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Buenos Aires, Argentina

Reinterpretation of the Higgs field, new quarks, and neutrino physics, in supersymmetry

March 2017, webinar

This talk is based in a Work in collaboration with

Carlos Muñoz

(IFT, Univ. Autónoma Madrid-CSIC)

arXiv: 1701.02652

- In this days it is easy to find a colleague saying: “supersymmetry is dead” -

This is really too much to say!!

Some models, and really some models with minimalistic choice of parameters, are suffering sever constraints. For instance the constraint version of the Minimal Supersymmetric Standar Model

… it is really to soon to buy a coffin for SUSY

Why this pessimistic feeling in some colleagues …..

The XX century

(Century described exquisite in the Tango "Cambalache" by E. S. Discepolo)

- Neutrinos where consistently massless (until 1998)

- Scientific community was very exciting with dark Matter direct detection experiments (ZEPLIN, CDMS, EDELWEISS …..)

- LEP, TEVATRON were a fantastic opportunity to discovered all the SM particles …. or at the end almost all in the XX century……...

- Everything was consistence with the standard Model but the Minimal Supersymmetric Standard Model was given fantastic predictions specially easy to be probed THANKS TO R-PARITY CONSERVATION

The XX century: The standard model

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \qquad \begin{matrix} e_i^c \\ - \end{matrix}, \qquad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix},$$

No need for ν_i^c The minimal fermionic spectrum is the above.

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The minimal fermionic spectrum is the above.

$SU(3)_c \times SU(2) \times U(1)_Y$ **Gauge invarinace**

A boson h (doublet of SU(2), the Higgs boson) is added to the spectrum to give mass to the particles.

we will need to wait till the XXI century to discovered it at the LHC

1998---> Neutrinos are not massless. This is the first evidence of particle physics beyond the standard model (second if you want to include dark matter but remember that at the moment we only have gravitational experiments confirming this)

But … there are many ways to give mass to the Neutrinos in the context of the standard Model with effect to give mass to the neutrinos and nothing more …..

The XX century: The MSSM

The Minimal Supersymmetric Standard Model, MSSM

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \qquad \begin{matrix} e_i^c \\ - \end{matrix}, \qquad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix},$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \; H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}.$$

