Measuring quark polarizations at ATLAS and CMS

Yevgeny Kats

Based on:


Motivation

ATLAS and CMS already measure **top quark** polarization.

**single top production**

\[
\frac{1}{\sigma} \frac{d\sigma}{d(\cos\theta^*_W)}
\]

**top pair production**

\[
\frac{1}{\sigma} \frac{d\sigma}{d(\cos\theta^*_t)}
\]

**EW process → polarized**

\[
q \rightarrow \mu + \text{jets, } t + \bar{t}, \text{ 19.7 fb}^{-1} \text{ (8 TeV)}
\]

**QCD process → unpolarized**

\[
b \rightarrow g \rightarrow t + \bar{t}
\]

**etc.**
Motivation

ATLAS and CMS already measure top quark polarization.

single top production

EW process $\rightarrow$ polarized

top pair production

QCD process $\rightarrow$ unpolarized

Polarization of tops from new physics processes will teach us about their production mechanism.
Motivation

ATLAS and CMS already measure **top quark** polarization.

Can we do analogous measurements for the **other quarks**?

Polarization of tops from **new physics** processes will teach us about their production mechanism.

Can we do analogous measurements for the **other quarks**?
For heavy quarks, $m_q \gg \Lambda_{\text{QCD}}$

- The quark is carried by a very energetic heavy-flavored hadron.

EPJC 29, 463 (2003) [hep-ex/0210031]
Heavy quarks \((b, c)\)

For heavy quarks, \(m_q \gg \Lambda_{\text{QCD}}\)

- The quark is carried by a very energetic heavy-flavored hadron.
- When it is a baryon, \(\mathcal{O}(1)\) fraction of the polarization is expected to be retained.

Mannel and Schuler, PLB 279, 194 (1992)
EPJC 29, 463 (2003) [hep-ex/0210031]
Heavy quarks ($b, c$)

For heavy quarks, $m_q \gg \Lambda_{\text{QCD}}$

- The quark is carried by a very energetic heavy-flavored hadron.
- When it is a baryon, $\mathcal{O}(1)$ fraction of the polarization is expected to be retained.

Mannel and Schuler, PLB 279, 194 (1992)

Evidence observed at LEP via $\Lambda_b (\approx bud)$ baryons in $Z \rightarrow b\bar{b}$.

\[
\mathcal{P}(\Lambda_b) = -0.23^{+0.24}_{-0.20}^{+0.08}_{-0.07} \quad \text{(ALEPH)} \quad \text{PLB 365, 437 (1996)}
\]

\[
\mathcal{P}(\Lambda_b) = -0.49^{+0.32}_{-0.30} \pm 0.17 \quad \text{(DELPHI)} \quad \text{PLB 474, 205 (2000)}
\]

\[
\mathcal{P}(\Lambda_b) = -0.56^{+0.20}_{-0.13} \pm 0.09 \quad \text{(OPAL)} \quad \text{PLB 444, 539 (1998) [hep-ex/9808006]}
\]

EPJC 29, 463 (2003) [hep-ex/0210031]
$b$-quark polarization retention

**chromomagnetic moment**

\[ \mu_b \propto \frac{1}{m_b} \]

\[ m_b \gg \Lambda_{\text{QCD}} \]

$b$ spin preserved during hadronization
**$b$-quark polarization retention**

- Chromomagnetic moment:
  \[ \mu_b \propto \frac{1}{m_b} \]
  \[ m_b \gg \Lambda_{\text{QCD}} \]
  \[ b \text{ spin } \text{preserved} \]
  \[ \text{during hadronization} \]

- $b$ spin preserved also during lifetime

- $b$ spin oscillates during lifetime

- $\Sigma_b$, $\Sigma^*_b$

- $\Lambda_b$ sample contaminated by $\Sigma_b^{(*)} \to \Lambda_b \pi$

- Fragmentation fraction $f(b \to \text{baryons}) \approx 8\%$
\[ \Lambda c \]  

\[ m_c \gg \Lambda_{QCD} \]  
as a rough approximation

\[ c \text{ spin } \text{preserved} \]  
during hadronization

\[ \mu_c \propto \frac{1}{m_c} \]  

\[ c \text{ spin } \text{preserved} \]  
also during lifetime

\[ c \text{ spin } \text{oscillates} \]  
during lifetime

\[ \Sigma_c(2455) \]

\[ \Sigma_c(2520) \]

\[ \Sigma_c, \Sigma_c^* \]

\[ \Lambda_c \text{ sample contaminated by } \Sigma_c^{(*)} \rightarrow \Lambda_c \pi \]

fragmentation fraction \[ f(c \rightarrow \text{baryons}) \approx 6\% \]
Dominant polarization loss effect

\[ \Sigma_b^{(*)} \rightarrow \Lambda_b \pi \text{ decays} \]

\[ r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)} = ? \]
**b-quark polarization retention**

Dominant polarization loss effect

\[ \Sigma_b^{(*)} \rightarrow \Lambda_b \pi \text{ decays} \]

\[
\begin{align*}
|\Lambda_{b,+1/2}\rangle & = |b_{+1/2}\rangle |S_0\rangle \\
|\Sigma_{b,+1/2}\rangle & = -\sqrt{\frac{1}{3}} |b_{+1/2}\rangle |T_0\rangle + \sqrt{\frac{2}{3}} |b_{-1/2}\rangle |T_{+1}\rangle \\
|\Sigma_{b,+1/2}^*\rangle & = \sqrt{\frac{2}{3}} |b_{+1/2}\rangle |T_0\rangle + \sqrt{\frac{1}{3}} |b_{-1/2}\rangle |T_{+1}\rangle \\
|\Sigma_{b,+3/2}^*\rangle & = |b_{+1/2}\rangle |T_{+1}\rangle \\
\end{align*}
\]

Production as a \( b \) spin eigenstate.

