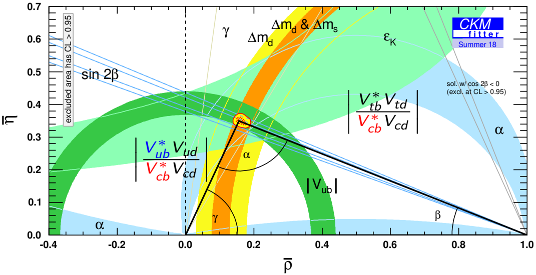
The Prospects for $|V_{ub}|$ and $|V_{cb}|$ at Belle II

Belle II

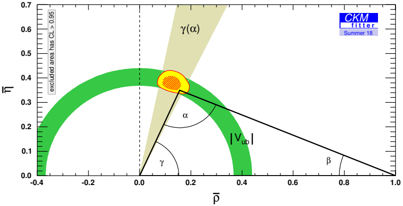
Alexander von Humboldt Stiftung / Foundation

KIT Karlsruher Institut für Technologie

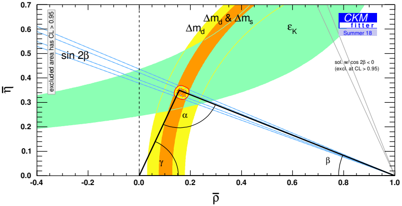
Why are $|V_{ub}|$ and $|V_{cb}|$ important?



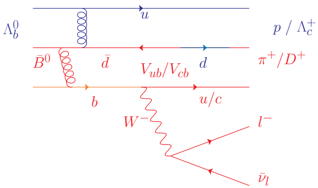
Trees

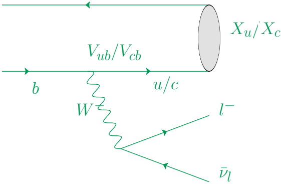


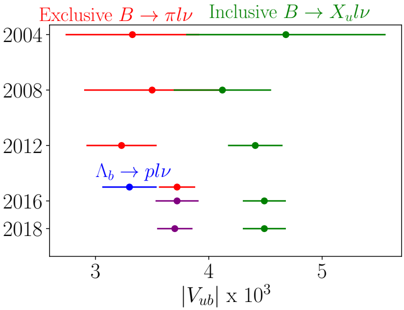
Loops

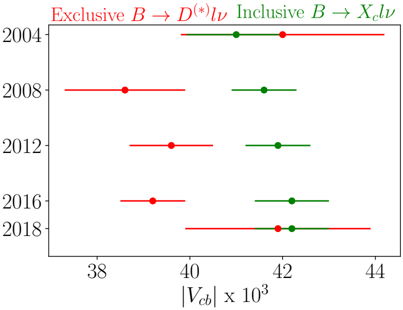


Status of $|V_{ub}|$ and $|V_{cb}|$









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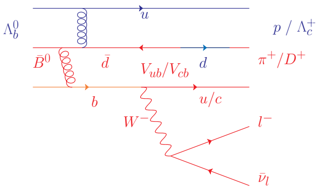
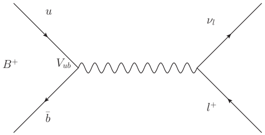
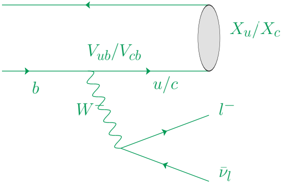
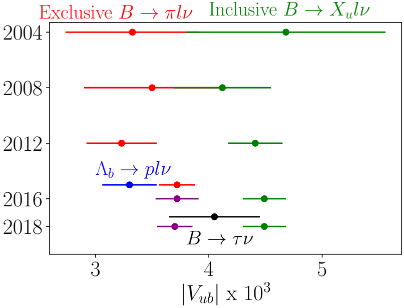
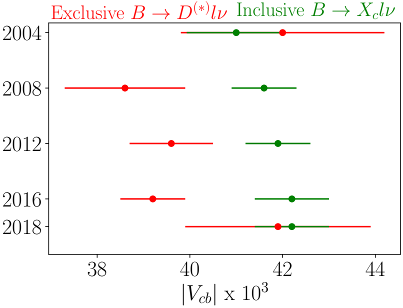




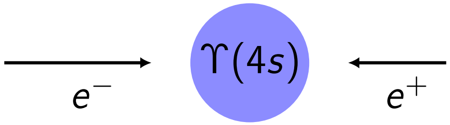






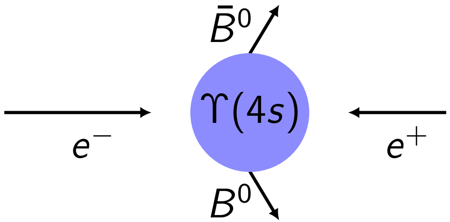
Semileptonic B reconstruction

- Collide e^+ and e^- at the energy to make $\Upsilon(4S)$ particles



Semileptonic B reconstruction

- Collide e^+ and e^- at the energy to make $\Upsilon(4S)$ particles
- $\Upsilon(4S)$ decays to B^+B^- and $B^0\bar{B}^0$ >96% of the time.



