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Semileptonic decays of heavy baryons to negative-parity baryons

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Work done with Gumaro Rendon (BNL)

The simplest Λ_b and Λ_c semileptonic decays: $J^P = \frac{1}{2}^+$ ground states

Charged-current decays

- $\Lambda_b \to \Lambda_c\, \ell^- \bar{\nu}_\ell$
- $\Lambda_b \to p\, \ell^- \bar{\nu}_\ell$
- $\Lambda_c \to \Lambda\, \ell^+ \nu_\ell$
- $\Lambda_c \to n\, \ell^+ \nu_\ell$

Neutral-current (rare) decays

- $\Lambda_b \to \Lambda\, \ell^+ \ell^-$
- $\Lambda_b \to n\, \ell^+ \ell^-$
- $\Lambda_c \to p\, \ell^+ \ell^-$

(and $\nu\bar{\nu}$ modes)

The form factors (describing the transition matrix elements of the vector, axial-vector, and tensor currents in the effective weak Hamiltonian) for all of the above have been calculated using lattice QCD.

What about final-state baryons with $J^P \neq \frac{1}{2}^+$?
Which of them narrow enough to use the single-hadron approach in a first lattice calculation?

N^* baryons ($I = \frac{1}{2}$)

			Status as seen in									
Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta\prime$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***						
$N(1520)$	$3/2^-$	****	****	****	****	**	****					
$N(1535)$	$1/2^-$	****	****	****	***	*	****					
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*				
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)$	$3/2^-$	***	**	***	***	*	*			*		
$N(1710)$	$1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**		*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*	**	*	*				*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

[PDG]

Λ^* baryons ($S = -1$, $I = 0$)

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi$, $\Lambda\gamma$
$\Lambda(1600)$	$1/2^+$	****	***	****	$\Lambda\pi\pi$, $\Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	****	****	****	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	****	****	***	$\Lambda\pi\pi$, $\Sigma(1385)\pi$
$\Lambda(1710)$	$1/2^+$	*	*	*	
$\Lambda(1800)$	$1/2^-$	***	***	**	$\Lambda\pi\pi$, $\Sigma(1385)\pi$, $N\overline{K}^*$
$\Lambda(1810)$	$1/2^+$	***	**	**	$N\overline{K}_2^*$
$\Lambda(1820)$	$5/2^+$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	$5/2^-$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	$3/2^+$	****	****	**	$\Sigma(1385)\pi$, $N\overline{K}^*$
$\Lambda(2000)$	$1/2^-$	*	*	*	
$\Lambda(2050)$	$3/2^-$	*	*	*	
$\Lambda(2070)$	$3/2^+$	*	*	*	
$\Lambda(2080)$	$5/2^-$	*	*	*	
$\Lambda(2085)$	$7/2^+$	**	**	*	
$\Lambda(2100)$	$7/2^-$	****	****	**	$N\overline{K}^*$
$\Lambda(2110)$	$5/2^+$	***	**	**	$N\overline{K}^*$
$\Lambda(2325)$	$3/2^-$	*	*		
$\Lambda(2350)$	$9/2^+$	***	***	*	
$\Lambda(2585)$		*	*		

$\Gamma_{\Lambda^*(1520)} \approx 16\text{MeV}$

[PDG]

Λ_c^* baryons ($C = +1,\ S = 0,\ I = 0$)

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$ or $\Sigma_c(2765)$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***

$\Gamma_{\Lambda_c^*(2595)} \approx 2.6\ \text{MeV}$

$\Gamma_{\Lambda_c^*(2625)} < 1.0\ \text{MeV}$

[PDG]

Note: for $m_c \to \infty$ the $\Lambda_c^*(2595)$ and $\Lambda_c^*(2625)$ baryons become mass-degenerate heavy-quark spin-symmetry partners. However, they are NOT related to the Λ_c by heavy-quark spin symmetry (the light degrees of freedom have different angular momentum).

Experimental situation

- CDF at Tevatron has measured the ratios of branching fractions [arXiv:0810.3213/PRD 2009]

$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^*(2595)\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\,\mu^-\bar{\nu}_\mu)} = 0.126 \pm 0.033^{+0.047}_{-0.038}$$

$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c^*(2625)\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\,\mu^-\bar{\nu}_\mu)} = 0.210 \pm 0.042^{+0.071}_{-0.050}$$

- LHCb has large $\Lambda_b \to \Lambda_c^*(2595, 2625)\mu^-\bar{\nu}_\mu$ samples and can also measure the $R(\Lambda_c^*)$ lepton-flavor-universality ratios with tau leptons [P. Böer *et al.*, arXiv:1801.08367/JHEP 2018]

- LHCb is planning an analysis of the rare decay $\Lambda_b \to \Lambda^*(1520)(\to p^+K^-)\mu^+\mu^-$ [Y. Amhis *et al.*, arXiv:2005.09602/EPJP 2021]

- BESIII has measured the inclusive semileptonic branching fraction [arXiv:1805.09060/PRL 2018]

$$\mathcal{B}(\Lambda_c \to Xe^+\nu_e) = (3.95 \pm 0.34 \pm 0.09) \times 10^{-2}$$

