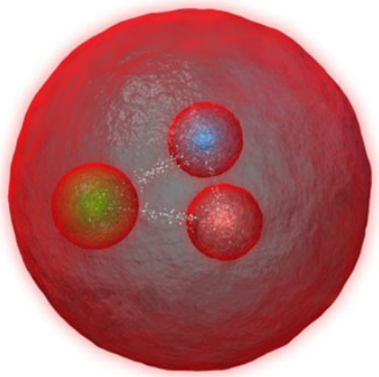
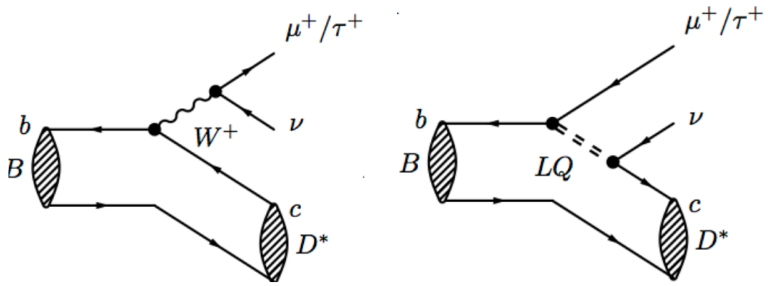
New predictions for $\Lambda_b \to \Lambda_c^+ \ell^- \bar{\nu}_\ell$ decays

Work of F. Bernlochner, Z. Ligeti, D. Robinson, WS, arXiv:1808.09464 [PRL]; 1812.07593 [PRD]

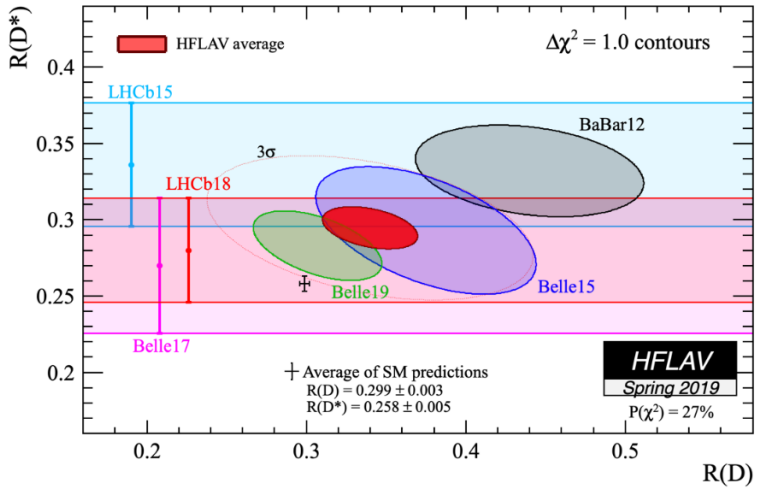


Motivation

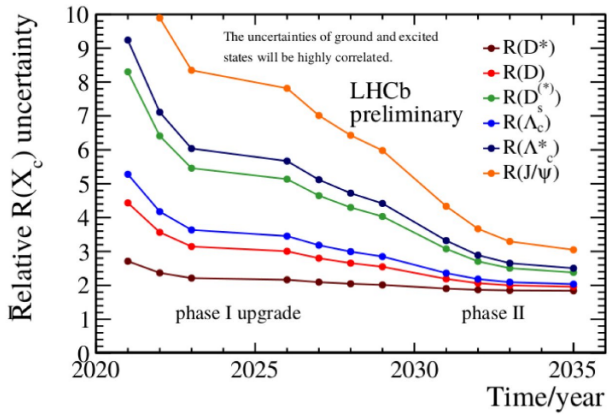
$$R\left(D^{(*)}\right) = \frac{\mathcal{B}(B \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

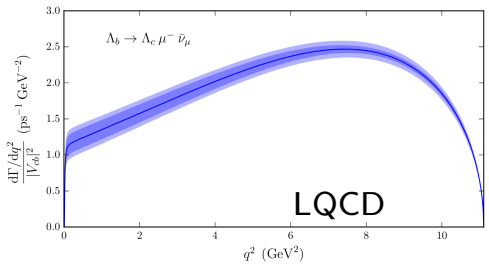


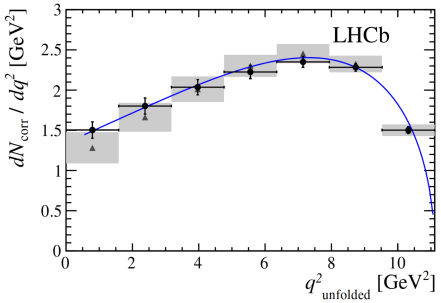
- Still a $\sim 3\sigma$ deviation from SM.



- New physics will influence several modes.
- Large LHCb dataset of Λ_b baryons.





