Advancing the semileptonic precision frontier at Belle II

Philipp Horak

Color meets Flavor Symposium

Siegen, July 15, 2026

University of Victoria

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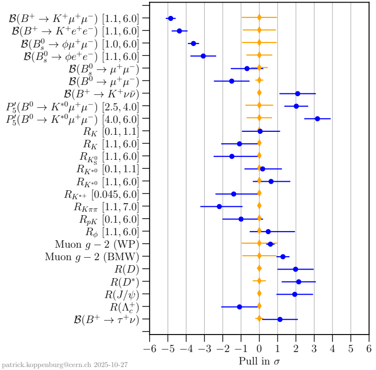
What is flavor physics telling us?



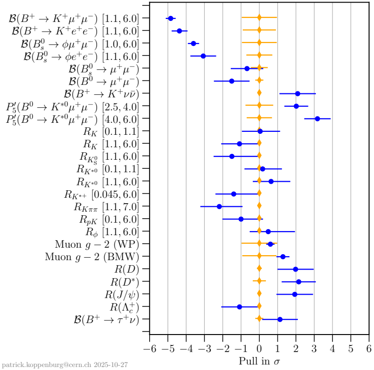
P. Koppenburg

The Standard Model is incomplete

- The SM can't explain dark matter, matter–antimatter asymmetry, . . .
- Several flavor measurements show persistent $\sim 3\sigma$ tensions

How can we determine if these tensions are genuine signs of **New Physics**?

What is flavor physics telling us?



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How can we determine if these tensions are genuine signs of **New Physics**?

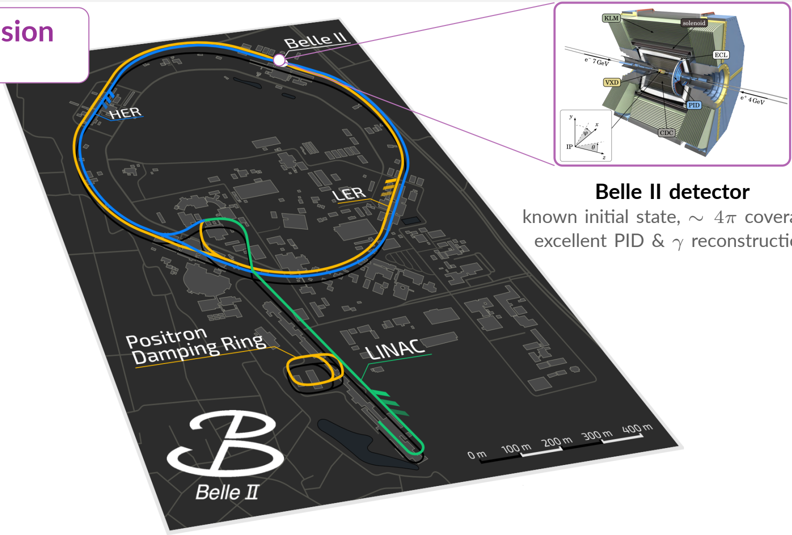
More precision

Theory 🤝 *Experiment*

More precision with the Belle II experiment

How to improve precision from B factories?

SuperKEKB
World-Record $\mathcal{L} = 5.1 \times 10^{34}$,
900 fb^{-1} collected



Belle II detector
known initial state, $\sim 4\pi$ coverage,
excellent PID & γ reconstruction

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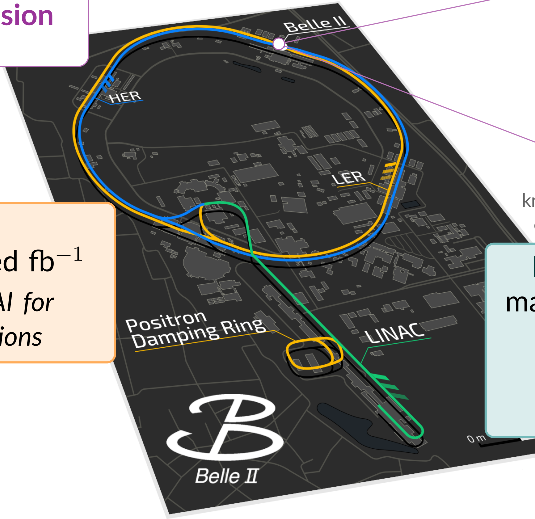
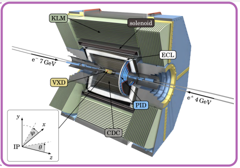


More data
maximize delivered fb^{-1}

State-of-the-art AI for Machine Operations



Belle II detector
known initial state, $\sim 4\pi$ coverage,
excellent PID & γ reconstruction

Better measurements
maximize output per fb^{-1}

Novel strategies
Improved modelling
Detector performance

The semileptonic B decay landscape

Two extremes — and the semileptonic middle ground

Belle II flavor program:

CP violation & Mixing · Rare / FCNC ($b \to s\ell\ell$, $B \to K^{(*)}\nu\bar{\nu}$) · Spectroscopy & exotics · Dark sector · τ mass/lifetime, couplings · Charm · Semileptonic $B \to X\ell\nu$

B **decays:**

Leptonic

$B^+ \to \tau^+\nu,\ \mu^+\nu$ (purely leptonic)

- ✓ Clean theory: one number, the decay constant f_B
- ✗ Missing ν reconstruction
- ✗ Helicity-suppressed ($\propto m_\ell^2$) $\Rightarrow$ tiny $\mathcal{B}$ $\mathcal{O}(10^{-4} - 10^{-7})$,

clean theory, hard experiment

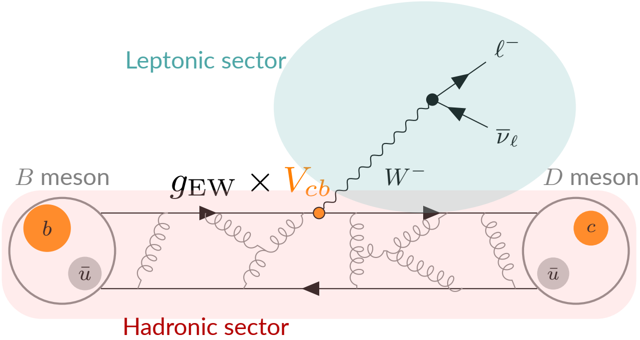
Hadronic

$B \to K\pi,\ DK,\ \pi\pi$ (purely hadronic)

