Models of Neutrino Mass Generation and Collider Signatures

Yonsei-BRL workshop

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원주 토지문화관

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Outline

- Seesaw Mechanism
  - Type I seesaw
  - Type II seesaw
  - Type III seesaw
- Radiative Origin of Neutrino Masses
  - Zee model
  - Zee-Babu model
  - Hybrid doubly charged Higgs model
  - Dark Scalar Model
- Supersymmetric Neutrino Mass

Majorana vs. Dirac Neutrino Masses

Majorana masses

CP conjugate

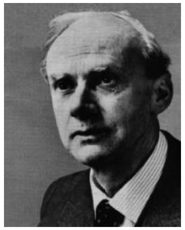
$$\boxed{m_{LL}\bar{\nu}_L\nu_L^c}$$

$$\boxed{M_{RR}\bar{\nu}_R\nu_R^c}$$

Violates L

Violates L_e, L_μ, L_τ

Neutrino=antineutrino



$$\boxed{m_{LR}\bar{\nu}_L\nu_R}$$

Conserves L

Violates L_e, L_μ, L_τ

Neutrino$\neq$antineutrino

Dirac mass

A fundametal question for neutrino mass:

- **Why** $m_\nu << m_{q,l}$ **?**

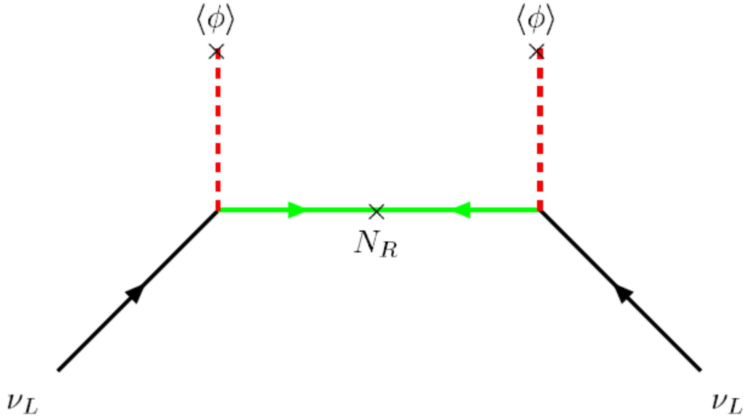
  (new scale, new particles, ..)
- Orthodox mechanism to achieve such a small ν mass generation ⇒ Seesaw mechanism (Type I)

  (Minkowski 77, Yanagida 79, Glashow 79, Gell-Mann, Ramond, Slanski 79, Mohapatra, Senjanovic 79)
- Add right handed neutrinos N_R to SM with Majorana mass:

$$\boxed{L_Y = h_\nu \overline{L}\,\phi N + M_R N N}$$

After electroweak symmetry breaking,
we get seesaw formula:

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \Rightarrow m_\nu = \frac{m_D^2}{M} << m_D$$



To obtain $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2} \sim 0.05$ eV, $m_D \sim m_t$ and $M_3 \sim 10^{15}$GeV (GUT!)

Neutrinos are Majorana

Seesaw mechanism tells us that there is a new symmetry breaking scale associated with RH neutrino mass: B-L symmetry.

Testing the seesaw mechanism

- Important questions for testing seesaw mechanism

(i) How big is the seesaw scale M_R ?

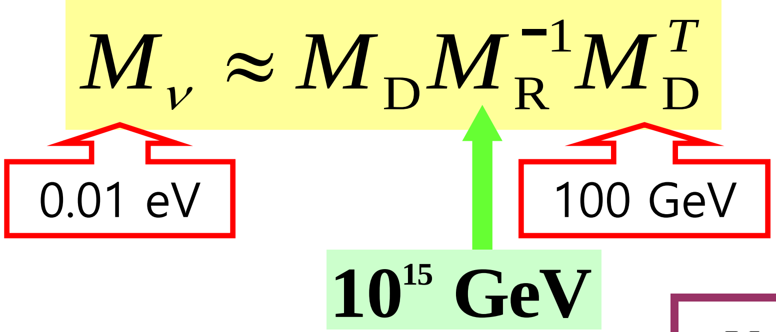
(ii) What is the new physics associated with this new scale ? –are there new forces, new Higgs fields, etc ?

- Elegantly it can connect to GUT , but difficult to test experimentally

- For testability at Collider, we need to lower the scale of seesaw to O(TeV), but fine tuning is required.

GUT Seesaw *vs.* TeV Seesaw

Natural case: no large cancellation in the leading seesaw term.



$$M_\nu \approx M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$$

0.01 eV

100 GeV

10^{15} GeV

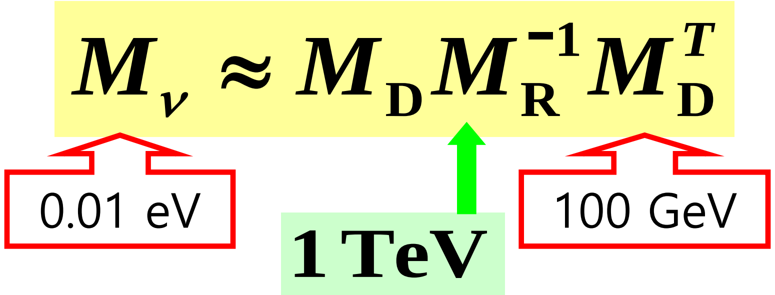
$$R \sim S \sim M_{\rm D} / M_{\rm R} \sim 10^{-13}$$

$$\text{Unitarity Violation} \sim 10^{-26}$$

$$V^\dagger V + \underline{S^\dagger S} = V V^\dagger + \underline{R R^\dagger} = 1$$

$$\begin{pmatrix} V & R \\ S & U \end{pmatrix}^\dagger \begin{pmatrix} 0 & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R} \end{pmatrix} \begin{pmatrix} V & R \\ S & U \end{pmatrix}^* = \begin{pmatrix} \overline{M}_\nu & 0 \\ 0 & \overline{M}_{\rm R} \end{pmatrix}$$

Unnatural case: large cancellation in the leading seesaw term.



$$M_\nu \approx M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$$

0.01 eV

100 GeV

1 TeV

$$R \sim S \sim M_{\rm D} / M_{\rm R} \sim 10^{-1}$$

$$\text{Unitarity Violation} \sim 10^{-2}$$

TeV-scale (right-handed) Majorana neutrinos: small masses of light Majorana neutrinos come from sub-leading perturbations.