Related theoretical work

- Quark-model studies of $\Lambda_b \to \Lambda_c^* \ell^- \bar{\nu}_\ell$, $\Lambda_b \to p^* \ell^- \bar{\nu}_\ell$, $\Lambda_b \to \Lambda^* \ell^+ \ell^-$, $\Lambda_c \to \Lambda^* \ell^+ \nu_\ell$, $\Lambda_c \to n^* \ell^+ \nu_\ell$
  M. Pervin, W. Roberts, S. Capstick, arXiv:nucl-th/0503030/PRC 2005
  L. Mott, W. Roberts, arXiv:1108.6129/IJMPA 2012
  M. Hussain, W. Roberts, arXiv:1701.03876/PRD 2017
  T. Gutsche *et al.*, arXiv:1807.11300/PRD 2018
  D. Bečirević *et al.*, arXiv:2006.07130/PRD 2020
  Y.-S. Li, X. Liu, F.-S. Yu, arXiv:2104.04962

- $\Lambda_b \to \Lambda_c^*(2595, 2625)\ell^+ \nu_\ell$ in HQET including $\mathcal{O}(\alpha_s, 1/m_b)$
  W. Roberts, NPB **389**, 549 (1993)
  A. Leibovich, I. Stewart, arXiv:hep-ph/9711257/PRD 1998
  P. Böer *et al.*, arXiv:1801.08367/JHEP 2018
  J. Nieves, R. Pavao, S. Sakai, arXiv:1903.11911/EPJC 2019
  M. Papucci, D. Robinson, arXiv:2105.09330

Related theoretical work

- $\Lambda_c \to \Lambda^*(1405)\ell^+\nu_\ell$ in chiral unitary (meson-baryon molecular) approach
  N. Ikeno, E. Oset, arXiv:1510.02406/PRD 2016

- Angular distribution of $\Lambda_b \to \Lambda^*(1520)(\to pK^-)\ell^+\ell^-$
  S. Descotes-Genon, M. Novoa-Brunet, arXiv:1903.00448/JHEP 2019

- $\Lambda_b \to \Lambda^*(1520)\ell^+\ell^-$ in HQET including $\mathcal{O}(\alpha_s)$ and/or $\mathcal{O}(1/m_b)$
  W. Roberts, NPB **389**, 549 (1993)
  D. Das, J. Das, arXiv:2003.08366/JHEP 2020
  M. Bordone, arXiv:2101.12028/Symmetry 2021

- LHCb sensitivity study of $\Lambda_b \to \Lambda^*(1520)(\to pK^-)\ell^+\ell^-$
  Y. Amhis *et al.*, arXiv:2005.09602/EPJP 2021

- **NEW!** Endpoint symmetries of baryon helicity amplitudes at $q^2 = q^2_{\text{max}}$
  G. Hiller and R. Zwicky, arXiv:2107.12993

Our lattice calculations

- $\Lambda_b \to \Lambda^*(1520)\ell^+\ell^-$
  S. Meinel and G. Rendon, arXiv:2009.09313/PRD 2021

- $\Lambda_b \to \Lambda_c^*(2595)\ell^-\bar{\nu}_\ell$ and $\Lambda_b \to \Lambda_c^*(2625)\ell^-\bar{\nu}_\ell$
  S. Meinel and G. Rendon, arXiv:2103.08775/PRD 2021

- **NEW!** $\Lambda_c \to \Lambda^*(1520)\ell^+\nu_\ell$
  S. Meinel and G. Rendon, arXiv:2107.13140 and arXiv:2107.13084

  NEW! In arXiv:2107.13140 we also improved the analysis of the $\Lambda_b \to \Lambda^*(1520)$ and $\Lambda_b \to \Lambda_c^*(2595, 2625)$ form factors by enforcing exact endpoint relations in the fits. The results shown in the following are from this improved analysis.

Our lattice calculations

- We use RBC/UKQCD ensembles with $2+1$ flavors of domain-wall fermions

Label	$N_s^3 \times N_t$	a [fm]	m_π [GeV]
C01	$24^3 \times 64$	0.1106(3)	0.4312(13)
C005	$24^3 \times 64$	0.1106(3)	0.3400(11)
F004	$32^3 \times 64$	0.0828(3)	0.3030(12)

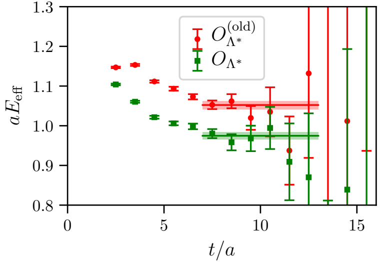
- The charm and bottom quarks are implemented using the "RHQ" (anisotropic clover) action

Our lattice calculations

- We work in the final-baryon rest frame to allow exact projection to $J^P = \frac{1}{2}^-$ or $\frac{3}{2}^-$ (G_{1u} or H_u irreps), and to ensure that the resonance-like energy level is well below any multi-hadron-like energy levels

- We use an interpolating field with covariant spatial derivatives to obtain an $L = 1$ structure,

$$(O_{\Lambda^*})_{j\gamma} = \epsilon^{abc}\,(C\gamma_5)_{\alpha\beta}\left(\frac{1+\gamma_0}{2}\right)_{\gamma\delta}\left[\tilde{s}^a_\alpha\,\tilde{d}^b_\beta\,(\tilde{\nabla}_j\tilde{u})^c_\delta - \tilde{s}^a_\alpha\,\tilde{u}^b_\beta\,(\tilde{\nabla}_j\tilde{d})^c_\delta + \tilde{u}^a_\alpha\,(\tilde{\nabla}_j\tilde{d})^b_\beta\,\tilde{s}^c_\delta - \tilde{d}^a_\alpha\,(\tilde{\nabla}_j\tilde{u})^b_\beta\,\tilde{s}^c_\delta\right]$$



