Heavy baryons in lattice QCD

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Evidence for $\Delta S = -\Delta Q$ Currents or Charmed-Baryon Production by Neutrinos*

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We report on the production by neutrinos of an event with negative strangeness. In an exposure of the Brookhaven National Laboratory 7-ft cryogenic bubble chamber to a broad-band neutrino beam 335 events were observed, one of which fits the reaction $\nu p \rightarrow \mu^- \Lambda^0 \pi^+ \pi^+ \pi^-$. Alternative explanations are examined and none found with a probability greater than $3 \times 10^{-5}$. The event thus represents a large violation of the $\Delta S = \Delta Q$ rule or alternatively the production and decay of a charmed baryon state. The most plausible mass for this state is found to be $2426 \pm 12$ MeV.

FIG. 1. View of event as seen in camera 3.
Lattice QCD (Brown et al., 2014)

[Brown, Detmold, Meinel, Orginos, arXiv:1409.0497]
1 Heavy-quark symmetries
2 Spectroscopy
3 Strong decays
4 Weak decays
Singly heavy baryons

In the limit $m_Q \to \infty$

- $J_{\text{light}}$ becomes conserved quantum number
- Interaction with heavy-quark spin vanishes

Expect corrections of order $\Lambda/m_Q$
Singly heavy baryons

Low-lying positive-parity states:

\[ 3 \otimes 3 = \bar{3}_A \oplus 6_S \]

\[ J_{\text{light}} = 0, \quad J^P = \frac{1}{2}^+ \]

\[ J_{\text{light}} = 1, \quad J^P = \frac{1}{2}^+, \frac{3}{2}^+ \]
Doubly-heavy baryons

In the limit \( m_Q \to \infty \)

- The two heavy quarks form a point-like diquark (\( \bar{3} \) color source)
- \( J_{\text{light}} \) becomes conserved quantum number
- Interaction with heavy-diquark spin vanishes
- Dynamics of light degrees of freedom is the same as in a heavy-light meson [Savage and Wise, PLB 248, 177 (1990)]
Doubly-heavy baryons: equal-flavor case

Low-lying positive-parity states: heavy diquark has $L = 0$; antisymmetric color wave function $\rightarrow$ Pauli principle implies symmetric spin wave function $\rightarrow J_{\text{heavy}} = 1$

\[ J_{\text{light}} = \frac{1}{2}, \quad J^P = \frac{1}{2}^+, \frac{3}{2}^+ \]
Doubly-heavy baryons: mixed-flavor case

Now, $J_{\text{heavy}} = 0$ and $J_{\text{heavy}} = 1$ both possible with $L = 0$.

\[ J_{\text{heavy}} = 0, \quad J_{\text{light}} = \frac{1}{2}, \quad J^P = \frac{1}{2}^+ \]

\[ J_{\text{heavy}} = 1, \quad J_{\text{light}} = \frac{1}{2}, \quad J^P = \frac{1}{2}^+, \frac{3}{2}^+ \]
Doubly-heavy baryons: equal-flavor case

Prediction for hyperfine splittings in the limit $m_Q \to \infty$:

\[
\frac{M(\Xi_{QQ}^*) - M(\Xi_{QQ})}{M(P_Q^*) - M(P_Q)} \to \frac{3}{4}
\]

[Brambilla, Vairo, Rosch, PRD 72, 034021 (2005)]
1 Heavy-quark symmetries

2 Spectroscopy
   - Ground states
   - Excited states

3 Strong decays

4 Weak decays
First dynamical lattice QCD calculation that includes mixed charm-bottom baryons.
Actions and parameters

- **u, d, s**: domain-wall fermions
  
  [Kaplan, PLB 288, 342 (1992); Furman and Shamir, NPB 439, 54 (1995)]

- **c**: relativistic heavy-quark action
  
  [El-Khadra, Kronfeld, Mackenzie, PRD 55, 3933 (1997)]

- **b**: lattice NRQCD
  
  [Lepage et al., PRD 46, 4052 (1992)]

- **Gauge field configurations generated by RBC/UKQCD**
  
  [Aoki et al. (RBC/UKQCD), PRD 83, 074508 (2011)]

