Introduction to BSM searches at the LHC

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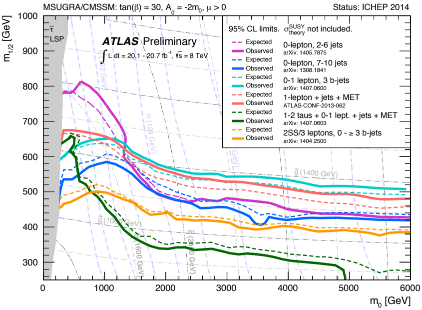
Tons of exclusion limits from LHC



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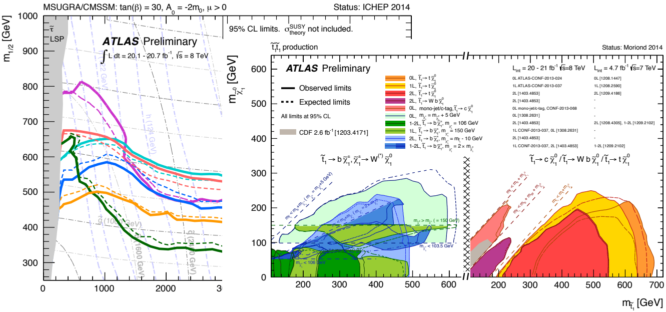

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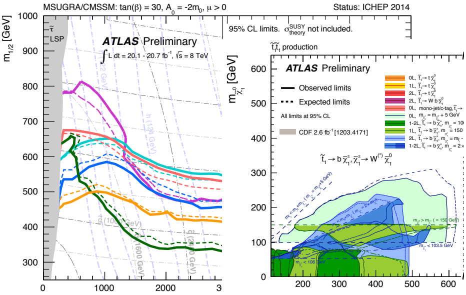

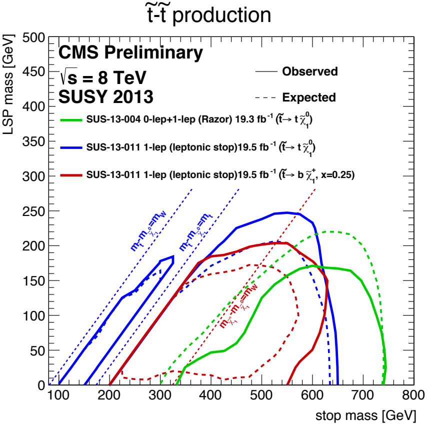

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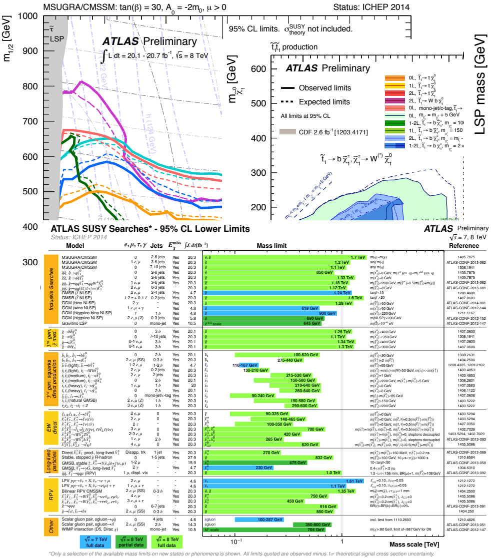

