Search for the Standard Model Higgs boson in the associated production channel $t\bar{t}H \rightarrow 4\ell$ with the ATLAS detector

David A. DeMarco

[1]University of Toronto

June 17, 2014

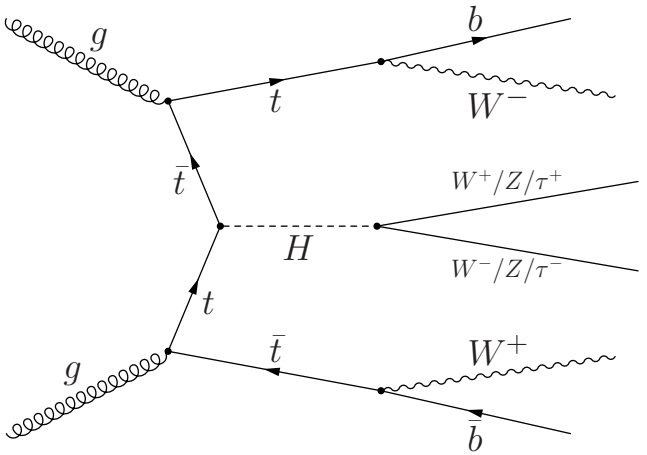
CAP Congress 2014
Laurentian University - Sudbury, Ontario

Introduction: $t\bar{t}H$ analyses

- Higgs boson studies are on-going, with significant effort continuing into measurements of its couplings to SM particles
  - Latest results agree with SM spin/parity prediction of 0^+
  - Initial coupling measurements do not show significant deviation from SM expectations
- Studies of $t\bar{t}H$ associated production offer direct probe of the Higgs-top quark coupling
- Current analysis of the 8 TeV dataset with the $t\bar{t}H \rightarrow 4\ell$ final state is presented here
- In collaboration with other multilepton final states, looking to place an optimal limit on the $t\bar{t}H$ cross-section
- Brief comments on extending this analysis to LHC Run 2 data are also given

$t\bar{t}H \rightarrow 4\ell$ signature

- The final state signature for the 4ℓ analysis includes:
  - 4 light charged leptons (e or μ)
    - Total charge of the leptons is zero
  - 2 b-quark jets
  - Possibly additional jets from radiation
  - Missing energy from leptonic decay of W bosons
- Requiring this signature allows sensitivity to 3 Higgs boson decay modes through various combinations of leptonic decays
  - $\mathbf{H \rightarrow W^+W^-}$, $\mathbf{H \rightarrow \tau^+\tau^-}$ and $\mathbf{H \rightarrow ZZ}$
- In the $H \rightarrow ZZ$ case, additional hadronic decays of the intermediate particles may result in a higher jet multiplicity



