



Semileptonic decays at Belle II

Philipp Horak
on behalf of the Belle II Collaboration

Collider Physics in the PNW

TRIUMF, February 18, 2026



**University
of Victoria**

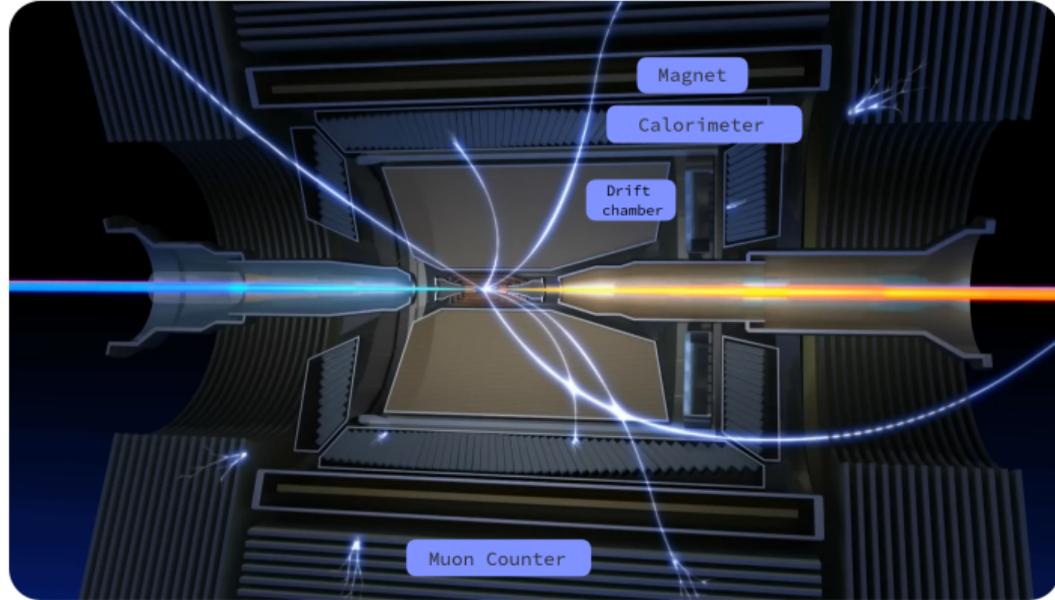
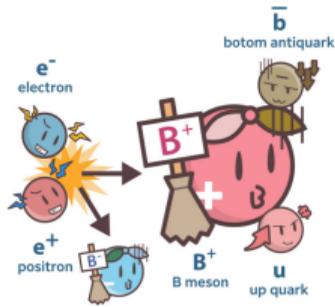
phorak@uvic.ca

The Belle II experiment

Luminosity frontier experiment

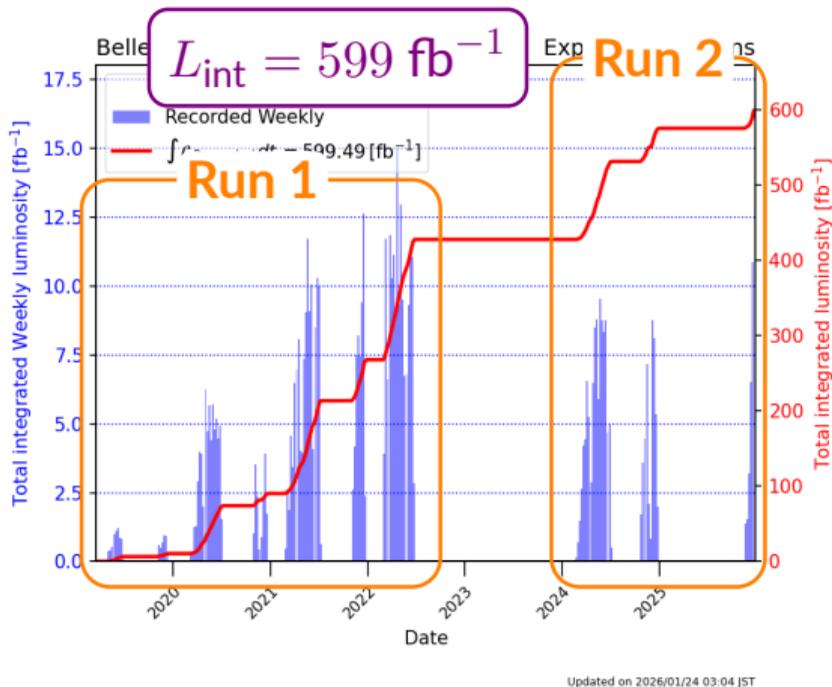


- Asymmetric e^+e^- collisions at 10.6 GeV



- High currents, nano beam scheme

Cute graphics, but what about the physics?

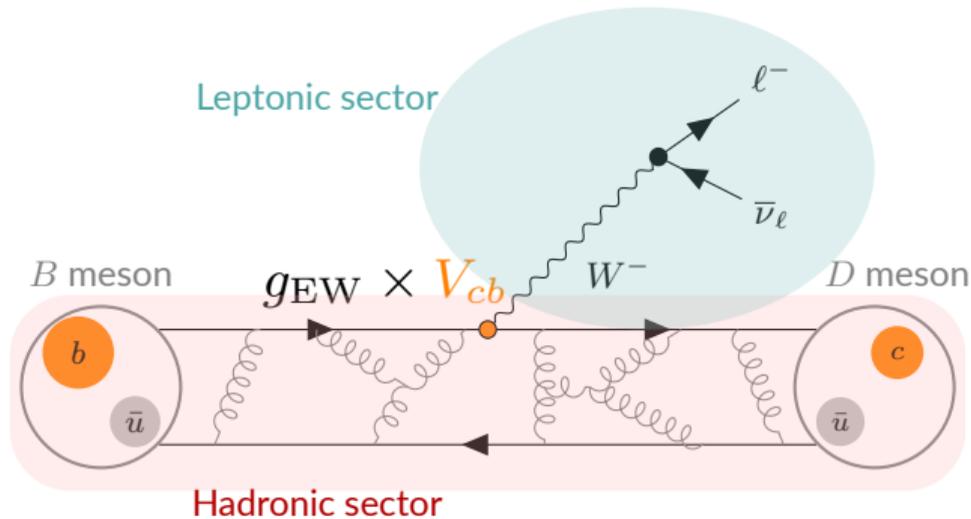


- World record instantaneous luminosity!
 - $5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Restarted at full swing November 2025
 - Run 2 operation until Summer 2026
- Current data-sample is $\sim 1\%$ of planned sample (50 ab^{-1})

Results so far with 365 fb^{-1}

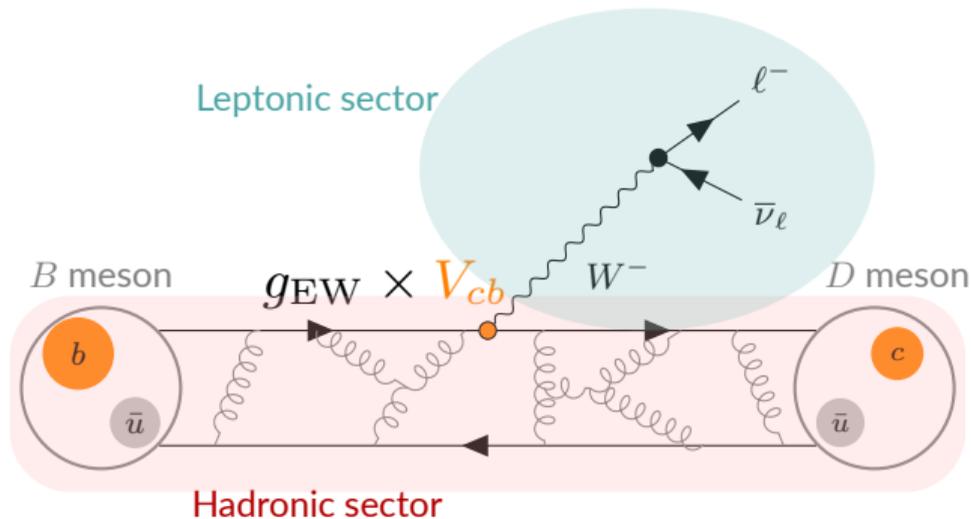
(Belle 711 fb^{-1} , BaBar 425 fb^{-1})

The semileptonic $b \rightarrow c$ decay



- High branching ratios: $\sim \frac{1}{4}$ of all B meson decays
- Factorizing leptonic and hadronic currents
- Tree-level CKM-favored process - no new physics expected

The semileptonic $b \rightarrow c$ decay



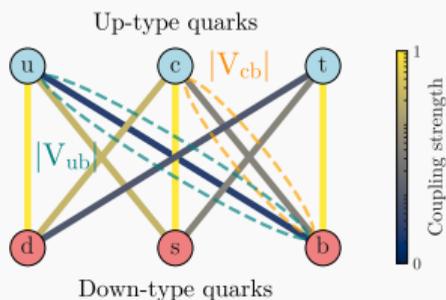
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$$b \rightarrow u \ell \bar{\nu}$$

- Similar factorization
- $(|V_{ub}|/|V_{cb}|)^2 \simeq 1/100$ suppressed

What's so interesting about semileptonic decays?

