STATUS OF STANDARD MODEL PREDICTIONS FOR $R_{D^{(*)}}$

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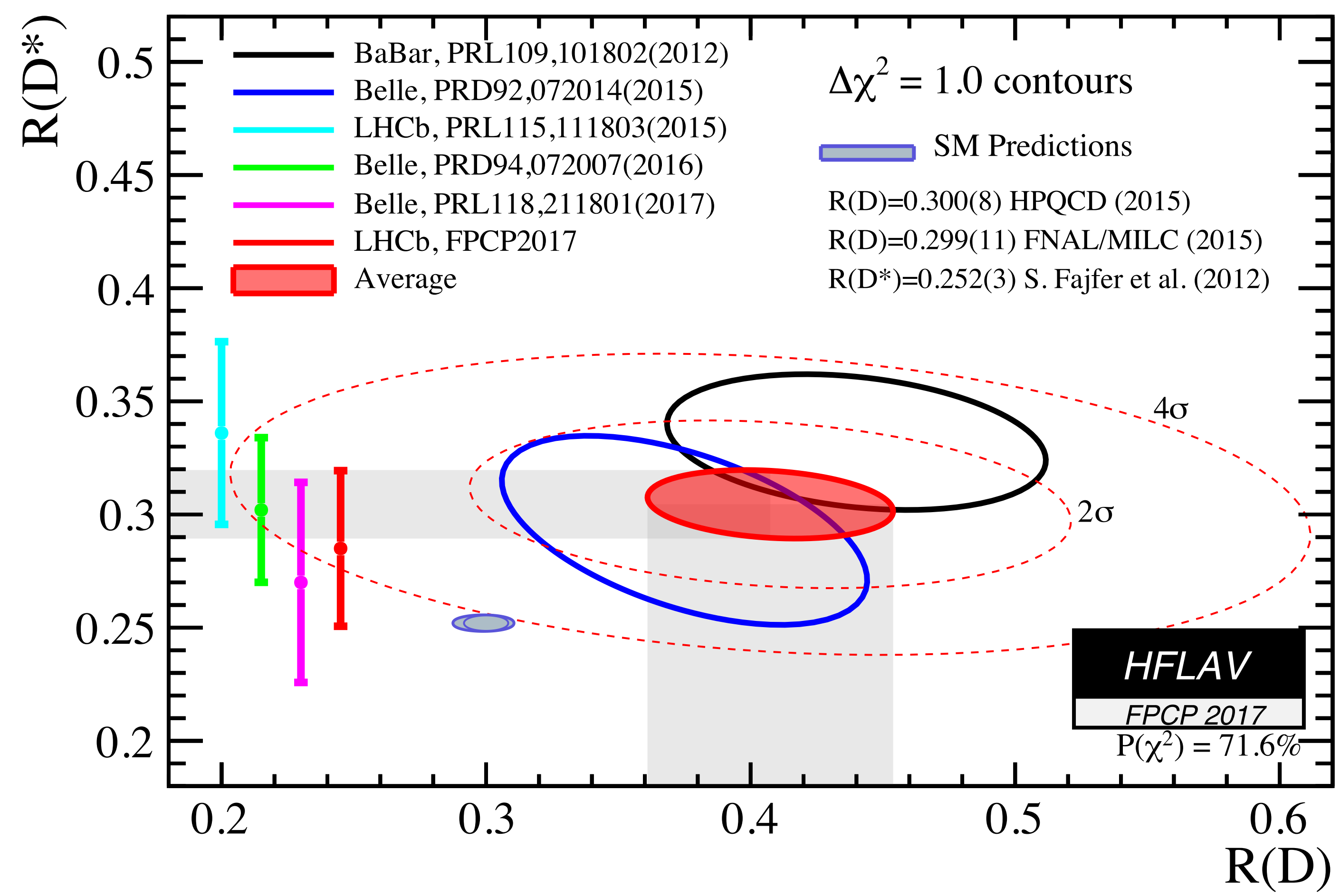
1703.05330
1708.07134

LEPTON UNIVERSALITY VIOLATION?

- Deviations in B→ $D^{(*)}\tau\nu$ decays found in multiple measurements over the last years, almost 4σ disagreeme with SM prediction

- Other hints of lepton universality violations in other decay modes



$$\mathrm{R}(J/\psi)|_{exp} = \frac{\mathrm{BR}(B_c \to J/\psi\,\tau\,\nu)}{\mathrm{BR}(B_c \to J/\psi\,\ell\,\nu)} = 0.71 \pm 0.17 \pm 0.18 \qquad vs \qquad \mathrm{R}(J/\psi)|_{th} = 0.25 - 0.28$$

$$\mathrm{R}(K)|_{exp} = \frac{\mathrm{BR}(B \to K\,\mu\,\mu)}{\mathrm{BR}(B \to K\,e\,e)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \qquad vs \qquad R(K)|_{exp} = 1.00 \pm 0.01$$

Is it New Physics? Interesting BSM interpretations → see talks in later sessions

R(D), R(D*), V_{CB}, …

- To assess discrepancy one need up-to-date predictions for the SM, with careful assessment of theoretical uncertainties
- Uncertainties come from form factors
  - FFs determined by combination of
    - data
    - lattice QCD
    - theoretical modeling
  - subset of FFs affect also V_{cb} exclusive determination and long standing discrepancy there between exclusive and inclusive determinations

B→D, D* DECAYS: NOTATION

$$\frac{\mathrm{d}\Gamma(\overline{B}\to Dl\nu)}{\mathrm{d}w} = \frac{G_F^2|V_{cb}|^2\,\eta_{\mathrm{EW}}^2\,m_B^5}{48\pi^3}\,(w^2-1)^{3/2}\,r_D^3\,(1+r_D)^2\,\mathcal{G}(w)^2\,,$$

$$\frac{\mathrm{d}\Gamma(\overline{B}\to D^*l\nu)}{\mathrm{d}w} = \frac{G_F^2|V_{cb}|^2\,\eta_{\mathrm{EW}}^2\,m_B^5}{48\pi^3}\,(w^2-1)^{1/2}\,(w+1)^2\,r_{D^*}^3(1-r_{D^*})^2$$

$$\times\left[1+\frac{4w}{w+1}\frac{1-2wr_{D^*}+r_{D^*}^2}{(1-r_{D^*})^2}\right]\mathcal{F}(w)^2\,,$$

with $r_{D^{(*)}} = m_{D^{(*)}}/m_B$ *and* $w = v\cdot v' = \dfrac{m_B^2+m_{D^{(*)}}^2-q^2}{2m_Bm_{D^{(*)}}}$

$$\mathcal{G}(w) = h_+ - \frac{1-r_D}{1+r_D}h_-\,,$$

$$\mathcal{F}(w)^2 = h_{A_1}^2\left\{2(1-2wr_{D^*}+r_{D^*}^2)\left(1+R_1\frac{w-1}{w+1}\right)+\left[(1-r_{D^*})+(w-1)\big(1-R_2\big)\right]^2\right\}$$

$$\times\left[(1-r_{D^*})^2+\frac{4w}{w+1}(1-2wr_{D^*}+r_{D^*}^2)\right]^{-1}\,,$$

$$R_1(w) = \frac{h_V}{h_{A_1}}\,,\qquad R_2(w) = \frac{h_{A_3}+r_{D^*}\,h_{A_2}}{h_{A_1}}\,.$$

R_i are angular distributions → can be accessed experimentally

$B \to D, D^*$ DECAYS: NOTATION

in case of τ decays one extra form factor in SM (more with NP)

→ define other ratios:

$$R_3(w) = \frac{h_{A_3} - r_{D^*} h_{A_2}}{h_{A_1}}\,, \qquad R_0(w) = \frac{h_{A_1}(w+1) - h_{A_3}(w - r_{D^*}) - h_{A_2}(1 - w r_{D^*})}{(1 + r_{D^*})\, h_{A_1}}$$

enter in rate suppressed by factors of m_τ^2/m_B^2

Determination of Form Factors?

