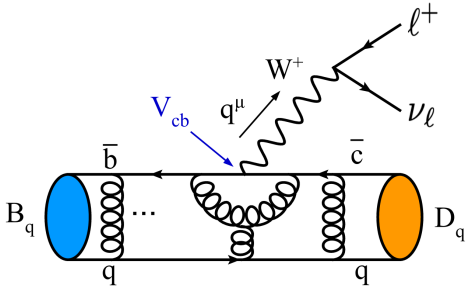
Recent Measurements of $|V_{cb}|$ and $|V_{ub}|$ with Belle (II)

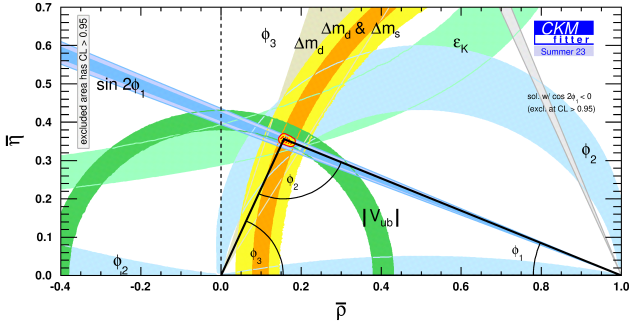
XXX Cracow EPIPHANY Conference on Precision Physics at High Energy Colliders

Moritz Bauer on behalf of Belle & Belle II | 12. 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





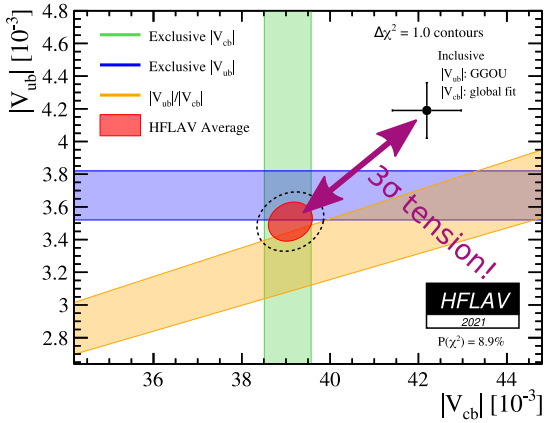
$$|V_{xb}| = \sqrt{\frac{\mathcal{B}(B \to X\ell\nu_\ell)}{\tau_B \cdot \Gamma_{\text{incl./excl.}}}}$$

$$X \in \{X_u, X_c, D^{(*)}, \pi, \ldots\}$$

Exclusive and Inclusive Measurements

- Exclusive:
  - Analysis: Reconstruct specific final state(s), e.g. as $B \to D\ell\nu$ for $|V_{cb}|$
  - Theory input: Lattice QCD (LQCD)
- Inclusive:
  - Analysis: Measure entirety of $B \to X_c\ell\nu$ / $B \to X_u\ell\nu$ decays for $|V_{cb}|$ / $|V_{ub}|$
  - Theory input: Heavy Quark Expansion
- $\approx 3\sigma$ tension between these two approaches

$\Rightarrow$ Severely limits precision tests in flavor physics



Ellipse: 68% CL

The Belle II Experiment

Vertex detectors

≈ 15 µm vertex resolution

Central Drift Chamber

≈ 0.4% p_T resolution

Particle Identification (π / K)

