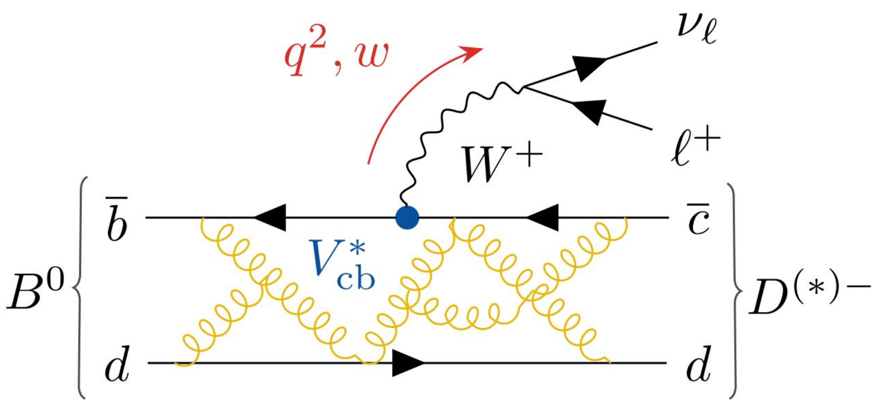
Measurements of LU in B→D(*)lν at B-Factories

LHCb workshop on exclusive semileptonic b→c decays

Michael Hedges



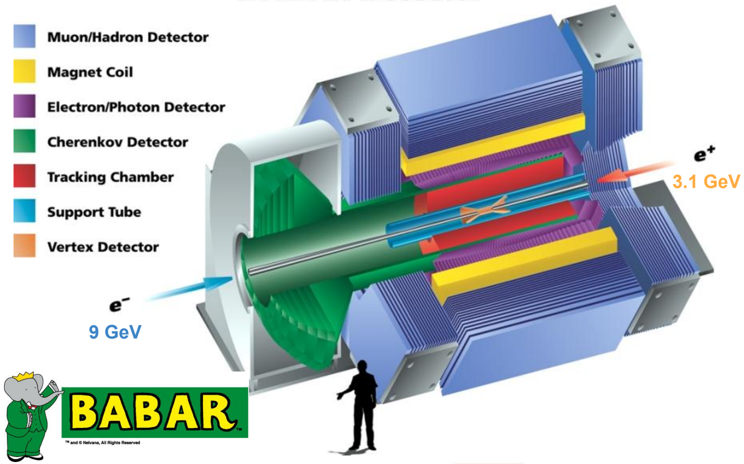
13 April 2023

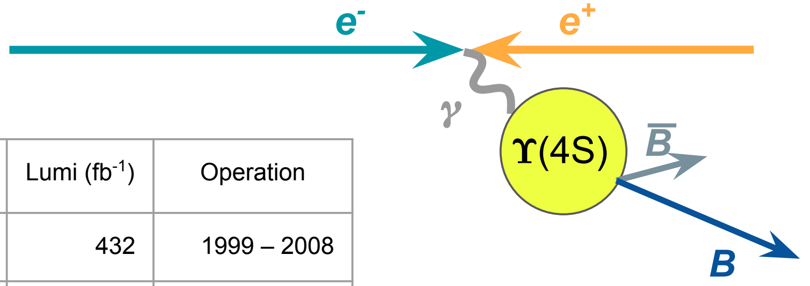
B-Factories

BABAR

BELLE

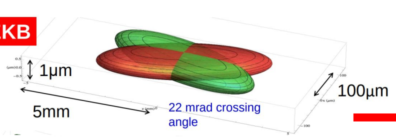
Belle II

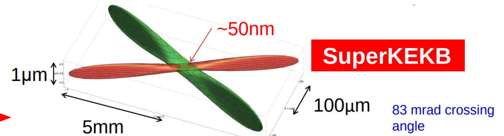


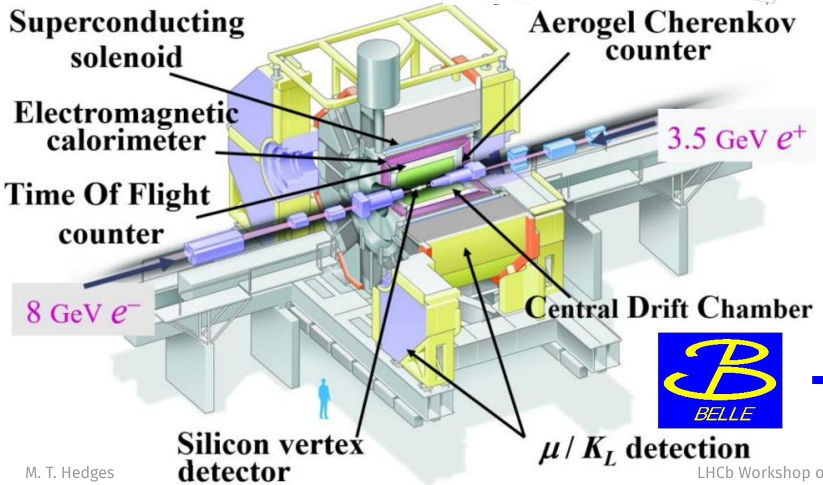


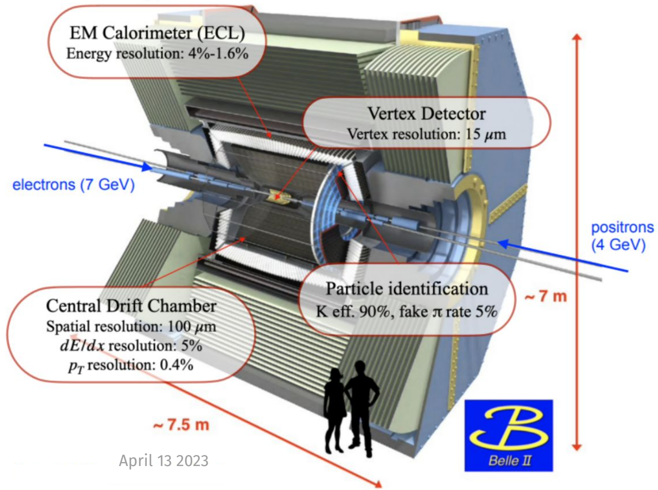
$\Upsilon(4S)$	Lumi (fb^{-1})	Operation
BaBar	432	1999 – 2008
Belle	711	1999 – 2010
Belle II	362	2018 – present

NB All experiments have additional data taken at other energies (not covered here)







