Latest results on semileptonic and electroweak penguin decays at Belle II

56th Rencontres de Moriond 2022

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on behalf of the Belle II collaboration

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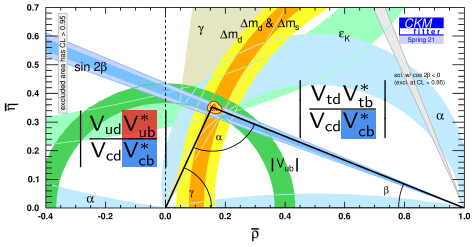
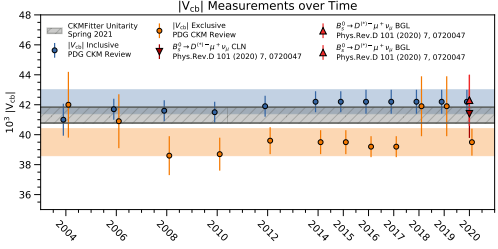
Semileptonic B Decays at Belle II

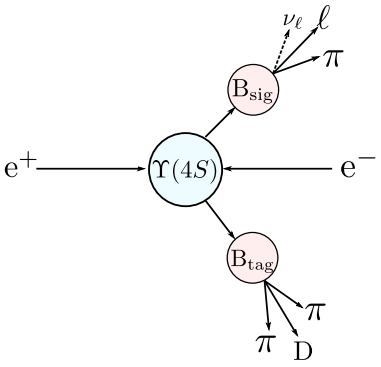


Precision CKM tests

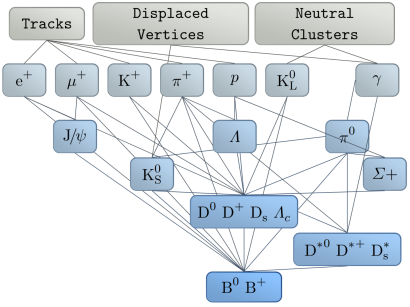


tension between excl. and incl. V_{xb}

Tag-Side Reconstruction using the Full Event Interpretation



- flavor constraint: $B^+_{tag} \to B^-_{sig}$
- kinematic constraint:
  $p_\nu = p_{e^+e^-} - p_{B_{tag}} - p_{X_c} - p_\ell$



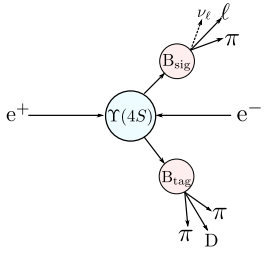
(Comp. Softw. Big Sci. (2019) 3: 6)

- MVA based tagging algorithm reconstruction B decays using a hierarchical approach
- reconstruction of $\mathcal{O}(10,000)$ distinct decay chains
- up to 30-50% improved efficiency at same purity compared to Belle Full Reconstruction

$B \to \pi e^+ \nu_e$

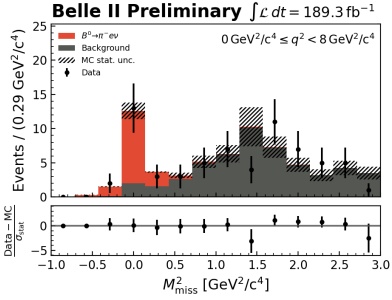
$|V_{ub}|$ from $B \to \pi e^+ \nu_e$

NEW



- reconstruct $B \to \pi e^+ \nu_e$ ($\pi = \pi^+/\pi^0$)
- main challenges: sample size, π^0 reconstruction
- likelihood fit of m^2_{miss} in three $q^2 = (p_e + p_{\nu_e})^2$ bins
- observed significance $3.8\sigma - 5.4\sigma$

