Flavour Tagging at ATLAS

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Heavy Flavour Production at the LHC, IPPP Durham

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Introduction

- \textit{b-tagging} = the identification of jets containing \textit{b}-hadrons
  \[\rightarrow\text{important tool for background suppression in a wide range of analyses }\]
  (e.g. top quark and Higgs sector, in the search for new phenomena)

- several dedicated \textit{algorithms} with varying levels of complexity and performance
- exploiting the \textit{long lifetime, high mass and decay multiplicity of b}-hadrons and the \textit{hard \textit{b}-quark fragmentation}
  \[\rightarrow\text{reconstructable secondary vertices and distinct track properties}\]

- performance characterized by power to separate \textit{b}-, \textit{c}- and light jets in simulated events
  (requires \textit{jet flavour labelling} based on simulation’s truth record)
  - \textbf{challenges}: dense and boosted environments, double \textit{b}-hadron jets, ...

- for use in physics analyses measurements of \textit{b}-jet tagging efficiency, \textit{c}-jet tagging efficiency and mistag rate required \[\rightarrow\text{data-to-MC scale factors (SF)}\]
  \[\rightarrow\text{eliminating / reducing dependence on simulations}\]
- several (complementary) calibration methods developed \[\rightarrow\text{combinations}\]
  - \textbf{challenges}: selecting samples with strong predominance of a single flavour, SF applicability to different simulations / processes, ...
Outline

1. Introduction

2. $b$-Tagging algorithms

3. Jet truth flavour labelling

4. Calibration of $b$-tagging algorithms

5. Summary
**b-Tagging algorithms**

- **lifetime-based**
  - impact parameter-based: (JetProb), IP3(2)D
  - vertex-based: SV(0)1, JetFitter
  → combinations: IP3D+SV1, IP3D+JetFitter, MV1, MV2 (Run 2)

- **muon-based**

- **b-jet trigger**

**Key objects**

- (small-R) calorimeter jets
  → jet axis used to **define b-hadron flight path**

- tracks reconstructed in the Inner Detector

- signal primary vertex (PV) of HS collision
  (with $\geq 2$ tracks)

**tracks-to-calo. jets association:**

- based on angular separation $\Delta R(\text{track}, \text{jet})$

- $\Delta R$ cut varies as a function of the jet $p_T$
  (decreasing with increasing jet $p_T$)

- exclusive
Impact parameter (IP)-based algorithms I

**Transverse IP** $d_0$: distance of closest approach of track to PV in the $r$-$\phi$ projection

**Longitudinal IP** $z_0$: distance between $z$ coordinates of the PV and the track at closest approach in $r$-$\phi$

Improving separation power by:

- introducing **sign**: “+” (“-”) - track intersects the jet axis in front of (behind) the PV
- using **significance**, e.g. $d_0/\sigma_{d_0}$

→ tracks from $b$-/$c$-hadron decays: large $d_0$ and $z_0$, “+” sign
→ exp. resolution generates a random sign, tails at “+” from long-lived particles, conversions,...

→ **JetProb**: relies on $d_0$ significance; simple, robust, no simulation dependence
Impact parameter(IP)-based algorithms II

**transverse** IP $d_0$: distance of closest approach of track to PV in the $r$-$\phi$ projection

**longitudinal** IP $z_0$: distance between $z$ coordinates of the PV and the track at closest approach in $r$-$\phi$

improving separation power by:

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→ exp. resolution generates a random sign, tails at “+” from long-lived particles, conversions,...

**IP3D**: LLR-based, relies on $d_0$ and $z_0$ significances as well as correlations

→ more powerful, 2D-PDFs from simulation
Explicit reconstruction of a *single, inclusive* secondary vertex (SV).

- using all associated, displaced tracks to form vertex candidates from track pairs ($\chi^2$ based)
- vertices compatible with long-lived particles and material interactions are rejected
- iterative procedure to combine all tracks from 2-track-vertices into single inclusive vertex

$\rightarrow$ small mistag rate
$\rightarrow$ SV finding efficiency: $\sim 70\%$

$\rightarrow$ **SV1**: LLR-based, exploiting vertex mass, energy fraction, number of 2-track vertices, $\Delta R(\text{jet}, \text{PV-SV})$
Vertex-based algorithms: JetFitter algorithm

Explicit reconstruction of the complete $b$-hadron decay chain.