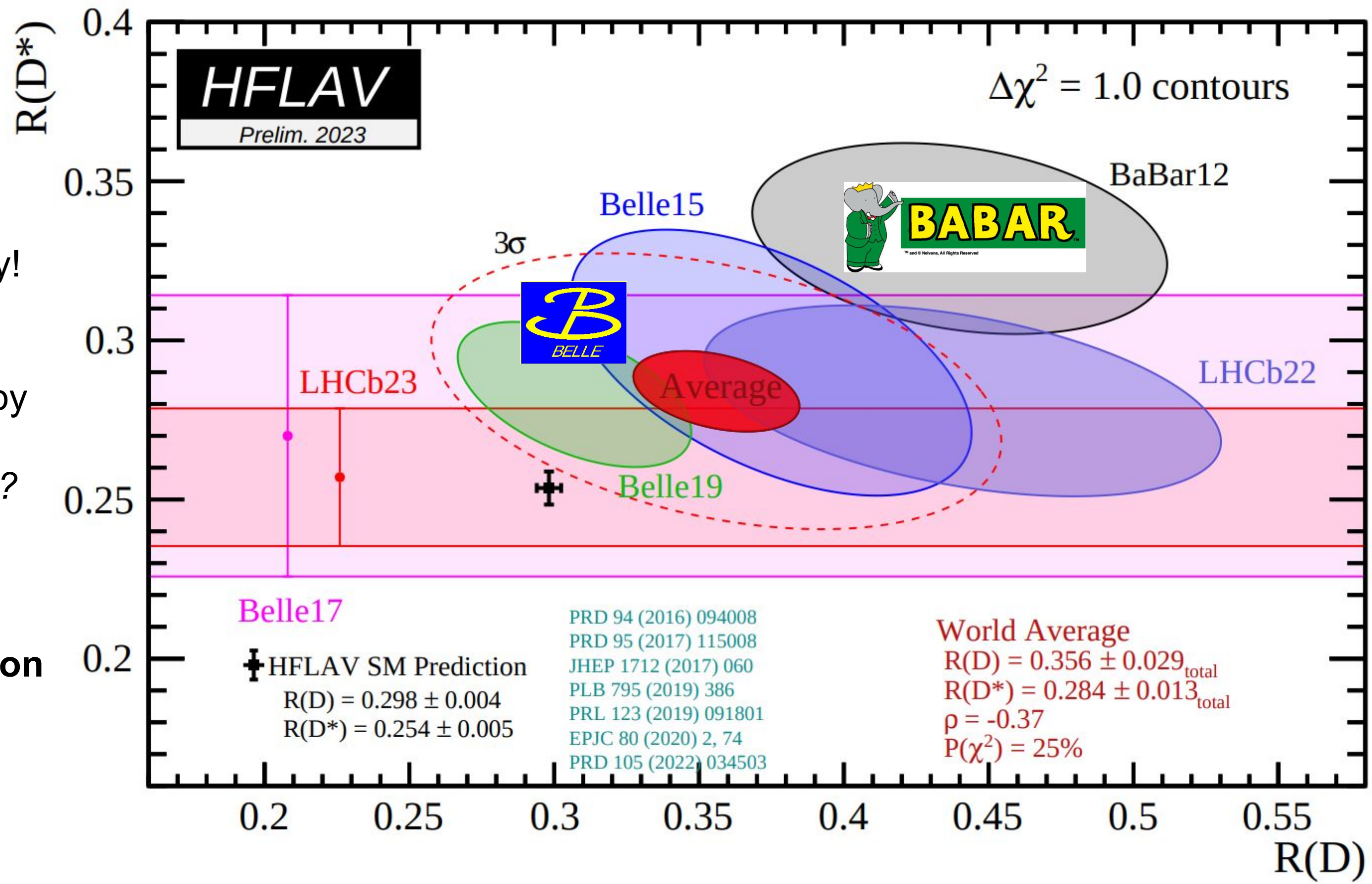


LU in B→D(*)lν

No news from B-factories today!

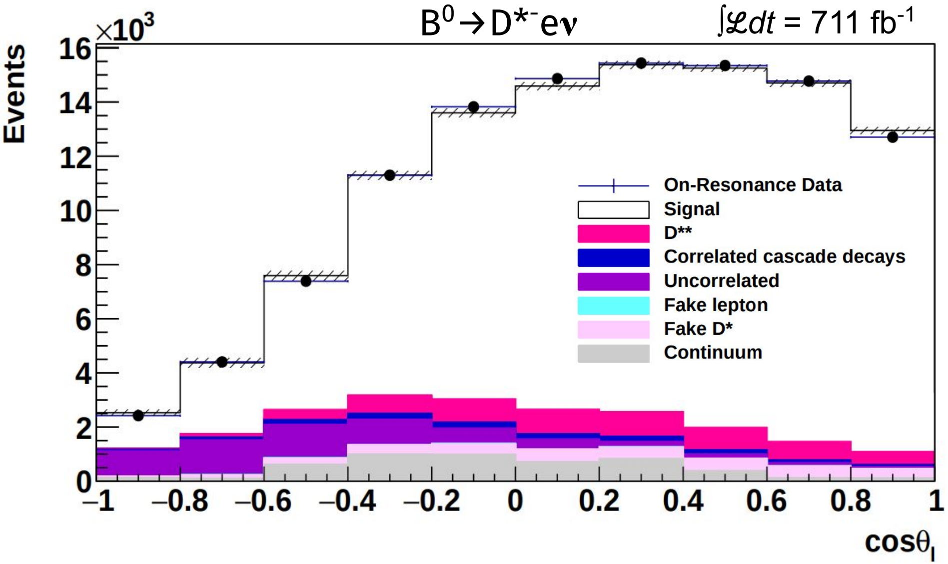
Original discrepancy reported by BaBar: ongoing 4D analysis of $|V_{cb}|$, *possible future update …?*

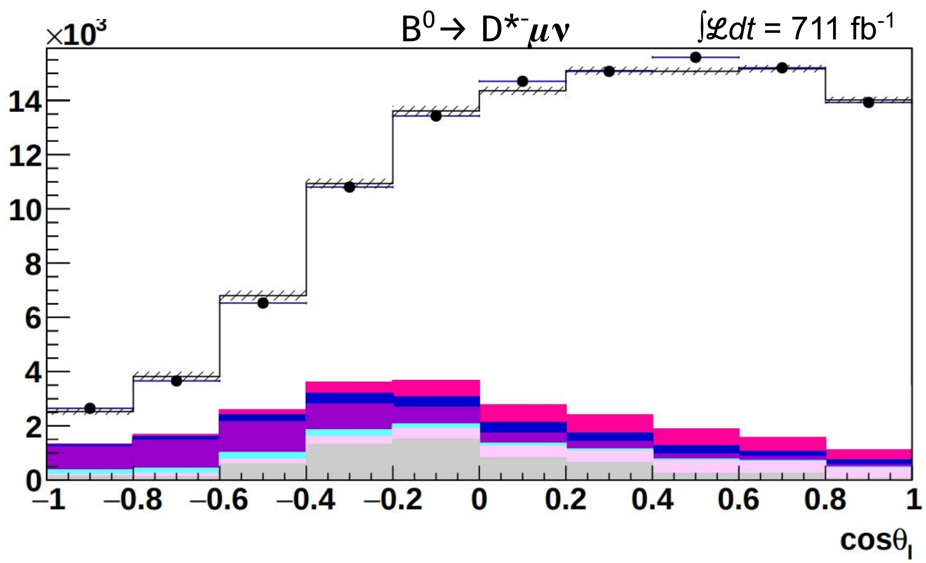
Several independent Belle II analyses ongoing, **updates soon**

