SUSY GUTs, DM and the LHC

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Collaborators [JCAP 1603 (2016) and in progress]

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Outline

- No SUSY signal at the LHC (talks by G. Landsberg, J. Mamuzic)
  Severe constraints on at least the simplest realisations of susy

- Still, we need to go beyond the SM, due to
  - *Neutrino masses & mixing*
  - *Baryon asymmetry in the universe*
  - *Origin of dark matter*
  - *Large number of arbitrary parameters (mostly in mass sector)*
  - *Hierarchy problem, **especially if further unification exists***

  In this respect, SUSY GUTs have very attractive features

- Non-minimal SUSY extensions
  - Break unification conditions of minimal schemes &/or
  - add new particles and interactions *(softer fitting constraints)*

- Combine GUTs, SUSY and Flavour Symmetries
- Different predictions in various GUTs

  SO(10), Pati-Salam *[NUHM]*

  SU(5), Flipped SU(5) *[non-universal sfermions]*
- ***Can we distinguish different scenarios***?
- **What are the expected *sparticle correlations in each scheme?***

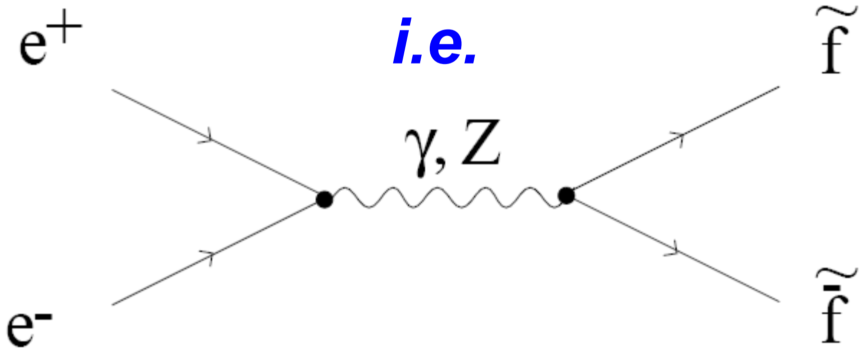
  Several constraints from DM considerations

  What can the LHC tell us on the underlying symmetries?

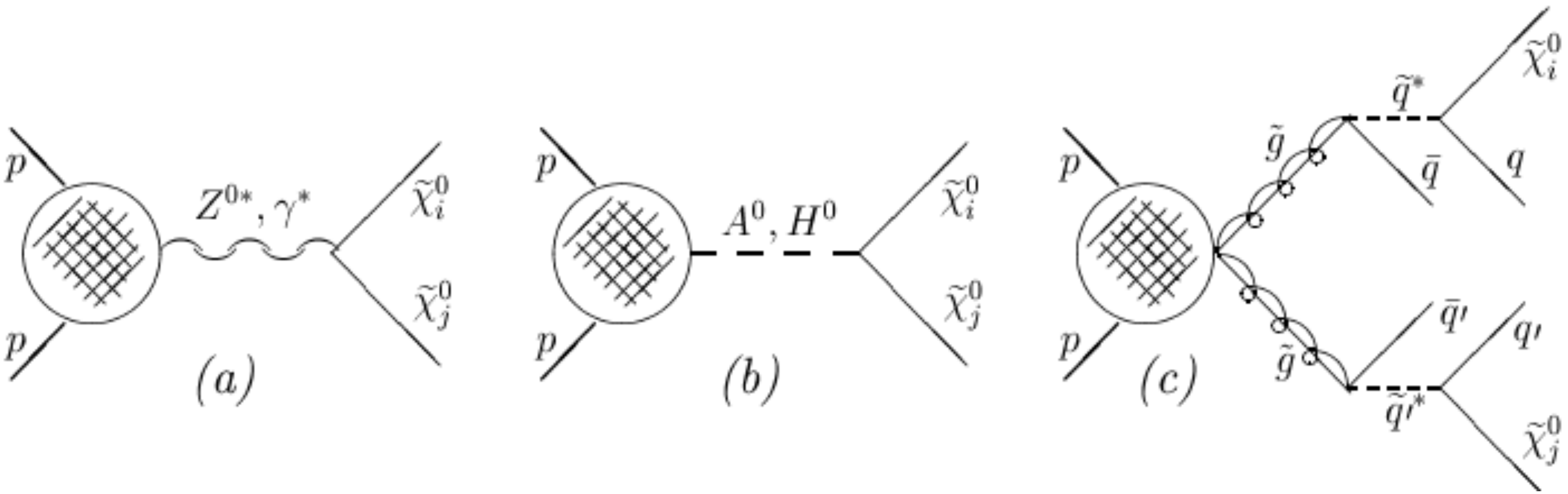
SUSY – new particles and interactions

Minimal SUSY Lagrangian– very simple rule: all SM interactions
+ those where 2 particles are substituted by antiparticles

