Update on the $\Lambda_b \to \Lambda^*(1520)\ell^+\ell^-$ form factors

[Meinel/Rendon. arXiv:2009.09313]

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March 10, 2021

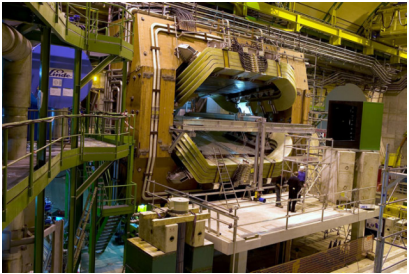
New Physics?

physicsworld

PARTICLES AND INTERACTIONS RESEARCH UPDATE

Has LHCb spotted physics beyond the Standard Model?

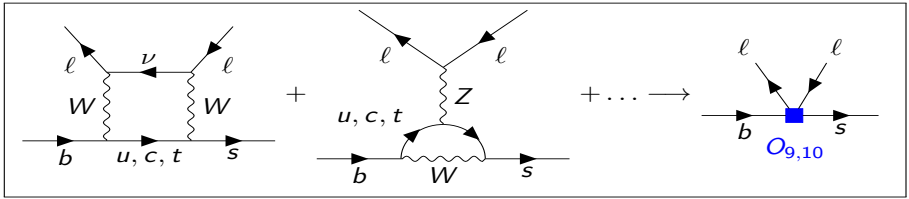
02 Aug 2013 Hamish Johnston

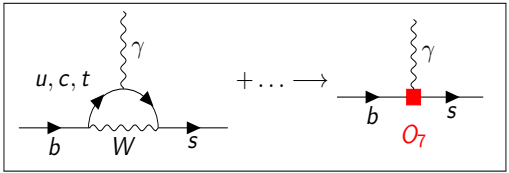


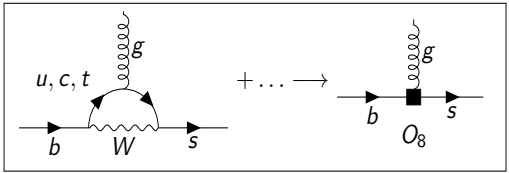
Is physics beyond the Standard Model lurking in LHCb?

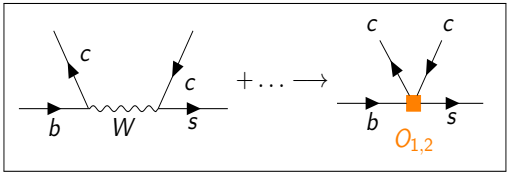
An analysis of data from the LHCb experiment at the CERN particle-physics lab suggests that the B-meson could decay in a way not predicted by the Standard Model of particle physics, according to theoretical physicists in Spain and France. The researchers believe that the deviation from the Standard Model has been measured with a confidence of 4.5σ – which is approaching the gold standard of 5σ required for a discovery in particle physics.

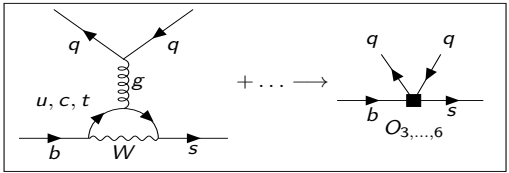
Effective weak Hamiltonian for $b \to s\ell^+\ell^-$ decays











Weak Decays: $b \to s\ell^+\ell^-$. Effective weak Hamiltonian.

Decay channels
$B^+ \to K^+\ell^+\ell^-$
$B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$
$B_s \to \phi(\to K^+K^-)\ell^+\ell^-$
$\Lambda_b^0 \to \Lambda^0(\to p^+\pi^-)\,\ell^+\ell^-$
$\Lambda_b^0 \to \Lambda^{*0}(\to p^+K^-)\,\ell^+\ell^-$

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \left[\, C_i O_i + C_i' O_i' \,\right]$$

$$\begin{aligned}
O_7^{(\prime)} &= e\, m_b/(16\pi^2)\ \bar{s}^a \sigma^{\mu\nu} P_{R(L)} b^a \quad F_{\mu\nu} \\
O_8^{(\prime)} &= g\, m_b/(16\pi^2)\ \bar{s}^a \sigma^{\mu\nu} P_{R(L)} b^b \quad G_{ab}^{\mu\nu}, \\
O_9^{(\prime)} &= e^2/(16\pi^2)\ \bar{s}^a \gamma^\mu P_{L(R)} b^a \quad \bar{\ell}\gamma_\mu \ell \\
O_{10}^{(\prime)} &= e^2/(16\pi^2)\ \bar{s}^a \gamma^\mu P_{L(R)} b^a \quad \bar{\ell}\gamma_\mu\gamma_5 \ell
\end{aligned}$$

[Grinstein/Savage/Wise. *Nucl. Phys.* B319 (1989)]

Hadronic matrix elements for $b \to s\ell^+\ell^-$ decays

For any decay $H_b \to H_s\ell^+\ell^-$:

Local contributions from O_7, O_9, O_10:

$$\langle H_s(p')|\bar{s}\Gamma b|H_b(p)\rangle$$

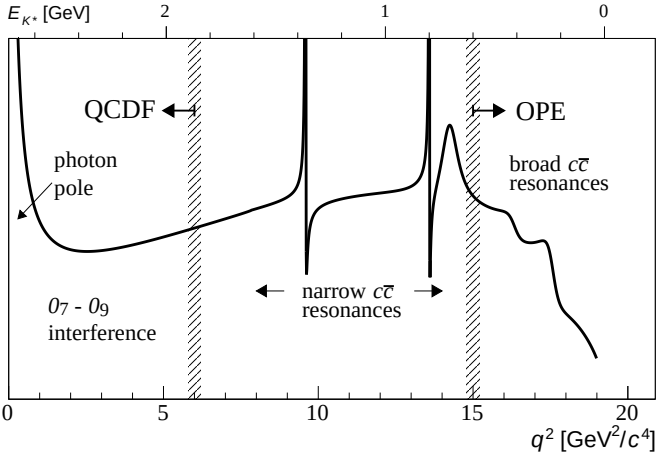
These can be calculated in lattice QCD.

