JET FLAVOR TAGGING IN ATLAS AND ITS APPLICATION IN ANALYSES
INTRODUCTION & MOTIVATION

INTRODUCTION

▸ Many new physics model final states, top quark decays, H→bb decay have at least one jet containing a b-hadron (b-jets) in the final state

▸ Important for ATLAS analysis program to reliably identify b-jets:
  ▸ High b-identification efficiency at high rejection of jets from c, s, u, d quarks and gluons
  ▸ Reliable description of performance in simulation

Potential new heavy resonance

+ your favorite SUSY/ new physics model here

Higgs branching ratio as function of the Higgs mass
THE DATASET

▸ Use ATLAS collision dataset recorded during Run 2 of the LHC (2015-2018) @ center-of-mass energy $\sqrt{s}=13$ TeV from proton-proton collisions
▸ 156 fb$^{-1}$ pp data delivered
▸ 147 fb$^{-1}$ recorded
▸ 139 fb$^{-1}$ “good for physics” (preliminary uncertainty 1.7%)
▸ Peak luminosity: $2.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$
▸ Average number of interactions: 33.7
THE ATLAS DETECTOR

- Covers ~full solid angle
- Four main subsystems
  - **Inner detector tracker (ID)** → charged particle track detection
  - Electromagnetic & hadronic calorimeter → clusters from electromagnetic or hadronic interactions
  - muon spectrometer
  - Before Run 2, “**Inner B-layer**” was added in the ID
    - Provides a tracking layer 3.3cm from the interaction point
    - Important for b-jet identification
PARTICLE IDENTIFICATION

PARTICLE DETECTION IN ATLAS

- Collect information from all subsystems to reconstruct & identify particles coming out of the collision point
- Reconstruct electrons, muons, hadronic jets and photons
- Neutrinos are reconstructed from the missing energy in the transverse (x-y) direction
Efficient track reconstruction and a precise measurement of track quantities and vertices is a key point to flavor tagging.

Flavour tagging relies fully on the tracks assigned to a hadronic jets.

A reconstructed primary vertex (interaction point of collision) defines the reference point for many flavor tagging quantities.

Tracks are assigned to jets using the angular distance between the track momenta and the jet axis.
PARTICLE IDENTIFICATION

TRACK RECONSTRUCTION IN ATLAS

- Create clusters from raw hits in the inner detector
- Iterative track-candidate finding algorithm using track seeds formed by $\geq 3$ clusters
- Pattern-recognition approach building first combinatorial candidates + stringent ambiguity solver

- Challenging in busy environments like energetic hadronic jets
  - Majority of jet tracks are in jet core
  - This may lead to tracking inefficiencies
- Algorithm can also resolve overlapping clusters of energy deposits ("merged clusters")
PARTICLE IDENTIFICATION

TRACKING: PERFORMANCE

- Tracking efficiency drops towards the center of jet where track density is maximal
- Efficiency drops with increasing jet $p_T$: straight and collimated tracks
- Efficiency drops with production radius (radial distance of decay of parent particle from beam axis):
  - Particles created beyond the first layers of the ID create fewer track clusters
  - Shorter flight length to next active layer: more merged cluster due to smaller average separation between particles
PARTICLE IDENTIFICATION

TRACKING: THE TRACK IMPACT PARAMETER

- Distance of closest approach of the track-trajectory to the Primary Vertex
  - In the transverse plane (x-y) ($d_0$)
  - In the $z$-direction between the primary vertex and the track helix at the closest approach in the transverse plane ($z_0$)
PARTICLE IDENTIFICATION

JET RECONSTRUCTION: PARTICLE FLOW (PFLOW) JETS

**TRACKING**
- BETTER RESOLUTION FOR LOW PT PARTICLES
- BETTER ANGULAR RESOLUTION
- TRACES PARTICLES TO HARD-SCATTER INTERACTION OR PILE-UP