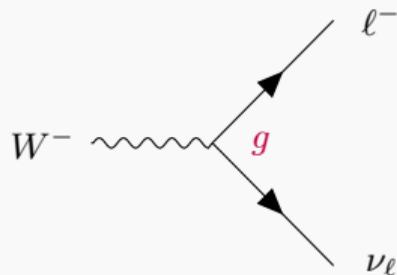
Quark mixing



- How large are the $b \leftrightarrow u$ and $b \leftrightarrow c$ couplings?

V_{cb} , V_{ub} puzzle

Lepton flavor universality

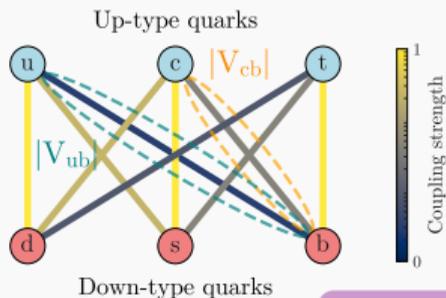


- Does the W couple equally to different lepton flavors?

$R(D)$, $R(D^*)$ anomaly

What's so interesting about semileptonic decays?

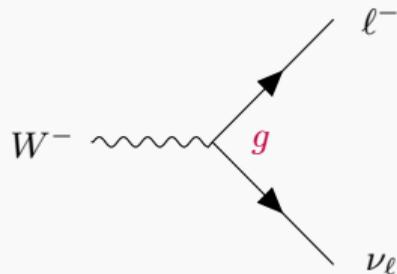
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+ Secret third topic

How can we utilize clean e^+e^- environments?

1. Hadronic tagging:

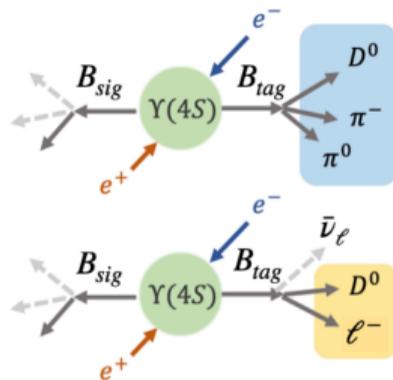
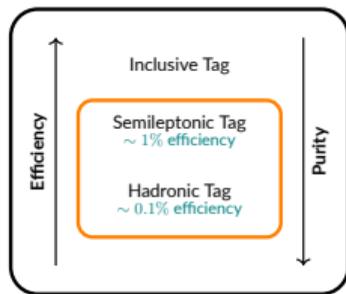
reconstruct B_{tag} by hadronic decay modes.

2. Semileptonic tagging:

reconstruct B_{tag} by semileptonic decay modes.

3. Inclusive tagging:

reconstruct B_{tag} without a specific final state.



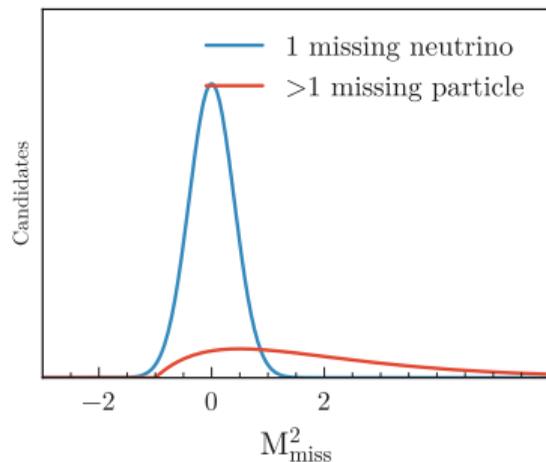
- Belle II employs Full Event Interpretation (FEI)

↳ Over 200 BDTs reconstruct $\mathcal{O}(10000)$ distinct decay chains

- Reconstruct B meson momentum using tag-side

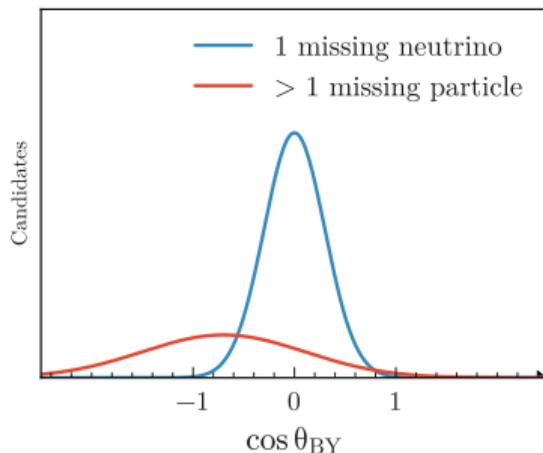
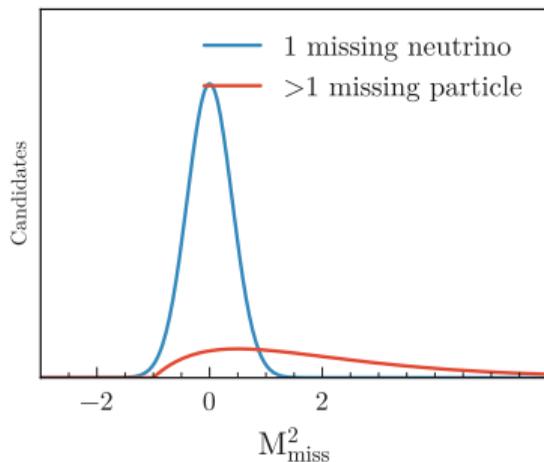
$$p_{\text{sig}} = p_{e^+e^-} - p_{\text{tag}}$$

Reconstruction with missing neutrinos



$M_{\text{miss}}^2 = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^{(*)\ell}})^2$
Squared 4-momentum of the undetected neutrino(s).

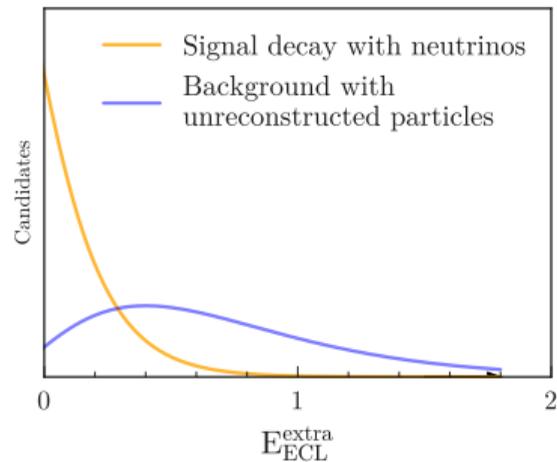
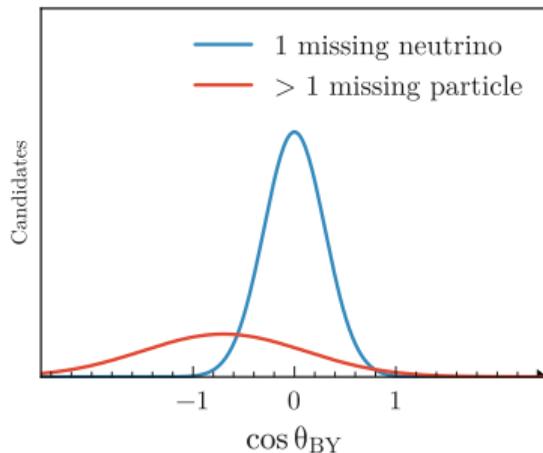
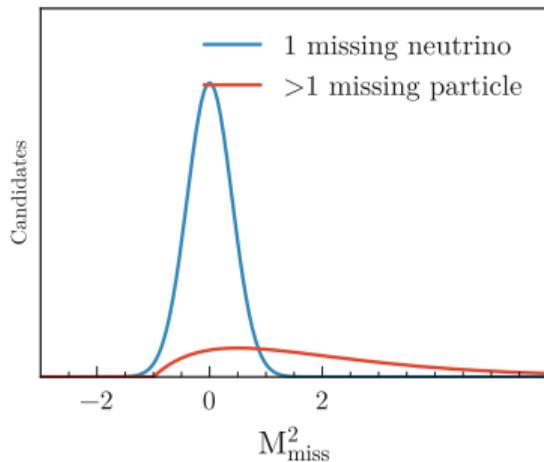
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$\cos \theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|}$
 Angle between B and $Y = D^{(*)}\ell$.

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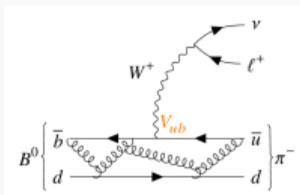
$\cos \theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|}$
Angle between B and $Y = D^{(*)}\ell$.

