Future prospects with cc/bb/tt final states and inclusive B production

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Implications of LHCb measurements and future prospects 2016
• **Motivations:**
  - benefits of forward measurements

• **Heavy quark pair observables:**
  - c/b-pairs
  - top-pairs

• **Impact/prospects of inclusive B production:**
  - understanding the R13/7 data
  - future checks
Motivations:
benefits of forward heavy flavour measurements
• Heavy quark mass
• Strong coupling

\[
\sum |M_{ij} \rightarrow Q\bar{Q}X|^2
\]
\( \hat{E} \): Perturbative Evolution

- Heavy quark mass
- Strong coupling

\[ \sum |M_{ij} \rightarrow Q\bar{Q}X|^2 \]

Constrain with data:
- Deep Inelastic Scattering
- Fixed Target
- Hadron Collisions
Deep Inelastic Scattering

Fixed Target

Hadron Collisions

Exclusive B hadrons:
- Convoluted with NP FF

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Deep Inelastic Scattering

Fixed Target

Hadron Collisions

Exclusive B hadrons:
- Convoluted with NP FF

Reconstructed Jets:
- flavour/charge tagged
- e.g. anti-kt R=0.7

\[ \hat{E} : \text{Perturbative Evolution} \]

\[ \hat{E}[Q_0, Q] \]

\[ \hat{E}[Q, mQ] \]

\[ \sum |M_{ij} \rightarrow Q\bar{Q}X|^2 \]

Constrain with data:
- Deep Inelastic Scattering
- Fixed Target
- Hadron Collisions

Constrain with data:
- Heavy quark mass
- Strong coupling

\[ b \rightarrow \text{jet} \]
Fully reconstruct B-hadron:
- Data from $P_T^B > 0$ GeV
- Efficiency poor
- Clean signal

Reconstruct b-jet:
- Data from $P_T > 20$ GeV
- Efficiency vs Mistag
  e.g. $\epsilon_b = 0.65$, $\kappa_l = 0.003$
  $\eta_j \in [2.2, 4.2]$

LHCb-PAPER-2015-016
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  LHCb-PAPER-2015-016
Why study forward \( pp \rightarrow Q_3 \bar{Q}_4 + X \)?

- \( x_i \): fraction of momentum
- \( y_j \): rapidity
- \( \sqrt{S} \): hadronic COM
- \( m_T \): transverse mass

\[
x_1, (2) = \frac{m_T}{\sqrt{S}} \left( e^{(-)} y_3 + e^{(-)} y_4 \right)
\]

LHCb acceptance: \( y_D \in [2.0, 4.5] \)
Require one of the top quarks within LHCb acceptance:

\[
2.5 < \eta(t) < 4.5
\]

\[
m_t \approx 173.0 \text{ GeV}
\]

Forward top quark production discussed in:

**hep-ex:** LHCb - arXiv:1506.00903

$pp \rightarrow b\bar{b}$

Require one of the $B$ hadrons within LHCb acceptance:

- $2.0 < y(B) < 4.5$
- $0 < p_T(B)[\text{GeV}] < 8$
- $m_b = 4.75$ GeV

Forward beauty quark production discussed in:

**hep-ex:** LHCb B measurement (7 TeV) - arXiv:1306.3663

Require one of the D hadrons within LHCb acceptance:

\begin{align*}
2.0 < y(D) < 4.5 \\
0 < p_T(D) \text{[GeV]} < 8 \\
m_c = 1.5 \text{ GeV}
\end{align*}

Forward charm quark production discussed in:

**hep-ex:** LHCb measurement (7/13 TeV) - arXiv:1302.2864 / 1510.01707

Heavy quark pair observables:
c/b/t-pairs
b/c-quark pair asymmetry

$$xf(x, Q^2) = (173 \text{ GeV})^2$$

Large-x
- quark asymmetry large
- gluon dilution small

$$gg \rightarrow X$$ symmetric
$$q\bar{q} \rightarrow X$$  $$f_q(x, Q) \neq f_{\bar{q}}(x, Q)$$
b/c-quark pair asymmetry

\[ Q^2 = 3 \times 10^4 \text{ GeV}^2 \]

\[ \text{NPDF 3.0 nlo, } \alpha_s(m_Z) = 0.118, 1\sigma \text{ CL} \]

\[ xf(x, Q^2) = (173 \text{ GeV})^2 \]

\[ \text{Requiring MQQ cut such as:} \]

\[ m_{Q\bar{Q}} > 100 \text{ GeV} \]

