Searches for squarks and gluinos with the ATLAS detector

WIN2019

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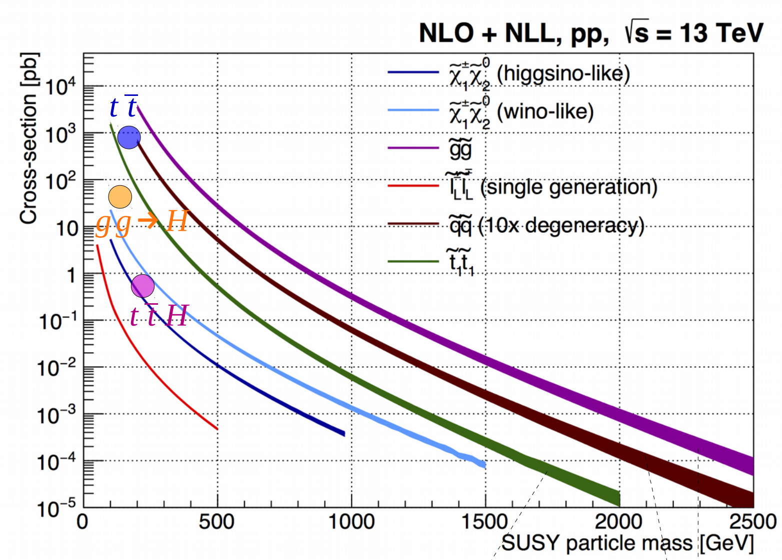
Introduction

- Supersymmetry at weak scale motivated by:
  - unification of forces
  - hierarchy problem
  - nature of Dark Matter
- Potential to discover partners for all Standard Model (SM) particles
- Light 3rd generation squarks motivated by naturalness
  - motivates also not too heavy gluinos
- High cross sections of strong production (depending on mass)

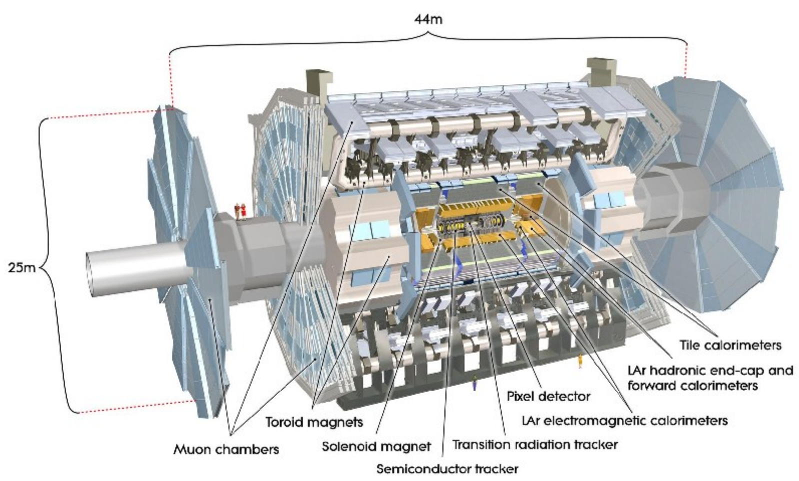


based on calculations in EPJC 74 (2014) 12

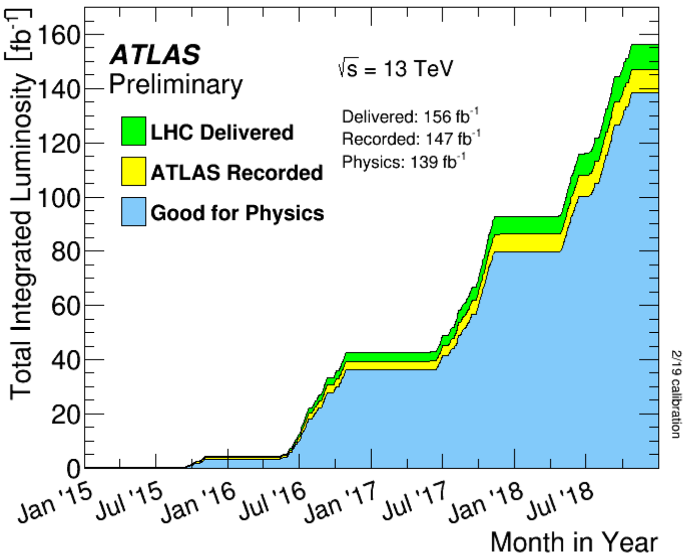
3rd generation squarks (stop/sbottom)

“strong production”: gluinos, 1st & 2nd generation squarks

The ATLAS detector



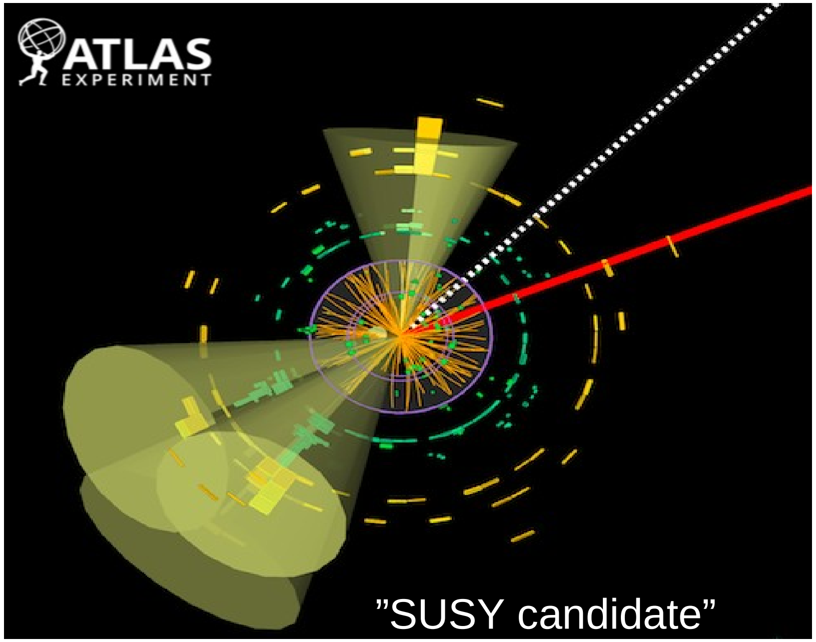
doi.org/10.1140/epjc/s10052-011-1593-6

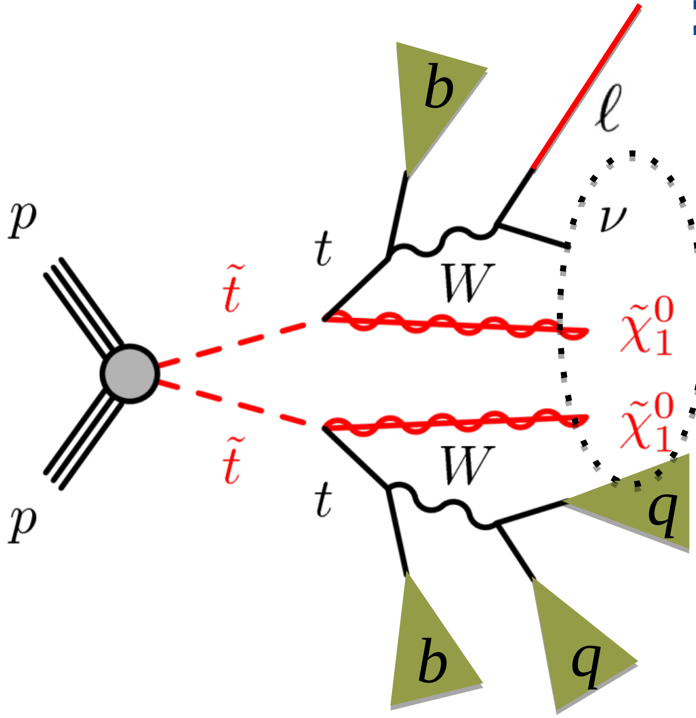


AtlasPublic/LuminosityPublicResultsRun2

- ATLAS is a multi-layer general-purpose detector at the LHC
- LHC Run 2 finished in 2018
- 139 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV ready to be analysed

Object reconstruction

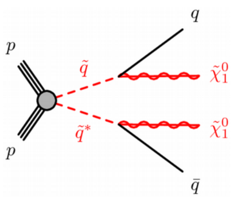


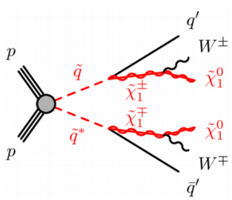


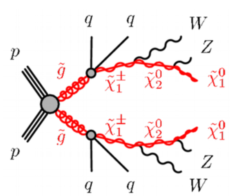
Typical SUSY signatures:

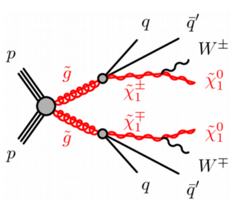
- hadronic jets initiated by quarks or gluons; *b*-jets can be identified due to long lifetime of B-mesons
- sometimes leptons (only electrons and muons in this presentation)
- missing transverse energy (E_T^{miss}) as indicator for invisible particles

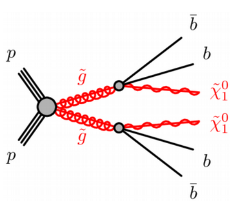
Strong production search program





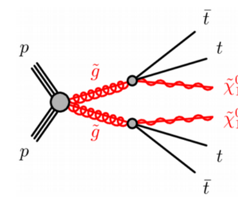


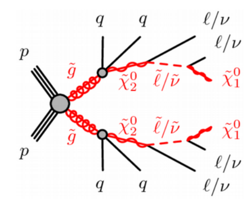


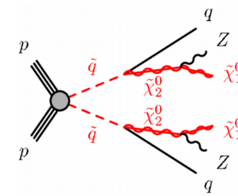


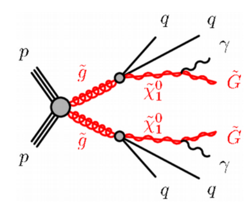
Channel	Published	Dataset
0l + 2-4j	PRD 97 (2018) 112001	36 fb^{-1}
0l + 7-11j	JHEP12 (2017) 034	36 fb^{-1}
multi-b	ATLAS-CONF-2018-041	80 fb^{-1}
1l + 2-9j	PRD 96 (2017) 112010	36 fb^{-1}
SFOS 2l	EPJC 78 (2018) 625	36 fb^{-1}
SS/3L	ATLAS-CONF-2019-015	139 fb^{-1}
γ + jets	PRD 97 (2018) 092006	36 fb^{-1}
τ + jets	PRD 99 (2019) 012009	36 fb^{-1}

