Direct Stop Pair Production in the Hadronic Channel at ATLAS

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ATLAS

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- ATLAS Run 1 results
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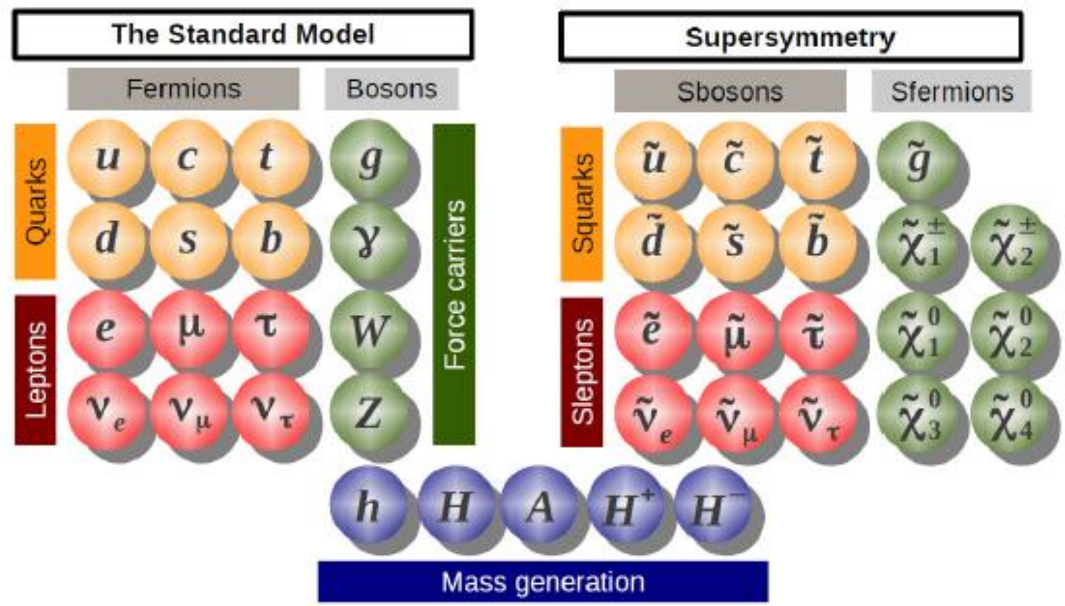
Supersymmetry and 3rd Generation

- Extension of Standard Model
  - Superpartner for every SM particle
  - Offers a solution to hierarchy problem, + lightest sparticle is a dark matter candidate

- Large Yukawa coupling and $\tilde{q}_R - \tilde{q}_L$ mixing mean 3rd generation squarks are expected to be lighter than other squarks
  - < TeV-scale is favoured



Supersymmetry and 3rd Generation

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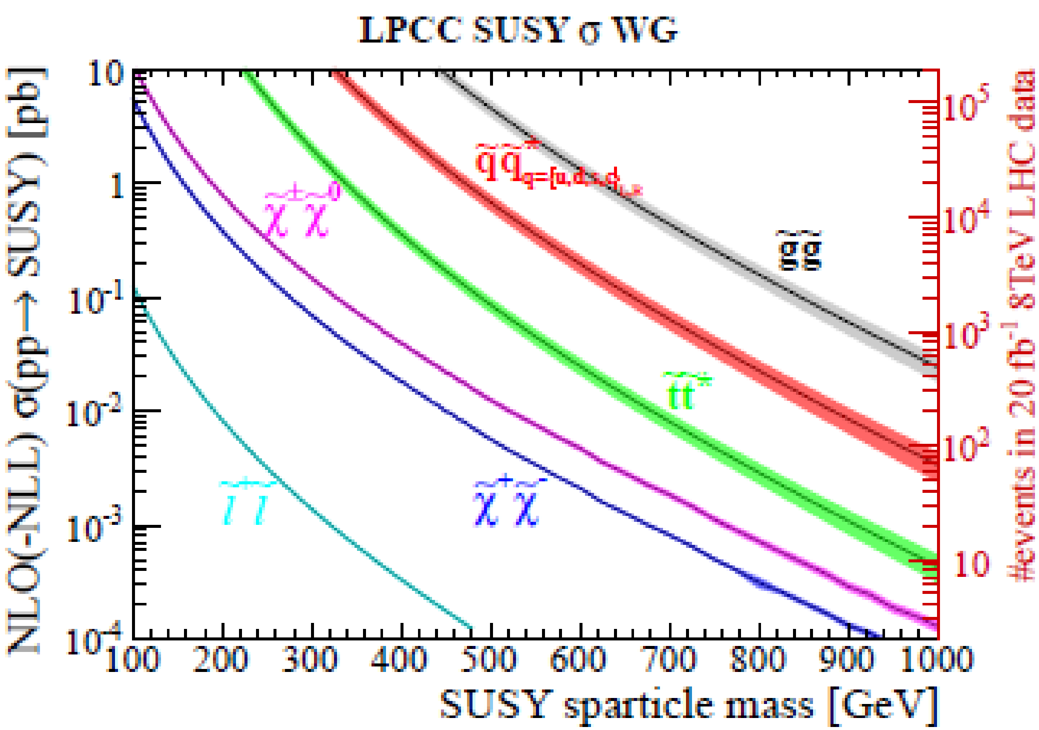
- Large Yukawa coupling and $\tilde{q}_R - \tilde{q}_L$ mixing mean 3rd generation squarks are expected to be lighter than other squarks
  - < TeV-scale is favoured
- Good news for LHC
  - Lower x-section but lighter than gluinos!



