ICHEP 2016

Chicago, IL

August 3-10, 2016

Search for SUSY in Photonic and Tau Channels with the ATLAS Detector

Bruce A. Schumm

Santa Cruz Institute for Particle Physics

University of California, Santa Cruz

for the ATLAS Collaboration

ATLAS Photonic and Tau-Based SUSY Signatures

We have performed SUSY-inspired searches for events in 13 TeV data using three general signatures, all requiring significant $\mathbf{E_t^{miss}}$:

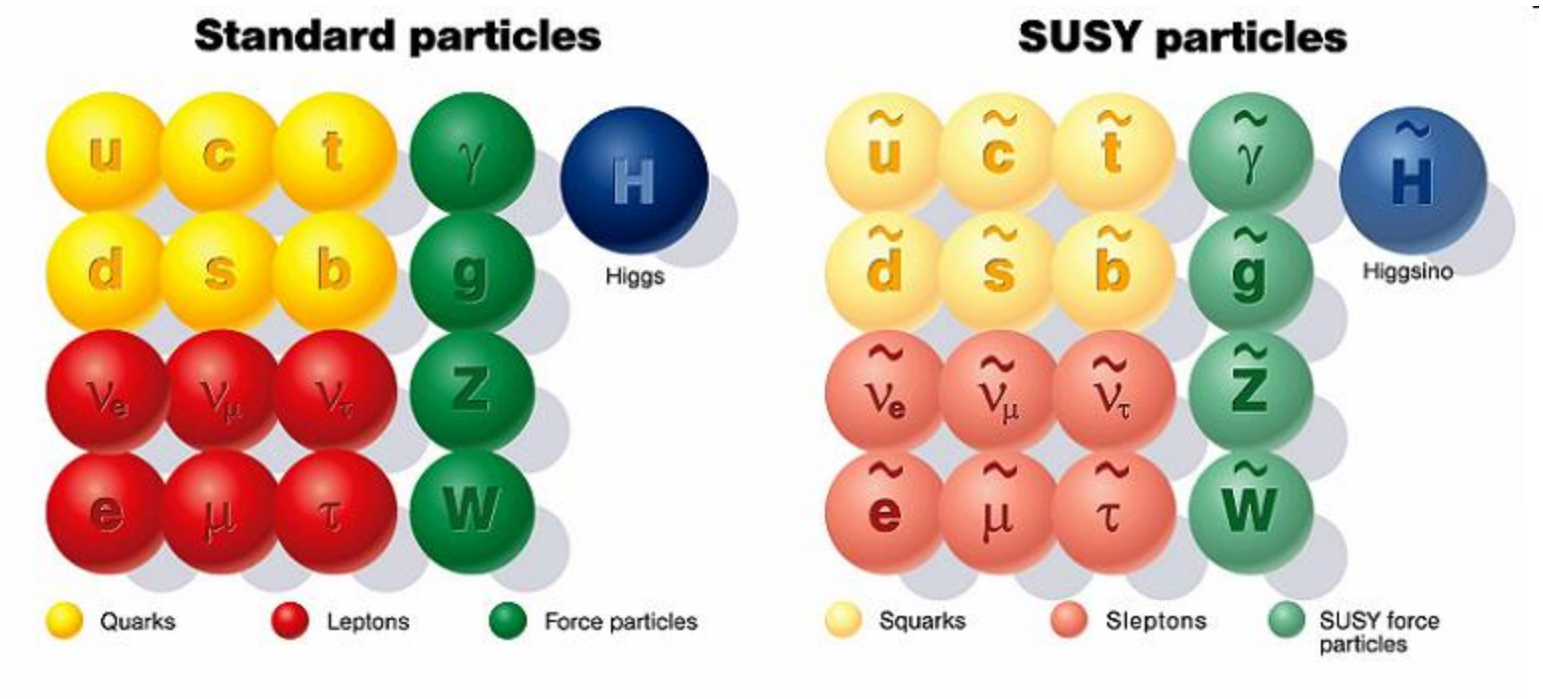
Diphoton + E_t^{miss}: 1 Signal Region (SR) requiring two photons plus E_t^{miss}, with no explicit requirements on the presence of other objects, but requiring significant overall transverse energy. (3.2 fb^{-1})

Photon + jets: 2 SRs requiring one or more photons accompanied by jets, plus E_t^{miss}. Significant overall transverse energy also required. (13.3 fb^{-1} ; **FIRST PUBLIC PRESENTATION**).

τ + X : Six SRs requiring one or more hadronic τ lepton decay, significant E_t^{miss} and at least one hard jet, and sometimes accompanied by substantial transverse energy/mass. (3.2 fb^{-1}).

SUSY States

SUSY posits a complete set of mirror states with $S_{SUSY} = |S_{SM} - ½|$



- Stabilize Higgs mass for GUTs
- Can provide reasonable dark-matter candidate (E_t^{miss})
- SU(3) x SU(2) x U(1) coupling unification

SUSY Breaking

But we know that SUSY is broken…

SUGRA: Local supersymmetry broken by **supergravity** interactions

Phenomenology: LSP (usually χ_1^0) carries $\mathbf{E_t^{miss}}$.

GMSB: Explicit couplings to intermediate-scale ($M_{EW} < \Lambda < M_{GUT}$) "messenger" **gauge** interactions **mediate** SUSY breaking.

Phenomenology: Gravitino ($\tilde{G}$) LSP ($\mathbf{E_t^{miss}}$); NLSP is χ_1^0 or slepton. χ_1^0 tends to be bino-like ➔ photonic signatures. Slepton tends to be $\tilde{\tau}$ ➔ tauonic signatures.

AMSB: Higher-dimensional SUSY breaking communicated to 3+1 dimensions via "Weyl **anomaly"**.

Phenomenology: LSP tends to be $\tilde{W}$, with χ_1^+, χ_1^0 nearly degenerate.

