The MSSM with a degenerate Higgs mass matrix

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Based on JHEP 1008:096 (arXiv:1007.0321) and JHEP 0908:011 (arXiv:0906.2957)
with Felix Brümmer, Sabine Kraml, Ritesh Singh, Arthur Hebecker

- Low energy, softly broken supersymmetry is well motivated.

- But the minimal SM extension has $\mathcal{O}(100)$ parameters coming from the susy breaking.

- After recquiring no CP violation and no FCNCs : $\mathcal{O}(20)$

- To reduce the number of parameters, one can :
  - Use « ad hoc» assumptions, like for the CMSSM
  - Assume a peculiar mechanism of susy breaking mediation like gauge/anomaly/ gaugino/radion mediations
  - And/or assume models for underlying UV physics

- MSSM Higgs potential :

$$V_{Higgs} = \begin{pmatrix} H_1^* & H_2 \end{pmatrix} \begin{pmatrix} |\mu|^2 + m_{H_1}^2 & B_\mu^* \\ B_\mu & |\mu|^2 + m_{H_2}^2 \end{pmatrix} \begin{pmatrix} H_1 \\ H_2^* \end{pmatrix} + (\text{quartic terms})$$

supersymmetric ($|\mu|^2$) — susy breaking (B_μ, $m_{H_1}^2$, $m_{H_2}^2$)

- Common assumption (e.g. CMSSM) : $m_{H_{1,2}}^2 = m_0^2$ at GUT scale.

- Here instead : $|\mu|^2 + m_{H_1}^2 = |\mu|^2 + m_{H_2}^2 = \pm B_\mu$ $(m_1^2 = m_2^2 = \pm m_3^2)$

Origin : MSSM Higgses from a GUT chiral adjoint ϕ :

$$\begin{aligned} \mathrm{Ad}(G) &= (\mathbf{1},\mathbf{2})_{-1/2} \oplus (\mathbf{1},\mathbf{2})_{1/2} \oplus \dots \\ \phi &= H_1 \oplus H_2 \oplus \dots \end{aligned}$$

If $\phi - \overline{\phi}$ (or $\phi + \overline{\phi}$) massless at tree level, then :

$$\begin{aligned} V \supset m^2 \mathbf{tr}(\phi + \overline{\phi})^2 &\supset m^2 (H_1 + \overline{H}_2)(\overline{H}_1 + H_2) \\ &= m^2\,|H_1|^2 + m^2\,|H_2|^2 + m^2\,(H_1 H_2 + h.c.) \end{aligned}$$

⇒ $m_1^2 = m_2^2 = m_3^2 = m^2$ (or $m_1^2 = m_2^2 = -m_3^2 = m^2$)

For which reason $\phi - \overline{\phi}$ could be massless ?

(or $\phi + \overline{\phi}$)

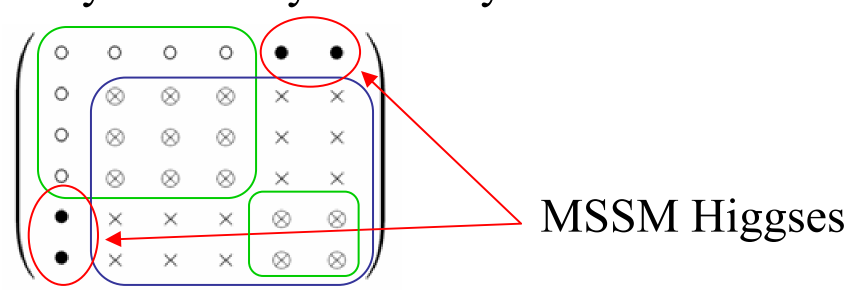
In models with (SUSY) composite Higgs :

- CFT with spontaneously broken approximate global symmetry : composite pGBS identified as Higgses , massless at tree level.

- Example : Holographic GUT [Nomura Poland Tweedie '06]
  CFT has $SU(6) \to SU(4) \times SU(2) \times U(1)$ spontaneously and coupled to an elementary sector with $SU(5) \times U(1)' \supset SU(6)$ weakly gauged (explicit breaking).

  5D description (with gauge-gravity correspondence) :
  - A slice of AdS^5 (warped) with $SU(6)$ spontaneously broken by ϕ on the IR brane and explicitly broken by boundary conditions on UV brane.

$\phi \sim$



  - The imaginary part of ϕ (half of the d.o.f.) contains the pGBs
    so $\phi - \overline{\phi}$ massless ⟹ **DHMM**

In models of SUSY gauge-Higgs unification :

- 5D vector superfield ⟺ 4D vector superfield & 4D chiral superfield

  $(\Sigma, \lambda_{1,2}, A^M)$ (λ_1, A^μ) $(\Sigma + iA^5, \lambda_2)$

  (λ_1, A^μ) ← 4D spin 1 : gauge

  $(\Sigma + iA^5, \lambda_2)$ ← 4D spin 0 : Higgs

  5D gauge invariance : no mass term for $A^5 \sim \phi - \overline{\phi}$ ⟹ **DHMM**

- Concrete example : SU(6) gauge-Higgs unification in (flat) 5D [Burdman Nomura '03]

- and also a large class of heterotic string models with anisotropic compactification
  [Antoniadis Gava Narain Taylor hep-th/9405024 ,
  Brignole Ibanez Munoz hep-th/9607405 ,
  Ratz @SUSY10 …]

Can the MSSM with DHMM be realistic ?

