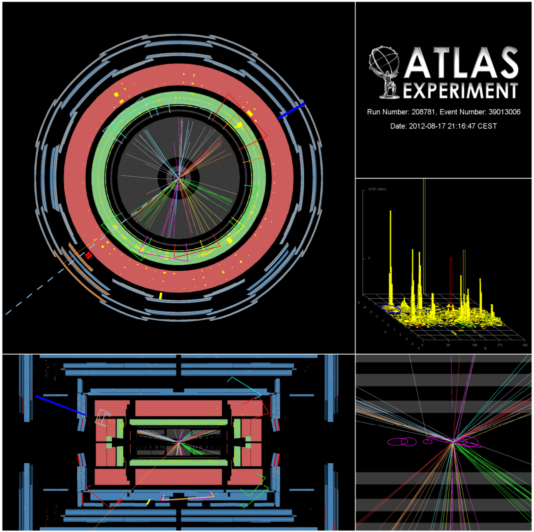
ATLAS SUSY Multi-Jet Search

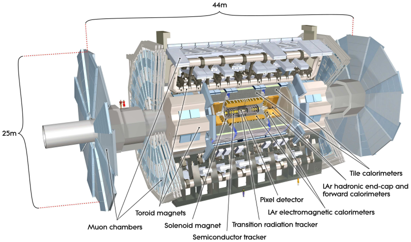
Christopher Young, CERN

BOOST 2013 Conference



Introduction

- A bit of a different talk:– a search implementing large radius jets rather than performance or theoretical ideas.
- The target of the search is final states with many jets produced from a cascade of heavy new coloured particles and $E_{\mathrm{T}}^{\mathrm{miss}}$ from invisible particles.
- Interpretation is in terms of several SUSY models but it is attempted to keep the selection reasonably general to maintain sensitivity to a variety of models.
- The analysis proceeds in two streams one using standard jets and the other using large radius jet masses.

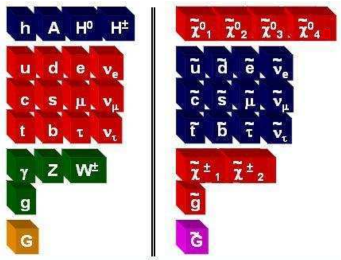


Outline

- Motivation for the Search
- Selection criteria - including M_J^{Σ} motivation
- Background determination - Multi-jet background
- Background determination - "Leptonic" backgrounds
- Results of the Analysis
- Interpretation of the Results

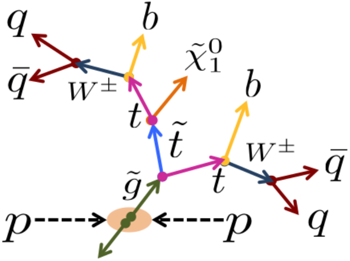
Motivation for the Search

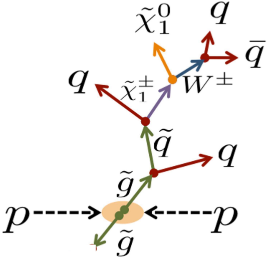
- SUSY gives a duplicate spectrum to the SM (+ extended Higgs sector)
- Focus on R-parity conserving models → $E_{\mathrm{T}}^{\mathrm{miss}}$ from lightest susy particle (LSP) being stable.
- LHC is a hadron collider → x-sec. for coloured particles are large.
- These can decay through long complicated processes leading to many particle final states.



Motivation for the Search

- The target final state here is many jets (up to 10) from the cascade decay and $E_{\mathrm{T}}^{\mathrm{miss}}$.
- SUSY scenarios can have decay modes through several different channels.
- Signals can have very large numbers of hard jets.
- Events with leptons are vetoed to reduce SM backgrounds (W+jets, $t\bar{t}$).
- Try to keep selection as general as possible.
- Models both with b-jets in the final state and without are considered.
- $E_{\mathrm{T}}^{\mathrm{miss}}$ cut kept softer than most other SUSY analyses.





