Right Handed Neutrinos

Sin Kyu Kang (Seoul Tech.)

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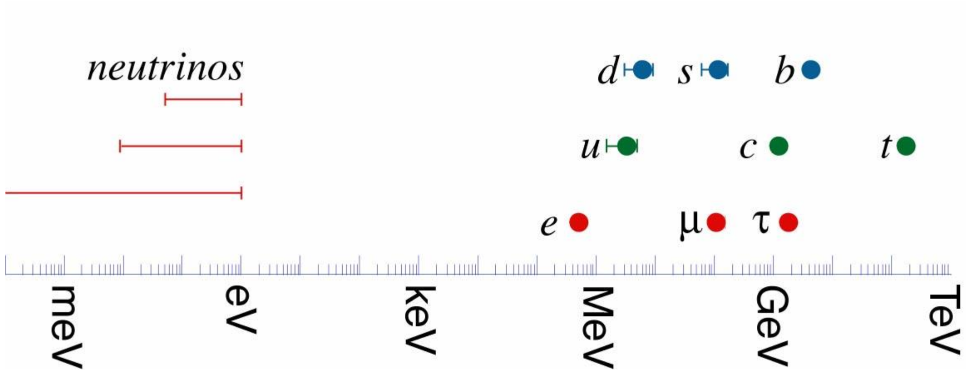
What we have learned

- Thanks to neutrino oscillations :
  - Neutrinos have tiny masses, not very hierarchical
  - Neutrinos mix a lot
  - Lepton Flavor is not conserved
- the first evidence for *incompleteness of Standard Model*



Very different from quarks

The Big Questions

- What is the origin of neutrino mass and mixing?
- Did neutrinos play a role in our existence?
- Did neutrinos play a role in birth of the universe?
- Did neutrinos play a role in forming galaxies?
- Are neutrinos telling us something about unification of matter and/or forces?
- Will neutrinos give us more surprises?

- The primary goal of my talk is to present how ν_R plays crucial roles in solving the questions

  - Why do we need ν_R ?
  - How do we find ν_R ?
  - Is ν_R related new symmetry beyond SM ?
  - Can ν_R be responsible for the origin of matter ?
  - Can ν_R be a DM candidate ?

Neutrinos in the Standard Model

- SM was formulated without any neutrino mass.
- In the SM, only left chiral fields are weak doublet and neutrino is part of weak doublet

$$\begin{pmatrix} \nu_{Le} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{L\mu} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{L\tau} \\ \tau_L \end{pmatrix}$$

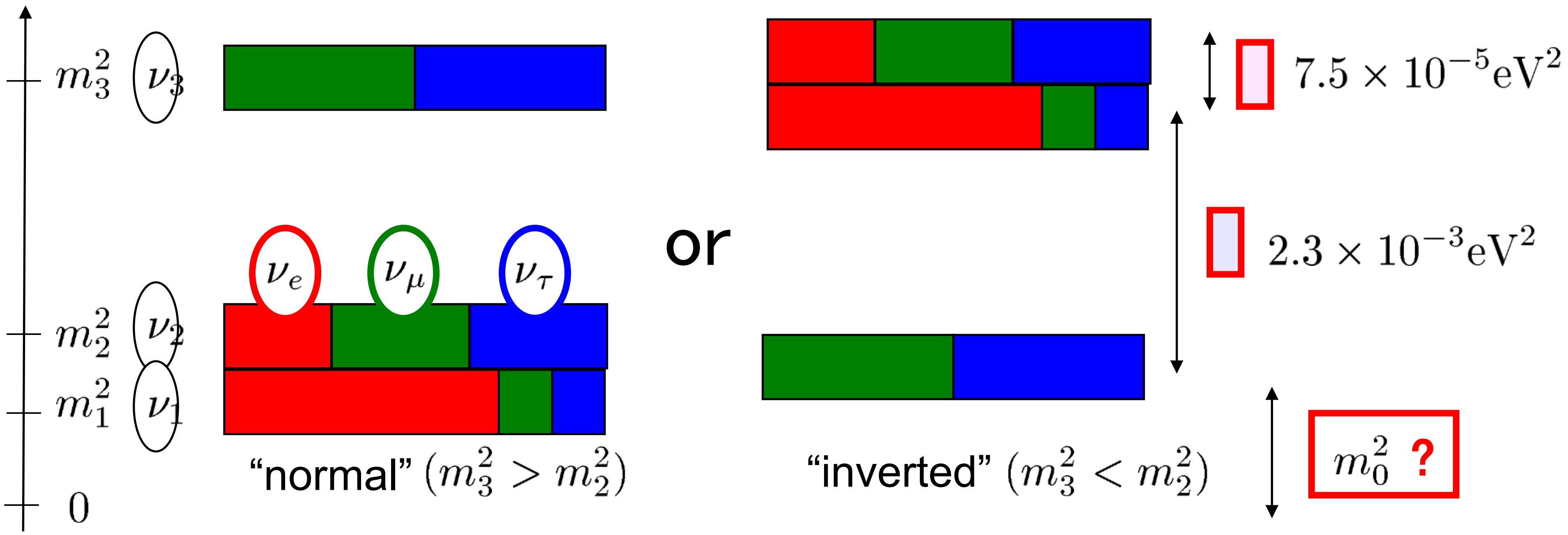
- In the SM, all RH fermions are gauge singlet, but no ν_R
- All neutrinos are LH and all antineutrinos are RH in the SM

➡ Inclusion of ν_R in the SM reflects extension of the SM

Why do we need ν_R ?