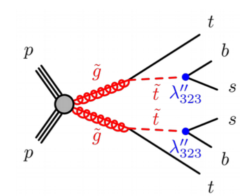
+ more dedicated searches for R-parity violating scenarios (not in this presentation)
+ dedicated search program for 3rd generation squarks (more later)











Strong multi-b

ATLAS-CONF-2018-041

- Decay channels:

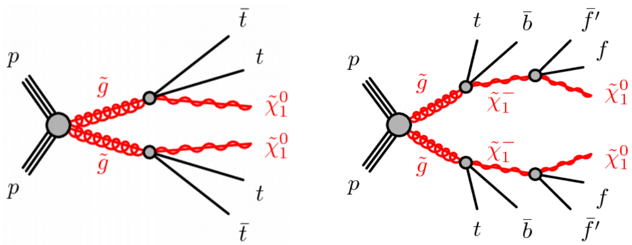
$$\tilde{g} \rightarrow t\,\bar{t} + \tilde{\chi}_1^0$$
$$\tilde{g} \rightarrow b\,\bar{b} + \tilde{\chi}_1^0$$

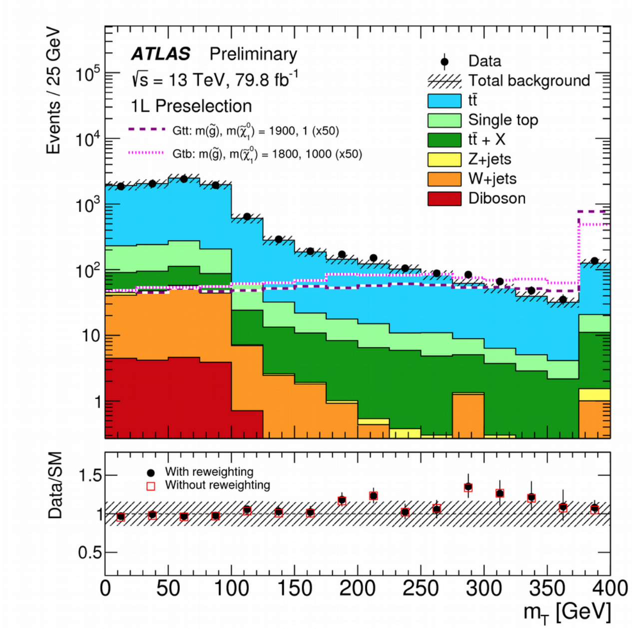
} via off-shell/on-shell 3rd generation squark

$$\tilde{g} \rightarrow t\,\bar{b} + \tilde{\chi}_1^0$$

via 3rd gen. squark & chargino

- Final state:
  - ≥ 3 b-jets, up to 12 jets, E_T^{miss}
  - 0 or 1 lepton
- Dominant background: $t\,\bar{t}$
- Cut-and-count and multi-bin signal regions dependent on jet and lepton multiplicity
- 1-lepton control regions with low m_T to normalise background to data (background-only fit), validation regions close to signal regions as cross check





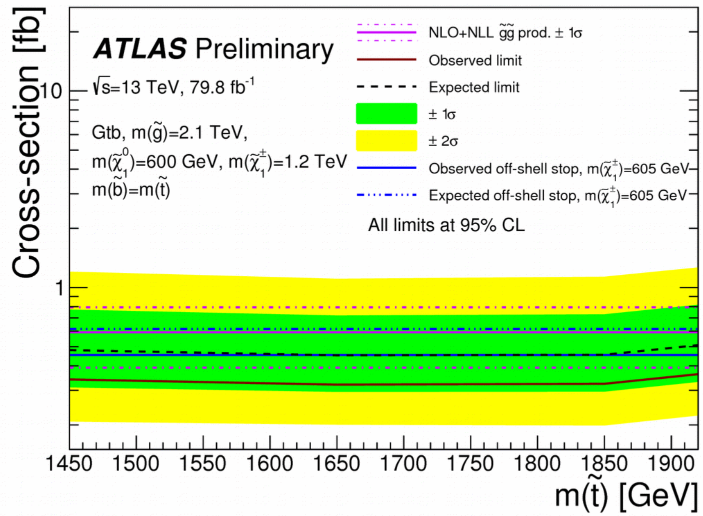
$$m_T = \sqrt{2\,p_T^l\,E_T^{miss}\left[1-\cos(\Delta\phi)\right]}$$

events passing the 1-l preselection

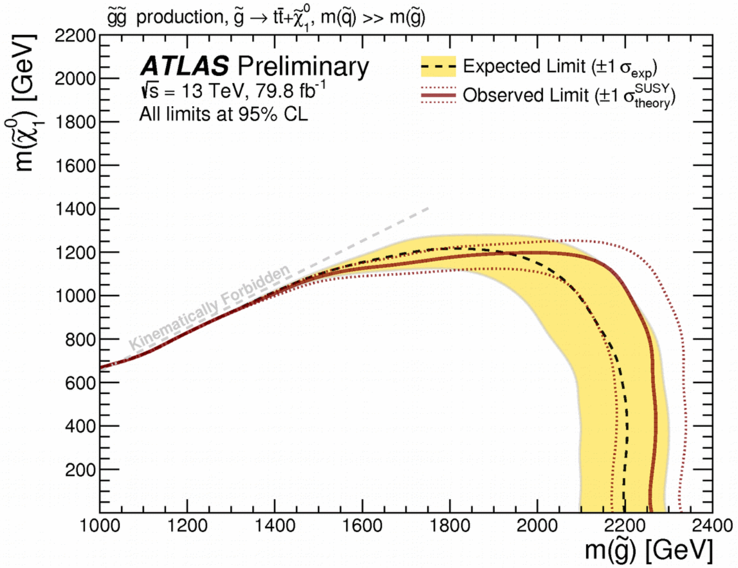
Strong multi-b

ATLAS-CONF-2018-041

on-shell stop
Gtb interpretation is new!



off-shell stop



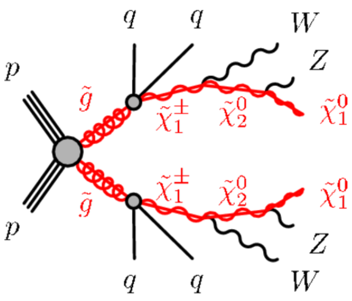
- No excess observed
- Interpretation based on different assumptions for $\tilde{g}, \tilde{t}/\tilde{b}, \tilde{\chi}_1^0, \tilde{\chi}_1^\pm$
- Exclusion limits based on multi-bin signal regions

SS/3L

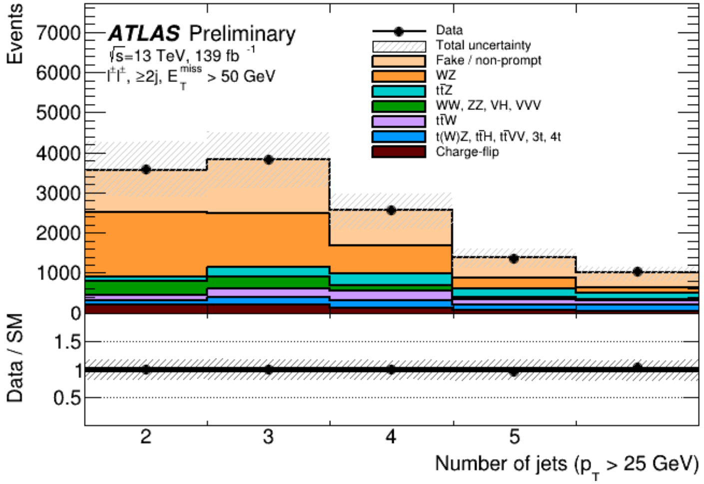
ATLAS-CONF-2019-015

- Decay channels:

$$\tilde{b}_1 \rightarrow t\,W + \tilde{\chi}_1^0$$
$$\tilde{g} \rightarrow t\,\bar{t} + \tilde{\chi}_1^0$$
$$\tilde{g} \rightarrow q\,\bar{q}\,W\,Z + \tilde{\chi}_1^0$$



- Final state:
  - ≥ 2 same-sign leptons, ≥ 6 jets, (E_T^{miss})
- Challenging backgrounds: $WZ + \text{jets}, t\,\bar{t} + W/Z$
  - high theory uncertainties
- Data-driven estimates for
  - fake/non-prompt leptons: matrix method
  - charge-flip electrons: weighted OS data



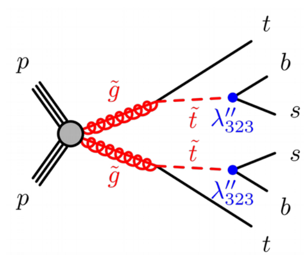
events passing loose preselection

SS/3L

ATLAS-CONF-2019-015

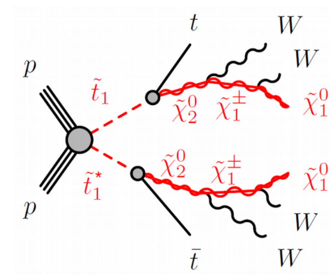
- More channels:
  - R-parity violating:

$$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow 3q$$
$$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq'l$$
$$\tilde{g} \rightarrow t\tilde{t}_1^*, \tilde{t}_1 \rightarrow qq'$$



  - 3L:

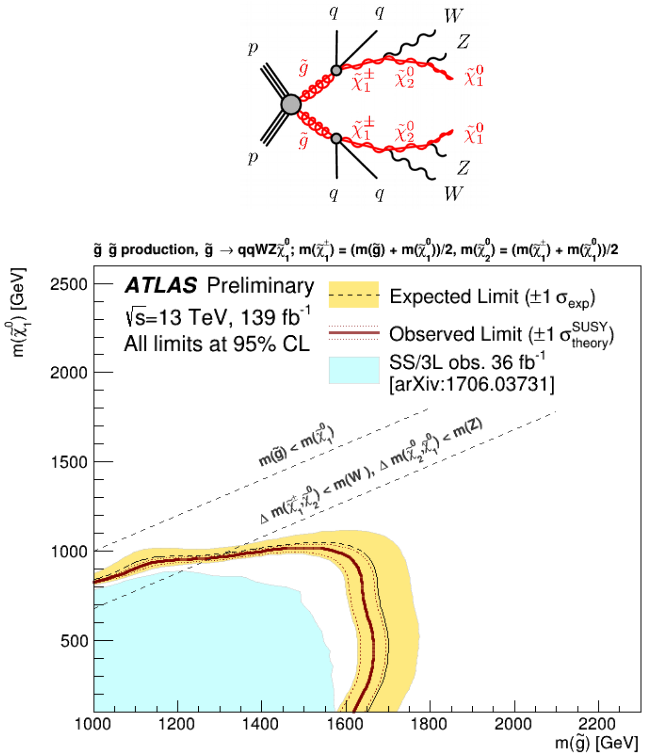
$$\tilde{t}_1 \rightarrow t W^{\pm}(W^*)\tilde{\chi}_1^0$$

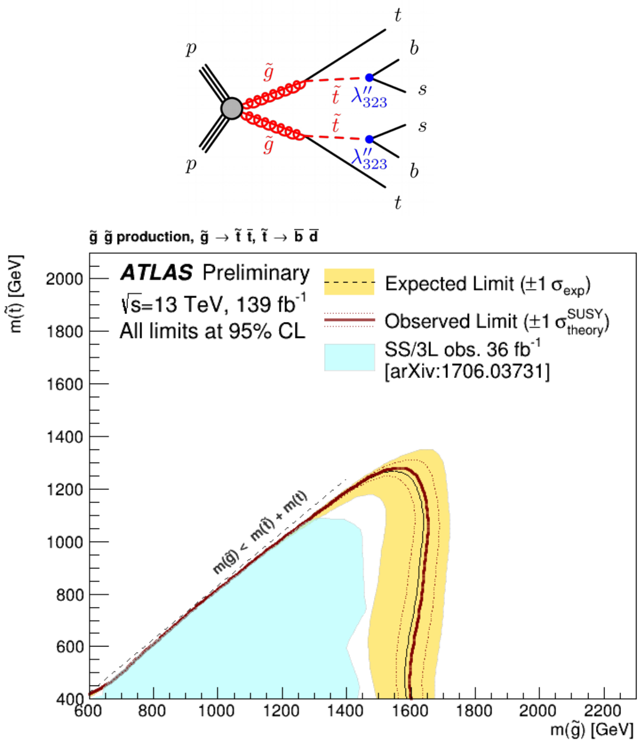


SR	N_ℓ	$N_{b\text{-jets}}^{(20\text{ GeV})}$	N_{jets}	p_T^{jets} [GeV]	E_T^{miss} [GeV]	m_{eff} [GeV]	$E_T^{\text{miss}}/m_{\text{eff}}$	Targeted Model
Rpc2L1b	≥ 2	≥ 1	≥ 6	40	-	-	> 0.25	$\tilde{b}_1 \to t\tilde{\chi}_1^-$
Rpc2L2b	≥ 2	≥ 2	≥ 6	25	> 300	> 1400	> 0.14	$\tilde{b}_1 \to t\tilde{\chi}_1^-$ $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0 / t\bar{b}\tilde{\chi}_1^-$
Rpc2L0b	≥ 2	$= 0$	≥ 6	40	> 200	> 1000	> 0.2	$\tilde{g} \to q\bar{q}' WZ\tilde{\chi}_1^0$
Rpc3LSS1b	≥ 3 (SS)	≥ 1	no cut but veto $81 < m_{e^\pm e^\pm} < 101$ GeV				> 0.14	$\tilde{t}_1 \to tW^\pm(W^*)\tilde{\chi}_1^0$
Rpv2L	≥ 2	≥ 0	≥ 6	40	–	> 2600	–	$\tilde{g} \to t\tilde{t}_1^*, \tilde{t}_1^* \to qq'$ ($\lambda'' \neq 0$) $\tilde{g} \to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to qq'\ell$ ($\lambda' \neq 0$) $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to 3q$ ($\lambda'' \neq 0$)

SS/3L

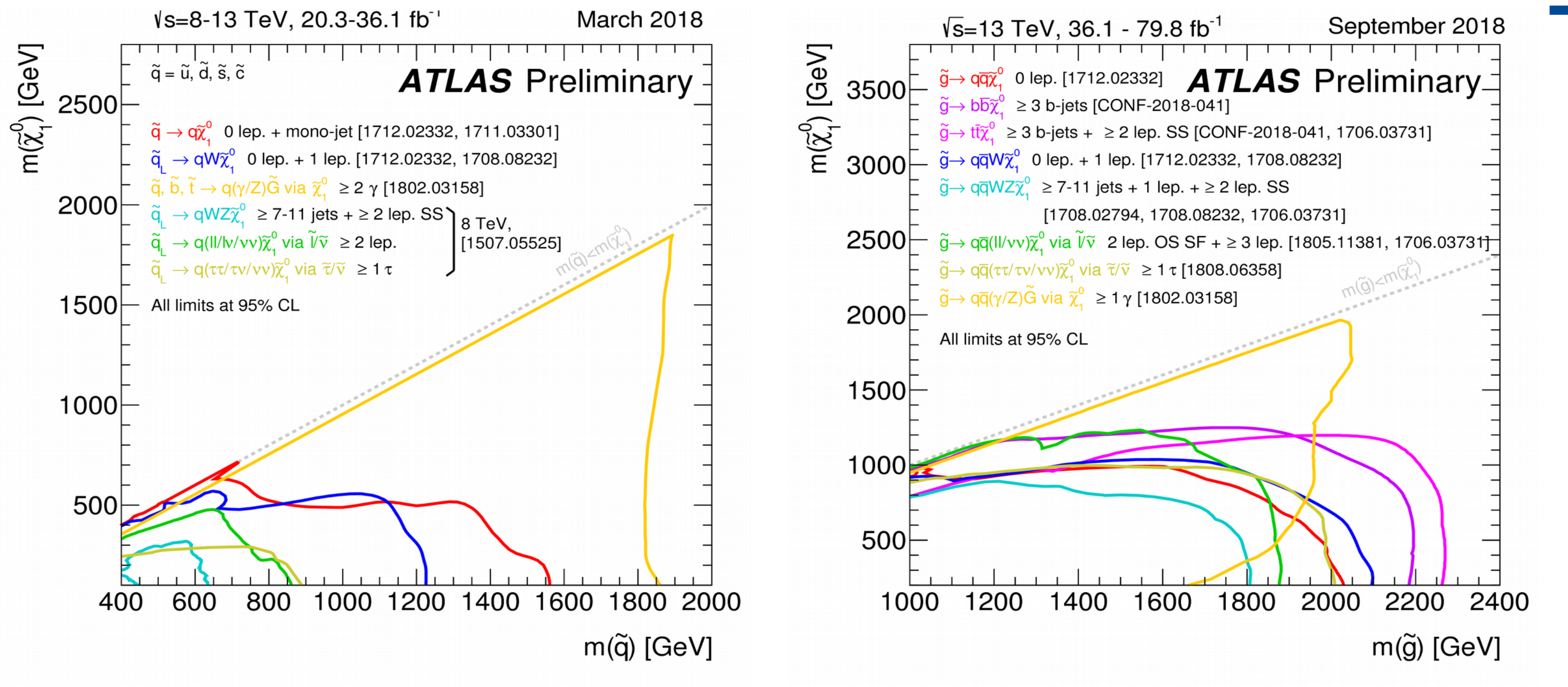
ATLAS-CONF-2019-015





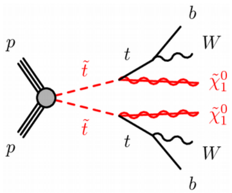
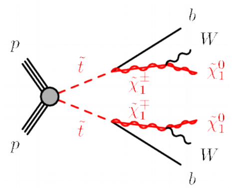
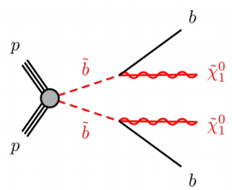
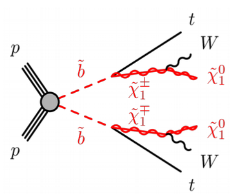
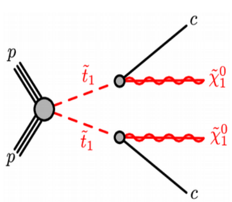
- No excess observed
- Limits for multiple scenarios including also 3rd generation squarks

Strong production summary plots

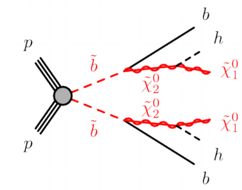
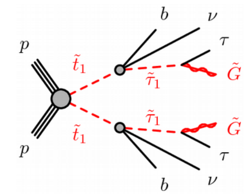
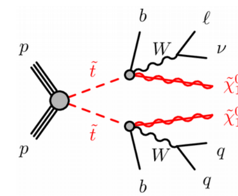
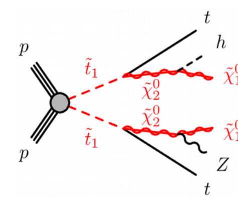
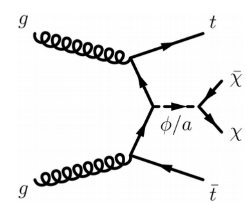


New updated summary plots coming soon!
All results and summary plots on:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

3rd generation search program

Channel	Published	Dataset
Stop 0l	JHEP 12 (2017) 085	36 fb^{-1}
Stop 1l	JHEP 06 (2018) 108 / ATLAS-CONF-2019-017	36 fb^{-1} / 139 fb^{-1}
Stop 2l	PRD 97 (2018) 032003	36 fb^{-1}
Stop to charm	JHEP 09 (2018) 050	36 fb^{-1}
Stop to stau	PRD 98 (2018) 032008	36 fb^{-1}
Stop to Z/h	ATLAS-CONF-2019-016	139 fb^{-1}
Sbottom	EPJC 76 (2016) 547	36 fb^{-1}
Sbottom with h	ATLAS-CONF-2019-011	139 fb^{-1}
DM + HF	EPJC 78 (2018) 18	36 fb^{-1}
tt spin correlation	arXiv:1903.07570	36 fb^{-1}

