Semileptonic and leptonic B decays at Belle II

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(on behalf of Belle II collaboration)

17 - 23 Aug 2025

Outline

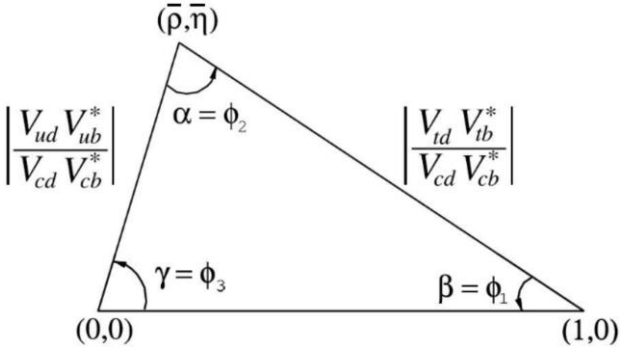
- Leptonic and Semileptonic decays prospects
- Belle II experiment
- Measurements: A general overview
- Interesting results from Belle II
- Summary

SM precision measurements

(Recipe for this talk)

Cabibbo-**K**obayashi-**M**askawa (CKM) matrix describes quark mixing and weak decays of quarks

- Precise measurement of parameters CP violation
  - ➤ test of SM

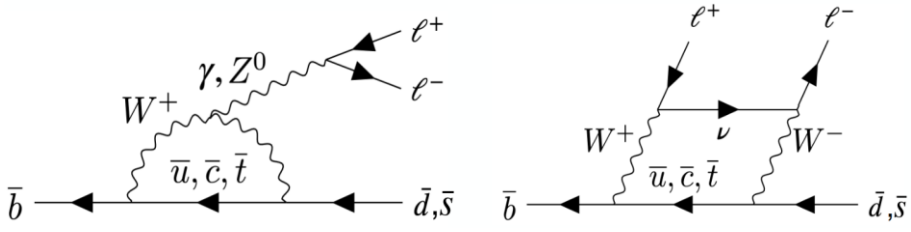


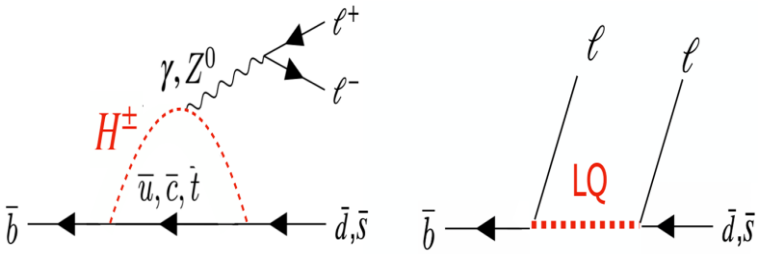
From semi-leptonic decays

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Electroweak penguins and Lepton Flavour Universality tests

See talk by R. Volpe (Belle II)



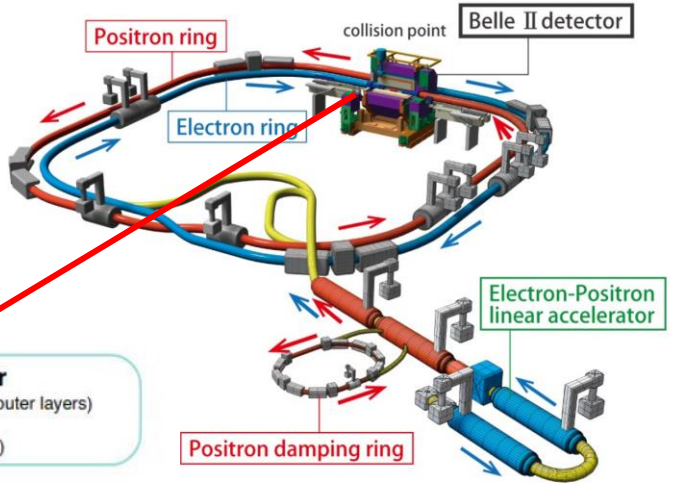


Belle II & SuperKEKB

2^{nd} generation B factory @ High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

