Search for direct production of electroweakinos in final states with one lepton, jets and missing transverse momentum with ATLAS detector

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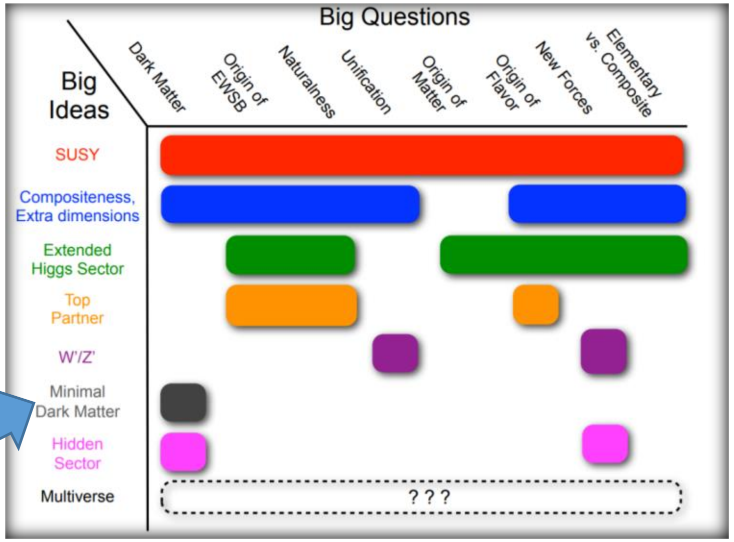
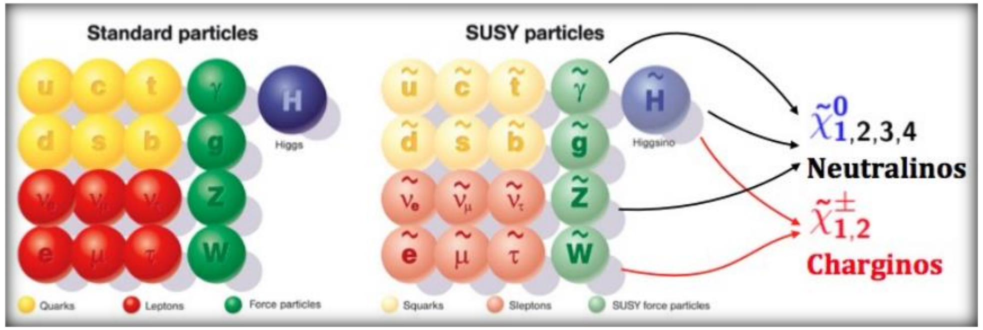
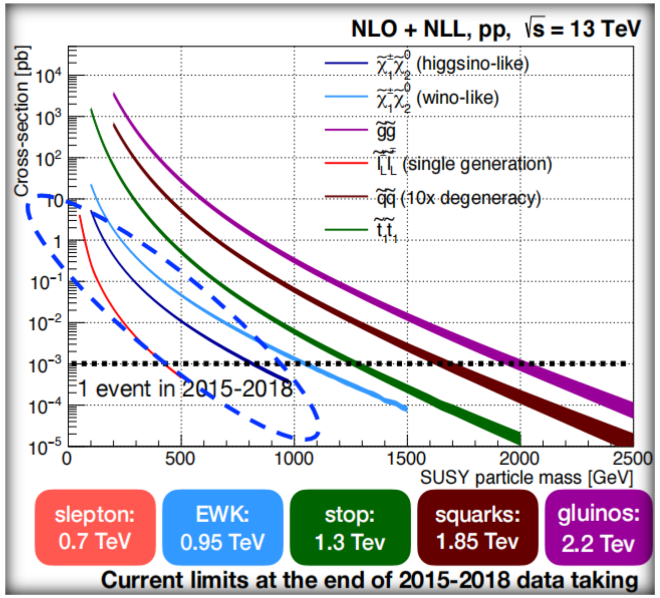
Introduction

- Standard model (SM) :
  - Advantage: Precisely describes the fundamental elements of the matter and the interactions between them.
  - Problems: hierarchy problem, grand unification of gauge couplings, dark matter... -> BSM physics is strongly motivated.



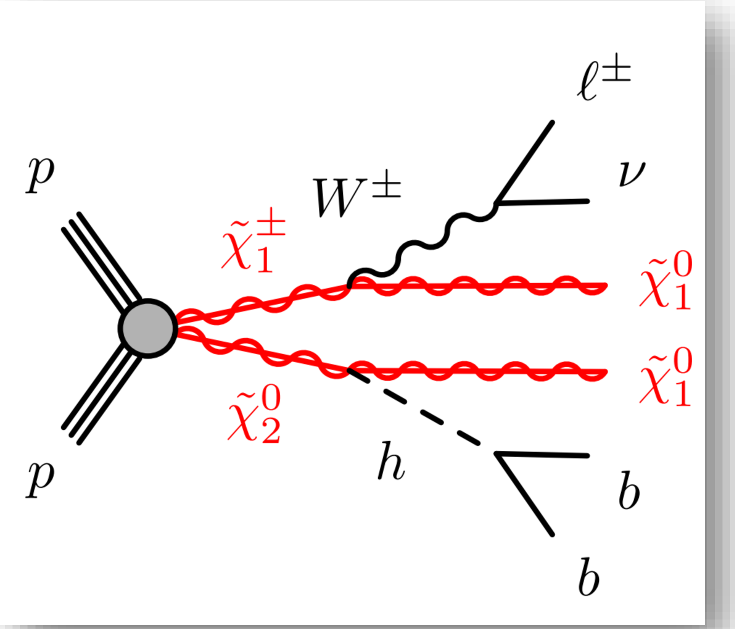
- Supersymmetry (SUSY): one of the most appealing BSM theories.
  - Introduce new symmetry between bosons and fermions.
  - No SUSY particles were discovered so far. -> Limits at LHC.



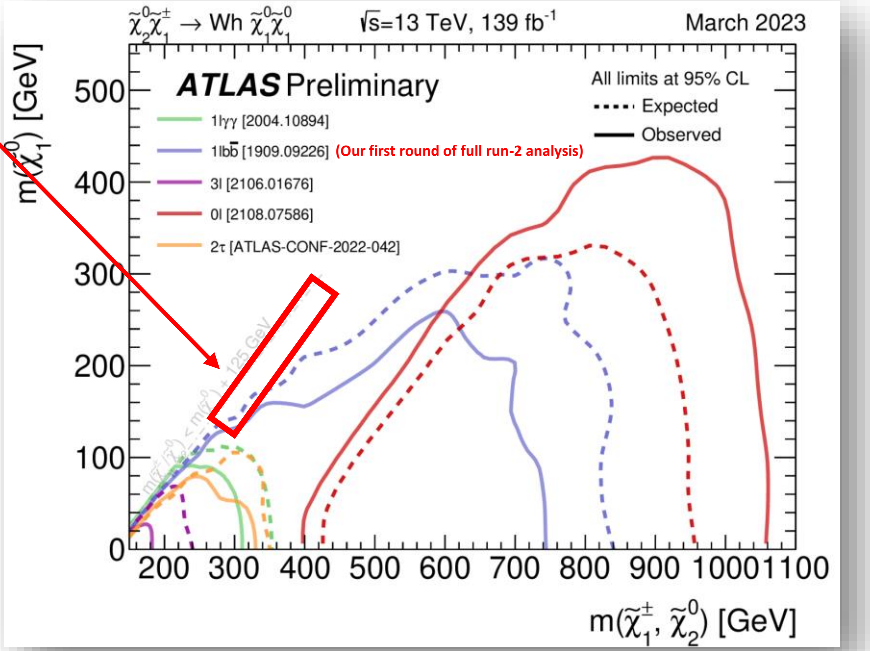


Introduction

- This presentation focus on electroweakino search targeting direct EWK production of **chargino-neutralino pairs**, decaying **into LSP via W/h boson**.
  - Final state: exactly **one isolated lepton** (ele or mu), **b-jets** and large **missing transverse momentum**.
  - Targeting **full Run 2 data** of **139 fb^{-1}**.
  - Target $m_h < \Delta m\ (\chi_1^{\pm}, \chi_1^{0}) < 250$ GeV



