Belle II results related to $b \to c$ anomalies

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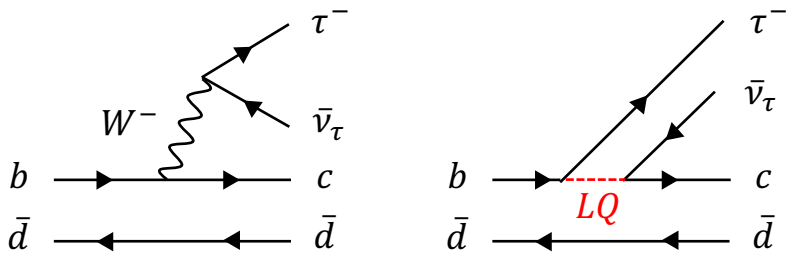
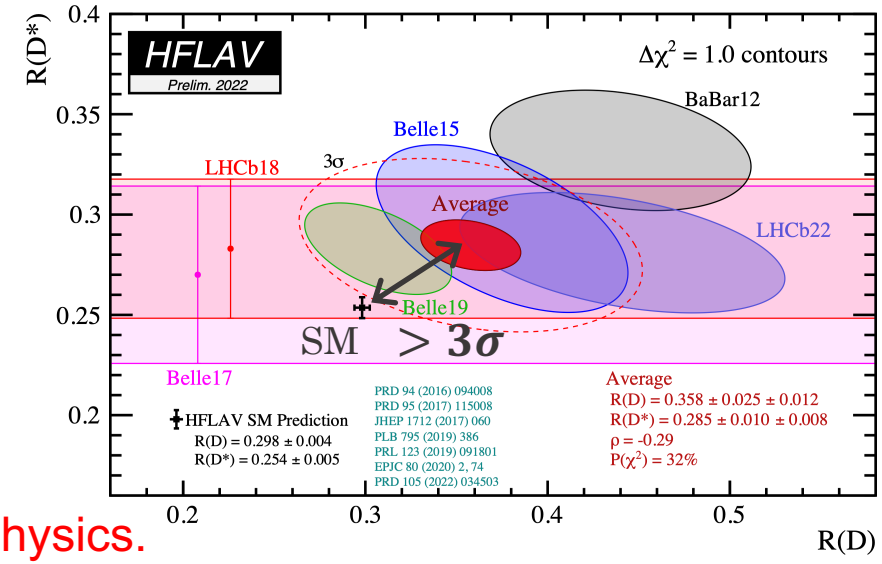
Anomalies in $b \to c$ Decays

The Standard Model (SM) postulates the universality of the lepton coupling, g_ℓ ($\ell = e, \mu, \tau$), to the electroweak gauge bosons.

1. $R(D^{(*)}) = \dfrac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$, $(\ell = e \text{ or } \mu)$

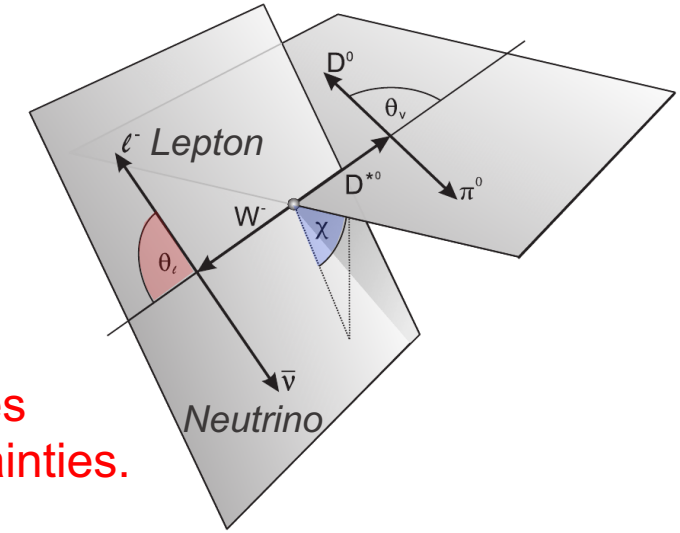




The tension with the SM could be a sign of New Physics.