- Electroweak symmetry breaking : 2 necessary conditions to get EWSB at low scale

$$m_1^2 m_2^2 - m_3^4 < 0, \quad m_1^2 + m_2^2 - 2m_3^2 > 0.$$

⟹ The RGEs must turn the DHMM equalities into these inequalities !

- To check this, get a full spectrum and impose more constraints :

  ⟹ need a **numerical code** and assume a **scenario**

- Code modification : **impose** $m^2_{H_{1,2}} = \varepsilon_H B_\mu - |\mu|^2$ **at high energy** with $\varepsilon_H = \pm 1$ (done in SuSpect, SoftSusy, and Spheno)

- Phenomenology of a specific, complete model of SUSY Gauge-Higgs unification. [Brümmer SF Kraml Hebecker '09]

- We investigated **2 representative scenarios** : [Brümmer SF Kraml Singh '10]
  - Universal soft terms (like « CMSSM with DHMM»)
  - Vanishing first two generations (like in SUSY Gauge-Higgs unification)

- Constraints : electroweak symmetry breaking and

Observable	Limit
m_h	> 114.4
m_t	173.1 ± 1.3
m_W	80.398 ± 0.025
SUSY mass limits	LEP bounds

Observable	Limit
$\mathrm{BR}(b \to s\gamma)$	$(3.52 \pm 0.34) \times 10^{-4}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$\leq 5.8 \times 10^{-8}$
Δa_μ^{SUSY}	$\leq 4.48 \times 10^{-9}$
Ωh^2	0.1131 ± 0.0034

- Likelihoods : $L_2(x, x_0, dx) = \exp\left[-\frac{(x-x_0)^2}{2\,dx^2}\right]$ $\quad L_1(x, x_0, dx) = \frac{1}{1+\exp[(x-x_0)/dx]}$

- Priors : - flat prior
  - naturalness prior (disfavouring fine-tuned points) : $1/c$

$$c = \max_i \left| \frac{\partial \ln m_Z}{\partial \ln a_i} \right|$$

- ~10x10^6 MCs for $\varepsilon_H = \pm 1$, $\mu > 0$ using SOFTSUSY, and MICROMEGAS to compute observables.

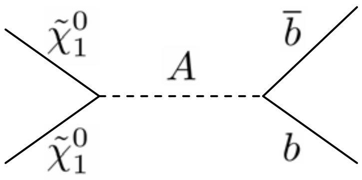
- Strongest constraint (with EWSB) : **dark matter**

  Assuming DM is only neutralino LSP : generically too high relic density

  ⇒ needs **enhanced annihilation**.

- Annihilation of bino component through pseudoscalar Higgs exchange (Higgs funnel) :

  Efficient for $m_A \sim 2m_{\tilde{\chi}_1^0}$



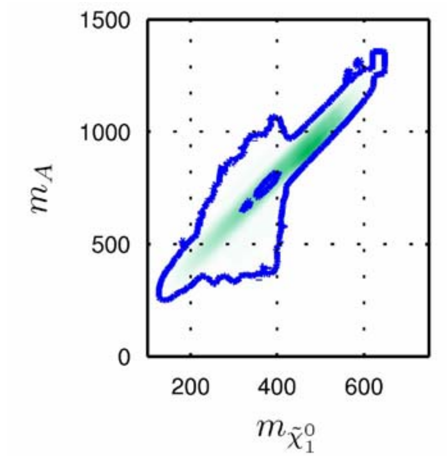
- Coannihilations with sleptons :

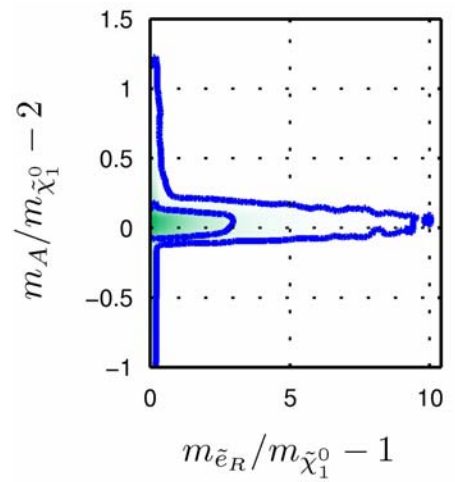
  Efficient for $m_{\tilde{e},\tilde{\tau}} \sim m_{\tilde{\chi}_1^0}$, $m_{\tilde{\chi}_1^0} < 500$ GeV

