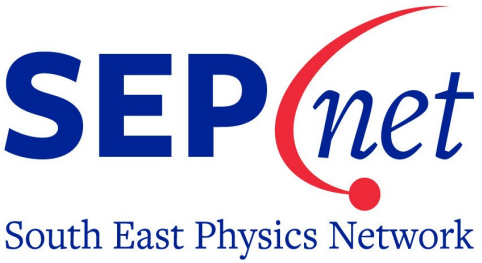
Electroweak SUSY searches in Compressed SUSY Scenarios using the 3-Lepton+E_T^{miss} signature

Supersymmetry: From M-theory to the LHC
12th January 2016

Yusufu Shehu

University of Sussex

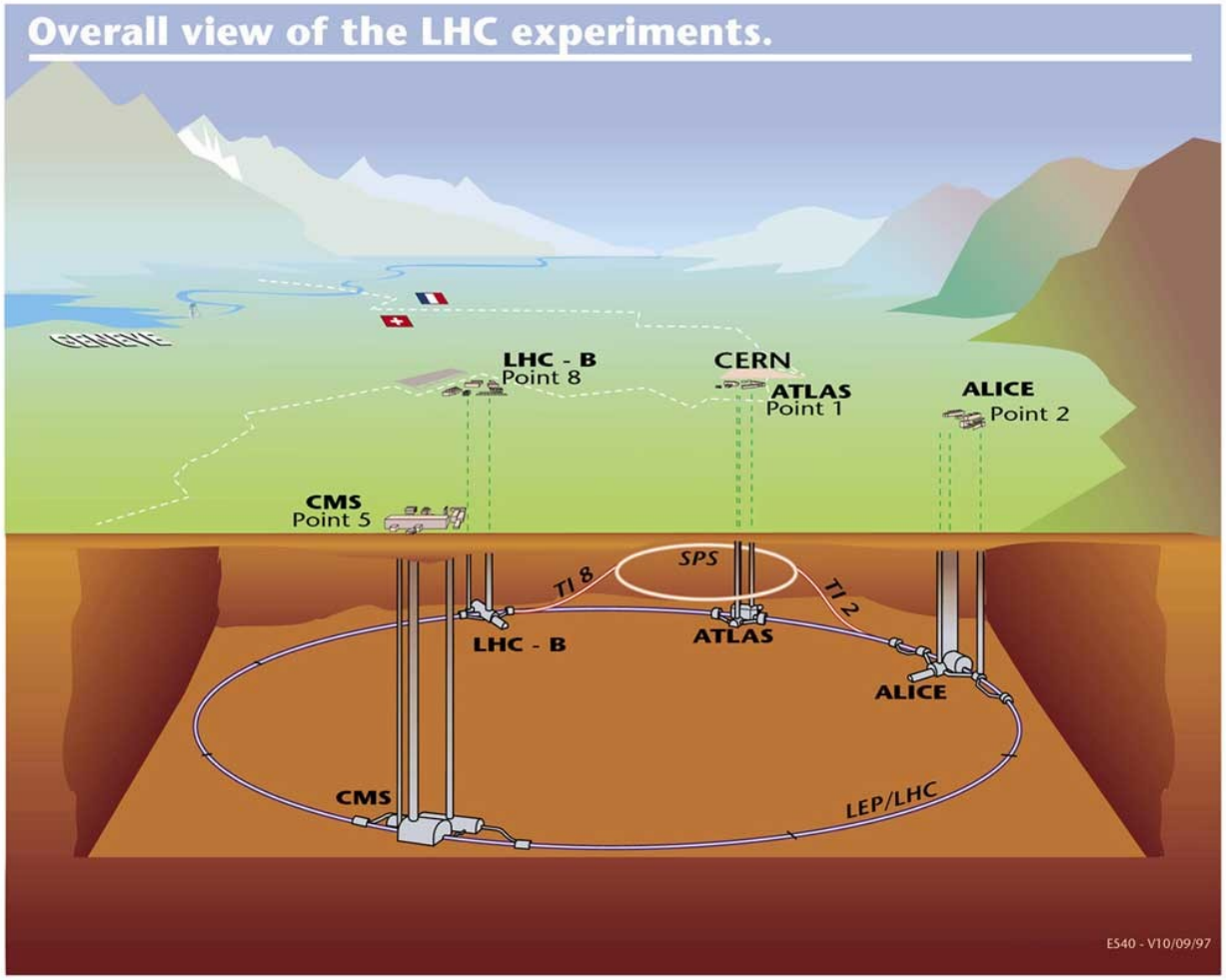


Outline

- Description of ATLAS Experiment
- Outline of Supersymmetry
- Motivation for Electroweak SUSY Searches
- Previous 8 TeV Results
- Nature of Compressed Spectra
- Using the Initial State Radiation (ISR) as a Probe into Compressed Scenarios
- 8 TeV Compressed Spectra Results
- Looking Into the Future
- Summary & Outlook

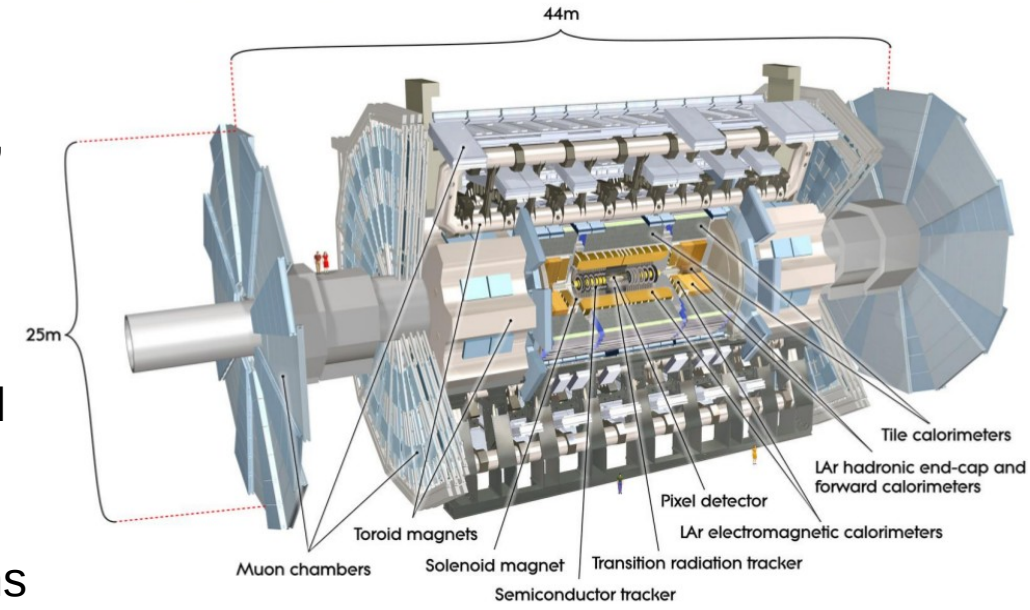
The Large Hadron Collider (LHC)

- **Large** scale **particle accelerator** and **collider** 50-150m beneath Franco-Swiss border.
- Collides **protons** (and sometimes heavy ions) in a large underground ring **27km** in circumference.
- Has seven **detector** experiments including four **large** detector experiments:
  - **ATLAS**
  - **CMS**
  - **LHCb**
  - **ALICE**
- Smaller more specialised experiments:
  - **TOTEM**
  - **MoEdal**
  - **LHCf**



The ATLAS Experiment

- Large **general purpose detector** on the Large Hadron Collider (LHC) ring.
- Designed to **reconstruct** electrons, muons, photons and hadronic jets from pp collisions at LHC.
- Optimized for **Higgs boson** discovery potential and **Beyond-the-Standard Model** (BSM) physics.
- Comprised of several **sub-detector** systems



ID

Inner Detector: High granularity, consists of Silicon microstrip detector, pixel detector and transition radiation tracker

ECAL

Electromagnetic Calorimeter: contains EM showers. Uses alternate layers of lead absorber plates and liquid Argon (LAr) detector

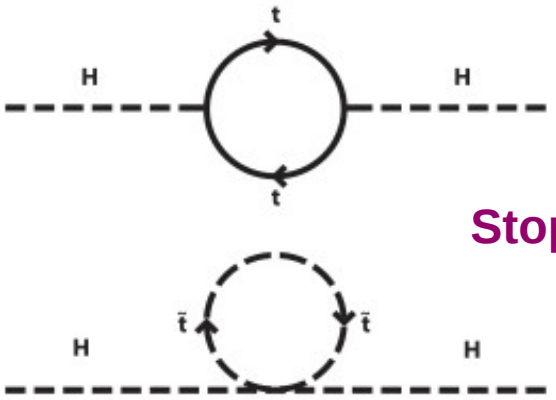
HCAL

Hadronic Calorimeter: Contains hadronic showers. Uses alternate layers of iron absorber plates, LAr and scintillating tile technologies

MS

Muon Spectrometer: 4 detector technologies in toroidal B-field. Gives precise measurement of position and momentum of muons

Motivation for Supersymmetry (SUSY)



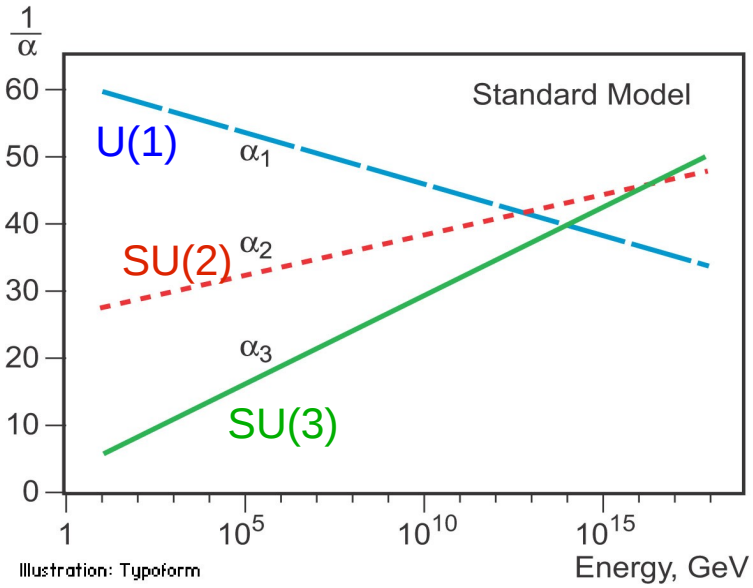
$$\Delta m_H^2 = -\frac{\lambda_f}{8\pi^2}\lambda_V^2 + \ldots\ldots$$

