Killing constrained supersymmetry softly...

Michael Krämer (RWTH Aachen University/SLAC)

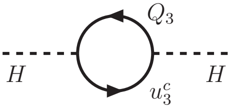
Thanks for the invitation to UC Irvine!

Outline

- Physics beyond the Standard Model at the LHC?
- Great expectations: the pre-LHC gold rush
- Global fits of supersymmetric models
- Beyond supersymmetry: simplified models
- Conclusions

Why new physics at the LHC?

- The naturalness problem: why is $M_{\mathrm{Higgs}} \ll M_{\mathrm{Planck}}$?



$$\delta M_{\mathrm{H}}^2 \sim \frac{3\lambda_t^2}{8\pi^2}\,\Lambda_{\mathrm{UV}}^2 \sim (0.3\,\Lambda_{\mathrm{UV}})^2$$

$\rightarrow$ new colored (top) partners with mass below about 500 GeV?

- Dark matter

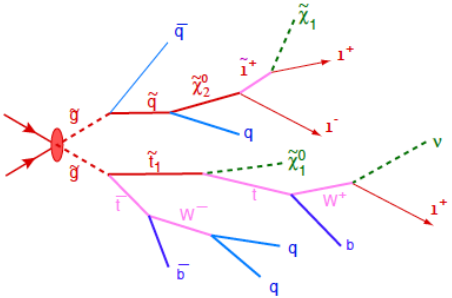
weakly interacting massive particle with mass below about 1 TeV?

New physics at the LHC?

- Naturalness & dark matter

  $\rightarrow$ new particles at the TeV-scale including a stable WIMP

  $\rightarrow$ generic LHC new physics signature: cascade decays with $E_{\mathrm{T,miss}}$



Supersymmetry is a prime example for this class of models.

Symmetry between fermions and bosons: $Q|\mathrm{boson}\rangle = |\mathrm{fermion}\rangle$

$Q|\mathrm{fermion}\rangle = |\mathrm{boson}\rangle$

with algebra $\{Q_\alpha, Q^\dagger_\beta\} = (\sigma^\mu)_{\alpha\beta} P_\mu$

→ SUSY is the unique maximal external symmetry in nature.

→ One needs to introduce superpartners to the Standard Model particles.

√ SUSY protects the Higgs mass from large radiative corrections:

$\rightarrow \delta m_H^2 \sim -\frac{\alpha}{\pi}(\Lambda^2 + \widetilde{m}_F^2)$

$\delta m_H^2 \sim \frac{\alpha}{\pi}(m_F^2 - \widetilde{m}_F^2) \rightarrow$ no fine-tuning if $\widetilde{m} \lesssim \mathcal{O}(1\ \mathrm{TeV})$

√ SUSY allows for coupling unification, radiative EWSB, dark matter (assuming R-parity), . . .

The Minimal Supersymmetric extension of the SM

- external symmetries: Poincaré symmetry & supersymmetry
- internal symmetries: SU(3)⊗SU(2)⊗U(1) gauge symmetries

Gauge Bosons $S = 1$	Gauginos $S = 1/2$
gluon, $W^\pm, Z, \gamma$	gluino, $\widetilde{W}, \tilde{Z}, \tilde{\gamma}$
Fermions $S = 1/2$	Sfermions $S = 0$
$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} \nu_L^e \\ e_L \end{pmatrix}$	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix} \begin{pmatrix} \tilde{\nu}_L^e \\ \tilde{e}_L \end{pmatrix}$
u_R, d_R, e_R	$\tilde{u}_R, \tilde{d}_R, \tilde{e}_R$
Higgs	Higgsinos
$\begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix} \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}$	$\begin{pmatrix} \widetilde{H}_2^0 \\ \widetilde{H}_2^- \end{pmatrix} \begin{pmatrix} \widetilde{H}_1^+ \\ \widetilde{H}_1^0 \end{pmatrix}$

- SUSY breaking $\rightarrow$ sparticle masses?

