Spectroscopy of open Heavy Flavour states with emphasis on $B_c$ and $b$-baryons

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on behalf of the LHCb Collaboration including results from ATLAS and CMS

Produced hadrons within LHCb acceptance during Run I ($3.0 \text{ fb}^{-1}$):

$D^0/\bar{D^0} \sim 4500 \times 10^9$
$B^0/\bar{B^0} \sim 150 \times 10^9$
$\Lambda_b/\bar{\Lambda}_b \approx 90 \times 10^9$
$B_c^\pm \approx 0.9 \times 10^9$
Outline

B and D meson spectroscopy
- New $D_s^{*-}$ states

$B_c$ meson
- Mass and lifetime
- Decay modes
- Excited $B_c$

B baryons
- Lifetime, and mass, for $\Lambda_b$, $\Xi_b^0$, $\Xi_b^-$, $\Omega_b^-$
- Decay modes and CPV

Double Heavy baryons
- search for $\Xi_{cc}$
What to learn from these states

- The theoretical tools developed/used to study production and decays of B mesons and quarkonia (NRQCD, HQET, QCD sum rules, light front quark model, HQE...) can be tested in novel context
- Double heavy states offer unique laboratory to study interplay of strong and weak interactions
- Spin of baryon allows to probe the helicity structure in b decays
- Theoretical literature more limited wrt B meson decays
- Some accurate predictions from Heavy Quark Expansion exist for lifetime ratios of b hadrons
- For many processes results from different approaches differ ➡️ measurements needed to probe and tune models
- Some prospects for measuring weak phases and CP violation in B_c and b-baryon decays
B and D meson spectroscopy

Though $B_{(s)}$ and $D_{(s)}$ meson spectra were already extensively studied before LHC, there’s still to learn from Run I data. New excited states and decay modes reported by LHCb.

First observation of the $B_{s2}^* \rightarrow B^{*+}K^-$ decays and world’s best measurement of the $B_{s1}, B_{s2}^*$ and $B^*$ masses

Four D excited states (probably 2S and 1D states) identified, and some structures around 3 GeV (likely 1F states)
Study of $\bar{D}^0 K^-\pi^+$ structures in $B^0_s \rightarrow \bar{D}^0 K^-\pi^+$ decays

Structure at 2860 MeV/$c^2$ interpreted through angular analysis as superposition of $J^P = 1^-$ and $3^-$ states (likely 1D) both with significance $> 10\sigma$

First observation of a spin 3 heavy hadron!

$3.0 \text{ fb}^{-1}$ arXiv:1407.7574
arXiv:1407.7712
The $B_c$ meson

A unique system in the standard model

- only meson made of two heavy quarks with open flavour
- peculiar production mechanism
- non relativistic system: spectroscopy similar to quarkonium
- decays only through weak interactions

A great "laboratory" for testing QCD-inspired potential models and weak decay mechanism of heavy-quark bound states.

Pre-LHC knowledge

- discovered at Tevatron (1998) in semileptonic modes
  - significance $> 5\sigma$ only with Tevatron Run II (2008)
- only two decay modes observed:
  - $B_c^+ \rightarrow J/\psi \ell^+ \nu_\ell$
  - $B_c^+ \rightarrow J/\psi \pi^+$
- Mass and lifetime measurements (CDF/D0):
  - 6 MeV/c$^2$ mass uncertainty ($< 0.3$ MeV/c$^2$ for other $B$ mesons)
  - 7% uncertainty on the lifetime ($< 0.7\%$ for other $B$ mesons)

\[ \sigma(B_c)_{\text{LHC}} / \sigma(B_c)_{\text{Tevatron}} \sim 10 \]

The era of precision $B_c$ studies started at LHC!
Measurements using the “easiest” fully reconstructed mode $B_c^+ \rightarrow J/\psi \pi^+$

$M(B_c) = 6273.7 \pm 1.3 \ (stat) \pm 1.6 \ (syst) \text{MeV}/c^2$

$M(B_c) = 6282 \pm 7 \ (stat) \text{MeV}/c^2$

$LHCb$ result limited by systematic uncertainty on momentum scale ($\pm 3 \times 10^{-4}$). Can be improved exploiting decays with lower Q-value:

$B^+ \rightarrow J/\psi D^+_s$

$M(B_c) = 6272 \pm 3 \ (stat) \text{MeV}/c^2$

$M(B_c) = 6274.0 \pm 1.8 \ (stat) \pm 0.4 \ (syst) \text{MeV}/c^2$

$B_c^+ \rightarrow J/\psi D^+_s$

$M(B_c) = 6274.7 \pm 1.2 \text{MeV}/c^2$

$B^+ \rightarrow J/\psi p\bar{p} \pi^+$

$M(B_c) = 6273.28 \pm 1.44 \ (stat) \pm 0.36 \ (syst) \text{MeV}/c^2$

$M(B_c) = 6274.0 \pm 1.8 \ (stat) \pm 0.4 \ (syst) \text{MeV}/c^2$

**syst. uncertainty from momentum scale reduced to 0.30 and 0.40 MeV/c$^2$ in the two cases**
Measured at LHCb using partially reconstructed semileptonic decays

\[ B_c^+ \rightarrow J/\psi (\mu^+ \mu^-) \mu^+ \nu_\mu X \]

- High rate: BR is \( \sim 20 \times \text{BR}(J/\psi \pi^+) \)
- Clean \( 3 - \mu \) signature: trigger/selection possible without bias on decay time

Need to account for uncertainties from
- ✗ signal decay model and feed-downs (missing kinematics)
- ✗ backgrounds from \( B \) decays with particle misidentification

\( \sim 9000 \) candidates selected with moderate background. Statistics allow to constrain the main uncertainties using data.

Lifetime obtained from fit to 2D distribution decay time vs \( M(J/\psi \mu) \)

\[ \tau(B_c) = 509 \pm 8 \, \text{(stat)} \pm 12 \, \text{(syst)} \, \text{fs} \]

Prediction range: 300 - 700 fs

\(< \) half uncertainty wrt previous world average

Expect further improvements from analysis on \( J/\psi \pi^+ \) mode
Many new decay modes discovered at LHC, mostly $J/\psi$ + hadrons modes ($b \to cW$):

- $B_c^+ \to J/\psi \pi^+\pi^-\pi^+$
  - $0.8 \, \text{fb}^{-1}$ PRL 108 (2012) 251802
  - $4.7 \, \text{fb}^{-1}$ prelim. CMS-PAS-BPH-11-003

- $B_c^+ \to \psi(2S)\pi^+$
  - $1.0 \, \text{fb}^{-1}$ PRD87 (2013) 071103

- $B_c^+ \to J/\psi D_s^+(*)$
  - $3.0 \, \text{fb}^{-1}$ PRD87 (2013) 112012

- $B_c^+ \to J/\psi K^+$
  - $1.0 \, \text{fb}^{-1}$ JHEP 09 (2013) 075

- $B_c^+ \to J/\psi K^+K^-\pi^+$
  - $3.0 \, \text{fb}^{-1}$ JHEP 11 (2013) 094

- $B_c^+ \to J/\psi 3\pi^+2\pi^-$
  - $3.0 \, \text{fb}^{-1}$ JHEP 05 (2014) 148

- $B_c^+ \to J/\psi p\bar{p}\pi^+$
  - $3.0 \, \text{fb}^{-1}$ arXiv:1408.0971

but also first observation of a $c \to sW$ transition (expected to account for $\sim 70\%$ of width, but experimentally more difficult):

- $B_c^+ \to B_s^0\pi^+$
  - $3.0 \, \text{fb}^{-1}$ PRL 111 (2013) 181801

Knowledge of some reference absolute BR still missing to determine absolute $B_c$ production. Production $\times$ BR measurements in $J/\psi \pi^+$ and $B_s^0\pi^+$ modes, combined with theoretical estimates for the BRs, indicate that $\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \sim 2\%$, at the upper edge of expectations.

More measurements and theoretical work needed!!
\[ \mathcal{B}(B_c^+ \to J/\psi \pi^+) / \mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu) \]

- Wide spread in predictions: 0.05 – 0.09
- Use semileptonic decays with J/ψ μ above B⁺ meson mass (low background)
- Main syst. uncertainty from model-dependence in extrapolation to full phase space

\[ R = \frac{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)} = 0.0469 \pm 0.0028 \pm 0.0046 \]

1.0 fb⁻¹ arXiv:1407.2126

at the lower end of range of expectations

\[ \text{LHCb measurement} \]

\[ \text{Predictions} \]

G. Graziani \[slide 10\]

Rencontres du Vietnam 2014
Excited $B_c$!

