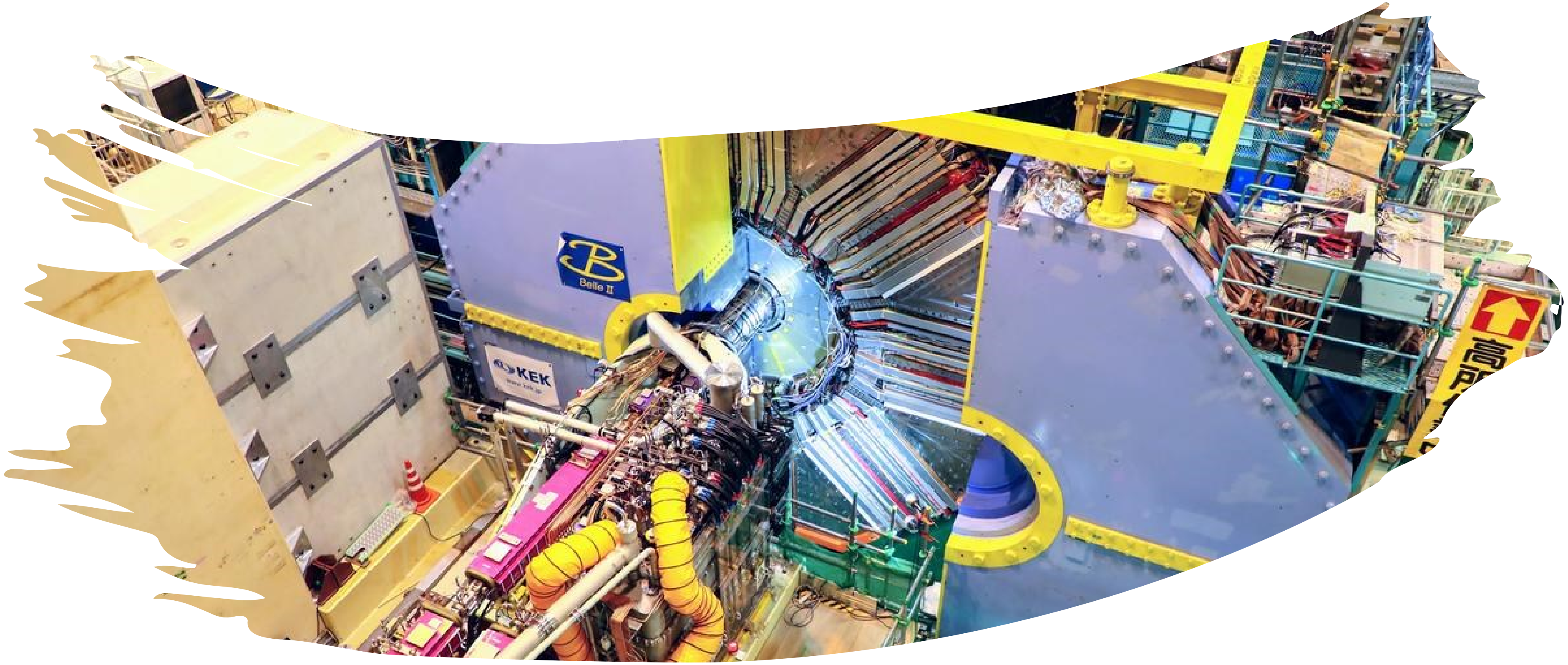

$B \to D^* \ell \bar{\nu}_\ell$ Angular Analysis

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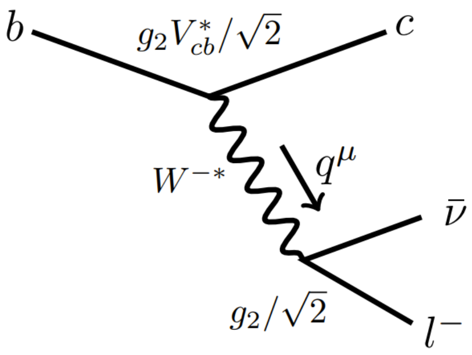
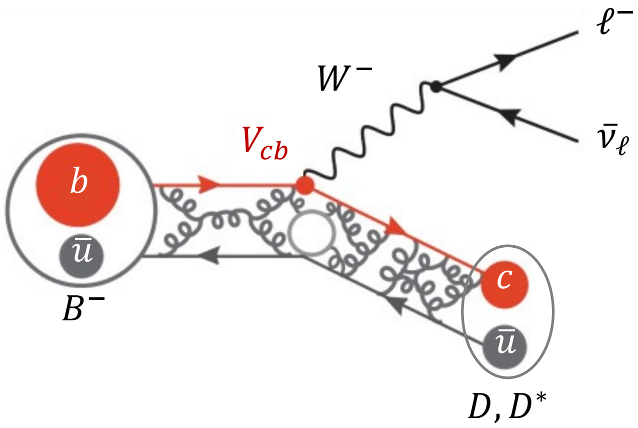
The $b \to c\ell\bar{\nu}_\ell$ Laboratory



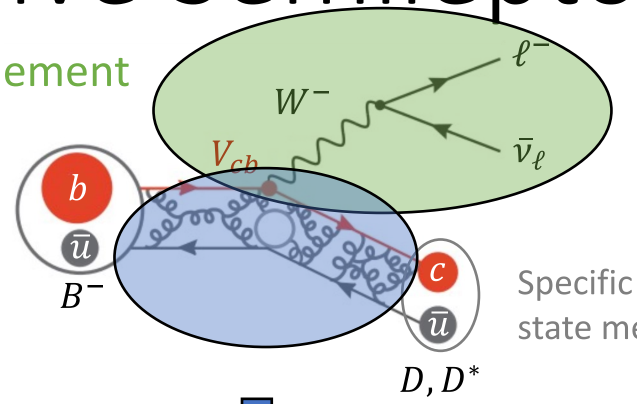
Main Theory Challenge



- Tree level process: large branching fraction (10%), theoretically relatively clean
- Universal lepton gauge coupling in the SM
- Experimentally only access to bound states $B \to D^{(*)}, D^{**}, \ldots, \Lambda_b \to \Lambda_c^*, \ldots$
- Precision description of the hadronic matrix element required for precision measurements