2. Angular asymmetries: $\Delta\mathcal{A}_x = \mathcal{A}_x^e - \mathcal{A}_x^\mu$

$$\mathcal{A}_x = \left[\int_0^1 - \int_{-1}^0\right] dx \frac{d\Gamma}{dx} \qquad \begin{cases} A_{\mathrm{FB}} : dx = d(\cos\theta_\ell) \\ S_3 : dx = d(\cos 2\chi) \\ \vdots \end{cases}$$



$\Delta\mathcal{A}_x$ provide theoretically and experimentally clean probes of light-lepton universality by large cancellation of uncertainties.

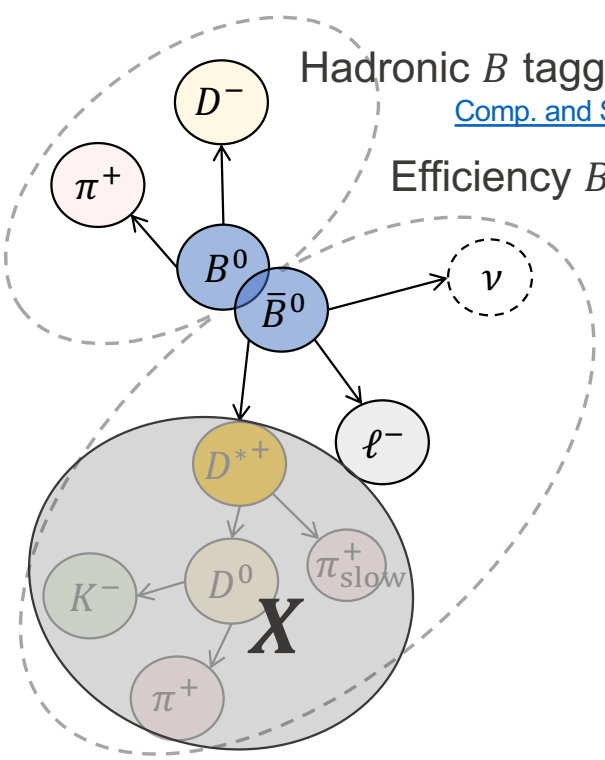
Data Sets & Reconstruction

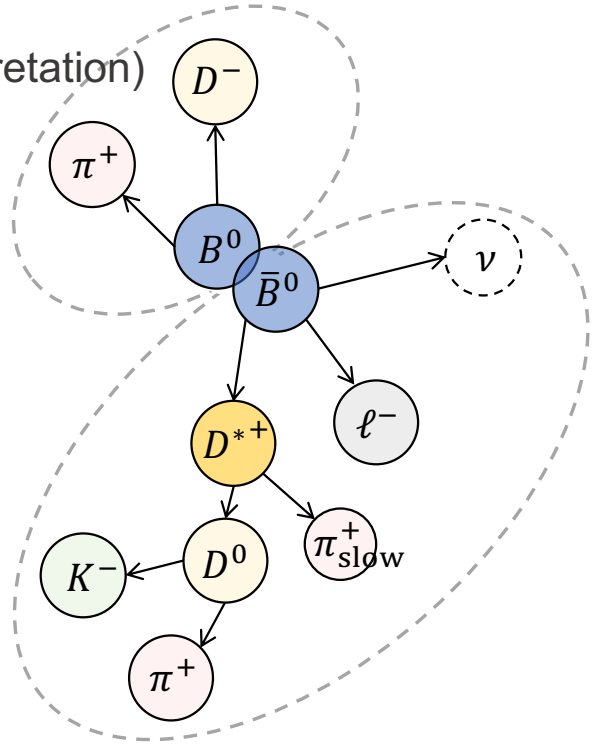
We analyzed $189\ \mathrm{fb}^{-1}$ data collected at Belle II by the summer of 2021.

One B meson from $\Upsilon(4S)$ decay is fully reconstructed with hadronic decays to tag $B\bar{B}$ events.
The signal semi-leptonic B decays are reconstructed via inclusive or exclusive modes.

Hadronic B tagging (Full Event Interpretation)
Comp. and Soft. For Big Sci. **3**, 6 (2019)

Efficiency B^0: 0.27%, B^+: 0.35%
arXiv:2008.06096





1. Inclusive signal B modes

Reconstruct other than a lepton inclusively as X.

