Measurement of vector boson associated Higgs production in $H \to b\bar{b}/c\bar{c}$ decay

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Introduction

What are we looking for?

- H produced associated with W/Z boson (VH mode)
- $H \to b\bar{b}/c\bar{c}$, V decays leptonically (except τ)

Why $H \to b\bar{b}/c\bar{c}$?

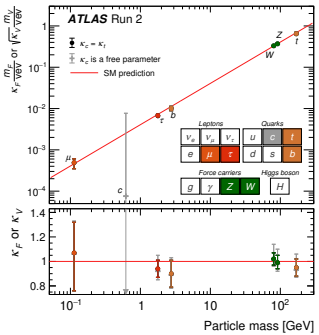
- $H \to b\bar{b}$ is dominant decay
- $H \to c\bar{c}$ is promising 2nd gen. fermion decay mode
- direct study of H-q couplings, hints to new physics

Why VH?

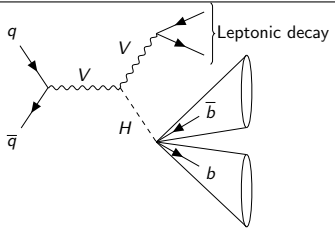
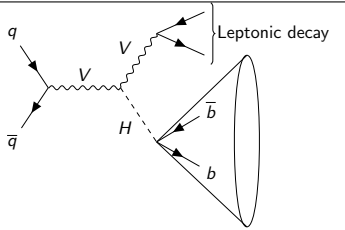
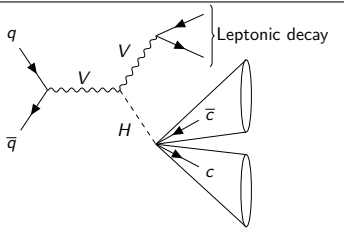
- most sensitive to $H \to b\bar{b}/c\bar{c}$ $\therefore$
  - relatively less background
  - effective lepton trigger
- can probe high transverse momentum (p_T) regime, low p_T suffers from higher bkg

Event selections	
Jets	≥ 2 signal jets
H candidate jet tag	2 b-tags for $VH(\to b\bar{b})$
	≥ 1 tight c-tag for $VH(\to c\bar{c})$
Leading H candidate jet	$p_T > 45$ GeV
Sub-leading H candidate jet	$p_T > 20$ GeV
Non-H candidate jet	$p_T > 30$ GeV
m_{bb} or m_{cc}	> 50 GeV

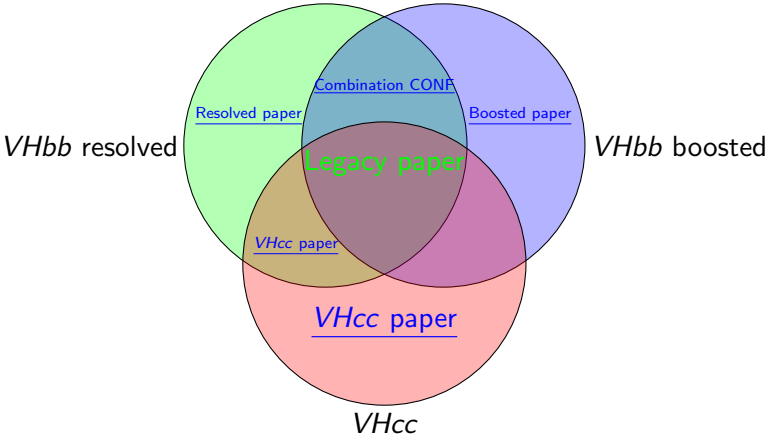
with additional channel specific cuts (see back up)



Introduction

VHbb		*VHcc*
Resolved $75\text{GeV} < p_T^V < 400\text{GeV}$	Boosted $p_T^V > 400\text{GeV}$	Resolved $p_T^V > 75\text{GeV}$
		
$Z \to \nu\nu$ (0-lepton), $W \to \ell\nu$ (1-lepton), $Z \to \ell\ell$ (2-lepton)		

