$b$-baryon mass measurements at LHCb

La Thuile 2013
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Motivations for heavy quark hadron spectroscopy

Experimental status before LHCb

Mass measurements of $\Lambda^0_b$, $\Omega^-_b$ and $\Xi^-_b$ at LHCb with $1 \text{ fb}^{-1}$ reconstructing $\Lambda^0_b \rightarrow J/\psi \Lambda$, $\Omega^-_b \rightarrow J/\psi \Omega^-$ and $\Xi^-_b \rightarrow J/\psi \Xi^-$

Momentum scale calibration
Candidate selection
Fits
Systematic uncertainties
Results

Summary and plans
Motivations for heavy quark hadron spectroscopy

Different QCD models predict masses, lifetimes, branching ratios, spin-parity etc. for many $c$- and $b$-hadrons.

Further confirmation and testing of models of the heavy quark interactions is provided by $c$- and $b$-hadron spectroscopy

$b$-baryon status: 16 predicted ground states ($J = 1/2$ and $3/2$)

- Weakly decaying: $\Lambda_b^0$, $\Xi_b^-$ and $\Omega_b^-$ baryons observed
- Strongly decaying: only charged $\Sigma_b^\pm$ observed
- Some first excited states seen: eg. $\Lambda_b^*^0$ at LHCb\(^1\)

Previous $\Xi_b^-$ and $\Omega_b^-$ mass measurements

- CDF and D0 measured both $\Xi_b^-$ and $\Omega_b^-$ baryon masses with a precision of several MeV/$c^2$.
- Agreement for $\Xi_b^-$ but significant inconsistency regarding the $\Omega_b^-$ mass.

<table>
<thead>
<tr>
<th></th>
<th>Value measured or predicted for $M_{\Omega_b^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0$^2$</td>
<td>6165 ± 10 ± 13 MeV/$c^2$</td>
</tr>
<tr>
<td>CDF$^3$</td>
<td>6054.4 ± 6.8 ± 0.9 MeV/$c^2$</td>
</tr>
<tr>
<td>Theory$^4$</td>
<td>6052.1 ± 5.6 MeV/$c^2$</td>
</tr>
</tbody>
</table>

- D0 measurement of $\Omega_b^-$ mass is more than 6 standard deviations away from the CDF one and only the CDF value is in agreement with main QCD models!
- Today, LHCb can measure these masses with a precision at the MeV/$c^2$ level.

Mass measurements at LHCb

- High precision mass measurements require good momentum measurement of the final state tracks.
- Thanks to its geometry and the excellent tracking devices, the LHCb detector has a very good momentum resolution.
- The two limitations are
  - Field map of 4 Tm dipole magnet known with finite precision
  - Detector alignment is never perfect

→ The track momentum measurement needs to be calibrated and the residual bias evaluated.
Momentum scale calibration for 2011 data at LHCb

- Time dependence from $J/\psi \rightarrow \mu^+ \mu^-$ (12 periods)
- Absolute momentum scale calibrated on $B^+ \rightarrow J/\psi K^+$
  (high statistics, $J/\psi$ mass constraint $\rightarrow$ main dependence on $K^+$)
- In bins of track slopes ($p_x/p_z$ and $p_y/p_z$) of the $K^+$ track

Figure: residual bias evaluated with other resonances
(multiplying the momentum of every final state track by $(1 - \alpha)$
shifts the reconstructed invariant mass to the PDG 2012 mass)

Assigned error on momentum scale: $\alpha_{max} = \pm 0.3 \times 10^{-3}$
Cut based selection

- $\Lambda^0_b$ selection based on selection with 2010 data
- Other two selections optimized using relative yield estimate from CDF and D0
- $\Xi_b^-$ and $\Omega_b^-$ selections almost identical
- Take advantage of decay topology and cut on flight distance

In all three cases use tracks with and without vertex detector information
$\Lambda_b^0 \to J/\psi \Lambda$ mass measurement - fit

**Signal:** two Gaussian functions with common mean

Yield: $6870 \pm 110$ (stat)