Structural Cancellation

Given diagonal M_R with 3 eigenvalues M_1, M_2 and M_3, the leading (i.e., type-I seesaw) term of the light neutrino mass matrix vanishes, if and only if M_D has rank 1,

$$\boldsymbol{M}_{\mathbf{D}} = m \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{pmatrix}$$

and if

$$\frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} = 0$$

$$\boldsymbol{M}_{\nu} \approx \boldsymbol{M}_{\mathbf{D}} \boldsymbol{M}_{\mathbf{R}}^{-1} \boldsymbol{M}_{\mathbf{D}}^{T} = \mathbf{0}$$

(Kersten, Smirnov 07).

Tiny ν-masses can be generated from tiny corrections to this complete "structural cancellation", by deforming M_D or M_R .

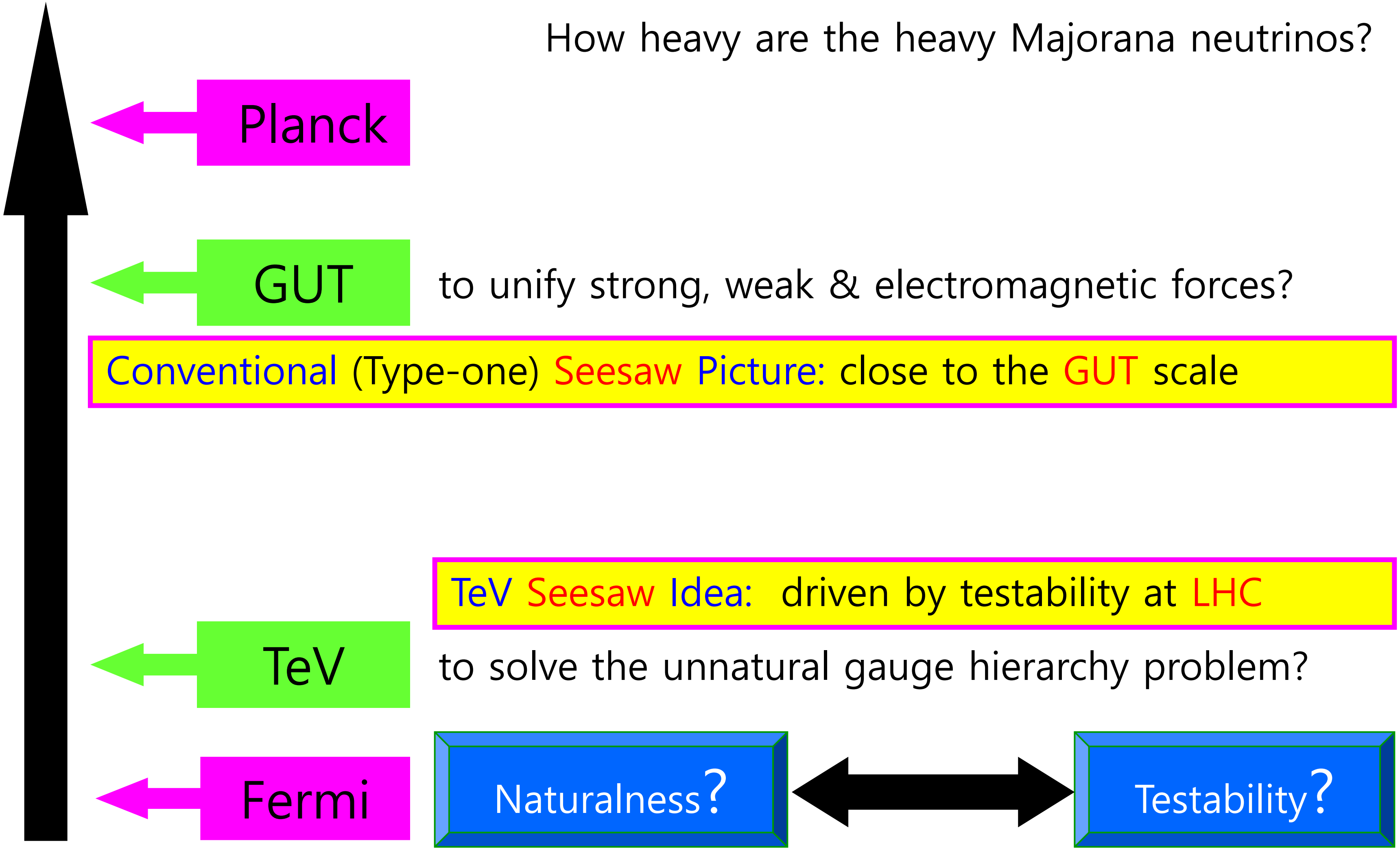
Simple example:

$$M'_{\rm D} = M_{\rm D} + \epsilon X_{\rm D}$$

$$\begin{aligned} M'_\nu &= M'_{\rm D} M_{\rm R}^{-1} M'^{T}_{\rm D} \\ &\approx \epsilon \left(M_{\rm D} M_{\rm R}^{-1} X_{\rm D}^T + X_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T \right) + \mathcal{O}(\epsilon^2) \end{aligned}$$

Is the seesaw scale very close to a fundamental physics scale?

How heavy are the heavy Majorana neutrinos?



Planck

GUT

to unify strong, weak & electromagnetic forces?

Conventional (Type-one) Seesaw Picture: close to the GUT scale

TeV Seesaw Idea: driven by testability at LHC

TeV

to solve the unnatural gauge hierarchy problem?

Fermi

Naturalness?

Testability?

Testability of Seesaw at LHC

- Two necessary conditions to test a seesaw model with heavy right-handed Majorana neutrinos at the LHC:

(A) Masses of heavy Majorana neutrinos must be of $O\,(1)$ TeV or below;
(B) Light-heavy neutrino mixing (i.e., M_D/M_R) must be large enough.

- LHC-collider signatures of heavy Majorana ν's are essentially decoupled from masses and mixing parameters of light Majorana ν's.

- Non-unitarity of the light neutrino flavor mixing matrix might lead to observable effects in neutrino oscillations and rare processes.

- Nontrivial limits on heavy Majorana neutrinos can be derived at the LHC, if the SM backgrounds are small for a specific final state.

