Search for the Higgs boson in H→bb decays with Run-2 data from the ATLAS detector at the LHC

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Motivation

- The Higgs boson with mH = 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.

  → Important test for the standard model
- Significance from Run-1 (ttH, WH, ZH productions combined)

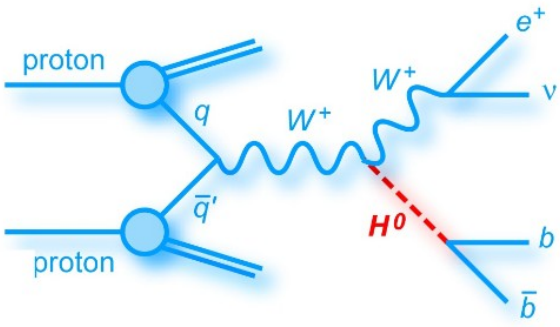
  → ATLAS: 1.7, CMS: 2.0, combined: 2.6
- The main problem is the high background.

In this analysis:

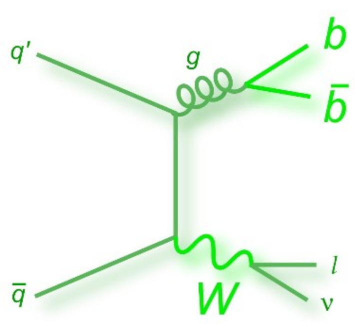
- There are many jet substructure methods developed recently.
- These are used in order to improve the background to signal ratio.

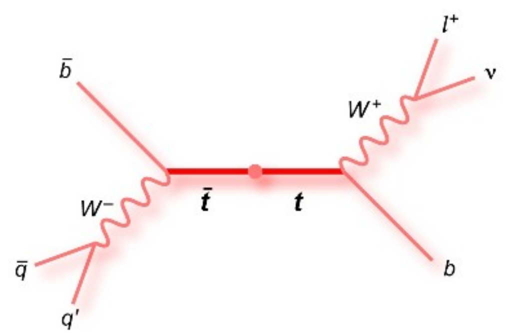
Introduction to WHbb

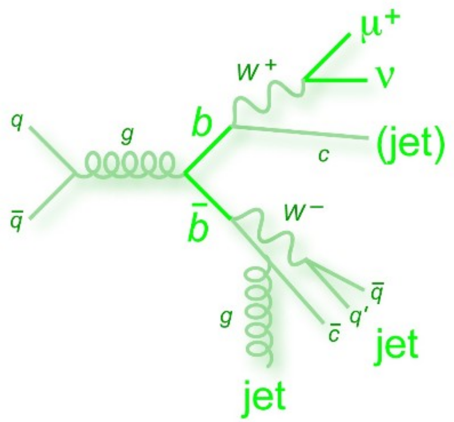
signal: associated production in 1 lepton channel



important backgrounds: W+jets, ttbar, QCD







The Higgs particle is produced with a high transverse momentum compared to the b-jets from the background

→ If it is produced boosted, the two b-jets form a single jet like final state (large-R jet)

→ Improve event selection by looking at the substructure of this large-R jet

Event Selection

	VH(bb)	ttbar	W+b
• All events (CxAOD)	287.87	465152.22	1481855.81
• Trigger	251.63	401576.78	1314265.68
• One lepton (electron or muon)	251.63	401576.78	1314265.68
• Missing transverse energy > 30 GeV	172.46	329984.85	927308.26
• W transverse momentum pT(W) > 120 GeV	51.20	91104.60	42202.76
• At least two jets	45.29	89879.88	35267.98
• Two b-tagged jets	11.70	6497.06	383.52
• $\|\min\Delta\varphi(MET,j1,j2,j3)\| > 1$	9.82	3597.15	270.26
• pT(leading b-jet) > 45 GeV	9.81	3558.40	261.08
• 95 < m(bb) [GeV] < 140 for signal region	8.17	777.05	44.51

