

Measurements of $|V_{cb}|$ and $|V_{ub}|$ at Belle and Belle II

Michele Aversano, on behalf of the Belle & Belle II Collaboration
Nagoya University

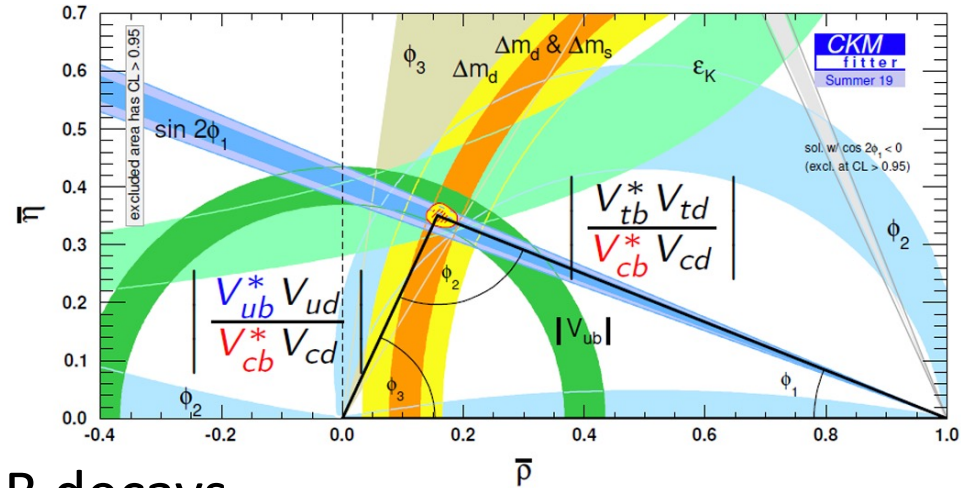
42nd International Conference on High Energy Physics
18-24 July 2024, Prague



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

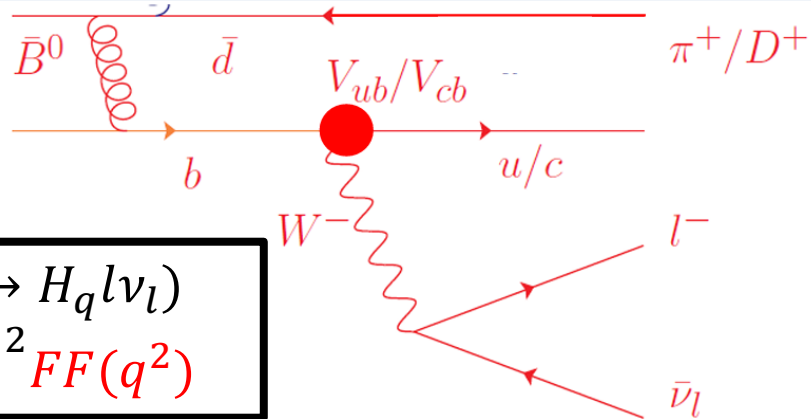
- $|V_{ub}|$ and $|V_{cb}|$ important to constrain CKM Unitarity

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$



- Precisely measured with semileptonic B decays

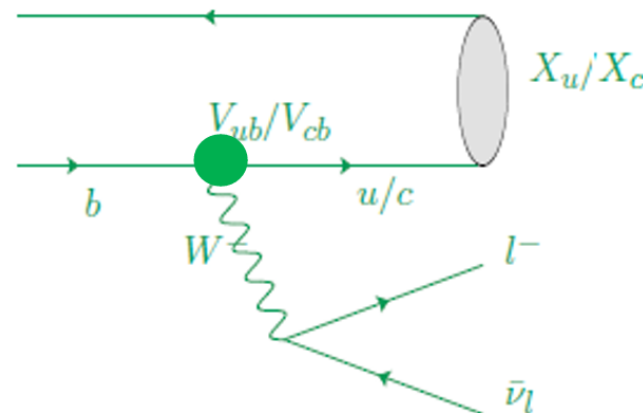
Exclusive: $B \rightarrow \pi/\rho \ell \nu$, $B \rightarrow D(*) \ell \nu$ etc.



$$BF(B \rightarrow H_q \ell \nu_l) \rightarrow |V_{qb}|^2 FF(q^2)$$

Form-factor from Theory

Inclusive: $B \rightarrow X_u \ell \nu$, $B \rightarrow X_c \ell \nu$



Longstanding tension among exclusive and inclusive determinations

$$BF(B \rightarrow X_q \ell \nu_l) \rightarrow |V_{qb}|^2 (1 + \dots)$$

OPE expansion from Theory

Recent results covered in this talk

$|V_{cb}|$

- Measurement of Angular Coefficients of $\bar{B} \rightarrow D^* l \bar{\nu}_l$: Implications for $|V_{cb}|$ and Tests of Lepton Flavor Universality
(**Belle**, [arXiv:2310.20286](https://arxiv.org/abs/2310.20286) accepted by PRL, [HEPData](https://hepdata.net))

$|V_{ub}|$

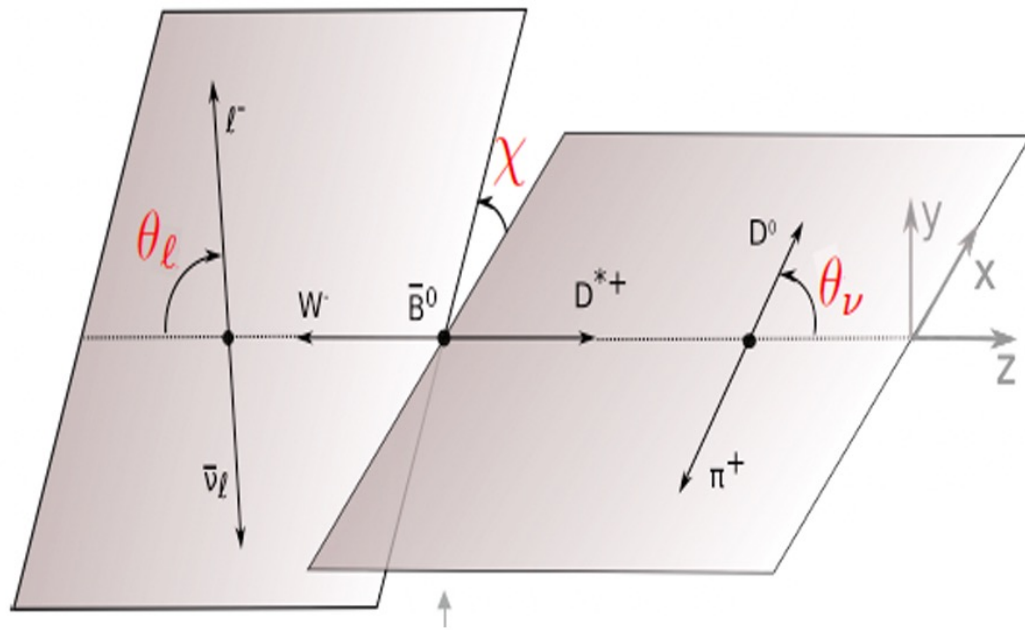
- Determination of $|V_{ub}|$ from simultaneous measurements of untagged $B^0 \rightarrow \pi^- l^+ \nu_l$ and $B^+ \rightarrow \rho^0 l^+ \nu_l$ decays
(**Belle II**, new result at Moriond 2024)
- First Simultaneous Determination of Inclusive and Exclusive $|V_{ub}|$
(**Belle**, [PRL 131, 211801](https://arxiv.org/abs/2310.20286))

