Searches for new physics with jet substructure

Steven Schramm,
on behalf of the ATLAS and CMS collaborations

QCHS 2018
Maynooth University
August 3, 2018
Introduction

- Jets are a useful tool to represent hadronic showers in a detector
- **ATLAS** + **CMS** primarily use the anti-$k_t$ jet algorithm
  - **ATLAS**: inputs are noise-suppressed calorimeter cell topological clusters
  - **CMS**: inputs are particle-flow objects (unified tracker+calorimeter info)
- Jets have different underlying sources: QCD, massive particle decays
- Jet substructure (JSS) can help differentiate between possible sources
- JSS is an increasingly important input to searches for new physics

**ATLAS simulation 2010**

**Key:**
- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

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Hadronic decays and collimation

- Hadronic decays of massive particles can come from many sources
  - Main examples: $W \rightarrow qq'$, $Z \rightarrow q\bar{q}$, $H \rightarrow b\bar{b}$, top$\rightarrow bW \rightarrow bqq'$
- Increased parent particle energy $\implies$ decay product collimation
  - Idea of “boosted decays”, rule-of-thumb $\Delta R \gtrsim 2m^X/p^X_T$
- High-$p_T$: all decay products within a single jet
  - Jet substructure distinguishes different parent particles (or $q$ vs $g$)

![Diagram showing expected jet mass and number of decay axes for different particles: gluon (not top), quark (not top), W, Z, H, top. Expected jet masses are labeled: 80, 91, 125, 175 GeV. Boosted decay vs. resolved decay.](image-url)
Jet substructure variables

- JSS variables look at the internal energy and angular structure of a jet
  - Idea: quark is one energetic region, W is two, top is three, etc
- Most intuitive JSS variable is the mass of the jet
  - Well-defined expectation for massive particle decays: parent mass
  - Ill-defined expectation for QCD jets: general peak at low values
    - Peak value depends on detector granularity, algorithms used, etc
- After mass cut, additional variables measure energy “dispersion”

[Graph showing normalized distribution of pruned jet mass]
Hadronic decay tagging

- Using these JSS variables, it is possible to identify $W/Z/\text{top}$
- Even simple two-JSS-variable cuts give impressive discrimination
- The use of double-b-tagging is very beneficial for $H\to bb$ identification
- Improvements both vs inclusive QCD and dominant $g\to bb$ background
- Such taggers have been used for many searches for new physics
## Searches with jet substructure made public in 2018

### ATLAS results

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Dataset</th>
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<tr>
<td>Mass-scan:</td>
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<tr>
<td>Di-quark+ISR</td>
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<td>$E_T^{\text{miss}}+X$:</td>
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<td>$E_T^{\text{miss}}+H(\rightarrow bb)$</td>
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<td>Di-top (lepton+jets)</td>
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- Introduction to jet substructure
- **Dijet resonance searches**
- Jet mass scan searches
- Vector-like quark searches
- Improving jet substructure for future searches
Many theories predict the decay of new particles to pairs of objects
- These cover spin 0, 1, and 2 parent particles: lots of possibilities!
- \( W' \rightarrow WZ, Z' \rightarrow WW/\ell\ell, G \rightarrow WW/ZZ/HH, A \rightarrow WW/ZZ/HH, \) etc
- All of these objects have large hadronic branching fractions
- Searches for hadronic decays are thus particularly interesting
- Look for a dijet mass resonance over the smooth QCD background
- Apply hadronic decay tagging to suppress the large QCD background
Dijet resonance searches

Fully-hadronic di-boson resonances

- Di-boson resonances: events with jet pairs tagged as WW, WZ, or ZZ
- Both experiments suppress QCD with jet tagging
- However, slightly different analysis/tagging strategies per jet pair
  - CMS: two exclusive regions of low and high purity (LP and HP)
  - ATLAS: only one region, very high purity (lower signal efficiency)

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**CMS Simulation** (13 TeV)

*Z' → WW*

**ATLAS Simulation Preliminary**

*HVT Z' → WW*

- Pre-Selection
- $|\Delta y|<1.2$
- $|A|<0.15$
- Mass cut
- $D_z$ cut

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Searches for new physics with substructure