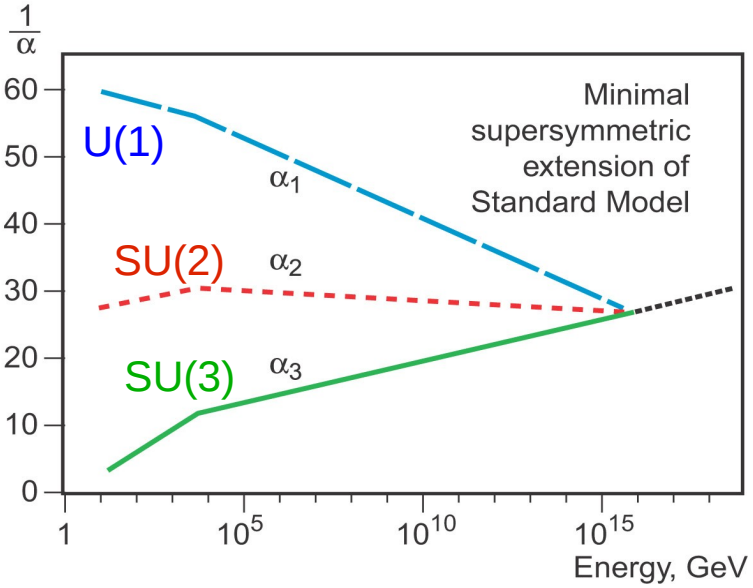
$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2}\lambda_V^2 + \ldots\ldots$$

Hierarchy Problem

- The **Higgs mass squared term** receives corrections for each SM fermion coupling due to additional higher order loops
- Quadratic divergences arise
- m_h >> observed
- **Introduce additional particles** with appropriate couplings to remove divergences

- At **High** energies, couplings of electromagnetic, weak and strong forces **unite** in SUSY models
- SUSY provides a possible **Dark Matter candidate**

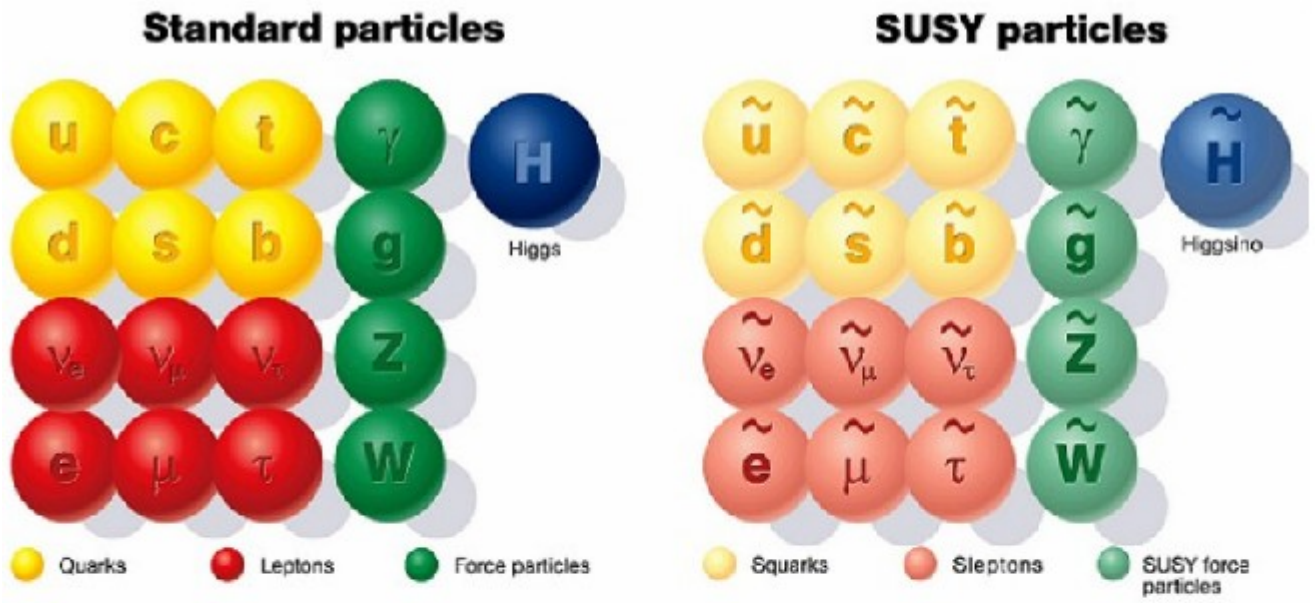




Supersymmetry: At a Glance

What is it?

- Supersymmetry is a **symmetry** that relates fermions to bosons
- **Symmetry algebra** is generated with an operator **Q** that can transform **fermions to bosons** and vice versa
- Each **SM** fermion and boson has a **superpartner** (sparticles), which have **identical** hyper-charge, isospin and colour but differ in **spin** by ½.

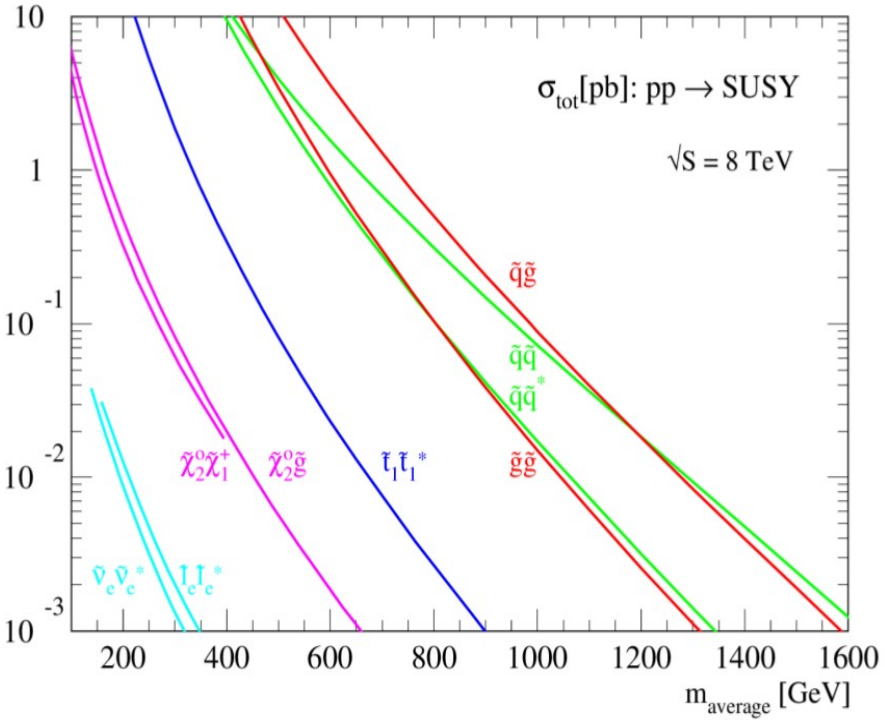


$$\hat{Q}\left|boson\right\rangle = \left|fermion\right\rangle \quad \hat{Q}\left|fermion\right\rangle = \left|boson\right\rangle$$

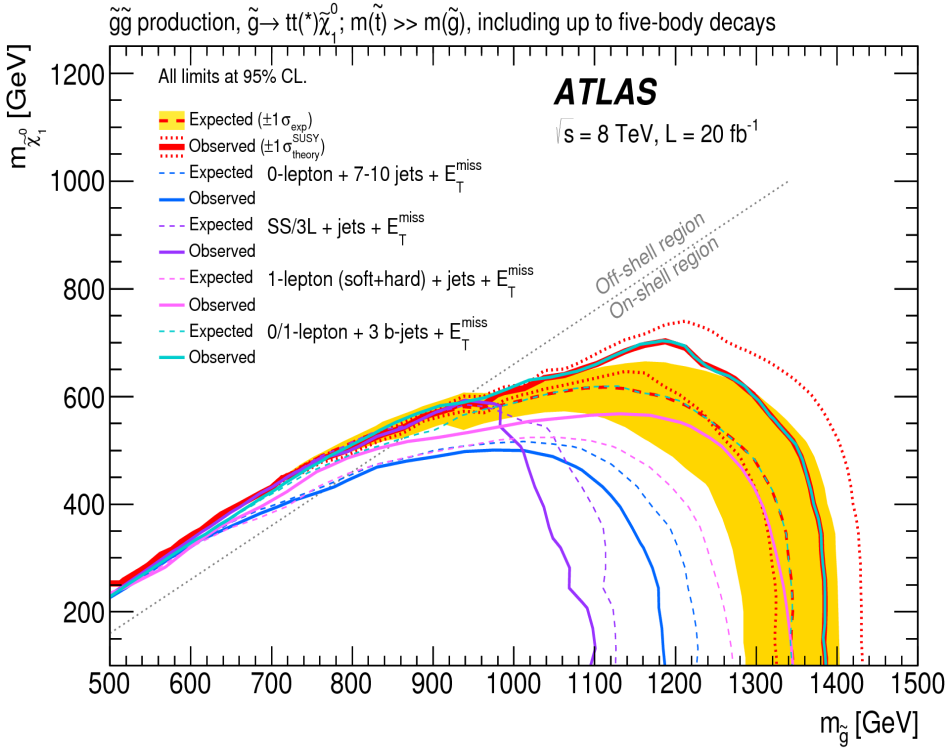
- **No Sparticles** with SM masses **observed**
- Generate **new** mass terms via **spontaneous SUSY symmetry breaking**
- Different possible SUSY breaking mechanisms (not in scope of talk)

