Search for Supersymmetry in the three lepton + ETmiss final state

Matthew Gignac
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Supersymmetry

Supersymmetry (SUSY) is an extension of the Standard Model (SM) of particle physics

→ All SM particles get a "super-partner" which differs by 1/2 unit of spin

SM particles				SUSY particles		
Particle	Name	Spin		Sparticle	Name	Spin
q	quarks	1/2		$\tilde{q}$	squarks	0
l	leptons	1/2	$Q, Q^\dagger$	$\tilde{l}$	sleptons	0
$W^\pm,\ W^0$	W-bosons	1	$\Longleftrightarrow$	$\tilde{W}^\pm,\ \tilde{W}^0$	winos	1/2
B	B-boson	1		$\tilde{B}$	bino	1/2
G	gluons	1		$\tilde{G}$	gluinos	1/2
$H_{1,2}$	Higgses	0		$\tilde{H}_{1,2}$	Higgsinos	1/2

"Gauginos" (winos, bino, gluinos)

→ Gauginos and higgsinos mix to form physical mass eigenstates:

- Two charged states called charginos: $\tilde{\chi}_i^\pm$ i=1,2
- Four neutral states called neutralinos: $\tilde{\chi}_j^0$ j=1,2,3,4

→ R-parity (P_R) conserving models →

- SUSY particles are pair produced
- Lightest Supersymmetric particle (LSP) is absolutely stable

SUSY particles: P_R = -1
SM particles: P_R= +1

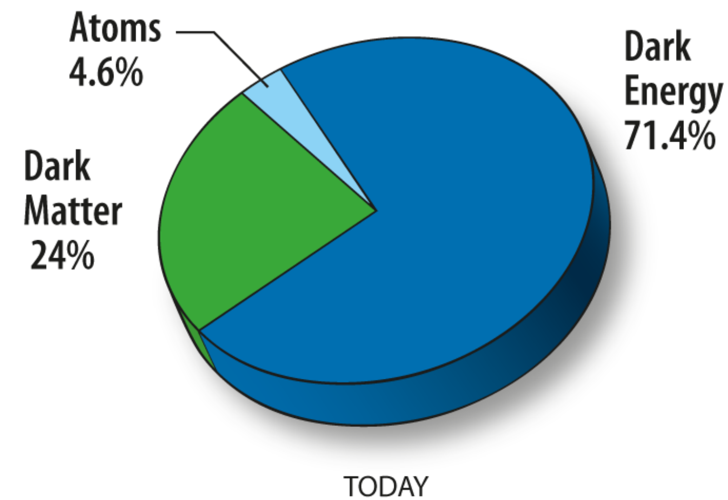
Why search for Supersymmetry?

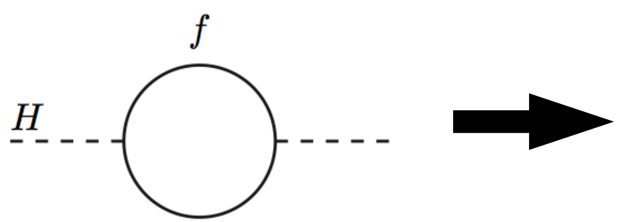
Standard model cannot explain the presence of a "dark matter" in the Universe

- ➔ SUSY can provide a dark matter candidate!

Hierarchy problem of the Standard Model

- ➔ Higgs boson receives massive quantum corrections to its mass
- ➔ SUSY provides cancellations to these large corrections





$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots .$$

Standard model put to rigorous tests in the absence of a signal

- ➔ SUSY searches typically probe the tails of distributions where the most rare Standard model events occur
- ➔ "Yesterday discovery is today's background"

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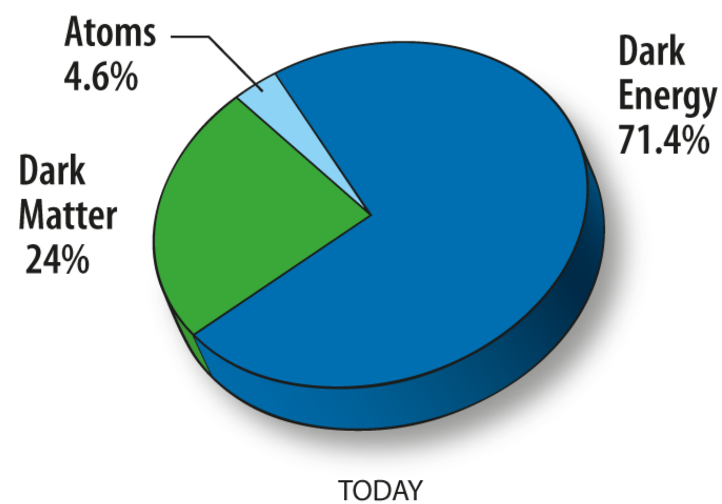

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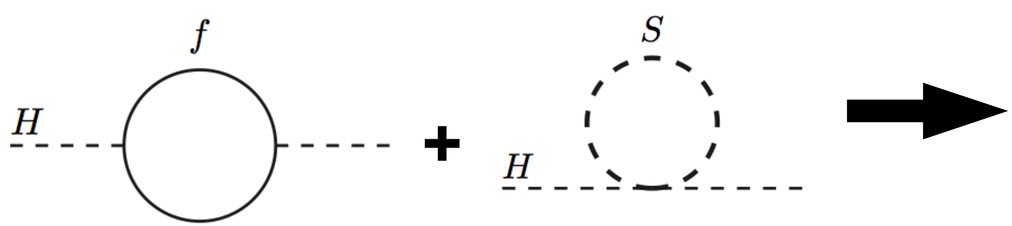


$$\Delta m_H^2 \sim 0$$

Standard model put to rigorous tests in the absence of a signal

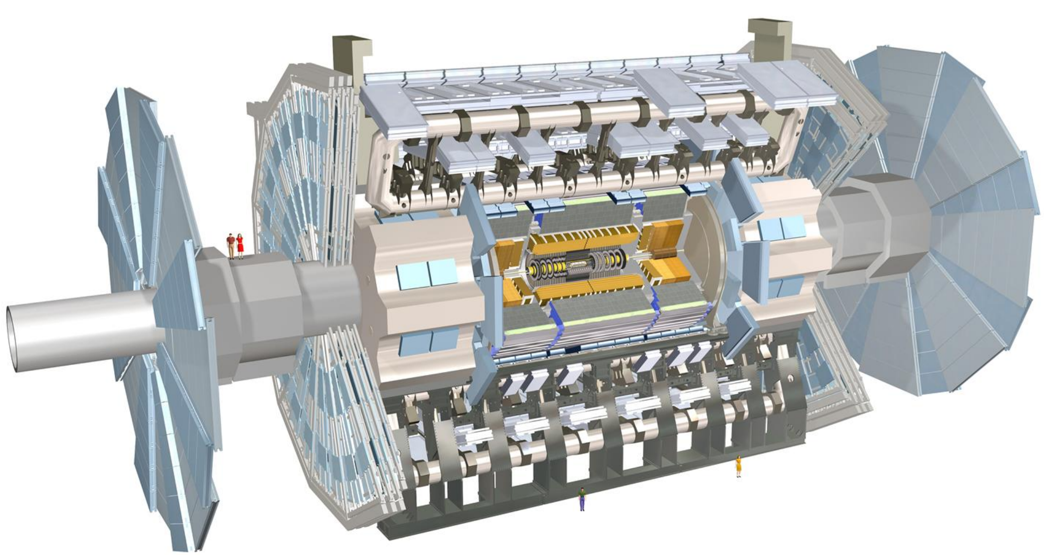
- ➔ SUSY searches typically probe the tails of distributions where the most rare Standard model events occur
- ➔ "Yesterday discovery is today's background"

