Lattice QCD calculation of form factors for $\Lambda_b \to \Lambda(1520)\ell^+\ell^-$ decays

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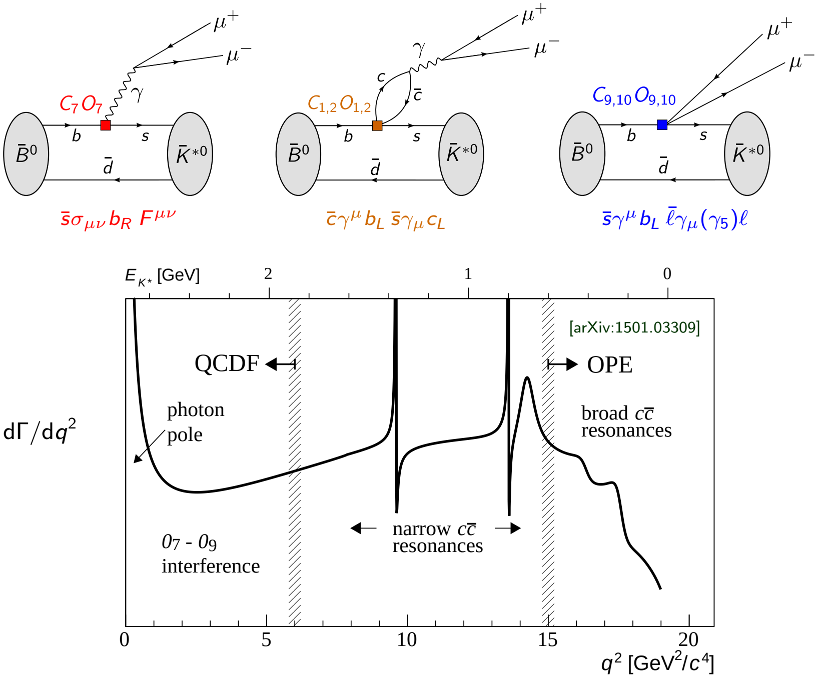
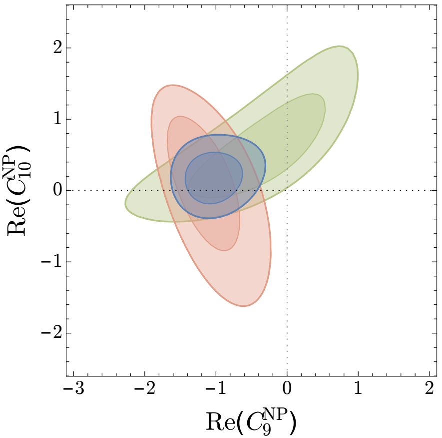
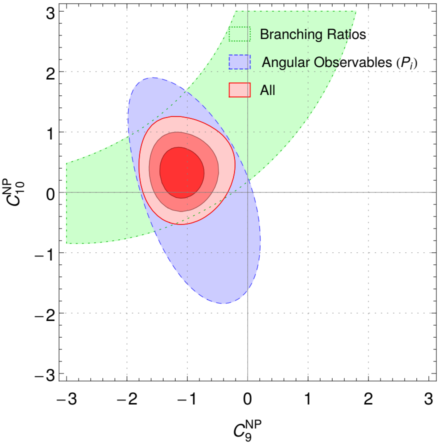

$C_7 O_7$
$\bar{s}\sigma_{\mu\nu} b_R F^{\mu\nu}$
$C_{1,2} O_{1,2}$
$\bar{c}\gamma^\mu b_L \bar{s}\gamma_\mu c_L$
$C_{9,10} O_{9,10}$
$\bar{s}\gamma^\mu b_L \bar{\ell}\gamma_\mu(\gamma_5)\ell$
$\bar{B}^0$
$\bar{K}^{*0}$
μ^+
μ^-
γ
b
s
$\bar{d}$
c
$\bar{c}$
E_{K^*} [GeV]
[arXiv:1501.03309]
QCDF
OPE
photon pole
broad $c\bar{c}$ resonances
$d\Gamma/dq^2$
O_7 - O_9 interference
narrow $c\bar{c}$ resonances
q^2 [GeV^2/c^4]
0
5
10
15
20
2
1
0

Fits of $C_i^{\mathrm{NP}} = C_i - C_i^{\mathrm{SM}}$
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)]