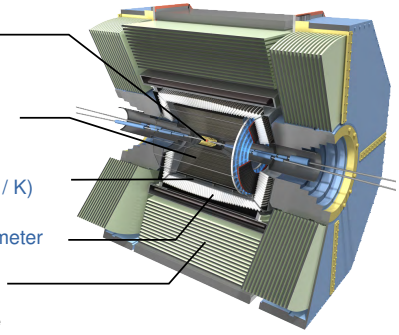
ϵ_K = 90% with 1.8% π fake rate

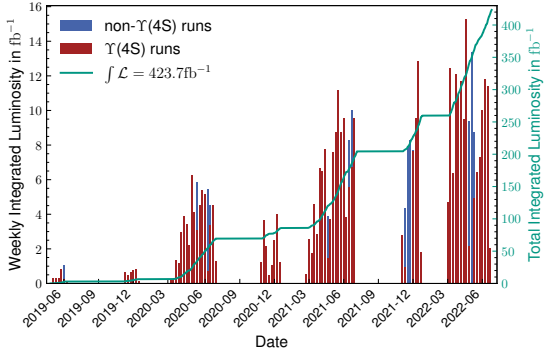
Elektromagnetic Calorimeter

Sensitive down to 20 MeV

K^0_L / μ^- detector

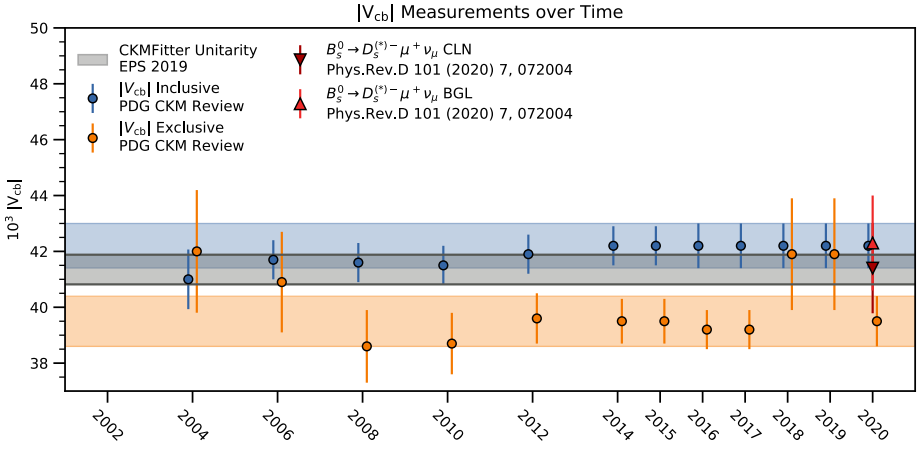
ϵ_μ = 90% with 1 - 2% π/K fake rate





Data set: 423.7 fb^{-1} **(≈ 1/2 Belle)**

$|V_{cb}|$



Credit: *Markus Prim*

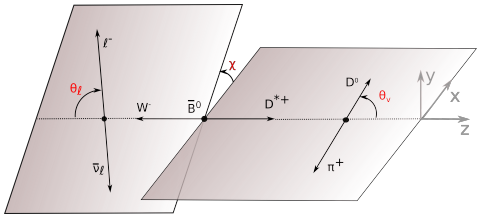
Belle II: $|V_{cb}|$ from $B^0 \to D^* \ell \nu$

PRD 108, 092013

- Reconstruction chain:

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

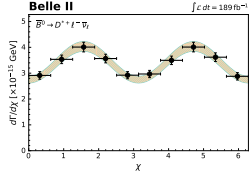
- Main syst.: Slow ($p < 0.4\text{GeV}/c$) pion efficiency

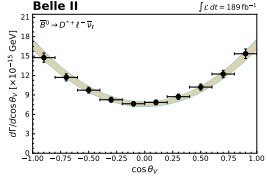


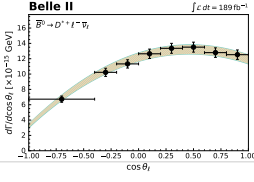
$$w = \frac{1}{m_B} p_B^\mu \frac{1}{m_{X_c}} p_{X_c \mu}$$

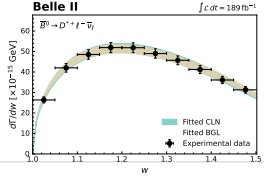
$$\cos\theta_{BY} = \frac{2E_B^* E_{D^*\ell}^* - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B^*||\vec{p}_{D^*\ell}^*|}$$

- 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
- $|V_{cb}|$ extraction: Fit these distributions with **CLN** Nucl. Phys. B530, 153 and **BGL** PRD 56, 6895 parameterizations







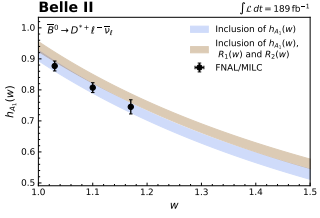


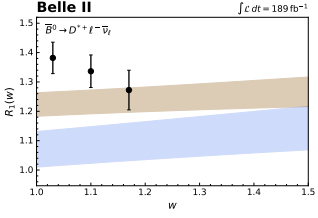
Belle II: $|V_{cb}|$ from B $\rightarrow$ D$^*\ell\nu$

