# Search for the Higgs boson in $H \rightarrow bb$ decays with Run-2 data from the ATLAS detector at the LHC

DPG Frühjahrstagung Hamburg

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Ilona Weimer

Supervised by Felix Müller

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$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

# Motivation

- The Higgs boson with $m_H$ = 125 GeV was discovered in 2012 with the experiments ATLAS and CMS at the Large Hadron Collider at CERN.
- Decay **H → bb** has the highest branching ratio, but could not be observed yet.

  → Significance from **Run-1** (ttH, WH, ZH productions combined)

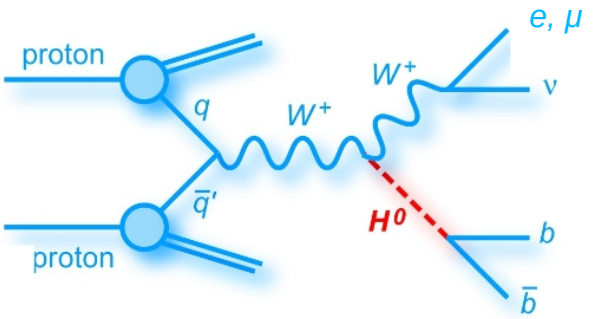
  ATLAS: 1.7, CMS: 2.0, combined: 2.6
- The main challenge is the **high background**.

In this study:

- Optimizing the analysis with Run-2 data in **WH, H → bb channel** using topologies with two nearby b-quarks within one large size jet