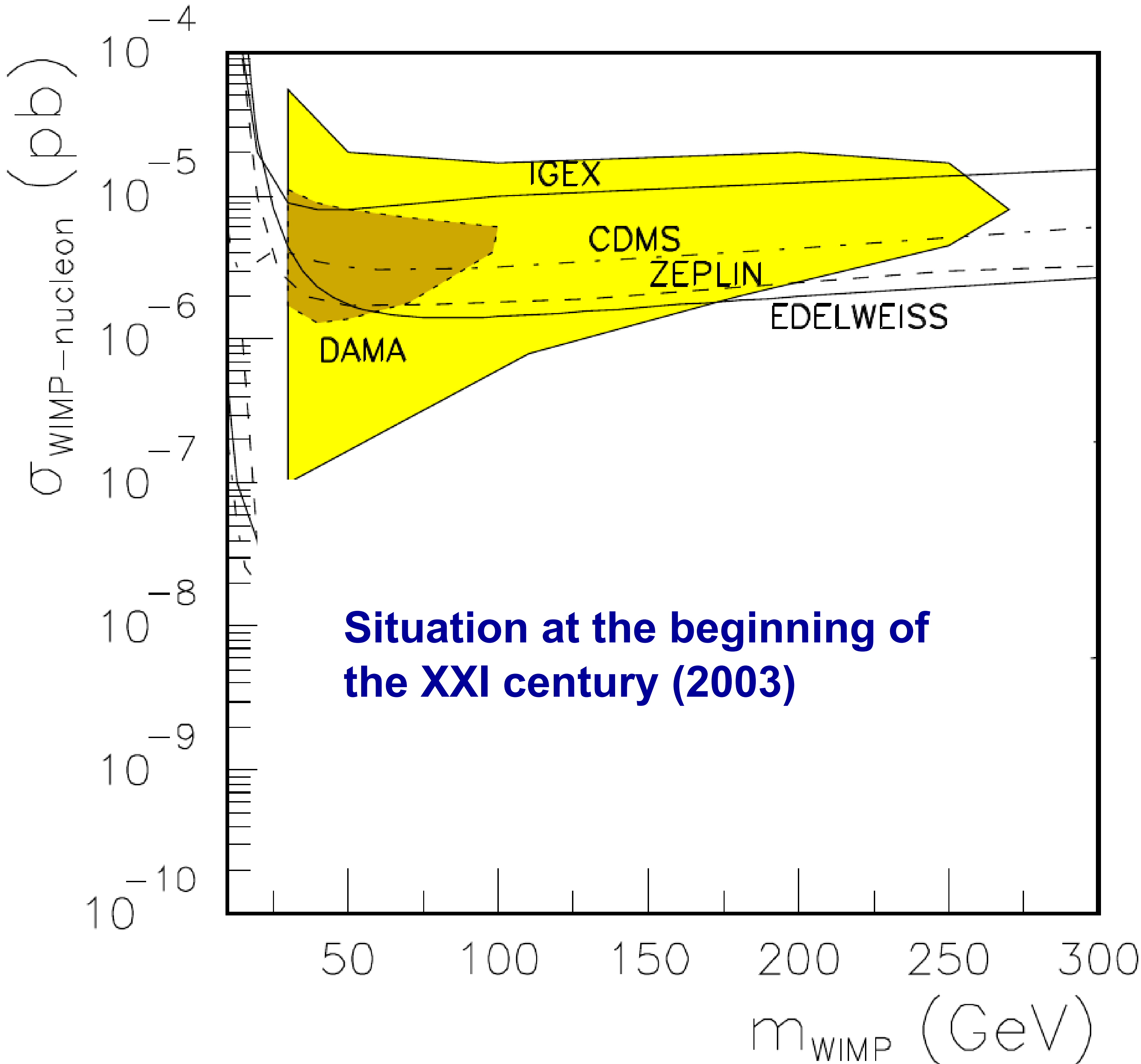
The minimal supersymmetric version of the SM was very promising:
- Higgs was expected to be really close to the Z mass

Thanks to R-parity conservation
- was given the possibility to detect missing energy in colliders.
- **Dark matter** in direct detection experiments was very promising

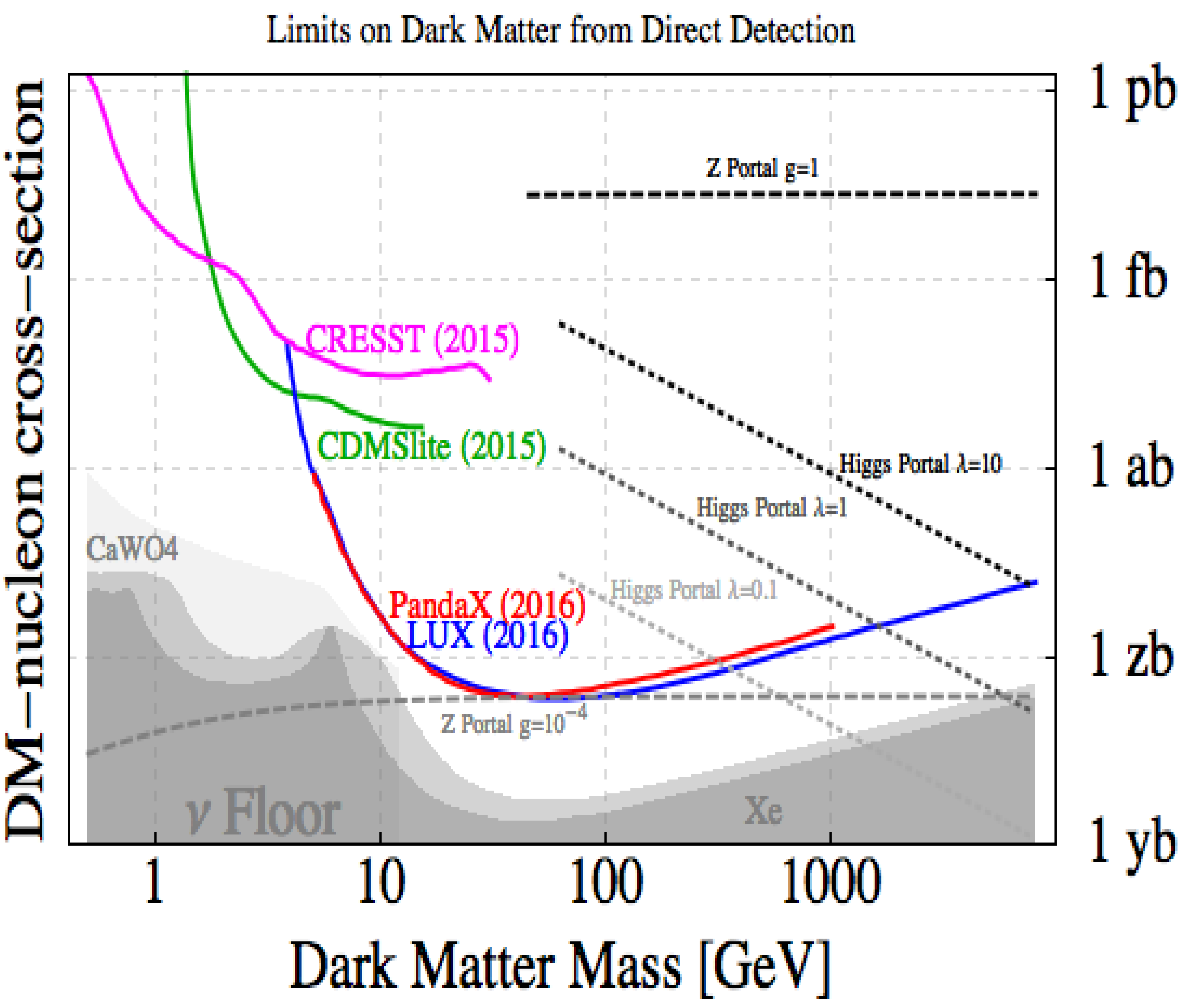
The XXI century: the situation today ….