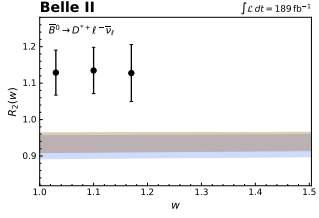
PRD 108, 092013

- 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
- $|V_{cb}|$ result compatible with both the excl. (1.5σ) and incl. (1.3σ) WAs
- Future: Higher precision through better understanding of slow pion efficiency in larger data sets

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%







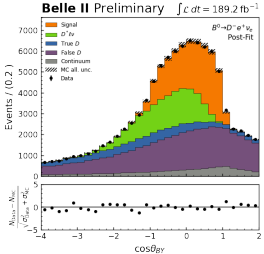
Belle II: $|V_{cb}|$ from B $\to$ D$\ell\nu$

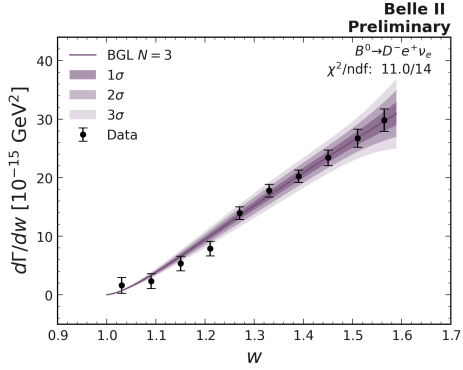
Preliminary, arXiv: 2210.13143

$B^- \to D^0 \ell \nu_\ell$ $\quad\quad$ $B^0 \to D^+ \ell \nu_\ell$

$\hookrightarrow K^- \pi^+$ $\quad\quad$ $\hookrightarrow K^- \pi^+ \pi^+$

- Key differences to B $\to$ D$^*\ell\nu$:
  - No slow pion but more backgrounds
  - Syst. uncer. dominated by background modelling: B $\to X_c \ell \nu_\ell$ BF/FFs and "fake" D PDFs
- 5 component fit in $\cos\theta_{BY}$ for each bin of w:



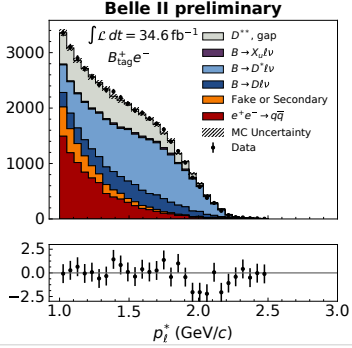


Measured $|V_{cb}| = (38.3 \pm 1.2) \times 10^{-3}$

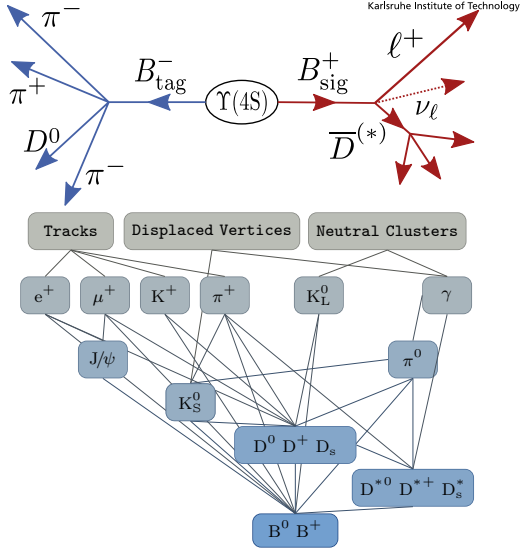
3% error, competitive with previous determinations

Full-Event Tagging

- e^-e^+ collisions “clean” compared to pp
  - $\approx$ 10 tracks in a typical $B\overline{B}$ event
- Full-Event Tagging: Use 2nd B e.g. with Full Event Interpretation (FEI). Keck, T. et al.
  - Higher purity & resolution with this MVA approach
- Trade-off: Challenging calibration & low efficiency



Calibration with momentum of lepton in B $\to$ X$\ell\nu_\ell$ decays. Correction factors of $\approx$ 0.6 due to poorly understood tagging channels.