Decay as a \( \Sigma_b \) or \( \Sigma_b^* \) mass eigenstate.

\[
\text{e.g.} \quad |b_{+1/2}\rangle |T_0\rangle = -\sqrt{\frac{1}{3}} \left| \Sigma_{b,+1/2} \right\rangle + \sqrt{\frac{2}{3}} \left| \Sigma_{b,+1/2}^* \right\rangle
\]

\[
\begin{align*}
\mathcal{P}(\Lambda_b) & = r \mathcal{P}(b) \\
\text{“diquarks”} \quad S & \quad \text{spin-0 isosinglet} \\
T & \quad \text{spin-1 isotriplet}
\end{align*}
\]
**b-quark polarization retention**

Dominant polarization loss effect

\[ \Sigma_b^{(*)} \rightarrow \Lambda_b \pi \text{ decays} \]

- \[ \Lambda_{b,+1/2} = |b_{+1/2}\rangle |S_0\rangle \]
- \[ |\Sigma_{b,+1/2}\rangle = -\sqrt{\frac{1}{3}} |b_{+1/2}\rangle |T_0\rangle + \sqrt{\frac{2}{3}} |b_{-1/2}\rangle |T_{+1}\rangle \]
- \[ |\Sigma^*_{b,+1/2}\rangle = \sqrt{\frac{2}{3}} |b_{+1/2}\rangle |T_0\rangle + \sqrt{\frac{1}{3}} |b_{-1/2}\rangle |T_{+1}\rangle \]
- \[ |\Sigma^*_{b,+3/2}\rangle = |b_{+1/2}\rangle |T_{+1}\rangle \]

**Production as a \( b \) spin eigenstate.**

**Decay as a \( \Sigma_b \) or \( \Sigma_b^* \) mass eigenstate.**

\[ |b_{+1/2}\rangle |T_{0}\rangle = -\sqrt{\frac{1}{3}} |\Sigma_{b,+1/2}\rangle + \sqrt{\frac{2}{3}} |\Sigma_{b,+1/2}^*\rangle \]

**“diquarks”**

- \( S \) \hspace{1cm} \( T \)
  - spin-0 isosinglet
  - spin-1 isotriplet

\[ A = \frac{\text{prob}(\Sigma_b^{(*)})}{\text{prob}(\Lambda_b)} = 9 \frac{\text{prob}(T)}{\text{prob}(S)} \]

\[ w_1 = \frac{\text{prob}(T_{+1})}{\text{prob}(T)} \text{ along axis of fragmentation} \]

Falk and Peskin

PRD 49, 3320 (1994)

[hep-ph/9308241]
**b-quark polarization retention**

Dominant polarization loss effect

\[ \Sigma_b^{(*)} \rightarrow \Lambda_b \pi \] decays

\[
\begin{align*}
|\Lambda_{b,+1/2}\rangle &= |b_{+1/2}\rangle |S_0\rangle \\
|\Sigma_{b,+1/2}\rangle &= -\sqrt{\frac{1}{3}} |b_{+1/2}\rangle |T_0\rangle + \sqrt{\frac{2}{3}} |b_{-1/2}\rangle |T_{+1}\rangle \\
|\Sigma_{b,+1/2}^*\rangle &= \sqrt{\frac{2}{3}} |b_{+1/2}\rangle |T_0\rangle + \sqrt{\frac{1}{3}} |b_{-1/2}\rangle |T_{+1}\rangle \\
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Production as a \( b \) spin eigenstate.
Decay as a \( \Sigma_b \) or \( \Sigma_b^* \) mass eigenstate.

e.g. \[ |b_{+1/2}\rangle |T_0\rangle = -\sqrt{\frac{1}{3}} |\Sigma_{b,+1/2}\rangle + \sqrt{\frac{2}{3}} |\Sigma_{b,+1/2}^*\rangle \]

\[ r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)} = ? \]

“diquarks”

\[
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\[
A = \frac{\text{prob}(\Sigma_b^{(*)})}{\text{prob}(\Lambda_b)} = 9 \frac{\text{prob}(T)}{\text{prob}(S)}
\]

\[ w_1 = \frac{\text{prob}(T_{+1})}{\text{prob}(T)} \quad \text{along axis of fragmentation} \]

\[ r \approx \frac{1 + (1 + 4w_1)A/9}{1 + A} \]
**b-quark polarization retention**

More precisely, need to account for $\Sigma_b^{(*)}$ widths (interference).