- **Two lattice spacings**: $a \approx 0.11$ fm, $a \approx 0.08$ fm

- **Box size**: $L \approx 2.7$ fm

- $m_u = m_d$

- Seven different pion masses in the range 230 ... 430 MeV (lowest three partially quenched)
Step 1: extract energies from two-point functions

\[
\langle O[c, c, b] O[c, c, b] \rangle \\
\langle O[c, c, b] O[\bar{c}, \bar{c}, \bar{b}] \rangle \\
\langle O[\bar{c}, \bar{c}, \bar{b}] O[\bar{c}, \bar{c}, \bar{b}] \rangle \\
A_1 A_1 e^{-Et} \\
A_1 A_2 e^{-Et} \\
A_2 A_2 e^{-Et}
\]
Step 1: extract energies from two-point functions

\[ aE_{\text{eff}}(t) = \ln \left[ C(t)/C(t + a) \right] \]
Step 1: extract energies from two-point functions

For a baryon “X” with $n_b$ bottom quarks and $n_c$ charm quarks, we compute the subtracted energies

$$E^{(\text{sub})}_X = E_X - \frac{n_c}{2} \overline{E}_{c\bar{c}} - \frac{n_b}{2} \overline{E}_{b\bar{b}},$$

where

$$\overline{E}_{c\bar{c}} = \frac{3}{4} E_{J/\psi} + \frac{1}{4} E_{\eta_c}, \quad \overline{E}_{b\bar{b}} = \frac{3}{4} E_{\Upsilon} + \frac{1}{4} E_{\eta_b}.$$
Step 2: chiral and continuum extrapolations

Quark-mass and volume dependence predicted by NLO $SU(4|2)$ heavy-hadron chiral perturbation theory [Mehen and Tiburzi, PRD 74, 054505 (2006)]

\[
E^{(\text{sub})}_{\Xi_{cb}^\prime} = E^{(\text{sub},0)} + d^{(\text{vv})} \frac{[m^{(\text{vv})}]^2}{4\pi f} + d^{(\text{ss})} \frac{[m^{(\text{ss})}]^2}{4\pi f} + a^2 \Lambda^3 \\
- \frac{g_1^2}{16\pi^2 f^2} \left[ \frac{4}{9} \mathcal{F}(m^{(\text{vs})}_\pi, 0, \mu) - \frac{1}{9} \mathcal{F}(m^{(\text{vv})}_\pi, 0, \mu) \right]
\]

\[
E^{(\text{sub})}_{\Xi_{cb}^*} = E^{(\text{sub},0)} + \Delta^{(0)} + c^{(\text{vv})} \frac{[m^{(\text{vv})}]^2}{4\pi f} + c^{(\text{ss})} \frac{[m^{(\text{ss})}]^2}{4\pi f} + a^2 \Lambda^3 \\
- \frac{g_1^2}{16\pi^2 f^2} \left[ \frac{32}{9} \mathcal{F}(m^{(\text{vs})}_\pi, \Delta^*, \mu) + \frac{4}{9} \mathcal{F}(m^{(\text{vs})}_\pi, 0, \mu) - \frac{8}{9} \mathcal{F}(m^{(\text{vv})}_\pi, \Delta^*, \mu) - \frac{1}{9} \mathcal{F}(m^{(\text{vv})}_\pi, 0, \mu) \right]
\]

\[
E^{(\text{sub})}_{\Xi_{cb}^*} = E^{(\text{sub},0)} + \Delta^{(0)} + c^{(\text{vv})} \frac{[m^{(\text{vv})}]^2}{4\pi f} + c^{(\text{ss})} \frac{[m^{(\text{ss})}]^2}{4\pi f} + a^2 \Lambda^3 \\
- \frac{g_1^2}{16\pi^2 f^2} \left[ \frac{16}{9} \mathcal{F}(m^{(\text{vs})}_\pi, -\Delta^*, \mu) + \frac{20}{9} \mathcal{F}(m^{(\text{vs})}_\pi, 0, \mu) - \frac{4}{9} \mathcal{F}(m^{(\text{vv})}_\pi, -\Delta^*, \mu) - \frac{5}{9} \mathcal{F}(m^{(\text{vv})}_\pi, 0, \mu) \right]
\]

