Investigating Beyond Standard Model

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- Standard Model – A Brief Tour
- Why BSM ?
- BSM Classification – How do we look into this?
- Low Scale & High Scale Models.
- Conclusions

- Standard Model (SM) is now well established as a valid theory of Particle Physics at low energy ∼ 100 GeV (1 GeV ∼ mass of proton).
- Precision matching of SM's predictions and experimental observations is spectacular – Discovery of Higgs Scalar (?)
  (SM is broken spontaneously once Higgs acquires vacuum expectation value – Higgs mechanism).

Symmetry Groups	Quarks	Leptons	Scalars (Higgs)	Gauge Bosons
$SU(3)_C$	3($\bar{3}$)	1	1	Gluon
$SU(2)_L$	2(1)	2(1)	2	W
$U(1)_Y$	NON-ZERO	NON-ZERO	NON-ZERO	B

Is it a complete theory?

What about Neutrino mass, Dark matter, Baryon Asymmetry of the Universe, and other aesthetic issues, like Unification, Fine tuning ?

Some recent important issues

- Both ATLAS and CMS have found a new boson around 122-127 GeV – seems to be SM Higgs.

  If it is so then its Stability criterion must be adjudged – RGE of Higgs Quartic Coupling λ.

  New physics includes exotic scalars, fermions, and may have extended gauge sector.

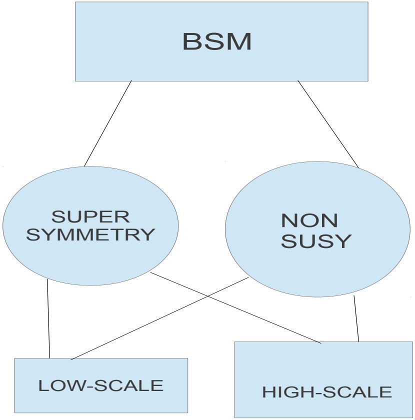
  The new particles that couple to SM Higgs will affect the RGE of λ – Vacuum Stability must be reexamined.

- Higgs to di-photon rate – impact on the BSM parameters.

  The light charged particles (Fermions or Bosons) that couple to SM Higgs and Photon will lead to extra contribution to $H \to \gamma\gamma$ process.

- Moderate θ_{13} can have different impact.

  Many conclusions in the context of Lepton Flavour Violation (LFV) and Neutrinoless Double Beta Decay ($0\nu\nu\beta$) might be changed.


BSM
SUPER SYMMETRY
NON SUSY
LOW-SCALE
HIGH-SCALE

Low Energy Models

- Low energy Model – TeV Scale? Why?
- Within the reach of the present experiments, like LHC.
- Either High Scale motivated or Simple Extension (either by particle or symmetry group(s)) of the SM.
- Left-Right Symmetry – motivated from High scale, where parity symmetry is spontaneously broken.

To start with ...

- What is Left-Right symmetry?

  Any connection with high scale physics?

  What is the scale of this theory?

- Neutrino Mass generation through Type-(I+II) seesaw

  $0\nu\beta\beta$ in LR model at Neutrino Experiments and at the LHC

- Impact of low energy data on the parameters of this model

Left-Right Symmetry

- A discrete symmetry that connects Left & Right sector
- Generic Structure is:

  $SU(N)_L \otimes SU(N)_R$

  Example: $SU(2)_L \otimes SU(2)_R \subset SO(10)$

  $SU(3)_L \otimes SU(3)_R \subset E(6)$

- We will talk about: $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ Gauge group.
- SM Extended by: a right-handed neutrino(ν_R), a bidoublet(Φ), and two triplet Higgs fields($\Delta_{L/R}$)
- $\Phi \equiv (2,2,0), \Delta_L \equiv (3,1,1), \Delta_R \equiv (1,3,1)$

Neutrino Mass generation

- Few new terms along with the SM Lagrangian:

$$\begin{aligned}\mathcal{L} &= f_L l_L^T C i\sigma_2 \Delta_L l_L + f_R l_R^T C i\sigma_2 \Delta_R l_R \\ &+ \bar{l}_R (y_D \Phi + y_L \tilde{\Phi}) l_L + V_{scalar}(\Phi, \Delta_{L/R})\end{aligned}$$

- Neutral fermion mass matrix:

$$M_\nu \equiv \begin{pmatrix} f_L v_L & y_D v \\ y_D^T v & f_R v_R \end{pmatrix},$$

where $< \Delta_L >= v_L$, $< \Delta_R >= v_R$.