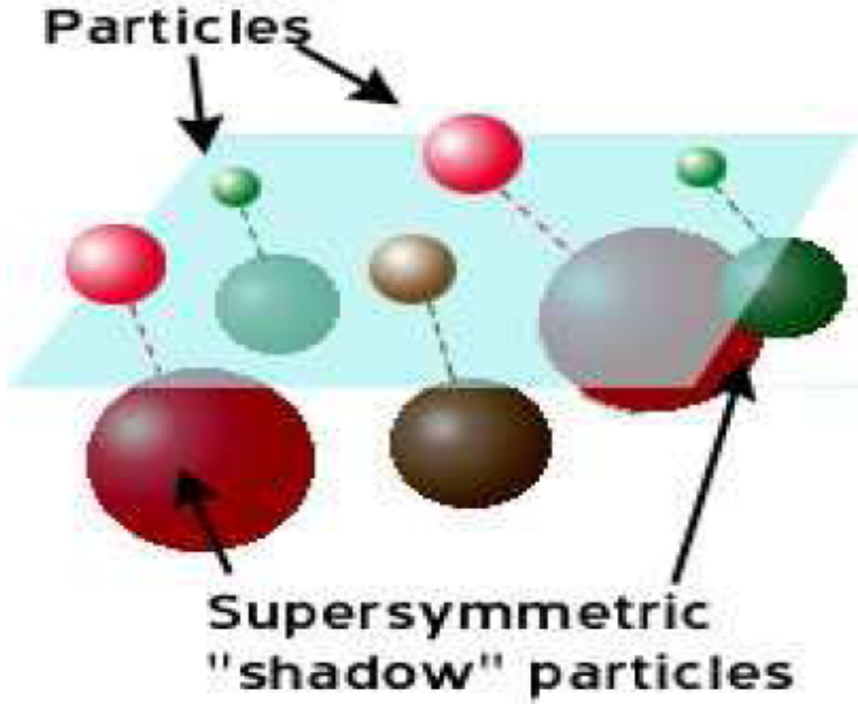
i.e.



Simplest SUSY models:
- *Missing Energy Signature*
- *LSP as Dark Matter (one of our basic requirements)*



Soft SUSY breaking terms



Inspired from supergravity assume universal soft breaking, $\mathcal{L}_{\text{soft}}$:

$$\sum_{\tilde{f},H} m_0^2 \tilde{f}\tilde{f} + \sum_{\lambda} m_{\frac{1}{2}} \lambda\lambda + \sum_{\tilde{f}} A_0 Y_f \tilde{f}\tilde{F} H_f + B\mu H_u H_d$$

m_0, $m_{\frac{1}{2}}$, A_0, $\tan\beta$, sign(μ)

The simplest models may be too restrictive

To search for/exclude SUSY unification need to first consider several alternative possibilities

Vast number of models
How to distinguish between them?

Try to address at the same time the origin of mass, combining GUT and flavour symmetries

Fermion hierarchies from flavour symmetries

(i.e. Why the top quark mass so much larger?)

A family symmetry generates the observed hierarchies

	Q_i	$\bar{U}_i$	$\bar{D}_i$	L_i	$\bar{E}_i$	H_2	H_1
$U(1)$	a_i	a_i	a_i	b_i	b_i	$-2a_3$	wa_3

Charges such that only 3 generation masses allowed

(0 flavour charges for 3rd generation)

The rest of the terms appear once the symmetry is broken

Frogatt-Nielsen mechanism

$$Q_i \bar{U}_j H_2 (<\theta> / M)^n$$

n depending on flavour charges

Similarly for other fermions, including neutrinos

$SU(5)$

(i) Assume the family symmetry is combined with $SU(5)$

(ii) Use the GUT structure ONLY to constrain $U(1)$ charges

Under this group we have the following relations:

$$
\begin{aligned}
Q_{(q,u^c,e^c)_i} &= Q_i^{10} \\
Q_{(l,d^c)_i} &= Q_i^{\bar{5}} \\
Q_{(\nu_R)_i} &= Q_i^{\nu_R}
\end{aligned}
$$

- M_{up} symmetric
- $M_{\ell^\pm} = M_{down}^T$
- L lepton mixing $\approx$ R down-quark one

$$Q_{1,2,3} = \bar{E}_{1,2,3} = 3, 2, 0$$

$$\bar{D}_{1,2,3} = L_{1,2,3} = 1, 0, 0$$

SL, Ross

$$\frac{M_u}{m_t} = \begin{pmatrix} \bar\epsilon^6 & \bar\epsilon^5 & \bar\epsilon^3 \\ \bar\epsilon^5 & \bar\epsilon^4 & \bar\epsilon^2 \\ \bar\epsilon^3 & \bar\epsilon^2 & 1 \end{pmatrix}, \quad \frac{M_{down}}{m_b} = \begin{pmatrix} \bar\epsilon^4 & \bar\epsilon^3 & \bar\epsilon^3 \\ \bar\epsilon^3 & \bar\epsilon^2 & \bar\epsilon^2 \\ \bar\epsilon & 1 & 1 \end{pmatrix}$$

