$\Lambda_b \to \Lambda_c^{(*)}$ form factors from lattice QCD

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The $\Lambda_b \to \Lambda_c^{(*)}$ form factors are needed mainly for:

- $\left|\frac{V_{ub}}{V_{cb}}\right|$ from $\frac{\Gamma(\Lambda_b \to p\, \mu^- \bar{\nu}_\mu)}{\Gamma(\Lambda_b \to \Lambda_c\, \mu^- \bar{\nu}_\mu)}$

- $|V_{cb}|$ from $\Gamma(\Lambda_b \to \Lambda_c\, \mu^- \bar{\nu}_\mu)$

- $R(\Lambda_c^{(*)}) = \frac{\Gamma(\Lambda_b \to \Lambda_c^{(*)}\, \tau^- \bar{\nu})}{\Gamma(\Lambda_b \to \Lambda_c^{(*)}\, \mu^- \bar{\nu})}$

Name	J^P	Mass [MeV]	Width [MeV]	Strong decay modes
Λ_c	$\frac{1}{2}^+$	2286.46(14)	$3.3(1) \times 10^{-9}$	stable
$\Lambda_c^*(2595)$	$\frac{1}{2}^-$	2592.25(28)	2.6(6)	$\Lambda_c\,\pi^+\pi^-$
$\Lambda_c^*(2625)$	$\frac{3}{2}^-$	2628.11(19)	< 0.97	$\Lambda_c\,\pi^+\pi^-$

(decays proceed partly through $\Lambda_c^* \to \Sigma_c^{(*)}(\to \Lambda_c \pi)\pi$)

[2017 Review of Particle Physics]

In the following, we will treat the Λ_c^* baryons as if they were stable.

Some notation to define the form factors:

$$\begin{aligned}
\langle \Lambda_{c\,\frac{1}{2}^+}(\mathbf{p}',s')|\,\bar{c}\Gamma b\,|\Lambda_b(\mathbf{p},s)\rangle &= \bar{u}(m_{\Lambda_{c\,\frac{1}{2}^+}},\mathbf{p}',s')\,\mathscr{G}^{(\frac{1}{2}^+)}[\Gamma]\,u(m_{\Lambda_b},\mathbf{p},s)\\
\langle \Lambda^*_{c\,\frac{1}{2}^-}(\mathbf{p}',s')|\,\bar{c}\Gamma b\,|\Lambda_b(\mathbf{p},s)\rangle &= \bar{u}(m_{\Lambda^*_{c\,\frac{1}{2}^-}},\mathbf{p}',s')\,\gamma_5\,\mathscr{G}^{(\frac{1}{2}^-)}[\Gamma]\,u(m_{\Lambda_b},\mathbf{p},s)\\
\langle \Lambda^*_{c\,\frac{3}{2}^+}(\mathbf{p}',s')|\,\bar{c}\Gamma b\,|\Lambda_b(\mathbf{p},s)\rangle &= \bar{u}_\lambda(m_{\Lambda^*_{c\,\frac{3}{2}^+}},\mathbf{p}',s')\,\gamma_5\,\mathscr{G}^{\lambda(\frac{3}{2}^+)}[\Gamma]\,u(m_{\Lambda_b},\mathbf{p},s)\\
\langle \Lambda^*_{c\,\frac{3}{2}^-}(\mathbf{p}',s')|\,\bar{c}\Gamma b\,|\Lambda_b(\mathbf{p},s)\rangle &= \bar{u}_\lambda(m_{\Lambda^*_{c\,\frac{3}{2}^-}},\mathbf{p}',s')\,\mathscr{G}^{\lambda(\frac{3}{2}^-)}[\Gamma]\,u(m_{\Lambda_b},\mathbf{p},s)
\end{aligned}$$

$$\sum_s u(m,\mathbf{p},s)\bar{u}(m,\mathbf{p},s) = m + \not{p}$$

$$\sum_{s'} u_\mu(m',\mathbf{p}',s')\bar{u}_\nu(m',\mathbf{p}',s') =$$

$$-(m' + \not{p}')\left(g_{\mu\nu} - \frac{1}{3}\gamma_\mu\gamma_\nu - \frac{2}{3m'^2}p'_\mu p'_\nu - \frac{1}{3m'}(\gamma_\mu p'_\nu - \gamma_\nu p'_\mu)\right)$$

$\frac{1}{2}^+ \to \frac{1}{2}^+$ vector and axial vector helicity form factors:

$$\begin{aligned}
\mathscr{G}^{(\frac{1}{2}^+)}[\gamma^\mu] \quad = \quad & f_0^{(\frac{1}{2}^+)}\,(m_{\Lambda_b} - m_{\Lambda_c})\frac{q^\mu}{q^2} \\
& + f_+^{(\frac{1}{2}^+)}\,\frac{m_{\Lambda_b} + m_{\Lambda_c}}{s_+}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda_c}^2)\frac{q^\mu}{q^2}\right) \\
& + f_\perp^{(\frac{1}{2}^+)}\left(\gamma^\mu - \frac{2m_{\Lambda_c}}{s_+}p^\mu - \frac{2\,m_{\Lambda_b}}{s_+}p'^\mu\right)
\end{aligned}$$

$$\begin{aligned}
\mathscr{G}^{(\frac{1}{2}^+)}[\gamma^\mu\gamma_5] \quad = \quad & -g_0^{(\frac{1}{2}^+)}\gamma_5\,(m_{\Lambda_b} + m_{\Lambda_c})\frac{q^\mu}{q^2} \\
& - g_+^{(\frac{1}{2}^+)}\gamma_5\,\frac{m_{\Lambda_b} - m_{\Lambda_c}}{s_-}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda_c}^2)\frac{q^\mu}{q^2}\right) \\
& - g_\perp^{(\frac{1}{2}^+)}\gamma_5\left(\gamma^\mu + \frac{2m_{\Lambda_c}}{s_-}p^\mu - \frac{2\,m_{\Lambda_b}}{s_-}p'^\mu\right)
\end{aligned}$$

$$s_\pm = (m_{\Lambda_b} - m_{\Lambda_c})^2 - q^2$$

[T. Feldmann and M. Yip, arXiv:1111.1844/PRD 2012]

