Semileptonic B and B_s decays at Belle

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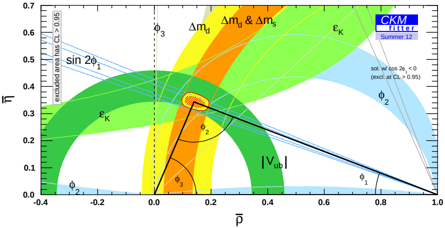
on behalf of the Belle Collaboration

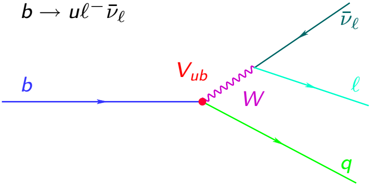
The 2013 European Physical Society Conference on High Energy Physics
18-24 July 2013
Stockholm, Sweden

- Introduction
- Belle detector and KEKB
- B_s^0 semileptonic decays
- Charmless semileptonic decays with hadronic tag
  - $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ decays
  - $\bar{B} \to \pi\ell^-\bar{\nu}_\ell$ decays
  - $\bar{B} \to \rho\ell^-\bar{\nu}_\ell$ decays
  - $B^- \to \omega\ell^-\bar{\nu}_\ell$ decays
  - $|V_{ub}|$ determination
- Conclusion

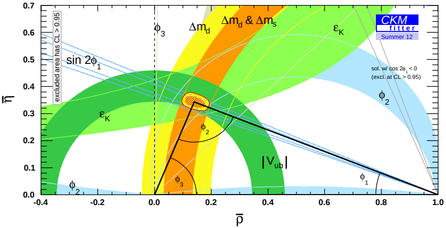
To test the unitarity of the CKM matrix and to search for new physics BSM it is important to have precisely measured values of the matrix elements. The values of $|V_{ub}|$ and $|V_{cb}|$ can be determined from $b \to u$ and $b \to c$ tree-level transitions in which semileptonic B-meson decays have relatively clean theoretical interpretation and QCD uncertainties are under control. Pure leptonic decays are even more clean theoretically but more difficult from experimental side.

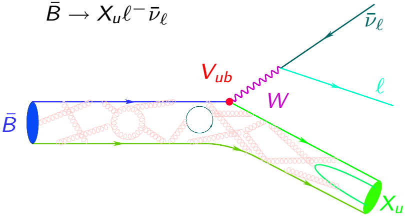


$b \to u\ell^- \bar{\nu}_\ell$

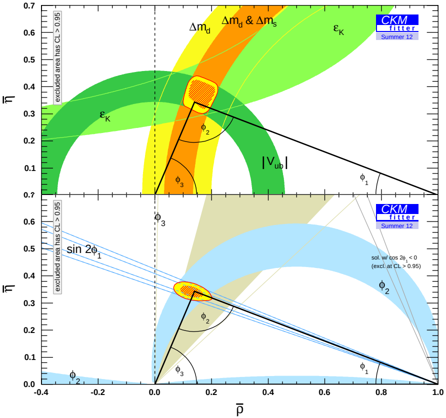


To test the unitarity of the CKM matrix and to search for new physics BSM it is important to have precisely measured values of the matrix elements. The values of $|V_{ub}|$ and $|V_{cb}|$ can be determined from $b \to u$ and $b \to c$ tree-level transitions in which semileptonic B-meson decays have relatively clean theoretical interpretation and QCD uncertainties are under control. Pure leptonic decays are even more clean theoretically but more difficult from experimental side.





To test the unitarity of the CKM matrix and to search for new physics BSM it is important to have precisely measured values of the matrix elements. The values of $|V_{ub}|$ and $|V_{cb}|$ can be determined from $b \to u$ and $b \to c$ tree-level transitions in which semileptonic B-meson decays have relatively clean theoretical interpretation and QCD uncertainties are under control. Pure leptonic decays are even more clean theoretically but more difficult from experimental side.



Sides of the UT are still less accurate than angles $\Rightarrow$ we need more precise measurements of semileptonic decays especially charmless for $|V_{ub}|$ element.