- Annihilation of higgsino component through $\tilde{\chi}^0$, $\tilde{\chi}^{\pm}$, Z exchange :

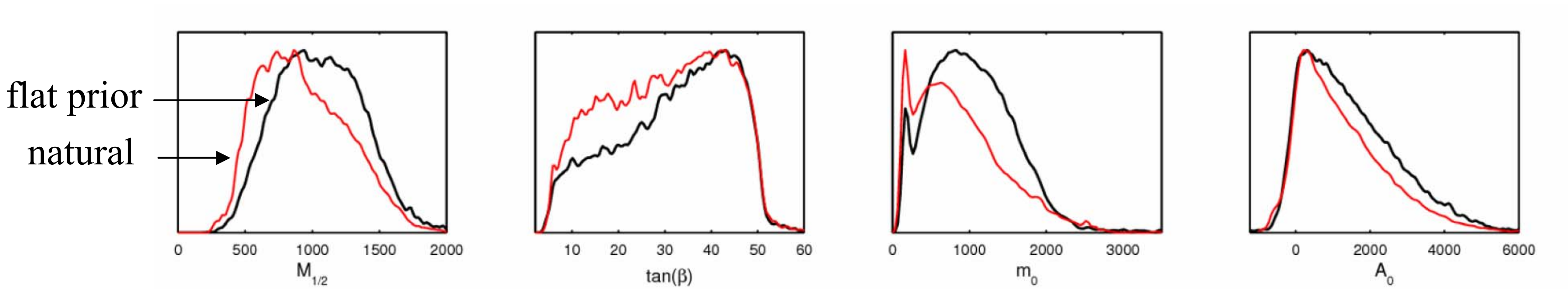
  Efficient for $f_H \gtrsim 0.25$

- Dark matter annihilation mechanisms :
  Mainly Higgs funnel, and slepton coannihilation