- Using the seesaw approximation ($f_R v_R >> y_D v$) we get

$$(m_\nu^{light})_{3\times3} = f_L v_L + \frac{v^2}{v_R} y_D^T f_R^{-1} y_D,$$

$$(m_R^{heavy})_{3\times3} = f_R v_R,$$

(JC, ZD, SG, SP; JHEP 1208 (2012) 008)

Neutrinoless Double beta decay($0\nu\beta\beta$)

- $(A, Z) \longrightarrow (A, Z+2) + 2e^-$
- Limit on half-life: $T_{1/2} < 3 \times 10^{25}$ yrs (Heidelberg-Moscow experiment using ^{76}Ge)

  Bound on the effective neutrino mass: $m_{eff} \leqslant 0.21 - 0.53$ eV
- Artifact of process like Lepton Number Violation (LNV) by two units
- Sources: Seesaw models / R-parity Violating SUSY etc.

  Signals to the presence of "Majorana" nature of neutrinos

- In the standard three generation picture the time period for neutrinoless double beta decay is given as,

$$\frac{\Gamma}{\ln 2} = G \left| \frac{\mathcal{M}_\nu}{m_e} \right|^2 |m_\nu^{ee}|^2,$$

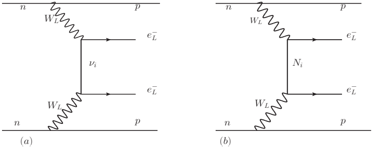
where G contains the phase space factors, m_e is the electron mass, $\mathcal{M}_\nu$ is the nuclear matrix element.

$$|m_\nu^{ee}| = |U_{ei}^2 \, m_i|,$$

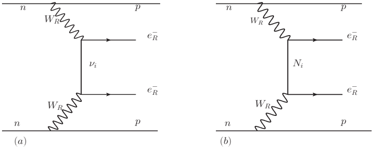
is the effective neutrino mass that appear in the expression for time period for neutrinoless double beta decay

- The unitary matrix U is the so called PMNS mixing matrix

Diagrams contributing to $0\nu\beta\beta$ in LR model; (JC, ZD, SG, SP; JHEP 1208 (2012) 008)

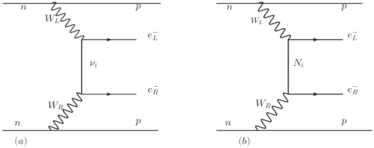


Contribution from light and heavy Majorana neutrino intermediate states from two W_L exchange

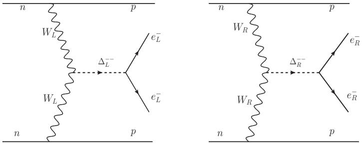


Contribution from light and heavy Majorana neutrinos from two W_R exchange

Diagrams contributing contd.
(JC, ZD, SG, SP; JHEP 1208 (2012) 008)



Contribution from light and heavy Majorana neutrino intermediate states from W_L and W_R exchange



Contribution from the charged Higgs intermediate states from W_L and W_R exchange

Charged Current interactions of leptons:

$$\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3} \Big[\overline{\ell}_{\alpha\, L}\, \gamma_\mu \left\{ (U_L)_{\alpha i} \nu_{L i} + (T)_{\alpha i} N^c_{R i} \right\} W^\mu_L$$

$$+ \overline{\ell}_{\alpha\, R}\, \gamma_\mu \left\{ (S)^*_{\alpha i} \nu^c_{L i} + (U_R)^*_{\alpha i} N_{R i} \right\} W^\mu_R \Big] + \text{h.c.}$$

where complete unitary mixing matrix, $\mathcal{U}$ is:

$$\mathcal{U} = \begin{pmatrix} (1 - \frac{1}{2} R R^\dagger)\, U'_L & R\, U'_R \\ -R^\dagger\, U'_L & (1 - \frac{1}{2}\, R^\dagger R)\, U'_R \end{pmatrix} = \begin{pmatrix} U_L & T \\ S & U_R \end{pmatrix}$$

with $R = m_D^\dagger\, M_R^{-1*}$

(JC, ZD, SG, SP; JHEP 1208 (2012) 008)

