Determination of $|V_{ub}|$ and $|V_{cb}|$ at Belle (II)

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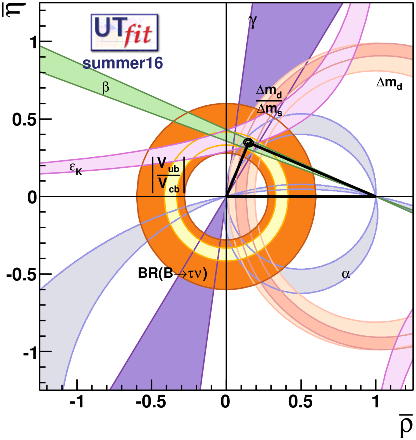
*On behalf of the Belle II collaboration

The importance of $|V_{ub}|$ and $|V_{cb}|$



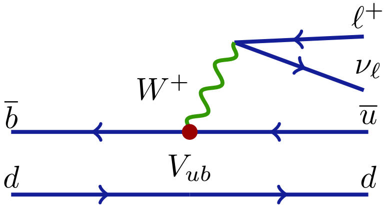
Back-reference to Abi Soffer's plenary talk in case you missed it

- Central for testing the CKM sector of the SM
- Era of searching for new physics (NP) → precision measurements
- $|V_{qb}|$ puzzle:
  - $\delta_{|V_{ub}|} \sim 4\,\%$, difference $\sim 3.5\sigma$
  - $\delta_{|V_{cb}|} \sim 2\,\%$, difference $\sim 2.9\sigma$
- $|V_{ub}|$ has **largest** error among unitarity triangle (UT) parameters, offers best handle on NP

Exclusive $|V_{qb}|$

From measurements of the branching decay rates to specific final states

- $|V_{ub}|$ determined exclusive $B \to X_u \ell \nu$ decays
  – most precise in $B \to \pi \ell \nu$ with $\ell = e,\ \mu$
- $|V_{cb}|$ determined exclusive $B \to X_c \ell \nu$ decays
  – most precise in $B \to D^{(*)} \ell \nu$ with $\ell = e,\ \mu$



Please see `arXiv:1606.08030` for a nice summary of BGL, BCL and CLN parametrizations

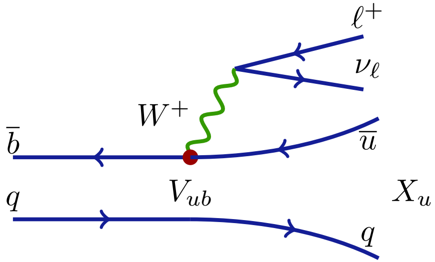
- $|V_{ub}|^{\text{excl.}} = (3.65 \pm 0.09_{\text{exp}} \pm 0.11_{\text{theo.}}) \times 10^{-3}$
  $B \to \pi \ell \nu$, LQCD, LCSR, BCL param.
- $|V_{cb}|^{\text{excl.}} = (39.05 \pm 0.47_{\text{exp}} \pm 0.58_{\text{theo.}}) \times 10^{-3}$
  $B \to D^* \ell \nu$, LQCD, CLN param.
  $(39.18 \pm 0.94_{\text{exp}} \pm 0.36_{\text{theo.}}) \times 10^{-3}$
  $B \to D \ell \nu$, LQCD, CLN param.

Theoretical input: Lattice QCD and Light-Cone Sum Rules

Inclusive $|V_{qb}|$

From measurements of the **total** or **partial** inclusive semi-leptonic branching decay rates

- $|V_{ub}|$ determined in inclusive charmless semileptonic decays $b \to u\ell\nu$
- $|V_{cb}|$ determined in inclusive charmed semileptonic decays $b \to c\ell\nu$



- $|V_{ub}|^{\text{incl.}} = \left(4.52 \pm 0.15_{\text{exp}}\,{}^{+0.11}_{-0.14}{}_{\text{theo}}\right) \times 10^{-3}$ GGOU
- $|V_{cb}|^{\text{incl.}} = (42.19 \pm 0.78) \times 10^{-3}$ Kinetic scheme