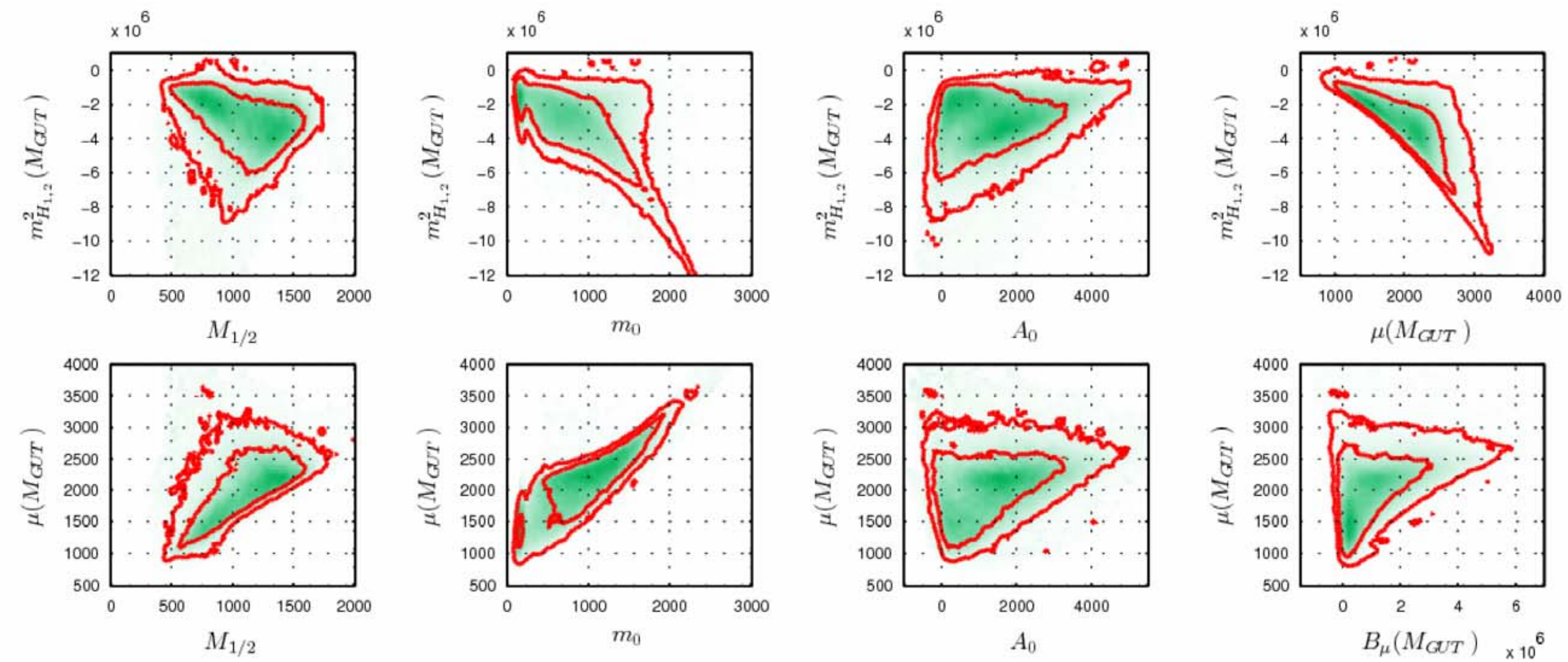




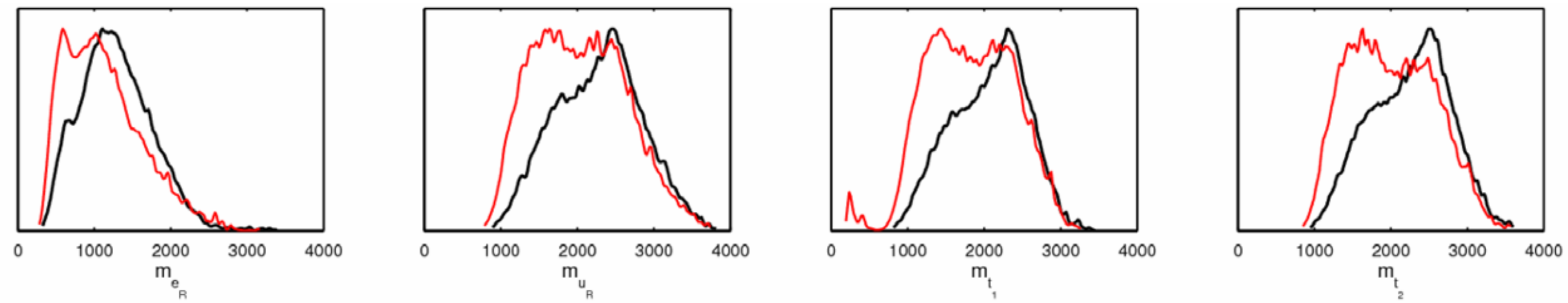
- UV parameters : 1D posterior pdfs, $\varepsilon_H = 1$



- UV parameters : 2D posterior pdfs, 68-95% contours (flat prior), $\varepsilon_H = 1$
  In green : profile likelihood



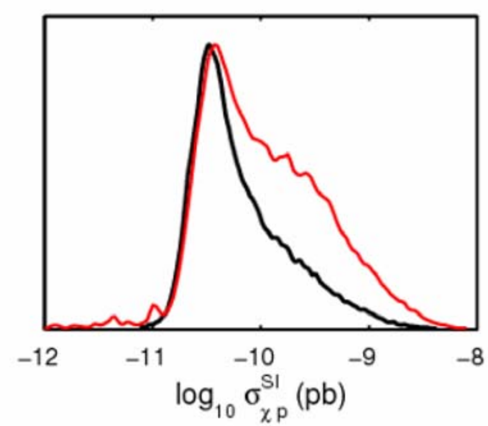
- Collider :
  - squarks and gluino are $\sim$ below 3 TeV, so can be discovered at LHC **14** TeV on the whole parameter space.



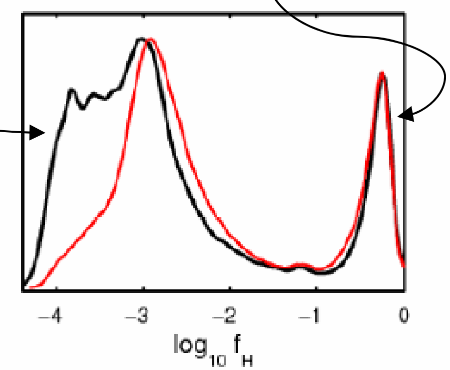
  - SFOS dilepton signal $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$ on $\sim$ half of the parameter space.
  - $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ dominant on the remaining part.

- Direct DM detection : current bound around 10^{-7} pb(SI).

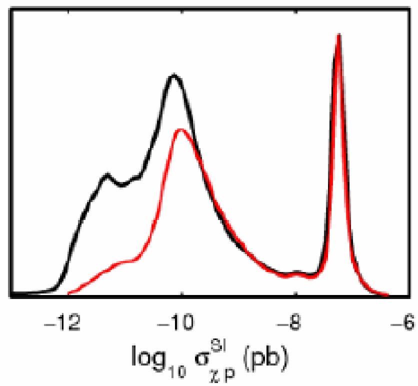
  $\Longrightarrow$ not within reach.