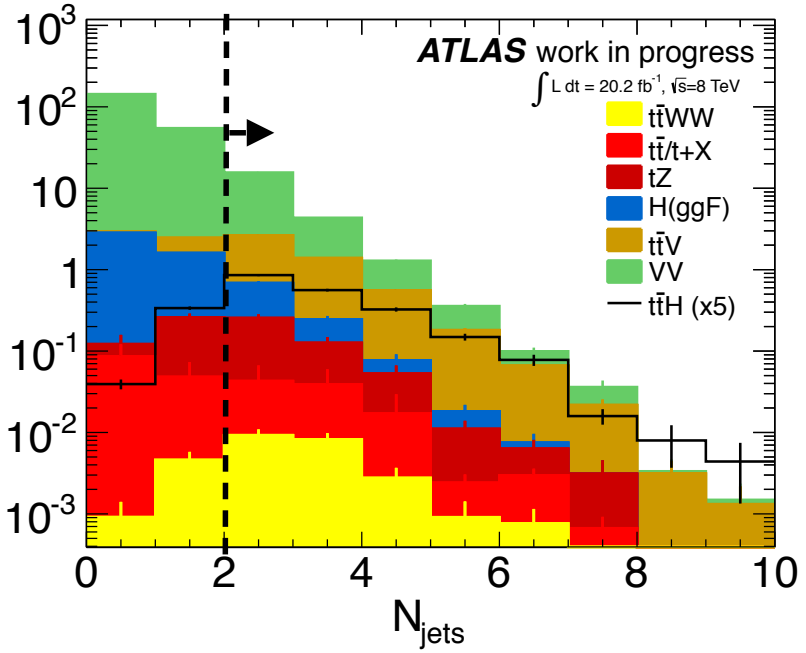
Background composition

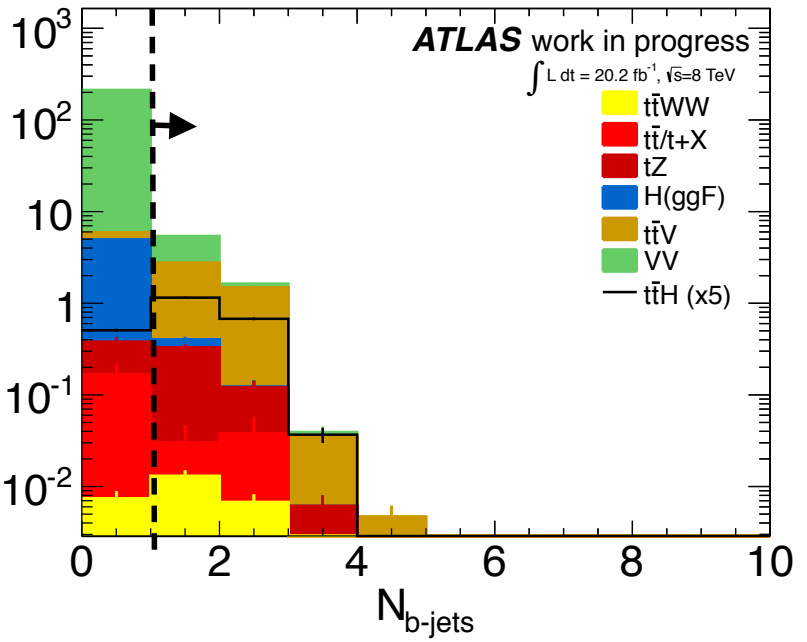
The major background sources for the 4ℓ channel include:

- $t\bar{t}Z/\gamma^*$
  - $\sim 75\%$ of total background
- Diboson $ZZ(+\text{ jets})$
  - $\sim 9\%$ of total background
- Single top tZ
  - $\sim 9\%$ of total background
- Small contributions from other Higgs production modes (ggF $H \to ZZ \to 4\ell$)
  - $\sim 2\%$
  - Can validate against other analyses
- Background from fake lepton objects
  - $\sim 2\%$
  - $t\bar{t}$+jets, Z+jets, WZ
  - Data-driven estimates

Background suppression: jet multiplicities

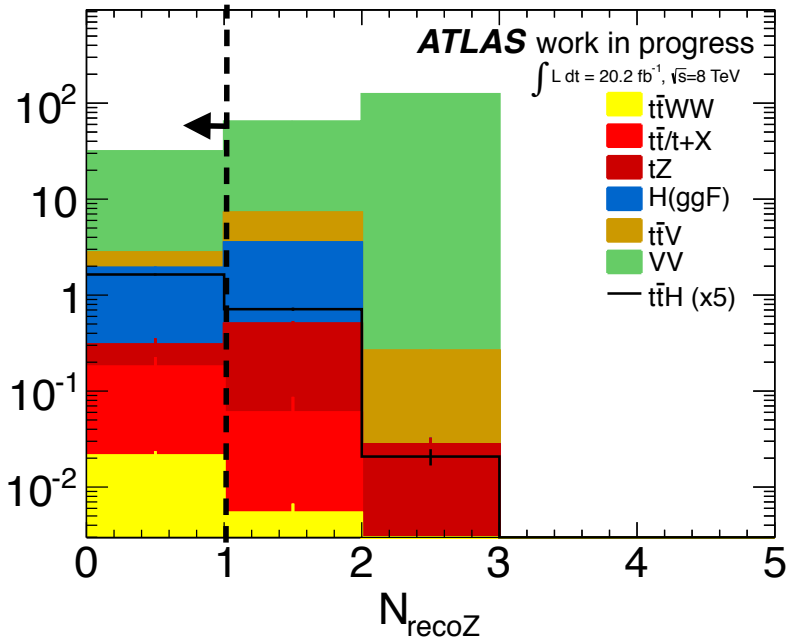
- Expected spectra for both the jet multiplicity and the number of b-jets differs between signal and the major backgrounds
  - Plots drawn at preselection, prior to signal region event selection
  - Signal expectation scaled $\times 5$
- Diboson background peaks at low jet multiplicity
- $t\bar{t}Z/\gamma^*$ background on top of signal
- **Cuts**: ≥ 2 jets, ≥ 1 b-jet