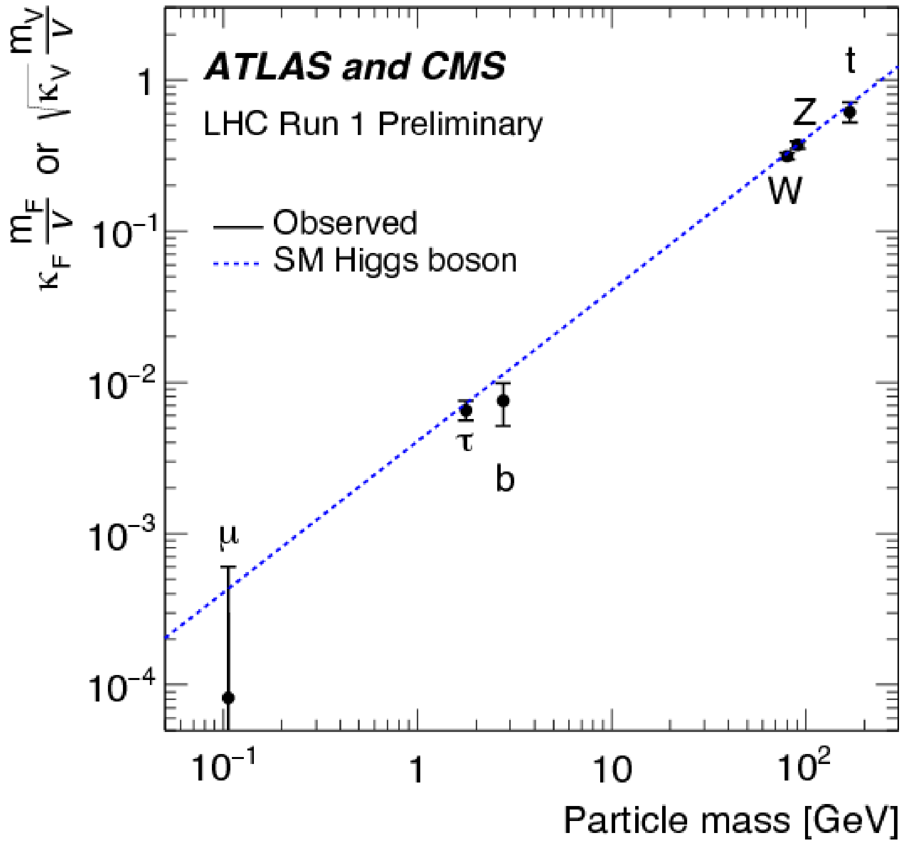
Massive Neutrinos

- No fundamental reason why neutrinos are massless.
- From the observation of neutrino oscillation, it turns out that neutrinos are massive particle → need to modify the SM



How to generate neutrino mass

- Masses in the SM

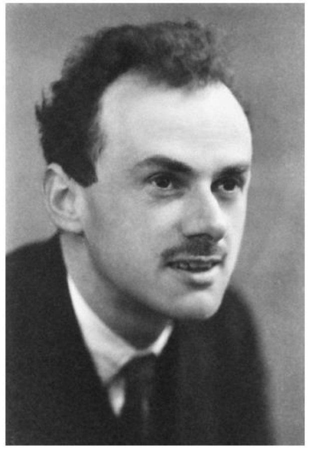


- Origin of masses → Higgs-induced spontaneous EW symmetry breaking.

- Fundamental parameter is Higgs VEV ~ 250 GeV.

- W, Z, t masses are near this scale.
- Others a lot smaller: ascribed to small Yukawa coupling constants.

How to generate neutrino mass



- Masses in the SM

  - existence of both f_L and f_R leads to a Yukawa interaction :

$$Y_f \bar{f}_L \varphi f_R$$

  - when φ gets VEV, mass term $Y_f \langle\varphi\rangle \overline{f}_L f_R$ arises : Dirac mass $\sim Y_f \langle\varphi\rangle$

  -To impart a Dirac mass to ν, we need ν_R so that $Y_\nu \langle\varphi\rangle \overline{\nu}_L \nu_R$ arise.

  -Dirac ν mass conserves lepton number.

  - $Y_\nu \sim 10^{-13}$ for $m_\nu < 0.1$ eV, → too small

Standard Model + Right Handed Neutrinos

- No (SM) principle prevents the occurrence of $M_R \nu^c{}_R \nu_R$
- M_R

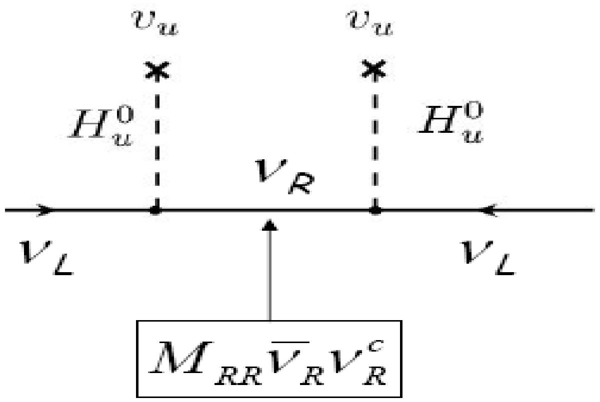
  - new scale in the theory → scale of lepton number violation

  - Not related to SM Higgs VEV
- Combining it with Dirac mass $m\nu_L\nu_R$, we can achieve tiny neutrino masses via seesaw mechanism (type I)

Seesaw Mechanism

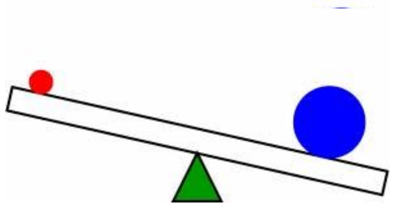
- Answer to the question: "Why is neutrino mass so small?"
- Neutrino mass matrix :

$$\begin{pmatrix} \bar{\nu}_L & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$



- Assuming : $m_D \ll M_R$, $\sim \begin{pmatrix} m_\nu & \\ & M_R \end{pmatrix}$

$$m_\nu = \frac{m_D^2}{M_R} \ll m_D$$

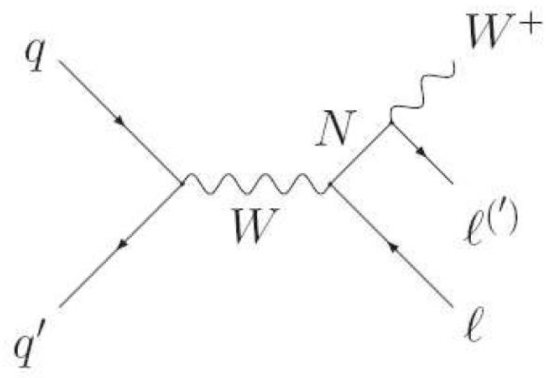


- To obtain $m_3 \sim (\Delta m^2_{\rm atm})^{1/2}$ for $m_D \sim m_t$, , $M_R \sim 10^{15}$GeV

What is the Seesaw scale ?