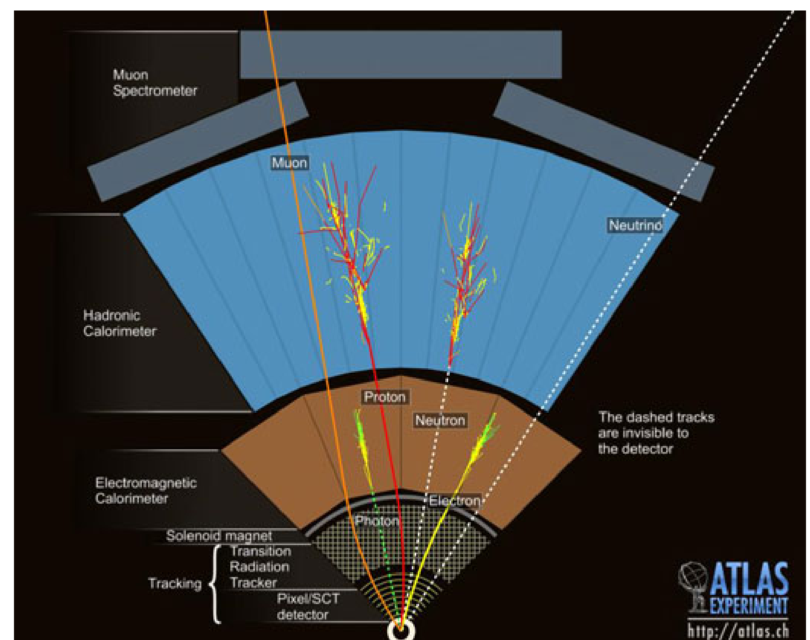
ATLAS Detector

ATLAS is a general purpose physics detector at the LHC

- Electrons and muons reconstructed using information from tracking, calorimeter, and muon systems
- Hadronically decaying taus identified using multi-variate techniques
- b-hadrons give displaced tracks and identified using neutral network algorithms
- Particles which don't interact with the detector contribute to missing transverse momentum

$$E_T^{miss} = -\sum_{i}^{N_{obj}} \vec{p}_T^{\,i}$$



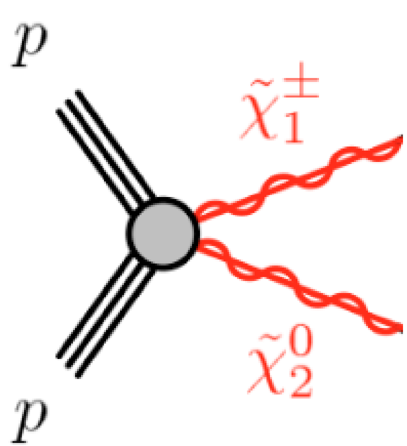


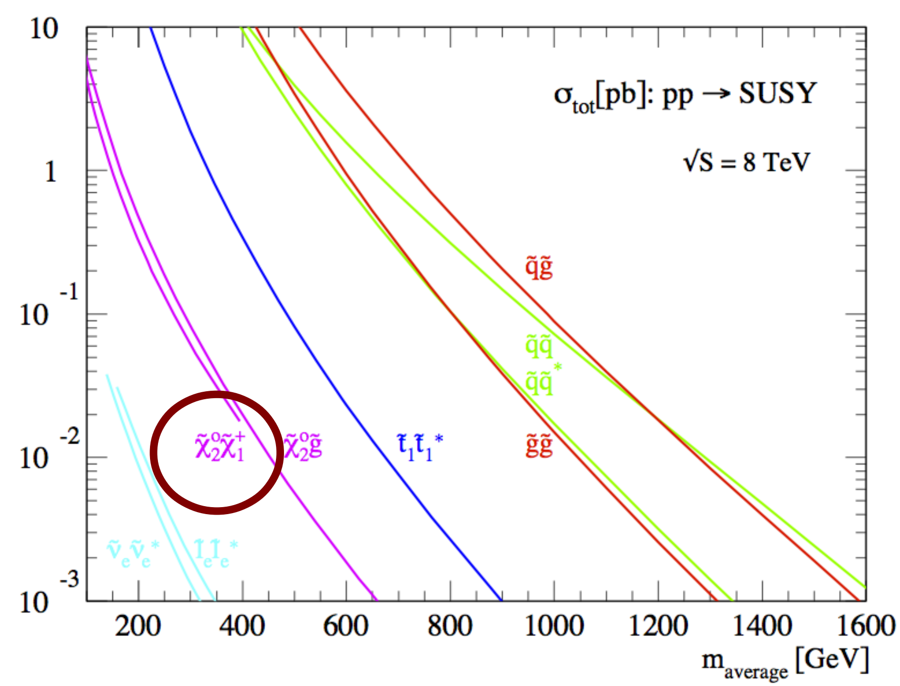
Electroweak SUSY production

Electroweak (EWK) production of charginos and neutralinos attractive signature

- Naturalness requires light higgsinos ⇒ could be accessible at the LHC
- EWK production is dominant if squarks and gluinos are heavy
- Large lepton multiplicity ⇒ clean final state at the LHC
- Full 2012 data set used, corresponding to 20.3 fb^{-1} ⇒ sensitive to rare processes