August 3, 2018
Dijet resonance searches

Fully-hadronic di-boson resonances

- After tagging, look for bumps in the dijet mass spectrum
  - Fully data-driven: fit the data to get the background prediction
- No significant excesses observed by either experiment
  - Not just the WW channel (shown), also in the WZ and ZZ channels
  - CMS also checks the qW and qZ channels, still no excess
- Proceed to set limits on various channels and signal interpretations

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**CMS data**

- Dijet invariant mass (GeV)
- Events / 100 GeV
- 1
- 10
- 2
- $10^3$
- $10^4$
- $10^5$

**ATLAS Preliminary**

- Data
- Fit
- Fit + HVT model A $m=2.0$ TeV
- Fit + HVT model A $m=3.5$ TeV

- ATLAS Preliminary $\sqrt{s} = 13$ TeV, 79.8 fb
- $\chi^2$/DOF = 6.7/6

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**Dijet resonance searches**

**Fully-hadronic di-boson resonances**

- Final result is combination of low and high purity signal regions
  - $Z' \rightarrow WW$ ruled with given parameter choice ruled out below 2.7 TeV
- Fully hadronic decay more only part of lively diboson search program
  - Fully hadronic channel has the equivalent or best (expected) sensitivity of all analyses considered for $m_{W'} \gtrsim 2$ TeV

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**ICHEP 2018**

**Observed Median expected**

**95% CL upper limits**

**HVT model B**

**Expected ± 1 std. deviation**

**Expected ± 2 std. deviation**

**σ_{TH} \times B(G_{Bulk} \rightarrow WW) \ k=0.5**

**σ_{TH} \times B(Z' \rightarrow WW) HVT_B**

Narrow width approximation

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**Searches for new physics with substructure**

**August 3, 2018**
Dijet resonance searches

Fully-hadronic di-boson resonances

- Final ATLAS result is from the single very high purity signal region
  - $Z' \rightarrow WW$ ruled with given parameter choice ruled out below 2.8 TeV
- Sensitivity gain with respect to previous result much beyond statistics
  - Clear benefit from working on improving analysis inputs
  - Mixture of new calo+track inputs and analysis-optimized $W/Z$-tagger

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**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 79.8 fb$^{-1}$

$VV \rightarrow qqqq$

- Observed 95% CL upper limit
- Expected 95% CL upper limit
- Expected limit $\pm 1\sigma$
- Expected limit $\pm 2\sigma$
- HVT model A, $g_V = 1$
- HVT model B, $g_V = 3$

$\sigma (pp \rightarrow V \times B(V \rightarrow WW+WZ))$ (fb)

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**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV

$VV \rightarrow qqqq$

- Current Result (79.8 fb$^{-1}$)
- Phys. Lett. B 777 (2018) 91 (Scaled to 79.8 fb$^{-1}$)

$\sigma (pp \rightarrow V \times B(V \rightarrow WW+WZ))$ (fb)
Di-Higgs($\rightarrow$bb) resonances

- Di-Higgs resonances: events with jet pairs tagged as $H(\rightarrow$bb)$H(\rightarrow$bb)
- Benefit from the very large $H\rightarrow$bb branching fraction
  - High sensitivity to new physics modifying the Higgs couplings
- Exploit powerful b-tagging discrimination together with substructure
  - Jet double-b-tagger, mass, and $\tau_{21}$ used for $H\rightarrow$ bb tagging

![Graph 1](13 TeV)

- CMS
- Simulation Preliminary
- Benchmark 2
- Benchmark 5
- Bulk graviton 1000 GeV
- Bulk graviton 1200 GeV

![Graph 2](13 TeV)

- CMS
- Simulation Preliminary
- Benchmark 2
- Benchmark 5
- Bulk graviton 1000 GeV
- Bulk graviton 1200 GeV
Di-Higgs($\rightarrow bb$) resonances

- Analysis performed for both fully-boosted and semi-resolved selections
  - Fully-boosted = 2 large double-b-tagged jets
  - Semi-resolved = 1 large double-b-tagged jet, 2 small b-tagged jets
- Interpreted for both resonant and non-resonant di-Higgs production
- Getting close to sensitivity needed to probe standard graviton models
- Note: analysis also done by ATLAS, not shown here
Introduction to jet substructure
Dijet resonance searches
Jet mass scan searches
Vector-like quark searches
Improving jet substructure for future searches
Jet mass scan searches

