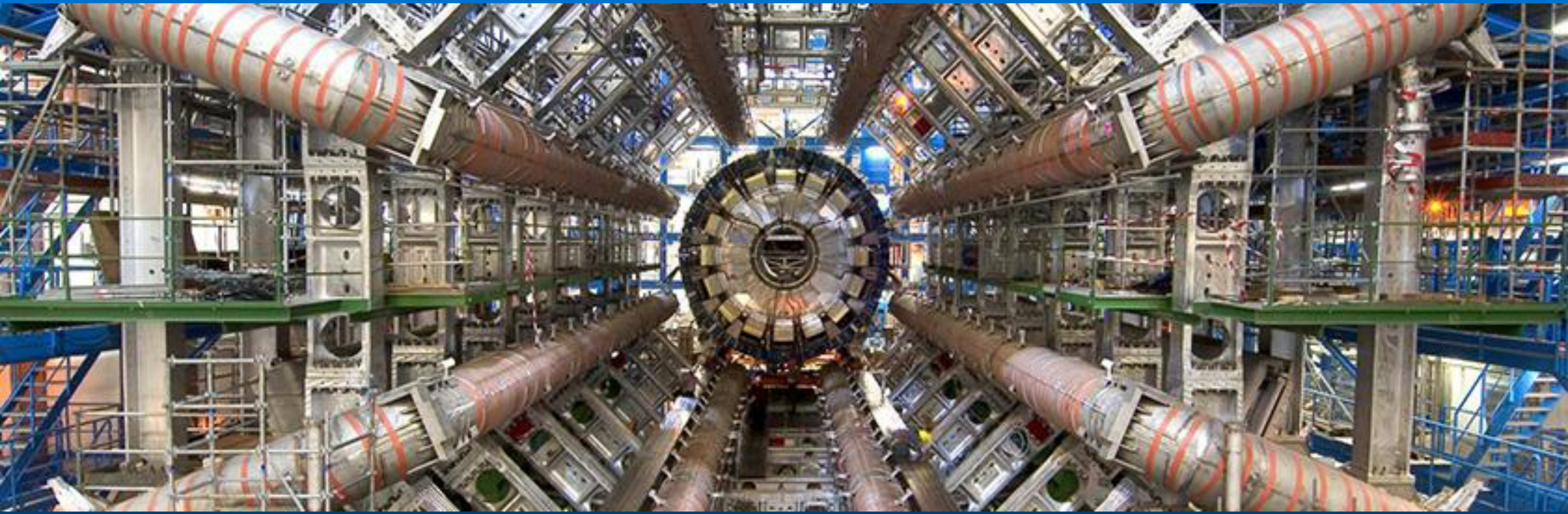
UNIVERSITY OF CAMBRIDGE

ATLAS EXPERIMENT

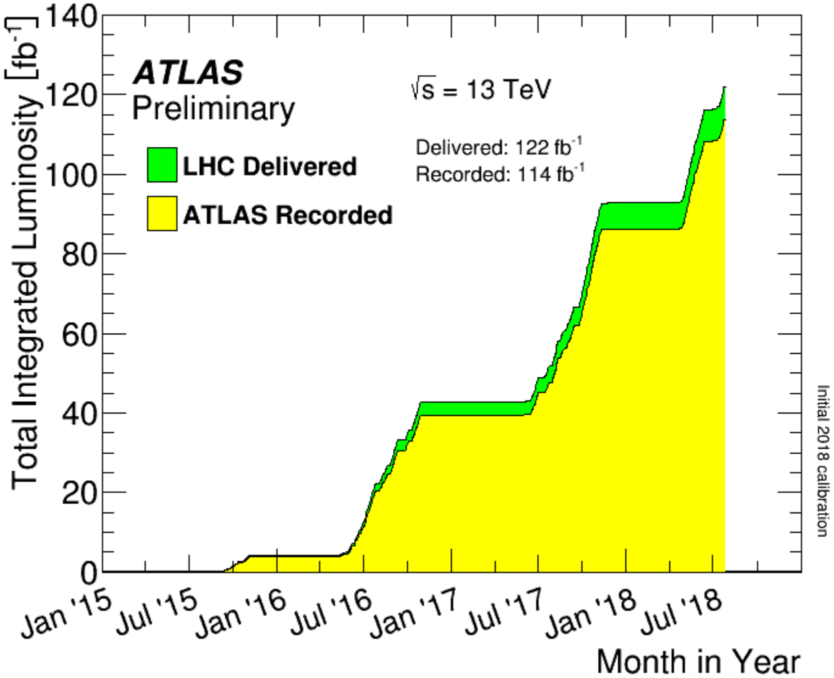
Searches for electroweak production of supersymmetric particles with ATLAS



Dr Sarah Williams, on behalf of the ATLAS collaboration

Introduction

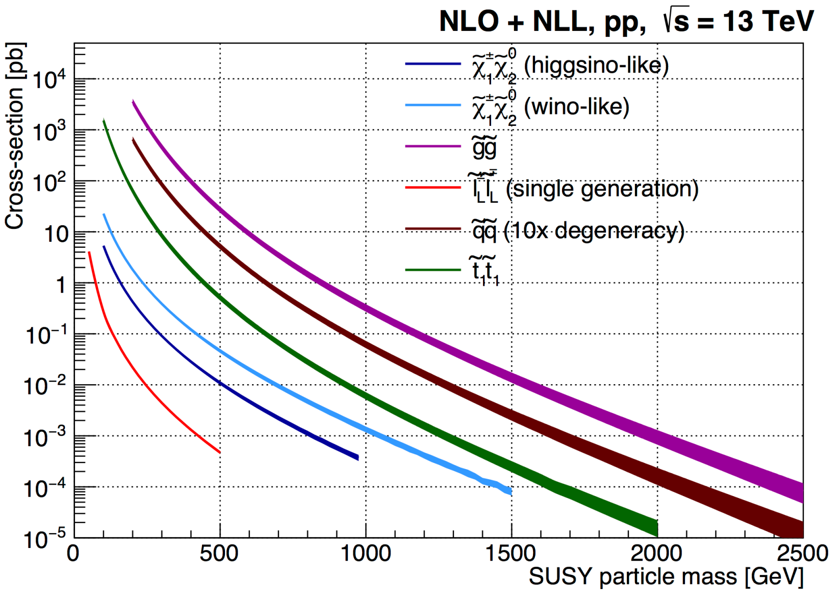
- This talk will summarize the status of ATLAS searches for electroweak SUSY production in run II.
- Increasing data-set sizes in run II have opened up sensitivity to:
    - New previously unexplored signal processes/decay channels.
    - Challenging areas of phase space.



In the interest of time, this talk will focus on a few new results and the innovations/ improvements that have enhanced our run-II sensitivity

Motivation for (electroweak) supersymmetry

- Supersymmetry provides a well-motivated candidate for BSM physics:
    - Dark matter candidate
    - Solution to the hierarchy problem (subject to naturalness constraints)
- Electroweak processes refer to the production of **sleptons** and **electroweakinos.**
- Electroweakinos are superpositions of **bino**, **wino** and **higgsino** fields:
    - Charginos $\tilde{\chi}_i^{\pm}$ (i=1,2)
    - Neutralinos $\tilde{\chi}_i^{0}$ (i=1,2,3,4)



https://arxiv.org/abs/1407.5066

EWK SUSY processes have lower production cross-sections but promising discovery channel if squarks/gluinos heavy…

Electroweak SUSY scenarios

Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

(1) $\tilde{\chi}_1^0$ is LSP

Electroweak SUSY scenarios

Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

$(1)\tilde{\chi}_1^0$ is LSP

Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

Electroweak SUSY scenarios

Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

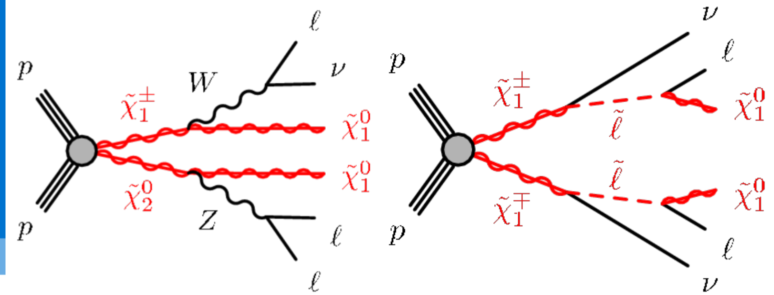
(1) $\tilde{\chi}_1^0$ is LSP

Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

1. Bino-like LSP with wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ that decay via gauge bosons or sleptons ("wino-bino" scenario).
2. Wino-like LSP with nearly degenerate $\tilde{\chi}_1^{\pm}$ => "disappearing track" signature.
3. Higgsino-like nearly-degenerate $\tilde{\chi}_1^0\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ triplet => "compressed" searches or disappearing track.
4. Direct slepton production

Electroweak SUSY scenarios (1)



Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

(1) $\tilde{\chi}_1^0$ is LSP

Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

1. Bino-like LSP with wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ that decay via gauge bosons or sleptons (“wino-bino” scenario).
2. Wino-like LSP with nearly degenerate $\tilde{\chi}_1^{\pm}$ => “disappearing track” signature.
3. Higgsino-like nearly-degenerate $\tilde{\chi}_1^0\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ triplet => “compressed” searches or disappearing track.
4. Direct slepton production

Electroweak SUSY scenarios

Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

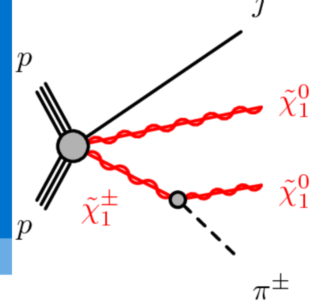
(1) $\tilde{\chi}_1^0$ is LSP

Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

1. Bino-like LSP with wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ that decay via gauge bosons or sleptons ("wino-bino" scenario).
2. Wino-like LSP with nearly degenerate $\tilde{\chi}_1^{\pm}$ => "disappearing track" signature.
3. Higgsino-like nearly-degenerate $\tilde{\chi}_1^0\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ triplet => "compressed" searches or disappearing track.
4. Direct slepton production

Electroweak SUSY scenarios (2)



Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

(1) $\tilde{\chi}_1^0$ is LSP

Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

1. Bino-like LSP with wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ that decay via gauge bosons or sleptons ("wino-bino" scenario).
2. Wino-like LSP with nearly degenerate $\tilde{\chi}_1^{\pm}$ => "disappearing track" signature.
3. Higgsino-like nearly-degenerate $\tilde{\chi}_1^0\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ triplet => "compressed" searches or disappearing track.
4. Direct slepton production

Electroweak SUSY scenarios

Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

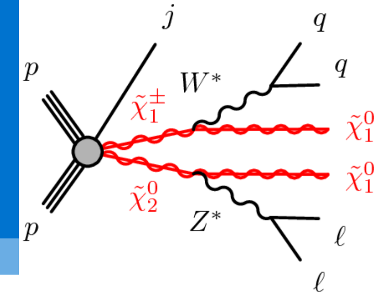
$(1)\tilde{\chi}_1^0$ is LSP

Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

1. Bino-like LSP with wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ that decay via gauge bosons or sleptons ("wino-bino" scenario).
2. Wino-like LSP with nearly degenerate $\tilde{\chi}_1^{\pm}$ => "disappearing track" signature.
3. Higgsino-like nearly-degenerate $\tilde{\chi}_1^0\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ triplet => "compressed" searches or disappearing track.
4. Direct slepton production

Electroweak SUSY scenarios (3)



Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

$(1)\tilde{\chi}_1^0$ is LSP

Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

1. Bino-like LSP with wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ that decay via gauge bosons or sleptons ("wino-bino" scenario).
2. Wino-like LSP with nearly degenerate $\tilde{\chi}_1^{\pm}$ => "disappearing track" signature.
3. Higgsino-like nearly-degenerate $\tilde{\chi}_1^0\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ triplet => "compressed" searches or disappearing track.
4. Direct slepton production

Electroweak SUSY scenarios

Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

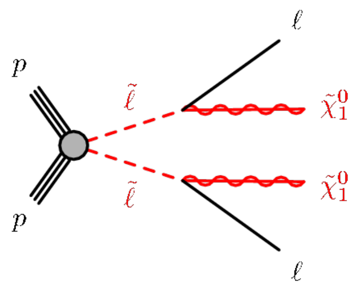
(1) $\tilde{\chi}_1^0$ is LSP

Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

1. Bino-like LSP with wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ that decay via gauge bosons or sleptons ("wino-bino" scenario).
2. Wino-like LSP with nearly degenerate $\tilde{\chi}_1^{\pm}$ => "disappearing track" signature.
3. Higgsino-like nearly-degenerate $\tilde{\chi}_1^0\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ triplet => "compressed" searches or disappearing track.
4. Direct slepton production

