Karlsruhe Institute of Technology

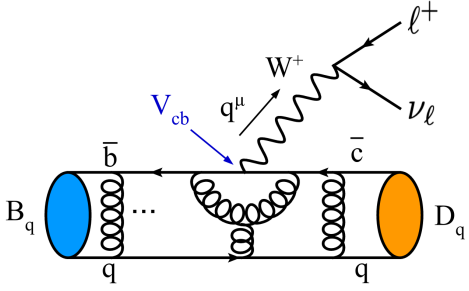
Recent Measurements of $|V_{cb}|$ and $|V_{ub}|$ with Belle (II)

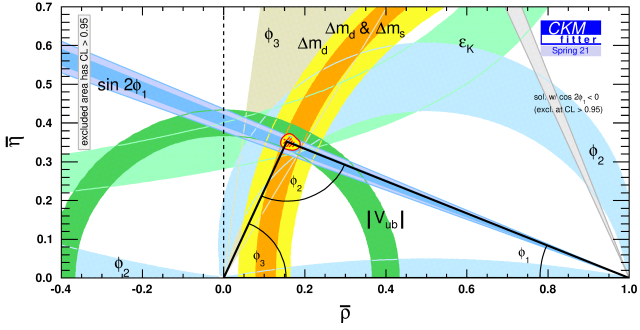
XXX Cracow EPIPHANY Conference on Precision Physics at High Energy Colliders

Moritz Bauer on behalf of Belle (II) | 09. January 2024

CKM Unitarity: $|V_{cb}|$ and $|V_{ub}|$

- $|V_{cb}|$ and $|V_{ub}|$ are central to unitarity tests used to constrain the CKM matrix and thus the SM
  - Explicitly: Direct comparison between ratio $|V_{ub}|/|V_{cb}|$ and angle ϕ_1
- Most precise determinations: Semileptonic B decays

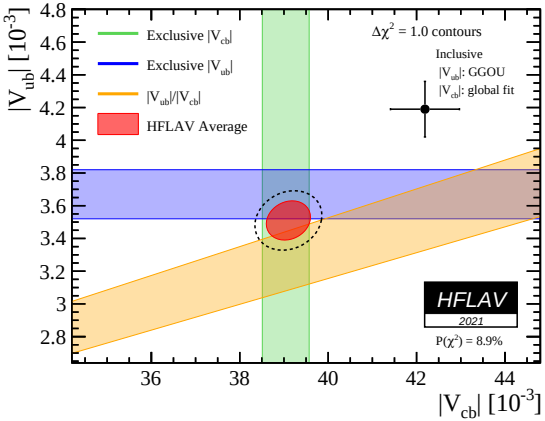




$$|V_{xb}| = \sqrt{\frac{\mathcal{B}(B \to X \ell \nu_\ell)}{\tau_B \cdot \Gamma_{\text{incl./excl.}}}}$$

Exclusive and Inclusive Measurements

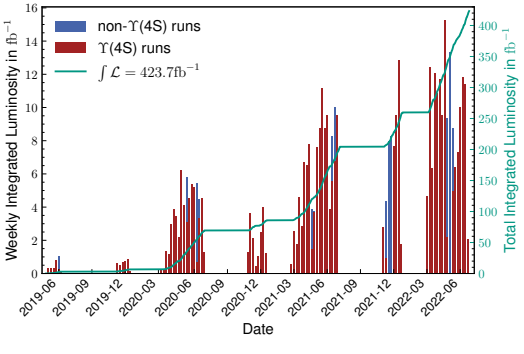
- Exclusive Measurements:
  - Analysis: Measure specific final state(s) (e.g. $B \to D\ell\nu_\ell$)
  - Theory input: Lattice QCD (LQCD)
  - Parametrizations $|V_{cb}|$: **Caprini-Lellouch-Neubert (CLN)** Nucl. Phys. B530, 153 and **Boyd-Grinstein-Lebed (BGL)** PRD 56, 6895
  - Parametrization $|V_{ub}|$: **Bourrely-Caprini-Lellouch (BCL)** Phys. Rev. D, 79, Jan 2009
- Inclusive Measurements:
  - Analysis: Measure entirety of $B \to X\ell\nu$ decays
  - Theory: Heavy Quark Expansion
    - Models (in this talk): Bosch-Lange-Neubert-Paz (BLNP) PRD 72, 073006 and Gambino-Giordano-Ossola-Uraltsev (GGOU) JHEP 10, 058 (2007)



- $\approx 3\sigma$ tension between these two approaches

$\Rightarrow$ Severely limits precision tests in flavor physics

The Belle II Experiment



Data set: 423.7 fb^{-1} ($\approx 1/2$ Belle)