THEORY INPUTS

BGL: UNITARITY CONSTRAINTS

- Boyd, Grinstein, Lebed ('95) (BGL): relate FFs to two point functions via dispersion relations, crossing symmetry, quark-hadron duality:

$$F_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{\infty} a_n z^n .$$

removes poles (Blanschke factors)

phase space factors

Taylor expand in

$$z_*(w) = \frac{\sqrt{w+1} - \sqrt{2}\,a}{\sqrt{w+1} + \sqrt{2}\,a}$$

- unitarity → constraints on a_n, e.g. for single channel: $\sum_{n=0}^{\infty} |a_n|^2 \leq 1.$

Can be used directly to fit spectra

HQET (+ UNITARITY)

- FFs are related by heavy quark symmetry (HQS)
- HQET → organize expansion in powers of α_s, Λ/m_b, Λ/m_c
- relations among form factors
- can be used to relate form factors measurements in e,μ to additional ffs in τ
- At LO: everything proportional to Isgur-Wise function ξ or 0
- At $O(\Lambda/m_b, \Lambda/m_c)$: subleading IW functions: χ_2, χ_3, η
- HQET + z-parameterization from unitarity:
  - Compute FF at $O(\alpha_s, \Lambda/m_b, \Lambda/m_c)$
  - Taylor expand IW functions

$$\frac{\mathcal{G}(w)}{\mathcal{G}(w_0)} \simeq 1 - 8a^2\rho_*^2 z_* + \left(V_{21}\rho_*^2 - V_{20}\right) z_*^2 \,.$$

$$\hat{\chi}_2(w) \simeq \hat{\chi}_2(1) + \hat{\chi}_2'(1)(w-1)\,, \qquad \hat{\chi}_3(w) \simeq \hat{\chi}_3'(1)(w-1)\,, \qquad \eta(w) \simeq \eta(1) + \eta'(1)(w-1)\,,$$

Fit input shapes to 6 parameters (3 slopes, 2 intercepts + ρ_*)

CLN: UNITARITY + HQET + QCD SUM RULES

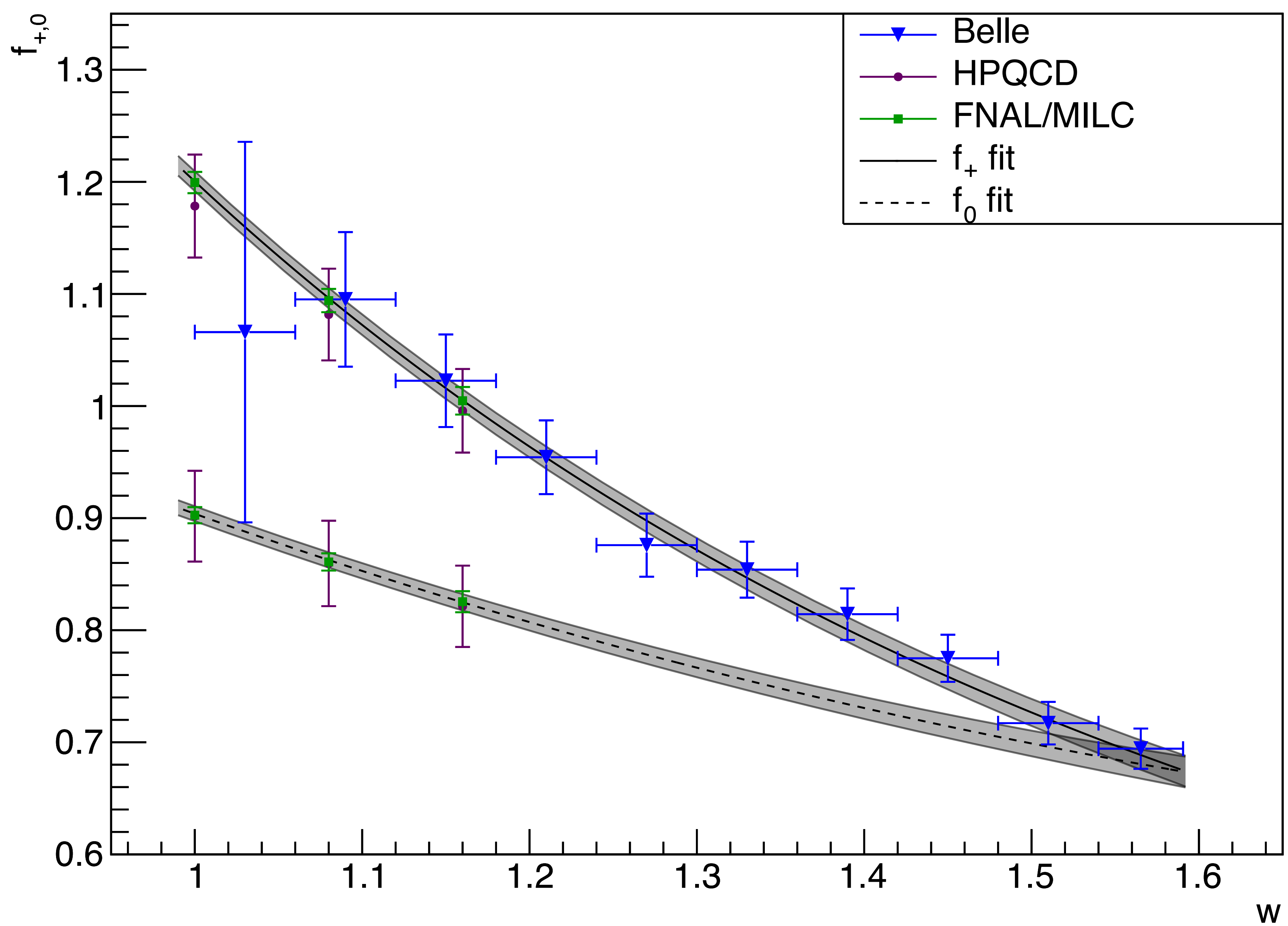
- Caprini Lellouch Neubert (CLN '98): Use NLO HQET and further constraints from QCD sum rules:
  - subleading IW functions determined
  - Only two parameters: normalization and ρ_*
  - Uncertainties small: <2% (?) → mostly neglected in experimental analyses (e.g. fix slopes to CLN prediction and float intercepts, …)

EXPERIMENTAL & LATTICE INPUTS

EXPERIMENTAL & LATTICE ACCESS TO SPECTRA

➤ B→Dlv: Belle, Lattice:

1510.03657

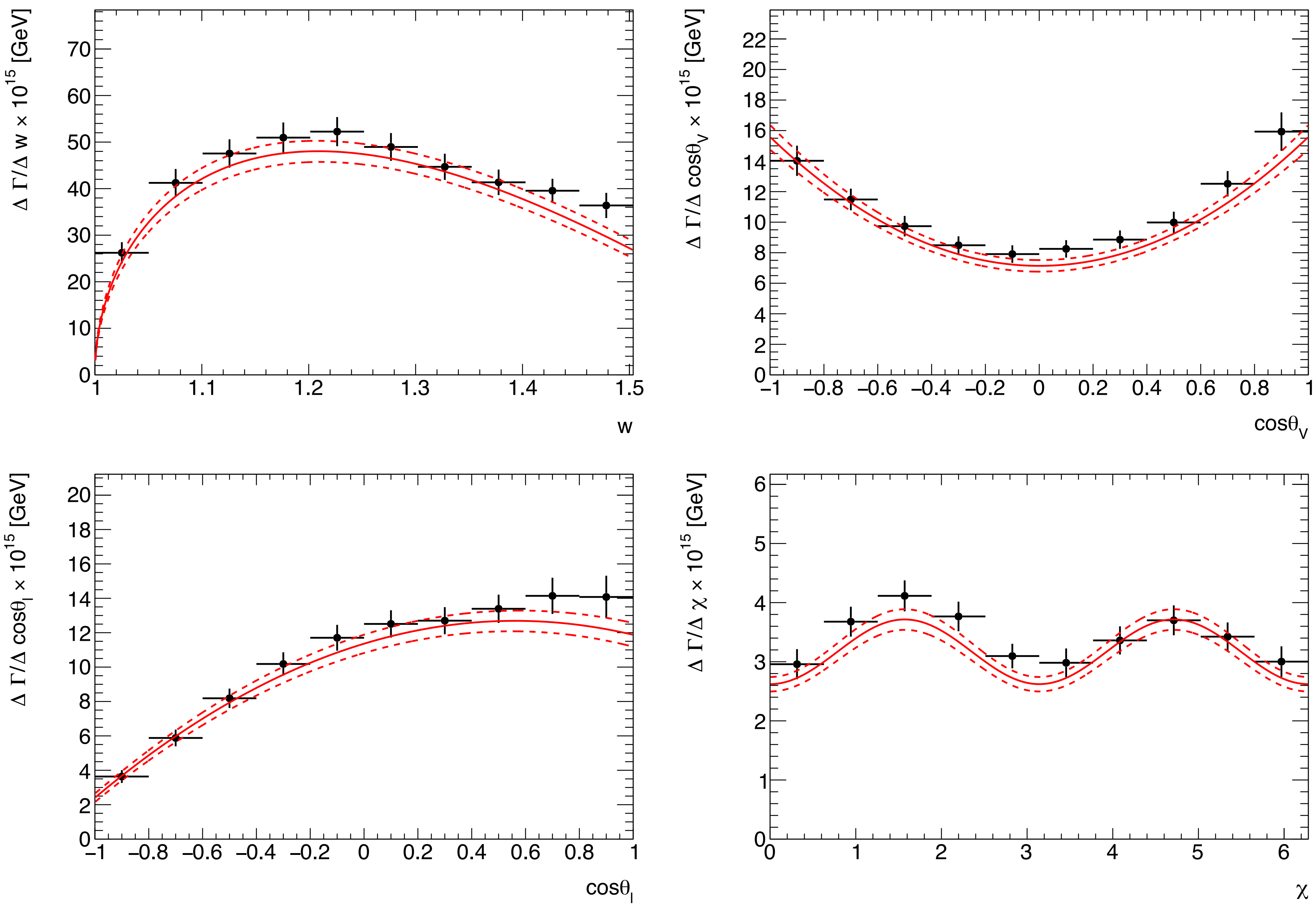


Lattice: good at small recoil, Exp: good at large recoil

EXPERIMENTAL ACCESS TO SPECTRA

- ➤ $B \to D^* l \nu$ (2017, Belle):

1702.01521



No lattice results yet for spectra (only preliminary info for finite lattice spacing)

NORMALIZATION AT ZERO RECOIL

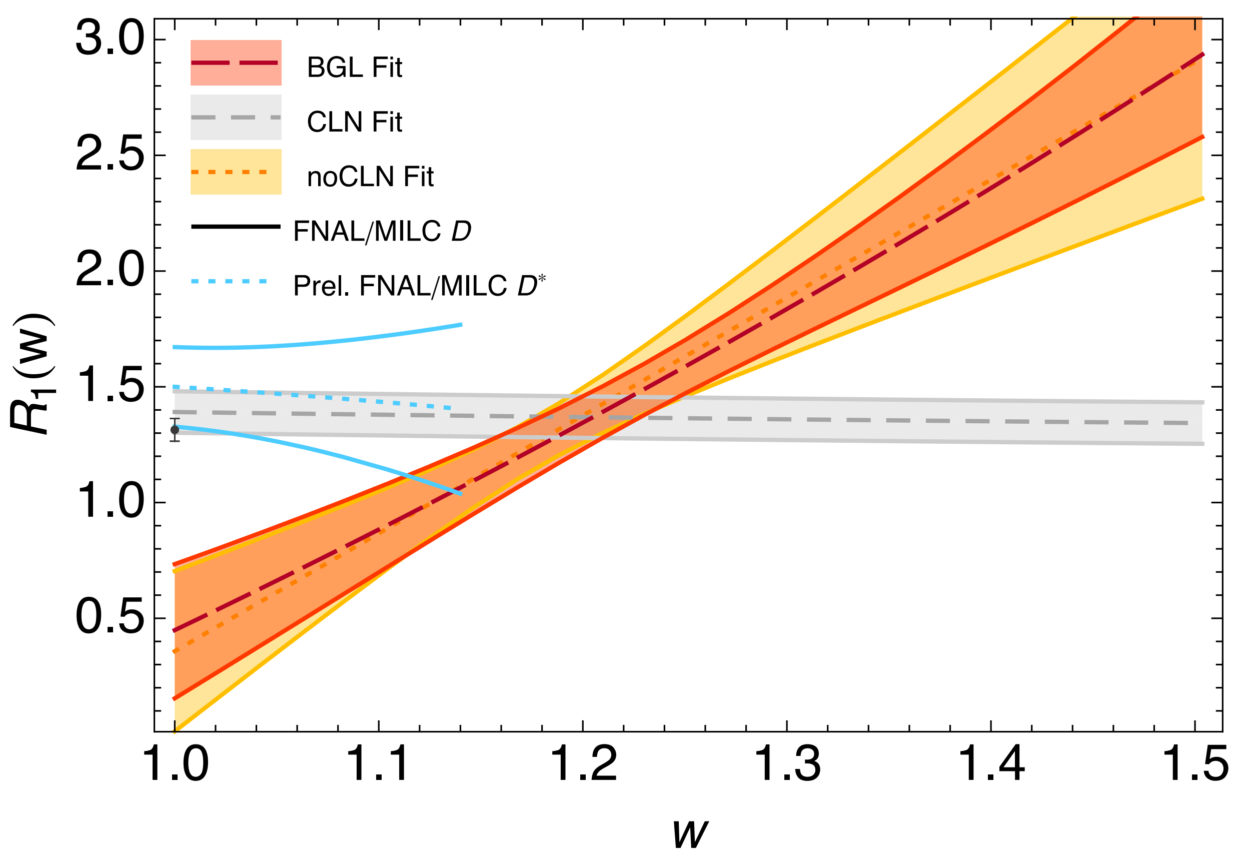
- Lattice measurements at zero recoil:

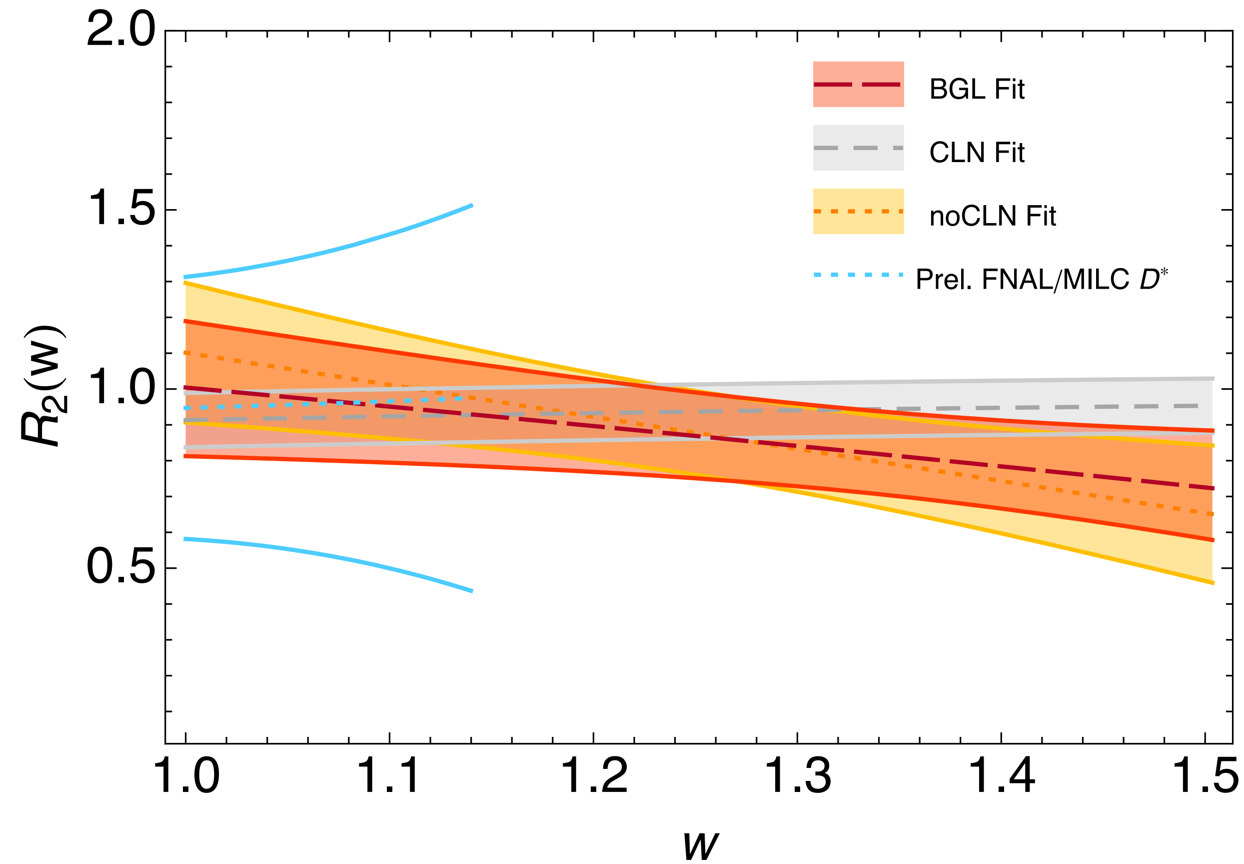
$$\mathcal{G}(1)_{\rm LQCD} = 1.054(8)\,, \qquad \mathcal{F}(1)_{\rm LQCD} = 0.906(13)\,,$$

1403.0635, 1503.07237

FIT RESULTS

BGL FIT IN B→D* USING BELLE SPECTRA





FNAL/MILC D = Lattice B→D + HQS

noCLN = fit of linearized $R_{1,2}$

- HQET predict $R_{1,2} = 1 + O(\Lambda/m_{b,c}, \alpha_s)$, slopes small
- BGL seem to suggest large HQS violations, not seen from lattice
- Using lattice to extract V_{cb}:

(if ~100% correl → more than 5σ discrepancy)

$$|V_{cb}|_{\rm CLN} = (38.2 \pm 1.5) \times 10^{-3}\,, \quad [1]\,,$$
$$|V_{cb}|_{\rm BGL} = (41.7^{+2.0}_{-2.1}) \times 10^{-3}\,, \quad [3]\,,$$
$$|V_{cb}|_{\rm BGL} = (41.9^{+2.0}_{-1.9}) \times 10^{-3}\,, \quad [4]\,.$$

- Some tension between data + lattice + HQS

OTHER FIT COMBINATIONS

Use NLO HQET and:

	Fit	QCDSR	Lattice QCD $\mathcal{F}(1)$	Lattice QCD $f_{+,0}(1)$	Lattice QCD $f_{+,0}(w>1)$	Belle Data
fix norm. to lattice zero-recoil results	$\mathrm{L}_{w=1}$	—	✓	✓	—	✓
	$\mathrm{L}_{w=1}$+SR	✓	✓	✓	—	✓
float norm. independently	NoL	—	—	—	—	✓
	NoL+SR	✓	—	—	—	✓
fit ξ to lattice B→D, use lattice for B→D norm*	$\mathrm{L}_{w\geq1}$	—	✓	✓	✓	✓
	$\mathrm{L}_{w\geq1}$+SR	✓	✓	✓	✓	✓
	th:$\mathrm{L}_{w\geq1}$+SR	✓	✓	✓	✓	—

"+SR": use QCD sum rules for priors on subleading IW functions

$$\hat{\chi}_2^{\mathrm{ren}}(1) = -0.06 \pm 0.02\,, \qquad \hat{\chi}_2'^{\,\mathrm{ren}}(1) = 0 \pm 0.02\,, \qquad \hat{\chi}_3'^{\,\mathrm{ren}}(1) = 0.04 \pm 0.02\,,$$

