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

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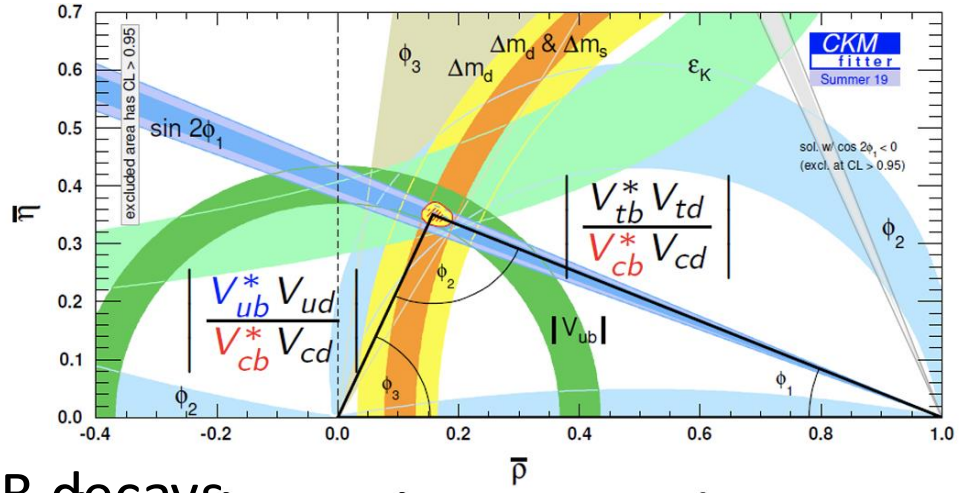
Determination of $|V_{ub}|$ and $|V_{cb}|$

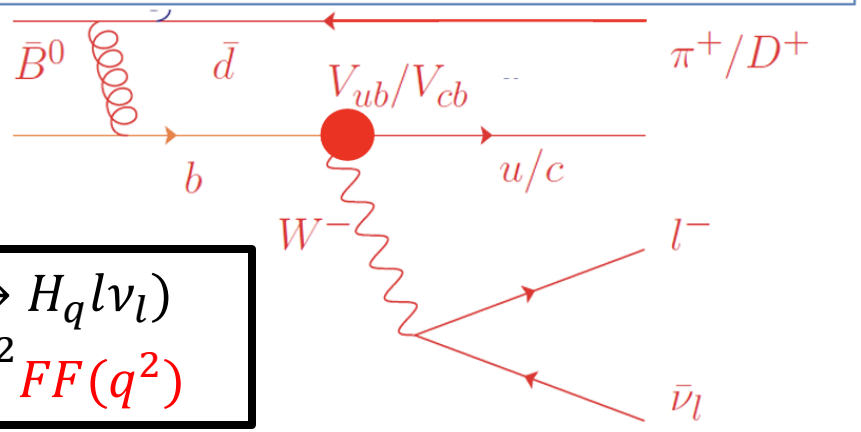
- $|V_{ub}|$ and $|V_{cb}|$ important to constrain CKM Unitarity

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



- Precisely measured with semileptonic B decays

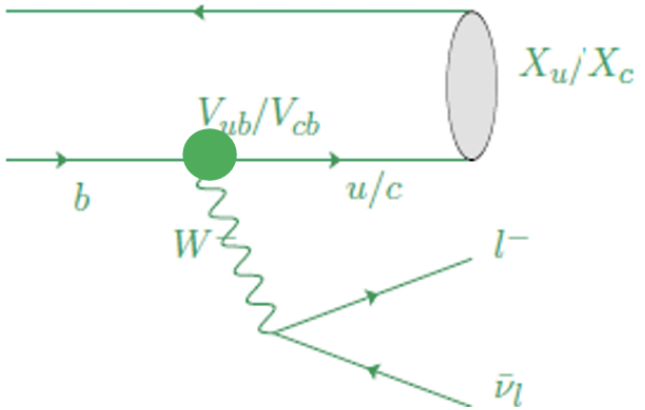
Exclusive: B→π/ρ ℓν, B→D(*)ℓν etc.



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

Form-factor from Theory

Inclusive: B→X_uℓν, B→X_cℓν



$$BF(B \to X_q l \nu_l) \to |V_{qb}|^2 (1 + \cdots)$$

OPE expantion from Theory

Longstanding tension among exclusive and inclusive determinations

Recent results covered in this talk

$|V_{cb}|$

- Measurement of Angular Coefficients of $\bar{B} \to D^* l \bar{\nu}_l$: Implications for $|V_{cb}|$ and Tests of Lepton Flavor Universality
  (**Belle**, arXiv:2310.20286 accepted by PRL, HEPData)

$|V_{ub}|$

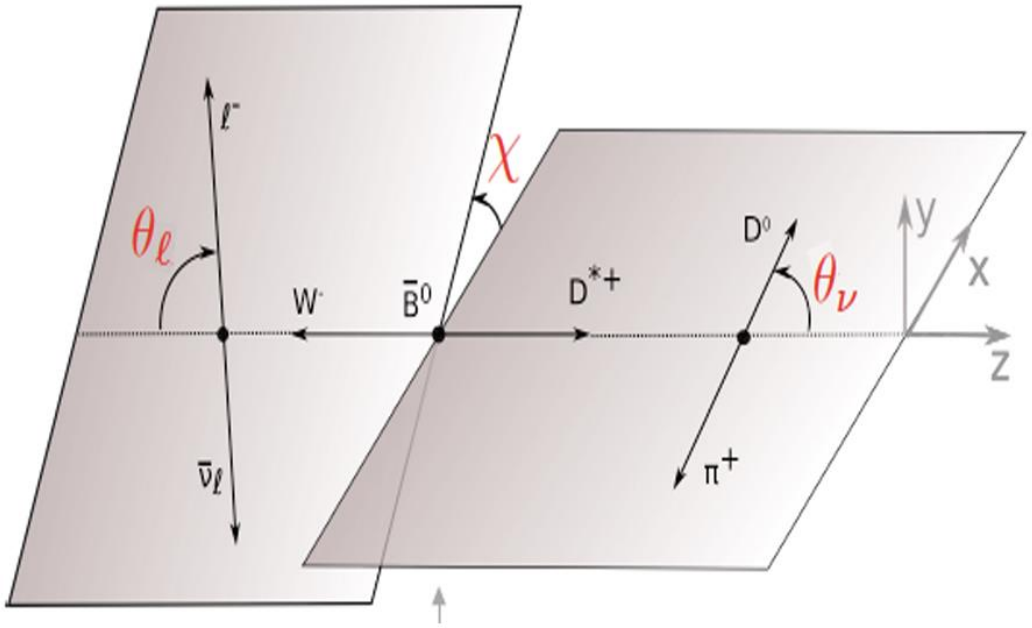
- Determination of $|V_{ub}|$ from simultaneous measurements of untagged $B^0 \to \pi^- l^+ \nu_l$ and $B^+ \to \rho^0 l^+ \nu_l$ decays
  (**Belle II**, new result at Moriond 2024)
- First Simultaneous Determination of Inclusive and Exclusive $|V_{ub}|$
  (**Belle**, PRL 131, 211801)