Status of $|V_{ub}|$ and $|V_{cb}|$

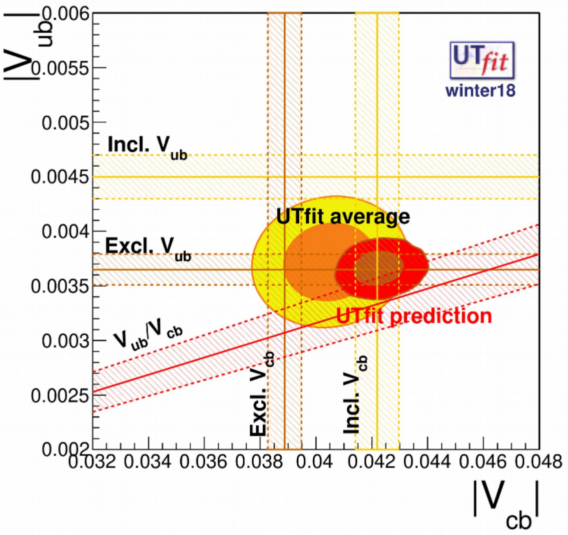


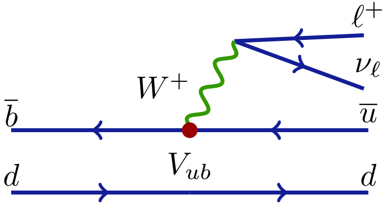
Image: Luca Silvestrini @ La Thuile 2018

Exclusive measurements prefer smaller values than inclusive ones.

Determination of exclusive $|V_{ub}|$ at B-factories

Differential $\mathcal{B}$ for pseudoscalar* $B^0 \to \pi^- \ell^+ \nu_\ell$ decay

$$\frac{d\mathcal{B}}{dq^2} = |V_{ub}|^2 \frac{G_F^2 \tau_B}{24\pi^3} p_\pi^3 |f_+^{B\pi}(q^2)|^2$$



Experimental measurement of the branching fraction and theoretical input on form factors needed to determine $|V_{ub}|$.

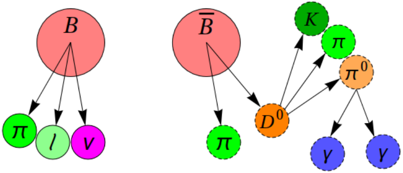
* Simplified for low mass charged leptons (e and μ)

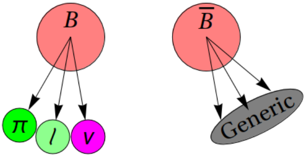
Experimental measurements at B factories

- Initial state well known: $e^+e^- \to \Upsilon(4S)$ (at rest)
- Neutrino escapes detection: $\mathrm{p}_{miss} = \mathrm{p}_{\Upsilon(4S)} - \mathrm{p}_{B_{rec}} - \mathrm{p}_{B_{comp}}$
- If neutrino is the only missing particle: $\mathrm{p}_\nu = \mathrm{p}_{miss}$

Reconstruction methods

Tagged measurement	Untagged measurement



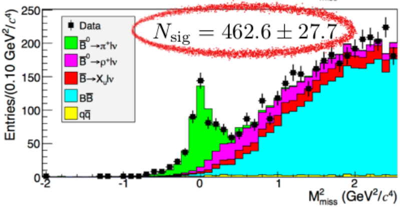


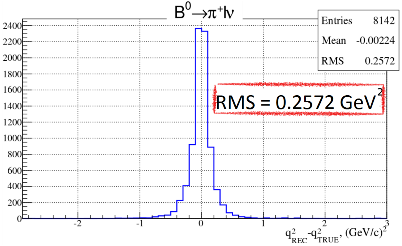
Many hadronic modes	Remaining tracks and clusters

Tagged $\rightarrow$ Efficiency $\rightarrow$ Untagged
Tagged $\leftarrow$ q^2 res. $\leftarrow$ Untagged

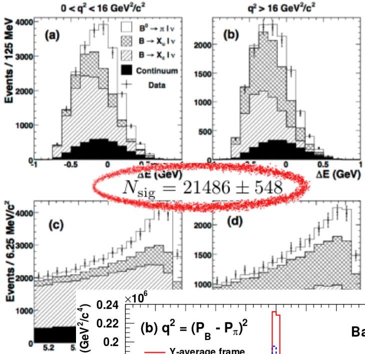
Tagged (Belle) vs. Untagged (Belle)

