Search for electroweak production of charginos and sleptons decaying to final states with two leptons and missing transverse momentum at Run II with the ATLAS detector

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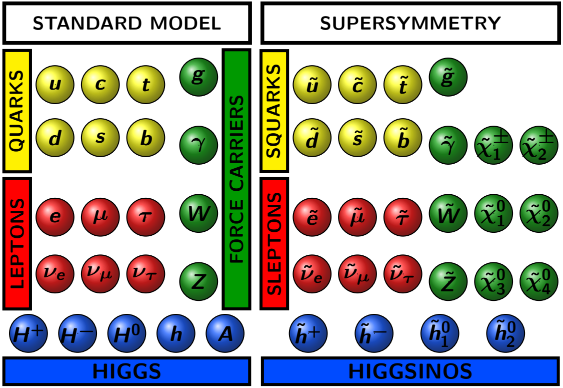
Introduction: SUperSYmmetry (SUSY)

Supersymmetry is a theoretical extension of the Standard Model (SM):

- It introduces a partner for each particle in the SM, whose spin differs by 1/2
- It would solve the hierarchy problem
- It allows force unification
- It introduces a new quantic number $R = (-1)^{3(B-L)+2S}$, such that

$$R = \begin{cases} +1 & \text{for } \textit{Particles} \\ -1 & \text{for } \textit{S-Particles} \end{cases}$$

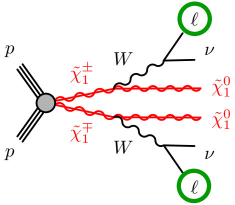
- If R is conserved, the lightest supersymmetric particle (LSP) is stable → dark matter candidate

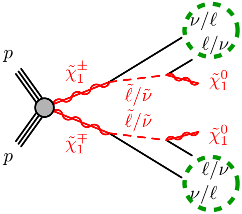


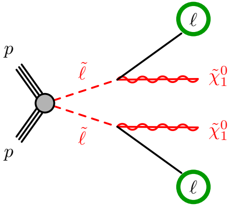
Charginos and **neutralinos** are combinations of supersymmetric charged and neutral partners of gauge and Higgs bosons:

$$\left.\begin{array}{l} \tilde{\chi}_i^{\pm},\ i = 1,2 \\ \tilde{\chi}_j^{0},\ j = 1,2,3,4 \end{array}\right\} \quad \text{Mass eigenstates}$$

Decays and interpretations







- Analysis and interpretation of results based on simplified models
- Analysis optimised for the first scenario, but results also interpreted in the other ones
- Only $\tilde{e}$ and $\tilde{\mu}$ considered in the last model and $\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\mu}_L$, $\tilde{\mu}_R$ assumed to be mass-degenerate
- Signature: 2 Opposite Sign (OS) leptons (electrons and muons) and Missing Transverse Energy (E_T^{miss})
- Results based on ATLAS-CONF-2019-008 unless stated otherwise

Analysis strategy: Global Outline

- Cut&Count analysis using full Run II data, corresponding to $\mathcal{L} = 139\ \text{fb}^{-1}$
- Analysis based on kinematic variable m_{T2} used to bound the masses of a pair of particles that are assumed to have each decayed semi-invisibly into one visible and one invisible particle
- Other useful variables: E_T^miss and E_T^miss significance, the latter used to evaluate the likelihood of the production of invisible particles
- Main background contributions: $t\bar{t}$ and Dibosons (VV)
- Preselection cuts applied:

Variable	Value
Lepton flavour[1]	$e\mu$ and ee, $\mu\mu$ with $\lvert m_{\ell\ell} - m_Z \rvert > 30$ GeV
Leading lepton p_T [GeV]	> 25
Sub-Leading lepton p_T [GeV]	> 25
Invariant Mass $m_{\ell\ell}$ [GeV]	> 25
m_{T2} [GeV]	> 60