- **Neutrinos are massive and strongly mix together.**

- **No evidence at all about dark Matter direct detection**
(ZEPLIN, CDMS, EDELWEISS ….. PANDA, LUX, CREEST)


IGEX
CDMS
ZEPLIN
EDELWEISS
DAMA
Situation at the beginning of the XXI century (2003)
$\sigma_{WIMP-nucleon}$ (pb)
m_{WIMP} (GeV)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
50
100
150
200
250
300

Experimental dark matter direct detection limits 2016



The XXI century: the situation today ….

- **Neutrinos are massive and strongly mix together.**

- **No evidence at all about dark Matter direct detection**
  (ZEPLIN, CDMS, EDELWEISS …..)

- All collider experiment are consistence with the SM. The last particle consistence with SM Higgs has also at the end appear in the XXI century with mass similar to **125 GeV**

- The Higgs was of order of the EW scale as it is expected in supersymmetry.

- But ….   the mass of the Higgs was a bit higher than MSSM expectations (but still consistence with the model)

Things were not so nice as was expected for R-PARITY CONSERVATION.

Situation at LHC (beginning 2017)

- The lower bounds on SUSY particles ($\lesssim$ TeV) are still reasonable
- Experimentalists use simplified models that don't cover full SUSY phase space (BR variations for example)
- Run 2 is still going on, for the moment with low luminosity of about 20 fb^{-1}
- Most SUSY searches assume R parity conservation (RPC), thus the LSP is stable, requiring missing energy in the final state for its detection
- If R parity is violated (RPV), SUSY particles can decay to standard model particles, and the bounds become significantly weaker

Minimal models are crucial to make predictions and understand physics

But …... we can ask:

¿was the minimal supersymmetric standard model too minimal and we are getting wrong predictions?