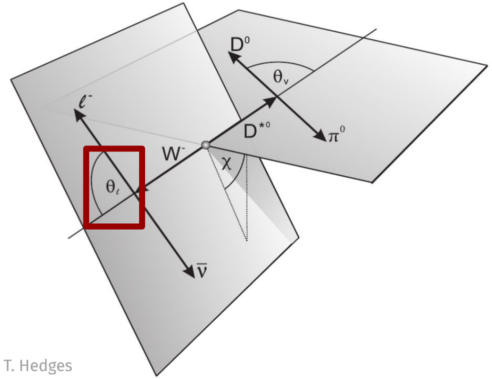


Belle untagged $|V_{cb}|$ and LU test

Belle 2018: First fully e/μ separated $|V_{cb}|$ measurement







$$\frac{\mathcal{B}(B^0 \to D^{*-} e^+ \nu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu)} = 1.01 \pm 0.01 \pm 0.03$$

Leading uncertainty comes from lepton ID

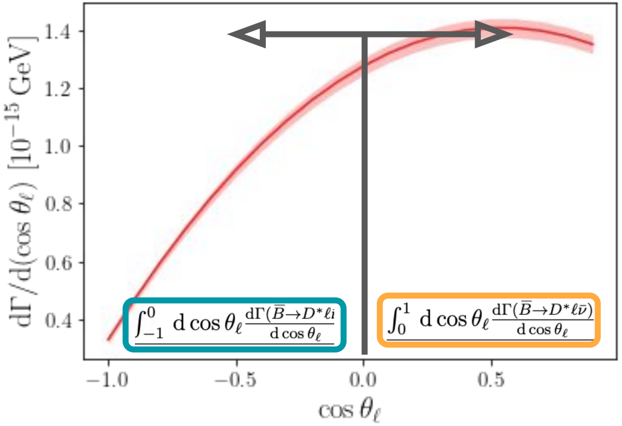
Most stringent test of LU in light-leptons at the time

[Phys. Rev. D 100, 052007 (2019)]

LU in Angular Observables

A new anomaly...? ([Eur. Phys. J. C 81, 984 (2021)])

Theorists report that Belle 2018 $|V_{cb}|$ shows **strong tension** in differences of A_{FB} between **electrons** and **muons**:

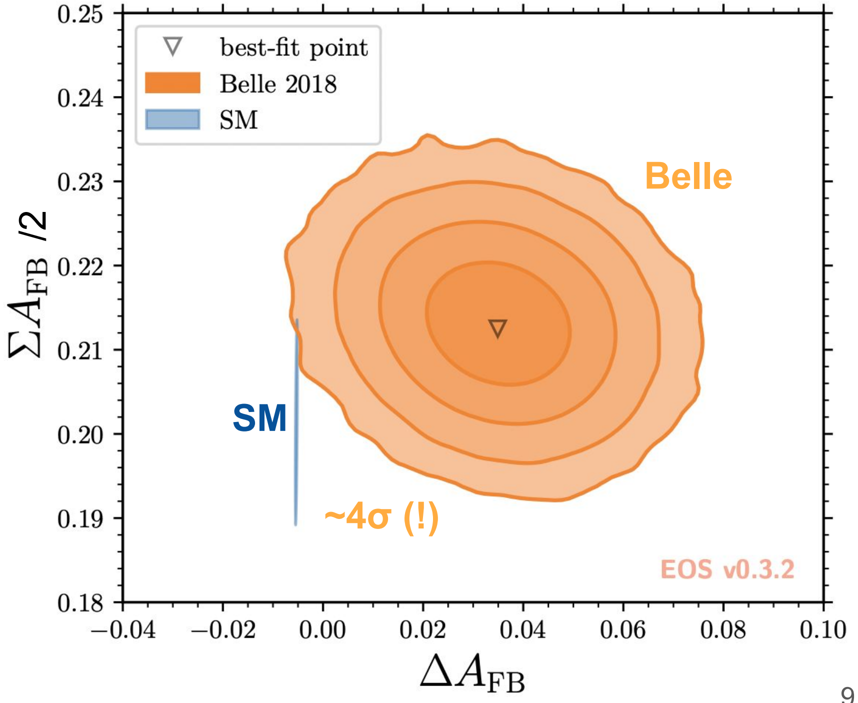


$$\Delta A_{FB} = A_{FB}(m_\ell = m_\mu) - A_{FB}(m_\ell = m_e)\,,$$
$$\sum A_{FB} = A_{FB}(m_\ell = m_\mu) + A_{FB}(m_\ell = m_e)$$

NP scenarios here cannot also explain R(D(*))

"There will therefore be far-reaching consequences for the field of particle physics, should this discrepancy be confirmed."

$$A_{FB} = \frac{\int_0^1 d\cos\theta_\ell \frac{d\Gamma(\bar{B}\to D^*\ell\bar{\nu})}{d\cos\theta_\ell} - \int_{-1}^0 d\cos\theta_\ell \frac{d\Gamma(\bar{B}\to D^*\ell\bar{\nu})}{d\cos\theta_\ell}}{\int_{-1}^1 d\cos\theta_\ell \frac{d\Gamma(\bar{B}\to D^*\ell\bar{\nu})}{d\cos\theta_\ell}}$$



$(\Delta)A_{FB}$ in Belle and Belle II

Tagged Belle and untagged Belle II (PRELIMINARY)

M. Prim et. al (arxiv:2301.07529)

TABLE VII. The forward-backward asymmetries for the four decay modes and $\bar{B}^0 B^-$ averages. The first uncertainty is statistical and the second uncertainty is systematic.

	$A_{\rm FB}$
$\bar{B}^0 \to D^{*+} e\bar{\nu}_e$	$0.218 \pm 0.030 \pm 0.008$
$\bar{B}^0 \to D^{*+} \mu\bar{\nu}_\mu$	$0.280 \pm 0.032 \pm 0.009$
$B^- \to D^{*0} e\bar{\nu}_e$	$0.239 \pm 0.023 \pm 0.007$
$B^- \to D^{*0} \mu\bar{\nu}_\mu$	$0.236 \pm 0.023 \pm 0.006$
$B^{(0,-)} \to D^{*(+,0)} e\bar{\nu}_e$	$0.230 \pm 0.018 \pm 0.005$
$B^{(0,-)} \to D^{*(+,0)} \mu\bar{\nu}_\mu$	$0.252 \pm 0.019 \pm 0.005$

$$R_{e\mu} = \frac{\mathcal{B}(B \to D^* e\bar{\nu}_e)}{\mathcal{B}(B \to D^* \mu\bar{\nu}_\mu)} = 0.990 \pm 0.021 \pm 0.023\,,$$

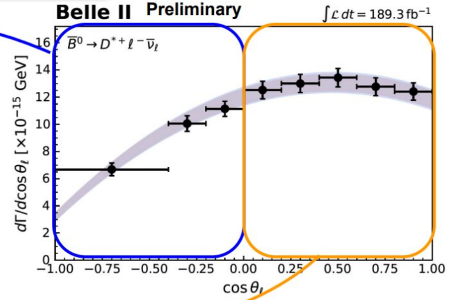
TABLE VIII. The difference of the forward-backward asymmetries for the $\bar{B}^0$ and B^- modes, and for the $\bar{B}^0 B^-$ averages. The first uncertainty is statistical and the second uncertainty is systematic.