Widths: $\sigma_1 = 6.4 \pm 0.5$ (stat) MeV/$c^2$
$\sigma_2 = 12.5 \pm 1.3$ (stat) MeV/$c^2$

Mass: $5619.53 \pm 0.13$ (stat) MeV/$c^2$

**Background:** exponential function
$\Xi_b^- \rightarrow J/\psi \Xi^-$ mass measurement - fit

**Signal: single Gaussian function**

Yield: $111 \pm 12$ (stat)
Width: $7.8 \pm 0.7$ (stat) MeV/$c^2$
Mass: $5795.8 \pm 0.9$ (stat) MeV/$c^2$

**Background: exponential function**
**Signal:** single Gaussian function with fixed width

- **Significance:** $> 6\sigma$
- **Yield:** $19 \pm 5$ (stat)
- **Width:** $7.2$ MeV/$c^2$ (fixed to $\Xi_b^-$ width scaled by MC ratio)
- **Mass:** $6046.0 \pm 2.2$ (stat) MeV/$c^2$

**Background:** exponential function
Systematic uncertainties

- Fits and candidate reconstruction repeated with different conditions (momentum scale, energy loss correction, fit parameters, etc.)
- Difference with respect to nominal fit taken as systematic uncertainty
- Summary table in MeV/c²:

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Lambda_b^0$</th>
<th>$\Xi_b^-$</th>
<th>$\Omega_b^-$</th>
<th>$\Xi_b^- - \Lambda_b^0$</th>
<th>$\Omega_b^- - \Lambda_b^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum scale</td>
<td>0.43</td>
<td>0.43</td>
<td>0.31</td>
<td>0.01</td>
<td>0.12</td>
</tr>
<tr>
<td>$dE/dx$ correction</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Hyperon mass</td>
<td>0.01</td>
<td>0.07</td>
<td>0.25</td>
<td>0.07</td>
<td>0.25</td>
</tr>
<tr>
<td>Signal model</td>
<td>0.07</td>
<td>0.01</td>
<td>0.24</td>
<td>0.07</td>
<td>0.25</td>
</tr>
<tr>
<td>Background model</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>0.45</td>
<td>0.45</td>
<td>0.47</td>
<td>0.10</td>
<td>0.37</td>
</tr>
</tbody>
</table>

- Biggest systematic uncertainty from momentum calibration
- In mass differences, the hyperon mass constraint and signal model become important
The final result for the \( \Lambda^0_b \) baryon mass is

\[
M(\Lambda^0_b) = 5619.53 \pm 0.13 \text{ (stat)} \pm 0.45 \text{ (syst)} \text{ MeV}/c^2
\]

Combining with the previous LHCb result (35 pb\(^{-1}\))

\[
M(\Lambda^0_b) = 5619.44 \pm 0.13 \text{ (stat)} \pm 0.38 \text{ (syst)} \text{ MeV}/c^2
\]

**CDF I** [110 pb\(^{-1}\)]

**CDF II** [220 pb\(^{-1}\)]

**LHCb** [35 pb\(^{-1}\)]

**ATLAS** [4.9 fb\(^{-1}\)]

Average \( 5619.4 \pm 0.6 \)

**LHCb** [35 pb\(^{-1}\) + 1.0 fb\(^{-1}\)]

New average \( 5619.5 \pm 0.4 \)

**References**

$\Xi_b$ final result

- D0 [1.3 fb$^{-1}$]
- CDF [4.2 fb$^{-1}$] $\Xi_b^- \rightarrow J/\psi \Xi^-$
- CDF [4.2 fb$^{-1}$] $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$
- PDG [2012] $5791.1 \pm 2.2$
- LHCb [1.0 fb$^{-1}$]
- New average $5795.2 \pm 0.9$


**LHCb measurement (1 fb$^{-1}$)**

\[
M(\Xi_b^-) = 5795.8 \pm 0.9 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ MeV}/c^2
\]

\[
M(\Xi_b^-) - M(\Lambda_b^0) = 176.2 \pm 0.9 \text{ (stat)} \pm 0.1 \text{ (syst)} \text{ MeV}/c^2
\]
$\Omega_b^-$ final result

