Unified Theories, Dark Matter and the LHC

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- *JCAP 1603 (2016)*
- *hep-ph/1806.06220, to appear in JHEP*
- *hep-ph/1806.11152, to appear in Frontiers in Physics*

***SUSY GUTs** have very attractive features*

- However: No signal found at the LHC
  *Severe constraints on **at least** the simplest models*

- **What happens beyond the simplest models?**
  - i.e. when breaking unification conditions of minimal schemes?
  - in RPV SUSY?

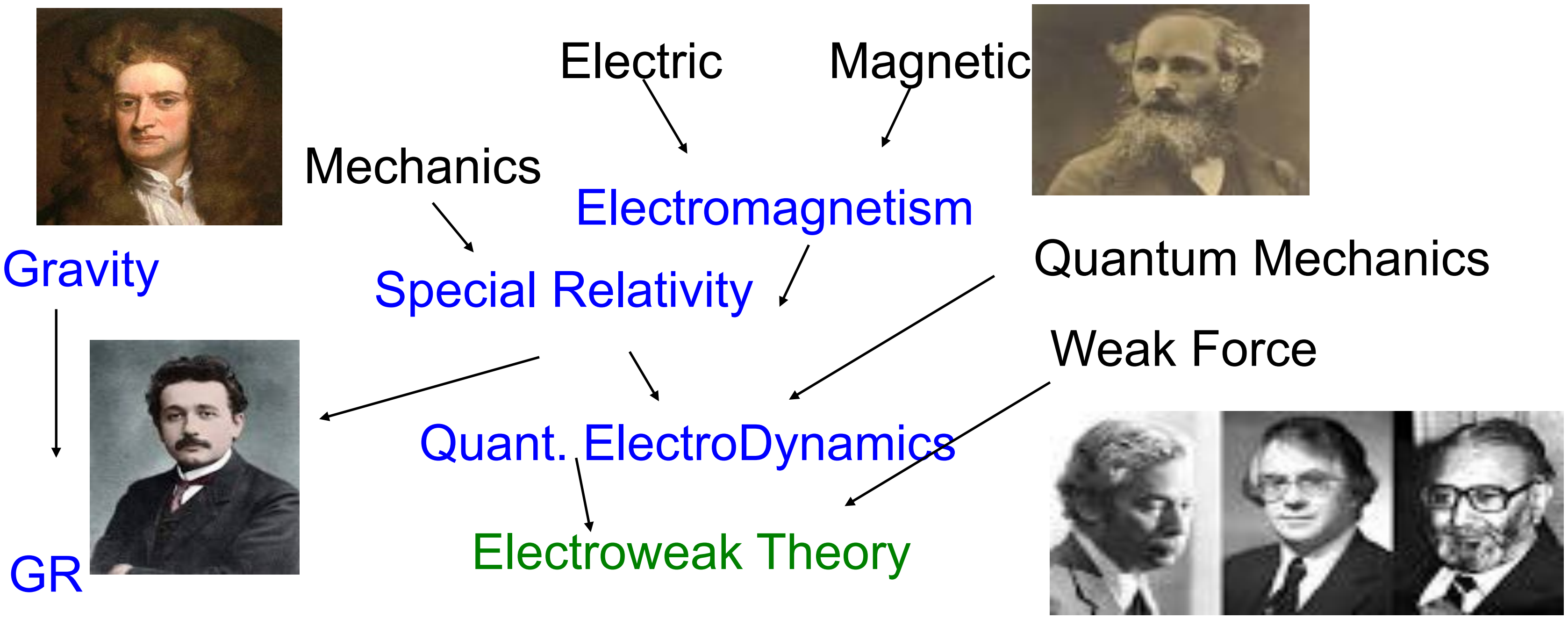
How much we need to deviate from simplest models?

How is the allowed parameter space enhanced?

Is it sufficient/natural enough to keep SUSY alive?

- Need to go beyond the SM, to explain:
  - *Neutrino masses & mixing*
  - *Baryon asymmetry in the universe*
  - *Origin of dark matter*
  - *Large number of arbitrary SM parameters (particularly masses)*
  - *Hierarchy problem,* ***especially if further unification exists***

So far, great success of Unification / natural to wish to extend!



Electric

Magnetic

Mechanics

Electromagnetism

Gravity

Special Relativity

Quantum Mechanics

Weak Force

Quant. ElectroDynamics

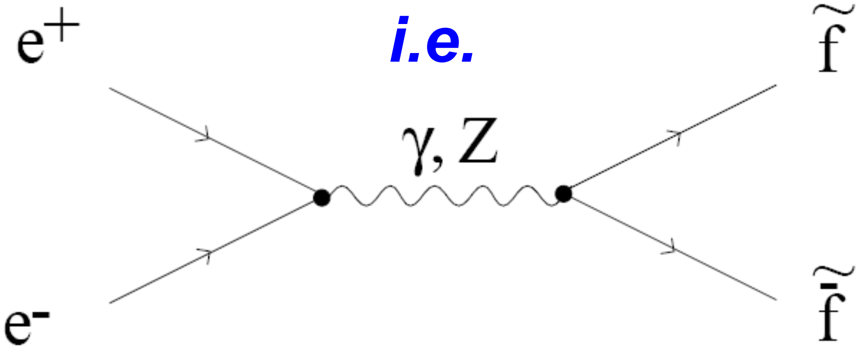
GR

Electroweak Theory

1) R-CONSERVING SUSY

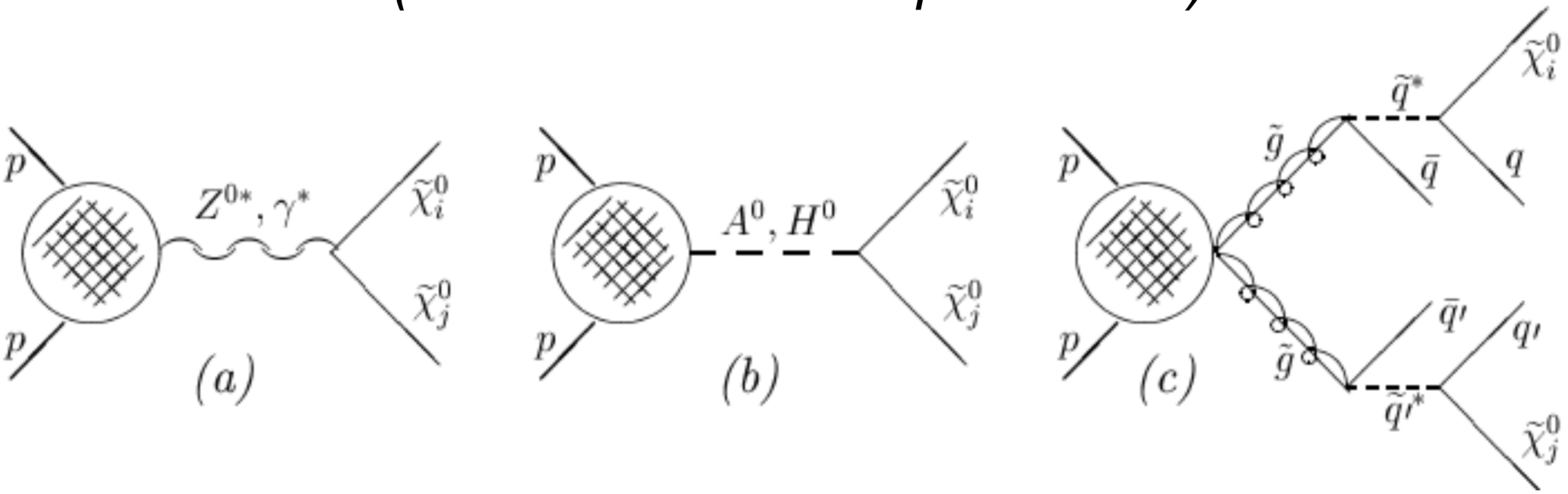
Minimal SUSY Lagrangian– very simple rule: *all SM interactions + those where 2 particles are substituted by sparticles*

i.e.