$\frac{|V_{ub}|}{|V_{cb}|}$

- Measurement of the Ratio of Partial Branching Fractions of Inclusive $\bar{B} \rightarrow X_u l \bar{\nu}_l$ to $\bar{B} \rightarrow X_c l \bar{\nu}_l$ and the Ratio of their Spectra with Hadronic Tagging
(**Belle**, [arXiv:2310.20286](https://arxiv.org/abs/2310.20286) submitted to PRD)

$|V_{cb}|$ from Angular Coefficients of $\bar{B} \rightarrow D^* l \bar{\nu}_l$

- Full Belle dataset of 711 fb^{-1} and hadronic B tagging
- Both charged and neutral B mesons with the decay chains $\bar{B}^0 \rightarrow D^{*+} l \bar{\nu}_l$ with $D^{*+} \rightarrow D^0 \pi^+ / D^+ \pi^0$, and $B^- \rightarrow D^{*0} l \bar{\nu}_l$ with $D^{*0} \rightarrow D^0 \pi^0$
- Non-resonant $e^+ e^-$ interactions are suppressed using a multivariate classifier
- The angular coefficients obtained from data in bins of the hadronic recoil parameter w



$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$$

Four-dimensional differential decay rate for $\bar{B} \rightarrow D^* l \bar{\nu}_l$ can be expressed in terms of 12 functions J_i that depend only on w

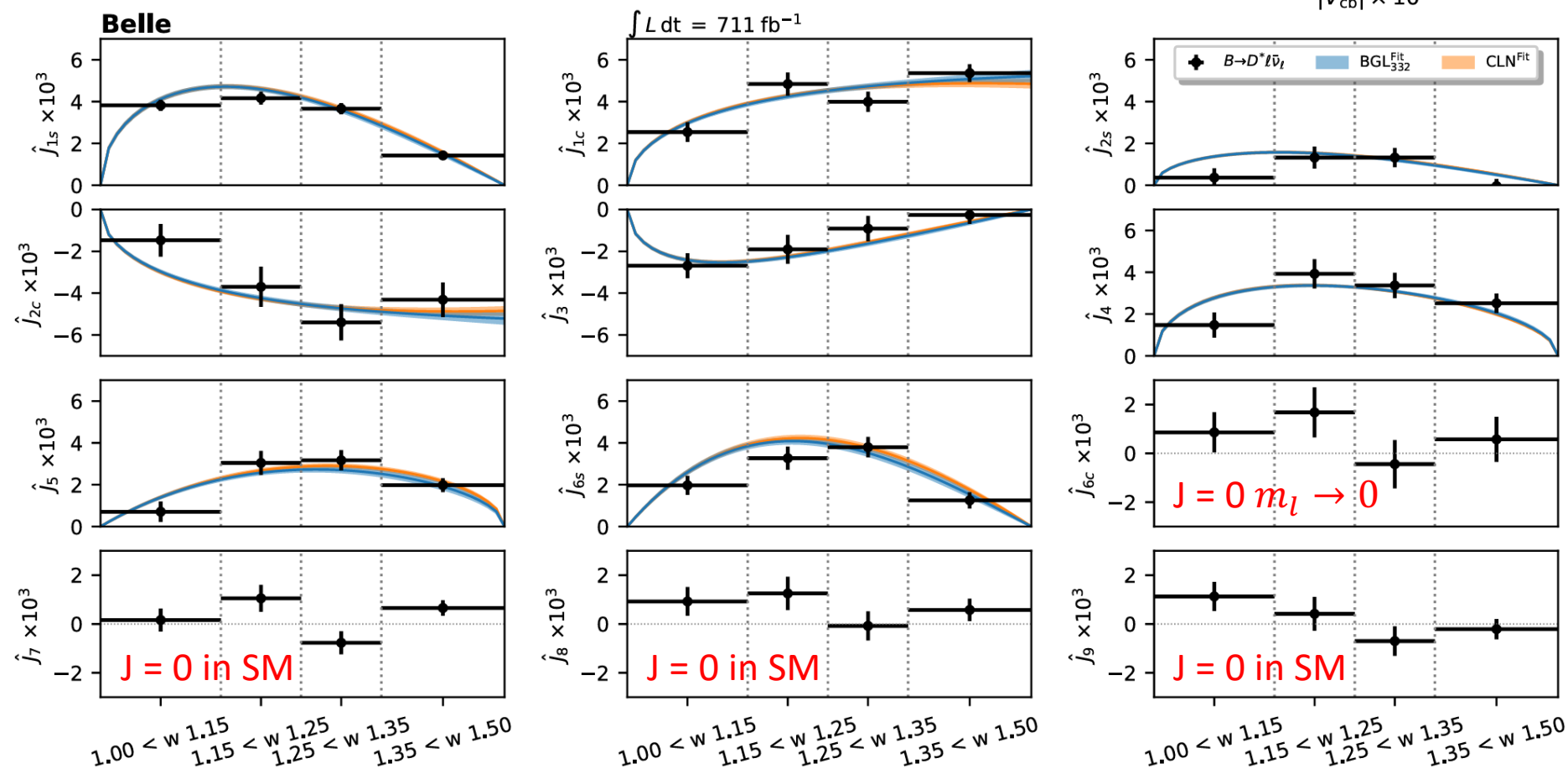
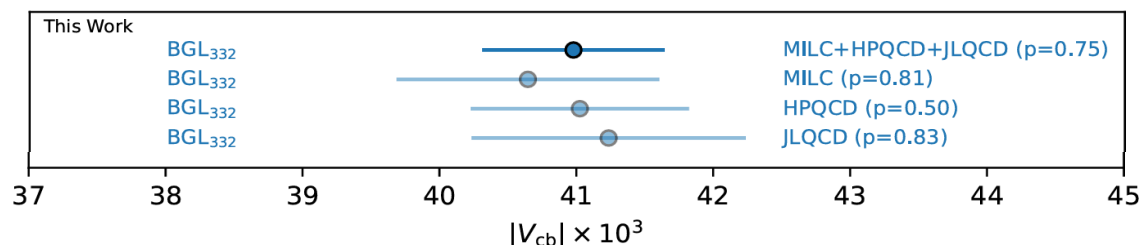
SM test and LFU test (with e vs μ) possible

