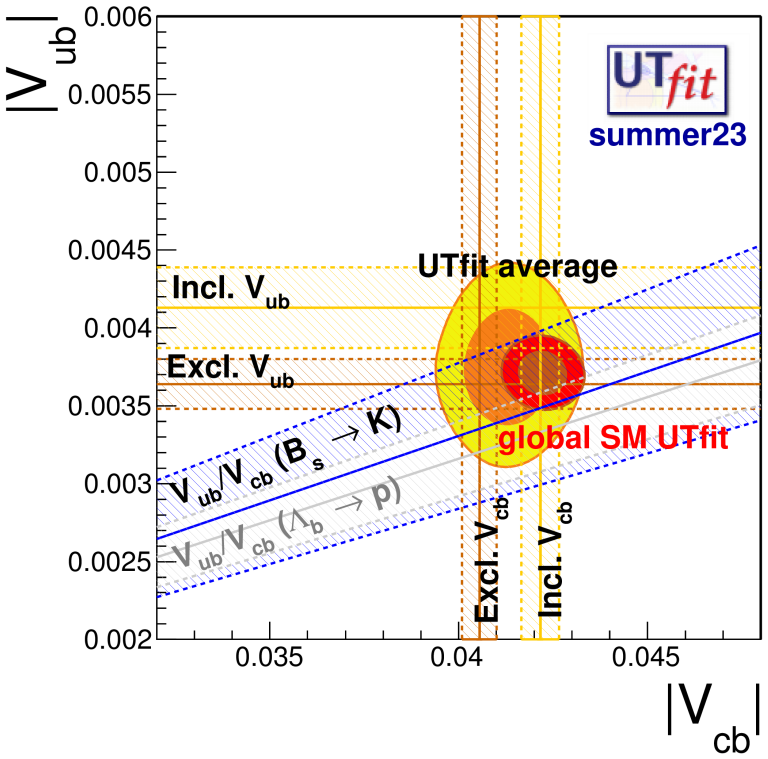
Semileptonic B-decays at Belle and Belle II

22^{nd} Lomonosov Conference on Elementary Particle Physics

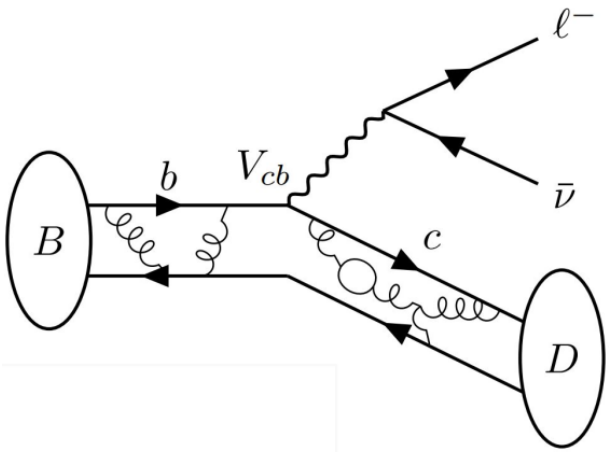
Nikolai Peters on behalf of the Belle II collaboration
Higher School of Economics
npeters@hse.ru

Motivation



$$\left|V_{qb}\right| = \sqrt{\frac{\mathcal{B}\left(B \to X_q \ell \nu_\ell\right)}{\tau_B \, \Gamma\left(B \to X_q \ell \nu_\ell\right)}}$$

Precise measurements important to constrain **CKM Unitarity**



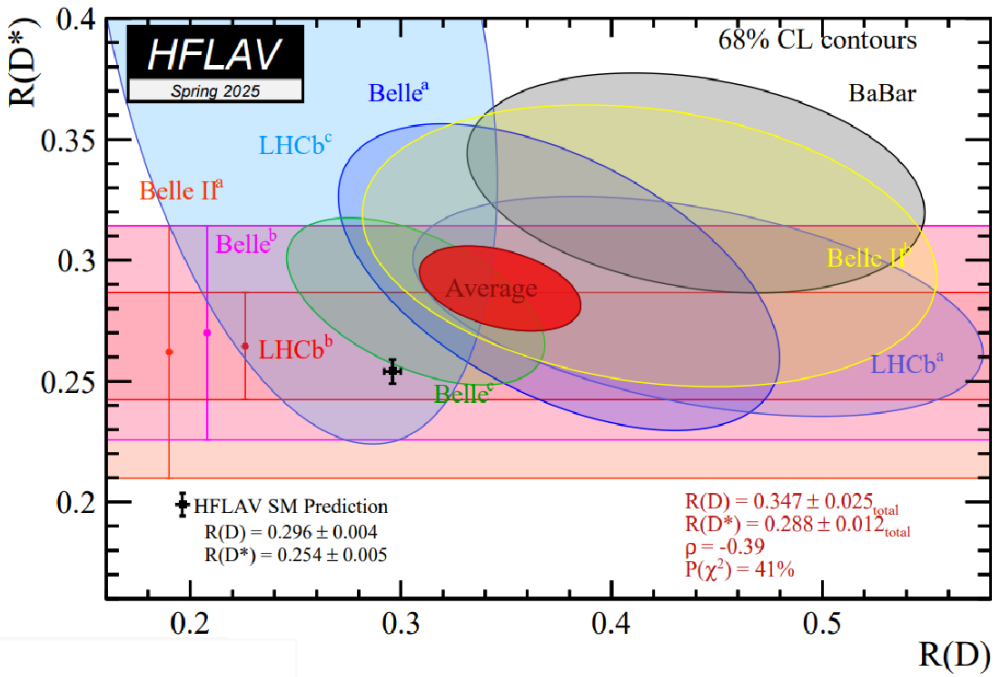
Direct information on V_{cb} and V_{ub} can be extracted from **semileptonic decay rate** exclusively or inclusively

Experimentally measured branching fraction

Predicted partial rate sans CKM factors (with V_{qb} set to 1)