$B^0 \to \pi^- e^+ \nu_e$



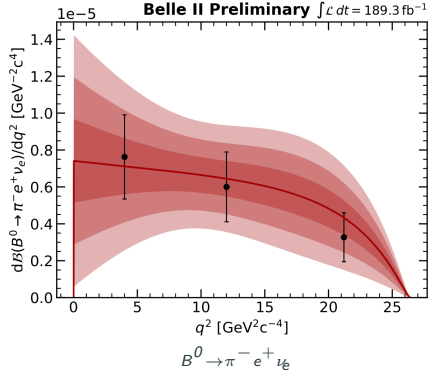
$$m^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{tag}} - p_\ell - p_\pi)^2$$

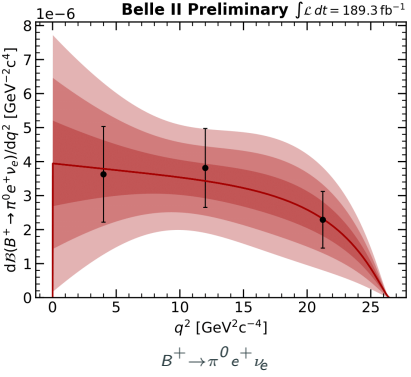
$$\mathcal{B}(B^0 \to \pi^- e^+ \nu_e) = (1.43 \pm 0.27\,(\text{stat.}) \pm 0.07\,(\text{sys.})) \times 10^{-4} \quad (\text{PDG: } (1.50 \pm 0.06) \times 10^{-4})$$

$$\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e) = (8.33 \pm 1.67\,(\text{stat.}) \pm 0.55\,(\text{sys.})) \times 10^{-5} \quad (\text{PDG: } (7.80 \pm 0.27) \times 10^{-5})$$

$|V_{ub}|$ from B $\to \pi e^+ \nu_e$

NEW





- unfolded q^2 spectrum translated into differential branching fraction $d\mathcal{B}/dq^2$
- χ^2 fit of $d\mathcal{B}/dq^2 \propto |V_{ub}|^2 f_+^2(q^2)$ using BCL form factor parameterization and lattice QCD constraints (Fermilab/MILC) (arXiv:1503.07839)
- combined fit $\to |V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$ (PDG: $(3.67 \pm 0.15) \times 10^{-3}$)

$B^0 \to D^{*-} \ell^+ \nu_\ell$

$|V_{cb}|$ from $B^0 \to D^{*-}\ell^+\nu_\ell$

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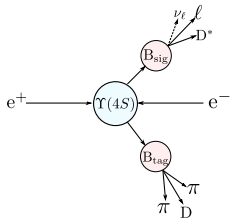
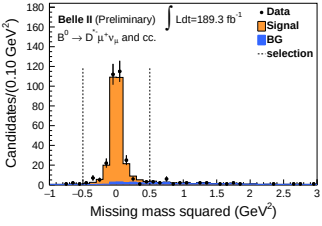
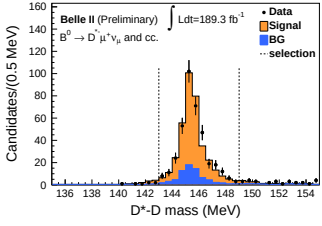
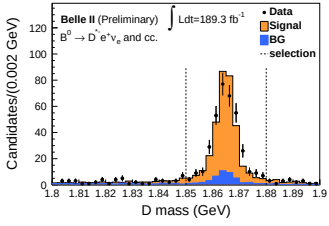


- reconstruct decay chain $B^0 \to D^{*-}(\to \bar{D}^0(\to K^+\pi^-)\pi^-)\ell^+$
- event selection based on:
  - m_D
  - $\Delta m = m_{D^*} - m_D$
  - $m^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{tag}} - p_\ell - p_{D^*})^2$
- main challenges: low momentum π efficiency







$\to \mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (5.27 \pm 0.22\,(\text{stat.}) \pm 0.38\,(\text{sys.}))\ \%$ (PDG: (5.66±0.22)%)