$|V_{cb}|$ from Angular Coefficients of $\bar{B} \rightarrow D^* l \bar{\nu}_l$



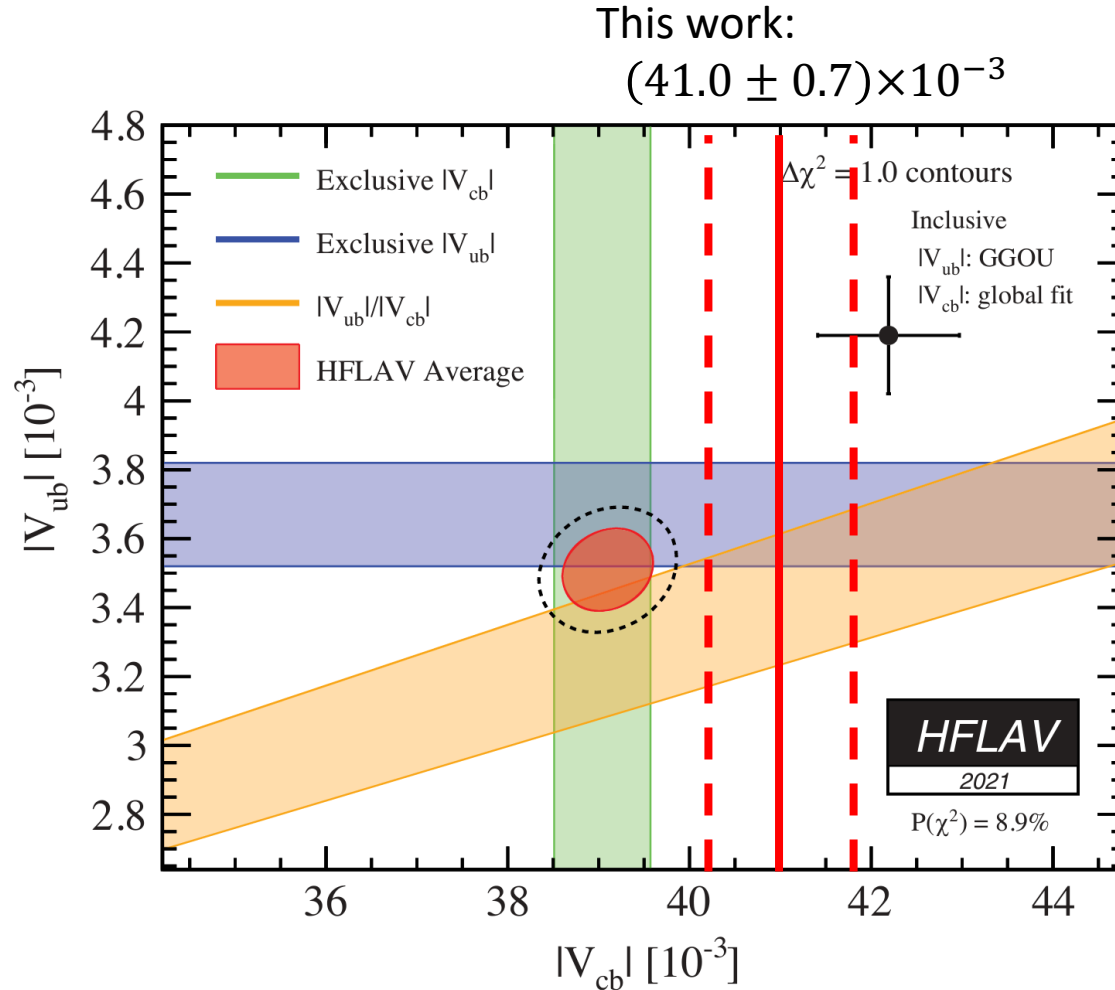
Fit result with BGL parameterizations :

$$|V_{cb}| = (41.0 \pm 0.3(stat) \pm 0.4(syst) \pm 0.5(theo))$$



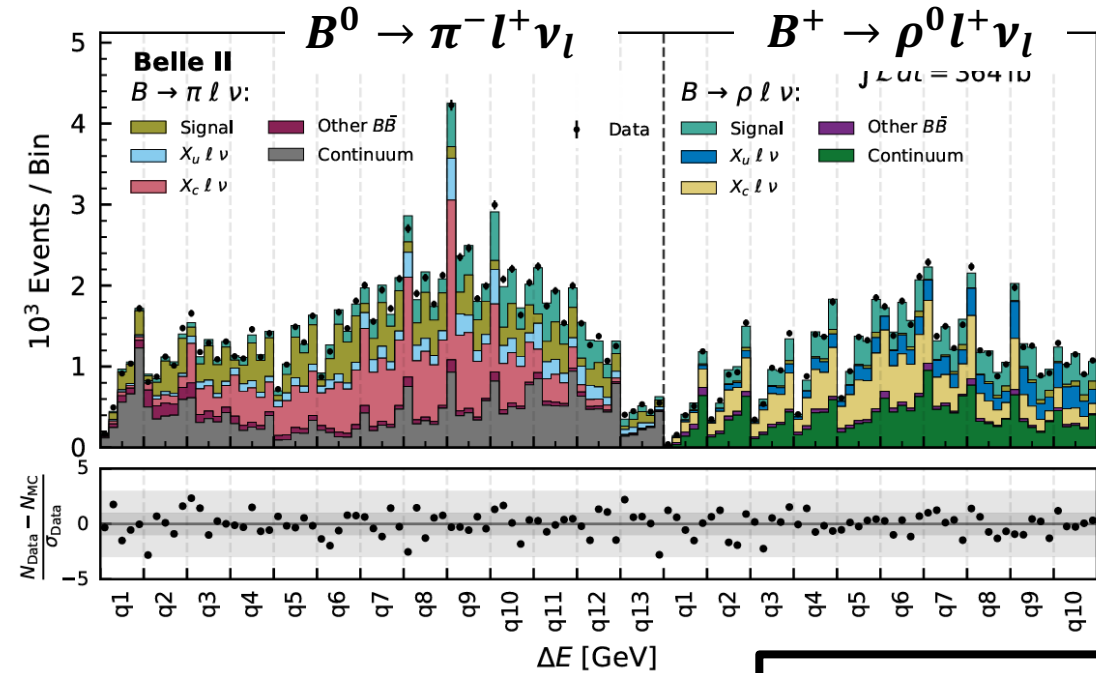
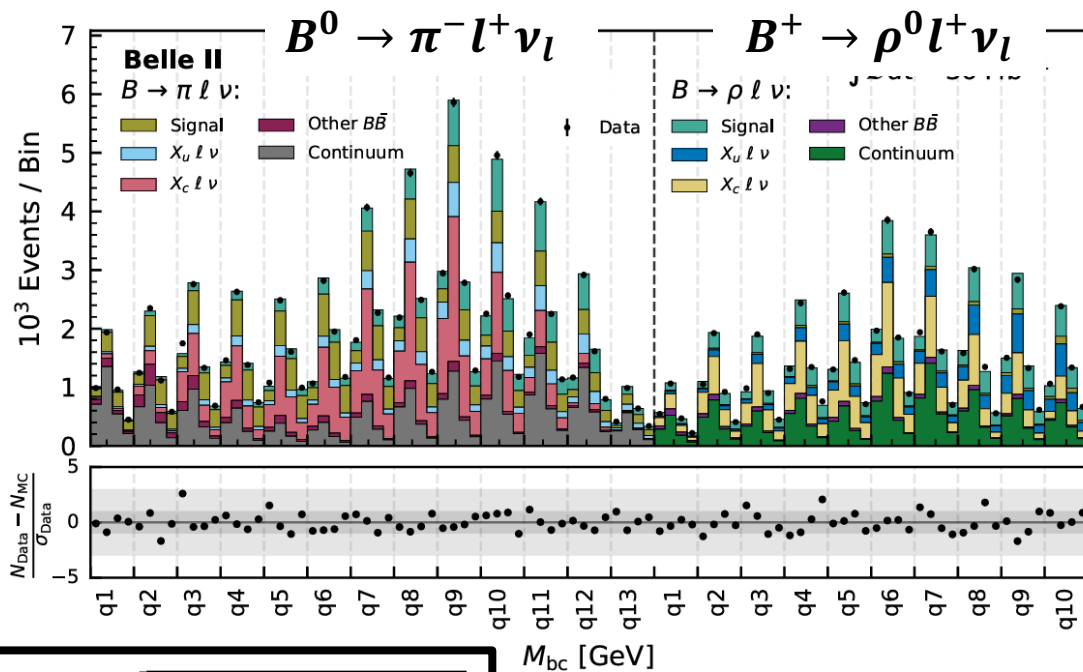
$|V_{cb}|$ from Angular Coefficients of $\bar{B} \rightarrow D^* l \bar{\nu}_l$