The **SUGRA** and **GMSB** scenarios supply the inspiration for the three signatures we have explored…

Classes of Models

Minimal Models

GUT unification ➔ few parameters

- mSUGRA/CMSSM, GMSB

e.g. GMSB:

Λ: SUSY breaking scale

M_{mes}: Messenger scale

N_5: Number of messenger fields

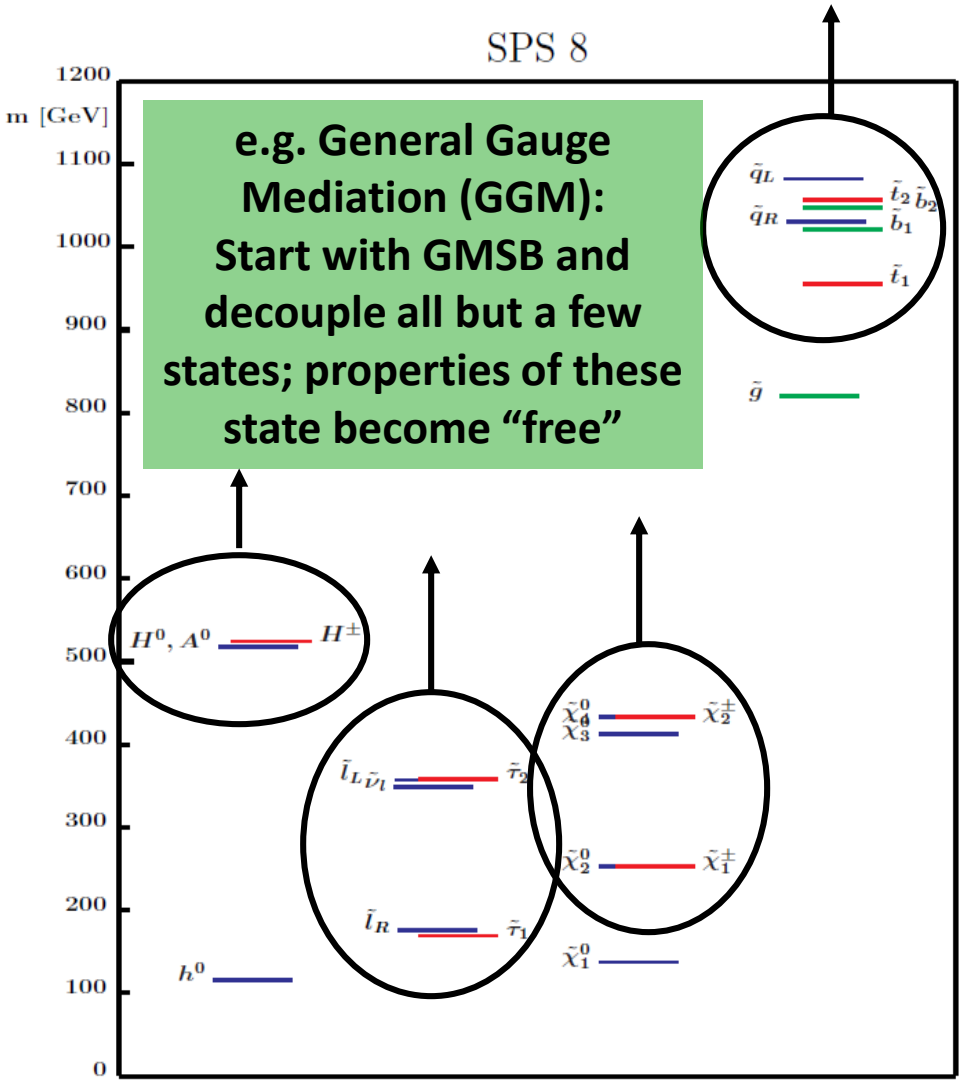
tanβ: Ratio of vev for the two Higgs doublets

C_{grav}: Gravitino mass parameter

sgn(μ): Sign of higgsino mass term

e.g. the "SPS 8" model is just a specific set of choices for the GMSB parameters.

Simplified Models



e.g. General Gauge Mediation (GGM): Start with GMSB and decouple all but a few states; properties of these state become "free"

Gauge Mediation Models

τ + X: GMSB model with $N_5 = 3$, leading to states with slepton NLSP. Λ and $\tan\beta$ are free parameters. Signal dominated by weak production for $\Lambda > 90$ TeV.

Diphoton + E_t^{miss} : Only accessible states are gluino and bino-like χ_1^0 NLSP. Gluino and χ_1^0 masses are free parameters. Signal solely from strong production of gluino pairs.

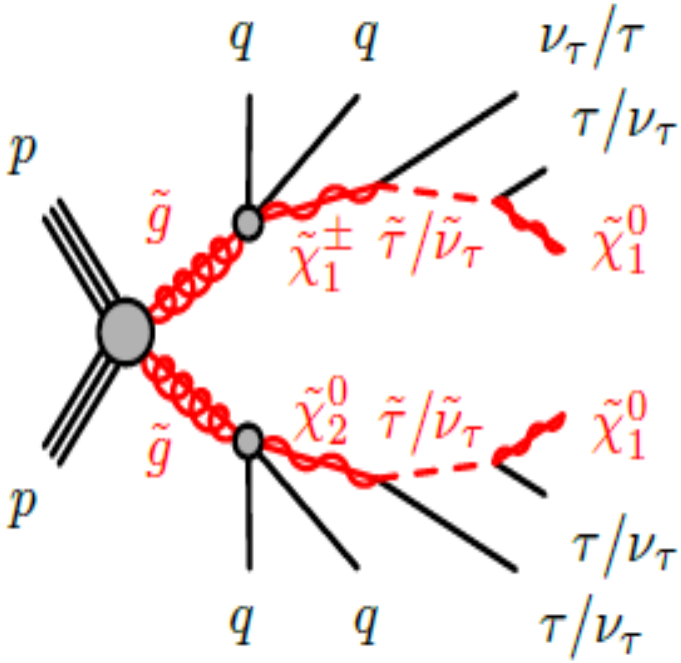
Photon + jets: Accessible states are gluino, bino, higgsinos. NLSP is bino-higgsino χ_1^0 admixture with 50/50 branching to $\gamma + \tilde{G}$ and $Z^0 + \tilde{G}$. Signal selection sensitive only to gluino-pair production. Gluino and combined bino/higgsino mass parameter are free.

