Ultimate precision on $|V_{ub}|$ from semileptonic and leptonic decays

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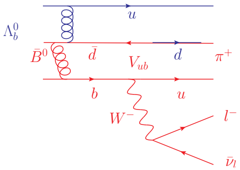
Towards the Ultimate Precision in Flavour Physics, Warwick

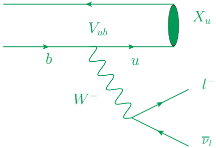
Karlsruher Institut für Technologie

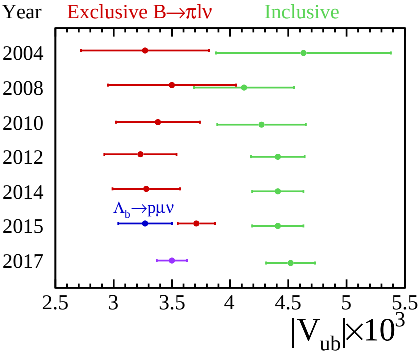
Belle II

April 18, 2018

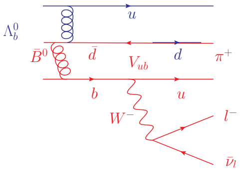
Status of $|V_{ub}|$

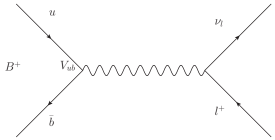


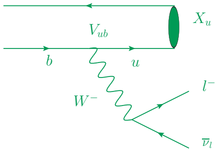


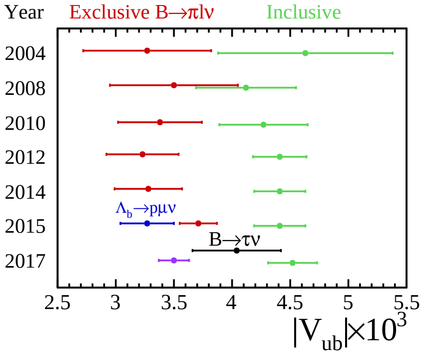


Status of $|V_{ub}|$

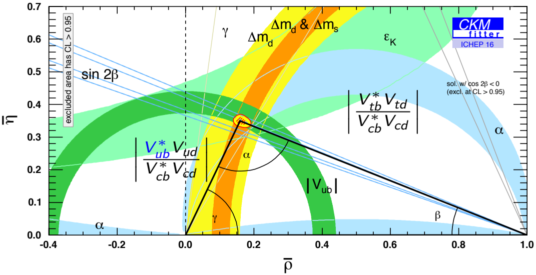






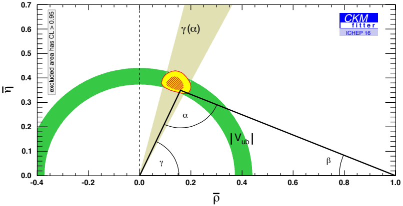


Why is $|V_{ub}|$ important?

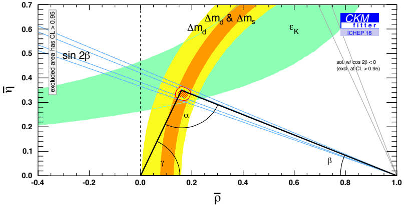


$$\left|\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right| \qquad \left|\frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}}\right|$$

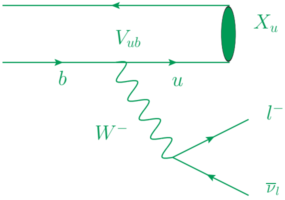
Trees



Loops



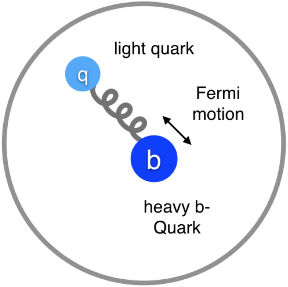
Inclusive theory



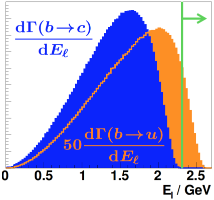
$$\frac{d^3\Gamma}{dp_X^+\,dp_X^-\,dE_\ell} = \frac{G_F^2|V_{ub}|^2}{192\pi^3}\int dk\, C(E_\ell, p_X^-, p_X^+, k)\, F(k) + O\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