Electroweak SUSY scenarios (4)



Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

(1) $\tilde{\chi}_1^0$ is LSP

Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

1. Bino-like LSP with wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ that decay via gauge bosons or sleptons (“wino-bino” scenario).
2. Wino-like LSP with nearly degenerate $\tilde{\chi}_1^{\pm}$ => “disappearing track” signature.
3. Higgsino-like nearly-degenerate $\tilde{\chi}_1^0\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ triplet => “compressed” searches or disappearing track.
4. Direct slepton production

Electroweak SUSY scenarios

Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

(1)$\tilde{\chi}_1^0$ is LSP

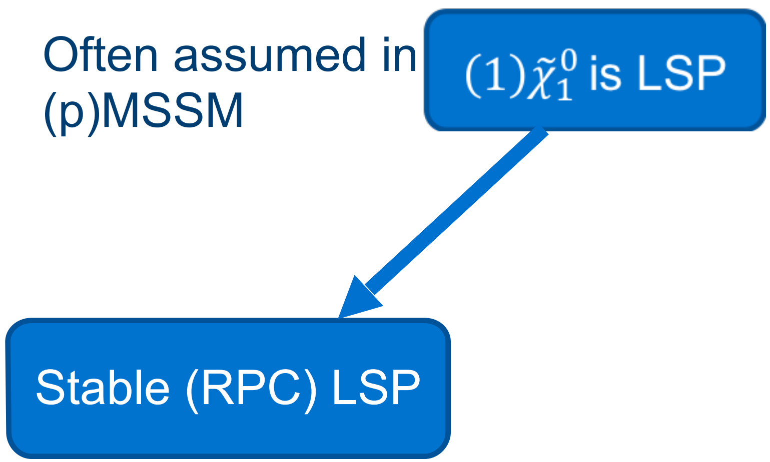
Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

1. Bino-like LSP with wino-like $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ that decay via gauge bosons or sleptons ("wino-bino" scenario).
2. Wino-like LSP with nearly degenerate $\tilde{\chi}_1^\pm$ => "disappearing track" signature.
3. Higgsino-like nearly-degenerate $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ triplet => "compressed" searches or disappearing track.
4. Direct slepton production

Electroweak SUSY scenarios

Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :



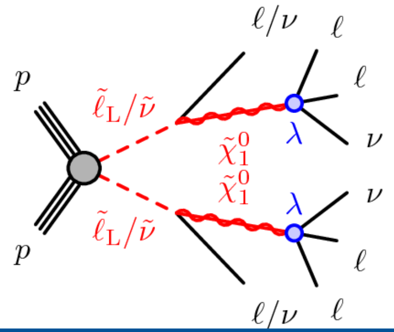
- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

Electroweak SUSY scenarios

Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

$(1)\tilde{\chi}_1^0$ is LSP



Stable (RPC) LSP

- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

Unstable (RPV) LSP

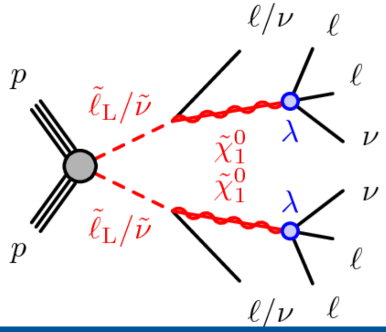
- LSP can decay via RPV λ coupling to leptonic final states

Electroweak SUSY scenarios

Assuming that LSP is a weakly interacting neutral particle => two options commonly feature in LHC simplified models for EWK SUSY :

Often assumed in (p)MSSM

(1) $\tilde{\chi}_1^0$ is LSP



(2) $\tilde{G}$ is LSP

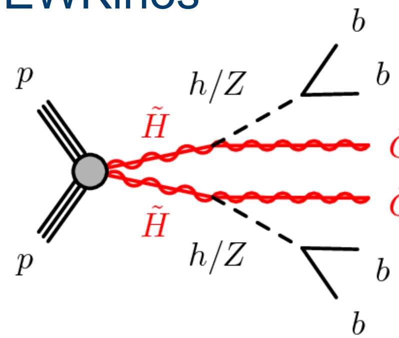
Stable (RPC) LSP

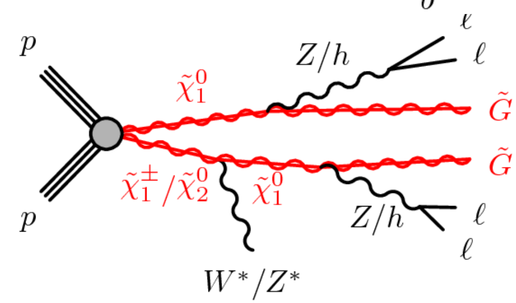
- Assuming pure states, LSP can be bino-like, wino-like or higgsino-like.
- Pair production of electroweakinos/ sleptons can give a wide range of topologies

Unstable (RPV) LSP

- LSP can decay via RPV λ coupling to leptonic final states

NLSPs can be higgsino-like EWKinos





Typical electroweak SUSY search

General SUSY analysis strategy already introduced in talk by Antonia Strübig

- Target signal scenario in decay channel with X leptons + Y jets + Z b-tagged jets ($\pm\vec{p}_T^{miss}$) (where X,Y,Z may be 0 or unconstrained), then define:

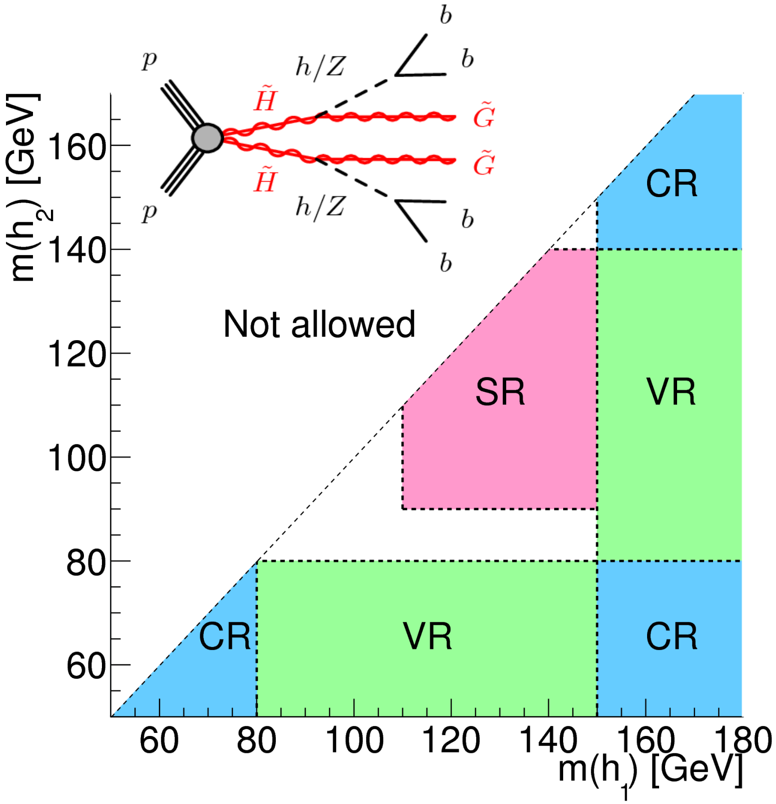


Image credit: 1806.04030

1. (Binned-) **signal regions** (SRs) to search for an excess of data over predictions.
2. **Control regions** (CRs) to extract normalization of dominant MC backgrounds.
3. **Validation regions** (VRs) to check background modelling.

…plus additional data-driven background estimates…

- Results interpreted using **simplified models** for the signature of interest.

ATLAS Run II electroweak searches

Table only includes searches for prompt EWK SUSY decays-> for long-lived searches see talk by Karri Dipetrillo

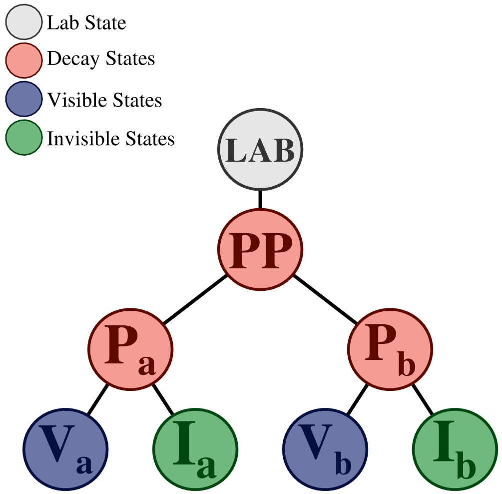
Signal	Decay mode	Channel	Lumi [fb^{-1}]	Details
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$	WW (RPC) WW (RPV $\tilde{\chi}_1^0$ decay)	2l+$\vec{p}_T^{miss}$ 4l	80 36	ATLAS-CONF-2018-042 arXiv:1804.03602
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$	WZ (RPC) WZ (RPV $\tilde{\chi}_1^0$ decay)	2l +ISR +$\vec{p}_T^{miss}$ 2l+jets/3l+ $\vec{p}_T^{miss}$ 2l+jets/3l+ $\vec{p}_T^{miss}$ 4l	36 36 36 36	Phys. Rev. D 97 (2018) 052010 (*) arXiv:1803.02762 arXiv:1806.02293 (RJR) arXiv:1804.03602
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ /$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$	Sleptons	2l/3l+ $\vec{p}_T^{miss}$ 2τ	36 36	arXiv:1803.02762 Eur. Phys. J. C 78 (2018) 154
$\tilde{H}\tilde{H}$	ZZ/hh + $\tilde{G}\tilde{G}$ (GGM/GMSB)	4b 4l	36 36	arXiv:1806.04030 arXiv:1804.03602
Zh	h-> neutralinos	2l+photon(s)	80	ATLAS-CONF-2018-019
$\tilde{l}\tilde{l}\ (\tilde{l}=\tilde{e},\tilde{\mu})$ $\tilde{l}\tilde{l}\ (\tilde{l}=\tilde{e},\tilde{\mu})$	RPC RPV	2l (+ISR) +$\vec{p}_T^{miss}$ 4l	36	arXiv:1803.02762 + (*) arXiv:1804.03602

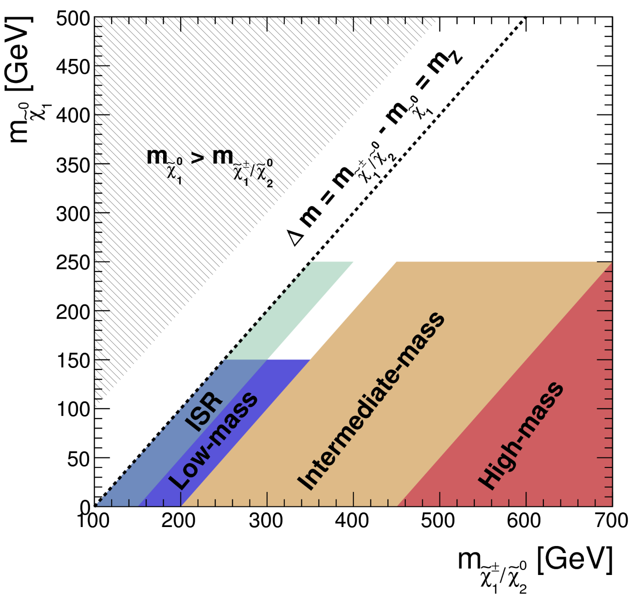
=> Already achieved rich search programme in terms of signal topology, RPC+RPV and different (N)LSP compositions (i.e. wino-bino, higgsino). The rest of this talk will discuss the three most recent results in more detail…

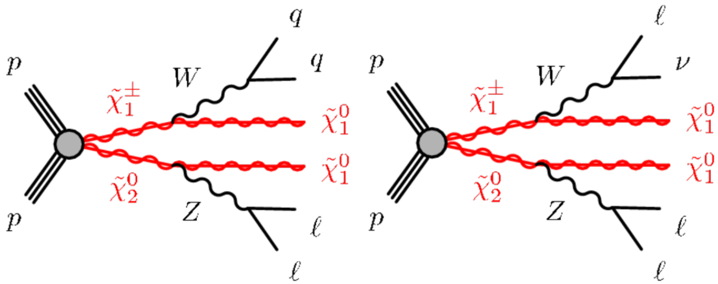
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow WZ$ using recursive jigsaw reconstruction (RJR)

arXiv:1806.02293

- Use measured event properties to approximate rest frames of intermediate particles in a "decay tree".
- RJR gives a new basis of observables based on energies and momenta of objects in these frames.