The half-life is,

$$\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = G\frac{|\mathcal{M}_\nu|^2}{m_e^2}\Big|\Big(U_{L_{e\,i}}^2\, m_i \quad + \quad p^2\frac{T_{e\,i}^2}{M_i} + p^2\frac{M_{W_L}^4}{M_{W_R}^4}\frac{U_{R_{e\,i}}^{*2}}{M_i}$$
$$+\frac{M_{W_L}^4}{M_{W_R}^4}S_{e\,i}^{*2}\, m_i \quad + \quad \frac{M_{W_L}^2}{M_{W_R}^2}U_{L_{e\,i}}S_{e\,i}^{*}m_i$$
$$+p^2\frac{M_{W_L}^2}{M_{W_R}^2}\frac{T_{e\,i}\,U_{R_{e\,i}}^{*}}{M_i} + \frac{U_{Lei}^2 m_i m_e^2}{M_{\Delta_L}^2} \quad + \quad p^2\frac{M_{W_L}^4}{M_{W_R}^4}\frac{U_{Rei}^2 M_i}{M_{\Delta_R}^2}\Big)\Big|^2$$

p^2 carries the informations about the Nuclear matrix elements and virtual momentum transfer

(JC, ZD, SG, SP; JHEP 1208 (2012) 008)

For our analysis we consider two cases:
(JC, ZD, SG, SP; JHEP 1208 (2012) 008)

- Type-I dominance:

$$m_\nu^{light} = \frac{v^2}{v_R} y_D^T f^{-1} y_D$$
$$m_R^{heavy} = f v_R$$

With a harmless choice (y_D is $\propto$ Identity matrix) we have the light & heavy neutrino mass relation: $m_i \propto 1/M_i$ $\Rightarrow$ followed from LR-symmetry

- Type-II dominance:

$$m_\nu^{light} = f_L v_L$$
$$m_R^{heavy} = f_R v_R$$

As an artifact of LR-symmetry $\Rightarrow$ light & heavy neutrino masses are related as: $m_i \propto M_i$

We did consider the following zones (JC, ZD, SG, SP; JHEP 1208 (2012) 008):

- Normal hierarchy (NH) refers to the arrangement which corresponds to $m_1 < m_2 << m_3$ with

$$m_2 = \sqrt{m_1^2 + \Delta m_{\rm sol}^2}\,, m_3 = \sqrt{m_1^2 + \Delta m_{\rm atm}^2 + \Delta m_{\rm sol}^2}$$

- Inverted hierarchy (IH) implies $m_3 << m_1 \sim m_2$ with

$$m_1 = \sqrt{m_3^2 + \Delta m_{\rm atm}^2}\,, m_2 = \sqrt{m_3^2 + \Delta m_{\rm sol}^2 + \Delta m_{\rm atm}^2}$$

- Quasi degenerate neutrinos correspond to $m_1 \approx m_2 \approx m_3 >> \sqrt{\Delta m_{atm}^2}$

The 3 σ ranges of the mass squared differences and mixing angles from global analysis of oscillation data

parameter	best-fit	3σ
$\Delta m^2_{\rm sol}[10^{-5}\text{eV}^2]$	7.58	6.99-8.18
$\|\Delta m^2_{\rm atm}\|[10^{-3}\text{eV}^2]$	2.35	2.06-2.67
$\sin^2\theta_{12}$	0.306	0.259-0.359
$\sin^2\theta_{23}$	0.42	0.34-0.64
$\sin^2\theta_{13}$	0.021	0.001-0.044