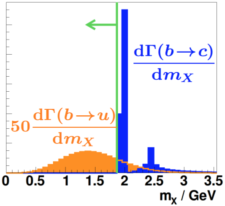
$$p_X^+ = E_X - |\vec{p}_X|\,, \qquad p_X^- = E_X + |\vec{p}_X|\,,$$

- $F(k)$ pdf of b quark momentum, k
- $C(E_\ell, p_X^-, p_X^+, k)$ computed perturbatively

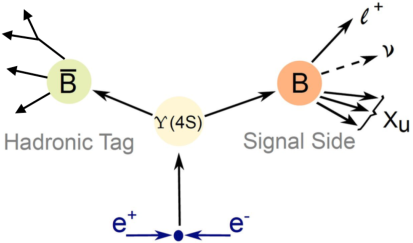


Experimental approach

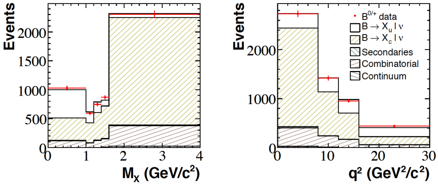




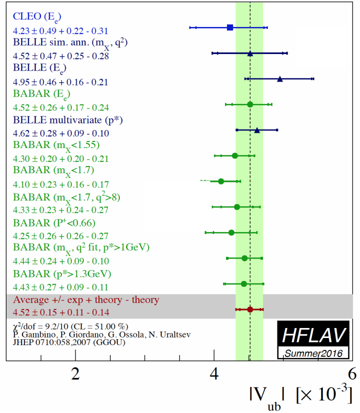
- Large background from $b \to c$ $(|V_{cb}|^2/|V_{ub}|^2 \sim 100)$
- Exploit $b \to c$ kinematic endpoints.
- $|V_{ub}| = \sqrt{\Delta\mathcal{B}/(\tau_B \Delta\Gamma)}$



Phys. Rev. Lett. 104, 021801



Inclusive $|V_{ub}|$ and its projection



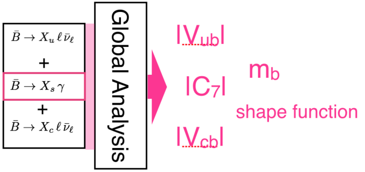
Framework	$\|V_{ub}\|[10^{-3}]$
BLNP	$4.44 \pm 0.15^{+0.21}_{-0.22}$
DGE	$4.52 \pm 0.16^{+0.15}_{-0.16}$
GGOU	$4.52 \pm 0.15^{+0.11}_{-0.14}$
ADFR	$4.08 \pm 0.13^{+0.18}_{-0.12}$
BLL (m_X/q^2 only)	$4.62 \pm 0.20 \pm 0.29$

Source	Error on $\mathcal{B}$ (irreducible limit)
$\mathcal{B}(D^{(*)}\ell\nu)$	1.2 (0.6)
Form factors $(D^{(*)}\ell\nu)$	1.2 (0.6)
Form factors & $\mathcal{B}(D^{(**)}\ell\nu)$	0.2
$B \to X_u\ell\nu$(SF)	3.6 (1.8)
$B \to X_u\ell\nu(g \to s\bar{s})$	1.5
$\mathcal{B}(B \to \pi/\rho/\omega\ell\nu)$	2.3
$\mathcal{B}(B \to \eta^{(\prime)}\ell\nu)$	3.2
$\mathcal{B}(B \to X_u\ell\nu)$ unmeasured/fragmentation	2.9 (1.5)
Continuum & Combinatorial	1.8
Secondaries, Fakes & Fit	1.0
PID& Reconstruction	3.1
BDT/Normalisation	3.1 (2.0)
Total	8.1
(Total reducible)	7.4
(Total irreducible)	3.2