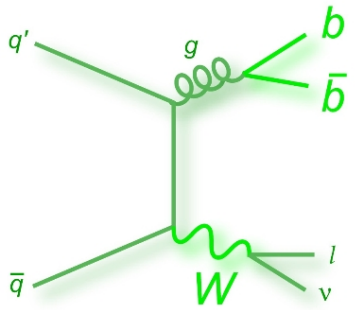
# WH, H → bb: signal and backgrounds

**signal**: associated production in 1 lepton channel



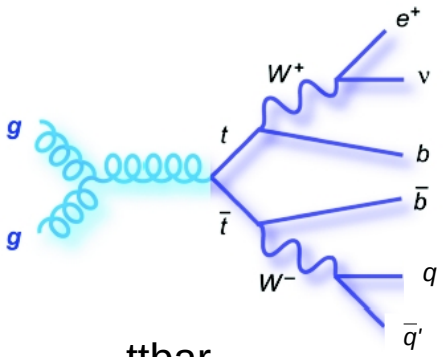

**dominant backgrounds**:

**irreducible:**

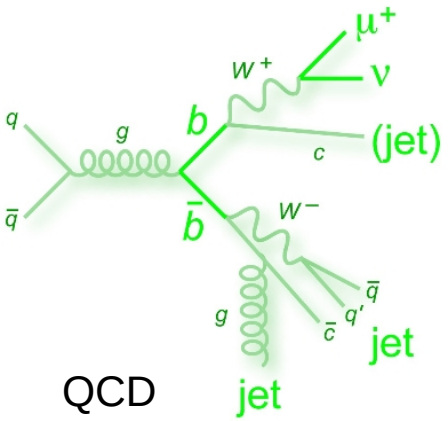



W+jets

**reducible:**




ttbar



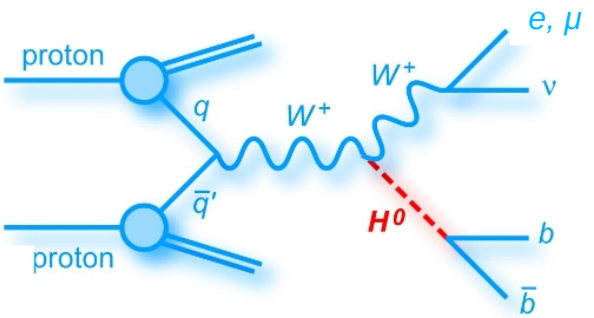

QCD jet

# Event Selection

**Selection of 1-lepton events**

**QCD suppression**

**Selection of H → bb decays**




$p_T(H) \approx p_T(W)$

