$\Lambda_b \rightarrow J/\psi \Lambda$ feasibility study in ATLAS

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On behalf of the ATLAS $\Lambda_b$ Polarization Working Group
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Outline

- Theoretical Interest
- \( \Lambda_b \) Production
- \( \Lambda_b \) Decay
- Validation of the Generation
- Acceptance Studies
- First Look at the Reconstruction
- Backgrounds
- Summary
Physics Motivation

- Measure the polarization of inclusively produced $\Lambda_b$ hyperons in ATLAS
- Testing models of heavy flavor production, HQET, PQCD, Factorization
- B-baryon lifetime puzzle in $\tau(\Lambda_b)/\tau(B^0)$: theory 0.9-1 vs. data $0.780 \pm 0.037$ (PDG)
- Search for New Physics beyond the Standard Model
- CP violation in baryons $\Lambda_b \rightarrow J/\psi \Lambda$
$\Lambda_b$ Production

- @ LHC the heavy flavors are produced mainly from gluon splitting in $P$-conserving strong interactions $\rightarrow \Lambda_b$ can be polarized only orthogonal to the production plane

- Generation process fast compared to the time scale of non-pertubative strong interactions and fragmentation $\rightarrow$ heavy quark velocity, spin, ... transferred to the decay products

What is responsible for the large polarizations observed in hyperons at several hundred GeV?
What causes this pattern?

Does it depend on quark mass?

Does it depend on $E$(c.m.)?

Could $P$ be even larger for $\Lambda_b$?
$\Lambda_b$ Production in ATLAS

- $L = 2 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$ (low) @ $\sqrt{s} = 14$ TeV
- $\sigma(pp\rightarrow b\bar{b}) \approx 500 \mu$b, $f(b\rightarrow \Lambda_b) \sim 8\%$
- $O(10^{12}) \Lambda_b$ per year $>>$ Tevatron
- $BR \; \Lambda_b \rightarrow \Lambda(p\pi^-) J/\psi(\mu^+\mu^-) = 1.74 \cdot 10^{-5}$
- $L$VL1: Single $\mu$ $p_T > 6$ GeV/c, $|\eta|<2.4$ + a second $\mu(5)$ or $\mu(3)$ + EM/Jet RoI
- $L$VL2 $J/\psi$ selection (softer 2nd $\mu$)

TDR estimation: in the first 3 years (30 fb$^{-1}$) $O(10^5)$

$\Lambda_b \rightarrow \Lambda(p\pi^-) J/\psi(\mu^+\mu^-)$ will be fully reconstruct allowing
$\sim 2\%$ precision of polarization determination

$+ \Lambda_b \rightarrow \Lambda(p\pi^-) J/\psi(e^+e^-)$ will add statistics
$\Lambda_b$ Decay

Most general matrix element of this color suppressed decay

$$\mathcal{M}(\lambda) = \bar{\Lambda}(p') \left[ A_1 \ell \gamma_5 + A_2 \frac{p \cdot e}{M_{\Lambda_b}} \gamma_5 + B_1 \ell + B_2 \frac{p \cdot e}{M_{\Lambda_b}} \right] \Lambda_b(p)$$

$A_{1,2} \& B_{1,2}$ (P-violating) calculated in HQET with factorization, where the decay amplitude can be expressed as convolutions of $\Lambda_b$, $\Lambda$ and $J/\psi$ distribution amplitudes plus other (universal) factors calculable via PQCD and/or extracted from other reactions.