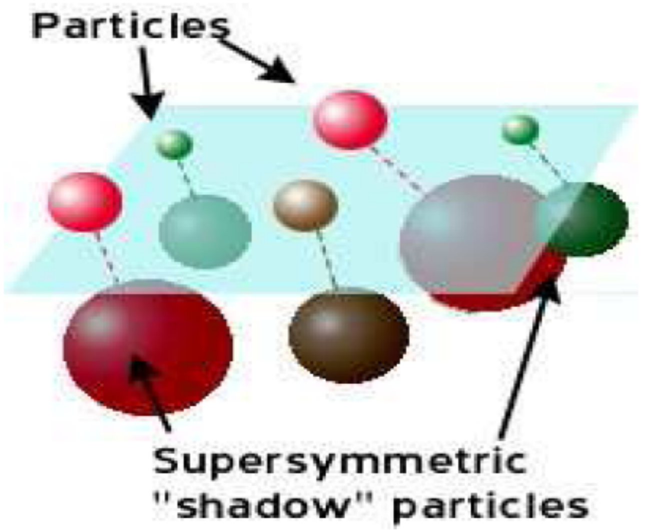


Look at Simplest SUSY models first:

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



SUSY has to be broken
Soft SUSY breaking terms



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

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

CMSSM choice:

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

- m0 *Universal soft masses.*
- m1/2 *Universal gaugino masses.*
- A0 *Universal Trilinear terms.*

The simplest models are too restrictive!

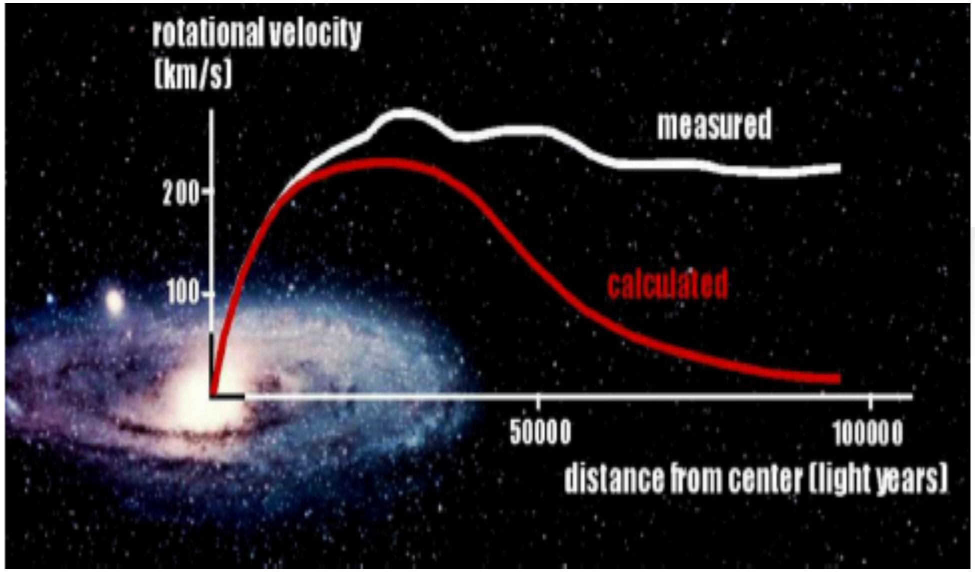
To search for/exclude SUSY unification need to first consider several alternative possibilities

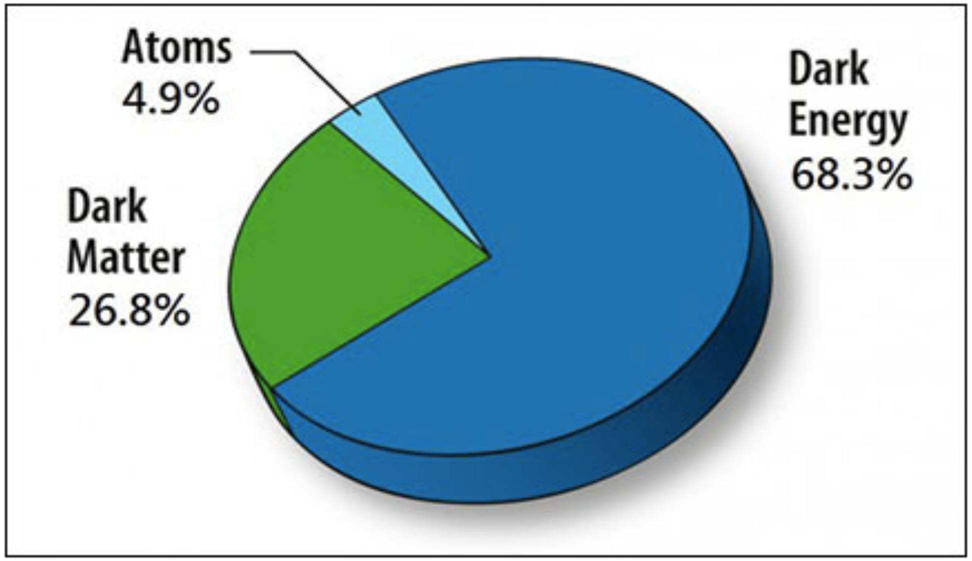
Problem: Vast number of models / How to distinguish them?

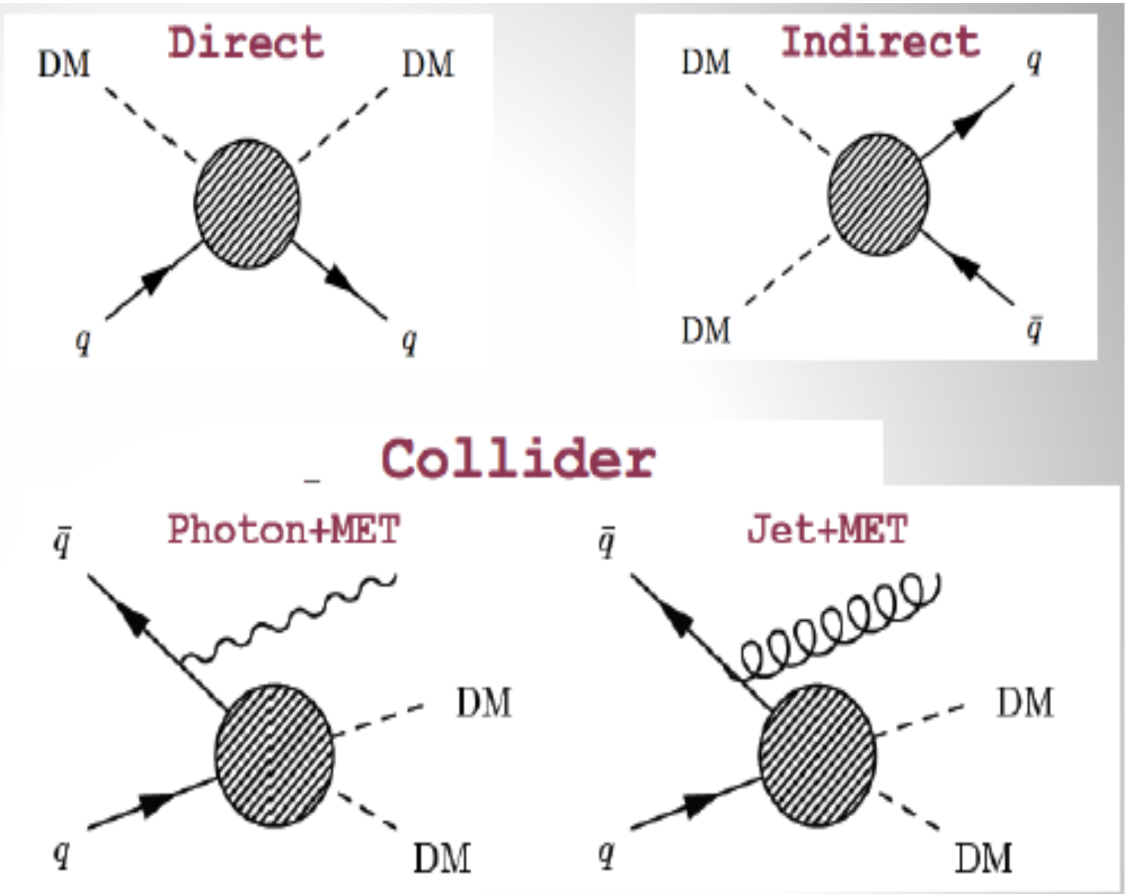
Combine GUT and flavour symmetries
also address the origin of mass

Compare with LHC data

As well as Dark Matter!