Tension between inclusive and exclusive V_{qb} measurements $2-3\sigma$

Motivation



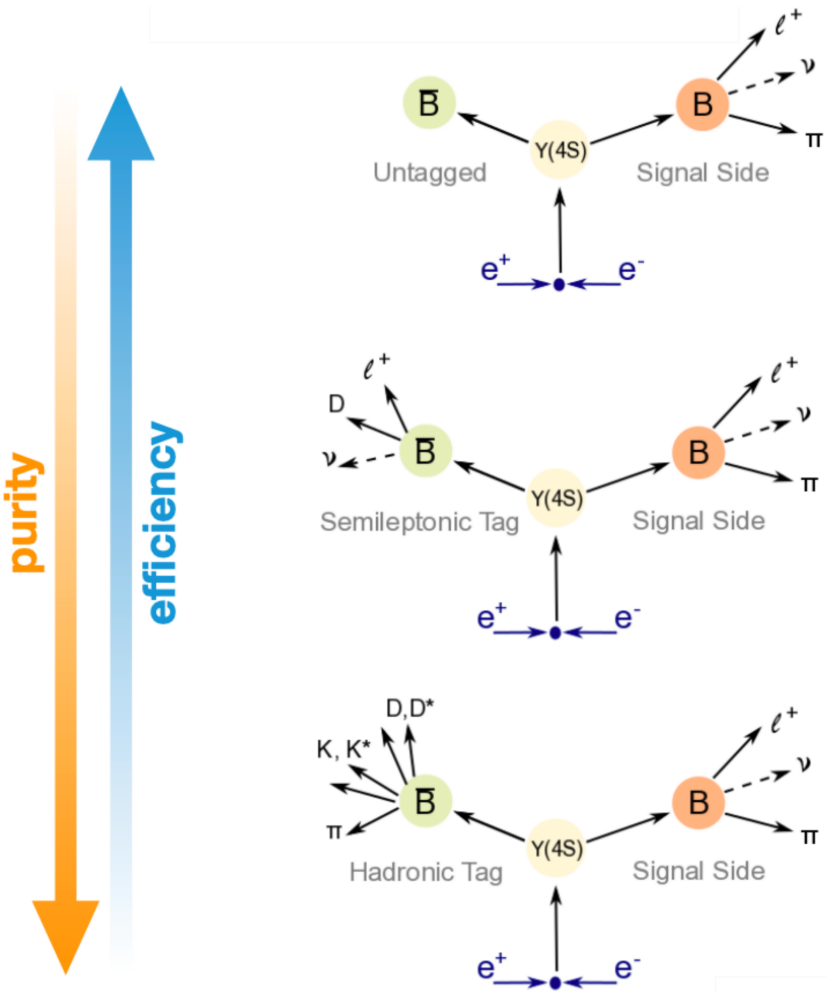
- In the Standard Model (SM), the W-boson couples equally to τ, μ, e Lepton-Flavor Universality (LFU)
- Semileptonic B decays are sensitive to new physics beyond SM
- Ratio measurements provide stringent LFU tests: branching fractions, angular asymmetry

- Measurement of ratio leads to partial cancellation of theoretical and experimental uncertainties

$$R(X_{\tau/\ell}) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)};\ \ell = e, \mu$$

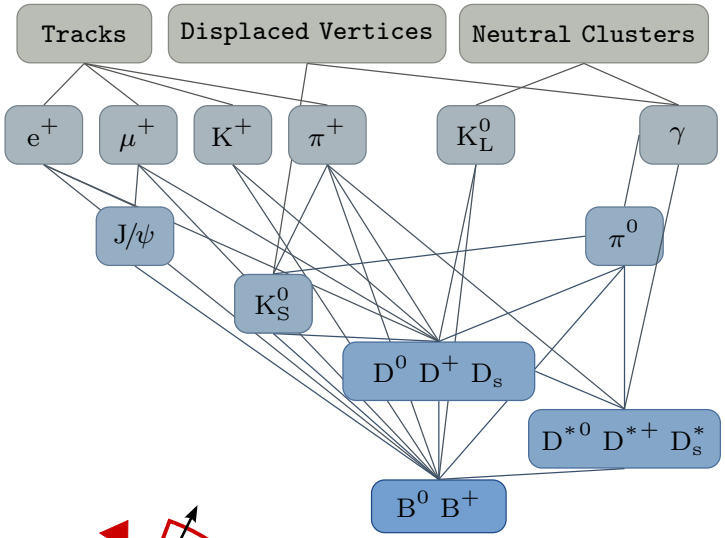
Tension of $R(D^{(*)}_{\tau/\ell})$ with SM $\sim 3.1\sigma$

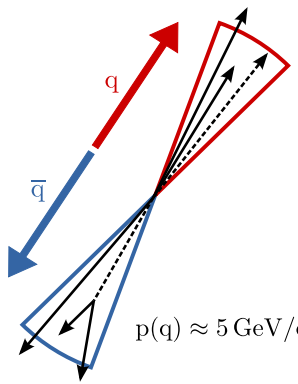
Kinematics at *B*-factories



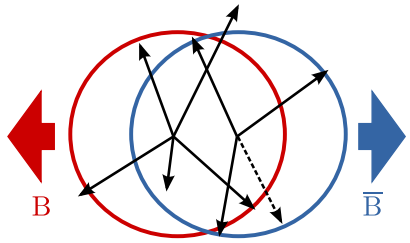
Strategy for event tagging

Schematic Overview of
Full Event Interpretation





$e^+e^- \to q\overline{q} \quad (q \in \{u, d, s, c\})$



$e^+e^- \to \Upsilon(4S) \to B\overline{B}$

Event topology in $\Upsilon(4S)$ frame

Test of lepton flavor universality with measurements of $R(D^{+})$ and $R(D^{*+})$ using semileptonic B tagging at the Belle II experiment

$$R(D^{(*)+}_{\tau/\ell}) = \frac{\mathcal{B}(B \to D^{(*)+}\tau\nu)}{\mathcal{B}(B \to D^{(*)+}\ell\nu)};\ \ell = e, \mu$$