NB: All states decay promptly, except gravitino $\tilde{G}$, which is stable.

mSUGRA-Inspired Model (Tau Signature)

- Two-step simplified model
- Gluino production followed by decay to intermediate state with $\chi_1^{\pm}$ and χ_2^0
- Decay of $\chi_1^{\pm}$ and χ_2^0 proceeds through $\tilde{\tau}$, $\tilde{\nu}_\tau$ to χ_1^0 LSP (suggested by SUSY "naturalness" requirements)
- Free parameters are gluino and χ_1^0 masses, with intermediate mass scale given by

$$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^{\pm}} = (m_{\tilde{g}} + m_{\tilde{\chi}_1^0})/2$$



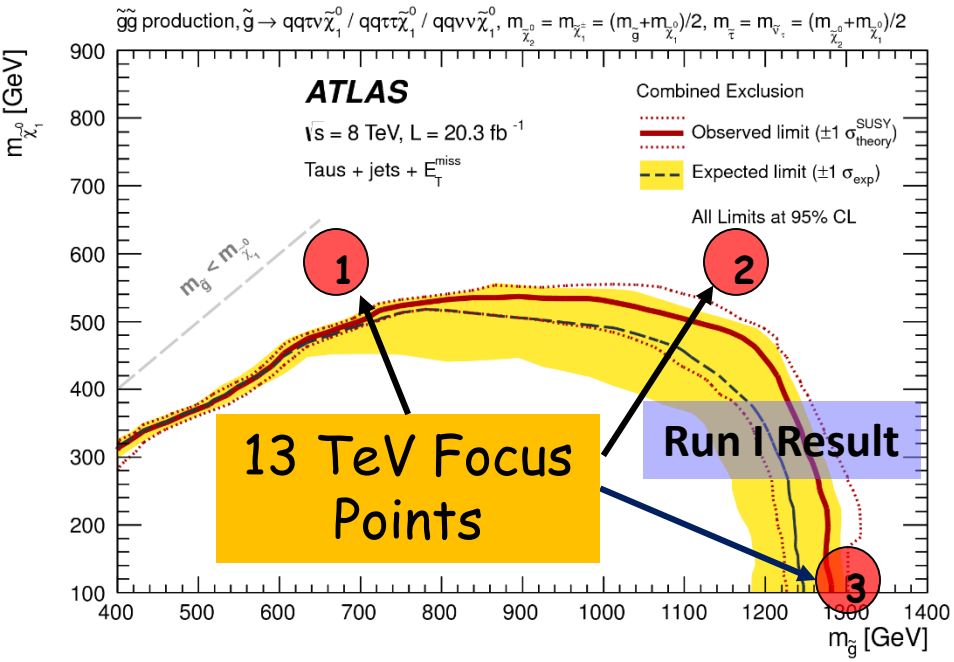
Tau and Photonic SUSY Models Summary

Summary of Main Attributes of SUSY Models Used to Guide the Formulation of Tau and Photonic SUSY Analyses

Signature	Model	NLSP	Production and **Free Parameters**
τ + X	mSUGRA inspired	$\chi_1^{\pm}$, χ_2^0 NLSP with stauonic couplings	Strong production Gluino mass, χ_1^0 mass
τ + X	GMSB	Slepton (dominated by stau over much of the parameter space)	Strong and EW production Λ, tanβ
Diphoton + E_t^{miss}	GGM	Bino-like χ_1^0	Strong production Gluino mass, χ_1^0 mass
Photon + jets	GGM	Higgsino-bino χ_1^0 admixture with 50/50 branching to γ/Z^0 + gravitino	Strong production Gluino mass, χ_1^0 mass

Single-Tau Analysis (3.2 fb^{-1})

Three SRs geared towards different regions of **mSUGRA simplified model**



SR definition for single-τ analysis

	1	2	3
1τ channel	Compressed SR	Medium-Mass SR	High-Mass SR
Trigger plateau	$E_T^{miss} > 180$ GeV, $p_T^{jet_1} > 120$ GeV		
Tau leptons	$N_\tau^{loose} = N_\tau^{medium} = 1$, $p_T^\tau > 20$ GeV		
Light leptons	$N_\ell = 0$		
Multi-jet rejection	$\Delta\phi(jet_{1,2}, \vec{p}_T^{\,miss}) \geq 0.4$		
p_T^τ	< 45 GeV	–	–
$p_T^{jet_1}$	> 300 GeV	–	> 220 GeV
$p_T^{jet_2}$	–	–	> 220 GeV
N_{jet}	≥ 2	≥ 5	≥ 5
m_T^τ	> 80 GeV	> 200 GeV	> 200 GeV
E_T^{miss}	> 300 GeV	> 300 GeV	–
H_T	–	> 550 GeV	> 550 GeV

Selection includes overall **production scale observables**:

- Transverse energy $\mathbf{H_T}$ (sum of transverse energy of all reconstructed objects)
- Transverse mass $\mathbf{m_T}$ (sum of H_T and E_t^{miss})

Single-Tau Analysis continued… (3.2 fb^{-1})

Backgrounds from boson, top and multijet production estimated via control regions:

- Softening overall energy-scale requirements, requiring/vetoing *b*-quark jets enrich top/W-boson production
- Fake τ's indicated by high transverse mass of τ candidate
- Multijet contributions enriched by lowering E_t^{miss} requirement

Backgrounds determined by simultaneous fit to signal and control regions

1τ channel	Compressed SR	Medium-Mass SR	High-Mass SR
Data	47	11	1
Total background	49.2 ± 6.2	15.0 ± 2.4	5.7 ± 1.2
Top	14.3 ± 4.5	6.0 ± 1.3	2.49 ± 0.87
$W(\tau\nu)$+jets	12.1 ± 1.3	2.78 ± 0.62	1.17 ± 0.33
$Z(\nu\nu)$+jets	13.9 ± 2.3	3.8 ± 1.1	0.83 ± 0.21
V+jets, other	6.24 ± 0.90	1.44 ± 0.32	0.75 ± 0.23
Diboson	1.85 ± 0.23	0.76 ± 0.16	0.20 ± 0.03
Multi-jet	0.74 ± 0.54	0.19 ± 0.18	0.24 ± 0.17

NB: Background estimation techniques common to all photonic and tau analyses

Multi-Tau Analysis (3.2 fb^{-1})

- 2 low-background multi-τ SRs geared towards **mSUGRA** model with high gluino mass and large mass gap
- 1 multi-τ SR geared towards **GMSB** model

