Some aspects of physics beyond the SM at the LHC

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Merida, México

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Main purposes of the LHC

★ Probe Higgs Mechanism

- Great LHC performance excluding almost all the mass range
- Maybe a Higgs signal at $m_h \sim 125\ \mathrm{GeV}$

★ Look for BSM

- Impresive LHC job excluding paradigmatic BSM scenarios
- No signal so far

Physics Beyond the Standard Model (BSM):

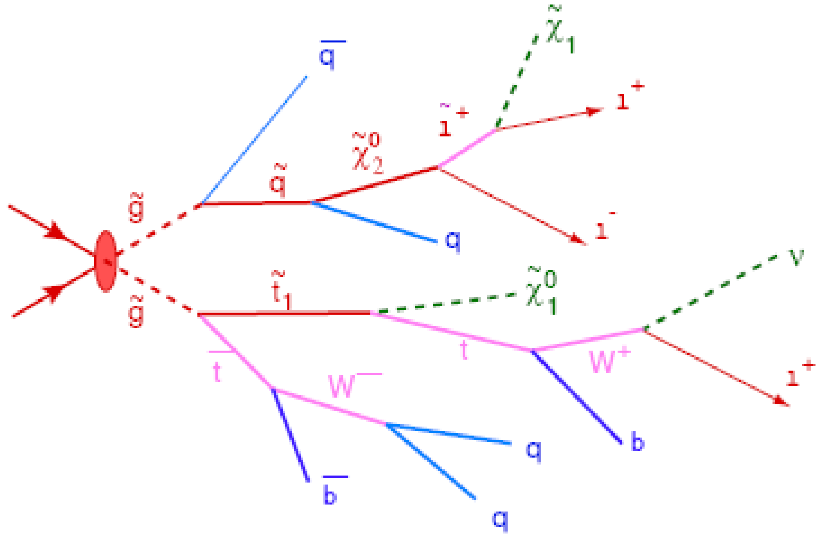
- ★ SUSY
  - MSSM
    - CMSSM
    - NUHM
    - Gauge-Med MSSM, ...
    - String-inspired MSSM...
  - NMSSM
  - Low ~~SUSY~~ MSSM....
- ★ Extra Dimensions: ADD, R-S, ...
- ★ Composite Higgs / Little Higgs...

Physics Beyond the Standard Model (BSM):

- ★ Dark Matter candidates
- ★ Flavour violation
- ★ Others: Z', W', 4th generation, ...

Two main strategies to constrain NP

- ***Direct searches (NP particles production)***



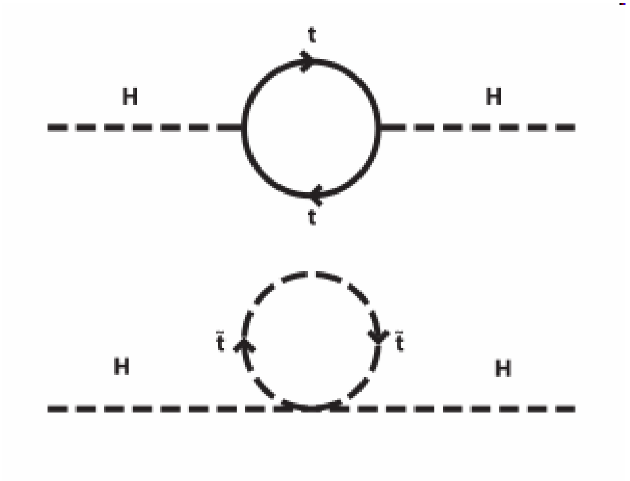
- ***Fingerprints in the effective theory***

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathrm{Higher-Dim\ Operators}$$

SUSY

Motivations:

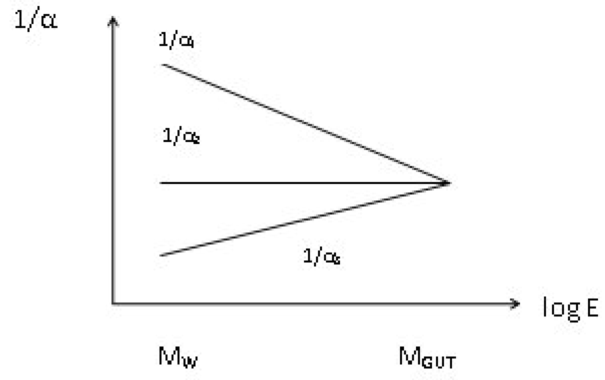
- ***Beautiful symmetry, strongly suggested by string theories***
- ***Elegant solution to the Hierarchy Problem***



SUSY

Nice features of SUSY (not designed for them)

- ***Gauge Unification***

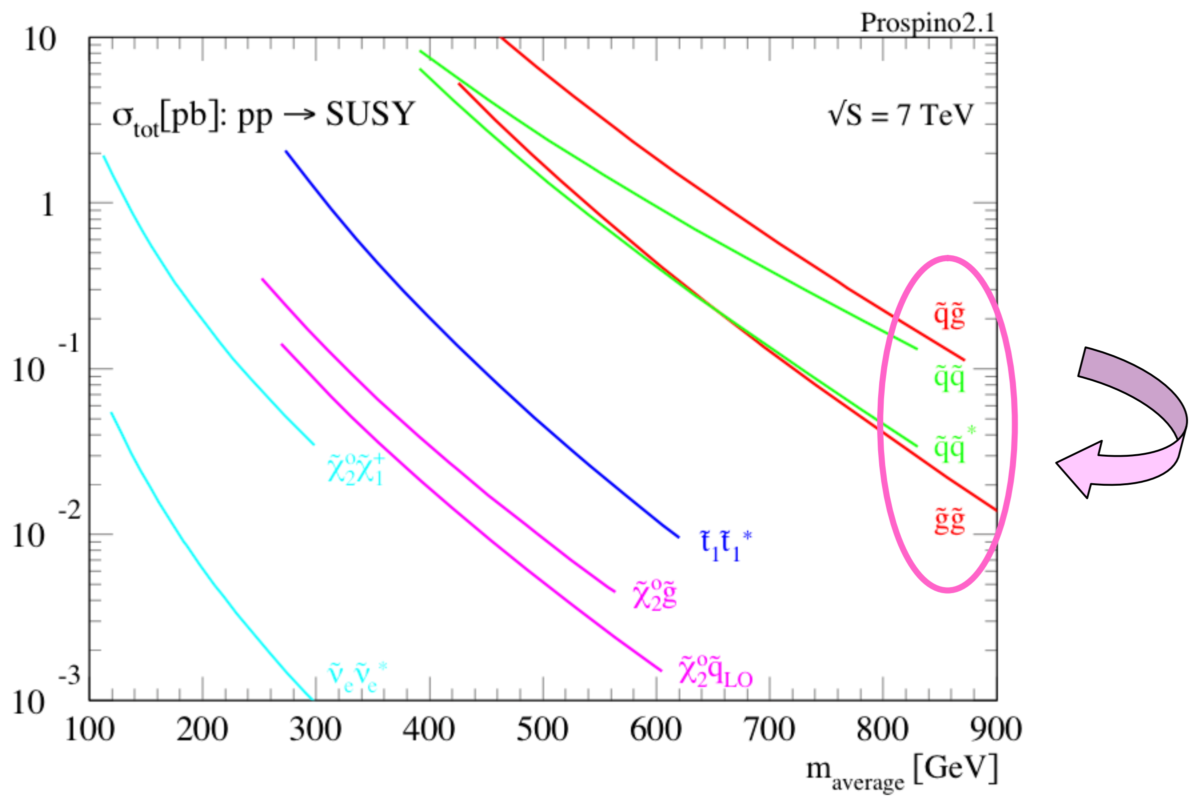


- ***Radiative EW breaking***
- ***Natural candidate for DM***

beautiful... but maybe false! ⇨ LHC test

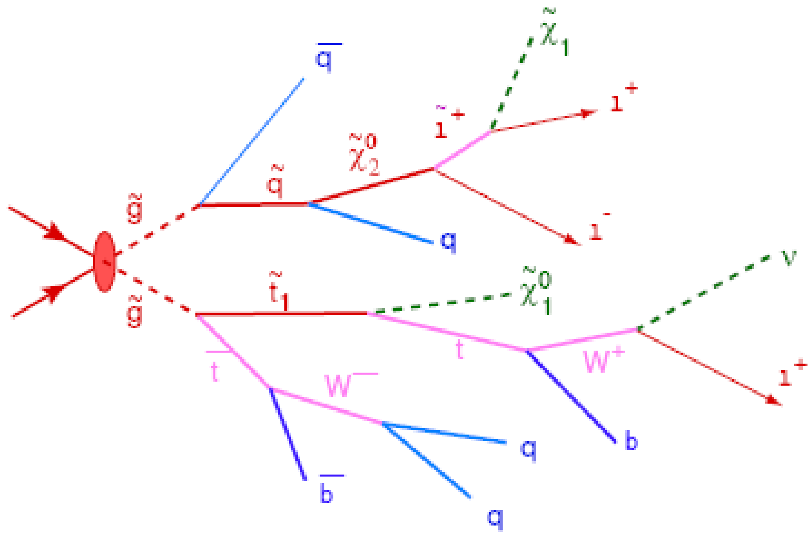
SUSY production at LHC

★ Highest cross-sections of SUSY production are normally gluino and/or squark pair- production



Typical SUSY signals

★ $\tilde{g}$, $\tilde{q}$ decay along cascades with diverse topology



★ Each cascade always gives an LSP (χ_1^0) among the final states

★ Always producing ≥ 2 jets (with/without leptons) + $\not{E}_T$

Typical SUSY signals

⇨ Most direct search of SUSY:

- jets with high p_T
- $\not{E}_T$
- 0-N leptons

It is not straightforward to translate LHC results into bounds in SUSY (MSSM)

MSSM has ~ 100 independent parameters !