- $|V_{cb}|$ in agreement with previous analysis on same dataset (PRD 108(2023) 012002)
- In agreement with latest inclusive results and HFLAV inclusive average



$|V_{ub}|$ from $B^0 \rightarrow \pi^- l^+ \nu_l$ and $B^+ \rightarrow \rho^0 l^+ \nu_l$

- Full Belle II Run1 dataset of 364 fb^{-1} , untagged
- Non-resonant $e^+ e^-$ interactions and B background suppressed using BDTs
- Signal yields extracted from 2 kinematic variables in bins of q^2 simultaneously for $\pi l \nu$ and $\rho l \nu$ mode $\rightarrow (13 + 10) \times 4 \times 5$ bins



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

Total branching ratio is the sum of all the partial ΔB_i in each q^2 bin

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

$|V_{ub}|$ from $B^0 \rightarrow \pi^- l^+ \nu_l$ and $B^+ \rightarrow \rho^0 l^+ \nu_l$

$$\mathcal{B}(B^0 \rightarrow \pi^- l^+ \nu_l) = (1.516 \pm 0.042(stat) \pm 0.059(syst)) \times 10^{-4}$$

Consistent with PDG

$$\mathcal{B}(B^+ \rightarrow \rho^0 l^+ \nu_l) = (1.625 \pm 0.079(stat) \pm 0.180(syst)) \times 10^{-4}$$

$|V_{ub}|$ extracted separately from $\pi l \nu$ and $\rho l \nu$ mode using χ^2 fits to the measured q^2 spectra

$$\chi^2 = \sum_{i,j=1}^N (\Delta B_i - \Delta \Gamma_i \tau) C_{ij}^{-1} (\Delta B_j - \Delta \Gamma_j \tau) + \sum_m \chi_{Theory,m}^2$$

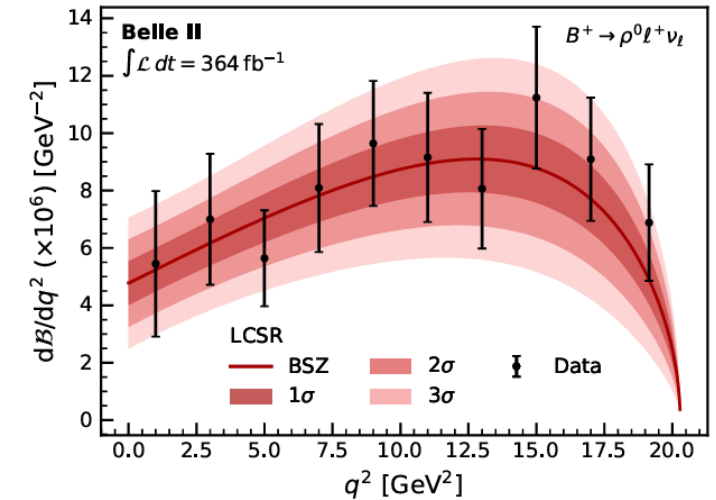
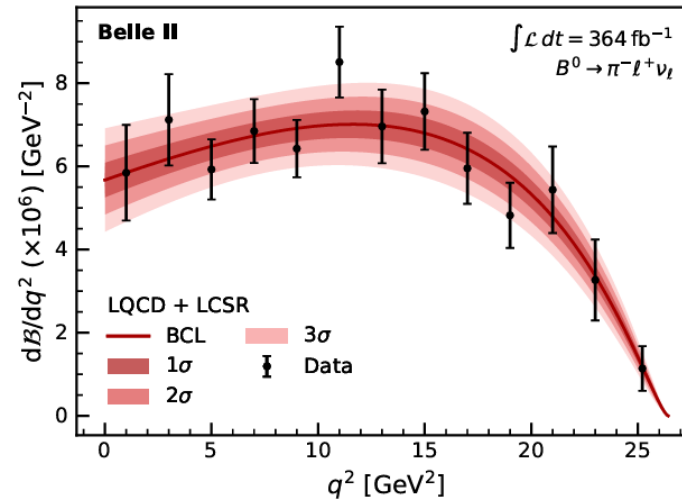
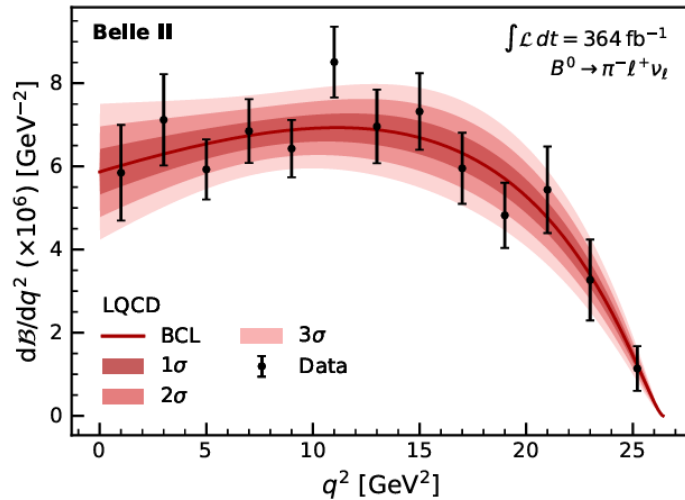
Form-factor
coefficients:

BCL for $B^0 \rightarrow \pi^- l^+ \nu_l$
BSZ for $B^+ \rightarrow \rho^0 l^+ \nu_l$

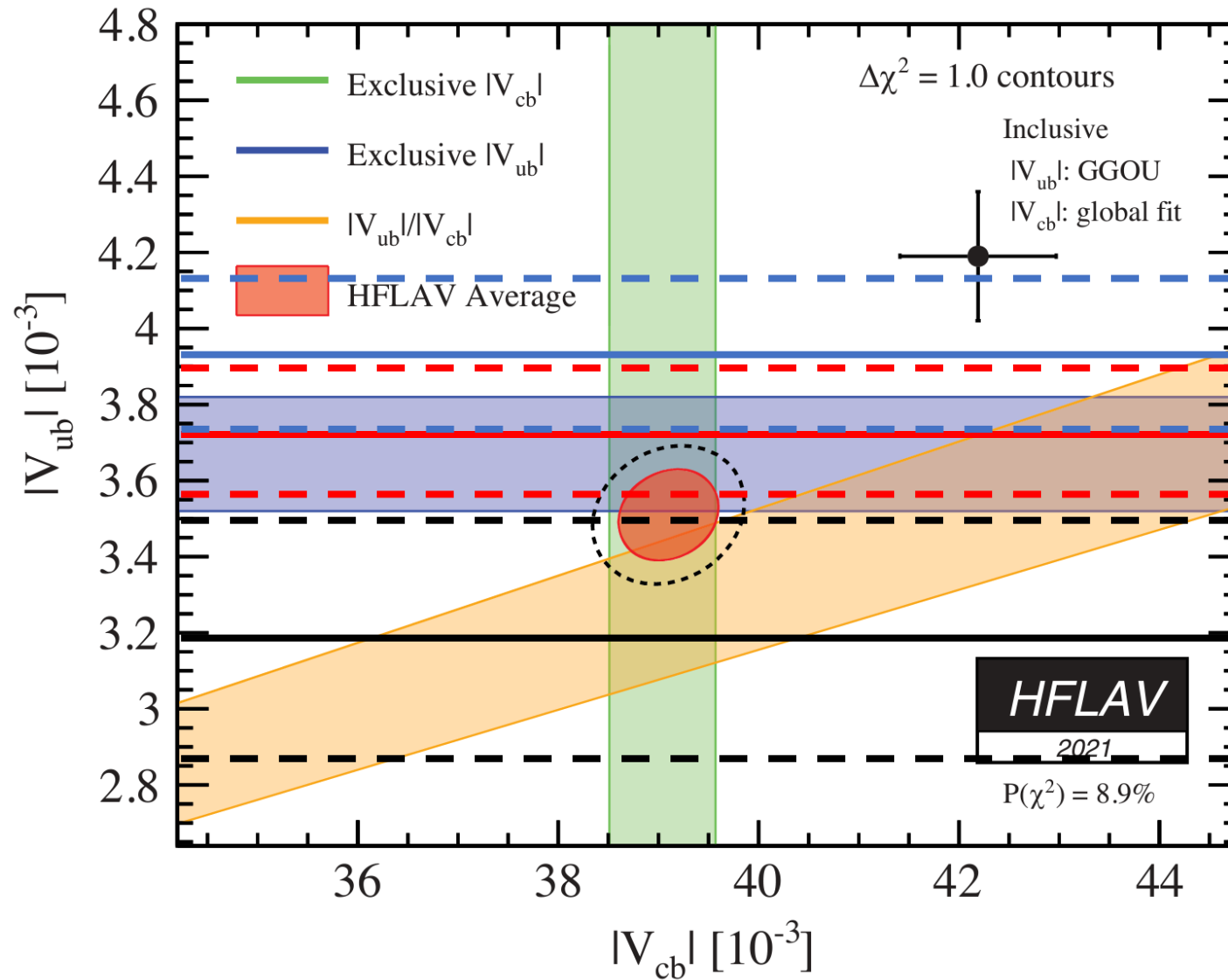
$B^0 \rightarrow \pi^- l^+ \nu_l$: $|V_{ub}| = (3.93 \pm 0.09(stat) \pm 0.13(syst) \pm 0.19(theo)) \times 10^{-3}$ LQCD constraints

$|V_{ub}| = (3.73 \pm 0.07(stat) \pm 0.07(syst) \pm 0.16(theo)) \times 10^{-3}$ LQCD+LCSR constraints

$B^+ \rightarrow \rho^0 l^+ \nu_l$: $|V_{ub}| = (3.19 \pm 0.12(stat) \pm 0.17(syst) \pm 0.26(theo)) \times 10^{-3}$ LCSR constraints



$|V_{ub}|$ from $B^0 \rightarrow \pi^- l^+ \nu_l$ and $B^+ \rightarrow \rho^0 l^+ \nu_l$



$B^0 \rightarrow \pi^- l^+ \nu_l$:
 $(3.93 \pm 0.19) \times 10^{-3}$
 $(3.73 \pm 0.16) \times 10^{-3}$