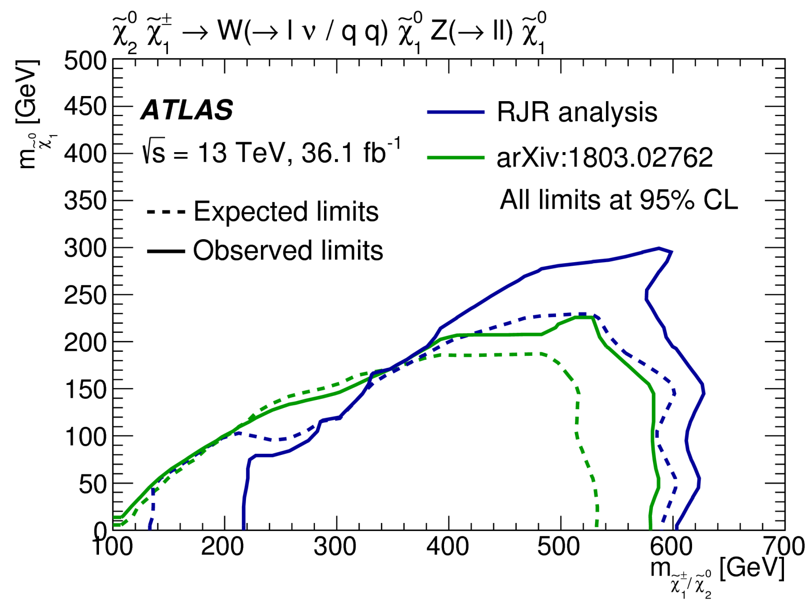


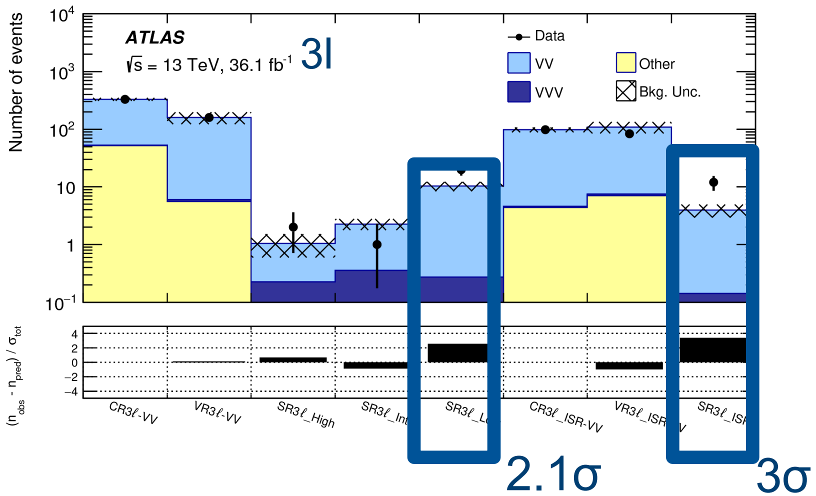
Recent result considers $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow WZ$ in

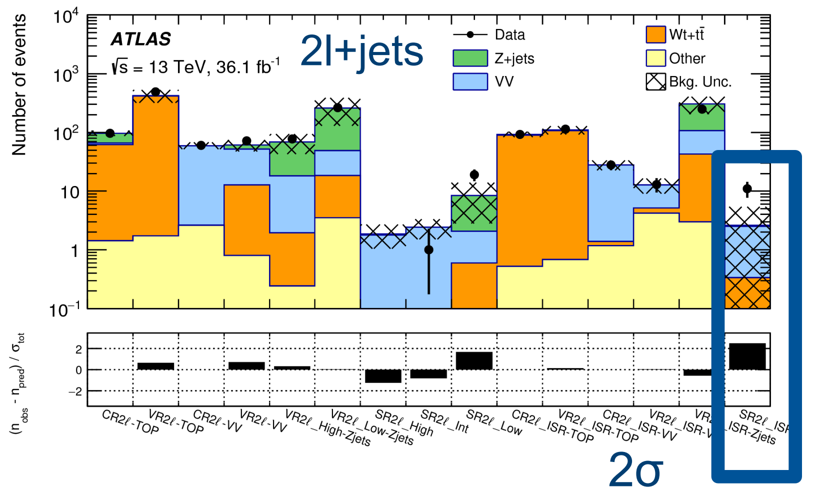
- **2 decay channels:** 2l+2j ($W \rightarrow jj, Z \rightarrow ll$) and 3l ($W \rightarrow l\nu, Z \rightarrow ll$) each of which have:
  - **4 SRs** targeting different mass splittings (Δm) between the $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ and the LSP.

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow WZ$ using recursive jigsaw reconstruction (RJR)

New techniques, and statistical combination of channels

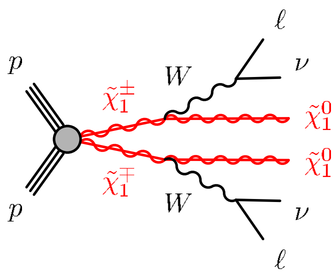




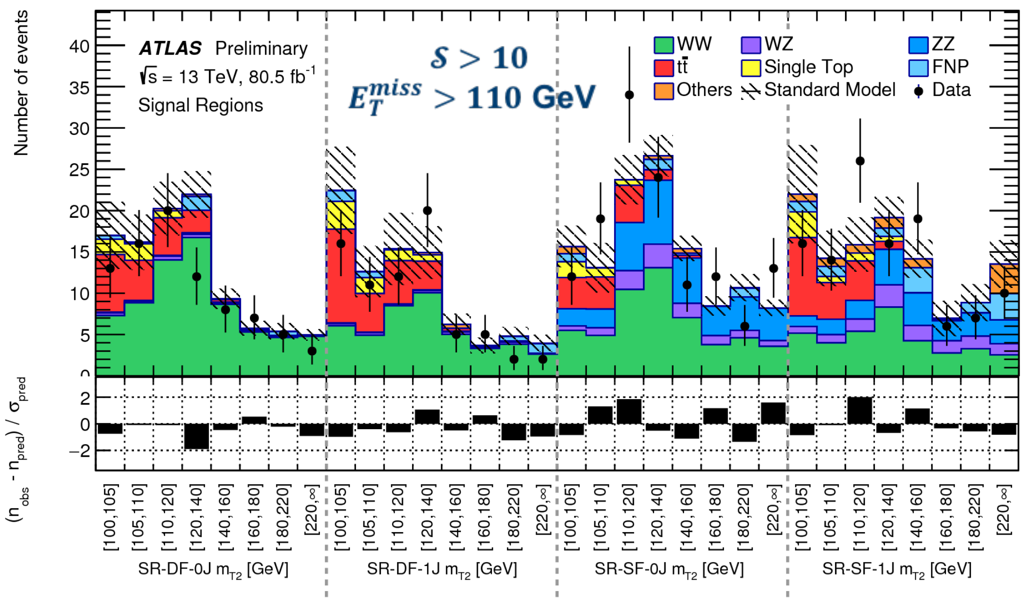


- Excesses seen in SRs targeting low and compressed mass splittings.
- Need to follow up with more data.

Chargino pair production $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \rightarrow WW\tilde{\chi}_1^0\tilde{\chi}_1^0$

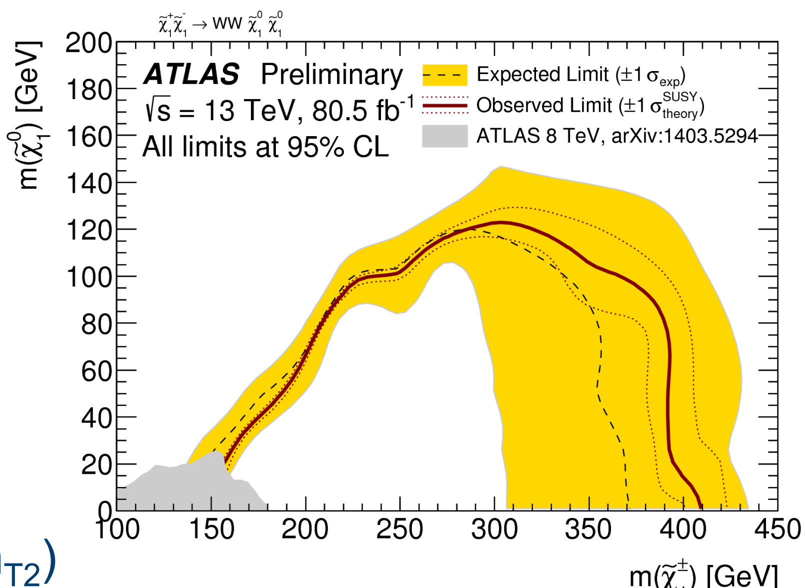


New variables and binned SRs



Different-flavour ($e^{\pm}\mu^{\mp}$) **Same-flavour ($e^{\pm}e^{\mp}$, $\mu^{\pm}\mu^{\mp}$)**

- Define SRs at high **missing transverse momentum significance ($\mathcal{S}$)** using **new object-based definition** (**ATLAS-CONF-2018-038**)

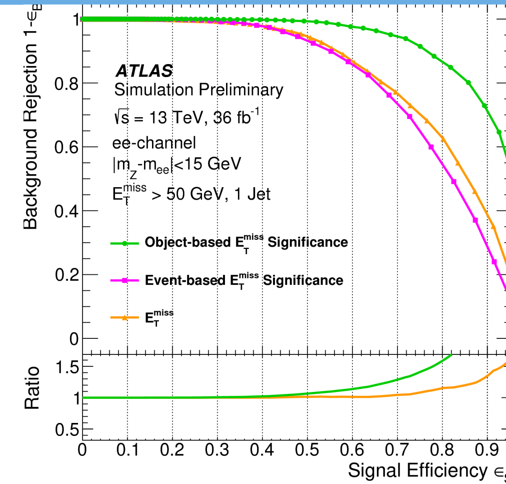


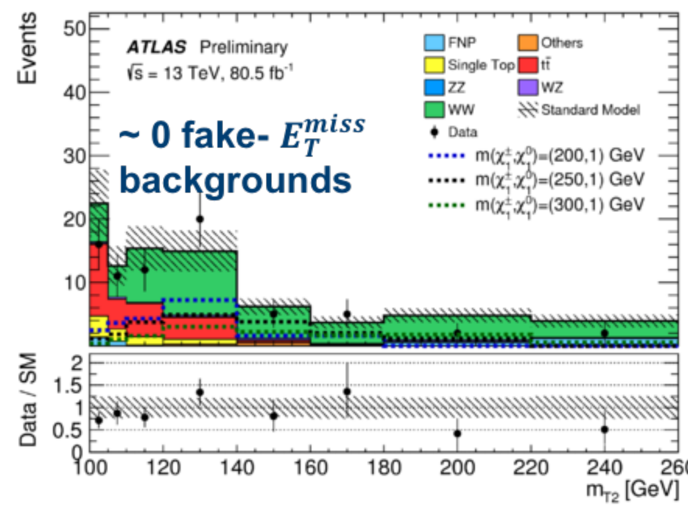
- Exploiting **shape fits** in **"stransverse mass"** (m_{T2}) and **jet multiplicity** greatly improves sensitivity

ATLAS-CONF-2018-042

New variables: object-based $\vec{p}_T^{miss}$ significance

- Indicates the degree to which the reconstructed E_T^{miss} is consistent with momentum resolution and particle identification efficiencies.
- **Event-based significance:** $\mathcal{S}=\frac{E_T^{miss}}{\sqrt{H_T}}$ or $\mathcal{S}=\frac{E_T^{miss}}{\sqrt{\sum E_T}}$
- **Object-based definition** determines $\mathcal{S}$ from the log-likelihood ratio that the reconstructed E_T^{miss} is consistent with the hypothesis of 0 real E_T^{miss}, based on the full event composition.