Existing results



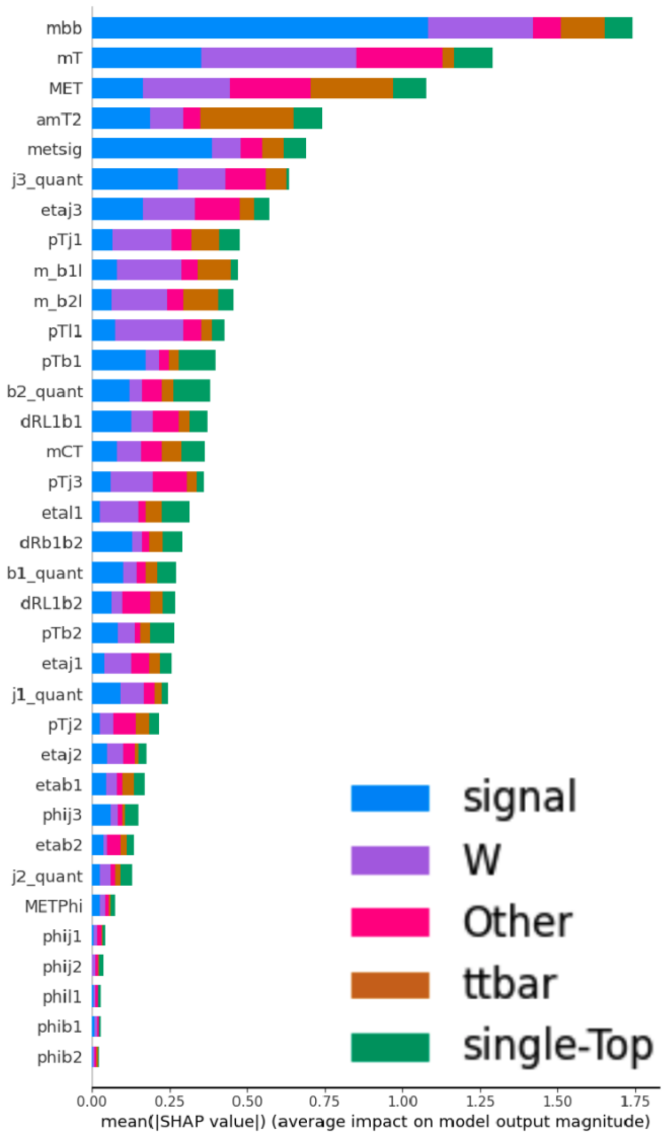
Event Classification: BDT Training

- Use BDT method to classify the events:
  - Framework: XGBoost
  - Input variables: including object-level and event-level variables.
  - Input samples: multiple signal sample ($m_h < \Delta m\ (\chi_1^{\pm}, \chi_1^0) < 250$ GeV) and SM background sample.
  - Events are classified in ***five different categories***: Signal and 4 background processes ($t\bar{t}$, Single-top, W+jets, Other minor background).
  - Trained in ***1 vs rest multi-classification procedure***. -> better than using a binary signal vs background classifiers.
  - Output: BDTscore (w) for signal and different background.

ML variable inputs
Object-level variables:
p_T^l, η^l, ϕ^l $p_T^{b_1}, \eta^{b_1}, \phi^{b_1}$ $p_T^{b_2}, \eta^{b_2}, \phi^{b_2}$ $p_T^{j_3}, \eta^{j_3}, \phi^{j_3}$ $b_{quantile}^{b_1}, b_{quantile}^{b_2}$ $b_{quantile}^{j_1}, b_{quantile}^{j_2}, b_{quantile}^{j_3}$
Event-level variables:
m_{bb} m_{CT} m_{T} $E_{\mathrm{T}}^{\mathrm{miss}}$ $\phi(E_{\mathrm{T}}^{\mathrm{miss}})$ a_{MT2} $E_{\mathrm{T}}^{\mathrm{miss}}$ Sig. [29] n_{Jets} $\Delta R_{b_1,b_2}$ m_{b1l} m_{b2l} $\Delta R_{l,b_1}$ $\Delta R_{l,b_2}$

Event Classification: BDT Training

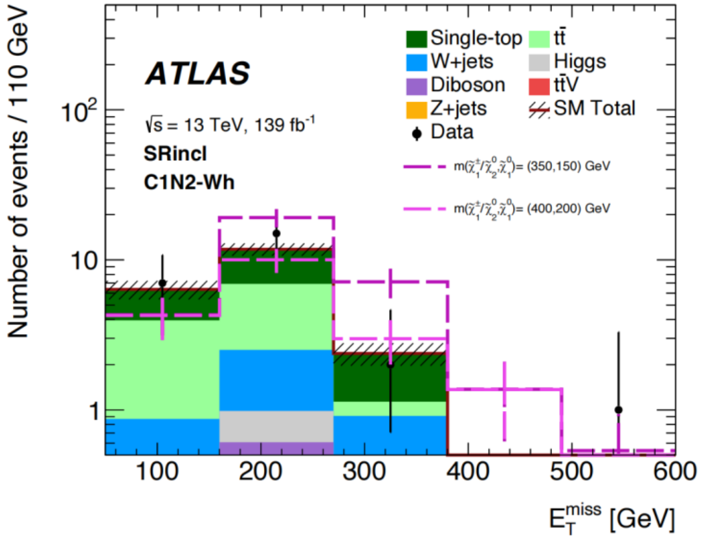
- **Used SHAP** (SHapley Adaptive exPlanations, 2017) 'State of the art for explaining feature importance' to understand the real impact of input features and how they are used in the model
- It evaluates the change in each output score when a feature is considered vs not considered.
- Rather intuitive results for the dominant variables:
  - m_{bb} has the greatest impact in the signal score
  - m_T and $\sigma_{E_T^{miss}}$ also have a large impact in the signal score
  - m_T has the largest impact for the W category, am_{T2} has the largest impact for the ttbar category