$$\eta(1) = 0.62 \pm 0.2\,, \qquad \eta'(1) = 0 \pm 0.2\,.$$

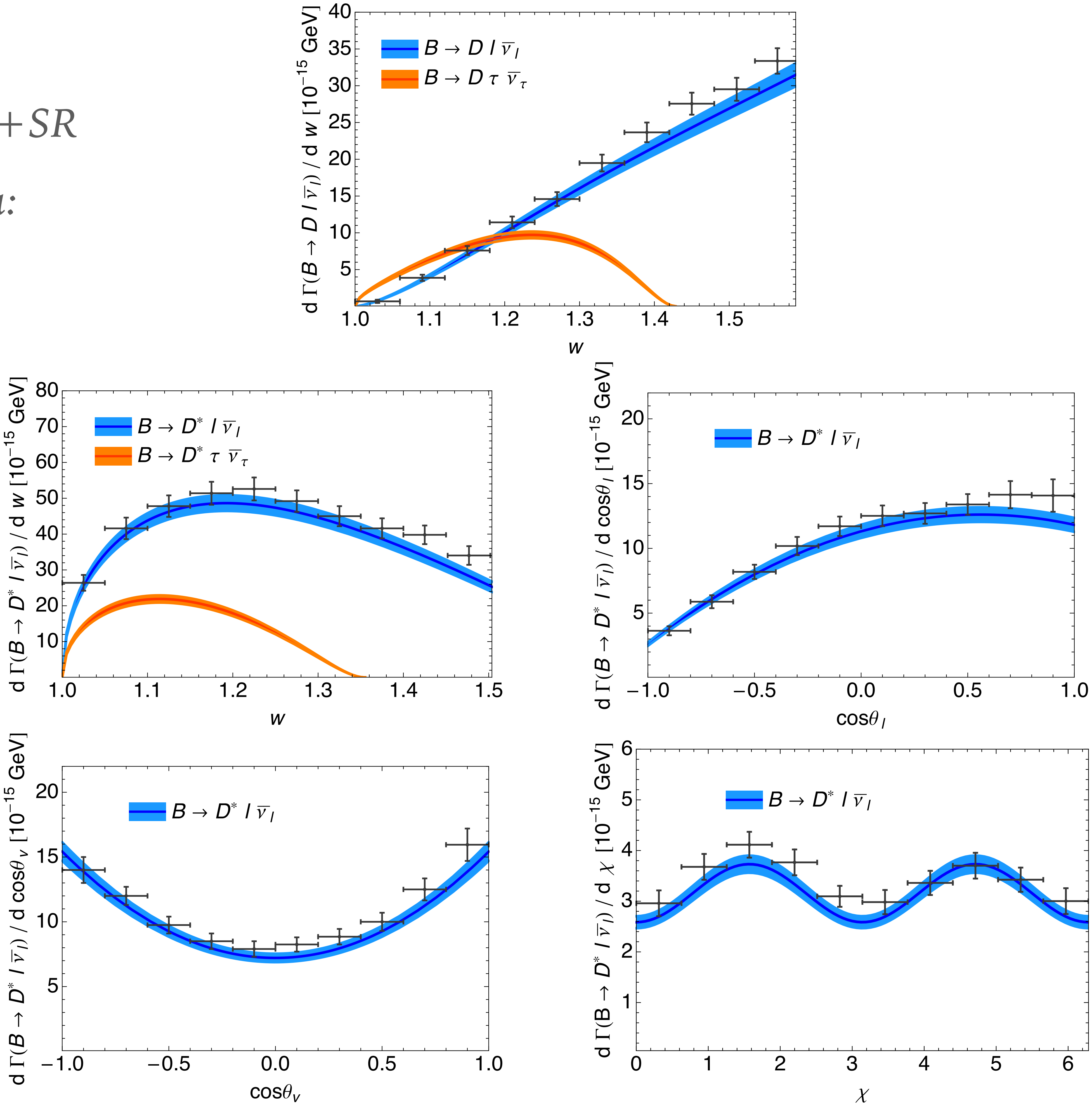
FIT RESULTS

	$L_{w=1}$	$L_{w=1}$+SR	NoL	NoL+SR	$L_{w\geq1}$	$L_{w\geq1}$+SR	th:$L_{w\geq1}$+SR
χ^2	40.2	44.0	38.7	43.1	49.0	53.8	7.4
dof	44	48	43	47	48	52	4
$\lvert V_{cb}\rvert \times 10^3$	38.8 ± 1.2	38.5 ± 1.1	—	—	39.1 ± 1.1	39.3 ± 1.0	—
$\mathcal{G}(1)$	1.055 ± 0.008	1.056 ± 0.008	—	—	1.060 ± 0.008	1.061 ± 0.007	1.052 ± 0.008
$\mathcal{F}(1)$	0.904 ± 0.012	0.901 ± 0.011	—	—	0.898 ± 0.012	0.895 ± 0.011	0.906 ± 0.013
$\bar{\rho}^2_*$	1.17 ± 0.12	1.19 ± 0.07	1.06 ± 0.15	1.19 ± 0.08	1.33 ± 0.11	1.24 ± 0.06	1.24 ± 0.08
$\hat{\chi}_2(1)$	-0.26 ± 0.26	-0.07 ± 0.02	0.36 ± 0.62	-0.06 ± 0.02	0.13 ± 0.22	-0.06 ± 0.02	-0.06 ± 0.02
$\hat{\chi}'_2(1)$	0.21 ± 0.38	-0.00 ± 0.02	0.14 ± 0.39	-0.00 ± 0.02	-0.36 ± 0.28	-0.00 ± 0.02	-0.00 ± 0.02
$\hat{\chi}'_3(1)$	0.02 ± 0.07	0.05 ± 0.02	0.18 ± 0.19	0.04 ± 0.02	0.09 ± 0.07	0.05 ± 0.02	0.04 ± 0.02
$\eta(1)$	0.30 ± 0.04	0.30 ± 0.03	-0.56 ± 0.80	0.35 ± 0.14	0.30 ± 0.04	0.30 ± 0.03	0.31 ± 0.04
$\eta'(1)$	0 (fixed)	-0.12 ± 0.16	0 (fixed)	-0.11 ± 0.18	0 (fixed)	-0.05 ± 0.09	0.05 ± 0.10
m_b^{1S} [GeV]	4.70 ± 0.05	4.70 ± 0.05	4.71 ± 0.05	4.70 ± 0.05	4.71 ± 0.05	4.71 ± 0.05	4.71 ± 0.05
δm_{bc} [GeV]	3.40 ± 0.02	3.40 ± 0.02	3.40 ± 0.02	3.40 ± 0.02	3.40 ± 0.02	3.40 ± 0.02	3.40 ± 0.02

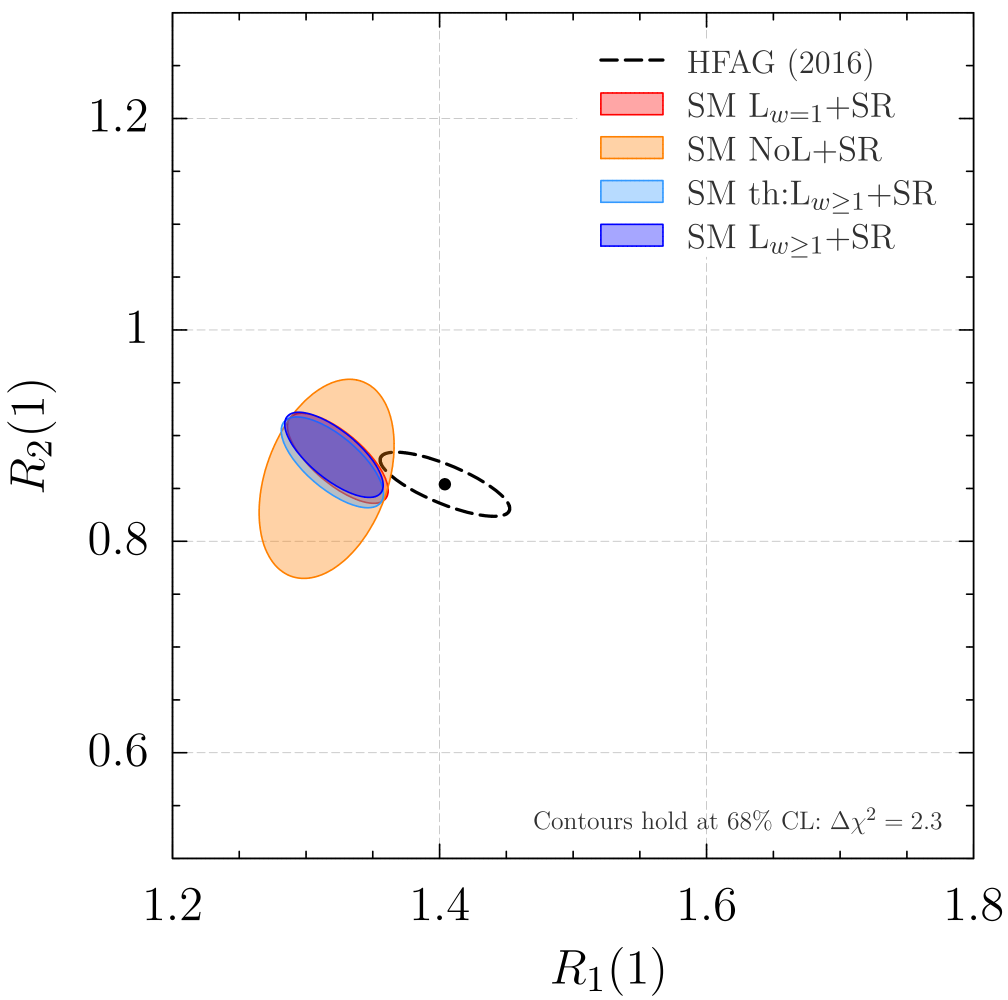
no signs of strong tensions, V_{cb} is still "low", data prefers a lower η than QCDSR input