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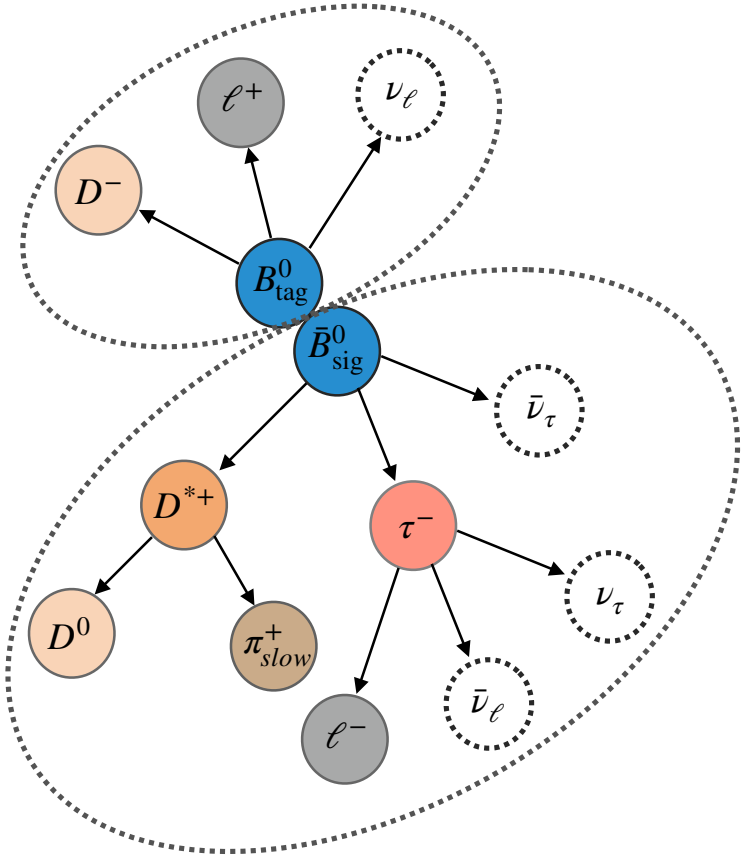
submitted to PRD

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

- First $R\left(D^{(*)}\right)$ Belle II measurement with **semileptonic B tagging**: $B^0_{\text{tag}} \to D^{(*)}\ell\nu_\ell$
- Neutral mode $\Upsilon(4S) \to B^0\bar{B}^0$ is studied
- Reconstruct B^0_{sig} candidates in $D^+\ell^-$ and $D^*\ell^-$ final states not associated with the B_{tag} candidate
- τ decays identification from $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$
- D mesons reconstructed in multiple hadronic decays on both sides: **tag** side 26 decay modes, **signal** – 13
- Require $\cos\theta^{\text{tag}}_{BY} \in [-1.75, 1.1]$ and $\cos\theta^{\text{sig}}_{BY} \in [-15, 1.1]$

Tag side

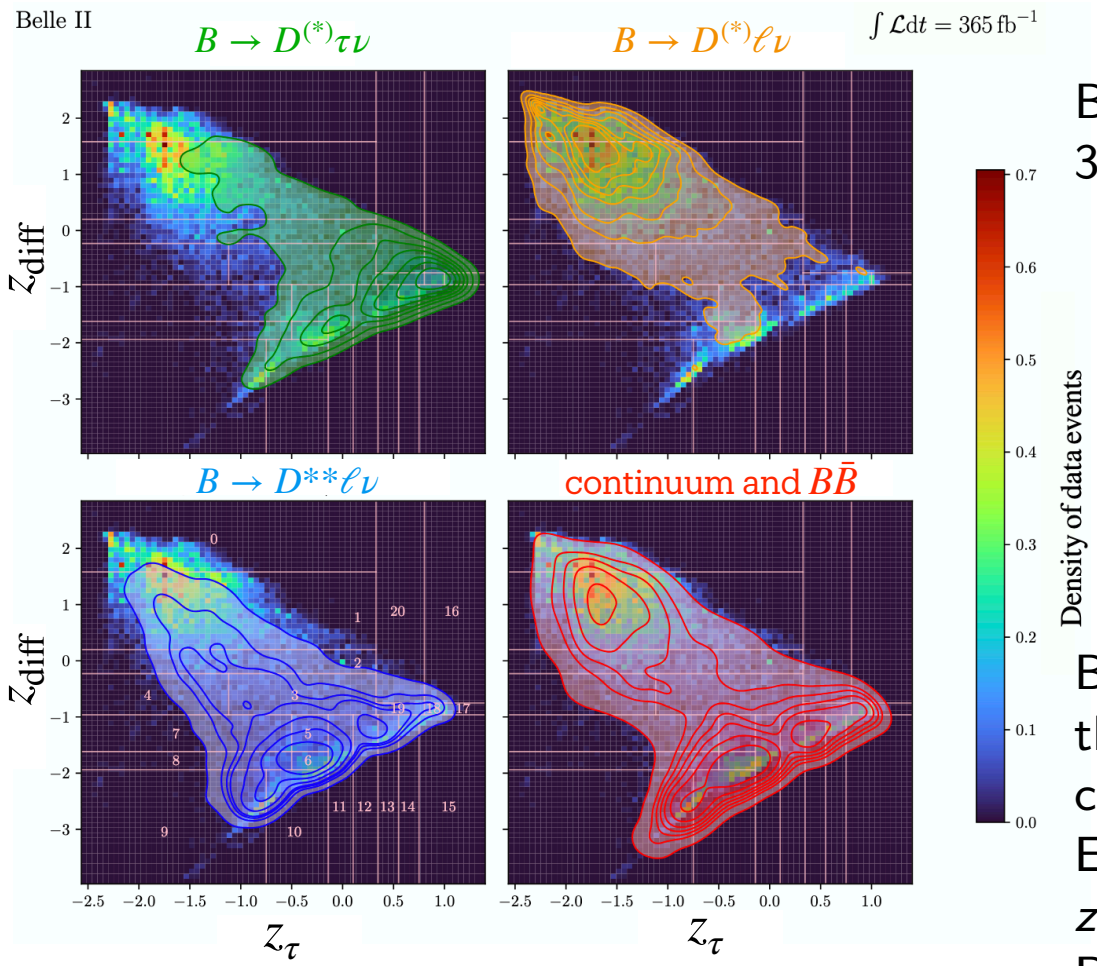


Signal side

$$\cos\theta_{BY} = \frac{2E_{\text{Beam}}\,E_Y - m_B^2 - m_Y^2}{2\,|\vec{p}_B|\,|\vec{p}_Y|},$$

$$Y = D^{(*)}\ell$$

$R(D^{(*)})$: analysis strategy



Densities of four fit categories in $(z_{\mathrm{diff}}, z_\tau)$ plane

BDT used to separate the events in 3 different types:

1. **Semitauonic** signal events: $B \to D^{(*)}\tau\nu$
2. **Semileptonic** events: $B \to D^{(*)}\ell\nu$ and $B \to D^{**}\ell\nu$
3. **Background** events: continuum and $B\bar{B}$

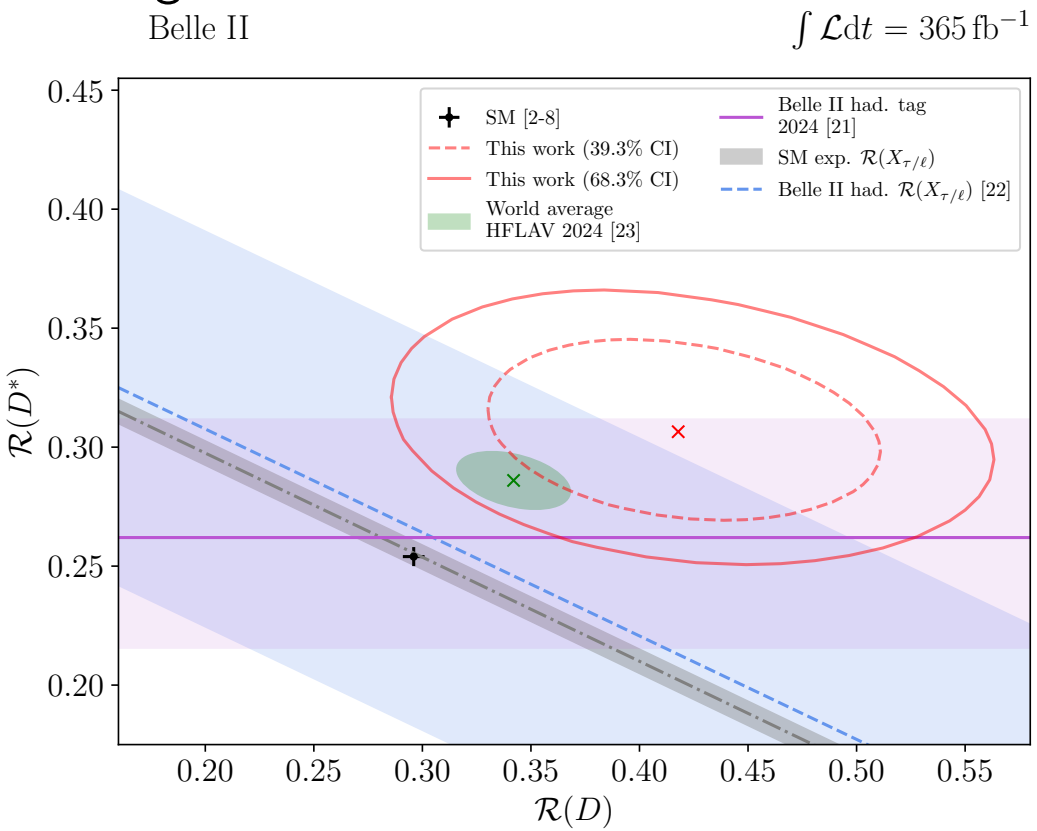
BDT trained on five input variables: the most discriminating variables are $\cos\theta_{BY}$ and E_{ECL}^{extra}

Each event is assigned a BDT score: $z_\tau, z_\ell, z_{\mathrm{bkg}}$

Define $z_{\mathrm{diff}} = z_\ell - z_{\mathrm{bkg}}$

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

- Extract signal and normalisation yields using a **2D binned likelihood fit** of z_τ and z_{diff}
- The fit is performed over 4 separate channels: $D^+e^-, D^+\mu^-, D^{*+}e^-, D^{*+}\mu^-$
- 10 fit parameters: 2 for the signal, 2 for the normalisation and 6 for the background



$$R\left(D^{*+}_{\tau/\ell}\right) = 0.306 \pm 0.034_{\text{stat}} \pm 0.018_{\text{syst}}$$
$$R\left(D^{+}_{\tau/\ell}\right) = 0.418 \pm 0.074_{\text{stat}} \pm 0.051_{\text{syst}}$$

Tension between the LFU-sensitive quantities $R\left(D_{\tau/\ell}\right) - R\left(D^*_{\tau/\ell}\right)$ and SM predictions **increases to 3.8σ**

$$R\left(D^{*+}_{e/\mu}\right) = 1.08 \pm 0.04_{\text{stat}} \pm 0.02_{\text{syst}}$$
$$R\left(D^{+}_{e/\mu}\right) = 1.07 \pm 0.05_{\text{stat}} \pm 0.02_{\text{syst}}$$

Consistent with the SM within $1.6\sigma - 1.2\sigma$

Measurement of the ratio of partial branching fraction of inclusive $\bar{B} \to X_u \ell \bar{\nu}$ to $\bar{B} \to X_c \ell \bar{\nu}$ and the ratio of their spectra with hadronic tagging

