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

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Implications of LHCb Measurements and future prospects
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Why bother with $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$?

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

**pro** arguments, sorted from weakest to strongest

- independent confirmation of results: same $b \rightarrow s \ell^+ \ell^-$ operators, different hadronic matrix elements
- $\Gamma_\Lambda \simeq 2.5 \cdot 10^{-6}$ eV: small width approximation fully applicable (compare $B \rightarrow K \pi \ell^+ \ell^-$ where non-res. $P$-wave contributions are unconstrained)
- doubly weak decay: complementary constraints on $b \rightarrow s \ell^+ \ell^-$ physics with respect to $B \rightarrow K^* \ell^+ \ell^-$
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$\Lambda_b \rightarrow \Lambda$ 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
[Meinel 1401.2685]

04.11.2015 $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi^-)\ell^+\ell^-$
**Λ_b → Λ Hadronic Matrix Elements**

![Graph showing the SM prediction and data for the branching ratio as a function of \( q^2 \) in GeV^2/c^4.]

**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
  - [Meinel 1401.2685]
Kinematics and Decay Topology

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

3 independent decay angles only for unpolarized \( \Lambda_b \)

- \( \cos \theta_\Lambda \sim \overline{k} \cdot q \)
  polar (helicity) angle in \( \Lambda \) 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

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

when considering only SM and chirality-flipped operators

$$K = 1 \left( K_{1ss} \sin^2\theta_\ell + K_{1cc} \cos^2\theta_\ell + K_{1c} \cos\theta_\ell \right)$$

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

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

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

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 $A^{\lambda \chi M}_{\lambda \chi M}$

\[ A^R_{\perp 1}, A^R_{\parallel 1}, A^R_{\perp 0}, A^R_{\parallel 0}, \text{ and } (R \leftrightarrow L) \]

\( \lambda \) dilepton chirality
\( \chi \) transversity state, similar as in $B \rightarrow K^* \ell^+ \ell^-$
\( M \) third component of dilepton angular momentum

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

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

\[ K_{2c} = \frac{\alpha}{2} \left[ |A^R_{\perp 1}|^2 + |A^R_{\parallel 1}|^2 - (R \leftrightarrow L) \right] \]

\[ \vdots \]

\( \alpha \): parity violating $\Lambda \rightarrow p \pi^-\pi^0$ coupling

full list of observables in the backup slides
Angular Observables

- matrix elements parametrized through 8 transversity amplitudes $A_{\lambda M}$

$$A_{\perp 1}^R, A_{\parallel 1}^R, A_{\perp 0}^R, A_{\parallel 0}^R,$$ and $(R \leftrightarrow L)$

$\lambda$ dilepton chirality

$\chi$ transversity state, similar as in $B \rightarrow K^* \ell^+ \ell^-$

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...$

$\alpha$: parity violating $\Lambda \rightarrow p \pi^-$ coupling

full list of observables in the backup slides
Observables at Low Recoil

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

Sensitivities to Wilson Coefficients $C_7, C_9, C_{10}$

\[
F_0 \sim \rho_1^\pm \sim |C_{79} \pm C_{7'9'}|^2 + |C_{10} \pm C_{10'}|^2
\]
\[
A_{FB}^{\ell} \sim \text{Re}\{\rho_2\} \sim \text{Re}\{C_{79}C_{10}^* - C_{7'9'}C_{10'}^*\}
\]
\[
A_{FB}^{\ell\Lambda} \sim \rho_3^\pm \sim \text{Re}\{(C_{79} \pm C_{7'9'})(C_{10} \pm C_{10'})\}
\]
\[
A_{FB}^{\Lambda} \sim \text{Re}\{\rho_4\} \sim |C_{79}|^2 - |C_{7'9'}|^2 + |C_{10}|^2 - |C_{10'}|^2
\]

- $\rho_1^\pm$, $\rho_2$ also arise in $B \to K(\ast)\ell^+\ell^-$ decays
- $\rho_3^\pm$, $\rho_4$ provide new and complementary constraints on Wilson coefficients!
  - $\rho_3^-$, $\rho_4$ also emerge in non-resonant $B \to K\pi\ell^+\ell^-$

[Das/Hiller/Jung/Shires 1406.6681]
New Types of Constraints

moch fit of $C_{9(9')}^{}$ given hypothetical measurements, while keeping

$$C_{10(10')}^{} = C_{10(10')}^{\text{SM}} \simeq (-4, 0) \text{ fixed}$$

- existing constraints
  - $\rho_1^\pm$ blue banded constraints
  - $\rho_2^{}$ golden banded constraint

- new constraints
  - $\rho_3^{}$ green banded constraints
  - $\rho_4^{}$ red hyperbolic constraint

black square: SM point

04.11.2015  $\Lambda_b \rightarrow \Lambda(\rightarrow \rho \pi^-) \ell^++\ell^-$
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New Types of Constraints

moch fit of $C_{9(9')}$ given hypothetical measurements, while keeping $C_{10(10')} = C^{SM}_{10(10')} \simeq (-4, 0)$ fixed

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black square: SM point
Fit

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)
  - $B, F_0, A^\ell_{FB}, A^\Lambda_{FB}$
  - 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]
- $\chi^2 / \text{d.o.f.} = 4.77 / 14 \Rightarrow p = 0.98$
- prefers $C_9^{NP} \simeq +1$!