Contributions from $O_{1,\ldots,6}$, O_8:

$$\int d^4x e^{iq\cdot x}\langle H_s(p')|TO_i(0)J^\mu_{em}(x)|H_b(p)\rangle \qquad (q = p - p')$$

Calculating these nonlocal matrix elements in lattice QCD is extremely difficult. We use OPE to account for these contributions as local matrix elements, O_7 and O_9, and get reabsorbed into C_7^{eff} and C_9^{eff}.

Hadronic matrix elements for $b \to s\ell^+\ell^-$ decays



[Blake/Gershon/Hiller. arXiv:1501.03309]

$b \to s\ell^+\ell^-$: R_K

Also,

$$R_K = \frac{\int_{1\ GeV^2}^{6\ GeV^2} \frac{d\mathcal{B}[B^+ \to K^+\mu^+\mu^-]}{dq^2} dq^2}{\int_{1\ GeV^2}^{6\ GeV^2} \frac{d\mathcal{B}[B^+ \to K^+e^+e^-]}{dq^2} dq^2}$$

Standard Model gives(e.g. HPQCD):

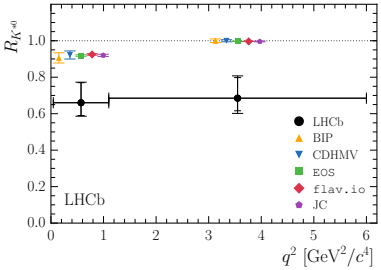
$$R_K = 1 + \mathcal{O}(10^{-3})$$

LHCb [Aaij et al. arXiv:1903.09252]:

$$R_K = 0.846^{+0.060}_{-0.054}(stat)^{+0.016}_{-0.014}(syst)$$

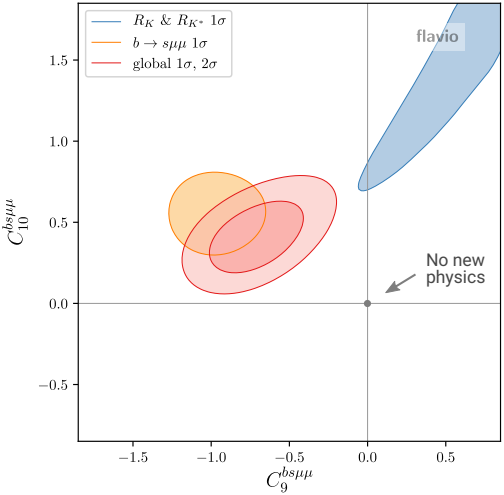
$b \to s\ell^+\ell^-$: $R_{K^\star}$

$$R_{K^\star} = \frac{\int \frac{d\mathcal{B}[B^0 \to K^{\star 0}\mu^+\mu^-]}{dq^2} dq^2}{\int \frac{d\mathcal{B}[B^0 \to K^{\star 0}e^+e^-]}{dq^2} dq^2}$$



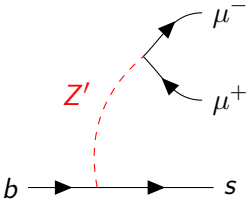
[Aaij et al. arXiv:1705.05802]

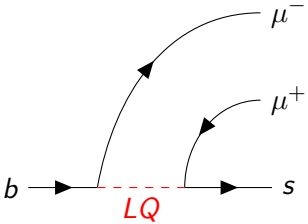
Weak Decays: $b \to s\ell^+\ell^-$



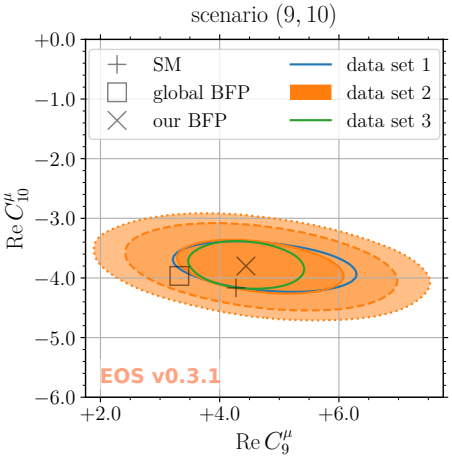
[Aebischer et al. arXiv:1903.10434]

Possible new physics scenarios





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



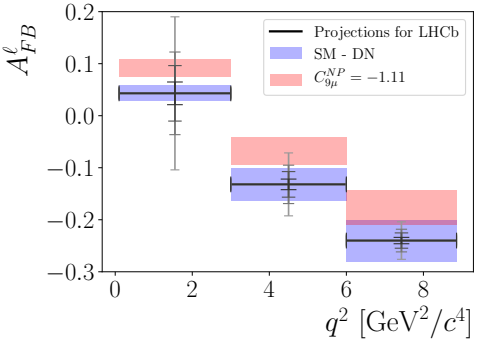
Different scenario comparison:

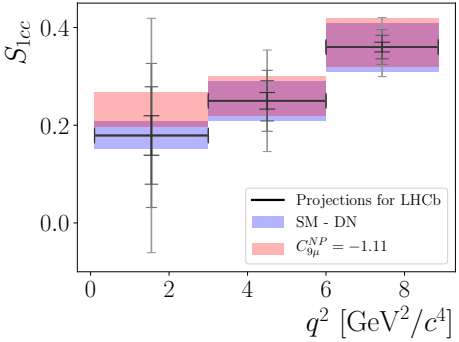
- "SM only" and "NP in C_9 only" scenarios equally efficient
- "NP in $C_{9,10}$" is "strongly disfavored"
- "NP in $C_{9,9',10,10'}$" is "decisively disfavored"

[Blake/Meinel/Dyk. arXiv:1912.05811]

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

SM vs NP in $C_{9\mu} = C_{9\mu}^{SM} - 1.11$





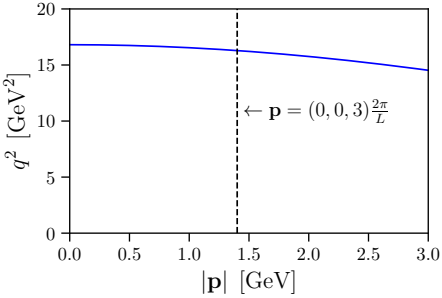
grey-scale markers represent: Run-2, Run-3, Run-4, Upgrade-2

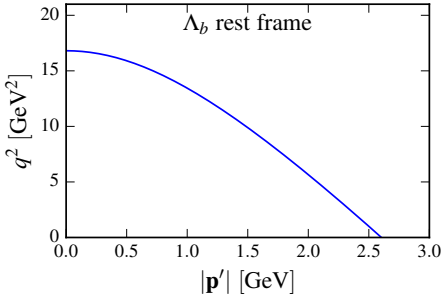
[Amhis et al. arXiv:2005.09602]

Lattice methods

- Gauge field configurations generated by the RBC and UKQCD collaborations
  [Aoki et al. arXiv:1011.0892]
- u, d, s quarks: domain-wall action
  [Kaplan. arXiv:hep-lat/9206013, Shamir. arXiv:hep-lat/9303005]
- All-mode averaging with 1 exact and 32 sloppy propagators per configuration
  [Shintani et al. arXiv:1402.0244]
- b quark: anisotropic clover action with three parameters, re-tuned more accurately with $B_s^{(*)}$ dispersion relation and HFS
- "Mostly nonperturbative" renormalization
  [El-Khadra et al. arXiv:hep-ph/0101023]

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





Lattice parameters

Label	$L^3 \times N_t$	$a(\mathrm{fm})$	$a\, m_{u,d}^{(sea)}$	$a\, m_s^{(sea)}$	$a\, m_{u,d}^{(val)}$	$a\, m_s^{(val)}$	$m_\pi(\mathrm{MeV})$
C005	$24^3 \times 64$	0.1106(3)	0.005	0.04	0.005	0.0323	≈ 340
C01	$24^3 \times 64$	0.1106(3)	0.01	0.04	0.01	0.0323	≈ 430
F004	$32^3 \times 64$	0.0828(3)	0.004	0.03	0.004	0.0248	≈ 300

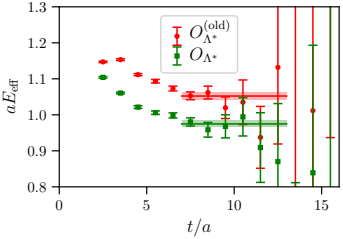
Lattice ensemble	Momenta	Source-sink separations	Configurations used
C005	$(0,0,2)\frac{2\pi}{L}$ $(0,0,3)\frac{2\pi}{L}$	$4-12$	311
C01	$(0,0,2)\frac{2\pi}{L}$ $(0,0,3)\frac{2\pi}{L}$	$4-12$	283
F004	$(0,0,2)\frac{2\pi}{L}$ $(0,0,3)\frac{2\pi}{L}$	$5-14$	251

$\Lambda(1520)$ interpolating field

The Old Λ Field

- $S = 3/2$ and $L = 0$.
- Flavor Octet.

$$\Lambda^{(\mathrm{old})}_{j\gamma} = \epsilon^{abc}\,(C\gamma_j)_{\alpha\beta}\,\left(\tilde{u}^a_\alpha\,\tilde{s}^b_\beta\,\tilde{d}^c_\gamma - \tilde{d}^a_\alpha\,\tilde{s}^b_\beta\,\tilde{u}^c_\gamma\right)$$



The New Λ Field

- $S = 1/2$ and $L = 1$.
- Flavor Singlet.

$$\Lambda_{j\gamma} = \epsilon^{abc}\,(C\gamma_5)_{\alpha\beta}\,\left[\tilde{s}^a_\alpha\,\tilde{d}^b_\beta\,(\nabla_j\tilde{u})^c_\gamma - \tilde{s}^a_\alpha\,\tilde{u}^b_\beta\,(\nabla_j\tilde{d})^c_\gamma + \tilde{u}^a_\alpha\,(\nabla_j\tilde{d})^b_\beta\,\tilde{s}^c_\gamma - \tilde{d}^a_\alpha\,(\nabla_j\tilde{u})^b_\beta\,\tilde{s}^c_\gamma\right]$$

