SUSY searches with ATLAS

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QFTHEP - Samara

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Outline: From Mysterious to Science



ATLAS and the LHC are zooming in on the world to understand the unknown.

- Supersymmetry (SUSY) = theory that can explain some of the holes in the Standard Model
- Summarise status of ATLAS searches for SUSY:
 - Bulk and small corners of phase space
 - Variety of different combinations of objects in final states
 - Statistical exclusion limits on some models
 - Searches with hints of new physics

Supersymmetry



- ▶ SM particles $\rightarrow 1/2 \text{ spin} \rightarrow \text{SUSY}$ particles
- R-Parity conservation: SUSY particles come in pairs
 - ► Lightest supersymmetric particle (LSP) is a dark matter candidate → missing energy
- Scalar top \rightarrow hierarchy problem / fine tuning

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Supersymmetry with ATLAS



Classify searches based on:

- Production cross-section
- Final states after decays
- Decay chain
- Lifetime
- R-parity conservation/breaking

- Simplified models
- LSP = $\tilde{\chi}_1^0$ or \tilde{G} or ...
- Assume prompt decays unless specified otherwise
- Frequently main backgrounds: tt & single top, W+jets, Z+jets, and multijets
- Discriminating variables: p_T of objects, number of leptons, number of jets, scalar sums of p_T (e.g. m_{eff}), E_T^{miss}, E_T^{miss}/m_{eff}, m_T, m_{T2}

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8 TeV Exclusion Summary

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATI AS Preliminary $\sqrt{s} = 7.8 \text{ TeV}$