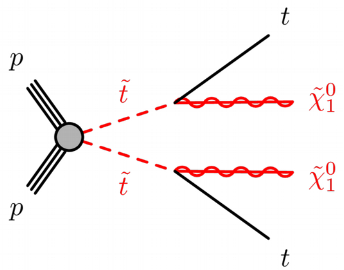






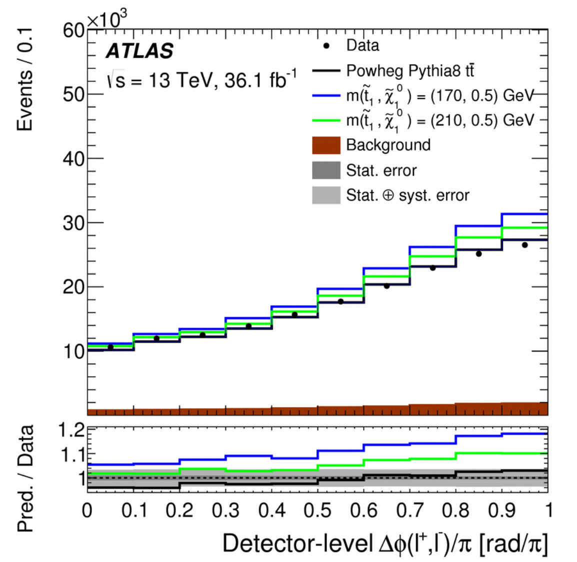
+ more dedicated searches for R-parity violating scenarios (not in this presentation)

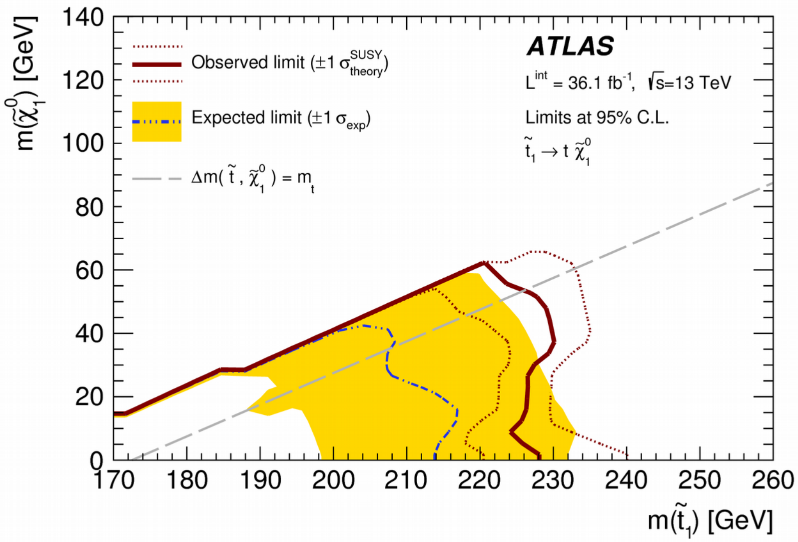
Spin correlation

arXiv:1903.07570

- Challenging region $m(\tilde{t}) \sim m(t)$:
  - stop pair hardly distinguishable from top pair
- Top lifetime shorter than decorrelation time
  - spin correlated for top pair but not for decay products of stop pair
  - make use of angular variables between leptons







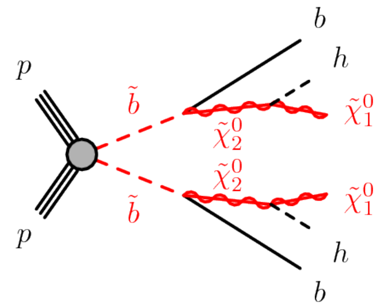
Sbottom with Higgs

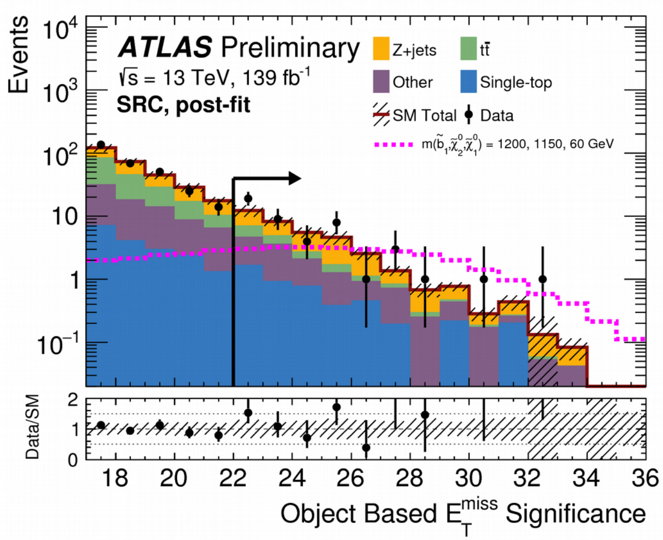
ATLAS-CONF-2019-011

- Two scenarios considered:
  - fixed $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130\,\mathrm{GeV}$
  - fixed $m(\tilde{\chi}_1^0) = 60\,\mathrm{GeV}$
- Final state: ≥ 4 jets, ≥ 3 *b*-jets, E_T^{miss}
- Methods:
  - associate *b*-jets to Higgs candidates
  - if not possible, use E_T^{miss} significance:

    new method calculating significance of E_T^{miss} with uncertainties of all objects:

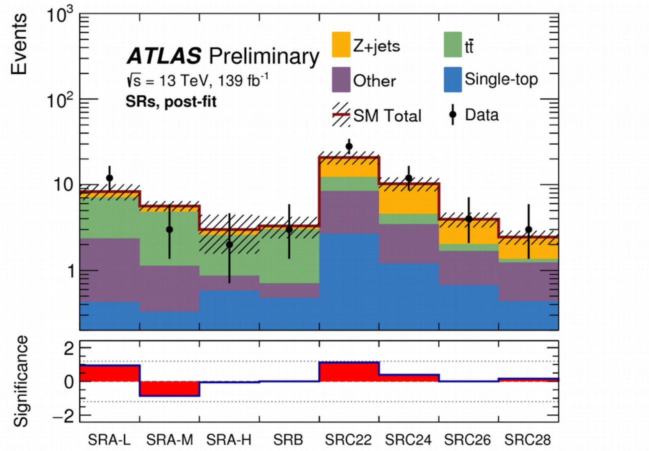
    ATLAS-CONF-2018-038
- Main backgrounds: $t\bar{t}$, $Z+\mathrm{jets}$
  - normalised to data in 1-lepton / 2-lepton control regions



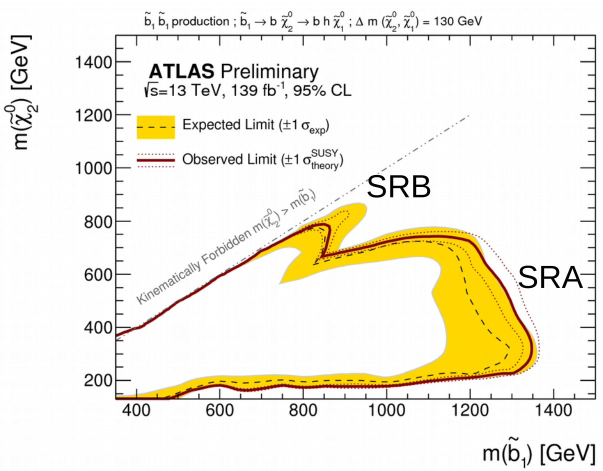


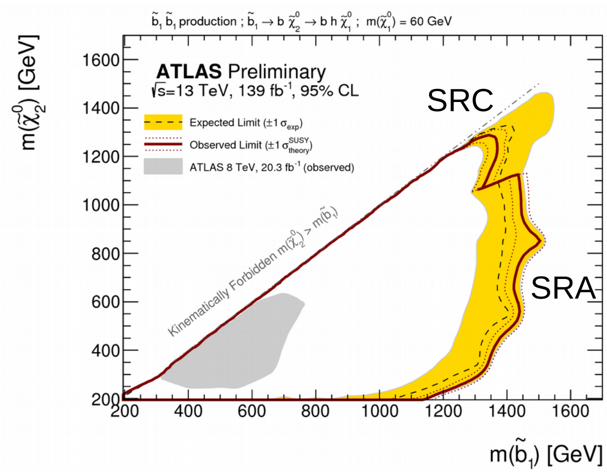
Sbottom with Higgs

ATLAS-CONF-2019-011



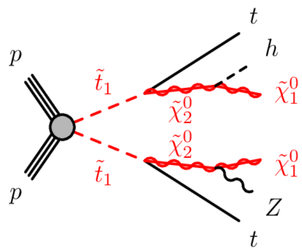
- 3 signal regions
  - SRA: “bulk” region, bins in m_{eff}
  - SRB: ISR selection
  - SRC: bins in E_T^{miss} significance
- No excess observed
- New exclusion limits for both scenarios