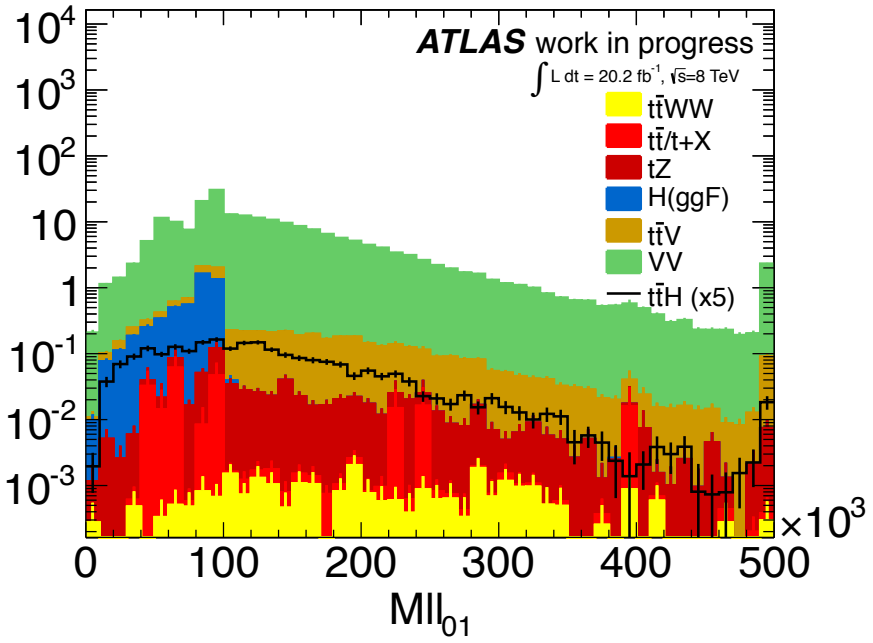




Background suppression: Z-veto

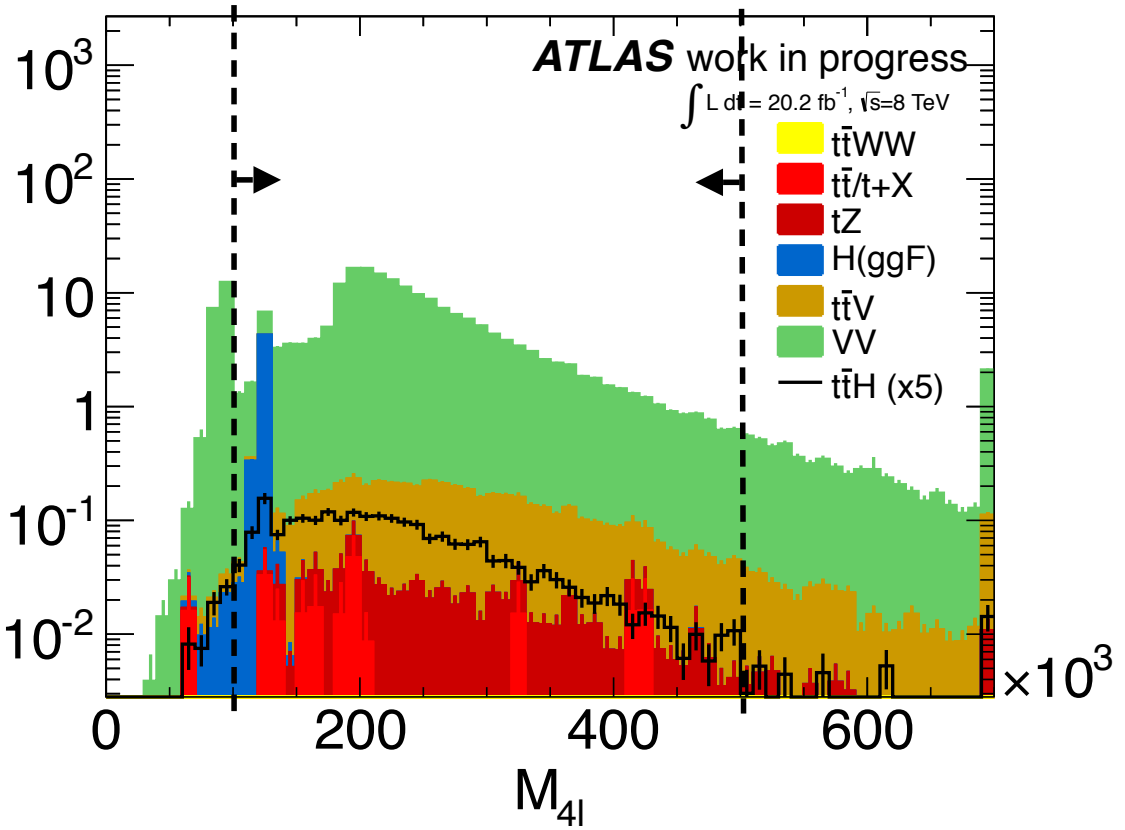
- Number of Z-boson candidate lepton pairs N_{recoZ} computed as number of opposite sign-same flavour lepton pairs within 10 GeV of Z mass (91 GeV)
  - Largest portions of leading backgrounds in $N_{\mathrm{recoZ}} = 1$ ($t\bar{t}Z$) and $N_{\mathrm{recoZ}} = 2$ (ZZ) bins
- Remaining background events from off-shell Z and γ^* continuum
- Effect on total signal is small due to comparatively low branching ratio of $H \to ZZ$
- **Cut**: require exactly 0 reconstructed Z-candidate lepton pairs (Z-veto)