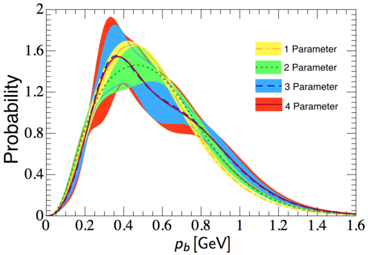
B2TiP report

$\|V_{ub}\|$ 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

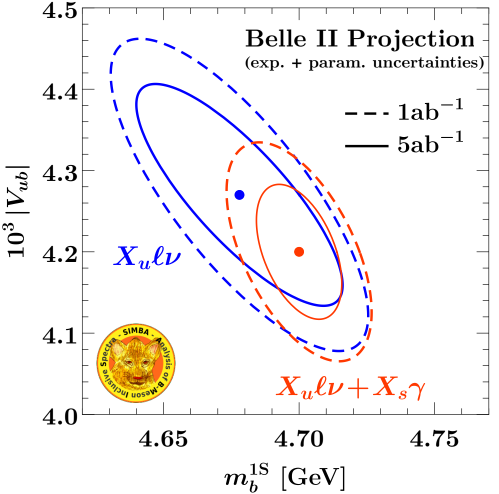
A global fit approach to inclusive $|V_{ub}|$



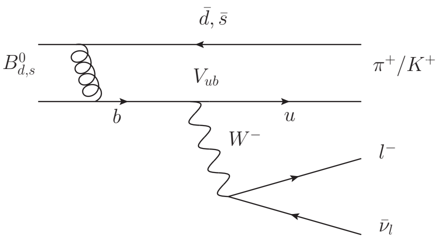
$$F(k) = \sum_n (c_n f_n(k))^2$$



SIMBA collaboration arXiv:1303.0958

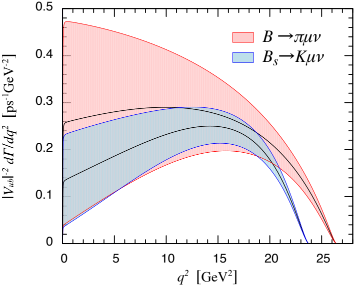


Exclusive theory



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

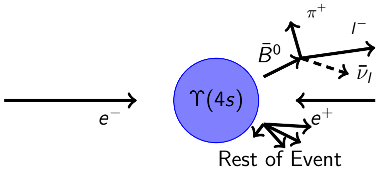
- Matrix element factorises $\mathcal{M} = -i\frac{G_F}{\sqrt{2}}V_{ub}H^\mu L_\mu$
- $\mathcal{B} \propto \mathcal{M}^2 \propto |V_{ub}|^2$



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

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

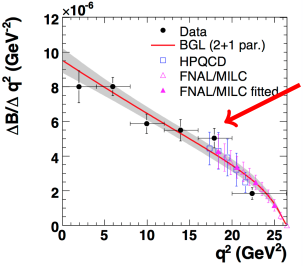
- Select good π and l candidates.

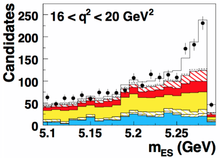


$$p_\nu = (E_{\text{miss}}, \mathbf{p}_{\text{miss}})$$
$$= p_{e^+e^-} - p_\pi - p_l$$
$$- \sum p_{tracks} - \sum p_{clusters}$$

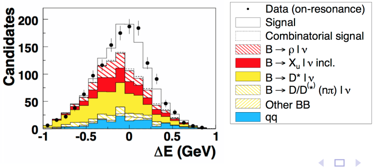
$$p_B = p_\pi + p_l + (P_{\text{miss}}, \mathbf{p}_{\text{miss}})$$