Direct production of lowest accessible neutralino and chargino mass eigenstates

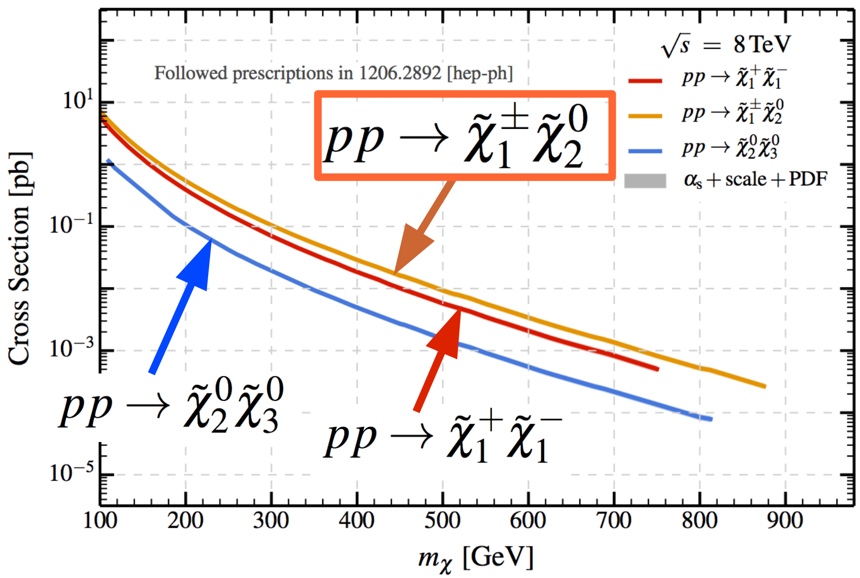


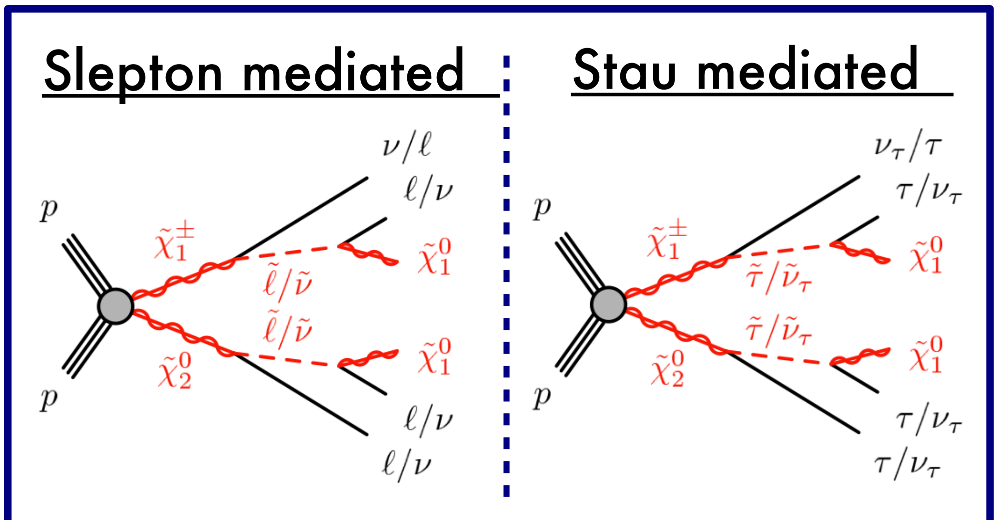


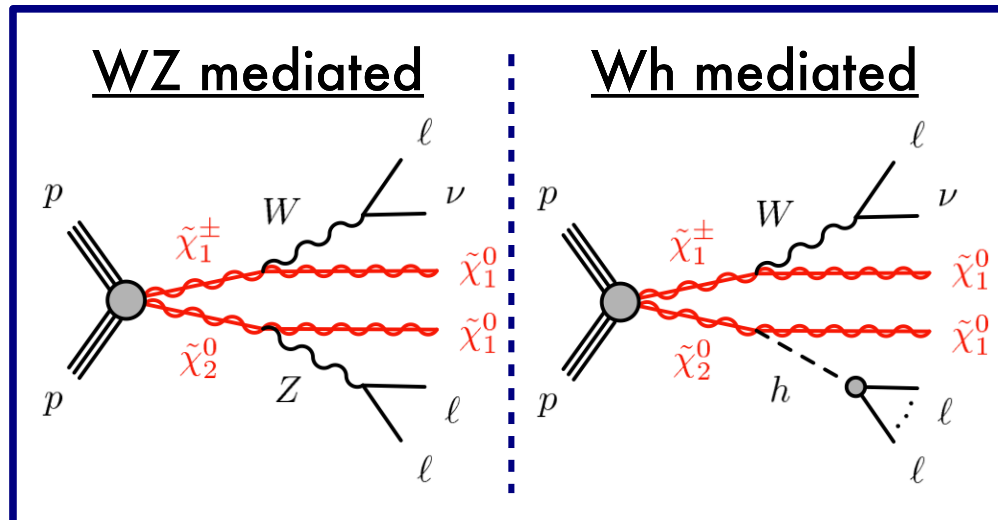
Electroweak SUSY sector

Direct production of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ has the largest production cross section

- ➔ Decay can proceed through sleptons and/or bosons
- ➔ W,Z and h assumed to have Standard Model branching ratios







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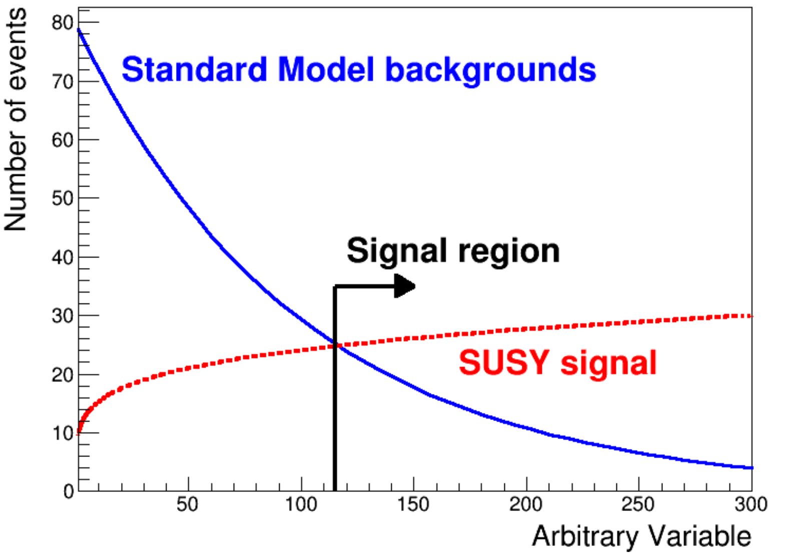
Beyond the Standard Model search strategy

1) Identify regions of the phase space which are statistically sensitive to the observation of SUSY

- ➔ These regions are called 'signal regions'
- ➔ They remain blind for the duration of the analysis



2) Estimate and validate Standard Model backgrounds

- ➔ Monte Carlo simulations and/or data driven techniques are typically used

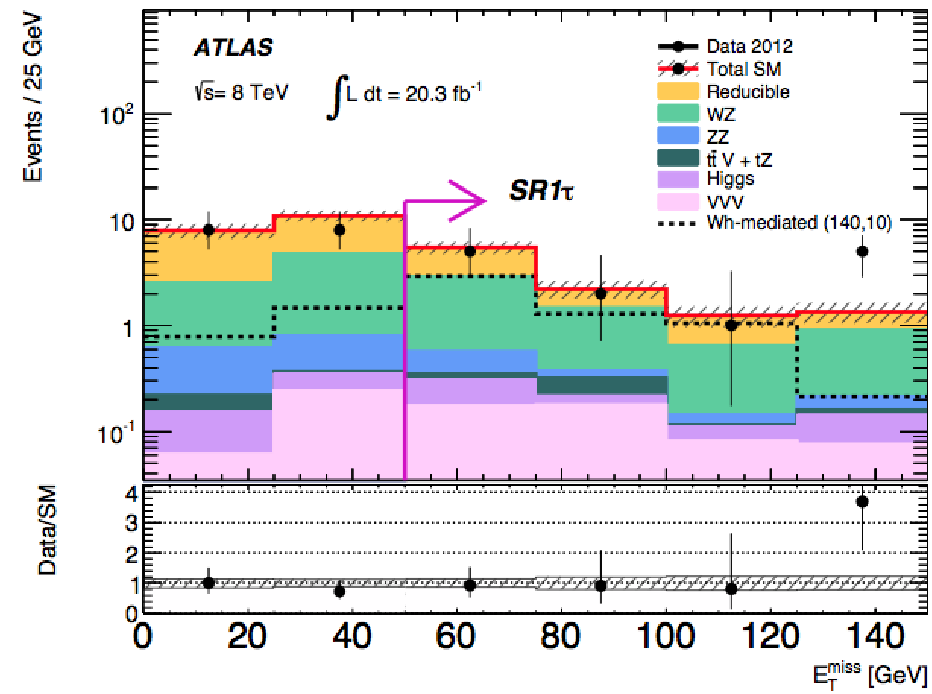
3) Unblind signal regions

- ➔ In the absence of an excess, set limits in particular SUSY models

Signal region selection

Signal regions are classified depending on the tau multiplicity

- ➔ Electron and muon only signal regions binned in:
  - Missing energy
  - Invariant mass of di-leptons
  - Transverse mass of the lepton and missing energy