Motivation for Electroweak SUSY Searches

arXiv:1412.2784



arXiv:1507.05525

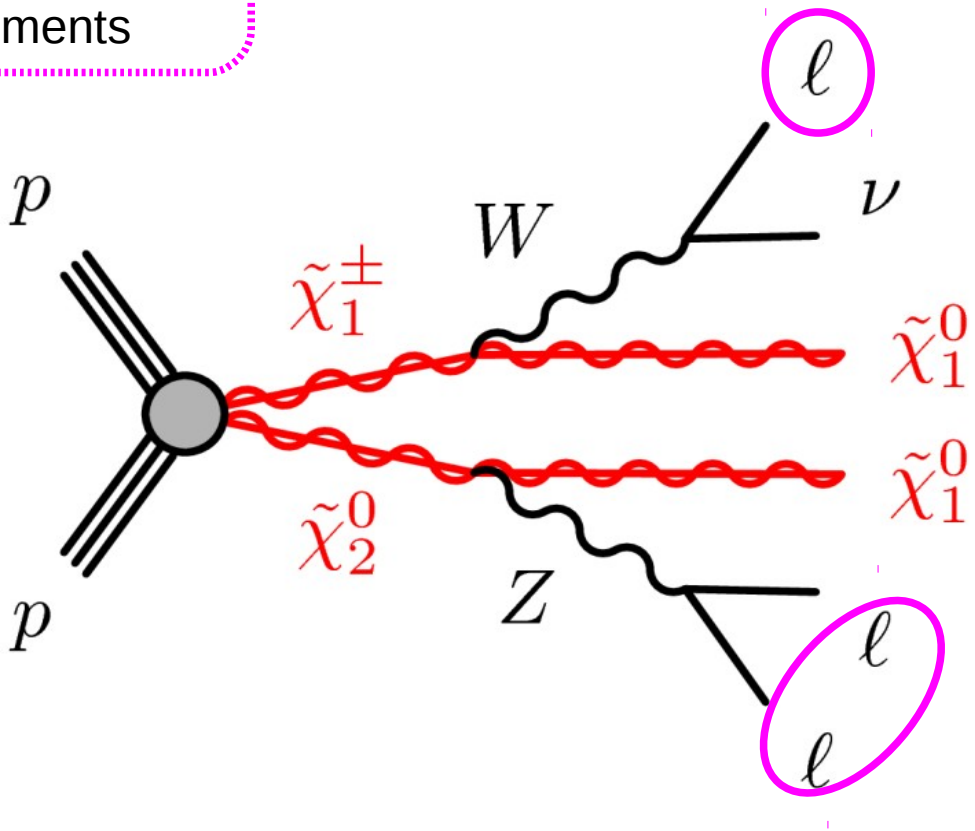


- Why Electroweak SUSY?
  - **Current** LHC limits push **squark/gluino** masses to > **1 TeV**.
  - If **gauginos** and **higgsinos** are **light** then weak production will **dominate**.
  - May lead to signatures with **multiple leptons and E_T^{miss}** - low SM background.

SUSY 3-Lepton Signature

Three isolated, hard leptons.

Use sizeable lepton p_T cuts and tight isolation requirements

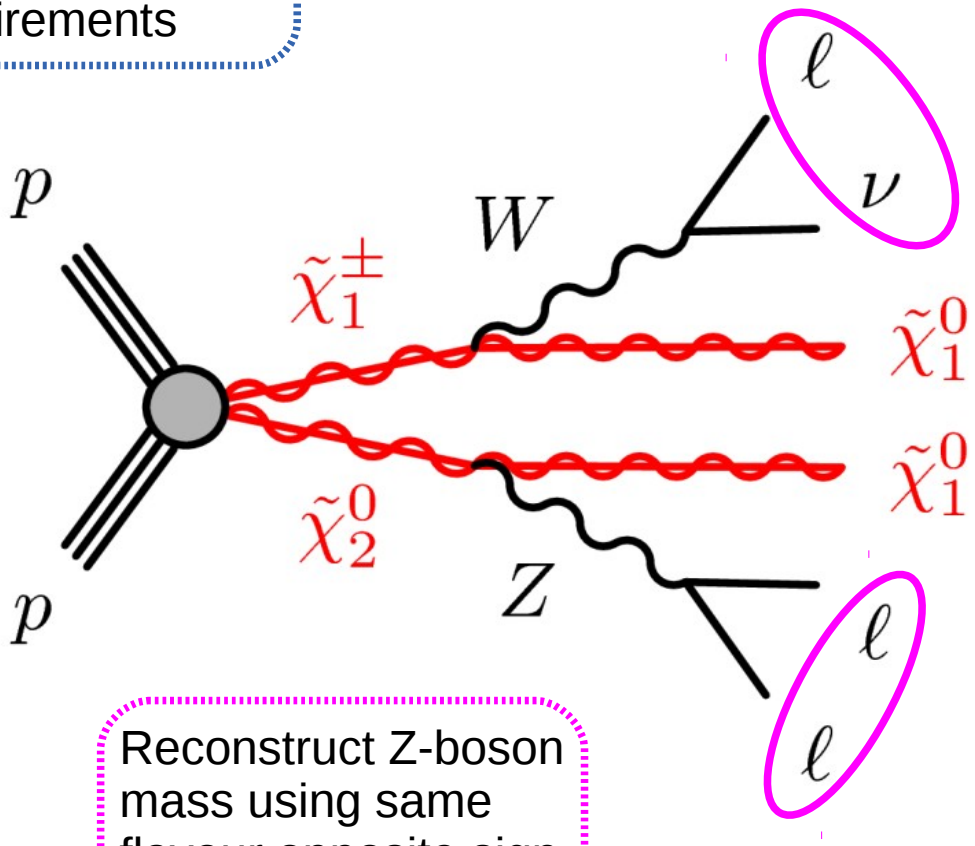


SUSY 3-Lepton Signature

Three isolated, hard leptons.

Use sizeable lepton p_T cuts and tight isolation requirements

For W-boson mass, using transverse mass calculation with lepton not from Z boson decay



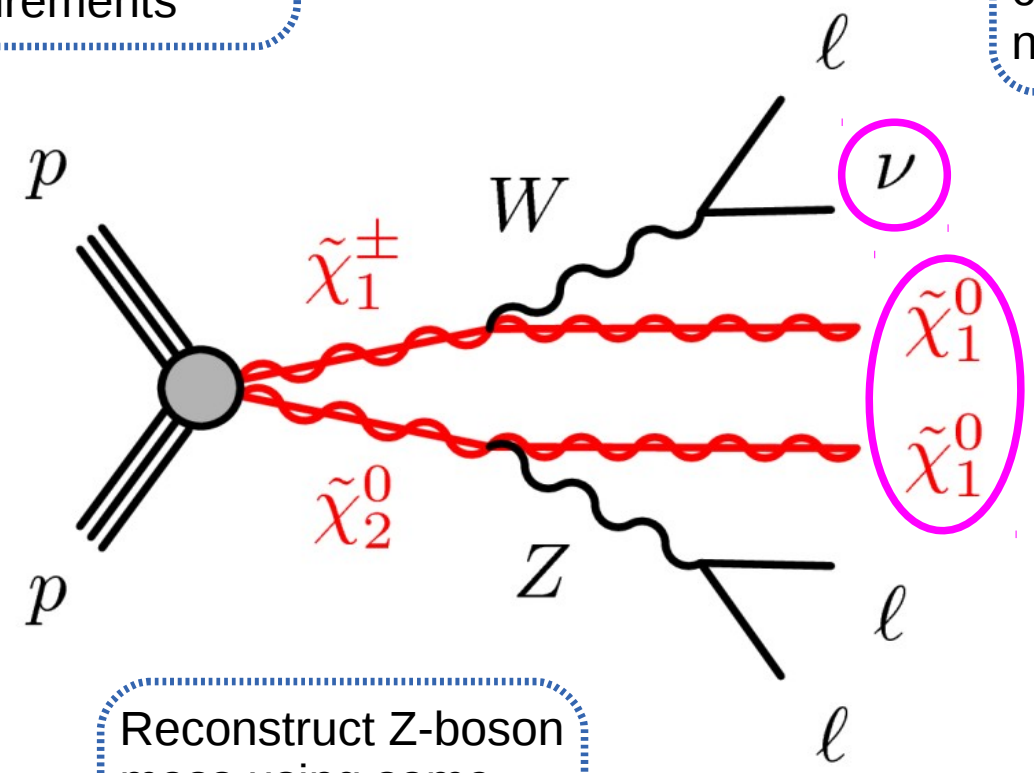
Reconstruct Z-boson mass using same flavour opposite sign lepton pair invariant mass

SUSY 3-Lepton Signature

Three isolated, hard leptons.

Use sizeable lepton p_T cuts and tight isolation requirements

For W-boson mass, using transverse mass calculation with lepton not from Z boson decay

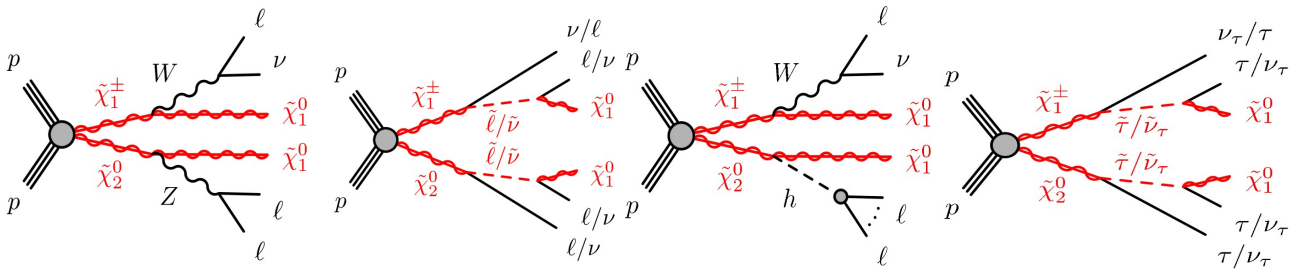


Neutrinos and lightest neutralinos seen as E_T^{miss} in final state.

Target with sizeable E_T^{miss} requirements.

Reconstruct Z-boson mass using same flavour opposite sign lepton pair invariant mass

8 TeV 3L Analyses

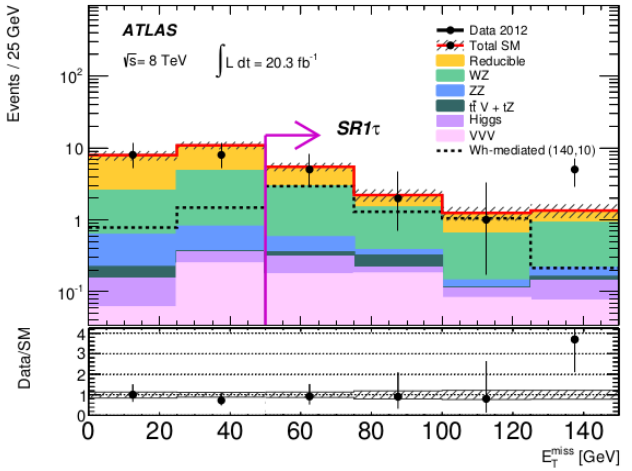


Twenty-five signal regions (SRs) to target four decay scenarios for chargino neutralino production. Regions are **statistically combined** for optimal sensitivity. Background estimated using MC and data-driven methods (**Matrix Method**).

