HELSINKI INSTITUTE OF PHYSICS

Overview of left-right symmetric extensions of the SM

Particle Physics Day / Katri Huitu, 7.11.2019

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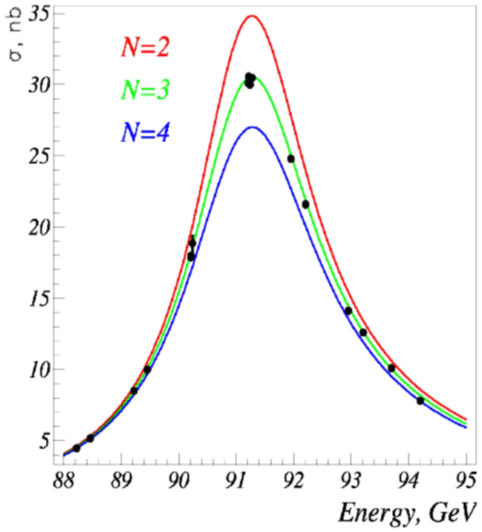
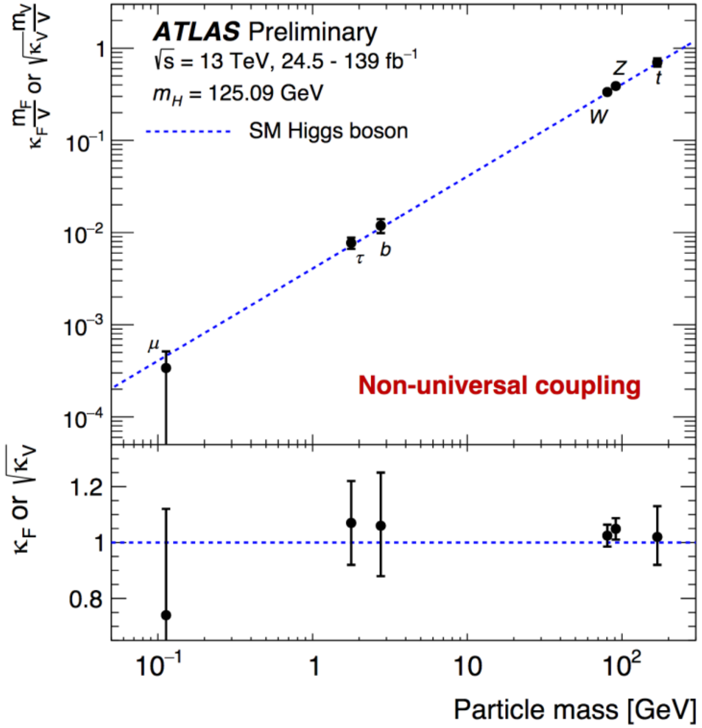
MOTIVATION

Problems in the Standard Model:

- Neutrino mass
- Dark matter
- Higgs mass
- Strong CP violation
- Weak CP violation
- No quantum gravity
- …

LEP Legacy, hep-ex/0503050





Some mundane questions:

Why three generations?

Why large mass differences?

Why left- and right-handed fermions are fundamentally different?

…

In recent years a multitude of BSM directions have appeared, both utilizing the ”old” BSM models with susy, extra dimensions, compositeness, and otherwise

BSM Theory after LHC Run II

fermionic partners
massive vectors
stops
gluinos
axions
dark photons
extended Higgs sectors
phase transitions
long-lived particles
gravitational waves
neutral naturalness
low-energy SUSY
compositeness
extra-dimensions
relaxion
landscape
UV-naturalness

Naturalness

Modified Naturalness

Un-Naturalness

Panico in EPS-HEP conference, 2019

A large number of models, including all kinds of combinations of earlier attempts.

Working close to experiments:

- Choose a model (personal preference is some well motivated model)
- Check the experimentally allowed parameter space (note: not a trivial task)
- Find testable predictions
- Discard the model/parameter region, if not viable

Left-right symmetric extensions of the Standard Model

Electromagnetic, strong and gravitational interactions conserve parity.
Maybe conserved at high energies also by weak interactions and dynamically broken

Pati, Salam (1974); Mohapatra, Pati (1975); Senjanovic, Mohapatra (1975)

If weak interactions were parity conserving at a high scale, every left-handed particle would need a right-handed counterpart

➡ right-handed neutrinos needed

After neutrinos were deemed massive, neutrino mass has also become a motivation.

