Taming second order power corrections and updated predictions for $R(D^{(*)})$ and $R(\Lambda_c)$ within and beyond the Standard Model

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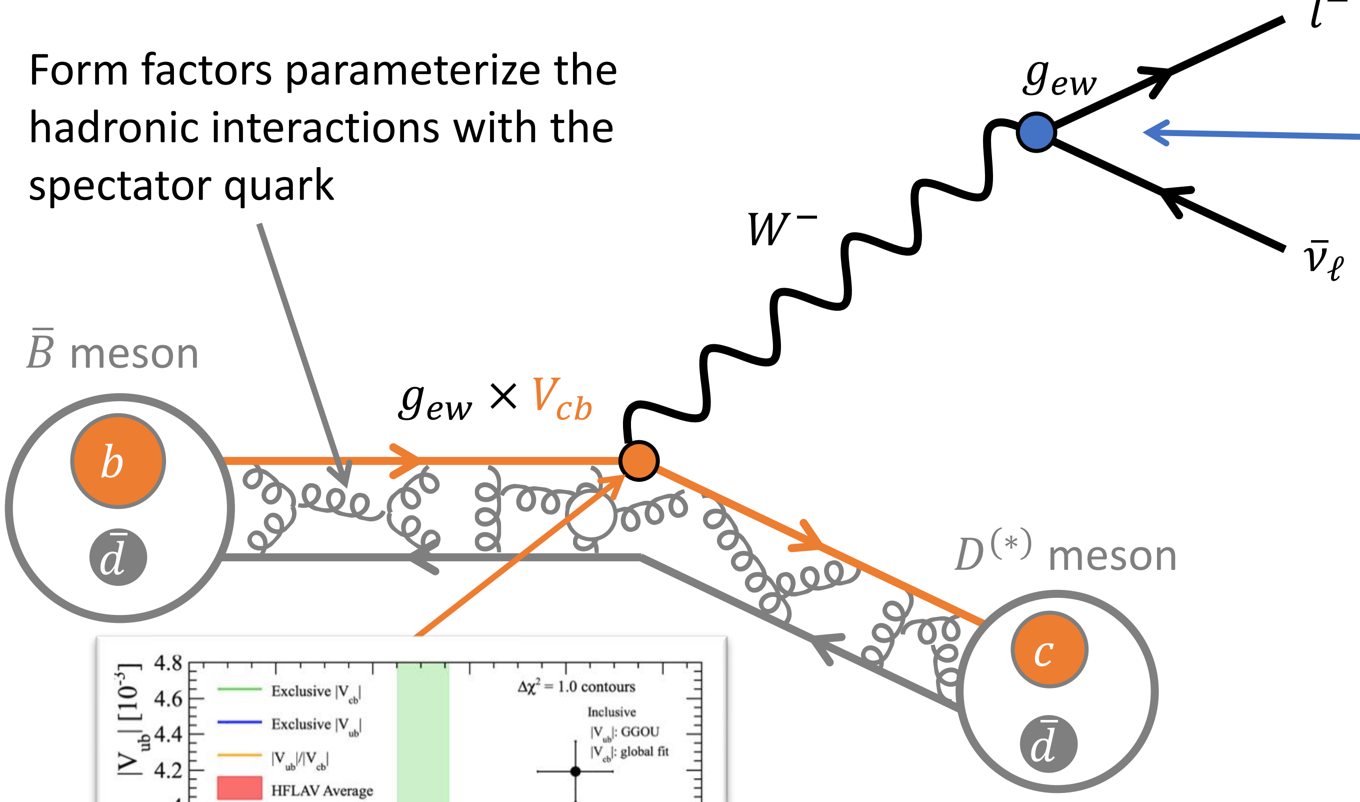
Emmy Noether-Programm

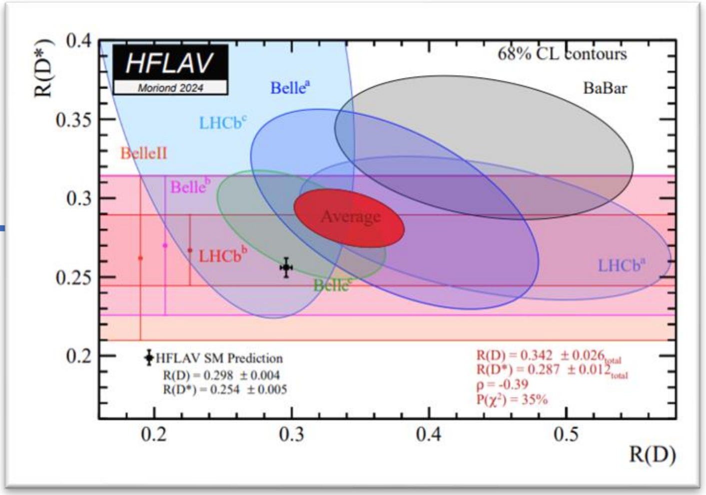
DFG Deutsche Forschungsgemeinschaft

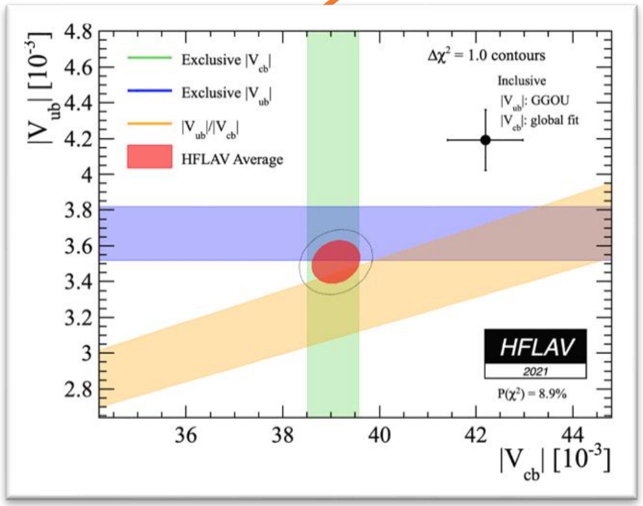
The $\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell$ decay