Complex computations:
→ *SUSY parameter space scans:* *SuperBayeS, MultiNest*
→ *RGE's, SUSY spectrum:* *SoftSusy*
→ *DM Observables:* *MicrOMEGAs, DarkSUSY*
→*SuperIso:* *Flavour Physics*
→*SModels:* *Comparisons with LHC data / Simplified Models*


E I S A
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Corfu, Greece 2017

Workshop on Particle Physics and Cosmology TOOLS
September 9 - 14, 2017

○ Study various GUTs: work in steps

-Start with LR symmetric GUTs / more constrained models

SO(10) versus LR-symmetric $SU(4) \times SU(2)_L \times SU(2)_R$ [422]

-Asymmetric $SU(4) \times SU(2)_L \times SU(2)_R$ [422]

- SU(5) / Flipped SU(5)

What are the distinct predictions *in each scheme?*

Several constraints from DM + LHC considerations

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***

4-2-2 Unification

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

-L-R symmetry, but asymmetric 4-2-2 also possible

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

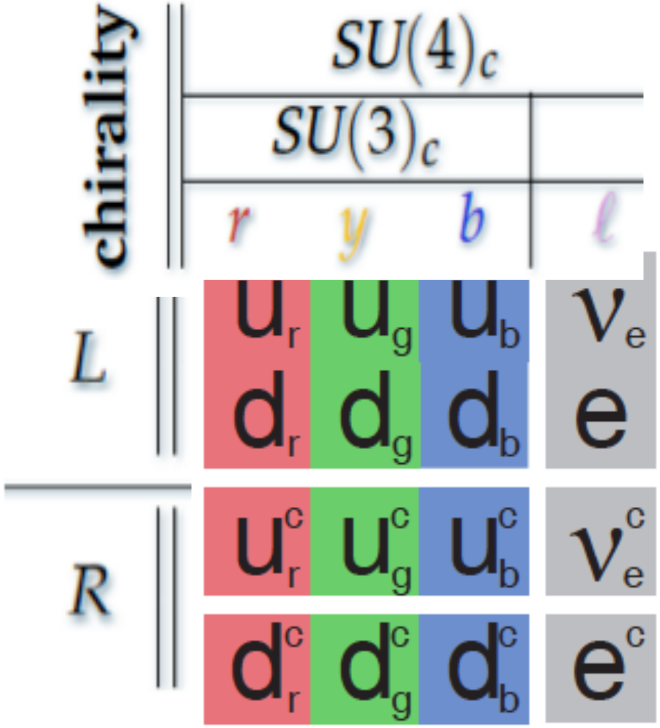
Pati, Salam,
Lazarides, Shafi, King
Antoniadis, Leontaris

$$G_{PS} \rightarrow \mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

$$M_1 = \frac{3}{5} M_2 + \frac{2}{5} M_3.$$

Condition for gaugino masses.

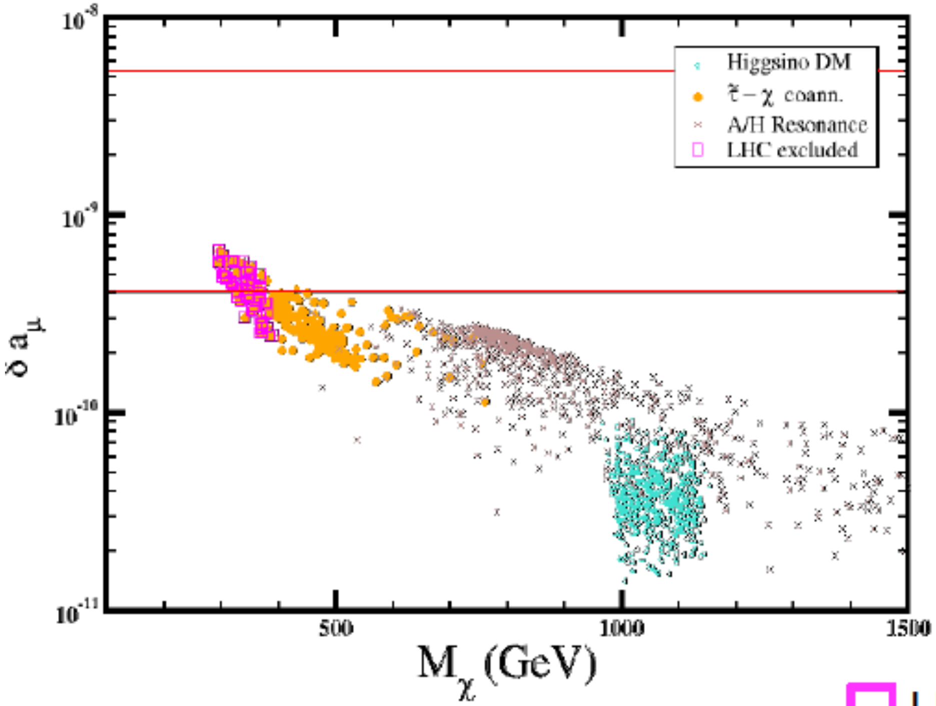
Fermions embedded as follows:



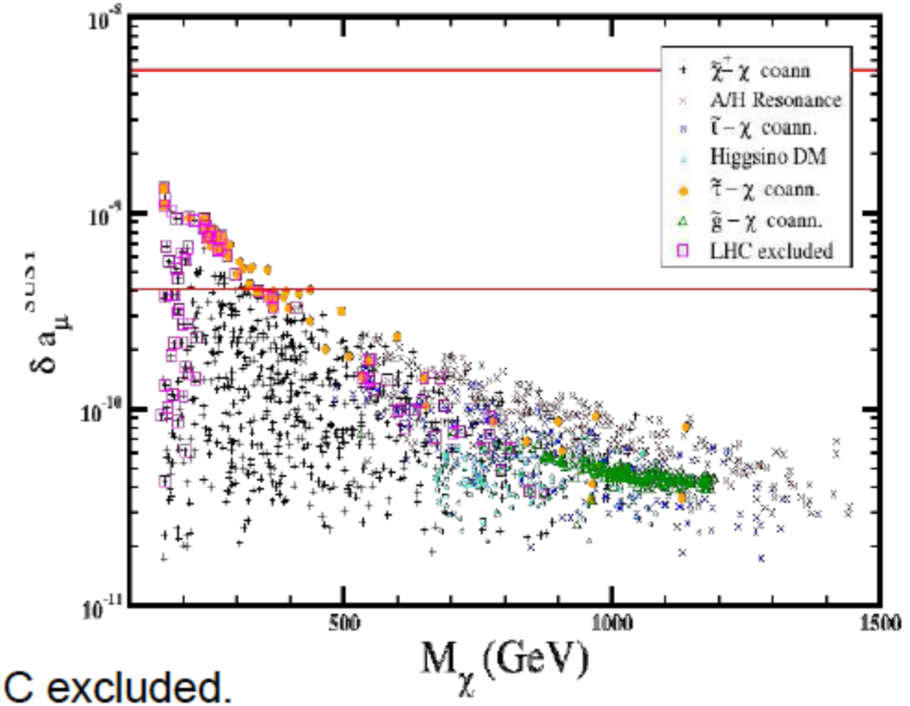
chirality	$SU(4)_c$			
	$SU(3)_c$			
	r	y	b	ℓ
L	u_r	u_g	u_b	ν_e
	d_r	d_g	d_b	e
R	u^c_r	u^c_g	u^c_b	ν^c_e
	d^c_r	d^c_g	d^c_b	e^c

Gluino coannihilations! - Smoking gun of 4-2-2

SO(10)



PS(4-2-2)



□ LHC excluded.