Matrix element of $B \to X_u \ell \bar{\nu}_\ell$ decay at first order

$$\mathcal{M}(B \to X_u \ell \bar{\nu}_\ell) = \frac{G_F}{\sqrt{2}} V_{ub} L^\mu H_\mu, \;\; L^\mu = \bar{u}_\ell \gamma^\mu (1 - \gamma^5) v_\nu$$

Hadronic current H_μ depends on specific final state.

The differential decay rate for $B \to \pi \ell \bar{\nu}_\ell$ process where $\ell = e, \mu$ can be expressed in terms of W boson momentum q:

$$\frac{\mathrm{d}\Gamma(B \to \pi \ell \bar{\nu}_\ell)}{\mathrm{d}q^2} = \frac{G_F^2 p_\pi^3}{24\pi^3} |V_{ub}|^2 |f_+(q^2)|^2, \qquad (1)$$

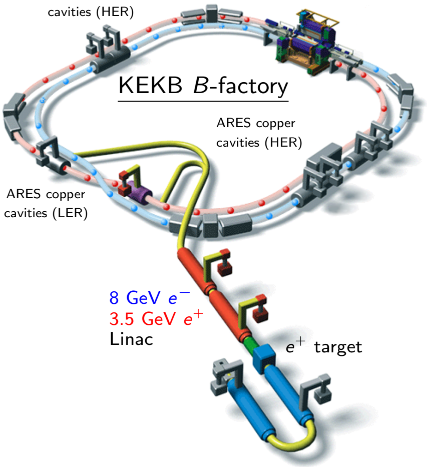
where all QCD uncertainties are hidden in the $f_+(q^2)$ vector form factor. Model independent parametrization of $f_+(q^2)$, which satisfies unitarity, analyticity and perturbative QCD scaling has been suggested by Bourrely, Caprini and Lellouch (BCL) [PRD **79**, 013008 (2009)]:

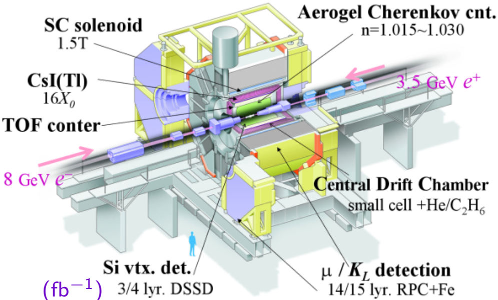
$$f_+(q^2, \vec{b}) = \frac{1}{1 - q^2/m_{B^*}^2} \sum_{k=0}^{K} b_k \, z(q^2)^k, \quad z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \qquad (2)$$

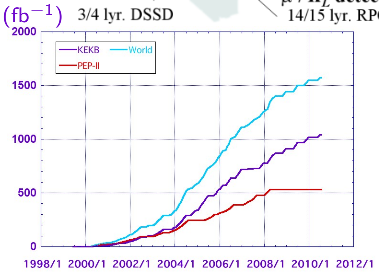
where $m_{B^*} = 5.325$ GeV$/c^2$ and $t_+ = (m_B + m_\pi)^2$. The optimal parameter $t_0 = 20.06$ GeV$^2/c^2$ provides fast series convergence since the physical q^2 region maps onto the disk $|z| < 0.28$. Unitarity and crossing symmetry properties of the form factor constrain the $\vec{b}$ parameters:

$$\sum_{j,k=0}^{K} B_{jk} b_j b_k \leq 1. \qquad (3)$$

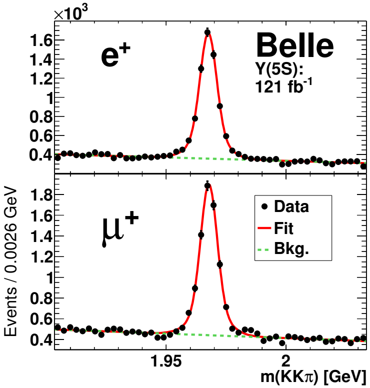
Belle detector and KEKB accelerator (1999-2010)





