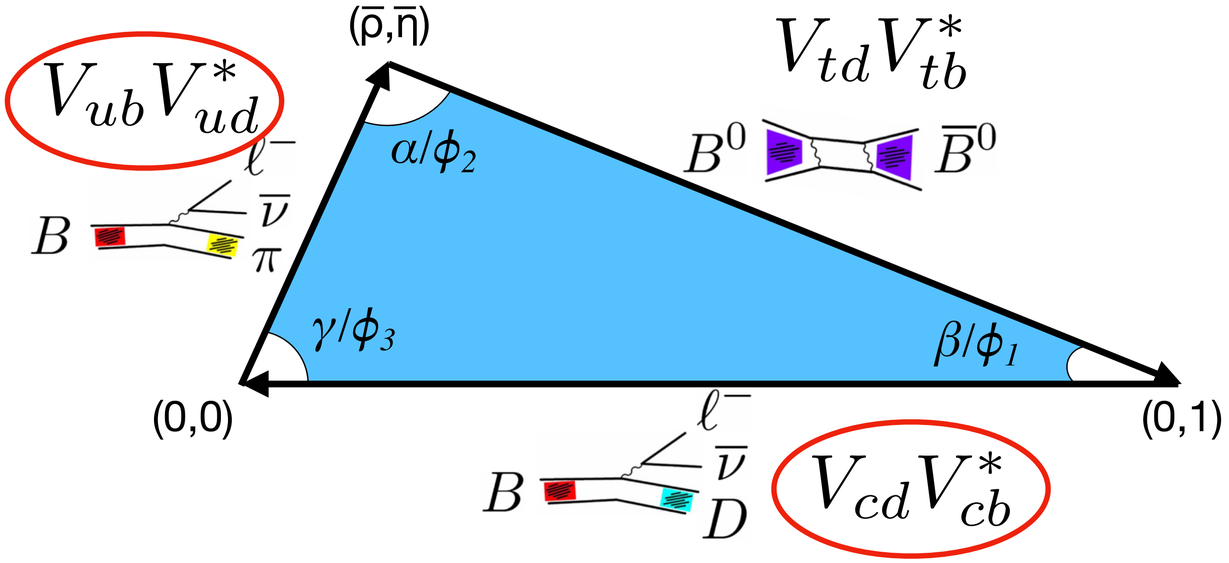


Particle Identification
Barrel: Time-Of-Propagation counters (TOP)
Forward: Aerogel RICH (ARICH)

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

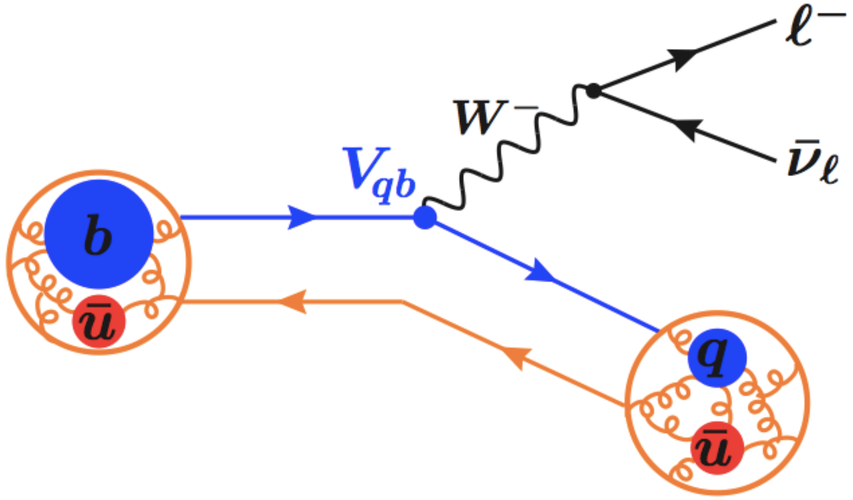
- Features:
  - Near-hermetic detector
  - Vertexing and tracking: σ vertex ~ 15μm, CDC spatial res. 100μm $\sigma(P_T)/P_T$ ~ 0.4%
  - Good at measuring neutrals, π^0, γ, K_L… $\sigma(E)/E$ ~ 2-4%

$|V_{cb}|$, $|V_{ub}|$ measurement through semi-leptonic B decays



Status of $|V_{cb}|$ and $|V_{ub}|$

Side	Observable		Dominant uncertainties
$\|V_{cb}\|$	$Br(b\to c l\nu)$	$Br(B\to D^{(*)} l\nu)$	Exclusive: Lattice QCD
		$Br(B\to X_c l\nu)$	
$\|V_{ub}\|$	$Br(b\to u l\nu)$	$Br(B\to \pi/\rho l\nu)$	Inclusive: experiment vs. phenomenology
		$Br(B\to X_u l\nu)$	



- $|V_{ub}|$ and $|V_{cb}|$ determinations based on inclusive and exclusive measurements differ by ~3σ
- Experimental focus is on understanding this discrepancy, as it limits the power of precision flavor physics

Exclusive:

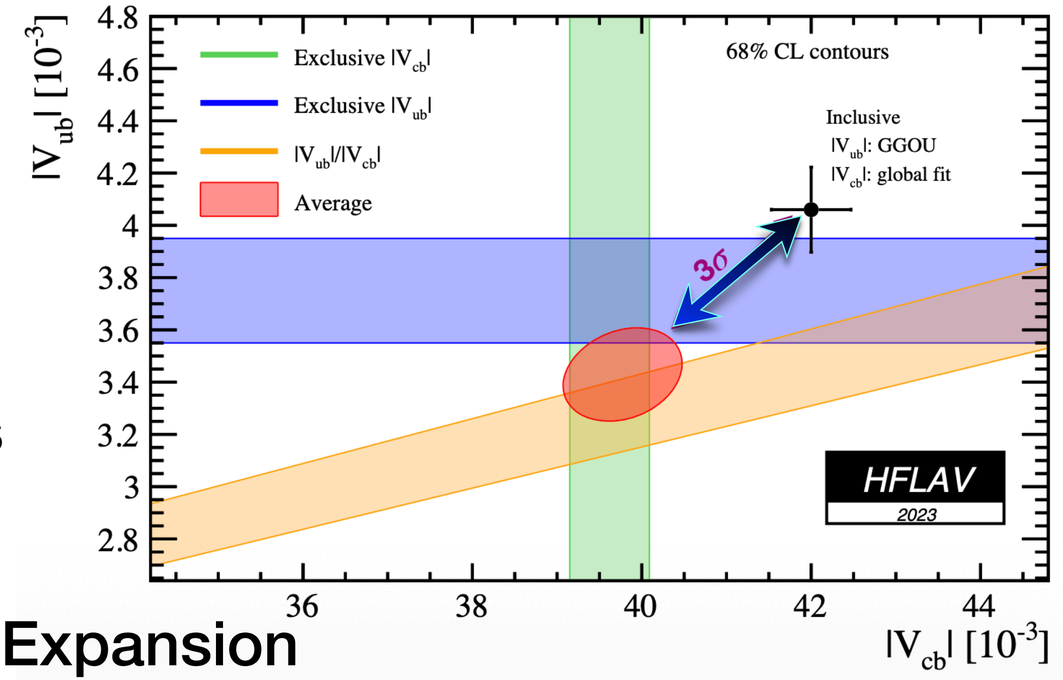
$$\frac{d\mathcal{B}}{dq^2}(B\to\pi\ell\nu)\propto|V_{ub}|^2 f_+^2(q^2)$$

Form Factors

Inclusive:

$$\mathcal{B}=|V_{qb}|^2\left[\Gamma(b\to q\,\ell\,\bar{\nu}_\ell)+1/m_{c,b}+\alpha_s+\ldots\right]$$

Heavy Quark Expansion

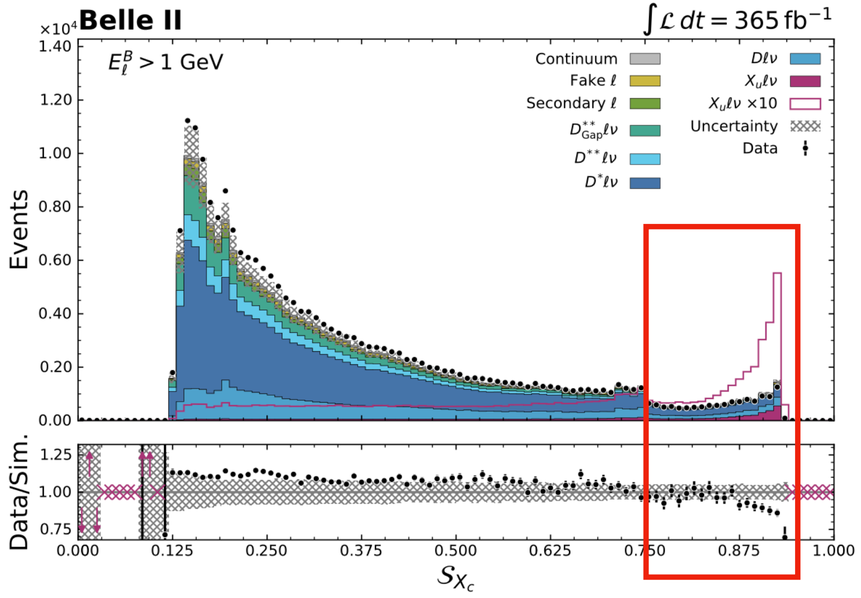


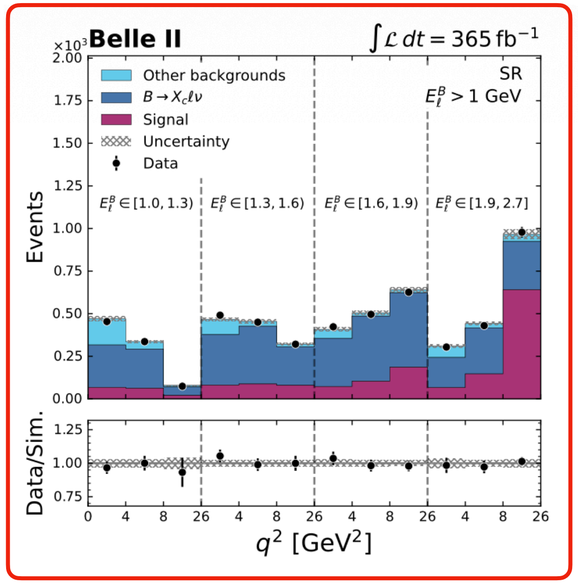
Measurement of $|V_{ub}|$ with $B \to X_u \ell \nu$