Our lattice calculations

- We use helicity-based definitions of the form factors

Transition	Current	Form factors
$\frac{1}{2}^+ \to \frac{1}{2}^-$	Vector	$f_0^{(\frac{1}{2}^-)}$, $f_+^{(\frac{1}{2}^-)}$, $f_\perp^{(\frac{1}{2}^-)}$
	Axial vector	$g_0^{(\frac{1}{2}^-)}$, $g_+^{(\frac{1}{2}^-)}$, $g_\perp^{(\frac{1}{2}^-)}$
	Tensor	$h_+^{(\frac{1}{2}^-)}$, $h_\perp^{(\frac{1}{2}^-)}$, $\widetilde{h}_+^{(\frac{1}{2}^-)}$, $\widetilde{h}_\perp^{(\frac{1}{2}^-)}$
$\frac{1}{2}^+ \to \frac{3}{2}^-$	Vector	$f_0^{(\frac{3}{2}^-)}$, $f_+^{(\frac{3}{2}^-)}$, $f_\perp^{(\frac{3}{2}^-)}$, $f_{\perp'}^{(\frac{3}{2}^-)}$
	Axial vector	$g_0^{(\frac{3}{2}^-)}$, $g_+^{(\frac{3}{2}^-)}$, $g_\perp^{(\frac{3}{2}^-)}$, $g_{\perp'}^{(\frac{3}{2}^-)}$
	Tensor	$h_+^{(\frac{3}{2}^-)}$, $h_\perp^{(\frac{3}{2}^-)}$, $h_{\perp'}^{(\frac{3}{2}^-)}$, $\widetilde{h}_+^{(\frac{3}{2}^-)}$, $\widetilde{h}_\perp^{(\frac{3}{2}^-)}$, $\widetilde{h}_{\perp'}^{(\frac{3}{2}^-)}$

- We parametrize the form factors using a series expansion in $(w - 1)$, where

$$w = v \cdot v' = (m_{\Lambda_Q}^2 + m_{\Lambda_q^*}^2 - q^2)/(2 m_{\Lambda_Q} m_{\Lambda_q^*})$$

Endpoint relations at $q^2 = q^2_{\rm max}$ now enforced in the parametrizations

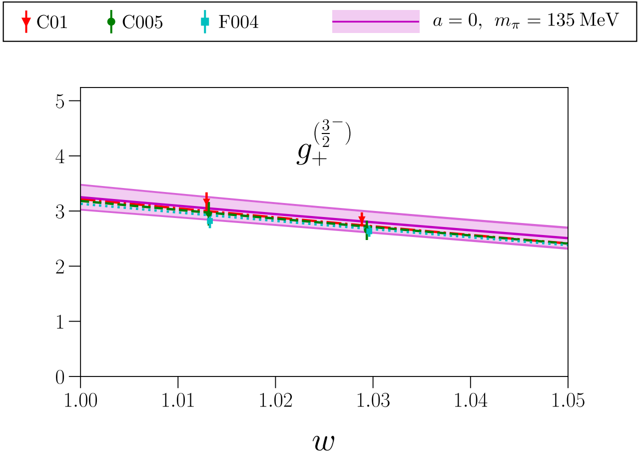
$$\begin{aligned} f_\perp^{(\frac{1}{2}^-)}(q^2_{\rm max}) &= f_+^{(\frac{1}{2}^-)}(q^2_{\rm max}), \\ h_\perp^{(\frac{1}{2}^-)}(q^2_{\rm max}) &= h_+^{(\frac{1}{2}^-)}(q^2_{\rm max}), \end{aligned}$$

$$\begin{aligned} f_\perp^{(\frac{3}{2}^-)}(q^2_{\rm max}) + f_{\perp'}^{(\frac{3}{2}^-)}(q^2_{\rm max}) &= 0, \\ 2(m_{\Lambda_Q} - m_{\Lambda^*_{q,3/2}})\, f_\perp^{(\frac{3}{2}^-)}(q^2_{\rm max}) + (m_{\Lambda_Q} + m_{\Lambda^*_{q,3/2}})\, f_+^{(\frac{3}{2}^-)}(q^2_{\rm max}) &= 0, \\ g_\perp^{(\frac{3}{2}^-)}(q^2_{\rm max}) - g_{\perp'}^{(\frac{3}{2}^-)}(q^2_{\rm max}) - g_+^{(\frac{3}{2}^-)}(q^2_{\rm max}) &= 0, \\ g_0^{(\frac{3}{2}^-)}(q^2_{\rm max}) &= 0, \\ h_\perp^{(\frac{3}{2}^-)}(q^2_{\rm max}) + h_{\perp'}^{(\frac{3}{2}^-)}(q^2_{\rm max}) &= 0, \\ 2(m_{\Lambda_Q} + m_{\Lambda^*_{q,3/2}})\, h_\perp^{(\frac{3}{2}^-)}(q^2_{\rm max}) + (m_{\Lambda_Q} - m_{\Lambda^*_{q,3/2}})\, h_+^{(\frac{3}{2}^-)}(q^2_{\rm max}) &= 0, \\ \widetilde{h}_\perp^{(\frac{3}{2}^-)}(q^2_{\rm max}) - \widetilde{h}_{\perp'}^{(\frac{3}{2}^-)}(q^2_{\rm max}) - \widetilde{h}_+^{(\frac{3}{2}^-)}(q^2_{\rm max}) &= 0. \end{aligned}$$