[1] Different Flavour (DF) and Same Flavour (SF) events

Analysis strategy: Signal Regions (SR)

- Using CL_s prescription, global cuts defining SRs being optimized from 3 benchmark points: $m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = (250, 1), (300, 50), (300, 100)$
- m_{T2}-binning optimized for the entire signal grid

- Inclusive SRs for calculating model-independent limits on possible Beyond Standard Model (BSM) physics
- Binned SRs for calculating model-dependent exclusion limits

Region	SR-DF-0J	SR-DF-1J	SR-SF-0J	SR-SF-1J
$n_{\text{non-b-tagged jets}}$	$= 0$	$= 1$	$= 0$	$= 1$
$m_{\ell_1\ell_2}$ [GeV]	> 100		> 121.2	
E_T^{miss} [GeV]	> 110			
E_T^{miss} significance	> 10			
$n_{b\text{-tagged jets}}$	$= 0$			
	Binned SRs		Inclusive SRs	
m_{T2} [GeV]	$\in [100, 105)$ $\in [105, 110)$ $\in [110, 120)$ $\in [120, 140)$ $\in [140, 160)$ $\in [160, 180)$ $\in [180, 220)$ $\in [220, 260)$ $\in [260, \infty)$		$\in [100, \infty)$ $\in [100, 120)$ $\in [120, 160)$ $\in [160, \infty)$	

Analysis strategy: Control Regions (CR)

Main contributions to the SM irreducible background are evaluated in dedicated CRs, normalizing them (*scale factors*) to data through a likelihood fit:

- WW (Dominant contribution)
- ZZ and WZ (in regions with SF events)
- $t\bar{t}$ and single top

The reducible background of fake and non-prompt (FNP) leptons estimated using the Matrix Method (MM)

Region	CR-WW	CR-VZ	CR-top
Lepton Flavour	DF	SF	DF
$n_{b\text{-tagged jets}}$	$= 0$	$= 0$	$= 1$
$n_{\text{non-b-tagged jets}}$	$= 0$	$= 0$	$= 0$
m_{T2} [GeV]	$\in [60, 65]$	> 120	> 80
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$\in [60, 100]$	> 110	> 110
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	$\in [5, 10]$	> 10	> 10
$m_{\ell_1\ell_2}$ [GeV]	> 100	$\in [61.2, 121.2]$	> 100

Analysis strategy: Validation Regions (VR)

The normalization of the irreducible background from the fit is validated in 6 different VRs:

- VR-WW-0, VR-WW-1 according to the multiplicity of non-b-tagged jets
- VR-VZ for *WZ* and *ZZ* productions
- VR-top-low, VR-top-high, VR-top-WW for modelling of the top-quark production in regions with different m_{T2} ranges or where the contribution from top-quark backgrounds is relevant

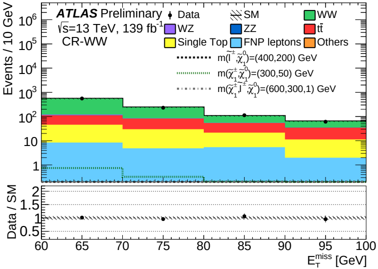
Region	VR-WW-0J	VR-WW-1J	VR-VZ	VR-top-low	VR-top-high	VR-top-WW
Lepton flavour	DF	DF	SF	DF	DF	DF
$n_{b\text{-tagged jets}}$	$= 0$	$= 0$	$= 0$	$= 1$	$= 1$	$= 1$
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$	$= 1$	$= 0$	$= 0$	$= 1$	$= 1$
m_{T2} [GeV]	$\in [65, 100]$	$\in [65, 100]$	$\in [100,120]$	$\in [80, 100]$	> 100	$\in [60, 65]$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 60	> 60	> 110	> 110	> 110	$\in [60, 100]$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	> 5	> 5	> 10	$\in [5, 10]$	> 10	$\in [5, 10]$
$m_{\ell_1 \ell_2}$ [GeV]	> 100	> 100	$\in [61.2, 121.2]$	> 100	> 100	> 100