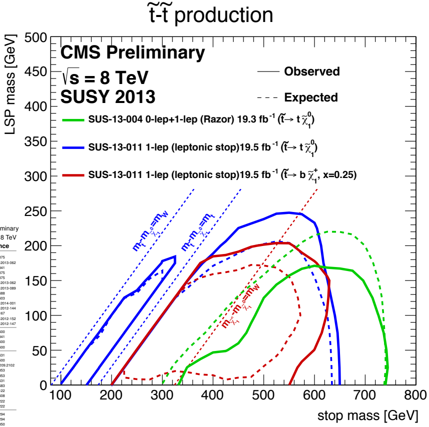

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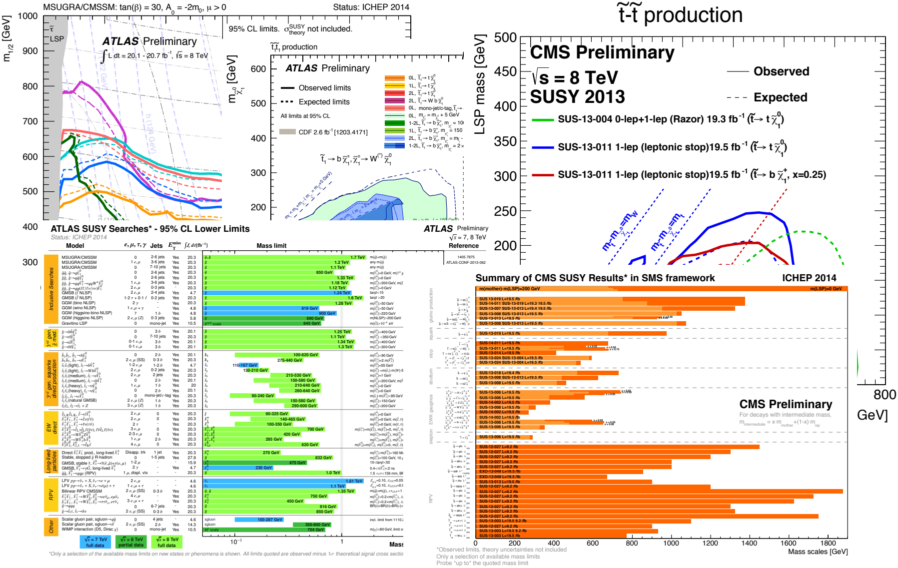
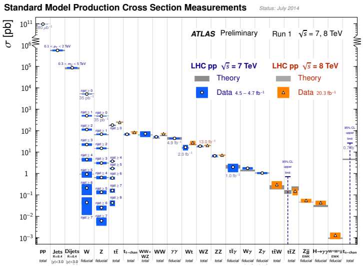
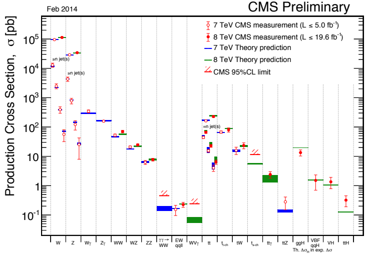
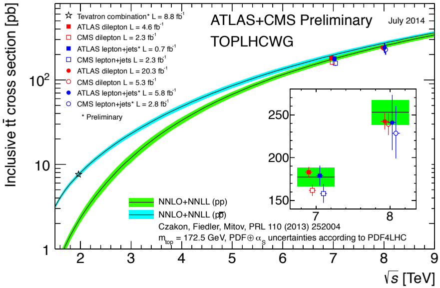
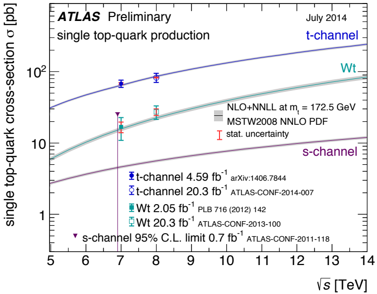


Good overall agreement of SM measurements









Outline

What are we looking for?