$$\frac{M_\ell}{m_\tau} = \begin{pmatrix} \bar\epsilon^4 & \bar\epsilon^3 & \bar\epsilon \\ \bar\epsilon^3 & \bar\epsilon^2 & 1 \\ \bar\epsilon^3 & \bar\epsilon^2 & 1 \end{pmatrix}, \quad m_{eff} \propto \begin{pmatrix} \bar\epsilon^2 & \bar\epsilon & \bar\epsilon \\ \bar\epsilon & 1 & 1 \\ \bar\epsilon & 1 & 1 \end{pmatrix}$$

$SO(10)$

- All L- and R-handed fermions in the 16 of $SO(10)$
- Both MSSM Higgs fields fit in a single 10 of $SO(10)$ $\Downarrow$

For all fermions, *L-R symmetric textures*, similar structure (different expansion parameters due to Higgs mixing)

Flipped $SU(5)$

$$Q_{(q,d^c,\nu^c)_i} = Q_i^{10}, \quad Q_{(l,u^c)_i} = Q_i^{\bar{5}}, \quad e^c \text{ singlet of } SU(5)$$

- Symmetric M_{down}
- $m_\nu^D = M_{up}^T$

Pati-Salam Unification

-Lepton number a 4th color – thus unifying quarks and leptons

-L-R symmetry $\mathbf{16} \xrightarrow{\text{PS}} (\mathbf{4}, \mathbf{2}, \mathbf{1}) + (\overline{\mathbf{4}}, \mathbf{1}, \mathbf{2})$

$SU(4)_C \times SU(2)_L \times SU(2)_R$

Fermions embedded as follows:

chirality	$SU(4)_c$			
	$SU(3)_c$			
	r	y	b	ℓ
L	u^r	u^y	u^b	ν_e^ℓ
	d^r	d^y	d^b	$e^{-\ell}$
R	u^r	u^y	u^b	ν_e^ℓ
	d^r	d^y	d^b	$e^{-\ell}$

u_r	u_g	u_b	ν_e
d_r	d_g	d_b	e
u^c_r	u^c_g	u^c_b	ν^c_e
d^c_r	d^c_g	d^c_b	e^c

$$F^{i\alpha a} = (4,2,1) = \begin{pmatrix} u^R & u^B & u^G & \nu \\ d^R & d^B & d^G & e^- \end{pmatrix}^i$$

$$\overline{F}^i_{x\alpha} = (\bar{4},1,\bar{2}) = \begin{pmatrix} \bar{d}^R & \bar{d}^B & \bar{d}^G & e^+ \\ \bar{u}^R & \bar{u}^B & \bar{u}^G & \bar{\nu} \end{pmatrix}^i$$

$$H^{\alpha b} = (4,1,2) = \begin{pmatrix} u_H^R & u_H^B & u_H^G & \nu_H \\ d_H^R & d_H^B & d_H^G & e_H^- \end{pmatrix}$$

$$\overline{H}_{\alpha x} = (\bar{4},1,\bar{2}) = \begin{pmatrix} \bar{d}_H^R & \bar{d}_H^B & \bar{d}_H^G & e_H^+ \\ \bar{u}_H^R & \bar{u}_H^B & \bar{u}_H^G & \bar{\nu}_H \end{pmatrix}$$

$$< H > \equiv < \nu_H > \qquad < \overline{H} > \equiv < \bar{\nu}_H >$$

MINIMAL MODIFICATIOS TO SOFT TERM UNIVERSALITY:

Non Universal SO(10)

$$W_{SO(10)} = \lambda^u_{ij} 16_i 10^u 16_j + \lambda^d_{ij} 16_i 10^d 16_j$$

$$Q_L, D, U, L, E, N \subseteq 16$$

$$H_u \subset 10^u ; H_u \subset 10^u$$

The soft term masses are taken at GUT as:

$$m_{16} = m_0 ; m_u = x_u m_0 ; m_d = x_d m_0 ;$$

Equivalent to NUHM

Trilinear terms:

$$A_0 = a_0 m_0$$

- ***Fermion fields in the same 16***
- ***2 Higgs fields in different 10 representations***

Non Universal SU(5)

$$W_{SU(5)} = Y_u^{ij} 10_i 10_j 5^u + Y_d^{ij} 10_i \bar{5}_j \bar{5}^d$$

$$(Q_L, U, E) \subseteq 10$$

$$H_u \subset 5^u ; H_d \subset \bar{5}^d$$

$$(D, L) \subseteq \bar{5}$$

The soft terms are taken at GUT as:

$$m_{10} = m_0 ;$$
$$m_5 = x_5 \cdot m_{10} ;$$
$$m_u = x_u \cdot m_{10} ;$$
$$m_d = x_d \cdot m_{10}.$$

$$A_{10,5} = a_0 \cdot m_{0,}$$

Okada, Shafi, Raza

Phys.Rev. D90 (2014)