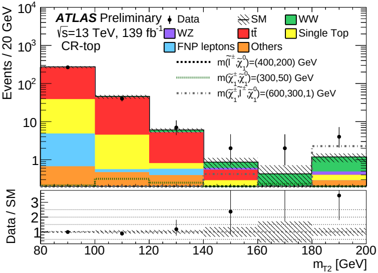
Systematic uncertainties

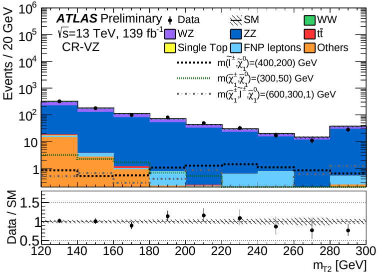
All relevant sources of experimental and theoretical systematic uncertainty are included in the likelihood fit:

- The dominant sources of systematic uncertainty are related to theory uncertainties in the MC modelling
- The largest sources of experimental uncertainty being related to the jet energy scale and resolution
- Minor sources of experimental uncertainty being related to b-jet identification efficiency, lepton energy scale and resolution, trigger efficiencies and re-weighting for different pile-up conditions
- Contributions to the uncertainty in the MM estimate of the FNP background

Results from likelihood fit: CRs



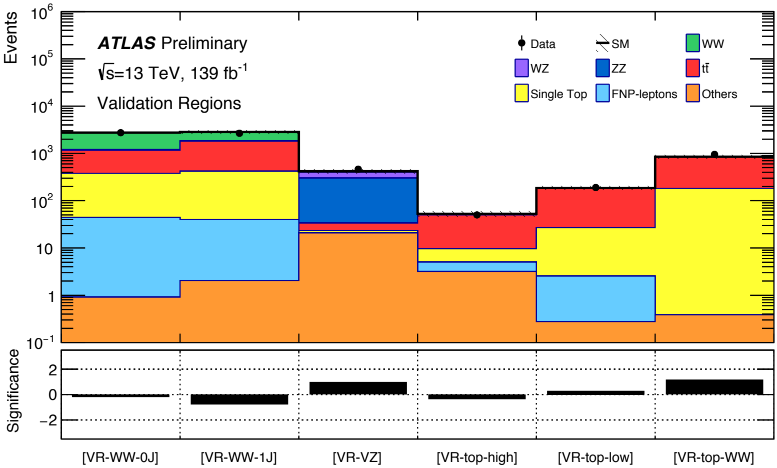




Scale Factors	Value
μ_{WW}	1.25 ± 0.11
μ_{VZ}	1.18 ± 0.05
μ_{top}	0.82 ± 0.06

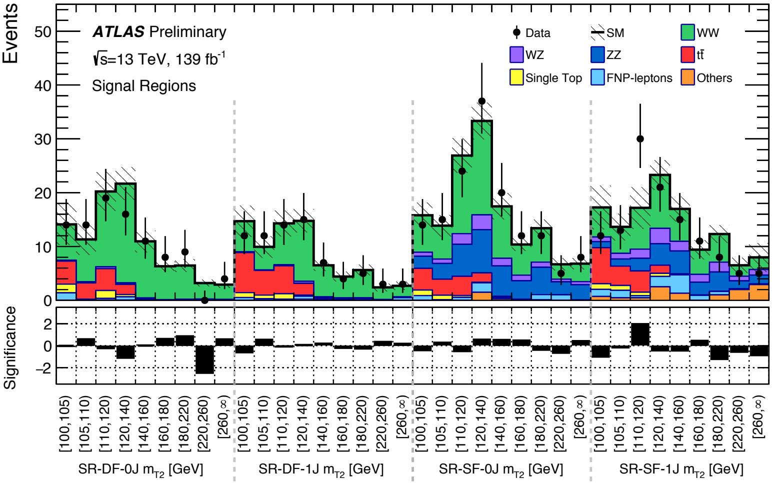
Results from likelihood fit: VRs

Good agreement between observed and fitted events in all of the VRs

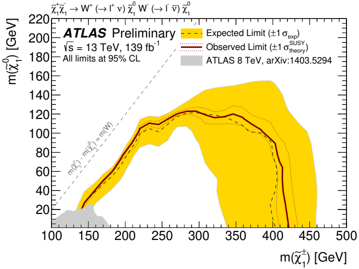


Results from likelihood fit: binned SRs

No significant excess in Data and Monte-Carlo (MC) comparison in none of the binned SRs

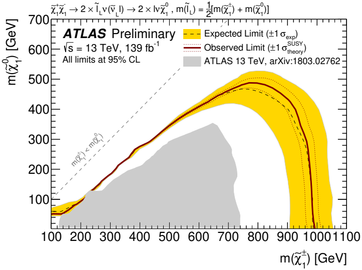


Results: Model-Dependent Limits

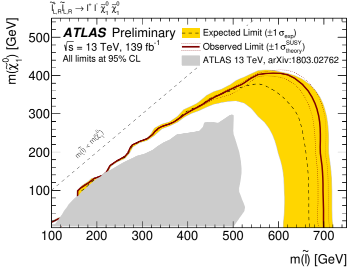