**CALORIMETERS**
- BETTER RESOLUTION FOR HIGH PT
- CAPTURES NEUTRAL PARTICLES

> Combine information from Trackers & Calorimeters
  > Tracks are assigned (or not) to signal contributions in the calorimeters, ideally represent individual particles
  > Improves energy and angular resolution
  > Reduces pile-up contribution

> Fixed radius of R=0.4
> Corrected for pile-up, calibrated using a simulation based pT, eta and energy corrections, and data-driven in-situ correction using reference objects
> Dedicated training of b-tagging algorithm for PFlow jets available
PARTICLE IDENTIFICATION

JET RECONSTRUCTION: LARGE-RADIUS ("LARGE-R") JETS

- For a two-body decay, distance $\Delta R$ between the decay production is given by: $\Delta R \approx 2m/p_T$
- Decay products from particles with high $p_T$ are expected to be merged in a single large-radius jet
- Reconstruct jets with a (fixed) radius of $R=1.0$
- Apply "grooming" for pile-up mitigation

Calibration: Simulation based jet $p_T$, eta and jet mass correction, and data-driven in-situ correction using reference objects
PARTICLE IDENTIFICATION

**JET RECONSTRUCTION: VARIABLE RADIUS JETS (VRTRACK)**

- At high pT, (sub)jets are **collimated** → cannot be resolved any more as separate jets with fixed-cone jet algorithm
- New jet collection in ATLAS to **resolve the decay products of H->bb decay**
  - Identify them as b-jets via b-tagging algorithm
- Jets have **variable size** which goes with \( R \sim 1/p_T(jet) \)
  - Defined by **three parameters**: \( \rho \) (dimensionless constant), \( R_{\text{min}}=0.02 \) (minimal size) and \( R_{\text{max}}=0.4 \) (maximal size)
    - Optimized to resolve b-hadrons in H->bb decay
- Use **only tracks** for reconstruction, good angular and momentum resolution
- Note: b-tagging algorithm with dedicated training for VRTrack jets available
The distinct signature of a b-hadron decay can be used to identify jets containing b-hadrons in ATLAS.

C-hadrons also have a slightly longer lifetime and a larger mass w.r.t light jets, lower track multiplicity, lifetime and mass w.r.t b-jets.

**Truth flavour definition**

(definition of a b-jet in simulation):

- Search for **b-hadrons** with \( p_T > 5 \text{GeV} \) within \( \Delta R < 0.3 \) within the jet.
- If no b-hadron found, search for **c-hadron**, then **tau-lepton**.
- Else: classify jet as **light jet**.

Long lifetime: significant mean flight length \( \langle l \rangle = \beta \gamma c t \)
Algorithm trained on simulated ttbar events (for jet pT<250GeV)

New: Add Z'->qq sample for a dedicated high-pT jet training (q=b,c,l) (for jet pT>250GeV)

Reweight pT spectrum of b- and c-jets to light jets to avoid algorithms to focus on differences in pT spectrum
THE LOW-LEVEL TAGGERS: OVERVIEW

- Two types of low-level tagger algorithm:
  - Impact parameter based
  - Displaced-vertices based
- Several output variables from each low-level tagger which are fed to high-level taggers
- RNNIP (recurrent neural network) added in 2019, taggers with RNNIP fully calibrated only since recently
The Atlas B-tagging Algorithm: Low-level Taggers

The Low-level Taggers: IPXD

- Tracks from decay at secondary vertices have tendentially larger impact parameters
- **IP2D** relies on the transverse impact parameter significance
- **IP3D** relies on both the transverse & longitudinal impact parameter significance and their correlation
- For each track in a jet, the light, b- and c- probabilities ($p_u$, $p_b$, $p_c$) are extracted using 1D (IP2D) or 2D templates (IP3D)
- The per-track contributions are summed to get a log-likelihood ratios LLR
  - Example: $\text{LLR}(u,b)$:
    \[
    \sum_{i=1}^{N} \log \left( \frac{p_b}{p_u} \right)
    \]