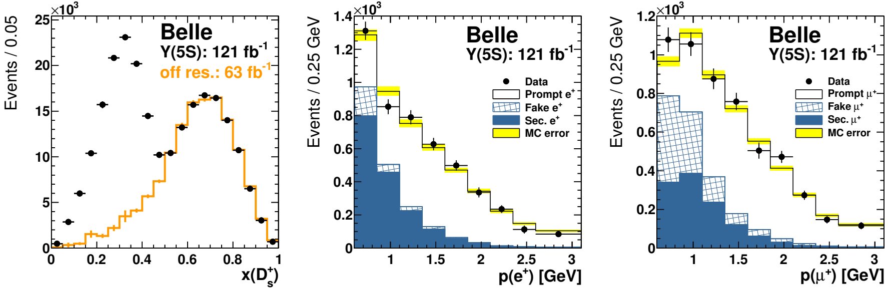


Energy region	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	Off reson./scan	Total
$\mathcal{L}$, fb^{-1}	6	25	3	711	121	100	> 1000



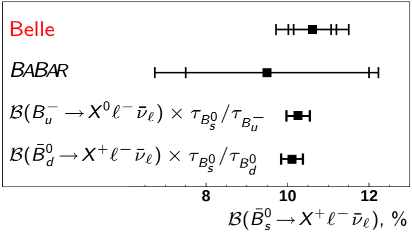
ℓ	$N(D_s^+\ell^+) \times 10^{-3}$	$\mathcal{R} \times 10^4$
e	4.26 ± 0.19	$428 \pm 20 \pm 13$
μ	4.76 ± 0.23	$470 \pm 23 \pm 16$

- 121 fb^{-1} @ $\Upsilon(5S)$ or $(7.1 \pm 1.3) \times 10^6$ $B_s^{0(*)}\bar{B}_s^{0(*)}$ pairs.
- B_s^0 meson is tagged by a D_s^+ meson reconstructed in the mode $D_s^+ \to \phi(K^+K^-)\pi$.
- To suppress continuum events low momentum D_s^+ meson is required $x(D_s^+) = p_{D_s^+}/p_{D_s^+}^{\max} < 0.5$
- Same charge for the lepton and D_s^+ meson to ensure they come from different B_s^0 mesons.
- Branching fraction from the $\mathcal{R} = N(D_s^+\ell^+)/N(D_s^+)$ ratio.
- Total number of selected D_s^+ mesons is $N(D_s^+) = (12.42 \pm 0.08) \times 10^4$ among which $N_{\text{cont}}(D_s^+) = (2.7 \pm 0.1) \times 10^4$ mesons are expected from continuum.

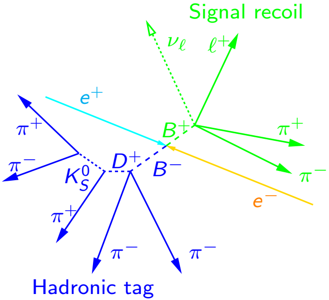


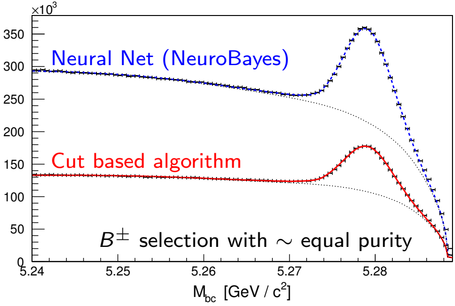
ℓ	$\mathcal{B}(\bar{B}_s^0 \to X^+\ell^-\bar{\nu}_\ell)$, %
e	$10.1 \pm 0.6_{\text{stat}} \pm 0.4_{\text{syst}} \pm 0.6_{\text{ext}}$
μ	$11.3 \pm 0.7_{\text{stat}} \pm 0.5_{\text{syst}} \pm 0.7_{\text{ext}}$
Combined	$10.6 \pm 0.5_{\text{stat}} \pm 0.4_{\text{syst}} \pm 0.6_{\text{ext}}$

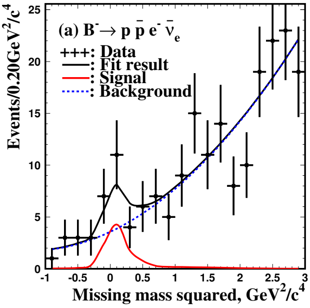
BABAR	3.2 fb^{-1}	PRD **85**, 011101 (2012)
Belle	121 fb^{-1}	PRD **87**, 072008 (2013)