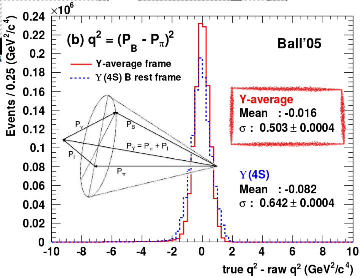
Belle [711 fb^{-1}] PRD88 032005





Belle [605 fb^{-1}] PRD83 071101



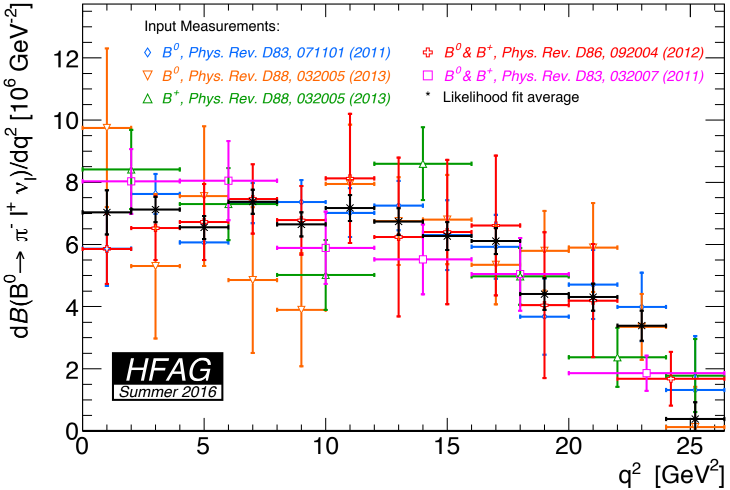


Tagged → Efficiency → Untagged

Tagged ← q^2 res. ← Untagged

Combined tagged/untagged Belle/BaBar

The most precise measurements averaged with a likelihood fit.



Theoretical input: form factor calculations

Low ⟵ q^2 region ⟶ High

LCSR	LQCD

- Low q^2 region ($q^2 <$ 6-7 GeV^2), mostly at $q^2 = 0$
- Unperturbative
- For pseudoscalar an vector decays

- Intermediate to high q^2 region ($q^2 > 14$ GeV^2)
- Unquenched (quark-loops in QCD vacuum incorporated)
- For a limited set of decays, hard to figure out for complex states

$|V_{ub}|$ extraction process

- Need to extrapolate theory input to a certain or full q^2 region
- Model dependent/independent: Whether the model makes any assumptions regarding FF shape

Calculation from $\Delta\mathcal{B}$

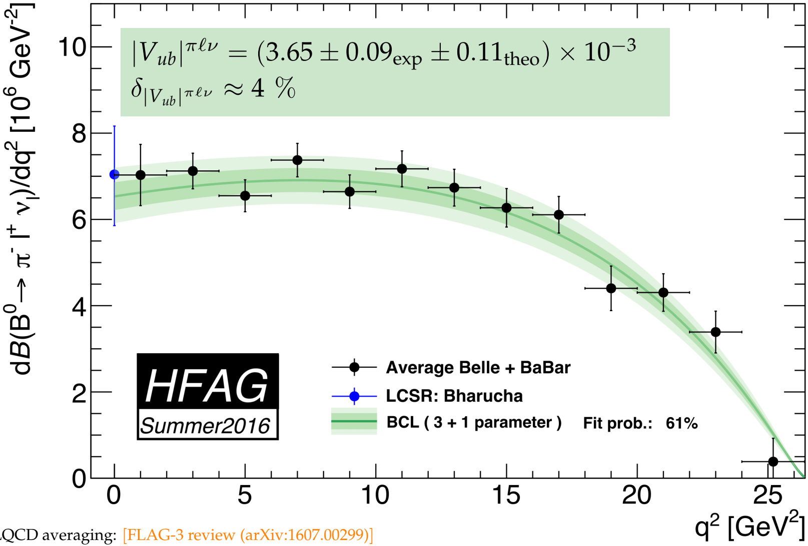
- Mostly obsolete process
- Measure partial branching ratio in a q^2 region ($\Delta\mathcal{B}$)
- Calculate reduced branching ratio in same region ($\Delta\zeta$)

$$|V_{ub}|^2 = \frac{\Delta\mathcal{B}(q^2_{\text{min}}, q^2_{\text{max}})}{\tau_B \Delta\zeta(q^2_{\text{min}}, q^2_{\text{max}})}$$