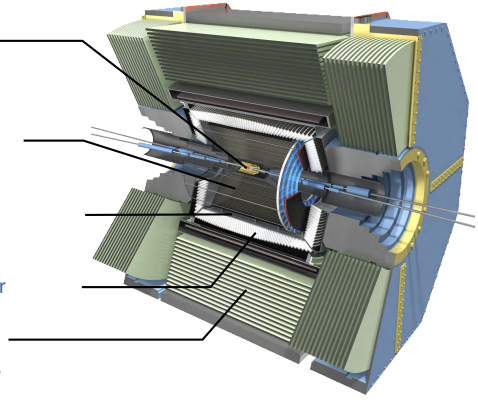
Vertex detectors
$\approx$ 15 µm vertex resolution

Central Drift Chamber
$\approx$ 0.4% p_T resolution

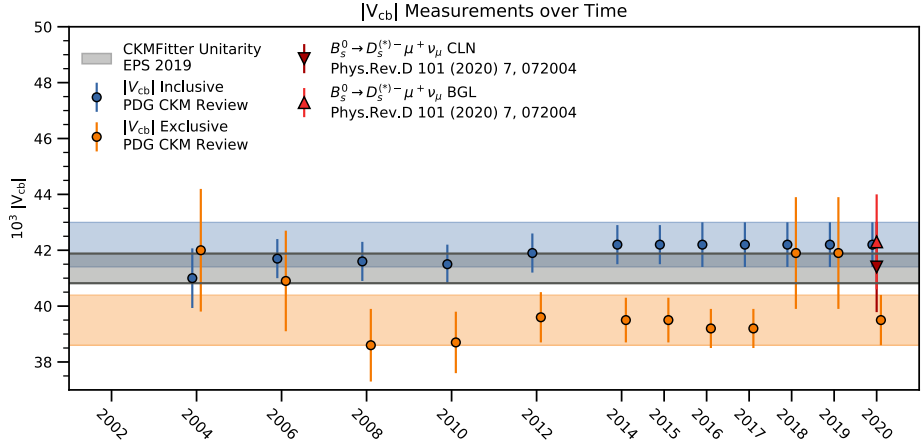
Particle Identification (π / K)
$\epsilon_K = 90\%$ with 1.8% π fake rate

Elektromagnetic Calorimeter
Sensitive down to 20 MeV

K^0_L / μ^- detector
$\epsilon_\mu = 90\%$ with 1 - 2% π/K fake rate



$|V_{cb}|$



Credit: *Markus Prim*

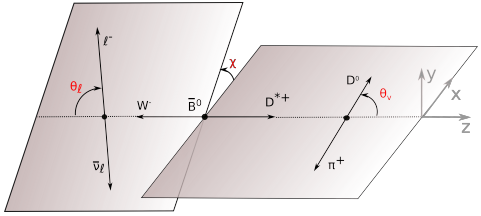
Belle II: $|V_{cb}|$ from $B \to D^* \ell \nu$

PRD 108, 092013

- Reconstruction chain:

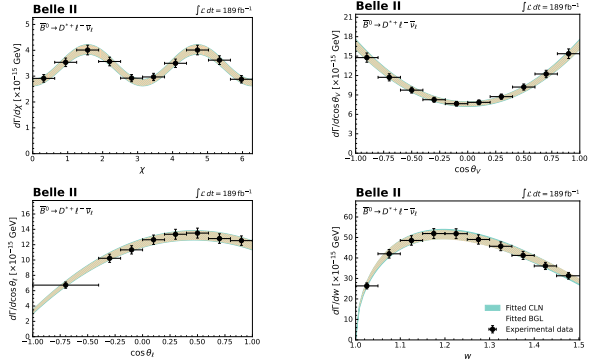
$$B \to D^{*+} \ell \nu_\ell$$
$$\hookrightarrow D^0 \pi^+_{slow}$$
$$\hookrightarrow K^- \pi^+$$

- Challenge: Slow ($p < 0.4\text{GeV}/c$) pion efficiency



$$w = \frac{1}{m_B} p_B^\mu \frac{1}{m_{X_c}} p_{X_c \mu}$$

- 2D fit in $\cos\theta_{BY}$ and $\Delta M = M(D^{*+}) - M(D^0)$ for each bin of χ, $\cos\theta_\ell$, $\cos\theta_v$ and w:



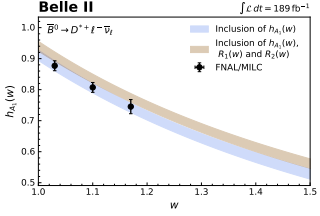
$$\cos\theta_{BY} = \frac{2E_B^* E_{D^*\ell}^* - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B^*||\vec{p}_{D^*\ell}^*|}$$

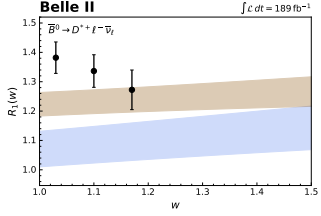
Belle II: $|V_{cb}|$ from B $\rightarrow$ D$^*\ell\nu$

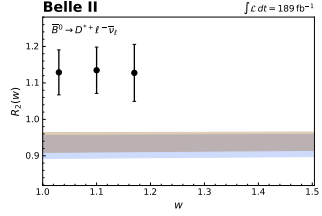
PRD 108, 092013

- $|V_{cb}|$ extraction: Fit shapes in χ, $\cos\theta_\ell$, $\cos\theta_v$ BGL and CLN parameterizations
- BGL truncation based on nested hypothesis test PRD 100, 013005
- Inclusion of LQCD constraint beyond zero-recoil (w = [1.03, 1.10, 1.17]) in two scenarios, disagreement with LQCD in R_1 and R_2:

BGL	Constraints on $h_{A_1}(w)$	Constraints on $h_{A_1}(w)$, $R_1(w)$, $R_2(w)$
$a_0 \times 10^3$	21.7 $\pm$ 1.3	25.6 $\pm$ 0.8
$b_0 \times 10^3$	13.19 $\pm$ 0.24	13.61 $\pm$ 0.23
$b_1 \times 10^3$	-6 $\pm$ 6	2 $\pm$ 6
$c_1 \times 10^3$	-0.9 $\pm$ 0.7	0.0 $\pm$ 0.7
$\|V_{cb}\| \times 10^3$	40.3 $\pm$ 1.2	38.3 $\pm$ 1.1
χ^2/ndf	39/33	75/39
p value	21%	0.04%







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

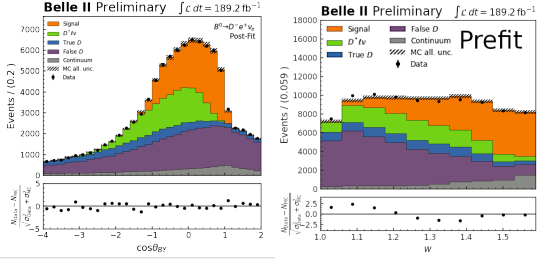
Preliminary, arXiv: 2210.13143

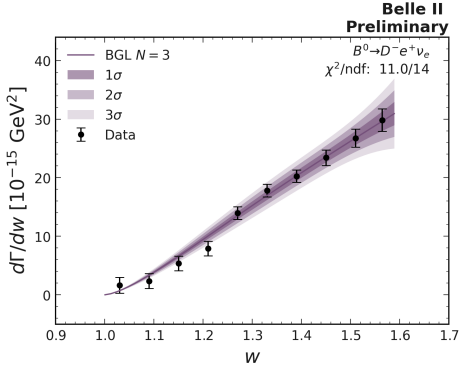
- Reconstruction chains:

$B \to D^0 \ell\nu_\ell$ ↳ $K^-\pi^+$

$B \to D^+ \ell\nu_\ell$ ↳ $K^-\pi^+\pi^+$

- Key differences to $B \to D^* \ell\nu$:
  - No slow pion
  - More backgrounds
- 5 component fit in $\cos\theta_{BY}$ for each bin of w:



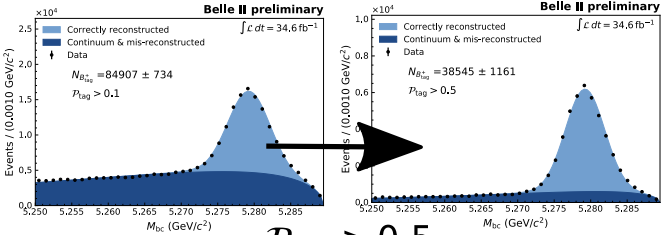


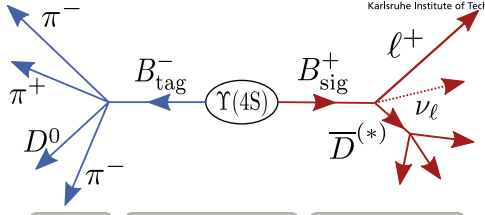
Measured $|V_{cb}| = (38.3 \pm 1.2) \times 10^{-3}$

