tH analysis: the feasibility of lifting top Yukawa degeneracies with ATLAS

Discovery Physics at the LHC Kruger Workshop 2014

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as part of my Masters
supervisor and co-supervisor:
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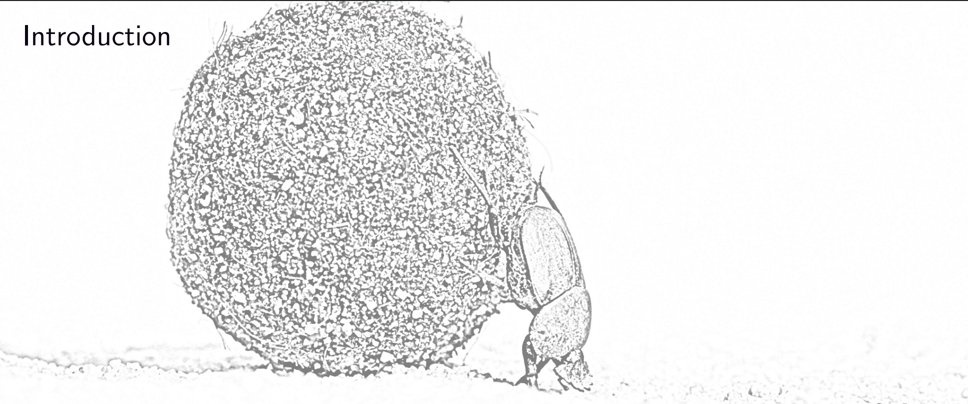
University of Cape Town

December 3, 2014

Introduction



With the LHC's first run, enough data has been accumulated to uncover the predicted Higgs boson. Focus of searches has shifted to measuring its properties – is it THE Standard Model Higgs?
Thus far, all measurements have indicated a compliance with the Standard Model. However, there remain non-SM areas that have not been entirely excluded. These are possible windows to new physics.

Content

fermionic and bosonic couplings

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Using all available data at 7 and 8 TeV, ATLAS and CMS have presented constraints on the fermion and vector boson couplings.

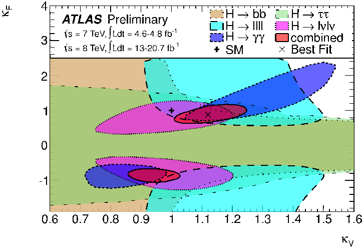

Figure : Correlation between coupling scale factors c_F (fermionic) and c_V (vector bosonic) with 68% CL contours from individual channels at ATLAS.[1]

[1] ATLAS collab. Combined coupling measurements of the Higgs-like boson with the ATLAS detector using up to 25 fb-1 of proton-proton collision data. ATLAS-CONF-2013-03

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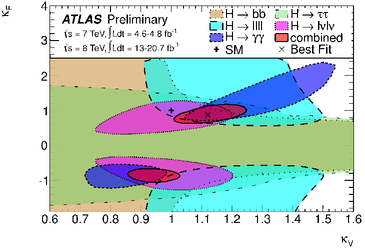
$$\kappa_V \equiv g_V / g_V^{SM} \quad \kappa_F \equiv g_f / g_f^{SM}$$

...essentially quantify the deviation from g^{SM}.



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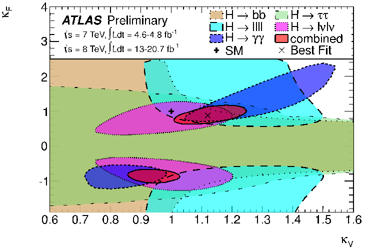
But: There are **two** minima in the fits – one complying with SM (1:1); the other in a region of new physics – at negative values.