Searches for supersymmetry

The SUSY parameter space is strongly constrained by

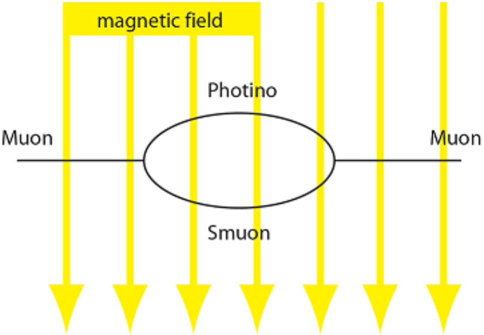
- SM precision observables:
  $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu\mu)$, $\mathrm{BR}(b \to \tau\nu)$, Δm_{B_s}, $(g-2)_\mu$, m_W, $\sin^2\theta_{\mathrm{eff}}$
- astrophysical observations:
  Ω_{DM}, direct and indirect DM detection limits
- direct sparticle and Higgs boson search limits from colliders:
  $m_{\tilde{\chi}^\pm}$, LEP limits on MSSM Higgs bosons
- LHC SUSY exclusions from jets+$E_{T\mathrm{miss}}$ searches
- the LHC Higgs signal

→ test supersymmetric models through global fits

[see e.g. SFitter, Mastercode, SuperBayes and Fittino]

Indirect SUSY searches

- the anomalous magnetic moment of the muon $(g-2)_\mu$:



→ SUSY loops: $a_\mu^{\mathrm{SUSY}} \sim \mathrm{sgn}(\mu)\tan\beta\, M_{\mathrm{SUSY}}^{-2}$

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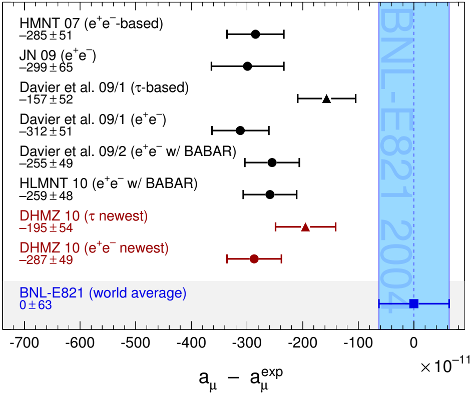
Davier, Hoecker, Malaescu, Zhang, arXiv:1010.4180v1



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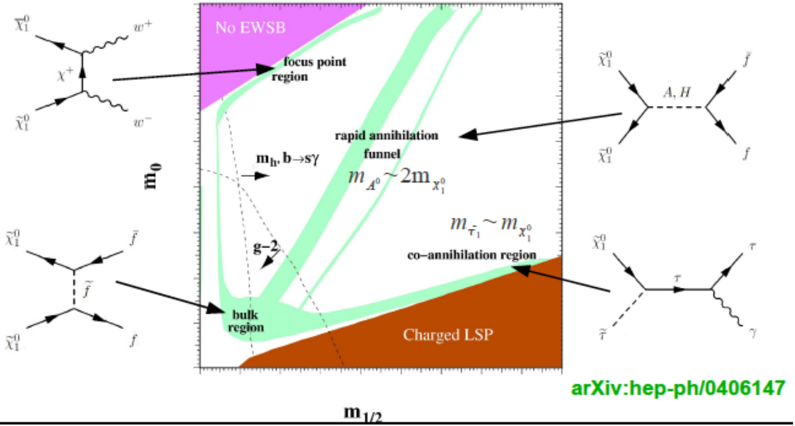
- Ω_{DM} is too large for large parts of the MSSM parameter space, special annihilation mechanisms are needed:



The constrained Minimal SuperSymmetric Model

Current data cannot constrain general SUSY models

→ Consider the constrained MSSM: a model with universal scalar and fermion sparticle masses M_0 and $M_{1/2}$ at the GUT scale

