# Measuring $|V_{ub}|$ exclusively and the prospects for Belle II

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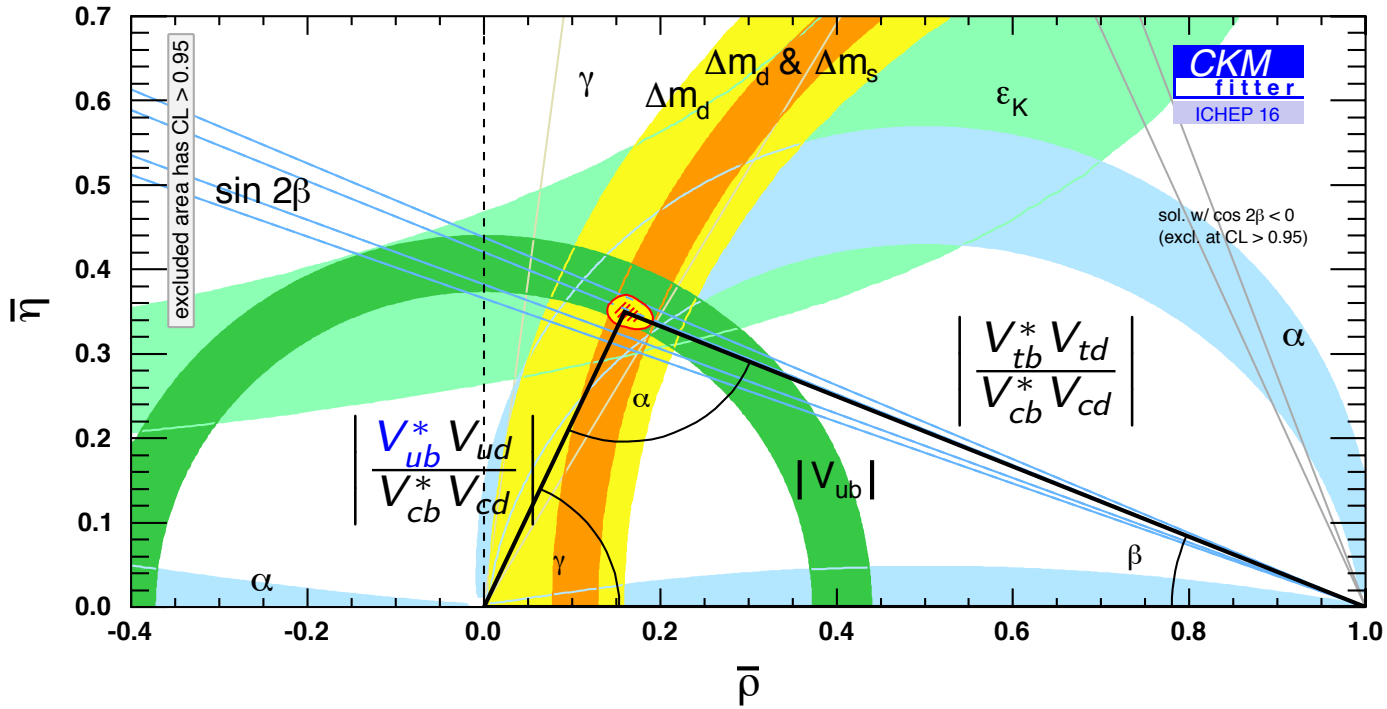
Challenges in Semileptonic B decays



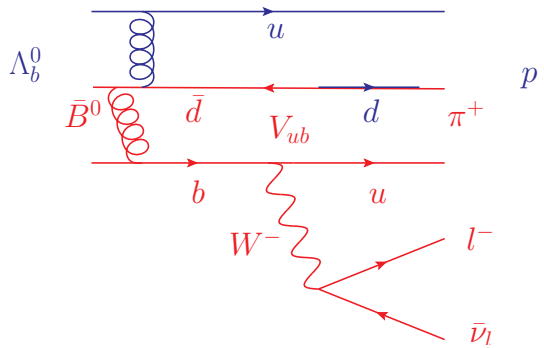
April 11, 2018

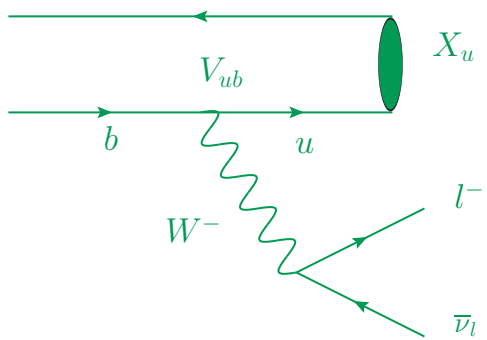
# Why is $|V_{ub}|$ important

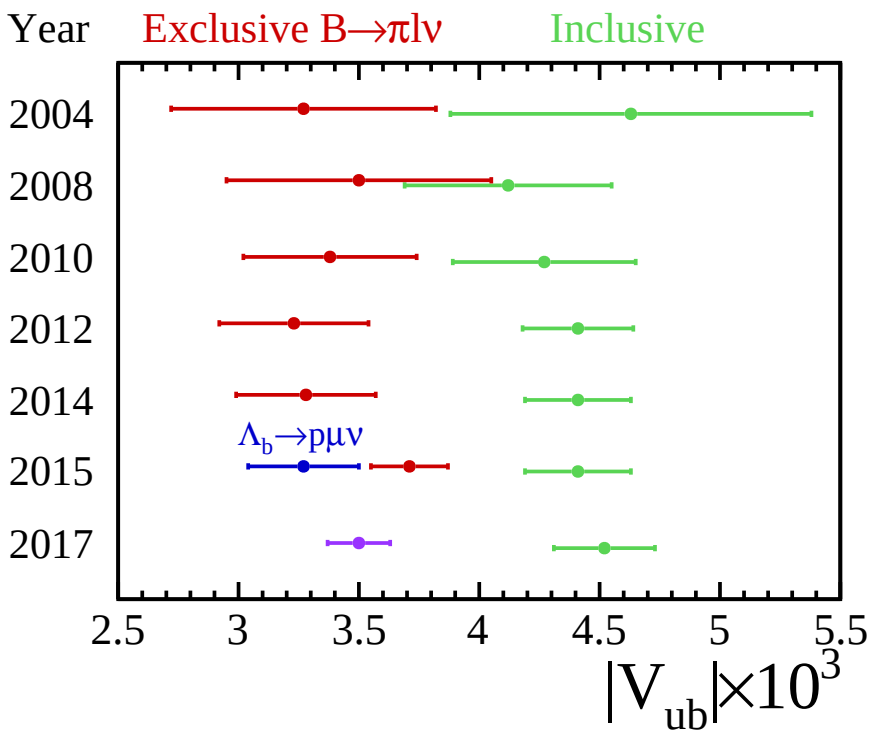
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \overset{\text{Unitarity}}{\Longrightarrow} V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$