Exclusive Semileptonic $B \to D^* \ell \bar{\nu}_\ell$

Leptonic Matrix Element



Specific final state meson

$\Gamma(B \to D^* \ell \bar{\nu}_\ell) \propto |V_{cb}|^2 \mathcal{F}(1)$ $\quad$ $\mathcal{F}(1) = h_{A_1}(1)$

Hadronic Matrix Elements cannot be calculated from first principles
→ Can be parameterized with form factors $h_X = h_X(w)$ and extracted from data
→ Lattice QCD must provide (at least) inputs on their normalization

$$\frac{\langle D^*(p')|\bar{c}\gamma^\mu b|B(p)\rangle}{\sqrt{m_B m_{D^*}}} = h_V \epsilon^{\mu\nu\alpha\beta} \epsilon^*_\nu v'_\alpha v_\beta$$

$$\frac{\langle D^*(p')|\bar{c}\gamma^\mu\gamma^5 b|B(p)\rangle}{\sqrt{m_B m_{D^*}}} = h_{A_1}(w+1)\epsilon^{*\mu} - h_{A_2}(\epsilon^* \cdot v)v^\mu - h_{A_3}(\epsilon^* \cdot v)v'^\mu$$

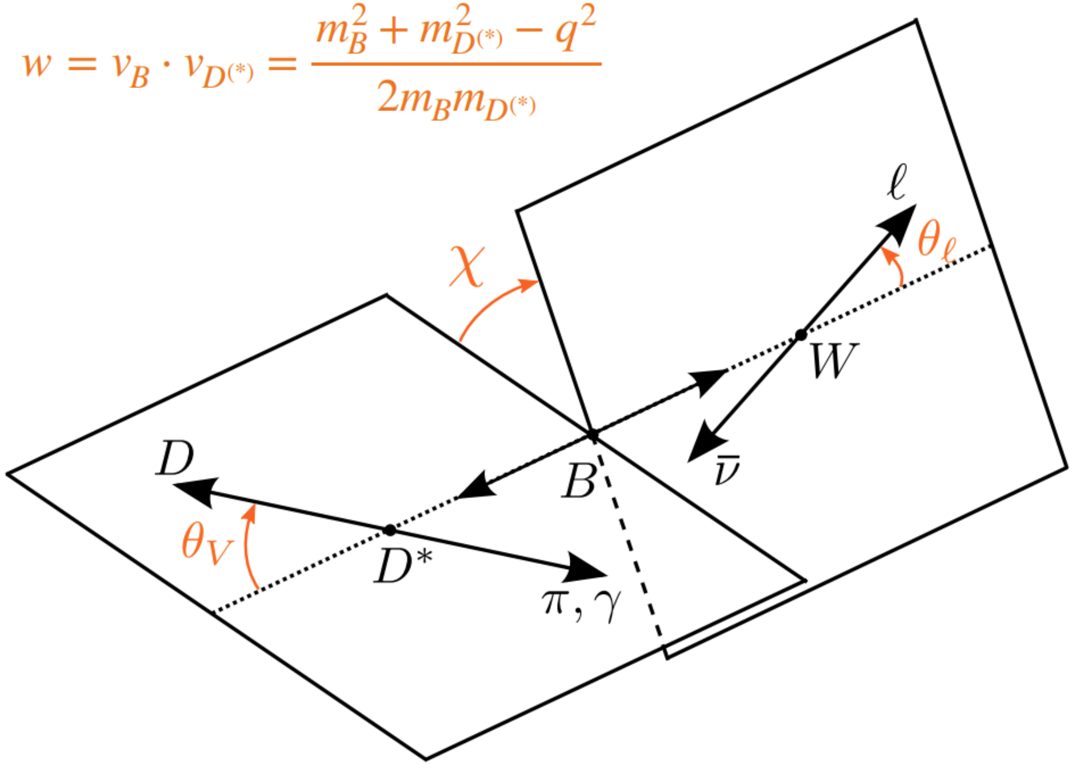
Heavy Quark Symmetry Basis

Common parameterizations for the form factors:

- BGL
- CLN
- BLPRXP

Exclusive Semileptonic $B \to D^* \ell \bar{\nu}_\ell$

$$w = v_B \cdot v_{D^{(*)}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$



- Form factors are a function of w only
- Angles provide information on, e.g.
  - Forward-backward asymmetry
  - Longitudinal polarization fraction
  - "S" observables sensitive to new physics
- Measure the 4 marginal distributions of the 4D differential decay rate