Historical Record

- The 1st ATLAS high jet multiplicity SUSY search used $1.34\,\mathrm{fb}^{-1}$ of 2011 data:
  arXiv:1110.2299
- This was updated to the full 2011 dataset:
  arXiv:1206.1760
- A conference note was published using the first $5.8\,\mathrm{fb}^{-1}$ of 2012 data:
  ATLAS-CONF-2012-103
- This latest version uses the full $20.3\,\mathrm{fb}^{-1}$ 2012 8 TeV dataset:
  arXiv:1308.1841

Selection

- The analysis is split into two “streams”.
- One stream splits events based on the presence of *b*-tagged jets.
- The other makes use of the sum of large radius jet masses.
- In both streams cleaning cuts are applied and events with electrons or muons with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ are vetoed.
- For the signal region selection in both streams data are triggered using multi-jet triggers. (there is no trigger $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement unlike in other SUSY searches allowing softer requirements to be used).
- For control region selections single lepton triggers are used.

Selection - flavour stream

- Events are categorised by the number of *b*-tagged jets in the event ($p_{\mathrm{T}} > 40$ GeV $|\eta| < 2.5$, 70% OP) into bins of 0, 1 or ≥ 2 tagged jets.
- Also count jets with $p_{\mathrm{T}} > 50$ GeV $|\eta| < 2.0$ and $p_{\mathrm{T}} > 80$ GeV $|\eta| < 2.0$.

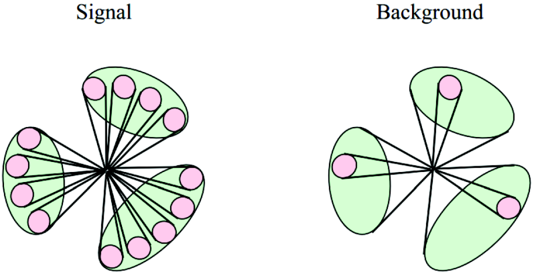
	Multi-jet + flavour stream						
Identifier	**8j50**			**9j50**			$\geq$ **10j50**
Jet $\lvert\eta\rvert$	< 2.0						
Jet p_{T}	$> 50\,\mathrm{GeV}$						
Jet count	$= 8$			$= 9$			≥ 10
b-jets ($p_{\mathrm{T}} > 40\ \mathrm{GeV}, \lvert\eta\rvert < 2.5$)	0	1	≥ 2	0	1	≥ 2	—
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$	$> 4\ \mathrm{GeV}^{1/2}$						

	Multi-jet + flavour stream					
Identifier	**7j80**			**8j80**		
Jet $\lvert\eta\rvert$	< 2.0					
Jet p_{T}	$> 80\,\mathrm{GeV}$					
Jet count	$= 7$			≥ 8		
b-jets ($p_{\mathrm{T}} > 40\ \mathrm{GeV}, \lvert\eta\rvert < 2.5$)	0	1	≥ 2	0	1	≥ 2
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$	$> 4\ \mathrm{GeV}^{1/2}$					

Selection - M_J^Σ stream

- The variable proposed in arXiv:1202.0558 is utilised.
- Anti-k_t 4 jets are re-clustered using the anti-k_t algorithm into radius 1.0 jets.
- The variable M_J^Σ is then formed from the sum of the masses of these large radius jets which have $p_\mathrm{T} > 100\,\mathrm{GeV}$ and $|\eta| < 1.5$.

$$M_J^\Sigma = \sum m_\mathrm{jet}^\mathrm{R=1.0}$$



Jay Wacker, SLAC

Selection - M_J^{Σ} stream

- The motivation behind this variable is not solely to look for boosted objects!
- The SUSY process is expected to be a cascade through several heavy particles.
- The jets are therefore expected to be distributed differently in η and ϕ to pure QCD processes.
- When forming fat jets there will be large mass jets where the jets come from different parts of the decay that are accidentally near each other.
- This is not expected to occur in QCD so often.
- M_J^{Σ} can therefore be thought more of an event shape variable rather than attempting to reconstruct hadronically decaying W and top particles.

Selection - M_J^{Σ} stream

- Selection requires a large number of Anti-k_t 4 jets above 50 GeV and additionally a cut on M_J^{Σ}.
- Two different cut values on M_J^{Σ} are used; 340 GeV and 420 GeV.