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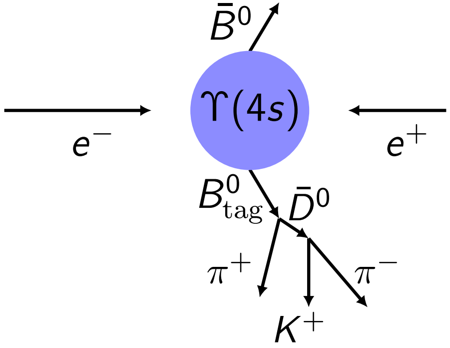

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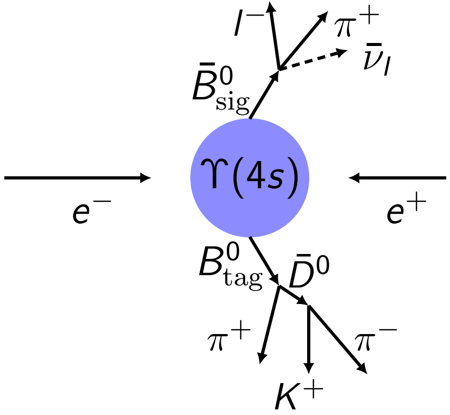

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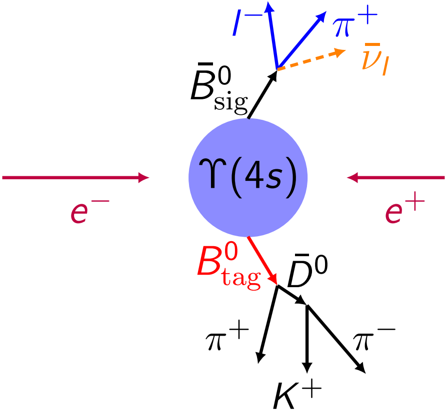
  - $p_\nu = p_{e^+e^-} - p_{\mu^-} - p_\pi - p_{B_{\text{tag}}}$



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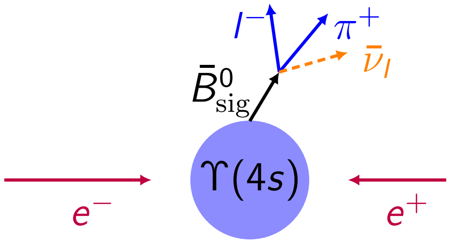

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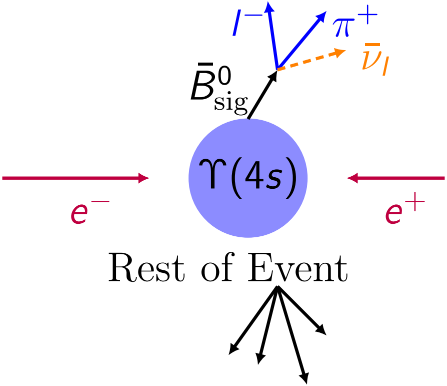
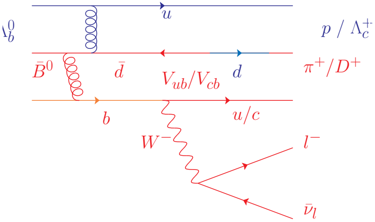
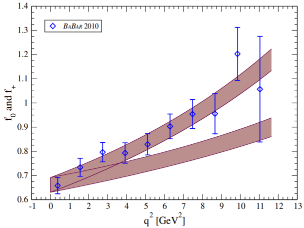
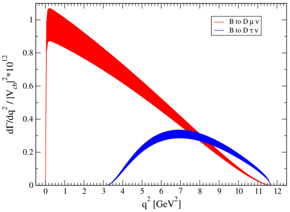
  - Study remaining B meson as signal (B_{sig})
  - $p_\nu = p_{e^+e^-} - p_{\mu^-} - p_\pi - p_{B_{\mathrm{tag}}}$
- Untagged approach:
  - Reconstruct signal first.
  - Inclusively sum over all tracks and clusters in remaining event or only use signal information e.g p_l, $\cos\theta_{BHl}$





- Matrix element factorises $\mathcal{M} = -i\frac{G_F}{\sqrt{2}} V_{qb} H^\mu L_\mu$
- $\mathcal{B} \propto \mathcal{M}^2 \propto |V_{qb}|^2$
- $H^\mu(f_i(q^2)) = \langle X \, |\bar{q}\gamma^\mu(1-\gamma_5)b| \, B\rangle$
- Form factors $f_i(q^2)$ computed with LCSR [see N. Gubernari] or LQCD [see A. Kronfeld]

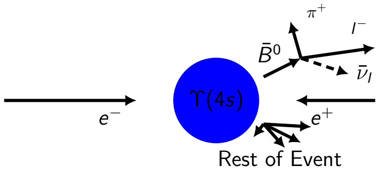




H. Na et al. PRD 92 054510 (2015)

Exclusive $|V_{ub}|$ from untagged $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$

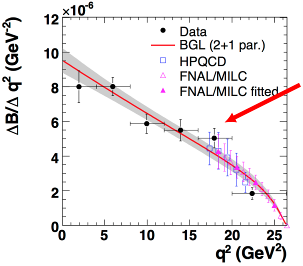
- Select good π and l candidates.

