Neutralino dark matter in Heterotic string scenarios

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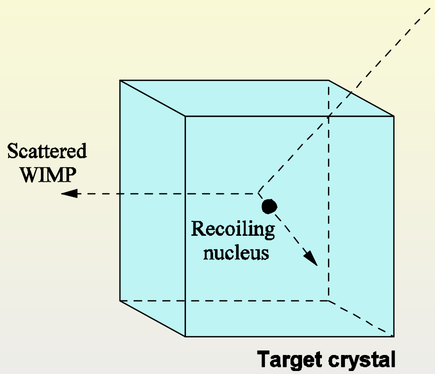
Neutralino dark matter

• The lightest Neutralino is a well motivated dark matter candidate: it is a WIMP and can be stable in supersymmetric theories with R-parity

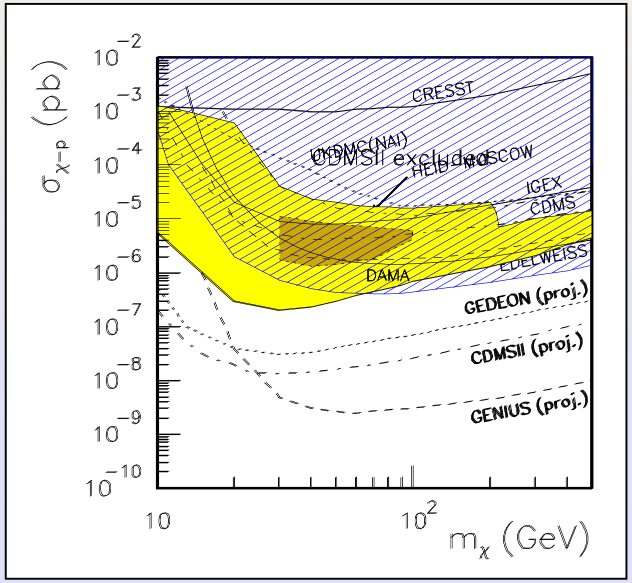


Direct detection through the elastic scattering of a WIMP with nuclei inside a detector.

Many experiments around the world are currently looking for this signal with increasing sensitivities

How large can the neutralino detection cross section be?

Could we explain a hypothetical WIMP detection with neutralino dark matter?



Neutralinos in SUGRA theories

• The theoretical predictions for the neutralino detection cross section have been studied extensively in Supergravity theories

1) The Soft supersymmetry-breaking terms are taken as inputs at the GUT scale and RGEs are used to evaluate the SUSY spectrum

$$M_i \quad m_i \quad A_{ijk}$$

• String scenarios provide explicit examples of SUGRA theories at the low-energy limit.

The soft terms are given in terms of the moduli fields, which characterise the size and shape of the compactified space.

The number of free parameters is reduced

• Are large neutralino detection cross sections still possible?

Large neutralino detection rates in general SUGRA

(a ~5 min. overview...)

The lightest Neutralino

- In the MSSM the mechanisms which allow for an increase in the detection cross section are well known

In the MSSM, the neutralino is a physical superposition of the $\tilde{B}$, $\tilde{W}$, $\tilde{H}_1$, $\tilde{H}_2$

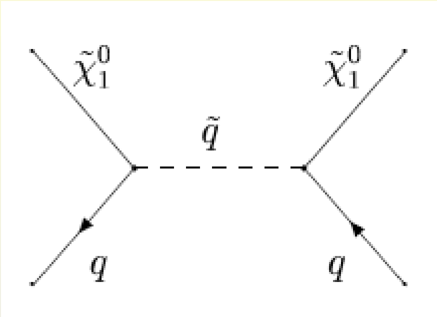
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 \end{pmatrix}$$

The detection properties of the neutralino depend on its composition

$$\tilde{\chi}_1^0 = \underbrace{N_{11}\,\tilde{B}^0 + N_{12}\,\tilde{W}_3^0}_{\text{Gaugino content}} + \underbrace{N_{13}\,\tilde{H}_d^0 + N_{14}\,\tilde{H}_u^0}_{\text{Higgsino content}}$$

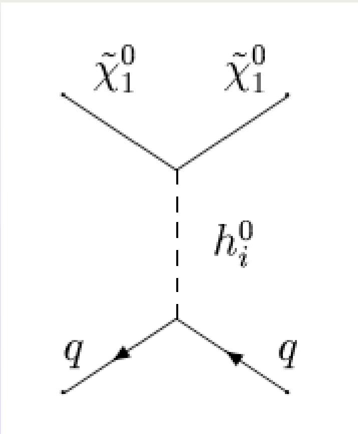
Large detection cross sections

- The scalar part of the cross section has two contributions



Squark-exchange

Higgs-exchange



Leading contribution. It can increase when

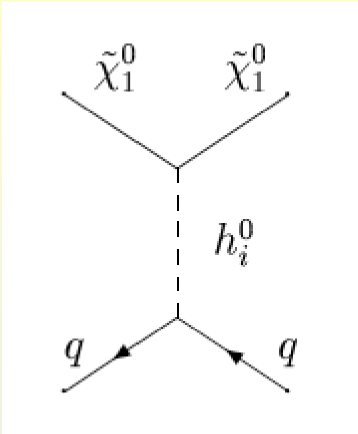
- The Higgsino components of the neutralino increase

$$\mu \downarrow$$

- The Higgs masses decrease

$$m_h,\ m_{H^0}\ m_{A^0} \downarrow$$

Large detection cross sections



<u>Higgs-exchange</u>

Leading contribution. It can increase when

- **The Higgsino components of the neutralino increase**

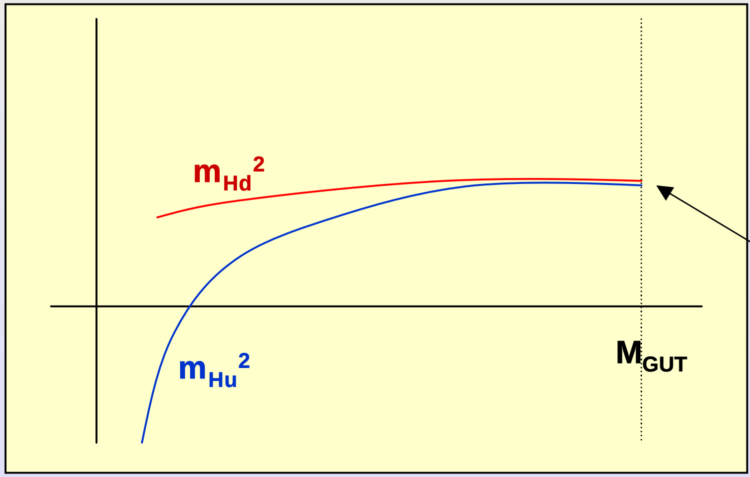
$$\mu \downarrow$$

- **The Higgs masses decrease**

$$m_h, \; m_{H^0} \; m_{A^0} \downarrow$$

<u>In terms of the mass parameters in the RGE</u>

$$m_A{}^2 \approx m_{H_d}^2 - m_{H_u}^2 - M_Z^2$$
$$\mu^2 \approx -m_{H_u}^2 - \tfrac{1}{2} M_Z^2$$