	Multi-jet + M_J^{Σ} stream		
Identifier	**$\geq$ 8j50**	**$\geq$ 9j50**	**$\geq$ 10j50**
Jet $\lvert\eta\rvert$	< 2.8		
Jet p_{T}	$> 50\,\mathrm{GeV}$		
Jet count	≥ 8	≥ 9	≥ 10
b-jets ($p_{\mathrm{T}} > 40\ \mathrm{GeV}, \lvert\eta\rvert < 2.5$)	—		
M_J^{Σ} [GeV]	$>$ 340 and $>$ 420 for each case		
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$	$> 4\ \mathrm{GeV}^{1/2}$		

Background Determination - Multi-jets

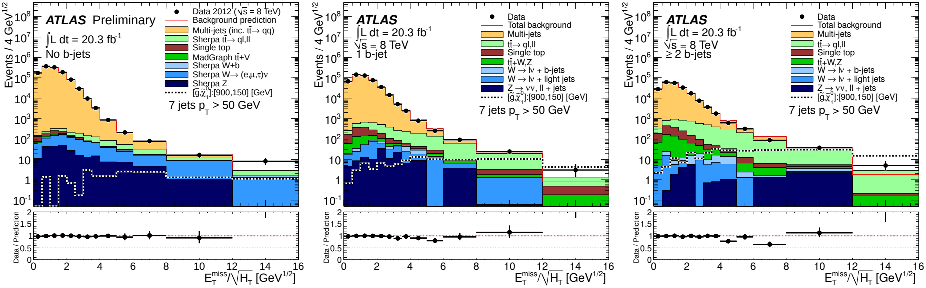
- Due to the softish cut on $E_{\mathrm{T}}^{\mathrm{miss}}$ multi-jet processes form a large proportion of the background.
- Fully data-driven method has been developed.
- For a large range of jet p_{T} the ATLAS resolution is $\propto \sqrt{p_{\mathrm{T}}}$.
- For events dominated by jet mis-measurement the quantity $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ will be approximately invariant under changes in jet multiplicity.
- Therefore the background can be determined by:

$$N^{\mathrm{predicted}}_{E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}>4.0,\mathrm{nJet}\geq 9} = N^{\mathrm{observed}}_{E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}<1.5,\mathrm{nJet}\geq 9} \frac{N^{\mathrm{observed}}_{E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}>4.0,\mathrm{nJet}=6}}{N^{\mathrm{observed}}_{E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}<1.5,\mathrm{nJet}=6}}$$

where all the numbers have the expected non-multi-jet background yields subtracted. (ABCD method)

Background Determination - Multi-jets

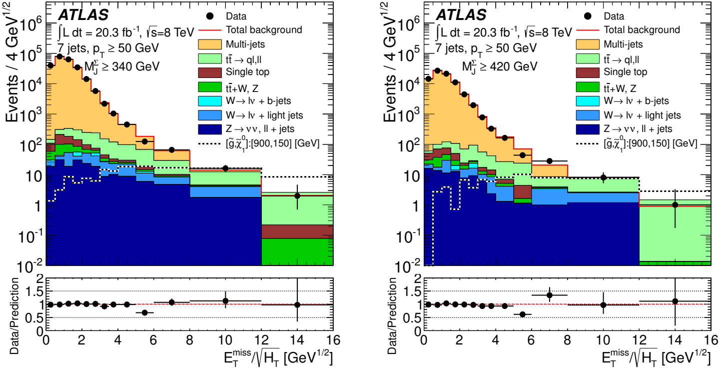
- The $E_{\mathrm{T}}^{\mathrm{miss}}$ is also affected by the amount of soft activity in the event.
- To capture the relative size of the soft and hard parts of the $E_{\mathrm{T}}^{\mathrm{miss}}$ the template is formed in bins of $\sum \mathrm{E}_{\mathrm{T}}^{\mathrm{CellOut}}/H_{\mathrm{T}}$.
- To test the method lower jet multiplicities are used.



Here template from 6 jet selection is used to predict distribution for 7 jet selection.

Background Determination - Multi-jets

- Method is also tested to work after cuts on M_J^Σ.

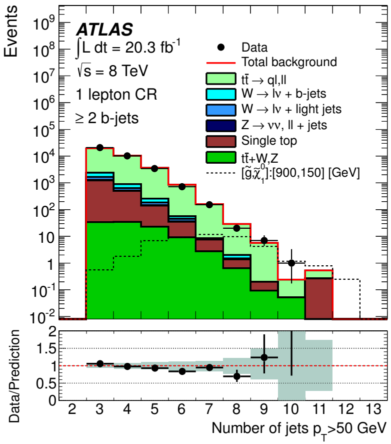


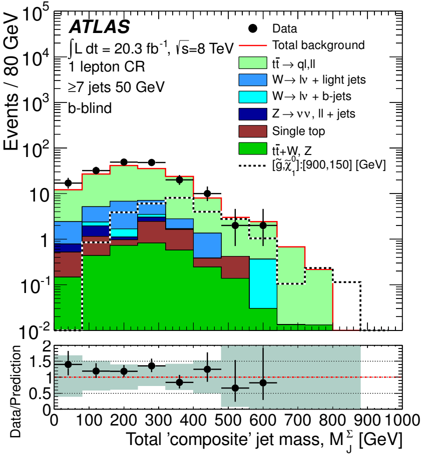
Here template from 6 jet selection is used to predict distribution for 7 jet selection.