Depending on the underlying physics model the searches can be based on different signatures:

- missing transverse energy, E_T^{miss};
  - $\Rightarrow$ good for e.g. R-parity conserving SUSY, but in general any model with neutral weakly interacting particle (DM, neutrinos, etc.), UED...
- high multiplicities leptons and/or jets;
  - $\Rightarrow$ good for e.g. R-parity violating SUSY, also black holes
- resonances in photons, jets, leptons, gauge bosons;
  - $\Rightarrow$ RPV SUSY, Randall-Sundrum models, new gauge bosons...
- long-lived particles, displaced vertices

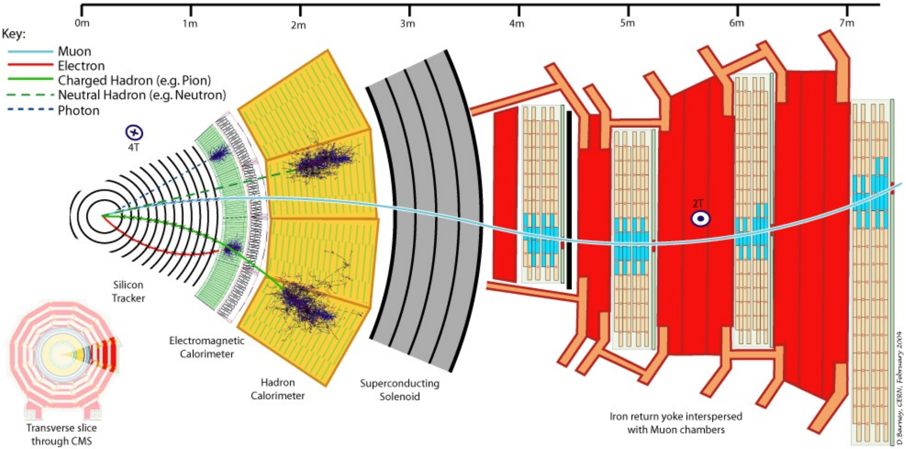
A single search is usually interpreted within one or two models, but often can put constraints on many different BSM physics, in sometimes surprising way. CheckMATE is a tool to reinterpret the results in arbitrary physics models.

What's in the menu?

The events are classified using objects that can be observed in the detector:

- missing energy in the transverse direction
- number of jets; can be anything between 0 (jet veto) and $\sim$10
- number of b-jets
- number of leptons (electrons and muons)
- number of taus (normally not classified as leptons unless decayed to e or μ)

How do we detect?



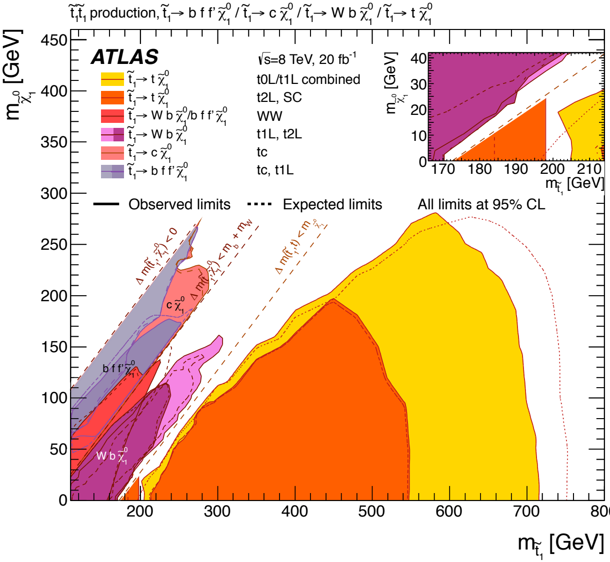
Link

Simplified models

Simplified models are used to interpret search results within a particular setting of supersymmetric models to avoid analyzing parameter space of $O(20)$ dimensions:

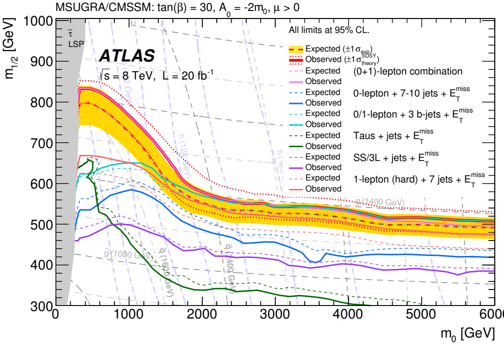
- assume one particular production process, e.g. gluino pair production or squark production or chargino production etc.; forget anything else;
- pick up one or two well specified decay chains; if more then one decay possible assume branching ratios according to gauge couplings;
- set masses of relevant particles, typically 2-3;