Introduction

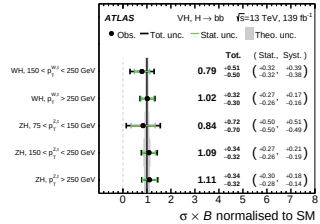


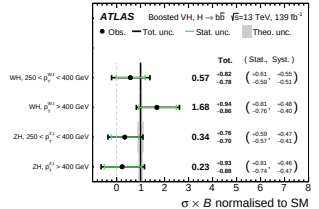
This analysis (Legacy paper) combines 3 topologies for the 1st time w/ improved analysis strategies using full run 2 data

Introduction

Deliverables

- *VHbb* standalone
  - Signal strength $\mu = \frac{\text{Rate}_{\text{obs.}}}{\text{Rate}_{\text{SM}}}$ for $VH(\rightarrow b\bar{b})$
  - Differential xsec in more bins
  - EFT interpretation
- *VHcc* standalone
  - Upper limit of $VH(\rightarrow c\bar{c})$ μ
  - H coupling with c quark
- $VH(bb/cc)$ combined
  - Ratio between H couplings
  - Hint to new physics





Observation compatible with SM in $VH(\rightarrow b\bar{b})$
Upper limit of 26× for $VH(\rightarrow c\bar{c})$ at 95% CL

Introduction

My work in the past year:

- Boost decision tree (BDT) training $\leftarrow$ focus of this talk
- Implementing c-jet veto
- Likelihood fit
- Study systematics in likelihood fit
- Presentation on behalf of the analysis group in several occasions

BDT training in $VH(\rightarrow b\bar{b}/c\bar{c})$

In previous analyses:

- Only $VH(\rightarrow b\bar{b})$ resolved used MVA as final discriminant
- $VH(\rightarrow b\bar{b})$ boosted & $VH(\rightarrow c\bar{c})$ used di-jet mass

Strategy now:

- All 3 topologies use BDT

$\Rightarrow$ Need to find optimal variables for each training region

BDT training in $VH(\rightarrow b\bar{b}/c\bar{c})$

Optimising training variable sets

- Use fewest variables as possible
  - only include those give significant improvement
  - 'bundle' up variables
    e.g. use sum of add. jet p_T instead of $p_T^{j_3}$, $p_T^{j_4}$ etc separately
- Keep the overall scheme simple
  share variable sets between regions if possible

BDT training in $VH(\rightarrow b\bar{b}/c\bar{c})$

Table on the right shows final training variable sets

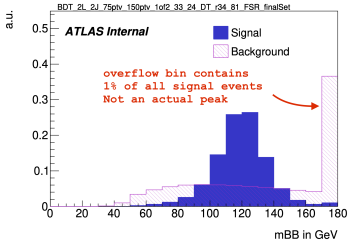
- $VH(\rightarrow c\bar{c})$ & $VH(\rightarrow b\bar{b})$ resolved share the same sets (Topology 'R')
- $VH(\rightarrow b\bar{b})$ boosted has its sets (Topology 'B')
- No separate list for individual # of jet final state

		$VH, H \rightarrow b\bar{b}/c\bar{c}$ Resolved			$VH, H \rightarrow b\bar{b}$ Boosted		
Name	Topology	0-lepton	1-lepton	2-lepton	0-lepton	1-lepton	2-lepton
mBB	R	×	×	×			
mJ	B				×	×	×
mBBJ also in 2J	R	×	×	×			
pTB1	R	×	×	×			
pTBTrkJ1	B				×	×	×
pTB2	R	×	×	×			
pTBTrkJ2	B				×	×	×
pTBTrkJ3	B				×	×	×
sumPtAddJets	R	×	×	×			
dRBB	R	×	×	×			
deltaRbTrkJbTrkJ	B				×	×	×
dEtaBB	R	×					
bin_btagB1	R	×	×	×			
bin_bTagBTrkJ1	B				×	×	×
bin_btagB2	R	×	×	×			
bin_bTagBTrkJ2	B				×	×	×
pTV	R & B	$\equiv E_T^{miss}$	×	×	$\equiv E_T^{miss}$	×	×
MET	R & B	×	×		×	×	
METSig	R			×			
dYVBB/deltaYVJ	R & B		×	×		×	×
dPhiVBB/absdeltaPhiVJ	R & B	×	×	×	×	×	×
dPhiLBmin	R		×				
MEff	R	×					
mTW	R		×				
Mtop	R		×				
mLL	R			×			
cosThetaLep	R & B			×			×
lepPtBalance	B					×	
pTL	B					×	
NAdditionalCaloJets	B				×	×	×
NMatchedTrackJetLeadFatJet	B				×	×	×
Colour	B				×	×	×
minDRBjets	R	×	×				