- ✓ Large rates
- ✓ Easy to reconstruct
- ✗ Non-factorizable QCD

rich experiment, hard theory

The semileptonic $b \to c$ decay



- Tree-level CKM-favored process
  - High branching ratios: $\sim \frac{1}{4}$ **of all B meson decays**
- Amplitude **factorizes:** leptonic and hadronic currents

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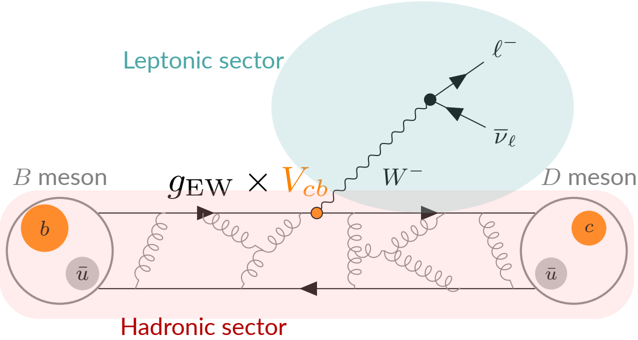
The semileptonic $b \to c$ decay

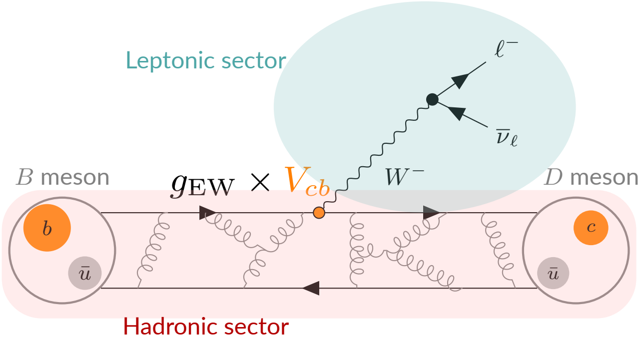


- Tree-level CKM-favored process
  - High branching ratios: $\sim \frac{1}{4}$ **of all B meson decays**
- Amplitude **factorizes:** leptonic and hadronic currents

$b \to u \ell \nu$

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

The semileptonic $b \to c$ decay

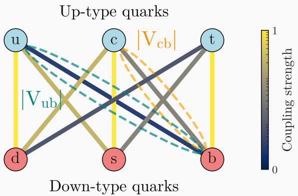


Clean observables / parameters

$R(D^{(*)}), V_{cb}, V_{ub}\ , A_{\mathrm{FB}}, P_\tau(D^*), F_{L,\tau}(D^{(*)})$

Two puzzles or three puzzles?

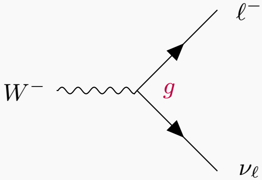
Quark mixing



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

V_{cb}, V_{ub} **puzzle**

Lepton flavor universality

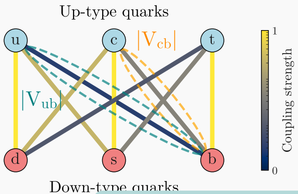


- Are the lepton flavor couplings universal?

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

Two puzzles or three puzzles?

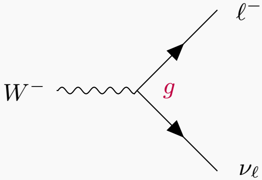
Quark mixing



- How large … $b \leftrightarrow c$ cou…

V_{cb}, V_{ub} **puzzle**

Lepton flavor universality



… flavor couplings

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

$B \to X_c \ell \nu$ hadronic system

Is there a third puzzle connecting the two?

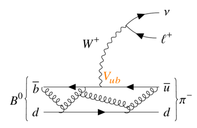
D^{**} **modelling**, $\mathcal{B}_{\mathrm{SL}}$ *gap*

Better measurements:

Maximize output per fb^{-1}

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

Exclusive

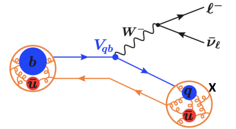


Reconstruct specific final states

Method: Parameterize the $b \to u/c$ 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

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

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

Experimental status and Belle II impact

Exclusive $|V_{cb}|$

$\bar{B} \to D\ell\bar{\nu}_\ell$

$\bar{B} \to D^*\ell\bar{\nu}_\ell$

Exclusive $|V_{ub}|$

$\bar{B} \to \pi\ell\bar{\nu}_\ell$

$\Lambda_b \to p\mu\bar{\nu}_\mu$

Inclusive $|V_{cb}|$

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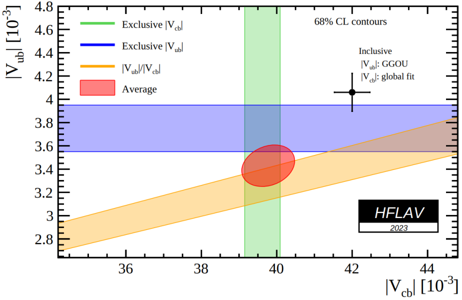
Inclusive $|V_{ub}|$

$\bar{B} \to X_u\ell\bar{\nu}_\ell$



Long-standing $\sim 3\sigma$ tension

$|V_{cb}|$ excl. — PRD 112 032010
$|V_{cb}|$ excl. — PRD 108 092013
$|V_{cb}|$ incl. — PRD 107 072002
$|V_{cb}|$ incl. — JHEP 10 068
$|V_{ub}|$ excl. — PRD 111 112009
$|V_{ub}|$ excl. — PRD 112 072002
$|V_{ub}|$ incl. — PRD 113 032004