Background suppression: $M_{4\ell}$ window

- Note the Z-mass resonance in the $M_{4\ell}$ spectrum from $ZZ^{(*)}$ events from on-shell $Z \to \ell^+\ell^-$ where one lepton radiates an off-shell boson $Z^*/\gamma^* \to \ell^+\ell^-$
- There is also high-mass discrimination between signal and background
- **Cut**: Require $100 < M_{4\ell} < 500$ GeV



Data-driven estimation of fake lepton background

Data-driven technique employed to estimate contribution from fake leptons (Z+jets, $t\bar{t}$):

1. Data estimate in control region (3 good leptons + 1 anti-lepton w. reversed selection)
   - Non-isolated electron objects
   - Reversed p_T cut for non-prompt muon objects
2. Extrapolate to SR using fake factor related to probability of loose lepton passing good lepton selection

$$N_{4\ell} = \epsilon_{\text{fake}} \times N_{3\ell+1\text{fake}} = \epsilon^2_{\text{fake}} \times N_{2\ell+2\text{fake}}$$

- ϵ factor taken from CRs well-separated from SR $\rightarrow$ working with 3ℓ analysis
- Current estimate order of magnitude smaller than signal
- Outstanding issues:
  - data-statistics limited $\rightarrow$ using $2\ell + 2\text{fake}$ CRs
  - Closure testing on ϵ factors with MC

Signal region, Monte Carlo

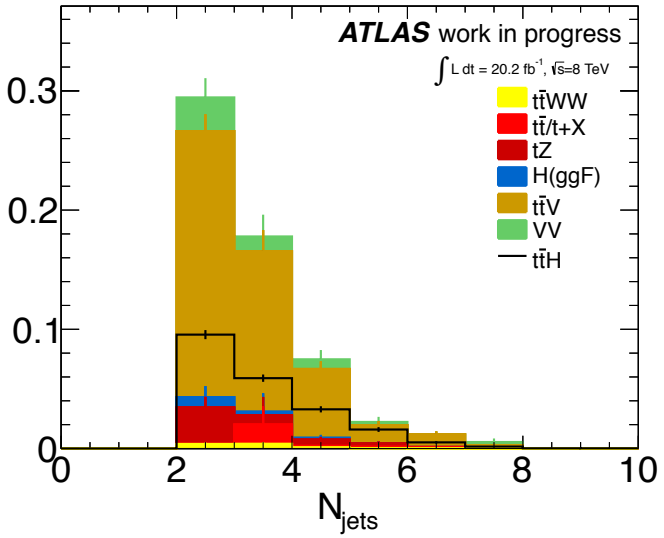
	$t\bar{t}H$	**Sum Bkg.**	$t\bar{t}V$	$t\bar{t}WW$	$t\bar{t}/t+X$	tZ	VV	H(ggF)
Preselection	0.48 ± 0.01	220 ± 1	4.77 ± 0.05	0.027 ± 0.003	0.21 ± 0.06	0.60 ± 0.03	209 ± 1	4.63 ± 0.06
Lepton p_T cuts	0.48 ± 0.01	219 ± 1	4.77 ± 0.05	0.027 ± 0.003	0.20 ± 0.05	0.60 ± 0.03	208 ± 1	4.61 ± 0.06
$M^{xy}_{\ell\ell} > 10$ GeV	0.47 ± 0.01	197 ± 1	4.61 ± 0.05	0.027 ± 0.003	0.17 ± 0.05	0.58 ± 0.03	188 ± 1	4.26 ± 0.06
$N_{\text{jets}} \geq 2$	0.39 ± 0.01	20.3 ± 0.2	3.69 ± 0.05	0.021 ± 0.002	0.07 ± 0.03	0.34 ± 0.02	15.6 ± 0.2	0.55 ± 0.02
Z-Veto	0.27 ± 0.01	2.04 ± 0.06	0.59 ± 0.02	0.017 ± 0.002	0.05 ± 0.03	0.06 ± 0.01	1.14 ± 0.05	0.18 ± 0.01
$N_{\text{b-jets}} \geq 1$	0.22 ± 0.01	0.70 ± 0.03	0.50 ± 0.02	0.012 ± 0.002	0.02 ± 0.02	0.05 ± 0.01	0.11 ± 0.02	0.013 ± 0.003
$100 < M_{4\ell} < 500$ GeV	0.21 ± 0.01	0.59 ± 0.03	0.44 ± 0.02	0.009 ± 0.002	0.02 ± 0.02	0.05 ± 0.01	0.054 ± 0.011	0.013 ± 0.003