MVA training in $VH(\rightarrow b\bar{b}/c\bar{c})$

Current status:

- All training setup finalised
- Final round of training coming up using latest Monte-Carlo sample
- Use final training results in likelihood fit



m_{bb} (top) & MVA score (bottom) distribution of signal (blue) & background (red)

Future prospect

- Analysis at final stage
  - Finalising systematic uncertainty scheme
  - Validating likelihood fit
- Paper should be out this summer
- Start to write my thesis

Thank you

Backup

Event selection

	$VH(\to b\bar{b})$ resolved & $VH(\to c\bar{c})$		
	0-lep	1-lep	2-lep
Jets	≥ 2 signal jets		
Candidate jets tag	2 b-tags for $VH(\to b\bar{b})$; ≥ 1 tight c-tag for $VH(\to c\bar{c})$		
Leading H candidate jet p_T	> 45 GeV		
Sub-leading H candidate jet p_T	> 20 GeV		
Non-H candidate jet p_T	> 30 GeV		
m_{bb} or m_{cc}	> 50 GeV		
Trigger	E_T^{miss} triggers	E_T^{miss} triggers + e channel: single electron trigger μ channel: single muon trigger ($p_T^V < 150$ GeV)	As for 1-lep but p_T^V limit for μ is 250 GeV
Jets	≤ 3 jets		-
Additional jets tagging	no tight c-tag for $VH(\to b\bar{b})$ no b-tag in $VH(\to c\bar{c})$	no tight c-tag for $VH(\to b\bar{b})$ no b-tag in $VH(\to c\bar{c})$	no b-tag in $VH(\to c\bar{c})$
Lepton	0 VH-loose lepton	1 WH-signal lepton >1 VH-loose lepton veto	2 VH-loose leptons $\geq$1 ZH-signal lepton Same flavour, opposite-charge for $\mu\mu$
E_T^{miss} $E_{T,trk}^{\text{miss}}$	>150 GeV > 30 GeV (only for $VH(\to c\bar{c})$)	>30 GeV (e channel) -	-
S_T	$> 120(150)$ GeV for 2(3) jets	-	-
$\lvert \min(\Delta\phi(E_T^{\text{miss}}, jet)) \rvert$	$> 20°(30°)$ for 2(3) jets	-	-
$\lvert \Delta\phi(E_T^{\text{miss}}, H) \rvert$	$> 120°$	-	-
$\lvert \Delta\phi(\text{jet 1, jet 2}) \rvert$	$< 140°$	-	-
m_T^W	-	< 120 GeV (for $VH(\to c\bar{c})$ only) > 20 GeV (for $p_T^V \in [75, 150]$ GeV only)	-
$m_{\ell\ell}$	-	-	$m_{\ell\ell} \in [81, 101]$ GeV
p_T^V regions	[150, 250] GeV, [250, 400] GeV for $VH(\to b\bar{b})$ (> 250 GeV for $VH(\to c\bar{c})$)	[75, 150] GeV, [150, 250] GeV, [250, 400] GeV for $VH(\to b\bar{b})$ (> 250 GeV for $VH(\to c\bar{c})$)	[75, 150] GeV, [150, 250] GeV, [250, 400] GeV for $VH(\to b\bar{b})$ (> 250 GeV for $VH(\to c\bar{c})$)