Non-universal soft terms, e.g., in the Higgs sector (NUHM)

$m_{Hu}{}^2 \Uparrow$

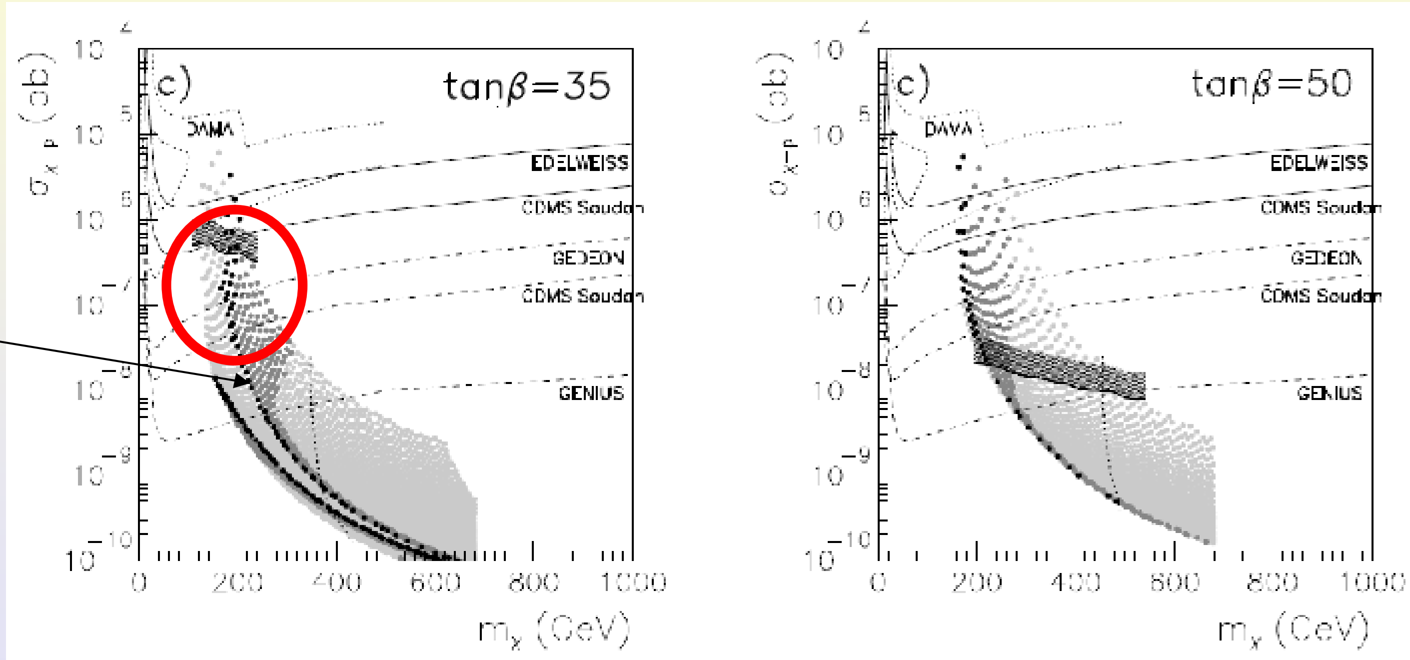
$m_{Hd}{}^2 \Downarrow$

Non-universal soft terms

- Example with non-universal Higgs masses at the GUT scale:

$$m_{H_u}^2 = 2m^2 \qquad m_{H_d}^2 = 0$$

Correct relic density

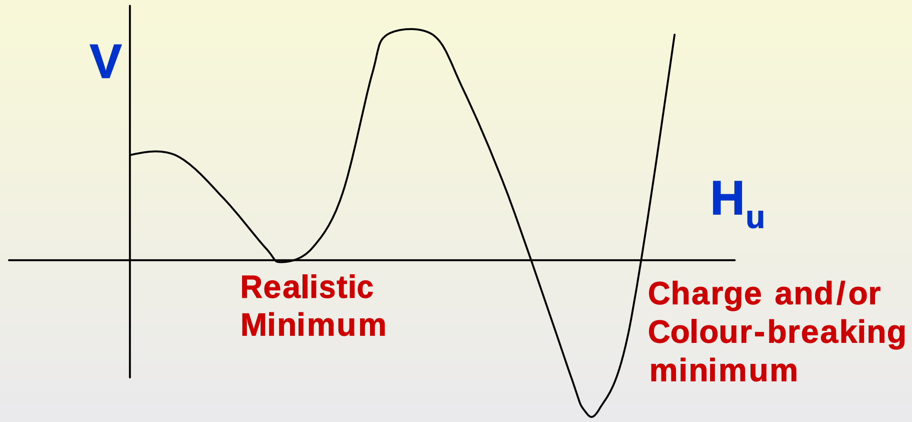


(S.Baek, D.G.C., G.Y.Kim, P.Ko, C.Muñoz´04)

▢	Experimentally allowed
■	Correct relic density

Charge and Colour breaking

The presence of scalar fields with Colour or Electric charge in SUSY theories may induce the occurrence of dangerous charge and colour-breaking minima, deeper than the realistic vacuum



The UFB-3 direction, where

$$\{H_u, \nu_{L_i}, e_{L_j}, e_{R_j}\}$$

take non-vanishing VEVs is the deepest one

The potential along the UFB-3 direction reads

Light sleptons ⇒ stronger constraints

$$V_{\rm UFB-3} \approx (m^2_{H_u} + m^2_{L_i})|H_u|^2 + \frac{|\mu|}{\lambda_{e_j}}({m_{L_j}}^2 + {m_{e_j}}^2 + m^2_{L_i})|H_u| - \frac{2m^4_{L_i}}{g'^2 + g_2^2}$$