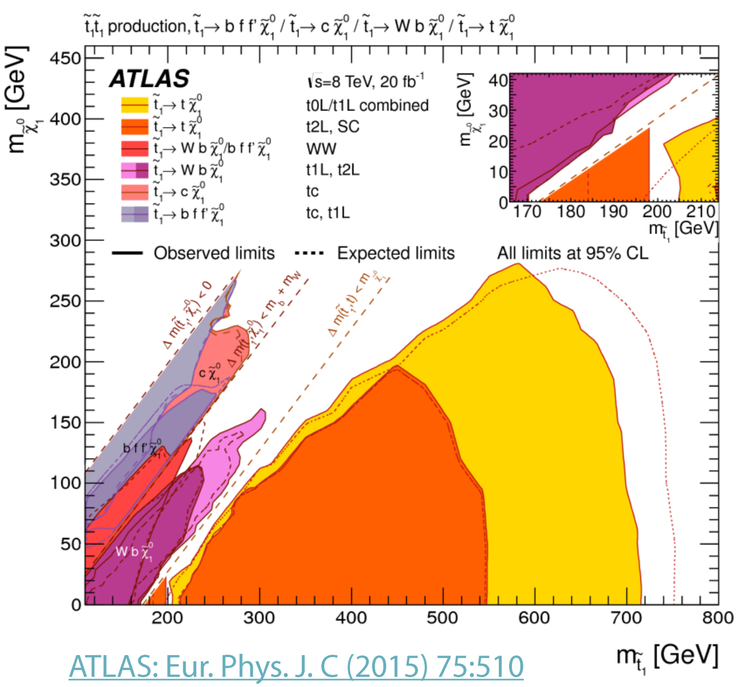
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections

ATLAS Run 1 3rd Gen Search Results

- Limits from 20.3 fb^{-1} $\sqrt{s}$ = 8 TeV data
  - 95% CL lower limits

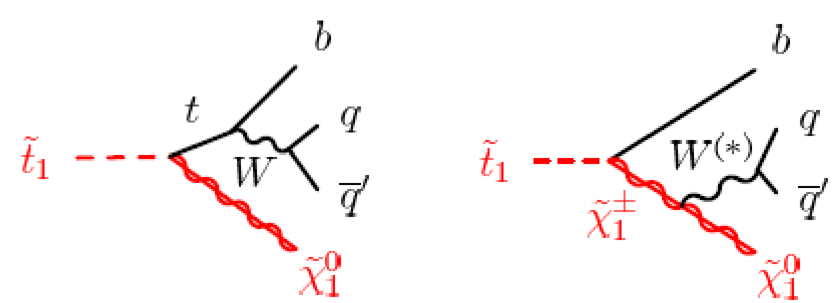
1 TeV

3rd gen. squarks direct production					
$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1 \to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV
$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1 \to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$ 110-167 GeV, 230-460 GeV
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$ 90-191 GeV, 210-700 GeV
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV
$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2 \to \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV



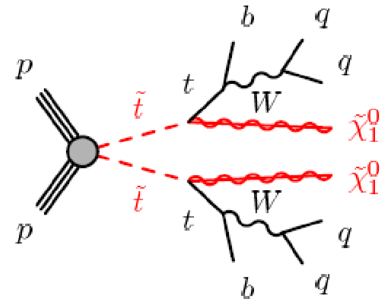
ATLAS: Eur. Phys. J. C (2015) 75:510

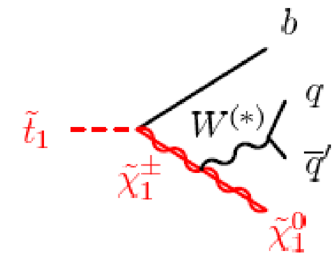
- $\tilde{t}_1 \to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ decays provides strongest limit on stop mass
  - $m_{\tilde{t}} < 700$ GeV excluded
- Still plenty of room for sub-TeV stop to be found!

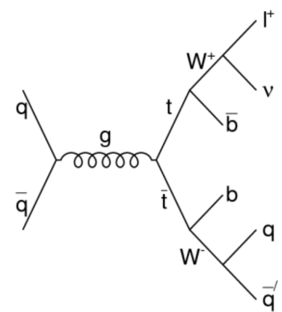


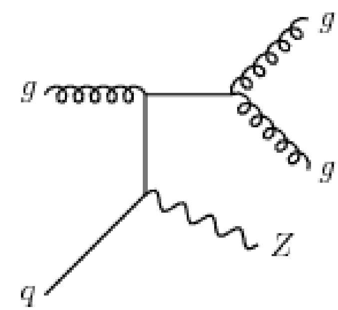
Hadronic Stop Search in Run 1

- $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, or $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$
  - Always pair-produced
- All hadronic final state
  - Largest branching ratio
  - Signal is hard to distinguish
    - Lots of high-p_T jets, E_T^{miss}…
- Main backgrounds:
  - $t\bar{t}$, single top, V + jets, $t\bar{t}$V + jets
  - Z(→ νν) + jets is very dangerous









- Signal regions (SR) defined to contain signal-like events, low bkg
- Use control regions (CR) to estimate background
  - Extrapolate from CR into related SR