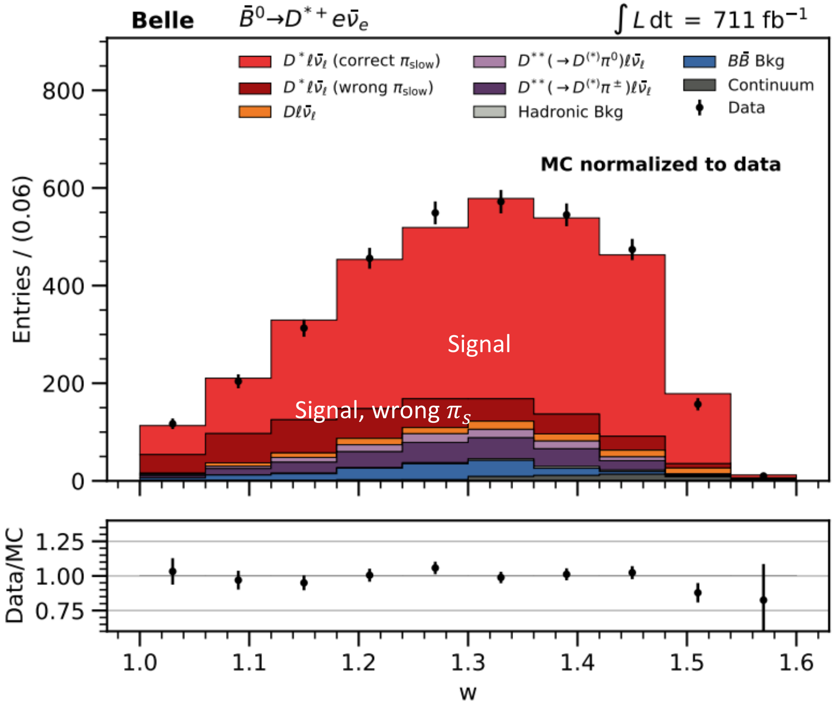
$$\frac{\mathrm{d}\Gamma(B \to D^* \ell \nu_\ell)}{\mathrm{d}w \mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_\mathrm{V} \mathrm{d}\chi} = \frac{6 m_\mathrm{B} m_{\mathrm{D}^*}^2}{8(4\pi)^4} \sqrt{w^2 - 1}(1 - 2wr + r^2) G_\mathrm{F}^2 \eta_\mathrm{EW}^2 |V_\mathrm{cb}|^2$$
$$\times \Big((1 - \cos\theta_\ell)^2 \sin^2\theta_\mathrm{V} H_+^2 + (1 + \cos\theta_\ell)^2 \sin^2\theta_\mathrm{V} H_-^2$$
$$+ 4 \sin^2\theta_\ell \cos^2\theta_\mathrm{V} H_0^2 - 2 \sin^2\theta_\ell \sin^2\theta_\mathrm{V} \cos 2\chi H_+ H_-$$
$$- 4 \sin\theta_\ell (1 - \cos\theta_\ell) \sin\theta_\mathrm{V} \cos\theta_\mathrm{V} \cos\chi H_+ H_0$$
$$+ 4 \sin\theta_\ell (1 + \cos\theta_\ell) \sin\theta_\mathrm{V} \cos\theta_\mathrm{V} \cos\chi H_- H_0 \Big) ,$$

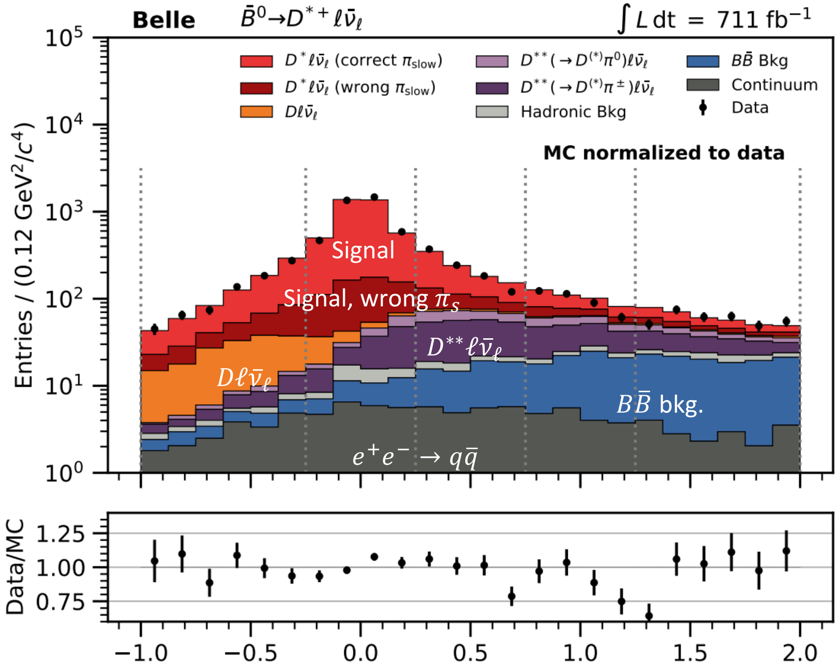
Differential Distributions of $B \to D^* \ell \bar{\nu}_\ell$

Belle, Prim, et al
Phys.Rev.D 108 (2023) 1, 012002
arXiv:2301.07529

$\bar{B}^0 \to D^{*+}(\to D^0\pi_s^+, D^+\pi_s^0)\ell\bar{\nu}_\ell$

$B^- \to D^{*0}(\to D^0\pi_s^0)\ell\bar{\nu}_\ell$





Background subtraction in independent variable to reduce model dependency.

Extraction Method: Missing Mass Squared

$$0 = m_\nu^2 = \mathrm{M}_{\mathrm{miss}}^2 = (p_{e^+e^-} - \mathrm{p_B} - \mathrm{p_{D^*}} - \mathrm{p_\ell})^2$$

+ Unfolding and Acceptance Correction (not today)

Differential Distributions of $B \to D^* \ell \bar{\nu}_\ell$

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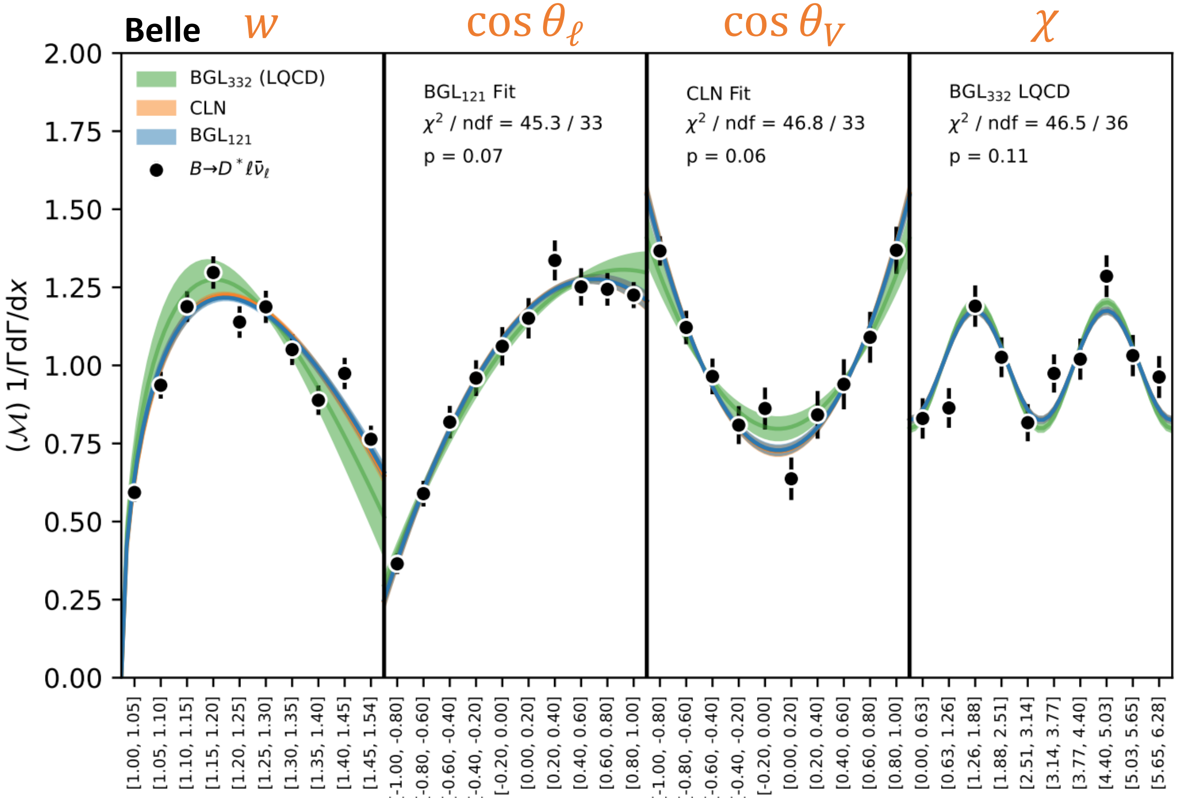