- exploiting topological structure of weak $b$- and $c$-hadron decays inside jet
- uses Kalman filter to find common line between and position of PV, SV and TV (tertiary, $c$-hadron decay vertex)
  → approximating $b$-hadron flight path
- one track sufficient to built vertex!

→ six variables: decay topology + vertex information

→ input for artificial neural network

→ three output nodes corresponding to the $b$-, $c$- and light jet hypotheses $P_{b/c/l}$

→ **final discriminating variables**: $\ln(P_b/P_l)$ (JetFitter), $\ln(P_b/P_c)$ (JetFitter($c$))
**Performance I**

- **figure of merit:** $b$-jet tagging efficiency vs. light (c-) jet rejection
- **defined by placing cuts on $b$-/c-/light jet distributions of the discriminating variables in simulated $t\bar{t}$ events**
- **clear hierarchy between standalone and combined algorithms**
  - $MV1 = IP3D+SV1+(IP3D+JetFitter)$ (NN)

![Graph of $b$-jet tagging efficiency vs. light-flavour jet rejection](image-url)

- $\sqrt{s}=7$ TeV, $t\bar{t}$
- $p_T^{jet}>20$ GeV, $|\eta^{jet}|<2.5$

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Performance II: Run 2 improvements

Improved performance in Run 2 due to

- upgrade of the Inner Detector: added fourth pixel layer, Insertable B-Layer (IBL)
- improved track reconstruction (shared hits at high jet $p_T$)
- revisited $b$-tagging algorithms: MV2cxx

- BDT combining 24 input variables from SV, IP(2)3D, JetFitter algorithms
- “xx” = $c$-jet fraction in simulated $\bar{t}t$ events used for training

→ small admixture of $c$-jets only slightly degrades light-jet reject, significantly improves $c$-jet rejection
Performance III: Run 2 improvements

Improved performance in Run 2 due to

- upgrade of the Inner Detector: added fourth pixel layer, Insertable B-Layer (IBL)
- improved track reconstruction (shared hits at high jet $p_T$)
- revisited $b$-tagging algorithms: **MV2cxx**
  - BDT combining 24 input variables from SV, IP(2)3D, JetFitter algorithms
  - “xx” = $c$-jet fraction in simulated $t\bar{t}$ events used for training

→ @70% $b$-tagging eff.: factor 4 (1.5-2) improved light-($c$-)jet rejection!
**Performance IV: differential**

- $b$-tagging depends on jet $p_T$ and $\eta$, as well as average number of pile-up interactions, different impact on $b$-/$c$- and light-jet efficiencies
- Degradation of $b$-jet tagging efficiency at
  - very low jet $p_T$: the $b$-hadron flight path is (too) short, tracks are (too) soft and not very displaced
  - high jet $p_T$: merging of tracks, detector inefficient for very late decays, increased track multiplicity due to fragmentation
Performance V: dense environment and boosted topologies

Scenario: searches for new physics at high masses
→ highly boosted and collimated decay products, e.g. \( h \rightarrow b\bar{b} \)

- R=0.4 calo. jets might not be able to resolve the products from the two \( b \)-hadron decays
→ large-R (e.g. 1.0) calo. jets: “Higgs jet”

- apply \( b \)-tagging to ghost-associated (R=0.2) track jets
  - small \( R \) parameters possible
  - low PU sensitivity
  - good angular resolution also in dense environment

- exploit large-R jet substructure to improve bkg. rejection?

![ATLAS Simulation Preliminary](image)

**ATLAS Simulation Preliminary**

\( \sqrt{s} = 8 \text{ TeV}, M = 2.0 \text{ TeV}, k_{M_0} = 1.0 \)

- anti-\( k \), track jets
- \( k \), calo subjets

- Double b-tagging @ 70% WP
- Hadronic top jet

- 68% mass window

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**Performance VI: double $b$-hadron jets**

- $b$-tagging algorithms currently optimized on $t\bar{t}$ samples, i.e. for jets containing a single $b$ hadron → no information on the number of $b$-hadrons
- competing effects if two $b$-hadron decays inside one jet ($\geq 2$ SVs, higher multiplicity of displaced tracks,...) likely improve (decrease) performance of IP-based and SV taggers (JetFitter)
- possible strategies to separate single and double $b$-hadron jets:
  - explicity reconstruct two $b$-hadron decay vertices / chains
  - exploit substructure, kinematic differences