Model e, μ, τ, γ Jets E_{π}^{miss} [$\mathcal{L} dt[\text{fb}^{-1}]$] Mass limit Reference MELICRAICMEEM 2.6 lets 20.3 1.7 TeV m(g)=m(g) 1405 7875 2-6 jets Yes 20.3 850 GeV $m(\tilde{t}_1^0)=0$ GeV, $m(1^{c1}$ ges. $\tilde{t}_1)=m(2^{c1}$ ges. $\tilde{t}_2)$ 1405 7875 à0. à→q1 $\tilde{q}\tilde{q}\gamma, \tilde{q} \rightarrow q\tilde{\eta}_{1}^{0}$ (compressed) 0-1 jet Yes 20.3 250 GeV $m(0) \cdot m(\hat{v}_{1}^{0}) = m(v)$ 1411.1559 20. 8-+y0€ 2.6 jets Yes 20.3 1.33 TeV m(f)=0 GeV 1405.7875 $\tilde{\chi}\tilde{\varrho}, \tilde{\varrho} \rightarrow qq \tilde{\ell}_1^+ \rightarrow qq W^+ \tilde{\ell}$ 3-6 ints Mps. 20 1.2 TeV m(\$1)<300 GeV, m(\$*1+0.5)m(\$1)+m(\$1) 1501 03555 0-3 jets 22. 2-+qq(11/1×1×18 1.32 TeV mit and Gev GMSB (2 NLSP) 1-2 T + 0-1 (0-2 jets Yes 20.3 tans >20 1407 0602 1.6 TeV GGM (bino NLSP) Yes 20.3 1.28 TeV m(行)>50 GeV ATLAS-CONF-2014-001 GGM (wino NLSP) Yes 4.8 619 GeV m(r)>50 GeV ATLAS-CONF-2012-144 GGM (higgsing-bing NLSP) 1.5 Yes 4.8 m(1)>220 GeV 1211.1167 GGM (higgsino NLSP) 0-3 jets Yes 5.8 mINLSPID-200 GeV ATLAS-CONF-2012-154 Gravitino LSE 0 mono-iei Yes 20.3 165 GeV m(G)>1.8 × 10⁻⁴ eV, m(F)=m(A)=1.5 TeV 1502.01518 2-1000 Mass 20 1 1.25 TeV m(t)-400 GeV 1407.0900 $\tilde{g} \rightarrow t \tilde{K}_1$ 0 7-10 jets Yes 20.3 1.1 TeV m(f) <350 GeV 1308.1841 0-1 e, µ 20.1 1.34 TeV m(1)-400 GeV 1407 0500 3-118 Yes S-stri 3.1 Yes 20.1 1.3 TeV m(t)-300 GeV 1407 0600 2.b 20.1 100-620 GeV 1508 2851 $\bar{h}_1\bar{h}_1, \bar{h}_1 \rightarrow b\bar{t}$ m(f)-90 GeV $b_1b_1, b_1 \rightarrow i C$ 2 r. a (SS) Yes 20.3 275-440 GeV $m(\tilde{x}_{1}^{*}) + 2 m(\tilde{x}_{1}^{*})$ 1404,2500 $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}_1^{\pm}$ 1-2 6.0 1.2.6 Yes 110.167.043 $m(\hat{x}_{1}^{2}) = 2m(\hat{x}_{1}^{2}), m(\hat{x}_{1}^{2}) = 55 \text{ GeV}$ 1209.2102, 1407.0583 $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{t}_1^0$ or $i\tilde{t}_1^0$ 2 c, µ 0-2 jets Yes 20.3 90-191 GeV 215-530 GeV m(R)=1 GeV 1403 4853 1412 4742 $\hat{h}\hat{h},\hat{h}\rightarrow\hat{R}$ 1-2.6 Yes 2 210-640 GeV m(t)=1 GeV 1407.0583.1406.1122 mo-iet/c-tag Yes 20.3 90-240 GeV m(i)-m(i)-85 GeV T₁T₁(natural GMSB) $2 e, \mu (Z)$ 20.3 m(1)>150 GeV 1403 5222 Yes 20.3 290-500 GeV m(1)-200 GeV 1403 5222 $\hat{\ell}_{L,R}\bar{\ell}_{L,R}, \hat{\ell} {\rightarrow} \ell \hat{\kappa}_1^0$ 20.3 90-325 GeV million Gent 1403 5294 Yes 20.3 140-465 GeV $m(\tilde{t}_1^0)=0$ GeV, $m(\tilde{t},\tilde{\tau})=0.5(m(\tilde{t}_1^0)+m(\tilde{t}_1^0))$ 1403.5294 21 Yes 20.3 100-350 GeV m(2)=0 GeV, m(2, 7)=0.5(m(2))+m(2)) 1407.0350 $\hat{\chi}^{+}_{1}\hat{\chi}^{0}_{2} \rightarrow \hat{l}_{1}r_{1}^{1}l(\hat{v}r), l\hat{v}l_{1}l(\hat{v}r)$ Yes 20.3 700 GeV $m(\hat{x}_{1}^{n})=m(\hat{x}_{2}^{n}), m(\hat{x}_{1}^{n})=0, m(\hat{x}_{1}^{n})=0.5(m(\hat{x}_{1}^{n})+m(\hat{x}_{1}^{n}))$ 1402 7029 $\hat{x}_1^{\dagger}\hat{x}_2^{\dagger} \rightarrow W\hat{t}_1^{0}Z\hat{t}_1^{0}$ 236.0 0-2 jets Yes 20.3 420 GeV $m(\tilde{t}_1^+)+m(\tilde{t}_2^0), m(\tilde{t}_1^0)=0$, sleptons decoupled 1403.5294.1402.7029 1501.07110 X¹X⁰→WX⁰hX⁰ h→hh(WW)rr/we Yes 20.3 250 GeV m(1) am(2) m(1) w(intercons decoupled Lilli Lin ale 4 c.µ 20.3 1405.5086 Yes 620 GeV m(E)+m(E), m(F)+0, m(7, 9)+0.5(m(F)+m(F)) Disapp. trk Direct $\hat{x}_1^* \hat{x}_1^-$ prod., long-lived \hat{x}_1^* Yes 270 GeV m(37)-m(87)=160 MeV, r(87)=0.2 m 1310.3978 Stable, stopped # R-hadron 1-5 jets Yes 27.9 832 GeV m(t)=100 GeV, 10 as<r(t)<1000 s 1310 6584 Stable # R-hadron tris 19.1 1411.6795 GMSB. stable $\tau, \hat{\chi}_1^0 \rightarrow \tau(\hat{c}, \hat{\mu}) + \tau(c, \mu)$ 1-2 µ 19.1 537 GeV 1411.6795 GMSB, $\hat{\chi}_{1}^{0} \rightarrow \gamma \hat{G}$, long-lived $\hat{\chi}_{1}^{0}$ Yes 20.3 435 GeV 2<r(R³)<3 ns, SPS8 model 1409.5542 àõ, x̃⁰1→oar (RPV) 1 µ, displ. vtx 20.3 1.0 TeV 1.5 correct56 mm BB(a)=1 m(2)=108 GeV ATLAS-CONF-2013-092 LFV $nn \rightarrow \hat{r}_{r} + X, \hat{r}_{r} \rightarrow r + u$ 21.4 46 1.61 Te\ UFV $pp \rightarrow P_r + X, P_r \rightarrow e(\mu) + \tau$ Jun =0.10, Jugan =0.05 4.6 1.1 TeV 1212.1272 Bilinear RPV CMSSM 2 e, µ (SS) 0.3 b Yes 20.3 m(g)=m(g), cr35p<1 mm 1404 2500 $\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow ee \dot{r}_{su}, eg \partial_{s}$ $4 e.\mu$ Mpg 20.3 750 GeV m(\$^0)>0.2×m(\$^1), Act+0 1405 5086 $\hat{x}_{1}^{+}\hat{x}_{1}^{-}, \hat{x}_{1}^{+} \rightarrow W \hat{x}_{1}^{0}, \hat{x}_{1}^{0} \rightarrow \tau \tau \bar{\nu}_{e}, e \tau \bar{\nu}_{e}$ Yes 20.3 450 GeV michol 20001 20040 1405.5086 6-7 jets 20.3 BR(/)=BR(/)+BR(/)+0% ATLAS-CONF-2013-091 $\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$ 2 c, µ (SS) 0.3 b Yes 20.3 850 GeV 1404.250 Other Scalar charm, č→ck 20.3 m(f)-200 GeV 1501.01325 10-1 Mass scale [TeV] full data full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