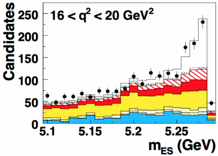


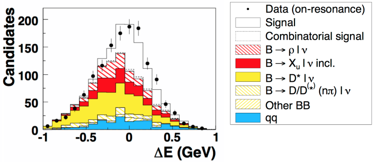
$$p_\nu = (E_{\text{miss}}, \mathbf{p}_{\text{miss}}) = p_{e^+e^-} - p_\pi - p_l - \sum p_{tracks} - \sum p_{clusters}$$

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

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



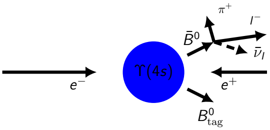


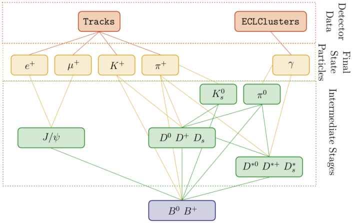


Measurement	Reference
BABAR (6 q^2 bins)	Phys. Rev. D83, 032007 (2011)
BABAR (12 q^2 bins)	Phys. Rev. D86, 092004 (2012)
Belle (13 q^2 bins)	Phys. Rev. D83, 071101 (2011)

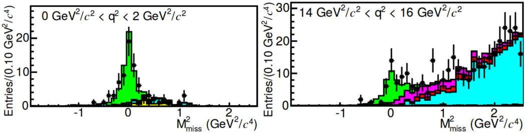
Exclusive $|V_{ub}|$ from tagged $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$

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

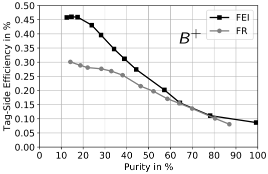


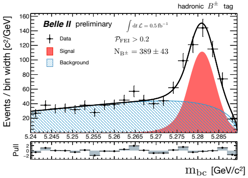


Measurement	Reference
Belle (13 q^2 bins)	Phys. Rev. D88, 032005 (2013)



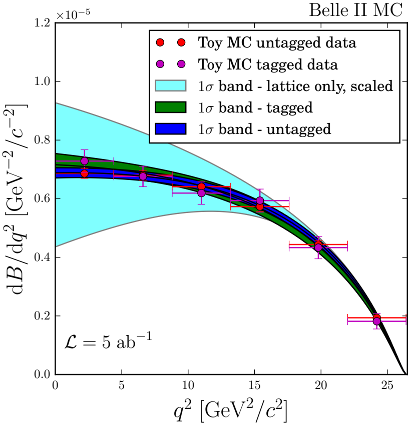
- Improved tag-side reconstruction algorithm: Full Event Interpretation
- Reconstructs O(5000) decay chains.
- Higher tag-side efficiency at lower purities.

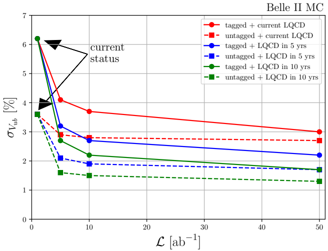




Projected $|V_{ub}|$ from $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ decays

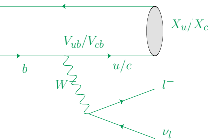
- MC tagged and untagged analyses peformed in the B2TIP report [arXiv:1808.10567]

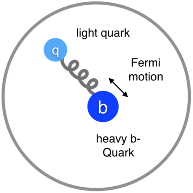




Source	Error (Limit) [%]	
	Tagged [%]	Untagged
Tracking efficiency	0.4	2.0
Pion identification	–	1.3
Lepton identification	1.0	2.4
Kaon veto	0.9	–
Continuum description	1.0	1.8
Tag calibration and $N_{B\bar{B}}$	4.5 (2.0)	2.0 (1.0)
$X_u \ell \nu$ cross-feed	0.9	0.5 (0.5)
$X_c \ell \nu$ background	–	0.2 (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)

$|V_{ub}|$ from inclusive decays



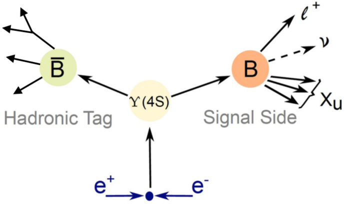


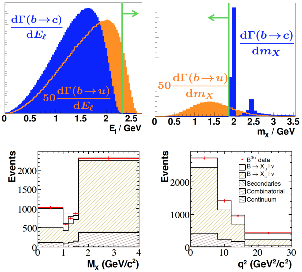
$$\frac{d^3\Gamma}{dp_X^+\, dp_X^-\, dE_\ell} = \frac{G_F^2|V_{ub}|^2}{192\pi^3}\int dk\, C(E_\ell, p_X^-, p_X^+, k)\, F(k) + O\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