$|V_{cb}|^{\mathrm{BGL}} = (40.6 \pm 0.9) \times 10^{-3}$

$|V_{cb}|^{\mathrm{CLN}} = (40.1 \pm 0.9) \times 10^{-3}$

With lattice QCD result at zero recoil

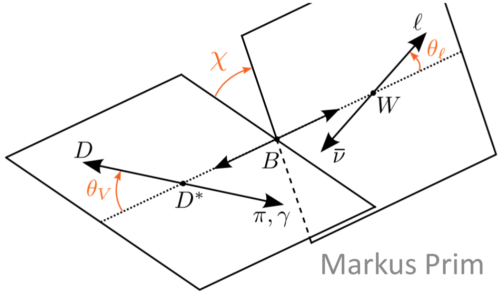
Lepton Flavor Universality Observables

$\Delta A_{FB} = A_{FB}^{\mu} - A_{FB}^{e} = 0.022 \pm 0.027$

$\Delta F_L = F_L^{\mu} - F_L^{e} = 0.034 \pm 0.024$

$$R_{e\mu} = \frac{\mathcal{B}(B \to D^* e \bar{\nu}_e)}{\mathcal{B}(B \to D^* \mu \bar{\nu}_\mu)} = 0.990 \pm 0.031$$

$$w = v_B \cdot v_{D^{(*)}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$



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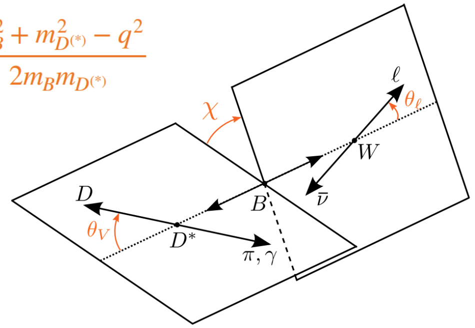


Angular Coefficients of $B \to D^* \ell \bar{\nu}_\ell$

Instead of binning in $w, \cos\theta_\ell, \cos\theta_V, \chi$, we now bin the data to determine the angular coefficients in bins of w and:

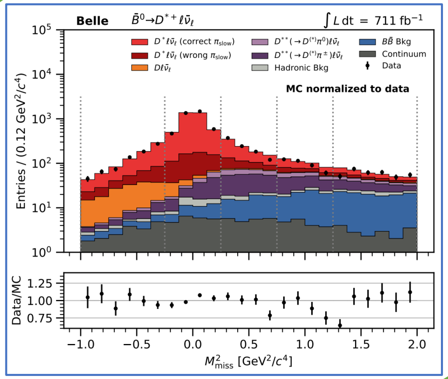
Phys.Rev.D 90 (2014) 9, 094003

$$\bar{J}_i = \frac{1}{N_i} \sum_{j=1}^{8} \sum_{k,l=1}^{4} \eta_{i,j}^{\chi} \eta_{i,k}^{\theta_\ell} \eta_{i,l}^{\theta_V} \left[\chi^{(j)} \otimes \chi^{(k)} \otimes \chi^{(l)} \right]$$

$J_i = J_i(w)$

Normalization Weights Unfolded Yields

J_i	η_i^{χ}	$\eta_i^{\theta_\ell}$	$\eta_i^{\theta_V}$	normalization N_i
J_{1s}	$\{+\}$	$\{+,a,a,+\}$	$\{-,c,c,-\}$	$2\pi(1)2$
J_{1c}	$\{+\}$	$\{+,a,a,+\}$	$\{+,d,d,+\}$	$2\pi(1)(2/5)$
J_{2s}	$\{+\}$	$\{-,b,b,-\}$	$\{-,c,c,-\}$	$2\pi(-2/3)2$
J_{2c}	$\{+\}$	$\{-,b,b,-\}$	$\{+,d,d,+\}$	$2\pi(-2/3)(2/5)$
J_3	$\{+,-,-,+,+,-,-,+\}$	$\{+\}$	$\{+\}$	$4(4/3)^2$
J_4	$\{+,+,-,-,-,-,+,+\}$	$\{+,+,-,-\}$	$\{+,+,-,-\}$	$4(4/3)^2$
J_5	$\{+,+,-,-,-,-,+,+\}$	$\{+\}$	$\{+,+,-,-\}$	$4(\pi/2)(4/3)$
J_{6s}	$\{+\}$	$\{+,+,-,-\}$	$\{-,c,c,-\}$	$2\pi(1)2$
J_{6c}	$\{+\}$	$\{+,+,-,-\}$	$\{+,d,d,+\}$	$2\pi(1)(2/5)$
J_7	$\{+,+,+,+,-,-,-,-\}$	$\{+\}$	$\{+,+,-,-\}$	$4(\pi/2)(4/3)$
J_8	$\{+,+,+,+,-,-,-,-\}$	$\{+,+,-,-\}$	$\{+,+,-,-\}$	$4(4/3)^2$
J_9	$\{+,+,-,-,+,+,-,-\}$	$\{+\}$	$\{+\}$	$4(4/3)^2$