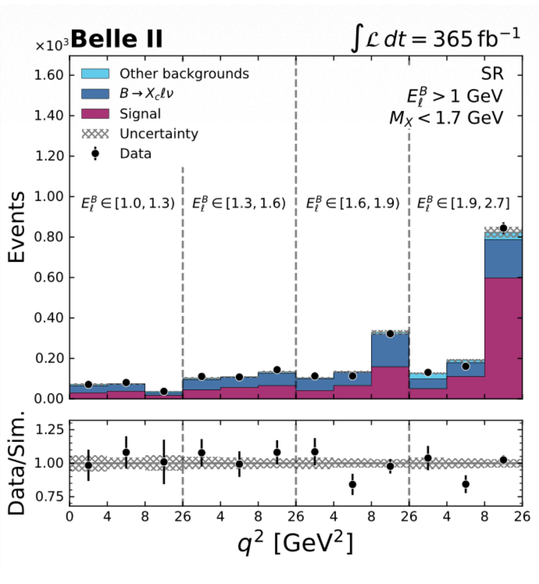
- **Reconstruction:** Combined signal lepton on the **signal side** with fully reconstructed hadronic B on **tag side**
- **Large backgrounds** from dominant decays $B \to X_c \ell \nu$
- Efficiently suppressed with MLP using different event shape variables
- Normalization and shape mismodelling **corrected** using control regions in data

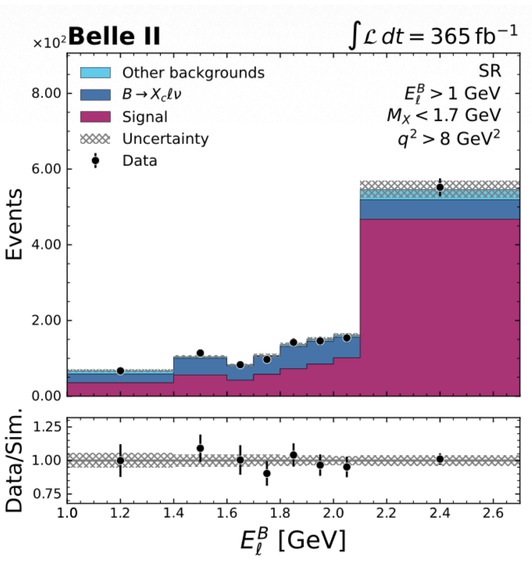
PRD 113 032004 (2026)

Nominal fit result









Acceptance / purity

$|V_{ub}|$ status from Belle II

- Determine from the measured **partial $|V_{ub}|$ branching fractions** in the 3 different phase space regions:

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell \nu)}{\tau_B \Delta\tilde{\Gamma}(B \to X_u \ell \nu)}}$$

- Nominal result: $E_l > 1$ GeV with GGOU,
- covering 87% of phase space

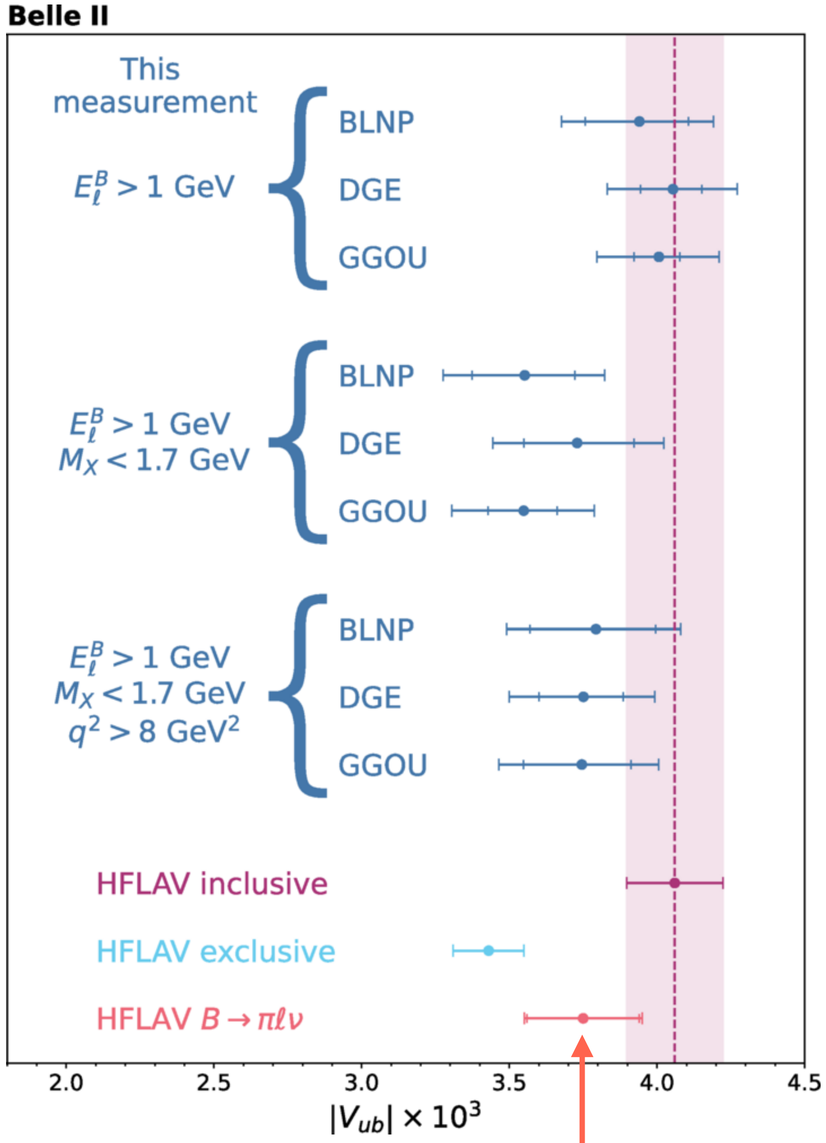
$$|V_{ub}| = 4.01 \pm 0.11(\text{stat.}) \pm 0.16(\text{syst.})^{+0.07}_{-0.08}(\text{theo})$$

- Dominant systematics

$B \to X_u \ell \nu$ modelling: (m_b, a) where $a = f(m_b, \mu_\pi^2)$ in Kagan-Neubert scheme

$B \to X_c \ell \nu$ composition differences between SR and CR

X_u fragmentation modelling



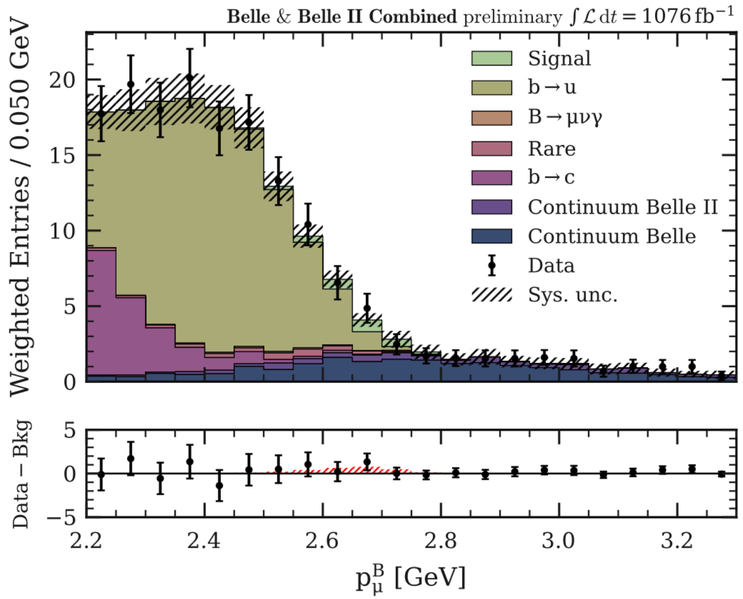
Exclusive Average for $B \to \pi \ell \nu$:

$|V_{ub}| = (3.75 \pm 0.06_{\text{exp}} \pm 0.19_{\text{theo}}) \times 10^{-3}$

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

- Belle&Belle II $Br(B \to \mu\nu)$ measurement w/ inclusive tagging @ 1076 fb^{-1} arXiv:2602.09800
  - Theoretical clean
  - Rare decay
  - Sensitive to new physics, e.g. charged Higgs

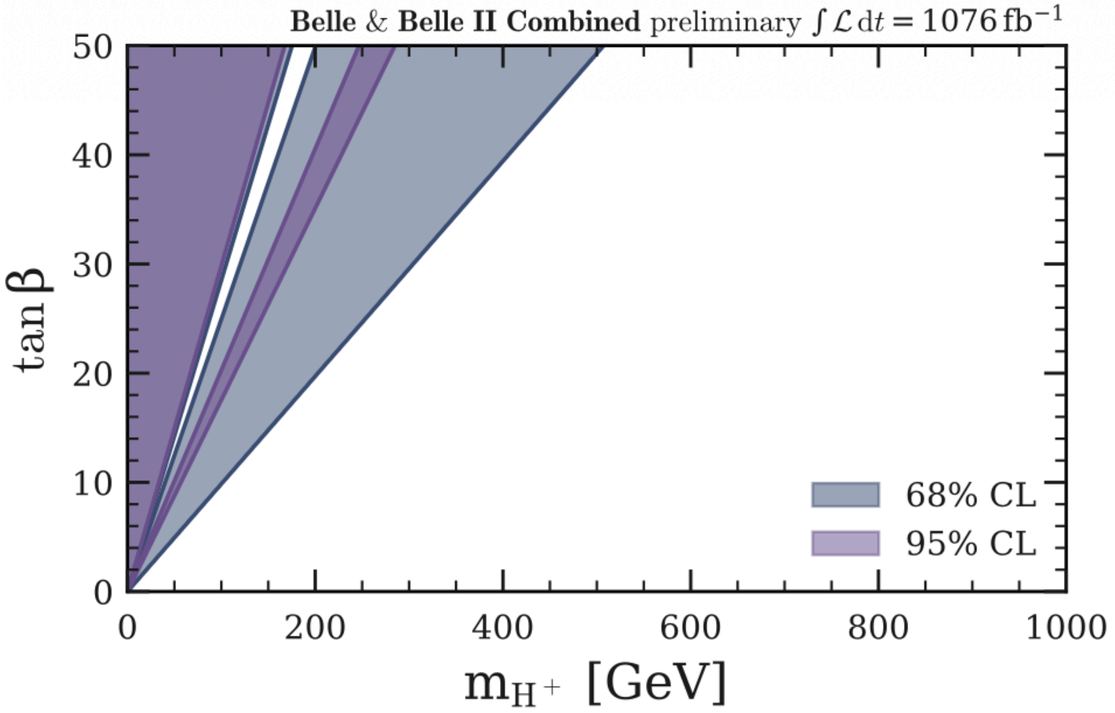
$$\mathcal{B}(B^+ \to \mu^+\nu_\mu) = \frac{G_F^2 m_B m_\mu^2}{8\pi}\left(1 - \frac{m_\mu^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_{B^+}$$