(most of them related to the unknown mechanism of ~~SUSY~~ and transmission to the observable sector):

$$\left\{ m_{ij}^2, M_a, A_{ij}, B, \mu \right\}$$

A usual strategy is to present the LHC data as constraints in the CMSSM

CMSSM

$$\{m_{ij}^2, M_a, A_{ij}, B, \mu\}$$

$$\{m, M, A, B, \mu\}$$ at M_X

EW breaking $\Rightarrow$

$$\{m, M, A, \tan\beta, \mathrm{sign}\ \mu\}$$

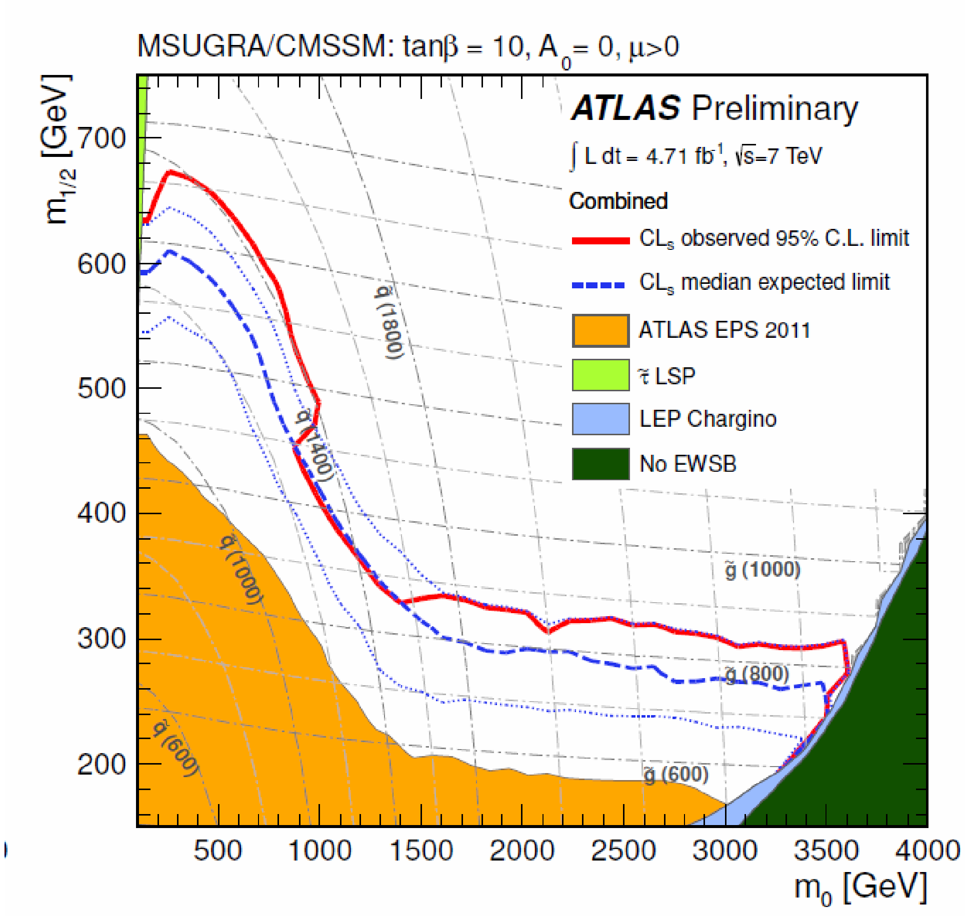
Typical Spectrum

$$M_{\tilde{g}} \sim m_{\tilde{q}} > m_{\tilde{l}}$$

$$M_{\tilde{g}} > M_{\chi^\pm} \gtrsim M_{\chi^0}$$

$$\chi_1^0 \equiv \mathrm{LSP}$$

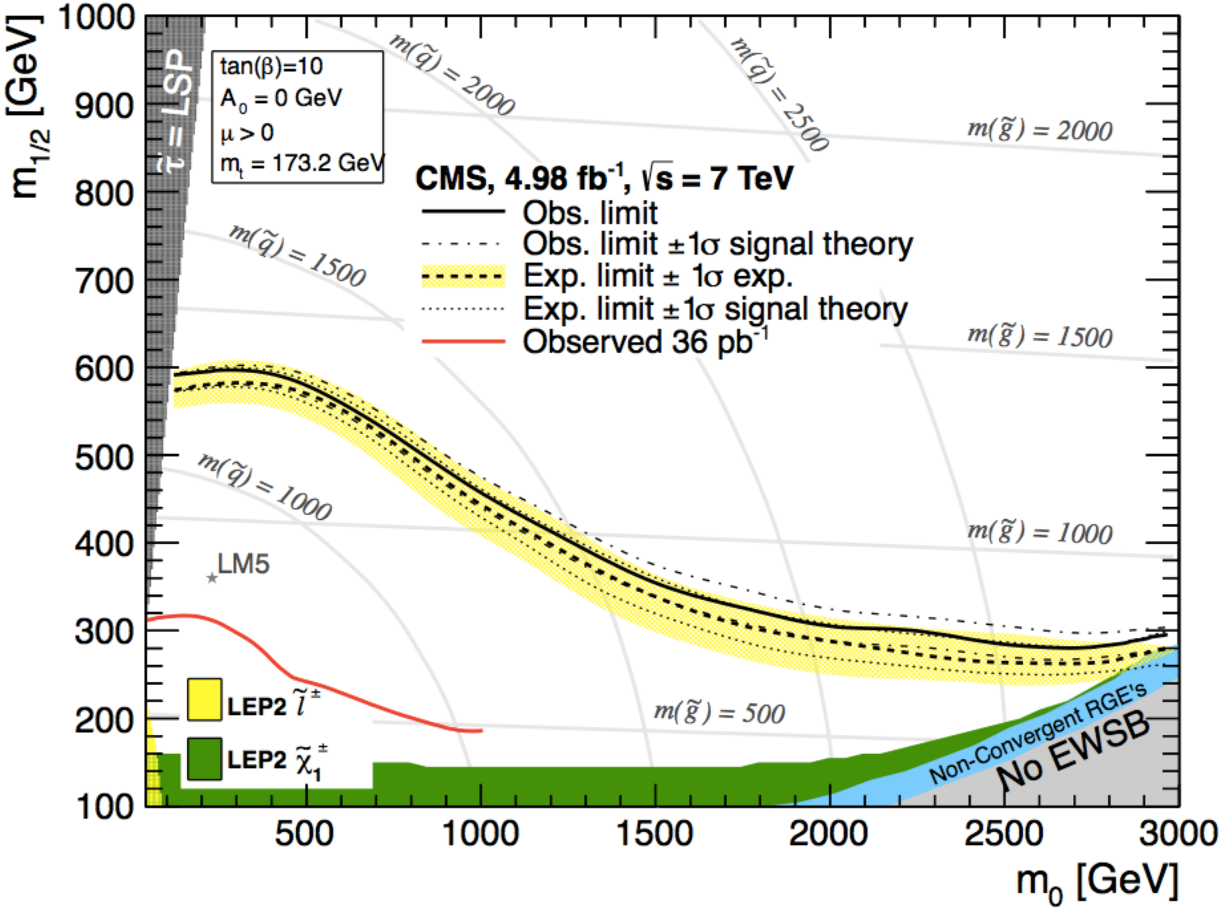
LHC constraints on the CMSSM



Mostly from multijet + $\not{E}_T$

$$\tan\beta = 10, \;\; A = 0$$

LHC constraints on the CMSSM



Mostly from multijet + $\not{E}_T$

$$\tan\beta = 10,\ A = 0$$

Roughly speaking,

For $M_{\tilde{g}} \sim m_{\tilde{q}}$, then $M_{\tilde{g}},\ m_{\tilde{q}}\ \gtrsim\ 1100\ \mathrm{GeV}$