Helicity amplitudes formalism: 4 combinations $\frac{1}{2} \rightarrow 1 + \frac{1}{2}$

$\begin{align*}
\alpha_+ &= |a_+| e^{i\alpha_+} = A(1/2, 0) \\
\alpha_- &= |a_-| e^{i\alpha_-} = A(-1/2, 0) \\
b_+ &= |b_+| e^{i\beta_+} = A(-1/2, -1) \\
b_- &= |b_-| e^{i\beta_-} = A(1/2, 1)
\end{align*}$

$\Rightarrow \alpha_b = \frac{|a_+|^2 + |b_+|^2 - |a_-|^2 - |b_-|^2}{|a_+|^2 + |b_+|^2 + |a_-|^2 + |b_-|^2}$

Normalization: Den=1
Probability Distribution

\[
\mathcal{W}(\Omega, \Omega_1, \Omega_2) = \frac{1}{(4\pi)^3} \sum_{i=0}^{i=19} f_{1i} f_{2i}(P_b, \alpha_\lambda) F_i(\theta, \theta_1, \theta_2, \phi_1, \phi_2)
\]

It depends on 4 complex helicity amplitudes, polarization \(P_b\) + 5 angles normalization + overall phase \(\Rightarrow (8-2) + 1\) unknowns + 5 observables

Helicity amplitudes (so \(\alpha_b\)) and \(P_b\) to be simultaneously determined

Each angle is defined in the rest frame of the decaying particle

<table>
<thead>
<tr>
<th>(i)</th>
<th>(f_{1i})</th>
<th>(f_{2i})</th>
<th>(F_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(a_+a^<em><em>+ + a</em>-a^</em><em>- + b</em>+b^<em><em>+ + b</em>-b^</em>_-)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>(a_+a^<em><em>+ + a</em>-a^</em><em>- + b</em>+b^<em><em>+ - b</em>-b^</em>_-)</td>
<td>(P_b)</td>
<td>(\cos \theta)</td>
</tr>
<tr>
<td>2</td>
<td>(a_+a^<em><em>+ - a</em>-a^</em><em>- + b</em>+b^<em><em>+ + b</em>-b^</em>_-)</td>
<td>(\alpha_\lambda)</td>
<td>(\cos \theta)</td>
</tr>
<tr>
<td>3</td>
<td>(a_+a^<em><em>+ - a</em>-a^</em><em>- + b</em>+b^<em><em>+ - b</em>-b^</em>_-)</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\cos \theta \cos \varphi)</td>
</tr>
<tr>
<td>4</td>
<td>(a_+a^<em><em>+ - a</em>-a^</em><em>- + b</em>+b^<em><em>+ + b</em>-b^</em>_-)</td>
<td>(1)</td>
<td>(d_{50}(\beta_2))</td>
</tr>
<tr>
<td>5</td>
<td>(a_+a^<em><em>+ - a</em>-a^</em><em>- + b</em>+b^<em><em>+ - b</em>-b^</em>_-)</td>
<td>(P_b)</td>
<td>(d_{50}(\beta_2)) (\cos \theta)</td>
</tr>
<tr>
<td>6</td>
<td>(a_+a^<em><em>+ - a</em>-a^</em><em>- + b</em>+b^<em><em>+ + b</em>-b^</em>_-)</td>
<td>(\alpha_\lambda)</td>
<td>(d_{50}(\beta_2)) (\cos \varphi)</td>
</tr>
<tr>
<td>7</td>
<td>(a_+a^<em><em>+ - a</em>-a^</em><em>- + b</em>+b^<em><em>+ - b</em>-b^</em>_-)</td>
<td>(P_b\alpha_\lambda)</td>
<td>(d_{50}(\beta_2)) (\cos \varphi)</td>
</tr>
<tr>
<td>8</td>
<td>(-3\text{Re}(a_+a^*<em>+\alpha</em>\lambda))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \sin \varphi_1)</td>
</tr>
<tr>
<td>9</td>
<td>(3\text{Im}(a_+a^*<em>+\alpha</em>\lambda))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \sin \varphi_1)</td>
</tr>
<tr>
<td>10</td>
<td>(-\frac{3}{2}\text{Re}(b_+b^*_+))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \sin \varphi_1)</td>
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<tr>
<td>11</td>
<td>(-\frac{3}{2}\text{Im}(b_+b^*_+))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \sin \varphi_1)</td>
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<tr>
<td>12</td>
<td>(-\frac{3}{2}\text{Re}(b_+b^*<em>+\alpha</em>\lambda))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \cos \varphi_1)</td>
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<tr>
<td>13</td>
<td>(\frac{3}{2}\text{Im}(b_+b^*<em>+\alpha</em>\lambda))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \cos \varphi_1)</td>
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<td>14</td>
<td>(\frac{3}{2}\text{Re}(b_+b^*<em>+\alpha</em>\lambda))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \cos \varphi_1)</td>
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<td>15</td>
<td>(\frac{3}{2}\text{Im}(b_+b^*<em>+\alpha</em>\lambda))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \cos \varphi_1)</td>
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<td>16</td>
<td>(-\frac{3}{2}\text{Re}(b_+b^*<em>+\alpha</em>\lambda))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \cos \varphi_1)</td>
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<td>17</td>
<td>(-\frac{3}{2}\text{Im}(b_+b^*<em>+\alpha</em>\lambda))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \cos \varphi_1)</td>
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<td>18</td>
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<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \cos \varphi_1)</td>
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<tr>
<td>19</td>
<td>(-\frac{3}{2}\text{Im}(b_+b^*<em>+\alpha</em>\lambda))</td>
<td>(P_b\alpha_\lambda)</td>
<td>(\sin \theta \cos \varphi_1)</td>
</tr>
</tbody>
</table>
MonteCarlo