Axial coupling $g_1$ taken from separate lattice calculation

[Detmold, Lin, Meinel, PRL 108, 172003 (2012)]
Step 2: chiral and continuum extrapolations

\[ m^2_{\pi} \text{ (GeV}^2) \]

\[
\begin{array}{c}
\Xi_{cb} \\
\Xi'_{cb} \\
\Xi^*_{cb}
\end{array}
\]

\[
\begin{array}{c}
E_{(sub)} \text{ (GeV)}
\end{array}
\]
Step 3: estimate systematic uncertainties

Evaluate fit functions at $a = 0$, $m_\pi = 135$ MeV, $L = \infty$ to obtain $E_X^{(\sub,\phys)}$.

Estimate chiral/continuum extrapolation systematic uncertainties by redoing fits with added higher-order terms (constrained to be natural-sized), and calculating

$$
\sigma_{\text{syst.},\text{HO}} = \sqrt{\sigma^2_{\text{NLO+HO}} - \sigma^2_{\text{NLO}}}
$$

Estimate NRQCD uncertainties using power counting.
Step 4: add experimental values of subtraction term

\[ M_X^{(\text{phys})} = E_X^{(\text{sub,phys})} + \left[ \frac{n_c}{2} \overline{M}_{c\bar{c}} + \frac{n_b}{2} \overline{M}_{b\bar{b}} \right]_{\text{PDG}} \]
Results

Doubly charmed: lattice QCD and SELEX

![Graph showing the mass of various doubly charmed baryons and mesons compared to different calculations and experiments.]

- SELEX, 2005
- Liu et al., 2010 ($a \approx 0.12$ fm)
- Briceno et al., 2012 ($a = 0$)
- D"urr et al., 2012 ($a \approx 0.07$ fm; stat. only)
- Namekawa et al., 2013 ($a \approx 0.09$ fm; stat. only)
- Alexandrou et al., 2014 ($a = 0$)
- Padmanath et al., 2013 ($a_s \approx 0.12$ fm; stat. only)
- Brown et al., 2014 ($a = 0$)
We observe a signal for the doubly charmed baryon $\Xi_{cc}^+$ in the charged decay mode $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ in data from SELEX, the charm hadroproduction experiment at Fermilab. We observe an excess of 15.9 events over an expected background of 6.1 ± 0.5 events, a statistical significance of 6.3$\sigma$. The observed mass of this state is 3519 ± 1 MeV/$c^2$, a Gaussian mass width of this state is 3 MeV/$c^2$, consistent with resolution; its lifetime is less than 33 fs at 90% confidence.
Confirmation of the doubly charmed baryon $\Xi_{cc}^+(3520)$ via its decay to $pD^+K^-$

**Abstract**

We observe a signal for the doubly charmed baryon $\Xi_{cc}^+$ in the decay mode $\Xi_{cc}^+ \to pD^+K^-$ to complement the previous reported decay $\Xi_{cc}^+ \to \Lambda_c^+K^-\pi^+$ in data from SELEX, the charm hadroproduction experiment at Fermilab. In this new decay mode we observe an excess of 5.62 events over a combinatoric background estimated by event mixing to be $1.38 \pm 0.13$ events. The mixed background has Gaussian statistics, giving a signal significance of $4.8\sigma$. The Poisson probability that a background fluctuation can produce the apparent signal is less than $6.4 \times 10^{-4}$. The observed mass of this state is $3518 \pm 3$ MeV/$c^2$, consistent with the published result. Averaging the two results gives a mass of $3518.7 \pm 1.7$ MeV/$c^2$. The observation of this new weak decay mode confirms the previous SELEX suggestion that this state is a double charm baryon. The relative branching ratio for these two modes is $0.36 \pm 0.21$.