- For $m_D \sim m_t$, neutrino mass of $m_\nu \leq 1$ eV implies $M_R \sim 10^{14}$ GeV.
  - close to the scale of Grand Unification ~ 10^{16} GeV

- For $m_D \sim m_e$, neutrino mass of $m_\nu \leq 1$ eV implies $M_R \sim 1$ TeV.
  -potentially testable at collider



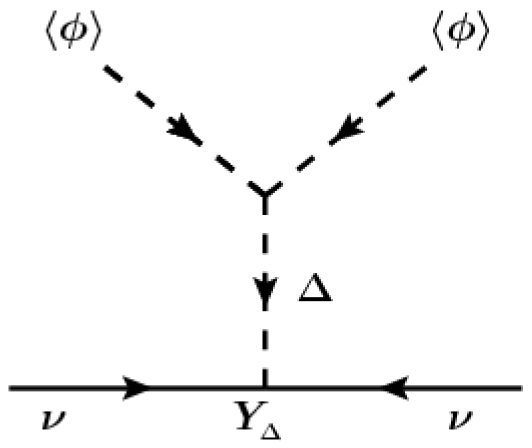
(however, couplings are too small)

What is the Seesaw scale ?

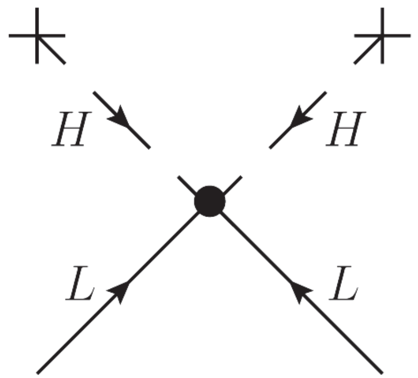
- νMSM (Asaka, Shaposnikov'06):
  - $M_{R1} \sim$ keV scale warm dark matter
  - $M_{R2(R3)} \sim$ few GeV with tiny Yukawa couplings
- Minimal SM accommodating DM, baryogenesis at the price of fine tuning.

Does neutrino mass imply ν_R ?

- No
- It is possible to arrange for lepton number violation without introducing ν_R
- Ex.) extending the scalar sector of the SM
  - SU(3) triplet Higgs ("type II" seesaw)
- radiative mass generations.



Weinberg operator



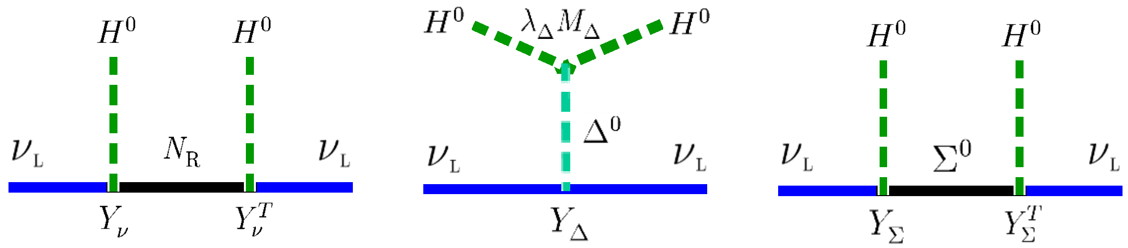
- Relaxing renormalizability, we can get Majorana mass via effective operators: (d=5 Weinberg op.)

$$\frac{\lambda}{M} LHHL \qquad \frac{\lambda\langle\phi^0\rangle^2}{M}\overline{(\nu_L^0)^c}\,\nu_L^0$$

- Nice for generating tiny ν mass providing that M is large enough.

- Underlying renormalizable theories yielding LLHH are constructed

  → tree level exchange of some heavy particle of mass M



How do we find ν_R ?

- Introduction of ν_R leads to a modification of the leptonic C.C. Lagrangian

$$\frac{g}{\sqrt{2}}\mathbf{U}^{ji}\bar{\ell}_j\gamma^\mu P_L \nu_i W_\mu^- + \text{c.c.}$$

j=physical neutrino states,   i=1,2,3 (charged lepton flavor)

-For SM, U corresponds to the 3x3 unitary matrix U_{PMNS}

-For SM+ν_R : U is deviated from unitarity

- The overall 6x6 mass matrix can be diagonalized by a unitary matrix

$$\begin{pmatrix} V & R \\ S & U \end{pmatrix}^\dagger \begin{pmatrix} M_{\text{L}} & M_{\text{D}} \\ M_{\text{D}}^T & M_{\text{R}} \end{pmatrix} \begin{pmatrix} V & R \\ S & U \end{pmatrix}^* = \begin{pmatrix} \widehat{M}_\nu & \mathbf{0} \\ \mathbf{0} & \widehat{M}_{\text{N}} \end{pmatrix}$$

$$-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}}\left[\overline{(e,\mu,\tau)_L}\, V\gamma^\mu \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}_L W_\mu^- + \overline{(e,\mu,\tau)_L}\, R\gamma^\mu \begin{pmatrix}N_1\\ N_2\\ N_3\end{pmatrix}_L W_\mu^-\right]$$

V : oscillations & other phenomena of light neutrinos,

R : production & detection of heavy neutrinos at collider

- They are two 3×3 sub-matrices of the 6×6 unitary matrix, hence they must be correlated with each other.
- This correlation characterizes the relationship between neutrino physics and coll ider physics.

- Non-unitarity of V will induce a departure from the SM expected values of some observables (e.g.: leptonic or semileptonic decays of pseudoscalar mesons like K, B, D..., cLFV process like $\ell \to \ell_1\ell_1\ell_2$ $\ell \to \ell'\gamma$, lepton flavor changing Z decays.

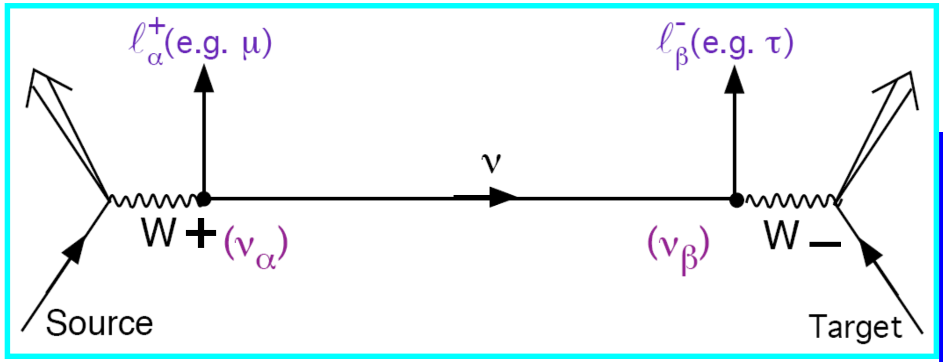
Physics associated with V

- Effects on neutrino oscillation (Antusch *et al* 06, Xing. 08):