$\sin^2\theta_{13}$ for:

$$\begin{aligned}
{\rm Daya-Bay:} \quad & 0.023\ ({\rm best-fit}), \\
& 0.009-0.037\ (3\sigma\ \ {\rm range}) \\
{\rm RENO:} \quad & 0.026\ ({\rm best-fit}) \\
& 0.015-0.041\ (3\sigma\ \ {\rm range})
\end{aligned}$$

With suitable choices of Majorana phases we achieve the following cancellation conditions in $|m_\nu^{ee}|$ in different hierarchical regime:

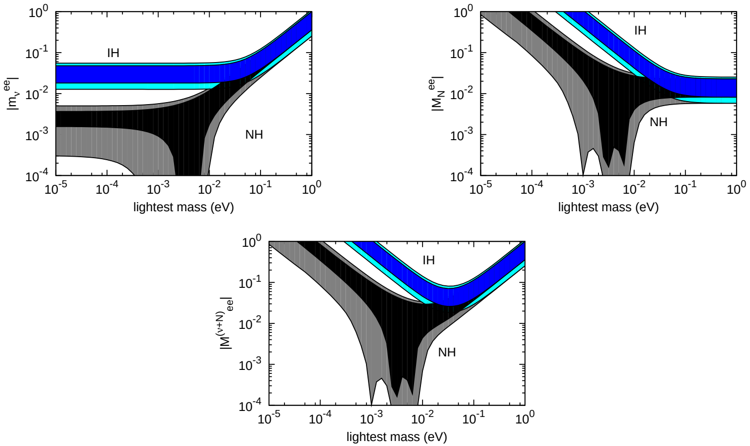
$$\begin{aligned} \tan^2\theta_{13} &= \sqrt{r}\ \sin^2\theta_{12} \\ &= \sqrt{r}\ \cos 2\theta_{12} \\ &= \sqrt{r} \\ &= 1/\sqrt{r} \end{aligned}$$

where $r = \left|\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}\right|$

	$\sqrt{r}$	$\sqrt{r}s^2_{12}$	$\sqrt{r}c2\theta_{12}$	t^2_{13}	$\sqrt{r}t^2_{13}$
Max	0.2	.072	.096	.046 (.037)	$10^{-3}\times$9(7)
Min	0.16	.042	.046	.001 (.009)	$10^{-3}\times$0.1(2)

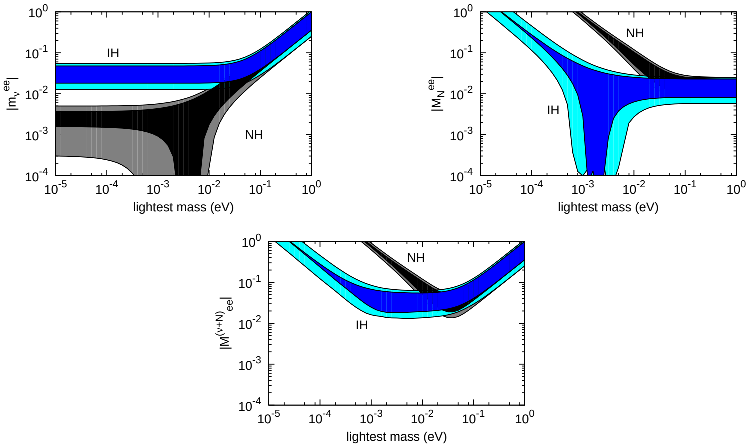
(JC, ZD, SG, SP; JHEP 1208 (2012) 008)

Plots for Type-I dominance



(JC, ZD, SG, SP; JHEP 1208 (2012) 008)

Plots for Type-II dominance



(JC, ZD, SG, SP; JHEP 1208 (2012) 008)

Contributions from Charged Higgs

- Effective mass from doubly charged Higgs exchange diagrams:

$$|m_{\Delta}^{ee}| \quad = \left| p^2 \frac{M_{W_L}^4}{M_{W_R}^4} \frac{2\,M_N}{M_{\Delta_R}^2} \right|$$

- LFV constraint: $M_N/M_{\Delta_R} < 0.1$

  Thus contribution is small compare to the RH-contribution.

- Further limit from 1-loop low energy data demands $M_{\Delta_{L/R}}$ to be very heavy $\sim$ 10 TeV.

