Discovery prospects of supersymmetry

Csaba Balázs
Centre of Excellence for Particle Physics and
Monash Centre for Astrophysics, Melbourne

“Supersymmetry has stood the test of time.
There is still no evidence for supersymmetry.”

Bruno Zumino

Supersymmetric models

Supersymmetry accommodates various models, depending on assumptions about

- particle content: MSSM, NMSSM, sMSSM…
- gauge group: SU(3)xSU(2)xU(1), SU(5), flipSU(5), SU(7), SO(10), E_6…
- symmetries of superpotential: R-symmetry, R-parity, Z_n…
- supersymmetry breaking mechanism: SuGra, AMSB, GMSB, inoMSB…

Example: MSSM = standard superfields, standard gauge group, typically w/ R-parity, no specific SSB mechanism

$$W_{\rm MSSM} = \overline{u}\mathbf{y_u} Q H_u - \overline{d}\mathbf{y_d} Q H_d - \overline{e}\mathbf{y_e} L H_d + \mu H_u H_d$$

mSuGra & CMSSM

MSSM soft supersymmetry breaking terms

$$\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} \;=\; & -\frac{1}{2}\left(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - (b H_u H_d + \text{c.c.})\,.
\end{aligned}$$

Minimal Super-Gravity inspired model: CMSSM

$$M_3 = M_2 = M_1 = m_{1/2},$$

$$\mathbf{m^2_Q} = \mathbf{m^2_{\overline{u}}} = \mathbf{m^2_{\overline{d}}} = \mathbf{m^2_L} = \mathbf{m^2_{\overline{e}}} = m_0^2\,\mathbf{1}, \qquad m^2_{H_u} = m^2_{H_d} = m_0^2,$$

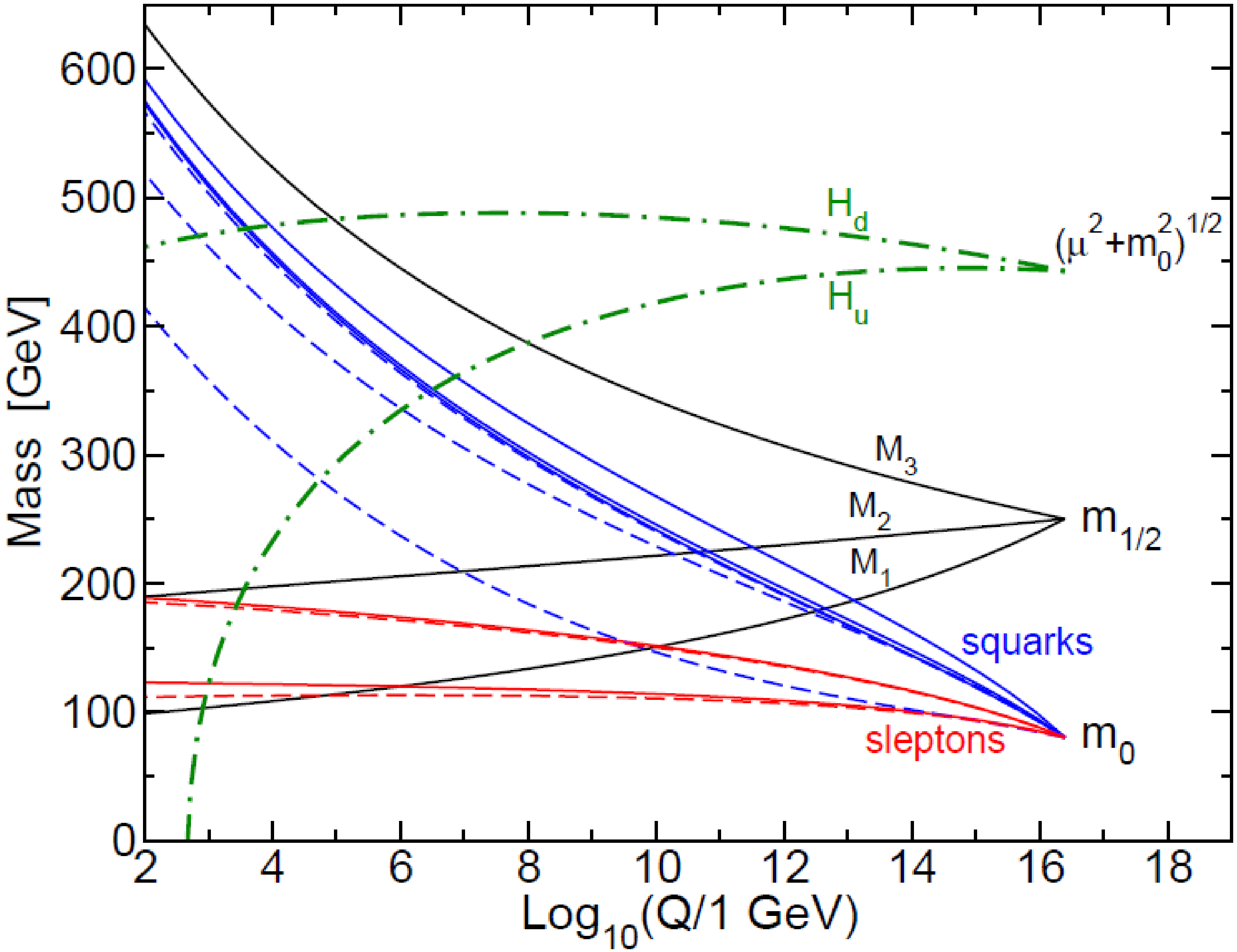
$$\mathbf{a_u} = A_0 \mathbf{y_u}, \qquad \mathbf{a_d} = A_0 \mathbf{y_d}, \qquad \mathbf{a_e} = A_0 \mathbf{y_e},$$

$$b = B_0 \mu,$$

Parameter space: $P = \{M_0, M_{1/2}, A_0, \tan\beta, \text{sign}\mu\}$

mSuGra & CMSSM

Given M_0, $M_{1/2}$, A_0 at M_{GUT} the ‘spectrum’ of superpartner masses and couplings can be calculated via RGE evolution



Supersymmetric models

Supersymmetry isn't probed directly by our experiments.

We test supersymmetric models,
with many more assumptions than just SUSY.

Supersymmetry discovery

Is supersymmetry a beautiful model or tough reality?

To answer this question we need experimental data!

Supersymmetry discovery

The most promising experimental probes of supersymmetry:

- Higgs sector, especially the lightest Higgs

  MSSM: 2 CP even neutral Higgses: h, H

  1 CP odd neutral Higgs: A

  2 charged Higgses: $H^{\pm}$

- superpartners, especially the lightest superpartner (LSP)

  mSuGra: LPS is lightest neutralino

  a bino/wino/higgsino admixture

- rare decays: $b \to s\gamma$, $B_s \to \mu^+\mu^-$, $B^+ \to \tau^+\nu_\tau$…

- precision measurements: $g_\mu - 2$, $sin^2\theta_W$, m_Z, m_W,

  ρ parameter…

Lightest Higgs in MSSM

Lightest Higgs mass at tree level:

$$m_{h^0} \; < \; m_Z |\cos(2\beta)|$$

1-loop corrections to lightest Higgs mass (small stop mix):

$$\Delta(m^2_{h^0}) = \frac{3}{4\pi^2} \cos^2\alpha \;\; y_t^2 m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2} / m_t^2\right)$$

as a result:

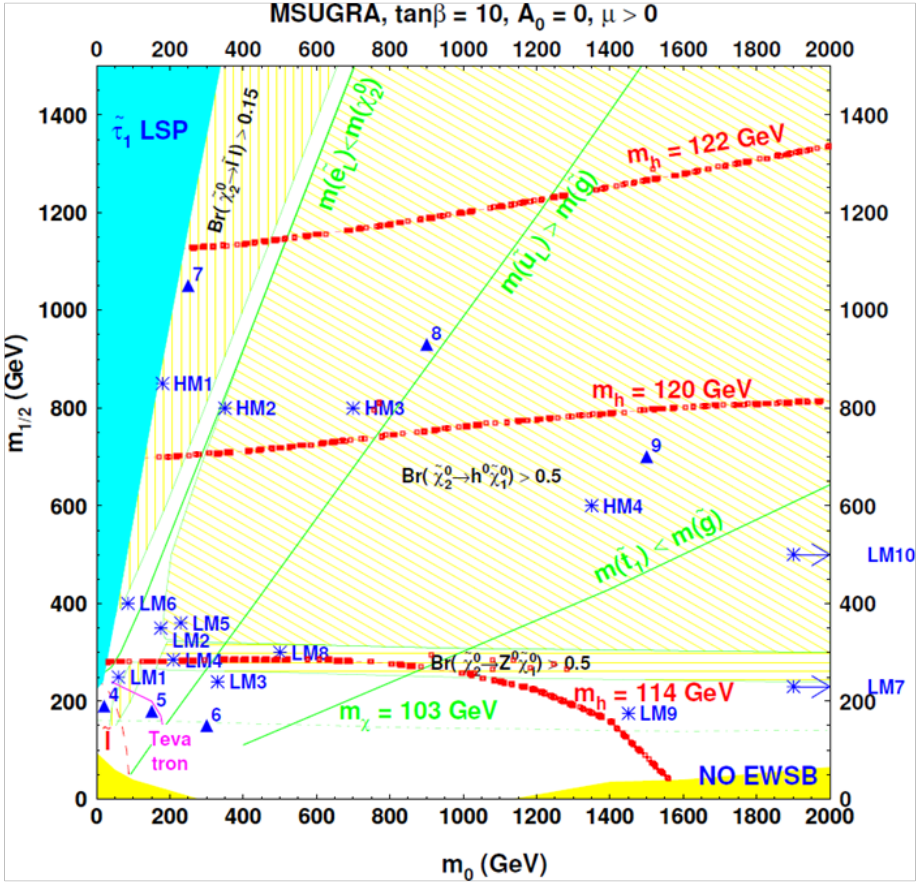
$$m_{h^0} \;\lesssim\; 135\,\text{GeV}$$