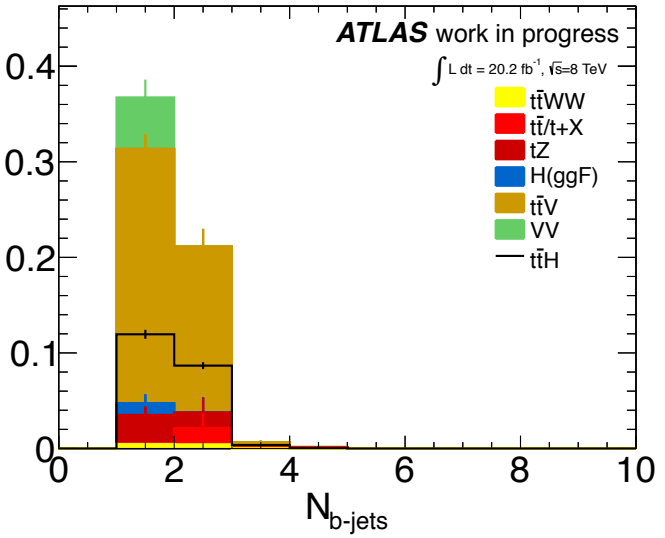
- Preselection includes:
  - Optimized object selections
  - 4 charged leptons, $Q_{total} == 0$
  - At least 1 trigger-matched lepton
- Lepton p_T cuts: $p^0_T > 25$ GeV, $p^1_T > 15$ GeV
- $M^{xy}_{\ell\ell} > 10$ GeV cut applied on OS-SF pairs $\rightarrow$ suppress Drell-Yan process

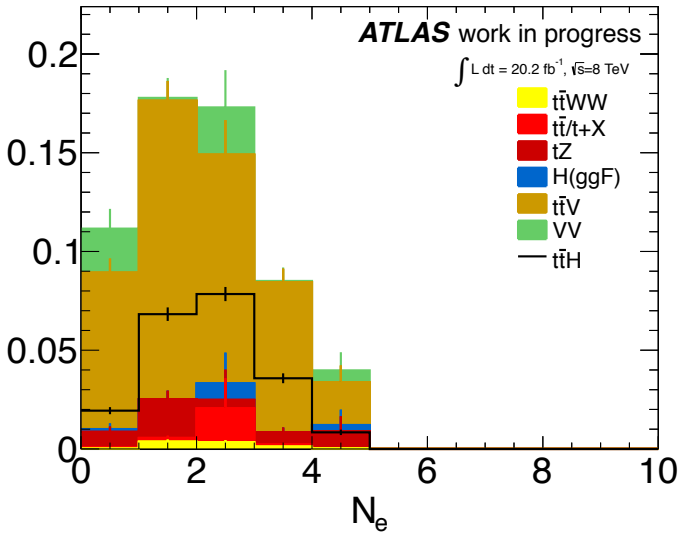
Note:

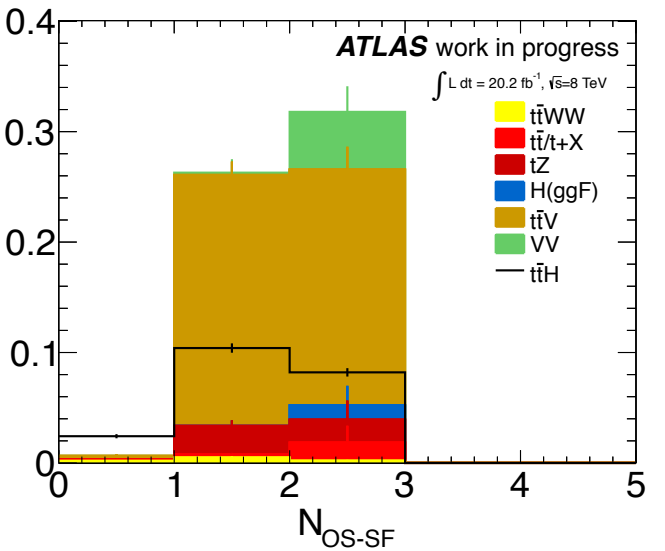
- Improvements:
  - Total signal cut by about 55%
  - Upwards of 99% of background events cut
- $\frac{S}{B} \approx 0.36$, clean channel
- Preliminary expected limit: $\sigma/\sigma_{\text{SM}} \approx 12.5$