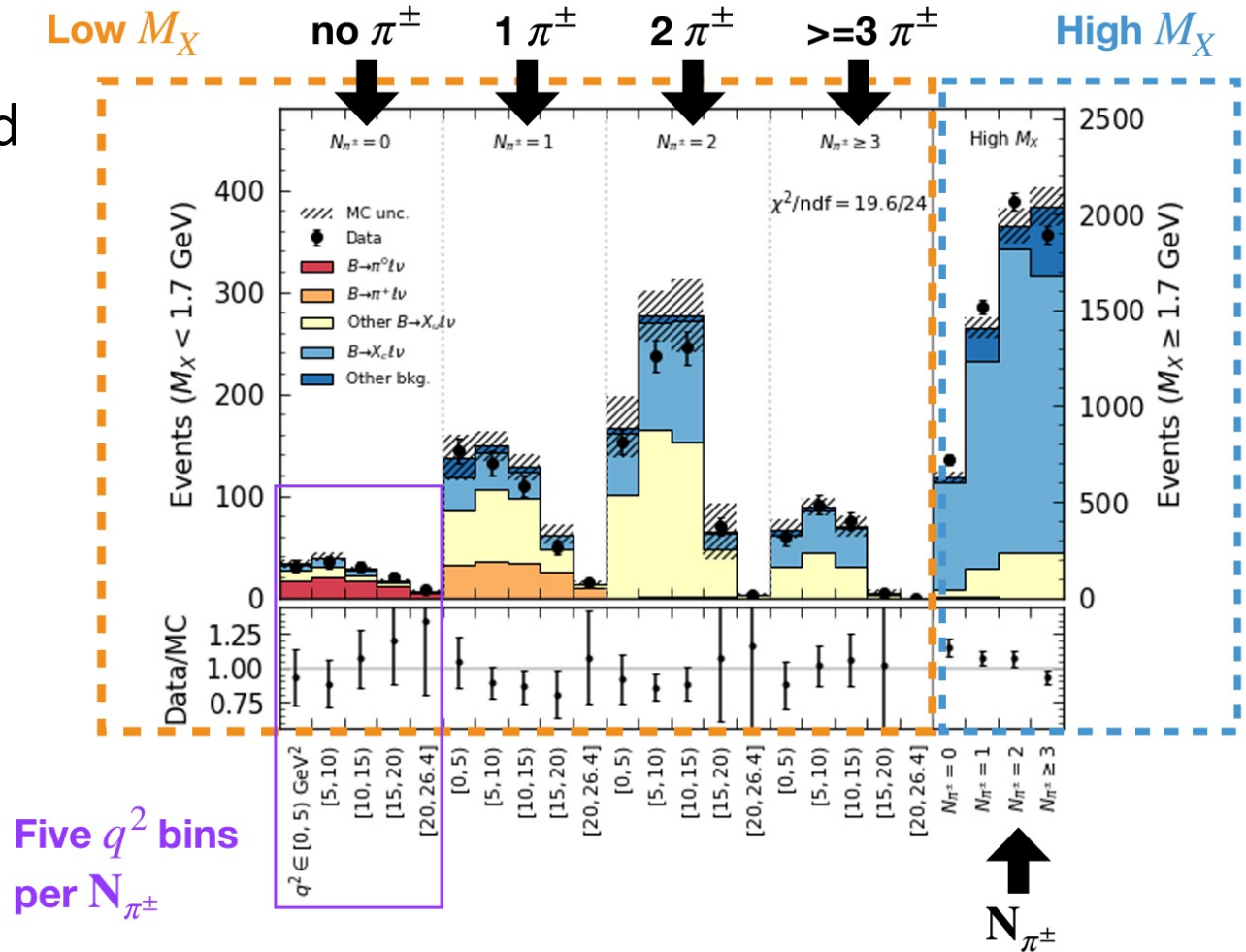
$B^+ \rightarrow \rho^0 l^+ \nu_l$:
 $(3.19 \pm 0.33) \times 10^{-3}$

Reducing the tension with $|V_{ub}|$ inclusive

Still large uncertainty

$|V_{ub}|$ from Inclusive and Exclusive B decays

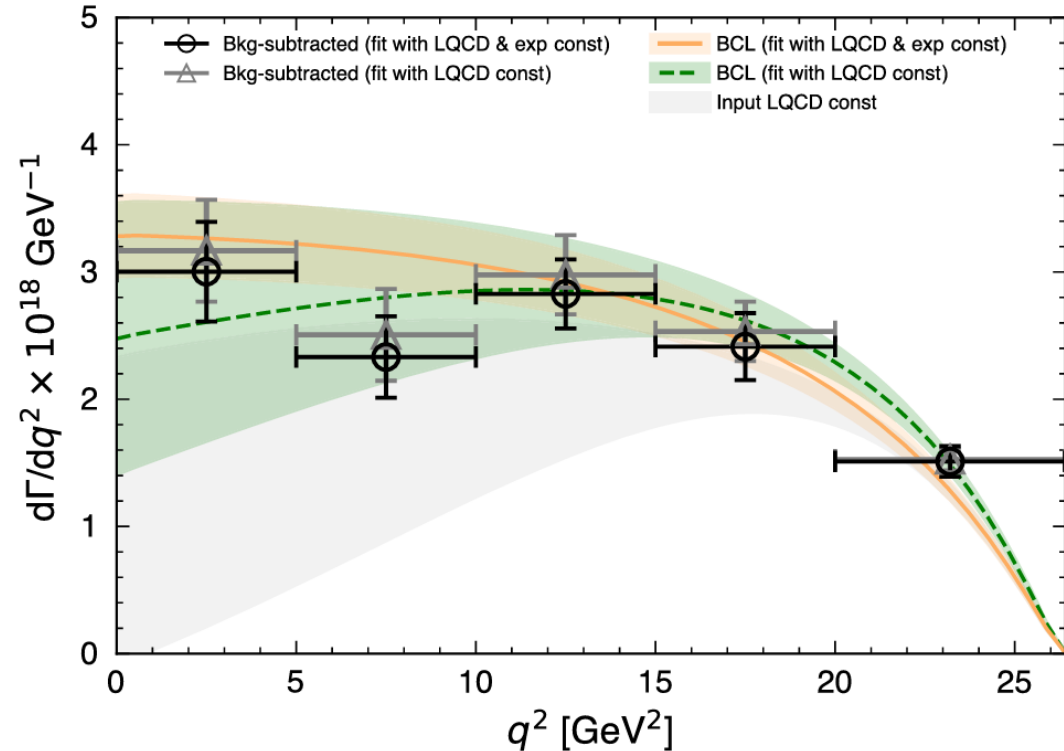
- Full Belle dataset of 711 fb^{-1} and hadronic B tagging
- Same analysis strategy from previous Belle analysis of $B \rightarrow X_u l \nu$ with hadronic tagging [PRD 104, 012008 (2021)]
- Extract signal in q^2 : N_{π^\pm} for $B \rightarrow \pi l \nu$ and other $B \rightarrow X_u l \nu$ simultaneously
- $b \rightarrow u$ enhanced region with Low M_X ($< 1.7 \text{ GeV}$) divided in 5 q^2 bins
- High M_X ($> 1.7 \text{ GeV}$) $b \rightarrow c$ background dominated region