2. Exclusive signal B modes

Reconstruct all B daughters through specific channels.

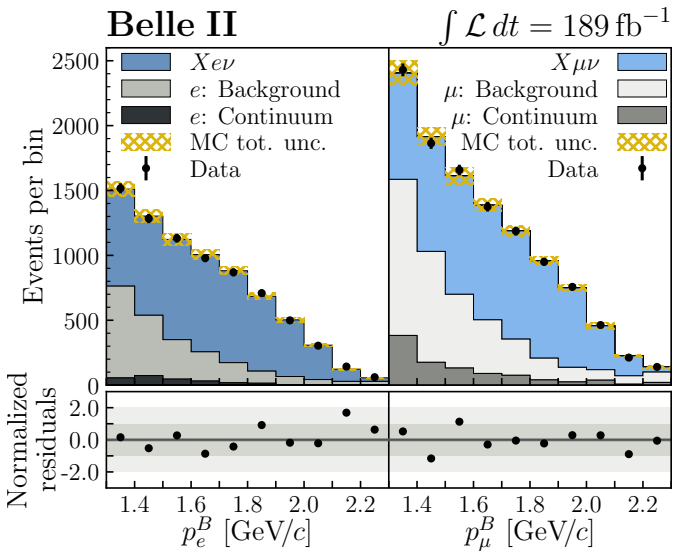
Light-Lepton Universality Test: $R(X_{e/\mu})$ Measurement

We tested light-lepton universality by $R(X_{e/\mu}) = \dfrac{\mathcal{B}(\bar{B} \to X e^- \bar{\nu}_e)}{\mathcal{B}(\bar{B} \to X \mu^- \bar{\nu}_\mu)}$ of

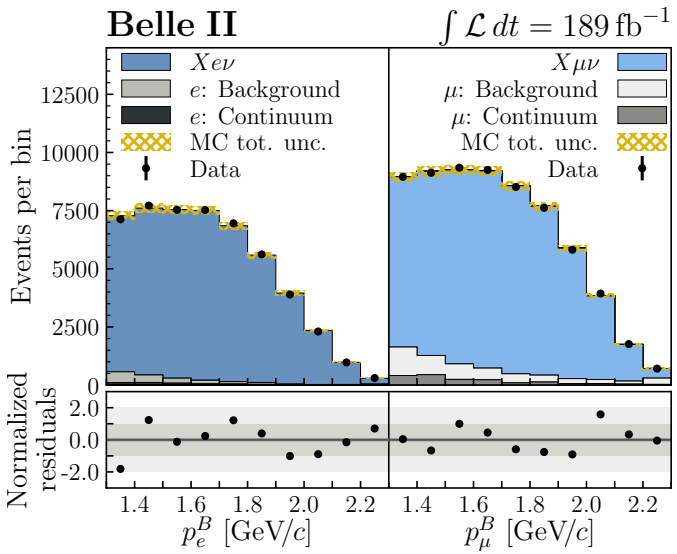
arXiv:2301.08266

the inclusive signal B modes through a fit on the lepton momentum in the $B_{\rm sig}$ rest frame, p_ℓ^B.

Control channel (B^0B^0/ B^+B^+)



Signal channel ($B^0\bar{B}^0$/B^+B^-)



$$R(X_{e/\mu}) = 1.033 \pm 0.010\,(\mathrm{stat}) \pm 0.019\,(\mathrm{syst})$$

First branching-fraction based e-μ universality test using inclusive semi-leptonic B decays
The most precise test of e-μ universality of semi-leptonic B decays

Consistent with SM $R(X_{e/\mu})_{\rm SM}$[1] by 1.2σ and the exclusive Belle $R(D^*{}_{e/\mu})$[2],[3].