# Status of $|V_{ub}|$

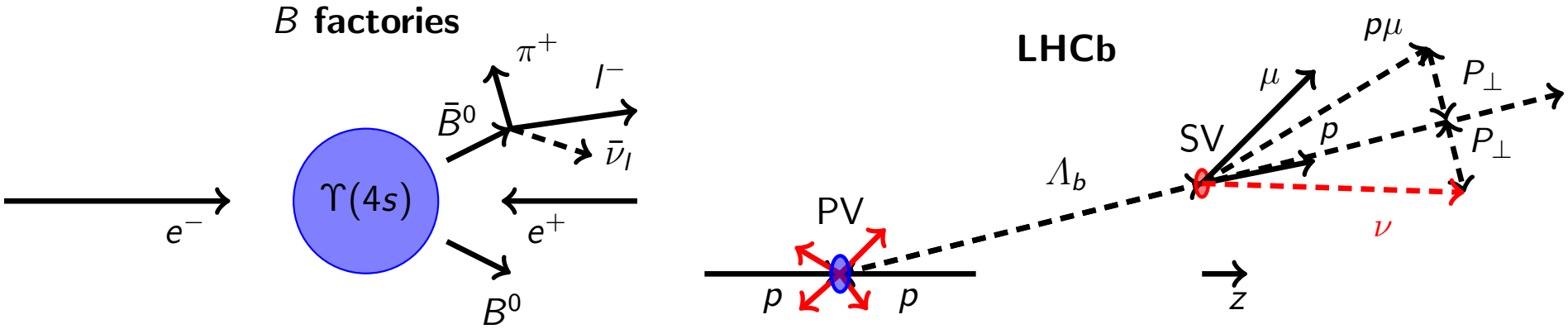


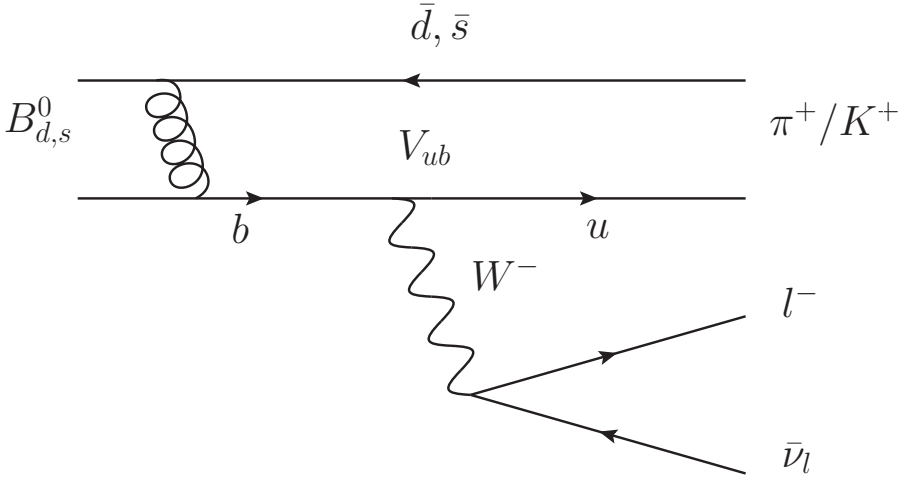
# Why are exclusive $|V_{ub}|$ measurements so challenging?

- Missing neutrino must be reconstructed to determine fit variables and $q^2 = m^2_{l\nu}$.



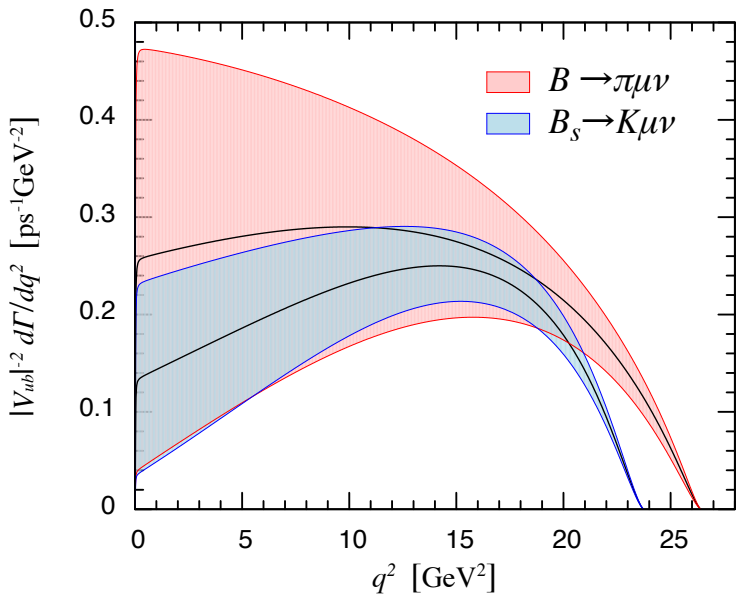

- Large background from $b \to cl\nu$ decays $|V_{cb}|^2/|V_{ub}|^2 \sim 100$
- Poorly understood background from other $b \to ul\nu$ decays.
- QCD interactions must computed non-perturbatively.

# Exclusive theory




- $H^\mu(f_i(q^2)) = \langle X\,|\bar{q}\gamma^\mu(1-\gamma_5)b|\,B\rangle$
- Form factors $f_i(q^2)$ computed with Light Cone Sum Rules or LQCD

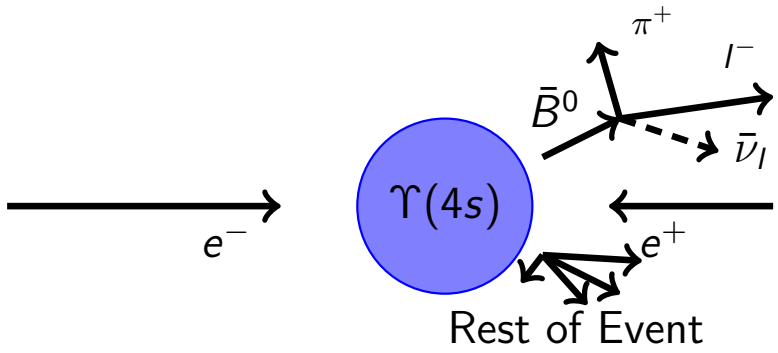
- Matrix element factorises $\mathcal{M} = -i\frac{G_F}{\sqrt{2}} V_{ub} H^\mu L_\mu$
- $\mathcal{B} \propto \mathcal{M}^2 \propto |V_{ub}|^2$




Phys. Rev. D91 (2015) 074510, arXiv:1501.0537.

