# SEARCHES FOR STRONG PRODUCTION OF SUPERSYMMETRIC PARTICLES

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# SUSY search program at the LHC

- Supersymmetry (SUSY) has the potential to
  - Provide a dark matter candidate;
  - Unify the forces at high energy;

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- Solve the fine-tuning problem of the Higgs mass.
- Broad search program to ensure that we get the most out of the LHC data.
- Presents results for strong production in R-Parity Conserved scenario
- Electroweak production was covered in Antonia's talk (LINK).
- Lauren's talk covered R-Parity Violated scenario (LINK) and Andrew's will conver Long Lived Particle scenario (LINK)
- Simplified models used for optimization and model-dependent exclusion limits.
  - Masses of non-relevant SUSY particles put very high.
  - 100% BR to specific final state.
- Check coverage in large pMSSM scans.
- Model-independent upper limits, HEP data, ..
- All results presented today with the 139/140 fb<sup>-1</sup> dataset



# Latest results from ATLAS in strong SUSY production

#### SUSY-2023-22

• Search for new phenomena with topquark pairs and large missing transverse momentum

#### SUSY-2019-23

 Search for top-squark pair production in final states containing a top quark, a charm quark and missing transverse momentum



phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



# Stop to top-N1 analysis 1L

- **Signature-based search strategy**: Events selection based on object multiplicities.
- Novel approach that provides sensitivity to a **wide range of parameter space**.

#### **Resolved «High-MET»,** $(p_T < 600 \text{ GeV})$ : "top-NN"

- Assigns score to all two and three (small-R) jet combinations (with exactly 1 b-jet) in event
- Combination with highest NN output value in each event is chosen as the top candidate
- 70% selection efficiency for top quarks with 200 GeV <  $p_T$  < 600 GeV

#### **Boosted** ( $p_T > 600 \text{ GeV}$ ):

- Reconstructed as large-*R* jet.
- Multivariate classifier uses substructure to tag top jets with 80% efficiency.

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### Stop to top-N1 analysis 1L

**Resolved** «High-MET»

 $N_{LargeR-jet} = 0$ 

Further split into '1b' and '2b' for events containing exactly one, or two or more, b-tagged jets



#### "Boosted»

 $N_{LargeR-jet} \ge 1$ 

Six orthogonal regions depending on whether large-R jet is top-tagged, and the number of b-tagged jets (1 or 2+) and whether they lie inside or outside the large-R jet



- For each region defined, a NN classifier is trained, using SUSY signal events from **across parameter space**.
- In high-MET regions, a second NN is also trained with *tt*+DM events as the signal

# Stop to top-N1 analysis 1L - Backgrounds Estimations

- Main backgrounds:
  - ttZ, tt1L, tt2L, W and single-top
- CRs binned in **mT** \* **q(l)**. Backgrounds with 1 leptonically-decaying W have endpoint at  $m_W$  (i.e. all but  $tt_{2L}$ ).
- Lepton charge discriminates between W+jets and tt<sub>1L</sub> (different cross-section for W<sup>+</sup> and W<sup>-</sup>).
- Normalisation factors derived for tt1L, tt2L, W and single-top backgrounds.





ttZ(→vv) has low cross section but identical signature as signal. Not fitted; Validated in 3 lepton VRs with two SFOS leptons compatible with Z (mimic v in SRs by vectorially adding to MET)

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# Stop to top-N1 analysis 1L - Results



# Stop to top-charm analysis

First LHC result in this final state!

- Stop pair production with decay to neutralino and SM top or charm
- Motivated by <u>non-minimal flavour violating extensions</u> of MSSM
- Only consider scenarios where top can be produced on-shell (2-body decay):  $\Delta(\tilde{t}_1, \tilde{\chi}_1) > 175 \text{ GeV}$
- Final state: Hadronically-decaying top, Charm quark, and Large Missing Transverse Momentum



b-tagging jets is well-established...