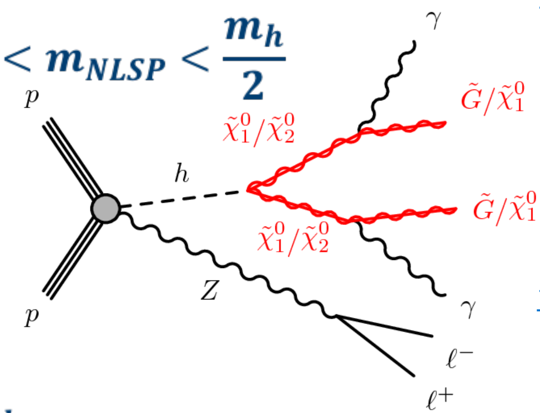
New definition greatly improved background suppression in the 1-jet bins (particularly for ee,μμ events where Z+jets is problematic)=> RH plot shows same-flavour 1-jet SRs…

Searches with photons: Zh with $h \rightarrow$ neutralinos

ATLAS-CONF-2018-019

Search for EWK SUSY through exotic Higgs decays

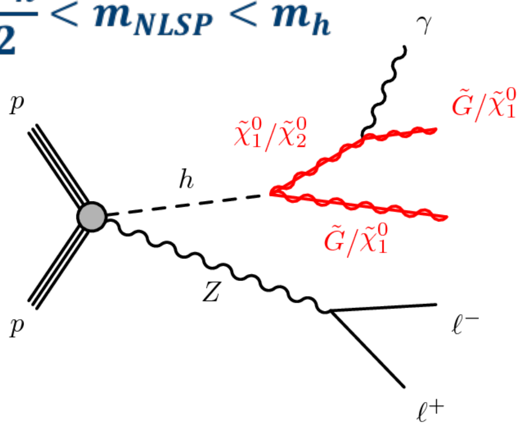
$0 < m_{NLSP} < \frac{m_h}{2}$



γE_T^{miss} system

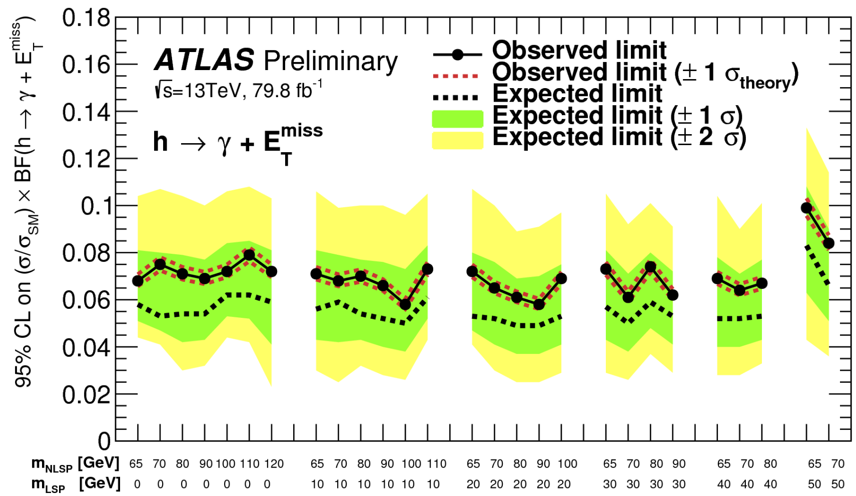
$Z\ (\rightarrow ll)$ system

$\frac{m_h}{2} < m_{NLSP} < m_h$



SR exploits balance between Z and γE_T^{miss} systems.

- Search for exotics Higgs decays in GMSB where 125 GeV Higgs decays to neutralinos that then decay to gravitinos+photon(s) (GMSB) or singlino+photon(s) (nMSSM)
- Improved limits on σ/σ_{SM} x BR for $h \rightarrow \gamma + E_T^{miss}$ and $h \rightarrow \gamma\gamma + E_T^{miss}$

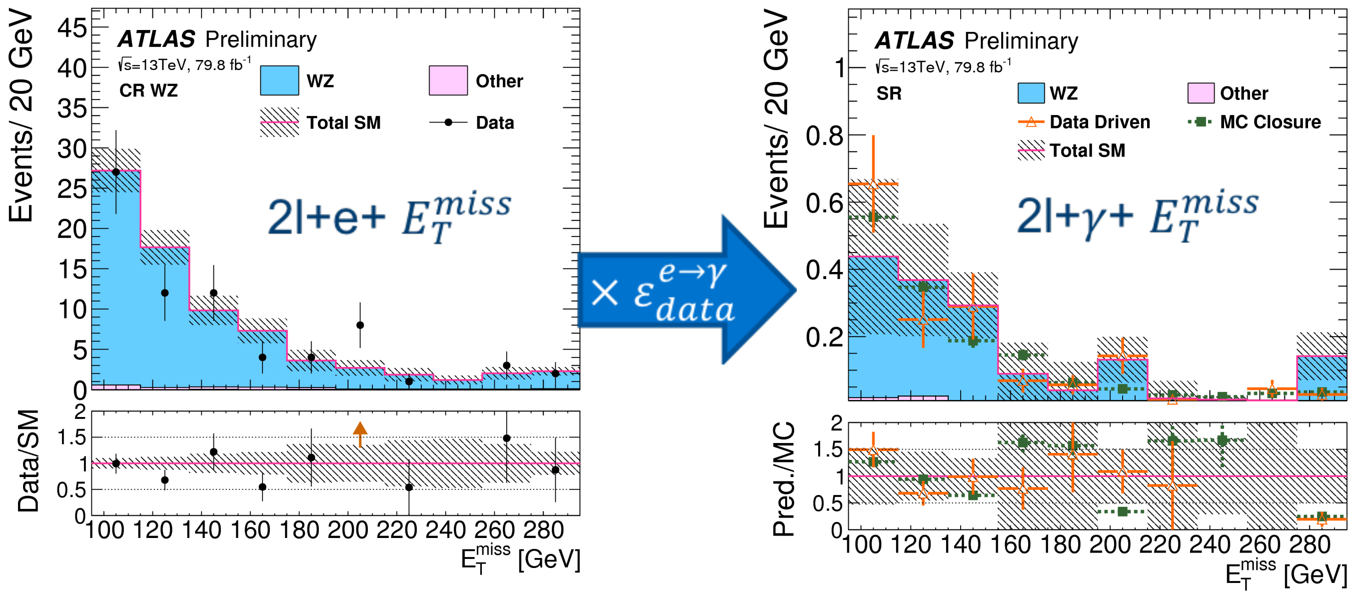


Background estimates for 2l+ $\vec{p}_T^{miss}$+ $\gamma(\gamma)$

Background	Estimation method
Electron faking a photon ($WZ \rightarrow e\nu ll$)	Data-driven (see below)
SM $Z\gamma$	Data-driven (CR)
Jet faking a photon (Z+jets)	Dåta-driven ”photon-factor”
Other SM processes with 2l+γ	MC (negligible)

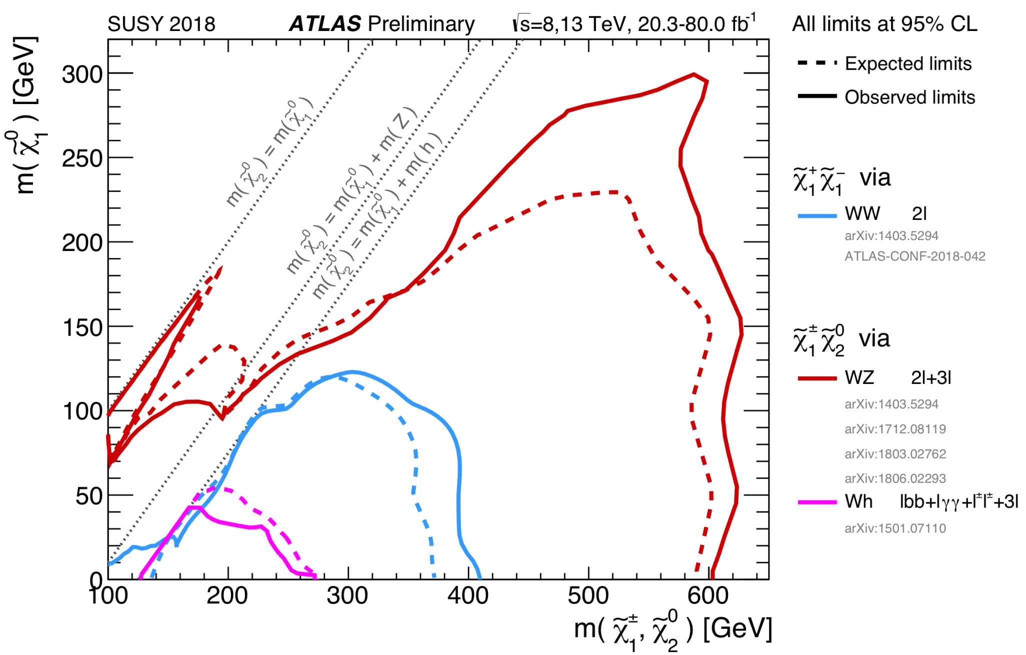
=> data-driven methods used for all dominant backgrounds!

WZ background in SR estimated scaling $ll + e$ events by data-driven $e \rightarrow \gamma$ mis-identification rate!



Summary: where could (EWK) SUSY be hiding?

Run II results extended the exclusion limits in a number of EWK SUSY scenarios. But there are still lots of interesting areas of phase space to explore…



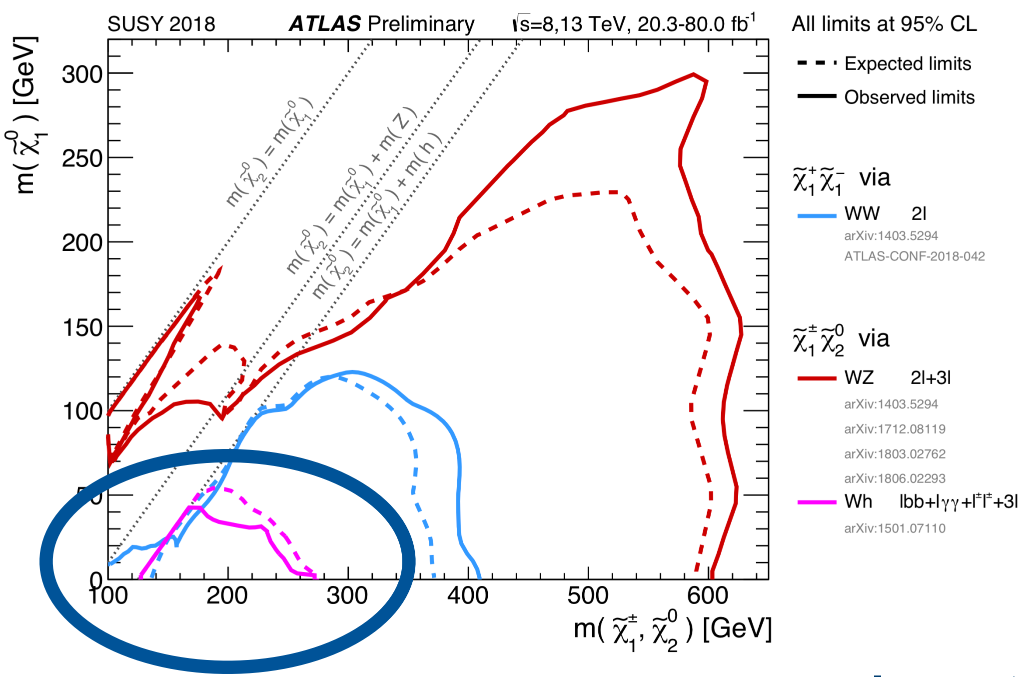
Above: summary plot for wino-like $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ and bino-like $\tilde{\chi}_1^0$

1. Challenging decay modes (i.e. decays through Higgs) and new final states.
2. Compressed and moderately compressed regions of phase space.
3. Mixed LSP scenarios (not currently included in simplified models)

Important message: do not confuse limits in simplified models with real limits on SUSY masses!

Summary: where could (EWK) SUSY be hiding?

Run II results extended the exclusion limits in a number of EWK SUSY scenarios. But there are still lots of interesting areas of phase space to explore…



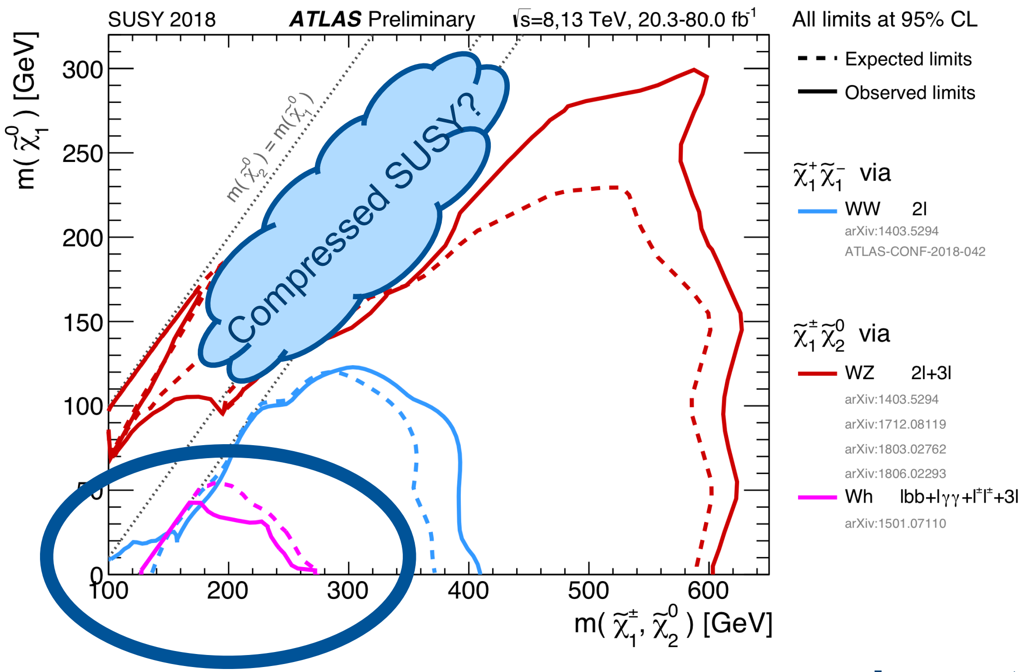
Above: summary plot for wino-like $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ and bino-like $\tilde{\chi}_1^0$

1. Challenging decay modes (i.e. decays through Higgs) and new final states.
2. Compressed and moderately compressed regions of phase space.
3. Mixed LSP scenarios (not currently included in simplified models)

Important message: do not confuse limits in simplified models with real limits on SUSY masses!

