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Search for direct top squark pair production in events with two tau leptons with the ATLAS detector

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### ATLAS is searching for "new physics" to explain some open questions about the Standard Model



Hierarchy problem

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#### Supersymmetry to the rescue



Supersymmetry fixing SM:

- $\tilde{G} = \text{dark}$  matter candidate
- top squark ("stop",  $\tilde{t}$ ) helps with hierarchy problem

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Intro Why SUS ATL Sign Met Plot Resu Con Bac

### Many SUSY searches performed by ATLAS, including for top squarks

C CUCY	Status: March 2016 Model	$e, \mu, \tau, \gamma$ Jets $E_{-}^{m}$	iss (£ dr(fb <sup>-1</sup> )	Mass limit	√x = 7.8 TeV	√s = 7, 8, 13 leV Reference
5 505 Y	MSUGRA/CMSSM 90,91, 	0-3 ε,μ/1-2 τ 2-10 jeta/3 έ γε 0 2-6 jeta γε mono-jet 1-3 jeta γε	s 20.3 6.8 s 3.2 6 s 3.2 6	980 GeV	<b>1.85 TeV</b> m(i)=m(j) m(t <sup>2</sup> )=0 Garl(m(1 <sup>-1</sup> gas, i)=m(2 <sup>n3</sup> gas, i) m(i)=m(t <sup>2</sup> )=5 GaV	1507.45525 ATLAS CONF-2015 062 To appear
od	● 68、3→06(ζ(tv)/v)よ <sup>0</sup> 日 25、25、3→06(1) ● 25、25→06(1) ● 25、25→06(1)→00(0 <sup>+</sup> ) <sup>2</sup> (5) 5) (5) (5) (5) (5) (5) (5)	2 κ,μ (off-Z) 2 jets Ye 0 2-6 jets Ye 1 κ,μ 2-6 jets Ye 2 κ,μ 0-3 jets -	s 20.3 a 3.2 a 3.3 20 20 20 20 20 20 20 20	820 GeV	m(t)+0 GeV 1.52 TeV 1.6 TeV 1.6 TeV 1.35 TeV m(t)+0 GeV 1.35 TeV m(t)+0 GeV	1503.03290 ATLAS-CONF-2015-062 ATLAS-CONF-2015-076 1501.03555
	gr 21, 2=-og/W27(     GMS8(/ NLSP)     GGM (bino NLSP)     GGM (bino NLSP)     GGM (biggstino-bino NLSP)     GGM (biggstino-bino NLSP)	0 /-10 jens Wa 1-2 + 0-1 / 0-2 jens Wa 2	a 3.2 e s 20.3 è s 20.3 è s 20.3 è s 20.3 è		1.4 1997 m(r) = 100 GeV 1.63 TeV traj > 20 1.34 TeV cr(NLSP)<0.1 mn 1.37 TeV m(t) = 490 GeV, cr(NLSP)<0.1 mn, pr04 1.37 TeV m(t) = 490 GeV, cr(NLSP)<0.1 mn, pr04	1602.06154 1407.0503 1507.05403 1507.05403
ts	GGM (higgsino NLSP) Gravitino LSP	2 e, μ (Z) 2 jets Ye 0 mono-jet Ye	s 20.3 P s 20.3 P <sup>4/2</sup> scale	900 GeV 965 GeV	$\begin{split} m(MLSP) {\sim} 430~GeV \\ m(G) {\sim} 1.8 \times 10^{-4}~eV, ~m(g) {=} m(g) {=} 1.5~TeV \end{split}$	1500.00290 1502.01518
usions	日本	0 3δ Ye 0-1 κ.μ 3δ Ye 0-1 κ.μ 3δ Ye	a 3.3 ē a 3.3 ē a 20.1 ē		1.78 TeV m(\tilde{i}) -0303 GeV 1.76 TeV m(\tilde{i}) -0 GeV 1.37 TeV m(\tilde{i}) -3303 GeV	ATLAS-CONF-2015-067 To appear 1407.0600