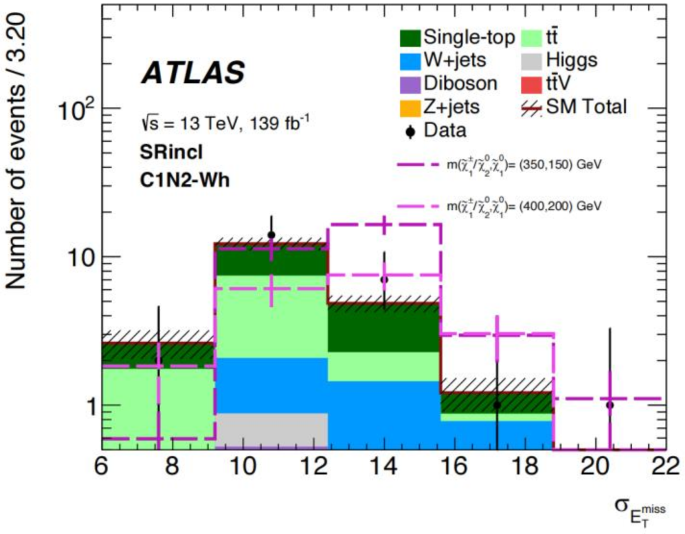


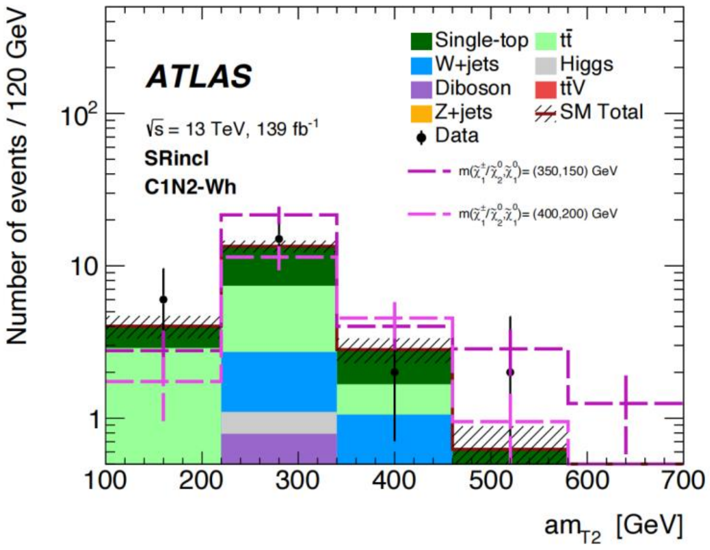
Event selection

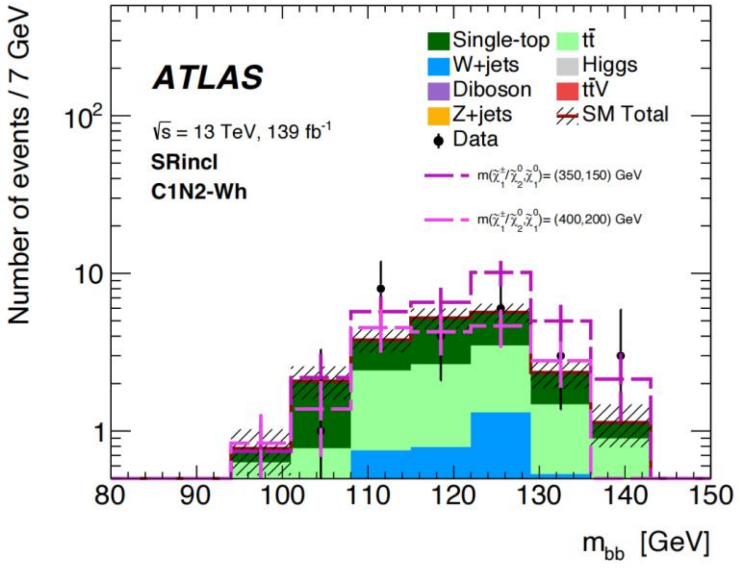
SR definition

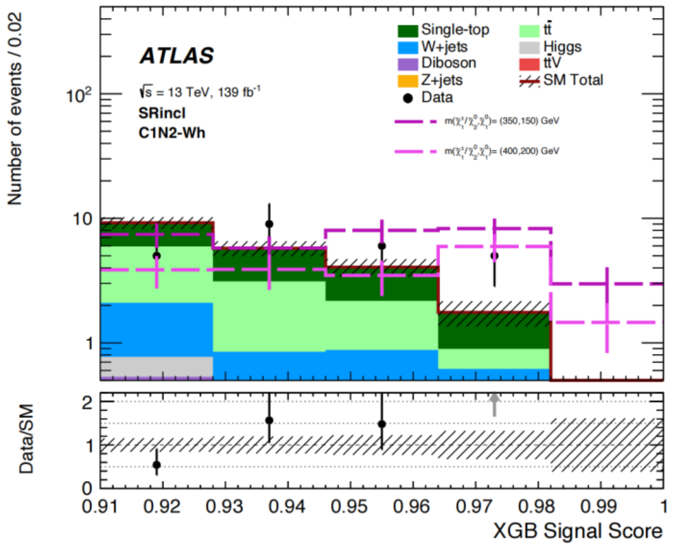
- Exactly one lepton with P_T > 27 GeV
- 2-3 Jets with P_T > 30 GeV
- Exactly two b-tagged jets
- 90 GeV < m_{bb} < 140 GeV
- E_T^{miss} > 50 GeV
- $\sigma_{E_T^{miss}}$ > 8
- $w_{sig} \in [0.91, 0.928, 0.948, 0.964, 1]$









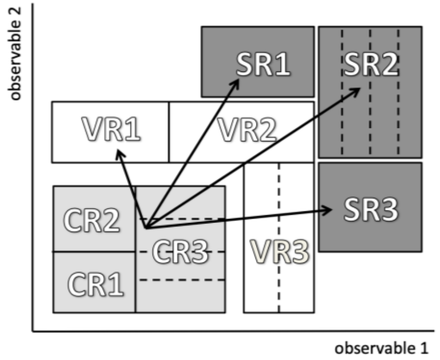


- As expected, events with high w_{sig} score have large E_T^{miss} , $\sigma_{E_T^{miss}}$ and am_{T2} and have m_{bb} close to the mass of higgs.

Background estimation

- Dominant background: $t\bar{t}$ (30% - 35%), Single-top(30% - 35%), W+jets (15% - 20%)
  - Define dedicated CRs to estimate the backgrounds and VRs to validate the estimation.
  - Use BDT score to define corresponding regions.
- Small background: Z+jets, diboson, $t\bar{t} + V$ and Higgs boson production processes

Variable	Regions		
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 50		
N_{lep} ($p_{\mathrm{T}} > 27$ GeV)	1		
N_{jet} ($p_{\mathrm{T}} > 30$ GeV)	2–3		
$N_{b-\mathrm{jet}}$ ($p_{\mathrm{T}} > 30$ GeV)	2		
m_{bb} [GeV]	$\in [50, 200]$		
$\sigma_{E_{\mathrm{T}}^{\mathrm{miss}}}$	> 5		
	CR $t\bar{t}$ (**CRttXGB**)	CR single-top (**CRstXGB**)	CR W+jets (**CRWXGB**)
w_{sig}	$\in [0.2, 0.3]$	$\in [0, 0.2]$	$\in [0.0, 0.2]$
$w_{t\bar{t}}$	> 0.73	–	–
w_{st}	< 0.2	> 0.45	< 0.2
$w_{\mathrm{W+jets}}$	< 0.4	–	> 0.65
	VR $t\bar{t}$ (**VRttXGB**)	VR single-top (**VRstXGB**)	VR W+jets (**VRWXGB**)
w_{sig}	$\in [0.4, 0.9]$	$\in [0.2, 0.9]$	$\in [0.2, 0.9]$
$w_{t\bar{t}}$	> 0.4	–	–
w_{st}	< 0.2	> 0.2	< 0.2
$w_{\mathrm{W+jets}}$	< 0.4	–	> 0.4



Low w_{sig} to reduce signal contamination.

