Searches for squarks and gluinos with the ATLAS detector

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On behalf of the ATLAS experiment

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ATLAS: Many searches, various final states, numerous models - limits around 1 TeV

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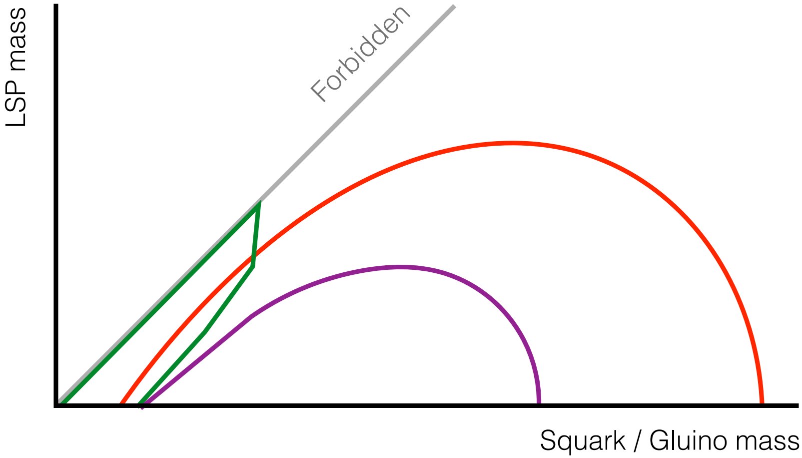

Overview

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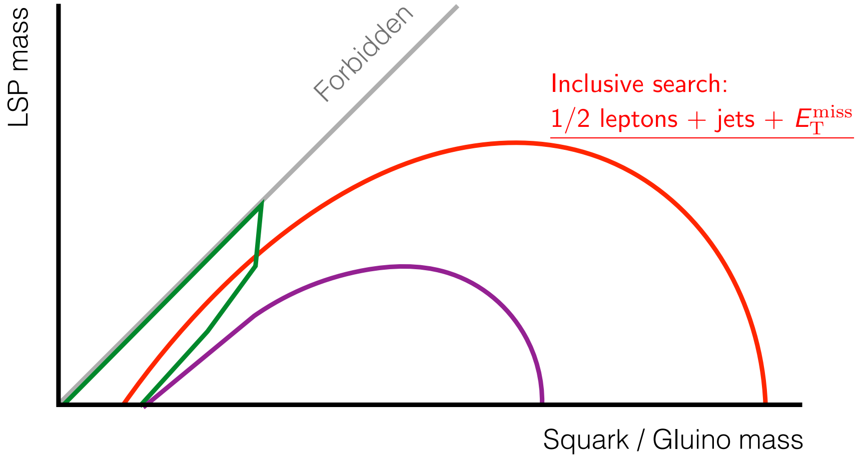

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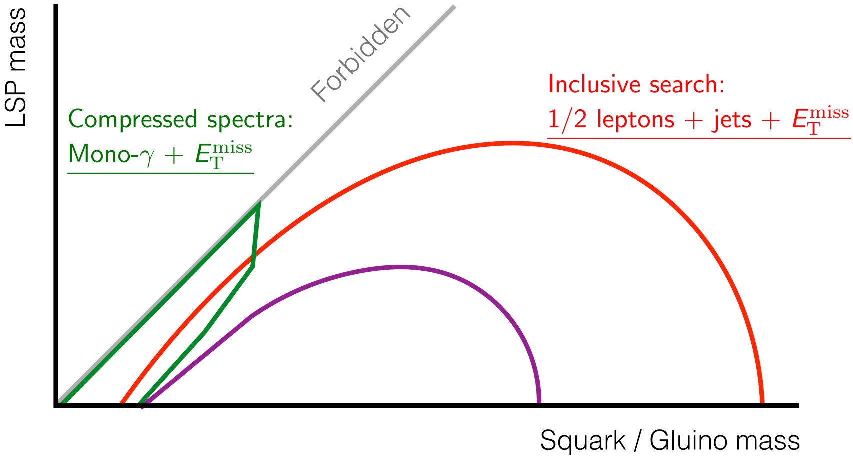

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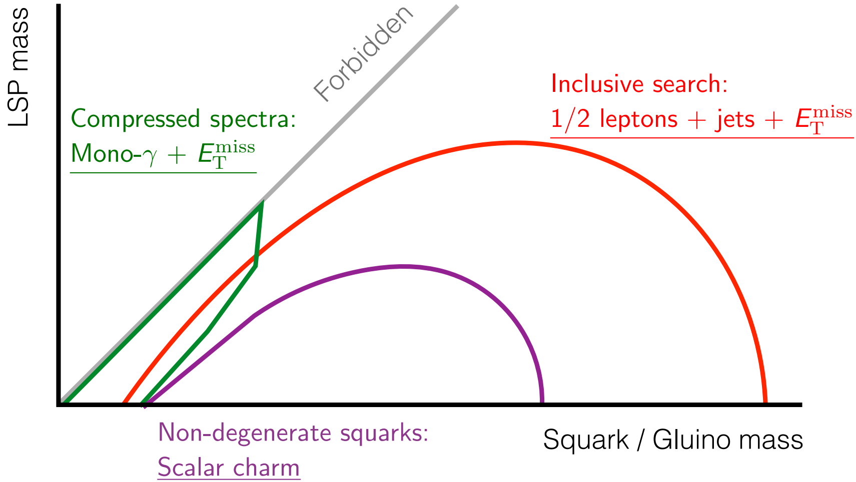
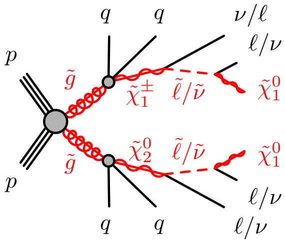
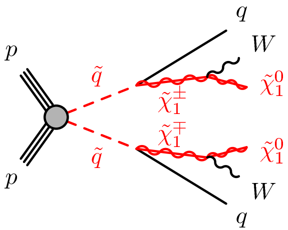