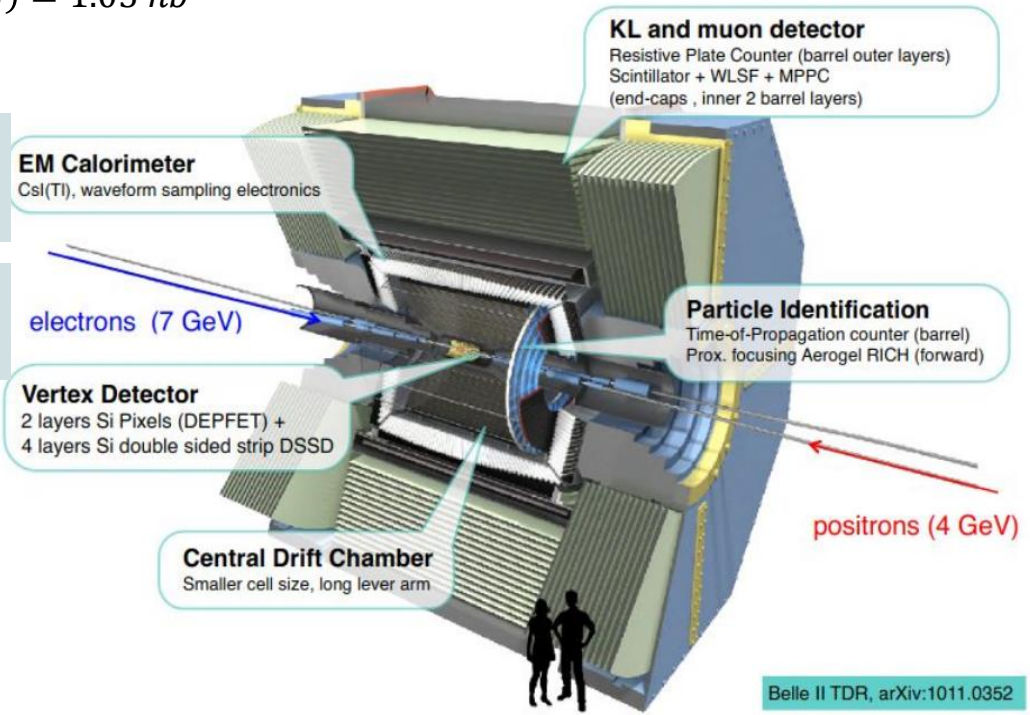
- Asymmetric collider: 7 GeV e^- and 4 GeV e^+ at $\sqrt{s}$ = 10.58 GeV (@Υ(4S) energies)

$$\sigma(e^+e^- \rightarrow \Upsilon(4S) = 1.05\, nb$$



Target
$\mathscr{L}$ = 6 x 10^{35} cm^{-2} s^{-1}
$\int\mathscr{L}$ dt = 50 ab^{-1}

Achieved
$\mathscr{L}$ = 5.1 x 10^{34} cm^{-2} s^{-1}
$\int\mathscr{L}$ dt = 575.47 fb^{-1}

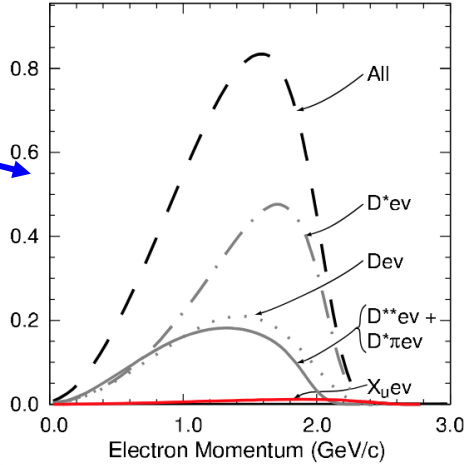


- **Luminosity-frontier**
- **Hermetic**
- Known initial conditions of e^+e^- and clean environment

Reconstruction techniques

- Leptonic or Semileptonic decays of B meson always involves a lepton and neutrino in final states
- **Advantage**: Lepton is a signal that is well defined
- **Disadvantage**: Neutrino not directly determined ➤ complicates reconstruction

High momentum lepton typically $p^*_l > 1$ GeV

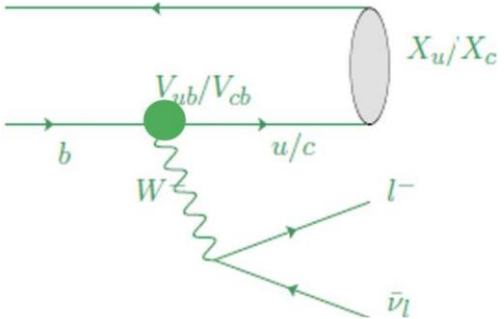


Hadron searches

- Involves two approaches (theoretically complementary)