Scalar top exclusions in simplified models



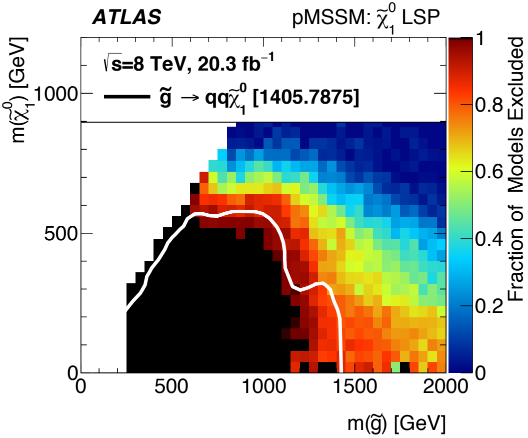
Constrained models

The search results can be also presented in "constrained" models (with a few free parameters). They are easy to present in one plot, but constrained models are disfavored by the current searches



Phenomenological models

Another approach is to scan "phenomenological" MSSM with $\sim$20 free parameters and plot density of excluded models in a 2-dimensional projection



Outline

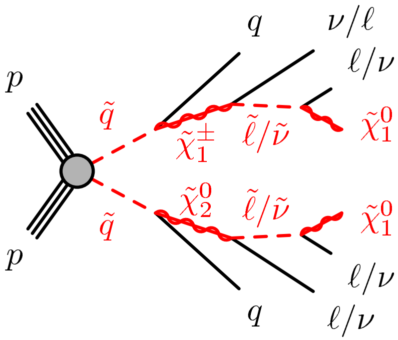
1. Looking for new physics

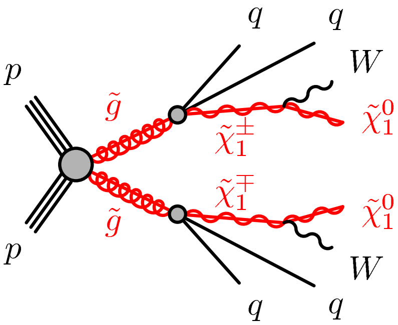
2. Specific examples for tutorial
   - ATLAS 2 leptons + jets; ATLAS-2013-089
   - ATLAS 2–6 jets + missing energy; ATLAS-2013-047

3. Conclusions

Simplified model

- particles involved: gluinos ($\tilde{g}$), squarks ($\tilde{q}$), charginos ($\tilde{\chi}^{\pm}$), neutralinos ($\tilde{\chi}_1^0$)
- final states with 2-leptons (ee, $\mu\mu$, or $e\mu$), and variable number of jets





Signal events selection

The search uses “razor” variables constructed from visible objects:

- construct two “mega-jets” using all visible jets and leptons
- iterate over all possible assignments of particles to the mega-jets and find one that minimizes the sum of the squared masses of the mega-jet four-vectors
- calculate characteristic mass M_R'

$$M_R' = \sqrt{(j_{1,E} + j_{2,E})^2 - (j_{1,L} + j_{2,L})^2}$$

- assign half of the missing transverse energy to each of the mega-jets

$$M_T^R = \sqrt{\frac{|\vec{E}_T^{\text{miss}}|(|\vec{j}_{1,T}| + |\vec{j}_{2,T}|) - \vec{E}_T^{\text{miss}} \cdot (\vec{j}_{1,T} + \vec{j}_{2,T})}{2}}$$

