Institut
"Jožef Stefan"
Ljubljana, Slovenija

University of Ljubljana
Faculty of Mathematics and Physics

LFU and semileptonic B decays at Belle

Luka Šantelj,

Jozef Stefan Institute and University of Ljubljana

On behalf of the Belle collaboration

ALPS 2023

Obergurgl, 26-31.3.2023

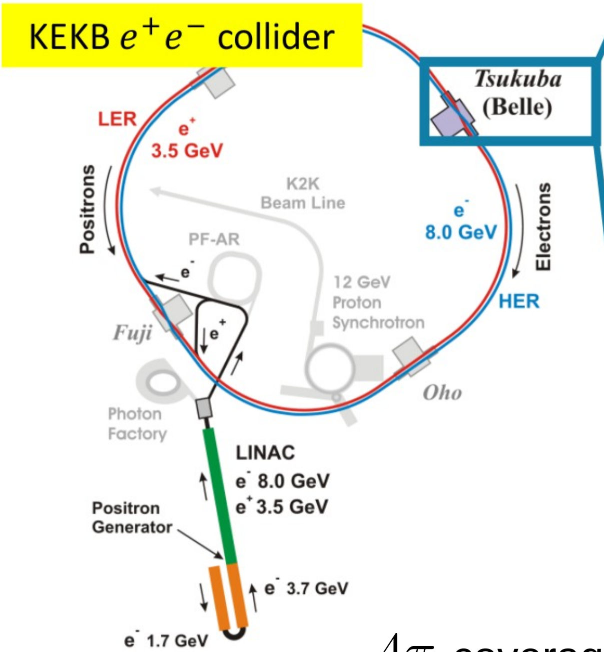
Outline

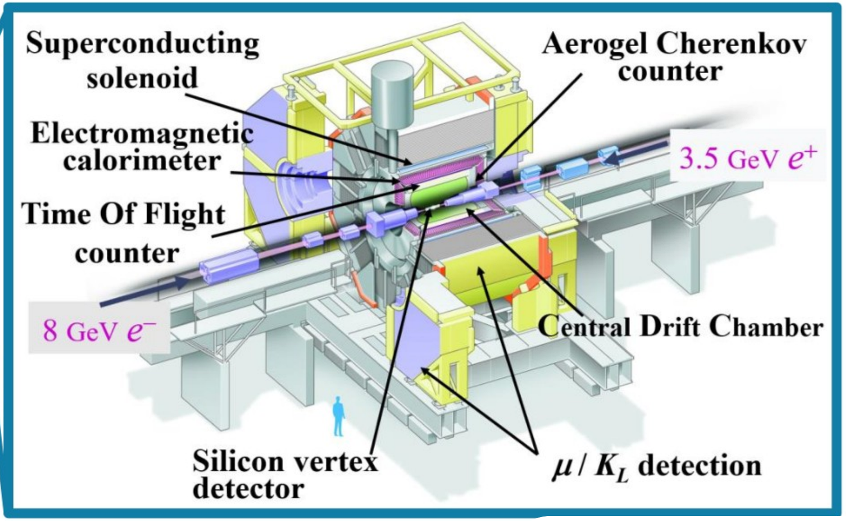
- The Belle experiment
- Summary of $R(D^{(*)})$ measurements
- Semileptonic B decays

  → Simultaneous Determination of Inclusive and Exclusive $|\mathbf{V_{ub}}|$

  → Measurement of Differential Distributions of $B \to D^{\star}\ell\nu_{\ell}$ and $|\mathbf{V_{cb}}|$
- Summary

The Belle experiment





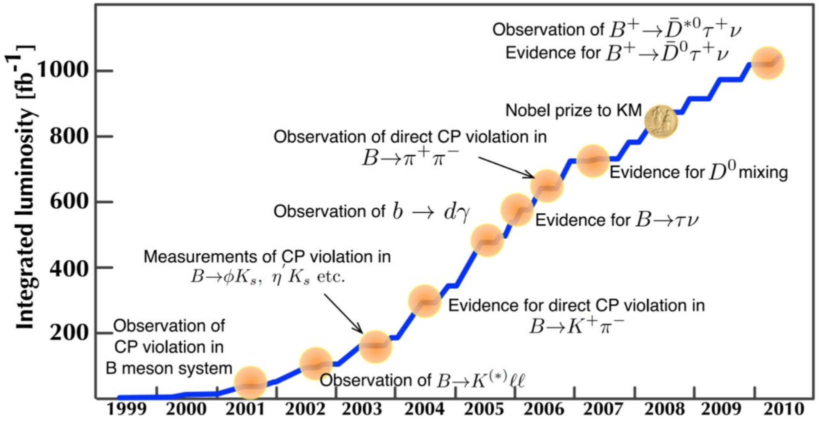
→ operated at the KEKB collider (from 1999-2010)

→ mostly at the energy of $\Upsilon(4S)$

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

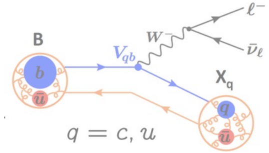
Process	No. of pairs
$e^+e^- \to \Upsilon(4S)$	772×10^6 $B\bar{B}$
$e^+e^- \to \Upsilon(5S)$	7.1×10^6 $B_s\bar{B}_s$

→ 4π coverage
→ clean e^+e^- environment with known initial state (BB pair)
→ good charged track reconstruction efficiency, particle identification, gamma reconstruction
→ excellent vertexing capabilities



LFU tests in semi-tauonic B decays

Lepton flavor universality tests: $\mathcal{R}(H_c) = \dfrac{\mathcal{B}(B \to H_c\, \tau\bar{\nu}_\tau)}{\mathcal{B}(B \to H_c\, \ell\bar{\nu}_\ell)}$ $H_C = D^{(*)}, J/\psi$ $(\ell = e, \mu)$



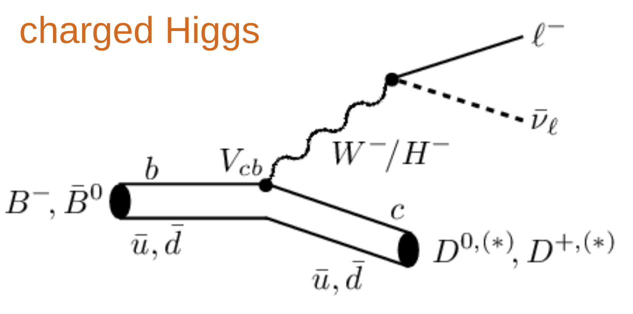
→ experimentally and theoretically convenient due to cancellation of several uncertainties in the ratio

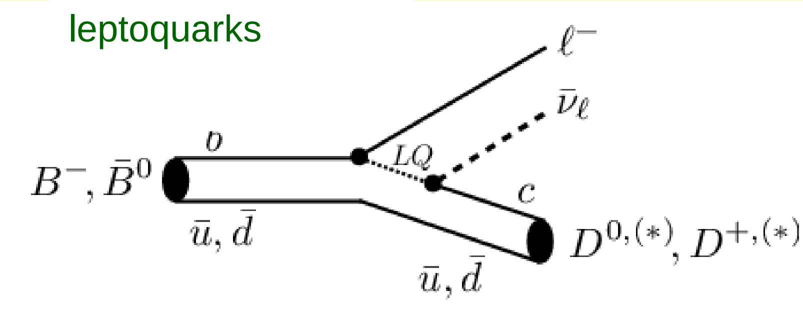
Kinematic variables: e.g. $q^2 = (p_B - p_{D^*})^2$ distributions

Polarization fractions: τ polarization, D^{*-} longitudinal polarization

Uncertainties of the SM predictions for $\mathcal{R}(H_c)$ range from 1% to 3%

→ sensitivity to NP contributions





Decay reconstruction basics

- relatively large branching fractions

- but multiple neutrinos (not detected!) in the final state → challenging decay reconstruction