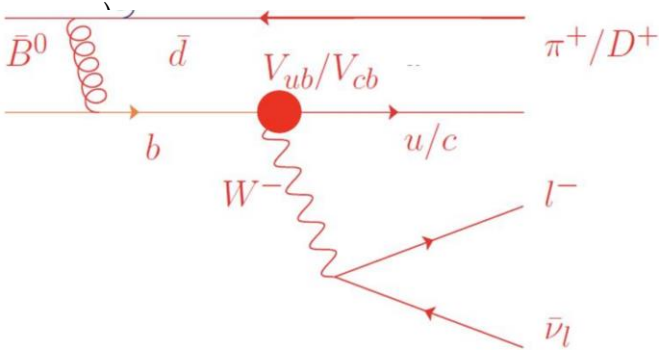
Inclusive searches

- $B \rightarrow X_{u,c}\, l\, \nu$
- Only the leptons are reconstructed



Exclusive searches

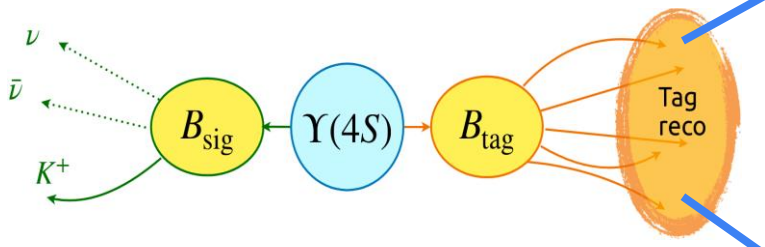
- Decay into exclusive final states ($B \rightarrow \pi l \nu$, $B \rightarrow D^* l\, \nu$)



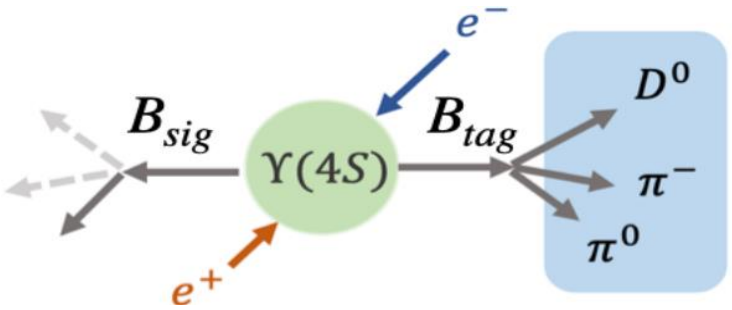
Neutrino reconstruction

- By exploiting the well known initial conditions of e^+e^- collision and reconstruction of companion B in the $B\bar{B}$ decays

Reconstructing B_{comp}

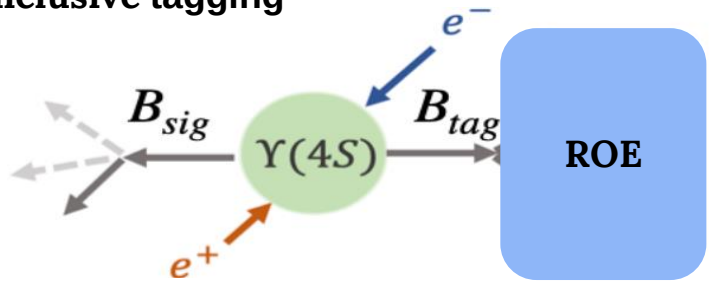


Hadronic tagging



Low efficiency, High purity and better kinematic constraint

Inclusive tagging

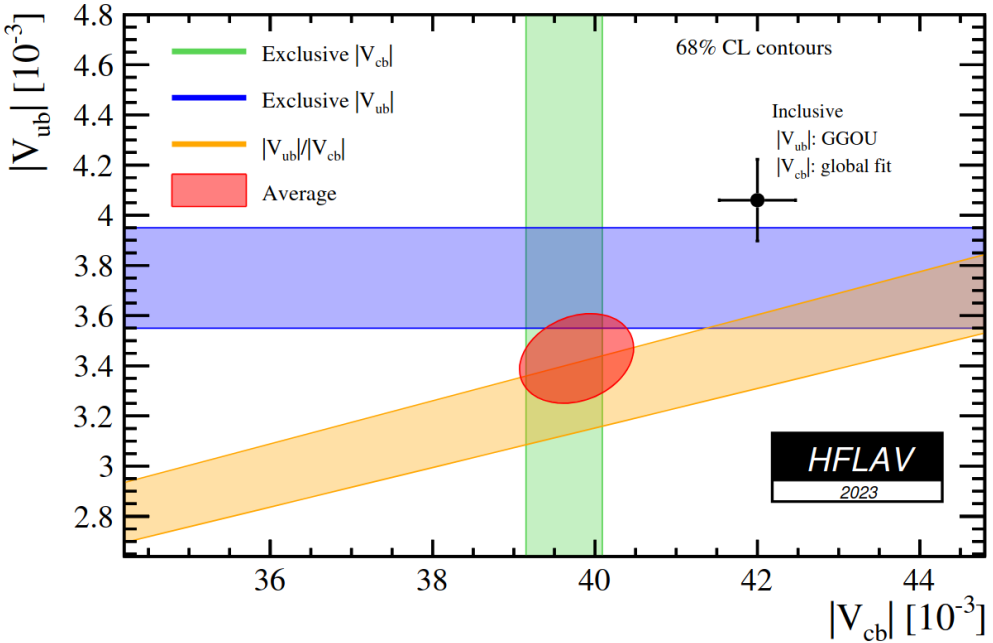


Full event Interpretation (FEI)

