Heavy baryon decay form factors from lattice QCD

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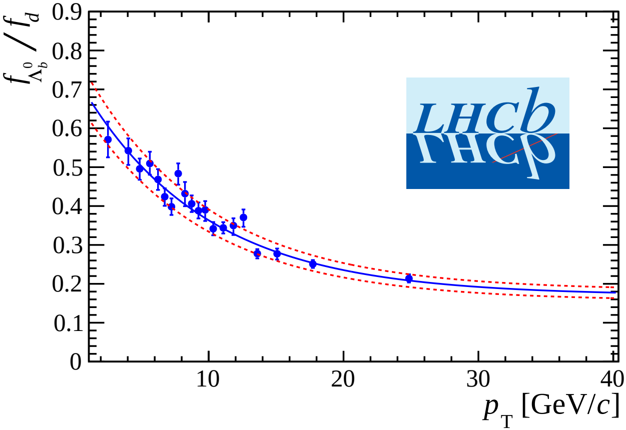
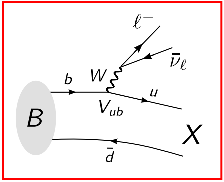
HC2NP 2016, Tenerife

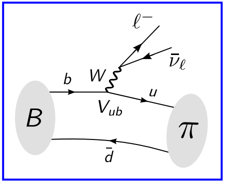
$$\frac{\text{Production fraction of } \Lambda_b}{\text{Production fraction of } B^0}$$



[LHCb Collaboration, JHEP 08, 143 (2014)]

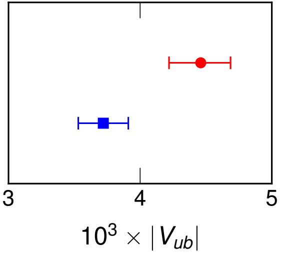
1. $|V_{ub}|$ and $|V_{cb}|$
2. $b \to c\tau^-\bar{\nu}$
3. $b \to s\mu^+\mu^-$



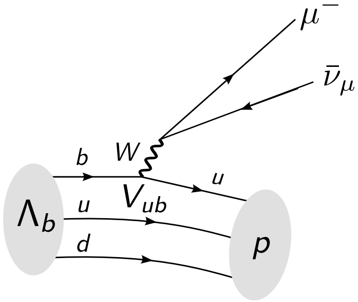


inclusive $B \to X_u \, \ell \, \bar{\nu}_\ell$

exclusive $B \to \pi \, \ell \, \bar{\nu}_\ell$



[Particle Data Group, November 2015]



μ^-
$\bar{\nu}_\mu$
W
b
u
V_{ub}
u
d
Λ_b
p

LHCb result:

$$\frac{\displaystyle\int_{15\ \mathrm{GeV}^2}^{q^2_{\max}} \frac{\mathrm{d}\Gamma(\Lambda_b \to p\,\mu^-\bar{\nu}_\mu)}{\mathrm{d}q^2}\mathrm{d}q^2}{\displaystyle\int_{7\ \mathrm{GeV}^2}^{q^2_{\max}} \frac{\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c\,\mu^-\bar{\nu}_\mu)}{\mathrm{d}q^2}\mathrm{d}q^2} \quad = \quad (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

$$(q = p - p').$$

[LHCb Collaboration, Nature Physics **11**, 743-747 (2015)]

To extract $|V_{ub}/V_{cb}|$ from this, need

$$\langle p\,|\,\bar{u}\gamma^\mu b\,|\Lambda_b\rangle,\ \ \langle p\,|\,\bar{u}\gamma^\mu\gamma_5 b\,|\Lambda_b\rangle,$$
$$\langle \Lambda_c|\,\bar{c}\gamma^\mu b\,|\Lambda_b\rangle,\ \ \langle \Lambda_c|\,\bar{c}\gamma^\mu\gamma_5 b\,|\Lambda_b\rangle$$

from lattice QCD.

Helicity form factors:

$$
\begin{aligned}
\langle F|\overline{q}\gamma^\mu b|\Lambda_b\rangle &= \overline{u}_F\bigg[(m_{\Lambda_b}-m_F)\frac{q^\mu}{q^2}\, f_0 \\
&\quad + \frac{m_{\Lambda_b}+m_F}{s_+}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_F^2)\frac{q^\mu}{q^2}\right) f_+ \\
&\quad + \left(\gamma^\mu - \frac{2m_F}{s_+}p^\mu - \frac{2m_{\Lambda_b}}{s_+}p'^\mu\right) f_\perp\bigg] u_{\Lambda_b},
\end{aligned}
$$

$$
\begin{aligned}
\langle F|\overline{q}\gamma^\mu\gamma_5 b|\Lambda_b\rangle &= -\overline{u}_F\,\gamma_5\bigg[(m_{\Lambda_b}+m_F)\frac{q^\mu}{q^2}\, g_0 \\
&\quad + \frac{m_{\Lambda_b}-m_F}{s_-}\left(p^\mu + p'^\mu - (m_{\Lambda_b}^2 - m_F^2)\frac{q^\mu}{q^2}\right) g_+ \\
&\quad + \left(\gamma^\mu + \frac{2m_F}{s_-}p^\mu - \frac{2m_{\Lambda_b}}{s_-}p'^\mu\right) g_\perp\bigg] u_{\Lambda_b}.
\end{aligned}
$$

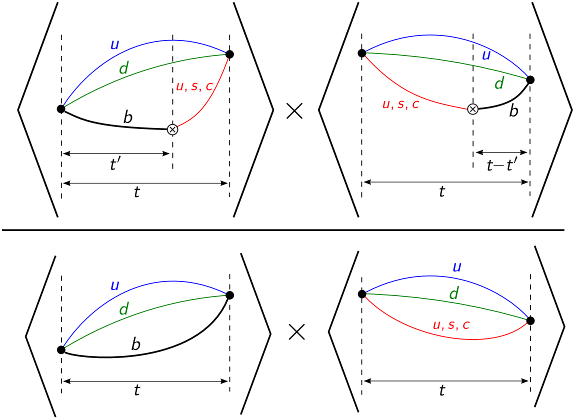
$$F = p, \Lambda_c, \quad \bar{q} = \bar{u}, \bar{c}, \quad s_\pm = (m_{\Lambda_b} \pm m_F)^2 - q^2$$

[T. Feldmann and M. Yip, PRD **85**, 014035 (2012)]

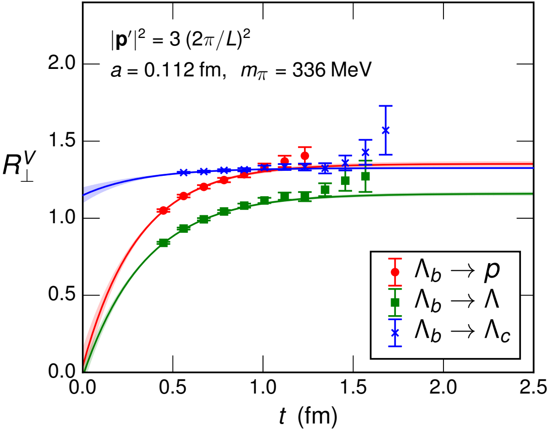
$\Lambda_b \to p\,\ell^-\,\bar{\nu}_\ell$ and $\Lambda_b \to \Lambda_c\,\ell^-\,\bar{\nu}_\ell$ form factors from lattice QCD with relativistic heavy quarks