All signal regions veto b-quarks ⇒ common in dominant background processes

Total of 24 almost statistically independent signal regions

$$m_T = \sqrt{2p_T^{\ell} E_T^{miss}(1 - \cos(\Delta\phi(\ell, E_T^{miss}))}$$

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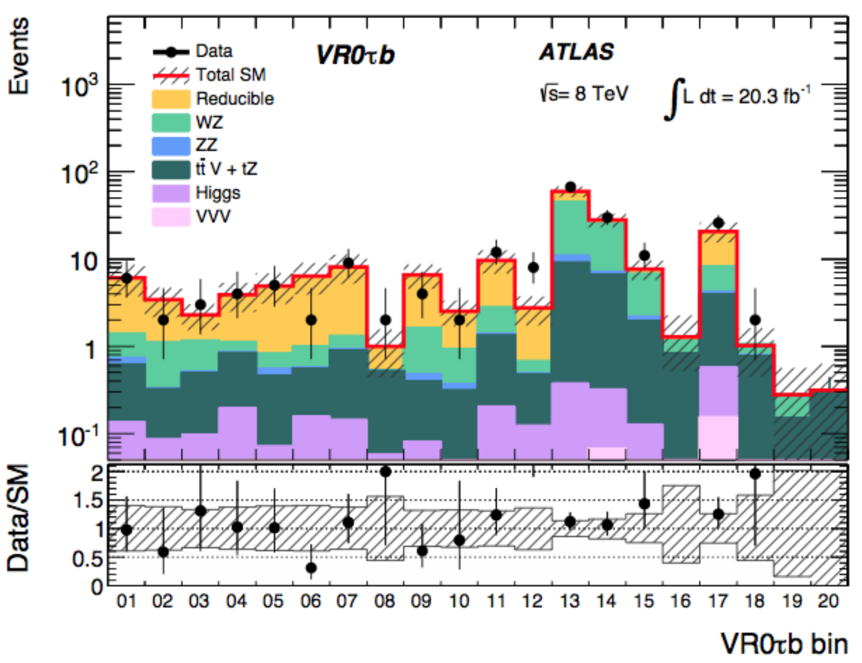
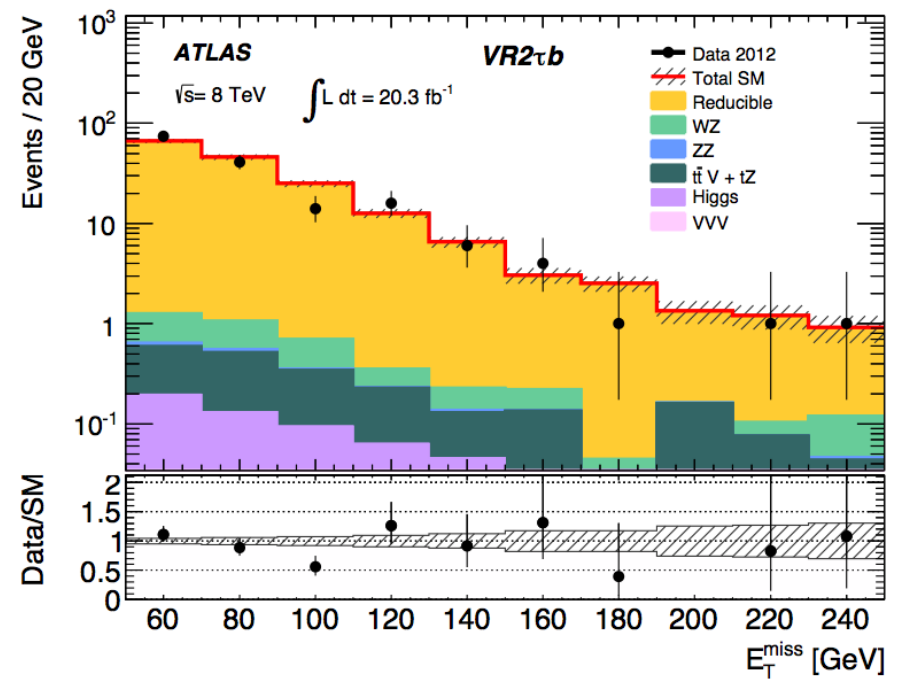
Validation regions

Validation regions used to verify background modelling and variable shapes

- Kinematically close to the signal regions
- Target dominant backgrounds
- Small signal contamination

Good agreement observed in all validation regions





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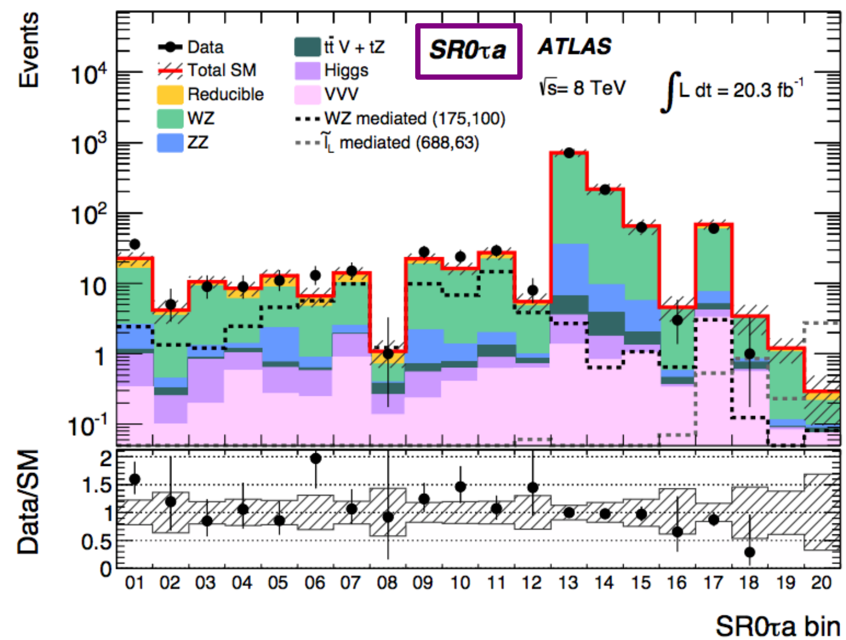
Unblinded signal regions

Good agreement seen in all validation regions, proceed to unblind signal regions

→ Observations are consistent with Standard Model expectations

Sample	SR0τb	SR1τ	SR2τa	SR2τb
WZ	0.68 ± 0.20	4.6 ± 0.6	$1.51^{+0.35}_{-0.33}$	$2.09^{+0.30}_{-0.31}$
ZZ	0.028 ± 0.009	0.36 ± 0.08	$0.049^{+0.016}_{-0.014}$	0.135 ± 0.025
$t\bar{t}V + tZ$	$0.17^{+0.32}_{-0.17}$	$0.16^{+0.18}_{-0.16}$	$0.21^{+0.27}_{-0.21}$	$0.023^{+0.015}_{-0.018}$
VVV	1.0 ± 1.0	0.5 ± 0.5	0.09 ± 0.09	0.031 ± 0.033
Higgs	0.49 ± 0.17	0.28 ± 0.12	0.021 ± 0.010	0.08 ± 0.04
Reducible	1.5 ± 0.4	4.3 ± 0.8	5.1 ± 0.7	4.9 ± 0.7
Total SM	3.8 ± 1.2	10.3 ± 1.2	6.9 ± 0.8	$7.2^{+0.7}_{-0.8}$
Data	3	13	6	5