Can do it by considering $\Sigma_b^{(*)}$ propagation:

$$|E\rangle \propto \int d\cos \theta \, d\phi \, \sum_{J,M} \langle J, M | \frac{1}{2}, +\frac{1}{2}; 1, m \rangle \frac{p_\pi(E)}{E - m_J + i\Gamma(E)/2} \times \sum_s \langle \frac{1}{2}, s; 1, M - s | J, M \rangle Y_1^{M-s}(\theta, \phi) \langle \theta, \phi | s \rangle$$

$$\rho(E) \propto \text{Tr}_{\theta,\phi} \langle E \rangle \langle E |$$

$$\rho \propto \int_{m_{\Lambda_b} + m_\pi}^{\infty} dE \, p_\pi(E) \exp \left( -E/T \right) \rho(E)$$

---

<table>
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<tr>
<td>$\Gamma_{\Sigma_b}$</td>
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<tr>
<td>$\Gamma_{\Sigma_b^*}$</td>
<td>$9 \pm 2$</td>
</tr>
<tr>
<td>$m_{\Sigma_b^*} - m_{\Sigma_b}$</td>
<td>$21 \pm 2$</td>
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$b$-quark polarization retention

More precisely, need to account for $\Sigma_b^{(*)}$ widths (interference).

\begin{align*}
r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)} & \approx \frac{1 + (0.23 + 0.38w_1)A}{1 + A}
\end{align*}

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Directional dependence, since

$$r_L \approx \frac{1 + (0.23 + 0.38w_1)A}{1 + A}$$

$$r_T \approx \frac{1 + (0.62 - 0.19w_1)A}{1 + A}$$

holds along the fragmentation axis.

$$w_1 = \frac{\text{prob}(T_{\pm 1})}{\text{prob}(T)}$$
Heavy quark polarization retention

\[ r_L \approx \frac{1 + (0.23 + 0.38w_1)A}{1 + A} \]

\[ r_T \approx \frac{1 + (0.62 - 0.19w_1)A}{1 + A} \]

\[ A = \frac{\text{prob}(\Sigma_b^{(*)})}{\text{prob}(\Lambda_b)} = 9 \frac{\text{prob}(T)}{\text{prob}(S)} \]

\[ w_1 = \frac{\text{prob}(T_{\pm 1})}{\text{prob}(T)} \]

What is known about \( A \) and \( w_1 \) (for both \( b \) and \( c \) quarks)?
Heavy quark polarization retention

\[ r_L \approx \frac{1 + (0.23 + 0.38w_1)A}{1 + A} \]
\[ r_T \approx \frac{1 + (0.62 - 0.19w_1)A}{1 + A} \]

\[ A = \frac{\text{prob}(\Sigma_b^\ast)}{\text{prob}(\Lambda_b)} = 9 \frac{\text{prob}(T)}{\text{prob}(S)} \]
\[ w_1 = \frac{\text{prob}(T_{\pm 1})}{\text{prob}(T)} \]

What is known about \( A \) and \( w_1 \) (for both \( b \) and \( c \) quarks)?

**Pythia tunes**  \[ 0.24 \lesssim A \lesssim 0.45 \] (based on light hadron data)
**DELPHI (LEP)**  \[ 1 \lesssim A \lesssim 10 \ (b) \quad w_1 = -0.36 \pm 0.30 \pm 0.30 \ (b) \]
**DELPHI-95-107**

**E791**  \[ A \approx 1.1 \ (c) \]
**PLB 379, 292 (1996)**

**CLEO (CESR)**  \[ w_1 = 0.71 \pm 0.13 \ (c) \]
**PRL 78, 2304 (1997)**

**Statistical hadronization**  \[ A \approx 2.6 \ (b \text{ and } c) \]
review: PLB 678, 350 (2009)

**Adamov & Goldstein**  \[ A \approx 6 \ (b \text{ and } c) \quad w_1 \approx 0.41 \ (b), 0.39 \ (c) \]
**PRD 64, 014021 (2001)**
Heavy quark polarization retention

\[ r_L \approx \frac{1 + (0.23 + 0.38w_1)A}{1 + A} \]

\[ r_T \approx \frac{1 + (0.62 - 0.19w_1)A}{1 + A} \]

\[ A = \frac{\text{prob} \left( \Sigma_b^{(*)} \right)}{\text{prob}(\Lambda_b)} = 9 \frac{\text{prob}(T)}{\text{prob}(S)} \]

\[ w_1 = \frac{\text{prob}(T_{\pm 1})}{\text{prob}(T)} \]

What is known about \( A \) and \( w_1 \) (for both \( b \) and \( c \) quarks)?

Overall, \( A \sim \mathcal{O}(1), \ 0 \leq w_1 \leq 1 \) \( \Rightarrow r_L, r_T \sim \mathcal{O}(1) \)

\( r_L \) consistent with \( \Lambda_b \) results from LEP
s-quark polarization retention?

➢ Cannot argue for polarization retention using heavy-quark limit.
  Cannot argue for polarization loss either!
**s-quark polarization retention!**

- Cannot argue for polarization retention using heavy-quark limit. Cannot argue for polarization loss either!

- Λ polarization studies were done in Z decays at LEP.

---

**CERN-OPEN-99-328**

**EPJC 2, 49 (1998) [hep-ex/9708027]**
Cannot argue for polarization retention using heavy-quark limit. Cannot argue for polarization loss either!

Λ polarization studies were done in Z decays at LEP. For $z > 0.3$:

$$\mathcal{P}(\Lambda) = -0.31 \pm 0.05$$ \textbf{ALEPH, CERN-OPEN-99-328}

$$\mathcal{P}(\Lambda) = -0.33 \pm 0.08$$ \textbf{OPAL, EPJC 2, 49 (1998) [hep-ex/9708027]}

Contributions from all quark flavors are included. For strange quarks only (non-negligible modeling uncertainty):

$$-0.65 \lesssim \mathcal{P}(\Lambda) \lesssim -0.49$$

Sizable polarization retention!
Nice sources of polarized quarks

Top pair production  \( pp \rightarrow t\bar{t} \)

- \( t \rightarrow W^+ b \) produces polarized \( b \) quarks.
  \( \leftarrow c\bar{s}, u\bar{d} \) produces polarized \( c, s, u, d \) quarks.