2.4σ over background-only hypothesis
Most precise measurement to date

$Br(B \to \mu\nu)$ = (4.4 ± 1.9 (stat) ± 1.0 (syst)) x 10^{-7}

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



Determination of exclusive $|V_{ub}|$

$$|V_{ub}| = 3.92^{+0.77}_{-0.96}(\text{stat.})^{+0.44}_{-0.49}(\text{syst.}) \pm 0.03(\text{theo})$$

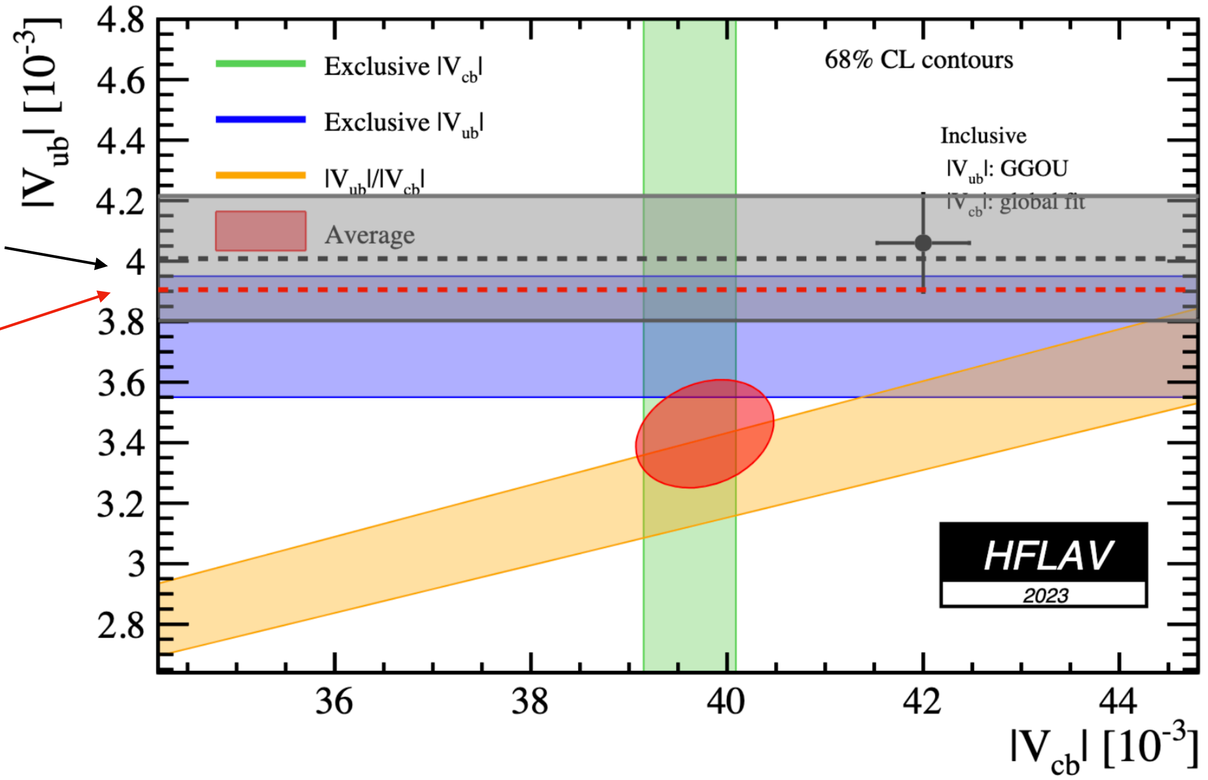
Compatible with both inclusive and exclusive determinations

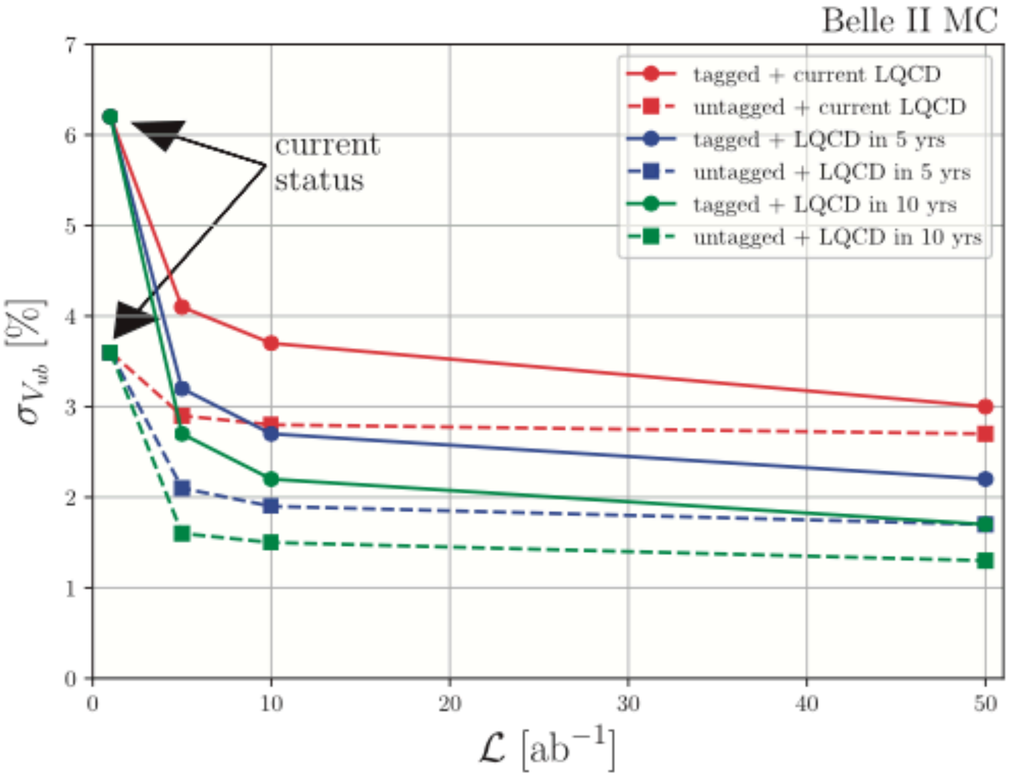
Inclusive $|V_{ub}|$ measurements

The Belle II Physics Book, PTEP 2019, 123C01

$B \to X_u \ell \nu$

$B \to \mu \nu$





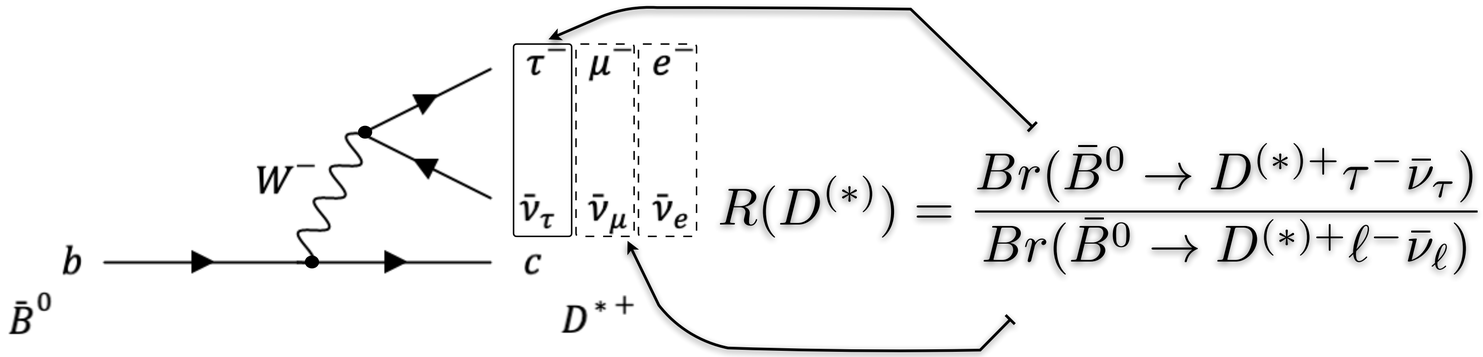
$$B \to X_u \ell \nu: \quad |V_{ub}| = (4.01 \pm 0.11 \pm 0.16^{+0.07}_{-0.08}) \times 10^{-3}$$

$$B \to \mu \nu: \quad |V_{ub}| = \left(3.90\,^{+0.77}_{-0.96}\,(\text{stat.})\,^{+0.43}_{-0.49}\,(\text{sys.}) \pm 0.03\,(\text{theo.})\right) \times 10^{-3}$$