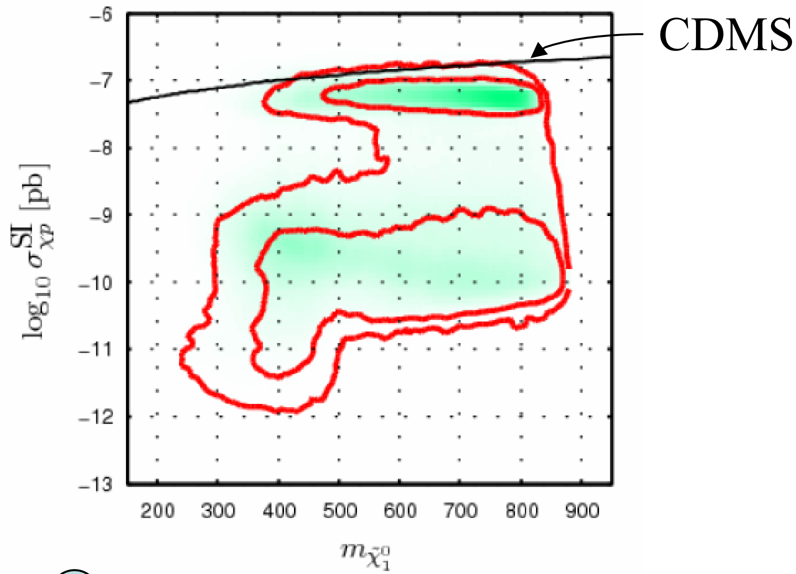


- Dark matter annihilation mechanisms :
  Higgs funnel, and higgsino component annihilation



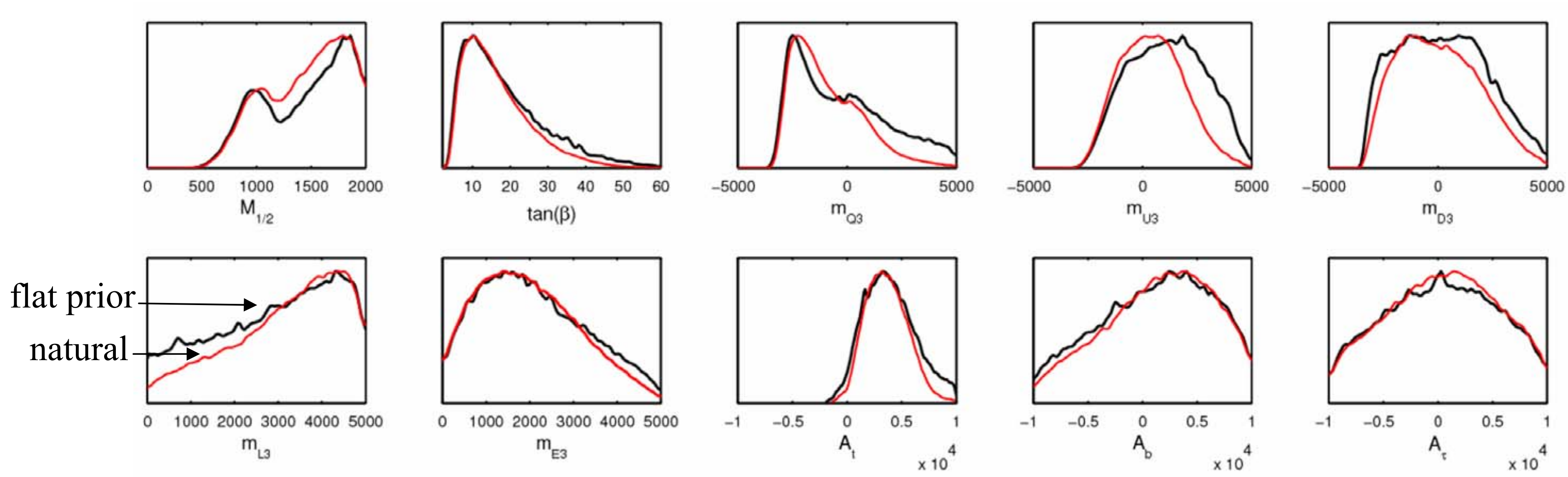
- Direct DM detection :





⇨ not far, and complementarity ☺

- UV parameters : 1D posterior probability density functions (pdfs), $\varepsilon_H = 1$



- Collider : SFOS dilepton $\tilde{\chi}^0_2 \rightarrow \tilde{\ell}^{\pm}\ell^{\mp} \rightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}^0_1$ on the whole parameter space.

Can the MSSM with DHMM be identified ?

- Spectrum with DHMM quite similar to other models… **no striking feature**

- If we knew the whole spectrum → bottom-up reconstruction

  But we have only the LHC...

  But we just want to test equalities.