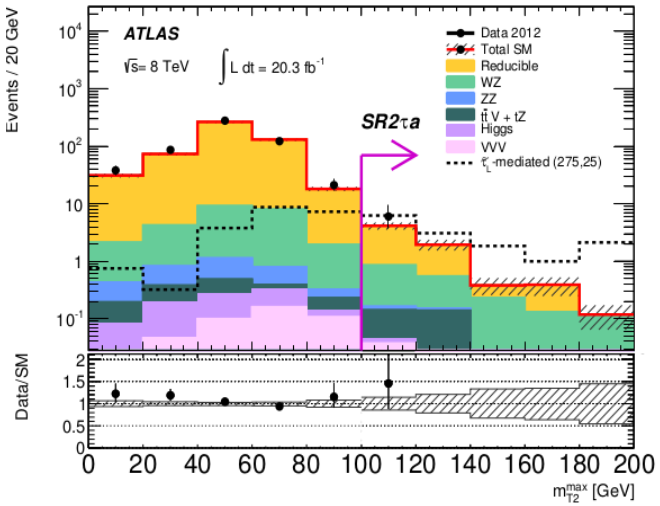
Key Variables

Signal region	SR0τa	SR0τb	SR1τ	SR2τa	SR2τb
Flavour/sign	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	$\ell^\pm\ell^\pm\ell'^\mp$	$\tau^\pm\ell^\mp\ell^\mp$, $\tau^\pm\ell^\mp\ell'^\mp$	$\tau\tau\ell$	$\tau^+\tau^-\ell$
b-tagged jet	veto	veto	veto	veto	veto
$E_{\mathrm{T}}^{\mathrm{miss}}$	binned	>50	>50	>50	>60
Other	m_{SFOS} binned m_{T} binned	$p_{\mathrm{T}}^{3^{\mathrm{rd}}\ell}>20$ $\Delta\phi_{\ell\ell'}^{\mathrm{min}}\leq 1.0$	$p_{\mathrm{T}}^{2^{\mathrm{nd}}\ell}>30$ $\sum p_{\mathrm{T}}^{\ell}>70$ $m_{\ell\tau}<120$ m_{ee} Z veto	$m_{\mathrm{T2}}^{\mathrm{max}}>100$	$\sum p_{\mathrm{T}}^{\tau}>110$ $70<m_{\tau\tau}<120$
Target model	$\tilde{\ell}$,WZ-mediated	Wh-mediated	Wh-mediated	$\tilde{\tau}_L$-mediated	Wh-mediated

JHEP 04 (2014)169

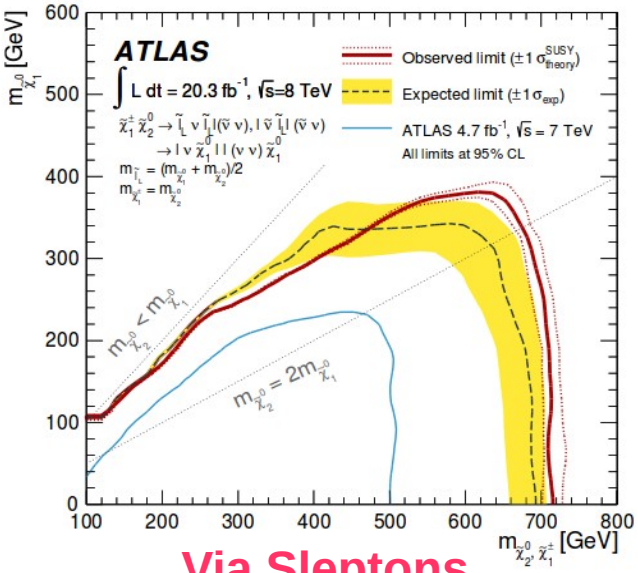


Expected distributions of SM background and observed data for $\mathbf{E_T^{miss}}$ in **SR1τ**

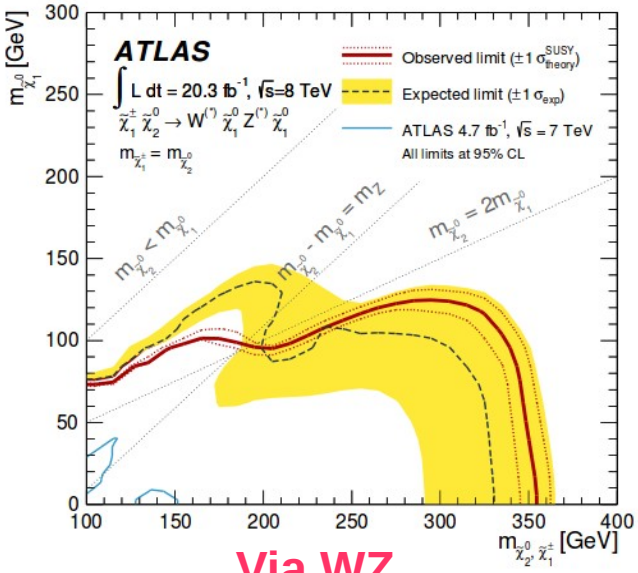


Expected distributions of SM background and observed data for $\mathbf{m_{T2}^{max}}$ in **SR2τa**

8 TeV 3L Limits



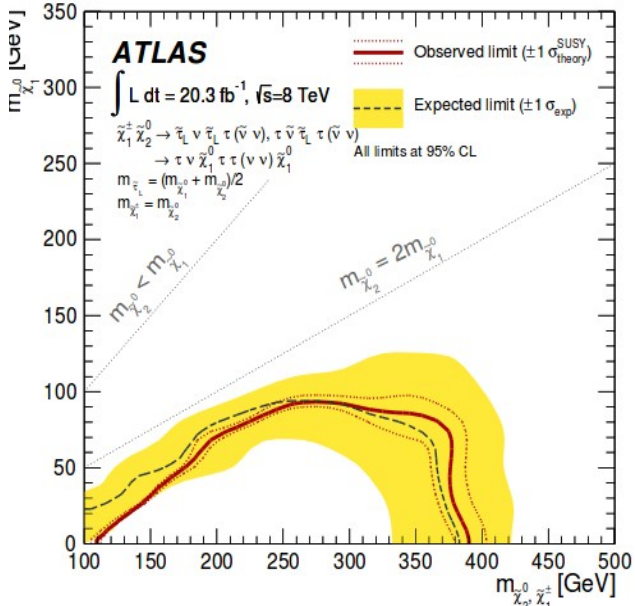
Via Sleptons



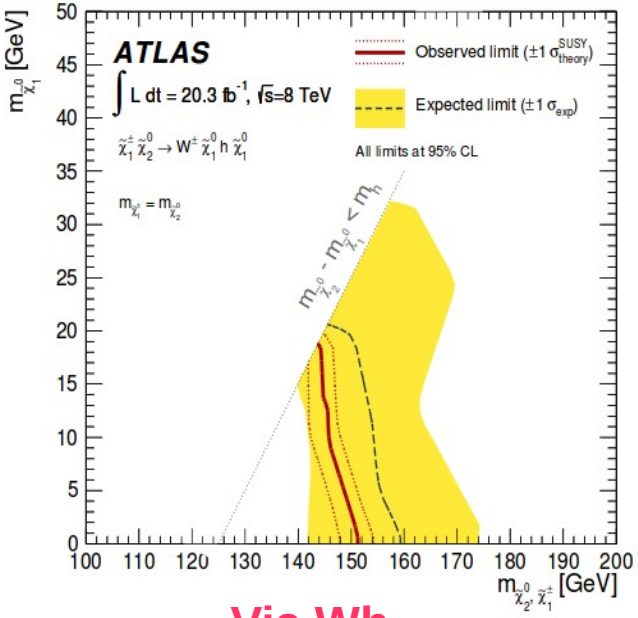
Via WZ

JHEP 04 (2014)169

Observed and expected 95% CL exclusion contours for $\tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^0$ production for:



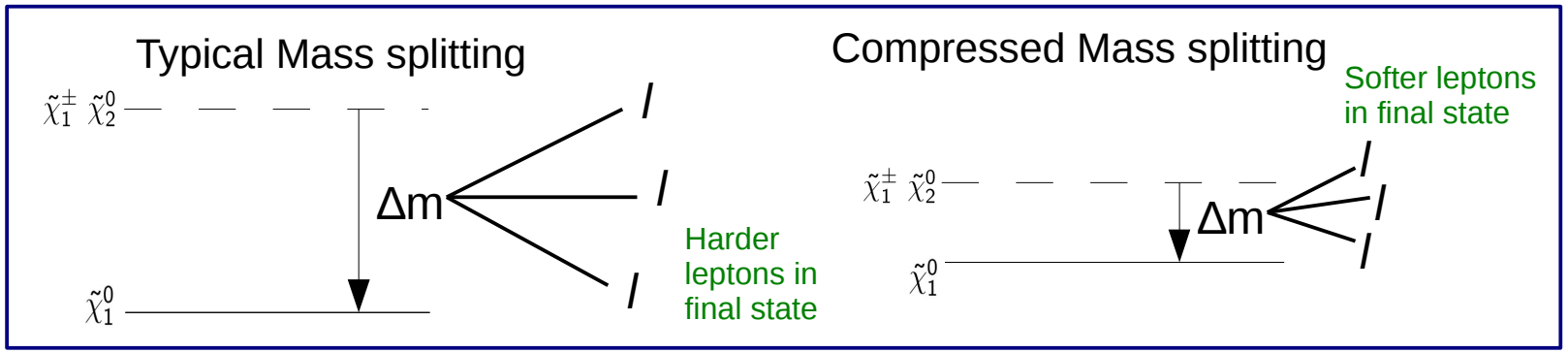
Via left-handed stau



Via Wh

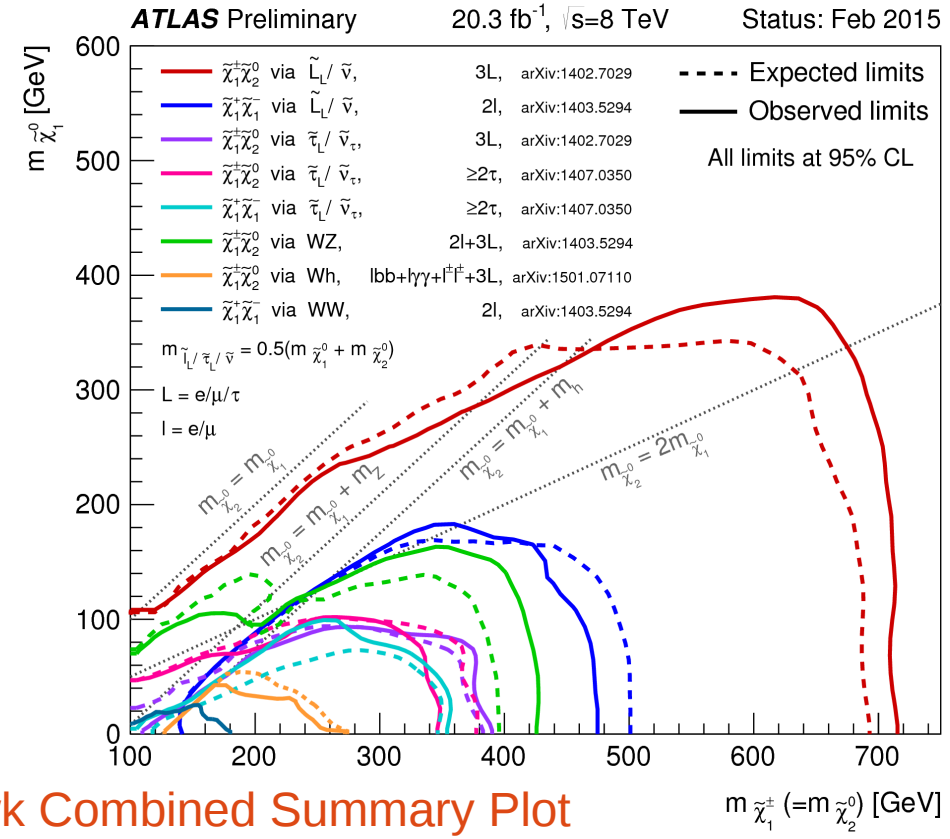
- Via Slepton/WZ: large improvements wrt 7 TeV results (blue lines)
- **NO SUSY YET!!**

Is SUSY hiding in Compressed Spectra?



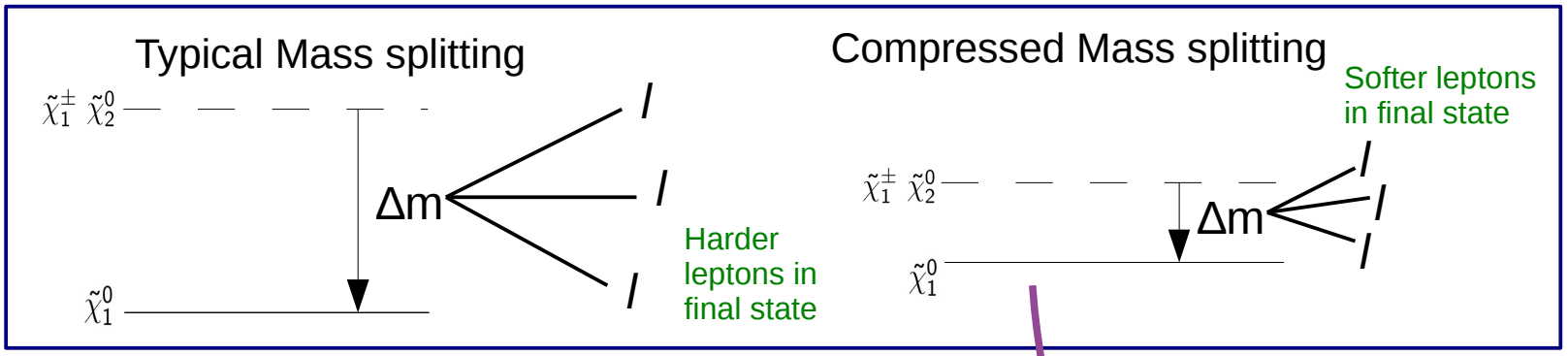
Compressed scenarios are where the mass gap between the $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^0$ is of order **10 – 50 GeV.**

- Leptons are **soft**.
- Experimentally challenging for **triggering**
- Experimentally challenging for **particle reconstruction and identification**.



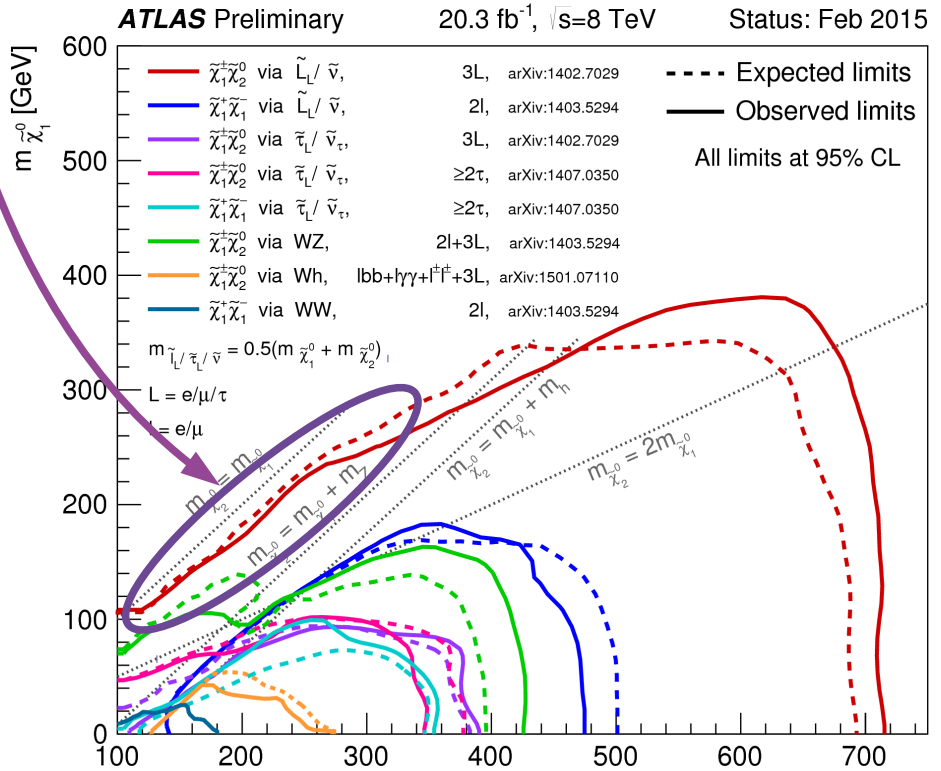
Ewk Combined Summary Plot

Is SUSY hiding in Compressed Spectra?



Compressed scenarios are where the mass gap between the $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^0$ is of order **10 – 50 GeV.**

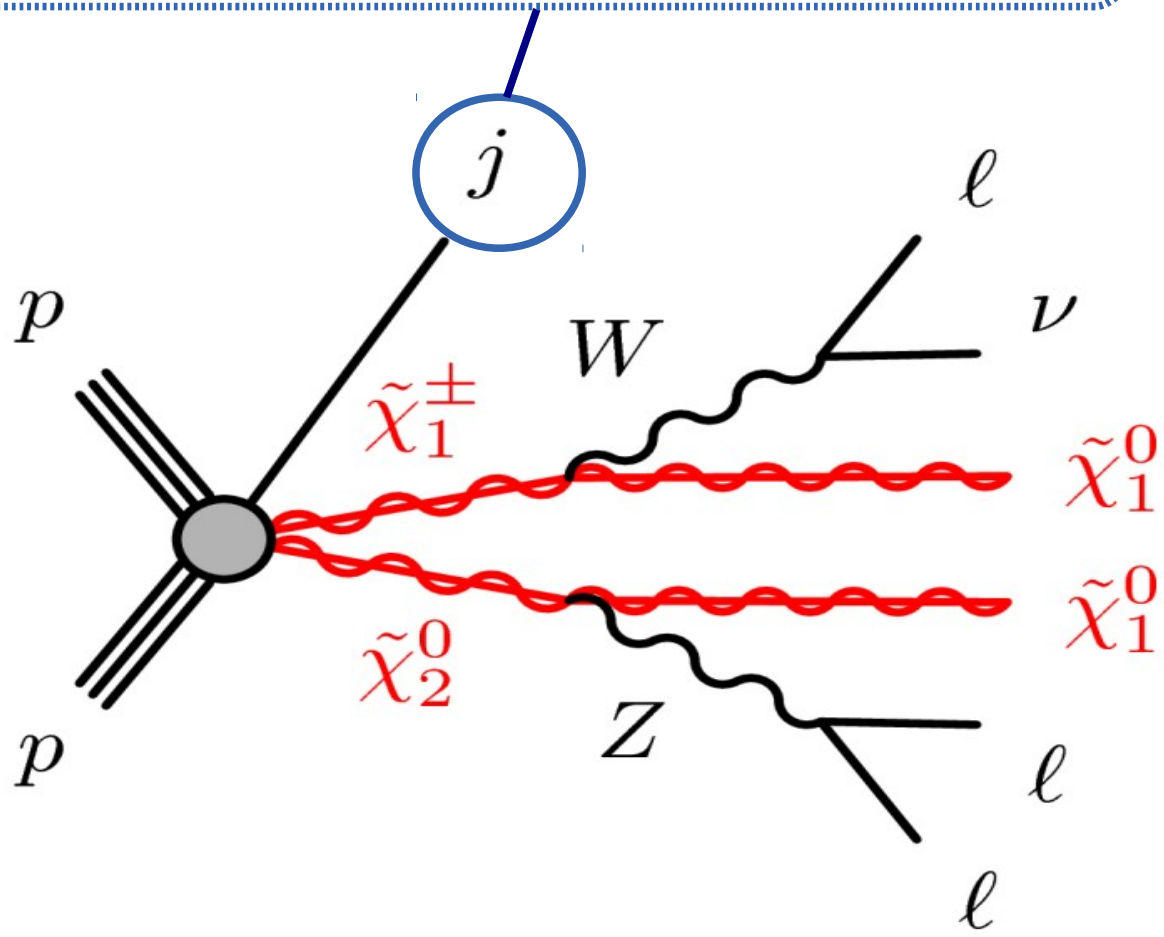
- Leptons are **soft**.
- Experimentally challenging for **triggering**
- Experimentally challenging for **particle reconstruction and identification**.



