Flavor physics with charm and bottom baryons

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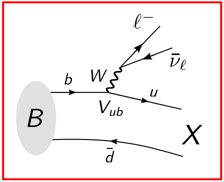
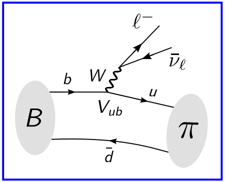
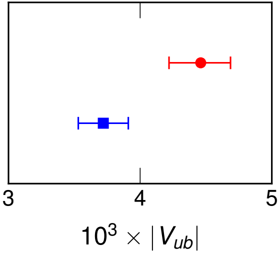
1. $b \to u\ell^-\bar{\nu}_\ell$ and $b \to c\ell^-\bar{\nu}_\ell$
2. $b \to c\tau^-\bar{\nu}$
3. $b \to s\ell^+\ell^-$
4. $c \to s\ell^-\bar{\nu}_\ell$
5. $c \to u\ell^+\ell^-$



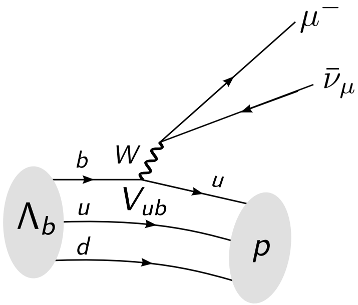


inclusive $B \to X_u \, \ell \, \bar{\nu}_\ell$

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



[Particle Data Group, 2016]



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

LHCb result:

[arXiv:1504.01568/Nature Physics 2015]

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

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

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.

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

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

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

[T. Feldmann and M. Yip, arXiv:1111.1844/PRD 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, arXiv:1503.01421/PRD 2015]

- Gauge field configurations generated by the RBC and UKQCD collaborations

  [Y. Aoki *et al.*, arXiv:1011.0892/PRD 2011]

- u, d, s quarks: domain-wall action

  [D. Kaplan, hep-lat/9206013/PLB 1992; V. Furman and Y. Shamir, hep-lat/9303005/NPB 1995]

- c, b quarks: "relativistic heavy-quark action"

  [A. El-Khadra, A. Kronfeld, P. Mackenzie, hep-lat/9604004/PRD 1997; Y. Aoki *et al.*, arXiv:1206.2554/PRD 2012]

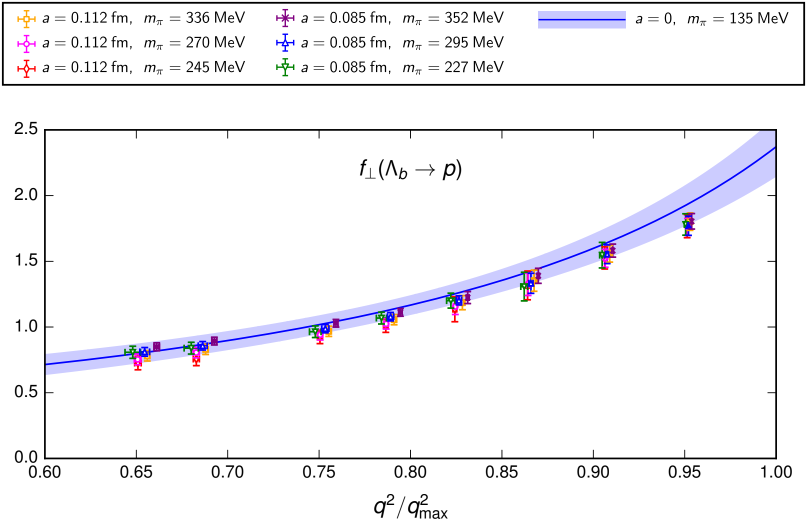
- "Mostly nonperturbative" renormalization

  [A. El-Khadra *et al.*, hep-ph/0101023/PRD 2001]

- $a \approx 0.11$ fm, 0.085 fm

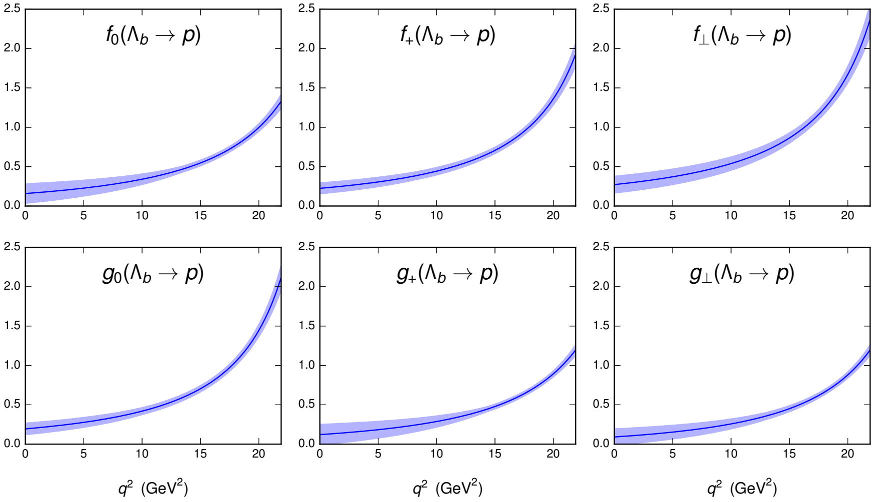
- $230\ \text{MeV} \leq m_\pi \leq 350\ \text{MeV}$

- Three-point functions with 12 source-sink separations

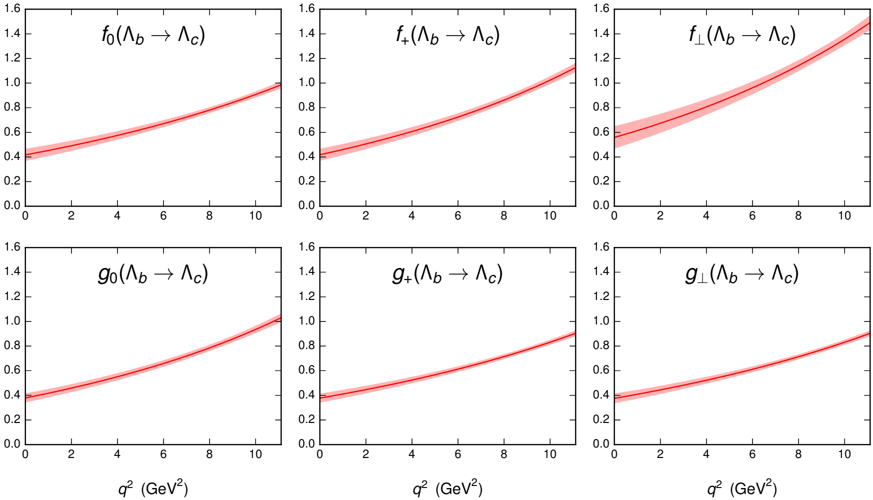


Combined chiral/continuum/kinematic extrapolation using modified z-expansion

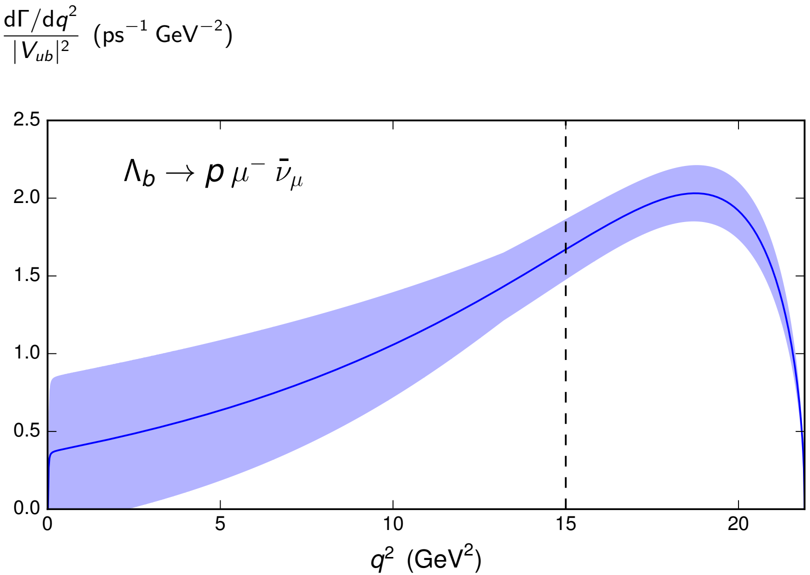
[C. Bourrely, I. Caprini, L. Lellouch, arXiv:0807.2722/PRD 2009]