Pushes into high x1 region

\[ gg \rightarrow X \text{ symmetric} \]

\[ q\bar{q} \rightarrow X \quad f_q(x, Q) \neq f_{\bar{q}}(x, Q) \]

Large-x

- quark asymmetry large
- gluon dilution small

Lab frame

\[ Q \]

\[ q \quad \text{high-x1} \]

\[ \bar{q} \quad \text{(g)} \]

\[ \bar{Q} \]
b-quark pair asymmetry (present)

RG, Ulrich Haisch, Ben D. Pecjak, Emanuele Re, arXiv: 1505.02429
see also Christopher Murphy arXiv:arXiv:1504.02493 (and Chris’s talk)

LHCb 7 TeV data - arXiv: 1406.4789

\[ b_1 = 0.4 \pm 0.4 \text{(stat.)} \pm 0.3 \text{(sys.)}\% \]

\[ b_2 = 2.0 \pm 0.9 \text{(stat.)} \pm 0.6 \text{(sys.)}\% \]

\[ b_3 = 1.6 \pm 1.7 \text{(stat.)} \pm 0.6 \text{(sys.)}\% \]
b-quark pair asymmetry (future)

- 5x Improvement in systematic = 6% relative uncertainty around Z-pole
- Start to probe sensitivity of ‘anomalous’ LEP measurements at~ 1-2%
- Theory improvements necessary: NNLO QCD, mixed QCD-EW@NNLO

Data projection, sys * 0.2
ΔΦ(b,\bar{b}) > 2.6 rad
2.0 < η_{b,\bar{b}} < 4.0
E_T b,\bar{b} > 20 GeV

NLO
NPDF2.3 (N)LO, \alpha_s(m_Z^2) = 0.119
\sqrt{s} = 13 TeV

• 5x Improvement in systematic = 6% relative uncertainty around Z-pole
• Start to probe sensitivity of ‘anomalous’ LEP measurements at~ 1-2%
• Theory improvements necessary: NNLO QCD, mixed QCD-EW@NNLO

top-quark pair asymmetry
Czakon, Fielder, Mitov, arXiv: 1411.3007

both: \mathcal{O}(\alpha_s^2 \alpha^2) \mathcal{O}(\alpha_s^3 \alpha)
t-quark pairs


\[ pp \rightarrow (t \rightarrow W^+ b)X \quad \text{vs} \quad pp \rightarrow (\bar{t} \rightarrow W^- b)X \]

- Count rate of top vs antitop
- Large stats (several 100k’s)**
  \[ pp \rightarrow l^\pm b - \text{jet}X \]
- Large asymmetric backgrounds
  \{Wj, Wb\bar{b}, ST - tch\}

**Scenario 2** (RG: arXiv:1409.8631)

\[ pp \rightarrow \mu^\pm e^\mp b - \text{jet}X \]

- Small stats (10k’s)**
- Very clean signal

** Assume 300 ifb
t-quark pairs (scenario 1)


\[ A^l = \int_{2.0}^{4.5} d\eta_l \left( \frac{d\sigma^{l+b}/d\eta_l - d\sigma^{l-b}/d\eta_l}{d\sigma^{l+b}/d\eta_l + d\sigma^{l-b}/d\eta_l} \right) \]

- Stats not an issue \( \mathcal{O}(10^5) \) events
- Problem is controlling backgrounds

\[ 2.0 < \eta(l,b) < 4.5 \]
\[ p_T(l/b) > 20/60 \text{ GeV} \]
\[ \Delta R(l^\pm, \text{jet}) \geq 0.5 \]
t-quark pairs (scenario 1)


\[ A^l = \int_{2.0}^{4.5} \left( \frac{d\sigma^{l+b}}{d\eta_l} - \frac{d\sigma^{l-b}}{d\eta_l} \right) \]