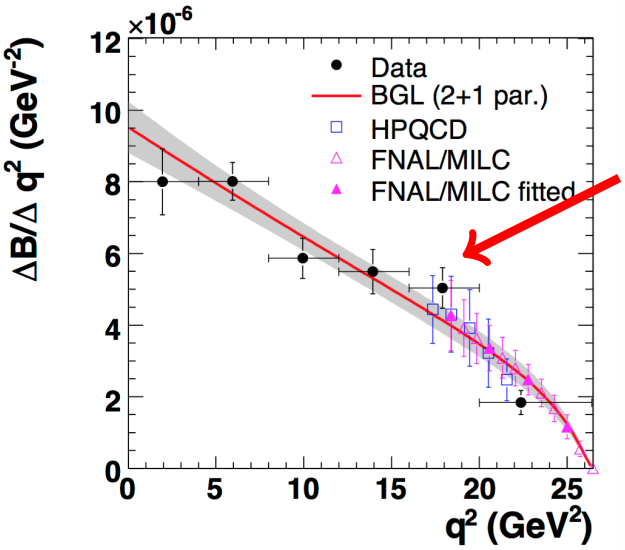
# Untagged $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ at the $B$ factories

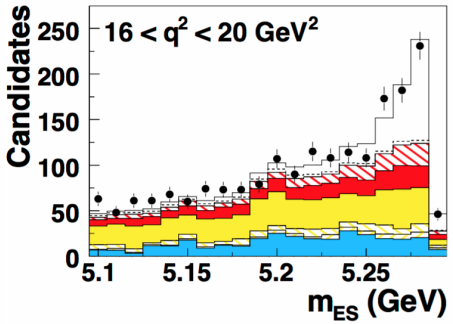
- Select good $\pi$ and $l$ candidates.

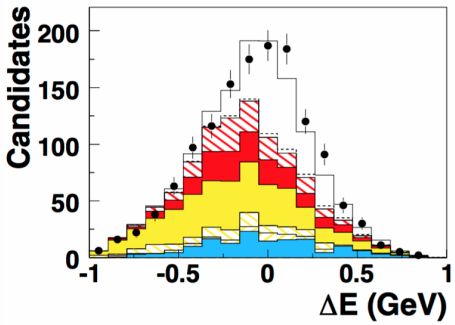


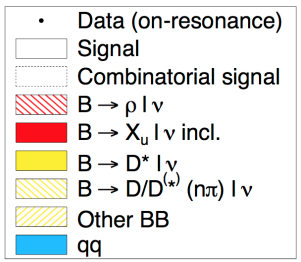

$$p_\nu = (E_{\text{miss}}, \mathbf{p}_{\text{miss}})$$
$$= p_{e^+e^-} - p_\pi - p_l - \sum p_{tracks} - \sum p_{clusters}$$
$$p_B = p_\pi + p_l + (P_{\text{miss}}, \mathbf{p}_{\text{miss}})$$

- Fit $M_{bc} = \sqrt{E^{*2}_{\text{beam}} - P^{*2}_B}$ and $\Delta E = E^*_B - E^*_{\text{beam}}$, $(* \implies \text{CoM})$.



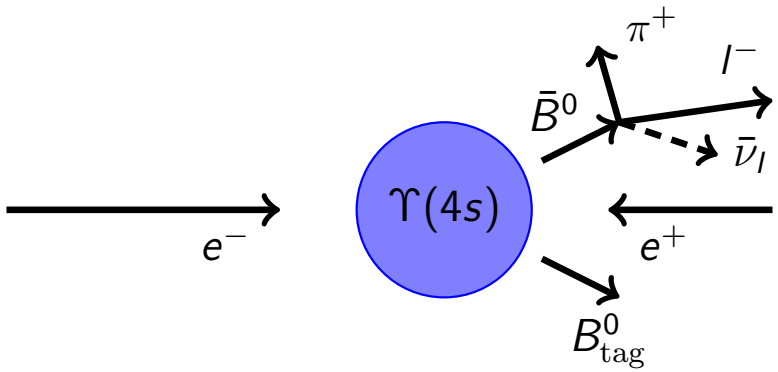



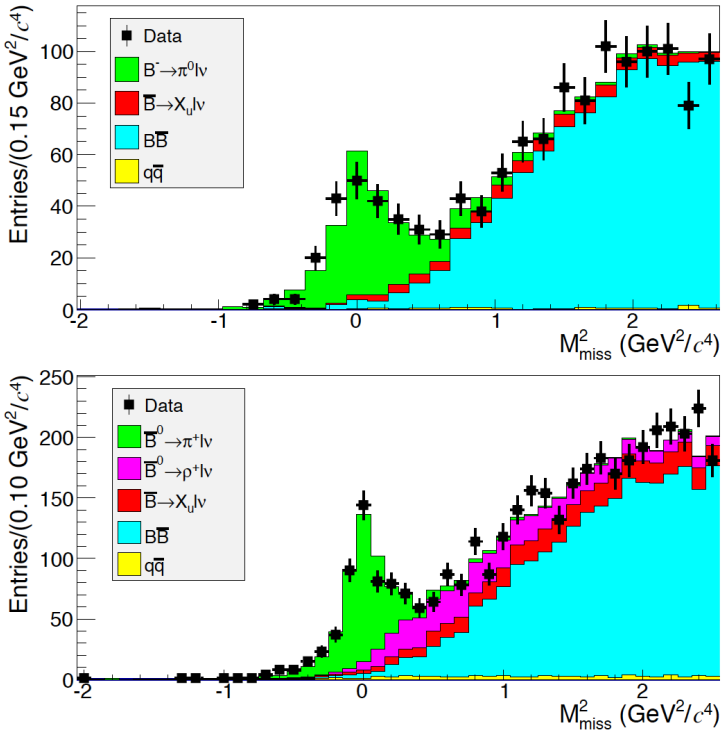




| Measurement | Reference |
|---|---|
| BABAR (6 $q^2$ bins) | Phys. Rev. D83, 032007 (2011) |
| BABAR (12 $q^2$ bins) | Phys. Rev. D86, 092004 (2012) |
| Belle (13 $q^2$ bins) | Phys. Rev. D83, 071101 (2011) |

# Tagged $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ at the $B$ factories




- Tag-side $B$ meson reconstructed in a number of modes.
- Reconstruct the neutrino via $p_\nu = p_{e^+e^-} - p_\pi - p_l - p_{B_{\rm tag}}$




- Fit the Missing Mass squared ($p_\nu^2$)
- Higher purity lower statistics.

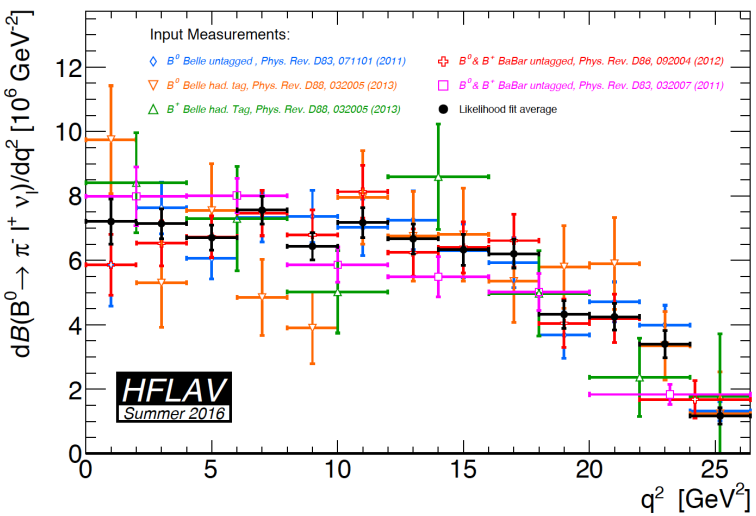
| Measurement | Reference |
|---|---|
| Belle (13 $q^2$ bins) | Phys. Rev. D88, 032005 (2013) |