Ewk Combined Summary Plot

Probing Compressed Masses with an ISR jet

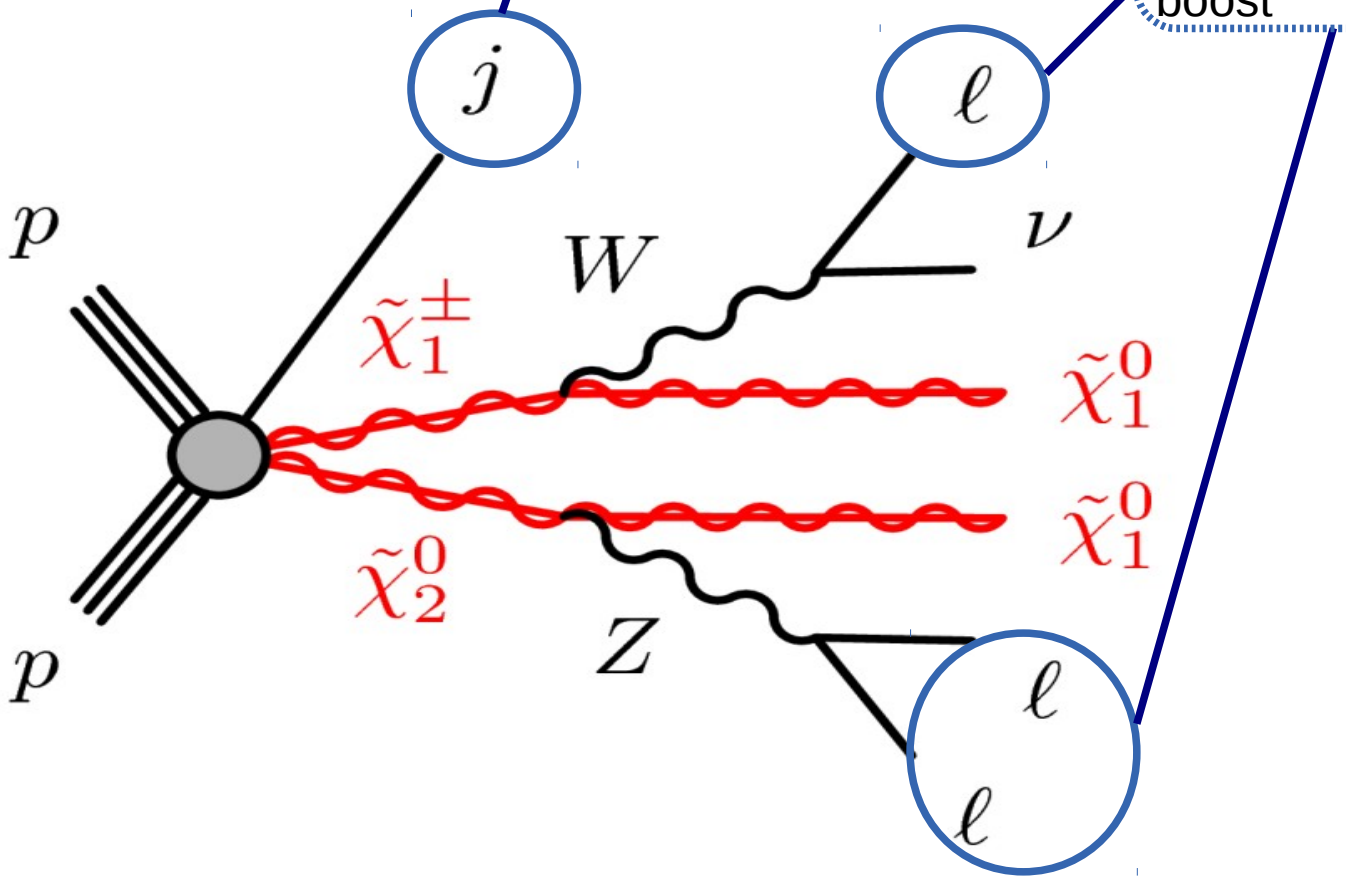
To improve the search sensitivity to **small mass gap** regions can utilize a **hard initial state radiation** (ISR). **Explored combined** lepton+jet+E_T^{miss} to trigger on ISR.



Probing Compressed Masses with an ISR jet

To improve the search sensitivity to **small mass gap** regions can utilize a **hard initial state radiation** (ISR). **Explored combined** lepton+jet+E_T^{miss} to trigger on ISR.

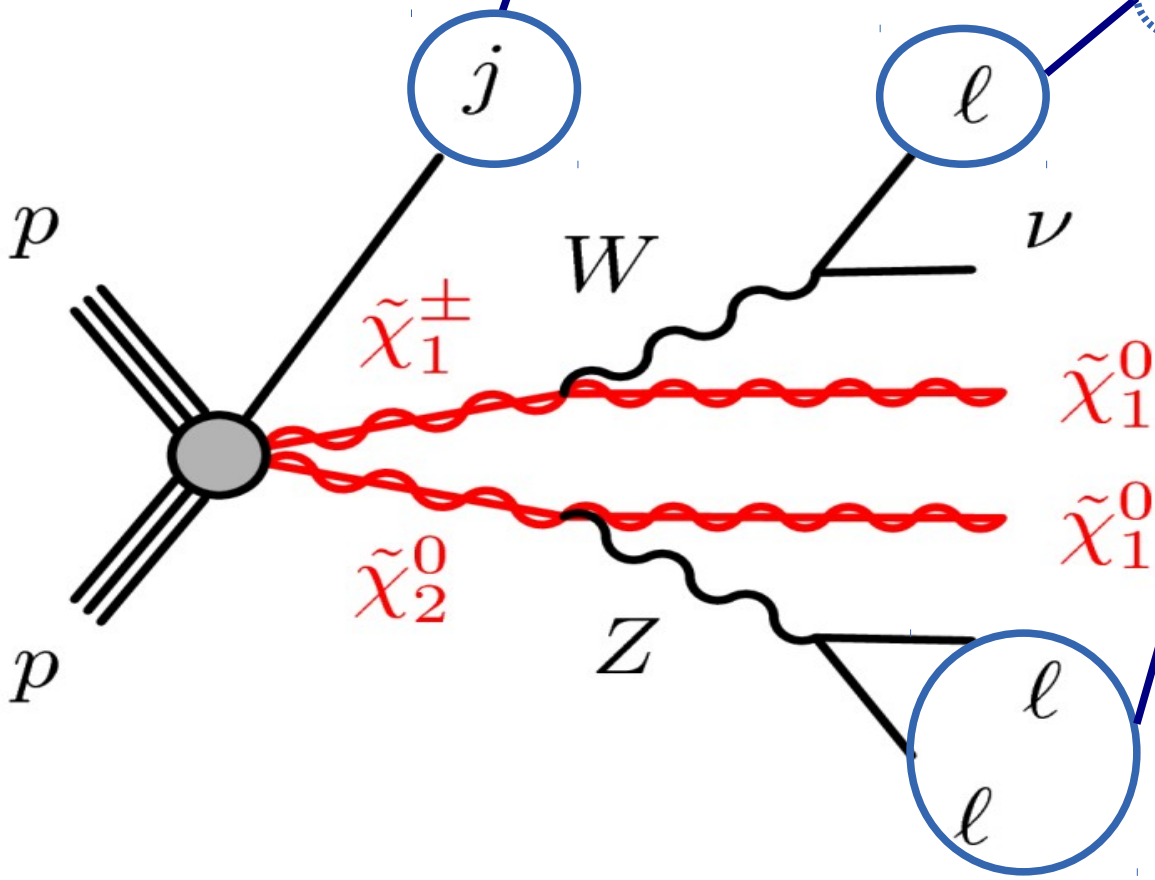
Recoiling ISR jet **boosts** final state particles, leptons remain relatively soft under boost



Probing Compressed Masses with an ISR jet

To improve the search sensitivity to **small mass gap** regions can utilize a **hard initial state radiation** (ISR). **Explored combined** lepton+jet+E_T^{miss} to trigger on ISR.

Recoiling ISR jet **boosts** final state particles, leptons remain relatively soft under boost



Using **ISR** allows soft lepton final states to be explored.
Used **Multilepton** triggers with **lower** pt thresholds

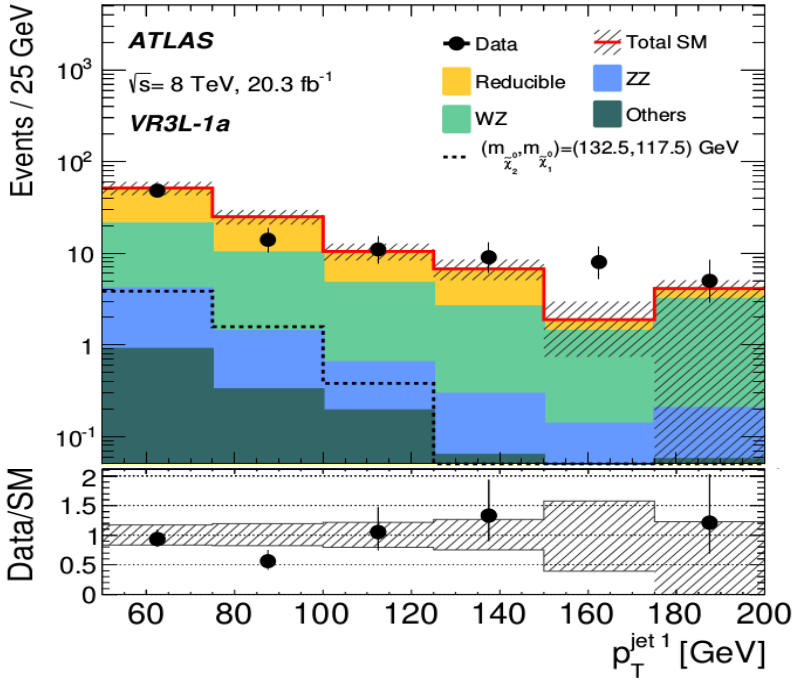
Background Estimation

Two main categories of background:

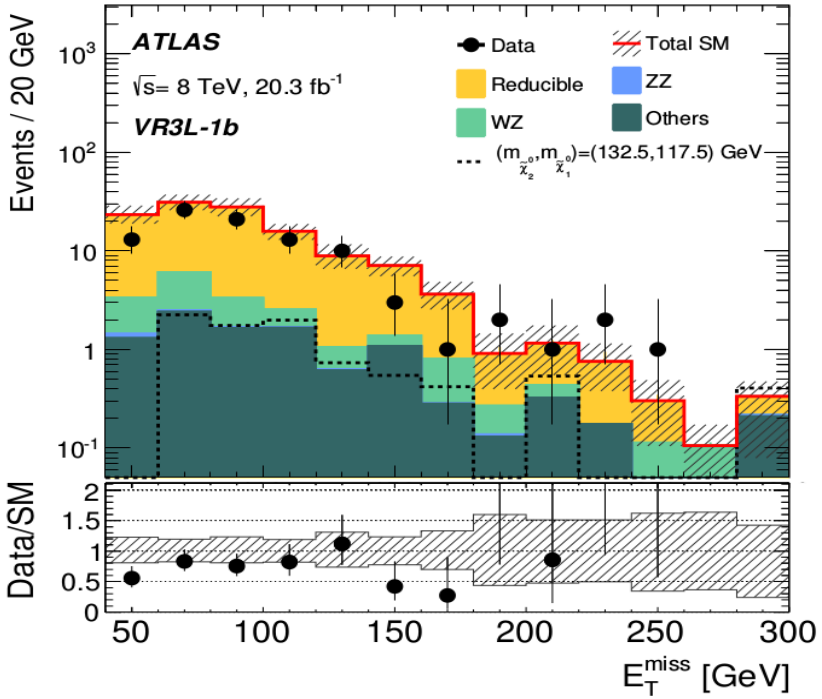
- **Reducible**: 1 or more **fake** light lepton/tau. Estimated with **data-driven Matrix Method**.
- **Irreducible**: Three leptons are all **real** and **prompt** in final state.
  - **Dominant** sources normalised to data in **Control Regions**.
  - **Sub-dominant** sources are simulated with **MC**.

arXiv:1509.07152

Submitted to PRD



VR3L-1a: ISR Validation region targeting low E_T^{miss} b-depleted backgrounds



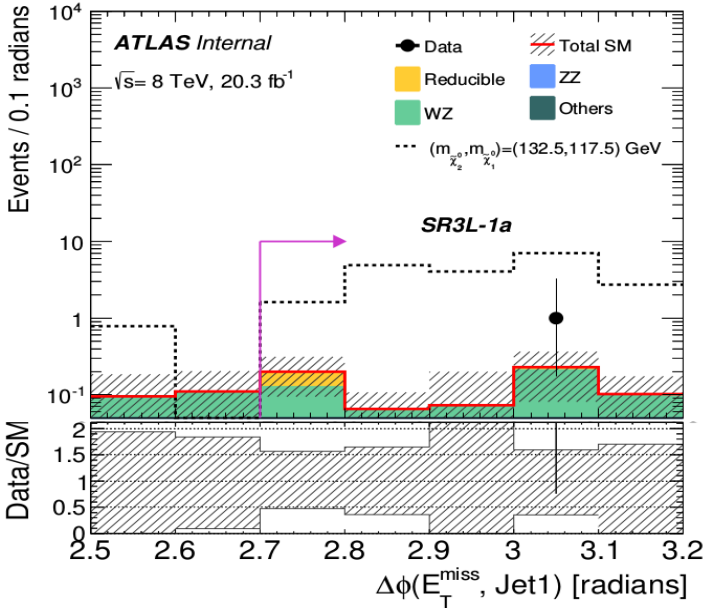
VR3L-1b: ISR Validation region targeting b-enriched backgrounds

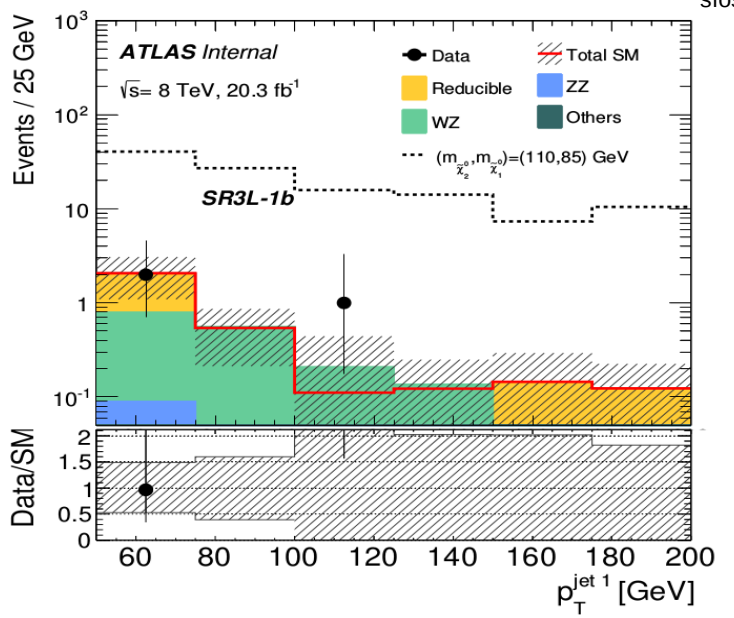
Validation regions
Test background modelling against data
Orthogonal to signal regions

ISR Signal Regions

	Common			
ℓ flavor/sign	$\ell^{\pm}\ell^{\mp}\ell$, $\ell^{\pm}\ell^{\mp}\ell'$			
$p_{\mathrm{T}}^{\mathrm{lep\,1}}$	< 30 GeV			
b-jet	veto			
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 50 GeV			
m_{SFOS}	veto 8.4–10.4 GeV			
SR	SR3ℓ-0a	SR3ℓ-0b	SR3ℓ-1a	SR3ℓ-1b
Central jets	no jets $p_{\mathrm{T}} > 50$ GeV		≥ 1 jet $p_{\mathrm{T}} > 50$ GeV	
$m_{\mathrm{SFOS}}^{\mathrm{min}}$	4–15 GeV	15–25 GeV	5–15 GeV	15–25 GeV
Other	$30 < m_{\ell\ell\ell} < 60$ GeV, $m_{\mathrm{T}} < 20$ GeV	$30 < m_{\ell\ell\ell} < 60$ GeV	$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet\,1}) > 2.7$ rad, $p_{\mathrm{T}}^{\mathrm{lep\,1}}/p_{\mathrm{T}}^{\mathrm{jet\,1}} < 0.2$	$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, 3\ell) > 0.7\pi$ rad

- Recoil from ISR jet boosts low p_T electrons to meet selection requirements
- Bin in m_{sfos}^{min} to target soft leptons
- SR3l-1a targets the smallest $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_2^0$ - $\tilde{\chi}_1^0$ mass splittings, selecting events with $5 < m_{sfos}^{min} < 15$ GeV
- SR3l-1b targets slightly larger mass splittings, selecting events with $15 < m_{sfos}^{min} < 25$ GeV





Topology of events containing ISR jets can be used to discriminate against SM background

arXiv:1509.07152

Submitted to PRD

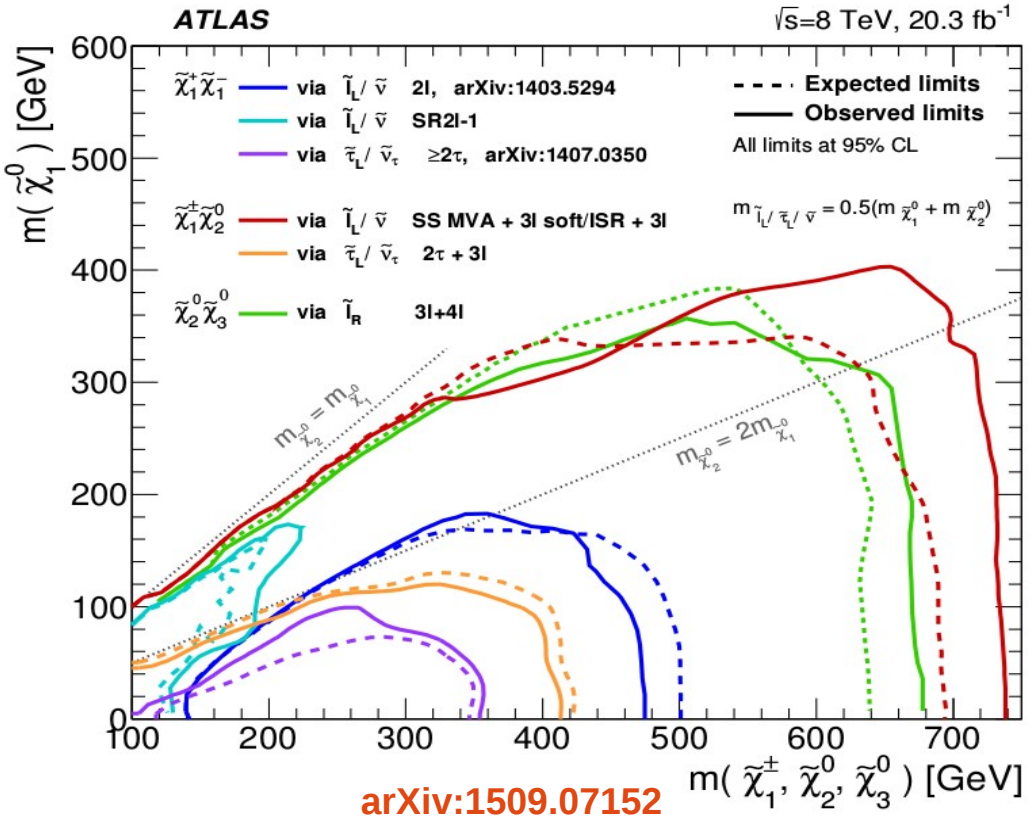
$\Delta\Phi(E_T^{miss}, jet_1)$ in SR3l-1a and p_T^{jet1} in SR3l-1b.