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

Phys. Rev. Lett. 104, 021801

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



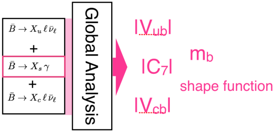


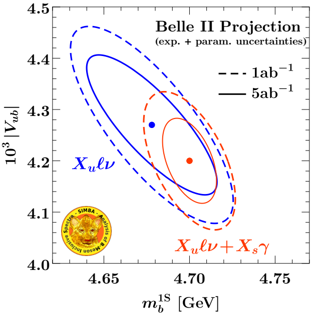
Future of inclusive $|V_{ub}|$

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

	Exp.	Theory	Total
605 fb^{-1}	6.0%	2.5-4.5%	6.5-7.5%
5 ab^{-1}	2.3%	2.5-4.5%	3.4-5.1%
50 ab^{-1}	1.7%	2.5-4.5%	3.0-4.8%

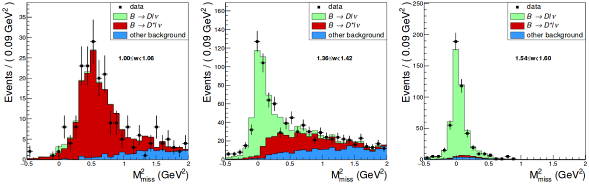
$$F(k) = \sum_n (c_n f_n(k))^2$$



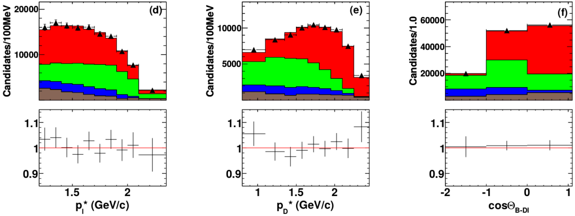


$|V_{cb}|$ from $B \to Dl\nu$

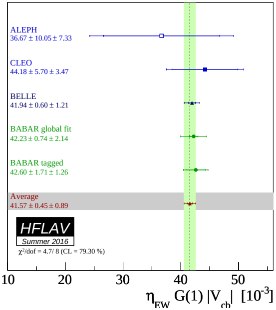
- Tagged: fit M^2_{miss} in bins of w [Phys. Rev. D93, 032006 (2016)] $w = (m_B^2 + m_{D^{(*)}}^2 - q^2)/(2m_B m_{D^{(*)}})$

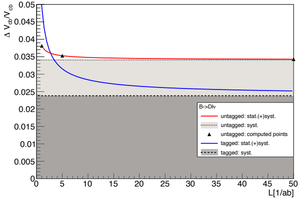


- Untagged fit of BaBar to p_D^*, p_l^* and $\cos\theta_{\text{BDl}}$



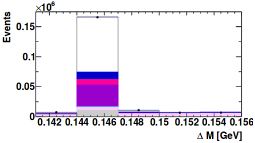
Latest LQCD (2015) PRD 92 054510, PRD 92 034506

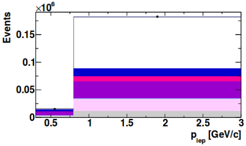


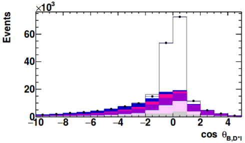


$|V_{cb}|$ from $B \to D^* l \nu$

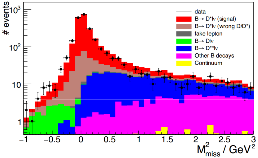
- Untagged: 3D fit ($\cos\theta_{BD^*l}$, p_l, ΔM) [Belle: PRD 82, 112007 (2010), arXiv:1809.03290]



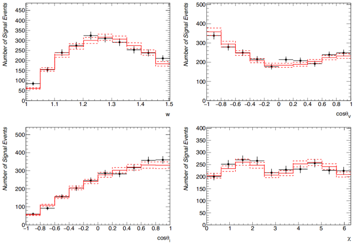




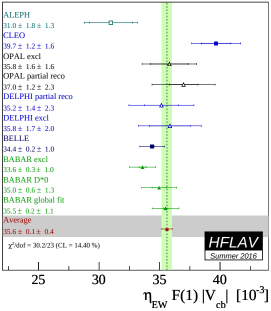
- Tagged fit to M^2_{miss} [Belle: arXiv:1702.01521]

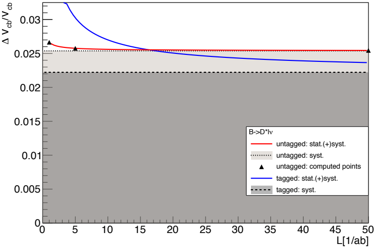


- Fits performed in 1D bins of angular variables and w.