- Easy to select a clean \( t\bar{t} \) sample (e.g., in lepton + jets).
- Kinematic reconstruction and charm tagging enable studying the different quark flavors separately.
- Statistics in Run 2 is as large as in \( Z \) decays at LEP.
Nice sources of polarized quarks

**Top pair production** $pp \rightarrow t\bar{t}$

- $t \rightarrow W^+ b$ produces polarized $b$ quarks.
  - $c\bar{s}$, $u\bar{d}$ produces polarized $c, s, u, d$ quarks.
- Easy to select a clean $t\bar{t}$ sample (e.g., in lepton + jets).
- Kinematic reconstruction and charm tagging enable studying the different quark flavors separately.
- Statistics in Run 2 is as large as in $Z$ decays at LEP.

**$W$+$c$ production** $pp \rightarrow W^- c$

- Polarized $c$ quarks.
Nice sources of polarized quarks

**Top pair production**  \( pp \rightarrow t\bar{t} \)

- \( t \rightarrow W^+ b \) produces polarized \( b \) quarks.
  - \( c\bar{s}, u\bar{d} \) produces polarized \( c, s, u, d \) quarks.
- Easy to select a clean \( t\bar{t} \) sample (e.g., in lepton + jets).
- Kinematic reconstruction and charm tagging enable studying the different quark flavors separately.
- Statistics in Run 2 is as large as in \( Z \) decays at LEP.

**\( W+c \) production**  \( pp \rightarrow W^- c \)

- Polarized \( c \) quarks.
- Order-of-magnitude higher statistics than \( t\bar{t} \), although backgrounds are higher too.
Measurement of $s$ polarization in $t\bar{t}$

Main steps:

- Typical single-lepton $t\bar{t}$ selection
- Typical kinematic reconstruction and global event interpretation
- Charm tagging
- $\Lambda$ reconstruction and polarization measurement
In the $\Lambda$ rest frame, the decay $\Lambda \rightarrow p \pi^-$ has the angular distribution

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta} = \frac{1}{2} \left( 1 + \alpha \mathcal{P}(\Lambda) \cos \theta \right)$$

where

$$\alpha = 0.642 \pm 0.013$$
Measurement of $s$ polarization in $t\bar{t}$

Statistical precision of roughly 16% possible at ATLAS/CMS in Run 2 (with 100 fb$^{-1}$ of data).
Measurement of $c$ polarization in $t\bar{t}$

Main steps:

- Typical single-lepton $t\bar{t}$ selection
- Typical kinematic reconstruction and global event interpretation
- $\Lambda_c$ reconstruction and polarization measurement
Measurement of $c$ polarization in $t\bar{t}$

<table>
<thead>
<tr>
<th>Selection</th>
<th>Expected events</th>
<th>Purity (example)</th>
<th>$\Delta A_{FB}/A_{FB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$1.7 \times 10^6 \ t\bar{t} + \mathcal{O}(10^5)$ bkg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda^+_c \rightarrow pK^-\pi^+$</td>
<td>$810 \times (\epsilon_{\Lambda_c}/25%)$</td>
<td>20%</td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11%</td>
</tr>
</tbody>
</table>

Statistical precision of order 10% possible at ATLAS/CMS in Run 2 (with 100 fb$^{-1}$ of data).
Measurement of $b$ polarization in $t\bar{t}$

Main steps:
- Typical single-lepton $t\bar{t}$ selection (w/soft-muon $b$ tag)
- Typical kinematic reconstruction and global event interpretation
- $Λ_b$ reconstruction (using inclusive, semi-inclusive or exclusive approach) and polarization measurement
Measurement of $b$ polarization in $t\bar{t}$

Statistical precision of about 10% possible at ATLAS/CMS in Run 2 (with 100 fb$^{-1}$ of data)

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<th>Expected events</th>
<th>Purity (example)</th>
<th>$\frac{\Delta A_{FB}}{A_{FB}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$3 \times 10^6 \ t\bar{t} + \mathcal{O}(10^6)$ bkg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft-muon $b$ tagging</td>
<td>$5 \times 10^5 \ t\bar{t} + \mathcal{O}(10^4)$ bkg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclusive</td>
<td>$34,400$</td>
<td>$\mathcal{O}(f_{\text{baryon}})$ (e.g., 7%)</td>
<td>$\pm 7%$</td>
</tr>
<tr>
<td>Semi-inclusive</td>
<td>$2300 \times (\epsilon_{\Lambda}/30%)$</td>
<td>$70%$</td>
<td>$\pm 8%$</td>
</tr>
<tr>
<td>Exclusive</td>
<td>$1040 \times (\epsilon_{\Lambda_c}/25%)$</td>
<td>$30%$</td>
<td>$\pm 19%$</td>
</tr>
</tbody>
</table>

$r_L = 0.6$
Measurement of $c$ polarization in $W+c$

ATLAS and CMS measured $W+c$ cross section at 7 TeV

ATLAS, JHEP 1405, 068 (2014) [arXiv:1402.6263]

in particular by relying on the decays

$$D^+ \rightarrow K^- \pi^+ \pi^+$$

Similar to our decay of interest

$$\Lambda^+_c \rightarrow pK^- \pi^+$$

(See backup slides for more details.)
Measurement of $c$ polarization in $W+c$

ATLAS and CMS measured $W+c$ cross section at 7 TeV

**ATLAS, JHEP 1405, 068 (2014) [arXiv:1402.6263]**

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$$D^+ \rightarrow K^- \pi^+ \pi^+$$