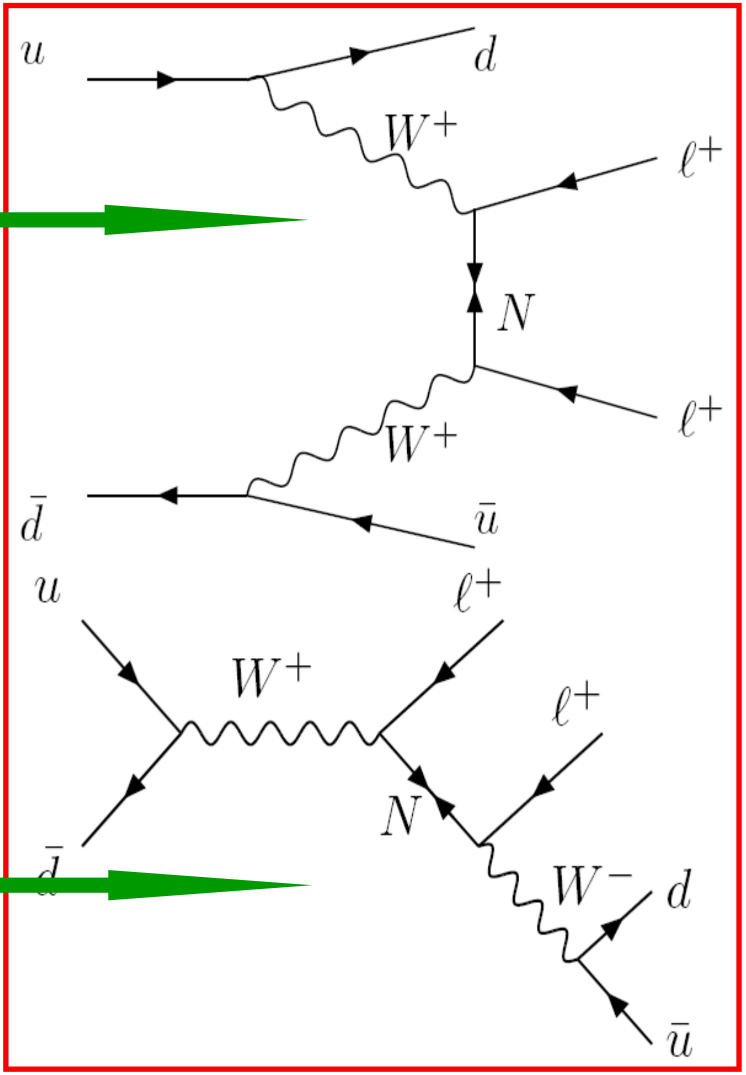
Collider Signature

Lepton number violation: like-sign dilepton events at LHC (~14 TeV).

collider analogue to 0νββ decay

dominant channel

N can be produced on resonance



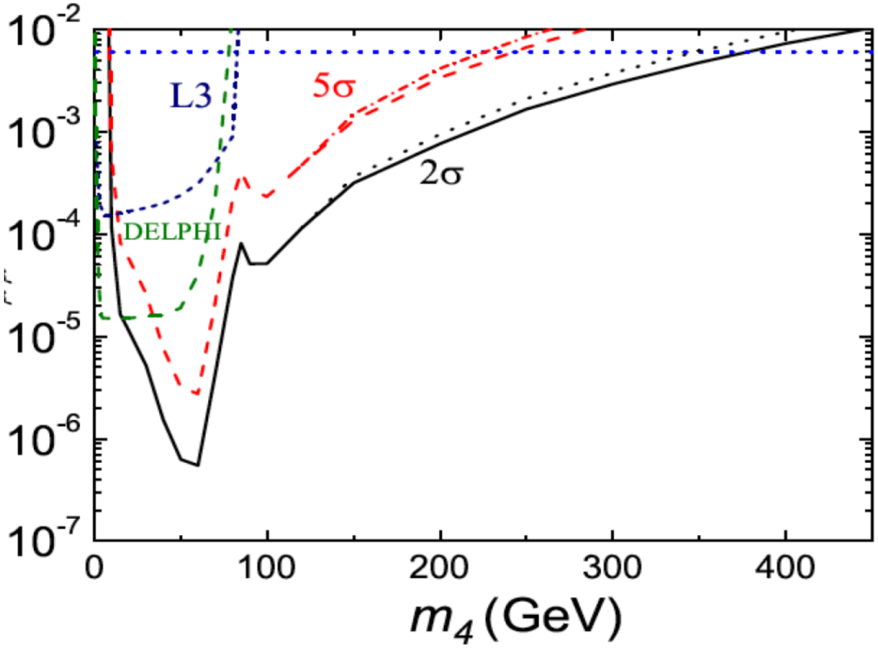
No missing energy is a characteristic feature of the processes

Cross section for the process can be approximated as

$$\sigma(pp \to \ell\ell W) \simeq \sigma(pp \to \ell N) Br(N \to \ell W)$$

$$\approx |U_{lN}|^2 \sigma$$

Search will be controlled by the mixing



Sensitivity reachable at LHC

Luminosity : 100 fb^{-1}

Atre et al. ‘09

Alternative to type I seesaw

Questions to Alternatives

Where are the RH neutrinos ?
Without RH neutrinos how do neutrinos get masses ?

(1) Extended Higgs / Fermion sectors

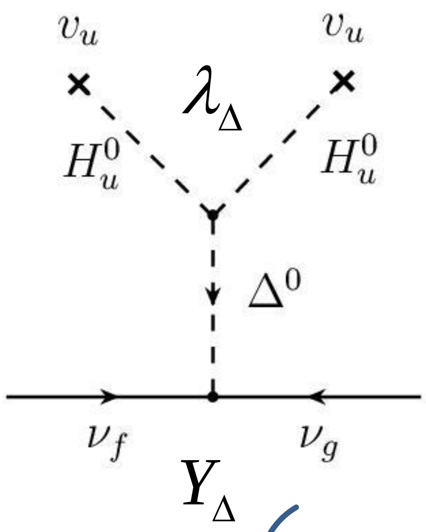
- Group theory demands that the new fields be singlet and/or triplet.
- Radiative generation of neutrino masses
- All new Physics is at the TeV scale

(2) R-parity violating SUSY models

Type II seesaw

(Higgs Triplet Mechanism)

Lazarides, Magg, Mohapatra, Senjanovic,
Shafi, Wetterich (1981)



No RH neutrinos

Higgs triplet: $(\Delta^{++}, \Delta^{+}, \Delta^{0})$

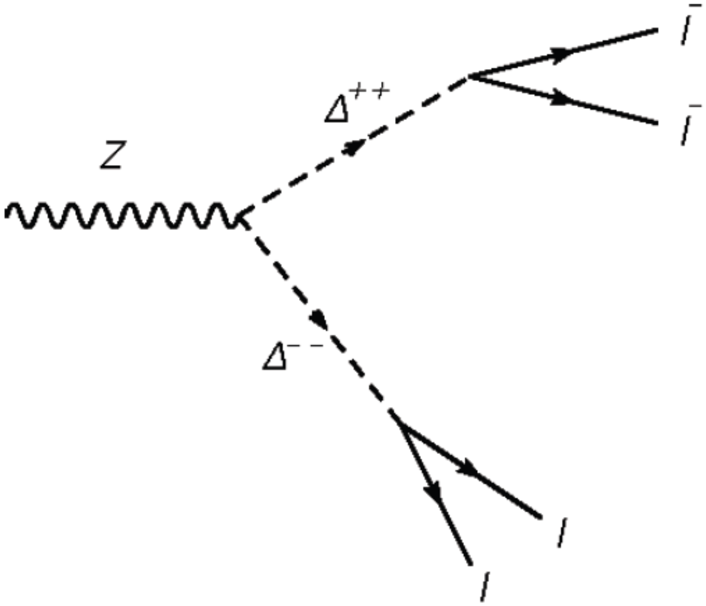
EW precision measurements:

$< \Delta^0 > / < H > < 0.03$

$$\boxed{m_{LL}^{II} \approx \lambda_\Delta Y_\Delta \frac{v_u^2}{M_\Delta}}$$

Type II: pair production of doubly charged Higgses, which decay into like- sign lepton (anti lepton) pairs

$M_\Delta = Y_\Delta v_\Delta$ can be constrained by experiments.



Hybrid See-Saw Matrix

Type II contribution
(frequently ignored)

Dirac matrix

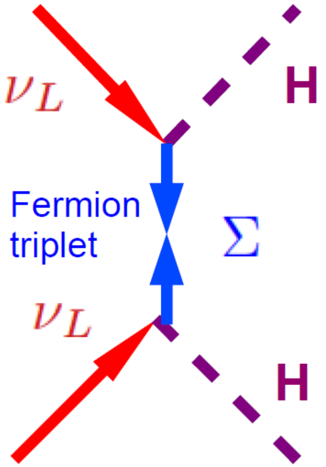
$$\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}\begin{pmatrix} m_{LL}^{II} & m_{LR} \\ m_{LR}^{T} & M_{RR}\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix}$$

Heavy Majorana matrix

Diagonalise to give effective mass $\rightarrow m_{LL}^{\nu}\overline{\nu}_L \nu_L^c$

Light Majorana matrix $\longrightarrow$ $\boxed{m_{LL}^{\nu} = m_{LL}^{II} - m_{LR} M_{RR}^{-1} m_{LR}^{T}}$

Type III seesaw

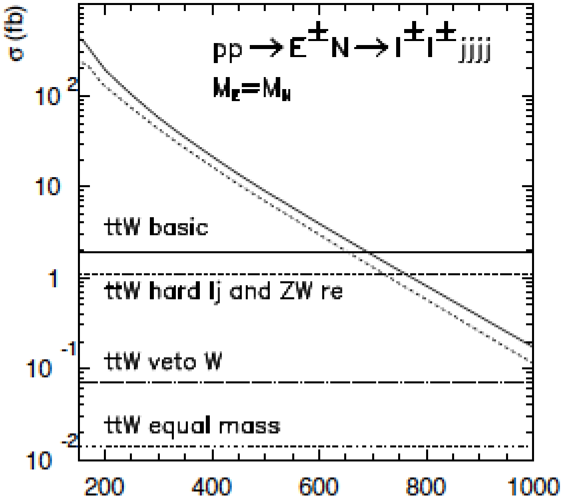


Ma, Roy,
Senjanovic,
Hambye

Introducing fermion triplet on top of SM (Σ^+, Σ^0, Σ^-)

$$L = Y_\Sigma H \overline{\Sigma} \nu_L + M_\Sigma \Sigma^T \Sigma + h.c. \ldots.$$

$$\boxed{m_\nu \approx Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2}$$



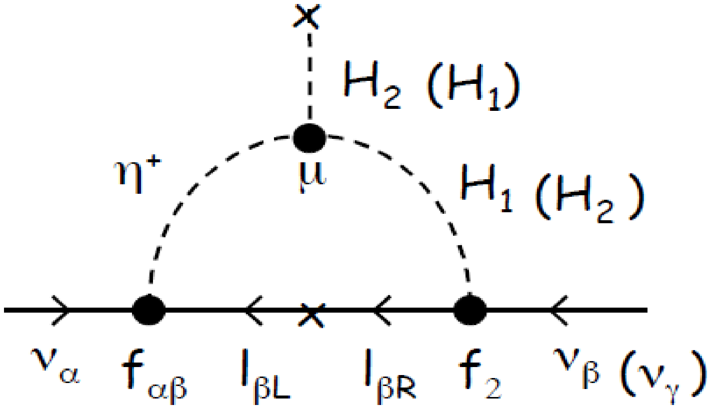
Collider Signature

$$pp \Rightarrow \Sigma^\pm \Sigma^0 \Rightarrow l^\pm l^\pm ZW$$

$$\Rightarrow l^\pm l^\pm jjjj$$

Radiative Origin of Neutrino Masses

Zee mechanism



No RH neutrinos (Zee'80)

new bosons: singlet η^+, doublet H_2

$$L_{Zee} = f_{\alpha\beta} \overline{l^c_\alpha} l_\beta \eta^+ + h.c$$

$$V = \mu H_1 H_2 \eta^+ + h.c$$

$$m_\nu = A\,[(f\,m^2 + m^2 f^T) - \\ - \; v\,(\cos\beta)^{-1}\,(f\,m\,f_2 + f_2{}^T m\; f^T)\,]$$

$$A \sim \ln(M_{H_2} / M_{H_1}) / (v \tan\beta)$$

$$\mathrm{m} = (\mathrm{m}_e\,, \mathrm{m}_\mu\,, m_\tau)$$

If only H_1 couples with leptons

$$\mathbf{m}_{zee} = \begin{pmatrix} 0 & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & 0 & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & 0 \end{pmatrix},$$

$$m_{\alpha\beta} = C f_{\alpha\beta}(m_\beta^2 - m_\alpha^2)$$

- The above mass matrix then leads to an almost massless neutrino desired for phenomenology.
But most cases can not reconcile the correct mixing pattern.

- For example if $f_{\alpha\beta}$ are of similar magnitudes then

$$m_{e\mu} << m_{\mu\tau} \approx m_{e\tau}$$

This case leads to the explanation of the atmospheric neutrino deficit but cannot solve the solar neutrino problem.

- By allowing hierarchy in $f_{\alpha\beta}$, it is possible to obtain bi-large pattern and simultaneous solutions to both anomalies, but solar mixing angle stays very close to maximal, in contrast to the non-maximal mixing required in the LMA solution.

Reviving Zee model

1). Introduction of couplings of both doublets with leptons
-> diagonal terms are non-zero
FCNC: e.g. $\tau \to \mu\mu\mu$, $\tau \to \mu ee$, $\tau \to \mu\mu e$, $\mu \to eee$ due to Higgs exchange --> 2-3 orders below the present bounds

2). Additional contributions to the mass matrix from other mechanism, e.g.