$\frac{1}{2}^+ \to \frac{1}{2}^-$ vector and axial vector helicity form factors:

$$\begin{aligned}
\mathscr{G}^{(\frac{1}{2}^-)}[\gamma^\mu] &= f_0^{(\frac{1}{2}^-)}\,(m_{\Lambda_b}+m_{\Lambda_c^*})\,\frac{q^\mu}{q^2} \\
&+ f_+^{(\frac{1}{2}^-)}\,\frac{m_{\Lambda_b}-m_{\Lambda_c^*}}{s_-}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2)\,\frac{q^\mu}{q^2}\right) \\
&+ f_\perp^{(\frac{1}{2}^-)}\left(\gamma^\mu + \frac{2m_{\Lambda_c^*}}{s_-}p^\mu - \frac{2\,m_{\Lambda_b}}{s_-}p'^\mu\right),
\end{aligned}$$

$$\begin{aligned}
\mathscr{G}^{(\frac{1}{2}^-)}[\gamma^\mu\gamma_5] &= -g_0^{(\frac{1}{2}^-)}\gamma_5\,(m_{\Lambda_b}-m_{\Lambda_c^*})\,\frac{q^\mu}{q^2} \\
&- g_+^{(\frac{1}{2}^-)}\gamma_5\,\frac{m_{\Lambda_b}+m_{\Lambda_c^*}}{s_+}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2)\,\frac{q^\mu}{q^2}\right) \\
&- g_\perp^{(\frac{1}{2}^-)}\gamma_5\left(\gamma^\mu - \frac{2m_{\Lambda_c^*}}{s_+}p^\mu - \frac{2\,m_{\Lambda_b}}{s_+}p'^\mu\right),
\end{aligned}$$

$$s_\pm = (m_{\Lambda_b} - m_{\Lambda_c^*})^2 - q^2$$

$\frac{1}{2}^+ \to \frac{3}{2}^+$ vector and axial vector helicity form factors:

$$\mathscr{G}^{\lambda(\frac{3}{2}^+)}[\gamma^\mu] = f_0^{(\frac{3}{2}^+)} \frac{m_{\Lambda_c^*}}{s_-} \frac{(m_{\Lambda_b} + m_{\Lambda_c^*})\, p^\lambda q^\mu}{q^2}$$

$$+ f_+^{(\frac{3}{2}^+)} \frac{m_{\Lambda_c^*}}{s_+} \frac{(m_{\Lambda_b} - m_{\Lambda_c^*})\, p^\lambda (q^2 (p^\mu + p'^\mu) - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2) q^\mu)}{q^2\, s_-}$$

$$+ f_\perp^{(\frac{3}{2}^+)} \frac{m_{\Lambda_c^*}}{s_+} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu - m_{\Lambda_c^*} p^\mu)}{s_-} \right)$$

$$+ f_{\perp'}^{(\frac{3}{2}^+)} \frac{m_{\Lambda_c^*}}{s_+} \left(p^\lambda \gamma^\mu + \frac{2\, p^\lambda p'^\mu}{m_{\Lambda_c^*}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu - m_{\Lambda_c^*} p^\mu)}{s_-} - \frac{s_+\, g^{\lambda\mu}}{m_{\Lambda_c^*}} \right)$$

$$\mathscr{G}^{\lambda(\frac{3}{2}^+)}[\gamma^\mu \gamma_5] = -g_0^{(\frac{3}{2}^+)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_+} \frac{(m_{\Lambda_b} - m_{\Lambda_c^*})\, p^\lambda q^\mu}{q^2}$$

$$- g_+^{(\frac{3}{2}^+)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_-} \frac{(m_{\Lambda_b} + m_{\Lambda_c^*})\, p^\lambda (q^2 (p^\mu + p'^\mu) - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2) q^\mu)}{q^2\, s_+}$$

$$- g_\perp^{(\frac{3}{2}^+)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_-} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda_c^*} p^\mu)}{s_+} \right)$$

$$- g_{\perp'}^{(\frac{3}{2}^+)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_-} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda p'^\mu}{m_{\Lambda_c^*}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda_c^*} p^\mu)}{s_+} + \frac{s_-\, g^{\lambda\mu}}{m_{\Lambda_c^*}} \right)$$

$\frac{1}{2}^+ \to \frac{3}{2}^-$ vector and axial vector helicity form factors:

$$\mathscr{G}^{\lambda(\frac{3}{2}^-)}[\gamma^\mu] = f_0^{(\frac{3}{2}^-)} \frac{m_{\Lambda_c^*}}{s_+} \frac{(m_{\Lambda_b} - m_{\Lambda_c^*})\, p^\lambda q^\mu}{q^2}$$

$$+ f_+^{(\frac{3}{2}^-)} \frac{m_{\Lambda_c^*}}{s_-} \frac{(m_{\Lambda_b} + m_{\Lambda_c^*})\, p^\lambda (q^2 (p^\mu + p'^\mu) - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2) q^\mu)}{q^2\, s_+}$$

$$+ f_\perp^{(\frac{3}{2}^-)} \frac{m_{\Lambda_c^*}}{s_-} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda_c^*} p^\mu)}{s_+} \right)$$

$$+ f_{\perp'}^{(\frac{3}{2}^-)} \frac{m_{\Lambda_c^*}}{s_-} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda p'^\mu}{m_{\Lambda_c^*}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda_c^*} p^\mu)}{s_+} + \frac{s_-\, g^{\lambda\mu}}{m_{\Lambda_c^*}} \right)$$

$$\mathscr{G}^{\lambda(\frac{3}{2}^-)}[\gamma^\mu \gamma_5] = -g_0^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_-} \frac{(m_{\Lambda_b} + m_{\Lambda_c^*})\, p^\lambda q^\mu}{q^2}$$

$$- g_+^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_+} \frac{(m_{\Lambda_b} - m_{\Lambda_c^*})\, p^\lambda (q^2 (p^\mu + p'^\mu) - (m_{\Lambda_b}^2 - m_{\Lambda_c^*}^2) q^\mu)}{q^2\, s_-}$$

$$- g_\perp^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_+} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu - m_{\Lambda_c^*} p^\mu)}{s_-} \right)$$

$$- g_{\perp'}^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda_c^*}}{s_+} \left(p^\lambda \gamma^\mu + \frac{2\, p^\lambda p'^\mu}{m_{\Lambda_c^*}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu - m_{\Lambda_c^*} p^\mu)}{s_-} - \frac{s_+\, g^{\lambda\mu}}{m_{\Lambda_c^*}} \right)$$