Simultaneous fit to data and theory

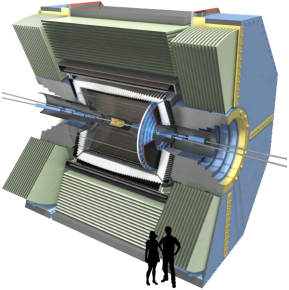
- Measure $\Delta\mathcal{B}/\Delta q^2$ spectrum in bins of q^2
- Extract from simultaneous fit (least squares) to data (shape + scale) and theory input (shape) by minimizing $\chi^2 = \chi^2_{\text{data}} + \chi^2_{\text{theory}}$

$|V_{ub}|$ from simultaneous fit to $B \to \pi \ell \nu$ data

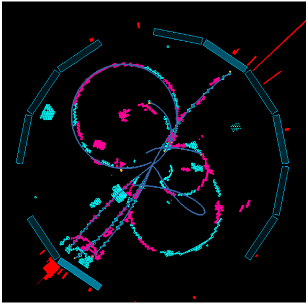


LQCD averaging: [FLAG-3 review (arXiv:1607.00299)]
LQCD: [Fermilab/MILC, Phys.Rev. D92 (2015) no.1, 014024]
LQCD: [RBC/UKQCD, Phys.Rev. D91 (2015) no.7, 074510]
LCSR: [A. Bharucha, JHEP 1205 (2012) 092]

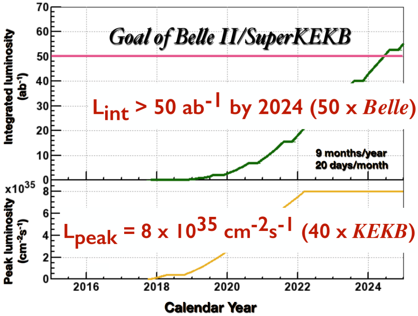
Expected improvements at Belle II



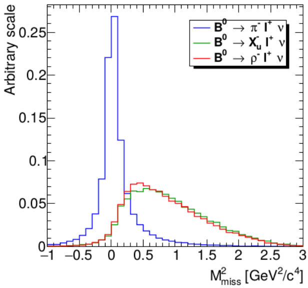
More on
Belle II prospects
in next talk
by A. Vossen

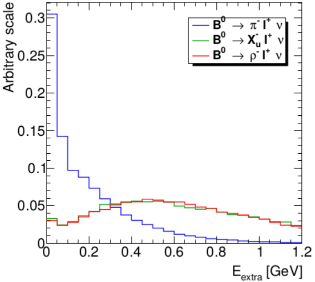


- First collisions in April 26th
- Higher luminosity (Belle $\times 40$)
- More data expected ($\sim 50\ \mathrm{ab}^{-1}$)
- Improved detector efficiency and purity (tracking, PID, K/π)
- Smarter software and more precise algorithms

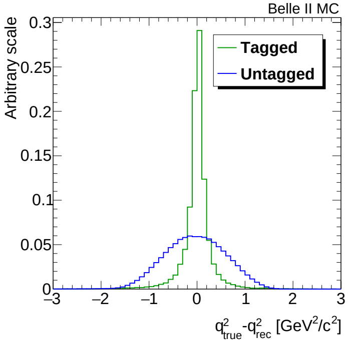


$B \to \pi \ell \nu$ tagged prospects at Belle II (MC study)





[B2TiP, to be published]



Better tagging algorithm with significantly higher tagging reconstruction efficiency

$B \to \pi \ell \nu$ efficiency compared to Belle tagged [Phys.Rev. D88 (2013) no.3, 032005]: 0.3 % $\to$ 0.55 %