C1: Single lepton trigger, exactly one lepton

C2: Missing transverse energy > 30 GeV

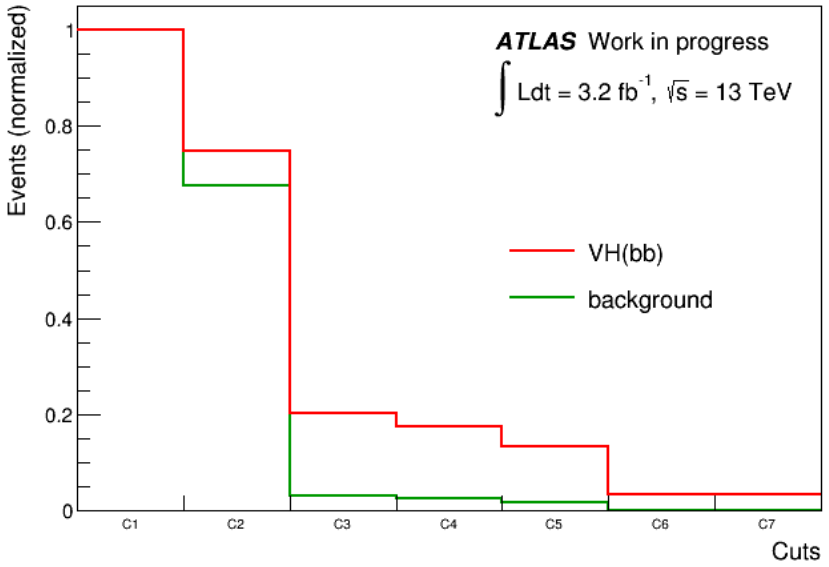
C3: W transverse momentum > 120 GeV

C4: At least two jets

C5: Exactly two b-tagged jets

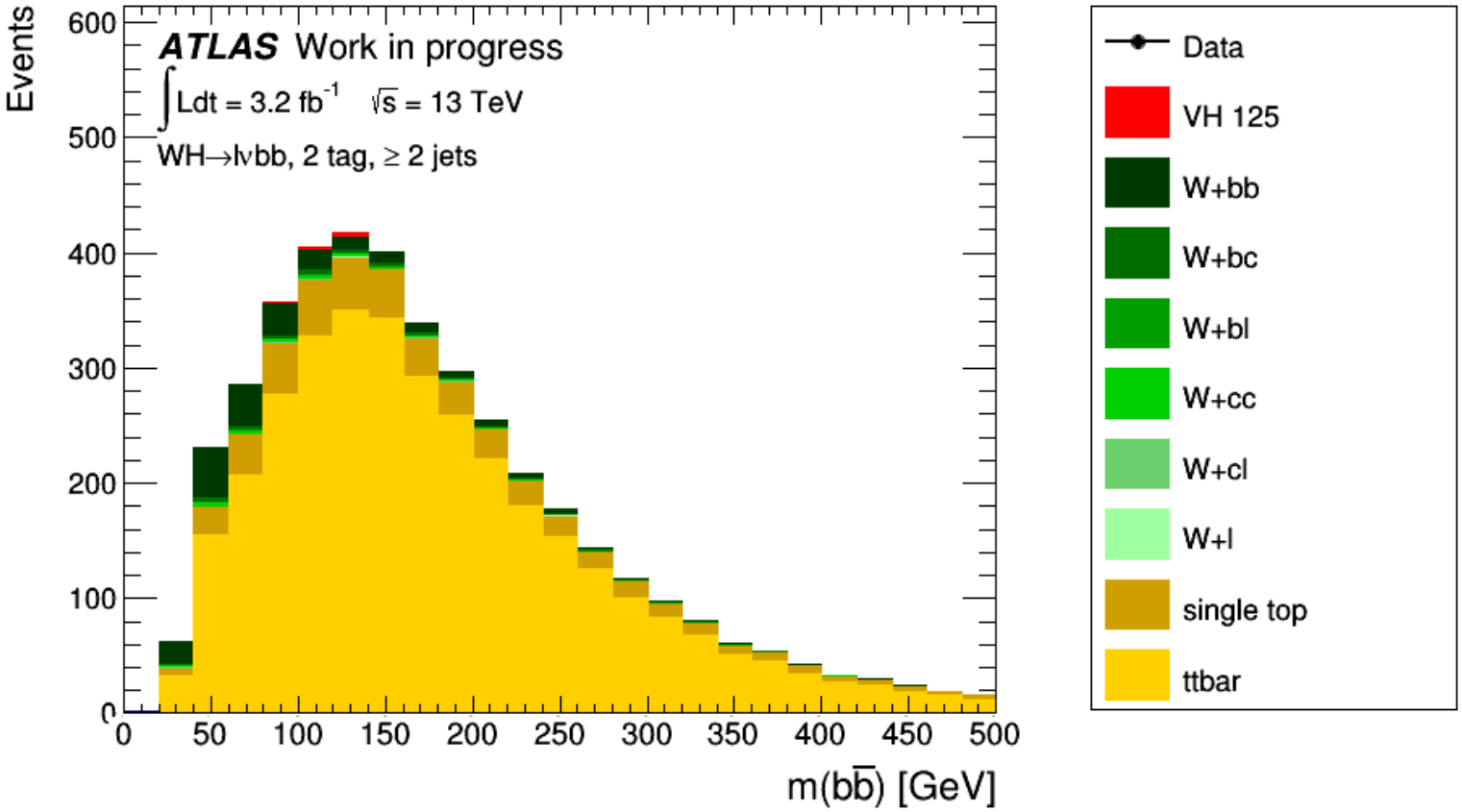
C6: |minΔφ(MET,j1,j2,j3)| > 1

C7: 95 < m(bb) [GeV] < 140 for signal region

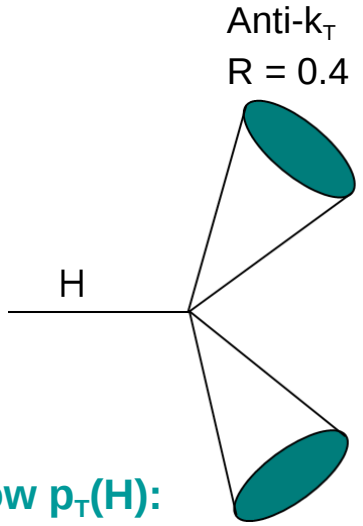



| | N(signal) | N(background) | **Significance** $Z=\sqrt{2\cdot((s+b)\cdot\ln\left(1+\frac{s}{b}\right)-s)}$ |