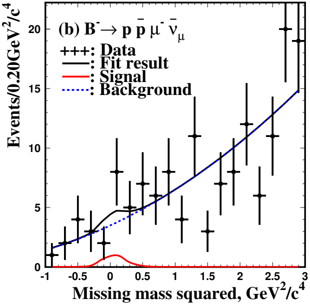


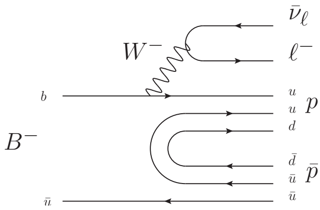
- Recently new reconstruction procedure of B hadronic decays based on NeuroBayes package has been introduced in Belle. [NIM A**654**, 432 (2011)]
- New procedure tries to reconstruct B meson in more than 1100 exclusive hadronic decay channels.
- Compared to the previous cut based algorithm it offers roughly twice efficiency gain and about 2.1×10^6 of $B^\pm$ and 1.4×10^6 of B^0 with 711 fb^{-1} collected at $\Upsilon(4S)$ resonance.
- Hadronic tag has been calibrated with charm semileptonic decays with precision 4.2 % for B^+ and 4.5 % for B^0.









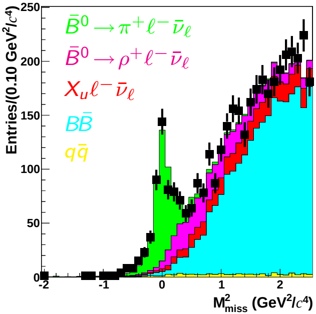


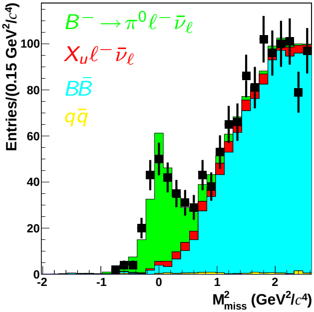
- No measurements to date
- U.L. from CLEO [PRD **68**, 012004 (2003)]: $\mathcal{B}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell) < 5.2 \times 10^{-3}$
- $\mathcal{B}$ prediction is $\sim 10^{-4}$ in [PLB **704**, 495 (2011)]
- Yield from unbinned maximum likelihood fit

Mode	$\mathcal{B}$ (10^{-6})	U.L. (10^{-6})
$B^- \to p\bar{p}e^-\bar{\nu}_e$	$8.2\ ^{+3.7}_{-3.2} \pm 0.6$	13.8
$B^- \to p\bar{p}\mu^-\bar{\nu}_\mu$	$3.1\ ^{+3.1}_{-2.4} \pm 0.7$	8.5
Combined sample	$5.8\ ^{+2.4}_{-2.1} \pm 0.9$	9.6

Submitted to PRL [arXiv:1306.3353]

$\bar{B} \to \pi\ell^-\bar{\nu}_\ell$ with hadronic tag at Belle





- 711 fb^{-1} @ $\Upsilon(4S)$ + 79 fb^{-1} off-peak data
- Yield from binned maximum likelihood fit
- Accepted by PRD [arXiv:1306.2781]

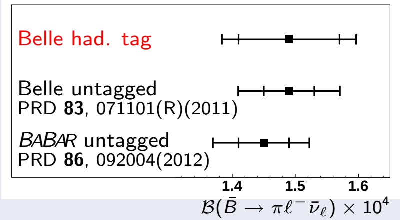
X_u	Yield	$\mathcal{B} \times 10^4$
π^+	462.6±27.7	$1.49 \pm 0.09 \pm 0.07$
π^0	232.2±22.6	$0.80 \pm 0.08 \pm 0.04$

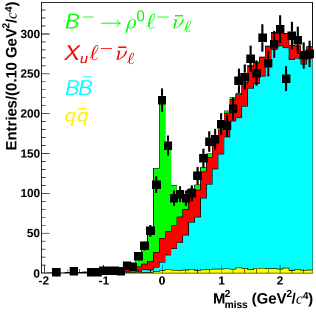
Test of isospin symmetry:

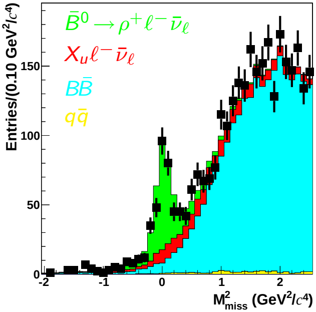
$$2 \times \frac{\mathcal{B}(B^- \to \pi^0\ell^-\bar{\nu}_\ell)}{\mathcal{B}(\bar{B}^0 \to \pi^+\ell^-\bar{\nu}_\ell)} \frac{\tau_{B^0}}{\tau_{B^+}} = 1.00 \pm 0.13$$

Combined branching fraction:

$$\mathcal{B}(\bar{B} \to \pi\ell^-\bar{\nu}_\ell) = (1.49 \pm 0.08_{\text{stat}} \pm 0.07_{\text{syst}}) \times 10^{-4}$$







- 711 fb^{-1} @ $\Upsilon(4S)$ + 79 fb^{-1} off-peak data
- Yield from binned maximum likelihood fit
- Accepted by PRD [arXiv:1306.2781]

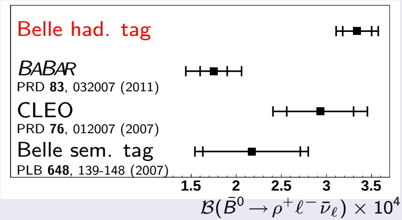
X_u	Yield	$\mathcal{B} \times 10^4$
ρ^+	343.3±28.3	$3.22 \pm 0.27 \pm 0.24$
ρ^0	621.7±35.0	$1.83 \pm 0.10 \pm 0.10$

Test of isospin symmetry:

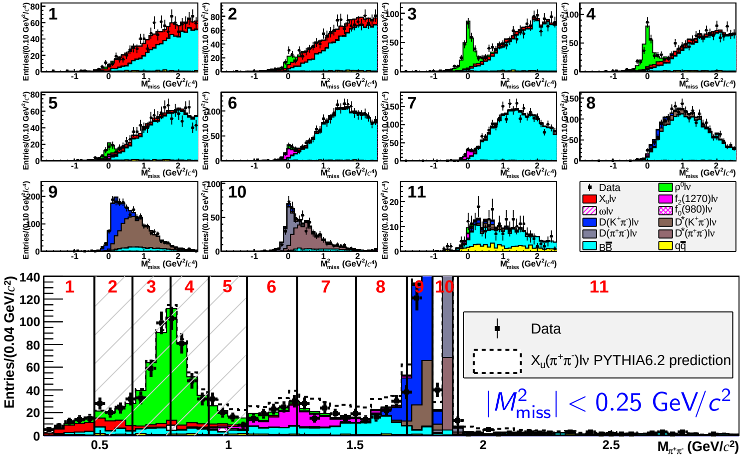
$$2 \times \frac{\mathcal{B}(B^- \to \rho^0 \ell^- \bar{\nu}_\ell)}{\mathcal{B}(\bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell)} \frac{\tau_{B^0}}{\tau_{B^+}} = 1.06 \pm 0.13$$

Combined branching fraction:

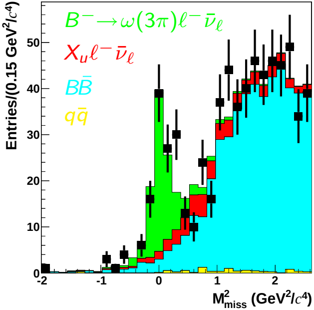
$$\mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell) = (3.34 \pm 0.16_{\text{stat}} \pm 0.17_{\text{syst}}) \times 10^{-4}$$

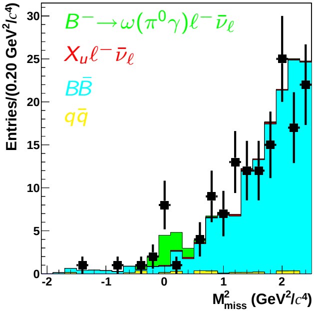


$\bar{B} \to \rho\ell^-\bar{\nu}_\ell$ with hadronic tag at Belle in bins of $M_{\pi\pi}$