- Pythia: probabilistic baryons production + spin information not used and no software tools for implementing polarization models available
- EvtGen provides the framework where we implemented the $\Lambda_b$ polarization model

Unpolarized $\Lambda_b$ from PythiaB

EvtGen
Set the Polarization level
Helicity amplitudes decay

HepMC for simulation


\[ a_+ = -0.0176 - 0.4290i \]
\[ a_- = 0.0867 + 0.2454i \]
\[ b_+ = -0.0810 - 0.2837i \]
\[ b_- = 0.0296 + 0.8124i \]

$\alpha_b = -0.457$  
P = -40%
Parameters check

\[ w(\cos \theta) = 1 + \alpha_b P_b \cos \theta \]

Polarization dependent!

<table>
<thead>
<tr>
<th>( P_b )</th>
<th>( \alpha_b P_b ) fit</th>
<th>Input ( \alpha_b P_b )</th>
</tr>
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<tbody>
<tr>
<td>0.4</td>
<td>-0.184( \pm 0.011 )</td>
<td>-0.183</td>
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<tr>
<td>0</td>
<td>0.010( \pm 0.011 )</td>
<td>0</td>
</tr>
<tr>
<td>-0.4</td>
<td>0.174( \pm 0.012 )</td>
<td>0.183</td>
</tr>
</tbody>
</table>
Parameter check (2)

\[ w(\cos\theta_1) = 1 + \gamma_1 (|a_\pm|^2, |b_\pm|^2) \alpha_\Lambda \cos\theta_1 \]
\[ w(\cos\theta_2) = 1 + \gamma_2 (|a_\pm|^2, |b_\pm|^2) \alpha_\Lambda (3 \cos\theta_2^2 - 1) \]

<table>
<thead>
<tr>
<th>Input</th>
<th>fit</th>
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<tbody>
<tr>
<td>(\gamma_1)</td>
<td>0.692</td>
</tr>
<tr>
<td>(\gamma_2)</td>
<td>0.122</td>
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</table>
Signal Mass Reconstruction

**Low $P_T(\mu)$ Dedicated ID algorithm**

Very preliminary results:
- full realistic detector simulation and reconstruction, but
  - no pile-up yet
  - no background yet

<table>
<thead>
<tr>
<th>h125</th>
<th>Entries</th>
<th>1078</th>
<th>Mean</th>
<th>3081</th>
<th>RMS</th>
<th>232</th>
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<tbody>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
<td>1.323 / 1</td>
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<td></td>
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<tr>
<td>Constant</td>
<td>$272.5 \pm 14.6$</td>
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<tr>
<td>Mean</td>
<td>$3092 \pm 2.0$</td>
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<tr>
<td>Sigma</td>
<td>$46.07 \pm 1.92$</td>
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<td></td>
<td></td>
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</table>