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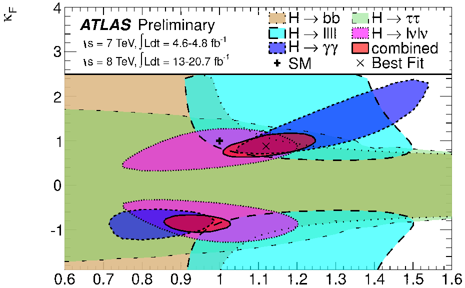
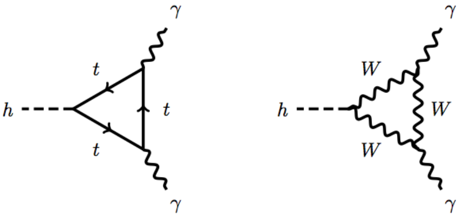
We need more sensitivity in the *relative* sign of κ_F...



most channels not sensitive to the relative sign between κ_V and $\frac{\kappa_V}{\kappa_F}$, as

$$\mathcal{N} \propto \frac{\kappa_x^2 \kappa_y^2}{\kappa_H}. \qquad (1)$$



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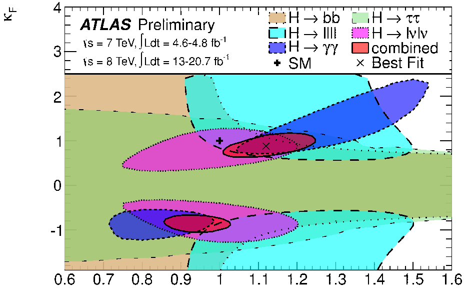
However, $H \to \gamma\gamma$ loop-induced $\to \kappa_\gamma$ function of κ_F and κ_V – scales as $|\alpha\kappa_V + \beta\kappa_F|^2$.



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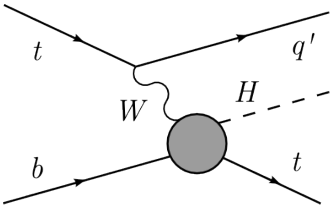
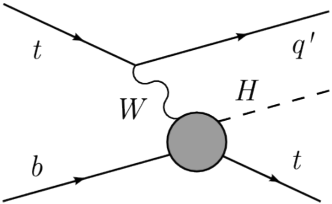
...interference term $\alpha\beta\kappa_F\kappa_V$ emerges, resulting in fits also favouring negative signs.

Resolving the degeneracies: the tH process

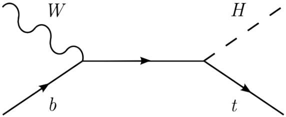


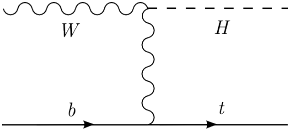
The *single* top production in association with the Higgs, *tH*, offers a unique opportunity to study the *relative* sign of the Yukawa coupling.

This is due to an interference...



...between bosonic and fermionic processes...





Due to the interference the cross-section of the tH process is enhanced for non-SM values...

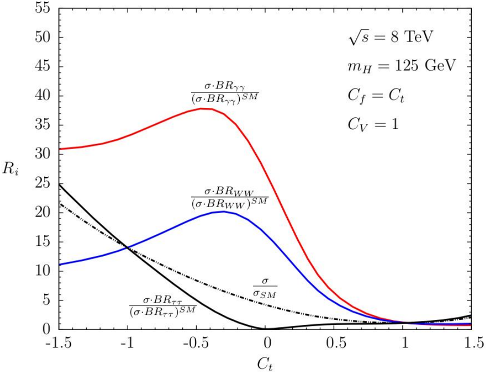
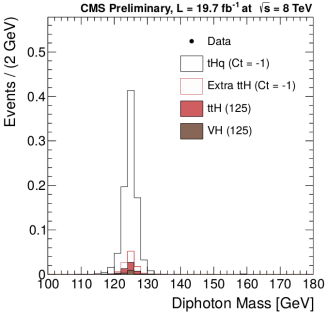


Figure : Cross section ratio as function of the top yukawa coupling, $c_t = c_F$, $c_V = 1$.[2]

[2] Sanjoy Biswas, Emidio Gabrielli, Fabrizio Margaroli, and Barbara Mele. Direct constraints on the top-Higgs coupling from the 8 TeV LHC data. JHEP, 07:073, 2013.

