Test of Lepton Universality using $\Lambda_b$ decays

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The Standard Model

Standard Model of Elementary Particles

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
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<tr>
<td>u</td>
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<td>νe</td>
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<td>ντ</td>
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- **Quarks**: U, C, T, D, S, B
- **Leptons**: E, Mu, Tau, Nu_e, Nu_μ, Nu_τ
- **Bosons**: G, H, Ψ, Z, W

- **Mass**: 2.4 MeV/c², 1.275 GeV/c², 172.44 GeV/c², 125.09 GeV/c²
- **Charge**: +2/3, +1/3, -1/3
- **Spin**: 1/2
The Standard Model

- **SM**: couplings of all (charged) leptons to the gauge bosons should be identical
  - (up to the order of mass/phase-space corrections)

- This means e.g. \( \frac{BR(Z\to \mu^+\mu^-)}{BR(Z\to e^+e^-)} = 1 \)
  - Here, \( BR \) is ‘branching ratio’ – probability of such a decay to occur

### Decay Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fraction ((\Gamma_i / \Gamma))</th>
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<tbody>
<tr>
<td>( \Gamma_1 )</td>
<td>( e^+e^- ) ( (3.363 \pm 0.004)% )</td>
</tr>
<tr>
<td>( \Gamma_2 )</td>
<td>( \mu^+\mu^- ) ( (3.366 \pm 0.007)% )</td>
</tr>
<tr>
<td>( \Gamma_3 )</td>
<td>( \tau^+\tau^- ) ( (3.370 \pm 0.008)% )</td>
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The Standard Model

SM: couplings of all (charged) leptons to the gauge bosons should be identical
- (up to the order of mass/phase-space corrections)

- This means e.g. \( \frac{BR(Z \to \mu^+ \mu^-)}{BR(Z \to e^+ e^-)} = 1 \)
  - Here, \( BR \) is ‘branching ratio’ – probability of such a decay to occur
  - Should be also true for virtual off-shell \( Z \) or \( \gamma \)
  - This implies e.g. \( \frac{BR(J/\psi \to \mu^+ \mu^-)}{BR(J/\psi \to e^+ e^-)} = 1 \)

- This property is called Lepton Universality
So, the Standard Model works?

• Well, all the animals leptons are equal, but some leptons...

• ...are more equal than others?

Slide credits: V.Gligorov
Insidious penguins

Tree-level decays
Very abundant (BR=10^{-2})
In excellent agreement with SM
Lepton-universal

Penguin decays
Very rare (BR=10^{-7})
Sensitive to New Physics contributions

\[ l = e \text{ or } \mu \]
Ratios of ratios of ratios...

- Few remarkable measurements in the $b \rightarrow sl^+l^-$ transitions:

\[
R_K = \frac{BR(B^+ \rightarrow K^+\mu^+\mu^-)}{BR(B^+ \rightarrow K^+e^+e^-)}
\]

\[
R_{K^*0} = \frac{BR(B^0 \rightarrow K^{*0}\mu^+\mu^-)}{BR(B^0 \rightarrow K^{*0}e^+e^-)}
\]

- Additional anomalies in angular analyses and absolute BR values
- New measurements from LHCb and BELLE II awaited
Theorist’s point of view

- Model-independent effective approach: $\mathcal{H}_{eff}(SM) \sim \sum C_i O_i$

- Precise predictions in the SM:
  - Wilson coefficients (short-distance effects)
  - Local operators (long-distance hadronic effects)

  $C_7^{SM} = -0.29, \quad C_9^{SM} = 4.1, \quad C_{10}^{SM} = -4.3$

Okay. What would that imply?

I dunno.
Theorist’s point of view

- Model-independent effective approach: $\mathcal{H}_{\text{eff}}(SM) \sim \sum C_i O_i$

- Precise predictions in the SM:
  - Soft photon
  - $C_7^{\text{SM}} = -0.29$, $C_9^{\text{SM}} = 4.1$, $C_{10}^{\text{SM}} = -4.3$
  - Local operators (long-distance hadronic effects)
  - Wilson coefficients (short-distance effects)

- To describe New Physics:
  - $C_i^{(\text{exp})} = C_i^{(SM)} + C_i^{(NP)}$
  - These effects look coherent

- Strong evidence for non-zero $C_9^{\mu(NP)}$

Fits of theory to the experimental data for $b \to s l^+ l^-$ using ~100 observables from various experiments.
Penguins or...?

Standard Model penguins

EMPEROR   KING   GENTOO   CHINSTRAP   ADELIE   YELLOW-EYED
ROYAL     SOUTHERN ROCKHOPPER   NORTHERN ROCKHOPPER   FIORDLAND CRESTED   ERECT CRESTED   MACARONI
SNARES CRESTED   AFRICAN   MAGELLANIC   GALAPAGOS   HUMBOLDT   LITTLE BLUE

KNOW YOUR PENGUINS
Penguins or...?