$L_{w>=1}+SR$

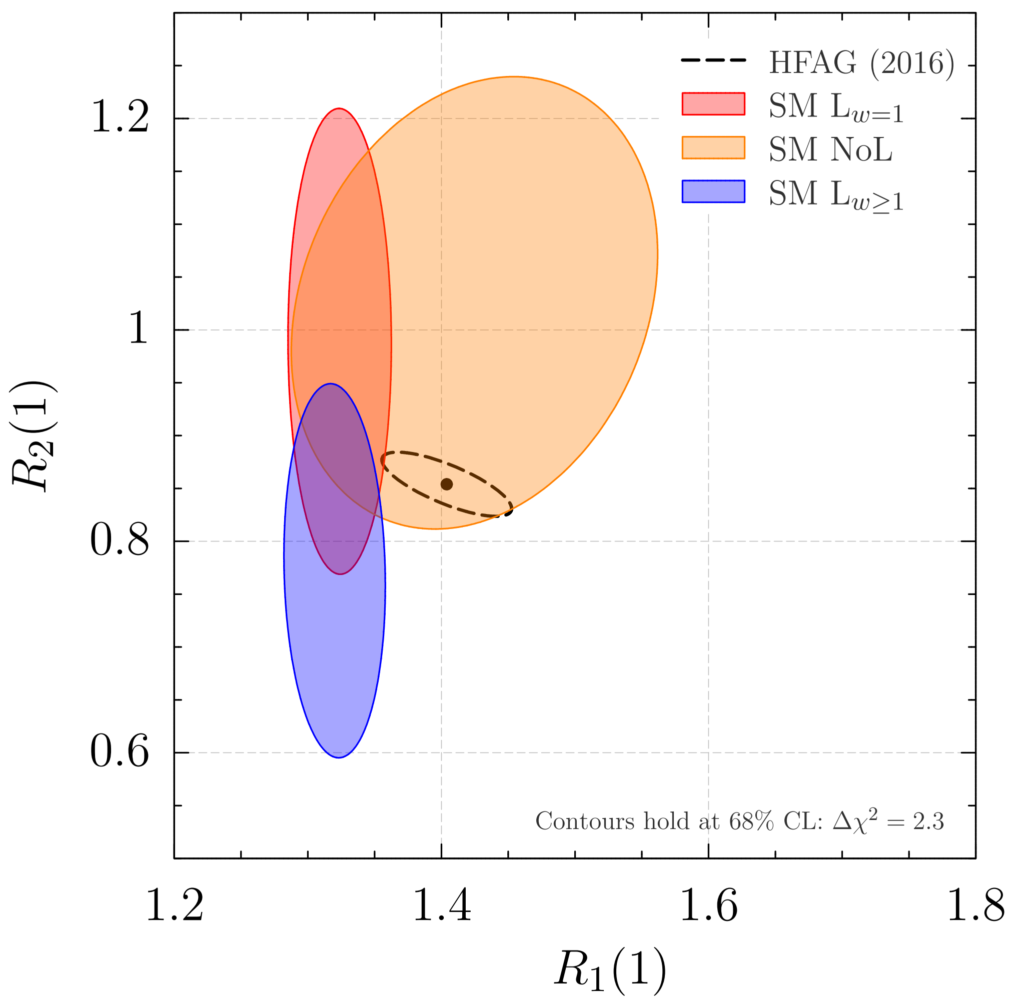
spectra:



FITS & $R_{1,2}$

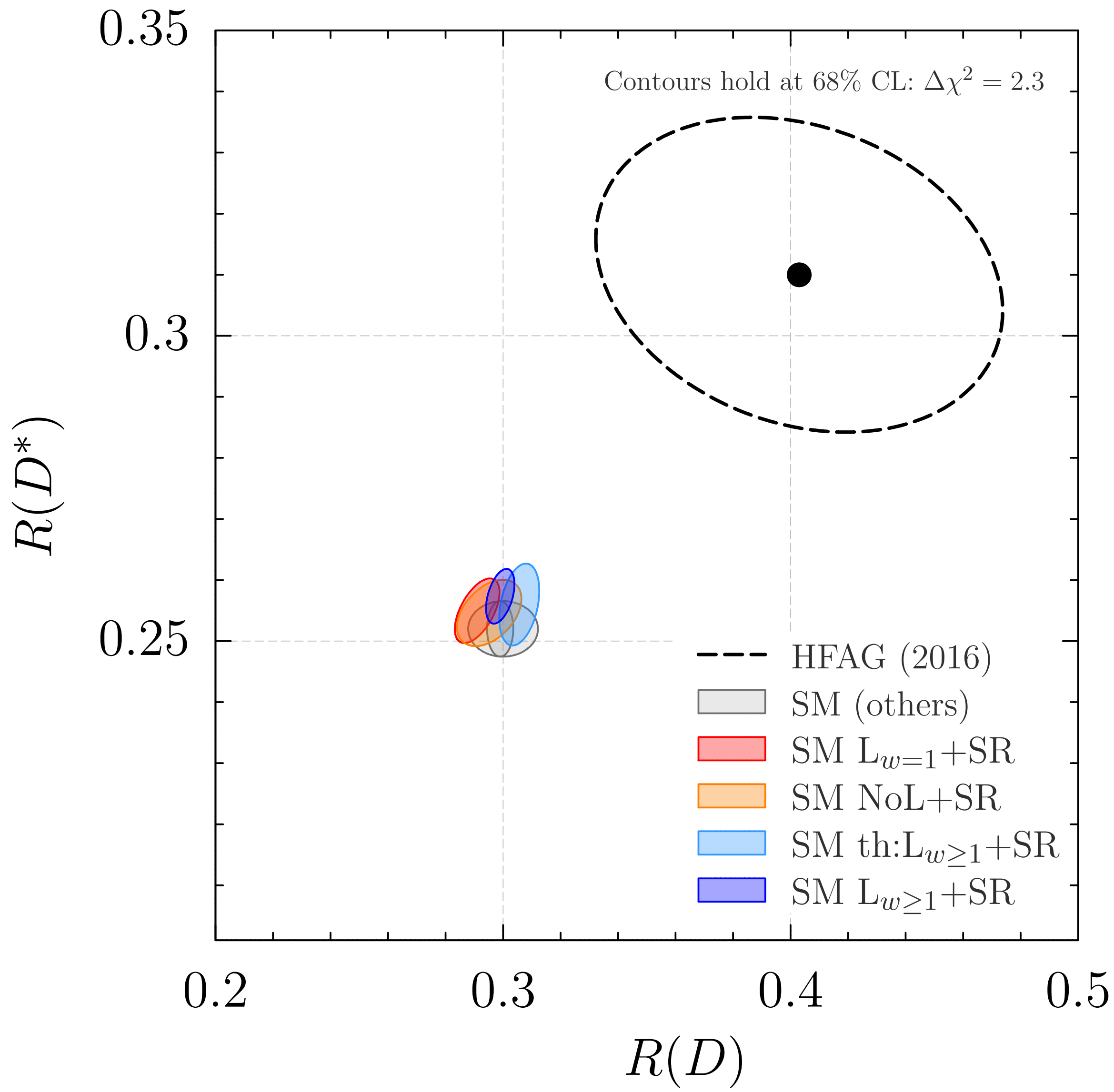


HFAG (2016)
SM $L_{w=1}$+SR
SM NoL+SR
SM th:$L_{w\geq 1}$+SR
SM $L_{w\geq 1}$+SR
Contours hold at 68% CL: $\Delta\chi^2 = 2.3$
$R_2(1)$
$R_1(1)$