An update on measurements of the Single Top channel



- CMS: $H \to \gamma\gamma$ at 8 TeV/19.6fb^{-1} - reported zero events passing acceptance cuts and 95% CL on $H \to \gamma\gamma$ event yield of 4.1 times the expectation. [3]
- ATLAS: $H \to \gamma\gamma$ cross-sections of $t\bar{t}H$ and tH channels combined at 7 and 8 TeV - strongly constrained negative Yukawa sector; 95% CL for c_F at -1.3 and +8.0.[4]

[3] CMS-PAS-HIG-14-001

[4] CERN-PH-EP-2014-179

This is a feasibility study based on

Lifting degeneracies in Higgs couplings using single top production in association with a Higgs boson

Marco Farina[a], Christophe Grojean[b,c], Fabio Maltoni[d], Ennio Salvioni[c,e] and Andrea Thamm[c,f] [*] [5]

taking $H \to b\bar{b}$.

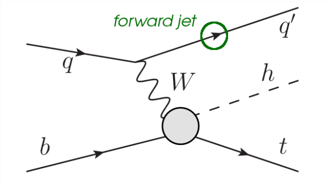
The analysis is done at truth level using 8 TeV samples and assuming 21fb^{-1} of integrated luminosity.

[5] Marco Farina, Christophe Grojean, Fabio Maltoni, Ennio Salvioni, and Andrea Thamm. Lifting degeneracies in Higgs couplings using single top production in association with a Higgs boson. JHEP, 1305:022, 2013.

Signal signature

Seek

- $H \to b\bar{b}$ channel (58%, dominant decay at this mass range)
- $t \to Wb$ (99.8%)
- $W \to \ell\nu$ (20%)
- a *forward jet* - characteristic high p_T jet, produced at Higgs and top production



Thus,

Signature

$$tHj \to 3\ b\text{-jets} + \ell(e^{\pm}/\mu^{\pm}) + j + MET$$

MC samples

Signal

Monte Carlo samples of tH process generated for $c_F = +1$ and $c_F = -1$ $(c_V = 1)$.

Backgrounds

- $tb\bar{b}j$ (*irreducible*)
- $tZj, Z \to b\bar{b}$ (*irreducible*)
- $t\bar{t}$, where one $Wb \to c\bar{s}b$, the c is mistagged and the s is taken as a forward jet (*reducible*)
- $t\bar{t}j$, where one $Wb \to c\bar{s}b$, the c or s is mistagged (*reducible*)

There is (at least) one leptonically decaying top in every event.

cross-sections

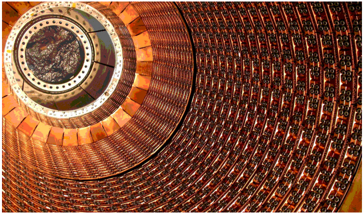
Process	Cross-Section (fb^{-1})	Generator
$c_F = +1$ tH	1.66	MadGraph + Pythia
$c_F = -1$ tH	27.81	MadGraph + Pythia
$tb\bar{b}j$	11.28	MadGraph + Pythia
tZj	6.27	MadGraph + Pythia
$t\bar{t}(j)$	210.85×10^3	POWHEG+ Pythia

Event Selection

A simple event count is done by implementing certain selection criteria for the signal and background.

Acceptance cuts are made from the outset, motivated by

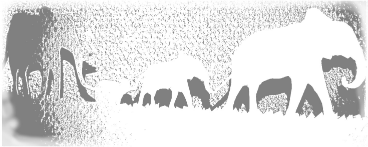
- suppression of low-momentum pileup and underlying event particles
- keeping the acceptance area to regions where the detector is of optimum efficiency.