|---|---|---|---|
| $p_T(W) > 250$ GeV | 1.512 | 28.394 | **0.281** |
| $p_T(W) < 250$ GeV | 6.625 | 784.0 | **0.236** |

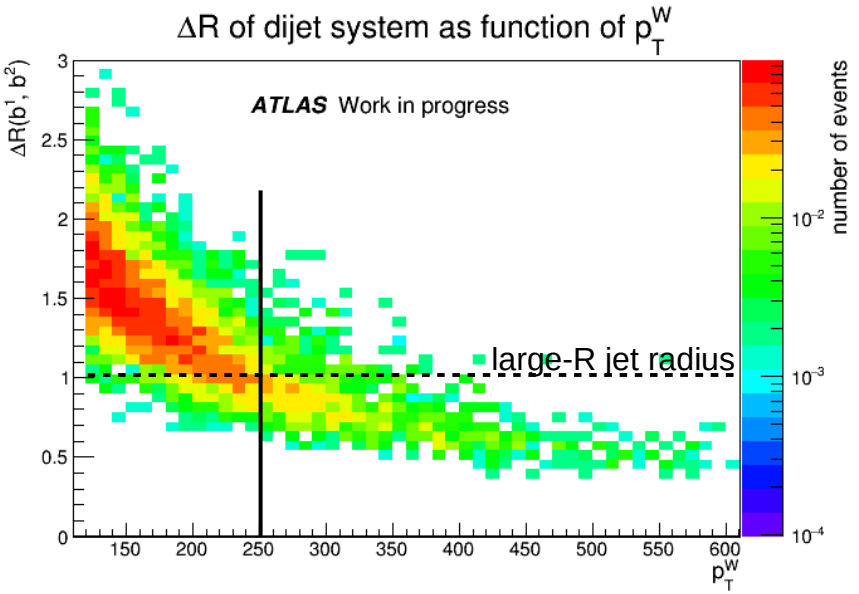
# Invariant mass of the b-jet system

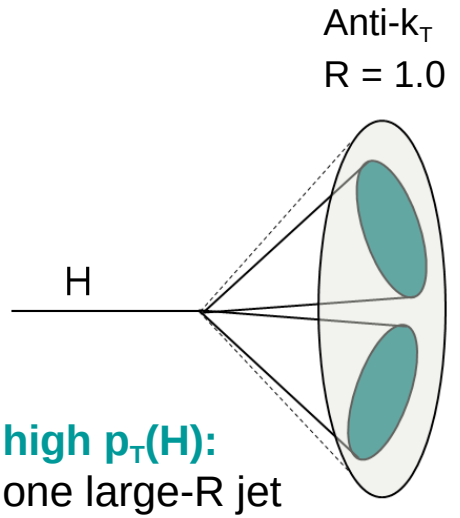


# Events with Higgs jet candidates




**low $p_T$(H):**
two small b-jets




**high $p_T$(H):**
one large-R jet

- The b-jets start to merge for a Higgs boson with $p_T(H) > 250$ GeV
- The decay products form one large size jet