Smallest gauge group where left-right symmetry can be implemented is
$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ Davidson (1979), Mohapatra, Marshak (1980)
Gauge symmetry could originate from SO(10) or E_6 unified model

Simple Left-Right Model with $SU(2)_L$ x $SU(2)_R$ x $U(1)_{B-L}$

Fermions:

$$(Q_L)^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} = \left(\mathbf{3}, \mathbf{2}, \mathbf{1}, \frac{1}{3}\right),\ (Q_R)^i = \begin{pmatrix} u_R^i \\ d_R^i \end{pmatrix} = \left(\mathbf{3}, \mathbf{1}, \mathbf{2}, \frac{1}{3}\right),$$

$$(L_L)^i = \begin{pmatrix} \nu_L^i \\ \ell_L^i \end{pmatrix} = (\mathbf{1}, \mathbf{2}, \mathbf{1}, -1),\ (L_R)^i = \begin{pmatrix} \nu_R^i \\ \ell_R^i \end{pmatrix} = (\mathbf{1}, \mathbf{1}, \mathbf{2}, -1)$$

with L,R the left- and right-chiral components, $P_{L,R} = (1 \pm \gamma_5)$

$$\boxed{Q = I_{3L} + I_{3R} + \frac{B - L}{2}}$$

Higgs sector: need to break $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ → $SU(2)_L \times U(1)_Y$

Break $SU(2)_R \times U(1)_{B-L}$ → $U(1)_Y$ by a triplet:

$$\Delta_R = \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix} = (\mathbf{1},\mathbf{1},\mathbf{3},2);\ \langle\Delta_R^0\rangle = v_R$$

For simplicity, assume that Δ_L is decoupled Chang, Mohapatra, Parida, PRL (1984)

$SU(2)_L \times U(1)_Y$ → $U(1)_{em}$ by a bidoublet:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} = (\mathbf{1},\mathbf{2},\mathbf{2},0);\ \langle\Phi\rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' e^{i\alpha} \end{pmatrix}$$

$v_R \gg \kappa \gg \kappa'$; $\kappa^2 + \kappa'^2 = v_{SM}^2$

$K^0 - \overline{K^0}$ mixing constrains $\approx \kappa\kappa' e^{i\alpha}$

Beall, Bander, Soni (1982)

Masses can be found from:

$$\mathcal{L}_Y = h^a_{q,ij}\bar{Q}_{L,i}\Phi_a Q_{R,j} + \tilde{h}^a_{q,ij}\tilde{Q}_{L,i}\widetilde{\Phi}_a Q_{R,j} + h^a_{\ell,ij}\bar{L}_{L,i}\Phi_a L_{R,j} + \tilde{h}^a_{\ell,ij}\bar{L}_{L,i}\widetilde{\Phi}_a L_{R,j}$$
$$+ f_{ij} L^T_{R,i} C i\tau_2 \Delta_R L_{R,j} + h.c.$$

With $\widetilde{\Phi} = i\sigma_2\Phi^*\,\sigma_2$

Quark masses:

$$M_u = h_u\kappa + \tilde{h}_u\, e^{-i\alpha}\kappa'; M_d = h_d e^{i\alpha}\kappa' + \tilde{h}_d\,\kappa$$

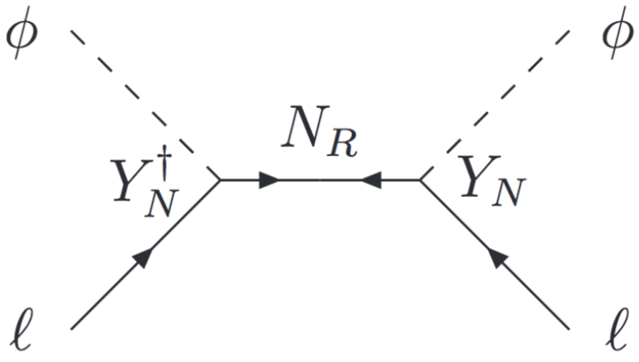
Charged lepton masses $M_\ell = h_\ell e^{i\alpha}\kappa' + \tilde{h}_\ell\,\kappa$