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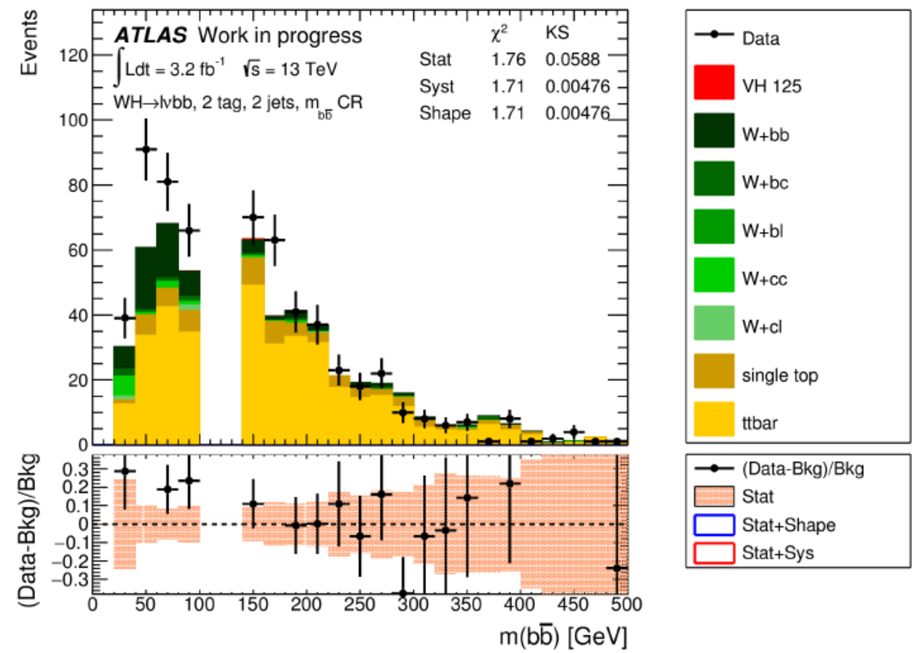
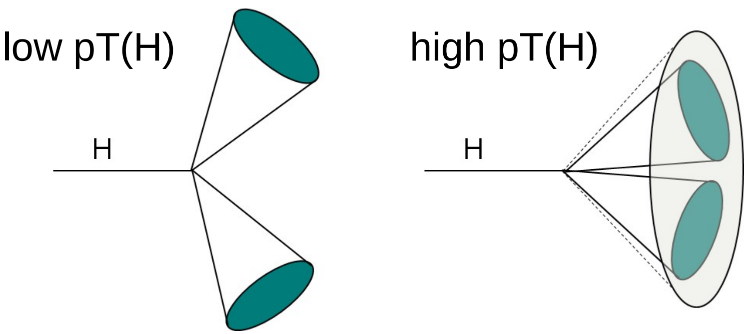
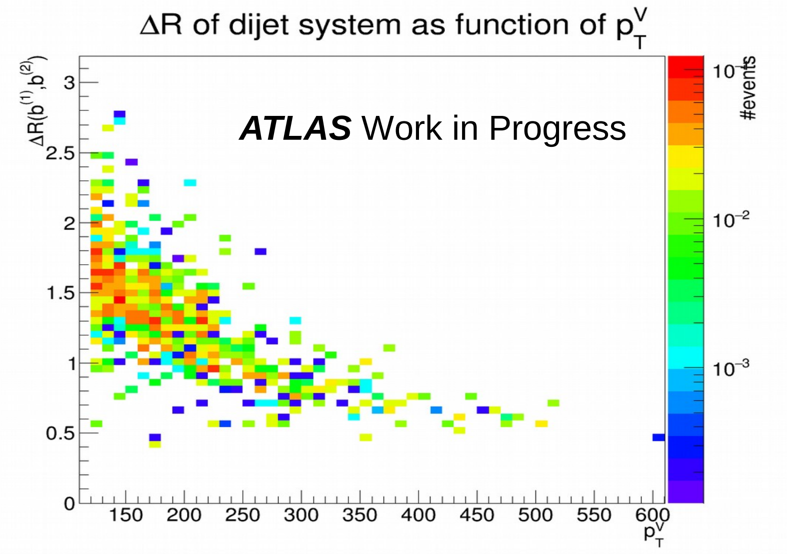


m(bb) after all cuts

Large-R jets and substructure

The b-jets are closer to each other for a boosted Higgs boson





The decay products are then located in one big jet

- The final state contains a large-R jet, which is not uniform inside (substructure)
- large-R jets are more likely for high pT(H)
- Studying events where both b-tagged jets are inside the large-R jet

  (ΔR(large-R jet, b-jet 1) and ΔR(large-R jet, b-jet 2) > 1.)