Early work (quenched, focused on Isgur-Wise function):

- K. C. Boweler *et al.* (UKQCD Collaboration), hep-lat/9709028/PRD 1998
- S. Gottlieb and S. Tamhankar, hep-lat/0301022/Lattice 2002

Our work:

- W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421/PRD 2015
  (vector and axial vector form factors)

- A. Datta, S. Kamali, S. Meinel, A. Rashed, arXiv:1702.02243/JHEP 2017
  (tensor form factors)

- Gauge field configurations generated by the RBC and UKQCD collaborations
  [Y. Aoki *et al.*, arXiv:1011.0892/PRD 2011]

- u, d, s quarks: domain-wall action
  [D. Kaplan, hep-lat/9206013/PLB 1992; V. Furman and Y. Shamir, hep-lat/9303005/NPB 1995]

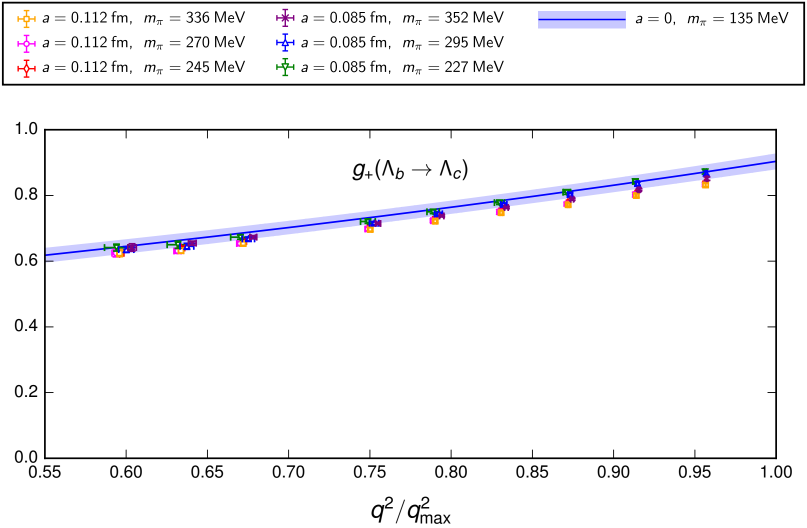
- c, b quarks: anisotropic clover with two or three parameters tuned nonperturbatively
  [A. El-Khadra, A. Kronfeld, P. Mackenzie, hep-lat/9604004/PRD 1997; Y. Aoki *et al.*, arXiv:1206.2554/PRD 2012]

- "Mostly nonperturbative" renormalization
  [A. El-Khadra *et al.*, hep-ph/0101023/PRD 2001]

- Three-point functions with 12 source-sink separations

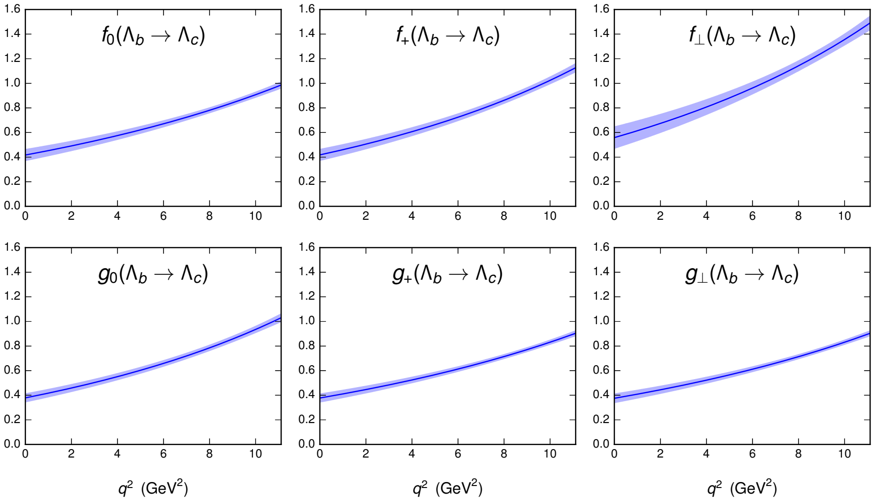
- Combined chiral/continuum/kinematic extrapolation using modified z-expansion [C. Bourrely, I. Caprini, L. Lellouch, arXiv:0807.2722/PRD 2009]

$N_s^3 \times N_t$	β	$am_{u,d}^{(\mathrm{sea})}$	$am_{u,d}^{(\mathrm{val})}$	$am_s^{(\mathrm{sea})}$	a (fm)	$m_\pi^{(\mathrm{sea})}$ (MeV)	$m_\pi^{(\mathrm{val})}$ (MeV)
$24^3 \times 64$	2.13	0.005	0.005	0.04	≈ 0.11	≈ 340	≈ 340
$24^3 \times 64$	2.13	0.005	0.002	0.04	≈ 0.11	≈ 340	≈ 270
$24^3 \times 64$	2.13	0.005	0.001	0.04	≈ 0.11	≈ 340	≈ 250
$32^3 \times 64$	2.25	0.006	0.006	0.03	≈ 0.08	≈ 360	≈ 360
$32^3 \times 64$	2.25	0.004	0.004	0.03	≈ 0.08	≈ 300	≈ 300
$32^3 \times 64$	2.25	0.004	0.002	0.03	≈ 0.08	≈ 300	≈ 230