$|V_{ub}|$ from Inclusive and Exclusive B decays



Only LQCD



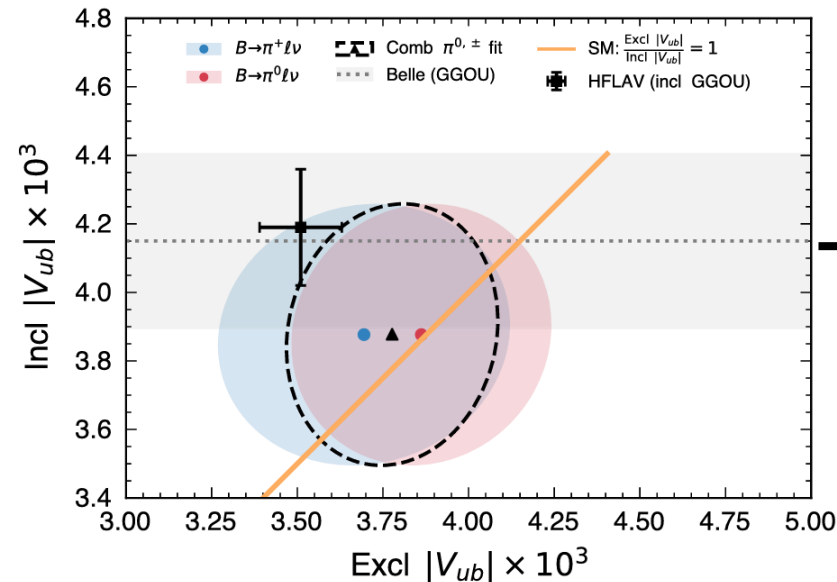
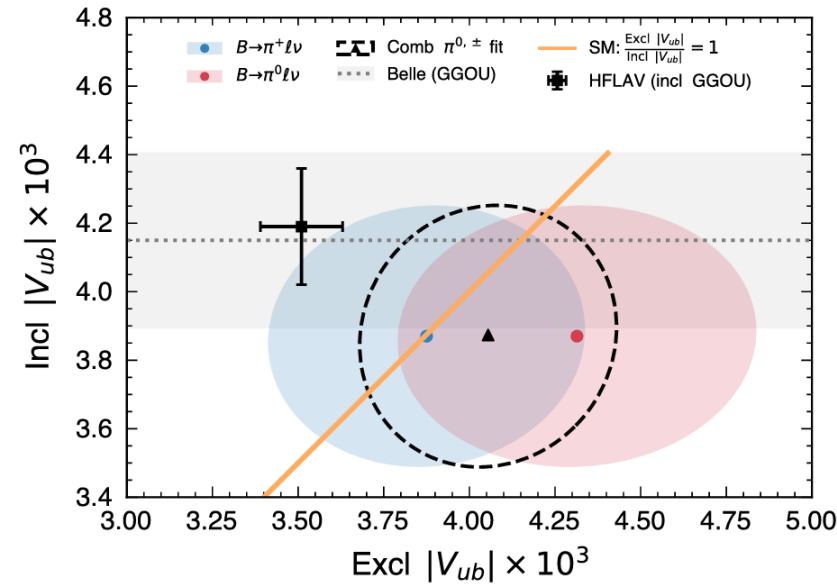
LQCD + exp.

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

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

$$|V_{ub}^{excl}| / |V_{ub}^{incl}| = 0.97 \pm 0.12 \text{ compatible with w.a. in } 1.2\sigma$$

Inclusive and exclusive weighted avg. $|V_{ub}| = (3.84 \pm 0.26) \times 10^{-3} \rightarrow$
 compatible within 0.8σ with $|V_{ub}^{CKM}| = (3.64 \pm 0.07) \times 10^{-3}$



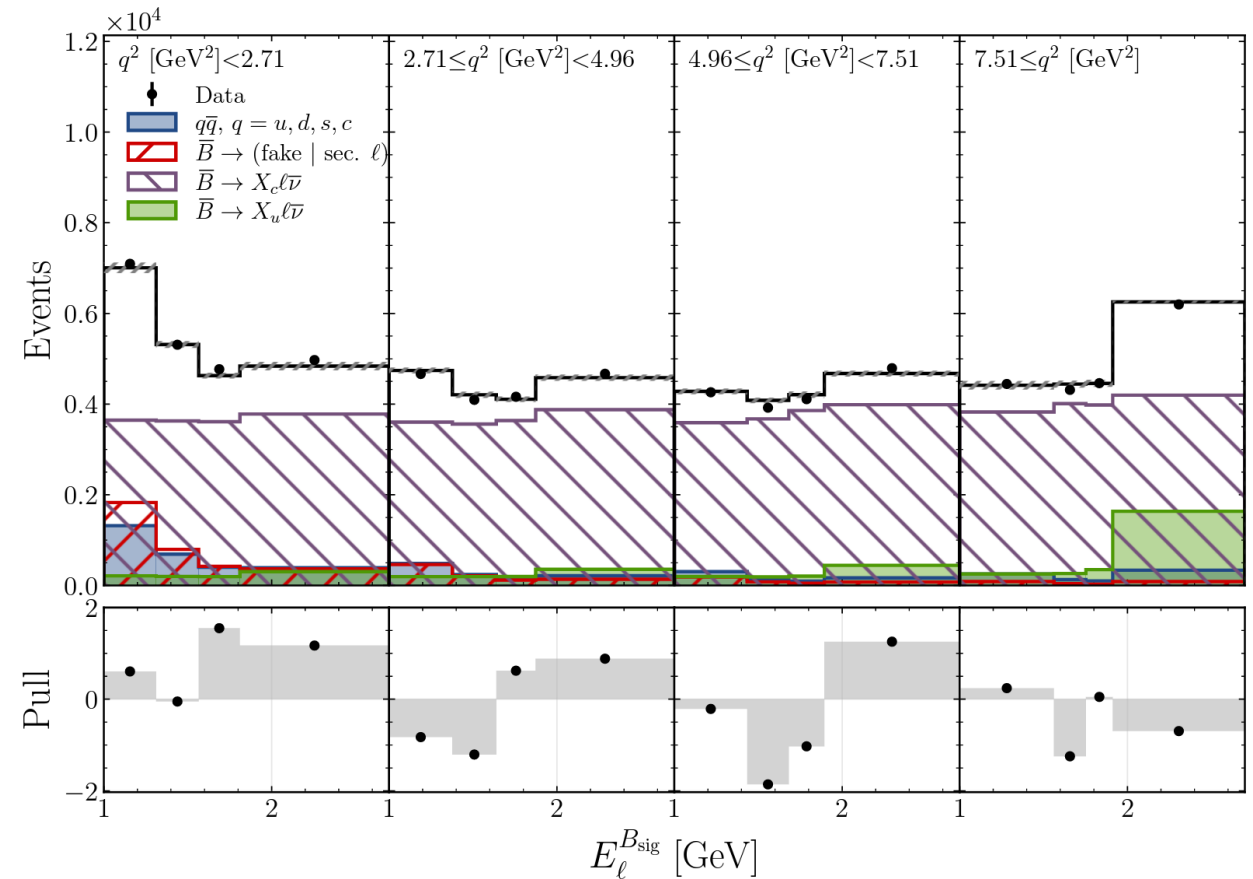
$|V_{ub}|/|V_{cb}|$ from Inclusive decays

- Full Belle dataset of 711 fb^{-1} and hadronic B tagging (using Belle II software)
- $B \rightarrow X_u l \nu$ yields extracted in $q^2: E_l^B$ (D^* veto and M_{miss}^2 requirement)
- $B \rightarrow X_c l \nu$ yields obtained by subtracting other contributions in total $B \rightarrow X l \nu$

$$\frac{\Delta\mathcal{B}(B \rightarrow X_u l \nu)}{\Delta\mathcal{B}(B \rightarrow X_c l \nu)} =$$

$$= 1.96(1 \pm 8.4\%(stat) \pm 7.9\%(syst)) \times 10^{-2}$$

$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{\frac{\Delta\mathcal{B}(B \rightarrow X_u l \nu) \Delta\Gamma(B \rightarrow X_u l \nu)}{\Delta\mathcal{B}(B \rightarrow X_c l \nu) \Delta\Gamma(B \rightarrow X_c l \nu)}}$$