→ determination of initial B momentum allows for evaluation of

$$q^2 = (p_B - p_{D^*})^2$$

momentum transfer to leptons

$$m^2_{\text{miss}} = (p_B - p_{D^{(*)}} - p_\ell)^2$$

missing mass

$$E_l^* = (p_\ell \cdot p_B)/m_B$$

charged lepton energy in B frame

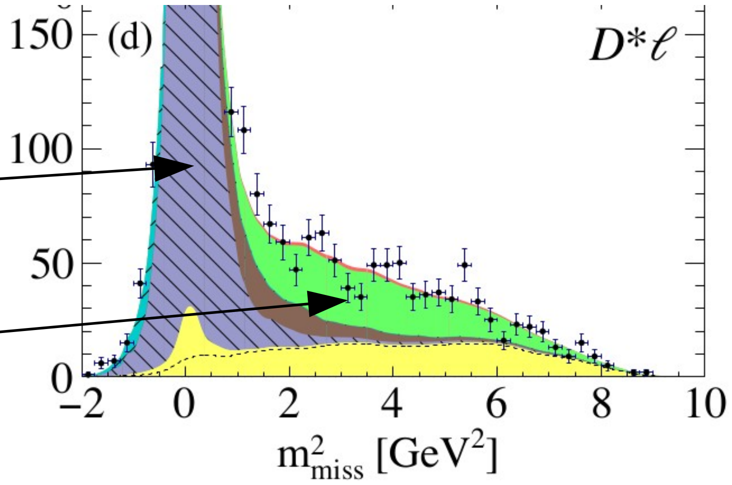
→ basis for SL decays with τ or ℓ (e, μ) separation

single neutrino

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

multiple neutrinos

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

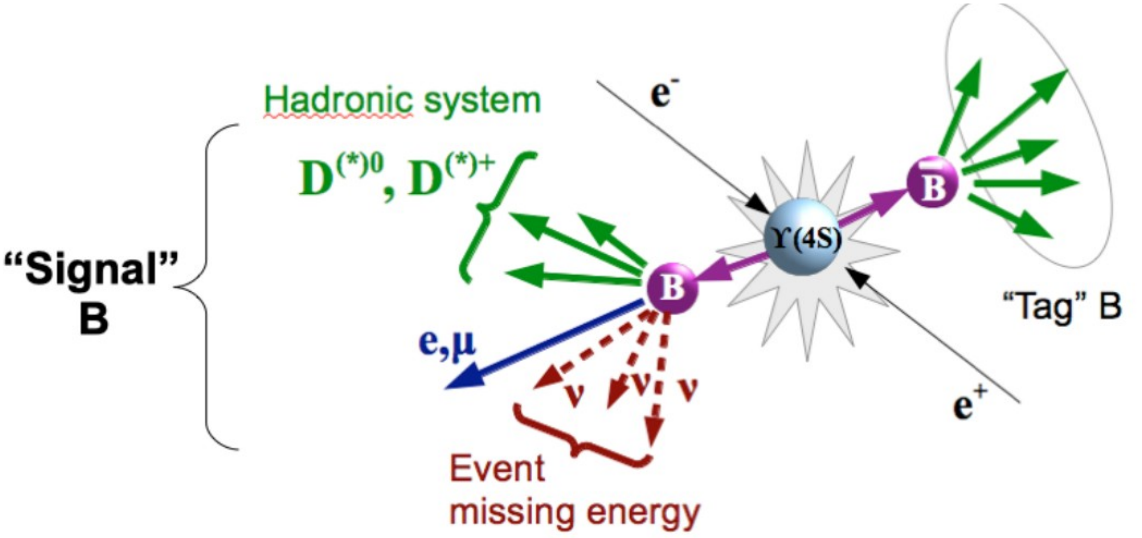


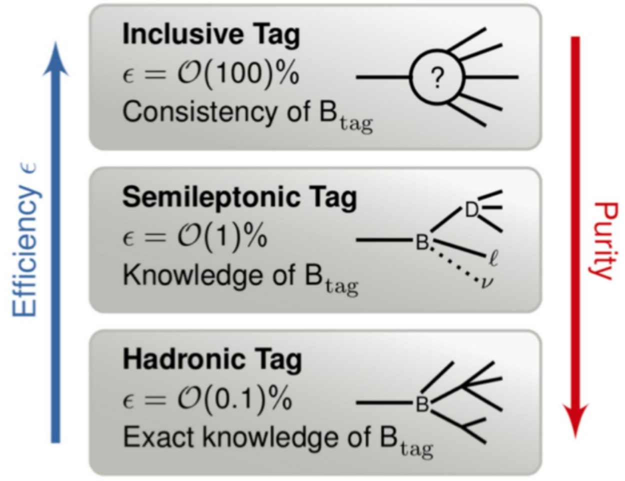
- accessible to **B factories** and **LHCb**

Decay reconstruction basics – Belle (B-factories)

- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

- fully known initial state + hermetic detector (4π) → **tagging techniques**





→ in SL decays with correct $B_{\rm tag}$ all particles in an event assigned (to $B_{\rm sig}$ or $B_{\rm tag}$)!

background events: larger $E_{\rm ECL}$

extra energy in the EM calorimeter

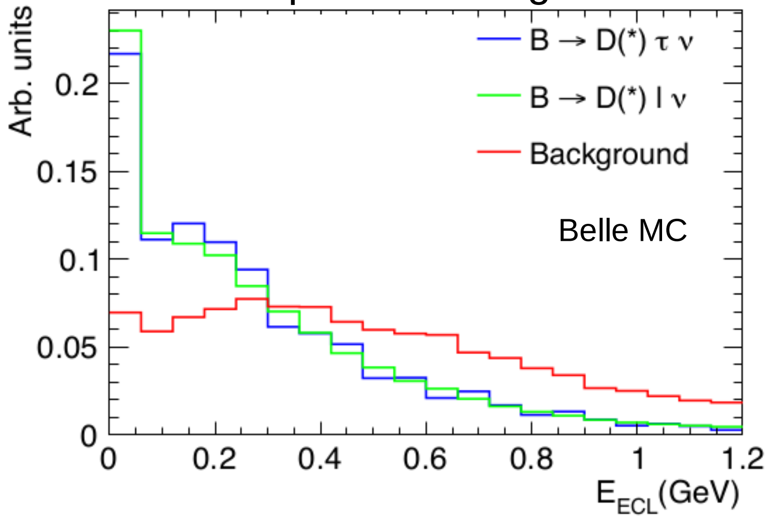
τ vs. ℓ (e,μ): $m^2_{\rm miss}$ + kinematics

Latest and most precise $\mathcal{R}(D^{(*)})$ from Belle – semi-leptonic tag

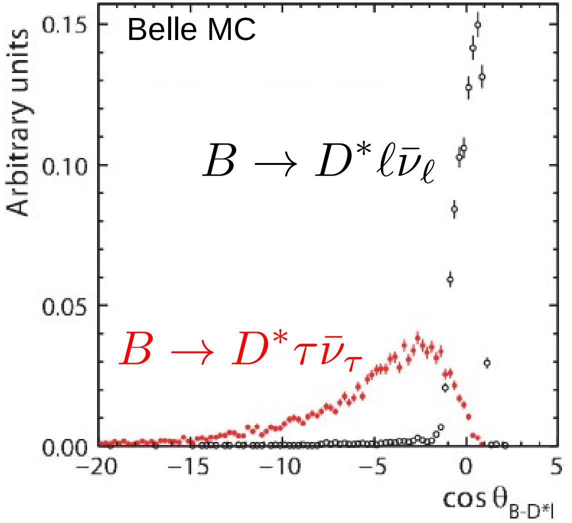
Phys. Rev. Lett. 124, 161803, arXiv:1910.05864