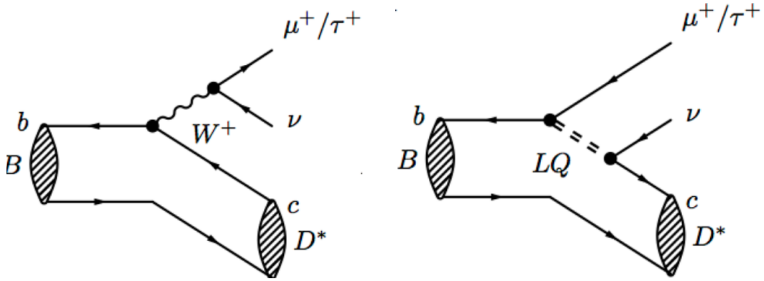


LQCD [S. Meinel et al. 1503.01421] LHCb [1709.01920]

- Available LQCD prediction and LHCb shape measurement.

Motivation

$$R\left(\Lambda_c^{(*)}\right) = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c^{(*)+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c^{(*)+}\ell^-\bar{\nu}_\ell)}$$



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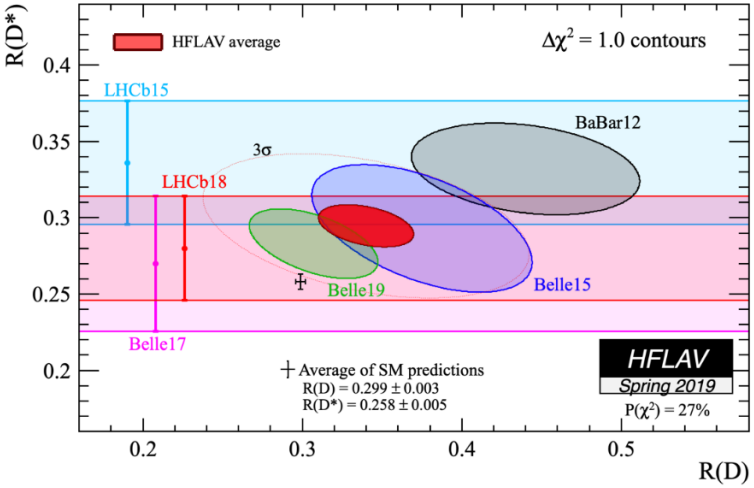

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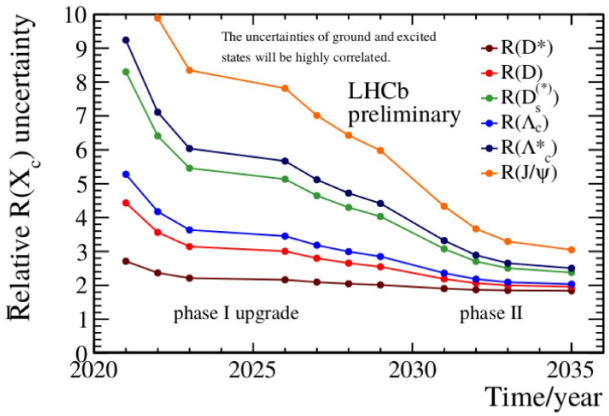
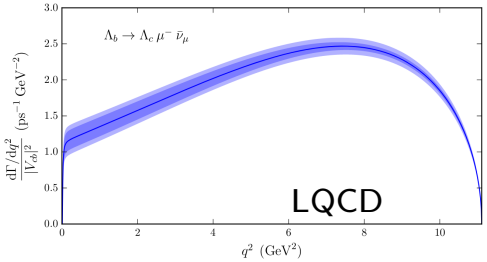
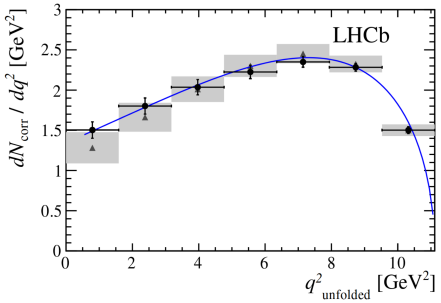






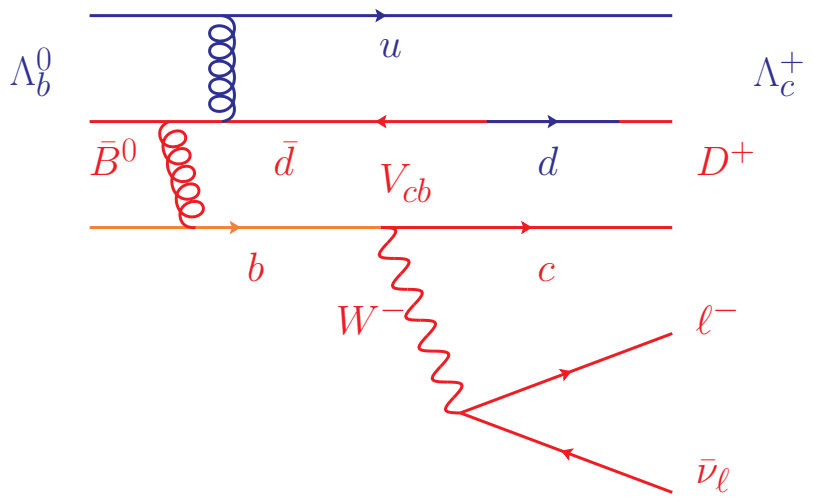
LQCD [S. Meinel et al. 1503.01421] LHCb [1709.01920]

- Available LQCD prediction and LHCb shape measurement.