	$\Delta A_{\rm FB}$
$\bar{B}^0 \to D^{*+} \ell\bar{\nu}_\ell$	$0.062 \pm 0.044 \pm 0.011$
$B^- \to D^{*0} \ell\bar{\nu}_\ell$	$-0.003 \pm 0.033 \pm 0.009$
$B \to D^* \ell\bar{\nu}_\ell$	$0.022 \pm 0.026 \pm 0.007$

Untagged $B^0 \to D^* l\nu$ (C. Lyu, ALPS 23)

- Ratio of branching fractions between e and μ $R_{e/\mu} = 1.001 \pm 0.009 \pm 0.021$
- Angular asymmetry

$$\mathcal{A}_{\rm FB} = \frac{\int_0^1 {\rm d}\cos\theta_\ell {\rm d}\Gamma/{\rm d}\cos\theta_\ell - \int_{-1}^0 {\rm d}\cos\theta_\ell {\rm d}\Gamma/{\rm d}\cos\theta_\ell}{\int_0^1 {\rm d}\cos\theta_\ell {\rm d}\Gamma/{\rm d}\cos\theta_\ell + \int_{-1}^0 {\rm d}\cos\theta_\ell {\rm d}\Gamma/{\rm d}\cos\theta_\ell}$$



Obtained results:

$$\mathcal{A}^e_{\rm FB} = 0.219 \pm 0.011 \pm 0.020\,,$$
$$\mathcal{A}^\mu_{\rm FB} = 0.215 \pm 0.011 \pm 0.022\,,$$
$$\Delta\mathcal{A}_{\rm FB} = (-4 \pm 16 \pm 18) \times 10^{-3}\,.$$

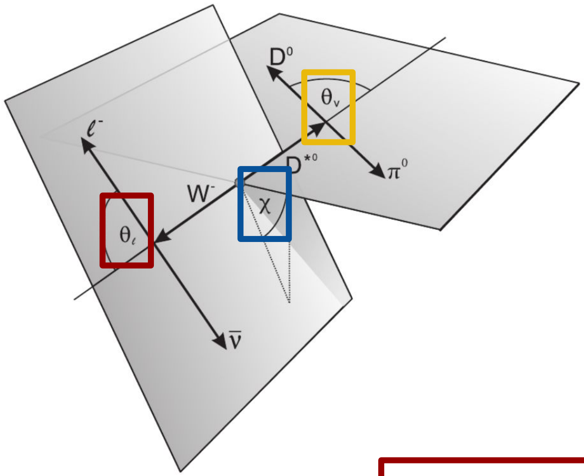
$\Delta\mathcal{A}_{\rm FB} = \mathcal{A}^\mu_{\rm FB} - \mathcal{A}^e_{\rm FB}$

Even more asymmetries (Phys. Rev. D 107, 015011)

Several more angular asymmetries were proposed to further investigate this tension

The main focus is on scenarios that do not change the ***q^2 spectrum*** of the decay (as there is no tension between electrons and muons there), but would **alter angular distributions**:

See talk by L. Mukherjee!



$$A_{FB}(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \frac{d^2\Gamma}{d\cos\theta_\ell dq^2},$$

$$S_3(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi/4} - \int_{\pi/4}^{\pi/2} - \int_{\pi/2}^{3\pi/4} + \int_{3\pi/4}^{\pi} + \int_{\pi}^{5\pi/4} - \int_{5\pi/4}^{3\pi/2} - \int_{3\pi/2}^{7\pi/4} + \int_{7\pi/4}^{2\pi}\right] d\chi \frac{d^2\Gamma}{dq^2 d\chi},$$

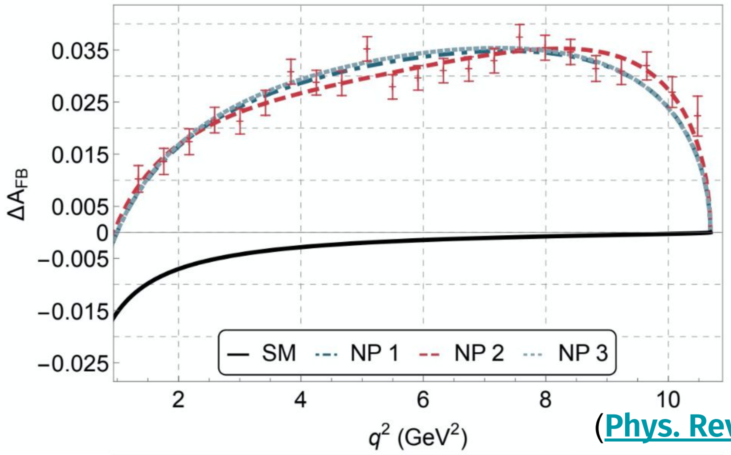
$$S_5(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi} - \int_{\pi}^{3\pi/2} + \int_{3\pi/2}^{2\pi}\right] d\chi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta^* \frac{d^3\Gamma}{dq^2 d\cos\theta^* d\chi},$$

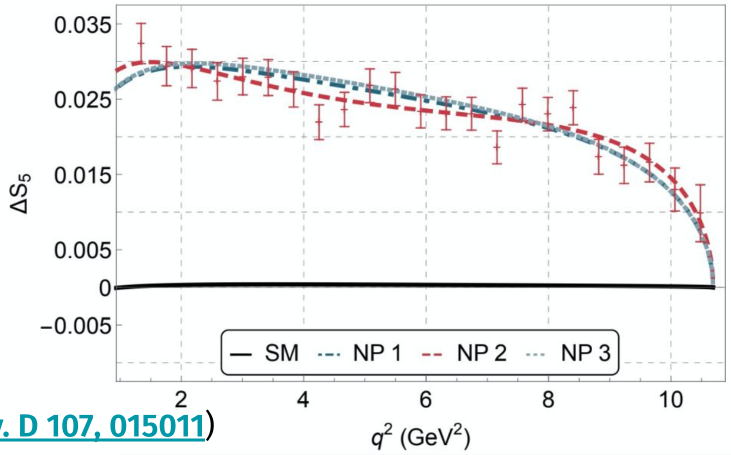
$$S_7(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi} - \int_{\pi}^{2\pi}\right] d\chi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta^* \frac{d^3\Gamma}{dq^2 d\cos\theta^* d\chi}.$$

Key: measure these as a function of ***$q^2 = (p_B - p_{D^*})^2$*** *or* ***w***

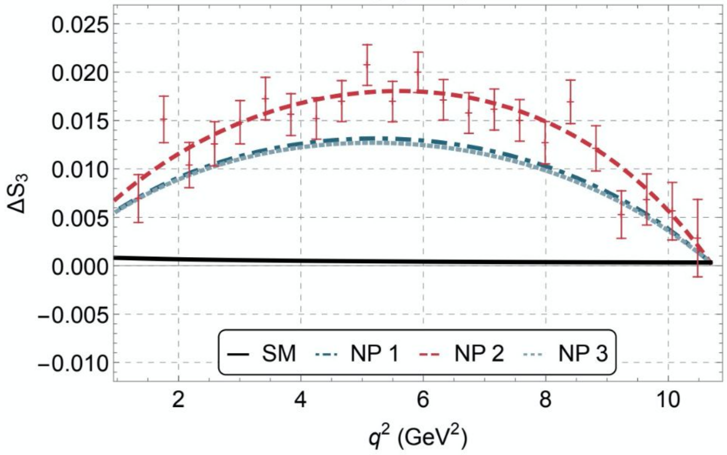
$$w = \frac{p_B \cdot p_{D^*}}{m_B m_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