Background Determination - “leptonic” backgrounds

- $Z \to \nu\nu$ forms an irreducible background and $t\bar{t}$ and W+jets can also contribute when the lepton is not reconstructed or is a hadronically decaying τ.
- These backgrounds use Monte Carlo with validation and normalisation in control regions requiring a single isolated electron or muon.
- A looser selection is required to form “validation” regions close kinematically to the SR.
- Additional criteria are then applied to emulate the primary process that would enter the SR:
    1. For W and $t\bar{t}$ the majority of the background is hadronic taus so the electron/muon is treated as a jet in the selection criteria.
    2. For Z the lepton p_{T} are added to the $E_{\mathrm{T}}^{\mathrm{miss}}$ to emulate $Z \to \nu\nu$.
- The Monte-Carlo is found to describe the data well within the experimental systematics.

Background Determination - “leptonic” backgrounds





Systematics and Statistics

- For Multi-jet background systematics come from the closure observed in many lower jet multiplicity or lower $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$, the relative fraction of b-jets, the uncertainty on the subtraction of the other backgrounds and changing the exact weighting procedure.
- For the “leptonic” backgrounds the Jet Energy Scale uncertainty, theoretical uncertainties (on the extrapolation between control and signal regions) and the statistics in the control regions dominate.
- For the flavour stream a profile likelihood fit is performed across all control regions and signal regions.
- For the M_J^{Σ} stream each signal region is treated separately with the corresponding “leptonic” control region with the same jet multiplicity and M_J^{Σ} requirements.

Signal regions - numbers

Signal region	8j50			9j50			10j50
b-jets	0	1	≥ 2	0	1	≥ 2	—
Observed events	40	44	44	5	8	7	3
Total after fit	35 ± 4	40 ± 10	50 ± 10	3.3 ± 0.7	6.1 ± 1.7	8.0 ± 2.7	1.37 ± 0.35
Fitted $t\bar{t}$	2.7 ± 0.9	11.8 ± 3.0	23.0 ± 5.0	0.36 ± 0.18	1.5 ± 0.5	3.2 ± 1.1	$0.06^{+0.09}_{-0.06}$
Fitted W+jets	$2.0^{+2.6}_{-2.0}$	$0.62^{+0.81}_{-0.62}$	$0.20^{+0.28}_{-0.20}$	-	$0.24^{+0.65}_{-0.24}$	-	-
Fitted others	$2.9^{+1.8}_{-1.8}$	$1.7^{+1.5}_{-1.2}$	$2.8^{+2.3}_{-2.0}$	0.03 ± 0.03	0.38 ± 0.25	$0.40^{+0.60}_{-0.24}$	0.08 ± 0.08
Total before fit	40	50	60	3.4	7	9	1.4
$t\bar{t}$ before fit	3.5	15	30	0.41	1.8	4	0.08
W+jets before fit	2.9	1.0	0.29	-	0.40	-	-
Others before fit	2.4	1.8	2.8	0.03	0.34	0.4	0.08
Multi-jets	27 ± 3	30 ± 10	26 ± 10	3.0 ± 0.6	4.0 ± 1.4	4.4 ± 2.2	1.23 ± 0.32
$\mathrm{N}^{95\%}_{\mathrm{BSM}}$ (exp)	16	23	26	5	7	8	4
$\mathrm{N}^{95\%}_{\mathrm{BSM}}$ (obs)	20	23	22	7	9	7	6
$\sigma^{95\%}_{\mathrm{BSM,max}}$(exp)[fb]	0.8	1.2	1.3	0.26	0.36	0.40	0.19
$\sigma^{95\%}_{\mathrm{BSM,max}}$(obs)[fb]	0.97	1.1	1.1	0.34	0.43	0.37	0.29
p_0	0.24	0.5	0.7	0.21	0.28	0.6	0.13
Significance (σ)	0.7	-0.02	-0.6	0.8	0.6	-0.28	1.14