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

- Measurement of the Ratio of Partial Branching Fractions of Inclusive $\bar{B} \to X_u l \bar{\nu}_l$ to $\bar{B} \to X_c l \bar{\nu}_l$ and the Ratio of their Spectra with Hadronic Tagging
  (**Belle**, arXiv:2311.00458 submitted to PRD)

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

- Full Belle dataset of 711 fb^{-1} and hadronic B tagging
- Both charged and neutral B mesons with the decay chains $\overline{B^0} \to D^{*+} l \bar{\nu}_l$ with $D^{*+} \to D^0 \pi^+ / D^+ \pi^0$, and $B^- \to D^{*0} l \bar{\nu}_l$ with $D^{*0} \to D^0 \pi^0$
- 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



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

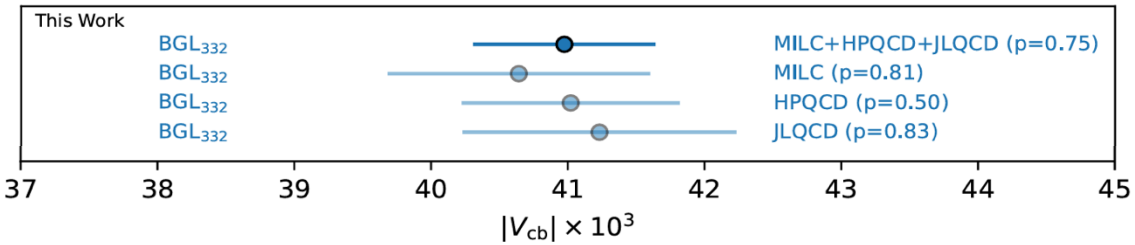
Four-dimensional differential decay rate for $\bar{B} \to D^* l \bar{\nu}_l$ can be expressed in terms of 12 functions J_i that depend only on w

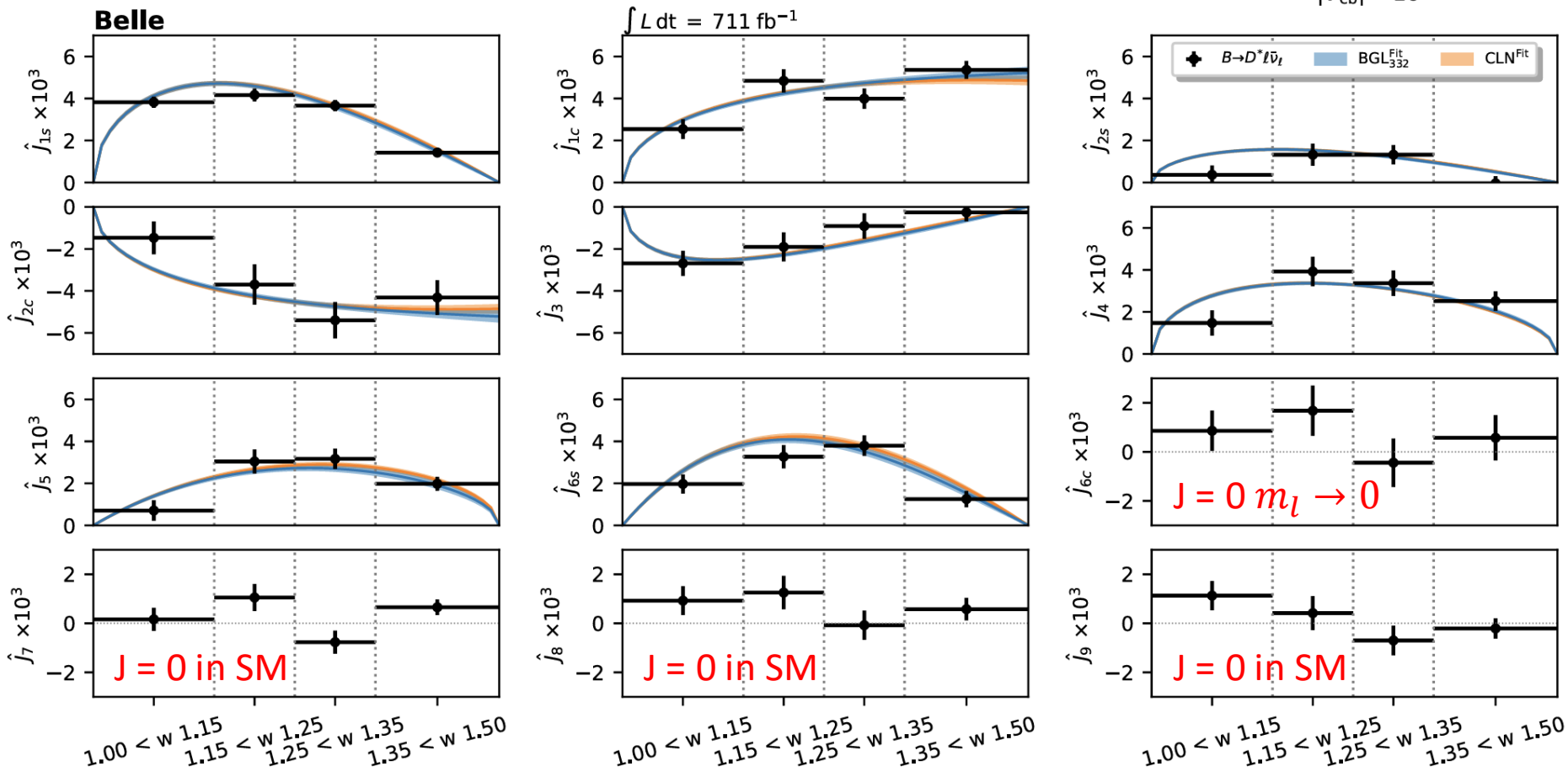
SM test and LFU test (with e vs μ) possible