Experimental status and Belle II impact

V_{cb}, V_{ub} puzzle | Lepton flavor universality | $b \to c$ modelling

$|V_{cb}|$ from $B \to D\ell\nu$
PRD 112 (2025), 032010
*C. Schwanda, **PH***

Exclusive $|V_{cb}|$

$\bar{B} \to D\ell\bar{\nu}_\ell$
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Exclusive $|V_{ub}|$

$\bar{B} \to \pi\ell\bar{\nu}_\ell$
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Inclusive $|V_{cb}|$

$\bar{B} \to X_c\ell\bar{\nu}_\ell$

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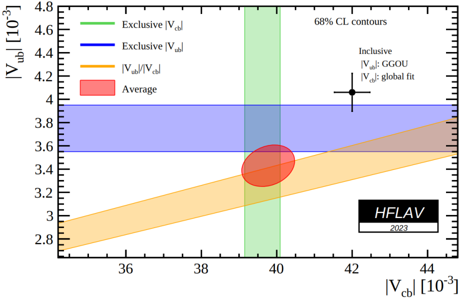

New hybrid model of $b \to u$ decays
arXiv:2603.25785, *submitted to JHEP*
*B. Kowalewski, T. Martinov, **PH***

Long-standing $\sim 3\sigma$ tension

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$|V_{ub}|$ incl. — PRD 113 032004

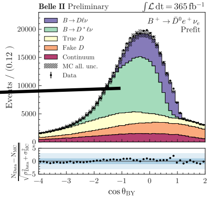
$|V_{cb}|$ from $B \to D\ell\nu$

PRD 112, 112009

V_{cb}, V_{ub} **puzzle** | Lepton flavor universality | $b \to c$ modelling

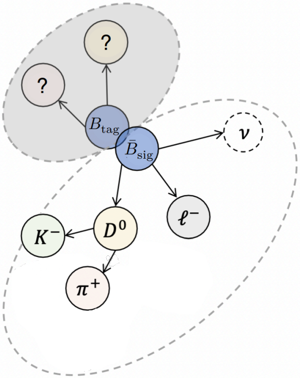
Excl. V_{cb}	**Excl.** V_{ub}
Incl. V_{cb}	**Incl.** V_{ub}

- $B \to D\ell\nu$ final state with inclusive tag method
  - Higher efficiencies enable fiducial cuts on clean candidates
  - No tag side calibration



Challenge:
Control over
background modelling

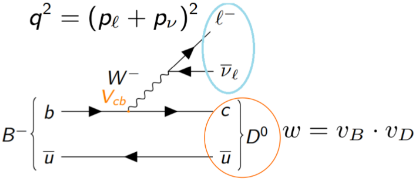
$365\ \mathrm{fb}^{-1}$



C. Schwanda (Vienna), **PH**

$|V_{cb}|$ from $B \to D\ell\nu$

PRD **112**, 112009



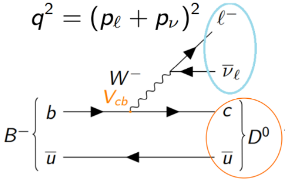
Novel reconstruction of q^2/w combining Rest-of-Event and $\Upsilon(4S)$ kinematics

C. Schwanda (Vienna), **PH**

$|V_{cb}|$ from $B \to D\ell\nu$

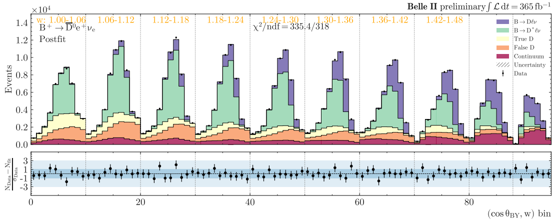
PRD **112**, 112009

$$q^2 = (p_\ell + p_\nu)^2$$



$$w = v_B \cdot v_D$$

Simultaneous fit in all w regions



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$|V_{cb}|$ from $B \to D\ell\nu$

PRD **112**, 112009

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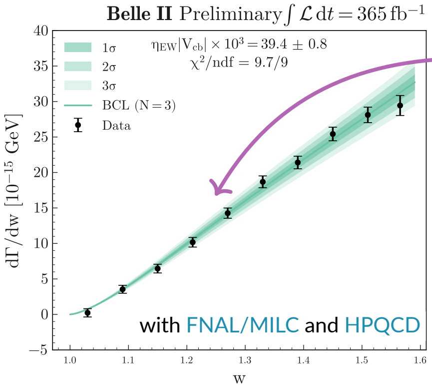

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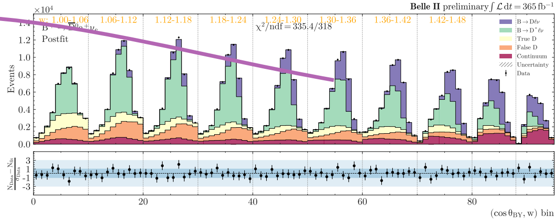

C. Schwanda (Vienna), **PH**

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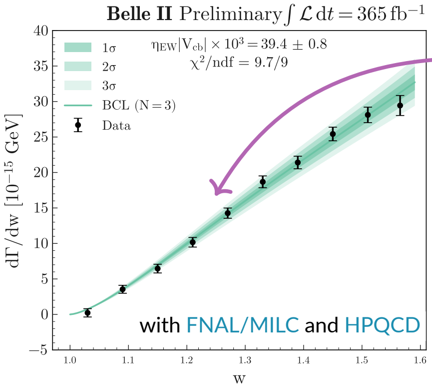
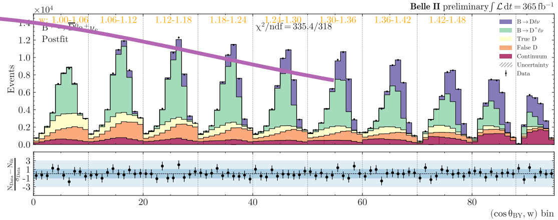
PRD **112**, 112009



with FNAL/MILC and HPQCD

Simultaneous fit in all w regions



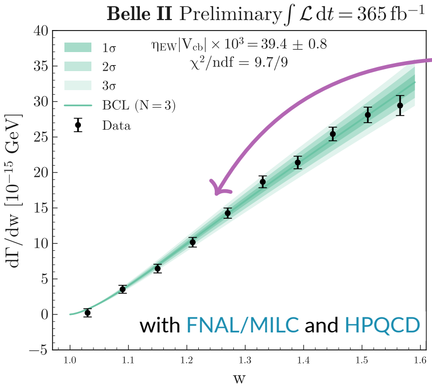
$$|V_{cb,\mathrm{BCL}}| = (39.2 \pm 0.4_{\mathrm{stat.}} \pm 0.6_{\mathrm{sys.}} \pm 0.5_{\mathrm{th.}}) \times 10^{-3}$$

World's most precise fully exclusive $|V_{cb}|$!