Production and detection of a neutrino beam via CC weak interactions:

$$A(W^+ \to l_\alpha^+ \nu_i) = \frac{V_{\alpha i}^*}{\sqrt{(VV^\dagger)_{\alpha\alpha}}}$$

$$\sum_i |A(W^+ \to l_\alpha^+ \nu_i)|^2 = 1$$



$$A(\nu_i W^- \to l_\beta^-) = \frac{V_{\beta i}}{\sqrt{(VV^\dagger)_{\beta\beta}}}$$

$$\sum_i |A(\nu_i W^- \to l_\beta^-)|^2 = 1$$

$$\mathrm{Prop}(\nu_i) = \exp\left(-i\frac{m_i^2}{2E}L\right)$$

$$\begin{aligned} A(\nu_\alpha \to \nu_\beta) &= \sum_i \left[A(W^+ \to l_\alpha^+ \nu_i) \cdot \mathrm{Prop}(\nu_i) \cdot A(\nu_i W^- \to l_\beta^-)\right] \\ &= \frac{1}{\sqrt{(VV^\dagger)_{\alpha\alpha}(VV^\dagger)_{\beta\beta}}} \sum_i \left[V_{\alpha i}^* \exp\left(-i\frac{m_i^2}{2E}L\right) V_{\beta i}\right] \end{aligned}$$

Like the case of the *non-standard* interactions in initial & final states.

Oscillation probability in vacuum

$$P(\nu_\alpha \to \nu_\beta) = \frac{\sum_i |V_{\alpha i}|^2 |V_{\beta i}|^2 + 2\sum_{i<j} \mathrm{Re}\left(V_{\alpha i} V_{\beta j} V^*_{\alpha j} V^*_{\beta i}\right) \cos\Delta_{ij} - 2\sum_{i<j} J^{ij}_{\alpha\beta} \sin\Delta_{ij}}{\left(VV^\dagger\right)_{\alpha\alpha} \left(VV^\dagger\right)_{\beta\beta}}$$

$$\Delta_{ij} \equiv \Delta m^2_{ij} L/(2E) \text{ with } \Delta m^2_{ij} \equiv m^2_i - m^2_j \quad |\Delta m^2_{13}| \approx |\Delta m^2_{23}| \gg |\Delta m^2_{12}|$$

Jarlskog invariants of CP violation: $J^{ij}_{\alpha\beta} \equiv \mathrm{Im}(V_{\alpha i} V_{\beta j} V^*_{\alpha j} V^*_{\beta i})$

"Zero-distance" (near-detector) effect at *L* = 0 :

$$\boxed{P(\nu_\alpha \to \nu_\beta)\,|_{L=0} = \frac{|(VV^\dagger)_{\alpha\beta}|^2}{(VV^\dagger)_{\alpha\alpha}(VV^\dagger)_{\beta\beta}}}$$

(Langacker , London, '88)

Physics associated with ν_R

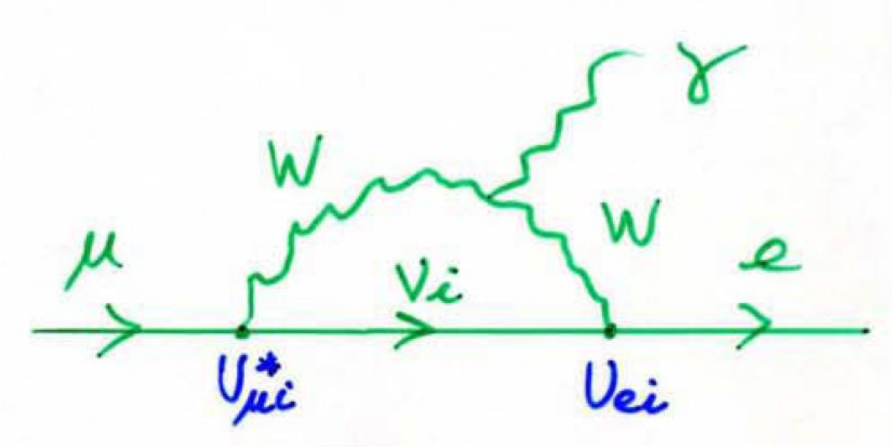
- For $M_R < EW$, production of ν_R in the Lab. is in principle possible.
- At $E < M_R$, ν_R only leaves indirect traces in the Lab.

→ lead to deviations from SM predictions in different observables

- M_R and Yukawa couplings mediate flavor violation in charged lepton sector such as $\mu \to e\gamma$ and unitary violation of PMNS mixing matrix.
- Searched for those processes in proposed exp. such as COMET, Mu2e can help to constrain ν_R properties.

$\mu \to e\gamma$

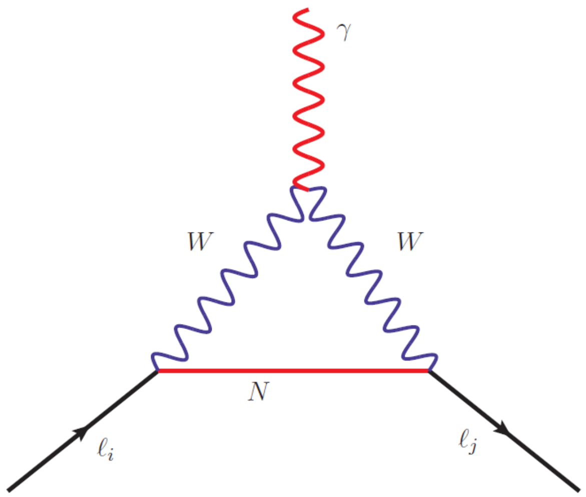
- In the SM with massive neutrinos



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i V_{\mu i}^{*} V_{ei} \frac{m_i^2}{M_W^2}\right|^2 \leq 10^{-54}$$

- Unobservably small compared with current limit $\sim 10^{-13}$
- Observation of LFV implies new physics beyond the model

- In the SM+ ν_R



$$Br(\mu \to e\gamma) = \frac{3\alpha}{8\pi}\left|\sum_i R_{\mu i}^* R_{ei}\hat{g}(r)\right|^2$$

$$\hat{g}(r) = r\left(1 - 6r + 3r^2 + 2r^3 - 6r^2\ln(r)\right)/(2(1-r)^4),$$

$$r = M_R^2/M_W^2$$

- Considering constraints on half-life time for ββ0ν & vacuum stability

(arXiv:1207.2027)

$$\mathrm{Br}(\mu \to e\gamma) = 2.82 \times 10^{-10}\left(\frac{M_D}{24.36\ \mathrm{GeV}}\right)^4\left(\frac{\mathrm{TeV}}{M_R}\right)^4$$

$R \sim M_D M_R^{-1}$

$\Rightarrow$ $M_R > 3.5\ \mathrm{TeV}$ for $Br(\mu \to e\gamma) < 4.2 \times 10^{-13}$

Comments on LFV in charged lepton sector

- LFV does NOT probe neutrino Majorana mass.