Exclusion limits at 95% CL set on the masses of the chargino, neutralino and sleptons for the simplified models considered

$\tilde{\chi}_1^\pm$ masses up to 420 GeV and 1 TeV are excluded



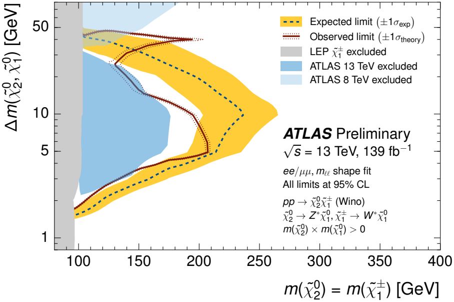
$\tilde{\ell}$ masses up to 700 GeV are excluded

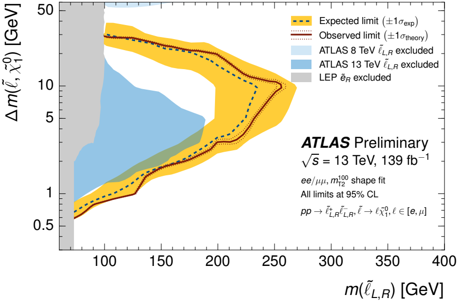


Compressed scenarios

ATLAS-CONF-2019-014

From the compressed analysis, exclusion limits set on small mass splitting scenarios





Conclusions

- A search for the electroweak production of charginos and sleptons decaying into final states with exactly two OS leptons and missing transverse momentum have been presented
- The analysis uses 139 fb^{-1} of $\sqrt{s} = 13$ TeV proton-proton collisions recorded by the ATLAS detector at the LHC between 2015 and 2018
- Three scenarios are considered:
  - The production of $\tilde{\chi}_1^{\pm}$ pairs, followed by their decays into final states with leptons and $\tilde{\chi}_1^0$, via either W-bosons or $\tilde{\ell}/\tilde{\nu}$
  - The direct production of $\tilde{\ell}$ pairs, where each slepton decays directly into $\tilde{\chi}_1^0$ and a lepton
- No significant deviations from the SM expectations are observed and limits at 95% CL are set on the masses of relevant SUSY particles in each of these scenarios
- These results significantly improve upon previous exclusion limits for the same scenarios