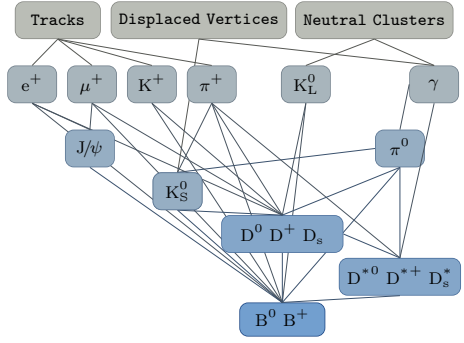
3% error, competitive with previous determinations

Full-Event Tagging

- $e^- e^+$ collisions “clean” compared to pp.
  - $\approx$ 10 tracks in a typical $B\bar{B}$ event
- Full-Event Tagging: Use 2nd B (B_{tag}) e.g. with Full Event Interpretation (FEI). Keck, T. et al.
  - Much higher purity and resolution with this approach
- Trade-off: Low efficiency and challenging calibration





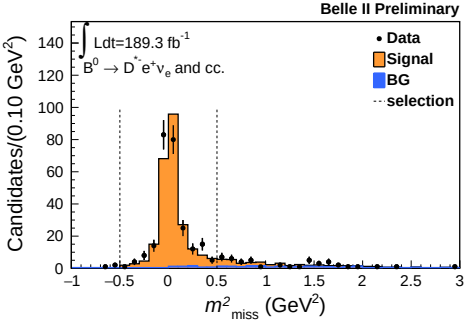


Belle II: $|V_{cb}|$ from Tagged $B \to D^* \ell \nu$

Preliminary, arXiv: 2301.04716

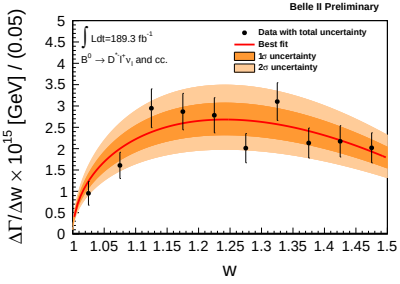
- Very pure signal selection with ΔM and missing mass from recoil of second B:

$$M^2_{\text{miss}} = (-p_{B_{\text{tag}}} - p_{D^* \ell})^2$$



- Major systematics: Slow $\pi^{\pm}$ & tagging calibration

- Fit CLN Nucl. Phys. B530, 153 parametrization to differential decay rates

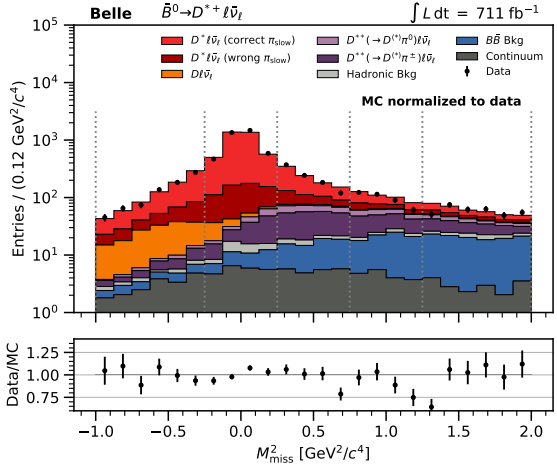


Result

$$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$$

Belle: Tagged Differential Measurements

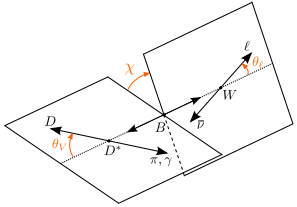
- Two results with 711 fb^{-1} Belle data set: Differential Distributions PRD 108, 012002 and Angular Coefficients $J(w)$ Submitted to PRL of $\text{B} \to \text{D}^{*} \ell \nu$
- Full-Event tagging and extraction of N_{events} in M^2_{miss}
- Challenging to calibrate tagging method
  $\to$ Use only normalized differential information and take absolute BF from HFLAV.
  - Improvement of $|V_{\text{cb}}|$ from high granularity in differential shapes