Signal regions - numbers

Signal region	7j80			8j80		
b-jets	0	1	≥ 2	0	1	≥ 2
Observed events	12	17	13	2	1	3
Total fitted events	11.0 ± 2.2	17 ± 6	25 ± 10	0.9 ± 0.6	1.5 ± 0.9	3.3 ± 2.2
Fitted $t\bar{t}$	$0.00^{+0.26}_{-0.00}$	5.0 ± 4.0	12 ± 9	$0.10^{+0.14}_{-0.10}$	$0.32^{+0.67}_{-0.32}$	$1.5^{+1.9}_{-1.5}$
Fitted W+jets	$0.07^{+0.38}_{-0.07}$	$0.29^{+0.37}_{-0.29}$	-	-	-	-
Fitted others	$1.9^{+1.1}_{-0.9}$	$0.71^{+0.31}_{-0.25}$	$2.6^{+1.7}_{-1.1}$	0.02 ± 0.02	0.02 ± 0.02	$0.32^{+0.36}_{-0.21}$
Total events before fit	12	16	23	0.8	1.8	3.3
$t\bar{t}$ before fit	0.34	4	10	0.08	0.6	1.5
W+jets before fit	0.46	0.29	-	-	-	-
Others before fit	1.8	0.89	3.0	0.02	0.02	0.35
Multi-jets	9.1 ± 1.6	11 ± 4	10 ± 4	0.75 ± 0.56	1.2 ± 0.5	1.4 ± 1.0
$\mathrm{N}^{95}_{\mathrm{BSM}}$ (exp)	10	17	14	4	4	6
$\mathrm{N}^{95}_{\mathrm{BSM}}$ (obs)	10	16	12	5	3.5	6
$\sigma^{95\%}_{\mathrm{BSM,max}}$ (exp) [fb]	0.5	0.8	0.7	0.18	0.18	0.31
$\sigma^{95\%}_{\mathrm{BSM,max}}$ (obs) [fb]	0.5	0.8	0.6	0.24	0.17	0.31
p_0	0.5	0.6	0.8	0.19	0.6	0.5
Significance (σ)	0.05	-0.14	-1.0	0.9	-0.28	-0.06

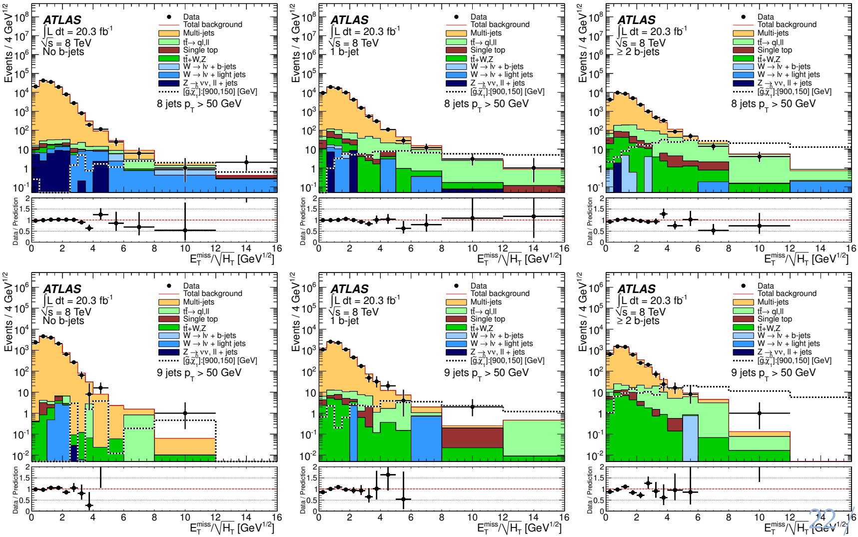
Signal regions - numbers

Signal region	8j50	
M_J^{Σ} [GeV]	340	420
Observed events	69	37
Total events after fit	75 ± 19	45 ± 14
Fitted $t\bar{t}$	17 ± 11	16 ± 13
Fitted W+jets	$0.8^{+1.3}_{-0.8}$	$0.4^{+0.7}_{-0.4}$
Fitted others	$5.2^{+4.0}_{-2.5}$	$2.8^{+2.9}_{-1.6}$
Total events before fit	90	40
$t\bar{t}$ before fit	27	14
W+jets before fit	0.8	0.4
Others before fit	5	2.8
Multi-jets	52 ± 15	27 ± 7
$\mathrm{N}^{95\%}_{\mathrm{BSM}}$ (exp)	40	23
$\mathrm{N}^{95\%}_{\mathrm{BSM}}$ (obs)	35	20
$\sigma^{95\%}_{\mathrm{BSM,max}}$ (exp) [fb]	1.9	1.1
$\sigma^{95\%}_{\mathrm{BSM,max}}$ (obs) [fb]	1.7	1.0
p_0	0.60	0.7
Significance (σ)	-0.27	-0.6