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

Fit result with **BGL parameterizations** :

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

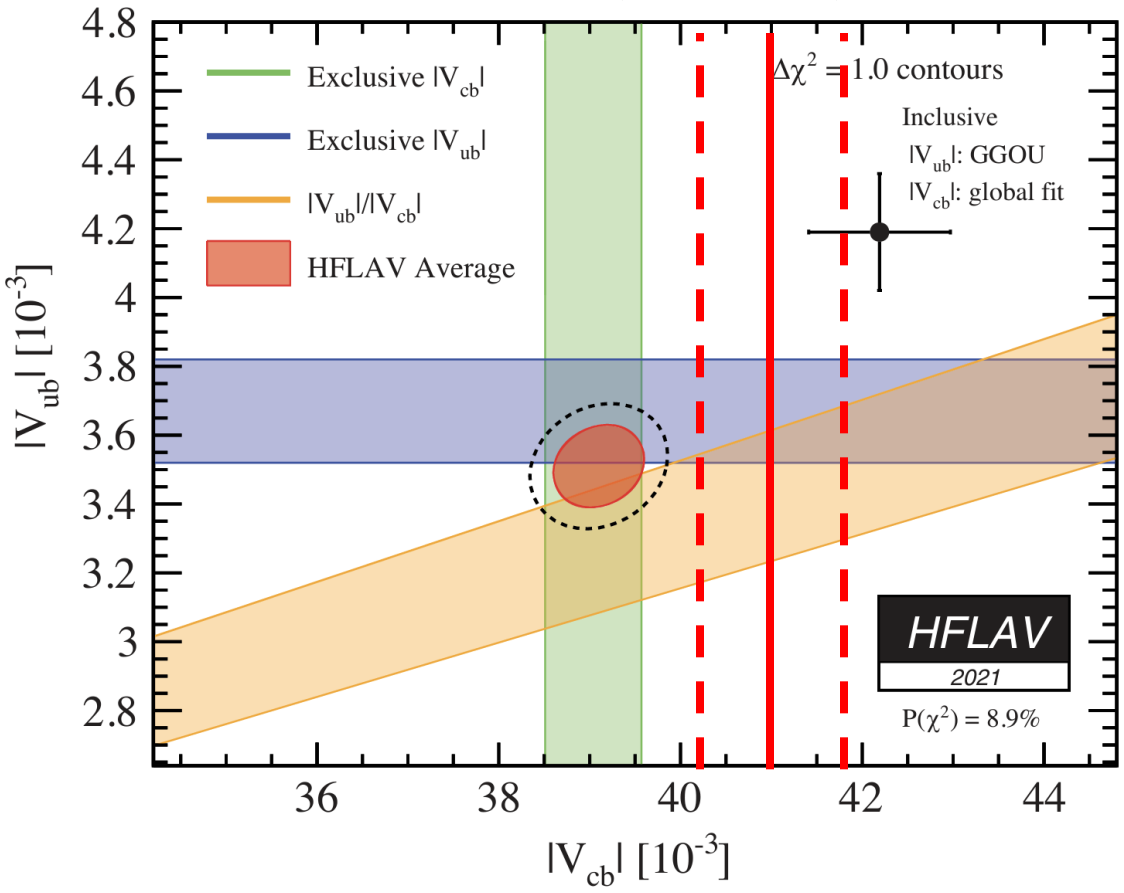




$|V_{cb}|$ from Angular Coefficients of $\bar{B} \to D^* l \bar{\nu}_l$

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

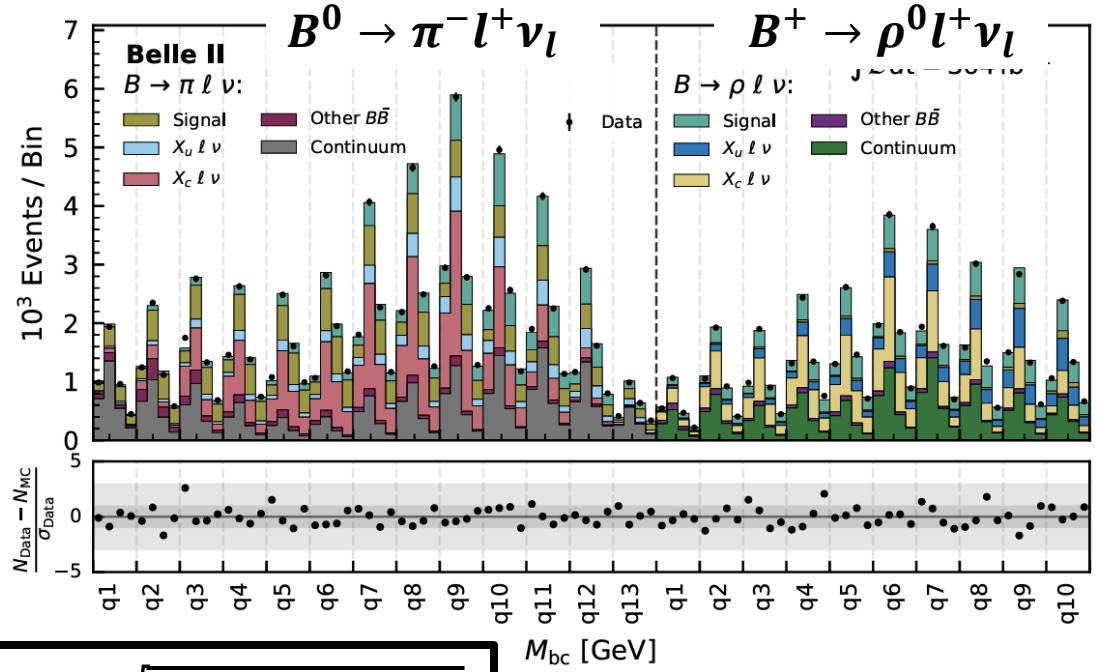
This work:
$(41.0 \pm 0.7) \times 10^{-3}$