First observation by ATLAS of an excited $B_c$ state decaying to $B_c^+ \pi^+ \pi^-$, compatible with expected 2S state $58 \pm 14$ candidates, significance is $5.2\sigma$ ($3.7\sigma$ in 7 TeV and $4.5\sigma$ in 8 TeV data alone). Mass and width consistent in the two datasets. Width compatible with experimental resolution.

$$M(B_c^+ (2S)) = 6842 \pm 4 \pm 5 \text{ MeV}$$

Prediction range 6835–6917 MeV

Likely to be $^32S_1 \rightarrow ^31S_1 (\rightarrow ^11S_0 \gamma_{\text{soft}}) \pi^+ \pi^-$ decay, with undetected soft ($\sim 50$ MeV) photon (production of vector state expected to be favoured).

(Trigger/selection efficiency different for the two samples)
B baryons

- limited knowledge on $b$-baryons before LHC:
- lifetime measured to better than 10% only for $\Lambda_b$:
  - result from LEP ($\tau(\Lambda_b)/\tau(B^0) \sim 0.8$) significantly below predictions, puzzling to explain
- most other states unobserved or $J^P$ not confirmed
- only one $\Lambda_b$ excited state observed

- accurate ($\mathcal{O}($%) $)$ HQE predictions for lifetime ratios of different $b$-hadrons, where difference are expected to be of order $(\Lambda_{QCD}/m_b)^2$ (see e.g. Lenz arXiv:1405.3601 for a summary)
- Valuable tests of HQE framework (on which we rely to understand e.g. $V_{ub}, V_{cb}, \Delta \Gamma$)
**Λ_b lifetime**

Measured relatively to B^0 using similar final states:

\[ \Lambda_b \rightarrow J/\psi \ p K^- \quad B^0 \rightarrow J/\psi \ K^{*0} (\rightarrow K^- \pi^+) \]

✓ most systematics cancel, small correction to acceptance ratio vs time evaluated from simulation

\[ \tau(\Lambda_b)/\tau(B^0) = 0.974 \pm 0.006 \pm 0.004 \]

in agreement with HQE predictions and ATLAS/CMS:

\[ \tau(\Lambda_b)/\tau(B^0) = 0.960 \pm 0.025 \pm 0.016 \]

\[ \tau(\Lambda_b)/\tau(B^0) = 0.989 \pm 0.034 \pm 0.020 \]

Long-standing puzzle seems to be solved!
**Ξ**₀ᵇ mass and lifetime

Using **Ξ**₀ᵇ → **Ξ**⁺ᶜ (→ **pK**⁻ **π**⁺) **π**⁻

× **Ξ**⁺ᶜ decay Cabibbo-suppressed, lose factor 3 in BR wrt **Ξ**⁺ → **Ξ**⁻ **π**⁺ **π**⁺,  **Ξ**⁻ → **Λ**(→ **pπ**⁻) **π**⁻

✓ but big gain in efficiency since no hyperons in final state!

✓ ideal normalization available: **Λ**₀ᵇ → **Λ**ᶜ(→ **pK**⁻ **π**⁺) **π**⁻ (identical final state)

\[ M(\Xi^0_b) = 5791.80 \pm 0.39 \pm 0.17 \pm 0.26 \Lambda_b \text{ MeV}/c^2 \]

First **Ξ**₀ᵇ lifetime measurement, relative to **Λ**₀ᵇ

\[ \tau(\Xi^0_b)/\tau(\Lambda_b) = 1.006 \pm 0.018 \pm 0.010 \]

Lifetime agree within 2%, as expected from HQE predictions

Also improving **Ξ**⁺ᶜ mass measurement by factor ∼4 wrt WA!
Absolute lifetime measurement using $J/\psi$-hyperon modes

- Clean signature from $J/\psi$ and detached hyperon decays
- Low efficiency for hyperon reconstruction
- Systematic limited by knowledge of absolute efficiency (evaluated from MC and validated with $B^0 \to J/\psi K^0_S$ and other data-driven checks)

World’s best measurements!
Consistent with previous (Tevatron) results, and HQE predictions.
For $\Xi_b^-$, expect further improvement from $\tau(\Xi_b^-)/\tau(\Lambda_b)$ analysis similar to the $\Xi_0^b$ case.