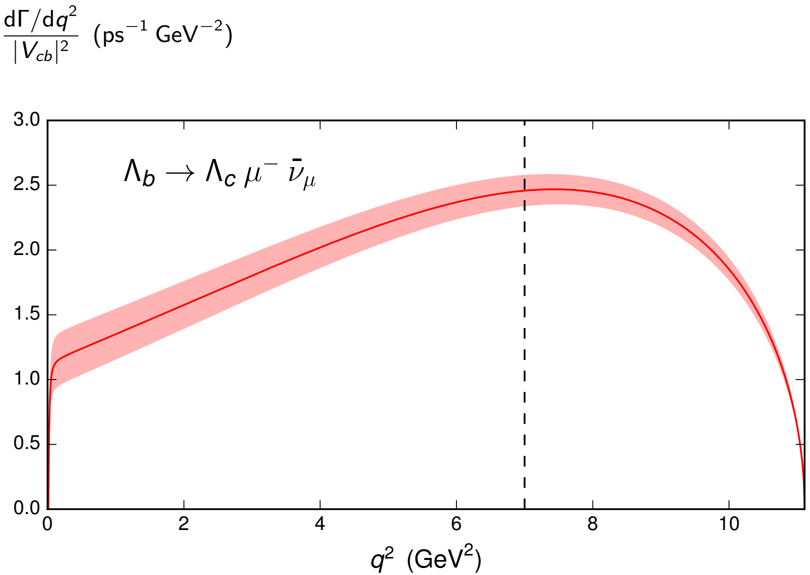
$f_0(\Lambda_b \to p)$
$f_+(\Lambda_b \to p)$
$f_\perp(\Lambda_b \to p)$
$g_0(\Lambda_b \to p)$
$g_+(\Lambda_b \to p)$
$g_\perp(\Lambda_b \to p)$
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
q^2 (GeV^2)



$f_0(\Lambda_b \to \Lambda_c)$
$f_+(\Lambda_b \to \Lambda_c)$
$f_\perp(\Lambda_b \to \Lambda_c)$
$g_0(\Lambda_b \to \Lambda_c)$
$g_+(\Lambda_b \to \Lambda_c)$
$g_\perp(\Lambda_b \to \Lambda_c)$
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)



dΓ/dq^2 / |V_cb|^2 (ps^-1 GeV^-2)
Λ_b → Λ_c μ^- ν̄_μ
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
q^2 (GeV^2)

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

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

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 %**

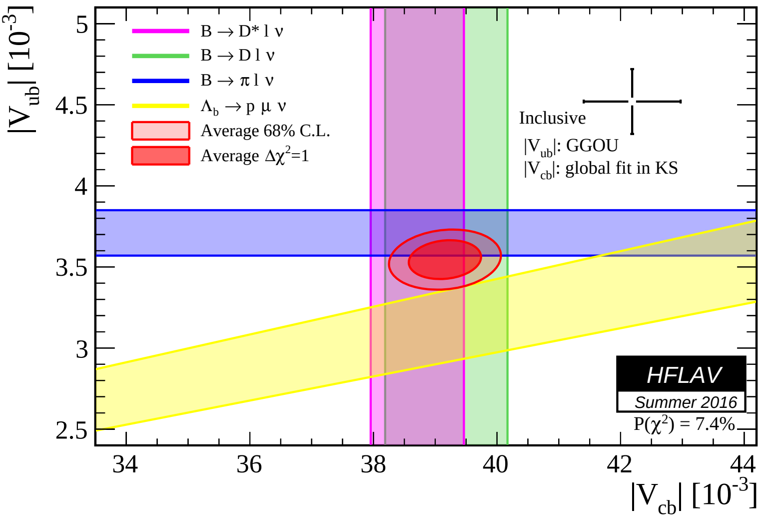
Note: the combined uncertainty takes into account the correlations between the individual uncertainties

Combine with LHCb measurement:

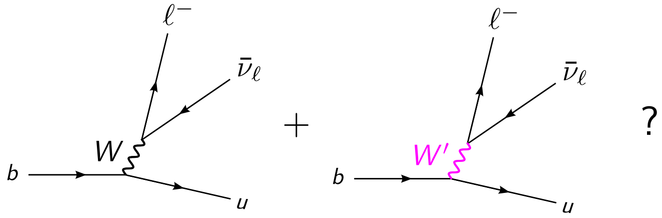
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004_{\,\mathrm{expt}} \pm 0.004_{\,\mathrm{lat}}$$

[LHCb Collaboration, arXiv:1504.01568/Nature Physics 2015]

$|V_{ub}|$, $|V_{cb}|$ status



Right-handed $b \to u$ currents beyond the Standard Model?



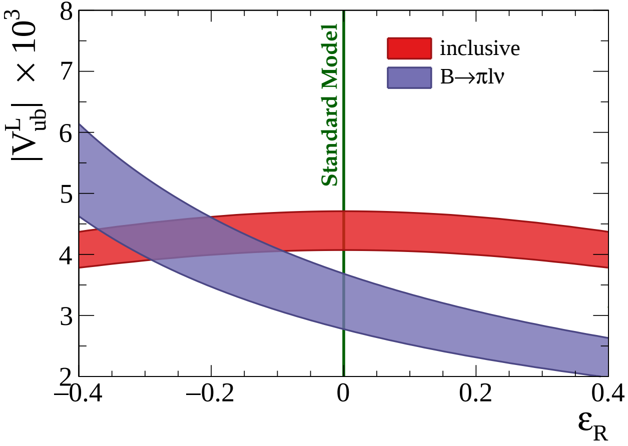
This could replace

$$V_{ub} \underbrace{\bar{u}_L \gamma^\mu b_L}_{V-A}$$

by

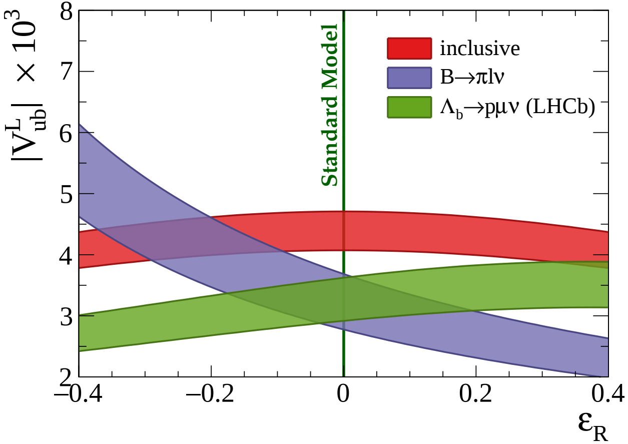
$$V_{ub}^L \left(\underbrace{\bar{u}_L \gamma^\mu b_L}_{V-A} + \epsilon_R \underbrace{\bar{u}_R \gamma^\mu b_R}_{V+A} \right)$$