Many searches performed but SUSY not (yet?) discovered

Strong Direct Production



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Strong Production: Search for gluinos (\tilde{g}) and 1st, 2nd generation sclar quarks (\tilde{q}) - 0ℓ and $\geq 1\ell$ analyses



- Searches cover a wide range of signal models
- Important discriminating variables: m_{eff}, E^{miss}_T, number of leptons, number of jets, lepton p_T

10.1007/JHEP04(2015)116, 10.1007/JHEP09(2014)176



 0ℓ

 1ℓ

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Strong Production: Search for \tilde{g} and 1st, 2nd generation \tilde{q} - recently combined 0ℓ and $\geq 1\ell$ analyses



Combination extends exclusion reach

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Z+MET+jets has 3σ excess



- Of the many strong production searches, this one saw an excess of 3σ
- Gauge Mediated model above = example signal model that can produce this excess
- $Z \to \ell^+ \ell^-$: 81 < $m_{\ell\ell}$ < 101 GeV
- Main backgrounds estimated using data. E.g. Z+jets: produce E^{miss}_T by smearing jets in p_T, φ



Third Generation Direct Production



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3rd Generation: Search for scalar tops summary



- ▶ $0 2\ell$ searches
- Some important discriminating variables: m_T, m_{T2}, E_T^{miss}, b-quark jet tagging
- 2-4 body decays



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3rd Generation: Search for scalar tops summary structure



3rd Generation: Scalar tops - Specialised Tools for Specific Features

Boosted parent particles

► Large sized jets (top figure : heavy t̃, light X̃⁰₁) (doi: JHEP11(2014)118)

Scalar top masses just above top quark mass

- Spin correlation (top figure inset) (doi: PhysRevLett.114.142001)
- Re-interpret tt
 cross-section measurement
 (bottom figure)
 (doi: EPJC/s10052-014-3109-7)



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3rd Generation: Scalar top - scalar tau 2ℓ



- ► Many additional signatures possible → check all the different corners of phase space
- Re-interpretation of a 2*l* search
 + additional signal region
- LSP = $\tilde{G} \sim \text{massless}$
- Targets diagonal boundary
- Signal regions: Vary jet p_T, m_{T2}



ATLAS-CONF-2014-014

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3rd Generation: Search for scalar tops - recently combined 0ℓ and 1ℓ analyses



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Electroweak Direct Production



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Electroweak Summary

- Small cross-sections
- Clean multi-lepton final states
- Low hadronic activity
- Searches using e, μ , τ



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Electroweak: Search for Charginos $(\tilde{\chi}_1^{\pm})$ and next-to-lightest Neutralinos $(\tilde{\chi}_2^0)$



- Hadronically decaying taus (0 e/µ)
- Not the best search channel; included for variety
- Minimize number of jets
- Some discriminating variables: E^{miss}_T, m_{T2}, and m_T (τ₁) + m_T (τ₂)

10.1007/JHEP10(2014)096



Long Lived and R-Parity Violating



What about if SUSY particles **can decay** into SM particles (R-parity violating)?