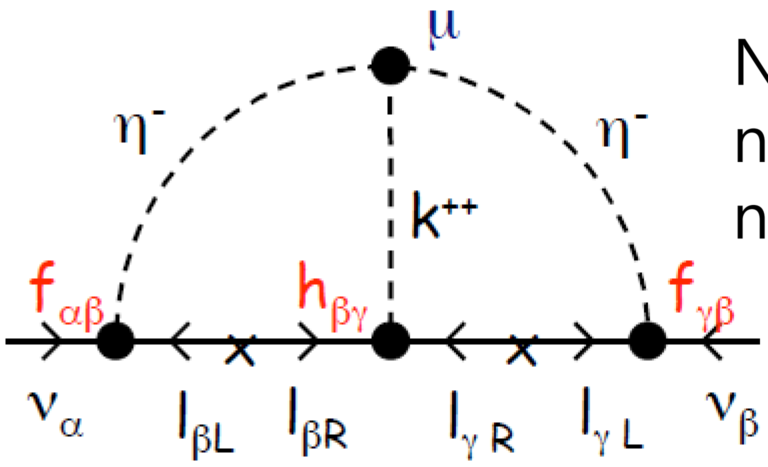
- Higgs triplet
- scalar singlet , two loops contribution

3). Introduction of new leptons: sterile neutrinos…

Testable model: →

Precision EW measurements
Searches for charged Higgs rare decays

Zee-Babu Model



$m_\nu \sim 8\, \mu\, f\, m_l\, h\, m_l\, f\, I$

No RH neutrinos (Babu'88 , Zee'86)

new scalar singlets η^+, and k^{++}

new interactions :

$$k^{++}\eta^-\eta^- \quad \& \quad l_{iR} l_{jR} k^{++}$$

- m_l = diag (m_e, m_μ, m_τ)
- f & h : matrices of couplings in the flavor basis

Features:

- nonzero diagonal entries are allowed in $m_{\nu\alpha\beta}$
- neutrino data require inverted hierarchy of couplings h
- f, h ~ 0.1

Further remark:

- Neutrino mass is doubly suppressed by lepton masses.

- There are enough free parameters not to be ruled out.

- Processes μ –> eee, τ –> μμμ, μμe, μee, eee
  at tree level act as constraints & opportunities
  for discovery

Hybrid Doubly Charged Higgs Model

(J. Ng et al.'07)

- Add to the SM the set of Higgs fields . Matter fields remain minimal
  1. One triplet T with SM q.n $(1, 2)$ carries no lepton number

$$T = \begin{pmatrix} T^0 & \frac{T^-}{\sqrt{2}} \\ \frac{T^-}{\sqrt{2}} & T^{--} \end{pmatrix}_{-2}$$

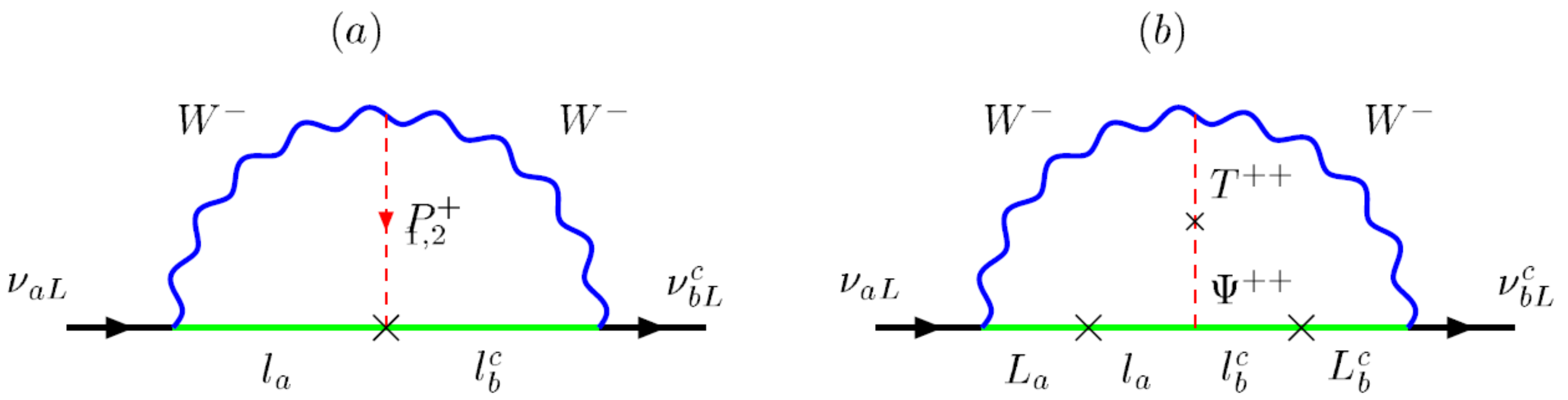
  2. A doubly charged singlet Higgs $\Psi^{++}$with q.n. $(0, 4)$ with lepton number 2

- New Yukawa term $Y_{ab}\overline{e^c_{aR}}e_{bR}\Psi$ is allowed. a, b are family indices.

$$\begin{aligned} V(\phi, T, \psi) &= -\mu^2\phi^\dagger\phi + \lambda_\phi(\phi^\dagger\phi)^2 - \mu_T^2 Tr(T^\dagger T) + \lambda_T[Tr(T^\dagger T)]^2 + \lambda'_T Tr(T^\dagger T T \\ &+ m^2\Psi^\dagger\Psi + \lambda_\Psi(\Psi^\dagger\Psi)^2 + \kappa_1 Tr(\phi^\dagger\phi T^\dagger T) + \kappa_2\phi^\dagger T T^\dagger\phi + \kappa_\Psi\phi^\dagger\phi\Psi^\dagger\Psi \\ &+ \rho Tr(T^\dagger T\Psi^\dagger\Psi) + \left[\lambda(\widetilde{\phi}^T T\widetilde{\phi}\,\Psi) - M(\phi^T T^\dagger\phi) + h.c.\right] . \end{aligned}$$

- Counting physical spin zero field
  1. Neutral scalars h^0 , t^0 from mixing of ϕ^0 T^0.
  2. Pseudoscalar t_a from the imagianary part of T^0
  3. A pair of charge scalar $P^{\pm}$ originates from $T^{\pm}$
  4. Two pairs of doubly charged scalars $P_{1,2}^{\pm\pm}$ from the mixing of $T^{\pm\pm}$, $\Psi^{\pm\pm}$