Process	Vector current	Axial vector current
$B \to \pi\,\ell\,\bar{\nu}_\ell$	✓	×
$B \to X_u\,\ell\,\bar{\nu}_\ell$	✓	✓
$\Lambda_b \to p\,\ell\,\bar{\nu}_\ell$	✓	✓



(using 2014 PDG values)

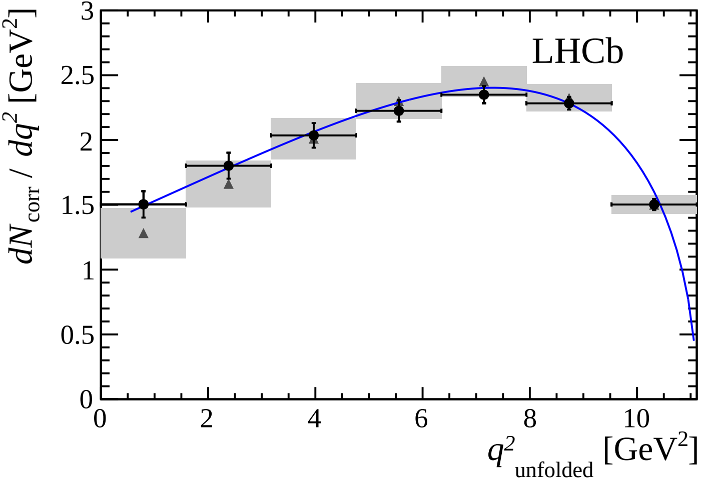
[LHCb Collaboration, arXiv:1504.01568/Nature Physics 2015]



(using 2014 PDG values; $\Lambda_b \to p\mu\bar{\nu}$ result normalized using $|V_{cb}|_{\text{excl.}}$)

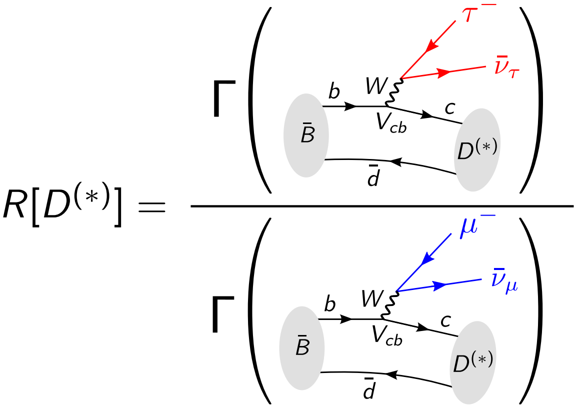
[LHCb Collaboration, arXiv:1504.01568/Nature Physics 2015]

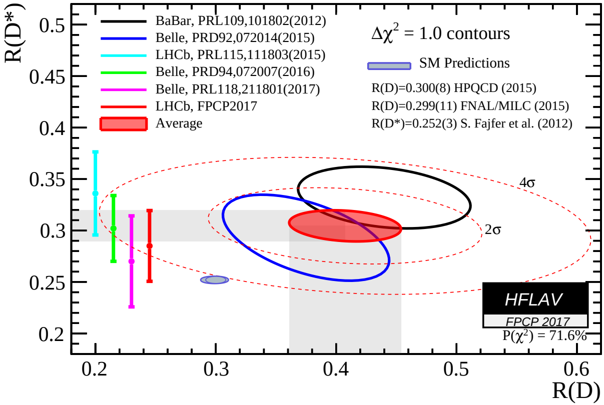
Measurement of the shape of the $\Lambda_b \to \Lambda_c \mu \bar{\nu}$ differential decay rate

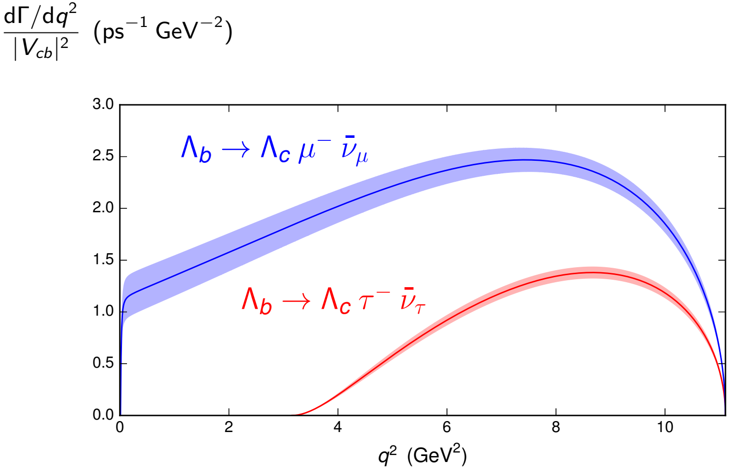


[LHCb Collaboration, arXiv:1709.01920; W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421/PRD 2015]

1. $b \to u\ell^-\bar{\nu}_\ell$ and $b \to c\ell^-\bar{\nu}_\ell$
2. $b \to c\tau^-\bar{\nu}$
3. $b \to s\ell^+\ell^-$
4. $c \to s\ell^-\bar{\nu}_\ell$
5. $c \to u\ell^+\ell^-$


$R[D^{(*)}] =$
Γ
τ^-
$\bar{\nu}_\tau$
b
W
c
V_{cb}
$\bar{B}$
$D^{(*)}$
$\bar{d}$
Γ
μ^-
$\bar{\nu}_\mu$
b
W
c
V_{cb}
$\bar{B}$
$D^{(*)}$
$\bar{d}$


BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
Δχ² = 1.0 contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
4σ
2σ
HFLAV
FPCP 2017
P(χ²) = 71.6%
R(D*)
R(D)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
0.6



Standard-model prediction:

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

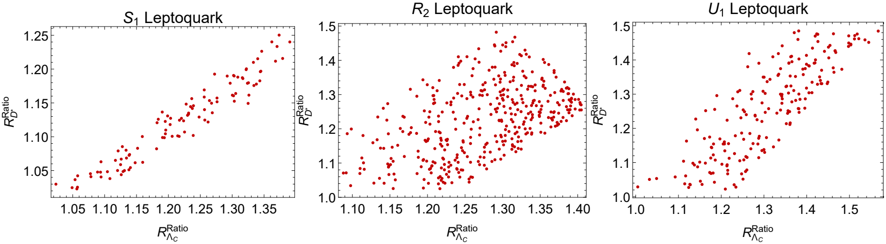
LHCb analysis is underway!

