The impact of $\Lambda_b \to \Lambda(\to p\pi^-)\mu^+\mu^-$ on global fits of rare $b \to s\mu^+\mu^-$ decays

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in collaboration with Stefan Meinel (ZH-TH-7/16)

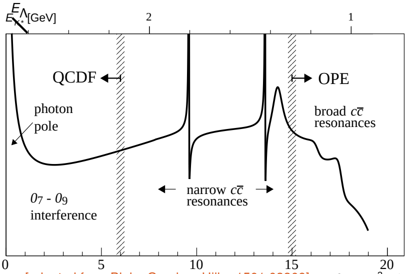
Motivation

- $b \to s\mu^+\mu^-$ decays are interesting *indirect* probes of physics Beyond the SM (BSM)
  - suppressed in the SM by GIM mechanism and α_e
  - BSM physics need not compete with large SM contribution
- presently: puzzling experimental anomalies
  - fits of $B \to K^*\mu^+\mu^-$ angular observables at odds with SM at the $\sim 4\sigma$ level

    [LHCb JHEP 1602 (2016) 104] [Descotes-Genon 1510.04239] [Beaujean EPJC74 (2014) 2897, err. ibid]
  - anomaly shifts coupling to vector lepton current ($\mathcal{C}_9$), while the shift in the axialvector lepton current is compatible with zero ($\mathcal{C}_{10}$)
  - $\mathcal{C}_9$ receives poorly-understood hadronic contributions from charmonium intermediate states
- $\Lambda_b \to \Lambda\mu^+\mu^-$ offers
  - independent confirmation of results: same $b \to s\mu^+\mu^-$ operators, different hadronic matrix elements (incl. charmonium contributions)
  - doubly weak decay: complementary constraints on $b \to s\mu^+\mu^-$ physics with respect to $B \to K^*\mu^+\mu^-$

therefore interesting to study impact of $\Lambda_b \to \Lambda\mu^+\mu^-$ on these fits

$\Lambda_b \to \Lambda$ Hadronic Matrix Elements



[adapted from Blake,Gershon,Hiller 1501.03309]

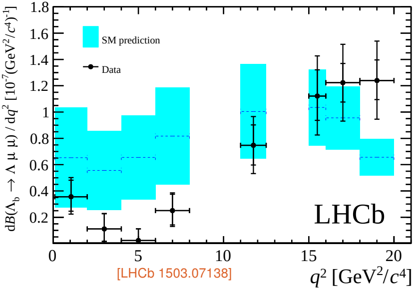
Large Recoil

- ✓ form factor relations
  [Feldmann/Yip 1111.1844]
- ✗ non-factorizable $\bar{c}c$
- ✗ weak-scattering
- ✗ form factors (only extrapolations)

Low Recoil

- ✓ form factor relations
- ✓ OPE
- ✓ form factors beyond leading power
  [Detmold/Meinel 1602.01399]

$\Lambda_b \to \Lambda$ Hadronic Matrix Elements



[LHCb 1503.07138]

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Low Recoil

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- ✓ OPE
- ✓ form factors beyond leading power
  [Detmold/Meinel 1602.01399]

Fit Inputs

[Meinel/DvD ZU-TH-7/16]

experimental constraints

- $B \to X_s \ell^+ \ell^-$ $(\ell = e, \mu)$ branching ratio [BaBar PRL112, 211802(2014)] [Belle PRD72, 092005(2005)]
- $B_s \to \mu^+ \mu^+$ branching ratio [CMS+LHCb Nature 522, 68(2015)]
- $\Lambda_b \to \Lambda \mu^+ \mu^-$ [LHCb JHEP 06, 115(2015)]
  - branching ratio $\mathcal{B}$, three angular observables: F_0, A^{ℓ}_{FB}, $A^{\Lambda}_{\mathrm{FB}}$
  - integrated over entire low recoil bin $q^2 \geq 15\,\mathrm{GeV}^2$, denotes as $\langle\cdot\rangle_{15,20}$

theoretical inputs

updated $\Lambda_b \to \Lambda$ form factors [Detmold/Meinel 1602.01399]