With additional supermultiplets, all superpartners below 1 TeV and all couplings remaining perturbative up to M_{GUT}

$$m_{h^0} \;\lesssim\; 150\,\text{GeV}$$

Lightest Higgs in mSuGra

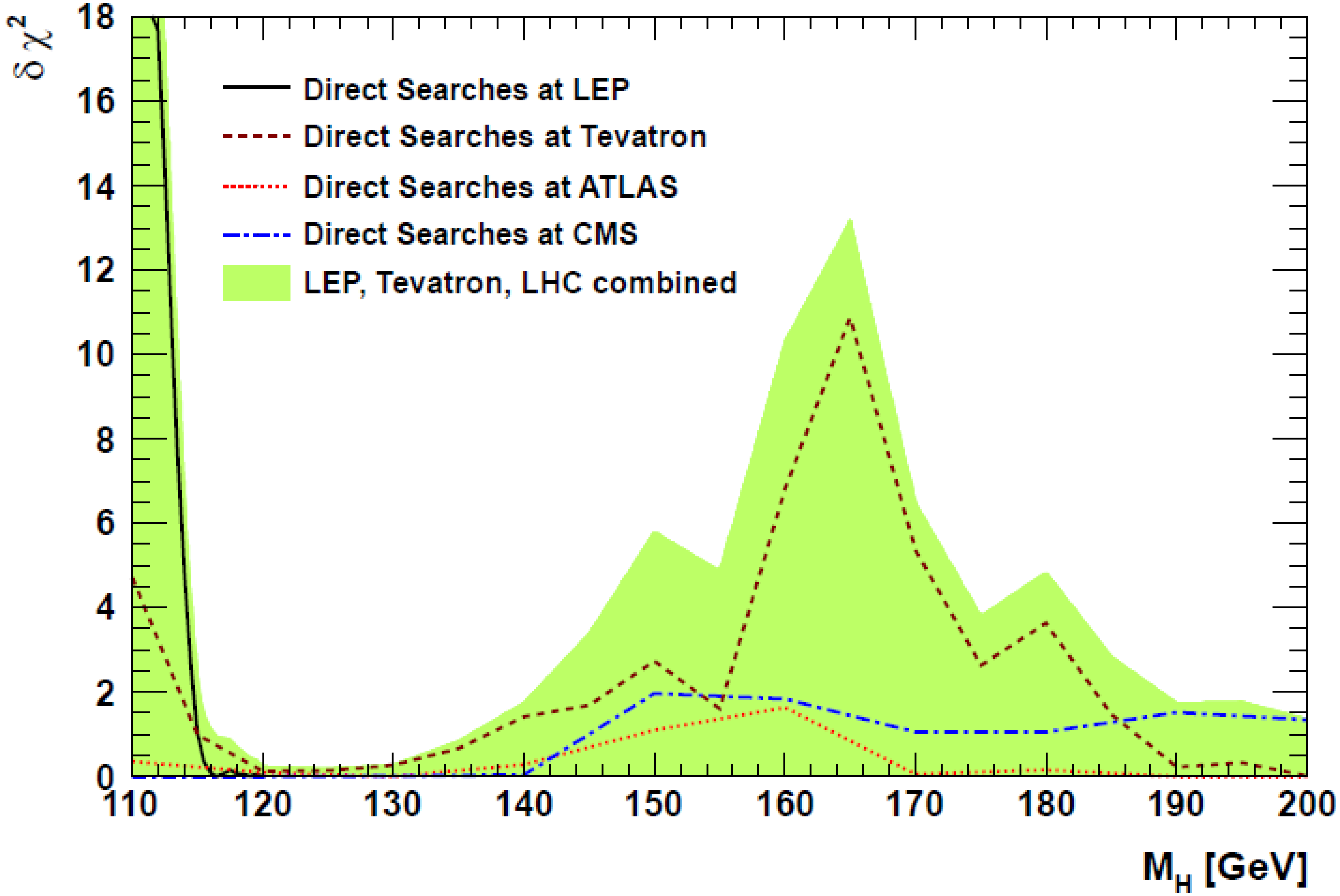
Fixing the lightest Higgs mass severely constrains mSuGra



In most mSuGra parameter space the lightest Higgs is standard model like

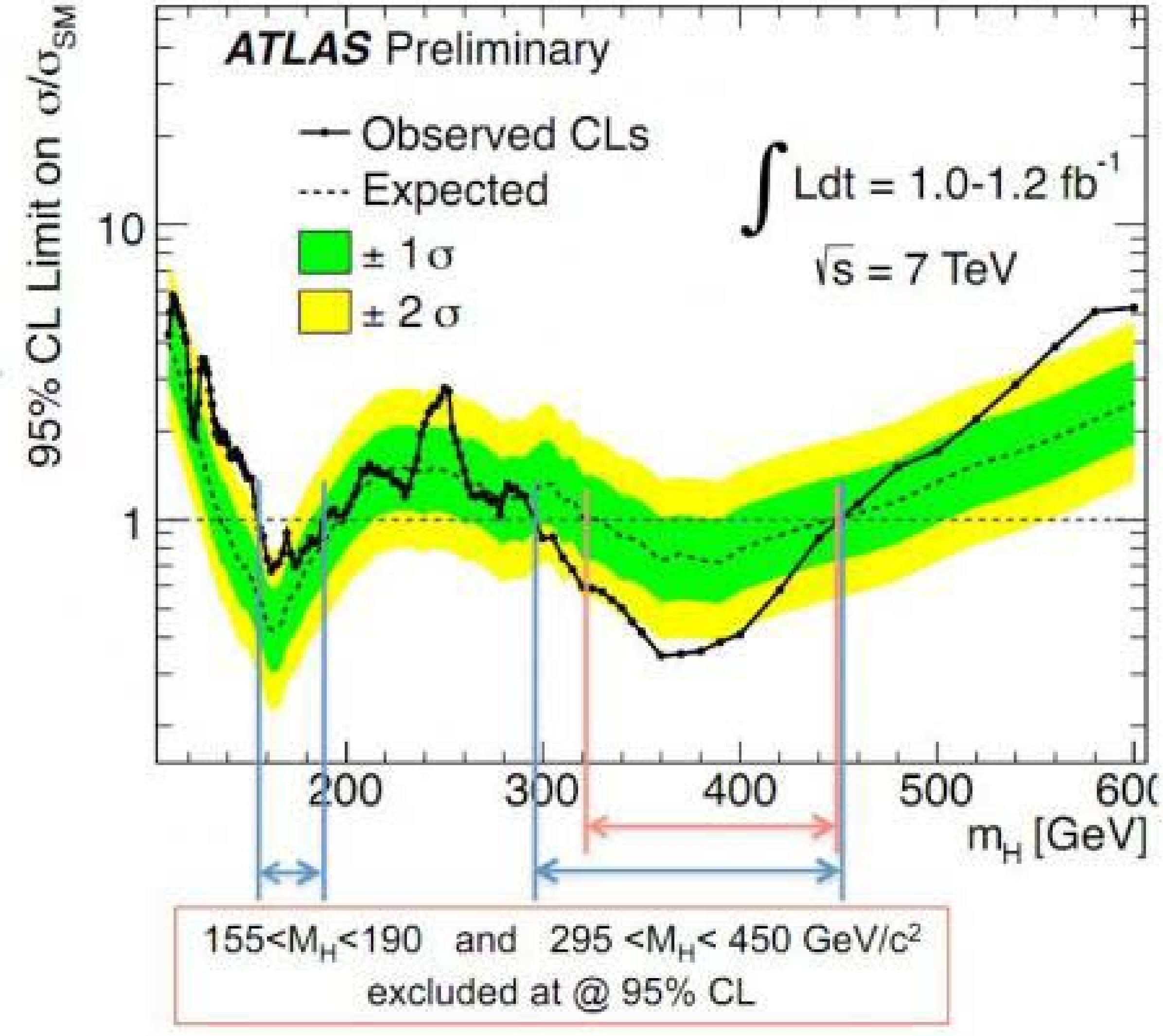
Lightest Higgs searches

The LHC will find/exclude a standard model like Higgs up to almost 1 TeV! The status of SM-like Higgs searches:



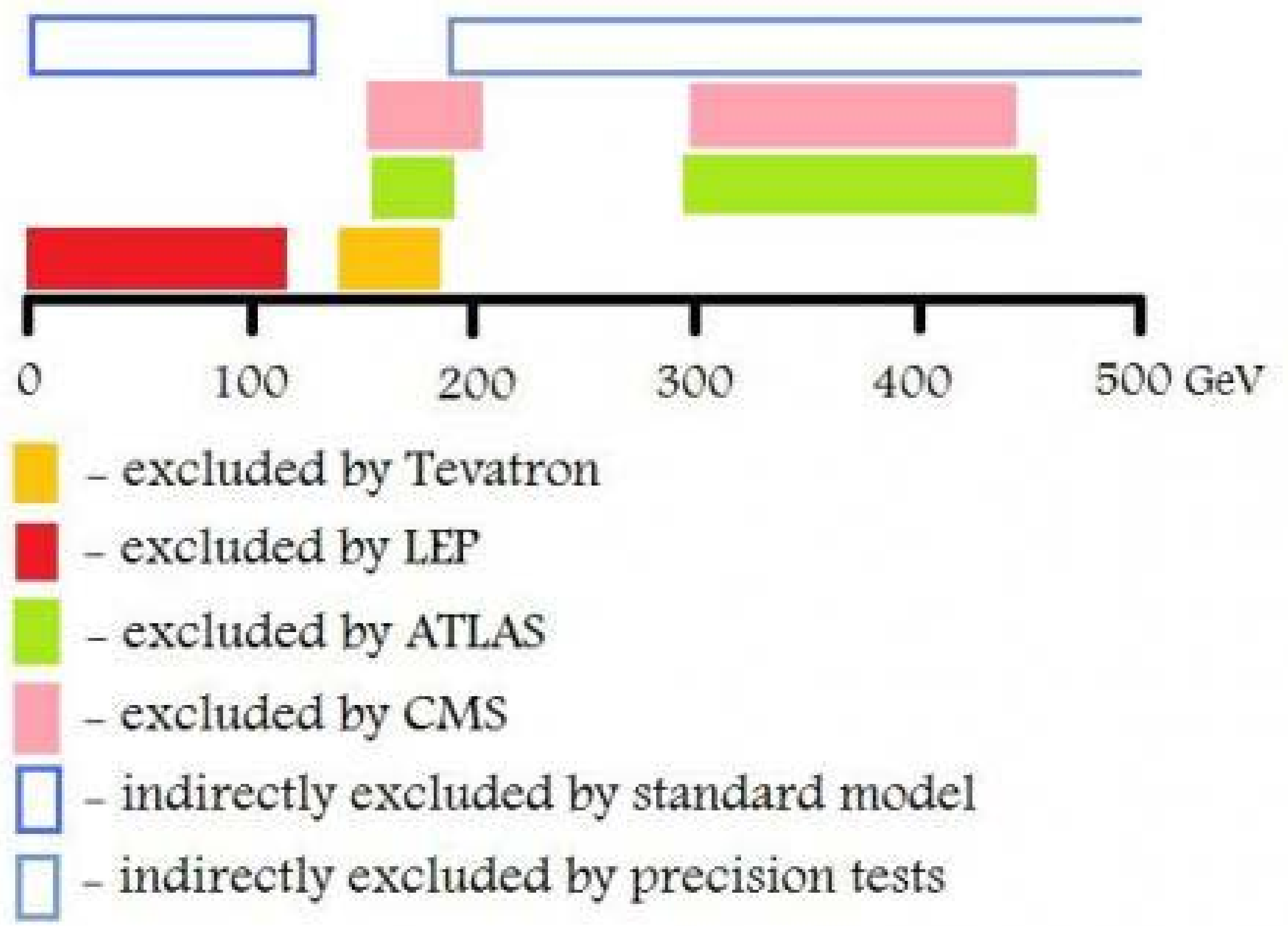
Lightest Higgs searches

Update from two days ago (also talk by R. Hirosky):



Lightest Higgs searches

Unofficial 'summary' from http://blog.vixra.org/:



Strong preference for MSSM! Maybe Gordy was right?

Higgs search drawback

Discovery of one or even several Higgs bosons does not prove the existence of supersymmetry

- for example: a two Higgs doublet standard model (2HDM) can exist without supersymmetry

The discovery of *superpartners* would provide a the clear evidence for supersymmetry.