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New Physics

KNOW YOUR PENGUINS
Power or indirect searches

Standard Model penguins

\[ l = e \text{ or } \mu \]

\[ \bar{b}, \bar{t}, \bar{c}, \bar{u} \]

New Physics

\[ W'(Z') \]

\[ b, s, \mu, \mu^- \]

\[ B^+, u \]

\[ K^+, u \]

- Most popular scenarios:
  - \(Z'\)
  - Leptoquarks
- In any case, these new particles should be accessible for direct observation at ATLAS and CMS in near future
Baryons

- We live in a world made of love baryons
- However, baryons are less explored than mesons
- Exploring another spin configuration
- Laws in the baryon system are not always similar to mesons

- We want to measure \( R_{pK} = \frac{BR(\Lambda_b \to pK\mu^+\mu^-)}{BR(\Lambda_b \to pKe^+e^-)} \)
How to build a proper detector to study $\Lambda^0_b \to pKl^+l^-$ decays?

Our wish list:
- Good acceptance of b-hadrons
- Good primary vertex resolution
- Good hadron PID
- Muon and electron PID
- Good invariant mass resolution
- Trigger on these events
- Reasonable size and cost
Backgrounds which help

• This is how the di-muon invariant mass looks in the $\Lambda_b^0 \to pK\mu^+\mu^-$ decay

• Two peaks are due to tree-level $\Lambda_b^0 \to pKJ/\psi(\to \mu^+\mu^-)$ and $\Lambda_b^0 \to pK\psi(2S)(\to \mu^+\mu^-)$ decays
  • Have nothing to do with penguins
  • Still, they are a nice reference for cross-checks
  • Most importantly, they are lepton-universal
The global strategy of the analysis

1) Compute $r_{J/\psi} = \frac{BR(\Lambda^0_b \to pK J/\psi(\rightarrow e^+e^-))}{BR(\Lambda^0_b \to pK J/\psi(\rightarrow \mu^+\mu^-))}$

- It should be a) equal to one and b) independent of the kinematical variables
- Very strong control of efficiencies, powerful cross-check

2) Same for $r_{\psi(2S)} = \frac{BR(\Lambda^0_b \to pK \psi(2S)(\rightarrow e^+e^-))}{BR(\Lambda^0_b \to pK \psi(2S)(\rightarrow \mu^+\mu^-))}$

Here we study $\Lambda^0_b \to pK l^+ l^-$

Use them as control and normalisation modes
The global strategy of the analysis

1) Compute \( r_{f/\psi} = \frac{BR(\Lambda^0_b \to pKJ/\psi(\to e^+e^-))}{BR(\Lambda^0_b \to pKJ/\psi(\to \mu^+\mu^-))} \)
   - It should be a) equal to one and b) independent of the kinematical variables
   - Very strong control of efficiencies, powerful cross-check

2) Same for \( r_{\psi(2S)} = \frac{BR(\Lambda^0_b \to pK\psi(2S)(\to e^+e^-))}{BR(\Lambda^0_b \to pK\psi(2S)(\to \mu^+\mu^-))} \)

3) Compute the double ratio
\[
R_{pK} = \frac{BR(\Lambda^0_b \to pK\mu^+\mu^-)}{BR(\Lambda^0_b \to pKJ/\psi(\mu^+\mu^-))} * \frac{BR(\Lambda^0_b \to pKJ/\psi(e^+e^-))}{BR(\Lambda^0_b \to pKe^+e^-)}
\]
   - Normalize to high-statistics modes
   - Cancel some uncertainties

Easy? Well, not so much
Troubles on our way

Some key beasts to fight:

- Systematic uncertainties
- Corrections to the simulation
- Electron reconstruction and trigger categories
- Bremsstrahlung
- Partially reconstructed backgrounds
- misID backgrounds
- Combinatorial background

\[ R_{pK} \]
• Misidentifications
  • Region of proton momentum lower than 20 GeV does not have a good PID
  • Apply a cut above 10 GeV
  • Include the rest into the fit
  • $B_s \rightarrow KKl^+l^-$, $B^0 \rightarrow \pi Kl^+l^-$, swaps...