Note: Correlation between tracks in jet not taken into account
THE LOW-LEVEL TAGGERS: RNNIP

- Recurrent neural network track-based tagger
- Uses information from track impact parameters in jet and their correlation
  - If one track with a large IP is found, a second track is often found as well as several tracks emerge from a displaced vertex
  - This correlation does not exist for tracks in light jets
- Track impact parameter significances, momentum fractions of tracks relative to the jet momenta, angular distances of tracks to jet axis, etc. are fed to neural network
- Up to 2x light jet rejection and 1.2x charm jet rejection w.r.t IPXD
- Shown to add information w.r.t IPXD: partly complementary

\[ D_{\text{RNN}}(b) = \ln \frac{p_b}{f_c p_c + f_{\tau} p_{\tau} + (1 - f_c - f_{\tau}) p_{\text{light}}} \]
THE ATLAS B-TAGGING ALGORITHM: LOW-LEVEL TAGGERS

THE LOW-LEVEL TAGGERS: SV1

- Single, displaced vertex in jet is reconstructed
  - Check all track pairs for a two-track vertex hypothesis
  - Remove vertices likely to originate from photon conversion, Ks or lambda decay
  - Apply quality criteria on the tracks and the fit to reconstruct the vertex
- Properties of the secondary vertex and the assigned tracks are used in high-level tagger

Transverse distance between primary & secondary vertex

Secondary vertex mass

Number of tracks from SV1 vertex
THE ATLAS B-TAGGING ALGORITHM: LOW-LEVEL TAGGERS

THE LOW-LEVEL TAGGERS: JETFITTER

- Topological reconstruction of heavy hadron decay along the Jet axis
- Based on a modified Kalman filter
- Uses intercepts of track with jet axis to reconstruct full decay topology
- Properties of 3rd vertex added to better distinguish from c-jets and to make possible c-tagging (in neural network based high-level taggers)

Reconstructed vertices mass

Fraction of jet energy carried by the vertex

Distance between B-hadron flight direction and jet axis
Improvement to RNNIP (impact-parameter based)
- Ordering of tracks according to their impact parameter significance is necessary in RNNIP as it operates on sequences
- RNNIP neural network uses Deep sets architecture
  - No track ordering required → allows faster training and optimization
- Slightly better performance with same NN parameters and input as RNNIP, can optimize better due to faster turnaround
- Not included yet in “official” taggers
THE OUTPUT DISCRIMINANTS

- Low-level tagger outputs are feed into Deep Fast neural network
- DNN creates output probabilities $p_b$, $p_c$, $p_u$
- Calculate output discriminant value: DL1 and DL1r (DL1r includes RNNIP)

Define single-cut operating points corresponding to an average b-tagging efficiency (in ttbar MC)
- 85%, 77%, 70%, 60%

$$D_{DL1(r)} = \ln\left( \frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_{\text{light}}} \right)$$
THE OUTPUT DISCRIMINANT

TAGGER PERFORMANCE: PFLOW JETS

- Improvements by up to a factor of 2 with recent improvements: inclusion of RNNIP and use of Deep Neural network instead of boosted decision trees (MV2)
- B-tagging efficiency and light and charm rejection pT-dependent

Light jet rejection for fixed-cut b-efficiency of 77%

Charm jet rejection 1:10 @70% b-efficiency

Light jet rejection 1:500 @ 70% b-efficiency

x1.5

x2
Several new physics models predict high-mass resonances decaying to at least one Higgs boson.

- Expect Higgs to be energetic \( \Rightarrow \) H-\( \rightarrow \)bb decay products collimated to single large-R jet.
- Up to present, tag small-R jets (VRTrack jets) assigned to single large-R jet ("double b-tagging").
- New approach creates dedicated tagging discriminant to identify H(X)-\( \rightarrow \)bb decays.