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**SELEX:** $m_{\Xi_{cc}^+} = 3518.7 \pm 1.7$ MeV

**Our lattice calculation:** $m_{\Xi_{cc}^+} = 3610 \pm 23 \pm 22$ MeV

**Isospin splitting from lattice QCD+QED:** $m_{\Xi_{cc}^{++}} - m_{\Xi_{cc}^+} = 2.16 \pm 0.11 \pm 0.17$ MeV [Borsanyi et al. (BMW), arXiv:1406.4088]
Newer searches do not find the $\Xi_{cc}$

Signal:

- **SELEX** [PRL 89, 112001 (2002)]: $\Sigma^-, \pi^-$ beam (600 GeV) on Cu/diamond fixed target

No signal:

- **FOCUS** [NPPS 115, 33 (2003)]: $\gamma$ ($\leq 250$ GeV) on BeO fixed target
- **BaBar** [PRD 74, 011103 (2006)]: $e^+e^-$ at $\sqrt{s} = 10.58$ GeV
- **Belle** [PRL 97, 162001 (2006)]: $e^+e^-$ at $\sqrt{s} = 10.58$ GeV
- **LHCb** [JHEP 1312, 090 (2013)]: $pp$ at $\sqrt{s} = 7$ TeV
Results

Singly charmed, singly bottom: lattice QCD vs. models

Lattice QCD (Brown et al., 2014)
Roncaglia et al., 1995
Silvestre-Brac, 1996
Ebert et al., 2002
Kiselev et al., 2002
He et al., 2004
Albertus et al., 2002
Martynenko, 2008
Roberts and Pervin, 2008
Bernotas et al., 2008
Zhang et al., 2008
Giannuzzi, 2009
Tang et al., 2012
Ghalenovi et al., 2014
Karliner and Rosner, 2014
Results

Triply heavy charm-bottom: lattice QCD vs. models

![Graph showing the comparison between lattice QCD and various models for the mass of the omega ccc and omega* ccc particles.](image)

- Lattice QCD (Brown et al., 2014)
- Ponce, 1978
- Hasenfratz et al., 1980
- Bjorken, 1985
- Tsuge et al., 1985
- Silvestre-Brac, 1996
- Jia, 2006
- Martynenko, 2008
- Roberts and Pervin, 2008
- Bernotas et al., 2008
- Gianuzzi, 2009
- Llanes-Estrada et al., 2011
- Wang, 2011
- Ghalenovi et al., 2014
**Results**

Prediction of heavy quark-diquark symmetry:

\[
\frac{M(\Xi_{*QQ}^*) - M(\Xi_{QQ})}{M(P_{*Q}^*) - M(P_Q)} \to \frac{3}{4} \quad (\text{for } m_Q \to \infty)
\]

[Brambilla, Vairo, Rosch, PRD 72, 034021 (2005)]

Test using lattice QCD:

<table>
<thead>
<tr>
<th>Splitting</th>
<th>This work (MeV)</th>
<th>Splitting</th>
<th>Experiment (MeV)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Xi_{cc}^* - \Xi_{cc})</td>
<td>82.8(9.2)</td>
<td>(D_{s}^* - D_s)</td>
<td>142.12(7)</td>
<td>0.58(6)</td>
</tr>
<tr>
<td>(\Omega_{cc}^* - \Omega_{cc})</td>
<td>83.8(5.5)</td>
<td>(D_{s}^* - D_s)</td>
<td>143.8(4)</td>
<td>0.58(4)</td>
</tr>
<tr>
<td>(\Xi_{bb}^* - \Xi_{bb})</td>
<td>34.6(7.8)</td>
<td>(B_{s}^* - B_s)</td>
<td>45.78(35)</td>
<td>0.76(17)</td>
</tr>
<tr>
<td>(\Omega_{bb}^* - \Omega_{bb})</td>
<td>35.7(5.7)</td>
<td>(B_{s}^* - B_s)</td>
<td>48.7(2.3)</td>
<td>0.73(12)</td>
</tr>
</tbody>
</table>
1. Heavy-quark symmetries

2. Spectroscopy
   - Ground states
   - Excited states

3. Strong decays

4. Weak decays
$\Omega_{bbb}$ excited states

[Meinel, PRD 85, 114510 (2012)]