Higgsino DM

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

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

A/H Resonances

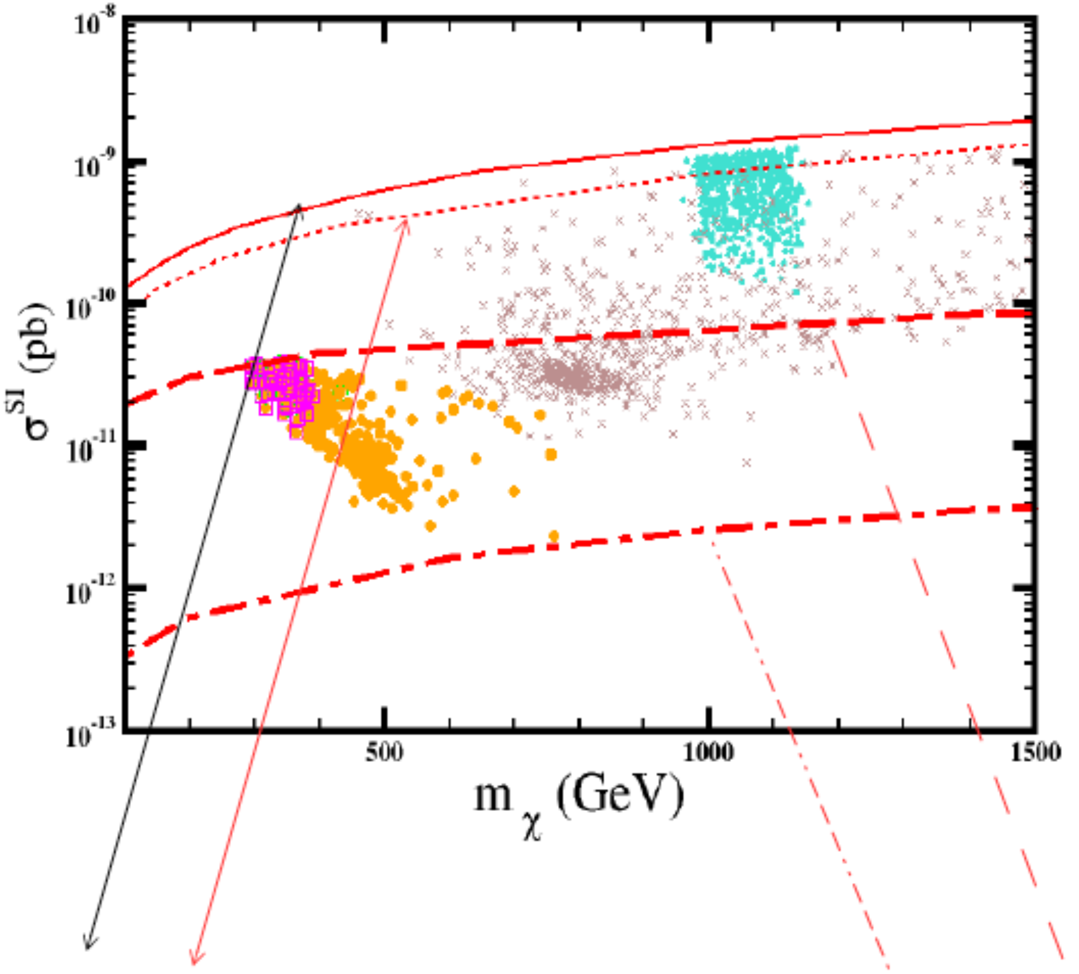
$$|m_A - 2m_\chi| \le 0.1\, m_\chi$$ ×

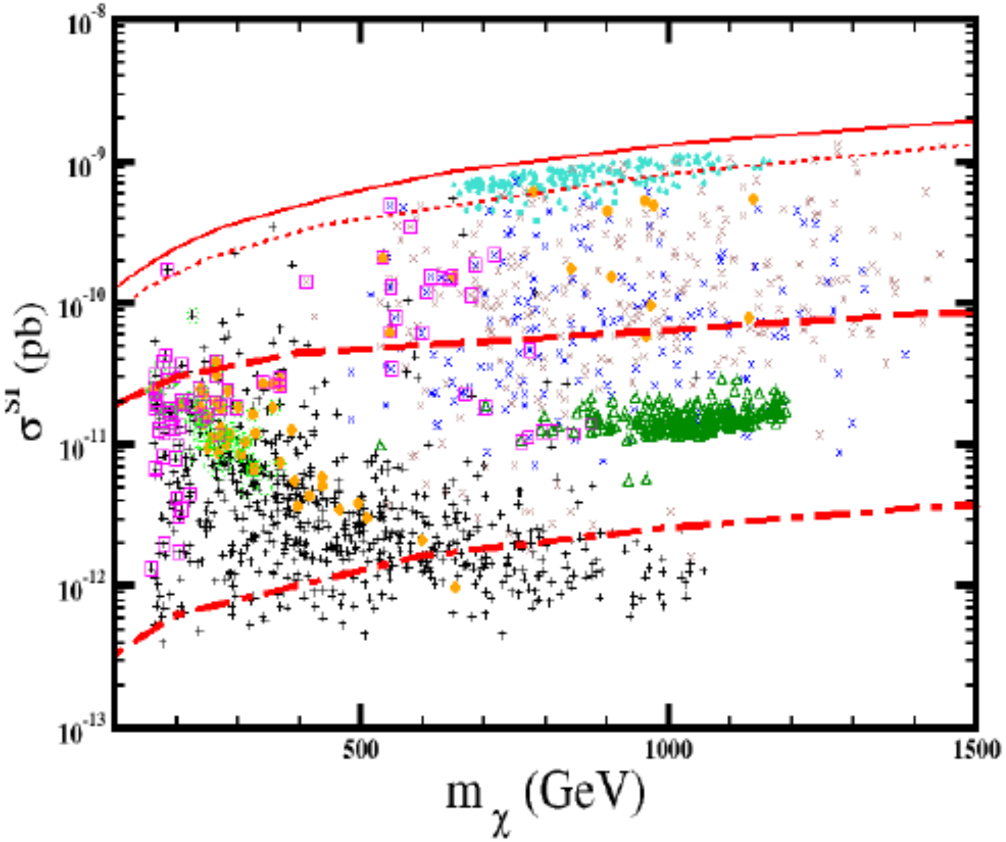
Coanihilations: $\left(m_z - m_{LSP}\right) < 0.1\, m_{LSP}$

$\tilde{\tau}$ $\tilde{\chi}^+$ Stop gluino

SO(10)

PS(4-2-2)