[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

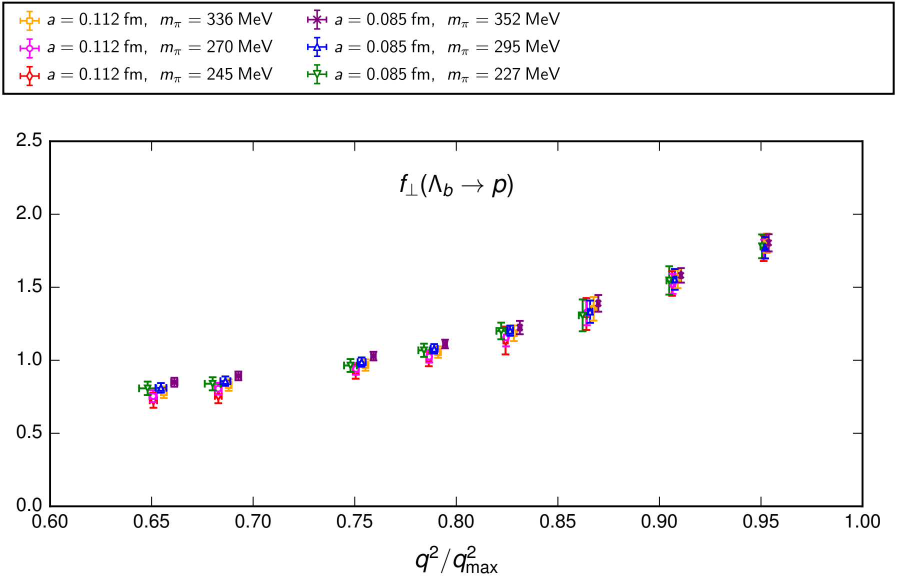
- Gauge field configurations generated by the RBC and UKQCD collaborations
  [Y. Aoki *et al.*, PRD **83**, 074508 (2011)]
- u, d, s quarks: domain-wall action
  [D. Kaplan, PLB **288**, 342 (1992); V. Furman and Y. Shamir, NPB **439**, 54 (1995)]
- c, b quarks: "relativistic heavy-quark action"
  [A. El-Khadra, A. Kronfeld, P. Mackenzie, PRD **55**, 3933 (1997); Y. Aoki *et al.*, PRD **86**, 116003]
- "Mostly nonperturbative" renormalization
  [A. El-Khadra *et al.*, PRD **64**, 014502 (2001)]
- $a \approx 0.11\,\text{fm},\ 0.085\,\text{fm}$
- $230\,\text{MeV} \leq m_\pi \leq 350\,\text{MeV}$
- Three-point functions with 12 source-sink separations



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



$|\mathbf{p}'|^2 = 3\ (2\pi/L)^2$
$a = 0.112$ fm, $m_\pi = 336$ MeV
$R_\perp^V$
t (fm)
0.0
0.5
1.0
1.5
2.0
2.5
$\Lambda_b \to p$
$\Lambda_b \to \Lambda$
$\Lambda_b \to \Lambda_c$



a = 0.112 fm, mπ = 336 MeV
a = 0.112 fm, mπ = 270 MeV
a = 0.112 fm, mπ = 245 MeV
a = 0.085 fm, mπ = 352 MeV
a = 0.085 fm, mπ = 295 MeV
a = 0.085 fm, mπ = 227 MeV
f⊥(Λb → p)
2.5
2.0
1.5
1.0
0.5
0.0
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
q²/q²max

Combined chiral/continuum/kinematic extrapolation using modified z-expansion

[C. Bourrely, I. Caprini, L. Lellouch, PRD **79**, 013008 (2009)]

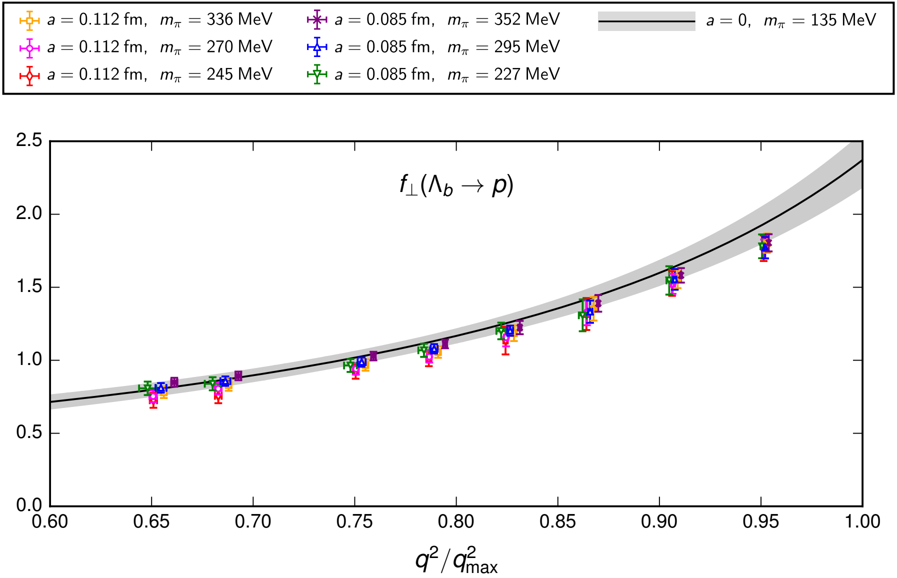
$$z^f(q^2) = \frac{\sqrt{t_+^f - q^2} - \sqrt{t_+^f - t_0}}{\sqrt{t_+^f - q^2} + \sqrt{t_+^f - t_0}},$$

"Nominal fit"

$$f(q^2) = \frac{1}{1 - q^2/(m_{\text{pole}}^f)^2}\left[a_0^f\left(1 + c_0^f\,\frac{m_\pi^2 - m_{\pi,\text{phys}}^2}{\Lambda_\chi^2}\right) + a_1^f\, z^f(q^2)\right] \times\left[1 + b^f\,\frac{|\mathbf{p}'|^2}{(\pi/a)^2} + d^f\,\frac{\Lambda_{\text{QCD}}^2}{(\pi/a)^2}\right],$$

"Nominal fit" in physical limit $a = 0$, $m_\pi = m_{\pi,\text{phys}}$:

$$f(q^2) = \frac{1}{1 - q^2/(m^f_{\text{pole}})^2}\left[a^f_0 + a^f_1\, z^f(q^2)\right]$$



Gray band = statistical uncertainty.

"Higher-order fit":

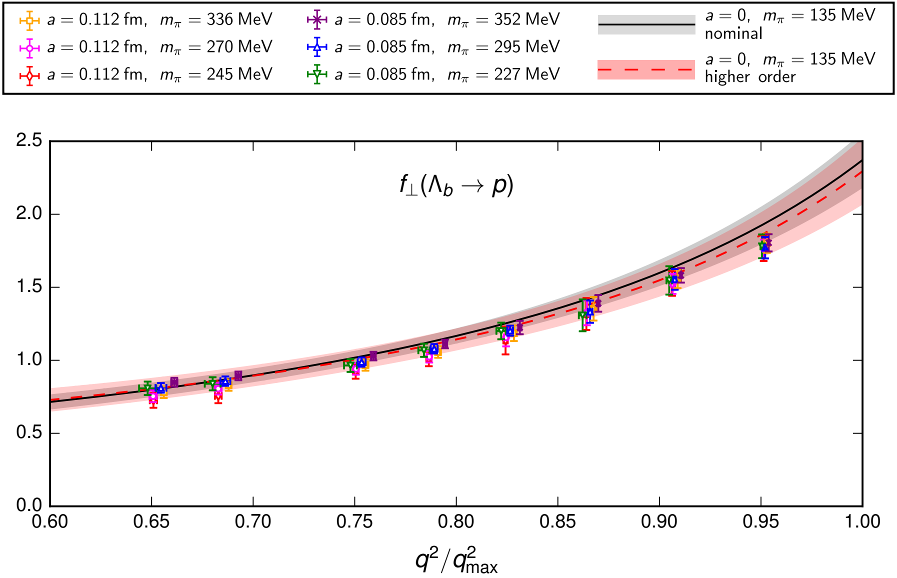
$$f_{HO}(q^2) = \frac{1}{1 - q^2/(m^f_{\rm pole})^2} \left[a_0^f \left(1 + c_0^f \frac{m_\pi^2 - m_{\pi,{\rm phys}}^2}{\Lambda_\chi^2} + \tilde{c}_0^f \frac{m_\pi^3 - m_{\pi,{\rm phys}}^3}{\Lambda_\chi^3} \right) \right.$$
$$\left. + a_1^f \left(1 + c_1^f \frac{m_\pi^2 - m_{\pi,{\rm phys}}^2}{\Lambda_\chi^2} \right) z^f(q^2) + a_2^f \, [z^f(q^2)]^2 \right]$$
$$\times \left[1 + b^f \, \frac{|\mathbf{p}'|^2}{(\pi/a)^2} + d^f \, \frac{\Lambda_{\rm QCD}^2}{(\pi/a)^2} + \tilde{b}^f \, \frac{|\mathbf{p}'|^3}{(\pi/a)^3} + \tilde{d}^f \, \frac{\Lambda_{\rm QCD}^3}{(\pi/a)^3} \right.$$
$$\left. + j^f \frac{|\mathbf{p}'|^2 \Lambda_{\rm QCD}}{(\pi/a)^3} + k^f \frac{|\mathbf{p}'| \Lambda_{\rm QCD}^2}{(\pi/a)^3} \right]$$

Higher-order fit parameters constrained with Gaussian priors to be natural-sized.