$Lattice QCD$
Silvestre-Brac 1996
$\Omega_{bbb}$ excited states

[Meinel, PRD 85, 114510 (2012)]

\[ E - E_1^{(7/2)^+} \] [MeV]

\[ E - E_1^{(3/2)^-} \] [MeV]
Ω_{ccc} excited states

Quark-mass dependence


(except for $\Omega_{bbb}$, only statistical uncertainties shown)
1. Heavy-quark symmetries
2. Spectroscopy
3. Strong decays
4. Weak decays
Strong decays

Schematically:

\[ \Sigma_Q \rightarrow \Lambda_Q + \pi \]
Strong decays in chiral perturbation theory

\[ \Gamma[\Sigma^{(*)}_Q \rightarrow \Lambda_Q \pi] = -2 \text{Im}[E_{\Sigma^{(*)}_Q}] = \frac{g_3^2}{6\pi f^2} |p_\pi|^3 \]
Computing $g_3$ (and $g_1, g_2$) in lattice QCD

Matrix elements of the axial current $A_\mu = \bar{d} \gamma_\mu \gamma_5 u$:

$$
\langle P^* | A_\mu | P \rangle = (g_1)_{\text{eff}} \times (\text{kinematic factors}),
$$

$$
\langle \Sigma^{(*)}_Q | A_\mu | \Sigma^{(*)}_Q \rangle = (g_2)_{\text{eff}} \times (\text{kinematic factors}),
$$

$$
\langle \Sigma^{(*)}_Q | A_\mu | \Lambda_Q \rangle = (g_3)_{\text{eff}} \times (\text{kinematic factors})
$$

(defined in heavy-quark limit $m_Q \to \infty$).

In heavy-hadron chiral perturbation theory,

$$
(g_1)_{\text{eff}} = g_1 + \text{NLO},
$$

$$
(g_2)_{\text{eff}} = g_2 + \text{NLO},
$$

$$
(g_3)_{\text{eff}} = g_3 + \text{NLO}.
$$

[Detmold, Lin, Meinel, PRD 84, 094502 (2011)]
Computing $g_3$ (and $g_1$, $g_2$) in lattice QCD

Our result:

$$g_1 = 0.449 \pm 0.047 \pm 0.019$$
$$g_2 = 0.84 \pm 0.20 \pm 0.04$$
$$g_3 = 0.71 \pm 0.12 \pm 0.04$$

[Detmold, Lin, Meinel, PRL 108, 172003 (2012); PRD 85, 114508 (2012)]
Resulting $\Sigma_b$ and $\Sigma_b^*$ decay widths

This work, $J = 1/2$

This work, $J = 3/2$

CDF, $\Sigma_b^\pm \rightarrow \Lambda_b \pi^\pm$

CDF, $\Sigma_b^{*\pm} \rightarrow \Lambda_b \pi^{\pm}$

$\mathcal{O}(\Lambda/m_b)$ correction is included in $\Gamma$.

[Detmold, Lin, Meinel, PRL 108, 172003 (2012); PRD 85, 114508 (2012)]
1 Heavy-quark symmetries
2 Spectroscopy
3 Strong decays
4 Weak decays
   • The charged-current decay $\Lambda_b \rightarrow p\mu\bar{\nu}_\mu$
   • The FCNC decay $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$
Testing CKM unitarity

\[ \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

\[ \begin{array}{c}
\text{figure based on: [CKMfitter, 2013]} \\
\text{■ = measurement of } |V_{ub}| \\
\text{■ = measurement of } \epsilon_K. \text{ Constraint depends on } |V_{cb}|^4
\end{array} \]
\[
B \rightarrow \pi \ell \bar{\nu}
\]

\[
\langle \pi|\bar{u}\gamma^\mu b|B\rangle = \left[ (p + p')^\mu - \frac{m_B^2 - m_\pi^2}{q^2} q^\mu \right] f_+(q^2) + \frac{m_B^2 - m_\pi^2}{q^2} q^\mu f_0(q^2)
\]

\[
\langle \pi|\bar{u}\gamma^\mu \gamma_5 b|B\rangle = 0
\]