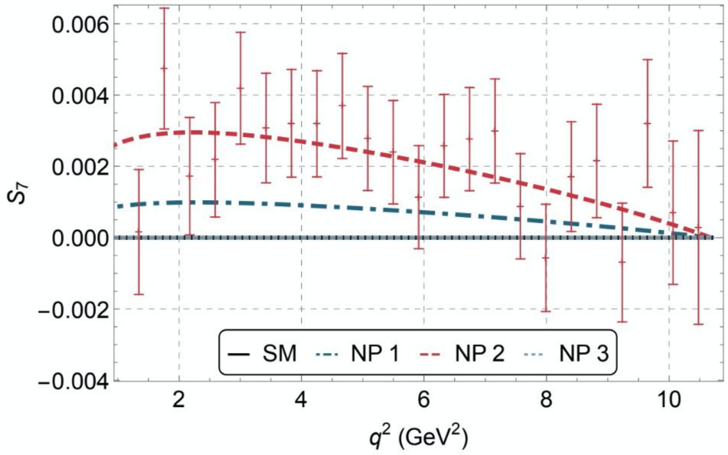
Projected Belle II Sensitivity





(Phys. Rev. D 107, 015011)





See talk by L. Mukherjee!

Belle II: Dedicated Experimental Measurement

- All angular asymmetry variables are +/- asymmetries:

$$\mathcal{A}(q^2) = \frac{N^+ - N^-}{N^+ + N^-}.$$

- Sensitive to LUV in the *delta* variables

$$\Delta\mathcal{A}(q^2) = \mathcal{A}^\mu(q^2) - \mathcal{A}^e(q^2).$$

- *Note*: strong cancellation of systematics already in $\mathscr{A}$

- A_{FB} analysis can be adapted as-is to S_i just by swapping variables:

$$A_x(w) \equiv \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}w}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right]\mathrm{d}x\,\frac{\mathrm{d}^2\Gamma}{\mathrm{d}w\mathrm{d}x}$$

$$\begin{aligned} A_{\mathrm{FB}} &: \mathrm{d}X \to \mathrm{d}(\cos\theta_l) \\ S_3 &: \mathrm{d}X \to \mathrm{d}(\cos 2\chi) \\ S_5 &: \mathrm{d}X \to \mathrm{d}(\cos\chi\cos\theta_V) \\ S_7 &: \mathrm{d}X \to \mathrm{d}(\sin\chi\cos\theta_V) \\ S_9 &: \mathrm{d}X \to \mathrm{d}(\sin 2\chi) \end{aligned}$$

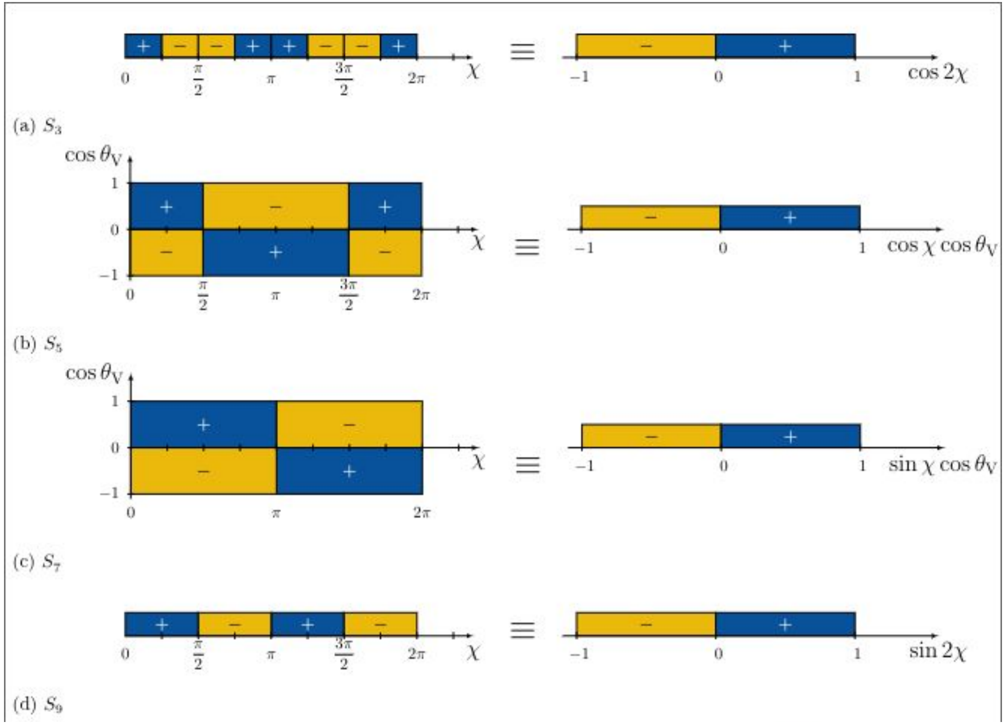
S variables: from 2D to 1D

$$\mathcal{S}_3(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^{\pi/4} - \int_{\pi/4}^{\pi/2} - \int_{\pi/2}^{3\pi/4} + \int_{3\pi/4}^{\pi} + \int_{\pi}^{5\pi/4} - \int_{5\pi/4}^{3\pi/2} - \int_{3\pi/2}^{7\pi/4} + \int_{7\pi/4}^{2\pi}\right] d\chi \frac{d^2\Gamma}{dw\,d\chi},$$