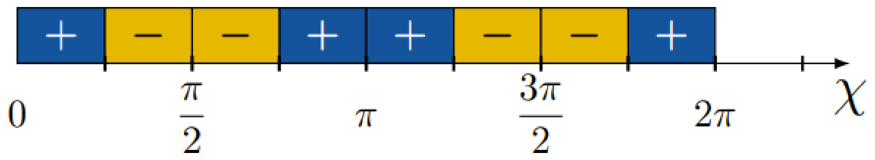
Same signal extraction strategy as before!

$$\frac{d\Gamma(B \to D^* \ell \nu_\ell)}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} = \frac{2 G_F^2 \eta_{EW}^2 |V_{cb}|^2 m_B^4 m_{D^*}}{2\pi^4} \times \Big(J_{1s} \sin^2\theta_V + J_{1c} \cos^2\theta_V$$
$$+ (J_{2s} \sin^2\theta_V + J_{2c} \cos^2\theta_V) \cos 2\theta_\ell + J_3 \sin^2\theta_V \sin^2\theta_\ell \cos 2\chi$$
$$+ J_4 \sin 2\theta_V \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_V \sin\theta_\ell \cos\chi + (J_{6s} \sin^2\theta_V + J_{6c} \cos^2\theta_V) \cos\theta_\ell$$
$$+ J_7 \sin 2\theta_V \sin\theta_\ell \sin\chi + J_8 \sin 2\theta_V \sin 2\theta_\ell \sin\chi + J_9 \sin^2\theta_V \sin^2\theta_\ell \sin 2\chi \Big).$$

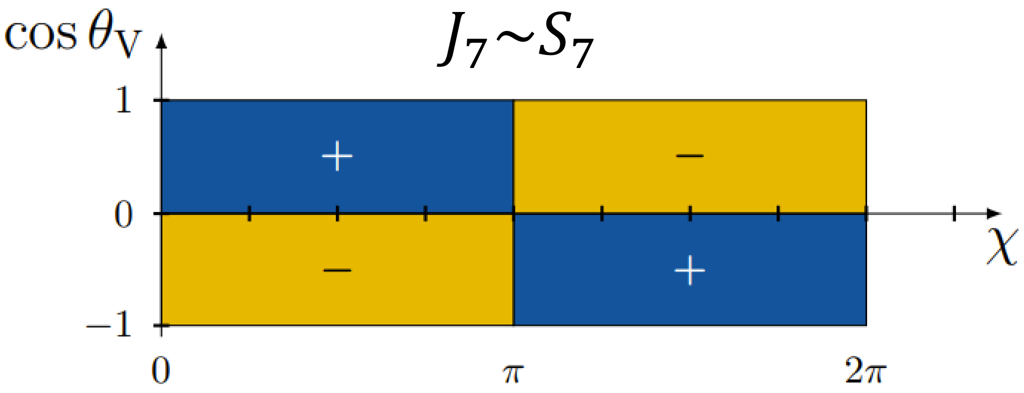
Angular Asymmetries in $B \to D^* \ell \bar{\nu}_\ell$