- using FEI (full event interpretation) for the tag-side $B \to D^{(*)} l \bar{\nu}_l$ reconstruction
- reconstructed signal modes: $D^{+}\ell^{-},\ D^{0}\ell^{-},\ D^{*+}\ell^{-},\ D^{*0}\ell^{-}\quad(\ell = e, \mu)$
- combine kinematic variables using BDT: $(\cos\theta_{B,D^{(*)}l},\ m^2_{\text{miss}},\ E_{\text{vis}}) \to \mathcal{O}_{\text{sig}}$

semi-leptonic / background



tau / light lepton



$$\equiv \frac{2E_{\text{beam}}E_{D^{(*)}\ell} - m_B^2 - m^2_{D^{(*)}\ell}}{2|\boldsymbol{p}_B||\boldsymbol{p}_{D^{(*)}\ell}|}$$

Latest and most precise $\mathcal{R}(D^{(*)})$ from Belle – semi-leptonic tag

Phys. Rev. Lett. 124, 161803, arXiv:1910.05864

- $E_{\mathrm{ECL}} - \mathcal{O}_{\mathrm{sig}}$ distributions of all samples are fit simultaneously, constraining $\mathcal{R}(D^{(*)0}) = \mathcal{R}(D^{(*)+})$

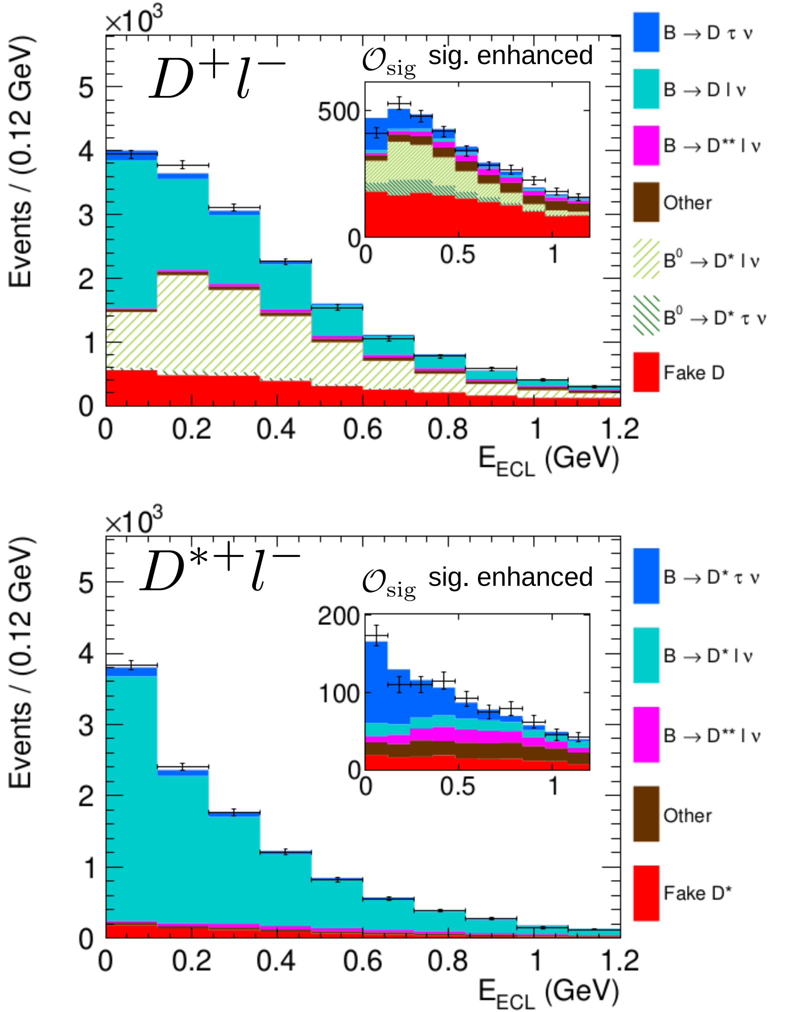
- free parameters: signal yields (τ, ℓ), $B \to D^{**} l \nu$ yield
  feed-down D^* yield

$$\mathcal{R}(D) = 0.307 \pm 0.037\,(\mathrm{stat}) \pm 0.016\,(\mathrm{syst})$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst})$$

Most precise values to date!

Main systematic uncertainties

Source	$\Delta\mathcal{R}(D)$ (%)	$\Delta\mathcal{R}(D^*)$ (%)
D^{**} composition	0.76	1.41
PDF shapes	4.39	2.25
Feed-down factors	1.69	0.44
Efficiency factors	1.93	4.12



Summary of existing B factory measurements

BELLE

Hadronic tag with $\tau \to \ell\nu\bar{\nu}$

BaBar: Phys. Rev. Lett. 109, 101802, arXiv:1205.5442

Belle: Phys. Rev. D 92, 072014, arXiv:1507.03233

Result	*BABAR*	Belle
$\mathcal{R}(D)$	$0.440 \pm 0.058 \pm 0.042$	$0.375 \pm 0.064 \pm 0.026$
$\mathcal{R}(D^*)$	$0.332 \pm 0.024 \pm 0.018$	$0.293 \pm 0.038 \pm 0.015$

Semi-leptonic tag with $\tau \to \ell\nu\bar{\nu}$

Belle: Phys. Rev. Lett. 124, 161803, arXiv:1910.05864

$$\mathcal{R}(D) = 0.307 \pm 0.037\,(\text{stat}) \pm 0.016\,(\text{syst})$$

$$\mathcal{R}(D^*) = 0.283 \pm 0.018\,(\text{stat}) \pm 0.014\,(\text{syst})$$

Hadronic tag with $\tau \to \pi\nu, \tau \to \rho\nu$

Belle τ polarization measurement

Phys. Rev. D 97 (1), 012004, arXiv:1709.00129

$$R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst})$$

$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst})$$

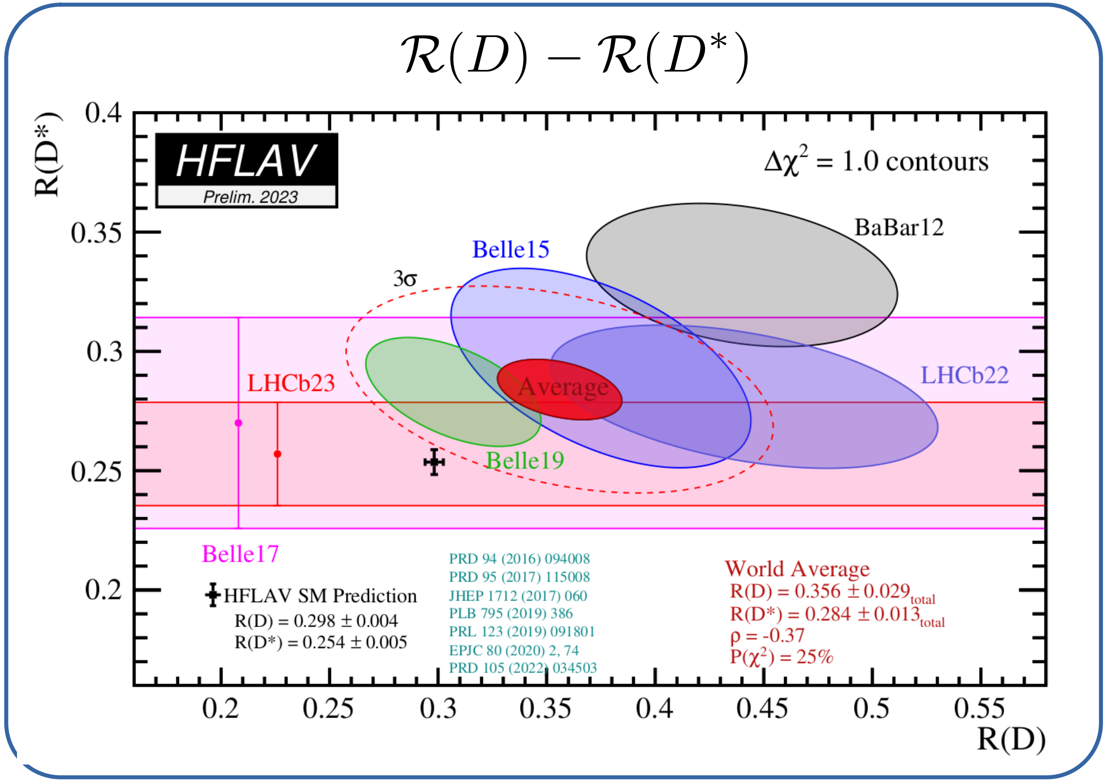
Inclusive tag with $\tau \to \pi\nu, \tau \to \ell\nu\bar{\nu}$