Neutrino masses $M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$; $m_D = h_\nu \kappa + \tilde{h}_\nu\, e^{-i\alpha}\kappa'$; $M_N = f v_R$

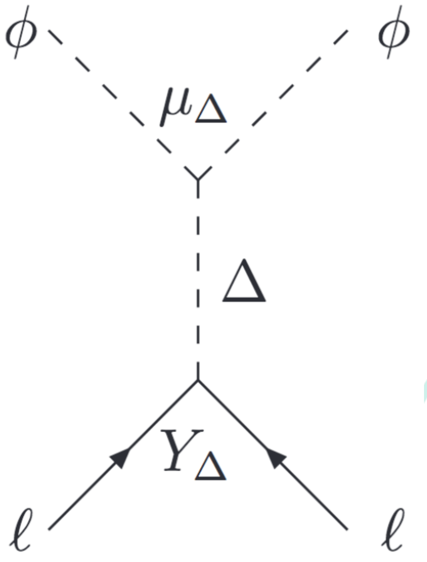
Type-I seesaw, no neutrino Majorana mass: $m_\nu = -m_D M_N^{-1}\, m_D^T$

Note: if Δ_L included, one gets also Majorana mass for the light neutrinos, and thus type-II seesaw

Gell-Mann, Ramond, Slansky (1979); Yanagida (1979); Mohapatra, Senjanovic (1980)



Type - I



Type - II

Gauge bosons, $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

New gauge bosons connected to enlarged gauge group W_R, W, Z_R, Z, γ

$$m_W^2 = \frac{g_L^2}{2}(\kappa^2 + \kappa'^2); \qquad m_{W_R}^2 = g_R^2 v_R^2$$

$$m_Z^2 = \frac{g_L^2}{2\ \cos^2\theta_W}(\kappa^2 + \kappa'^2); \quad m_{Z_R}^2 = 2(g_R^2 + g_{BL}^2)v_R^2$$

Theoretically $\frac{g_R}{g_L} \gtrsim 0.55$; the smaller the ratio is, the heavier Z_R is

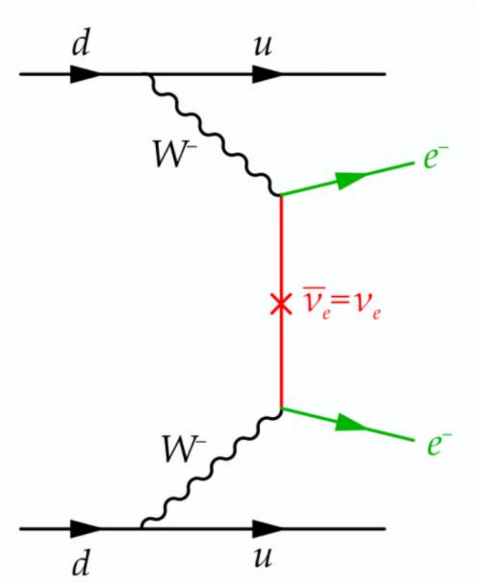
Mixings $\approx \frac{g_R}{g_L}\frac{m_V}{m_{V_R}}$, $V = W, Z$