Let's start the construction of the minimal natural supersymmetric model from the beginning

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \qquad \begin{matrix} e_i^c \\ - \end{matrix}, \qquad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \; \begin{matrix} d_i^c \\ u_i^c \end{matrix},$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \; H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

$$\begin{aligned} W &= \mu \, H_u \, H_d + Y_{ij}^e \, H_d \, L_i \, e_j^c + Y_{ij}^d \, H_d \, Q_i \, d_j^c - Y_{ij}^u \, H_u \, Q_i \, u_j^c \\ &+ \mu_i H_u \, L_i + \lambda_{ijk} \, L_i \, L_j \, e_k^c + \lambda'_{ijk} \, L_i \, Q_j \, d_k^c + \lambda''_{ijk} \, u_i^c \, d_j^c \, d_k^c \,, \end{aligned}$$

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \qquad \begin{matrix} e_i^c \\ - \end{matrix}, \qquad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix},$$

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$$\begin{aligned} W &= \mu\, H_u\, H_d + Y_{ij}^e\, H_d\, L_i\, e_j^c + Y_{ij}^d\, H_d\, Q_i\, d_j^c - Y_{ij}^u\, H_u\, Q_i\, u_j^c \\ &+ \mu_i H_u\, L_i + \lambda_{ijk}\, L_i\, L_j\, e_k^c + \lambda'_{ijk}\, L_i\, Q_j\, d_k^c + \lambda''_{ijk}\, u_i^c\, d_j^c\, d_k^c\,, \end{aligned}$$

The MSSM

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \qquad \begin{matrix} e_i^c \\ - \end{matrix}, \qquad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \; \begin{matrix} d_i^c \\ u_i^c \end{matrix},$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \; H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

$$\begin{aligned} W &= \mu H_u H_d + Y_{ij}^e H_d L_i e_j^c + Y_{ij}^d H_d Q_i d_j^c - Y_{ij}^u H_u Q_i u_j^c \\ &+ \mu_i H_u L_i + \lambda_{ijk} L_i L_j e_k^c + \lambda'_{ijk} L_i Q_j d_k^c + \lambda''_{ijk} u_i^c d_j^c d_k^c , \end{aligned}$$

In the simplest construction only zero or very high values are allowed: the mu problem.

Proton decay, at least this term must go.

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ - \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix},$$

Y= -1/2

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

Y= -1/2 Y= +1/2

$$\begin{aligned} W &= Y_{ij}^e H_d L_i e_j^c + Y_{ij}^d H_d Q_i d_j^c - Y_{ij}^u H_u Q_i u_j^c \\ &+ \lambda_{ijk} L_i L_j e_k^c + \lambda'_{ijk} L_i Q_j d_k^c . \end{aligned}$$

We don't have mass for the chargino ….. this is excluded …..

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$$\begin{aligned} W &= Y_{ij}^e \, H_d \, L_i \, e_j^c + Y_{ij}^d \, H_d \, Q_i \, d_j^c - Y_{ij}^u \, H_u \, Q_i \, u_j^c \\ &+ \lambda_{ijk} \, L_i \, L_j \, e_k^c + \lambda'_{ijk} \, L_i \, Q_j \, d_k^c \, . \end{aligned}$$

We don't have mass for the chargino ….. this is excluded …..

Right-handed neutrinos and reinterpretation of the Higgs superfields

$$\hat{L}_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix} \quad .$$

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$$\begin{aligned} W &= Y_{ij}^e \, H_d \, L_i \, e_j^c \; + Y_{ij}^d \, H_d \, Q_i \, d_j^c \; - Y_{ij}^u \, H_u \, Q_i \, u_j^c \; - Y_{ij}^\nu \, H_u \, L_i \, \nu_j^c \\ &+ \lambda_{ijk} \, L_i \, L_j \, e_k^c + \lambda'_{ijk} \, L_i \, Q_j \, d_k^c + \frac{1}{3} \kappa_{ijk} \, \nu_i^c \, \nu_j^c \, \nu_k^c + \lambda_i \, H_u \, H_d \, \nu_i^c \, . \end{aligned}$$

Right-handed neutrinos and reinterpretation of the Higgs superfields

$$\hat{L}_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix} \quad .$$

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$$\begin{aligned} W \quad = \quad & Y_{ij}^e \, H_d \, L_i \, e_j^c \; + Y_{ij}^d \, H_d \, Q_i \, d_j^c \; - Y_{ij}^u \, H_u \, Q_i \, u_j^c \; - Y_{ij}^\nu \, H_u \, L_i \, \nu_j^c \\ + \quad & \lambda_{ijk} \, L_i \, L_j \, e_k^c + \lambda'_{ijk} \, L_i \, Q_j \, d_k^c + \frac{1}{3} \kappa_{ijk} \, \nu_i^c \, \nu_j^c \, \nu_k^c + \lambda_i \, H_u \, H_d \, \nu_i^c \, . \end{aligned}$$