- 2% total uncertainty with 365 fb^{-1} vs 2.8% with 711 fb^{-1} at Belle

C. Schwanda (Vienna), **PH**

$|V_{cb}|$ from $B \to D\ell\nu$



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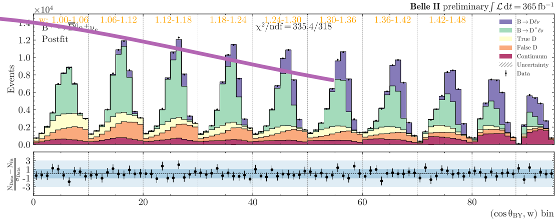

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#1: *Improved precision through better strategies*

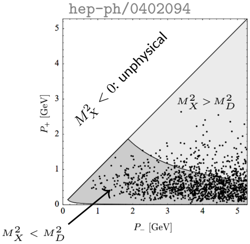
C. Schwanda (Vienna), **PH**

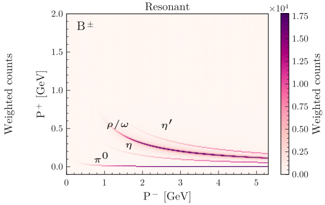
Inclusive $|V_{ub}|$: the hybrid model

2603.25785, *submitted to JHEP*

Excl. V_{cb}	**Excl.** V_{ub}
Incl. V_{cb}	**Incl.** V_{ub}

$P_\pm = E_X \mp |\vec{p}_X|$





The challenge

Inclusive $B \to X_u \ell\nu$ must describe *all* hadronic final states:

Non-resonant (high M_X): HQE, different models on the market
Resonant (low M_X): $\pi, \rho, \omega, \eta, \eta'$ — measured separately

Models that allow event generation:

DFN [De Fazio, Neubert '99]

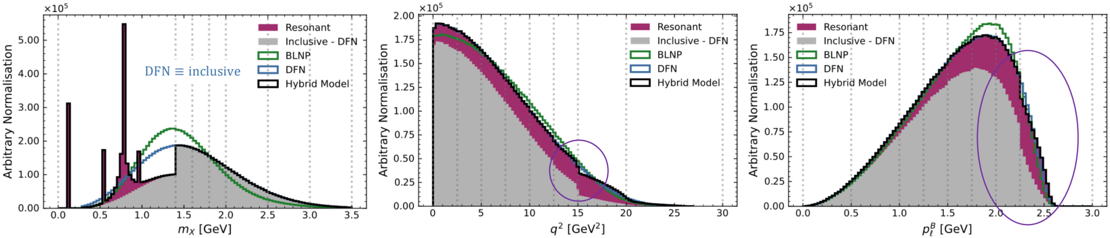
BLNP [Bosch, Lange, Neubert, Paz '04/'05]

B. Kowalewski (Victoria), T. Martinov (Trieste), **PH**

Shortcomings of the conventional method

2603.25785, *submitted to JHEP*

V_{cb}, V_{ub} **puzzle** | Lepton flavor universality | $b \to c$ modelling

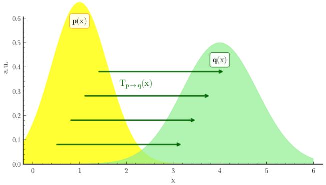


1. Large M_X discontinuity at 1.4 GeV bin boundary
2. More subtle discontinuities in q^2 and E_ℓ^B
3. Spectral moments of inclusive model not conserved (HQE predictions)
4. Negative weights spoil the hybrid for some theory models

B. Kowalewski (Victoria), T. Martinov (Trieste), **PH**

Optimal transport: a new solution

2603.25785, *submitted to JHEP*



Fundamentally binned vs fundamentally unbinned

Earth Mover's Distance

$$\mathrm{EMD} = \min_T \sum_{i,j} T_{ij}\, C_{ij}$$

$$C_{ij} = \sqrt{(\Delta P_-)^2 + (\Delta P_+)^2}$$

Reassign inclusive events kinematically closest to the resonant decays

B. Kowalewski (Victoria), T. Martinov (Trieste), **PH**

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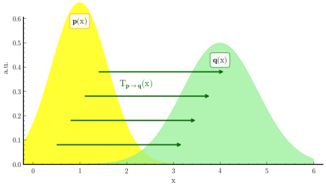

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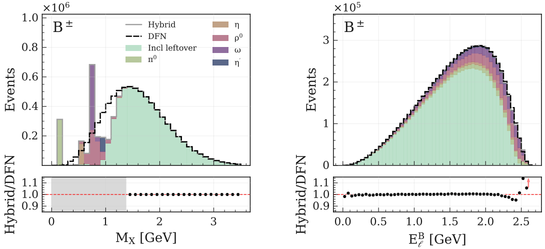

- Constructing hybrid through optimal transport solves multiple problems:
  - No discontinuities
  - No negative weights
  - Flexible vs. inputs
  - Conserves HQE properties of the incl.