Control Region Definitions

ATLAS: JHEP 09 (2014) 015

$t\bar{t}$ CR

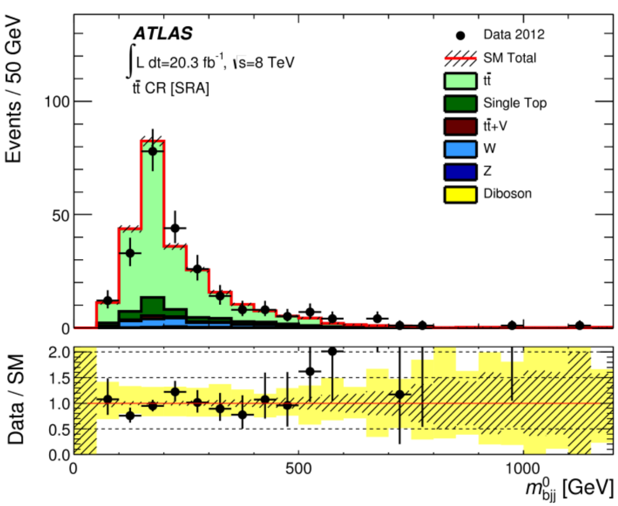
- Targets semileptonic $t\bar{t}$ events
- Essentially a looser SR
  - Requires a single lepton
  - Lepton mass + E_T^{miss} must be in *W* mass window

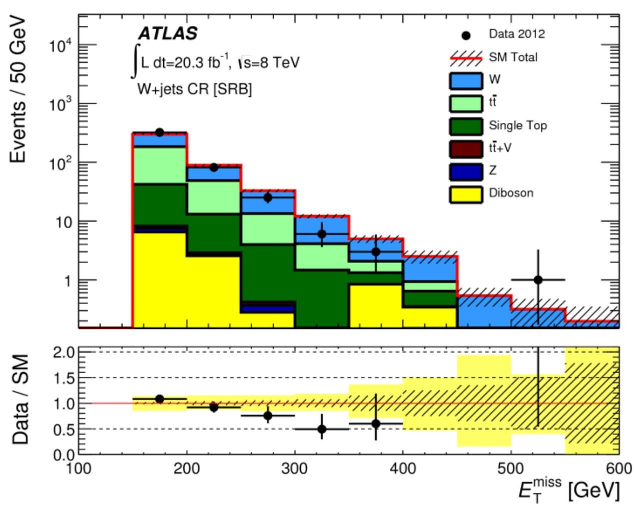
W+Jets CR

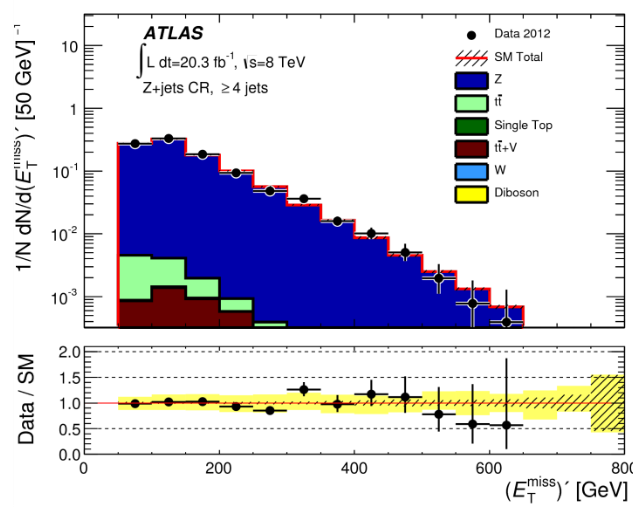
- Similar to $t\bar{t}$ CR
- Enhances *W* + heavy flavour jet fraction
- Requires leading reclustered *R=1.2* jet to be low mass
  - i.e. < 40 GeV

Z+Jets CR

- Exploits $Z \rightarrow ee/\mu\mu$ events to model $Z \rightarrow \nu\nu$ events
- Requires 2 leptons
  - Dilepton mass at Z mass
- Lepton p_T added to E_T^{miss} to mimic neutrinos