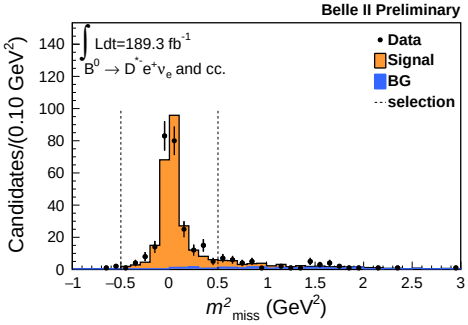


Belle II: $|V_{cb}|$ from Tagged $B^0 \to D^* \ell \nu$

Preliminary, arXiv: 2301.04716

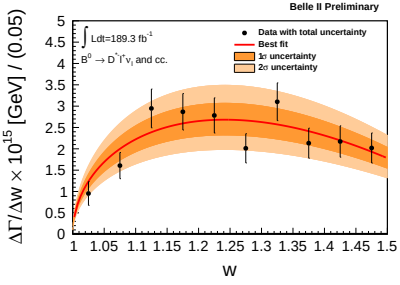
- Very pure signal selection with ΔM and missing mass from recoil of second B:

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



- Major syst. uncerts.: Slow $\pi^{\pm}$ & tagging calibration

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

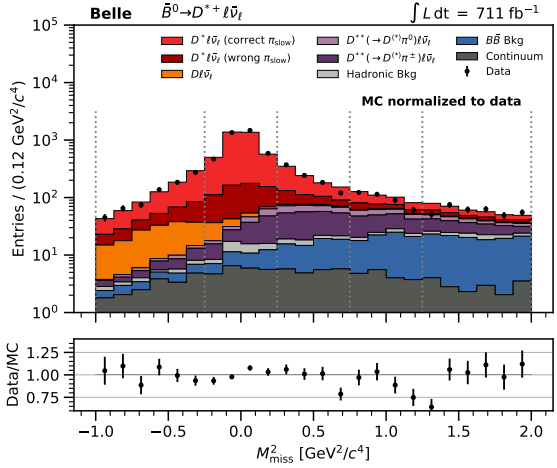


Result

$$|V_{cb}| = (37.9 \pm 2.0_{\text{stat}} \pm 1.9_{\text{syst}}) \times 10^{-3}$$

Belle: Tagged $B^0 \to D^* \ell \nu$ Measurements

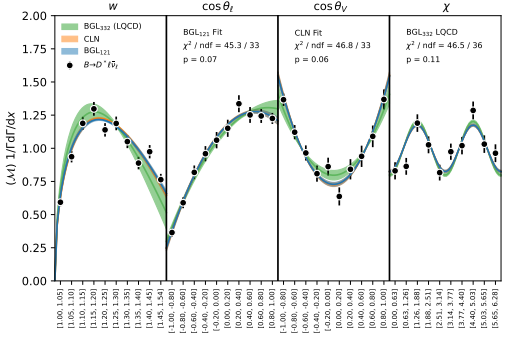
- Two results with 711 fb^{-1} Belle data set: Differential Distributions PRD 108, 012002 and Angular Coefficients $J(w)$ Submitted to PRL of $B \to D^* \ell \nu$
- Full-Event tagging and extraction of N_{events} in M^2_{miss}
- Challenging to calibrate tagging method
  $\to$ Use only normalized differential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



Belle: Differential Distributions and Angular Distributions

PRD 108, 012002 and arXiv:2310.20286

- Established approach: Fit projections in 160 bins of $w, \cos\theta_\ell, \cos\theta_V$ and χ
- 3 fit scenarios with different LQCD constraints
- Full LQCD information: Tension with $R_2(w)$
  - Also observed by Belle II



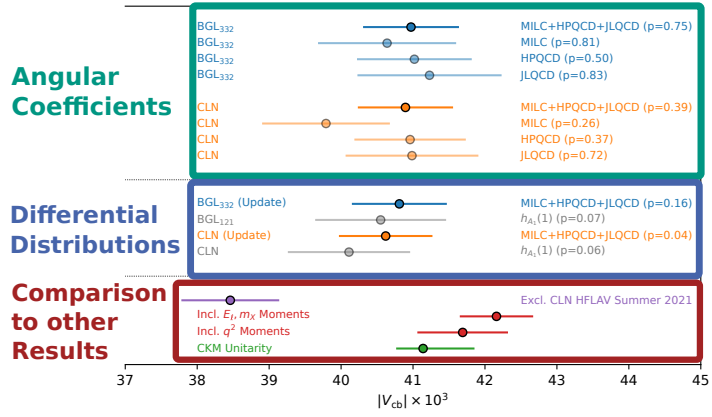
- Novel approach: Directly fit 8 angular coefficients J(w)