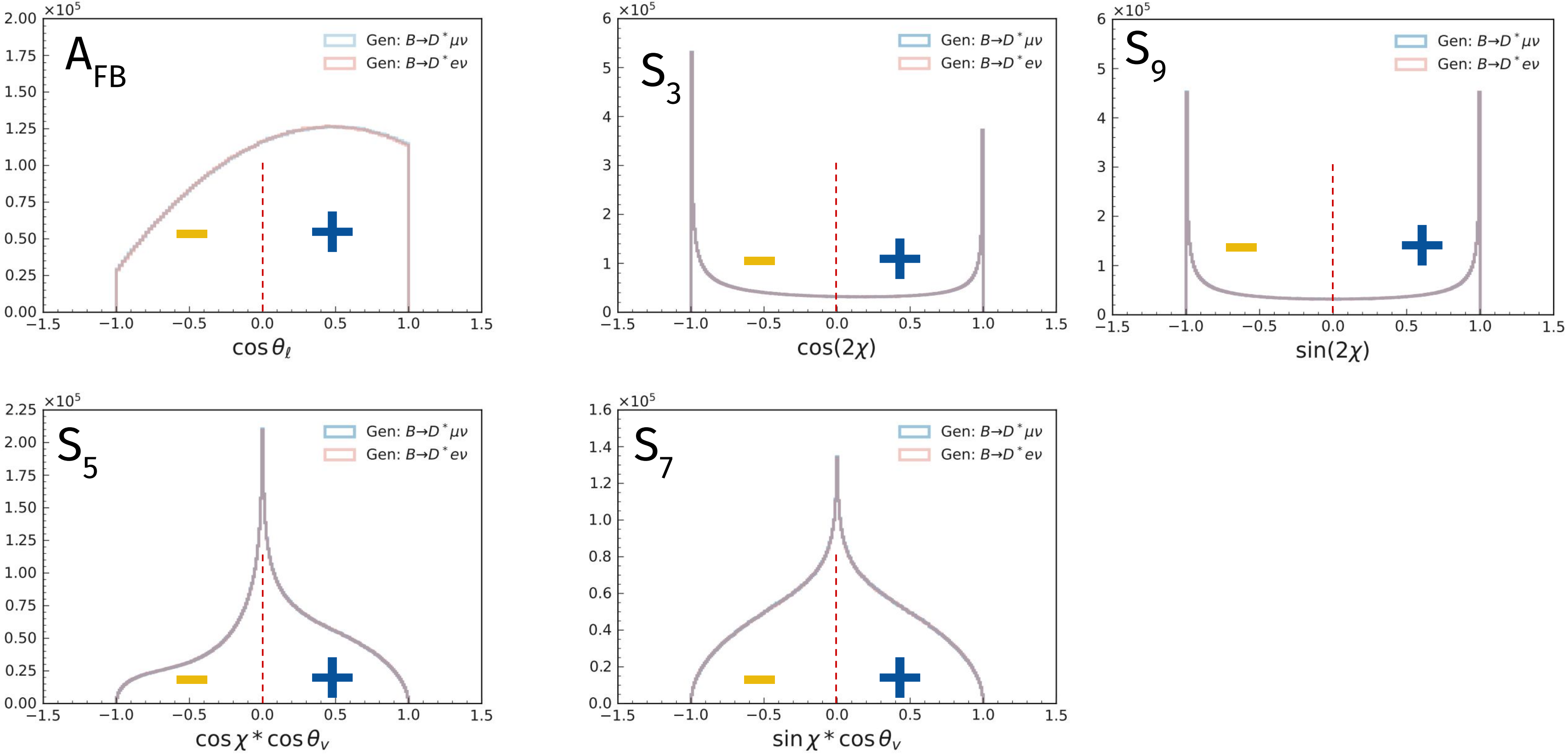
$$\mathcal{S}_5(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^{\pi/2} + \int_{3\pi/2}^{2\pi} - \int_{\pi/2}^{\pi} - \int_{\pi}^{3\pi/2}\right] d\chi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_V \frac{d^3\Gamma}{dw\,d\cos\theta_V\,d\chi}.$$

$$\mathcal{S}_7(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^{\pi} - \int_{\pi}^{2\pi}\right] d\chi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_V \frac{d^3\Gamma}{dw\,d\cos\theta_V\,d\chi},$$

$$\mathcal{S}_9(w) = \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi} + \int_{\pi}^{3\pi/2} - \int_{3\pi/2}^{2\pi}\right] d\chi \frac{d^2\Gamma}{dw\,d\chi},$$



Angular asymmetry variables at generator MC (EvtGen)



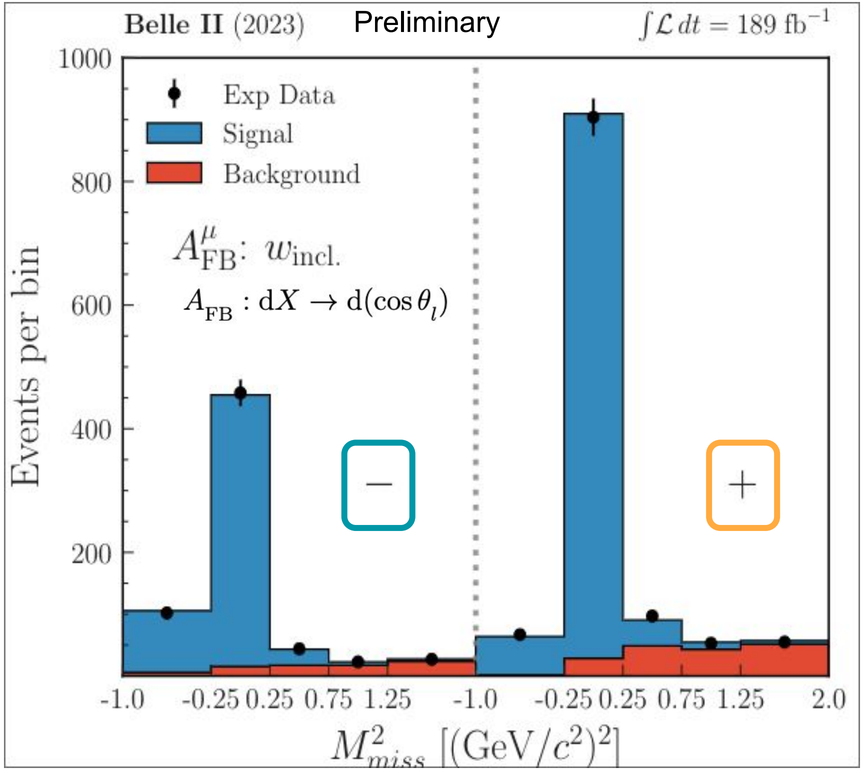
$$\mathcal{A}(q^2) = \frac{N^+ - N^-}{N^+ + N^-}$$

World's first experimental measurement of complete set of angular asymmetries

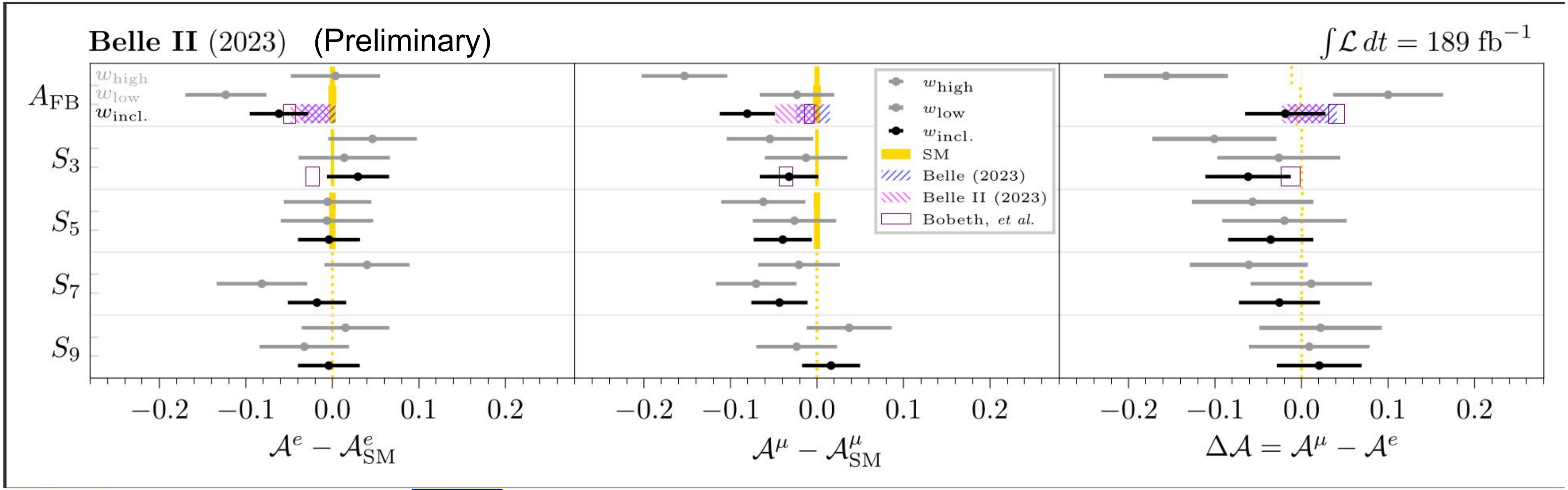
Hadronically tagged B^0-> $D^*l\nu$ (single ν in event)
→*high purity, kinematically constrained sample*