Right-handed neutrinos and reinterpretation of the Higgs superfields

$$\hat{L}_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix} \; .$$

$$L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix}, \; L_4^c = \begin{pmatrix} e_4^c \\ \nu_4^c \end{pmatrix}.$$

We can write in a simple compact form

$$W = Y^e_{IJk} L_I L_J e^c_k + Y^d_{Ijk} L_I Q_j d^c_k - Y^u_{4jk} L^c_4 Q_j u^c_k - Y^\nu_{4Jk} L^c_4 L_J \nu^c_k + \frac{1}{3}\kappa_{ijk} \nu^c_i \nu^c_j \nu^c_k \, ;$$

$$W = Y^e_{IJk} L_I L_J e^c_k + Y^d_{Ijk} L_I Q_j d^c_k - Y^u_{4jk} L^c_4 Q_j u^c_k - Y^\nu_{4Jk} L^c_4 L_J \nu^c_k + \frac{1}{3}\kappa_{ijk} \nu^c_i \nu^c_j \nu^c_k ;$$

is equivalent to:

$$\begin{aligned} W &= Y^e_{ij} H_d L_i e^c_j + Y^d_{ij} H_d Q_i d^c_j - Y^u_{ij} H_u Q_i u^c_j - Y^\nu_{ij} H_u L_i \nu^c_j \\ &+ \lambda_{ijk} L_i L_j e^c_k + \lambda'_{ijk} L_i Q_j d^c_k + \frac{1}{3}\kappa_{ijk} \nu^c_i \nu^c_j \nu^c_k + \lambda_i H_u H_d \nu^c_i . \end{aligned}$$

When the right sneutrinos acquire VEVs of order the EW scale, an effective μ-term from **ν** is generated (μ**ν**SSM)

L-F, C. Muñoz, PRL 2006

-Producing Higgsino masses beyond the experimental bounds μ ≥ 100 GeV

Effective Neutrino mass matrix

$$M_\nu = m^T M^{-1} m$$

$m_\nu \sim m_D^2/M_M = (Y_\nu\, v_u)^2/(k\, v_{\nu^c}) \sim (10^{-6}\; 10^2)^2/10^3 = 10^{-11}$ GeV $= 10^{-2}$ eV

Like the electron Yukawa

Using Diagonal Yukawas for Neutrinos

$$\left(m_{eff|real}\right)_{ij} \simeq \frac{v_u^2}{6\kappa\nu^c} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\,\delta_{ij}\right) - \frac{1}{2M_{eff}} \left[\nu_i \nu_j + \frac{v_d \left(Y_{\nu_i}\nu_j + Y_{\nu_j}\nu_i\right)}{3\lambda} + \frac{Y_{\nu_i} Y_{\nu_j} v_d^2}{9\lambda^2}\right]$$

$$M_{eff} \equiv M \left[1 - \frac{v^2}{2M\left(\kappa\nu^{c^2} + \lambda v_u v_d\right)\, 3\lambda\nu^c} \left(2\kappa\nu^{c^2} \frac{v_u v_d}{v^2} + \frac{\lambda v^2}{2}\right)\right] \qquad \frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}$$

We have neglected all the terms of order $Y_\nu^2 \nu^2,\; Y_\nu^3 \nu$ and $Y_\nu \nu^3$

Lightest doublet-like Higgs

Tree level bound
On the Lightest Higgs

$$m_h^2 \le M_Z^2\left(\cos^2 2\beta + \frac{2\lambda^2\cos^2\theta_W}{g_2^2}\sin^2 2\beta\right) \approx M_Z^2\left(\cos^2 2\beta + 3.62\,\lambda^2\sin^2 2\beta\right)$$

MSSM

$$\lambda^2 = \lambda_i\lambda_i$$

Landau pole condition (GUT) $\Longrightarrow$ $\lambda^2 \lesssim (0.7)^2$ $\quad \lambda \equiv \lambda_i \lesssim 0.7/\sqrt{3} \approx 0.4$

for $\tan\beta = 2(4)$ $\Longrightarrow$ $m_h \lesssim 111(98)\ \mathrm{GeV}$ Tree Level

