Heavy flavor production in ATLAS

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for the ATLAS Collaboration
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Heavy flavor production

- heavy flavor production at LHC provides testing ground of QCD (calculations) at the energy frontier
  - NLO contributions are large
  - large theoretical uncertainties due to factorization scale and renormalization scale

- heavy flavor tagging is a crucial ingredient in many new physics searches
  - needed to understand the QCD background
  - requires a deep understanding of the detector performance

- several heavy flavor results from ATLAS
  - inclusive b-jet and $b\bar{b}$ dijet production cross section
  - $J/\psi$ and $\Upsilon$ production
  - exclusive B production

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arXiv:1106.5325 [hep-ex]
A. Cerri (353)
The ATLAS detector

- precise innermost tracking detector
  - pixels, strip and transition radiation straws
- hermetic calorimeter with excellent energy and rapidity resolution
  - liquid argon EM calorimeter, iron tile HCAL
- stand-alone muon trigger & tracking system
The ATLAS detector

- precise innermost tracking detector
 像素，条形和过渡辐射细管
- 封闭式 calorimeter 有出色的能量和 rapidity resolution
 液体 argon EM calorimeter, 铁瓷砖 HCAL
- stand-alone muon trigger & tracking system

Secondary vertex reconstruction:
- pixel module as described in simulation
- tomography made with data using vertices from hadronic interactions
The ATLAS detector

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- stand-alone muon trigger & tracking system

Jet energy scale:

- well described response by simulation
- 2010 (w/o significant pileup): uncertainty 2-3 %

\[ r_{\text{trk}} \equiv \frac{\sum p_T^{\text{track}}}{p_T^{\text{jet}}} \]
\[ R_{r_{\text{trk}}} \equiv \frac{\langle r_{\text{trk}}^{\text{data}} \rangle}{\langle r_{\text{trk}}^{\text{MC}} \rangle} \]
The ATLAS detector

- precise innermost tracking detector
  
  *pixels, strip and transition radiation straws*

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  *liquid argon EM calorimeter, iron tile HCAL*

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**Muon reconstruction setup:**

- high efficient stand-alone and combined muon reconstruction efficiency
- very well modeled by simulation

combined reconstruction efficiency
(Inner Detector and Muon System)
Inclusive b-jet cross sections: dataset and strategy (1)

**ATLAS-CONF-2011-056**

- **data taken between March and August 2010**
  - p-p collisions at $\sqrt{s} = 7$ TeV
  - integrated luminosity: $\mathcal{L} = 3.0$ pb$^{-1}$
  - trigger: level 1 jet trigger, MBTS trigger (extend to low jet $p_T$)
    
    *trigger efficiency: $\varepsilon_{\text{trig}} \sim 98\%$*

- **measurements**
  - inclusive cross section: $20$ GeV $< p_T^{\text{jet}} < 260$ GeV, $0 < |y^{\text{jet}}| < 2.1$
  
  \[
  \frac{d^2\sigma_b}{dp_T dy} = \frac{1}{\Delta p_T \Delta y} \frac{N_{b} \cdot \text{frac}_{b}}{\varepsilon_{\text{trig}} \cdot \varepsilon_{\text{sel}} \cdot \varepsilon_{\text{btag}} \cdot \mathcal{L}} \times C
  \]

  - dijet cross section: $m_{jj} < 670$ GeV for $p_T^{\text{jet}} > 40$ GeV, $0 < |y^{\text{jet}}| < 2.1$
  
  \[
  \frac{d\sigma_{b\bar{b}}}{dM} = \frac{1}{\Delta M} \frac{N_{b\bar{b}} \cdot \text{frac}_{b}}{\varepsilon_{\text{trig}} \cdot \varepsilon_{\text{sel}} \cdot \varepsilon_{\text{btag}} \cdot \mathcal{L}} \times C
  \]
Inclusive b-jet cross sections: dataset and strategy (1)