$\tau(\Xi_b^-) = 1.55^{+0.10}_{-0.09} \pm 0.03$ ps

$\tau(\Omega_b^-) = 1.54^{+0.26}_{-0.21} \pm 0.05$ ps
Several recent first observations and precision measurements of $\Lambda_b$ decay channels

- **First observation of a $b$-baryon decay to double-charm $\Lambda_b \rightarrow \Lambda_c D^-$** provides best measurement of $\Lambda_b$ mass
  \[ m(\Lambda_b) = 5619.30 \pm 0.24 \pm 0.18 \text{ MeV}/c^2 \]

- \[ B(\Lambda_b \rightarrow \Lambda_c \pi^-) = (4.30 \pm 0.03^{+0.12}_{-0.11} \pm 0.26 f_{\Lambda_b}/f_d \pm 0.21 \text{norm}) \times 10^{-3} \]
  measured from $\sim 45000 \Lambda_b \rightarrow \Lambda_c(\rightarrow J/\psi pK^-)\pi^- \text{ decays}$ using $B^0 \rightarrow D^-\pi^+$ as normalization mode, and the ratio of fragmentation fraction $f_{\Lambda_b}/f_d$ measured in semileptonic mode (PRD 85, 032008 (2012)).

- Precision improved from 70% to 8% !

- **Observation of $\Lambda_b/\Xi_b$ decays to $D^0_pK^-$**
  Can be used to measure CKM angle $\gamma$ using decays common to $D^0$ and $\bar{D}^0$ (à la $B^0 \rightarrow D^0K^{*0}$). Observed so far with CF $D^0 \rightarrow K^-\pi^+$ mode.

- **Measurement of the P-violating asymmetry $\alpha_b$ in $\Lambda_b \rightarrow J/\psi \Lambda$**
  \[ \frac{dN_{\Lambda_b}}{d\cos \theta} \propto \frac{1}{2}(1 + \alpha_b P \cos \theta) \]
  ($P$ is $\Lambda_b$ polarization)
  Test of non-perturbative QCD predictions
  \[ \alpha_b = 0.05 \pm 0.17 \pm 0.07 \]
  \[ \alpha_b = 0.30 \pm 0.16 \pm 0.06 \]

\[ \text{Candidates} \quad / \quad / \quad / \quad / \quad \]
\[ m(\Lambda_b^*) \quad / \quad \text{MeV}/c^2 \]

\[ 20.2 < p_T(\Lambda_b) < 40 \text{ GeV}/c \]

- $B(\Lambda_b \rightarrow \Lambda_c \pi^-) = (4.30 \pm 0.03^{+0.12}_{-0.11} \pm 0.26 f_{\Lambda_b}/f_d \pm 0.21 \text{norm}) \times 10^{-3}$
- $B(\Lambda_b \rightarrow \Lambda_c \pi^-) = (4.30 \pm 0.03^{+0.12}_{-0.11} \pm 0.26 f_{\Lambda_b}/f_d \pm 0.21 \text{norm}) \times 10^{-3}$
- $\alpha_b = 0.05 \pm 0.17 \pm 0.07$
- $\alpha_b = 0.30 \pm 0.16 \pm 0.06$

\[ 1.0 \text{ fb}^{-1} \quad \text{arXiv:1405.6842} \]

\[ 20.2 < p_T(\Lambda_b) < 40 \text{ GeV}/c \]

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CPV in $\Lambda_b$ decays

- First observation of the CS $\Lambda_b \to J/\psi p\pi^-$ decay, proceeding through 2 amplitudes with different weak phase: can exhibit direct CPV, sensitive to new physics
- BR and CP asymmetry measured wrt CF mode $\Lambda_b \to J/\psi pK^-$

$$\frac{B(J/\psi p\pi^-)}{B(J/\psi pK^-)} = (8.24 \pm 0.25 \pm 0.42)\%$$

$$\Delta A_{CP} = A_{CP}(J/\psi p\pi^-) - A_{CP}(J/\psi pK^-) = (5.7 \pm 2.3 \pm 1.2)\%$$