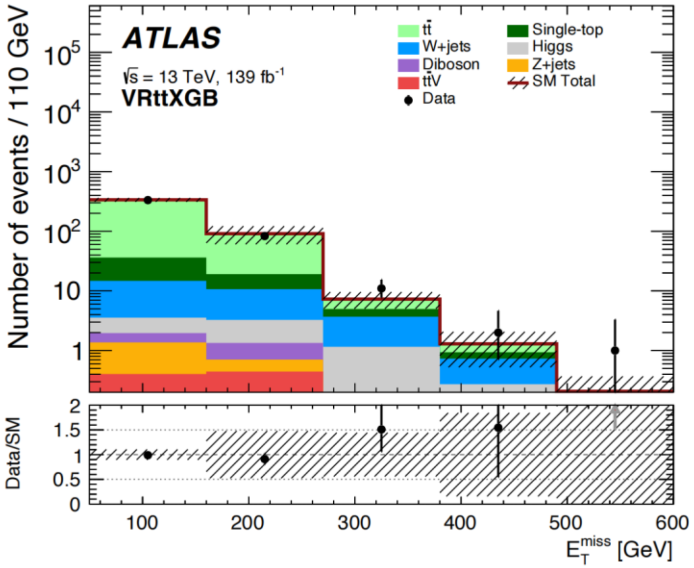
Use BDTscore cuts for each background to maximize the background purity in corresponding CR.

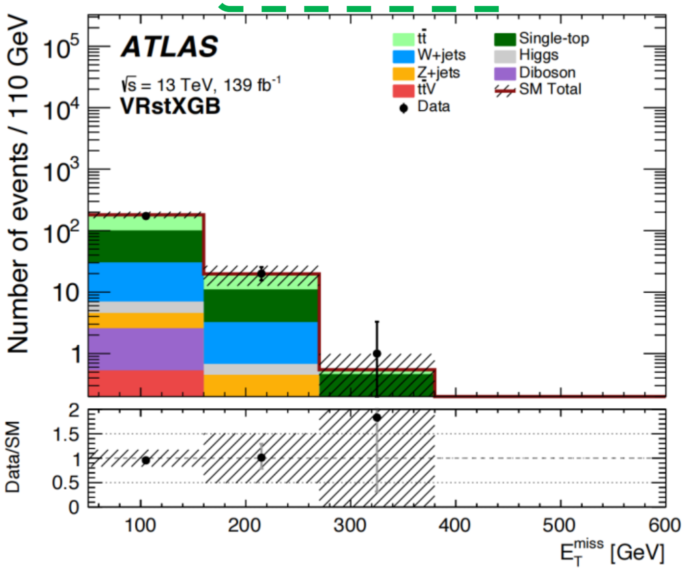
Higher w_{sig} than CR to approach SR.

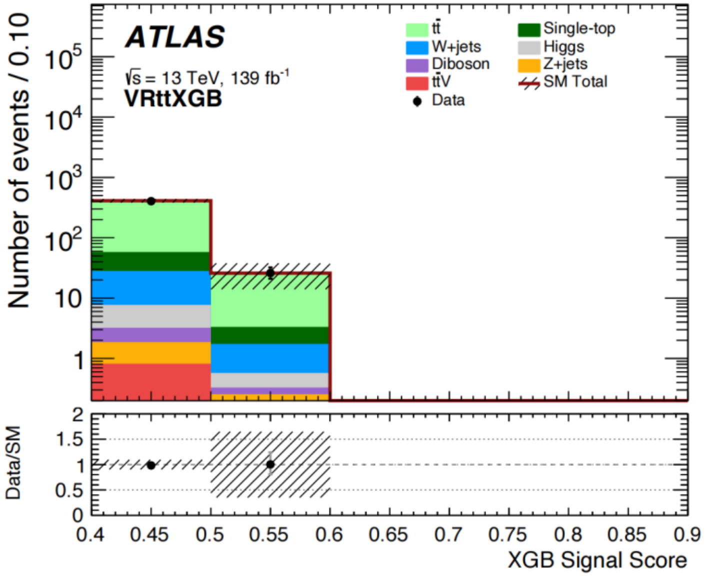
Background estimation

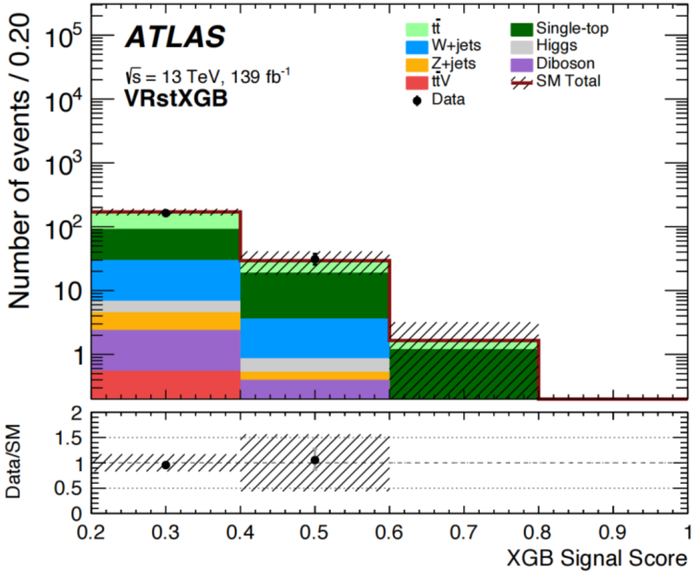
$t\bar{t}$ VR

Single-top VR









The data and the background expectation in all VRs agree well within around 1σ

Systematic Uncertainties

C1C1-Wh model	SRXGB Bin 1 [0.91, 0.928)	SRXGB Bin 2 [0.928, 0.948)	SRXGB Bin 3 [0.948, 0.964)	SRXGB Bin 4 [0.964, 1]
Total background expectation	9.4	5.7	4.2	2.2
Total background systematic uncertainty	±2.1	±2.0	±1.4	±0.7
Theoretical systematic uncertainties				
$t\bar{t}$	±1.1	±0.7	±0.5	±0.10
Single top	±1.2	±0.9	±0.9	±0.4
W+jets	±0.17	±0.14	±0.12	±0.04
Other backgrounds	±0.14	±0.13	±0.13	±0.10
MC statistical uncertainties				
MC statistical uncertainty	±1.0	±0.8	±0.7	±0.4
Uncertainties in the background normalisation				
Normalisation of dominant backgrounds	±1.3	±0.9	±0.5	±0.19
Experimental systematic uncertainties				
Jet energy resolution	±1.1	±1.2	±0.6	±0.4
Jet energy scale	±0.5	±0.31	±0.33	±0.07
b-tagging	±0.12	±0.8	±0.05	±0.06
Pile-up/JVT	±0.4	±0.5	±0.29	±0.09
Lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ uncertainties	±0.05	±0.4	±0.14	±0.12