Proved directly in [R. Zwicky and G. Hiller, arXiv:2107.12993] and also independently derived by us through matching to a non-helicity basis

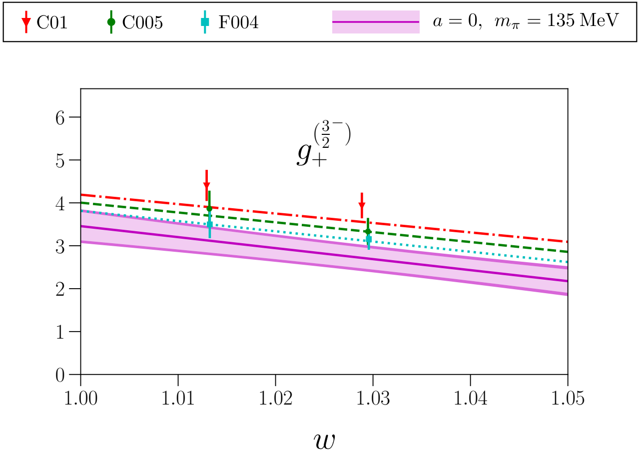
Sample form-factor results: $\Lambda_b \to \Lambda^*(1520)$

We have data for two different Λ_b momenta, $\mathbf{p}/\frac{2\pi}{L} = (0,0,2),\ (0,0,3)$



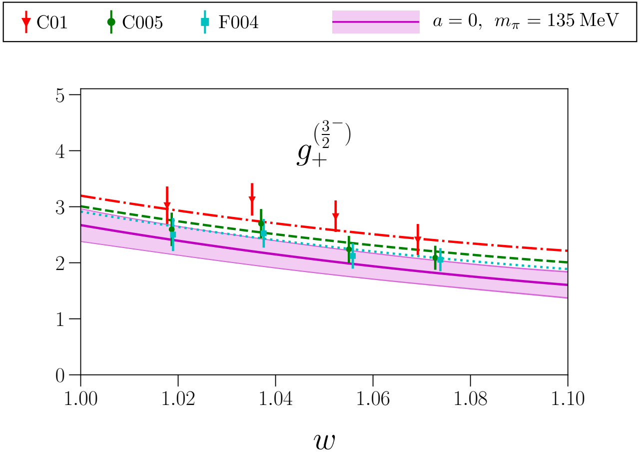
Sample form-factor results: $\Lambda_b \to \Lambda_c^*(2625)$

We have data for two different Λ_b momenta, $\mathbf{p}/\frac{2\pi}{L} = (0,0,2),\ (0,0,3)$



Sample form-factor results: $\Lambda_c \to \Lambda^*(1520)$

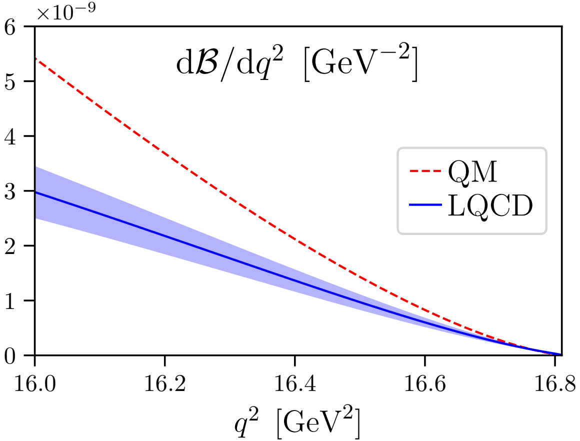
We have data for **four** different Λ_c momenta, $\mathbf{p}/\frac{2\pi}{L} = (0,0,1), (0,1,1), (1,1,1), (0,0,2)$



Here we also enforce additional endpoint relations at $q^2 = 0$.

$\Lambda_b \to \Lambda^*(1520)\mu^+\mu^-$ differential branching fraction near $q^2_{\rm max}$