Belle D^{*-} polarization measurement

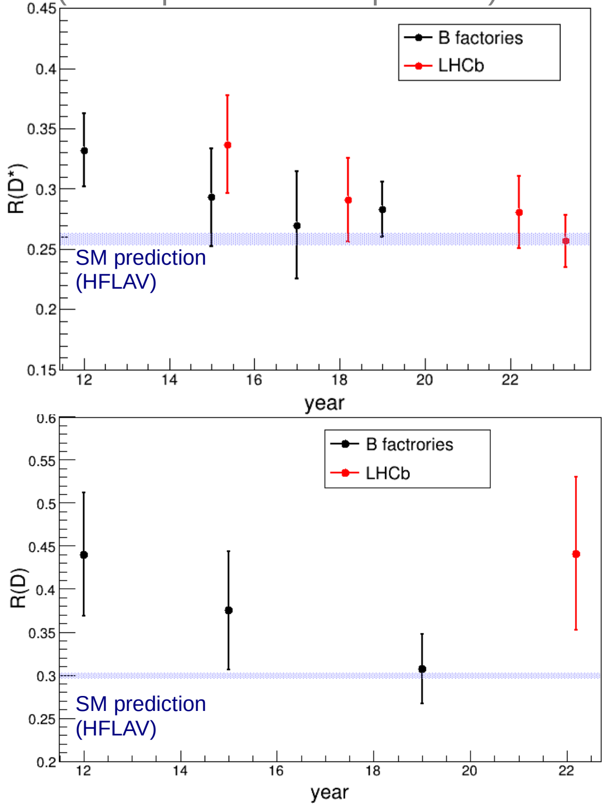
arXiv:1903.03102

$$F_{L,\tau}(D^*) = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{sys})$$

Consistency with the SM predictions



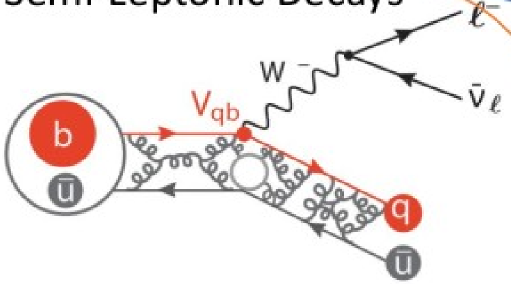
Timeline of published results
(not all points are independent)



→ present world average of $\mathcal{R}(D) - \mathcal{R}(D^*)$ deviates from the SM with significance of $\sim 3.16\ \sigma$.

$|V_{ub}|$ and $|V_{cb}|$ from semileptonic B decays

Semi-Leptonic Decays



Inclusive $|V_{ub}|$

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

Inclusive $|V_{cb}|$

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

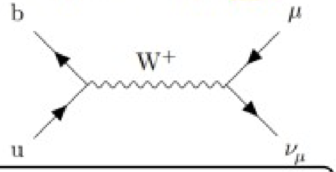
Operator Product Expansion

$$BR \propto |V_{qb}|^2 [1 + \frac{c_5(\mu)\langle O_5 \rangle(\mu)}{m_b^2} + \frac{c_6(\mu)\langle O_6 \rangle(\mu)}{m_b^3} + O(m_b^4)]$$

+ Shape Function / Fermi Motion

Leptonic Decays

Leptonic $|V_{ub}|$



$$BR \propto |V_{ub}|^2 f_B^2 m_l^2$$

f_B : B-Meson decay constant

Exclusive $|V_{ub}|$

$B \to \pi, \rho, \omega \ell \bar{\nu}_\ell$

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

$B_s \to K \mu \bar{\nu}_\mu$

Exclusive $|V_{cb}|$

$B_{(s)} \to D_{(s)}^{(*)} \ell \bar{\nu}_\ell$

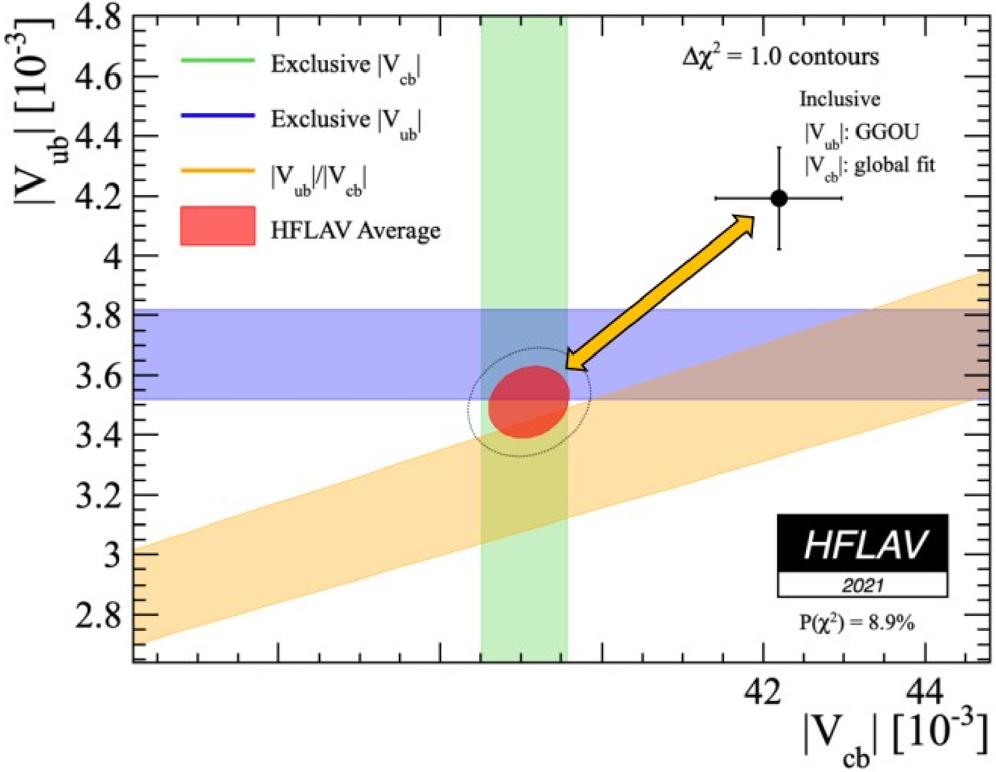
$$BR \propto |V_{qb}|^2 f^2$$

Form Factors

$\langle B | H_\mu | P \rangle = (p + p')_\mu f_+$

*from M.Prim @ DISCRETE22

Experimental status



→ longstanding significant discrepancy between $|V_{ub}|$ and $|V_{cb}|$ as determined from inclusive or exclusive measurements

→ several new results on $|V_{xb}|$ by Belle and Belle II recently

First Simultaneous Determination of Inclusive and Exclusive $|V_{ub}|$

Preliminary

$|V_{ub}^{\text{excl.}}|/|V_{ub}^{\text{incl.}}| = 0.84 \pm 0.04$

- full Belle dataset (711 fb^{-1})