$|V_{ub}|/|V_{cb}|$: reconstruction

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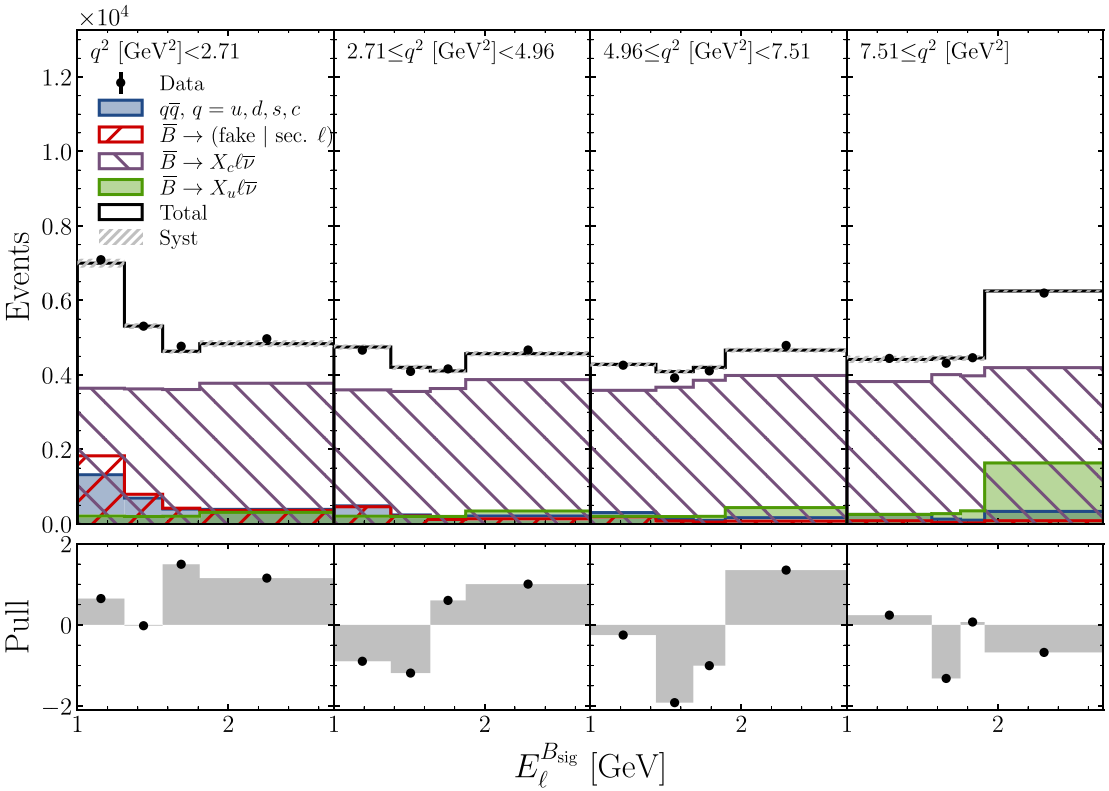


Dataset and Tagging:

711 fb^{-1} Belle data (772 $\times$ 10^6 $B\bar{B}$ pairs) with improved Belle II hadronic tagging algorithm

- K^+ and K_S reconstruction for tagging $\boldsymbol{b \to c}$ decay
  - $\boldsymbol{N(K) > 0}$ signal depleted sample for $\boldsymbol{X_c \ell \nu}$ decays
  - $\boldsymbol{N(K) = 0}$ signal enhanced sample to extract signal yields
- Inclusive D^* reconstruction for $\boldsymbol{b \to c}$ veto via **soft pion** and **high** $\boldsymbol{M^2_{miss}}$

1D fit to E_ℓ in $\boldsymbol{u}$-depleted sample to get $\boldsymbol{N^{X_c \ell \nu}}$

2D fit to $E_\ell \times q^2$ in $\boldsymbol{u}$-enhanced sample to get $\boldsymbol{N^{X_u \ell \nu}}$

$|V_{ub}|/|V_{cb}|$: results

Unfolding $B \to X_u \ell \nu$ and $B \to X_c \ell \nu$ yields in ratio with corrected efficiencies

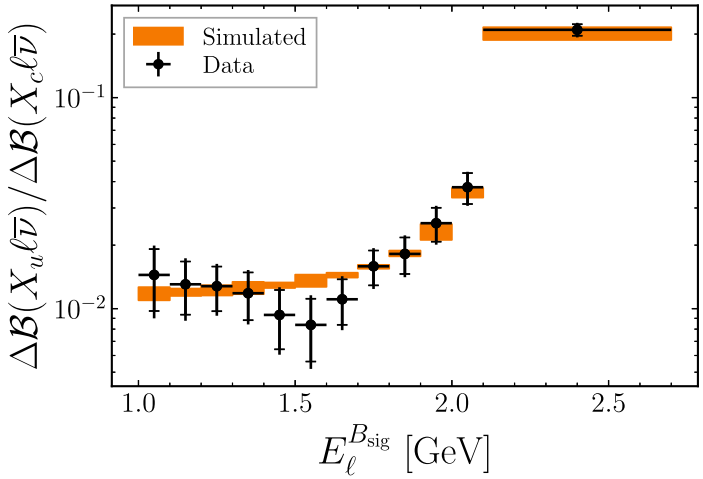
$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell \nu)\,\Delta\Gamma(B \to X_c \ell \nu)}{\Delta\mathcal{B}(B \to X_c \ell \nu)\,\Delta\Gamma(B \to X_u \ell \nu)}}$$

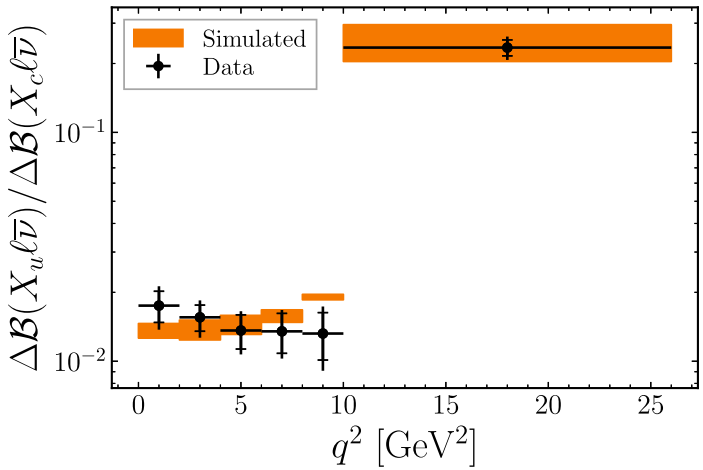
Theory decay rates:

$$\Delta\Gamma^{\mathrm{GGOU}}(B \to X_u \ell \nu) = 58.5^{+2.7}_{-2.3}\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma^{\mathrm{BLNP}}(B \to X_u \ell \nu) = 61.5^{+6.4}_{-5.1}\,\mathrm{ps}^{-1}$$

$$\Delta\Gamma^{\mathrm{Kin}}(B \to X_c \ell \nu) = 29.7 \pm 1.2\,\mathrm{ps}^{-1}$$





Branching fraction for BLNP and GGOU:

$$\frac{|V_{ub}|}{|V_{cb}|} = \left(9.81 \pm 0.42_{\mathrm{stat.}} \pm 0.38_{\mathrm{syst.}} \pm 0.51_{\Delta\Gamma(B\to X_u\ell\nu)} \pm 0.20_{\Delta\Gamma(B\to X_c\ell\nu)}\right) \times 10^{-2}$$

$$\frac{|V_{ub}|}{|V_{cb}|} = \left(10.06 \pm 0.43_{\mathrm{stat.}} \pm 0.39_{\mathrm{syst.}} \pm 0.23_{\Delta\Gamma(B\to X_u\ell\nu)} \pm 0.20_{\Delta\Gamma(B\to X_c\ell\nu)}\right) \times 10^{-2}$$