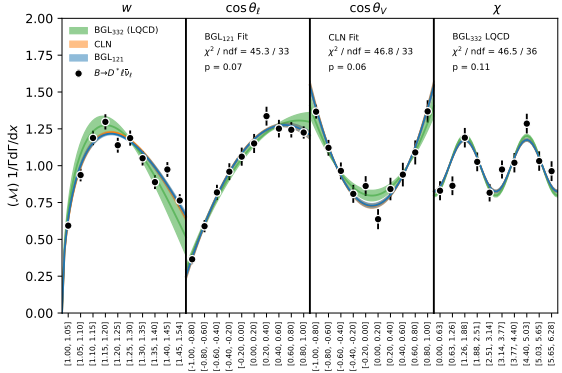


Belle: Differential Distributions

PRD 108, 012002

- Established approach: Fit projections in 160 bins of $w, \cos\theta_\ell, \cos\theta_V$ *and* χ
- Three fit szenarios:
  - Constraint on FF normalization at $w = 0$ (“nominal”) Fermilab Lattice, MILC (2014)
  - Additional constraint for h_{A_1} FF at $w > 0$ Fermilab Lattice, MILC (2021)
  - Additional constraints for all FFs at $w > 0$
- Last scenario: Tension with $R_2(w)$ constraint





Result

$$|V_{cb}| = (40.7 \pm 1.0) \times 10^{-3}$$

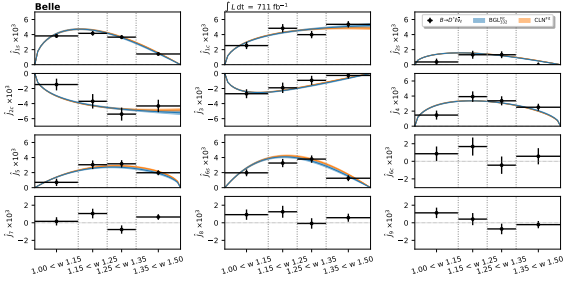
In agreement with inclusive $|V_{cb}|$

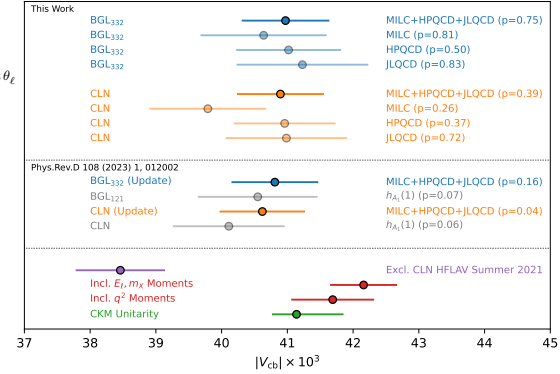
Belle: Angular Coefficients

Submitted to PRL, arXiv:2310.20286

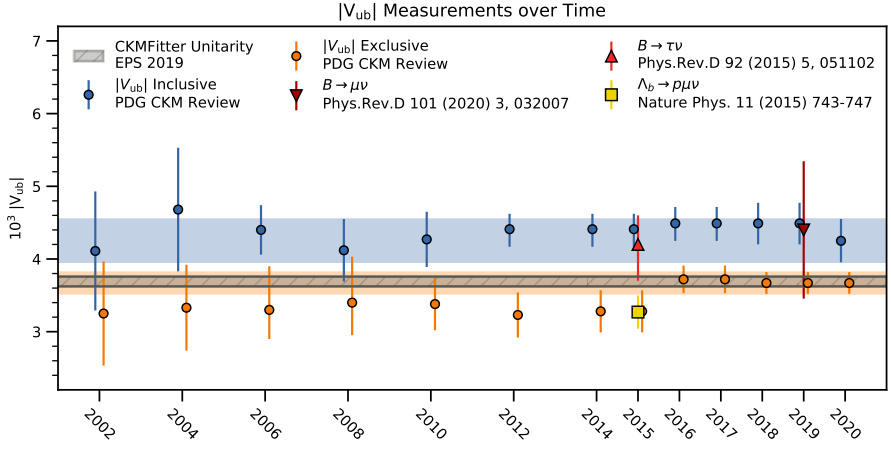
- Directly fit 8 out of 12 angular coefficients J(w) with BGL and CLN parametrizations

$$\frac{\mathrm{d}\Gamma(\bar{B}\to D^*\ell\bar{\nu}_\ell)}{\mathrm{d}w\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_V\,\mathrm{d}\chi} = \frac{2G_F^2\eta_{EW}^2|V_{cb}|^2 m_B^4 m_{D^*}}{2\pi^4}\times\Big(J_{1s}\sin^2\theta_V + J_{1c}\cos^2\theta_V + (J_{2s}\sin^2\theta_V + J_{2c}\cos^2\theta_V)\cos 2\theta_\ell + J_3\sin^2\theta_V\sin^2\theta_\ell\cos 2\chi + J_4\sin 2\theta_V\sin 2\theta_\ell\cos\chi + J_5\sin 2\theta_V\sin\theta_\ell\cos\chi + (J_{6s}\sin^2\theta_V + J_{6c}\cos^2\theta_V)\cos\theta_\ell + J_7\sin 2\theta_V\sin\theta_\ell\sin\chi + J_8\sin 2\theta_V\sin 2\theta_\ell\sin\chi + J_9\sin^2\theta_V\sin^2\theta_\ell\sin 2\chi\Big)$$