What if the new particle couples directly to non-top-quarks?
- The standard dijet or di-b-jet searches are aimed at such new physics
- Trigger thresholds limit such searches to $m_X \gtrsim 500$ GeV

However, what if the new physics is light, with $m_X$ of $\mathcal{O}(100$ GeV)?
- Di-jet style searches quickly lose sensitivity

Consider an ISR object recoiling off of the new physics particle
- Trigger thresholds on ISR object $\implies$ new particle is boosted
- Boosted jet contains decay products of new particle $\implies$ $m_{\text{jet}} \approx m_X$

Look for new physics resonances in the jet mass distribution
Jet mass correlations

- Two important factors to using the jet mass spectrum for a search:
  1. It must be well calibrated with a sufficient resolution to spot bumps
  2. Any selections applied must not shape the jet mass distribution

  The first can be verified using the W/Z peak in data and MC
  - The peak is clearly visible and centred around the correct mass value

  The second is difficult, as JSS variables are correlated with the mass
  - Simple discriminants change the shape, advanced taggers make bumps
Mass-decorrelated taggers

- The correlation between JSS variables and mass is challenging
  - Need to suppress large QCD background, but can’t use normal variables
- ATLAS and CMS have created mass-decorrelated QCD discriminants
  - ATLAS uses linear fit to remove correlations (originally used by CMS)
  - CMS has moved to using 5% k-NN regression for further decorrelation
- Result: QCD suppression without shaping the jet mass spectrum
  - Vibrant topic: now many approaches to jet mass decorrelation
Low-mass di-quark resonances

- CMS analysis performed for the case of ISR jets
- Clear W/Z peak visible in data, well described by the fit
- No significant excess observed (in this $p_T$ bin)
  - Limits are set on the production of light $Z'$ bosons
- All $p_T$ bins are also combined
  - Result: $2.9\sigma$ local ($2.2\sigma$ global) excess at 115 GeV, visible below

### CMS

![Data plot](image)

- $p_T$: 500-600 GeV
- $Z'(qq)$, $g_q = 0.17$, $m_{Z'} = 135$ GeV

### CMS

![Limit plot](image)

- 95% CL upper limits
- Observed
- Expected
- $1$ std. deviation
- $2$ std. deviation
- Theory, $g_q = 0.08$
- Theory, $g_q = 0.17$
Jet mass scan searches

Low-mass di-quark resonances

- ATLAS analysis performed for the case of ISR jets and photons
- Different analysis selection $\implies$ less obvious W/Z peak
  - It is visible, it’s just considered part of the background below
- No significant excess observed (2.4$\sigma$ local, 1.2$\sigma$ global at 140 GeV)
- Limits are set on the production of light Z$'$ bosons
CMS has performed a similar analysis for di-b-quarks

- Same idea, just require a double-b-tagged signal candidate jet
- Done using two different jet sizes, $R = 0.8$ and $R = 1.5$
- Complementary mass coverage for new particles
- Clear $W/Z$ peak and potential hints towards the $H_{bb}$ peak ($R = 0.8$)
Jet mass scan searches

Low-mass di-b-quark resonances

- Use \( R = 0.8 \) selection for \( m_{Z'} < 175 \text{ GeV} \) and \( R = 1.5 \) above
  - Clear complementary nature of the two selections
- No significant excesses observed in either case
  - Set limits for both scalar (\( \Phi \)) and pseudoscalar (\( A \)) interpretations

![Graph showing resonance mass vs. \( g_{q\Phi} \) and \( g_{qA} \)](image)

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- Introduction to jet substructure
- Dijet resonance searches
- Jet mass scan searches
- **Vector-like quark searches**
- Improving jet substructure for future searches
Vector-like quarks (VLQs)

- VLQs couple to one fermion (usually third generation) and one boson
  - Potential explanation for the LHCb flavour anomalies
- VLQ events are expected to result in very busy final states
  - This typically includes multiple decays of massive particles
- Consider the example of di-$B$ production:
  - Each final state contains two, three, or four massive particle decays
  - Lots of room to exploit jet substructure: $W$, $Z$, $H$, and top tagging
- Given complexity of final state, many related but distinct searches
Semi-leptonic VLQ pair-production