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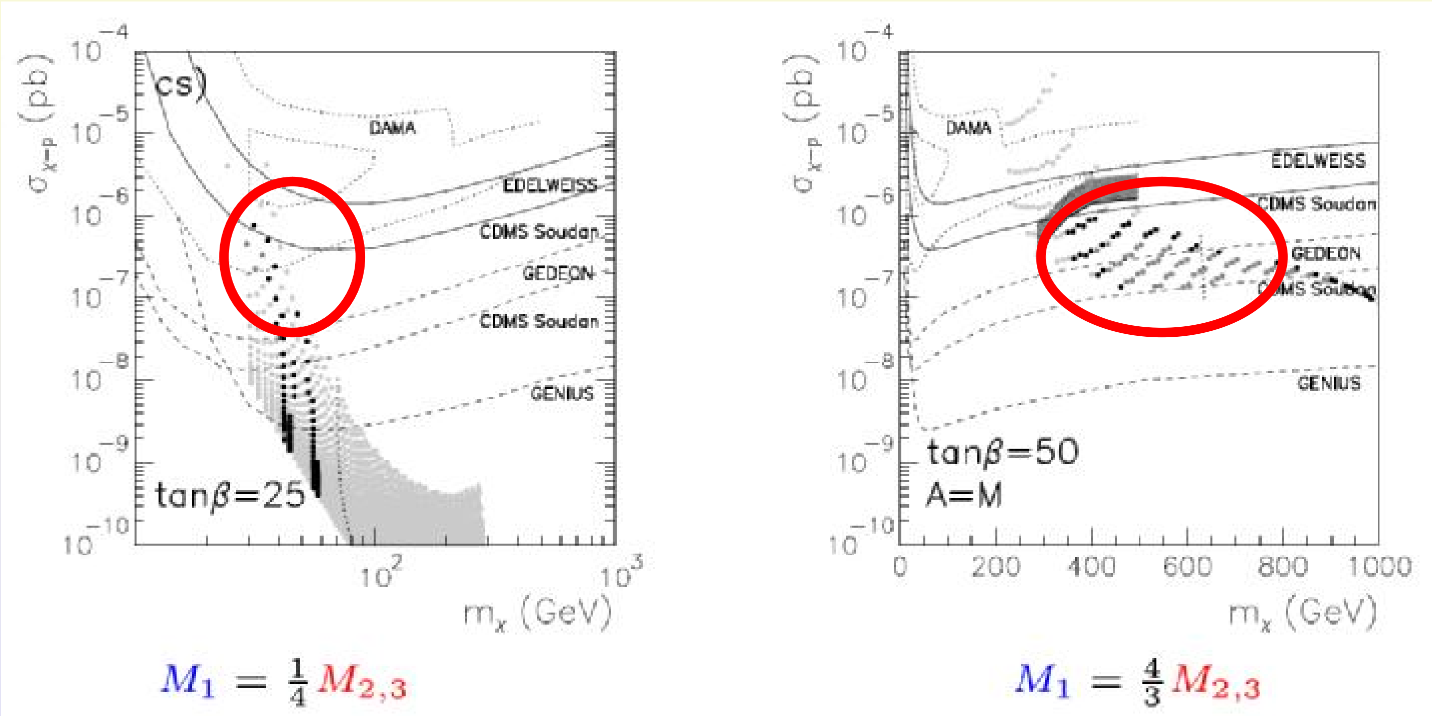
Non-universal soft terms

- **With non-universalities in both the scalar and gaugino sectors neutralinos in the detectable range can be obtained with masses of order 10-500 GeV**



Very light Bino-like neutralinos with masses ~10 GeV.

Heavy Higgsino-like neutralinos with masses ~500 GeV.

An explicit (and well motivated) example ...

The neutralino in Heterotic string scenarios

Role of constraints in the parameter space?

Are large neutralino detection cross sections attainable?

Heterotic Orbifolds

• After compactification of the Heterotic Superstring on a 6-dimensional orbifold, the resulting 4D Supergravity is described by:

$$f_a = k_a S$$

$$K = -\log(S+S^*) - \sum_i \log(T_i + T_i^*) + \sum_\alpha |C_\alpha|^2 \prod_i (T_i + T_i^*)^{n_\alpha^i}$$

From which the soft terms are calculated

• The breaking of SUSY is due to the auxiliary fields of the dilaton (S) and moduli (T_i) fields developing a VEV. A convenient parameterisation of these is

$$F^S = \sqrt{3} m_{3/2} (S+S^*) \sin\theta$$
$$F^{T_i} = \sqrt{3} m_{3/2} (T_i + T_i^*) \Theta_i \cos\theta$$

The Goldstino angle, θ , determines which is the field responsible for the breaking of SUSY.

Heterotic Orbifolds

- As a function of the gravitino mass, $m_{3/2}^2$, the Goldstino angle, θ , and the modular weights, n_i , the soft masses read

$$M = \sqrt{3}\, m_{3/2}^2 \sin\theta$$

$$m_i^2 = m_{3/2}^2 \left(1 + n_i \cos^2\theta\right)$$

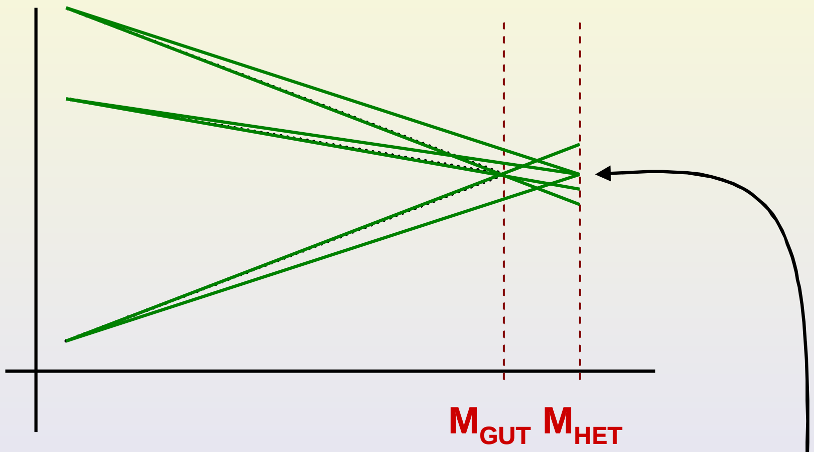
$$A_{\alpha\beta\delta} = -\sqrt{3}\, m_{3/2}^2 \sin\theta - m_{3/2}^2 \cos\theta \left(3 + n_\alpha + n_\beta + n_\delta\right)$$

- **Few free parameters,** $\left(m_{3/2}^2, \theta, n_i\right)$
- **Non-universal scalar masses**, in general, due to the effect of the modular weights
- **Gaugino masses larger than scalar masses**, $M > m_i$
- **The gravitino is not the LSP**, $m_{3/2} > M, m$

Heterotic Orbifolds

• In the heterotic superstring successful unification of the gauge couplings at $M_{GUT} \approx 2x10^{16}$ GeV is not automatic.

Instead, unification would take place at energies around $M_{HET} \approx 5x10^{17}$ GeV .



Large one-loop threshold corrections are needed in order to alter the RGEs and regain unification. These corrections can be obtained for particular choices of the modular weights of the fields.

(Ibáñez, Lüst, Ross 91)

