Search for direct top squark pair production in events with a Higgs or Z boson, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

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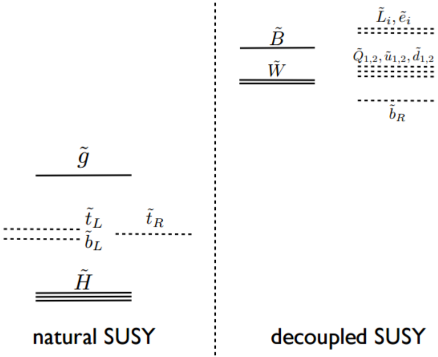
$\tilde{t}_2 \to \tilde{t}_1 + Z/h$ analysis

Motivations



Why the stop?

- In many SUSY models, could have mass < 1 TeV
- Top quark partner → **coupling** with *Higgs* of $\mathcal{O}(1)$
- Could hint to solutions to the **Hierarchy problem**
- Helicity eigenstates mix to form two **mass eigenstates**, $\tilde{t}_1$ and $\tilde{t}_2$

$\widetilde{t}_2 \rightarrow \widetilde{t}_1 + Z/h$ ANALYSIS

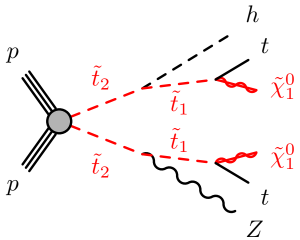
MOTIVATIONS

- Dedicated searches for direct $\widetilde{t}_1$ pair production optimized for **simplified decays** ($\widetilde{t}_1 \rightarrow \widetilde{\chi}_1^0 + t$) with low sensitivities for multi-step processes.

- Targeting the complex decay chain of the heavier $\widetilde{t}_2$ with a Z or h boson

$$\widetilde{t}_2 \rightarrow \widetilde{t}_1 + Z/h$$

in the **kinematic region:** $m_{\widetilde{t}_1} = m_{\widetilde{\chi}_1^0} + m_t$



$\tilde{t}_2 \rightarrow \tilde{t}_1 + Z/h$ analysis

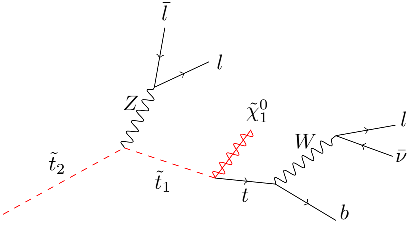
Motivations

Signal models:

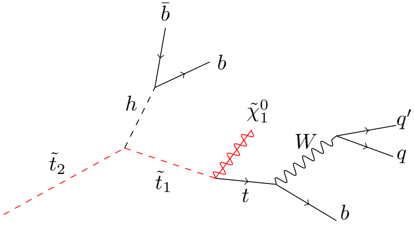
- $\tilde{t}_2$ produced in pair
- **Simplified model branches:** $\mathcal{B} = 100\%$ in either $\tilde{t}_1 + Z$ or $\tilde{t}_1 + h$
- **Signal Grid:** multiple $(m_{\tilde{t}_2}, m_{\tilde{\chi}_1^0})$ signal mass models
- **Remember!** $m_{\tilde{t}_1} = m_{\tilde{\chi}_1^0} + m_t$

Dataset: 36.1 fb^{-1} ATLAS data, $\sqrt{s}$ = 13 TeV, [2015 + 2016]

StopZ



StopH

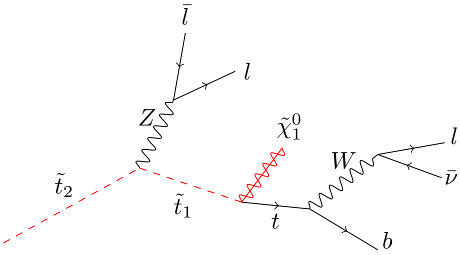


StopZ decay branch

StopZ decay strategy

StopZ decay branch

Signature



Signature:

- **Large** E_T^{miss}
  (due to ν and $\tilde{\chi}^0$)
- 3 **leptons** (e, μ)
  (2 of them must be consistent with a Z leptonic decay)
- 1 **b-tagged jet**
  (from the t decay)

SM Backgrounds:

- **Fakes** & **non-prompt lepton:** data driven
- $t\bar{t} + Z$: modeled with `aMc@NloPythia8`
- **Multibosons (mostly WZ):** modeled with `Sherpa 2.2.1`

StopZ decay branch

Signal Region definitions

Optimization by maximizing discovery significance performed on 3 mass points $(m_{\tilde{t}_2}, m_{\tilde{\chi}_1^0})$ lead to 3 **Signal Region** definitions, based on the mass splitting between $\tilde{t}_2$ and $\tilde{t}_1$:

- $\mathbf{SR}_C^{3\ell 1b}$: small mass splitting between $\tilde{t}_2$ and $\tilde{t}_1$, soft Z boson
- $\mathbf{SR}_B^{3\ell 1b}$: intermediate mass splitting
- $\mathbf{SR}_A^{3\ell 1b}$: high mass splitting between $\tilde{t}_2$ and $\tilde{t}_1$, boosted Z boson

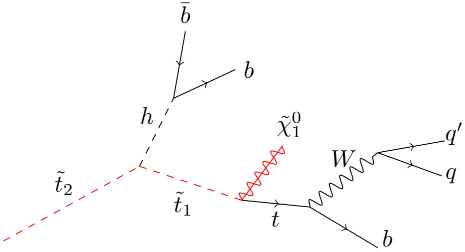
Var/region	$SR_A^{3\ell 1b}$	$SR_B^{3\ell 1b}$	$SR_C^{3\ell 1b}$
$m^{\ell\ell}$ [GeV]	< 15	< 15	< 15
p_T^{lep} [Gev]	> 40	> 40	> 40
p_T^{jet} [GeV]	> 250	> 80	> 60
p_T^{bjet} [GeV]	> 40	> 40	> 40
$n_{bjets}(p_T > 30$ GeV)	≥ 1	≥ 1	≥ 1
$n_{jets}(p_T > 30$ GeV)	≥ 6	≥ 6	≥ 5
E_T^{miss} [GeV]	> 100	> 180	> 140
$p_T^{\ell\ell}$ [GeV]	> 150	–	< 80

StopH decay branch

StopH decay strategy

StopH decay branch

Signature



Signature:

- **Large E_T^{miss}** (ν and $\tilde{\chi}^0$)
- 3 **b-tagged jets** (2 of them must be compatible with Higgs decay)
- 1 **lepton (e, μ)** ($p_T > 30 GeV$)

SM Backgrounds:

$t\bar{t}$ ($> 80\%$)

$V + jets$

$t\bar{t} + H$

StopH decay branch

Signal Regions

Optimization performed on 3 mass points ($m_{\tilde{t}_2}$, $m_{\tilde{\chi}_1^0}$) lead to 3 **Signal Region** definitions, based on the mass splitting between $\tilde{t}_2$ and $\tilde{t}_1$:

- **SR**$_C^{1\ell 4b}$: small mass splitting between $\tilde{t}_2$ and $\tilde{t}_1$, soft Higgs
- **SR**$_B^{1\ell 4b}$: intermediate mass splitting
- **SR**$_A^{1\ell 4b}$: high mass splitting between $\tilde{t}_2$ and $\tilde{t}_1$, boosted Higgs

Requirement/region	$SR_A^{1\ell 4b}$	$SR_B^{1\ell 4b}$	$SR_C^{1\ell 4b}$
n_{bjets}	≥ 4	≥ 4	≥ 4
n_{lep}	1–2	1 – 2	1 – 2
m_T [GeV]	–	> 150	> 125
H_T [GeV]	> 1000	–	–
E_T^{miss} [GeV]	> 120	> 150	> 150
p_T^{bjet} [GeV]	–	–	< 140
p_T^{bb} [GeV]	> 300	–	–
m_{bb} [GeV]	95 – 155	–	–
n_{jet} ($p_T > 60$ GeV)	≥ 6	≥ 5	–
n_{jet} ($p_T > 30$ GeV)	–	–	≥ 7

Bottom quarks coming from the Higgs boson decay identified as the **most collimated pair**.

$$H_T \equiv \sum ||p_{Ti}||$$
$$(||p_{Ti}|| \geq 30 \text{ GeV})$$

Sensitive to large expected signal **hadronic activity**

StopH decay branch

Control regions

Due to the relatively big differences between the various Signal regions, **multiple Control regions** are necessary for the normalization of $t\bar{t}$ production:

- for $SR_A^{1\ell 4b}$, $SR_B^{1\ell 4b}$, $SR_C^{1\ell 4b}$ by $CRT_A^{1\ell 4b}$, $CRT_B^{1\ell 4b}$, $CRT_C^{1\ell 4b}$ respectively (≈ 85 % purity)
- the selection inverts the SRs E_T^{miss} and the relax/inverts the m_T selection

Requirement/Region	$CRT_A^{1\ell 4b}$	$CRT_B^{1\ell 4b}$	$CRT_C^{1\ell 4b}$
n_{bjets}	≥ 4	≥ 4	≥ 4
n_{lep}	$1-2$	$1-2$	$1-2$
m_T [GeV]	–	> 100	< 125
E_T^{miss} [GeV]	< 120	< 150	< 150
p_T^{bjet} [GeV]	–	–	< 140
p_T^{bb} [GeV]	> 300	–	–
m_{bb} [GeV]	$95-155$	–	–
n_{jets} ($p_T > 60$ GeV)	≥ 5	≥ 5	–
n_{jets} ($p_T > 30$ GeV)	–	–	≥ 7

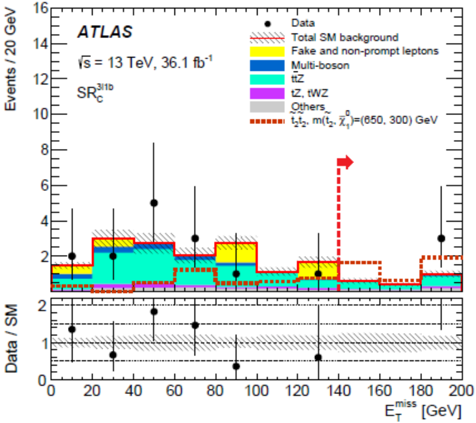
Results

Results

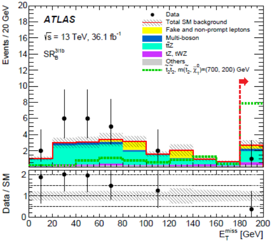
RESULTS

STOPZ DECAY BRANCH - KINEMATIC DISTRIBUTIONS

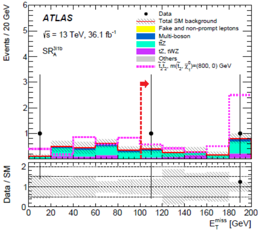
$SR_{C}^{3\ell 1b}$



$SR_{B}^{3\ell 1b}$



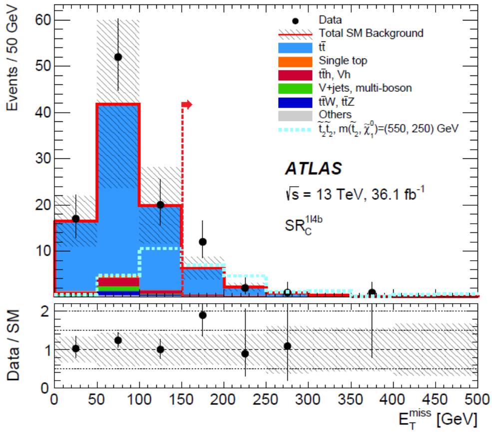
$SR_{A}^{3\ell 1b}$



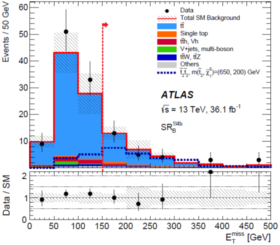
Results

StopH decay branch - Kinematic distributions

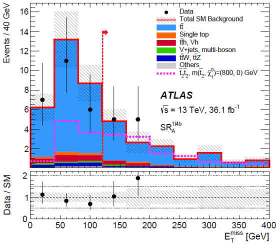
$SR_C^{1\ell 4b}$



$SR_B^{1\ell 4b}$



$SR_A^{1\ell 4b}$



Results
Yields

StopZ decay branch

	$SR_A^{3\ell 1b}$	$SR_B^{3\ell 1b}$	$SR_C^{3\ell 1b}$
Observed events	**2**	**1**	**3**
Total (post-fit) SM events	$\mathbf{1.9 \pm 0.4}$	$\mathbf{2.7 \pm 0.6}$	$\mathbf{2.0 \pm 0.3}$
Fit output, multi-boson	0.26 ± 0.08	0.28 ± 0.10	0.23 ± 0.05
Fit input, multi-boson	0.35	0.37	0.30

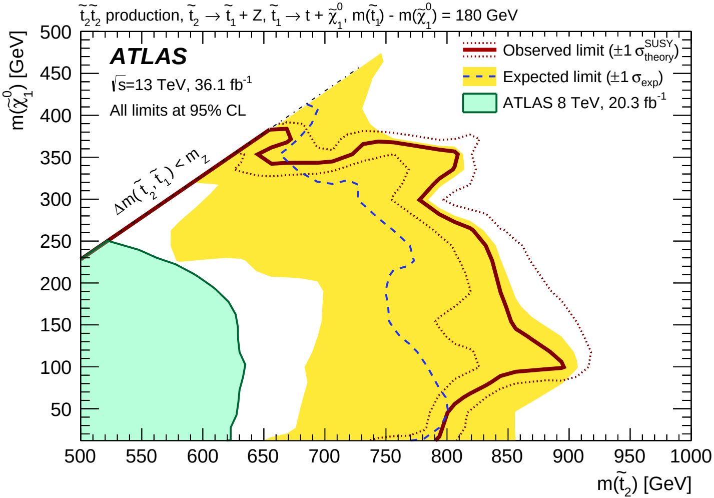
StopH decay branch

	$SR_A^{1\ell 4b}$	$SR_B^{1\ell 4b}$	$SR_C^{1\ell 4b}$
Observed events	**10**	**28**	**16**
Total (post-fit) SM events	$\mathbf{13.6 \pm 3.0}$	$\mathbf{29 \pm 5}$	$\mathbf{10.5 \pm 3.2}$
Fit output, $t\bar{t}$	11.3 ± 2.9	24 ± 5	9.3 ± 3.1
Fit input, $t\bar{t}$	7.1	14	6.0

Results

StopZ - Exclusion Limits

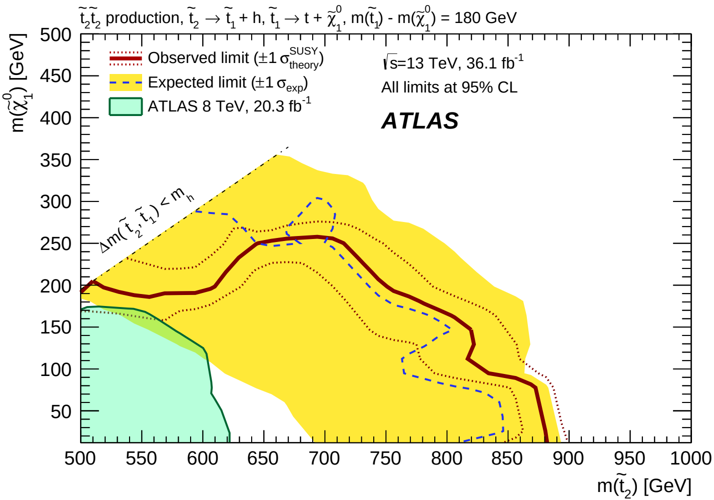
Excluded models in the $\tilde{t}_2$ - $\tilde{\chi}_1^0$ space



Results

StopH - Exclusion Limits

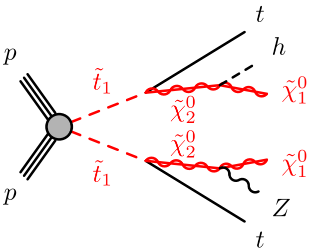
Excluded models in the $\tilde{t}_2$ - $\tilde{\chi}_1^0$ space



$\tilde{t}_1 \to \tilde{\chi}_2^0 + t$ reinterpretation
Motivations

Results are **reinterpreted** in a search for $\tilde{t}_1$ production:

$$\tilde{t}_1 \to \tilde{\chi}_2^0 + t$$

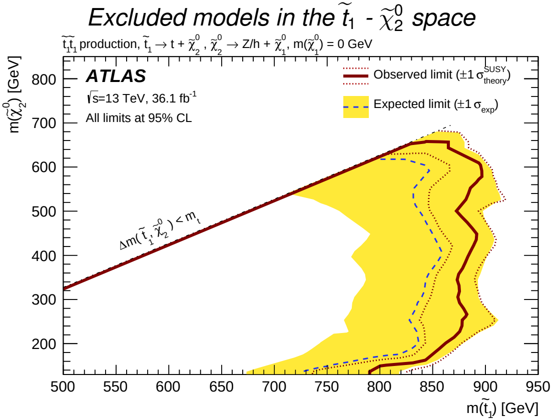


Signal model:

- $m_{\tilde{\chi}_1^0}$ = 0.5 GeV (*GMSB-like*)
- $\mathcal{B}(\tilde{t}_1^0 \to \tilde{\chi}_2^0 + t)$ = 100%
- $\mathcal{B}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + Z/h)$ = 50% for each decay branch
- $\Delta(m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}) \geq 130$ GeV (on-shell Z and h decays)

Results

Stop1 Reinterpretation - Exclusion Limits



– No specific analysis strategy have been applied for this reinterpretation.

– The two SRs with best expected sensitivity from the Higgs decay and Z decay selections are **statistically combined** to derive the limits

RECAP AND CONCLUSIONS

- A search for direct $\tilde{t}_2$ pair production has been presented, targeting the decay $\tilde{t}_2 \rightarrow \tilde{t}_1 + Z/h$ with 100% BR
- The search aims at the kinematic region with $m_{\tilde{t}_1} = m_{\tilde{\chi}_1^0} + m_t$
- Three **Signal Regions** have been defined for each of the two decay branches, based on the mass splitting between $\tilde{t}_2$ and $\tilde{t}_1$
- **Data agree with the SM background expectation** within uncertainties for both stopZ and stopH decay branches and thus exclusion limits for new physics BSM are extracted, up to $\sim$ 850 GeV for $\mathrm{m}_{\tilde{t}_2}$ and $\sim$ 250 GeV $\mathrm{m}_{\tilde{\chi}_1^0}$
- Exclusion limits are extracted for the $\tilde{t}_1 \rightarrow \tilde{\chi}_2^0 + t$ decay as well, covering $\tilde{t}_1$ masses up to 900 GeV

arXiv:1706.03986v1


THANKS
FOR YOUR ATTENTION
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BACKUP

Backup

StopZ - Background and Fakes estimation

Dominant backgrounds for the stopZ search are:

- **Fakes and non-prompt lepton:** estimated with data driven matrix-method
- $t\bar{t} + Z$: modeled with `aMc@NloPythia8`, normalised with dedicated Control Region (CRTZ$^{3\ell 1b}$)
- **Multibosons (mostly WZ):** modeled with `Sherpa 2.2.1`, normalised with dedicated Control Region (CRVV$^{3\ell 1b}$)

The selections of the control regions were chosen to be the as close as possible (but statistically independent) to the SR selection:

- **CRTZ**$^{3\ell 1b}$: targets the associated production of a $t\bar{t}$ pair and a Z boson. An upper cut on $E_T^{miss} < 100$ GeV ensures orthogonality ($\approx$ 60% purity).
- **CRVV**$^{3\ell 1b}$: targets the production of multiple bosons (VV + VVV). A b-veto ensures orthogonality (about 80% purity)

Backup

Model-independent limits

Signal selection	$\langle\epsilon\sigma\rangle^{95}_{\rm obs}$[fb]	$S^{95}_{\rm obs}$	$S^{95}_{\rm exp}$
SR3l1bA	0.13	4.8	$4.1^{+1.8}_{-0.5}$
SR3l1bB	0.11	4.1	$5.3^{+1.6}_{-1.2}$
SR3l1bC	0.16	5.8	$4.8^{+1.1}_{-1.0}$
SR1L4bA	0.27	10.0	$11.2^{+3.0}_{-3.6}$
SR1L4bB	0.34	12.4	$12.5^{+6.4}_{-2.2}$
SR1L4bC	0.31	11.3	$10.0^{+3.2}_{-2.2}$

Signal model-independent 95% CL upper limits on the visible cross section ($\langle\epsilon\sigma\rangle^{95}_{obs}$), the visible number of signal events $S^{95}_{\rm obs}$ and the number of signal events given the background events $S^{95}_{\rm exp}$

Backup

StopZ - Theory uncertainties

Truth level uncertainties, already included in the final interpretation.

- $t\bar{t}+Z, W$: **Scale uncertainties** evaluated with `MadGraph+Pythia8` samples. **Generator uncertainties** evaluated with Sherpa samples
- *diboson*: **Scale uncertainties** evaluated with dedicated `Sherpa` samples
- $t\bar{t}+W$ *Cross Section*: theoretical uncertainties for the $t\bar{t}+W$ cross section are 13%

Var/region	SR3ℓ1bC	SR3ℓ1bA	SR3ℓ1bB	CRTZ-3ℓ1b	CRVV-3ℓ1b
$t\bar{t}+Z$	6%	7%	12%	1%	2%
$t\bar{t}+W$	20%	32%	25%	7%	24%
diboson$(WZ+ZZ)$	19%	48%	37%	30%	30%

Backup

StopH - Theory uncertainties

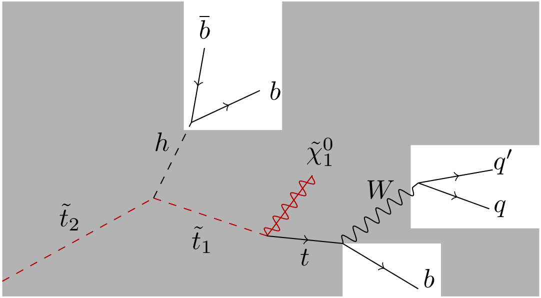
Truth level uncertainties, already included in the final interpretation

- $t\bar{t}$: **Generator/Hard scatter uncertainties** evaluated by comparing the predictions from `POWHEG-BOX` with `aMc@NLO 2.1.1`.
  Fragmentation/Hadronization evaluated by comparing the predictions from `POWHEG` with `Pythia 6.428` and `Herwig++ 2.7.1`.
  Additional Radiation evaluated with dedicated `Powheg+Pythia` samples
- $t\bar{t} + HF$: **Fraction uncertainties** truth level reweighting of the $t\bar{t} \geq 1b$ and $t\bar{t} \geq 1c$ components of the nominal $t\bar{t}$ sample varied up by 50%

Var/region	SR1ℓ4bC	SR1ℓ4bB	SR1ℓ4bA
$t\bar{t}+ \geq 1b$	7.1%	4.3%	0.5%
$t\bar{t}+ \geq 1c$	0.1%	2.5%	2.3%

Backup

Higgs boson reconstruction - χ^2

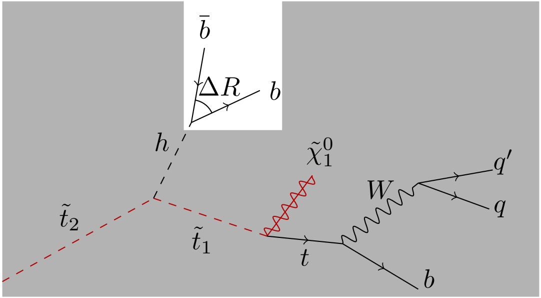


$$|M_{J_1+J_2} - M_W| < 30\ GeV \tag{1}$$

$$\chi_i^2 = \frac{(m_{t_i^{cand}} - m_t)^2}{10\% m_t} + \frac{(m_{H_i^{cand}} - m_H)^2}{10\% m_H} \tag{2}$$

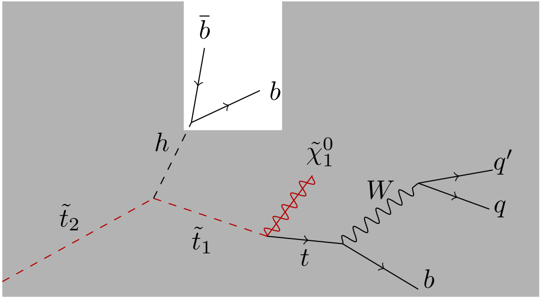
Backup

Higgs boson reconstruction - dR



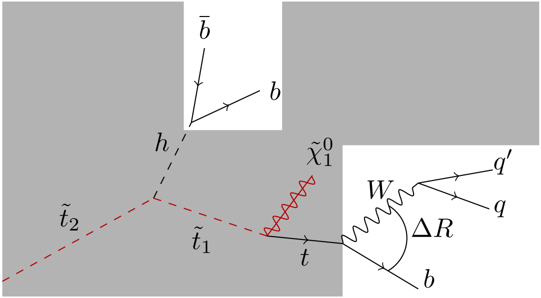
BACKUP

HIGGS BOSON RECONSTRUCTION - p_T^{bb}



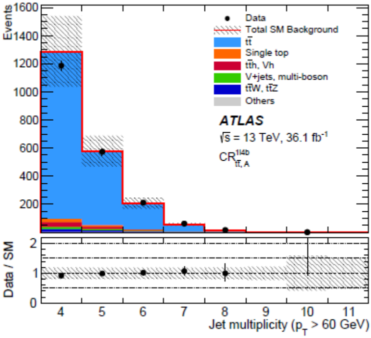
Backup

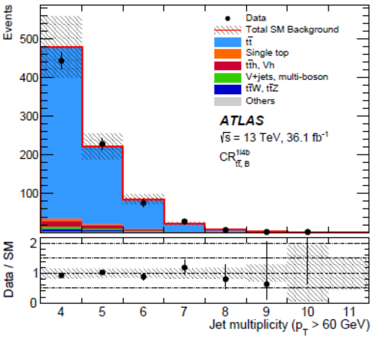
Higgs boson reconstruction - top reconstruction



Backup

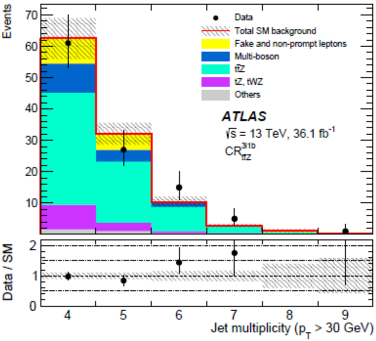
StopH - Control region kinematic distributions

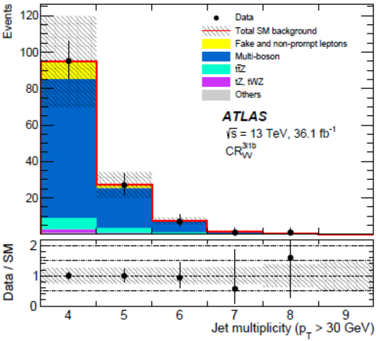




Backup

StopZ - Control region kinematic distributions





Backup

StopZ - Yields

	$SR^{3\ell 1b}A$	$SR^{3\ell 1b}B$	$SR^{3\ell 1b}C$
Observed events	**2**	**1**	**3**
Total (post-fit) SM events	**1.9** $\pm$ **0.4**	**2.7** $\pm$ **0.6**	**2.0** $\pm$ **0.3**
Fit output, multi-boson	0.26 ± 0.08	0.28 ± 0.10	0.23 ± 0.05
Fit output, $t\bar{t}Z$	1.1 ± 0.3	1.4 ± 0.5	1.2 ± 0.3
tZ, tWZ	0.43 ± 0.23	0.36 ± 0.19	0.19 ± 0.10
Fake or non-prompt leptons	$0.00^{+0.30}_{-0.00}$	0.45 ± 0.19	$0.00^{+0.30}_{-0.00}$
Others	0.09 ± 0.02	0.23 ± 0.06	0.36 ± 0.06
Fit input, multi-boson	0.35	0.37	0.30
Fit input,$t\bar{t}Z$	1.2	1.5	1.4

Backup

StopH - Yields

	$SR_A^{1\ell 4b}$	$SR_B^{1\ell 4b}$	$SR_C^{1\ell 4b}$
Observed events	**10**	**28**	**16**
Total (post-fit) SM events	**13.6 ± 3.0**	**29 ± 5**	**10.5 ± 3.2**
Fit output, $t\bar{t}$	11.3 ± 2.9	24 ± 5	9.3 ± 3.1
Single top	0.50 ± 0.18	1.7 ± 0.4	0.24 ± 0.07
V+jets, multi-boson	0.20 ± 0.15	0.23 ± 0.10	0.01 ± 0.01
$t\bar{t}\,h$, Vh	0.89 ± 0.16	1.19 ± 0.35	0.56 ± 0.13
$t\bar{t}\,W$, $t\bar{t}\,Z$	0.36 ± 0.21	1.09 ± 0.31	0.10 ± 0.10
Others	0.37 ± 0.20	1.33 ± 0.69	0.34 ± 0.18
Fit input, $t\bar{t}$	7.1	14	6.0

Backup

StopZ - Control regions

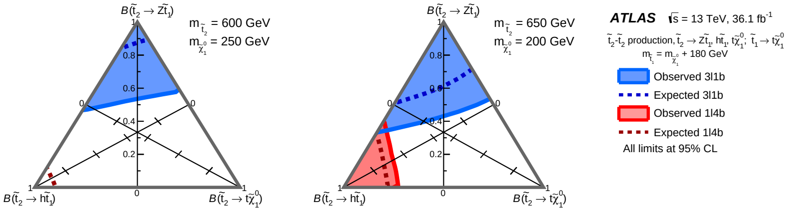
Two control regions have been designed to measure from data the normalisation of the two main backgrounds of this decay branch, $t\bar{t} + Z$ and multi-boson production (VV). The selections of the control regions were chosen to be the as close as possible to the SR selection:

- CRTZ$^{3\ell 1b}$: targets the associated production of a $t\bar{t}$ pair and a Z boson. An upper cut on $E_T^{miss} < 100$ GeV ensures orthogonality ($\approx$ 60% purity).
- CRVV$^{3\ell 1b}$: targets the production of multiple bosons (VV + VVV). A b-veto (n_b = 0)ensures orthogonality (about 80% purity)

Var/Region	CRTZ$^{3\ell 1b}$	CRVV$^{3\ell 1b}$
$m_{\ell\ell}$ [GeV]	76.2–106.2	76.2–106.2
Leading lepton pT [GeV]	> 40	> 40
Leading jet pT [GeV]	> 60	> 30
n_{b-jets}	≥ 1	0
$n_{jets}(pT > 30 GeV)$	≥ 4	≥ 4
E_T^{miss} [GeV]	< 100	–
$pt^{\ell\ell}$ [GeV]	–	–

Backup

Triangular plots



Backup

StopZ - Analysis Strategy

Optimization by maximizing discovery significance performed on 3 mass points $(m_{\tilde{t}_2}, m_{\tilde{\chi}_1^0})$ lead to 3 **Signal Region** definitions, based on the mass splitting between $\tilde{t}_2$ and $\tilde{t}_1$:

- $\mathbf{n}_{jet}$ jet multiplicity
- $\mathbf{n}_{bjet}$ b-jet multiplicity
- $\mathbf{E}_T^{miss}$ missing transverse energy
- $\mathbf{p}_T^{jet}$ leading jet transverse momentum
- $\mathbf{p}_T^{bjet}$ leading b-jet transverse momentum
- $\mathbf{p}_T^{lep}$ leading lepton transverse momentum
- $\mathbf{p}_T^{\ell\ell}$ transverse momentum of the $\ell\ell$ reconstructed pair
- $\Delta\mathbf{m}_{\ell\ell}$ mass of the reconstructed $\ell\ell$ pair from the Z boson decay minus the mass of the Z boson

Backup

StopH - Analysis Strategy

Optimization by maximizing discovery significance performed on 3 mass points $(m_{\tilde{t}_2}, m_{\tilde{\chi}_1^0})$ lead to 3 **Signal Region** definitions, based on the mass splitting between $\tilde{t}_2$ and $\tilde{t}_1$:

$\mathbf{m}_T$	lepton transverse mass
$\mathbf{H}_T$	sum of jets transverse momenta $\geq$ 30 GeV
$\mathbf{E}_T^{miss}$	missing transverse energy
$\mathbf{p}_T^{bjet}$	leading b-jet transverse momentum
$\mathbf{p}_T^{bb}$	transverse momentum of the $b\bar{b}$ reconstructed pair
$\mathbf{n}_{jet}$	jet multiplicity
$\mathbf{n}_{bjet}$	b-tagged jet multiplicity
$\mathbf{m}_{bb}$	mass of the reconstructed $b\bar{b}$ pair from the Higgs boson

Bottom quarks coming from the Higgs boson decay identified as the **most collimated pair**.

$$H_T \equiv \sum ||p_{Ti}||, \; for\ jet\ momenta\ ||p_{Ti}|| \; \geq \; 30 GeV$$

Sensitive to large expected signal **hadronic activity**