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)} \tau \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell)}$$

Form factors parameterize the hadronic interactions with the spectator quark





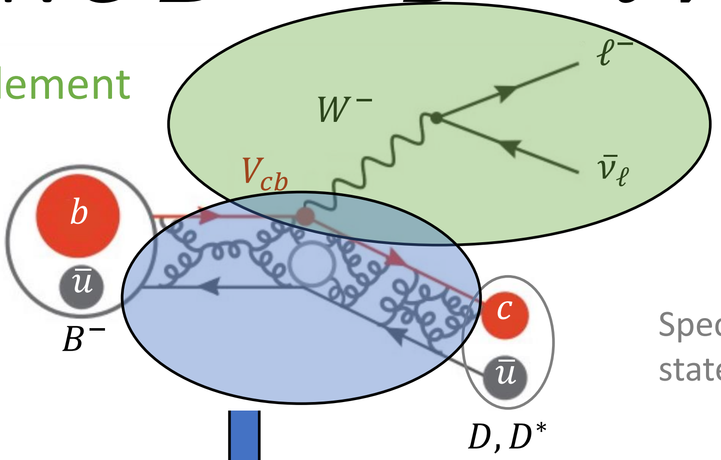


Good understanding of the form factors is crucial for precise predictions and determinations of observables

$R(D^{(*)})$, A_{FB}, $P_\tau(D^{(*)})$, $F_{L,\tau}(D^{(*)})$, $|V_{cb}|$

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

Leptonic Matrix Element



Specific final state meson

$$\Gamma(B \to D\ell\bar{\nu}_\ell) \propto |V_{cb}|^2 \mathcal{G}(1) \qquad \mathcal{G}(1) = h_+(1)$$

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

Hadronic Matrix Elements can not be calculated from first principles

→ Can be parameterized with form factors $h_X = h_X(w)$ and extracted from data

→ Theory must provide (at least) inputs on their normalization

$$\frac{\langle D(p')|\bar{c}\gamma^\mu b|B(p)\rangle}{\sqrt{m_B m_D}} = h_+(v+v')^\mu + h_-(v-v')^\mu$$

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

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

Heavy Quark Symmetry Basis

Form factors in the framework of HQET:
$B \to D\ell\bar{\nu}_\ell$ and
$B \to D^*\ell\bar{\nu}_\ell$ are linked!

Form Factors for $\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell$

Expansion to order $\mathcal{O}\left(1/m_{b,c}^{(2)}\right), \mathcal{O}(1/(m_b m_c))$

$$\frac{\langle H_c | \bar{c} \Gamma b | H_b \rangle}{\sqrt{m_{H_c} m_{H_b}}} \propto 1 + \underbrace{\frac{1}{2m_c} + \frac{1}{2m_b}}_{+3} + \overbrace{\underbrace{\frac{1}{4m_c^2}}_{+20} + \frac{1}{2m_b^2} + \frac{1}{4m_c m_b}}^{+32}$$

$\eta(w), \chi_2(w), \chi_3(w)$

Proliferation of non-perturbative parameters

Residual Chiral Expansion for $\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell$

Expansion to order $\mathcal{O}\left(1/m_{b,c}^{(2)}\right)$, $\mathcal{O}(1/(m_b m_c))$

$$\frac{\langle H_c|\bar{c}\Gamma b|H_b\rangle}{\sqrt{m_{H_c} m_{H_b}}} \propto 1 + \underbrace{\frac{1}{2m_c} + \frac{1}{2m_b}}_{+3} + \overbrace{\underbrace{\frac{1}{4m_c^2}}_{+20 \to +1} + \frac{1}{2m_b^2} + \frac{1}{4m_c m_b}}^{+32 \to +3}$$

$\varphi_1(w), \beta_2(w), \beta_3(w)$ (+32 → +3)

$\eta(w), \chi_2(w), \chi_3(w)$ (+3)

$\varphi_1(w)$ (+20 → +1)

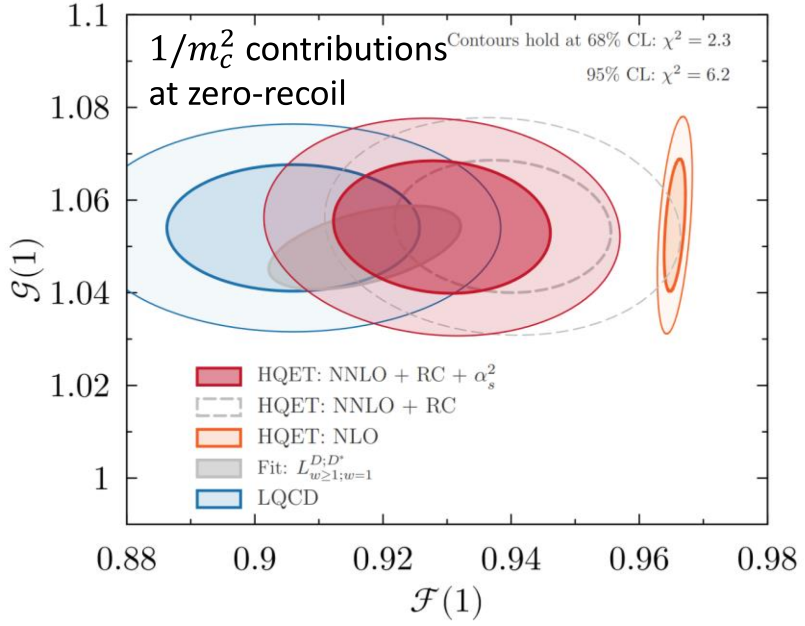
Number of Isgur-Wise functions under control

Supplemental power counting in θ based on the transverse residual momentum $\gamma_\mu D_\perp^\mu$

RCE conjecture: Matrix elements involving (many) $D_\perp$ OP insertions are typically small. Truncation at $\mathcal{O}(\theta^2)$ captures all NLO + NNLO with zero OP insertions

→ Drastic reduction of the non-perturbative parameters of the surviving Isgur-Wise functions

NNLO corrections are sizeable!