qr	$ \begin{array}{c} \mathbf{e} & \phi_{1}\phi_{1}, \phi_{2} \rightarrow 0\left[ \hat{r}_{1}^{2} \\ \phi_{2}\phi_{1}, \phi_{3} \rightarrow 0\left[ \hat{r}_{1}^{2} \\ \phi_{3}\phi_{3}\phi_{3}\phi_{3}\phi_{3}\phi_{3}\phi_{3}\phi_{3}$	0 2.b Ye 2 κ,μ (55) 0.3.b Ye 1.2 κ,μ 1.2.b Ye 0.2 κ,μ 0.2 jets/1.2.b Ye 0 mono-jet/c-tag Ye 2 κ,μ (Z) 1.b Ye 3 κ,μ (Z) 1.b Ye 1 κ,μ 6 jets + 2.b Ye	s 3.2 k, a 3.2 k, a 3.2 k, a 3.2 k, a 20.3 k, b 20	840 GeV 325-540 GeV 205-510 GeV 205-715 GeV 785-705 GeV 190-600 GeV 290-610 GeV	mt(1):100 GeV mt(1):50 GeV, mt(1):= mt(1):100 GeV mt(1):= 3mt(1):mt(1):450 GeV mt(1):=100 Mt(1):450 GeV mt(1):100 GeV mt(1):100 GeV mt(1):100 GeV	ATLAS CONF-2015 086 1602,99058 1250,2102,1407,0503 0698516, ATLAS CONF-20 1407,0903 1403,5022 1403,5022 1403,5022 1506,08616
	$\begin{array}{c} \left\{ \begin{array}{c} t_{11} t_{12} t$	2 κ.μ Ο Υκ 2 κ.μ Ο Υκ 3 κ.μ Ο Υκ 2 3 κ.μ Ο Υκ 2 3 κ.μ Ο 2 μHs Υκ 7/γγ κ.μ Υ Ο-2 μ Υκ 4 κ.μ Ο Υκ 1 κ.μ γ Υ	a 20.3 7 a 20.3 8 a 20.5	90-335 GeV 140-475 GeV 335 GeV 715 GeV 425 GeV (70 GeV 635 GeV 115-370 GeV	ကရီး)-16-664/ ကရီး)-16-664 (RE 7)-0.2 (RH ဒီ)- ကရီး)-16-664 (RE 7)-0.2 (RH ဒီ)- ကရီး)-16-664 (RE 7)-0.2 (RH 2)- (RE 7)-87(2), (RE 7)-0.2 (RH 2)- (RE 7)-(RE 7), (RE 7)-0.2 (RH 2)-(RE 7), (RE 7)-(RE 7), (RE 7), (RE 7), (RE 7), (RE 7), (RE 7)-(RE 7), (RE 7)	1403.5294 1403.5294 1407.0390 1402.7029 1403.5294, 1402.7029 d 1501.07110 1405.5086 1507.65400
	Divert (1)() mont, lang-level (1) Divert (1)() mont, lang-level (1) Stable, stopped (2) Photomo (2) Divert (2) Divert (2) Divert (2) (2) Divert (2) Divert (2) Divert (2) (2) Divert (2) Divert (2) Divert (2) (2) Divert (2) Divert	1         Disapp. trk         1 jot         Ye           0         1-5 jots         Ye         Ye           0         1-5 jots         Ye         Ye           dEdxts trk         -         -         -           dEdyst trk         -         -         -	a 20.3 K a 18.4 K 3.2 k 19.1 K 20.3 K 20.3 K 20.3 K 20.3 K	270 GeV 455 GeV 250 GeV 537 GeV 440 GeV 1.0 TeV 1.0 TeV	<ul> <li>市谷) 中部行→188.040 パイジーク2.06</li> <li>市谷) 中部行→1875→188.040 パイジーク3.06</li> <li>市谷) 中部行→160 246 10.04×10.05</li> <li>市谷) 中部行→160 246 10.04×10.05</li> <li>市谷) 中部行→160 246 10.04×10.05</li> <li>市谷(24, 10.04×10.05)</li> <li>市谷(24, 10.04×10.05)</li> <li>市谷(25, 10.05)</li> <li>市谷(</li></ul>	1310.3875 1506.65332 1310.6884 Xiv.qqnew 1411.6782 1403.5542 1504.65162 1504.65162
	$ \begin{array}{c} U^{T}V_{i} g_{i} = r_{i}r_{i} + X_{i} r_{i} - r_{i}q_{i}r_{i}r_{j}r_{i}r_{i}r_{i}r_{i}r_{i}r_{i}r_{i}r_{i$	OLCT.μT	20.5 F. a 20.5 F. b 20.5 K <sup>2</sup> 20.5 K <sup>2</sup> 20.3 K <sup>2</sup> 20.3 F. 20.3 F. 20.3 F. 20.3 F. 20.3 F. 20.3 F. 20.3 F. 20.3 F. 20.5 F. 20	760 GeV 450 GeV 917 GeV 910 GeV 320 GeV	1.7 TeV 1.45 TeV 1.45 TeV m(k+0)2, ct_{10} <t nn<br="">m(k)=02, ct_{10}<t nn<br="">m(k)=02 cm(k), due 80(y)=80(y)=86(y)=60(y) m(k)=600 ceV 80(y)=80(y</t></t>	1503,84450 1404,2503 1405,5085 1403,5085 1502,85885 1502,85885 1404,2503 1601,87453
	Officer Scalar charm, $\bar{c} \rightarrow c \bar{c}^{0}$	2 c.µ 28 -	20.3 ri 8 20.3 Z	0.4-1.0 TeV 510 GeV	m(1 <sup>2</sup> ) <2015 m(1 <sup>2</sup> ) <201 GeV	1501.01325