$\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell$ SM vs NP theory

$$\langle \Lambda_c(p',s')|\bar{c}\gamma_\nu b|\Lambda_b(p,s)\rangle = \bar{u}(p',s')\big[f_1\gamma_\mu + f_2 v_\mu + f_3 v'_\mu\big]u(p,s)\,,$$
$$\langle \Lambda_c(p',s')|\bar{c}\gamma_\nu\gamma_5 b|\Lambda_b(p,s)\rangle = \bar{u}(p',s')\big[g_1\gamma_\mu + g_2 v_\mu + g_3 v'_\mu\big]\gamma_5\, u(p,s)\,,$$

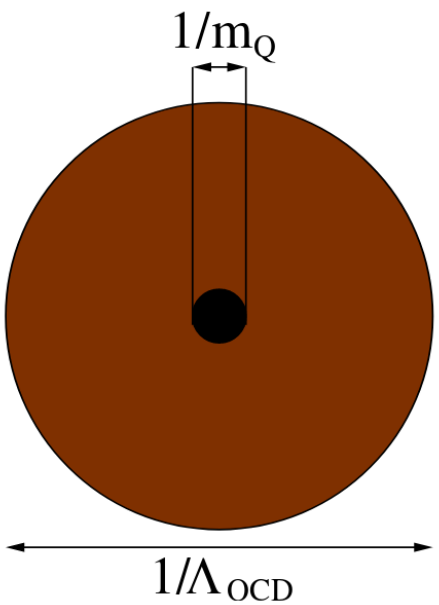
- In the SM can parametrise hadronic matrix elements in terms of 6 form factors.
- Form factors are functions of $w = v \cdot v' = (m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2)/(2m_{\Lambda_b}m_{\Lambda_c})$
- New physics introduces the possibility of scalar, pseudoscalar and tensor terms with 6 new form factors.

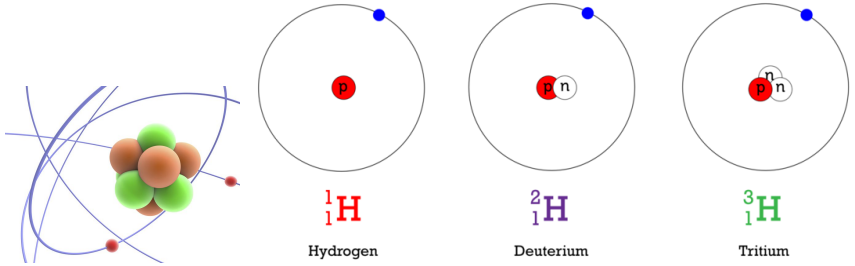


$$\langle \Lambda_c(p',s')|\bar{c}\, b|\Lambda_b(p,s)\rangle = h_S\, \bar{u}(p',s')\, u(p,s)\,,$$
$$\langle \Lambda_c(p',s')|\bar{c}\gamma_5 b|\Lambda_b(p,s)\rangle = h_P\, \bar{u}(p',s')\,\gamma_5\, u(p,s)\,,$$
$$\langle \Lambda_c(p',s')|\bar{c}\,\sigma_{\mu\nu}\, b|\Lambda_b(p,s)\rangle = \bar{u}(p',s')\big[h_1\,\sigma_{\mu\nu} + i\,h_2(v_\mu\gamma_\nu - v_\nu\gamma_\mu) + i\,h_3(v'_\mu\gamma_\nu - v'_\nu\gamma_\mu) + i\,h_4(v_\mu v'_\nu - v_\nu v'_\mu)\big]u(p,s)\,.$$

Heavy Quark Symmetries

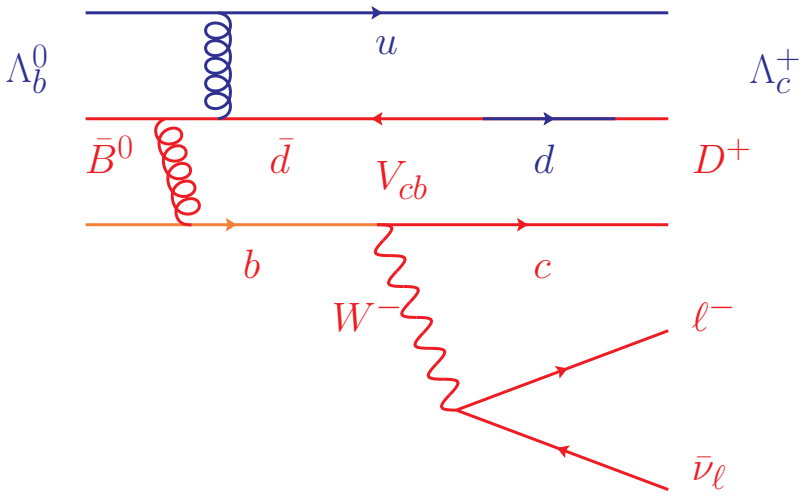
- In the $m_Q \gg \Lambda_{\rm QCD}$ limit, the heavy quark acts a fixed color source with fixed velocity v^μ Isgur & Wise
- $\implies$ for $Q\bar{q}$ wave function of light quarks insensitive to spin and flavour of Q.
- Analogous situation in atomic physics:
  - Different isotopes have same chemistry as they feel the same electric field $\sim$ flavour symmetry.
  - Hyperfine levels of atoms almost degenenerate $\sim$ Spin symmetry