- **An attempt** :

Use Bayesian evidence to test equalities $m_1^2 = m_2^2$, $m_2^2 = m_3^2$, $m_1^2 = m_3^2$
i.e use the Savage-Dickey density ratio to test (separately) the hypothesis

$$\Delta m_{12}^2 = m_{H_1}^2 - m_{H_2}^2 = 0$$
$$\Delta m_{13} = (|\mu|^2 + m_{H_1}^2) - B_\mu = 0$$
$$\Delta m_{23} = (|\mu|^2 + m_{H_2}^2) - B_\mu = 0$$

(giving factorizable prior to these parameters)

Conclusion :

- Different classes of interesting UV models (SUSY Gauge-Higgs unification, SUSY composite Higgses) give the MSSM with DHMM $\left(m_1^2 = m_2^2 = \pm m_3^2 \right)$

- Viable phenomenology can be achieved for various scenarios
  Dominant constraints : EWSB and dark matter

- The investigated scenarios have good discovery potential for LHC at 14 TeV

To do :

- Find methods to test the DHMM relation

The end

Thank you for your attention !

More

A discrimination study

- A study case : we tried to fit a benchmark point of SUSY GHU with the CMSSM, assuming a realistic set of data that the LHC could provide.
  [Les Houches BSM working group report '10]

- Conclusions (for this benchmark point) :

- Sparticle masses alone are not sufficient

- If the **heavy Higgs sector is known**, B-physics observables permit the discrimination.

In models with (SUSY) composite Higgs :

- CFT with spontaneously broken approximate global symmetry : composite pGBS identified as Higgses , massless at tree level.

- Example : Holographic GUT [Nomura Poland Tweedie '06]
  CFT has $SU(6) \to SU(4) \times SU(2) \times U(1)$ spontaneously and coupled to an elementary sector with $SU(5) \times U(1)' \supset SU(6)$ weakly gauged (explicit breaking).

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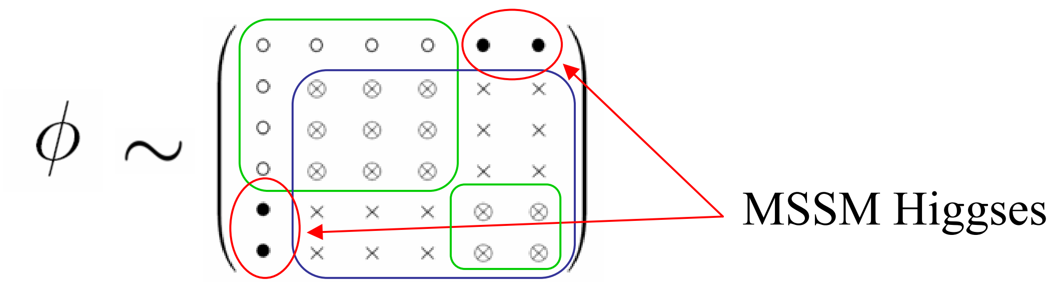
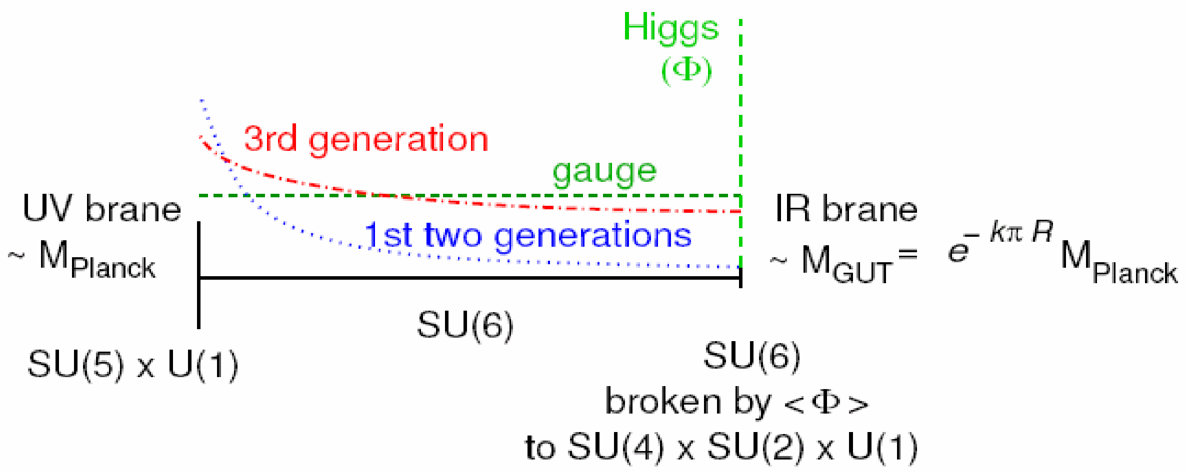


  - The imaginary part of ϕ (half of the d.o.f.) contains the pGBs
    so $\phi - \overline{\phi}$ massless ⟹ **DHMM**

- Gauge and matter fields in the bulk



⟹ Hierarchical soft terms structure dictated by profiles

- Other model : Partially Supersymmetric composite Higgs [Gripaios Redi '10]

⟹ Spectrum of ESUSY (More Minimal SSM) [see talk by A. Lessa]

In models of SUSY gauge-Higgs unification :

