Towards an LHC observable NMSSM grid

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in collaboration with
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and with thanks to
Ulrich Ellwanger & Tilman Plehn

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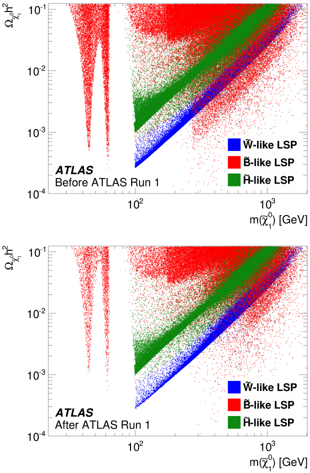
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

HIGH ENERGY PHYSICS MASTER JOINT PROGRAM

Introduction: SUSY grids at run 1

ATLAS run 1 SUSY summary (JHEP 1510 (2015) 134)

- randomly choose 500 000 000 pMSSM parameter configurations
- compute spectrum and observables
- discard points incompatible with experimental constraints
- evaluate whether production processes are accessible at LHC
- generate events and evaluate whether the point is excluded by ATLAS searches (45 000 fully simulated points)



⟹ ultimate goal: perform a full scan of the NMSSM parameter space including all of the run 2 SUSY searches

⟹ first step: find a (small) grid in cNMSSM parameter space accessible at run 2

semi-constrained $\mathbb{Z}_3$-invariant NMSSM

Higgs superpotential

$$W_H = \mu \widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

Higgs sector

$$\Re\left(H_u^0, H_d^0, S\right) \longrightarrow \left(h_1^0, H_2^0, H_3^0\right)$$

$$\Im\left(H_u^0, H_d^0, S\right) \longrightarrow \left(A_1, A_2\right)$$

Neutralino sector

$$\left(\tilde{B}, \tilde{W}, \tilde{H}_u, \tilde{H}_d, \tilde{S}\right) \longrightarrow \left(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0\right)$$

free parameters

$$\lambda, \kappa, A_\lambda, A_\kappa, \tan\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}, \mu_{\text{eff}} \equiv \lambda \langle S \rangle, M_{1/2}, m_0, A_0$$

$$M_1, M_2, M_3, m^2_{\tilde{q}_i}, m^2_{\tilde{u}_i}, m^2_{\tilde{d}_i}, m^2_{\tilde{\ell}_i}, m^2_{\tilde{e}_i}, A_t, A_b, A_\tau$$

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$$M_1, M_2, M_3, m_{\tilde{q}_i}^2, m_{\tilde{u}_i}^2, m_{\tilde{d}_i}^2, m_{\tilde{\ell}_i}^2, m_{\tilde{e}_i}^2, A_t, A_b, A_\tau$$

A lot of research is done on NMSSM phenomenology

(a not exhaustive selection of recent results)

Benchmark points (LHCHXSWGNMSSM)

- $\tilde{\chi}_2^0(\tilde{B}) \to \tilde{\chi}_1^0(\tilde{S}) H_2^0(125\,\text{GeV})$

  (Ellwanger, Teixeira, JHEP 1504 (2015) 172)
- ggF $\to A_1(26\,\text{GeV}) \to b\bar{b}$

  (Allanach, Badziak, Hugonie, Ziegler, Phys. Rev. D92 (2015) 015006)
- $H_2^0 \to 2H_1^0(37\,\text{GeV}) \to 4A_1(7\,\text{GeV})$

  (Barducci, Belanger, Hugonie)

750 GeV diphoton excess

ggF $\to H_2^0/H_3^0 \to A_1 A_1 \to 2(\gamma\gamma)$

$M(H_2) \approx 730\,\text{GeV}$, $M(H_3) \approx 760\,\text{GeV}$

- $M(A_1) = 211\,\text{MeV} \lesssim 2M(\mu^\pm)$

  (Ellwanger, Hugonie, 1602.03344)
- $M(A_1) = 135\,\text{MeV} \approx M(\pi^0)$

  (Domingo, Heinemeyer, Kim, Rolbiecki, Eur. Phys. J. C76 (2016) 249)

Neutralino dark matter

$\tilde{\chi}_1^0$ with large singlino content:

- Galactic Center Excess from $\tilde{\chi}_1^0\tilde{\chi}_1^0(30 - 70\,\text{GeV}) \to b\bar{b}, \tau^+\tau^-$

  (Butter, Plehn, Rauch, Zerwas, Henrot-Versillé, Lafaye, Phys. Rev. D93 (2016) 015011)
- $\tilde{\chi}_1^0\tilde{\chi}_1^0(\gtrsim 10\,\text{GeV}) \to \nu_\mu\nu_\mu$ in the sun

  (Enberg, Munir, de los Heros, Werder, 1506.05714)
- blind spots: $\sigma_{SI} \approx 0$

  (Badziak, Olechowski, Szczerbiak, JHEP 1603 (2016) 179)

Other dark matter candidates

- right-handed sneutrino $\tilde{\nu}_R$

  (Cerdeño, Peiró, Robles, JCAP 1604 (2016) 011)
- gravitino $\tilde{G}$

  (Hasenkamp, Winkler, Nucl. Phys. B877 (2013) 419)

and much more ...