\[
\frac{d\Gamma}{dq^2} = |\eta_{EW}|^2 \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p'|^3 |f_+(q^2)|^2 \quad \text{(for } m_\ell = 0)\]
The $|V_{ub}|$ puzzle

from $B \rightarrow \pi \ell \bar{\nu}_\ell$

from $B \rightarrow X_u \ell \bar{\nu}_\ell$

$10^3 \times |V_{ub}|$


[Gulez et al. (HPQCD), PRD 73, 074502 (2006); Bailey et al. (FNAL/MILC), PRD 79, 054507 (2009); Particle Data Group, 2013]
Measuring $|V_{ub}|$ at the LHC

$B \to \pi \ell \bar{\nu}_\ell$:
Difficult to isolate from background because $pp$ collisions produce many pions

$\Lambda_b \to p \ell \bar{\nu}_\ell$:
More distinctive final state.
Data analysis at LHCb in progress.

[Egede, private communication]
Λ_b production rate at the LHC

[Aaij et al. (LHCb), JHEP 08, 143 (2014)]
${\Lambda_b \rightarrow p \mu^- \bar{\nu}_\mu}$

At leading order in $1/m_b$ expansion (static limit), only two form factors:

$$\langle N^+(p') | \bar{u} \Gamma Q | \Lambda_Q(v) \rangle = \bar{u}_N \left[ F_1(p' \cdot v) + \gamma F_2(p' \cdot v) \right] \Gamma u_{\Lambda_Q}$$
$\Lambda_b \rightarrow p \mu^- \bar{\nu}_\mu$

Lattice QCD calculation using domain-wall $u, d, s$ quarks and Eichten-Hill static $b$ quark:

[Detmold, Lin, Meinel, Wingate, PRD 88, 014512 (2013)]:

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{Plot showing $F_1$ and $F_2$ as functions of $E_N - m_N$ (GeV).}
\end{figure}
$\Lambda_b \to p \mu^- \bar{\nu}_\mu$

Predicted differential decay rate $/|V_{ub}|^2$: 

Outer error band includes $\sqrt{|p'|^2 + \Lambda_{QCD}^2}$ uncertainty from static approximation
\[ \Lambda_b \rightarrow p \mu^- \bar{\nu}_\mu \]

\[ \Lambda_b \rightarrow p \] form factors with relativistic \( b \) quarks:

\[
\begin{align*}
\langle N^+ | \bar{u} \gamma^\mu b | \Lambda_b \rangle &= \bar{u}_N \left[ f_1^V \gamma^\mu - f_2^V i\sigma^{\mu\nu} q_\nu / m_{\Lambda_b} + f_3^V q^\mu / m_{\Lambda_b} \right] u_{\Lambda_b}, \\
\langle N^+ | \bar{u} \gamma^\mu \gamma_5 b | \Lambda_b \rangle &= \bar{u}_N \left[ f_1^A \gamma^\mu - f_2^A i\sigma^{\mu\nu} q_\nu / m_{\Lambda_b} + f_3^A q^\mu / m_{\Lambda_b} \right] \gamma_5 u_{\Lambda_b} 
\end{align*}
\]

Lattice QCD calculation in progress [Meinel, arXiv:1401.2685]:

- domain-wall \( u, d, s \) quarks
- RHQ \( b \) quarks
\[ \Lambda_b \rightarrow p \mu^- \bar{\nu}_\mu \]

preliminary

\[ f^V_1 \]

\[ f^V_2 \]

\[ f^V_3 \]

\[ f^A_1 \]

\[ f^A_2 \]

\[ f^A_3 \]

\[ q^2 \text{ (GeV}^2) \]
\[ \Lambda_b \rightarrow p \mu^- \bar{\nu}_\mu \]

\[ \frac{d\Gamma/dq^2}{|V_{ub}|^2} \quad (ps^{-1} \text{ GeV}^{-2}) \]

Total uncertainties shown.
Heavy-quark symmetries

Spectroscopy

Strong decays

Weak decays

• The charged-current decay $\Lambda_b \to p\mu\bar{\nu}_\mu$

• The FCNC decay $\Lambda_b \to \Lambda\mu^+\mu^-$
$b \to s \ell^+ \ell^-$ decays