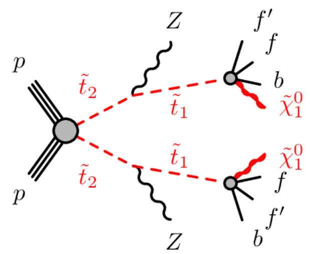




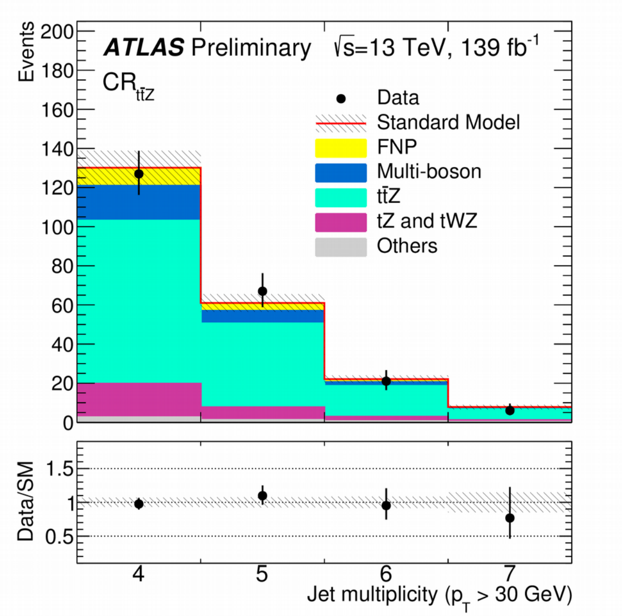
Stop to Z/h

ATLAS-CONF-2019-016



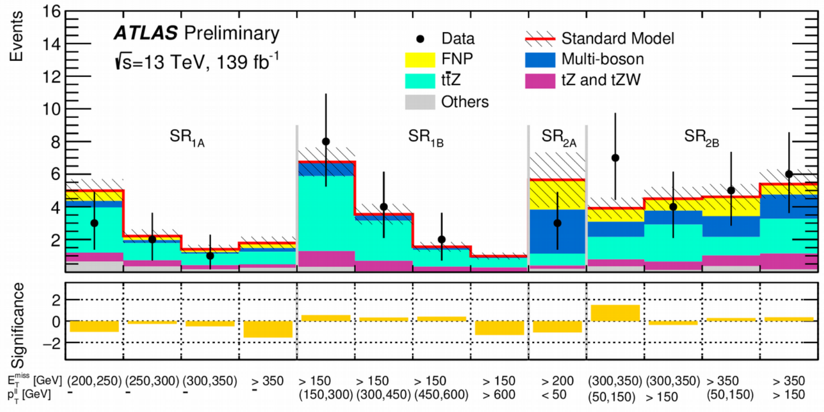


- Two scenarios considered:
- Final state:
  - ≥ 3 leptons, 2 same-flavor opposite sign with $m_{ll} \sim m(Z)$
  - ≥ 3 jets, E_T^{miss}
- 2 signal regions for each scenario
  - targeting high/low $\Delta m(\chi_2^0, \tilde{\chi}_1^0)$ and $\Delta m(\tilde{t}_2, \tilde{\chi}_1^0)$
- Main backgrounds: $t\bar{t}+Z$, multi-boson
  - normalised to data in low-E_T^{miss} control regions
  - leading systematic uncertainty
- Fake and non-prompt lepton estimated with matrix method
- Validation regions for all backgrounds

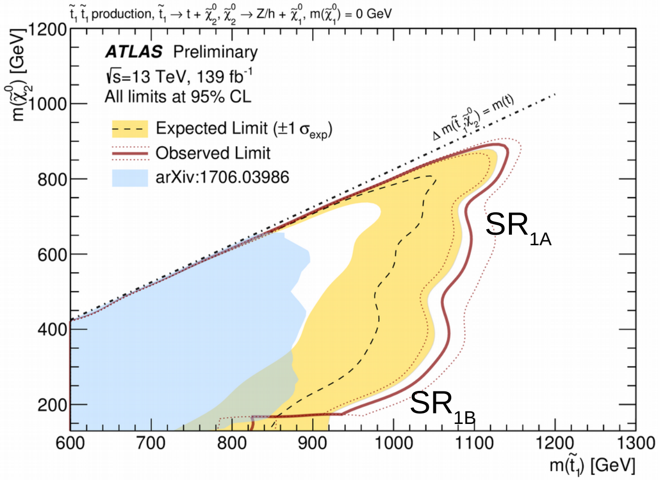


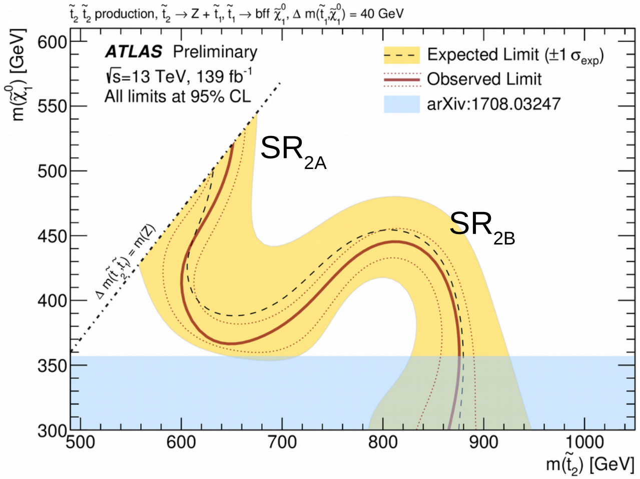
Stop to Z/h

ATLAS-CONF-2019-016



- Multi-bin signal regions
- No excess found
- New limits in both scenarios

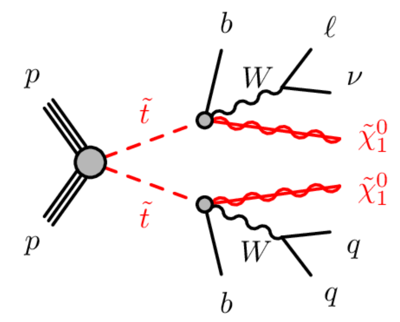


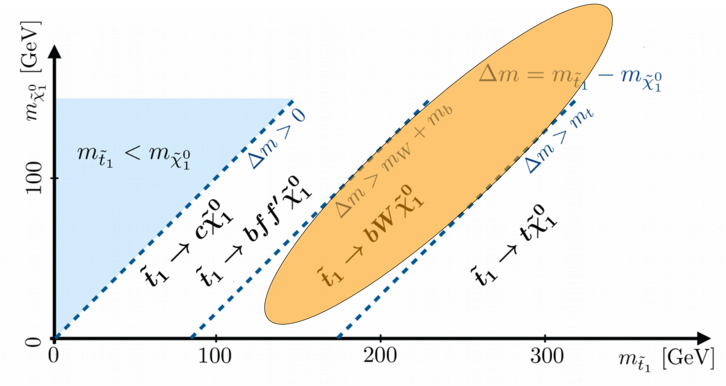


3-body stop

ATLAS-CONF-2019-017

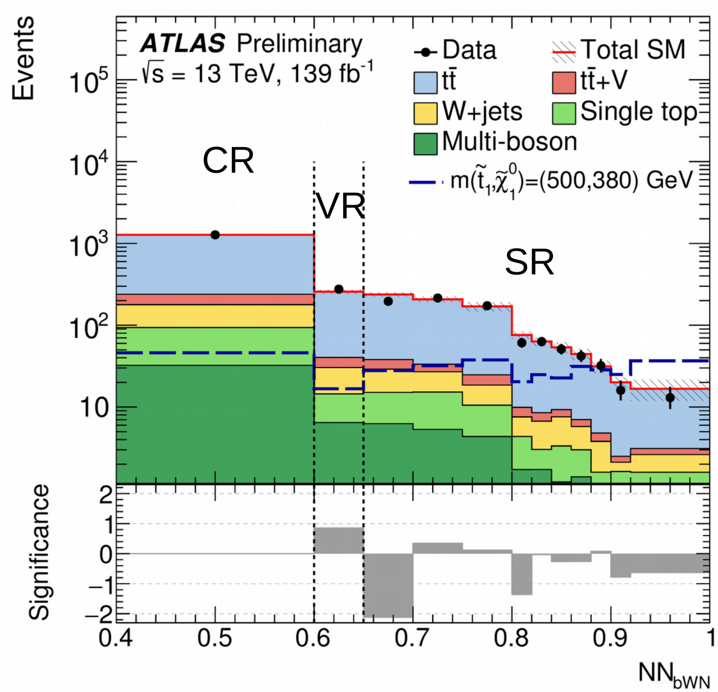
- Targeting region $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(t)$
- Final state:
  - ≥ 4 jets, ≥ 1 *b*-jet, E_T^{miss}
  - 1 lepton
- Neural network (NN) design to distinguish from background:
  - jet 4-vectors + 12 other variables
  - trained with truth-smeared signal samples for larger statistics
- Main background: $t\bar{t}$ (di-leptonic with missed lepton)
- Control region for background normalisation and and validation region both orthogonal in NN discriminator