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

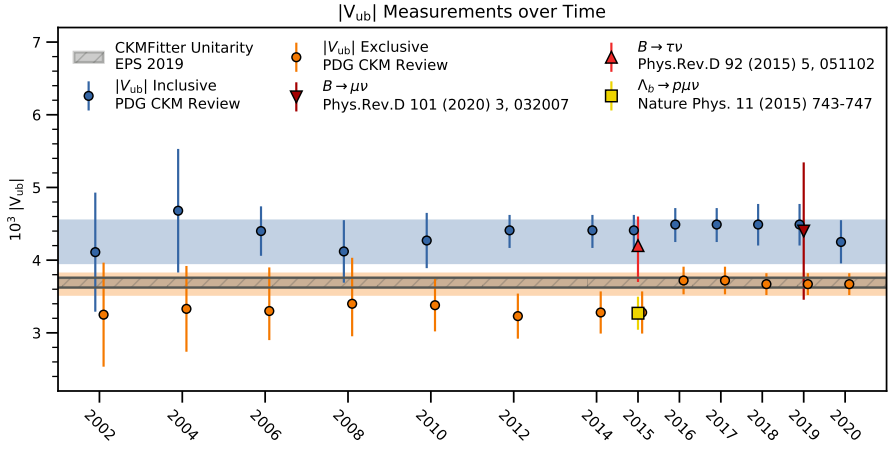
Belle: Tagged $B^0 \to D^* \ell \nu$ Results

PRD 108, 012002 and arXiv:2310.20286 (Submitted to PRL)

- Both publications: Variety of results with different LQCD inputs and BGL/CLN parametrizations
- Determinations with both methods yield higher $|V_{cb}|$ than excl. HFLAV average
- Most results compatible with
  - inclusive determinations in PLB 822, 136679 & JHEP 2022, 68
  - CKM unitarity



$|V_{ub}|$

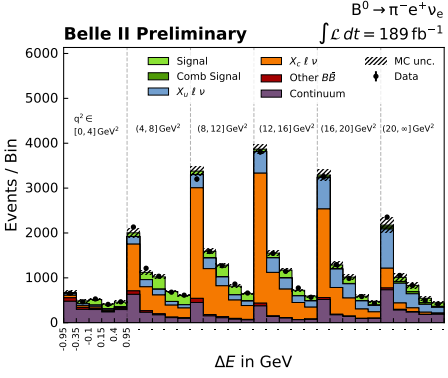


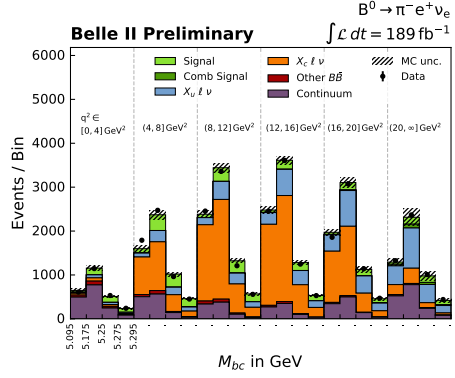
Credit: *Markus Prim*

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

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
- Main systematic uncertainties: Background (Light quark production, B $\rightarrow \rho \ell \nu_\ell$) modelling
  - Future: Simultaneous determinations to control this





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

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

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

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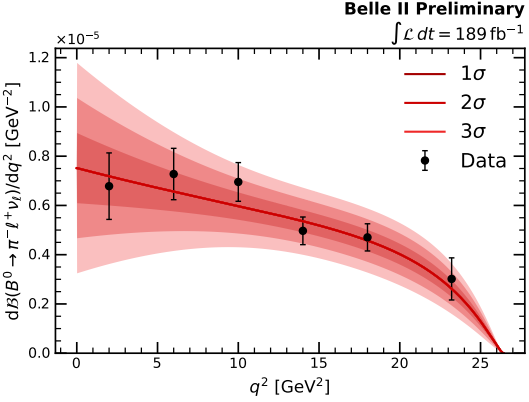


- $|V_{ub}|$ fitted with **Bourrely-Caprini-Lellouch (BCL)** expansion Phys. Rev. D, 79, Jan 2009
  - Includes LQCD constraints
  - Fit in q^2 reduces theory uncertainties in $|V_{ub}|$ extraction