[Grinstein, Savage, Wise, NPB 319, 271 (1989)]
$b \rightarrow s\ell^+\ell^-$ effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left( C_i O_i + C_i' O_i' \right)$$

with

$$O_7^{(')} = \frac{e m_b}{16\pi^2} \bar{s} \sigma^{\mu\nu} P_{R(L)} b \ F^{(\text{e.m.})}_{\mu\nu},$$

$$O_9^{(')} = \frac{e^2}{16\pi^2} \bar{s} \gamma^{\mu} P_{L(R)} b \ \bar{\ell} \gamma_{\mu} \ell,$$

$$O_{10}^{(')} = \frac{e^2}{16\pi^2} \bar{s} \gamma^{\mu} P_{L(R)} b \ \bar{\ell} \gamma_{\mu} \gamma_5 \ell$$

$$[P_{R,L} = (1 \pm \gamma_5)/2]$$

In the Standard Model, at $\mu = m_b$, to order NNLL:

<table>
<thead>
<tr>
<th></th>
<th>$C_7$</th>
<th>$C_9$</th>
<th>$C_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.331</td>
<td>4.211</td>
<td>-4.103</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$C_7'$</th>
<th>$C_9'$</th>
<th>$C_{10}'$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.006</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

[Altmannshofer et al., JHEP 0901, 019 (2009)]
The decay $B^0 \rightarrow K^{*0} (\rightarrow K^- \pi^+) \mu^+ \mu^-$
The decay $B^0 \to K^{*0}(\to K^-\pi^+)\mu^+\mu^-$

Many observables. Gives powerful constraints on Wilson coefficients.
Deviations from the Standard Model?

Angular observables [Descotes-Genon, Matias, Virto, PRD 88, 074002 (2013)]:

\[
\left\langle P_3 \right\rangle = f(q^2, H, L, X, P_5, \xi)
\]

(\text{using narrow-width approximation for } K^*)

Differential decay rates [Horgan, Liu, Meinel, Wingate, PRL 112, 212003 (2014)]:

\[
\frac{d\beta}{dq^2} (10^{-7} \text{ GeV}^{-2})
\]

\[ B^0 \to K^{*0} \mu^+ \mu^- \]

\[ B_s^0 \to \phi \mu^+ \mu^- \]

\[ B^+ \to K^{*+} \mu^+ \mu^- \]
Deviations from the Standard Model?

Fitting the Wilson coefficients $C_9$, $C_9'$ to the data:

- new $Z'$ gauge boson? [Gauld, Goertz, Haisch, JHEP 1401, 069 (2014)]
The decay $\Lambda_b \rightarrow \Lambda(\rightarrow p\,\pi^-)\,\mu^+\mu^-$

- Same or better new-physics sensitivity compared to $B^0 \rightarrow K^{*0}(\rightarrow K^-\pi^+)\mu^+\mu^-$
- $\Lambda$ is stable in QCD. Narrow-width approximation is exact. $\Lambda_b \rightarrow \Lambda$ form factors are “gold-plated” quantities in lattice QCD
The decay $\Lambda_b \rightarrow \Lambda (\rightarrow p \pi^-) \mu^+ \mu^-$

Using form factors from lattice QCD with static $b$ quarks:


Updated LHCb results with 3 fb$^{-1}$ and angular analysis are forthcoming.
Summary

Heavy baryons are interesting and useful.

- Many states remain to be discovered.

- In the absence of experimental data, lattice QCD results for doubly and triply heavy baryons provide tests of models and effective field theories.

- The decay $\Lambda_b \rightarrow p \mu \bar{\nu}$ will allow the first determination of $|V_{ub}|$ at the LHC (using form factors from lattice QCD).

- The decay $\Lambda_b \rightarrow \Lambda(\rightarrow p \pi^-) \mu^+ \mu^-$ will test recent hints of new physics in $b \rightarrow s \mu^+ \mu^-$ (using form factors from lattice QCD).