- Similar case for $\Lambda_b \to K_S^0 p\pi^-$, the first observed 3-body charmless $b$-baryon decay

$$\Delta A_{CP} = A_{CP}(K_S^0 p\pi^-) - A_{CP}(\Lambda_c(\to K_S^0 p)\pi^-) = (22 \pm 13 \pm 3)\%$$

Limits set on many other similar modes

3.0 fb$^{-1}$ arXiv:1406.0755

1.0 fb$^{-1}$ JHEP 04 (2014) 087
Double heavy baryons

- Only one of such states reported so far by SELEX (PLB 628 18, PRL 89 112001):
  - $\Xi_{cc}$ candidate with anomalous lifetime and prod. cross section.
  - Not confirmed at B factories and Tevatron
- LHCb sensitivity not far from predicted yield
  - Search performed on $0.65 \, \text{fb}^{-1}$. Negative result: 95% CL upper limits set on $R \equiv \sigma(\Xi_{cc}) \frac{B(\Xi_{cc} \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}$ as a function of $\Xi_{cc}$ lifetime and mass

95% CL upper limits range from $1.4 \times 10^{-2}$ ($\tau = 100$ fs) to $3.4 \times 10^{-4}$ (400 fs)
(predictions $\sim 10^{-5} - 10^{-4}$)

Does not exclude SELEX results ($\tau < 33$ fs)
The era of precision physics with $B_c$ and $b$-baryon states has started at LHC!

Mass and lifetime measurements provide accurate tests of effective models

<table>
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<th>HQE2014</th>
<th>pre-LHC</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau(\Lambda_b)/\tau(B^0)$</td>
<td>0.935 ± 0.054</td>
<td>0.912 ± 0.025</td>
<td>0.974 ± 0.007</td>
</tr>
<tr>
<td>$\tau(\Xi^0_b)/\tau(\Xi^-_b)$</td>
<td>0.95 ± 0.06</td>
<td>unmeasured</td>
<td>0.95 ± 0.07</td>
</tr>
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</table>

experiments often ahead of prediction accuracy... theoretical progress on $b$-baryon and double heavy states would be very useful!

Bright future for such physics at LHC with Run II data, and LHCb upgrade phase (from 2019):

- spectroscopy of $B_c$ and $b$-baryons has just started, still some time to make predictions!
- first CPV measurements with $\Lambda_b$ decays, many other interesting modes accessible in the near future, e.g. $\Lambda_b/\Xi_b \to D^0 p K^-$, $B_c^+ \to D^+_s D^0$ can contribute to CKM angle $\gamma$ determination
- the quest for double heavy baryons $\Xi_{QQ}$ ($Q = b, c$) started
**$D_s^*$ new states**

Results for mass and width of the $J^P = 1^-$ and $3^-$ states at 2860 MeV/$c^2$. Also best measurements for the already known $D_{s2}^*(2573)^-$ state.

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV/$c^2$)</th>
<th>Width (MeV/$c^2$)</th>
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<tbody>
<tr>
<td>$D_{s1}^*(2860)^-$</td>
<td>$2859 \pm 12 \pm 6 \pm 23$</td>
<td>$159 \pm 23 \pm 27 \pm 72$</td>
</tr>
<tr>
<td>$D_{s3}^*(2860)^-$</td>
<td>$2860.5 \pm 2.6 \pm 2.5 \pm 6.0$</td>
<td>$53 \pm 7 \pm 4 \pm 6$</td>
</tr>
<tr>
<td>$D_{s2}^*(2573)^-$</td>
<td>$2568.39 \pm 0.29 \pm 0.19 \pm 0.18$</td>
<td>$16.9 \pm 0.5 \pm 0.4 \pm 0.4$</td>
</tr>
</tbody>
</table>

(uncertainties are due to statistical, experimental systematic, model dependence effects)
first baryonic $B_c^+$ decay!