• Partially reconstructed backgrounds
  • One or more particles can be lost
  • In particular, semileptonic decays having same *visible* final state
  • Or from excited states of final state hadrons...
  • Usually located below the signal peak so of less concern

• Combinatorial background
But there’s an elephant in the room

- The most significant background is coming from **combining the random tracks**
- We train a Boosted Decision Tree to distinguish between signal and combinatorial background
- Exploit the difference in kinematics and geometry

**LHCb unofficial**

No BDT cut

\[ \Lambda_b \text{ mass} \]

**Found It!!!**

**Congratulations, it only took you 65298 seconds**

**1000 times less background!** LHCb unofficial

BDT cut applied
Electron reconstruction and bremsstrahlung

- **Electrons** emit **bremsstrahlung** in interactions with material.
- To reconstruct the true energy of the electron, we search for emitted photons and **correct for their energy**.
- It is not always possible to find the ‘proper’ photon: ECAL is too busy.
- **Poor resolution on electron modes**.

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**LHCb simulation**

\[ \Lambda_b \rightarrow pK\mu^+\mu^- \]

**LHCb simulation**

\[ \Lambda_b \rightarrow pK^+e^-e^- \]
• As I just said, ECAL is very busy – plenty of electrons, photons and $\pi^0$
• Thus, it is hard to trigger on electrons
  • Compare with super-easy triggering on muons: only muons fly through the muon chamber

• To gain more statistics, we can trigger on
  • Leptons – electron or muon (L0Lepton = L0L)
  • Hadrons – proton or kaon – too inefficient to be accounted for
  • Rest of the event (L0TIS = L0I)

• Trigger efficiencies in these cases are very different
  • So these ‘trigger categories’ are analyzed separately
  • Separate fits, separate results...
  • Only in the end, results are combined
Efficiencies and corrections

- \( R_{pK} = \frac{BR(\Lambda_b \rightarrow pK\mu^+\mu^-)}{BR(\Lambda_b \rightarrow pKJ/\psi(\mu^+\mu^-))} \times \frac{BR(\Lambda_b \rightarrow pKJ/\psi(e^+e^-))}{BR(\Lambda_b \rightarrow pKe^+e^-)} \)

- What we really measure is a number of events \( N \)

- \( R_{pK} = \frac{N(\Lambda_b \rightarrow pK\mu^+\mu^-)}{\varepsilon(\Lambda_b \rightarrow pK\mu^+\mu^-)} \times \frac{\varepsilon(\Lambda_b \rightarrow pKJ/\psi(\mu^+\mu^-))}{N(\Lambda_b \rightarrow pKJ/\psi(\mu^+\mu^-))} \times \frac{N(\Lambda_b \rightarrow pKJ/\psi(e^+e^-))}{\varepsilon(\Lambda_b \rightarrow pKJ/\psi(e^+e^-))} \times \frac{\varepsilon(\Lambda_b \rightarrow pKe^+e^-)}{N(\Lambda_b \rightarrow pKe^+e^-)} \)

- Efficiencies (\( \varepsilon \)) are taken from the simulation
  - An important step is to correct for possible data-simulation discrepancies

- Having a correct simulation is very important at LHCb
  - Work not on the trigger efficiency plateau
  - Ageing, different running conditions...
  - We are doing high-precision measurements

- Corrections are quite small but important though
Corrections to the simulation

• Correct for event multiplicity, kinematics, trigger and PID response
• Corrections are data-driven

• When done, check the data-MC agreement in the BDT variable
Fits to real data

- Include signal peak and background components
- Fits in the $J/\psi$ window:

LHCb unofficial muons

LHCb unofficial electrons
Cross-checks: \( r_{J/\psi} \)

- Single ratio \( BR(\Lambda_b \to pKJ/\psi(e^+e^-))/BR(\Lambda_b \to pK J/\psi(\mu^+\mu^-)) \): requires full efficiency control
- **Blind**: multiplied by a blinding factor [equal for all categories]
- 1) compare blinded **central value** per dataset
Cross-checks: $r_{J/\psi}$

- Single ratio $BR(\Lambda_b \to pKJ/\psi(e^+e^-))/BR(\Lambda_b \to pK J/\psi (\mu^+\mu^-))$: requires full efficiency control
- **Blind**: multiplied by a blinding factor [equal for all categories]
- 1) compare blinded **central value** per dataset
- 2) check the **trend** in various variables in each category

(and 82374659834769 similar plots)
Cross-checks: $r_J/\psi$ and friends

- Single ratio $BR(\Lambda_b \rightarrow pKJ/\psi(e^+e^-))/BR(\Lambda_b \rightarrow pKJ/\psi(\mu^+\mu^-))$: requires full efficiency control
- **Blind**: multiplied by a blinding factor [equal for all categories]
  - 1) compare blinded central value per dataset
  - 2) check the trend in various variables in each category
  - ... (tens of other cross-checks inbetween...)
- N) **unblind** and check if the central value is compatible with 1
- Then perform similar studies for $\Lambda_b \rightarrow pK\psi(2S)$:

![Graph showing_BR(Λb → pKJ/ψ(ε^+ε^-))/BR(Λb → pKJ/ψ(μ^+μ^-))_ against various variables.](image)
When we are happy with all the cross-checks, we can study the non-resonant mode.

