Semileptonic decays of heavy baryons to negative-parity baryons

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November 22nd, 2021

Simplest semileptonic decays: $J^P=1/2^+$ ground states

Charged current decays:

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

Neutral current (rare) decays:

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

Next simplest decays?

Name	J^P	Mass[MeV]	Width [MeV]
$\Lambda^*(1520)$	$\frac{3}{2}^-$	$1519.42(19)$	$15.73(26)$
$\Lambda_c^*(2595)$	$\frac{1}{2}^-$	$2592.25(28)$	2.6(6)
$\Lambda_c^*(2625)$	$\frac{3}{2}^-$	$2628.11(19)$	≤ 0.97

Experimental Situation

- LHCb has large $\Lambda_b \to \Lambda_c^\star(2595, 2625)\mu^-\overline{\nu}_\mu$ # of samples and can measure $R(\Lambda_c^\star)$ ratios
- LHCb is planning an analysis of $\Lambda_b \to \Lambda^\star(1520)\left(\to p^+K^-\right)\ell^-\ell^+$ [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 $\Lambda_b \to \Lambda_c^\star \ell^- \bar{\nu}_\ell$, $\Lambda_b \to p^\star \ell^- \bar{\nu}_\ell$, $\Lambda_b \to \Lambda^\star \ell^+ \ell^-$, $\Lambda_c \to \Lambda^\star \ell^+ \nu_\ell$, $\Lambda_c \to n^\star \ell^+ \nu_\ell$

  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

- $\Lambda_b \to \Lambda_c^\star(2595, 2625)\mu^- \overline{\nu}_\mu$ in HQET up to $O(\alpha_s,\, 1/m_b)$

  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

- $\Lambda_c \to \Lambda^\star(1405)\ell^+\nu_\ell$ in chiral unitary approach

  N. Ikeno, E. Oset, arXiv:1510.02406/PRD 2016

- Angular distribution of $\Lambda_b \to \Lambda^\star(1520)\left(\to p^+K^-\right)\ell^-\ell^+$

  S. Descotes-Genon, M. Novoa-Brunet, arXiv:1903.00448/JHEP 2019

- $\Lambda_b \to \Lambda^\star(1520)\ell^+\ell^-$ in HQET up to $O(\alpha_s)$ or $O(1/m_b)$

  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 $\Lambda_b \to \Lambda^\star(1520)\left(\to p^+K^-\right)\ell^-\ell^+$

  Y. Amhis et al., arXiv:2005.09602/EPJP 2021

- Endpoint symmetries of baryon helicity amplitudes at $q^2 = q^2_{max}$

  G. Hiller and R. Zwicky, arXiv:2107.12993

Our lattice calculations

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

  S. Meinel and G. Rendon, arXiv:2009.09313/PRD 2021

- $\Lambda_b \to \Lambda_c^\star(2595)\ell^-\overline{\nu}_\ell$ and $\Lambda_b \to \Lambda_c^\star(2625)\ell^-\overline{\nu}_\ell$

  S. Meinel and G. Rendon, arXiv:2103.08775/PRD 2021

- $\Lambda_c \to \Lambda^\star(1520)\ell^+\nu_\ell$

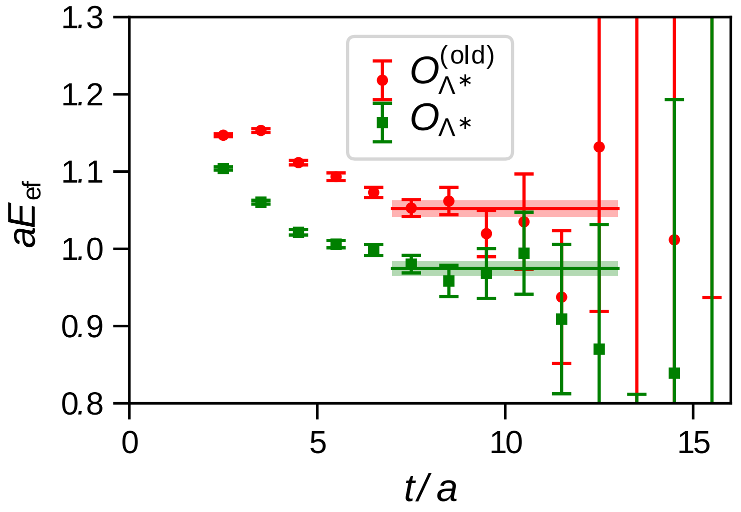
  S. Meinel and G. Rendon, arXiv:2107.13140 and arXiv:2107.13084

Also, in arXiv:2107.13140 we also improve the analysis on $\Lambda_b \to \Lambda^\star(1520)$ and $\Lambda_b \to \Lambda_c^\star(2595, 2625)$ form factors enforcing exactly endpoint relations during the fits. Any results shown for these two processes are using this improved analysis.

Our lattice calculations

- We work on the baryon rest frame to allow the exact projection to $J^P = 1/2^-$ or $3/2^-$ (G_{1u} or H_u irreps).
- We use an interpolating field with derivatives to obtain an L=1 quantum number, that is,

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



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	$h_+^{(\frac{3}{2}^-)}, h_\perp^{(\frac{3}{2}^-)}, h_{\perp'}^{(\frac{3}{2}^-)}, \widetilde{h}_+^{(\frac{3}{2}^-)}, \widetilde{h}_\perp^{(\frac{3}{2}^-)}, \widetilde{h}_{\perp'}^{(\frac{3}{2}^-)}$

$$w(q^2) = v \cdot v' = \frac{m_{\Lambda_b}^2 + m_{\Lambda^*}^2 - q^2}{2 m_{\Lambda_b} m_{\Lambda^*}}$$

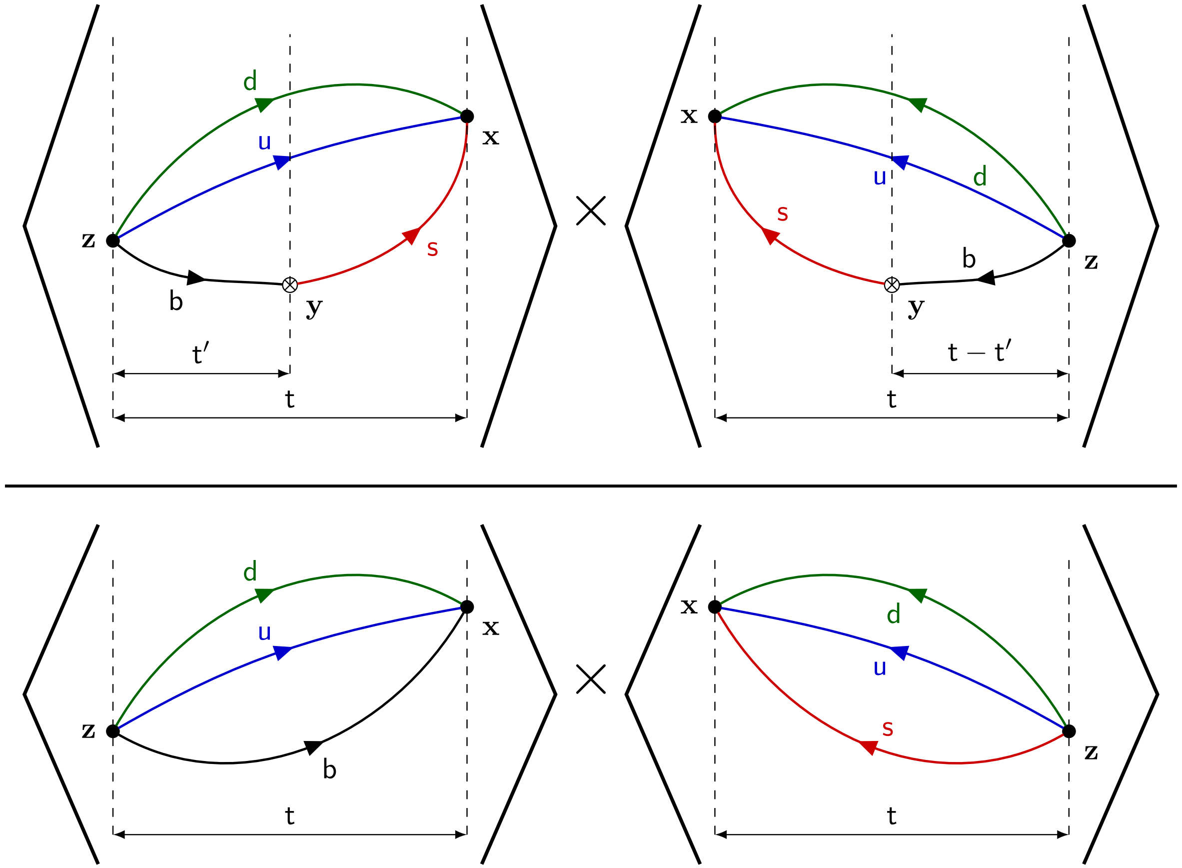
Our lattice calculations

- 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 where simulated using "RHQ" (anisotropic clover) action