Experimental constraints

Measurement	Value and error	Unit
$M(H_2)$	$125.09 \pm 0.24\,(\text{exp}) \pm 3\,(\text{theo})$	[GeV]
$M(\tilde{\chi}_1^0)$	$< M(\tilde{t}_1), M(\tilde{b}_1), M(\tilde{\tau}_1^\pm), M(\tilde{\chi}_1^\pm)$	
$\Omega_{\text{CDM}} h^2$	$0.1188 \pm 0.0010\,(\text{exp}) \pm 10\,\%\,(\text{theo})$	
$\sigma^{\text{SI}}(\tilde{\chi}_1^0 - {}^{54}\text{Xe})$	$<$ LUX limits	
$M(\tilde{\chi}_1^\pm)$	> 103	[GeV]
$M(H^\pm)$	> 78.6	[GeV]
$\text{BR}(B \to X_s\gamma)$	$3.43 \pm 0.21\,(\text{exp}) \pm 0.07\,(\text{theo})$	$[10^{-4}]$
$\text{BR}(B_s^0 \to \mu^+\mu^-)$	$2.9 \pm 0.7\,(\text{exp})$	$[10^{-9}]$
$\text{BR}(B^+ \to \tau^+\nu_\tau)$	$1.14 \pm 0.22\,(\text{exp})$	$[10^{-4}]$

`SFitter`: MCMC scan of NMSSM parameter space based on a χ^2 distribution computed from experimental constraints

`NMSSMTools`: computation of Higgs and sparticle masses, couplings and decays in the NMSSM

`micrOMEGAs`: computation of relic density and direct detection cross sections of neutralino dark matter

ATLAS' supersymmetry searches at 13 TeV

0-lepton analysis (1605.03814)

search for one-step decays

- $\tilde{q} \to q\tilde{\chi}_1^0$
- $\tilde{g} \to qq\tilde{\chi}_1^0$

in events with E_T^{miss}, jets and no leptons

	2jm 0L	4jt 0L	5j 0L
Leptons	no lepton		
E_T^{miss} [GeV] $>$	200	200	200
p_T(jets) [GeV] $>$	300, 50	200, 100, 100, 100	200, 100, ..., 100
$\Delta\varphi(\vec{\text{jet}}_{1\ldots3}, \vec{E}_T^{miss}) >$	0.4	0.4	0.4
$\Delta\varphi(\vec{\text{jet}}_{>3}, \vec{E}_T^{miss}) >$	–	0.2	0.2
$A >$	–	0.04	0.04
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] $>$	15	–	–
$E_T^{miss}/m_{\text{eff}}(N_j) >$	–	0.2	0.25
m_{eff}(incl.) [GeV] $>$	1600	2200	1600

Event generation

MadGraph5_aMC@NLO: cross section computation and generation of hard events for $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production

Pythia6: sparticle decays and showering of hard events with the k_T-jet MLM scheme

Delphes: fast simulation of the ATLAS detector's response

MadAnalysis: implementation of cut-based ATLAS analyses to compare with upper limits derived from data

ATLAS' supersymmetry searches at 13 TeV

1-lepton analysis (1605.04285)

search for two-step decays

- $\tilde{g} \to qq\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$

in events with E_T^{miss}, jets and one isolated lepton

	5j SL	4j low-x HL	5j HL
Leptons	one soft lepton	one hard lepton	
p_T(lepton) [GeV]	< 35, $> 7(8)$	> 35	
E_T^{miss} [GeV] $>$	375	200	250
p_T(jets) [GeV] $>$	200, 200, 30, 30, 30	325, 150, 150, 150	225, 50, . . ., 50
m_T [GeV] $>$	100	425	125
H_T [GeV] $>$	1100	–	–
$A >$	0.02	0.04	0.04
$E_T^{\text{miss}}/m_{\text{eff}}$(incl.) $>$	–	–	0.1
m_{eff}(incl.) [GeV] $>$	–	2000	1800

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Preliminary results: SFitter scan – Profile likelihood in $M_{1/2} : m_0$