- B tagging using MVA
- Hierarchical approach to reconstruct about $\mathcal{O}(10^4)$ final states

Comput. Softw. Big Sci 3, 6 (2019)

Status of exclusive and inclusive measurements



$$|V_{ub}|_{\text{exc}} = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3},$$
$$|V_{ub}|_{\text{inc}} = (4.13 \pm 0.12^{+0.13}_{-0.14} \pm 0.18) \times 10^{-3},$$
$$|V_{ub}|_{\text{CKM}} = (3.64^{+0.07}_{-0.07}) \times 10^{-3},$$
$$|V_{cb}|_{\text{exc}} = (39.4 \pm 0.8) \times 10^{-3},$$
$$|V_{cb}|_{\text{inc}} = (42.2 \pm 0.8) \times 10^{-3},$$
$$|V_{cb}|_{\text{CKM}} = (41.1^{+0.7}_{-0.4}) \times 10^{-3},$$
$$|V_{ub}|/|V_{cb}|_{\text{exc}} = (9.4 \pm 0.5) \times 10^{-2},$$
$$|V_{ub}|/|V_{cb}|_{\text{inc}} = (9.8 \pm 0.6) \times 10^{-2},$$
$$|V_{ub}|/|V_{cb}|_{\text{LHCb}} = (8.4 \pm 0.7) \times 10^{-2}.$$

Phys. Rev. D107, 052008 (2023)

- $|V_{ub}|_{exe}$ and $|V_{ub}|_{inc}$ exhibits 1.4 σ tension
- $|V_{cb}|$ exhibits 2.5 σ tensions
- CKM global fits prefer $|V_{ub}|_{inc}$ and $|V_{cb}|_{exe}$
- Ratio are in good agreement for both
- Suppression of $b \to u$ transitions leads to large stat errors

LHCb results from Λ_b decays

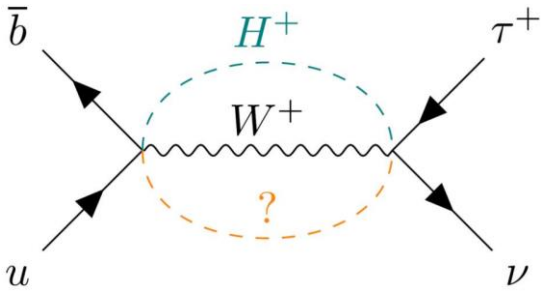
Nat. Phys. 11, 743 (2015)

Leptonic decays: Branching fraction of $B \to \tau\nu$ with Hadronic FEI

- Possible only for charged B
- Easy to deal with from the theoretical side
- Experimentally challenging due to $|V_{ub}|$ sensitivity
- Direct determination of $|V_{ub}|$ independent from exclusive and inclusive $B \to X_u\, l\, \nu$

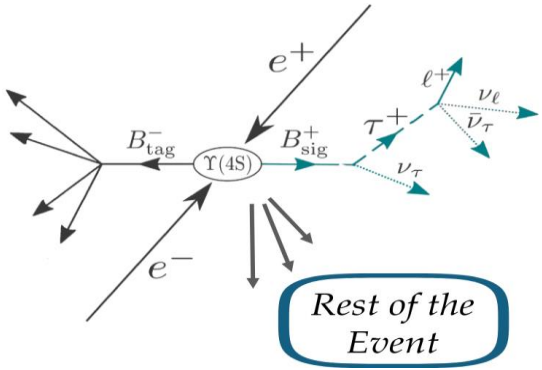
$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left[1 - \frac{m_\tau^2}{m_B^2}\right]^2 f_B^2 |V_{ub}|^2 \tau_B,$$

f_B: From LQCD or QCD sum rules



- Good probes for NP
- Sensitive to BSM from 2HDM or SUSY extension of SM
- Enhancement of suppression by a factor of 4 expected

Reconstruction



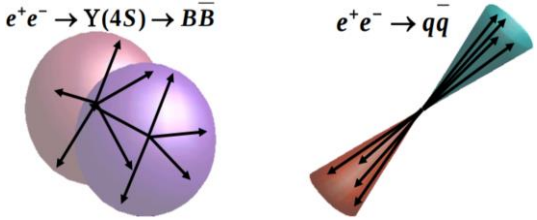
Tag side

- Reconstruct using FEI
- $\Delta E = E^*_{tag} - \sqrt{s}/2$
- $M^2_{BC} = \sqrt{S}/4 - p^2_B$

Signal

1. $\tau^+ \to \boldsymbol{e^+}\nu_e\bar{\nu}_\tau$
2. $\tau^+ \to \boldsymbol{\mu^+}\nu_\mu\bar{\nu}_\tau$
3. $\tau^+ \to \boldsymbol{\pi^+}\bar{\nu}_\tau$
4. $\tau^+ \to \rho^+\bar{\nu}_\tau$ with $\rho^+ \to \boldsymbol{\pi^+\pi^0}$