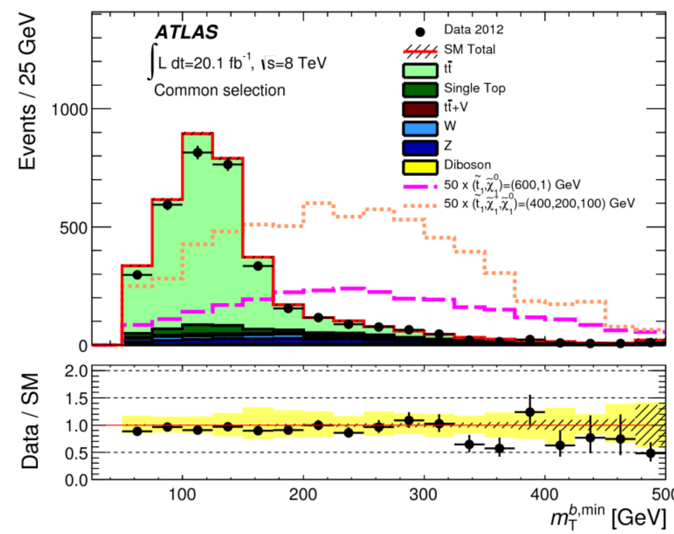


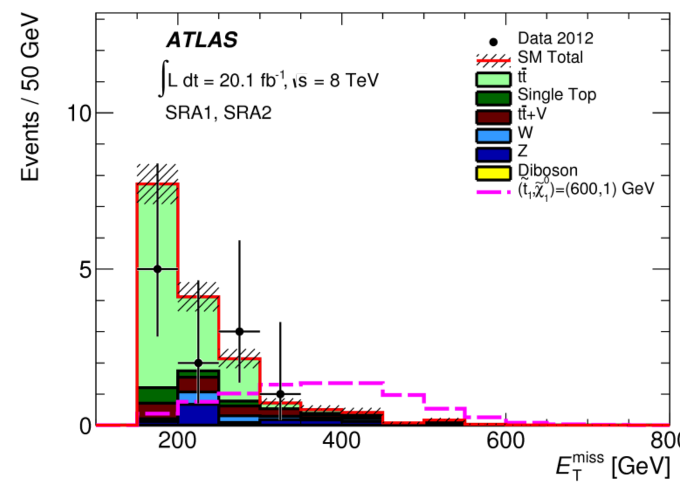




Signal Region Definitions

- Three signal regions:
  - SRA: nominal signal region, targets fully resolved top decays
    - > 6 jets, two high mass reclustered jets
  - SRB: targets events with partially resolved top decays
    - 4-5 jets, exploits top candidate asymmetry
  - SRC: targets $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ events
    - = 5 jets (enhances sensitivity to $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0$ splitting), uses angular variables to further reduce bkg
- Number of observed events goes directly into significance
- No excess observed – set limits!

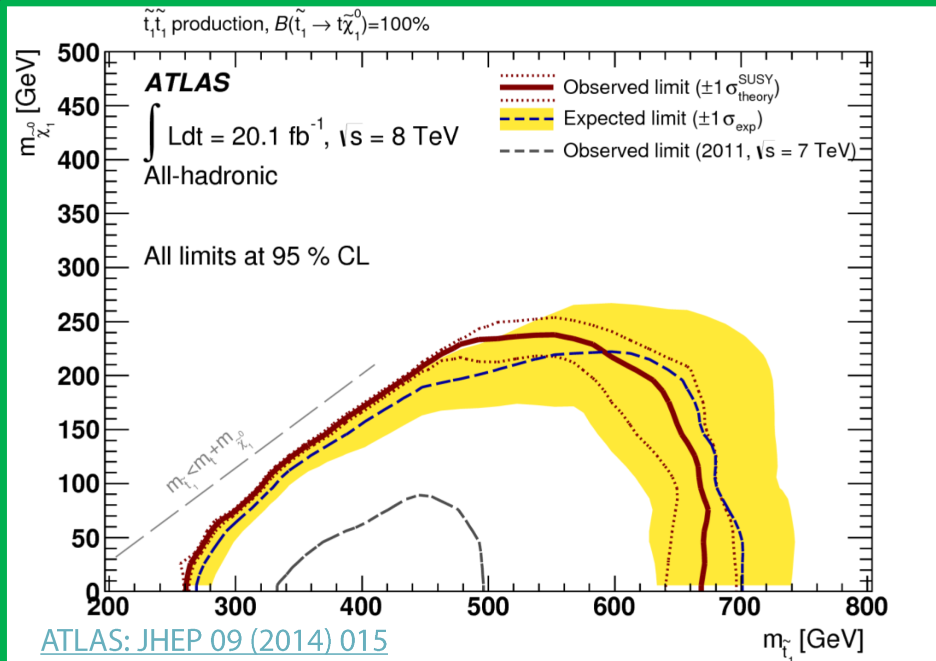




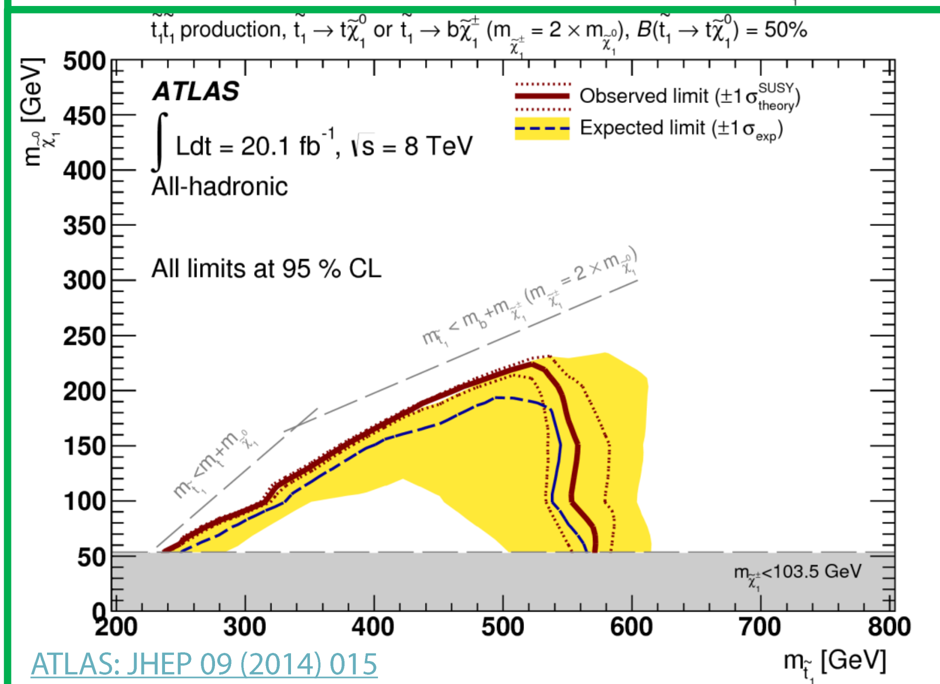
Top right: $m_T^{b,min}$: transverse mass of bjet closest in φ to $\boldsymbol{p}_T^{miss}$, common selection
Bottom right: E_T^{miss} in SRA

ATLAS: JHEP 09 (2014) 015

S… ions



[ATLAS: JHEP 09 (2014) 015]



[ATLAS: JHEP 09 (2014) 015]