- hadronic reconstruction of B_{tag}

  → allows for reconstruction of $B \to X_u \ell \nu$

  $q^2 = (p_B - p_{X_u})^2$ and $N_{\pi^\pm}$ in X_u

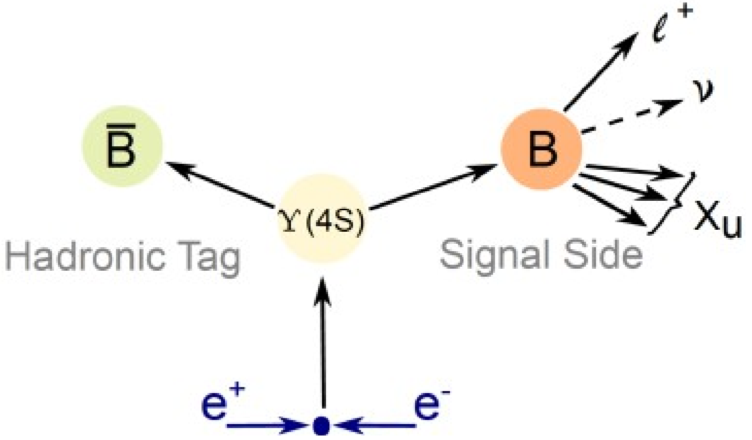
  $B^+ \to \pi^0 \ell^+ \nu$ | $B^0 \to \pi^- \ell^+ \nu$ | other $B \to X_u \ell \nu$

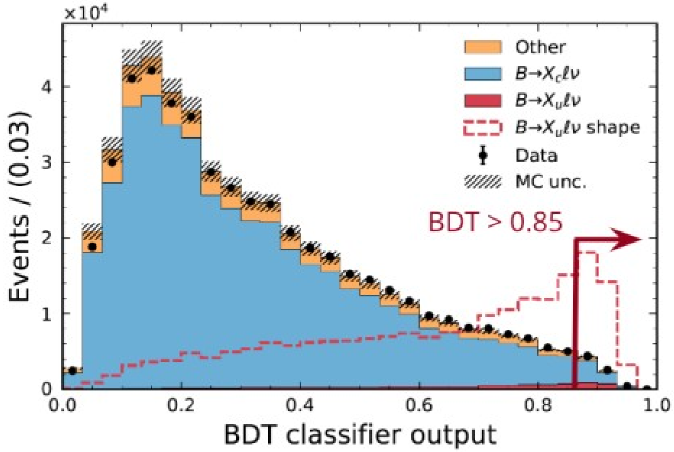
- electron or muon with $E_\ell^B = |\mathbf{p}_\ell^B| > 1\,\text{GeV}$

- BDT with 11 training features to suppress $B \to X_c \ell \nu$

  $M^2_{miss}, \chi^2_{vtx}, \#K$

- X_u thrust in the CMS to increase $B \to \pi \ell \nu$ significance





First Simultaneous Determination of Inclusive and Exclusive $|V_{ub}|$

- Likelihood fit with binned templates' normalisations and $B \to \pi\ell\nu$ form factor parameters free

$$-2\log\mathscr{L} = -2\log\prod_i \mathrm{Poisson}\left(\eta_{\mathrm{obs}}, \eta_{\mathrm{pred}}\cdot(1+\epsilon\cdot\theta)\right) + \theta\rho_\theta^{-1}\theta^T + \chi^2_{\mathrm{FF}}$$

- BCL modeling of FF is used with parameters constrained to the LQCD or LQCD+exp. fits.

- all systematics (additive and multiplicative) are added as nuisance parameters for each template.

- dominant systematics are: $B \to X_u\ell\nu$ modeling, $u \to X_u$ fragmentation and rescontruction efficiencies (tagging, etc.)

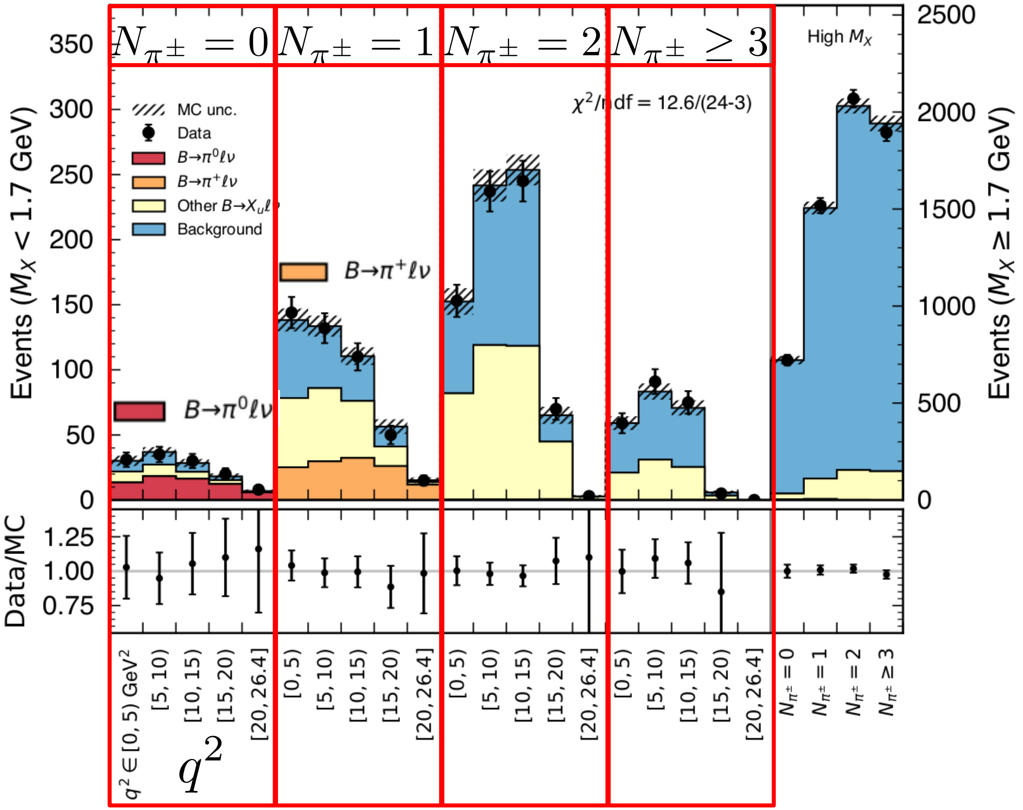
- finally $|V_{ub}|$ is extracted via:

$$\mathscr{B}(B \to X_u\ell\nu) = \mathscr{B}(B \to \pi^0\ell\nu) + \mathscr{B}(B \to \pi^+\ell\nu) + \mathscr{B}(B \to X_u^{\mathrm{other}}\ell\nu)$$

$$\Delta\mathscr{B}(B \to X_u\ell\nu) = \mathscr{B}(B \to X_u\ell\nu)\cdot\epsilon_{\Delta\mathrm{PS:E}_\ell^B>1\mathrm{GeV}}$$