- cLFV is sensitive to new physics at the 1–1000 TeV scale, which will be (indirectly) related to the mechanism for neutrino mass

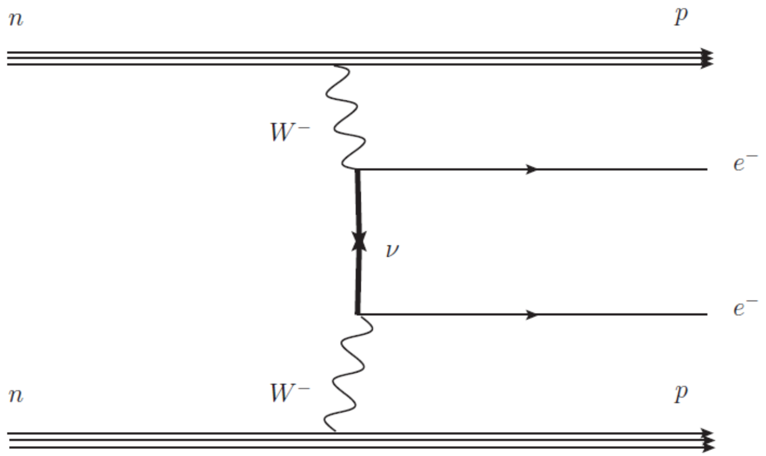
- A signal for LFV will provide extremely valuable information on BSM

- Ratios of various LFV channels may give crucial insight on the model

$\Rightarrow$ *archeological* evidence

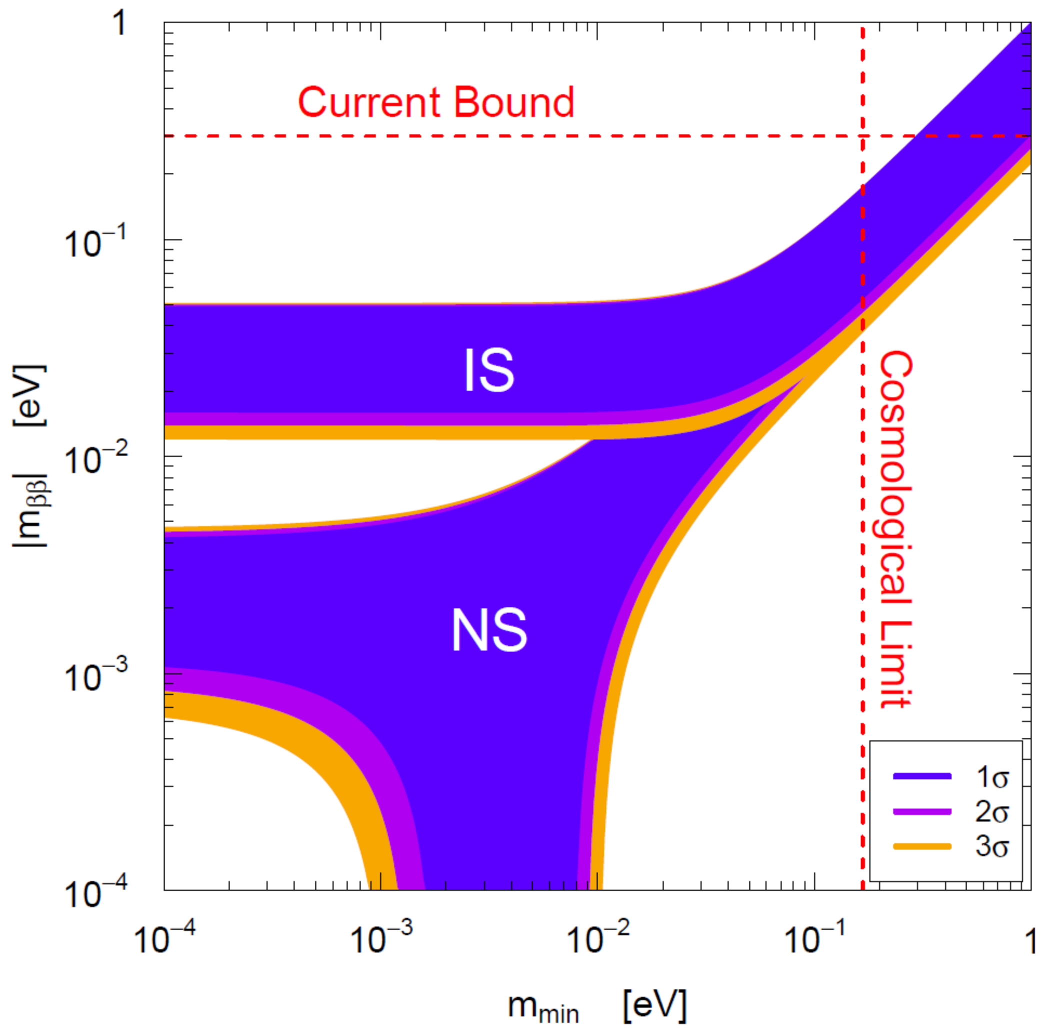
Neutrinoless double beta decay : $(A, Z) \to (A, Z+2) + 2e^-$

- Observation of this process implies lepton number violation and possibly existence of Majorana neutrinos



$$\tau^{-1} \simeq G_{0\nu} \left| \sum_i \mathcal{M}_i (U_\nu)^2_{ei} \frac{m_i}{m_e} + \sum_I^{M_I \ll 100\mathrm{MeV}} \mathcal{M}_I \Theta^2_{eI} \frac{m_i}{m_e} + \sum_I^{M_I \gg 100\mathrm{MeV}} \tilde{\mathcal{M}}_I \Theta^2_{eI} \frac{m_p}{m_i} \right| .$$