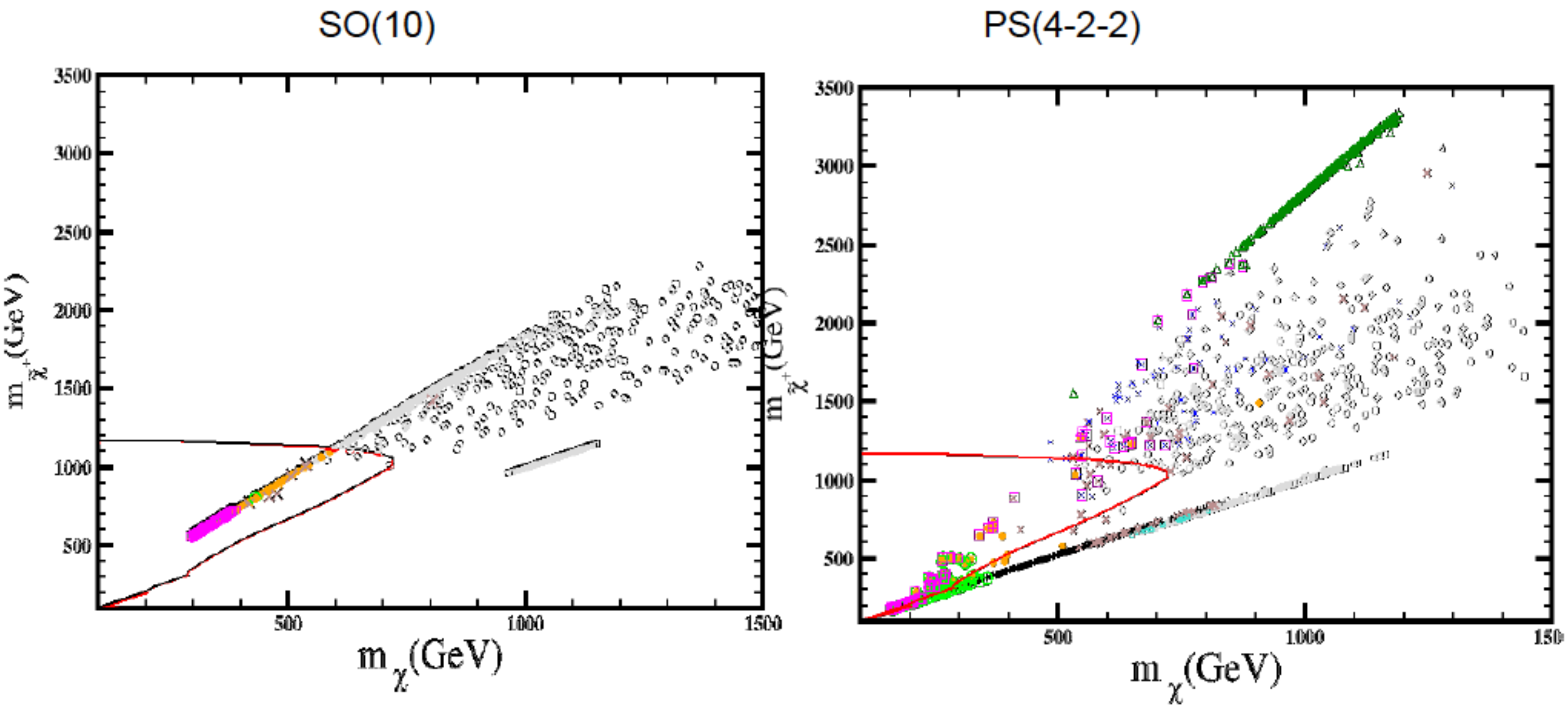




Xenon 1T

Darwin

LZ


SO(10)

PS(4-2-2)

Higgsino DM ●

A/H Resonances ✕

Coanihilations:

● $\tilde{\tau}$

+ $\tilde{\chi}^{+}$

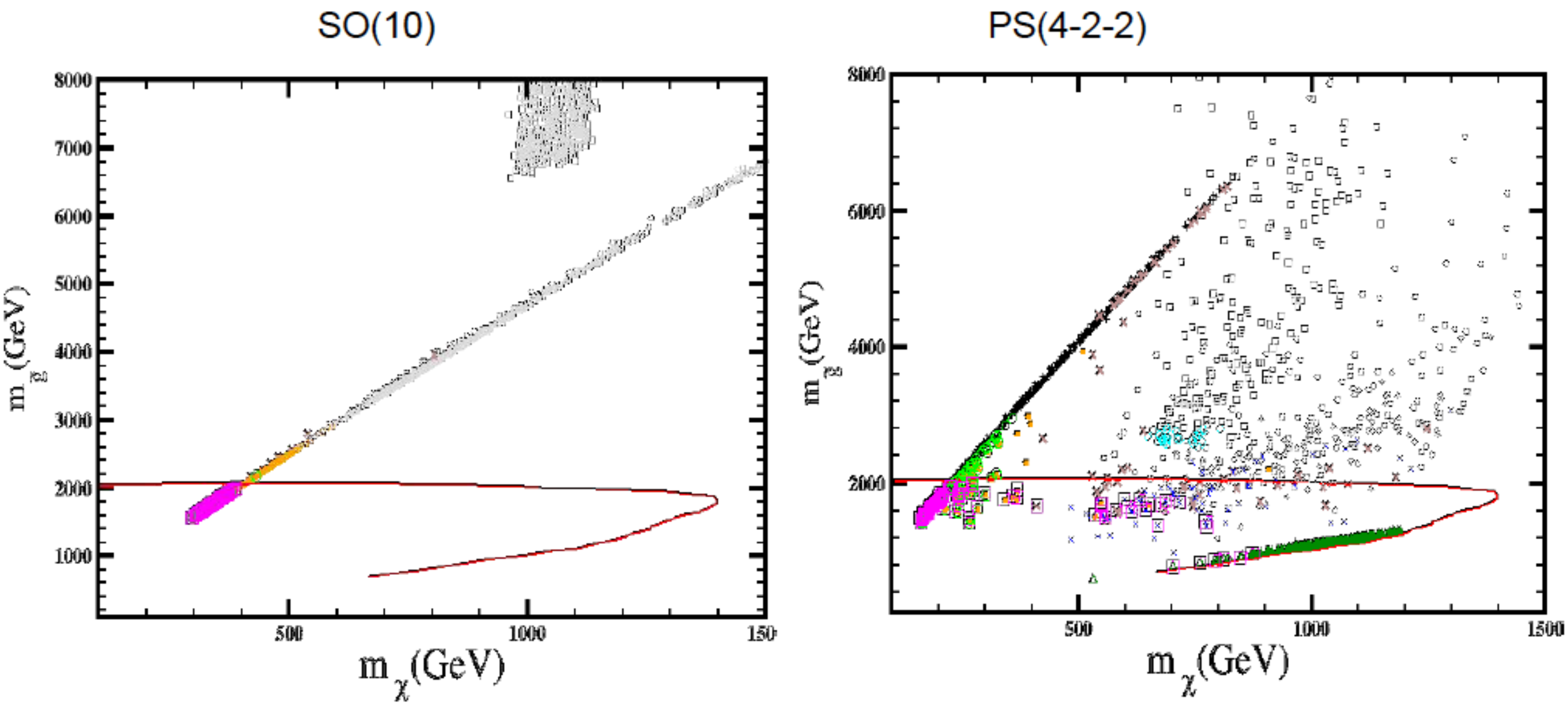
✕ $\tilde{t}$

▲ $\tilde{g}$

□ LHC excluded.

○ good (g-2)

◆ Not tested at the LHC



Higgsino DM ●

A/H Resonances ×

Coanihilations:

● $\tilde{\tau}$

+ $\tilde{\chi}^{+}$

□ LHC excluded.

