Natural SUSY after the 8 TeV LHC run

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based on:
Phys.Rev. D88 (2013) 075001
KK, E.Sessolo

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Outline

1. Definition of fine tuning

2. Reinterpretation of the LHC exclusion bounds

3. Limits on natural spectra

4. Conclusions

Fine tuning

Is the electro-weak scale stable?

$$\frac{1}{2}M_Z^2 = -\mu^2 + \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{\tan^2\beta - 1}$$

Fine tuning

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Barbieri Giudice-Measure: $\Delta_{p_i} = \left|\frac{\partial \log M_Z^2}{\partial \log p_i^2}\right| = \frac{p_i^2}{M_Z^2}\left|\frac{\partial M_Z^2}{\partial p_i^2}\right|$

p_i – parameters of the model

FT ~ mass scale difference p_i/M_Z

Fine tuning

RGE running:

$$\frac{d}{dt}m_{H_u}^2 = \frac{1}{16\pi^2}[6Y_t^2(A_t^2 + m_{H_u}^2 + m_{Q_3}^2 + m_{U_3}^2) - (6g_2^2M_2^2 + \frac{6}{5}g_1^2M_1^2)$$

$$\frac{d}{dt}m_{Q_3}^2 = \frac{1}{16\pi^2}[-\frac{32}{3}g_3^2M_3^2 + ...]$$

If SUSY broken at Λ:

$$m_{H_u}(EW) = f(m_{Q_3}(\Lambda), m_{U_3}(\Lambda), A_t(\Lambda), M_3(m_{Q_3}(\Lambda))$$

FT ~ log(SSB scale)

Fine tuning

RGE running:

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If SUSY broken at Λ:

$$m_{H_u}(EW) = f(m_{Q_3}(\Lambda), m_{U_3}(\Lambda), A_t(\Lambda), M_3(m_{Q_3}(\Lambda))$$

Limits for Δ = 100 (1%):

FT ~ log(SSB scale)

$$|\mu| \lesssim 645\mathrm{GeV}$$

$$|M_3| \lesssim 8500\mathrm{GeV} \cdot \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-1}$$

$$(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2) \lesssim (3700\mathrm{GeV})^2 \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-1}$$

3rd generation!

Fine tuning vs LHC

Direct SUSY searches:

95% exc. limits on the masses of stops, sbottoms, gluinos

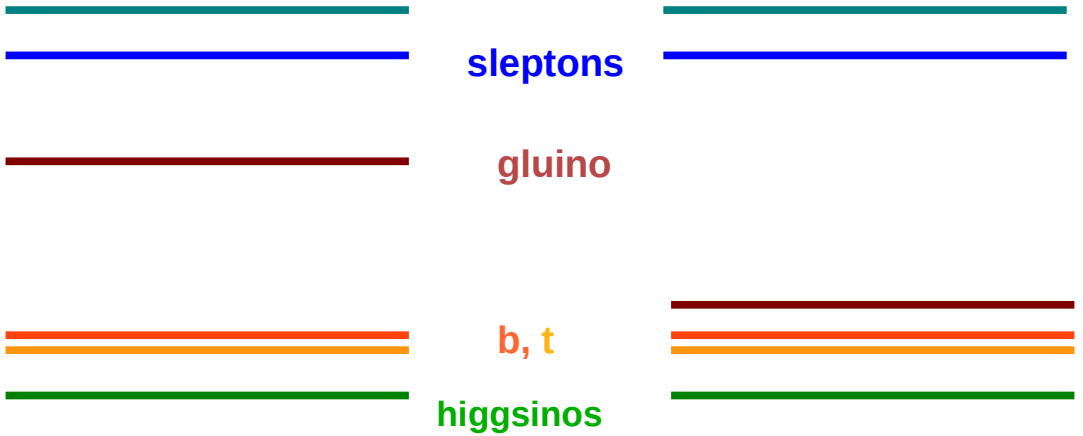
Higgs mass ~ 125 GeV

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm susy}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm susy}^2}\left(1 - \frac{X_t^2}{12M_{\rm susy}^2}\right)\right]$$

$$X_t = A_t - \mu \cot\beta$$

Natural spectra

Scenario 1	Scenario 2
$M_1 = 3\,\text{TeV}$	$M_1 = 3\,\text{TeV}$
$M_2 = 1.5\,\text{TeV}$	$M_2 = 1.5\,\text{TeV}$
$M_3 = 1.6\,\text{TeV}$	$0.1\,\text{TeV} \leq M_3 \leq 1.6\,\text{TeV}$
$m_{\tilde{L}_{1,2,3}} = m_{\tilde{e}_1} = m_{\tilde{e}_2} = m_{\tilde{e}_3} = 3\,\text{TeV}$	$m_{\tilde{L}_{1,2,3}} = m_{\tilde{e}_1} = m_{\tilde{e}_2} = m_{\tilde{e}_3} = 3\,\text{TeV}$
$0.075\,\text{TeV} \leq \mu \leq 0.63\,\text{TeV}$	$0.075\,\text{TeV} \leq \mu \leq 0.63\,\text{TeV}$
$0.1\,\text{TeV} \leq m_{\tilde{Q}_3}, m_{\tilde{u}_3} \leq 1.4\,\text{TeV}$	$0.1\,\text{TeV} \leq m_{\tilde{Q}_3}, m_{\tilde{u}_3} \leq 1.4\,\text{TeV}$
$\tilde{t}_{1,2}$, $\tilde{b}_1$, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$	$\tilde{g}$, $\tilde{t}_{1,2}$, $\tilde{b}_1$, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$



Experimental constraints

We generate 5000 model points in a sample that satisfy:

Measurement	Mean or range	Error: exp., th.	Distribution
$\Omega_\chi h^2$	0.1199	0.0027, 10%	2σ upper limit
BR $\left(\overline{B} \to X_s\gamma\right)\times 10^4$	3.43	0.22, 0.21	2σ
BR $\left(B_s \to \mu^+\mu^-\right) \times 10^9$	3.2	$+1.5, -1.2$, 10%	2σ
$m_b(m_b)^{\overline{MS}}$	4.18 GeV	0.03 GeV, 0	Gaussian
M_t	173.5 GeV	1.0 GeV, 0	Gaussian
α_s	0.1184 GeV	0.0007 GeV, 0	Gaussian

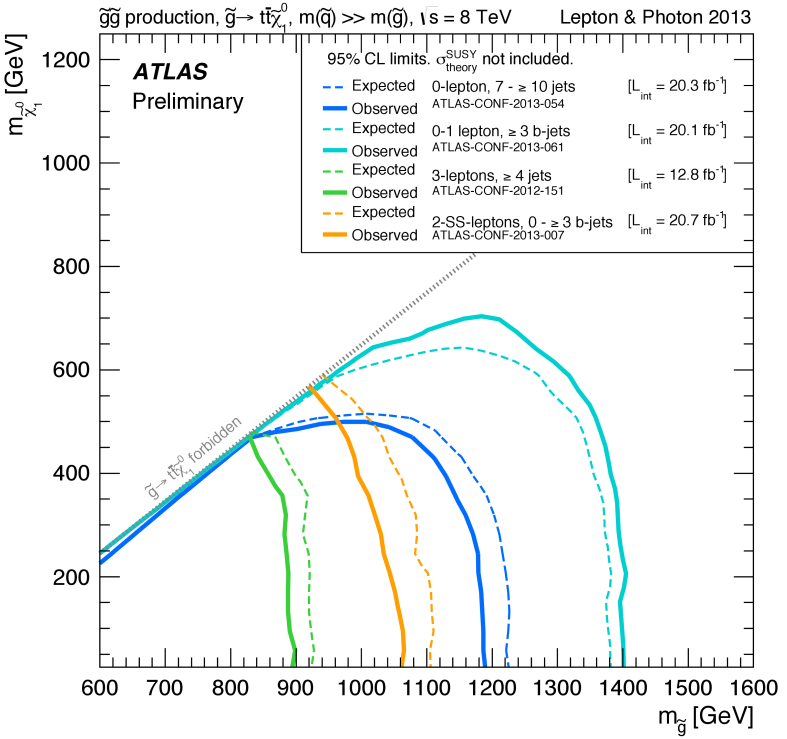
LHC limits →

Higgs mass at 125.7 GeV →

LHC limits on SUSY

LHC limits for Simplified Models

reinterpretation needed for more complicated scenarios



Our way to do:

- full simulation of event generation + detector response (`PYTHIA6, PGS4`)
- closely follows the experimental analysis

$$s_i = \varepsilon_i \times \sigma_{\mathrm{NLO+NLL}} \times \int L$$

- validated against the official limits

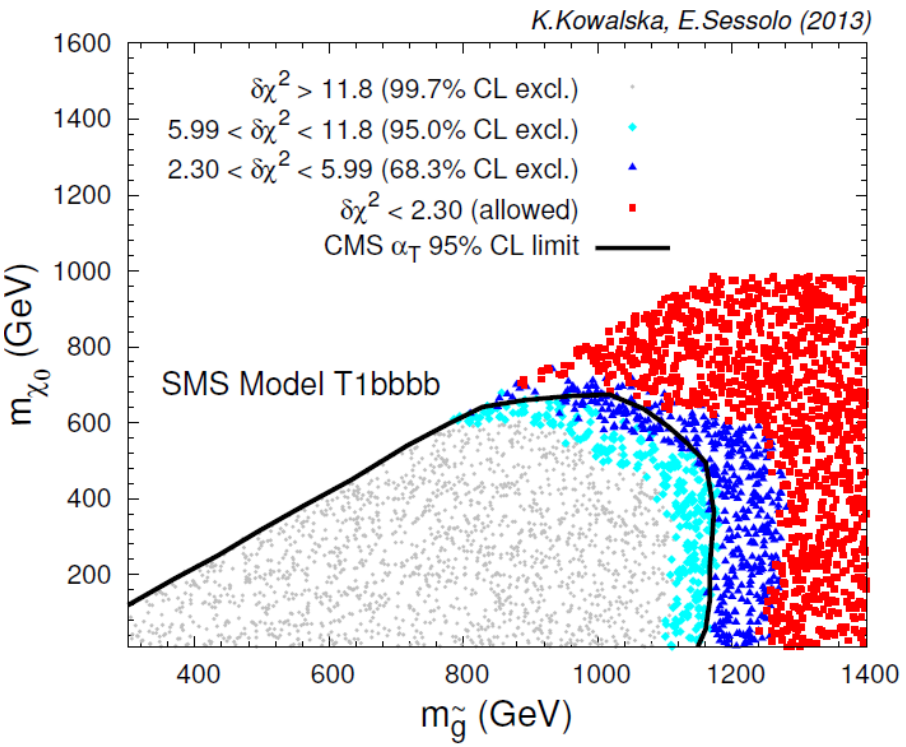
SUSY Likelihood:

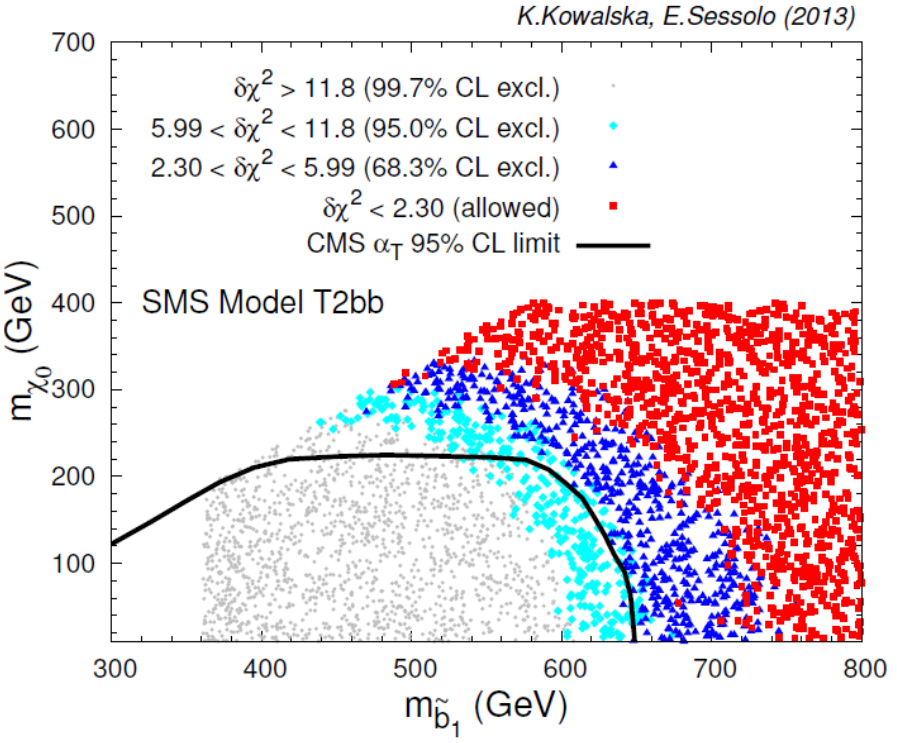
$$\mathcal{L}_i(o_i, s_i, b_i) = \int P(o_i|s_i, \bar{b}_i) \exp\left(-\frac{(b-\bar{b})^2}{2\delta b^2}\right) d\bar{b}_i$$

$$\mathcal{L}_{\mathrm{tot}} = \sum_i \mathcal{L}_i$$

Allows for combination of searches

LHC limits on SUSY

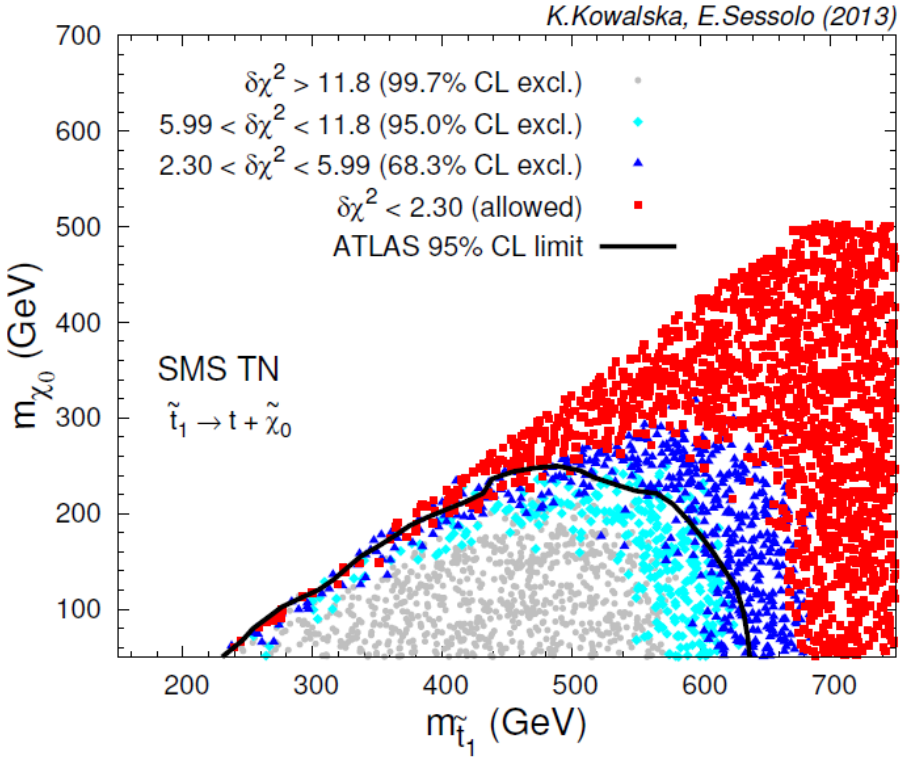




CMS 0-leptons + (b-) jets $+E_T^{\mathrm{miss}}$ with α_T, $12\mathrm{fb}^{-1}$

CMS-SUS-12-028

LHC limits on SUSY



$\mathrm{ATLAS\ 1\text{-}lepton} + 4(1\mathrm{b}\text{-})\ \mathrm{jets} + E_T^{\mathrm{miss}},\ 21\mathrm{fb}^{-1}$

ATLAS-CONF-2013-037

Scenario 1 – light stops and higgsinos

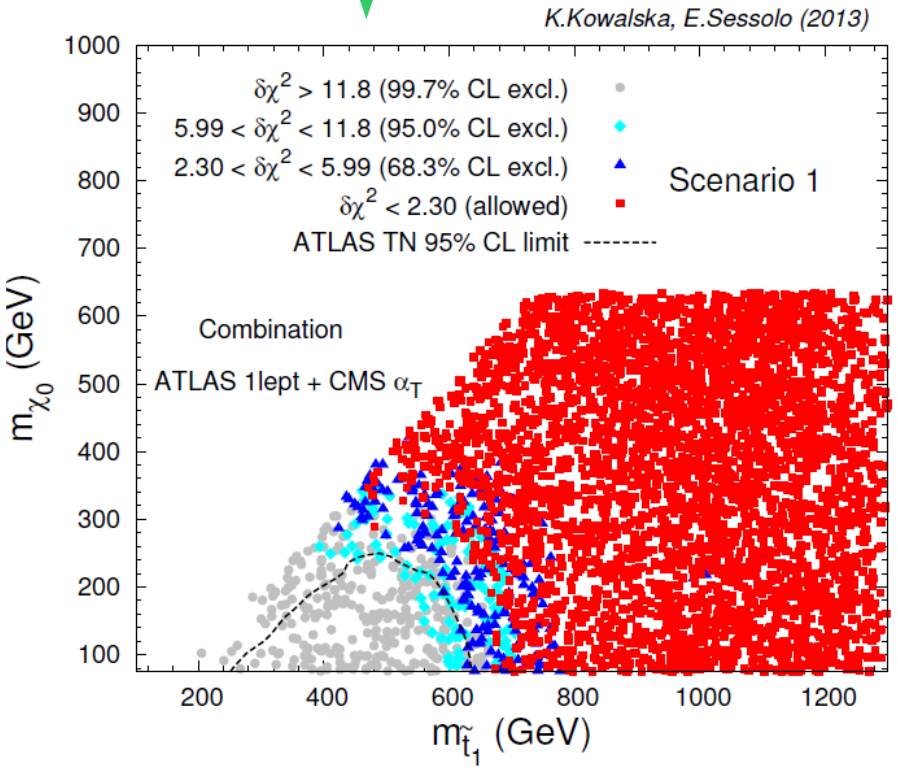
Dominant decay channels:

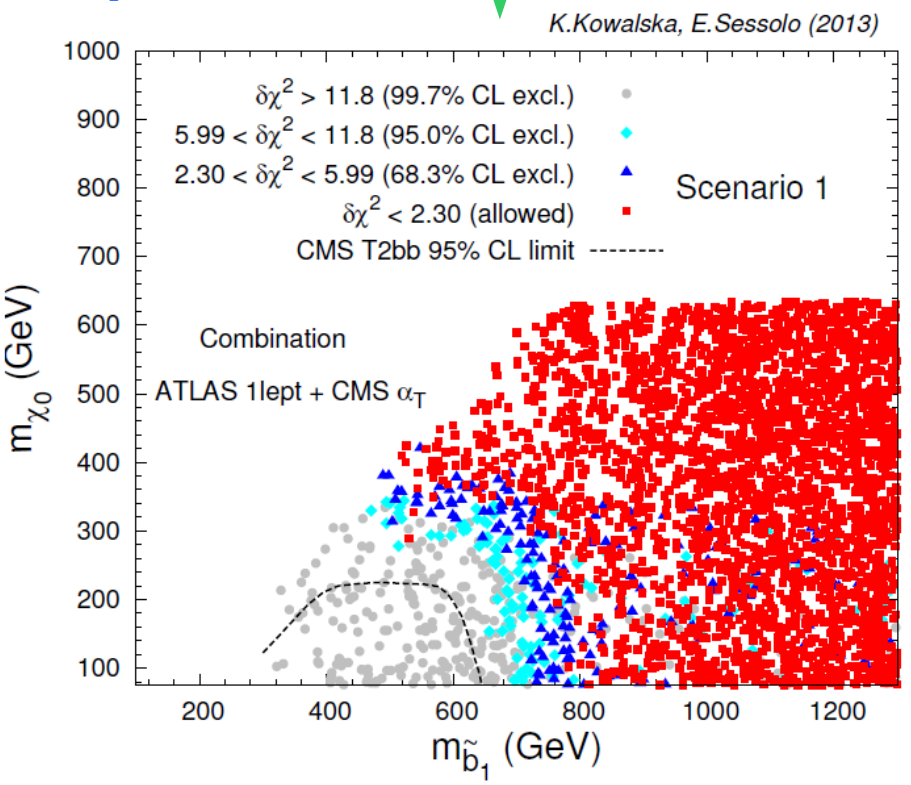
$$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$$

$$\tilde{b}_1 \rightarrow t\tilde{\chi}_1^- \quad \text{chargino invisible}$$

$$m_{\tilde{t}_1} < m_{\tilde{b}_1}$$

ATLAS 1 lepton
CMS 0 leptons





Scenario 1 – light stops and higgsinos

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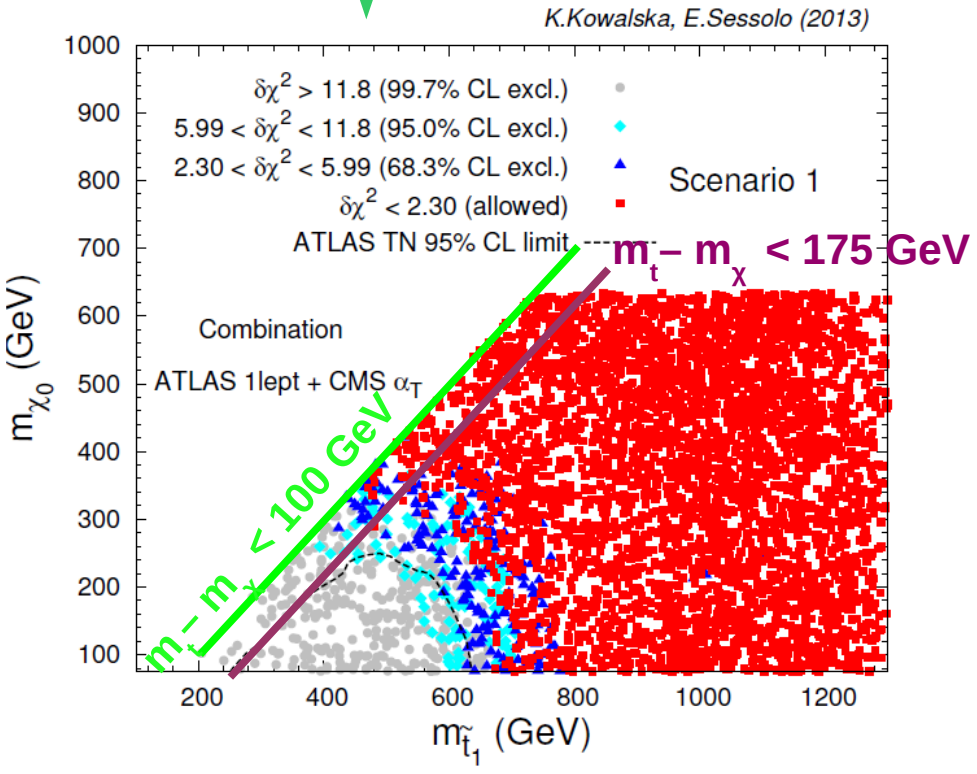
$$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$$

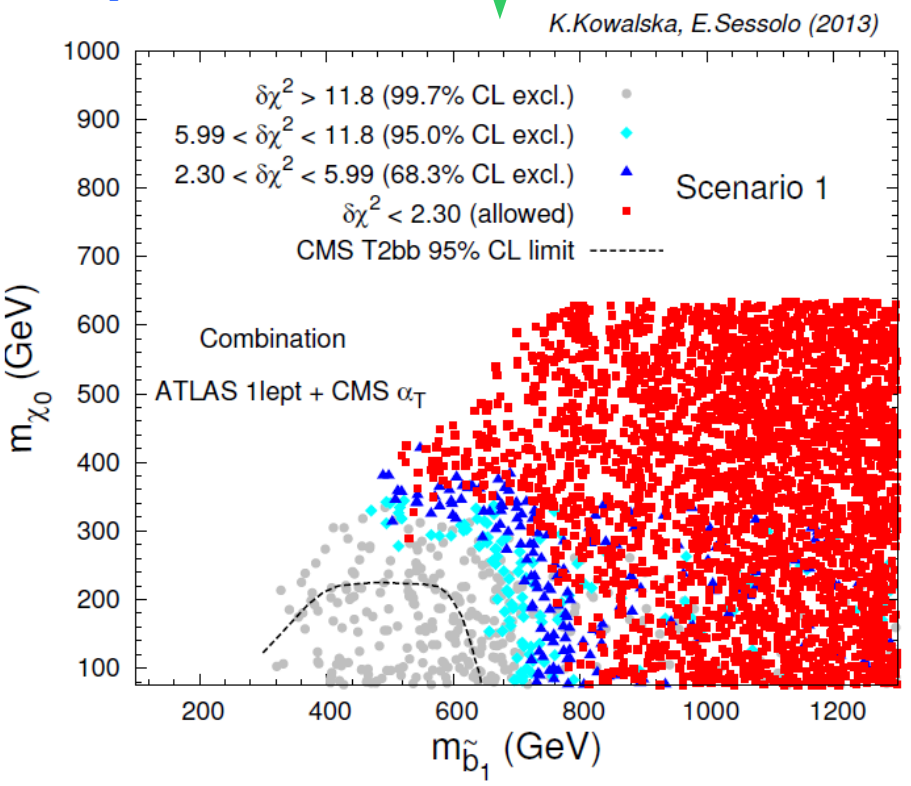
$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^- \rightarrow$$ 0 leptons b-jets

ATLAS 1 lepton
CMS 0 leptons

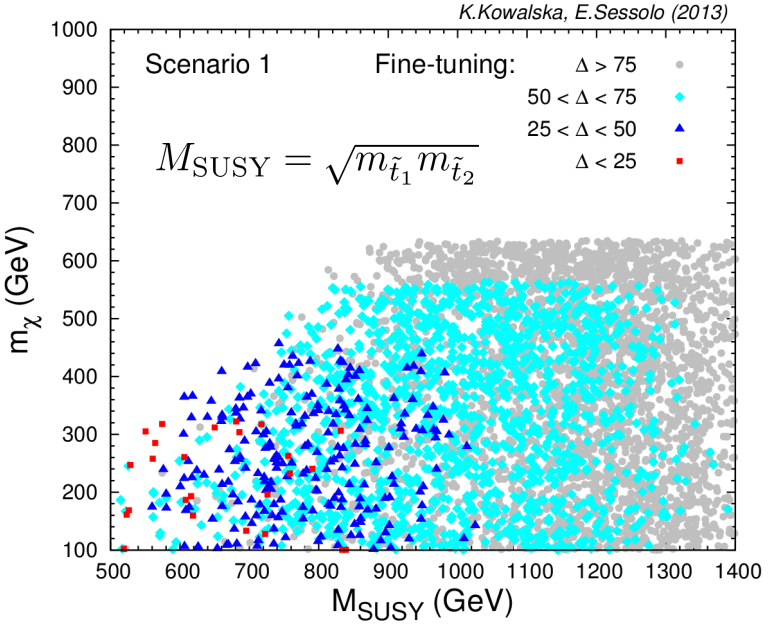
$$\tilde{b}_1 \rightarrow t\tilde{\chi}_1^-$$ chargino invisible