- D0 [1.3 fb$^{-1}$]
- CDF [4.2 fb$^{-1}$]
- PDG [2012] 6071 ± 40
- LHCb [1.0 fb$^{-1}$]
- CDF+LHCb average 6048.9 ± 2.1

14/20
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LHCb measurement (1 fb$^{-1}$)

$$M(\Omega_b^-) = 6046.0 \pm 2.2 \text{ (stat)} \pm 0.5 \text{ (syst)} \text{ MeV/c}^2$$

$$M(\Omega_b^-) - M(\Lambda_b^0) = 426.4 \pm 2.2 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ MeV/c}^2$$
LHCb gives the most precise $\Lambda^0_b$, $\Xi_b^-$ and $\Omega_b^-$ mass measurements to date.

$\Lambda^0_b$ and $\Xi_b^-$ results in agreement with previous measurements.

$\Omega_b^-$ result in agreement with CDF measurement, but in disagreement with D0 measurement.

LHCb has also performed high precision mass measurements of other long-lived $b$-hadrons like $B^+, B^0, B_s^5$ and $B_c^6$.

Soon new measurements with $b$-baryons including 2011+2012 data ($1 \, \text{fb}^{-1} + 2 \, \text{fb}^{-1}$): $\Lambda^0_b$, $\Xi_b^-$ and $\Omega_b^-$ lifetimes.

Excellent prospects for further spectroscopy at LHCb in the years to come: expect additional 5 fb$^{-1}$ at least by 2017 with a $b$-hadron production cross section twice as large.

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Thank you for your attention
BACKUP SLIDES
The LHCb experiment at CERN

- LHCb - single-arm forward spectrometer at the LHC
- Recording $pp$ collisions with $\sqrt{s} = 7$ TeV (in 2011) and 8 TeV (in 2012)
- Optimized for measurements in heavy-flavour physics
- Comprizes tracking detectors, RICH detectors, calorimeters and muon chambers.
- The tracking system: Vertex Locator (VeLo), Tracker Turicensis (TT), Inner-Tracker (IT) and Outer Tracker (OT)
### Theoretical predictions

<table>
<thead>
<tr>
<th>Modelling color hyperfine (HF) interactions (Annals Phys.324:2-15,2009)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- $M(\Xi_b^-) = 5795 \pm 5 \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>- $M(\Omega_b^-) = 6052.1 \pm 5.6 \text{ MeV}/c^2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>QCD sum rule approach in the Heavy Quark Effective Theory (HQET) framework (Phys.Rev.D77:014031,2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- $M(\Lambda_b^0) = 5637^{+68}_{-56} \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>- $M(\Xi_b^-) = 5780^{+73}_{-68} \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>- $M(\Omega_b^-) = 6036 \pm 81 \text{ MeV}/c^2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sum rule approach in full QCD (Phys.Rev.D78:094015,2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- $M(\Lambda_b^0) = 5690 \pm 130 \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>- $M(\Xi_b^-) = 5750 \pm 130 \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>- $M(\Omega_b^-) = 5890 \pm 180 \text{ MeV}/c^2$</td>
</tr>
</tbody>
</table>
Theoretical predictions II

- $M(\Omega_b^-) = 6039.1 \pm 8.3 \ \text{MeV}/c^2$

- $M(\Lambda_b^0) = 5680 \pm 110 \ \text{MeV}/c^2$
- $M(\Xi_b^-) = 5780 \pm 100 \ \text{MeV}/c^2$
- $M(\Omega_b^-) = 6030 \pm 90 \ \text{MeV}/c^2$

- $M(\Lambda_b^0) = 5622 \pm 100 \ \text{MeV}/c^2$
- $M(\Xi_b^-) = 5812 \pm 100 \ \text{MeV}/c^2$
- $M(\Omega_b^-) = 6065 \pm 100 \ \text{MeV}/c^2$

(Universal) quark-constituent model (arXiv:1205.6918)
Results only given in figure.