#### c-tagging jet not so much!

- High-level DNN tagger (DL1r) leverages jet topology, impact parameter taggers, and secondary vertex finding algorithms
- Multidimensional output ( $p_b$ ,  $p_c$ ,  $p_{light}$ ) combined for c-tagging
- b-tag takes precedence: avoids high b-mistag rates

$$DL1_r = \log\left(\frac{p_c}{f_b p_b + (1 - f_b)p_u}\right) \quad \frac{\varepsilon_c}{20\%} \quad \frac{b \text{-rej. light rej.}}{57}$$

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### Stop to top-charm analysis - Analysis strategy



- Four signal regions targeting different regions of parameter space.
- Trigger on Missing Transverse Energy (MET), 0 Leptons  $(\mu/e)$ ,  $\geq 1$  b-tagged and  $\geq 1$  c-tagged.
- **SRD** (Compressed region)
  - **Required ISR JET**
  - Binned in  $m_{eff}$  and  $m_T(j,MET)_{close}$
  - Multi class NN to separate signal and tt-like and Vjets-like events.
- **SRB,SRC** (Intermediate selection)
  - Binned  $m_T(j,MET)_{close}$
- SRA (bulk selection)
  - High  $m_{T2}$  (top and c-tagged jet)



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### Stop to top-charm analysis – Backgrounds Estimation



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 $Z(\rightarrow vv)$ +jets CRs defined with 2 (SFOS) leptons required.

### Stop to top-charm analysis – Backgrounds Estimation



- A profile-likelihood fit is done yielding almost all normalization factors consistent with 1
- Most discrepancy for single-top SF. This is quite common in the extreme phase spaces in SUSY
- Three different ttbar normalization factors are considered
  - CRD  $tt_{750} \rightarrow tt_{1000} \rightarrow tt_{1250}$  binned in HT
  - Highly correlated with increasing pT ttbar events  $\rightarrow$  need increasing correction



NFs extracted from Control Regions applied to corresponding Validation Regions:

- Post-fit excesses in VRs < 2 sigma
- These are not used in the fit, they are used to validate the profile-likelihood fit in Control Regions



#### Stop to top-charm analysis - results



- Each signal region is binned to increase sensitivity
- SRA, SRB and SRCs have excesses but within 2 sigma.
- Data agrees well with SM prediction. Largest deficit in  $SRD1500_{[\geq 100]} \sim 1.8$  sigma

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# Stop to top-charm analysis - results

- First LHC result in this final state!
- $m(\tilde{t}_1) \lesssim 800$  GeV excluded for high mass,
- $m(\tilde{t}_1) \lesssim 600$  GeV for compressed
- Results for BR( $\tilde{t}_1 \rightarrow t \, \tilde{\chi}_1$ ) = 50%

• Scan in BR( $\tilde{t}_1 \rightarrow t \tilde{\chi}_1$ ) at fixed N1 mass = 1 GeV



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# Summary and Outlook

- Two recent results using Run 2 data presented in this talk.
  - Strong production of stops motivated by RPC SUSY
  - Novel ML-based analysis strategies featuring improved background modelling, object reconstruction, ...
- No significant excesses seen over SM backgrounds
  - Limits set on stop pair production cross-section
  - Including interpretations in DM models
- Many Run 2 results already public from ATLAS Collaboration!
- Run 3 ongoing: many new analyses in the works!