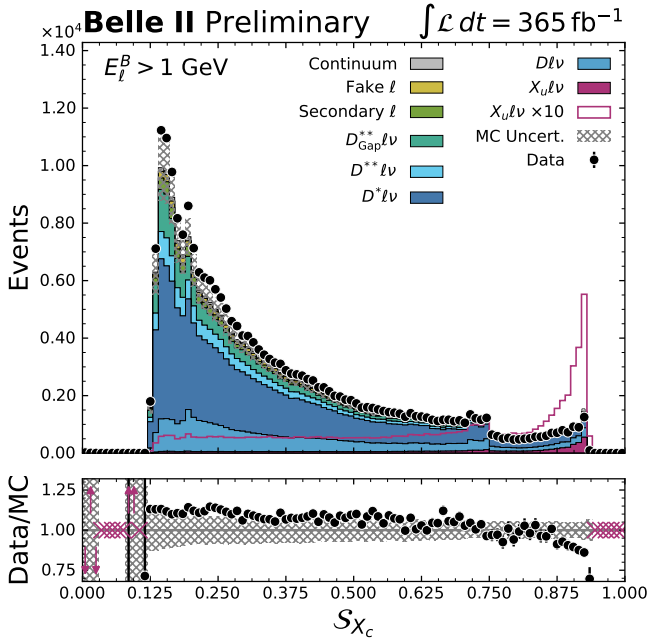
Measurement of inclusive $B \to X_u \ell \nu$ partial branching fractions and $|V_{ub}|$ at Belle II

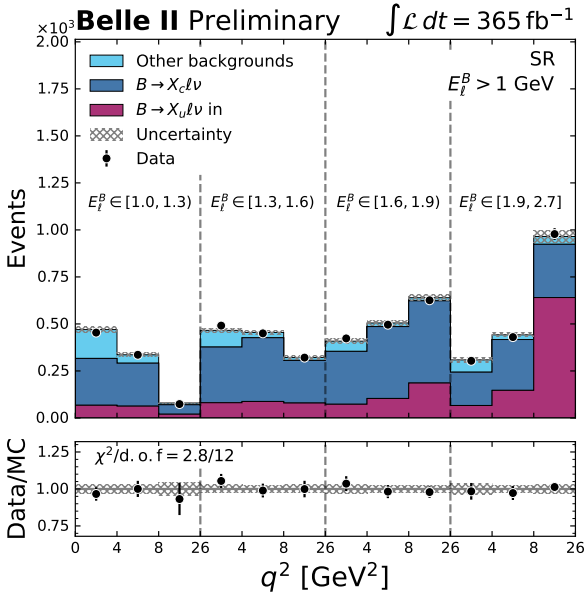
V_{ub}: reconstruction

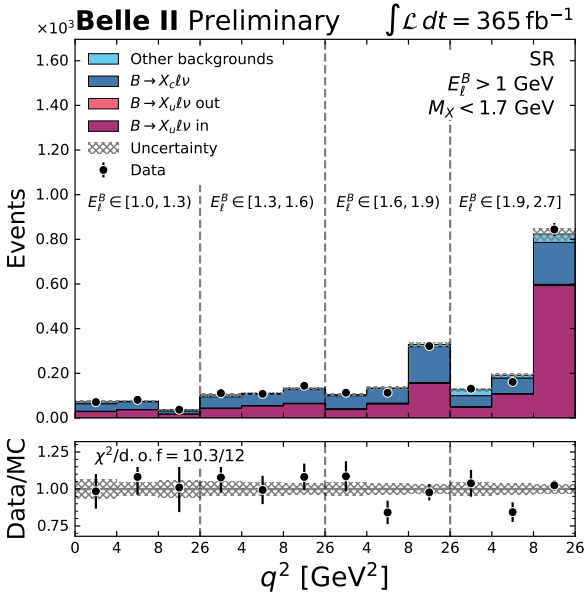
- Hadronic tagging + reconstructed e or μ
- Neutrino characterised as missing energy
- Hadronic system X characterised from rest-of-event

Background suppression

- **Continuum** suppression via a NN using Event Geometry variables
- $\boldsymbol{X_c\ell\nu}$ suppression via a NN using the worse reconstruction of $B \to X_c\ell\nu$ decays and low momentum π properties to reject $B \to D^*\ell\nu$ decays + kaon veto







Analysis based on available kinematic constants:
3 main kinematical variables to suppress $X_c\ell\nu$:

1. $E_\ell(B)$ - lepton energy (in B_{sig} rest-frame)
2. M_X - mass of hadronic system
3. q^2 - lepton neutrino system 4-momentum squared

Binned template fit with 3 components: $\boldsymbol{X_u\ell\nu}$, $\boldsymbol{X_c\ell\nu}$ – main background, others backgrounds – **fake/secondary leptons + continuum**

Simultaneous Fit with the control sample, to correct the shape of the $X_c\ell\nu$ background

V_{ub}: results

Phase Space	Fit Variables
$E_\ell^B > 1\ GeV$	$E_\ell^B : q^2$
$E_\ell^B > 1\ GeV$ $M_X < 1.7\ GeV$	$E_\ell^B : q^2$
$E_\ell^B > 1\ GeV$ $M_X < 1.7\ GeV$ $q^2 > 8\ GeV^2$	E_ℓ^B