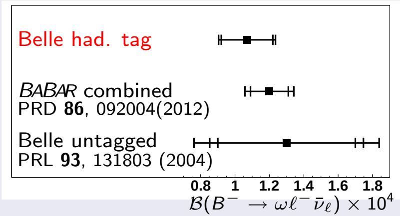
- The extracted yield of the $B^- \to \rho^0\ell^-\bar{\nu}_\ell$ decay nicely agrees with the $M^2_{\rm miss}$ fit alone.
- Belle does not see the $\bar{B} \to X_u(\pi\pi)\ell^-\bar{\nu}_\ell$ non-resonance decay predicted by PYTHIA6.2 in data: $N^{\rm PYTHIA}_{\pi\pi\ell^-\bar{\nu}_\ell} = 334.9$, $N^{\rm fit}_{\pi\pi\ell^-\bar{\nu}_\ell} = 45.8 \pm 45.4$
- The extracted yield of the $B^- \to f_2\ell^-\bar{\nu}_\ell$ decay is 2-3 times higher than the ISGW2 model prediction: $N^{\rm ISGW2}_{f_2\ell^-\bar{\nu}_\ell} = 58.4$, $N^{\rm fit}_{f_2\ell^-\bar{\nu}_\ell} = 154.4 \pm 22.2$

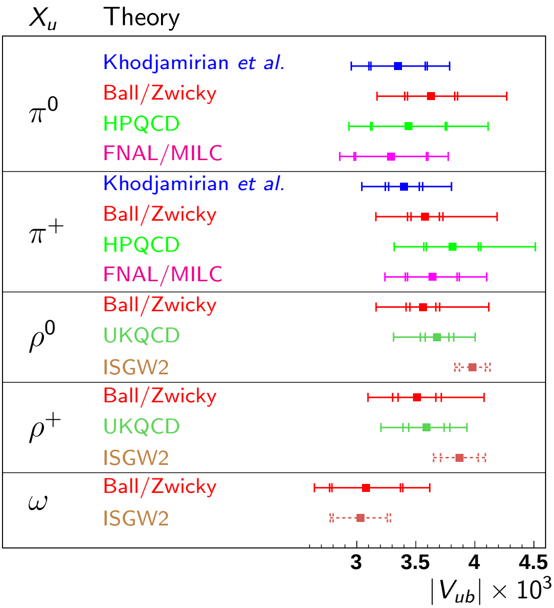




- 711 fb^{-1} @ $\Upsilon(4S)$ + 79 fb^{-1} off-peak data
- Yield from binned maximum likelihood fit
- Accepted by PRD [arXiv:1306.2781]

X_u	Yield	$\mathcal{B} \times 10^4$
$\omega(3\pi)$	96.7±14.5	$1.07 \pm 0.16 \pm 0.07$
$\omega(\pi\gamma)$	9.0±4.0	$1.06 \pm 0.47 \pm 0.07$





Khodjamirian *et al.*
PRD **83**, 094031 (2011)

Ball/Zwicky
PRD **71**, 014015 (2005)
PRD **71**, 014029 (2005)

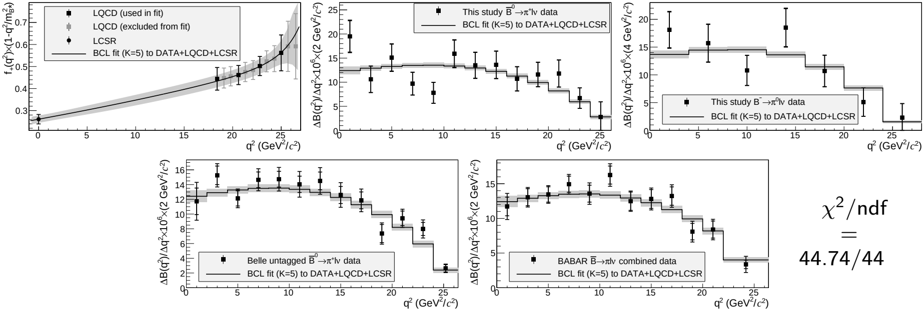
HPQCD
PRD **73**, 074502 (2006)

FNAL/MILC
PRD **79**, 054507 (2009)

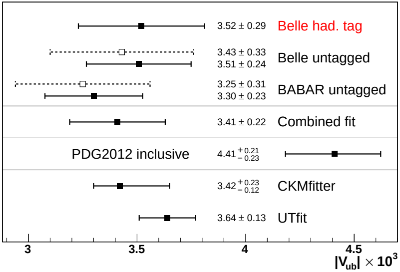
UKQCD
PLB **416**, 392 (1998)

ISGW2
PRD **52**, 2783 (1995)
Theory error is not available.