$1/2\ \ell$ + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$, Signals

- arXiv: 1501.03555 [hep-ex], submitted to JHEP
- Many models targeted
  - Gluino ($\tilde{g}$) and squark ($\tilde{q}$) production
  - Decays via charginos ($\tilde{\chi}_1^{\pm}$) and sleptons ($\tilde{l}$) $\rightarrow$ leptons in final state
- Four regions, 1 & 2 leptons (decay chain length), soft and hard (mass splittings)
  - Soft: $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger, $p_T^{\ell} < 25\,\mathrm{GeV}$
  - Hard: Combined $\ell + E_{\mathrm{T}}^{\mathrm{miss}}(+\mathrm{jet})$ triggers





- Discrimination from N_{jets}, $E_{\mathrm{T}}^{\mathrm{miss}}$, m_T, m_{eff}, topological information
- $m_T = \sqrt{2 p_T^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - cos[\Delta\phi(\vec{\ell}, \mathbf{p}_T^{\mathrm{miss}})])}$
- $m_{\mathrm{eff}} = E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{i=1}^{N_{\mathrm{jets}}} p_{T,i}^{\mathrm{jet}} \left(+ \sum_{i=1}^{N_{\ell}} p_{T,i}^{\ell} \right)$

1/2 ℓ + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$, Mega jets

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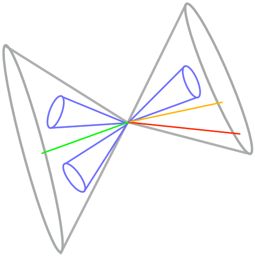
- Split event into two 'mega jets'



- Exploit symmetry to approximate rest frame - 'R-frame': 'Razor variables'

- Discrimination from N_{jets}, E_T^{miss}, m_T, m_{eff}, topological information
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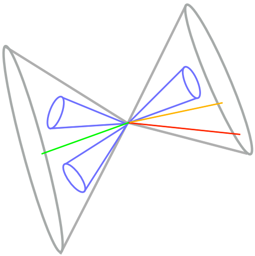
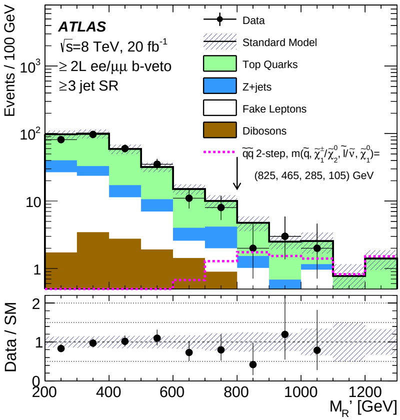




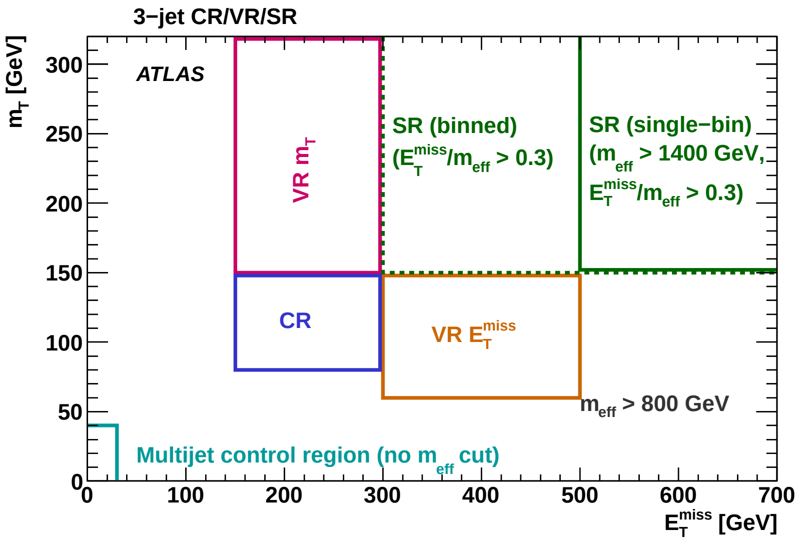
- Exploit symmetry to approximate rest frame - 'R-frame': 'Razor variables'

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

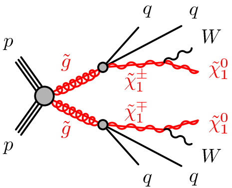
  E: Energy in R-frame

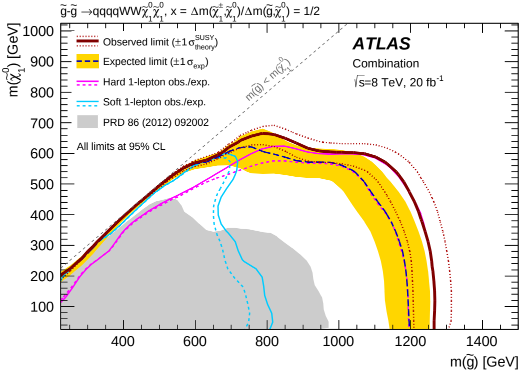
  L: Longitudinal momentum

SM backgrounds controlled with semi data-driven estimate

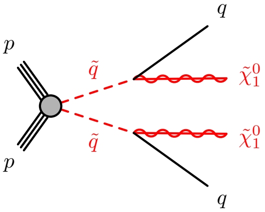


- Interpret results in a variety of models
- Here: $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqW\tilde{\chi}_1^0$