<table>
<thead>
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<th>5496</th>
<th>RMS</th>
<th>309.9</th>
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<tbody>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
<td>$3.057e-011 / -2$</td>
<td></td>
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<tr>
<td>Constant</td>
<td>$59.31 \pm 117.08$</td>
<td></td>
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<tr>
<td>Mean</td>
<td>$5638 \pm 167.4$</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Sigma</td>
<td>$36.07 \pm 321.52$</td>
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</table>

<table>
<thead>
<tr>
<th>Entries</th>
<th>31800</th>
<th>Mean</th>
<th>1118</th>
<th>RMS</th>
<th>10.63</th>
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<tbody>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
<td>$5.341e-011 / -3$</td>
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<tr>
<td>Constant</td>
<td>$211 \pm 14.7$</td>
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<tr>
<td>Mean</td>
<td>$1115 \pm 0.2$</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Sigma</td>
<td>$2.875 \pm 0.173$</td>
<td></td>
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</tr>
</tbody>
</table>
Backgrounds

- **Background dominated by J/ψ from b-hadrons**
  + Λ from heavier hadrons & fragmentation (prompt J/ψ contribution negligible)

- **fake muons & combinatorial background found negligible in similar topologies** (e.g. B^0 → J/ψ K_s)

- **real J/ψ Λ from cascade decay estimated at percent level** (ex. \( \Xi^-_b \rightarrow \Xi^- \) J/ψ → Λ π^0, J/ψ)

- **B^0 → J/ψ Ks** where a proton mass is given to a π rejected with mass constraints

- **real Λ_b not directly produced**
  (ex. \( \Sigma_b^{+,−,0,1/2} \) or \( \Sigma_b^{*,+,−,0,3/2} \) → Λ_b π^+,−,0)
  Try to reconstruct \( \Sigma_b^{(*)} \) too to reduce the dilution
Summary

- High physics potential in $\Lambda_b$ polarization study
- Reliable MC production of polarized $\Lambda_b$ with any decay model: modified EvtGen is properly working
- Clear direction on the work still necessary:
  - Optimizing of $J/\psi$ and $\Lambda$ reconstruction strategies
  - Complete background studies
  - Maximum likelihood method on “real” samples

Clean $\Lambda_b$ signals (CDF, D0) + ATLAS rates should permit early polarization measurements at the few percent level and a lot more exciting physics
Back-up slides
Baryon Lifetimes

Disagreement between experimental data and theory τ(Λ_b)/τ(B^0) = 0.780±0.037 vs 0.9-1 (th)

Quark spectator: Γ(b)= 9/192π^3 · V_{cb}^2 G_F^2 m_b^5
does not explain b-hadrons lifetimes differences

Correction effects:
- Pauli interference: 2 indistinguishable final states → destructive interference
Baryon Lifetime (2)

- Weak Annihilation in virtual $W$ ($V_{ub} \ll 1$, imp. for D-mesons)

- Weak Interference: helicity suppressed in $b$-mesons, not $b$-baryons
CP violation

- CP violation in $\Lambda_b \to J/\psi \Lambda$ expected small: decay dominated by a single tree level $b \to ccs$.
- Good candidate for New Physics search
- Interesting test in a process $\Delta B=1$: 
  CP-violation seen so far only in $\Delta S=2$ & $\Delta B=2$
- Necessity to analyze both $\Lambda_b$ and anti-$\Lambda_b$ to better constraint the unknown strong phases
- Check of $\alpha(\Lambda_b) = -\alpha(\Lambda_b)$, triple-product correlations
  (ex. PRD 66, 094004 (2002)), . . .
EvtGen Comparison

5 angular distributions generated using EvtGen with both the probability function and helicity amplitudes

**GOOD AGREEMENT**
Cuts @ Generator Level

Event kinematics independent from the input model

Cuts: request of reconstructed

- $p_T(\mu) > 4, 2.5 \text{ GeV/c} + |\eta(\mu)| < 2.7$
- $p_T(p,\pi) > 0.5 \text{ GeV/c} + |\eta| < 2.7$

Angular distribution shapes changed by the cuts!
Corrections: weight factors from pure phase space events