Backup

E_T^{miss} significance

Previously, the event-based E_T^{miss} significance $\mathcal{S}$ was defined as

$$\mathcal{S} = \frac{E_T^{miss}}{\sqrt{\sum E_T}}$$

assuming E_T^{miss} being calculated using calorimeter signals only. A new approach is to consider the log-likelihood ratio:

$$\mathcal{S}^2 = 2\ln\left(\frac{\max_{p_T^{inv}\neq 0}\mathcal{L}(E_T^{miss}|p_T^{inv})}{\max_{p_T^{inv}=0}\mathcal{L}(E_T^{miss}|p_T^{inv})}\right)$$

Last expression can be rewritten in terms of total variances σ_L^2 and σ_T^2 in the longitudinal and transverse directions to the E_T^{miss}, and a correlation factor ρ_{LT} of the longitudinal L and transverse T measurements:

$$\mathcal{S}^2 = \frac{|E_T^{miss}|^2}{\sigma_L^2(1-\rho_{LT}^2)}$$

Systematic uncertainties

All relevant sources of experimental and theoretical systematic uncertainty affecting the SM background estimates and the signal predictions are included in the likelihood fit:

- The dominant sources of systematic uncertainty are related to theory uncertainties in the MC modelling
  - For dibosons production, relevant contributions from renormalisation and factorisation scales are accounted for
  - For $t\bar{t}$ production, uncertainties in the parton shower simulation, modelling of initial- and final-state radiation, choice of the event generator are the dominant contributions
  - For single top-quark production, an uncertainty is associated with the treatment of the interference between the Wt and $t\bar{t}$ samples
- The largest sources of experimental uncertainty being related to the jet energy scale (JES) and jet energy resolution (JER)
- Minor sources of experimental uncertainty being related to soft-term resolution, scale, b-jet identification efficiency, lepton energy scale and resolution, trigger efficiencies and re-weighting procedure to account for different pile-up conditions
- Contributions to the uncertainty in the MM estimate of the FNP background

Results from likelihood fit: CRs

Region	CR-WW	CR-VZ	CR-top
Observed events	962	811	321
Fitted backgrounds	962 ± 31	811 ± 28	321 ± 18
Fitted WW	670 ± 60	19.1 ± 1.9	5.5 ± 2.7
Fitted WZ	11.8 ± 0.7	188 ± 7	0.32 ± 0.15
Fitted ZZ	0.29 ± 0.06	577 ± 23	–
Fitted $t\bar{t}$	170 ± 50	1.8 ± 1.3	270 ± 16
Fitted Single top	88 ± 8	0.65 ± 0.35	38.6 ± 2.6
Other backgrounds	0.17 ± 0.06	19 ± 7	2.21 ± 0.20
FNP	21 ± 8	5^{+6}_{-5}	4.2 ± 2.2
Simulated WW	528	15.1	4.3
Simulated WZ	9.9	158	0.27
Simulated ZZ	0.24	487	–
Simulated $t\bar{t}$	210	2.2	327
Simulated Single top	107	0.8	46.7

Results from likelihood fit: VRs

Regions	VR-WW-0J	VR-WW-1J	VR-VZ	VR-top-low	VR-top-high	VR-top-WW
Observed events	2742	2671	464	190	50	953
Fitted backgrounds	2760 ± 120	2840 ± 250	420 ± 40	185 ± 17	53 ± 7	850 ± 80
Fitted WW	1550 ± 150	990 ± 120	17.6 ± 2.2	2.1 ± 0.7	2.6 ± 1.3	16.1 ± 2.5
Fitted WZ	34.2 ± 2.0	27.0 ± 2.3	99 ± 9	$0.05^{+0.17}_{-0.05}$	$0.2^{+0.6}_{-0.2}$	0.53 ± 0.13
Fitted ZZ	0.50 ± 0.06	0.39 ± 0.07	268 ± 25	–	–	$0.01^{+0.03}_{-0.01}$
Fitted $t\bar{t}$	790 ± 110	1400 ± 270	10.5 ± 3.2	157 ± 15	40 ± 7	650 ± 70
Fitted Single top	336 ± 32	380 ± 40	2.2 ± 1.4	24.3 ± 2.6	4.6 ± 1.4	182 ± 15
Other backgrounds	0.92 ± 0.30	2.1 ± 0.5	21^{+27}_{-21}	0.28 ± 0.06	3.20 ± 0.20	0.39 ± 0.11
FNP	44 ± 23	38 ± 21	$0.2^{+2.1}_{-0.2}$	2.3 ± 1.4	1.8 ± 0.5	–
Simulated WW	1230	790	14.0	1.6	2.0	12.8
Simulated WZ	28.8	22.8	84	0.04	0.1	0.45
Simulated ZZ	0.42	0.33	226	–	–	0.01
Simulated $t\bar{t}$	960	1700	13	190	49	790
Simulated Single top	406	462	2.6	29.4	5.6	220