Signal region distributions



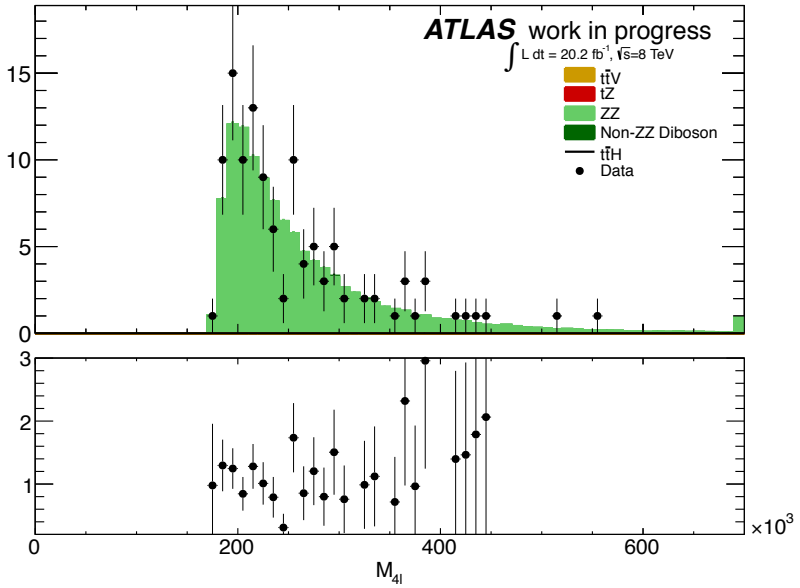


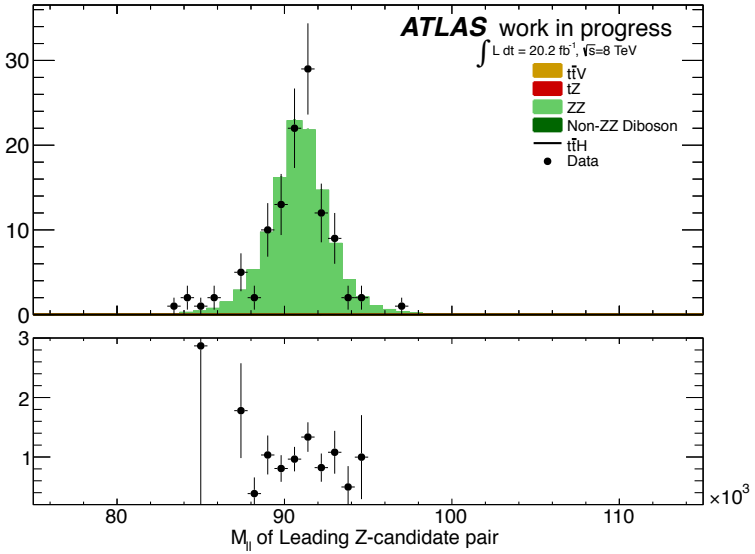


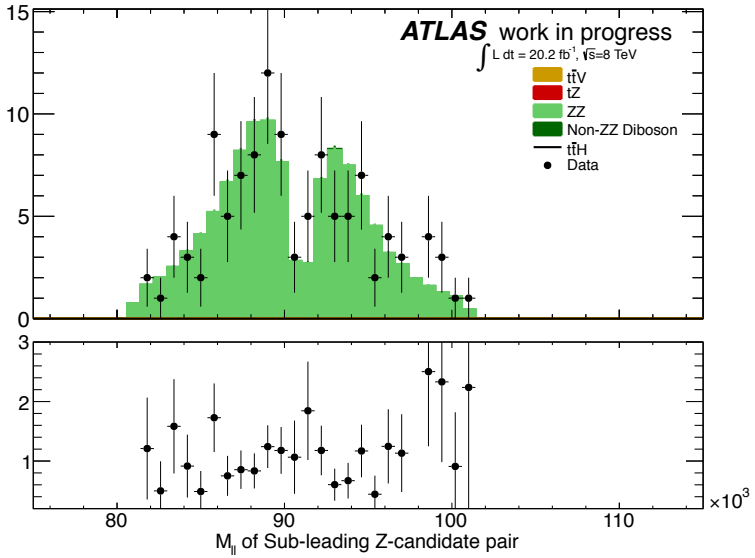


ZZ validation region

- Orthogonal validation region
  - $N_{\mathrm{recoZ}} == 2$
  - Reversed jet multiplicity cuts ($N_{\mathrm{jet}} \leq 2$, no b-jets)
  - No $M_{4\ell}$ cut applied
- Data/MC agreement gives confidence in ZZ estimate in SR
- Consider use as normalization







Possible improvements and prospects for $t\bar{t}H \to 4\ell$ @ 13 TeV

A number of remaining items:

- Finalize MC bkg. estimates (CR normalizations) and fake bkg. estimates
- Fully consider systematics, perform combination and set a limit on the cross-section with the related analyses
  - Related channels: $2\ell_{(\mathrm{SS})}$, $2\ell_{(\mathrm{SS})} + \tau$, 3ℓ and $\ell + 2\tau$

Significant improvements are expected with Run 2 data

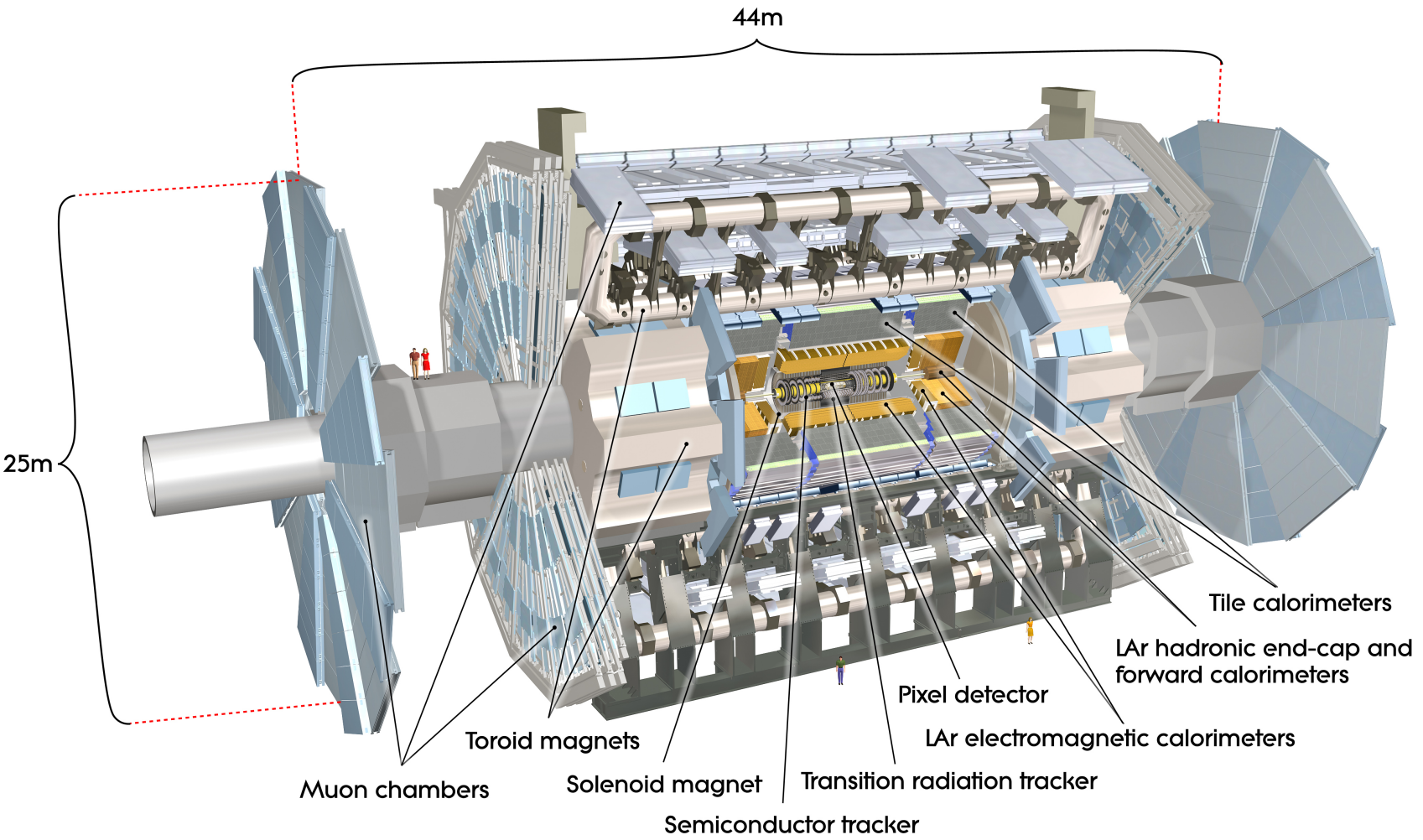
- Increased CoM energy to 13 TeV $\to$ factor of 5 in cross-section of $t\bar{t}H$ prod.
- Increased luminosity $\to$ aim: 40-45 fb^{-1} of data per year
- Can expect a very sensitive analyses with full Run 2 data