Modified data correlation matrix to include other sources of uncertainty.

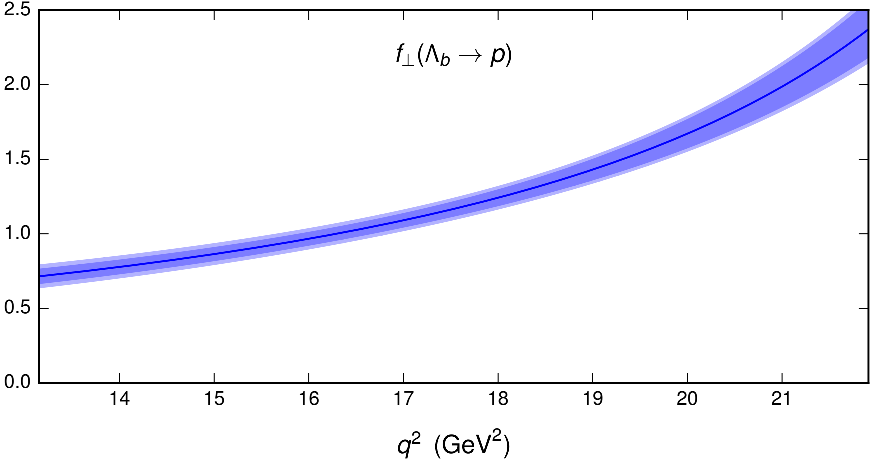
"Higher-order fit" in physical limit $a = 0$, $m_\pi = m_{\pi,\text{phys}}$:

$$f_{\text{HO}}(q^2) = \frac{1}{1 - q^2/(m^f_{\text{pole}})^2} \left[a^f_0 + a^f_1\, z^f(q^2) + a^f_2\, [z^f(q^2)]^2 \right]$$

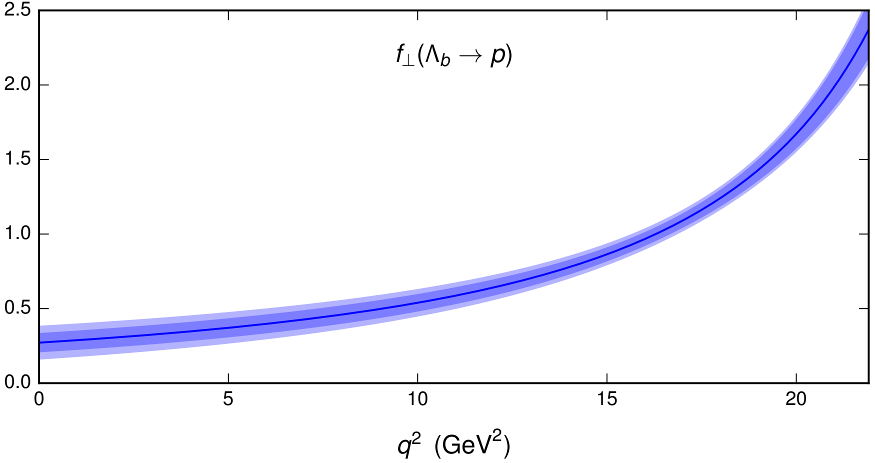

a = 0.112 fm, mπ = 336 MeV
a = 0.112 fm, mπ = 270 MeV
a = 0.112 fm, mπ = 245 MeV
a = 0.085 fm, mπ = 352 MeV
a = 0.085 fm, mπ = 295 MeV
a = 0.085 fm, mπ = 227 MeV
a = 0, mπ = 135 MeV nominal
a = 0, mπ = 135 MeV higher order
f⊥(Λb → p)
2.5
2.0
1.5
1.0
0.5
0.0
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
q²/q²max

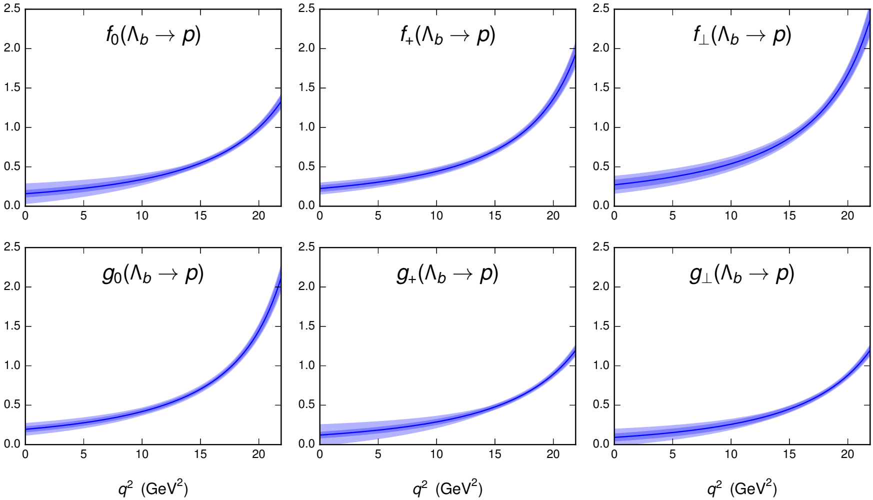
Compute systematic uncertainty of any observable O using

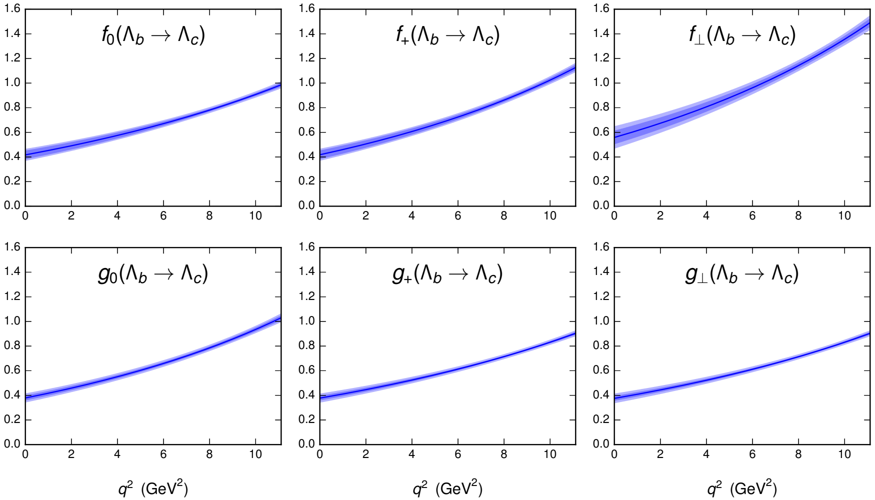
$$\sigma_{O,\text{syst.}} = \max\left(|O_{\text{HO}} - O|,\ \sqrt{|\sigma^2_{\text{HO}} - \sigma^2_O|} \right)$$

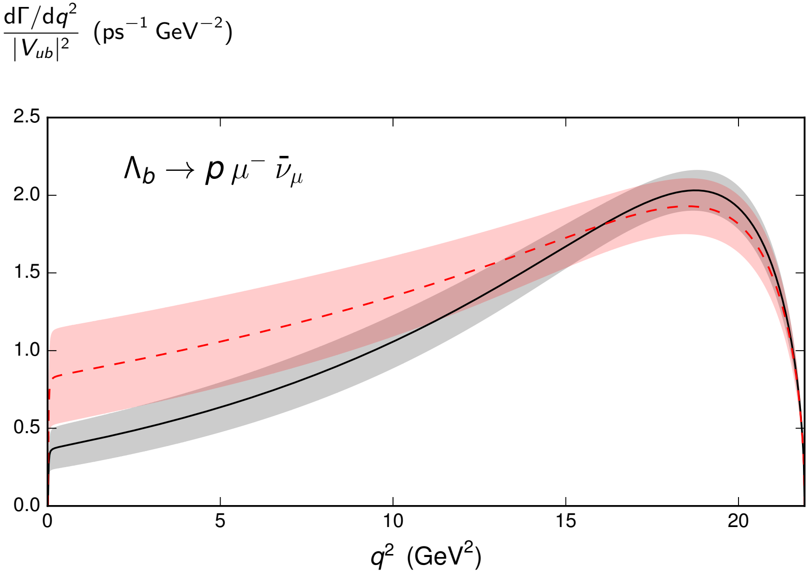


$f_\perp(\Lambda_b \to p)$
2.5
2.0
1.5
1.0
0.5
0.0
14
15
16
17
18
19
20
21
q^2 (GeV^2)

