$\Lambda_b \to \Lambda^*$ and $\Lambda_b \to \Lambda_c^*$ form factors from lattice QCD

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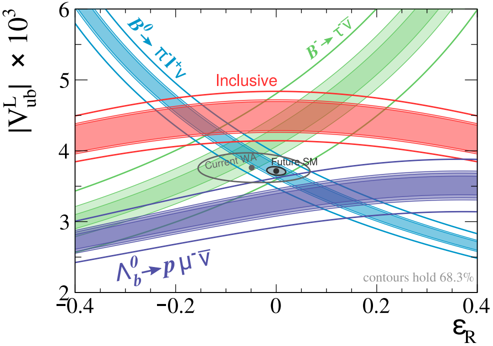
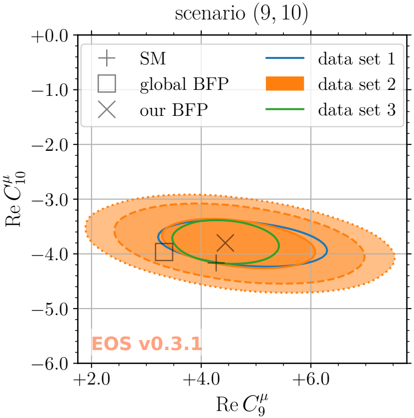
b-baryon Fest, November 5-6, 2020 (updated January 5: corrected sign of tensor FFs)

b baryons provide important constraints on physics beyond the SM



[J. Albrecht *et al.*, `arXiv:1709.10308`]



[T. Blake *et al.*, `arXiv:1912.05811`/PRD 2020]

$\Lambda_b \to p, \Lambda, \Lambda_c$: precision

- Uncertainties in $|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\bar{\nu}$ ($q^2 > 15$ GeV^2) and $\Lambda_b \to \Lambda_c\mu\bar{\nu}$ ($q^2 > 7$ GeV^2)
  - 2015: experiment 5%, lattice QCD 5%
  - $\sim$2030: experiment 1-2%, lattice QCD ???
- Uncertainty in $R(\Lambda_c)$:
  - 2015 lattice QCD 3%, experiment ???
- $\Lambda_b \to \Lambda(\to p\pi)\mu^+\mu^-$
  - Angular observables at high q^2: 2016 lattice QCD uncertainties are much smaller than 2018 experimental uncertainties
  - Differential BF at high q^2: 2016 lattice QCD uncertainties are somewhat smaller than 2015 experimental uncertainties
  - Differential BF at low q^2: 2016 lattice QCD uncertainties are somewhat LARGER than 2015 experimental uncertainties

Improved lattice QCD calculations for $\Lambda_b \to p, \Lambda, \Lambda_c$ are in progress (see extra slide).

Additional b-baryon decay modes

Other decays to QCD-stable baryons?

- $\Xi_b^- \to \Xi^- \ell^+ \ell^-$
- $\Omega_b^- \to \Omega^- \ell^+ \ell^-$
- $\Xi_b^- \to \Xi_c^0 \, \ell^- \bar{\nu}_\ell$
- ...

Lattice calculations of the form factors would be straightforward.

Decays to QCD-unstable baryon resonances:

- $\Lambda_b \to \Lambda^* \ell^+ \ell^-$
- $\Lambda_b \to \Lambda_c^* \ell^- \bar{\nu}_\ell$
- ...

Lattice calculations of the form factors are possible for 1) narrow resonances, using single-hadron treatment; 2) general two-body-only resonances, using Lellouch-Lüscher finite-volume formalism, but this is very challenging.

1. $\Lambda_b \to \Lambda^*(1520)$ form factors

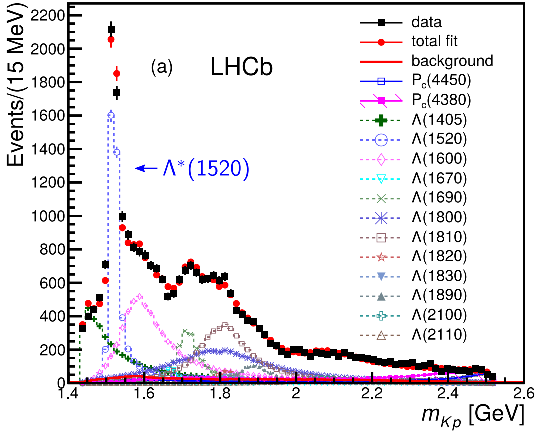
   [SM and Gumaro Rendon, arXiv:2009.09313]

2. $\Lambda_b \to \Lambda_c^*(2595)$ and $\Lambda_b \to \Lambda_c^*(2625)$ form factors

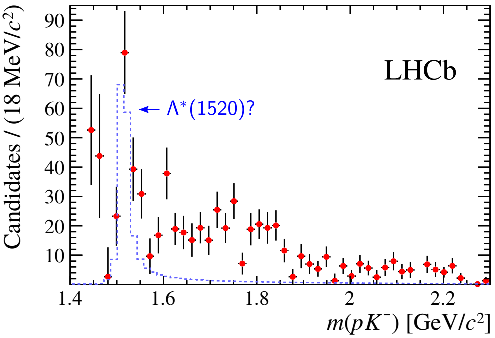
$\Lambda_b \to pK^-\mu^+\mu^-$ observed by LHCb