- first calculation of full set of 10 form factors
- Lattice QCD expected to work as well as for $B \to K$ form factors
- full correlation information available

Fit Scenarios

[Meinel/DvD ZU-TH-7/16]

carry out Bayesian fit in three scenarios using EOS [http://github.com/eos/eos DvD/Beaujean/Bobeth]

- SM(ν-only) only fit free-floating nuisance parameters (form factors, CKM, . . .), keep $\mathcal{C}_{9,10}$ at SM values
- (9,10) in addition to nuisance parameters also fit $\mathcal{C}_{9,10}$
- (9,9',10,10') in addition to nuisance parameters also fit SM-like $\mathcal{C}_{9,10}$ contribution and BSM-like $\mathcal{C}_{9',10'}$, which have flipped quark chiralities

goodness of fit criteria for each scenario:

- χ^2 and p value at best-fit point

for model comparions (Bayes factor), for each scenario:

- evidence, obtained through black-box algorithm for adaptive importance sampling [Beaujean PhD thesis]

Fit Results: SM(ν-only)

preliminary!

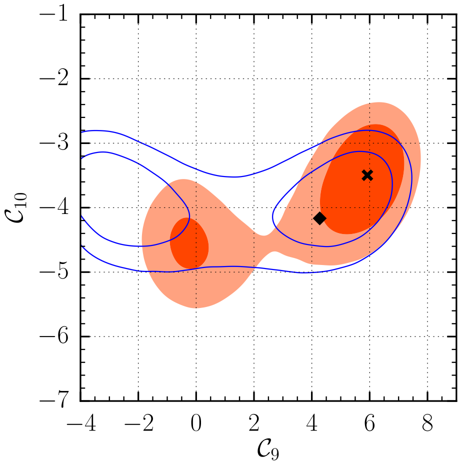
Constraint	Pull value [σ] SM(ν-only)	(9, 10)	(9, 9′, 10, 10′)
	$\Lambda_b \to \Lambda\mu^+\mu^-$		
$\langle\mathcal{B}\rangle_{15,20}$	$+0.86$		
$\langle F_0\rangle_{15,20}$	$+1.41$		
$\langle A_{FB}^{\ell}\rangle_{15,20}$	$+3.13$		
$\langle A_{FB}^{\Lambda}\rangle_{15,20}$	-0.26		
	$\overline{B}_s \to \mu^+\mu^-$		
$\int d\tau\mathcal{B}(\tau)$	-0.72		
	$\overline{B} \to X_s\ell^+\ell^-$		
$\langle\mathcal{B}\rangle_{1,6}$ (BaBar)	$+0.47$		
$\langle\mathcal{B}\rangle_{1,6}$ (Belle)	$+0.17$		
	χ^2 at best-fit point		
	13.40		

goodness of fit

- $\chi^2 = 13.4$ for 7 d.o.f.
- p value: 0.06
  - a-prior threshold: 0.03
  - barely acceptable
- one pull above 3σ!

Fit Results: (9,10)

preliminary!



best-fit point:

- $B \to K^* \mu^+ \mu^-$: $\mathcal{C}_9^{NP} \simeq -1$
- our fit prefers $\mathcal{C}_9^{NP} \simeq +1.5$, $\mathcal{C}_{10}^{NP} \simeq +1$!

lines: 68%, 95% prob. regions (incl. only)

areas: 68%, 95% prob. regions (all data)

♦: SM point ×: global mode

Fit Results: (9,10)

preliminary!