$\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell$ form factors in Heavy Quark Effective Theory

- When $b \to c$ only velocity change $v \to v'$ felt and potentially a $\vec{s}_Q$ flip.
- $\implies$ All form factors are related to a single function of $w = v \cdot v'$, $\zeta(w)$ (Isgur Wise function)
- In particular at leading order in HQET one finds:



$$f_1(w) = g_1(w) = h_S(w) = h_P(w) = h_1(w) = \zeta(w)\,,$$
$$f_2(w) = f_3(w) = g_2(w) = g_3(w) = h_2(w) = h_3(w) = h_4(w) = 0\,.$$

- At 0 recoil, $w = 1$, no change in color field $\zeta(1) = 1$

Higher order corrections to form factors

- Now we consider higher order corrections at orders α_s, $\Lambda_{\rm QCD}/m_{b,c}$, $\alpha_s\Lambda_{\rm QCD}/m_{b,c}$ and $\Lambda^2_{\rm QCD}/m_c^2$

$$\bar{\Lambda}_\Lambda = \text{energy of light degrees of freedom in } m_Q \to \infty \implies m_{\Lambda_Q} = m_Q + \bar{\Lambda}_\Lambda + \cdots$$

$$f_1 = \zeta(w)\left\{1 + \hat{\alpha}_s C_{V_1} + \varepsilon_c + \varepsilon_b + \hat{\alpha}_s\left[C_{V_1} + 2(w-1)C'_{V_1}\right](\varepsilon_c + \varepsilon_b) + \frac{\hat{b}_1 - \hat{b}_2}{4m_c^2}\right\} + \ldots,$$

where $\varepsilon_{c,b} = \bar{\Lambda}_\Lambda/(2\,m_{c,b})$ [prior work: Falk & Neubert, hep-ph/9209269]

- Remarkable simplication at $\mathcal{O}(\Lambda_{\rm QCD}/m_{b,c})$ compared to B mesons. No sub-leading Isgur Wise functions (SIW).
- Only 2 sub-leading IW functions, $\hat{b}_1(w), \hat{b}_2(w)$ at $\mathcal{O}(\Lambda^2_{\rm QCD}/m_c^2)$

Decay	$N_{\rm IW}$ at $\mathcal{O}(1)$	$N_{\rm SIW}$ at $\mathcal{O}(\Lambda_{\rm QCD}/m_{b,c})$	$N_{\rm SIW}$ at $\mathcal{O}(\Lambda^2_{\rm QCD}/m_c^2)$
$\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell$	1	0	2
$B \to D^* l\nu$	1	3	6

- Decay $\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell$ is simpler as light quarks (ud) in a spin 0 state, $J = 0$.