$|V_{cb}|$ from $B \to D^* l\nu$





- Analysis of arXiv:1702.01521 by independent groups

[D.Bigi et. al., PLB (2017) 441, B.Grinstein et al., PLB 771 (2017) 359]

BGL Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	27.9/32	31.4/35
$\lvert V_{cb}\rvert$	$0.0417\,(^{+20}_{-21})$	$0.0404\,(^{+16}_{-17})$
a_0^f	0.01223(18)	0.01224(18)
a_1^f	$-0.054\,(^{+58}_{-43})$	$-0.052\,(^{+27}_{-15})$
a_2^f	$0.2\,(^{+7}_{-12})$	$1.0\,(^{+0}_{-5})$
$a_1^{\mathcal{F}_1}$	$-0.0100\,(^{+61}_{-56})$	$-0.0070\,(^{+54}_{-52})$
$a_2^{\mathcal{F}_1}$	0.12 (10)	$0.089\,(^{+96}_{-100})$
a_0^g	$0.012\,(^{+11}_{-8})$	$0.0289\,(^{+57}_{-37})$
a_1^g	$0.7\,(^{+3}_{-4})$	$0.08\,(^{+8}_{-22})$
a_2^g	$0.8\,(^{+2}_{-17})$	$-1.0\,(^{+20}_{-0})$

CLN Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	34.3/36	34.8/39
$\lvert V_{cb}\rvert$	0.0382 (15)	0.0382 (14)
$\rho^2_{D^*}$	$1.17\,(^{+15}_{-16})$	1.16 (14)
$R_1(1)$	$1.391\,(^{+92}_{-88})$	1.372 (36)
$R_2(1)$	$0.913\,(^{+73}_{-80})$	$0.916\,(^{+65}_{-70})$
$h_{A_1}(1)$	0.906 (13)	0.906 (13)

- New LQCD at non-zero recoil imminent: arXiv1901.00216

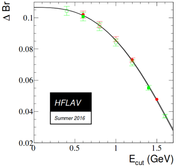
$|V_{cb}|$ from inclusive $B \to X_c l \nu$ decays

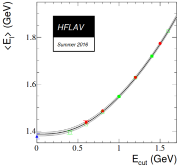
$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 \left(1 + \frac{c_5(\mu)O_5(\mu)}{m_b^2} + \frac{c_6(\mu)O_6(\mu)}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right)\right)$$

- Operator Product Expansion (OPE):
  - O_i: hadronic matrix elements (non-perturbative)
  - c_i: coefficients (perturbative)

Order	Kinetic	1S
$\mathcal{O}(1)$	$m_b,\ m_c$	m_b
$\mathcal{O}(1/m_b^2)$	$\mu_\pi^2,\ \mu_G^2$	$\lambda_1,\ \lambda_2$
$\mathcal{O}(1/m_b^3)$	$\rho_D^3, \rho_{\mathrm{LS}}^3$	$\rho_1,\ \tau_{1-3}$

- Moments of E_l, M_X can be expressed with same OPE formulation.
- $\implies$ Measure moments to constrain expansion parameters.

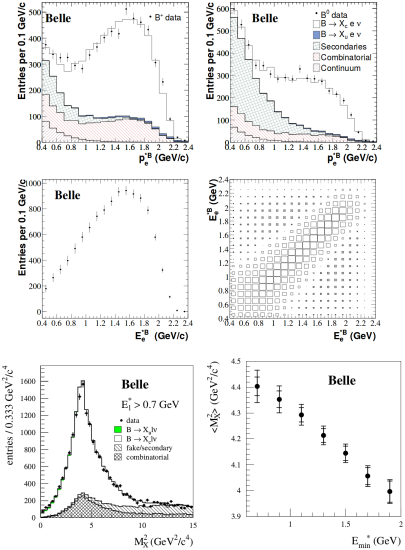




	$\lvert V_{cb}\rvert$ [10^{-3}]	$m_b^{\rm kin}$ [GeV]	$m_c^{\rm MS}$ [GeV]	μ_π^2 [GeV^2]	ρ_D^3 [GeV^3]	μ_G^2 [GeV^2]	ρ_{LS}^3 [GeV^3]
value	42.19	4.554	0.987	0.464	0.169	0.333	−0.153
error	0.78	0.018	0.015	0.076	0.043	0.053	0.096
$\lvert V_{cb}\rvert$	1.000	−0.257	−0.078	0.354	0.289	−0.080	−0.051
$m_b^{\rm kin}$		1.000	0.769	−0.054	0.097	0.360	−0.087
$m_c^{\rm MS}$			1.000	−0.021	0.027	0.059	−0.013
μ_π^2				1.000	0.732	0.012	0.020
ρ_D^3					1.000	−0.173	−0.123
μ_G^2						1.000	0.066
ρ_{LS}^3							1.000

Inclusive $|V_{cb}|$ at Belle

- Analyses used 140 fb^{-1} and older tagging $\implies \times\mathcal{O}(10)$ statistics with Belle dataset.
- PRD 75, 032001 (2007):
  - Fit of p_l for $B \to X_c e \nu_e$ in B rest frame.
  - Unfolded E_e and determined its moments and a $\mathcal{B}$
- PRD 75, 032005 (2007):
  - Fit of M_X^2 for $B \to X_c l \nu_l$
  - Calculated moments of this distribution.
- Expect 1.2% uncertainty on inc. $|V_{cb}|$ from Belle II with 5 ab^{-1}