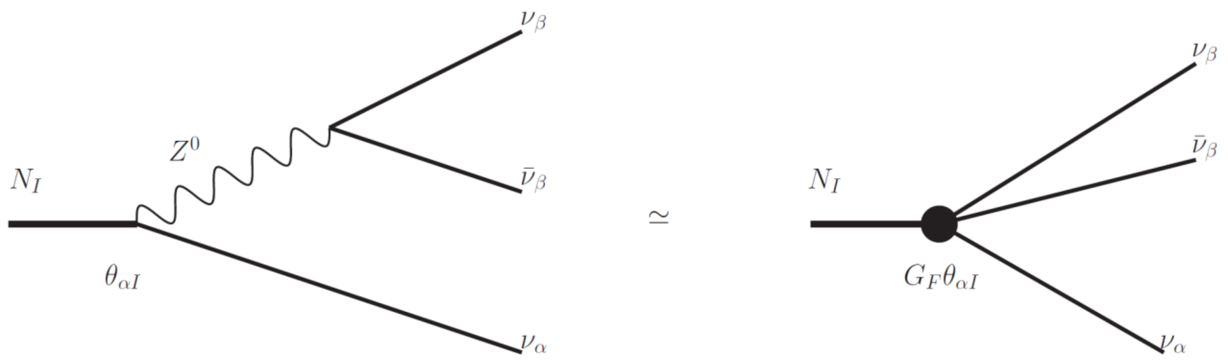
Neutrinoless double beta decay : $(A, Z) \rightarrow (A, Z+2) + 2e^-$



Collider experiments

Depending on the masses M_R , there are different ways to probe signature of ν_R in collider experiments

Intensity frontier : If kinematically possible, ν_R participate in all processes that involve active neutrinos, but with a possibility suppressed by R_α^2.
This makes it possible to produce them in meson decays for M_R <a few GeV.



Collider experiments

Depending on the masses M_R , there are different ways to probe signature of ν_R in collider experiments

High Energy frontier :

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

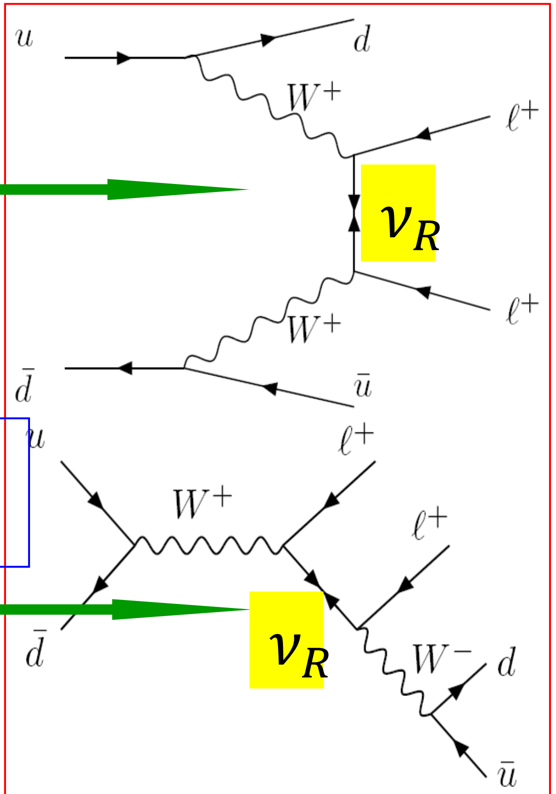
S-channel is dominant & cross section observable only if $R_{l\nu_R} > 10^{-2}$ for $M_R \sim 100$ GeV

(del Aguila,Aguilar-Savedra, Pittau '07, Cai, Han, Li, Ruiz'18)

collider analogue to 0νββ decay

ν_R can be produced on resonance

But, observed neutrino masses via seesaw for $M_R \sim 100$ GeV implies $R_{l\nu_R} \sim 10^{-6}$, making it hard to observe



Is ν_R related new symmetry beyond SM ?

- If one adds three ν_R's to implement the seesaw mechanism, the model admits an anomaly free new symmetry, B−L.
- One can therefore extend the standard model symmetry to either $SU(3) \times SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$ or left-right symmetric extension $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.
- In either case, ν_R carries the B−L quantum number and its Majorana mass breaks this symmetry

$\Rightarrow$ M_R can at most be the scale of B−L symmetry breaking.

- But, we don't know the scale of B-L breaking.
- TeV scale of B-L is possible.

Is ν_R related new symmetry beyond SM ?

- GUT
  - The most natural GUT for seesaw model is SO(10)
  - Come with ν_R (16-d spinor rep.)
    - anomaly-free for any multiplets
    - Smallest simple anomaly-free group with chiral fermions
    - Smallest chiral representation contains all standard model fermions
  - Once SO(10) broken to the standard model, M_R becomes allowed by the EW gauge invariance

$$M_R \sim h M_{GUT}$$

- Unifies the quarks and leptons, and treat the neutrinos in the same way as for the other elementary particles.
- A SO(10) GUT naturally contains a GUT scale mass for right-handed neutrinos and allows the sea-saw mechanism

$$m_{\nu} \sim m_D^2 / m_R$$

$$m_D \sim m_u$$

- SO(10) $\qquad\qquad$ ν **mass**

$\downarrow$

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

$$\Big\downarrow \Delta(B-L) \neq 0 \qquad \begin{pmatrix} 0 & 0 \\ 0 & M \end{pmatrix}$$

- Standard Model $+\nu_R$

$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

$\downarrow$

Seesaw

$$\begin{pmatrix} \frac{m^2}{M} & 0 \\ 0 & M \end{pmatrix}$$

Roles of ν_R in cosmology

- Origin of Matter

  - Seesaw model has been proposed so as to achieve tiny neutrino masses.

  - Another advantage of seesaw model is to provide a nice mechanism of baryogenesis via leptogenesis.

  - However, baryogenesis realized in seesaw model requires very heavy right handed majorana neutrinos which are impossible to probe at collider.

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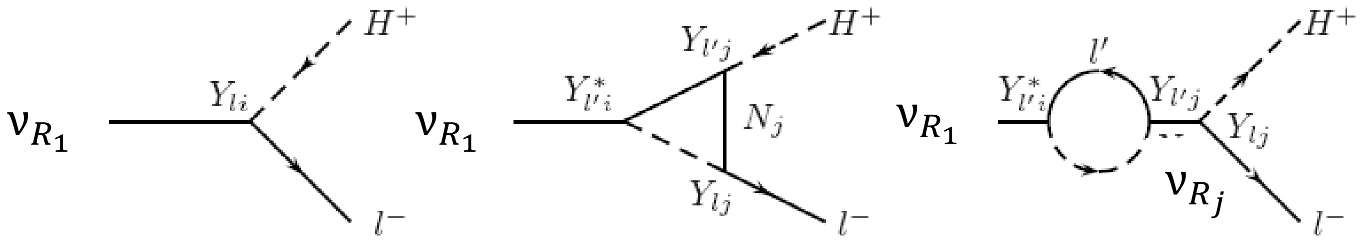
Leptogenesis

- Generate *L* from the direct CP violation in right-handed neutrino decay



(Fukugita, Yanagida'86)

$$\Gamma\left(\nu_{R_1} \to l^- H^+\right) - \Gamma\left(\nu_{R_1} \to l^+ H^-\right) \propto Im(Y_{1j} Y_{1k} Y^*_{lk} Y^*_{lj})$$

- *L* gets converted to *B* via Sphaleron process
  - ⇒ More matter than anti-matter
  - ⇒ *We have survived "The Great Annihilation"*

- No new interactions needed other than those already used for generating neutrino masses.