Hadronic B_{tag} efficiency improvement

Hadronic tag channels

B^+ modes	B^0 modes
$B^+ \to \bar{D}^0\pi^+$	$B^0 \to D^-\pi^+$
$B^+ \to \bar{D}^0\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^0\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-$	$B^0 \to D_s^+D^-$
$B^+ \to D_s^+\bar{D}^0$	$B^0 \to D^{*-}\pi^+$
$B^+ \to \bar{D}^{*0}\pi^+$	$B^0 \to D^{*-}\pi^+\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D_s^{*+}D^-$
$B^+ \to D_s^{*+}\bar{D}^0$	$B^0 \to D_s^+D^{*-}$
$B^+ \to D_s^+\bar{D}^{*0}$	$B^0 \to D_s^{*+}D^{*-}$
$B^+ \to \bar{D}^0K^+$	$B^0 \to J/\psi K_S^0$
$B^+ \to D^-\pi^+\pi^+$	$B^0 \to J/\psi K^+\pi^+$
$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K_S^0\pi^+\pi^-$
$B^+ \to J/\psi K^+\pi^+\pi^-$	
$B^+ \to J/\psi K^+\pi^0$	
$B^+ \to J/\psi K_S^0\pi^+$	
New channels	
$B^+ \to D^-\pi^+\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^0D^+$	$B^0 \to \bar{D}^0\pi^+\pi^-$
$B^+ \to \bar{D}^0D^+K_S^0$	$B^0 \to D^-D^0K^+$
$B^+ \to \bar{D}^{*0}D^+K_S^0$	$B^0 \to D^-D^{*0}K^+$
$B^+ \to \bar{D}^0D^{*+}K_S^0$	$B^0 \to D^{*-}D^0K^+$
$B^+ \to \bar{D}^{*0}D^{*+}K_S^0$	$B^0 \to D^{*-}D^{*0}K^+$
$B^+ \to \bar{D}^0D^0K^+$	$B^0 \to D^-D^+K_S^0$
$B^+ \to \bar{D}^{*0}D^0K^+$	$B^0 \to D^{*-}D^+K_S^0$
$B^+ \to \bar{D}^0D^{*0}K^+$	$B^0 \to D^-D^{*+}K_S^0$
$B^+ \to \bar{D}^{*0}D^{*0}K^+$	$B^0 \to D^{*-}D^{*+}K_S^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0\pi^0$	$B^0 \to D^{*-}\pi^+\pi^0\pi^0$

D^+, D^{*+}, D_s^+ modes	D^0, D^{*0} modes
$D^+ \to K^-\pi^+\pi^+$	$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0$
$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+\pi^0$	$D^0 \to \pi^-\pi^+$
$D^+ \to K_S^0\pi^+$	$D^0 \to \pi^-\pi^+\pi^0$
$D^+ \to K_S^0\pi^+\pi^0$	$D^0 \to K_S^0\pi^0$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$D^0 \to K_S^0\pi^+\pi^-$
$D^{*+} \to D^0\pi^+$	$D^0 \to K_S^0\pi^+\pi^-\pi^0$
$D^{*+} \to D^+\pi^0$	$D^0 \to K^-K^+$
$D_s^+ \to K^+K_S^0$	$D^0 \to K^-K^+K_S^0$
$D_s^+ \to K^+\pi^+\pi^-$	$D^{*0} \to D^0\pi^0$
$D_s^+ \to K^+K^-\pi^+$	$D^{*0} \to D^0\gamma$
$D_s^+ \to K^+K^-\pi^+\pi^0$	
$D_s^+ \to K^+K_S^0\pi^+\pi^-$	
$D_s^+ \to K^-K_S^0\pi^+\pi^+$	
$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	
$D_s^+ \to \pi^+\pi^+\pi^-$	
$D_s^{*+} \to D_s^+\pi^0$	
New channels	
$D^+ \to \pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0\pi^0$
$D^+ \to \pi^+\pi^+\pi^-$	$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$D^0 \to \pi^-\pi^+\pi^+\pi^-$
$D^+ \to K^+K_S^0K_S^0$	$D^0 \to \pi^-\pi^+\pi^0\pi^0$
$D^{*+} \to D^+\gamma$	$D^0 \to K^-K^+\pi^0$
$D_s^+ \to K_S^0\pi^+$	
$D_s^+ \to K_S^0\pi^+\pi^0$	
$D_s^{*+} \to D_s^+\pi^0$	

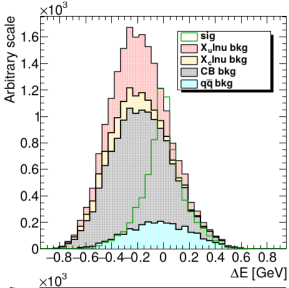
New channels

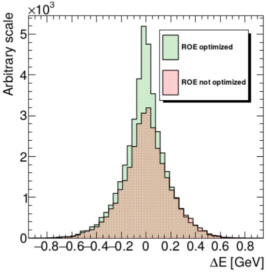
[B2TiP, to be published]