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



In simple terms:

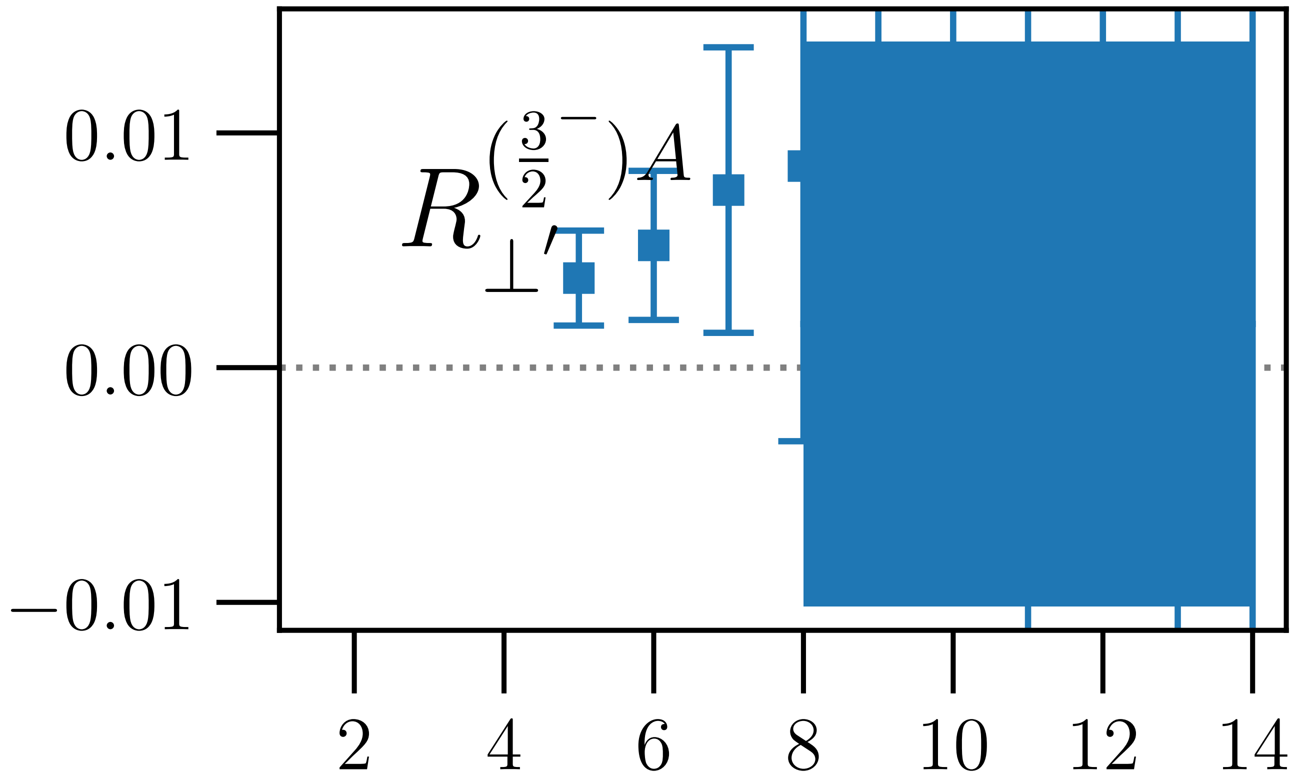
- Project to desired parity and spin at source and sink
- Project to desired FF at the current

Advantages:

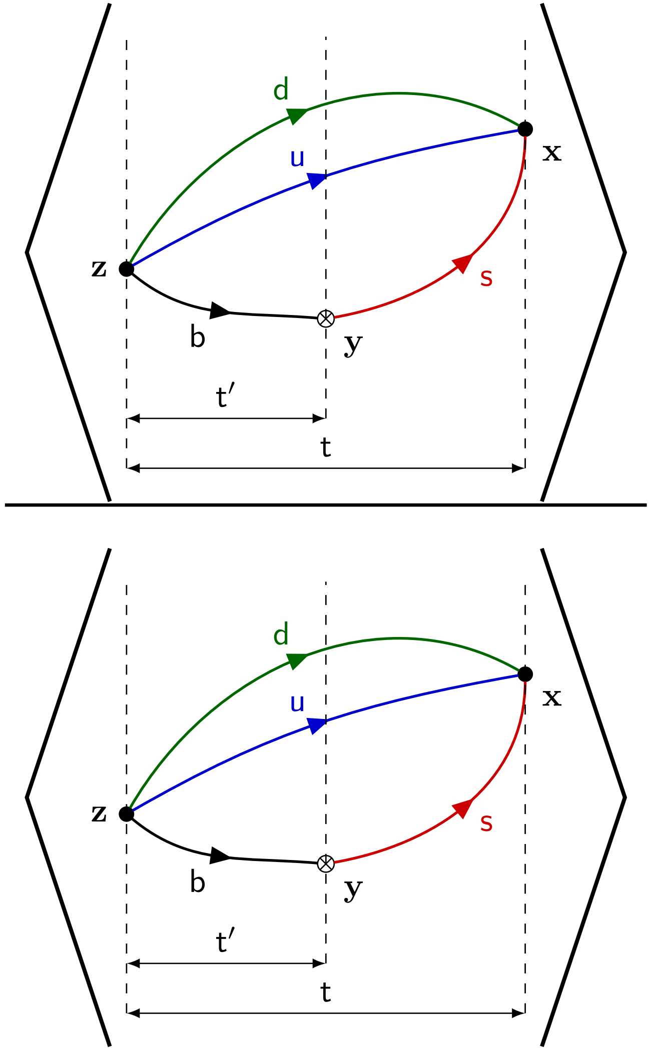
- Overlap factors cancel out
- Time dependence cancels out at infinite time

$$R_f(p,t) \to |f(p)|^2 \text{ at large t}$$

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



Extracting form factors from ratios of 3pt functions



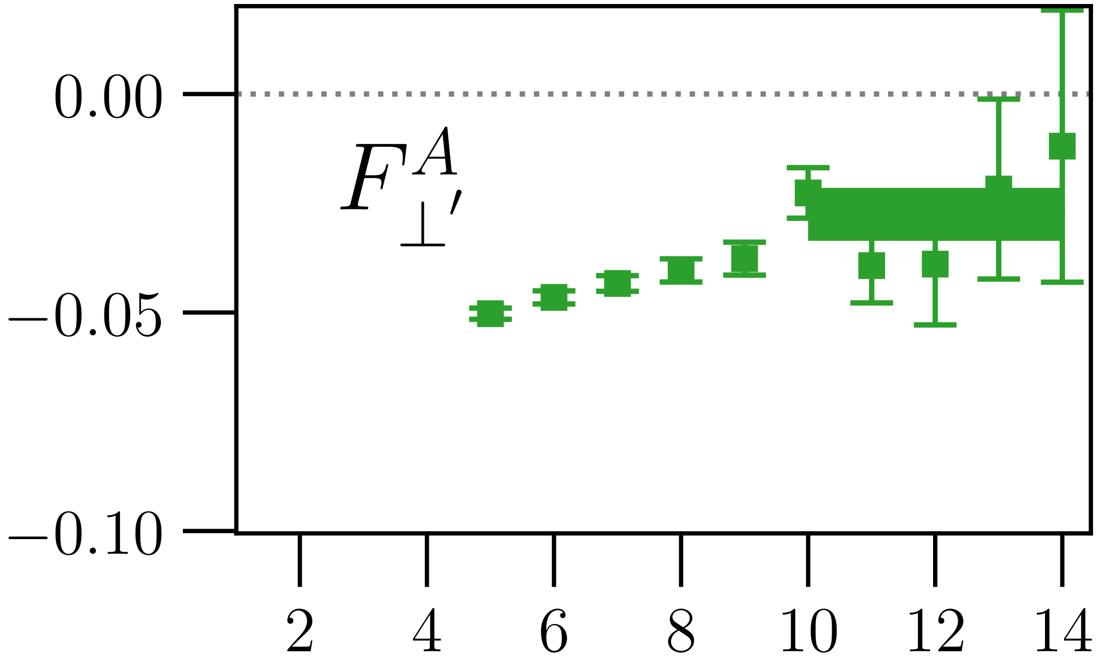
Schematically:

- Determine FF's using 3pt/2pt ratios
- Choose reference FF
- Determine all other FF's relative magnitudes and signs using 3pt/3pt