- ✓ **The uncertainties in the Normalization of dominate background contribute 9 - 16% for each SR.**
- ✓ **The dominant experimental uncertainty arises from the JER (12% - 20%) followed by the JES and b-tagging**
- ✓ **The MC statistical uncertainties contribute up to 19% depending on the SR.**

Fit strategy

- Fit using HistFitter:
  - **Background only fit**: Only the CRs are used to constrain the fit parameters. Any potential signal contribution is neglected everywhere. -> To calculate background estimation in SRs and VRs.
  - **Model-dependent fit**: Both CRs and SRs are used in the fit. The signal contribution is taken into account as predicted by the tested model in all the regions. -> To calculate the exclusion limits.
  - **Model-independent fit**: Both CRs and SRs are used in the fit. The signal is independently considered in each SR without specific model. -> To derive model-independent upper limits.

Results: Background only fit

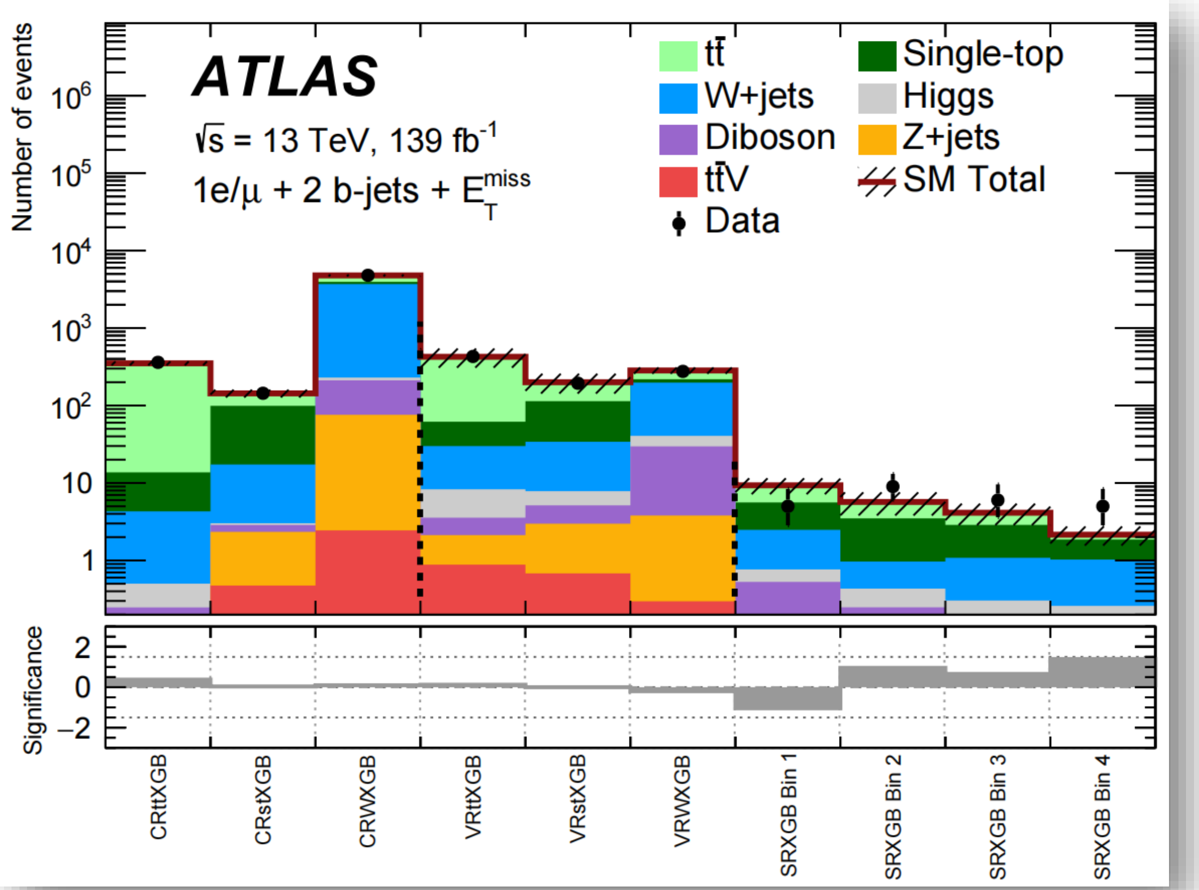
Fit parameter

mu_ $t\bar{t}$ = 1.00 $\pm$ 0.29

mu_single-top = 0.95 $\pm$ 0.19

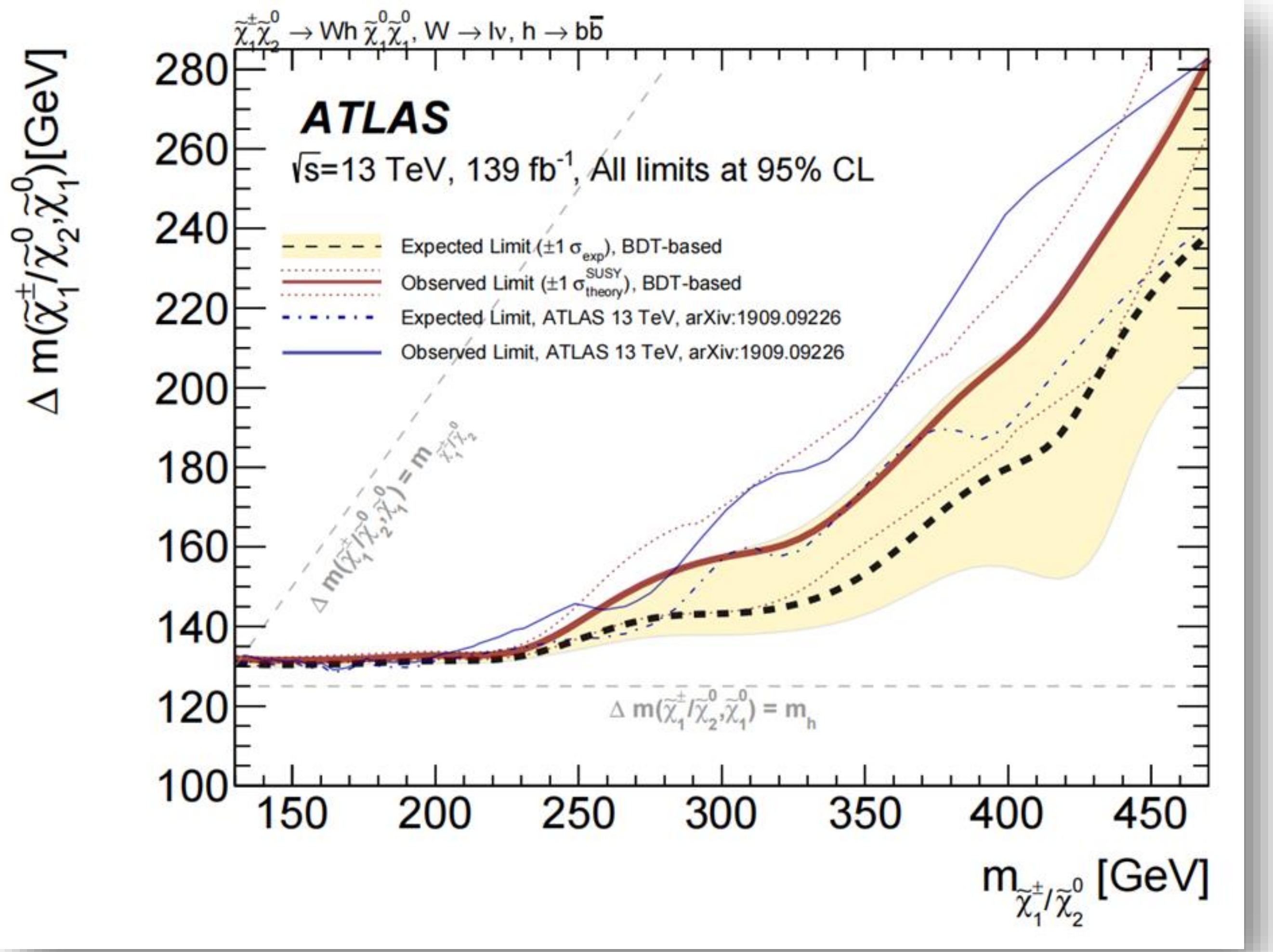
mu_W+jets = 1.30 $\pm$ 0.05

Pull plot



No significant excesses are observed in data above the SM prediction.

Results: Model-dependent fit