B. Kowalewski (Victoria), T. Martinov (Trieste), **PH**

Optimal transport: a new solution

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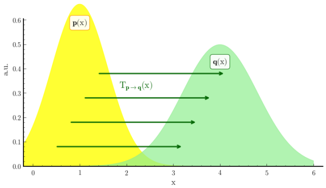

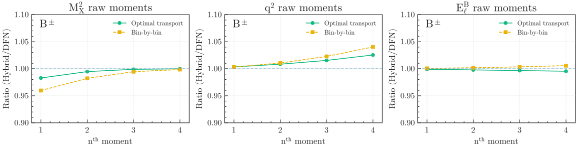

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Reassign inclusive events kinematically closest to the resonant decays

$\langle M_X^2 \rangle$ error: $7.0\% \to 0.7\%$ $\quad \langle E_\ell^B \rangle$: $2.2\% \to 0.2\%$
Mean over all moments: $4.1\% \to 1.0\%$

B. Kowalewski (Victoria), T. Martinov (Trieste), **PH**

Optimal transport: a new solution

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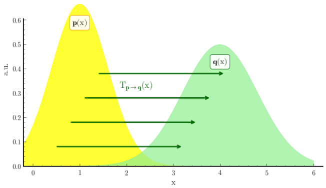

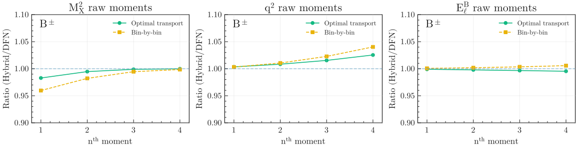

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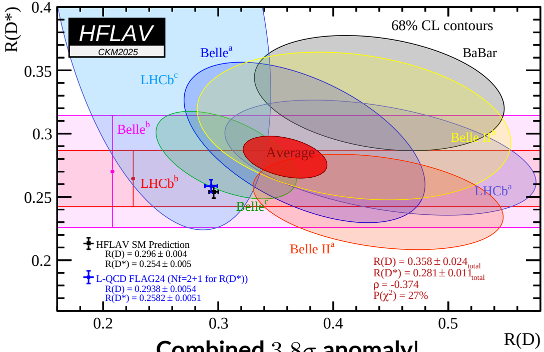
#2: *More precision through better modelling*

B. Kowalewski (Victoria), T. Martinov (Trieste), **PH**

Belle II contributions to LFU, $R(D^{(*)})$

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



Combined 3.8σ anomaly!

Belle II: τ/ℓ universality

$R(D^*)$, $R(D)$ had. tag	$\sim 10\%$, 16%	to be subm.
$R(D^+)$, $R(D^{*+})$ SL tag	$\sim 13\%$, 22%	PRD 112 (2025)
$R(X_{\tau/\ell})$ had. tag	$\sim$17%	PRL 132 (2024)

Belle II: e/μ universality

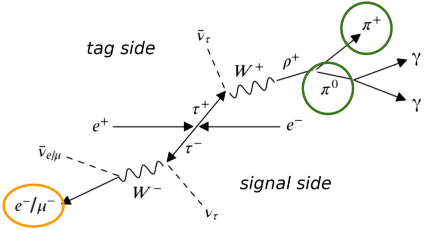
$R_{e/\mu}(B \to D^*\ell\nu)$	∼2%	PRD 108 (2023)
$R_{e/\mu}(B \to D\ell\nu)$ ★	∼2%	PRD **112**, 112009
$R(X_{e/\mu})$	∼2%	PRL 131 (2023)
$R_\mu(\tau \to \ell\nu\nu)$ ★	∼0.4%	JHEP **08** 205

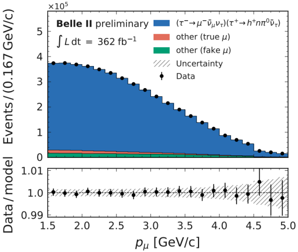
...

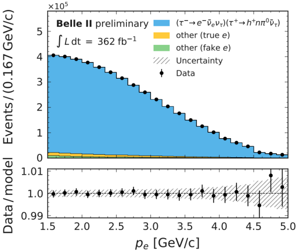
★ P. Feichtinger, Z. Gruberová, M. Villanueva, G. Inguglia, A. Martini, P. Rados, G. Raeuber, A. Rostomyan, **PH**

Light-lepton universality in τ decays

JHEP **2024** (08) 205







$$R_\mu = \frac{\mathcal{B}(\tau \to \mu\nu\nu)}{\mathcal{B}(\tau \to e\nu\nu)} \overset{\mathrm{SM}}{=} 0.9726$$

Tag: $\tau \to \pi^\pm(\pi^0)\nu$ low bkg, high eff.
Binned ML fit in p_ℓ ($362\,\mathrm{fb}^{-1}$, $\texttt{pyhf}$)

$$R_\mu = 0.9675 \pm 0.0007_{\mathrm{stat}} \pm 0.0036_{\mathrm{syst}}$$
$$g_\mu / g_e\big|_\tau = 0.9974 \pm 0.0019$$ **(world best)**

Leading sys: charged lepton ID 0.32%, total syst. 0.37%

P. Feichtinger, Z. Gruberová, M. Villanueva, G. Inguglia, A. Martini, P. Rados, G. Raeuber, A. Rostomyan, **PH**

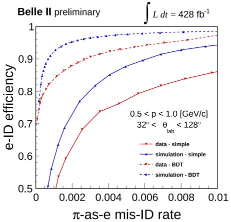
Better particle identification

arXiv:2606.26274 (subm.)

V_{cb}, V_{ub} puzzle | Lepton flavor universality | $b \to c$ modelling

BDT replaces likelihood PID
+ better triggers
$\hookrightarrow$ 1-prong tag ($\tau \to \pi^{\pm}(\pi^0)\nu$) viable
$\hookrightarrow$ $> 2\times$ **stat. gain** vs BaBar
with **less data** (362 vs 467 fb^{-1})

Efficiency:
$\varepsilon_e = 99.7\%, \quad \varepsilon_\mu = 93.9\%$
Fake rates:
$\pi \to e: \; 0.9\%, \quad \pi \to \mu: \; 3.1\%$
Kinematic restriction: $\theta_\ell \in (0.82, 2.13)$, $p_\ell \in (1.5, 5.0)$ GeV



- R_μ lepton ID systematic 0.32%
  - Comparable to BaBar with more complex algorithm

Belle II LeptonID group, **PH**

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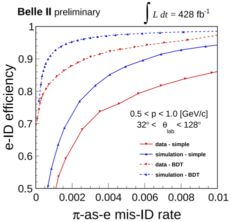


Belle II LeptonID group, **PH**

- R_μ lepton ID systematic 0.32%
  - Comparable to BaBar with more complex algorithm

***#3:** More precision with better detector performance*

How well do we understand $b \to c\ell\nu$?