$E_{\text{ECL}}^{\text{extra}}$
Sum of energies of neutral clusters not used in B_{tag} or Y .

V_{cb} , V_{ub} puzzle

Two methods to measure $|V_{cb}|$, $|V_{ub}|$

Exclusive



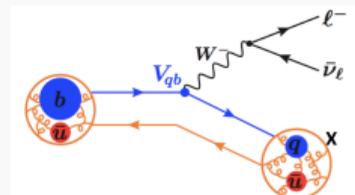
Reconstruct specific final states

- $B \rightarrow D^{(*)} \ell \nu$ for $|V_{cb}|$
- $B \rightarrow \pi \ell \nu$ for $|V_{ub}|$

Method: Parameterize the $b \rightarrow u/c$ transition with *form factors*, normalize using **Lattice QCD** inputs

$$\mathcal{B} \propto |V_{cb}|^2 f^2(q^2)$$

Inclusive



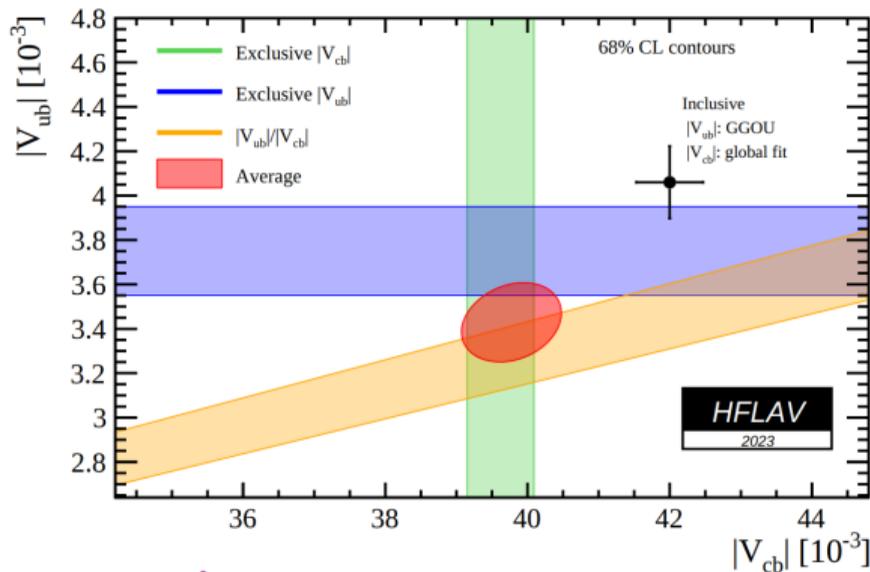
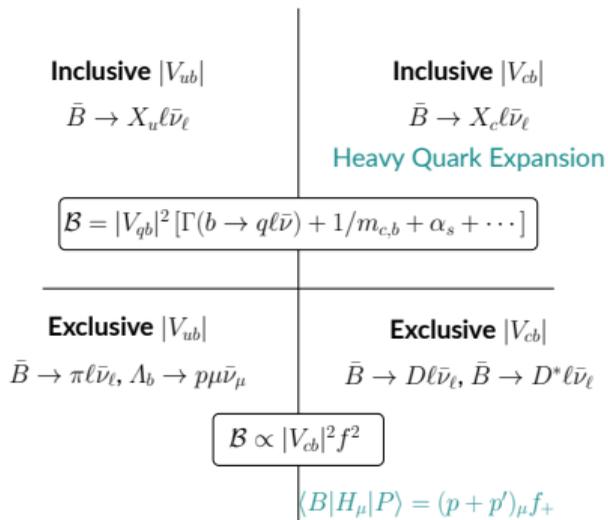
Sum over all hadronic states

- $B \rightarrow X_c \ell \nu$ for $|V_{cb}|$
- $B \rightarrow X_u \ell \nu$ for $|V_{ub}|$

Method: Summing over all final states treats b as quasi-free; Expand decay rate in $1/m_b$ and α_s using **Heavy Quark Expansion**

$$\Gamma \propto |V_{cb}|^2 [1 + \mathcal{O}(1/m_b) + \mathcal{O}(\alpha_s)]$$

Experimental status on the CKM elements

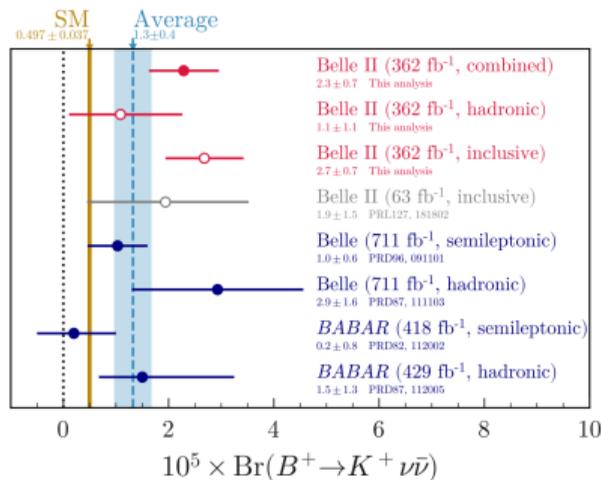
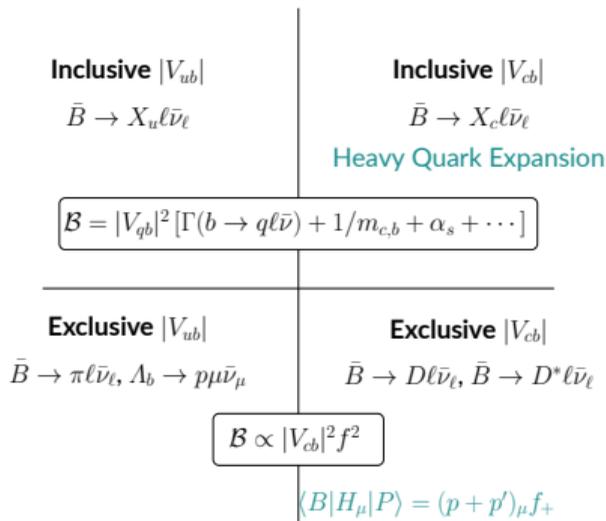


Long-standing $\sim 3\sigma$ tension

Experimental status on the CKM elements



Evidence for $B \rightarrow K\nu\nu$ [PRD 109, 112006]



Long-standing $\sim 3\sigma$ tension

Fael et al. 2512.19138:

Using the expression for the total rate in Eq. (3.16) and the inputs in Table 1, we obtain the inclusive branching ratios,

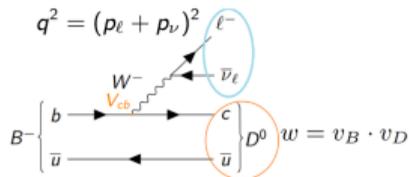
$$\text{Br}(B^0 \rightarrow X_s \nu \bar{\nu}) \times 10^5 = 3.351 \pm 0.058_{V_{cb}} \pm 0.029_{\text{param}} \pm 0.043_{\text{HQE}} \pm 0.065_{\text{scale}}, \quad (4.1)$$

$|V_{cb}|$ and $|V_{ub}|$ in the Belle II era

■ **Exclusive** $|V_{cb}|$ [PRD 112, 112009] (also [PRD 108, 092013])

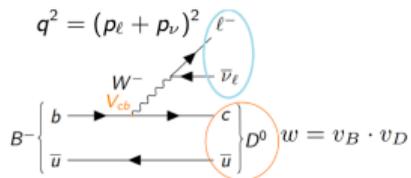
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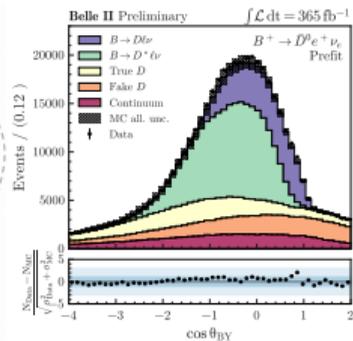
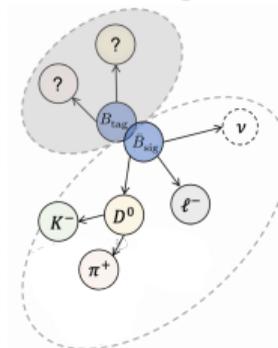


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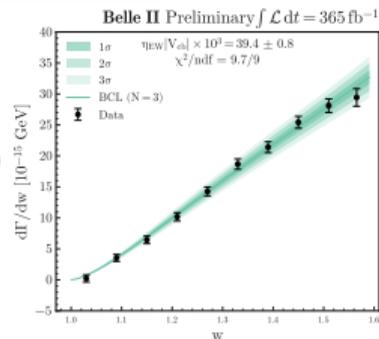
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Inclusive tag