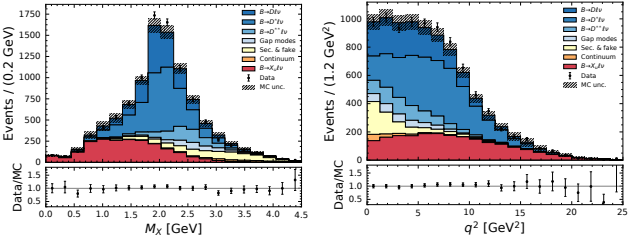
Result:

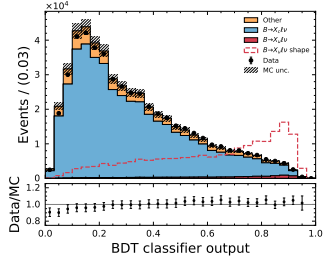
$$|V_{ub}| = (3.55 \pm 0.12_{stat} \pm 0.13_{syst} \pm 0.17_{theo}) \times 10^{-3}$$

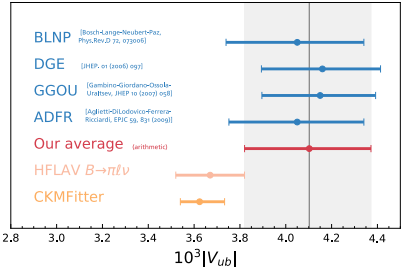
Belle: $|V_{ub}|$ from Tagged Inclusive B $\to X_u \ell \nu_\ell$

PRD 104, 012008

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





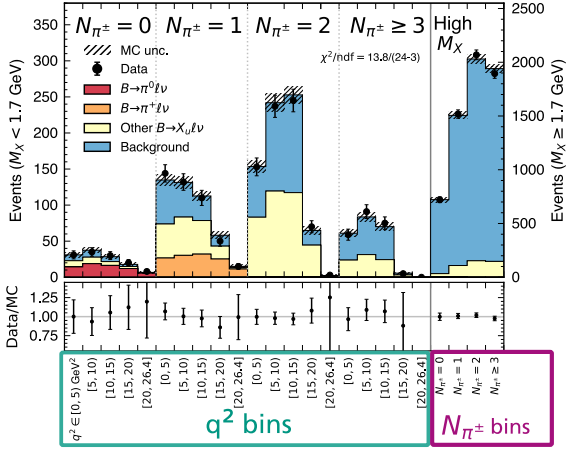


Result: $|V_{ub}| = (4.10 \pm 0.09_{stat} \pm 0.22_{syst} \pm 0.15_{theo}) \times 10^{-3} \Rightarrow$
Compatible within 1.3σ with excl. HFLAV

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
  - BCL constraint for B $\to \pi \ell \nu_\ell$ FFs taken from a global fit of LQCD + previous exp. results (shown) or pure LQCD input

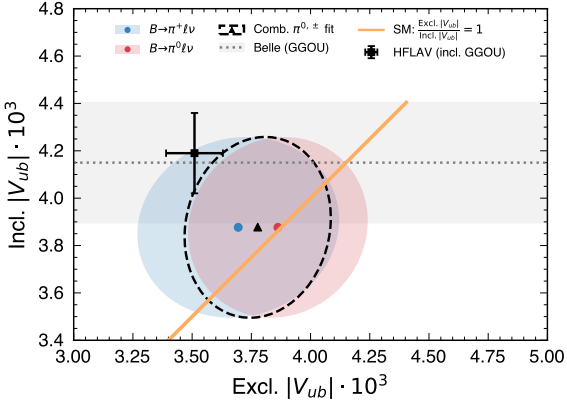
Results (with exp. constraint)

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

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

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

$\Rightarrow$ **Compatible with unity**



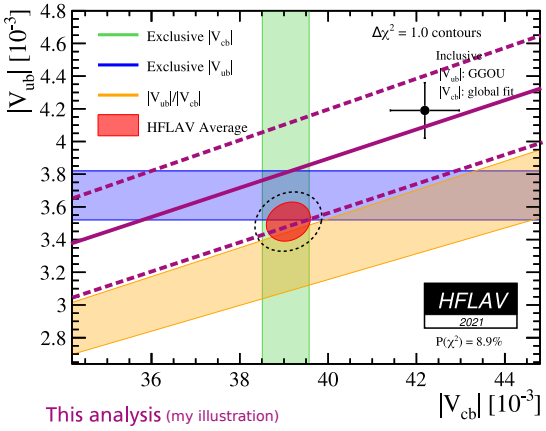
Belle: Ratio of $|V_{ub}|$ and $|V_{cb}|$ from Tagged Inclusive Decays