BSM phenomenology of $\Lambda_b \to \Lambda_c \tau \bar{\nu}$

[A. Datta, S. Kamali, S. Meinel, A. Rashed, arXiv:1702.02243/JHEP 2017]

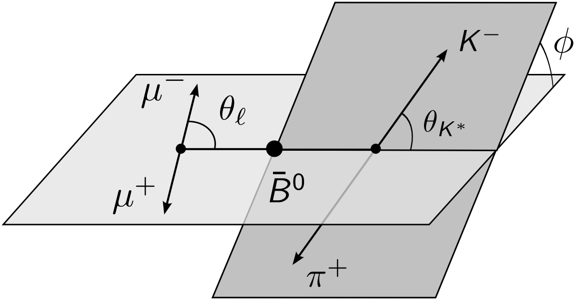
Example: Leptoquark models

	spin	$SU(3)_c$	$SU(2)_L$	$U(1)_{Y=Q-T_3}$
S_1	0	$\bar{3}$	1	$1/3$
R_2	0	3	2	$7/6$
U_1	1	3	1	$2/3$

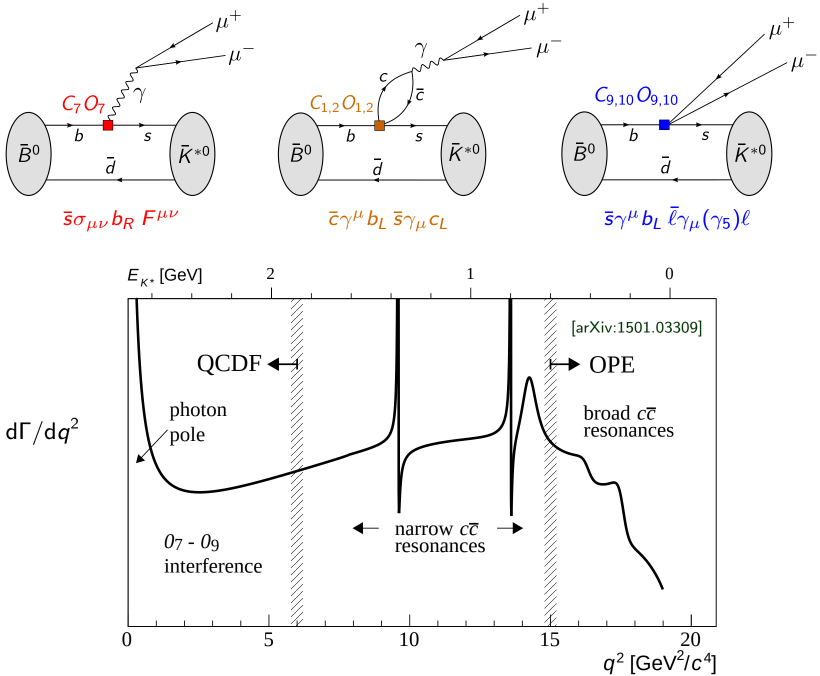


$$R_{D^*}^{\rm Ratio} = \frac{R[D^*]^{\rm SM+NP}}{R[D^*]^{\rm SM}}, \qquad R_{\Lambda_c}^{\rm Ratio} = \frac{R[\Lambda_c]^{\rm SM+NP}}{R[\Lambda_c]^{\rm SM}}$$

1. $b \to u\ell^- \bar{\nu}_\ell$ and $b \to c\ell^- \bar{\nu}_\ell$
2. $b \to c\tau^- \bar{\nu}$
3. $b \to s\ell^+\ell^-$
4. $c \to s\ell^- \bar{\nu}_\ell$
5. $c \to u\ell^+\ell^-$



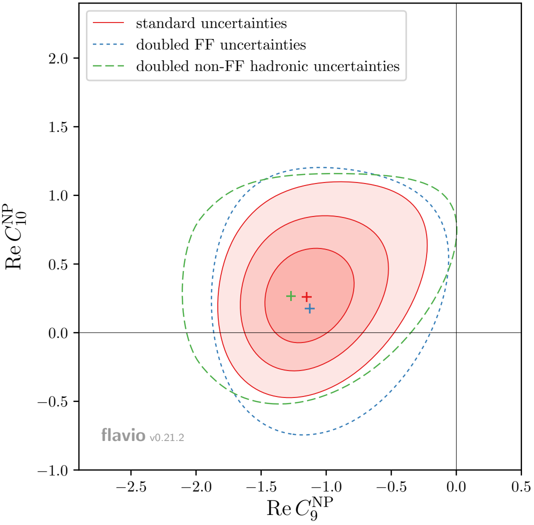
μ^-
θ_ℓ
μ^+
$\bar{B}^0$
K^-
ϕ
θ_{K^*}
π^+



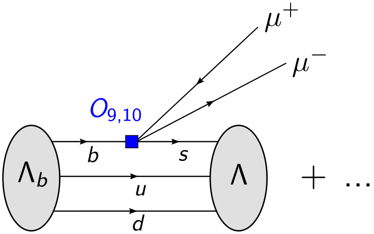
μ^+
μ^-
γ
$C_7 O_7$
$\bar{B}^0$
b
s
$\bar{d}$
$\bar{K}^{*0}$
$\bar{s}\sigma_{\mu\nu} b_R F^{\mu\nu}$
$C_{1,2} O_{1,2}$
c
$\bar{c}$
$\bar{c}\gamma^\mu b_L \bar{s}\gamma_\mu c_L$
$C_{9,10} O_{9,10}$
$\bar{s}\gamma^\mu b_L \bar{\ell}\gamma_\mu(\gamma_5)\ell$
E_{K^*} [GeV]
2
1
0
[arXiv:1501.03309]
QCDF
OPE
photon
pole
broad $c\bar{c}$
resonances
$d\Gamma/dq^2$
0_7 - 0_9
interference
narrow $c\bar{c}$
resonances
0
5
10
15
20
q^2 [GeV^2/c^4]

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

[W. Altmannshofer, C. Niehoff, P. Stangl, D. Straub, arXiv:1703.09189/EPJC 2017]



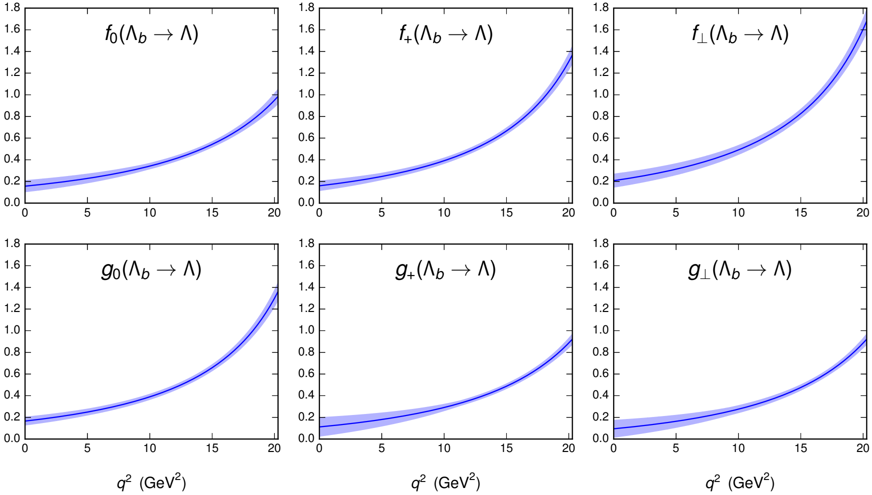
Complementary information can be obtained from $\Lambda_b \to \Lambda\mu^+\mu^-$



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

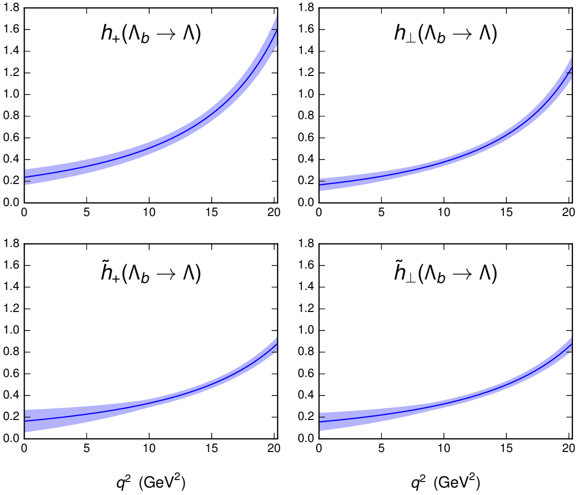
Λ has nonzero spin and is stable under strong interactions.