Residual Chiral Expansion for $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$

Expansion to order $\mathcal{O}\left(1/m_{b,c}^{(2)}\right)$, $\mathcal{O}(1/(m_b m_c))$

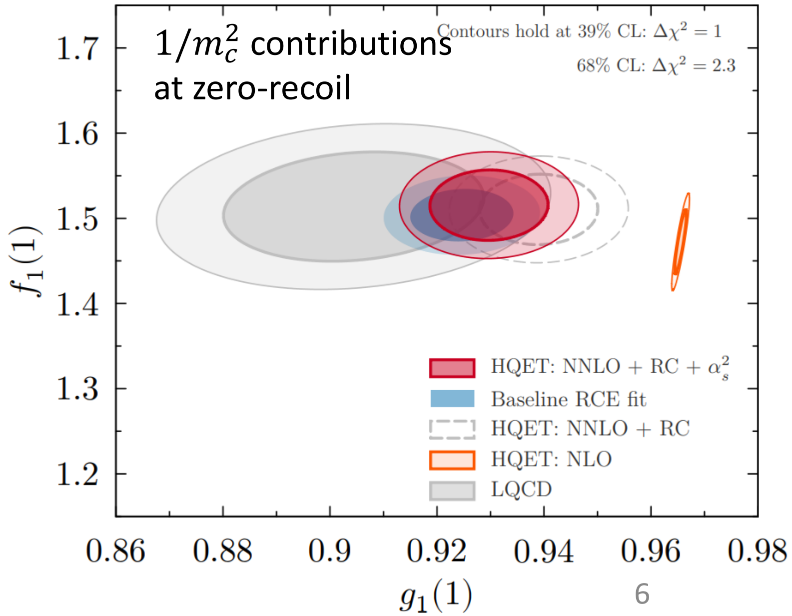
$$\frac{\langle H_c|\bar{c}\Gamma b|H_b\rangle}{\sqrt{m_{H_c} m_{H_b}}} \propto 1 + \underbrace{\frac{1}{2m_c} + \frac{1}{2m_b}}_{+0} + \overbrace{\underbrace{\frac{1}{4m_c^2}}_{\substack{+2 \to +1 \\ \varphi_1(w)}} + \frac{1}{2m_b^2} + \frac{1}{4m_c m_b}}^{\substack{\varphi_1(w) \\ +5 \to +1}}$$

The same power counting can and was applied to the $\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$ decay

→ An alternative process to test the RC:

Fit all IW functions vs. the subset surviving the RC

NNLO corrections are sizeable!



Parameterization of the IW functions

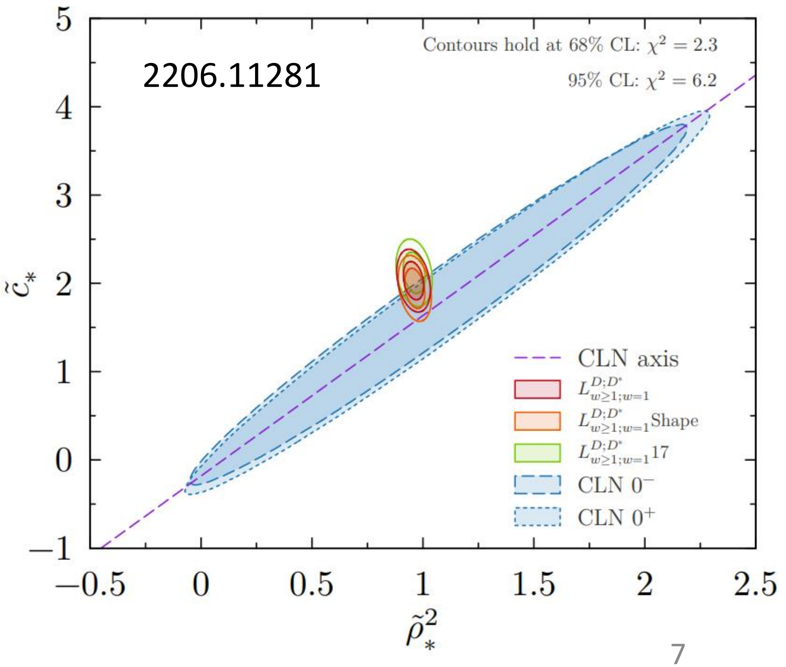
- Parameterization required to fit the experimental/lattice data
- Leading order IW function expressed wrt. to the conformal map $w \to z_*$

$$\frac{\xi(w)}{\xi(w_0)} = 1 - 8a^2\rho_*^2 z_* + 16(2c_* a^4 - \rho_*^2 a^2)z_*^2 + \cdots$$

Slope at w_0 Curvature at w_0 Conformal parameter $z_*(w), z_*(w_0) = 0$

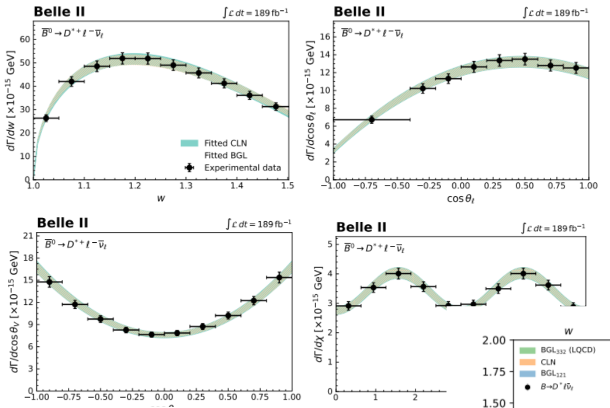
No CLN-type major-axis approximation

- (Sub-)Subleading IW functions $X(w) = X(1) + X'(1)(w-1) + \cdots$
- This still yields to many free parameters ⇒ overfitting/biases
- How to truncate? ⇒ Akaike information Criterion (AIC)