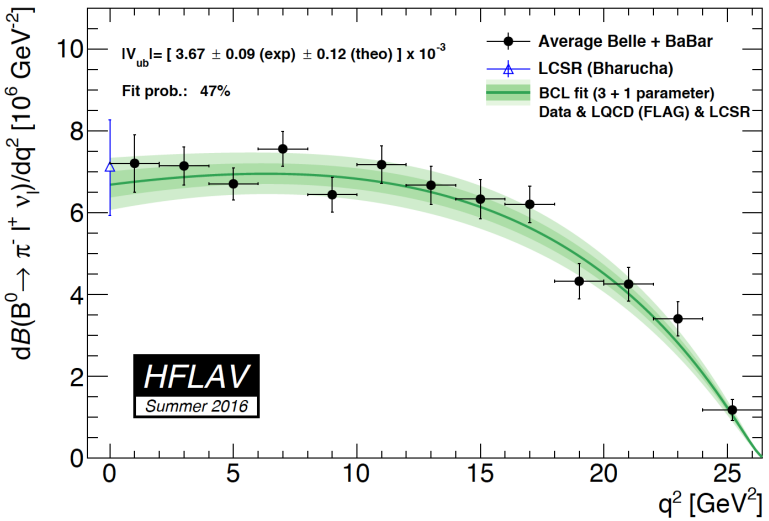
# Global $|V_{ub}|$ determination from $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ decays

- Fit data and form factor, $f_+(q^2)$ under a BCL parametrisation.

$$f_+(q^2, \vec{b}) = \frac{1}{1 - q^2/m_{B*}^2} \sum_{k=0}^{K-1} b_k \left[ z^k - (-1)^{k-K} \frac{k}{K} z^K \right], z = \frac{\sqrt{1 - q^2/t_+} - \sqrt{1 - t_0/t_+}}{\sqrt{1 - q^2/t_+} + \sqrt{1 - t_0/t_+}}$$

$$\chi^2 = (\Delta\vec{\mathcal{B}} - \tau_B \Delta\vec{\Gamma}(\vec{b}, |V_{ub}|))^T C^{-1} (\Delta\vec{\mathcal{B}} - \tau_B \Delta\vec{\Gamma}(\vec{b}, |V_{ub}|)) + (\vec{b} - \vec{b}_{LQCD})^T C_{LQCD}^{-1} (\vec{b} - \vec{b}_{LQCD})$$



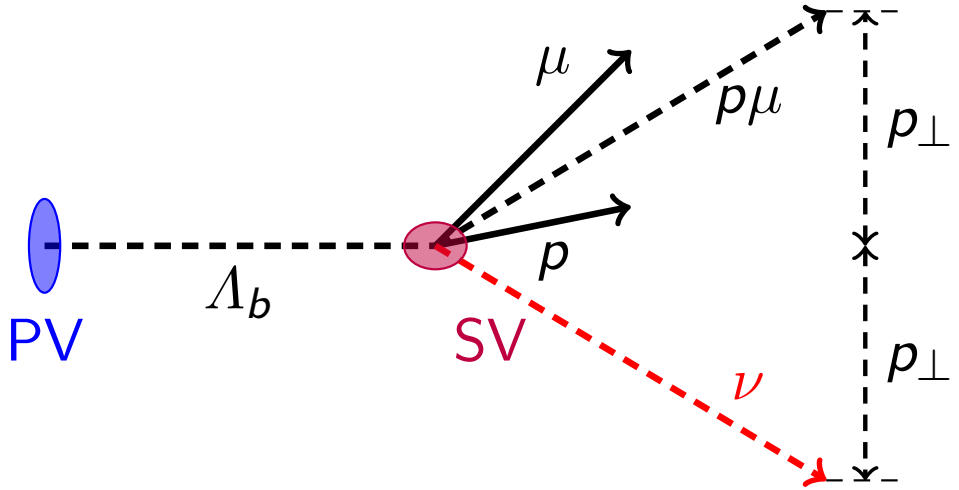




$$|V_{ub}| = (3.70 \pm 0.10(exp.) \pm 0.12(th.)) \times 10^{-3} \text{ ( data + LQCD) 4.2\%}$$
$$|V_{ub}| = (3.67 \pm 0.09(exp.) \pm 0.12(th.)) \times 10^{-3} \text{ ( data + LQCD + LCSR) 4\%}$$

# $|V_{ub}|$ from $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ decays at LHCb

- Fit the corrected mass for $q^2$ >15 GeV$^2$:

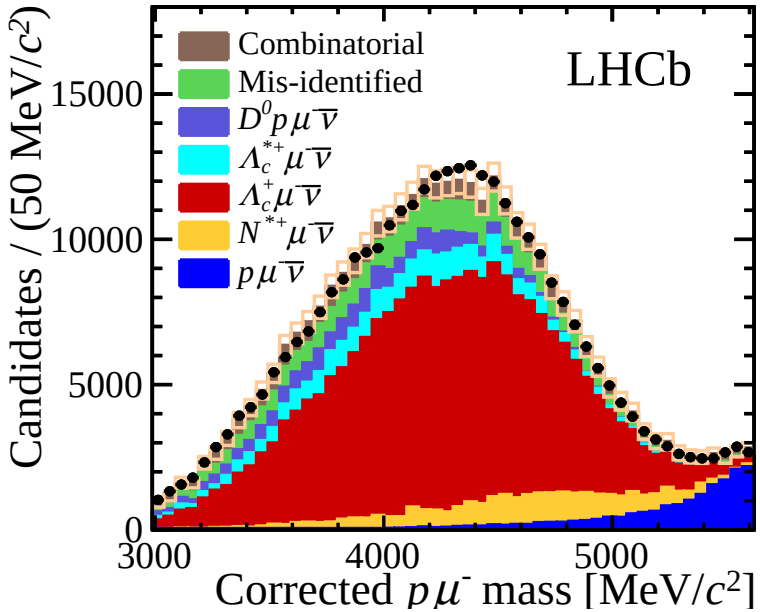
$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$




$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,GeV^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu)_{q^2>7\,GeV^2}} R_{FF}$$