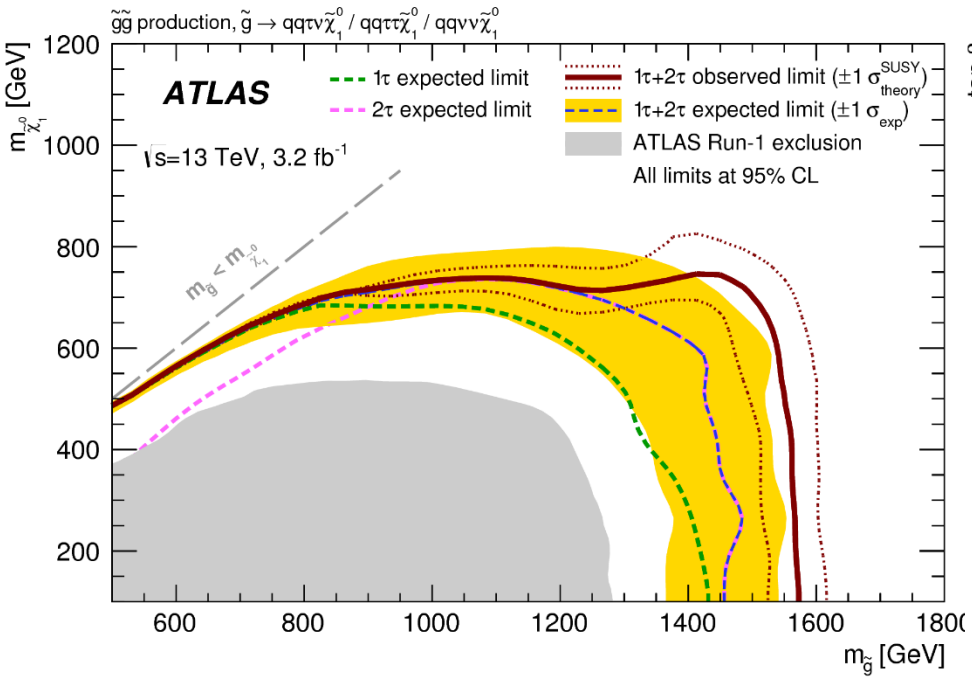
2τ channel	Compressed SR	High-Mass SR	GMSB SR
Trigger plateau	$E_T^{miss} > 180$ GeV, $p_T^{jet_1} > 120$ GeV		
Tau leptons	$N_\tau^{loose} \geq 2$, $p_T^\tau > 20$ GeV		
Multi-jet rejection	$\Delta\phi(jet_{1,2}, \vec{p}_T^{miss}) \geq 0.4$		
$m_T^{\tau_1} + m_T^{\tau_2}$	–	> 350 GeV	> 150 GeV
H_T	–	> 800 GeV	> 1700 GeV
N_{jet}	≥ 2	≥ 3	≥ 2
$m_{T2}^{\tau\tau}$	> 60 GeV	–	–
m_T^{sum}	> 1400 GeV	–	–

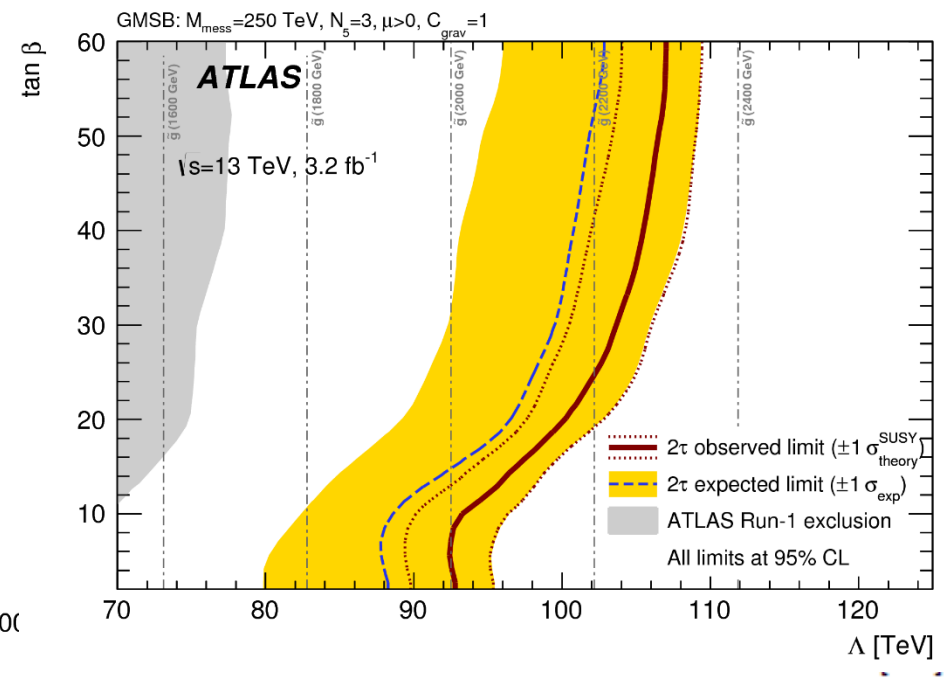
2τ channel	Compressed SR	High-Mass SR	GMSB SR
Data	4	0	0
Total background	4.2 ± 3.0	3.2 ± 1.2	0.69 ± 0.24
Top	$2.5^{+2.9}_{-2.5}$	0.87 ± 0.78	0.20 ± 0.20
$W(\tau\nu)$+jets	0.51 ± 0.38	1.75 ± 0.65	0.31 ± 0.14
$Z(\tau\tau)$+jets	0.04 ± 0.02	0.13 ± 0.06	0.04 ± 0.02
$Z(\nu\nu)$+jets	0.28 ± 0.12	0.07 ± 0.03	0.02 ± 0.01
$W(\ell\nu)$+jets	0.37 ± 0.34	0.12 ± 0.07	0.02 ± 0.01
Diboson	0.25 ± 0.10	0.21 ± 0.08	0.06 ± 0.02
Multi-jet	0.21 ± 0.21	0.07 ± 0.07	0.06 ± 0.06

Model-Dependent Limits for Tau Analyses (3.2 fb^{-1})

These results can be used to set limits on the two tau-analysis models

- mSUGRA-inspired χ_1^0-gluino mass plane (5 SRs combined)
- GMSB tanβ-Λ plane (single GMSB SR)