$\Lambda_b \to \Lambda$ vector and axial vector form factors

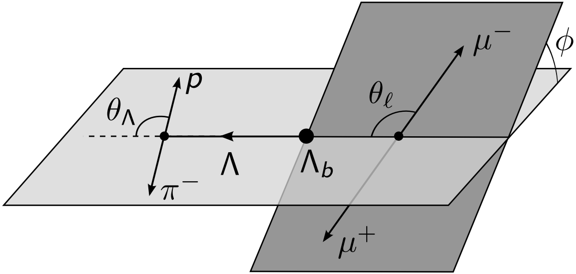


[W. Detmold and S. Meinel,arXiv:1602.01399/PRD 2016]

$\Lambda_b \to \Lambda$ tensor form factors



[W. Detmold and S. Meinel,arXiv:1602.01399/PRD 2016]

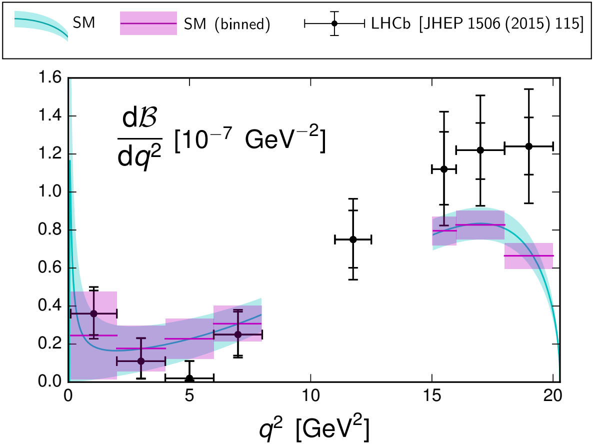


For unpolarized Λ_b:

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

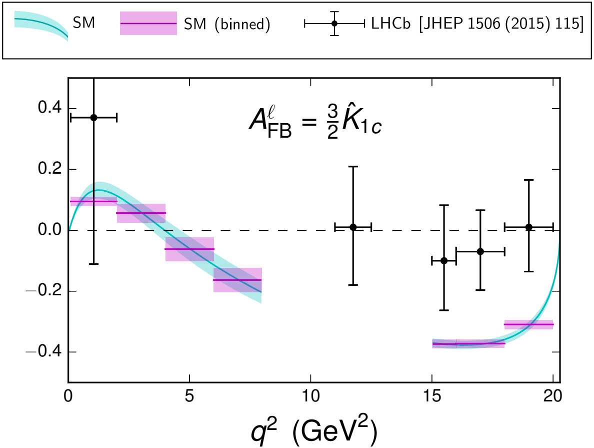
$$\Rightarrow \quad \frac{d\Gamma}{dq^2} = 2K_{1ss} + K_{1cc}$$

[T. Gutsche *et al.*, arXiv:1301.3737/PRD 2013; P. Böer, T. Feldmann, D. van Dyk, arXiv:1410.2115/JHEP 2015]



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

[W. Detmold and S. Meinel,arXiv:1602.01399/PRD 2016]



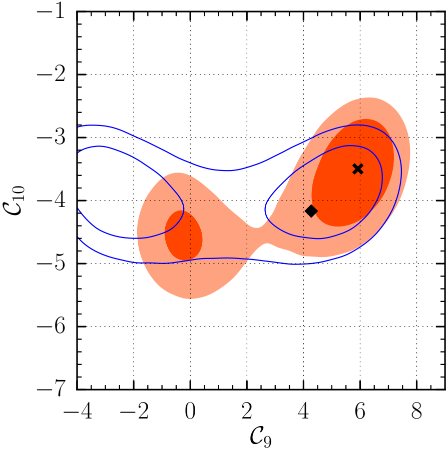
3σ discrepancy at high q^2.

[W. Detmold and S. Meinel,arXiv:1602.01399/PRD 2016]

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

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

[S. Meinel and D. van Dyk, arXiv:1603.02974/PRD 2016]



[S. Meinel and D. van Dyk, arXiv:1603.02974/PRD 2016]

Opposite shift in C_9 compared to fits of only mesonic decays!

- Statistical fluctuation?
- Breakdown of OPE for charm-loop effects?

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.*, arXiv:1306.2384/PRD 2013

[2] C. Bouchard *et al.*, arXiv:1306.0434/PRL 2013

[3] J. A. Bailey *et al.*, arXiv:1509.06235/PRD 2016

[4] D. Du *et al.*, arXiv:1510.02349/PRD 2016

[5] R. R. Horgan, Z. Liu, S. Meinel, M. Wingate, arXiv:1310.3722/PRD 2014

[6] R. R. Horgan, Z. Liu, S. Meinel, M. Wingate, arXiv:1310.3887/PRL 2014

[7] J. Flynn, A. Jüttner, T. Kawanai, E. Lizarazo, O. Witzel, arXiv:1511.06622/PoS 2015

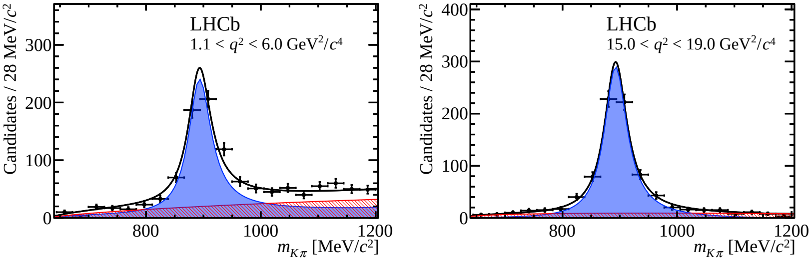
[8] W. Detmold, C.-J. D. Lin, S. Meinel, M. Wingate, arXiv:1212.4827/PRD 2013

[9] W. Detmold, S. Meinel, arXiv:1602.01399/PRD 2016

[10] S. Meinel, D. van Dyk, arXiv:1603.02974/PRD 2016

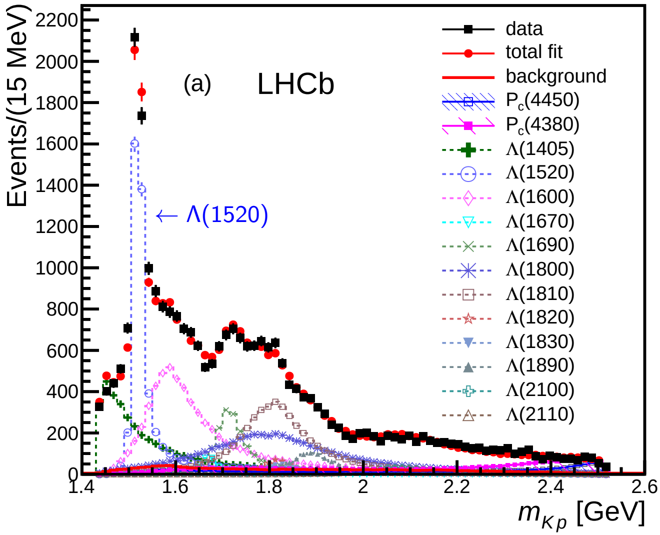
[11] S. Meinel, G. Rendon, arXiv:1608.08110/PoS 2016

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



[LHCb Collaboration, arXiv:1606.04731/JHEP 2016]

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



[LHCb Collaboration, arXiv:1507.03414/PRL 2015]