 \rightarrow final state without SUSY particles \sim no stable LSP.



What about if the SUSY particles have **long lifetimes**?

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Long Lived / RPV

- ► SUSY particles with long lifetimes (e.g. ğ or X̃₁)
- Analyses depend on where in the detector the decay occurs





What is coming up in the near future ?

- LHC 2015 = 13 TeV
- How much data is needed before we publish?

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13 TeV Strong Direct Production





Production cross-section 8 TeV \rightarrow 13 TeV: Main backgrounds: $\times 2 - 3$ Gluino pairs: $\times \sim 10$

Discovery sensitivity: $\sim 3\sigma$ with 2 - 10 fb⁻¹ for masses heavier than those excluded at 8 TeV

ATL-PHYS-PUB-2015-005

Conclusions

- ATLAS has probed a significant amount of phase space
- No SUSY particles discovered ... yet?
- ▶ Study the $Z + E_{T}^{miss}$ +jets excess further with 13 TeV data
- First signs of SUSY at 13 TeV could be seen with just $2 10 \text{fb}^{-1}$



 $13~{\rm TeV}$ data taking has started !

On-Z Region	E _T miss [GeV]	H _T [GeV]	n _{jets}	<i>m_{tt}</i> [GeV]	SF/DF	E _T ^{miss} sig. [√GeV]	fst	$\Delta \phi(\mathrm{jet}_{12}, E_\mathrm{T}^\mathrm{miss})$
SR-Z	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	-	-	> 0.4
Control regio	ons							
Seed region	-	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	< 0.9	< 0.6	-
CReµ	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	DF	-	-	> 0.4
CRT	> 225	> 600	≥ 2	$m_{\ell\ell} \notin [81,101]$	SF	-	-	> 0.4
Validation re	gions							
VRZ	< 150	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	-	-	-
VRT	150-225	> 500	≥ 2	$m_{\ell\ell} \notin [81, 101]$	SF	-	-	> 0.4
VRTZ	150-225	> 500	≥ 2	$81 < m_{\ell\ell} < 101$	SF	-	-	> 0.4

$$H_{\rm T} = \sum_{i} p_{\rm T}^{\rm jet~i} + p_{\rm T}^{\rm lepton~1} + p_{\rm T}^{\rm lepton~2}$$

$$p_{\rm T}^{\rm lepton~1} > 25~{\rm GeV}, ~p_{\rm T}^{\rm lepton~2} > 10-14~{\rm GeV}, ~~p_{\rm T}^{\rm jet} > 35~{
m GeV}$$

Other cuts for $10~{\rm GeV} < p_{\rm T}^{\rm lepton} < 25~{\rm GeV}$ leptons are tighter than for $p_{\rm T}^{\rm lepton} > 25~{\rm GeV}$ leptons

Other cuts for $35~{\rm GeV} < p_{\rm T}^{\rm jet} < 50~{\rm GeV}$ jets are tighter than for $p_{\rm T}^{\rm jet} > 50~{\rm GeV}$ jets

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13 TeV Strong Direct Production 2



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$$m_T(a) = \sqrt{2p_T^a p_T^{miss} \left(1 - \cos\left(\Delta\phi\right)\right)}$$

where a = e/ μ/τ (assumed massless).

$$m_{\mathrm{T2}}\left(b,c\right) = \sqrt{\min_{\mathbf{q}_{\mathrm{T}}^{\mathrm{b}} + \mathbf{q}_{\mathrm{T}}^{\mathrm{c}} = \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}} \left(\max\left[m_{\mathrm{T}}^{2}\left(\mathbf{p}_{\mathrm{T}}^{b}, \mathbf{q}_{\mathrm{T}}^{b}\right), m_{\mathrm{T}}^{2}\left(\mathbf{p}_{\mathrm{T}}^{c}, \mathbf{q}_{\mathrm{T}}^{c}\right)\right]\right)$$

where b,c = hadronic tau, jet, lepton+jet, etc.

$$\begin{split} H_T &= \sum_i p_T^{\text{jet i}} \\ m_{eff} &= E_T^{\text{miss}} + \sum_i p_T^{\text{jet i}} + \sum_j p_T^{\text{lepton j}} + \sum_k p_T^{\text{hadronic tau k}} \end{split}$$

Exact definitions are highly analysis dependent (number of jets, pt cut off, etc.).