- adds input to baryon production studies in $b$ decays, after observing enhancement at low $M(p\bar{p})$ in $B$ meson decays

- provides another precise $B_c$ mass measurements

- larger statistics will allow search for $p$ excited states

Decay observed with $7.3\sigma$ significance

$$\frac{B(B_c^+ \to J/\psi p\bar{p}\pi^+)}{B(B_c^+ \to J/\psi \pi^+)} = 0.143 \pm 0.034 \pm 0.013$$

consistent with expectation from spectator decay model + factorization

$$\frac{B(B_c^+ \to J/\psi p\bar{p}\pi^+)}{B(B_c^+ \to J/\psi \pi^+)} \sim \frac{B(B^0 \to D^{*-} p\bar{p}\pi^+)}{B(B^0 \to D^{*-} \pi^+)} = 0.17 \pm 0.02$$

3.0 fb$^{-1}$ arXiv:1408.0971

(simulation uses uniform phase space model)
New excited $b$-baryon states

Two spectroscopy results from the first LHC data

New neutral $\Xi^*_b$ observed by CMS, decaying to $\Xi^*_b\pi^+$, likely to be a $J^P = 3/2^+$ state

$5.3\text{ fb}^{-1}$ PRL 108, 252002 (2012)

Two new states $\Lambda^*_b(5912)$ and $\Lambda^*_b(5920)$ observed by LHCb in $\Lambda_b\pi^+\pi^-$ spectrum, compatible with orbitally excited $\Lambda_b$

$1.0\text{ fb}^{-1}$ PRL 109, 172003 (2012)

$\Lambda^*_b(5920)$ confirmed by CDF (arXiv:1309.6269)
First observation of a $b$-baryon decay to double-charm provides best measurement of $\Lambda_b$ mass

$$m(\Lambda_b) = 5619.30 \pm 0.24 \pm 0.18 \text{ MeV/c}^2$$

main systematic uncertainty from $\Lambda_c, D^-$ lifetime values

$$\mathcal{B}(\Lambda_b \to \Lambda_c D^-) = (4.7 \pm 0.6) \times 10^{-4}$$

$$\mathcal{B}(\Lambda_b \to \Lambda_c D_s^-) = (1.1 \pm 0.1) \times 10^{-2}$$
\[ \frac{dN_{\Lambda_b}}{d\cos \theta} \propto \frac{1}{2} (1 + \alpha_b P \cos \theta) \]

Angular analysis of \( \Lambda_b \rightarrow J/\psi (\mu^+ \mu^-) \Lambda (p \pi^-) \)

- P-violating asymmetry \( \alpha_b \) related to helicity amplitudes
  \[ \alpha_b = |M_{+1/2,0}|^2 - |M_{-1/2,0}|^2 + |M_{-1/2,-1}|^2 - |M_{+1/2,+1}|^2 \]
  can be determined from angular fit (even with null average \( \Lambda_b \) polarization \( P \)).

Average \( P = 0 \) for ATLAS, using a symmetric rapidity interval around 0 (\( P(p_T, \eta) = -P(p_T, -\eta) \)); \( P \) measured in LHCb

- No CPV assumed in \( \Lambda_b \) and \( \Lambda \) decays.

\[ \begin{array}{c|c|c}
\hline
P & 1.0 \text{ fb}^{-1} \text{ PLB 724 (2013) 27} & 4.6 \text{ fb}^{-1} \text{ PRD 89 092009 (2014)} \\
\hline
\alpha_b & 0.06 \pm 0.07 \pm 0.02 & 0 (\text{fixed}) \\
\hline
|M_{+1/2,0}|^2 & 0.05 \pm 0.17 \pm 0.07 & 0.30 \pm 0.16 \pm 0.06 \\
|M_{-1/2,0}|^2 & 0.01 \pm 0.04 \pm 0.03 & 0.17^{+0.12}_{-0.17} \pm 0.09 \\
|M_{-1/2,-1}|^2 & 0.57 \pm 0.06 \pm 0.03 & 0.59^{+0.06}_{-0.07} \pm 0.03 \\
|M_{+1/2,-1}|^2 & 0.51 \pm 0.05 \pm 0.02 & 0.79^{+0.04}_{-0.05} \pm 0.02 \\
|M_{+1/2,+1}|^2 & -0.10 \pm 0.04 \pm 0.03 & 0.08^{+0.13}_{-0.08} \pm 0.06 \\
\hline
\end{array} \]

\( \alpha_b \) values from ATLAS and LHCb in agreement, above range -0.2 to -0.1 indicated by most predictions

Polarization measured at LHCb below predicted values of 10-20 % (\text{PLB 649 (2007) 152, PLB 614 (2005) 165})

while consistent with vanishing polarization at small \( x \), observed for \( \Lambda \) baryons in fixed-target experiments.