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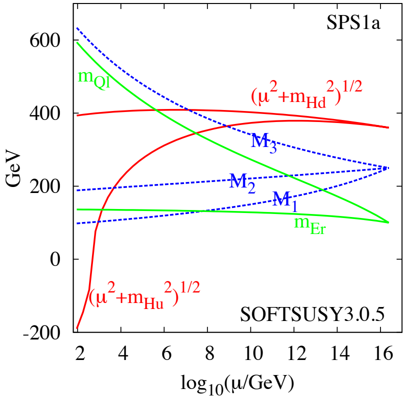
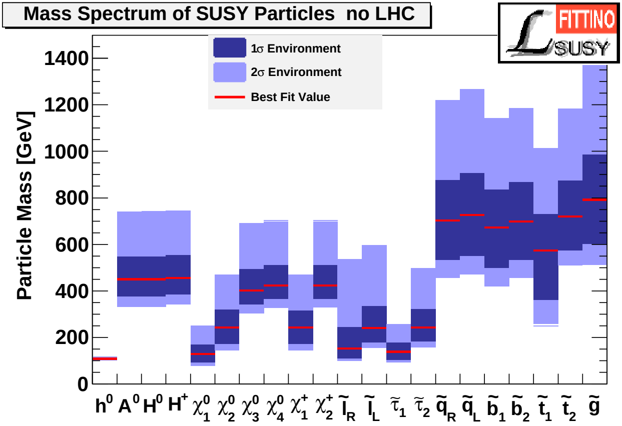
low scale masses $\xleftarrow{\text{RG evolution}}\!\!\!\!\rightarrow$ high scale parameters



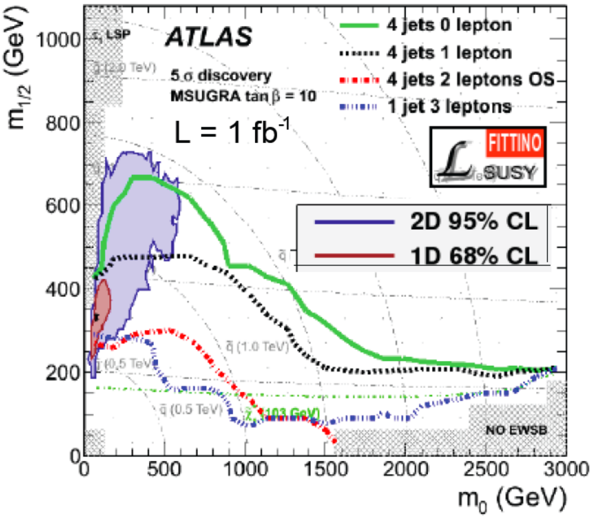
The constrained MSSM: global fits pre-LHC

cMSSM fit to B, K and EWK observables, $(g-2)_\mu$ and Ω_{DM}:



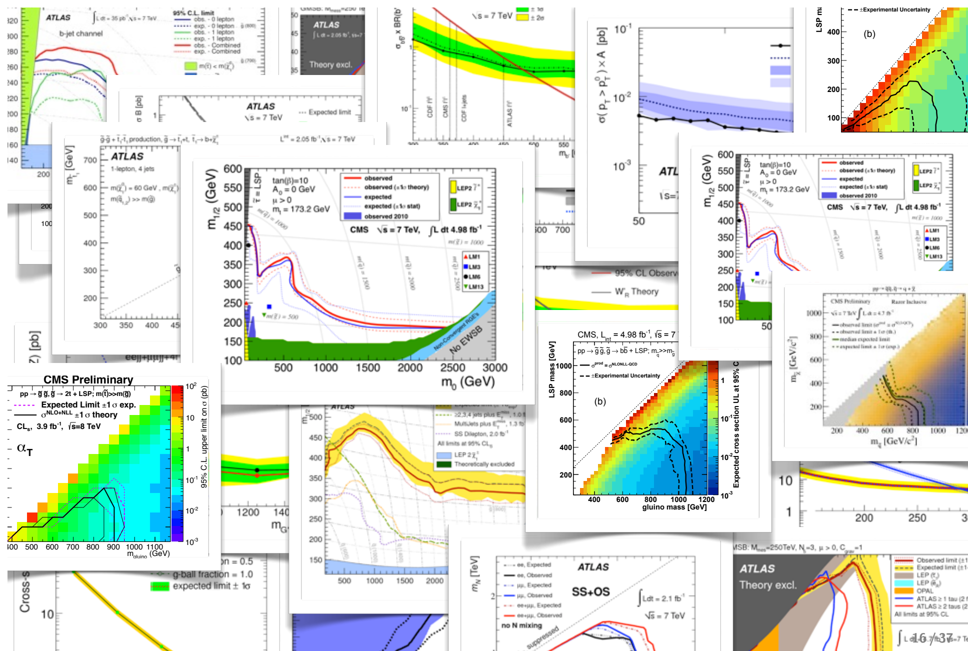
→ SUSY is just around the corner...