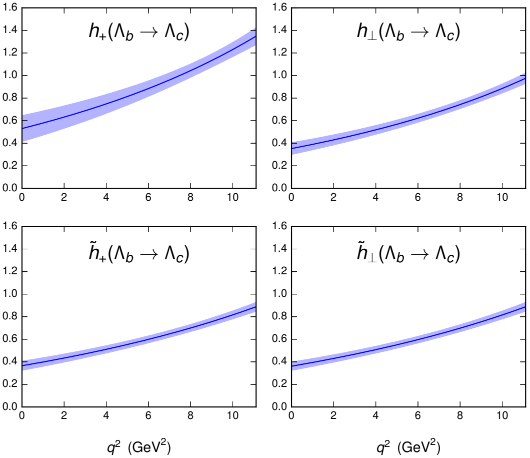


$a = 0.112$ fm, $m_\pi = 336$ MeV
$a = 0.112$ fm, $m_\pi = 270$ MeV
$a = 0.112$ fm, $m_\pi = 245$ MeV
$a = 0.085$ fm, $m_\pi = 352$ MeV
$a = 0.085$ fm, $m_\pi = 295$ MeV
$a = 0.085$ fm, $m_\pi = 227$ MeV
$a = 0$, $m_\pi = 135$ MeV
$g_+(\Lambda_b \to \Lambda_c)$
1.0
0.8
0.6
0.4
0.2
0.0
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
$q^2/q^2_{\rm max}$

Vector and axial vector form factors:

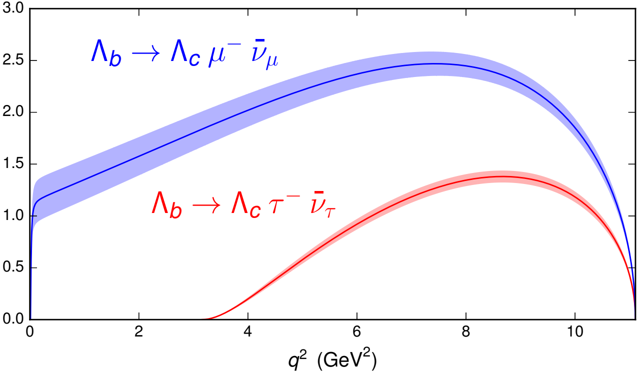


Tensor form factors:



Differential decay rates in the standard model:

$\frac{d\Gamma/dq^2}{|V_{cb}|^2}$ (ps^{-1} GeV^{-2})



Integrated decay rates in the standard model:

$$\frac{1}{|V_{cb}|^2}\Gamma(\Lambda_b \to \Lambda_c\, \mu^- \bar{\nu}_\mu) \;=\; (21.5 \;\pm\; 0.8_{\,\mathrm{stat}} \;\pm\; 1.1_{\,\mathrm{syst}})\;\;\mathrm{ps}^{-1}$$

(6.3% uncertainty $\rightarrow$ 3.2% for $|V_{cb}|$)

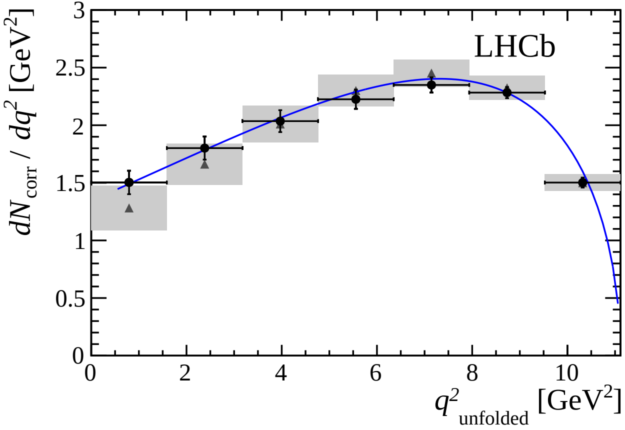
$$\frac{1}{|V_{cb}|^2}\int_{7\ \mathrm{GeV}^2}^{q^2_{\mathrm{max}}} \frac{\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c\, \mu^- \bar{\nu}_\mu)}{\mathrm{d}q^2}\mathrm{d}q^2 \;=\; (8.37 \;\pm\; 0.16_{\,\mathrm{stat}} \;\pm\; 0.34_{\,\mathrm{syst}})\;\;\mathrm{ps}^{-1}$$

(4.5% uncertainty $\rightarrow$ 2.3% for $|V_{cb}|$)

$$R(\Lambda_c) = \frac{\Gamma(\Lambda_b \to \Lambda_c\, \tau^- \bar{\nu}_\tau)}{\Gamma(\Lambda_b \to \Lambda_c\, \mu^- \bar{\nu}_\mu)} \;=\; 0.3328 \;\pm\; 0.0074_{\,\mathrm{stat}} \;\pm\; 0.0070_{\,\mathrm{syst}}$$

(3.1% uncertainty)

The shape of the $\Lambda_b \to \Lambda_c \mu^- \bar{\nu}_\mu$ decay rate measured by LHCb (black data points) agrees with our lattice QCD prediction (gray).



[LHCb Collaboration, arXiv:1709.01920/PRD 2017]

BSM phenomenology of $\Lambda_b \to \Lambda_c \, \tau^- \bar{\nu}$

[A. Datta, S. Kamali, S. Meinel, A. Rashed, arXiv:1702.02243/JHEP 2017]

- We have shown that a future measurement of $R(\Lambda_c)$ can provide useful constraints on all of the couplings g_L, g_R, g_S, g_P, g_T.
- The paper contains plots showing the correlations between $R(D^{(*)})$ and $R(\Lambda_c)$ for several leptoquark models.

We work in the Λ_c^* rest frame to allow exact spin-parity projection. We use the interpolating field

$$(\Lambda_c^*)_{j\gamma} = \epsilon^{abc}\,(C\gamma_5)_{\alpha\beta}\Big[\tilde{c}^a_\alpha\,\tilde{d}^b_\beta\,(\nabla_j\tilde{u})^c_\gamma - \tilde{c}^a_\alpha\,\tilde{u}^b_\beta\,(\nabla_j\tilde{d})^c_\gamma + \tilde{u}^a_\alpha\,(\nabla_j\tilde{d})^b_\beta\,\tilde{c}^c_\gamma - \tilde{d}^a_\alpha\,(\nabla_j\tilde{u})^b_\beta\,\tilde{c}^c_\gamma\Big]$$

(˜ denotes Gaussian smearing) [S. Meinel and G. Rendon, arXiv:1608.08110/Lattice2016]

This requires light-quark propagators with derivative sources.