✓ **Exceed previous constraints at low Δm $(\chi_1^{\pm}/\chi_2^0, \chi_1^0)$ by up to 40 GeV in the range of 200 – 260 GeV and 280 – 470 GeV in m $(\chi_1^{\pm}, \chi_2^0)$.**

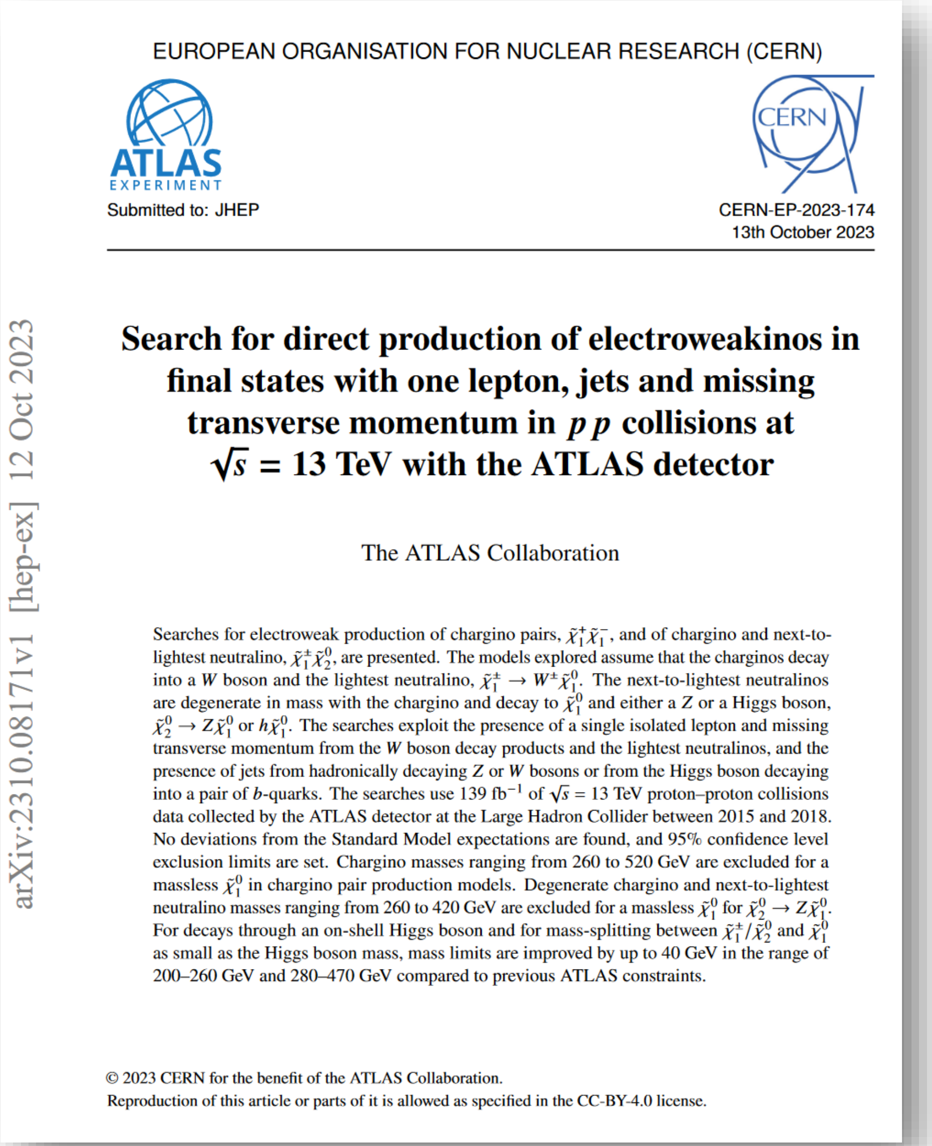
Results: Model-independent fit

Table 12: The number of observed events, total SM background, 95% CL upper limits on the visible cross-section ($\langle \epsilon\sigma \rangle^{95}_{obs}$) and on the number of signal events (S^{95}_{obs}). The fifth column (S^{95}_{exp}) shows the 95% CL upper limit on the number of signal events, given the expected number (with ± 1 standard deviation excursions on the expectation) of background events. The last three columns indicate the CL_B value that provides a measure of compatibility of the observed data with the 95% CL signal strength hypothesis relative to fluctuations of the background, the discovery p-value (p_0) that measures compatibility of the observed data with the background-only (zero signal strength) hypothesis relative to fluctuations of the background and the corresponding Gaussian significance (Z). Larger values indicate greater relative compatibility. The p_0 is not calculated in signal regions with a deficit relative to the nominal background prediction and here the p_0 value is capped at 0.50.