$$|V_{ub}| = \sqrt{\frac{\mathscr{B}}{\tau_B\cdot\Gamma}}$$

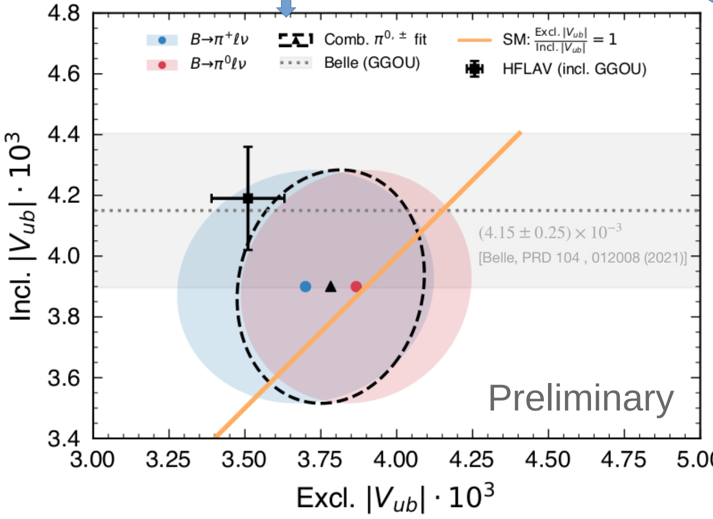
Preliminary

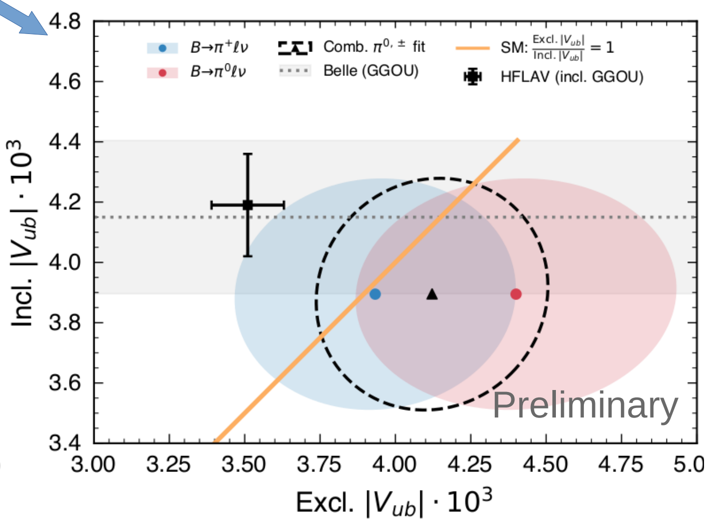


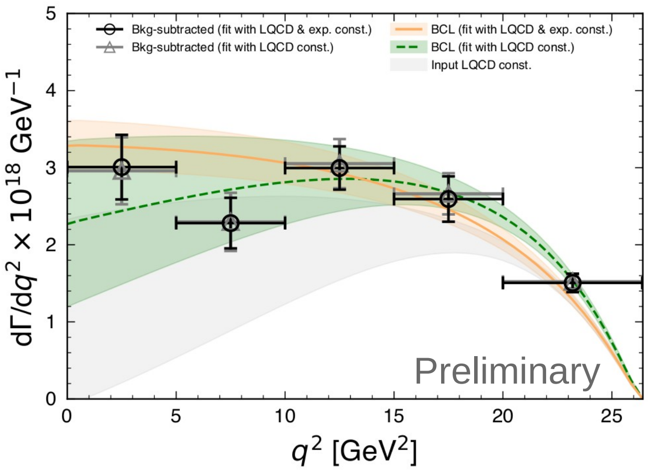
First Simultaneous Determination of Inclusive and Exclusive $|V_{ub}|$

Various fit scenarios considered:

→ separate $B^+ \to \pi^0 \ell^+ \nu$ and $B^0 \to \pi^- \ell^+ \nu$ and combined.
→ (LQCD+exp.) and (LQCD only) constraints for $B \to \pi \ell \nu$ form factors.







$$\left|V_{ub}^{\text{excl.}}\right| = (3.78 \pm 0.23 \pm 0.16 \pm 0.14) \times 10^{-3}$$
$$\left|V_{ub}^{\text{incl.}}\right| = (3.90 \pm 0.20 \pm 0.32 \pm 0.09) \times 10^{-3}$$

for (LQCD+exp.) combined fit

Weighted average of excl. & incl.

$(3.85 \pm 0.26) \times 10^{-3}$

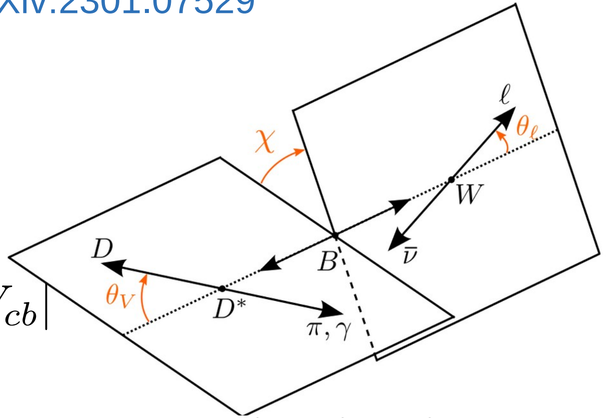
CKM global fit (w/o $|V_{ub}|$): $(3.64 \pm 0.07) \times 10^{-3}$, **compatible within 0.8σ**

$$\left|V_{ub}^{\text{excl.}}\right| / \left|V_{ub}^{\text{incl.}}\right| = 0.97 \pm 0.12$$

→ compatible with the W.A. and with the SM

Measurement of Differential Distributions of $B \to D^{\star}\ell\nu_{\ell}$ and $|\mathbf{V_{cb}}|$

arXiv:2301.07529



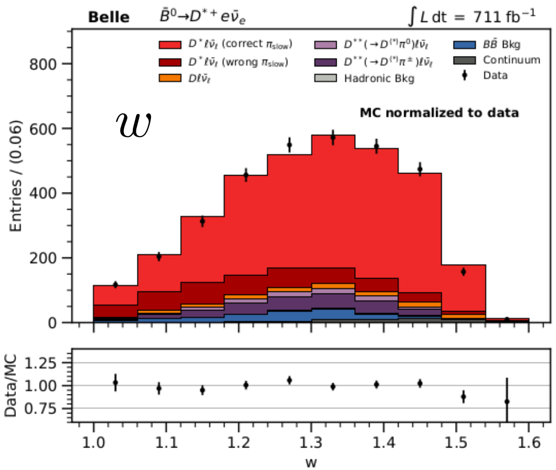
- full Belle dataset (711 fb^{-1}), 4 separate decay modes: $B^{\pm,0}, \ell = e, \mu$

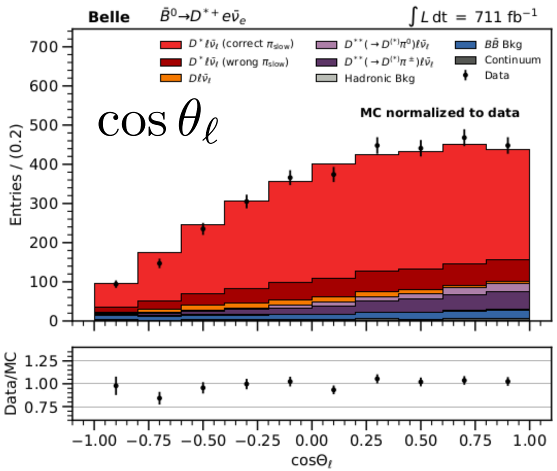
- hadronic reconstruction of B_{tag} using Belle II tools (Full Event Interpretation)

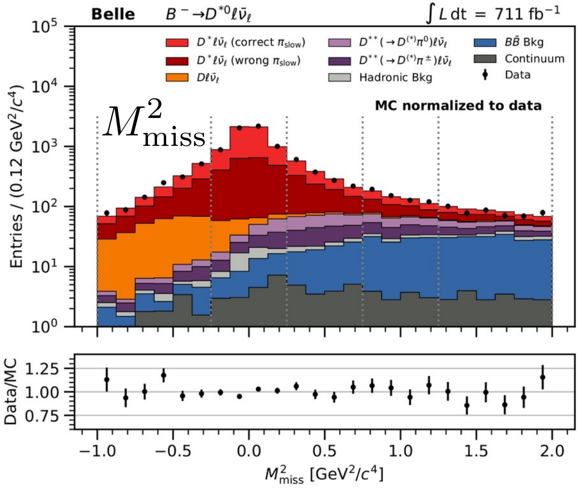
- fit the form factor parametrisation to the measured differential shapes in $w, \cos\theta_\ell, \cos\theta_V, \chi$ and use W.A. branching fraction to determine $|V_{cb}|$

- for each decay in each bin background is subtracted via fitting of model independent variable: $M^2_{\text{miss}} = p^2_{\text{miss}} = \left(p_{e^+e^-} - p_{\text{tag}} - p_{D^*} - p_\ell\right)^2$
  → resulting in 160 fits

$w = v \cdot v' = (m_B^2 + m_{D^*}^2 - q^2)/(2m_B m_{D^*})$
hadronic recoil parameter







Measurement of Differential Distributions of $B \to D^\star \ell \nu_\ell$ and $|\mathbf{V_{cb}}|$