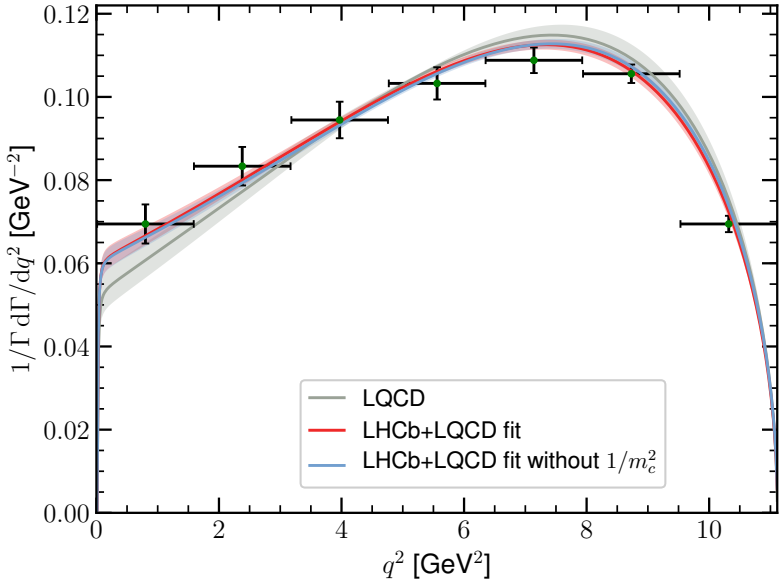
HQET fit

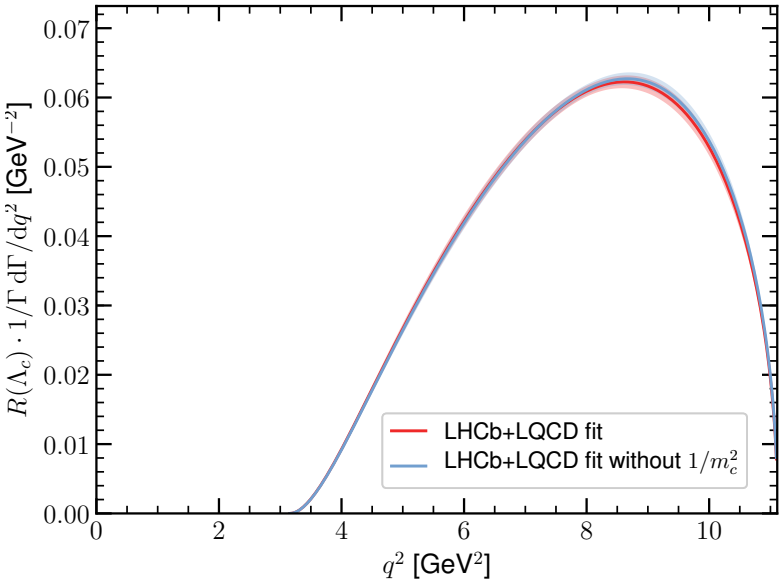
- Perform fits to LQCD Predictions and to LHCb differential shape measurement.
- $\zeta(w) = 1 + (w-1)\,\zeta' + \frac{1}{2}(w-1)^2\,\zeta''$
- $\hat{b}_{1,2}$ assumed constants.

	including $\mathcal{O}(\Lambda_{\rm QCD}^2/m_c^2)$			neglecting $\mathcal{O}(\Lambda_{\rm QCD}^2/m_c^2)$		
ζ'	-2.04	$\pm$	0.08	-2.06	$\pm$	0.08
ζ''	3.16	$\pm$	0.38	3.28	$\pm$	0.36
$\hat{b}_1/\text{GeV}^2$	-0.46	$\pm$	0.15	0^*		
$\hat{b}_2/\text{GeV}^2$	-0.39	$\pm$	0.39	0^*		
m_b^{1S}/GeV	4.72	$\pm$	0.05	4.69	$\pm$	0.04
$\delta m_{bc}/\text{GeV}$	3.40	$\pm$	0.02	3.40	$\pm$	0.02
χ^2/ndf	7.20/20			18.8/22		
$R(\Lambda_c)$	0.3237	$\pm$	0.0036	0.3252	$\pm$	0.0035

- 1% uncertainty on $R(\Lambda_c)$ compared to 3% from LQCD $\implies$ most precise $R(\Lambda_c)$ to date.
- First estimate from data of $\mathcal{O}(\Lambda_{\rm QCD}^2/m_c^2)$ HQET corrections for an exclusive decay.
- $\hat{b}_1 = -0.46$ GeV^2 smaller than model dependent estimate $\hat{b}_1 = -3\bar{\Lambda}_\Lambda^2 = -2$ GeV^2