+ Lattice QCD:
FNAL/MILC + HPQCD



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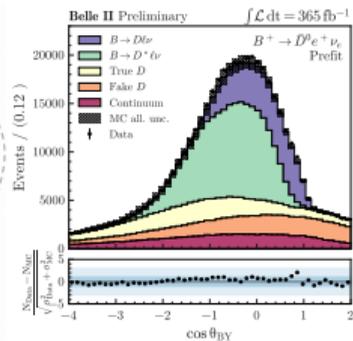
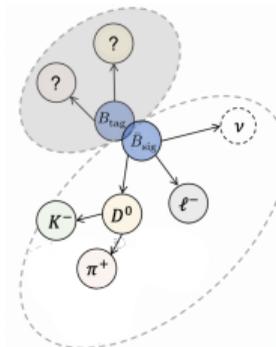
$$- |V_{cb}| = (39.2 \pm 0.4_{\text{stat.}} \pm 0.6_{\text{sys.}} \pm 0.5_{\text{th.}}) \times 10^{-3}$$

365 fb⁻¹

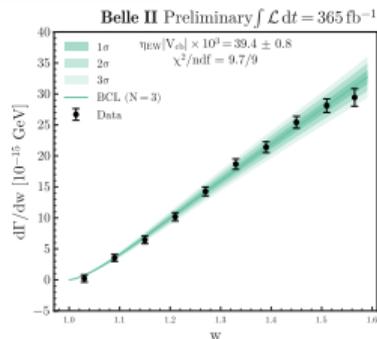
World-best (fully) exclusive V_{cb}



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- Reconstruct spectral moments of $B \rightarrow X_c \ell \nu$
- Novel method with reduced parameters ($\langle q^2 \rangle$ moments)

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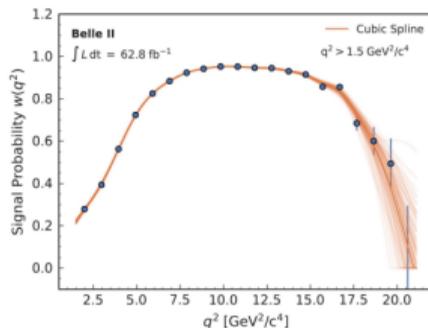
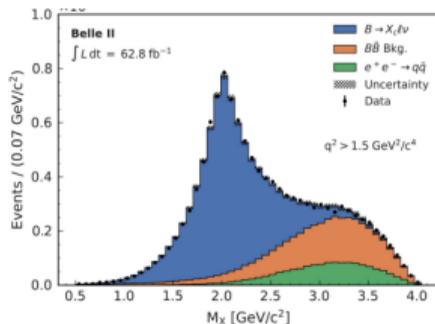
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How to measure moments:

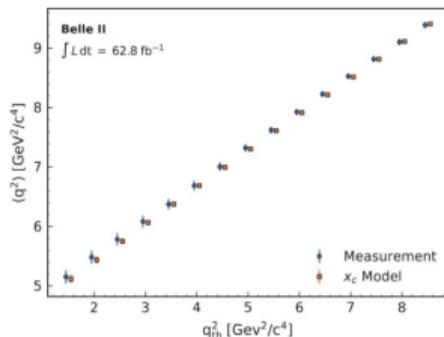
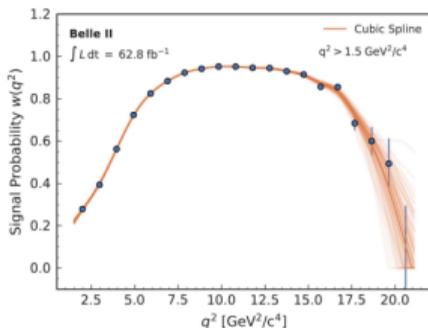
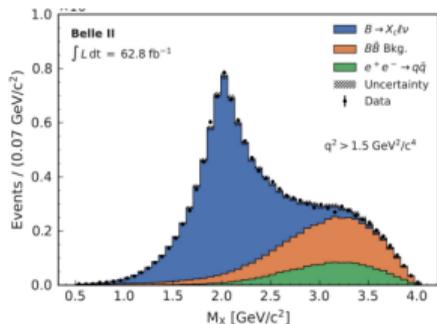
$$\langle q^{2n} \rangle = \frac{\sum_i w_i(q^2) (q^{2n}_{\text{calib},i})}{\sum_i w_i(q^2)} \times \mathcal{C}_{\text{cal}} \times \mathcal{C}_{\text{acc}}$$

Calibrated q^2 dist. accounting for data/MC differences

Residual bias corr. factor

Correct for resolution & selection effects

Background subtraction weights



$|V_{cb}|$ and $|V_{ub}|$ in the Belle II era

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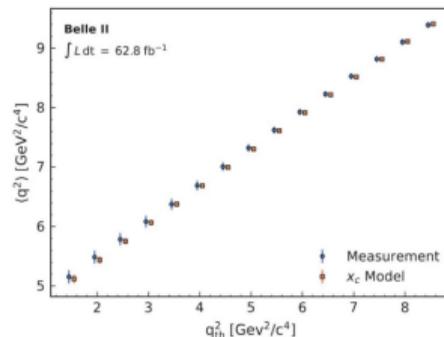
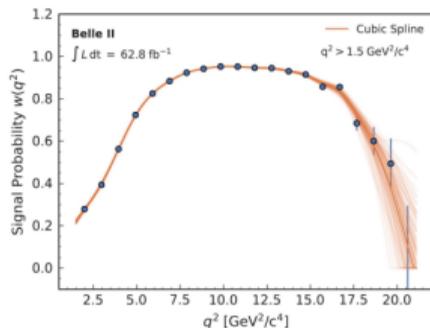
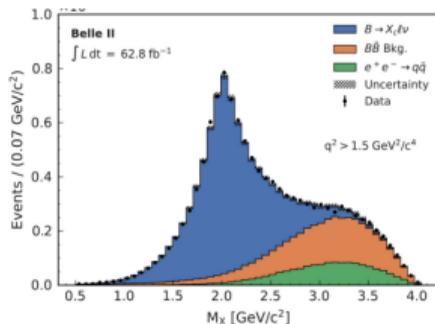
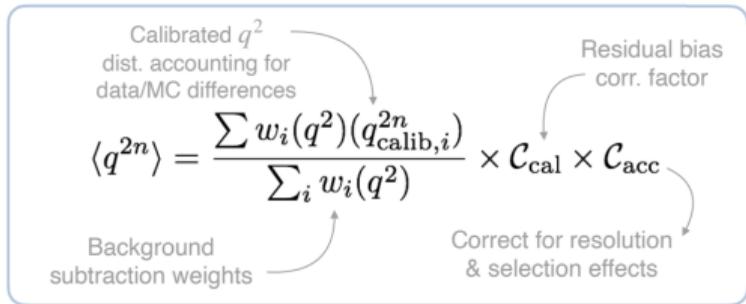
$$- |V_{cb}| = (41.7 \pm 0.7) \times 10^{-3} \text{ (Belle + Belle II)}$$

62 fb⁻¹

Novel inclusive V_{cb} determination



How to measure moments:



$|V_{cb}|$ and $|V_{ub}|$ in the Belle II era

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Inclusive tag-side

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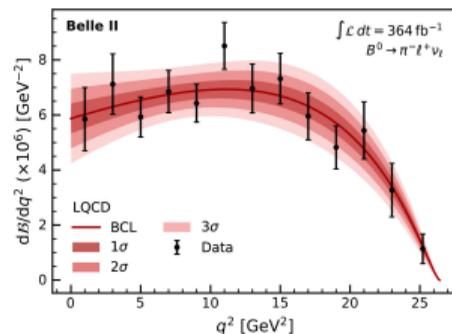
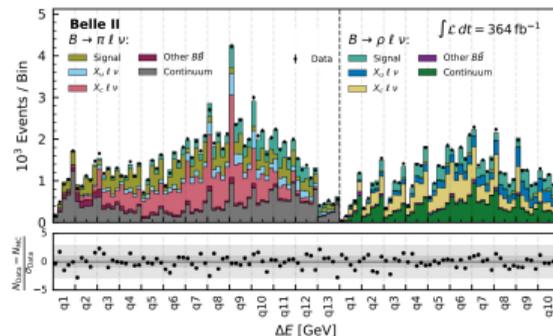
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- **Exclusive $|V_{ub}|$** [PRD 111, 112009]