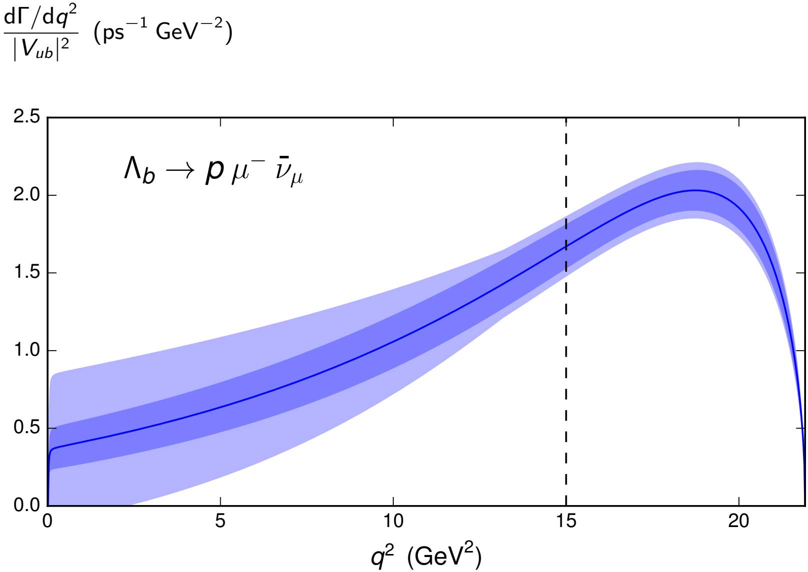

$f_\perp(\Lambda_b \to p)$
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
q^2 (GeV^2)


$f_0(\Lambda_b \to p)$
$f_+(\Lambda_b \to p)$
$f_\perp(\Lambda_b \to p)$
$g_0(\Lambda_b \to p)$
$g_+(\Lambda_b \to p)$
$g_\perp(\Lambda_b \to p)$
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
q^2 (GeV^2)


$f_0(\Lambda_b \to \Lambda_c)$
$f_+(\Lambda_b \to \Lambda_c)$
$f_\perp(\Lambda_b \to \Lambda_c)$
$g_0(\Lambda_b \to \Lambda_c)$
$g_+(\Lambda_b \to \Lambda_c)$
$g_\perp(\Lambda_b \to \Lambda_c)$
q^2 (GeV^2)
q^2 (GeV^2)
q^2 (GeV^2)



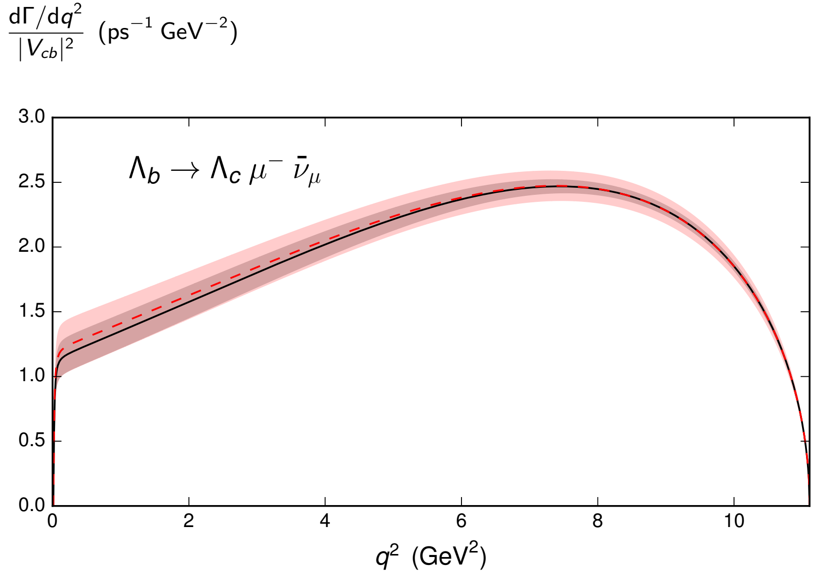
$\frac{d\Gamma/dq^2}{|V_{ub}|^2}$ (ps^{-1} GeV^{-2})
$\Lambda_b \to p\,\mu^-\,\bar{\nu}_\mu$
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
q^2 (GeV^2)



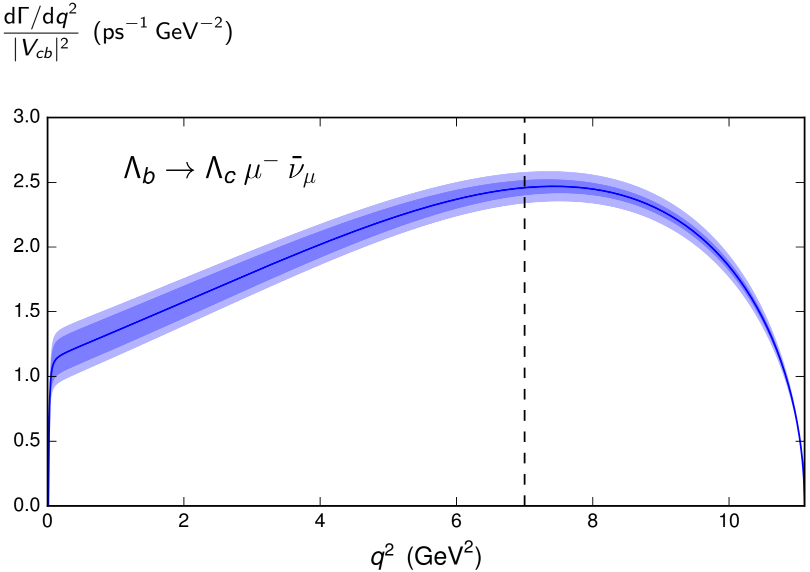
$\frac{d\Gamma/dq^2}{|V_{ub}|^2}$ (ps^{-1} GeV^{-2})
$\Lambda_b \to p\,\mu^-\,\bar{\nu}_\mu$
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
q^2 (GeV^2)

$$\frac{1}{|V_{ub}|^2}\int_{15\ \mathrm{GeV}^2}^{q^2_{\mathrm{max}}} \frac{\mathrm{d}\Gamma(\Lambda_b \to p\,\mu^-\bar{\nu}_\mu)}{\mathrm{d}q^2}\mathrm{d}q^2$$

$$= (12.31 \pm 0.76_{\mathrm{stat}} \pm 0.77_{\mathrm{syst}})\ \mathrm{ps}^{-1}$$



$\frac{d\Gamma/dq^2}{|V_{cb}|^2}$ (ps^{-1} GeV^{-2})
$\Lambda_b \to \Lambda_c\, \mu^-\, \bar{\nu}_\mu$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
q^2 (GeV^2)



$\frac{d\Gamma/dq^2}{|V_{cb}|^2}$ (ps^{-1} GeV^{-2})
$\Lambda_b \to \Lambda_c\, \mu^-\, \bar{\nu}_\mu$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
q^2 (GeV^2)

$$\frac{1}{|V_{cb}|^2} \int_{7\ \text{GeV}^2}^{q^2_{\text{max}}} \frac{\text{d}\Gamma(\Lambda_b \to \Lambda_c\ \mu^- \bar{\nu}_\mu)}{\text{d}q^2} \text{d}q^2$$

$$= (8.37 \pm 0.16_{\text{stat}} \pm 0.34_{\text{syst}})\ \text{ps}^{-1}$$

$$\frac{|V_{cb}|^2}{|V_{ub}|^2} \frac{\int_{15\ \mathrm{GeV}^2}^{q^2_{\max}} \frac{\mathrm{d}\Gamma(\Lambda_b \to p\,\mu^- \bar{\nu}_\mu)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{7\ \mathrm{GeV}^2}^{q^2_{\max}} \frac{\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c\,\mu^- \bar{\nu}_\mu)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

$$= 1.471 \pm 0.095_{\,\mathrm{stat.}} \pm 0.109_{\,\mathrm{syst.}}$$

Systematic uncertainties in the ratio of decay rates:

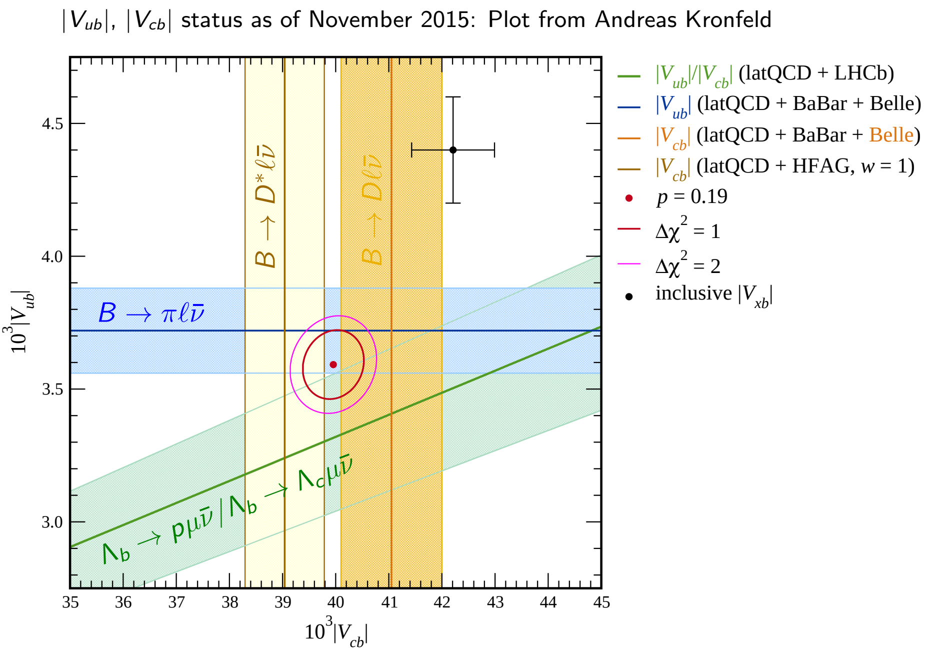
Finite volume	4.9 %
Continuum extrapolation	2.8 %
Chiral extrapolation	2.6 %
RHQ parameters	2.3 %
Matching & improvement	2.1 %
Isospin breaking/QED	2.0 %
Scale setting	1.8 %
z expansion	1.3 %
Combined	**7.3 %**

Note: the combined uncertainty takes into account the correlations between the individual uncertainties

Combine with LHCb measurement:

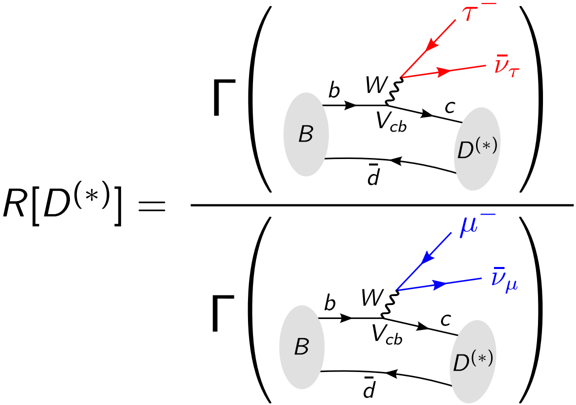
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004_{\,\mathrm{expt}} \pm 0.004_{\,\mathrm{lat}}$$

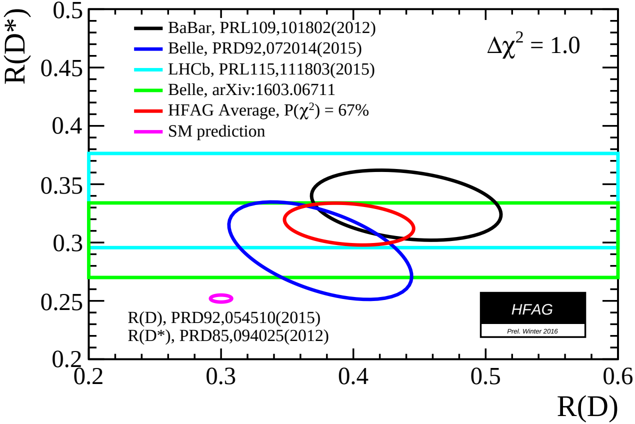
[LHCb Collaboration, Nature Physics **11**, 743-747 (2015)]



$|V_{ub}|$, $|V_{cb}|$ status as of November 2015: Plot from Andreas Kronfeld
$|V_{ub}|/|V_{cb}|$ (latQCD + LHCb)
$|V_{ub}|$ (latQCD + BaBar + Belle)
$|V_{cb}|$ (latQCD + BaBar + Belle)
$|V_{cb}|$ (latQCD + HFAG, w = 1)
p = 0.19
$\Delta\chi^2 = 1$
$\Delta\chi^2 = 2$
inclusive $|V_{xb}|$
$B \to D^*\ell\bar{\nu}$
$B \to D\ell\bar{\nu}$
$B \to \pi\ell\bar{\nu}$
$\Lambda_b \to p\mu\bar{\nu} \,|\, \Lambda_b \to \Lambda_c\mu\bar{\nu}$
$10^3|V_{ub}|$
$10^3|V_{cb}|$
4.5
4.0
3.5
3.0
35
36
37
38
39
40
41
42
43
44
45

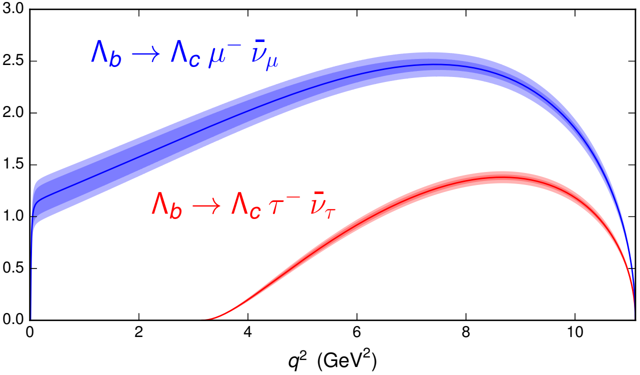
1. $|V_{ub}|$ and $|V_{cb}|$
2. $b \to c\tau^- \bar{\nu}$
3. $b \to s\mu^+\mu^-$


R[D^(*)] =
Γ
τ⁻
ν̄_τ
W
b
c
V_cb
B
D^(*)
d̄
Γ
μ⁻
ν̄_μ
W
b
c
V_cb
B
D^(*)
d̄



[http://www.slac.stanford.edu/xorg/hfag/]

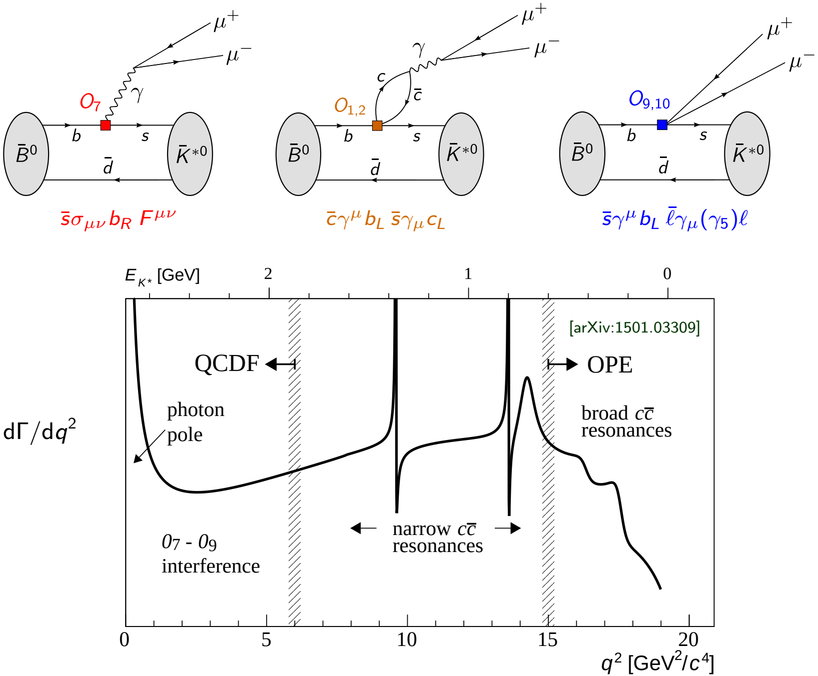
$$\frac{d\Gamma/dq^2}{|V_{cb}|^2} \ (\mathrm{ps}^{-1}\ \mathrm{GeV}^{-2})$$