Substructure of the large-R jet:

- There are many substructure variables available.
- Cuts on these variables can be used to distinguish signal from background.
- The most promising candidates are the N-subjettiness and energy correlation functions:

  They use the angles between the jet-constituents.

Expected number of events

2 jets, Integrated luminosity = 3.2 fb^-1	pT(W) < 200 GeV			200 GeV < pT(W) < 250 GeV			pT(W) > 250 GeV		
	N(WH)	N(bkg)	Z	N(WH)	N(bkg)	Z	N(WH)	N(bkg)	Z
Standard selection (see slide 3)	2.9713	145.79	0.2453	0.7404	9.2641	0.2401	0.7247	4.2350	0.3428
Large-R matching to 2 b-jets	0.0096	0.1881	0.0218	0.1560	1.3253	0.1330	0.5846	3.9448	0.2875
Large-R unmatched	2.9618	145.62	0.2446	0.5844	7.9388	0.2049	0.1401	0.2902	0.2425
Combined			0.2456			0.2443			0.3761

significance $Z = \sqrt{2 \cdot \left((s+b) \cdot \ln\left(1 + \frac{s}{b}\right) - s \right)}$

Substructure variables

N-subjettiness $\tau_N = \frac{1}{d_0} \sum_k p_{T,k} min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k})$ 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
- N = number of subjet candidates, k runs over all constituents of jet J
- tauN $\rightarrow$ 0 if the jet consists of N subjets, tauN >> 0 for more than N subjets
- tau ratios τ_N / τ_{N-1} give the best results

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

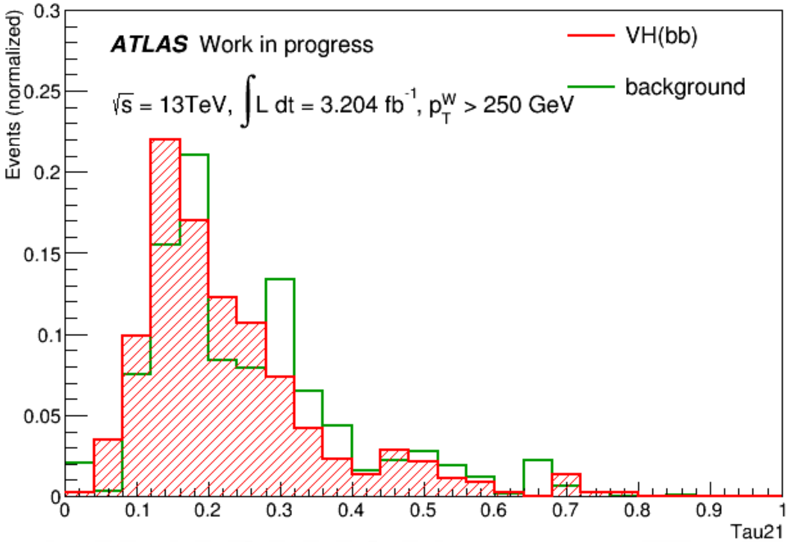
$$E_{CF1} = \sum_{i \in J} p_{T,i},$$
$$E_{CF2}(\beta) = \sum_{i<j \in J} p_{T,i} p_{T,j} (\Delta R_{ij})^{\beta},$$
$$E_{CF3}(\beta) = \sum_{i<j<k \in J} p_{T,i} p_{T,j} p_{T,k} (\Delta R_{ij} \Delta R_{ik} \Delta R_{jk})^{\beta}$$