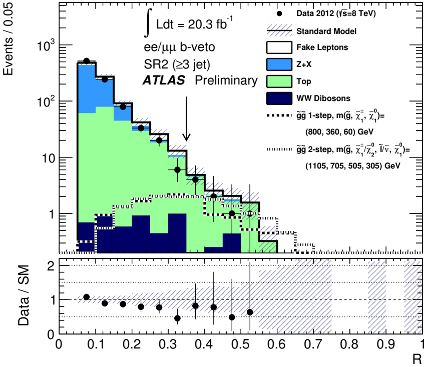
Razor variable

- define razor variable

$$R = \frac{M_T^R}{M_R'}$$

- R tends to have low values for Standard Model backgrounds, while supersymmetric processes have larger values

select events with
$R > 0.35$
or
$R > 0.5$



Signal regions

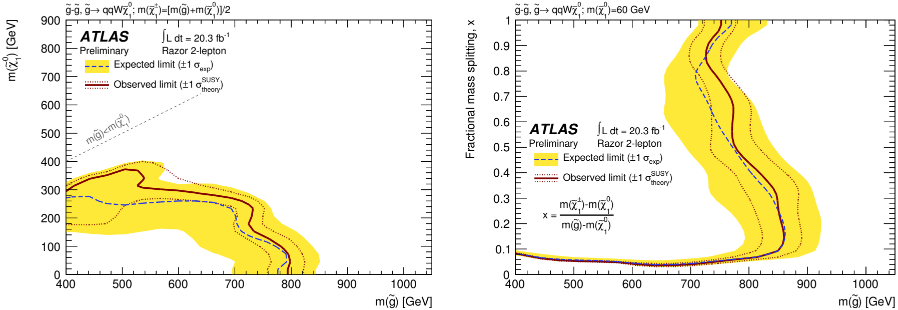
	b-jets	Z-veto	N_{Jets}	Jet p_{T}	R Range	M'_R Range [GeV]	M'_R bins
Signal Regions							
$ee/\mu\mu$ SR 1	No	Yes	≤ 2	> 50	R >0.5	400< M'_R	8
$e\mu$ SR 1	No	No	≤ 2	> 50	R >0.5	400< M'_R	8
$ee/\mu\mu$ SR 2	No	Yes	≥ 3	> 50	R >0.35	800< M'_R	5
$e\mu$ SR 2	No	No	≥ 3	> 50	R >0.35	800< M'_R	5
Discovery Regions							
$ee/\mu\mu$ DR	No	Yes	≤ 2	> 50	R >0.5	600< M'_R	1
$e\mu$ DR	No	No	≤ 2	> 50	R >0.5	600< M'_R	1

Understanding results

channel	$ee/\mu\mu$ SR1	$e\mu$ SR1	$ee/\mu\mu$ SR2	$e\mu$ SR2
Observed events	102	87	8	8
Fitted bkg events	117 ± 16	103 ± 15	11.0 ± 2.8	10.1 ± 2.7
Fitted DibosonWW events	32 ± 8	28 ± 7	0.9 ± 0.3	0.44 ± 0.15
Fitted ZX events	6.8 ± 1.5	3.6 ± 0.3	0.57 ± 0.14	0.22 ± 0.06
Fitted Top events	66 ± 11	55 ± 10	8.9 ± 2.4	8.6 ± 2.4
Fitted reducible bkg. events	13 ± 7	16 ± 8	$0.7^{+1.0}_{-0.7}$	$0.8^{+1.1}_{-0.8}$
MC exp. SM events	115	101	12.8	10.4
MC exp. DibosonWW events	29	26	0.8	0.50
MC exp. ZX events	8.2	3.5	0.70	0.19
MC exp. Top events	65	56	10.6	8.9
Exp. reducible bkg events	13	16	0.7	0.8
95 % C.L. upper limit on N_{BSM}	$28\ (35^{\uparrow 48}_{\downarrow 25})$	$24\ (31^{\uparrow 43}_{\downarrow 23})$	$6.7\ (8.5^{\uparrow 12.4}_{\downarrow 6.0})$	$7.1\ (8.4^{\uparrow 12.2}_{\downarrow 5.9})$
95 % C.L. upper limit on σ_{BSM} [fb]	$1.4\ (1.7^{\uparrow 2.3}_{\downarrow 1.2})$	$1.2\ (1.5^{\uparrow 2.1}_{\downarrow 1.1})$	$0.33\ (0.42^{\uparrow 0.61}_{\downarrow 0.29})$	$0.35\ (0.41^{\uparrow 0.60}_{\downarrow 0.29})$
p_0-value (Gauss. σ)	0.76 (−0.70)	0.80 (−0.86)	0.77 (−0.75)	0.69 (−0.49)