(JC, ZD, SG, SP; JHEP 1208 (2012) 008)

1-loop muon decay data:

- Including Radiative Corrections in Δr:

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8(1 - M_W^2/M_Z^2)M_W^2}(1 + \Delta r)$$

- Experimental fits to Δr:

$$\Delta r \equiv \Delta r_0 \pm \Delta r_\sigma = 0.0362 \pm 0.0006$$

- This puts correlated bounds on M_N, v_R, M_{W_2}, M_H.
  (JC, JG, RS, RS; JHEP 1207 (2012) 038)

Low energy data and Phenomenological Aspects

Impact of Low energy data

- $K_L - K_S$ mass difference ($< (3.483 \pm 0.006) \times 10^{-12}$ MeV) puts bound on $M_{W_R} >$ 2.5 TeV

  (Soni $et.al.$ PRL48 (1982) 848,
  Mohapatra $et.al.$ Nucl.Phys. B802 (2008) 247-279)

- Assuming $M_{W_R} > M_N$: $M_{W_R} >$ 1.8–2.5 TeV

  The heavy neutrino mass limit: $M_N >$ 700–1000 GeV

- From 1-loop muon decay data: Correlated bounds on v_R, M_{W_R}, M_N, M_H.

  (JC, JG, RS, RS; JHEP 1207 (2012) 038)

Other sources..

Mohapatra *et.al*. Nucl.Phys. B802 (2008) 247-279;
Frank *et.al*. Phys. Rev. D82 (2010) 033012

- Flavour Changing Neutral Higgs (FCNH) contribution

- $B_d - \bar{B}_d < ((117.0 \pm 0.8) \times 10^{-10}$ MeV);

  $B_s - \bar{B}_s < ((3.337 \pm 0.033) \times 10^{-10}$ MeV)

- Direct & Indirect CP violation

- Neutron Electric Dipole Moment (EDM)

Phenomenological aspects

- Full LR symmetric model is implemented in FeynRules.

  Now in MADGRAPH-5, CalcHEP, LanHEP, FeynArts Left-Right Symmetric Model is available to us ☺.

  This code is not yet publicly available ☹

  Will be made soon ☺

- Interfacing with GoSam is in process.

- The decays of W_R, Z_2, N_R are studied considering different light & heavy neutrino mixings.

  (JC, JG, RS, RS; JHEP 1207 (2012) 038)

To do..

We are making a *Catalog* that includes:

Productions of different processes involving

W_R, Z_2, N_R, and charged Scalars

considering different light & heavy neutrino mixings.

(JC, JG, RS; in preparation)

High Scale Models

- High Scale: $10^{16} - 10^{19}$ GeV.
- Grand Unified Theory – Unification of Fundamental Forces.
- Larger Symmetry Groups to accommodate SM.
- May be Supersymmetric or not.
- Main issues: Symmetry Breaking, Gauge Coupling Unification, Fermion masses etc.
- Non-Universal Gaugino Masses.

- Gauginos are SUSY partners of Gauge Bosons – Fermions by nature.
- Gaugino mass (at high scale) can arise from the operator:
  $\mathcal{L} \sim [Tr(F_{\mu\nu}\mathbf{\Phi_D}F^{\mu\nu})]$.
- $\mathbf{\Phi_D}$ is the D-dimensional Higgs

  belongs to the symmetric product of the adjoint representation.
- For $Singlet$ scalar field all the gauginos are degenerate.

  The GUT breaking scalars $(non - singlet)$ lead to no-universal gaugino masses.