$|V_{cb}|$ from $B^0 \to D^{*-}\ell^+\nu_\ell$

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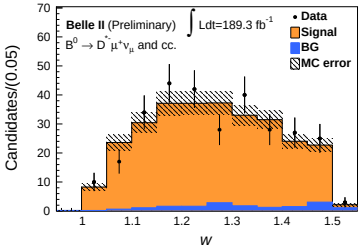
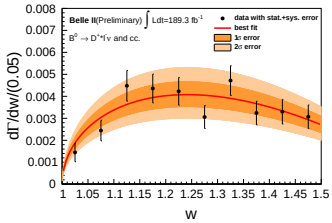
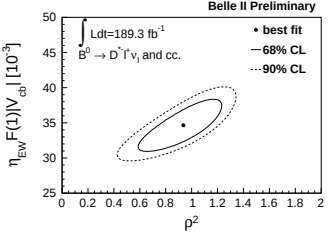


$w = (m_B^2 + m_{D^*}^2 - q^2)/(2 m_B m_{D^*})$



- fit $\frac{d\Gamma}{dw} \propto \mathcal{F}^2(w)|V_{cb}|^2\eta_{EW}^2$ using CLN form factor parameterization, $R_1(1)$ & $R_2(1)$ constrained to HFLAV averages (Nucl. Phys. B530, 153 (1998))
  - $\eta_{EW}F(1)|V_{cb}| = (35.3 \pm 0.4\times)10^{-3}$
  - $\rho^2 = 0.94 \pm 0.21$



$\rightarrow |V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$ (PDG: $(39.5 \pm 0.9) \times 10^{-3}$)

$B \to X_c \ell \nu_\ell$

q^2 Moments from B $\to X_c \ell \nu_\ell$

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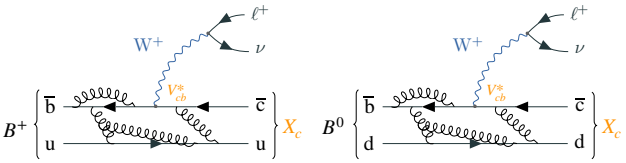
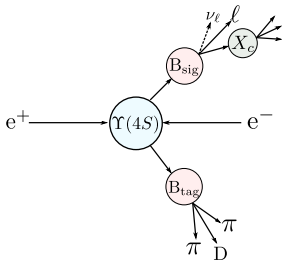
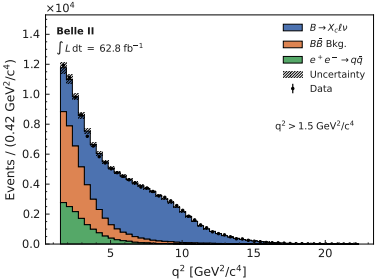




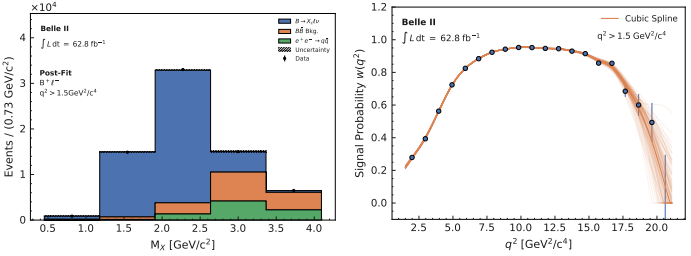
- HQE: Γ, $\langle M_X^n \rangle$, $\langle E_\ell^{*n} \rangle$, ...
- global fit: $|V_{cb}|$ and HQE parameters at $\mathcal{O}(1/m_b^3)$ (model-independent)
- reparameterization invariance: 13 $\to$ 8 HQE parameters for Γ at $\mathcal{O}(1/m_b^4)$ (arxiv:1812.07472)
- parameter reduction also valid for q^2 moments



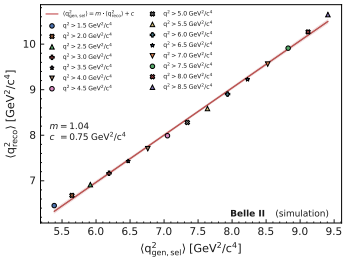
$$q^2 = (p_\ell + p_{\nu_\ell})^2$$

q^2 Moments from B $\to X_c \ell \nu_\ell$

Bkg. Subtraction



q^2 Calibration



$$\langle q^{2n} \rangle = \frac{\sum_i w_i(q^2) q^{2n}_{\text{calib},i}}{\sum_i w_i(q^2)} \times \mathcal{C}_{\text{calib}} \times \mathcal{C}_{\text{gen}}$$

- likelihood fits to M_X distributions to determine background normalization
- bkg. subtraction via event-wise weights
- event-wise calibration removing resolution & selection effects
- main challenges: background modeling at low q^2, impact of $B \to X_c \ell \nu_\ell$ modeling on calibration

q^2 Moments from B $\to X_c \ell \nu_\ell$

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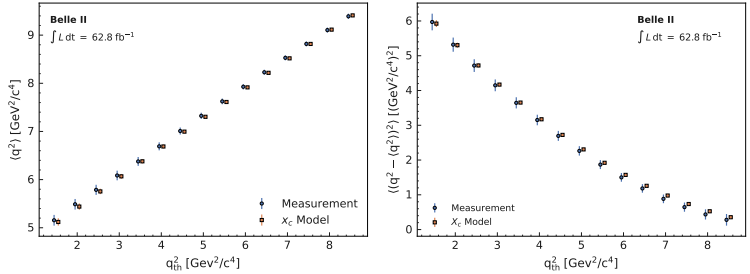

- q^2 moments as functions of lower q^2 thresholds
- first measurements for lower q^2 thresholds in the region $1.5 - 2.5\,\mathrm{GeV}^2$ (covering up to 77% of available phase space)
- to be submitted to PRD soon, expect new inclusive $\left|V_{cb}\right|$ fit in the near future

$B \to K^{*}\ell\ell$

Branching Fraction of B $\to$ K*$\ell^+\ell^-$

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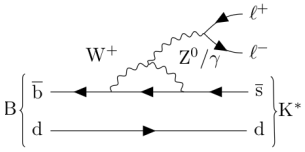


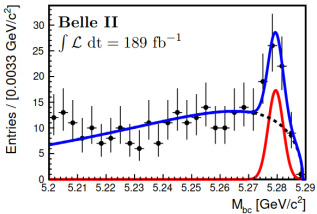
- reconstruct $B \to K^*(\to K^+\pi^-, K^+\pi^0, K^0_S\pi^+)\ell^+\ell^-$
- 2D likelihood fit to $M_{\rm bc} = (s/4 - p^{*2}_{\rm B})^{1/2}$ and $\Delta E = E^*_{\rm B} - \sqrt{s}/2$
- BF measurement over entire q^2 range excluding J/ψ & $\psi(2S)$ resonances
- observed signal significance $3.6\sigma - 5.9\sigma$

$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.28 \pm 0.29^{+0.08}_{-0.07}) \times 10^{-6}$ (PDG: $(1.06\pm0.09)\times10^{-6}$)

$\mathcal{B}(B \to K^*e^+e^-) = (1.04 \pm 0.48^{+0.09}_{-0.09}) \times 10^{-6}$ (PDG: $(1.19\pm0.20)\times10^{-6}$)

$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.22 \pm 0.28^{+0.08}_{-0.07}) \times 10^{-6}$ (PDG: $(1.06\pm0.10)\times10^{-6}$)

$\to$ independent check of $R(K^{(*)})$ anomalies with a few 1 ab^{-1}



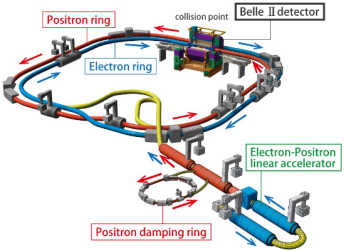
$B \to K^*\ell^+\ell^-$

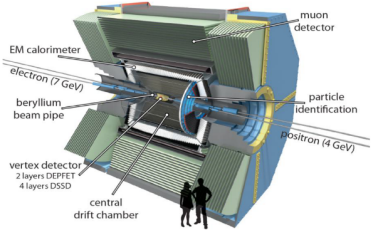
Summary

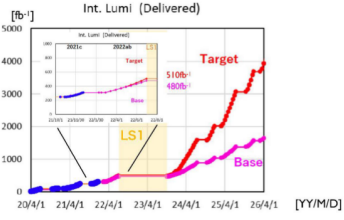
- precision measurements of $|V_{cb}|$ and $|V_{ub}|$ import aspect of semileptonic physics program at Belle II
- LFU vioaltion in $b \to s\ell\ell$ transistions one focus of the EW penguin program
- first results (all new for Moriond):
  - $|V_{ub}|$ from $B \to \pi e^+ \nu_e$
  - $|V_{cb}|$ from $B^0 \to D^{*-} \ell^+ \nu_\ell$
  - q^2 moments of $B \to X_c \ell \nu_\ell$
  - BF measurements for $B \to K^* \ell^+ \ell^-$

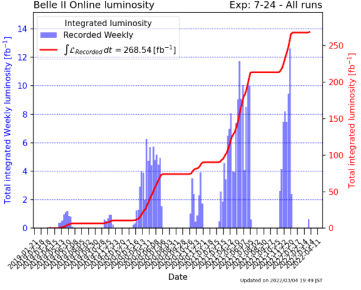
BACKUP

SuperKEKB and Belle II Detector









$B \to \pi e^+ \nu_e$ Branching Fractions

q^2 bin	Signal efficiency	Unfolded signal yield	$\Delta\mathcal{B}$
	$B^0 \to \pi^- e^+ \nu_e$		
0 GeV$^2 \leq q^2 <$ 8 GeV^2	$(0.189 \pm 0.002)\%$	15.5 ± 4.6	$(0.61 \pm 0.18(\text{stat}) \pm 0.03(\text{syst})) \times 10^{-4}$
8 GeV$^2 \leq q^2 <$ 16 GeV^2	$(0.239 \pm 0.003)\%$	15.3 ± 4.8	$(0.48 \pm 0.15(\text{stat}) \pm 0.02(\text{syst})) \times 10^{-4}$
16 GeV$^2 \leq q^2 \leq$ 26.4 GeV^2	$(0.229 \pm 0.003)\%$	10.3 ± 4.2	$(0.34 \pm 0.14(\text{stat}) \pm 0.02(\text{syst})) \times 10^{-4}$
Sum	–	41.1 ± 7.8	$(1.43 \pm 0.27(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4}$
Fit over full q^2 range	$(0.217 \pm 0.002)\%$	42.0 ± 7.9	$(1.45 \pm 0.27(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-4}$
World average	–	–	$(1.50 \pm 0.06) \times 10^{-4}$

q^2 bin	Signal efficiency	Unfolded signal yield	$\Delta\mathcal{B}$
	$B^+ \to \pi^0 e^+ \nu_e$		
0 GeV$^2 \leq q^2 <$ 8 GeV^2	$(0.329 \pm 0.004)\%$	12.9 ± 4.7	$(2.90 \pm 1.12(\text{stat}) \pm 0.19(\text{syst})) \times 10^{-5}$
8 GeV$^2 \leq q^2 <$ 16 GeV^2	$(0.439 \pm 0.005)\%$	18.1 ± 5.1	$(3.05 \pm 0.91(\text{stat}) \pm 0.20(\text{syst})) \times 10^{-5}$
16 GeV$^2 \leq q^2 \leq$ 26.4 GeV^2	$(0.451 \pm 0.006)\%$	14.5 ± 4.9	$(2.38 \pm 0.85(\text{stat}) \pm 0.16(\text{syst})) \times 10^{-5}$
Sum	–	45.5 ± 8.5	$(8.33 \pm 1.67(\text{stat}) \pm 0.55(\text{syst})) \times 10^{-5}$
Fit over full q^2 range	$(0.402 \pm 0.003)\%$	43.9 ± 8.3	$(8.06 \pm 1.62(\text{stat}) \pm 0.53(\text{syst})) \times 10^{-5}$
World average	–	–	$(7.80 \pm 0.27) \times 10^{-5}$

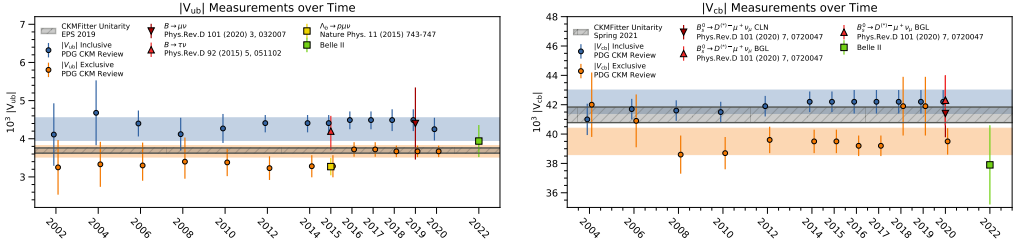
$B \to \pi e^+ \nu_e$ Systematic Uncertainties

Source	% of $\mathcal{B}(B^0 \to \pi^- e^+ \nu_e)$			% of $\mathcal{B}(B^+ \to \pi^0 e^+ \nu_e)$		
q^2 bin index	1	2	3	1	2	3
$N_{B\bar{B}}$				2.9		
f_{+0}				1.2		
FEI calibration		3.2			3.1	
Tracking		0.6			0.3	
π^0 efficiency		–			4.8	
Signal efficiency ϵ	1.3	1.2	1.4	1.3	1.2	1.3
Electron ID	1.0	0.4	0.4	1.0	0.5	0.5
Pion ID	0.4	0.4	0.4		–	
Total	4.8	4.7	4.8	6.7	6.7	6.7

$B^0 \to D^{*-}\ell^+\nu_\ell$ Systematic Uncertainties

Systematic sources	Relative uncertainty (%)
FEI efficiency	3.9
Low momentum π efficiency	4.1
Tracking efficiency	0.9
Lepton particle identification	2.0
Background	1.2
$N_{B\bar{B}}$	2.9
f_{+0}	1.2
$\mathcal{B}\left(D^{*-} \to \pi^- \bar{D}^0\right)$	0.7
$\mathcal{B}\left(\bar{D}^0 \to K^+\pi^-\right)$	0.8
ECL energy	1.0
Form factor	0.1
MC statistics	1.8
Total	7.3

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



(Credit: Markus Prim)

- measured $|V_{xb}|$ values compatible with WA
- precision limited data sample size
- future improvements with untagged analyses of SL decays ($\epsilon_{\text{tagged}} < 1\%$ vs. $\epsilon_{\text{untagged}} \approx (20 - 30)\%$)

q^2 Moments from B $\to X_c \ell \nu_\ell$

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell\,\nu_\ell$	$(6.6 \pm 1.1) \times 10^{-3}$	$(6.2 \pm 1.0) \times 10^{-3}$
$B \to D_2^*\,\ell\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to D\eta\,\ell\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to D^*\eta\,\ell\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to X_c\ell\nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

q^2 Moments from B $\to X_c \ell \nu_\ell$

	q^2_{cut} [Gev$^2/c^4$]	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
	$\langle q^2 \rangle$ [Gev$^2/c^4$]	5.16	5.49	5.79	6.09	6.38	6.69	7.01	7.32	7.62	7.93	8.23	8.53	8.82	9.10	9.39
Calibration (MC Statistics)	Calib. Curve (Stat. Unc.)	0.63	0.56	0.49	0.43	0.38	0.33	0.29	0.26	0.25	0.26	0.28	0.30	0.33	0.37	0.40
	Bias Corr. (Stat. Unc.)	0.10	0.09	0.09	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06
Calibration (X_c Model)	$\mathcal{B}(B \to D\ell\nu)$	0.10	0.09	0.08	0.07	0.06	0.05	0.04	0.04	0.03	0.02	0.02	0.01	0.01	0.00	0.00
	$\mathcal{B}(B \to D^*\ell\nu)$	0.33	0.29	0.24	0.21	0.17	0.14	0.11	0.09	0.07	0.05	0.04	0.03	0.02	0.01	0.00
	$\mathcal{B}(B \to D^{**}\ell\nu)$	0.71	0.63	0.55	0.48	0.40	0.34	0.28	0.23	0.18	0.13	0.10	0.07	0.05	0.03	0.02
	Non-Res. X_c Dropped	0.31	0.63	0.75	0.76	0.69	0.60	0.48	0.39	0.32	0.25	0.18	0.14	0.11	0.08	0.06
	Non-Res. X_c Repl. w/ D_1', D_0^*	0.34	0.49	0.51	0.45	0.37	0.29	0.18	0.10	0.04	0.02	0.00	0.03	0.03	0.03	0.01
	$B \to D\ell\nu$ Form Factor	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	$B \to D^*\ell\nu$ Form Factor	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.03
Calibration (Reconstruction)	PID Uncertainty	0.14	0.12	0.11	0.09	0.08	0.07	0.05	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01
	N_γ Reweighted	0.30	0.27	0.24	0.22	0.20	0.18	0.16	0.14	0.14	0.13	0.13	0.12	0.11	0.10	0.10
	N_{tracks} Reweighted	1.09	1.00	0.92	0.85	0.78	0.72	0.65	0.60	0.55	0.51	0.47	0.44	0.41	0.38	0.35
	$E_{\text{miss}} - p_{\text{miss}}$ Reweighted	0.26	0.22	0.21	0.19	0.18	0.17	0.15	0.15	0.14	0.14	0.13	0.12	0.12	0.11	0.09
	Tracking Efficiency	0.13	0.12	0.11	0.10	0.09	0.09	0.08	0.07	0.06	0.06	0.05	0.05	0.05	0.04	0.04
Background Subtraction	Spline Smooth. Factor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bkg. Yield & Shape	1.39	1.15	0.90	0.77	0.63	0.47	0.33	0.23	0.16	0.10	0.06	0.03	0.02	0.05	0.06
Other	Non-Closure Bias	0.18	0.21	0.16	0.11	0.06	0.05	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.02
	Stat. Uncertainty	0.27	0.24	0.21	0.20	0.18	0.16	0.16	0.15	0.14	0.14	0.13	0.13	0.13	0.13	0.13
	Syst. Uncertainty	2.14	1.99	1.80	1.64	1.44	1.23	1.02	0.88	0.77	0.69	0.62	0.59	0.57	0.56	0.57
	Total Uncertainty	2.16	2.00	1.81	1.65	1.45	1.24	1.03	0.89	0.78	0.70	0.64	0.61	0.59	0.58	0.58

$B \to K^* \ell^+ \ell^-$ Systematic Uncertainties

Source	Systematic (%)
signal shape	~ 1.0
μ identification	$^{+1.9}_{-0.8}$
e identification	$^{+0.9}_{-0.5}$
K^+ identification	0.4
π^+ identification	2.5
K^0_S identification	2.0
π^0 identification	3.4
FastBDT	$1.3 - 1.7$
limited MC statistics	< 0.5
signal cross feed	$\sim 1\%$
tracking	$1.2 - 1.5$
$f^{+-(00)}$	1.2
number of $B\bar{B}$ pairs	2.9
Total	$^{+6.7}_{-6.0}$

Expected $R(\mathrm{D}^{(*)})$ Precision