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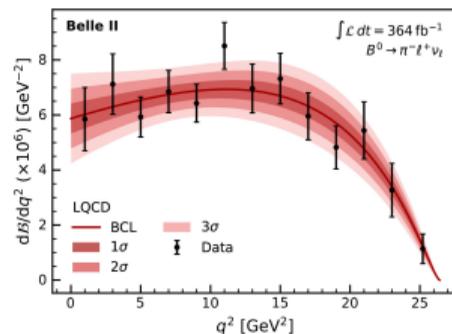
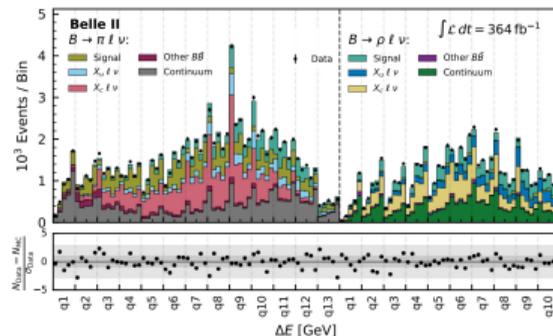


- **Exclusive** $|V_{ub}|$ [PRD 111, 112009]

$$- |V_{ub}| = (3.93 \pm 0.09_{\text{stat.}} \pm 0.07_{\text{stat.}} \pm 0.19_{\text{theo.}}) \times 10^{-3}$$

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World-best (fully) exclusive V_{cb}



- **Inclusive** $|V_{cb}|$ [PRD 104, 112011; PRD 107, 072002; JHEP 10 (2022) 068]

- $|V_{cb}| = (41.7 \pm 0.7) \times 10^{-3}$ (Belle + Belle II)

62 fb⁻¹

Novel inclusive V_{cb} determination



- **Exclusive** $|V_{ub}|$ [PRD 111, 112009]

- $|V_{ub}| = (3.93 \pm 0.09_{\text{stat.}} \pm 0.07_{\text{stat.}} \pm 0.19_{\text{theo.}}) \times 10^{-3}$

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- **Inclusive** $|V_{ub}|$ [PRD 113, 032004]

$|V_{cb}|$ and $|V_{ub}|$ in the Belle II era

- **Exclusive** $|V_{cb}|$ [PRD 112, 112009] (also [PRD 108, 092013])

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

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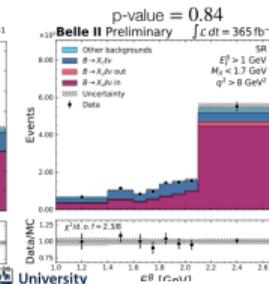
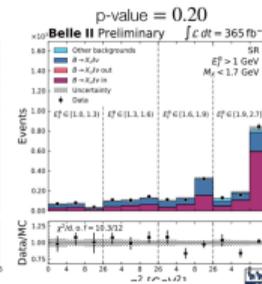
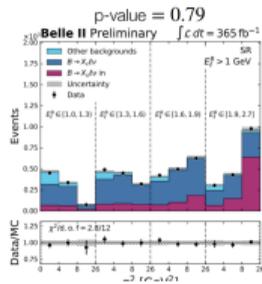
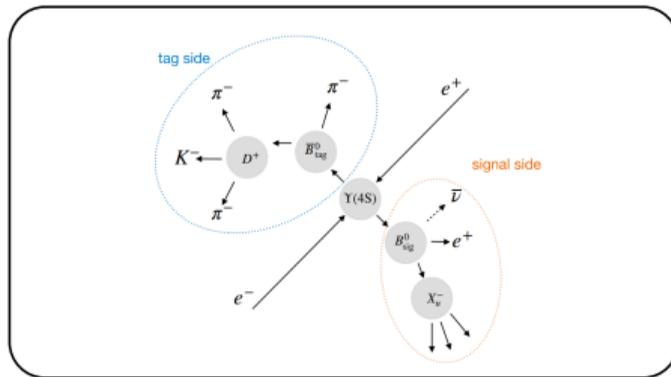
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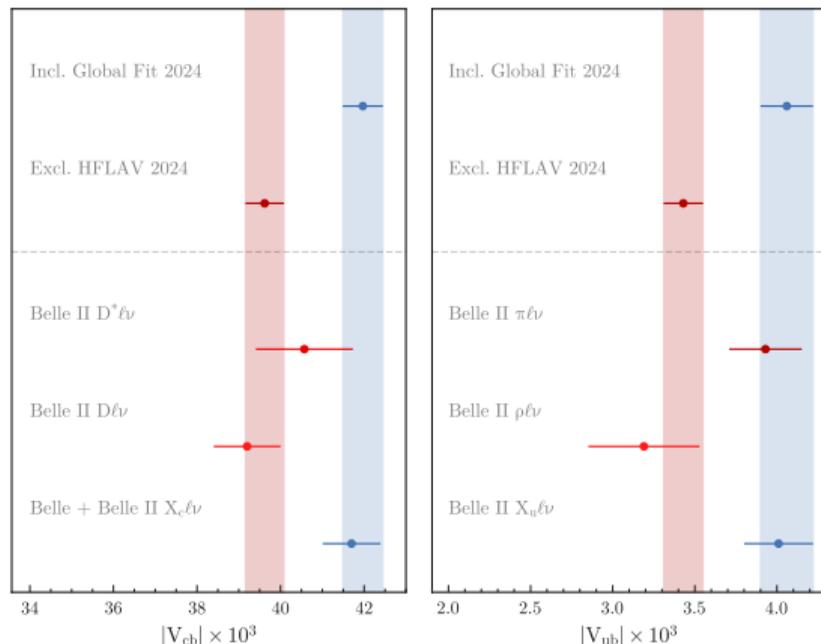
$$- |V_{ub}| = (4.01 \pm 0.19_{\text{exp.}} \pm 0.08_{\text{theo.}}) \times 10^{-3}$$

365 fb⁻¹

World-best[†] inclusive V_{ub}



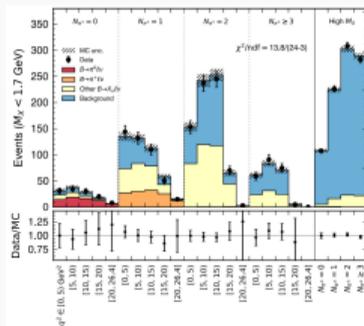
[[†] Depending on model / region, compare BABAR PRD 95 072001]



New era of precision with Belle II

Looking ahead

Simultaneous determinations



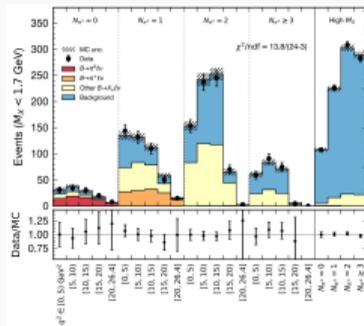
- Measure inclusive and exclusive $|V_{ub}|$ at Belle
 - Eliminate experimental differences!
- Compatible but statistically limited
 - $\Rightarrow \mathcal{O}(10 \text{ ab}^{-1})$ @ Belle II?
 - \Rightarrow Extend to $|V_{cb}|$?



[PRL 131, 211801]

Looking ahead

Simultaneous determinations



- Measure inclusive and exclusive $|V_{ub}|$ at Belle
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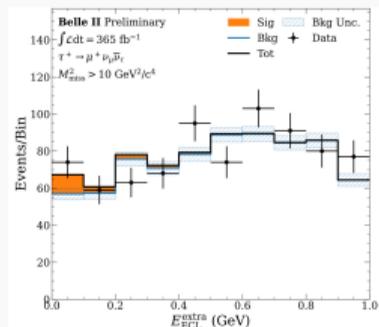
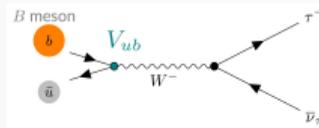
Leptonic decays



[PRD 112, 072002]



[arXiv:2602.09800]



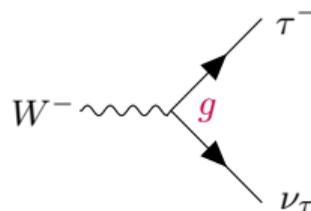
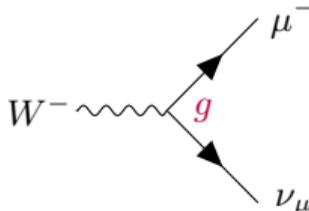
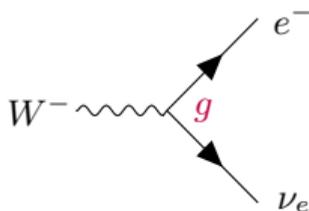
- Direct V_{qb} coupling!
- Orders of magnitude lower branching ratios
 - $\Rightarrow \mathcal{O}(10 \text{ ab}^{-1})$ @ Belle II?
 - $\Rightarrow B_c \rightarrow \ell \nu$ @ FCC-ee?