Results: Model-Independent Limits

Region	SR-DF-0J	SR-DF-0J	SR-DF-0J	SR-DF-0J
m_{T2} [GeV]	∈[100,∞)	∈[160,∞)	∈[100,120)	∈[120,160)
Observed events	95	21	47	27
Fitted backgrounds	97 ± 15	18.8 ± 2.4	45 ± 9	33 ± 5
Fitted WW	76 ± 10	18.2 ± 2.3	29 ± 4	29 ± 4
Fitted WZ	1.53 ± 0.17	0.40 ± 0.07	0.66 ± 0.11	0.47 ± 0.07
Fitted ZZ	0.20 ± 0.04	0.14 ± 0.03	$0.06^{+0.23}_{-0.06}$	–
Fitted $t\bar{t}$	13 ± 7	–	11 ± 6	2.1 ± 1.2
Fitted single top	3.7 ± 2.0	–	3.3 ± 1.8	0.42 ± 0.25
Other backgrounds	0.24 ± 0.08	0.07 ± 0.02	0.08 ± 0.02	0.09 ± 0.05
FNP leptons	1.8 ± 0.6	–	1.4 ± 0.4	0.47 ± 0.17
$S^{0.95}_{\rm obs}$	33.9	12.7	23.8	11.8
$S^{0.95}_{\rm exp}$	$35.1^{+13.9}_{-10.0}$	$11.0^{+4.9}_{-3.2}$	$22.8^{+9.1}_{-6.5}$	$15.1^{+6.3}_{-4.5}$
$\sigma^{0.95}_{\rm obs}$ [fb]	0.24	0.09	0.17	0.08
p_0	0.50	0.33	0.44	0.50

Region	SR-SF-0J	SR-SF-0J	SR-SF-0J	SR-SF-0J
m_{T2} [GeV]	∈[100,∞)	∈[160,∞)	∈[100,120)	∈[120,160)
Observed events	147	37	53	57
Fitted backgrounds	145 ± 12	37.3 ± 3.0	56 ± 6	51 ± 5
Fitted WW	73 ± 8	18.1 ± 2.1	27.6 ± 3.0	27 ± 4
Fitted WZ	10.8 ± 0.8	3.08 ± 0.26	3.55 ± 0.29	4.2 ± 0.5
Fitted ZZ	38.6 ± 2.6	13.8 ± 1.0	11.1 ± 0.8	13.7 ± 1.5
Fitted $t\bar{t}$	13 ± 4	–	11 ± 4	1.9 ± 0.7
Fitted single top	2.4 ± 1.4	–	2.2 ± 1.3	0.15 ± 0.09
Other backgrounds	2.1 ± 1.5	$0.10^{+0.33}_{-0.10}$	$0.2^{+1.4}_{-0.2}$	1.76 ± 0.30
FNP leptons	5.4 ± 1.4	2.2 ± 0.4	1.1 ± 0.6	2.0 ± 0.5
$S^{0.95}_{\rm obs}$	35.5	14.3	17.8	23.5
$S^{0.95}_{\rm exp}$	$33.5^{+13.6}_{-9.3}$	$14.5^{+6.3}_{-4.2}$	$20.0^{+8.1}_{-5.6}$	$18.7^{+7.8}_{-5.3}$
$\sigma^{0.95}_{\rm obs}$ [fb]	0.25	0.10	0.13	0.17
p_0	0.44	0.50	0.50	0.25