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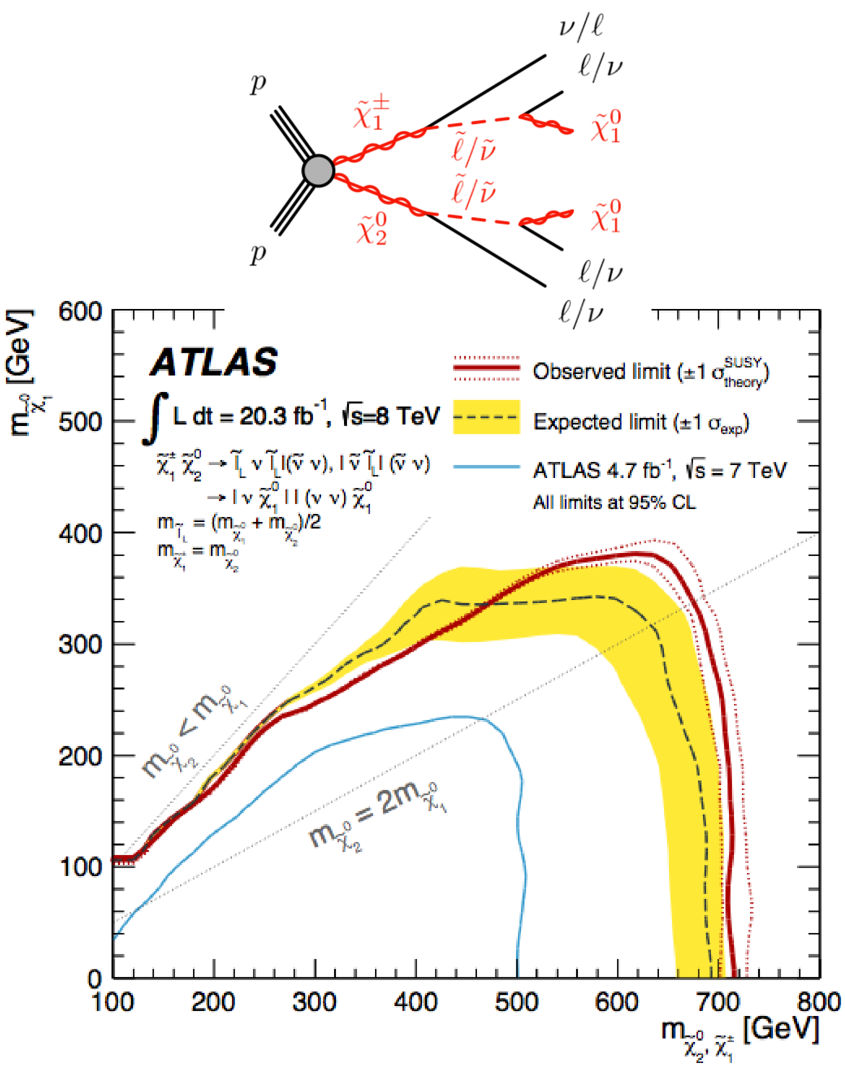
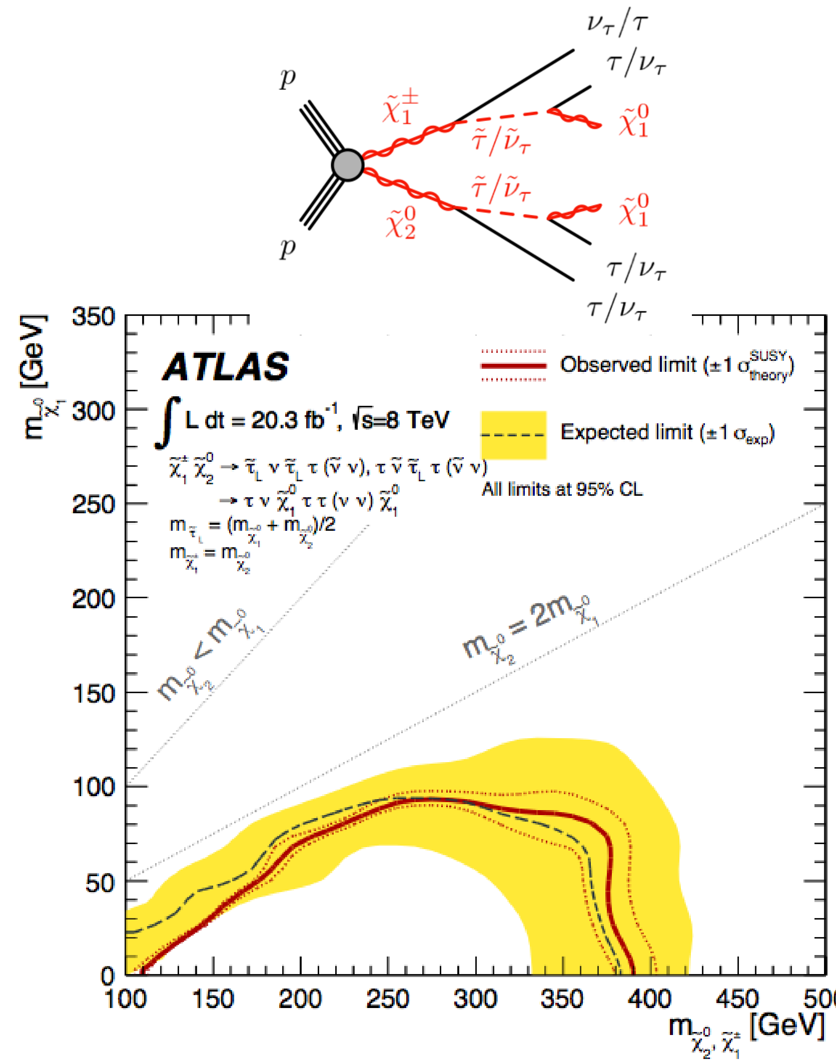
Interpretation in SUSY simplified models

Limits set at 95% CL for chargino and neutralino production

Decay via sleptons



Decay via staus



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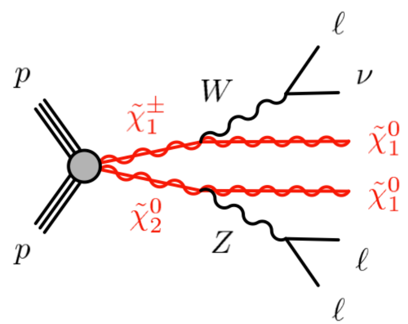
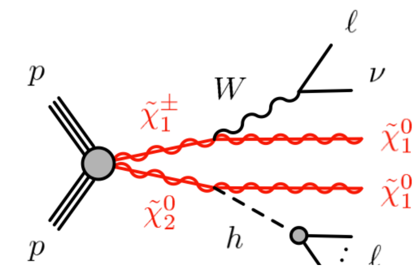
Interpretation in SUSY simplified models

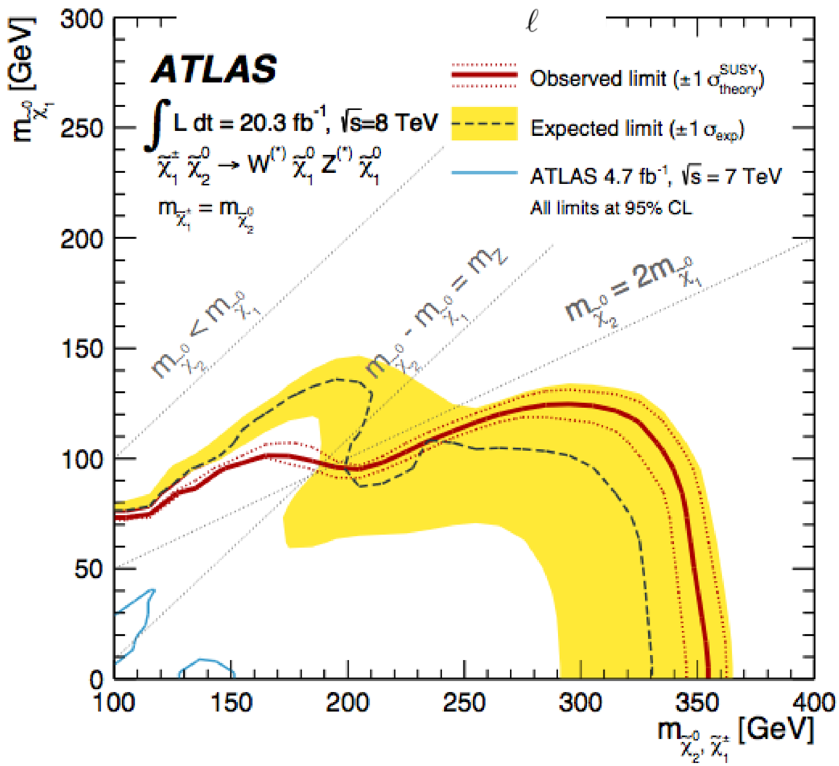
Limits set at 95% CL for chargino and neutralino production