	Probes all Dirac structures	Final hadron QCD-stable	Charged tracks 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]
$\Lambda_b^0 \to \Lambda^{*0}(\to p^+ K^-)\, \ell^+ \ell^-$	✓	×	✓	This work

[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)

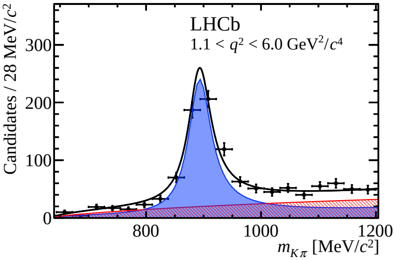
[7] J. Flynn, A. Jüttner, T. Kawanai, E. Lizarazo, O. Witzel, PoS **LATTICE2015**, 345

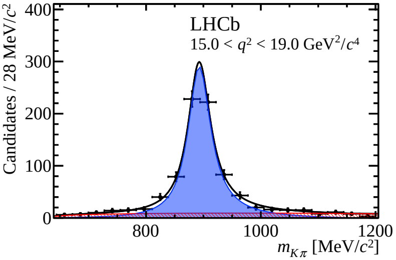
[8] W. Detmold, C.-J. D. Lin, S. Meinel, M. Wingate, PRD **87**, 074502 (2013)

[9] W. Detmold, S. Meinel, PRD **93**, 074501 (2016) - see extra slides at the end!

[10] S. Meinel, D. van Dyk, PRD **94**, 013007 (2016) - see extra slides at the end!

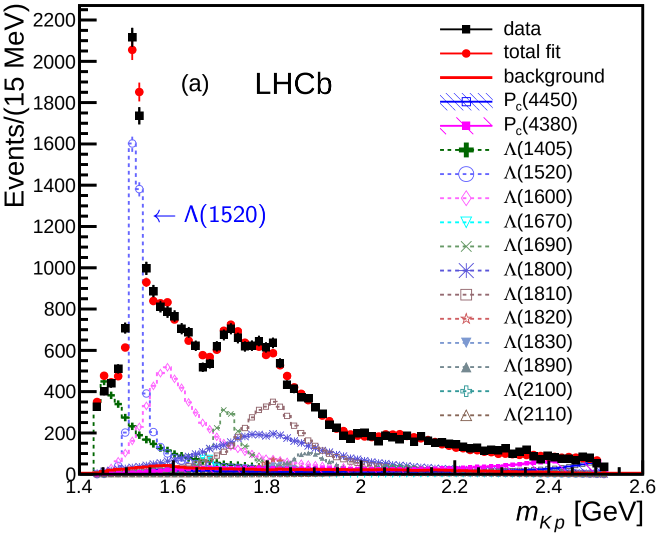
The $K^*(892)$ resonance in $B^0 \to K^+\pi^-\mu^+\mu^-$





[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: ∗∗∗∗

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	$\Sigma(1385)\pi(\rightarrow \Lambda\pi\pi)$	
Γ_6	$\Lambda(\pi\pi)_{S\text{-wave}}$	
Γ_7	$\Sigma\pi\pi$	(0.9 ± 0.1) %
Γ_8	$\Lambda\gamma$	(0.85$\pm$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:

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

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_+, $h_\perp$, $h_{\perp'}$, $\widetilde{h}_+$, $\widetilde{h}_\perp$, $\widetilde{h}_{\perp'}$)

$\Lambda(1520)$ interpolating operators

To allow exact J^P projection, work in $\Lambda(1520)$ rest frame.

First attempt: use

$$\Lambda^{(1)}_{j\gamma} = \epsilon^{abc}\,(C\gamma_j)_{\alpha\beta}\,\left(\tilde{u}^a_\alpha\,\tilde{s}^b_\beta\,\tilde{d}^c_\gamma - \tilde{d}^a_\alpha\,\tilde{s}^b_\beta\,\tilde{u}^c_\gamma\right)$$

where the ˜ denotes Gaussian smearing.