Summary: where could (EWK) SUSY be hiding?

Run II results extended the exclusion limits in a number of EWK SUSY scenarios. But there are still lots of interesting areas of phase space to explore…



Above: summary plot for wino-like $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ and bino-like $\tilde{\chi}_1^0$

1. Challenging decay modes (i.e. decays through Higgs) and new final states.
2. Compressed and moderately compressed regions of phase space.
3. Mixed LSP scenarios (not currently included in simplified models)

Important message: do not confuse limits in simplified models with real limits on SUSY masses!

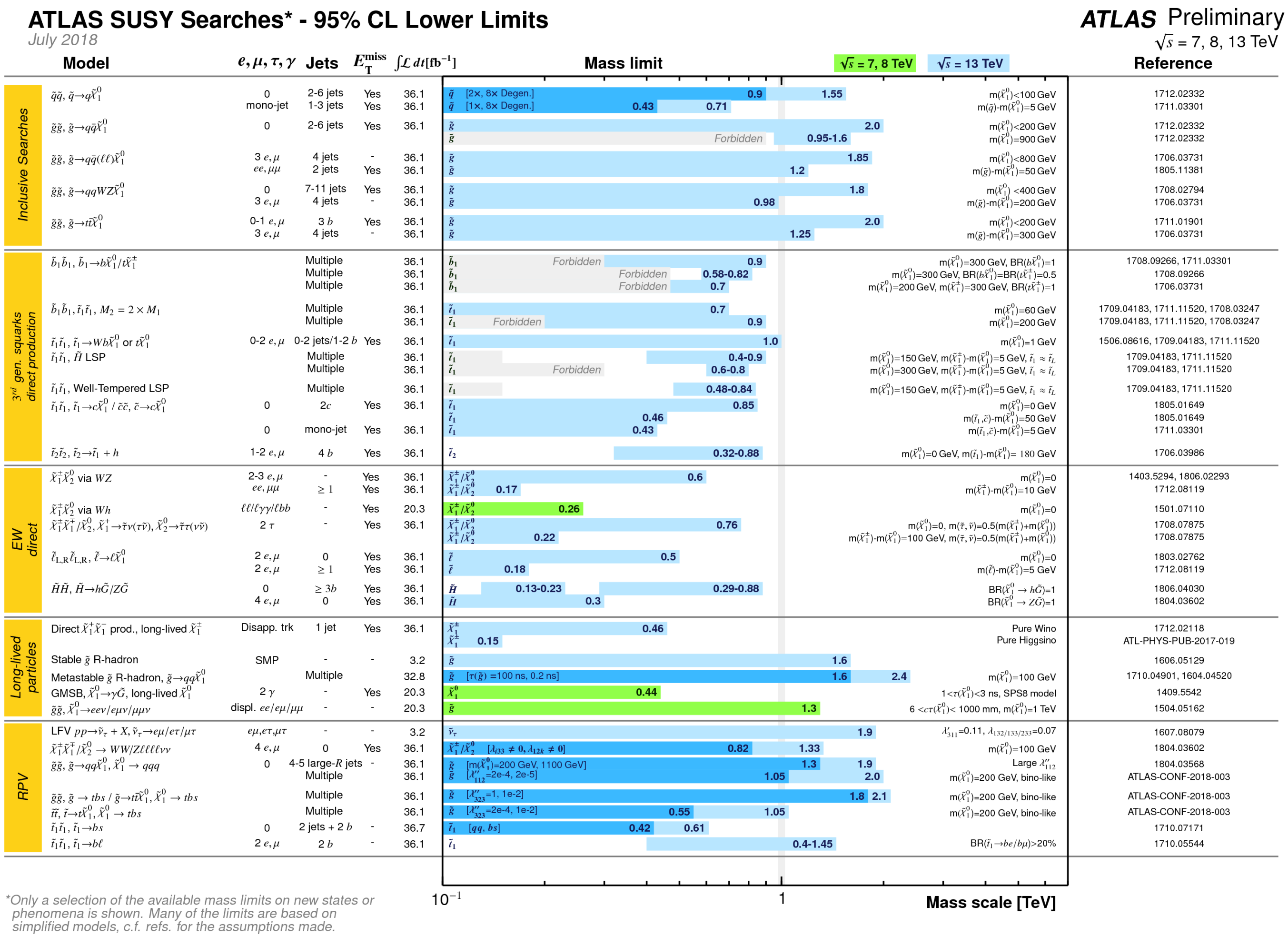
Conclusions

- 36 fb^{-1} in 2015-2016 enabled:
  - New limits on higgsinos and compressed scenarios
  - Extension of run I limits in many scenarios.
  - Excesses in some low/compressed SRs.
- 80 fb^{-1} in 2015-2017 enabled:
  - First ATLAS run II results for several challenging signatures.

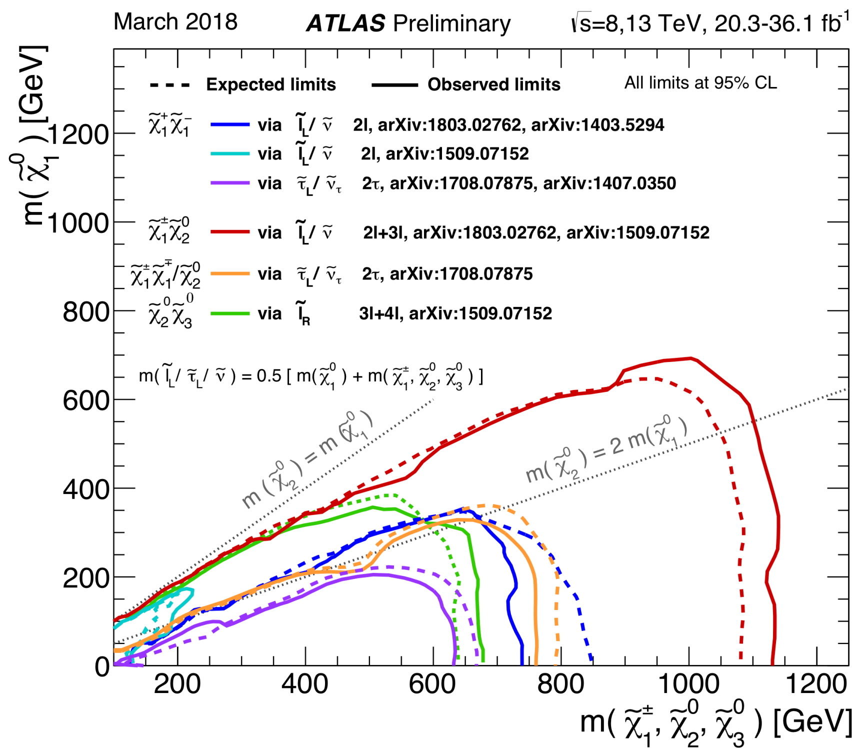
The success of our electroweak SUSY programme in run II owes a lot to those who have worked hard in operations, computing and combined performance areas throughout run II -> a team effort!

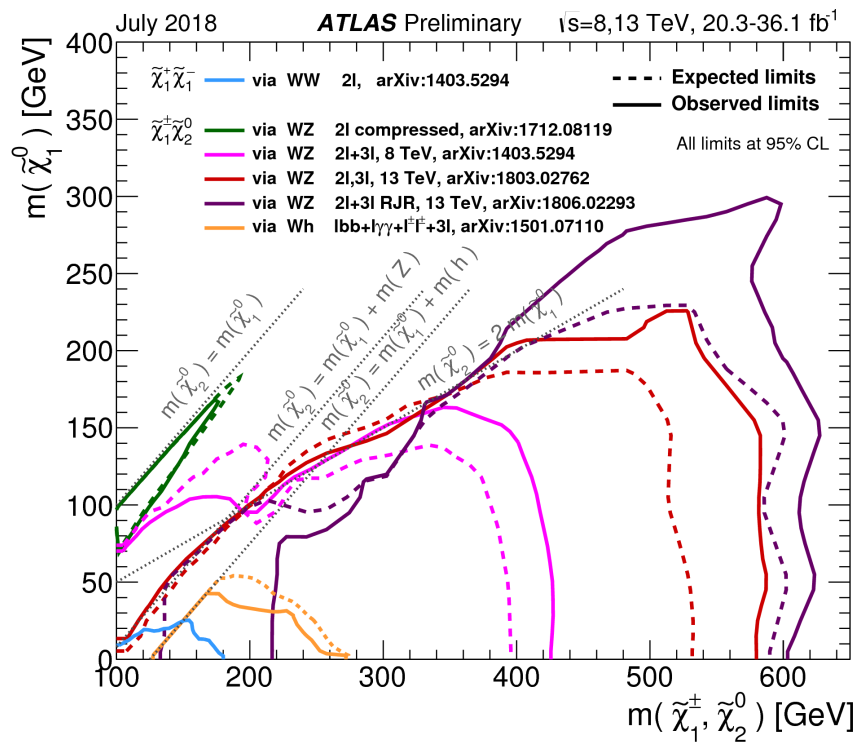
Maybe the O(150) fb^{-1} expected by the end of run II will unearth convincing evidence for supersymmetry…