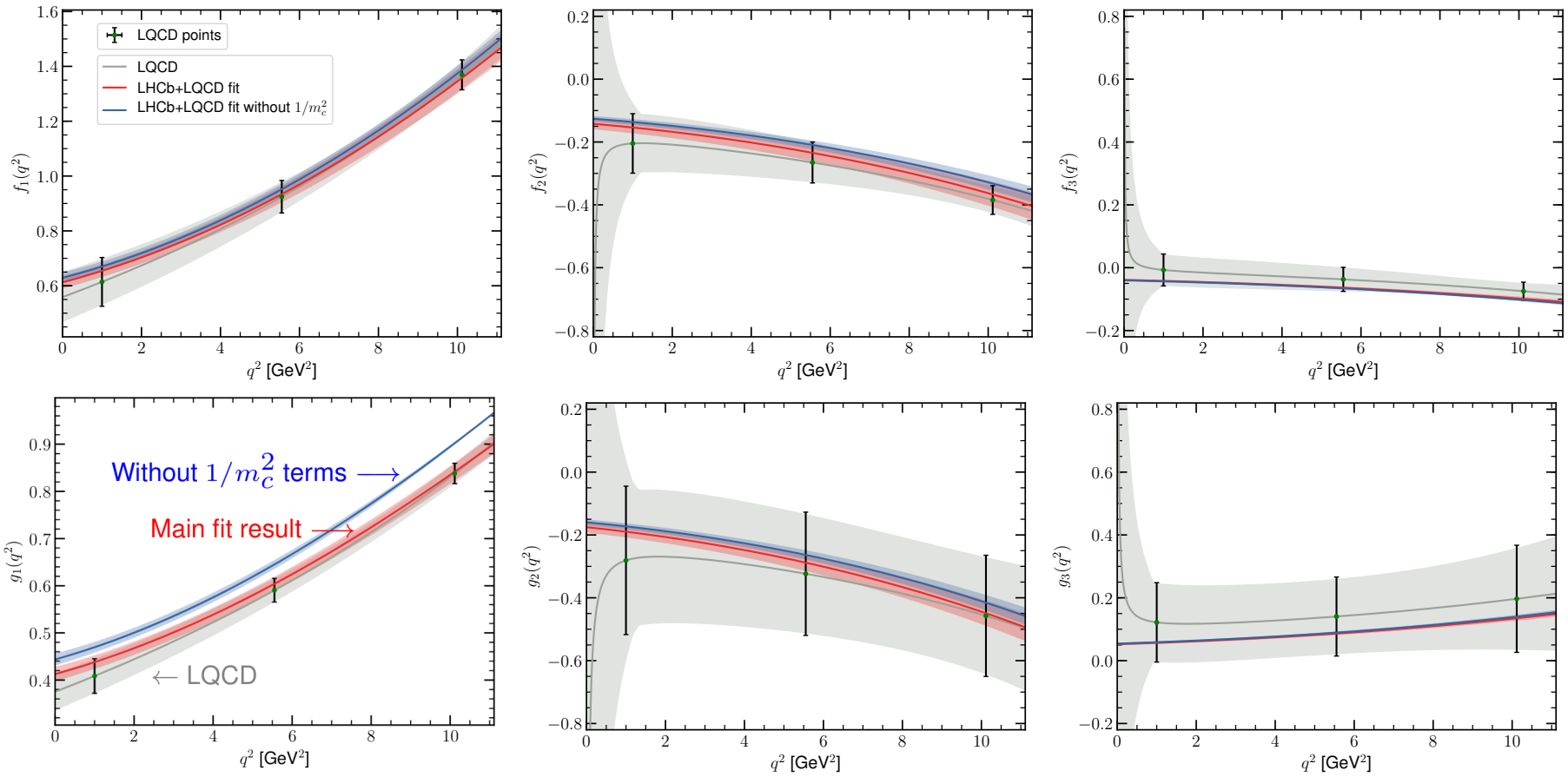
from [Falk & Neubert, hep-ph/9209269]





SM Form factors

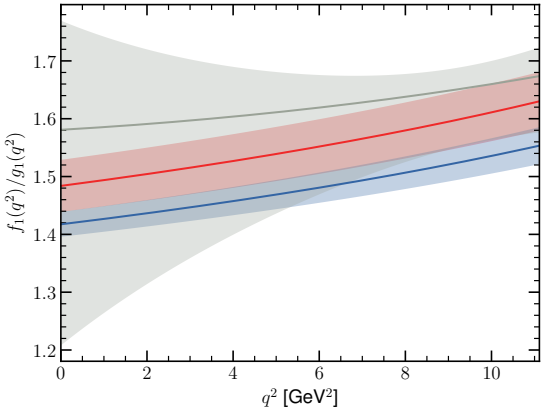
- Predict SM form factors under HQET from fitted parameters.
- Compare these with LQCD predictions.
- $\mathcal{O}(\Lambda_{\text{QCD}}^2/m_c^2)$ corrections necessary to match LQCD.