shaded areas: 68%, 95% prob. regions
◆: SM point  ×: local modes
Conclusion

– the decay $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi^-)\ell^+\ell^-$ yields powerful constraints on $b \rightarrow s\ell^+\ell^-$ Wilson coefficients
  – 10 angular observables
  – independent check of the tension in $B \rightarrow K^*\ell^+\ell^-$
  – complementary information to existing $B \rightarrow K^*\ell^+\ell^-$ constraints
– theory status
  – low recoil: catching up to $B \rightarrow K^*\ell^+\ell^-$
  – large recoil: much work ahead!
– fit prefers $C_{9}^{NP} \sim +1, C_{7,10}^{NP} \sim 0$
  – compare $B \rightarrow K^*\ell^+\ell^-$: $C_{9}^{NP} \sim -1$
Backup Slides
$\Lambda \rightarrow N\pi$ Hadronic Matrix Element

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

– equations of motions reduce independent matrix elements to 2
– we choose to express them through
  – decay width $\Gamma_\Lambda$
  – parity-violating coupling $\alpha$

– within small width approximation, $\Gamma_\Lambda$ cancels
– $\alpha$ well known from experiment: $\alpha_{\rho\pi^-} = 0.642 \pm 0.013$ [PDG average]
\[ \Lambda_b \rightarrow \Lambda(\rightarrow \Lambda N \pi) \ell^+ \ell^- \] Angular Observables

\begin{align*}
K_{1ss} &= \frac{1}{4} \left[ |A_{\perp 1}^R|^2 + |A_{\parallel 1}^R|^2 + 2|A_{\perp 0}^R|^2 + 2|A_{\parallel 0}^R|^2 + (R \leftrightarrow L) \right] \\
K_{1cc} &= \frac{1}{2} \left[ |A_{\perp 1}^R|^2 + |A_{\parallel 1}^R|^2 + (R \leftrightarrow L) \right] \\
K_{1c} &= -\Re \left( A_{\perp 1}^R A_{\parallel 1}^{*R} - (R \leftrightarrow L) \right) \\
K_{2ss} &= -\frac{\alpha}{2} \Re \left( A_{\perp 1}^R A_{\parallel 1}^{*R} + 2A_{\perp 0}^R A_{\parallel 0}^{*R} + (R \leftrightarrow L) \right) \\
K_{2cc} &= -\alpha \Re \left( A_{\perp 1}^R A_{\parallel 1}^{*R} + (R \leftrightarrow L) \right) \\
K_{2c} &= \frac{\alpha}{2} \left[ |A_{\perp 1}^R|^2 + |A_{\parallel 1}^R|^2 - (R \leftrightarrow L) \right] \\
K_{3sc} &= -\frac{\alpha}{\sqrt{2}} \Im \left( A_{\perp 1}^R A_{\perp 0}^{*R} - A_{\parallel 1}^R A_{\parallel 0}^{*R} + (R \leftrightarrow L) \right) \\
K_{3s} &= -\frac{\alpha}{\sqrt{2}} \Im \left( A_{\perp 1}^R A_{\parallel 0}^{*R} - A_{\parallel 1}^R A_{\perp 0}^{*R} + (R \leftrightarrow L) \right) \\
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\end{align*}
Simple Observables

start with integrated decay width

\[ \Gamma = 2K_{1ss} + K_{1cc} \]

define further observables \( \mathcal{X} \) as weighted \((\omega_{\mathcal{X}})\) integrals

\[ \mathcal{X} = \frac{1}{\Gamma} \int \frac{d^3\Gamma}{d\cos\theta_\ell \ d\cos\theta_\Lambda \ d\phi} \omega_{\mathcal{X}}(\cos\theta_\ell, \cos\theta_\Lambda, \phi) d\cos\theta_\ell \ d\cos\theta_\Lambda \ d\phi \]

A  leptonic forward-backward asymmetry

\[ A_{FB}^{\ell} = \frac{3}{2} \frac{K_{1c}}{2K_{1ss} + K_{1cc}} \quad \text{with} \quad \omega_{A_{FB}^{\ell}} = \text{sign} \cos\theta_\ell \]

B  fraction of longitudinal dilepton pairs

\[ F_0 = \frac{2K_{1ss} - K_{1cc}}{2K_{1ss} + K_{1cc}} \quad \text{with} \quad \omega_{F_0} = 2 - 5 \cos^2\theta_\ell \]
Simple Observables

start with integrated decay width

\[ \Gamma = 2K_{1ss} + K_{1cc} \]

define further observables \( X \) as weighted \( (\omega_X) \) integrals

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

C hadronic forward-backward asymmetry

\[ A_{FB}^\Lambda = \frac{1}{2} \frac{2K_{2ss} + K_{2cc}}{2K_{1ss} + K_{1cc}} \quad \text{with} \quad \omega_{A_{FB}^\Lambda} = \text{sign} \cos \theta_\Lambda \]

D combined forward-backward asymmetry

\[ A_{FB}^{\ell \Lambda} = \frac{3}{4} \frac{K_{2c}}{2K_{1ss} + K_{1cc}} \quad \text{with} \quad \omega_{A_{FB}^{\ell \Lambda}} = \text{sign} \cos \theta_\Lambda \, \text{sign} \cos \theta_\ell \]