Backup: ATLAS SUSY summary plot

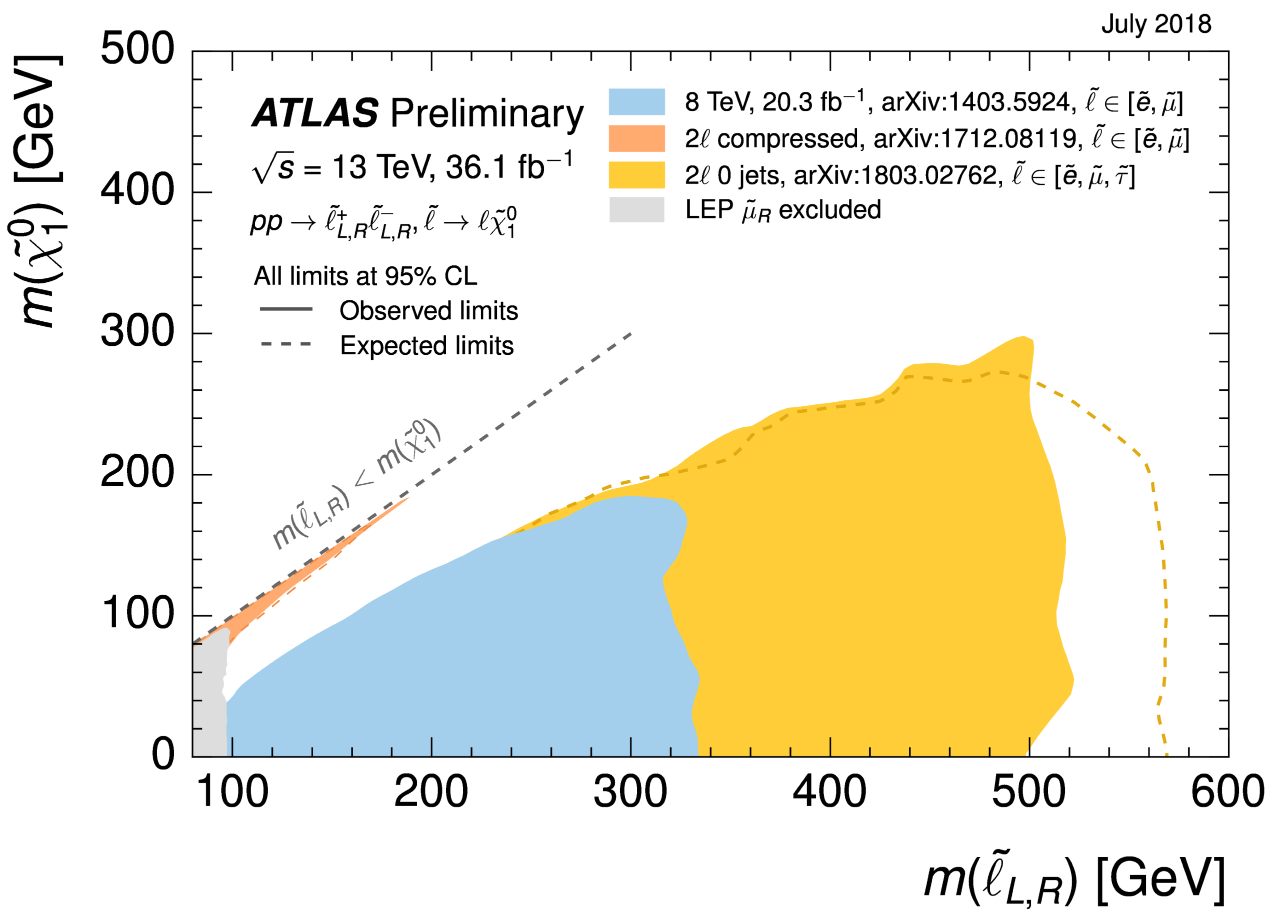


Backup: ATLAS summary plots for slepton vs boson mediated decays

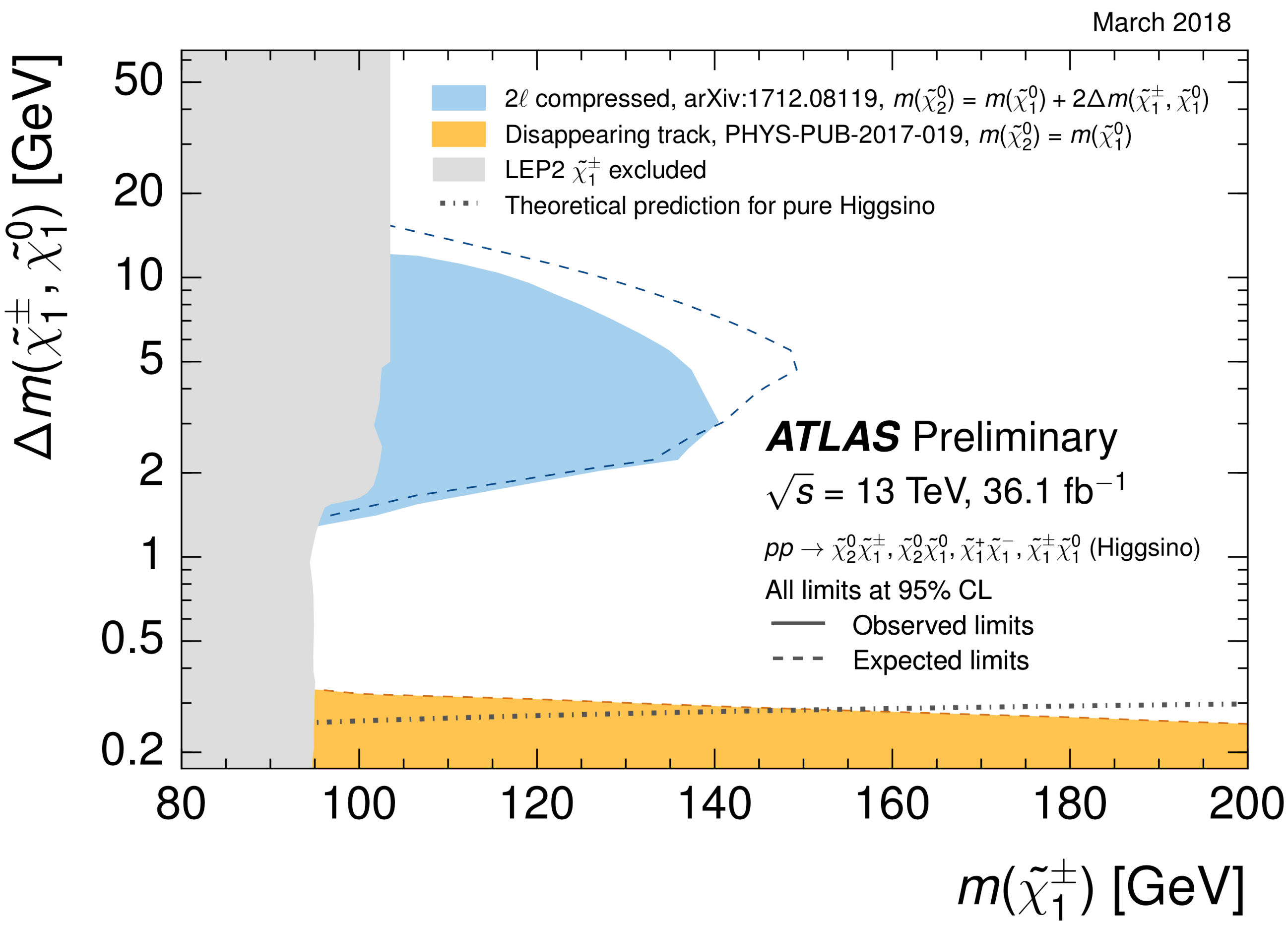




Backup: ATLAS summary plot for direct slepton production



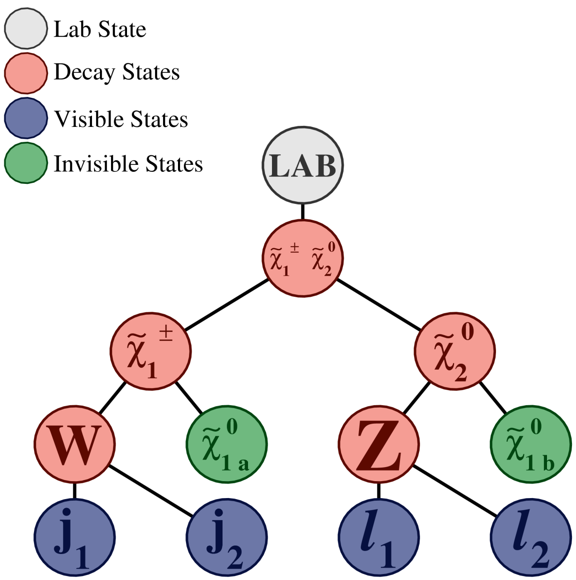
Backup: ATLAS summary plot for higgsinos



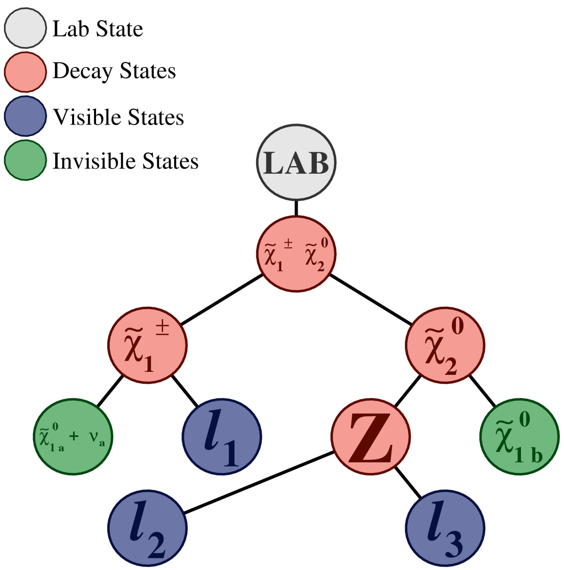
Backup: RJR analysis decay trees

1806.02293

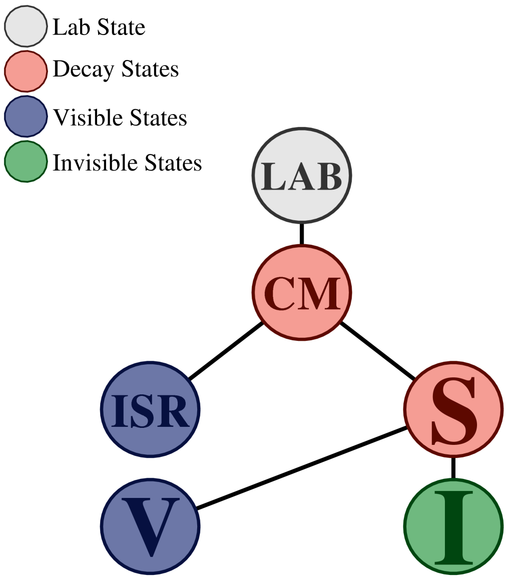
2l+jets channel



3l channel



ISR tree (2l+jets and 3l)



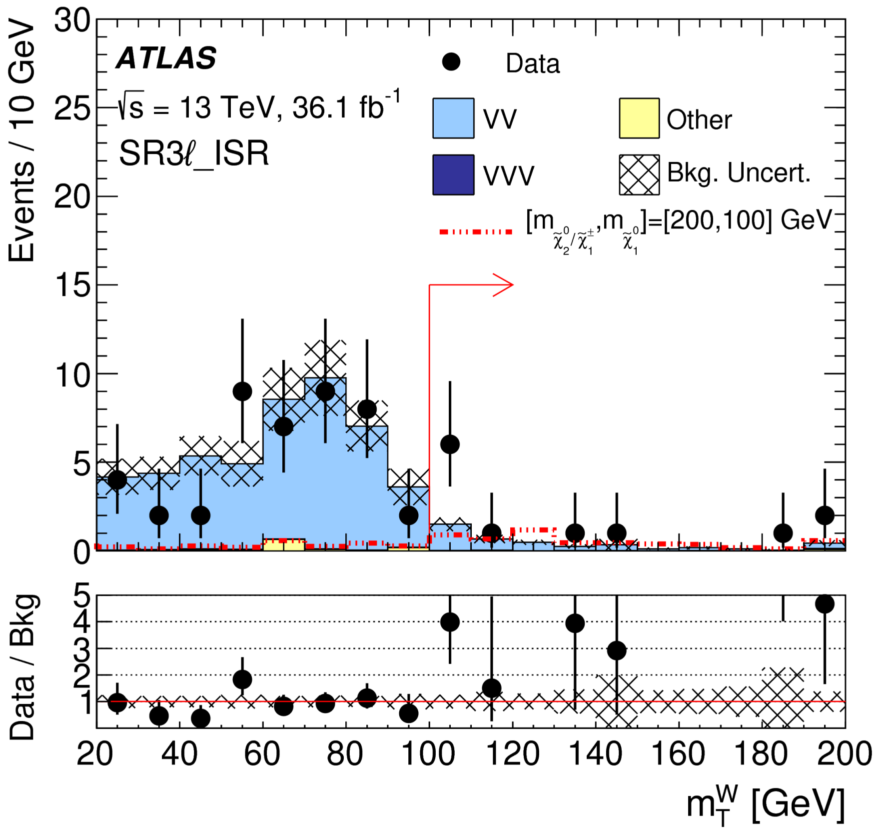
Backup: RJR SR/CR/VRs for 2l+jets ‘standard’ decay tree

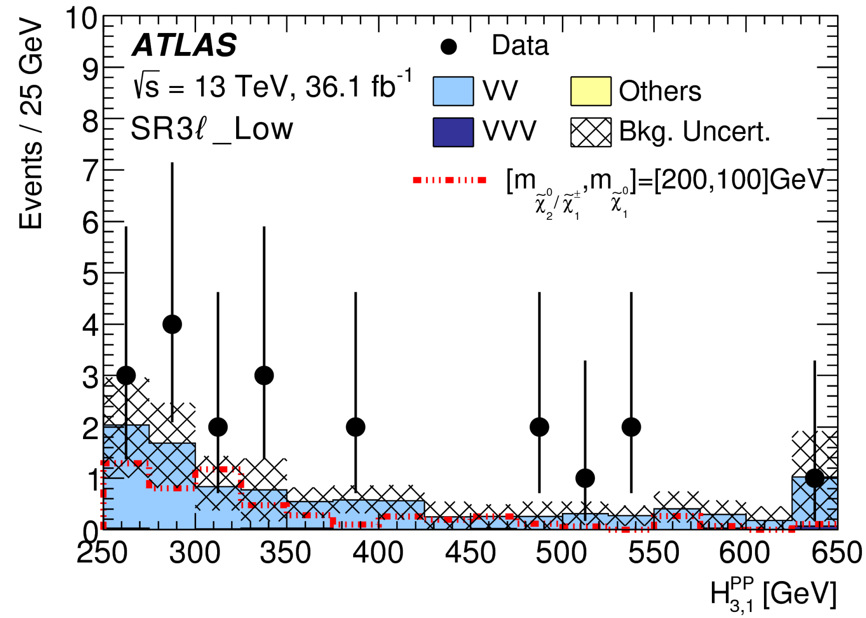
Region	n_{leptons}	n_{jets}	$n_{b\text{-tag}}$	$p_T^{\ell_1,\ell_2}$ [GeV]	$p_T^{j_1,j_2}$ [GeV]	$m_{\ell\ell}$ [GeV]	m_{jj} [GeV]	m_T^W [GeV]
CR2ℓ-VV	$\in [3,4]$	≥ 2	$=0$	> 25	> 30	$\in (80,100)$	> 20	$\in (70,100)$
								if $n_{\text{leptons}} = 3$
CR2ℓ-Top	$= 2$	≥ 2	$=1$	> 25	> 30	$\in (80,100)$	$\in (40,250)$	–
VR2ℓ-VV	$= 2$	≥ 2	$=0$	> 25	> 30	$\in (80,100)$	$\in (40,70)$	–
							or $\in (90,500)$	–
VR2ℓ-Top	$= 2$	≥ 2	$=1$	> 25	> 30	$\in (20,80)$	$\in (40,250)$	–
						or > 100		–
VR2ℓ_High-Zjets	$= 2$	≥ 2	$= 0$	> 25	> 30	$\in (80,100)$	$\in (0,60)$	–
							or $\in (100,180)$	–
VR2ℓ_Low-Zjets	$= 2$	$= 2$	$= 0$	> 25	> 30	$\in (80,100)$	$\in (0,60)$	–
							or $\in (100,180)$	–
SR2ℓ_High	$= 2$	≥ 2	$= 0$	> 25	> 30	$\in (80,100)$	$\in (60,100)$	–
SR2ℓ_Int	$= 2$	≥ 2	$= 0$	> 25	> 30	$\in (80,100)$	$\in (60,100)$	–
SR2ℓ_Low	$= 2$	$= 2$	$= 0$	> 25	> 30	$\in (80,100)$	$\in (70,90)$	–