Superpartner searches

Collider searches for superpartners

Limits …

You know what: see talk by F. Le Diberder

The lightest superpartner

Most superpartner masses may be out of the LHC's reach

- example: split-SUSY

But the lightest superpartner should be below 1-2 TeV otherwise supersymmetry will develop it's own small hierarchy problem

Unfortunately a 1-2 TeV LSP is challenging for the LHC

In mSuGra|CMSSM the lightest neutralino is the LSP

Due to the conservation of R-parity

$$P_R = (-1)^{3(\mathrm{B-L})+2s}$$

the lightest neutralino is stable, thus a dark matter candidate

So WMAP imposes severe constraints on mSuGra! (p40)

Dark matter searches

Dark matter searches will discover or impose a strong constraint on the mass and interactions of the LSP

- dark matter abundance (WMAP, PLANCK…)

  average DM energy density to critical cosmological dens.

$$\frac{\rho_X}{\rho_{\text{crit}}} = \Omega\left(m_X,\, \sigma_{XX\to 2\times SM}\right)$$

- dark matter direct searches (XENON, CDMS…)

  spin (in)dep. DM-nucleon elastic scattering cross section

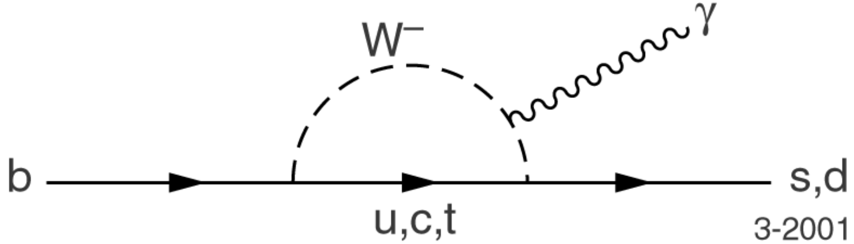
$$\sigma_{\text{SI}}\left(m_X,\, \sigma_{Xq\to Xq}\right),\, \sigma_{\text{SD}}\left(m_X,\, \sigma_{Xq\to Xq}\right)$$

- dark matter indirect searches (Fermi-LAT, PAMELA…)

  probe annihilation modes of DM

Rare processes|decays

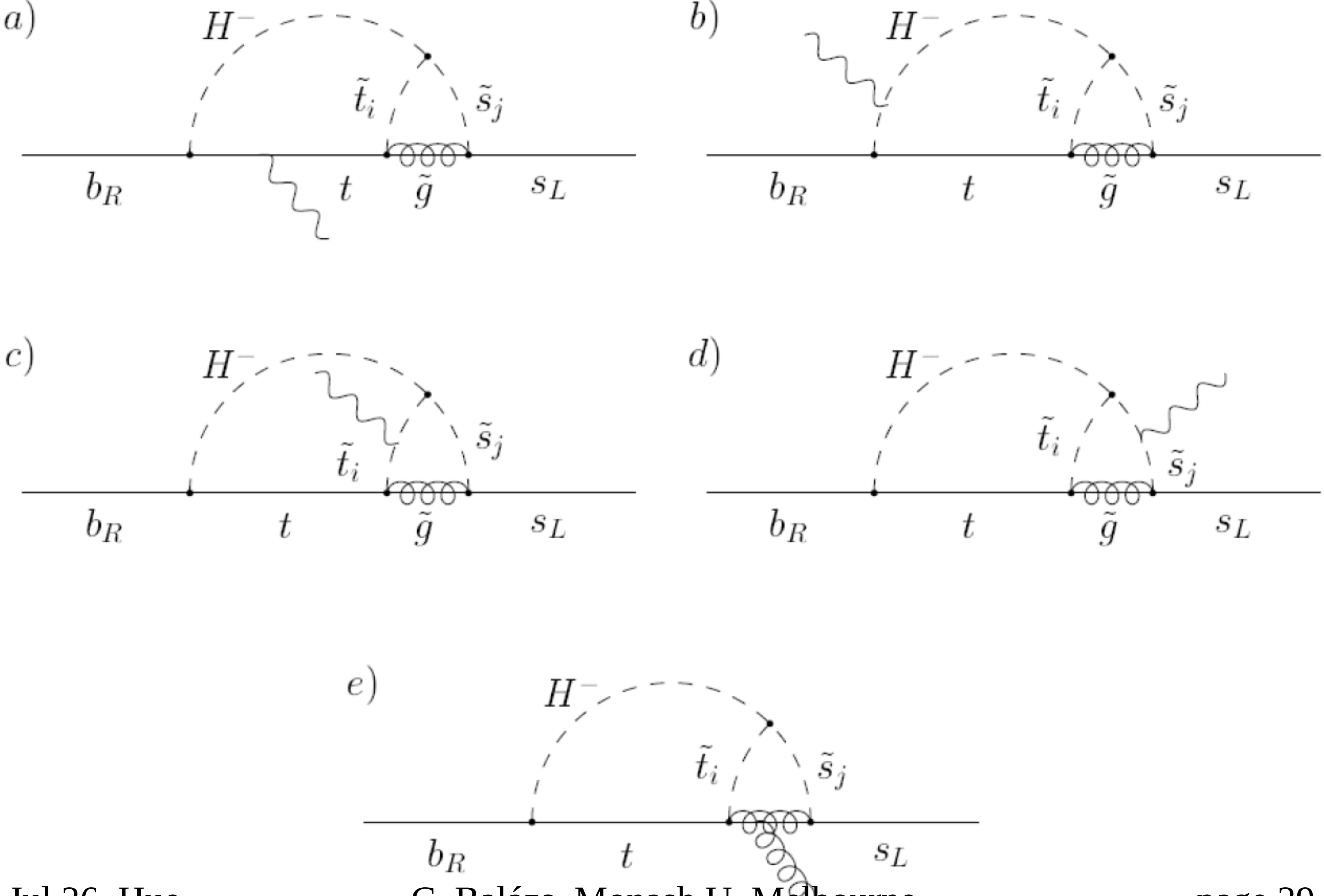
Rare processes are rare because in the standard model they are suppressed. In typical cases they are forbidden at three level and can only process via loops. Such a process, for example, is the flavor violating decay of $b \to s\gamma$. In the SM this is mediated by a *W* loop



If superpartner masses are comparable to that of the heavy SM particles (as expected), than their loop contributions are similar in order of magnitude to that of the SM. This makes rare processes a good place to look for virtual effects of supersymmetry.

Rare decays

Some supersymmetric 2-loop contributions to Br($b \to s\gamma$)



$Br(b \to s\gamma)$ *in mSuGra*

The experimentally measured value of $Br(b \to s\gamma)$

$$B(b \to s\gamma)|_{\rm exp} = (3.55 \pm 0.26) \times 10^{-4}$$

only slightly differs from the value calculated in the SM

$$B(b \to s\gamma)|_{\rm SM} = (3.15 \pm 0.23) \times 10^{-4}$$

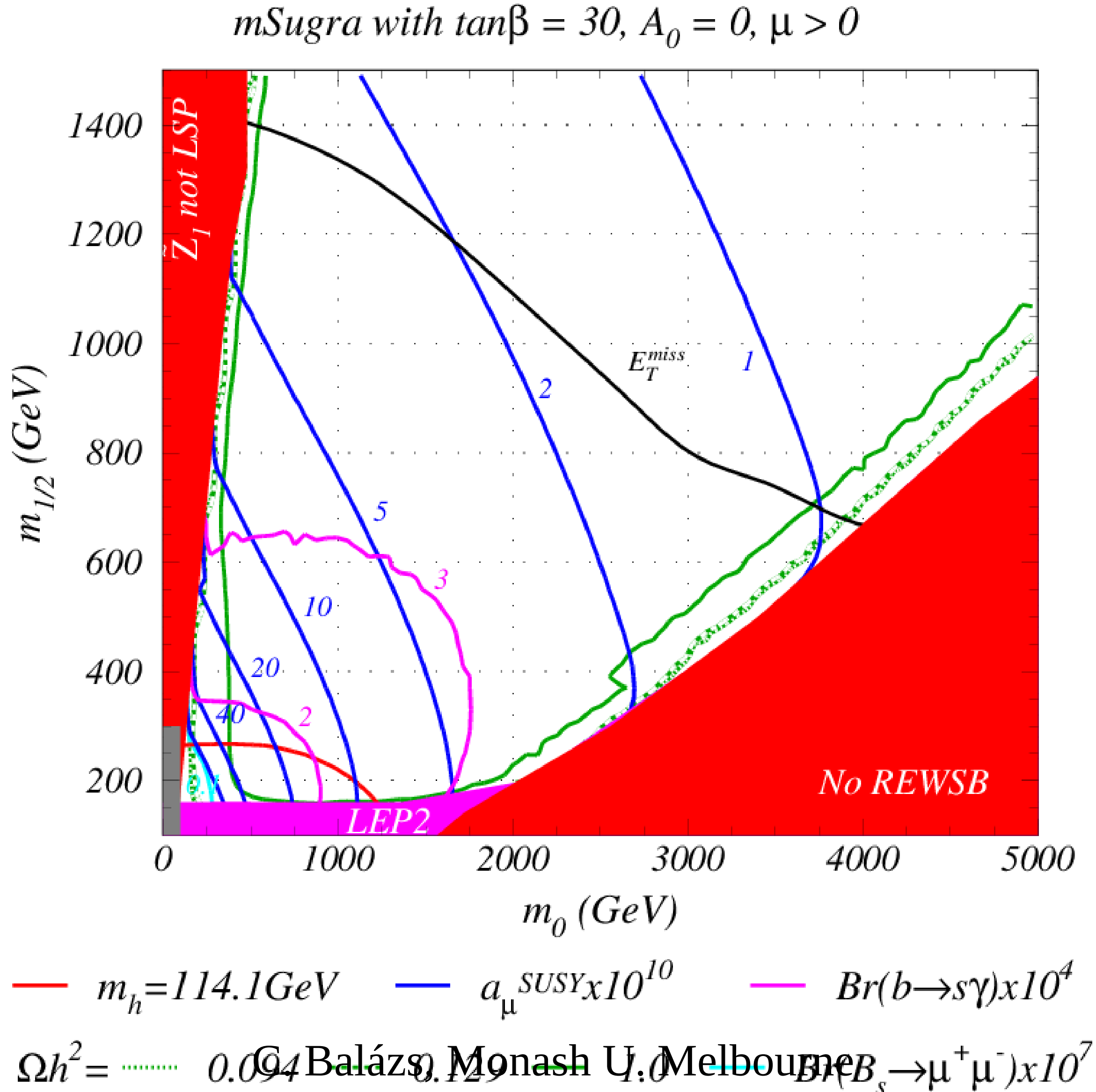
so the contribution of supersymmetric loop contributions

$$\mathcal{BR}(b \to s\gamma)|_{\chi^\pm} \propto \mu A_t \tan\beta f(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\tilde{\chi}^+})$$

cannot be excessive. This imposes further constraints on mSuGra.