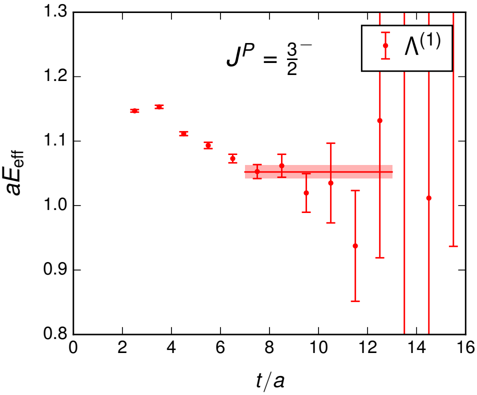
$SU(2)$ singlet.

Project to $J^P = \frac{3}{2}^-$ using

$$P^{jk} = \left(g^{jk} - \frac{1}{3}\gamma^j\gamma^k\right)\frac{1-\gamma_0}{2}$$

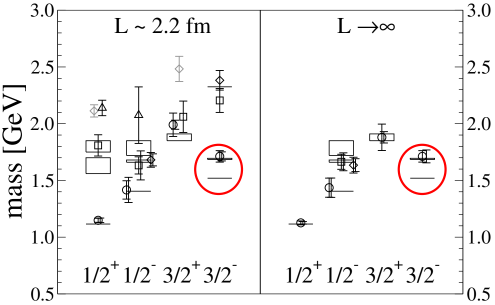
Two-point function computed on RBC/UKQCD $24^3 \times 64$ ensemble [Y. Aoki *et al.*, PRD **83**, 074508 (2011)], $am_l = 0.005$, $am_s = 0.04$(sea), $am_s = 0.0323$(valence), $a \approx 0.112$ fm, $m_\pi \approx 330$ MeV.

All-mode-averaging [E. Shintani *et al.*, PRD **91**, 114511 (2015)] with 32 sloppy measurements per config, 1 exact measurement per config, so far using 311 configurations.



The form factor results obtained using this operator looked bad.

Other groups doing Λ-baryon spectroscopy using interpolating operators of this form did not see the Λ(1520)!



[G. P. Engel, C. B. Lang, A. Schäfer, PRD **87**, 034502 (2013)]

Second attempt: use

$$\Lambda^{(2)}_{j\gamma} = \epsilon^{abc}(C\gamma_5)_{\alpha\beta}\left[\tilde{s}^a_\alpha\ \tilde{d}^b_\beta\ (\nabla_j\tilde{u})^c_\gamma - \tilde{s}^a_\alpha\ \tilde{u}^b_\beta\ (\nabla_j\tilde{d})^c_\gamma + \tilde{u}^a_\alpha\ (\nabla_j\tilde{d})^b_\beta\ \tilde{s}^c_\gamma - \tilde{d}^a_\alpha\ (\nabla_j\tilde{u})^b_\beta\ \tilde{s}^c_\gamma\right]$$

(Terms with derivatives on the strange quark have been eliminated using "integration by parts"; this works at zero momentum only.)

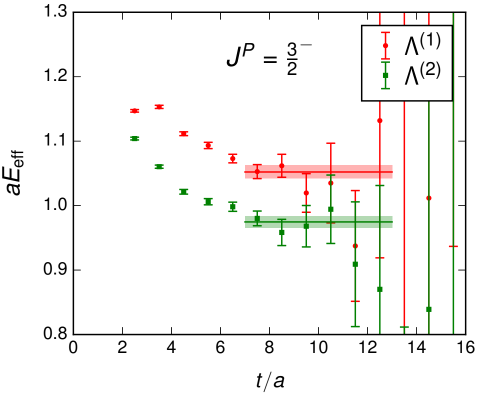
$\rightarrow$ $SU(2)$ and $SU(3)$ singlet; *naturally* negative parity in nonrelativistic QM.

Requires propagators with derivative sources.

Project to $J^P = \frac{3}{2}^-$ using

$$P^{jk} = \left(g^{jk} - \frac{1}{3}\gamma^j\gamma^k\right)\frac{1+\gamma_0}{2}$$

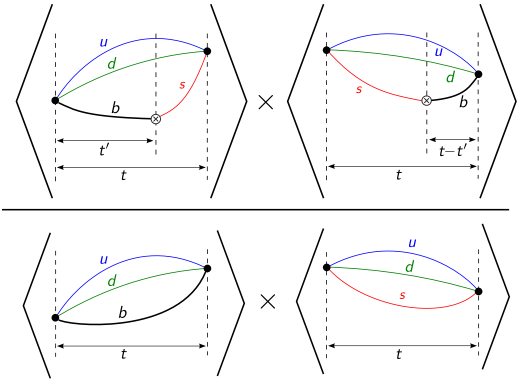
(note the plus sign!)