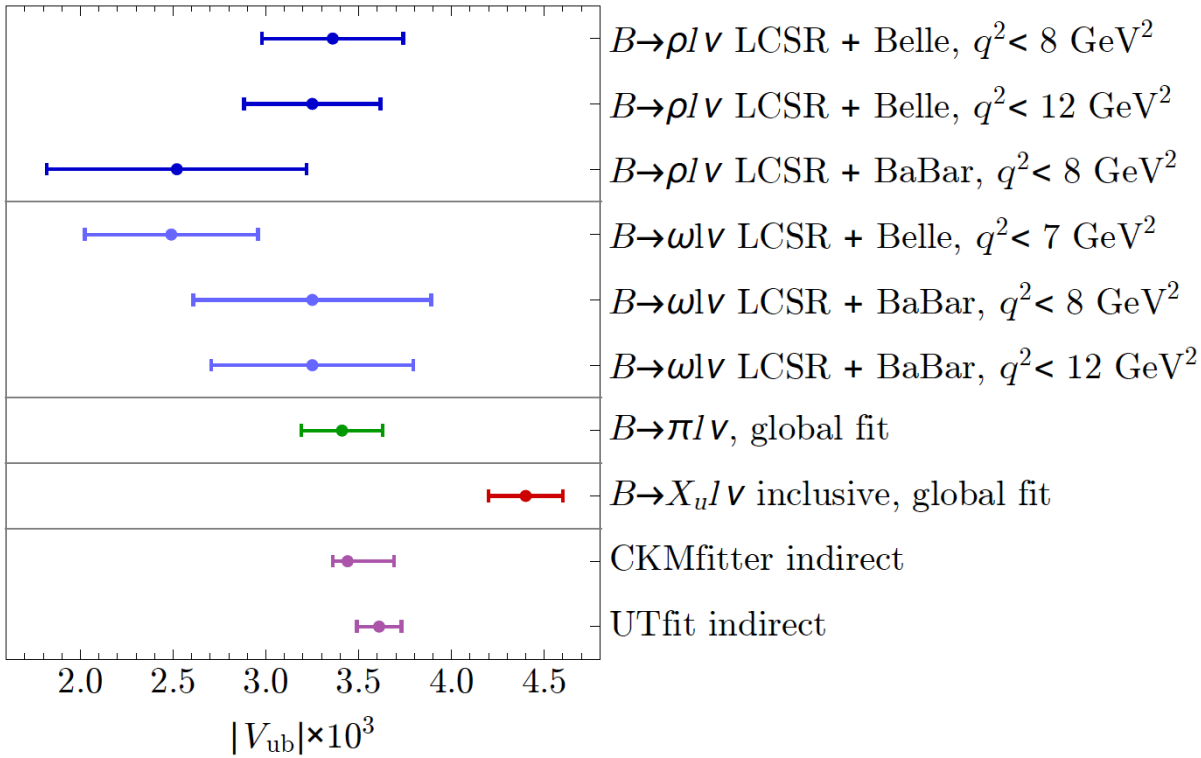
- $|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}$

Nat. Phys. volume 11, (2015)
CERN-THESIS-2016-167



# Other exclusive $b \to u l \nu$ decays

- Several measurements of $B \to \rho l \nu$ and $B \to \omega l \nu$ decays.

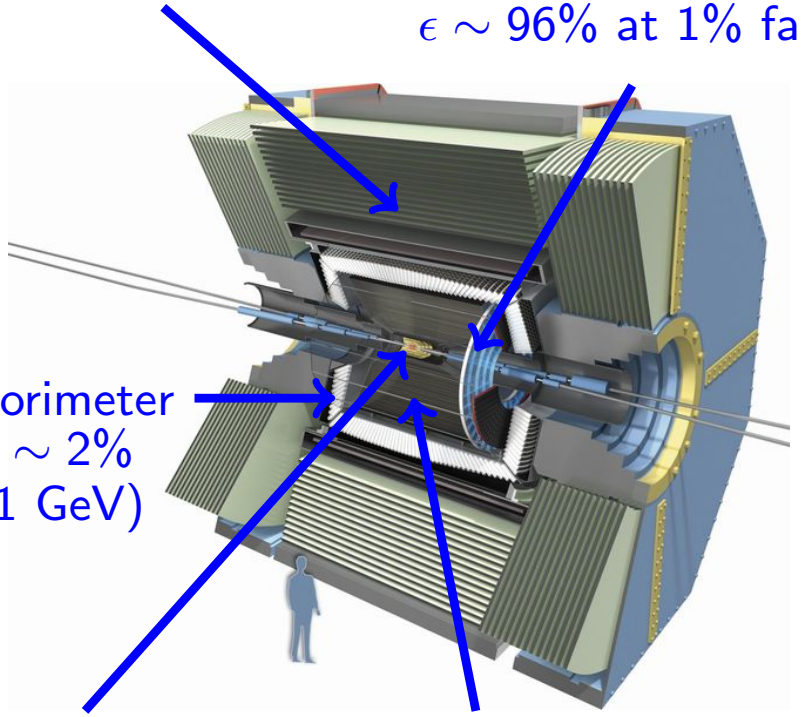



J. High Energ. Phys. (2016)

# Belle II

$K_L$ and Muon detector
$\epsilon \sim 90\%$ at 1% fake

Time of Propagation and RICH detectors
$K/\pi$ separation
$\epsilon \sim 96\%$ at 1% fake



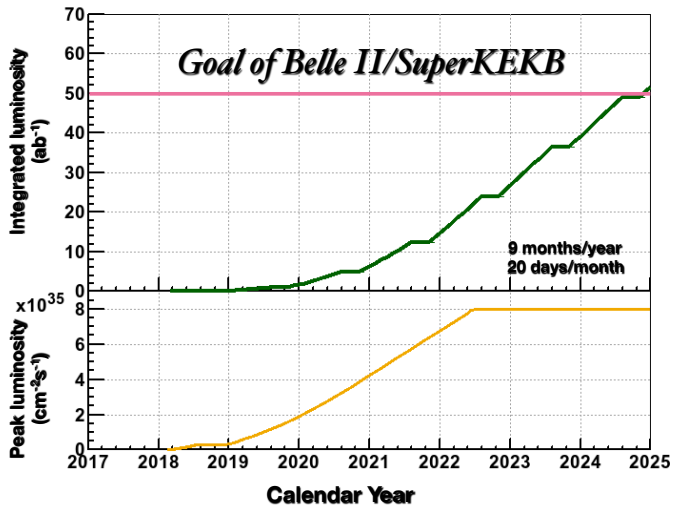
EM Calorimeter
$\sigma_E/E \sim 2\%$
$(E = 1$ GeV$)$

Vertex detector
$\sigma_{z0} \sim 15$ $\mu$m
$\times 2$ better than Belle

Drift chamber
Tracking

$\times 40$ peak $\mathcal{L}$
Ultimate aim $\int \mathcal{L} = 50$ ab$^{-1}$
$\times 20$ beam bkg.