We project to $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$ using

$$P^{(\frac{1}{2}^-)}_{jk} = \frac{1}{3}\gamma_j\gamma_k\frac{1+\gamma_0}{2},$$

$$P^{(\frac{3}{2}^-)}_{jk} = \left(g_{jk} - \frac{1}{3}\gamma_j\gamma_k\right)\frac{1+\gamma_0}{2}.$$

- Gauge field configurations generated by the RBC and UKQCD collaborations

  [Y. Aoki *et al.*, arXiv:1011.0892/PRD 2011]

- u, d, s quarks: domain-wall action

  [D. Kaplan, hep-lat/9206013/PLB 1992; V. Furman and Y. Shamir, hep-lat/9303005/NPB 1995]

- All-mode averaging with 1 exact and 32 sloppy propagators per configuration

  [E. Shintani *et al.*, arXiv:1402.0244/PRD 2015]

- c, b quarks: anisotropic clover with three parameters, re-tuned more accurately to $D_s^{(*)}$ and $B_s^{(*)}$ dispersion relation and HFS

- "Mostly nonperturbative" renormalization

  [A. El-Khadra *et al.*, hep-ph/0101023/PRD 2001]

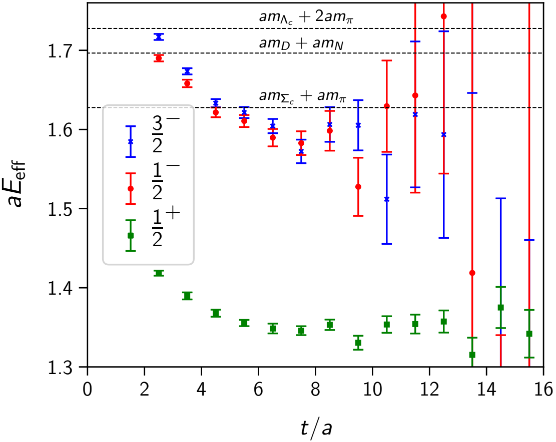
- Three-point functions with 7 source-sink separations (plan to add 2 more)

$N_s^3 \times N_t$	β	$am_{u,d}$	am_s	a (fm)	m_π (MeV)	Run status
$24^3 \times 64$	2.13	0.01	0.04	≈ 0.111	≈ 430	1/4 of cfgs done
$24^3 \times 64$	2.13	0.005	0.04	≈ 0.111	≈ 340	1/4 of cfgs done
$32^3 \times 64$	2.25	0.004	0.03	≈ 0.083	≈ 300	1/4 of cfgs done
$48^3 \times 96$	2.31	0.002144	0.02144	≈ 0.071	≈ 230	planned

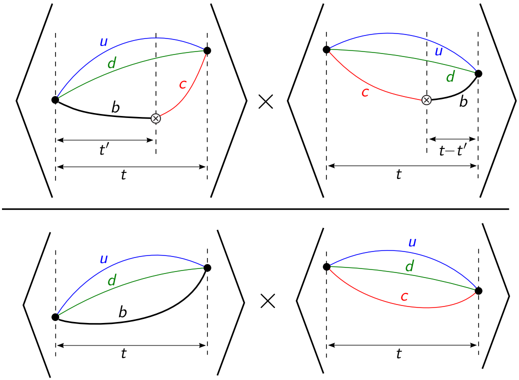
Λ_c^* two-point functions preliminary

Results from $24^3 \times 64$, $am_{u,d} = 0.005$ ensemble, 78 configs $\times$ 32 sources

$a^{-1} = 1.785(5)$ GeV



Extracting the form factors from ratios of 3pt and 2pt functions



t = source-sink separation
t' = current insertion time

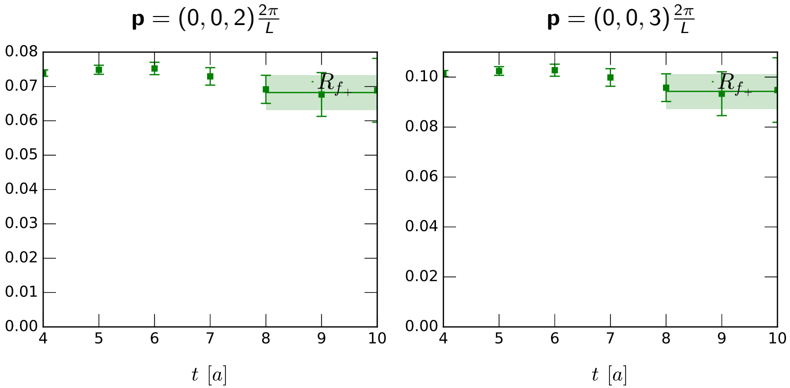
We have data for two different Λ_b momenta: $\mathbf{p} = (0,0,2)\frac{2\pi}{L} \approx 0.9$ GeV and $\mathbf{p} = (0,0,3)\frac{2\pi}{L} \approx 1.4$ GeV

Schematically,

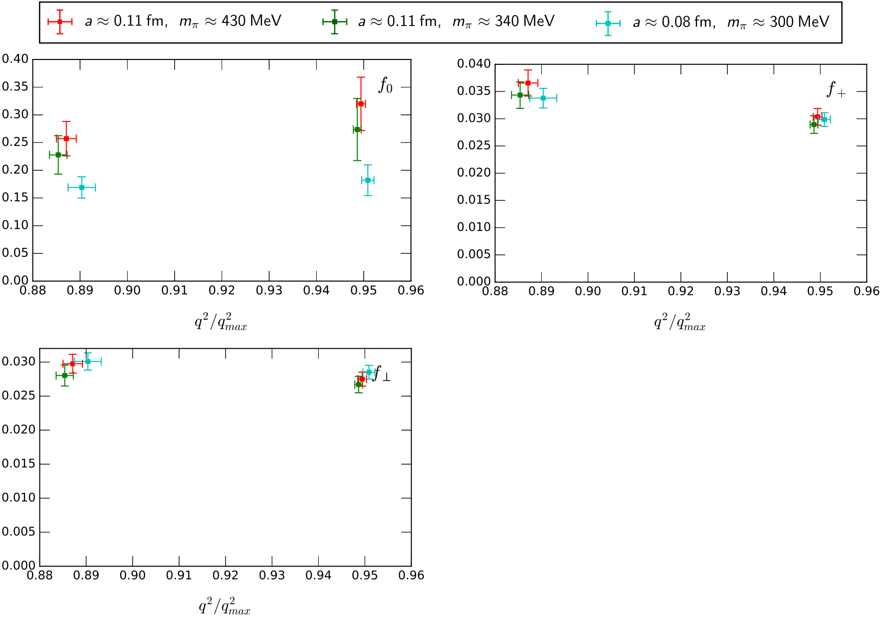
$$
\begin{aligned}
R_f(\mathbf{p}, t) &= \sqrt{(\text{kinematic factors}) \times (\text{polarization vectors}) \times (\text{ratio at } t' = t/2)} \\
&\to f(\mathbf{p}) \quad \text{for large } t
\end{aligned}
$$