ISR Signal Region Yields and Limits

	SR3ℓ-0a	SR3ℓ-0b	SR3ℓ-1a	SR3ℓ-1b
WZ	$0.59^{+0.47}_{-0.32}$	$5.0^{+1.5}_{-1.2}$	$0.54^{+0.20}_{-0.19}$	1.6 ± 0.4
ZZ	$0.23^{+0.09}_{-0.07}$	0.66 ± 0.16	0.024 ± 0.013	$0.10^{+0.05}_{-0.04}$
Reducible	$2.8^{+1.5}_{-2.2}$	$9.7^{+3.1}_{-3.6}$	0.09 ± 0.08	$1.4^{+1.0}_{-1.1}$
Others	$0.0033^{+0.0036}_{-0.0033}$	0.07 ± 0.05	0.013 ± 0.010	0.038 ± 0.021
Total SM	$3.7^{+1.6}_{-2.2}$	$15.4^{+3.5}_{-3.9}$	$0.67^{+0.22}_{-0.21}$	$3.1^{+1.1}_{-1.2}$
Data	4	15	1	3

- Observed and expected limits for direct slepton production **in red.**
- The limits for $\tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^0$ production and decay via SM Gauge bosons are not shown as compressed spectra signal regions have small sensitivity to these scenarios and did not improve significantly on published limits
- Pushed observed limits to 720 GeV for massless $\tilde{\chi}_1^0$ and improved sensitivity along the diagonal.

- Yields show no excesses beyond standard model expectations
- Limits are calculated by combining all 3L disjoint regions
- For overlapping signal regions, the best expected exclusion region is used

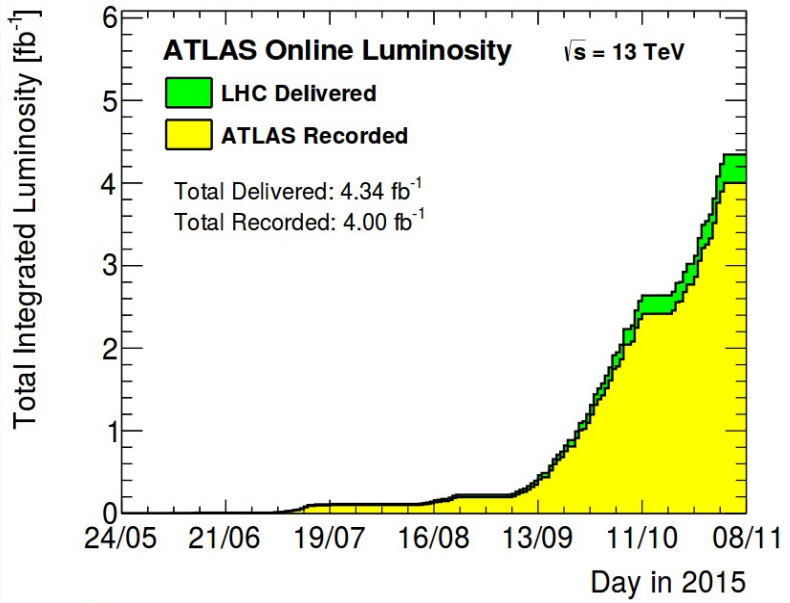


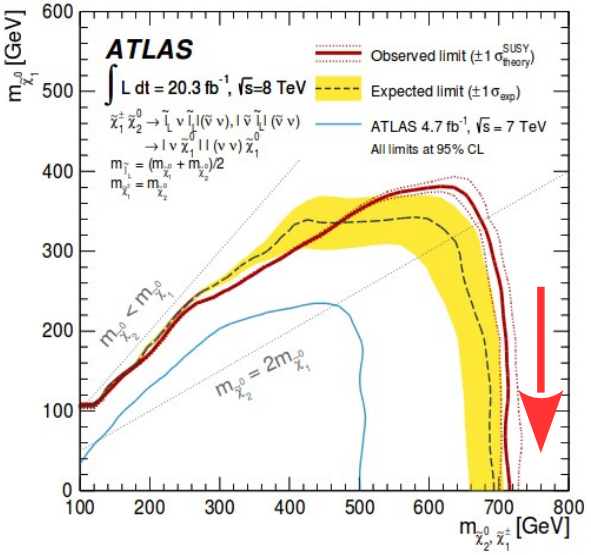
arXiv:1509.07152

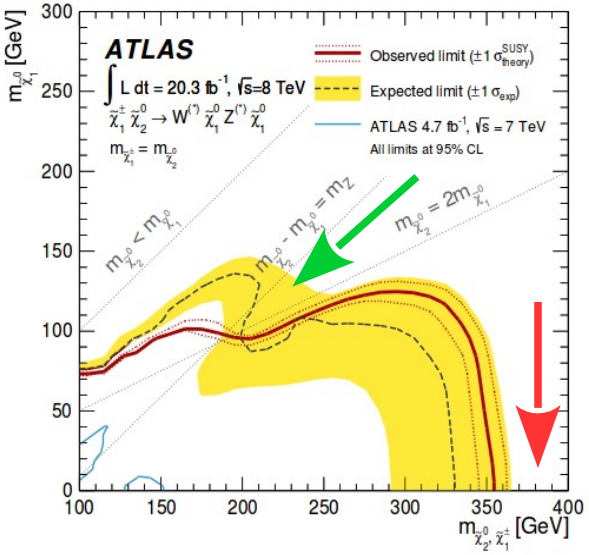
Submitted to PRD

Plans for Run-2

- 4.0 fb^{-1} of *pp* collisions recorded at $\sqrt{s}$ = 13 TeV
- Will include 2016 data for Run2 analysis
- Improving on Run1 strategy, two pronged approach targeting intermediate and high mass C1N2,N1 regions
- Compressed spectra investigation to follow later

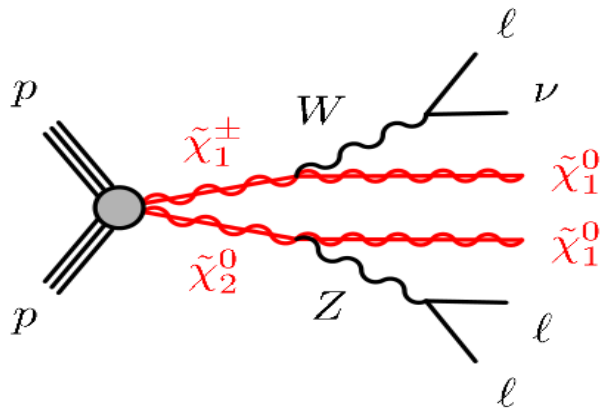




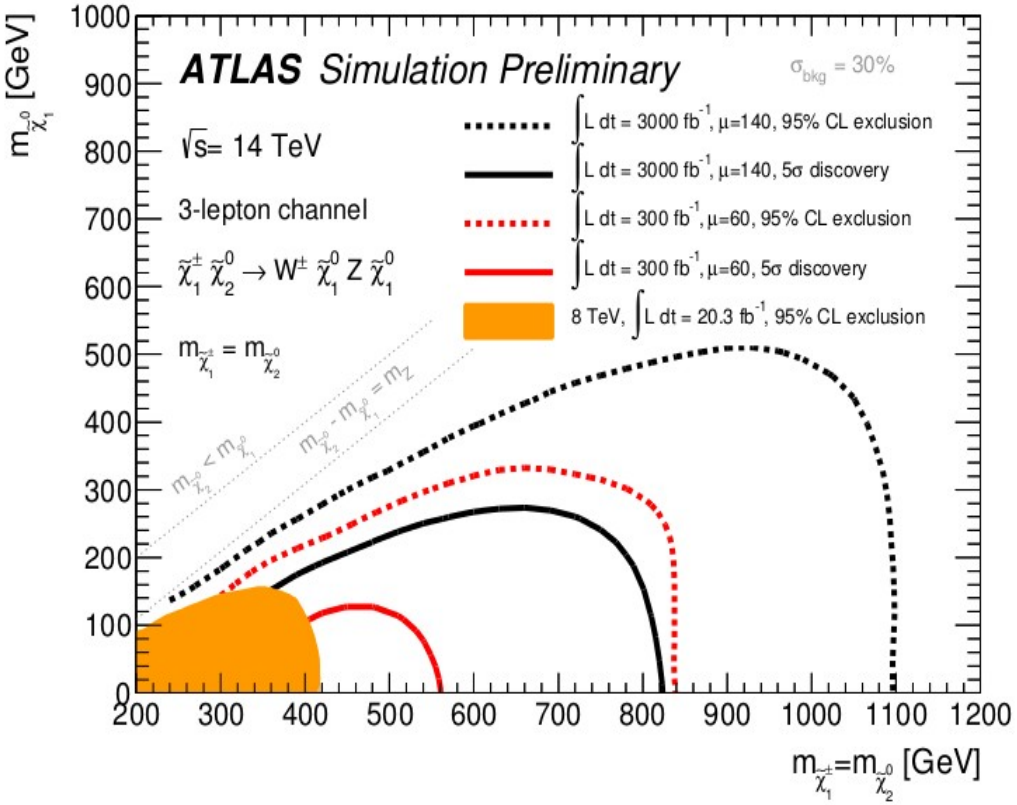


Intermediate, **high** mass regions

3L Searches for SUSY at High Luminosity LHC



In addition to compressed spectra, sensitivity to electroweak SUSY 3L signatures explored under high luminosity LHC (HL-LHC) conditions.



Upgrade scenarios at √s = 14 TeV:
300 fb^{-1} and <μ> ~ **60** (LHC)
3000 fb^{-1} and <μ> ~ **140** (HL-LHC)
Reoptimisation of **3L** analysis under these conditions

Higher energies and luminosities show possible improvement in sensitivity to electroweak SUSY 3-lepton channel.

ATL-PHYS-PUB-2014-010

Summary & Outlook

- **3-Lepton** final states in **electroweak SUSY** processes are key to **potential** discovery of SUSY.
- Significant region of parameter space previously explored, however not the compressed region.
- Final states with **soft leptons** can be explored with **3 lepton + ISR jet analysis**.
- No **excess** seen above SM **expectations** but significant improvements on existing limits.
- With **Run-2** data and High Luminosity LHC conditions in the future expect greater sensitivity with possibility of **discovery**!

Back-up