Event selection

	$VH(\to b\bar{b})$ boosted				
	0-lep	1-lep		2-lep	
		e sub-channel	μ sub-channel	e sub-channel	μ sub-channel
Trigger	E_T^{miss}	Single lepton	E_T^{miss}	Single lepton	E_T^{miss}
Leptons	0 VH-loose lepton	1 WH-signal lepton no second VH-loose lepton		≥ 1 ZH-signal lepton 2 VH-loose leptons	
E_T^{miss}	> 250 GeV	> 50 GeV	-	-	
p_T^V	$p_T^V > 400$ GeV				
Large-R jet	at least one large-R jet, $p_T > 250$ GeV, $\lvert\eta\rvert < 2$				
Track-Jets	at least two track-jets, $p_T > 10$ GeV, $\lvert\eta\rvert < 2.5$, matched to the leading large-R jet				
b-jets	leading two track-jets matched to the leading large-R must be b-tagged				
m_J	> 50 GeV				
$\min \Delta\phi(E_T^{\text{miss}}, \text{jets})$	$> 30°$	-			
$\Delta\phi(E_T^{\text{miss}}, H_{\text{cand}})$	$> 120°$	-			
$\Delta\phi(E_T^{\text{miss}}, E_{T,\text{trk}}^{\text{miss}})$	$< 90°$	-			
$m_{\ell\ell}$	-			66 GeV $< m_{\ell\ell} < 116$ GeV	
lepton flavor	-			two lepton same flavour	
lepton charge	-			opposite sign muons	

Definitions

S_T	scalar sum of the p_T of the jets in the event
ϕ	azimuthal angle around the beam
(Sub)Leading	object with (second)highest p_T
jet 1 & jet 2	2 selected jets forming the Higgs candidate with jet 1 being the leading jet
E_T^{miss}	missing transverse momentum
η	pseudorapidity

Definitions

Jets

	p_T	$\lvert\eta\rvert$	
Signal jet	> 20 GeV	< 2.5	specific jet cleaning procedure
Forward jet	> 30 GeV	$> 2.5, < 4.5$	specific jet cleaning procedure
Large R jet	> 250 GeV	< 2.0	
Track jet	> 10 GeV	< 2.5	

Electrons

	p_T	η	ID	d_0^{sig} w.r.t. BL	$\lvert\Delta z_0 \sin\theta\rvert$	Isolation
VH-Loose	>7 GeV	$\lvert\eta\rvert < 2.47$	LH Loose	< 5	< 0.5 mm	Loose_VarRad
ZH-Signal	>27 GeV	Same as VH-Loose				
WH-Signal	Same as ZH-Signal		LH Tight	Same as ZH-Signal		HighPtCaloOnly

Definitions

Muons

	p_T	η	ID	d_0^{sig} w.r.t. BL	$\lvert\Delta z_0 \sin\theta\rvert$	Isolation
VH-Loose	>7 GeV	$\lvert\eta\rvert < 2.7$	Loose quality	< 3	< 0.5 mm	Loose_VarRad
ZH-Signal	>27 GeV	$\lvert\eta\rvert < 2.5$	Same as VH-Loose			
WH-Signal	>25 GeV when $p_T^V > 150$ GeV >27 GeV when $p_T^V < 150$ GeV	$\lvert\eta\rvert < 2.5$	Medium quality	< 3	< 0.5 mm	HighPtTrackOnly

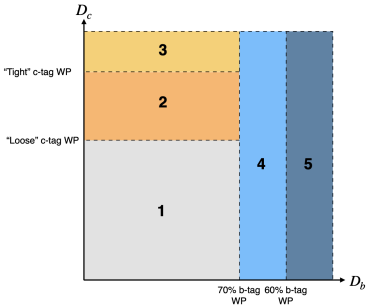
Taus

p_T	η	n_{trk}	ID
>20 GeV	$\lvert\eta\rvert < 2.5$	1 or 3 tracks	Loose

Definitions

Tagging	Region on D_b-D_c plane
b-tagged	4+5
Tight c-tagged	3
Loose c-tagged	2+3
Not tagged	1

$D_b = \ln\left(\frac{p_b}{f_c p_c + (1-f_c)p_u}\right)$ and $D_c = \ln\left(\frac{p_c}{f_b p_b + (1-f_b)p_u}\right)$ are scores calculated by considering the probability p_i of a jet identified as i flavour jet and of fraction f_j of j flavour jets in the sample



Pseudo-continuous flavour tagging scheme that ensures $VH(\rightarrow b\bar{b})$ & $VH(\rightarrow c\bar{c})$ are orthogonal