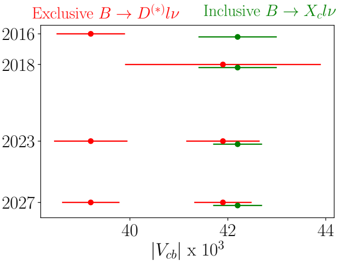


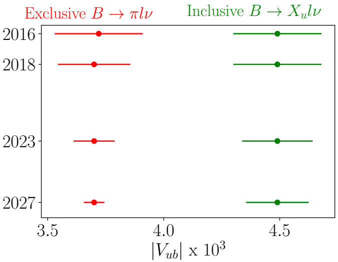
Summary of $|V_{ub}|$ projections

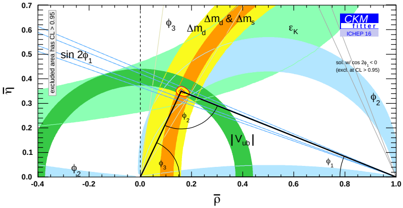
	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\|V_{ub}\|$ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	7.0	8.0
5 ab^{-1}	1.1	(0.9, 1.0)	1.8	1.7	3.2
50 ab^{-1}	0.4	(0.3, 1.0)	1.2	0.9	1.7
$\|V_{ub}\|$ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.7	7.0	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

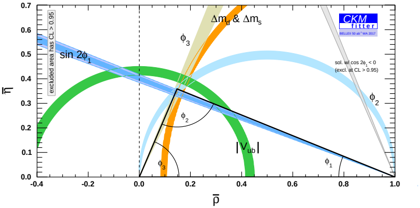
Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\|V_{cb}\|$ incl.	$42.2 \cdot 10^{-3} \cdot (1 \pm 1.8\%)$	1.2%	–
$\|V_{cb}\|$ excl.	$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\rm ex.} \pm 1.4\%_{\rm th.})$	1.8%	1.4%
$\|V_{ub}\|$ incl.	$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\rm ex.} \pm 2.5\%_{\rm th.})$	3.4%	3.0%
$\|V_{ub}\|$ excl. (WA)	$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\rm ex.} \pm 3.0\%_{\rm th.})$	2.4%	1.2%

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









Conclusion

- Exclusive determination of $|V_{ub}|$ from $B \to \pi l \nu$ decays will be most precise (1-2%)
- Exclusive and inclusive determinations of $|V_{cb}|$ will have a precision of $1 - 1.5\%$.
- Precision tree level determinations of $|V_{ub}|$ and γ will allow a stringent testing of any incompatibility with loop level CKM observables.

$B \to D^{(*)} l\nu$ form factor parametrisations

$$\frac{d\Gamma}{dw}_{B\to Dl\nu} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2(w^2-1)^{3/2} \times \mathcal{G}^2(w)|V_{cb}|^2$$

$$w = (m_B^2 + m_{D^{(*)}}^2 - q^2)/(2m_B m_{D^{(*)}})$$

CLN [Nucl. Phys. B530, 153 (1998)]

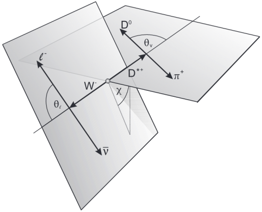
$$\mathcal{G}(z) = \mathcal{G}(1)(1 - 8\rho^2 z + (51\rho^2 - 10)z^2) - (252\rho^2 - 84)z^3))$$

$$z(w) = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$$

BGL [Phys. Rev. Lett, 74,4603 (1995)]

$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_n a_{i,n} z^n$$

$$\frac{d\Gamma}{dw}_{B\to D^* l\nu} = \iiint \frac{d\Gamma}{dw d\theta_l d\theta_\nu d\chi} d\theta_l d\theta_\nu d\chi$$

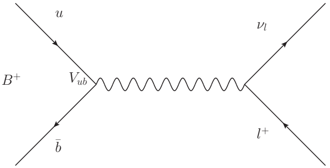


$$\frac{d\Gamma}{dq} = \frac{G_F^2 m_{D^*}^3}{48\pi^3}(m_B - m_{D^*})^2(w^2-1)^{3/2} \times u(w)\mathcal{F}^2(w)|V_{cb}|^2$$

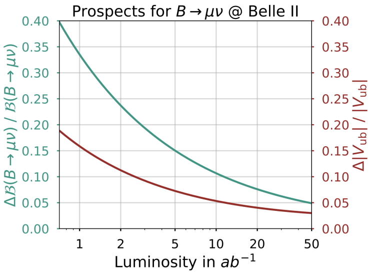
CLN pars F(1), ρ^2, $R_1(1)$ and $R_2(1)$

$|V_{ub}|$ from leptonic decays

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



- $\mathcal{B}$s are hierarchical with lepton mass due to helicity suppresion.
- $f_B = 187.1 MeV (0.7\%)$
- 3 σ evidence for $B \to \mu\nu$ [see talk of M. Prim]



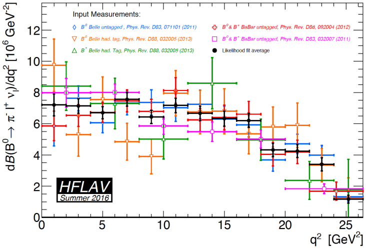
- Expect 3% uncertainty on $|V_{ub}|$ from $B \to \tau\nu$ tagged and $B \to \mu\nu$ untagged.