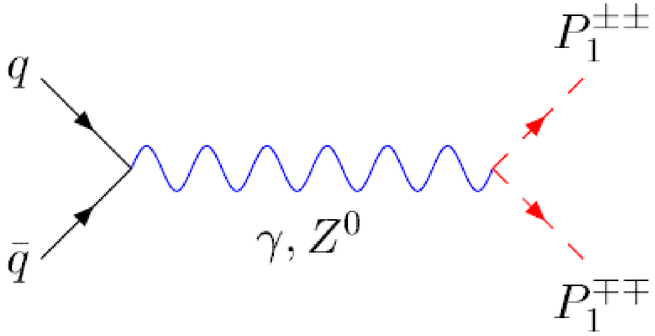
Radiative Neutrino Masses



$$(m_\nu)_{ab} = \frac{1}{\sqrt{2}} g^4 m_a\, m_b\, v_T Y_{ab} \sin(2\delta) \left[I(M_W^2, M_{P_1}^2, m_a, m_b) - I(M_W^2, M_{P_2}^2, m_a, m_b) \right]$$

$$I(M_W^2, M_{P_i}^2, m_a^2, m_b^2) = \int \frac{d^4q}{(2\pi)^4} \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m_a^2} \frac{1}{k^2 - M_W^2} \frac{1}{q^2 - M_W^2} \frac{1}{q^2 - m_b^2} \frac{1}{(k-q)^2}$$

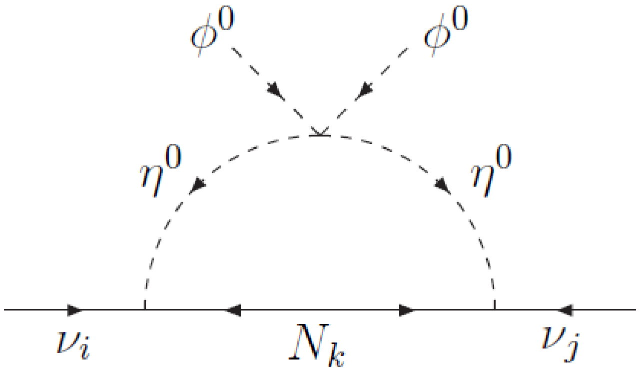
- Controlling factor of the absolute scale for m_ν is v_T
- There is a G.I.M. cancellation bet $P_1^{\pm\pm}$ and $P_2^{\pm\pm}$
- It is further suppress by two helicity flips of internal charged lepton line
- Suppress by the 2-loop factor
- $(m_\nu)_e{}^e$ element is very small
- Expected to be in the sub-eV range
- For the masses
  1. $M \sim v_T$: The mass of $P_{1,2}^{\pm\pm}$ is expected to be in the range $200 - 600$ GeV if $m \lesssim 1$ TeV. Otherwise $P_2^{\pm\pm} > TeV$.
  2. $M \sim v \gg v_T$: Here, only the mass of $P_1^{\pm\pm}$ is expected to be at the weak scale. All others $\gg$ TeV. Out of reach of LHC
- LHC must find at least one doubly charged Higgs or rule out the model
- Pair producion via Drell-Yan



Dark Scalar Model (Deshpande & Ma ’78, E. Ma’02)

- SM be extended to include 3 RH neutrinos N and a second scalar doublet (η^+, η^0)
- → odd under Z_2 symmetry

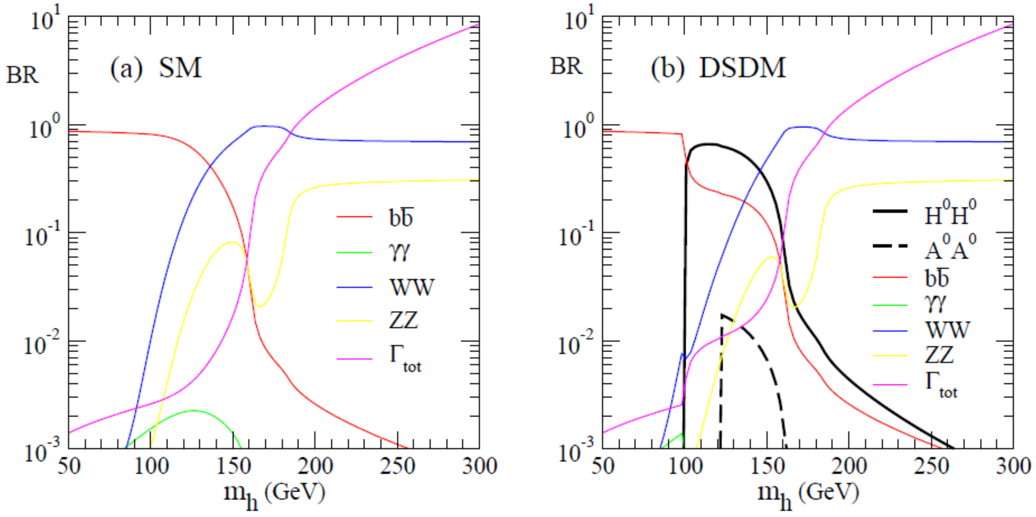
- The usual Yukawa term $(\nu\phi^0 - \ell\phi^+)N$ forbidden but $(\nu\eta^0 - \ell\eta^+)N$ is allowed.