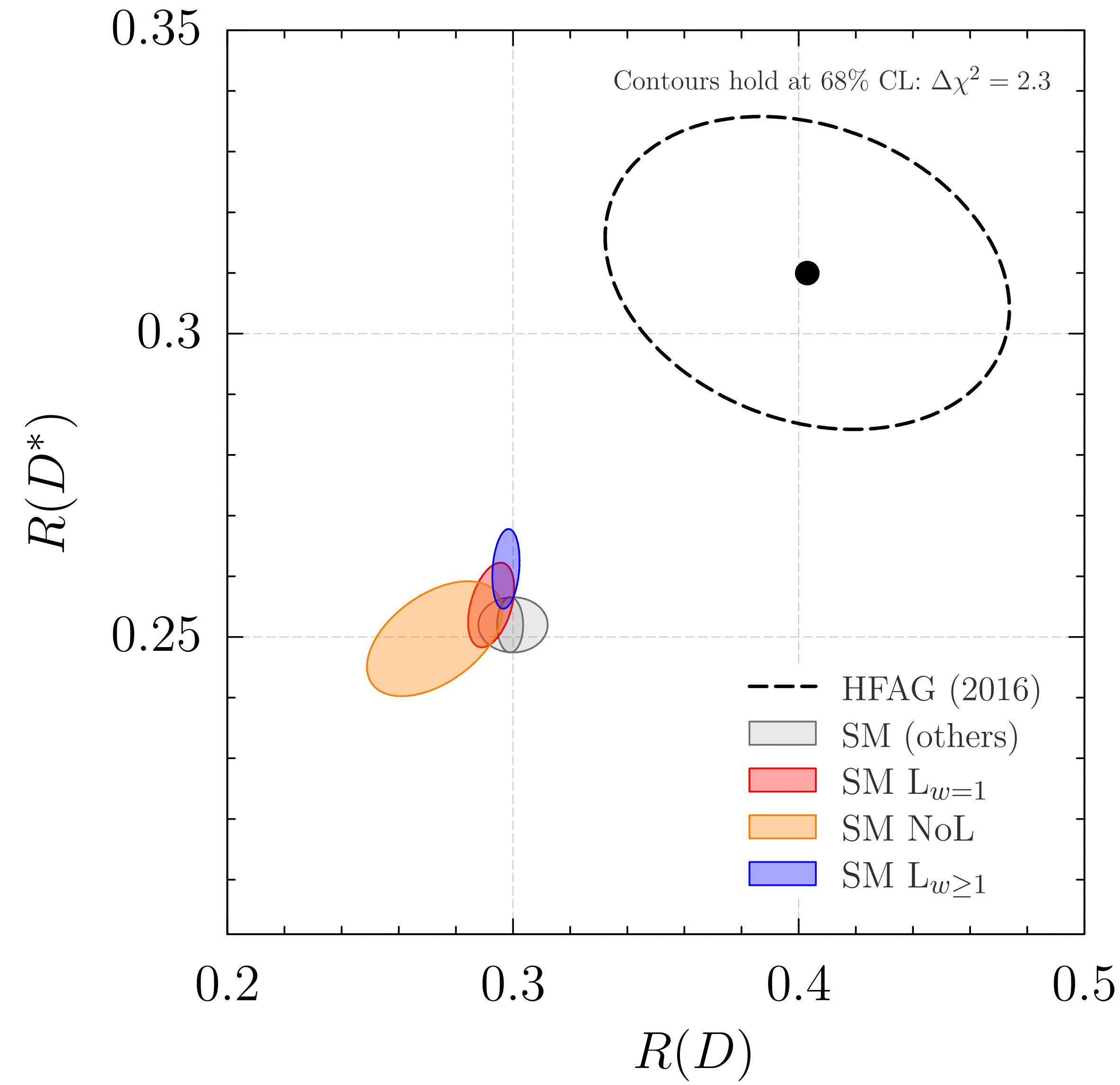


HFAG (2016)
SM $L_{w=1}$
SM NoL
SM $L_{w\geq 1}$
Contours hold at 68% CL: $\Delta\chi^2 = 2.3$
$R_2(1)$
$R_1(1)$

R(D) AND R(D*)



Contours hold at 68% CL: $\Delta\chi^2 = 2.3$
0.35
0.3
0.25
$R(D^*)$
0.2
0.3
0.4
0.5
$R(D)$
HFAG (2016)
SM (others)
SM $L_{w=1}$+SR
SM NoL+SR
SM th:$L_{w\geq1}$+SR
SM $L_{w\geq1}$+SR



Contours hold at 68% CL: $\Delta\chi^2 = 2.3$
0.35
0.3
0.25
$R(D^*)$
0.2
0.3
0.4
0.5
$R(D)$
HFAG (2016)
SM (others)
SM $L_{w=1}$
SM NoL
SM $L_{w\geq1}$

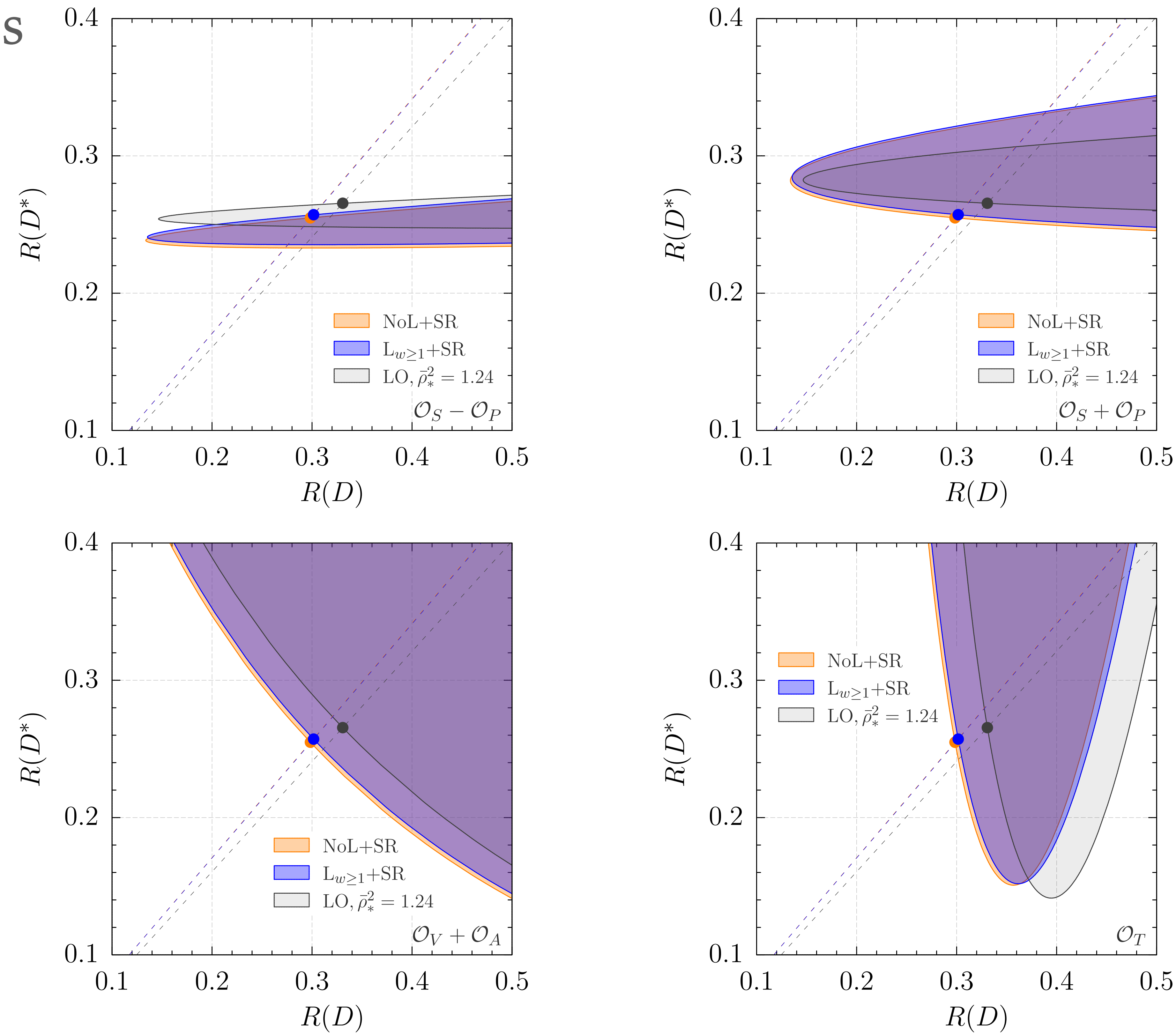
R(D) AND R(D*)