Region	$H_{4,1}^{\text{PP}}$ [GeV]	$H_{1,1}^{\text{PP}}$ [GeV]	$\frac{p_{T\,\text{PP}}^{\text{lab}}}{p_{T\,\text{PP}}^{\text{lab}}+H_{T\,4,1}^{\text{PP}}}$	$\frac{\min(H_{1,1}^{\text{P}_a},H_{1,1}^{\text{P}_b})}{\min(H_{2,1}^{\text{P}_a},H_{2,1}^{\text{P}_b})}$	$\frac{H_{1,1}^{\text{PP}}}{H_{4,1}^{\text{PP}}}$	$\Delta\phi_V^{\text{P}}$	$\min\Delta\phi(j_1/j_2,\vec{p}_T^{\,\text{miss}})$
CR2ℓ-VV	> 200	–	< 0.05	> 0.2	–	$\in (0.3,2.8)$	–
CR2ℓ-Top	> 400	–	< 0.05	> 0.5	–	$\in (0.3,2.8)$	–
VR2ℓ-VV	> 400	> 250	< 0.05	$\in (0.4,0.8)$	–	$\in (0.3,2.8)$	–
VR2ℓ-Top	> 400	–	< 0.05	> 0.5	–	$\in (0.3,2.8)$	–
VR2ℓ_High-Zjets	> 600	–	< 0.05	> 0.4	–	$\in (0.3,2.8)$	–
VR2ℓ_Low-Zjets	> 400	–	< 0.05	–	$\in (0.35,0.60)$	–	–
SR2ℓ_High	> 800	–	< 0.05	> 0.8	–	$\in (0.3,2.8)$	–
SR2ℓ_Int	> 600	–	< 0.05	> 0.8	–	$\in (0.6,2.6)$	–
SR2ℓ_Low	> 400	–	< 0.05	–	$\in (0.35,0.60)$	–	> 2.4

=> SRs use RJR variables relating to energy/mass scale, angular variables and object momenta in several rest frames.

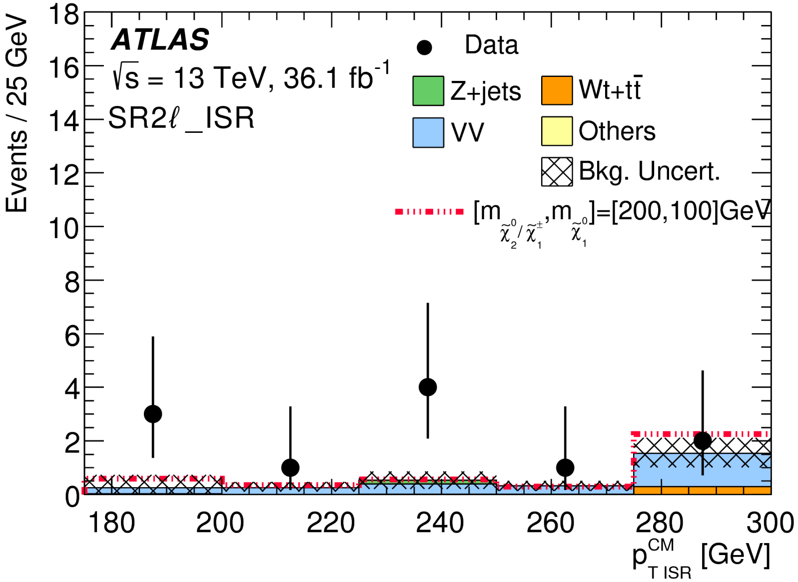
Backup: RJR analysis SR distributions for 3l channel

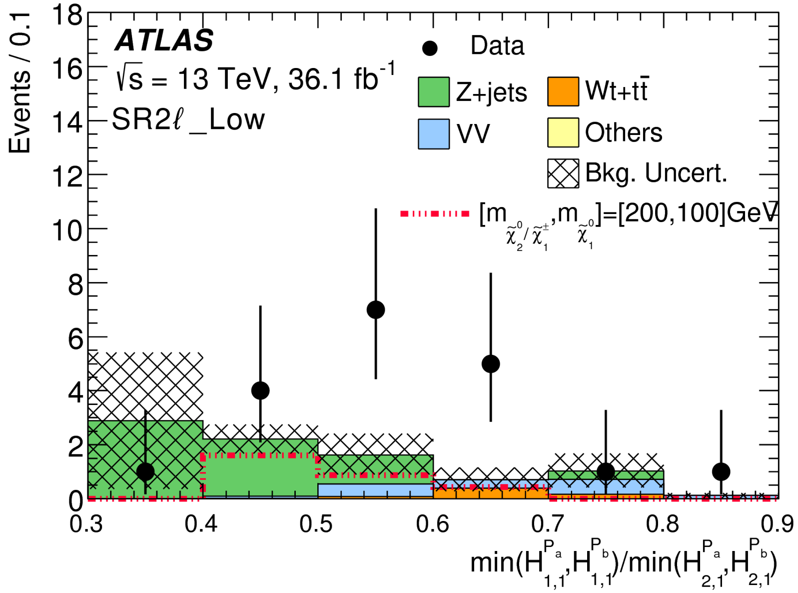




$H_{3,1}^{PP}$ =sum of the magnitudes of the visible and invisible momenta in the rest frame of the pair produced system-> scale variable that behaves like m_{eff}

Backup: RJR analysis SR distributions in 2l+jets channel





$p^{CM}_{T\,ISR}$= transverse momentum of the ISR system in the centre of mass frame.

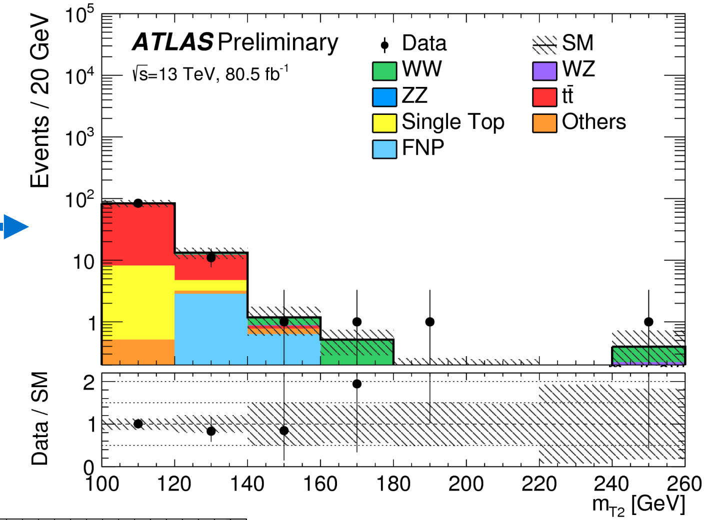
$$\frac{\min(H^{P_a}_{1,1}, H^{P_b}_{1,1})}{min(H^{P_a}_{2,1}, H^{P_b}_{2,1})}$$

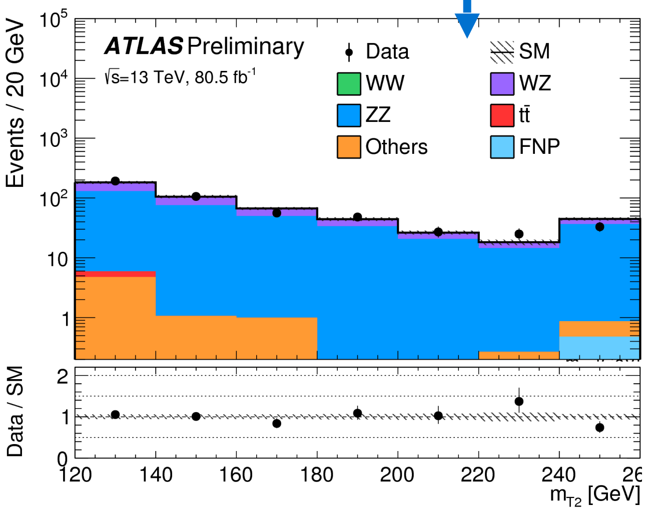
=>Compares scale due to one object + E_T^{miss} in respective production frames to two. Good discrimination against Z+jets

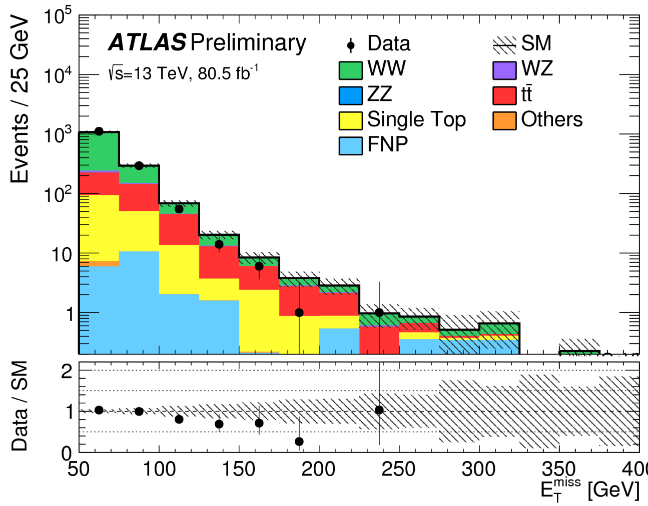
Backup: 2l+ $\vec{p}_T^{miss}$ analysis background estimation

ATLAS-CONF-2018-042

Region	CR-VZ	CR-WW	CR-top
Lepton flavour	SF	DF	DF
$n_{b\text{-tagged jets}}$	$= 0$	$= 0$	$= 1$
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$	$= 0$	$= 0$
m_{T2} [GeV]	> 120	$\in [60,65]$	> 100
E_T^{miss} [GeV]	> 110	> 60	> 110
E_T^{miss} significance	> 10	> 5	> 5
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	< 30	–	–







Data-driven normalization for all major backgrounds!