Constraint	Pull value $[\sigma]$ SM(ν-only)	(9, 10)	$(9, 9', 10, 10')$
	$\Lambda_b \to \Lambda\mu^+\mu^-$		
$\langle\mathcal{B}\rangle_{15,20}$	$+0.86$	-0.17	
$\langle F_0\rangle_{15,20}$	$+1.41$	$+1.41$	
$\langle A^{\ell}_{FB}\rangle_{15,20}$	$+3.13$	$+2.60$	
$\langle A^{\Lambda}_{FB}\rangle_{15,20}$	-0.26	-0.24	
	$\overline{B}_s \to \mu^+\mu^-$		
$\int \mathrm{d}\tau \mathcal{B}(\tau)$	-0.72	$+0.75$	
	$\overline{B} \to X_s\mu^+\mu^-$		
$\langle\mathcal{B}\rangle_{1,6}$ (BaBar)	$+0.47$	-0.26	
$\langle\mathcal{B}\rangle_{1,6}$ (Belle)	$+0.17$	-0.35	
	χ^2 at best-fit point		
	13.40	9.60	

goodness of fit:

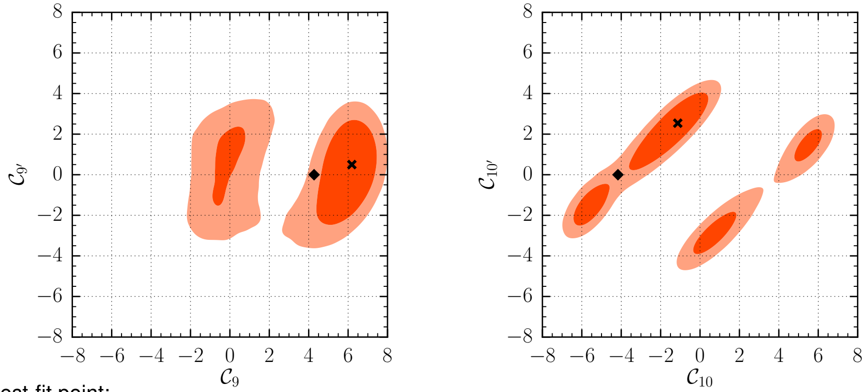
- χ^2 reduced to 9.60, only 5 d.o.f.
- p value: 0.09
  - acceptable
- A^{ℓ}_{FB} pull reduced to below 3σ!
- $\mathcal{C}_9^{NP} \simeq 1$ driven by $\langle\mathcal{B}\rangle_{15,20}$

model comparison:

- posterior odds compared to SM(ν-only) are 1:158
- decisively in favour of SM(ν-only)

Fit Results: (9,9',10,10')

preliminary!



best-fit point:

- $\mathcal{C}_9^{NP} \simeq +1$, $\mathcal{C}_{10}^{NP} = \mathcal{C}_{10'} = +2$
- driven by $\langle\mathcal{B}\rangle_{15,20}$ and $B_s \to \mu^+\mu^-$

areas: 68%, 95% prob. regions (all data)

◆: SM point ×: global mode

Fit Results: (9,9',10,10')

preliminary!

Constraint	Pull value [σ] SM(ν-only)	(9, 10)	(9, 9', 10, 10')
	$\Lambda_b \to \Lambda\mu^+\mu^-$		
$\langle\mathcal{B}\rangle_{15,20}$	$+0.86$	-0.17	-0.08
$\langle F_0\rangle_{15,20}$	$+1.41$	$+1.41$	$+1.41$
$\langle A_{FB}^{\ell}\rangle_{15,20}$	$+3.13$	$+2.60$	$+0.72$
$\langle A_{FB}^{\Lambda}\rangle_{15,20}$	-0.26	-0.24	-1.08
	$\overline{B}_s \to \mu^+\mu^-$		
$\int \mathrm{d}\tau\mathcal{B}(\tau)$	-0.72	$+0.75$	$+0.37$
	$\overline{B} \to X_s\mu^+\mu^-$		
$\langle\mathcal{B}\rangle_{1,6}$ (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

goodness of fit:

- χ^2 reduced to 3.87, only 3 d.o.f.
- p value: 0.28
  - good

model comparison:

- posterior odds compared to SM(ν-only) are $1 : 10^5$
- decisively in favour of SM(ν-only)

Conclusion

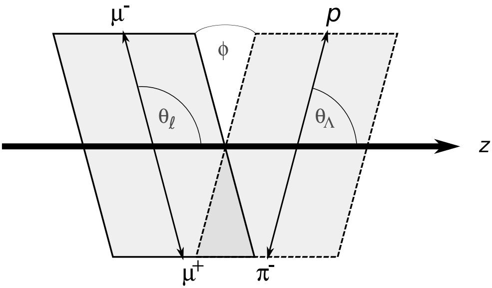
- the decay $\Lambda_b \to \Lambda(\to p\pi^-)\mu^+\mu^-$ yields powerful constraints on $b \to s\mu^+\mu^-$ Wilson coefficients
  - independent check of the tension in $B \to K^*\mu^+\mu^-$
  - complementary information to existing $B \to K^*\mu^+\mu^-$ constraints
  - same level of constrainting power as first LHCb data on $B \to K^*\mu^+\mu^-$
- theory status
  - low recoil: competetive with $B \to K^*\mu^+\mu^-$ at low recoil
  - large recoil: much work ahead!
- our nominal fit prefers $\mathcal{C}_9^{NP} \simeq +1.5$, $\mathcal{C}_{10}^{NP} \simeq +1$
  - compare $B \to K^*\mu^+\mu^-$: $\mathcal{C}_9^{NP} \sim -1$
  - SM still wins in model comparison with at least 158 : 1
  - large pull in A_{FB}^{ℓ} likely statistical fluctuation, looking forward to update after LHCb run 2

$\Lambda_b \to \Lambda\mu^+\mu^-$ ready for inclusion in global fits!

Appendix

Kinematics and Decay Topology

$$\Lambda_b(p) \to \Lambda(k)\,[\to p(k_1)\,\pi^-(k_2)]\,\ell^+(q_1)\,\ell^-(q_2)$$



3 independent decay angles

only for unpolarized Λ_b

- $\cos\theta_\Lambda \sim \overline{k}\cdot q$
  polar (helicity) angle in Λ rest frame
- $\cos\theta_\ell \sim k\cdot\overline{q}$
  polar (helicity) angle in $\ell^+\ell^-$ rest frame
- $\cos\phi \sim \overline{k}\cdot\overline{q}$
  azimuthal angle between decay planes

where $\overline{k} = k_1 - k_2$, $\overline{q} = q_1 - q_2$

Angular Distribution of $\Lambda_b \to \Lambda[\to p\pi^-]\ell^+\ell^-$

we define the angular distribution as

$$\frac{8\pi}{3}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_\Lambda\,\mathrm{d}\phi} \equiv K(q^2, \cos\theta_\ell, \cos\theta_\Lambda, \phi)$$

when considering only SM and chirality-flipped operators

$$\begin{aligned}
K = 1 &\left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right)\\
+\cos\theta_\Lambda &\left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\\
+\sin\theta_\Lambda\sin\phi &\left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\\
+\sin\theta_\Lambda\cos\phi &\left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)
\end{aligned}$$

no further observables possible up to mass-dimension six $\qquad K_n \equiv K_n(q^2)$

Angular Observables

– matrix elements parametrized through 8 transversity amplitudes $A^{\lambda}_{\chi_M}$

$$A^R_{\perp_1}\,,\ A^R_{\|_1}\,,\ A^R_{\perp_0}\,,\ A^R_{\|_0}\,,\ \text{and } (R \leftrightarrow L)$$

- λ dilepton chirality
- χ transversity state, similar as in $B \to K^*\ell^+\ell^-$
- M |third component| of dilepton angular momentum

– express angular observables through transversity amplitudes, e.g.