- **ATLAS**: require exactly one lepton, otherwise all hadronic decays
- **Two signal regions which are fit simultaneously**
  - **RECOSR**: reconstruct hadronic $B, \bar{B}$ mass from large jets ($\geq 1$ $W$-tag)
  - **BDTSR**: use BDT to discriminate standard model from $B, \bar{B}$
    - Leading variables: $S_T \left(= E_{T}^{\text{miss}} + p_{T}^{\ell} + \sum p_{T}^{\text{jet}, R=0.4}\right)$ and $m_{\text{jet}, R=1.0}^{\text{leading}}(p_T)$
- **Jet substructure** plays key role in both signal regions
No significant deviations from the standard model are observed.

Proceed to set limits on the di-$B$ production cross-section:

- Singlet model ruled out for $B$ masses below $\sim 1.15$ TeV

Also provide limits in 2D plane of $BR(B \rightarrow Hb)$ vs $BR(B \rightarrow Wt)$.

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**Vector-like quark searches**

**Semi-leptonic VLQ pair-production**

Left: EXOT-2017-34

Right: EXOT-2017-34
Vector-like quark searches

Semi-leptonic VLQ pair-production

- CMS: dedicated selections for one-lepton, 2-leptons, and 3-leptons
  - Also considers di-$T$ production in same paper, not shown further
- 1-lepton channel relies extensively on jet substructure
  - Jet mass and $\tau_{21}$ are used to suppress backgrounds
  - Two b-tagged sub-jets in the large jet may be required after mass+$\tau_{21}$
- Jet substructure is also part of the 16-way categorization: $(W, H)$-jets

![Graphs showing data and distributions for CMS analysis]
Semi-leptonic VLQ pair-production

- No significant deviations from the standard model are observed
- Includes combination of 1-lepton, 2-lepton, and 3-lepton channels
- Proceed to set limits on the di-$B$ production cross-section
  - Singlet model ruled out for $B$ masses below $\sim 1.15$ TeV
  - Also provide limits in 2D plane of $\text{BR}(B \to Wt)$ vs $\text{BR}(B \to Hb)$
- Note: inverted x and y axes with respect to ATLAS plot
Vector-like quark searches

Fully-hadronic VLQ pair-production

- Fully hadronic analysis includes a lot of hadronically decaying particles
  - Boosted W/Z, Higgs, and top jets have non-negligible overlap
  - Dynamic jet size: build large jets from small jets (reclustering)
- Multi-class DNN trained on a mix of low-level and high-level variables
  - First stage: discriminate vs QCD for each signal type independently
  - Second step: likelihoods of discriminants for signal ambiguity resolution

ATLAS Simulation Preliminary
\( \sqrt{s} = 13 \text{ TeV} \)
\(|\eta| < 2.5\)
\(150 < p_T < 2000 \text{ GeV}\)
\(m > 40 \text{ GeV}\)

- V-boson jet
- Higgs-boson jet
- Top-quark jet
- Background jet

ATLAS Simulation Preliminary
\( \sqrt{s} = 13 \text{ TeV} \)
\(|\eta| < 2.5\)
\(150 < p_T < 2000 \text{ GeV}\)
\(m > 40 \text{ GeV}\)

VLQ DNN
V&Higgs-tagged

\(\log_{10}(D^V_{\text{DNN}} / D^H_{\text{DNN}})\)
Vector-like quark searches

**Finitely hadronic VLQ pair-production**

- Probe several different all-hadronic signal regions
  - No significant excess observed
- Proceed to set limits on the di-$B$ production cross-section
  - Singlet model ruled out for $B$ masses below $\sim 0.95$ TeV
- Also provide limits in the same 2D plane, not shown
  - Better sensitivity to the $\text{BR}(B \rightarrow Hb)$ part of the 2D plane
- Introduction to jet substructure
- Dijet resonance searches
- Jet mass scan searches
- Vector-like quark searches
- **Improving jet substructure for future searches**
New jet definitions