Continuum suppression

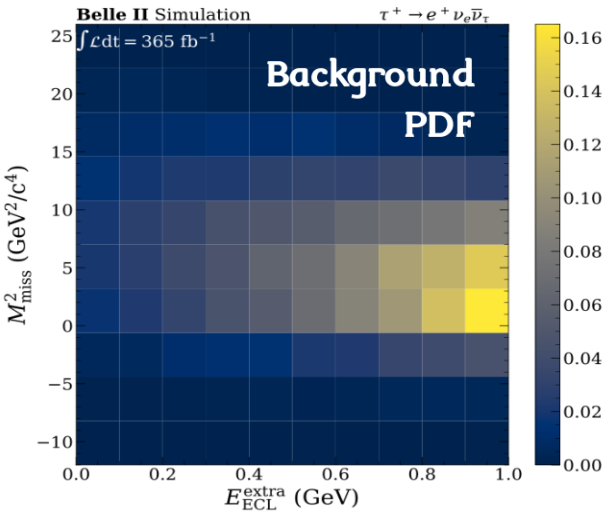


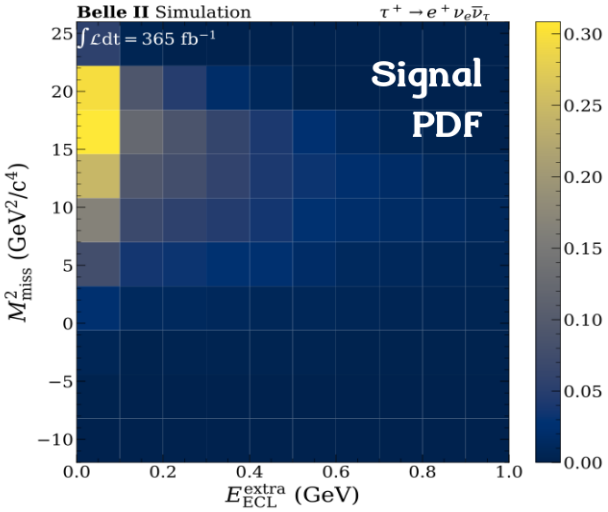
Event shape variables that describes the decay topologies, uncorrelated with fit variables used to train an BDT to suppress continuum events

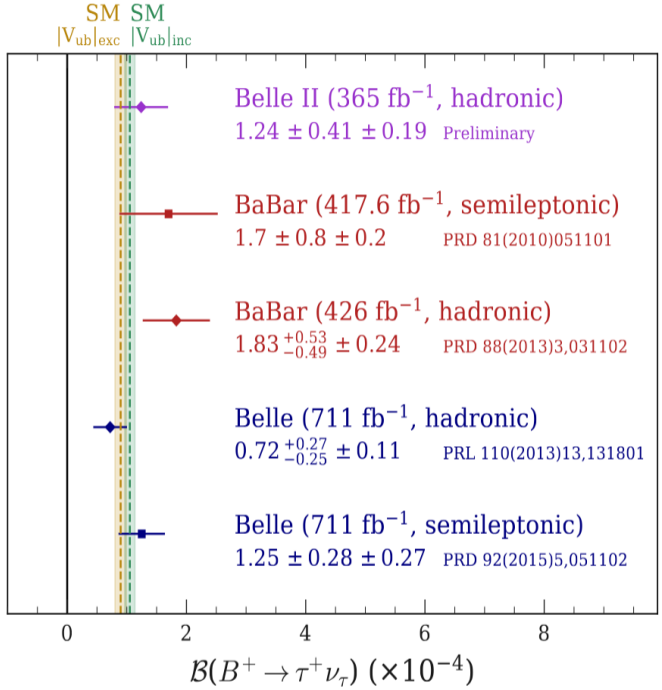
- ➔ Separate BDTs for leptonic and hadronic τ decays
- ➔ BDT output O_{cs}

Signal extraction

Binned likelihood fit based to $E(extra)_{ECL}$ and $M^2{}_{miss}$ using shapes from MC



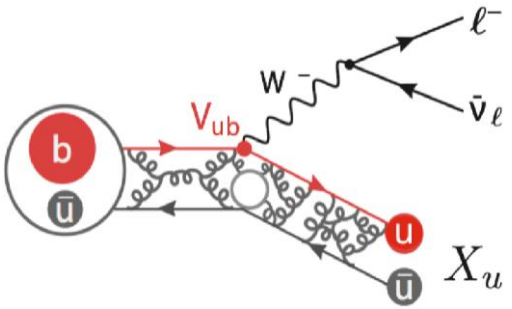




Submitted to PRD arXiv:2502.04885

Inclusive Charmless Semileptonic B decays : Improved determination of $|V_{ub}|$ from $B^0 \to X_u\, l\, \nu$