Additional ideas for Run 2 analysis include:

- Loosened object selections, re-optimization ($H \to 4\ell$ analysis)
- Inclusion of hadronic τ decays to increase event acceptance
- Application of multivariate analysis scheme for better selection efficiency

Back-up Slides

The ATLAS detector



$t\bar{t}H \rightarrow 4\ell$ signature

- The final state signature for the 4ℓ analysis includes:
  - 4 light charged leptons (e or μ)
    - Total charge of the leptons is zero
  - 2 b-quark jets
  - Possibly additional jets from radiation
  - Missing energy from leptonic decay of W bosons
- Requiring this signature allows three Higgs boson decays to be combined in order to increase statistics
  - $\mathbf{H \rightarrow W^+W^-}$: In this case, all W's (from the Higgs as well as the top quarks) are required to decay leptonically, $W^{\pm} \rightarrow \ell^{\pm}\nu$
  - $\mathbf{H \rightarrow \tau^+\tau^-}$: Here the charged leptons come from leptonic W decays and the leptonic decays $\tau^{\pm} \rightarrow \nu_{\tau}(W^{\pm} \rightarrow \ell^{\pm}\nu)$
  - $\mathbf{H \rightarrow ZZ}$: The 4 charged leptons may come from a combination of leptonic decays of the top quark W's and $Z \rightarrow \ell^+\ell^-$ decays
- In the $H \rightarrow ZZ$ case, additional hadronic decays of the intermediate particles may result in a higher jet multiplicity

Signal region definition

Cut	Requirement	Motivation
Lepton p_T	$p_T^0 > 25$ GeV, $p_T^1 > 15$ GeV	Prompt leptons from signal event
$M_{\ell\ell}^{xy}$ min.	$M_{\ell\ell}^{xy} > 10$ GeV for any OS-SF lepton pair xy	Discriminate against soft leptons from Drell-Yan radiation
Number of jets	$N_{\text{jets}} \geq 2$	Minimum jet multiplicity for signal, allowing for additional jets
Number of b-jets	$N_{\text{b-jets}} \geq 1$	Require 1 b-tag, allow for missed tag on second expected b-jet
Z-veto	If $81 < M_{\ell\ell}^{xy} < 101$ for any OS-SF lepton pair xy, remove event	Discriminate against dominant backgrounds containing Z-bosons
$M_{4\ell}$ window	$100 < M_{4\ell} < 500$ GeV	Minimum removes Z peak, exploits high-mass spectrum differences