Backup: 2l+ $\vec{p}_T^{miss}$ analysis background estimation

Region	VR-WW-0J	VR-WW-1J	VR-VZ	VR-top-low	VR-top-high
Lepton flavour	DF	DF	SF	DF	DF
$n_{b\text{-tagged jets}}$	$=0$	$=0$	$=0$	$=1$	$=1$
$n_{\text{non-}b\text{-tagged jets}}$	$=0$	$=1$	$=0$	$=0$	$=1$
m_{T2} [GeV]	$\in$ [65,100]	$\in$[65,100]	$\in$[100,120]	$\in$[80,100]	>100
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>60	>60	>110	>110	>110
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	>5	>5	>10	>5	>5
$\lvert m_{\ell\ell} - m_Z\rvert$ [GeV]	–	–	<30	–	–

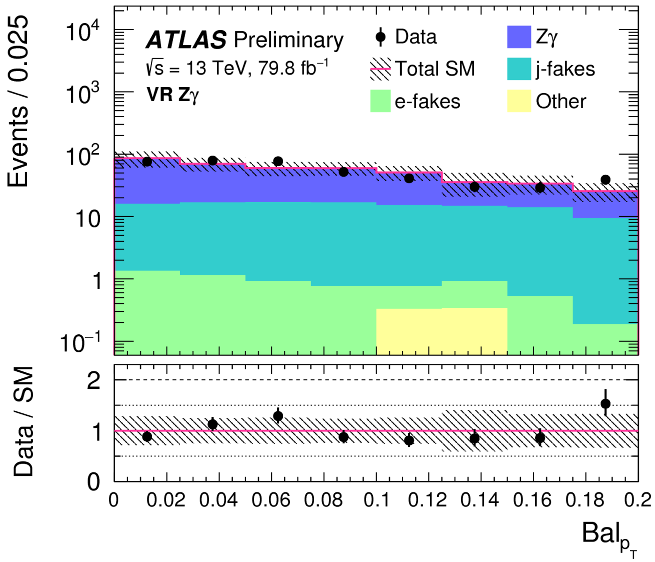
- VRs defined for all dominant background processes, with additional VR-top-low at low m_{T2} to ensure contamination in the WW CRs/VRs is well-modelled.
- To validate modelling of WW background at high m_{T2}, used a 3l WZ selection with $E_T^{miss} = [40{,}120]$ GeV and examined the m_{T2} distribution when one of the leptons is added to the $\vec{p}_T^{miss}$ vector to mimic a neutrino.

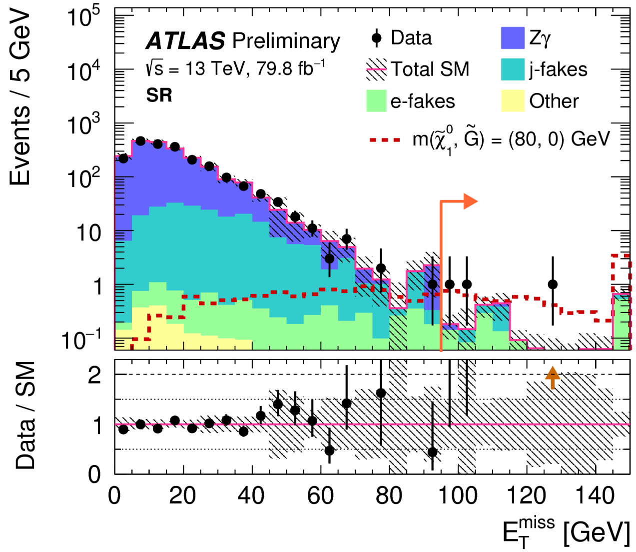
Backup: Zh-> neutralinos search analysis regions

Cut	CR WZ	CR $Z\gamma$	VR $Z\gamma$	VR jets	SR
Pass triggers and vetos	✓	✓	✓	✓	✓
2 signal leptons	✓	✓	✓	✓	✓
At least 1 signal photon	> 25 GeV(electron)	> 25 GeV	> 25 GeV	> 25 GeV	> 25 GeV
$m_{\ell\ell}^{\text{win}}$	81-101 GeV	81-101 GeV	81-101 GeV	85-120 GeV	81-101 GeV
$E_{\text{T}}^{\text{miss}}$	> 95 GeV	20-35 GeV	35-70 GeV	> 35 GeV	> 95 GeV
$\text{Bal}_{p_{\text{T}}}$	< 0.2	< 0.2	< 0.2	-	< 0.2
$\Delta\phi_{\ell\ell,\gamma E_{\text{T}}^{\text{miss}}}$	> 2.8	-	-	< 2.2	> 2.8
$\Delta\phi(\ell,\ell)$	< 1.4	< 2.0	< 2.0	-	< 1.4

$$Bal_{p_T} = \frac{|p_T^{ll} - p_T^{\gamma E_T^{miss}}|}{p_T^{\gamma E_T^{miss}}}$$

=> Asymmetry of the *ll* and γE_T^{miss} *systems.*





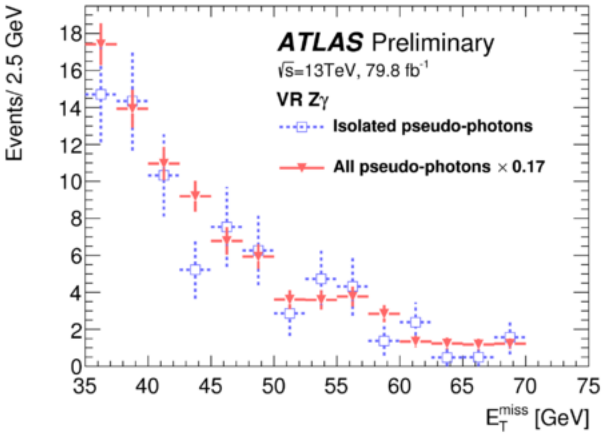
Final results in SR: 2.1 ± 0.5 expected vs 3 observed

Backup: Zh-> neutralinos search

Background from jets faking photons:

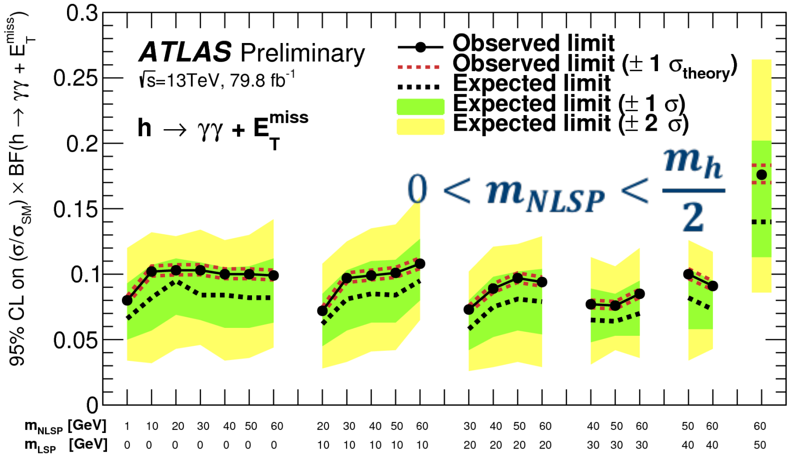
•Apply photon ”fake-factor” to events containing “pseudo-photons” (satisfying a loose criteria but failing the tight criteria required by the analysis).

•Reduce statistical uncertainty by removing isolation requirement on pseudo-photons and applying an additional factor (0.17) to account for the difference.



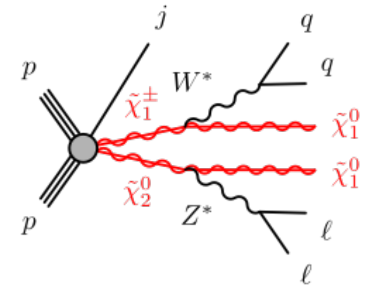
Results for $h \rightarrow \gamma\gamma + E_T^{miss}$ region:

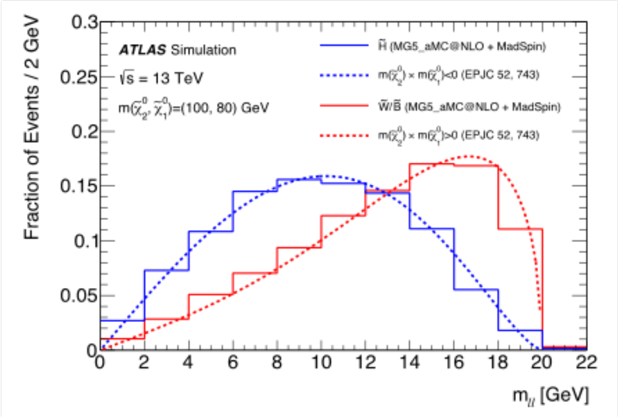
Over all BR ranges from 5-18% depending on LSP and NLSP masses!



Backup: Compressed EW searches

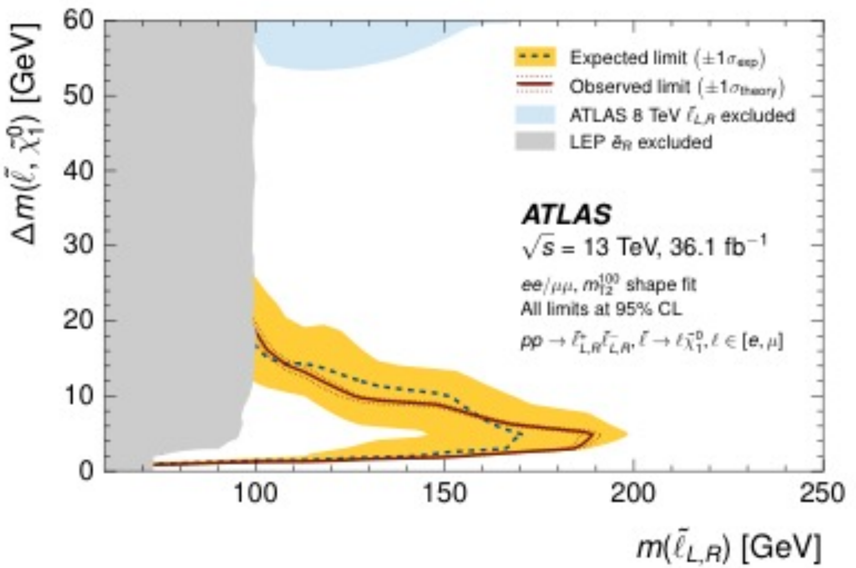
Phys. Rev. D 97 (2018) 052010

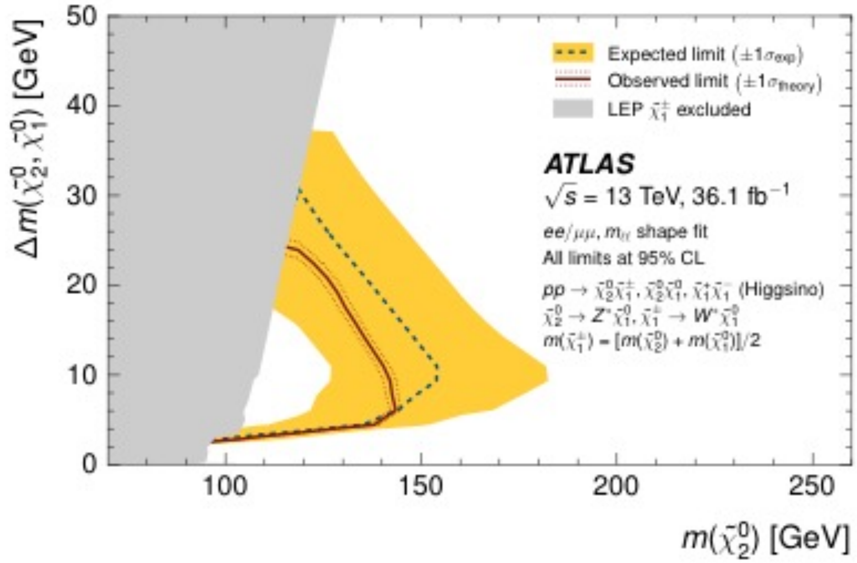




Improved performance for low p_T lepton reconstruction and shape fits

- Select 2 soft leptons recoiling against ISR jet and exploit kinematic endpoint of signal distributions (m_{ll} for $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ and m_{T2} for slepton pair production).





Backup: Statistical analysis in SUSY searches

For most SUSY searches construct likelihood for hypothesis testing based on data and predicted SM background in all SRs/CRs:

Signal strength parameter, and normalisation parameters for dominant backgrounds

Systematic uncertainties modelled by (unit) gaussian

$$\mathcal{L}(\boldsymbol{n}, \boldsymbol{\theta}^{0} | \mu_s, \boldsymbol{\mu_b}, \boldsymbol{\theta}) = \prod_{i \in CR} P(n_i | \lambda_i(\mu_s, \boldsymbol{\mu_b}, \boldsymbol{\theta})) \times \prod_{j \in SR} P(n_j | \lambda_j(\mu_s, \boldsymbol{\mu_b}, \boldsymbol{\theta})) \times P_{syst}(\boldsymbol{\theta}^{0}, \boldsymbol{\theta})$$

Data yields in SRs/CRs

Poisson probabilities for the CRs and SRs. For binned SRs/CRs include each bin as a separate region.

Backup: Statistical analysis in SUSY searches

Perform three different simultaneous fits using this likelihood function

1. **Background-only fit:** set μ_s=0 and fit nuisance parameters to the observed data in the control regions.

2. **Exclusion fit:** simultaneous fit to data in all SRs and CRs, including signal contribution. Perform hypothesis test and reject μ_s=1 hypothesis if "CL_s" value (approximate p-value) <0.05.

3. **Discovery fit:** inject signal contribution into SR only (no contribution in CRs). Calculate upper limit on signal contribution in SR, and p-value for background-only hypothesis.

=> All of this is handled effectively using the **HistFitter** package (**arXiv:1410.1280**)