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

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

Λ(1520) MASS

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

Λ(1520) WIDTH

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

Λ(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	$\Sigma(1385)\pi(\to \Lambda\pi\pi)$	
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:

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

$$= \bar{u}_\lambda(p',s') \Bigg[f_0 \, \frac{(m_{\Lambda_b} - m_{\Lambda^*}) \, p^\lambda q^\mu}{m_{\Lambda_b} \, q^2}$$

$$+ f_+ \, \frac{(m_{\Lambda_b} + m_{\Lambda^*}) \, p^\lambda (q^2(p^\mu + p'^\mu) - (m_{\Lambda_b}^2 - m_{\Lambda^*}^2) q^\mu)}{m_{\Lambda_b} \, q^2 \, s_+}$$

$$+ f_\perp \left(\frac{p^\lambda \gamma^\mu}{m_{\Lambda_b}} - \frac{2\, p^\lambda (m_{\Lambda_b} p'^\mu + m_{\Lambda^*} p^\mu)}{m_{\Lambda_b} \, s_+} \right)$$

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

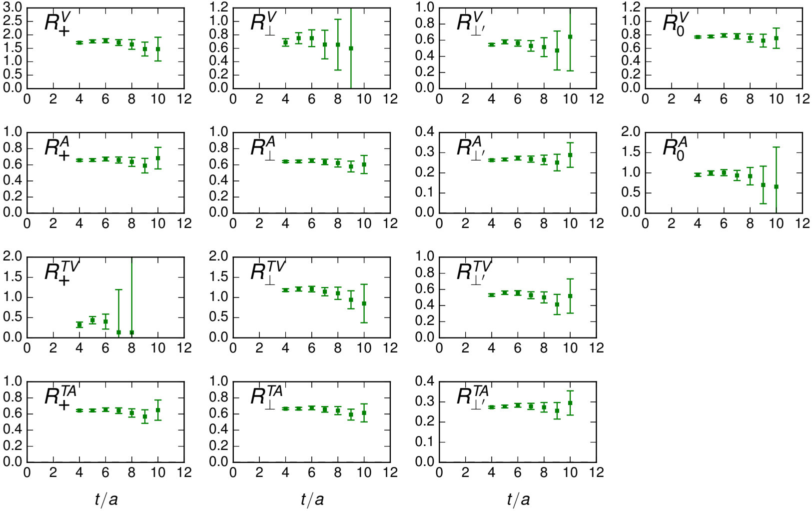
where $s_\pm = (m_{\Lambda_b} \pm m_{\Lambda^*})^2 - q^2$

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

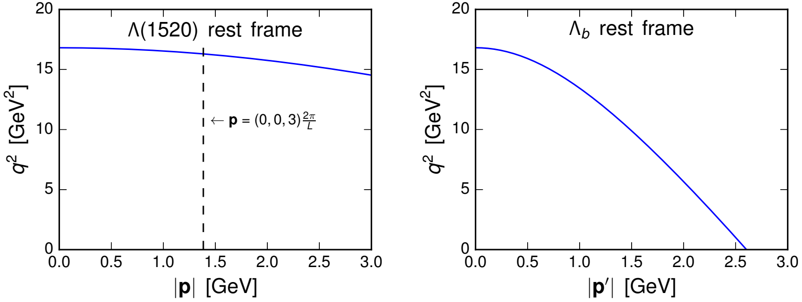
and tensor currrent (h_+, $h_\perp$, $h_{\perp'}$, $\widetilde{h}_+$, $\widetilde{h}_\perp$, $\widetilde{h}_{\perp'}$)

[S. Meinel, G. Rendon, arXiv:1608.08110/PoS 2016]

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/PoS 2016]



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

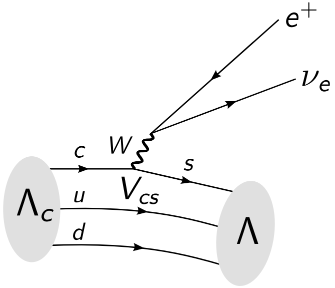
[R. R. Horgan *et al.*, arXiv:0906.0945/PRD 2009]

1. $b \to u\ell^- \bar{\nu}_\ell$ and $b \to c\ell^- \bar{\nu}_\ell$
2. $b \to c\tau^- \bar{\nu}$
3. $b \to s\ell^+ \ell^-$
4. $c \to s\ell^- \bar{\nu}_\ell$
5. $c \to u\ell^+ \ell^-$

BES III Collaboration, 2015:

First direct measurements of Λ_c branching fractions at $e^+e^- \to \Lambda_c \overline{\Lambda}_c$ threshold. Including

$$\mathcal{B}(\Lambda_c \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\,\%$$ [arXiv:1510.02610/PRL 2015]



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$$\mathcal{B}(\Lambda_c \to \Lambda e^+\nu_e) = (3.63 \pm 0.38 \pm 0.20)\,\%$$ [arXiv:1510.02610/PRL 2015]

From the introduction of their paper:

> Since the first observation of the Λ_c^+ baryon in e^+e^- annihilations at the Mark II experiment [4] in 1979, much theoretical effort has been applied towards the study of its SL decay properties. However, predictions of the branching fraction (BF) $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)$ in different theoretical models vary in a wide range from 1.4% to 9.2% [5–15], depending on the choice of various Λ_c^+ wave function models and the nature of decay dynamics. In addition, theoretical calculations prove to be quite challenging for lattice quantum chromodynamics (LQCD) due to the complexity of form factors, which describes the hadronic part of the decay dynamics in $\Lambda_c^+ \to \Lambda e^+\nu_e$ [16]. Thus, an accurate measurement of $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)$ is a key ingredient in calibrating LQCD calculations, which, in turn, will play an important role in understanding different Λ_c^+ SL decays.

$\Lambda_c \to \Lambda \ell^+ \nu_\ell$ form factors and decay rates from lattice QCD with physical quark masses

[S. Meinel, PRL **118**, 082001 (2017)]

- RBC/UKQCD ensembles with $2+1$ flavors of domain-wall fermions
  [Y. Aoki *et al.*, arXiv:1011.0892/PRD 2011; T. Blum *et al.*, arXiv:1411.7017/PRD 2016]

- Charm action: anisotropic clover
  [Z. Brown, W. Detmold, S. Meinel, K. Orginos, arXiv:1409.0497/PRD 2014]

- $c \to s$ currents: "Mostly nonperturbative" renormalization
  [A. El-Khadra *et al.*, hep-ph/0101023/PRD 2001],
  one-loop coefficients computed by Christoph Lehner
  [C. Lehner, arXiv:1211.4013/PoS 2012]

- Three-point functions with 12 source-sink separations

$N_s^3 \times N_t$	a [fm]	$am_{u,d}$	m_π [MeV]	$am_s^{(\mathrm{val})}$	$m_{\eta_s}^{(\mathrm{val})}$ [MeV]
$48^3 \times 96$	0.1142(15)	0.00078	139(2)	0.0362	693(9)
$24^3 \times 64$	0.1119(17)	0.005	336(5)	0.04	761(12)
$24^3 \times 64$	0.1119(17)	0.005	336(5)	0.03	665(10)
$32^3 \times 64$	0.0849(12)	0.004	295(4)	0.03	747(10)
$32^3 \times 64$	0.0848(17)	0.006	352(7)	0.03	749(14)