Signal channel	Observed events	Total SM background	$\langle \epsilon\sigma \rangle^{95}_{\mathrm{obs}}$[fb]	S^{95}_{obs}	S^{95}_{exp}	$\mathrm{CL_B}$	p_0	Z
SR (inclusive)	25	21.4 ± 4.2	0.12	16.2	$13.4^{+5.5}_{-4.0}$	0.70	0.29	0.57
SR Bin 2–4	20	12.0 ± 3.0	0.13	17.9	$10.7^{+4.7}_{-3.1}$	0.92	0.06	1.58
SR Bin 3–4	11	6.3 ± 1.6	0.09	12.0	$7.4^{+3.5}_{-2.3}$	0.89	0.08	1.42
SR Bin 4	5	2.2 ± 1.0	0.06	8.0	$5.1^{+2.7}_{-1.6}$	0.86	0.08	1.37

Summary

- Presented a search for direct EWK production of **chargino-neutralino**, decaying to **1L** via **W/h** and **LSP.**
- The search is performed in events with one isolated lepton, b-jets and E_T^{miss} based on full Run-2 data.
- The BDT-based approach is used to improve the sensitivity in the complex compressed phase-space.
- No significant deviation from the expected Standard Model background is observed.
- The current search improve previous constraints at low $\Delta\mathrm{m}$ ($\chi_1^{\pm}/\chi_2^0, \chi_1^0$) by up to 40 GeV in the range of 200 – 260 GeV and 280 – 470 GeV in m ($\chi_1^{\pm}, \chi_2^0$).
- Model-independent fit results are also provided.
- More details in arvix (https://arxiv.org/abs/2310.08171).



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Submitted to: JHEP

CERN-EP-2023-174
13th October 2023

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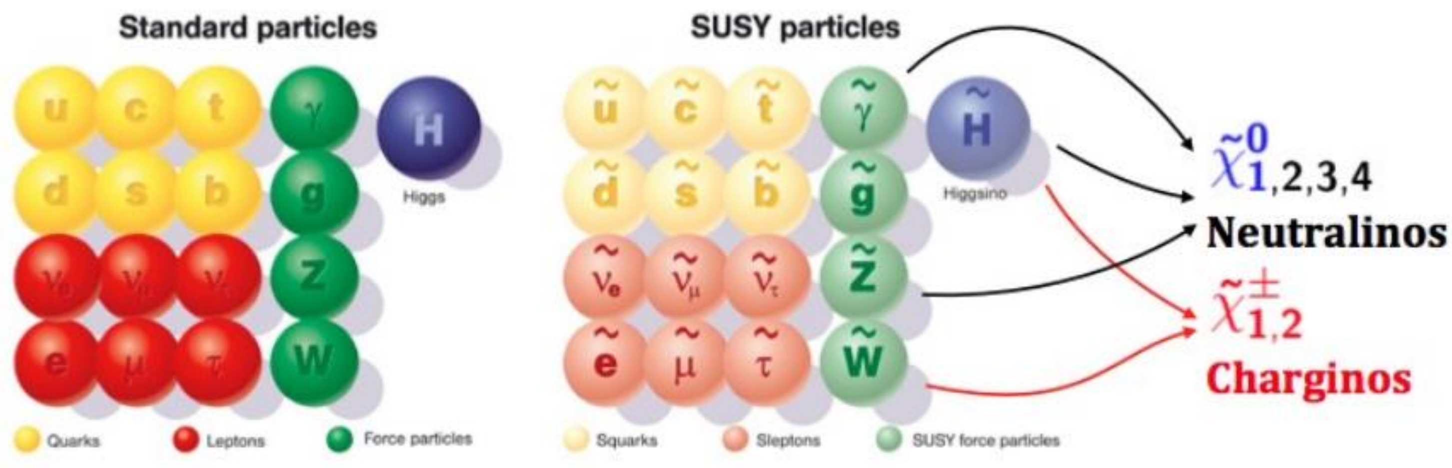
Search for direct production of electroweakinos in final states with one lepton, jets and missing transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

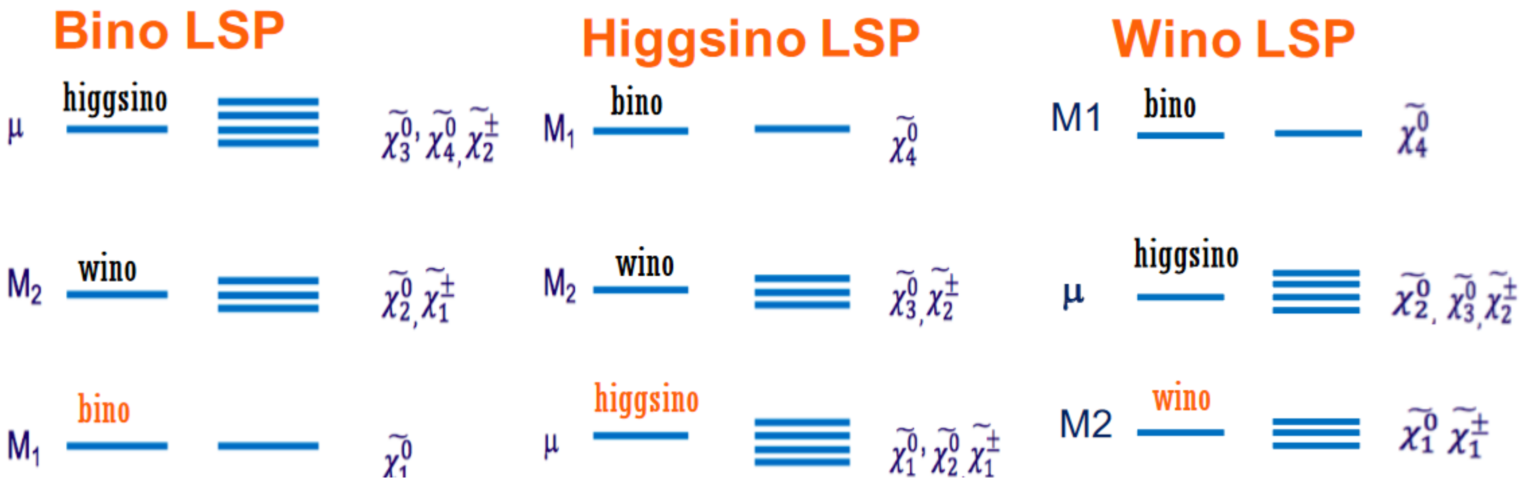
The ATLAS Collaboration

Searches for electroweak production of chargino pairs, $\tilde{\chi}_1^+\tilde{\chi}_1^-$, and of chargino and next-to-lightest neutralino, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, are presented. The models explored assume that the charginos decay into a W boson and the lightest neutralino, $\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0$. The next-to-lightest neutralinos are degenerate in mass with the chargino and decay to $\tilde{\chi}_1^0$ and either a Z or a Higgs boson, $\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$ or $h\tilde{\chi}_1^0$. The searches exploit the presence of a single isolated lepton and missing transverse momentum from the W boson decay products and the lightest neutralinos, and the presence of jets from hadronically decaying Z or W bosons or from the Higgs boson decaying into a pair of b-quarks. The searches use 139 fb^{-1} of $\sqrt{s}$ = 13 TeV proton–proton collisions data collected by the ATLAS detector at the Large Hadron Collider between 2015 and 2018. No deviations from the Standard Model expectations are found, and 95% confidence level exclusion limits are set. Chargino masses ranging from 260 to 520 GeV are excluded for a massless $\tilde{\chi}_1^0$ in chargino pair production models. Degenerate chargino and next-to-lightest neutralino masses ranging from 260 to 420 GeV are excluded for a massless $\tilde{\chi}_1^0$ for $\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$. For decays through an on-shell Higgs boson and for mass-splitting between $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ as small as the Higgs boson mass, mass limits are improved by up to 40 GeV in the range of 200–260 GeV and 280–470 GeV compared to previous ATLAS constraints.