$$K_{1cc} = \frac{1}{2}\left[|A^R_{\perp_1}|^2 + |A^R_{\|_1}|^2 + (R \leftrightarrow L)\right]$$

$$K_{2c} = \frac{\alpha}{2}\left[|A^R_{\perp_1}|^2 + |A^R_{\|_1}|^2 - (R \leftrightarrow L)\right]$$

$$\vdots$$

α: parity violating $\Lambda \to p\pi^-$ coupling

full list of observables in the backup slides

Angular Observables

– matrix elements parametrized through 8 transversity amplitudes $A^{\lambda}_{\chi_M}$

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$$\vdots$$

α: parity violating $\Lambda \to p\pi^-$ coupling

full list of observables in the backup slides

$\Lambda \to N\pi$ Hadronic Matrix Element

- $\Lambda \to N\pi$ is a parity-violating weak decay
- branching fraction $\mathcal{B}[\Lambda \to N\pi] = (99.7 \pm 0.1)\%$ [PDG, our naive average]

- equations of motions reduce independent matrix elements to 2
- we choose to express them through
  - decay width Γ_Λ
  - parity-violating coupling α

- within small width approximation, Γ_Λ cancels
- α well known from experiment: $\alpha_{p\pi^-} = 0.642 \pm 0.013$ [PDG average]

$\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-$ Angular Observables

$$K_{1ss} = \frac{1}{4}\left[|A^R_{\perp_1}|^2 + |A^R_{\|_1}|^2 + 2|A^R_{\perp_0}|^2 + 2|A^R_{\|_0}|^2 + (R \leftrightarrow L)\right]$$

$$K_{1cc} = \frac{1}{2}\left[|A^R_{\perp_1}|^2 + |A^R_{\|_1}|^2 + (R \leftrightarrow L)\right]$$

$$K_{1c} = -\operatorname{Re}\left(A^R_{\perp_1} A^{*R}_{\|_1} - (R \leftrightarrow L)\right)$$

$$K_{2ss} = -\frac{\alpha}{2}\operatorname{Re}\left(A^R_{\perp_1} A^{*R}_{\|_1} + 2A^R_{\perp_0} A^{*R}_{\|_0} + (R \leftrightarrow L)\right)$$

$$K_{2cc} = -\alpha\operatorname{Re}\left(A^R_{\perp_1} A^{*R}_{\|_1} + (R \leftrightarrow L)\right)$$

$$K_{2c} = \frac{\alpha}{2}\left[|A^R_{\perp_1}|^2 + |A^R_{\|_1}|^2 - (R \leftrightarrow L)\right]$$

$$K_{3sc} = -\frac{\alpha}{\sqrt{2}}\operatorname{Im}\left(A^R_{\perp_1} A^{*R}_{\perp_0} - A^R_{\|_1} A^{*R}_{\|_0} + (R \leftrightarrow L)\right)$$

$$K_{3s} = -\frac{\alpha}{\sqrt{2}}\operatorname{Im}\left(A^R_{\perp_1} A^{*R}_{\|_0} - A^R_{\|_1} A^{*R}_{\perp_0} + (R \leftrightarrow L)\right)$$

$$K_{4sc} = \frac{\alpha}{\sqrt{2}}\operatorname{Re}\left(A^R_{\perp_1} A^{*R}_{\perp_0} - A^R_{\|_1} A^{*R}_{\|_0} + (R \leftrightarrow L)\right)$$

$$K_{4s} = \frac{\alpha}{\sqrt{2}}\operatorname{Re}\left(A^R_{\perp_1} A^{*R}_{\|_0} - A^R_{\|_1} A^{*R}_{\perp_0} - (R \leftrightarrow L)\right)$$

Observables at Low Recoil

- 3 forward-backward asymmetries: A_{FB}^{ℓ}, A_{FB}^{Λ}, $A_{FB}^{\ell\Lambda}$
- rate of longitudinally-polarized leptons: F_0
- LHCb has measured them with the exception of $A_{FB}^{\ell\Lambda}$

