\( \Lambda_b \rightarrow \Lambda^0 \mu \mu \) angular analysis

Luca Pescatore

on behalf of the LHCb collaboration
Rare decays and $\Lambda_b$

- Rare decays are suppressed in the SM and can happen at loop level only.
  - Flavour Changing Neutral Current processes → forbidden at tree level in the SM
  - New Physics can enter in the loop
    - Very sensitive to new physics effects → small SM component: BR typically $\sim 10^{-6}$ or less
    - No evidence in direct searches so far → loops can probe high energy scales

$\Lambda_b$ decays

- Has non-zero spin: unlike B mesons allows to improve the understanding of the helicity structure
- Particular hadronic physics (heavy quark + diquark)
- Different treatments of form factors depending on the $q^2$ region → can be tested comparing predictions as a function of $q^2$

\[ q^2 = m_{\mu\mu}^2 \]

T. Gutsche et al., PRD87 (2013) 074031

arXiv:1501.0339v1
$\Lambda_b \rightarrow \Lambda^0 \mu\mu$ branching ratio

- Reconstructed using the $\Lambda^0 \rightarrow p\pi$ mode
- $J/\psi \Lambda^0$ used to normalise the BR
- Particular topology with long-lived $\Lambda^0$: only background from $B \rightarrow K_S$ decays
- Analysis on $3\text{fb}^{-1}$: ~300 observed events

Branching ratio:

- $1.1 < q^2 < 6.0$: $0.09^{+0.06}_{-0.05}$ (stat) $+0.01_{-0.01}$ (syst) $+0.02_{-0.02}$ (norm)
- $15.0 < q^2 < 20.0$: $1.18^{+0.09}_{-0.08}$ (stat) $+0.03_{-0.03}$ (syst) $+0.27_{-0.07}$ (norm)

LHCB-PAPER-2015-009
to be submitted to JHEP

First evidence for signal above $3\sigma$ level at low $q^2$

Inner error: stat. + syst.
Outer error: including normalisation (dominant)

Already observed at CDF (PRL 107 2011 201802) and LHCb (PLB725 2013 25) only in $q^2$ above $\psi(2S)$.
Angular analysis

- In $\Lambda_b \rightarrow \Lambda^0 \mu\mu$ the $\Lambda^0$ decays weakly
  $\rightarrow$ unlike for B decays the hadronic side asymmetry is also interesting
- Measure two forward-backward asymmetries: in dimuon and $\Lambda^0$ system
- Selection based on a neural network classifier
- Fit one-dimensional angular distributions

\[
\frac{d\Gamma}{dq^2 d\cos \theta_h} \propto (1 + 2A^h_{FB} \cos \theta_h)
\]

\[
\frac{d\Gamma}{dq^2 d\cos \theta_\ell} \propto \frac{3}{8} (1 + \cos \theta_\ell)(1 - f_L) + A^\ell_{FB} \cos \theta_\ell + \frac{3}{4} f_L \sin^2 \theta_\ell
\]
Angular analysis

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**Forward-backward asymmetry in the dimuon system**

\[
\frac{d\Gamma}{dq^2 d\cos \theta_h} \propto (1 + 2A_{FB}^h \cos \theta_h)
\]

\[
\frac{d\Gamma}{dq^2 d\cos \theta_\ell} \propto \frac{3}{8} (1 + \cos \theta_\ell)(1 - f_L) - A_{FB}^\ell \cos \theta_\ell + \frac{3}{4} f_L \sin^2 \theta_\ell
\]
Angular analysis

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New!

Fraction of longitudinally polarised dimuons

$$\frac{d\Gamma}{dq^2 d\cos \theta_h} \propto (1 + 2A^h_{FB} \cos \theta_h)$$

$$\frac{d\Gamma}{dq^2 d\cos \theta_\ell} \propto \frac{3}{8} \left(1 + \cos \theta_\ell \right) \left(1 - f_L \right) + A^\ell_{FB} \cos \theta_\ell + \frac{3}{4} f_L \sin^2 \theta_\ell$$
Angular analysis

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$$PDF^{tot}(\cos \theta_i) = [f^{theory}(\cos \theta_i) + f^{bkg}(\cos \theta_i)] \times \varepsilon(\cos \theta_i)$$

Most challenging:
  asymmetric acceptance.

15 < $q^2 < 20$ GeV$^2$/c$^4$

LHCb Preliminary

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Angular analysis: results

- Asymmetries as a function of $q^2$
- Only where the signal significance is above $3\sigma$
- Physical boundaries in the parameter-space: → using Feldman-Cousins inspired “plug-in” method

- $A_{FB}^h$ is in good agreement with SM prediction
- $A_{FB}^l$ is compatible within 2 sigma but consistently above the prediction
  → Could be due large $c\bar{c}$ contributions.

LHCb Preliminary

Theory: arXiv:1401.2685

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Preliminary
Summary

- Updated measurement of $\Lambda_b \rightarrow \Lambda^0 \mu \mu$ with errors improved by a factor of $\sim$3
- First evidence of signal at low $q^2$
- First measurement of angular observables
- The study of $\Lambda_b$ and its decays is still young but staidly growing: recent measurements of mass, lifetime, polarisations and more.