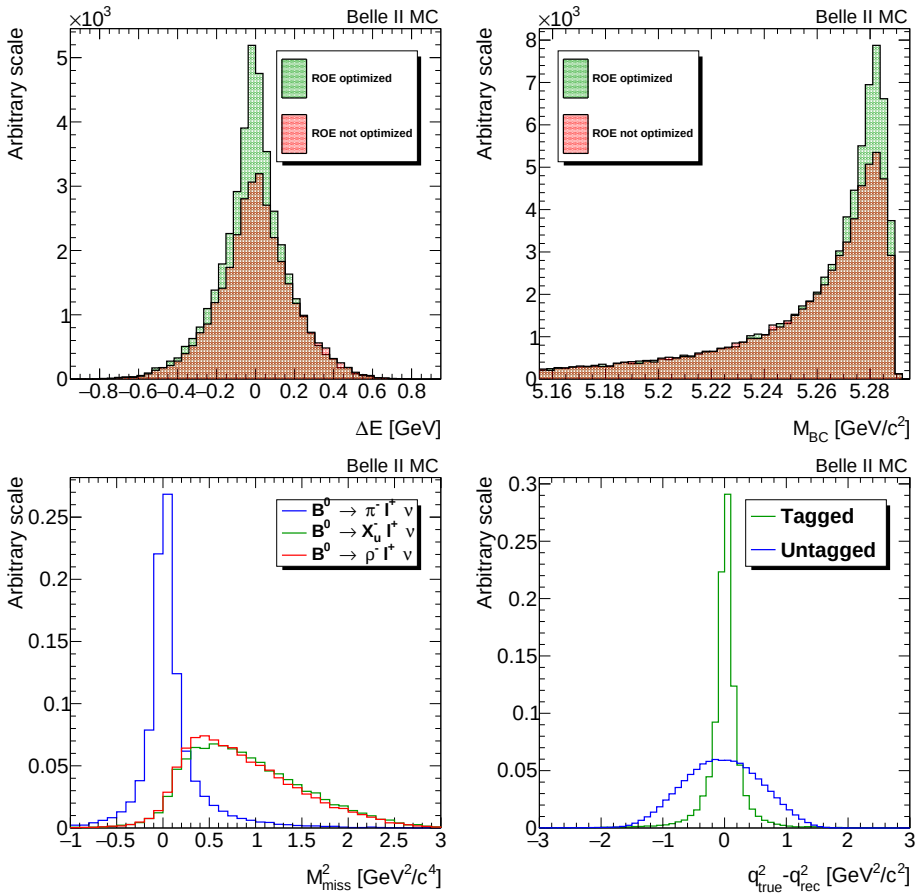
**SuperKEKB luminosity projection**



# $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ prospects

- Tagged and untagged analyses performed on Belle II MC.
- Untagged use optimised BDT selections for tracks and clusters in the Rest of the event.
- Tagged uses the Belle 2 tagging algorithm (FEI)

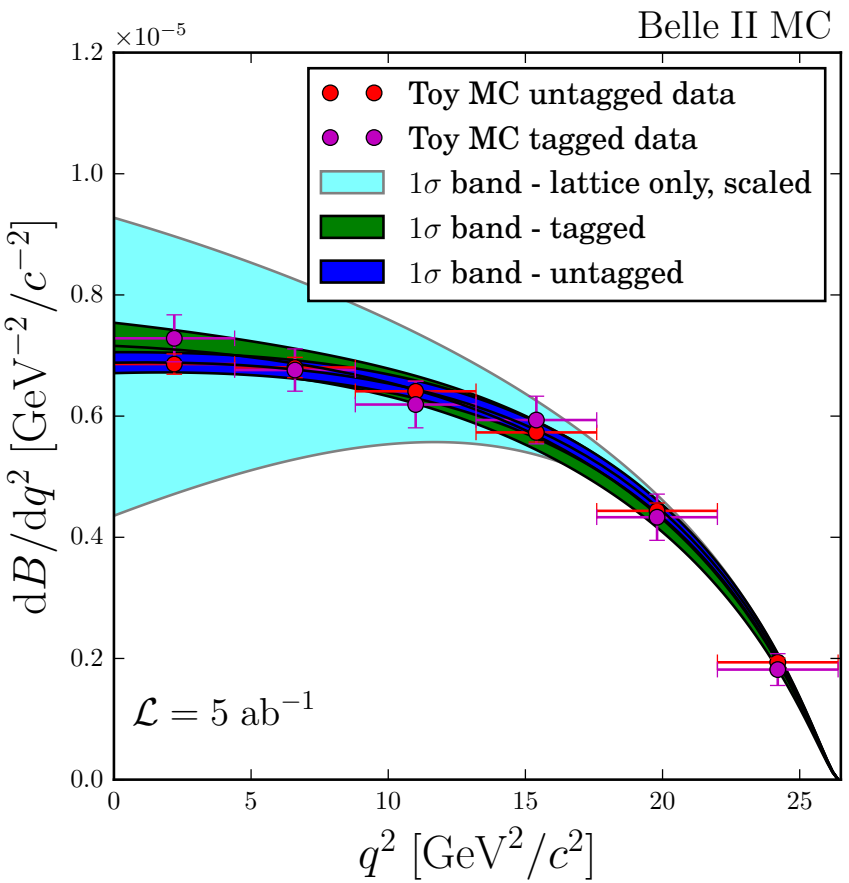
| | Belle $\epsilon$ | Belle II $\epsilon$ |
|---|---|---|
| untagged | 7.7-15% | 20% |
| tagged | 0.3% | 0.55% |

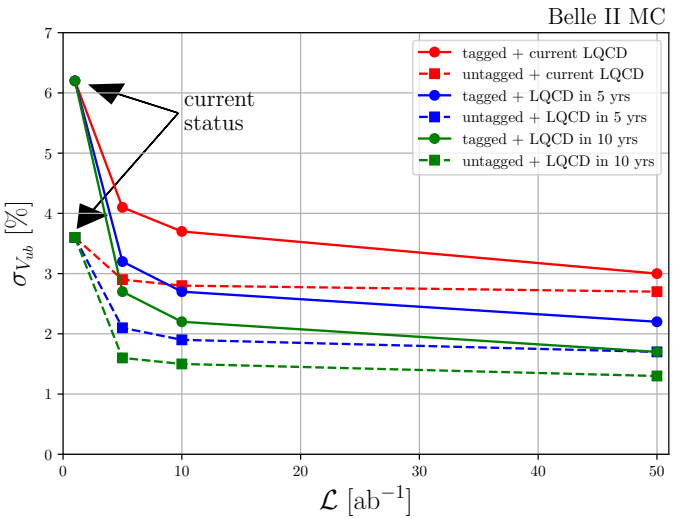


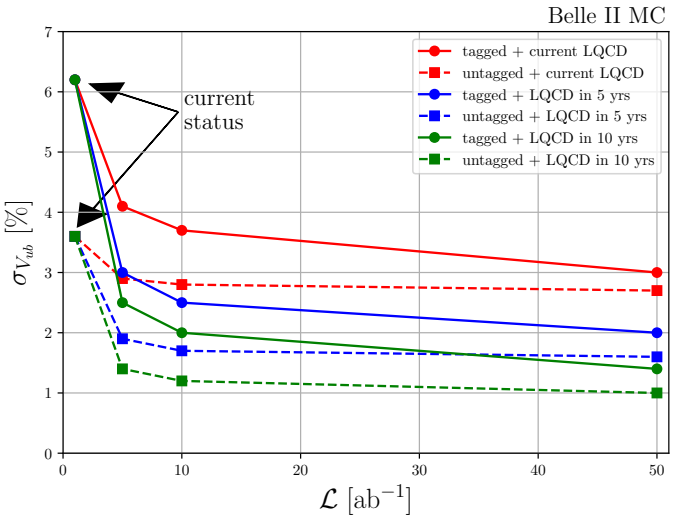
# Previous Belle $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ systematics