Heterotic Orbifolds

The simplest possibility corresponds to the following choice of modular weights

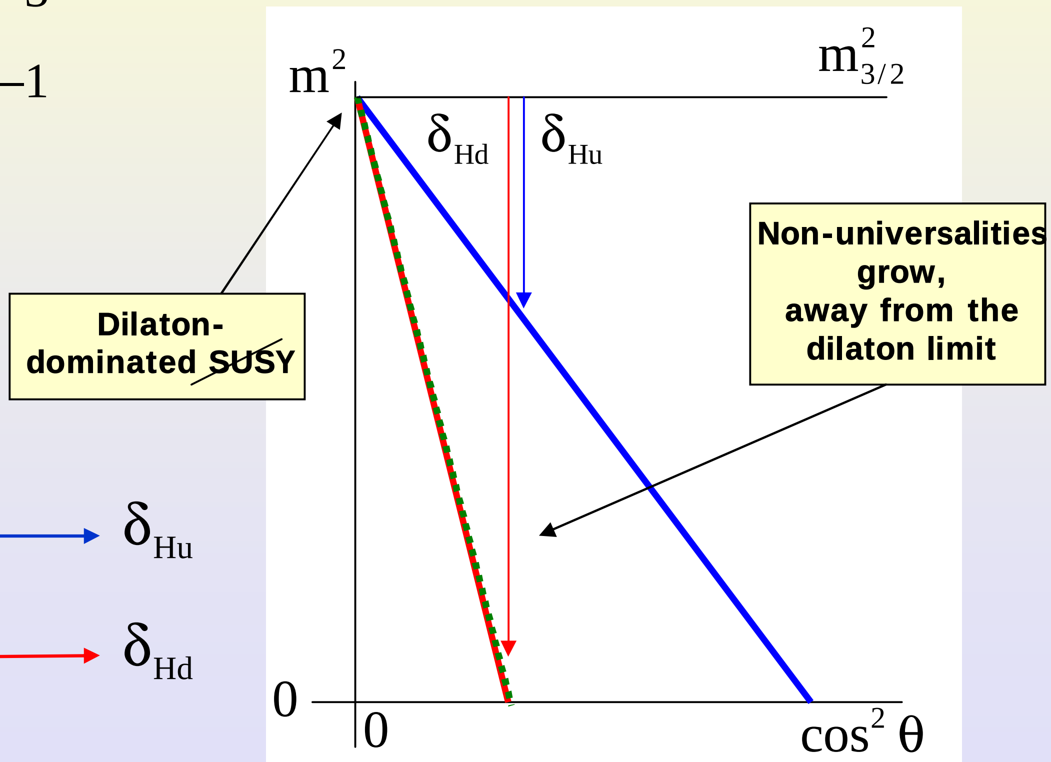
$$n_L = n_E = -3 \qquad n_U = -2 \qquad n_Q = n_D = -1 \qquad n_{Hu} + n_{Hd} = -5, -4$$

(Ibáñez, Lüst, Ross 91)

For instance, with $\begin{cases} n_{Hd} = -3 \\ n_{Hu} = -1 \end{cases}$

$$m^2_{L,E} = m^2_{3/2}\left(1 - 3\cos^2\theta\right)$$
$$m^2_U = m^2_{3/2}\left(1 - 2\cos^2\theta\right)$$
$$m^2_{Q,D} = m^2_{3/2}\left(1 - \cos^2\theta\right)$$

$$m^2_{Hu} = m^2_{3/2}\left(1 - \cos^2\theta\right) \rightarrow \delta_{Hu}$$
$$m^2_{Hd} = m^2_{3/2}\left(1 - 3\cos^2\theta\right) \rightarrow \delta_{Hd}$$



Heterotic Orbifolds

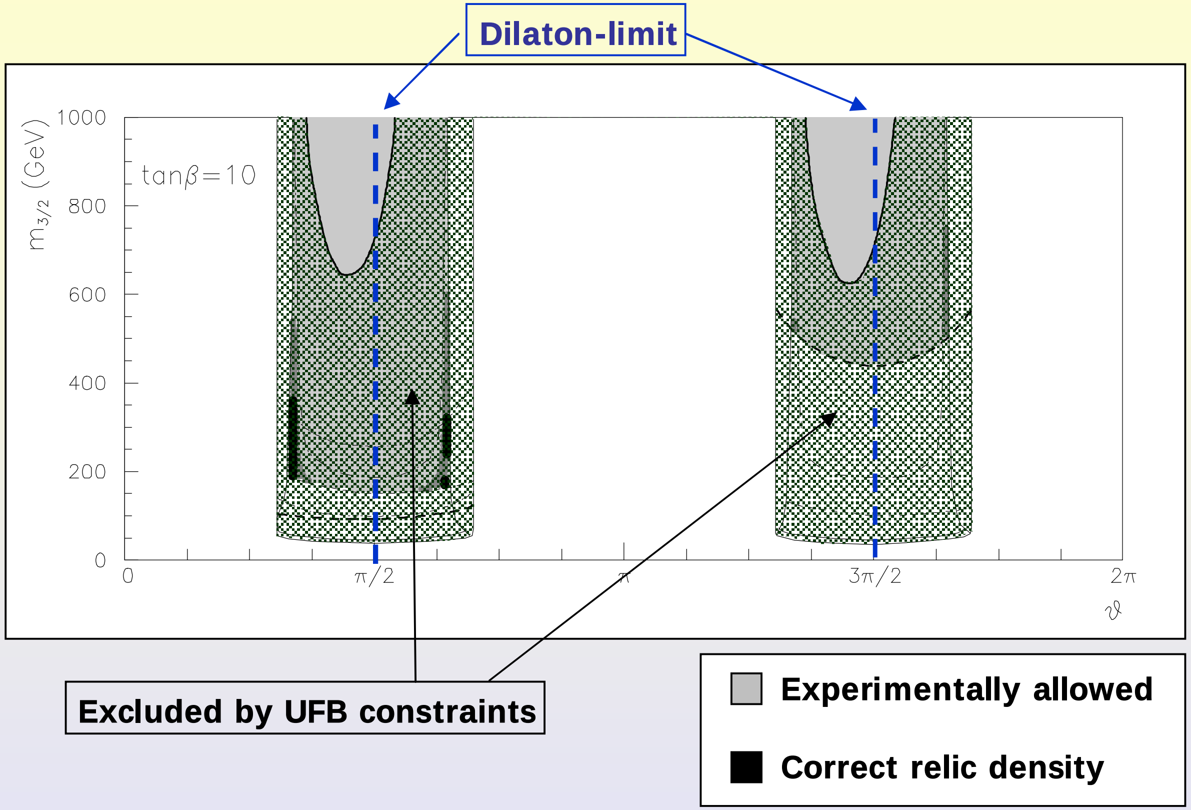
$$m^2_{L,E} = m^2_{3/2}\left(1-3\cos^2\theta\right)$$

$$m^2_{U} = m^2_{3/2}\left(1-2\cos^2\theta\right)$$

$$m^2_{Q,D} = m^2_{3/2}\left(1-\cos^2\theta\right)$$

$$m^2_{Hu} = m^2_{3/2}\left(1-\cos^2\theta\right)$$

$$m^2_{Hd} = m^2_{3/2}\left(1-3\cos^2\theta\right)$$



• The smallness of the slepton masses implies <u>strong UFB constraints</u>. Most of the parameter space is excluded for this reason.