Sensitivities to Wilson Coefficients $\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}$

$$F_0 \sim \rho_1^{\pm} \sim |\mathcal{C}_{79} \pm \mathcal{C}_{7'9'}|^2 + |\mathcal{C}_{10} \pm \mathcal{C}_{10'}|^2$$

$$A_{FB}^{\ell} \sim \text{Re}\{\rho_2\} \sim \text{Re}\{\mathcal{C}_{79}\mathcal{C}_{10}^{*} - \mathcal{C}_{7'9'}\mathcal{C}_{10'}^{*}\}$$

$$A_{FB}^{\ell\Lambda} \sim \rho_3^{\pm} \sim \text{Re}\{(\mathcal{C}_{79} \pm \mathcal{C}_{7'9'})(\mathcal{C}_{10} \pm \mathcal{C}_{10'})\}$$

$$A_{FB}^{\Lambda} \sim \text{Re}\{\rho_4\} \sim |\mathcal{C}_{79}|^2 - |\mathcal{C}_{7'9'}|^2 + |\mathcal{C}_{10}|^2 - |\mathcal{C}_{10'}|^2$$

- $\rho_1^{\pm}$, ρ_2 also arise in $B \to K^{(*)}\ell^+\ell^-$ decays
- $\rho_3^{\pm}$, ρ_4 provide new and complementary constraints on Wilson coefficients!
  - ρ_3^{-}, ρ_4 also emerge in non-resonant $B \to K\pi\ell^+\ell^-$
    [Das/Hiller/Jung/Shires 1406.6681]

Simple Observables

start with integrated decay width

$$\Gamma = 2K_{1ss} + K_{1cc}$$

define further observables X as weighted (ω_X) integrals

$$X = \frac{1}{\Gamma} \int \frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_\ell \,\mathrm{d}\cos\theta_\Lambda \,\mathrm{d}\phi} \omega_X(\cos\theta_\ell, \cos\theta_\Lambda, \phi) \mathrm{d}\cos\theta_\ell \,\mathrm{d}\cos\theta_\Lambda \,\mathrm{d}\phi$$

A leptonic forward-backward asymmetry

$$A^\ell_{\mathrm{FB}} = \frac{3}{2} \frac{K_{1c}}{2K_{1ss} + K_{1cc}} \qquad \text{with } \omega_{A^\ell_{\mathrm{FB}}} = \text{sign} \cos\theta_\ell$$

B fraction of longitudinal dilepton pairs

$$F_0 = \frac{2K_{1ss} - K_{1cc}}{2K_{1ss} + K_{1cc}} \qquad \text{with } \omega_{F_0} = 2 - 5\cos^2\theta_\ell$$

Simple Observables

start with integrated decay width

$$\Gamma = 2K_{1ss} + K_{1cc}$$

define further observables X as weighted (ω_X) integrals

$$X = \frac{1}{\Gamma} \int \frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_\Lambda\,\mathrm{d}\phi} \omega_X(\cos\theta_\ell, \cos\theta_\Lambda, \phi) \mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_\Lambda\,\mathrm{d}\phi$$

C hadronic forward-backward asymmetry

$$A^\Lambda_{\mathrm{FB}} = \frac{1}{2} \frac{2K_{2ss} + K_{2cc}}{2K_{1ss} + K_{1cc}} \qquad \text{with } \omega_{A^\ell_{\mathrm{FB}}} = \text{sign} \cos\theta_\Lambda$$

D combined forward-backward asymmetry

$$A^{\ell\Lambda}_{\mathrm{FB}} = \frac{3}{4} \frac{K_{2c}}{2K_{1ss} + K_{1cc}} \qquad \text{with } \omega_{A^\ell_{\mathrm{FB}}} = \text{sign} \cos\theta_\Lambda \ \text{sign} \cos\theta_\ell$$