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#### https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/



# Search for top squark to tau slepton signal over $t\bar{t}$ background





- ▶ 0-2 e or  $\mu$
- $\blacktriangleright 2-0 \tau_{had}$



Channels:

- lepton-lepton = 2 e or  $\mu$
- lepton-hadron =  $1 \tau_{had}$  and (1 e or  $\mu$ )
- hardon-hadron =  $2 \tau_{had}$



### Selection cuts isolate regions of phase space to maximize/minimize signal to background

#### Intro

- Method
- Analysis method Variables Signal regions SR cuts
- Plots
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observable 2

Just count # events in phase space regions:

- Control: scale simulation to data for dominant backgrounds
- Validation: check scaling
- Signal: maximized signal to background





observable 1

Analysis blinded to reduce human bias

Data set from 2012: 8 TeV,  $20 \text{fb}^{-1}$ 

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# Several kinematic variables separate signal from background



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- Number of b-jets
- Probes of decaying particles' masses, e.g.  $m_{\mathrm{T2}}\left(\mathrm{b}\ell,\mathrm{b} au
  ight)$
- Sums/ratios of momenta e.g.

• 
$$H_{\rm T} = p_{\rm T}^{\rm jet1} + p_{\rm T}^{\rm jet2}$$
  
•  $\frac{p_{\rm T}^{\ell} + p_{\rm T}^{\star}}{\sum_{i}^{all} p_{\rm T}(i)}$ 

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## Design analyses around unknown signal masses: $m(\tilde{t})$ and $m(\tilde{\tau})$





## Main cuts separating each channel/SR are $m_{\mathrm{T2}}(t) \rightarrow m(\tilde{t})$ and $m_{\mathrm{T2}}(W) \rightarrow m(\tilde{\tau})$



- ▶ SRHM  $m_{T2}(W) > 120$  GeV vs SRHH  $m_{T2}(W) > 50$  GeV
- ▶ SRHM  $m_{T2}(t) > 180 \text{ GeV}$  vs SRHH all top squark masses
- 2 leptons  $m_{\mathrm{T2}}(W)$  and jet  $p_{\mathrm{T}}$  & multiplicity
- SRLM  $m_{T2}(t) < 60$  GeV vs SRHH all top squark masses