$\tan\beta = 5.44$

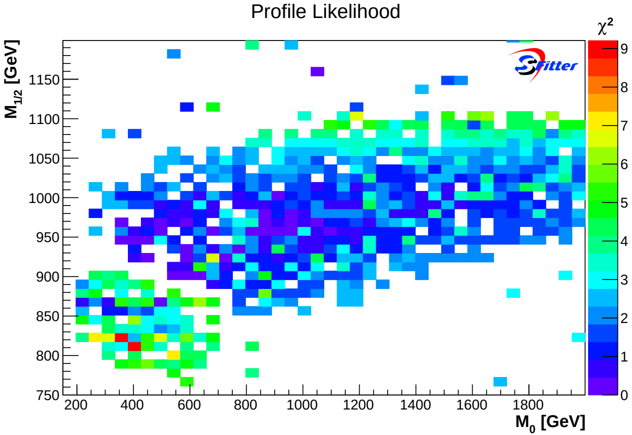
$A_\lambda^{\text{GUT}} = 1400$ GeV

$A_\kappa^{\text{GUT}} = 1488$ GeV

$\lambda^{\text{SUSY}} = 0.6$

$\kappa^{\text{SUSY}} = 0.18$

$\mu_{\text{eff}} = 208.7$ GeV



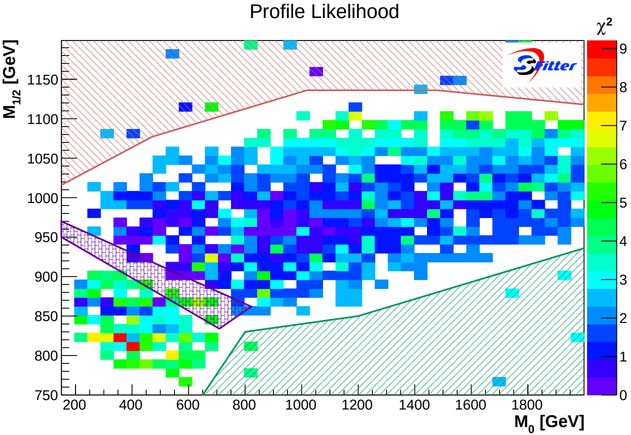
$\Longrightarrow$ scan in $\{m_0, M_{1/2}, A_0\}$ space with fixed other parameters

$\Longrightarrow$ identify regions compatible with all constraints

$\Longrightarrow$ choose points in this region suitable to construct a grid

Preliminary results: SFitter scan – Profile likelihood in $M_{1/2}$: m_0

- no 125 GeV Higgs
- wrong relic density
- wrong $b \to s\gamma$
- excluded by LUX



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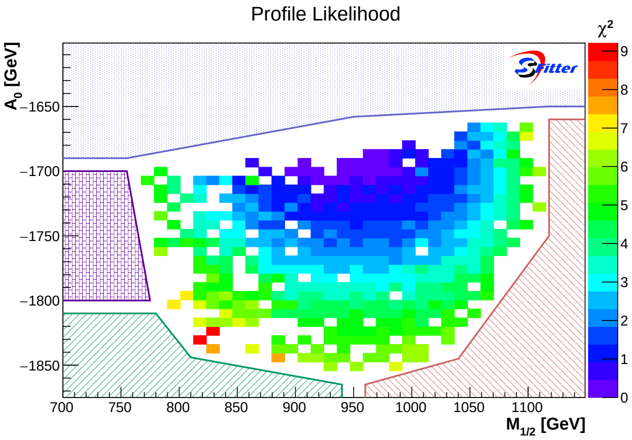

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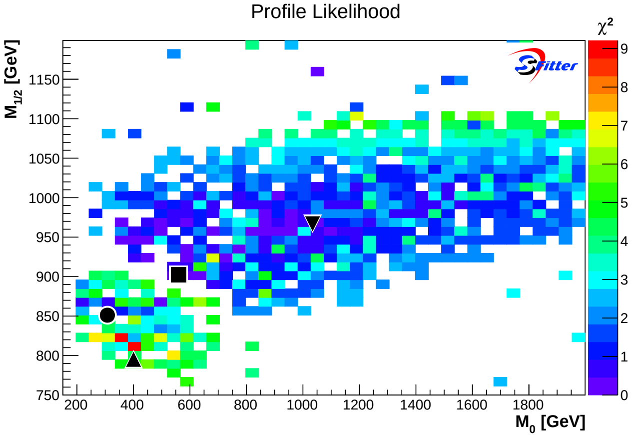
$m_0^\blacktriangle = 400.3$ GeV
$M_{1/2}^\blacktriangle = 795.2$ GeV
$A_0^\blacktriangle = -1715$ GeV

$m_0^\bullet = 307.7$ GeV
$M_{1/2}^\bullet = 851.1$ GeV
$A_0^\bullet = -1706$ GeV

$m_0^\blacksquare = 559.8$ GeV
$M_{1/2}^\blacksquare = 902.1$ GeV
$A_0^\blacksquare = -1698$ GeV