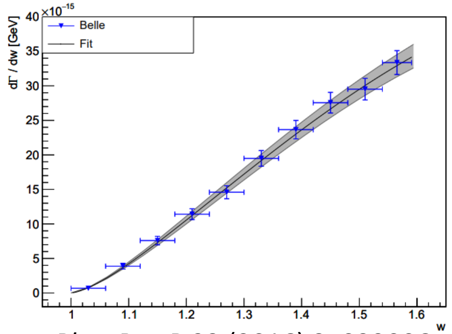
Confronting theory with lattice and exp. data

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

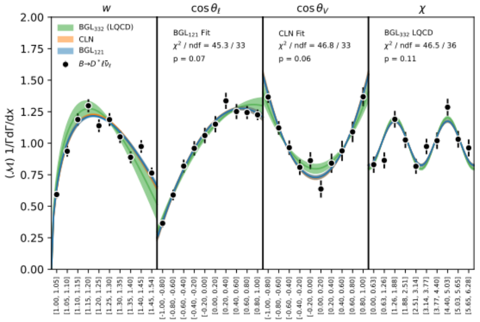


Phys.Rev.D 108 (2023) 9, 9

New input, Belle II untagged measurement replaces Belle untagged measurement



Phys.Rev.D 93 (2016) 3, 032006



Phys.Rev.D 108 (2023) 1, 012002

Lattice Inputs

Phys.Rev.D 92 (2015) 3, 034506, *Eur.Phys.J.C* 82 (2022) 12, 1141, *Eur.Phys.J.C* 83 (2023) 1, 21 (erratum)

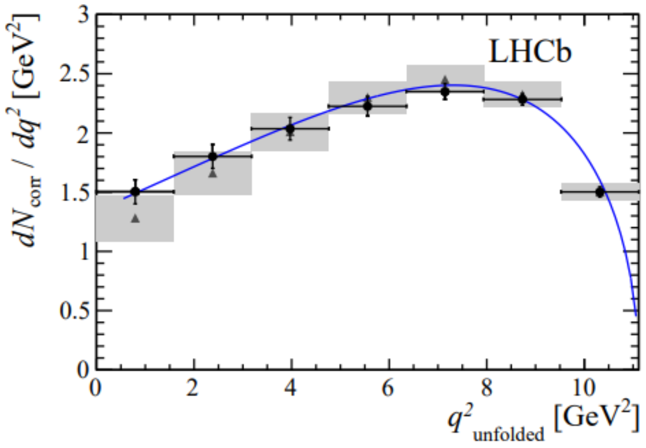
Phys.Rev.D 109 (2024) 9, 094515

Phys.Rev.D 109 (2024) 7, 074503

HFLAV isospin averages for $\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell$