Example: R_{f_+} for $\Lambda_b \to \Lambda_c^* \left(\frac{3}{2}^-\right)$ preliminary

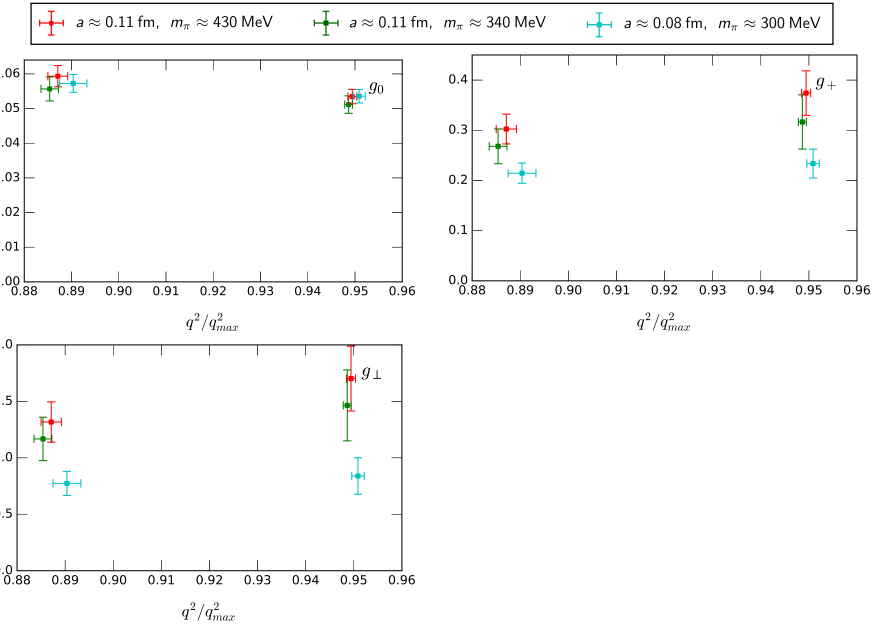
Results from $24^3 \times 64$, $am_{u,d} = 0.005$ ensemble, 78 configs $\times$ 32 sources



$\Lambda_b \to \Lambda_c^* \left(\frac{1}{2}^-\right)$ vector form factors preliminary

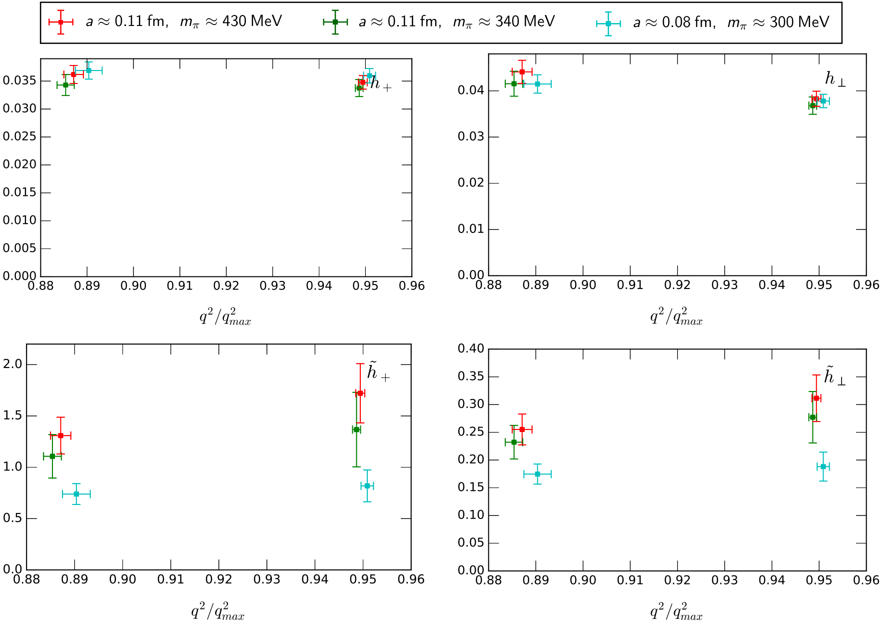


$\Lambda_b \to \Lambda_c^* \left(\frac{1}{2}^-\right)$ axial vector form factors   preliminary