Enriched $b$-jet sample using MV1@60%. Other MVA inputs: track-jet width, distances between tracks / subjets
Jet truth flavour labelling

Run 1
- select partons with $p_T > 5$ GeV
- cone-based matching to reco. jet: $\Delta R < 0.3$

Run 2
- select weakly decaying hadrons with $p_T > 5$ GeV
- *exclusive* cone-based matching to reco. jet: $\Delta R < 0.3$
- alternative: ghost-association

Order of labelling
- if $b$ parton(hadron) is found $\rightarrow b$ jet
- else if $c$ parton(hadron) is found $\rightarrow c$ jet
- else if tau is found $\rightarrow$ tau jet
- else light jet

Comments
- several analyses already used Run 2 baseline in Run 1
- cone-based matching and ghost-association agree at the 1% level in case of $b$-jets (in $t\bar{t}$)
- difference has non-negligible impact on light-jet rejection
- cone-based labelling coherent with track-jet association $\rightarrow$ baseline!
- $g \rightarrow b\bar{b}/c\bar{c}$ jets are labelled as $b$-/c-jets $\leftarrow$ agrees with $b$-tagging point of view
Calibration of $b$-tagging algorithms

- the performance of $b$-tagging algorithms is optimized and evaluated using simulations, usually of inclusive $\bar{t}t$ events
- cannot expect simulations to describe all effects (modelling, detector) that impact the performance of $b$-tagging algorithms accurately
  → measurements of the $b$/$c$- and light-jet tagging efficiencies needed; as function of jet $p_T$ and $\eta$
- requires extracting samples of jets dominated by a single jet flavour
- results are presented in terms of data-to-simulation scale factors

$$SF = \frac{\varepsilon_{x}^{\text{data}}}{\varepsilon_{x}^{\text{MC}}}, \quad x = b, c, \text{light}$$

**assumption**: SFs are process independent
i.e. SF measured in a $\bar{t}t$ dilepton sample, applicable to a $W+\text{jets}$ sample

**SFs are MC generator dependent**
→ current approach: MC-to-MC SFs
  better: derive SFs for different MC generators
Calibration methods: an overview

**b-jet tagging efficiency calibration**
- muon-based methods (dijet samples)
  - $p_T^{rel}$
  - system8
- $t\bar{t}$-based methods (single-/dilepton $t\bar{t}$) ← inclusive!
  - tag counting
  - kinematic selection
  - kinematic fit
  - combinatorial likelihood ← most precise!
→ **combined** with muon-based methods

**c-jet tagging efficiency calibration**
- $W+c$ method (soft-muon tagged)
- $D^*$ method ($D^* \rightarrow D^0 (\rightarrow K\pi\pi)$)

**Mistag rate calibration**: negative tag method

**Differences**: purity, inclusiveness, simulation dependence, precision
Calibration results

**b-jet tagging efficiency scale factor**

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<th>$b$-jet tagging efficiency scale factor</th>
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**Combined (stat+syst)**

**Combined (stat)**

**Combinatorial likelihood on $t\bar{t}$**

**Dijet**

**ATLAS $= 7$ TeVs**

$\int L dt = 4.7 \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$

$\mu = 70\%$

**MV1, $\varepsilon_b = 70\%$**

**c-jet tagging efficiency scale factor**

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<th>c-jet tagging efficiency scale factor</th>
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**Scale factor (stat)**

**Scale factor (stat+syst)**

**Scale factor (stat)**

$\int L dt = 4.7 \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$

$\mu = 70\%$

**ATLAS**

$\mu = 70\%$

$|\eta_{\text{jet}}| < 1.2$

**Mistag rate scale factor**

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**Total uncertainties for MV1@70%**: $b$-jet calib. 2-8% (comb. like.), $c$-jet calib. 8-15% ($D^*$), light-jet calib. 15-40%
Calibration results: dense environments I

- **top**: $b$-jet tagging efficiency for jets from the hadronic top decay in single-lepton $t\bar{t}$ events as function of
  - **left**: the minimal distance to a close-by jet
  - **right**: the distance between the jet axis and the PV-SV axis

  → SFs: $\sim 1$ and flat across jet $p_T$

- **bottom**: comparison of SFs with jets from the leptonic top decay → compatible
Efficiency for two $b$-tagged (MV1@70\%) track jets ghost-associated to large-R calo. jet.
Impact of (heavy flavour) modelling on $b$-tagging efficiencies

- **calibration’s goal**: resolve (minimize) simulation dependence
  (including detector response, reconstruction,...)