Now also using isospin average for $\bar{B} \to D^{(*)} \ell \bar{\nu}_\ell$

$\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$



Phys.Rev.D 96 (2017) 11, 112005

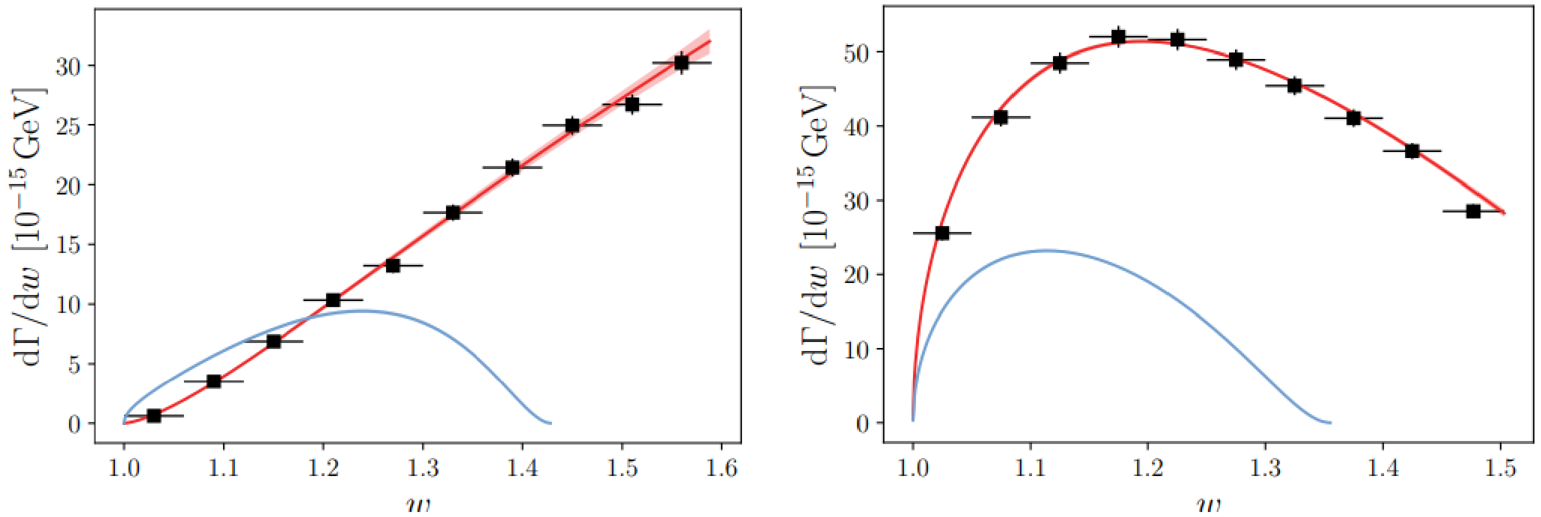
Lattice Inputs

Phys.Rev.D 92 (2015) 3, 034503

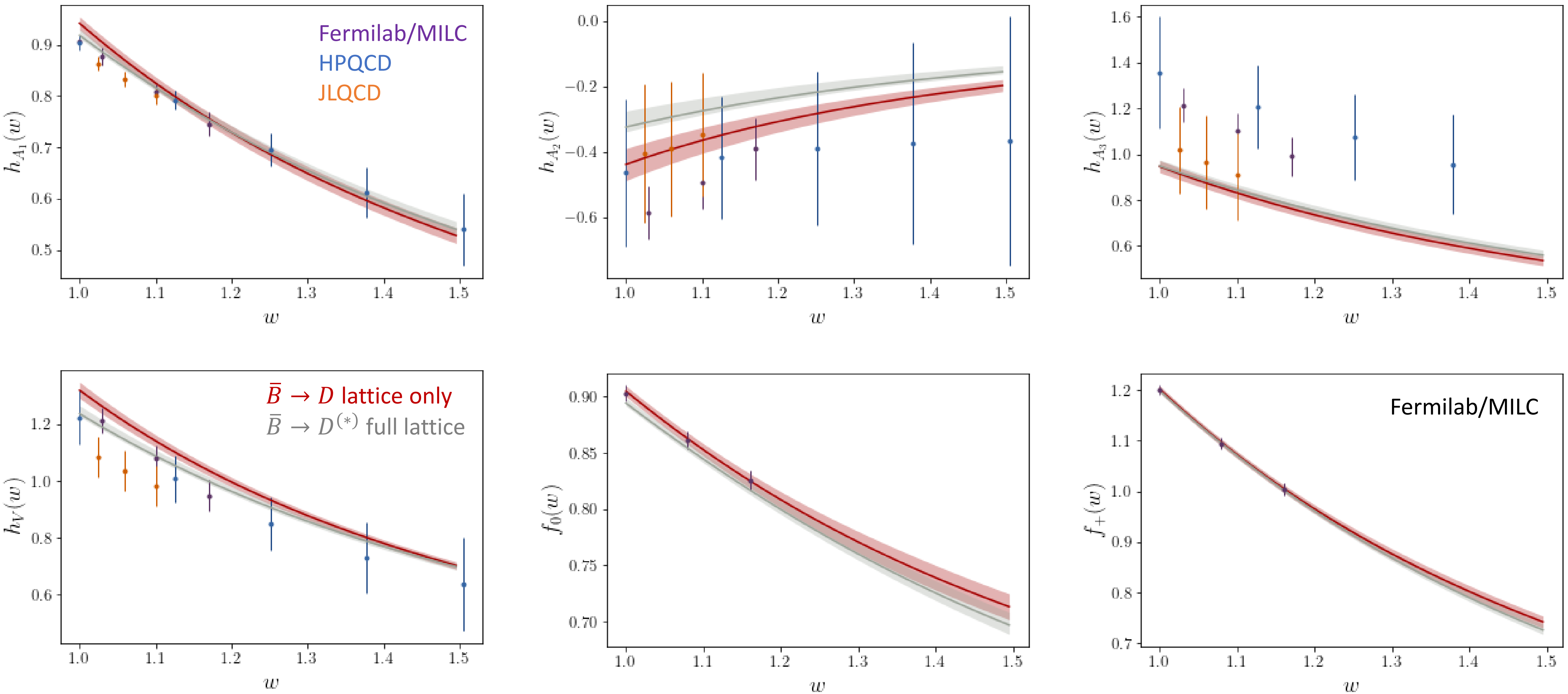
$\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$ fitted w-spectra

- Fitted are the w spectra, the $\bar{B} \to D$ lattice (and the $\bar{B} \to D^*$ lattice)
- The expansion parameters for the Isgur-Wise functions are determined based on AIC
  - entering at zero-recoil: $|V_{cb}|$, m_b^{1S}, δm_{bc}, ρ_1, λ_2, ρ_*^2, c_*, D, $\hat{\eta}(1)$
  - and beyond: $\hat{\eta}'(1)$, $\hat{\chi}_2(1)$, $\hat{\chi}_2'(1)$, $\hat{\chi}_3'(1)$, $\hat{\varphi}_1'(1)$, $\hat{\beta}_2(1)$, $\hat{\beta}_3'(1)$

Leading order Isgur-Wise function at $\mathcal{O}(z_*^3)$ (no major axis approximation)