- Suppressed by a factor $|V_{ub}|^2/\,|V_{cb}|^2$ making their observation possible only in kinematic regions that are not polluted by the much more frequent $b \to c$ transition
- Requires cuts in phase-space regions, which renders OPE ineffective

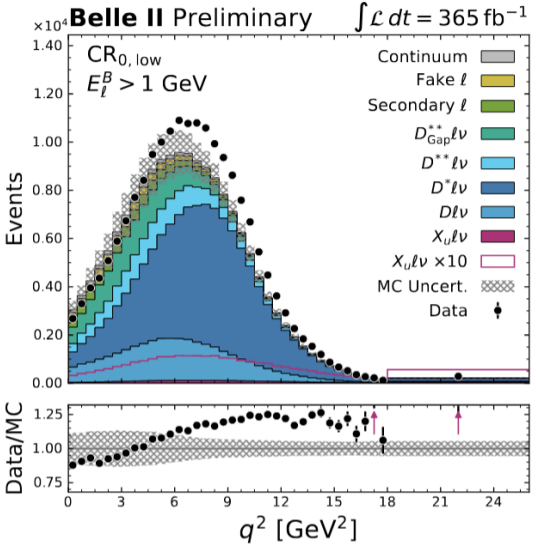


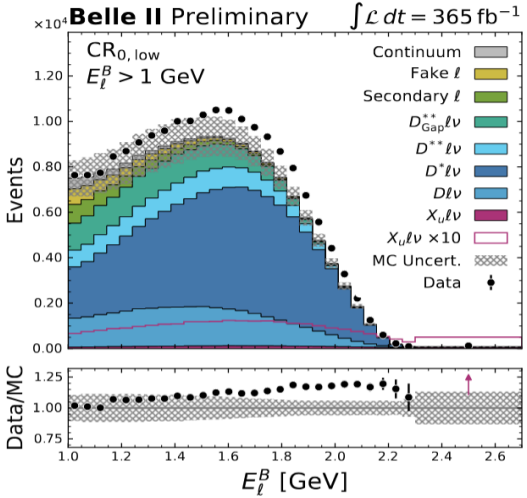
- $|V_{ub}|$from inclusive partial BF in various phase-space regions

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

$\Delta\Gamma$ from theoretical inputs

- BLNP PRD 72, 073006
- GGOU JHEP 10, 058 (2007)
- DGE JHEP 01, 097 (2006)





Background suppression

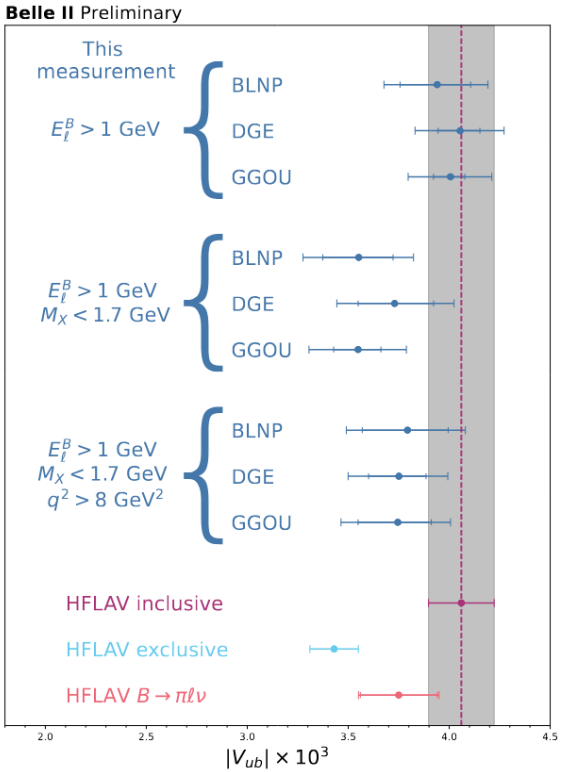
- MLP based classifiers to suppress $B^0 \rightarrow X_c\, l\, \nu$ **and** Continuum decays