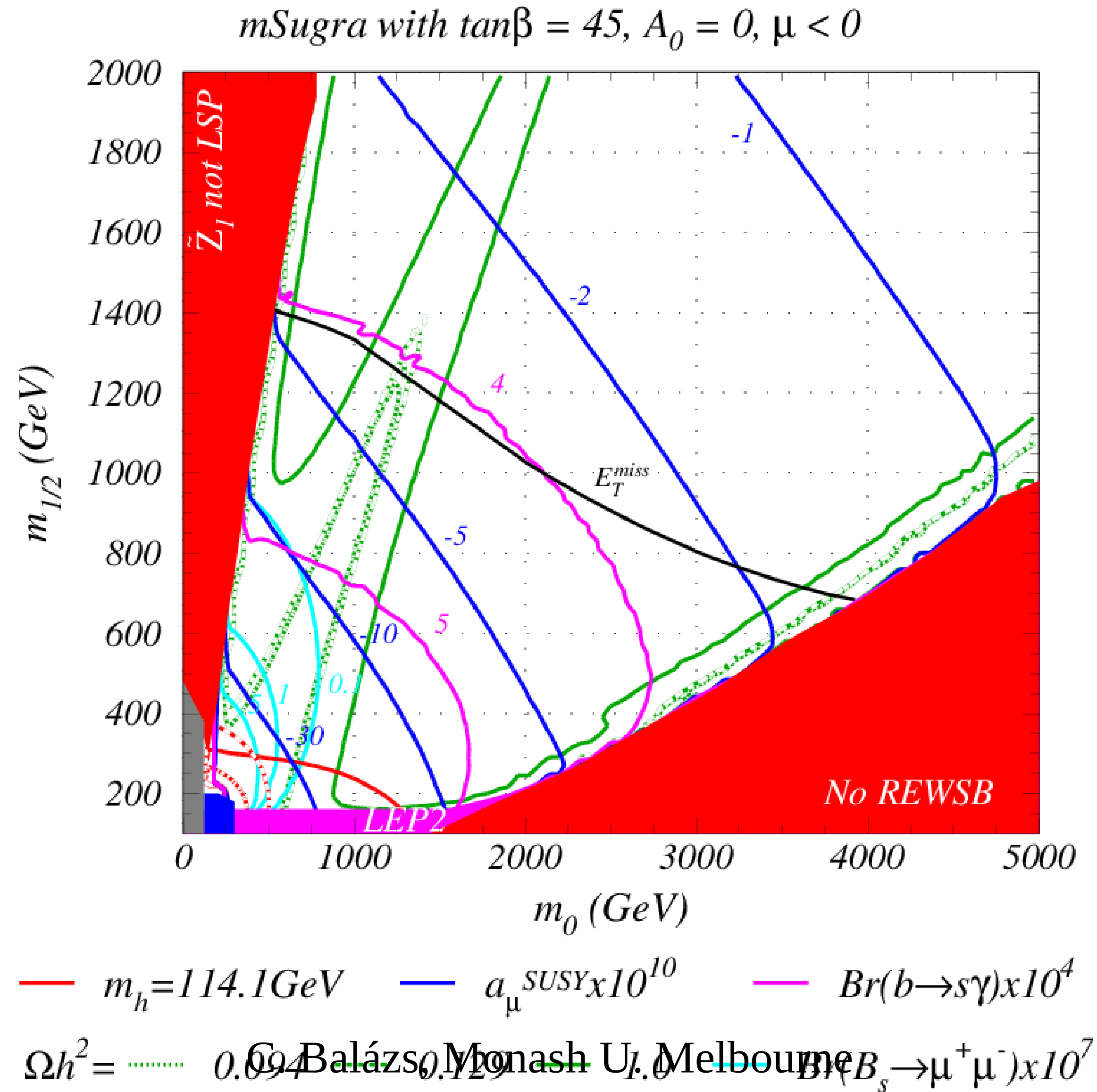
$Br(b\to s\gamma)$ in mSuGra

$Br(b\to s\gamma)$ increases with increasing M_0 and $M_{1/2}$



$Br(b \to s\gamma)$ in mSuGra

$Br(b \to s\gamma)$ increases with $tan\beta$



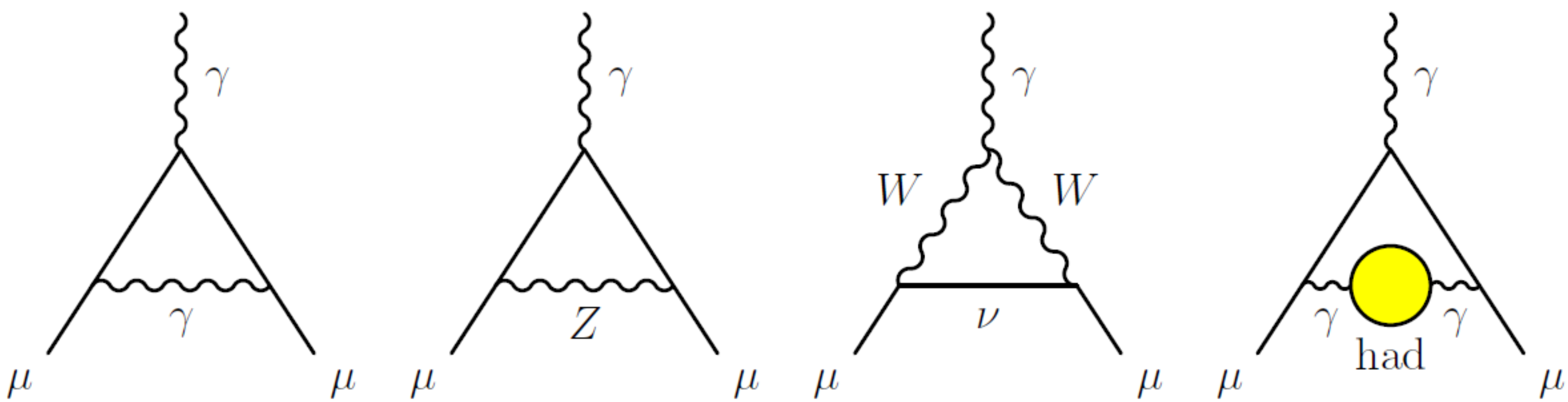
Precision measurements

Exceptionally precise measurements can be sensitive for small supersymmetric loop contributions . A typical example is the anomalous magnetic moment of the muon

$$a_\mu^{\rm exp} = 11\,659\,208.9(5.4)(3.3) \times 10^{-10}$$

Equally remarkable is the SM calculation of $a_\mu = g_\mu - 2$

Contributions come from QED, weak, hadronic processes

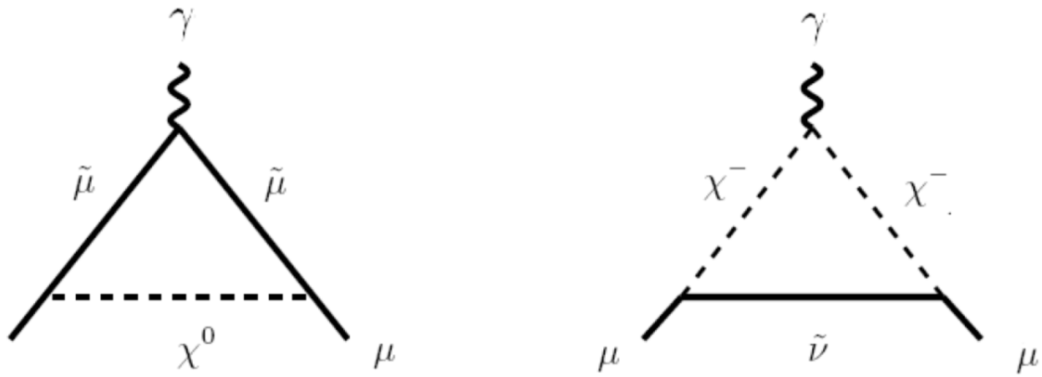


yielding

$$a_\mu^{\rm SM} = 116\,591\,834(2)(41)(26) \times 10^{-11}$$

a_μ in supersymmetry

The difference between the experimental and SM values may come from supersymmetric particles in loops



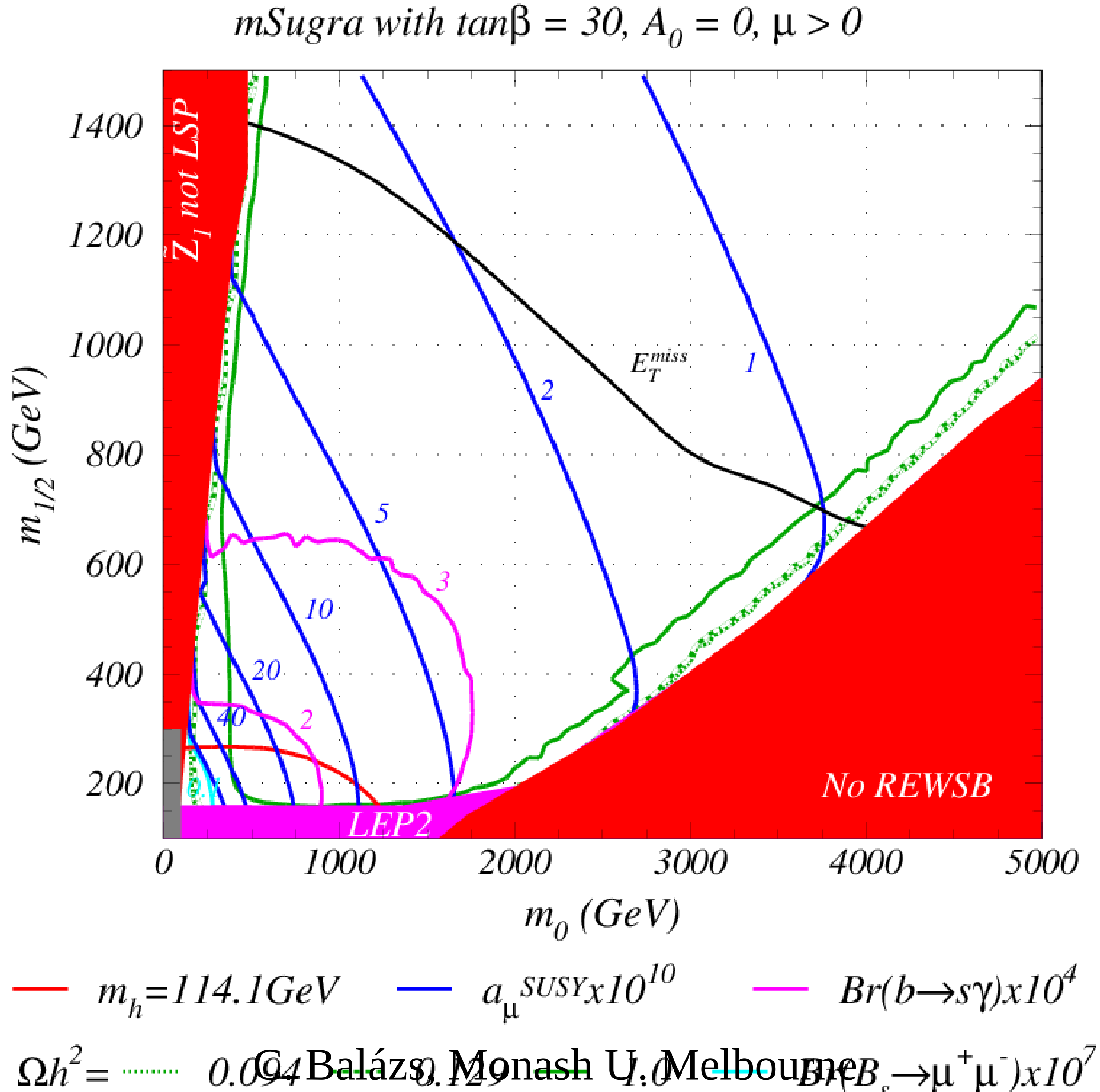
The typical supersymmetric contribution to a_μ is

$$a_\mu^{\rm SUSY} \simeq \pm 130 \times 10^{-11} \cdot \left(\frac{100 \text{ GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta$$