[Meinel/Rendon. arXiv:1608.08110]

Form factor definitions

$$\langle \Lambda^*(\mathrm{p}', s')| \, \bar{s}\Gamma b \, |\Lambda_b(\mathrm{p}, s)\rangle = \bar{u}_\lambda(m_{\Lambda^*}, \mathrm{p}', s') \, G^\lambda[\Gamma] \, u(m_{\Lambda_b}, \mathrm{p}, s),$$

$$\sum_s u(m_{\Lambda_b}, \mathrm{p}, s)\bar{u}(m_{\Lambda_b}, \mathrm{p}, s) = m_{\Lambda_b} + p,$$

$$\sum_{s'} u_\mu(m_{\Lambda^*}, \mathrm{p}', s')\bar{u}_\nu(m_{\Lambda^*}, \mathrm{p}', s') = -(m_{\Lambda^*} + p')\left(g_{\mu\nu} - \frac{1}{3}\gamma_\mu\gamma_\nu - \frac{2}{3m_{\Lambda^*}^2}p'_\mu p'_\nu - \frac{1}{3m_{\Lambda^*}}(\gamma_\mu p'_\nu - \gamma_\nu p'_\mu)\right).$$

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

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

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

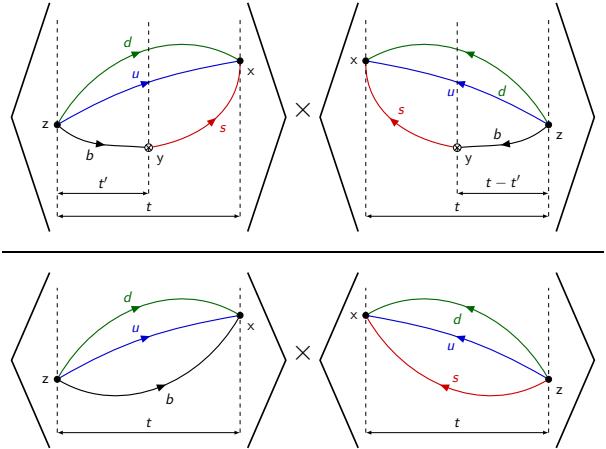
$$
\begin{aligned}
G^\lambda[\gamma^\mu \gamma_5] \quad = \quad & -g_0 \gamma_5 \frac{m_{\Lambda^*}}{s_-} \frac{(m_{\Lambda_b} + m_{\Lambda^*})\, p^\lambda q^\mu}{q^2} \\
& - g_+ \gamma_5 \frac{m_{\Lambda^*}}{s_+} \frac{(m_{\Lambda_b} - m_{\Lambda^*})\, p^\lambda (q^2 (p^\mu + p'^\mu) - (m_{\Lambda_b}^2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

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

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

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

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



In simple terms,

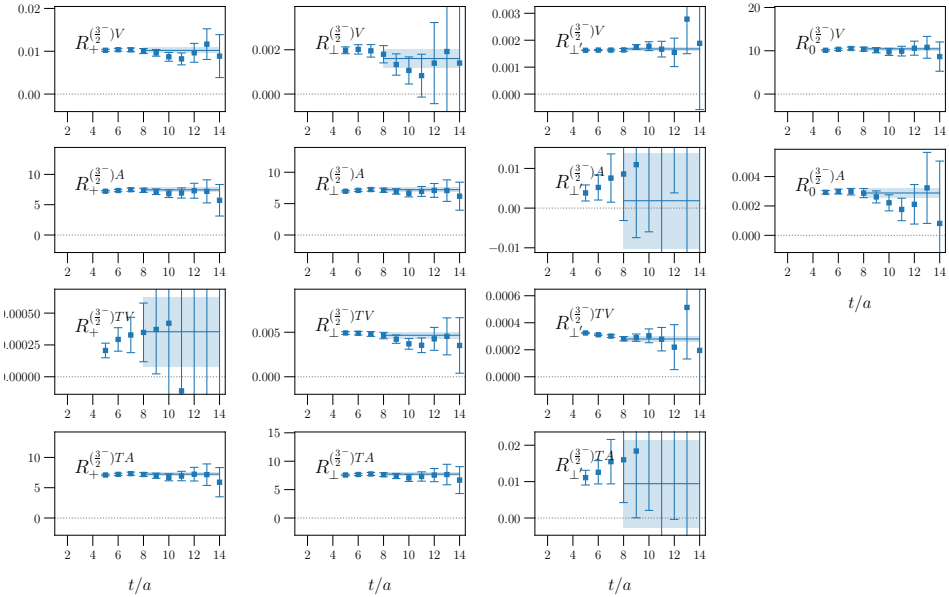
- Project to desired parity and spin at source and sink
- Project to desired FF at the current

Advantages:

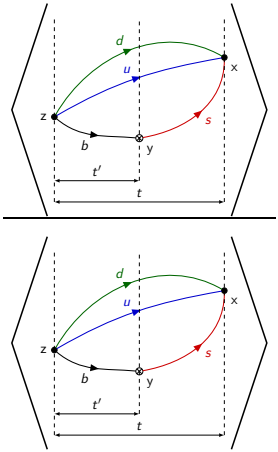
- Overlap factors cancel out
- Time dependence cancels out at infinite time