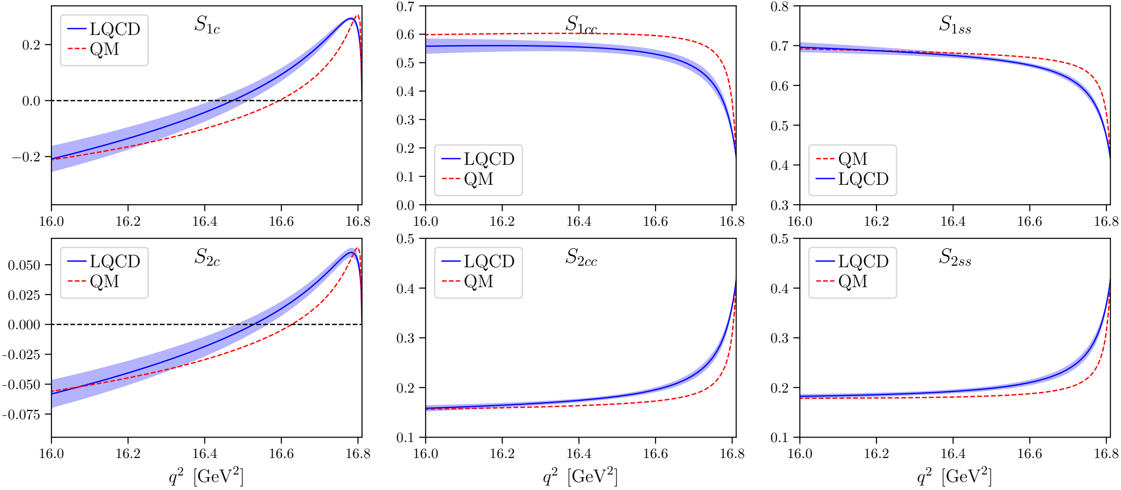
Quark model vs. lattice QCD



QM = using form factors from [L. Mott, W. Roberts, arXiv:1108.6129/IJMPA 2012]

$\Lambda_b \to \Lambda^*(1520)(\to pK^-)\mu^+\mu^-$ angular observables near $q^2_{\rm max}$

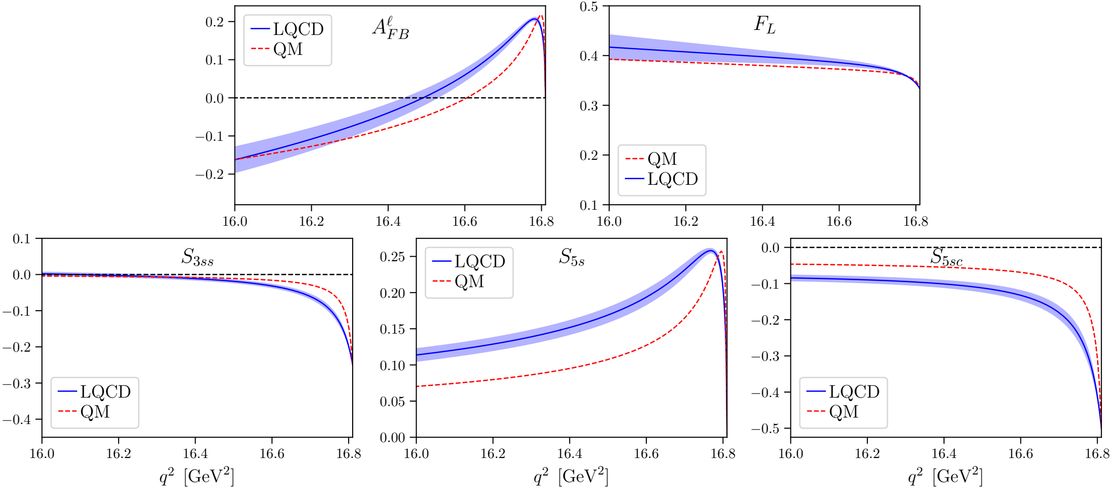
Quark model vs. lattice QCD



See [S. Descotes-Genon, M. Novoa-Brunet, arXiv:1903.00448/JHEP 2019] for definitions. The lepton mass is neglected here.

$\Lambda_b \to \Lambda^*(1520)(\to pK^-)\mu^+\mu^-$ angular observables near $q^2_{\rm max}$

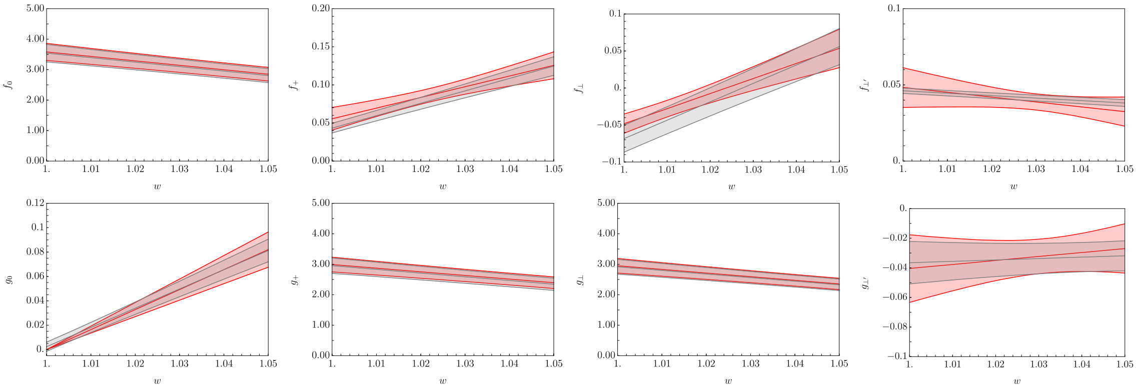
Quark model vs. lattice QCD



See [S. Descotes-Genon, M. Novoa-Brunet, arXiv:1903.00448/JHEP 2019] for definitions. The lepton mass is neglected here.