Heterotic Orbifolds

$$m_{L,E}^2 = m_{3/2}^2\left(1-3\cos^2\theta\right)$$

$$m_U^2 = m_{3/2}^2\left(1-2\cos^2\theta\right)$$

$$m_{Q,D}^2 = m_{3/2}^2\left(1-\cos^2\theta\right)$$

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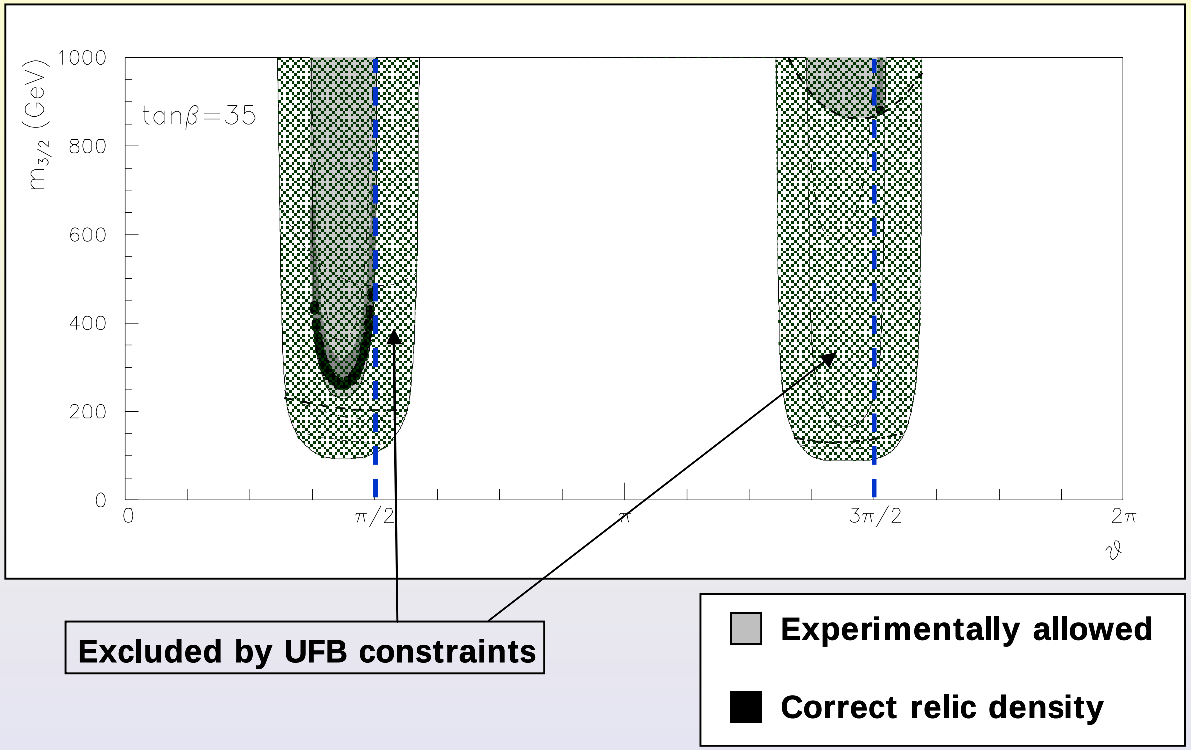
$$m_{Hd}^2 = m_{3/2}^2\left(1-3\cos^2\theta\right)$$



- The smallness of the slepton masses implies <u>strong UFB constraints</u>. Most of the parameter space is excluded for this reason.

- For larger values of tanβ the UFB constraints become more stringent and the whole parameter space is disfavoured

Heterotic Orbifolds

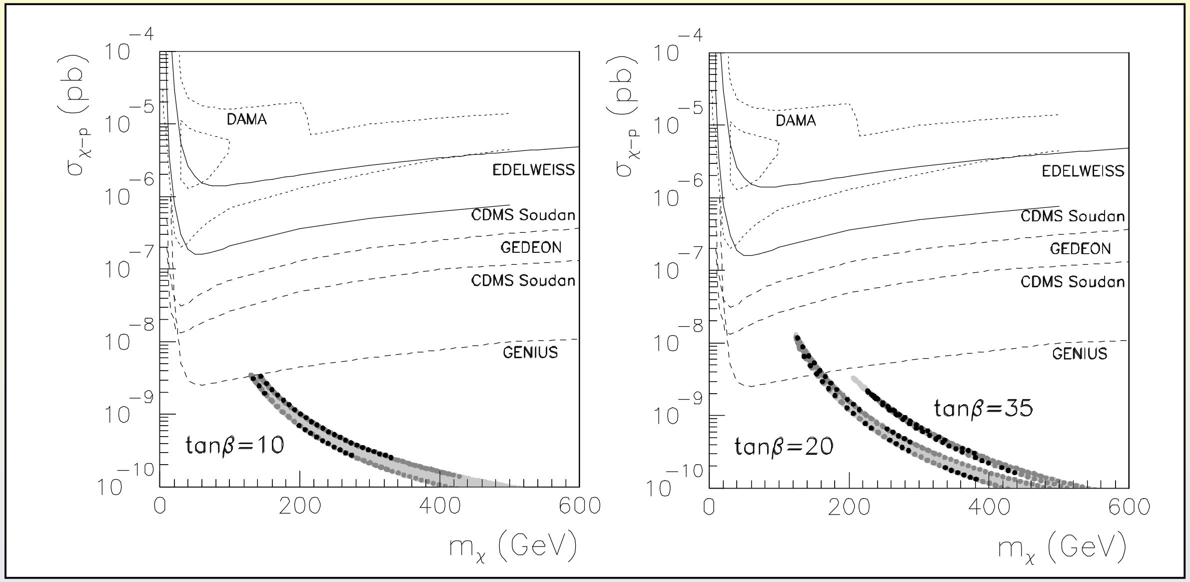
$$m^2_{L,E} = m^2_{3/2}\left(1 - 3\cos^2\theta\right)$$

$$m^2_{U} = m^2_{3/2}\left(1 - 2\cos^2\theta\right)$$

$$m^2_{Q,D} = m^2_{3/2}\left(1 - \cos^2\theta\right)$$

$$m^2_{Hu} = m^2_{3/2}\left(1 - \cos^2\theta\right)$$

$$m^2_{Hd} = m^2_{3/2}\left(1 - 3\cos^2\theta\right)$$



• **Even if we ignored the effect of the UFB constraints, the predictions for neutralino direct detection are <u>far from present and near-future sensitivities</u>.**

The neutralino is mostly Bino.

"Optimised Case"

We can think of an "optimised case" in which the slepton masses are increased in order to avoid UFB constraints:

$$n_L = n_E = -1 \qquad n_{Hd} = -3 \qquad n_{Hu} = -1$$

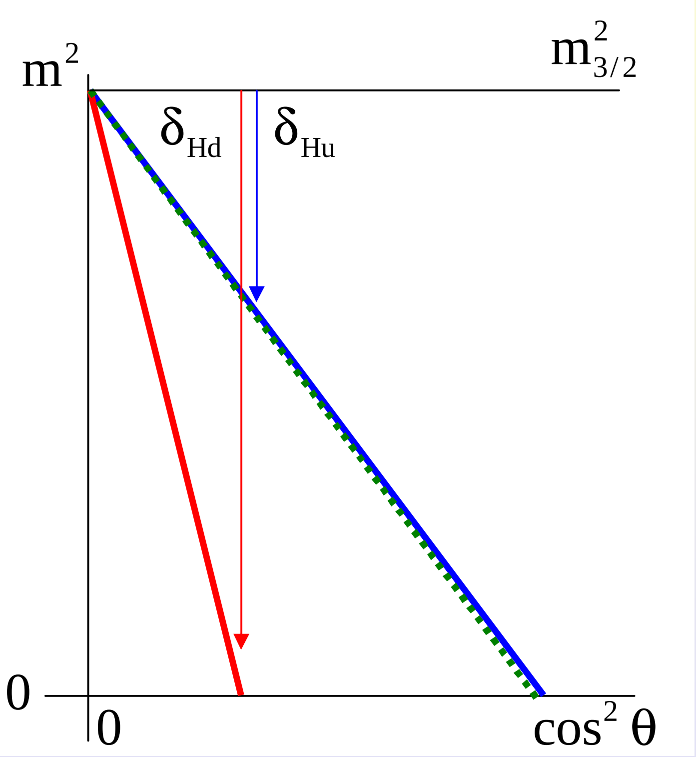
$$m^2_{L,E} = m^2_{3/2}\left(1-\cos^2\theta\right)$$

$$m^2_U = m^2_{3/2}\left(1-2\cos^2\theta\right)$$

$$m^2_{Q,D} = m^2_{3/2}\left(1-\cos^2\theta\right)$$

$$m^2_{Hu} = m^2_{3/2}\left(1-\cos^2\theta\right)$$

$$m^2_{Hd} = m^2_{3/2}\left(1-3\cos^2\theta\right)$$



"Optimised Case"