Pure doublet $\longrightarrow$ $\lambda_i \to 0$ or $A_{\lambda_i} = \frac{2\mu}{\sin 2\beta} - \frac{2}{\lambda_i}\sum_{j,k}\kappa_{ijk}\lambda_j\nu_k^c$

Easier than in the MSSM to have the lightest doublet-like Higgs with mass around 125 GeV

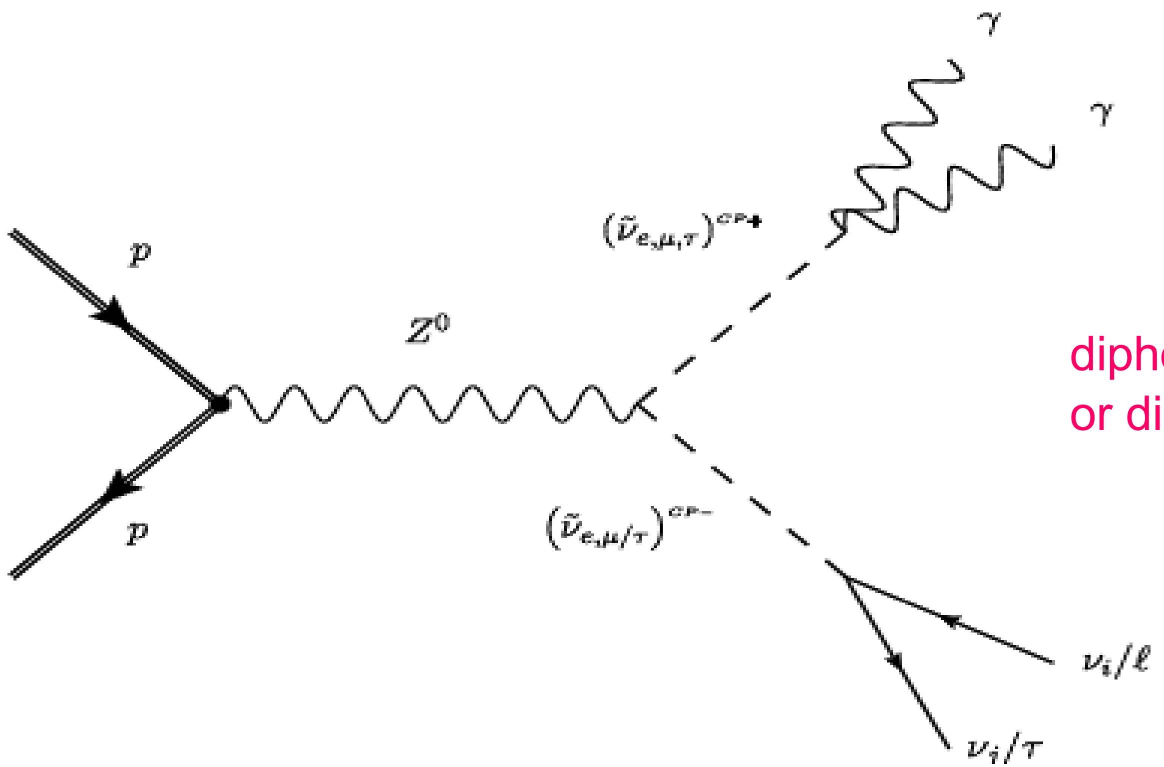
- If the lightest Higgses are dominated by right-handed sneutrinos the mixing helps to increase the mass of the lightest doublet-like Higgs

- 1 loop contributions increase the lightest doublet-like Higgs mass

- Possible to relax the Landau pole constraint (lower scale). We are not going to use this here.