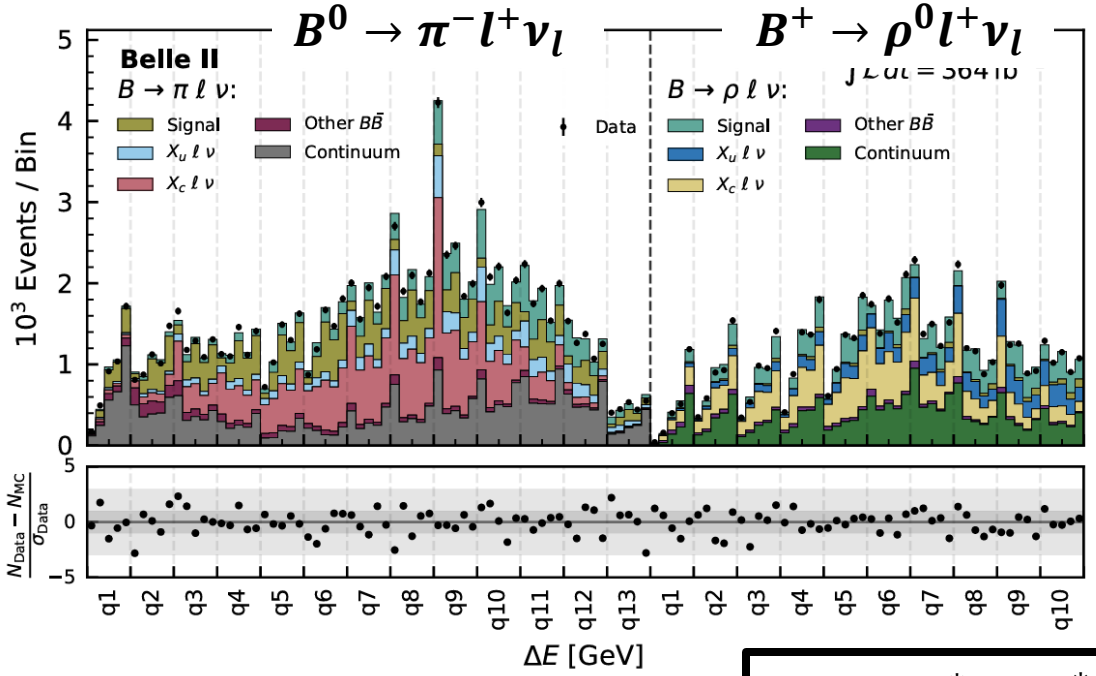


$|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu_l$ and $B^+ \to \rho^0 l^+ \nu_l$

Preliminary

- 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 $\to (13 + 10) \times 4 \times 5$ bins





$$M_{bc} = \sqrt{E^{*2}_{beam} - \left|\overrightarrow{p^*_B}\right|^2}$$

$$\Delta E = E^*_B - E^*_{beam}$$

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

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

Belle II

Preliminary

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

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

Consistent with PDG

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

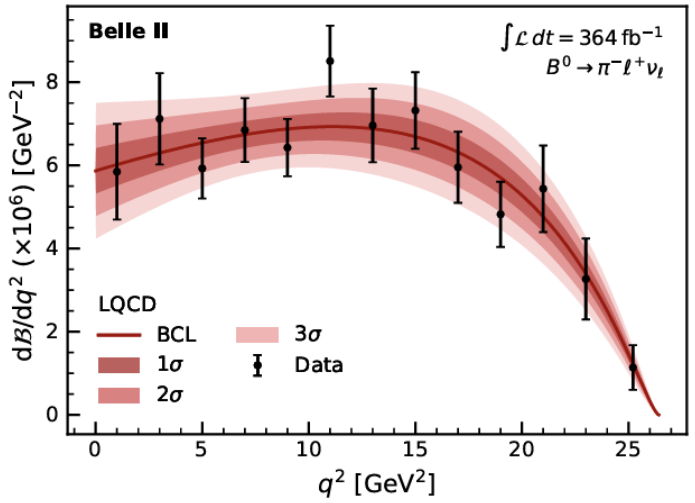
$$\chi^2 = \sum_{i,j=1}^{N} (\Delta B_i - \Delta\Gamma_i \tau) C_{ij}^{-1} \left(\Delta B_j - \Delta\Gamma_j \tau\right) + \sum_m \chi^2_{Theory,m}$$

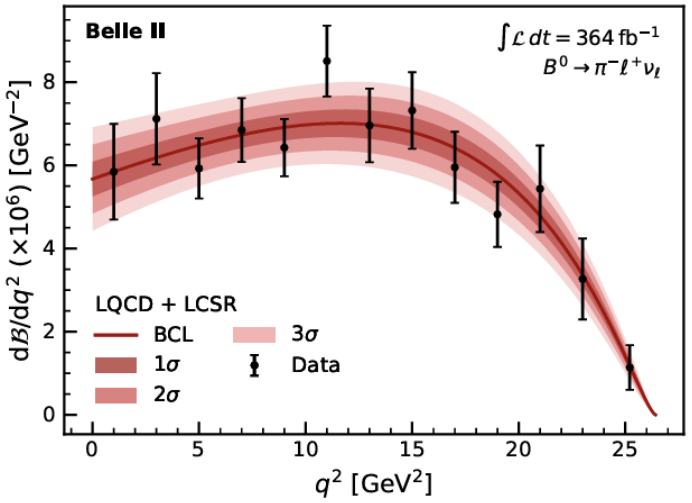
Form-factor coefficents: BCL for $B^0 \to \pi^- l^+ \nu_l$; BSZ for $B^+ \to \rho^0 l^+ \nu_l$