- Exclusion area within solid red line
- Top left: limits placed by hadronic $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ only
- Bottom left: limits placed by combining $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ decays

ec

y

sp

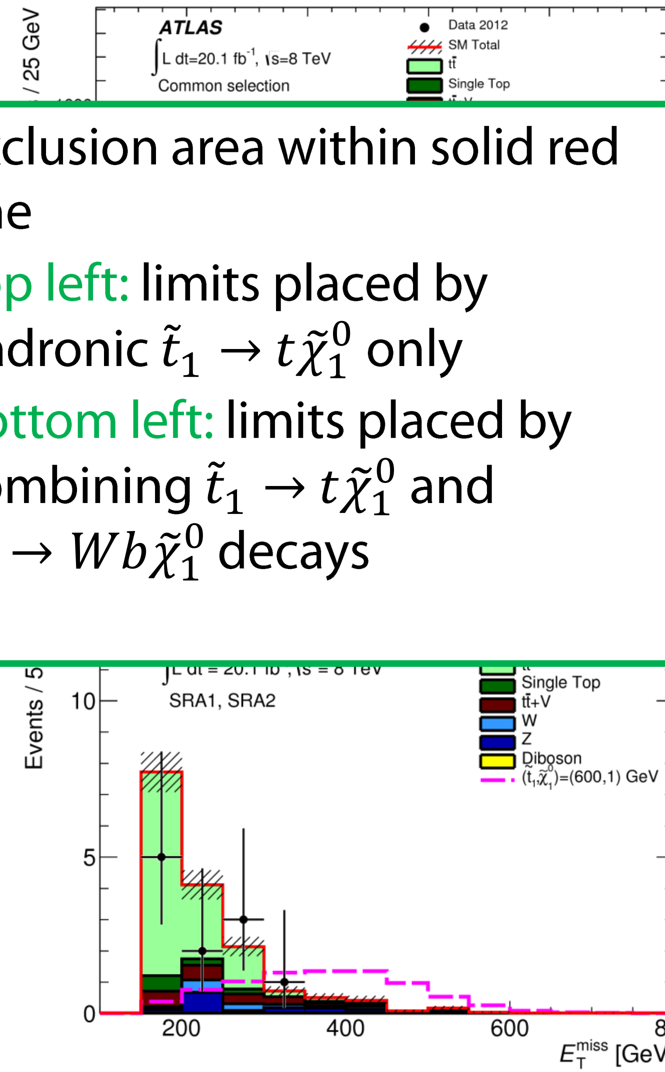
k

nto

osest in φ

selection

RA1,SRA2



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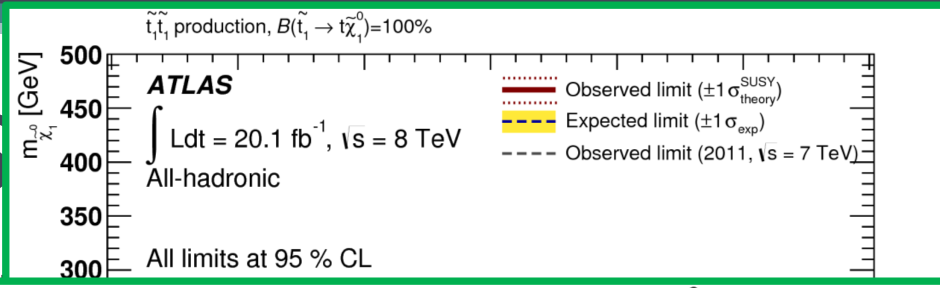
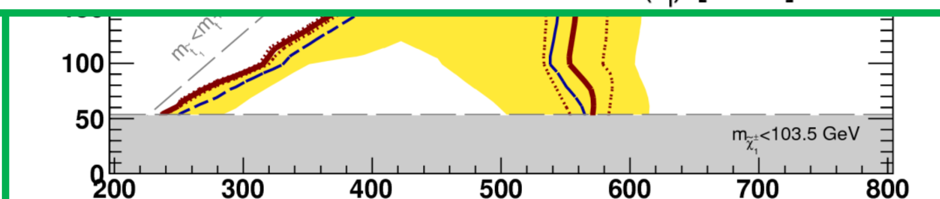
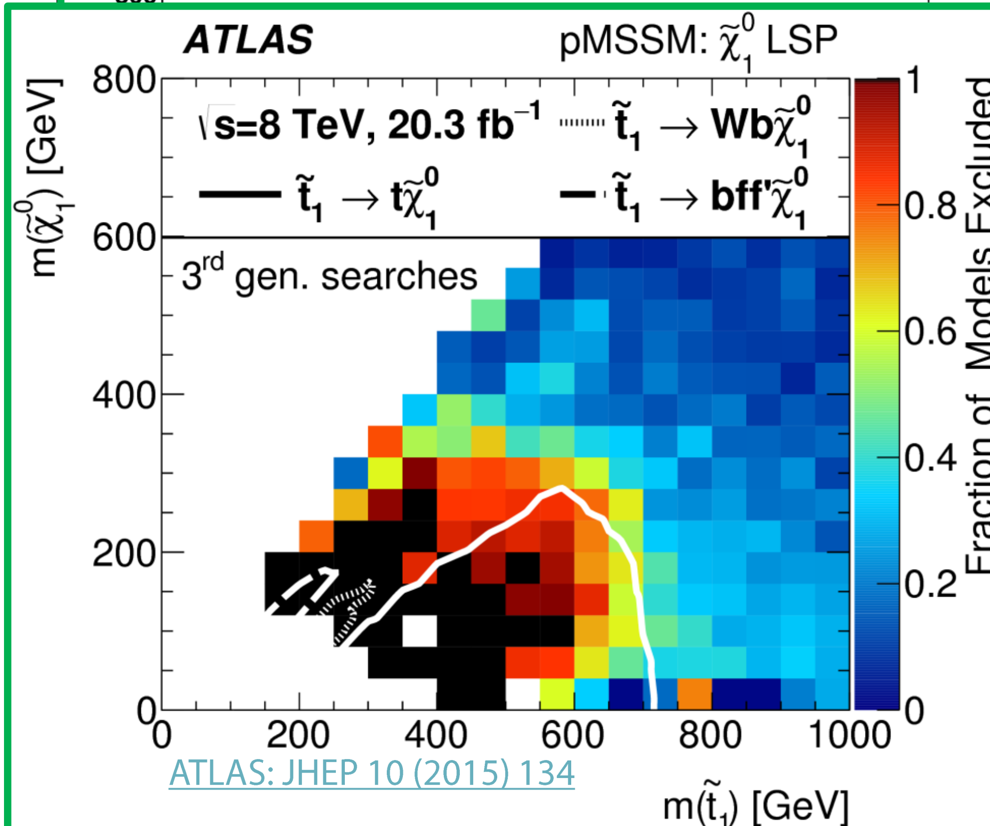
S… ions