**Selection of large-R jets (J) containing two b-jets (b1, b2): "Higgs jet" candidates**

- $\Delta R(J, b1) < 1.$ and $\Delta R(J, b2) < 1.$
- For $p_T(W) < 250$ GeV → 1.5 % of events contain Higgs jets
- For $p_T(W) > 250$ GeV → 59.0 % of events contain Higgs jets

# Expected number of events

***ATLAS*** Work in progress, Integrated luminosity = 3.2 $fb^{-1}$, $p_T(W) > 250$ GeV

| | N(signal) | N(bkg) | **Z** |
|---|---|---|---|
| Standard selection | 1.512 | 28.394 | **0.281** |
| With Higgs jet | 1.170 | 16.46 | **0.285** |
| Without Higgs jet | 0.342 | 11.93 | **0.098** |
| Combined | | | **0.301** |

→ Improvement of significance for events with Higgs jets

→ Overall significance improvement by 7 %

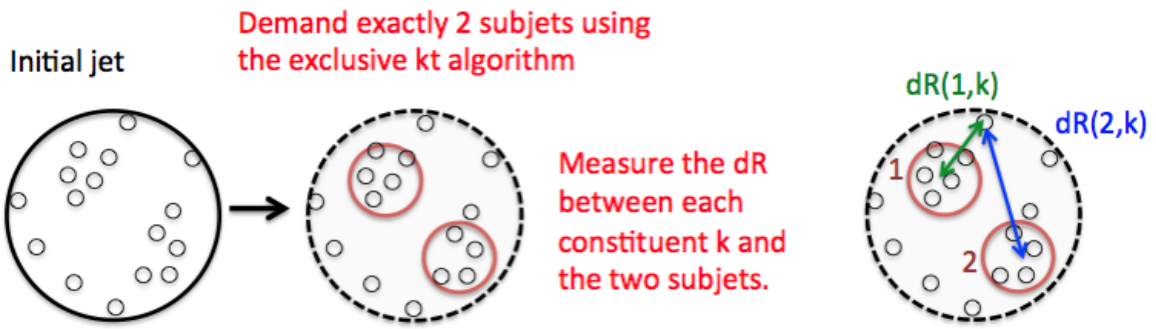
→ Substructure within the Higgs jet candidates can further improve the discrimination between signal and background

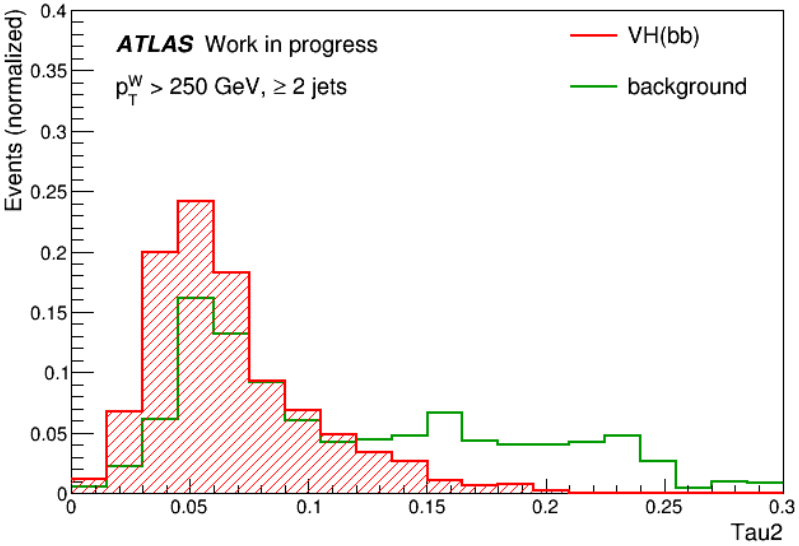
# Jet substructure: N-subjettiness

**N-subjettiness** $\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \, min\left(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\right)$ where $d_0 \equiv \sum_k p_{T,k} \cdot R$

- a measure for the probability that a large-R jet is composed of exactly N subjets
- uses the angles between the jet constituents
- N = number of subjet candidates, k runs over all constituents of jet J
- $\tau_N \rightarrow 0$: all radiation aligned with candidate subjets → N or fewer subjets
- $\tau_N >> 0$: more than N subjets