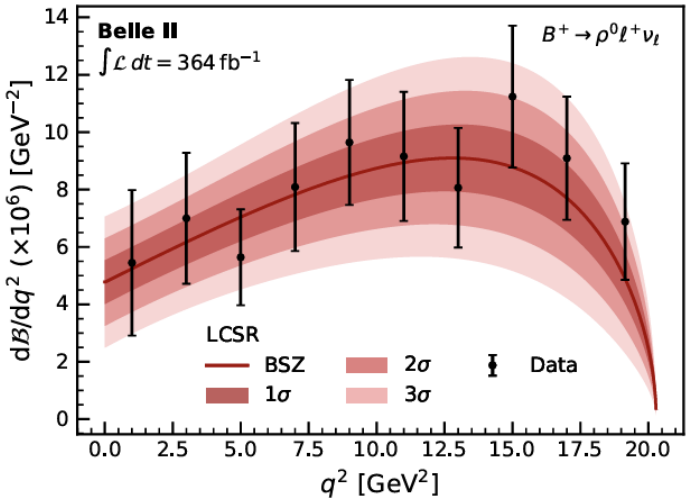
$B^0 \to \pi^- l^+ \nu_l$: $|V_{ub}| = (3.93 \pm 0.09(stat) \pm 0.13(syst) \pm 0.19(theo)) \times 10^{-3}$ **LQCD constraints**

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

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







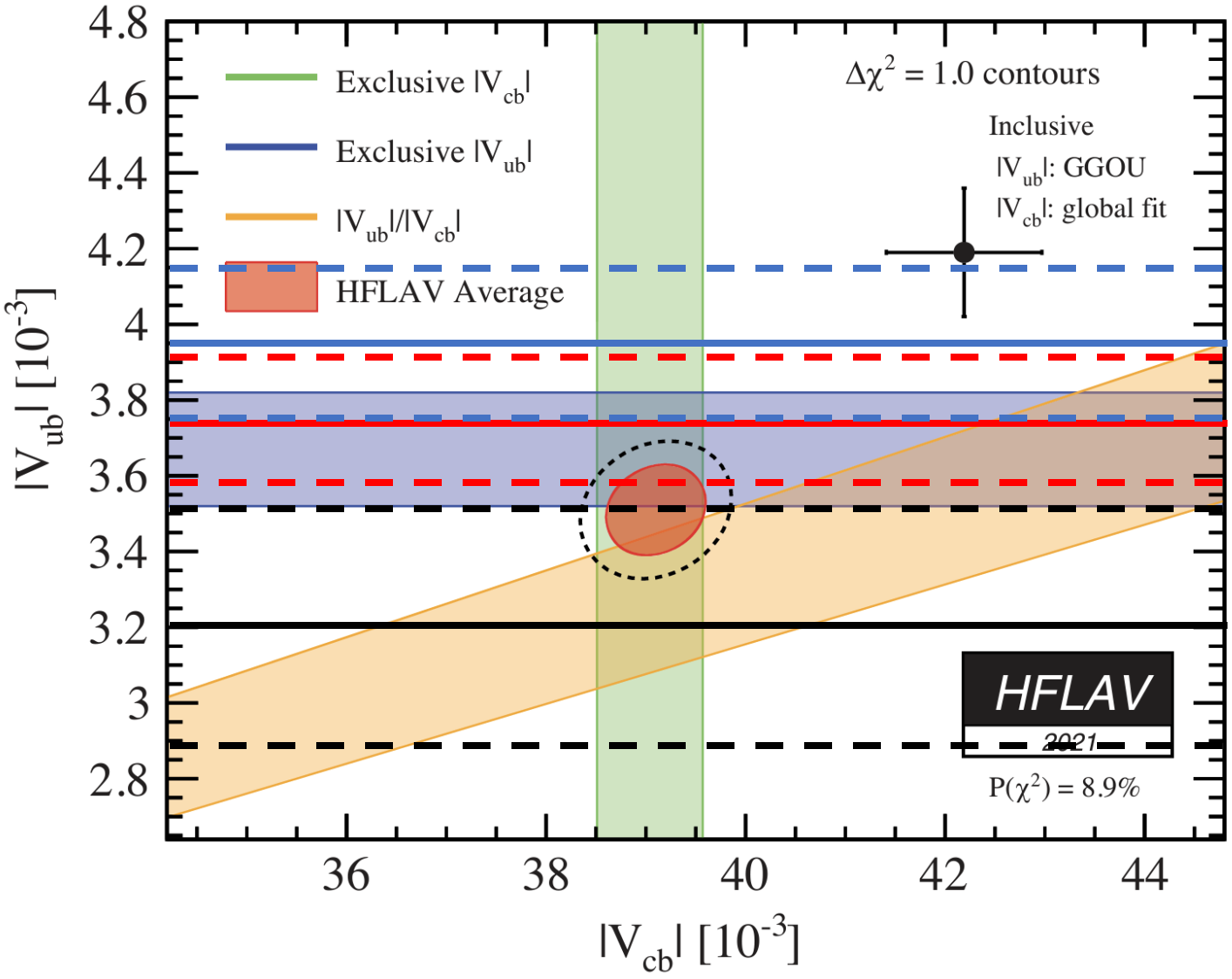
$|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu_l$ and $B^+ \to \rho^0 l^+ \nu_l$