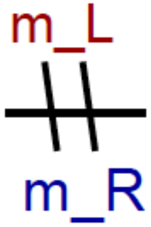
○ good (g-2)

× $\tilde{t}$

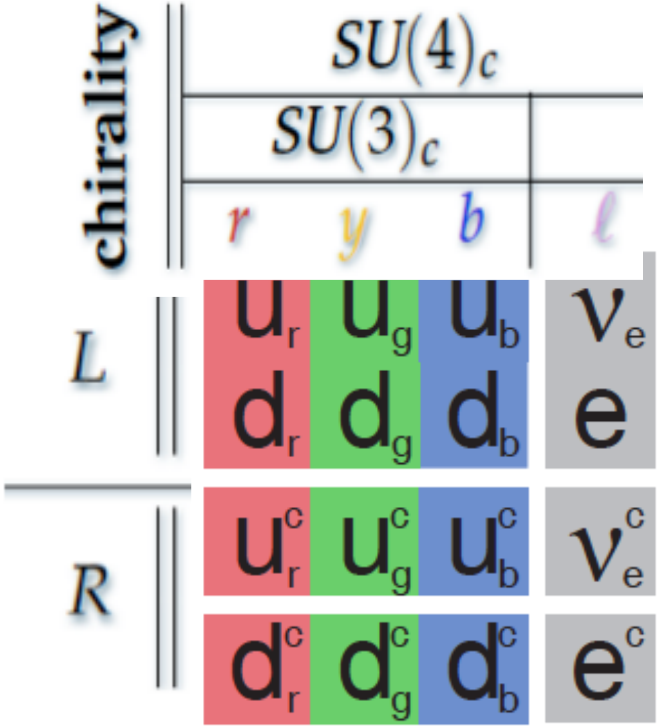
▲ $\tilde{g}$

4-2-2 Unification – LR asymmetry

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

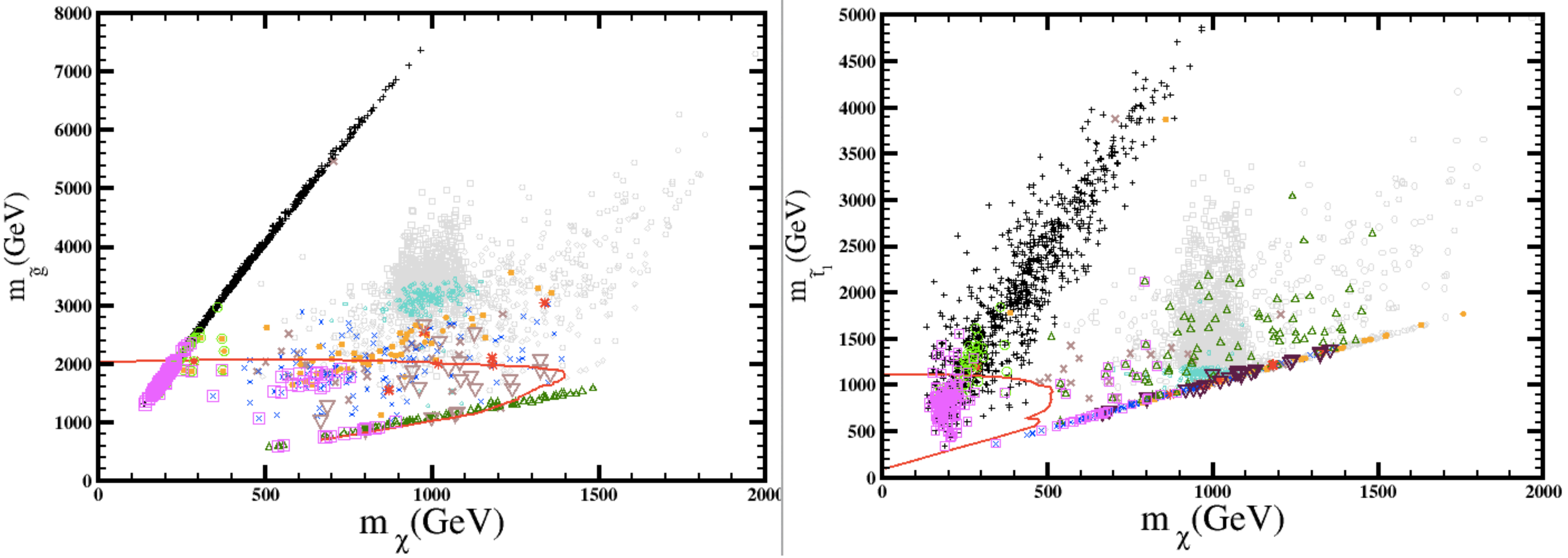


New Parameter $x_{LR} = \frac{m_L}{m_R}$



chirality	$SU(4)_c$			
	$SU(3)_c$			
	r	y	b	ℓ
L	u_r	u_g	u_b	ν_e
	d_r	d_g	d_b	e
R	u^c_r	u^c_g	u^c_b	ν^c_e
	d^c_r	d^c_g	d^c_b	e^c

PS(4-2-2) *L/R Asymetry*



Higgsino DM ●

A/H Resonances ×

□ LHC excluded.

○ good (g-2)

Coanihilations:

● $\tilde{\tau}$ ✚ $\tilde{\chi}^{+}$

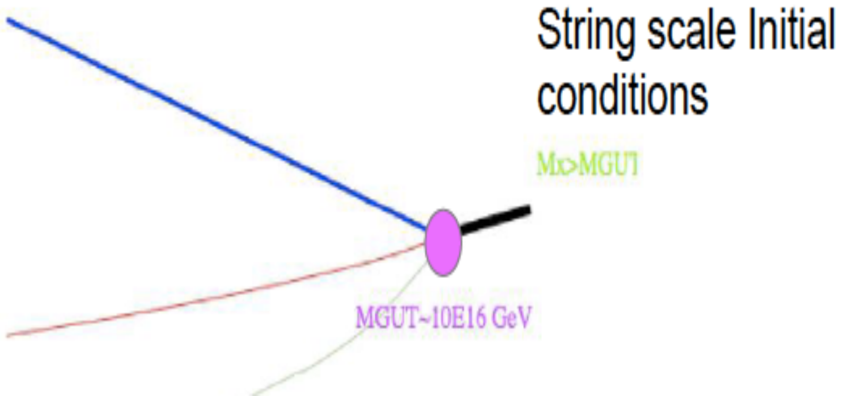
× $\tilde{t}$ ▲ $\tilde{g}$

$\tilde{\tau}-\tilde{\nu}$

✳

△ $\tilde{b}$

Non-universal SU(5)



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

m_{10} m_5 m_u , m_d

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

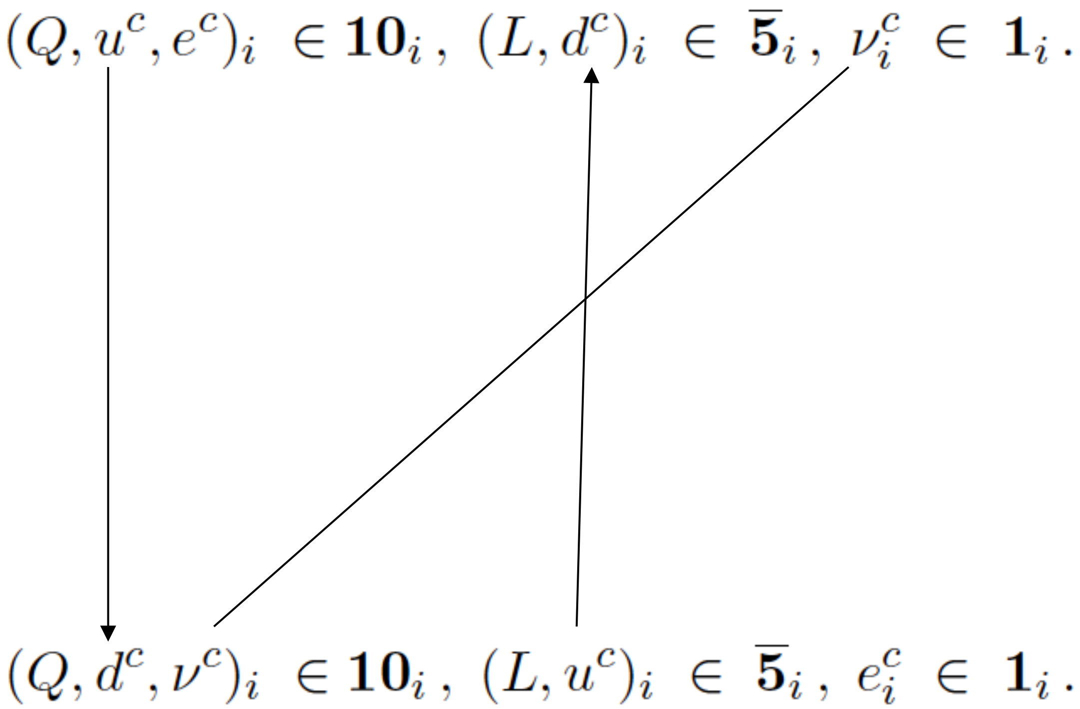
$(D, L) \subseteq \bar{5}$

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

Okada, Shafi, Raza, Ellis, Mustafaev, Olive, Velasco-Sevilla

- *Different soft masses for fermions in different representations*
- *Also: 2 Higgs fields in different 10 representations*