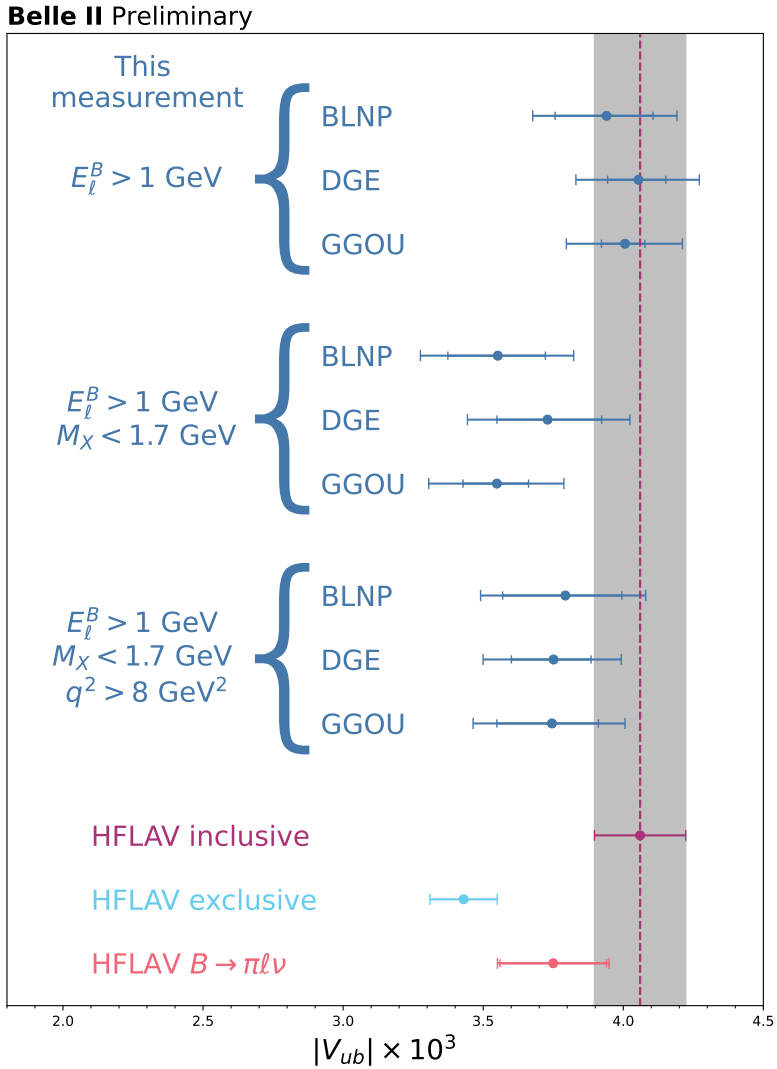
3 different fits in the 3 different phase spaces to extract the signal strength

For **broadest phase-space** region with **most reliable theoretical prediction**:

$$\Delta\mathcal{B}\,(B \to X_u \ell \nu) = (1.54 \pm 0.08 \pm 0.12) \times 10^{-3}$$

The obtained value of $|V_{ub}|$ using a partial decay rate predicted by the GGOU framework is

$$|V_{ub}| = \left(4.01 \pm 0.11 \pm 0.16^{+0.09}_{-0.07}\right) \times 10^{-3}$$



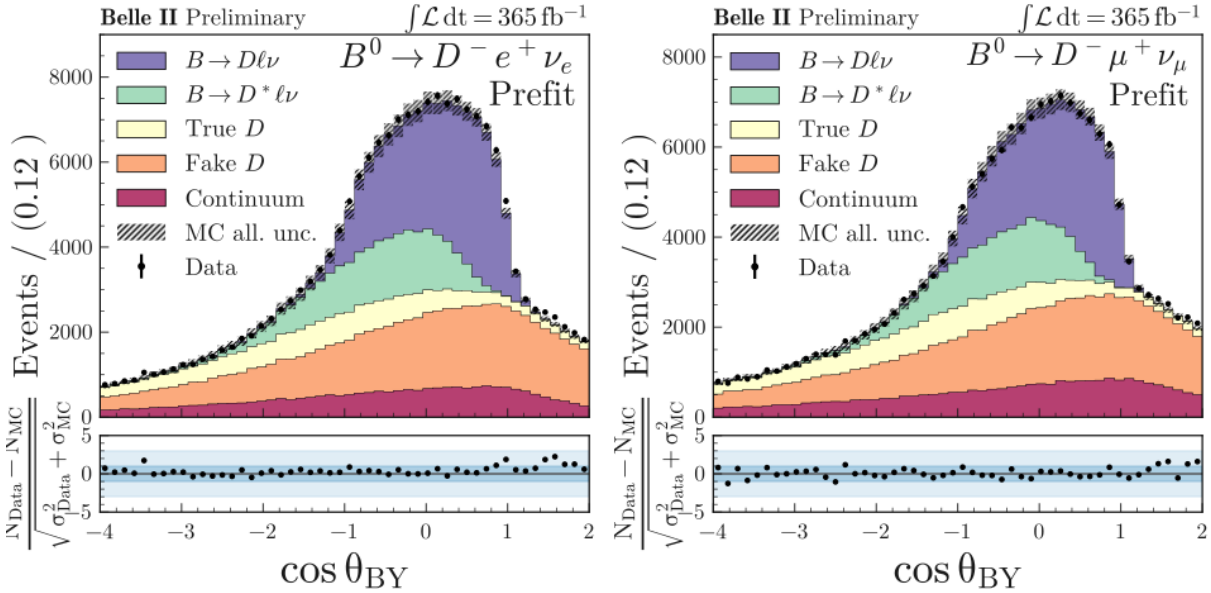
Measurement is **competitive** with other measurements

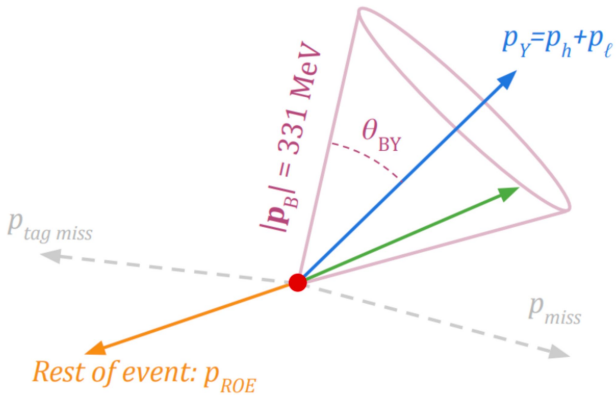
Determination of $|V_{cb}|$ using $B \to D\ell\nu_\ell$ Decays at Belle II

V_{cb}: reconstruction

arXiv.2506.15256
submitted to PRD

- Candidate $B \to D\ell\nu$ formed from $\ell(e, \mu)$ and D ($\to K\pi, \to K\pi\pi$)
- Reduce experimental uncertainties due to isospin symmetry and separate analysis of B^0 and B^+ decays
- Inclusive reconstruction of neutrino momentum