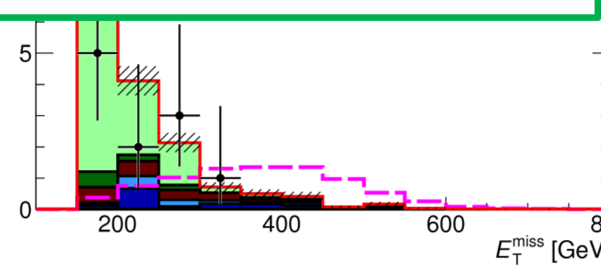
ATLAS: JHEP 10 (2015) 134

ATLAS: JHEP 09 (2014) 015

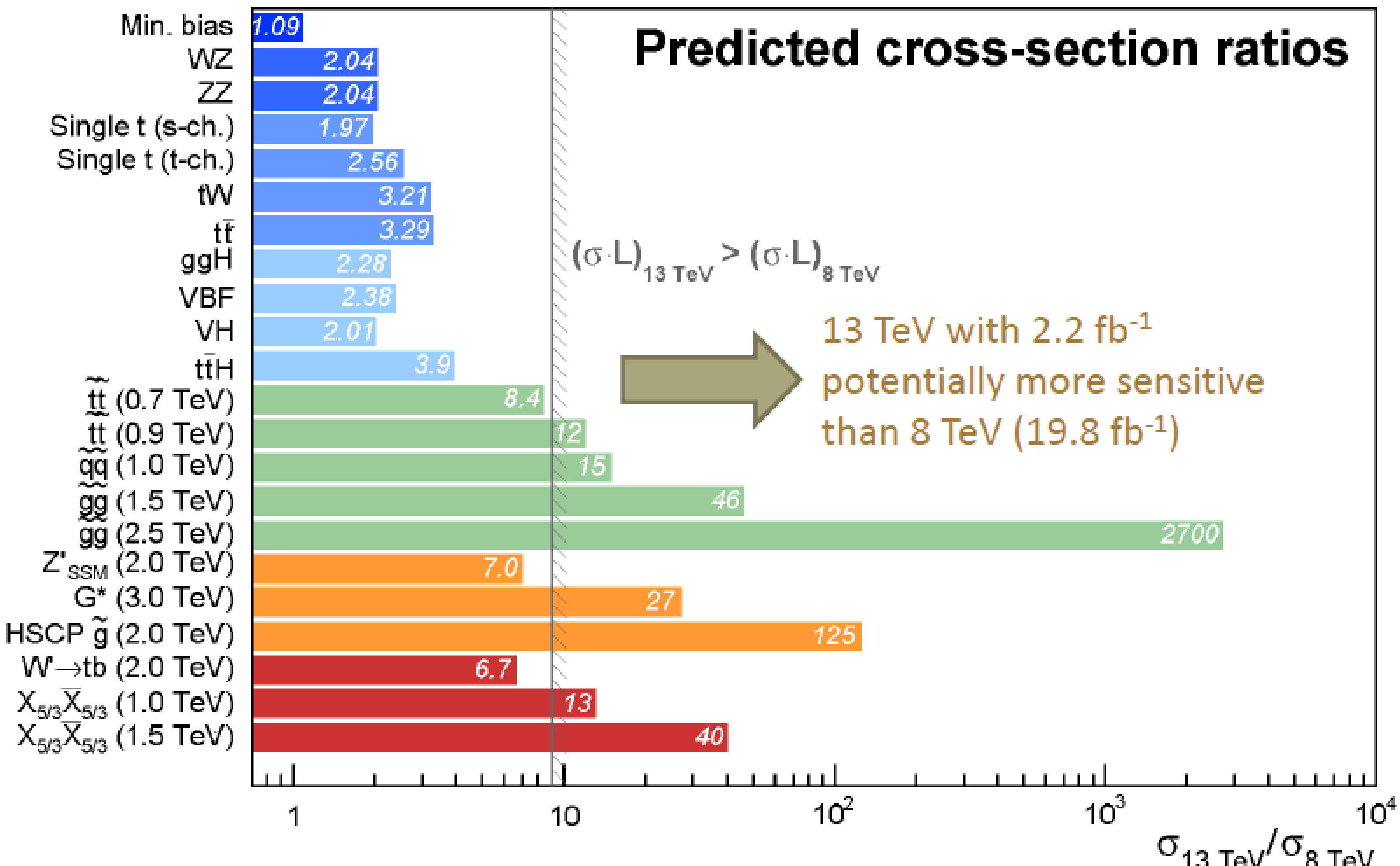
- pMSSM scan over 310,000 models
  - 19 free parameters
- White lines are exclusion limits provided by individual searches
- Each square represents a number of possible pMSSM models
- Colour of square indicates fraction of those models excluded