$q^2 \approx m^2_{J/\psi}$

$q^2 \notin [0.98, 1.1] \cup [8.0, 11] \cup [12.5, 15]$ GeV^2



[arXiv:1507.03414/PRL 2015]



[arXiv:1703.00256/JHEP 2017]

$\Lambda_b \to \Lambda^*(1520)\mu^+\mu^-$

- The $\Lambda^*(1520)$ is the lightest isospin-0, $J^P = \frac{3}{2}^-$ strange baryon resonance. It has a mass of 1519.5 ± 1.0 MeV, a width of 15.6 ± 1.0 MeV, and decays mainly into $N\bar{K}$, $\Sigma\pi$, or $\Lambda\pi\pi$.

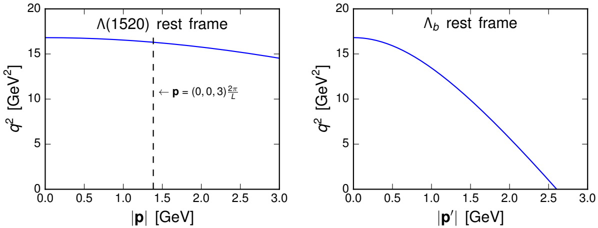
- The phenomenology of $\Lambda_b \to \Lambda^*(1520)\mu^+\mu^-$ was recently studied in:
  - S. Descotes-Genon, M. Novoa-Brunet, `arXiv:1903.00448`/JHEP 2019
  - D. Das, J. Das, `arXiv:2003.08366`/JHEP 2020
  - Y. Amhis *et al.*, `arXiv:2005.09602`

- The form factors have previously been calculated in a quark model:
  - L. Mott, W. Roberts, `arXiv:1108.6129`/IJMPA 2012

$\Lambda_b \to \Lambda^*(1520)$ on the lattice

We use the narrow-width approximation: we assume that the lowest finite-volume energy level with the correct quantum numbers corresponds to the $\Lambda^*(1520)$. Even in this approximation, the calculation is substantially more challenging than for $\Lambda_b \to \Lambda$:

- At nonzero momenta, the irreducible representations of the lattice symmetry groups mix positive and negative parities and also mix $J = \frac{1}{2}$ and $J = \frac{3}{2}$. We must therefore work in the $\Lambda^*(1520)$ rest frame and give momentum to the Λ_b instead. This limits us to near $q^2_{\rm max}$.



$\Lambda_b \to \Lambda^*(1520)$ on the lattice

- The simplest choices of three-quark interpolating fields with $I = 0$ and $J^P = \frac{3}{2}^-$ dominantly couple to higher-lying ($S = 3/2$, $L = 0$, flavor-$SU(3)$ octet) states. We found it necessary to use an interpolating field with an ($S = 1/2$, $L = 1$, flavor-$SU(3)$ singlet) structure obtained using covariant spatial derivatives. This requires additional quark propagators with derivative sources.

- Correlation functions for negative-parity "excited" baryons have even more statistical noise than correlation functions for the lightest baryons $\rightarrow$ need many samples on many gauge configurations

Data sets and hadron masses

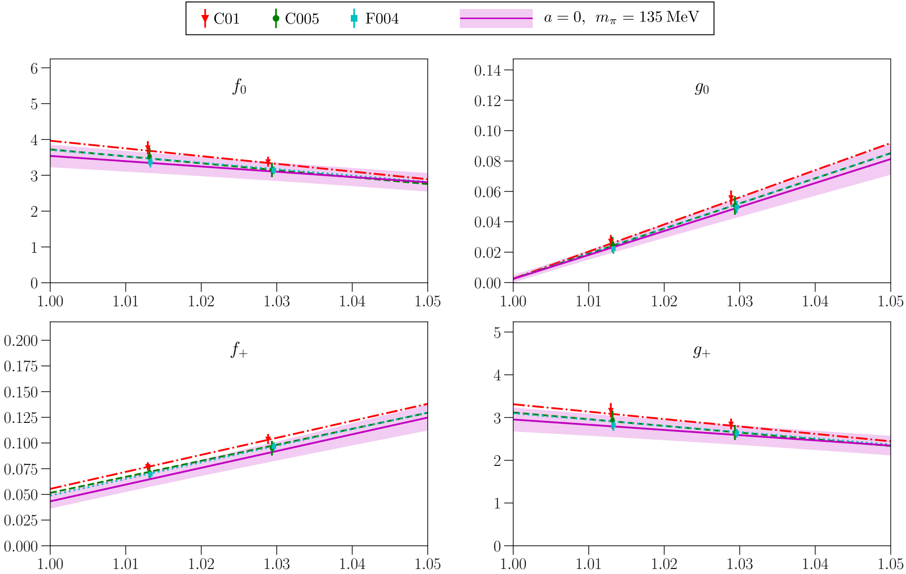
We use gauge-field configurations generated by the RBC and UKQCD Collaborations, with $2+1$ flavors of domain-wall fermions.