Submitted to PRD, arXiv: 2311.00458

- Ratio avoids uncert. from tag efficiency
- $B \to X_u \ell \nu_\ell$ yields extracted in $q^2 : p_\ell^B$ fit
- Dominant uncertainty from predictions of partial rates

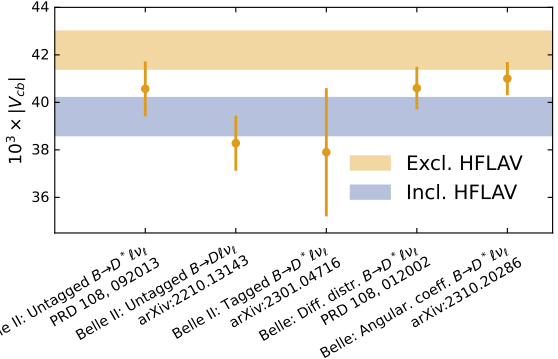
Result (with BLNP model for $B \to X_u \ell \nu_\ell$)

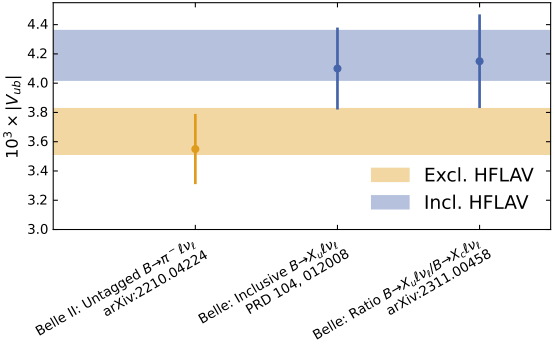
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.0972(1 \pm 4.2\%_{stat} \pm 3.9\%_{syst} \pm 5.2\%_{\Delta\Gamma(B\to X_c \ell\nu_\ell)} \pm 2.0\%_{\Delta\Gamma(B\to X_u \ell\nu_\ell)})$$



Ellipse: 68% CL

Summary





9 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!

Backup

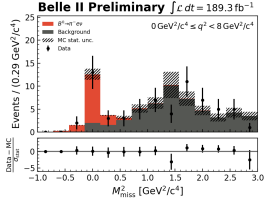
Belle II: $|V_{ub}|$ from Tagged B $\rightarrow \pi e^{-} \nu_{\ell}$

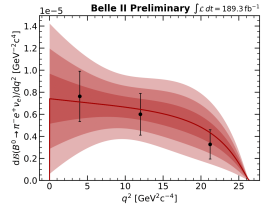
Preliminary, arXiv: 2206.08102

- 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)

Result:

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





Parameterizations and Models

- Exclusive $|V_{cb}|$ parametrizations:
  - **Boyd-Grinstein-Lebed (BGL)** PRD 56, 6895: Maps complex q^2 plane to unit disk and parametrizes form factors as power series
    - BGL truncation possible with nested hypothesis test PRD 100, 013005
  - **Caprini-Lellouch-Neubert (CLN)** Nucl. Phys. B530, 153: Additional bounds from Heavy Quark Effective Theory (HQET)
- Exclusive $|V_{ub}|$ parametrization:
  - **Bourrely-Caprini-Lellouch (BCL)** Phys. Rev. D, 79, Jan 2009: Similar to BGL but avoids truncation effects at large q^2 relevant for e.g. $B \to \pi \ell \nu_\ell$

- Inclusive $|V_{ub}|$ Models (in this talk):
  - **Bosch-Lange-Neubert-Paz (BLNP)** PRD 72, 073006
  - **Gambino-Giordano-Ossola-Uraltsev (GGOU)** JHEP 10, 058 (2007)
  - **Dressed Gluon Exponentiation (DGE; Andersen & Gardi)** JHEP01(2006)097
  - **Aglietti-Di Lodovido-Ferrera-Ricciardi (ADFR)** EPJC 59, 831–840 (2009)