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#### t mass-probing variable



$$m_{\mathrm{T2}}(t) = m_{\mathrm{T2}} \left( \mathrm{b}\ell, \mathrm{b}\tau \right)$$

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#### W mass-probing variable



$$m_{\mathrm{T2}}(W) = m_{\mathrm{T2}}\left(\ell, \tau\right)$$

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#### No excesses seen in any signal region

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Plots

Results

SR counts Combined Exclusion

Conclusions

Backup

Analysis	Expected bkgd	Observed
	(nom. $\pm$ stat. & syst.)	
Lepton-hadron low mass		
SRLM	$22.1 \pm 4.7$	20
Lepton-hadron high mass		
SRHM	$2.1 \pm 1.5$	3
Hadron-hadron		
SRHH	$3.1 \pm 1.2$	3

2-leptons channel has many SRs : no excess.

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### Use SR/channel that gives best expected CLs for combination



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#### Summary

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- Top squark could help fix an open problem in the Standard Model
- $\blacktriangleright$  Low and high  $\tilde{t}$  masses probed as a function of the  $\tilde{\tau}$  mass
- No excesses observed.
- $\blacktriangleright$  Set limits on  $m(\tilde{t})$  as a function of  $m(\tilde{\tau})$ 
  - Heaviest top squark mass excluded  $\sim 660~{\rm GeV}$
- $\blacktriangleright$  Expecting  $\sim 25 {\rm fb}^{-1}$  this year
  - Should be sensitive to  $m(\tilde{t}) \sim 800 \text{ GeV}$

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#### Region cuts are all orthogonal to each other

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- Regional Cuts
- $\begin{array}{c} m_{T2} \text{ Upper} \\ \text{Limits} \\ \text{Real/fake } \tau \\ \text{Estimation} \\ \text{SRLM Exclusion} \\ \text{SRHM Exclusion} \\ \text{SRHH Exclusion} \\ \text{SRLL Exclusion} \\ \end{array}$

Region	$N_{\tau_{had}}$	$N_{\mu}$	$N_{jet}$	$N_{b-jet}$	$E_{T}^{miss}$	$\Delta \phi(j_{1,2}, p_T^{\text{miss}})$	$m_{T2}(\tau_{had}, \ell)$	$m_{\mathrm{T}}^{\mathrm{sum}}(\tau_{\mathrm{had}}, \ell)$
SRHH	2	0	$\geq 2$	$\geq 1$	> 150  GeV	$\ge 0.5$	> 50  GeV	> 160  GeV
CRHHTop	1	1	$\geq 2$	$\geq 1$	> 100  GeV	$\ge 0.5$	-	[70,120] GeV
CRHHWjets	1	1	$\geq 2$	0	> 100  GeV	$\ge 0.5$	< 40  GeV	[80,120] GeV
VRHHTop	1	1	$\geq 2$	$\geq 1$	> 120  GeV	$\ge 0.5$	< 40  GeV	[120,140] GeV
VRHHWjets	1	1	$\geq 2$	0	> 120  GeV	$\ge 0.5$	< 40  GeV	[120,150] GeV
CRHHQCD	$\geq 2^a$	0	$\geq 2$	$\geq 1$	$> 150 { m ~GeV}$	$\le 0.5^{b}$	-	-

<sup>a</sup>For the multi-jet control region (CRHHQCD), no identification criteria are applied to tau leptons. <sup>b</sup>The  $\Delta \phi$  requirement only applies to the sub-leading jet  $j_2$ .