$\Lambda^{(1)}$ cannot form $SU(3)$ singlet [H.-X. Chen *et al.*, PRD **78**, 054021 (2008)], couples dominantly to the $\Lambda(1690)$.

$\Lambda^{(2)}$ is $SU(3)$ singlet, couples dominantly to the $\Lambda(1520)$ $\rightarrow$ use this operator!

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



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

b quark implemented using RHQ action [Y. Aoki *et al.*, PRD **86**, 116003 (2012)]

Compute (for vector current in this example)

$$\mathscr{R}^{jk\mu\nu}(\mathbf{p},t,t')^V = \frac{\mathrm{Tr}\Big[P^{jl}\; C_l^{(3,\mathrm{fw})}(\mathbf{p},\gamma^\mu,t,t')\;(\not{p}+m_{\Lambda_b})\;C_m^{(3,\mathrm{bw})}(\mathbf{p},\gamma^\nu,t,t-t')\,P^{mk}\Big]}{\mathrm{Tr}\Big[P^{lm}\;C_{lm}^{(2,\Lambda^*)}(t)\Big]\,\mathrm{Tr}\Big[(\not{p}+m_{\Lambda_b})\;C^{(2,\Lambda_b)}(\mathbf{p},t)\Big]}$$

and contract with the polarization vectors

$$\begin{aligned}
\epsilon^{(0)} &= (\,q^0,\;\mathbf{q}\,),\\
\epsilon^{(+)} &= (\,|\mathbf{q}|,\;(q^0/|\mathbf{q}|)\mathbf{q}\,),\\
\epsilon^{(\perp,j)} &= (\,0,\;\mathbf{e}_j\times\mathbf{q}\,)
\end{aligned}$$

as follows:

$$\begin{aligned}
\mathscr{R}_0^V(\mathbf{p},t,t') &= g_{jk}\,\epsilon_\mu^{(0)}\epsilon_\nu^{(0)}\,\mathscr{R}^{jk\mu\nu}(\mathbf{p},t,t')^V,\\
\mathscr{R}_+^V(\mathbf{p},t,t') &= g_{jk}\,\epsilon_\mu^{(+)}\epsilon_\nu^{(+)}\,\mathscr{R}^{jk\mu\nu}(\mathbf{p},t,t')^V,\\
\mathscr{R}_\perp^V(\mathbf{p},t,t') &= p_j\,p_k\,\epsilon_\mu^{(\perp,l)}\epsilon_\nu^{(\perp,l)}\,\mathscr{R}^{jk\mu\nu}(\mathbf{p},t,t')^V,\\
\mathscr{R}_{\perp'}^V(\mathbf{p},t,t') &= \left[\epsilon_j^{(\perp,m)}\epsilon_k^{(\perp,m)}-\frac{1}{2}\,p_j\,p_k\right]\epsilon_\mu^{(\perp,l)}\epsilon_\nu^{(\perp,l)}\,\mathscr{R}^{jk\mu\nu}(\mathbf{p},t,t')^V.
\end{aligned}$$

Then compute

$$R_0^V(\mathbf{p},t) = \sqrt{\frac{12\, E_{\Lambda_b} m_{\Lambda_b}^2 \;\; \mathscr{R}_0^V(\mathbf{p},t,t/2)}{(E_{\Lambda_b}-m_{\Lambda_b})(m_{\Lambda_b}-m_\Lambda)^2(E_{\Lambda_b}+m_{\Lambda_b})^2}} = f_0 + ...,$$

$$R_+^V(\mathbf{p},t) = \sqrt{\frac{12\, E_{\Lambda_b} m_{\Lambda_b}^2 \;\; \mathscr{R}_+^V(\mathbf{p},t,t/2)}{(E_{\Lambda_b}+m_{\Lambda_b})(m_{\Lambda_b}+m_\Lambda)^2(E_{\Lambda_b}-m_{\Lambda_b})^2}} = f_+ + ...,$$