Test of Lepton Flavor Universality

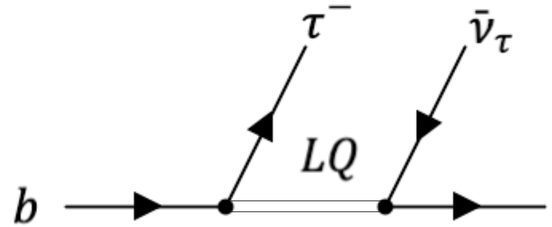
LFU test with semileptonic *B* decays

- 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**



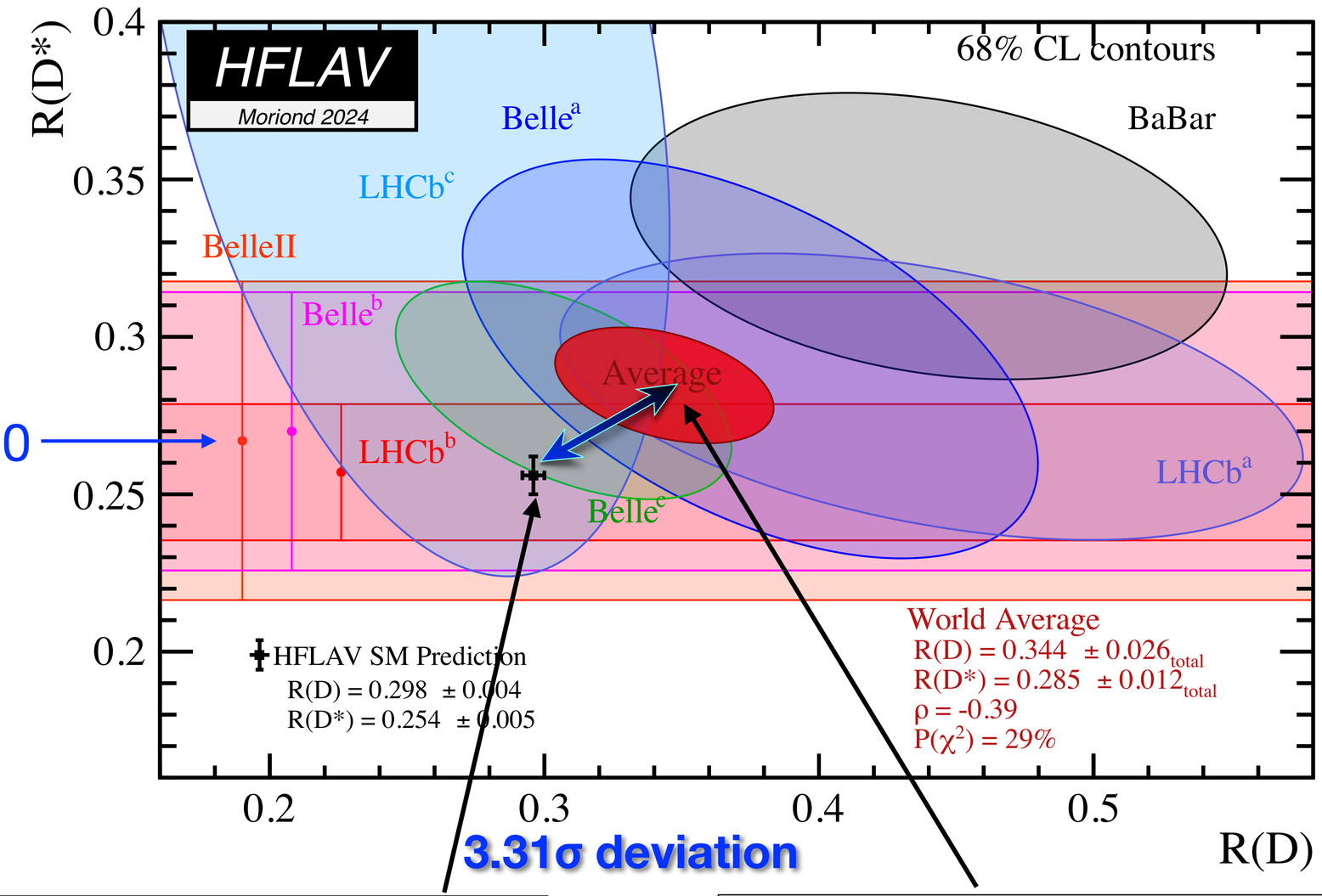
$$R(D^{(*)}) = \frac{Br(\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)}{Br(\bar{B}^0 \to D^{(*)+}\ell^-\bar{\nu}_\ell)}$$

- 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]



“*B* anomaly” in semileptonic decays

PRD 110 072020



3.31σ deviation

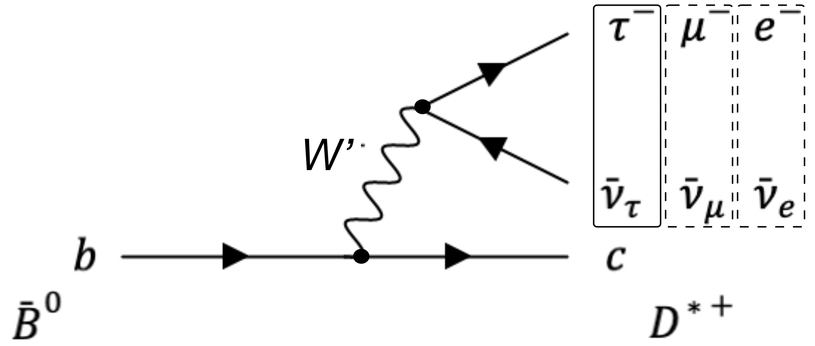
Standard Model prediction

Experimental average results

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

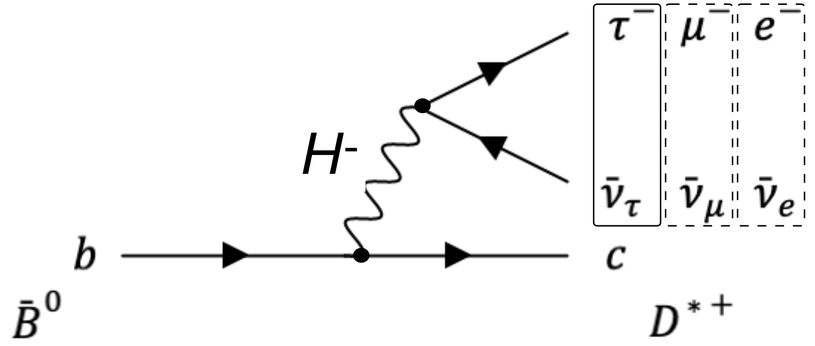
In general, there are three typical candidate scenarios to explain the anomaly observed in $R(D^{(*)})$

- Heavy vector bosons
  - Constrained from $W' \to \tau\nu$ and $Z' \to \tau\tau$ search

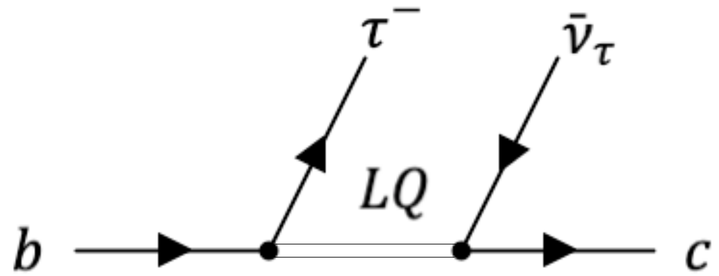


- Charged Higgs
  - Constrained from $B_c \to \tau\nu$ and $H^{\pm} \to \tau\nu$,still allowed
  - Previously, it was rejected by $B_c \to \tau\nu$ measurement, however, recovered by recalculating the B_c lifetime.

    PRD 105 095011(2022)



- Leptoquark
  - $gg \to LQ\ LQ^*$, still broad parameter regions are allowed

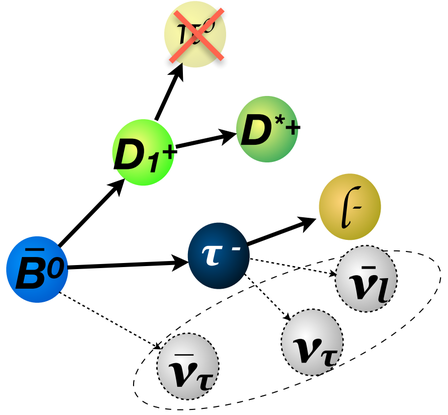


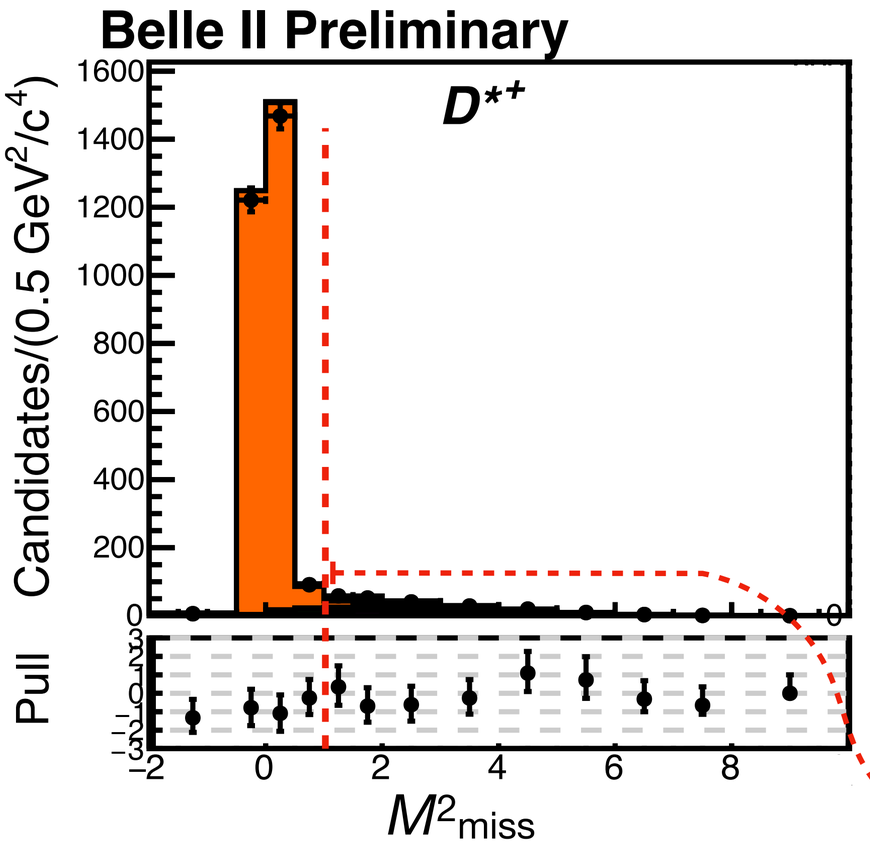
$R_{\tau/\ell}(D^{(*)})$ with hadronic tag