Acceptance cuts are $p_T > 25$ GeV and $|\eta| < 2.5$ on all jets and leptons (except for forward jet).

summary of selection criteria

- $p_T^b, p_T^\ell, p_T^j > 25\ \mathrm{GeV}$
- $\eta^\ell, \eta^b < 2.5$
- 1 lepton: acts as trigger
- 1 forward jet $\rightarrow$ forward jet selection:
  if 1 of top 2 highest p_T non-b-tagged jets at $> 2.5\eta$.
- ≥ 3 b-jets
- a b-jet pair where 65 $\mathrm{GeV} < m_{bb} < 145 GeV$



electron/muon no. (trigger)

no. of $\ell = 1$ cut

	with acceptance cuts		
no. of leptons/event	0	1	2
$c_F = +1$:	48%	52%	0%
$c_F = -1$:	45%	55%	0%
$tbbj$	25%	75%	0%
$tZbbj$	50%	50%	0%
$t\bar{t}$	44%	51%	5%

,

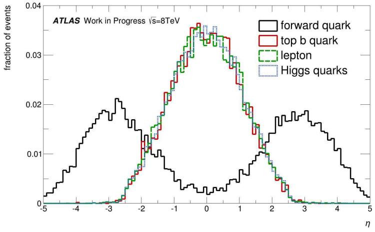
Sensitivities

- $c_F = +1$: 0.01
- $c_F = -1$: 0.22

η comparisons

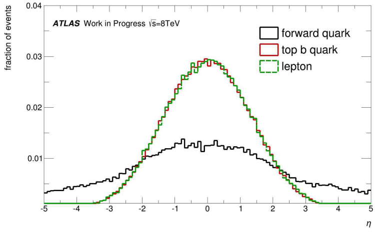
A fine distinction between signal and $t\bar{t}$ bg lies in the η distributions...

SIGNAL



(a) η distribution for c_F =-1

$t\bar{t}$ BACKGROUND



(b) η distribution for $t\bar{t}$

- important characteristic of signal: high p_T jets at high η

η comparisons

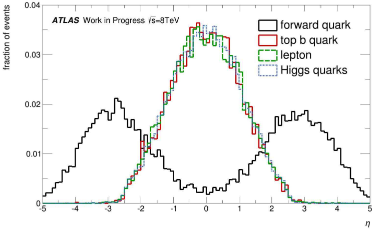


Figure : η distribution for c_F =-1

→ set requirement: one of top two highest p_T jets at $|\eta| > 2.5$

Sensitivities

- $c_F = +1$: 0.01
- $c_F = -1$: 0.27

b jet no.

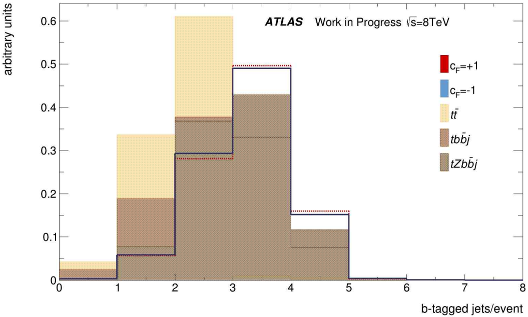


Figure : no. of b jets/event for all samples.

Sensitivities

- $c_F = +1$: 0.08
- $c_F = -1$: 1.63

constraint on no. of b-jets ($\geqslant 3$)

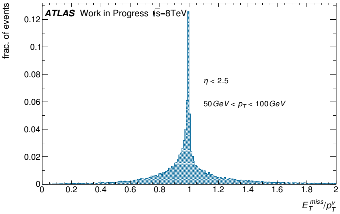
- 99% cut on $t\bar{t}$
- $\sim$ 34% cut on signal

- $p_T > 25 GeV$, $|\eta| < 2.5$ cuts applied.

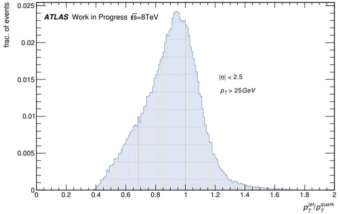
reconstructed Higgs mass

Salient difference between signal and all backgrounds is presence of a Higgs boson.

- In order to reduce b-jet combinations, first reconstructed W and top quark...
  - work with $E_{\mathrm{T}}^{\mathrm{miss}}$: estimate p_z^{ν} by setting a W mass constraint.
  - reconstruct top quark through W+b.