$\mathcal{O}(1/m_b, \alpha_s)$ HQET fit to our 2020 $\Lambda_b \to \Lambda^*(1520)$ lattice results

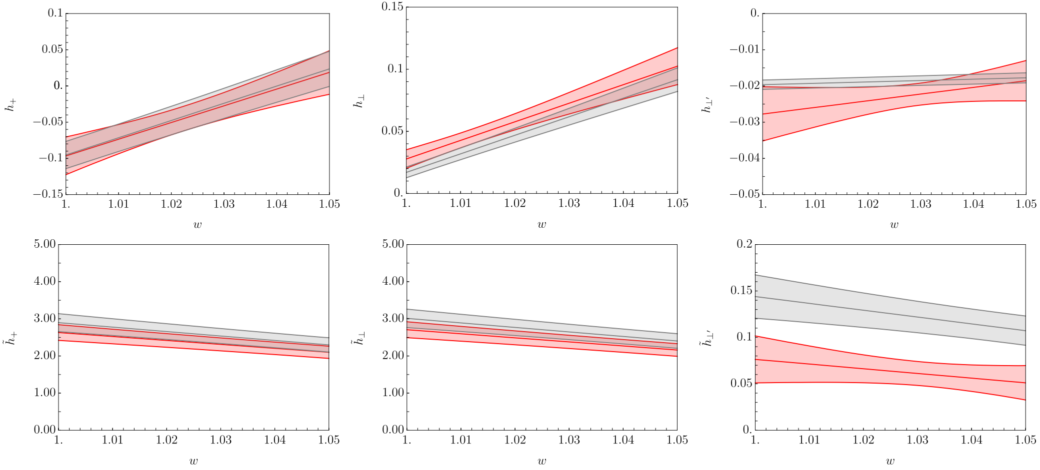
The fit to the V & A form factors has good quality [M. Bordone, arXiv:2101.12028/Symmetry 2021]



Gray = lattice QCD vector and axial-vector form factors, Red = HQET fit

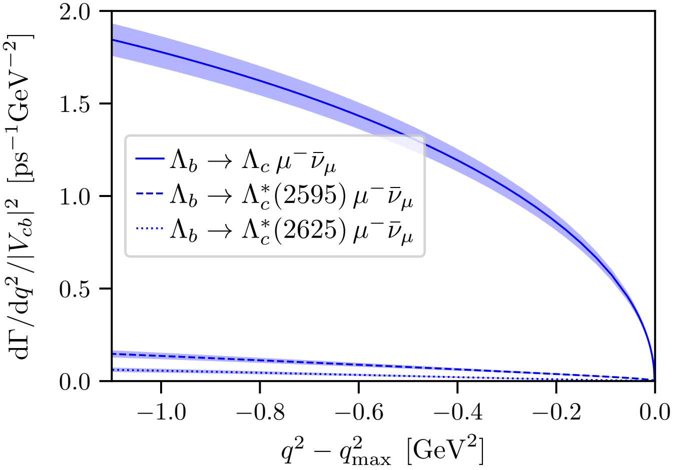
$\mathcal{O}(1/m_b, \alpha_s)$ HQET fit to our 2020 $\Lambda_b \to \Lambda^*(1520)$ results

... but the prediction for one of the tensor form factors deviates [M. Bordone, arXiv:2101.12028/Symmetry 2021]



Gray = lattice QCD tensor form factors (not included in the HQET fit), Red = HQET fit

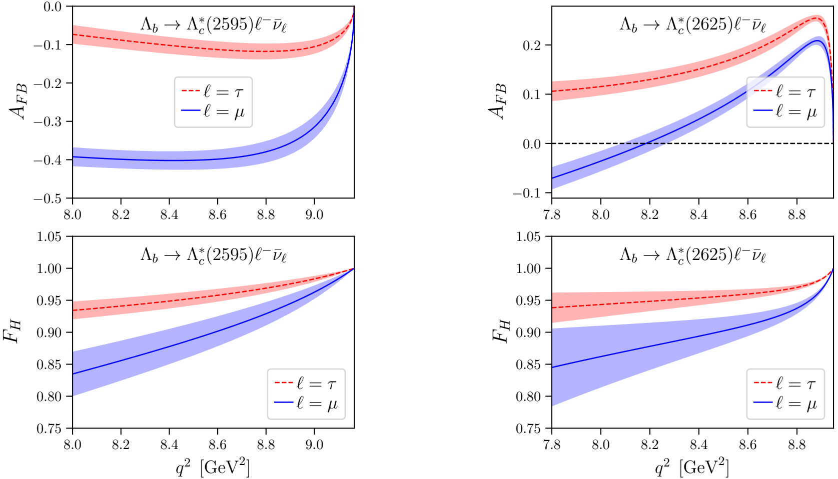
$\Lambda_b \to \Lambda_c^{(*)} \mu^- \bar{\nu}_\mu$ differential decay rates near $q^2_{\rm max}$ from lattice QCD



[$\Lambda_b \to \Lambda_c$ form factors from W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421/PRD 2015]

The relative size of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ differential decay rates is opposite to the expectation from LO HQET.

$\Lambda_b \to \Lambda_c^* \ell^- \bar{\nu}_\ell$ angular observables from lattice QCD



LO HQET would predict the angular observables for the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ final states to be equal.