Similar to our decay of interest

$$\Lambda_c^+ \rightarrow p K^- \pi^+$$

(See backup slides for more details.)
Measurement of $b$ polarization in QCD events

Inclusive QCD production: $pp \rightarrow b\bar{b} + X$

- Enormous cross section, but **unpolarized** at the leading order.
Measurement of $b$ polarization in QCD events

Inclusive QCD production: $pp \rightarrow b \bar{b} + X$

- Enormous cross section, but **unpolarized** at the leading order.
- At NLO $\rightarrow$ **transverse** polarization
  (an opportunity to measure $r_T$)
  $\rightarrow$ strong kinematic dependence
  $\rightarrow$ suppressed at high momenta $P(b) \sim \alpha_s \frac{m_b}{p_b}$

Bernreuther, Brandenburg, Uwer, PLB 368, 153 (1996)
Dharmaratna and Goldstein, PRD 53, 1073 (1996)

FIG. 7. Polarization of up, strange, charm, and bottom quarks at the subprocess CM momentum of (a) 13 GeV/c for gluon fusion and (b) 9 GeV/c for annihilation. Other parameters are identical to Fig. 5.
Measurement of $b$ polarization in QCD events

Inclusive QCD production:  $pp \rightarrow b\bar{b} + X$

- Enormous cross section, but **unpolarized** at the leading order.
- At NLO $\rightarrow$ **transverse** polarization
  
  (an opportunity to measure $r_T$)
  
  $\rightarrow$ strong kinematic dependence
  $\rightarrow$ suppressed at high momenta  
  $\mathcal{P}(b) \sim \alpha_s \frac{m_b}{p_b}$

Existing LHCb analysis:

Measurements of the $\Lambda_b^0 \rightarrow J/\psi \Lambda$
  
  decay amplitudes and the $\Lambda_b^0$
  
  polarisation in $pp$ collisions at
  
  $\sqrt{s} = 7$ TeV

PLB 724, 27 (2013)  
[arXiv:1302.5578]

$\mathcal{P}(\Lambda_b) = 0.06 \pm 0.07 \pm 0.02$

Suboptimal due to inclusiveness over the kinematics.

**FIG. 7.** Polarization of up, strange, charm, and bottom quarks at the subprocess CM momentum of (a) 13 GeV/c for gluon fusion and (b) 9 GeV/c for annihilation. Other parameters are identical to Fig. 5.
Measuring $A$ directly

$A$ is simply the ratio of the $\Sigma_b^{(*)}$ and direct $\Lambda_b$ yields, independent of the $b$ polarization:

$$A = \frac{\text{prob} \left( \Sigma_b^{(*)} \right)}{\text{prob} \left( \Lambda_b \right)} = 9 \frac{\text{prob}(T)}{\text{prob}(S)}$$

Can be measured by any experiment that can reconstruct

$$\Sigma_b^{(*)\pm,0} \to \Lambda_b \pi^{\pm,0}$$

In particular, LHCb, ATLAS, CMS in inclusive QCD samples.

Could have been done even at the Tevatron.

CDF, PRD 85, 092011 (2012) [arXiv:1112.2808]
Measuring $A$ directly

$A$ is simply the ratio of the $\Sigma_b^{(*)}$ and direct $\Lambda_b$ yields, independent of the $b$ polarization:

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Can be measured by any experiment that can reconstruct

$$\Sigma_b^{(*)\pm,0} \rightarrow \Lambda_b \pi^{\pm,0}$$

In particular, LHCb, ATLAS, CMS in inclusive QCD samples.

Same holds for

$$\Sigma_c^{(*)++,+,0} \rightarrow \Lambda_c^+ \pi^{\pm,0}$$

where $B$ factories can also help.

_Belle_, PRD 89, 091102 (2014) [arXiv:1404.5389]
Measuring $w_1$ directly

The angular distribution of $\Sigma_b^{(*)} \rightarrow \Lambda_b\pi$ is sensitive to $w_1$, independent of the $b$ polarization:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta} = \frac{1}{2} + \frac{9}{8} a \left( w_1 - \frac{2}{3} \right) \left( \cos^2 \theta - \frac{1}{3} \right)$$

where $a$ is given in the plot.

Can be measured by any experiment that can reconstruct these decays (e.g., LHCb, ATLAS, CMS).

Same holds for $\Sigma_c^{(*)}$ and $\Lambda_c$. 
Summary: motivated measurements

In $t\bar{t}$ production (ATLAS, CMS)
- Longitudinal $\Lambda_b$ polarization in $b$ jets $\rightarrow r_L$ for bottom
- Longitudinal $\Lambda_c$ polarization in $c$ jets $\rightarrow r_L$ for charm
- Longitudinal $\Lambda$ polarization in $s$ jets $\rightarrow$ long. pol. FF for strange
- (far future) Longitudinal $\Lambda$ polarization in $u, d$ jets $\rightarrow$ long. pol. FFs for up, down

In $W+c$ production (ATLAS, CMS, maybe LHCb)
- Longitudinal $\Lambda_c$ polarization $\rightarrow r_L$ for charm
  (Esp. LHCb may also try separating out the $\Sigma_c^{(*)}$ contributions.)