…osest in φ
… selection
…RA1,SRA2

…14) 015



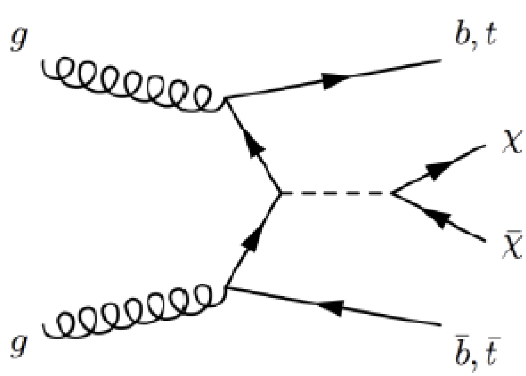
Stop Discovery Potential at 13TeV

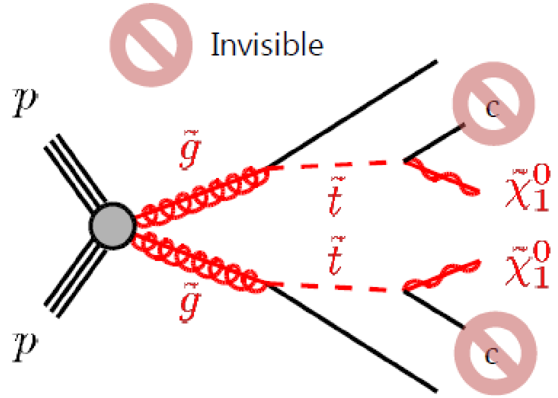


Jim Olsen, CMS/ATLAS End of year event, 15/12/15

Hadronic Stop Search in Run 2

- Can improve on Run 1 limits with just 5fb^{-1} of data!
- Big R&D effort to improve every aspect of the analysis
  - Top reconstruction, tau veto, γ + jets studies…
- Start with simplified model, but alternate model interpretations are also being studied
  - DM+*tt* search, Gtc decays, pMSSM





Conclusions

- Supersymmetry is a good candidate for BSM physics
- ATLAS has a rich programme of SUSY searches
- In Run 1, 3rd generation squark searches placed limits up to 700 GeV on stop mass
  - Strongest limit came from $\tilde{t}_1 \to t\tilde{\chi}_1^0$
- Run 2 has great discovery potential!
  - Hadronic stop search is still developing

Backup

Stop 0L signal region definitions

Common selection

Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$
N_{lep}	0
b-tagged jets	≥ 2
$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 150 GeV$
$\left\|\Delta\phi\left(\mathrm{jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\right)\right\|$	$> \pi/5$
$\left\|\Delta\phi\left(\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss,track}}\right)\right\|$	$< \pi/3$
$m_{\mathrm{T}}^{b,\,\mathrm{min}}$	> 175 GeV

SR A (fully resolved $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$)

	SRA1	SRA2	SRA3	SRA4
anti-k_t $R = 0.4$ jets	≥ 6, $p_{\mathrm{T}} > 80, 80, 35, 35, 35, 35$ GeV			
m_{bjj}^{0}	< 225 GeV		[50,250] GeV	
m_{bjj}^{1}	< 250 GeV		[50,400] GeV	
$\min[m_{\mathrm{T}}\left(\mathrm{jet}^i, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\right)]$	–		> 50 GeV	
τ veto	yes			
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 250 GeV	> 300 GeV	> 350 GeV

SR B (partially resolved $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$)

	SRB1	SRB2
anti-k_t $R = 0.4$ jets	4 or 5, $p_{\mathrm{T}} > 80, 80, 35, 35, (35)$ GeV	5, $p_{\mathrm{T}} > 100, 100, 35, 35, 35$ GeV
$\mathcal{A}_{m_t}$	< 0.5	> 0.5
$p_{\mathrm{T,jet},\,R=1.2}^{0}$	–	> 350 GeV
$m_{\mathrm{jet},\,R=1.2}^{0}$	> 80 GeV	$[140, 500]$ GeV
$m_{\mathrm{jet},\,R=1.2}^{1}$	$[60, 200]$ GeV	–
$m_{\mathrm{jet},\,R=0.8}^{0}$	> 50 GeV	$[70, 300]$ GeV
$m_{\mathrm{T}}^{\mathrm{min}}$	> 175 GeV	> 125 GeV
$m_{\mathrm{T}}\left(\mathrm{jet}^3, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\right)$	> 280 GeV for 4-jet case	–
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$	–	$> 17\sqrt{\ }$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 325 GeV	> 400 GeV

SR C ($\tilde{t}_1 \rightarrow b\chi_1^{\pm} \rightarrow bW\tilde{\chi}_1^0$)

	SRC1	SRC2	SRC3
anti-k_t $R = 0.4$ jets	5, $p_{\mathrm{T}} > 80, 80, 35, 35, 35$ GeV		
$\|\Delta\phi\left(b, b\right)\|$	$> 0.2\pi$		
$m_{\mathrm{T}}^{b,\,\mathrm{min}}$	> 185 GeV	> 200 GeV	> 200 GeV
$m_{\mathrm{T}}^{b,\,\mathrm{max}}$	> 205 GeV	> 290 GeV	> 325 GeV
τ veto	yes		
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 160 GeV	> 160 GeV	> 215 GeV

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Stop 0L control region definitions

CRs for only SRA are shown; only requirements different from common selection are shown.