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)

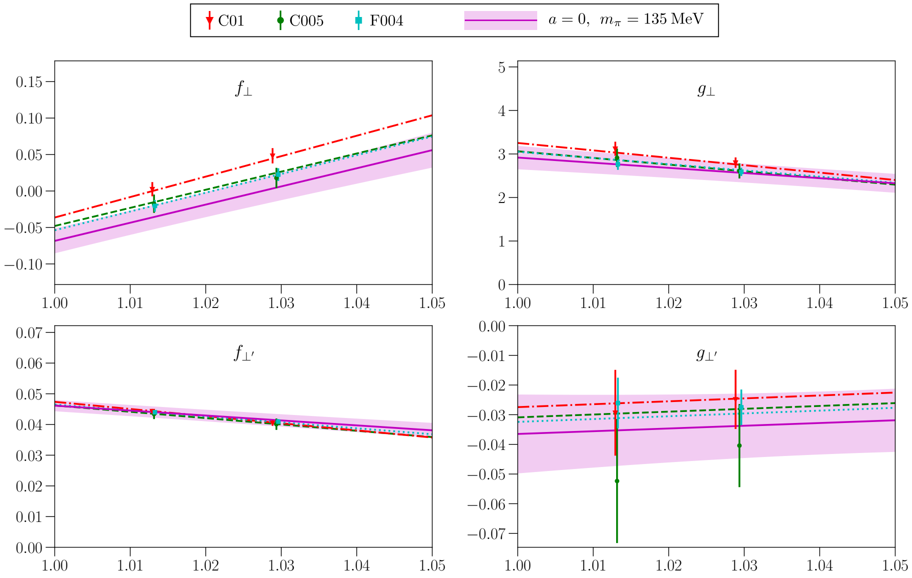
Label	m_K [GeV]	m_N [GeV]	m_Λ [GeV]	m_Σ [GeV]	m_{Λ^*} [GeV]	m_{Λ_b} [GeV]
C01	0.5795(19)	1.2647(51)	1.3494(61)	1.3877(61)	1.825(16)	5.793(17)
C005	0.5501(19)	1.1649(58)	1.2659(66)	1.3173(60)	1.740(17)	5.726(17)
F004	0.5361(24)	1.1197(59)	1.2382(54)	1.303(12)	1.757(15)	5.722(23)

$m_{\Lambda^*} - m_\Sigma - m_\pi$ ranges from approximately $+80$ to $+150$ MeV (physical value: $+192$ MeV),
$m_{\Lambda^*} - m_N - m_K$ ranges from approximately -20 to $+100$ MeV (physical value: $+89$ MeV)

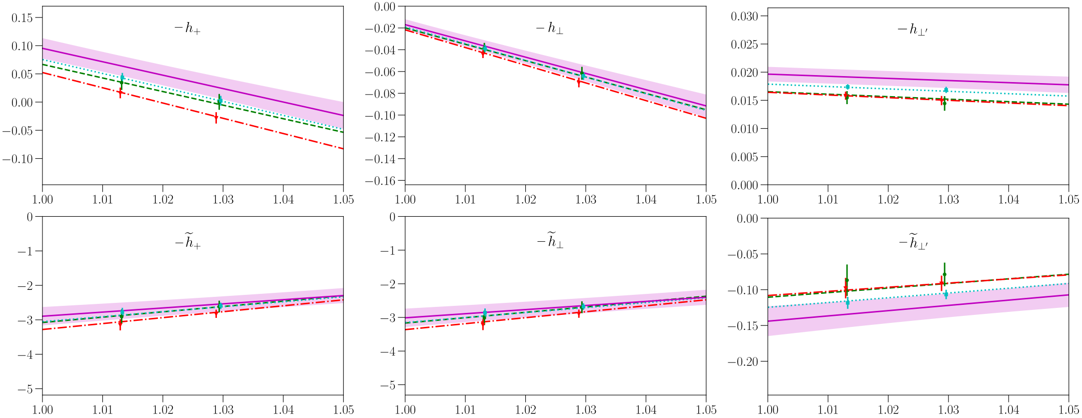
$\Lambda_b \to \Lambda^*(1520)$ form factors as a function of $w = v \cdot v'$



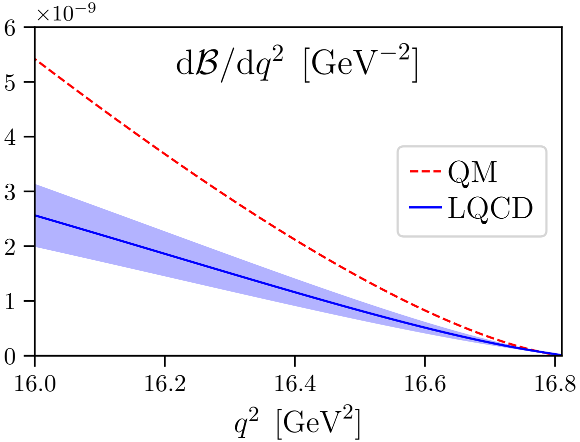
$\Lambda_b \to \Lambda^*(1520)$ form factors as a function of $w = v \cdot v'$