What is Leptogenesis Scale ?

- Two classes of models depending on $\boldsymbol{\nu_R}$ mass pattern

  - **High Scale leptogenesis**: Expected in GUT theories:
    Adequate asymmetry→ $M \geq 10^9 GeV$ for lightest $\boldsymbol{\nu_R}$
    (for hierarchical masses) (Buchmuller, Plumacher,di Bari; Davidson, Ibarra)

  - **Resonant leptogenesis**: **degenerate** $\boldsymbol{\nu_R}$'s
    → self energy diagram dominates: $\dfrac{1}{M_i^2 - M_j^2 + M\Gamma}$

    Resonance when $M_i \cong M_j$; works for **all B-L scales**.
    (Liu and Segre'94; Covi et al'95 ; Flanz et al.'95 Pilaftsis'97)

Can we prove it experimentally?

- Unfortunately, no:
  - it is difficult to reconstruct relevant CP-violating phases from experiments
- But, we will probably believe it if the following observations happen in the experiments
  - CP violation in neutrino oscillation
  - neutrinoless double beta decay
  - lepton flavor violations ($\mu \to e$ conversion, $\tau \to \mu\gamma$)

Possible probe of the primordial lepton asymmetry

- Since $\eta_B \approx 10^{-2} \varepsilon_l \kappa$ small efficiency κ means large ε_l;
  - Good option: search for where κ is tiny so ε_l is order 1

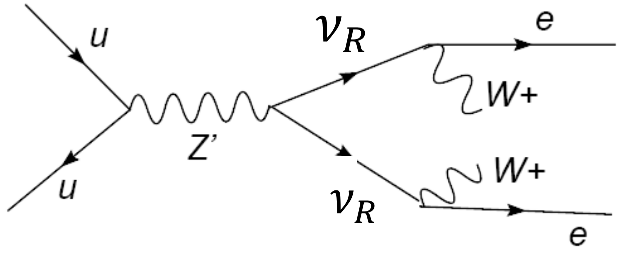
$$\varepsilon_l = \frac{\sum_\alpha [\Gamma(\nu_R \to l_\alpha^+ W^-) - \Gamma(\nu_R \to l_\alpha^- W^+)]}{\sum_\alpha [\Gamma(\nu_R \to l_\alpha^+ W^-) + \Gamma(\nu_R \to l_\alpha^- W^+)]}$$

- It can be detectable at LHC by searching for same sign leptons

(Blanchet, Chacko, Granor, Mohapatra'09)

(Ex) In SM+$U(1)_{B-L}$

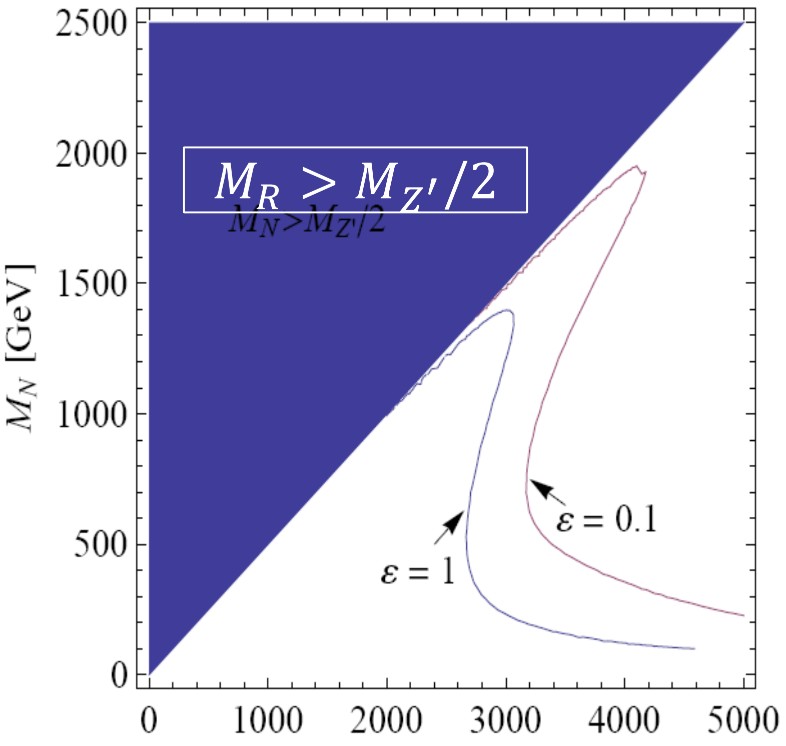
At LHC, PP→Z'→$\nu_R \nu_R$,



- -Look for a CP violating observable !

- Direct link between primordial lepton asymmetry and CP violating LHC observable:

$$\boxed{\frac{\Sigma_{\alpha\beta}[\Gamma(l_\alpha^+ l_\beta^+) - \Gamma(l_\alpha^- l_\beta^-)]}{\Sigma[\Gamma^{++} + \Gamma^{--}]} = \frac{2\varepsilon_l}{3}}$$