- data taken between March and August 2010
  - p-p collisions at \( \sqrt{s} = 7 \text{ TeV} \)
  - integrated luminosity: \( \mathcal{L} = 3.0 \text{ pb}^{-1} \)
  - trigger: level 1 jet trigger, MBTS trigger (extend to low jet \( p_T \))
    - trigger efficiency: \( \varepsilon_{\text{trig}} \sim 98\% \) 
    - systematic uncertainty negligible

- measurements
  - inclusive cross section: \( 20 \text{ GeV} < p_{T_{\text{jet}}} < 260 \text{ GeV}, 0 < |y_{\text{jet}}| < 2.1 \)
  - dijet cross section: \( m_{jj} < 670 \text{ GeV} \) for \( p_{T_{\text{jet}}} > 40 \text{ GeV}, 0 < |y_{\text{jet}}| < 2.1 \)

\[
\frac{d^2 \sigma_b}{dp_T dy} = \frac{1}{\Delta p_T \Delta y} \times \varepsilon_{\text{trig}} \varepsilon_{\text{sel}} \varepsilon_{\text{btag}} \mathcal{L} \times C
\]

\[
\frac{d\sigma_{b\bar{b}}}{dM} = \frac{1}{\Delta M} \times \varepsilon_{\text{trig}} \varepsilon_{\text{sel}} \varepsilon_{\text{btag}} \mathcal{L} \times C
\]

systematic uncertainty: \( \pm 0.1 \text{ pb}^{-1} \)

unfolding corrections (resolution effects)
Inclusive b-jet cross sections: dataset and strategy (1)

- data taken between March and August 2010
  - p-p collisions at $\sqrt{s} = 7$ TeV
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  - systematic uncertainty: $\pm 0.1 \text{ pb}^{-1}$

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will be covered in detail in the following

\[ \frac{d^2 \sigma_b}{dp_T dy} = \frac{1}{\Delta p_T \Delta y} \frac{N_b \cdot \text{frac}_b}{\varepsilon_{\text{trig}} \cdot \varepsilon_{\text{sel}} \cdot \varepsilon_{\text{btag}} \cdot \mathcal{L}} \times C \]

selection and reconstruction efficiency

\[ \frac{d\sigma_{b\bar{b}}}{dM} = \frac{1}{\Delta M} \frac{N_{b\bar{b}} \cdot \text{frac}_b}{\varepsilon_{\text{trig}} \cdot \varepsilon_{\text{sel}} \cdot \varepsilon_{\text{btag}} \cdot \mathcal{L}} \times C \]

unfolding corrections (resolution effects)
b-jet topology

- exploit long lifetime of the B-hadrons
  - displaced decay vertex

Event display of a top pair e+mu dilepton candidate with two b-tagged jets.
b-tagging with secondary vertexing (SVO)

ATLAS-CONF-2010-099, ATLAS-CONF-2011-089

- iterative secondary vertexing seeding from track pairs
  - vertex mass < 6 GeV, largest $\chi^2$/n.d.o.f. per track < 7
  - exclusion of vertices on pixel layers (material)
- separation power: decay length significance
  - $b$-tag if $L/\sigma_L > 5.72$ ($\approx 50\%$ efficiency on MC tt)
- calibration ($\varepsilon_{b\text{tag}}, \text{mistag rate}$) using $p_T^{rel}$ method & secondary vertex mass
  - data: $\mu$-enriched sample, MC: $\mu$-filtered sample for templates to $p_T^{rel}$

\[ K_{\varepsilon_b}^{\text{data/sim}} = \frac{\varepsilon_b^{\text{data}}}{\varepsilon_b^{\text{sim}}} \]

relative transverse $\mu$ momentum

\[ K_{\varepsilon_l}^{\text{data/sim}} = \frac{\varepsilon_l^{\text{data}}}{\varepsilon_l^{\text{sim}}} \]

template fits to secondary vertex invariant mass (combined with negative tags)
b-tagging with secondary vertexing (SV0)  
**ATLAS-CONF-2010-099, ATLAS-CONF-2011-089**

- iterative secondary vertexing seeding from track pairs  
  - **vertex mass** < 6 GeV, largest $\chi^2$/n.d.o.f. per track < 7  
  - exclusion of vertices on pixel layers (material)  
- separation power: decay length significance  
  - **b-tag** if $L/\sigma_L > 5.72$ (~50% efficiency on MC tt)