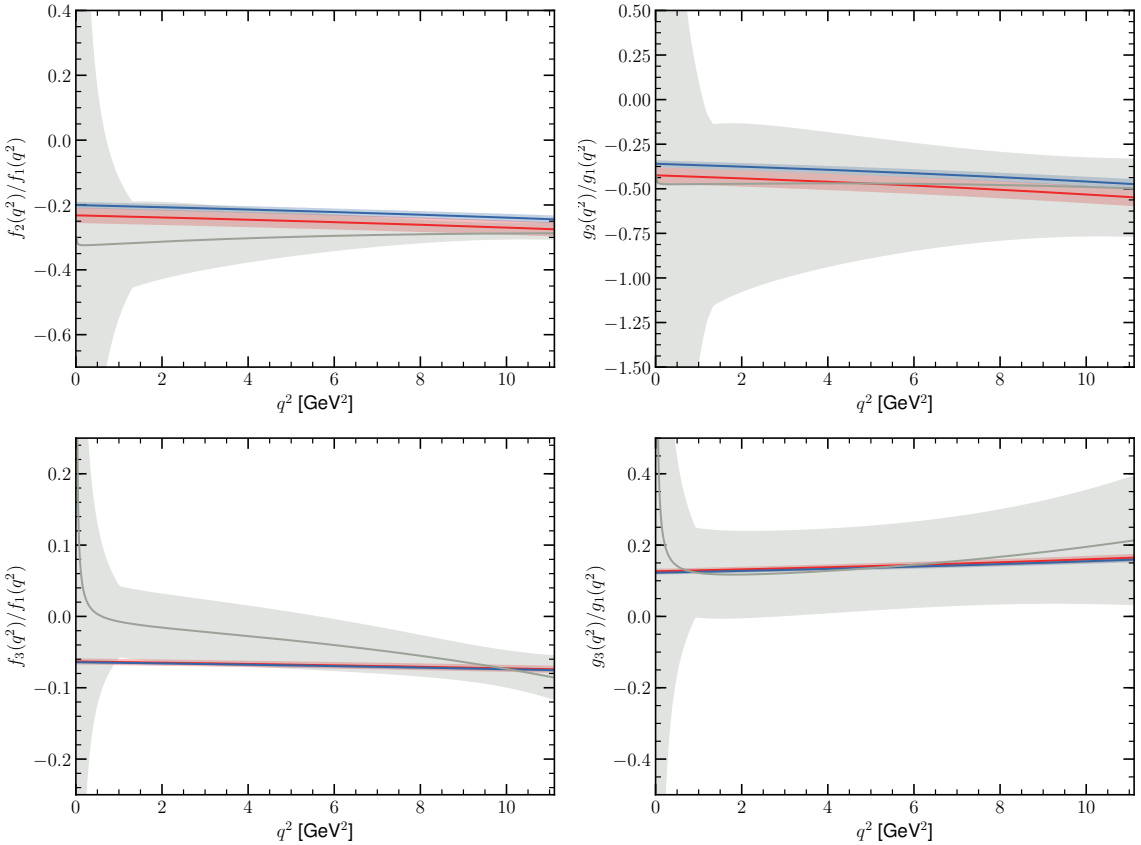
SM Form factor ratios

- We now construct several form factor ratios f_1/g_1, $f_{i=2,3}/f_1$ and $g_{i=2,3}/g_1$

- $f_1/g_1 \sim \mathcal{O}(1)$ as expected.



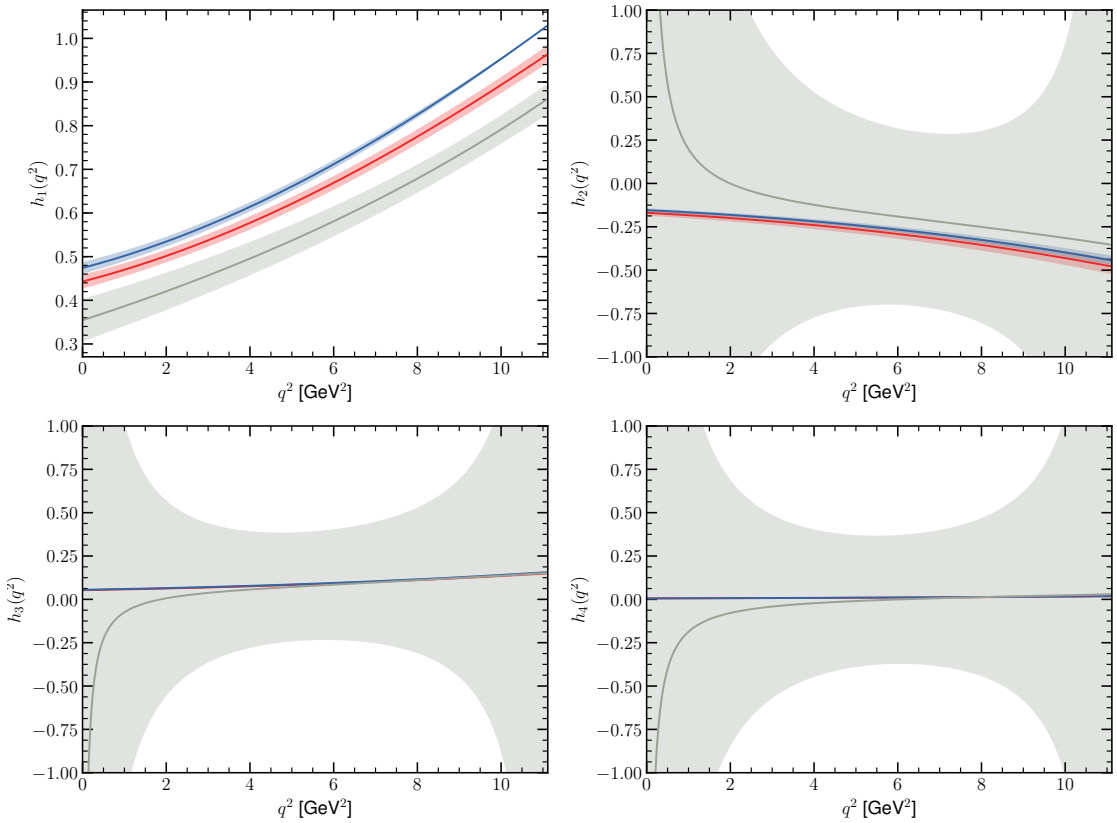
- $f_{i=2,3}/f_1$ and $g_{i=2,3}/g_1$ are $\mathcal{O}(\alpha_s, \varepsilon_{c,b})$