N. Escudero, D.E. L-F, C. Muñoz and R. Ruiz de Austri, *JHEP* **12** (2008) 099

Left-handed sneutrino LSP (NLSP considering the gravitino as dark matter)



diphoton + missing energy
or diphoton + leptons

Work in preparation: Ghosh, Lara, L-F, Muñoz, Ruiz de Austri

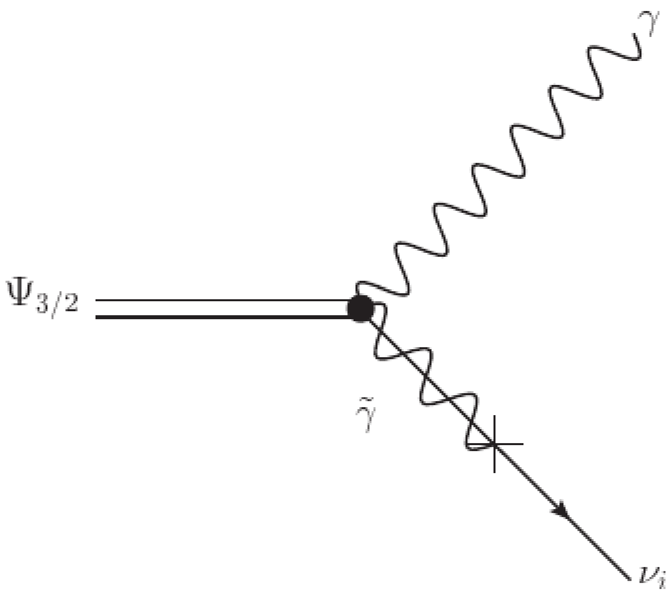
Remember that since R-parity is not conserved, the left-handed sneutrino is part of the Higgs sector in this model

What about dark matter?

We can not forget that supersymmetry is at the end supergravity

Gravitino Dark Matter in the ***μνSSM***

If the gravitino is the LSP can be the Dark Matter



$$\Gamma(\Psi_{3/2} \to \sum_i \gamma \nu_i) \simeq \frac{m_{3/2}^3}{64\pi M_P^2} |U_{\tilde{\gamma}\nu}|^2$$

$$M_P \simeq 2.4 \times 10^{18}\,\mathrm{GeV}$$

$$|U_{\tilde{\gamma}\nu}|^2 = \sum_{i=1}^{3} |N_{i1}\,\cos\theta_W + N_{i2}\,\sin\theta_W|^2$$

The same result for the decay width holds for the conjugated processes $\Psi_{3/2} \to \gamma \bar{\nu}_i$

Proposal for new quarks

Proposal for new quarks

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \qquad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \qquad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \qquad \begin{matrix} d_i^c \\ u_i^c \end{matrix},$$

For the first 3 families, each lepton representation has its quark counterpart

$$L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix}_{Y=-1/2}, \; L_4^c = \begin{pmatrix} e_4^c \\ \nu_4^c \end{pmatrix}_{Y=+1/2},$$

Proposal for new quarks

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix},$$

Then, doing the same for the new family We have

$$\underset{Y=-1/2}{L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix}}, \quad \underset{Y=+1/2}{L_4^c = \begin{pmatrix} e_4^c \\ \nu_4^c \end{pmatrix}}, \quad \underset{Y=+1/6}{Q_4 = \begin{pmatrix} u_4 \\ d_4 \end{pmatrix}}, \quad \underset{Y=-1/6}{Q_4^c = \begin{pmatrix} d_4^c \\ u_4^c \end{pmatrix}},$$

Proposal for new quarks

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$$L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix}_{Y=-1/2}, \; L_4^c = \begin{pmatrix} e_4^c \\ \nu_4^c \end{pmatrix}_{Y=+1/2}, \; Q_4 = \begin{pmatrix} u_4 \\ d_4 \end{pmatrix}_{Y=+1/6}, \; Q_4^c = \begin{pmatrix} d_4^c \\ u_4^c \end{pmatrix}_{Y=-1/6},$$

