Search for the Higgs boson in the $Z(H \to WW^*) \to \ell\ell\ell\nu\ell\nu$ channel via cut-based analysis of data from the ATLAS detector

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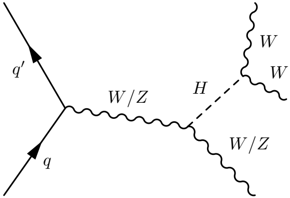
Outline

1. Introduction: the Higgs-strahlung process
2. Analysis strategy
3. Background processes
4. Signal and control regions
5. Current state of the analysis

Motivation

- A particle resembling the Standard Model (SM) Higgs boson was discovered at a mass of $\approx 125\mathrm{GeV}$.
- Theoretical values of Higgs boson properties have been calculated for a wide range of mass values.
- Measure these properties for the discovered particle to check compatibility with the SM:
  - Spin (measured 0^+ to 2.3σ)
  - Strengths of coupling to other particles

Associated production



- Higgs-strahlung (associated production) modes are particularly sensitive to couplings between Higgs and vector bosons.

$$\sigma \propto g_{HWW}^4 \qquad \text{or} \qquad \sigma \propto g_{HZZ}^2 \times g_{HWW}^2$$

- The main limitation is the relatively small cross-section (compared to gluon-gluon fusion, the dominant mode).
  - For $m_H = 125$ GeV @ $\sqrt{s} = 8\text{TeV}$:

	ggF	WH	ZH
[pb]	19.5	0.697	0.394

Channel of Interest

- This analysis examines the $Z(H \to WW) \to \ell^+\ell^-\ell^+\nu\ell^-\overline{\nu}$ channel
  - We target purely leptonic final states, as this avoids a great deal of background associated with jets.

- Signal events thus contain:
  - 4 charged leptons (e or μ; τ decay before reaching the detector) with total charge 0
  - A same-flavour opposite-sign (SFOS) pair of leptons with invariant mass near m_Z
  - Missing transverse energy (E_T^{miss}) from neutrinos

- How many events are expected? Consider the product of the relevant branching ratios:

$$q\overline{q}_{ZH} \times (Z_{e/\mu} + Z_\tau \times \tau_{e/\mu}) \times H_{WW} \times (W_{e/\mu} + W_\tau \times \tau_{e/\mu})^2 \approx 0.001$$

Therefore, one can expect: $20.7\text{fb}^{-1} \times 0.3943\text{pb} \times 0.001 \approx 8$ events

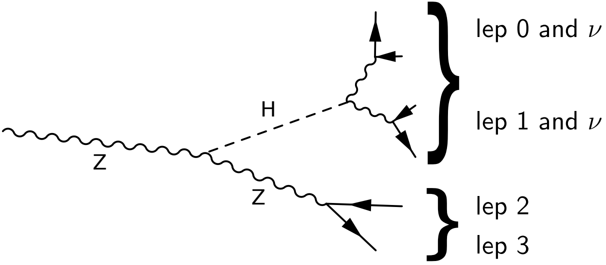
- Furthermore, one must consider the acceptance of the detector, and the criteria which are imposed on lepton isolation and quality.

Analysis Strategy

- Limited number of events $\rightarrow$ focus on setting an upper limit on the ZH production cross-section (σ). More data in coming years will allow a full calculation.

- Select events based on certain criteria (cuts) that are optimized to produce the lowest expected limit (95% Confidence Level exclusion on $\sigma/\sigma_{\mathrm{SM}}$)

Lepton labeling scheme



0 and 1: Higgs-candidate leptons

2 and 3: Z-candidate leptons
(SFOS pair with mass closest to m_Z)

Background Processes

- The dominant background process is $Z(Z^*/\gamma^*) \rightarrow \ell^+\ell^-\ell'^+\ell'^-$
  - These lepton pairs are both SFOS
  - For this reason, we define two signal regions, containing events with 1 or 2 SFOS lepton pairs, respectively.
- $t\bar{t}Z$ contributes significantly at pre-selection, but can be greatly reduced by restricting the number of jets allowed and vetoing all b-jets.
- VVV is responsible for the next largest contribution — ZZZ and ZWW in particular.
- WZ and Z+jets account for some background due to the production of 'fake' leptons.

Topological cuts

Knowing this, what cuts will improve signal sensitivity?