$\Lambda_b \to \Lambda^*(1520)$ form factors as a function of $w = v \cdot v'$

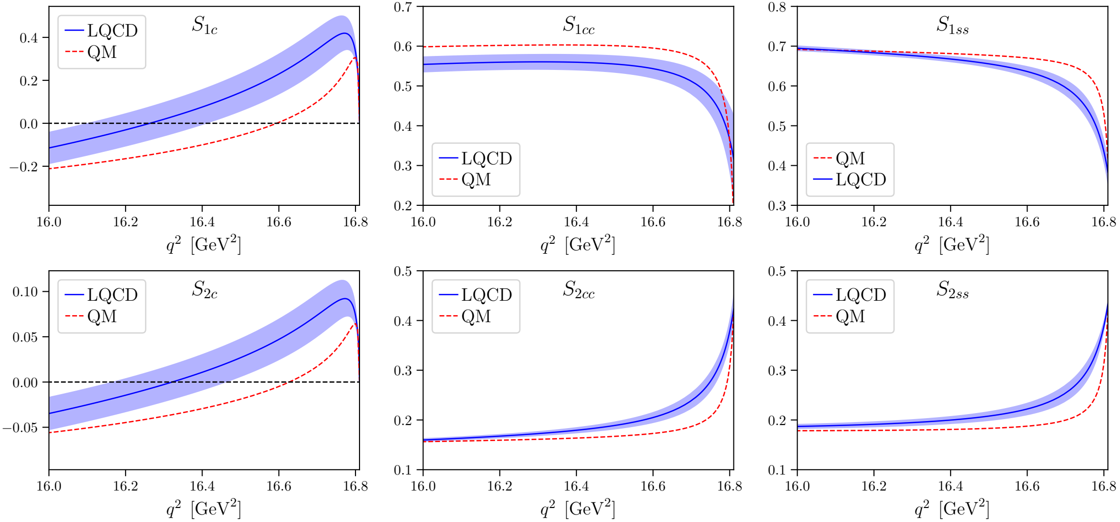


$\Lambda_b \to \Lambda^*(1520)\ell^+\ell^-$ observables



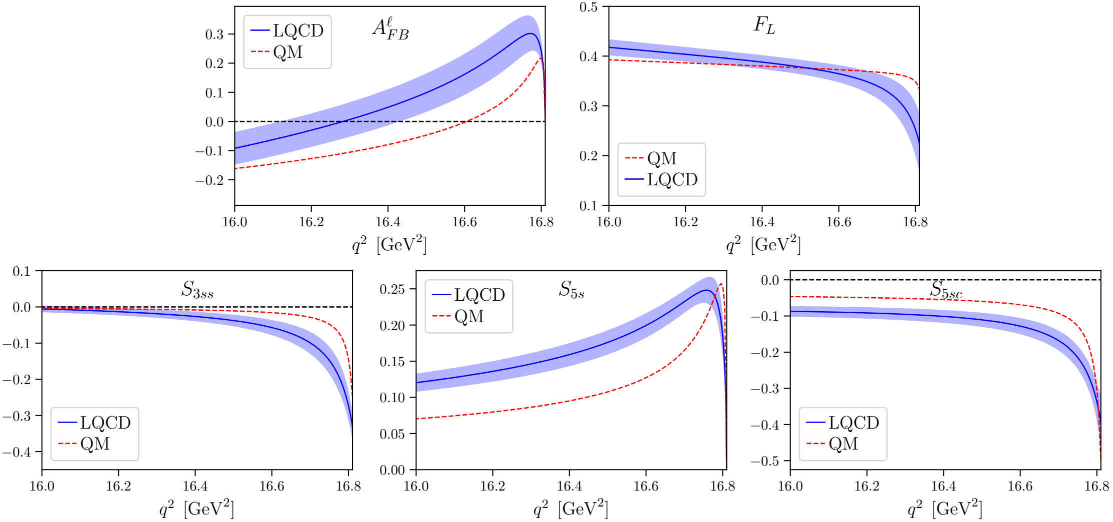
QM = using form factors from [L. Mott, W. Roberts, arXiv:1108.6129/IJMPA 2012]

$\Lambda_b \to \Lambda^*(1520)(\to pK^-)\ell^+\ell^-$ observables



See [S. Descotes-Genon, M. Novoa-Brunet, arXiv:1903.00448/JHEP 2019] for definitions

$\Lambda_b \to \Lambda^*(1520)(\to pK^-)\ell^+\ell^-$ observables



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1. $\Lambda_b \to \Lambda^*(1520)$ form factors

2. $\Lambda_b \to \Lambda_c^*(2595)$ and $\Lambda_b \to \Lambda_c^*(2625)$ form factors

   [SM and Gumaro Rendon, in preparation. Results are preliminary.]