where the sign is the relative sign between μ and $M_{1/2}$

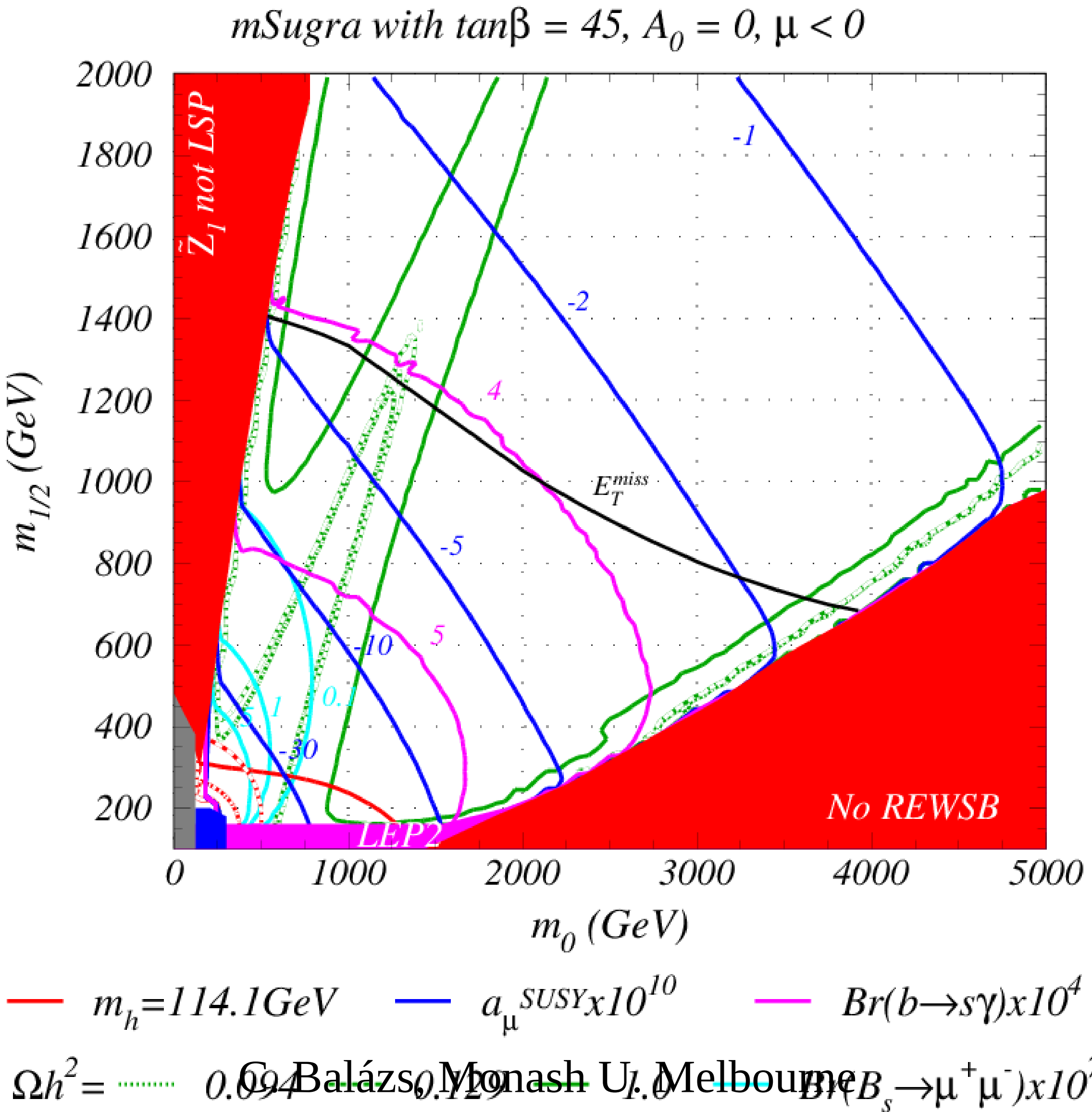
a_μ in mSuGra

a_μ^{SUSY} decreases with increasing M_0 and $M_{1/2}$



a_μ in mSuGra

a_μ^{SUSY} increases with $tan\beta$



Global fits: likelihood

To enhance the experimental sensitivity for supersymmetry, we can combine all available experimental information about, say, mSuGra to find out its viability. One can calculate a likelihood at which the model simultaneously reproduces *M* observations:

$$\mathcal{L}(D|P) = \prod_{i=1}^{M} \frac{1}{\sqrt{2\pi}\sigma_i} \exp\left(- \left(\frac{d_i - t_i(P)}{\sqrt{2}\sigma_i} \right)^2 \right)$$

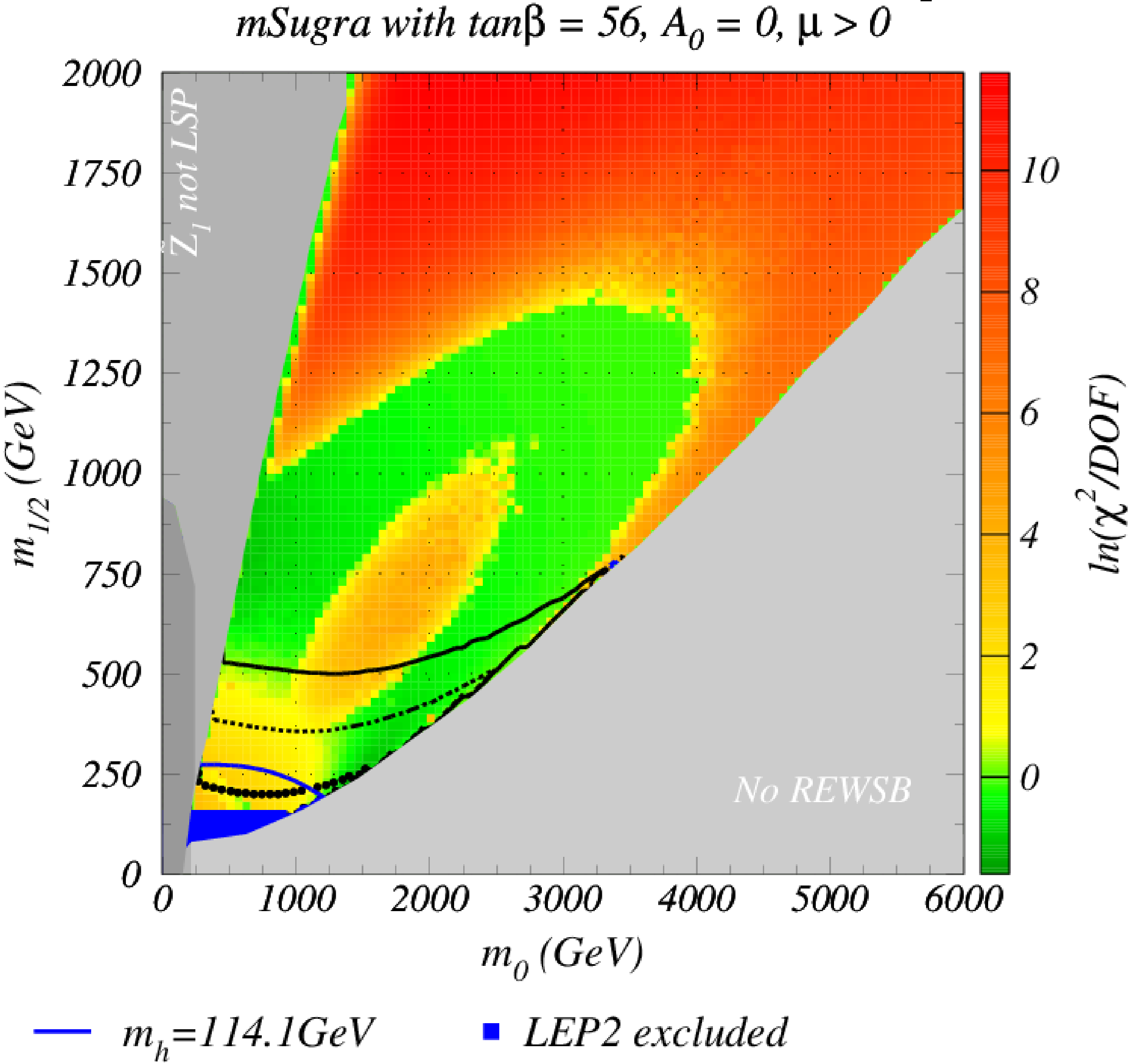
We can calculate this likelihood as the functions of the parameters *P* over the full parameter space of mSuGra.

Global fits: experiments

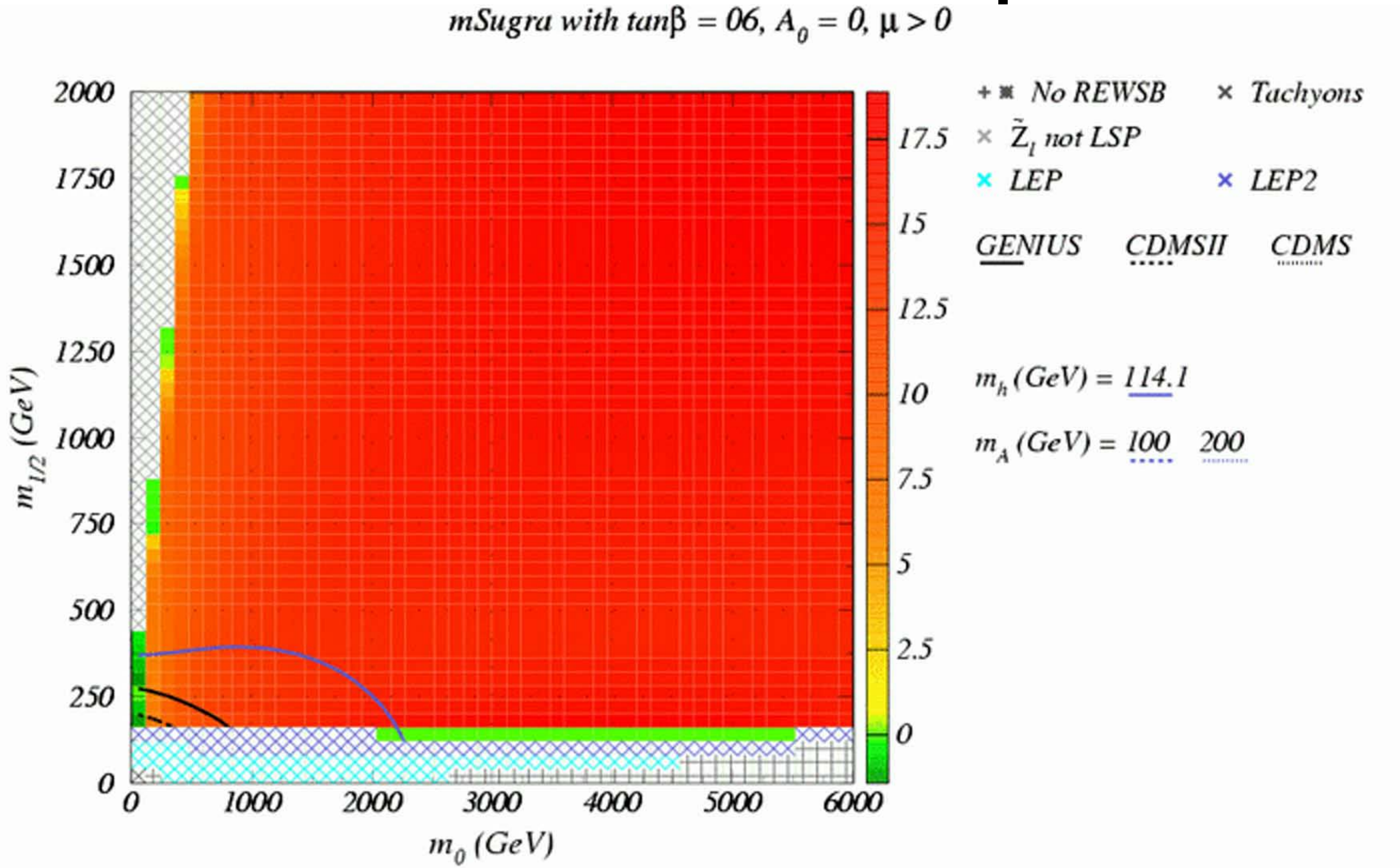
In a recent NmSuGra study we used the following data