Signal regions - numbers

Signal region	9j50		10j50	
M_J^Σ [GeV]	340	420	340	420
Observed events	13	9	1	1
Total events	17 ± 7	11 ± 5	$3.2^{+3.7}_{-3.2}$	2.2 ± 2.0
$t\bar{t}$	5 ± 4	$3.4^{+3.6}_{-3.4}$	$0.8^{+0.8}_{-0.8}$	$0.6^{+0.9}_{-0.6}$
W+jets	-	-	-	-
Others	$0.58^{+0.54}_{-0.33}$	$0.39^{+0.32}_{-0.30}$	0.12 ± 0.12	0.06 ± 0.06
Multi-jets	12 ± 4	7.0 ± 2.3	$2.3^{+3.6}_{-2.3}$	$1.6^{+1.8}_{-1.6}$
$\mathrm{N}^{95\%}_{\mathrm{BSM}}$ (exp)	13	11	5	5
$\mathrm{N}^{95\%}_{\mathrm{BSM}}$ (obs)	11	10	4	4
$\sigma^{95\%}_{\mathrm{BSM,max}}$ (exp) [fb]	0.7	0.5	0.23	0.23
$\sigma^{95\%}_{\mathrm{BSM,max}}$ (obs) [fb]	0.5	0.5	0.2	0.2
p_0	0.7	0.6	0.8	0.7
Significance (σ)	-0.6	-0.34	-0.8	-0.6

Signal regions



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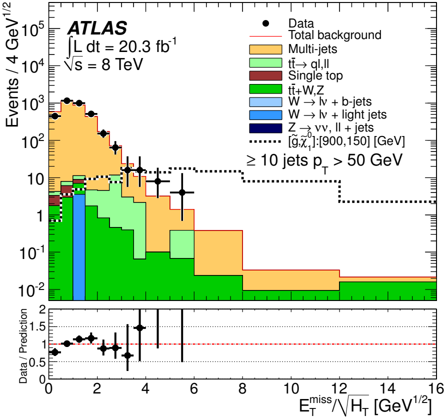

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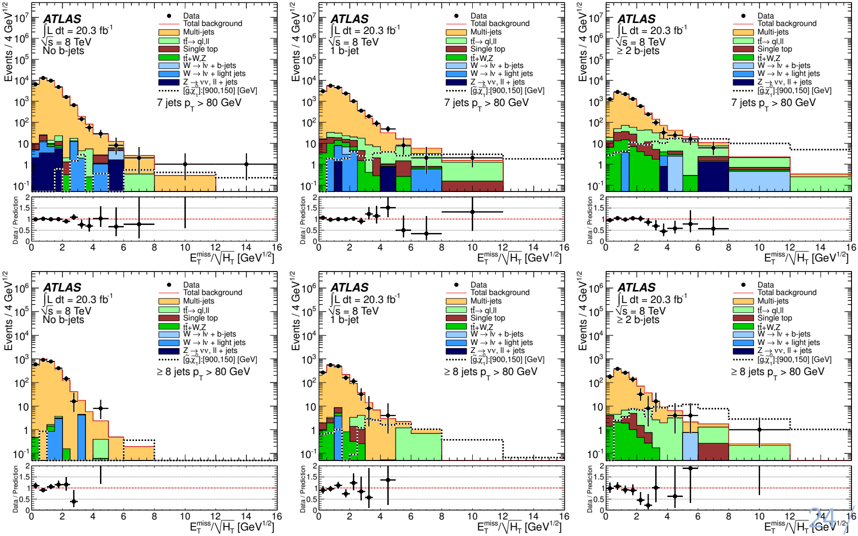