$\Lambda_b \to \Lambda_c^* \, \ell^- \bar{\nu}_\ell$

Name	J^P	Mass [MeV]	Width [MeV]	Decays to
$\Lambda_c^*(2595)$	$\frac{1}{2}^-$	2592.25(28)	2.6(6)	$\Lambda_c \, \pi^+ \pi^-$
$\Lambda_c^*(2625)$	$\frac{3}{2}^-$	2628.11(19)	< 0.97	$\Lambda_c \, \pi^+ \pi^-$

Motivations include:

- Tests of lepton-flavor universality with $R(\Lambda_c^*)$
  [P. Böer *et al.*, arXiv:1801.08367/JHEP 2018]
- Tests of HQET
  [A. Leibovich, I. Stewart, arXiv:hep-ph/9711257/PRD 1998;
  P. Böer *et al.*, arXiv:1801.08367/JHEP 2018]
- Knowledge of $\Lambda_b \to \Lambda_c^*$ form factors can tighten global unitarity constraints on other $b \to c$ form factors (including mesonic form factors)
  [T. Cohen, H. Lamm, R. Lebed, arXiv:1909.10691/PRD 2019]

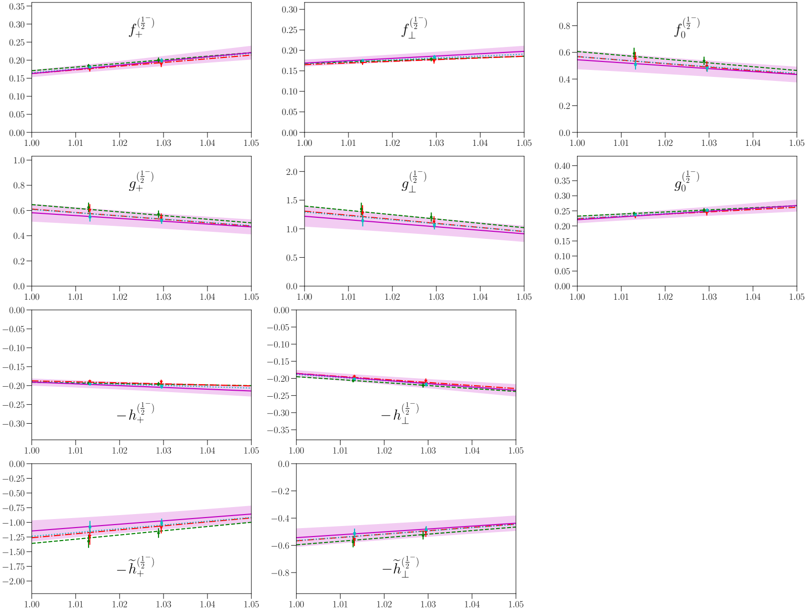
Data sets and hadron masses

Same three ensembles as used for $\Lambda_b \to \Lambda^*(1520)$. Resulting hadron masses in GeV:

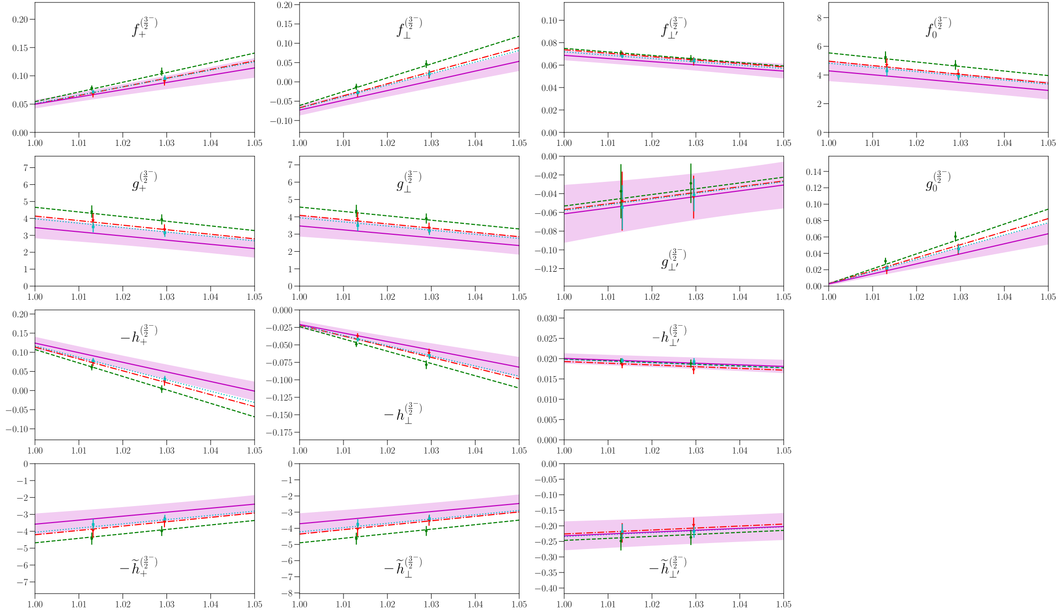
Label	m_π	m_D	m_N	m_{Λ_c}	m_{Σ_c}	$m_{\Lambda^*_{c,1/2}}$	$m_{\Lambda^*_{c,3/2}}$	m_{Λ_b}
C01	0.4312(13)	1.9119(54)	1.2647(51)	2.4652(82)	2.617(10)	2.882(12)	2.909(12)	5.793(17)
C005	0.3400(11)	1.8942(54)	1.1649(58)	2.4038(75)	2.565(12)	2.819(13)	2.839(13)	5.726(17)
F004	0.3030(12)	1.8880(70)	1.1197(59)	2.367(12)	2.550(19)	2.781(18)	2.815(18)	5.722(23)