$$m_{\tilde{t}_1} < m_{\tilde{b}_1}$$





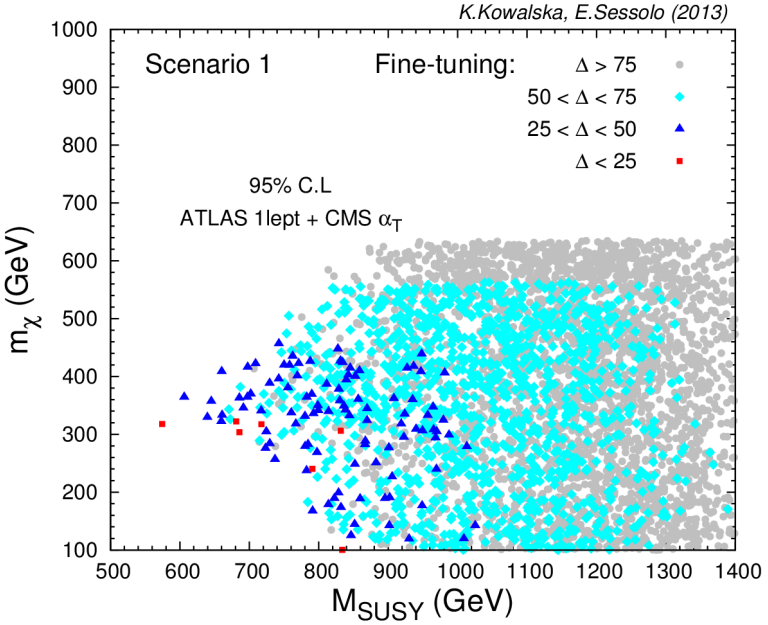
Scenario 1 – light stops and higgsinos



Δ due to third generation and higgsinos

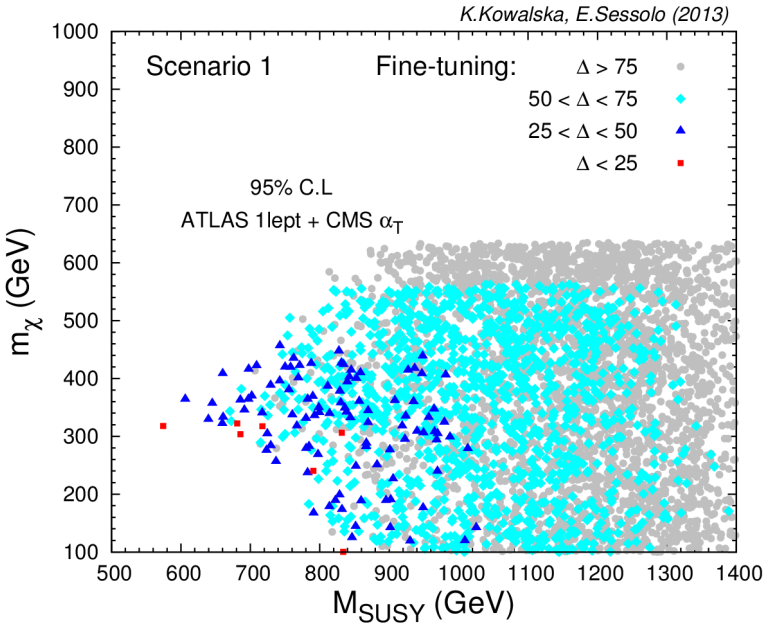
$\Delta_{\tilde{g},\tilde{w}} \sim 2$

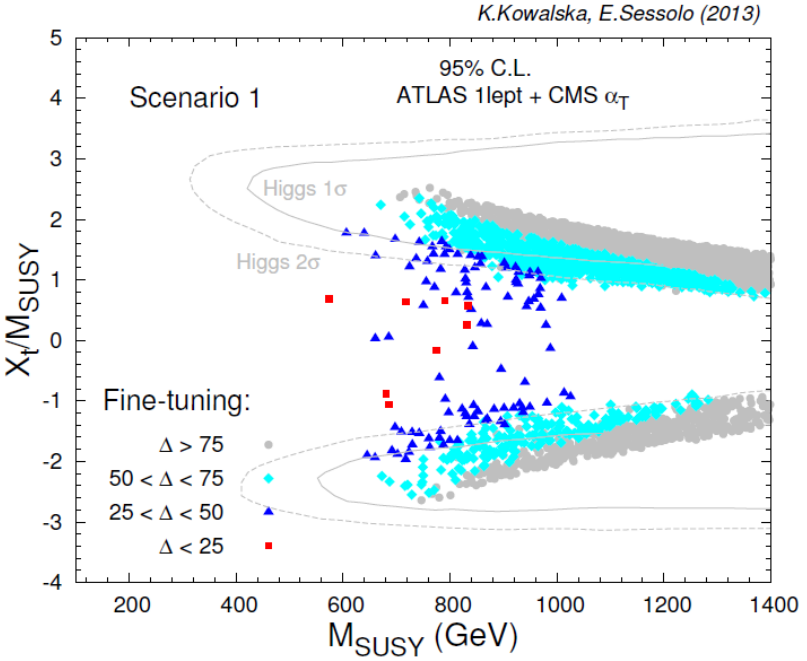
Scenario 1 – light stops and higgsinos



Low fine tuning disfavored by the LHC SUSY

Scenario 1 – light stops and higgsinos





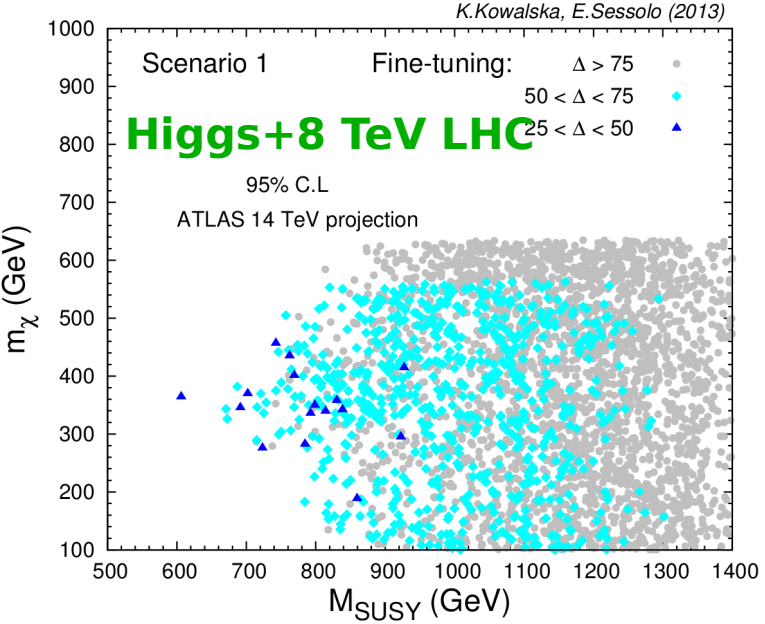
Low fine tuning disfavored by the LHC SUSY

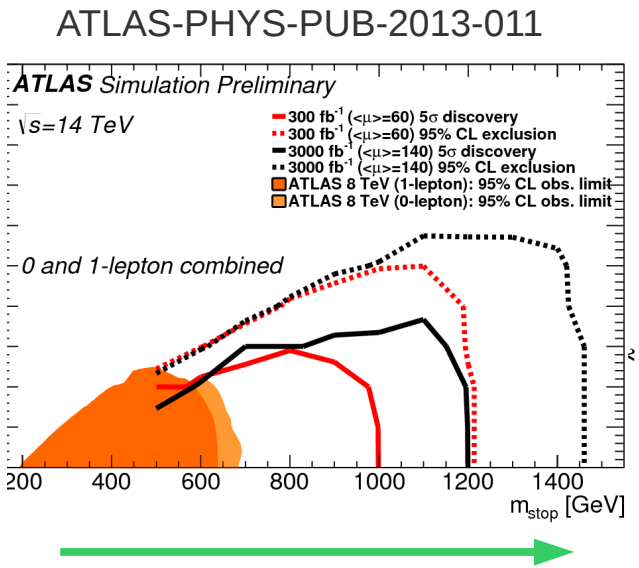
Low fine tuning in tension with the Higgs mass

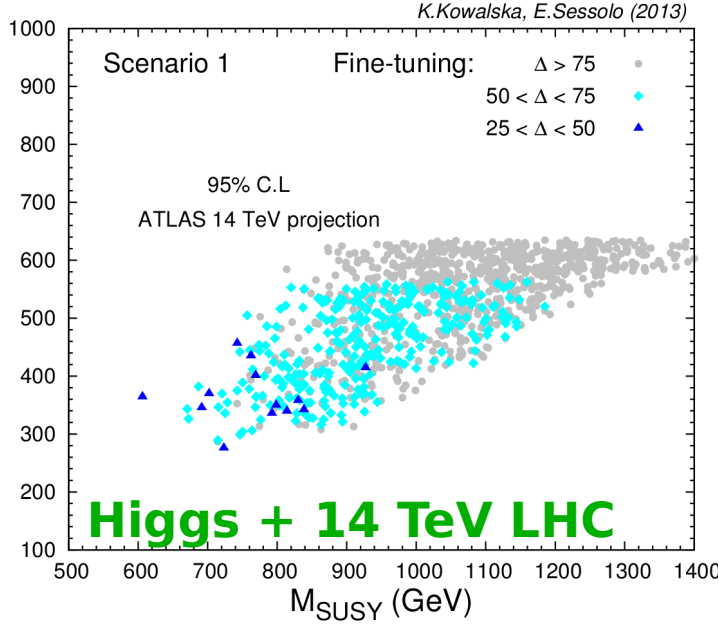
MSSM with FT better than 4% disfavoured by the LHC

Scenario 1 – light stops and higgsinos

Prospects at LHC 14 TeV:



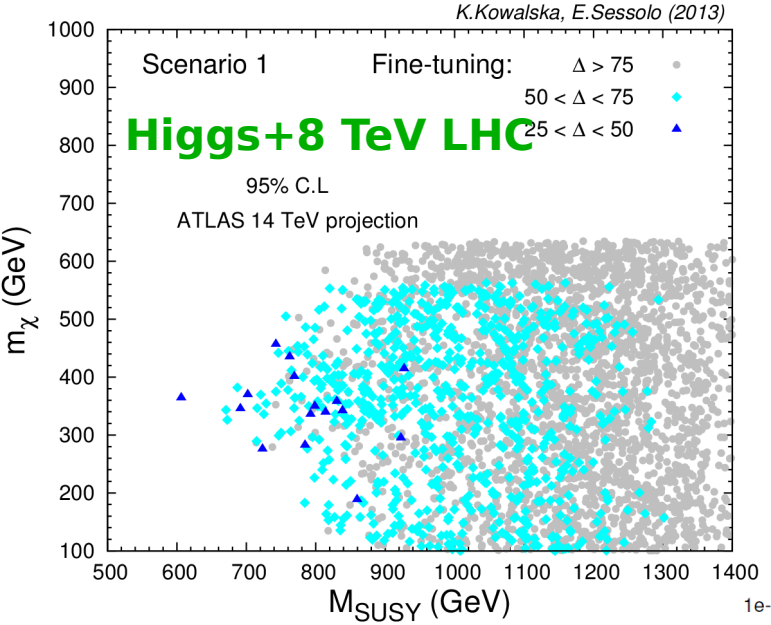




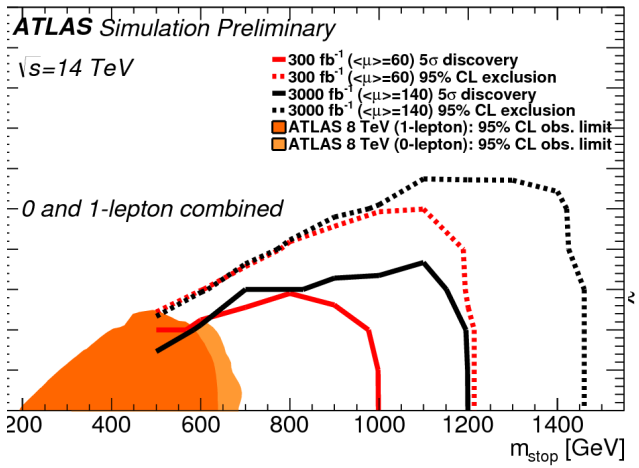
Compressed spectra still to be explored

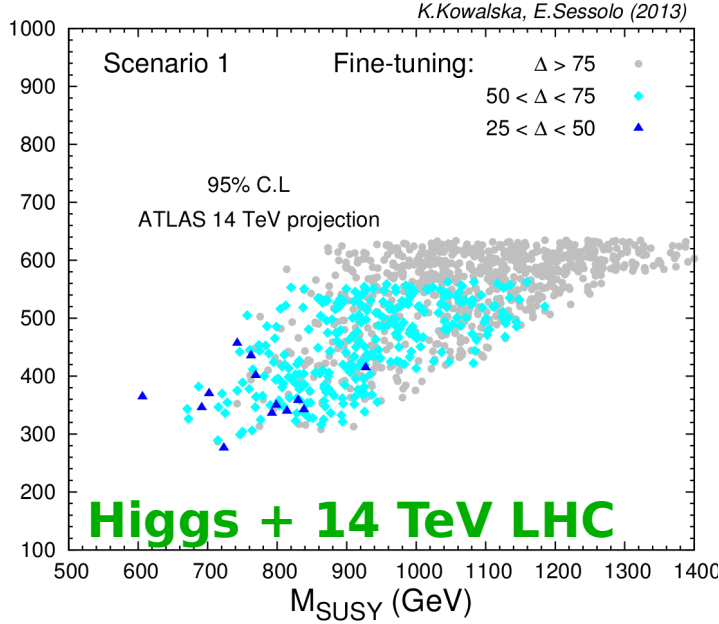
Scenario 1 – light stops and higgsinos

Prospects at LHC 14 TeV:

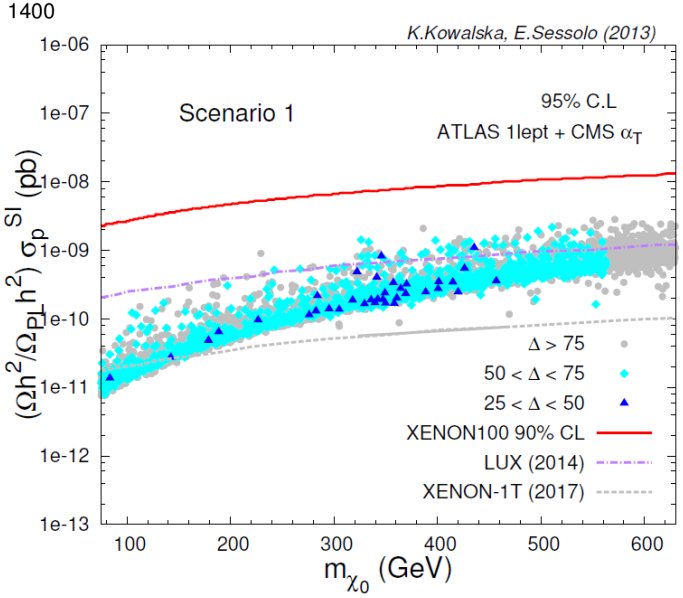


ATLAS-PHYS-PUB-2013-011





Prospects in DM searches:



Compressed spectra still to be explored

Fully tested by XENON 1T

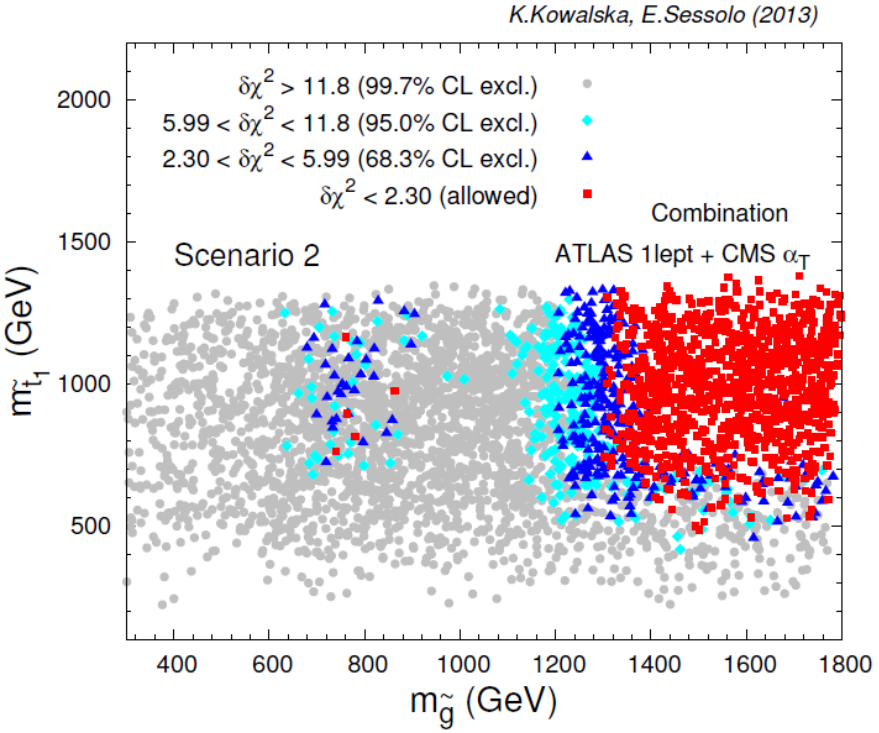
Scenario 2 – stops, gluinos and higgsinos

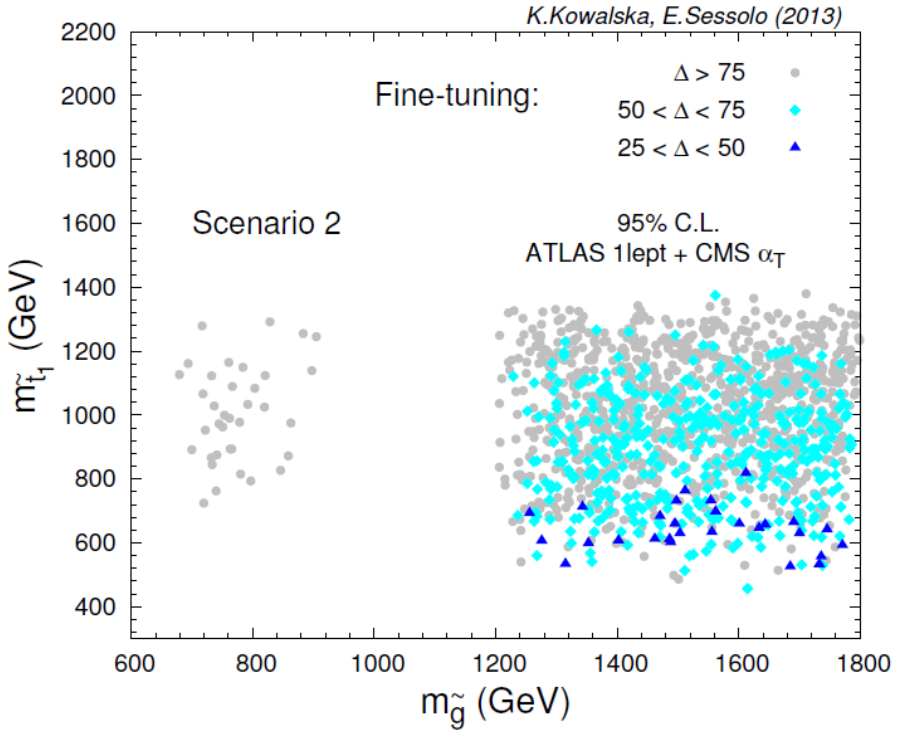
Dominant decay channels:

$$\tilde{t}_1 \to t\tilde{\chi}_1^0 \qquad \tilde{b}_1 \to t\tilde{\chi}_1^- \qquad \tilde{g} \to q\tilde{q}\tilde{\chi}_1^0$$

$$\tilde{g} \to b\tilde{b}\tilde{\chi}_1^0 \qquad \tilde{g} \to t\tilde{t}\tilde{\chi}_1^0$$

ATLAS 1 lepton
CMS 0 leptons



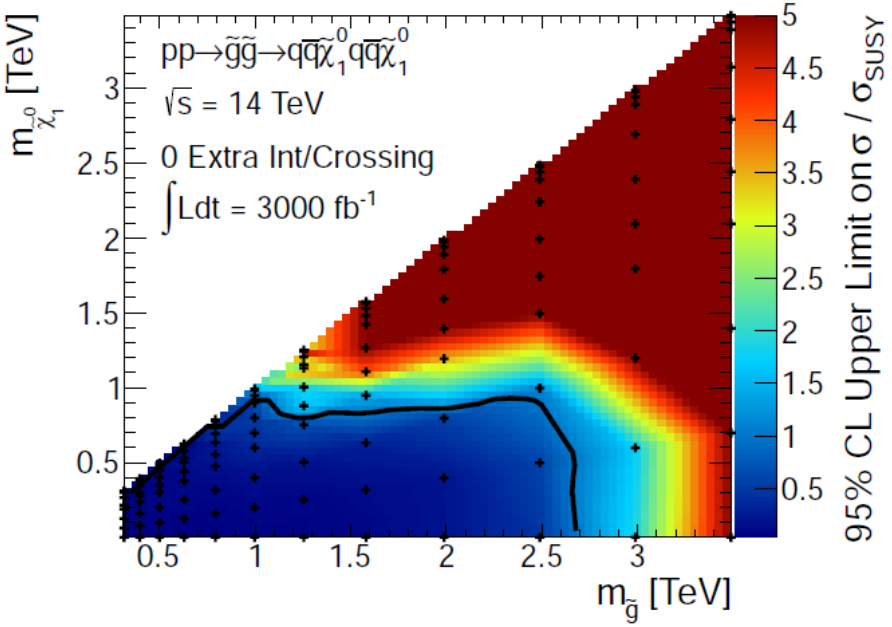


Scenario 2 – stops,gluinos and higgsinos

Prospects at LHC 14 TeV:

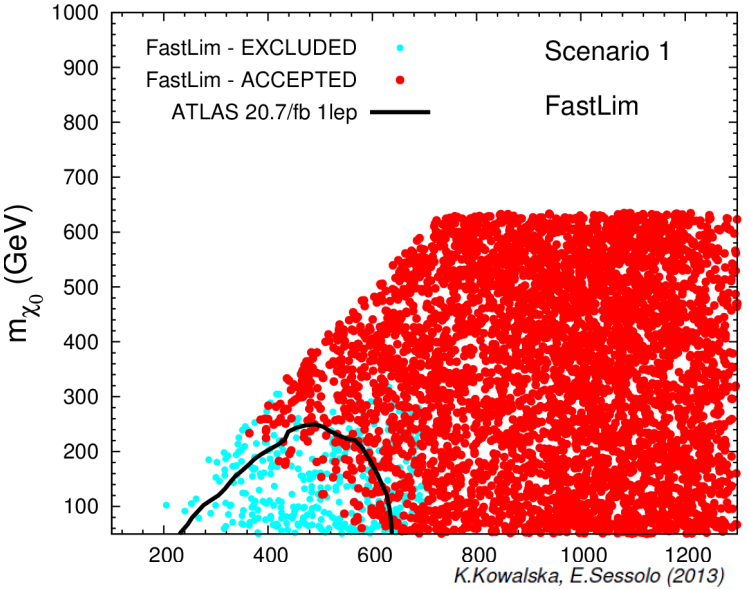
T.Cohen, T. Golling, M. Hance, A. Henrichs, K. Howe, J. Loyal, S. Padhi, J.G. Wacker

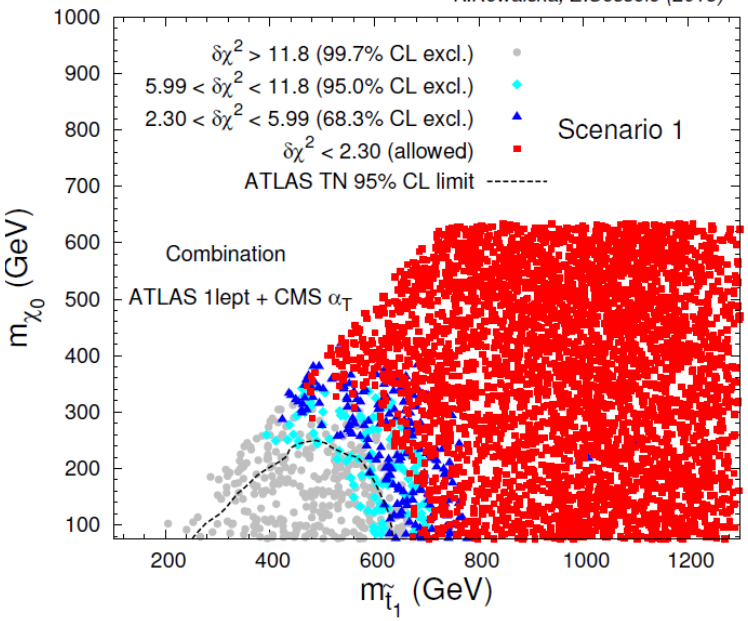
JHEP04(2014)117, arXiv:1311.6480



Natural spectra with gluinos < 2.6 TeV should be tested

Comparison with other tools





11 ATLAS searches at 21 f^{-1}

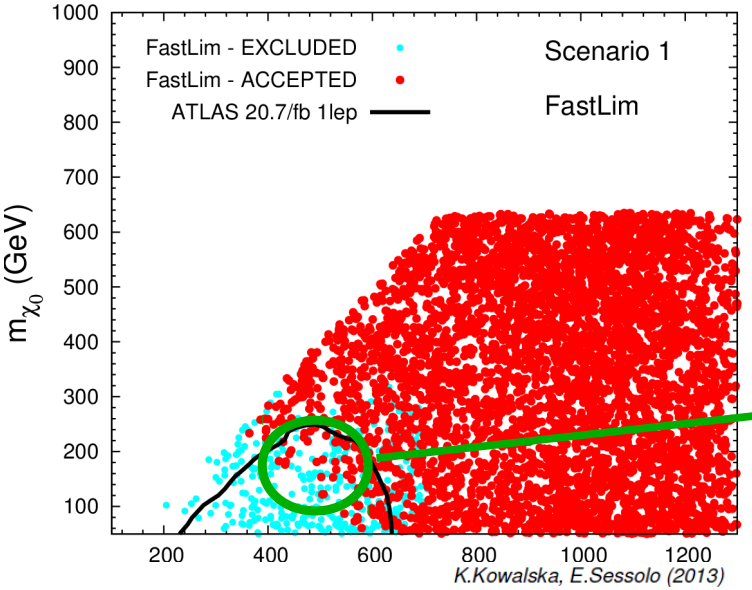
Point excluded if it is excluded in any bin

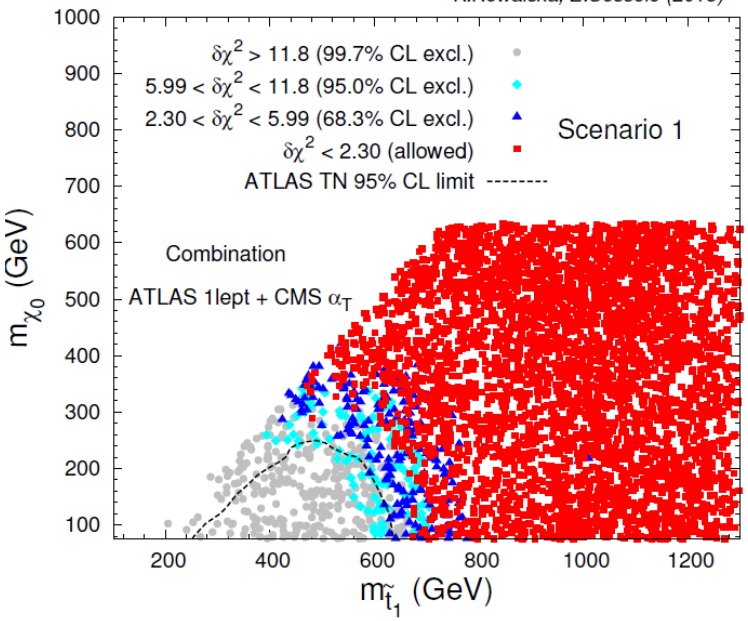
FASTLIM

M. Papucci, K. Sakurai, A. Weiler, L. Zeune

ArXiv:1402.0492

Comparison with other tools





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Points “almost” excluded,

eg: $CL_s = 0.053$ in one bin

Statistical combination of likelihoods from all bins → slightly stronger exclusion

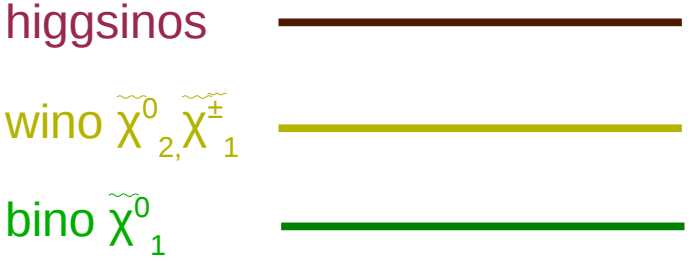
Conclusions

- LHC provides strong limits for natural SUSY spectra.
- Combination of searches gives stronger bounds.
- There is sill some hope for naturalness (compressed spectra), but FT better than 4% is disfavored .

BACKUP

Scenario 3 – stops, gluinos and EW-inos

EW-ino sector:



$$\mu = 630 \text{ GeV} \rightarrow \Delta_\mu \sim 100$$

$$\Delta m_{\tilde{\chi}^0_2} - \Delta m_{\tilde{\chi}^0_1} > m_{\tilde{l}} \rightarrow$$

$$\tilde{\chi}^0_2 \rightarrow l^+ l^- \tilde{\chi}^0_1$$

$$\tilde{\chi}^\pm_1 \rightarrow \nu_l l^\pm \tilde{\chi}^0_1$$

Scenario 3 – stops, gluinos and EW-inos

EW-ino sector:

higgsinos

wino $\tilde{\chi}^0_2, \tilde{\chi}^\pm_1$

bino $\tilde{\chi}^0_1$

$$\mu = 630 \text{ GeV} \rightarrow \Delta_\mu \sim 100$$

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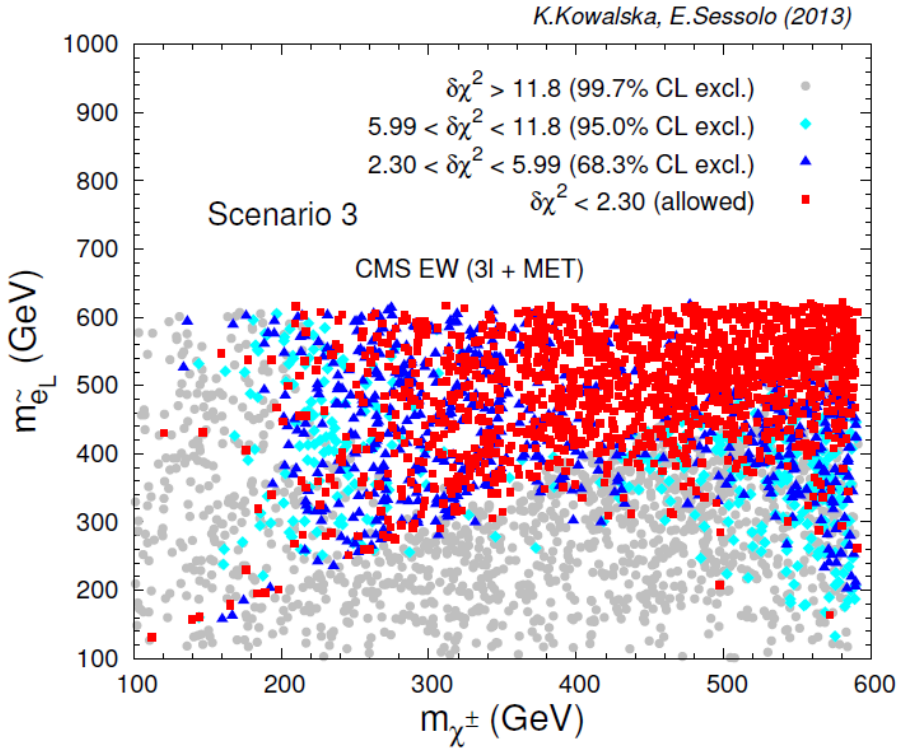

Scenario 3 – stops, gluinos and EW-inos

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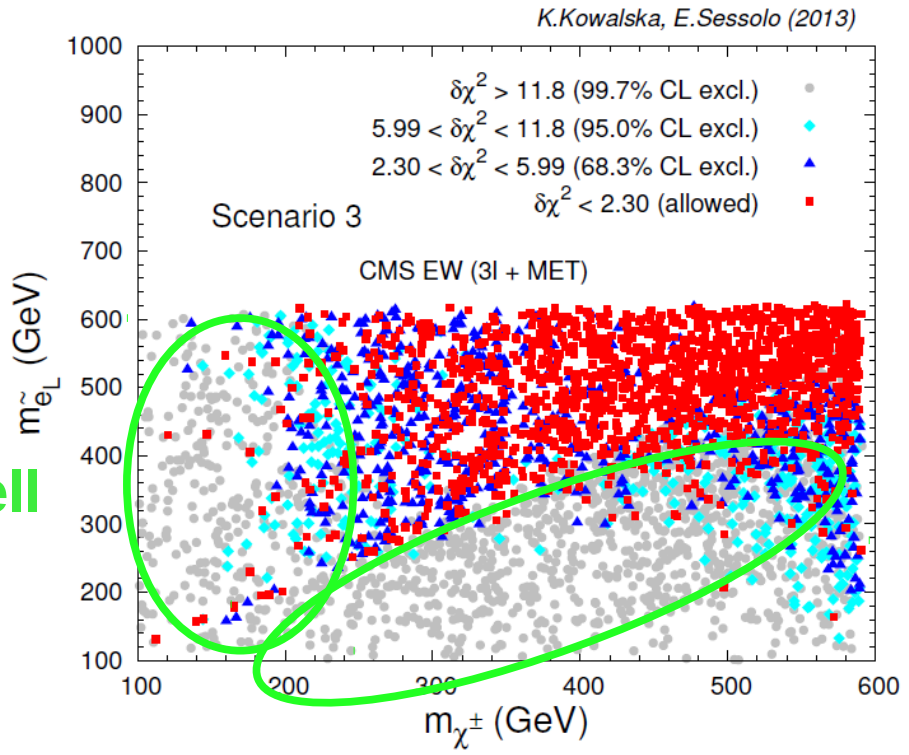


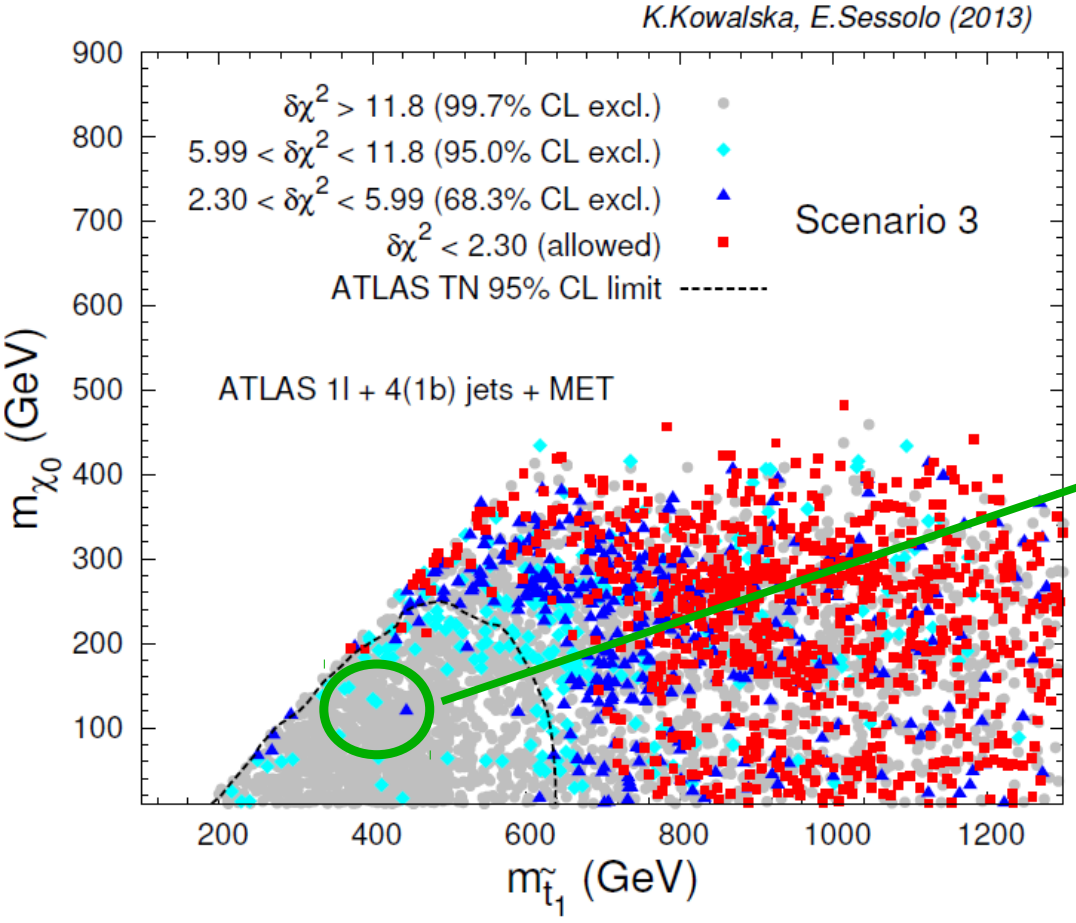
off-shell

on-shell

Scenario 3 – stops, gluinos and EW-inos

Combination of searches:

- stronger bounds due to various topologies
- bounds can be weakened by long decay chains



$$\tilde{t} \to \tilde{b}\tilde{\chi}_1^+$$

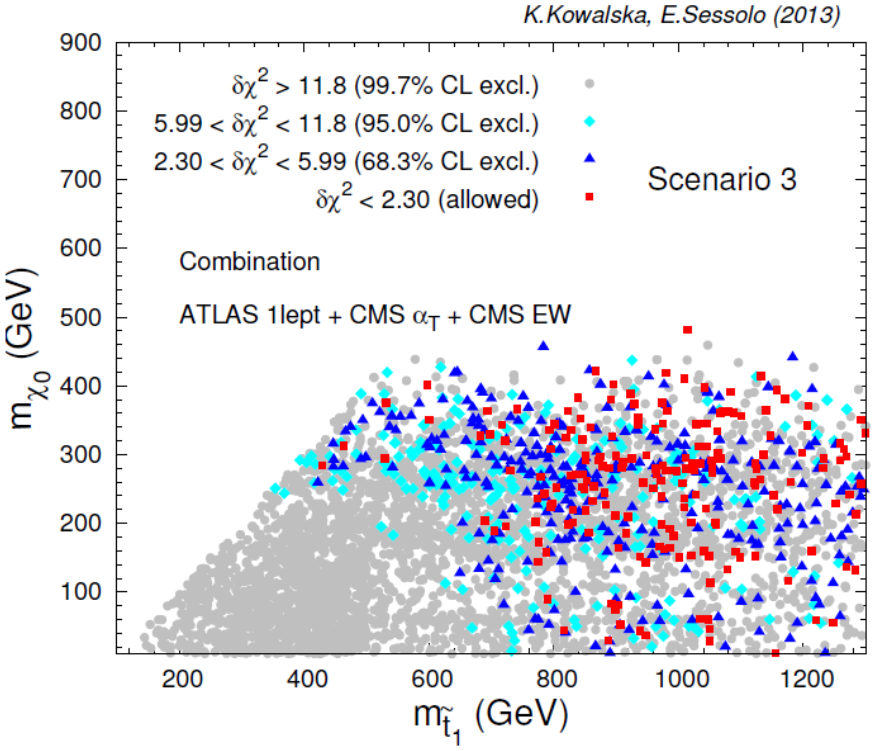
$$\tilde{\chi}_1^+ \to \tau^+ \nu_\tau \tilde{\chi}_1^0$$

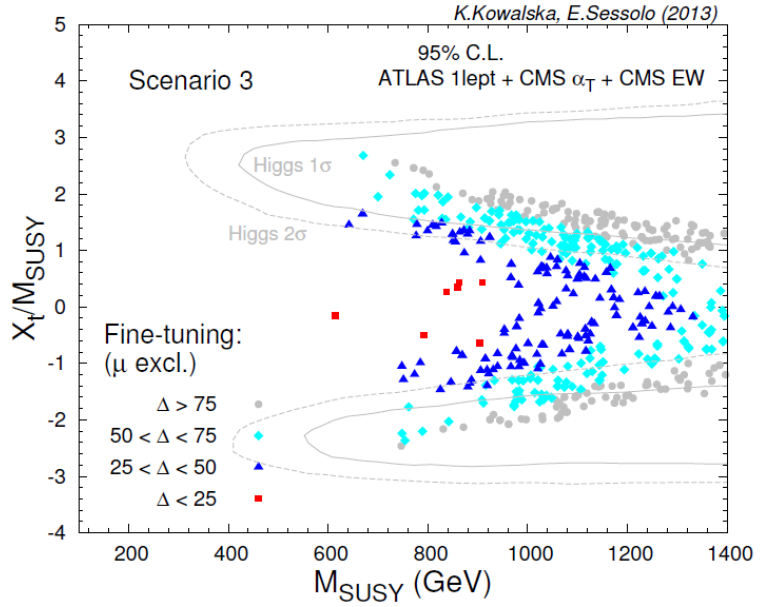
$$\tau^+ \to \text{ hadronically}$$

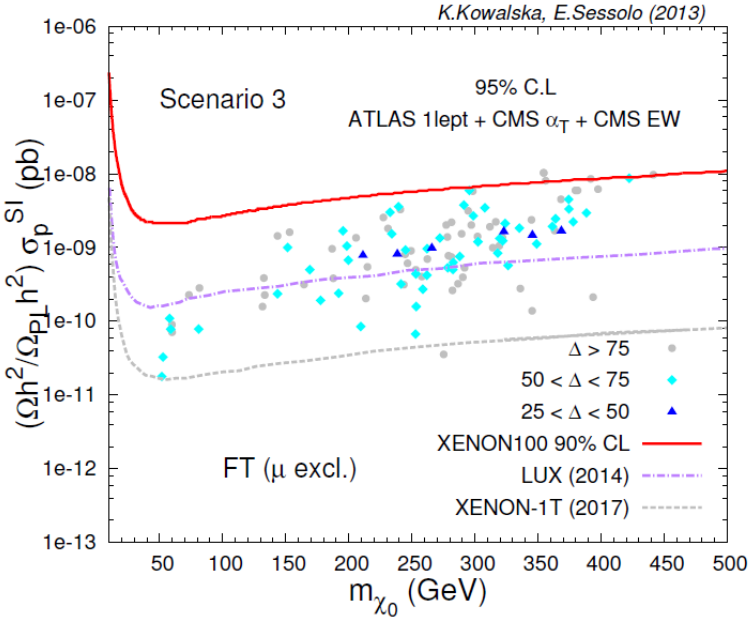
No hard leptons in the final state

Scenario 3 – stops, gluinos and EW-inos

ATLAS 1 lepton
CMS 0 leptons
CMS 3 leptons

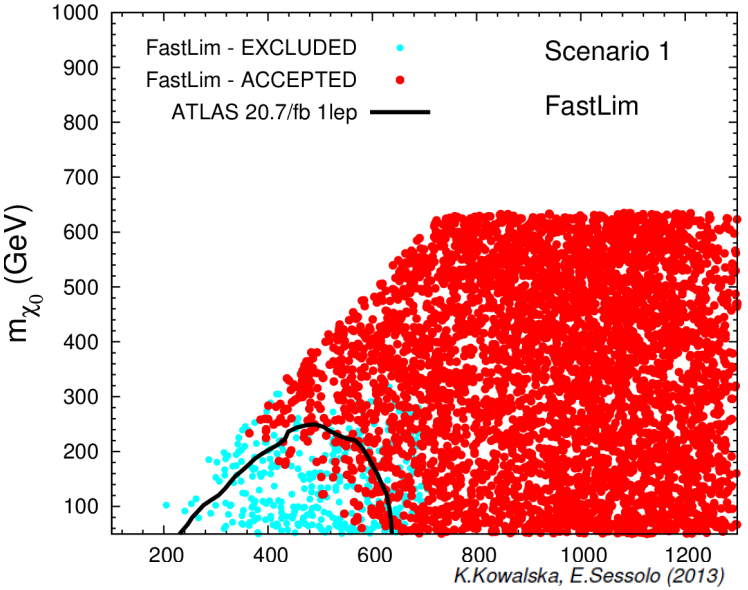


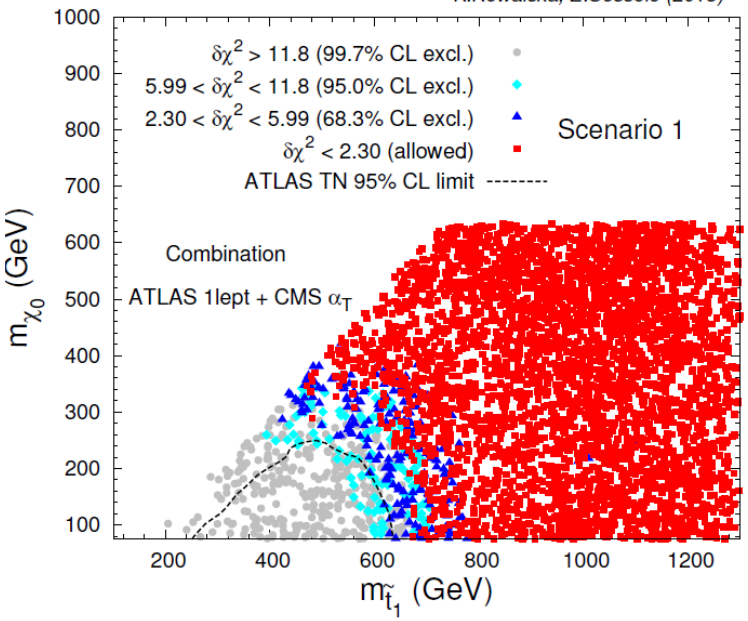




Not included fine tuning due to μ

Comparison with other tools





11 ATLAS searches at 21 f^{-1}

FASTLIM

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