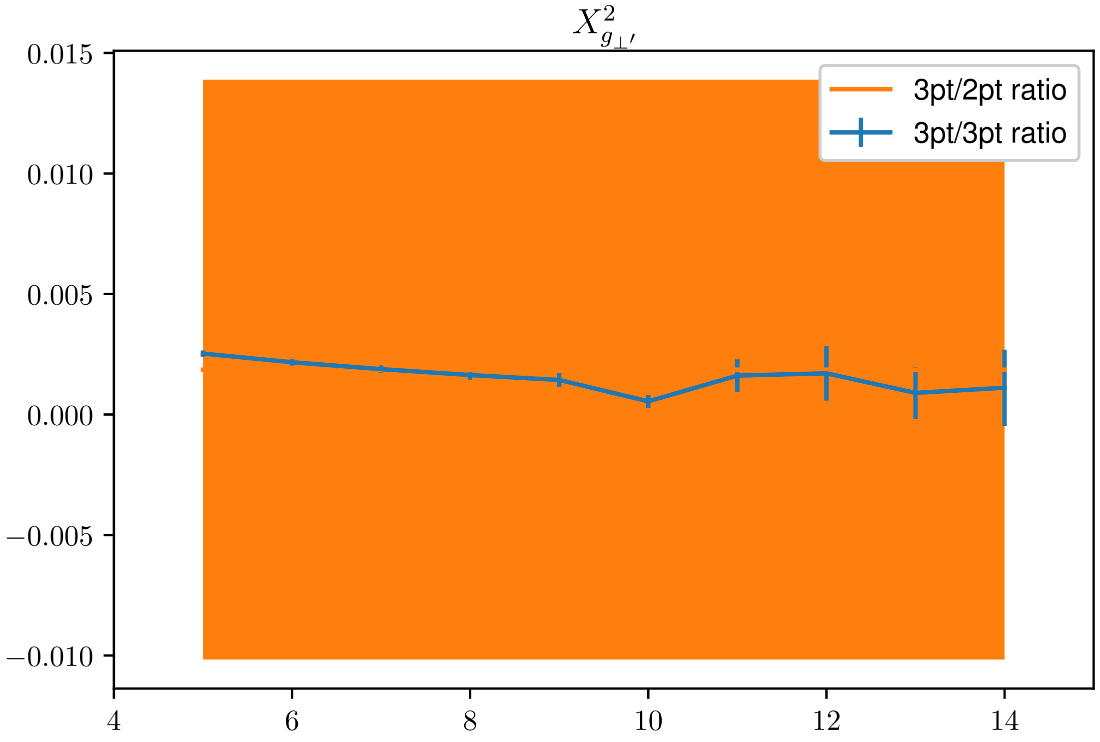
Advantages:

- Same source and sink, so reduced noise
- Don't have to determine FF's phase separately

Extracting form factors from ratios of 3pt functions

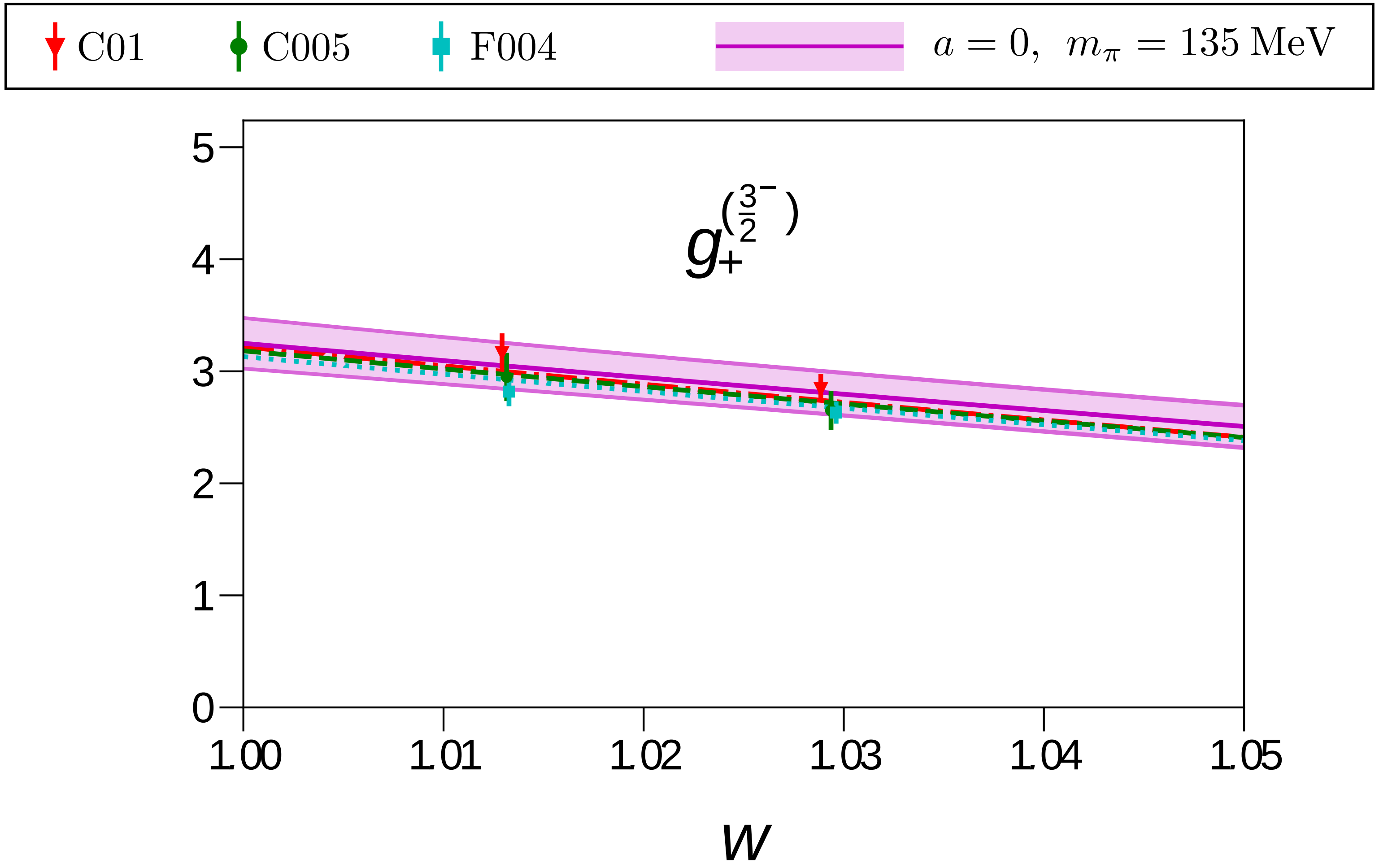


Extracting form factors from ratios of 3pt functions



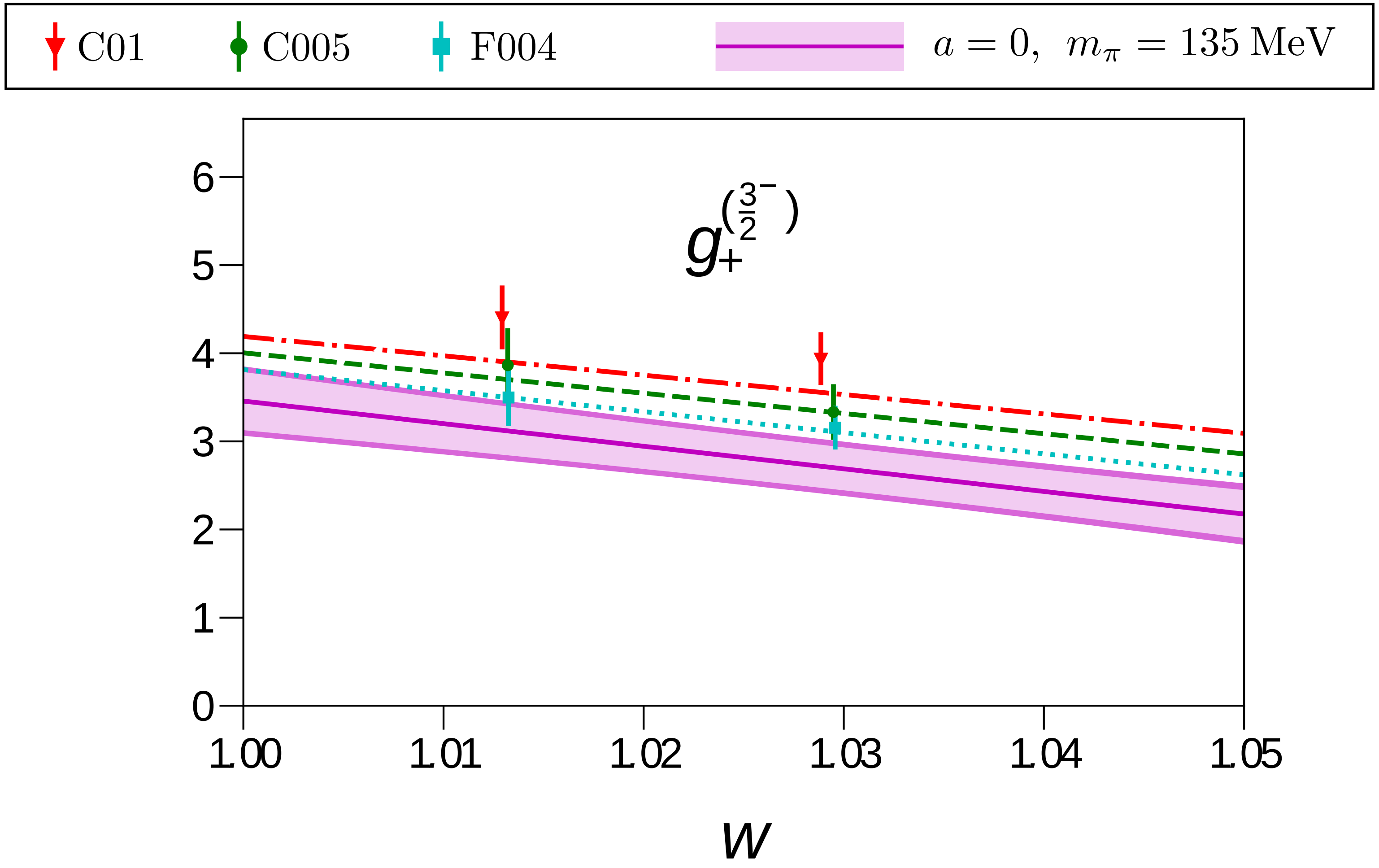
Sample form-factor results: $\Lambda_b \to \Lambda^*(1520)$