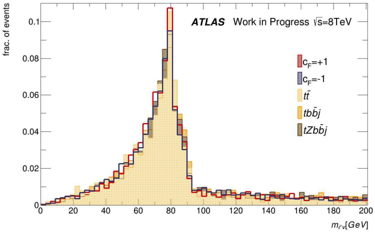


energy ratio between $E_{\mathrm{T}}^{\mathrm{miss}}$ and truth neutrino

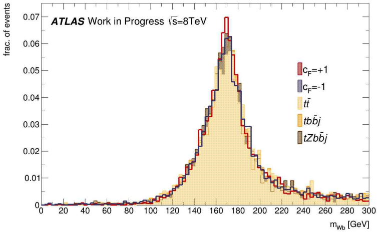


p_T ratio between truth b jet and truth b quark

reconstructed W boson and top quark

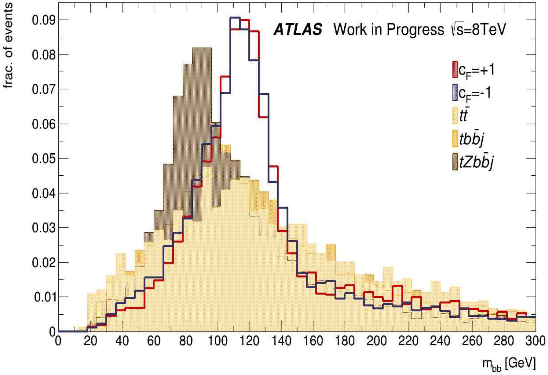


reconstructed W boson mass for all samples



reconstructed top mass for all samples

reconstructed Higgs



m_{bb} constraint

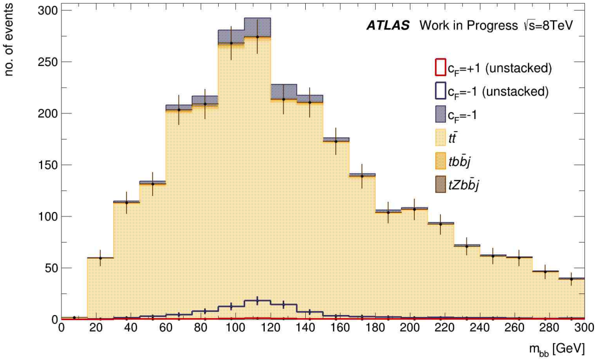
- $65\ \mathrm{GeV} < m_{bb} < 145 GeV$

Sensitivities

- $c_F = +1$: 0.08
- $c_F = -1$: 1.74

- The Z boson is clearly evident at $\sim 90\ \mathrm{GeV}$.
- The $t\bar{t}$ and $tbbj$ events are widely distributed.

Final expected distribution...



- an excess of 62 ± 1 over 1274 ± 16 events is expected in the region $65 \text{ GeV} < m_{bb} < 145 \text{ GeV}$

cut flow table

table of number of scaled events + significance of signal after each cut:

cuts	$\kappa_F = +1$	$\kappa_F = -1$	tbbj	tZbbj	$t\bar{t}$	Σ(bg)	$\frac{S}{\sqrt{B}}$ (SM)	$\frac{S}{\sqrt{B}}$ (non-SM)
initial	35	592	240	134	4491105	4491479	0.02	0.28
1 lepton	18	325	180	67	2217352	2217599	0.01	0.22
1 fwd jet	7	136	58	24	258299	258381	0.01	0.27
$\geqslant$ 3 central jets	6	122	44	20	193120	193184	0.01	0.28
$\geqslant$ 2 b-jets	6	119	41	20	134949	135009	0.02	0.32
$\geqslant$ 3 b-jets	4	88	25	13	2903	2940	0.08	1.63
m_{bb}	2	62	12	8	1254	1274	0.08	1.74

considering effects of systematic uncertainties

- What is the effect of systematic uncertainties on the significance value?