- calibration methods exploiting *inclusive jet samples* are doing a good job
  - still rely on simulation for e.g. (ratios of) flavour fractions, distributions of discriminant variables,... → accounted by applying dedicated uncertainties

- modelling uncertainties dominant for certain methods and phase space regions → can be resolved by refined, more data-driven methods, e.g. combinatorial likelihood method

- more difficult in case of methods relying on *non-inclusive jet samples*:
  - SFs applicable to *inclusive* jet samples if the differences of jet properties (affecting $b$-tagging) between the *non-inclusive* and the *inclusive* sample are well described

\[
\varepsilon = \alpha \cdot \varepsilon_{\text{excl}}
\]

\[
SF = \frac{\alpha_{\text{data}}}{\alpha_{\text{MC}}} \cdot SF_{\text{excl}}
\]

if $\alpha_{\text{data}} = \alpha_{\text{MC}}$ → $SF = SF_{\text{excl}}$

\[
\alpha_{\text{data}} = \alpha_{\text{MC}}? 
\]

If not → need to extrapolate, i.e. estimate $\frac{\alpha_{\text{data}}}{\alpha_{\text{MC}}}$.

---

Pythia-default

Incl. c-jet sample

SMT c-jet sample

**ATLAS Simulation Preliminary**

\begin{aligned}
\text{c-jet tagging efficiency } &\varepsilon_{c} \\
\text{b-tagging operating point } &\varepsilon_{b}
\end{aligned}

\begin{align*}
\varepsilon_{\text{data}} &\approx \varepsilon_{\text{MC}} \\
\varepsilon_{\text{data}} &\neq \varepsilon_{\text{MC}} \\
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\varepsilon_{\text{data}} &\neq \varepsilon_{\text{MC}} \\
\varepsilon_{\text{data}} &\approx \varepsilon_{\text{MC}}
\end{align*}
Extrapolation to inclusive jet samples

- **goal**: estimate $\alpha_{\text{data}}$ from simulation where heavy quark fragmentation and heavy hadron decay properties are corrected to best knowledge:

  $$\alpha_{\text{data}} \approx \frac{\alpha_{\text{corr}}}{\alpha_{\text{MC}}} \cdot \text{SF}_{\text{excl}}$$

  $\rightarrow \text{SF} \approx \frac{\alpha_{\text{corr}}}{\alpha_{\text{MC}}} \cdot \text{SF}_{\text{excl}}$

- ratio $\rightarrow$ SF extrapolation relatively independent from reference simulation

**Example**: corrections applied in $W+c$ calibration (reference MC: Pythia 6)

- the fragmentation fractions ($e^+e^-$ and $e^\pm p$ data)
- the *total* branching ratio of the semileptonic decay of $c$-hadrons (PDG)
- the branching ratios of some *exclusive* semileptonic decays (PDG)
- the topological branching ratios of hadronic $n$-prong decays (PDG / EvtGen)
- the momentum of the decay muon in the rest frame of the $c$-hadron $p^*(\text{EvtGen})$

(the impact of the $c$-quark fragmentation function was evaluated, but not corrected)
Extrapolation to inclusive jet samples

- **goal**: estimate $\alpha_{\text{data}}$ from simulation where heavy quark fragmentation and heavy hadron decay properties are corrected to best knowledge:

$$\alpha_{\text{data}} \approx \alpha_{\text{corr}}^{\text{MC}}$$

$$\rightarrow \text{SF} \approx \frac{\alpha_{\text{corr}}^{\text{MC}}}{\alpha_{\text{MC}}} \cdot \text{SF}_{\text{excl}}$$

- ratio $\rightarrow$ SF extrapolation relatively independent from reference simulation