- ***Fermions in different representations***
- ***2 Higgs fields in different 10 representations***

Ellis, Mustafaev, Olive, Velasco-Sevilla

Flipped SU(5) - versus SU(5)

SU(5) $(Q, u^c, e^c)_i \in \mathbf{10}_i\,,\ (L, d^c)_i \in \bar{\mathbf{5}}_i\,,\ \nu_i^c \in \mathbf{1}_i\,.$

Flipped SU(5) $(Q, d^c, \nu^c)_i \in \mathbf{10}_i\,,\ (L, u^c)_i \in \bar{\mathbf{5}}_i\,,\ e_i^c \in \mathbf{1}_i\,.$

$$m_{10} = m_0, \quad m_5 = x_5 \cdot m_{10} \quad m_R = x_R \cdot m_{10}$$

$$m_{H_u} = x_u \cdot m_{10} \quad m_{H_d} = x_d \cdot m_{10} \,;$$

Different field assignment in representations – different predictions

(i.e. more freedom with stop masses as compared to SO(10), SU(5))

Could have gone even further *(model dependent)*
Flavour symmetries determine soft SUSY terms

$$\mathcal{L}_{m^2} = m_0^2(\phi_1^*\phi_1 + \phi_2^*\phi_2 + \phi_3^*\phi_3 + \left(\frac{\langle\theta\rangle}{M_{\rm fl}}\right)^{q_2-q_1}\phi_1^*\phi_2 + \left(\frac{\langle\theta\rangle}{M_{\rm fl}}\right)^{q_3-q_1}\phi_1^*\phi_3 + \left(\frac{\langle\theta\rangle}{M_{\rm fl}}\right)^{q_3-q_2}\phi_2^*\phi_3 + \text{h.c.}).$$

L-R symmetric

$$\begin{pmatrix} 1 & \tilde{\epsilon}^{|a+2b|} & \tilde{\epsilon}^{|a+b|} \\ \tilde{\epsilon}^{|a+2b|} & 1 & \tilde{\epsilon}^{|b|} \\ \tilde{\epsilon}^{|a+b|} & \tilde{\epsilon}^{|b|} & 1 \end{pmatrix}$$

SU(5)

$$\mathbf{E}_L \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^2 \\ \lambda^2 & 1 & 1 \\ \lambda^2 & 1 & 1 \end{pmatrix} \quad \mathbf{E}_R \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\begin{aligned} Q_{(q,u^c,e^c)_i} &= Q_i^{10} \\ Q_{(l,d^c)_i} &= Q_i^{\bar{5}} \\ Q_{(\nu_R)_i} &= Q_i^{\nu_R} \end{aligned}$$

$$\frac{M_\ell}{m_\tau} = \begin{pmatrix} \bar{\epsilon}^4 & \bar{\epsilon}^3 & \bar{\epsilon} \\ \bar{\epsilon}^3 & \bar{\epsilon}^2 & 1 \\ \bar{\epsilon}^3 & \bar{\epsilon}^2 & 1 \end{pmatrix}$$

L: (1,0,0)
R: (3,2,0)

Dark Matter –various possibilities

Higgsino χ_1^0:

$$h_f > 0.1, \quad |m_A - 2m_\chi| > 0.1\, m_\chi .$$

$$h_f \equiv |N_{13}|^2 + |N_{14}|^2 ,$$

A/H resonances:

$$|m_A - 2m_\chi| \leq 0.1\, m_\chi .$$

$\tilde{\tau}$ coannihilations:

$$h_f < 0.1, \quad (m_{\tilde{\tau}_1} - m_\chi) \leq 0.1\, m_\chi$$

$\tilde{\tau} - \tilde{\nu}_\tau$ coannihilations:

$$h_f < 0.1, \quad (m_{\tilde{\tau}_1} - m_\chi) \leq 0.1\, m_\chi, \quad (m_{\tilde{\mu}_1} - m_\chi) \leq 0.1\, m_\chi .$$

$\tilde{t}_1$ coannihilations:

$$h_f < 0.15, \quad (m_{\tilde{t}_1} - m_\chi) \leq 0.1\, m_\chi .$$

Set 1
$100\ \text{GeV} \leq m_0 \leq 10\ \text{TeV}$
$50\ \text{GeV} \leq m_{1/2} \leq 10\ \text{TeV}$
$-10\ \text{TeV} \leq A_0 \leq 10\ \text{TeV}$
$2 \leq \tan\beta \leq 65$
Set 2
$100\ \text{GeV} \leq m_0 \leq 2500\ \text{GeV}$
$50\ \text{GeV} \leq m_{1/2} \leq 2500\ \text{GeV}$
$-10\ \text{TeV} \leq A_0 \leq 10\ \text{TeV}$
$2 \leq \tan\beta \leq 65$