Fit shown for non-resonant \( \Lambda_b \rightarrow pK \mu^+ \mu^- \)

\( \Lambda_b \rightarrow pK e^+ e^- \) is kept blind!

(We should not know the \( R_{pK} \) value before all the cross-checks passed!)

Finally, the result:
• When we are happy with all the cross-checks, we can study the non-resonant mode
• Fit shown for non-resonant $\Lambda_b \rightarrow pK \mu^+ \mu^-$
• $\Lambda_b \rightarrow pK e^+ e^-$ is kept blind!
  • (We should not know the $R_{pK}$ value before all the cross-checks passed!)

Finally, the result: $R_{pK} = X \pm Y \text{(stat)} \pm Z \text{(syst)}$
Backup slides below
Constraining New Physics models

• Putting **indirect** constraints on New Physics models – reaching the scale higher than accessible for the LHC direct searches...

... But also performing the direct searches in the forward region
The transitions between same-charge quarks – FCNC* – are forbidden at the tree level.

They proceed via penguin diagrams.

This makes these processes very rare, but also sensitive to the possible New Physics contributions.

And this is where we observe something intriguing...

* FCNC = Flavor Changing Neutral Currents
• Few remarkable measurements in the $b \to s l^+ l^-$ transitions:

$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$

$$R_{K^*0} = \frac{BR(B^0 \to K^{*0} \mu^+ \mu^-)}{BR(B^0 \to K^{*0} e^+ e^-)}$$

• Also some anomalies in the $b \to c l^+ \nu_l$ transitions
• New/updated measurements expected from LHCb and BELLE-II
Corrections in work

- Some variables are not properly modeled in the simulation:
  - e.g. generated kinematics of the decay:

![Graphs and histograms showing corrections and sPlot analysis](image-url)
Cross-checks

• So, now we know how to get yields and efficiencies
• Various tests to be performed before unblinding the final result

\[ R_{pK} = \frac{N(\Lambda_b \to pK\mu^+\mu^-)}{\varepsilon(\Lambda_b \to pK\mu^+\mu^-)} \times \frac{\varepsilon(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))}{N(\Lambda_b \to pKJ/\psi(\mu^+\mu^-))} \times \frac{N(\Lambda_b \to pKJ/\psi(e^+e^-))}{\varepsilon(\Lambda_b \to pKJ/\psi(e^+e^-))} \times \frac{\varepsilon(\Lambda_b \to pKe^+e^-)}{N(\Lambda_b \to pKe^+e^-)} \]

Should be 1 if everything is correct

• Should not only be 1, but also independent of kinematical variables (e.g. flat in bins of \( p_T(\Lambda_b) \))
• Evaluate separate BRs and compare to PDG
  • \( BR(\Lambda_b \to pK\mu^+\mu^-) \)
  • \( BR(\Lambda_b \to pK\psi(2S)) \) with \( \psi(2S) \to \mu^+\mu^- \) or \( e^+e^- \)
  • \( BR(\Lambda_b \to pK\gamma) \) with conversions \( \gamma \to e^+e^- \)
  • ...

\( J/\psi(1S) \), \( \psi(2S) \), photon pole, interference, \( C_7^{(\prime)}, C_9^{(\prime)} \)
What about baryons?

- We live in a world made of love baryons
  - However, baryons are less explored than mesons
- Exploring another spin configuration
- Laws in the baryon system are not always similar to mesons
  - E.g. charmonia \((c\bar{c})\) states production
    \[
    \frac{BR(\Lambda_b \rightarrow pK\psi(2S))}{BR(B^0 \rightarrow K^*\psi(2S))} = 0.21, \quad \frac{BR(\Lambda_b \rightarrow pK\chi_c)}{BR(B^0 \rightarrow K^*\chi_c)} = 1.02, \quad \text{while} \quad \frac{BR(\Lambda_b \rightarrow pK\chi_c)}{BR(B^0 \rightarrow K^*\chi_c)} = 0.46, \quad \frac{BR(\Lambda_b \rightarrow pK\chi_c)}{BR(B^0 \rightarrow K^*\chi_c)} = 0.20
    \]
- We want to measure \(R_{PK} = \frac{BR(\Lambda_b \rightarrow \Lambda^*\mu^+\mu^-)}{BR(\Lambda_b \rightarrow \Lambda^*e^+e^-)}\)
  with \(\Lambda^* \rightarrow pK\)