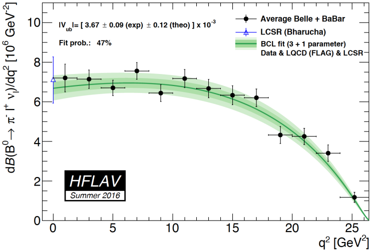
	5 ab^{-1}	50 ab^{-1}
Had. tag	7.5	3.2
SL. tag	6.3	2.8

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

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

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





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

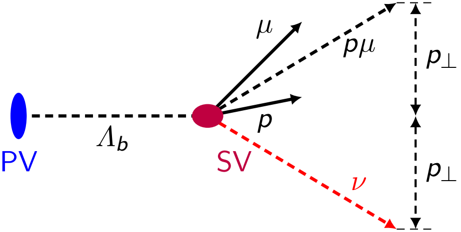
Previous Belle $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_l$ systematics

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)

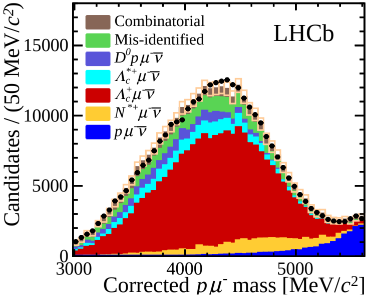
$|V_{ub}|$ from $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ decays at LHCb

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

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



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



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

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.

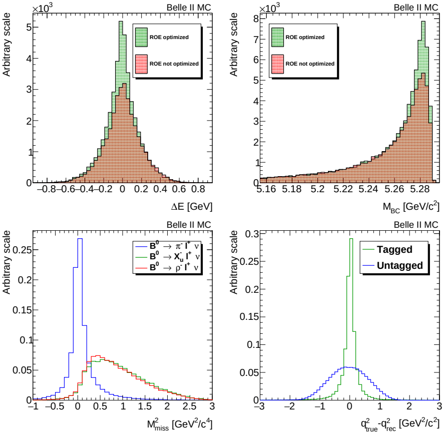
Albrecht et al. arXiv:1709.10308v5

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

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

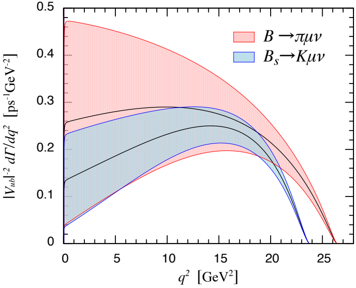
- Tagged and untagged analyses performed on Belle II MC.
- Untagged use optimised BDT selections for tracks and clusters in the Rest of the event.
- Tagged uses the Belle 2 tagging algorithm (FEI)

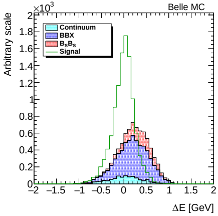
	Belle ϵ	Belle II ϵ
untagged	7.7-15%	20%
tagged	0.3%	0.55%

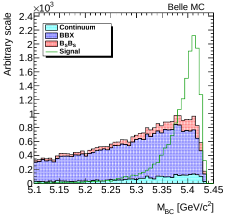


$\bar{B}_s^0 \to K^+ \mu^- \overline{\nu}_\mu$ Prospects

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







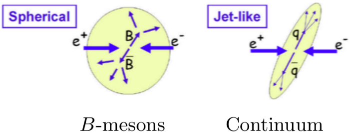
- At Belle II expect 60M $B_s^{(*)}\bar{B}_s^{(*)}$ pairs in 1ab^{-1}
- 5-10% precision on the decay rate with 1ab^{-1}