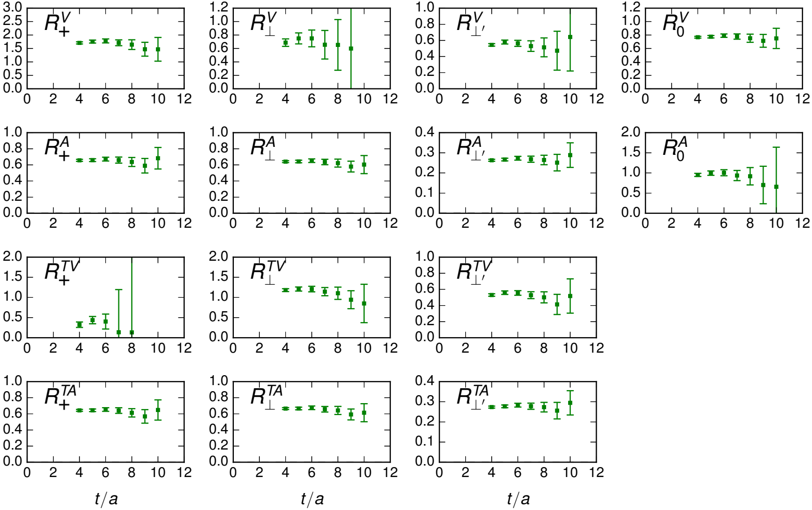
$$R_\perp^V(\mathbf{p},t) = \sqrt{-\frac{9\, E_{\Lambda_b} m_{\Lambda_b}^2 \;\; \mathscr{R}_\perp^V(\mathbf{p},t,t/2)}{(E_{\Lambda_b}-m_{\Lambda_b})^4(E_{\Lambda_b}+m_{\Lambda_b})^3}} = f_\perp + ...,$$

$$R_{\perp'}^V(\mathbf{p},t) = \sqrt{-\frac{2\, E_{\Lambda_b} m_{\Lambda_b}^2 \;\; \mathscr{R}_{\perp'}^V(\mathbf{p},t,t/2)}{(E_{\Lambda_b}-m_{\Lambda_b})^4(E_{\Lambda_b}+m_{\Lambda_b})^3}} = f_{\perp'} + ...$$

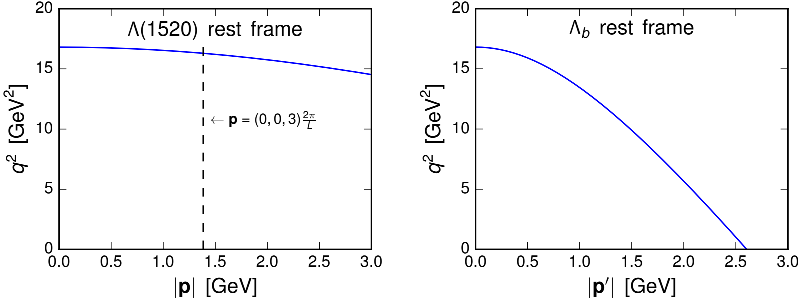
Here, "$+...$" denotes excited-state contamination that vanishes exponentially as $t \to \infty$.

The relations for the other ten form factors are very similar.

Preliminary results at $\mathbf{p} = (0,0,3)\frac{2\pi}{L}$ from 78 cfgs $\times$ 32 srcs:



Problem:



Λ(1520) rest frame
$\leftarrow \mathbf{p} = (0,0,3)\frac{2\pi}{L}$
q^2 [GeV^2]
$|\mathbf{p}|$ [GeV]
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Λ_b rest frame
q^2 [GeV^2]
$|\mathbf{p}'|$ [GeV]
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0

Next steps

- Moving NRQCD for b quark to cover wider q^2 range

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

- Planned data sets:

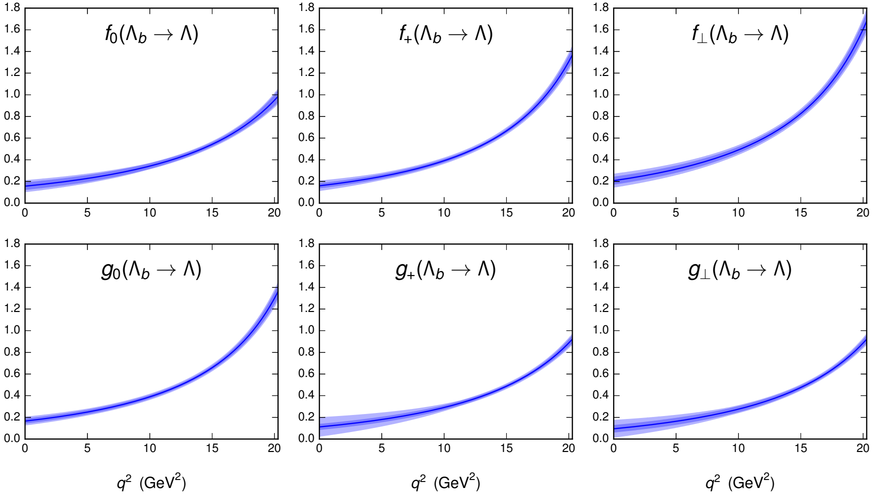
$N_s^3 \times N_t$	a [fm]	$a\, m_{u,d}^{(\mathrm{sea})}$	$a\, m_s^{(\mathrm{sea})}$	$a\, m_{u,d}^{(\mathrm{val})}$	$a\, m_s^{(\mathrm{val})}$	$N_{\mathrm{cfg}} \times N_{\mathrm{src}}$
$24^3 \times 64$	0.112	0.005	0.04	0.005	0.0323	778×32
$24^3 \times 64$	0.112	0.01	0.04	0.01	0.0323	705×32
$32^3 \times 64$	0.085	0.004	0.03	0.004	0.0248	627×32

- Chiral/continuum/kinematic extrapolations of the form factors

- Phenomenology of $\Lambda_b \to \Lambda(1520)(\to p^+ K^-)\mu^+\mu^-$

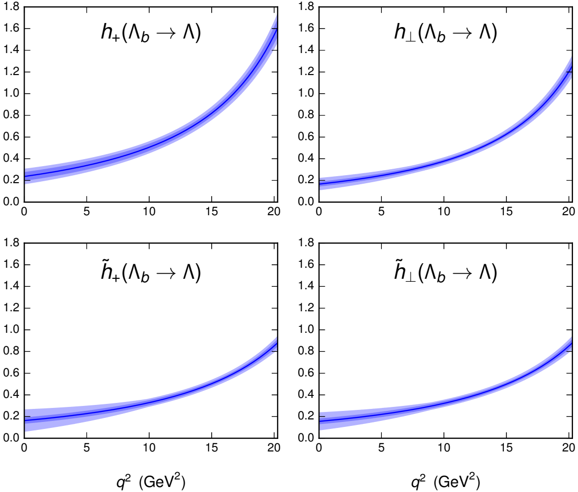
Extra slides: $\Lambda_b \to \Lambda(1115)\mu^+\mu^-$

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

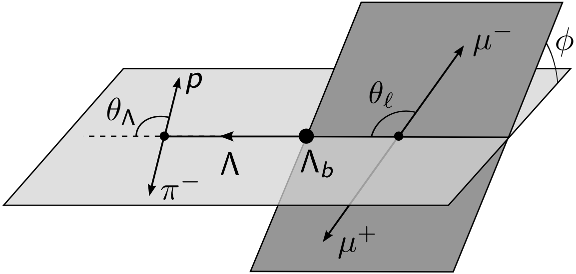


[W. Detmold and S. Meinel, PRD **93**, 074501 (2016)]

$\Lambda_b \to \Lambda$ tensor form factors



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



For unpolarized Λ_b:

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

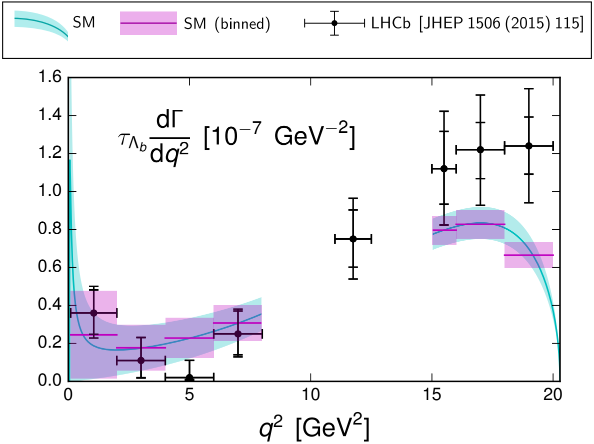
$$+ \left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\cos\theta_\Lambda$$

$$+ \left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\sin\theta_\Lambda\sin\phi$$