[1] J. High Energy Phys. **11**, 007 (2022), [2] Phys. Rev. D **100**, 052007 (2019), [3] arXiv:2301.07529

Light-Lepton Universality Test: Angular Asymmetry

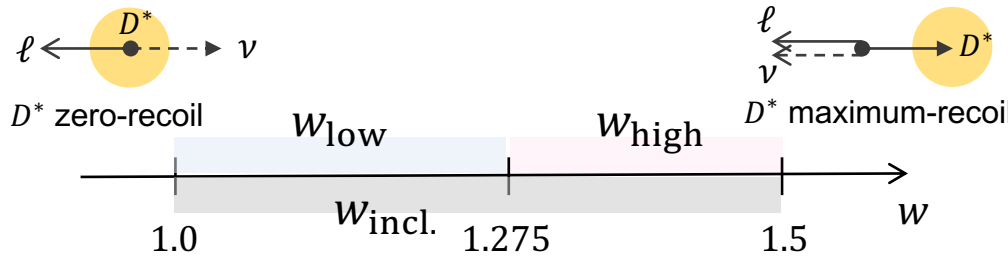
New for Moriond

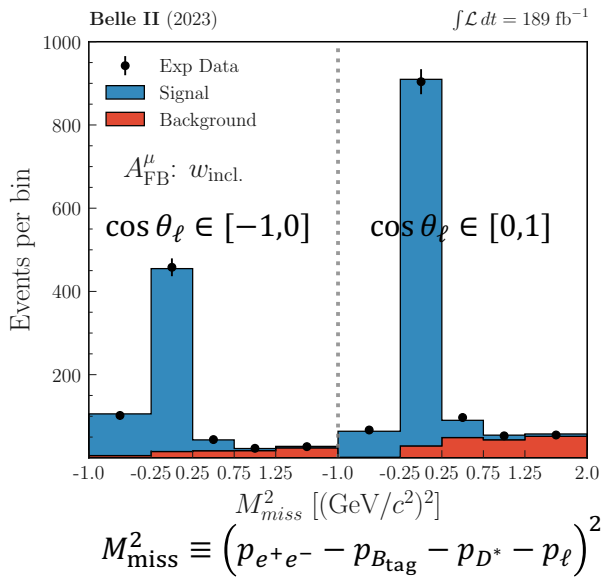
We tested lepton universality by comparing five angular asymmetries of e and μ, $\Delta\mathcal{A}_x(w) = \mathcal{A}_x^{\mu}(w) - \mathcal{A}_x^{e}(w)$, using exclusive $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays.

Angular observable

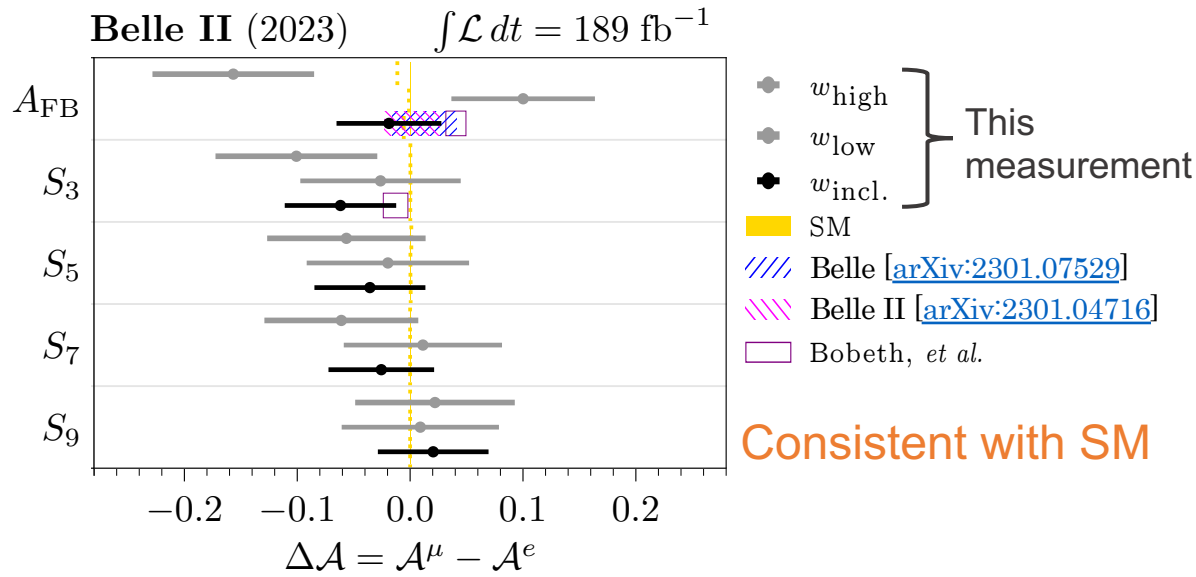
$$\mathcal{A}_x(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dx \frac{d^2\Gamma}{dwdx}$$