$|V_{ub}|/|V_{cb}|$ from Inclusive decays

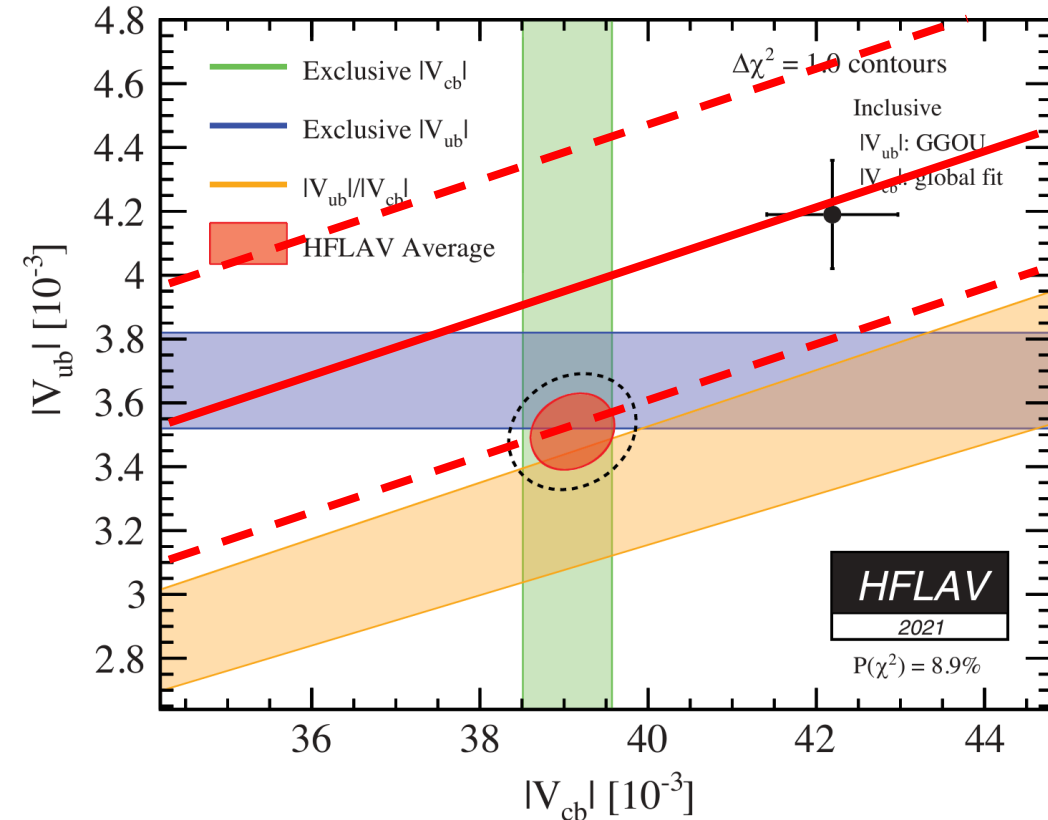
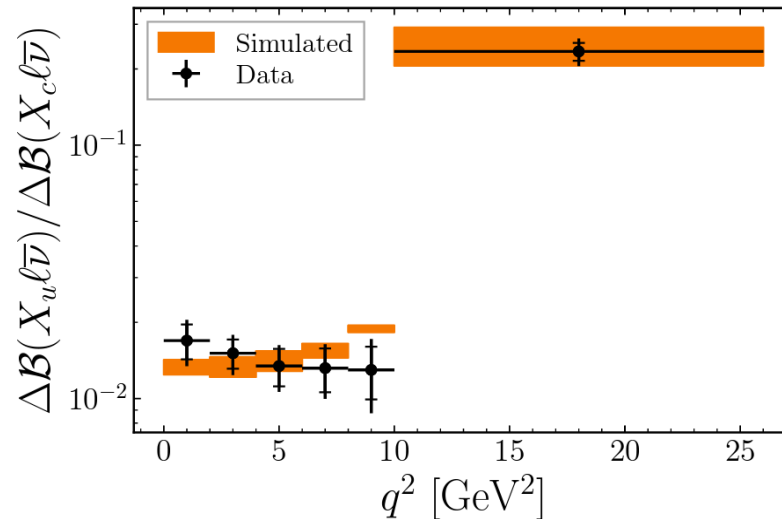
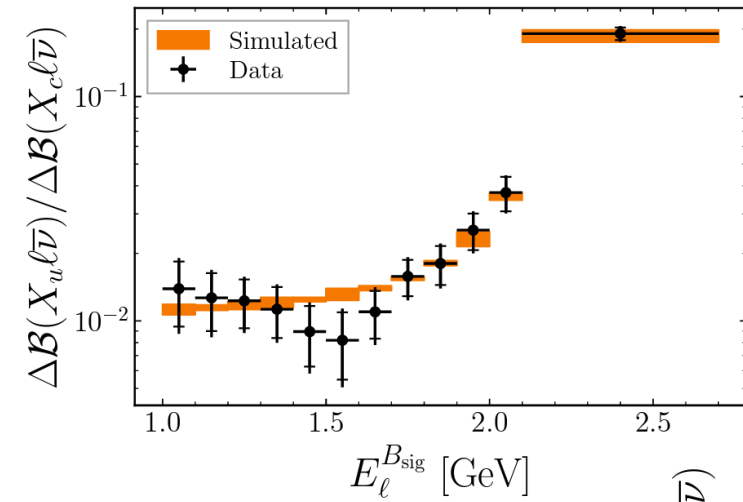


Preliminary

Using two theoretical calculations for the partial decay rate of $B \rightarrow X_u l \bar{\nu}$:

$$|V_{ub}|/|V_{cb}|_{BLNP} = 0.0972(1 \pm 4.2\%(stat) \pm 3.9\%(syst) \pm 5.2\%(\Delta\Gamma(B \rightarrow X_u l \bar{\nu})) \pm 2.0\%(\Delta\Gamma(B \rightarrow X_c l \bar{\nu})))$$

$$|V_{ub}|/|V_{cb}|_{GGOU} = 0.0996(1 \pm 4.2\%(stat) \pm 3.9\%(syst) \pm 2.3\%(\Delta\Gamma(B \rightarrow X_u l \bar{\nu})) \pm 2.0\%(\Delta\Gamma(B \rightarrow X_c l \bar{\nu})))$$



Summary

- Improved measurements of $|V_{cb}|$ and $|V_{ub}|$ are essential to increase the constraining power of the Unitarity Triangle fit
- Known initial state kinematics and hermetic detectors make Belle and Belle II ideal for these studies
- Belle and Belle II are producing many updated and improved measurements of $|V_{cb}|$ and $|V_{ub}|$, with both inclusive and exclusive decays

[Link to the \$|V_{cb}|\$ workshop held last year during the Belle II Physics Week](#)