⇨ CMSSM is in trouble

- The reason is that with such large masses, the EW breaking is fine-tuned

- We cannot “forget” about the fine-tuning problem, since the main reason to consider Weak-Scale SUSY was to avoid the Hierarchy Problem (fine-tuning of EW breaking in the SM)

About fine-tuning

$$V(H_1, H_2) = m^2_{H_1}|H_1|^2 + m^2_{H_2}|H_2|^2 - 2B\mu H_1 H_2$$

$$+\frac{1}{8}(g^2 + g'^2)\,(|H_1|^2 - |H_2|^2)^2$$

$$M_Z^2 = \frac{m^2_{H_d} - m^2_{H_u}\tan^2\beta}{\tan^2\beta - 1} - 2\mu^2$$

$$(\ \tan\beta \equiv \frac{v_u}{v_d}\ )$$

Note that $m^2_{H_d}$, $m^2_{H_u}$ receive radiative contributions from other soft terms along the running from M_X to M_{EW} :

$$\text{large } m_{\tilde{t}},\ M_{\tilde{g}}, \ldots \ \Rightarrow\ \text{large } |m_{H_d}|,\ |m_{H_u}|$$

Unnatural fine-tuning unless $M_{\rm soft} \lesssim \mathcal{O}(\rm TeV)$

Actually, the fine-tuning problem is more general and severe

$$m_h^2 \simeq \underbrace{M_Z^2 \cos^2 2\beta}_{} + \frac{3}{2\pi^2}\frac{m_t^4}{v^2}\left[\log\frac{M_{\rm SUSY}}{M_t} + f(A_t)\right] + \cdots$$

tree-level contrib.
(≤ M_Z^2)

$M_{\rm SUSY} \sim m_{\tilde t}$

valid for any MSSM

$$m_h \simeq 125 \text{ GeV}$$

$\Rightarrow$

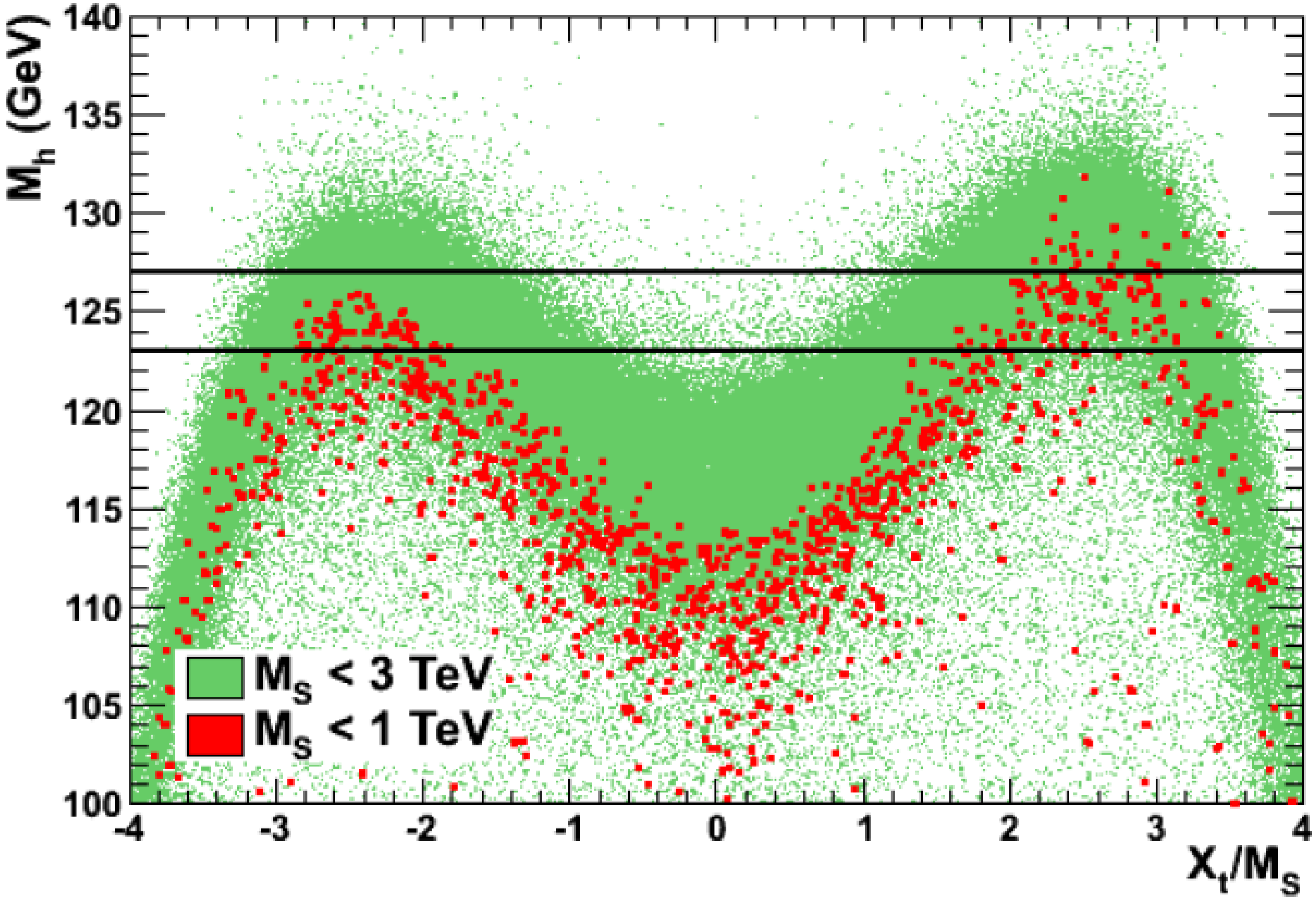
$m_{\tilde t} \gtrsim 3$ TeV → fine-tuning in the EW breaking

$A_t \simeq \sqrt{6} m_{\tilde t}$ (i.e. maximal) → also fine-tuned unless you have a good reason for it

Fine-tuning in most MSSMs

maybe strings ? (see Aparicio, Cerdeno, Ibanez, 2012)

Arbey et al 2012



$$\sim (A_t - \mu \cot\beta)/m_{\tilde{t}}$$

Quick estimate of the degree fine-tuning

$$v^2 = \frac{-m^2}{\lambda}$$

m^2 contains several contributions (depending on the BSM scenario)

Take the largest one, say $\tilde{m}^2$

Then, the fine-tuning (degree of cancellation) is

$$c = \frac{\tilde{m}^2}{m^2} = \frac{\tilde{m}^2}{\lambda v^2} = 2\frac{\tilde{m}^2}{m_h^2}$$

In the MSSM, for non-small tan β, $m^2 \simeq m_{H_u}^2 + \mu^2$

$$\Rightarrow \quad c \simeq 2\frac{\mu^2}{m_h^2}$$

This approximately coincides with the Barbieri-Giudice definition:

$$\frac{\Delta v^2}{v^2} \simeq c\frac{\Delta\theta}{\theta}$$

For $m_{\tilde{t}} \sim 3 \text{ TeV}$ ⟶ $c \sim 100$

i.e. SUSY is fine-tuned at ~ 1%

Is the CMSSM, or even the general MSSM, dead ??