The constrained MSSM: great expectations



SUSY! SUSY! SUSY from the LHC!

Summary of BSM searches at the LHC: limits, limits and more limits...



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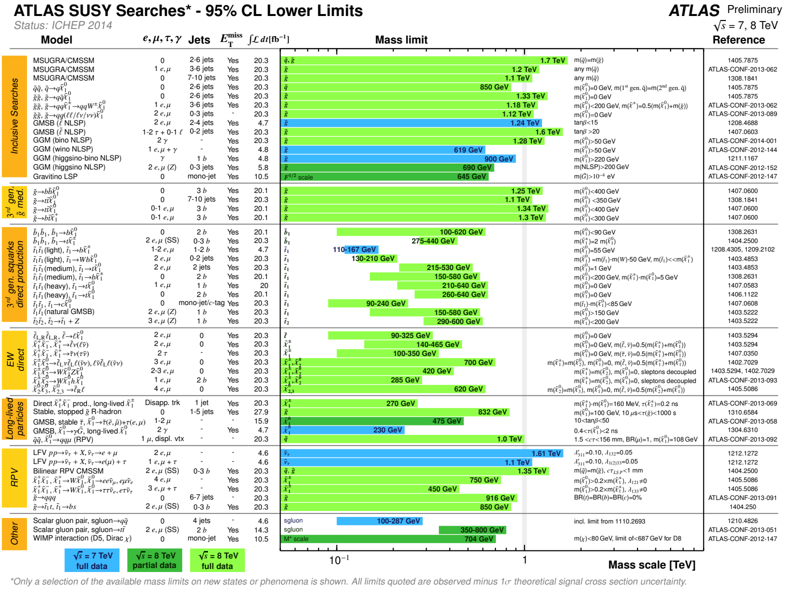
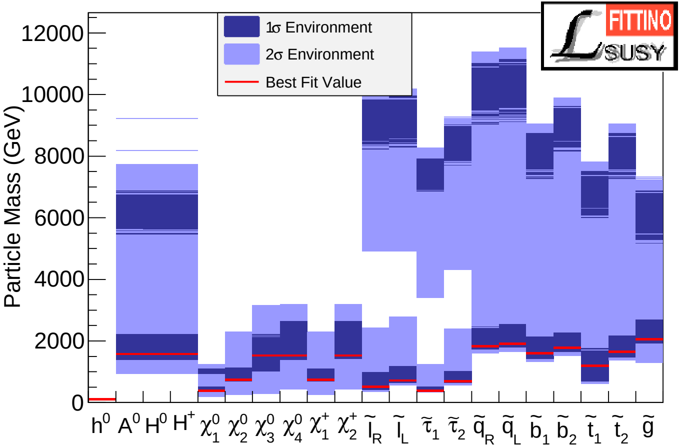


cMSSM fit including LHC exclusions and Higgs properties:



The constrained MSSM: global fits post LHC-8

To summarize the picture in the constrained MSSM:

- sparticles and $H, A, H^{\pm}$ beyond the current LHC reach
- branching ratios of the light Higgs h close to the SM values
- the branching ration for $B_s \to \mu\mu$ close to the SM value
- no dark matter signal in current direct or indirect searches

- The cMSSM looks like the SM with dark matter.
- The cMSSM could mean grim prospects for LHC phenomenology.
- The cMSSM cannot solve the hierarchy problem.

We find that the cMSSM is pretty dull. But is it already dead?

How dead is the cMSSM?

Estimate the *p*-value:

> *If the cMSSM at the best fit point is the true description of nature, what is the probability p to get a minimal χ^2 as bad or worse that the one observed?*

For a set of observables with Gaussian uncertainties, only need # of degrees of freedom and $\chi_{\min}$ to calculate the *p*-value.