- Studied several hundred different jet definitions (more here)
- Compared current with short-list of options in detail
  - All short-listed options have better pileup stability
  - Some short-listed options have visibly better tagging performance
- Result: promising new jet definition(s) to be used in future searches

### Plots

- **Jet Grooming Method**
  - Soft Drop
  - Recursive Soft Drop
  - Bottom-up Soft Drop
  - Pruning
  - Trimming

- **Jet mass pile-up dependence, \( \Delta (M / \delta N_V) \)**
  - Unmodified, trimming (\(R_{tail} = 0.2, f_{tail} = 5\%\))
  - CS+SK, trimming (\(R_{tail} = 0.2, f_{tail} = 5\%\))
  - CS+SK, Soft Drop (\(x_{cut} = 0.1, \beta = 0.0\))
  - CS+SK, Soft Drop (\(x_{cut} = 0.1, \beta = 0.5\))
  - CS+SK, Soft Drop (\(x_{cut} = 0.1, \beta = 1.0\))

### Signal Tagging Efficiency vs. Background Rejection Factor

- **ATLAS Simulation Preliminary**
  - \(500 \text{ GeV} < p_T^{true} < 1000 \text{ GeV}, |y|^{true} < 1.2\)
  - \(\sqrt{s} = 13 \text{ TeV}, 68\% \text{ mass window} + \tau_{32} \text{ top tagger}\)
Deep learning for jet tagging

- Deep learning is being used in many areas of CMS
  - Double-b-tagging: \( \sim 50\% \) higher \( H \rightarrow bb \) efficiency for same 1\% QCD
  - Top-tagging: smaller, but still huge gains from using deep learning
- Analyses using these new taggers should see large improvements!

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**CMS Simulation Preliminary**

- **2016 (13 TeV)**
  - 300 < jet \( p_T \) < 2000 GeV
  - 40 < jet \( m_{SD} \) < 200 GeV

  - **DeepDoubleBvL, AUC = 97.3\%**
  - **double-b, AUC = 91.3\%**

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**CMS Simulation Preliminary**

- **1000 < \( p_T \) < 1400 GeV, |\( n \)| < 1.5**

  - Top vs QCD multijet

  - **BDT (w/o b-tag)**
  - **BDT (Full)**
  - **DNN (Particle kinematics)**
  - **DNN (Particle full)**
**Full in situ jet $p_T$ calibration**

- **Full in situ** evaluation of large jet $p_T$ calibration and uncertainty
- Preparing the way for the era of precision jet substructure searches
- Balance probe jet against well measured reference object
  - Forward probe jet against central reference jet
  - Probe jet against $Z(\rightarrow \ell\ell)$, photon, or system of calibrated jets
- Large jet $p_T$ uncertainties now at 1% level (before: 5% level)

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**Graphical Representation**

- $J_1$, $J_2$, $J_3$ at different angles
- $Z$ boson or $\gamma$ at different angles
- $p_T^{\text{recoil}}$ and $\Delta\phi$
- $\alpha$

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**ATLAS Preliminary**

$\sqrt{s} = 13$ TeV, 36.2 fb$^{-1}$

Trimmed $R = 1.0$ anti-$k_t$ (LCW+JES+JMS)

- $\gamma$+jet
- $Z$+jet
- Statistical component
- Multi-jet

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**ATLAS Experiment** JETM-2018-02

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Searches for new physics with substructure

August 3, 2018
Full in situ jet mass calibration

- Full in situ evaluation of large jet mass calibration and uncertainty
- Preparing the way for the era of precision jet substructure searches
- Fit mass peak using $W$ and top jets in semi-leptonic $t\bar{t}$ events
  - Limited kinematic range due to stats and decay collimation
  - Extend coverage using double-ratio of (calorimeter/track),(data/MC)
- Mass uncertainties now at few-percent level (before: 5% level)
Summary
Summary