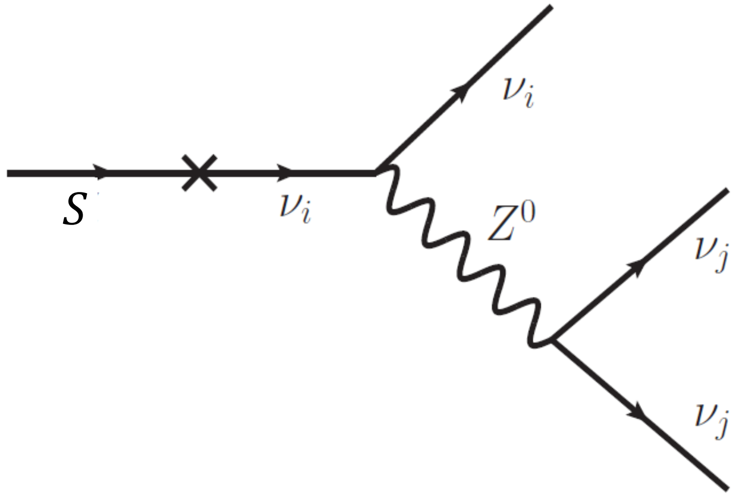


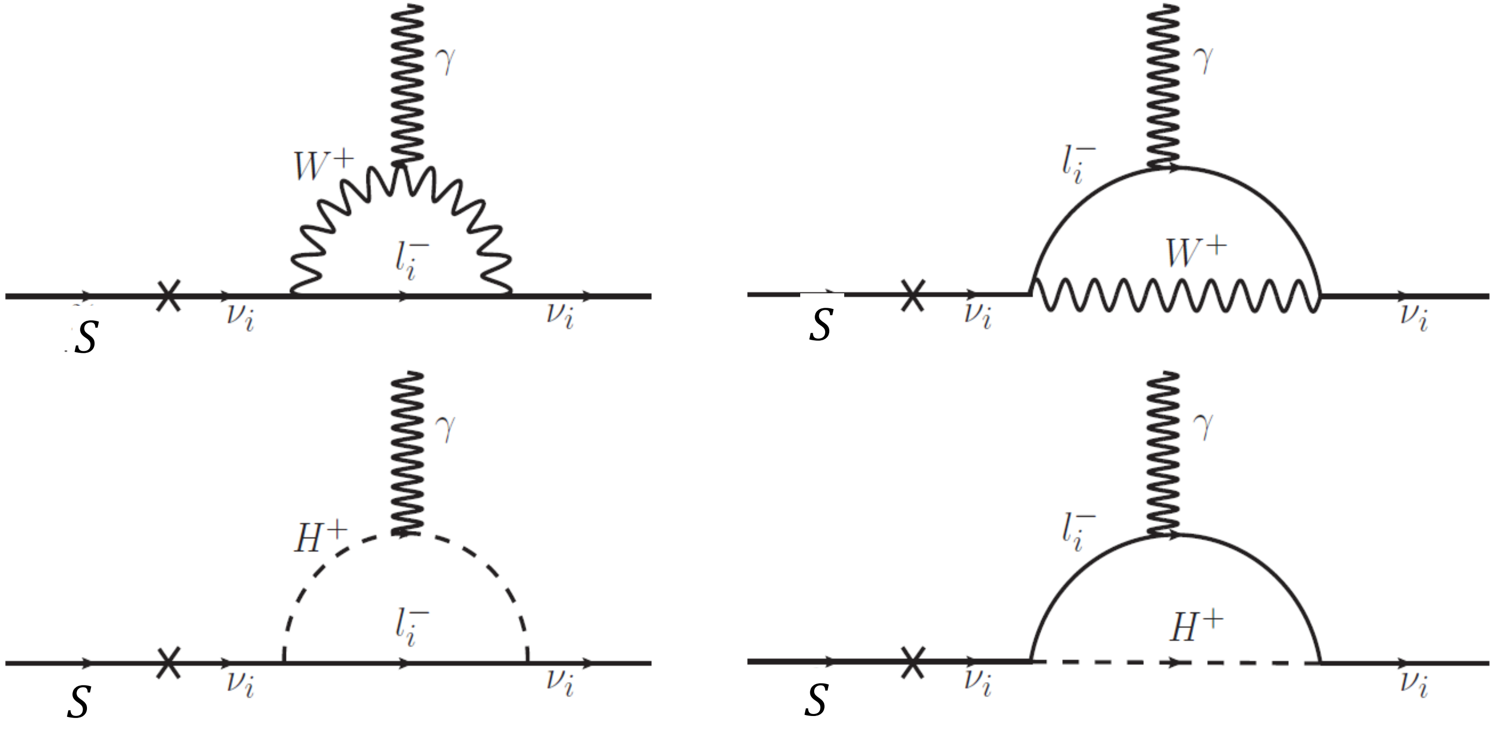
- For a ranges of Z′-ν_R mass,
  κ very small so that ε_l~0.1-1;
  (right & above colored curves allowed)
  → visible at LHC:
- Lower bound on Mz′ >2.5 TeV for $g' = 0.2$

Can ν_R be a Dark Matter?

- KeV scale Dark Matter (Kusenko, Merler, SK, Patra,…)

- Relic abundance of ν_R can be achieved via freeze-in through out of equilibrium decay of new scalar ϕ
- Decays of ϕ into a pair of ν_{R1} can occur via the interaction term generated after $\nu_{R2(3)}$ decoupled and ϕ got VEV, $\frac{|Y_{\nu 2}|^2 v_\phi}{M_{R2}} \phi \; \nu_{R1}\nu_{R1}$
- Decay rate of $\phi \to \nu_{R1}\nu_{R1}$: $\Gamma(\phi \to \nu_{R1}\nu_{R1}) = \frac{|Y_{\nu 2}|^4 v_\phi^2}{32\pi m_{R_2}^2} m_\phi$
- Solving Boltzmann Eq. : $\Omega_S h^2 \approx \frac{1.09\times 10^{27} m_{R1} v_\phi^2}{g_*^S \sqrt{g_*^\rho} m_\phi m_{R_2}^2} |Y_{\nu 2}|^4$
- BP for relic density : $v_\phi = 100\; GeV$, $m_\phi = 80\; GeV$, $Y_{\nu 2} = 10^{-3}$, $m_{R2} = 15\; TeV$, $m_{R1} = 7\; keV$





$$\Gamma_{3\nu} \cong sin^2 2\theta_S G_F^2 \left(\frac{m_S^5}{768\pi^3}\right)$$

$$\cong 8.7 \times 10^{-31} s^{-1} \left(\frac{sin^2 2\theta_S}{10^{-10}}\right)\left(\frac{m_S}{1\ keV}\right)^5$$

$$\Gamma_{\nu\gamma} \cong 6.8 \times 10^{-33} s^{-1} \left(\frac{sin^2 2\theta_S}{10^{-10}}\right)\left(\frac{m_S}{1\ keV}\right)^5$$

- Radiative decay can lead to 3.55 KeV X-ray line

$for\ \ m_{R1} = 7.1\, keV, and\ \ sin^2 2\theta_R \sim 10^{-11}$ $\qquad \Gamma_{total} \sim\ 10^{-26}\ \mathrm{s}^{-1}$

Conclusion

- We had exciting discoveries in the last years in neutrino physics, implying that the Standard model has to be extended in some way.
- ν_R may be required for deep understanding of tiny neutrino masses.
- ν_R may affect various phenomena probed in particle physics and cosmology.
- We find no evidence for ν_R so far.
- ν_R can play an essential role in the existence of our universe and be a dark matter candidate.
- Possibility of the existence of ν_R will continue to be studied.