Scenario	$R(D)$	$R(D^*)$	Correlation
$\mathrm{L}_{w=1}$	0.292 ± 0.005	0.255 ± 0.005	41%
$\mathrm{L}_{w=1}$+SR	0.291 ± 0.005	0.255 ± 0.003	57%
NoL	0.273 ± 0.016	0.250 ± 0.006	49%
NoL+SR	0.295 ± 0.007	0.255 ± 0.004	43%
$\mathrm{L}_{w\geq1}$	0.298 ± 0.003	0.261 ± 0.004	19%
$\mathrm{L}_{w\geq1}$+SR	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.257 \pm 0.003}$	**44%**
th:$\mathrm{L}_{w\geq1}$+SR	0.306 ± 0.005	0.256 ± 0.004	33%
Data [9]	0.403 ± 0.047	0.310 ± 0.017	−23%
Refs. [48, 52, 54]	0.300 ± 0.008	—	—
Ref. [53]	0.299 ± 0.003	—	—
Ref. [34]	—	0.252 ± 0.003	—

- Reduced uncert on SM predictions
- Consistency between different fits
- Discrepancy with data still present and sizable

NLO HQET FOR SM+NP

➤ NLO HQET calculation also for form factors entering BSM contributions



CONCLUSIONS

- Experimental data in e,μ & Lattice results are improving determination of $B \to D(*)$ form factors
- Apparent "tension" in current inputs between HQS, lattice and Belle $B \to D^*$ distributions (can't self-consistently use lattice+BGL to extract V_{cb})
  - Future lattice $B \to D^*$ spectra and Belle II data (and non-unfolded BGL Belle fit?) will have something to say on this
- Updated R(D), R(D*) predictions still show large discrepancy with measurements
- Updated BSM predictions for R(D), R(D*)
- Results included in Hammer package

BACKUP

FORM FACTOR DEFINITIONS

- B→D:

$$\langle D|\,\bar{c}\,b\,|\overline{B}\rangle = \sqrt{m_B m_D}\,h_S\,(w+1)\,,$$

$$\langle D|\,\bar{c}\gamma^5 b\,|\overline{B}\rangle = \langle D|\,\bar{c}\gamma^\mu\gamma^5 b\,|\overline{B}\rangle = 0\,,$$

$$\langle D|\,\bar{c}\gamma^\mu b\,|\overline{B}\rangle = \sqrt{m_B m_D}\,\big[h_+(v+v')^\mu + h_-(v-v')^\mu\big],$$

$$\langle D|\,\bar{c}\sigma^{\mu\nu} b\,|\overline{B}\rangle = i\sqrt{m_B m_D}\,\big[h_T\,(v'^\mu v^\nu - v'^\nu v^\mu)\big],$$

- B→D*:

$$\langle D^*|\,\bar{c}b\,|\overline{B}\rangle = 0\,,$$

$$\langle D^*|\,\bar{c}\gamma^5 b\,|\overline{B}\rangle = -\sqrt{m_B m_{D^*}}\,h_P\,(\epsilon^*\cdot v)\,,$$

$$\langle D^*|\,\bar{c}\gamma^\mu b\,|\overline{B}\rangle = i\sqrt{m_B m_{D^*}}\,h_V\,\varepsilon^{\mu\nu\alpha\beta}\,\epsilon^*_\nu v'_\alpha v_\beta\,,$$

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

$$\langle D^*|\,\bar{c}\sigma^{\mu\nu} b\,|\overline{B}\rangle = -\sqrt{m_B m_{D^*}}\,\varepsilon^{\mu\nu\alpha\beta}\big[h_{T_1}\epsilon^*_\alpha(v+v')_\beta + h_{T_2}\epsilon^*_\alpha(v-v')_\beta + h_{T_3}(\epsilon^*\cdot v)v_\alpha v'_\beta\big].$$

NLO HQET FF EXPRESSIONS

$B \to D$

$$\hat{h}_+ = 1 + \hat{\alpha}_s\Big[C_{V_1} + \frac{w+1}{2}\,(C_{V_2} + C_{V_3})\Big] + (\varepsilon_c + \varepsilon_b)\,\hat{L}_1\,,$$

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

$$\hat{h}_S = 1 + \hat{\alpha}_s\,C_S + (\varepsilon_c + \varepsilon_b)\bigg(\hat{L}_1 - \hat{L}_4\,\frac{w-1}{w+1}\bigg)\,,$$

$$\hat{h}_T = 1 + \hat{\alpha}_s\big(C_{T_1} - C_{T_2} + C_{T_3}\big) + (\varepsilon_c + \varepsilon_b)\big(\hat{L}_1 - \hat{L}_4\big)\,.$$

$B \to D^*$

$$\hat{h}_V = 1 + \hat{\alpha}_s\,C_{V_1} + \varepsilon_c\big(\hat{L}_2 - \hat{L}_5\big) + \varepsilon_b\big(\hat{L}_1 - \hat{L}_4\big)\,,$$

$$\hat{h}_{A_1} = 1 + \hat{\alpha}_s\,C_{A_1} + \varepsilon_c\bigg(\hat{L}_2 - \hat{L}_5\,\frac{w-1}{w+1}\bigg) + \varepsilon_b\bigg(\hat{L}_1 - \hat{L}_4\,\frac{w-1}{w+1}\bigg)\,,$$

$$\hat{h}_{A_2} = \hat{\alpha}_s\,C_{A_2} + \varepsilon_c\big(\hat{L}_3 + \hat{L}_6\big)\,,$$

$$\hat{h}_{A_3} = 1 + \hat{\alpha}_s\big(C_{A_1} + C_{A_3}\big) + \varepsilon_c\big(\hat{L}_2 - \hat{L}_3 + \hat{L}_6 - \hat{L}_5\big) + \varepsilon_b\big(\hat{L}_1 - \hat{L}_4\big)\,,$$

$$\hat{h}_P = 1 + \hat{\alpha}_s\,C_P + \varepsilon_c\big[\hat{L}_2 + \hat{L}_3(w-1) + \hat{L}_5 - \hat{L}_6(w+1)\big] + \varepsilon_b\big(\hat{L}_1 - \hat{L}_4\big)$$

$$\hat{h}_{T_1} = 1 + \hat{\alpha}_s\Big[C_{T_1} + \frac{w-1}{2}\,(C_{T_2} - C_{T_3})\Big] + \varepsilon_c\hat{L}_2 + \varepsilon_b\hat{L}_1\,,$$

$$\hat{h}_{T_2} = \hat{\alpha}_s\,\frac{w+1}{2}\,(C_{T_2} + C_{T_3}) + \varepsilon_c\hat{L}_5 - \varepsilon_b\hat{L}_4\,,$$

$$\hat{h}_{T_3} = \hat{\alpha}_s\,C_{T_2} + \varepsilon_c\big(\hat{L}_6 - \hat{L}_3\big)\,.$$

HQET R_i EXPRESSIONS

$$R_1(1) \simeq 1.34 - 0.12\,\eta(1)\,,$$

$$R_2(1) \simeq 0.98 - 0.42\,\eta(1) - 0.54\,\hat{\chi}_2(1)\,.$$

$$R_1'(1) \simeq -0.15 + 0.06\,\eta(1) - 0.12\,\eta'(1)\,,$$

$$R_2'(1) \simeq 0.01 - 0.54\,\hat{\chi}_2'(1) + 0.21\,\eta(1) - 0.42\,\eta'(1)\,.$$

$$R_3(1) \simeq 1.19 - 0.26\,\eta(1) - 1.20\,\hat{\chi}_2(1)\,,$$

$$R_0(1) \simeq 1.09 + 0.25\,\eta(1)\,,$$

$$R_3'(1) \simeq -0.08 - 1.20\,\hat{\chi}_2'(1) + 0.13\,\eta(1) - 0.26\,\eta'(1)\,,$$

$$R_0'(1) \simeq -0.18 + 0.87\,\hat{\chi}_2(1) + 0.06\,\eta(1) + 0.25\,\eta'(1)\,.$$