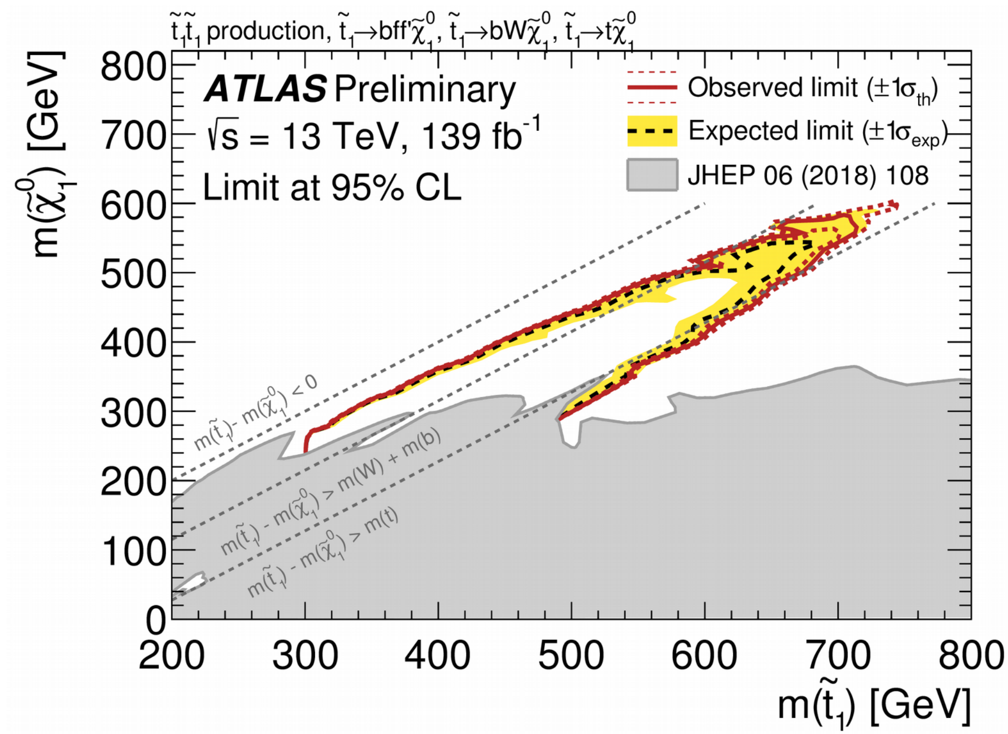




3-body stop

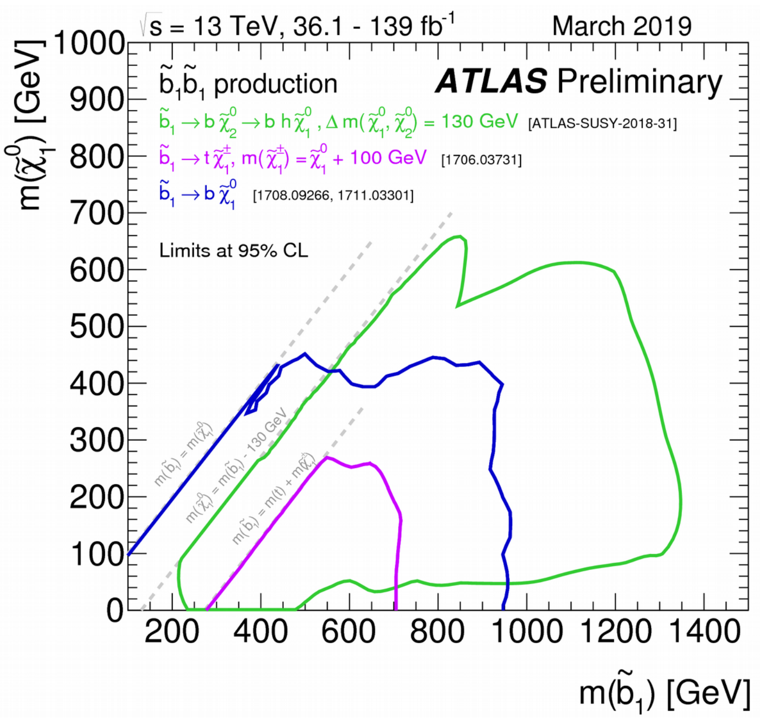
ATLAS-CONF-2019-017

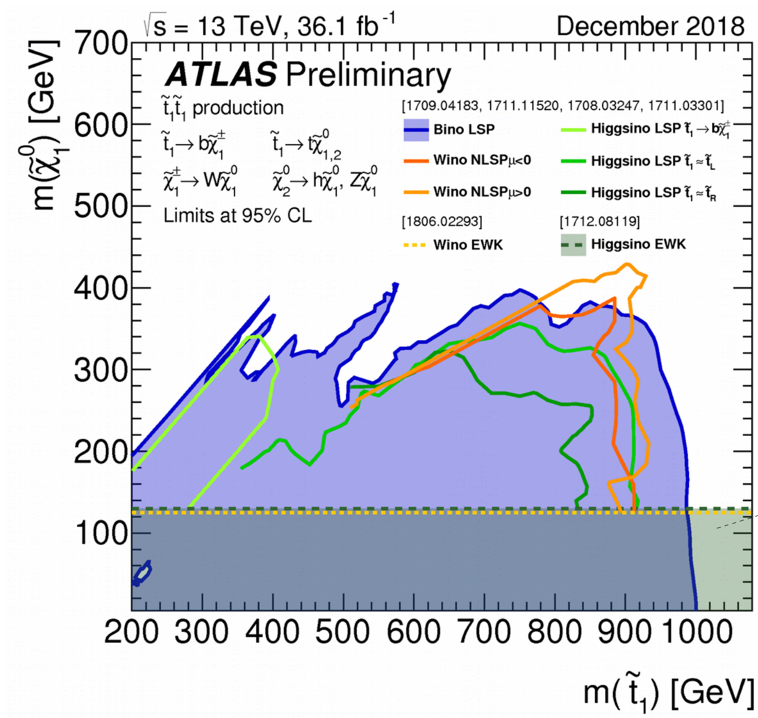




- No excess observed
- 10-bin fit in SR
- Large improvement of exclusion limits in $\tilde{t}_1 - \tilde{\chi}^1_0$ plane

3rd generation summary plots





electro-
weak
searches

New updated summary plots coming soon!
All results and summary plots on:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

Conclusion

- Broad search program for squarks and gluinos @ATLAS

  First results with full Run 2 dataset public!
  - updated results of previous searches
  - new scenarios in difficult phase space / longer decay-chains considered
  - new methods used
- No excess above Standard Model expectation observed
- New exclusion limits
- In simplified models, e.g.:
  - gluinos (into top/bottom pair) up to 2.2 TeV
  - sbottoms (with Higgs) up to 1.45 TeV
  - stops (3-body decay) up to 720 GeV
- And more incoming, stay tuned!

Appendix

Strong multi-b

Gtt 1-lepton

Criteria common to all regions: ≥ 1 signal lepton, $N_{b\text{-jets}} \geq 3$

Targeted kinematics	Type	N_{jet}	m_{T}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	$m_{\text{eff}}^{\text{incl}}$	M_J^{Σ}
Region B (Boosted, Large Δm)	SR	≥ 5	> 150	> 120	> 500	> 2200	> 200
	CR	$= 5$	< 150	–	> 300	> 1700	> 150
Region M (Moderate Δm)	SR	≥ 6	> 150	> 160	> 450	> 1800	> 200
	CR	$= 6$	< 150	–	> 400	> 1500	> 100
Region C (Compressed, small Δm)	SR	≥ 7	> 150	> 160	> 350	> 1000	–
	CR	$= 7$	< 150	–	> 350	> 1000	–

Gtt 0-lepton

Targeted kinematics	Type	N_{lepton}	$N_{b\text{-jets}}$	N_{jet}	$\Delta\phi_{\text{min}}^{4\text{j}}$	m_{T}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	$m_{\text{eff}}^{\text{incl}}$	M_J^{Σ}
Region B (Boosted, Large Δm)	SR	$= 0$	≥ 3	≥ 7	> 0.4	–	> 60	> 350	> 2600	> 300
	CR	$= 1$	≥ 3	≥ 6	–	< 150	–	> 275	> 1800	> 300
Region M (Moderate Δm)	SR	$= 0$	≥ 3	≥ 7	> 0.4	–	> 120	> 500	> 1800	> 200
	CR	$= 1$	≥ 3	≥ 6	–	< 150	–	> 400	> 1700	> 200
Region C (Compressed, moderate Δm)	SR	$= 0$	≥ 4	≥ 8	> 0.4	–	> 120	> 250	> 1000	> 100
	CR	$= 1$	≥ 4	≥ 7	–	< 150	–	> 250	> 1000	> 100

Gbb

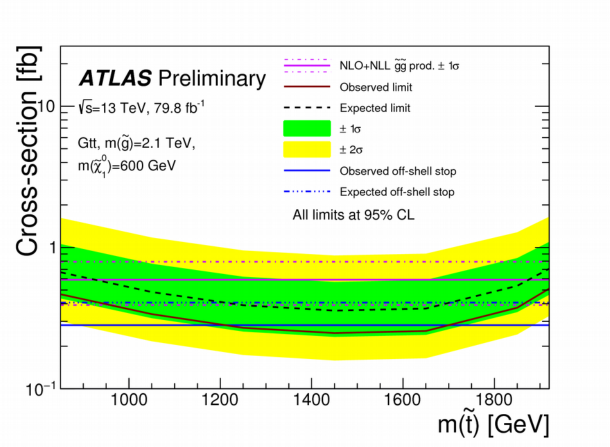
Criteria common to all regions: $N_{\text{jet}} \geq 4$

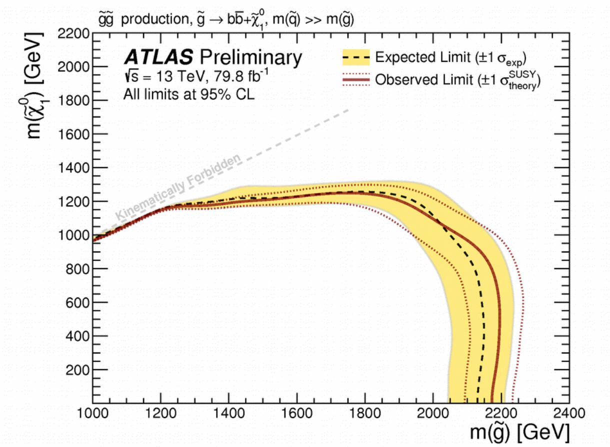
Targeted kinematics	Type	N_{lepton}	$N_{b\text{-jets}}$	$\Delta\phi_{\text{min}}^{4\text{j}}$	m_{T}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	m_{eff}	Others
Region B (Boosted, Large Δm)	SR	$= 0$	≥ 3	> 0.4	–	–	> 400	> 2800	–
	CR	$= 1$	≥ 3	–	< 150	–	> 400	> 2500	–
Region M (Moderate Δm)	SR	$= 0$	≥ 4	> 0.4	–	> 90	> 450	> 1600	–
	CR	$= 1$	≥ 4	–	< 150	–	> 300	> 1600	–
Region C (Compressed, small Δm)	SR	$= 0$	≥ 4	> 0.4	–	> 155	> 450	–	–
	CR	$= 1$	≥ 4	–	< 150	–	> 375	–	–
Region VC (Very Compressed, very small Δm)	SR	$= 0$	≥ 3	> 0.4	–	> 100	> 600	–	$p_{\text{T}}^{\text{j}_1} > 400$, $\text{j}_1 \neq b$, $\Delta\phi^{\text{j}_1} > 2.5$
	CR	$= 1$	≥ 3	–	< 150	–	> 600	–	

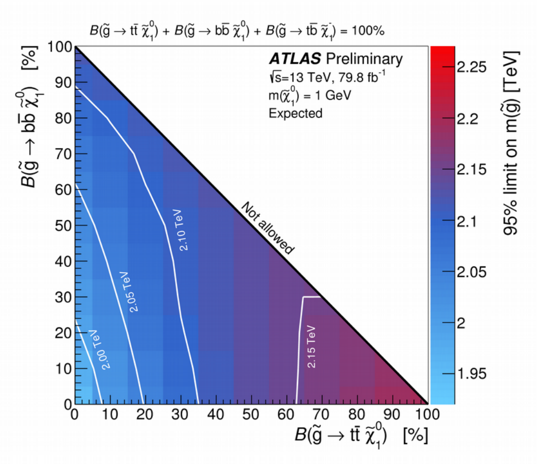
Dominant systematic uncertainties varying in each signal bin:

- Jet energy scale: 0.5% - 15%
- Jet energy resolution: 1% - 19%
- *b*-tagging efficiency / misstagging rate: 1% - 7%
- single-top modelling uncertainties: 4-35%
- *W/Z*+jets factorisation and renormalisation: 0-50%