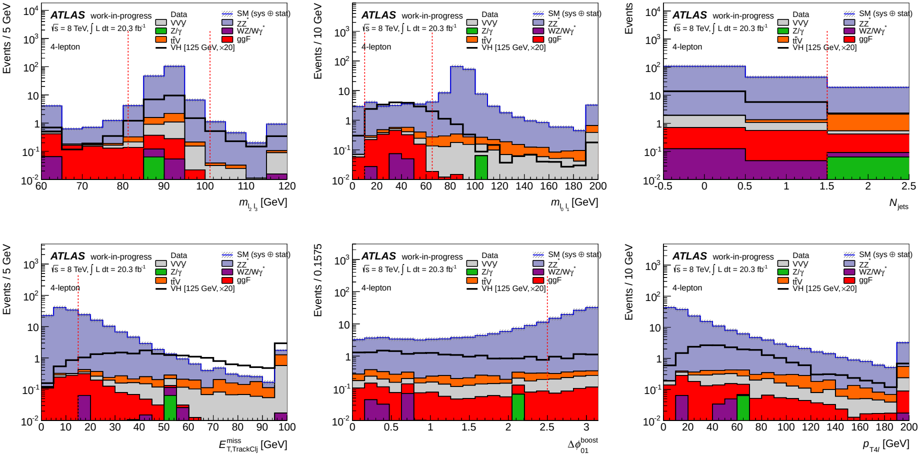
- Z-selection: choose $m_{23} \approx m_Z$
- ZZ rejection: choose $m_{01} \neq m_Z$
- Low jet multiplicity, no b-jets
- Require a minimum $E_{\mathrm{T}}^{\mathrm{miss}}$
- Require $\Delta\phi_{01}^{\mathrm{boost}} < 2.5$
  - In the frame of the decaying spin-0 Higgs boson, the product W^+W^- will have opposite spin, and be travelling in opposite directions. They will therefore have the same helicity.
  - By the decay topology of these Ws — (anti-)neutrinos must have (right-)left-handed helicity — the resulting leptons will then have *low* angular separation.
  - The Higgs boson's frame is highly boosted. In the lab frame, all these decay products will have low separation.
  - The transverse momentum of the Z-decay products can be used to calculate the boosted Higgs frame and thus $\Delta\phi_{01}^{\mathrm{boost}}$.

Topological cuts

Signal Selections		
Pre-selection	4 isolated leptons ($p_{\mathrm{T}} > 15$ GeV), trigger, total charge zero	
	one SFOS lepton pair	two SFOS lepton pairs
$E_{\mathrm{T}}^{\mathrm{miss}}$ cut	$E_{\mathrm{T,STVF}}^{\mathrm{miss}} > 20\mathrm{GeV}$, $E_{\mathrm{T,TrackHWW}}^{\mathrm{miss}} > 15\mathrm{GeV}$	
p_{T}^{ℓ} cuts	leading p_{T} lepton: $p_{\mathrm{T}} > 25$ GeV sub-leading p_{T} lepton: $p_{\mathrm{T}} > 20$ GeV	
Jet multiplicity	$N_{\mathrm{jet}} \leq 1$	
top-veto	$N_{b-\mathrm{tag}} = 0$	
Dilepton mass cuts	$\lvert m_{\ell_2\ell_3} - m_Z \rvert < 10$ GeV $10\ \mathrm{GeV} < m_{\ell_0\ell_1} < 65$ GeV	
Angular cut	$\Delta\phi_{01}^{\mathrm{boost}} < 2.5$	
$p_{\mathrm{T}4\ell}$ cut		$p_{\mathrm{T}4\ell} > 30$ GeV
$m_{4\ell}$ cut		$m_{4\ell} > 140$ GeV
Overlap removal	remove overlap with dilep and WH SS analysis	

- Overlap removal cuts ensure orthogonality with other $H \to WW$ analyses, which is important since results from these analyses are combined.