Flipped SU(5) - versus SU(5)



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

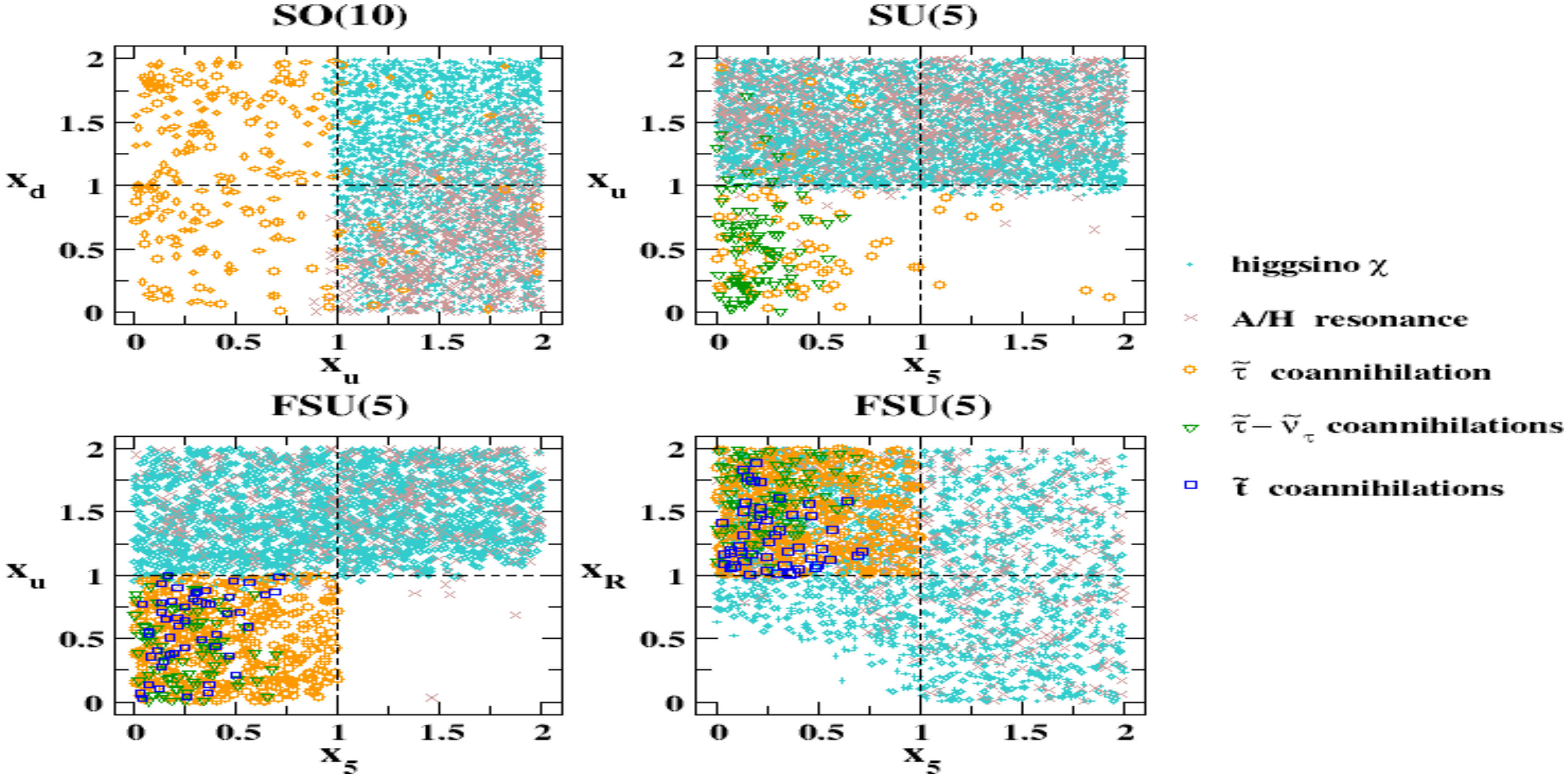
Flipped SU(5) $(Q, d^c, \nu^c)_i \in \mathbf{10}_i\,,\ (L, u^c)_i \in \bar{\mathbf{5}}_i\,,\ e^c_i \in \mathbf{1}_i\,.$

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

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

Different field assignment in representations – different predictions

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



Correlations between the non-universal soft scalar masses and DM in different SUSY GUTS – **very rich structure**

(***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

Flavour symmetries may also determine soft SUSY terms

Would break soft term universality even further!

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

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)

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

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

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

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

SO FAR

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

- SO(10), 4-2-2, SU(5) and flipped SU(5) lead to very different predictions, and are distinguishable in future searches
  - Gluino, chargino coannihilations in 4-2-2
  - Stop coannihilations in 4-2-2, Flipped SU(5)
  - Sbottom, stau-sneutrino coannihilations in LR-asymmetric 422

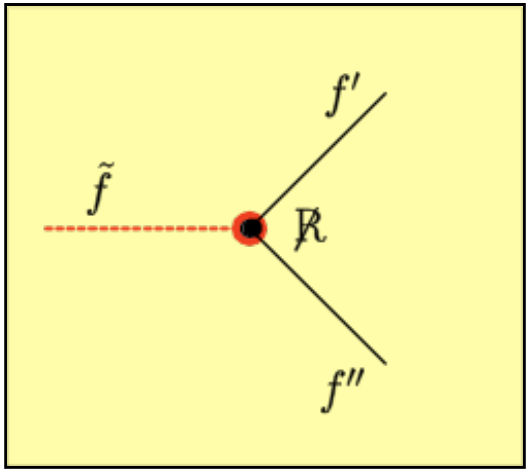
- Different spectra/mass-correlations for the same LSP mass, connecting possible observations with the underlying unified theory

- Some (but not many) solutions compatible with g-2, particularly for 4-2-2, due to the *modified gaugino mass relations*

2) R-VIOLATING SUSY

In addition to the Yukawa couplings generating fermion masses

$h_{ij} L_i H_1 \bar{E}_j \qquad h'_{ij} Q_i H_1 \bar{D}_j \qquad h''_{ij} Q_i H_2 \bar{U}_j$



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

- These *violate baryon & lepton number*
- If simultaneously present, rapid (unacceptable) *p* decay