Simultaneous fit with BCL parametrization to the recent form factor predictions and the available $\bar{B} \to \pi \ell^- \bar{\nu}_\ell$ data provides the most precise value of $|V_{ub}|$.



$$\chi^2/\text{ndf} = 44.74/44$$



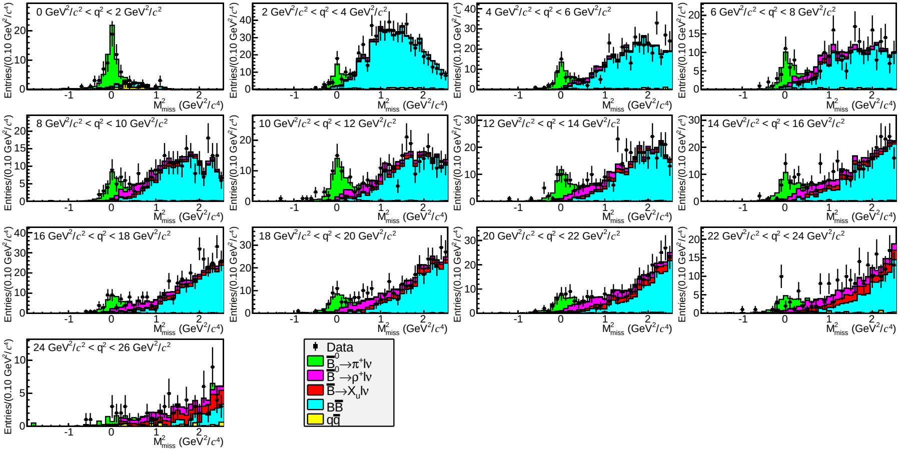
The dashed lines represent $|V_{ub}|$ values quoted in the original papers.

- LCSR JHEP **1205**, 092 (2012) [arXiv:1203.1359]
- LQCD PRD **79**, 054507 (2009) [arXiv:0811.3640]
- Belle had. tag Accepted by PRD [arXiv:1306.2781]
- Belle PRD **83**, 071101(R) (2011) [arXiv:1012.0090]
- BABAR PRD **86**, 092004 (2012) [arXiv:1208.1253]

Conclusion

- Belle was decomissioned at 2010 but analysis of the collected data still improves our knowledge in B physics.
- Belle measured inclusive semileptonic branching fraction of the B_s^0 meson with the world best precision.
- New neural net based hadronic tag at Belle offers twice efficiency gain compared to the previous cut based technique.
- The first evidence of baryonic semileptonic decay of B_u^- meson at Belle.
- New measurement of $\bar{B} \to \pi \ell^- \bar{\nu}_\ell$ with hadronic tag at Belle consistent with the untagged results.
- New measurement of $\bar{B} \to \rho \ell^- \bar{\nu}_\ell$ decay with hadronic tag at Belle with precision of twice better than the world average. Belle does not see $\bar{B} \to X_u(\pi\pi)\ell^- \bar{\nu}_\ell$ non-resonance decay in the data. For the first time the $B^- \to f_2 \ell^- \bar{\nu}_\ell$ decay is seen in Belle data and extracted yield is 2-3 times larger than ISGW2 prediction.
- Measured branching fraction of the $B^- \to \omega \ell^- \bar{\nu}_\ell$ decay is in agreement with the previous measurements.
- Using the pion modes, a recent LCSR calculation, lattice QCD results and a model-independent description of the hadronic form factor, a value of the CKM matrix element $|V_{ub}|$ is extracted.
- The tension between exclusive and inclusive measurements of $|V_{ub}|$ remains significant at 3σ level.

Backup



$$\chi^2/\text{ndf} = 813.165/1026$$

Differential branching fractions in bins of q^2 are also extracted!