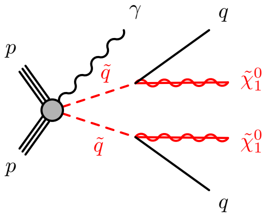




- Soft lepton regions contribute to improved sensitivity in compressed regions
- Significant improvement over 2011 results



- arXiv: 1411.1559 [hep-ex], PRD 91, 012008 (2015)
- Compressed spectra ($\tilde{q}$ and $\tilde{\chi}_1^0$ close in mass) ⇒ soft decay products, low $E_{\mathrm{T}}^{\mathrm{miss}}$



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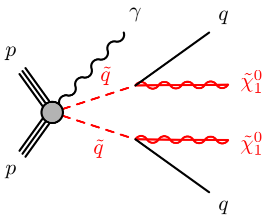
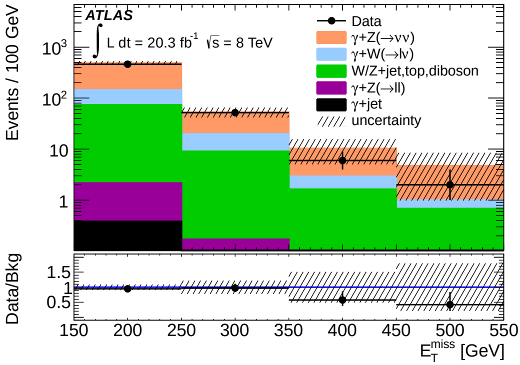
- Compressed spectra ($\tilde{q}$ and $\tilde{\chi}_1^0$ close in mass) $\Rightarrow$ soft decay products, low $E_{\mathrm{T}}^{\mathrm{miss}}$
- ISR photon boosts system $\Rightarrow$ higher $E_{\mathrm{T}}^{\mathrm{miss}}$





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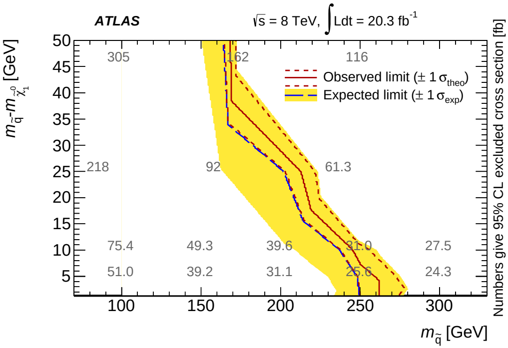
- Veto leptons and > 1 jet
- Background $W\gamma$ (15%) and $Z\gamma$ (70%) normalized in lepton CRs

Monophoton, Results

Process	Event yield
$Z(\to \nu\nu) + \gamma$	$389 \pm 36 \pm 10$
$W(\to \ell\nu) + \gamma$	$82.5 \pm 5.3 \pm 3.4$
$W/Z + \text{jet}, t\bar{t}, \text{diboson}$	$83 \pm 2 \pm 28$
$Z(\to \ell\ell) + \gamma$	$2.0 \pm 0.2 \pm 0.6$
$\gamma + \text{jet}$	$0.4^{+0.3}_{-0.4}$
Total background	$557 \pm 36 \pm 27$
Data	521

Systematic uncertainties $\sim$ 15%

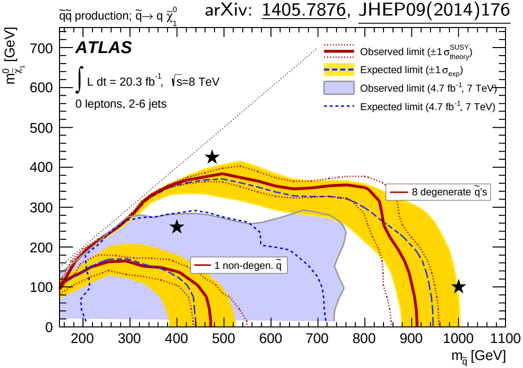
- CR statistics (6%)
- $e \to \gamma$ mis-ID (5%)



- Best exclusion along 'diagonal'
- Also sets limits for DM and more general models

Scalar charm, Overview

arXiv: 1405.7876, JHEP09(2014)176



- Inclusive $\tilde{q}$ searches weaker if only one light $\tilde{q}$: $\sigma/8$
- In MSSM squarks can mix
  - Weak flavour physics constraints on $\tilde{t} - \tilde{c}$ mixing
- Charm jet tagging gives improved sensitivity to $\tilde{c}$
- First dedicated search for scalar charm quark

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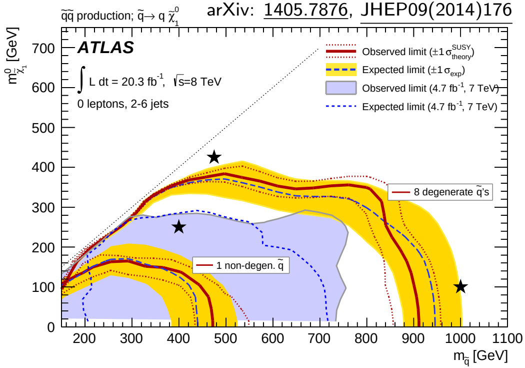
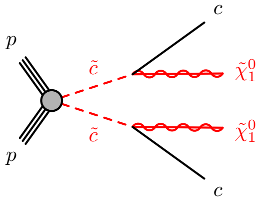


arXiv: 1501.01325 [hep-ex], accepted by PRL (this morning!)