Tensor form factors

- Fitted values for $\zeta(w)$, $\hat{b}_{1,2}$ allow us to predict form factors associated with possible NP interactions.
- Can compare with LQCD predictions in [Datta, Kamali, Meinel, Rashed, 1702.02243]

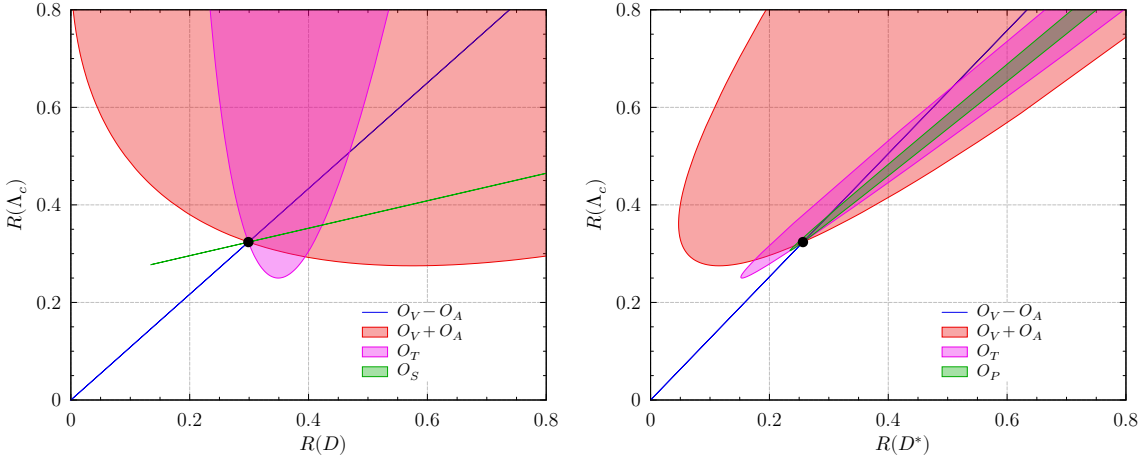
- 4 tensor form factors: h_1, h_2, h_3, h_4
- In chosen HQET basis: $h_1 = \mathcal{O}(1)$, $h_{2,3,4} = \mathcal{O}(\alpha_s, \varepsilon_{c,b})$
- While in LQCD basis all 4 $\mathcal{O}(1)$
- Tension in h_1 to be understood.



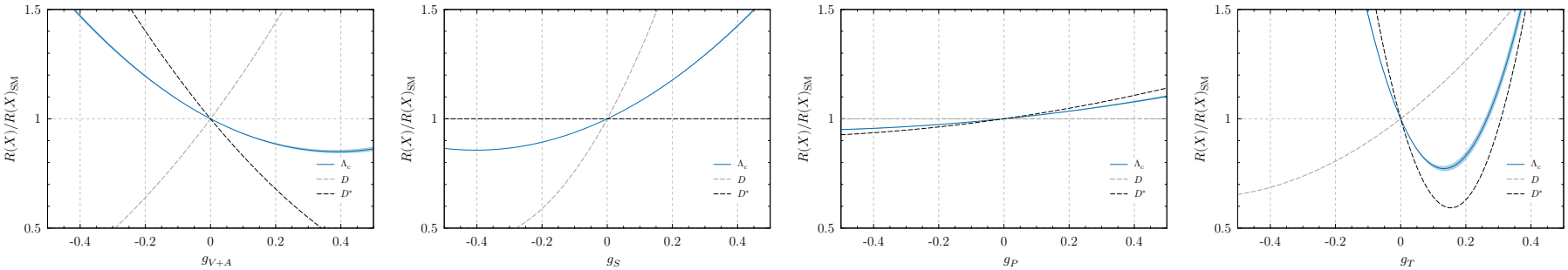
$R(\Lambda_c)$ sensitivity to new physics

- Switch on several possible new physics operators, $O(V-A)$, $O(V+A)$, $O(T)$ and $O(S)$ and compute allowed regions in $R(\Lambda_c)$ vs $R(D)$ and $R(\Lambda_c)$ vs $R(D^*)$

- NP coefficients real at boundaries.
- Inner region requires phase between NP and SM.



- Can look at $R(X)_{NP}/R(X)_{SM}$ as a function of potential NP couplings (real) for $X = D$, D^* and Λ_c



Conclusion

- Computed SM and NP form factors of $\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell$ decays up to $\mathcal{O}(\Lambda_{\text{QCD}}^2/m_c^2)$ using HQET
- HQET based fit made to LHCb measurements and LQCD predictions for $\zeta(w)$ and $\hat{b}_{1,2}$.
- First determination of the magnitude of $\mathcal{O}(\Lambda_{\text{QCD}}^2/m_c^2)$ corrections in HQET for an exclusive decay.
- Most precise value of $R(\Lambda_c) = 0.3237 \pm 0.0036$ to date. A factor of three times more precise than LQCD prediction alone.
- NP form factors are computed using parameters from HQET fit and were used to assess the sensitivity of $R(\Lambda_c)$ to NP.