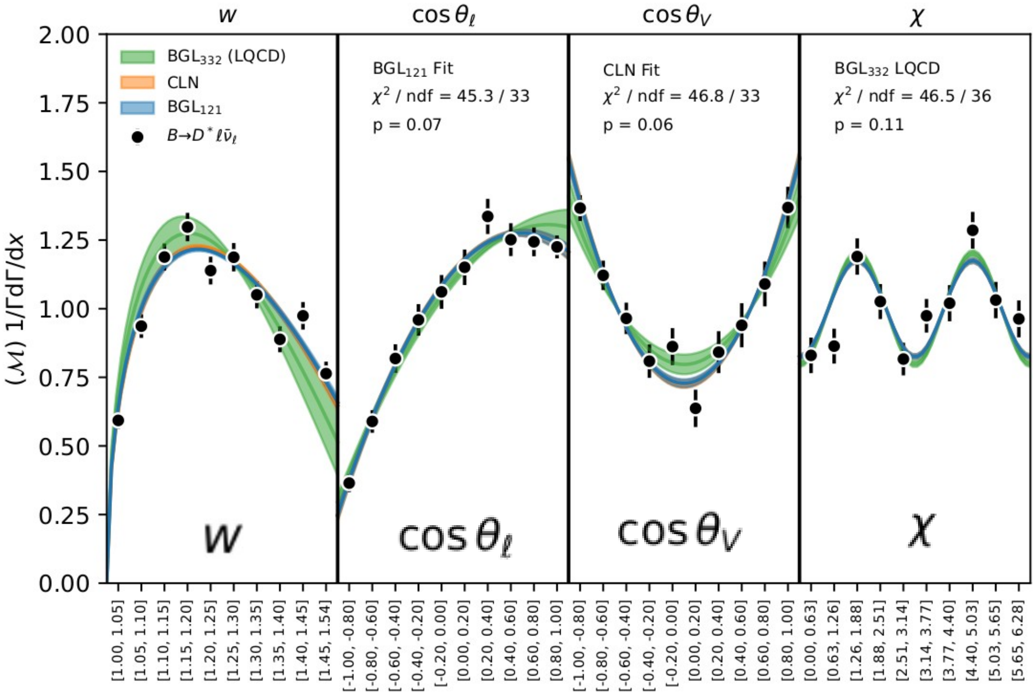
arXiv:2301.07529

- shapes are corrected for resolution and acceptance effects
- averaged shapes are used to fit BGL and CLN parametrization to the data
- External constraints on branching fraction (HFLAV) and $h_X = h_{A_1}(1) = 0.906 \pm 0.013$

FF at zero-recoil (FNAL/MILC)

$$\chi^2 = \left(\frac{\Delta \vec{\Gamma}^{\mathrm{m}}}{\Gamma^{\mathrm{m}}} - \frac{\Delta \vec{\Gamma}^{\mathrm{p}}(\vec{x})}{\Gamma^{\mathrm{p}}(\vec{x})} \right) C_{\mathrm{exp}}^{-1} \left(\frac{\Delta \vec{\Gamma}^{\mathrm{m}}}{\Gamma^{\mathrm{m}}} - \frac{\Delta \vec{\Gamma}^{\mathrm{p}}(\vec{x})}{\Gamma^{\mathrm{p}}(\vec{x})} \right)^T$$
$$+ (\Gamma^{\mathrm{ext}} - \Gamma^{\mathrm{p}}(\vec{x}))^2 / \sigma(\Gamma^{\mathrm{ext}})^2$$
$$+ (h_X - h_X^{\mathrm{LQCD}}) C_{\mathrm{LQCD}}^{-1} (h_X - h_X^{\mathrm{LQCD}})$$

$\vert\mathbf{V_{cb}}\vert$	BGL_{121}	CLN
$B^+ \to D^{*0} \ell \bar{\nu}_\ell$	42.0 ± 1.2	41.4 ± 1.2
$\bar{B}^0 \to D^{*+} \ell \bar{\nu}_\ell$	38.5 ± 1.3	38.3 ± 1.1
$B \to D^* \ell \bar{\nu}_\ell$	40.6 ± 0.9	40.1 ± 0.9



Measurement of Differential Distributions of $B \to D^{\star}\ell\nu_\ell$ and $|\mathbf{V_{cb}}|$

BELLE

arXiv:2301.07529

- additional fit scenarios are tested:
  using recent lattice constraints on B→ D* FF
  beyond zero recoil

- D* longitudinal polarization fraction

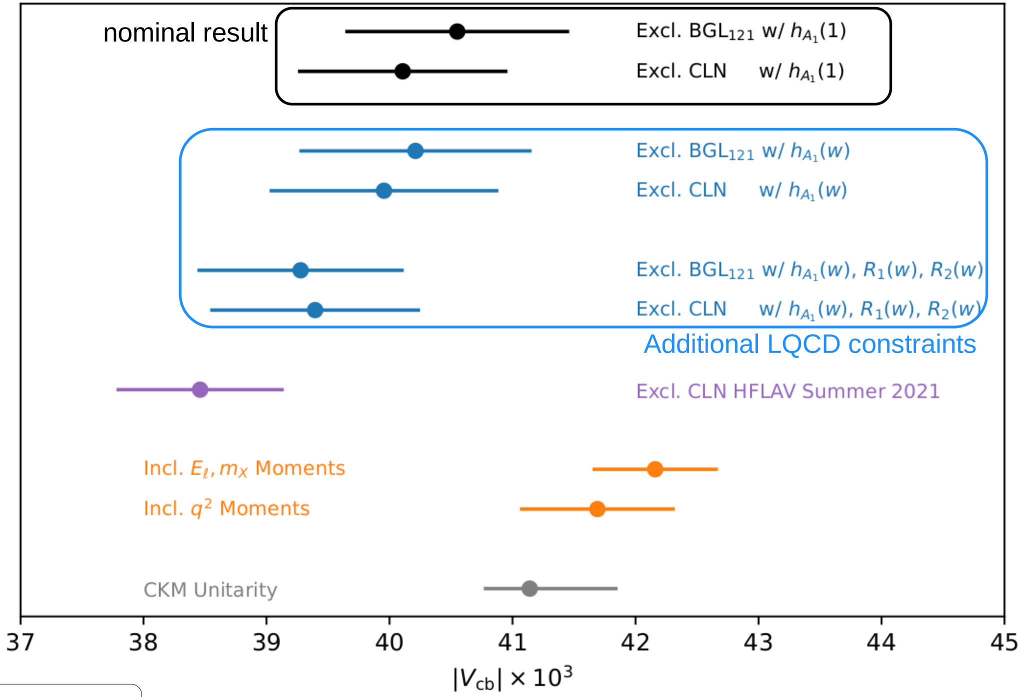
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_V} = \frac{3}{2}\left(F_L\cos^2\theta_V + \frac{1-F_L}{2}\sin^2\theta_V\right)$$

	F_L^{D*}
$B \to D^*\ell\bar{\nu}_\ell$	$0.501 \pm 0.012 \pm 0.003$

- Forward-Backward asymmetry

	$\Delta A_{FB} = A_{FB}^{\mu} - A_{FB}^{e}$
$B \to D^*\ell\bar{\nu}_\ell$	$0.022 \pm 0.026 \pm 0.007$

- LFU ratio $R_{e\mu} = \frac{\mathcal{B}(B \to D^* e\bar{\nu}_e)}{\mathcal{B}(B \to D^* \mu\bar{\nu}_\mu)} = 0.990 \pm 0.021 \pm 0.023$



- All consistent with no LFU violation.

