Measurements of isospin amplitudes in $\Lambda_b^0$ and $\Xi_b^0$ decays at LHCb

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Motivation

• **$K \rightarrow \pi\pi$ decays: $\Delta I = 1/2$** rule is a well known disparity in the isospin amplitudes $A_0$ and $A_2$
  - $R = \text{Re } A_2/\text{Re } A_0$

<table>
<thead>
<tr>
<th>Experimental Measurement [1]</th>
<th>$22.45 \pm 0.06$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical Calculation [2]</td>
<td>$16.0 \pm 0.15$</td>
</tr>
<tr>
<td>Lattice Calculation [1]</td>
<td>$19.9 \pm 2.3 \pm 2.4$</td>
</tr>
<tr>
<td>&quot;no QCD&quot; limit [2]</td>
<td>$\sqrt{2}$</td>
</tr>
</tbody>
</table>

- $\Delta I = 1/2$ rule doesn’t translate easily to heavy flavour mesons (obtained from fits to data):
  - $D \rightarrow \pi\pi$ [3]: $|A_0/A_2| \approx 2.5$ (O(1) enhancement)
  - $B \rightarrow \pi\pi$ [4]: $|A_0/A_2| \approx 1.5$ (Close to "no QCD" limit)

Note $A_i$ is notated with final state isospin in subscript, on all slides

← $31.1 \pm 10.9$ (OLD)

Motivation

• The $\Lambda_b$ is predicted to be an iso-scalar by the quark model
  • Needs experimental support

• Isospin suppression commonly assumed in past analyses of $\Lambda_b$ decays
  • Pentaquark analysis in $\Lambda_b \rightarrow J/\psi \ p \ K^-$ assumed suppression of $\Lambda_b \rightarrow J/\psi \ \Sigma^*$ w.r.t. $\Lambda_b \rightarrow J/\psi \ \Lambda^*$
  • Measurement of $V_{ub}$ from $\Lambda_b \rightarrow p \mu \nu$ assumed suppression of $\Lambda_b \rightarrow N^* \mu \nu$

• Diquark structure of $\Lambda_b$
  • Baryons hypothesized to be built from a light diquark (ud) and a heavy quark.
  • If present, would be another suppression of isospin violation.
  • Commonly, isospin breaking is seen at ~1% in rate.
\[ \Lambda_b \to J/\psi \Lambda(\Sigma^0), \Xi_b^0 \to J/\psi \Xi^0(\Lambda) \]

- Quark model assumes \( \Lambda_b \) as isospin 0, and \( \Xi_b^0 \) as isospin 1/2

- \( b \to c\bar{c}s \) is purely isospin 0
  - Naively, isospin breaking cannot be generated at tree level, if light quarks are just spectators
  - Isospin 1 final state could be generated through \( \Lambda - \Sigma \) mixing, an exchange diagram, or through NP amplitudes
  - Tree diagram \( \propto V_{cb}^* V_{cs} \sim \lambda^2 \)
  - Exchange diagram \( \propto V_{ub}^* V_{us} \sim \lambda^4 \)

- \( b \to c\bar{c}d \) changes isospin in \( \Xi_b^0 \) decay

- According to the quark model,
  - \( \Lambda_b \to J/\psi \Lambda \) is purely \( \Delta I = 0 \) (\( A_0 \) amplitude)
  - \( \Lambda_b \to J/\psi \Sigma^0 \) is purely \( \Delta I = 1 \) (\( A_1 \) amplitude)
  - \( \Xi_b^0 \to J/\psi \Xi^0 \) is purely \( \Delta I = 0 \) (\( A_{1/2} \) amplitude)
  - \( \Xi_b^0 \to J/\psi \Lambda \) is purely \( \Delta I = 1/2 \) (\( A_0 \) amplitude)

- Neither \( \Lambda_b \to J/\psi \Sigma^0 \) nor \( \Xi_b^0 \to J/\psi \Lambda \) had been observed before.
Signal Decays

• Our $\Lambda_b$ signal decays are:
  • $\Lambda_b \to J/\psi \Lambda$
  • $\Lambda_b \to J/\psi \Sigma^0, \Sigma^0 \to \Lambda \gamma$