Normalized decay rate $\Delta\zeta = \int d\Gamma / |V_{ub}|^2$ is based on form factor prediction from theory.

X_u	Theory	q^2 GeV/c^2	N^{fit}	$\Delta\mathcal{B}$ 10^{-4}	$\Delta\zeta$ ps^{-1}	$\|V_{ub}\|$ 10^{-3}
π^0	LCSR1	< 12	119.6 ± 16.2	0.423 ± 0.057	$4.59^{+1.00}_{-0.85}$	$3.35 \pm 0.23 \pm 0.09^{+0.36}_{-0.31}$
	LCSR2	< 16	168.2 ± 18.9	0.588 ± 0.066	$5.44^{+1.43}_{-1.43}$	$3.63 \pm 0.20 \pm 0.10^{+0.60}_{-0.40}$
	HPQCD	> 16	58.6 ± 10.5	0.196 ± 0.035	$2.02^{+0.55}_{-0.55}$	$3.44 \pm 0.31 \pm 0.09^{+0.59}_{-0.39}$
	FNAL				$2.21^{+0.47}_{-0.42}$	$3.29 \pm 0.30 \pm 0.09^{+0.37}_{-0.30}$
π^+	LCSR1	< 12	247.2 ± 18.9	0.808 ± 0.062	$4.59^{+1.00}_{-0.85}$	$3.40 \pm 0.13 \pm 0.09^{+0.37}_{-0.32}$
	LCSR2	< 16	324.2 ± 22.6	1.057 ± 0.074	$5.44^{+1.43}_{-1.43}$	$3.58 \pm 0.12 \pm 0.09^{+0.59}_{-0.39}$
	HPQCD	> 16	141.3 ± 16.0	0.445 ± 0.050	$2.02^{+0.55}_{-0.55}$	$3.81 \pm 0.22 \pm 0.10^{+0.66}_{-0.43}$
	FNAL				$2.21^{+0.47}_{-0.42}$	$3.64 \pm 0.21 \pm 0.09^{+0.40}_{-0.33}$
ρ^0	LCSR3	< 16	476.5 ± 30.5	1.431 ± 0.091	$13.7^{+3.4}_{-3.4}$	$3.56 \pm 0.11 \pm 0.09^{+0.54}_{-0.37}$
	UKQCD	full range	621.7 ± 35.0	1.834 ± 0.103	$16.5^{+3.5}_{-2.3}$	$3.68 \pm 0.10 \pm 0.10^{+0.29}_{-0.34}$
	ISGW2				$14.1\pm??$	$3.98 \pm 0.11 \pm 0.10^{+?.??}_{-?.??}$
ρ^+	LCSR3	< 16	268.8 ± 25.0	2.574 ± 0.239	$13.7^{+3.4}_{-3.4}$	$3.51 \pm 0.16 \pm 0.13^{+0.53}_{-0.36}$
	UKQCD	full range	343.3 ± 28.3	3.222 ± 0.266	$16.5^{+3.5}_{-2.3}$	$3.59 \pm 0.15 \pm 0.13^{+0.28}_{-0.33}$
	ISGW2				$14.1\pm??$	$3.87 \pm 0.16 \pm 0.15^{+?.??}_{-?.??}$
ω	LCSR3	< 12	61.3 ± 11.4	0.611 ± 0.113	$7.88^{+1.86}_{-1.86}$	$3.08 \pm 0.29 \pm 0.11^{+0.44}_{-0.31}$
	ISGW2	full range	96.7 ± 14.5	1.069 ± 0.160	$14.1\pm??$	$3.03 \pm 0.23 \pm 0.11^{+?.??}_{-?.??}$

LCSR1 PRD 83 (2011) 094031 HPQCD PRD 73 (2006) 074502 LCSR2 PRD 71 (2005) 014015 FNAL PRD 79 (2009) 054507
LCSR3 PRD 71 (2005) 014029 UKQCD PLB 416 (1998) 392 ISGW2 PRD 52 (1995) 2783

Note nice agreement between $\bar{B} \to \pi\ell^-\bar{\nu}_\ell$ and $\bar{B} \to \rho\ell^-\bar{\nu}_\ell$ modes with LCSR(2,3) prediction.