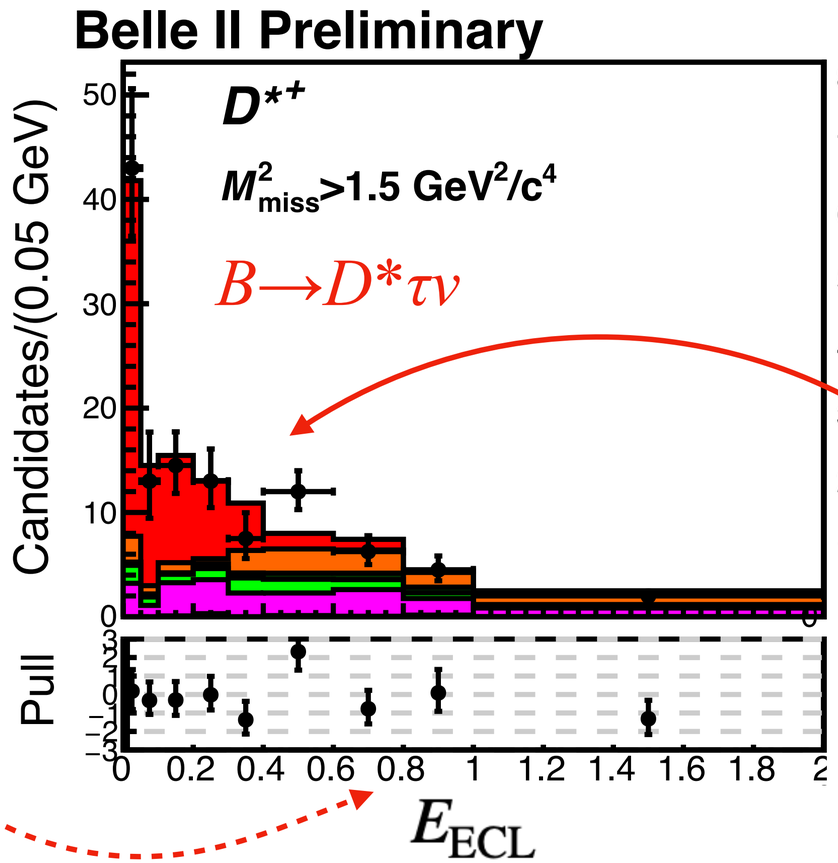
- Belle II UPDATED result for $R(D^{(*)})$ @ 365 fb^{-1}
  - Hadronic tag with FEI
  - Leptonic τ decays
  - $B \to D^{*+}$, $D^{*0}(\pi^0)$, $D^{*0}(\gamma)$, D^{+},D^{0},$\tau/\ell\nu$

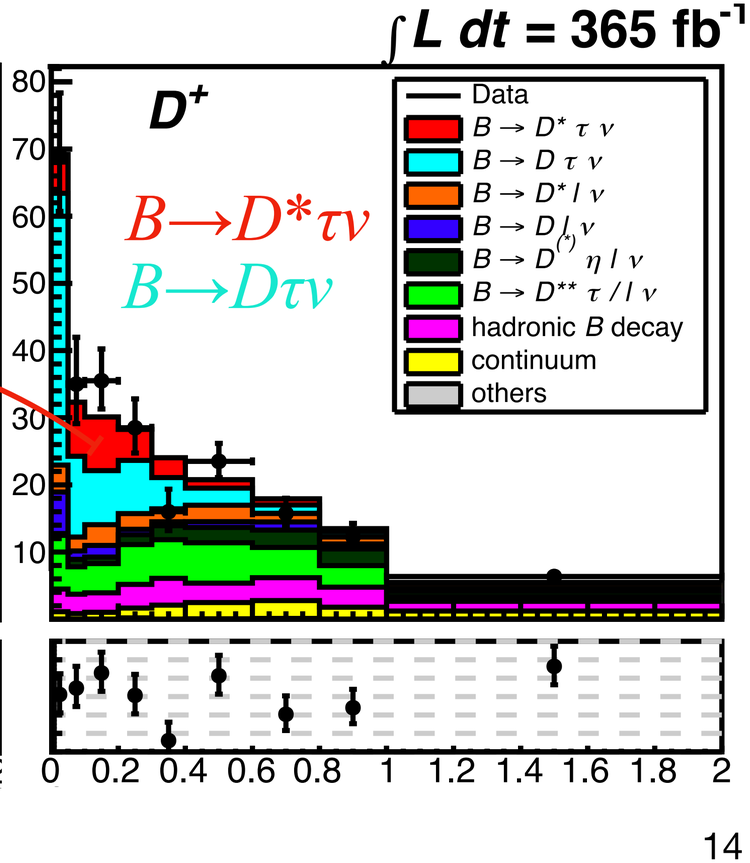
$$E_{\mathrm{ECL}} = \sum_i E_i^{\gamma}$$

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









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

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

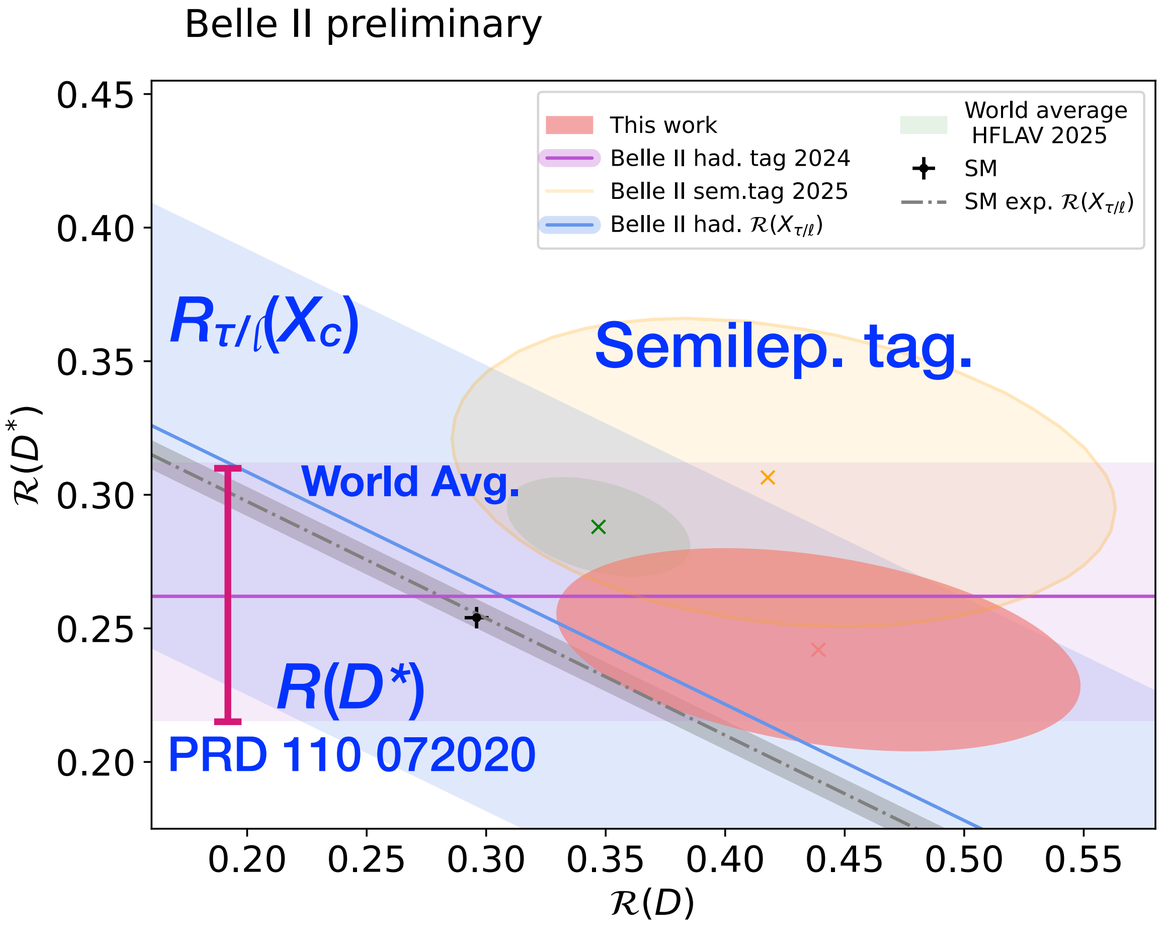
Source	Uncertainty	
	R(D*)	R(D)
Statistical uncertainty	±8.3%	±16.3%
Simulation sample size	±4.8%	±8.4%
$B \to D^{(*)} \eta l \nu$ branch fraction	±2.8%	±3.6%
$B \to D^{**} l \nu$ branch fraction	±0.3%	±1.3%
…	…	…