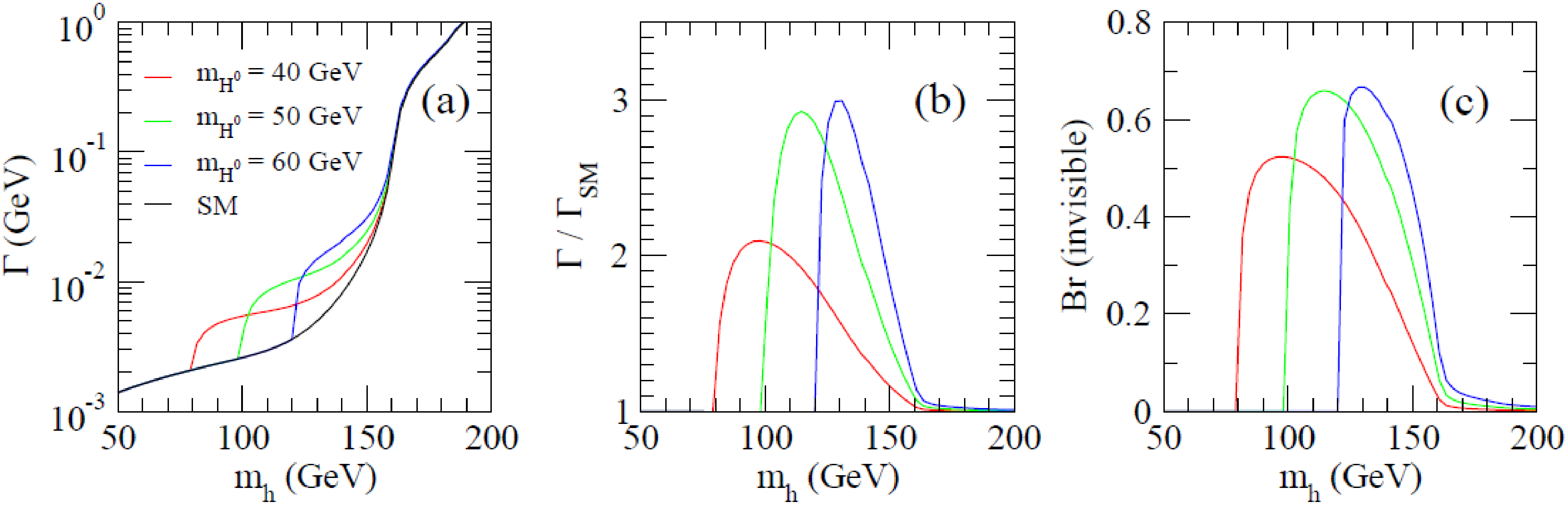


$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik}h_{jk}M_k}{16\pi^2}\left[\frac{m_R^2}{m_R^2 - M_k^2}\ln\frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2}\ln\frac{m_I^2}{M_k^2}\right].$$

- $\langle \eta^0 \rangle = 0$ because of conserved Z_2 symmetry
- If $\mathrm{Re}\,\eta^0$ or $\mathrm{Im}\,\eta^0$ is the lightest particle of odd Z_2, it is a possible dark matter candidate

Impact on the SM Higgs search at LHC



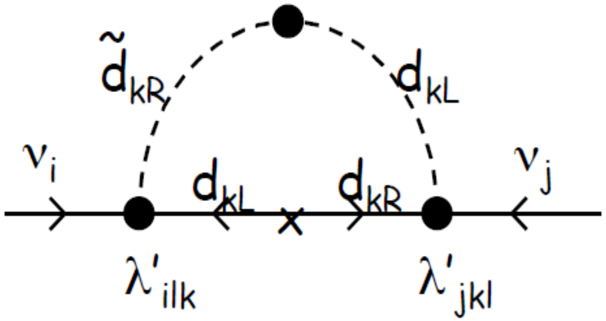

10^0
10^{-1}
10^{-2}
10^{-3}
Γ (GeV)
m_{H^0} = 40 GeV
m_{H^0} = 50 GeV
m_{H^0} = 60 GeV
SM
(a)
50
100
150
200
m_h (GeV)
Γ / Γ_{SM}
1
2
3
(b)
50
100
150
200
m_h (GeV)
Br (invisible)
0
0.2
0.4
0.6
0.8
(c)
50
100
150
200
m_h (GeV)

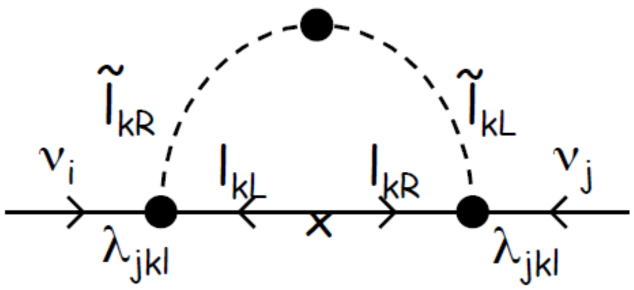
Supersymmetric Origin of Neutrino Masses

SUSY with trilinear R-parity violating couplings

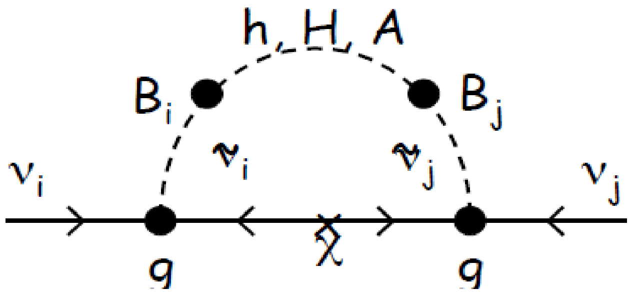
(Hall & Suzuki)

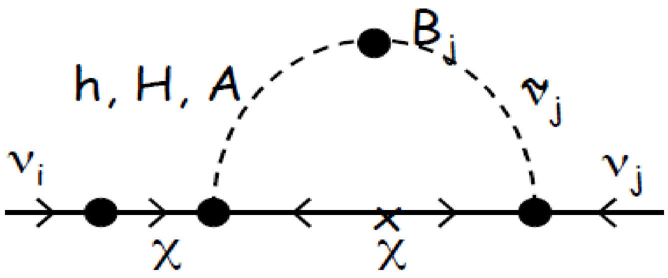
$$\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c$$





$$\delta m_\nu \approx \frac{\lambda\lambda^*}{16\pi^2} m_l \ln(m_l^2 / m_{\tilde{l}}^2) + \frac{\lambda'\lambda'^*}{16\pi^2} m_b \ln(m_b^2 / m_{\tilde{b}}^2)$$

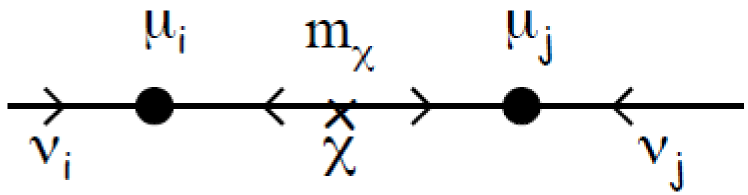




B_m- soft symmetry breaking parameter

Bi-linear R-parity violating term (Pilaftsis et al. ,EJChun & Kang, Valle et al)

$W = -\mu_\alpha L_\alpha H_U$



$m_{ij} = X\,\mu_i\,\mu_j,\; X \sim \cos^2\beta/m$

Only one neutrino acquires mass, mixing is determined by μ_i/μ_j

Neutrinos: natural hierarchy of mass parameters:
- tree level - one mass, large mixing
- loops - other masses, mixing

$$\mu_m \sim 10^{-4}\ GeV$$

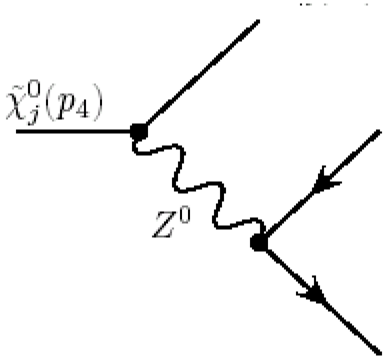
Violation of universality of soft symmetry breaking terms:
both Higgs-lepton and flavor universality
e.g. B_m are different at GUT

Tests : rich phenomenology
- colliders,
- rare decays,
- new neutrino interactions...