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

Must determine sign from 3pt directly


$R_{+}^{(\frac{3}{2}^-)V}$
$R_{\perp}^{(\frac{3}{2}^-)V}$
$R_{\perp'}^{(\frac{3}{2}^-)V}$
$R_{0}^{(\frac{3}{2}^-)V}$
$R_{+}^{(\frac{3}{2}^-)A}$
$R_{\perp}^{(\frac{3}{2}^-)A}$
$R_{\perp'}^{(\frac{3}{2}^-)A}$
$R_{0}^{(\frac{3}{2}^-)A}$
$R_{+}^{(\frac{3}{2}^-)TV}$
$R_{\perp}^{(\frac{3}{2}^-)TV}$
$R_{\perp'}^{(\frac{3}{2}^-)TV}$
$R_{+}^{(\frac{3}{2}^-)TA}$
$R_{\perp}^{(\frac{3}{2}^-)TA}$
$R_{\perp'}^{(\frac{3}{2}^-)TA}$
t/a
t/a
t/a
t/a

Extracting form factors from ratios of 3pt functions



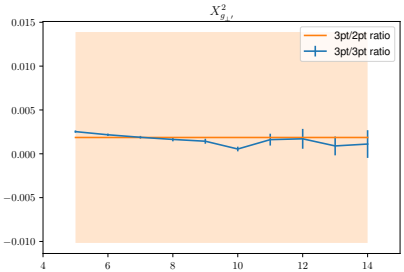
Schematically,

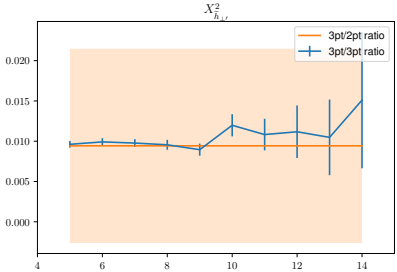
- Determine FF's using 3pt/2pt ratios
- Choose reference FF
- Determine all other FF's relative magnitudes and signs using 3pt/3pt

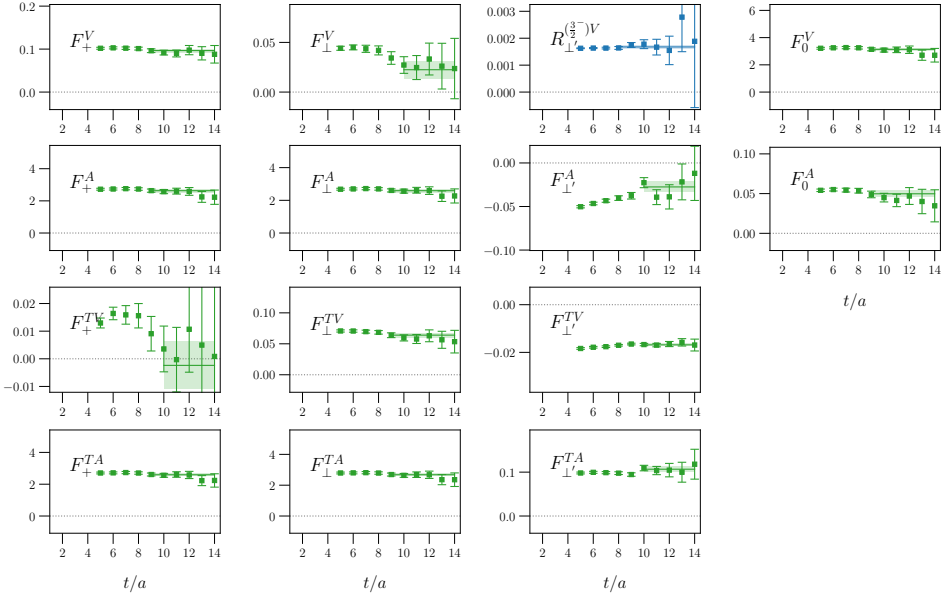
Advantages:

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

3pt/2pt vs 3pt/2pt






F_+^V
$F_\perp^V$
$R_{\perp'}^{(\frac{3}{2}^-)V}$
F_0^V
F_+^A
$F_\perp^A$
$F_{\perp'}^A$
F_0^A
F_+^{TV}
$F_\perp^{TV}$
$F_{\perp'}^{TV}$
F_+^{TA}
$F_\perp^{TA}$
$F_{\perp'}^{TA}$
t/a
t/a
t/a
t/a

Physical extrapolation

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

$$f(q^2) = F^f \left[1 + C^f \frac{m_\pi^2 - m_{\pi,\mathrm{phys}}^2}{(4\pi f_\pi)^2} + D^f a^2 \Lambda^2 \right] + A^f \left[1 + \tilde{C}^f \frac{m_\pi^2 - m_{\pi,\mathrm{phys}}^2}{(4\pi f_\pi)^2} + \tilde{D}^f a^2 \Lambda^2 \right] (w-1),$$