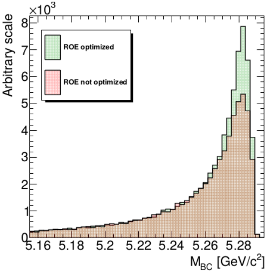
Tag	Old	New
B^+	0.28 %	0.49 %
B^0	0.19 %	0.33 %

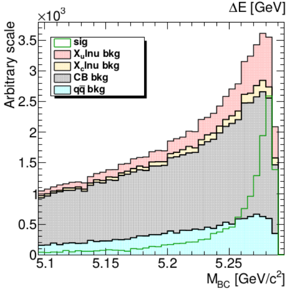
- More channels included in the tag reconstruction
- Best candidate selection allows also inclusion of high multiplicity modes

$B \to \pi\ell\nu$ untagged at Belle II (MC study)









RestOfEvent (ROE): tracks and cluster not used in signal B reco

Perform "clean-up" of ROE to discard extra tracks and clusters from beam BKG

$B \to \pi\ell\nu$ efficiency compared to Belle untagged [Phys.Rev. D83 (2011) 071101]:
11 % $\to$ 20 %

[B2TiP, to be published]

Assumptions for lattice forecasts

We provide 5 types of the lattice input

- current: input with the current precision basically taken from the updated FLAG-3 review (in preparation; to be appeared on the FLAG webpage: `http://itpwiki.unibe.ch/flag/`).
- 5 yr w/o EM: We assume a factor of 2 reduction of the lattice QCD uncertainty in the next five years and that the uncertainty of the EM correction is negligible (for processes insensitive to the EM correction).
- 5 yr w/ EM: LQCD uncertainty is reduced by a factor of 2 but add in quadrature 1% uncertainty from the EM correction.
- 10 yr w/o EM: We assume a factor of 5 reduction of the lattice QCD uncertainty in the next ten years (or as a milestone of lattice QCD simulations). We also assume that the EM correction will be under control and its uncertainty is negligible.
- 10 yr w/ EM: LQCD uncertainty is reduced by a factor of 5 but add in quadrature 1% uncertainty from the EM correction.

Error scaling

Total error scaling with integrated luminosity L

$$\sigma_{\text{tot}}(L) = \sqrt{(\sigma^2_{\text{stat}}(L_0) + \sigma^2_{\text{sysred}}(L_0)) \times \frac{L_0}{L} + \sigma^2_{\text{sysirred}}(L_0)}$$

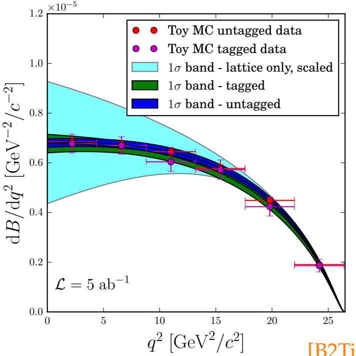
Systematics

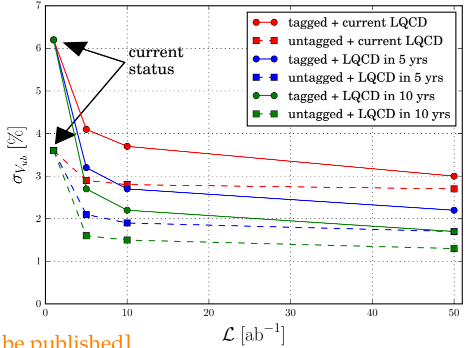
- Belle II systematics estimated from Belle
- Reducible and irreducible systematics (with L)
- Tagged: 4.6 % red., 2.0 % irred., biggest contribution: tagging algorithm
- Untagged: 4.2 % red., 1.6 % irred., biggest contribution: $X_{u,c}\ell\nu$, FF shapes and background

[B2TiP, to be published]

$|V_{ub}|$ from $B \to \pi\ell\nu$ @ Belle II

Toy MC studies based on Belle II MC, LQCD forecasts estimated at 5 years (5, 10 ab^{-1}) and 10 years (50 ab^{-1})





[B2TiP, to be published]

$|V_{ub}|^{\pi\ell\nu}$ from simultaneous fit for $L = 5\ \text{ab}^{-1}$, including lattice forecasts and error scaling.