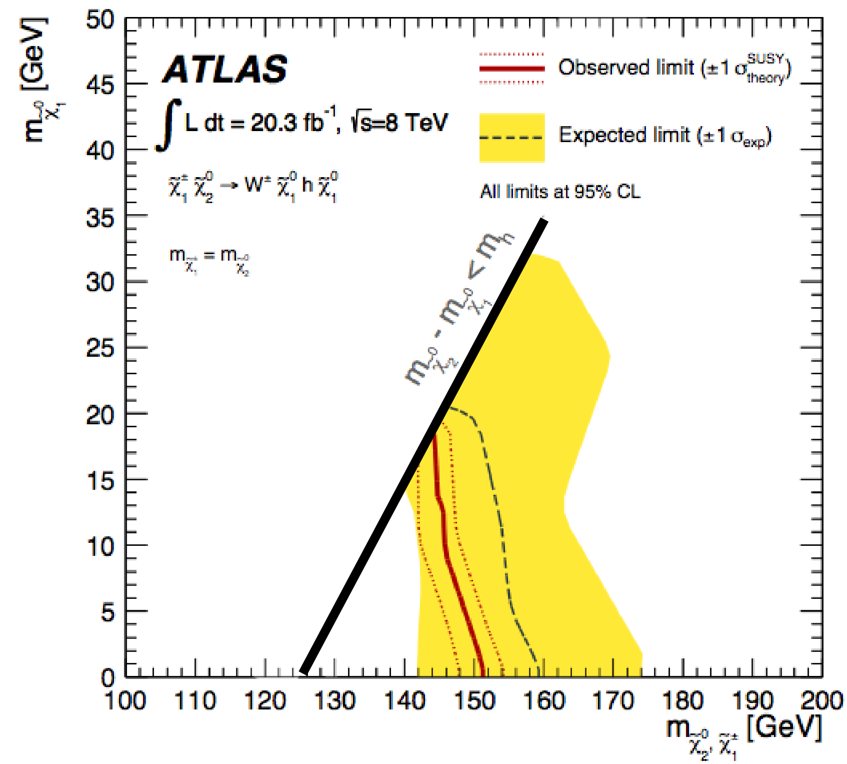
Decay via WZ



Decay via Wh







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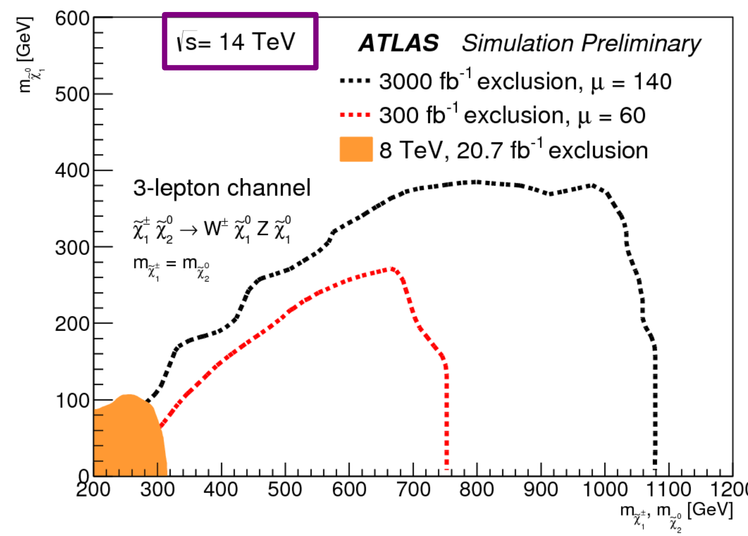
Conclusions

- ➔ Presented the results for a SUSY search in the three lepton final state
  - Based on 20.3 fb^{-1} of data collected by the ATLAS detector in 2012
  - Target the direct production of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ in R-parity conserving models
  - Explored intermediate decays through sleptons, staus, WZ and Wh
- ➔ Observations were consistent with Standard model expectations
- ➔ Limits were set in the context of simplified SUSY models
- ➔ ATLAS will begin data taking in 2015
  - Centre of mass energy increased to ~14 TeV
  - Stay tuned!



ATL-PHYS-PUB-2013-011

Additional Slides

Monte Carlo Generator

Process	Generator + fragmentation/hadronisation	Cross-section	Tune	PDF set
Dibosons				
WW, WZ, ZZ	POWHEG-r2129 [34, 35] + PYTHIA-8.165 [38]	NLO QCD with MCFM-6.2 [39, 40]	AU2 [36]	CT10 [37]
* WZ, ZZ	aMC@NLO-2.0.0.beta3 [41] + HERWIG-6.520 [42] (or + PYTHIA-6.426)	NLO QCD with MCFM-6.2	AU2	CT10
ZZ via gluon fusion (*not incl. in* POWHEG)	gg2VV [43] + HERWIG-6.520	NLO	AUET2B [44]	CT10
$W\gamma$, $Z\gamma$	SHERPA-1.4.1 [45]	NLO	(internal)	CT10
Tribosons				
WWW, ZWW	MADGRAPH-5.0 [46] + PYTHIA-6.426	NLO [47]	AUET2B	CTEQ6L1 [48]
Higgs				
via gluon fusion	POWHEG-r2092 + PYTHIA-8.165	NNLL QCD, NLO EW [49]	AU2	CT10
via vector-boson-fusion	POWHEG-r2092 + PYTHIA-8.165	NNLO QCD, NLO EW [49]	AU2	CT10
associated W/Z production	PYTHIA-8.165	NNLO QCD, NLO EW [49]	AU2	CTEQ6L1
associated $t\bar{t}$-production	PYTHIA-8.165	NNLO QCD [49]	AU2	CTEQ6L1
Top+Boson				
$t\bar{t}W$, $t\bar{t}Z$	ALPGEN-2.14 [50] + HERWIG-6.520	NLO [51, 52]	AUET2B	CTEQ6L1
* $t\bar{t}W$, $t\bar{t}Z$	MADGRAPH-5.0 + PYTHIA-6.426	NLO	AUET2B	CTEQ6L1
$t\bar{t}WW$	MADGRAPH-5.0 + PYTHIA-6.426	NLO [52]	AUET2B	CTEQ6L1
tZ	MADGRAPH-5.0 + PYTHIA-6.426	NLO [53]	AUET2B	CTEQ6L1
$t\bar{t}$	POWHEG-r2129 + PYTHIA-6.426	NNLO+NNLL [54–59]	PERUGIA2011C	CT10
Single top				
t-channel	ACERMC-38 [60] + PYTHIA-6.426	NNLO+NNLL [61]	AUET2B	CTEQ6L1
s-channel, Wt	MC@NLO-4.06 [62, 63] + HERWIG-6.520	NNLO+NNLL [64, 65]	AUET2B	CT10
W+jets, Z+jets	ALPGEN-2.14 + PYTHIA-6.426 (or + HERWIG-6.520)	DYNNLO-1.1 [66] with MSTW2008 NNLO [67]	PERUGIA2011C	CTEQ6L1

Electroweak SUSY sector

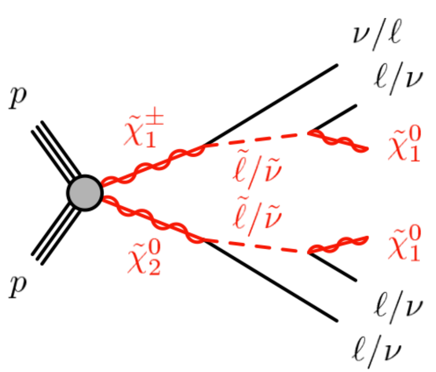
Simplified supersymmetric models used for optimization and interpretation

- Masses and decay modes of the relevant particles are the only free parameters
- Wino like $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ and mass degenerate, bino like $\tilde{\chi}_1^0$

Results also interpreted in the context of the phenomenological MSSM

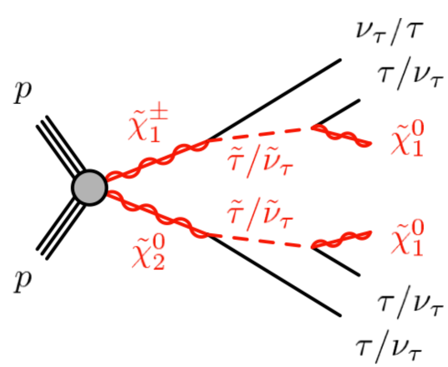
Slepton mediated

$$\mathrm{BR}(\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm} \to \tilde{\ell}_L) = 50\%$$
$$\mathrm{BR}(\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm} \to \tilde{\nu}_\ell) = 50\%$$
$$m_{\tilde{\ell}_L, \tilde{\nu}_\ell} = \frac{m_{\tilde{\chi}_2^0} + m_{\tilde{\chi}_1^0}}{2}$$



Stau mediated

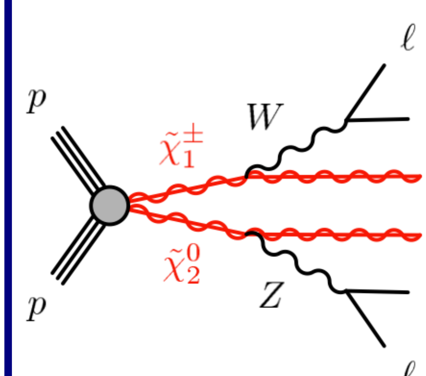
$$\mathrm{BR}(\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm} \to \tilde{\tau}) = 50\%$$
$$\mathrm{BR}(\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm} \to \tilde{\nu}_\tau) = 50\%$$
$$m_{\tilde{\tau}, \tilde{\nu}_\tau} = \frac{m_{\tilde{\chi}_2^0} + m_{\tilde{\chi}_1^0}}{2}$$



WZ mediated

$$\mathrm{BR}(\tilde{\chi}_1^{\pm} \to W + \tilde{\chi}_1^0) = 100\%$$
$$\mathrm{BR}(\tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0) = 100\%$$