Belle II

Preliminary

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

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

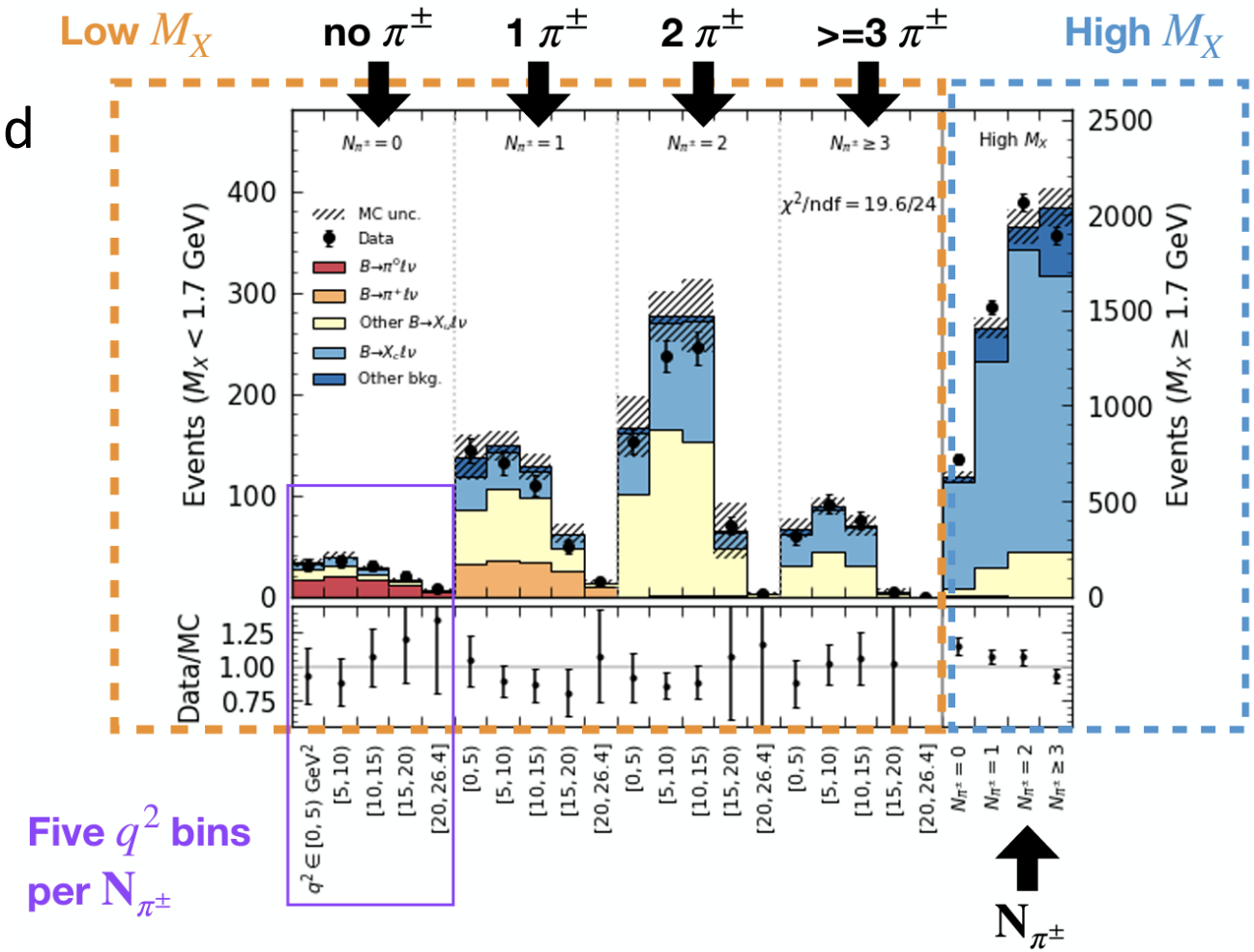


Reducing the tension with $|V_{ub}|$ inclusive

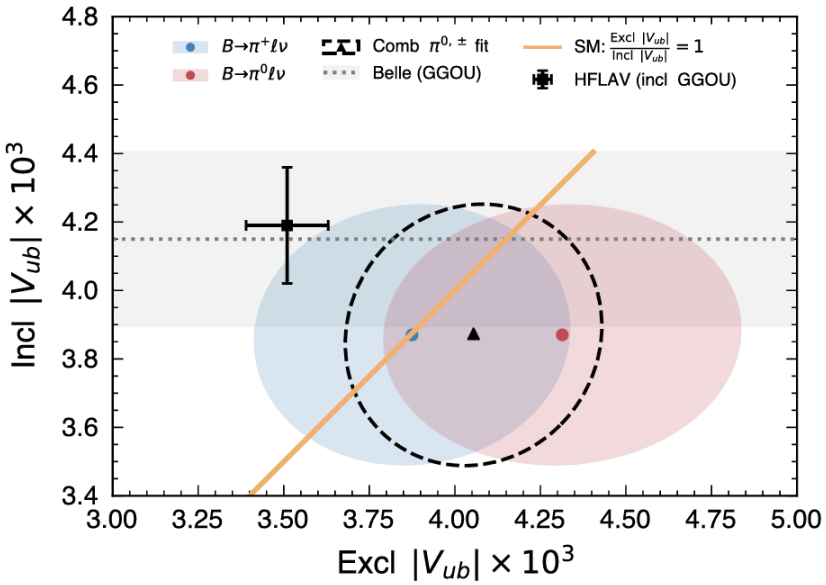
Still large uncertainty

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

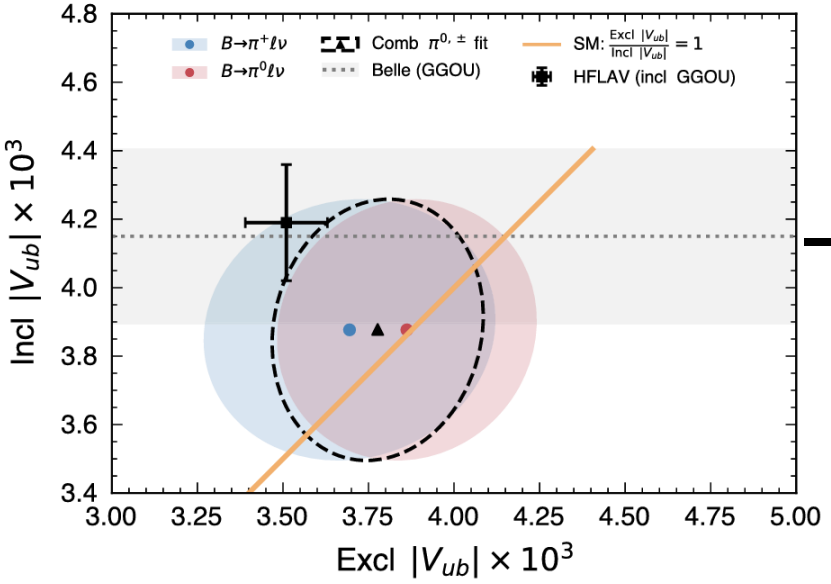
- Full Belle dataset of 711 fb^{-1} and hadronic B tagging
- Same analysis strategy from previous Belle analysis of $B \to X_u l\nu$ with hadronic tagging [PRD 104 , 012008 (2021)]
- Extract signal in q^2: $N_{\pi^\pm}$ for $B \to \pi l\nu$ and other $B \to X_u l\nu$ simultaneously
- $b \to u$ enhanced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