$m_0^\blacktriangledown = 1034$ GeV
$M_{1/2}^\blacktriangledown = 966.9$ GeV
$A_0^\blacktriangledown = -1705.9$ GeV



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Preliminary results: SFitter scan – Profile likelihood in $M(\tilde{u}_R)$: $M(\tilde{g})$

$M(\tilde{g})^{\blacktriangle} = 1.78$ TeV

$M(\tilde{u}_R)^{\blacktriangle} = 1.62$ TeV

$M(\tilde{\chi}^0_1)^{\blacktriangle} = 107.8$ GeV

$M(\tilde{g})^{\bullet} = 1.89$ TeV

$M(\tilde{u}_R)^{\bullet} = 1.70$ TeV

$M(\tilde{\chi}^0_1)^{\bullet} = 108.6$ GeV

$M(\tilde{g})^{\blacksquare} = 2.01$ TeV

$M(\tilde{u}_R)^{\blacksquare} = 1.85$ TeV

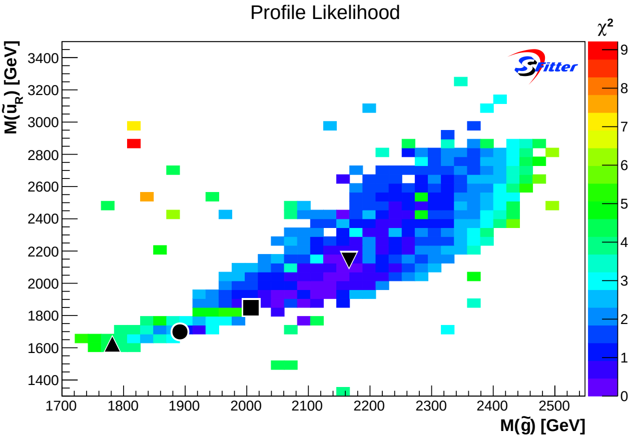
$M(\tilde{\chi}^0_1)^{\blacksquare} = 109.3$ GeV

$M(\tilde{g})^{\blacktriangledown} = 2.17$ TeV

$M(\tilde{u}_R)^{\blacktriangledown} = 2.14$ TeV

$M(\tilde{\chi}^0_1)^{\blacktriangledown} = 110.1$ GeV

$S^2_{15} \simeq 65\,\%$



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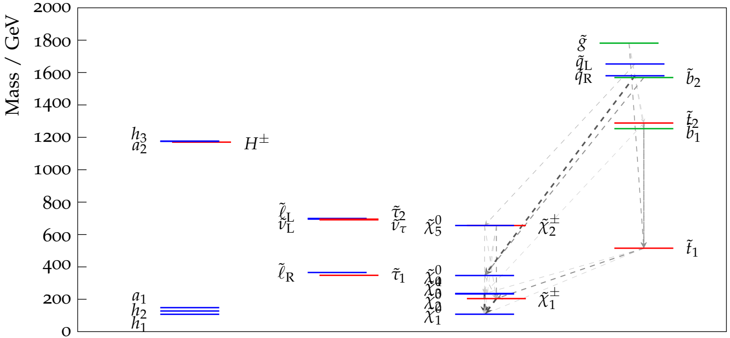
Preliminary results: Benchmark points in ATLAS simulation at 13 TeV

		▲	●	■	▼	ATLAS*
$\sigma(pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q})$ [pb]		30.70 ± 0.06	20.25 ± 0.05	10.46 ± 0.02	3.25 ± 0.01	
$\epsilon\sigma \cdot 3.2\,\text{fb}^{-1}$	4jt 0L	4.99 ± 0.33	2.93 ± 0.20	1.99 ± 0.13	0.70 ± 0.04	< 8.7
	5j 0L	1.61 ± 0.15	0.93 ± 0.09	0.61 ± 0.05	0.24 ± 0.02	< 5.0
	4j low-x HL	2.90 ± 0.22	2.44 ± 0.17	1.26 ± 0.09	0.46 ± 0.03	< 3.9
	5j HL	1.40 ± 0.14	1.39 ± 0.12	0.60 ± 0.05	0.24 ± 0.02	< 2.8

* model-independent upper limits at 95 % CL

Mass spectrum of point ▲:



Conclusions

- We found a cNMSSM grid compatible with all the experimental constraints that should be accessible at LHC run 2.
- The 0/1-lepton analyses should be able to discover or exclude a big number of parameter configurations with $50\,\text{fb}^{-1}$ of 14 TeV data. Other searches (like stop analyses) could be more sensitive to this grid.
- Complementary, future results of direct detection experiments will probe the grid.
- Our ongoing work will
  - include more experimental results as input measurements;
  - evaluate the capability of the grid configurations to explain the Galactic Center Excess;
  - consider the possibility that the lightest Higgs boson has a mass of 125 GeV.