$$\mathcal{A}_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}.$$

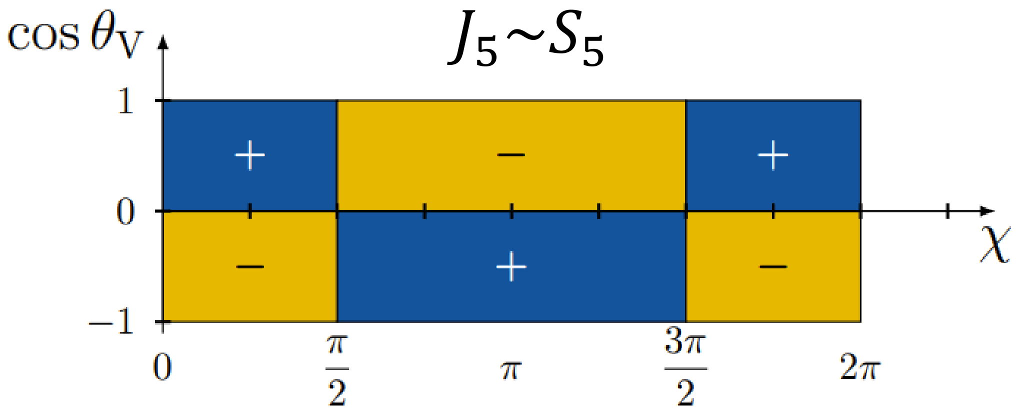
$J_3 \sim S_3$



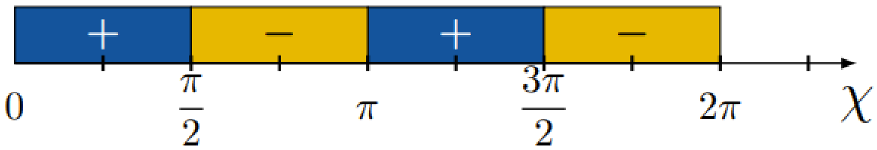
$J_7 \sim S_7$



$J_5 \sim S_5$

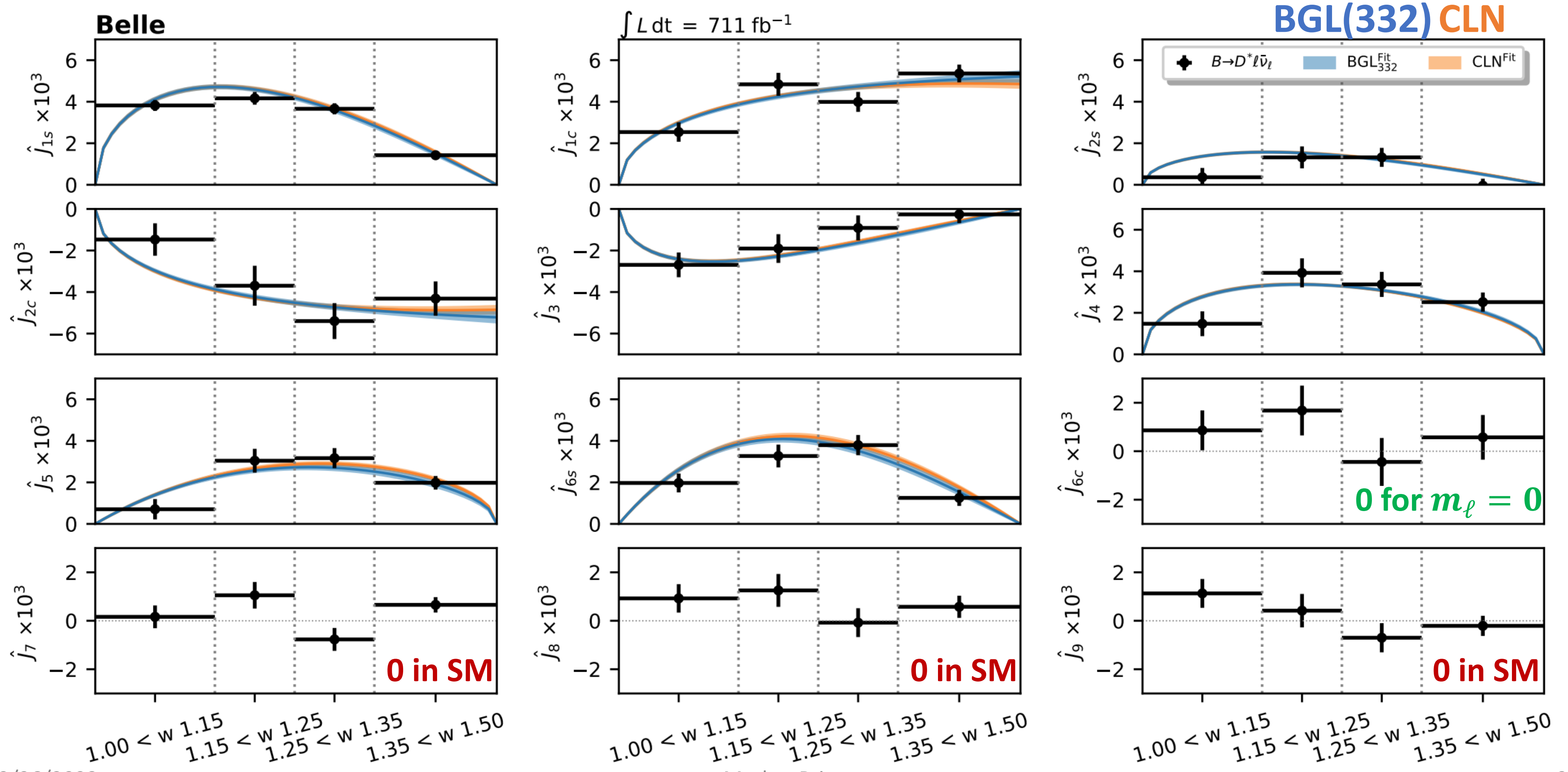