In QCD production (LHCb, ATLAS, CMS)
- Transverse $\Lambda_b$ (and $\Lambda_c$?) polarization
  as a function of the event kinematics $\rightarrow r_T$ for bottom (charm?)
Summary: motivated measurements

In QCD production (LHCb, ATLAS, CMS)

- $\Sigma_b^{(*)}$ yields (relative to direct $\Lambda_b$) $\rightarrow A$ for bottom
  and pion angular distribution $\rightarrow w_1$

- $\Sigma_c^{(*)}$ yields (relative to direct $\Lambda_c$) $\rightarrow A$ for charm
  and pion angular distribution $\rightarrow w_1$

In new-physics samples, once discovered (ATLAS, CMS)

- Measure quark polarizations $\rightarrow$ learn about the new physics
  (Statistics will likely be a severe limitation.)

In $t\bar{t}$ and $W+c$ production in the long term (ATLAS, CMS, LHCb)

- Measurements of polarized fragmentation functions.

Thank You!
Supplementary Slides
Mass splittings and widths

**bottom system**

\[ m_{\Lambda_b} = 5619.5 \pm 0.4 \text{ MeV} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\Sigma_b} - m_{\Lambda_b} )</td>
<td>194 ± 2</td>
</tr>
<tr>
<td>( m_{\Sigma_b^*} - m_{\Lambda_b} )</td>
<td>214 ± 2</td>
</tr>
<tr>
<td>( \Delta \equiv m_{\Sigma_b^*} - m_{\Sigma_b} )</td>
<td>21 ± 2</td>
</tr>
<tr>
<td>( \Gamma_{\Sigma_b} )</td>
<td>7 ± 3</td>
</tr>
<tr>
<td>( \Gamma_{\Sigma_b^*} )</td>
<td>9 ± 2</td>
</tr>
</tbody>
</table>

**charm system**

\[ m_{\Lambda_c} = 2286.5 \pm 0.2 \text{ MeV} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{\Sigma_c} - m_{\Lambda_c} )</td>
<td>167.4 ± 0.1</td>
</tr>
<tr>
<td>( m_{\Sigma_c^*} - m_{\Lambda_c} )</td>
<td>231.9 ± 0.4</td>
</tr>
<tr>
<td>( \Delta \equiv m_{\Sigma_c^*} - m_{\Sigma_c} )</td>
<td>64.5 ± 0.5</td>
</tr>
<tr>
<td>( \Gamma_{\Sigma_c} )</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>( \Gamma_{\Sigma_c^*} )</td>
<td>15 ± 1</td>
</tr>
</tbody>
</table>
Measurement of $b$ polarization in $Z$ decays

$Z$ production: $pp \rightarrow Z \rightarrow b\bar{b}$

- Longitudinally polarized $b$ quarks (similar to $t\bar{t}$)
- Large cross section
  \[
  \frac{\sigma(pp \rightarrow Z \rightarrow b\bar{b})}{\sigma(pp \rightarrow t\bar{t} \rightarrow W^+W^-b\bar{b})} \sim 10
  \]
- Large QCD background (at 8 TeV, $S/B \approx 1/15$ even for $p_T^Z > 200$ GeV) dilutes the asymmetry.

Probably less effective than $t\bar{t}$. 

**$\Lambda_b$ polarization measurement**

Which $\Lambda_b$ decay to use?

We picked semileptonic mode **inclusive** in charm hadrons (large BR, no hadronic uncertainties).
**Λ₃b** polarization measurement

Which Λ₃b decay to use?

We picked **semileptonic mode inclusive** in charm hadrons (large BR, no hadronic uncertainties).

Includes also:

\[ \Lambda_b \rightarrow p \, D^0 \, \ell^- \, \bar{\nu}_\ell \] small contribution
Λ\(_b\) polarization measurement

For the inclusive semileptonic decays

\[ Λ_b \rightarrow X_c \ell^- \bar{\nu} \]

Λ\(_b\) polarization is encoded in the angular distributions

\[ \frac{1}{\Gamma_{Λ_b}} \frac{dΓ_{Λ_b}}{d \cos θ_i} = \frac{1}{2} \left( 1 + α_i \mathcal{P}(Λ_b) \cos θ_i \right) \quad i = \ell \text{ or } ν \]

where

\[ α_\ell = \frac{-\frac{1}{3} + 4x_c + 12x_c^2 - \frac{44}{3}x_c^3 - x_c^4 + 12x_c^2 \log x_c + 8x_c^3 \log x_c}{1 - 8x_c + 8x_c^3 - x_c^4 - 12x_c^2 \log x_c} \approx -0.26 \]

\[ α_ν = 1 \]

\( \mathcal{O}(Λ_{QCD}/m_b) \) corrections are absent, and \( α_s \) corrections are few %.

Manohar, Wise
PRD 49, 1310 (1994)
[hep-ph/9308246]

Czarnecki, Jezabek, Korner, Kuhn, PRL 73, 384 (1994)
Czarnecki, Jezabek, NPB 427, 3 (1994)
$\Lambda_b$ polarization measurement

\[ \Lambda_b \rightarrow X_c \ell^- \bar{\nu} \quad (\text{BR} \approx 10\% \text{ per flavor}) \]

- **Soft-muon $b$ tagging**
  - e.g. CMS-PAS-BTV-09-001

- **Neutrino reconstruction using...**
  - $\Lambda_b$ mass constraint
  - $\Lambda_b$ flight direction

  - Dambach, Langenegger, Starodumov

- **Neutrino $A_{FB}$ measurement** (in the $\Lambda_b$ rest frame)

- **Approaches regarding semileptonic $B$-meson background:**
  - **Inclusive** keep it
  - **Semi-inclusive** demand $\Lambda \rightarrow p\pi^- \pi^-$ among decay products
  - **Exclusive** demand a fully-reconstructible $\Lambda_c$ decay

*See paper for many additional details...*
Λc polarization measurement

\[ \Lambda_c^+ \rightarrow p K^- \pi^+ \]  \hspace{1cm} (BR ≈ 6.7\%)

➢ Three tracks reconstructing the Λc mass.