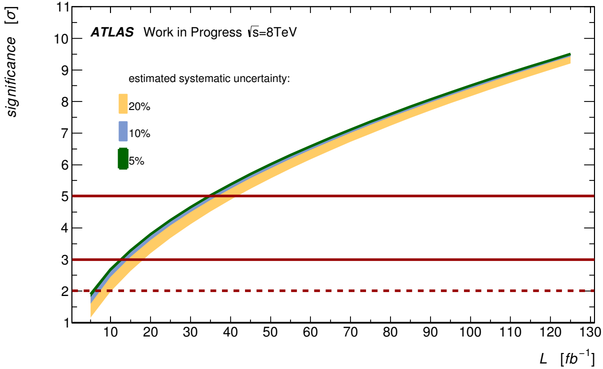
Summary of significance calculations in the SM and non-SM case, assuming systematic uncertainties of 0, 5, 10 and 20%

tH signal	$S/\sqrt{B}$	$S/\sqrt{B+(0.05B)^2}$	$S/\sqrt{B+(0.1B)^2}$	$S/\sqrt{B+(0.2B)^2}$
$c_F = +1$:	0.08	0.03	0.02	0.01
$c_F = -1$:	1.74	0.85	0.47	0.24

projection to 14 TeV energies

The situation is much improved when considering higher centre-of-mass energies + boosted cross-sections (RUN II)

Process	8 TeV [fb]	14 TeV [fb]
tH ($c_F = -1$)	234	982
$t\bar{t}(j)$	240×10^3	833×10^3



Conclusion

- At truth-level and 8 TeV, a sensitivity of $\sim 1.7\sigma$ is reached for anomalous coupling $c_F = -1$.
- This is significantly reduced when including estimates of systematic uncertainty $\rightarrow$ meaningful exclusion of the $c_F = -1$ cross-section unlikely.
- Results of the feasibility study were used to project the significance to 14 TeV, in anticipation of the LHC's upcoming run...
  - Cross-sections were rescaled to match new centre-of-mass energy.
  - Even with a systematic uncertainty of 20% in background, already at $\sim 20\text{fb}^{-1}$, degeneracy may be resolved.
  - Full-fledged analysis at 13/14 TeV with reconstructed data a worthwhile endeavour.

An update on tH measurements in $H \to b\bar{b}$ channel

Recently, CMS published[6]

Search for $H \to b\bar{b}$ in association with single top quarks as a test of Higgs boson couplings

The CMS Collaboration

in which they drew a 95% CL upper limit at 7.62 times the rate expected for the anomalous signal (expected sensitivity of 5.22).

[6] CMS PAS HIG-14-015

Potential extensions to analysis: lepton charge asymmetry

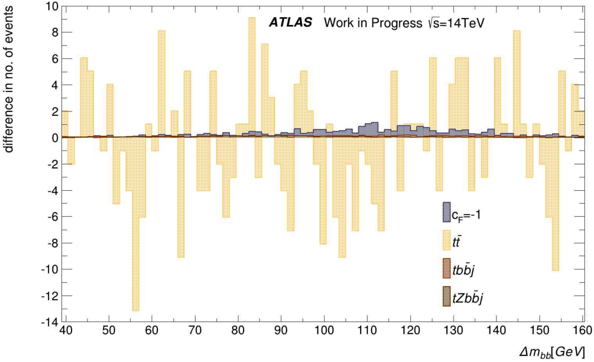
- charge-asymmetric initial state pp at the LHC $\rightarrow$ single top yields more ℓ^+ [7]
- however, $t\bar{t}$ channel symmetric to LO ...@ NLO, t more centrally produced than $\bar{t}$$\rightarrow$ slightly more ℓ^- produced

	frac. pos. leptons	**frac. neg. leptons**
sample $c_F = -1$	66%	33%
sample $t\bar{t}$	49.6%	50.4%

This asymmetry may prove useful: taking the difference in ℓ^+ & ℓ^- events means eliminating $t\bar{t}$ background, save for fluctuations.

[7] Matthew T. Bowen. Using charge asymmetries to measure single top quark production at the LHC. 558 Phys.Rev., D73:097501, 2006.

Potential extensions to analysis: lepton charge asymmetry



- Unfortunately, very little statistics (1 event or less per bin) remain.