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

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

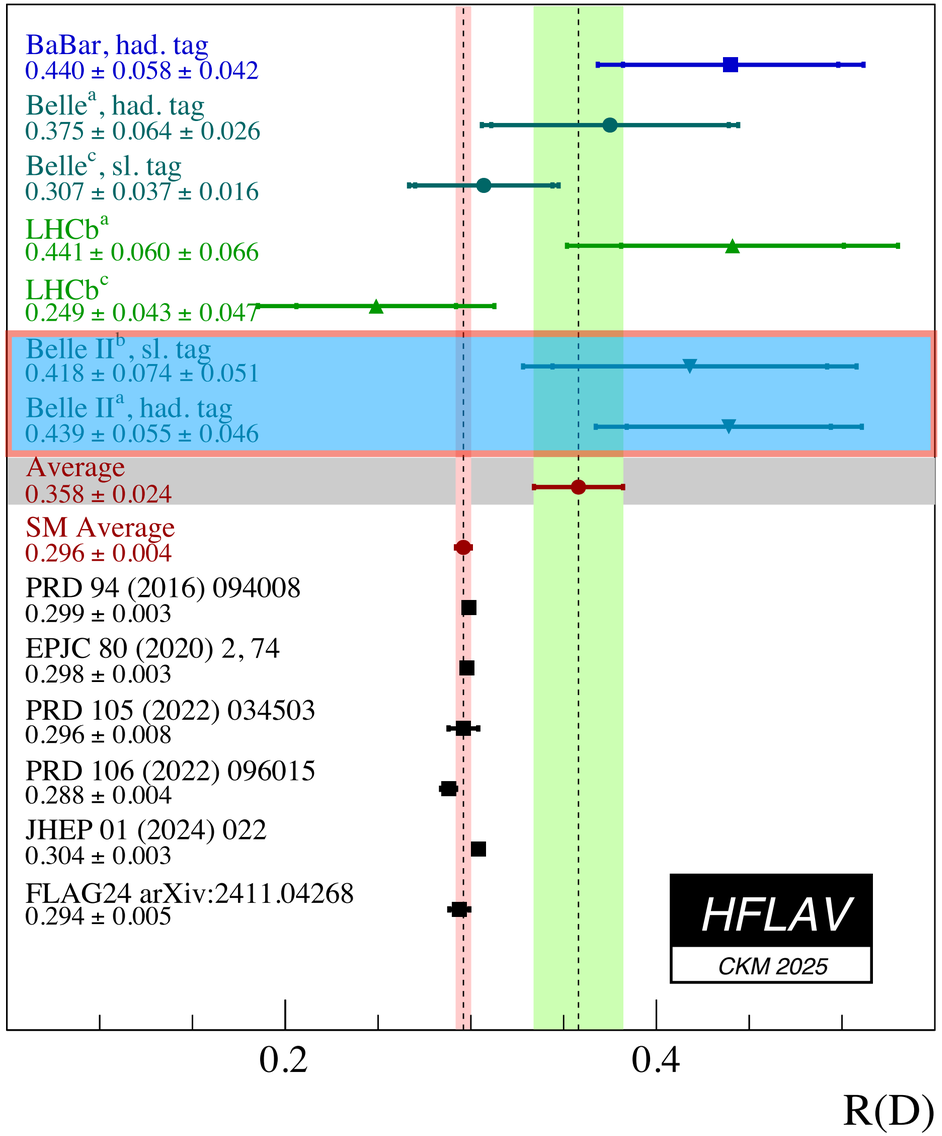
$R_{\tau/\ell}(D) = 0.439 \pm 0.055\ (\text{stat}) \pm 0.045\ (\text{syst})$

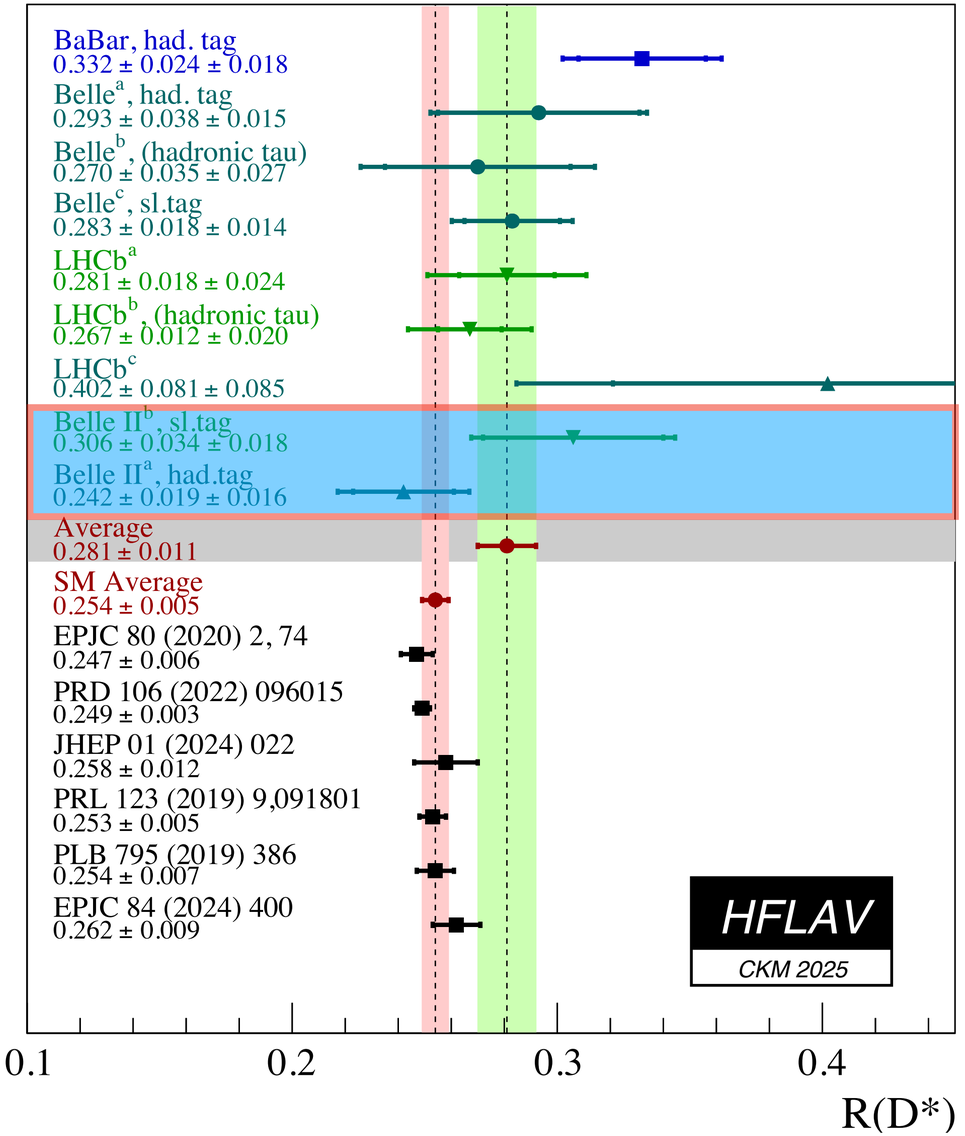
$R_{\tau/\ell}(D^*) = 0.242 \pm 0.019\ (\text{stat}) \pm 0.016\ (\text{syst})$