Due to the increase of the stau mass, the region excluded due to tachyons is reduced. Also, the UFB constraints are less stringent.

$$m^2_{L,E} = m^2_{3/2}\left(1-\cos^2\theta\right)$$

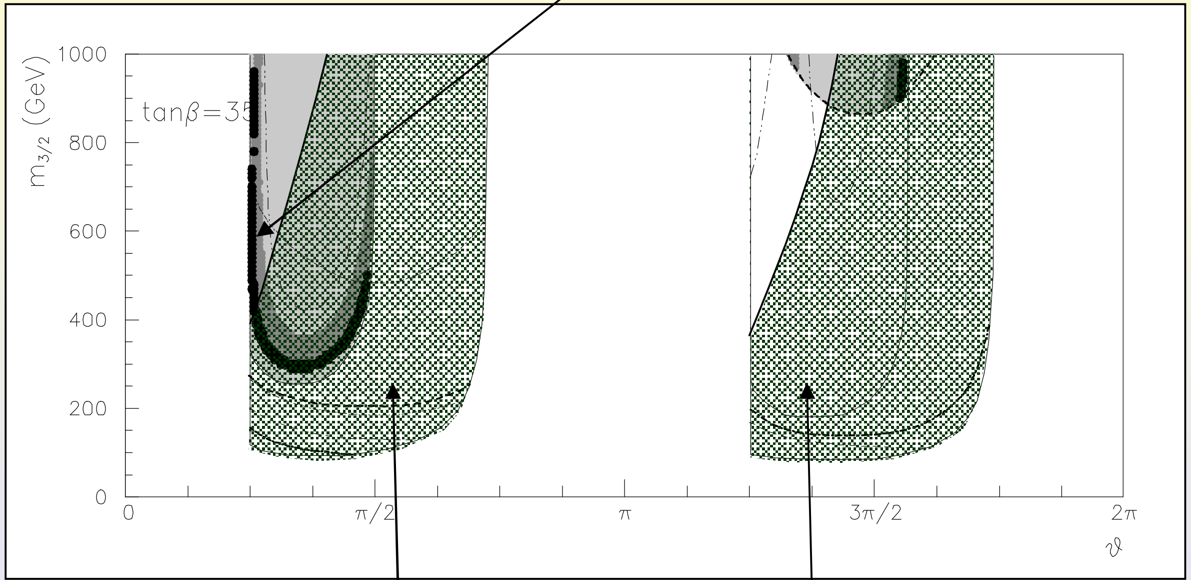
$$m^2_{U} = m^2_{3/2}\left(1-2\cos^2\theta\right)$$

$$m^2_{Q,D} = m^2_{3/2}\left(1-\cos^2\theta\right)$$

$$m^2_{Hu} = m^2_{3/2}\left(1-\cos^2\theta\right)$$

$$m^2_{Hd} = m^2_{3/2}\left(1-3\cos^2\theta\right)$$

Allowed region



Excluded by UFB constraints

- **Some regions allowed by the UFB constraints for tan**$\beta \geq 30$

"Optimised Case"

We can think of an "optimised case" in which the slepton masses are increased in order to avoid UFB constraints:

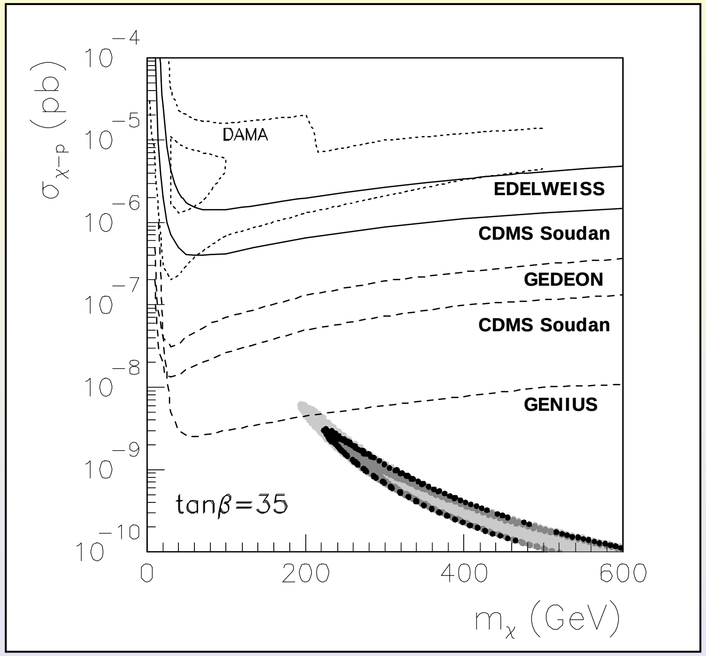
$$m_{L,E}^2 = m_{3/2}^2\left(1-\cos^2\theta\right)$$

$$m_U^2 = m_{3/2}^2\left(1-2\cos^2\theta\right)$$

$$m_{Q,D}^2 = m_{3/2}^2\left(1-\cos^2\theta\right)$$

$$m_{Hu}^2 = m_{3/2}^2\left(1-\cos^2\theta\right)$$

$$m_{Hd}^2 = m_{3/2}^2\left(1-3\cos^2\theta\right)$$



- **Some regions allowed by the UFB constraints for tan**$\beta \geq 30$
- **The predictions for** $\sigma_{\chi-p}$ **are still small. Due to the smallness of** m_{Hu}^2 **the neutralino is Bino-like**

Other cases

• **We have completed the analysis with other possible scenarios leading to unification of the gauge couplings with the same qualitative results.**

• **The non-universalities are always negative (negative modular weights)**

$$m_i^2 = m_{3/2}^2 \left(1 + n_i \cos^2 \theta\right)$$

Slepton masses are typically very small, thus leading to stringent UFB constraints

The Higgs mass parameter m_{Hu}^2 **cannot be efficiently increased, implying low** $\sigma_{\chi-p}$

D-term contribution

- **An anomalous U(1) is usually present in Heterotic string compactifications.**

Although its anomaly is cancelled by the Green-Schwartz mechanism, it generates a Fayet-Ilioupoulos contribution to the D-term. Some scalar fields develop large VEVs in order to cancel the FI term.

This generates and additional non-universality among the scalar masses, which depends on their U(1) charges (q_i)

$$m_i^2 = m_{3/2}^2\left(1 + n_i \cos^2\theta + \overbrace{\frac{q_i}{q_C}\left((6-n_C)\cos^2\theta - 5\right)}\right)$$

The non-universality can be large, even in the dilaton limit:

$$m_i^2 = m_{3/2}^2\left(1 - 5\frac{q_i}{q_C}\right)$$

It can even be positive if $\frac{q_i}{q_C} < 0$

- **Increase m_τ and help avoiding UFB constraints**
- **Increase m_{Hu} and help increasing the neutralino detection cross section**

D-term contribution

The non-universality ...