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



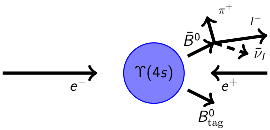


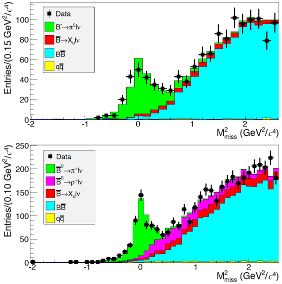
Measurement	Reference
BABAR (6 q^2 bins)	Phys. Rev. D83, 032007 (2011)
BABAR (12 q^2 bins)	Phys. Rev. D86, 092004 (2012)
Belle (13 q^2 bins)	Phys. Rev. D83, 071101 (2011)



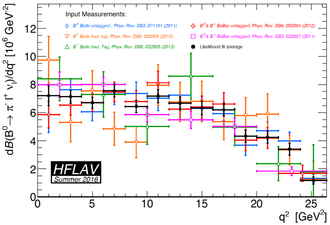
Tagged $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ at the B factories

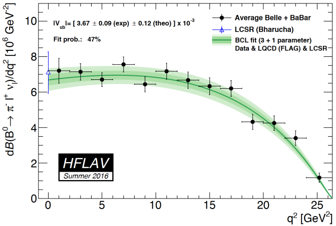
- $p_\nu = p_{e^+e^-} - p_\pi - p_l - p_{B_{\text{tag}}}$
- Fit Missing Mass Squared (p_ν^2)





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

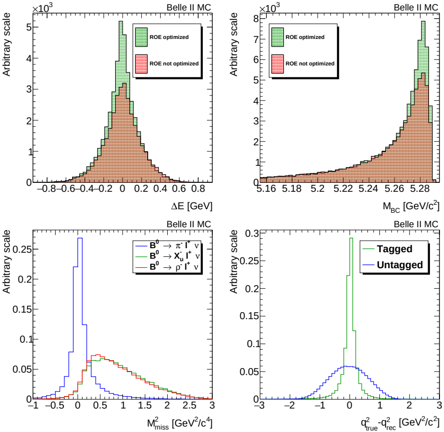




$\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ prospects

- 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)

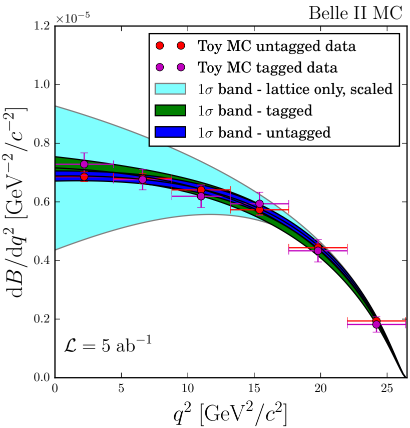
	Belle ϵ	Belle II ϵ
untagged	7.7-15%	20%
tagged	0.3%	0.55%

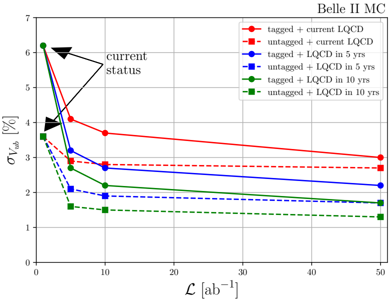


Previous Belle $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ systematics

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

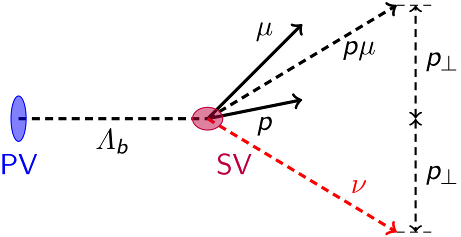




$|V_{ub}|$ from $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ decays at LHCb

- Fit the corrected mass for $q^2 > 15\ \mathrm{GeV}^2$:

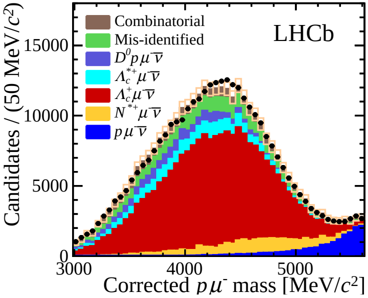
$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$



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

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

Nat. Phys. volume 11, (2015)



Prospects for $|V_{ub}|$ from $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ decays

Table 1 | Summary of systematic uncertainties.

Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

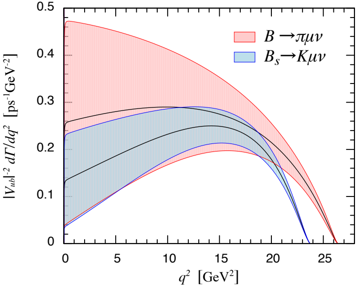
- $\mathcal{B}(\Lambda_c \to pK\pi)$ improves in line with Belle II data
- Account for increased luminosity, collision energy and trigger improvements.
- A differential q^2 measurement would reduce the theory uncertainty.

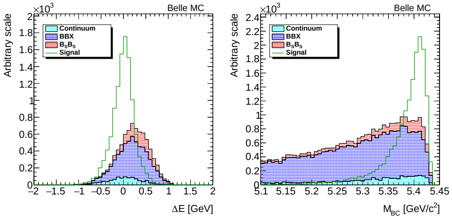
Albrecht et al. arXiv:1709.10308v5

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%

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

- Smaller theoretical uncertainty than $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$
- LHCb measurement to come!

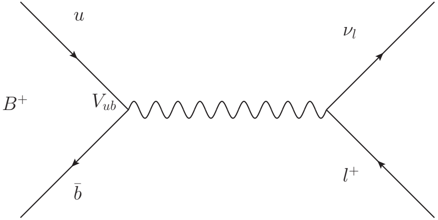




- At Belle II expect 60M $B_s^{(*)}\bar{B}_s^{(*)}$ pairs in 1ab^{-1}
- 5-10% precision on the decay rate with 1ab^{-1}

$|V_{ub}|$ from leptonic decays

$$\mathcal{B}(B^- \to l^- \bar{\nu}_l) = \frac{G_F^2 m_B m_l^2}{8\pi}\left(1 - \frac{m_l^2}{m_B^2} f_B^2\right)|V_{ub}|^2 \tau_B$$

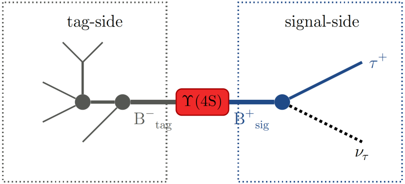


- $\mathcal{B}$s are hierarchical with lepton mass due to helicity suppresion.
- $f_B = 187.1 MeV (0.7\%)$ is the decay constant.

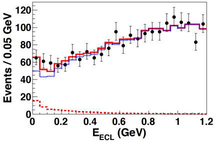
l	$\mathcal{B}_{\rm SM}$	711 fb^{-1}	5 ab^{-1}	50 ab^{-1}
τ	$(7.71 \pm 0.62) \times 10^{-5}$	61179 ± 5031	430231 ± 35378	4302312 ± 353781
μ	$(3.46 \pm 0.28) \times 10^{-7}$	275 ± 23	1933 ± 159	19333 ± 1590
e	$(0.811 \pm 0.065) \times 10^{-11}$	0.0064 ± 0.0005	0.0453 ± 0.0037	0.4526 ± 0.0372