Signal extraction in ν invariant mass-squared (M^2_{miss})
in two w-bins plus w-inclusive range

$$w = \frac{p_B \cdot p_{D^*}}{m_B m_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$



$(\Delta)A_{FB}$++



Belle tagged $|V_{cb}|$

Bobeth, et al (excludes *tiny* range of *w*, $O(10^{-3})$ effect)

SM uncertainties (very small)

Belle II untagged $|V_{cb}|$

Overall agreement Chi2/ndf (p-val): *(stat unc dominates)*

	w_inc	w_lo & w_hi
$\mathscr{A}$	15.0 / 10 (p = 0.13)	27.7 / 20 (p = 0.12)
LUV-sensitive $\{\Delta A_{FB}\ \Delta S_3\ \Delta S_5\}$	2.1 / 3 (p = 0.56)	10.2 / 6 (p = 0.12)

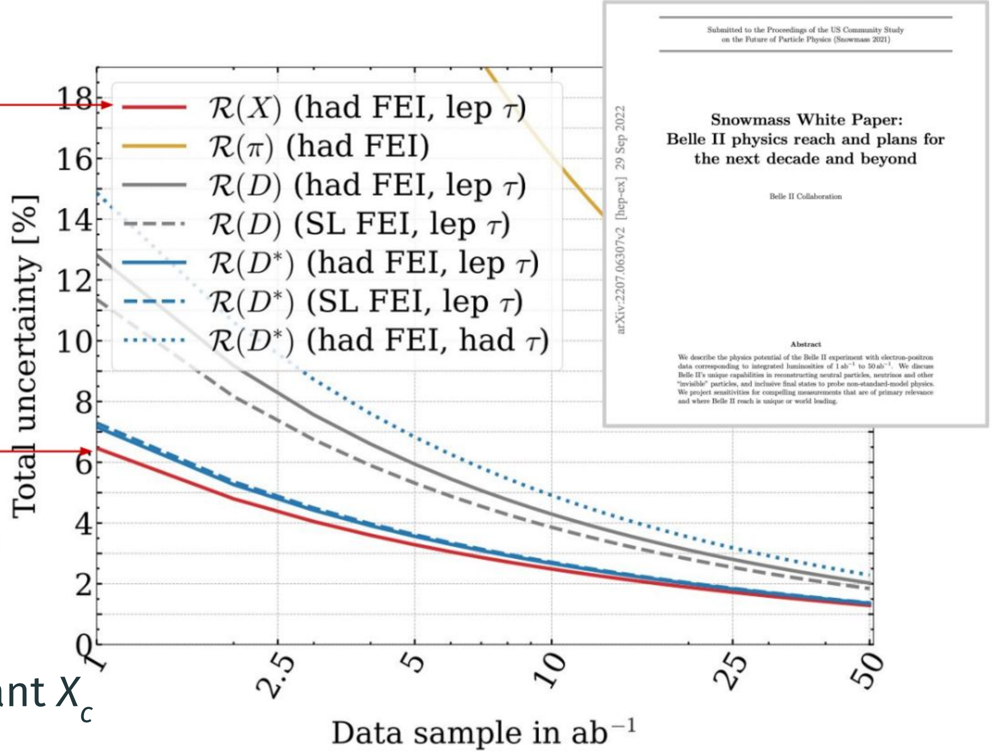
Bonus: LU in inclusive decays

Inclusive LU test

An intriguing claim…

The **strongest** test of **τ/ℓ universality** will come from the *inclusive* measurement:

$$\mathcal{R}(X) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$$



Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

arXiv:2207.06307v2 [hep-ex] 29 Sep 2022

Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond

Belle II Collaboration

Abstract

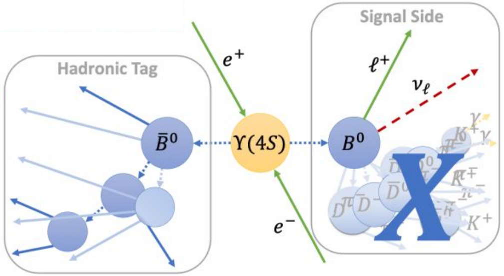
We describe the physics potential of the Belle II experiment with electron-positron data corresponding to integrated luminosities of 1 ab^{-1} to 50 ab^{-1}. We discuss Belle II's unique capabilities in reconstructing neutral particles, neutrinos and other "invisible" particles, and inclusive final states to probe non-standard-model physics. We project sensitivities for compelling measurements that are of primary relevance and where Belle II reach is unique or world leading.

No published results from B-factories

~ ⅔ overlap with D and D*
~ ⅓ contribution from D** and nonresonant X_c

R(X) is critical **cross-check** of *R(D(*))* **and complimentary** test of LU arXiv:2301.08266

LU: INCLUSIVE $R(X_{e/\mu}) = \frac{\mathcal{B}(B\to Xe\nu)}{\mathcal{B}(B\to X\mu\nu)}$

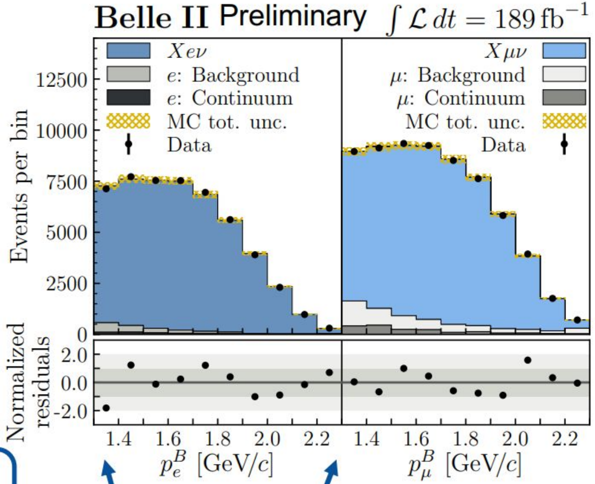


- Challenging to model & control miscellaneous backgrounds
- Same flavor B pair used as background-enriched control sample, high momentum cut to suppress backgrounds
- Signal extracted in simultaneous fit to the **lepton momentum in the B_{sig} rest frame, p_ℓ^B**.