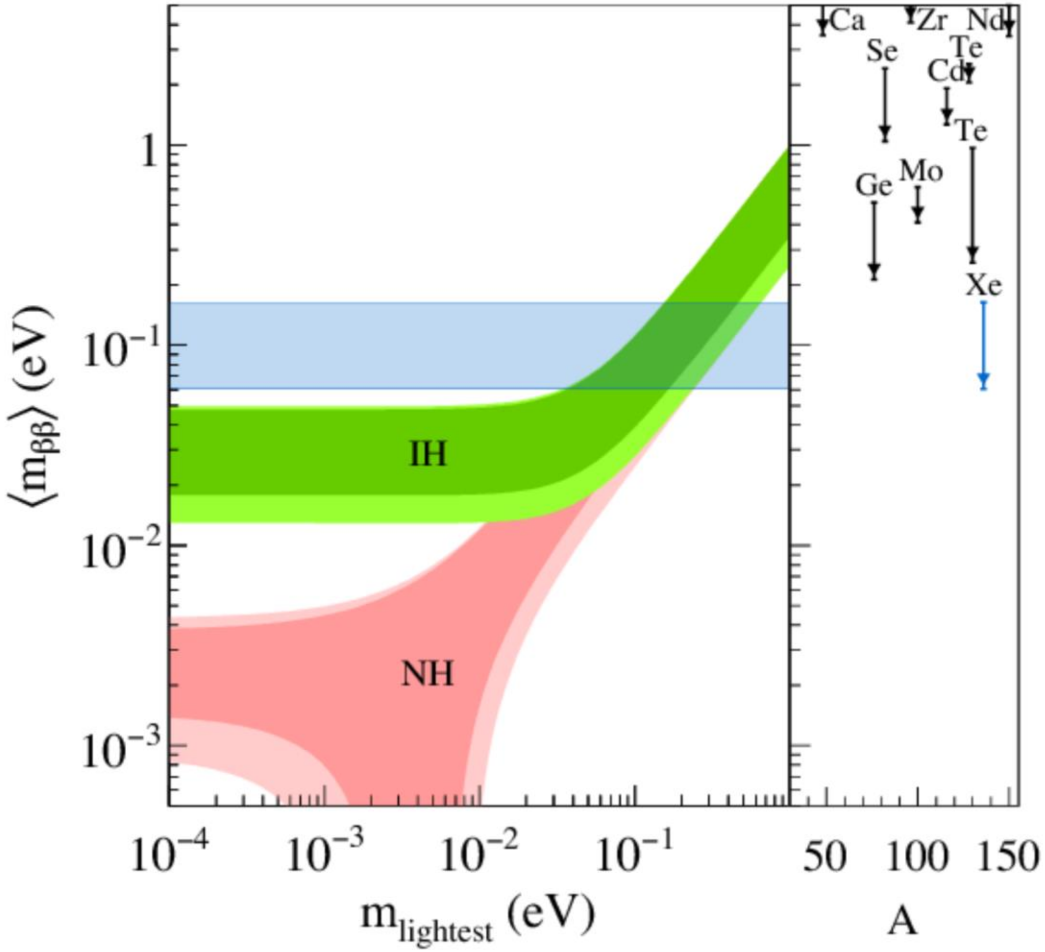
Tests of left-right model

J. Engel et al, Rept.Prog.Phys (2017)

Lepton number violating processes:

Neutrinoless double beta decay, $0\nu\beta\beta$





Lepton number violation in

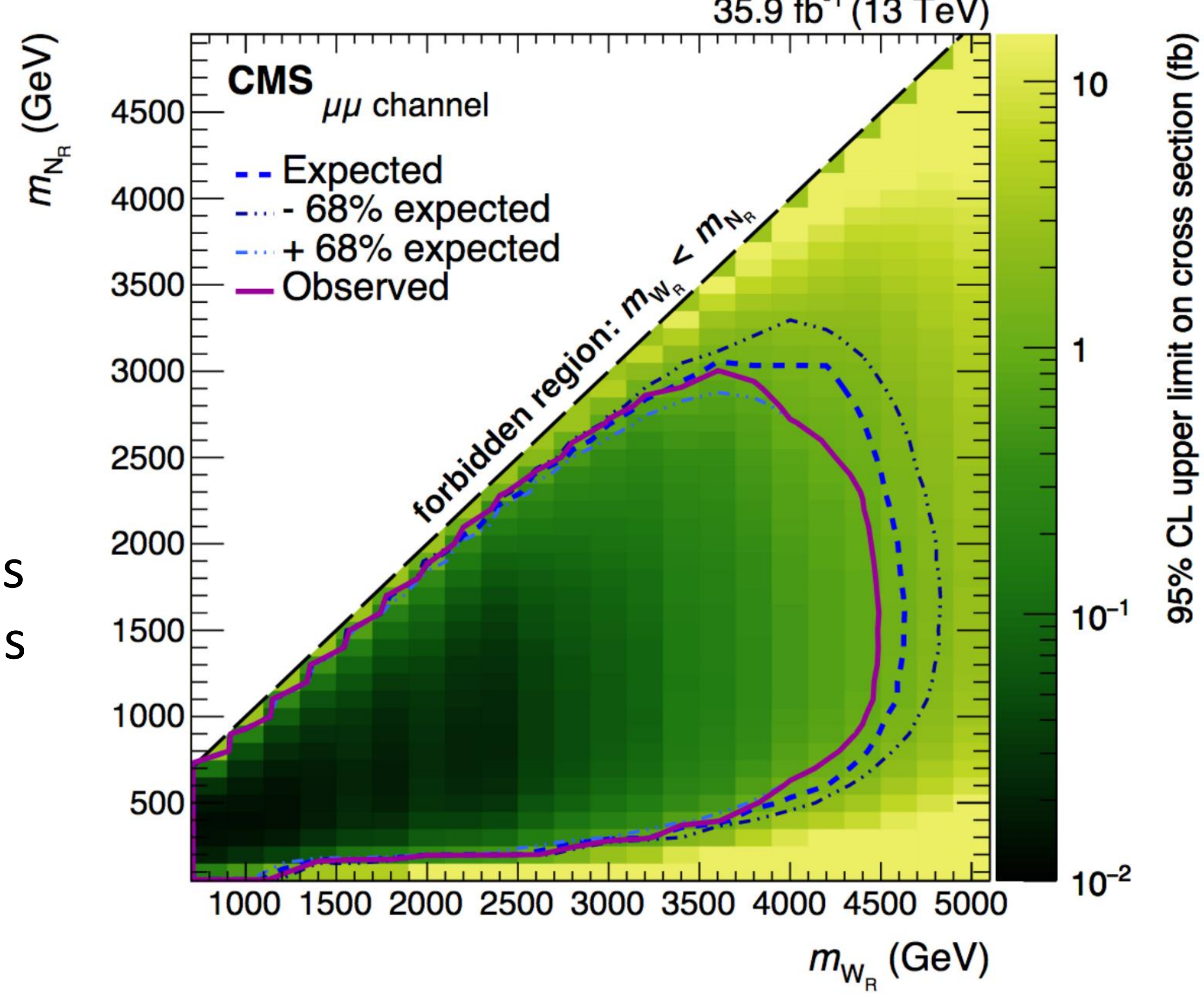
Meson decays, $\tau \to \mu, e\gamma, \mu \to e\gamma, \mu \leftrightarrow e$ –conversion,…

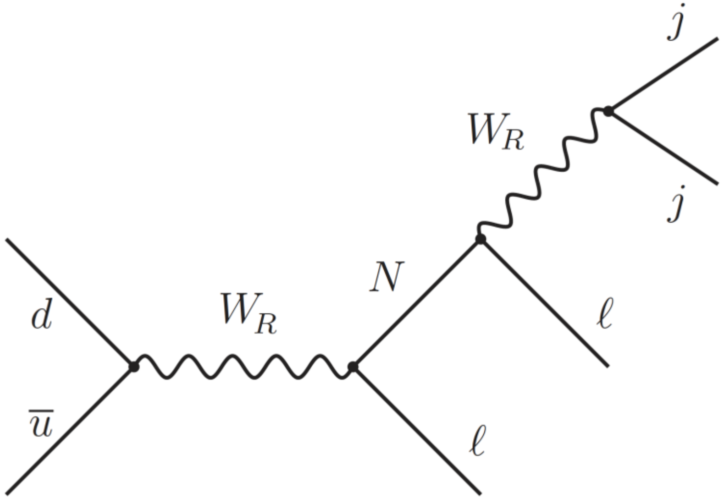
CMS, JHEP 05 (2018), arXiv: 1803.11116

$$W_R \to N_R \ell \to \ell\ell jj$$

N_R Majorana → similar amounts of same sign and opposite sign dileptons

Keung, Senjanovic, PRL 50 (1983) 1427





Discovery of W_R and N_R would be a clear signal of left-right symmetry

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \Delta_R = \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix}$$

Physical scalars:

Φ: 4 singly charged d.o.f.; 2 scalar and 2 pseudoscalar d.o.f.

