The decay $\Lambda_b \to \Lambda(\to p\pi^-)\ell^+\ell^-$

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Implications of LHCb Measurements and future prospects
November 4th, 2015

based on arXiv:1410.2115, in collaboration with P. Böer and Th. Feldmann

Why bother with $\Lambda_b \to \Lambda\ell^+\ell^-$?

$B \to K^*\ell^+\ell^-$ is being measured with increasing precision. Why spend effort on $\Lambda_b \to \Lambda\ell^+\ell^-$?

pro arguments, sorted from weakest to strongest

- independent confirmation of results: same $b \to s\ell^+\ell^-$ operators, different hadronic matrix elements
- $\Gamma_\Lambda \simeq 2.5 \cdot 10^{-6}$ eV: small width approximation fully applicable (compare $B \to K\pi\ell^+\ell^-$ where non-res. P-wave contributions are unconstrained)
- doubly weak decay: complementary constraints on $b \to s\ell^+\ell^-$ physics with respect to $B \to K^*\ell^+\ell^-$

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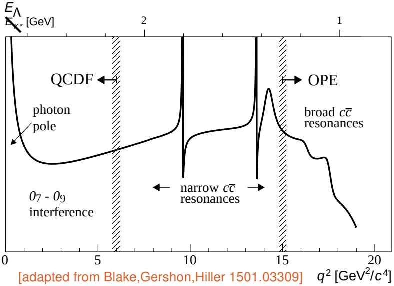
$\Lambda_b \to \Lambda$ Hadronic Matrix Elements



[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

Low Recoil

✓ form factor relations

✓ OPE

✓ form factor (leading power only)
[Detmold/Lin/Meinel/Wingate 1212.4827]

w.i.p. FF beyond leading power
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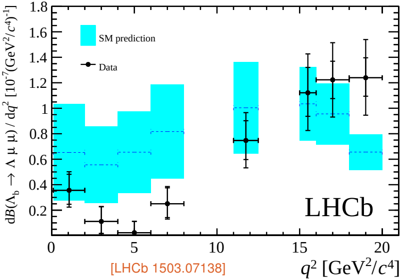

[LHCb 1503.07138]

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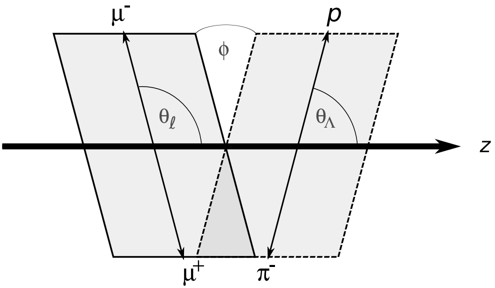
Kinematics and Decay Topology

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



3 independent decay angles

only for unpolarized Λ_b

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

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

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

$K_n \equiv K_n(q^2)$

Angular Observables

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

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

- 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.

$$K_{1cc} = \frac{1}{2}\left[|A_{\perp_1}^{R}|^2 + |A_{\|_1}^{R}|^2 + (R \leftrightarrow L)\right]$$
$$K_{2c} = \frac{\alpha}{2}\left[|A_{\perp_1}^{R}|^2 + |A_{\|_1}^{R}|^2 - (R \leftrightarrow L)\right]$$
$$\vdots$$

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

full list of observables in the backup slides

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Observables at Low Recoil

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

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

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

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

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

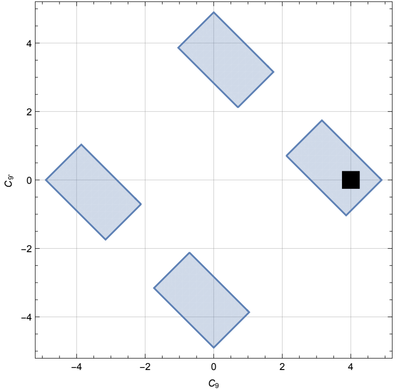
$$A^{\Lambda}_{\mathrm{FB}} \sim \mathrm{Re}\{\rho_4\} \sim |\mathcal{C}_{79}|^2 - |\mathcal{C}_{7'9'}|^2 + |\mathcal{C}_{10}|^2 - |\mathcal{C}_{10'}|^2$$

- $\rho_1^{\pm}$, 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]