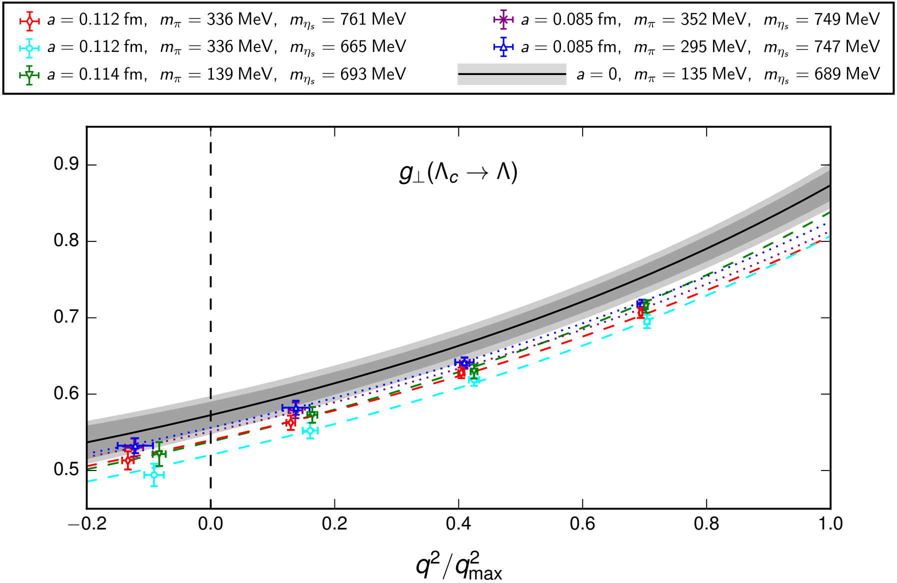
Combined chiral/continuum/kinematic extrapolation using modified z-expansion

[C. Bourrely, I. Caprini, L. Lellouch, arXiv:0807.2722/PRD 2009]

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \qquad t_+ = (m_D + m_K)^2, \qquad t_0 = (m_{\Lambda_c} - m_\Lambda)^2$$

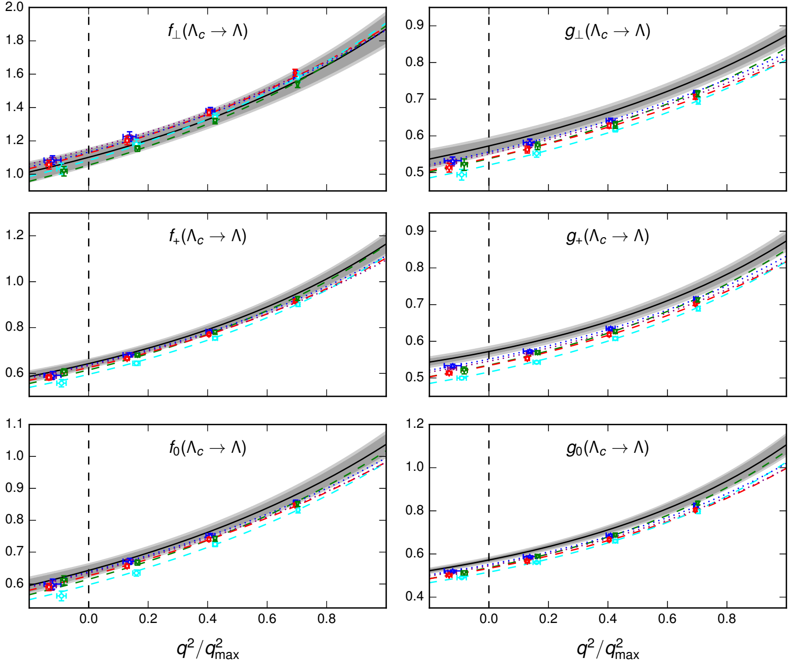
Nominal fit:

$$\begin{aligned} f(q^2) \quad = \quad & \frac{1}{1 - q^2/(m^f_{\rm pole})^2} \Bigg[a_0^f \left(1 + c_0^f \frac{m_\pi^2 - m_{\pi,\rm phys}^2}{\Lambda_\chi^2} + c_{s,0}^f \frac{m_{\eta_s}^2 - m_{\eta_s,\rm phys}^2}{\Lambda_\chi^2} \right) \\ & \qquad + a_1^f \, z(q^2) + a_2^f \, [z(q^2)]^2 \Bigg] \\ & \times \left[1 + b^f \, a^2 |\mathbf{p}'|^2 + d^f \, a^2 \Lambda_{\rm QCD}^2 \right] \end{aligned}$$



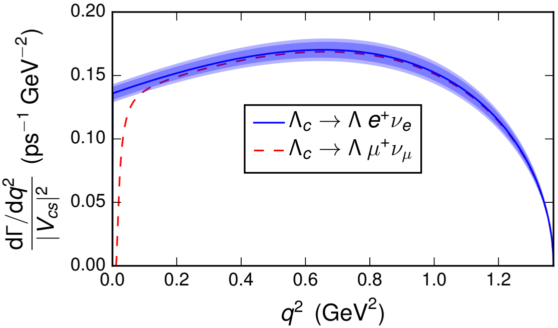
Inner band: statistical uncertainty from nominal fit only

Outer band: includes systematic uncertainty estimated using higher-order fit



$f_\perp(\Lambda_c \to \Lambda)$
$g_\perp(\Lambda_c \to \Lambda)$
$f_+(\Lambda_c \to \Lambda)$
$g_+(\Lambda_c \to \Lambda)$
$f_0(\Lambda_c \to \Lambda)$
$g_0(\Lambda_c \to \Lambda)$
$q^2/q^2_{\rm max}$
$q^2/q^2_{\rm max}$

Predicted differential and total decay rates without $|V_{cs}|^2$:



$$\frac{\Gamma(\Lambda_c \to \Lambda\ell^+\nu_\ell)}{|V_{cs}|^2} = \begin{cases} 0.2007(71)(74)\ \mathrm{ps}^{-1}, & \ell = e, \\ 0.1945(69)(72)\ \mathrm{ps}^{-1}, & \ell = \mu. \end{cases}$$

Taking the indirectly determined $|V_{cs}| = 0.97344(15)$ from UTFit and $\tau_{\Lambda_c} = 0.200(6)$ ps from PDG, the branching fractions predicted by lattice QCD are

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell) = \begin{cases} 0.0380(19)_{\text{LQCD}}(11)_{\tau_{\Lambda_c}}, & \ell = e, \\ 0.0369(19)_{\text{LQCD}}(11)_{\tau_{\Lambda_c}}, & \ell = \mu. \end{cases}$$

These agree with the BESIII measurements
[arXiv:1510.02610/PRL 2015; arXiv:1611.04382/PLB 2017]

$$\mathcal{B}(\Lambda_c \to \Lambda \ell^+ \nu_\ell)_{\text{BESIII}} = \begin{cases} 0.0363(43), & \ell = e, \\ 0.0349(53), & \ell = \mu. \end{cases}$$

Alternatively, we can use the lattice QCD results together with the BESIII measurements and τ_{Λ_c} to determine $|V_{cs}|$:

$$|V_{cs}| = 0.949(24)_{\rm LQCD}(51)_{\rm Exp.} \quad \text{from } \; \Lambda_c \to \Lambda \ell^+ \nu_\ell.$$

For comparison:

$$|V_{cs}| = \begin{cases} 1.008(5)_{\rm LQCD}(16)_{\rm Exp.} & \text{from } \; D_s \to \ell^+ \nu_\ell \;\; [1,2], \\ 0.975(25)_{\rm LQCD}(7)_{\rm Exp.} & \text{from } \; D \to K \ell^+ \nu_\ell \;\; [1,3], \\ 0.975(38)_{\rm LQCD}(4)_{\rm Exp.} & \text{from } \; D \to K \ell^+ \nu_\ell \;\; [4], \\ 0.978(35)_{\rm LQCD+Exp.} & \text{from } \; D \to K \ell^+ \nu_\ell \;\; [5] \end{cases}$$