$\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$ fitted form factors



$|V_{cb}|$ from $\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$

Using the w-spectra and only the $\bar{B} \to D$ LQCD we find

$$|V_{cb}| = (38.6 \pm 0.5) \times 10^{-3}$$

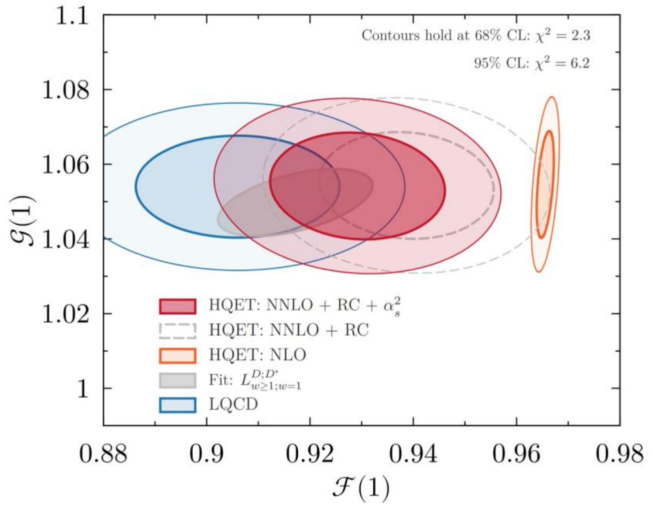
Inputs → Slide 8

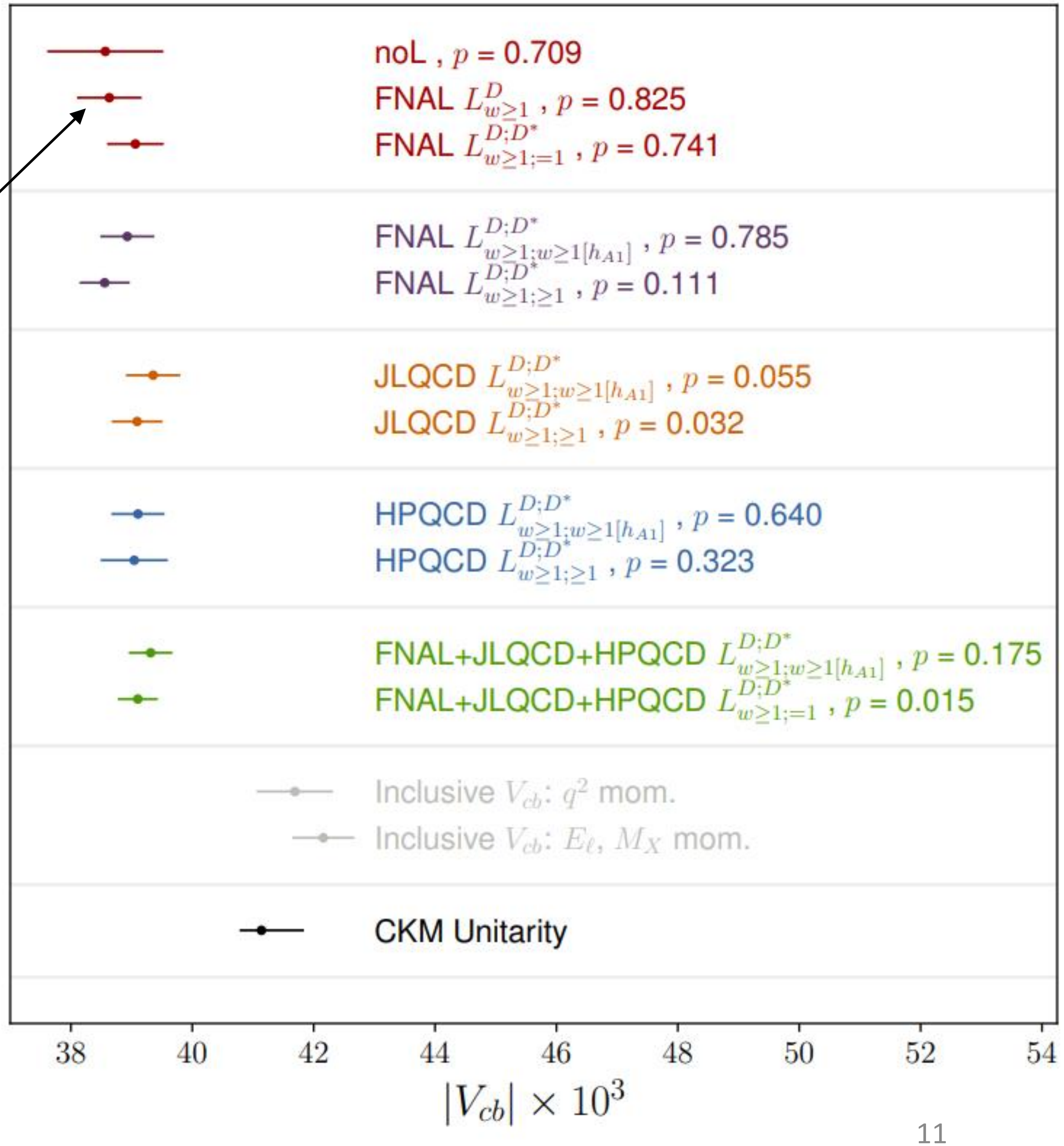
Reminder:

$$\Gamma(B \to D\ell\bar{\nu}_\ell) \propto |V_{cb}|^2 \mathcal{G}(1)$$

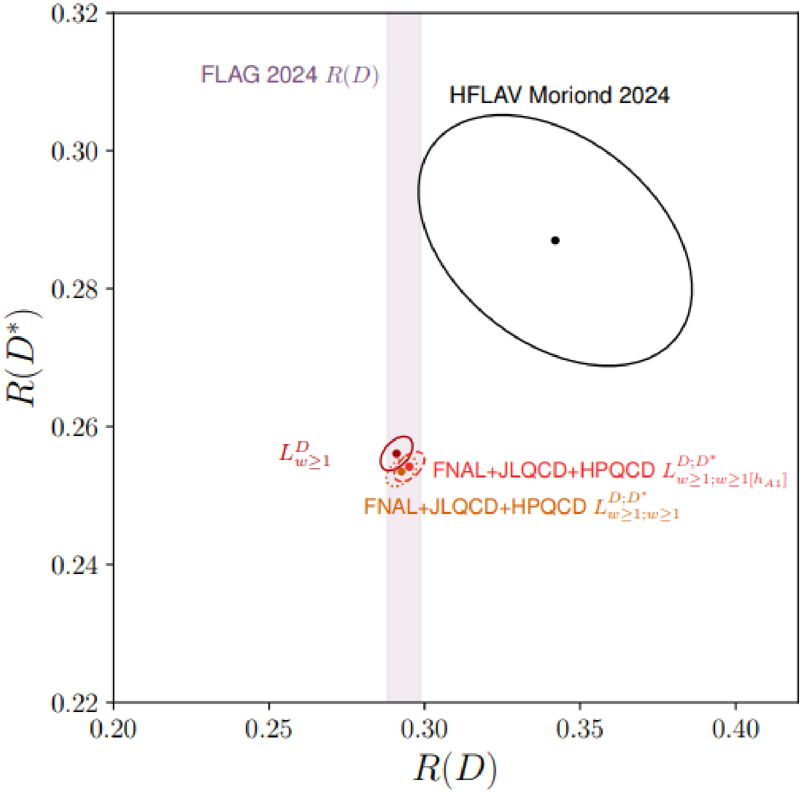
$$\Gamma(B \to D^*\ell\bar{\nu}_\ell) \propto |V_{cb}|^2 \mathcal{F}(1)$$