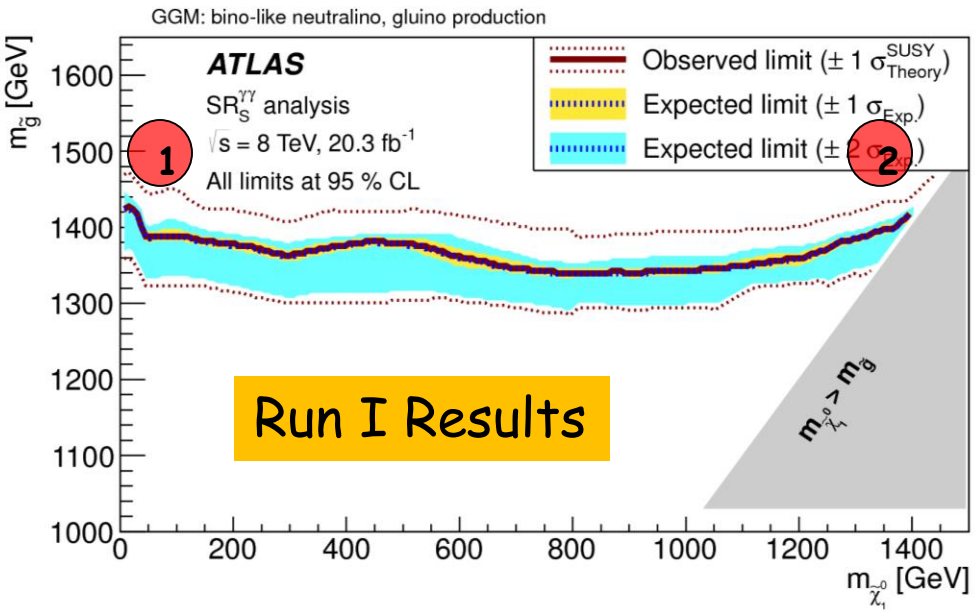




Limits as high as 1570 GeV set on gluino mass in this context

http://arxiv.org/abs/1607.05979

Diphoton + E_t^{miss} Analysis (3.2 fb^{-1})



(m_g,m_χ) focus points for optimization:

- (1500, 100) for low-mass χ_1^0 1
- (1500,1300) for high-mass χ_1^0 2

No significant difference found for optimal selection for 3 fb^{-1} at 13 TeV

➔ single diphoton+E_t^{miss} SR

p_T^γ [GeV]	E_T^{miss} [GeV]	M_{eff} [GeV]	$\Delta\phi_{min}(jet, E_T^{miss})$	$\Delta\phi_{min}(\gamma, E_T^{miss})$
75	175	1500	0.5	0.0

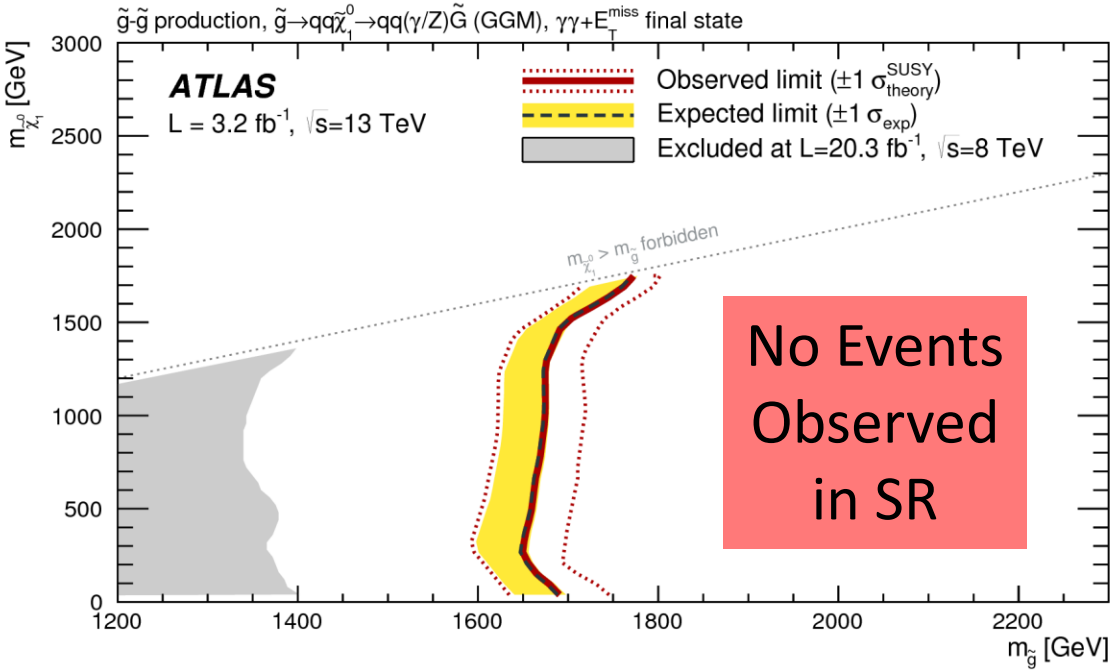
Significant requirements only on E_t^{miss} and transverse mass scale M_{eff}

➔ fully efficient even for $m_{bino} \rightarrow m_{gluino}$ and $m_{bino} \rightarrow 0$

Diphoton + E_t^{miss} Results (3.2 fb^{-1})

Source	Number of events
QCD ($\gamma\gamma$, γj, jj)	$0.05^{+0.20}_{-0.05}$
$e \rightarrow \gamma$ fakes	0.03 ± 0.02
$W\gamma\gamma$	0.17 ± 0.08
$Z\gamma\gamma$	0.02 ± 0.02
Sum	$0.27^{+0.22}_{-0.10}$

Optimization calls for demanding requirements on E_t^{miss} and M_{eff} leaving little background