Observable	Limit type	$d_i \pm \sigma_{i,e}$	$\sigma_{i,t}^{SUSY}$
m_h	lower limit	up to 114.4 GeV [44]	3.0 GeV [45]
$m_{\tilde{\tau}_1}$	lower limit	73.0 or[1] 87.0 GeV [38]	10 %
$m_{\tilde{e}_R}$	lower limit	73.0 or[1] 100. GeV [38]	10 %
$m_{\tilde{\mu}_R}$	lower limit	73.0 or[1] 95.0 GeV [38]	10 %
$m_{\tilde{\nu}_e}$	lower limit	43.0 or[1] 94.0 GeV [38]	10 %
$m_{\tilde{t}_1}$	lower limit	65.0 or[1] 95.0 GeV [38]	10 %
$m_{\tilde{b}_1}$	lower limit	59.0 or[2] 95.0 GeV [38]	10 %
$m_{\tilde{q}_1}$	lower limit	318.0 GeV [38]	10 %
$m_{\tilde{W}_1}$	lower limit	43.0 or[3] 92.4 GeV [38]	10 %
$m_{\tilde{Z}_1}$	lower limit	50.0 GeV [38]	10 %
$m_{\tilde{g}}$	lower limit	195.0 GeV [38]	10 %
Δa_μ	central value	$(29.0 \pm 9.0)\times 10^{-10}$ [46]	~~negligible~~
Δm_d	central value	$(5.07 \pm 0.04)\times 10^{11}$ ps^{-1} [47]	1 % [41]
$B(b \to s\gamma)$	central value	$(3.50 \pm 0.17)\times 10^{-4}$ [47]	10 % [48]
$B(B^+ \to \tau + \nu_\tau)$	central value	$(1.73 \pm 0.35)\times 10^{-4}$ [49]	10 % [41]
$B(B_s \to \mu^+\mu^-)$	upper limit	4.7×10^{-8} [49]	10 % [50]
Ωh^2	upper limit	0.1143 ± 0.0034 [51]	10 % [41]
σ_{SI}	upper limit	CDMS 2008 [52]	20 % [42, 43]

Likelihood maps



Likelihood maps



Profile likelihoods

To simply visualize likelihoods we can project out the variables that we are not interested in. It is customary to maximize likelihoods

$$\mathcal{L}^{max}(D|p_i;H) = \max_{p_1,\ldots,p_{i-1},p_{i+1},\ldots,p_n} (\mathcal{L}(D|P;H))$$

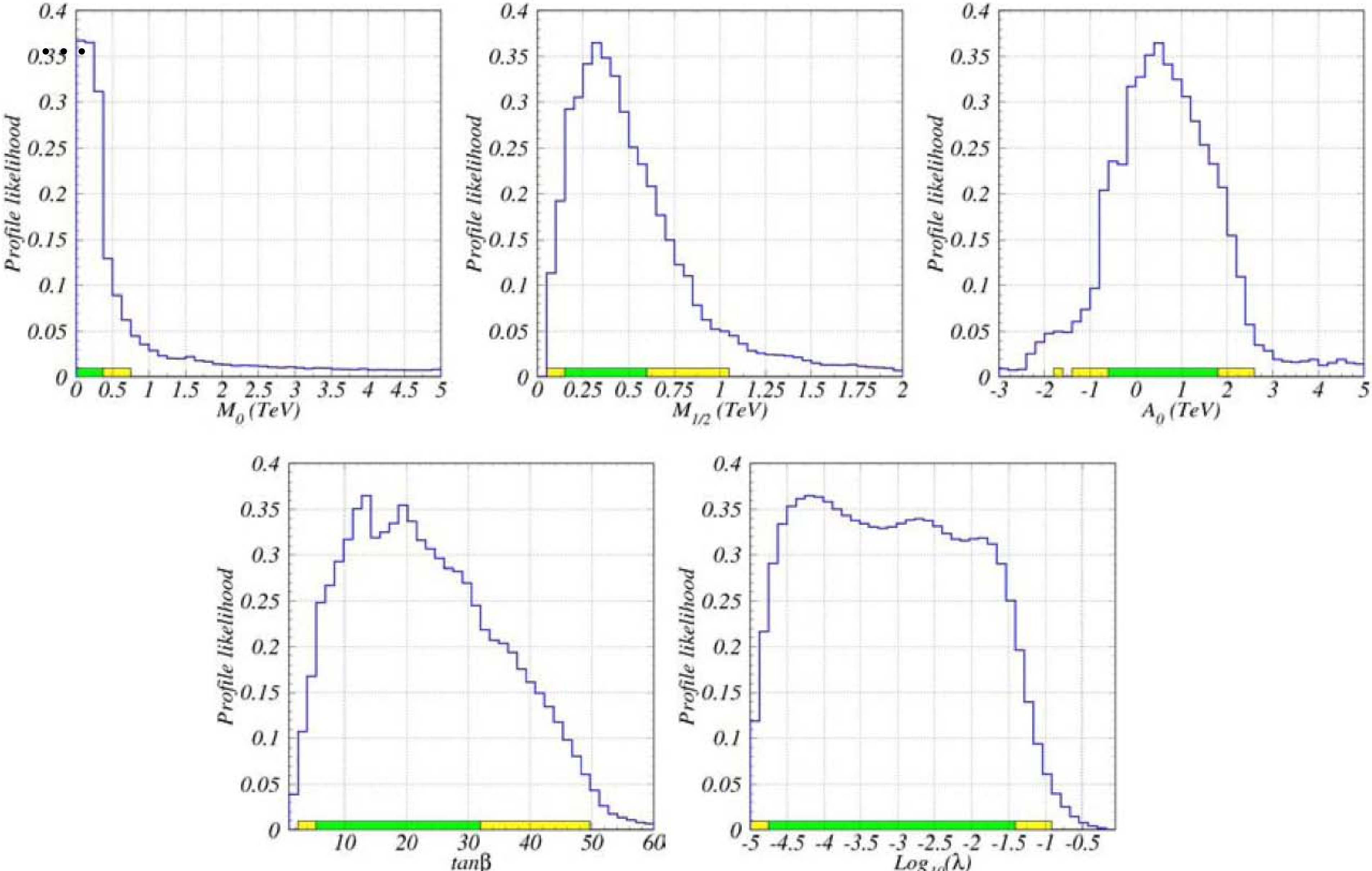
and call the result *profile likelihood*. Likelihoods can be profiled to more than one variables.

We can project to variables that are functions of parameters creating profile likelihoods of, say, superpartner masses.

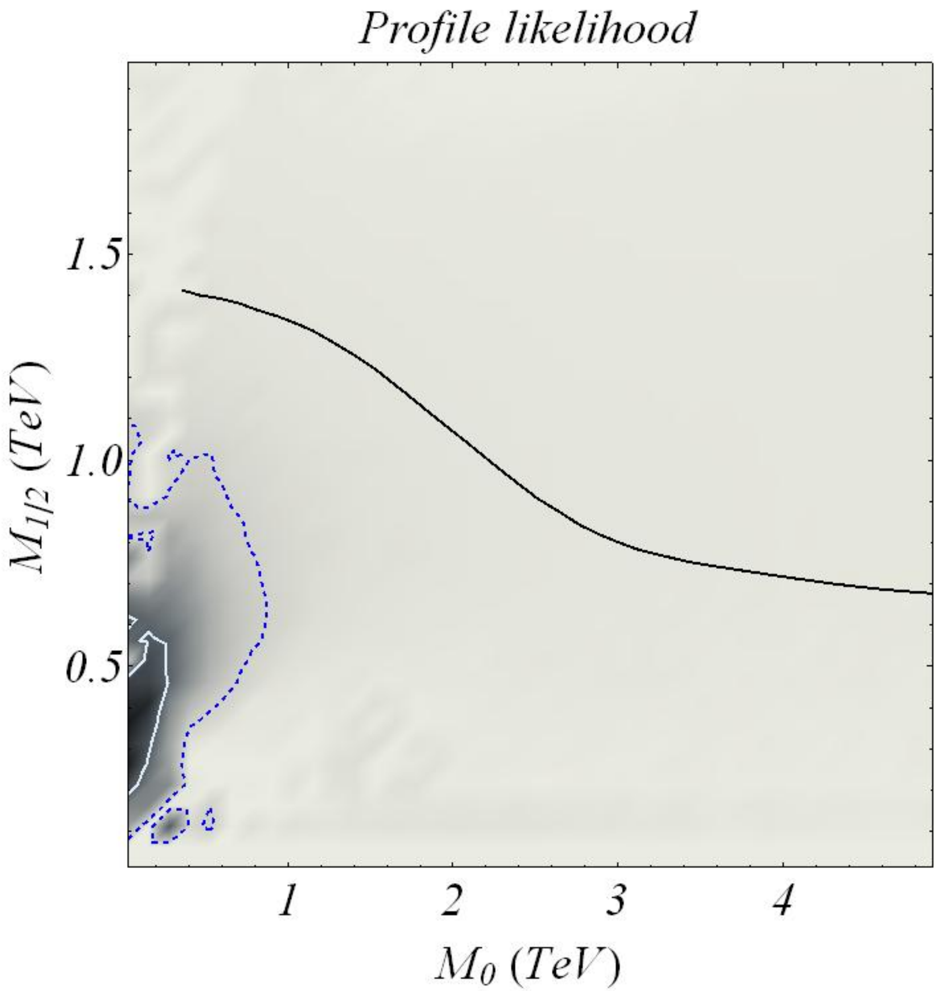
We can also define *confidence intervals* requiring *x* percent of likelihood contained inside them:

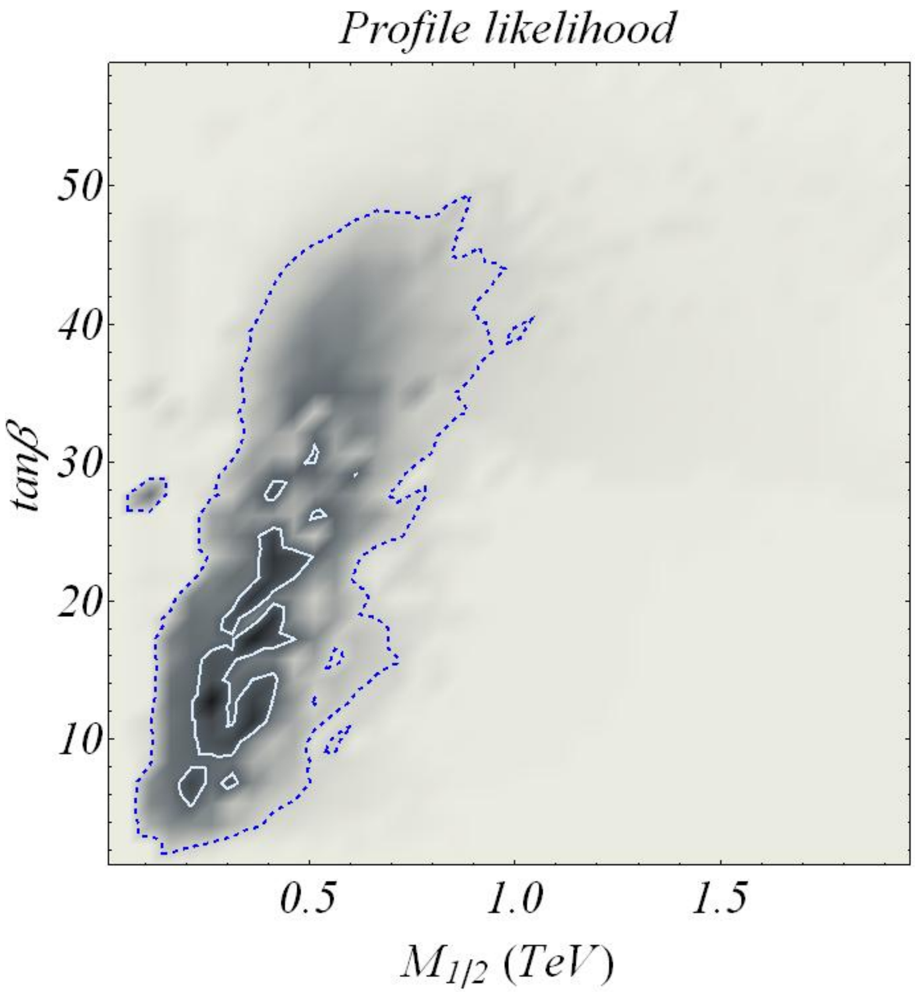
$$x = \int_{\mathcal{R}_x} \mathcal{P}(p_i|D)\, dp_i$$