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

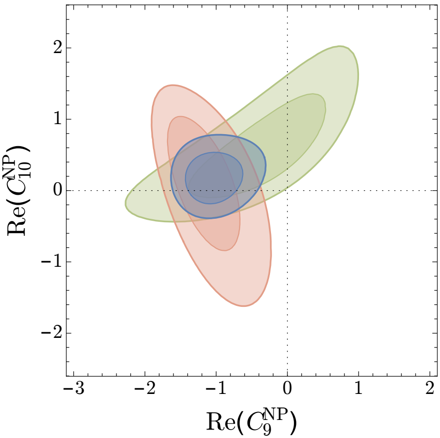
[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]

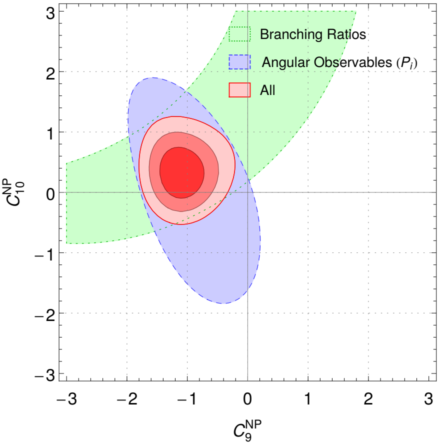
1. $|V_{ub}|$ and $|V_{cb}|$
2. $b \to c\tau^- \bar{\nu}$
3. $b \to s\mu^+\mu^-$



μ^+
μ^-
γ
O_7
b
s
$\bar{d}$
$\bar{B}^0$
$\bar{K}^{*0}$
$\bar{s}\sigma_{\mu\nu} b_R F^{\mu\nu}$
c
$\bar{c}$
$O_{1,2}$
$\bar{c}\gamma^\mu b_L\, \bar{s}\gamma_\mu c_L$
$O_{9,10}$
$\bar{s}\gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$
E_{K^*} [GeV]
2
1
0
[arXiv:1501.03309]
QCDF
OPE
photon
pole
$d\Gamma/dq^2$
broad $c\bar{c}$
resonances
narrow $c\bar{c}$
resonances
O_7 - O_9
interference
0
5
10
15
20
q^2 [GeV^2/c^4]

Fits of $C_i^{\rm NP} = C_i - C_i^{\rm SM}$
to experimental data for mesonic $b \to s\mu^+\mu^-$ decays

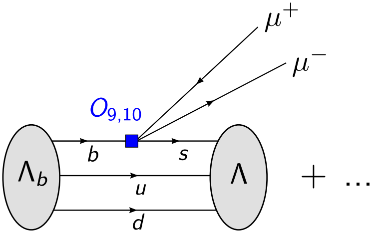




[W. Altmannshofer, D. Straub,
EPJC **75**, 382 (2015) and arXiv:1503.06199]

[S. Descotes-Genon, L. Hofer, J. Matias, J. Virto,
JHEP **1606**, 092 (2016)]

Complementary information can be obtained from $\Lambda_b \to \Lambda\mu^+\mu^-$

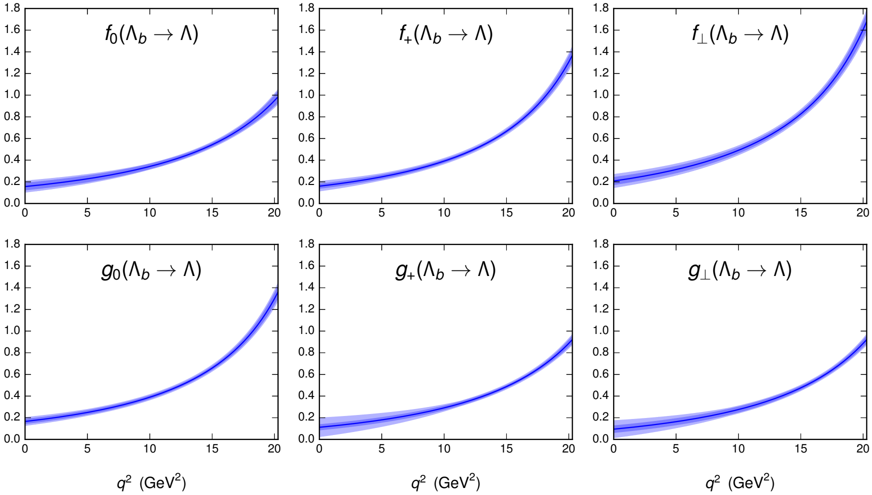


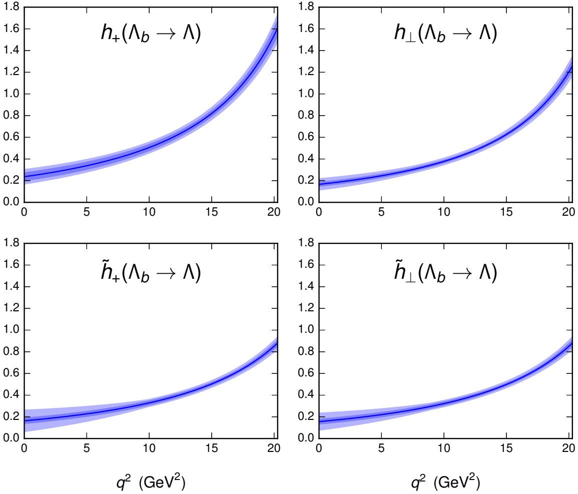
Combines the best aspects of $B \to K^*\mu^+\mu^-$ and $B \to K\mu^+\mu^-$:

Λ has nonzero spin and is stable under strong interactions.

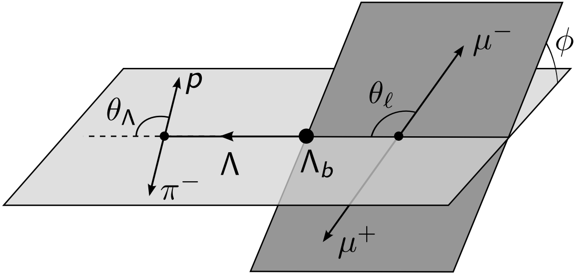
$\Lambda_b \to \Lambda\,\ell^+\ell^-$ form factors, differential branching fraction, and angular observables from lattice QCD with relativistic b quarks

[W. Detmold, C. Lehner, S. Meinel, PRD **92**, 034503 (2015)]





$h_+(\Lambda_b \to \Lambda)$
$h_\perp(\Lambda_b \to \Lambda)$
$\tilde{h}_+(\Lambda_b \to \Lambda)$
$\tilde{h}_\perp(\Lambda_b \to \Lambda)$
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
0 5 10 15 20
q^2 (GeV^2)
q^2 (GeV^2)

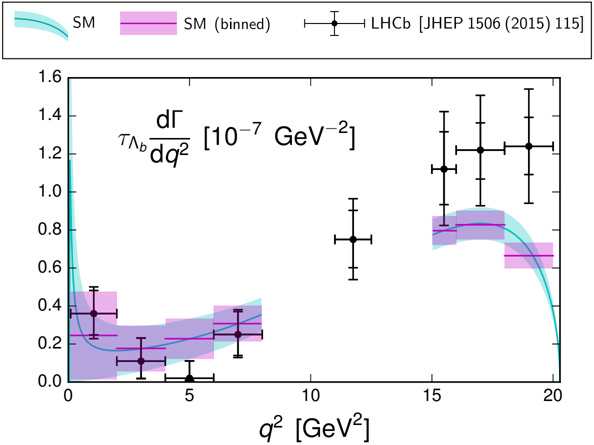


For unpolarized Λ_b:

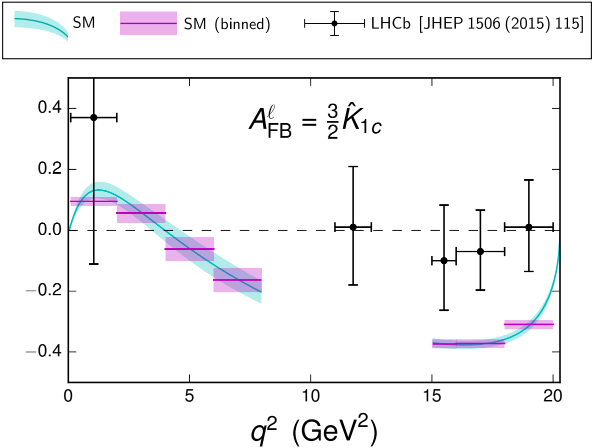
$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_\Lambda\, d\phi} = \frac{3}{8\pi}\Big[\left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right)$$
$$+ \left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\cos\theta_\Lambda$$
$$+ \left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\sin\theta_\Lambda\sin\phi$$
$$+ \left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)\sin\theta_\Lambda\cos\phi\Big]$$

$$\Rightarrow \quad \frac{d\Gamma}{dq^2} = 2K_{1ss} + K_{1cc}$$

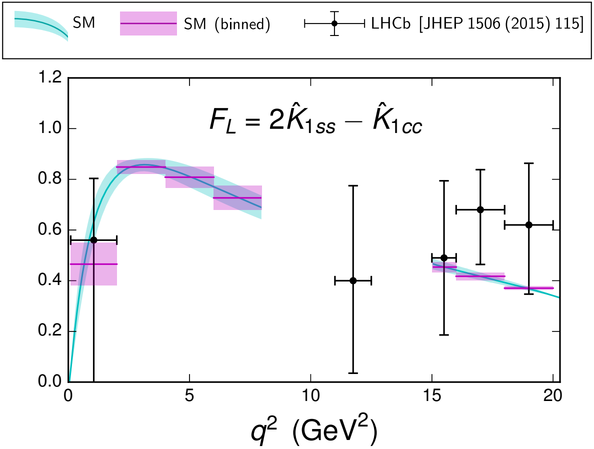
[T. Gutsche *et al.*, PRD **87**, 074031 (2013); P. Böer, T. Feldmann, D. van Dyk, JHEP **1501**, 155 (2015)]

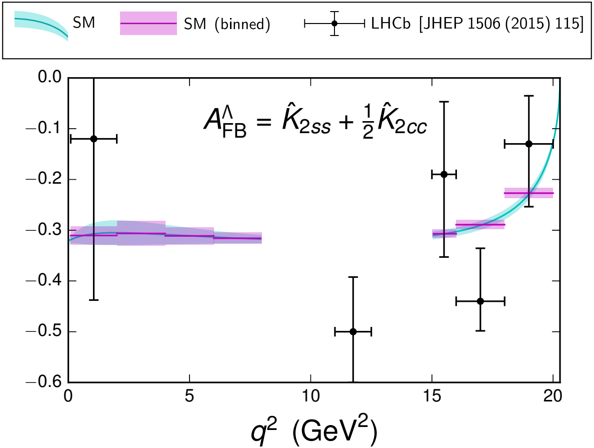


Hint of an *excess* at high q^2 – contrary to mesonic $b \to s\mu^+\mu^-$ decays.



3σ discrepancy at high q^2.


SM
SM (binned)
LHCb [JHEP 1506 (2015) 115]
$F_L = 2\hat{K}_{1ss} - \hat{K}_{1cc}$
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
q^2 (GeV^2)

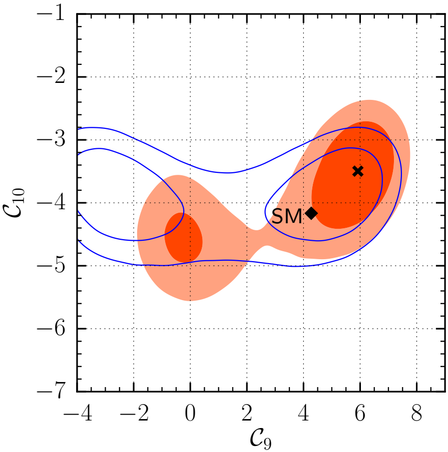


This is nonzero because $\Lambda \to p^+\pi^-$ is a parity-violating weak decay.

Using $\Lambda_b \to \Lambda\mu^+\mu^-$ data within a Bayesian analysis of $|\Delta B| = |\Delta S| = 1$ decays

[S. Meinel and D. van Dyk, PRD **94**, 013007 (2016)]

Constraint	Scenario SM(ν-only)	Scenario (9, 10)	Scenario $(9, 9', 10, 10')$
$\Lambda_b \to \Lambda\mu^+\mu^-$	Pull value $[\sigma]$		
$\langle\mathcal{B}\rangle_{15,20}$	$+0.86$	-0.17	-0.08
$\langle F_L\rangle_{15,20}$	$+1.41$	$+1.41$	$+1.41$
$\langle A_{\rm FB}^{\ell}\rangle_{15,20}$	$+3.13$	$+2.60$	$+0.72$
$\langle A_{\rm FB}^{\Lambda}\rangle_{15,20}$	-0.26	-0.24	-1.08
$\bar{B}_s \to \mu^+\mu^-$	Pull value $[\sigma]$		
$\int \mathcal{B}(\tau)\,{\rm d}\tau$	-0.72	$+0.75$	$+0.37$
$\bar{B} \to X_s\ell^+\ell^-$	Pull value $[\sigma]$		
$\langle\mathcal{B}\rangle_{1,6}$ (BaBar)	$+0.47$	-0.26	-0.10
$\langle\mathcal{B}\rangle_{1,6}$ (Belle)	$+0.17$	-0.35	-0.24
	χ^2 and p-value at best-fit point		
	$\chi^2 = 13.40$, $p = 0.06$	$\chi^2 = 9.60$, $p = 0.09$	$\chi^2 = 3.87$, $p = 0.28$



blue = without $\Lambda_b \to \Lambda\mu^+\mu^-$, red = with $\Lambda_b \to \Lambda\mu^+\mu^-$

✖ = best-fit point with $\Lambda_b \to \Lambda\mu^+\mu^-$:

$$C_9 - C_9^{\rm SM} = +1.6^{+0.7}_{-0.9}$$
$$C_{10} - C_{10}^{\rm SM} = +0.7^{+0.5}_{-0.8}$$

Fits of $\Lambda_b \to \Lambda(\to p^+\pi^-)\mu^+\mu^-$ data only

Fit scenarios:

- SM(ν-only):

$$p = 0.013$$

- 9:

$$p = 0.015$$

- SM(ν-only, 100 times wider priors for subleading OPE corrections):

$$p = 0.37$$

Overview of exclusive $b \to s\ell^+\ell^-$ decays

	Probes all Dirac structures	Final hadron QCD-stable	Charged hadrons from b-decay vertex	LQCD Refs.
$B^+ \to K^+\ell^+\ell^-$	×	✓	✓	[1, 2, 3, 4]
$B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$	✓	×	✓	[5, 6, 7]
$B_s \to \phi(\to K^+K^-)\ell^+\ell^-$	✓	×	✓	[5, 6, 7]
$\Lambda_b^0 \to \Lambda^0(\to p^+\pi^-)\,\ell^+\ell^-$	✓	✓	×	[8, 9, 10]
$\Lambda_b^0 \to \Lambda^{*0}(\to p^+K^-)\,\ell^+\ell^-$	✓	×	✓	[11]

[1] C. Bouchard *et al.*, PRD **88**, 054509 (2013)

[2] C. Bouchard *et al.*, PRL **111**, 162002 (2013)

[3] J. A. Bailey *et al.*, PRD **93**, 025026 (2016)

[4] D. Du *et al.*, PRD **93**, 034005 (2016)

[5] R. R. Horgan, Z. Liu, S. Meinel, M. Wingate, PRD **89**, 094501 (2014)

[6] R. R. Horgan, Z. Liu, S. Meinel, M. Wingate, PRL **112**, 212003 (2014)

[7] J. Flynn, A. Jüttner, T. Kawanai, E. Lizarazo, O. Witzel, PoS **LATTICE2015**, 345

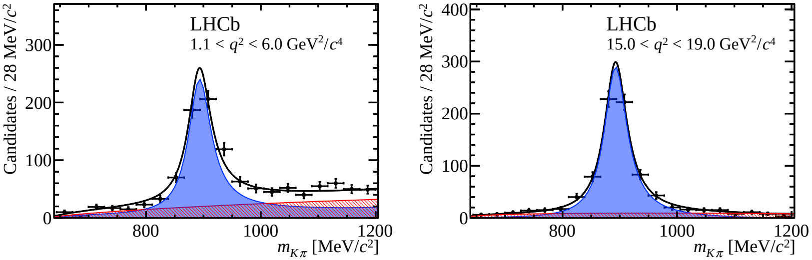
[8] W. Detmold, C.-J. D. Lin, S. Meinel, M. Wingate, PRD **87**, 074502 (2013)