$|V_{ub}|$

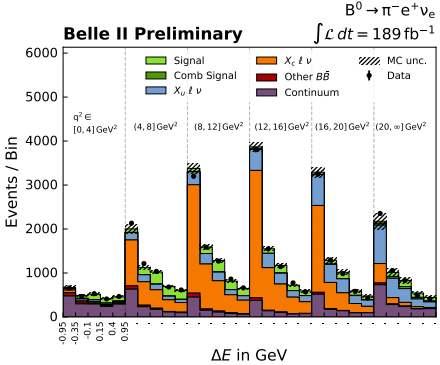


Credit: *Markus Prim*

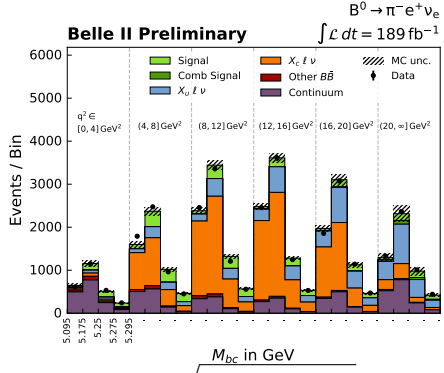
Belle II: $|V_{ub}|$ from B $\to \pi^+ \ell \nu_\ell$

Preliminary, arXiv:2210.04224

- Form factors given as function of (squared) momentum transfer $q^2 = (p_B - p_\pi)^2$
- Signal fit of beam-constrained mass M_{bc} and energy difference ΔE in 6 bins of q^2
- Dominating systematic uncertainties: Background (Continuum, B $\to \rho \ell \nu_\ell$) modelling



$$\Delta E = E_B^* - E_{\text{beam}}^*$$



$$M_{\text{bc}} = \sqrt{{E_{\text{beam}}^*}^2 - |\vec{p}_B^*|^2}$$

Belle II: $|V_{ub}|$ from B $\to \pi^+ \ell \nu_\ell$

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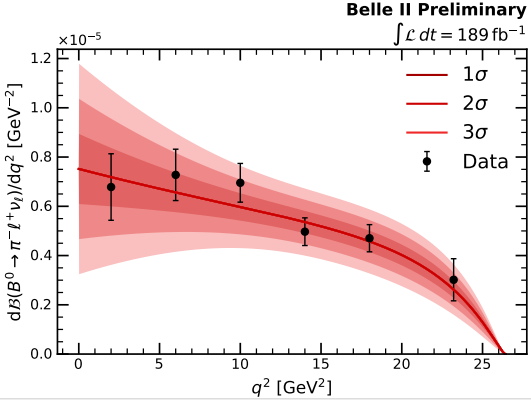


- $|V_{ub}|$ extracted from LQCD and in **Bourrely-Caprini-Lellouch (BCL)** parametrization Phys. Rev. D, 79, Jan 2009
  - Fit in q^2 reduces theory uncertainties in $|V_{ub}|$ extraction

Result:

$$|V_{ub}| = (3.55 \pm 0.12_{stat} \pm 0.13_{syst} \pm 0.17_{theo}) \times 10^{-3}$$

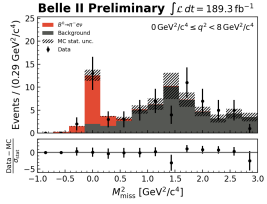
Belle II: $|V_{ub}|$ from Tagged B $\rightarrow \pi e^{-} \nu_{\ell}$

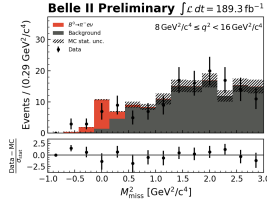
Preliminary, arXiv: 2206.08102

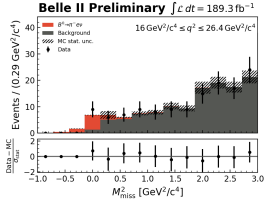
- Tagged analysis with fit of M^2_{miss} in three bins of q^2
- Using 189 fb^{-1} data set ($\approx 1/2$ of current)
- Charged and neutral pions but only electron channel (so far)
- Still heavily dominated by statistical uncertainties