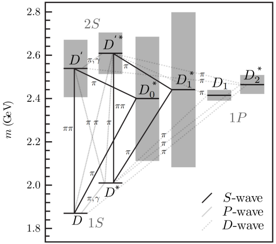
see [R. van Tonder]

V_{cb}, V_{ub} puzzle | Lepton flavor universality | **$b \to c$ modelling**

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

$\mathrm{D}^0\ell^+\nu_\ell$	$\mathrm{D}^{*0}\ell^+\nu_\ell$	$\mathrm{D}^{**0}\ell^+\nu_\ell$ + Other	Gap
$2.31\,\%$	$5.05\,\%$	$2.38\,\%$	$\sim 1.05\,\%$

Updating with recent HFLAV gives 1.8%!



D^{**} and gap limit measurements

University of Victoria

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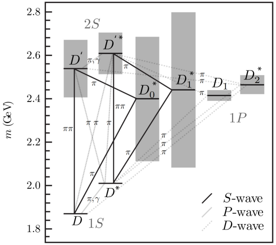

D^{**} **and gap limit measurements**

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

Well measured

Room for improvement

Some hints from BaBar & Belle

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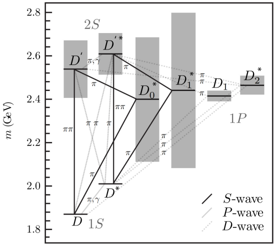

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Some hints from BaBar & Belle

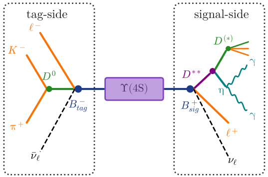
"Best guess"

Disentangling the gap

Search for $B \to D\eta\ell\nu$ at Belle II

- Never measured — will set first experimental limits
- Candidate to (partially) explain $\mathcal{B}_{\text{incl}} - \sum \mathcal{B}_{\text{excl}}$ deficit
- Belle II: excellent $\eta \to \gamma\gamma$ reconstruction
- If gap-sized: $< 10\%$ precision; else UL at $\mathcal{O}(10^{-4})$

In preparation with B. Kowalewski, P. Prasad (Victoria)



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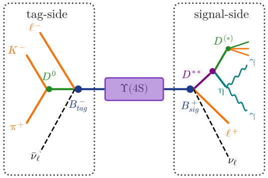
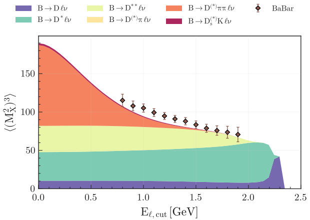




Gap from moments: missing-contribution analysis

- Moments of incl. distributions measured: $\langle M_X^n \rangle$, $\langle E_\ell^n \rangle$, ...
- Subtract contributions of well-measured excl. modes
- Invert residual moments $\to$ glimpse of the gap shape
  - **gap model-independent indirect analysis**

In preparation with D. van Dyk (Durham), M. Prim (Bonn)

More data

Maximize delivered fb^{-1}

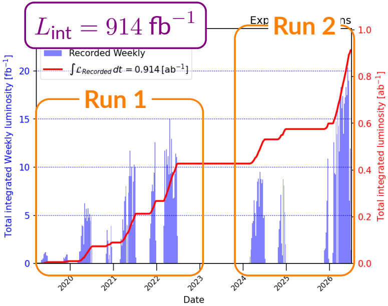
Data taking hurdles

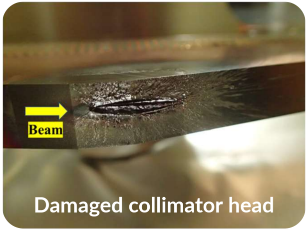
✓ Strong Belle II physics program in per-fb^{-1} performance

⚠ Data accumulation has not kept up with projections

- **Major problem:** Occurrences of Sudden Beam Loss (**SBL**)

SBL $=$ Significant current lost without precursor

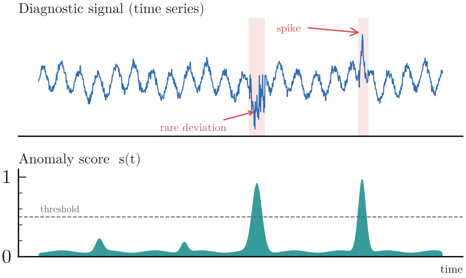




$\Rightarrow$ **Countermeasures required to unlock the full Belle II physics potential**

Anomaly detection for beam diagnostics

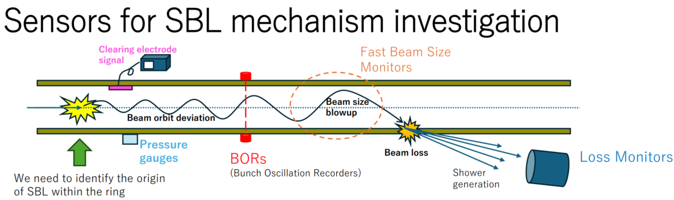
Time-series anomaly detection



Anomaly score $s(t)$ that spikes at rare behavior

- Many methods on the market
  - Kalman filter
  - (Deep-)LSTM
  - Auto-encoder / transformers

SuperKEKB beam diagnostics



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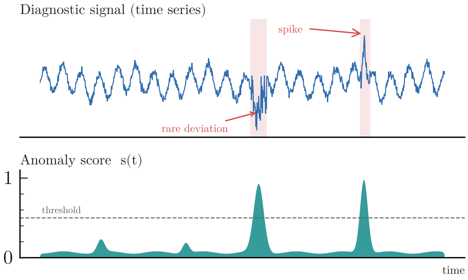