Δ: 2 doubly charged d.o.f.; 2 singly charged, 1 scalar, 1 pseudoscalar d.o.f.

W_R, W, Z_R, Z, γ: need 4 charged and 2 neutral longitudinal d.o.f.

➡ $H^{\pm\pm}, H_1^\pm, A, H_{1,2}^0, h$

Of these, $H_1^\pm, A, H_1^0$ are nearly degenerate in mass and heavy from FCNC requirements; maybe not reachable at the LHC

$H^{\pm\pm}, H_2^0$ do not (almost) couple to hadrons, and limits for their masses are < 1 TeV

Supersymmetric left-right model (SUSYLR)

$R_{parity}=(-1)^{3(B-L)+2s}$ is an exact symmetry as B-L is a gauge symmetry;

if $SU(2)_R x U(1)_{B-L}$ is broken by L=±2 triplet, remains unbroken also after symmetry breaking ⇒ LSP a dark matter candidate

Mohapatra, PRD (1986); Font, Ibanez, Quevedo, PLB (1989); Martin PRD (1992)

⇒ proton remains stable

There is no SUSY CP problem because of parity invariance

Kuchimanchi, PRL (1996), Mohapatra, Rasin, PRL (1996)

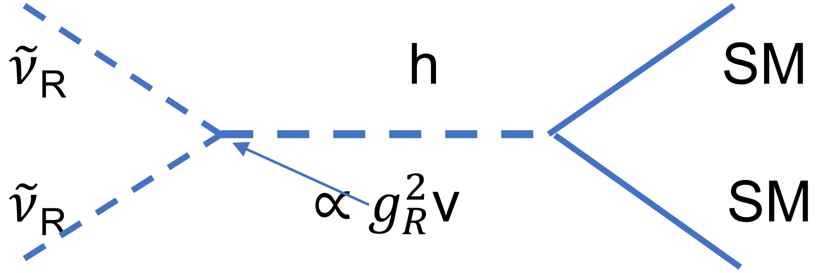
Also strong CP problem may be solved

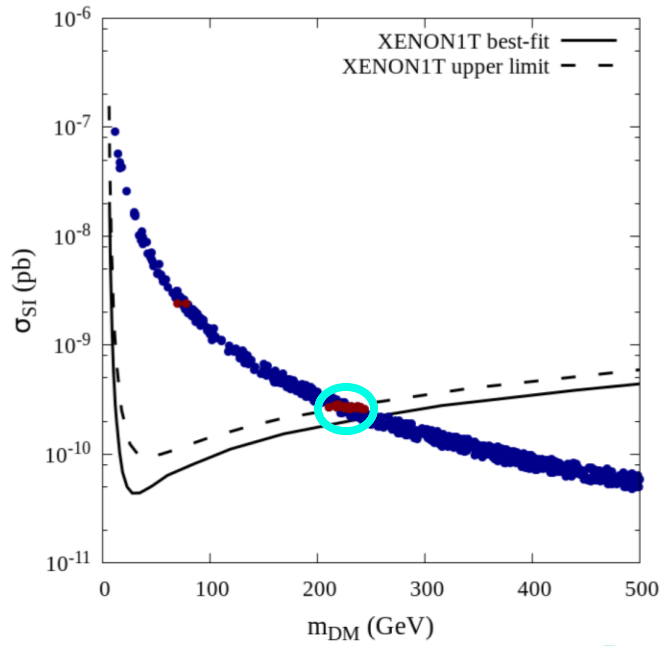
Beg, Tsao (1978); Mohapatra, Rasin, (1996); Babu, Dutta, Mohapatra (2002)