Simplified model $\tilde{c} \to c\tilde{\chi}_1^0$



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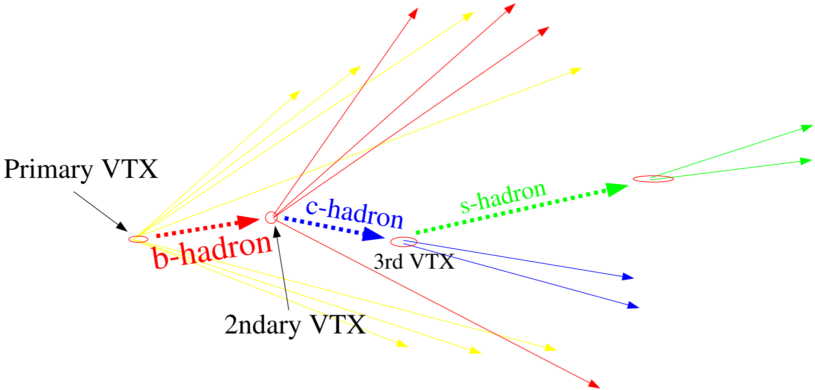
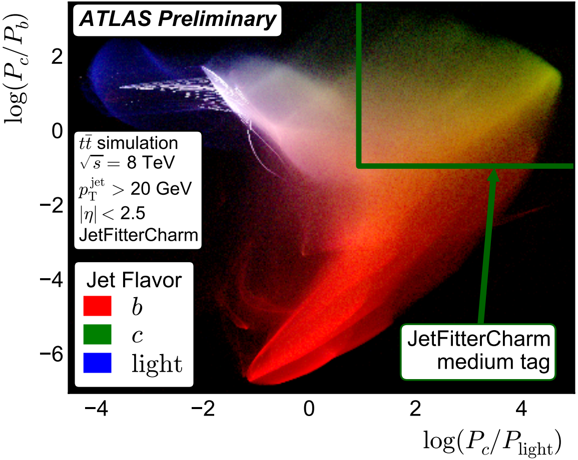
- 2 high-p_T c-jets
- High E_T^{miss}
- No leptons



- JetFitterCharm - impact parameter and secondary vertex
- *c*-jets occupy middle ground between *b*-jets and light-jets
- Image from here

2-variable cut on P_c, P_b, P_{light}, ATL-PHYS-PUB-2015-001, more information



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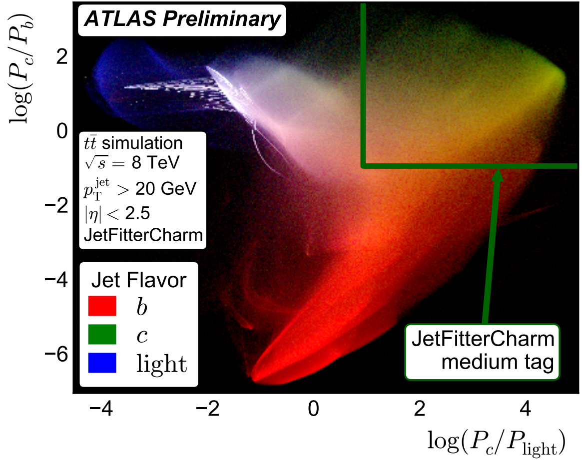
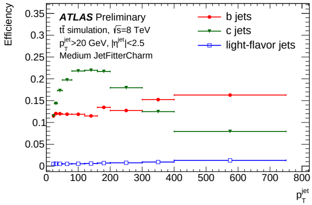
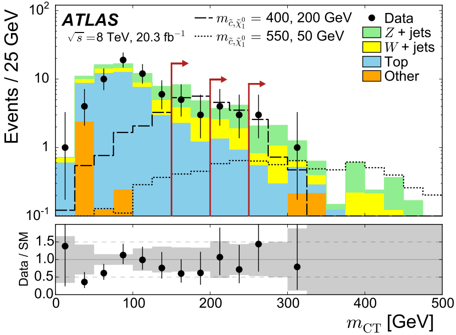




$\epsilon_c \sim 0.15$

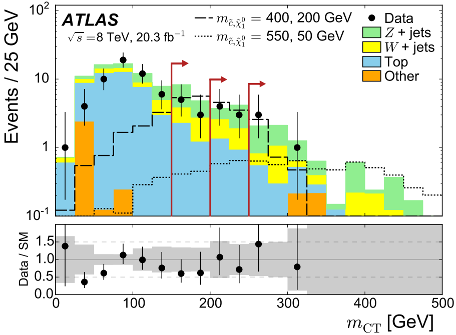
$\epsilon_b \sim 0.12$

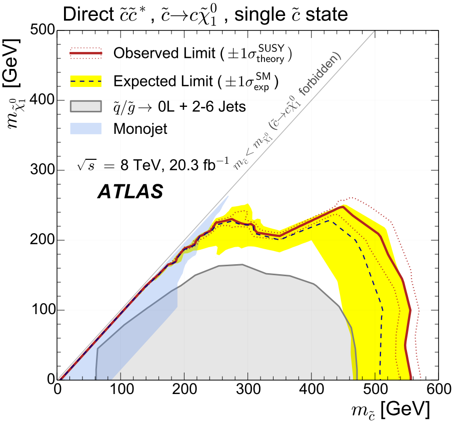
$\epsilon_{\text{light}} \sim 0.008$



- Kinematic selection (m_{CT} and m_{cc})
- $m^2_{\mathrm{CT}}(j_1, j_2) = [E_{T,1} + E_{T,2}]^2 - [\mathbf{p}_{T,1} - \mathbf{p}_{T,2}]^2$
  - $E_{\mathrm{T}} = \sqrt{p^2_{\mathrm{T}} + m^2}$
  - $m^{\max}_{\mathrm{CT}} = \frac{m^2(\tilde{c}) - m^2(\tilde{\chi}^0_1)}{m(\tilde{c})}$