$$f(q^2) = F^f + A^f (w-1)$$

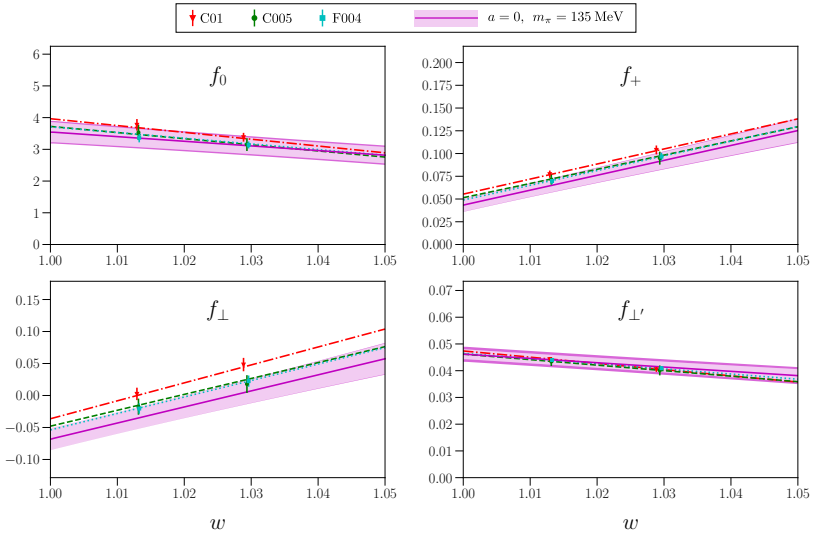
Systematic Uncertainties

$$
\begin{aligned}
f_{\mathrm{HO}}(q^2) \;=\; & F^f_{\mathrm{HO}}\left[1 + C^f_{\mathrm{HO}}\frac{m_\pi^2 - m_{\pi,\mathrm{phys}}^2}{(4\pi f_\pi)^2} + H^f_{\mathrm{HO}}\frac{m_\pi^3 - m_{\pi,\mathrm{phys}}^3}{(4\pi f_\pi)^3}\right. \\
& \left. + D^f_{\mathrm{HO}} a^2\Lambda^2 + E^f_{\mathrm{HO}} a\Lambda + G^f_{\mathrm{HO}} a^3\Lambda^3\right] \\
& + A^f_{\mathrm{HO}}\left[1 + \tilde{C}^f_{\mathrm{HO}}\frac{m_\pi^2 - m_{\pi,\mathrm{phys}}^2}{(4\pi f_\pi)^2} + \tilde{H}^f_{\mathrm{HO}}\frac{m_\pi^3 - m_{\pi,\mathrm{phys}}^3}{(4\pi f_\pi)^3}\right. \\
& \left. + \tilde{D}^f_{\mathrm{HO}} a^2\Lambda^2 + \tilde{E}^f_{\mathrm{HO}} a\Lambda + \tilde{G}^f_{\mathrm{HO}} a^3\Lambda^3\right](w-1)
\end{aligned}
$$

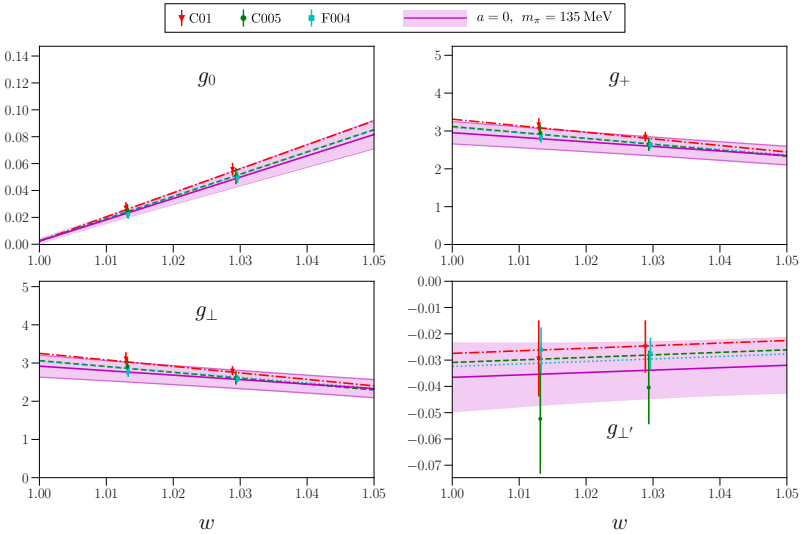
Systematic Uncertainties

$$\sigma_{O,\mathrm{syst}} = \max\left(|O_{\mathrm{HO}} - O|,\ \sqrt{|\sigma^2_{O,\mathrm{HO}} - \sigma^2_{O}|}\right)$$