Exclusion limits

To obtain exclusion limits, check each point in $m(\tilde{g})$–$m(\tilde{\chi}_1^0)$. Here we look at the process with an intermediate chargino. The limits will depend on the chargino mass relative to gluino and the lightest neutralino.

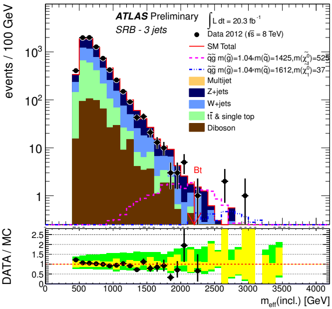


Scope of the search

This search targets production of squarks and gluinos decaying hadronically:

- no leptons
- 2–6 light jets
- significant missing energy
- large effective mass defined using transverse momenta of jets and missing transverse energy:

$$m_{\text{eff}} = E_T^{\text{miss}} + \sum_{j=1}^{N} p_T^j$$



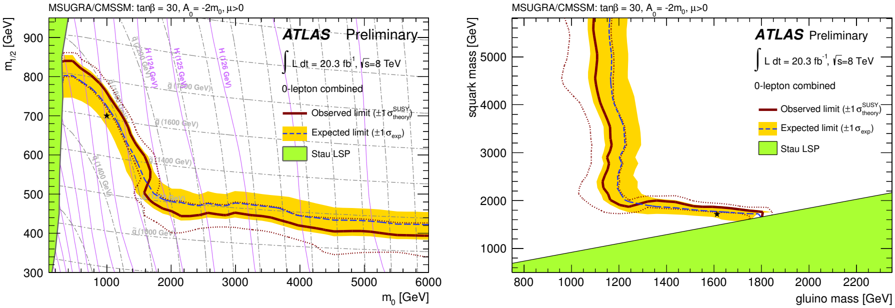
Signal regions

Requirement	Channel									
	A (2-jets)		B (3-jets)		C (4-jets)		D (5-jets)	E (6-jets)		
	L	M	M	T	M	T	–	L	M	T
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV] $>$	160									
$p_{\mathrm{T}}(j_1)$ [GeV] $>$	130									
$p_{\mathrm{T}}(j_2)$ [GeV] $>$	60									
$p_{\mathrm{T}}(j_3)$ [GeV] $>$	–		60		60		60	60		
$p_{\mathrm{T}}(j_4)$ [GeV] $>$	–		–		60		60	60		
$p_{\mathrm{T}}(j_5)$ [GeV] $>$	–		–		–		60	60		
$p_{\mathrm{T}}(j_6)$ [GeV] $>$	–		–		–		–	60		
$\Delta\phi(\mathrm{jet}_i, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}} >$	0.4 ($i = \{1, 2, (3$ if $p_{\mathrm{T}}(j_3) > 40$ GeV$)\}$)				0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_{\mathrm{T}} > 40$ GeV jets)					
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(Nj) >$	0.2	–[a]	0.3	0.4	0.25	0.25	0.2	0.15	0.2	0.25
m_{eff}(incl.) [GeV] $>$	1000	1600	1800	2200	1200	2200	1600	1000	1200	1500