Parameter space scans with 2 sets:

Set 1 is broader, up to 10 TeV
Combined data accommodated easier with a heavy spectrum and Higgsino LSP

Set 2 zooms to the lower mass spectrum where co-annihilations are expected

Complex computations:

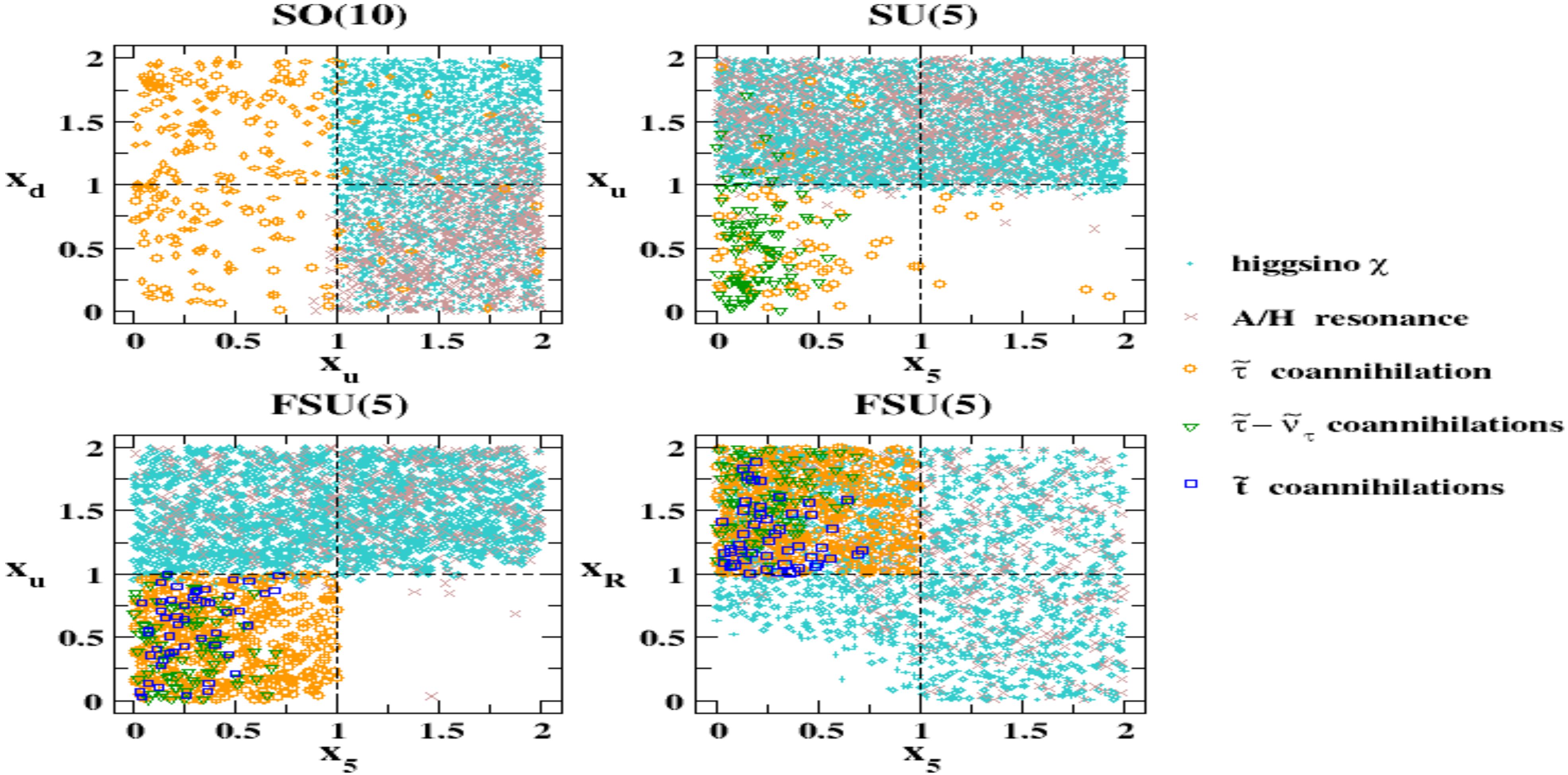
→ *SUSY Search: SuperBayeS, MultiNest*

→ *RGE's: SoftSusy*