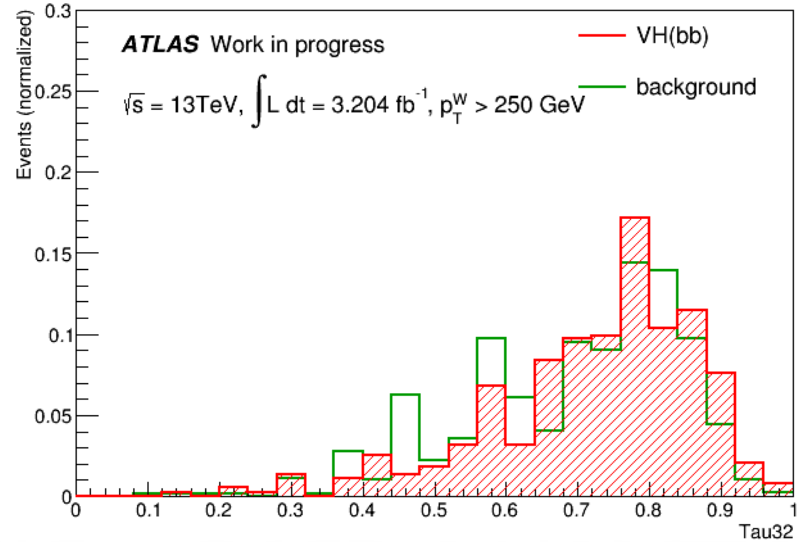
- identification of a substructure of N particles (similar to tauN)
- ECF(N+1) $\rightarrow$ 0 if there are N particles
- ECF ratios: C2, D2

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

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

N-subjettiness variables





Optimal cut values chosen such to maximize the signal significance.

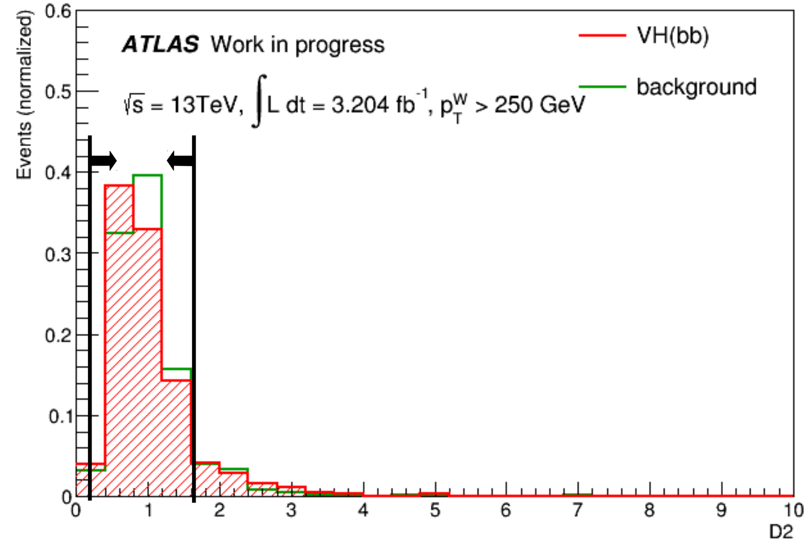
Cuts on the N-subjettiness variables did not improve the significance

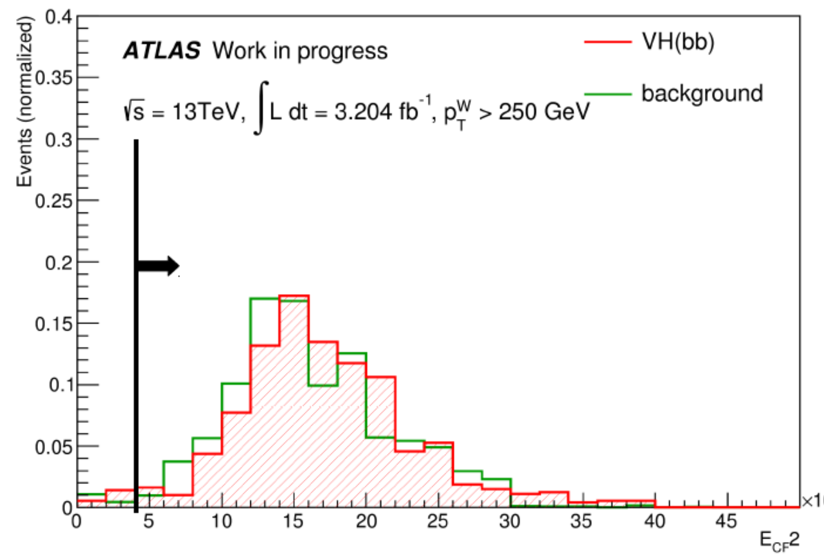
Energy Correlation Variables

Without cuts:
→ WH = 2.297 events, bkg. = 14.397 events,
Significance = 0.59

D2: two cuts at 0.2 and 1.6 (taking only the events inside this window)
→ WH = 1.592 ev., bkg. = 5.349 ev., signif. = 0.66

ECF2: one cut at 4
→ WH = 1.770 ev., bkg. = 6.588 ev., signif. = 0.66

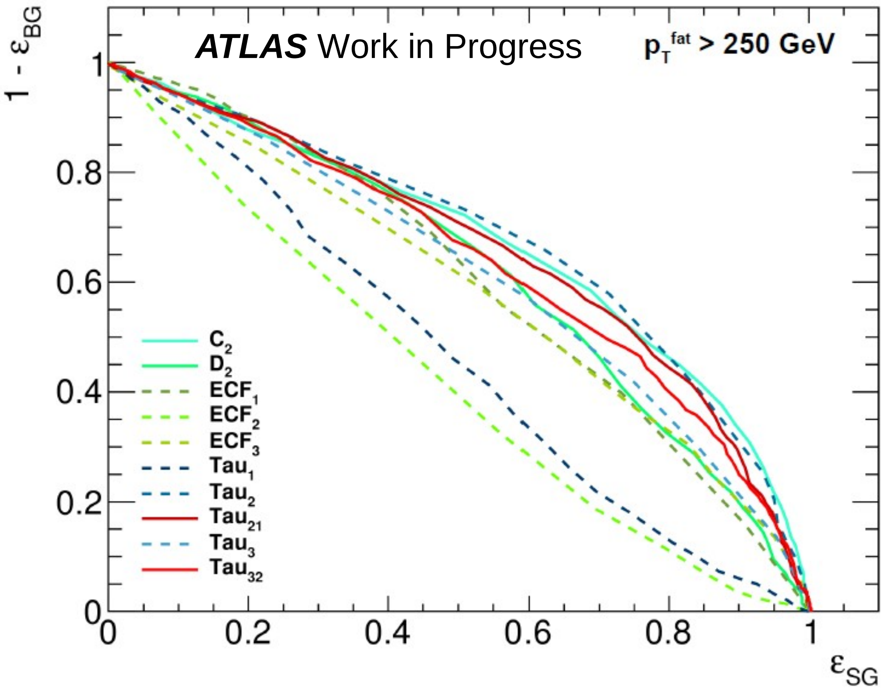




Comparison of substructure discriminants

A ROC curve (= receiver operating characteristic) is very useful to find out which variables can suppress a lot of background without loosing too much signal.

2 jets, Integrated luminosity = 3.2 fb^-1	pT(W) > 250 GeV		
	N(WH)	N(bkg)	Z
Without substructure cut	2.297	14.397	0.59
D2 cuts at 0.2 and 1.6	1.592	5.349	0.66
ECF2 cut at 4	1.770	6.588	0.66



Summary and outlook

- Cuts on substructure variables are useful in order to increase the significance

  → best results for D2, ECF2

  → cuts on the other variables did not improve the results

- Problem: statistics are very small
- There are many other substructure variables which could also improve the results
- Combining different substructure variables in a multivariate method would be another interesting approach

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: |minΔφ(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]