NmSuGra profiles: para 1D

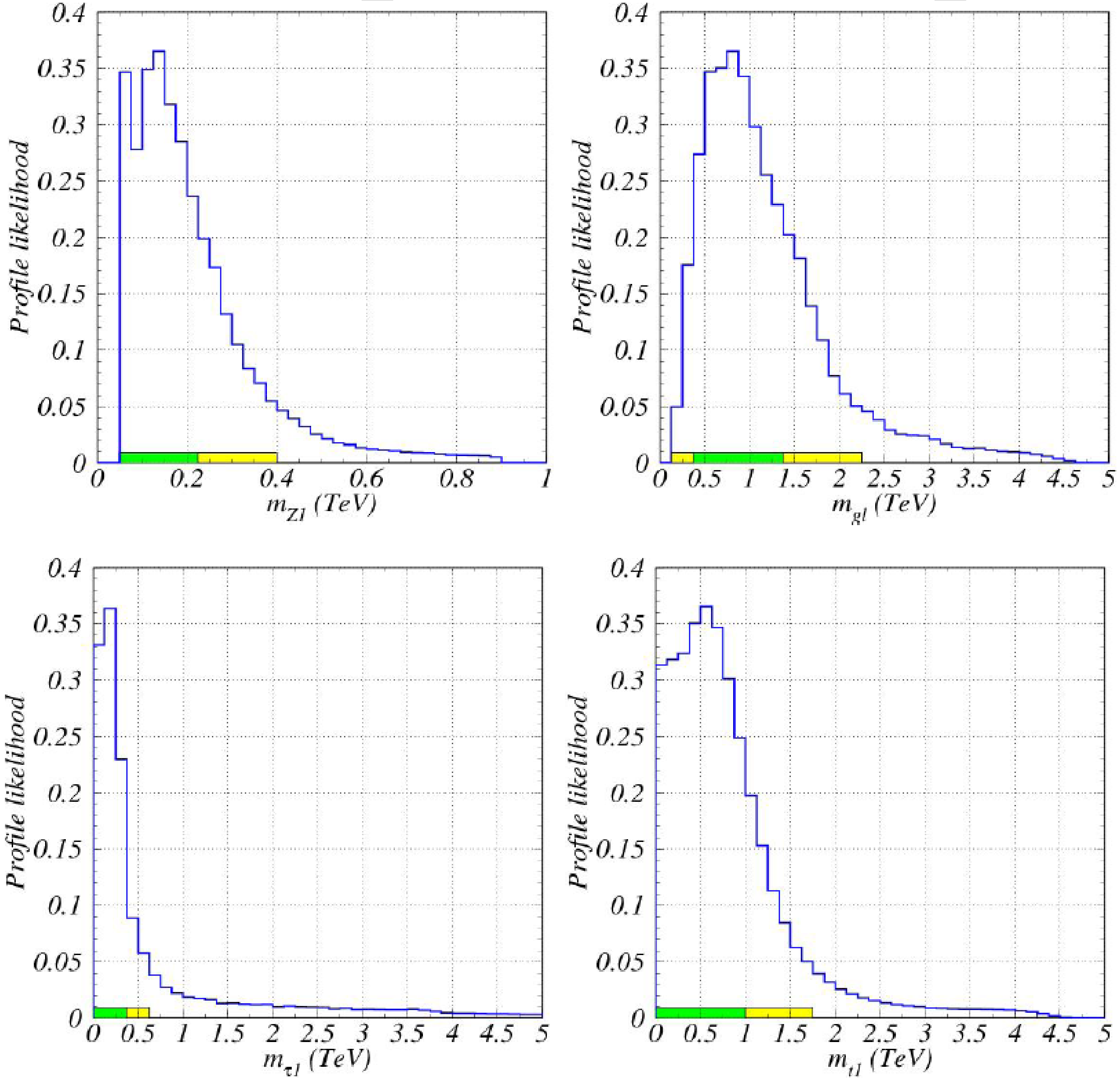


NmSuGra profiles: para 2D





NmSuGra profiles: spartners



Parameter inference

If|when supersymmetry is found we would like to reconstruct the superpotential from data. The supersymmetric model will be selected by the ‘best fit’ to data. Here I will assume that Nature’s choice is NmSuGra ☺. Then we calculate the probability that the parameters acquire values *P* in the light of the data *D*

$$\mathcal{P}(P \mid D) = \mathcal{L}(D \mid P)\,\mathcal{P}(P)\,/\,\mathcal{P}(D)$$

This is called, for historic reasons, the *posterior probability*. We can visualize the posterior probability by integrating over the parameters that we are not interested in.

$$\mathcal{P}(p_i|D;H) = \int \mathcal{P}(P|D;H)\,dp_1 \ldots dp_{i-1}\,dp_{i+1} \ldots dp_n$$

This is called *marginalization*.

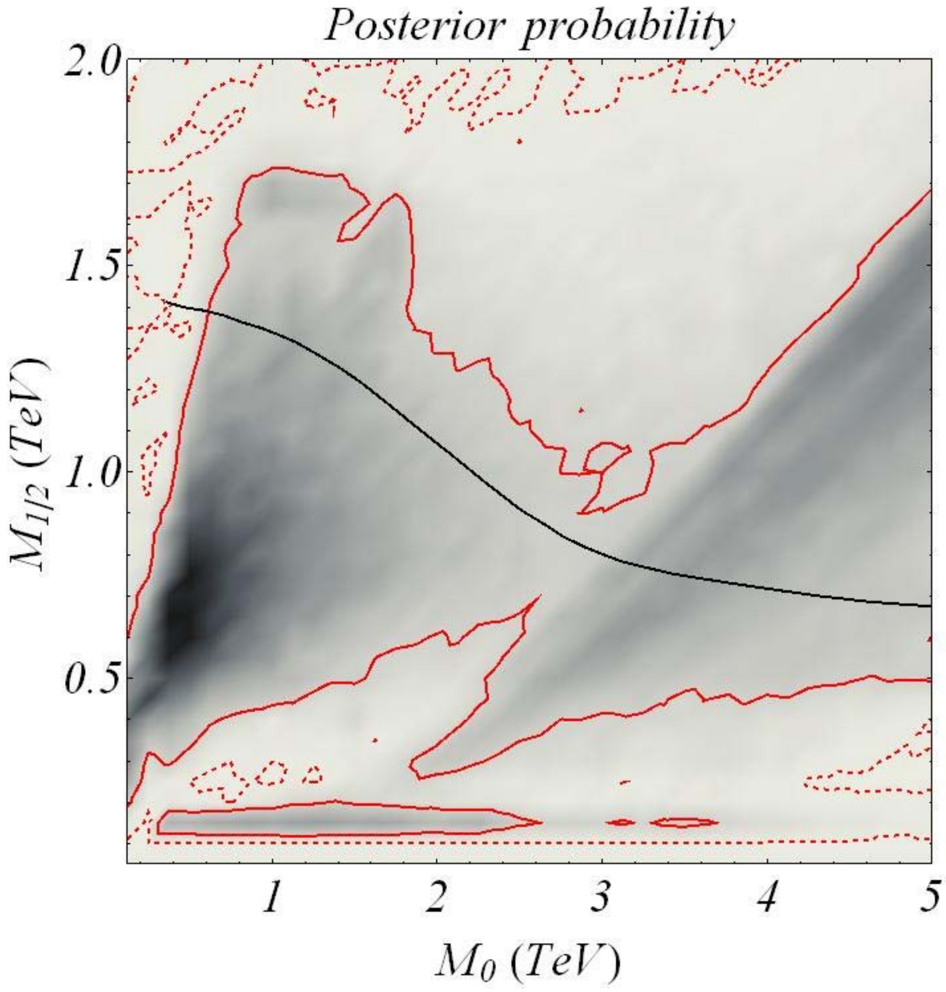
Parameter inference: priors

Unfortunately, the posterior probability

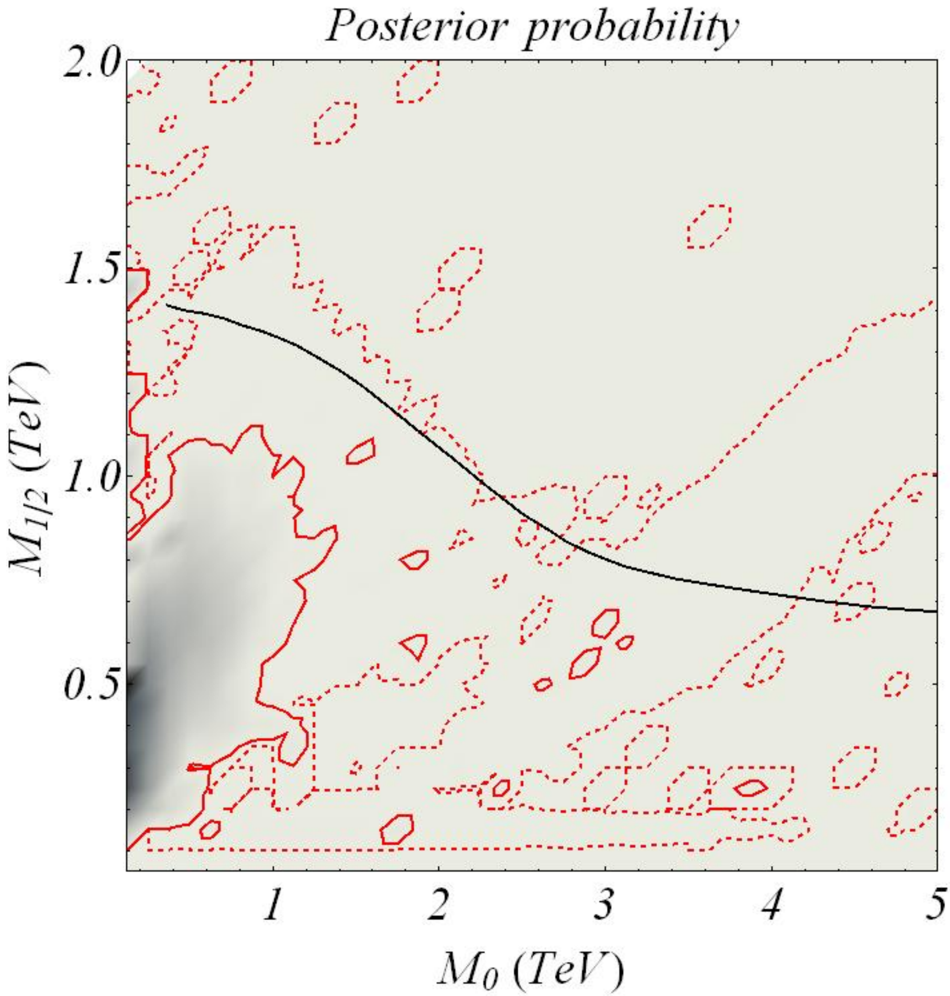
$$\mathcal{P}(P \mid D) = \mathcal{L}(D \mid P)\mathcal{P}(P)/\mathcal{P}(D)$$

depends on the probability $\mathcal{P}(P)$ that the parameters acquire values P prior to considering the data. This raises the question: Are all values of the theory parameters have the same probability to begin with? This is a non-trivial question to answer and has led to vigorous discussions in the literature. Presently we use various priors to estimate the uncertainty arising from the prior itself.