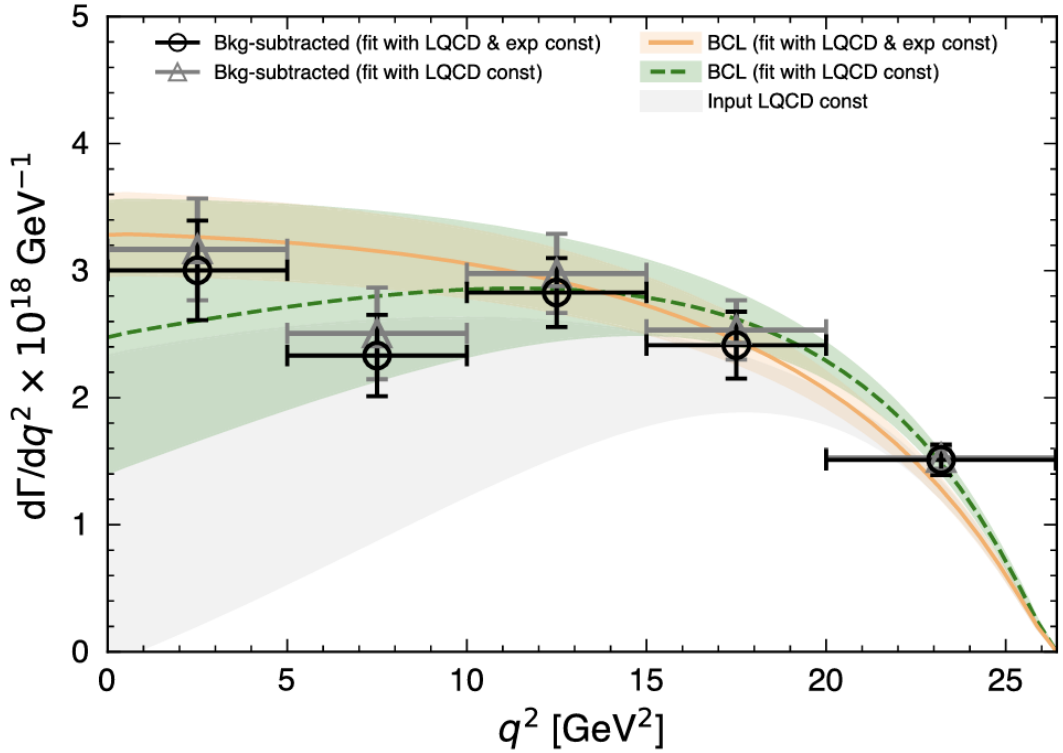
$|V_{ub}|$ from Inclusive and Exclusive B decays



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. $|V_{ub}| = (3.84 \pm 0.26) \times 10^{-3}$ → compatible within 0.8σ with $|V_{ub}^{CKM}| = (3.64 \pm 0.07) \times 10^{-3}$