Example: $\tau_2$




**τ ratios** $\tau_N / \tau_{N-1}$ give the best results

# Jet substructure: Energy correlation functions

**1-point, 2-point and 3-point energy-correlation functions:**

$$E_{CF1} = \sum_{i \in J} p_{T,i},$$

$$E_{CF2}(\beta) = \sum_{i<j \in J} p_{T,i}\, p_{T,j} (\Delta R_{ij})^{\beta},$$

$$E_{CF3}(\beta) = \sum_{i<j<k \in J} p_{T,i}\, p_{T,j}\, p_{T,k} (\Delta R_{ij}\, \Delta R_{ik}\, \Delta R_{jk})^{\beta}$$

- identification of a substructure of N particles (similar to $\tau_N$)
- $E_{CF}(N+1) \rightarrow 0$ if there are N particles
- Dimensionless $E_{CF}$ ratios: $C_2$, $D_2$

$$e_2^{(\beta)} = \frac{E_{CF2}(\beta)}{E_{CF1}(\beta)^2} \qquad e_3^{(\beta)} = \frac{E_{CF3}(\beta)}{E_{CF1}(\beta)^3}$$

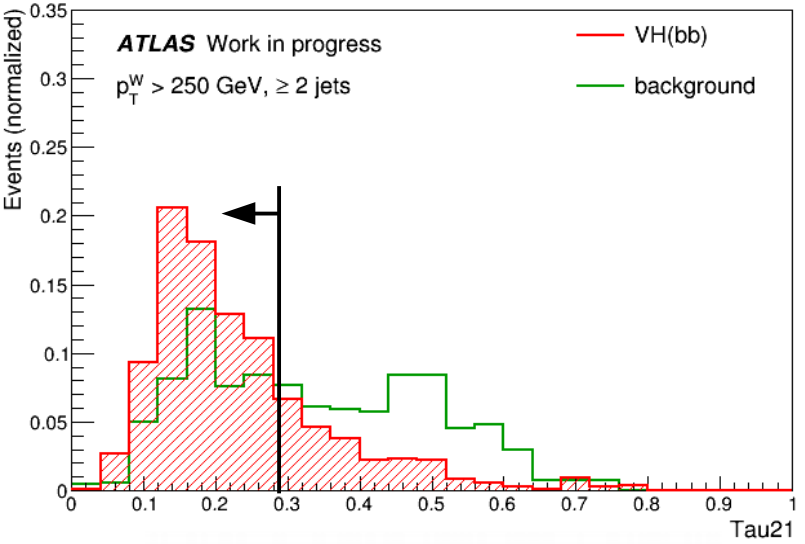
$$\Rightarrow \quad C_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^2} \qquad D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

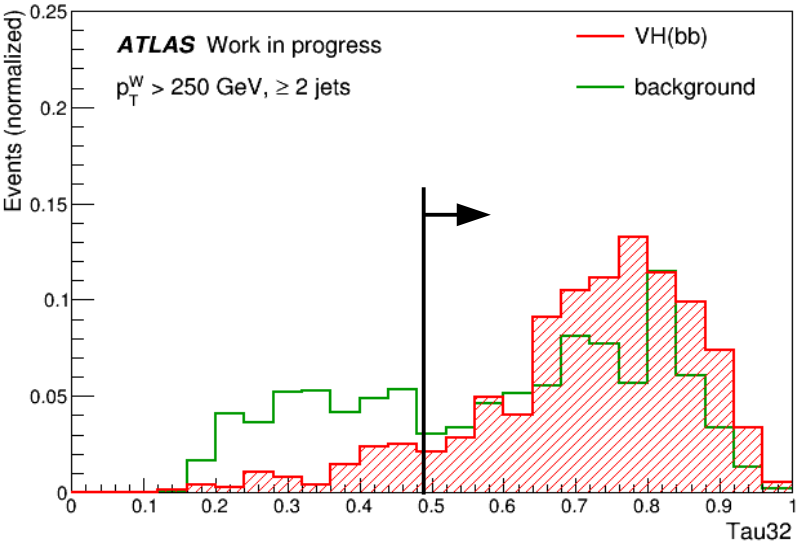
# N-subjettiness discriminants

Optimal cut values chosen such that signal significance is maximized

**Integrated luminosity = 3.2 fb$^{-1}$**

| ***ATLAS*** Work in progress | $p_T(W) > 250$ GeV, events with Higgs jet candidate | | |
|---|---|---|---|
| | N(signal) | N(bkg) | **Z** |
| Without substructure cut | 1.170 | 16.46 | **0.285** |
| Tau21 cut at 0.295 | 0.927 | 7.528 | **0.331** |
| Tau32 cut at 0.495 | 1.055 | 10.95 | **0.314** |