2.0 < \eta(l,b) < 4.5
\( p_T(l,b) < 4.5 \)
\( \eta > 2.0 \)
\( m_t = 173.25 \text{ GeV} \)

\[ \frac{dA^l}{d\eta_l} \text{ (fb)} \]

Multi channel fit to different (b)-jet multiplicity final states?
t-quark pairs (scenario 2)

Scenario 2 (RG: arXiv:1409.8631)

\[
A_{fb}^{ll} = \int d\Delta_y \frac{(d\sigma^{\mu eb}(\Delta_y > 0) - d\sigma^{\mu eb}(\Delta_y < 0))}{d\sigma^{\mu eb}/d\Delta_y}
\]

2.0 < \eta(e, \mu, b) < 4.5
\[p_T(e, \mu, b) > 20 \text{ GeV}\]
\[\Delta R(l^+, \text{jet}) \geq 0.5\]

### Table III. Signal contribution to the numerator of the inclusion

<table>
<thead>
<tr>
<th>Process</th>
<th>Numerator</th>
<th>Denominator</th>
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<tbody>
<tr>
<td>Numerator = NNPDF2.3 NLO 119</td>
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### Table IV. Signal contribution to the denominator and the inclusion

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\[\delta A_{fb}^{ll} \simeq 0.5\%\]

stat. 300 ifb
summary 1

• c/b-jet pair cross section and asymmetries - 13/14 TeV
  ★ Perform differentially in MQQ bins (Z-pole, and 100-150, 150-200, ..etc.)
  ★ Also provide the symmetric cross section (not just asymmetry)!
  ★ Measurements of sigma_bb/sigma_cc at different working points
    - Important validation of jet flavour tagging > 100 GeV

• top measurements - 13/14 TeV
  ★ 13 TeV: cross section measurement (lb,lbj,lbb, l+l-b, ..etc.) feed into PDFs
  ★ 13 TeV: precision measurement of forward rate of t vs tbar?
    - Probably challenging to fit multi-backgrounds (Wb,Wj, ..etc.)
  ★ 14 TeV: asymmetry measurement for l+l-b final state (stats limited)
Anomalies in inclusive B production?

LHCb-Paper-201(6?)-013 - Preliminary

\[ b \rightarrow sll = \text{Old News} \]
Anomalies in inclusive B production?

$LHCb-Paper-201(6?)-013$ - Preliminary

$b \rightarrow sl\ell = \text{Old News}$
Anomalies in inclusive B production?

LHCb-Paper-201(6?)-013 - Preliminary

\( b \rightarrow sll = \text{Old News} \)
Inclusive measurement: \( pp \rightarrow BX \)

\[
x_{1,(2)} = \frac{m_T}{\sqrt{S}} \left( e^{(-)y_3} + e^{(-)y_4} \right)
\]
Impact of this data on input PDFs?

\[ \chi^2 / N_{\text{dat}} = 39/6 \]

Fit to data very poor.

Tried fitting with 1000 replica input PDF set

Impact on PDFs actually rather small

Low-x data already constrained by low-Q2 low-x HERA Charm data
Impact of this data on input PDFs?

Predictions containing the information from B ratio

Small shift in right direction

Reduced cross section

Constraining Charm data from HERA

arXiv: 1211.1182
Comparison with CMS data

Extract ratio from CMS measurement arXiv: 1609.00873

Big difference: minimum $p_T$ cut, lower rapidity

Could perform similar measurements in LHCb acceptance
Differentially in $p_T$

Already have enough stats for this measurement
summary 2

• c/b-jet pair cross section and asymmetries - 13/14 TeV
  ★ Perform differentially in MQQ bins (Z-pole, and 100-150, 150-200 ,..etc.)
  ★ Also provide the symmetric cross section (not just asymmetry)!
  ★ Measurements of sigma_bb/sigma_cc at different working points
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• Inclusive B production
  ★ Could perform ratio differentially in pT, or with cuts to compare to CMS
  ★ Include bin-by-bin correlations, and can compute normalised cross section