SUSY Searches in Run II with ATLAS

Chris Young, CERN

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Introduction

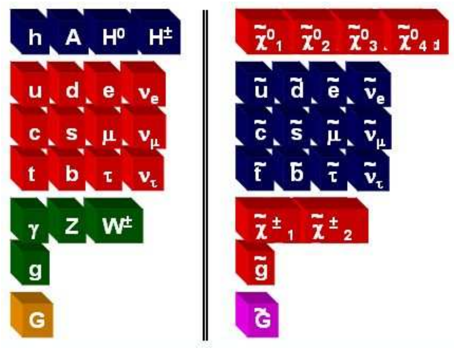
- Supersymmetry is the leading theoretical extension to the Standard model of particle physics.
- It predicts a number of additional particles which are the subject of many searches by the general purpose experiments at the LHC.
- Today I will discuss some of the ATLAS searches for strongly produced R-parity conserving supersymmetric particles.
- It isn't possible to cover all of the ATLAS searches for SUSY with the Run II data (it would also become a boring list).
- Therefore I will concentrate on 4 searches which I am either more connected with and/or I think would be interesting to this audience.

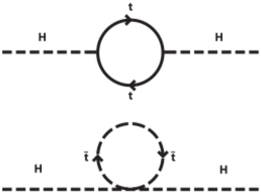
Outline

- The outline of my talk is:
  - Introduction to SUSY
  - Introduction to ATLAS
  - 0-lepton m_{eff} search
  - 0-lepton high jet multiplicity search
  - Z+(jets+)$E_{\text{T}}^{\text{miss}}$ search
  - Stop search with 1-lepton
  - Conclusions

Introducing SUSY

- Supersymmetry postulates that every Standard Model particle has a supersymmetric partner differing in spin by a 1/2.
- This solves the hierarchy problem associated with the Higgs boson as the top loop is cancelled by the loop of it's partner.
- The partners with the same quantum numbers mix to form mass eigenstates.





R-Parity Conservation

- To prevent proton decay it is common to introduce a conservation law known as R-parity where all supersymmetric particles have -1 and Standard Model particles have +1.
- This means that the lightest supersymmetric particle is stable and all supersymmetric particles need to be produced in pairs.
- As the lightest supersymmetric particle (LSP) is stable we usually consider it to be the lighest neutralino ($\tilde{\chi}_1^0$) as we haven't observed any coloured or charged stable massive particles.
- This will lie at the end of any chain of decay of produced SUSY particles and will pass through the detector undetected.
- This gives a characteristic signal for the models that we are searching for.
- It also makes the LSP a suitable **dark matter candidate!**

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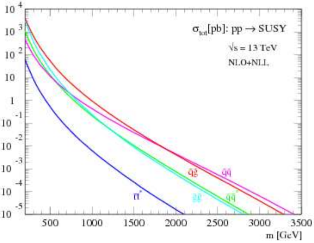
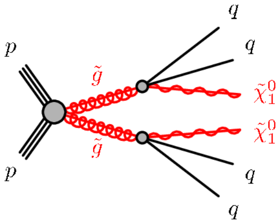
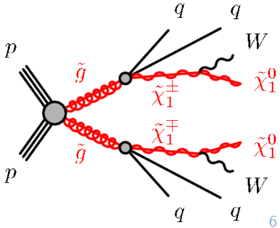
SUSY Particle Production and Decay

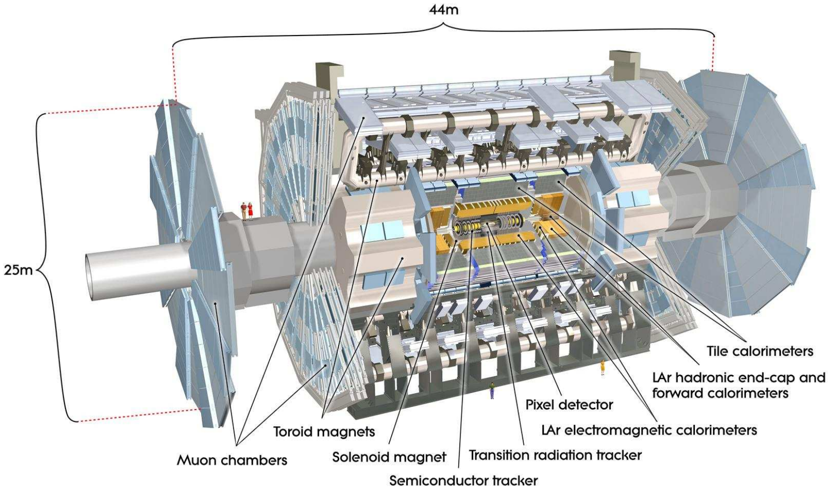
- The SUSY particles with the highest cross-section are those which carry colour-charge; the partners of the gluon; the gluino ($\tilde{g}$), and the quarks; the squarks ($\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}$).
- The searches described here are targeting the gluino and the stop.
- These are pair produced and then decay to SM particles and the LSP.
- There are a variety of ways that they can decay which depend on the masses of the different SUSY particles.
- In the models we consider here we pick single decay modes to set limits on the different models.



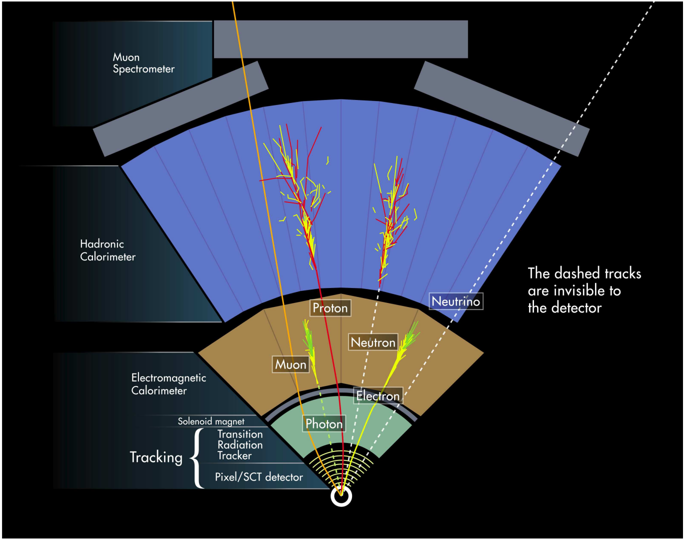




The ATLAS Detector



Object Reconstruction



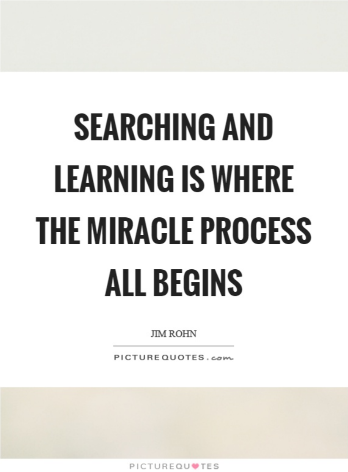
Object Reconstruction

- Using a combination of the inner detector and the muon spectrometer we reconstruct muons.
- Using a combination of the EM calorimeter and the inner detector we reconstruct electrons and photons.
- Jets are formed from calorimeter energy deposits.
- At the analysis level there is an overlap removal which ensures that electrons (which leave deposits in the calorimeter) aren't also counted as jets.
- Tau identification uses a combination of the inner detector track information as well as the shape of the showers in the calorimeter.
- These form the basic objects upon which the analyses are based.

Missing Transverse Energy: $E_{\mathrm{T}}^{\mathrm{miss}}$

- The conservation of momentum means that in the transverse plane to the beam all the particles momenta should balance.
- If we have a particle which doesn't interact with the detector then an imbalance will be observed and this 2-vector is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$.
- The ATLAS $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction uses all the calibrated objects described on the previous slide including jets down to 20 GeV.
- For central jets with $20 < p_{\mathrm{T}} < 60\,\mathrm{GeV}$ we require that they are associated with the primary vertex.
- For soft-activity below this threshold neutral particles are ignored and with tracks from the primary vertex not associated with hard objects are used.

0-lepton m_{eff} search

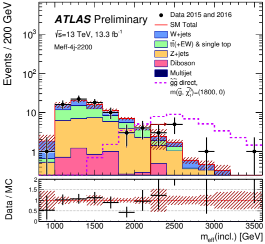


0-lepton m_{eff} search: Intro.

- The first search I will talk about is the traditional 0-lepton m_{eff} based search (link)
- This search has maintained the same methodology for many years and forms one of the key components of the ATLAS search for SUSY.
- During LS1 there was an effort to see how well we covered the more general SUSY parameter space and for models with "bino" LSP 89% of the models excluded by ATLAS could be excluded by this search alone.
- The motivation behind the search is that in the Standard model only $Z \to \nu\nu$ produces real $E_{\mathrm{T}}^{\mathrm{miss}}$ without the presence of leptons such that by vetoing leptons and then requiring many hard jets the standard model background is much reduced while maintaining large signal acceptance.

0-lepton m_{eff} search: Variables

- The primary variable is m_{eff} which is defined as the scalar sum of all the jets in the event along with the $E_{\mathrm{T}}^{\mathrm{miss}}$.
- This is motivated by the mass of the two produced SUSY particles being significantly greater than the SM background.
- Cuts on the angle between the $E_{\mathrm{T}}^{\mathrm{miss}}$ and jets, along with the ratio between $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_{eff} reduce the QCD background from jet mis-measurement to negligible levels.
- Requiring the jets to be relatively central and the event shape to be "rounder" reduces the backgrounds from V+jets.



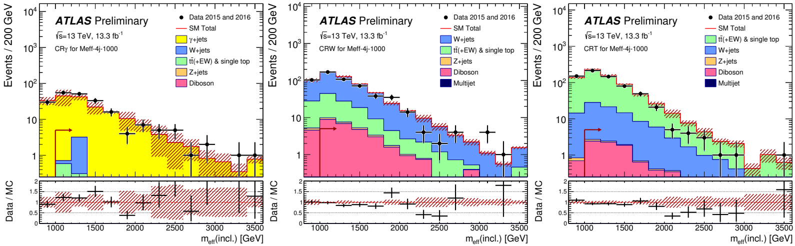
0-lepton m_{eff} search: Variables

Requirement	Signal Region					
	Meff-4j-1000	**Meff-4j-1400**	**Meff-4j-1800**	**Meff-4j-2200**	**Meff-4j-2600**	**Meff-5j-1400**
$E_{\text{T}}^{\text{miss}}$ [GeV] $>$	250					
$p_{\text{T}}(j_1)$ [GeV] $>$	200					500
$p_{\text{T}}(j_4)$ [GeV] $>$	100			150		50
$p_{\text{T}}(j_5)$ [GeV] $>$	–					50
$\|\eta(j_{1,2,3,4})\| <$	1.2	2.0			–	
$\Delta\phi(\text{jet}_{1,2,(3)}, \boldsymbol{E}_{\text{T}}^{\text{miss}})_{\text{min}} >$	0.4					
$\Delta\phi(\text{jet}_{\text{i}>3}, \boldsymbol{E}_{\text{T}}^{\text{miss}})_{\text{min}} >$	0.4					0.2
Aplanarity $>$	0.04					–
$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}(N_{\text{j}}) >$	0.25		0.2			0.3
m_{eff}(incl.) [GeV] $>$	1000	1400	1800	2200	2600	1400

Targeted signal	$\tilde{g}\tilde{g}$, $\tilde{g} \to q\bar{q}W\tilde{\chi}_1^0$	
Requirement	Signal Region	
	Meff-6j-1800	**Meff-6j-2200**
$E_{\text{T}}^{\text{miss}}$ [GeV] $>$	250	
$p_{\text{T}}(j_1)$ [GeV] $>$	200	
$p_{\text{T}}(j_6)$ [GeV] $>$	50	100
$\|\eta(j_{1,\ldots,6})\| <$	2.0	–
$\Delta\phi(\text{jet}_{1,2,(3)}, \boldsymbol{E}_{\text{T}}^{\text{miss}})_{\text{min}} >$	0.4	
$\Delta\phi(\text{jet}_{\text{i}>3}, \boldsymbol{E}_{\text{T}}^{\text{miss}})_{\text{min}} >$	0.2	
Aplanarity $>$	0.08	
$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}(N_{\text{j}}) >$	0.2	0.15
m_{eff}(incl.) [GeV] $>$	1800	2200

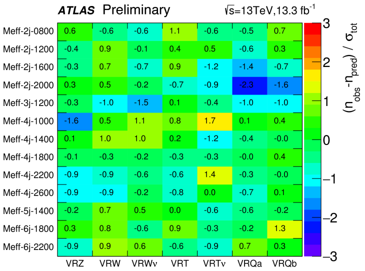
0-lepton m_{eff} search: Background Estimation

- The primary backgrounds to the search are $Z \to \nu\nu$+jets, $W \to l\nu$+jets, and $t\bar{t}$(including $t\bar{t} + V$ and single top).
- Those featuring leptons usually make it to the signal region either because the lepton is a hadronic τ or because it failed the ID or p_{T} criteria.
- The $Z \to \nu\nu$ background is estimated from a photon sample.
- The $W \to l\nu$+jets, and $t\bar{t}$ backgrounds are estimated from regions requiring a lepton and are separated by the requirement of a b-tagged jet.
- The ratios between the "control regions" and the SR are taken from MC.
- A simultaneous fit is performed across the different regions.



0-lepton m_{eff} search: Results and Interpretation

- Validation regions with tightened criteria (or $Z \to ll$) are used to test the background estimate close to the SR.
- The yields in all the signal regions are consistent with the background estimation (lowest p-value 0.06).
- Therefore limits are set on the various models taking the best signal region at each point in the parameter space.



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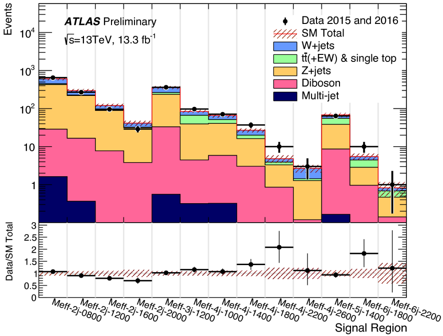

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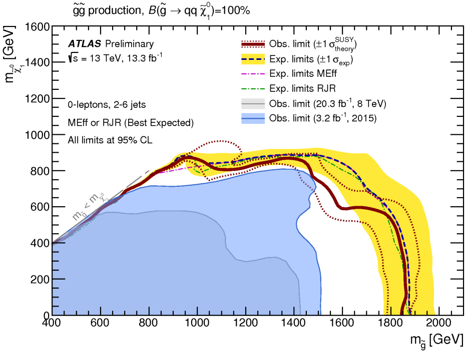
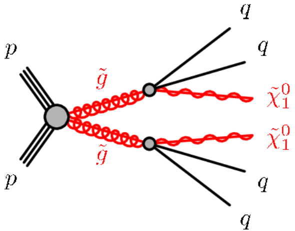
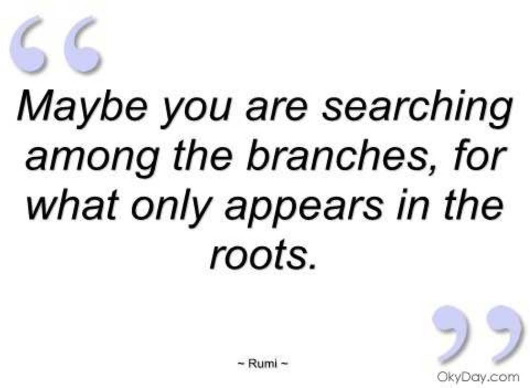




0-lepton high jet multiplicity search



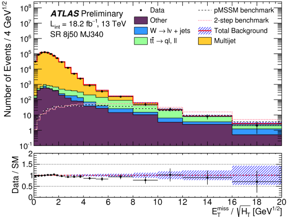
0-lepton high jet multiplicity search: Intro

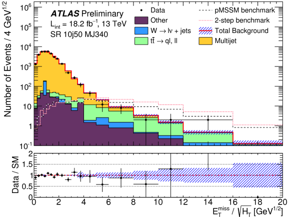
- The next search is another 0-lepton search but targetting longer decay chains (link).
- When more particles are involved in the decay the available energy for the LSP is reduced and therefore so is the $E_{\mathrm{T}}^{\mathrm{miss}}$.
- This search therefore counts jets up to very high multiplicity and has a much softer cut on $E_{\mathrm{T}}^{\mathrm{miss}}$.
- While the $t\bar{t}$ and EW backgrounds are estimated in the same way as the first search a major component of the background is now QCD multi-jets which requires a specific data-driven approach.
- The analysis also employs a cut on the sum of the masses of large radius jets to take advantage of the "accidental substructure" present in these signals.

Signal region	8j50	9j50	10j50
$R = 0.4$ jet $\|\eta\|$		< 2.0 for all SRs	
$R = 0.4$ jet p_T		> 50 GeV for all SRs	
N_{jet}	≥ 8	≥ 9	≥ 10
M_J^{Σ}		> 340 GeV or > 500 GeV	
$E_T^{miss}/\sqrt{H_T}$		$> 4\,\mathrm{GeV}^{1/2}$ for all SRs	

0-lepton high jet multiplicity search: Background Estimation

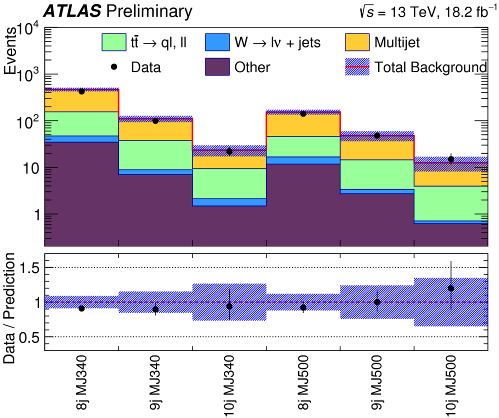
- This search is designed for the determination of the multijet background.
- $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_T}$, where H_T is the scalar sum of jet p_{T}, is an estimator of the significance of the $E_{\mathrm{T}}^{\mathrm{miss}}$ from jet measurements.
- This means that for high jet multiplicities the shape of this distribution is invariant under changes in jet multiplicity.
- A template of the shape of this distribution is taken using 6-jet events, and then applied to the signal region multiplicities (≥ 8).
- Intermediate jet multiplicities and value of $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_T}$ are used to validate the method.





0-lepton high jet multiplicity search: Results

- Again good agreement is seen in all the signal regions with the SM background estimation.
- Limits are set using the best expected signal region.



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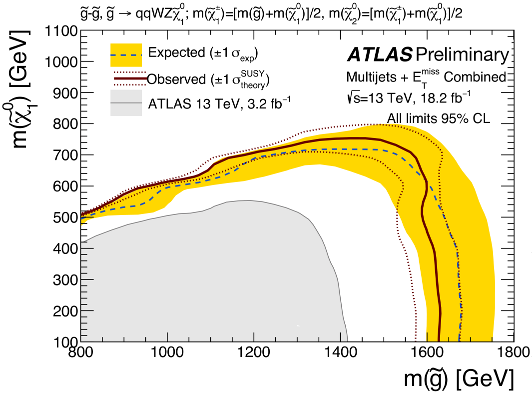

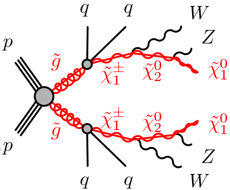

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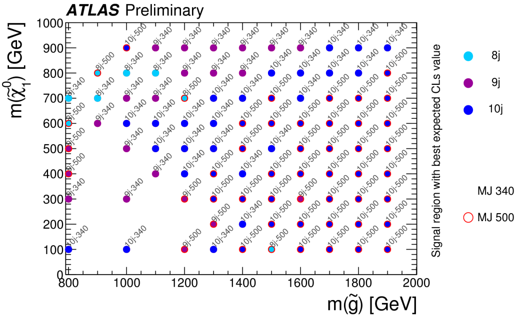
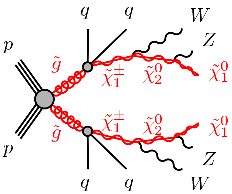
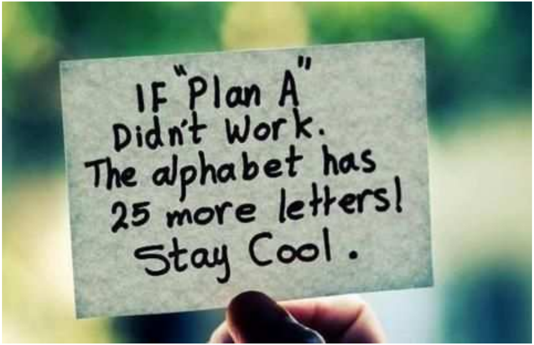


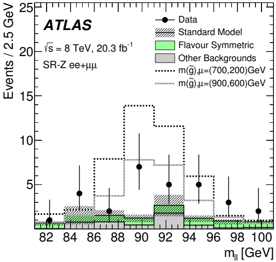


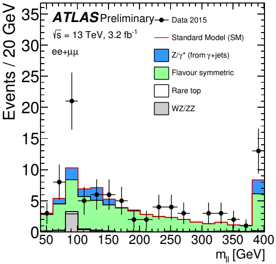
Z+(jets+)$E_{\mathrm{T}}^{\mathrm{miss}}$ search



Z+(jets+)$E_{\mathrm{T}}^{\mathrm{miss}}$ search: Intro

- This search has given some interesting results in the recent past.
- The 2012 dataset yielded 29 events on an expected background of 10.6 ± 3.2 - a 3 sigma excess (arXiv:1503.03290).
- With the 2015 data the search was repeated with ∼the same selection.
- 21 events were observed compared to the expectation of 10.3 ± 2.3 - a 2.2 sigma excess (ATLAS-CONF-2015-082)
- CMS saw no excess with the Run I data or in 2015.
- Now I will discuss the results with 14.7fb^{-1}of 2015+2016 data.





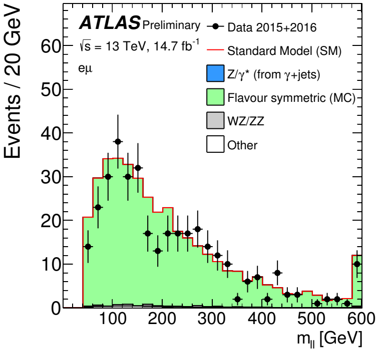
Z+(jets+)E_T^{miss} search: Backgrounds

- A series of different regions are used to estimate and validate the background estimation.

On-shell Z regions	E_T^{miss} [GeV]	H_T^{incl} [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	SF/DF	$\Delta\phi(jet_{12}, p_T^{miss})$	$m_T(\ell_3, E_T^{miss})$ [GeV]	$n_{b\text{-}jets}$
Signal region								
SRZ	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	> 0.4	–	–
Control regions								
CRZ	< 60	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	> 0.4	–	–
CR-FS	> 225	> 600	≥ 2	$61 < m_{\ell\ell} < 121$	DF	> 0.4	–	–
CRT	> 225	> 600	≥ 2	> 40, $m_{\ell\ell} \notin [81, 101]$	SF	> 0.4	–	–
CRγ	–	> 600	≥ 2	–	0ℓ, 1γ	–	–	–
Validation regions								
VRZ	< 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	> 0.4	–	–
VRT	100–200	> 600	≥ 2	> 40, $m_{\ell\ell} \notin [81, 101]$	SF	> 0.4	–	–
VR-S	100–200	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	> 0.4	–	–
VR-FS	100–200	> 600	≥ 2	$61 < m_{\ell\ell} < 121$	DF	> 0.4	–	–
VR-WZ	100–200	–	–	–	3ℓ	–	< 100	0
VR-ZZ	< 100	–	–	–	4ℓ	–	–	0
VR-3L	60–100	> 200	≥ 2	$81 < m_{\ell\ell} < 101$	3ℓ	> 0.4	–	–

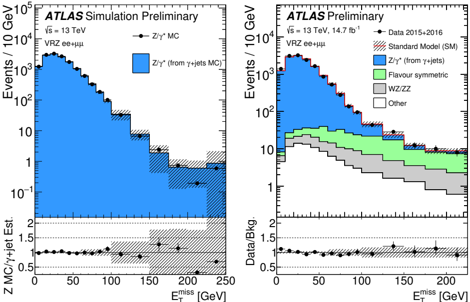
Z+(jets+)$E_{\mathrm{T}}^{\mathrm{miss}}$ search: Backgrounds - $t\bar{t}$++

- The flavour symmetric background is taken from an opposite flavour selection with a slightly widened m_{ll} window.
- Efficiency factors are applied to account for the differences in reconstruction, identification and trigger between electrons and muons.
- This estimation is checked in the region outside the Z peak in the SF selection.



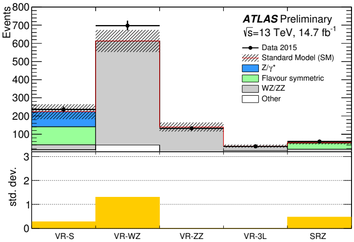
Z+(jets+)$E_{\mathrm{T}}^{\mathrm{miss}}$ search: Backgrounds - Z+jets

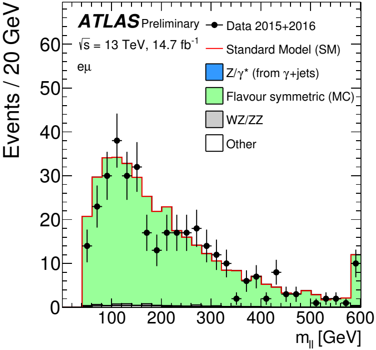
- The Z+jets background comes from using a photon sample.
- The photon sample is used to model the hadronic part of the $E_{\mathrm{T}}^{\mathrm{miss}}$.
- The difference in the resolution between reconstructed Z bosons and photons is then added to the events by smearing the photon p_{T}.
- The γ p_{T} is then re-weighted.
- The correlation between m_{ll} and the photon smearing is considered.
- Contamination from $\gamma + V$ in the CR is also considered.



Z+(jets+)$E_{\mathrm{T}}^{\mathrm{miss}}$ search: Results

- Validation regions at intermediate $E_{\mathrm{T}}^{\mathrm{miss}}$ are used to x-check the background estimation.
- Additional VRs with multiple leptons check the MC modelling of the di-boson background.
- All regions (including the Signal Region!) show good agreement with the prediction.



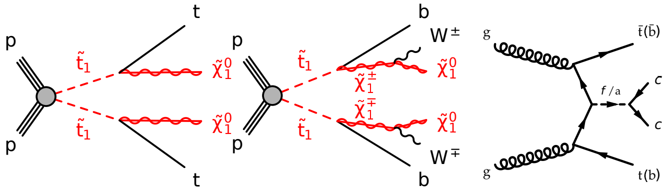


Stop search with 1-lepton

"What is coming
is better than
what is gone."

Stop search with 1-lepton: Intro.

- The stop ($\tilde{t}$) particle has a much lower x-section than the $\tilde{g}$, and often looks similar to $t\bar{t}$ production (link)
- Therefore the searches for the stop are much more targetted and make greater use of kinematic variables.
- Three different models are considered in this analysis.
- Several signal regions are optimised for different mass points of these models.



Stop search with 1-lepton: Signal Regions

Common event selection	
Trigger	E_T^{miss} trigger
Lepton	exactly one signal lepton (e, μ), no additional baseline leptons
Jets	at least two signal jets, and $\lvert\Delta\phi(\text{jet}_i, \vec{p}_T^{miss})\rvert > 0.4$ for $i \in \{1, 2\}$
Hadronic τ veto*	veto events with a hadronic τ decay and $m_{T2}^{\tau} < 80$ GeV

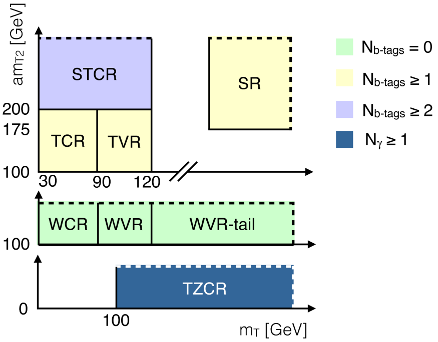
Variable	SR1	tN_high
Number of (jets, b-tags)	$(\geq 4, \geq 1)$	$(\geq 4, \geq 1)$
Jet $p_T >$ [GeV]	(80 50 40 40)	(120 80 50 25)
E_T^{miss} [GeV]	> 260	> 450
$E_{T,\perp}^{miss}$ [GeV]	–	> 180
$H_{T,sig}^{miss}$	> 14	> 22
m_T [GeV]	> 170	> 210
am_{T2} [GeV]	> 175	> 175
topness	> 6.5	–
m_{top}^{χ} [GeV]	< 270	–
$\Delta R(b, \ell)$	< 3.0	< 2.4
Leading large-R jet p_T [GeV]	–	> 290
Leading large-R jet mass [GeV]	–	> 70
$\Delta\phi(\vec{p}_T^{miss}, 2^{nd}\text{large-R jet})$	–	> 0.6

Variable	bC2x_diag	bC2x_med	bCbv
Number of (jets, b-tags)	$(\geq 4, \geq 2)$	$(\geq 4, \geq 2)$	$(\geq 2, = 0)$
Jet $p_T >$ [GeV]	(70 60 55 25)	(170 110 25 25)	(120 80)
b-tagged jet $p_T >$ [GeV]	(25 25)	(105 100)	–
E_T^{miss} [GeV]	> 230	> 210	> 360
$H_{T,sig}^{miss}$	> 14	> 7	> 16
m_T [GeV]	> 170	> 140	> 200
am_{T2} [GeV]	> 170	> 210	–
$\lvert\Delta\phi(\text{jet}_i, \vec{p}_T^{miss})\rvert (i = 1)$	> 1.2	> 1.0	> 2.0
$\lvert\Delta\phi(\text{jet}_i, \vec{p}_T^{miss})\rvert (i = 2)$	> 0.8	> 0.8	> 0.8
Leading large-R jet mass [GeV]	–	–	$[70, 100]$
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	–	–	> 1.2

Variable	DM_low	DM_high
Number of (jets, b-tags)	$(\geq 4, \geq 1)$	$(\geq 4, \geq 1)$
Jet $p_T >$ [GeV]	(60 60 40 25)	(50 50 50 25)
E_T^{miss} [GeV]	> 300	> 330
$H_{T,sig}^{miss}$	> 14	> 9.5
m_T [GeV]	> 120	> 220
am_{T2} [GeV]	> 140	> 170
$\min(\Delta\phi(\vec{p}_T^{miss}, \text{jet}_i))$ $(i \in \{1-4\})$	> 1.4	> 0.8
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	> 0.8	–

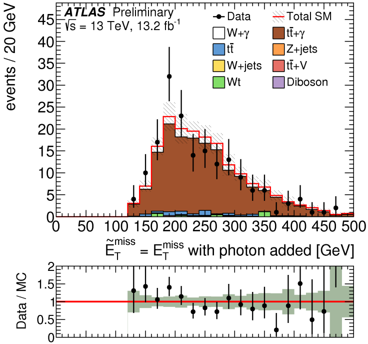
Stop search with 1-lepton: Background estimation

- The background estimation follows the CR procedure seen in the other ATLAS searches.
- A set of CRs is setup for each of the 3 SR categories.
- The kinematic variables used mean that the method of single top, $t\bar{t}$ and $t\bar{t}$+V entering the SRs are different such that it is desired to split these.



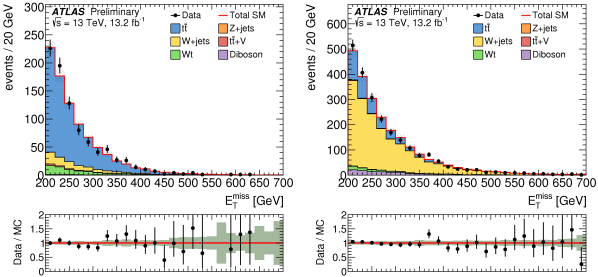
Stop search with 1-lepton: Background estimation - $t\bar{t}$+V

- This is done using a $t\bar{t} + \gamma$ sample due to the similarity in the feynman diagrams.
- The same generator setup is used in the two cases and NLO studies show that the k-factors for the two processes in this kinematic regime are very similar (and don't vary much as a function of the kinematics).



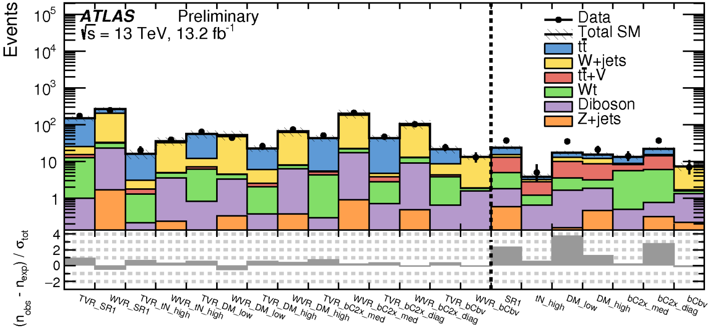
Stop search with 1-lepton: Background estimation - $t\bar{t}$ and single top

- The variable am_{T2} is used to obtain a sample of reasonably pure single top with similar kinematics to that in the signal region.
- There is still significant $t\bar{t}$ in this region however such that the normalisations of $t\bar{t}$ and single top become highly anti-correlated.
- The simultaneous fit procedure is ideal for accounting for this correctly.



Stop search with 1-lepton: - Results

- The background estimation is validated in 2-lepton regions.
- The results of the fit in the signal regions show 3 mild excesses (which are all correlated).



Stop search with 1-lepton: Results

Signal region	SR1	tN_high	bC2x_diag	bC2x_med	bCbv	DM_low	DM_high
Observed	37	5	37	14	7	35	21
Total background	24 ± 3	3.8 ± 0.8	22 ± 3	13 ± 2	7.4 ± 1.8	17 ± 2	15 ± 2
$t\bar{t}$	8.4 ± 1.9	0.60 ± 0.27	6.5 ± 1.5	4.3 ± 1.0	0.26 ± 0.18	4.2 ± 1.3	3.3 ± 0.8
W+jets	2.5 ± 1.1	0.15 ± 0.38	1.2 ± 0.5	0.63 ± 0.29	5.4 ± 1.8	3.1 ± 1.5	3.4 ± 1.4
Single top	3.1 ± 1.5	0.57 ± 0.44	5.3 ± 1.8	5.1 ± 1.6	0.24 ± 0.23	1.9 ± 0.9	1.3 ± 0.8
$t\bar{t} + V$	7.9 ± 1.6	1.6 ± 0.4	8.3 ± 1.7	2.7 ± 0.7	0.12 ± 0.03	6.4 ± 1.4	5.5 ± 1.1
Diboson	1.2 ± 0.4	0.61 ± 0.26	0.45 ± 0.17	0.42 ± 0.20	1.1 ± 0.4	1.5 ± 0.6	1.4 ± 0.5
Z+jets	0.59 ± 0.54	0.03 ± 0.03	0.32 ± 0.29	0.08 ± 0.08	0.22 ± 0.20	0.16 ± 0.14	0.47 ± 0.44
$t\bar{t}$ NF	1.03 ± 0.07	1.06 ± 0.15	0.89 ± 0.10	0.95 ± 0.12	0.73 ± 0.22	0.90 ± 0.17	1.01 ± 0.13
W+jets NF	0.76 ± 0.08	0.78 ± 0.08	0.87 ± 0.07	0.85 ± 0.06	0.97 ± 0.12	0.94 ± 0.13	0.91 ± 0.07
Single top NF	1.07 ± 0.30	1.30 ± 0.45	1.26 ± 0.31	0.97 ± 0.28	–	1.36 ± 0.36	1.02 ± 0.32
$t\bar{t} + W/Z$ NF	1.43 ± 0.21	1.39 ± 0.22	1.40 ± 0.21	1.30 ± 0.23	–	1.47 ± 0.22	1.42 ± 0.21
p_0 (σ)	0.012 (2.2)	0.26 (0.6)	0.004 (2.6)	0.40 (0.3)	0.50 (0)	0.0004 (3.3)	0.09 (1.3)
$N^{\mathrm{limit}}_{\mathrm{non-SM}}$ exp. (95% CL)	$12.9^{+5.5}_{-3.8}$	$5.5^{+2.8}_{-1.1}$	$12.4^{+5.4}_{-3.7}$	$9.0^{+4.2}_{-2.7}$	$7.3^{+3.5}_{-2.2}$	$11.5^{+5.0}_{-3.4}$	$9.9^{+4.6}_{-2.9}$
$N^{\mathrm{limit}}_{\mathrm{non-SM}}$ obs. (95% CL)	26.0	7.2	27.5	9.9	7.2	28.3	15.6

Conclusions

Conclusions

- I have described a few of the ATLAS searches for Supersymmetry using the Run II data.
- (Further details and the rest of the searches can be found on the ATLAS public pages here)
- So far there are no significant excesses such that we could claim evidence of SUSY.
- There are some excesses in certain channels (like the stop 1-lepton search) which we hope might turn into something exciting!
- So the search for SUSY continues - with the full 2015/2016 data and the large dataset that will (hopefully) be taken next year, the sensitivity will increase sigificantly.
- In particular, with the large integrated luminosity there will be good sensitivity to lower x-section SUSY particle production modes like the partners of the EW bosons, and further sensitivity to the stop and sbottom particles.