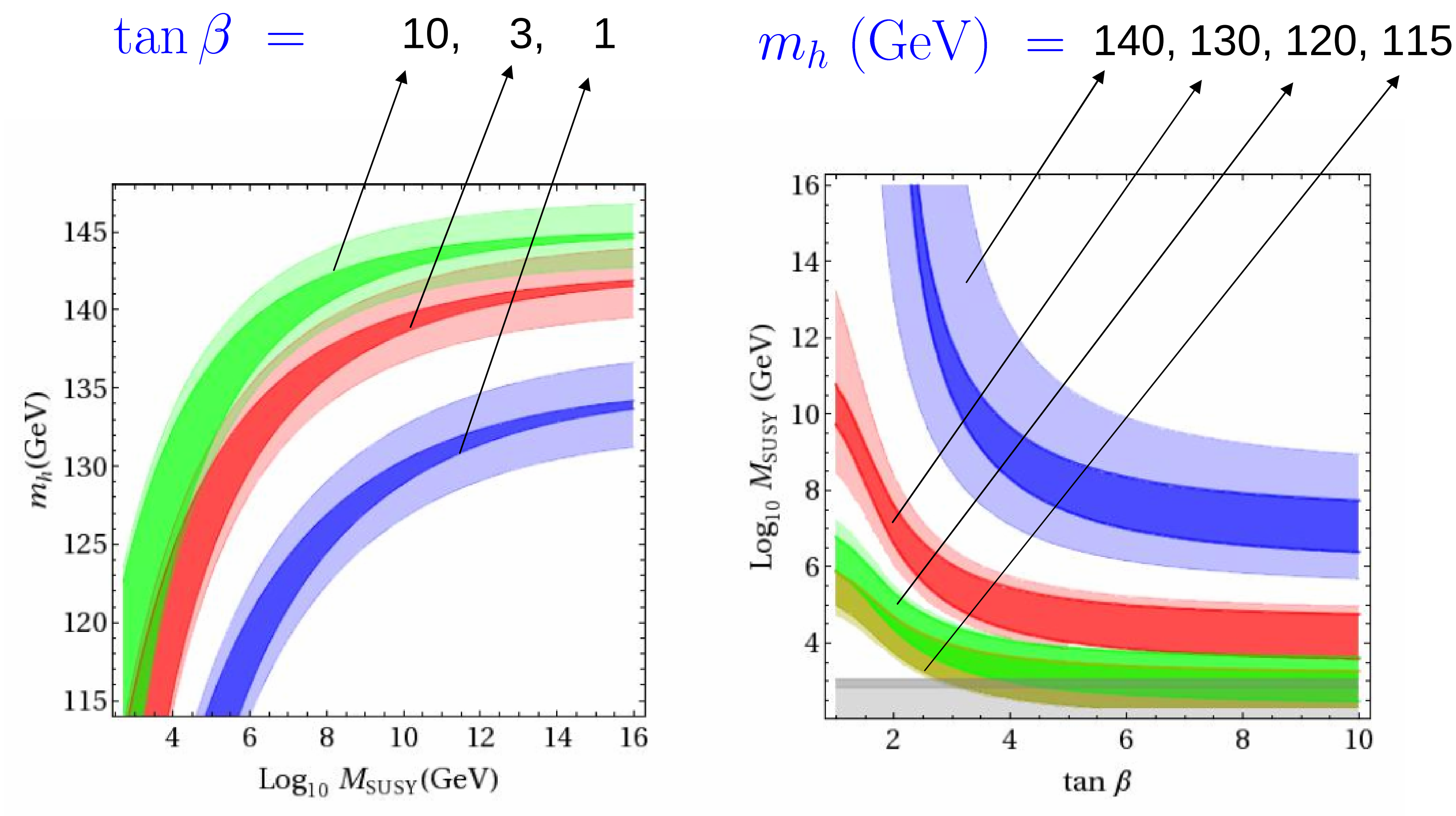
(Parenthesis.....

We have used that

Lower bounds on m_h ⟹ Lower bounds on M_{SUSY}

But the reverse is also true:

Upper bounds on m_h ⟹ Upper bounds on M_{SUSY}



Cabrera, JAC, Delgado 2011

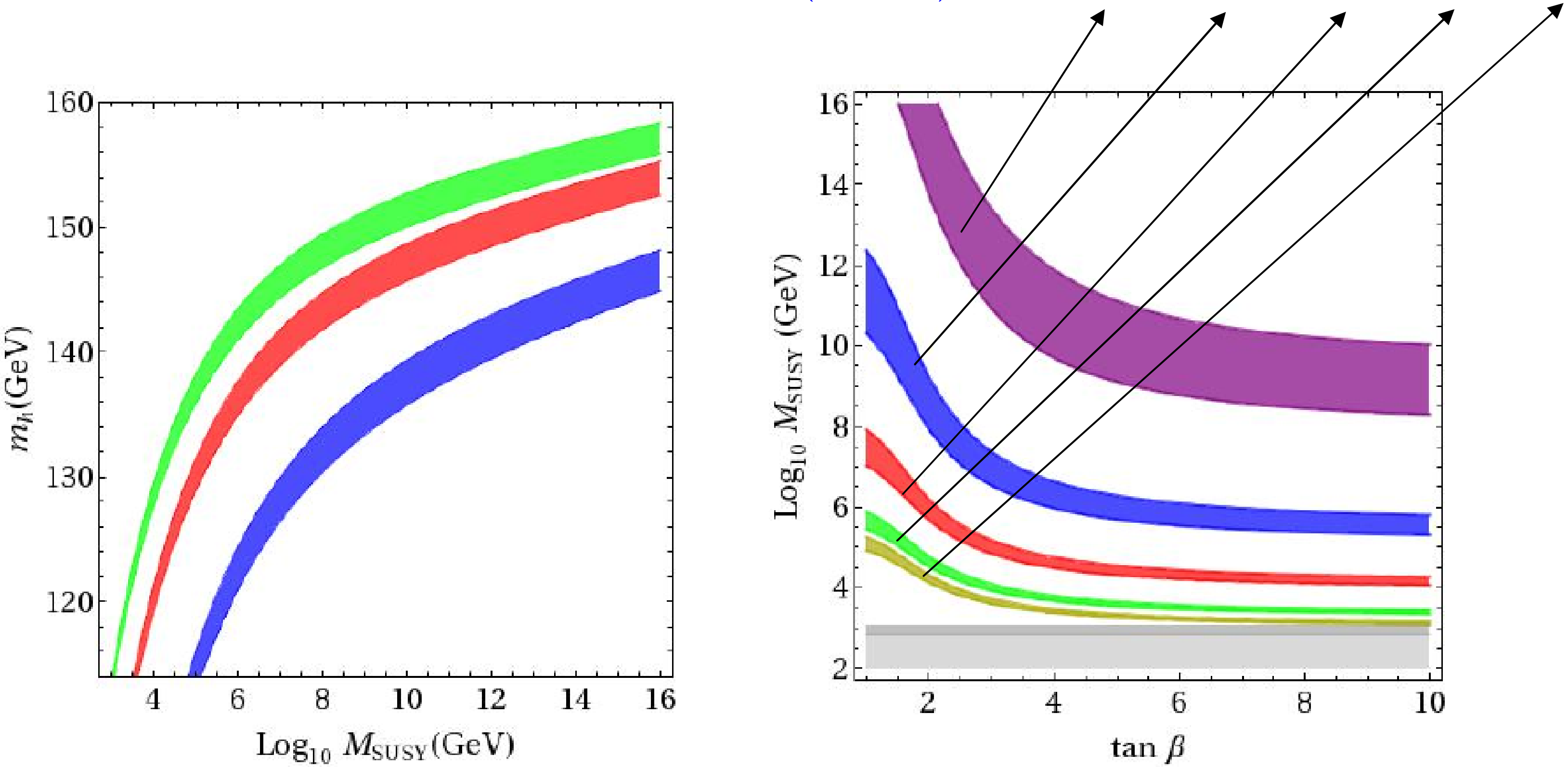
E.g.

$$m_h < 130 \text{ GeV} \;\Rightarrow\; M_{\text{SUSY}} < 10^{12} \text{ GeV}$$

Implications for Landscape considerations

Relevant example: Split SUSY

$$m_h \text{ (GeV)} \; = \;$$ 150, 140, 130, 120, 115



$$m_h < 130 \text{ GeV} \;\Rightarrow\; M_{\text{SUSY}} < 10^8 \text{ GeV}$$

....Parenthesis)

For $m_{\tilde{t}} \sim 3$ TeV ⟶ $c \sim 100$

i.e. SUSY is fine-tuned at ~ 1%

Is the CMSSM, or even the general MSSM, dead ??