→ *Relic Density: MicroOMEGAs*

→ *Direct DM detection: DarkSUSY*

→ *SusyBSG: B-Physics*



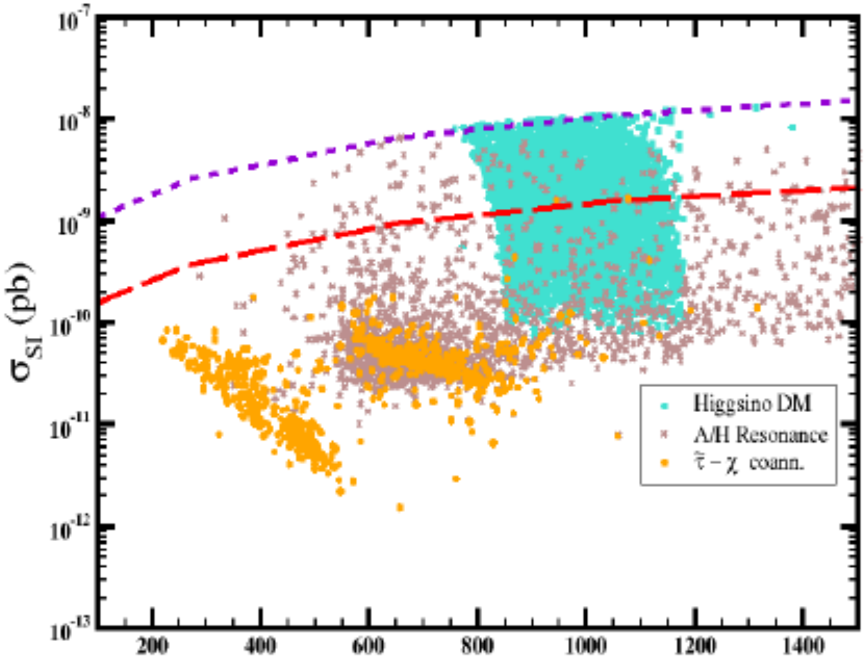
Correlations between the non-universal soft scalar masses
and DM in different SUSY GUTS

(CMSSM fpr xu,d,5,R = 1 / too restrictive)

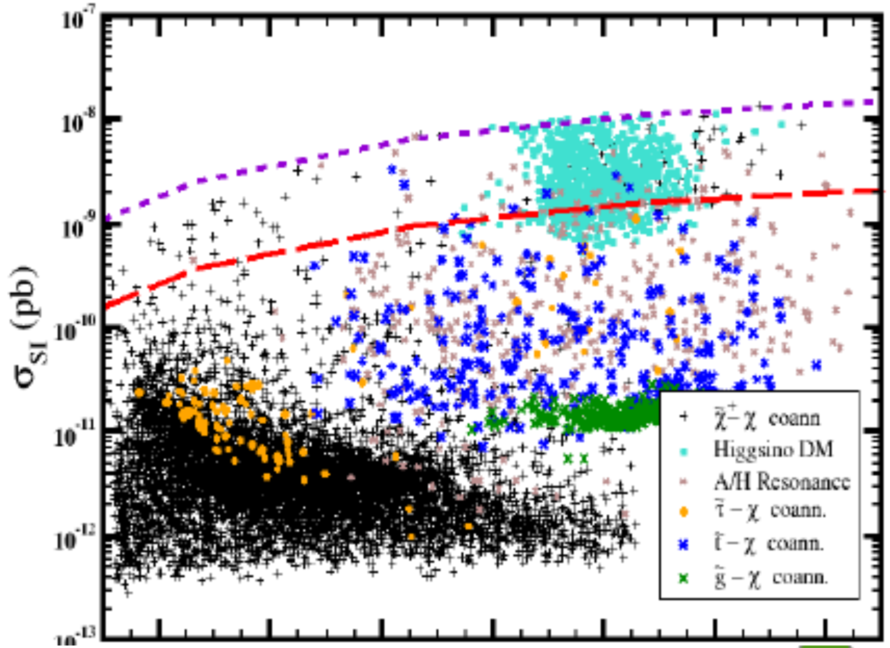
SO(10) [and SU(5)]: stop mass tends to become very heavy