Signal extraction

- Templated Binned likelihood fits

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

$|V_{ub}|$ extraction



In the broadest phase-space region where theoretical uncertainties are more reliable

$$\Delta\mathcal{B}(B \to X_u \ell\nu)_1 = (1.54 \pm 0.08 \pm 0.12) \times 10^{-3}$$

$$|V_{ub}| = (4.01 \pm 0.11 \pm 0.16^{+0.07}_{-0.08}) \times 10^{-3}$$

Exceeds the HFLAV exclusive average

Compatible with average of $B \rightarrow \pi l \nu$

Agreement with other measurements

Exclusive semileptonic: Measurement of $|V_{cb}|$ from $B \to D\, l\, \nu$

- Differential decay width can be expressed as a function of $w = v_B v_D$

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

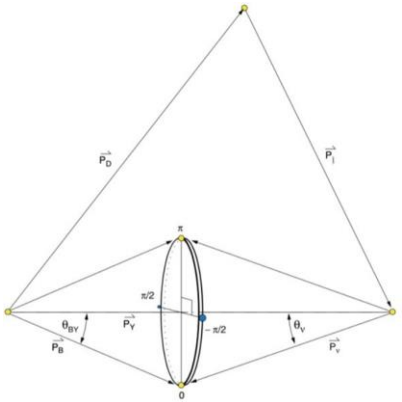
$$\frac{d\Gamma(B \to D\ell\nu_\ell)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 (w^2 - 1)^{3/2} \eta_{EW}^2 (1 + \delta_C^{+,0}) \mathcal{G}^2(w) |V_{cb}|^2 ,$$

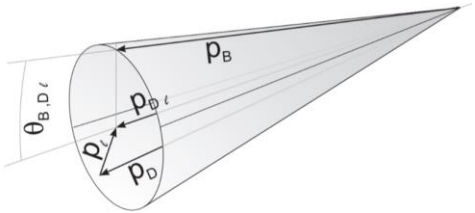
$$\eta_{EW} = 1.0066 \pm 0.0050$$

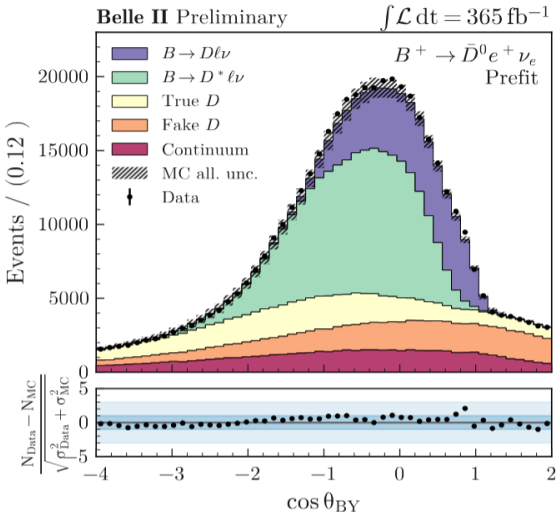
- Two parametrization of G(w) exist
  - BCL PRD 79, 013008 (2009)
  - CLN Nucl. Phys. B 530, 153 (1998)

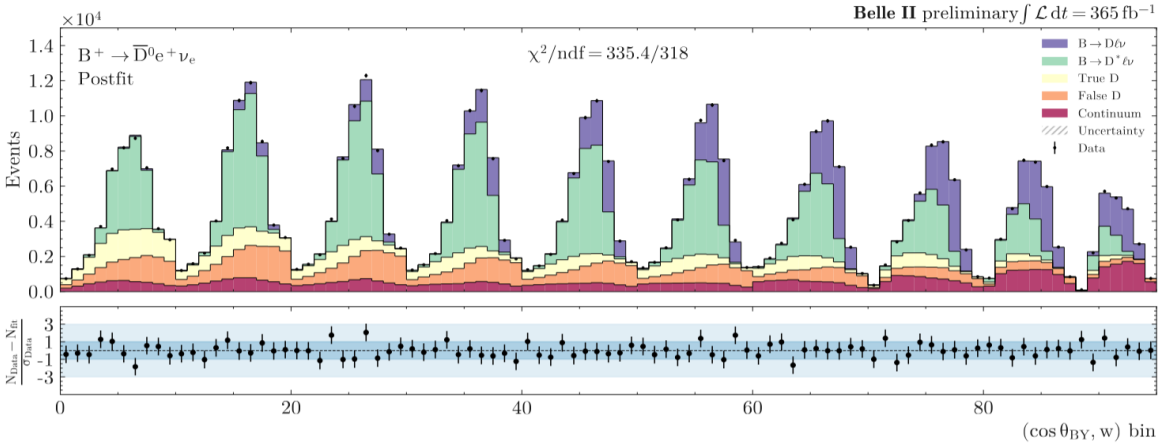
- $B \to Dlv$ reconstructed from $D \to K\pi, K\pi\pi^0$
- Signals reconstructed using ML fits to (Diamond frame)