Can even be positive if $\frac{q_i}{q_C} < 0$

- **Increase m_τ and help avoiding UFB constraints**

For example, using the previous modular weights but assuming $\frac{q_\tau}{q_C} = -2$

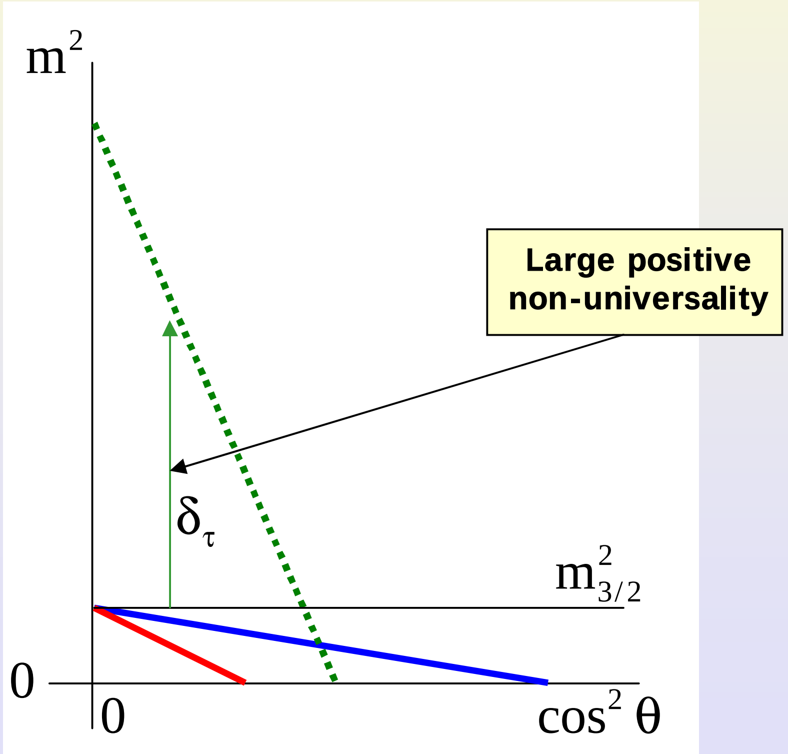
$$m^2_{L,E} = m^2_{3/2}\left(11 - 19\cos^2\theta\right)$$

$$m^2_U = m^2_{3/2}\left(1 - 2\cos^2\theta\right)$$

$$m^2_{Q,D} = m^2_{3/2}\left(1 - \cos^2\theta\right)$$

$$m^2_{Hu} = m^2_{3/2}\left(1 - \cos^2\theta\right)$$

$$m^2_{Hd} = m^2_{3/2}\left(1 - 3\cos^2\theta\right)$$



D-term contribution

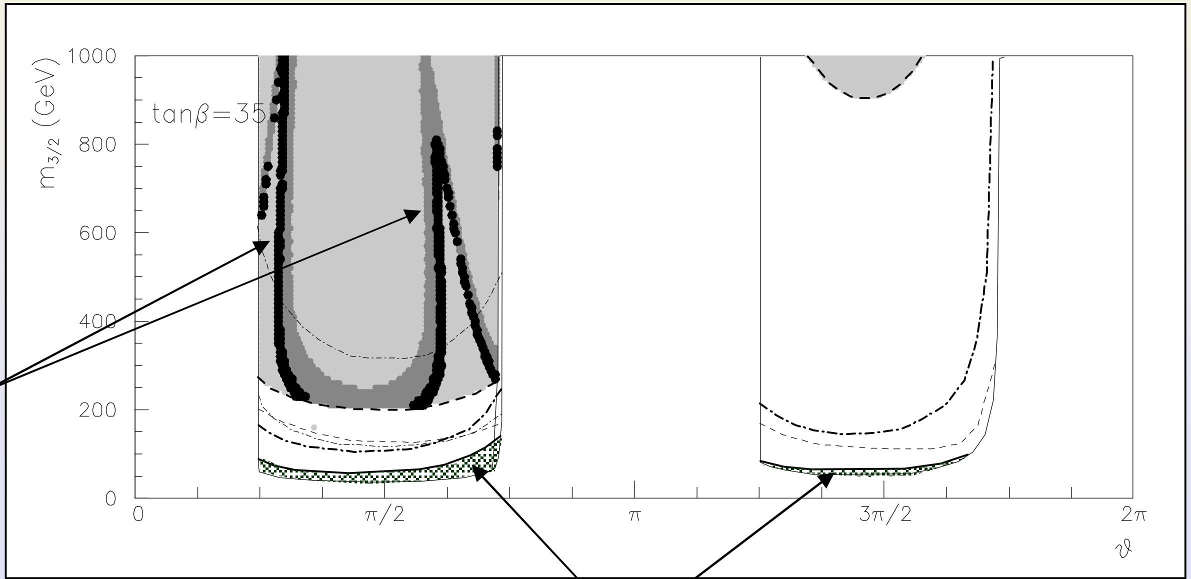
The non-universality ...

Can even be positive if $\frac{q_\tau}{q_C} < 0$

- **Increase m_τ and help avoiding UFB constraints**

For example, using the previous modular weights but assuming $\frac{q_\tau}{q_C} = -2$

- **Most of the parameter space allowed by UFB costraints**
- **Larger values of tanβ are permitted**
- **Correct relic density without the need of coannihilations (smaller pseudoscalar mass)**



Excluded by UFB constraints

D-term contribution

The non-universality …

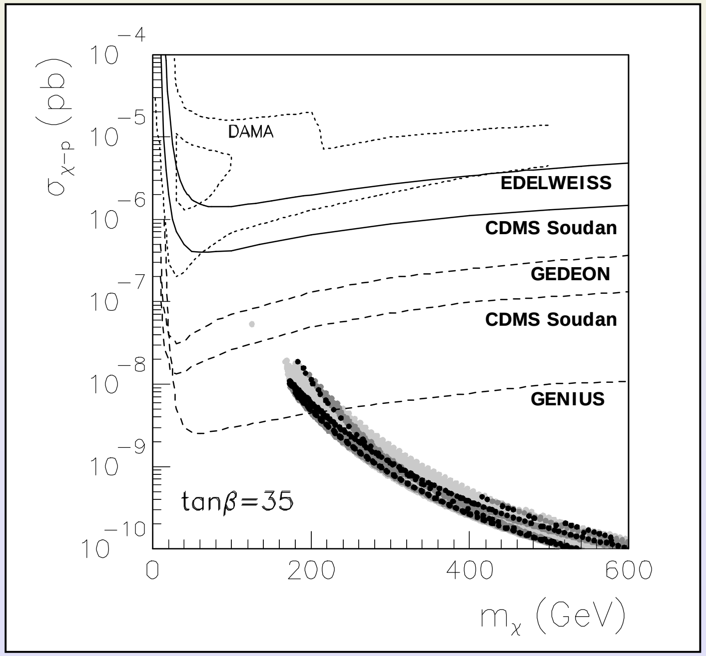
Can even be positive if $\frac{q_\tau}{q_C} < 0$

- **Increase m_τ and help avoiding UFB constraints**

For example, using the previous modular weights but assuming $\frac{q_\tau}{q_C} = -2$

- **However, the detection cross section does not increase much.**

The smallness of m^2_{Hu} implies that the neutralino is mostly Bino.