[1] S. Aoki *et al.* (FLAG), arXiv:1607.00299/EPJC 2017

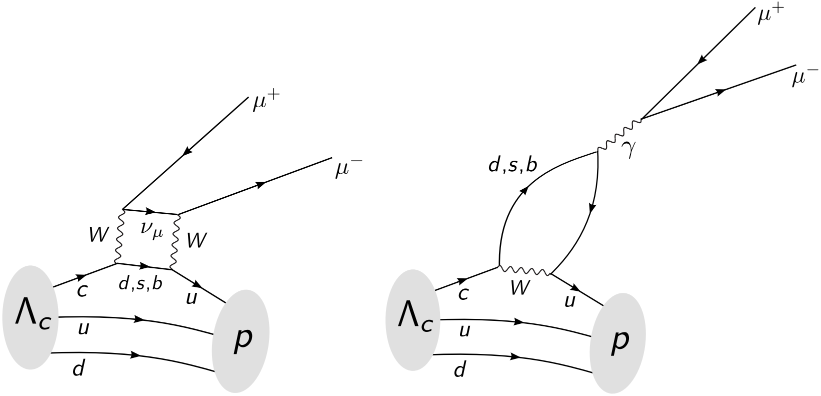
[2] A. Bazavov *et al.* (Fermilab Lattice and MILC), arXiv:1407.3772/PRD 2014

[3] H. Na *et al.* (HPQCD), arXiv:1008.4562/PRD 2010

[4] V. Lubicz *et al.* (ETMC), arXiv:1706.03017

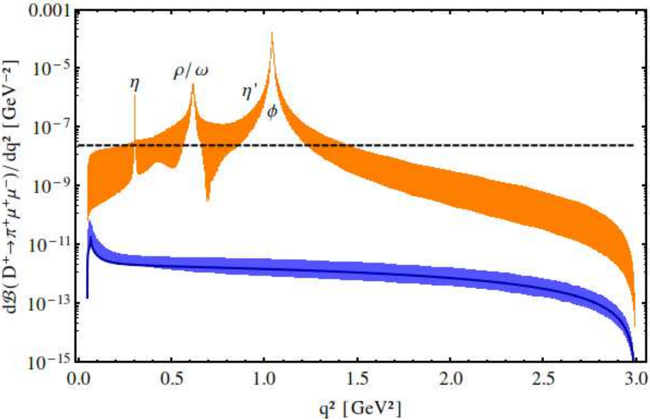
[5] L. Riggio, G. Salerno, S. Simula, arXiv:1706.03657

1. $b \to u\ell^-\bar{\nu}_\ell$ and $b \to c\ell^-\bar{\nu}_\ell$
2. $b \to c\tau^-\bar{\nu}$
3. $b \to s\ell^+\ell^-$
4. $c \to s\ell^-\bar{\nu}_\ell$
5. $c \to u\ell^+\ell^-$



Interesting for LHCb!

$c \to u\,\mu^+\mu^-$ decays are dominated by resonant contributions from nonlocal matrix elements.

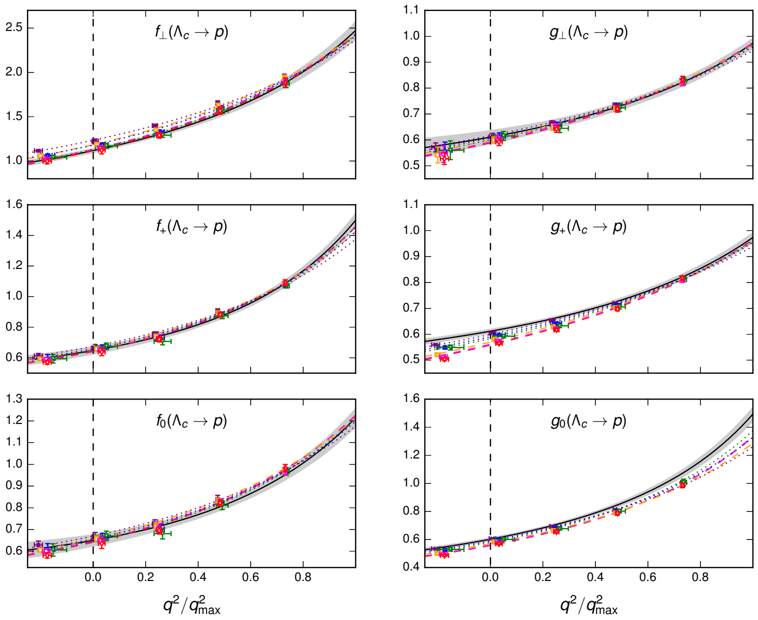


[S. de Boer, G. Hiller, arXiv:1510.00311/PRD 2016]

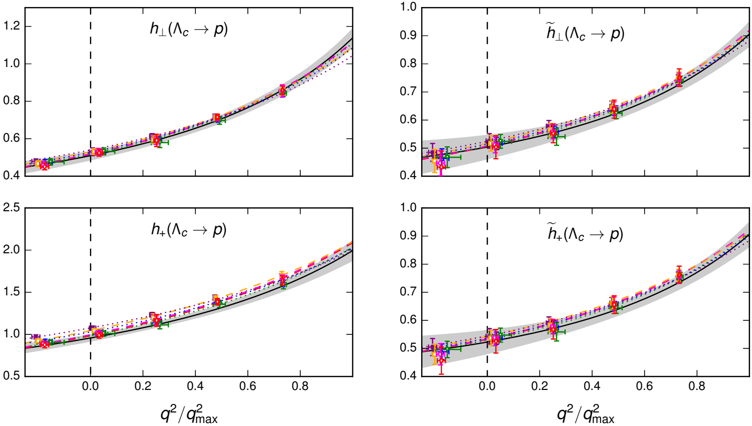
Why are the short-distance $\Lambda_c \to p$ form factors still useful?

- BSM couplings could be much larger than SM couplings.
Lepton-flavor-violating modes such as $\Lambda_c \to p\, e^+ \mu^-$ are short-distance only.
- $\Lambda_c \to p$ form factors are useful as input for factorization approximation of $\Lambda_c \to p\, V(\to \ell^+ \ell^-)$
- Study m_Q-dependence of $\Lambda_Q \to p$ form factors
(previous lattice calculations: $m_Q = m_b$, $m_Q = \infty$)
- Charged-current decay $\Lambda_c \to n\, \ell^+ \nu_\ell$

Vector and axial vector form factors – preliminary; only stat. uncertainty shown



Tensor form factors – preliminary; only stat. uncertainty shown



Conclusions and Outlook

- Thanks to the LHC and LQCD, Λ_b decays are providing new information on important puzzles in flavor physics:
    - $|V_{ub}|$ and $|V_{cb}|$ exclusive-inclusive discrepancy
    - New physics in $b \to c\tau\bar{\nu}$ transitions?
    - New physics in $b \to s\ell^+\ell^-$ transitions?
- The lattice QCD calculation of the $\Lambda_c \to \Lambda\,\ell^+\nu_\ell$ decay rate agrees with the BESIII measurement. Valuable cross-check.
- Currently finalizing analysis of $\Lambda_c \to p$ form factors, and thinking about phenomenology.
- Higher-precision lattice calculations of $\Lambda_b \to \Lambda_c, \Lambda, p$ form factors and studies of new decay channels are underway.
- More LHCb measurements are coming.