| Source | Error (Limit) [%] | |
|---|---|---|
| | Tagged [%] | Untagged |
| Tracking efficiency | 0.4 | 2.0 |
| Pion identification | – | 1.3 |
| Lepton identification | 1.0 | 2.4 |
| Kaon veto | 0.9 | – |
| Continuum description | 1.0 | 1.8 |
| Tag calibration and $N_{B\overline{B}}$ | 4.5 (2.0) | 2.0 (1.0) |
| $X_u \ell \nu$ cross-feed | 0.9 | 0.5 (0.5) |
| $X_c \ell \nu$ background | – | 0.2 (0.2) |
| Form factor shapes | 1.1 | 1.0 (1.0) |
| Form factor background | – | 0.4 (0.4) |
| Total | 5.0 | 4.5 |
| (reducible, irreducible) | (4.6, 2.0) | (4.2, 1.6) |

# Projected $|V_{ub}|$ from $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ decays

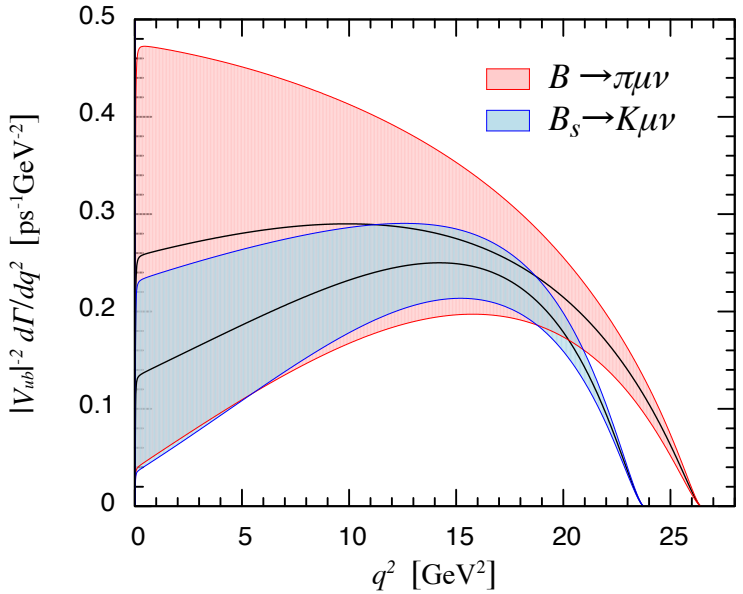


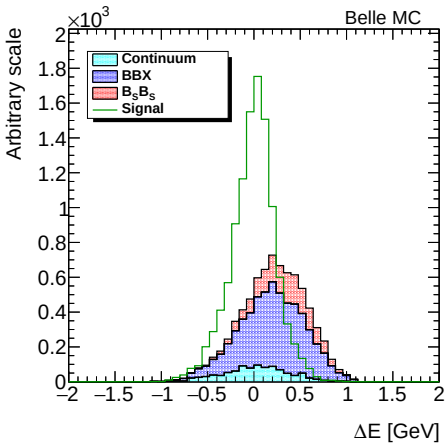



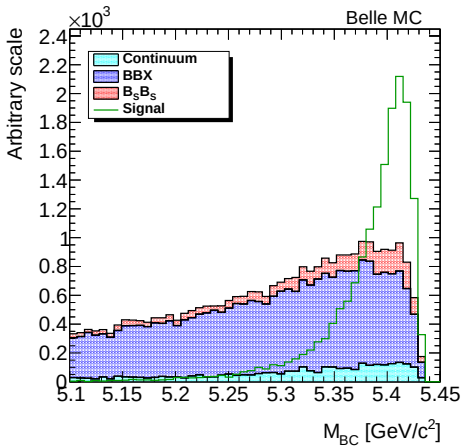



# $\bar{B}^0_s \to K^+ \mu^- \bar{\nu}_\mu$ Prospects

- Smaller theoretical uncertainty than $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$
- Only expect 60M $B_s^{(*)} \bar{B}_s^{(*)}$ pairs in $1\text{ab}^{-1}$