Flipped SU(5)]: stop-coannihilations possible

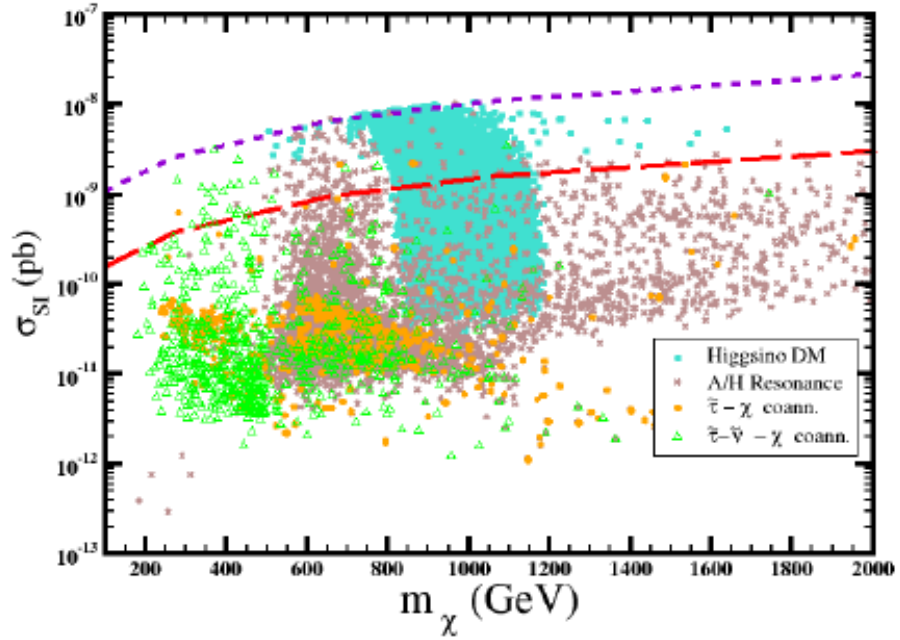
SO(10)



PS(4-2-2)

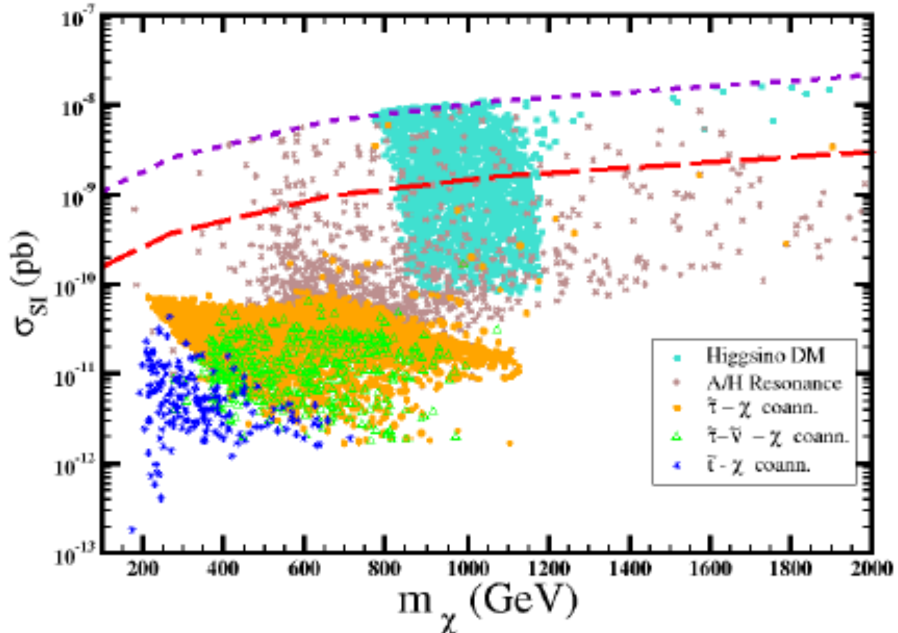


SU(5)