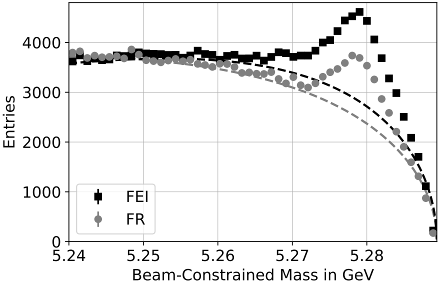
Tagging performance

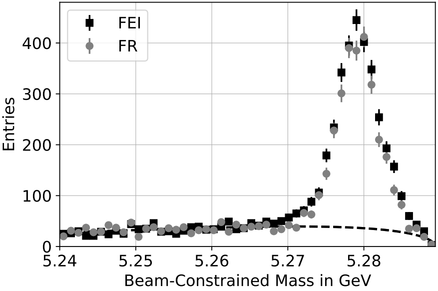
$$m_{bc} = \sqrt{E_B^2 - p_B^2}$$

$$E_B = \sqrt{s}/2$$

Different event topologies



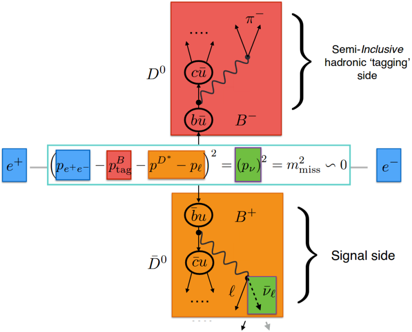


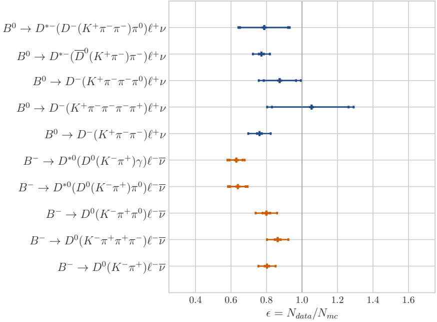


FR = Full Reconstruction

Calibration of hadronic tagging

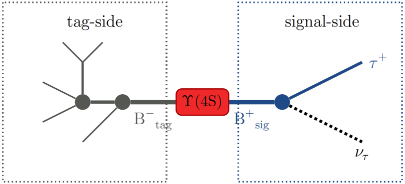
- Use the FEI on Belle data to reconstruct several well known semileptonic decays.
- $\epsilon = N_{DATA}/N_{MC}$



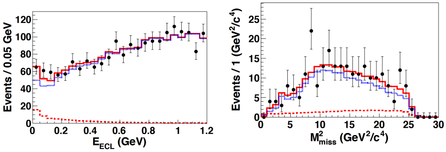


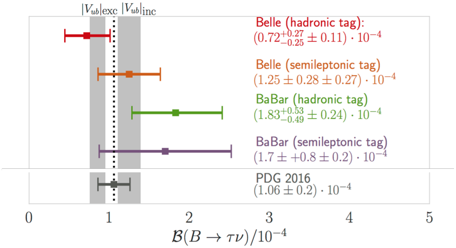
$\epsilon_{\text{charged}} = 0.74 \pm 0.05$ $\qquad$ $\epsilon_{\text{neutral}} = 0.86 \pm 0.07$

- 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
$B_{\rm tag}$ 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

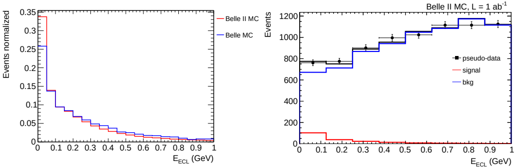
Belle Semileptonic

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

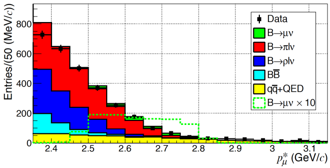
	$\int \mathcal{L}$ (ab^{-1})	1	5	50
Had. tag	stat. uncertainty (%)	29.2	13.0	4.1
	syst. uncertainty (%)	12.6	6.8	4.6
	total uncertainty (%)	31.6	14.7	6.2
SL. tag	stat. uncertainty (%)	19.0	8.5	2.7
	syst. uncertainty (%)	17.9	8.7	4.5
	total uncertainty (%)	26.1	12.2	5.3

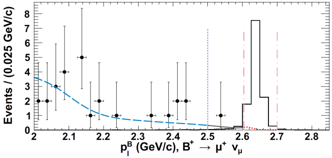


$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	18.0	(7.1, 2.2)	19.5	2.5	19.6
5 ab^{-1}	6.5	(2.7, 2.2)	7.3	1.5	7.5
50 ab^{-1}	2.1	(0.8, 2.2)	3.1	1.0	3.2
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (SL tagged)					
711 fb^{-1}	11.3	(10.4, 1.9)	15.4	2.5	15.6
5 ab^{-1}	4.2	(4.4, 1.9)	6.1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

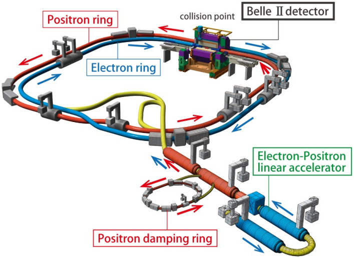


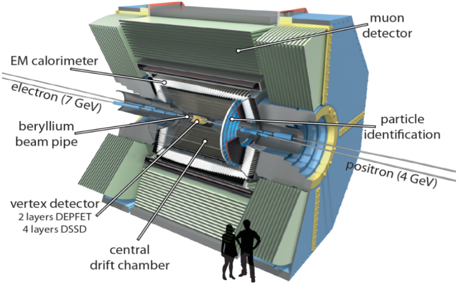


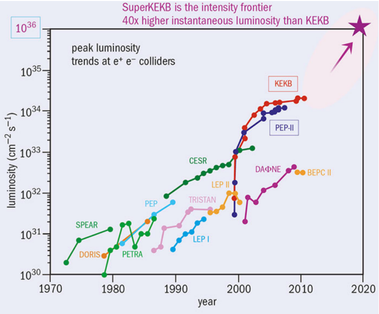
- Untagged using CoM p^*_μ
- Tagged use $p^B_\mu = m_B/2 \implies$ high resolution but smaller statistics.

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	$\sim 13\%$	-	-

The Belle II Experiment







See P. Urquijo's talk