Preliminary

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

- **Most precise** BF based lepton universality test in semileptonic B-meson decays to date
- **First inclusive** measurement
- Syst. unc. dominated by **lepton ID**



Consistent with SM[1] within 1.2 σ

$p_\ell^B > 1.3$ GeV!

March 28, 2023 | Henrik Junkerkalefeld

JHEP 11, 007 2022

Summary

Lepton Universality tests in $B \to D(*)l\nu$ continue to be of critical importance

From first hints to new tests, B-factories continue to leverage unique kinematic control to provide stringent measurements

R(D(*)) updates coming soon

New LU tests in Δ-asymmetries and *R(X)* have only just started: *more work ongoing now!*

Backup

Uncertainty on ΔA_{FB} in Bobeth et. al

We find that the minimal tension with respect to the SM for the combined $A_{\rm FB}^{(e)}$, $A_{\rm FB}^{(\mu)}$ occurs for maximal anti-correlation ($\rho = -1$), which is not a realistic value. The correlation determined in the fit to the 80×80 covariance matrix is actually very small. Adopting nevertheless this most conservative choice of $\rho = -1$ still leads to a tension of 3.6σ. We emphasize again that this result is not changed by employing the pseudo-Monte Carlo approach with Cholesky decomposition for the fit as done in [53], nor by the d'Agostini effect (the plots shown in Figure 1 include the corresponding shifts). Therefore, even adopting this maximally conservative procedure, our results amount to evidence for μ-e-non-universality beyond the SM in charged-current $b \to c\ell\nu$ transitions. However, our finding hinges on the approximate validity of the data and specifically the correlation matrices given in Ref. [3].

Systematic uncertainties on ΔA_{FB}

Belle II

Statistical uncertainty dominates: **strong cancellation** of remaining systematics

PRELIMINARY

$w < 1.275$	Central	Exp Stat	MC shape	Unf. & eff.	Lep. ID	π_{slow} eff.	$\mathcal{B}(D^{**})$	K_S^0 eff.	form factors	SM
A_{FB}^{μ}	0.248	0.041	0.003	0.010	0.0011	0.0004	0.0000	0.0001	1.62×10^{-5}	0.0045
A_{FB}^{e}	0.149	0.044	0.005	0.010	0.0036	0.0005	0.0000	0.0002	2.07×10^{-5}	0.0046
ΔA_{FB}	0.099	0.060	0.006	0.014	0.0038	0.0006	0.0000	0.0002	4.10×10^{-6}	0.0000
$S_3{}^{\mu}$	0.160	0.046	0.003	0.011	0.0005	0.0002	0.0000	0.0002	1.29×10^{-5}	0.0019
$S_3{}^{e}$	0.133	0.050	0.006	0.012	0.0005	0.0006	0.0000	0.0001	1.09×10^{-5}	0.0019
ΔS_3	0.026	0.067	0.007	0.017	0.0007	0.0006	0.0000	0.0004	2.00×10^{-6}	0.0000
$S_5{}^{\mu}$	0.146	0.045	0.003	0.011	0.0004	0.0004	0.0000	0.0002	1.45×10^{-5}	0.0035
$S_5{}^{e}$	0.166	0.050	0.006	0.012	0.0010	0.0005	0.0000	0.0001	2.09×10^{-5}	0.0035
ΔS_5	-0.019	0.068	0.007	0.017	0.0011	0.0006	0.0000	0.0001	6.4×10^{-6}	0.0000
$S_7{}^{\mu}$	0.060	0.044	0.003	0.011	0.0002	0.0002	0.0000	0.0001	9.61×10^{-7}	0.0000
$S_7{}^{e}$	0.088	0.049	0.006	0.012	0.0004	0.0002	0.0000	0.0002	9.83×10^{-7}	0.0000
ΔS_7	0.028	0.066	0.007	0.017	0.0005	0.0004	0.0000	0.0001	2.20×10^{-8}	0.0000
$S_9{}^{\mu}$	0.003	0.044	0.003	0.011	0.0005	0.0003	0.0000	0.0002	1.40×10^{-6}	0.0000
$S_9{}^{e}$	0.035	0.049	0.006	0.012	0.0004	0.0002	0.0000	0.0001	9.29×10^{-7}	0.0000
ΔS_9	0.032	0.066	0.007	0.017	0.0005	0.0004	0.0000	0.0003	4.7×10^{-7}	0.0000
$w > 1.275$										
A_{FB}^{μ}	0.045	0.047	0.005	0.011	0.0018	0.0007	0.0000	0.0001	6.86×10^{-6}	0.0030
A_{FB}^{e}	0.213	0.049	0.007	0.011	0.0037	0.0007	0.0000	0.0001	5.52×10^{-6}	0.0030
ΔA_{FB}	0.168	0.067	0.009	0.016	0.0042	0.0001	0.0000	0.0002	1.84×10^{-6}	0.0001
$S_3{}^{\mu}$	0.117	0.047	0.005	0.011	0.0004	0.0002	0.0000	0.0002	1.30×10^{-5}	0.0020
$S_3{}^{e}$	0.016	0.048	0.007	0.012	0.0005	0.0004	0.0000	0.0001	1.01×10^{-5}	0.0020
ΔS_3	0.101	0.067	0.008	0.016	0.0006	0.0002	0.0000	0.0001	2.90×10^{-6}	0.0000
$S_5{}^{\mu}$	0.160	0.046	0.005	0.011	0.0003	0.0001	0.0000	0.0001	3.10×10^{-6}	0.0037
$S_5 e$	0.215	0.048	0.006	0.011	0.0007	0.0005	0.0000	0.0003	4.42×10^{-6}	0.0037
ΔS_5	0.055	0.066	0.008	0.016	0.0008	0.0008	0.0000	0.0003	1.32×10^{-6}	0.0000
$S_7{}^{\mu}$	0.020	0.045	0.004	0.011	0.0004	0.0001	0.0000	0.0001	9.40×10^{-7}	0.0000
$S_7{}^{e}$	0.045	0.046	0.006	0.011	0.0002	0.0001	0.0000	0.0001	1.10×10^{-6}	0.0000
ΔS_7	0.066	0.064	0.008	0.015	0.0004	0.0001	0.0000	0.0001	1.60×10^{-7}	0.0000
$S_9{}^{\mu}$	0.040	0.047	0.005	0.011	0.0004	0.0002	0.0000	0.0001	7.28×10^{-7}	0.0000
$S_9{}^{e}$	0.020	0.048	0.006	0.012	0.0003	0.0003	0.0000	0.0001	2.37×10^{-7}	0.0000
ΔS_9	0.020	0.067	0.008	0.016	0.0005	0.0002	0.0000	0.0001	4.91×10^{-6}	0.0000

Table XII: Unblinded central values and leading uncertainties for $(\Delta)A_{\mathrm{FB}}^{\ell}$, $(\Delta)S_3^{\ell}$, $(\Delta)S_5^{\ell}$, $(\Delta)S_7^{\ell}$, and $(\Delta)S_9^{\ell}$.