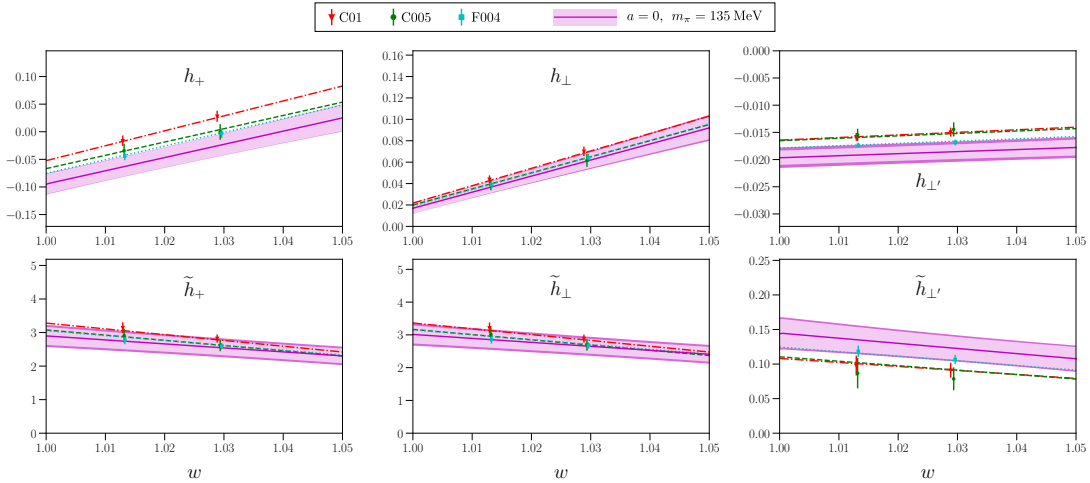
Vector form factors



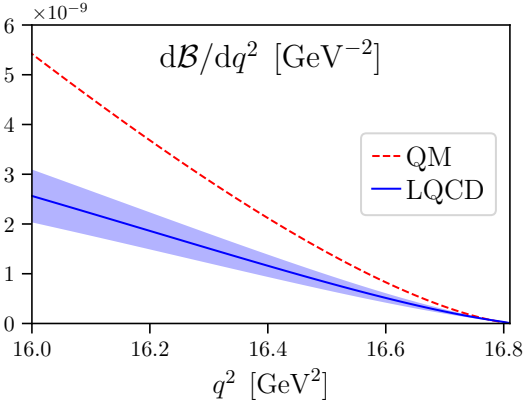
Axial vector form factors



(Pseudo) Tensor form factors

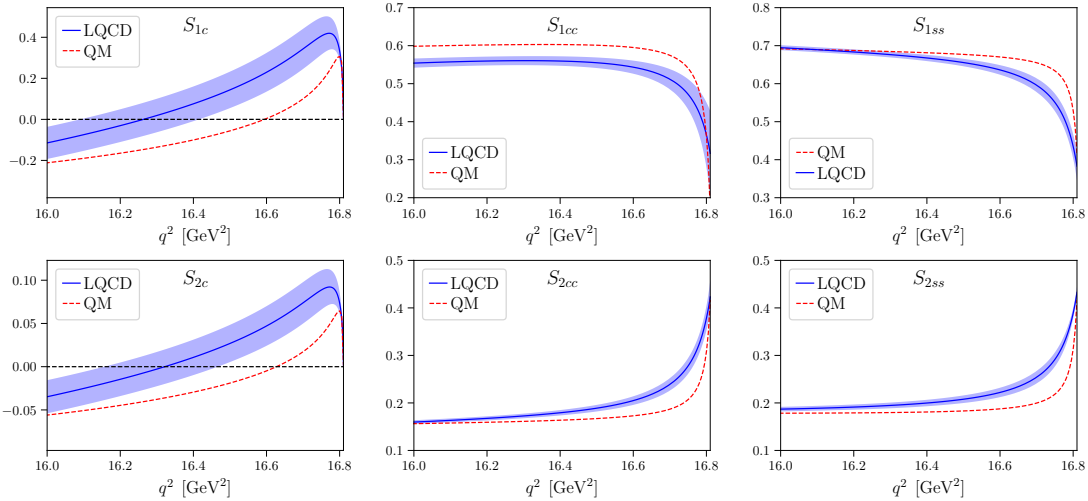


$\Lambda_b \to \Lambda^\star(1520)\ell^+\ell^-$ observables



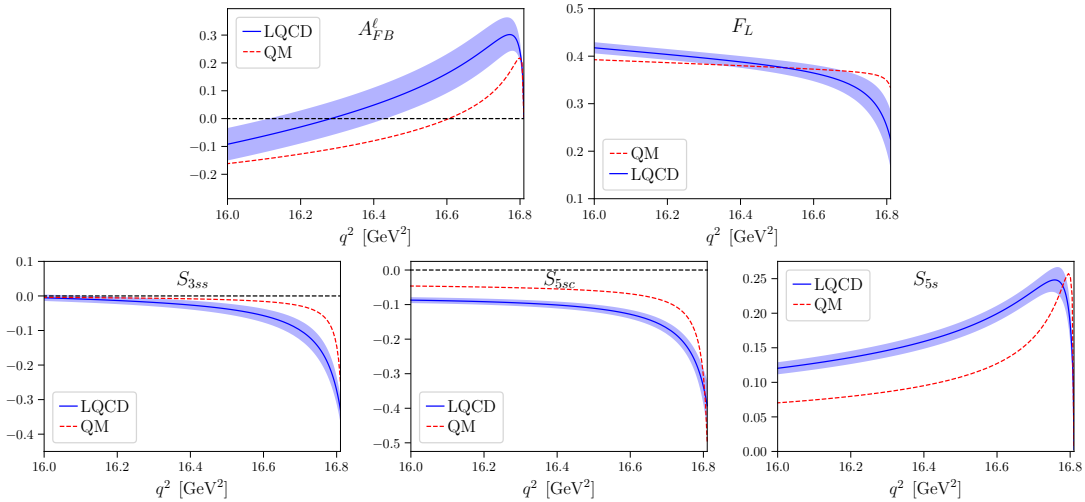
QM stands for quark model FF results in [Mott/Roberts. arXiv:1108.6129]

