Natural MSSM after the LHC 8 TeV run

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SUSY 14
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Based on

K. Kowalska and EMS

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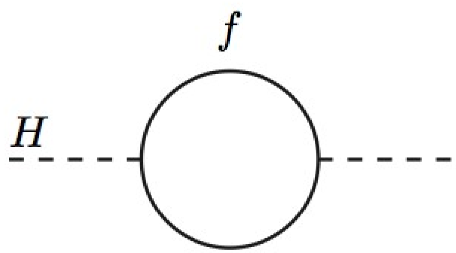
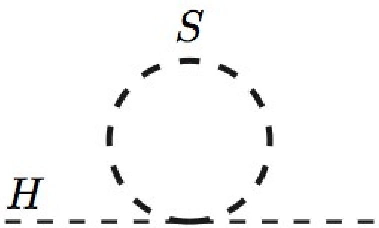
Naturalness and fine tuning

SUSY solves the hierarchy problem





$$\Delta m_h \sim -2(y_t - y_t)\Lambda^2 - \frac{3y_t^2}{8\pi^2}(m^2_{\tilde{Q}_3} + m^2_{\tilde{u}_3} + |A_t|^2)\ln\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

… but leaves logarithmic dependence...

Naturalness and fine tuning

In MSSM minimization scalar potential yields

(limit of large $\tan\beta$)

$$\frac{M_Z^2}{2} \sim -\mu^2 - m_{H_u}^2 + \Delta m_{H_u}^2$$

→ **Residual fine tuning!**

LEADING LOG APPROX

$$\Delta_{p_i} = \left| \frac{\partial \log M_Z^2}{\partial \log p_i^2} \right| = \frac{p_i^2}{M_Z^2} \left| \frac{\partial M_Z^2}{\partial p_i^2} \right|$$

$$p_i = \mu, m_{\tilde{Q}_3}, m_{\tilde{u}_3}, A_t, M_2, M_3$$

Naturalness and fine tuning

$\max\{\Delta_{p_i}\} = 10$ (or 10% fine tuning) : ← Natural

$|\mu| \lesssim 200\ \mathrm{GeV}$

$$|M_2| \lesssim (1700\ \mathrm{GeV}) \ln\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-1/2}$$

$$m^2_{\tilde{Q}_3} + m^2_{\tilde{u}_3} + |A_t|^2 \lesssim (1200\ \mathrm{GeV})^2 \ln\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-1}$$

$$|M_3| \lesssim (2700\ \mathrm{GeV}) \ln\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-1}$$

(see K.Kowalska's talk on Friday)

$\max\{\Delta_{p_i}\} = 100$ (or 1% fine tuning) : ← This paper

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

$$|M_2| \lesssim (5200\ \mathrm{GeV}) \ln\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-1/2}$$

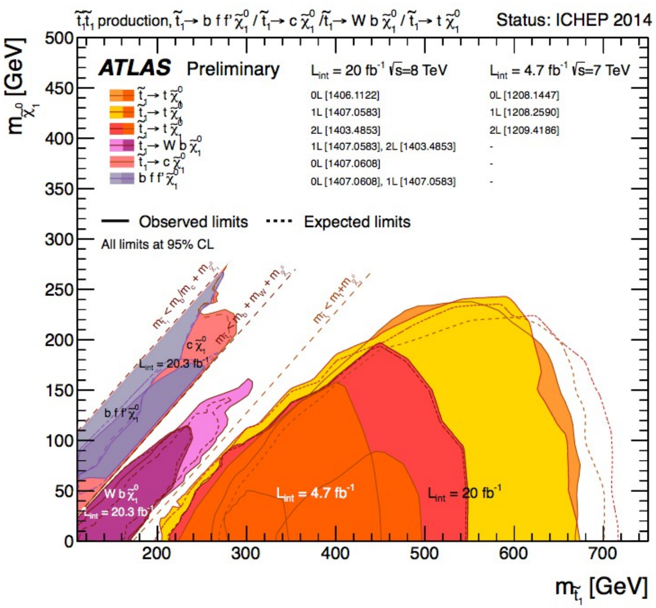
$$m^2_{\tilde{Q}_3} + m^2_{\tilde{u}_3} + |A_t|^2 \lesssim (4000\ \mathrm{GeV})^2 \ln\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-1}$$

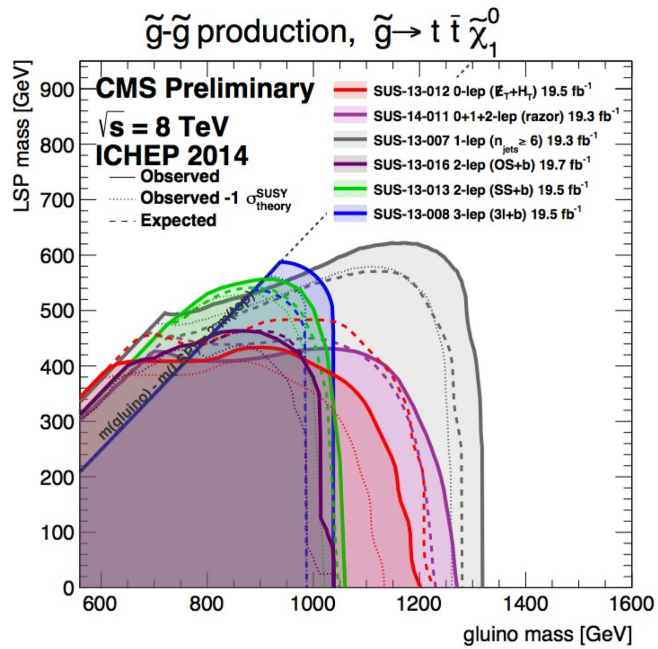
$$|M_3| \lesssim (8500\ \mathrm{GeV}) \ln\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-1}$$

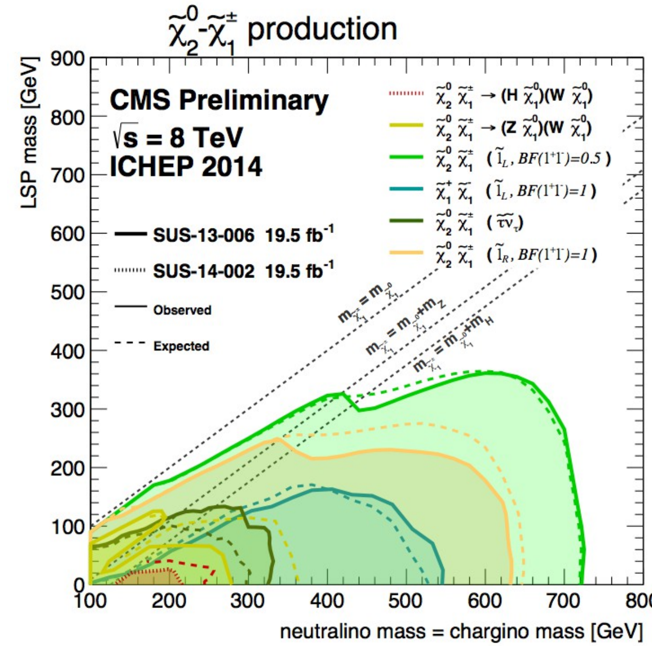
Fine tuning vs LHC

Direct SUSY searches:

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







Higgs mass at 125.5 GeV

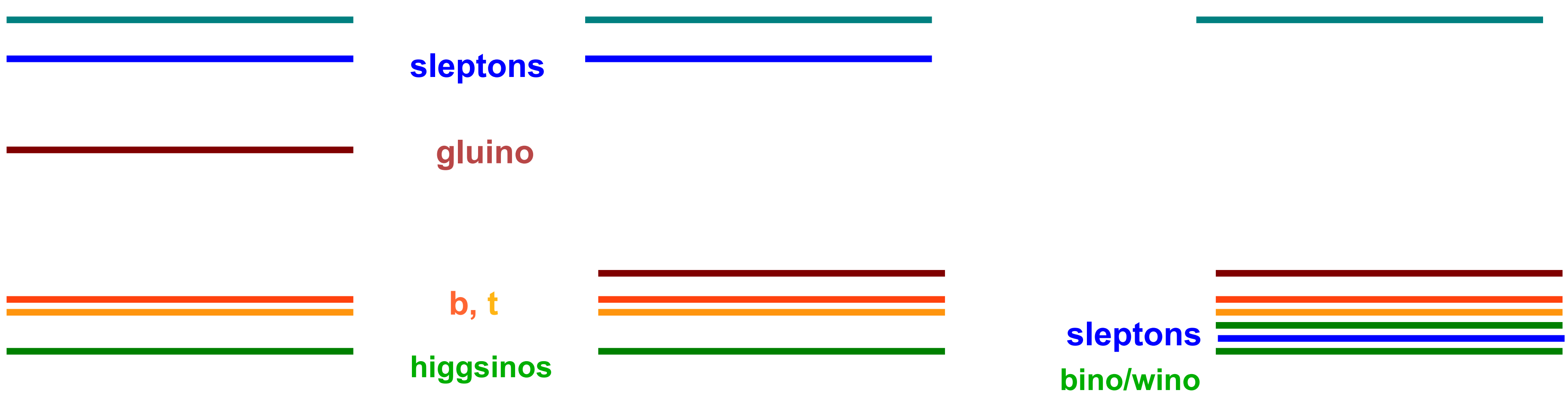
$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm susy}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm susy}^2}\left(1 - \frac{X_t^2}{12M_{\rm susy}^2}\right)\right]$$

How many realistic MSSM models with Δ ≤100 survived LHC 8 TeV run?

$\Lambda \sim 10$ TeV here

Natural spectra

Scenario 1	Scenario 2	Scenario 3
$M_1 = 3\,\text{TeV}$	$M_1 = 3\,\text{TeV}$	$0.01\,\text{TeV} \leq M_1 \leq 0.4\,\text{TeV}$ $M_1 < M_2$
$M_2 = 1.5\,\text{TeV}$	$M_2 = 1.5\,\text{TeV}$	$0.1\,\text{TeV} \leq M_2 \leq 0.63\,\text{TeV}$
$M_3 = 1.6\,\text{TeV}$	$0.1\,\text{TeV} \leq M_3 \leq 1.6\,\text{TeV}$	$0.1\,\text{TeV} \leq M_3 \leq 1.6\,\text{TeV}$
$m_{\tilde{L}_{1,2,3}} = m_{\tilde{e}_1} = m_{\tilde{e}_2} = m_{\tilde{e}_3} = 3\,\text{TeV}$	$m_{\tilde{L}_{1,2,3}} = m_{\tilde{e}_1} = m_{\tilde{e}_2} = m_{\tilde{e}_3} = 3\,\text{TeV}$	$0.1\,\text{TeV} \leq m_{\tilde{L}_{1,2,3}}, m_{\tilde{e}_1}, m_{\tilde{e}_2}, m_{\tilde{e}_3} \leq 0.63\,\text{TeV}$
$0.075\,\text{TeV} \leq \mu \leq 0.63\,\text{TeV}$	$0.075\,\text{TeV} \leq \mu \leq 0.63\,\text{TeV}$	$\mu = 0.63\,\text{TeV}$
$0.1\,\text{TeV} \leq m_{\tilde{Q}_3}, m_{\tilde{u}_3} \leq 1.4\,\text{TeV}$	$0.1\,\text{TeV} \leq m_{\tilde{Q}_3}, m_{\tilde{u}_3} \leq 1.4\,\text{TeV}$	$0.1\,\text{TeV} \leq m_{\tilde{Q}_3}, m_{\tilde{u}_3} \leq 1.4\,\text{TeV}$
$\tilde{t}_{1,2}$, $\tilde{b}_1$, $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^\pm_1$	$\tilde{g}$, $\tilde{t}_{1,2}$, $\tilde{b}_1$, $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^\pm_1$	sleptons, $\tilde{g}$, $\tilde{t}_{1,2}$, $\tilde{b}_1$, $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^\pm_1$



Experimental constraints

Each case we generate 5000 model points that satisfy:

Measurement	Mean or range	Error: exp., th.	Distribution
$\Omega_\chi h^2$	0.1199	0.0027, 10%	2σ upper limit
$\mathrm{BR}\left(\overline{B} \to X_s \gamma\right) \times 10^4$	3.43	0.22, 0.21	2σ
$\mathrm{BR}\left(B_s \to \mu^+ \mu^-\right) \times 10^9$	3.2	$+1.5, -1.2$, 10%	2σ
$\Delta M_{B_s} \times 10^{11}$	1.166 GeV	0.008 GeV, 0.158 GeV	2σ
$\sin^2 \theta_{\mathrm{eff}}$	0.23146	0.00012, 0.00015	2σ
M_W	80.385 GeV	0.015 GeV, 0.015 GeV	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 125.5 GeV →

LHC limits on SUSY

LHC limits for Simplified Models   Reinterpretation needed for complex scenarios.

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

$\text{CMS 0-leptons} + (b\text{-}) \text{ jets} + E_T^{\text{miss}} \text{ with } \alpha_T, 12\text{fb}^{-1}$ → Stops, sbottoms, gluinos

$\text{CMS 3-lepton} + \text{E}_T^{\text{miss}}, 9\text{fb}^{-1}$ → Winos

Our way to do:

- full simulation of event generation + detector response

  (PYTHIA6, PGS4)
- closely follows the experimental analysis

  $$s = \varepsilon_A \times \sigma \times \int L$$
- validated against the official limits

SUSY Likelihood:

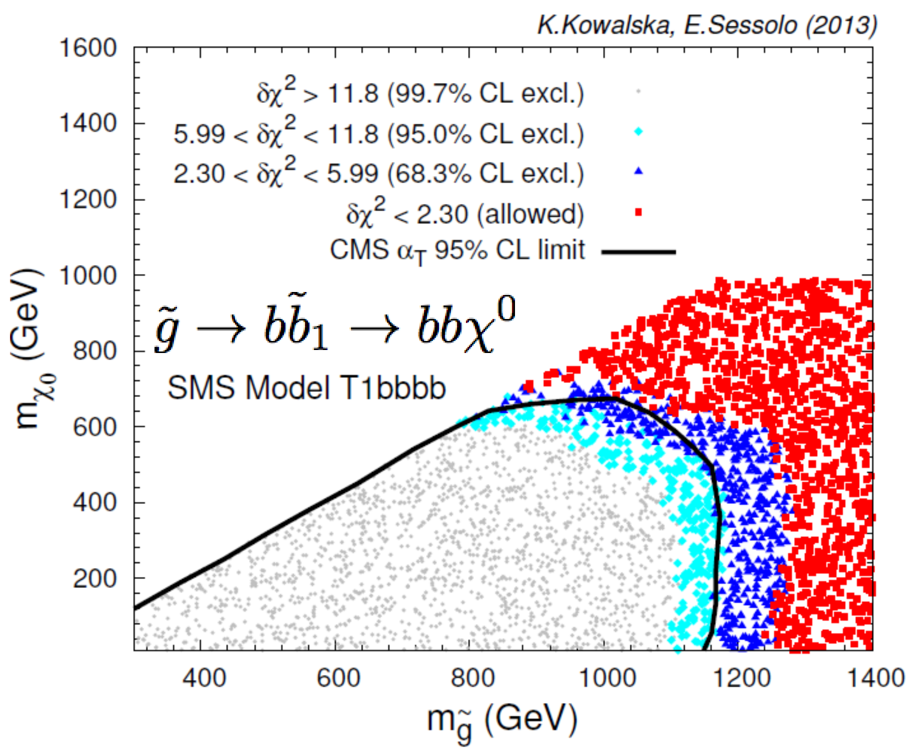
$$\mathcal{L}_i(o_i, s_i, b_i) = \int P(o_i|s_i, \bar{b}_i) \exp\left(-\frac{(b-\bar{b})^2}{2\delta b^2}\right) d\bar{b}_i$$

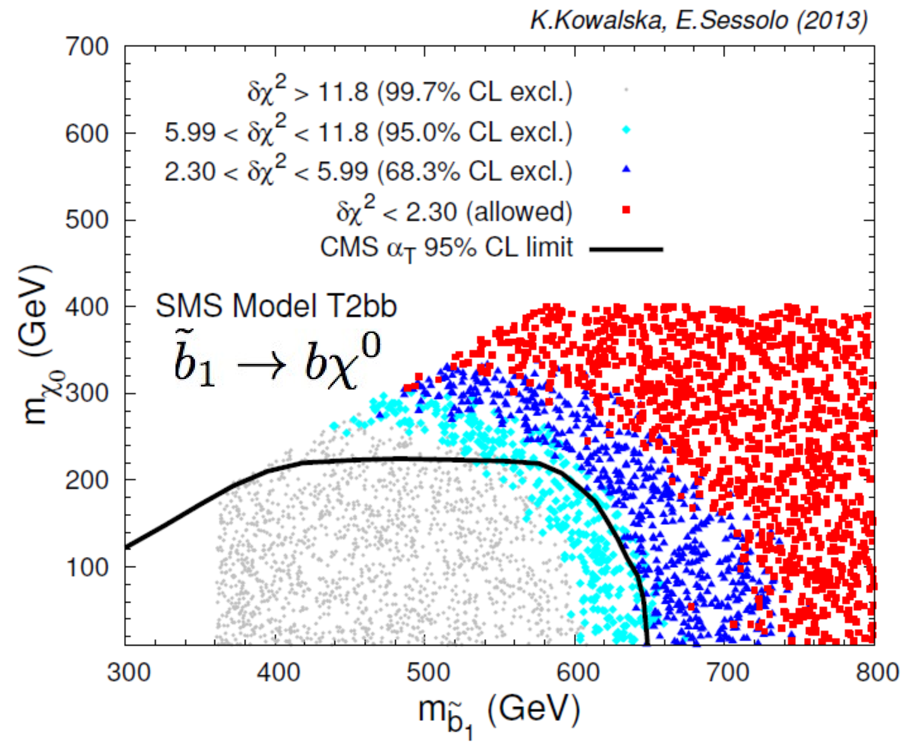
$$\sum_i \ln \mathcal{L}_i$$

Allows for combination of searches

Validation

(In this paper we didn't consider compressed spectra)





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

CMS-SUS-12-028

Validation

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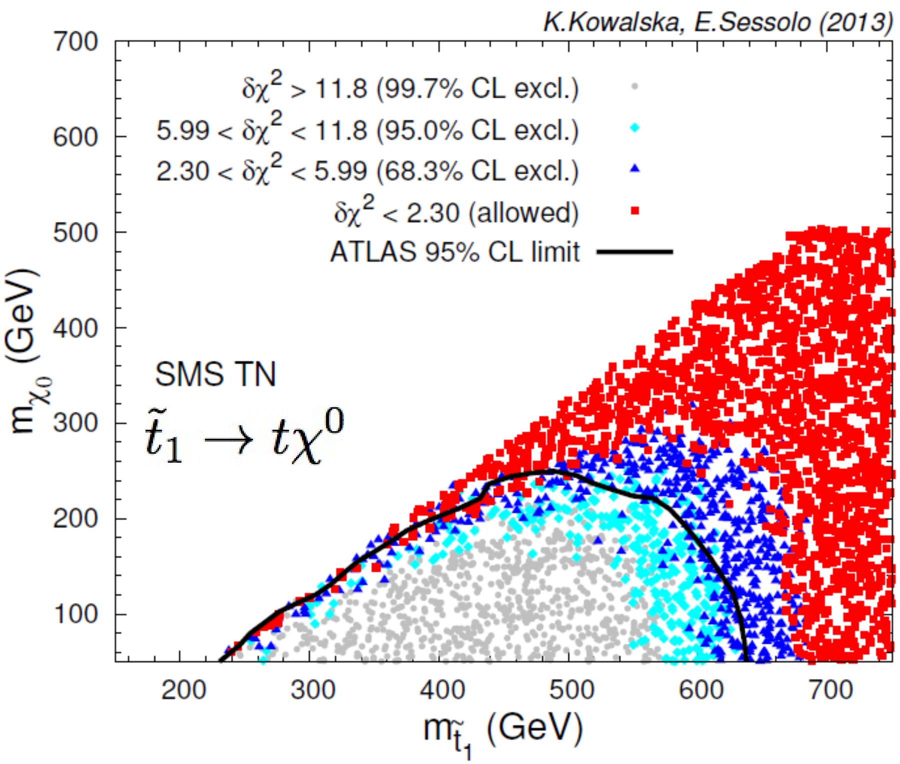
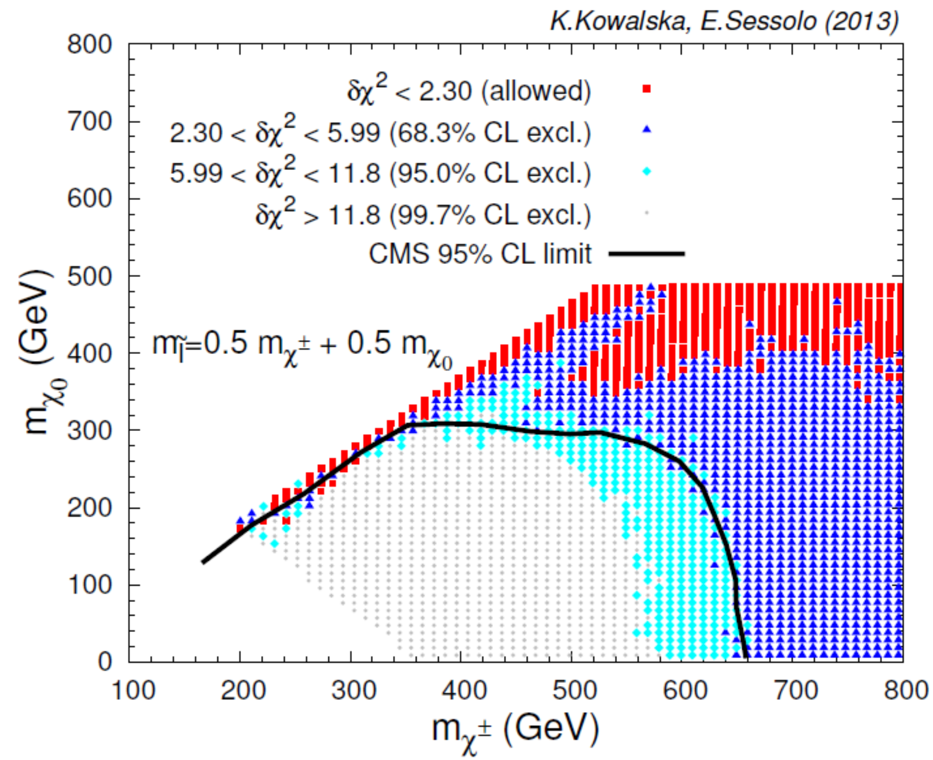




ATLAS 1-lepton + 4(1b-) jets + E_T^{miss}, 21fb^{-1}

ATLAS-CONF-2013-037

CMS 3-lepton $+\text{E}_T^{\text{miss}}$, 9fb^{-1}

CMS-SUS-12-022

Scenario 1 – light stops and higgsinos

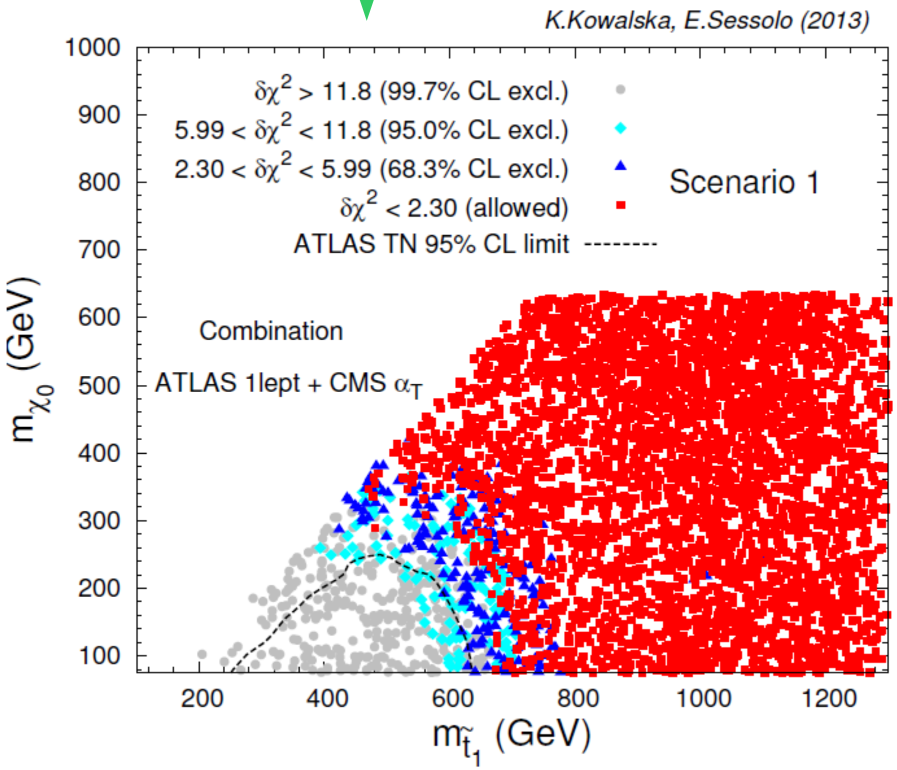
Dominant decay channels:

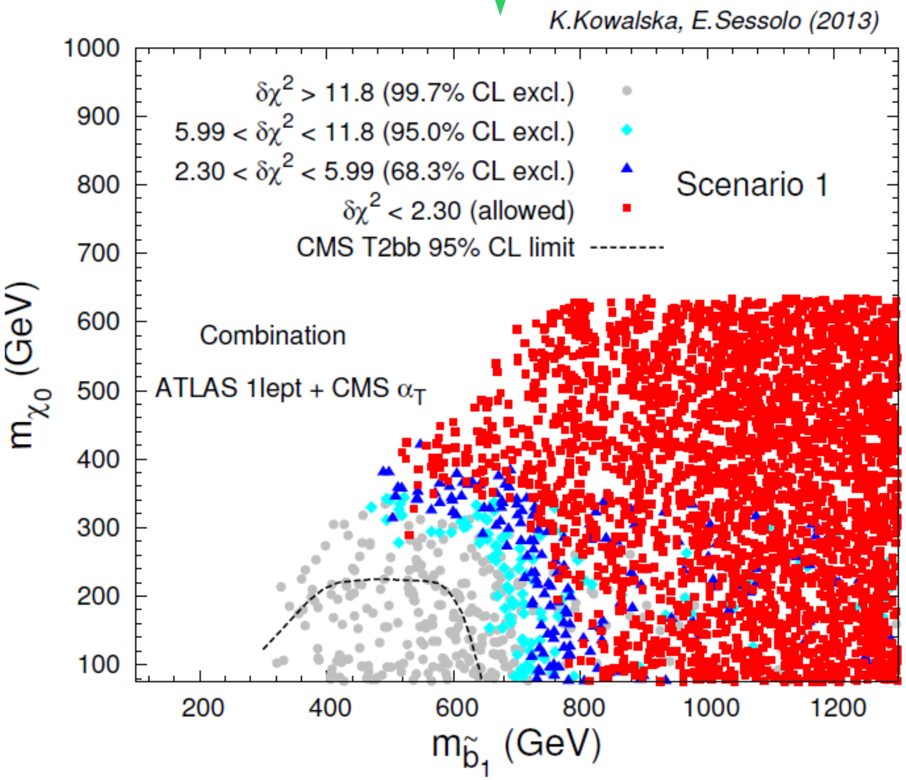
$$\tilde{t}_1 \to t\tilde{\chi}_1^0$$

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

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

ATLAS 1 lepton
CMS 0 leptons





Scenario 1 – light stops and higgsinos

Dominant decay channels:

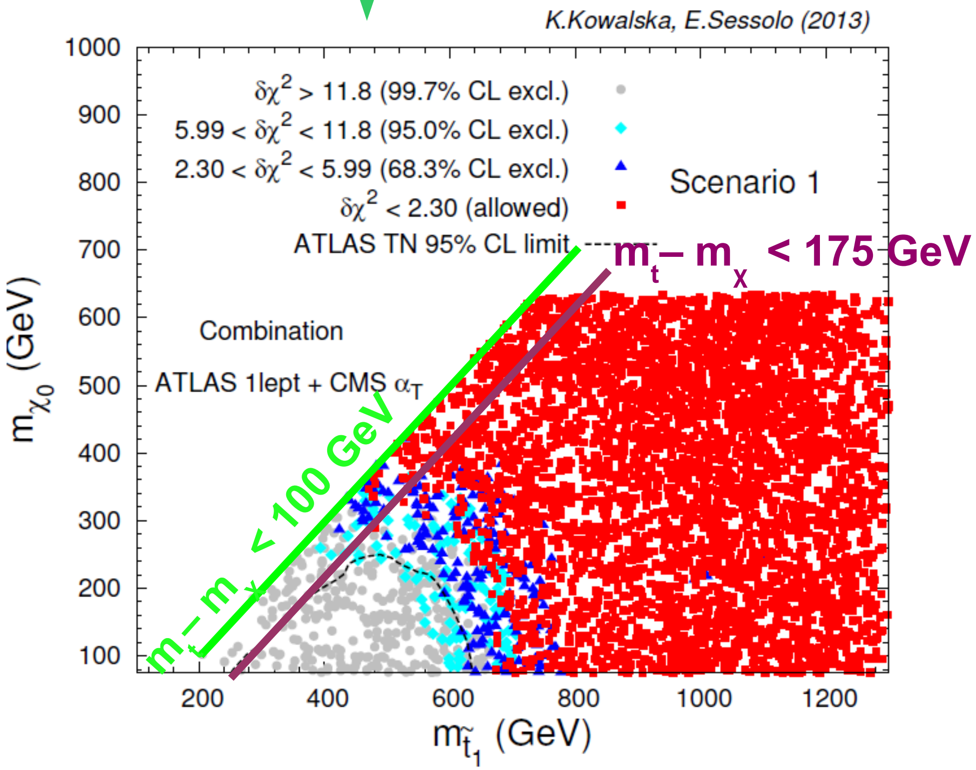
$$\tilde{t}_1 \to t\tilde{\chi}_1^0$$

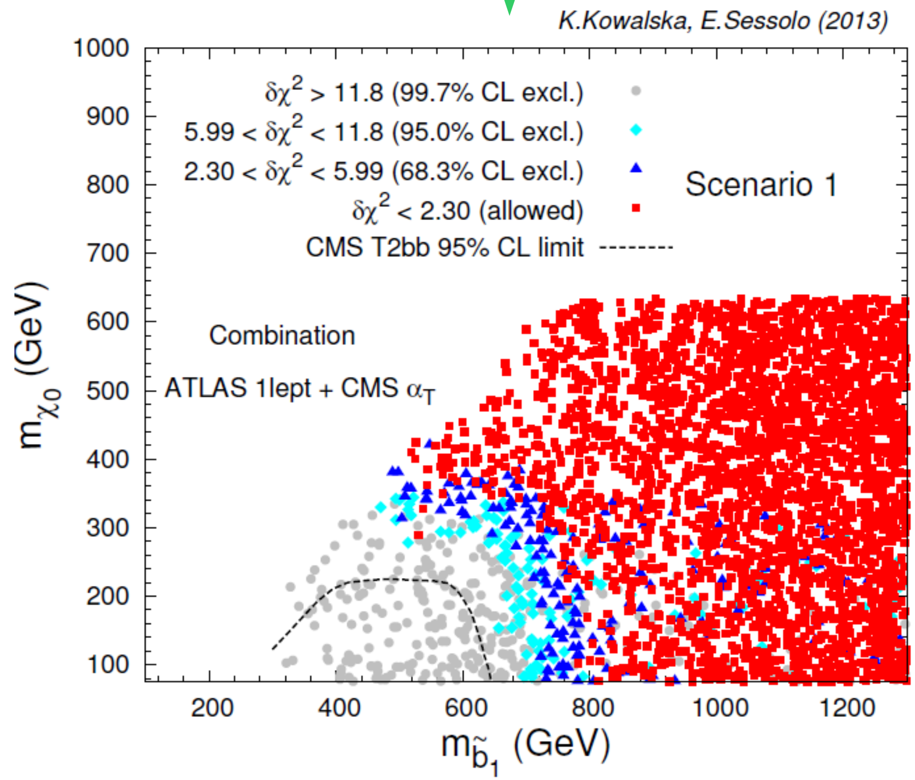
$$\tilde{t}_1 \to b\tilde{\chi}_1^- \to$$ 0 leptons b-jets

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

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

ATLAS 1 lepton
CMS 0 leptons





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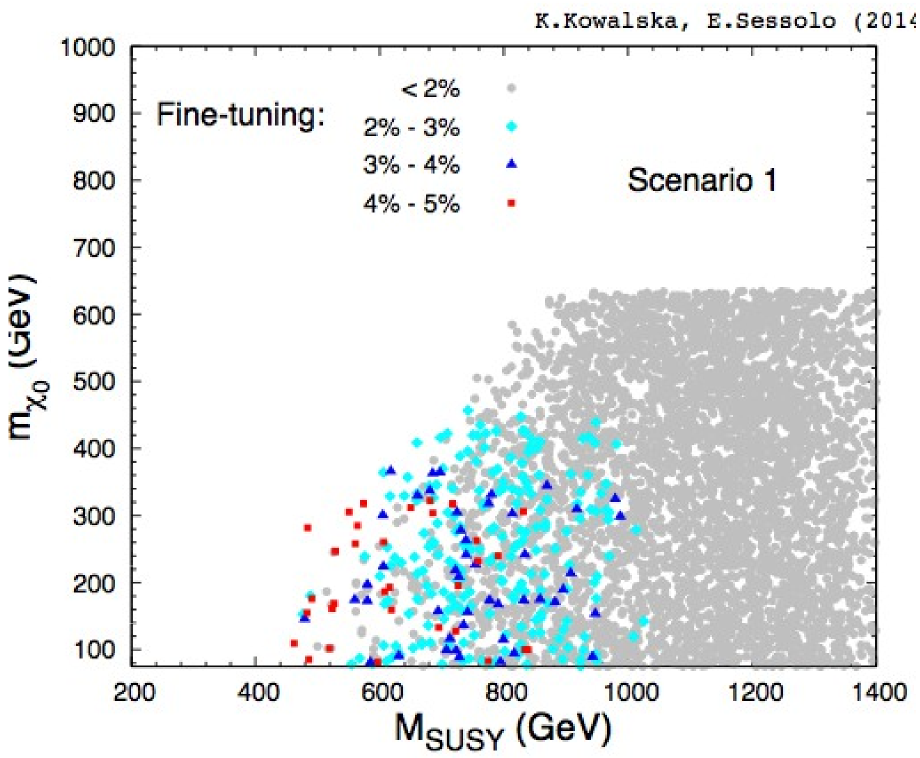
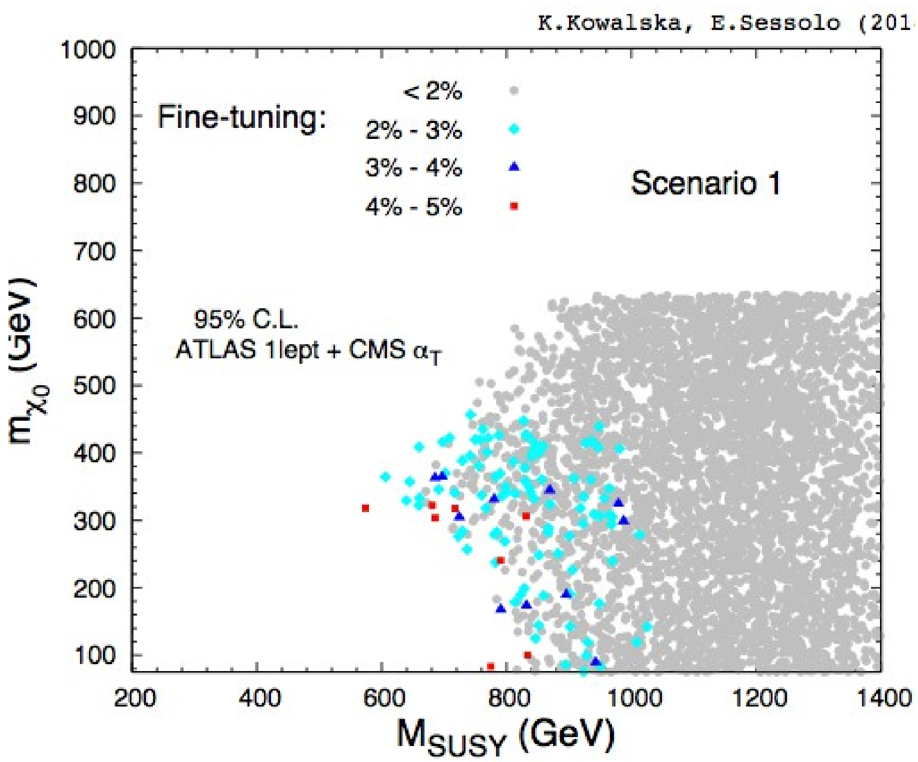


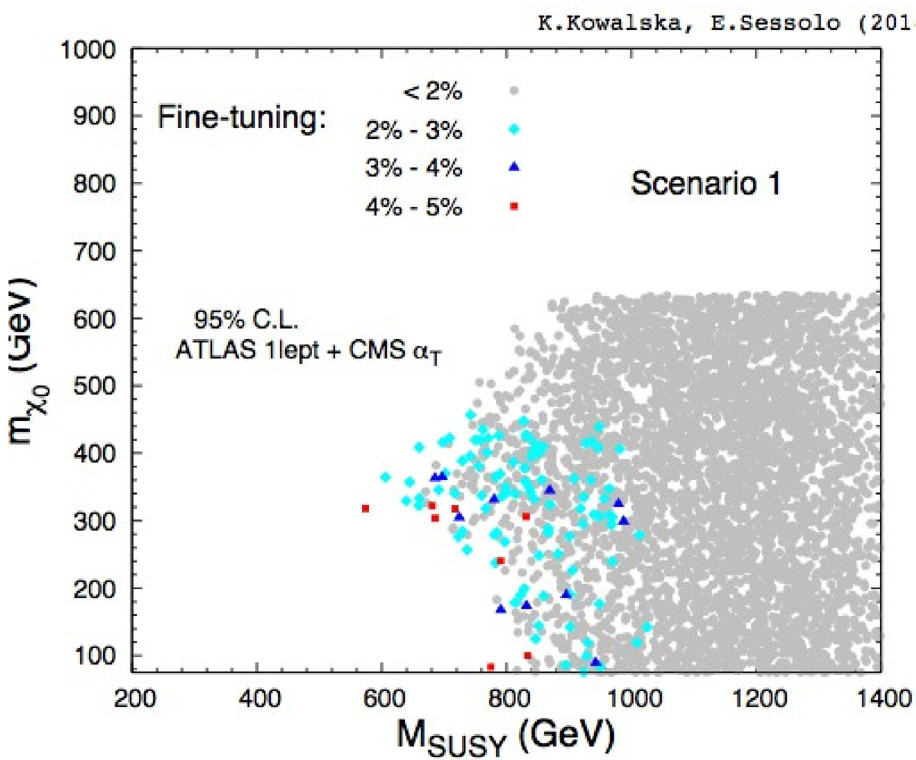
No points fine tuning > 5%
Mostly due to b → s gamma

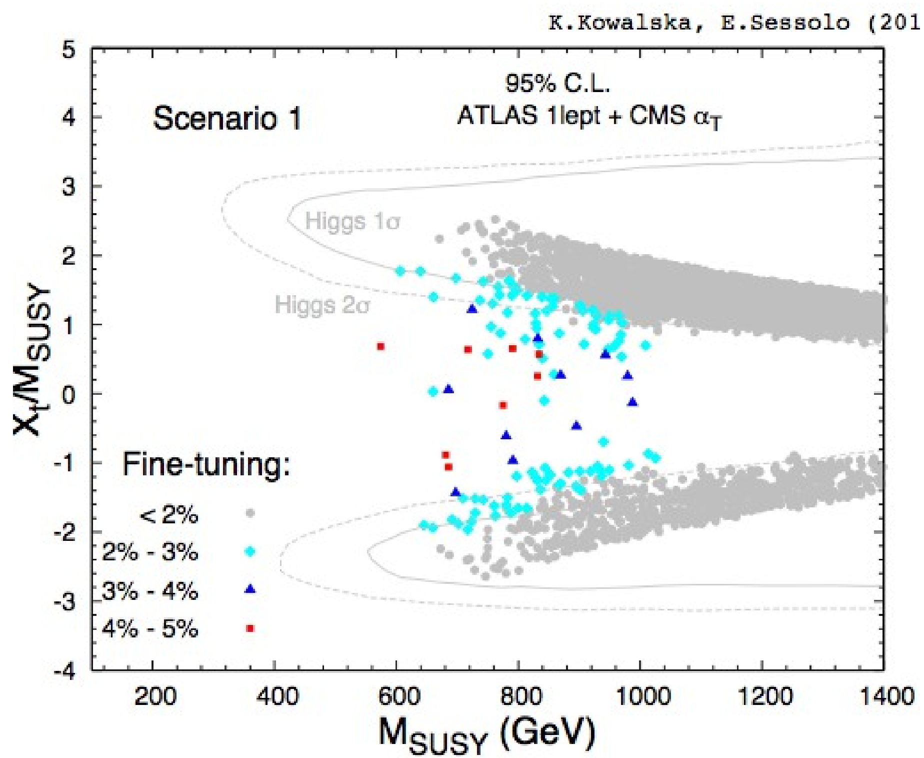
Scenario 1 – light stops and higgsinos



LHC cuts most point FT > 3%
(but some left)

Scenario 1 – light stops and higgsinos





LHC cuts most point FT > 3% (but some left)

Higgs mass cuts all FT > 3% (3 GeV th. err.)

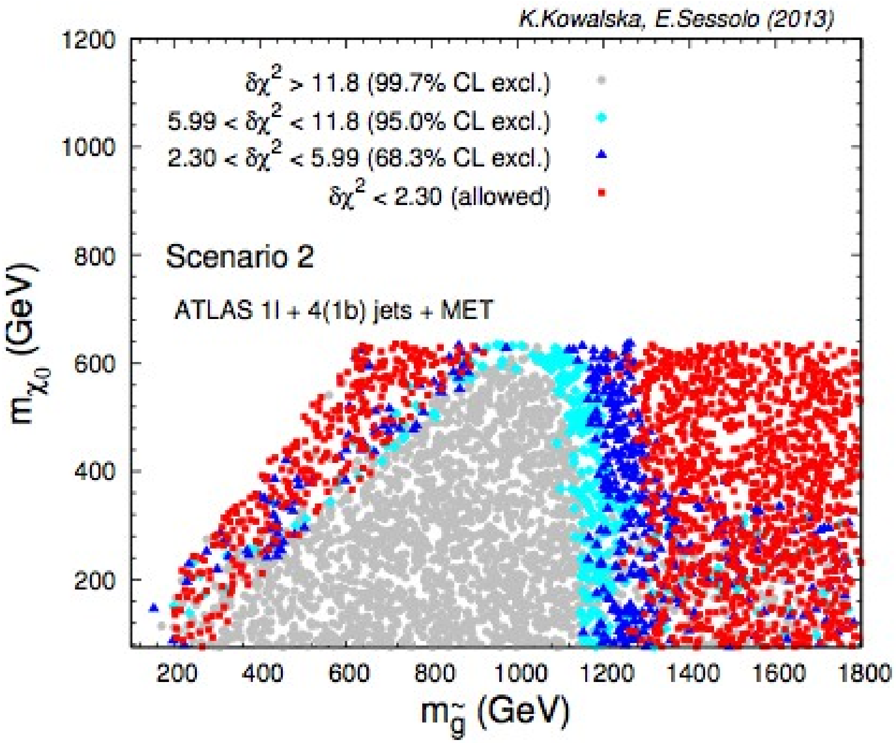
Scenario 2 – stops, gluinos and higgsinos

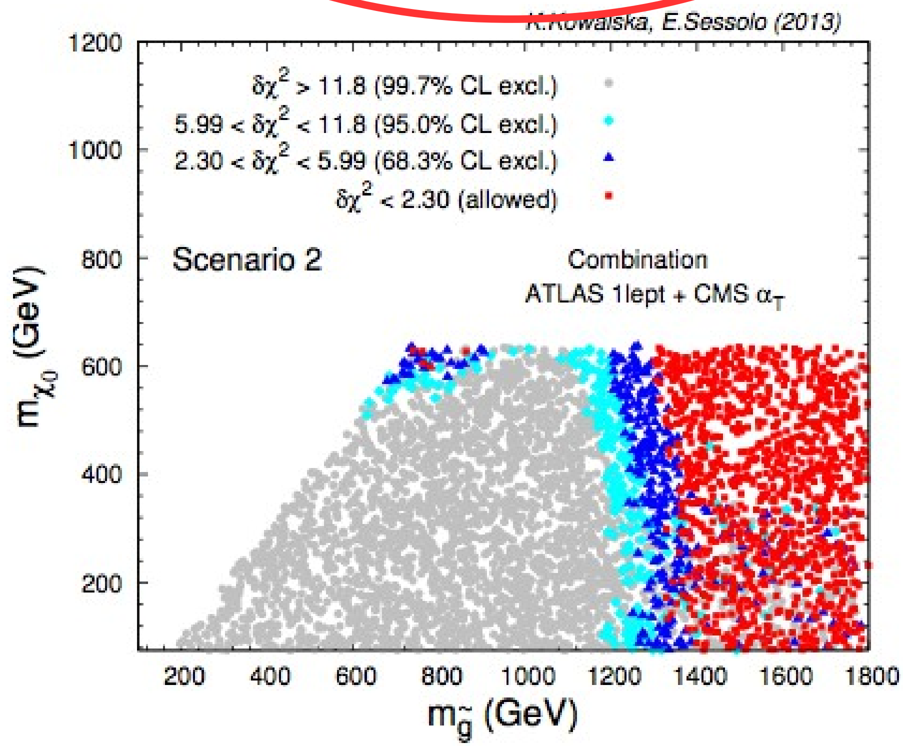
Dominant decay channels:

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

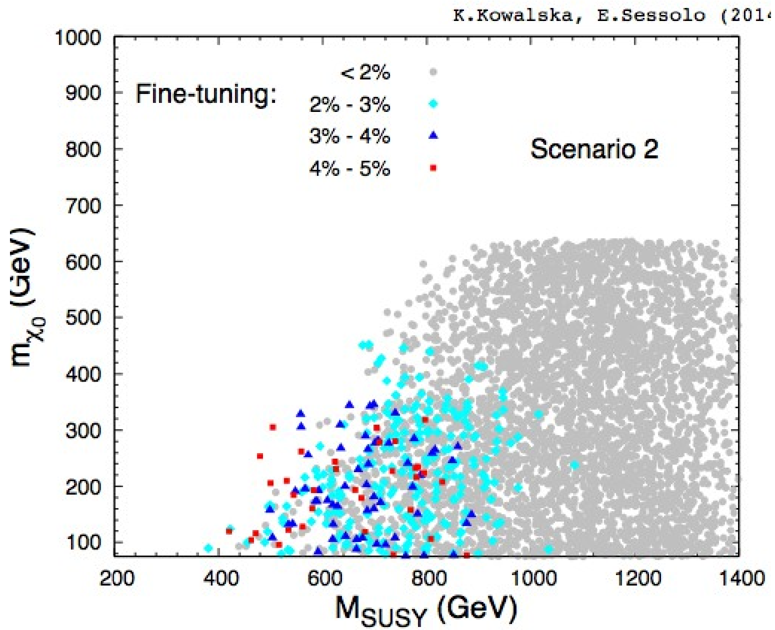
$$\tilde{g} \to q\tilde{q}\tilde{\chi}_1^0$$

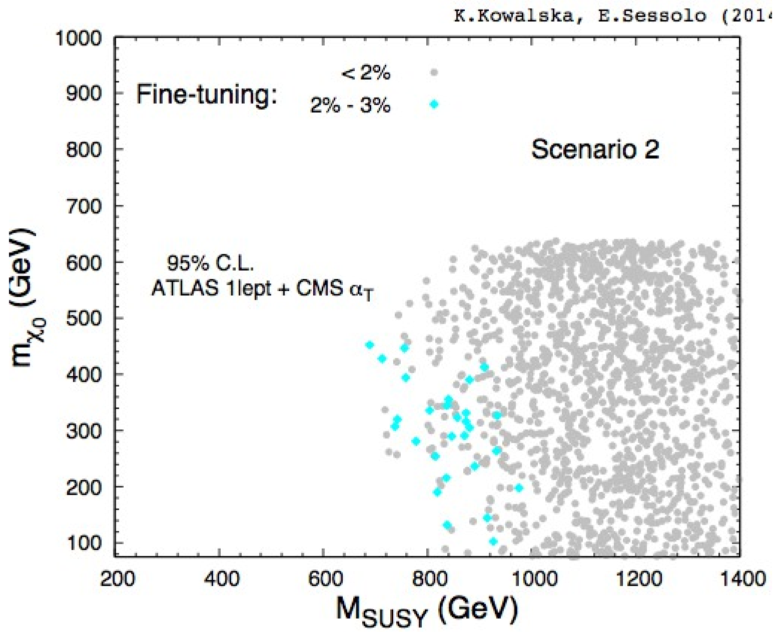
$$\tilde{g} \to b\tilde{b}\tilde{\chi}_1^0 \qquad \tilde{g} \to t\tilde{t}\tilde{\chi}_1^0$$



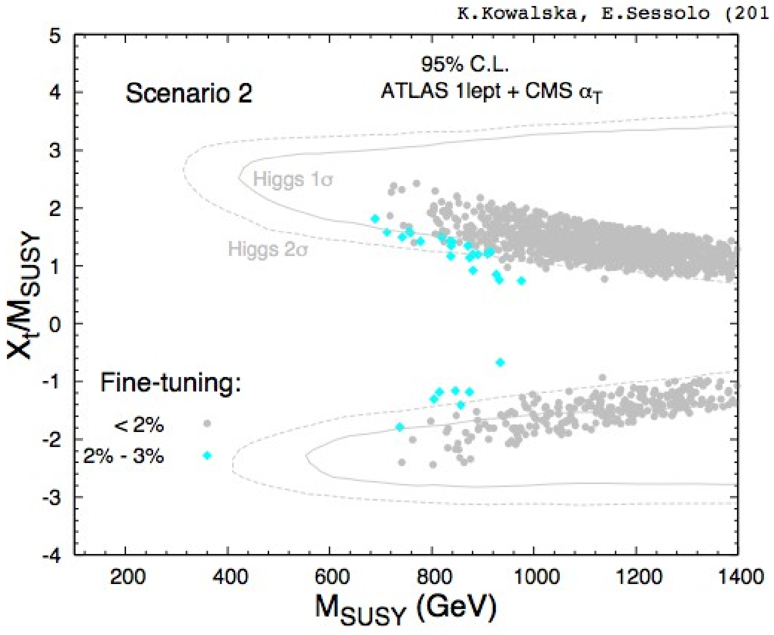


Scenario 2 – stops, gluinos and higgsinos





Pre LHC



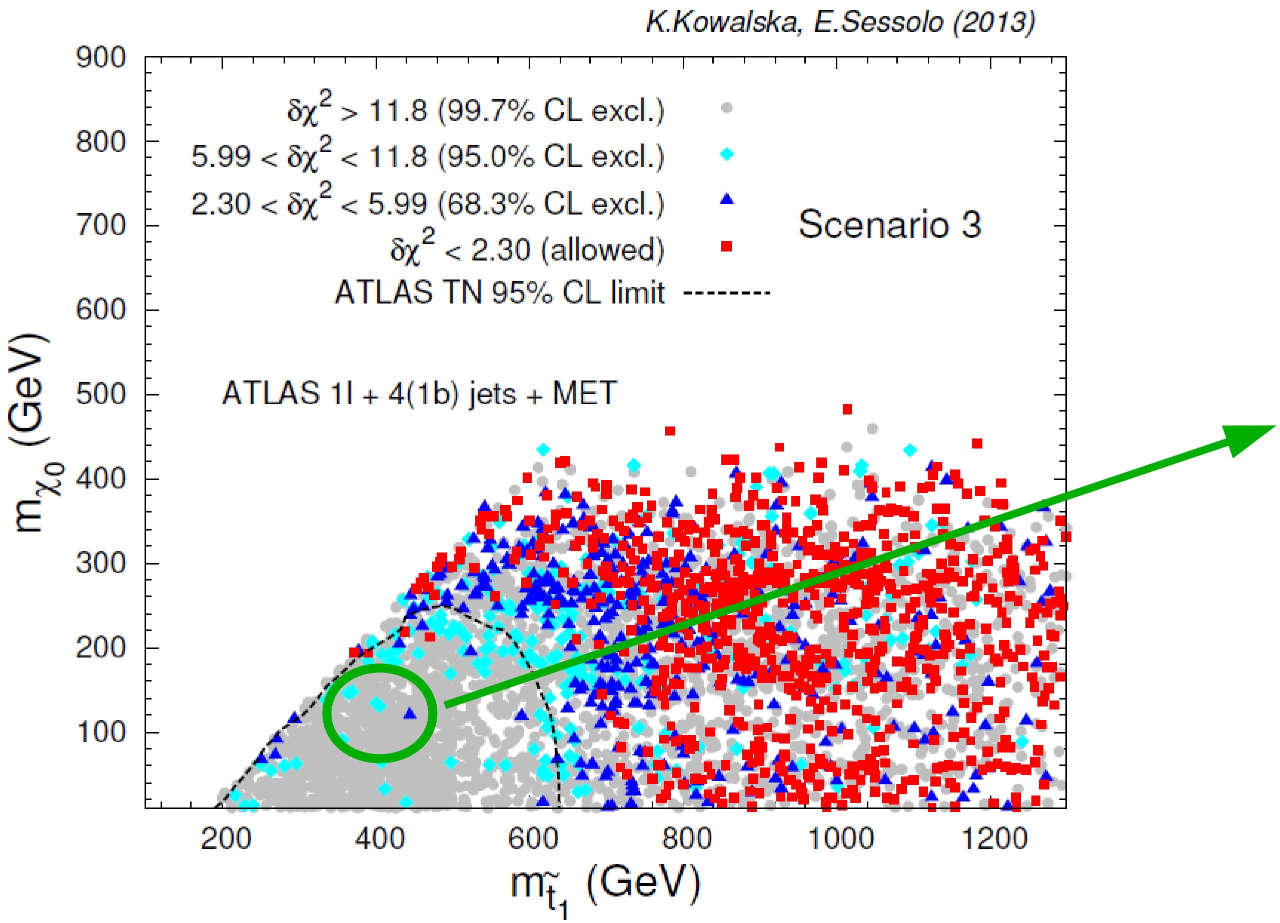
Post LHC

Higgs

Scenario 3 – stops, gluinos and EW-inos

Combination of searches:

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



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

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

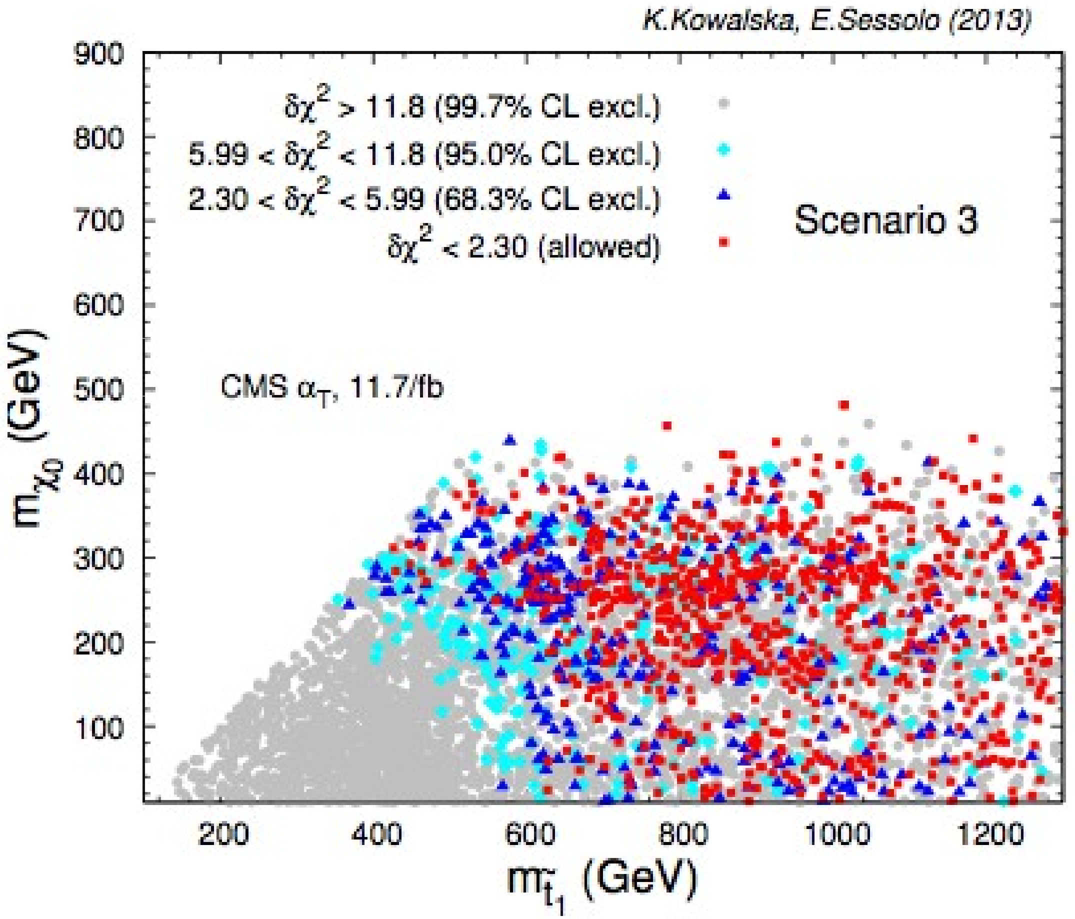
$$\tau^+ \to \text{ hadronically}$$

No hard leptons in the final state

Scenario 3 – stops, gluinos and EW-inos

Combination of searches:

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



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↓

Hadronic search excludes

Scenario 3 – stops, gluinos and EW-inos

Combination of searches:

- stronger bounds due to various topologies
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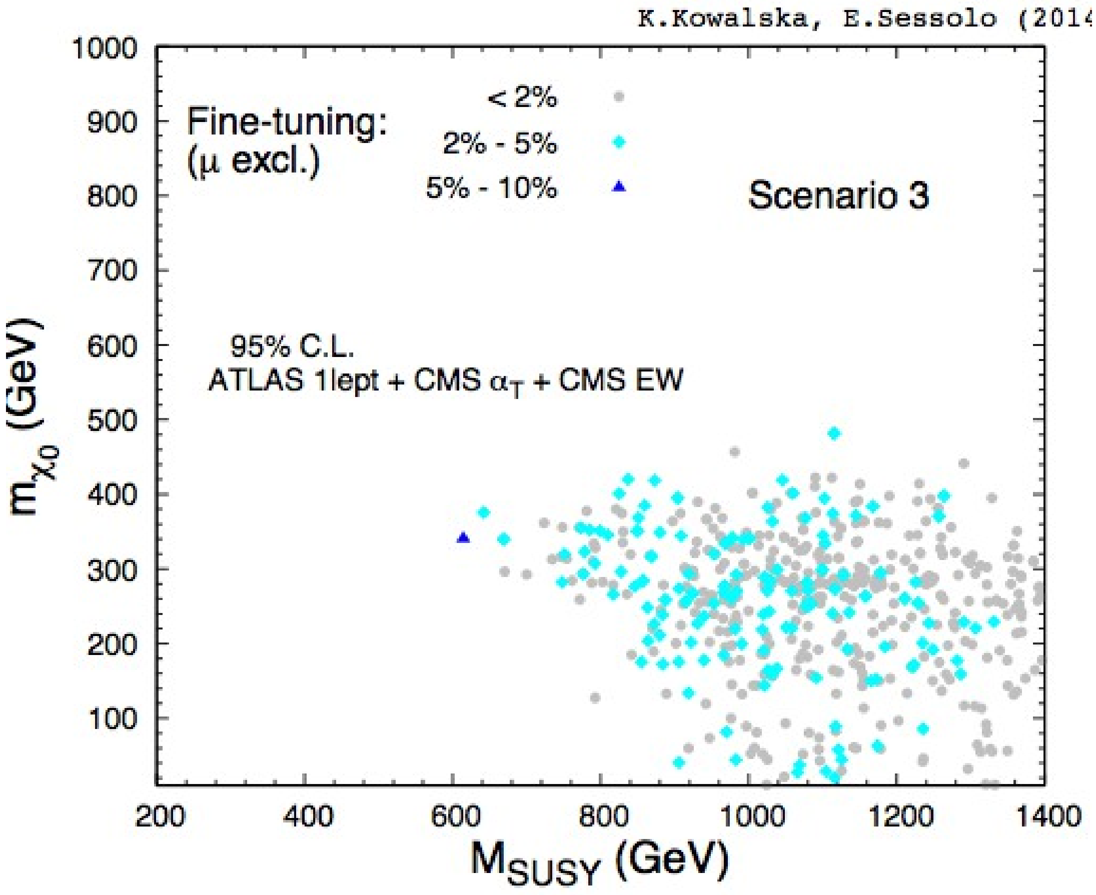


$$\tilde{t} \rightarrow b\tilde{\chi}_1^+$$

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

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

↓

Hadronic search excludes

1 point FT = 5%-10% left

Conclusions

- LHC provides strong limits for natural SUSY spectra, but most gen. definition of naturalness already in trouble because of Higgs and other constraints.

- $\Lambda \sim 10$ TeV:
  Compressed spectra ==> maybe FT > 5%
  Higgs ==> FT < 3%.

- Two competing effects:

  1. Complex decay chain soften simplify model limits
  2. Statistical combinations strengthen simp.mod. limits

BACKUP

Outline

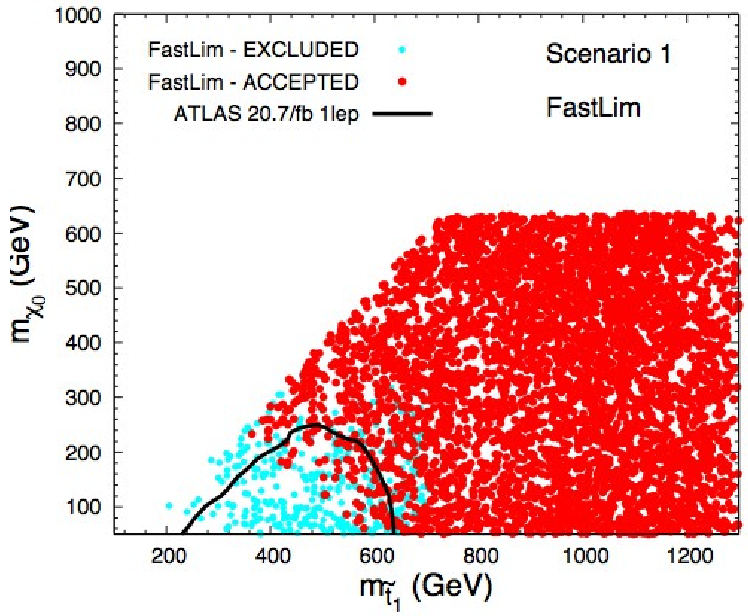
1. Definition of fine tuning

2. Reinterpretation of the LHC exclusion bounds

3. Limits on natural spectra

4. Conclusions

Comparison with other tools



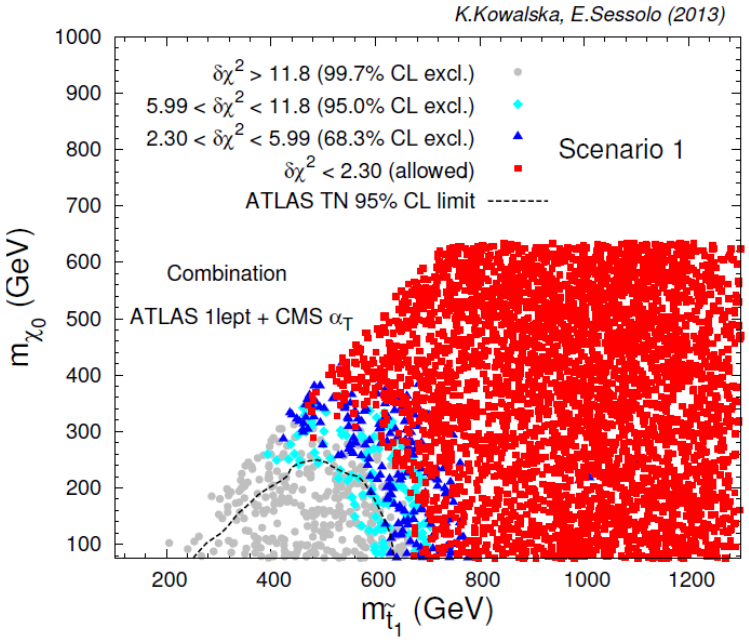
11 ATLAS searches at 21 f^{-1}

Point excluded if it is excluded in any bin

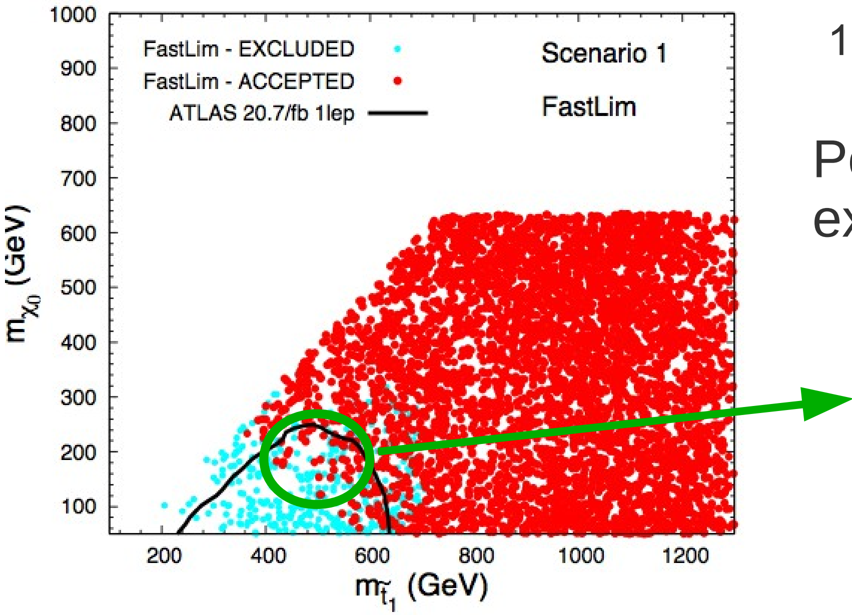
FASTLIM

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

ArXiv:1402.0492



Comparison with other tools



11 ATLAS searches at 21 f^{-1}

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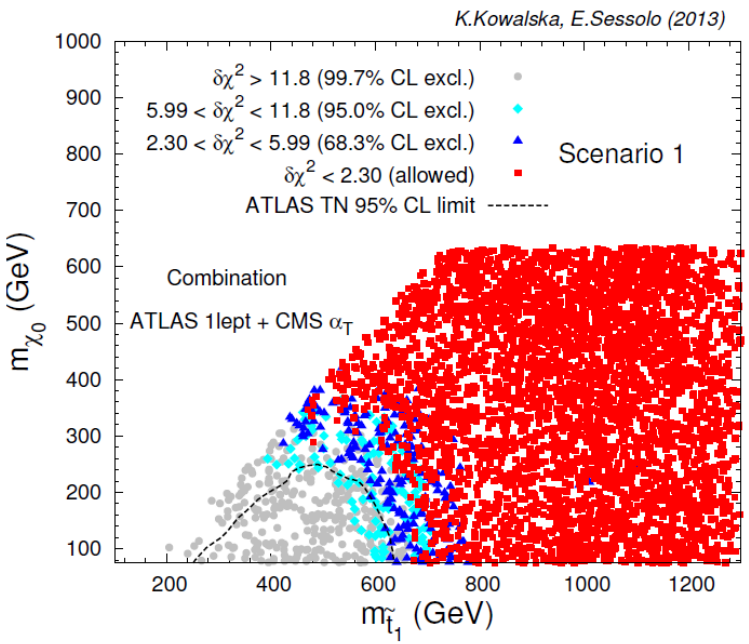
Point excluded if it is excluded in any bin

Points “almost” excluded,

eg: CL_s = 0.053 in one bin



Statistical combination of likelihoods from all bins → slightly stronger exclusion

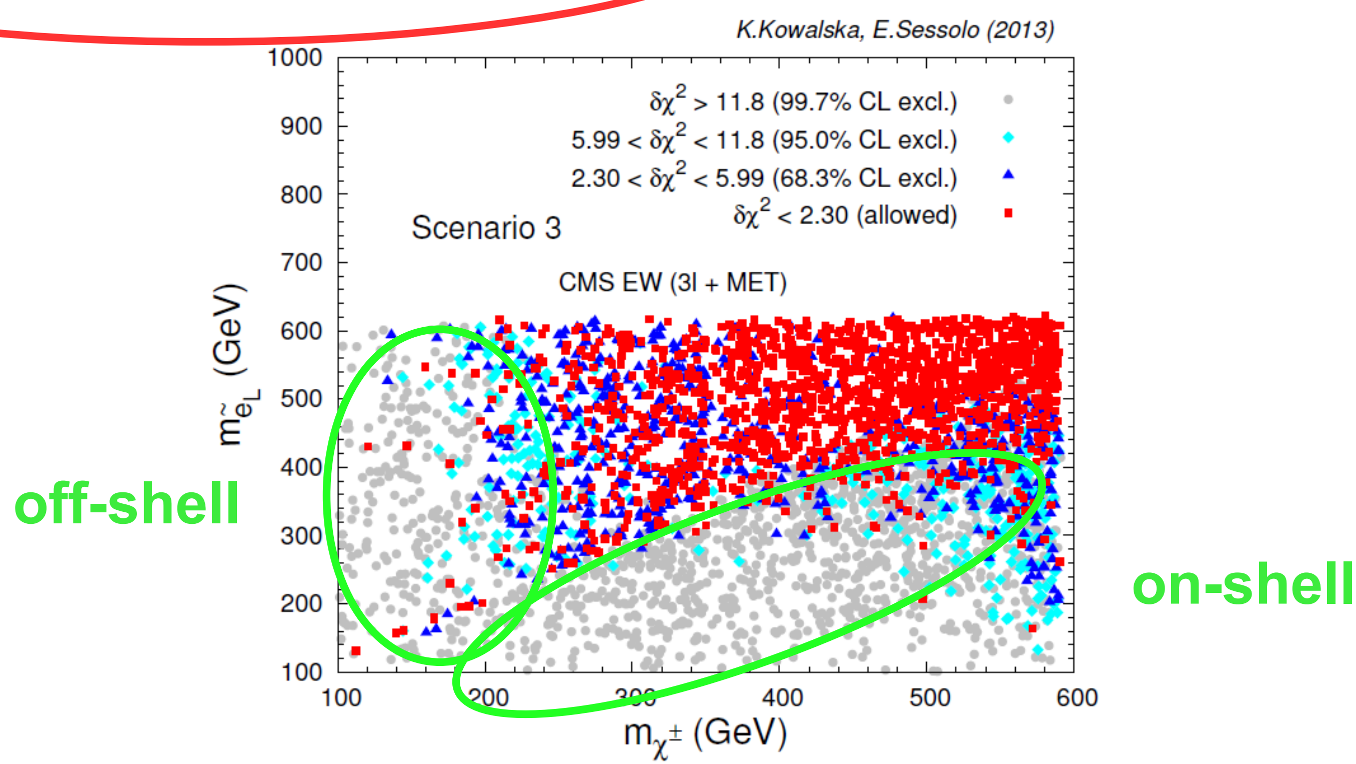
Enrico Maria Sessolo

Scenario 3 – light sleptons, winos, binos

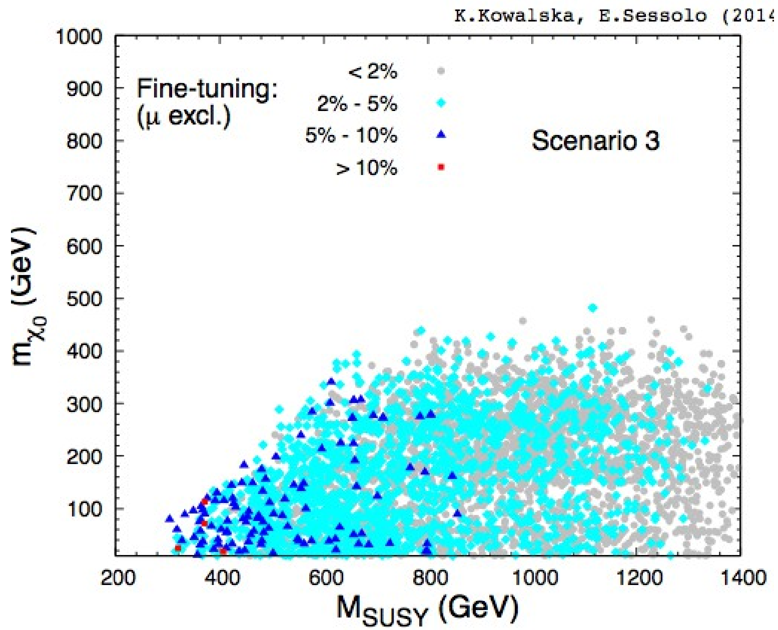
Dominant decay channels:

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

$$\tilde{\chi}_1^\pm \to \nu_l l^\pm \tilde{\chi}_1^0 \qquad \tilde{\chi}_2^0 \to l^+ l^- \tilde{\chi}_1^0 \qquad \tilde{g} \to b\tilde{b}\tilde{\chi}_1^0 \qquad \tilde{g} \to t\tilde{t}\tilde{\chi}_1^0$$



Scenario 3 – light sleptons, winos, binos



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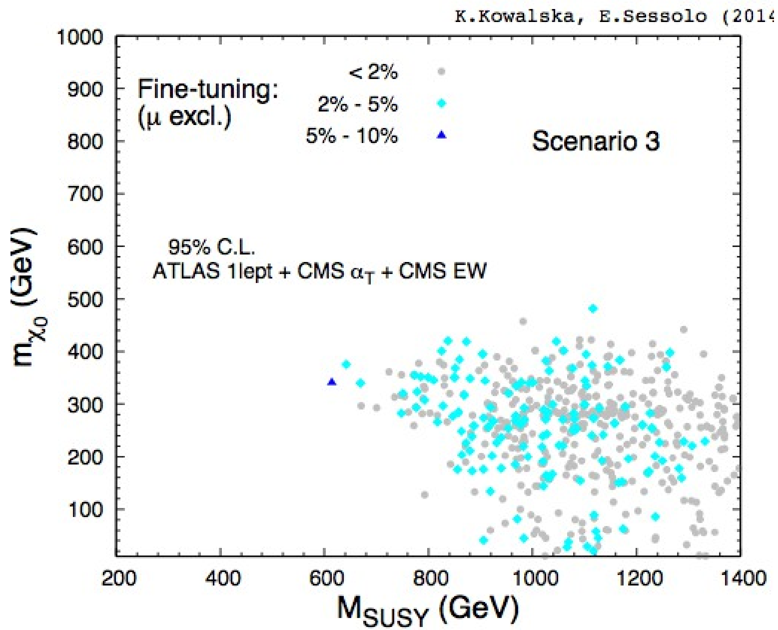
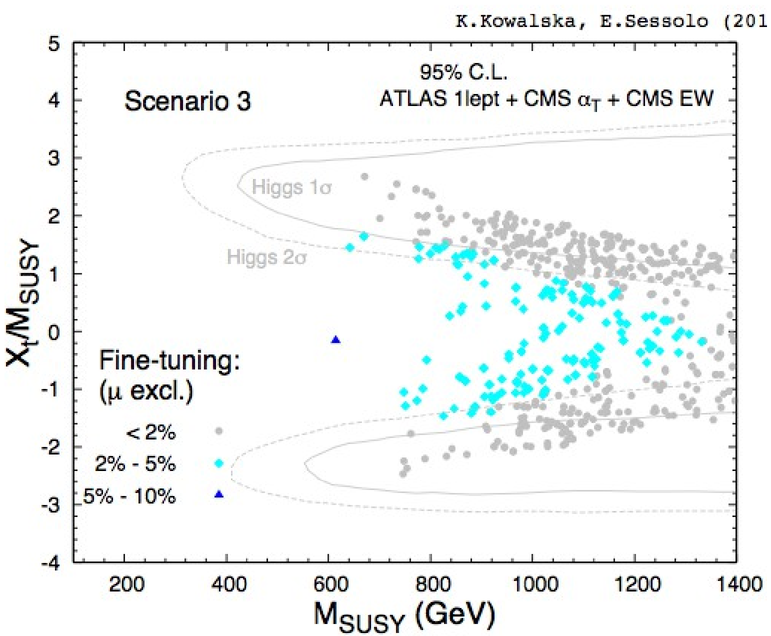


Post LHC



Higgs

Naturalness and fine tuning

$\max\{\Delta_{p_i}\} = 10$ (or 10% fine tuning) :

$$|\mu| \lesssim 200 \text{ GeV}$$

$$m^2_{\tilde{Q}_3} + m^2_{\tilde{u}_3} + |A_t|^2 \lesssim (1200 \text{ GeV})^2 \ln\left(\frac{\Lambda}{\text{TeV}}\right)^{-1}$$

$$|M_2| \lesssim (1700 \text{ GeV}) \ln\left(\frac{\Lambda}{\text{TeV}}\right)^{-1/2}$$

$$|M_3| \lesssim (2700 \text{ GeV}) \ln\left(\frac{\Lambda}{\text{TeV}}\right)^{-1}$$

$\Lambda \sim 10^{16}$ GeV (but see K.Kowalska's talk on Friday)

$\max\{\Delta_{p_i}\} = 100$ (or 1% fine tuning) :

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

$$m^2_{\tilde{Q}_3} + m^2_{\tilde{u}_3} + |A_t|^2 \lesssim \underbrace{(4000 \text{ GeV})^2}_{5} \ln\left(\frac{\Lambda}{\text{TeV}}\right)^{-1}$$

$$|M_2| \lesssim \underbrace{(5200 \text{ GeV})}_{5} \ln\left(\frac{\Lambda}{\text{TeV}}\right)^{-1/2}$$

$$|M_3| \lesssim \underbrace{(8500 \text{ GeV})}_{30} \ln\left(\frac{\Lambda}{\text{TeV}}\right)^{-1}$$