Region	SR-DF-1J	SR-DF-1J	SR-DF-1J	SR-DF-1J
m_{T2} [GeV]	∈[100,∞)	∈[160,∞)	∈[100,120)	∈[120,160)
Observed events	75	15	38	22
Fitted backgrounds	75 ± 9	15.1 ± 2.7	39 ± 6	21.3 ± 2.8
Fitted WW	48 ± 8	13.4 ± 2.6	17.7 ± 2.5	17.1 ± 2.8
Fitted WZ	1.54 ± 0.21	0.53 ± 0.12	0.43 ± 0.09	0.59 ± 0.11
Fitted ZZ	0.08 ± 0.01	$0.07^{+0.24}_{-0.07}$	–	0.01 ± 0.00
Fitted $t\bar{t}$	20 ± 7	0.09 ± 0.03	17 ± 6	2.4 ± 0.9
Fitted single top	2.8 ± 1.4	–	2.6 ± 1.3	0.21 ± 0.13
Other backgrounds	0.80 ± 0.13	0.25 ± 0.05	0.19 ± 0.10	0.34 ± 0.04
FNP leptons	2.2 ± 0.6	0.71 ± 0.16	0.87 ± 0.29	0.59 ± 0.16
$S^{0.95}_{\rm obs}$	25.1	10.2	16.8	12.3
$S^{0.95}_{\rm exp}$	$25.3^{+10.3}_{-7.2}$	$10.3^{+4.6}_{-3.0}$	$17.6^{+7.3}_{-5.1}$	$11.9^{+5.2}_{-3.3}$
$\sigma^{0.95}_{\rm obs}$ [fb]	0.18	0.07	0.12	0.09
p_0	0.50	0.50	0.50	0.45

Region	SR-SF-1J	SR-SF-1J	SR-SF-1J	SR-SF-1J
m_{T2} [GeV]	∈[100,∞)	∈[160,∞)	∈[100,120)	∈[120,160)
Observed events	120	29	55	36
Fitted backgrounds	124 ± 12	36 ± 5	48 ± 8	40 ± 4
Fitted WW	48 ± 6	14.1 ± 2.1	18.1 ± 2.4	16.0 ± 2.2
Fitted WZ	13.4 ± 1.0	5.2 ± 0.6	3.62 ± 0.33	4.7 ± 0.5
Fitted ZZ	22.2 ± 1.8	9.1 ± 1.1	4.8 ± 0.5	8.2 ± 0.9
Fitted $t\bar{t}$	16 ± 8	$0.07^{+0.10}_{-0.07}$	14 ± 7	1.6 ± 0.8
Fitted single top	3.3 ± 1.7	–	2.6 ± 1.4	0.7 ± 0.4
Other backgrounds	11.1 ± 4.0	5.6 ± 2.1	$1.7^{+2.4}_{-1.7}$	3.8 ± 1.3
FNP leptons	10.3 ± 1.5	1.80 ± 0.34	3.1 ± 0.6	5.3 ± 0.7
$S^{0.95}_{\rm obs}$	30.6	11.2	27.3	12.6
$S^{0.95}_{\rm exp}$	$33.3^{+12.9}_{-9.5}$	$15.3^{+6.5}_{-4.5}$	$21.9^{+9.0}_{-6.2}$	$15.5^{+6.5}_{-4.2}$
$\sigma^{0.95}_{\rm obs}$ [fb]	0.22	0.08	0.19	0.09
p_0	0.50	0.50	0.26	0.50