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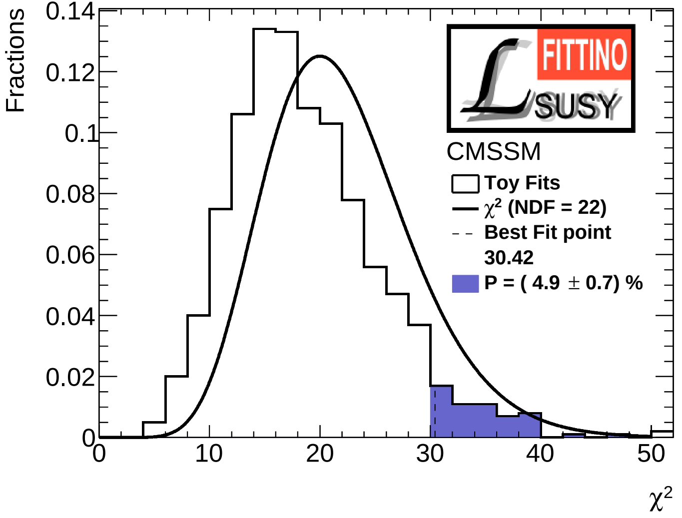
Unfortunately, the uncertainties are, in general, non-Gaussian, so we have to perform toy fits:

- generate (1000) pseudo-measurements by smearing the experimental observables about the best-fit prediction;
- repeat the global fit for each of these pseudo-measurements.

How often do we get a minimal χ^2 as bad or worse than the one of the best-fit point? $\rightarrow$ p-value

How dead is the cMSSM?



How dead is the cMSSM? The impact of $(g-2)_\mu$ and the Higgs

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  $p = (51 \pm 3)\%$

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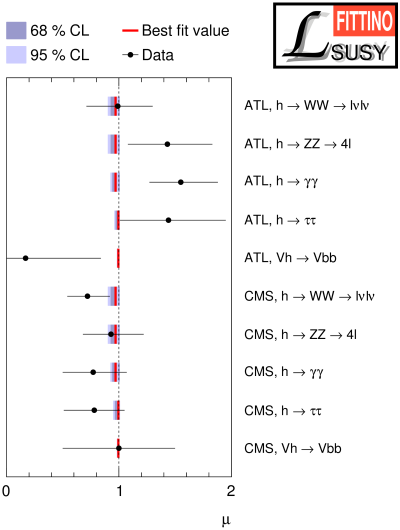
- without $(g-2)_\mu$:
  $p = (51 \pm 3)\%$
- without Higgs properties:
  $p = (1.3 \pm 0.4)\%$
- including 10 Higgs rate and 4 Higgs mass measurements:
  $p = (4.9 \pm 0.7)\%$



[...using HiggsSignals]

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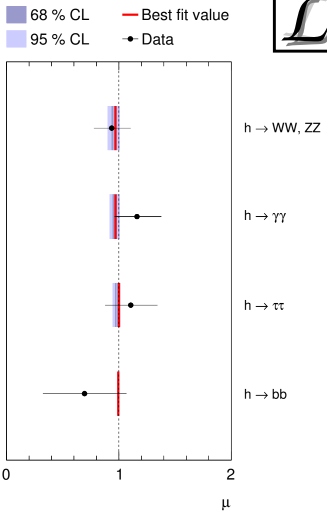
- without $(g-2)_\mu$:
  $p = (51 \pm 3)\%$
- without Higgs properties:
  $p = (1.3 \pm 0.4)\%$
- including 4 Higgs rate and 1 Higgs mass measurements:
  $p = (8.3 \pm 0.8)\%$

The p-value depends on the parametrization of the Higgs observables.



[. . . using HiggsSignals]

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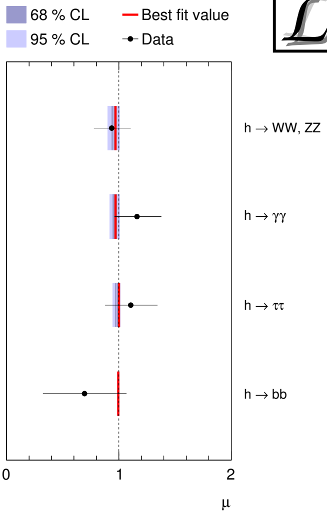
The cMSSM is a dull zombie...



[...using HiggsSignals]

Global SUSY/BSM fits: outlook

Future global SUSY/BSM fits should

- include the Higgs observables; ✓
- calculate the p-value using toy fits; ✓
- address more general models;
- include a larger set of LHC observables.

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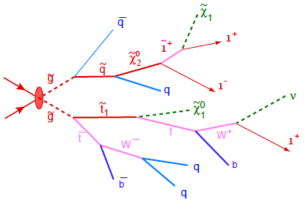
Use simplified models?

Do not analyse data in terms of



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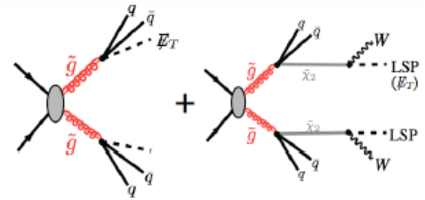
but rather in terms of few simple topologies like

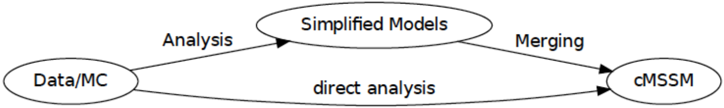


Towards model independent searches: simplified models

However...

- how do we choose the right simplified models?
- need to translate interpretation of data obtained using simplified models to interpretation of physics models
- need to assume that acceptance and detector efficiency of simplified models is similar for a specific model; how to quantify the error?
- what about backgrounds? Specific models may have additional sources of background which are not included in simplified models

The error in the translation simplified model $\longleftrightarrow$ physics model

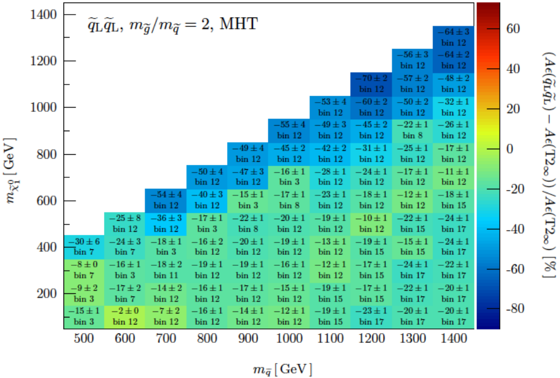


needs to be quantified

Towards model independent searches: simplified models

- Compare simplified model T2 with squark production in the MSSM
  [Edelhäuser, Heisig, MK, Oymanns, Sonneveld (1410.0965)]

acceptance $\times$ efficiency



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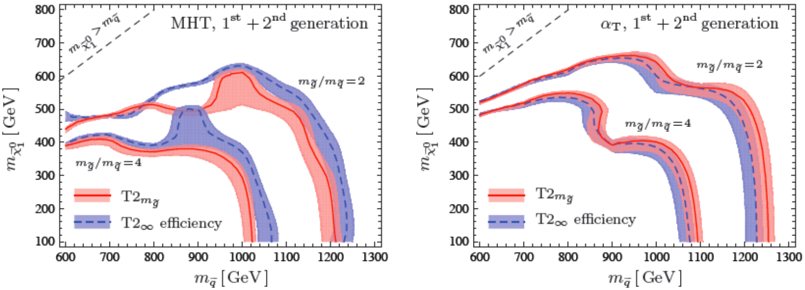
mass limits



$\rightarrow$ simplified models provide a reliable tool to interpret LHC searches in a more model-independent way.

Summary and conclusions

Where could new physics hide?