	Model	S	ignatur	e∫	<i>L dt</i> [fb <sup>-</sup>	Mass limit	Reference
sət	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$	0 e, µ mono-jet	2-6 jets 1-3 jets	$E_T^{miss}$ $E_T^{miss}$	140 140	[1x,8x Degen.] 1.0 1.85 m(t_1^n)<400 GeV   [8x Degen.] 0.9 m(d_1)=5 GeV m(d_2)=0.5 GeV	2010.14293 2102.10874
earch	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\chi_1$	0 e,µ	2-6 jets	$E_T^{aabs}$	140	2.3 m(k <sup>*</sup> <sub>1</sub> )=0 GeV   Forbidden 1.15-1.95 m(k <sup>*</sup> <sub>1</sub> )=1000 GeV	2010.14293 2010.14293
e Se	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}V\tilde{\chi}_{1}^{0}$	1 e,μ ee, μμ	2-6 jets 2 jets	Fmiss	140 140	2.2 m(t <sup>2</sup> )<600 GeV	2101.01629 2204 13072
visr	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$	0 e. µ	7-11 jets	$E_T^{miss}$	140	1.97 m(ž) <600 GeV	2008.06032
Inch	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{t} \tilde{\chi}_1^0$	0-1 e, µ	3 b	$E_T^{\rm miss}$	140	2.45 m(g)-m(r)=200 GeV	2211.08028
	διδ.	0 e.u	2 h	Emiss	140	1.25 m(g)m(X)=300 GeV	2101.12527
	·····			-/		0.68 10 GeV<∆m(b <sub>1</sub> , X <sub>1</sub> )<20 GeV	2101.12527
arks	$b_1b_1, b_1 \rightarrow b\tilde{\chi}_2^{\prime\prime} \rightarrow bh\tilde{\chi}_1^{\prime\prime}$	0 e,μ 2 τ	6 b 2 b	$E_T^{\text{finits}}$	140 140	Forbidden 0.23-1.35 Δm(k <sup>2</sup> <sub>2</sub> , k <sup>*</sup> <sub>1</sub> )=130 GeV, m(k <sup>*</sup> <sub>1</sub> )=00 GeV   0 0.13-0.85 Δm(k <sup>2</sup> <sub>2</sub> , k <sup>*</sup> <sub>1</sub> )=130 GeV, m(k <sup>*</sup> <sub>1</sub> )=0 GeV	1908.03122 2103.08189
2din	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0-1 e, µ	≥ 1 jet	$E_T^{miss}$	140	1.25 m(t <sup>2</sup> )=1 GeV	2004.14060, 2012.03795
t bu	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow Wb \mathcal{X}'_1$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\pi}, bv \neq 1 \rightarrow \pi \tilde{G}$	1 e,μ 1.2 τ	3 jets/1 b 2 jets/1 b	Emiss	140	1 Forbidden 1.05 m(X)=500 GeV	2012.03/99, AI LAS-CONF-20 2108.07665
s" ge	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	0 e.µ	2 c	Emiss Efinisa	36.1	0.85 m(f)=0 GeV	1805.01649
	$\bar{x} = \bar{x} + \bar{x}^0 + \bar{y}^0 + \pi (\bar{x}^0)$	1-2 e u	1.4 h	E <sub>T</sub> Fmiss	140	1 0.55 m(r <sub>1</sub> ,t)-m(t <sub>1</sub> )=5 GeV	2102.10874
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e,µ	1.6	$E_T^{miss}$	140	2 Forbidden 0.86 m( $\tilde{\chi}_1^0$ =360 GeV, m( $\tilde{r}_1$ )=m( $\tilde{\chi}_1^0$ =40 GeV	2006.05880
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via $WZ$	Multiple ℓ/jets cc, μμ	s ≥ 1 jet	$E_T^{miss}$ $E_T^{fniss}$	140 140	<sup>+</sup> / <sub>1</sub> / <sup>0</sup> / <sub>2</sub> 0.96 m(ℓ <sub>1</sub> <sup>+</sup> )=0, wino-bino <sup>+</sup> / <sub>1</sub> / <sup>2</sup> / <sub>2</sub> 0.205 m(ℓ <sub>1</sub> <sup>+</sup> )=5 GeV, wino-bino	2106.01676, 2108.0758 1911.12606
	$\tilde{\chi}_{1}^{*}\tilde{\chi}_{1}^{\mp}$ via WW	2 e, µ		$E_T^{miss}$	140	m(ℓ <sub>1</sub> <sup>0</sup> )=0, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh	Multiple <i>l</i> /jets	8	$E_T^{mas}$	140	*/X <sup>*</sup> <sub>2</sub> Forbidden 1.06 m(X <sup>*</sup> <sub>1</sub> )=70 GeV, who-bino	2004.10894, 2108.0758
s s	$\tilde{x}_1 x_1 \sqrt{a} \tilde{v}_L / v$ $\tilde{\tau}_2 \tilde{\tau}_{\rightarrow \tau} \tilde{v}_1^0$	2 τ		Emiss	140	TR-TR1 0.34 0.48 m(c,r)=0.34 m(c,r)=0.34	ATLAS-CONF-2023-025
国歌	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e, µ	0 jets	Emiss	140	0.7 m(t <sup>2</sup> )=0	1908.08215
	$\hat{H}\hat{H}$ , $\hat{H} \rightarrow h\hat{G}/Z\hat{G}$	0 e.u	> 3 h	Emiss	140	0.94 BR/2 <sup>0</sup> = 10 GRV	To appear
		4 e, µ	0 jets	Efficies	140	$9$ 0.55 BR( $\tilde{t}_{i}^{i} \rightarrow Z\tilde{G}$ )=1	2103.11684
		2 e,µ	≥ 2 jets	$E_T^{miss}$	140	Image: Market of the second	2204.13072
	$\text{Direct} \tilde{\mathcal{X}}_1^* \tilde{\mathcal{X}}_1^-$ prod., long-lived $\tilde{\mathcal{X}}_1^\pm$	Disapp. trk	1 jet	$E_T^{\rm miss}$	140	2 0.66 Pure Wino	2201.02472 2201.02472
es es	Stable 2 R-hadron	pixel dE/dx		Emiss	140	2.05	2205.06013
-62	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\ell}_1^0$	pixel dE/dx		$E_T^{miss}$	140	ir(ĝ) =10 ns] 2.2 m(l <sup>0</sup> )=100 GeV	2205.06013
o ad	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep		$E_T^{mas}$	140	$\tilde{\mu}$ 0.7 $\tau(\tilde{t}) = 0.1 \text{ ns}$	2011.07812
		pixel dE/dx		$E_T^{\rm miss}$	140	0.36 T(Č) = 10 ns	2205.06013
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{\pm} \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 c, µ	0 inte	rmiss	140	<sup>+</sup> / <i>k</i> <sup>0</sup> / <sub>1</sub> [BR(Zr)=1, BR(Zr)=1] 0.625 1.05 Pure Wino	2011.10543
	$\chi_1 \chi_1 / \chi_2 \rightarrow w w/Z U U v v$ $\tilde{e} \tilde{e} \rightarrow a a \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow a a a$	+ c, μ	≥8 jets	~T	140	m(t_1)=200 GeV m(t_2)=50 GeV 1250 GeV 1250 GeV 1250 GeV	To appear
>	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$		Multiple		36.1	[X''_112=20-4, 10-2] 0.55 1.05 m(t_1^0)=200 GeV, bino-like	ATLAS-CONF-2018-003
RP	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_{1}^{\pm}, \tilde{\chi}_{1}^{\pm} \rightarrow bbs$		$\geq 4b$		140	Forbidden 0.95 m(X <sup>2</sup> )=500 GeV	2010.01015
	$i_1i_1, i_1 \rightarrow os$ $\tilde{i}_1\tilde{i}_1, \tilde{i}_1 \rightarrow al$	2 e.u	2 jets + 2 l 2 h		36.7	1 (qq, bs) 0.42 0.61 0.4-1.45 BB(f <sub>1</sub> →be/bu)>20%	1710.07171 1710.05544
		1 μ	DV		136	$\frac{1}{10} \left[10^{-10} < \lambda'_{214} < 10^{-8}, 30^{-10} < \lambda'_{214} < 30^{-9}\right] \qquad 1.0 \qquad 1.6 \qquad BR(\hat{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_1 = 100\%, \sin\theta_1 = 1$	2003.11956
	$\tilde{\chi}_{1}^{\pi}/\tilde{\chi}_{2}^{o}/\tilde{\chi}_{1}^{o}, \tilde{\chi}_{1,2}^{0} \rightarrow tbs, \tilde{\chi}_{1}^{+} \rightarrow bbs$	1-2 e, µ	≥6 jets		140	0.2-0.32 Pure higgsino	2106.09609