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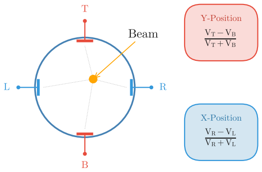


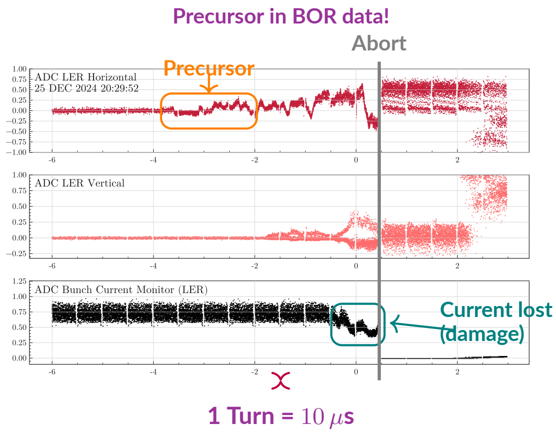
Mode:	*Bunch-by-bunch & Turn-by-turn*
Bunches:	$\sim$2300 circulating
Turn duration:	$\approx 10\ \mu$s

$\approx$ **200 million hits/s**

Sampling rate of BOR system

Detecting SBL precursors: the challenge

to be submitted



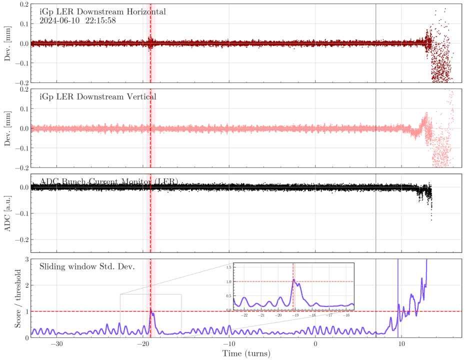
Goal: algorithmic detection of anomalous behavior

+ As early as possible, to mitigate damage to accelerator
– Avoid false alarms, to maximize operation time

H. Haigh, G. Inguglia, C. Krause, **PH**

Learning what “normal” looks like

to be submitted



	Simple score
Method	sliding window std. dev.
Detects precursors	✓
False alarms	✗ (baseline osc.)

H. Haigh, G. Inguglia, C. Krause (all Vienna), **PH**

University of Victoria

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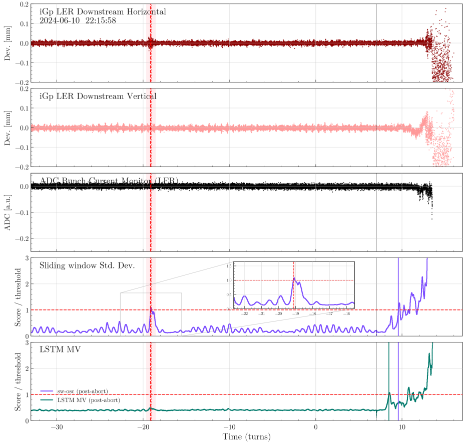
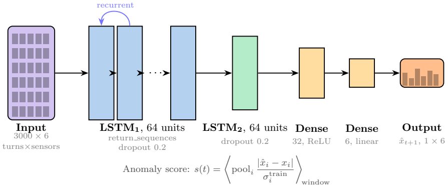
to be submitted



	Simple score	DeepLSTM
Method	sliding window std. dev.	semi-supervised LSTM
Detects precursors	✓	✓
False alarms	$\sim 10\%$	$\to 0$

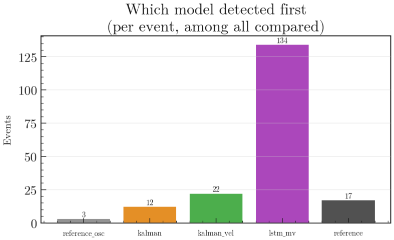


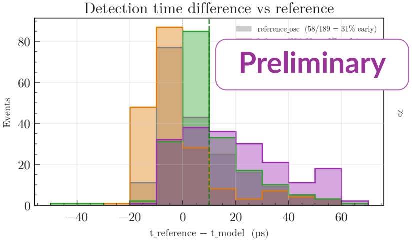
H. Haigh, G. Inguglia, C. Krause (all Vienna), **PH**

Early warnings and the path to deployment

to be submitted

80% of 2024c SBL events:
≥ 1 turn ($\approx 10\ \mu$s) advance warning over conventional loss monitors





Preliminary

Next: real-time FPGA deployment

Working with hardware experts to implement the algorithm on FPGA for online abort-trigger integration

- Convert model to firmware via **hls4ml**
- Latency budget $\lesssim 1\ \mu$s to preserve predictive lead time

with H. Nakayama (KEK), T. Blake (Victoria), K. Yoshihara (Hawaii)

H. Haigh, G. Inguglia, C. Krause (all Vienna), **PH**

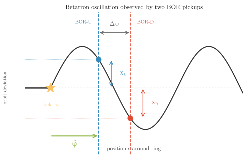
Locating the SBL source: phase analysis

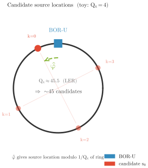
in preparation

After an SBL, we can tell if it is compatible with any given position on the ring

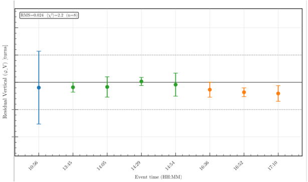
Cross-check with pressure burst, collimator positions, etc.