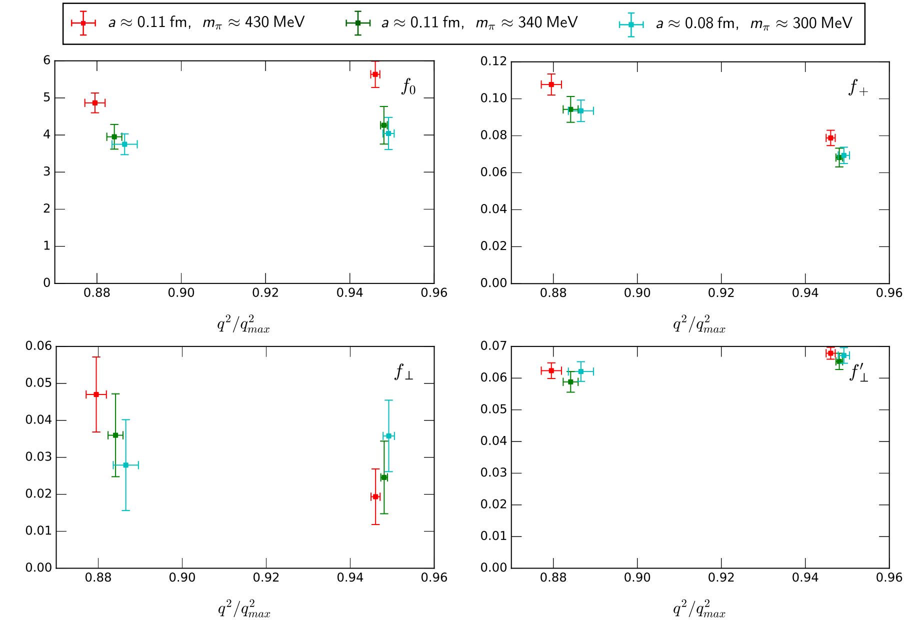


$\Lambda_b \to \Lambda_c^* \left(\frac{1}{2}^-\right)$ tensor form factors

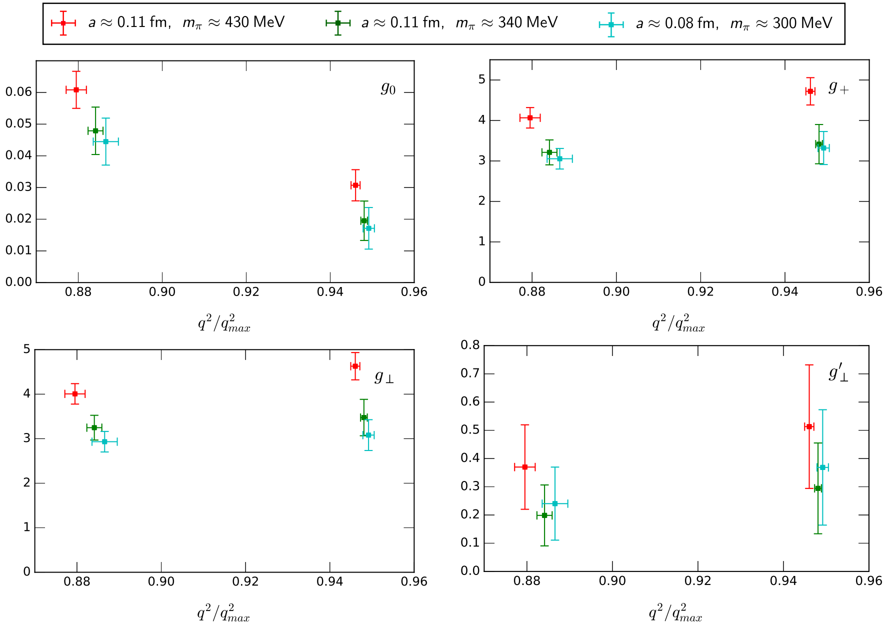
preliminary



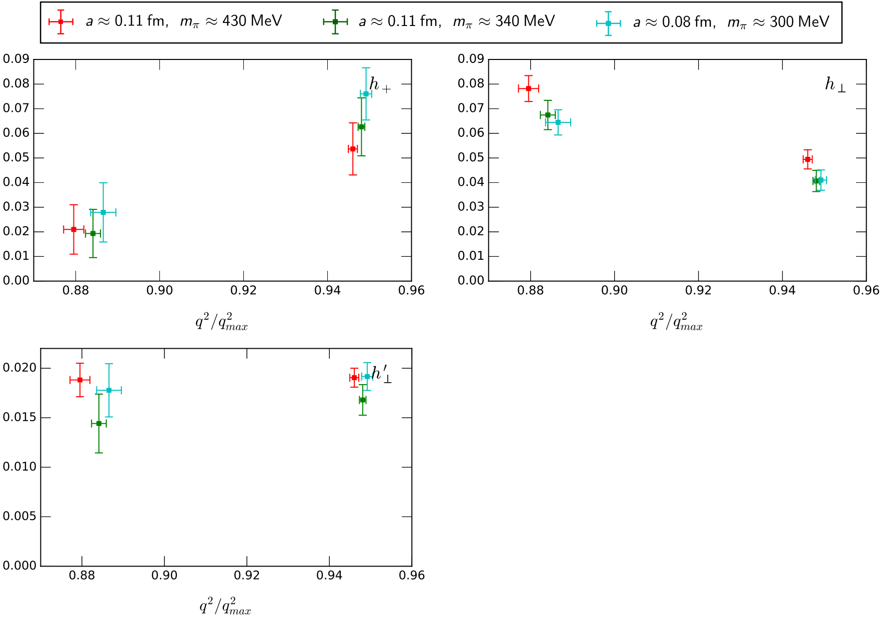
$\Lambda_b \to \Lambda_c^* \left(\frac{3}{2}^-\right)$ vector form factors   preliminary



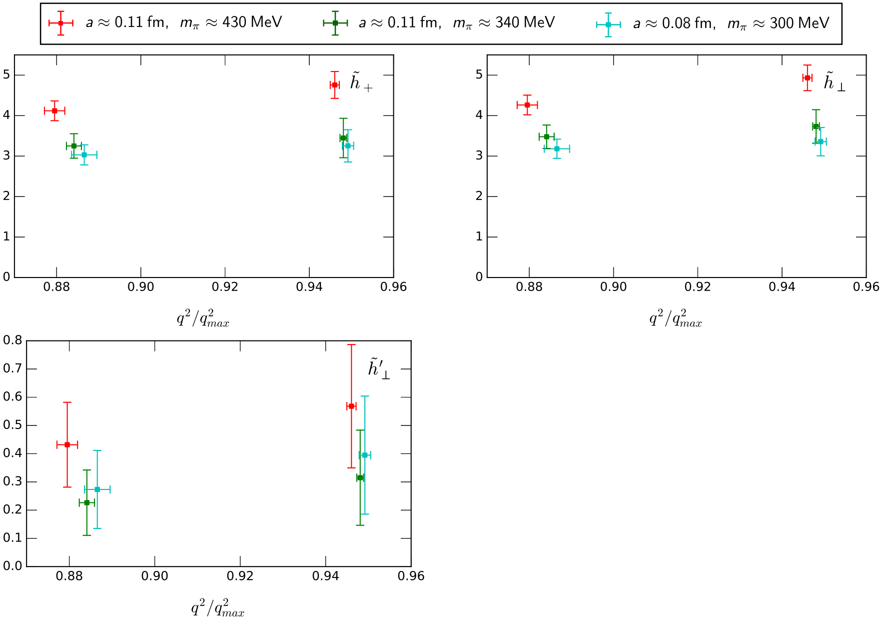
$\Lambda_b \to \Lambda_c^* \left(\frac{3}{2}^-\right)$ axial vector form factors preliminary