$\Lambda_b \to \Lambda_c^* \ell^- \bar{\nu}_\ell$: Lattice QCD vs. zero-recoil sum rules and HQET

- Zero-recoil sum rules for $\Lambda_b \to X_c \ell^- \bar{\nu}_\ell$ are nearly saturated by the lattice results for $X_c = \Lambda_c$ [T. Mannel, D. van Dyk, arXiv:1506.08780/PLB 2015],

  but, allowing for $\mathcal{O}(1/m^4)$ and $\mathcal{O}(1/m^5)$ corrections in the heavy-quark expansion, there is just enough room to accommodate also $X_c = \Lambda_c^*(2595), \Lambda_c^*(2625)$.

  [P. Böer *et al.*, arXiv:1801.08367/JHEP 2018]

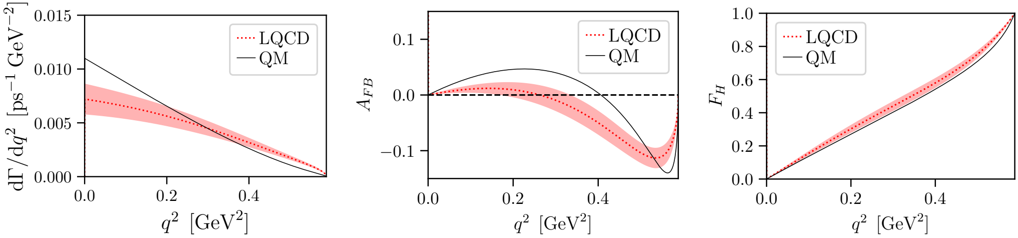
- HQET including only $\mathcal{O}(1/m, \alpha_s)$ corrections does not allow a good fit to the lattice results for the $\Lambda_b \to \Lambda_c^*(2595, 2625)$ form factors. In particular, the results for the spin-1/2 final state $\Lambda_c^*(2595)$ imply very large $1/m_c^2$ corrections.

  [M. Papucci, D. Robinson, arXiv:2105.09330]

  The spin-1/2 $\Lambda_c^*(2595)$ may may have an exotic structure and may correspond to two poles, similar to the strange $\Lambda^*(1405)$.

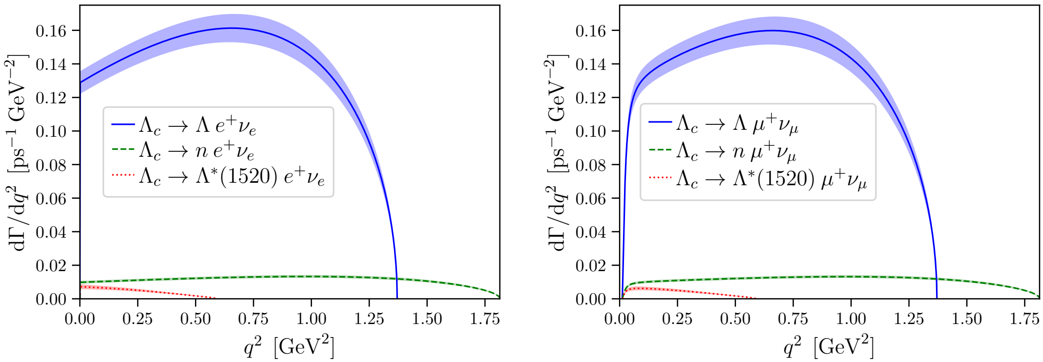
  [J. Nieves, R. Pavao, S. Sakai, arXiv:1903.11911/EPJC 2019]

$\Lambda_c \to \Lambda^*(1520) e^+ \nu_e$ observables: quark model vs. lattice QCD



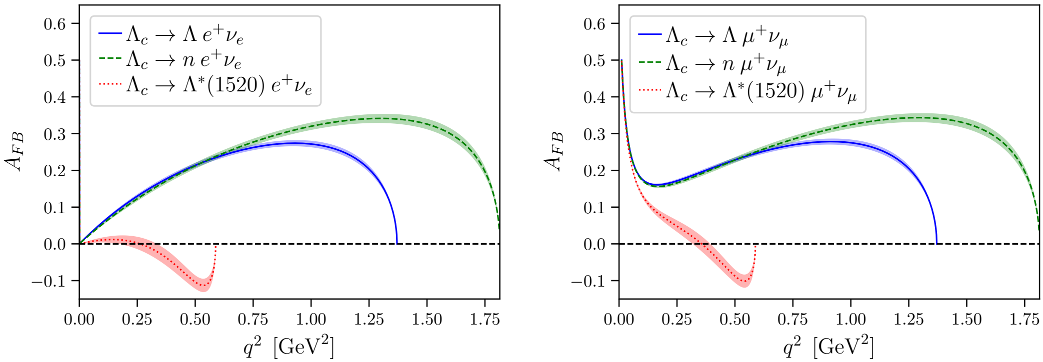
QM = using form factors from M. Hussain, W. Roberts, `arXiv:1701.03876`/PRD 2017

$\Lambda_c \to \{\Lambda, n, \Lambda^*(1520)\}\ell^+\nu_\ell$ differential decay rates from lattice QCD