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



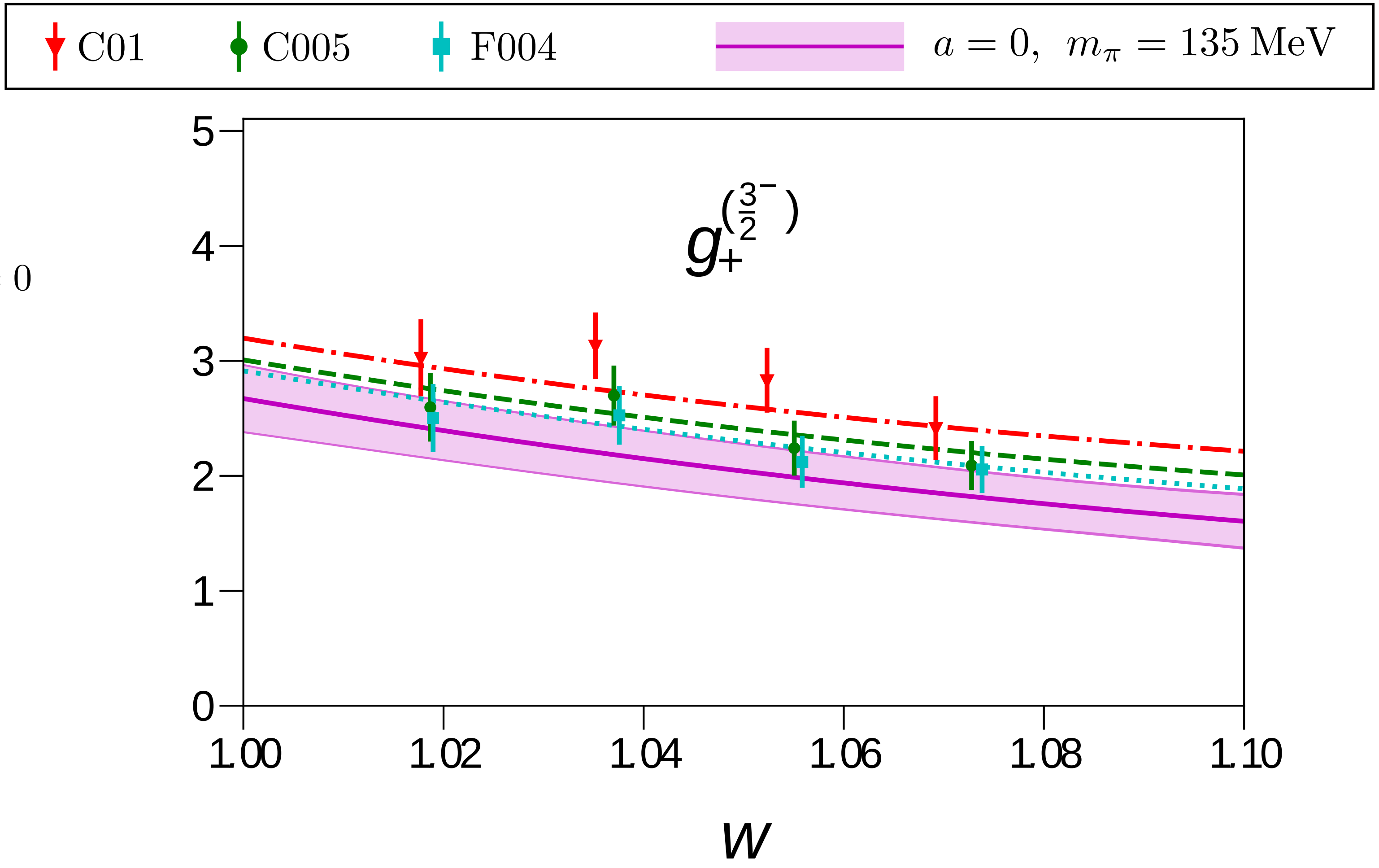
Sample form-factor results: $\Lambda_b \to \Lambda_c^*(2595, 2625)$

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



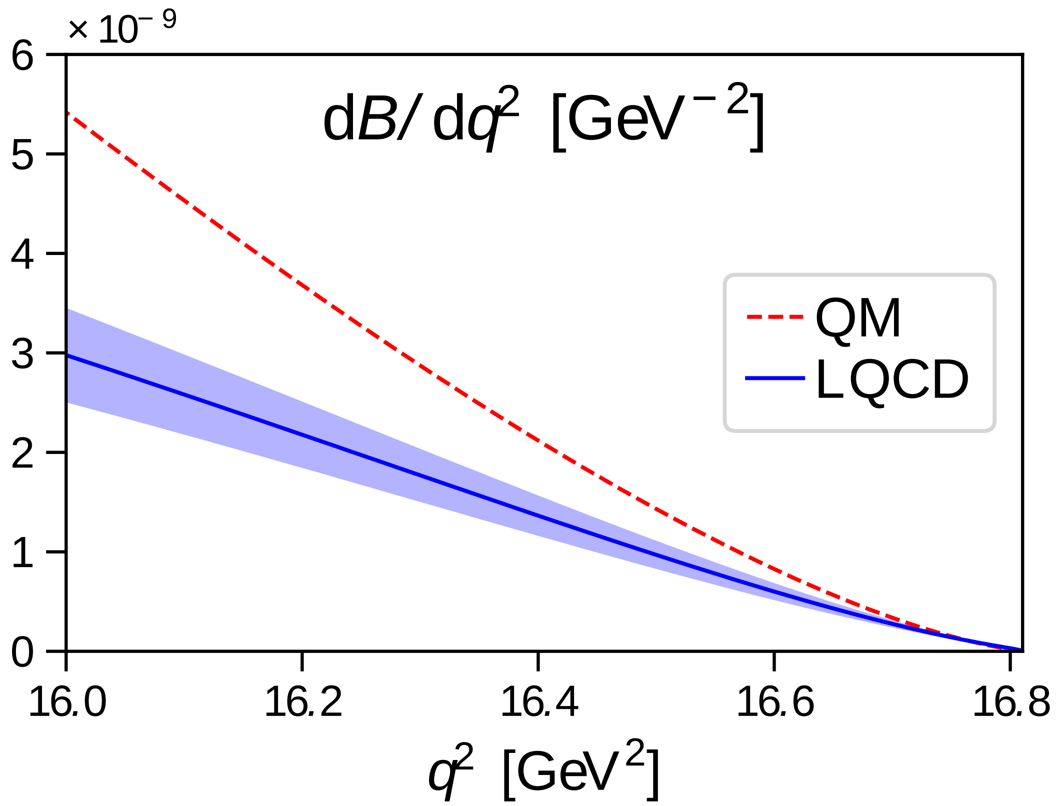
Sample form-factor results: $\Lambda_c \to \Lambda^*(1520)$