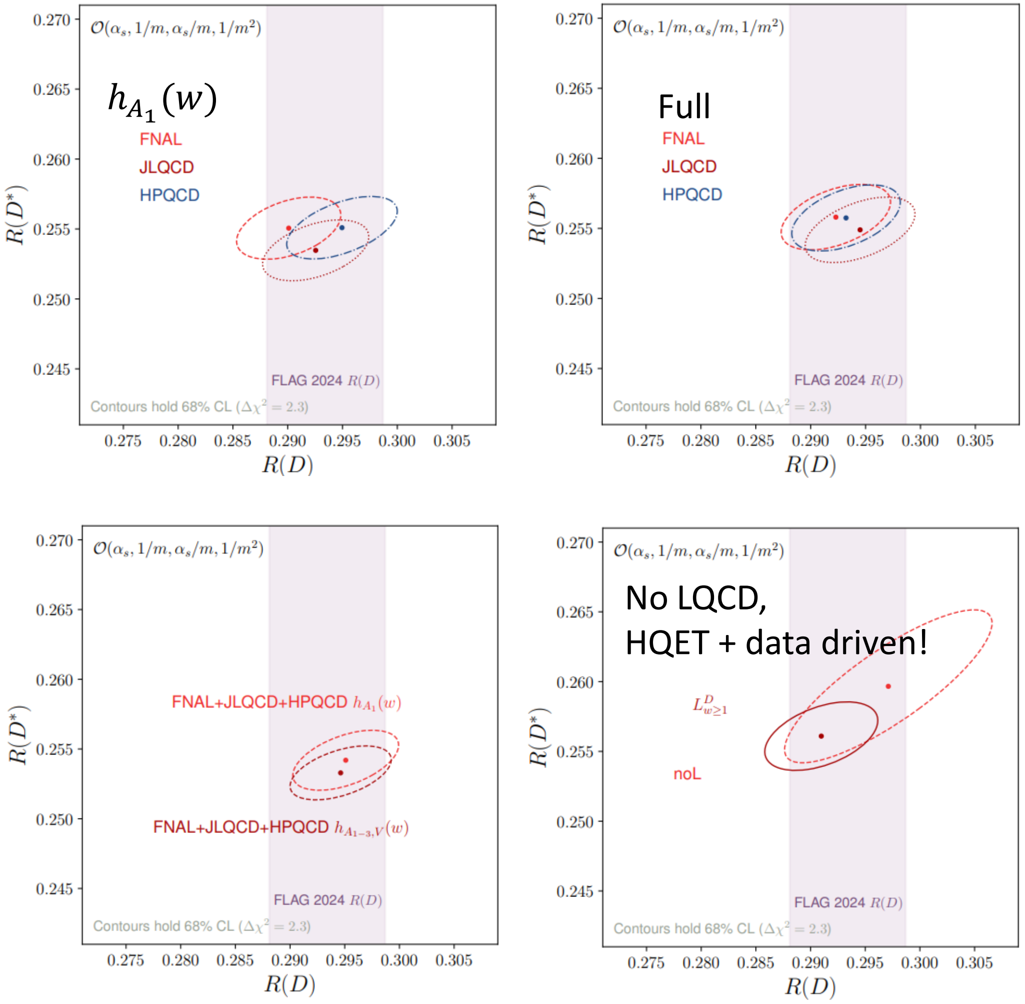
HQET (+ LQCD) yields a larger $\mathcal{F}(1)$, and thus $|V_{cb}|$ is smaller