We can be more precise about the situation and prospects of the CMSSM by performing

Global fits of the CMSSM

≡ Use all availble exp. information (dominated by LHC) to show favoured/disfavoured regions in the CMSSM parameter space

⤷ Frequentist approach

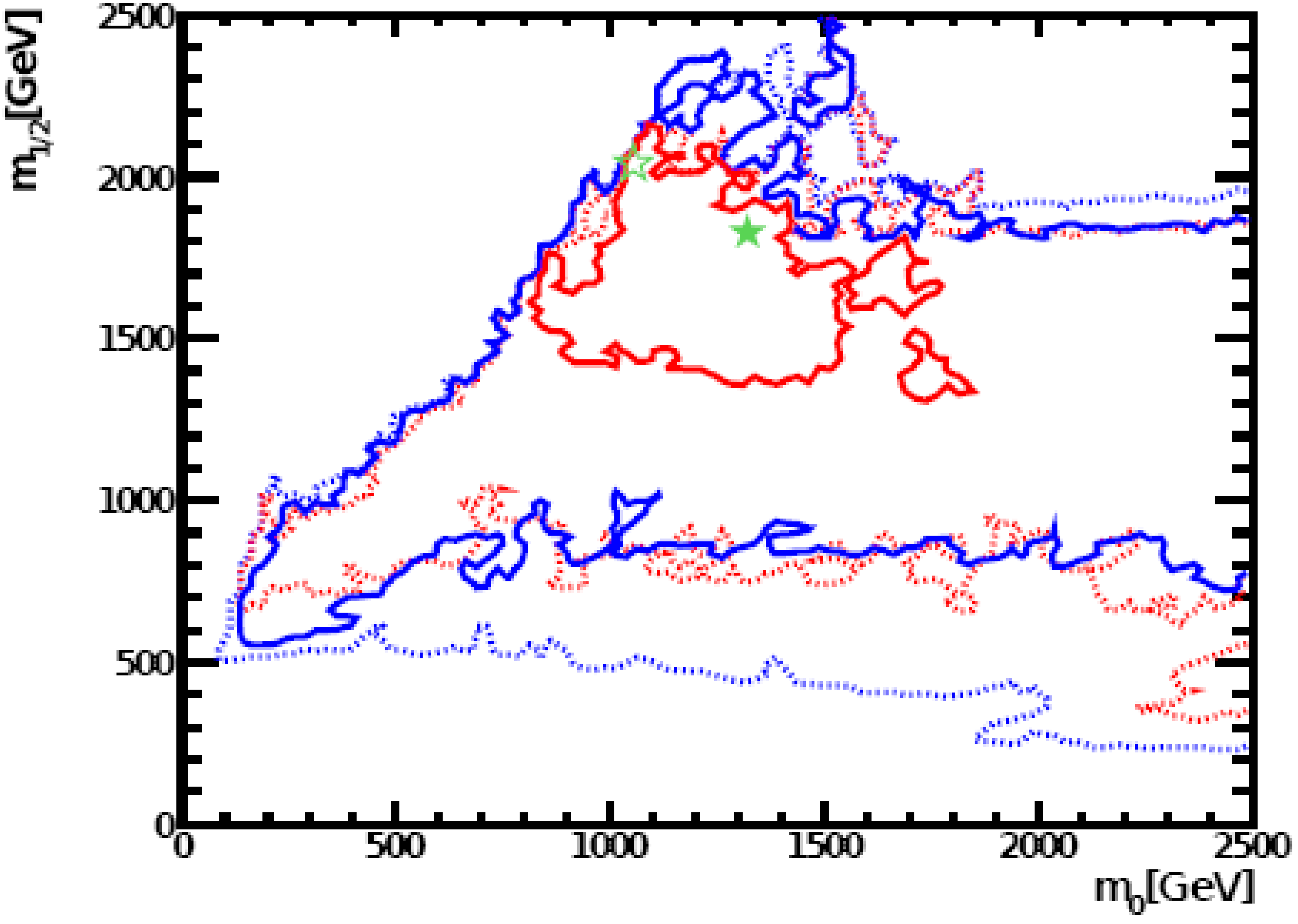
⤷ Bayesian approach

(these types of analysis can be followed for any BSM scenario, not only CMSSM)

Frequentist approach

Scan the parameter space of the CMSSM (or whatever model), evaluating the likelihood (based on the χ^2)

This leads to zones of estimated probability (inside contours of constant χ^2) around the best fit points in the parameter space.



68%
95%
68% before Higgs signal
95% before Higgs signal

Buchmueller et al. 2012

Bayesian approach

- ★ Given a model, defined by: θ_i
- ★ And some Exp. data ,

you evaluate, using the Bayes Theorem, the probability density in the parameter space

$$p(\theta_i|\mathrm{data})$$

Bayesian approach

Posterior (pdf)

Likelihood ($\mathcal{L}$)

prior

$$p(\theta_i|\text{data}) = \frac{p(\text{data}|\theta_i)\ p(\theta_i)}{p(\text{data})}$$

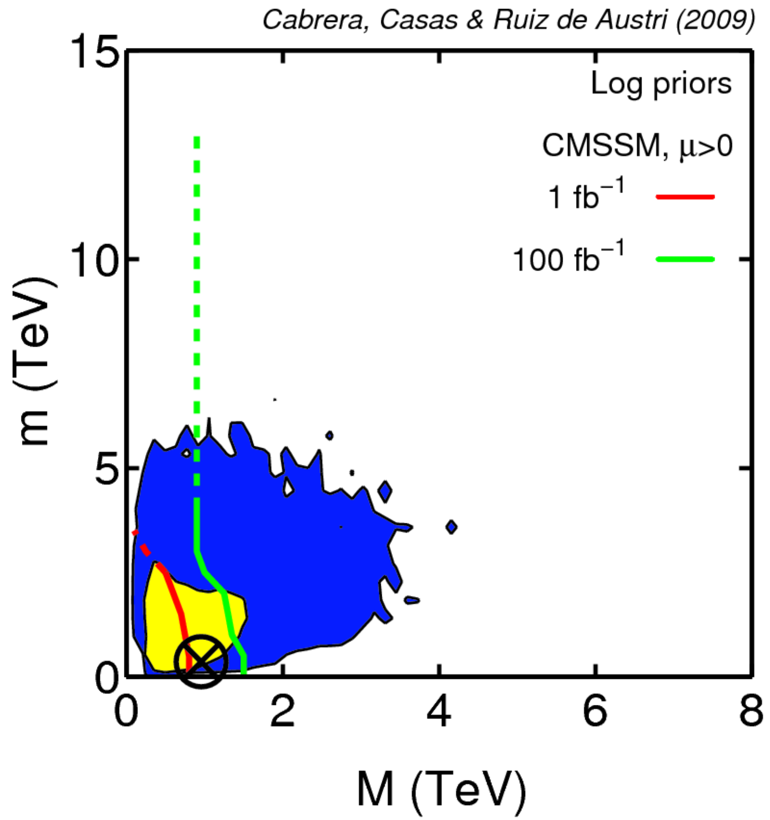
parameters of the model

norm. constant

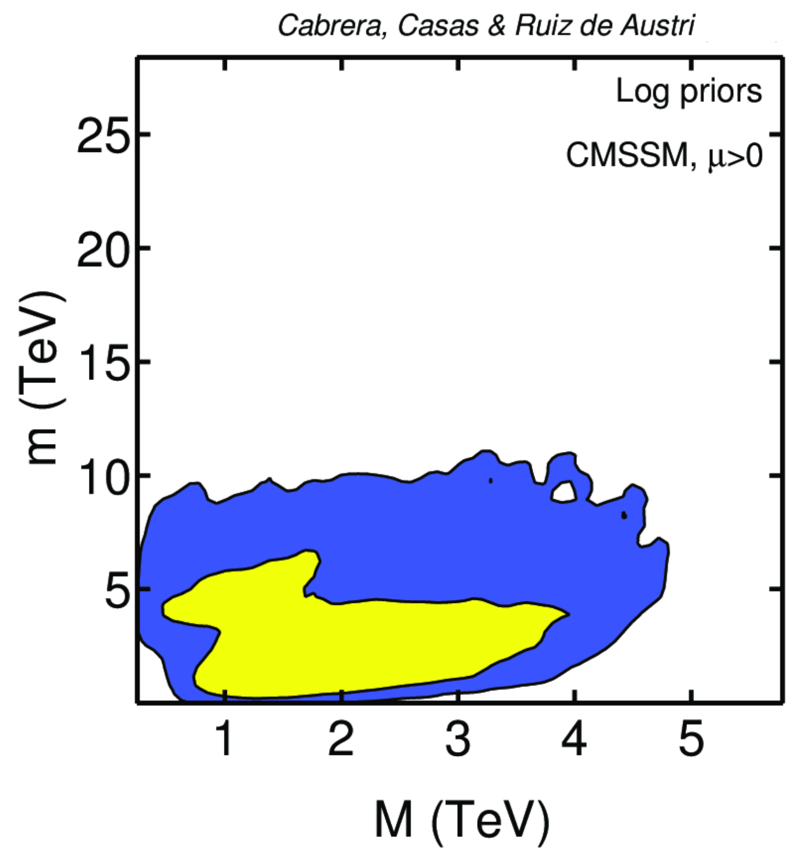
Posterior: our state of knowledge about θ_i after we have seen the data