$J_9 \sim S_9$



Preliminary

Angular Coefficients of $B \to D^* \ell \bar{\nu}_\ell$



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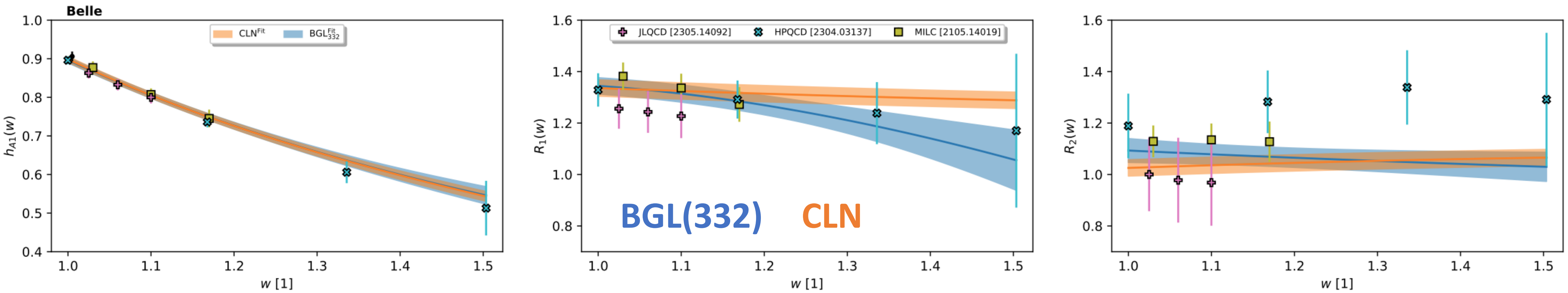
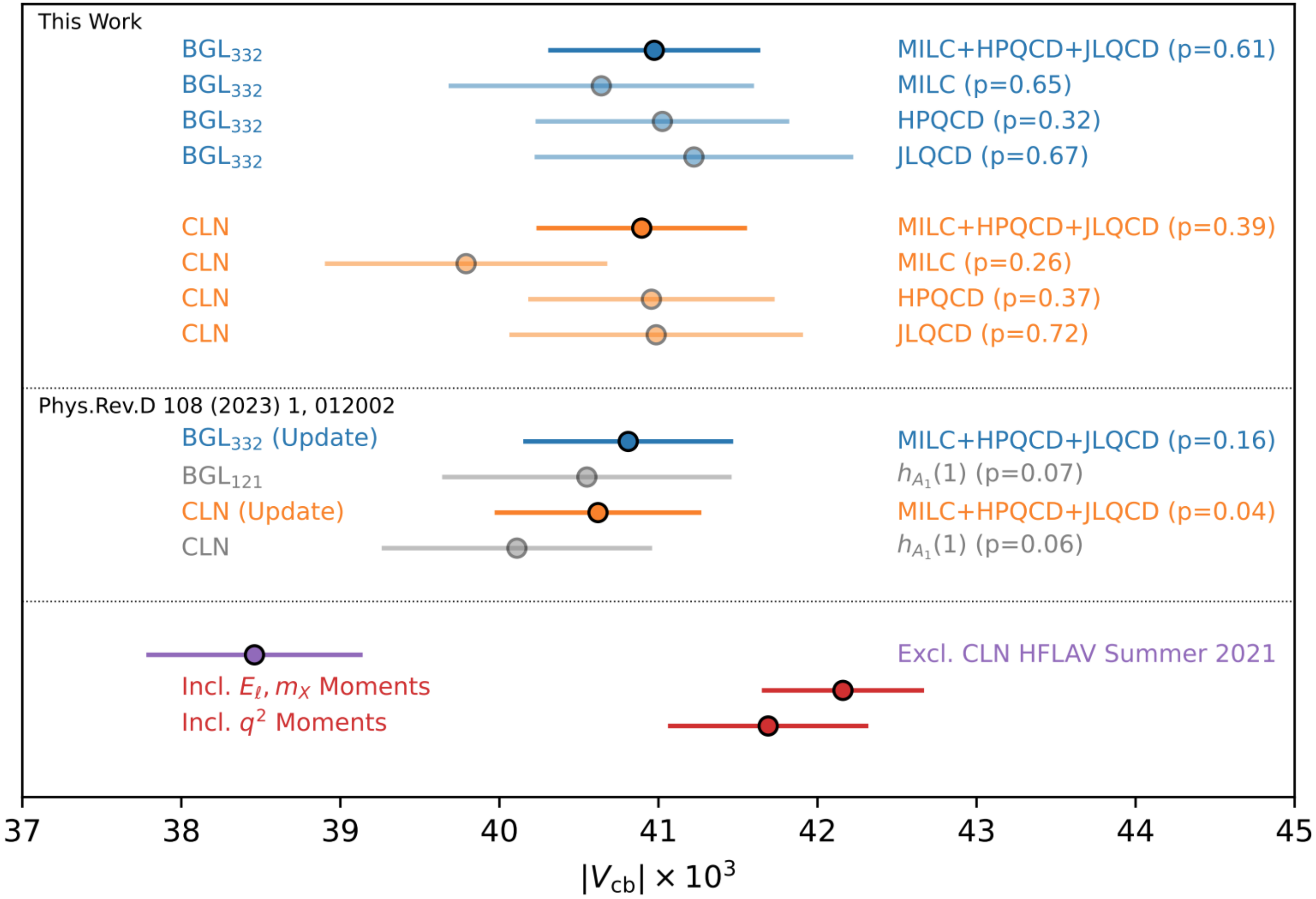
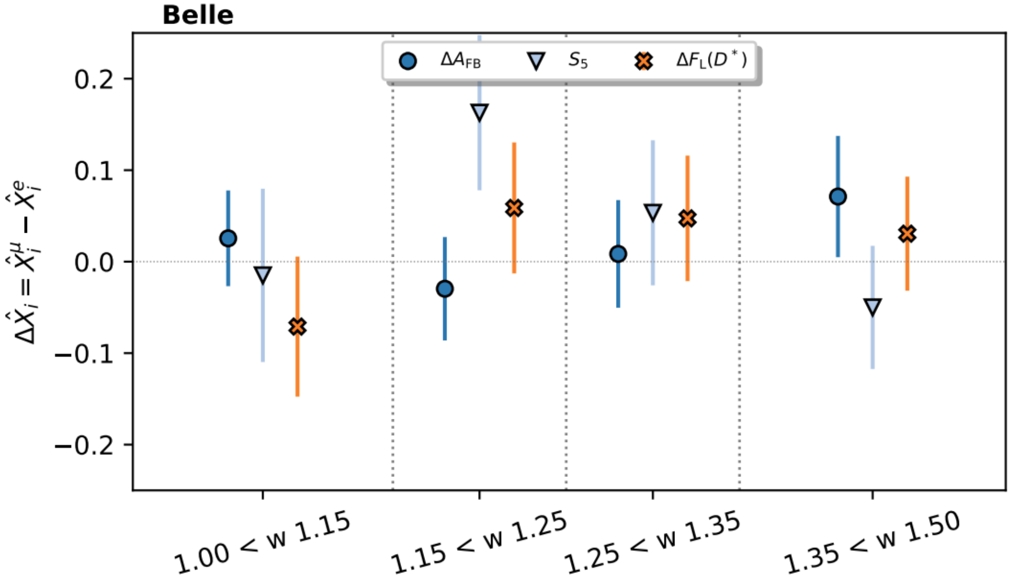