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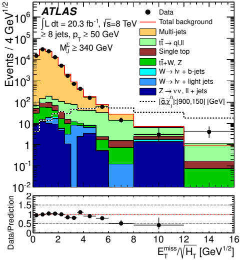
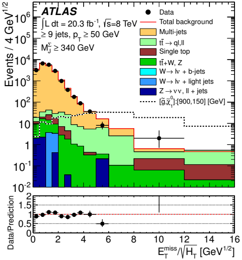
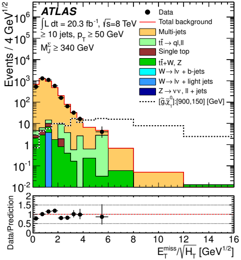
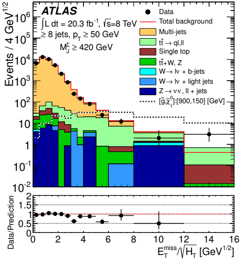
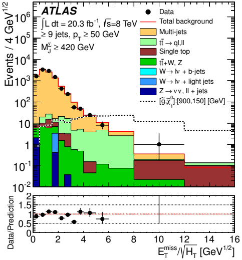
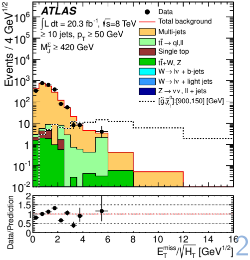






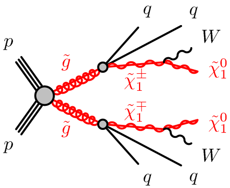


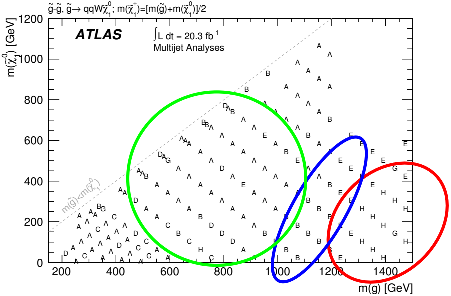




Interpretation

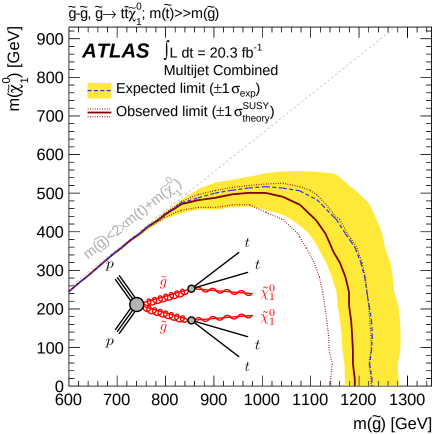
- No significant excess above the Standard Model prediction is observed so limits are set in several models of Supersymmetry.
- In each model the stream which gives the best expected limit is used.
- In the vicinity of the limit this is almost always the 50 GeV regions in the “flavour” stream.
- At higher masses the M_J^Σ stream is seen to do better such that this may be promising for its use in the future.

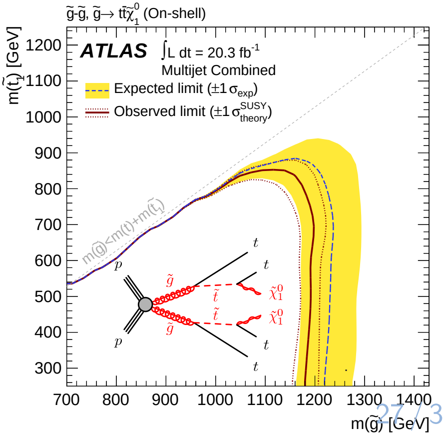




Interpretation

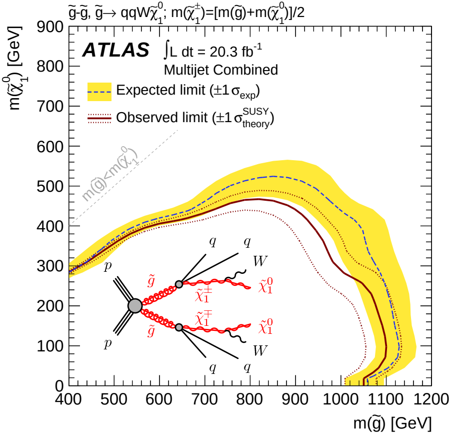
- Gluino pair production where they decay:
  1. $\tilde{g} \rightarrow t + \bar{t} + \tilde{\chi}_1^0$
  2. $\tilde{g} \rightarrow \bar{t} + \tilde{t}\,;\ \tilde{t} \rightarrow t + \tilde{\chi}_1^0$