$\delta_{|V_{ub}|^{\pi\ell\nu}}$ estimates for 5, 10 and 50 ab^{-1}:
Tagged: 3.2, 2.7 and 1.7 %
Untagged: 2.1, 1.9 and 1.3 %

LQCD forecasts: [A. Kronfeld, T. Kaneko, S. Simula]

Determinations of exclusive $|V_{cb}|$

- As mentioned, $B \to D^{(*)}\ell\nu$ preferred channels
- Measurement of differential decay rate as a function of $w = v_B \cdot v_{D^{(*)}}$ (recoil variable from 4-velocities)

Differential $\mathcal{B}$ of $B \to \bar{D}^*\ell^+\nu$ for massless fermions

$$\frac{d\Gamma}{dw} = |V_{cb}|^2 \frac{G_F^2 m_{D^*}^3}{48\pi^3}(m_B - m_{D^*})^2 \chi(w) \eta_{EW}^2 \mathcal{F}^2(w)$$

and $B \to \bar{D}\ell^+\nu$ for massless fermions

$$\frac{d\Gamma}{dw} = |V_{cb}|^2 \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 (w^2 - 1)^{3/2} \eta_{EW}^2 \mathcal{G}^2(w)$$

where $\chi(w)$ is a phase-space function, η_{EW} is the EW correction and $\mathcal{F}(w)$ and $\mathcal{G}(w)$ contain the appropriate information on $D^{(*)}$ form factors $\to$ similar procedure for extraction as in case of V_{ub}!

Exclusive $|V_{cb}|$ opportunities at Belle II

No extensive MC studies performed, but some predictions can be made

- Belle precision limited by systematics (hadronic tag calibration, tracking efficiency) $\rightarrow$ need to bring them down to improve excl. $|V_{cb}|$ precision
- Replace CLN with model-independent BGL parametrization $\rightarrow$ this issue might play a role in the excl./incl. puzzle

Authors of `arXiv:1703.06124` have reanalyzed $B \rightarrow D^* \ell \nu$ results from `arXiv:1702.01521` $\rightarrow$ large differences between CLN to BGL parametrizations.

BGL result closer to incl. values, but further studies needed.

Summary

- Current precision $\delta_{|V_{ub}|} \approx 4\,\%$ and $\delta_{|V_{cb}|} \approx 2\,\%$
- $|V_{ub}|$ puzzle persists, error still large compared to other CKM parameters (waiting on Belle II data)
  - Belle II MC study with 50 ab^{-1} for tagged/untagged excl. $B \to \pi \ell \nu$ predicts errors of about 1.7/1.3 %
- $|V_{cb}|$ puzzle also persists, waiting for more data while looking into existing results with better extraction methods
- Predictions for branching ratio precision of $B \to \pi \ell \nu$ on full Belle II sample enter the order of $1 - 2\,\%$ $\to$ good precision for LUV studies in these channels
- Errors of inclusive $|V_{qb}|$ are limited by theoretical uncertainties $\to$ more data needed to constrain the dominant sources

Thank you!

BACKUP

Belle II prospects for exclusive $|V_{ub}|$: $B \to (\rho, \omega)\ell\nu$

No extensive studies for these projections.
Possible to assume sample sizes in the future based on Belle (hadronic tag) @ 711 fb^{-1} with efficiency improvements:

- $N_{\rho^0} = (621.7 \pm 35.0) \to \sim$ 80k ($\delta_{\text{stat}} \approx 0.5\%$) @ 50 ab^{-1}
- $N_{\rho^+} = (343.3 \pm 28.3) \to \sim$ 44k ($\delta_{\text{stat}} \approx 0.7\%$) @ 50 ab^{-1}
- $N_{\omega(3\pi)} = (96.7 \pm 14.5) \to \sim$ 12.5k ($\delta_{\text{stat}} \approx 1.3\%$) @ 50 ab^{-1}

- With such sample possible to do a full helicity angle analysis
- Also possible to check for right-handed currents
- Will contribute to better understanding of the $b \to u$ spectrum
- Can we expect lattice for these modes by then?