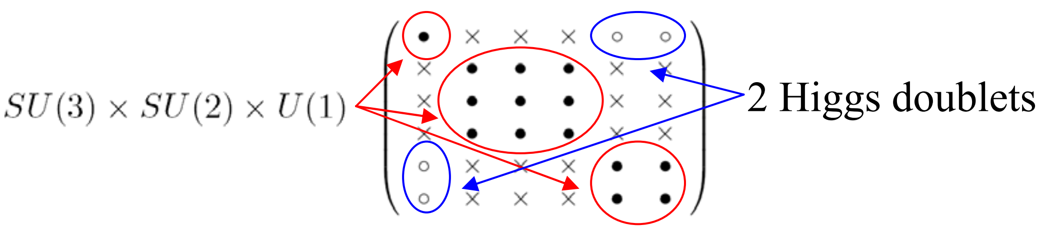
- 5D vector superfield ⟺ 4D vector superfield & 4D chiral superfield

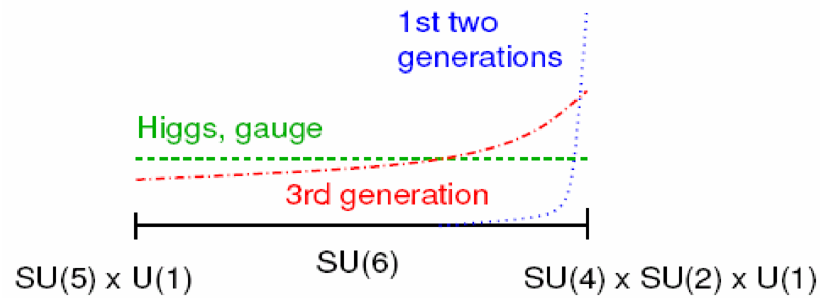
$$(\Sigma, \lambda_{1,2}, A^M) \qquad (\lambda_1, A^\mu) \qquad (\Sigma + iA^5, \lambda_2)$$

4D spin 1 : gauge — 4D spin 0 : Higgs

5D gauge invariance : no mass term for $A^5 \sim \phi - \overline{\phi}$ ⟹ **DHMM**

- Example : SU(6) gauge-Higgs unification in (flat) 5D [Burdman Nomura '03]
  - Boundary conditions select the SM gauge fields and Higgses in the 5D adjoint





  - Higgs and matter in the bulk : 1st two generation soft terms are suppressed

⟹ Again a different spectrum

Why such sign combinations ?

- We have : $B\mu(M_Z) < m_1^2(M_Z) \sim m_1^2(M_{GUT}) = |B\mu(M_{GUT})|$

  > 0 (convention) — **EWSB** — **RGE** — **GHU**

- And $B\mu$ dominated by $16\pi^2 \frac{d}{dt} B\mu = \mu(6A_t|y_t|^2 + 6g_2^2 M_2) + \ldots$

⟹ The overall sign of this RGE is fixed by $\mathrm{sgn}(\mu)$

For a given ε_H , only one $\mathrm{sgn}(\mu)$ is allowed.

Which sign combination is selected ?

Need to study $16\pi^2 \frac{d}{dt} B\mu = \mu(6A_t|y_t|^2 + 6g_2^2 M_2) + \ldots$

- A_t is dominated by the gluino mass : $16\pi^2 \frac{d}{dt} A_t = \frac{32}{3} g_3^2 M_3 + 6g_2 M_2 + \ldots$

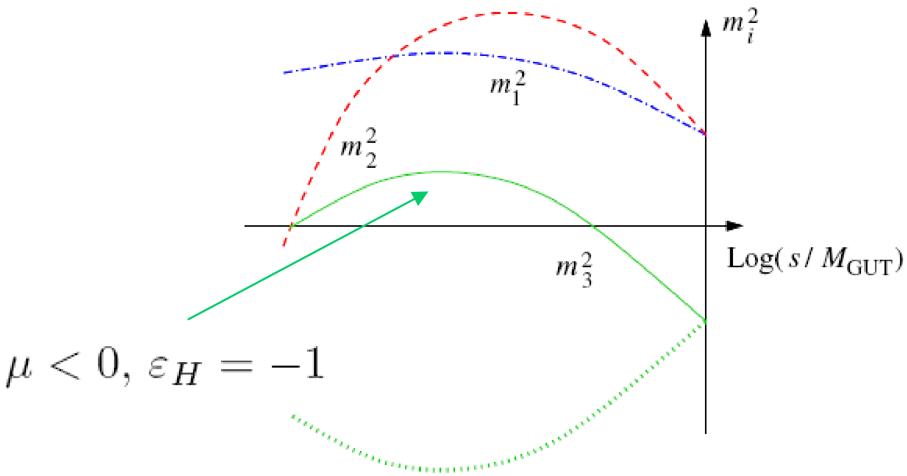
  ⇒ A_t strongly decreases when E decreases