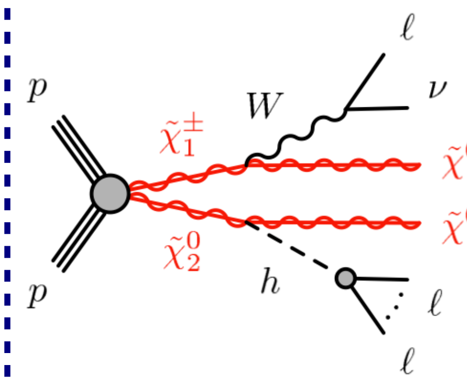
W and Z and have SM masses and BRs



Wh mediated

$$\mathrm{BR}(\tilde{\chi}_1^{\pm} \to W + \tilde{\chi}_1^0) = 100\%$$
$$\mathrm{BR}(\tilde{\chi}_2^0 \to h + \tilde{\chi}_1^0) = 100\%$$

W and h and have SM masses and BRs



$m_H = 125$ GeV

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Signal region selection

Select events with exactly three leptons (electrons,muons or hadronically decaying taus)

- Dominant backgrounds: WZ, ttbar, W and Z +jets
- Backgrounds are suppressed with cuts on various kinematic variables
- SR0τa: 20 statistically independent signal regions with cuts on mSFOS, mT and Etmiss
- All signal regions statistically independent with the exception of SR2τa and SR2τb

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

$$m_T = \sqrt{2p_T^{\ell}E_T^{miss}(1-\cos(\Delta\phi(\ell, E_T^{miss}))}$$

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Validation regions

Validation regions (VR) used to verify background modelling and variable shapes

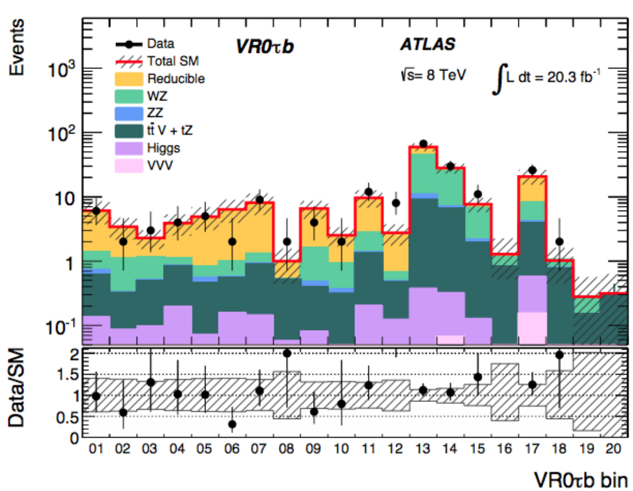
- Defined to be close kinematically close to the signal regions with small expected signal contamination
- Target dominant backgrounds: ttbar, WZ, W+jets and Z+jets
- Good agreement observed in all regions

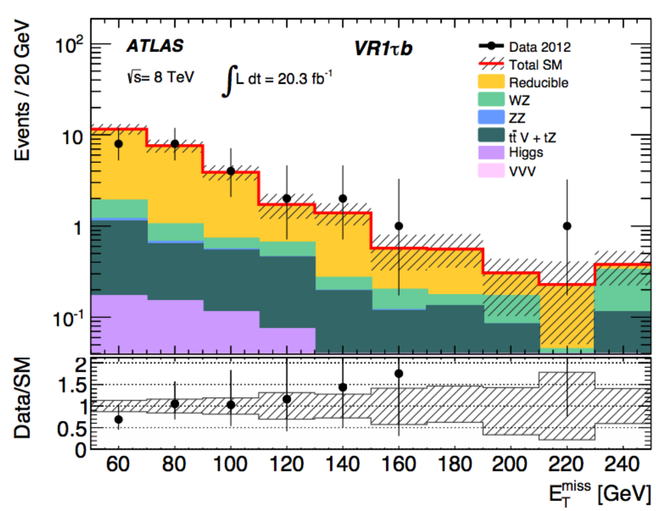
Region name	$N(\ell)$	$N(\tau)$	Flavour/sign	Z boson	$E_{\mathrm{T}}^{\mathrm{miss}}$	$N(b\text{-tagged jets})$	Target process
VR0τnoZa	3	0	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	m_{SFOS} & $m_{3\ell}$ veto	35–50	–	WZ^*, Z^*Z^*, Z^*+jets
VR0τZa	3	0	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	request	35–50	–	WZ, Z+jets
VR0τnoZb	3	0	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	m_{SFOS} & $m_{3\ell}$ veto	> 50	1	$t\bar{t}$
VR0τZb	3	0	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	request	> 50	1	WZ
VR0τb	3	0	$\ell^+\ell^-\ell$, $\ell^+\ell^-\ell'$	binned	binned	1	WZ, $t\bar{t}$
VR1τa	2	1	$\tau^\pm\ell^\mp\ell^\mp$, $\tau^\pm\ell^\mp\ell'^\mp$	–	35–50	–	WZ, Z+jets
VR1τb	2	1	$\tau^\pm\ell^\mp\ell^\mp$, $\tau^\pm\ell^\mp\ell'^\mp$	–	> 50	1	$t\bar{t}$
VR2τa	1	2	$\tau\tau\ell$	–	35–50	–	W+jets, Z+jets
VR2τb	1	2	$\tau\tau\ell$	–	> 50	1	$t\bar{t}$

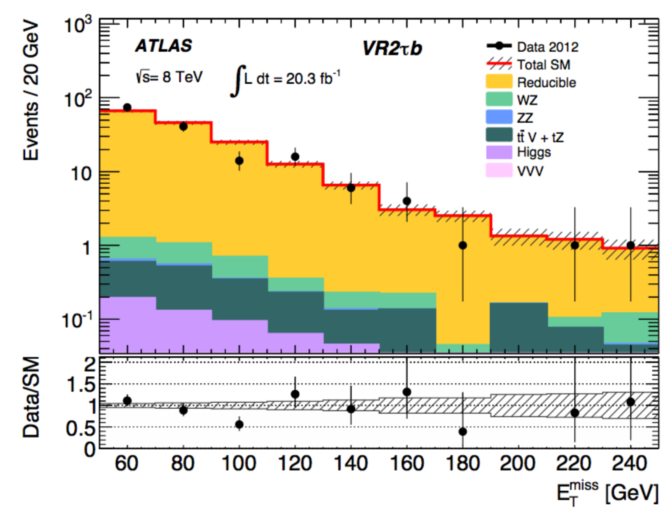
0τ VRs

1τ VRs

2τ VRs







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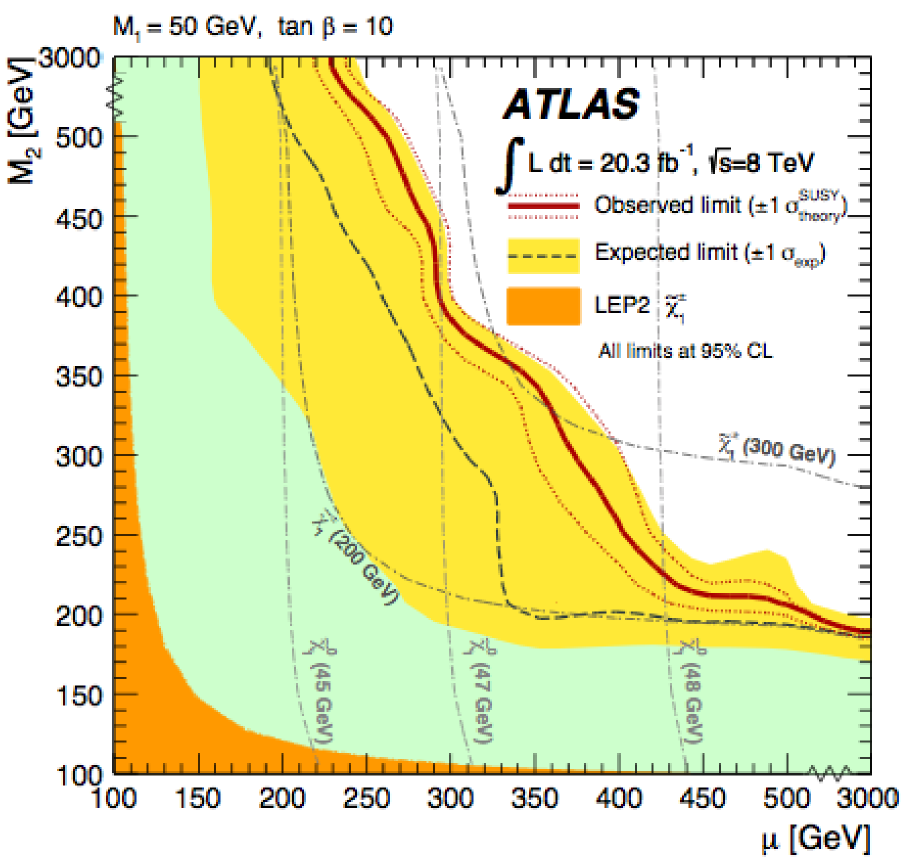
Phenomenological MSSM

Results interpreted in the context of the pMSSM

- Sleptons,heavy higgs, squarks and gluinos are "decoupled"
- M1 fixed to 50 GeV to get the correct dark matter relic density – Z funnel
- Includes all chargino and neutralino production modes (higher mass eigenstates)
- Decays through WZ drive the limit in the bulk



Parameters of the model

- M1: mass parameter of bino field
- M2: mass parameter of the wino fields
- μ: mass parameter of the higgsino fields
- $\tan\beta \equiv \langle H_2 \rangle / \langle H_1 \rangle$

Parameters above determine the properties of the neutralinos and charginos

- Production cross section
- Branching fractions
- Masses

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Background modelling

Standard model backgrounds classified into two categories:

➔ **Irreducible backgrounds**: 3 real,prompt leptons

- Diboson production: WZ and ZZ
- Triboson production: VVV
- Top + vector boson: ttV and tZ
- Higgs production

} Estimated using Monte Carlo predictions

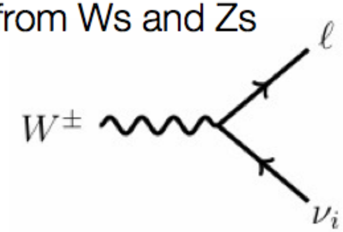
➔ **Reducible backgrounds**: One or two 'fake' leptons

- Top quark: single and pair production
- Diboson production: WW
- Single boson production: W or Z

} Estimated using a data drive technique

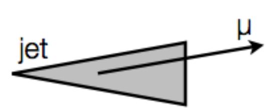
Real leptons

prompt leptons coming from Ws and Zs

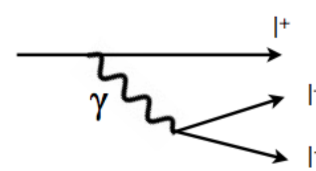


Fake leptons

HF/LF fakes from jets



Conversion leptons from photon radiation



Data driven estimate: Matrix Method

- Matrix method
  - Relates tight (T) and loose (L) leptons to real (R) and fake (F) objects
  - Leading lepton real ~99% of the time, reduces matrix to 4x4

$$\begin{pmatrix} N_{TT} \\ N_{TL'} \\ N_{L'T} \\ N_{L'L'} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1(1-\epsilon_2) & \epsilon_1(1-f_2) & f_1(1-\epsilon_2) & f_1(1-f_2) \\ (1-\epsilon_1)\epsilon_2 & (1-\epsilon_1)f_2 & (1-f_1)\epsilon_2 & (1-f_1)f_2 \\ (1-\epsilon_1)(1-\epsilon_2) & (1-\epsilon_1)(1-f_2) & (1-f_1)(1-\epsilon_2) & (1-f_1)(1-f_2) \end{pmatrix} \cdot \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

  - Coefficients are real lepton efficiency (ϵ) and fake rate (f)
  - Invert matrix and solve for number of fake leptons passing tight requirements

$$N_{Fake \to TT} = \epsilon_1 f_2 \times N_{RF} + f_1 \epsilon_2 \times N_{FR} + f_1 f_2 \times N_{FF}$$

  - Semi-data driven (see next slide)

Matrix Method: Fake rates

- Fake rates depend on
  - Fake type (HF, LF, Conversions)
  - Process it originates from (ttbar, V+jets, etc)
- Determine a weighted average fake rate to be used in region XR

$$f^{\ell}_{XR} = \sum_{i,j} (SF^{i} \times R^{i,j}_{XR} \times Fij)$$

i = fake type
j = process

  - Fij ⇒ fake efficiency for fake type i from process j in region XR
  - Rij ⇒ fraction of fake type i and process j in region XR
  - SF^{i} ⇒ scale factor for fake type i
- Scale factors measured in dedicated CR's
  - Assumed to be region independent

Object selection

Electrons

- Baseline
  - IsEMmedium++
  - pT> 10 GeV & |η| < 2.47
  - Author 1 or 3
  - Good OQ
  - Overlap removal
- Signal
  - IsEMtight++
  - Isolation cuts
  - D0 significance and z0 cuts

Muons

- Baseline
  - STACO loose
  - pT> 10 GeV & |η| < 2.40
  - ID hit requirements
  - Overlap removal
- Signal
  - Isolation cuts
  - D0 significance and z0 cuts

MET

- Egamma10noTau_Default

Taus

- Baseline
  - pT>20 GeV & |η| < 2.50
  - nTrack == 1 || 3
  - |charge| == 1
- Signal
  - EleBDTLoose==0
  - MuonVeto==0
  - JetBDTSigMedium==1

Overlap removal

- Discard lowest ET ele if ΔR(ele,ele)<0.05
- Discard jet if ΔR(jet,ele)<0.2
- **Discard tau if ΔR(tau,ele)<0.2**
- **Discard tau if ΔR(tau,mu)<0.2**
- Discard ele if ΔR(jet,ele)<0.4
- Discard mu if ΔR(jet,mu)<0.4
- Discard ele & mu if ΔR(mu,ele)<0.01
- Discard both muons if ΔR(mu,mu)<0.05
- Discard both leptons if Δm(SFOS)<12 GeV
- **Discard jet if ΔR(jet,signal tau) < 0.2**

Triggers

- Lowest unprescaled single isolated and double lepton triggers

Trigger selection

Single and di-lepton triggers used

- Lepton is required to have fired the trigger and meet pT requirements
- Logical OR taken for all trigger bits

Trigger	p_{T} threshold [GeV]
Single Isolated e	25
Single Isolated μ	25
Double e	14,14 25,10
Double μ	14,14 18,10
Combined $e\mu$	14(e),10(μ) 18(μ),10(e)

Systematic uncertainties

Systematic uncertainties for signal regions

	SR0τa	SR0τb	SR1τ	SR2τa	SR2τb
Cross-section	4–25%	37%	9%	3.1%	3.0%
Generator	3.2–35%	11%	3.1%	6%	< 1%
Statistics on irreducible background	0.8–26%	8%	5%	5%	3.1%
Statistics on reducible background	0.4–29%	14%	8%	13%	12%
Electron misidentification probability	0.3–10%	1.3%	< 1%	–	–
Muon misidentification probability	0.1–24%	2.2%	< 1%	–	–
τ misidentification probability	–	–	8%	4%	5%

Binning of SR0τa

Binned in mSFOS, mT and mET

SR0τa bin	m_{SFOS}	m_{T}	$E_{\text{T}}^{\text{miss}}$	3ℓ Z veto
1	12–40	0–80	50–90	no
2	12–40	0–80	>90	no
3	12–40	>80	50–75	no
4	12–40	>80	>75	no
5	40–60	0–80	50–75	yes
6	40–60	0–80	>75	no
7	40–60	>80	50–135	no
8	40–60	>80	>135	no
9	60–81.2	0–80	50–75	yes
10	60–81.2	>80	50–75	no
11	60–81.2	0–110	>75	no
12	60–81.2	>110	>75	no
13	81.2–101.2	0–110	50–90	yes
14	81.2–101.2	0–110	>90	no
15	81.2–101.2	>110	50–135	no
16	81.2–101.2	>110	>135	no
17	>101.2	0–180	50–210	no
18	>101.2	>180	50–210	no
19	>101.2	0–120	>210	no
20	>101.2	>120	>210	no