Region	$N_{b-\mathrm{jet}}$	$H_{\rm T}/m_{\rm eff}$	$\frac{p_{\mathrm{T}}^{\ell} + p_{\mathrm{T}}^{\tau_{\mathrm{had}}}}{m_{\mathrm{eff}}}$	$m_{T2}(b\ell, b)$	$m_{\rm T2}(b\ell, b\tau_{\rm had})$	$m_{\rm T}(\ell, p_{\rm T}^{\rm miss})$	$m_{\rm eff}$
SRLM	$\geq 2$	< 0.5	> 0.2	< 100  GeV	< 60  GeV	-	-
CRTtLM	$\geq 2$	-	> 0.2	< 100  GeV	110 - 160  GeV	> 100  GeV	-
CRTfLM	$\geq 2$	-	> 0.2	< 100  GeV	$110-160~{\rm GeV}$	< 100  GeV	-
CRWLM	0	< 0.5	> 0.2	-	-	> 40  GeV	< 400  GeV
VRTLM	$\geq 2$	> 0.5	> 0.2	< 100  GeV	$60-110~{\rm GeV}$	-	-
Region	$N_{b-jet}$	$E_{T}^{miss}$	$m_{\text{eff}}$	$H_{\rm T}/m_{\rm eff}$	$m_{T2}(b\ell, b\tau_{had})$	$m_{T2}(\ell, \tau_{had})$	$m_T(\ell, p_T^{miss})$
SRHM	$\geq 1$	> 150  GeV	> 400  Ge	V < 0.5	> 180  GeV	> 120  GeV	-
CRTtHM	$\geq 1$	> 150  GeV	> 400  Ge	V < 0.5	> 180  GeV	20-80  GeV	> 120  GeV
CRTfHM	$\geq 1$	> 150  GeV	> 400  Ge	V < 0.5	> 180  GeV	20-80  GeV	< 120  GeV
CRWHM	0	> 150  GeV	> 400  Ge	V < 0.5	-	20-80  GeV	40-100  GeV
VRHM	$\geq 1$	$< 150 { m ~GeV}$	> 400  Ge	V < 0.5	$> 180 { m ~GeV}$	> 80  GeV	-



### $m_{\mathrm{T2}}$ Upper Limits



wietho

Plots

Results

Conclusions

Backup

 $\begin{array}{c} {\rm Regional\ Cuts}\\ m_{{\rm T}2} \\ {\rm Upper}\\ {\rm Limits} \end{array}$ 

Real/fake auEstimation SRLM Exclusion SRHM Exclusion SRHH Exclusion SRLL Exclusion





$m_{\mathrm{T2}}$	Max Value for	Max Value for
	Signal	$tar{t}$ background
$m_{\mathrm{T2}}\left(\mathrm{b}\ell,\mathrm{b} au ight)$	top squark mass	top mass
$am_{\mathrm{T2}}(\mathrm{b}\ell,\mathrm{b})$		top mass
$m_{\mathrm{T2}}\left(\ell, au ight)$	If chargino not virtual	W mass
	(not true here):	
	chargino mass	



### Fake and $\tau$ background estimation done with MC

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- SRLM Exclusion SRHM Exclusion SRHH Exclusion SRLL Exclusion

- ► Fit for tt
  (
  τ<sup>true</sup>), tt
  (
  τ<sup>fake</sup>), and W+jets seperately in the background-only fit with a CR for each.
- W+jets CRs: Use b-veto to isolate.
- ▶  $t\bar{t}$  CRs: Use an  $m_{T2}$  variable to isolate  $t\bar{t}$  and then  $m_T^{\ell}$  to distinguish true and fake taus.
- $\blacktriangleright$  The same-sign method (tau has same sign charge as  ${\rm e}/\mu)$  was also tested

#### Summary of results:

- Both methods give similar results to within the uncertainties.
- MC method was chosen because of a lack of statistics in the same-sign method.

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#### Exclusion plot for lepton-hadron Low Mass channel



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#### Exclusion plot for lepton-hadron High Mass channel



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#### Exclusion plot for hadron-hadron channel



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#### Exclusion plot for lepton-lepton channel



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