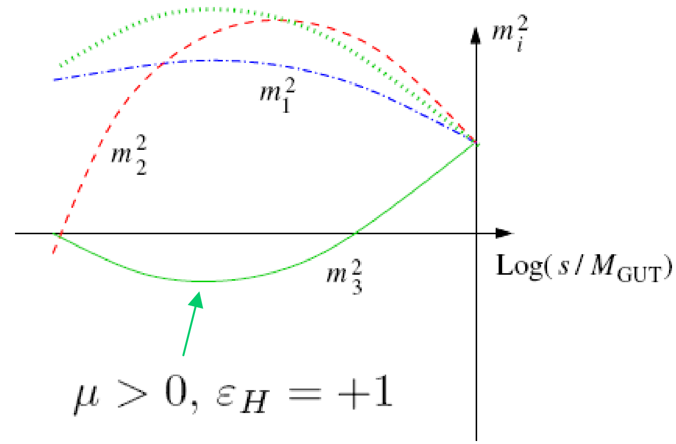
- A_t can become sufficiently negative to compensate M_2 and invert the running of $B\mu$

- This behaviour is roughly universal

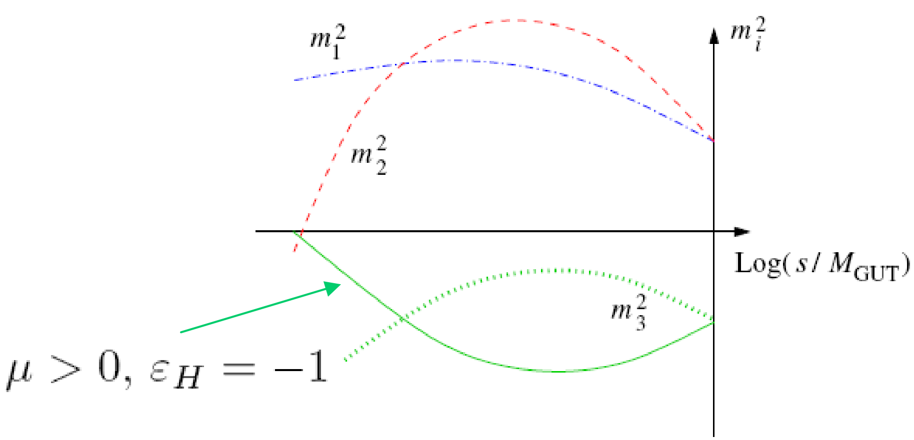
  ⇒ Only the initial value $A_t(M_{GUT})$ matters.

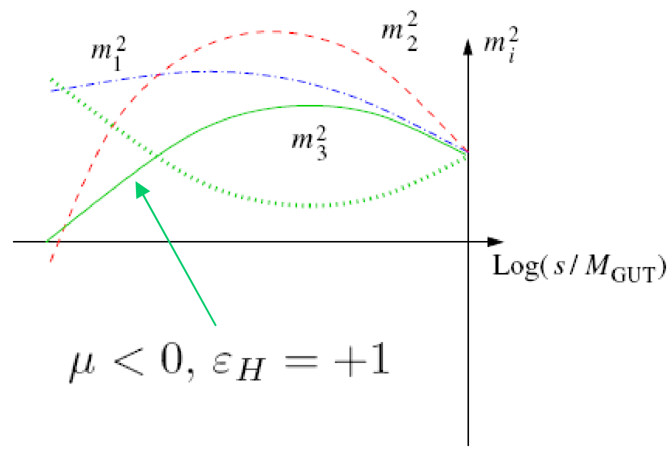
- If $A_t(M_{GUT})$ large and positive :





- If $A_t(M_{GUT})$ small or negative :





How to calculate the spectrum of such models ?

Use a spectrum calculator… (SuSpect) [hep-ph/0211331]

…but the pattern of inputs and constraints is different from other models :

- Usually : μ and $B\mu$ calculated from the 2 equations of Higgs potential minization. at each iteration.

$$\begin{cases} \mu^2 = \frac{1}{2}\left(\tan 2\beta \left(m_{H_u}^2 \tan\beta - m_{H_d}^2 \cot\beta\right) - M_Z^2\right) \\ B\mu = \frac{1}{2}\sin 2\beta \left(m_{H_d}^2 + m_{H_u}^2 + 2\mu^2\right) \end{cases}$$

- But in our model : $\mu,\ B\mu,\ m_{H_u}^2,\ m_{H_d}^2$ fixed from high scale relation…

- First solution : compute $\tan\beta$ and M_Z at each iteration.

But unstable for $\tan\beta \gtrsim 15$! (Potential fix : fixed point => dichotomy)

- Second solution : Simply impose $m_{H_{u,d}}^2 \equiv \varepsilon_H B\mu - \mu^2$ at high energy.

⇒ input parameters : $\tan\beta,\ M_{1/2},\ \mathrm{sgn}(\mu)\ \ldots$

+ matter sector parameters (in the 5D model : 2 mixing angles ϕ_Q and ϕ_L)