**Example**: corrections applied in $W+c$ calibration (reference MC: Pythia 6)

- the production fractions ($e^+e^-$ and $e^\pm p$ data)
- the *total* branching ratio of the semileptonic decay of $c$-hadrons (PDG) $\leftarrow$ today: EvtGen*!
- the branching ratios of some *exclusive* semileptonic decays (PDG) $\leftarrow$ today: EvtGen*!
- the topological branching ratios of hadronic $n$-prong decays (PDG / EvtGen) $\leftarrow$ does not cancel!
- the momentum of the decay muon in the rest frame of the $c$-hadron (EvtGen)

*with ATLAS decay table

(the impact of the $c$-quark fragmentation function was evaluated, but not corrected)
Heavy hadron production fractions

- large differences in production fractions between generators
- existing measurements
  - for $b$-hadrons: HFAG (Tevatron), HFAG (Tevatron + LEP + LHCb)
  - for $c$-hadrons: several measurements in $e^+e^-$ and $e^\pm p$ data → combination differ among each other and with simulation (Pythia 6 is rather close!)
- impact on $b$-tagging efficiencies is rather small; more pronounced for $c$-hadrons whose tagging efficiencies are rather different
  - for MV1@70%: $\varepsilon(D^+)/\varepsilon(D^0) \sim 1.8$
  - $\varepsilon(B^+)/\varepsilon(B^0) \sim 1.03$
Heavy hadron branching fractions

- inclusive and prominent exclusive semi-leptonic decays of dominant, weakly decaying heavy hadrons measured to high precision
  → implemented in EvtGen via ATLAS dec. table!
  (other generators show large differences)

- many exclusive hadronic decays are measured, but still make up only a relatively small fraction of all hadronic decays
  e.g. \(D^+\): 60%, \(b\)-baryons: much less

- large differences between the number of implemented exclusive hadronic decays in different generators (EvtGen » Pythia8 » Pythia6 » Herwig) and their branching fractions

- BUT: mainly the number of charged decay products has an impact on the tagging efficiency
  - unfortunately here the situation is not much better
Inclusive charged particle multiplicities

- only for the $D^0$ the topological (inclusive) n-prong fractions are measured from which one can infer the hadronic ones...
- the mean of inclusive charged particle multiplicities is measured for the admixture of $B^0$, $B^+$, $B_s$, $\Lambda_b$: EvtGen (4.76) $\times$ 4.97 $\pm$ 0.07 $\ll$ Pythia 6 (5.20)
- BUT: $b$-tagging efficiency depends on spectrum - large differences between generators

→ dominant (extrapolation) uncertainty in $p_T^{\text{rel}}$, $W+c$ and $D^*$ calibrations!
Using EvtGen ...

- harmonizes heavy hadron decays
- reduces the differences in the $b$-jet tagging efficiency predicted by generators significantly; only small differences at the % level, mainly at low jet $p_T$ remain
- harmonization less pronounced in case of the $c$-jet tagging efficiency - fragmentation fractions, tracks from fragmentation, etc. have a stronger impact
Summary on HF modelling

- using EvtGen harmonizes the $b$-jet tagging efficiencies significantly, but cannot resolve the simulation dependency of SFs completely (especially for $c$-jets), since only affects heavy flavour decay modelling.
- Other corrections are still needed when extrapolating SFs to inclusive samples.
- Only comparisons between different generators allow to assess modelling uncertainties other than semi-leptonic branching fractions.
- Theoretically varying those within their measured uncertainties would suffice, but more complicated to do.
- The estimated SF extrapolation factors (rel. unc.) are for MV1:
  - $p_T^{rel} : \sim 1$ (3%);
  - $W+c$: 0.86 – 0.95 (3-7%); $D^*$: 0.82 – 0.92
  (the corrected eff. extrapolation factors are $W+c$: 0.7 – 0.75 $\ll D^*$: 0.5 – 0.6)
Summary

- several dedicated algorithms to identify jets containing $b$-hadrons
- high performing combined algorithm further improved for Run 2
- several methods to calibrate $b$-jet, $c$-jet tagging efficiencies and light-jet mistag rate
- using EvtGen consistently to decay heavy hadrons in Run 2 simulations reduced generator dependency of the $b$-jet tagging efficiency significantly
- $b$-tagging of small-R track jets ghost-associated to large-R calo. jets improves $b$-tagging in dense and boosted topologies
- work ongoing to better exploit jet substructure and to improve single and double $b$-hadron jet separation
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