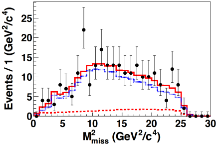
$B^- \to \tau^- \bar{\nu}_\tau$ status

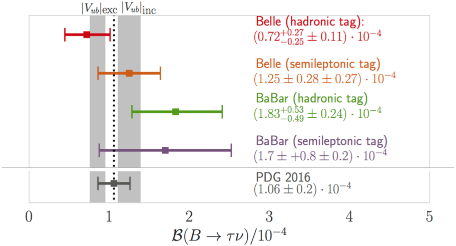
- Reconstruct B_{tag} hadronically or semileptonic.
- τ reconstructed in $e^- \nu_\tau \bar{\nu}_e$, $\mu^- \nu_\tau \bar{\nu}_\mu$, $\pi^- \bar{\nu}_\tau$, $\rho^- \bar{\nu}_\tau$,



- Fit sum of remaining energy in the EM calorimeter (E_{ECL})







Projecting $|V_{ub}|$ from $B^- \to \tau^- \bar{\nu}_\tau$

Belle Hadronic

Source	$\mathcal{B}$ syst. error (%)
Signal PDF	4.2
Background PDF	8.8
Peaking background	3.8
B_{tag} efficiency	7.1
Particle identification	1.0
π^0 efficiency	0.5
Tracking efficiency	0.3
τ branching fraction	0.6
MC efficiency statistics	0.4
K_L^0 efficiency	7.3
$N_{B^+B^-}$	1.3
Total	14.7

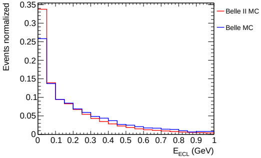
Belle Semileptonic

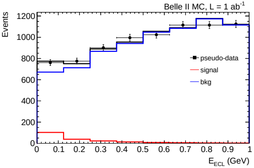
TABLE III. List of systematic uncertainties.

Source	Relative uncertainty (%)
Continuum description	14.1
Signal reconstruction efficiency	0.6
Background branching fractions	3.1
Efficiency calibration	12.6
τ decay branching fractions	0.2
Histogram PDF shapes	8.5
Best candidate selection	0.4
Charged track reconstruction	0.4
π^0 reconstruction	1.1
Particle identification	0.5
Charged track veto	1.9
Number of $B\bar{B}$ pairs	1.4
Total	21.2

- Pseudo analysis performed on Belle 2 MC

	$\int \mathcal{L}$ (ab^{-1})	1	5	50
Had. tag	stat. uncertainty (%)	29.2	13.0	4.1
	syst. uncertainty (%)	12.6	6.8	4.6
	total uncertainty (%)	31.6	14.7	6.2
SL. tag	stat. uncertainty (%)	19.0	8.5	2.7
	syst. uncertainty (%)	17.9	8.7	4.5
	total uncertainty (%)	26.1	12.2	5.3

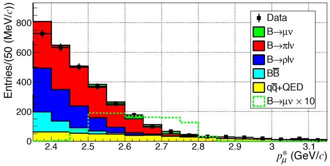


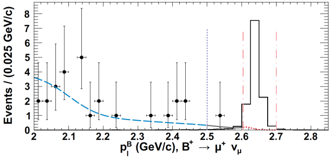


$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	18.0	(7.1, 2.2)	19.5	2.5	19.6
5 ab^{-1}	6.5	(2.7, 2.2)	7.3	1.5	7.5
50 ab^{-1}	2.1	(0.8, 2.2)	3.1	1.0	3.2
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (SL tagged)					
711 fb^{-1}	11.3	(10.4, 1.9)	15.4	2.5	15.6
5 ab^{-1}	4.2	(4.4, 1.9)	6.1	1.5	6.3
50 ab^{-1}	1.3	(2.3, 1.9)	2.6	1.0	2.8

$|V_{ub}|$ from $B^- \to \mu^- \bar{\nu}_\mu$ decays

Experiment	Upper limit @ 90% C.L.	Comment
Belle	2.7×10^{-6}	Fully reconstructed hadronic tag, 711 fb^{-1}
Belle	1.7×10^{-6}	Untagged analysis, 253 fb^{-1}
BaBar	1.0×10^{-6}	Untagged analysis, 468×10^6 $B\bar{B}$ pairs
Belle	2.9×10^{-7}	Untagged analysis, 711 fb^{-1}





- Untagged using CoM p^*_μ
- Tagged use $p^B_\mu = m_B/2 \implies$ high resolution but smaller statistics.