• Our $\Xi^0_b$ signal decays are:
  • $\Xi^0_b \to J/\psi \Xi^0, \Xi^0 \to \Lambda \pi^0$
  • $\Xi^0_b \to J/\psi \Lambda$

• All four signal modes are reconstructed as $J/\psi \Lambda$
  • $J/\psi \to \mu^+ \mu^-$
  • $\Lambda \to p \pi^-$

• We perform selections involving multivariate classifiers that exploit the isolation of the $J/\psi$ in all our signal decays, using the full LHCb data-set (Run 1 + Run2)
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Not reconstructed
Observables of Interest

• In the $\Lambda_b$ decays:
  \[ \mathcal{R}_{\Lambda_b} \equiv \frac{|A_1|^2}{|A_0|^2} = \frac{B(\Lambda_b \to J/\psi \Sigma^0)}{B(\Lambda_b \to J/\psi \Lambda)} \cdot \Phi_{\Lambda_b} = \frac{N_{\text{corr}}(\Lambda_b \to J/\psi \Sigma^0)}{N_{\text{corr}}(\Lambda_b \to J/\psi \Lambda)} \cdot \Phi_{\Lambda_b} \]

• In the $\Xi_b^0$ decays:
  \[ \mathcal{R}_{\Xi_b} \equiv \frac{B(\Xi_b^0 \to J/\psi \Lambda)}{B(\Xi_b^0 \to J/\psi \Xi^0)} = \frac{N_{\text{corr}}(\Xi_b^0 \to J/\psi \Lambda)}{N_{\text{corr}}(\Xi_b^0 \to J/\psi \Xi^0)} \]
  \[\left| \frac{A_0}{A_{1/2}} \right| = \frac{1}{\lambda} \sqrt{\mathcal{R}_{\Xi_b} / \Phi_{\Xi_b}}\]

• We do not measure $\Xi_b^0 \to J/\psi \ (\Xi^0 \to \Lambda\pi^0)$ directly.
  • Instead we measure $\Xi_b^- \to J/\psi \ (\Xi^- \to \Lambda\pi^-)$ and use isospin to relate it to the $\Xi_b^0$ decay

$N_{\text{corr}}$ - efficiency corr. yield
\[\Phi_{\Lambda_b}, \Phi_{\Xi_b} - \text{Phase space corr. factors}\]
\[\lambda = |V_{us}|/|V_{ud}| - \text{CKM suppression}\]
**Fits and Upper Limit**

**Run 2**

- **Data**: Various decay modes of B mesons into J/ψ or Υ states.
- **Total fit**: Overall fit to the data.
- **Comb. bkg.**: Combination background.
- **Other part. rec. bkg.**: Other partial reconstructed backgrounds.

- **95% CL Upper Limit**: A plot showing the upper limit on the decay rate of certain B mesons.

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**arXiv:1912.0211**

**LHCb**

- **m(J/ψΞ^-)**: The mass distribution of the J/ψ meson in Ξ^- decays.
- **P value**: Plot showing the p-values for different CLs.

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Results

• $\mathcal{R}_{\Lambda b} < 2.1 \cdot 10^{-3} @ 95\%$ C.L.

  $\Rightarrow |A_1/A_0| = \sqrt{R} < 1/21.8 @ 95\%$ C.L.

• $\Xi^0_b \rightarrow J/\psi \Lambda: \textbf{First observation}$ of Cabibbo suppressed mode

  • Significance of observation: $5.6 \sigma$

  • $\mathcal{R}_{\Xi_b} \equiv \frac{\mathcal{B}(\Xi^0_b \rightarrow J/\psi \Lambda)}{\mathcal{B}(\Xi^0_b \rightarrow J/\psi \Xi^0)} = (8.2 \pm 2.1 \pm 0.9) \cdot 10^{-3}$

  $\Rightarrow |A_0/A_{1/2}| = 0.37 \pm 0.06 \pm 0.02$
Interpretation – SU(3)$_F$ Analysis \cite{5}

- Dery et. al. perform a general SU(3)$_F$ analysis of baryonic $b \to c\bar{c}q$ ($q = s, d$)

- $b \to c\bar{c}s$ decays: $\Lambda_b \to \Lambda J/\psi$  
  $\Lambda_b \to \Sigma^0 J/\psi$  
  $\Xi^0_b \to \Xi^0 J/\psi$  
  $\Xi^-_b \to \Xi^- J/\psi$