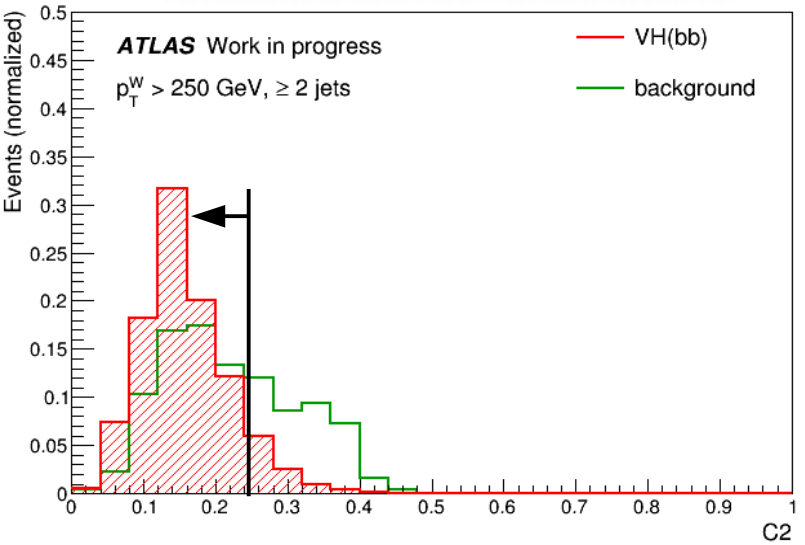


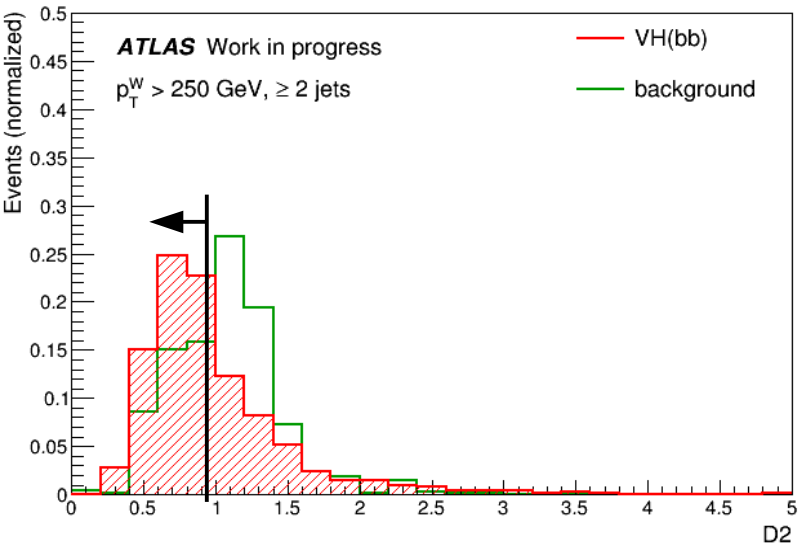



# Energy correlation variables

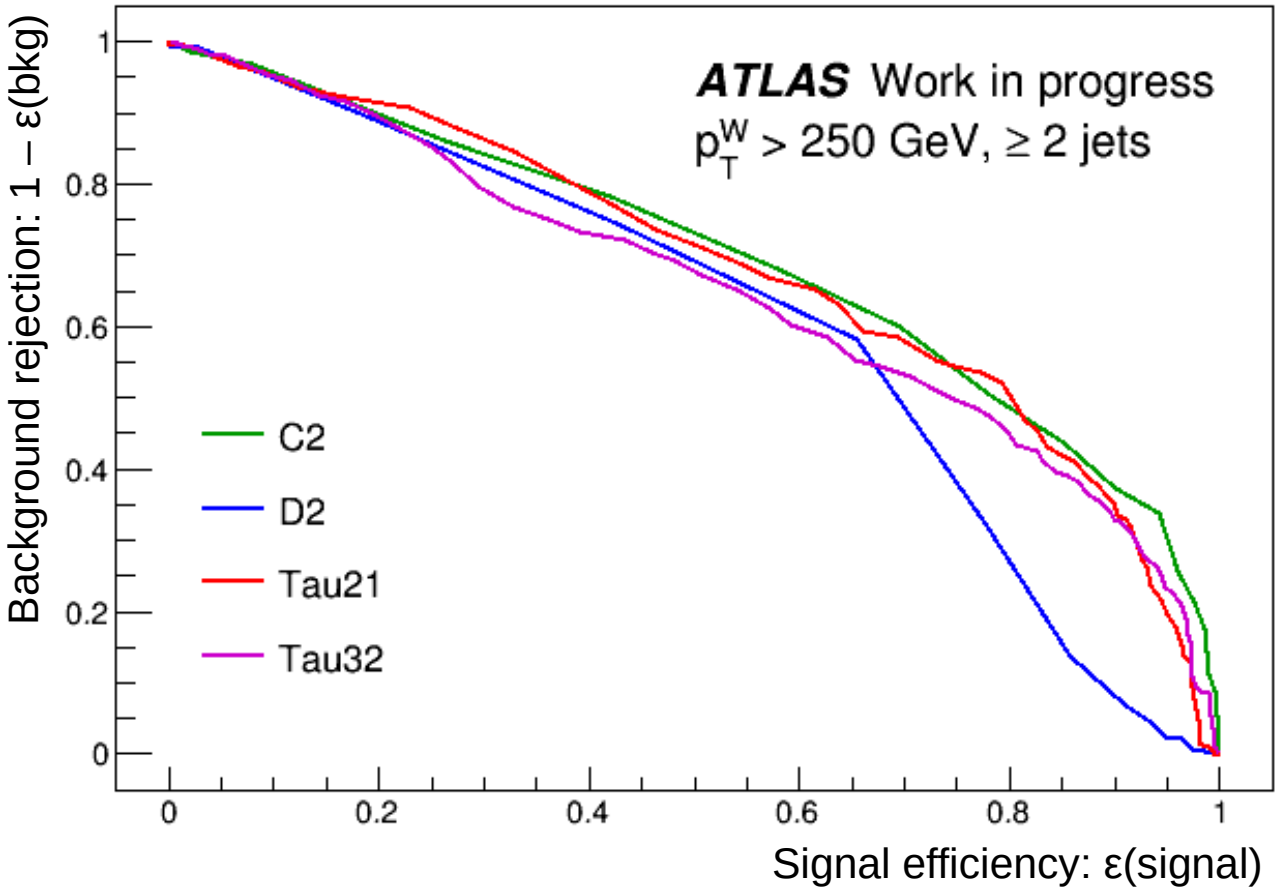
**Integrated luminosity = 3.2 fb$^{-1}$**

| ***ATLAS*** Work in progress | $p_T(W) > 250$ GeV, events with Higgs jet candidate | | |
|---|---|---|---|
| | N(signal) | N(bkg) | **Z** |
| Without substructure cut | 1.170 | 16.46 | **0.285** |
| C2 cut at 0.25 | 1.102 | 10.65 | **0.332** |
| D2 cut at 0.9 | 0.765 | 6.61 | **0.292** |