Topological cuts



Cutflow

	$Z(H \to WW)$	$W(H \to WW)$	$Z(H \to \tau\tau)$	$H \to ZZ$	$t\bar{t}H$	$V(H)$ (125 GeV)	Total Bkg.	Sig.
Pre-selection	0.91 ± 0.13	-	0.17 ± 0.03	1.42 ± 0.03	0.18 ± 0.01	1.09 ± 0.16	168.29 ± 23.76	0.08 ± 0.02
1 SFOS pair (SR7)	0.44 ± 0.06	-	0.08 ± 0.01	-	0.11 ± 0.00	0.53 ± 0.08	3.53 ± 0.52	0.27 ± 0.06
$E_{\mathrm{T}}^{\mathrm{miss}}$ cut	0.39 ± 0.06	-	0.07 ± 0.01	-	0.10 ± 0.00	0.45 ± 0.07	2.84 ± 0.42	0.26 ± 0.05
p_{T} cuts	0.39 ± 0.06	-	0.07 ± 0.01	-	0.10 ± 0.00	0.45 ± 0.07	2.83 ± 0.42	0.26 ± 0.06
$N_{\mathrm{jet}} \leq 1$	0.35 ± 0.05	-	0.06 ± 0.01	-	0.01 ± 0.00	0.41 ± 0.06	1.80 ± 0.28	0.29 ± 0.06
top-veto	0.33 ± 0.05	-	0.05 ± 0.01	-	-	0.38 ± 0.06	1.62 ± 0.26	0.29 ± 0.06
Z selection	0.29 ± 0.04	-	0.05 ± 0.01	-	-	0.34 ± 0.05	1.39 ± 0.22	0.28 ± 0.06
$10\mathrm{GeV} < m_{01} < 65\mathrm{GeV}$	0.26 ± 0.04	-	0.03 ± 0.01	-	-	0.29 ± 0.04	0.76 ± 0.13	0.31 ± 0.07
$\Delta\phi_{01}^{boost} < 2.5$	0.24 ± 0.04	-	0.01 ± 0.00	-	-	0.25 ± 0.04	0.43 ± 0.08	0.35 ± 0.08
WHSS OR	0.24 ± 0.04	-	0.01 ± 0.00	-	-	0.25 ± 0.04	0.43 ± 0.08	0.35 ± 0.08
$\ell\nu\ell\nu$ OR	0.23 ± 0.03	-	0.01 ± 0.00	-	-	0.24 ± 0.04	0.42 ± 0.08	0.34 ± 0.08
2 SFOS pairs (SR8)	0.47 ± 0.07	-	0.09 ± 0.02	1.41 ± 0.03	0.08 ± 0.00	0.56 ± 0.08	164.76 ± 23.26	0.04 ± 0.01
$E_{\mathrm{T}}^{\mathrm{miss}}$ cut	0.41 ± 0.06	-	0.07 ± 0.01	0.52 ± 0.02	0.07 ± 0.00	0.48 ± 0.07	40.80 ± 6.78	0.08 ± 0.02
p_{T} cuts	0.41 ± 0.06	-	0.07 ± 0.01	0.51 ± 0.02	0.07 ± 0.00	0.48 ± 0.07	40.76 ± 6.77	0.08 ± 0.02
$N_{\mathrm{jet}} \leq 1$	0.37 ± 0.05	-	0.06 ± 0.01	0.35 ± 0.02	0.01 ± 0.00	0.43 ± 0.06	32.39 ± 5.53	0.08 ± 0.02
top-veto	0.34 ± 0.05	-	0.06 ± 0.01	0.32 ± 0.02	-	0.40 ± 0.06	29.47 ± 5.06	0.07 ± 0.02
Z selection	0.30 ± 0.04	-	0.05 ± 0.01	0.14 ± 0.01	-	0.35 ± 0.05	27.85 ± 4.81	0.07 ± 0.01
$10\mathrm{GeV} < m_{01} < 65\mathrm{GeV}$	0.27 ± 0.04	-	0.03 ± 0.01	0.13 ± 0.01	-	0.30 ± 0.04	2.64 ± 0.43	0.18 ± 0.04
$\Delta\phi_{01}^{boost} < 2.5$	0.25 ± 0.04	-	0.01 ± 0.00	0.12 ± 0.01	-	0.26 ± 0.04	1.93 ± 0.33	0.18 ± 0.04
$p_{\mathrm{T}4\ell} > 30\mathrm{GeV}$	0.22 ± 0.03	-	0.01 ± 0.00	0.11 ± 0.01	-	0.23 ± 0.03	1.36 ± 0.24	0.19 ± 0.04
$m_{4\ell} > 140\mathrm{GeV}$	0.21 ± 0.03	-	0.01 ± 0.00	-	-	0.22 ± 0.03	1.31 ± 0.22	0.19 ± 0.04
WHSS OR	0.21 ± 0.03	-	0.01 ± 0.00	-	-	0.22 ± 0.03	1.31 ± 0.22	0.19 ± 0.04
$\ell\nu\ell\nu$ OR	0.20 ± 0.03	-	0.01 ± 0.00	-	-	0.21 ± 0.03	1.23 ± 0.22	0.18 ± 0.04