Already in use in 2026ab run-period

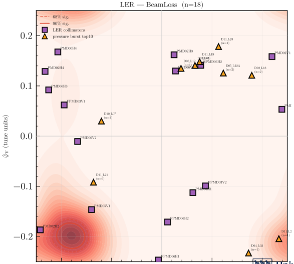




Knocker validation



Preliminary: Comparing extracted ϕ with collimator positions



> ### Method: BOR phase reconstruction
> Two pickups at betatron phase separation $\Delta\psi$:
>
> $X_U = A\sin\varphi,\ X_D = A\sin(\varphi + \Delta\psi)$
>
> Extract source-phase phi_i per-bunch ϕ_i
>
> Assumes single dominant kick source per event

H. Nakayama, T.-S. Lau, **PH**

Anomaly detection across the accelerator

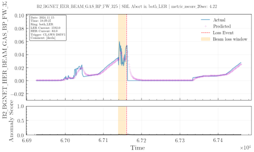
in preparation

DeepLSTM model but on big data

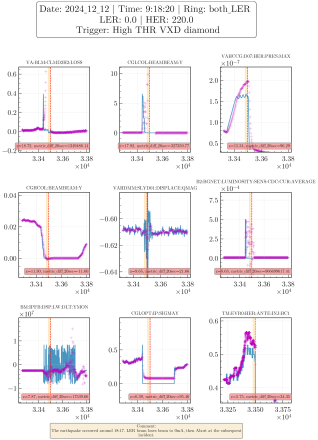
- Extend from BOR to all SuperKEKB process variables:
  - currents, pressures, voltages, loss monitors, ...

$\rightarrow$ rank most anomalous PVs by how anomalous they are before abort

Example: rising beam-gas pressure before SBL



Top-9 anomalous PVs before an SBL



N. Rück, C. Gottschlich, M. Prim (all Bonn), **PH**

Summary

$|V_{cb}|$, $|V_{ub}|$
exclusive vs. inclusive tension

Lepton flavor universality
new physics or mismodelling?

$b \to c$ modelling
what fills the gap?

Better measurements

- CKM elements
  - $|V_{cb}|$ from $B \to D\ell\nu$, inclusive-tag recoil
  - $|V_{ub}|$ — optimal-transport hybrid model
- Lepton universality
  - τ-LFU: R_μ via BDT-based lepton ID
  - $R(D^{(*)})$ at Belle II
- $b \to c$ gap
  - $B \to D\eta\ell\nu$ gap-mode search
  - Gap shape from moment inversion

More data

- ✓ ML-based SBL detection — earlier beam aborts
- ✓ BOR phase analysis — locate SBL source
- ▶ FPGA deployment via hls4ml
- ▶ Full-machine anomaly monitoring (PV database)

Thank you!

Back-up

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

V_{cb}, V_{ub} puzzle | Lepton flavor universality | $b \to c$ modelling

$|V_{cb}|$ Exclusive

$\boxed{B \to D\ell\nu}$

Phys. Rev. D 112 (2025), 032010

C. Schwanda, **PH**

$B^0 \to D^{*-}\ell^+\nu$

PRD 108 (2023), 092013

C. Lyu, F. U. Bernlochner, C. Schwanda, D. Dorner, L. Cao

$|V_{ub}|$ Exclusive

$B^0 \to \pi^-\ell^+\nu_\ell, B^+ \to \rho^0\ell^+\nu_\ell$

PRD 111 (2025) 112009

S. Granderath, J. Dingfelder, P. M. Lewis, F. U. Bernlochner

$B \to \tau\nu, B \to \mu\nu$

PRD 112 (2025) 072002, PRD 113 (2026) 112012

$|V_{cb}|$ Inclusive

$B \to X_c\ell\nu$ q^2 moments

PRD 107 (2023) 072002 JHEP 10 (2022) 068

M. Welsch, F. U. Bernlochner

$|V_{ub}|$ Inclusive

$B \to X_u\ell\nu$

PRD 113 (2026), 032004

T. Martinov, M. Hohmann, L. Cao, K. Tackmann, F. U. Bernlochner, M. Graf-Schreiber, M. Khan, M. Angelsmark, P. Urquijo

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

- **Exclusive $|V_{cb}|$** [PRD **112**, 112009] (also [PRD **108**, 092013])
  - $|V_{cb}| = (39.2 \pm 0.4_{\text{stat.}} \pm 0.6_{\text{sys.}} \pm 0.5_{\text{th.}}) \times 10^{-3}$

$365\ \text{fb}^{-1}$ *World-best (fully) exclusive V_{cb}*

- **Inclusive $|V_{cb}|$** [PRD **107**, 072002; JHEP **10** (2022) 068]
  - $|V_{cb}| = (41.7 \pm 0.7) \times 10^{-3}$ (Belle + Belle II)

$62\ \text{fb}^{-1}$ *Novel inclusive V_{cb} determination*

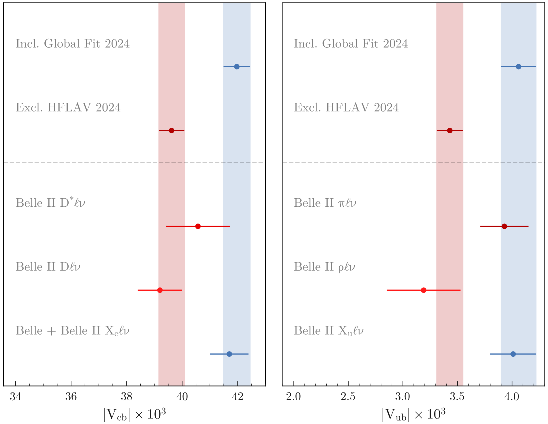
- **Exclusive $|V_{ub}|$** [PRD **111**, 112009]
  - $|V_{ub}| = (3.93 \pm 0.09_{\text{stat.}} \pm 0.07_{\text{stat.}} \pm 0.19_{\text{theo.}}) \times 10^{-3}$

$365\ \text{fb}^{-1}$ *World-best exclusive V_{ub}*

- **Inclusive $|V_{ub}|$** [PRD **113**, 032004]
  - $|V_{ub}| = (4.01 \pm 0.19_{\text{exp.}} \pm 0.08_{\text{theo.}}) \times 10^{-3}$

$365\ \text{fb}^{-1}$ *World-best† inclusive V_{ub}*

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



New era of precision with Belle II