X R-parity *(SM: +1 , SUSY: -1)*

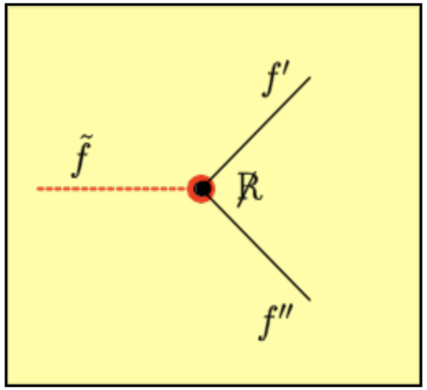
Forbids all terms with ΔL, ΔB

***LSP: stable**, dark matter (DM) candidate*

Main Signal: Missing Energy

✓ Other symmetries, allowing *only ΔL, or only ΔB*

LSP: unstable */ do we lose SUSY DM (?)*

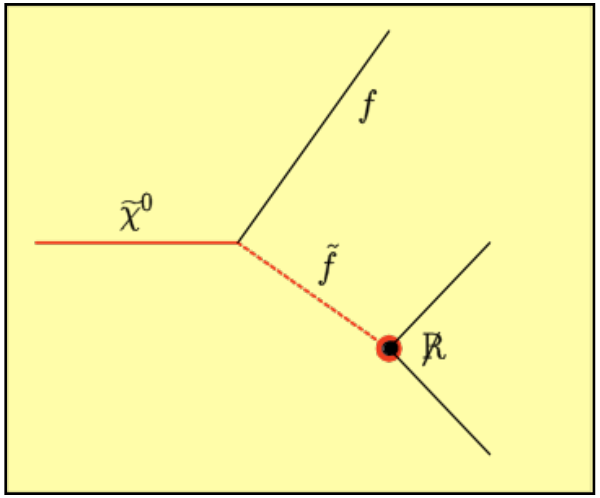


Signals: Multilepton and/or multijet events

Single sparticle productions possible

45 possible couplings! (9+27+9)

Various channels studied at the LHC, but assuming a single coupling dominance



For ΔL (LLE, LQD) we look for:
- ΔL_i, new final state topologies
-isolated leptons within jets with small missing energy

For ΔB (UUD) bigger difficulties, except for t,b

EXAMPLE:
Simple Models for small **LLE:**
MSSM pair sparticle productions

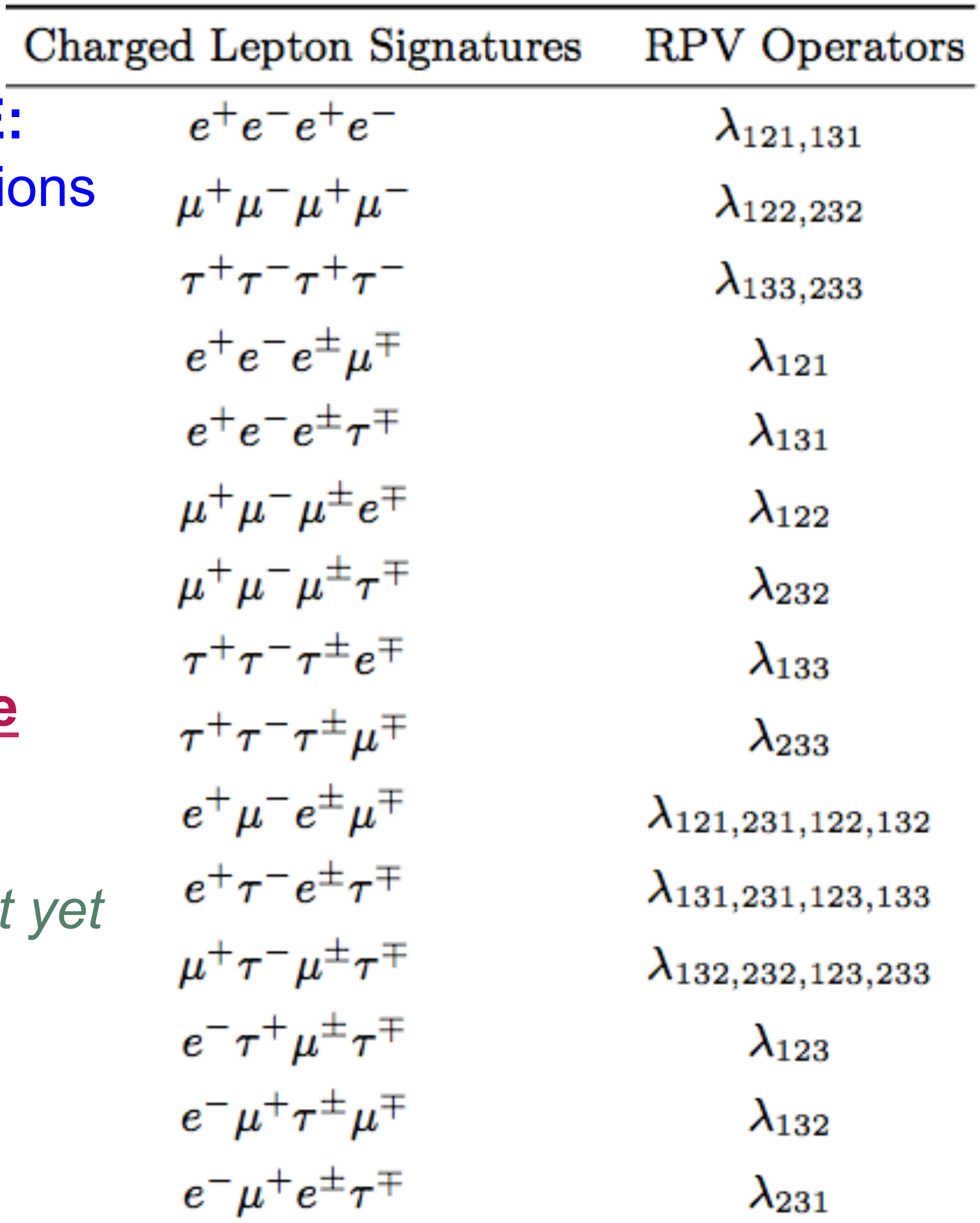
Direct decay to 2 LSP X_0

RPV decay of X_0

[C]MSSM + 1RPV + RGEs

Single coupling dominance

Without such assumptions,
the parametric space has not yet
been fully scanned



Charged Lepton Signatures	RPV Operators
$e^+e^-e^+e^-$	$\lambda_{121,131}$
$\mu^+\mu^-\mu^+\mu^-$	$\lambda_{122,232}$
$\tau^+\tau^-\tau^+\tau^-$	$\lambda_{133,233}$
$e^+e^-e^\pm\mu^\mp$	λ_{121}
$e^+e^-e^\pm\tau^\mp$	λ_{131}
$\mu^+\mu^-\mu^\pm e^\mp$	λ_{122}
$\mu^+\mu^-\mu^\pm\tau^\mp$	λ_{232}
$\tau^+\tau^-\tau^\pm e^\mp$	λ_{133}
$\tau^+\tau^-\tau^\pm\mu^\mp$	λ_{233}
$e^+\mu^-e^\pm\mu^\mp$	$\lambda_{121,231,122,132}$
$e^+\tau^-e^\pm\tau^\mp$	$\lambda_{131,231,123,133}$
$\mu^+\tau^-\mu^\pm\tau^\mp$	$\lambda_{132,232,123,233}$
$e^-\tau^+\mu^\pm\tau^\mp$	λ_{123}
$e^-\mu^+\tau^\pm\mu^\mp$	λ_{132}
$e^-\mu^+e^\pm\tau^\mp$	λ_{231}

Predictions for R-violating operators in different GUTS:

What type of processes favoured in different groups?

(proceed similarly to discussion for fermion mass terms)

(Ellis, SL, Ross - 1997)

Single coupling dominance not generically valid!

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

Also, can deviate from soft term universality in RPV as well!

CONCLUSIONS

NEED TO EXTEND THE SM

SUSY GUTs look nice in this respect!

No sign of SUSY so far. BUT:

There are still several viable models with or without RPV

Only the simplest ones have been studied extensively

We cannot yet exclude SUSY without
properly investigating
these additional possibilities