Scalar charm, Results





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  - $E_{\rm T} = \sqrt{p_{\rm T}^2 + m^2}$
  - $m^{\rm max}_{\rm CT} = \frac{m^2(\tilde{c}) - m^2(\tilde{\chi}_1^0)}{m(\tilde{c})}$

- $\sim$ 100 GeV improvement in exclusion over inclusive $\tilde{q}/\tilde{g}$ (grey)

Summary

Run I:

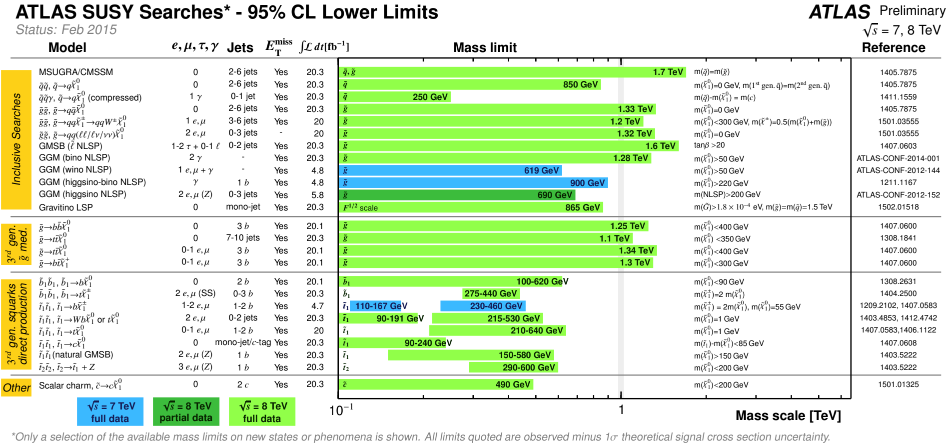
- Diverse and comprehensive range of SUSY searches for squarks and gluinos
- 'Gaps' left by more general searches systematically filled
  - Here: 1/2 ℓ + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$, monophoton, scalar charm

Run II:

- Preparation in earnest, big increase in production cross-sections at 13 TeV
- First results will be for inclusive searches
  - Less sensitive to larger systematics of early data
  - Probing highest masses ⇒ biggest cross-section boost ⇒ fastest gains
- Let's hope for a discovery this time next year!

BONUS
SLIDES

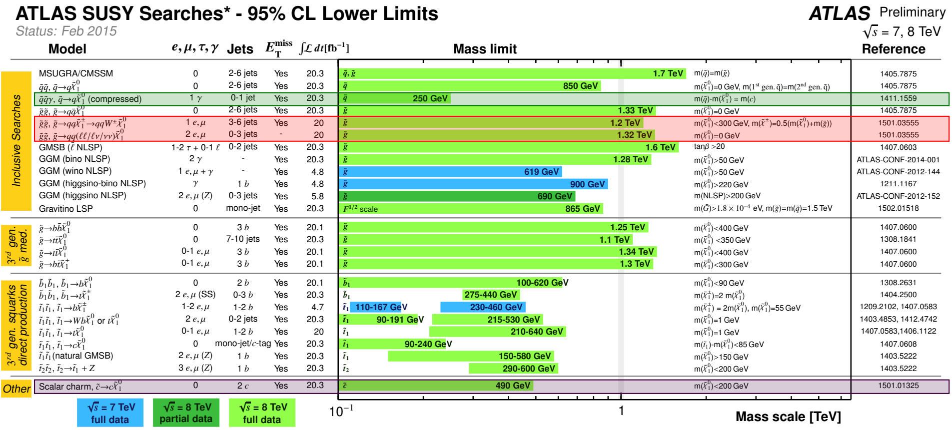
Full details at ATLAS SUSY public results page



ATLAS SUSY

Full details at ATLAS SUSY public results page

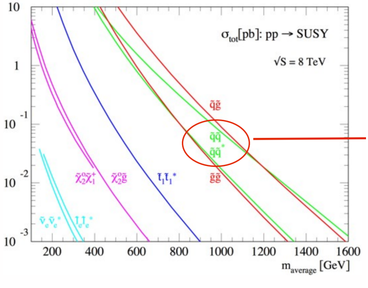
$1/2\ \ell$ + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$, monophoton, scalar charm



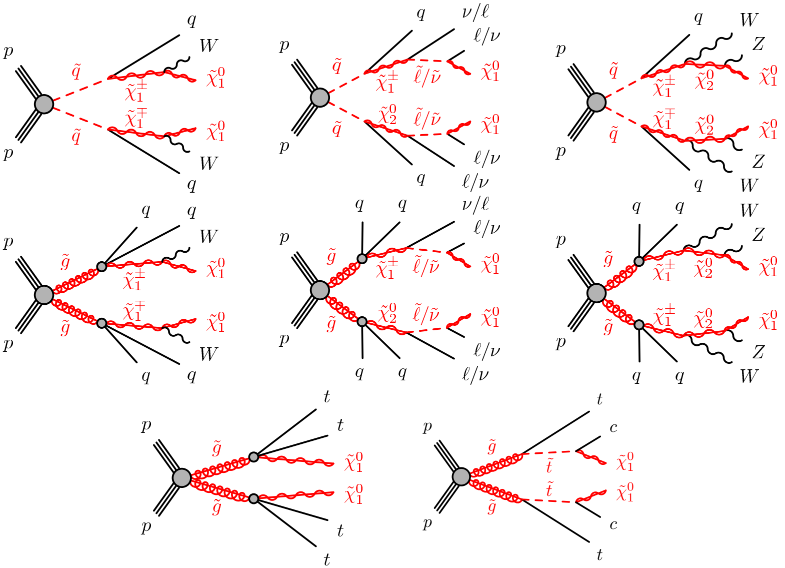
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Squarks and gluinos