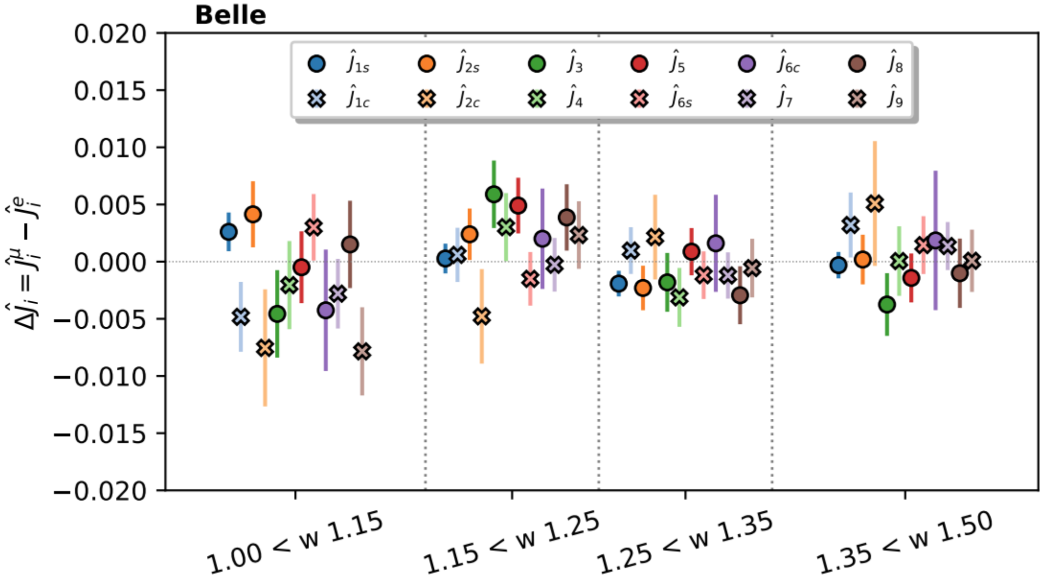
Preliminary

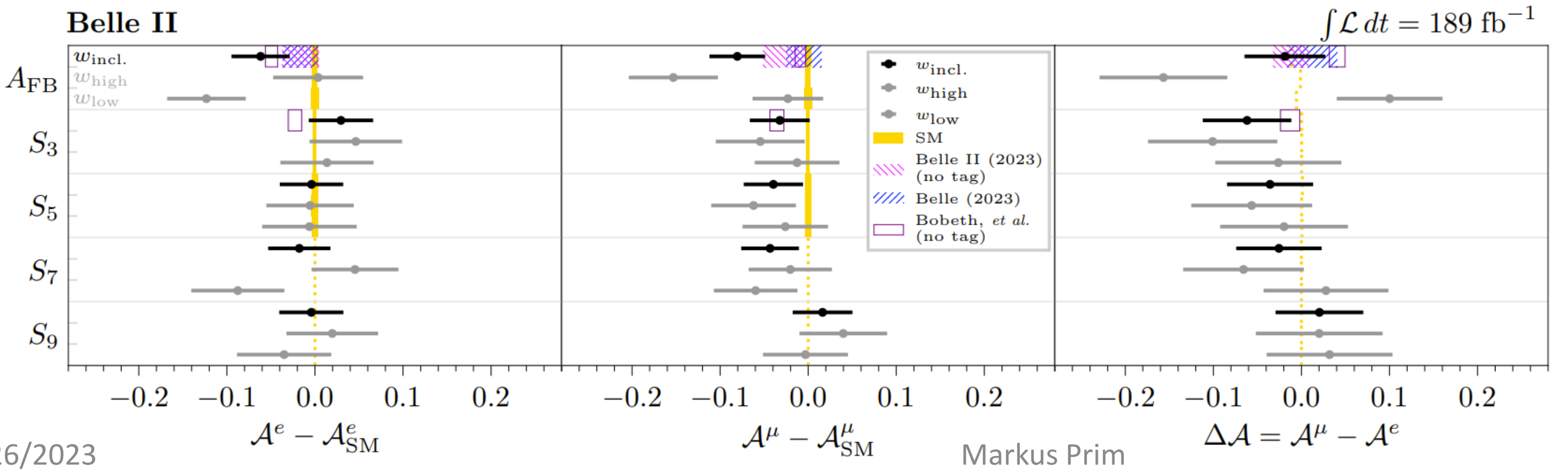
Overview on $|V_{cb}|$



Angular Coefficients of $B \to D^* \ell \bar{\nu}_\ell$







$$\left\langle S_i^{(\ell)} \right\rangle \equiv \frac{\left\langle J_i^{(\ell)} \right\rangle + \left\langle \bar{J}_i^{(\ell)} \right\rangle}{\Gamma^{(\ell)} + \bar{\Gamma}^{(\ell)}},$$

Backup

$B \to D^* \ell \bar{\nu}_\ell$ Form Factor Parameterizations

$m_\ell = 0$: $h_{A_1}(w)$ and the form factor ratios $R_1(w) = \frac{h_V}{h_{A_1}}$ and $R_2(w) = \frac{h_{A_3} + r^* h_{A_2}}{h_{A_1}}$

Boyd-Grinstein-Lebed (BGL)

- applies a conformal transformation to approximate the form factors as a series expansion
- parameterize the form factors in terms of $\{a_n, b_n, c_n\}$ expansion coefficients

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{n_a} a_n z^n$$

$$z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

$$f(z) = \frac{1}{P_f(z)\phi_f(z)} \sum_{n=0}^{n_b} b_n z^n$$

$$F_1(z) = \frac{1}{P_{F_1}(z)\phi_{F_1}(z)} \sum_{n=0}^{n_c} c_n z^n \qquad c_0 = \left(\frac{(m_B - m_{D^*})\phi_{F_1}(0)}{\phi_f(0)}\right) b_0$$

Caprini-Lellouch-Neubert (CLN)

- incorporates quark model inputs from QCD sum rules
- obtains a prediction for a z expansion of h_{A_1}, with coefficients depending only on a slope parameter ρ^2, and normalizations $R_1(1)$ and $R_2(1)$

$$h_{A_1}(z) = h_{A_1}(w=1) \times (1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3)$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

$$\frac{d\widehat{\Gamma}^{(\ell)}}{dw} \equiv \frac{1}{2}\frac{d(\Gamma^{(\ell)}+\bar{\Gamma}^{(\ell)})}{dw}, \tag{3}$$

$$\frac{1}{\widehat{\Gamma}^{(\ell)}}\frac{d\widehat{\Gamma}^{(\ell)}}{d\cos\theta_\ell} = \frac{1}{2} + \left\langle A_{\mathrm{FB}}^{(\ell)}\right\rangle \cos\theta_\ell + \frac{1}{4}\left(1-3\left\langle \widetilde{F}_L^{(\ell)}\right\rangle\right)\frac{3\cos^2\theta_\ell - 1}{2}, \tag{4}$$

$$\frac{1}{\widehat{\Gamma}^{(\ell)}}\frac{d\widehat{\Gamma}^{(\ell)}}{d\cos\theta_D} = \frac{3}{4}\left(1-\left\langle F_L^{(\ell)}\right\rangle\right)\sin^2\theta_D + \frac{3}{2}\left\langle F_L^{(\ell)}\right\rangle\cos^2\theta_D, \tag{5}$$

$$\frac{1}{\widehat{\Gamma}^{(\ell)}}\frac{d\widehat{\Gamma}^{(\ell)}}{d\chi} = \frac{1}{2\pi} + \frac{2}{3\pi}\left\langle S_3^{(\ell)}\right\rangle\cos 2\chi + \frac{2}{3\pi}\left\langle S_9^{(\ell)}\right\rangle\sin 2\chi, \tag{6}$$