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



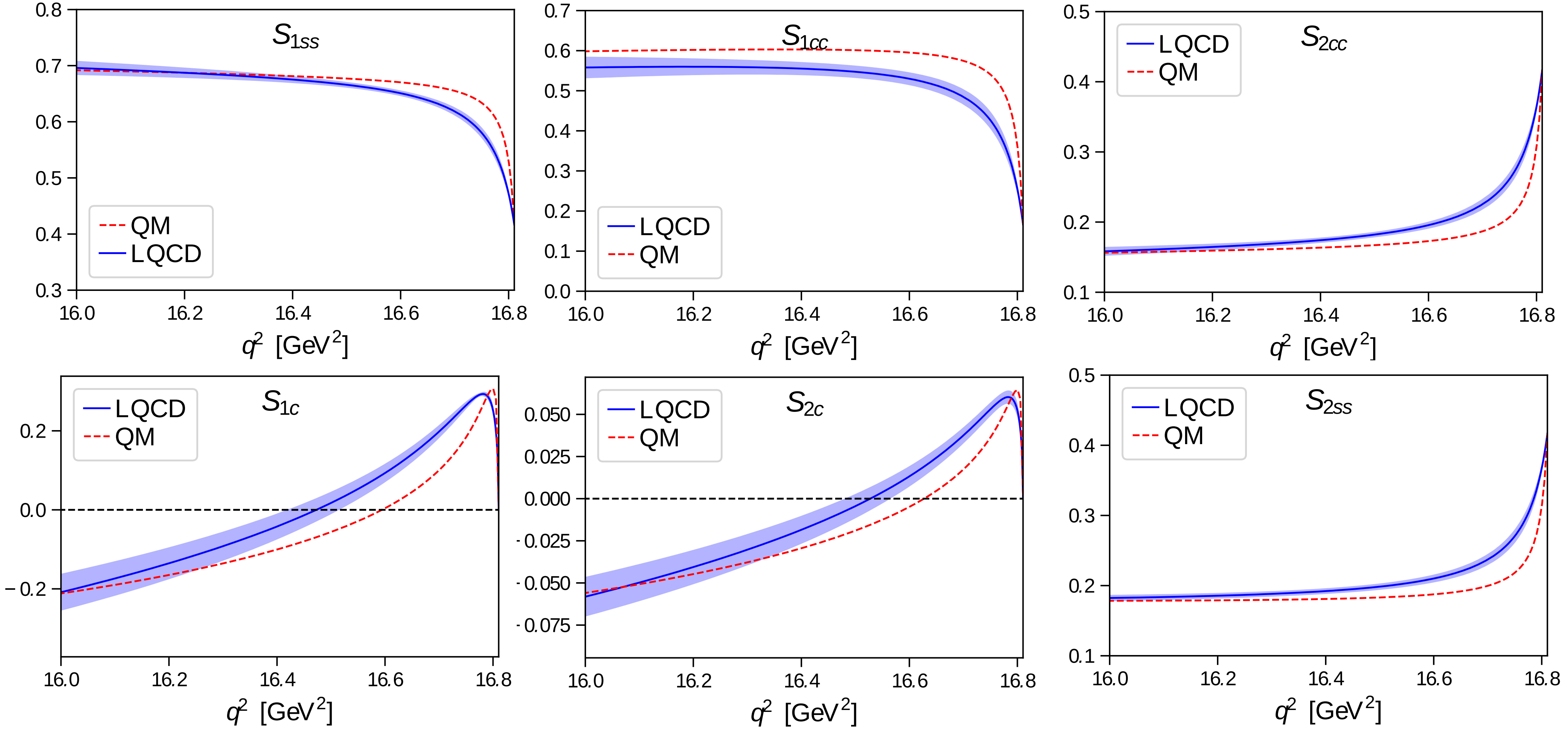
We also enforce $q^2 = 0$ endpoint relations

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



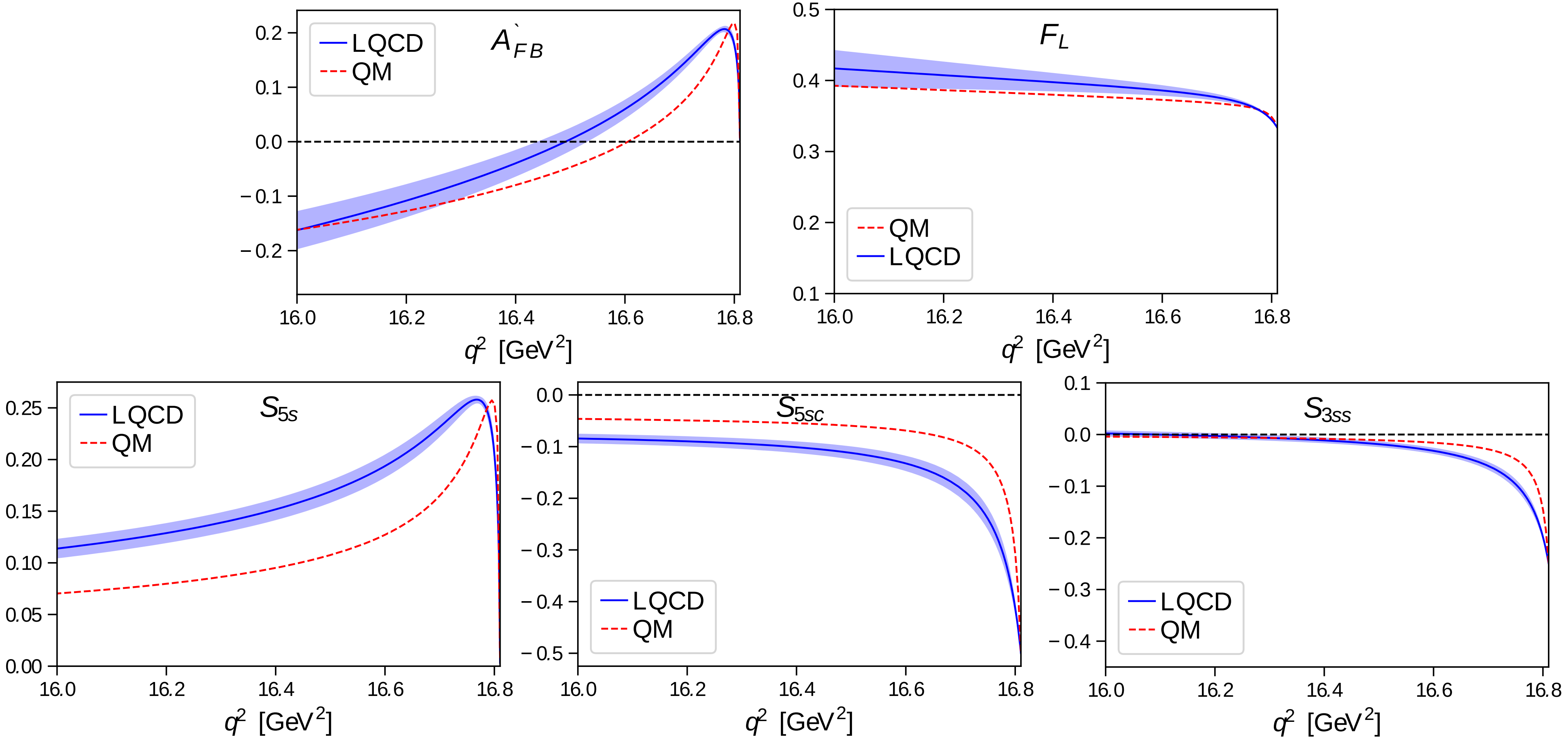
QM = using form factors from [L. Mott, W. Roberts, arXiv:1108.6129/IJMPA 2012]

$\Lambda_b \to \Lambda^*(1520)(\to pK^-)\mu^+\mu^-$ differential branching fraction near q_{max}



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

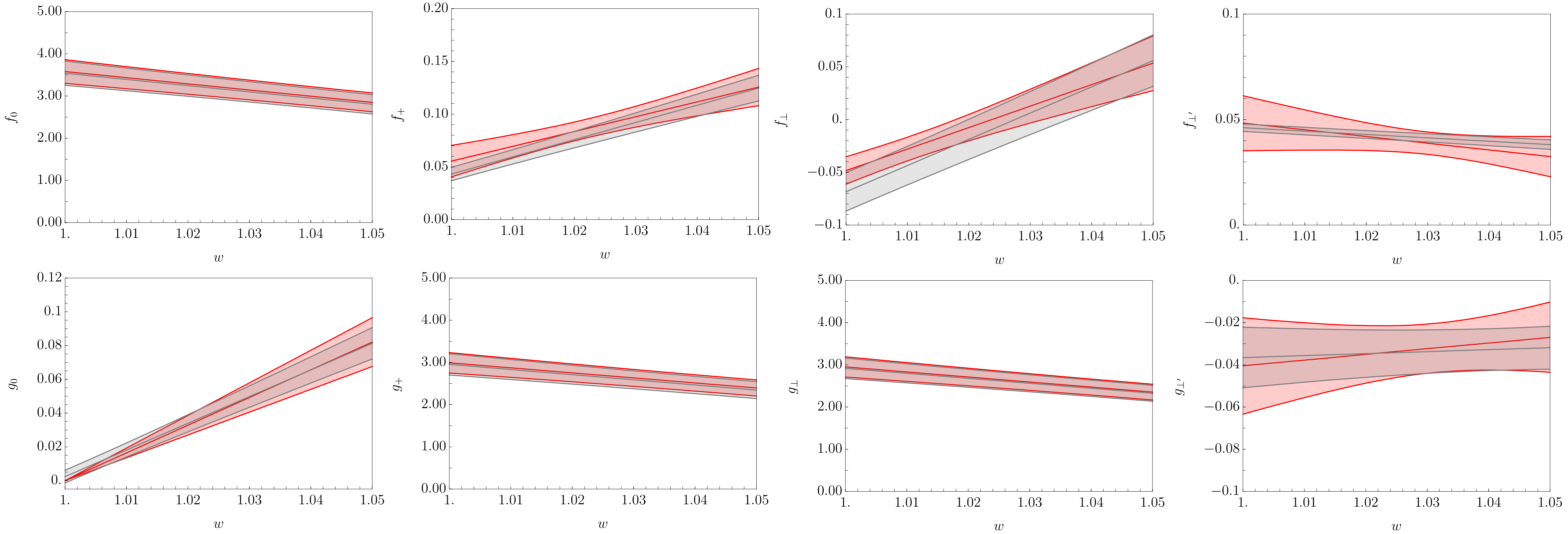
$\Lambda_b \to \Lambda^*(1520)(\to pK^-)\mu^+\mu^-$ differential branching fraction near q_{max}