For these data sets, the $\Lambda_c^*(2595)$ and $\Lambda_c^*(2625)$ are in fact stable (their masses are lower than the sum of masses of possible decay products)

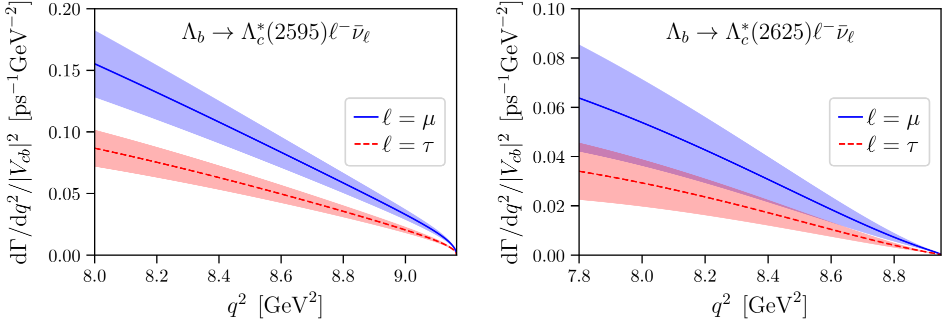
$\Lambda_b \to \Lambda_c^*(2595)$ form factors as a function of $w = v \cdot v'$



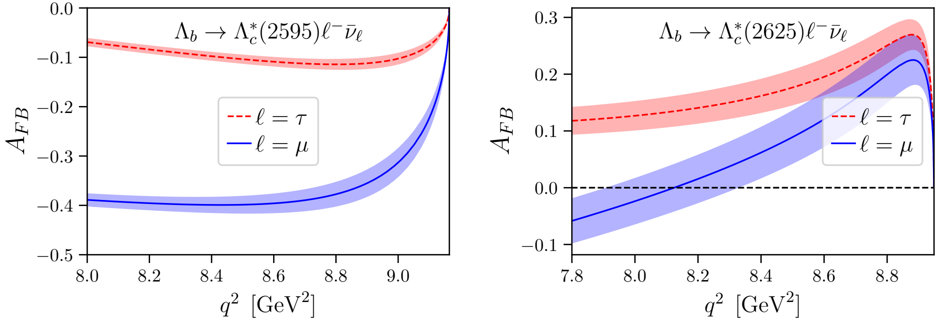
$\Lambda_b \to \Lambda_c^*(2625)$ form factors as a function of $w = v \cdot v'$



$\Lambda_b \to \Lambda_c^* \ell^- \bar{\nu}_\ell$ observables

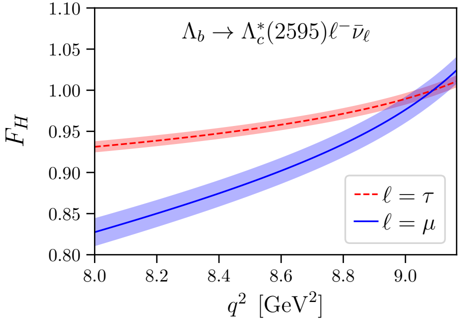


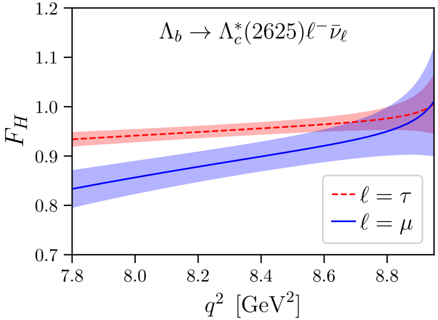
$\Lambda_b \to \Lambda_c^* \ell^- \bar{\nu}_\ell$ observables



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

$\Lambda_b \to \Lambda_c^* \ell^- \bar{\nu}_\ell$ observables





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

Questions/Challenges

- What is the best way to isolate the $\Lambda^*(1520)$ contribution from the $\Lambda_b \to pK^-\mu^+\mu^-$ decay distribution?

- For $\Lambda_b \to \Lambda^*(1520)$, $q^2_{\rm max} \approx 16.8\,\text{GeV}^2$ means that there is not much phase space above the narrow-charm-resonance region. Is this enough to treat charm effects with the OPE?

- Lattice calculations in the Λ^* rest frame could reach lower q^2 using the moving-NRQCD action for the b-quark (which allows higher Λ_b momenta).

- I have attempted HQET fits (including $1/m_Q$ effects) to our lattice results for the $\Lambda_b \to \Lambda_c^*$ form factors. The fits have very bad χ^2, with fit curves far away from the lattice data for some of the form factors. Are $1/m_Q^2$ corrections large?

- Can our lattice QCD results be combined with experimental measurements of the $\Lambda_b \to \Lambda_c^* \mu^- \bar{\nu}$ decay distribution to predict $R(\Lambda_c^*)$?