➢ Backgrounds under the mass peak can be suppressed in various ways.

➢ Spin analyzing powers \( \alpha_i \) seem to be large for \( K^- \), small for \( p \) and \( \pi^+ \).

Also, \( \alpha_i \) can be determined (e.g., in LHCb) from a sample of \( \Lambda_c \)'s produced from inclusive \( b \)-hadron decays by calibrating on \( \Lambda_c^+ \rightarrow \Lambda \pi^+ \) (where \( \alpha_\Lambda = -0.91 \pm 0.15 \)).

NA32: Jeżabek, Rybicki, Ryłko, PLB 286, 175 (1992)

Precise values not essential for new physics samples if SM calibration samples are available.
**Λ polarization measurement**

\[ \Lambda \rightarrow p \pi^- \quad (\text{BR} \approx 64\%) \]

- Pair of tracks from a highly displaced vertex reconstructing the Λ mass.
- Spin analyzing power \( \alpha \approx 0.64 \)
- ATLAS and CMS already have experience with Λ’s

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**ATLAS**

\( \sqrt{s} = 7 \text{ TeV} \)

\[ \int L \text{dt} = 190 \mu \text{b}^{-1} \]

**CMS**

\( \sqrt{s} = 7 \text{ TeV} \)

- Yield: \( 1460 \times 10^3 \)
- Mean: 1116.0 MeV/c^2
- Avg \( \sigma \): 3.4 MeV/c^2

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PRD 85, 012001 (2012) [arXiv:1111.1297]

JHEP 05, 064 (2011) [arXiv:1102.4282]
Measurement of $c$ polarization in $W+c$

ATLAS and CMS measured $W+c$ cross section at 7 TeV

ATLAS, JHEP 1405, 068 (2014) [arXiv:1402.6263]

in particular by relying on the decays

$D^+ \rightarrow K^- \pi^+ \pi^+$

Similar to our decay of interest

$\Lambda_c^+ \rightarrow pK^- \pi^+$
Example: $D^+ \rightarrow K^- \pi^+ \pi^+$ in ATLAS

ATLAS, JHEP 1405, 068 (2014) [arXiv:1402.6263]
Example: $D^+ \rightarrow K^- \pi^+ \pi^+$ in ATLAS

ATLAS, JHEP 1405, 068 (2014) [arXiv:1402.6263]
Example: \( D^+ \rightarrow K^- \pi^+ \pi^+ \) in ATLAS

ATLAS, JHEP 1405, 068 (2014) [arXiv:1402.6263]
Example: $D^+ \rightarrow K^- \pi^+ \pi^+$ in CMS

$\Lambda_c^+ \to pK^-\pi^+$ vs. $D^+ \to K^-\pi^+\pi^+$

Same signature (3-prong displaced vertex, mass peak), but:

- The $\Lambda_c^+ \to pK^-\pi^+$ signal peak is smaller:

$$\frac{f(c \to D^+) \mathcal{B}(D^+ \to K^-\pi^+\pi^+)}{f(c \to \Lambda_c^+) \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} \approx 5.3$$

while background is roughly the same.

Ambiguity resolution: in the lab frame, $|\vec{p}(p)| > |\vec{p}(\pi^+)|$.

- The $\Lambda_c^+$ vertex is less displaced:

$$\tau_{\Lambda_c^+} \approx \frac{\tau_{D^0}}{2} \approx \frac{\tau_{D_s^+}}{2.5} \approx \frac{\tau_{D^+}}{5}$$

E.g., in CMS analysis, < 20% of events had a good secondary vertex
(events contain about 61% $D^0$, 24% $D^+$, 8% $D_s^+$, 6% $\Lambda_c^+$)
Improvements for $W+c$ in Run 2

- **Statistics x 60** (cross section x 3, luminosity x 20)
  
  (S/B remains similar because cross sections increase by similar factors.)

- **Upgrades to ATLAS and CMS pixel detectors**

  **ATLAS**: installed IBL
  
  Innermost layer at: **3.3 cm** (vs. **5.0 cm in Run 1**)
  
  Smaller pixel size: **50 x 250** (vs. **50 x 400**) $\mu$m$^2$

  **CMS**: pixel detector upgrade in winter 2016-2017
  
  Innermost layer at: **3.0 cm** (vs. **4.4 cm now**)
  
  Pixel size unchanged: **100 x 150 $\mu$m$^2$**
Backgrounds: ATLAS $D^+$ example

ATLAS, JHEP 1405, 068 (2014) [arXiv:1402.6263]
\( \Lambda_c \) polarization backgrounds in \( W+c \)

**PEAKING COMPONENTS (REAL \( \Lambda_c \))**

- \( c \)'s in *multijet*: unpolarized
- \( W^+ \rightarrow c\bar{s} \) in *top*: polarized like the signal
- \( b \)'s in *top, W+b\bar{b}, multijet*: polarization due to electroweak \( b \rightarrow \Lambda_c, \Sigma_c^{(*)} \)

  Control region with highly-displaced \( \Lambda_c \)'s (\( \tau_b \approx 7 \tau_{\Lambda_c} \)).