Observables



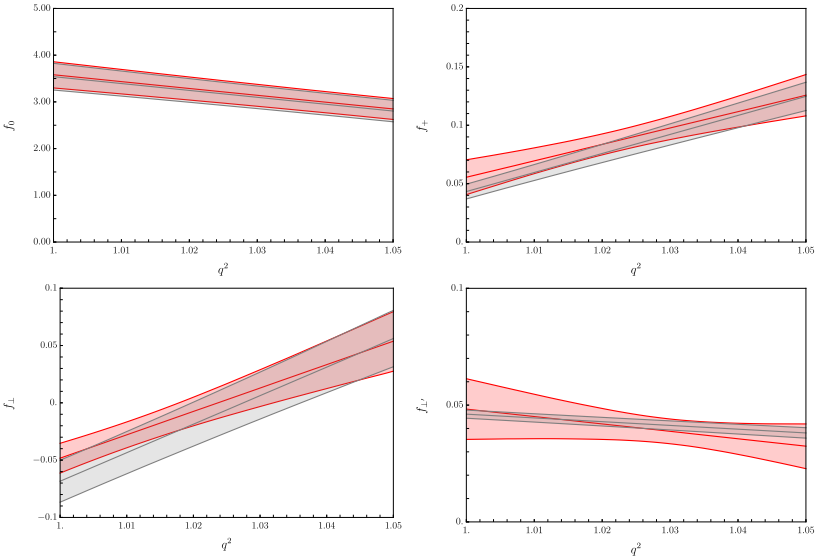
See [Descotes-Genon/Novoa Brunet. arXiv:1903.00448] for definitions

Observables

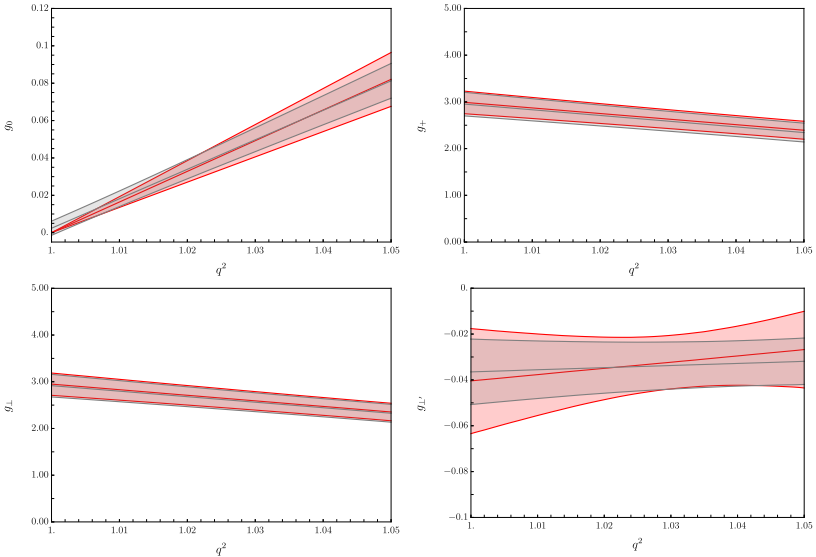


See [Descotes-Genon/Novoa Brunet. arXiv:1903.00448] for definitions

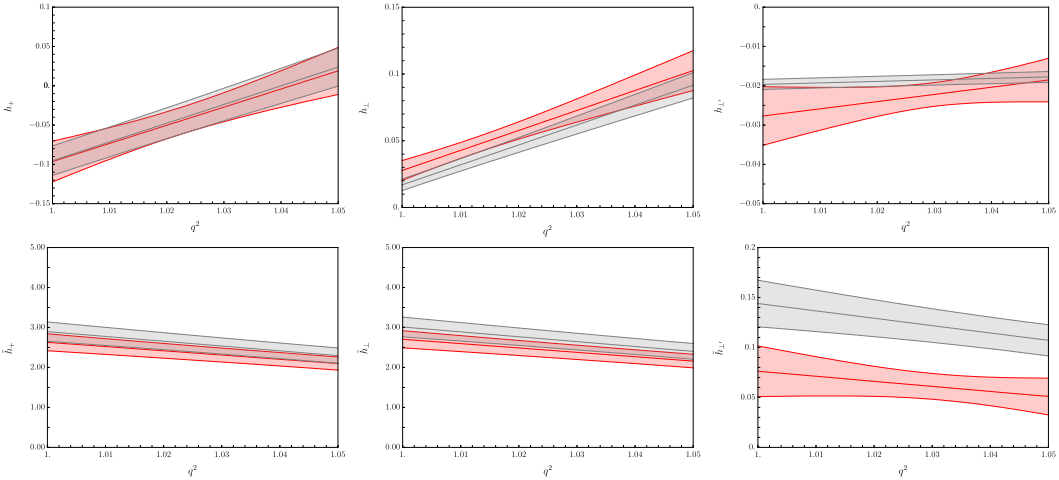
HQET: [Bordone. arXiv:2101.12028]



HQET: [Bordone. arXiv:2101.12028]



HQET: [Bordone. arXiv:2101.12028]



Conclusions

- The $q^2_{max} = 16.8\mathrm{GeV}^2$. Not a lot of range above the charm resonances.
- Could reach lower q^2 range using moving-NRQCD action for the b-quark which allows higher Λ_b momenta.
- Lattice results and HQET agree.
- Lattice results could be combined with sum-rules to reach lower q^2 ranges.