$$\begin{aligned} W &= Y_{ij}^e \, H_d \, L_i \, e_j^c + Y_{ij}^d \, H_d \, Q_i \, d_j^c - Y_{ij}^u \, H_u \, Q_i \, u_j^c - Y_{ij}^\nu \, H_u \, L_i \, \nu_j^c \\ &+ \lambda_{ijk} \, L_i \, L_j \, e_k^c + \lambda'_{ijk} \, L_i \, Q_j \, d_k^c + \frac{1}{3} \kappa_{ijk} \, \nu_i^c \, \nu_j^c \, \nu_k^c + \lambda_i \, H_u \, H_d \, \nu_i^c \\ &+ \lambda'_{i4k} \, L_i \, Q_4 \, d_k^c + Y_{4k}^d \, H_d \, Q_4 \, d_k^c - Y_{4k}^u \, H_u \, Q_4 \, u_k^c + Y_{j4k}^Q \, Q_j \, Q_4^c \, \nu_k^c + \underbrace{Y_{44k}^Q \, Q_4 \, Q_4^c \, \nu_k^c}_{\text{Mass term for the new quarks}} \end{aligned}$$

Proposal for new quarks

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \qquad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \qquad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \qquad \begin{matrix} d_i^c \\ u_i^c \end{matrix},$$

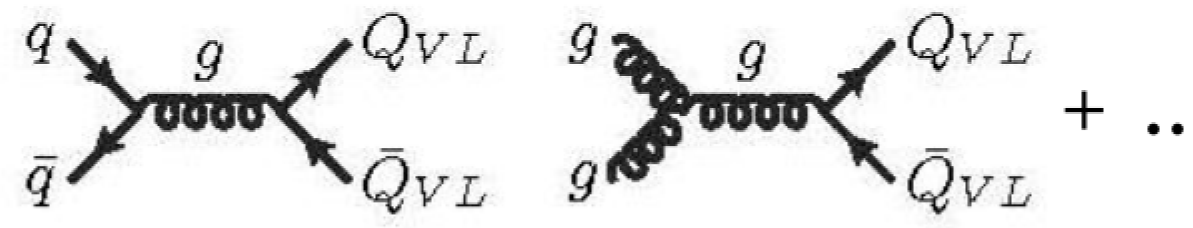
$$L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix}, \; L_4^c = \begin{pmatrix} e_4^c \\ \nu_4^c \end{pmatrix}, \; Q_4 = \begin{pmatrix} u_4 \\ d_4 \end{pmatrix}, \; Q_4^c = \begin{pmatrix} d_4^c \\ u_4^c \end{pmatrix},$$

The superpotential can be written in a very simple way;

$$W = Y^e_{IJk} L_I L_J e^c_k + Y^d_{IJk} L_I Q_J d^c_k - Y^u_{4Jk} L^c_4 Q_J u^c_k - Y^\nu_{4Jk} L^c_4 L_J \nu^c_k + Y^Q_{J4k} Q_J Q^c_4 \nu^c_k + \frac{1}{3}\kappa_{ijk} \nu^c_i \nu^c_j \nu^c_k . \tag{14}$$

Detection at the LHC

Pair production processes dominated by QCD are model independent



A recent search by ATLAS, arXiv:1505.04306 for all values of BRs into:

(assuming for simplicity that the new quarks couple only to the 3th generation)

T $\longrightarrow$ W b   **T** $\longrightarrow$ Z t   **T** $\longrightarrow$ h_{SM} t ⇒ m_T > 715 - 950 GeV

B $\longrightarrow$ W t   **B** $\longrightarrow$ Z b   **B** $\longrightarrow$ h_{SM} b ⇒ m_B > 575 - 813 GeV

However, new BRs are possible in our framework, modifying the analysis

T $\longrightarrow$ H t, A t, H^+ t, $\tilde{H}_u^0$ t, ν_L $\tilde{t}$

J.A. Aguilar-Saavedra, L-F, C. Muñoz, in preparation

Conclusion

- In SUSY with right-handed neutrinos (violating R-parity) we have been able to **reinterpret the Higgs superfields as a "4th family" of lepton superfields.**

From the theoretical viewpoint, this seems to be more satisfactory than the situation where the Higgses are disconnected from the rest of the matter as in the SM or in usual SUSY models

- Fields with the same color, electric charge and spin naturally mix
- R-parity violation, multilepton final states, displaced vertices,...

- Within this framework, the first scalar particle discovered at the LHC is mainly a right sneutrino belonging to a 4th-family vector-like doublet representation

Inspired by this interpretation, we have proposed a vector-like quark doublet representation in the low-energy SUSY spectrum

- New heavy quarks (T, B) could be produced and detected

Thank you

END