- \( W+c\bar{c} \): can be estimated from the wrong-sign sample

**SMOOTH COMPONENTS (FAKE \( \Lambda_c \))**

At the very least, can be extrapolated from sidebands (up to a certain systematic uncertainty).
A variable sensitive to the polarization:

$$A_{FB} = \frac{N(\cos \theta_{K^-} > 0) - N(\cos \theta_{K^-} < 0)}{N}$$

Statistical uncertainty:

$$\sigma(A_{FB}) = \sqrt{\frac{1 - A_{FB}^2}{N}} \approx \frac{1}{\sqrt{N}}$$

The signal contribution:

$$A_{FB,S} = \frac{\alpha_{K^-} P(\Lambda_c) S}{2N}$$

Significance of observing non-zero $P(c)$:

$$\frac{|A_{FB,S}|}{\sigma(A_{FB})} = \frac{|\alpha_{K^-} P(\Lambda_c)|}{2\frac{S}{\sqrt{N}}}$$
Statistical precision for $W+c$ in Run 2

A ballpark figure

➢ Start with the ATLAS $D^+$ peak.
➢ Account for the difference between the $D^+ \rightarrow K^-\pi^+\pi^+$ and $\Lambda_c^+ \rightarrow pK^-\pi^+$ rates.
➢ Assume Run 2 statistics (100 fb$^{-1}$)

Without the displacement issue, $S/\sqrt{N} \approx 47$.
For, e.g., $|\alpha_K-P(\Lambda_c)| = 0.4$, this gives 11% precision.

Suppose that relaxed displacement requirements increase $N$ by a factor of 2 while still losing 1/2 of $S$.
Still, $3\sigma$ significance for observing non-zero $P(c)$. 
Cannot use decays of protons or neutrons, but can again consider the $\Lambda \approx sud$.

Naïve quark model: all the $\Lambda$ spin is on the $s$ ☹

Nucleon DIS + flavor SU(3): $u$ and $d$ carry about $-20\%$ each ☑

Burkardt and Jaffe, PRL 70, 2537 (1993) [hep-ph/9302232]

Further inputs possible in the future from:

• Polarized DIS and polarized $pp$ collisions
  e.g., COMPASS, EPJC 64, 171 (2009)
  Deng (STAR), Phys.Part.Nucl. 45, 73 (2014)

• Lattice QCD
  QCDSF, PLB 545, 112 (2002) [hep-lat/0208017]
  CSSM and QCDSF/UKQCD, PRD 90, 014510 (2014) [arXiv:1405.3019]
  Chambers et al., PRD 92, 114517 (2015) [arXiv:1508.06856]
Cannot use decays of protons or neutrons, but can again consider the $\Lambda (\approx sud)$.

Naïve quark model: all the $\Lambda$ spin is on the $s$ 😞

Nucleon DIS + flavor SU(3): $u$ and $d$ carry about $-20\%$ each 😊

Burkardt and Jaffe, PRL 70, 2537 (1993) [hep-ph/9302232]

Studies of $u$, $d$ jets in $t\bar{t}$ samples will require much more statistics than $s$, also because:

- No $u$ or $d$ tagging; $c$-tag veto only partially effective
  (Can define separate $u$ and $d$ samples, contaminated by $c$ and $s$ respectively, using $W_{\text{leptonic}}$ charge.)
- Fragmentation fractions of $u$, $d \rightarrow \Lambda$ smaller than $s \rightarrow \Lambda$
New physics example

Suppose a jets + MET excess is being attributed to:

\[ pp \rightarrow \tilde{s}_R \tilde{s}_R^* \]
\[ \tilde{s}_R \rightarrow s \tilde{\chi}_1^0 \]

\( m \) (GeV)

\( \tilde{s}_R \)
RH strange squark

\( 200 \)

\( \tilde{\chi}_1^0 \)
bino (stable)

\( 150 \)
New physics example

Suppose a jets + MET excess is being attributed to:

\[ p p \rightarrow \tilde{s}_R \tilde{s}_R^* \]

\[ \tilde{s}_R \rightarrow s \tilde{\chi}^0_1 \]

This scenario was barely beyond the reach of Run 1.

PRD 90, 052008 (2014) [arXiv:1407.0608]
New physics example

Suppose a jets + MET excess is being attributed to:

\[ pp \rightarrow \tilde{s}_R \tilde{s}_R^* \]
\[ \tilde{s}_R \rightarrow s \tilde{\chi}_1^0 \]

This scenario was barely beyond the reach of Run 1.

*The masses of interest are unfortunately not shown.

JHEP 06, 055 (2014) [arXiv:1402.4770]

CMS-PAS-SUS-13-009
New physics example

Suppose a jets + MET excess is being attributed to:

\[ pp \rightarrow \tilde{s}_R \tilde{s}_R^* \]
\[ \tilde{s}_R \rightarrow s \tilde{\chi}_1^0 \]

Test this interpretation by measuring the \( s \)-quark polarization.

Rough estimate (see paper for details):
for 3 ab\(^{-1}\) of 14 TeV data: statistical precision of better than 30%
(even without optimization of selection cuts, without accounting for the expected detector upgrades, and without combining ATLAS and CMS)