Strong multi-b – exclusions

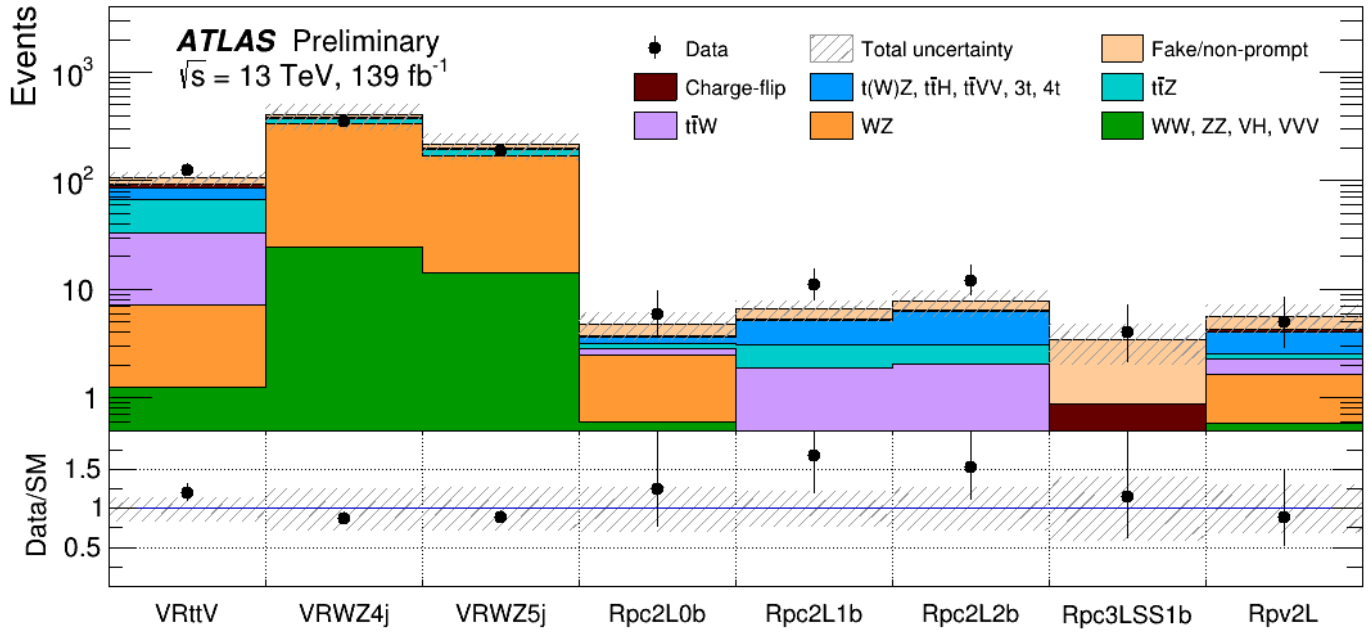






- Different visualisation methods in multi-parameter phase space

SS/3L



ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Data
Total uncertainty
Fake/non-prompt
Charge-flip
t(W)Z, $t\bar{t}H$, $t\bar{t}VV$, 3t, 4t
$t\bar{t}Z$
$t\bar{t}W$
WZ
WW, ZZ, VH, VVV
Events
Data/SM
VRttV
VRWZ4j
VRWZ5j
Rpc2L0b
Rpc2L1b
Rpc2L2b
Rpc3LSS1b
Rpv2L

SS/3L

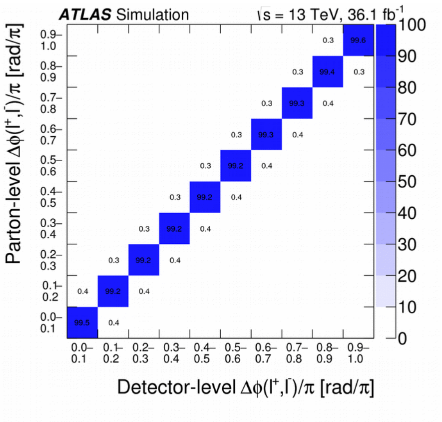
- Systematics:
  - cross section uncertainty of VV, $t\bar{t}+W/Z/H$ processes
  - factorisation and renormalisation scales from generator-provided up/down weights
  - modelling uncertainties obtained by comparing with alternative generators/same generator with different event tune
  - overall: 35-45% $t\bar{t}+W$, 25-45% $t\bar{t}+Z$, 40-45% WZ
- Matrix method:
  - F/NP leptons usually filtered out by lepton isolation criteria
  - Loosen criteria, measure how many leptons pass this and the nominal (tight) lepton selection
  - Obtain probabilities from MC events
  - 30-80% uncertainty on probability

$$\begin{pmatrix} N^{tt} \\ N^{t\bar{t}} \\ N^{\bar{t}t} \\ N^{\bar{t}\bar{t}} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1 \tilde{r}_2 & r_1 \tilde{f}_2 & f_1 \tilde{r}_2 & f_1 \tilde{f}_2 \\ \tilde{r}_1 r_2 & \tilde{r}_1 f_2 & \tilde{f}_1 r_2 & \tilde{f}_1 f_2 \\ \tilde{r}_1 \tilde{r}_2 & \tilde{r}_1 \tilde{f}_2 & \tilde{f}_1 \tilde{r}_2 & \tilde{f}_1 \tilde{f}_2 \end{pmatrix} \begin{pmatrix} N^{tt}_{rr}/\,(r_1 r_2) \\ N^{tt}_{rf}/\,(r_1 f_2) \\ N^{tt}_{fr}/\,(f_1 r_2) \\ N^{tt}_{ff}/\,(f_1 r_2) \end{pmatrix}$$

t : passes tight criteria, $\bar{t}$: does not pass tight criteria
r : real lepton, f : fake lepton

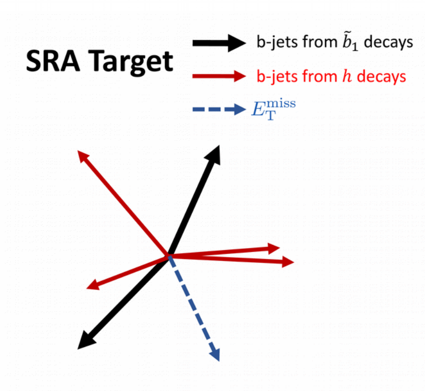
Spin correlation

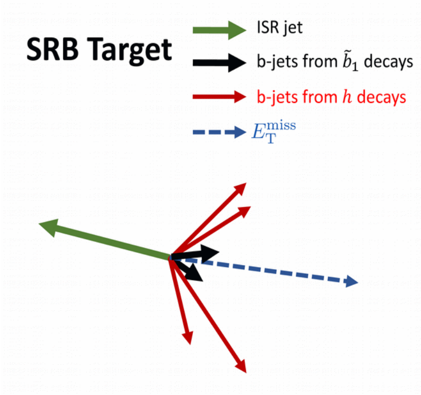
- Selection:
  - inclusive: 2 OFOS leptons, ≥ 2 jets, ≥ 1 b-jet
- Unfolding procedure: Background-substracted data are corrected for detector acceptance and resolution effects.
- Systematic uncertainties:
  - $t\bar{t}$ modelling: matrix-element generator, hadronisation and parton-shower model, amount of ISR/FSR, choice of PDF set
  - normalisation of other backgrounds
  - only small detector uncertainties

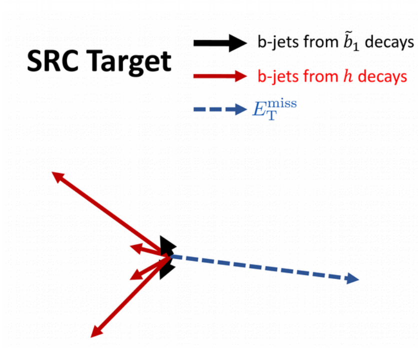


Sbottom with Higgs

- Decay hierarchy predicted in MSSM, when: is lightest neutral boson, LSP is bino-like, $\tilde{\chi}_2^0$ is wino-higgsino mixture







SRA:
- “bulk” region
- all objects high p_T and resolved
- *max-min* method: remove b-jets most likely from sbottoms (pair with max ΔR), then find Higgs candidate (pair with min ΔR)
- use lower bound on invariant mass of Higgs candidate

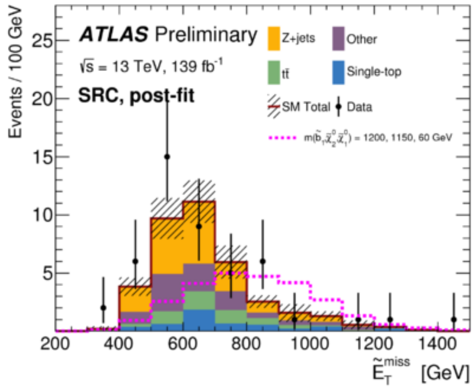
SRB:
- “compressed” region, small $\Delta m(\tilde{b}_1, \tilde{\chi}_2^0)$ $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130\,\mathrm{GeV}$
- soft b-jets from sbottoms
- use ISR-like selection
- reconstruct two Higgs candidates with high ΔR
- use mass window around Higgs mass for avg. cand. mass

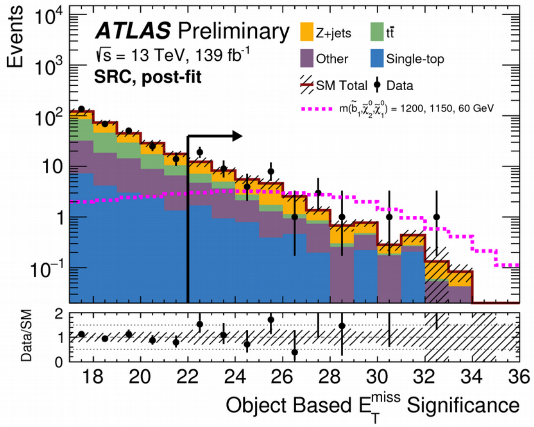
SRC:
- “compressed” region, small $\Delta m(\tilde{b}_1, \tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0) = 60\,\mathrm{GeV}$
- soft b-jets from sbottoms
- require lower b-multiplicity
- visible and invisible hemisphere
- more Z+jets background