Lepton-flavor universality

Lepton-flavor universality

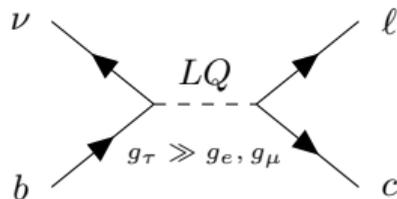
- In the Standard Model, W couples equally to e, μ, τ

↔ Lepton-Flavor Universality (LFU)



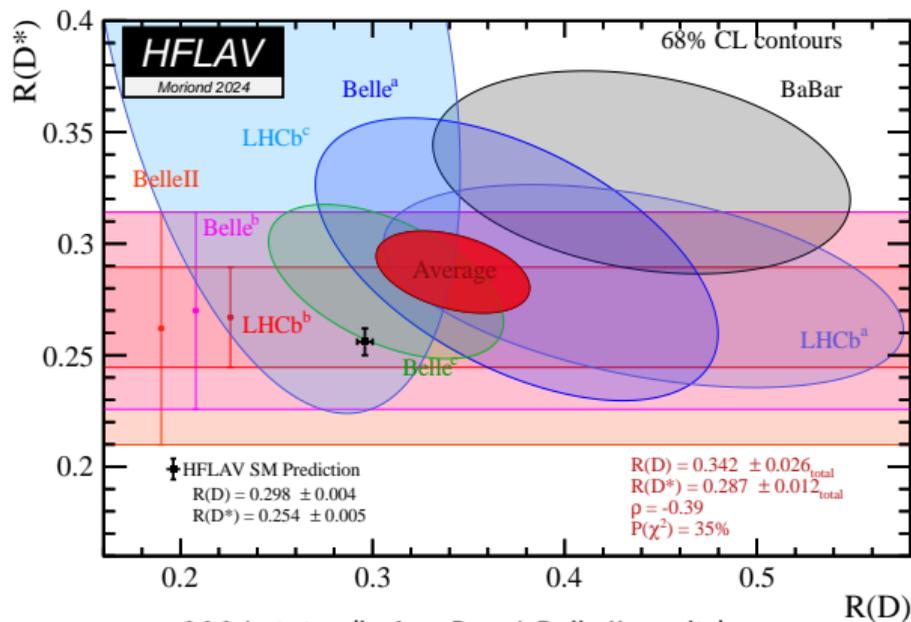
- Different Non-SM contributions can violate LFU:

- Charged Higgs
- SUSY
- Lepto-quarks
- etc.



Experimental status for $R(D^{(*)})$

- Measurements performed at Belle, BaBar, Belle II, LHCb



$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu_\ell)}$$

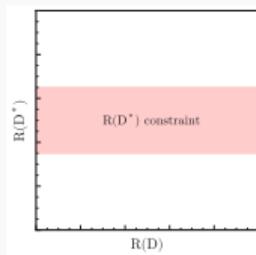
| Experiment | Channels | τ decay mode | Tagging / Notes |
|--------------------|-----------------------|---|--------------------|
| BaBar | $R(D), R(D^*)$ | $\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau$ | Hadronic tag |
| Belle ^a | $R(D), R(D^*)$ | $\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau$ | Hadronic tag |
| Belle ^b | $R(D^*), P_\tau(D^*)$ | $\tau^- \rightarrow \pi^- (\pi^0) \nu_\tau$ | Hadronic tag |
| Belle ^c | $R(D), R(D^*)$ | $\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau$ | Semileptonic tag |
| LHCb ^a | $R(D), R(D^*)$ | $\tau^- \rightarrow \mu^- \nu_\mu \nu_\tau$ | |
| LHCb ^b | $R(D^*)$ | $\tau^- \rightarrow 3\pi^- (\pi^0) \nu_\tau$ | via $K(D^*)$ ratio |
| LHCb ^c | $R(D^+), R(D^{*+})$ | $\tau^- \rightarrow \mu^- \nu_\mu \nu_\tau$ | |
| Belle II | $R(D^*)$ | $\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau$ | Hadronic tag |

See: [\[HFLAV\]](#)

Belle II results of $R(D^{(*)})$ and $R(X)$ measurements

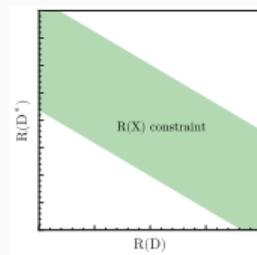
$R(D^*)$ PRD 110, 072020

Partial Run 1: 189 fb^{-1}
Hadronic tag-side
Leptonic τ decay



$R(X_c)$ PRL 132, 211804

Partial Run 1: 189 fb^{-1}
Hadronic tag-side
Leptonic τ decay



Most recent:

$R(D)$ and $R(D^*)$

Full Run 1: 365 fb^{-1}

Semileptonic tag-side

Leptonic τ decay

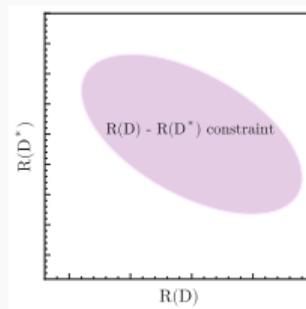
PRD 112, 032010

Full Run 1: 365 fb^{-1}

Hadronic tag-side

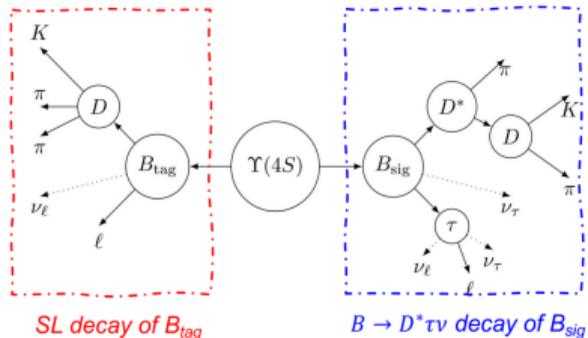
Leptonic τ decay

To be submitted



SL vs. hadronic tag-side

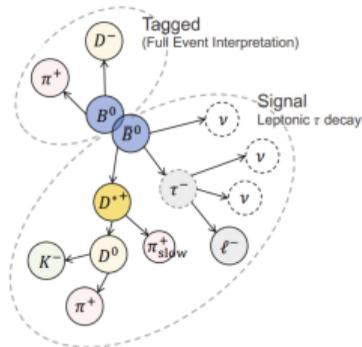
Semileptonic tag



- ↑ Higher efficiency
- ↓ Lower purity
- Restricted to B^0 modes only
- Leptonic $\tau \rightarrow \ell \nu \nu$

Signal extraction with High-level features

Hadronic tag



- ↓ Lower efficiency
- ↑ Higher purity
- + Both B^0 and B^+ modes
- Leptonic $\tau \rightarrow \ell \nu \nu$

Signal extraction with Low-level features

Comparison: Results & Systematics

Semileptonic tag



$$R(D^{*+}) = 0.306 \pm 0.034_{\text{stat}} \pm 0.018_{\text{sys}}$$

$$R(D^+) = 0.418 \pm 0.074_{\text{stat}} \pm 0.051_{\text{sys}}$$

$$(\rho = -0.24)$$

[$R(D) / R(D^*)$]

| | |
|-----------------|-----------|
| Simulation size | 8% / 4% |
| Lepton ID | 9% / 1% |
| SL Gap | 6% / 0.1% |

| | |
|-------------------------|------------------|
| Total systematic | 12% / 6% |
| Statistical | 18% / 11% |

- World average: 0.6σ
- SM prediction: 1.7σ

Hadronic tag



$$R(D^*) = 0.242 \pm 0.019_{\text{stat}} \pm 0.016_{\text{sys}}$$

$$R(D) = 0.439 \pm 0.055_{\text{stat}} \pm 0.045_{\text{sys}}$$

$$(\rho = -0.4_{\text{stat}} - 0.2_{\text{sys}})$$

[$R(D) / R(D^*)$]

| | |
|-----------------|---------|
| Simulation size | 8% / 5% |
| SL Gap | 3% / 3% |
| Continuum bkg | 2% / 2% |

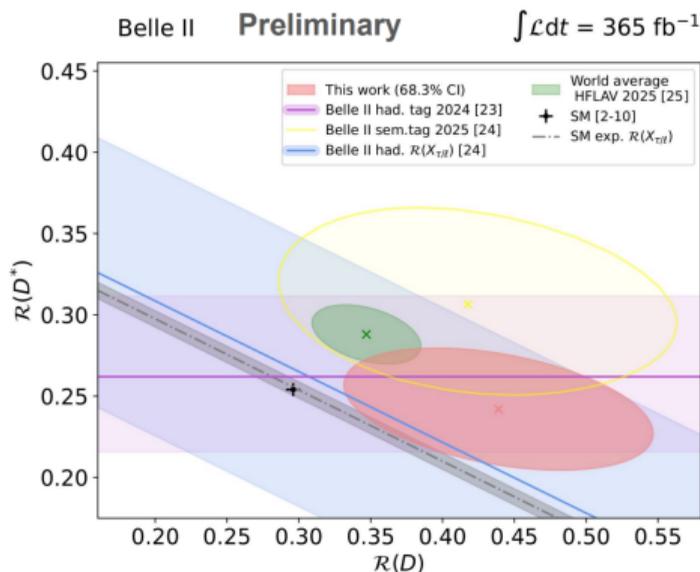
| | |
|-------------------------|-----------------|
| Total systematic | 10% / 7% |
| Statistical | 16% / 8% |

- World average: 1.3σ
- SM prediction: $2\sigma / 1.5\sigma$

Most precise hadronic tag!