Dark matter in SUSYLR

Frank, Fuks, KH, Rai, Waltari (2017);
Chatterjee, Frank, Fuks, KH, Mondal, Rai, Waltari (2019)

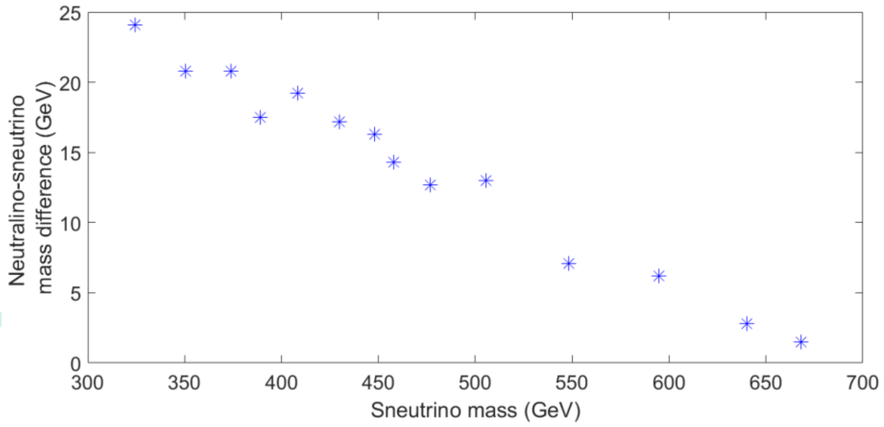
1) partners of right-handed neutrinos can produce DM





Right-sneutrino mass is the only free parameter
→ relic density determines $m_{\tilde{\nu}_R} \approx 250$ GeV

Right sneutrino LSP with coannihilations with another sneutrino or neutralinos: $m_{\tilde{\nu}_R} \approx 700$ GeV



2) SUSY partners of gauge bosons or Higgses can be the dark matter

Chatterjee, Frank, Fuks, KH, Mondal, Rai, Waltari (2019)

Bidoublet higgsinos form a nearly degenerate set of four neutralinos and two charginos

➡ Coannihilations cannot be avoided, when the lightest higgsino is the LSP

The Planck-value for relic density is achieved with 750 GeV LSP higgsino (could be silghtly decreased with further coannihilations, with e.g. sneutrino)

Note that in this case the spectrum is rather heavy and compressed

➡ difficult to detect.

3) Right-handed neutrinos can contribute to dark matter

Bhattacharya, Ma, Wegman (2014)

In the minimal form need to take into account the one-loop corrections to scalar potential to stabilize the model and $v_R \lesssim 10$ TeV

In addition to h, A_1, H_1, $H_1^{\pm}$ could be within LHC reach:
almost degenerate with mass $\gtrsim$ 700 GeV

One $H^{\pm\pm}$ light, not much heavier than 1 TeV ➡ possibility to exclude the model

$H^{\pm\pm} \rightarrow \ell^{\pm}\,\ell'^{\pm}$; $m_{H^{\pm\pm}} \gtrsim$ 700 GeV, if decays to electrons or muons

…KH, Maalampi, PLB (1995), KH, Maalampi, Raidal, (1994); KH, Maalampi, Pietilä, Raidal (1997); Barenboim, KH, Maalampi, Raidal (1997); Dutta, Mohapatra (1998); Chacko, Mohapatra (1998); KH, Pandita, Puolamäki (1998); Babu, Mohapatra (2008); Frank, Korutlu (2011); Chun, Sharma, PLB (2013); Basso, Fuks, Krauss, Porod (2015); Babu, Patra (2016); Frank, Ghosh, KH, Rai, Saha, Waltari (2014); Frank, Fuks, KH, Rai, Waltari, (2017); Chatterjee, Frank, Fuks, KH, Mondal, Rai, Waltari, (2019)…

Conclusions

Need some experimental guidance

Meanwhile:

consider relevant possibilities
check all possible implications
indirect experiments can provide the scale

Experiments need to know the new type of signals to analyze
and
theorists need to apply experimental results to their favourite theory

For the field it is essential to fully use the LHC potential