ATLAS work-in-progress

Cutflow – background breakdown

	ZZ^*	$t\bar{t}V$	VVV	$WZ/W\gamma^*$	Z/γ^*
Pre-selection	164.15 ± 23.17	2.05 ± 0.31	1.83 ± 0.26	0.19 ± 0.09	0.07 ± 0.06
1 SFOS pair (SR7)	1.61 ± 0.24	0.89 ± 0.15	0.87 ± 0.13	0.10 ± 0.07	0.06 ± 0.06
$E_{\mathrm{T}}^{\mathrm{miss}}$ cut	1.11 ± 0.17	0.84 ± 0.14	0.79 ± 0.12	0.04 ± 0.02	0.06 ± 0.06
p_{T} cuts	1.10 ± 0.17	0.84 ± 0.14	0.79 ± 0.12	0.04 ± 0.02	0.06 ± 0.06
$N_{\mathrm{jet}} \leq 1$	0.93 ± 0.15	0.09 ± 0.03	0.74 ± 0.11	0.03 ± 0.02	-
top-veto	0.88 ± 0.14	0.02 ± 0.01	0.69 ± 0.10	0.03 ± 0.02	-
Z selection	0.76 ± 0.12	0.02 ± 0.01	0.59 ± 0.09	0.02 ± 0.02	-
$10\mathrm{GeV} < m_{01} < 65\mathrm{GeV}$	0.61 ± 0.10	0.01 ± 0.01	0.12 ± 0.02	0.02 ± 0.01	-
$\Delta\phi_{01}^{boost} < 2.5$	0.30 ± 0.05	0.01 ± 0.01	0.10 ± 0.02	0.02 ± 0.01	-
WHSS OR	0.30 ± 0.05	0.01 ± 0.01	0.10 ± 0.02	0.02 ± 0.01	-
$\ell\nu\ell\nu$ OR	0.30 ± 0.05	0.01 ± 0.01	0.10 ± 0.02	0.01 ± 0.01	-
2 SFOS pairs (SR8)	162.54 ± 22.94	1.16 ± 0.18	0.96 ± 0.14	0.09 ± 0.05	-
$E_{\mathrm{T}}^{\mathrm{miss}}$ cut	38.75 ± 6.49	1.07 ± 0.17	0.89 ± 0.13	0.09 ± 0.05	-
p_{T} cuts	38.71 ± 6.48	1.07 ± 0.17	0.89 ± 0.13	0.09 ± 0.05	-
$N_{\mathrm{jet}} \leq 1$	31.31 ± 5.37	0.18 ± 0.04	0.82 ± 0.12	0.07 ± 0.05	-
top-veto	28.58 ± 4.93	0.04 ± 0.02	0.77 ± 0.11	0.07 ± 0.05	-
Z selection	27.07 ± 4.69	0.04 ± 0.02	0.66 ± 0.10	0.06 ± 0.05	-
$10\mathrm{GeV} < m_{01} < 65\mathrm{GeV}$	2.42 ± 0.40	0.02 ± 0.01	0.14 ± 0.02	0.06 ± 0.05	-
$\Delta\phi_{01}^{boost} < 2.5$	1.73 ± 0.30	0.01 ± 0.01	0.13 ± 0.02	0.06 ± 0.05	-
$p_{\mathrm{T}4\ell} > 30\mathrm{GeV}$	1.17 ± 0.20	0.01 ± 0.01	0.12 ± 0.02	0.06 ± 0.05	-
$m_{4\ell} > 140\mathrm{GeV}$	1.11 ± 0.19	0.01 ± 0.01	0.12 ± 0.02	0.06 ± 0.05	-
WHSS OR	1.11 ± 0.19	0.01 ± 0.01	0.12 ± 0.02	0.06 ± 0.05	-
$\ell\nu\ell\nu$ OR	1.04 ± 0.18	0.01 ± 0.01	0.12 ± 0.02	0.06 ± 0.05	-

ATLAS work-in-progress

ZZ Control Region

- Measure mismodelling of ZZ by examining a *control region* orthogonal to the signal regions:
  - Reverse the invariant mass cut on the Higgs candidate lepton pair. Select instead those events with $m_{l_0 l_1}$ *greater* than $65\mathrm{GeV}$. Now the lepton pair is more likely another Z candidate.
  - Apply all other cuts as before.