NmSuGra posteriors



linear priors



log priors

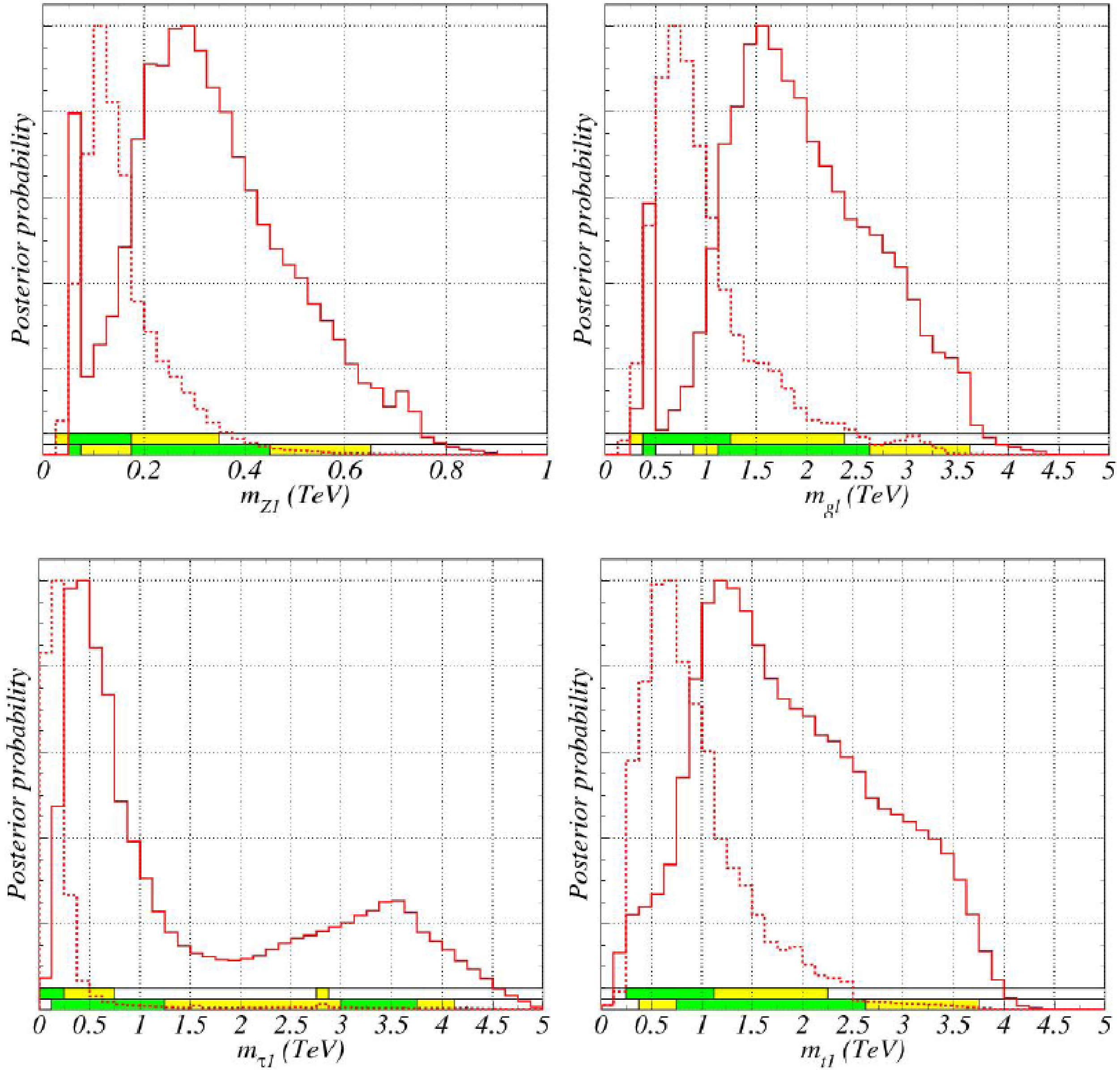
NmSuGra posteriors

Despite the considerable prior dependence, prior *in*dependent quantitative conclusions can be drawn.

- Based on present data only, there's about 50% chance to see superpartners at the LHC in NmSuGra

NmSuGra posteriors

…

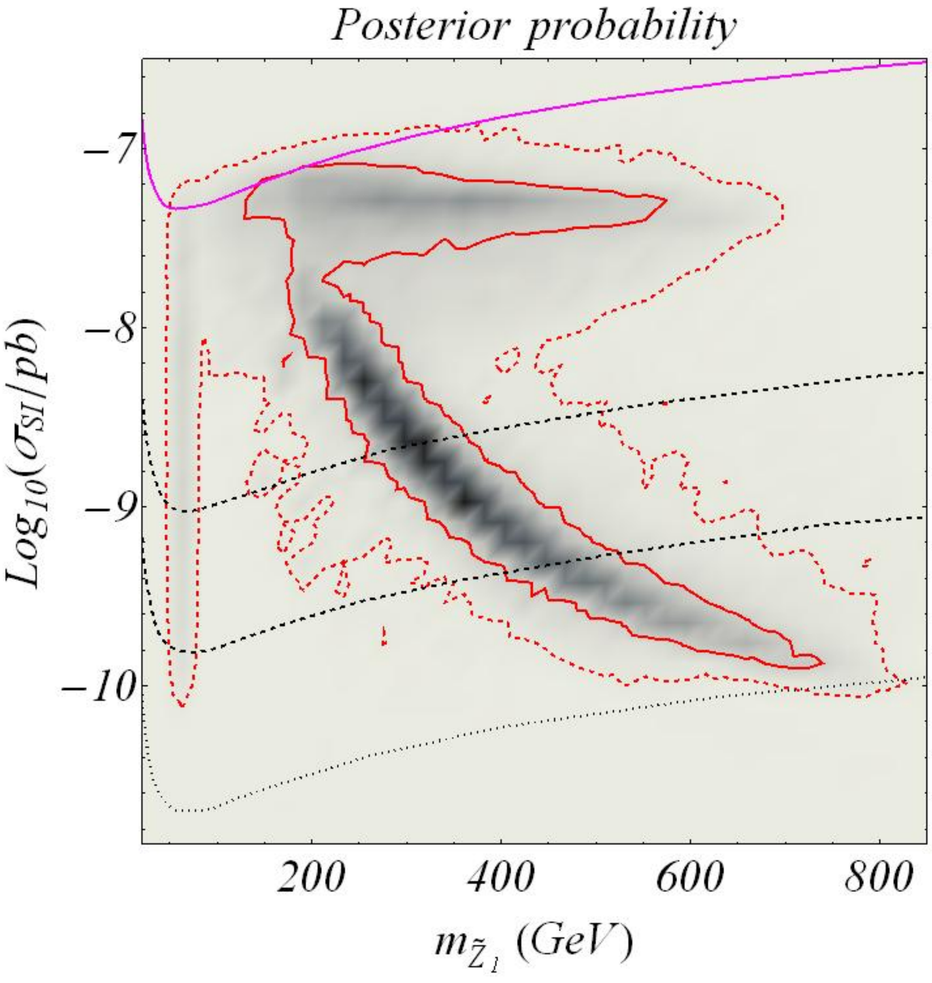


NmSuGra posteriors

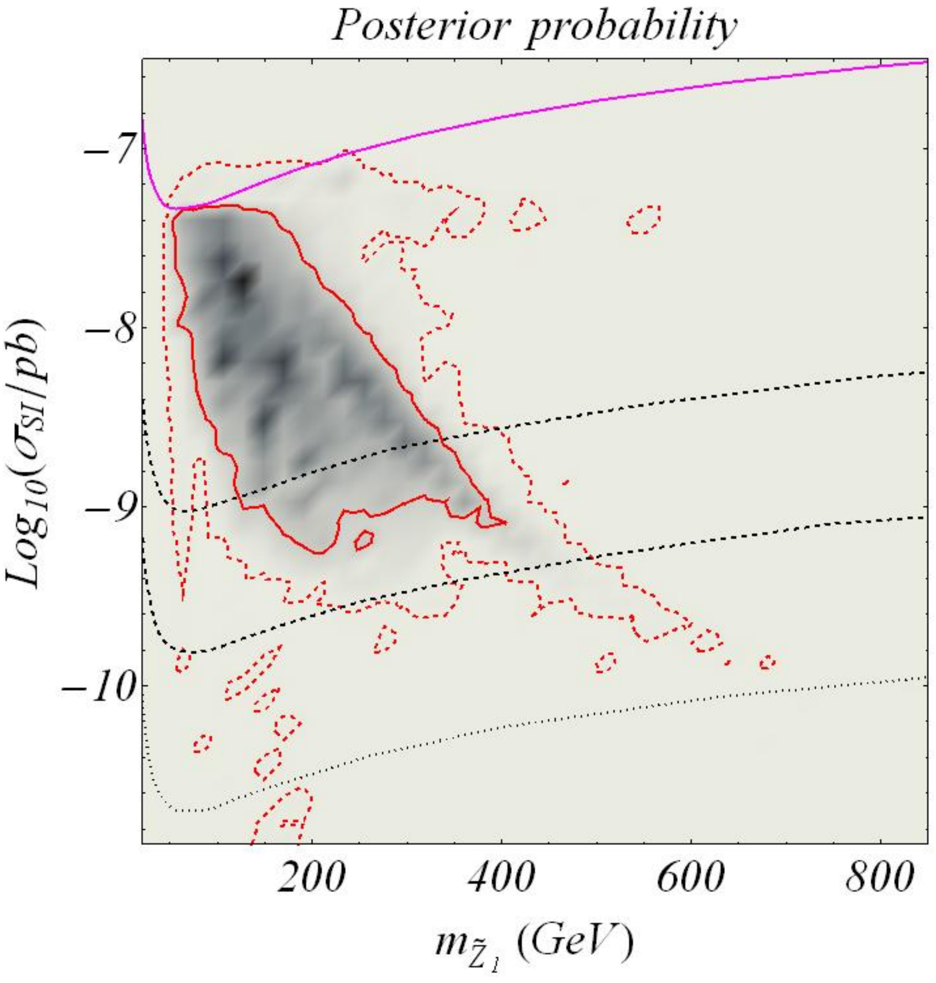
Despite the considerable prior dependence, prior *in*dependent quantitative conclusions can be drawn.

- Based on present data only, there's about 50% chance to see superpartners at the LHC in NmSuGra
- ton size dark matter direct detection experiments will cover the present 95 % CL region of NmSuGra

NmSuGra posteriors



linear priors



log priors

NmSuGra posteriors

Despite the considerable prior dependence, prior *in*dependent quantitative conclusions can be drawn.

- Based on present data only, there's about 50% chance to see superpartners at the LHC in NmSuGra
- ton size dark matter direct detection experiments will cover the present 95 % CL region of NmSuGra
- in the next decade experiments combined will explore the present 99 % CL region NmSuGra parameter space
- if NmSuGra is not found in the next decade it will not be relevant for electroweak symmetry breaking, dark matter, experimental anomalies, for physics beyond the standard model!

Conclusions

Supersymmetric models are already strongly constrained by experiments

Supersymmetric models will be *substantially tested* by experiments over the next decade

The simplest supersymmetric models can be discovered within the *next decade*

Supersymmetric models cannot be excluded experimentally (in our lifetime), but they can be made ‘redundant’