THANK YOU!

systematic uncertainties

$$N = L \times \sigma \times acceptance \times \underline{efficiency}$$

This analysis is rough: uncertainties are largely ignored as we are only looking into the feasibility of the work.
Uncertainties that will have to be considered for an extended analysis are uncertainties in

- jet energy scale
- jet energy resolution – broadens m_{bb} distribution
- lepton ID, reconstruction and trigger
- b, c and light jet tagging (increased 3 b-jet events in $t\bar{t}$ background, missed signal events...)
- background and signal modelling (PDF distributions, renormalisation, factorisation, calculations of cross-sections, mass measurements...)
- pile-up effects: affects jet energy scales and resolutions – more prominent for 14 TeV run.

Amplitude equation for tH process

The core process is Wb $\to$ tH. The amplitude in the high-energy, hard-scattering regime for this is

$$\mathcal{A} = \frac{g}{\sqrt{2}}\left[(c_F - c_V)\frac{m_t\sqrt{s}}{m_W v}\,A\left(\frac{t}{s},\varphi;\xi_t,\xi_b\right) + \left(c_V\,\frac{2m_W}{v}\frac{s}{t} + (2c_F - c_V)\,\frac{m_t^2}{m_W v}\right)\,B\left(\frac{t}{s},\varphi;\xi_t,\xi_b\right)\right]$$

We see that

- when $c_F = c_V$, the first term cancels
- when $c_F \neq c_V$, the term remains and grows $\propto \sqrt{s}$.

Significance formula

In order to get an estimate for the significance, do a simple event selection and count for each sample.

The p-value for an observation of $N = S + B$ events in a *background-only hypothesis* is

$$p = 1 - \Phi(\frac{N - B}{\sqrt{B}}) \tag{2}$$

where $\Phi(\frac{N-B}{\sqrt{B}})$ is the cumulative distribution function for background-only.

The z-value is the significance,

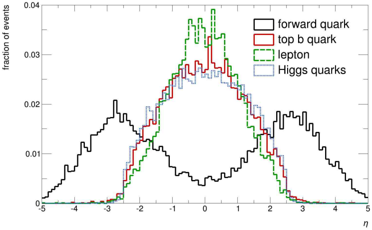
$$\begin{aligned} Z &= \Phi^{-1}(1-p) \\ &= \frac{N-B}{\sqrt{B}} \\ &= \frac{S}{\sqrt{B}}. \end{aligned}$$

This holds for $S << B$.

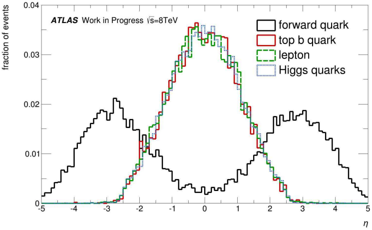
As a general rule:

- $> 3\sigma$: "evidence"
- $> 5\sigma$: "observation"