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

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

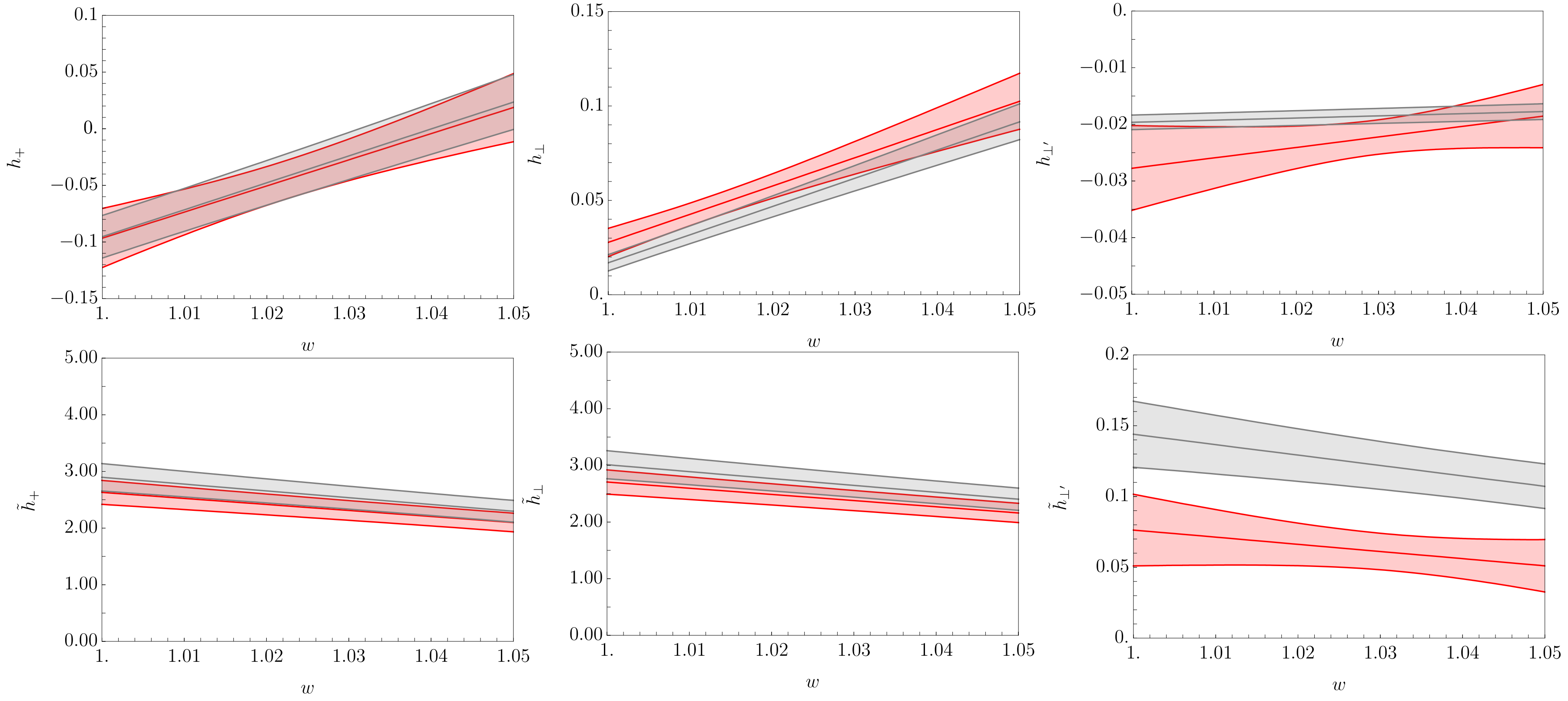
The fit to the V & A form factors has good quality [M. Bordone, arXiv:2101.12028/Symmetry 2021]



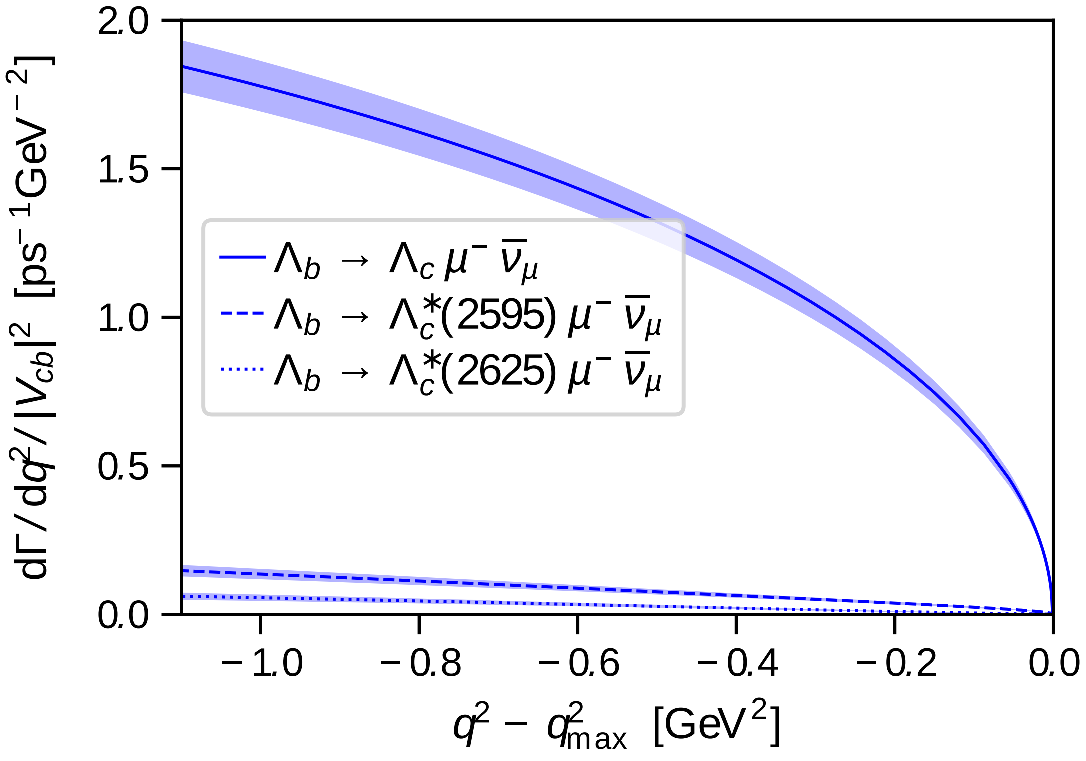
In gray are lattice results and in red are HQET