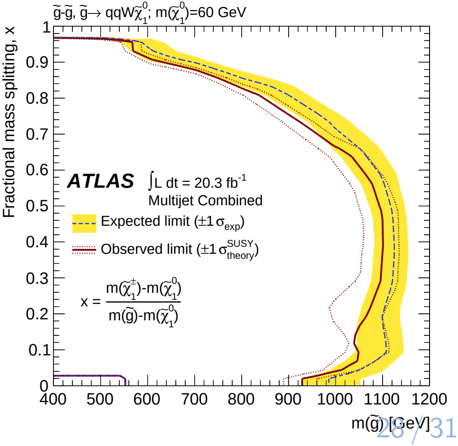




Limits - One Step Decay

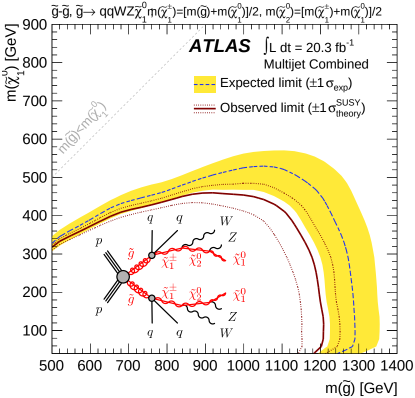
- Gluino pair production where they decay:
  1. $\tilde{g} \rightarrow q + \bar{q}^{'} + \tilde{\chi}_1^{\pm}\ ;\ \tilde{\chi}_1^{\pm} \rightarrow W^{\pm} + \tilde{\chi}_1^0$

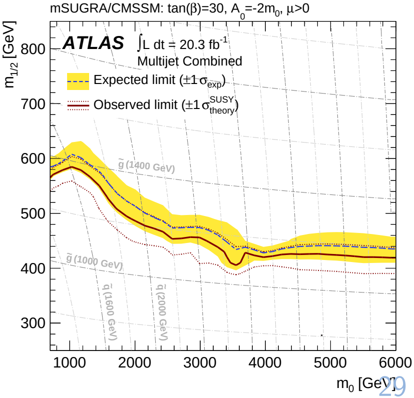




Limits - 2-step decay and MSUGRA/CMSSM

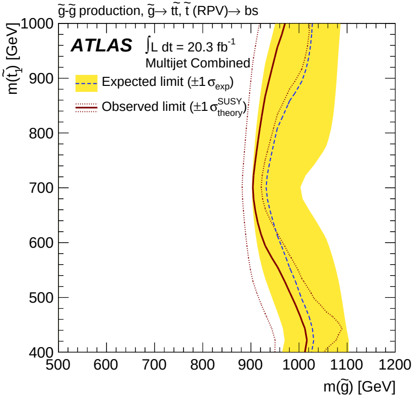
- Gluino pair production where they decay:
  1. $\tilde{g} \to q + \bar{q}' + \tilde{\chi}_1^\pm \,;\, \tilde{\chi}_1^\pm \to W^\pm + \tilde{\chi}_2^0 \,;\, \tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0$
- A plane of the MSUGRA/CMSSM space.





Limits - RPV gluino-stop model

- As the $E_{\mathrm{T}}^{\mathrm{miss}}$ cut is soft it was found the analysis was also sensitive to an RPV SUSY model where the $E_{\mathrm{T}}^{\mathrm{miss}}$ is generated from neutrinos in b-jets.
- Gluinos are pair-produced and then decay:
  - $\tilde{g} \rightarrow \bar{t} + \tilde{t}$. The stop then decays $\tilde{t} \rightarrow b + s$



Conclusions

- I have presented a search for SUSY in the channel requiring many jets ($\geq 7 \rightarrow \geq 10$), $E_{\mathrm{T}}^{\mathrm{miss}}$ and no high p_{T} isolated leptons.
- The analysis contained selections based on b-jet multiplicity and on M_J^{Σ}.
- No excess above the SM background was observed and limits were set in various planes of SUSY.
- The flavour stream was in general more sensitive than the M_J^{Σ} stream (in the models studied near the current limits).
- However, the M_J^{Σ} stream shows better sensitivity to masses beyond the current limits such that this variable may be more useful in future searches.