η comparisons



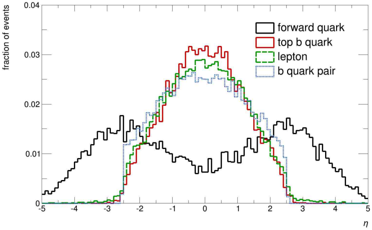
(a) η distribution for $c_F = +1$



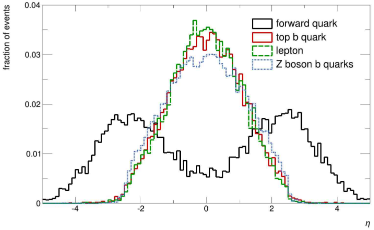
(b) η distribution for c_F =-1

- wider η distribution for b quarks in $c_F = +1$ MC

η comparisons



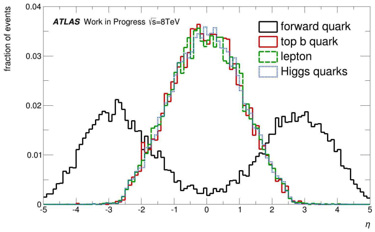
(a) η distribution for bg tbbj



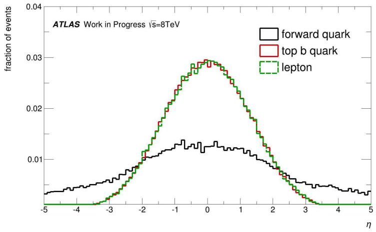
(b) η distribution for bg tZbbj

- backgrounds mimic signal

η comparisons



(a) η distribution for c_F =-1



(b) η distribution for $t\bar{t}$

- important characteristic of signal: non b-tagged jets at high η

η comparisons

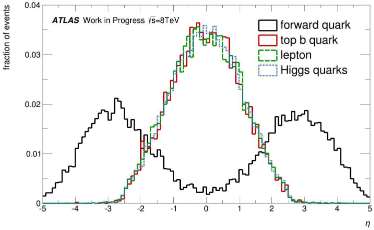


Figure : η distribution for c_F =-1

$\rightarrow$ set requirement high p_T jet at $|\eta| > 2.5$

Sensitivities

- $c_F = +1$: 0.081
- $c_F = -1$: 1.612

Jets will have lower p_T values than the matched truth quarks.

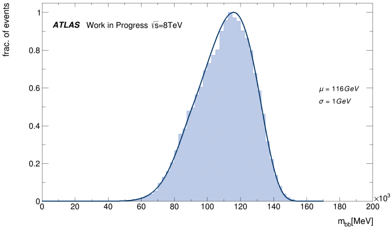


Figure : reconstructed higgs using only jets matched to truth quarks, fitted with a Bukin function.

Figure shows the mean invariant mass of Higgs b jet pairs – jet p_T scale is shifted to a lower mean value which motivates a window of constraint on Higgs mass off-centre of the measured 125 GeV value.

m_{bb}cut

- $65\ \mathrm{GeV} < m_{bb} < 14GeV$

Jets used in reconstruction:

- Only jets matched to truth b quarks from Higgs decay
- basic $p_T > 25GeV$ and $\eta > 2.5$ cuts applied.

Reconstructing the W Boson

The neutrino z-component was calculated by using the W mass and four-momentum conservation,

$$p_z^{\nu} = \frac{1}{2(E_{\ell^2} - p_z^{\ell^2})} \langle p_z^{\ell}[2(p_x^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} cos\phi + p_y^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} sin\phi) - m_{\ell}^2 + M_W^2] \pm \sqrt{E_{\ell}^2[(2p_x^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} cos\phi + 2p_y^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} sin\phi - m_{\ell}^2 + M_W^2)^2 - 4E_{\mathrm{T}}^{\mathrm{miss}2}(E_{\mathrm{T}}^{\mathrm{miss}2}{}_{\ell} - p_z^{\ell^2})]} \quad (3)$$

The minimum value for p_z^{ν} is selected. If the value within the square root is negative, $E_{\mathrm{T}}^{\mathrm{miss}}$ is recalculated so that discriminant is 0,

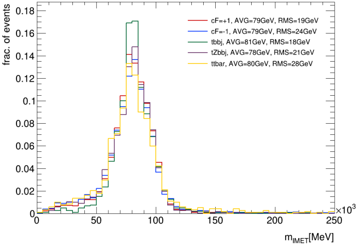
$$E_{\mathrm{T}}^{\mathrm{miss}} = \frac{1}{2[E_{\ell}^2 - p_z^{\ell^2} - (p_x^{\ell} cos\phi + p_y^{\ell} sin\phi)^2]} \langle -(p_x^{\ell} cos\phi + p_y^{\ell} sin\phi) \times (m_{\ell}^2 - M_W^2) \pm \sqrt{(m_{\ell}^2 - M_W^2)^2} \quad (4)$$

and choosing the value that results in a valid value for eq. 3.

Higgs reconstruction using top information

W boson is reconstructed using $\ell + MET$ $\rightarrow$ top is reconstructed using W + best matched b jet $\rightarrow$ Higgs is reconstructed using remaining b jets (if a 4 b jet event, pair is chosen with invariant mass closest to truth Higgs mass):

reconstructed W:



reconstructed top: