HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

Searches for Electroweak Production of Supersymmetric Gauginos and Sleptons with the ATLAS Detector

Christian Sander (DESY) on behalf of the ATLAS collaboration

25th International Conference on Supersymmetry and the Unification of Fundamental Interactions - Mumbai - 14th December 2017

Motivation

Radiative EWSB → Minimisation condition

$$\frac{M_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{\tan^2\beta - 1} - |\mu|^2$$

Tree level:

- For large tan β $\rightarrow M_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \cdots$

→ light Higgsinos

One-loop:

- SUSY and SM contributions to $\Sigma_{u/d}$ should not be too different

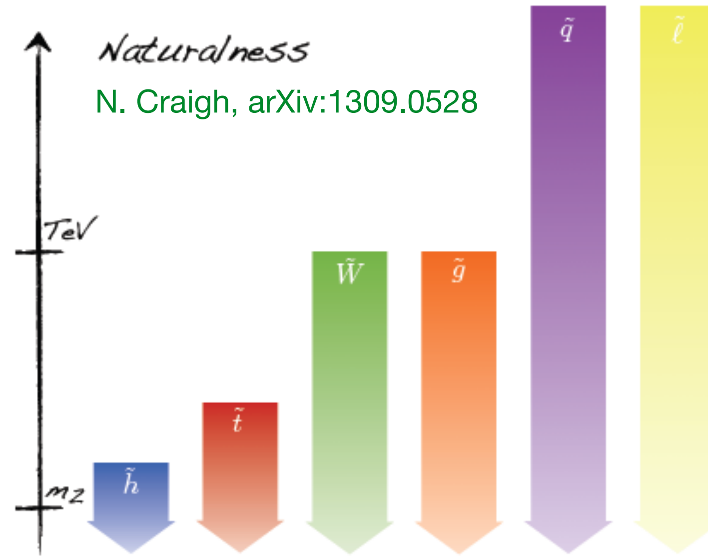
→ light winos (≲ TeV) and even lighter stops

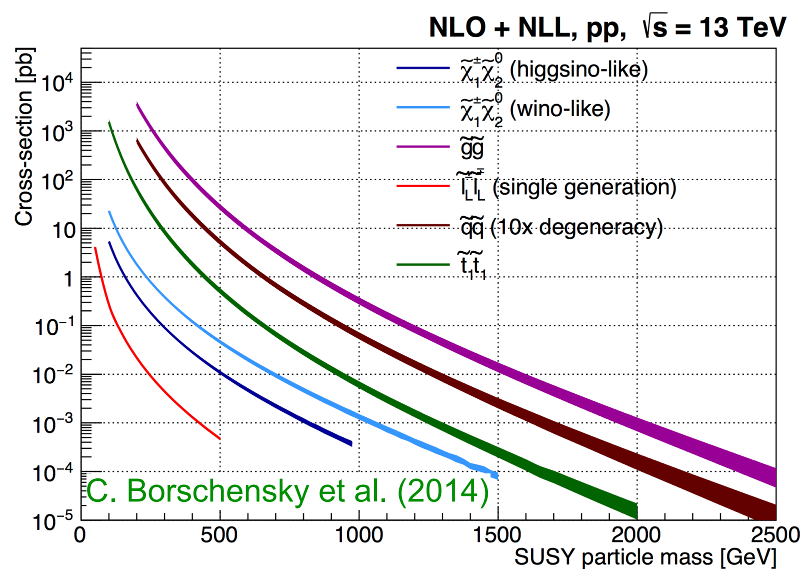
Two-loop:

- Stabilisation of other scalar masses

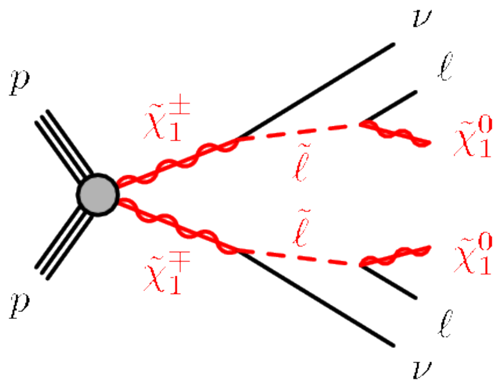
→ light gluinos $\rightarrow m_{\tilde{g}} \lesssim 2m_{\tilde{t}}$

Light higgsinos, charginos and neutralinos, possibly accessible at LHC

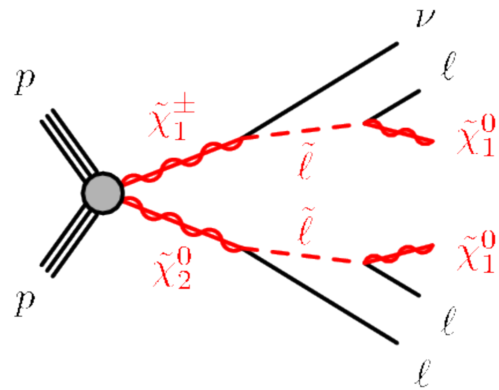




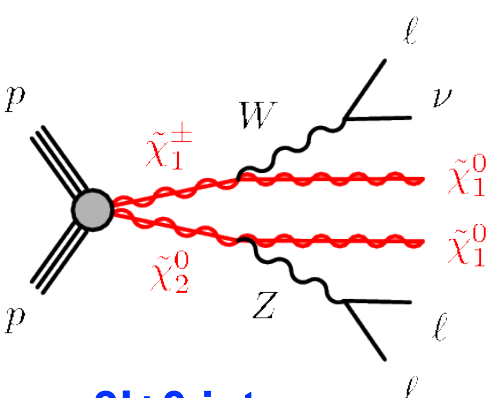
RPC Signatures - Light Leptons



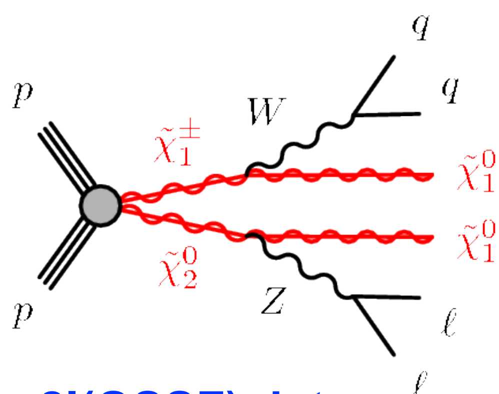
2l+0 jets



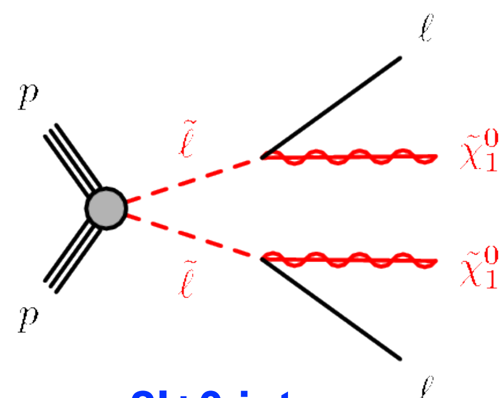
3l+0 jets



3l+0 jets



2l(OSSF)+jets



2l+0 jets

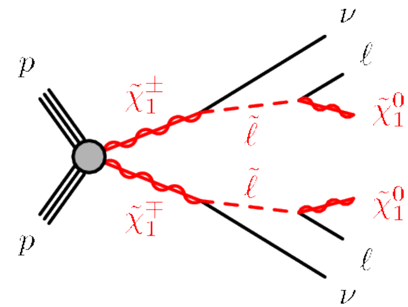
Updated results with full 2015+2016 data set (36.1 fb^{-1}) *ATLAS-CONF-2017-039*

2L/3L Search Strategy

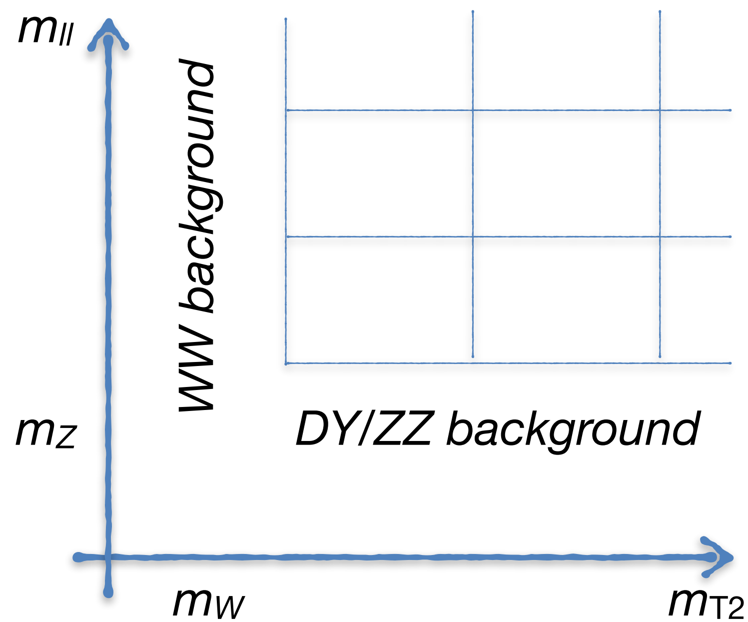
Triggers: Di-lepton (*ee*, *eμ* or *μμ*) with thresholds ranging from 8-22 GeV and single-photon triggers (for bg estimation) with thresholds ranging from 35-140 GeV

Objects:

- Electrons: p_T > 25/20/10 GeV, $|\eta|$ < 2.47
- Muons: p_T > 25/20/10 GeV, $|\eta|$ < 2.7
- Jets: p_T > 60 GeV, $|\eta|$ < 4.5
- *b*-jets: p_T > 20 GeV, $|\eta|$ < 2.4 (MC2c10, ~77% efficiency)



Schematic strategy for 2l SF



Search variables: **2l+0 jets**

m_{ll}, charge / flavour of lepton-pair, and m_{T2}

$$m_{T2} = \min_{\mathbf{q}_T} \left[\max \left(m_T(\mathbf{p}_T^{\ell 1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2}, \mathbf{p}_T^{\text{miss}} - \mathbf{q}_T) \right) \right]$$

with

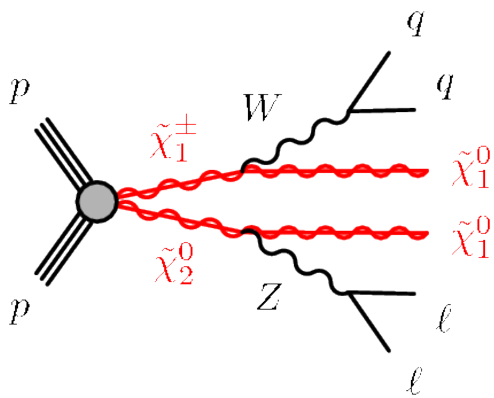
$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}$$

ATLAS-CONF-2017-039

2L/3L Search Strategy Cont.

Search variables: 2l + 2 jets

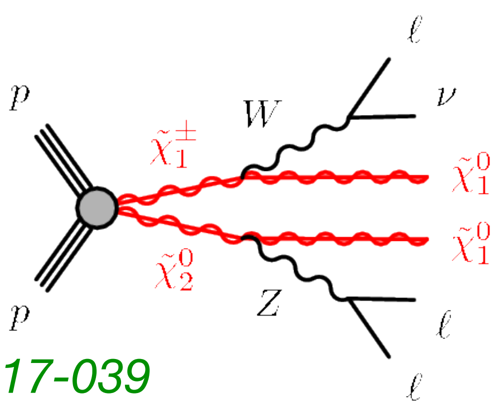
- N_{jets}, m_{ll}, m_{jj}, $p_{\mathrm{T}}(Z/W)$, m_{T2}, $\Delta R(jj)$, $\Delta R(ll)$, $\Delta\phi(\mathrm{MET},Z/W)$, MET/$p_{\mathrm{T}}(Z/W)$, $\Delta\phi(\mathrm{MET,ISR})$, $\Delta\phi(\mathrm{MET,jet_1})$, MET/ISR, $|\eta(Z)|$, p_{T} (jet$_3$)



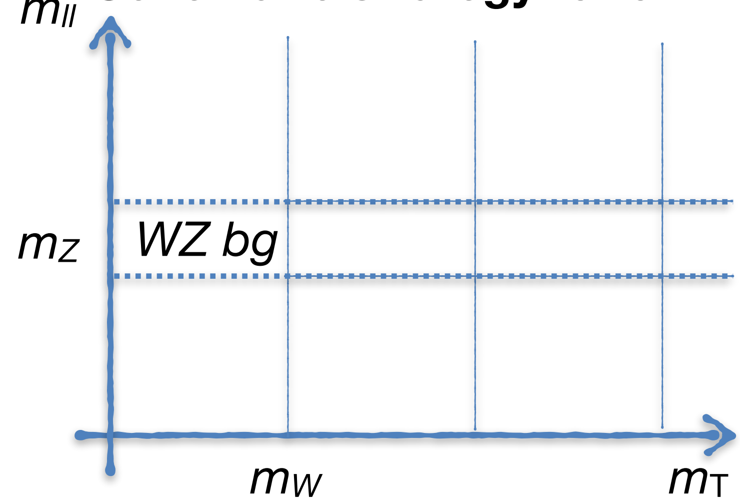
2ℓ+jets signal region definitions	SR2-int	SR2-high	SR2-low-2J	SR2-low-3J
$n_{\mathrm{non-b-tagged\ jets}}$	≥ 2		2	3-5
$m_{\ell\ell}$ [GeV]	81-101		81-101	86-96
m_{jj} [GeV]	70-100		70-90	70-90
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>150	> 250	>100	>100
p_{T}^{Z} [GeV]	>80		> 60	> 40
p_{T}^{W} [GeV]	>100			
m_{T2} [GeV]	>100			
$\Delta R_{(jj)}$	<1.5			<2.2
$\Delta R_{(\ell\ell)}$	<1.8			
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},Z)}$			< 0.8	
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},W)}$	0.5-3.0		> 1.5	< 2.2
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{Z}$			0.6 – 1.6	
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{W}$			< 0.8	
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\mathrm{ISR})}$				> 2.4
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\mathrm{jet1})}$				> 2.6
$E_{\mathrm{T}}^{\mathrm{miss}}$/ISR				0.4-0.8
$\lvert\eta(Z)\rvert$				< 1.6
$p_{\mathrm{T}}^{\mathrm{jet3}}$ [GeV]				> 30

Search variables: 3l + 0 jets

- m_{SFOS}, MET, $p_{\mathrm{T}}(l_3)$, N_{jets}, $m_{\mathrm{T,min}}$, $p_{\mathrm{T}}(lll)$, p_{T} (jet$_1$)



Schematic strategy for 3l



ATLAS-CONF-2017-039

2L/3L Background Estimation

Irreducible: SM processes with prompt leptons and genuine MET from neutrinos

- From simulation; normalised to data in control regions (CRs)
- Minor backgrounds (Z/γ^*+jets or Higgs for 2l+0 jets) directly from simulation
- For 2l+jets: Z/γ^*+jets estimated from γ+jets data

Reducible: One or more non-prompt "fakes" (heavy flavour decays, photon conversions, or mis-ID of light-flavoured jets)

- For 2l+0 jets/2l+2 jets estimated via **Matrix Method**
  - Measure efficiencies for prompt (R) and non-prompt (F) taus in CRs
  - Define "loose" (L) leptons in addition to "tight" (T) signal leptons
  - Obtain from (LL, LT, TL, TT) the numbers for (FF, FR, RF, RR)
- For 3l via **Fake-Factor Method**: Apply T/L ratio from CR to SR with loose leptons

Background predictions tested in validation regions (VRs)

Background estimation summary			
Channel	2ℓ+0jets	2ℓ+jets	3ℓ
Fake leptons	Matrix method (MM)		Fake factor method (FF)
$t\bar{t}+Wt$	CR	MC	FF
VV	CR	MC	CR (WZ-only)
Z/γ+jets	MC	γ+jet template	FF
Higgs/ VVV/ top+V	MC		

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2L/3L Results

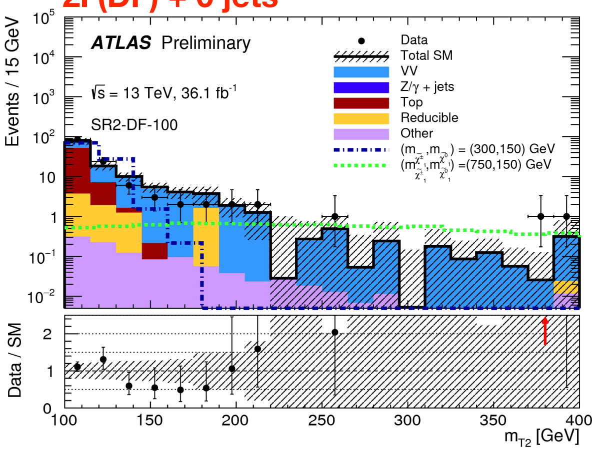
ATLAS-CONF-2017-039

Important systematic uncertainties:

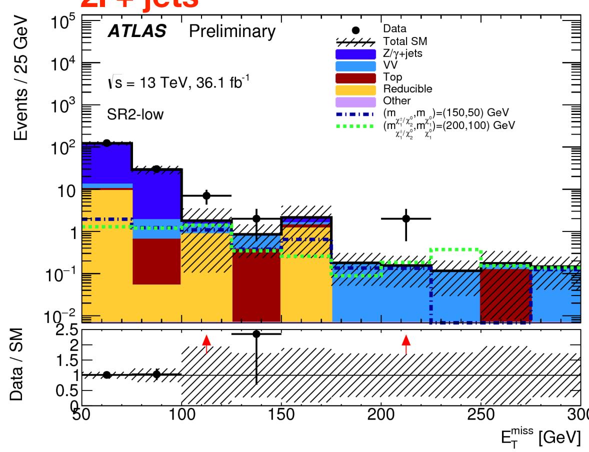
- **JES** and **JER** for 2L/3L+0 jets
- **MET modelling** for 2L/3L+0 jets
- **MC modelling** for 2L+jets: *VV* modelling (30-40%)
- ***Z*+jets estimation:** for 2l+jets 40-70%
- **Statistical uncertainty on bg prediction:** 10-70% (5-30%) for 2l (3l)+0 jets
- … many smaller uncertainties

Some selected distributions:

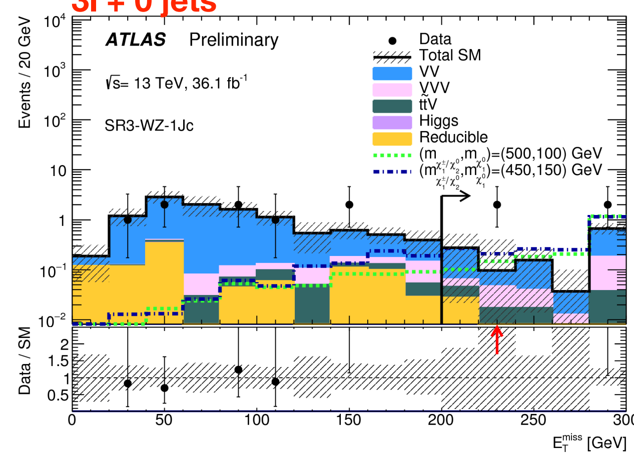
2l (DF) + 0 jets



2l + jets

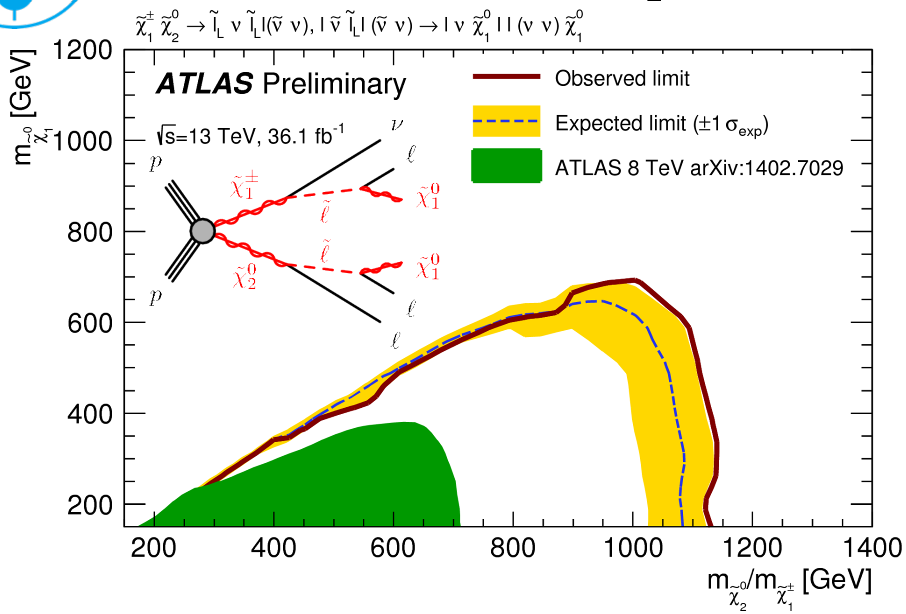


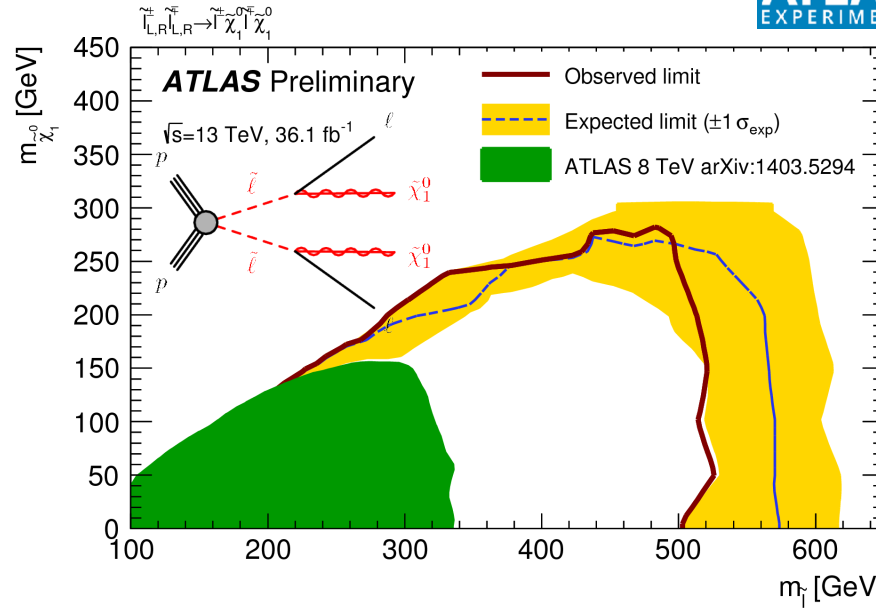
3l + 0 jets

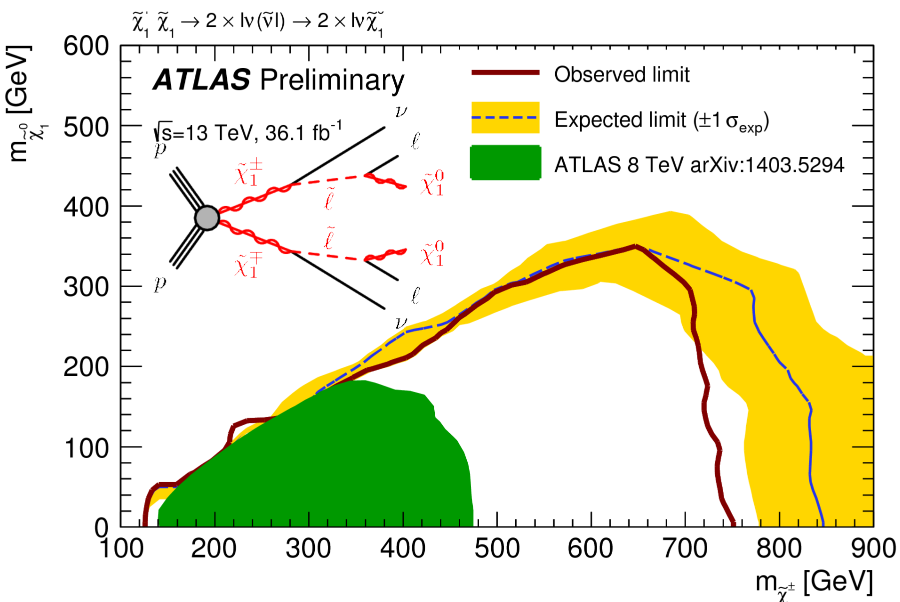


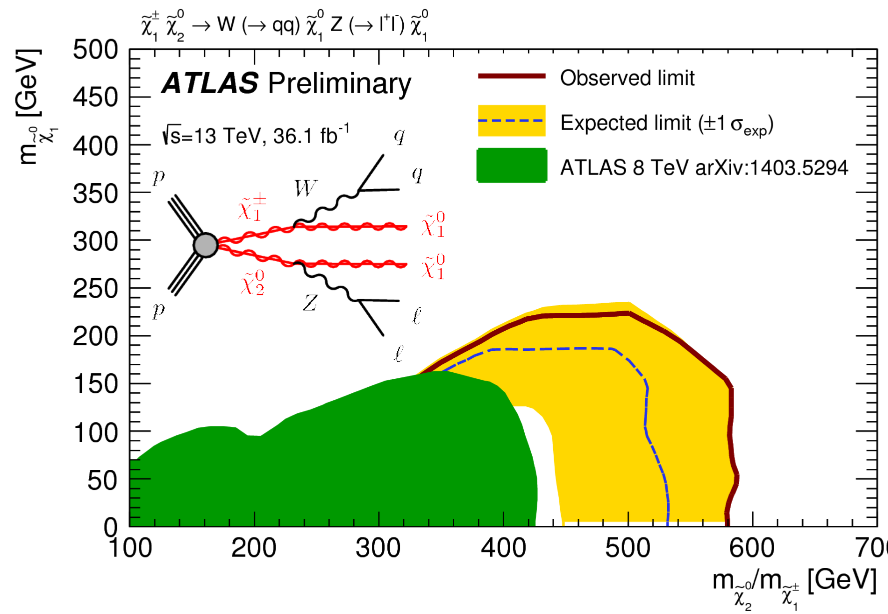
No significant excess above SM expectation observed in any SR → Limits

2L/3L Interpretations *ATLAS-CONF-2017-039*

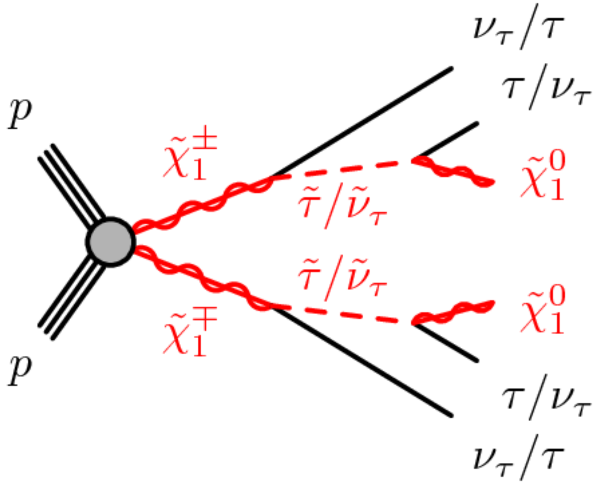


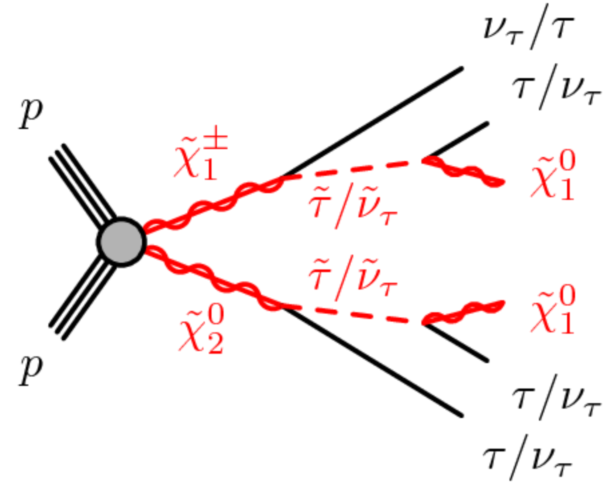






RPC Signatures - Taus

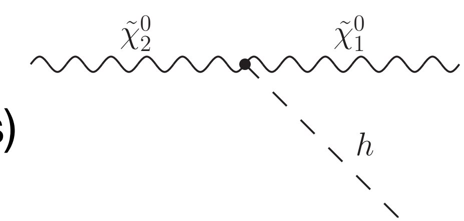




Final states with tau leptons well motivated *Djouadi et al., arXiv hep-ph/0104115*

- Large mixing in 3rd generation sfermion sector (e.g. large tan β)
  → Staus can be significantly lighter than other sleptons, i.e.

- Depending on chargino and neutralino mixing matrix:
  Possibility of enhanced decays to higgs (→ more bs and taus)



- Light stau as NLSP may help to predict right amount of relic DM density via co-annihilation channels

Di-Tau Event Selection

SUSY-2016-23, 1708.07875, submitted to EPJ C

Triggers:

- Asymmetric di-tau: $p_{\mathrm{T}} > 80/50$ GeV
- Di-tau+MET: $p_{\mathrm{T}} > 35/25$ GeV + MET>50 GeV (offline MET > 150 GeV)

Taus:

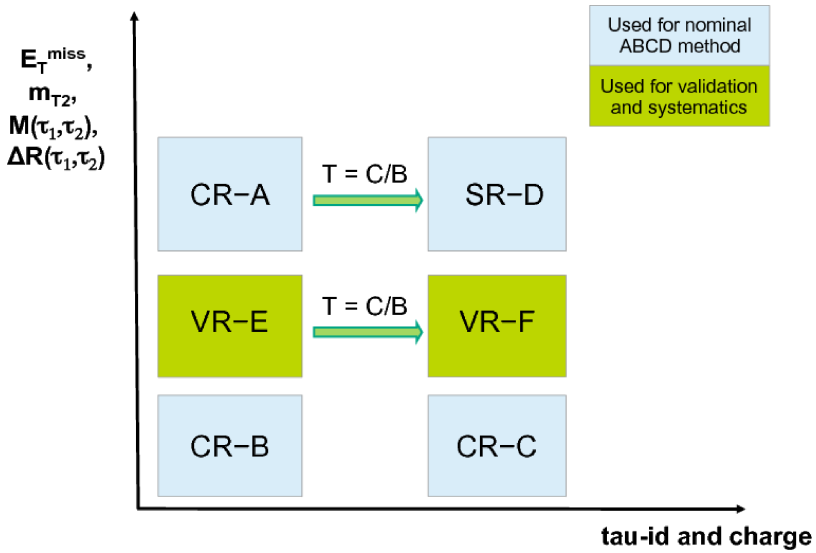
- $p_{\mathrm{T},1} > 95$ (50) GeV and $p_{\mathrm{T},2} > 65$ (40) GeV for asymmetric (di-tau+MET) trigger
- $|\eta| < 2.47$ excluding $1.37 < |\eta| < 1.52$
- Reco. efficiencies 60%(50%), 55%(40%), and 45%(30%) for loose/medium/tight for 1- (3-) prongs

Two SRs, optimised for small and large mass differences ($m_{\tilde{\tau}} - m_{\mathrm{LSP}}$)

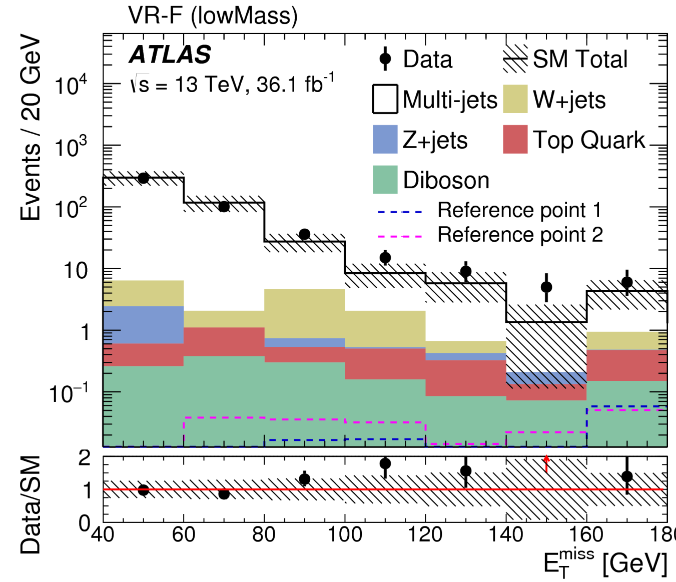
<table>
<tr><th>SR-lowMass</th><th colspan="2">SR-highMass</th></tr>
<tr><td colspan="3">At least one opposite-sign tau pair
b-jet veto
Z-veto</td></tr>
<tr><td>At least two medium tau candidates</td><td colspan="2">at least one medium and one tight tau candidates</td></tr>
<tr><td></td><td colspan="2">$m(\tau_1, \tau_2) > 110$ GeV</td></tr>
<tr><td>$m_{\mathrm{T2}} > 70$ GeV</td><td colspan="2">$m_{\mathrm{T2}} > 90$ GeV</td></tr>
<tr><td>Di-tau+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger</td><td>di-tau+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger</td><td>asymmetric di-tau trigger</td></tr>
<tr><td>$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV</td><td>$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV</td><td>$E_{\mathrm{T}}^{\mathrm{miss}} > 110$ GeV</td></tr>
<tr><td>$p_{\mathrm{T},\tau_1} > 50$ GeV</td><td>$p_{\mathrm{T},\tau_1} > 80$ GeV</td><td>$p_{\mathrm{T},\tau_1} > 95$ GeV</td></tr>
<tr><td>$p_{\mathrm{T},\tau_2} > 40$ GeV</td><td>$p_{\mathrm{T},\tau_2} > 40$ GeV</td><td>$p_{\mathrm{T},\tau_2} > 65$ GeV</td></tr>
</table>

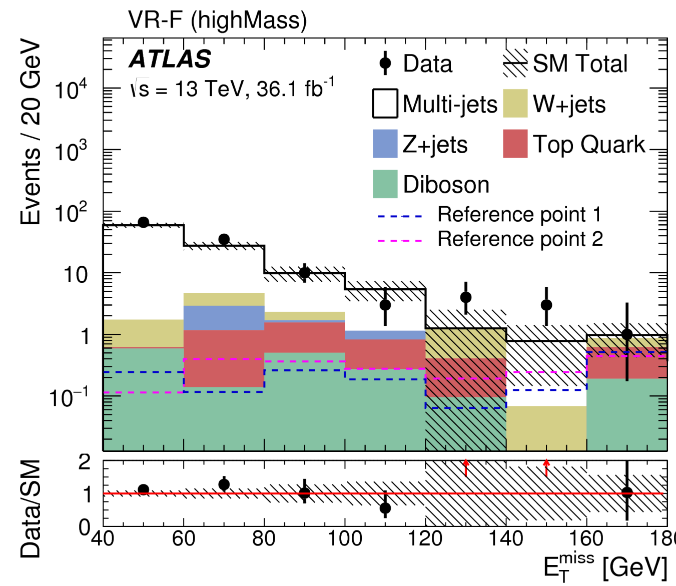
Multi-Jet Background Estimation

Fake taus from multi-jet events with ABCD method:



SR	Sample	CR-B	CR-C	CR-A	T = C/B	Multi-jet in SR-D
lowMass	**Data**	**556**	**674**	**8**	1.16 ± 0.07	4.3 ± 4.0
	Z+jets	3.4 ± 2.1	19 ± 5	0.8 ± 0.4		
	W+jets	8.9 ± 1.8	20 ± 5	1.8 ± 1.0		
	Diboson	0.94 ± 0.12	3.3 ± 0.2	0.29 ± 0.07		
	Top	1.61 ± 0.30	4.7 ± 0.5	1.4 ± 1.1		
	Multi-jet	*541 ± 24*	*627 ± 27*	*3.7 ± 1.6*		
	Reference point 1	0.06 ± 0.01	0.16 ± 0.02	1.68 ± 0.16		
highMass	**Data**	**1565**	**836**	**5**	0.43 ± 0.04	1.3 ± 1.1
	Z+jets	56 ± 31	93 ± 42	0.02 ± 0.29		
	W+jets	151 ± 22	125 ± 17	1.1 ± 0.4		
	Diboson	9.6 ± 1.1	20.5 ± 2.0	0.8 ± 0.4		
	Top	9.2 ± 1.5	25.4 ± 3.4	0.01 ± 0.01		
	Multi-jet	*1340 ± 50*	*570 ± 50*	*3.1 ± 0.6*		
	Reference point 2	0.53 ± 0.08	2.37 ± 0.21	1.92 ± 0.16		

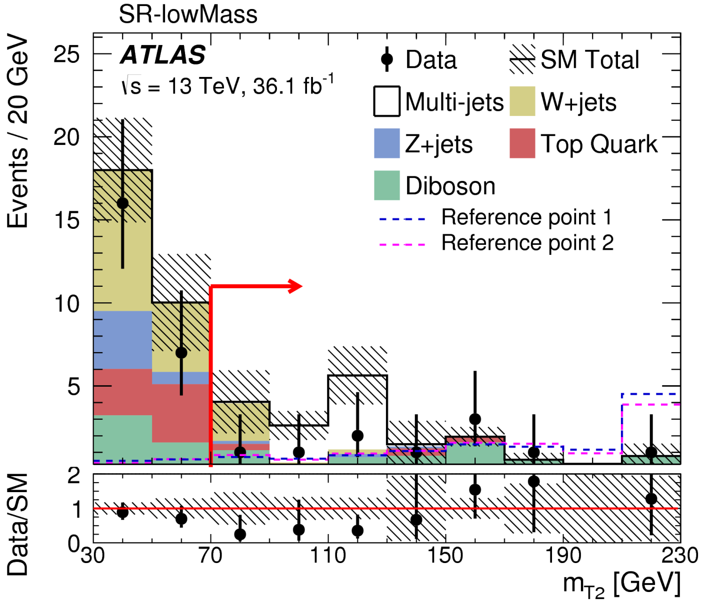


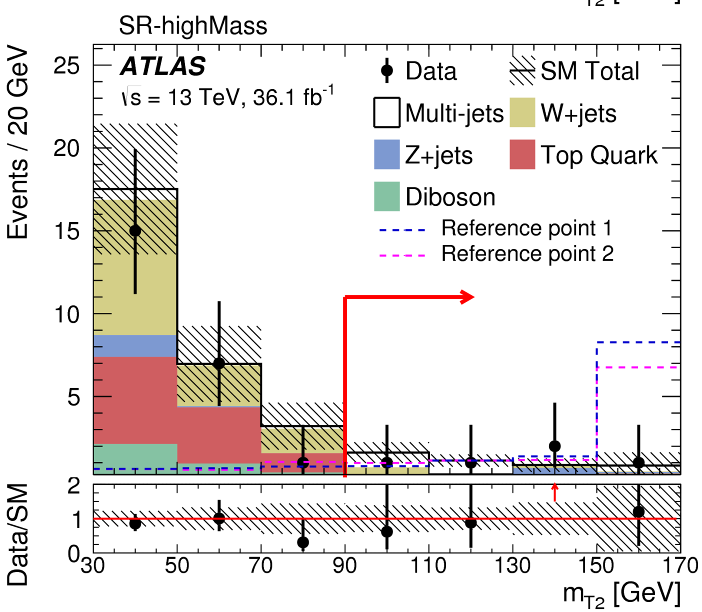


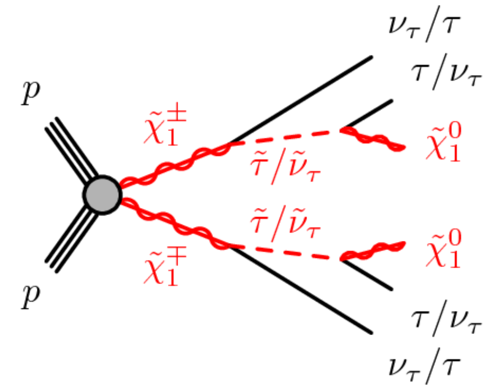
SUSY-2016-23

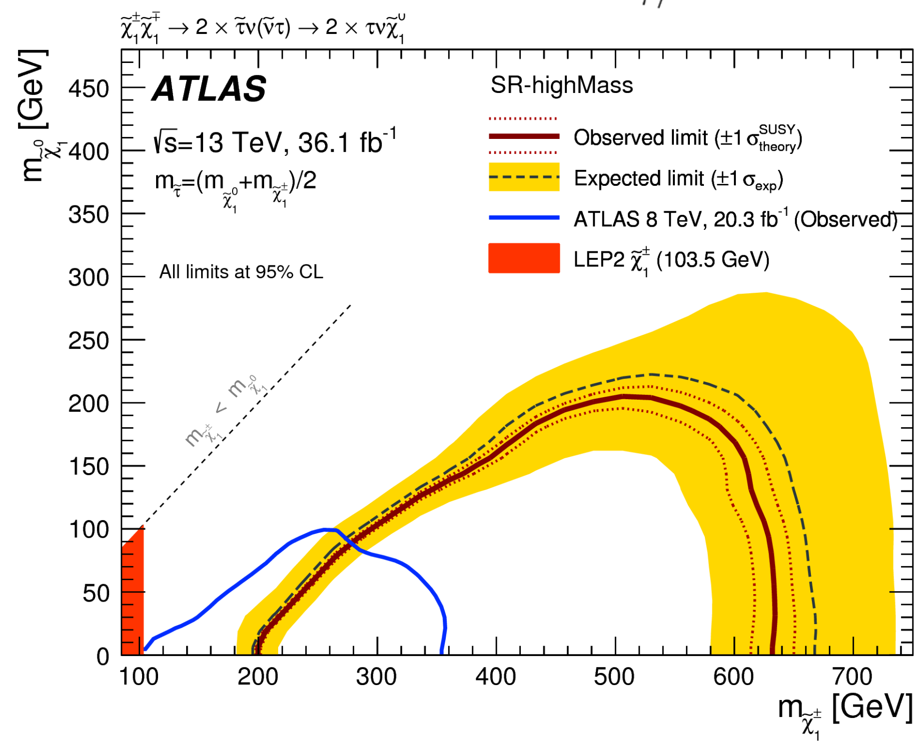
Di-Tau Results

SUSY-2016-23

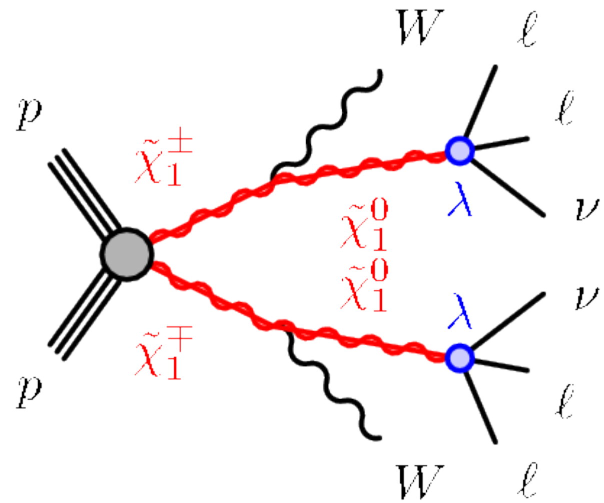








Multilepton RPV Signatures



R-parity violation: LSP is no DM candidate; but other advantages of SUSY remain

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2,$$

Typically larger multiplicities in final state (→ 4 leptons), and less MET

ATLAS-CONF-2016-075

Event Selection & Bg Estimation

Triggers: Various single and double lepton triggers

Search regions:

Sample	$N(e,\mu)$ signal	$N(e,\mu)$ loose	Z boson	m_{eff} [GeV]
SRA	>= 4	>= 0	veto	> 600
CR-SRA	= 2	>= 2	veto	> 600
SRB	>= 4	>= 0	veto	> 900
CR-SRB	= 2	>= 2	veto	> 900
VR	>= 4	>= 0	veto	< 600
CR-VR	= 2	>= 2	veto	< 600

Irreducible bgs: *ZZ*, *ttZ*, *ttWW*, *tWZ*, *VVZ* (*ZZZ*, *WZZ*, *WWZ*), Higgs (*ggH*, *WH*, *ZH*, *ttH*), *tttt*, *tttW* with 4 non-prompt leptons

- Estimated from simulation

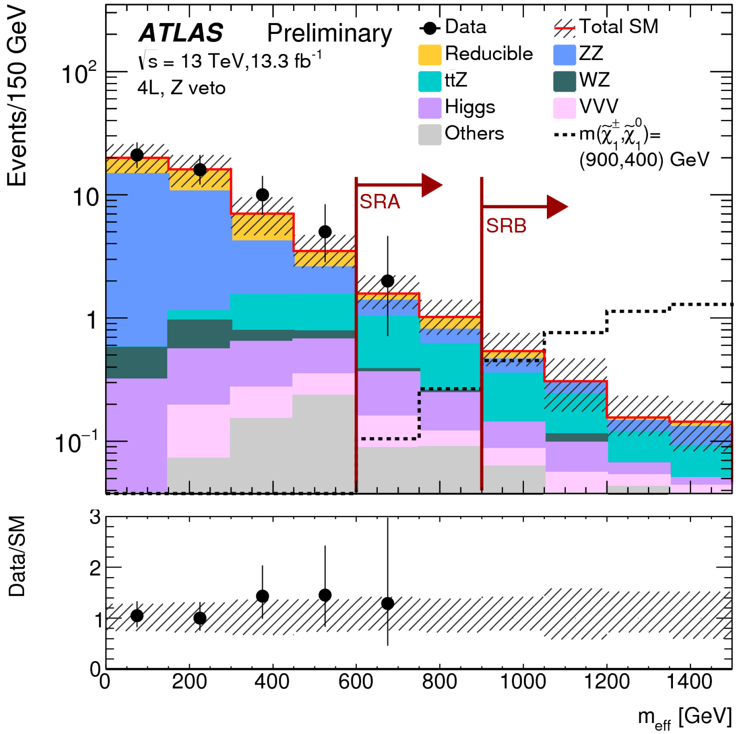
Reducible bgs with one or more "fakes" *tt*, *Z*+jets, *WZ*, *WWW*, *ttW*, *ttt* (and above processes with less than 4L)

- Applying fake factors to CRs with one or two leptons of loose quality

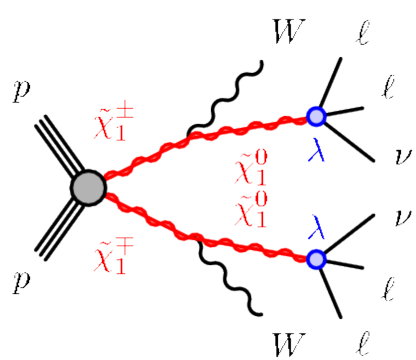
Check background estimation in validation regions (e.g. at small m_{eff})

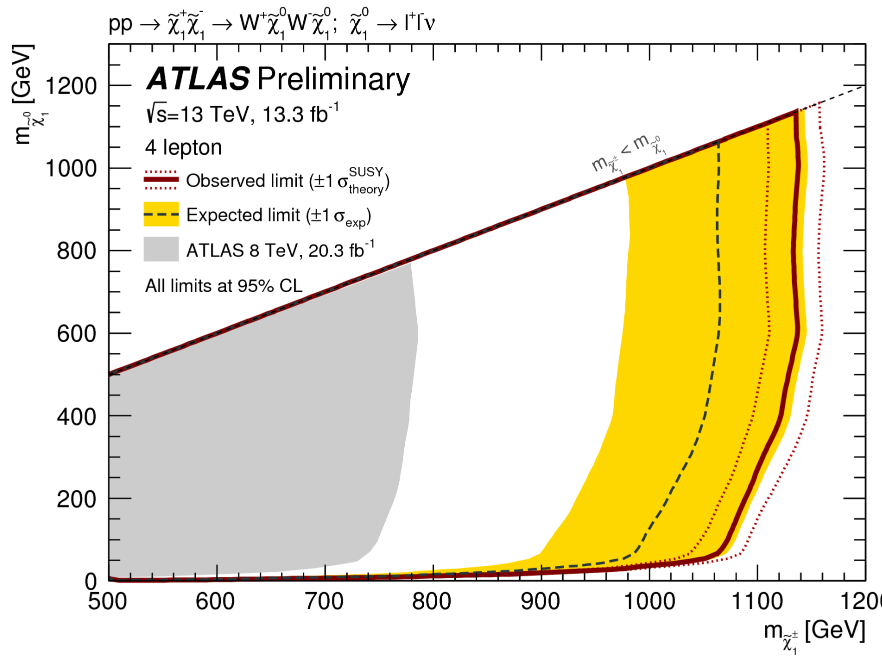
ATLAS-CONF-2016-075

4L Results



Sample	VR	SRA	SRB
Irreducible			
ZZ	29 ± 5	0.6 ± 0.4	0.20 ± 0.19
$t\bar{t}Z$	2.05 ± 0.24	1.43 ± 0.23	0.47 ± 0.09
Higgs	1.7 ± 1.4	0.4 ± 0.4	0.11 ± 0.11
VVZ	0.72 ± 0.14	0.31 ± 0.06	0.123 ± 0.027
Others	0.28 ± 0.07	0.32 ± 0.04	0.181 ± 0.022
1-fake ℓ reducible	1.14 ± 0.07	0.168 ± 0.018	0.069 ± 0.014
2-fake ℓ reducible	16 ± 6	0.48 ± 0.24	0.11 ± 0.05
Σ SM	51 ± 6	3.6 ± 0.6	1.26 ± 0.26
Data	53	2	0

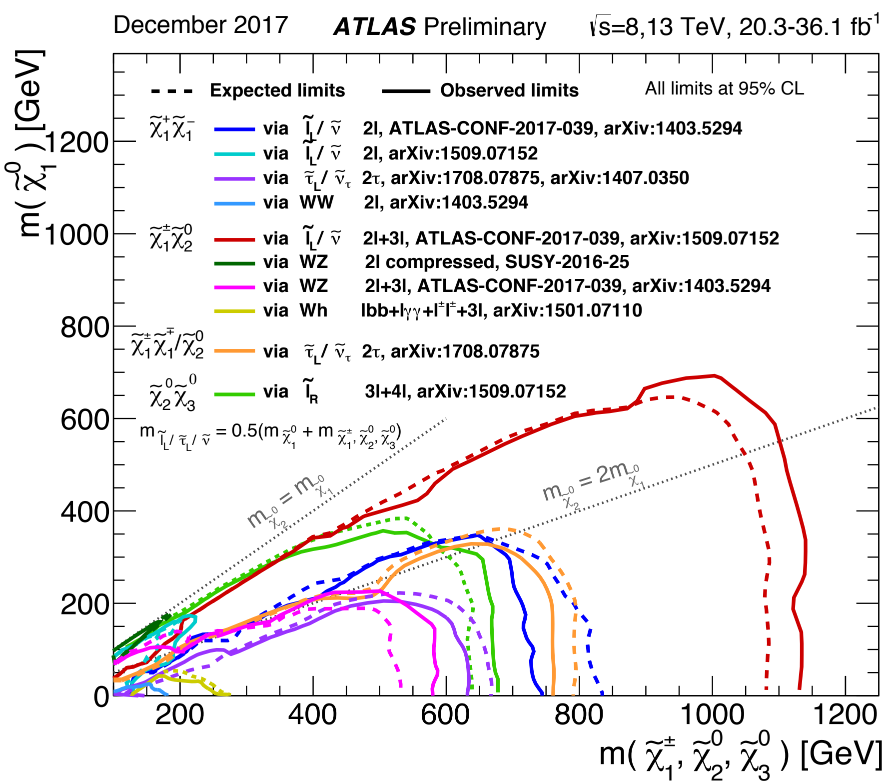




ATLAS-CONF-2016-075

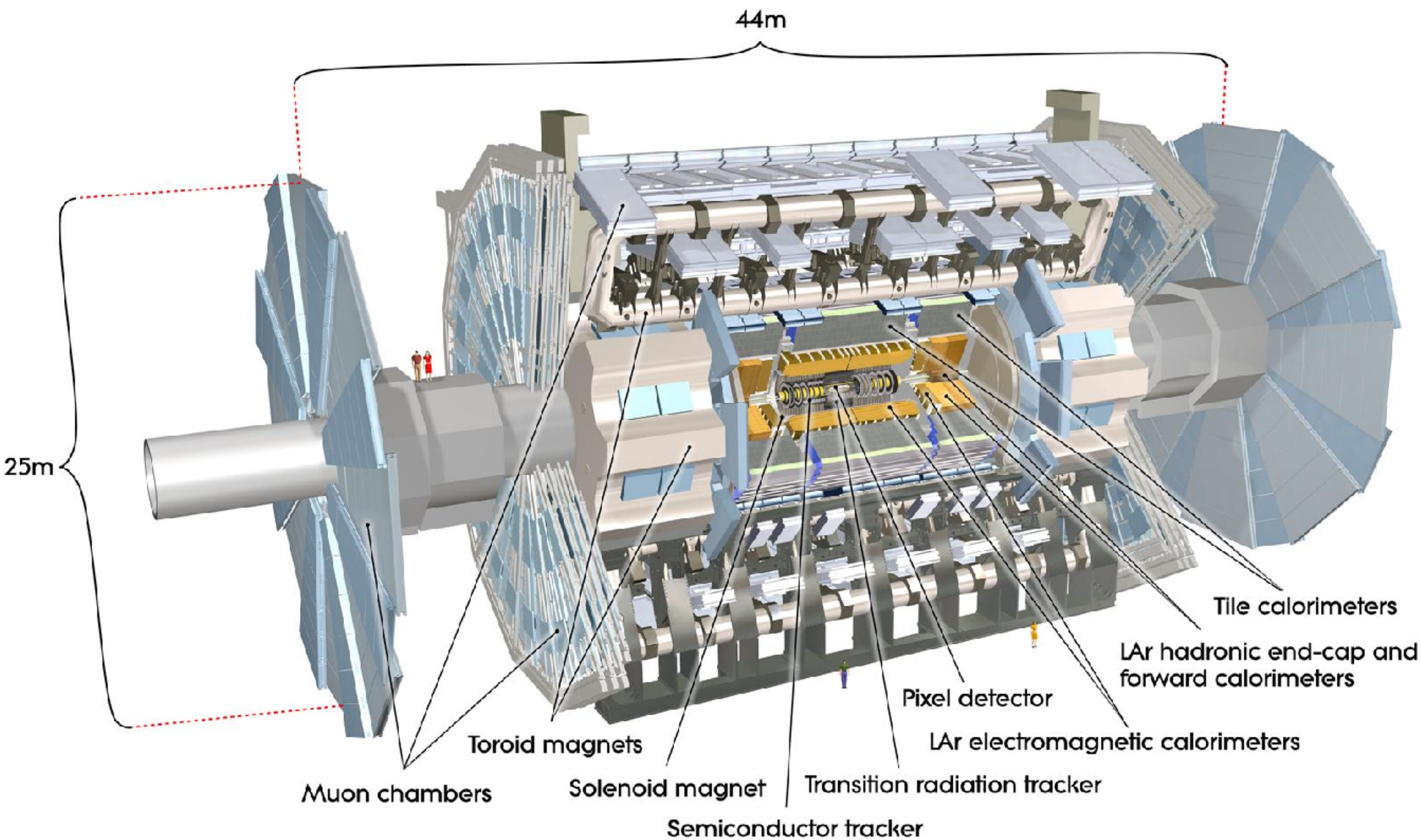
Summary

- Comprehensive searches program with multiple leptons for electroweak SUSY partners at ATLAS
- No significant deviation from SM expectation was observed and limits on various RPC and RPV SUSY models have been derived
- More results at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults




Backup

ATLAS



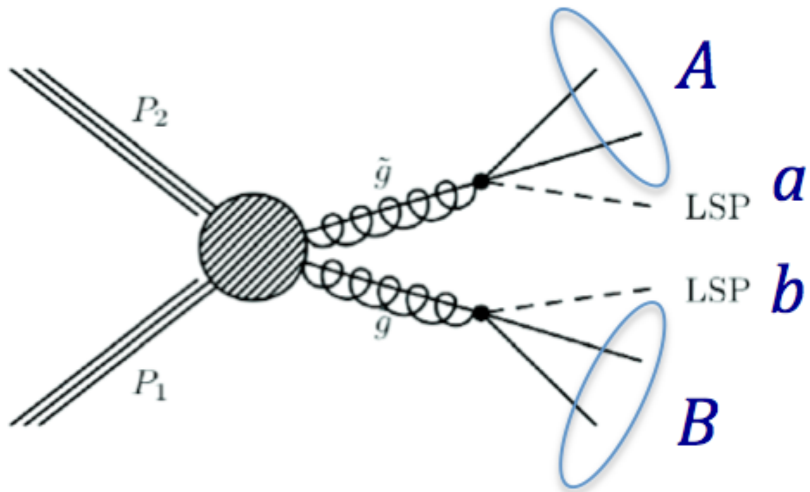
44m
25m
Muon chambers
Toroid magnets
Solenoid magnet
Semiconductor tracker
Transition radiation tracker
Pixel detector
LAr electromagnetic calorimeters
LAr hadronic end-cap and
forward calorimeters
Tile calorimeters

Monte Carlo

Process	Generator(s)	Full/fast sim.	Cross-section calculation	Tune	PDF set
WZ, WW	Sherpa 2.2.1 [57]	Fullsim	NLO [58]	Default	NNPDF30NNLO [59]
ZZ	Sherpa 2.2.2 [57]	Fullsim	NLO [58]	Default	NNPDF30NNLO [59]
VVV	Sherpa 2.2.1	Fullsim	NLO [58]	Default	NNPDF30NNLO
ggH, VBF, ggZH	Powheg v2 [60] + Pythia 8.186 [56]	Fullsim	NNLO+NNLL [61]	AZNLO [62]	CT10 [63]
ZH, WH	Pythia 8.186	Fullsim	NNLO+NNLL	A14 [64]	NNPDF23LO
$t\bar{t}H$	aMC@NLO [65] 2.3.2 + Pythia 8.186	Fullsim	NLO [66]	A14	NNPDF23LO [67]
$t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}WW$	MadGraph5_aMC@NLO 2.2.2 [68] + Pythia 8.186	Fullsim	NLO [66]	A14	NNPDF23LO
$t\bar{t}Z^{\dagger}$	Sherpa 2.2.1	AF-II	NLO [66]	Default	NNPDF30NNLO
tWZ	aMC@NLO 2.3.2 + Pythia 8.186	Fullsim	NLO [66]	A14	NNPDF23LO
$t\bar{t}(W)$, $t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO 2.2.2 + Pythia 8.186	Fullsim	NLO [68]	A14	NNPDF23LO
$t\bar{t}$	Powheg v2 + Pythia 6.428 [69]	Fullsim	NNLO+NNLL [70]	Perugia2012 [71]	CT10
Z+jets, W+jets	MadGraph5_aMC@NLO 2.2.2 + Pythia 8.186	Fullsim	NNLO [72]	A14	NNPDF23LO
SUSY signal	MadGraph5_aMC@NLO 2.2.2 + Pythia 8.186	AF-II	NLO+NLL [45–52]	A14	NNPDF23LO

M_{T2}

Generalisation of transverse mass to final states with two invisible particles



$$M_{T2}^2 = \min_{p_T^a + p_T^b = \not{E}_T} \left(\max \left(m_T^2(p_T^a, p^A), m_T^2(p_T^b, p^B) \right) \right)$$

SRs, CRs, and VRs for 2L+0Jets

m_{T2} [GeV]	$m_{\ell\ell}$ [GeV]	SF bin	DF bin
2ℓ+0jets binned signal region definitions			
100-150	111-150	SR2-SF-a	SR2-DF-a
	150-200	SR2-SF-b	
	200-300	SR2-SF-c	
	> 300	SR2-SF-d	
150-200	111-150	SR2-SF-e	SR2-DF-b
	150-200	SR2-SF-f	
	200-300	SR2-SF-g	
	> 300	SR2-SF-h	
200-300	111-150	SR2-SF-i	SR2-DF-c
	150-200	SR2-SF-j	
	200-300	SR2-SF-k	
	> 300	SR2-SF-l	
> 300	> 111	SR2-SF-m	SR2-DF-d
2ℓ+0jets inclusive signal region definitions			
> 100	> 111	SR2-SF-loose	-
> 130	> 300	SR2-SF-tight	-
> 100	-	-	SR2-DF-100
> 150	-	-	SR2-DF-150
> 200	-	-	SR2-DF-200
> 300	-	-	SR2-DF-300

2ℓ+0jets control and validation region definitions

Region	CR2-VV-DF	CR2-VV-SF	CR2-Top	VR2-VV-SF/DF	VR2-Top
lepton flavour	SF	DF	DF	SF (DF)	DF
$n_{\text{central non-b-tagged jets}}$	0	0	0	0	0
$n_{\text{central b-tagged jets}}$	0	0	≥ 1	0	≥ 1
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	< 20	—	—	> 20 (–)	—
m_{T2} [GeV]	> 130	$50 - 75$	$75 - 100$	$75 - 100$	> 100

SRs, CRs, and VRs for 2L+Jets

2ℓ+jets signal region definitions

	SR2-int	SR2-high	SR2-low-2J	SR2-low-3J
$n_{\text{non-b-tagged jets}}$	≥ 2		2	3-5
$m_{\ell\ell}$ [GeV]	81-101		81-101	86-96
m_{jj} [GeV]	70-100		70-90	70-90
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>150	> 250	>100	>100
p_{T}^{Z} [GeV]	>80		> 60	> 40
p_{T}^{W} [GeV]	>100			
m_{T2} [GeV]	>100			
$\Delta R_{(jj)}$	<1.5			<2.2
$\Delta R_{(\ell\ell)}$	<1.8			
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},Z)}$			< 0.8	
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},W)}$	0.5-3.0		> 1.5	< 2.2
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{Z}$			0.6 – 1.6	
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{W}$			< 0.8	
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\mathrm{ISR})}$				> 2.4
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\mathrm{jet1})}$				> 2.6
$E_{\mathrm{T}}^{\mathrm{miss}}/\mathrm{ISR}$				0.4-0.8
$\lvert\eta(Z)\rvert$				< 1.6
$p_{\mathrm{T}}^{\mathrm{jet3}}$ [GeV]				> 30

2ℓ+jets validation region definitions

	VR2-int(high)	VR2-low-2J(3J)	VR2-VV-int	VR2-VV-low
loose selection				
$n_{\text{non-b-tagged jets}}$	≥ 2	2 (3-5)	1	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>150 (250)	>100	>150	>150
$m_{\ell\ell}$ [GeV]	81-101	81-101 (86-96)		81-101
m_{jj} [GeV]	<60,>100	<60,>100		
p_{T}^{Z} [GeV]	>80	> 60(40)		
p_{T}^{W} [GeV]	>100			
$\lvert\eta(Z)\rvert$		(< 1.6)		
$p_{\mathrm{T}}^{\mathrm{jet3}}$ [GeV]		(> 30)		
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\mathrm{jet})}$			>0.4	>0.4
m_{T2} [GeV]	>100[*]		>100	
$\Delta R_{(\ell\ell)}$	<1.8[*]			<0.2
tight selection				
$\Delta R_{(jj)}$	<1.5	(<2.2)		
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},W)}$	0.5-3.0	> 1.5(< 2.2)		
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},Z)}$		< 0.8(−)		
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{W}$		< 0.8(−)		
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{Z}$		0.6 – 1.6(−)		
$E_{\mathrm{T}}^{\mathrm{miss}}/\mathrm{ISR}$		(0.4 – 0.8)		
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\mathrm{ISR})}$		(> 2.4)		
$\Delta\phi_{(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\mathrm{jet1})}$		(> 2.6)		

SRs, CRs, and VRs for 3L+Jets

3ℓ binned signal region definitions							
m_{SFOS} [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$p_{\mathrm{T}}^{\ell_3}$ [GeV]	$n_{\mathrm{non-b-tagged\ jets}}$	$m_{\mathrm{T}}^{\mathrm{min}}$ [GeV]	$p_{\mathrm{T}}^{\ell\ell\ell}$ [GeV]	$p_{\mathrm{T}}^{\mathrm{jet1}}$ [GeV]	Bins
<81.2	>130	20-30 >30		>110			SR3-slep-a SR3-slep-b
>101.2	>130	20-50 50-80 >80		>110			SR3-slep-c SR3-slep-d SR3-slep-e
81.2-101.2	60-120 120-170 >170		0	>110			SR3-WZ-0Ja SR3-WZ-0Jb SR3-WZ-0Jc
81.2-101.2	120-200 >200	>35	≥ 1	>110 110-160 >160	<120	>70	SR3-WZ-1Ja SR3-WZ-1Jb SR3-WZ-1Jc

3ℓcontrol and validation region definitions						
	$p_{\mathrm{T}}^{\ell_3}$ [GeV]	m_{SFOS} [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$m_{\mathrm{T}}^{\mathrm{min}}$ [GeV]	n non−b−tagged jets	n b−tagged jets
CR3-WZ-inc	>20	81.2–101.2	>120	<110	–	0
CR3-WZ-0j	>20	81.2–101.2	>60	<110	0	0
CR3-WZ-1j	>20	81.2–101.2	>120	<110	>0	0
VR3-Za	>30	81.2–101.2	40–60	–	–	–
VR3-Zb	>30	81.2–101.2	>60	–	–	>0
VR3-offZa	>30	$\notin [81.2, 101.2]$	40–60	–	–	–
VR3-offZb	>20		>40	–	–	>0
VR3-Za-0J	>20	81.2–101.2	40–60	–	0	0
VR3-Za-1J			40–60	–	>0	0

2L+0 Jets Results

SR2-	SF-a	SF-b	SF-c	SF-d	SF-e	SF-f	SF-g
Observed	56	28	19	13	10	6	6
Fitted background events							
Total SM	47 ± 12	25 ± 5	25 ± 4	14 ± 7	5.2 ± 1.4	1.9 ± 1.2	3.8 ± 1.9
$t\bar{t}$	10 ± 4	7.4 ± 3.5	7.3 ± 3.0	2.7 ± 1.7	–	–	$0.11^{+0.21}_{-0.11}$
Wt	1.0 ± 1.0	1.3 ± 0.7	1.6 ± 0.6	1.1 ± 1.1	–	–	–
VV	21 ± 4	11.3 ± 2.9	12.6 ± 2.4	3.9 ± 2.4	4.4 ± 1.3	1.8 ± 1.2	2.8 ± 1.6
FNP	$2.1^{+2.9}_{-2.1}$	–	–	5 ± 4	–	–	0.9 ± 0.4
Z/γ+jets	13 ± 9	4.7 ± 2.6	3.3 ± 3.2	$1.2^{+1.7}_{-1.2}$	0.7 ± 0.6	$0.02^{+0.21}_{-0.02}$	–
other	0.18 ± 0.08	0.12 ± 0.05	0.11 ± 0.04	0.09 ± 0.05	0.050 ± 0.03	0.03 ± 0.01	0.05 ± 0.02

SR2-	SF-h	SF-i	SF-j	SF-k	SF-l	SF-m
Observed	0	1	3	2	2	7
Fitted background events						
Total SM	3.1 ± 1.0	1.9 ± 0.9	1.6 ± 0.5	1.5 ± 0.6	1.8 ± 0.8	2.6 ± 0.9
$t\bar{t}$	–	–	–	–	–	–
Wt	–	–	–	–	–	–
VV	3.0 ± 1.0	1.5 ± 0.8	1.6 ± 0.5	1.4 ± 0.6	1.7 ± 0.8	2.6 ± 0.9
FNP	–	–	–	–	–	–
Z/γ+jets	$0.02^{+0.11}_{-0.02}$	0.42 ± 0.20	–	$0.02^{+0.20}_{-0.02}$	–	$0.02^{+0.06}_{-0.02}$
other	0.03 ± 0.01	0.03 ± 0.02	–	0.04 ± 0.02	0.02 ± 0.01	0.02 ± 0.02

2L+0 Jets Results

SR2-	DF-a	DF-b	DF-c	DF-d
Observed	67	5	4	2
Fitted background events				
Total SM	57 ± 7	9.6 ± 1.9	$1.5^{+1.7}_{-1.5}$	0.6 ± 0.6
$t\bar{t}$	24 ± 8	–	–	–
Wt	4.5 ± 1.0	–	–	–
VV	26 ± 6	8.8 ± 1.8	$1.5^{+1.7}_{-1.5}$	0.6 ± 0.6
FNP	1.75 ± 0.18	0.57 ± 0.23	–	–
Z/γ+jets	–	–	–	–
other	0.40 ± 0.09	0.17 ± 0.07	0.07 ± 0.07	0.02 ± 0.02

SR2-	SF-loose	SF-tight	DF-100	DF-150	DF-200	DF-300
Observed	153	9	78	11	6	2
Fitted background events						
Total SM	133 ± 22	9.8 ± 2.9	68 ± 7	11.5 ± 3.1	2.1 ± 1.9	0.6 ± 0.6
$t\bar{t}$	27 ± 11	–	24 ± 8	–	–	–
Wt	5.0 ± 2.2	–	4.5 ± 1.0	–	–	–
VV	70 ± 11	9.6 ± 3.0	37 ± 8	10.8 ± 3.0	2.0 ± 1.9	0.6 ± 0.6
FNP	6 ± 4	0.0 ± 0.0	2.17 ± 0.29	0.42 ± 0.23	–	–
Z/γ+jets	23 ± 14	$0.09^{+0.34}_{-0.09}$	–	–	–	–
others	0.79 ± 0.23	0.09 ± 0.01	0.67 ± 0.16	0.26 ± 0.08	0.09 ± 0.07	0.02 ± 0.02

2L+Jets Results

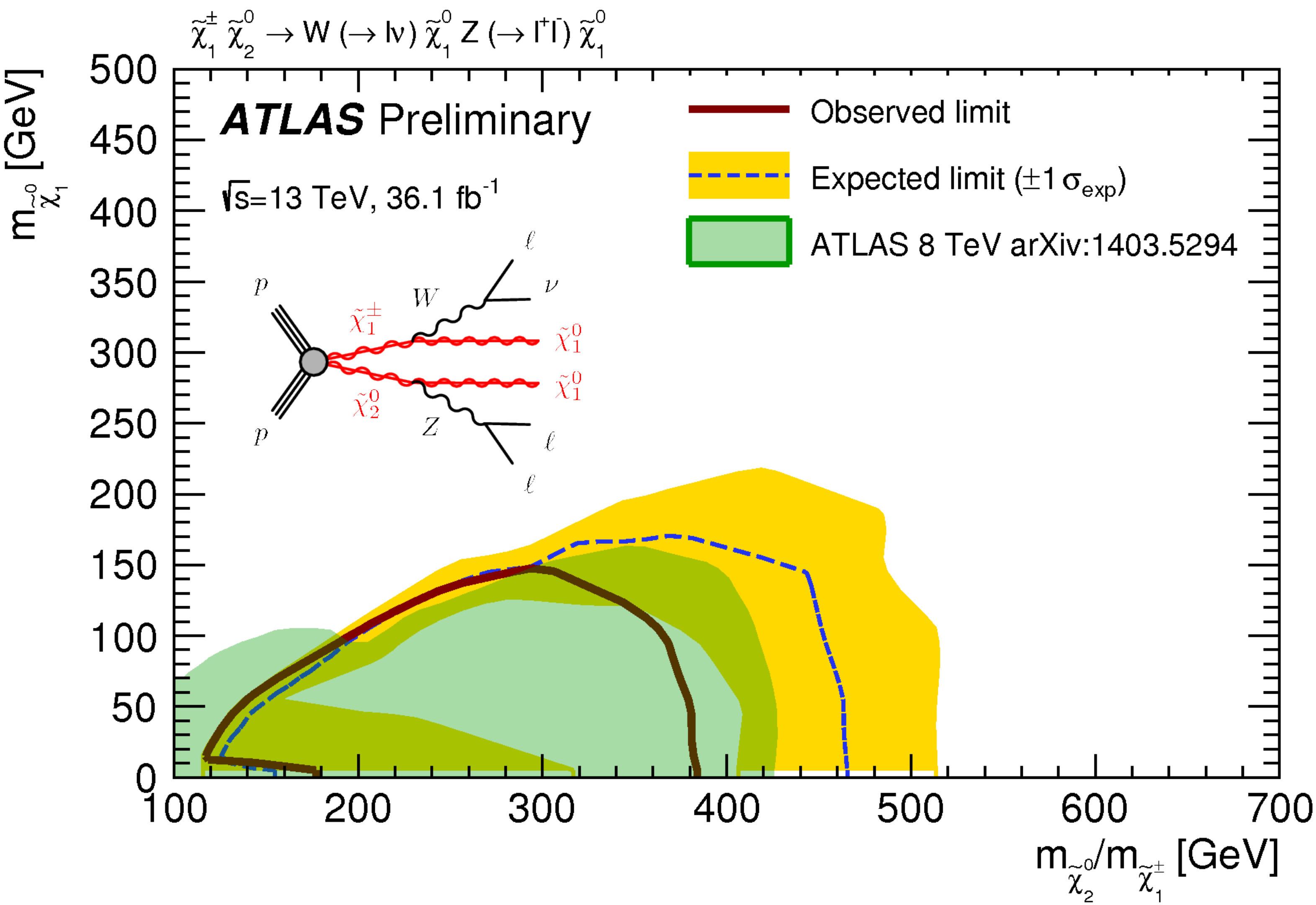
SR2-	int	high	low (combined)
Observed	2	0	11
Expected events			
Total SM	4.1 ± 2.6	1.6 ± 1.6	4.2 ± 3.8
VV	4.0 ± 1.8	1.6 ± 1.1	1.7 ± 1.0
$t\bar{t}$	0.15 ± 0.11	0.04 ± 0.03	0.8 ± 0.4
FNP	$0.0^{+0.2}_{-0.0}$	$0.0^{+0.1}_{-0.0}$	$0.7^{+1.8}_{-0.7}$
Z+jets	$0.0^{+1.8}_{-0.0}$	$0.0^{+1.2}_{-0.0}$	$1.0^{+2.7}_{-1.0}$

3L Results

SR3-	WZ-0Ja	WZ-0Jb	WZ-0Jc	WZ-1Ja	WZ-1Jb	WZ-1Jc
Observed	21	1	2	1	3	4
Fitted background events						
Total SM	21.74 ± 2.85	2.68 ± 0.46	1.56 ± 0.33	2.21 ± 0.53	1.82 ± 0.26	1.26 ± 0.34
WZ	19.48 ± 2.90	2.46 ± 0.46	1.33 ± 0.31	1.79 ± 0.48	1.49 ± 0.22	0.92 ± 0.28
ZZ	0.81 ± 0.23	0.06 ± 0.03	0.05 ± 0.01	0.05 ± 0.02	0.02 ± 0.01	0.02 ± 0.00
VVV	0.31 ± 0.07	0.13 ± 0.04	0.13 ± 0.03	0.11 ± 0.02	0.12 ± 0.03	0.23 ± 0.05
$t\bar{t}$V	0.04 ± 0.02	0.01 ± 0.01	0.01 ± 0.01	0.14 ± 0.04	0.12 ± 0.02	0.08 ± 0.02
Higgs	–	–	–	0.01 ± 0.00	–	–
FNP	1.10 ± 0.54	0.02 ± 0.01	0.04 ± 0.02	0.11 ± 0.06	0.07 ± 0.04	0.01 ± 0.00

SR3-	slep-a	slep-b	slep-c	slep-d	slep-e
Observed	4	3	9	0	0
Fitted background events					
Total SM	2.23 ± 0.79	2.79 ± 0.43	5.41 ± 0.93	1.42 ± 0.38	1.14 ± 0.23
WZ	1.08 ± 0.38	1.98 ± 0.31	3.85 ± 0.70	0.91 ± 0.26	0.76 ± 0.17
ZZ	0.02 ± 0.01	$0.01^{+0.01}_{-0.01}$	0.13 ± 0.03	0.06 ± 0.02	0.03 ± 0.01
VVV	0.26 ± 0.08	0.34 ± 0.05	0.72 ± 0.12	0.36 ± 0.10	0.25 ± 0.05
$t\bar{t}$V	0.07 ± 0.03	0.09 ± 0.02	0.20 ± 0.04	0.07 ± 0.02	0.02 ± 0.01
Higgs	0.01 ± 0.00	0.01 ± 0.01	0.03 ± 0.02	0.01 ± 0.00	–
FNP	0.80 ± 0.46	0.36 ± 0.18	0.48 ± 0.25	–	0.08 ± 0.04

3L Interpretation



Di-Tau SRs, CRs for Fake-Factor

CR-A	SR-D (SR-lowMass)
Di-tau+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	
≥ 2 loose tau leptons (SS)	≥ 2 medium tau leptons (OS)
$m(\tau_1, \tau_2) < 250$ GeV	
$\Delta R(\tau_1, \tau_2) > 1.5$	
$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
$m_{\mathrm{T2}} > 70$ GeV	$m_{\mathrm{T2}} > 70$ GeV
VR-E	**VR-F**
Di-tau trigger	
≥ 2 loose tau leptons (SS)	≥ 2 medium tau leptons (OS)
$m(\tau_1, \tau_2) < 250$ GeV	
$\Delta R(\tau_1, \tau_2) > 1.5$	
$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
$50 < m_{\mathrm{T2}} < 70$ GeV	$50 < m_{\mathrm{T2}} < 70$ GeV
CR-B	**CR-C**
Di-tau trigger	
≥ 2 loose tau leptons (SS)	≥ 2 medium tau leptons (OS)
$m(\tau_1, \tau_2) < 250$ GeV	
$\Delta R(\tau_1, \tau_2) > 1.5$	
$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
$20 < m_{\mathrm{T2}} < 50$ GeV	$20 < m_{\mathrm{T2}} < 50$ GeV

CR-A	SR-D (SR-highMass)
Di-tau+$E_{\mathrm{T}}^{\mathrm{miss}}$ or asymmetric di-tau trigger	
≥ 2 loose tau leptons (OS)	≥ 2 medium tau leptons (OS)
< 1 medium tau < 1 tight tau leptons	≥ 1 tight tau lepton
$\Delta R(\tau_1, \tau_2) > 1.8$	
$E_{\mathrm{T}}^{\mathrm{miss}} > 110$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 110$ GeV
$m_{\mathrm{T2}} > 90$ GeV	$m_{\mathrm{T2}} > 90$ GeV
VR-E	**VR-F**
Di-tau or asymmetric di-tau trigger	
≥ 2 loose tau leptons (OS)	≥ 2 medium tau leptons (OS)
< 1 medium tau < 1 tight tau leptons	≥ 1 tight tau lepton
$\Delta R(\tau_1, \tau_2) > 1.8$	
$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
$60 < m_{\mathrm{T2}} < 90$ GeV	$60 < m_{\mathrm{T2}} < 90$ GeV
CR-B	**CR-C**
Di-tau or asymmetric di-tau trigger	
≥ 2 loose tau leptons (OS)	≥ 2 medium tau leptons (OS)
< 1 medium tau < 1 tight tau leptons	≥ 1 tight tau
$\Delta R(\tau_1, \tau_2) > 1.8$	
$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
$10 < m_{\mathrm{T2}} < 60$ GeV	$10 < m_{\mathrm{T2}} < 60$ GeV

Di-Tau SRs, CRs, and VRs

Z-VR	Top-VR
At least one opposite-sign tau lepton pair	At least one opposite-sign tau lepton pair
Tau $p_T > 50, 40$ GeV	Tau $p_T > 50, 40$ GeV
$E_T^{miss} > 60$ GeV	$E_T^{miss} > 60$ GeV
At least two medium tau leptons	at least one medium and one loose tau lepton
b-jet veto	at least one b-jet
$m_{T2} < 10$ GeV	$m_{T2} > 10$ GeV
	m_{CT} top-tagged

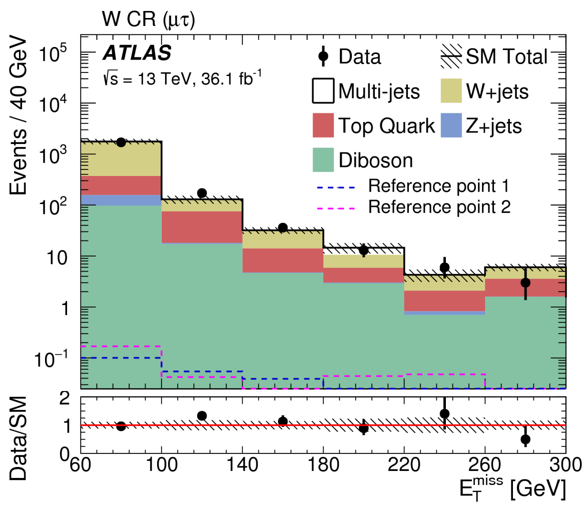
W-CR	W-VR
One isolated muon and one medium tau lepton with opposite sign	One isolated muon and one medium tau lepton with opposite sign
b-jet veto	b-jet veto
$m(\mu, \tau) > 70$ GeV	$m(\mu, \tau) > 70$ GeV
$E_T^{miss} > 60$ GeV	$E_T^{miss} > 60$ GeV
$50 < m_{T,\mu} < 150$ GeV	$50 < m_{T,\mu} < 150$ GeV
$m_{T,\mu} + m_{T,\tau} > 80$ GeV	$m_{T,\mu} + m_{T,\tau} > 80$ GeV
$0.5 < \Delta R(\mu, \tau) < 3.5$	$0.5 < \Delta R(\mu, \tau) < 4.5$
$10 < m_{T2} < 60$ GeV	$m_{T2} > 60$ GeV

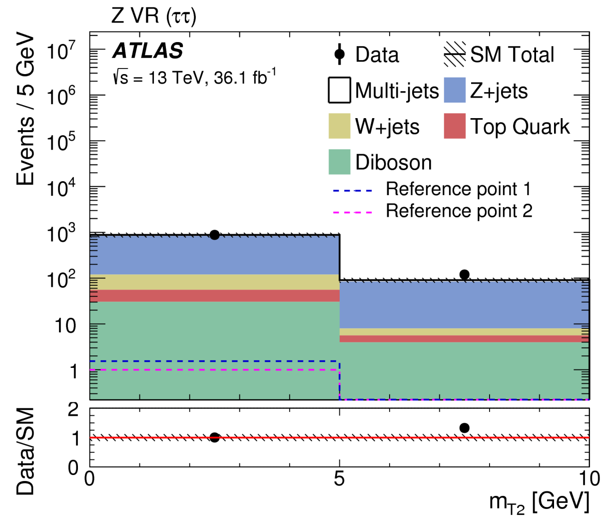
WW-VR	ZZ-VR
One opposite-sign lepton (e or μ) pair	One opposite-sign lepton (e or μ) pair
$\mu\ p_T >$30 GeV, $e\ p_T > 40$ GeV	$\mu\ p_T >$30 GeV, $e\ p_T > 40$ GeV
Jet veto	Jet veto
$m_{\ell\ell} > 50$ GeV	$m_{\ell\ell} > 50$ GeV
$E_T^{miss} > 50$ GeV	$E_T^{miss} > 50$ GeV
$m_{T,\mu} > 100$ GeV	$m_{T,\mu} > 100$ GeV
$m_{T2} > 70$ GeV	$m_{T2} > 70$ GeV
Two isolated leptons (e or μ) with different flavour	two isolated leptons (e or μ) with same flavour
m_{CT} top tag veto	$\Delta R(\ell, \ell) < 1.5$
	$\|m_{\ell\ell} - m_Z\| < 15$ GeV

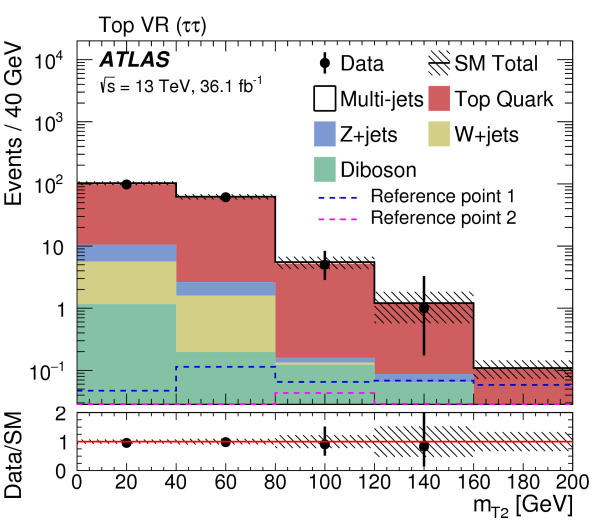
Di-Tau Systematic Uncertainties

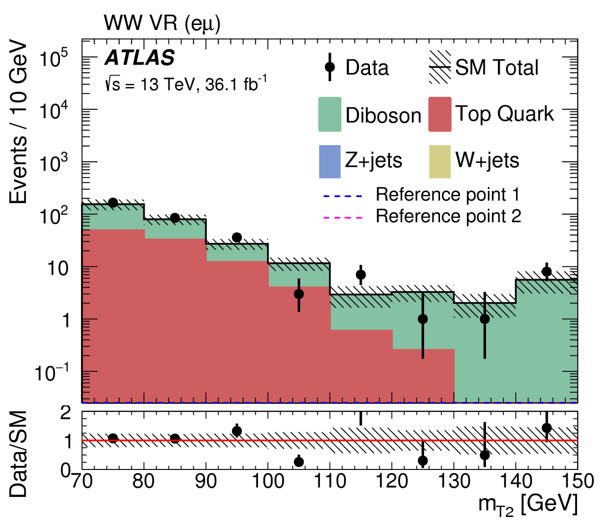
Source of systematic uncertainty	SR-lowMass	SR-highMass
Normalisation uncertainties of the multi-jet background	32	32
Statistical uncertainty of MC samples	18	24
Multi-jet estimation	14	13
Pile-up reweighting	8	8
Jet energy scale and resolution	11	4
Tau identification and energy scale	6	8
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution and scale	2	6
Total	40	38

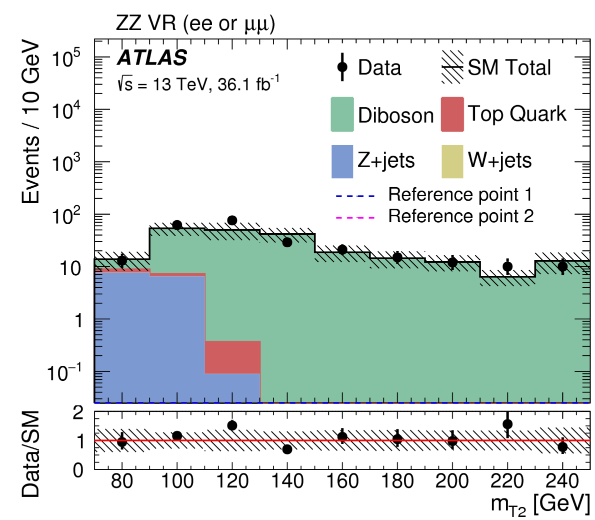
Di-Tau CRs


W CR (μτ)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Data
SM Total
Multi-jets
W+jets
Top Quark
Z+jets
Diboson
Reference point 1
Reference point 2
Events / 40 GeV
Data/SM
E_T^miss [GeV]

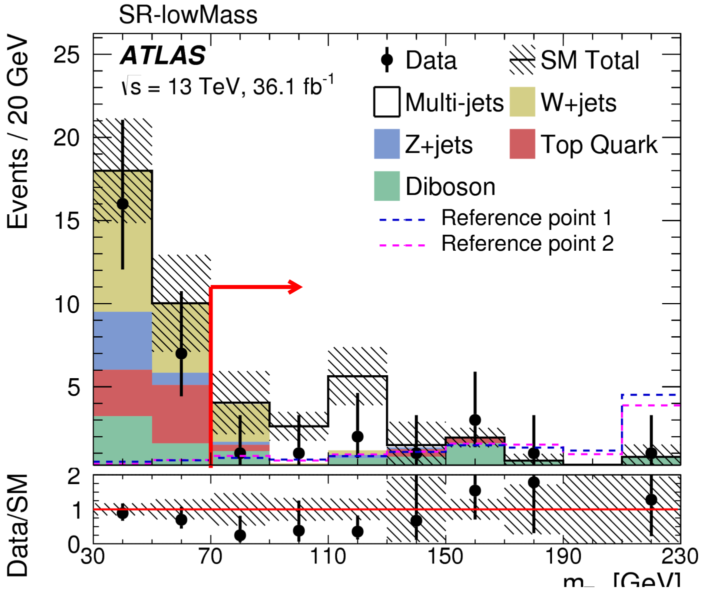

Z VR (ττ)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Data
SM Total
Multi-jets
Z+jets
W+jets
Top Quark
Diboson
Reference point 1
Reference point 2
Events / 5 GeV
Data/SM
m_T2 [GeV]

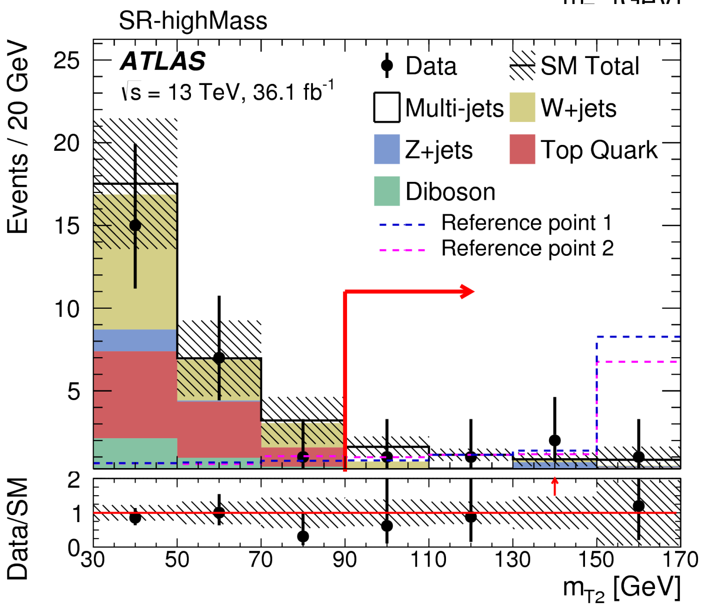

Top VR (ττ)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Data
SM Total
Multi-jets
Top Quark
Z+jets
W+jets
Diboson
Reference point 1
Reference point 2
Events / 40 GeV
Data/SM
m_T2 [GeV]

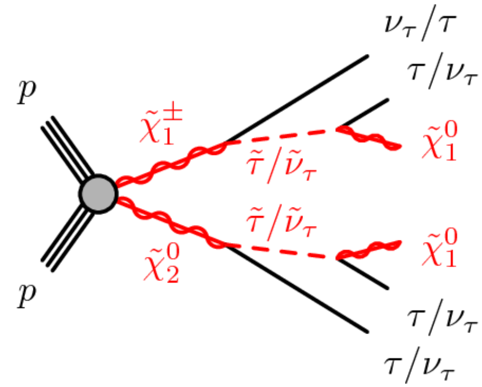

WW VR (eμ)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Data
SM Total
Diboson
Top Quark
Z+jets
W+jets
Reference point 1
Reference point 2
Events / 10 GeV
Data/SM
m_T2 [GeV]

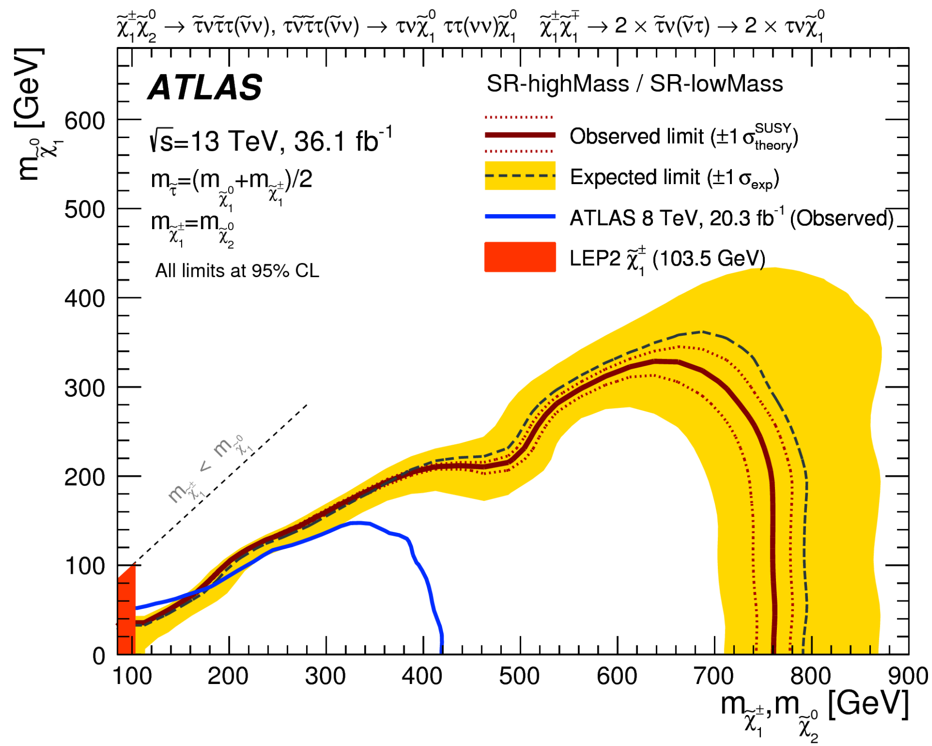

ZZ VR (ee or μμ)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Data
SM Total
Diboson
Top Quark
Z+jets
W+jets
Reference point 1
Reference point 2
Events / 10 GeV
Data/SM
m_T2 [GeV]

Di-Tau Results









Matrix Method

$$
\begin{bmatrix} N_{TT} \\ N_{Tl} \\ N_{lT} \\ N_{ll} \end{bmatrix} = \begin{bmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{bmatrix} \begin{bmatrix} N_{LL}^{RR} \\ N_{LL}^{RF} \\ N_{LL}^{FR} \\ N_{LL}^{FF} \end{bmatrix},
$$

$$
\begin{aligned}
N_{LL}^{RR} &= \quad (1-f_1)(1-f_2)N_{TT} - [f_2(1-f_1)]\, N_{Tl} - [f_1(1-f_2)]\, N_{lT} + f_1 f_2 N_{ll} \\
N_{LL}^{RF} &= -(1-f_1)(1-r_2)N_{TT} + [r_2(1-f_1)]\, N_{Tl} + [f_1(1-r_2)]\, N_{lT} + f_1 r_2 N_{ll} \\
N_{LL}^{RF} &= -(1-f_2)(1-r_1)N_{TT} + [f_2(1-r_1)]\, N_{Tl} + [r_1(1-f_2)]\, N_{lT} + f_2 r_1 N_{ll} \\
N_{LL}^{FF} &= \quad (1-r_1)(1-r_2)N_{TT} - [r_2(1-r_1)]\, N_{Tl} - [r_1(1-r_2)]\, N_{lT} + r_1 r_2 N_{ll}.
\end{aligned}
$$

with *r* and *f* being the efficiencies for “real” (prompt) and “fake” (non-prompt) leptons