- Jet substructure (JSS) is an increasingly important tool
- ATLAS and CMS searches for new physics are using JSS extensively
  - **Dijet resonance searches**: tag the jets to suppress QCD
  - **Mass scan searches**: inherently rely on JSS for the jet mass
  - **Vector like quark searches**: substructure-rich topologies
  - This is just a subset of the searches which use JSS!
- ATLAS and CMS are hard at work improving JSS for the future
  - New jet definitions promise substantial gains to jet tagging
  - Huge improvements from machine learning with deep neural networks
  - Advanced mass-decorrelation taggers should help mass scan searches
  - *In situ* calibrations ready to usher in a new era of precision JSS searches
- JSS is still growing, and there is lots of room for further improvement!
Backup Material
Jet substructure variable definitions

- $D^{\beta=1}_2$: ratio of energy correlation functions,
  $$D^{\beta=1}_2 = \frac{ECF_3 (ECF_1)^3}{(ECF_2)^3}$$

- $ECF_1 = \sum_{i \in \text{constit}} p_T^i$
- $ECF_2 = \sum_{i,j \in \text{constit}} p_T^i p_T^j \Delta R_{ij}$
- $ECF_3 = \sum_{i,j,k \in \text{constit}} p_T^i p_T^j p_T^k \Delta R_{ij} \Delta R_{ik} \Delta R_{jk}$

- $\tau_{21} = \tau_2/\tau_1$ is the “$n$-subjettiness”
  - $\tau_N$ is similar to $ECF_N$, but angles are calculated with respect to $N$ axes
Low-mass di-quark resonances

[Graph showing data and prediction for events per 5 GeV, with observed and expected distributions for different processes.]

Z' mass (GeV)

Local p-value

Data / Prediction

50 100 150 200 250 300

35.9 fb⁻¹ (13 TeV)

Steven Schramm (Université de Genève)

Searches for new physics with substructure

August 3, 2018
Low-mass di-quark resonances

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \)

Jet channel

Data
- W + jets
- Z + jets
- Background est.
- Bkg. stat. uncert.
- Bkg. syst. uncert.

Data - background est.

Events / GeV

0.98
0.99
1
1.01
1.02

ATLAS-1

= 13 TeV, 36.1 fb

Jet channel

SR

Data

Background est.

Z' (160 GeV)

Events / GeV

Low-mass di-quark resonances

Left: EXOT-2017-01

Right: EXOT-2017-01
Multi-class tagging, step 1

\[ P(V) = \log_{10} \left( \frac{D_V^{\text{DNN}}}{0.9 \cdot D_{\text{DNN}}^{\text{background}} + 0.05 \cdot D_t^{\text{DNN}} + 0.05 \cdot D_H^{\text{DNN}}} + 0.05 \cdot D_t^{\text{DNN}} + 0.05 \cdot D_H^{\text{DNN}} \right) \]

\[ P(H) = \log_{10} \left( \frac{D_H^{\text{DNN}}}{0.9 \cdot D_{\text{DNN}}^{\text{background}} + 0.05 \cdot D_V^{\text{DNN}} + 0.05 \cdot D_t^{\text{DNN}}} \right) \]

\[ P(V) = \log_{10} \left( \frac{D_t^{\text{DNN}}}{0.9 \cdot D_{\text{DNN}}^{\text{background}} + 0.05 \cdot D_V^{\text{DNN}} + 0.05 \cdot D_H^{\text{DNN}}} \right) \]

**Graphs:**

- **ATLAS Simulation Preliminary**
  - *\(|\eta| < 2.5\)*
  - *150 < \(p_T\) < 2000 GeV*
  - *m > 40 GeV*

- **Legend:**
  - Red: V-boson jet
  - Green: Higgs-boson jet
  - Blue: Top-quark jet
  - Black: Background jet
Multi-class tagging, step 2

\[ P(V) = \log_{10} \left( \frac{D^V_{DNN}}{0.9 \cdot D^\text{background}_{DNN} + 0.05 \cdot D^t_{DNN} + 0.05 \cdot D^H_{DNN}} \right) \]

\[ P(H) = \log_{10} \left( \frac{D^H_{DNN}}{0.9 \cdot D^\text{background}_{DNN} + 0.05 \cdot D^V_{DNN} + 0.05 \cdot D^t_{DNN}} \right) \]

\[ P(V) = \log_{10} \left( \frac{D^t_{DNN}}{0.9 \cdot D^\text{background}_{DNN} + 0.05 \cdot D^V_{DNN} + 0.05 \cdot D^H_{DNN}} \right) \]