Backup

SUSY EWK model





Data and simulated samples

- Data: full Run-2 data, corresponding to 139 fb^{-1} data collected between 2015 and 2018.
- Background samples:

Process	Generator	Parton shower and hadronisation	Tune	PDF	Cross-section
$t\bar{t}$	Powheg Box v2 [67–70]	Pythia 8.230 [47]	A14 [61]	NNPDF2.3LO [48]	NNLO+NNLL [71]
Single top	Powheg Box v2 [72–74]	Pythia 8.230	A14	NNPDF2.3LO	NLO+NNLL [75]
W/Z+jets	Sherpa 2.2.1 & 2.2.11 [76]	Sherpa 2.2.1 & 2.2.11	Sherpa standard	NNPDF3.0NNLO	NNLO [77]
Diboson	Sherpa 2.2.1 [76] & 2.2.2	Sherpa 2.2.1 & 2.2.2	Sherpa standard	NNPDF3.0NNLO	NLO [77]
Multiboson	Sherpa 2.2.1 & 2.2.2	Sherpa 2.2.1 & 2.2.2	Sherpa standard	NNPDF3.0NNLO	NLO [77]
$t\bar{t}+V$	MadGraph5_aMC@NLO v2.3.3	Pythia 8.210	A14	NNPDF2.3LO	NLO [78]
$t\bar{t}+h$	Powheg Box v2	Pythia 8.230	AZNLO [79]	CTEQ6L1 [80]	NLO [81]
Vh	Powheg Box v2	Pythia 8.212	A14	NNPDF2.3LO	NLO [81]

- Signal samples:
  - LSP is bino-like; $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ are wino-like and mass-degenerate
  - Generated using **aMC@NLO +Pythia 8**. Cross sections calculated at **NLO+NLL**.
  - The production cross-section of both processes decreases as the mass of the $\tilde{\chi}_1^{\pm}$ increases.
  - The cross-section is 0.62 fb (1.34fb) for C1N2(1000,0) and C1C1(1000,0).

Object reconstruction

Cut	Value/description
Preselected jet	
Algorithm	anti-k_t-4, EMPFlow
Acceptance	$p_T > 20$ GeV, $\|\eta\| < 4.5$
Signal jet	
Acceptance	$p_T > 30$ GeV, $\|\eta\| < 2.8$
JetVertexTagger	JVT @ *tight* working point for $p_T < 60$ GeV and $\|\eta\| < 2.4$
Signal *b*-jet	
b-tagger Algorithm	DL1r @ 77 % PC working point
Acceptance	$p_T > 30$ GeV, $\|\eta\| < 2.8$

Cut	Value/description
Preselected Electron	
Algorithm	AuthorElectron
Acceptance	$p_T >$ 7GeV, $\|\eta^{clust}\| < 2.47$
Quality	LooseAndBLayerLLH
IP	$\|\Delta z_0 \sin(\theta)\|$<0.5 mm
Signal Electron	
Acceptance	$p_T >$ 7GeV, $\|\eta^{clust}\| < 2.47$
Quality	TightLLH
Isolation	PLVLoose for $p_T < 75$ GeV PLVTight for $p_T > 75$ GeV
IP	$d_0/\sigma(d_0) < 5$

Cut	Value/description
Preselected muon	
Acceptance	$p_T > 6$ GeV, $\|\eta\| < 2.7$
Quality	Medium
IP	$\|\Delta z_0 \sin(\theta)\|$<0.5 mm
Signal muon	
Acceptance	$p_T > 6$ GeV, $\|\eta\| < 2.5$
Isolation	PLVLoose for $p_T < 75$ GeV PflowTight_VarRad for $p_T > 75$ GeV
IP	$d_0/\sigma(d_0) < 3$

Large-R Jet

- Anti-k_t algorithm (R = 1.0)
- Trimmed with $f_{cut} = 0.05$ and $R_{sub} = 0.2$
- $p_T > 200$ GeV; $|\eta| < 2.0$
- **W/Z-tagging**: 3-var, 50% WP

Met

- baseline objects + TST.
- Tight WP.

✓ **AnalysisOverlap removal procedure** applied to **baseline objects** and relied on **SUSY background forum recommendation.**

✓ **Dedicated isolation** study performed for **electron/muon identification.**

trigger

- Events are recorded with the ORing of a list of single lepton (electron and muon) triggers.

Trigger	Trigger name	Year	HLT cut [GeV]	Offline cut [GeV]
single electron trigger	HLT_e24_lhmedium_L1EM20VH	2015	24	25
	HLT_e60_lhmedium	2015	60	61
	HLT_e120_lhloose	2015	120	121
	HLT_e26_lhtight_nod0_ivarloose	2016-2018	26	27
	HLT_e60_lhmedium_nod0	2016-2018	60	61
	HLT_e140_lhloose_nod0	2016-2018	140	141
single muon trigger	HLT_mu20_iloose_L1MU15	2015	20	21
	HLT_mu26_ivarmedium	2016-2018	26	27.3
	HLT_mu50	2015-2018	50	52.5

Some key variables

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos[\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\ell}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}})])},$$

$$\sigma_{E_{\mathrm{T}}^{\mathrm{miss}}} = \sqrt{2 \ln \left[\frac{\max_{\boldsymbol{p}_{\mathrm{T}}^{\mathrm{inv}} \neq 0} \mathcal{L}\left(E_{\mathrm{T}}^{\mathrm{miss}} | \boldsymbol{p}_{\mathrm{T}}^{\mathrm{inv}}\right)}{\max_{\boldsymbol{p}_{\mathrm{T}}^{\mathrm{inv}} = 0} \mathcal{L}\left(E_{\mathrm{T}}^{\mathrm{miss}} | \boldsymbol{p}_{\mathrm{T}}^{\mathrm{inv}}\right)} \right]}.$$

$$am_{\mathrm{T2}} = \min(m_{\mathrm{T2}}(\ell + j_1, j_2), m_{\mathrm{T2}}(\ell + j_2, j_1))$$

m_{T2} is defined as $\min[\max(m_{\mathrm{T}}^2(p_\alpha, p), m_{\mathrm{T}}^2(p_\beta, q))]$

Systematic Uncertainties

- Theoretical uncertainty:
  - Signal:
    - factorization, renormalization, CKKW
  - Ttbar & single-top:
    - Parton Shower, Hard Scattering, ISR, FSR, interference between single-top Wt and ttbar production.
  - Wjets & Zjets:
    - Renorm, Factor, RenormFactor, PDF, CKKW, QSF, EWK correction.
  - Diboson & ttV & tth & Vh:
    - Renorm, Factor, RenormFactor, PDF

- Experimental uncertainty:
  - jet energy scale (JES)
  - jet energy resolution (JER)
  - E_T^{miss} modeling
  - lepton reconstruction and identification
  - pile-up/JVT

✓ For **major bkgs** with dedicated CRs: **uncertainty calculated based on transfer factor from CR to SR.**

✓ For **small bkgs** : Estimated using yields uncertainty. cross-section uncertainties are considered.