New Types of Constraints

moch fit of $\mathcal{C}_{9(9')}$ given hypothetical measurements, while keeping

$$\mathcal{C}_{10(10')} = \mathcal{C}_{10(10')}^{\mathrm{SM}} \simeq (-4, 0) \text{ fixed}$$



- existing constraints
  - $\rho_1^{\pm}$ blue banded constraints
  - ρ_2 golden banded constraint
- new constraints
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black square: SM point

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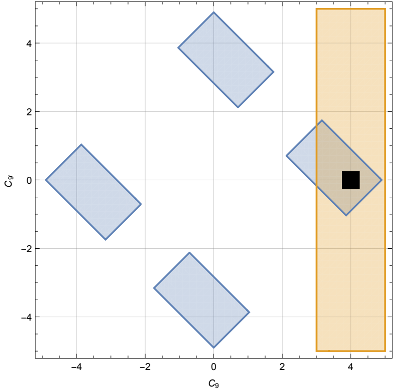

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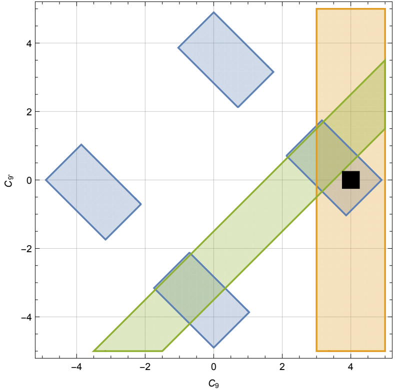

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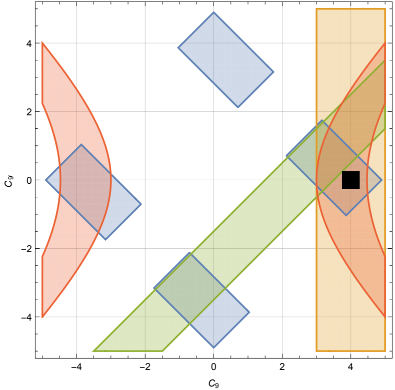

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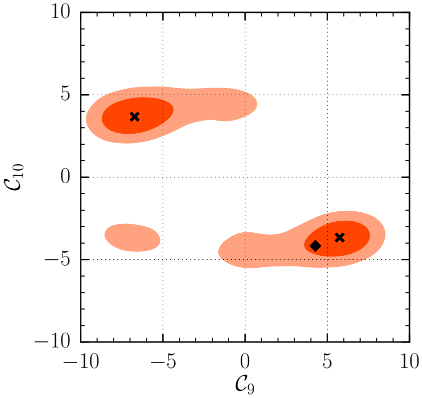
Fit

preliminary! [Meinel,DvD w.i.p.]



setup as in [Beaujean,Bobeth,DvD 1310.2478]

- $B \to X_s\{\gamma, \ell^+\ell^-\}$ (Belle,BaBar)
- $B_s \to \mu^+\mu^+$ (CMS+LHCb)
- $\Lambda_b \to \Lambda\ell^+\ell^-$ (LHCb)
  - $\mathcal{B}$, F_0, A^ℓ_{FB}, A^Λ_{FB}
  - low-recoil data only!
- $\Lambda_b \to \Lambda$ form factors
  - lattice results in heavy-quark limit [Detmold,Lin,Meinel,Wingate 1212.4827]
  - sum rule results in large-energy limit [Feldmann,Yip 1111.1844]
- χ^2/d.o.f. $= 4.77/14 \Rightarrow p = 0.98$
- prefers $\mathcal{C}_9^{NP} \simeq +1$!

shaded areas: 68%, 95% prob. regions

♦: SM point ×: local modes

Conclusion

- the decay $\Lambda_b \to \Lambda(\to p\pi^-)\ell^+\ell^-$ yields powerful constraints on $b \to s\ell^+\ell^-$ Wilson coefficients
  - 10 angular observables
  - independent check of the tension in $B \to K^*\ell^+\ell^-$
  - complementary information to existing $B \to K^*\ell^+\ell^-$ constraints
- theory status
  - low recoil: catching up to $B \to K^*\ell^+\ell^-$
  - large recoil: much work ahead!
- fit prefers $\mathcal{C}_9^{NP} \sim +1$, $\mathcal{C}_{7,10}^{NP} \simeq 0$
  - compare $B \to K^*\ell^+\ell^-$: $\mathcal{C}_9^{NP} \sim -1$

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

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

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

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

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

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

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

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

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

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

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

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

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

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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

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