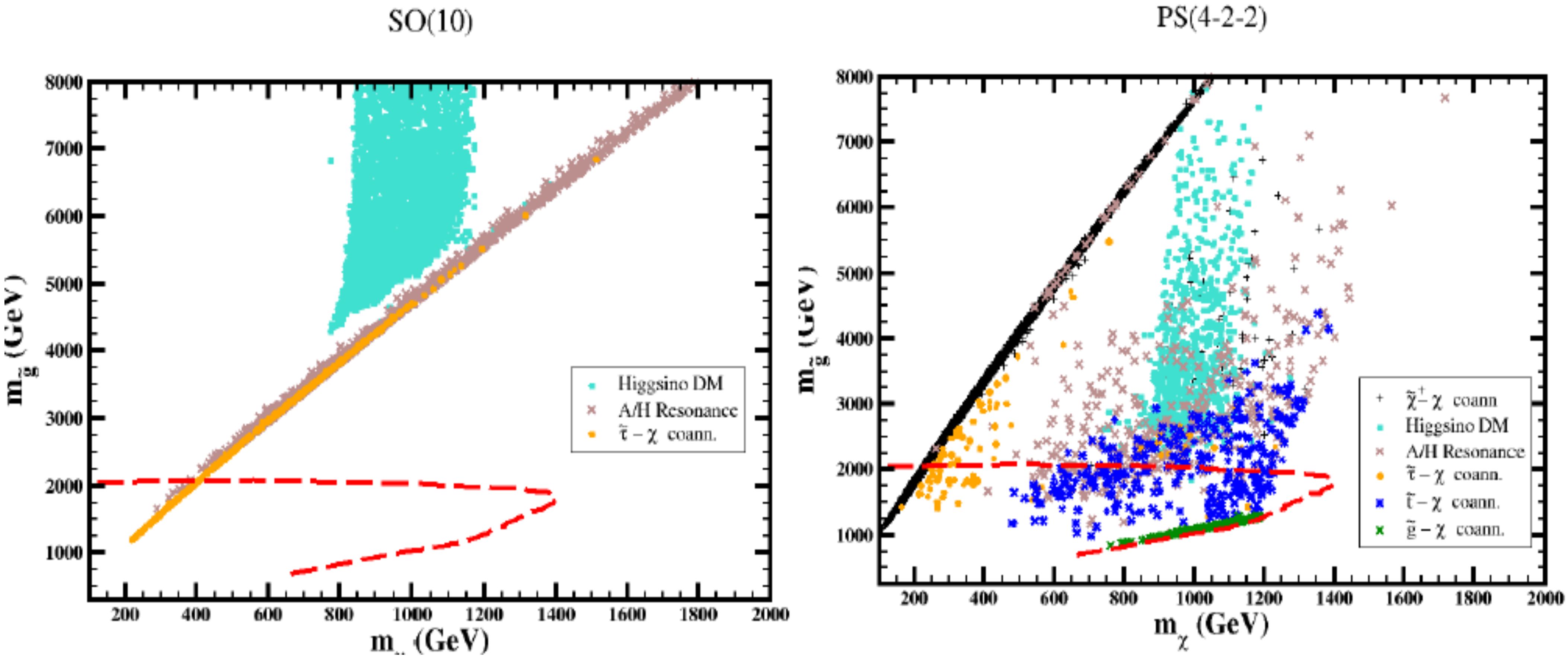


ez, PASCOS

Flip-SU(5)



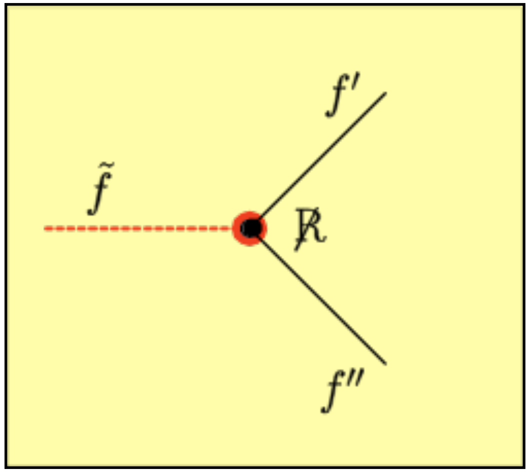
Sparticle correlations



For completeness: Some comments on R-violating SUSY

In addition to couplings generating fermion masses,

Also $\lambda_{ijk} L_i L_j \bar{E}_k$ $\quad \lambda'_{ijk} L_i Q_j \bar{D}_k$ $\quad \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$



VERY RICH FLAVOUR STRUCTURE

45 couplings *violating lepton or baryon number*

X : Unacceptable proton decay - kill all couplings via **R-parity** *(Fayet)*

✓ OR, allow subsets by **baryon / lepton parities** *(i.e. Ibanez, Ross)*

Colliders: Multi-lepton/jet events *instead of* ***missing energy***

Single sparticle productions possible

LSP: unstable – *but,* ***gravitino DM*** *a viable possibility*

Its RPV-decays suppressed by:

- *Gravitino vertex (~1/Mp)*
- *Phase space (light gravitino)*
- *Loop factors (~ fermion mass)*

-Neutrino- neutralino mixing

[Takayama, Yamaguchi], [Chemtob, Moreau]
[Buchmuler, Covi, Hamaguchi, Ibarra, Yanagida]
[SL, P. Osland, A. Raklev]

Predictions for R-violating operators in different GUTS:
What type of processes favoured in different groups?
(proceed similarly to discussion for fermion mass terms)

L-R symmetric – SO(10):
similar LLE,LQD,UDD (only generation matters)

- Bounds on products of couplings, due to correlations, translated to individual bounds /very restrictive [Ellis, SL, Ross]

-1 coupling dominance disfavoured

- Single sparticle productions disfavoured over MSSM ones, with RPV decays

SU(5) – with U(1) charges chosen to match lepton data

Very different expected correlations
Larger hierarchies and dominance of fewer couplings
Single sparticle productions better accommodated

Neutralinos-charginos couple to all 45 operators
Ideal channels to study simultneously all hierarchies
[Bomark, Choudhury, Kvellestad, SL, Osland, Raklev]

Conclusions

- Can identify patterns of soft SUSY-breaking terms at the GUT scale, *compatible with DM predictions and LHC spectra*

- The models predict different spectra for the same LSP mass, connecting possible observations with the underlying unified theory.

- In particular, SO(10), SU(5), flipped SU(5) and Pati-Salam lead to very different predictions, and are distinguishable in future searches.

- Flipped SU(5) and PS predict stop-LSP coannihilations that are absent in the other groups and can be explored in LHC searches.