Extra slides

References: b and c baryon decay form factors from lattice QCD

Early work on $\Lambda_b \to \Lambda_c$ (quenched, focused on Isgur-Wise function):

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

Our lattice calculations, using RBC/UKQCD $2+1$ flavor ensembles:

Transition	m_Q	a [fm]	m_π [MeV]	Reference
$\Lambda_b \to \Lambda$	∞	0.083, 0.111	230–360	WD, DL, SM, MW, arXiv:1212.4827/PRD 2013
$\Lambda_b \to p$	∞	0.083, 0.111	230–360	WD, DL, SM, MW, arXiv:1306.0446/PRD 2013
$\Lambda_b \to p$	phys.	0.083, 0.111	230–360	WD, CL, SM, arXiv:1503.01421/PRD 2015
$\Lambda_b \to \Lambda_c$	phys.	0.083, 0.111	230–360	WD, CL, SM, arXiv:1503.01421/PRD 2015
$\Lambda_b \to \Lambda$	phys.	0.083, 0.111	230–360	WD, SM, arXiv:1602.01399/PRD 2016
$\Lambda_b \to \Lambda^*$	phys.	0.083, 0.111	300–430	SM, GR, arXiv:2009.09313
$\Lambda_b \to \Lambda_c^*$	phys.	0.083, 0.111	300–430	SM, GR, in preparation
$\Lambda_c \to \Lambda$	phys.	0.083, 0.111, 0.114	140–360	SM, arXiv:1611.09696/PRL 2017
$\Lambda_c \to p$	phys.	0.083, 0.111	230–360	SM, arXiv:1712.05783/PRD 2018

Forthcoming improved calculation of $\Lambda_b \to p, \Lambda, \Lambda_c$ form factors

- Remove data sets with $m_{u,d}^{(\mathrm{val})} < m_{u,d}^{(\mathrm{sea})}$, add three new ensembles to better control finite-volume effects, chiral and continuum extrapolations
- 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
- Fully nonperturbative renormalization (?)

$N_s^3 \times N_t$	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
$32^3 \times 64$	2.13	0.005	0.005	0.04	≈ 0.111	≈ 340	≈ 340	done
$24^3 \times 64$	2.13	0.005	0.005	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	≈ 0.073	≈ 230	≈ 230	ongoing

$\Lambda_b \to \Lambda_c^*(\frac{1}{2}^-, \frac{3}{2}^-)$ form factor definitions

In the following we use the notation

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

and

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

$\Lambda_b \to \Lambda_c^*(\frac{1}{2}^-, \frac{3}{2}^-)$ form factor definitions

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

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

$\Lambda_b \to \Lambda_c^*(\frac{1}{2}^-, \frac{3}{2}^-)$ form factor definitions

$$\begin{aligned}
\mathscr{G}^{(\frac{1}{2}^-)}[i\sigma^{\mu\nu} q_\nu] \quad = \quad & -h_+^{(\frac{1}{2}^-)} \, \frac{q^2}{s_-} \left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda^*_{c,1/2}}^2) \frac{q^\mu}{q^2} \right) \\
& -h_\perp^{(\frac{1}{2}^-)} \, (m_{\Lambda_b} - m_{\Lambda^*_{c,1/2}}) \left(\gamma^\mu + \frac{2 \, m_{\Lambda^*_{c,1/2}}}{s_-} \, p^\mu - \frac{2 \, m_{\Lambda_b}}{s_-} \, p'^\mu \right),
\end{aligned}$$

$$\begin{aligned}
\mathscr{G}^{(\frac{1}{2}^-)}[i\sigma^{\mu\nu} \gamma_5 q_\nu] \quad = \quad & -\widetilde{h}_+^{(\frac{1}{2}^-)} \gamma_5 \frac{q^2}{s_+} \left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_{\Lambda^*_{c,1/2}}^2) \frac{q^\mu}{q^2} \right) \\
& -\widetilde{h}_\perp^{(\frac{1}{2}^-)} \gamma_5 \, (m_{\Lambda_b} + m_{\Lambda^*_{c,1/2}}) \left(\gamma^\mu - \frac{2 m_{\Lambda^*_{c,1/2}}}{s_+} \, p^\mu - \frac{2 m_{\Lambda_b}}{s_+} \, p'^\mu \right).
\end{aligned}$$

$\Lambda_b \to \Lambda_c^*(\frac{1}{2}^-, \frac{3}{2}^-)$ form factor definitions

$$
\begin{aligned}
\mathscr{G}^{\lambda(\frac{3}{2}^-)}[\gamma^\mu] \quad = \quad & f_0^{(\frac{3}{2}^-)} \frac{m_{\Lambda^*_{c,3/2}}}{s_+} \frac{(m_{\Lambda_b} - m_{\Lambda^*_{c,3/2}})\, p^\lambda q^\mu}{q^2} \\
& + f_+^{(\frac{3}{2}^-)} \frac{m_{\Lambda^*_{c,3/2}}}{s_-} \frac{(m_{\Lambda_b} + m_{\Lambda^*_{c,3/2}})\, p^\lambda (q^2 (p^\mu + p'^\mu) - (m^2_{\Lambda_b} - m^2_{\Lambda^*_{c,3/2}}) q^\mu)}{q^2\, s_+} \\
& + f_\perp^{(\frac{3}{2}^-)} \frac{m_{\Lambda^*_{c,3/2}}}{s_-} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda^*_{c,3/2}} p^\mu)}{s_+} \right) \\
& + f_{\perp'}^{(\frac{3}{2}^-)} \frac{m_{\Lambda^*_{c,3/2}}}{s_-} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda p'^\mu}{m_{\Lambda^*_{c,3/2}}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda^*_{c,3/2}} p^\mu)}{s_+} + \frac{s_-\, g^{\lambda\mu}}{m_{\Lambda^*_{c,3/2}}} \right),
\end{aligned}
$$