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

However, tensor form factors (not included in fit) show deviations

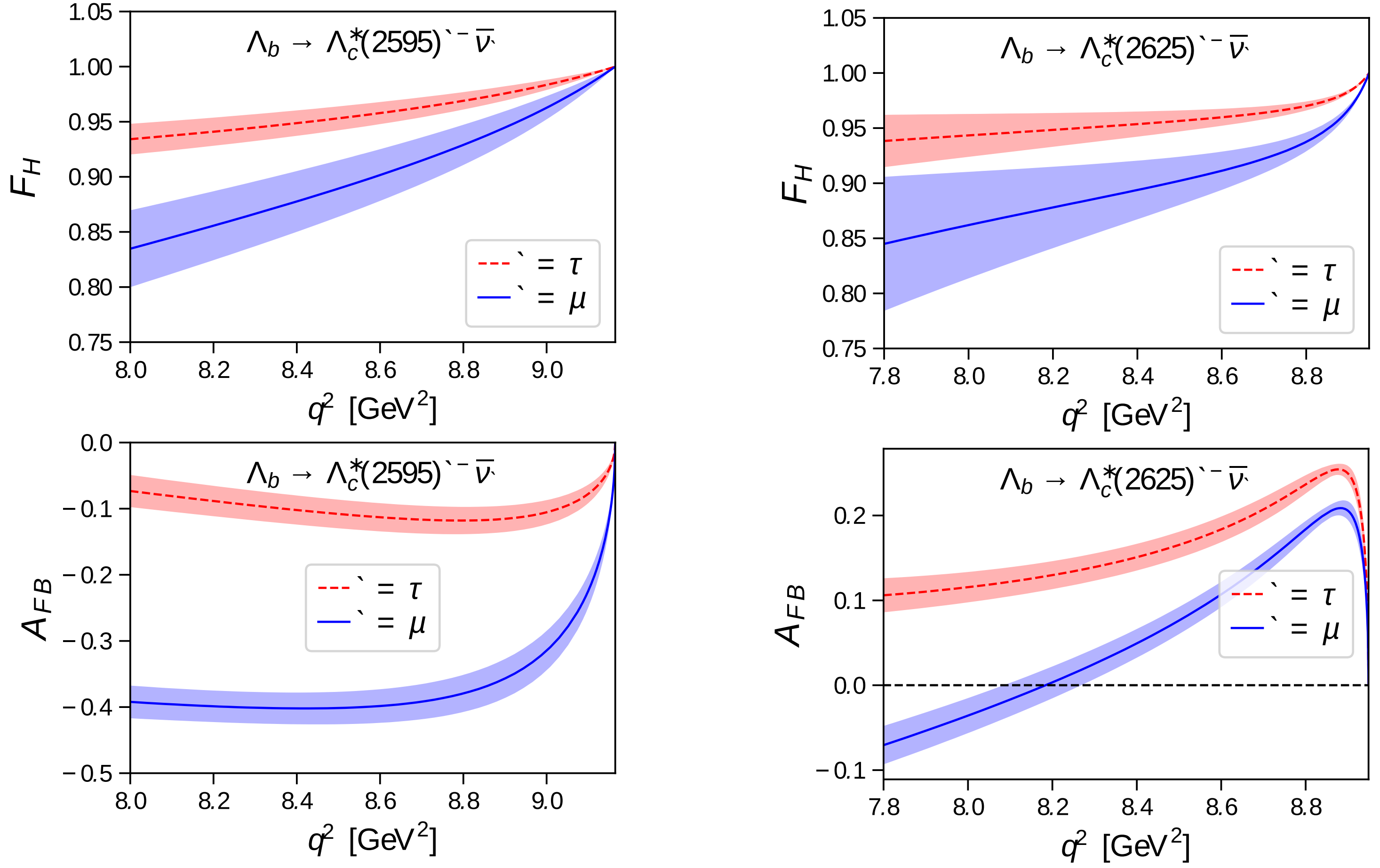


$\Lambda_b \to \Lambda_c^{(*)} \mu^- \overline{\nu}_\mu$ differential decay rates near q^2_{max} from lattice QCD



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

$\Lambda_b \to \Lambda_c^{(*)} \ell^- \overline{\nu}_\ell$ angular observables near q^2_{max} from lattice QCD



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

$\Lambda_b \to \Lambda_c^{(*)}\ell^-\overline{nu}_\ell$: HQET results

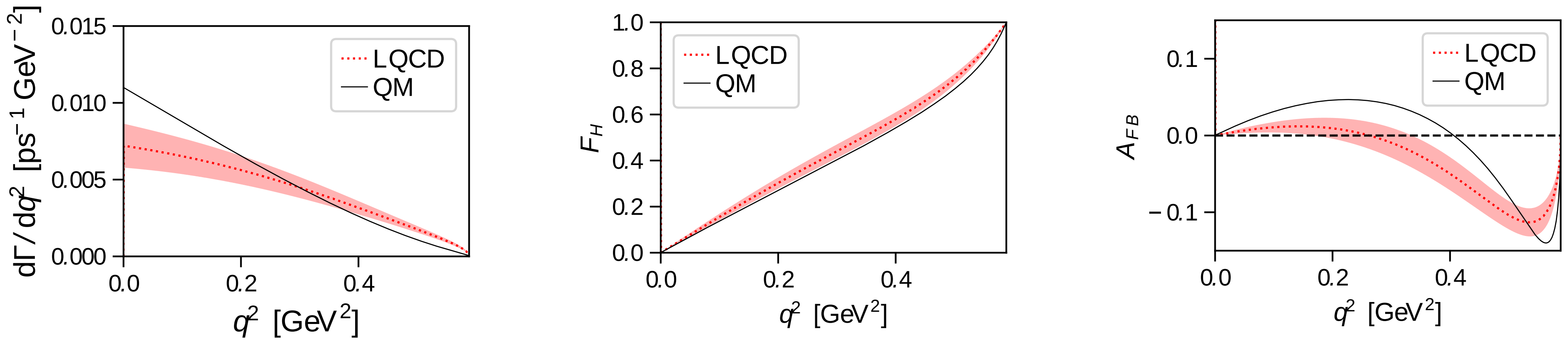
- HQET including only $O(1/m, \alpha_s)$ corrections does not allow a good fit to the lattice results for the $\Lambda_b \to \Lambda_c^*(2595, 2625)$ form factors. In particular, the results for the spin-1/2 final state ${}^*_c(2595)$ imply very large $1/m_c^2$ corrections.

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

- The spin-1/2 ${}^*_c(2595)$ may may have an exotic structure and may correspond to two poles similar to the strange ${}^*(1405)$.

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

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



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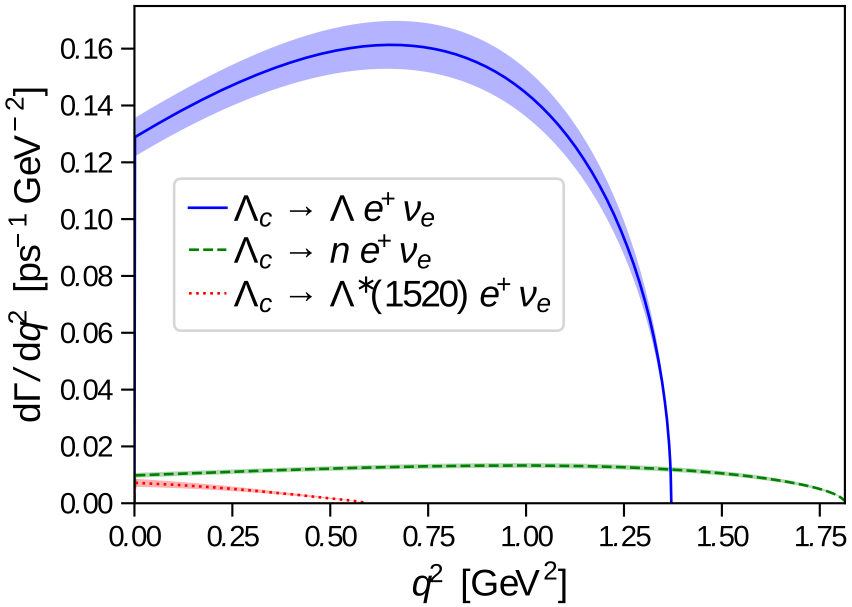
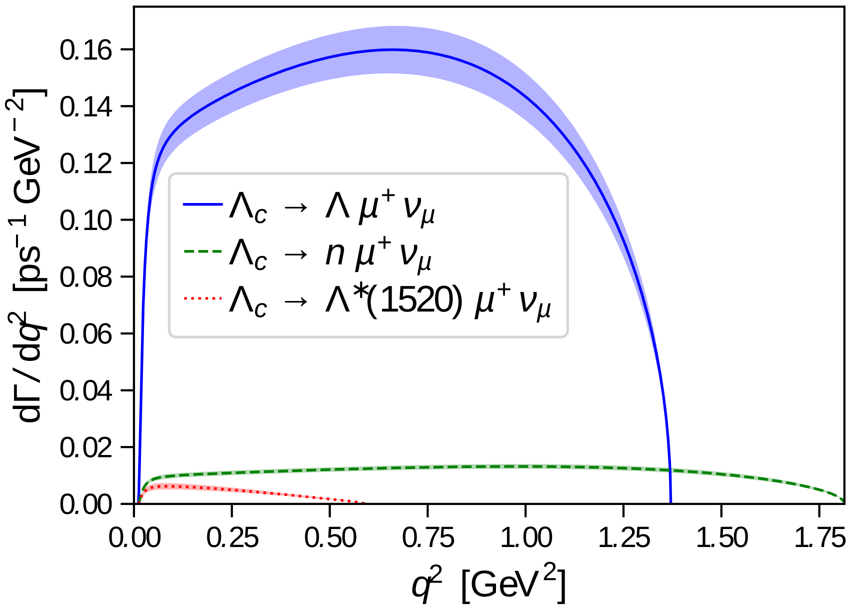
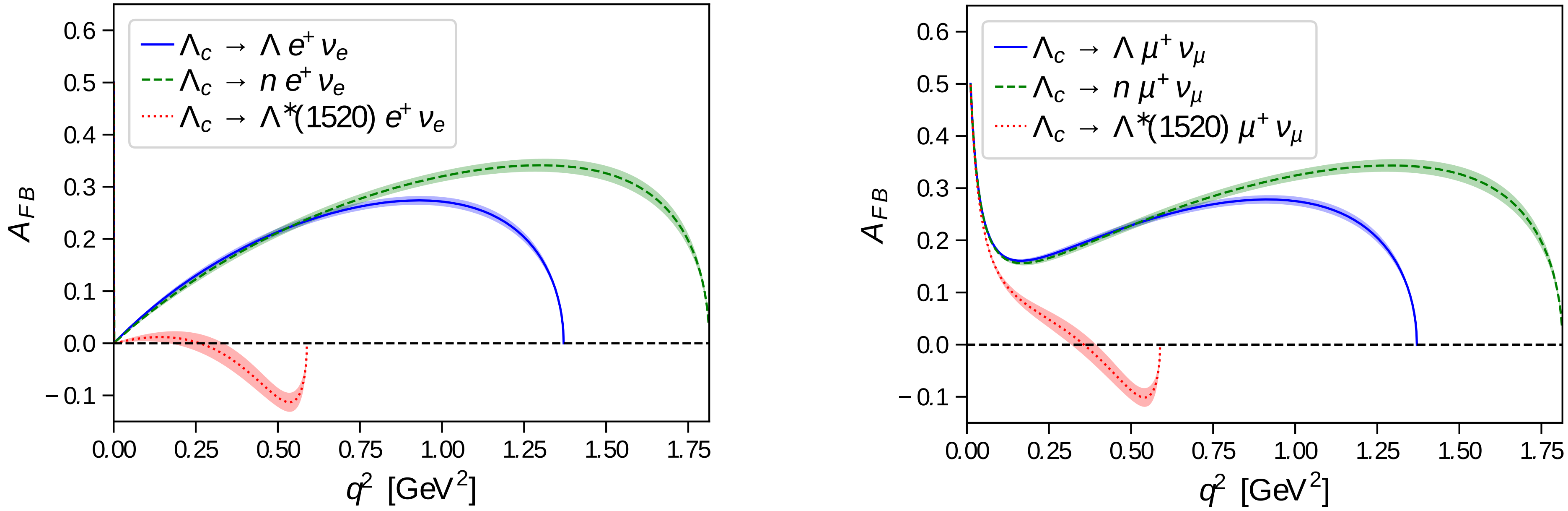
$\Lambda_c \to \{\Lambda, n, \Lambda^*(1520)\}\, \ell^+ \nu_\ell$ differential decay rates from lattice QCD