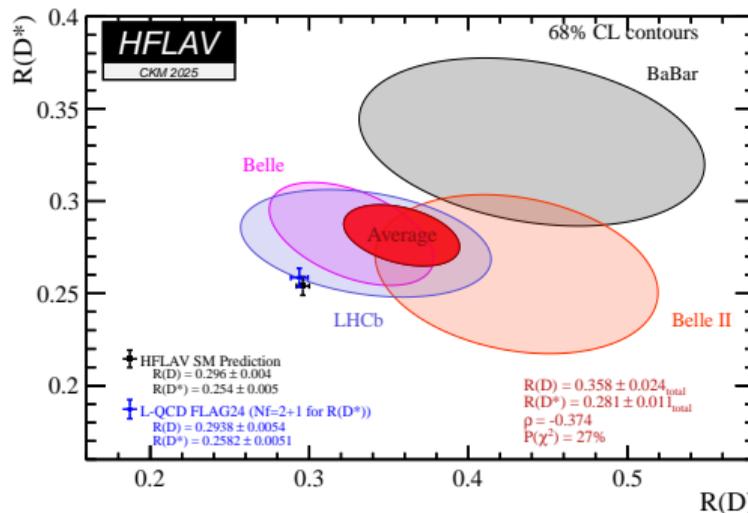
$R(D), R(D^*)$ in the Belle II era

Belle II results in good agreement with each other and closer to World Average



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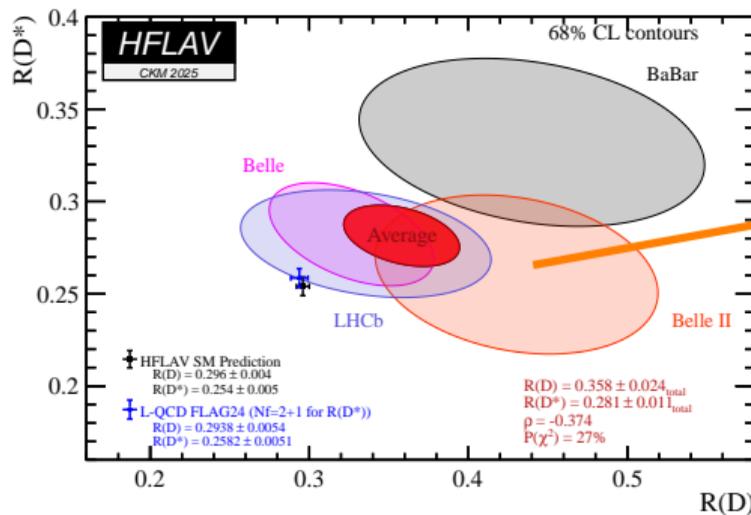
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Global tension with Run 1 Belle II results increases to 3.8σ !

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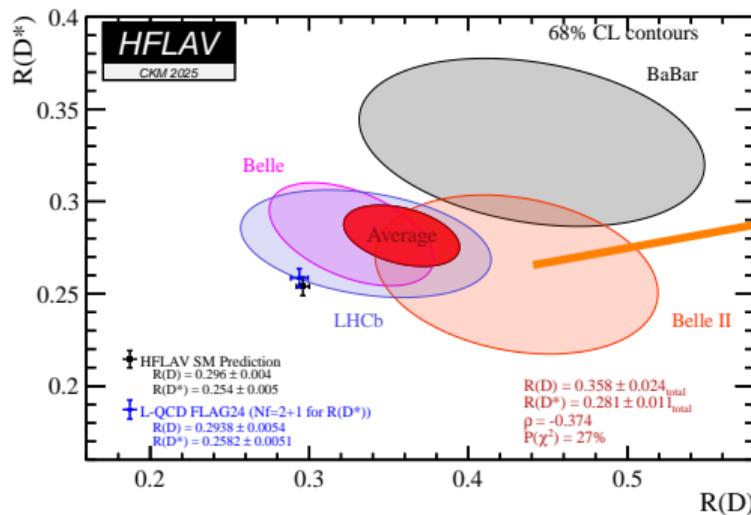
Statistically limited

Global tension with Run 1 Belle II results increases to 3.8σ !

$R(D)$, $R(D^*)$ in the Belle II era

Belle II results in good agreement with each other and closer to World Average

New Physics or
problematic modeling?



Statistically limited

Global tension with Run 1 Belle II results increases to 3.8σ !

secret third topic

What is the composition of semileptonic decays?

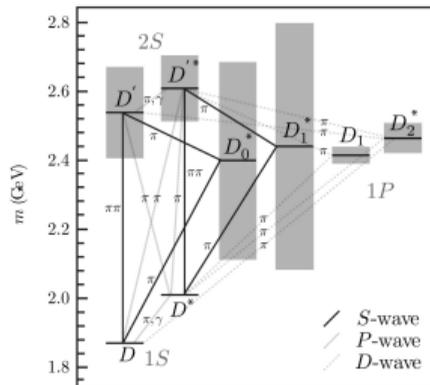
See: [R. van Tonder]

$$\mathcal{B}(B^+ \rightarrow X_c^0 \ell^+ \nu_\ell) \approx 10.79\%$$

| | | | |
|---------------------------------|------------------------------------|--|----------------------|
| $D^0 \ell^+ \nu_\ell$ 2.31 % | $D^{*0} \ell^+ \nu_\ell$ 5.05 % | $D^{**0} \ell^+ \nu_\ell + \text{Other}$ 2.38 % | Gap $\sim 1.05\%$ |
|---------------------------------|------------------------------------|--|----------------------|

Updating with recent HFLAV gives 1.8%!

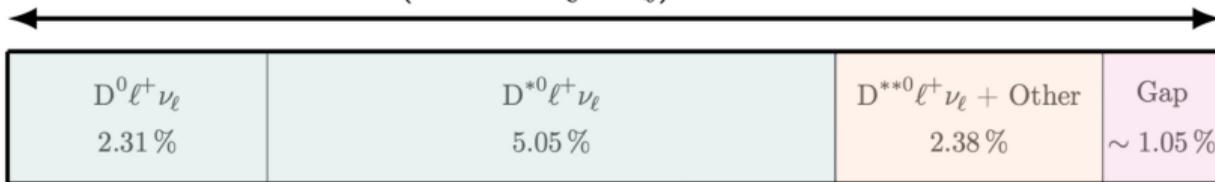
D^{**} and gap leading systematic for many measurements!



What is the composition of semileptonic decays?

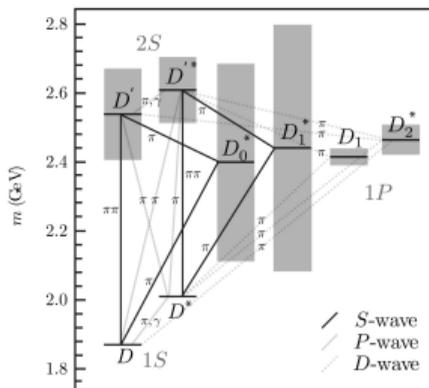
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| Decay | $\mathcal{B}(B^+)$ | $\mathcal{B}(B^0)$ |
|---|---------------------------------|---------------------------------|
| $B \rightarrow D \ell^+ \nu_\ell$ | $(2.4 \pm 0.1) \times 10^{-2}$ | $(2.2 \pm 0.1) \times 10^{-2}$ |
| $B \rightarrow D^* \ell^+ \nu_\ell$ | $(5.5 \pm 0.1) \times 10^{-2}$ | $(5.1 \pm 0.1) \times 10^{-2}$ |
| $B \rightarrow D_1 \ell^+ \nu_\ell$ | $(6.6 \pm 0.1) \times 10^{-3}$ | $(6.2 \pm 0.1) \times 10^{-3}$ |
| $B \rightarrow D_2^* \ell^+ \nu_\ell$ | $(2.9 \pm 0.3) \times 10^{-3}$ | $(2.7 \pm 0.3) \times 10^{-3}$ |
| $B \rightarrow D_0^* \ell^+ \nu_\ell$ | $(4.2 \pm 0.8) \times 10^{-3}$ | $(3.9 \pm 0.7) \times 10^{-3}$ |
| $B \rightarrow D_1' \ell^+ \nu_\ell$ | $(4.2 \pm 0.9) \times 10^{-3}$ | $(3.9 \pm 0.8) \times 10^{-3}$ |
| $B \rightarrow D\pi\pi \ell^+ \nu_\ell$ | $(0.6 \pm 0.9) \times 10^{-3}$ | $(0.6 \pm 0.9) \times 10^{-3}$ |
| $B \rightarrow D^*\pi\pi \ell^+ \nu_\ell$ | $(2.2 \pm 1.0) \times 10^{-3}$ | $(2.0 \pm 1.0) \times 10^{-3}$ |
| | ? | |
| $B \rightarrow X_c \ell \nu_\ell$ | $(10.8 \pm 0.4) \times 10^{-2}$ | $(10.1 \pm 0.4) \times 10^{-2}$ |

Well measured

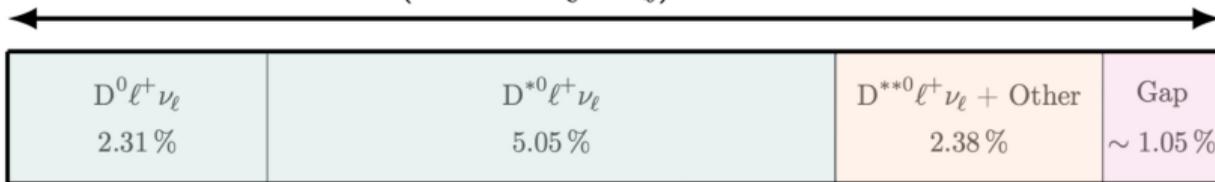
Room for improvement

Some hints from BaBar & Belle

What is the composition of semileptonic decays?