Sbottom with Higgs

- Dominating systematic uncertainties:
  - experimental: jet energy scale & jet energy resolution, *b*-tagging efficiency and mis-tagging (dominant in SRC)
  - theoretical: top quark pair and Z+jets modelling

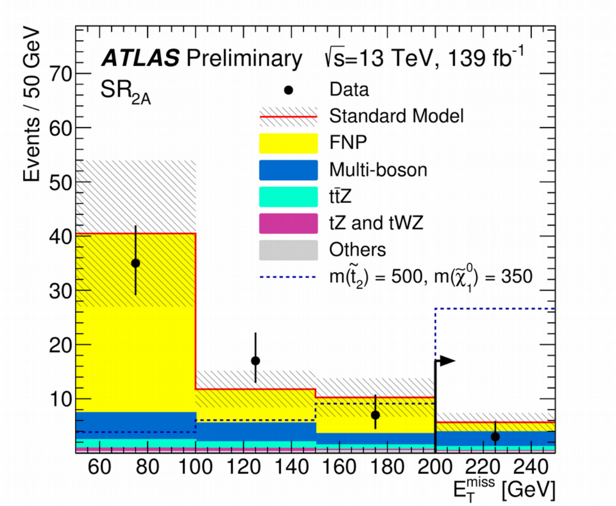
Region	SRA	SRB	SRC
Total background expectation	17.1	3.3	37.9
Total background error	2.8 (16%)	0.9 (27%)	6.2 (16%)
Systematic, experimental	1.4 (8%)	0.3 (10%)	3.0 (8%)
Systematic, theoretical	2.3 (13%)	0.6 (18%)	3.2 (8%)
Statistical, MC samples	0.7 (4%)	0.4 (12%)	2.0 (5%)

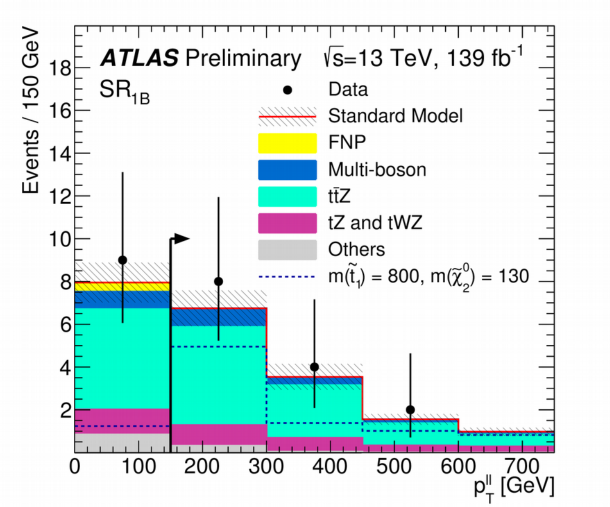




$$S^2 = 2\ln\left(\frac{\max_{p_T^{\text{inv}}\neq 0}\mathcal{L}(E_T^{\text{miss}}|p_T^{\text{inv}})}{\max_{p_T^{\text{inv}}=0}\mathcal{L}(E_T^{\text{miss}}|p_T^{\text{inv}})}\right)$$

Stop to Z/h





	SR_{1A}	SR_{1B}	SR_{2A}	SR_{2B}
Total systematic uncertainty (%)	13	13	29	15
Diboson theoretical uncertainties (%)	2	3	11	5
$t\bar{t}Z$ theoretical uncertainties (%)	3	6	4	5
Other theoretical uncertainties (%)	6	9	2	9
MC and FNP statistical uncertainties (%)	6	<1	14	7
Diboson fitted normalisation (%)	2	3	11	6
$t\bar{t}Z$ fitted normalisation (%)	5	9	2	7
Fake/non-prompt leptons efficiency (%)	4	<1	14	2
Jet energy resolution (%)	4	3	2	2
Jet energy scale (%)	1	4	<1	1
b-tagging (%)	3	5	1	5

3-body stop

Jet 4-vectors (up to 8) → Recurrent neural network (RNN)

→ Shallow neural network NN_{bWN}

Input variable	Description
E_T^{miss}	Missing transverse energy
$\phi(\vec{p}_T^{miss})$	Azimuthal angle of the $\vec{p}_T^{miss}$
m_T	Transverse mass
$\Delta\phi(\ell, \vec{p}_T^{miss})$	Azimuthal angle between $\vec{p}_T^{miss}$ and lepton
m_{bl}	Invariant mass of leading b-tagged jet and lepton
$p_T^{b_{jet}}$	Transverse momentum of the leading b-tagged jet
n_{jet}	Jet multiplicity
n_{b-tag}	Number of b-tagged jets @ 77%
$p_T(\ell)$	Transverse momentum of lepton
$\eta(\ell)$	Pseupdorapidity of lepton
$\phi(\ell)$	Azimuthal angle of lepton
$E(\ell)$	Energy of lepton

Dominant systematic uncertainty: $t\,\bar{t}$ hadronisation/fragmentation (16%)

MC samples

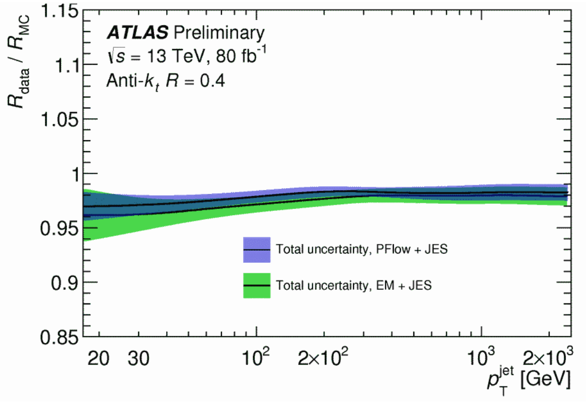
Process	Generator + fragmentation/hadronization	Tune	PDF set	Cross-section order
Gbb/Gtb/Gtt	MadGraph5_aMC@NLO-2.2.2 + Pythia v8.186	A14	NNPDF2.3	NLO+NLL [30,31,32,33,34,35]
$t\bar{t}$	Powheg-Box v2 + Pythia-8.230	A14	NNPDF3.0	NNLO+NNLL [36]
Single top Wt-channel (s/t)	Powheg-Box v1 (v2) + Pythia-6.428 (-8.230)	PERUGIA2012	CT10	NNLO+NNLL [37,38,39]
$t\bar{t}W/t\bar{t}Z$	MadGraph5_aMC@NLO-2.2.2 + Pythia-8.186	A14	NNPDF2.3	NLO [40]
4-tops	MadGraph-2.2.2 + Pythia-8.186	A14	NNPDF2.3	NLO [40]
$t\bar{t}H$	MadGraph5_aMC@NLO-2.2.1 + Herwig++-2.7.1	UEEE5	CT10	NLO [41]
Dibosons WW, WZ, ZZ	Sherpa-2.2.1	Default	NNPDF3.0	NLO [42,43]
W/Z**+jets**	Sherpa-2.2.1	Default	NNPDF3.0	NNLO [44]

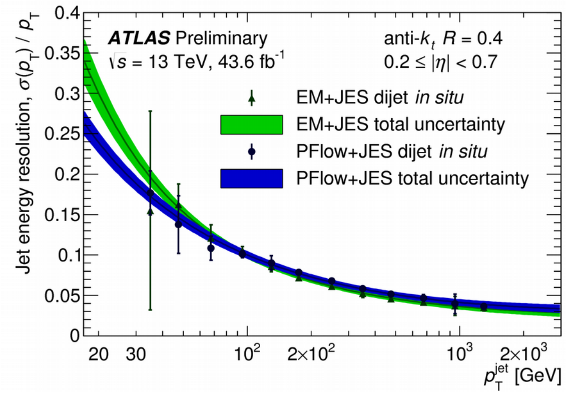
strong multi-b

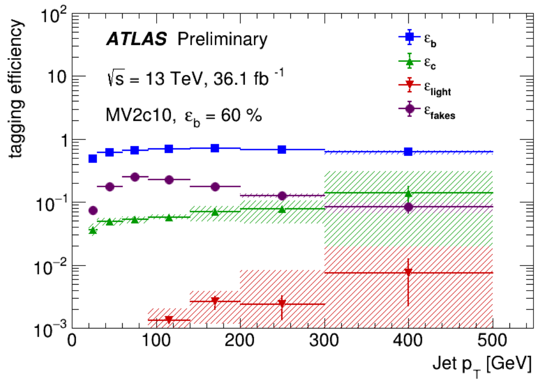
Physics process	Generator	Parton shower	Cross-section normalisation	PDF set	Tune
SUSY Signals	MG5_aMC@NLO 2.6.2 [31]	Pythia 8.212 [32]	NNLO+NNLL [33,34,35,36,37]	NNPDF2.3LO [38]	A14 [39]
$t\bar{t}Z/\gamma^*$, $t\bar{t}W$	MG5_aMC@NLO 2.3.3	Pythia 8.210	NLO [31]	NNPDF2.3LO	A14
Diboson	Sherpa 2.2.2 [40]	Sherpa 2.2.2	Generator NLO	NNPDF3.0NNLO [41]	Sherpa default
$t\bar{t}h$	Powheg v2 [42]	Pythia 8.230	NLO [43]	NNPDF2.3LO	A14
Wh, Zh	Pythia 8.186 [44]	Pythia 8.186	NLO [43]	NNPDF2.3LO	A14
$t\bar{t}WW$, $t\bar{t}t\bar{t}$	MG5_aMC@NLO 2.2.2	Pythia 8.186	NLO [31]	NNPDF2.3LO	A14
$t\bar{t}t$	MG5_aMC@NLO 2.2.2	Pythia 8.186	LO	NNPDF2.3LO	A14
tZ	MG5_aMC@NLO 2.3.3	Pythia 8.186	LO	NNPDF2.3LO	A14
tWZ	MG5_aMC@NLO 2.3.3	Pythia 8.212	Generator NLO	NNPDF2.3LO	A14
Triboson	Sherpa 2.2.2	Sherpa 2.2.2	Generator NLO	NNPDF3.0NNLO	Sherpa default

stop with Z

Detector uncertainties







- Jet energy scale (top left), jet energy resolution (top right) and *b*-tagging efficiencies.
- JETM-2018-006, JETM-2018-005, ATLAS-CONF-2018-045