[9] W. Detmold, S. Meinel, PRD **93**, 074501 (2016)

[10] S. Meinel, D. van Dyk, PRD **94**, 013007 (2016)

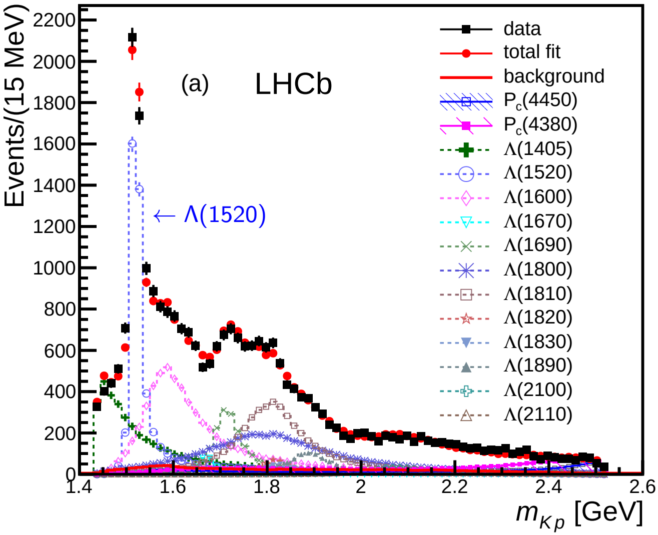
[11] S. Meinel, G. Rendon, arXiv:1608.08110

The $K^*(892)$ resonance in $B^0 \to K^+\pi^-\mu^+\mu^-$



[LHCb Collaboration, arXiv:1606.04731]

Λ^* resonances in $\Lambda_b \to K^- p^+ \mu^+ \mu^-$ at $q^2 = m^2_{J/\psi}$



[LHCb Collaboration, PRL **115**, 072001 (2015)]

$\Lambda(1520)\ 3/2^-$

$I(J^P) = 0(\frac{3}{2}^-)$ Status: ∗∗∗∗

$\Lambda(1520)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1519.5 ±1.0 OUR ESTIMATE				

$\Lambda(1520)$ WIDTH

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
15.6 ±1.0 OUR ESTIMATE				

$\Lambda(1520)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\overline{K}$	(45 ±1) %
Γ_2	$\Sigma\pi$	(42 ±1) %
Γ_3	$\Lambda\pi\pi$	(10 ±1) %
Γ_4	$\Sigma(1385)\pi$	
Γ_5	$\Sigma(1385)\pi(\rightarrow \Lambda\pi\pi)$	
Γ_6	$\Lambda(\pi\pi)_{S\text{-wave}}$	
Γ_7	$\Sigma\pi\pi$	(0.9 ±0.1) %
Γ_8	$\Lambda\gamma$	(0.85±0.15) %
Γ_9	$\Sigma^0\gamma$	

Naive treatment as if it were a stable particle in the following.

Helicity form factors for $\Lambda_b \to \Lambda(1520)$

Vector current:

$$\langle \Lambda^*(p', s') |\, \bar{s}\gamma^\mu b \,| \Lambda_b(p, s) \rangle$$

$$= \bar{u}_\lambda(p', s') \Bigg[f_0 \, \frac{(m_{\Lambda_b} - m_{\Lambda^*})\, p^\lambda q^\mu}{m_{\Lambda_b}\, q^2} + f_+ \, \frac{(m_{\Lambda_b} + m_{\Lambda^*})\, p^\lambda (q^2(p^\mu + p'^\mu) - (m_{\Lambda_b}^2 - m_{\Lambda^*}^2) q^\mu)}{m_{\Lambda_b}\, q^2\, s_+} + f_\perp \left(\frac{p^\lambda \gamma^\mu}{m_{\Lambda_b}} - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda^*} p^\mu)}{m_{\Lambda_b}\, s_+} \right) + f_{\perp'} \left(\frac{p^\lambda \gamma^\mu}{m_{\Lambda_b}} - \frac{2\, p^\lambda p'^\mu}{m_{\Lambda_b} m_{\Lambda^*}} + \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda^*} p^\mu)}{m_{\Lambda_b}\, s_+} + \frac{s_-\, g^{\lambda\mu}}{m_{\Lambda_b} m_{\Lambda^*}} \right) \Bigg] u(p, s)$$

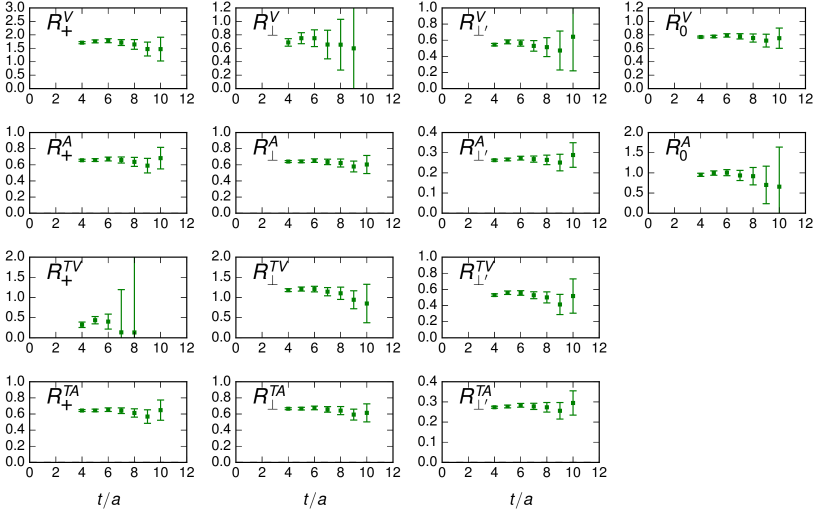
where $s_\pm = (m_{\Lambda_b} \pm m_{\Lambda^*})^2 - q^2$

Similar for axial-vector current (g_0, g_+, $g_\perp$, $g_{\perp'}$)

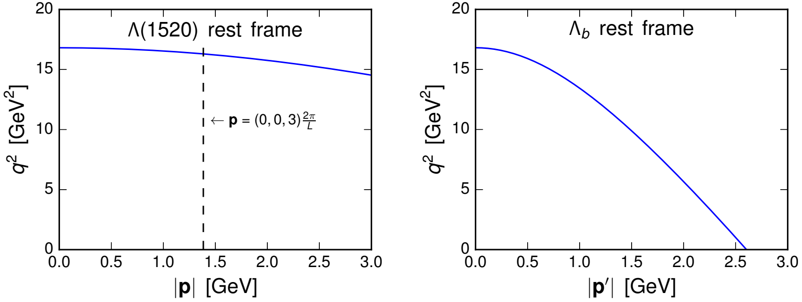
and tensor currrent (h_+, $h_\perp$, $h_{\perp'}$, $\widetilde{h}_+$, $\widetilde{h}_\perp$, $\widetilde{h}_{\perp'}$)

[S. Meinel, G. Rendon, arXiv:1608.08110]

Lattice calculation in $\Lambda(1520)$ rest frame.
Preliminary results at $\mathbf{p}_{\Lambda_b} = (0,0,3)\frac{2\pi}{L}$ (≈ 1.4 GeV):



[S. Meinel, G. Rendon, arXiv:1608.08110]



Plan to use moving-NRQCD action for b quark to reach higher $\mathbf{p}_{\Lambda_b}$.

[R. R. Horgan *et al.*, PRD **80**, 074505 (2009)]

Outlook

$b \to u\ell^- \bar{\nu}$ and $b \to c\ell^- \bar{\nu}$:

- $\Lambda_b \to p$ and $\Lambda_b \to \Lambda_c$ form factors directly at physical pion mass ($48^3 \times 96$ RBC/UKQCD ensemble)

- $\Lambda_b \to \Lambda_c(2595)$ and $\Lambda_b \to \Lambda_c(2625)$ form factors

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

- $\Lambda_b \to \Lambda(1520)$ form factors

$c \to s\ell^+\nu$:

- $\Lambda_c \to \Lambda$ and $\Lambda_c \to \Lambda(1520)$ form factors

$c \to u\ell^+\ell^-$:

- $\Lambda_c \to p$ form factors