	$t\bar{t}$ CR	Z + jets CR	Multijet CR
Trigger	electron (muon)	electron (muon)	same
N_{lep}	1	2	same
p_{T}^{ℓ}	$> 35(35)$ GeV	$> 25(25)$ GeV	–
$p_{\text{T}}^{\ell_2}$	same	$> 10(10)$ GeV	same
$m_{\ell\ell}$	–	$[86, 96]$ GeV	–
$E_{\text{T}}^{\text{miss,track}}$	–	–	same
$\left\|\Delta\phi\left(\mathbf{p}_{\text{T}}^{\text{miss}}, \mathbf{p}_{\text{T}}^{\text{miss,track}}\right)\right\|$	–	–	–
$\left\|\Delta\phi\left(\text{jet}, \mathbf{p}_{\text{T}}^{\text{miss}}\right)\right\|$	$> \pi/10$	–	< 0.1
$m_{\text{T}}^{b,\text{ min}}$	> 125 GeV	–	–
$m_{\text{T}}\left(\ell, \mathbf{p}_{\text{T}}^{\text{miss}}\right)$	$[40, 120]$ GeV	–	–
$\min[m_{\text{T}}\left(\text{jet}^i, \mathbf{p}_{\text{T}}^{\text{miss}}\right)]$	–	–	–
m_{bjj}^0 or m_{bjj}^1	< 600 GeV	–	–
$E_{\text{T}}^{\text{miss}}$	> 150 GeV	< 50 GeV	> 150 GeV
$\left(E_{\text{T}}^{\text{miss}}\right)'$	–	> 70 GeV	–

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Stop 0L Event Yields

Background estimates taken from profile likelihood fit; statistical, detector and theoretical systematic uncertainties included

	SRA1	SRA2	SRA3	SRA4	SRB	SRC1	SRC2	SRC3
Observed events	11	4	5	4	2	59	30	15
Total SM	15.8 ± 1.9	4.1 ± 0.8	4.1 ± 0.9	2.4 ± 0.7	2.4 ± 0.7	68 ± 7	34 ± 5	20.3 ± 3.0
$t\bar{t}$	10.6 ± 1.9	1.8 ± 0.5	1.1 ± 0.6	0.49 ± 0.34	$0.10^{+0.14}_{-0.10}$	32 ± 4	12.9 ± 2.0	6.7 ± 1.2
$t\bar{t} + W/Z$	1.8 ± 0.6	0.85 ± 0.29	0.82 ± 0.29	0.50 ± 0.17	0.47 ± 0.17	3.2 ± 0.8	1.9 ± 0.5	1.3 ± 0.4
Z + jets	1.4 ± 0.5	0.63 ± 0.22	1.2 ± 0.4	0.68 ± 0.27	1.23 ± 0.31	15.7 ± 3.5	9.0 ± 1.9	6.1 ± 1.3
W + jets	1.0 ± 0.5	0.46 ± 0.21	0.21 ± 0.19	$0.06^{+0.10}_{-0.06}$	0.49 ± 0.33	8 ± 4	4.8 ± 2.2	2.8 ± 1.2
Single top	1.0 ± 0.4	0.30 ± 0.17	0.44 ± 0.14	0.31 ± 0.16	0.08 ± 0.06	7.2 ± 2.9	4.5 ± 1.8	2.9 ± 1.4
Diboson	< 0.4	< 0.13	0.32 ± 0.17	0.32 ± 0.18	0.02 ± 0.01	1.1 ± 0.8	$0.6^{+0.7}_{-0.6}$	$0.6^{+0.7}_{-0.6}$
Multijets	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.24 ± 0.24	0.06 ± 0.06	0.01 ± 0.01
σ_{vis} (obs) [fb]	0.33	0.29	0.33	0.32	0.21	0.78	0.62	0.40
σ_{vis} (exp) [fb]	$0.48^{+0.21}_{-0.14}$	$0.29^{+0.13}_{-0.09}$	$0.29^{+0.14}_{-0.09}$	$0.25^{+0.13}_{-0.07}$	$0.24^{+0.13}_{-0.06}$	$1.03^{+0.42}_{-0.29}$	$0.73^{+0.31}_{-0.21}$	$0.55^{+0.24}_{-0.15}$
N^{95}_{obs}	6.6	5.7	6.7	6.5	4.2	15.7	12.4	8.0
N^{95}_{exp}	$9.7^{+4.3}_{-3.0}$	$5.8^{+2.6}_{-1.8}$	$5.9^{+2.8}_{-1.9}$	$5.0^{+2.6}_{-1.4}$	$4.7^{+2.6}_{-1.2}$	$20.7^{+8.4}_{-5.8}$	$14.7^{+6.2}_{-4.2}$	$11.0^{+4.9}_{-3.1}$

Expected and observed 95% CL upper limits on cross sections and event yields shown for each SR

ATLAS: JHEP 09 (2014) 015

Useful references

- Stop 0L Run 1 paper:
  - ATLAS: JHEP 09 (2014) 015
- Sbottom Run 1 paper:
  - http://arxiv.org/abs/1308.2631
- 3rd generation SUSY search summary paper:
  - ATLAS: Eur. Phys. J. C (2015) 75:510
- pMSSM reinterpretation paper:
  - http://arxiv.org/abs/1508.06608
- First look at Run 2 data (squark/gluino inclusive search):
  - https://cds.cern.ch/record/2037905/