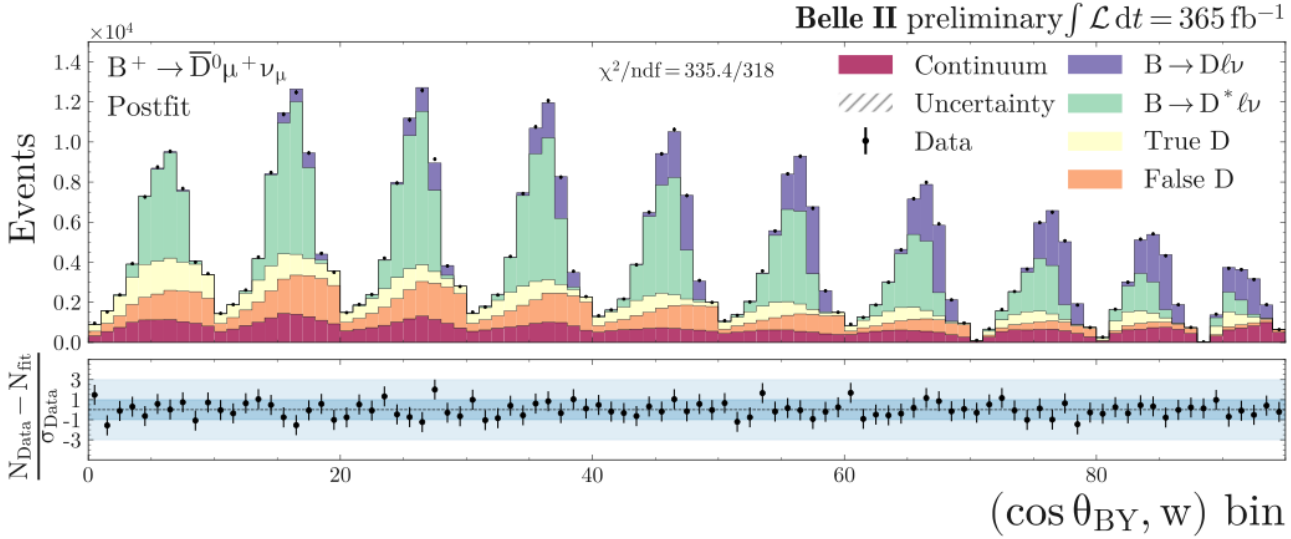
Analysis based on available kinematic constants:

$$\cos\theta_{BY} = \frac{2E_{\text{Beam}}\,E_Y - m_B^2 - m_Y^2}{2\,|\vec{p}_B|\,|\vec{p}_Y|}$$

$$w = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}$$

Backgrounds: $B \to D^*\ell\nu$; continuum events $e^+e^- \to q\bar{q}$, $(q = u, d, s, c)$

V_{cb}: results

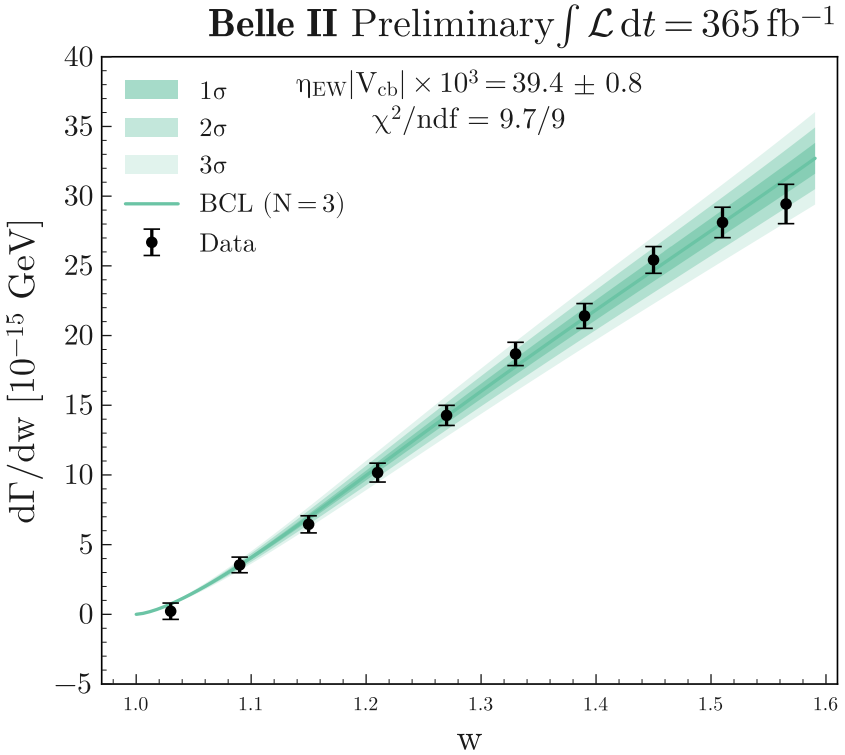


Branching fractions of each mode measured with **fit on $\cos\theta_{BY}$ in bins of w**

- $\mathcal{B}\left(B^0 \to D^- \ell^+ \nu_\ell\right) =$ $(2.06 \pm 0.05(\text{stat.}) \pm 0.10(\text{sys.}))\%$
- $\mathcal{B}\left(B^+ \to \bar{D}^0 \ell^+ \nu_\ell\right) =$ $(2.31 \pm 0.04(\text{stat.}) \pm 0.09(\text{sys.}))\%$

Fit differential decay rates using Bourrely-Caprini-Lellouch (BCL) form factor parameterization: $|\boldsymbol{V_{cb}}|_{\boldsymbol{BCL}} =$ $\boldsymbol{(39.2 \pm 0.4_{stat.} \pm 0.6_{sys.} \pm 0.5_{th.}) \times 10^{-3}}$

Most precise measurement with $B \to D\ell\nu_\ell$ data



Conclusion

- Study of semileptonic decays is an important way to constraint and check SM parameters
- Many semileptonic B decay results from Belle (II)
  - $R(D^{(*)})$ LFU tests consistent with SM
  - Long-standing $|V_{xb}|$ puzzle still remains
- Urge for futher analysis
- Belle II starts new data taking in November 2025

Additional slides

V_{cb}: charged mode reconstruction