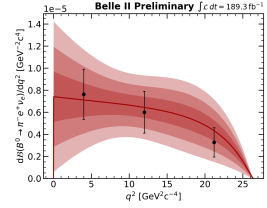
Result:

$$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$$





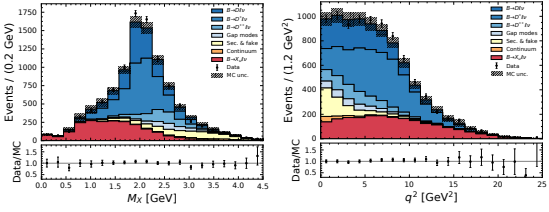


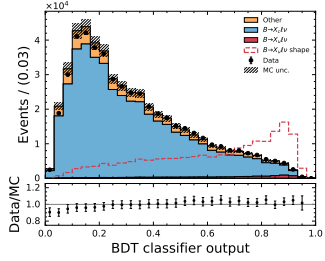


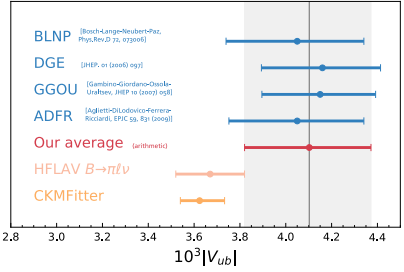
Belle: $|V_{ub}|$ from Tagged Inclusive B $\to X_u \ell \nu_\ell$

PRD 104, 012008

- Challenge: Covering large (up to 86%) phase space only possible with huge B $\to X_c \ell \nu_\ell$ bkg.
  - Decreases theory uncertainties
- Solution: Tagging and MVA discrimination





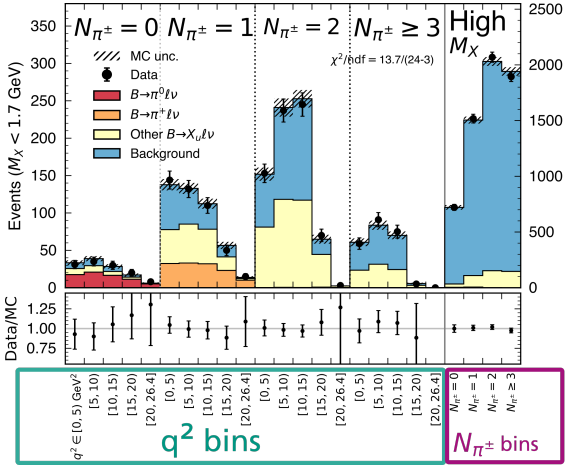


Result: $|V_{ub}| = (4.10 \pm 0.09_{stat} \pm 0.22_{syst} \pm 0.15_{theo}) \times 10^{-3} \Rightarrow$
Compatible within 1.3σ with excl. HFLAV

Belle: $|V_{ub}|$ from Simultaneous B $\to \pi \ell \nu_\ell$ and B $\to X_u \ell \nu_\ell$

PRL 131, 211801

- Improved treatment of shared systematic uncertainties by simultaneous determination
- 2D-fit in bins of
  - q^2 : number of charged pions ($N_{\pi^\pm}$)
- Only fit in $N_{\pi^\pm}$ for $M_X > 1.7\,\text{GeV}$
- Dominant systematic uncertainties:
  - Exclusive: Tagging efficiency calibration (4.1%) and B $\to X_u \ell \nu_\ell$ model (3.5%)
  - Inclusive: B $\to X_u \ell \nu_\ell$ model (10.9%) and the u $\to X_u$ fragmentation (5.3%)



Belle: $|V_{ub}|$ from Simultaneous B $\to \pi \ell \nu_\ell$ and B $\to X_u \ell \nu_\ell$

PRL 131, 211801

- Multiple scenarios in the $|V_{ub}|$ fit:
  - Separated for $\pi^\pm$ / π^0 or (isospin) combined
  - With (shown) or without experimental constraint

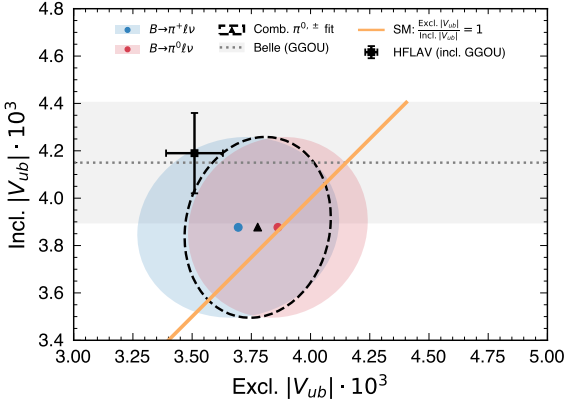
Results (with exp. constraint)

$$|V_{ub}^{excl}| = (3.78 \pm 0.23_{stat} \pm 0.16_{syst} \pm 0.14_{theo}) \times 10^{-3}$$

$$|V_{ub}^{incl}| = (3.88 \pm 0.20_{stat} \pm 0.31_{syst} \pm 0.09_{theo}) \times 10^{-3}$$