Search at Collider

SUSY without R-parity as a theory of massive neutrinos can be testable in collider !

Key idea : *Probing of decays of LSP (lightest SUSY particle)*



Decay amplitude $\propto G_F \left|\eta_i\right|^2 M^3_{\chi^0} \Longleftrightarrow \begin{cases} m_{\nu_{ij}} = c\eta_i\eta_j \\ \eta_i \propto (\lambda'\mu)_i \end{cases}$

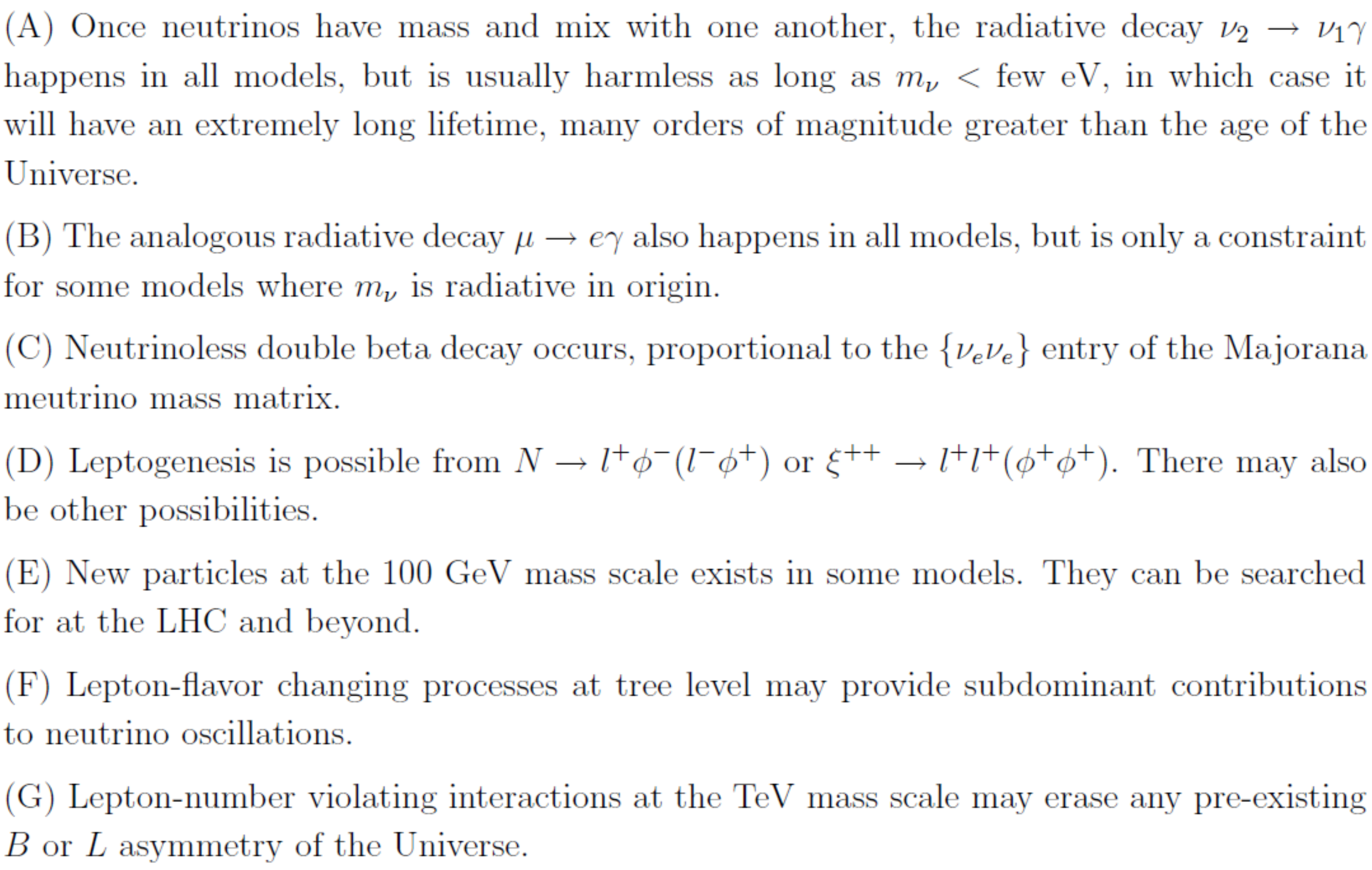
Conclusions

- Tiny neutrino masses can be generated through various mechanism, such as seesaw mechanism, radiative generations.

- The models for neutrino mass generations contains new particles, and peculiar processes mediated by them can be searched at collider.

Concluding Remark

Generic consequences of neutrino mass



(A) Once neutrinos have mass and mix with one another, the radiative decay $\nu_2 \rightarrow \nu_1\gamma$ happens in all models, but is usually harmless as long as $m_\nu <$ few eV, in which case it will have an extremely long lifetime, many orders of magnitude greater than the age of the Universe.

(B) The analogous radiative decay $\mu \rightarrow e\gamma$ also happens in all models, but is only a constraint for some models where m_ν is radiative in origin.

(C) Neutrinoless double beta decay occurs, proportional to the $\{\nu_e\nu_e\}$ entry of the Majorana neutrino mass matrix.

(D) Leptogenesis is possible from $N \rightarrow l^+\phi^-(l^-\phi^+)$ or $\xi^{++} \rightarrow l^+l^+(\phi^+\phi^+)$. There may also be other possibilities.

(E) New particles at the 100 GeV mass scale exists in some models. They can be searched for at the LHC and beyond.

(F) Lepton-flavor changing processes at tree level may provide subdominant contributions to neutrino oscillations.

(G) Lepton-number violating interactions at the TeV mass scale may erase any pre-existing B or L asymmetry of the Universe.

Effective operator, S. Weinberg 1979

$$\frac{\lambda_{ij}}{M}\,(l_i H)^T (l_j H)$$

$$m_{ij} = \frac{\lambda_{ij}\langle H\rangle^2}{M}$$

For $M \approx M_{pl}$ and $\lambda_{ij} \approx 1$

$$m_{ij} \sim 10^{-5}\ \text{eV}$$

- Contributions ~ 10^{-5} eV are still relevant for phenomenology. Sub-dominant structures of mass matrix can be generated by Planck scale interactions

- Neutrino mass matrix can get relevant contributions from new physics at all possible scales from the EW to Planck scale and from various mechanisms