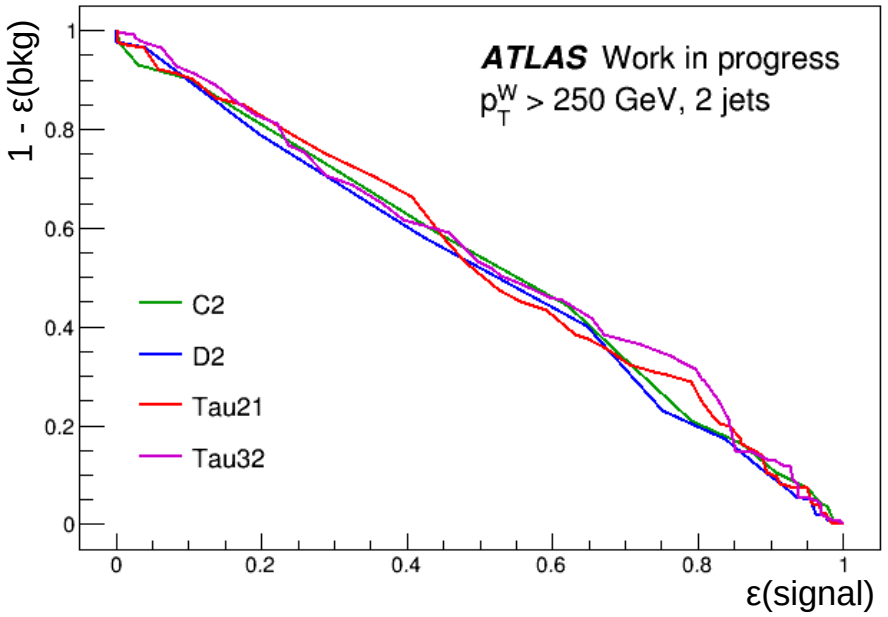



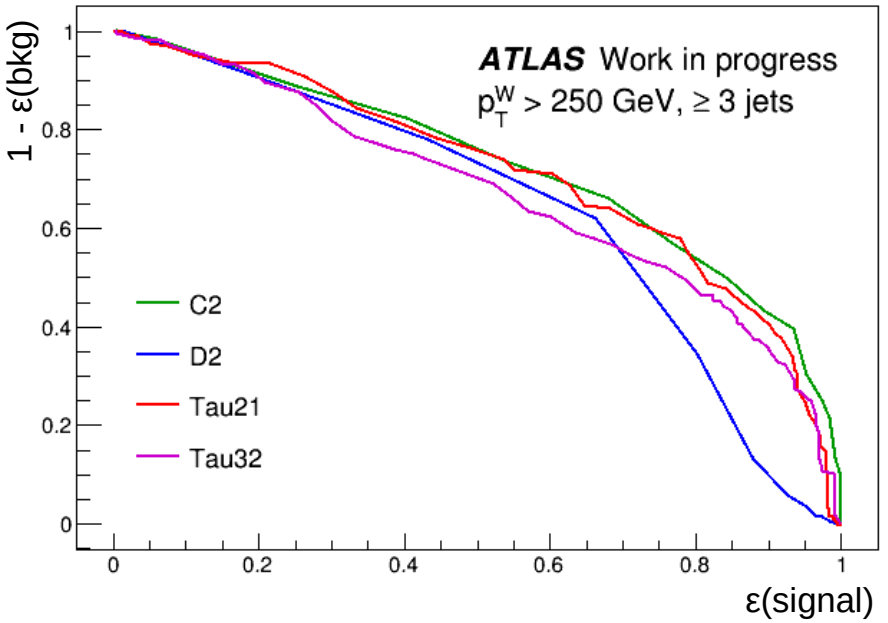
# Comparison of substructure discriminants




In the region with high signal efficiency, the best discrimination comes from the C2 variable.

# Comparison of substructure discriminants




Events with exactly 2 jets:

almost no discrimination power

**Main improvement from events with ≥ 3 jets**

# Summary and outlook

- An **optimization** of the analysis WH, H → bb has been shown.
- **Jet substructure information** can be used to **increase the significance**

  → Largest improvements for events with Higgs-jet candidates:

  C2 (16.5 %), Tau21 (16.1 %)

  → Overall improvement for $p_T$(W) > 250 GeV: **C2 (15.0 %), Tau21 (14.7 %)**
- Other substructure variables to be tested
- Eventually combining different substructure variables in a multivariate method

# Backup slides

# Event Selection

C0: All events (CxAOD)

C1: Pass trigger && trigger matching

Electron : HLT_e24_lhmedium_L1EM20VH (L1_EM18VH for MC) OR HLT_e60_lhmedium1 OR HLT_e120_lhloose

Muon : HLT_mu20_iloose_L1MU15 OR HLT_mu50

C2: N(VHLooseElectrons)+N(WHLooseMuons) = 1 && N(WHSignalElectrons)+N(WHSignalMuons) = 1

C3: MET > 30 GeV

C4: mT(W) > 20 GeV

C5: pT(W) > 120 GeV

C6: N(signal jets)+N(forward jets) ≥ 2

C7: N(signal jets) ≥ 2

C8: |min$\Delta\varphi$(MET,j1,j2,j3)| > 1 - j1,j2: leading signal jets, j3: 3rd leading signal jet or leading forward jet if 3rd signal jet does not exist

C9: pT(leading b-jet) > 45 GeV

C10: 95 < m(bb) [GeV] < 140 with after correction (use 2 leading b-jets if available)

C11: pT(W) < 500 GeV

# Substructure variables

- N-subjettiness: Tau1, Tau2, Tau3, Tau1_wta, Tau2_wta, Tau3, Tau3_wta
- N-subjettiness ratios: Tau21, Tau32, Tau21_wta, Tau32_wta
- kT splitting scale: Split12, Split23, Split34
- Z-Cut: ZCut12, ZCut23, ZCut34
- Dipolarity: Dip12, Dip13, Dip23, DipExcl12
- Angularity, Sphericity, Apolarity
- kT Delta R: KtDR
- kT Mass drop: Mu12
- PlanarFlow
- Energy correlations: ECF1, ECF2, ECF3
- ECF ratios: C2, D2
- Thrust: ThrustMin, ThrustMaj
- FoxWolfram: FoxWolfram0, FoxWolfram1, FoxWolfram2, FoxWolfram3, FoxWolfram4

  [ https://twiki.cern.ch/twiki/bin/view/AtlasProtected/JetSubstructureTools ]