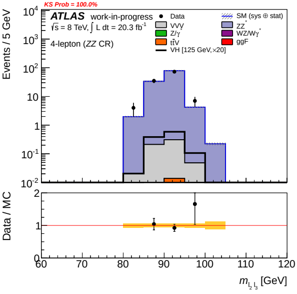
	$Z(H \to WW)$	Obs.	Total Bkg.	Data/MC	ZZ^*	$t\bar{t}V$	VVV	$WZ/W\gamma^*$	Z/γ^*
ZZ CR	0.03 ± 0.00	119	115.30 ± 6.88	1.03 ± 0.11	114.71 ± 6.83	0.02 ± 0.01	0.56 ± 0.04	0.00 ± 0.00	0.00 ± 0.00
ZZ CR - $eeee$	0.01 ± 0.00	25	19.72 ± 1.42	1.27 ± 0.27	19.62 ± 1.41	0.00 ± 0.00	0.11 ± 0.01	0.00 ± 0.00	0.00 ± 0.00
ZZ CR - $\mu\mu\mu\mu$	0.02 ± 0.00	34	39.25 ± 2.69	0.87 ± 0.16	39.05 ± 2.68	0.01 ± 0.01	0.18 ± 0.02	0.00 ± 0.00	0.00 ± 0.00
ZZ CR - $ee\mu\mu$	0.01 ± 0.00	60	56.33 ± 3.37	1.07 ± 0.15	56.04 ± 3.35	0.01 ± 0.01	0.28 ± 0.02	0.00 ± 0.00	0.00 ± 0.00

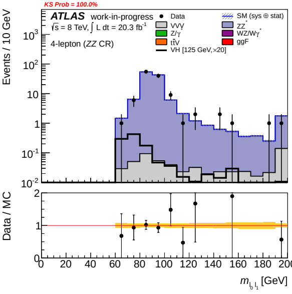
ATLAS work-in-progress

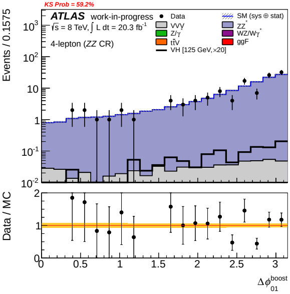
- Obtain a normalization factor for ZZ from data/MC comparison:

$$1.03 \pm 0.09\ \text{(stat.)} \pm 0.09\ \text{(syst.)}$$

ZZ Control Region

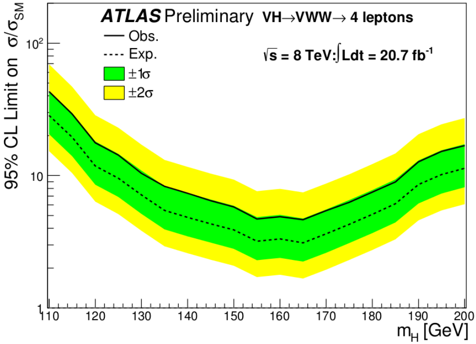






Results

- The results from this analysis are currently in the approval process for unblinding (using both the 7 and 8TeV datasets).
- The final results will hopefully be included in a Higgs combination paper.
- Previous result: the expected and observed limits on ZH production cross-section are $9.6\sigma_{\mathrm{SM}}$ and $14.3\sigma_{\mathrm{SM}}$ for m_H=125GeV.



From ATLAS-CONF-2013-075

Future

- The LHC energy upgrade to $13\mathrm{TeV}$ will provide this analysis with higher statistics, which it desparately needs.
  - This will allow a better limit calculation and eventually a full calculation of the cross-section.

- ZH production is also relevant in linear e^+e^- colliders (ILC?)

Backup slides

Cross-section and BRs