$$w \equiv \frac{m_B^2 + m_D^2 - (p_B - p_{D^*})^2}{2m_B m_{D^*}}$$: recoil parameter





$$M^2_{\mathrm{miss}} \equiv \left(p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_{D^*} - p_\ell\right)^2$$



Consistent with SM

First e-μ universality test of differential angular observables in w

No evidence of lepton universality violation with at least p-values of 0.12

Summary

The experimental results indicate deviations from the Standard Model by $> 3\sigma$.
New Physics could contribute to the lepton universality violations.

The Belle II experiment performed two light-lepton universality tests.

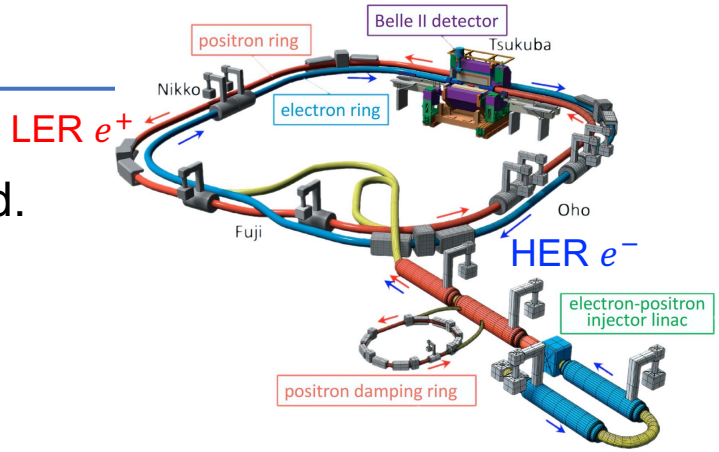
1. $R(X_{e/\mu}) = 1.033 \pm 0.010\ (\text{stat}) \pm 0.019\ (\text{syst})$
2. $\Delta A_{\text{FB}}(w)$, $\Delta S_3(w)$, $\Delta S_5(w)$, $\Delta S_7(w)$, $\Delta S_9(w)$

Both tests are world-leading/first results and are consistent with the SM expectation.

Appendix

SuperKEKB/Belle II Experiment

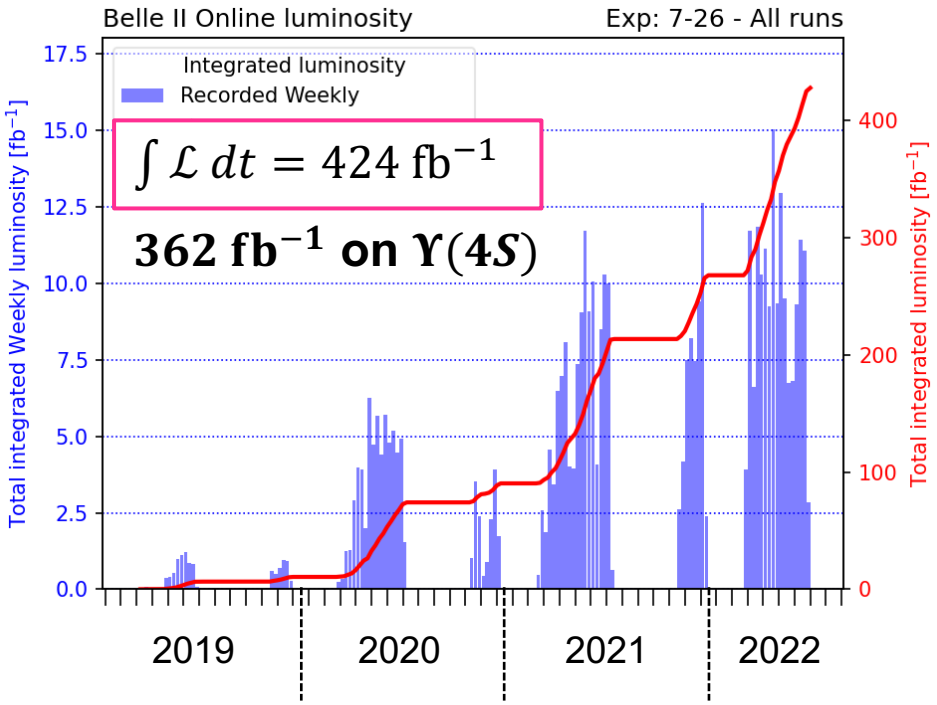
Electron-positron collider
at a center of mass energy of the $\Upsilon(4S)$ resonance or around.

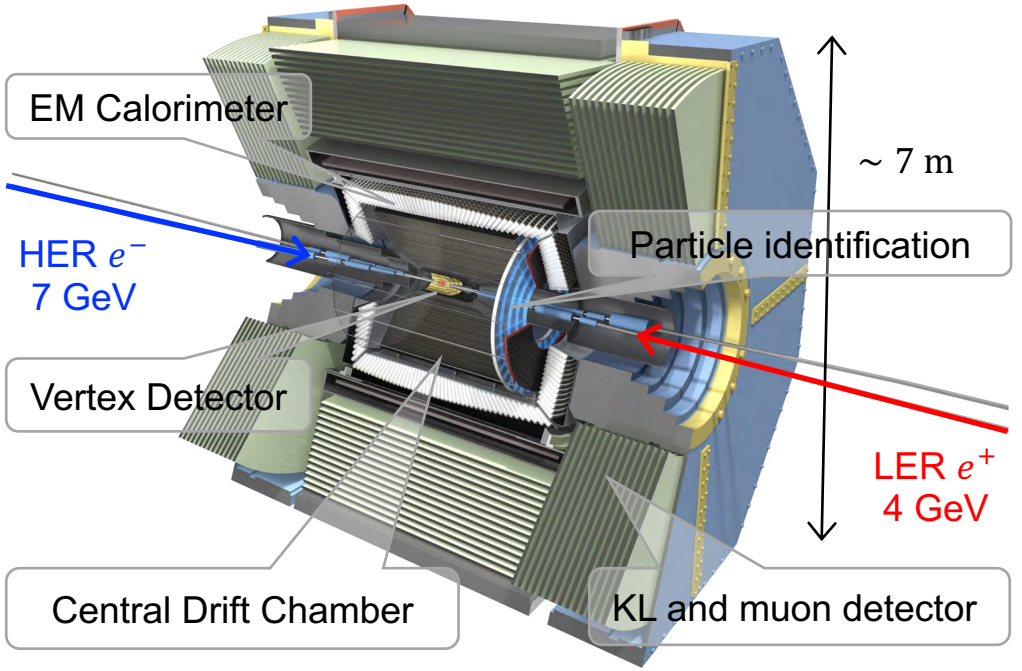


The world's highest instantaneous luminosity:

$$\mathbf{4.7 \times 10^{34}\ cm^{-2}s^{-1}}$$

(KEKB record: $2.1 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$)





Systematic Uncertainties on $R(X_{e/\mu})$

Table I: Statistical and systematic uncertainties on the value of $R(X_{e/\mu})$ from the most significant sources.

Source	Uncertainty [%]
Sample size	1.0
Lepton identification	1.9
$X_c\,\ell\,\nu$ branching fractions	0.1
$X_c\,\ell\,\nu$ form factors	0.2
Total	2.2

The modeling of charmed D meson decays by varying the branching ratio of each decay $D \to K^+$anything within its uncertainty while fixing the total event normalization.
The effect is negligible.

χ^2 Tests of Angular Asymmetries

In the full w region, $w_{incl.}$:

Angular observables	χ^2/N_{dof}	p-value
$\mathcal{A}$	$15.0/10$	0.13
$\Delta A_{\mathrm{FB}}(w)$, $\Delta S_3(w)$, $\Delta S_5(w)$	$2.1/3$	0.56
$\Delta S_7(w)$, $\Delta S_9(w)$	$0.6/2$	0.32

In the sub-w region, w_{high} & w_{low}:

Angular observables	χ^2/N_{dof}	p-value
$\mathcal{A}$	$27.7/20$	0.12
$\Delta A_{\mathrm{FB}}(w)$, $\Delta S_3(w)$, $\Delta S_5(w)$	$10.2/6$	0.12
$\Delta S_7(w)$, $\Delta S_9(w)$	$1.1/4$	0.89

Uncertainties on Angular Asymmetries

The systematic uncertainties are dominated by the sample size of MC statistics.

Obs.	w bin	Total	Stat.	MC stat.	LID	π_{slow}
A_{FB}^{e}	w_{low}	0.047	0.044	0.015	0.004	0.001
	w_{high}	0.052	0.049	0.017	0.004	0.001
	$w_{\text{incl.}}$	0.034	0.032	0.011	0.004	0.001
A_{FB}^{μ}	w_{low}	0.043	0.041	0.013	0.001	0.001
	w_{high}	0.050	0.047	0.016	0.002	0.001
	$w_{\text{incl.}}$	0.032	0.030	0.010	0.001	0.001
ΔA_{FB}	w_{low}	0.064	0.060	0.020	0.004	0.001
	w_{high}	0.072	0.067	0.024	0.004	0.001
	$w_{\text{incl.}}$	0.046	0.044	0.015	0.004	0.001
S_3^{e}	w_{low}	0.053	0.050	0.018	0.000	0.001
	w_{high}	0.051	0.048	0.018	0.000	0.000
	$w_{\text{incl.}}$	0.036	0.034	0.012	0.000	0.000
S_3^{μ}	w_{low}	0.048	0.045	0.016	0.001	0.000
	w_{high}	0.050	0.047	0.016	0.000	0.000
	$w_{\text{incl.}}$	0.034	0.032	0.011	0.001	0.000
ΔS_3	w_{low}	0.071	0.067	0.024	0.001	0.000
	w_{high}	0.072	0.067	0.025	0.001	0.000
	$w_{\text{incl.}}$	0.049	0.046	0.017	0.001	0.000
S_5^{e}	w_{low}	0.053	0.050	0.018	0.001	0.000
	w_{high}	0.051	0.048	0.017	0.001	0.000
	$w_{\text{incl.}}$	0.036	0.034	0.012	0.001	0.000
S_5^{μ}	w_{low}	0.048	0.045	0.016	0.001	0.000
	w_{high}	0.049	0.046	0.016	0.000	0.000
	$w_{\text{incl.}}$	0.034	0.032	0.011	0.000	0.000
ΔS_5	w_{low}	0.072	0.068	0.024	0.001	0.000
	w_{high}	0.070	0.066	0.023	0.001	0.000
	$w_{\text{incl.}}$	0.049	0.046	0.016	0.001	0.000
S_7^{e}	w_{low}	0.052	0.049	0.018	0.001	0.000
	w_{high}	0.049	0.046	0.017	0.000	0.000
	$w_{\text{incl.}}$	0.034	0.032	0.012	0.000	0.000
S_7^{μ}	w_{low}	0.047	0.044	0.015	0.000	0.000
	w_{high}	0.047	0.045	0.015	0.000	0.000
	$w_{\text{incl.}}$	0.032	0.031	0.011	0.000	0.000
ΔS_7	w_{low}	0.070	0.066	0.023	0.001	0.001
	w_{high}	0.068	0.064	0.022	0.000	0.000
	$w_{\text{incl.}}$	0.047	0.044	0.016	0.000	0.000
S_9^{e}	w_{low}	0.052	0.048	0.018	0.000	0.000
	w_{high}	0.051	0.048	0.018	0.000	0.000
	$w_{\text{incl.}}$	0.036	0.034	0.012	0.000	0.000
S_9^{μ}	w_{low}	0.047	0.044	0.016	0.000	0.000
	w_{high}	0.049	0.047	0.016	0.000	0.001
	$w_{\text{incl.}}$	0.033	0.032	0.011	0.000	0.000
ΔS_9	w_{low}	0.070	0.065	0.024	0.000	0.000
	w_{high}	0.071	0.067	0.024	0.001	0.001
	$w_{\text{incl.}}$	0.049	0.046	0.017	0.000	0.000