![Diagram](image)

- Feed neural network with \( p_{bT}, p_{cT}, p_u \) output of DL1 tagger for up to three leading VRTrack subjets.
- Use also kinematics of large-R jet.
- Exploits also the correlation of tagger outputs from VRTrack jets in large-R jet.

Output probabilities for Higgs, top and multijet.
NOT ONLY B-TAGGING

NOT ONLY B-TAGGING... THE H→BB TAGGER – PERFORMANCE

\[ D_{Xbb} = \ln \left( \frac{p_{Higgs}}{f_{top} \cdot p_{top} + (1 - f_{top}) \cdot p_{multijet}} \right) \]

- For the full range of signal efficiencies, the Xbb tagger achieves an equal or higher multijet or top jet rejection w.r.t MV2 or DL1r double b-tag
- @60% Higgs-efficiency: Xbb tagger performs equally than DL1r double b-tag for multijet rejection and 1.6 times better for top jet rejection
- Note: No analysis using this tagger has been published yet, calibration work in progress
NOT ONLY B-TAGGING

- Without any retraining of the DL1(r) algorithm, charm tagging can be done
- Uses the same output: probabilities $p_b, p_c, p_u$
  - Advantage w.r.t old MV2 algorithm: retraining needed as single output instead of probabilities for each flavor
- Just need to rewrite output discriminant definition

\[
DL1r = \log \frac{p_b}{f_c p_c + (1 - f_c) p_u}
\]

\[
DL1r_c = \log \frac{p_c}{f_b p_b + (1 - f_b) p_u}
\]

- Analysis using charm tagging with “official” DL1 algorithm work in progress
  - VH(->cc) (V=W,Z)
CALIBRATION OF THE B-TAGGING ALGORITHM: OVERVIEW

- Taggers trained in simulation using several input variables like secondary vertex masses, number of tracks, etc.
- Check whether tagger input is well understood in simulation and training wasn’t done on a completely different setup
- Calibrate b-efficiency, charm & light mistag rate
  - Use samples enriched by either b-, charm or light jets
  - Calculate efficiencies in data and MC and compare
  - Calculate MC-to-data correction factor ("Scale Factor", SF)
- Scale Factors are ratios in performance data to MC
- SF are ideally close to 1
CALIBRATION

**B-EFFICIENCY CALIBRATION**

- Select dilepton ttbar events
  - ==1 e, ==1 mu, == 2 jets
- Extract calibration using the 2 jets in event
- Data-driven corrections to background reduce uncertainty to percent level
  - Non-b-jet contribution constrained in fit
CHARM MISTAG EFFICIENCY CALIBRATION

- Select ttbar lepton+jets sample
  - == 1 lepton, ETmiss, ==4 jets
- Perform measurement on jets assigned to hadronically decaying W-boson
  - Exploit large branching ratio W->cX
- Extract charm mistag efficiency in likelihood fit
CALIBRATION

LIGHT MISTAG EFFICIENCY CALIBRATION

- Challenging due to high light jet rejection (1:100-1:1000)
- Modifications to tagger:
  - Make use of symmetry of signed impact parameter distribution for light jets and strong asymmetry for b & charm jets
  - Decrease b-jet response
  - Light jet response unchanged
- Measure mistag rate of modified (“flipped”) tagger
- Calibration of leading jet in Z(\(\rightarrow\)ll)+jets events
- Reduce uncertainties by constraining non-light flavour in fit

ORIGINAL TAGGER  \rightarrow  FLIPPED TAGGER  \leftarrow  CALIBRATION

Add additional uncertainty \rightarrow estimate using MC ("extrapolation uncertainty")
Data and MC efficiencies are consistent, the MC-to-data correction factors (“Scale Factors”) are compatible with 1

Post-processing to measured scale factors:
- Due to insufficient statistics, cannot measure b-efficiency for jets with \( p_T > 400 \text{GeV} \): apply additional uncertainties to scale factor central value for \( p_T = 400 \text{GeV} \) due to physics and detector modeling effects (“high-\( p_T \) extrapolation”)
- Smooth results as function of \( p_T \) using a non-parametric regression-technique: do not expect discontinuities in kinematic modeling