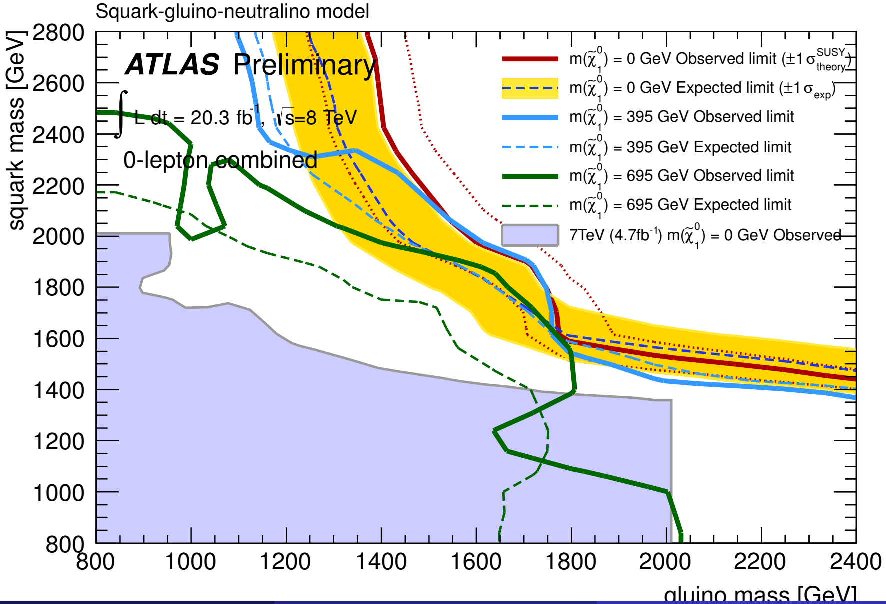
Results

Signal Region	**A-loose**	**A-medium**	**B-medium**	**B-tight**	**C-medium**	**C-tight**
			MC expected events			
Diboson	428.6	15.0	4.3	0.0	25.5	0.0
Z/γ^*+jets	2044.4	83.1	20.6	2.3	119.4	2.6
W+jets	2109.0	58.8	16.4	2.1	88.7	1.0
$t\bar{t}$(+EW) + single top	785.9	8.2	2.0	0.3	45.9	0.3
			Fitted background events			
Diboson	430 ± 190	15 ± 7	4.3 ± 2.0	–	26 ± 11	–
Z/γ^*+jets	1870 ± 320	57 ± 11	16 ± 5	0.2 ± 0.5	80 ± 29	$0.0^{+0.6}_{-0.0}$
W+jets	1540 ± 260	42 ± 11	10 ± 4	1.6 ± 1.2	55 ± 18	0.7 ± 0.9
$t\bar{t}$(+EW) + single top	870 ± 180	7.8 ± 2.8	2.2 ± 2.0	0.6 ± 0.7	50 ± 11	0.9 ± 0.9
Multi-jets	33 ± 33		0.1 ± 0.1	–	–	–
Total bkg	4700 ± 500	122 ± 18	33 ± 7	2.4 ± 1.4	210 ± 40	1.6 ± 1.4
Observed	5333	135	29	4	228	0
$\langle\epsilon\sigma\rangle^{95}_{\rm obs}$[fb]	66.07	2.52	0.73	0.33	4.00	0.12
$S^{95}_{\rm obs}$	1341.2	51.3	14.9	6.7	81.2	2.4
$S^{95}_{\rm exp}$	$1135.0^{+332.7}_{-291.5}$	$42.7^{+15.5}_{-11.4}$	$17.0^{+6.6}_{-4.6}$	$5.8^{+2.9}_{-1.8}$	$72.9^{+23.6}_{-18.0}$	$3.3^{+2.1}_{-1.2}$
p_0 (Z_n)	0.45 (0.1)	0.27 (0.6)	0.50 (0.0)	0.34 (0.4)	0.34 (0.4)	0.50 (0.0)

Exclusions in constrained MSSM



Exclusions in simplified models



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Early Run II expectations