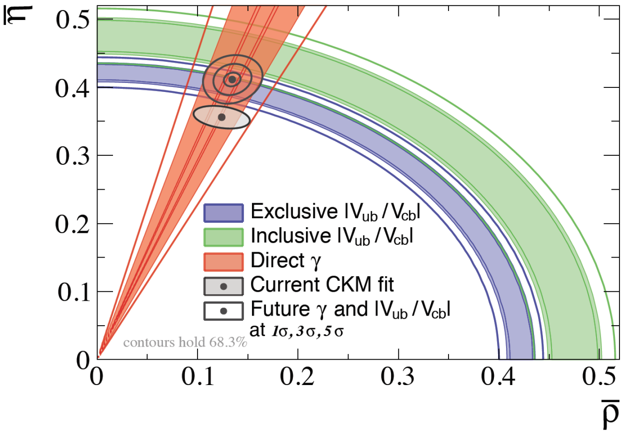
50 ab^{-1}	$\mathcal{B}$Stat.	$\mathcal{B}$Syst.	$\lvert V_{ub}\rvert$
Belle II Untagged	$\sim 5\%$	$\sim 5\%$	3-4%
Belle II tagged	$\sim 13\%$	-	-

Summary of $|V_{ub}|$ projections

	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}
$\|V_{ub}\|$	3.8%	3.3%	2.4%

The future of the UT



Albrecht et al. arXiv:1709.10308v5

Conclusion

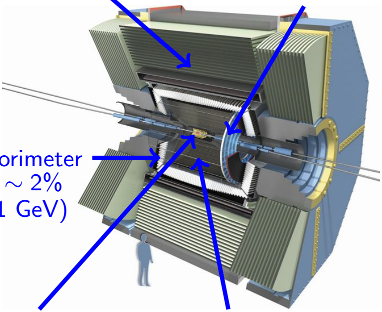
- Most precise determination of $|V_{ub}|$ from $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ decays (untagged).
- Exclusive $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ uncertainty of 1.3% vs inclusive uncertainty of (3-4.8%)
- Precision tree level determinations of $|V_{ub}|$ and γ will allow a stringent testing of NP in loop level CKM observables.

Belle II Improvements

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

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

$\times 40\mathcal{L}$
Ultimate aim $\int \mathcal{L} = 50$ ab^{-1}

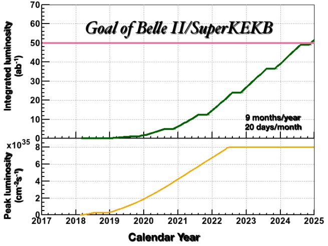


EM Calorimeter
$\sigma_E/E \sim 2\%$
($E = 1$ GeV)

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

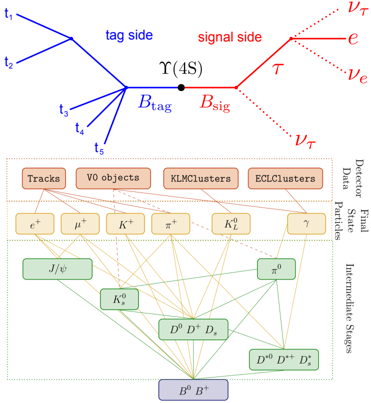
Drift chamber
Tracking

SuperKEKB luminosity projection



Improved algorithms at Belle II

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

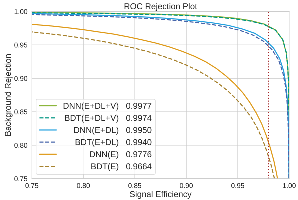


Tagging ε on MC

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%

[1] Belle Full Reconstruction algorithm.

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



[1] T. Keck; [2] J. Gemmler; [2] D. Weyland