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Backup

### Stop to top-charm analysis - results



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Other results for Stop-N1



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### Stop-NN and DM-NN

Table 3: Summary of the selections on the stop-NN and DM-NN output values that define CRs, VRs and SRs. Signal efficiencies, computed as the fraction of signal events in a given category with a NN output value in the range accepted in the SR, are also reported. The quoted range encompasses efficiencies estimated for all signals across the simulated parameter space. In boosted categories, only efficiencies for  $\tilde{t}_1 \tilde{t}_1$  signals with  $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > 500$  GeV are quoted.

		stop-N	N		DM-NN			
Category	CR	VR	SR		CR	VR	SR	
	Range	Range	Range	Eff.	Range	Range	Range	Eff.
High- $E_{\rm T}^{\rm miss}$ 1b	[0.2, 0.64)	[0.64, 0.79)	[0.79, 1.0]	0.4-0.9	[0.3, 0.69)	[0.69, 0.87)	[0.87, 1.0]	0.3-0.4
High- $E_{\rm T}^{\rm miss}$ 2b	[0.1, 0.56)	[0.56, 0.70)	[0.70, 1.0]	0.5-0.9	[0.3, 0.60)	[0.60, 0.76)	[0.76, 1.0]	0.6-0.8
Boosted 1b-lep-1t	[0.0, 0.65)	[0.65, 0.80)	[0.80, 1.0]	0.5-0.9				
Boosted 1b-had-1t	[0.0, 0.65)	[0.65, 0.85)	[0.85, 1.0]	0.6-0.9				
Boosted 2b-1t	[0.0, 0.75)	[0.75, 0.95)	[0.95, 1.0]	0.6-0.8				
Boosted 1b-lep-0t	[0.0, 0.70)	[0.70, 0.85)	[0.85, 1.0]	0.6-0.8				
Boosted 1b-had-0t	[0.0, 0.75)	[0.75, 0.95)	[0.95, 1.0]	0.4-0.8				
Boosted 2b-0t	[0.0, 0.65)	[0.65, 0.80)	[0.80, 1.0]	0.6-0.9				