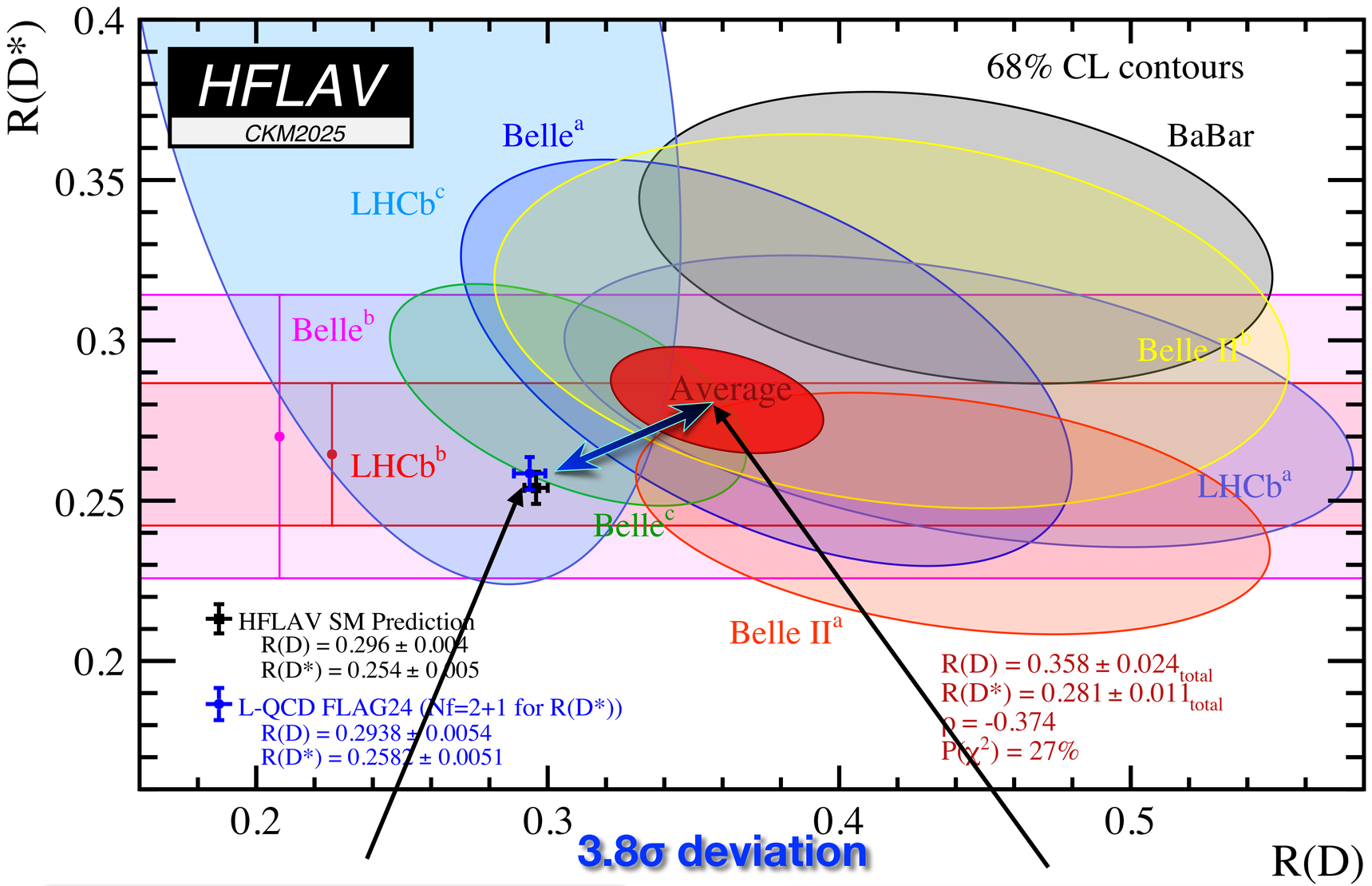
"*B* anomaly" in semileptonic decays

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





“*B* anomaly” in semileptonic decays 2025



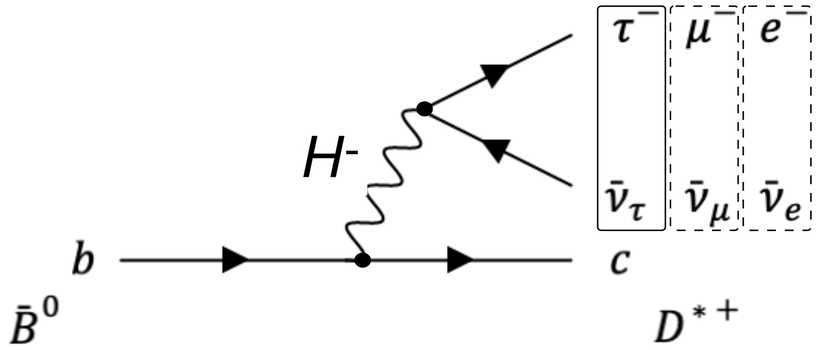
3.8σ deviation

Standard Model prediction

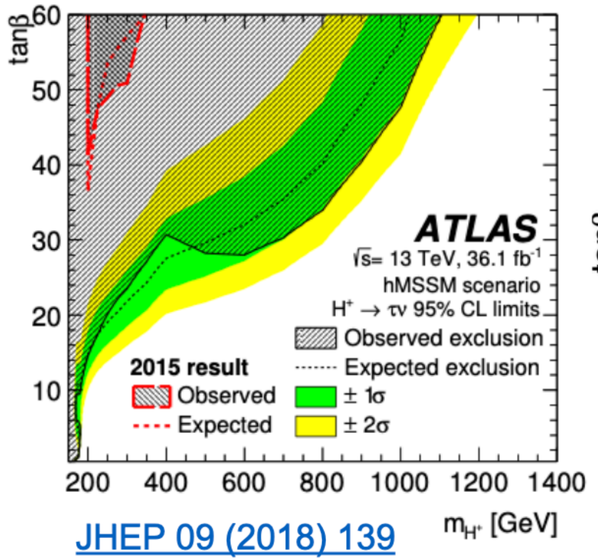
Experimental average results

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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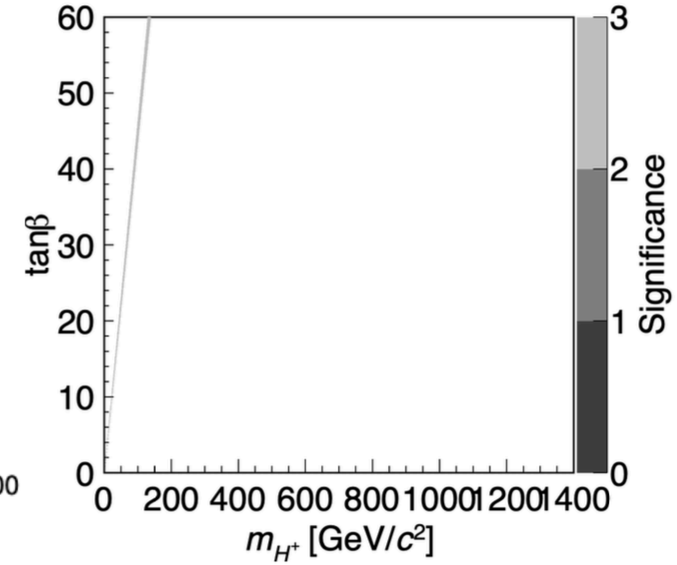
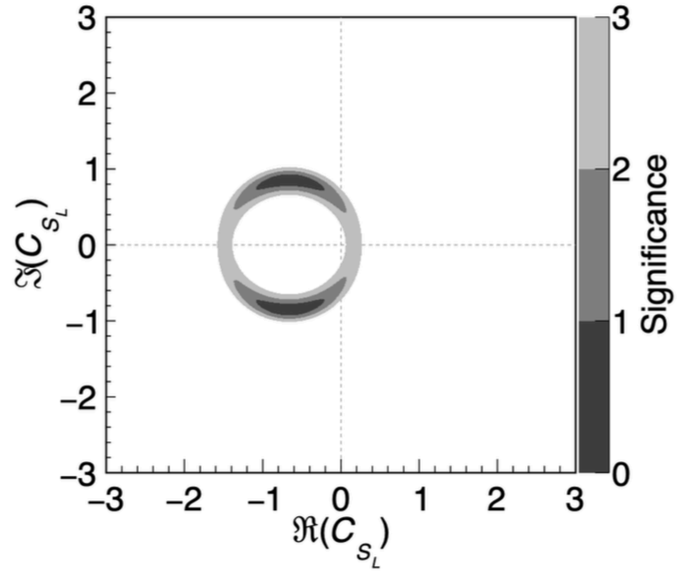


General 2HDM



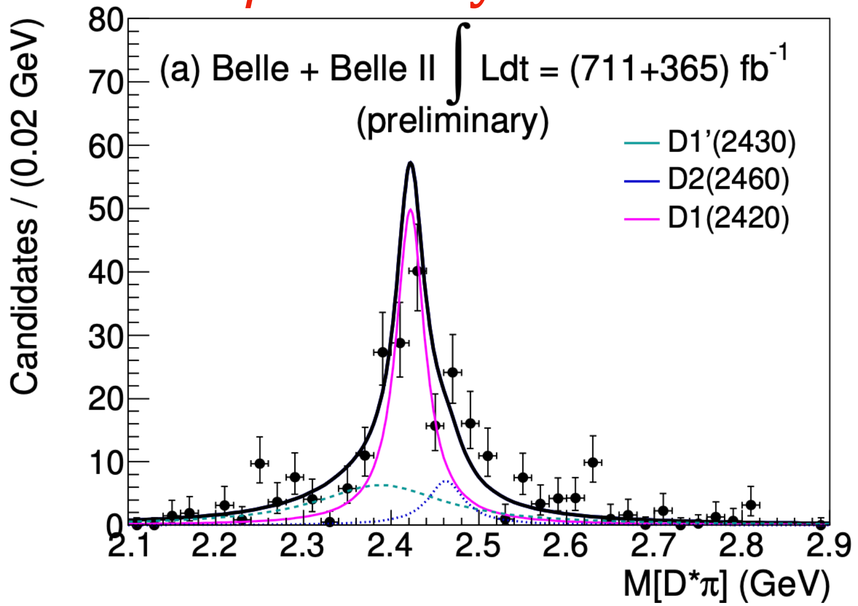
- Charged Higgs in 2HDM (type II) is disfavored
- General 2HDM still survives

Measurement of $B \to D^{(*)}\eta\pi$ at Belle and Belle II

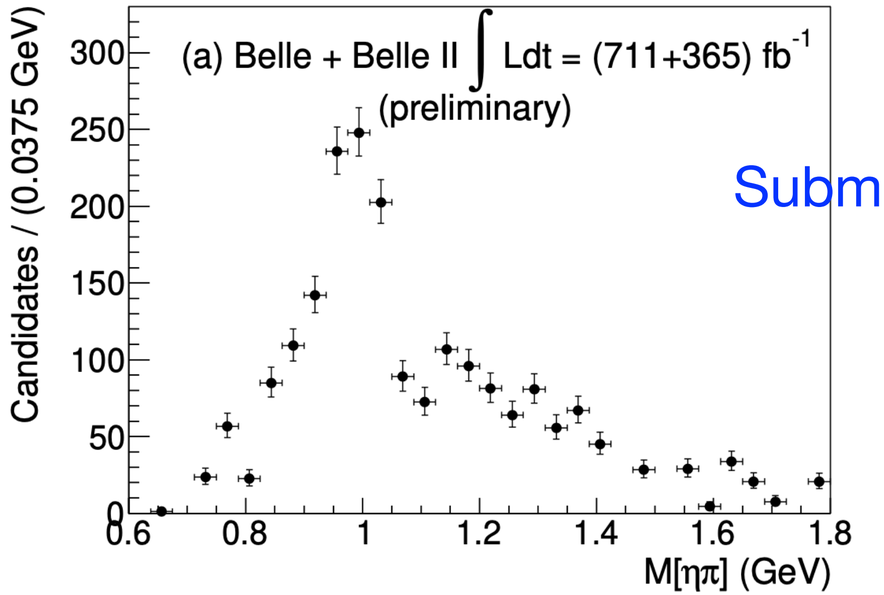
- Deficit of in sum of BFs with $b \to c\ell\nu$ transition vs inclusive measurement $B \to X_c\ell\nu$
- Proposal: unmeasured $B \to D^{(*)}\eta\ell\nu$ modes are responsible for gap
- Perform 3 body reconstruction (i.e. no assumptions on resonances) in Belle and Belle II data with:

$$\mathcal{B}(B \to D^{(*)}\eta\ell\nu_\ell) \approx \frac{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}{\mathcal{B}(B \to D^{(*)}\pi)} \times \mathcal{B}(B \to D^{(*)}\eta\pi)$$