Likelihood: probability of obtaining the data if θ_i are true

Prior: what we know about θ_i before seeing the data



$m_h \geq 114$ GeV



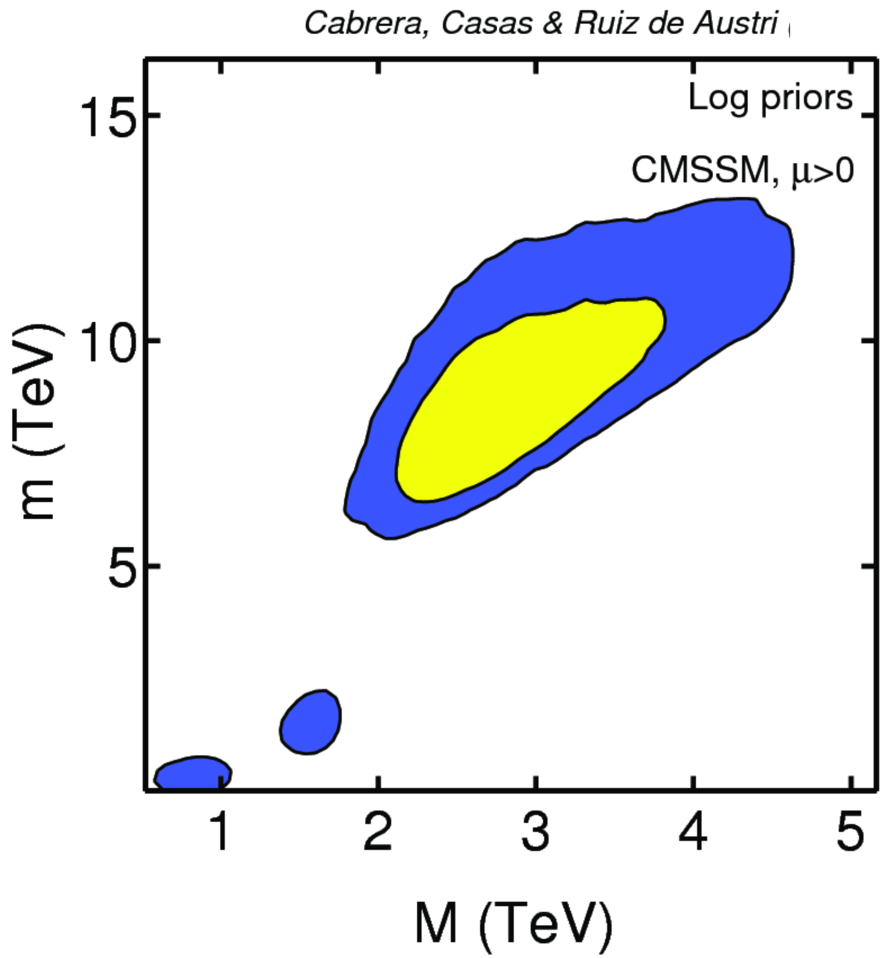
$m_h \simeq 125$ GeV

68%

95%

preliminar

After including DM constraints



Not only the CMSSM is fine-tuned at ~1%, but even if the model is true, the chances to be discovered at the LHC are decreasing dramatically.

Some questions

★ To which extent the problems of CMSSM remain in general MSSMs ?

★ Are there natural way-outs (maybe beyond MSSM) ?

(Frequentist vs Bayesian approaches

Frequentist

- Based just on the likelihood: $p(\mathrm{data}|\theta_i)$
- It does not give $p(\theta_i|\mathrm{data})$
- It does not penalize fine-tunings

Bayesian

- Based on the likelihood $p(\mathrm{data}|\theta_i)$ and the prior $p(\theta_i)$
- It does give $p(\theta_i|\mathrm{data})$
- It does penalize fine-tunings

Since naturalness arguments are deep down statistical arguments, one might expect that an effective penalization of fine-tunings arises from the Bayesian analysis itself.

...and this is really what happens.

Cabrera, Ruiz de Austri, J.A.C. 09

Method:

Instead solving μ^2 in terms of M_Z and the other soft terms and, treat M_Z as another exp. data

☆ Approximate the likelihood as

$$\mathcal{L} = N_Z \, e^{-\frac{1}{2}\left(\frac{M_Z - M_Z^{\rm exp}}{\sigma_Z}\right)^2} \mathcal{L}_{\rm rest}$$

$$\simeq \delta(M_Z - M_Z^{\rm exp}) \, \mathcal{L}_{\rm rest}$$

Likelihood associated to the other observables

★ Use M_Z to marginalize μ

$$p(s,m,M,A,B|\,\mathrm{data}) = \int d\mu\; p(s,m,M,A,B,\mu|\mathrm{data})$$
$$\simeq \mathcal{L}_{\mathrm{rest}} \left[\frac{d\mu}{dM_Z}\right]_{\mu_Z} p(s,m,M,A,B,\mu_Z)\ .$$

$$p(s,m,M,A,B|\,\mathrm{data}) = 2\,\mathcal{L}_{\mathrm{rest}}\,\frac{\mu_Z}{M_Z}\,\frac{1}{c_\mu}\,p(s,m,M,A,B,\mu_Z)$$

fine-tuning

penalization !

In practice you pick up a Jacobian factor:

$$\{\mu, y_t, B\} \xrightarrow{\;\boldsymbol{J}\;} \{M_Z, m_t, \tan\beta\}$$

$$J = \left[\frac{E}{R_\mu^2}\right] \frac{y}{y_{\rm low}} \frac{t^2-1}{t(1+t^2)} \frac{B_{\rm low}}{\mu_Z}$$

model-independent part !

- It contains the fine-tuning penalization
- It penalizes large tan β
- It applies to any MSSM (not just CMSSM)

)

Not only the CMSSM is fine-tuned at ~1%, but even if the model is true, the chances to be discovered at the LHC are decreasing dramatically.

Some questions

- ★ To which extent the problems of CMSSM remain in general MSSMs ?

- ★ Are there natural way-outs (maybe beyond MSSM) ?

Original motivations for the CMSSM

- *Minimal CP and Flavour violation*
- *Simplicity (-> universality in the soft terms)*
- *~ arises in some theoretically motivated scenarios (e.g. minimal SUGRA or Dilaton-dominated SUSY)*

Only the first one is robust

⤷

Going beyond CMSSM is very plausible

⤷

Does it solve the problems of the CMSSM?

Going beyond CMSSM

Some present directions:

- ***Promote CMSSM → pMSSM***

  Definition of pMSSM: no new CP phases, flavor-diagonal sfermion mass matrices and trilinear couplings,1st/2nd generation degenerate and A-terms negligible, lightest neutralino is the LSP. (19 parameters)

- ***This includes the possibility of a lighter 3rd generation***

- ***Also certain types of spectrum that can evade detection at LHC:***

  - Heavy LSP
  - "Squashed spectrum"

  } small p_T s

Note however that

★ The 3rd generation cannot be too light (for m_h=125 GeV)

→ fine-tuning

...unless you have a large enough tree-level m_h

⇒ go beyond MSSM
- Low-scale ~~SUSY~~
- NMSSM and similar

★ Arrange the SUSY spectrum to fool LHC is possible, but it sounds artificial

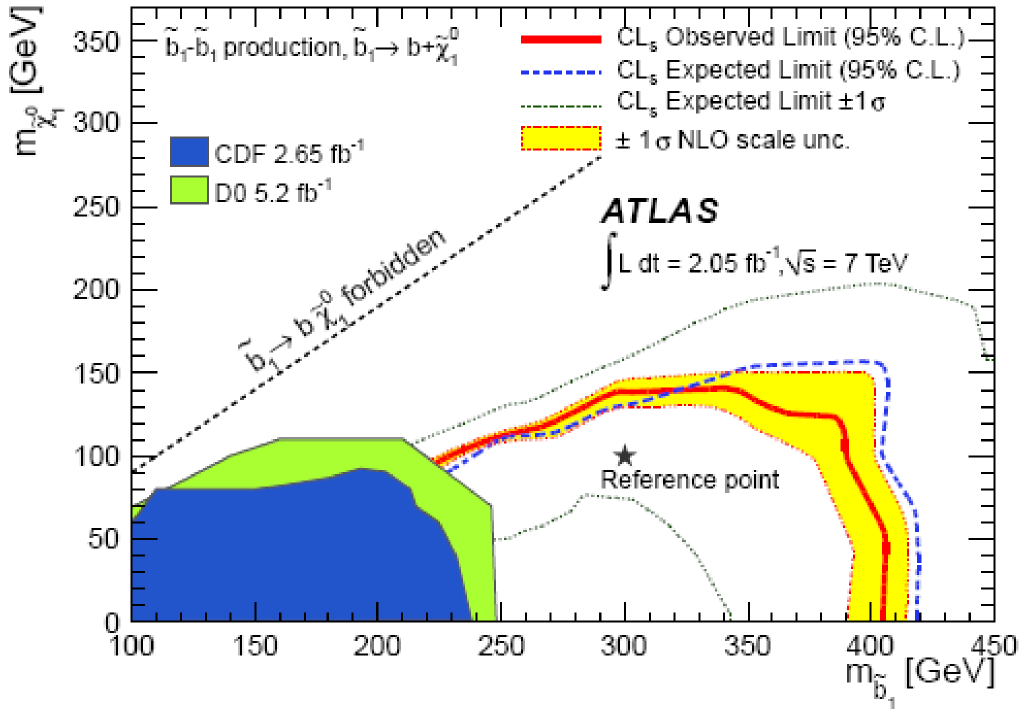
All this represents new challenges for the data analysis:

- ★ Test pMSSM
- ★ Test a light 3rd generation
- ★ Test “Squashed Spectrum” or heavy LSP
- ★ Detect heavy SUSY

Search for a light 3rd generation

Look for direct stop or sbottom pair production or through gluino decays

$$m_{\tilde{t}}, m_{\tilde{b}} \lesssim 400 \text{ GeV}$$



⇒ Still plenty of room for a 3rd generation

Test a “Squashed Spectrum” or heavy LSP

The study of events with ET + jets + multileptons may play a crucial role to test these scenarios

Detect heavy SUSY (heavy squarks and gluino)

- Look in alternative channels, like chargino/neutralino.

- Design new kinematic variables

etc.

Simplified model interpretation

This is an effective strategy to interpret the exp results without using a particular scenario (like CMSSM)

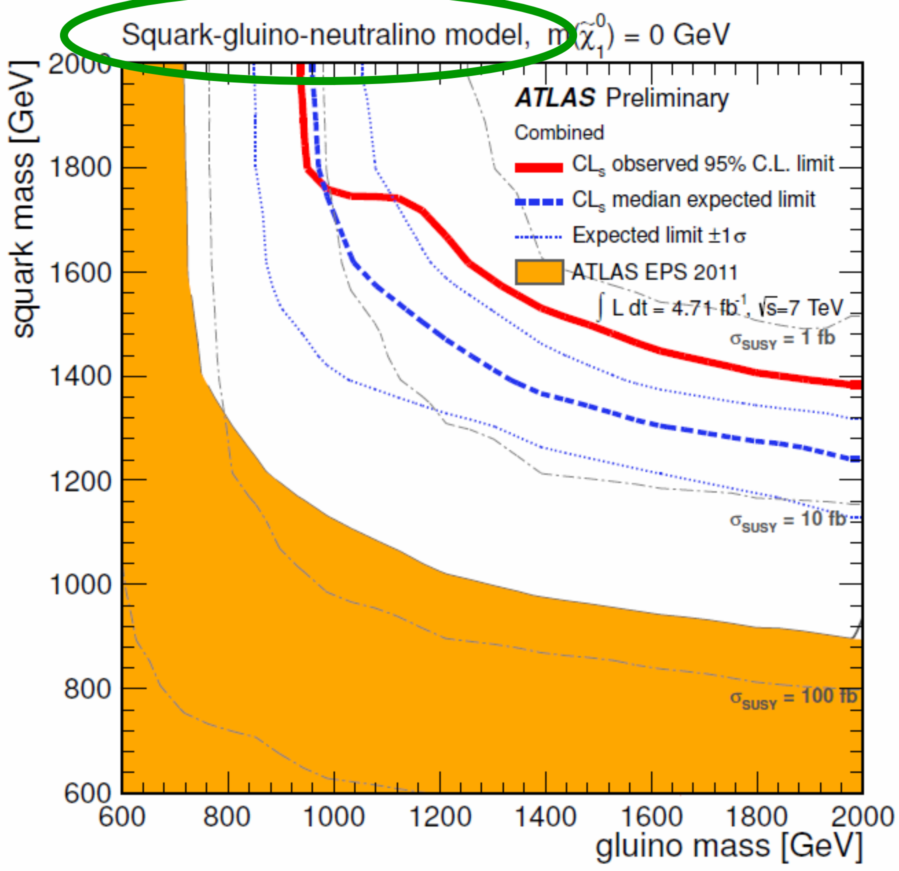
A simplified model is defined by an effective Lagrangian describing the interactions of a small number of new particles.

Simplified models can equally well be described by a small number of masses and cross-sections. These parameters are directly related to collider physics observables, making simplified models a particularly effective framework for evaluating searches (...) of new physics.

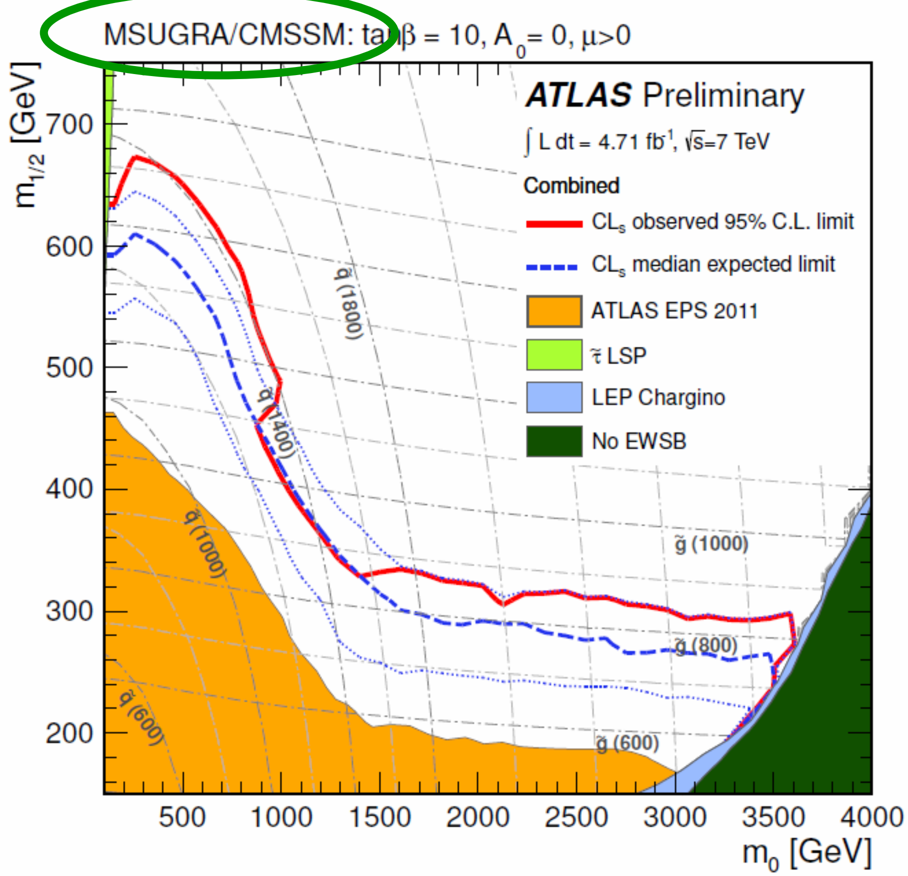
D. Alves et al, arXiv:1105.2838

E.g. direct squark or gluino decays $\tilde{q} \longrightarrow q\chi_1^0$ $\tilde{g} \longrightarrow q\bar{q}\chi_1^0$

are dominant if all the other masses have multi-TeV values. Of course additional complexity can be built in.



Squark-gluino-neutralino model, $m(\tilde{\chi}_1^0)$ = 0 GeV
ATLAS Preliminary
Combined
CL_s observed 95% C.L. limit
CL_s median expected limit
Expected limit ±1σ
ATLAS EPS 2011
$\int L\,dt$ = 4.71 fb^{-1}, $\sqrt{s}$=7 TeV
σ_{SUSY} = 1 fb
σ_{SUSY} = 10 fb
σ_{SUSY} = 100 fb
squark mass [GeV]
gluino mass [GeV]
600
800
1000
1200
1400
1600
1800
2000



MSUGRA/CMSSM: tanβ = 10, A_0= 0, μ>0
ATLAS Preliminary
$\int L\,dt$ = 4.71 fb^{-1}, $\sqrt{s}$=7 TeV
Combined
CL_s observed 95% C.L. limit
CL_s median expected limit
ATLAS EPS 2011
$\tilde{\tau}$ LSP
LEP Chargino
No EWSB
$\tilde{q}$ (1800)
$\tilde{q}$ (1400)
$\tilde{q}$ (1000)
$\tilde{q}$ (600)
$\tilde{g}$ (1000)
$\tilde{g}$ (800)
$\tilde{g}$ (600)
$m_{1/2}$ [GeV]
m_0 [GeV]
200
300
400
500
600
700
500
1000
1500
2000
2500
3000
3500
4000

Concerning other BSM scenarios (Extra Dimensions, 4th generation, etc.), LHC is already putting impressive constraints in most of them, through especialized searches.