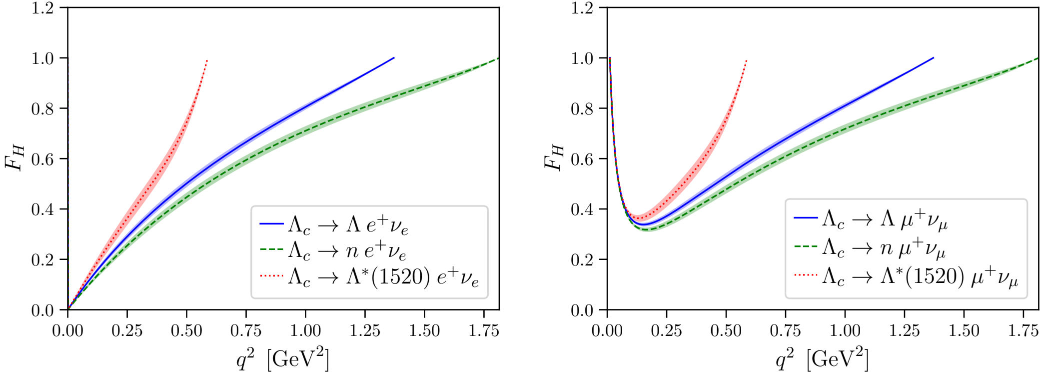


[$\Lambda_c \to \Lambda$ and $\Lambda_c \to n$ form factors from S. Meinel, arXiv:1611.09696/PRL 2017; arXiv:1712.05783/PRD 2018]

$\Lambda_c \to \{\Lambda, n, \Lambda^*(1520)\}\ell^+\nu_\ell$ angular observables from lattice QCD



$\Lambda_c \to \{\Lambda, n, \Lambda^*(1520)\}\ell^+\nu_\ell$ angular observables from lattice QCD



What about Λ_c semileptonic decays to other hadrons?

BESIII has measured the *inclusive* branching fraction [arXiv:1805.09060/PRL 2018]

$$\mathcal{B}(\Lambda_c \to X e^+ \nu)_{\text{BESIII}} = 3.95(0.34)(0.09)\,\%.$$

On the other hand, using lattice QCD we predict

$$\left[\mathcal{B}(\Lambda_c \to \Lambda e^+ \nu_e) + \mathcal{B}(\Lambda_c \to n e^+ \nu_e) + \mathcal{B}(\Lambda_c \to \Lambda^*(1520) e^+ \nu_e)\right]_{\text{LQCD}} = 4.32(0.23)(0.07)\,\%.$$

By subtracting this from the BESIII measurement, we obtain an upper limit on the sum of branching fraction to *all other hadrons*:

$$\mathcal{B}(\Lambda_c \to X e^+ \nu_e)_{X \neq \Lambda, n, \Lambda^*(1520)} < 0.15\,\% \text{ at } 68\% \text{ CL, Feldman-Cousins}.$$

Quark-model predictions for $\mathcal{B}(\Lambda_c \to \Lambda^*(1405) e^+ \nu_e)$ [M. Hussain, W. Roberts, arXiv:1701.03876/PRD 2017; Y.-S. Li, X. Liu, F.-S. Yu, arXiv:2104.04962] already sightly exceed this limit, whereas a study in unitarized chiral perturbation theory in which the $\Lambda^*(1405)$ emerges as a kaon-nucleon molecule [N. Ikeno, E. Oset, arXiv:1510.02406/PRD 2016] predicts $\mathcal{B}(\Lambda_c \to \Lambda^*(1405) e^+ \nu_e)$ to be much smaller than this limit.

Summary

- We have updated our analysis of the $\Lambda_b \to \Lambda_c^*(2595)$ ($J^P = \frac{1}{2}^-$), $\Lambda_b \to \Lambda_c^*(2625)$ ($J^P = \frac{3}{2}^-$), $\Lambda_b \to \Lambda^*(1520)$ ($J^P = \frac{3}{2}^-$) form factors, ensuring that endpoint relations at $q^2_{\rm max}$ are satisfied exactly and not just approximately. The angular observables now exactly take on the values predicted by rotational symmetry at $q^2_{\rm max}$ (e.g., $F_L(q^2_{\rm max}) = \frac{1}{3}$). The old results remain consistent with the new results within $1-2$ sigma.
- Our $\Lambda_b \to \Lambda_c^*$ lattice results are not well described by HQET at $\mathcal{O}(1/m_{b,c}, \alpha_s)$. In particular, the results for the spin-1/2 final state $\Lambda_c^*(2595)$ imply very large higher-order corrections.

  Note that some authors have suggested a molecular/two-pole structure for the $\Lambda_c^*(2595)$.
- We have performed the first lattice-QCD determination of the $\Lambda_c \to \Lambda^*(1520)$ ($J^P = \frac{3}{2}^-$) form factors. In contrast to the Λ_b decays, the results cover the full kinematic range.
- The quark-model prediction for the integrated decay rate $\Gamma(\Lambda_c \to \Lambda^*(1520)e^+\nu_e)$ by Hussain and Roberts agrees with our lattice-QCD prediction, but there are deviations in the differential distribution.
- By subtracting from the inclusive branching fraction $\mathcal{B}(\Lambda_c \to Xe^+\nu_e)$ measured by BESIII the lattice-QCD predictions of $\mathcal{B}(\Lambda_c \to \Lambda e^+\nu_e)$, $\mathcal{B}(\Lambda_c \to n e^+\nu_e)$, and $\mathcal{B}(\Lambda_c \to \Lambda^*(1520)e^+\nu_e)$, we have obtained an upper limit on the sum of branching fractions to all other final states. Quark-model predictions for $\mathcal{B}(\Lambda_c \to \Lambda^*(1405)e^+\nu_e)$ slightly exceed this limit.