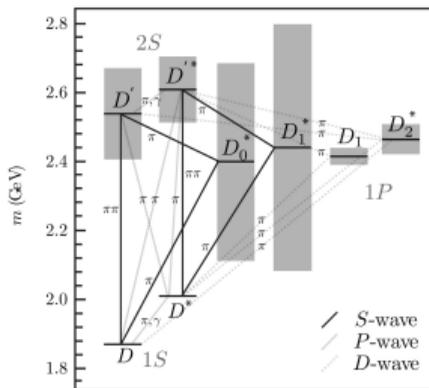
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| $B \rightarrow D \pi \pi \ell^+ \nu_\ell$ | $(0.6 \pm 0.9) \times 10^{-3}$ | $(0.6 \pm 0.9) \times 10^{-3}$ |
| $B \rightarrow D^* \pi \pi \ell^+ \nu_\ell$ | $(2.2 \pm 1.0) \times 10^{-3}$ | $(2.0 \pm 1.0) \times 10^{-3}$ |
| $B \rightarrow D \eta \ell^+ \nu_\ell$ | $(4.0 \pm 4.0) \times 10^{-3}$ | $(4.0 \pm 4.0) \times 10^{-3}$ |
| $B \rightarrow D^* \eta \ell^+ \nu_\ell$ | $(4.0 \pm 4.0) \times 10^{-3}$ | $(4.0 \pm 4.0) \times 10^{-3}$ |
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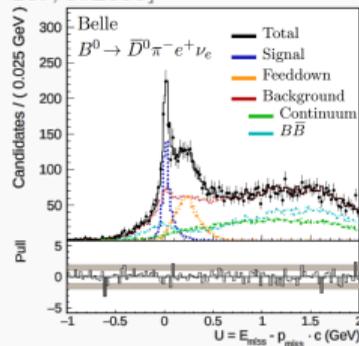
"Best guess"

What can we do?



High precision D^{**}

PRD 107, 092003]



- Improve the $D\pi(\pi)\ell\nu$ modes

- Understand the D^{**} hierarchy

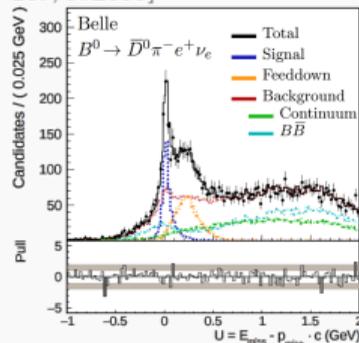
Huge potential with
 $\mathcal{O}(10 \text{ ab}^{-1})$

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High precision D^{**}

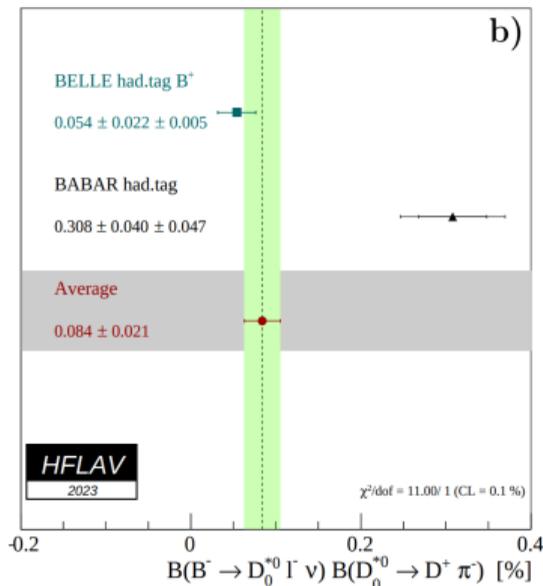
PRD 107, 092003]



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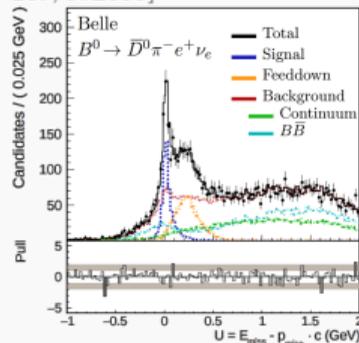


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PRD 107, 092003]



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Huge potential with
 $\mathcal{O}(10 \text{ ab}^{-1})$

Find gap modes



- $B \rightarrow D^{(*)}\eta l\nu$ never measured before
- Primary candidate for gap mode

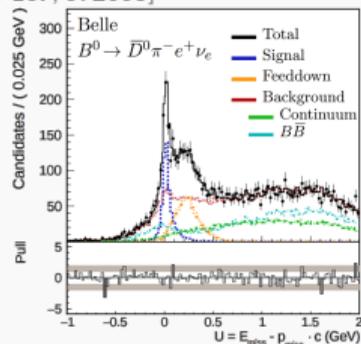
Sensitivity with $\mathcal{O}(1 \text{ ab}^{-1})$

What can we do?



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PRD 107, 092003]



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Sensitivity with $\mathcal{O}(1 \text{ ab}^{-1})$

Revisiting \mathcal{B}_{SL}

| | $\mathcal{B}_{SL}(X)$ (%) | $\mathcal{B}_{SL}(X_c)$ (%) |
|--------------------------------------|---------------------------|-----------------------------|
| Belle ($E_\ell > 0.6 \text{ GeV}$) | - | 10.54 ± 0.31 |
| Belle ($E_\ell > 0.4 \text{ GeV}$) | - | 10.58 ± 0.32 |
| CLEO (incl.) | 10.91 ± 0.26 | 10.72 ± 0.26 |
| CLEO ($E_\ell > 0.6$) | 10.69 ± 0.25 | 10.50 ± 0.25 |
| BaBar (incl.) | 10.34 ± 0.26 | 10.15 ± 0.26 |
| BaBar SL $E_\ell > 0.6 \text{ GeV}$ | - | 10.68 ± 0.24 |
| Our Average | - | 10.48 ± 0.13 |

- How large is the gap?
- Last measurement in 2007
 - Slight tensions

Different \mathcal{B}_{SL} would have many implications

Summary

Belle II is uniquely positioned for semileptonic decays

- Pushing precision frontier on V_{cb} and V_{ub}
- First $R(D)$, $R(D^*)$ run1 measurements on the board
- Best candidate for uncovering the details of the SL spectrum

If not Belle II, then only FCC-ee!

Thank you!

Back-up

V_{qb} measurements at Belle II

$|V_{cb}|$ Exclusive

$$B \rightarrow D\ell\nu \text{ (incl. tag)}$$

Phys. Rev. D 112 (2025), 032010

$$B^0 \rightarrow D^{*-}\ell^+\nu \text{ (incl. tag)}$$

Phys. Rev. D 108 (2023), 092013

$|V_{cb}|$ Inclusive

$$B \rightarrow X_c\ell\nu \text{ (} q^2 \text{ moments, had. tag)}$$

Phys. Rev. D 107 (2023) 072002

JHEP 10 (2022) 068

$$B \rightarrow X_c\ell\nu \text{ (} M_X \text{ moments, had. tag)}$$

arXiv:2009.04493

$|V_{ub}|$ Exclusive

$$B^0 \rightarrow \pi^-\ell^+\nu_\ell, B^+ \rightarrow \rho^0\ell^+\nu_\ell \text{ (incl. tag)}$$

Phys. Rev. D 111 (2025) 112009

$$B \rightarrow \tau\nu \text{ (had. tag)}$$

Phys. Rev. D 112 (2025), 072002

$$B \rightarrow \mu\nu \text{ (incl. tag)}$$

Paper in preparation

$|V_{ub}|$ Inclusive

$$B \rightarrow X_u\ell\nu \text{ (had. tagged)}$$

Paper in preparation