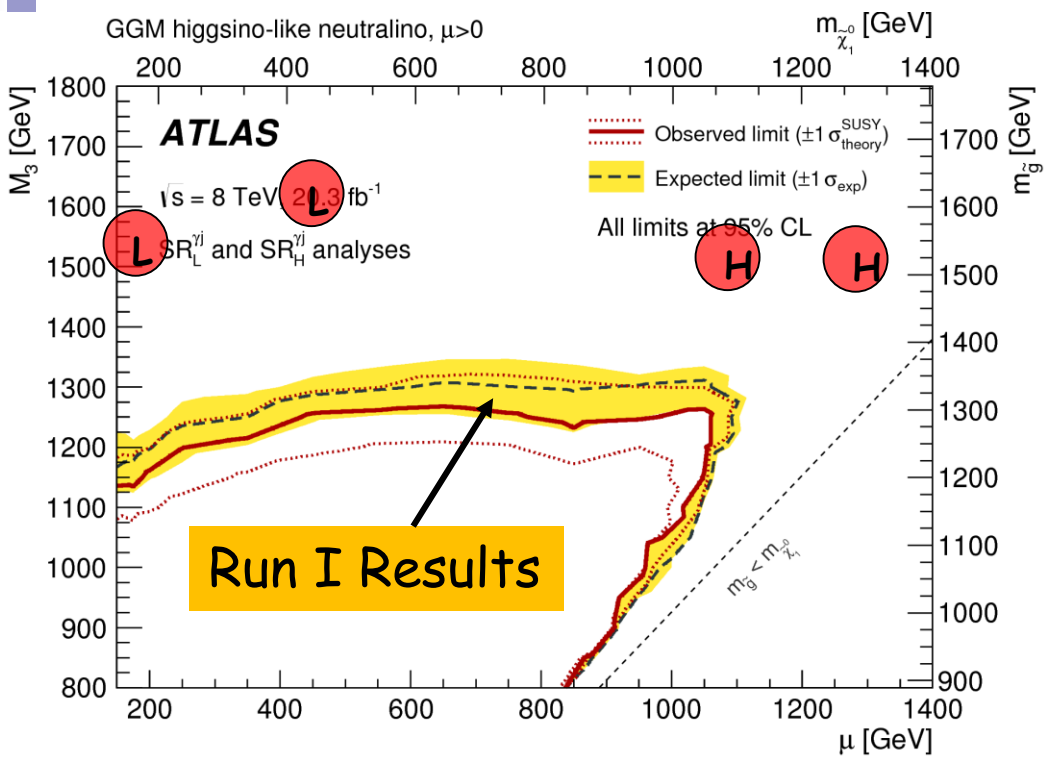


No Events Observed in SR

Gluino mass limits (for case of purely bino-like NLSP) in range of 1600-1750 GeV

https://arxiv.org/pdf/1606.09150.pdf

Photon + Jets Analysis (13.3 fb^{-1})



Separate optimization for:

- low-mass bino ("L"; many jets in cascade)
- high-mass bino ("H"; large E_t^{miss})

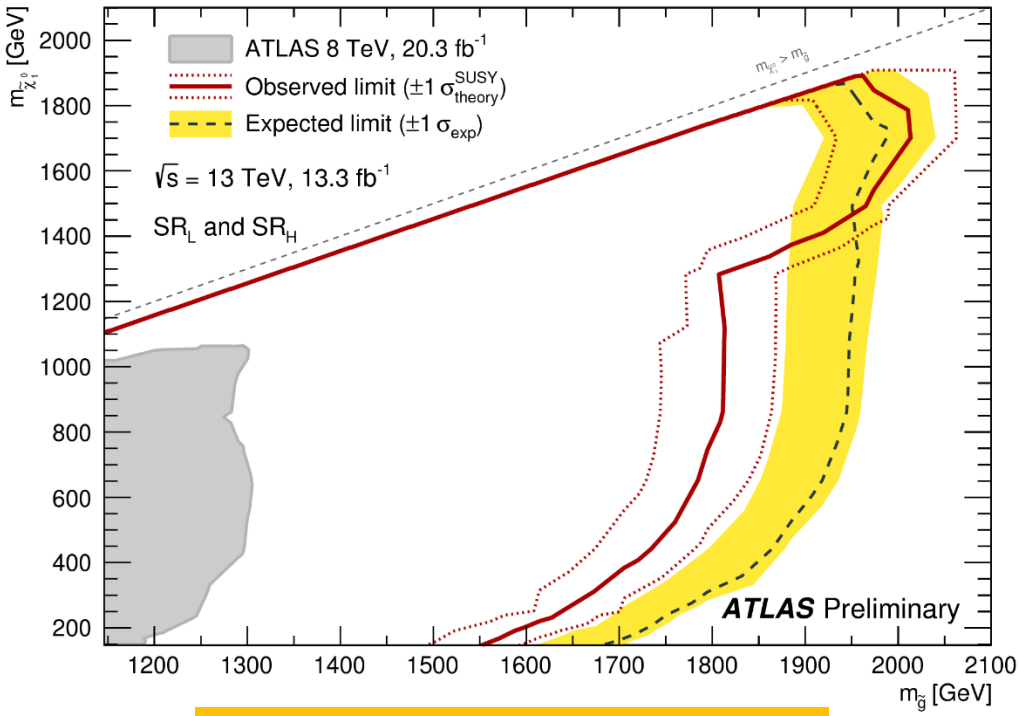
	L SR_L	H SR_H
$N_{photons}$	> 0	> 0
p_T^{γ}	> 145 GeV	> 400 GeV
$N_{leptons}$	0	0
N_{jets}	> 4	> 2
$\Delta\phi(\text{jet}, E_T^{miss})$	> 0.4	> 0.4
$\Delta\phi(\gamma, E_T^{miss})$	> 0.4	> 0.4
E_T^{miss}	> 200 GeV	> 400 GeV
m_{eff}	> 2000 GeV	> 2000 GeV
R_T^4	< 0.90	-

Optimization reckoned by considering two points in each region (see "L" and "H" above)

Photon + Jets Results (13.3 fb^{-1}) PRELIMINARY

FIRST PUBLIC PRESENTATION

Observation of 3 events (SR_L) when 0.78 ± 0.18 are expected is 2% likely.



ATLAS-CONF-2016-066

Signal Region	SR_L	SR_H
Observed events	3	1
Expected SM events	0.78 ± 0.18	1.49 ± 0.45
$\gamma + \text{jet}$	0.18 ± 0.11	0.70 ± 0.24
$W + \gamma$	0.30 ± 0.07	0.37 ± 0.09
$Z + \gamma$	0.08 ± 0.08	0.32 ± 0.32
$t\bar{t} + \gamma$	0.10 ± 0.04	0.03 ± 0.01
$e \to \gamma$ fakes	0.07 ± 0.03	0.00 ± 0.00
$j \to \gamma$ fakes	0.04 ± 0.01	0.00 ± 0.00
$\gamma\gamma/W\gamma\gamma/Z\gamma\gamma$	0.01 ± 0.00	0.07 ± 0.01

Combined-SR gluino mass limits (for case of higgsino/bino NLSP with 50/50 γ/Z branching) as high as 2 TeV