$$
\begin{aligned}
\mathscr{G}^{\lambda(\frac{3}{2}^-)}[\gamma^\mu \gamma_5] \quad = \quad & -g_0^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda^*_{c,3/2}}}{s_-} \frac{(m_{\Lambda_b} + m_{\Lambda^*_{c,3/2}})\, p^\lambda q^\mu}{q^2} \\
& - g_+^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda^*_{c,3/2}}}{s_+} \frac{(m_{\Lambda_b} - m_{\Lambda^*_{c,3/2}})\, p^\lambda (q^2 (p^\mu + p'^\mu) - (m^2_{\Lambda_b} - m^2_{\Lambda^*_{c,3/2}}) q^\mu)}{q^2\, s_-} \\
& - g_\perp^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda^*_{c,3/2}}}{s_+} \left(p^\lambda \gamma^\mu - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu - m_{\Lambda^*_{c,3/2}} p^\mu)}{s_-} \right) \\
& - g_{\perp'}^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda^*_{c,3/2}}}{s_+} \left(p^\lambda \gamma^\mu + \frac{2\, p^\lambda p'^\mu}{m_{\Lambda^*_{c,3/2}}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu - m_{\Lambda^*_{c,3/2}} p^\mu)}{s_-} - \frac{s_+\, g^{\lambda\mu}}{m_{\Lambda^*_{c,3/2}}} \right),
\end{aligned}
$$

$\Lambda_b \to \Lambda_c^*(\frac{1}{2}^-, \frac{3}{2}^-)$ form factor definitions

$$\begin{aligned}
\mathscr{G}^{\lambda(\frac{3}{2}^-)}[i\sigma^{\mu\nu}q_\nu] \quad = \quad & -h_+^{(\frac{3}{2}^-)} \frac{m_{\Lambda^*_{c,3/2}}}{s_-} \frac{p^\lambda(q^2(p^\mu + p'^\mu) - (m^2_{\Lambda_b} - m^2_{\Lambda^*_{c,3/2}})q^\mu)}{s_+} \\
& -h_\perp^{(\frac{3}{2}^-)} \frac{m_{\Lambda^*_{c,3/2}}}{s_-}(m_{\Lambda_b} + m_{\Lambda^*_{c,3/2}}) \left(p^\lambda \gamma^\mu - \frac{2\,p^\lambda(m_{\Lambda_b} p'^\mu + m_{\Lambda^*_{c,3/2}} p^\mu)}{s_+} \right) \\
& -h_{\perp'}^{(\frac{3}{2}^-)} \frac{m_{\Lambda^*_{c,3/2}}}{s_-}(m_{\Lambda_b} + m_{\Lambda^*_{c,3/2}}) \left(p^\lambda \gamma^\mu - \frac{2\,p^\lambda p'^\mu}{m_{\Lambda^*_{c,3/2}}} + \frac{2\,p^\lambda(m_{\Lambda_b} p'^\mu + m_{\Lambda^*_{c,3/2}} p^\mu)}{s_+} + \frac{s_-\, g^{\lambda\mu}}{m_{\Lambda^*_{c,3/2}}} \right),
\end{aligned}$$

$$\begin{aligned}
\mathscr{G}^{\lambda(\frac{3}{2}^-)}[i\sigma^{\mu\nu}q_\nu\gamma_5] \quad = \quad & -\tilde{h}_+^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda^*_{c,3/2}}}{s_+} \frac{p^\lambda(q^2(p^\mu + p'^\mu) - (m^2_{\Lambda_b} - m^2_{\Lambda^*_{c,3/2}})q^\mu)}{s_-} \\
& -\tilde{h}_\perp^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda^*_{c,3/2}}}{s_+}(m_{\Lambda_b} - m_{\Lambda^*_{c,3/2}}) \left(p^\lambda \gamma^\mu - \frac{2\,p^\lambda(m_{\Lambda_b} p'^\mu - m_{\Lambda^*_{c,3/2}} p^\mu)}{s_-} \right) \\
& -\tilde{h}_{\perp'}^{(\frac{3}{2}^-)} \gamma_5 \frac{m_{\Lambda^*_{c,3/2}}}{s_+}(m_{\Lambda_b} - m_{\Lambda^*_{c,3/2}}) \left(p^\lambda \gamma^\mu + \frac{2\,p^\lambda p'^\mu}{m_{\Lambda^*_{c,3/2}}} + \frac{2\,p^\lambda(m_{\Lambda_b} p'^\mu - m_{\Lambda^*_{c,3/2}} p^\mu)}{s_-} - \frac{s_+\, g^{\lambda\mu}}{m_{\Lambda^*_{c,3/2}}} \right).
\end{aligned}$$