- SUSY has 12 $\tilde{q}$ - two for each SM quark
- Usually treat 3rd generation separately, i.e. $m_{\tilde{t}_{1,2}}$, $m_{\tilde{b}_{1,2}}$, $m_{\tilde{q}}$: $q = u, d, s, c$
- 'Traditional' squark and gluino searches: $\tilde{g}$ and first two generation $\tilde{q}$
- Highest cross sections for SUSY production at a *pp* machine
- Signatures: $\tilde{g} \rightarrow \tilde{q}q \rightarrow q\tilde{\chi}_1^0 q$: high $E_{\mathrm{T}}^{\mathrm{miss}}$, jets, (leptons)



1/2 ℓ + jets + $E_{\mathrm{T}}^{\mathrm{miss}}$, Signal models



More details on public page

Model	Soft		Hard	
	single-lepton	dimuon	single-lepton	dilepton
mSUGRA/CMSSM			✓	
bRPV mSUGRA/CMSSM			✓	
nGM			✓	
NUHMG			✓	
mUED		✓		✓
$\tilde{g}\tilde{g}$ production, $\tilde{g} \to tc\tilde{\chi}_1^0$			✓	
$\tilde{g}\tilde{g}$ production, $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$			✓	
$\tilde{g}\tilde{g}$ production, $\tilde{g} \to qqW\tilde{\chi}_1^0$	✓		✓	
$\tilde{q}\tilde{q}$ production, $\tilde{q} \to qW\tilde{\chi}_1^0$	✓		✓	
$\tilde{g}\tilde{g}$ production, $\tilde{g} \to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$			✓	✓
$\tilde{q}\tilde{q}$ production, $\tilde{q} \to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$				✓
$\tilde{g}\tilde{g}$ production, $\tilde{g} \to qqWZ\tilde{\chi}_1^0$			✓	

R-frame calculation details here

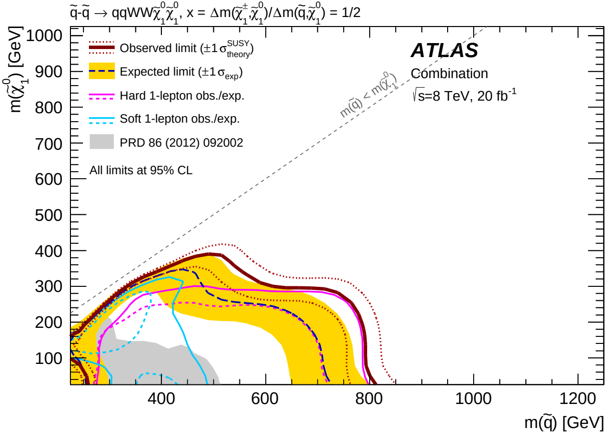
Razor variables:

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

$$M_{\mathrm{T}}^R = \sqrt{\frac{|\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}|(|\vec{j}_{1,\mathrm{T}}| + |\vec{j}_{2,\mathrm{T}}|) - \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}} \cdot (\vec{j}_{1,\mathrm{T}} + \vec{j}_{2,\mathrm{T}})}{2}}$$

$$R = \frac{M_{\mathrm{T}}^R}{M_R'}$$

Full set of exclusion plots on public page; here: $\tilde{q}$- $\tilde{\chi}_1^0$ plane

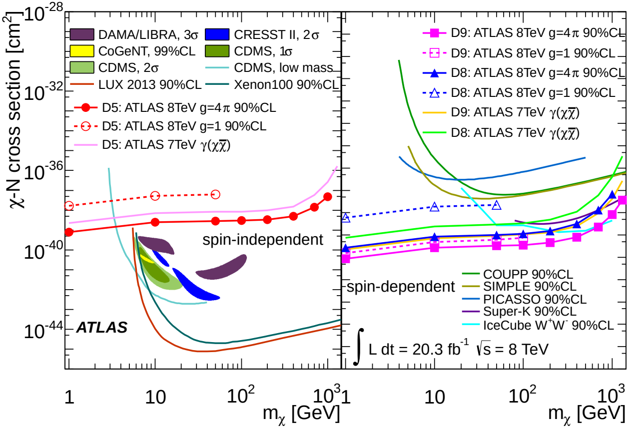


Monophoton, Example cutflow

$m_{\tilde{q}} = 200$ GeV, $m_{\tilde{\chi}_1^0} = 195$ GeV; 10,000 events generated; more details on public page

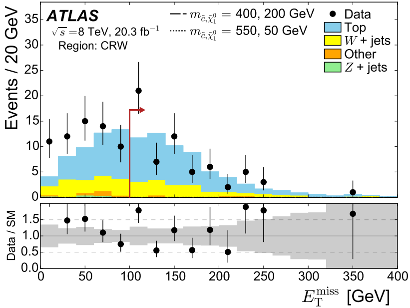
Nominal	9989
Pre-selected:	
1. Trigger	8582
2. Good vertex	8574
3. Cleaning cuts	8213
SR Cuts:	
1. $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV	4131
2. At least one loose photon with $p_{\mathrm{T}} > 125$ GeV($\|\eta\| < 2.37$)	2645
3. The leading photon is tight with $\|\eta\| < 1.37$	2068
4. The leading photon is isolated	1898
5. $\Delta\phi(\gamma^{\mathrm{leading}}, \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$	1887
6. Jet veto: $N_{\mathrm{jet}} \leq 1$ and $\Delta\phi(\mathrm{jet}, \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$	1219
7. Lepton veto	1188