- $b \to c\bar{c}d$ decays: $\Xi^0_b \to \Lambda J/\psi$  
  $\Xi^0_b \to \Sigma^0 J/\psi$  
  $\Lambda_b \to n J/\psi$  
  $\Xi^-_b \to \Sigma^- J/\psi$

- From three separate assumptions:
  1. Working in the SU(3)$_F$ limit
  2. $\Lambda$ and $\Sigma^0$ are isospin eigenstates (i.e. don’t mix)
  3. $|V^*_ub V_{us}/V^*_cb V_{cs}| \to 0$

  Predictions:
  - $A(\Lambda_b \to J/\psi \Sigma^0) = 0$
  - $|A(\Xi^0_b \to \Lambda J/\psi)/A(\Xi^0_b \to \Xi^0 J/\psi)| = \frac{1}{\sqrt{6}} \left| \frac{V^*_cb V_{cd}}{V^*_cb V_{cs}} \right|$

\cite{5} arXiv:2001.05397 – DGGS
Interpretation – SU(3)$_F$ Analysis [5]

- Isospin and SU(3)$_F$ breaking effects would lead at the same time to a deviation in $A(\Lambda_b \to \Sigma^0 \ J/\psi)$ and $A(\Xi_b^0 \to \Lambda \ J/\psi)/A(\Xi_b^0 \to \Xi^0 \ J/\psi)$

- $\Sigma^0 - \Lambda$ mixing:
  - $|\Lambda^0_{\text{phys}}\rangle = \cos \theta_m |\Lambda^0\rangle - \sin \theta_m |\Sigma^0\rangle$
  - $|\Sigma^0_{\text{phys}}\rangle = \sin \theta_m |\Lambda^0\rangle + \cos \theta_m |\Sigma^0\rangle$

- $\mathcal{R}_{\Lambda_b} \equiv \frac{A(\Lambda_b \to J/\psi \Sigma^0_{\text{phys}})}{A(\Lambda_b \to J/\psi \Lambda^0_{\text{phys}})} = \frac{\langle J/\psi \Sigma^0_{\text{phys}} | H | \Lambda_b \rangle}{\langle J/\psi \Lambda^0_{\text{phys}} | H | \Lambda_b \rangle} = \theta_m + \frac{\langle J/\psi \Sigma^0 | H_1 | \Lambda_b \rangle}{\langle J/\psi \Lambda^0 | H_0 | \Lambda_b \rangle} = \theta_m + \theta_f^{\text{dyn}} = \theta_f$

- $\theta_m \sim \theta_f \sim 1^\circ \Rightarrow \mathcal{R}_{\Lambda_b} = |\theta_f| \sim 0.02$

Comparison and Conclusions

- DGGS prediction for \( \frac{A_0(\Xi_b^0 \rightarrow \Lambda J/\psi)}{A_1(\Xi_b^0 \rightarrow \Xi^0 J/\psi)} \approx 0.41 \) agrees very well with our measurement of 
  
  \( (0.37 \pm 0.06 \pm 0.02) \).

- DGGS expect a 20% correction from SU(3)_F breaking effects.

- Our measurement is not yet sensitive enough to probe size of these corrections.

- DGGS prediction for \( \frac{A_0(\Lambda_b \rightarrow \Lambda J/\psi)}{A_1(\Lambda_b \rightarrow \Sigma^0 J/\psi)} \sim 0.02 \) is close to our upper limit of \( 1/21.8 = 0.046 \).

- DGGS stress that a deviation from predicted value would point to isospin violation in the dynamical contribution to mixing.
Comparison and Conclusions

• We have provided more support for the iso-scalar status of the $\Lambda_b$.
  • An isospin 1 component would be seen through the $\Delta I = 1$ channel.
  • In principle, could mix with the isospin 1 $\Sigma^0_b$.

• Experimental verification provided for the assumption of isospin suppression made in past analyses involving $\Lambda_b$.

• No isospin or SU(3)$_F$ breaking effects seen yet in $\Lambda_b$ and $\Xi_b$ decays.
  • With increasing statistics expected from Run 3 datasets, and additional channels to be probed, LHCb is well poised to make a first observation of isospin breaking in baryonic decays.

THANK YOU!!