- calibration (ε_{btag}, mistag rate) using $p_T^{rel}$ method & secondary vertex mass  
  - data: μ-enriched sample, MC: μ-filtered sample for templates to $p_T^{rel}$

**Relative transverse μ momentum**

![Diagram](image)

**Template fits to secondary vertex invariant mass**  
(combined with negative tags)
b-tagging efficiency & data/MC scale factor

- scale factors for b-tag efficiency and mistag rate
  - $p_T^{rel}$ method is used up to $p_T > 80$ GeV, then collimation becomes dominant
  - above $p_T > 80$ GeV: value of highest $p_T$ bin taken with double syst. uncertainty for jet
  - obtained as $\varepsilon_{b-tag}(p_T, y)$, $\varepsilon_{bb-tag}(M, y)$
  - mistag rate between 0.2 and 1%

![Graph showing b-tagging efficiency vs. jet $p_T$](image)
Extraction of $N_b$ and $N_{bb}$

- light, charm and b-quark templates for SV0 mass/sum vertex mass obtained from MC QCD samples

- main sources of syst. uncertainties
  - b-tagging efficiencies, mistag rate
  - jet energy scale, b-jet energy correction

- unfolding to compare to “truth b-jets”
  - a jet is labelled as a b-jet if a b-quark is found within an $\eta$-$\phi$ cone of $R = 0.3$ of the truth jet direction
  - bin-by-bin unfolding correction applied
Inclusive b-jet cross sections: dataset and strategy (2)

- **2010 data set & reconstruction setup**
  - trigger: $\mu$ trigger with $p_T > 5$ GeV (matched to an offline $\mu$ with $p_T > 4$ GeV)
  - integrated luminosity (for prescaled trigger): $\mathcal{L} = 4.8 \text{ pb}^{-1}$
  - jet reconstruction: anti-$k_t$ with $R = 0.4$, jet $p_T$ corrected for $\nu$ and $\mu$ using a MC correction function
  - $\mu$-jet association if $\mu$ and jet are within a $\eta$-$\phi$ cone of $R = 0.4$

- **measurement**
  - inclusive cross section: $25 \text{ GeV} < p_T^{b-jet} < 180 \text{ GeV}, 0 < |y^{jet}| < 2.1$

**Template fit using $p_T^{\text{rel}}$ templates from MC** (binned maximum likelihood)

$$\frac{d\sigma}{dp_T^{b-jet}} = \frac{F_b}{B \epsilon_{\mu J} \epsilon_{\mu J}} \frac{N^{Jets}}{\Delta p_T^{b-jet}}$$

- branching ratio of inclusive decay $b \rightarrow \mu X$
- efficiency to detect and select a jet with associated $\mu$

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A. Salzburger - EPS-HEP 2011 - Heavy flavor production in ATLAS
Inclusive b-jet cross section

- **POWHEG (NLO):**
  - broad agreement, steeper drop

- **PYTHIA (LO):**
  - not expected to get normalization correct, scaled by 0.52*, but shape well described

*0.52 is calculated by normalizing the PYTHIA prediction to the measured integrated cross section

\[ p_T^{\text{rel}} \text{ and SV0 method agree well!} \]
b-jet to inclusive jet production: ratio measurement

- many systematic uncertainties cancel in the ratio
  - luminosity uncertainty cancels
  - largely independent of jet energy scale
  - dominated by uncertainty on b-tagging efficiency

- Inclusive jet cross section measurement from ATLAS

- POWHEG underestimates the b-jet fraction by $30\%$ ($\approx 1\sigma$ effect)
Inclusive bb dijet cross section

\[ \sqrt{s}=7\text{TeV}, \ L\sim3\ \text{pb}^1 \]

\begin{itemize}
  \item **POWHEG (NLO):**
    - predicts systematically higher cross-section
  \item **PYTHIA (LO):**
    - renormalized by 0.52
    - shape reasonably well described
\end{itemize}
Conclusions