Limits for multiple generic higher-dimensional operators



Plots and tables on public page

- Use $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger, $20.3\mathrm{fb}^{-1}$
  - Leading jet $p_{\mathrm{T}} > 130$GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 150$GeV
- Event Cleaning
- Lepton veto
- Leading two jets c-tagged
- Jet 2 $p_{\mathrm{T}} > 100$GeV
- $m_{\mathrm{CC}} > 200$GeV
- Three SR: $m_{\mathrm{CT}} > \{150, 200, 250\}$ GeV



Z + jets $\approx 50\%$

W + jets $\approx 25\%$

$t\bar{t}$ or single t $\approx 25\%$

Scalar charm, Control regions

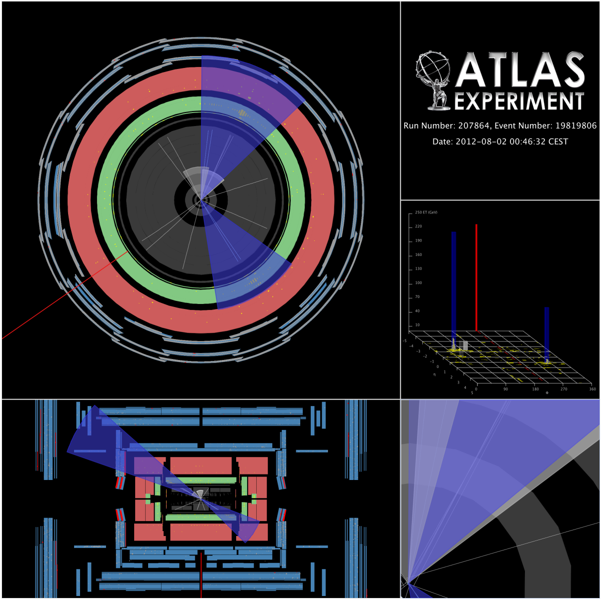
All control regions: *c*-tag leading two jets, use single-lepton triggers, relax some cuts for statistics

- CRW: Single lepton, 40 GeV $< m_{\mathrm{T}} <$ 100 GeV
- CRZ: OSSF leptons, $|m_{\ell\ell} - 90 \text{ GeV}| < 15$ GeV
- CRT: One e, one μ
- CRQCD: Jet smearing method, $\Delta\phi_{\min}(\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}, 3 \text{ jets}) < 0.4$

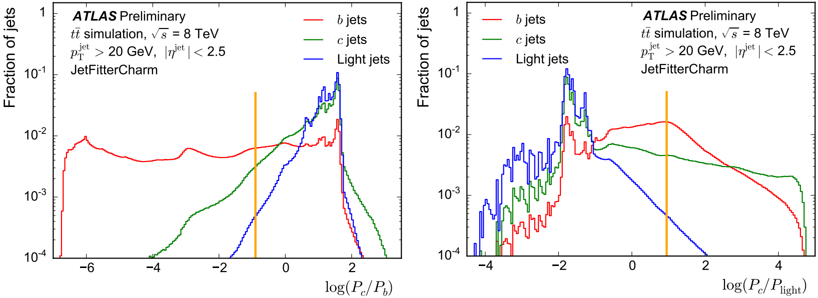
Scalar charm, SRs and CRs

Cut	Description	Signal regions	Control regions		
		SRs	CRZ	CRT	CRW
1	Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton		
2	Event cleaning	Common to all SR and CR			
3	Lepton selection	—	2 SF OS	2 DF OS	1
		No further e/μ (after overlap removal) with $p_{\mathrm{T}} > 7(6)$ GeV for $e(\mu)$.			
4	$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	—	> 50 GeV	> 100 GeV
	$\vec{p}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{T}^{\mathrm{2leptons}}$	—	> 100 GeV	—	—
5	Leading jet p_{T}	> 130 GeV	> 50 GeV	> 50 GeV	> 130 GeV
6	Second jet p_{T}	> 100 GeV	> 50 GeV		
7	c-tagging	leading 2 jets ($p_{\mathrm{T}} > 50$ GeV, $\|\eta\| < 2.5$)			
8	$\Delta\phi_{\mathrm{min}}(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, 3\text{ jets})$	> 0.4	—		
9	$E_{\mathrm{T}}^{\mathrm{miss}}/(E_{\mathrm{T}}^{\mathrm{miss}} + p_{\mathrm{T}}^{\mathrm{2jets}})$	> 0.25	—		
10	Leading lepton p_T	—	> 70 GeV	> 25 GeV	> 50 GeV
11	m_{ll}	—	90 ± 15 GeV	> 50 GeV	—
12	m_T	—			$40 - 100$ GeV
13	m_{cc}	> 200 GeV	—		
14	m_{CT}	$> 150, 200, 250$ GeV	—	—	> 150 GeV