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

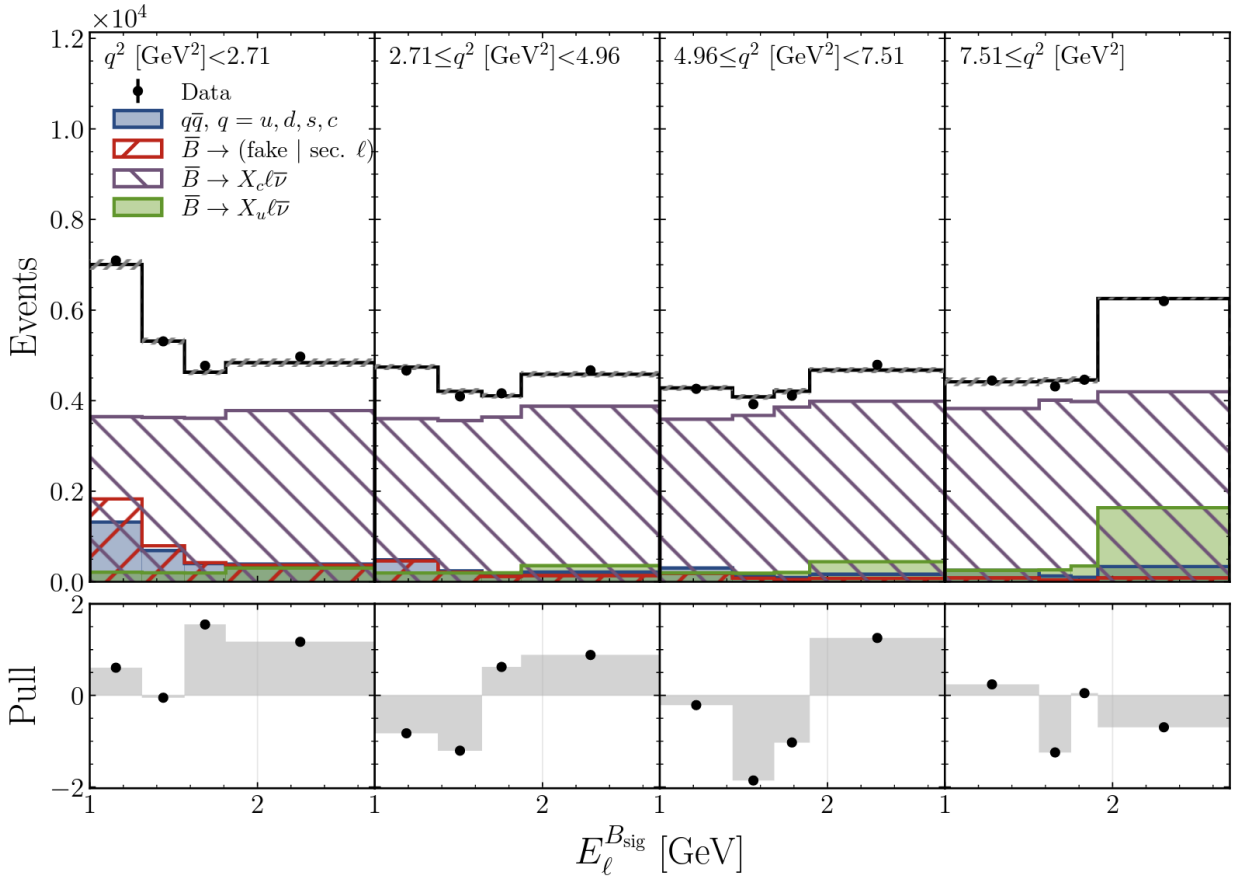
Preliminary

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

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

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

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



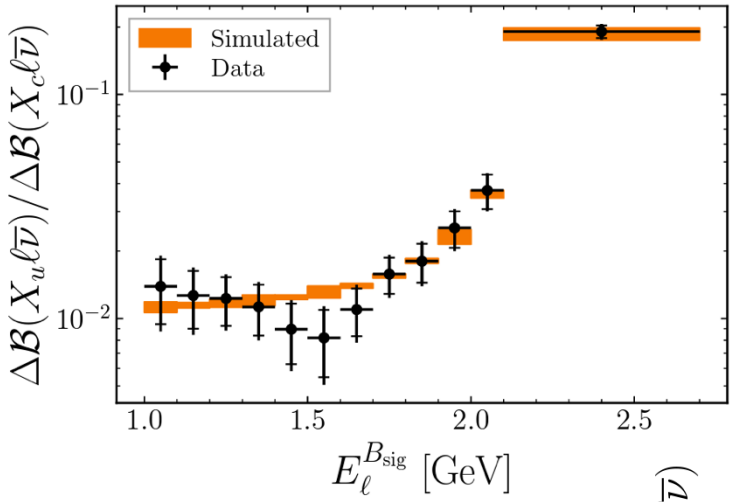
$|V_{ub}|/|V_{cb}|$ from Inclusive decays

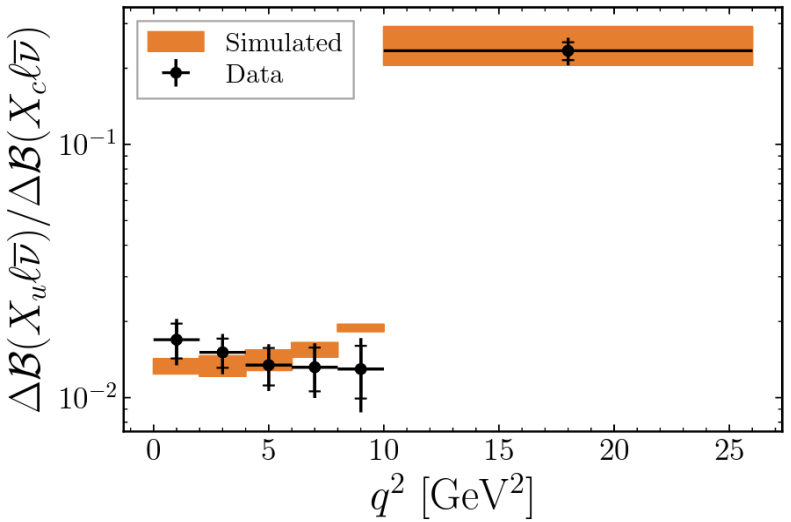
Preliminary

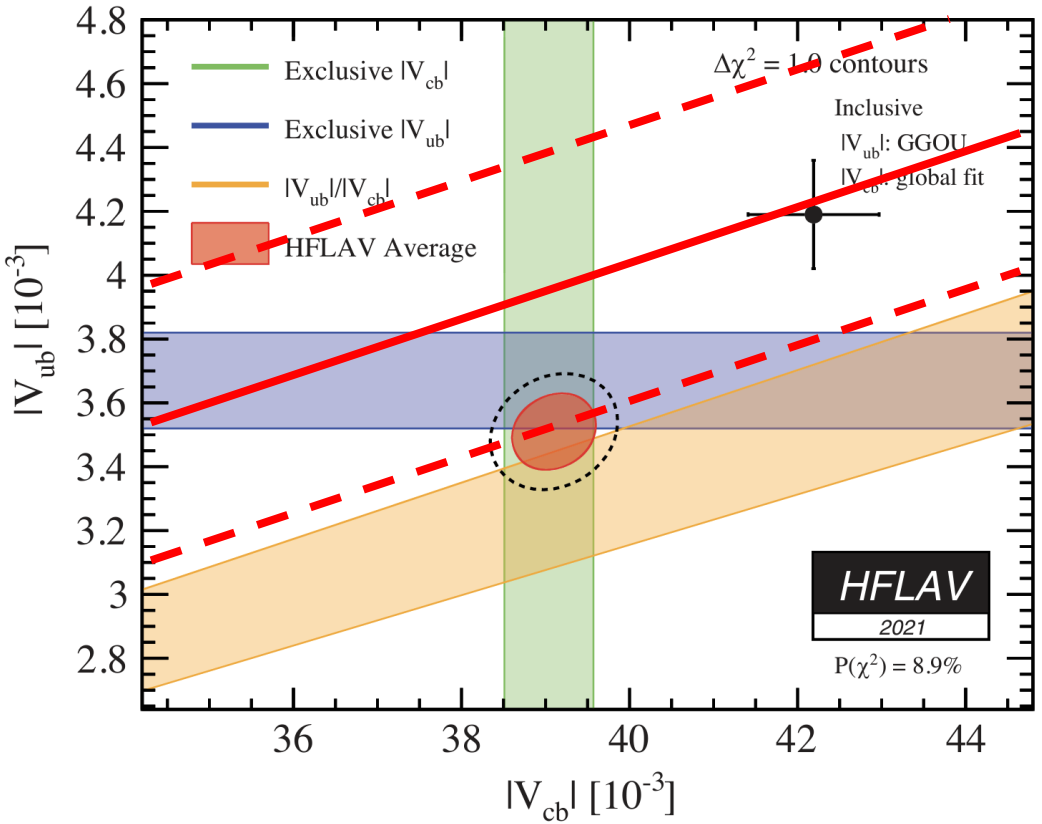
Using two theoretical calculations for the partial decay rate of $B \to X_u l\nu$:

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

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







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 |Vcb| workshop held last year during the Belle II Physics Week