  (JC, AR; Phys.Lett.B673:57-62,2009)

$SU(5) \supset SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

- Rank = 4, Number of generators = 24 (Dimension of the adjoint representation)
- $5 \otimes \overline{5} = 1 \oplus 24.$

  $5 \otimes 5 = 10_a \oplus 15_s.$
- $(24 \otimes 24)_{sym} = 1 \oplus 24 \oplus 75 \oplus 200$
- The simplest illustrative example is that of SU(5) with a Φ_{24} scalar

  $\mathcal{L}_{dim-5} = -\frac{\eta}{M_{Pl}} \left[\frac{1}{4c} Tr(F_{\mu\nu} \mathbf{\Phi_{24}} F^{\mu\nu})\right].$
- 5 = $(3,1)_{-2} \oplus (1,2)_3$
- $< \Phi_{24} >= \frac{v_{24}}{\sqrt{15}}$ diag$(1, 1, 1, -3/2, -3/2)$
- $\delta_1 = \delta_2/3 = -\delta_3/2 = 3/\sqrt{15}$

$SU(5) \supset SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

- $10 \otimes \overline{10} = 1 \oplus 24 \oplus 75.$
  $10 = (\bar{3},1)_{-\frac{4}{3}} \oplus (3,2)_{\frac{1}{3}} \oplus (1,1)_2.$
- $< \Phi_{24} >= \frac{v_{24}}{\sqrt{90}}\,\text{diag}(-4,-4,-4,1,1,1,1,1,1,6)$

  Gives same δ_is, calculated before.
- $< \Phi_{75} >$ is traceless and orthogonal to $< \Phi_{24} >$:

  $< \Phi_{75} >= \frac{v_{75}}{\sqrt{12}}\,\text{diag}(1,1,1,-1,-1,-1,-1,-1,-1,3)$
- $\delta_1 = -5\delta_2/3 = -5\delta_3 = 4/\sqrt{3}$
- $15 \otimes \overline{15} = 1 \oplus 24 \oplus 200$
  $15 = (6,1)_{-\frac{4}{3}} \oplus (3,2)_{\frac{1}{3}} \oplus (1,3)_2.$
- $< \Phi_{200} >$ is traceless and orthogonal to $< \Phi_{24} >$, and $< \Phi_{75} >$:

  $< \Phi_{200} >= \frac{v_{200}}{\sqrt{21}}\,\text{diag}(\underbrace{1,..,1}_{6},\underbrace{-2,..,-2}_{6},2,2,2)$
- $\delta_1 = 5\delta_2 = 10\delta_3 = 1/\sqrt{21}$

- Gaugino Mass ratio $M_i : M_j : M_k = \delta_i : \delta_j : \delta_k$

- Ratios are computed interms of the intermediate gauge groups.

  SM gaugino masses can be reconstructed

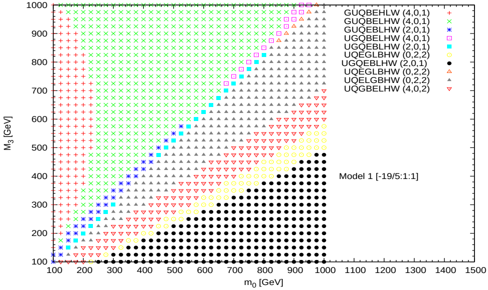
- Gaugino mass relation (for intermediate breaking chain G_{422D}):

$$M_{4C} = M_3, M_{2R} = M_{2L} = M_2, M_1 = \frac{2}{5}\ M_{4C} + \frac{3}{5}\ M_{2R}$$

Non-universal Gaugino Mass ratios are calculated for other breaking patterns of $SO(10)$ and $E(6)$

(JC, AR; Phys.Lett.B673:57-62,2009, arXiv:1006.1252)
(SB, JC; Phys.Rev.D81:015007,2010)

Low Scale Phenomenology of High Scale model – Bridging with RGEs



m_0 vs M_3, indicating *one of the Best* Signals and SUSY particle mass hierarchy. This non-universal Gaugino mass ratio is achieved for $SO(10) \xrightarrow{210} SU(5)' \otimes U(1)$. (JC, TM, PK in preparation.)

So in brief..

- The precise knowledge of low energy data is very important
- Studies are going on to understand the compatibility of different parameters of TeV and High scale models.

  The correlations among them are being studied more precisely considering higher order contributions.
- Constraints from LFV, 1-loop muon decay, $K_L - K_S$ mass difference along with the LHC data are leaving little room for exploring phenomenological aspects within the present collider reach.
- High Scale Models are not "*untouchables*" – one can have indirect impact on low scale observables.
- Model discriminations are other issues – we need to look at.

  We may have to look for Data driven Theory.