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









Distribution of fit for $\cos(\theta_{BY})$ in various bins of W

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

Most precise measurement to date using $B \to D l \nu$

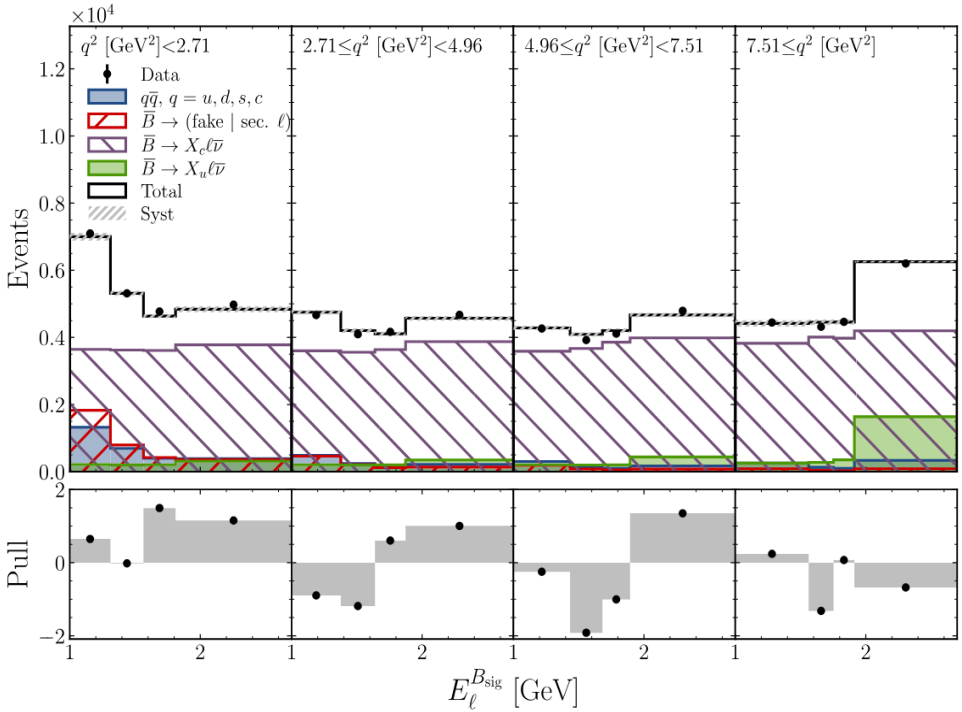
$|V_{cb}|$ measurement

By fitting the differential decay rate to BCL parametrization

$$|V_{cb}| = (39.2 \pm 0.4\,(\text{stat.}) \pm 0.6\,(\text{sys.}) \pm 0.5\,(\text{th.})) \times 10^{-3}$$

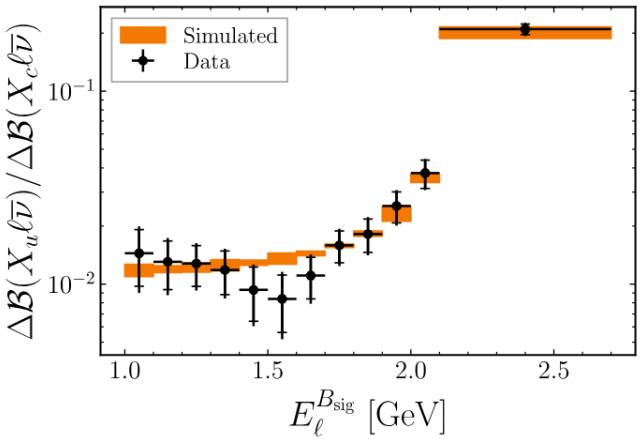
$|V_{ub}|/|V_{cb}|$ measurement using inclusive decays

- First direct determination of $\frac{\Delta B(B \to X_u\, l\, \nu)}{\Delta B(B \to X_c\, l\, \nu)}$ using hadronic tagged samples
- Splitting the B → $X_u\, l\, \nu$ samples into signal enhanced and depleted subsets to get data driven estimates of signal and background yields



$N(X_u\, l\, \nu)$: 2D binned fits to signal enhanced sample

$N(X_c\, l\, \nu)$: 1D binned fit to u-depleted sample



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

Theory decay rates:

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

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

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

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

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

$$\frac{\Delta\mathcal{B}(\bar{B} \to X_u \ell\bar{\nu})}{\Delta\mathcal{B}(\bar{B} \to X_c \ell\bar{\nu})} = (1.99 \pm 0.17_{\mathrm{stat}} \pm 0.16_{\mathrm{syst}}) \times 10^{-2}$$

Summary

- Semileptonic and Leptonic B decays provide key tests of the Standard Model and are sensitive to New Physics
- Improved measurements
  - Improved extraction of $|V_{ub}|$ from $B \rightarrow X_u l \nu$ decays
  - Measurement of $|V_{cb}|$ from $B \rightarrow D l \, \nu$ decays

- New measurements from Belle II
  - $\frac{|V_{ub}|}{|V_{cb}|}$ from inclusive $B \rightarrow X l \nu$ decays
  - $|V_{ub}|$ from $B \rightarrow \tau \nu$ decays

Thank you