Predictions for $R(D^{(*)})$



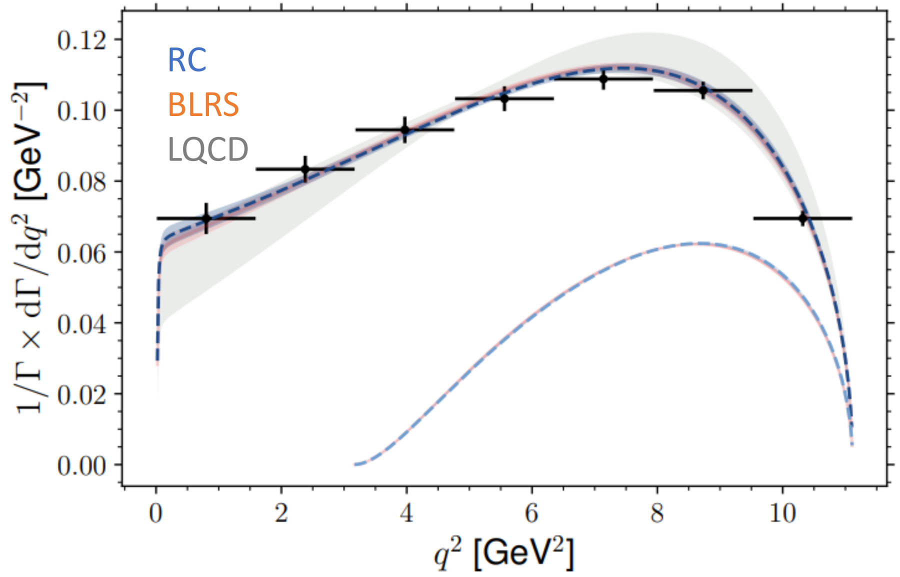


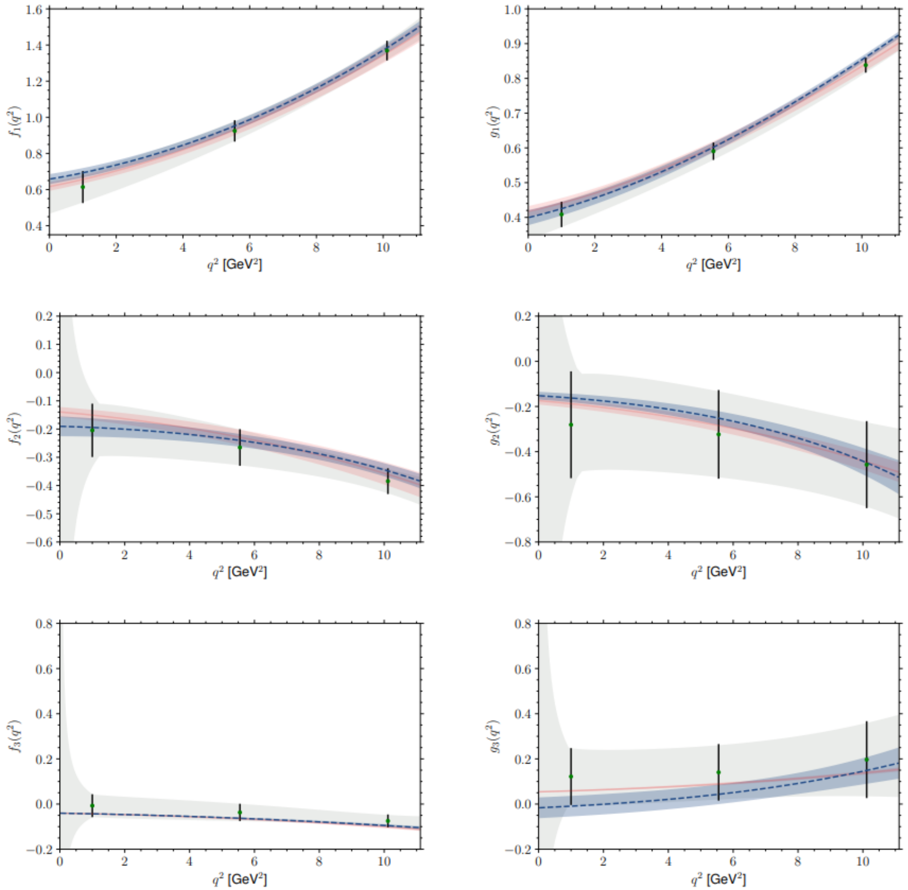
Using the w-spectra and only the $\bar{B} \to D$ LQCD we find

Inputs → Slide 8

$$\boldsymbol{R(D) = 0.291 \pm 0.003,}$$
$$\boldsymbol{R(D^*) = 0.256 \pm 0.002,}$$
$$\boldsymbol{\rho = 0.457}$$

$\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$ fitted w-spectra and form factors





Using the w-spectra and LQCD we find
$\boldsymbol{R(\Lambda_c) = 0.325 \pm 0.004}$ Inputs → Slide 8

Does the RC work? → Result in agreement with
BLRS $R(\Lambda_c) = 0.323 \pm 0.004$

Summary & Conclusion

- **Residual Chiral Expansion** allows us to fit NNLO HQET in exclusive $b \to c\ell\bar{\nu}_\ell$ decays
  - $1/m^2$ corrections are important to match HQET result to LQCD result
- Updated $|V_{cb}|$ and $R(D^{(*)})$ with new experimental and lattice data for $B \to D^{(*)}\ell\bar{\nu}_\ell$
  - Results stable with new lattice / experimental data
  - No significant changes with respect to previous result
- Updated $R(\Lambda_c)$ provides an independent decay to test the RC
  - RC results compatible with other approaches

$|V_{cb}|$
$= (38.6 \pm 0.5) \times 10^{-3}$

$R(D) = 0.291 \pm 0.003$
$R(D^*) = 0.256 \pm 0.002$
$\rho = 0.457$ using $f_{+/0}(w)$

$R(\Lambda_c) = 0.325 \pm 0.004$

Backup

$\bar{B} \to D^{(*)}$ form factors

$\bar{B} \to D^{(*)}$ form factors are described by two (four) form factors in the SM.
Key idea: Exploit expansion of $\bar{B} \to D^{(*)}$ form factors into leading $\hat{h}(w) = h(w)/\xi(w)$ and sub-leading $\mathcal{O}(1/m_{b,c}^{(2)})$ and $\mathcal{O}(1/(m_b m_c))$ Isgur-Wise functions.

$$\hat{h}_+ = 1 + \hat{\alpha}_s \left[C_{V_1} + \frac{w+1}{2}(C_{V_2} + C_{V_3}) \right] + \sum_{Q=c,b} \varepsilon_Q \hat{L}_1^{(Q)} - \varepsilon_c \varepsilon_b \hat{M}_8 ,$$

$$\hat{h}_- = \hat{\alpha}_s \frac{w+1}{2}(C_{V_2} - C_{V_3}) + \varepsilon_c \hat{L}_4^{(c)} - \varepsilon_b \hat{L}_4^{(b)} ,$$

$$\hat{h}_V = 1 + \hat{\alpha}_s C_{V_1} + \varepsilon_c [\hat{L}_2^{(c)} - \hat{L}_5^{(c)}] + \varepsilon_b [\hat{L}_1^{(b)} - \hat{L}_4^{(b)}] + \varepsilon_c \varepsilon_b \hat{M}_9 ,$$

$$\hat{h}_{A_1} = 1 + \hat{\alpha}_s C_{A_1} + \varepsilon_c \left(\hat{L}_2^{(c)} - \hat{L}_5^{(c)} \frac{w-1}{w+1} \right) + \varepsilon_b \left(\hat{L}_1^{(b)} - \hat{L}_4^{(b)} \frac{w-1}{w+1} \right) + \varepsilon_c \varepsilon_b \hat{M}_9 ,$$

$$\hat{h}_{A_2} = \hat{\alpha}_s C_{A_2} + \varepsilon_c [\hat{L}_3^{(c)} + \hat{L}_6^{(c)}] - \varepsilon_c \varepsilon_b \hat{M}_{10} ,$$

$$\hat{h}_{A_3} = 1 + \hat{\alpha}_s (C_{A_1} + C_{A_3}) + \varepsilon_c [\hat{L}_2^{(c)} - \hat{L}_3^{(c)} + \hat{L}_6^{(c)} - \hat{L}_5^{(c)}] + \varepsilon_b [\hat{L}_1^{(b)} - \hat{L}_4^{(b)}] + \varepsilon_c \varepsilon_b [\hat{M}_9 + \hat{M}_{10}] ,$$

The $\bar{B} \to D$ and $\bar{B} \to D^*$ form factors are not independent but linked via $\hat{L}$ and $\hat{M}$.