Scalar charm, Event display



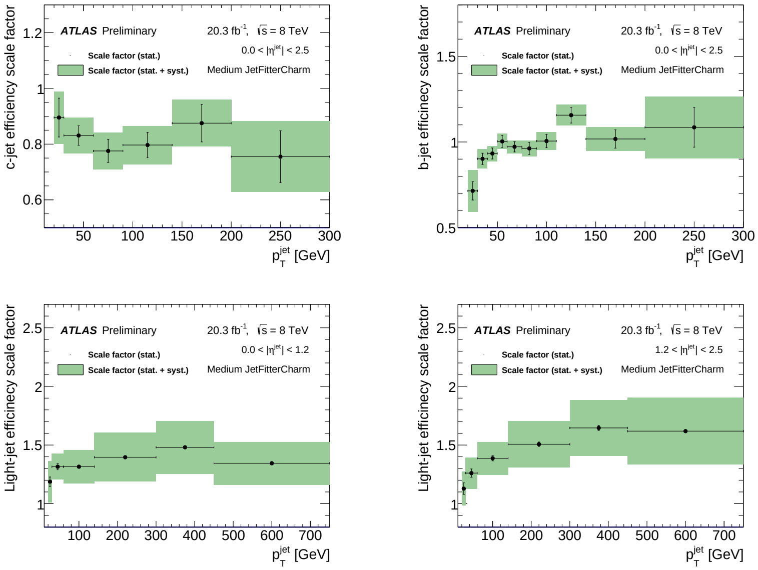
Public note at ATL-PHYS-PUB-2015-001



Algorithm	Variable Name	Description
Kinematic	p_T^{cat}	p_{T} category of jet, divisions [GeV]: 15, 25, 35, 50, 80, 120, 200, ∞
	η^{cat}	$\lvert\eta\rvert$ category of jet, divisions: 0, 0.7, 1.5, 2.5
IP3D	$\log(\mathcal{L}_b/\mathcal{L}_{\mathrm{light}})$	log ratio between b-jet and light-jet likelihood value
SV1	$n_{\mathrm{trk}}^{\mathrm{SV1}}$	Number of tracks matched to the vertex
	$n_{2\mathrm{t}}$	Number of two-track vertices found in the jet
	m_{vx}	Secondary vertex mass
	L/σ_L	Secondary vertex flight-length significance
JetFitter	m_{chain}	Invariant mass of decay products
	S_d^{JF}	Total vertex flight-length significance
	n_{vx}	Number of reconstructed vertices with ≥ 2 tracks
	$n_{\mathrm{trk}}^{\mathrm{JF}}$	Number of tracks matched to vertices with ≥ 2 tracks
	$n_{1\mathrm{t}}$	Number of single-track vertices
	L_{xy}^1	Transverse displacement of the secondary vertex
	L_{xy}^2	Transverse displacement of the tertiary vertex
	$\min\varphi_{\mathrm{trk}}$	Minimum track rapidity along jet axis
	$\langle\varphi_{\mathrm{trk}}\rangle$	Mean track rapidity along jet axis
	$\max\varphi_{\mathrm{trk}}$	Maximum track rapidity along jet axis
SV1, JetFitter (variables input from both)	$E_{\mathrm{vx}}/E_{\mathrm{jet}}$	Ratio of the vertex track energy sum to the jet track energy sum

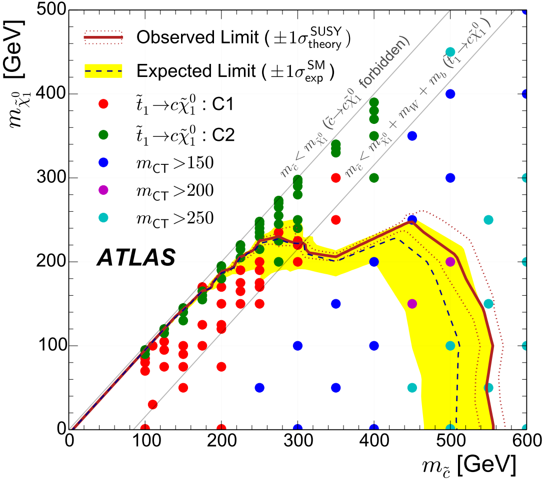
Summary of the variables used by the JetFitterCharm neural network. JetFitterCharm uses a 'charm tuned' variant of the standard JetFitter used by other ATLAS tagging algorithms. The charm tuned JetFitter also adds the variables L_{xy}^1, L_{xy}^2, and φ_{trk}. Note that φ_{trk} is the track rapidity computed with respect to the jet axis.

JetFitterCharm, Calibration



Scalar charm, results

	Control Regions			Signal Regions, m_{CT} [GeV]		
	CRT	CRZ	CRW	>150	>200	>250
Top	129 ± 11 (124)	7.3 ± 0.8 (7.1)	45 ± 7 (44)	7.4 ± 2.7 (7.1)	3.9 ± 1.6 (3.7)	1.6 ± 0.7 (1.5)
Z+jets	0.1 ± 0.0 (0.1)	47 ± 7 (43)	0.1 ± 0.1 (0.1)	14 ± 3 (13)	7.7 ± 1.7 (7.0)	4.3 ± 1.2 (3.9)
W+jets	< 0.1 (< 0.1)	< 0.1 (< 0.1)	15 ± 9 (16)	7.2 ± 4.5 (7.4)	4.1 ± 2.6 (4.2)	1.9 ± 1.2 (1.9)
Multijets	–	–	–	0.3 ± 0.3	0.2 ± 0.2	0.05 ± 0.05
Others	0.1 ± 0.1	1.4 ± 0.8	1.3 ± 0.8	0.5 ± 0.3	0.4 ± 0.3	0.4 ± 0.3
Total	129 ± 11	56 ± 7	62 ± 7	**30 ± 6**	**16 ± 3**	**8.2 ± 1.9**
Data	129	56	62	**19**	**11**	**4**



- Using lowest expected $\mathrm{CL_s}$ for three m_{CT} regions and $\tilde{t} \rightarrow c\tilde{\chi}^0_1$ c-tagged regions
- Observed band: $\tilde{c}$ xsec varied down / up

- Excludes $\tilde{c}$ from $m_{\tilde{c}} = m_{\tilde{\chi}^0_1}$ to $m_{\tilde{c}} = 490$ GeV and $m_{\tilde{\chi}^0_1} < 200$ GeV