New physics could have a

- split spectrum and thus reduced production cross section (e.g. "natural" SUSY with light stops)
- different decay pattern (e.g. compressed spectra)

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For LHC13 we need to

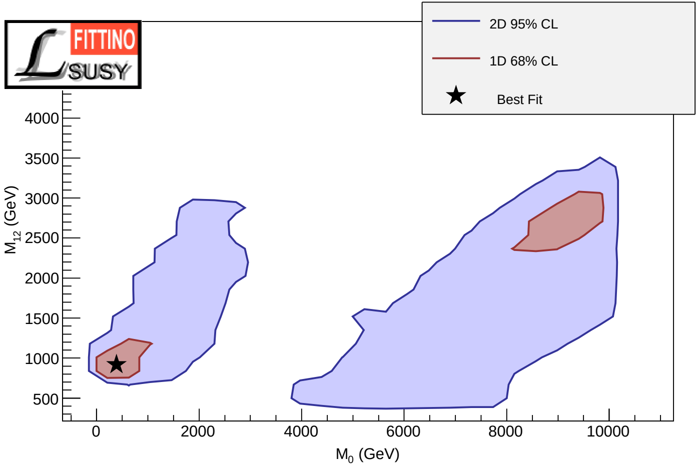
- explore a wider range of BSM models
- move towards more model-independent searches (effective field theories, simplified models, . . .)
- increase the precision of the theoretical predictions (higher-order corrections, pdfs, . . .)

However, new physics could simply be unnatural . . .

Backup slides

The constrained MSSM: global fits post LHC-8

cMSSM fit including LHC exclusions and Higgs properties:



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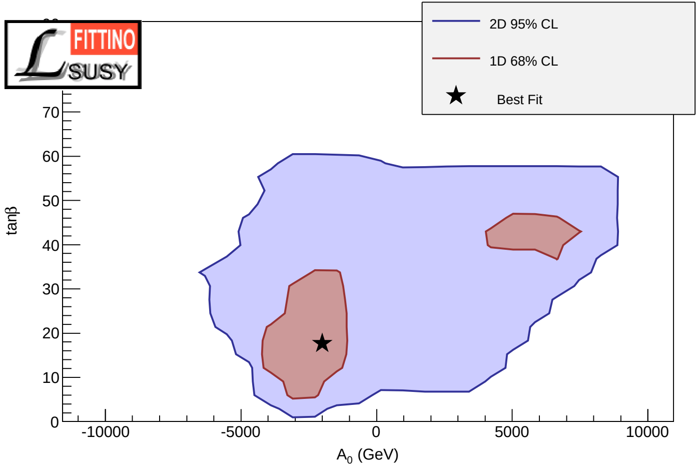

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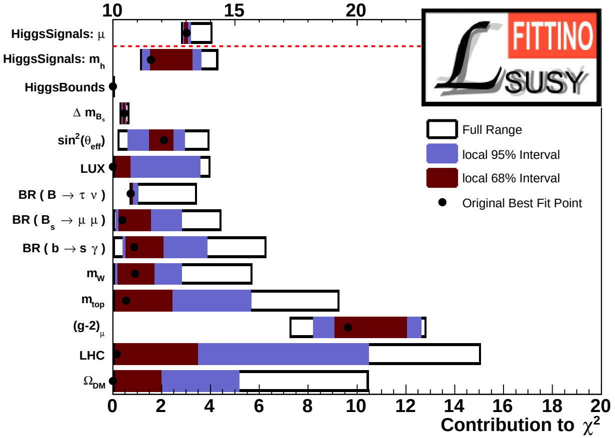

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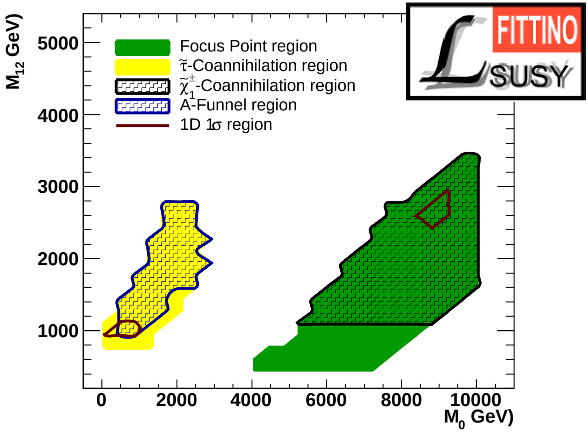

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