D-term contribution

The non-universality …

Can even be positive if $\frac{q_i}{q_C} < 0$

- **Increase m_τ and help avoiding UFB constraints**
- **Increase m_{Hu} and help increasing the neutralino detection cross section**

For example, assuming now $\frac{q_\tau}{q_C} = \frac{q_{Hu}}{q_C} = -2$

$$m_{L,E}^2 = m_{3/2}^2 \left(11 - 19\cos^2\theta\right)$$ ↑

$$m_U^2 = m_{3/2}^2 \left(1 - 2\cos^2\theta\right)$$

$$m_{Q,D}^2 = m_{3/2}^2 \left(1 - \cos^2\theta\right)$$

$$m_{Hu}^2 = m_{3/2}^2 \left(11 - 17\cos^2\theta\right)$$ ↑

$$m_{Hd}^2 = m_{3/2}^2 \left(1 - 3\cos^2\theta\right)$$

D-term contribution

The non-universality ...

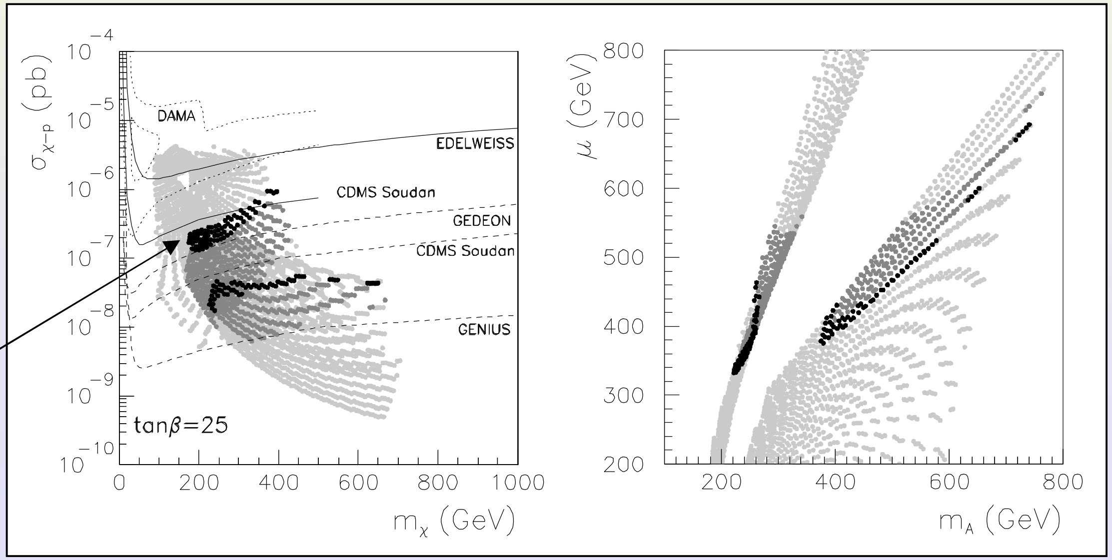
Can even be positive if $\frac{q_i}{q_C} < 0$

- Increase m_τ and help avoiding UFB constraints
- Increase m_{Hu} and help increasing the neutralino detection cross section

For example, assuming now $\frac{q_\tau}{q_C} = \frac{q_{Hu}}{q_C} = -2$

- Thanks to the increase in m^2_{Hu}, the Higgsino components of the neutralino increase.

Large detection cross sections become possible, fulfilling all the experimental and astrophysical constraints.



D-term contribution

The non-universality …

Can even be positive if $\frac{q_i}{q_C} < 0$

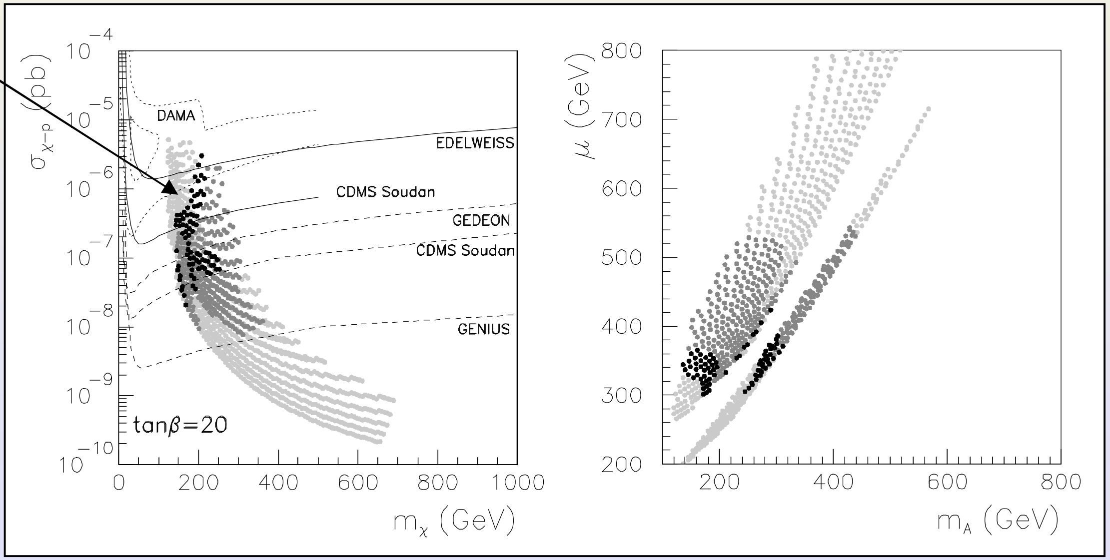
Or more negative with $\frac{q_i}{q_C} > 0$

- **Increase m_τ and help avoiding UFB constraints**
- **Increase m_{Hu} and help increasing the neutralino detection cross section**
- **Decrease m_{Hd} (and therefore the Higgs masses), thus increasing the neutralino detection cross section**

- **Further decreasing m^2_{Hu} leads to a decrease of the Higgs masses and implies an extra increase of $\sigma_{\chi-p}$**

$$\frac{q_\tau}{q_C} = \frac{q_{Hu}}{q_C} = -2$$

$$\frac{q_{Hd}}{q_C} = \frac{1}{2}$$



Conclusions

• The identification of dark matter is still an open problem pointing towards physics beyond the SM, Supersymmetric dark matter being one of the most attractive possibilities.

The lightest neutralino in general SUGRA theories could explain a hypothetical detection of WIMP dark matter in the next generation experiments due to non-universalities in the scalar masses.

• SUGRA scenarios arising from compactifications of the Heterotic String

– The parameter space is very constrained by tachyons in the scalar sector, as well as by experimental and astrophysical constraints.

– The smallness of the scalar masses implies stringent UFB constraints

– The presence of an anomalous U(1) ameliorates the behaviour under UFB constraints and allows for larger non-universalities in the Higgs sector.

As a consequence, large neutralino detection cross sections can be obtained, within the reach of present experiments.