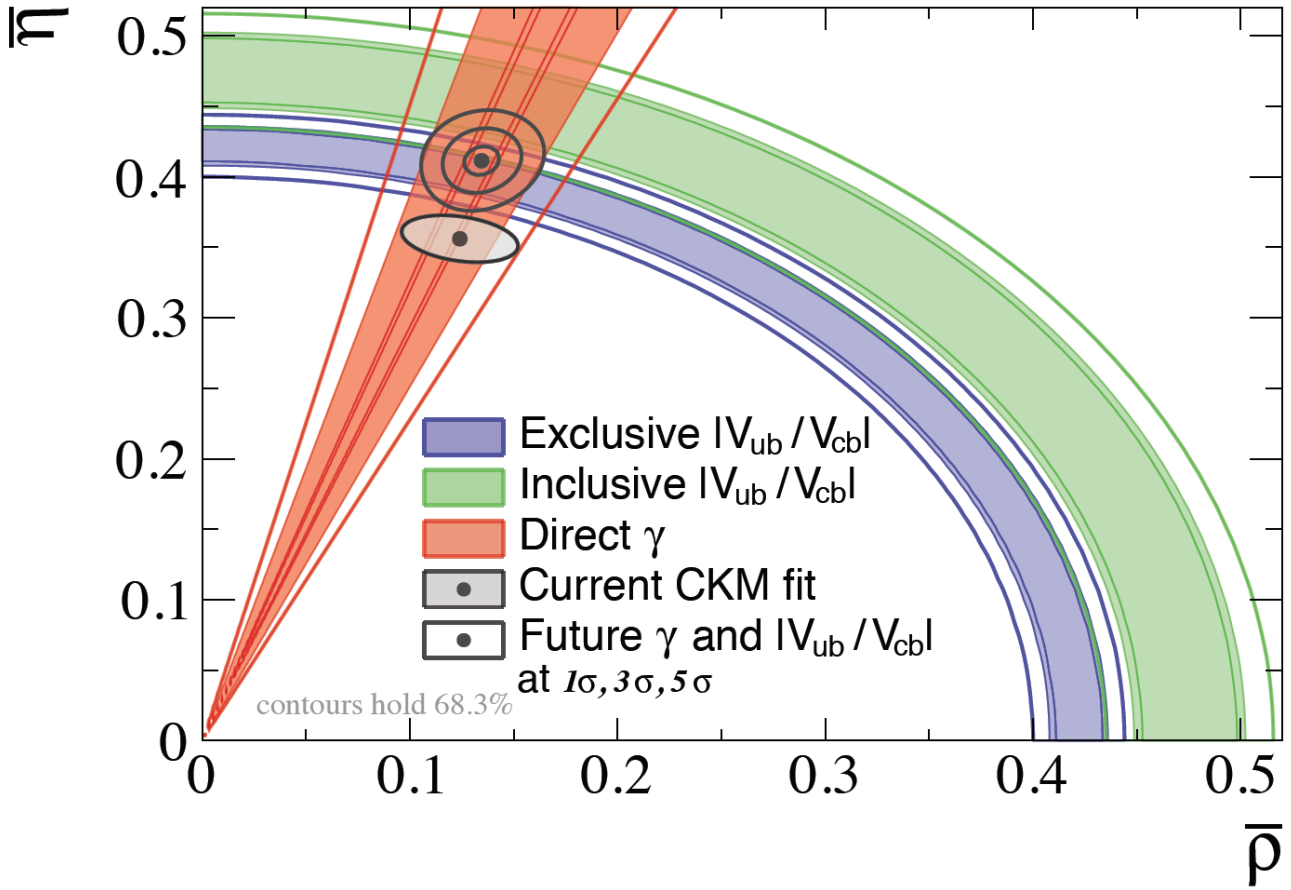

- 5-10% precision on the decay rate with $1\text{ab}^{-1}$

# Projections of $|V_{ub}|$

| | Statistical | Systematic (reducible, irreducible) | Total Exp | Theory | Total |
|---|---|---|---|---|---|
| $\|V_{ub}\|$ exclusive (had. tagged) | | | | | |
| 711 fb$^{-1}$ | 3.0 | (2.3, 1.0) | 3.8 | 7.0 | 8.0 |
| 5 ab$^{-1}$ | 1.1 | (0.9, 1.0) | 1.8 | 1.7 | 3.2 |
| 50 ab$^{-1}$ | 0.4 | (0.3, 1.0) | 1.2 | 0.9 | 1.7 |
| $\|V_{ub}\|$ exclusive (untagged) | | | | | |
| 605 fb$^{-1}$ | 1.4 | (2.1, 0.8) | 2.7 | 7.0 | 7.5 |
| 5 ab$^{-1}$ | 1.0 | (0.8, 0.8) | 1.2 | 1.7 | 2.1 |
| 50 ab$^{-1}$ | 0.3 | (0.3, 0.8) | 0.9 | 0.9 | 1.3 |
| $\|V_{ub}\|$ inclusive | | | | | |
| 605 fb$^{-1}$ (old $B$ tag) | 4.5 | (3.7, 1.6) | 6.0 | 2.5–4.5 | 6.5–7.5 |
| 5 ab$^{-1}$ | 1.1 | (1.3, 1.6) | 2.3 | 2.5–4.5 | 3.4–5.1 |
| 50 ab$^{-1}$ | 0.4 | (0.4, 1.6) | 1.7 | 2.5–4.5 | 3.0–4.8 |
| $\|V_{ub}\|$ $B \to \tau\nu$ (had. tagged) | | | | | |
| 711 fb$^{-1}$ | 18.0 | (7.1, 2.2) | 19.5 | 2.5 | 19.6 |
| 5 ab$^{-1}$ | 6.5 | (2.7, 2.2) | 7.3 | 1.5 | 7.5 |
| 50 ab$^{-1}$ | 2.1 | (0.8, 2.2) | 3.1 | 1.0 | 3.2 |
| $\|V_{ub}\|$ $B \to \tau\nu$ (SL tagged) | | | | | |
| 711 fb$^{-1}$ | 11.3 | (10.4, 1.9) | 15.4 | 2.5 | 15.6 |
| 5 ab$^{-1}$ | 4.2 | (4.4, 1.9) | 6.1 | 1.5 | 6.3 |
| 50 ab$^{-1}$ | 1.3 | (2.3, 1.9) | 2.6 | 1.0 | 2.8 |

| LHCb | 8 fb$^{-1}$ | 22 fb$^{-1}$ | 50 fb$^{-1}$ |
|---|---|---|---|
| $\|V_{ub}\|/\|V_{cb}\|$ | 3.4% | 2.9% | 2.1% |
| $\|V_{ub}\|$ | 3.8% | 3.3% | 2.4% |

# The future of the UT



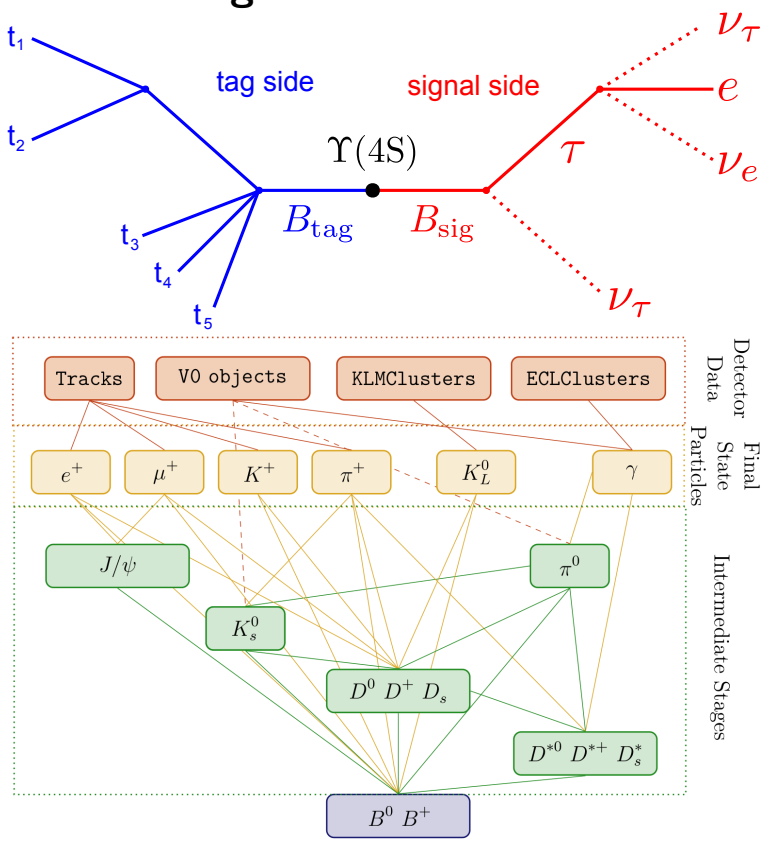

Albrecht et al. arXiv:1709.10308v5

# Conclusion

- The most precise determination of $|V_{ub}|$ is expected to come from $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ decays 1-2% at Belle II.
- This will be a crucial ingredient in global CKM fits.

# Improved algorithms at Belle II

## New Full Event Interpretation (FEI) algorithm for tag-side reconstruction




Tagging $\varepsilon$ on MC

| Tag | FR[1] | FEI Belle | FEI Belle II |
|---|---|---|---|
| Hadronic $B^+$ | 0.28% | 0.76% | 0.66% |
| SL $B^+$ | 0.67% | 1.80% | 1.45% |
| Hadronic $B^0$ | 0.18% | 0.46% | 0.38% |
| SL $B^0$ | 0.63% | 2.04% | 1.94% |

Belle Full Reconstruction algorithm.

## Deep NN based $e^+e^- \to q\bar{q}$ background suppression