Summary and Conclusions

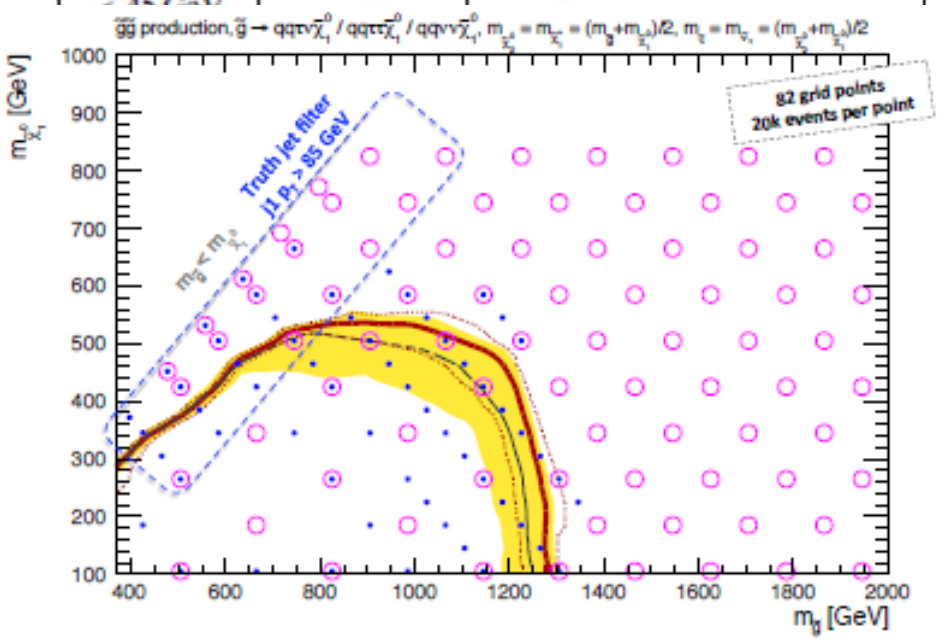
- We have searched for evidence of SUSY in association with photons and tau leptons in 3-13 fb^{-1} of 13 TeV ATLAS data
- Five tau-leptonic and three photonic SRs were developed to maximize sensitivity to simplified strong-production models of gauge-mediated and gravity-mediated SUSY breaking. No significant excess relative to expected SM backgrounds was observed for any of these eight SRs.
- In the context of these simplified models, limits set on the mass of the gluino are as high as 2 TeV.
- Due to the requirement of a high transverse energy scale and associated jets, these eight SRs were insensitive to EW production; the development of simplified-model SRs sensitive to EW production at 13 TeV is underway.
- A sixth tau-leptonic SR was optimized to search for evidence for a specific model of gauge-mediated SUSY (GMSB), sensitive to both strong and EW production in a constrained scenario.
- No excess was observed in this ninth SR, and limits were set in the Λ-tanβ parameter space of GMSB.

Back-Up

mSUGRA-Inspired Model

	Simplified Model SRs		
	Compressed	Medium-Δm	Large-Δm
Trigger selection	$p_T^{jet1} > 120$ GeV $E_T^{miss} > 180$ GeV		
Taus	$N_\tau^{medium} = 1$ $p_T > 20$ GeV		
Light leptons	$N_\ell^{baseline} = 0$		
Multijet rejection	$\Delta\phi(jet_{1,2}, p_T^{miss}) \geq 0.4$		
Signal selection			
p_T^τ	[illegible]		
p_T^{jet1}			
p_T^{jet2}			
m_T			
E_T^{miss}			
H_T			
N_{jet}			

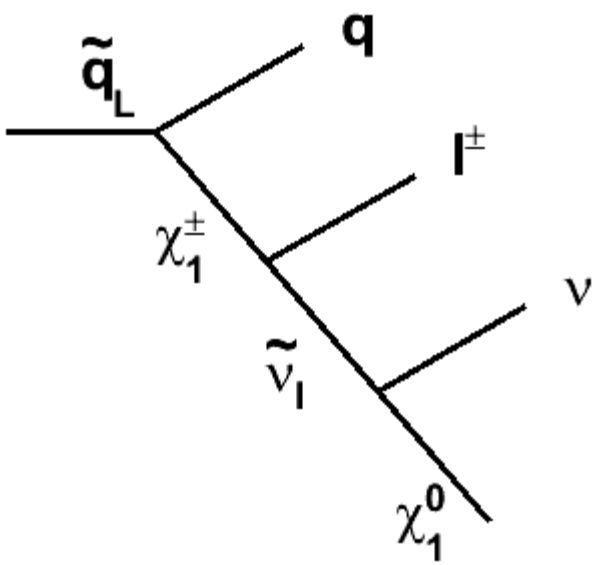
	Simplified Model SRs		GMSB SR
	High Mass	$\sum m_T^{jets} + \sum m_T^{taus}$-based	
Trigger selection	$p_T^{jet1} > 120$ GeV $E_T^{miss} > 180$ GeV		
Taus	$N_\tau^{loose} \geq 2$ $p_T > 20$ GeV		
	$\Delta\phi(jet_{1,2}, p_T^{miss}) \geq 0.4$		
	≥ 350 GeV	-	≥ 150 GeV
	≥ 800 GeV	-	≥ 1700 GeV
	≥ 3	≥ 2	≥ 2
	-	> 60 GeV	–
	-	> 1400 GeV	–



R Parity

To avoid lepton/baryon number violation can require that "SUSYness" is conserved, i.e., preserves a multiplicative "parity" quantum number R such that $R_{SM} = +1$; $R_{SUSY} = -1$

If you can't get rid of SUSYness, then lightest supersymmetric particle (LSP) is stable
➔ **dark matter, missing energy (E_T^{miss})**



LSP is typically a "neutralino" (dark matter must be neutral); admixture of $\tilde{W}^0, \tilde{\mathbf{B}}^{\mathbf{0}}, \tilde{H}^0$, known as "$\chi_1{}^0$", or gravitino $\tilde{G}$, whose identity is not that relevant to the phenomenology