Thank you for listening!
Backup
Angular analysis: uncertainties

- **Statistical uncertainties:**
  - Lepton side PDF has physical boundaries → can bias the uncertainties
  - Likelihood-ordering method treating nuisance parameters with the plug-in method used for uncertainties (arXiv:1109.0714)
    - ✓ Based on toy experiments
    - ✓ Well defined frequentist coverage

  Dark area: region of the parameter space where the PDF is positive.

- **Systematics:**
  - Effect of a non-flat efficiency on the integration of the full 5D angular PDF
  - Data-MC discrepancies (MC used for most of the efficiencies)
  - Particular choice of background parameterisation
  - Effect of finite angular resolution → asymmetric bin migration
Feldman-Cousins method

- Feldman-Cousins method plug-in method to extract confidence bands
  - Choose Parameters of Interest (PoI) and fit data with PoI free and fixed
  - Generate toys with PoI fixed to tested values and nuisance parameters (all other parameters) from fixed fit on data.
  - Fit toys with free and fixed PoI
  - Look how many times log likelihood ratio in data is smaller than MC
  - Scan values to look for 68%, 95% etc.

\[
\left( \frac{\log L_{\text{free}}}{\log L_{\text{fixed}}} \right)_{\text{data}} < \left( \frac{\log L_{\text{free}}}{\log L_{\text{fixed}}} \right)_{\text{MC}}
\]

Statistica Sinica 19 (2009) 301
arXiv:1109.0714v1

- Starts to be widely used in LHCb
- Allows to consider nuisance parameters: no confidence belt
- Guarantees full coverage
- Returns 2-side intervals and upper limits in a unified approach
Using $J/\psi \Lambda$ for cross-check

![Graphs showing leptonic and hadronic angles for $J/\psi \Lambda$ decay candidates at LHCb.](image)

L. Pescatore
Rare decays at LHCb
HEPFT, 2014
Angular acceptances

In LHCb long-lived particles, like $\Lambda^0$, can be reconstructed with hits in the VELO (log) or without hits in the VELO (downstream).

- Up- and down-stream events are characterised by different efficiency and resolution
- A simultaneous fit is performed on the two categories
Table 6: Measured values of leptonic and hadronic angular observables. The first uncertainties are statistical and the second systematic. The statistical uncertainties on $A_{	ext{FB}}^{\ell}$ and $f_L$ are also reported in Fig. 12, evaluated as two-dimensional 68% confidence level regions. The uncertainties reported in this table are estimates obtained using the Feldman-Cousins method where only one of the two observables is treated as parameter of interest at a time.

<table>
<thead>
<tr>
<th>$q^2$ interval [ GeV$^2$/c$^4$ ]</th>
<th>$A_{	ext{FB}}^{\ell}$</th>
<th>$f_L$</th>
<th>$A_{	ext{FB}}^{h}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1–2.0</td>
<td>0.37 $^{+0.37}_{-0.48}$ ± 0.03</td>
<td>0.56 $^{+0.23}_{-0.56}$ ± 0.08</td>
<td>$-0.12^{+0.31}_{-0.28}$ ± 0.15</td>
</tr>
<tr>
<td>11.0–12.5</td>
<td>0.01 $^{+0.19}_{-0.18}$ ± 0.06</td>
<td>0.40 $^{+0.37}_{-0.36}$ ± 0.06</td>
<td>$-0.50^{+0.10}_{-0.00}$ ± 0.04</td>
</tr>
<tr>
<td>15.0–16.0</td>
<td>$-0.10^{+0.18}_{-0.16}$ ± 0.03</td>
<td>0.49 $^{+0.30}_{-0.30}$ ± 0.05</td>
<td>$-0.19^{+0.14}_{-0.16}$ ± 0.03</td>
</tr>
<tr>
<td>16.0–18.0</td>
<td>$-0.07^{+0.13}_{-0.12}$ ± 0.04</td>
<td>0.68 $^{+0.15}_{-0.21}$ ± 0.05</td>
<td>$-0.44^{+0.10}_{-0.05}$ ± 0.03</td>
</tr>
<tr>
<td>18.0–20.0</td>
<td>0.01 $^{+0.15}_{-0.14}$ ± 0.04</td>
<td>0.62 $^{+0.24}_{-0.27}$ ± 0.04</td>
<td>$-0.13^{+0.09}_{-0.12}$ ± 0.03</td>
</tr>
<tr>
<td>15.0–20.0</td>
<td>$-0.05^{+0.09}_{-0.09}$ ± 0.03</td>
<td>0.61 $^{+0.11}_{-0.14}$ ± 0.03</td>
<td>$-0.29^{+0.07}_{-0.07}$ ± 0.03</td>
</tr>
</tbody>
</table>
fL values

![Graph showing fL values vs. q^2 [GeV^2/c^4]](image)

LHCb

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Confidence regions

LHCb

[11.0, 12.5] GeV²/c⁴

LHCb

[15.0, 16.0] GeV²/c⁴

LHCb

[16.0, 18.0] GeV²/c⁴

LHCb

[18.0, 20.0] GeV²/c⁴
Recent $\Lambda_b$ measurements at LHCb:

- Lifetime: $1.482 \pm 0.021$ ps (PRL 111 (2013) 102003)
- Polarisation: $0.06 \pm 0.09$ (PLB 724 (2013) 27)
- Mass: $5619.44 \pm 0.51$ (PRL 110 (2013) 182001)
- Hadronization fraction: (PRD 85 (2012) 032008)
  $$f_\Lambda/f_d = (0.387 \pm 0.043) + (0.067 \pm 0.017)(\eta - 3.198)$$
q^2 spectrum DNA

Fit on J/ψΛ mass

Candidates per 10 MeV/c²

\[ M(Λμμ) \text{ [MeV/c}^2\text{]} \]

LHCb
Selection

<table>
<thead>
<tr>
<th>Variable</th>
<th>DecayTreeFitter $\chi^2$</th>
<th>$\Lambda_b$ lifetime and DIRA $IP\chi^2$ of $\Lambda_b$, p, $\pi$ and $\mu$</th>
<th>$\mu$ PID $\Lambda^0$, $IP\chi^2$, FD $\Lambda^0$, $p$ and $\pi$ $p_T$</th>
</tr>
</thead>
</table>

Flight distance

Momenta help distinguishing combinatorial

DecayTreeFitter: $\chi^2$ of a kinematically constrained refit

PID using information from RICH and muon detector

Training: signal MC and sideband background

Efficiency evaluated

Optimisation

Maximised:
- Significance at high $q^2$
- Punzi FoM at low $q^2$
(best for unobserved signals)

$P = \frac{S}{n\sigma/2 + \sqrt{B}}$

Moriond EW, YSF  
L. Pescatore
Angular analysis

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![Graph showing angular analysis results](image)
**Λ_b → Λ^0μμ** branching ratio

- Already observed at CDF ([PRL 107 2011 201802](#)) and LHCb ([PLB725 2013 25](#)) but only in the low q^2 region
- Reconstructed using the Λ→ππ mode
- J/ψΛ as normalisation to limit systematics
- Analysis on 3fb^-1: ~300 observed events
- Peaking background from B→KS decays modelled in fit.

**Branching ratio:**

- 1.1 < q^2 < 6.0 \( 0.09 \pm 0.05 \) (stat) \( \pm 0.02 \) (norm)
- 15.0 < q^2 < 20.0 \( 1.18 \pm 0.08 \) (stat) \( \pm 0.27 \) (norm)

LHCB-PAPER-2015-009

to be submitted to JHEP

Relative branching fraction

First observation at 3σ level at low q^2

Inner error: total systematic
Outer error: statistical (dominant)
Λ_b→Λ^0\mu\mu branching ratio

- Already observed at CDF (PRL 107 2011 201802) and LHCb (PLB725 2013 25) but only in the low q^2 region.
- Reconstructed using the Λ→pπ mode.
- J/ψΛ as normalisation to limit systematics.
- Analysis on 3fb^{-1}: ~300 observed events.
- Peaking background from B→K_S decays modelled in fit.

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Branching ratio:

- 1.1 < q^2 < 6.0: 0.09^{+0.06}_{-0.05} (stat) + 0.01 (syst) + 0.02 (norm)
- 15.0 < q^2 < 20.0: 1.18^{+0.09}_{-0.08} (stat) + 0.03 (syst) + 0.27 (norm)

Compatible with the SM within 1.5σ.
Prediction: PRD 87 (2013) 074502

Inner error: stati + syst
Outer error: including normalisation (dominant)
\( \Lambda_b \rightarrow \Lambda^0 \mu\mu \) branching ratio

- Already observed at CDF (PRL 107 2011 201802) and LHCb (PLB725 2013 25) but only in the high \( q^2 \) region, above \( \psi(2S) \)
- Reconstructed using the \( \Lambda \rightarrow p\pi \) mode
- \( J/\psi \Lambda \) as normalisation to limit systematics
- Analysis on 3fb\(^{-1}\): \( \sim \)300 observed events
- Peaking background from \( B \rightarrow K_S \) decays modelled in fit.

**Branching ratio:**

\[
\begin{align*}
1.1 < q^2 < 6.0 & \quad 0.09^{+0.06}_{-0.05} \text{ (stat)} + 0.01^{+0.01}_{-0.01} \text{ (syst)} + 0.02^{+0.02}_{-0.02} \text{ (norm)} \\
15.0 < q^2 < 20.0 & \quad 1.18^{+0.09}_{-0.08} \text{ (stat)} + 0.03^{+0.03}_{-0.03} \text{ (syst)} + 0.27^{+0.27}_{-0.27} \text{ (norm)}
\end{align*}
\]

**First observation at 3\( \sigma \) level at low \( q^2 \)**

Compatible with the SM within 1.5\( \sigma \).
Prediction: PRD 87 (2013) 074502

Inner error: stat + syst
Outer error: including normalisation (dominant)

LHCB-PAPER-2015-009 to be submitted to JHEP