Overview of recent Belle and Belle II results

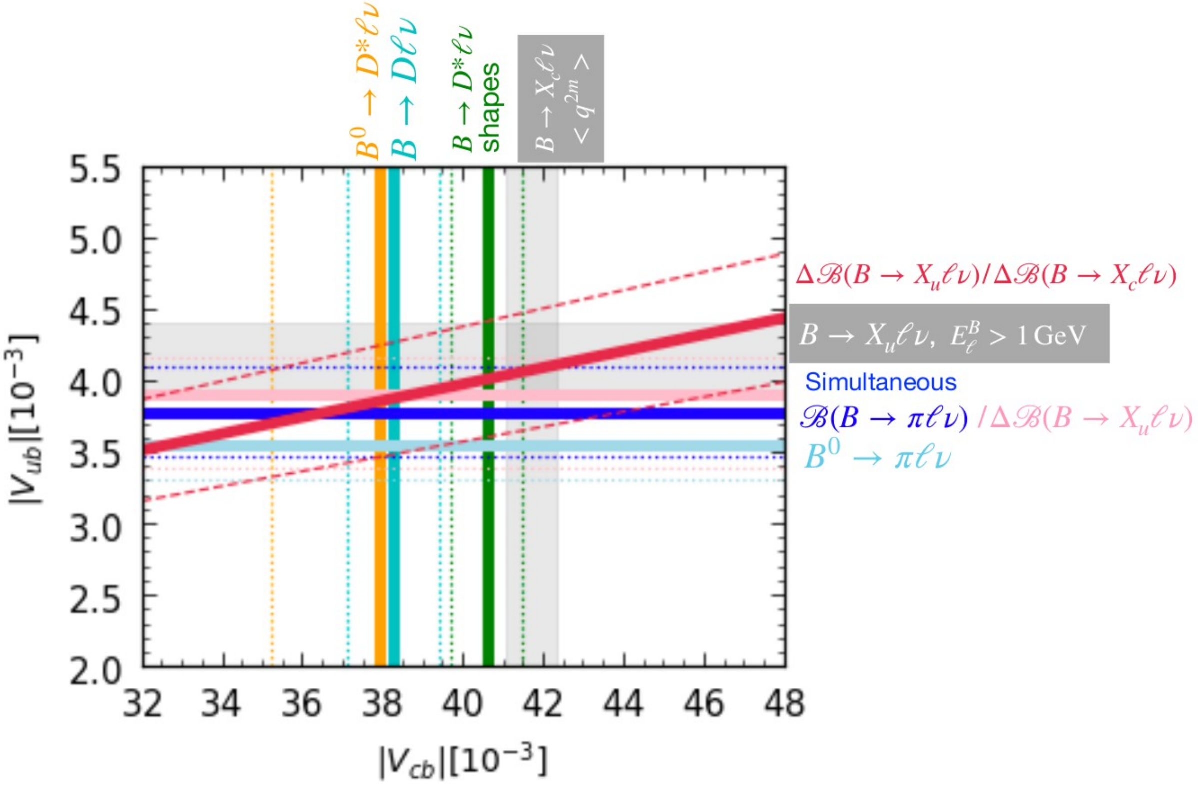
$|V_{cb}|$

Belle II	$B^0 \to D^*\ell\nu$	arXiv:2301.04716
Belle II	$B \to D\ell\nu$	arXiv:2210.13143
BELLE	$B \to D^*\ell\nu$ shapes	arXiv:2301.07529
BELLE / Belle II	$B \to X_c\ell\nu$ $< q^{2m} >$	PRD 104 , 112011 (2021) arXiv:2205.06372 JHEP 10 (2022) 068

$|V_{ub}|$

BELLE	$\Delta\mathcal{B}(B \to X_u\ell\nu)/\Delta\mathcal{B}(B \to X_c\ell\nu)$	preliminary
BELLE	$B \to X_u\ell\nu,\ E_\ell^B > 1\,\mathrm{GeV}$	PRD 104 , 012008 (2021)
BELLE	Simultaneous $\mathcal{B}(B \to \pi\ell\nu)$ / $\Delta\mathcal{B}(B \to X_u\ell\nu)$	preliminary
Belle II	$B^0 \to \pi\ell\nu$	arXiv:2210.04224

Hadronic tag   Untagged



→ more results are yet to come, which will help to resolve the inclusive/exclusive puzzle

→ continuous effort from exp. and theory side still needed

Summary

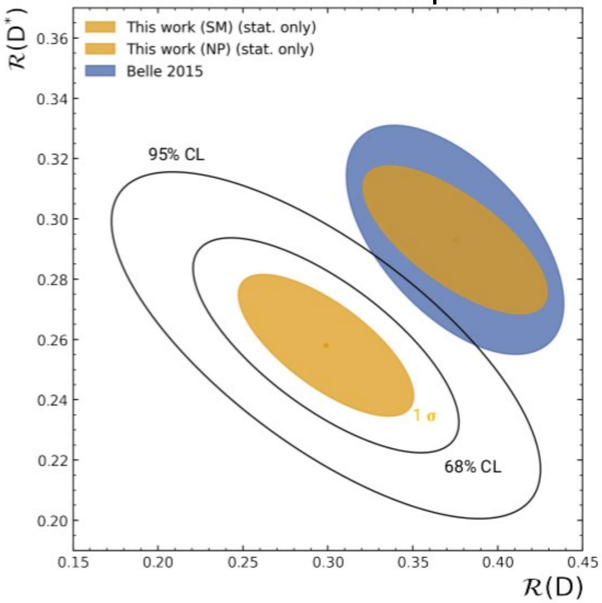
- even 10+ years after the stop of its operation Belle keeps producing important physics results

- “legacy” $\mathcal{R}(D^{(*)})$ measurement (had. tagging with leptonic tau dacays) based on the Belle II tools (FEI → increased efficiency, improved MC modeling, etc.) and many other measurements in the pipeline

- Belle II has up to now collected ~1/2 of Belle data set size and gradual boost is expected in the next year

  → due to detector and data analyses improvements already producing competitive/leading results (stay tuned for the new $\mathcal{R}(D^{*})$ and more coming soon)

stat. uncert. MC expectation



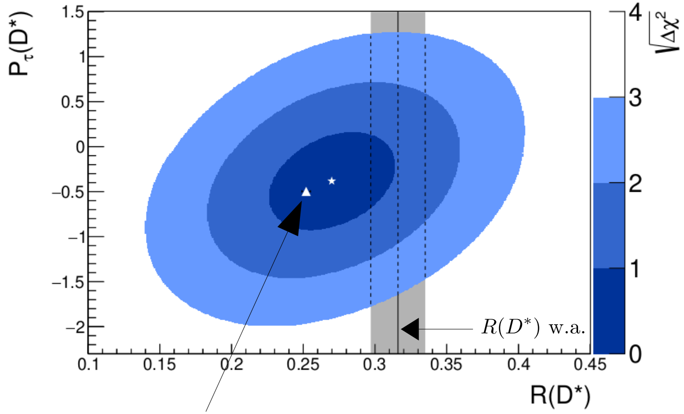
Thank you!

Related observables in semi-tauonic decays

Belle τ polarization measurement

Phys. Rev. D 97 (1), 012004, arXiv:1709.00129

$$P_\tau(D^{(*)}) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \quad \Gamma^\pm - \tau \text{ helicity}$$

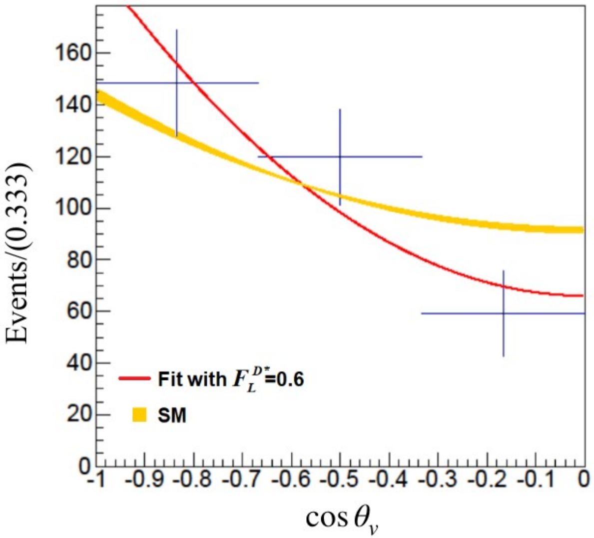


SM expectation

Phys. Rev. D 88, 094012 (2013) arXiv:1309.0301

Belle D^{*-} longitudinal polarization fraction

arXiv:1903.03102



Phys. Rev. D 98, 095018 (2018) arXiv:1808.03565

consistent with the SM at 1.6σ