Tau + X Search

Baseline requirement (all SRs): E_t^{miss} > 180 GeV; leading jet p_T > 120 GeV

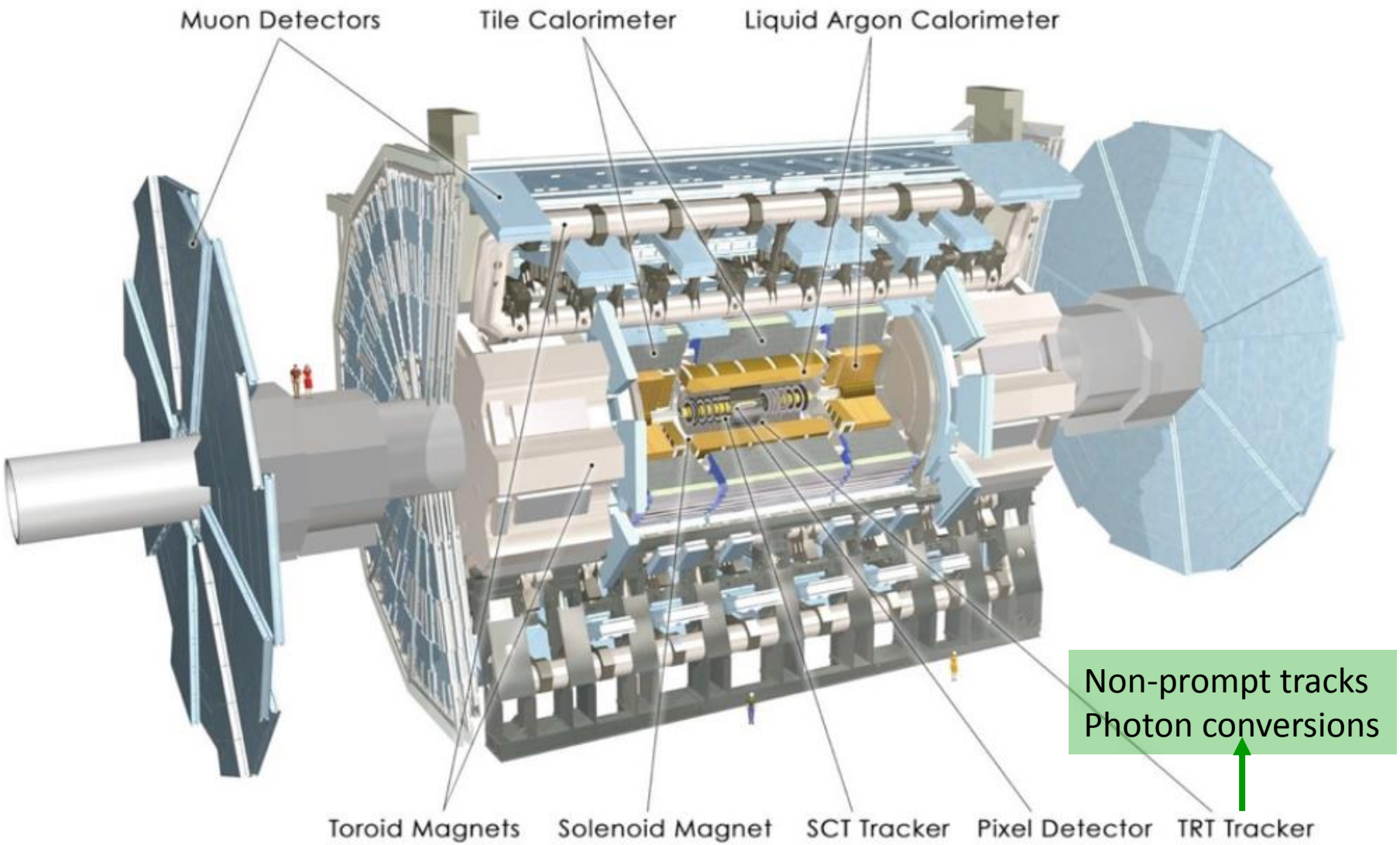
3 single-τ SRs geared towards mSUGRA model with varying mass gap between gluino and χ_1^0.

	Simplified Model SRs		
	Compressed	Medium-Δm	Large-Δm
Trigger selection	$p_T^{jet1} > 120$ GeV $E_T^{miss} > 180$ GeV		
Taus	$N_\tau^{medium} = 1$ $p_T > 20$ GeV		
Light leptons	$N_\ell^{baseline} = 0$		
Multijet rejection	$\Delta\phi(jet_{1,2}, p_T^{miss}) \geq 0.4$		
Signal selection			
p_T^τ	< 45 GeV	–	–
p_T^{jet1}	≥ 300 GeV	–	≥ 220 GeV
p_T^{jet2}	–	–	≥ 220 GeV
m_T	≥ 80 GeV	≥ 200 GeV	≥ 200 GeV
E_T^{miss}	≥ 300 GeV	≥ 300 GeV	–
H_T	–	≥ 550 GeV	≥ 550 GeV
N_{jet}	–	≥ 5	≥ 5

2 low-background multi-τ SRs for mSUGRA with high gluino mass and large mass gap; 1 multi-τ SR geared towards GMSB

	Simplified Model SRs		GMSB SR
	High Mass	$\sum m_T^{jets} + \sum m_T^{taus}$-based	
Trigger selection	$p_T^{jet1} > 120$ GeV $E_T^{miss} > 180$ GeV		
Taus	$N_\tau^{loose} \geq 2$ $p_T > 20$ GeV		
Multijet rejection	$\Delta\phi(jet_{1,2}, p_T^{miss}) \geq 0.4$		
Signal selection			
$m_T^{\tau 1} + m_T^{\tau 2}$	≥ 350 GeV	-	≥ 150 GeV
H_T	≥ 800 GeV	-	≥ 1700 GeV
N_{jet}	≥ 3	≥ 2	≥ 2
m_{T2}	-	> 60 GeV	–
$\sum m_T^{jets} + \sum m_T^{taus}$	-	> 1400 GeV	–

The ATLAS Detector



Non-prompt tracks
Photon conversions

Favorite Discriminating Variables

E_T^{miss}: Transverse momentum imbalance

- LSP escapes detection (RP conserving SUSY)

M_{eff}, H_T, etc: Transverse energy scale

- Strong production can reach high mass scales
- "Scale chasing"

$\Delta\phi_X$: Minimum ϕ separation between E_T^{miss} vector and any object of type X.

- LSP produced in intermediate-to-high mass decay
- Separation between LSP and decay sibling
- Jet backgrounds tend to have small separation (combinatoric)

Heavy Flavor: "Natural" preference for 3rd generation

- b jets, τ jets