- presented inclusive b-jet cross section as a function of transverse momentum and rapidity (with two methods that yield consistent results)
  - secondary vertex based, semi-leptonic b-decays via µ associated to jet

- inclusive $b\bar{b}$ dijet cross section measurement as a function of the dijet mass

- measurements are dominated by systematic uncertainties
  - jet energy scale and b-tagging efficiency

- measurement compared with POWHEG (NLO) and PYTHIA (LO) predictions
  - POWHEG, PYTHIA describe shape dependence on $y$, $p_T$ rather well
  - POWHEG shows an underestimation of the b-jet to inclusive jet fraction by about 30% ($\approx 1\sigma$ effect)
<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Operational Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>80 M</td>
<td>96.9%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>99.1%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>97.5%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>99.5%</td>
</tr>
<tr>
<td>Tile calorimeter</td>
<td>9800</td>
<td>97.9%</td>
</tr>
<tr>
<td>Hadronic endcap LAr calorimeter</td>
<td>5600</td>
<td>99.6%</td>
</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>99.8%</td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>99.9%</td>
</tr>
<tr>
<td>LVL1 Muon RPC trigger</td>
<td>370 k</td>
<td>99.5%</td>
</tr>
<tr>
<td>LVL1 Muon TGC trigger</td>
<td>320 k</td>
<td>100%</td>
</tr>
<tr>
<td>MDT Muon Drift Tubes</td>
<td>350 k</td>
<td>99.8%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
<td>98.5%</td>
</tr>
<tr>
<td>RPC Barrel Muon Chambers</td>
<td>370 k</td>
<td>97.0%</td>
</tr>
<tr>
<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>98.4%</td>
</tr>
</tbody>
</table>
Simulation & Reconstruction setup

- **Track and vertex reconstruction in Inner Detector (ID)**
  - track reconstruction with $p_T > 400$ MeV and 6 silicon cluster requirements
  - multi-adaptive primary vertex finding (requiring at least 10 tracks in the PV)
  - iterative secondary vertex reconstruction

- **Jet reconstruction**
  - jets reconstructed from topological clusters on EM scale
  - anti-$k_t$ algorithm, with $R = 0.4$

- **Muon reconstruction (for b-tagging calibration)**
  - combined muon reconstruction starting from stand-alone muon tracks
  - combination of muon track and ID track parameters

- **Simulation**
  - simulated data from event generator output processed by Geant4 detector simulation
  - reconstructed with identical setup as data (applying detector condition calibration)
SV0 mass templates
### b-tagging calibration: summary of systematics

#### Table 1: Systematic uncertainties on the efficiency scale factor

<table>
<thead>
<tr>
<th>Source</th>
<th>25 &lt; $p_T^{\text{jet}}$ &lt; 40 GeV</th>
<th>40 &lt; $p_T^{\text{jet}}$ &lt; 60 GeV</th>
<th>60 &lt; $p_T^{\text{jet}}$ &lt; 85 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modelling of the $b$-hadron direction</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Non-$b$-jet templates</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Jet $p_T$ spectrum</td>
<td>6%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Scale factor for inclusive $b$-jets</td>
<td>5%</td>
<td>4%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$p_T^{\text{rel}}$ template statistics</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Modelling of $b$-decays</td>
<td>1.3%</td>
<td>0.2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Fake muons in $b$-jets</td>
<td>0.7%</td>
<td>0.7%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Modelling of $b$-production</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Fragmentation</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>12%</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>

#### Table 2: Systematic uncertainties on the mistag rate scale factor

<table>
<thead>
<tr>
<th>Source</th>
<th>20 &lt; $p_T$ &lt; 40 GeV</th>
<th>$p_T$ &gt; 40 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track Impact Parameter Resolutions</td>
<td>12%</td>
<td>14%</td>
</tr>
<tr>
<td>Run Dependence, Trigger</td>
<td>16%</td>
<td>19%</td>
</tr>
<tr>
<td>Other</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>21%</td>
<td>24%</td>
</tr>
</tbody>
</table>
Summary of (fractional) systematic errors: SV0 method