But, there is another way to explore NP without relying on particular scenarios

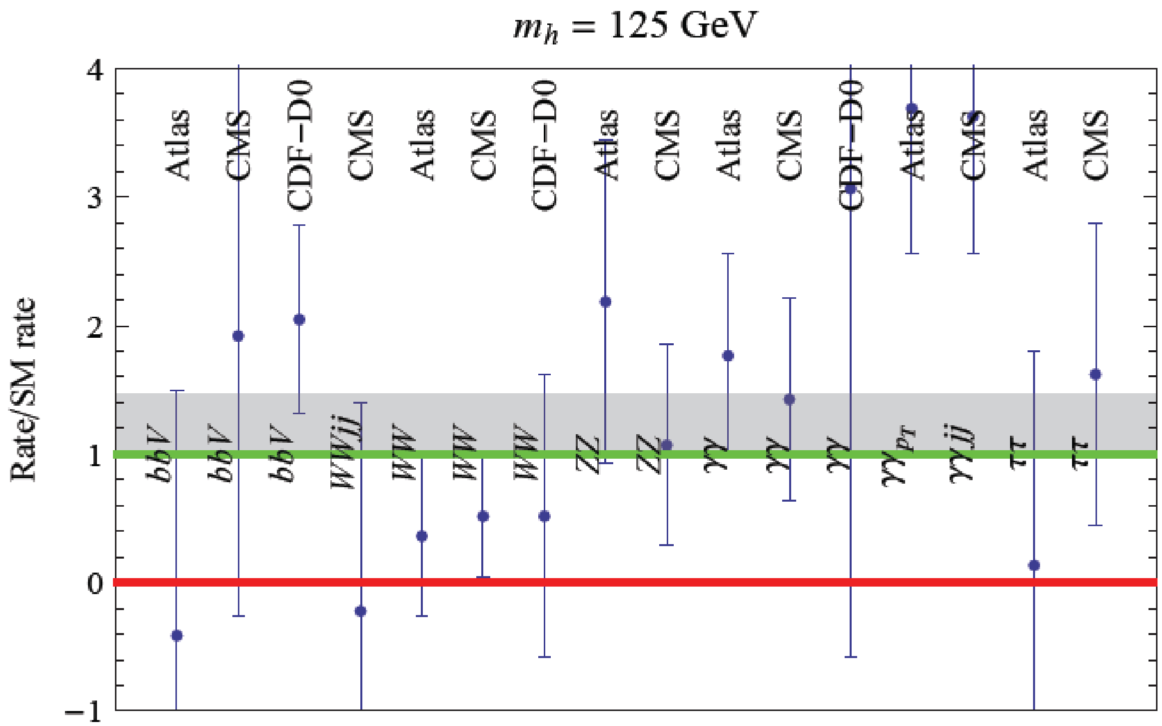
... look for fingerprints in the effective theory (indirect searches)

In the past:

(LEP) EW precision tests ⟶ Bounds on NP

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \underbrace{\rm Higher-Dim\ Operators}_{\rm NP}$$

The idea is to use the information about the Higgs couplings, from data on Higgs production and decay, to constrain (or detect) BSM operators involving the Higgs, in a way as mod-indep as possible.



Of course the data are still inconclusive

But there are already groups exploring, under the assumption of a Higgs at 125 GeV, how the present data shed any light on NP.

Assuming: 1 light Higgs-like mode + no FCNC + MFV

$$\mathcal{L}^{(2)} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D^\mu\Sigma\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \cdots\right)$$
$$- \frac{v}{\sqrt{2}}\lambda^u_{ij}\,\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(u^{(i)}_R, 0\right)^T\left(1 + c_u\,\frac{h}{v} + c_{2u}\,\frac{h^2}{v^2} + \cdots\right) + h.c.$$
$$- \frac{v}{\sqrt{2}}\lambda^d_{ij}\,\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(0, d^{(i)}_R\right)^T\left(1 + c_d\,\frac{h}{v} + c_{2d}\,\frac{h^2}{v^2} + \cdots\right) + h.c.$$
$$- \frac{v}{\sqrt{2}}\lambda^l_{ij}\,\left(\bar{\nu}^{(i)}_L, \bar{l}^{(i)}_L\right)\Sigma\left(0, l^{(i)}_R\right)^T\left(1 + c_l\,\frac{h}{v} + c_{2l}\,\frac{h^2}{v^2} + \cdots\right) + h.c.$$

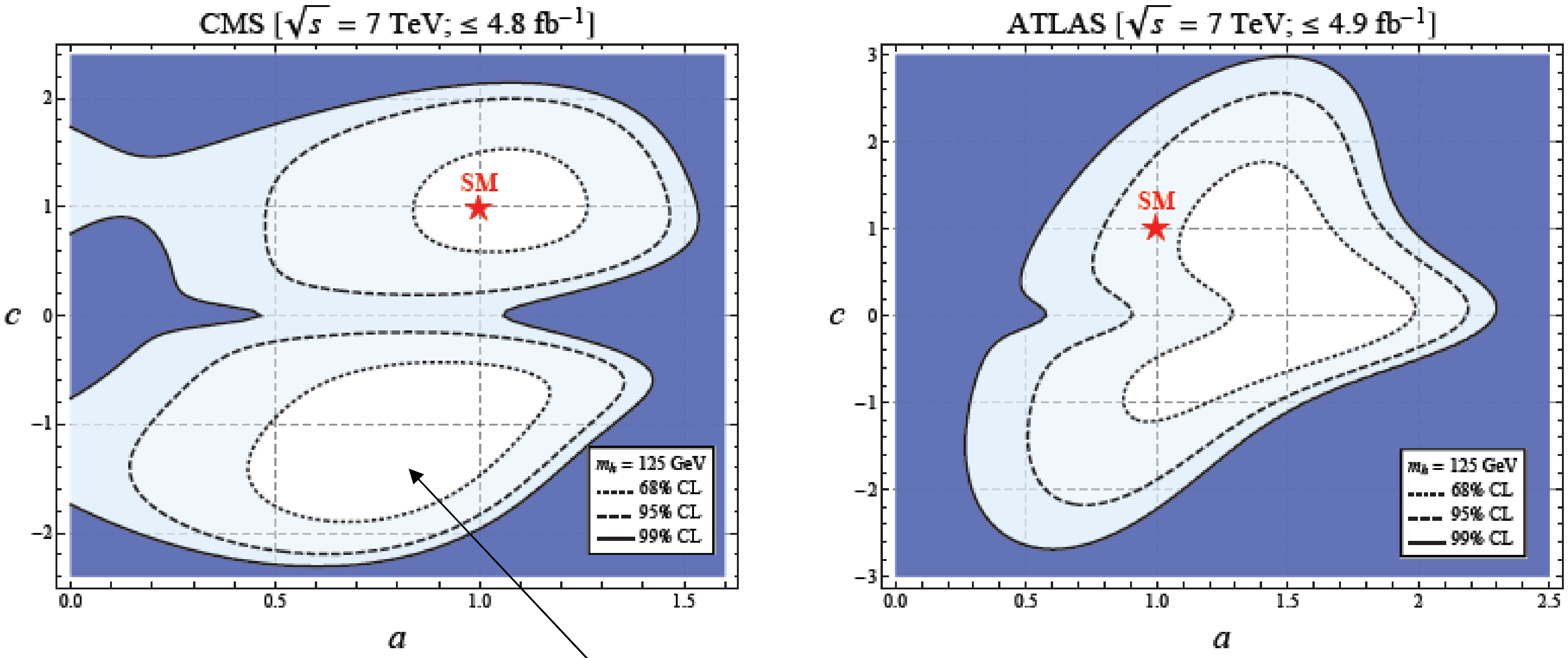
Contino et al.; Espinosa et al.; Strumia et al.; Elis et al.; Falkowski et al. ....

Simplifying assumption: $c_d = c_u = c_l \equiv c$

& neglect higher orders:

$\{c, a\} \equiv$ NP parameter space

$c = a = 1 \equiv$ SM



"favoured"

The reason is that $BR(h \to \gamma\gamma) \sim |1.8c - 8.3a|^2$

⇨ Excess in $\gamma\gamma$ described by negative c

CONCLUSIONS

- LHC is constraining BSM physics at an impressive efficience
- No sign of NP yet
- SUSY (and other NP scenarios) are starting to be in trouble
- New challenges to optimize the LHC discovery potential
- Direct and indirect searches can play complementary roles