Ratio: $|V_{ub}^{excl}|/|V_{ub}^{incl}| = 0.97 \pm 0.12 \qquad (\rho = 0.1)$

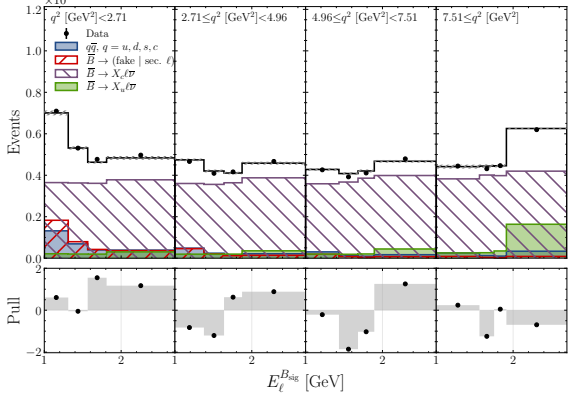
$\Rightarrow$ **Compatible with unity**



Belle: Ratio of $|V_{ub}|$ and $|V_{cb}|$ from Tagged Inclusive Decays

Submitted to PRD, arXiv: 2311.00458

- Data-driven modelling of B $\to X_c \ell \nu_\ell$ bkg. using N_K sideband
- Ratio avoids uncert. from tag efficiency
- B $\to X_u \ell \nu_\ell$ yields extracted in $q^2 : p_\ell^B$ fit



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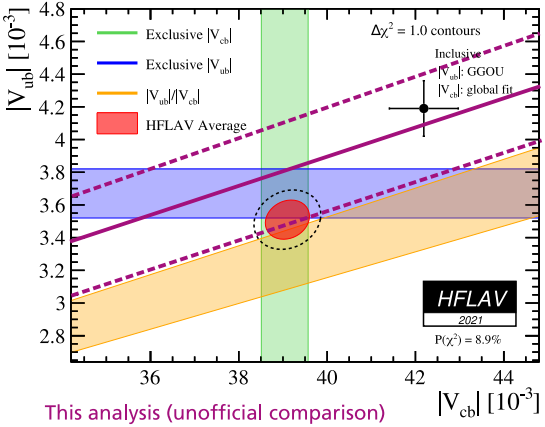
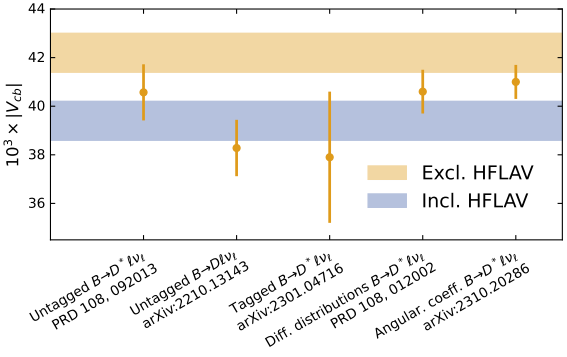
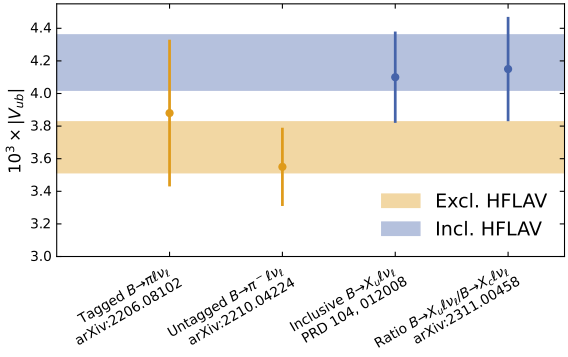
Result (with BLNP model for $B \to X_u \ell \nu_\ell$)

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.0972(1 \pm 4.2\%_{stat} \pm 3.9\%_{syst} \pm 5.2\%_{B \to X_c \ell \nu_\ell} \pm 2.0\%_{B \to X_u \ell \nu_\ell})$$



Summary





10 Measurements shown today: Belle II is ramping up with many new measurements and we're squeezing the last drop from the well-understood Belle data set!