The form factors for transitions to n and Λ were taken 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



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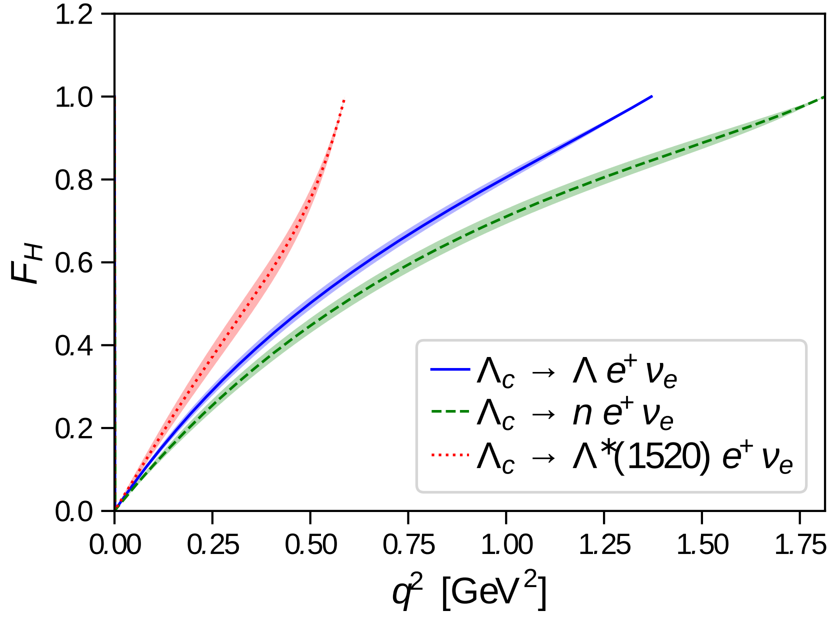

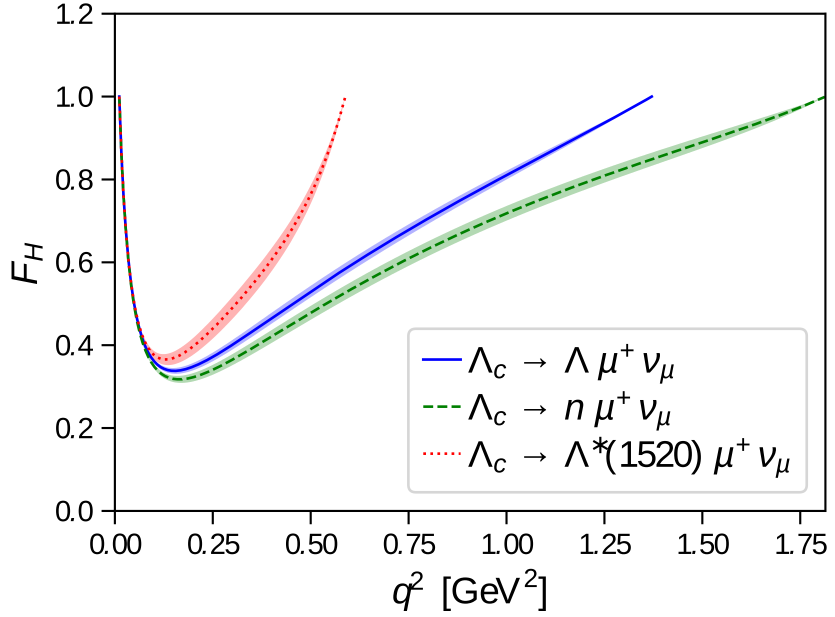

The form factors for transitions to n and Λ were taken from S. Meinel, arXiv:1611.09696/PRL 2017; arXiv:1712.05783/PRD 2018

Bounding $\mathcal{B}(\Lambda_c \to \Lambda^*(1405)e^+\nu_e)$

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

$$\mathcal{B}(\Lambda_c \to Xe^+\nu_e)_{\text{BESIII}} = 3.95(0.34)(0.09)\%$$

Using lattice QCD we predict

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

Subtracting this to the BESIII result, we obtain an upper bound on the branching fraction to all other hadrons:

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

Quark-model predictions for $\mathcal{B}(\Lambda_c \to \Lambda^*(1405))$ [M. Hussain, W. Roberts, arXiv:1701.03876/PRD 2017; Y.-S. Li, X. Liu, F.-S. Yu, arXiv:2104.04962] already exceeds this bound slightly. However, in unitarized chiral perturbation theory, where $\Lambda^*(1405)$ emerges as a kaon-nucleon molecule [N. Ikeno, E. Oset, arXiv:1510.02406/PRD 2016] predicts a much smaller branching fraction.

Summary

- We have updated our results for $\Lambda_b \to \Lambda_c^*(2595)$, $\Lambda_b \to \Lambda_c^*(2625)$, and $\Lambda_b \to \Lambda^*(1520)$ form factors enforcing q^2_{max} endpoint relations. Angular observables now take the exact values predicted by rotational symmetry. The old results remain consistent within 1-2 sigma.
- Our $\Lambda_b \to \Lambda_c^*$ results are not very well described by HQET up to $O(1/m_b, \alpha_s)$. In particular, results for spin-1/2 particle, $\Lambda_c(2625)$, imply very large $1/m_c^2$ corrections. Some authors have suggested $\Lambda_c^*(2625)$ has a two pole structure like the strange $\Lambda^*(1405)$.
- We have performed the first lattice-QCD determination of the $_c \to^* (1520)(J^P = 3/2^-)$ form factors. These results do cover the entire kinematic range.
- Using the Λ_c inclusive branching fraction from BESIII and subtracting lattice results for $\Lambda_c \to \Lambda$, $\Lambda_c \to n$ and $\Lambda_c \to \Lambda^*(1520)$. With this we have put an upper limit on $\Lambda_c \to \Lambda^*(1405)$. Quark-model results slightly exceed this upper limit.