$B^0 \to D^{*-}\eta\pi$ mainly from $B \to D^{**0}\eta$



$B^+ \to D^0\eta\pi$ mainly from $B^+ \to D^0 a_0^+$



Submitted to JHEP

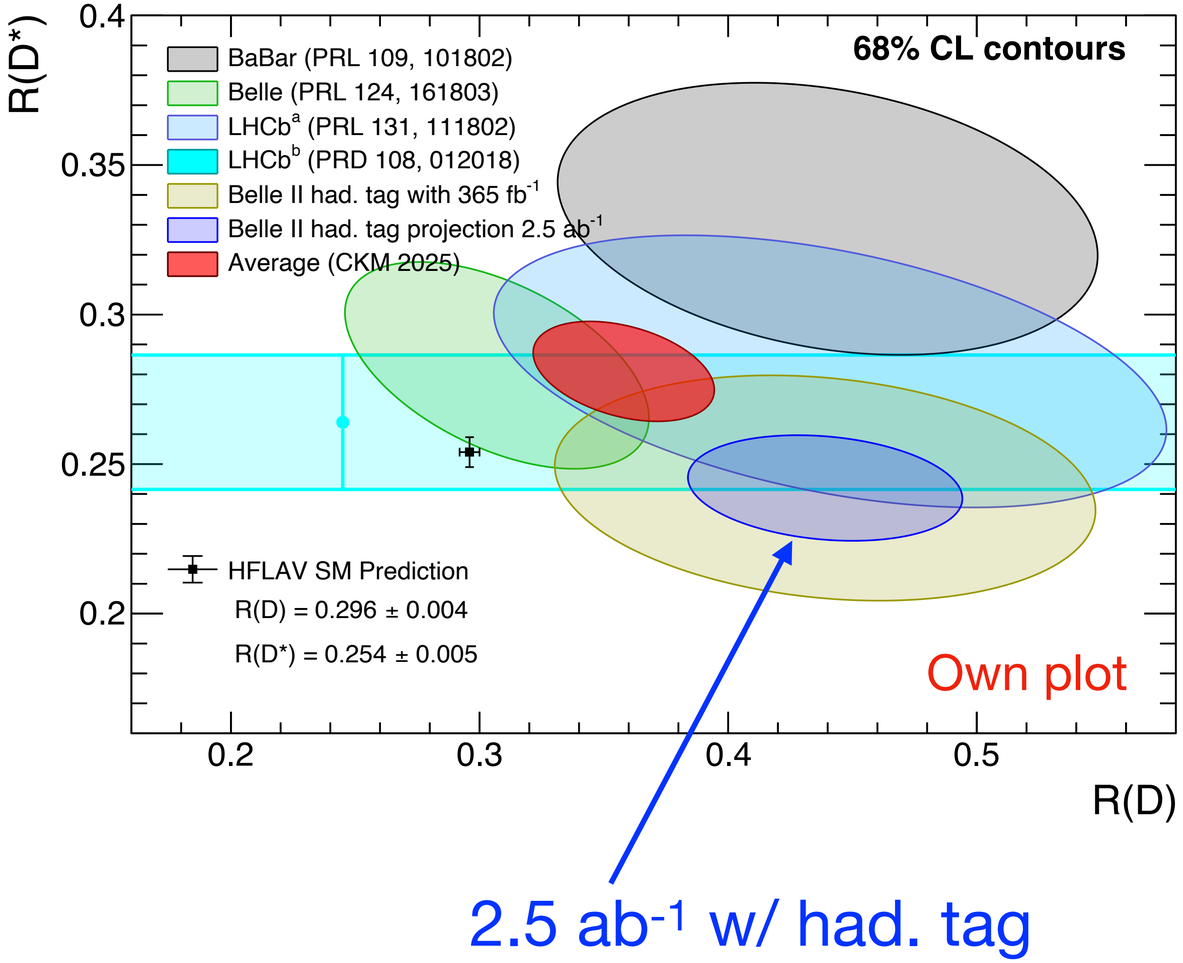
$$\mathcal{B}(B^0 \to D^{*-}\eta\pi^+) = (2.78 \pm 0.24 \pm 0.19) \times 10^{-4}$$

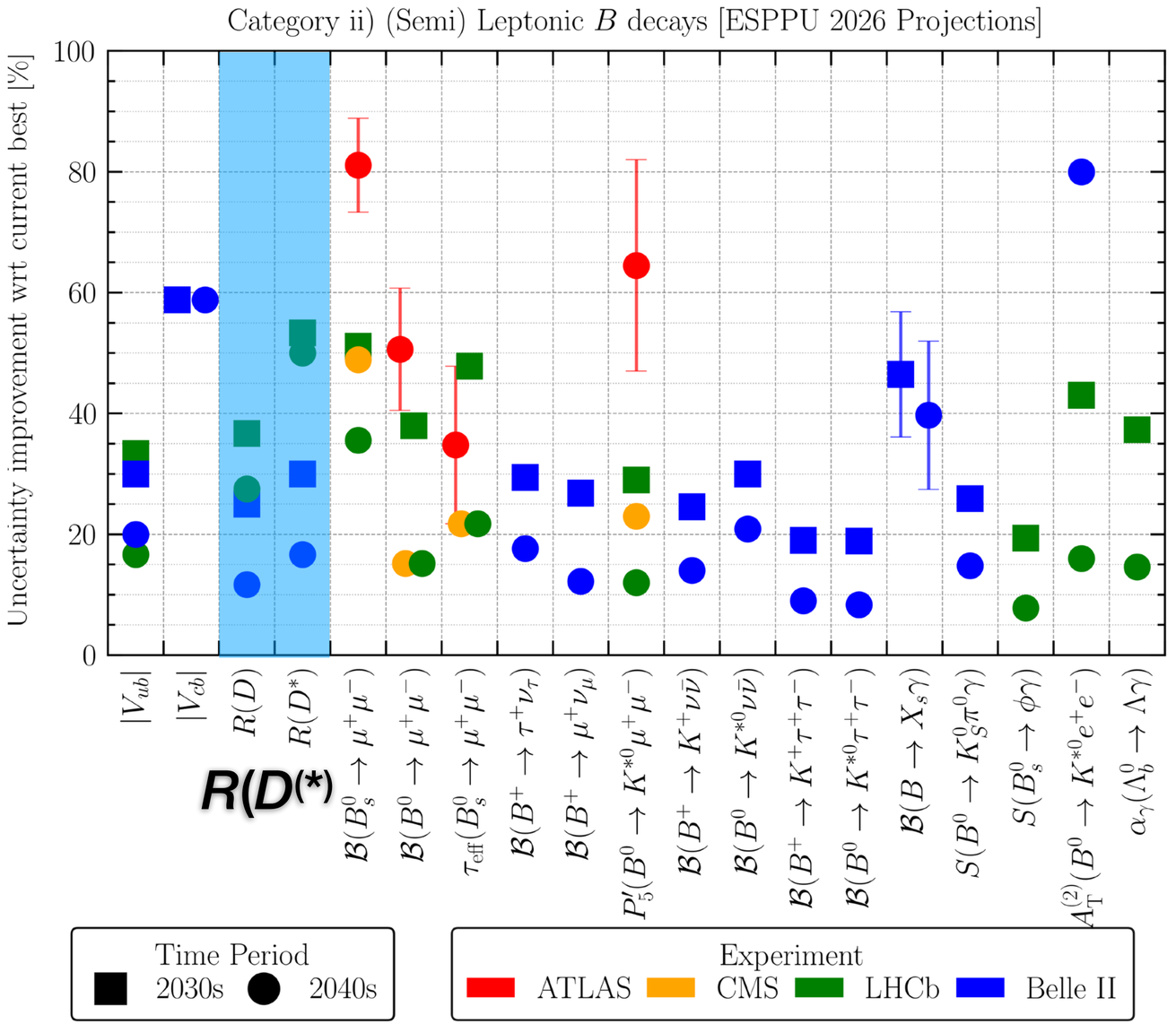
$$\mathcal{B}(B^+ \to \bar{D}^0\eta\pi^+) = (5.70 \pm 0.26 \pm 0.44) \times 10^{-4}$$

Unlikely $B \to D^{(*)}\eta\ell\nu$ modes are responsible for gap

Expected sensitivity of LFU test at Belle II

Own plot generated based on HFLAV and Belle II projections





Summary and prospects

- Belle II proceed two measurement of inclusive $|V_{ub}|$

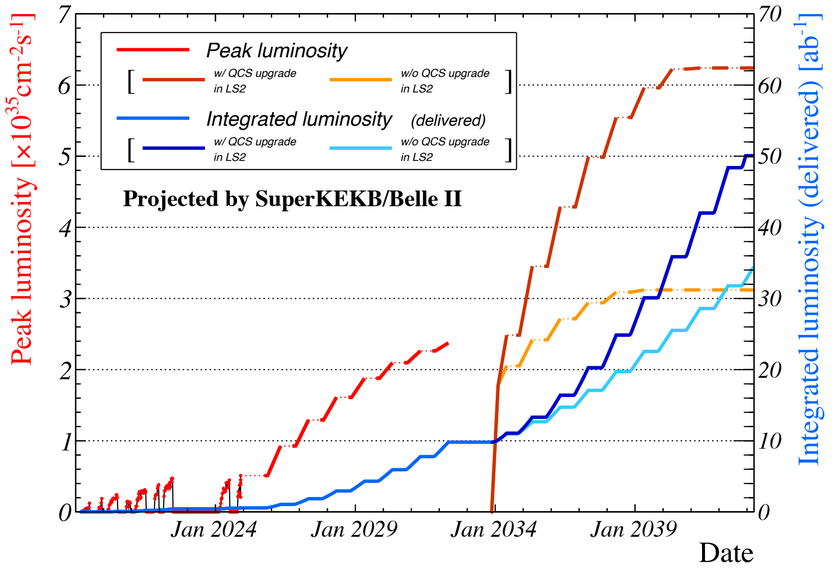
$$B \to X_u \ell \nu: \quad |V_{ub}| = (4.01 \pm 0.11 \pm 0.16^{+0.07}_{-0.08}) \times 10^{-3}$$

$$B \to \mu\nu: \quad |V_{ub}| = \left(3.90^{+0.77}_{-0.96}\,(\text{stat.})^{+0.43}_{-0.49}\,(\text{sys.}) \pm 0.03\,(\text{theo.})\right) \times 10^{-3}$$

- $R(D^{(*)})$ shows 3.8σ deviation between experimental average value and standard model prediction
  - Hint of Lepton Flavor Universality Violation
- Belle II performed new tests of LFU
  - 365 fb^{-1} data
    - 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 !!!
- Measurement of $B \to D^{(*)}\eta\pi$ at Belle and Belle II
  - Unlikely $B \to D^{(*)}\eta\ell\nu$ modes are responsible for gap

$$\mathcal{B}(B^0 \to D^{*-}\eta\pi^+) = (2.78 \pm 0.24 \pm 0.19) \times 10^{-4} \quad \mathcal{B}(B^+ \to \bar{D}^0\eta\pi^+) = (5.70 \pm 0.26 \pm 0.44) \times 10^{-4}$$

Backup

Semi-leptonic *B* decays