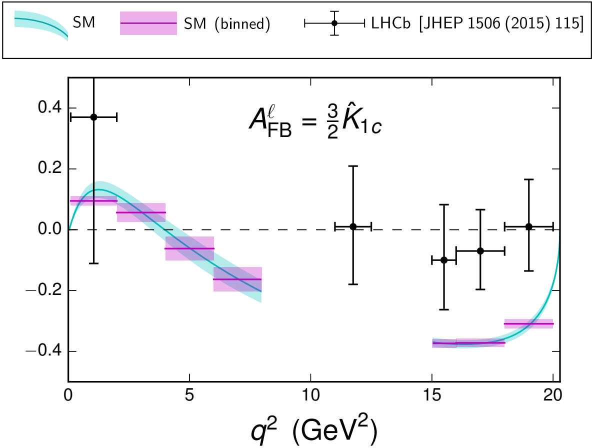
$$+ \left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)\sin\theta_\Lambda\cos\phi\Big]$$

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

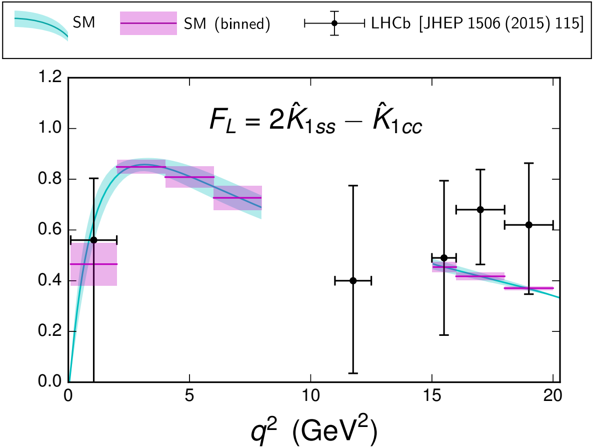
[T. Gutsche *et al.*, PRD **87**, 074031 (2013); P. Böer, T. Feldmann, D. van Dyk, JHEP **1501**, 155 (2015)]



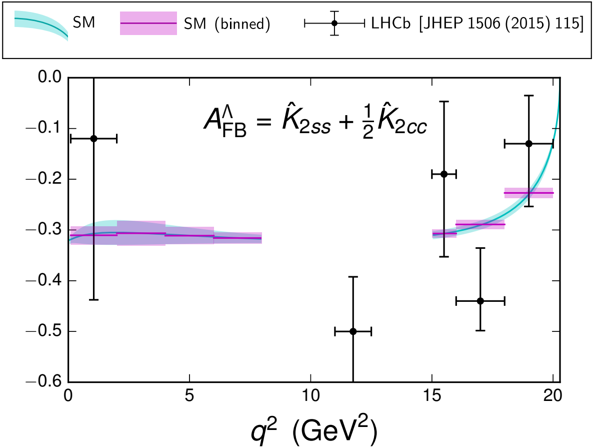
[W. Detmold and S. Meinel, PRD **93**, 074501 (2016)]



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



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

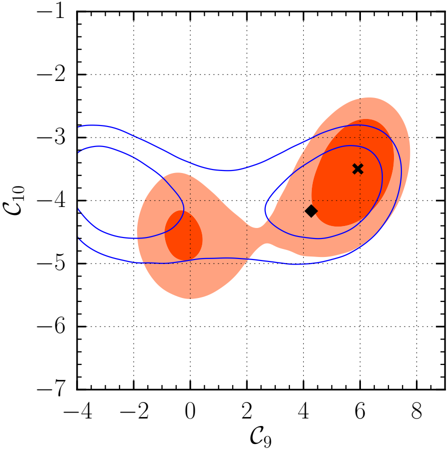


[W. Detmold and S. Meinel, PRD **93**, 074501 (2016)]

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
$\langle F_L\rangle_{15,20}$	$+1.41$	$+1.41$	$+1.41$
$\langle A_{\rm FB}^{\ell}\rangle_{15,20}$	$+3.13$	$+2.60$	$+0.72$
$\langle A_{\rm FB}^{\Lambda}\rangle_{15,20}$	-0.26	-0.24	-1.08
$\bar{B}_s \to \mu^+\mu^-$	Pull value [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, PRD **94**, 013007 (2016)]



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

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

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