$\Lambda_b \to \Lambda_c^* \left(\frac{3}{2}^-\right)$ tensor form factors part 1 preliminary



$\Lambda_b \to \Lambda_c^* \left(\frac{3}{2}^-\right)$ tensor form factors part 2 preliminary



$\Lambda_b \to \Lambda_c^*$ next steps:

- 4×statistics
- third lattice spacing
- chiral/continuum extrapolations

The lattice form factor results are limited to high q^2.

To predict $R(\Lambda_c^*)$, it will be helpful to combine the lattice results with experimental data for the shape of the $\Lambda_b \to \Lambda_c^* \mu\bar{\nu}$ differential decay rates, making use of HQET.

[P. Boer, M. Bordone, E. Graverini, P. Owen, M. Rotondo, and D. Van Dyk, arXiv:1801.08367]

An improved calculation of $\Lambda_b \to p, \Lambda, \Lambda_c$ $(\frac{1}{2}^+)$ form factors is also underway:

- remove data sets with $m_{u,d}^{(\mathrm{val})} < m_{u,d}^{(\mathrm{sea})}$, add two new ensembles
- for $\Lambda_b \to \Lambda$: physical $m_s^{(\mathrm{val})}$
- more accurate tuning of charm and bottom actions
- all-mode-averaging for higher statistics
- better source smearing

$N_s^3 \times N_t$	β	$am_{u,d}^{(\mathrm{sea})}$	$am_{u,d}^{(\mathrm{val})}$	$am_s^{(\mathrm{sea})}$	a (fm)	$m_\pi^{(\mathrm{sea})}$ (MeV)	$m_\pi^{(\mathrm{val})}$ (MeV)	Status
$24^3 \times 64$	2.13	0.005	0.005	0.04	≈ 0.111	≈ 340	≈ 340	done
~~$24^3 \times 64$~~	~~2.13~~	~~0.005~~	~~0.002~~	~~0.04~~	~~≈ 0.111~~	~~≈ 340~~	~~≈ 270~~	
~~$24^3 \times 64$~~	~~2.13~~	~~0.005~~	~~0.001~~	~~0.04~~	~~≈ 0.111~~	~~≈ 340~~	~~≈ 250~~	
$48^3 \times 96$	2.13	0.00078	0.00078	0.0362	≈ 0.114	≈ 140	≈ 140	done
$32^3 \times 64$	2.25	0.006	0.006	0.03	≈ 0.083	≈ 360	≈ 360	done
$32^3 \times 64$	2.25	0.004	0.004	0.03	≈ 0.083	≈ 300	≈ 300	done
~~$32^3 \times 64$~~	~~2.25~~	~~0.004~~	~~0.002~~	~~0.03~~	~~≈ 0.083~~	~~≈ 300~~	~~≈ 230~~	
$48^3 \times 96$	2.31	0.002144	0.002144	0.02144	≈ 0.071	≈ 230	≈ 230	planned

Expected completion: 2020. Hope to reduce total uncertainties by factor of 2.

Extra slides

Breakdown of uncertainties in partially integrated $\Lambda_b \to p\mu\bar{\nu}_\mu$ and $\Lambda_b \to \Lambda_c\mu\bar{\nu}_\mu$ decay rates (in percent):

	$\zeta_{p\mu\bar{\nu}}(15\ \mathrm{GeV}^2)$	$\zeta_{\Lambda_c\mu\bar{\nu}}(7\ \mathrm{GeV}^2)$	$\dfrac{\zeta_{p\mu\bar{\nu}}(15\ \mathrm{GeV}^2)}{\zeta_{\Lambda_c\mu\bar{\nu}}(7\ \mathrm{GeV}^2)}$
Statistics	6.2	1.9	6.5
Finite volume	5.0	2.5	4.9
Continuum extrapolation	3.0	1.4	2.8
Chiral extrapolation	2.6	1.8	2.6
RHQ parameters	1.4	1.7	2.3
Matching & improvement	1.7	0.9	2.1
Missing isospin breaking/QED	1.2	1.4	2.0
Scale setting	1.7	0.3	1.8
z expansion	1.2	0.2	1.3
Total	8.8	4.5	9.8

Note: the individual systematic uncertainties are correlated in a complicated way. Use the total uncertainty only.

[W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421/PRD 2015]

Λ_b and Λ_c decay form factors from lattice QCD: References

	m_b	a [fm]	m_π [MeV]	Reference
$\Lambda_b \to \Lambda$	∞	0.11, 0.08	230–360	arXiv:1212.4827/PRD 2013
$\Lambda_b \to p$	∞	0.11, 0.08	230–360	arXiv:1306.0446/PRD 2013
$\Lambda_b \to p$	phys.	0.11, 0.08	230–360	arXiv:1503.01421/PRD 2015
$\Lambda_b \to \Lambda_c$	phys.	0.11, 0.08	230–360	arXiv:1503.01421/PRD 2015, arXiv:1702.02243/JHEP 2017
$\Lambda_b \to \Lambda$	phys.	0.11, 0.08	230–360	arXiv:1602.01399/PRD 2016
$\Lambda_b \to \Lambda^*(\frac{3}{2}^-)$	phys.	0.11	340	arXiv:1608.08110/Lattice 2016
$\Lambda_c \to \Lambda$		0.11, 0.08	**140**–360	arXiv:1611.09696/PRL 2017
$\Lambda_c \to p$		0.11, 0.08	230–360	arXiv:1712.05783/PRD 2018