Uncertainties:
- Charm jet mistag efficiency calibration: Uncertainties @1-2%
- B-tag efficiency calibration: Uncertainties @1-2%
- Light jet mistag efficiency calibration: Uncertainties @10-20%

Extrapolation to high jet \( p_T \) using simulation.
Analyses can be impacted in several ways by flavor tagging

- **Performance** (b-efficiency vs. charm & light mistag rate):
  - Signal efficiency depends on the b-tag efficiency working point
  - Analyses with a lot of b-jet in the final state can suffer from background from charm mistag if rejection is too low
    - Example: VH(H->aa->bbbb), 4 top, ttH(bb)

- **Efficiency calibration** (uncertainty):
  - Uncertainties from efficiency calibration can have impact on analysis sensitivity
    - Examples: analyses using data-driven background (low-or high mass dijet resonance searches)

- As example, present dijet resonance search with full Run2 dataset
ANALYSIS EXAMPLE: DI-JET RESONANCE SEARCH

**DIJET RESONANCE SEARCH (ARXIV:1910.08447)**

- Search for high-mass resonance coupling to quark and/or gluons
- Heavy gauge bosons (Z' \( \rightarrow \) bb), Kaluza-Klein Graviton G\( \rightarrow \) bb, excited quarks b*(\( \rightarrow \) qb)
- Decay to **two high-energetic hadronic jets**

![Invariant di-jet mass spectrum produced in QCD processes: smoothly falling with m(jj)](image)

- New heavy resonance with mass M
- New physics as (Gaussian-shaped) peak on smoothly falling mass spectrum

- Inclusive search and with \( \geq 1 \) or \( \geq 2 \) b-tagged jets
- Search performed on full Run2 ATLAS data
- First ATLAS analysis using new DL1r tagger
- Flagship measurement for high-pT jet b-tagging
DIJET RESONANCE SEARCH: IMPORTANT ANALYSIS FEATURES

- Background estimation purely data-driven
- Modeled by a smoothly falling parametric function
- Determine function coefficients by fit in control regions

Signal models considered

QCD processes mainly t-channel production; signal s-channel production

Categories: Inclusive or \( \geq 1 \) or \( \geq 2 \) b-tags

Select high pT (b-tagged) jets

\[
f(x) = p_1(1 - x)^{p_2} x^{p_3 + p_4 \ln x}
\]
**ANALYSIS EXAMPLE: DI-JET RESONANCE SEARCH**

**DIJET RESONANCE SEARCH: IMPORTANCE OF B-TAGGING**

- Expected signal yield sensitive to b-tag efficiency calibration @high jet pT
- Sensitive to high-pT extrapolation uncertainty
- Reduced in current calibration: improved method, simulations (inner detector simulation) and use of RNNIP

- Efficiency to pass the b-tagging selection after the remaining event selection
- Signal selection efficiency decreases with pT due to decreasing b-tagging efficiency with pT
ANALYSIS EXAMPLE: DI-JET RESONANCE SEARCH

DIJET RESONANCE SEARCH: RESULTS

- Scan curve in continuous mass interval using a sliding-window fit
- No significant deviation from the Standard Model background
- Better limits observed in 2b-category w.r.t previous analysis
  - Increased high-pT efficiency for new DL1r tagger (due to dedicated high-pT training)
  - Lower systematic uncertainties of high-pT calibration (extrapolated calibration)

Previous analysis (data15+16) scaled to 139fb-1 luminosity

New limits with improved calibration & new DL1r b-tagger
CONCLUSIONS

- Flavour tagging important input to physics analysis in ATLAS
- Not only b-tagging possible but also charm and H->bb tagging
- Tagger training and input variables well understood, tagging efficiencies in data and simulation well in agreement
- Constant improvements on taggers and calibrations
- ATLAS analyses profit from the recent improvements on taggers and calibrations