# Testable Seesaw Variants



**Sudhanwa Patra**

**MPIK, Heidelberg**

**Based on My Recent Works:**

**ArXiv: 1506.03456 [hep-ph] (2015)**

**ArXiv: 1505.07453 [hep-ph] (2015)**

**Phys. Rev. D91 (2015) 1, 015018**

**Phys. Rev. D90 (2014) 5, 053014**

**Eur.Phys.J. C74 (2014) 10, 3078**

**Nucl.Phys. B881 (2014) 444-466**

**WIN2015, 12th June 2015**

# Plan of the Talk



## Low scale Seesaw Variants and SM extensions

- Neutrino Mass
- Lepton Number Violation and Neutrinoless Double beta decay
- Lepton Flavor Violation and non-uniarity effects
- Collider Study

## Low scale Seesaw Variants and Left-Right Theories

## Low scale Seesaw Variants and GUT Connection

## Conclusion

# Elusive Neutrinos And Neutrino Oscillation

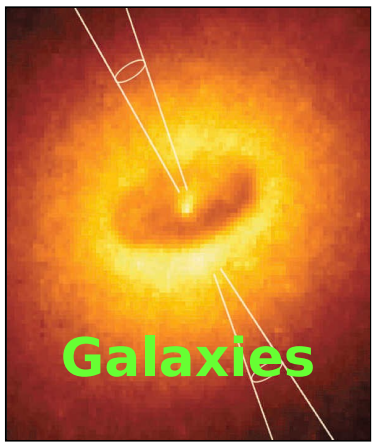


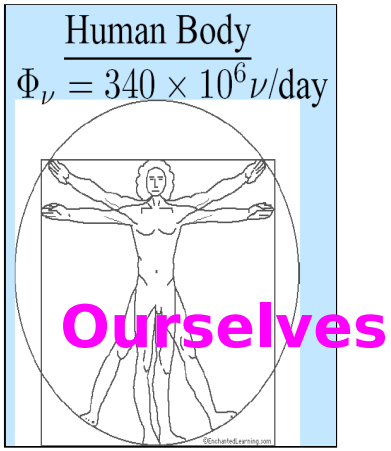

**Neutrinos: Lightest neutral leptons, take part in weak interaction**

**Neutrino was postulated to conserve energy-momentum**

$$n \longrightarrow p + e^{-} + \bar{\nu}_e$$

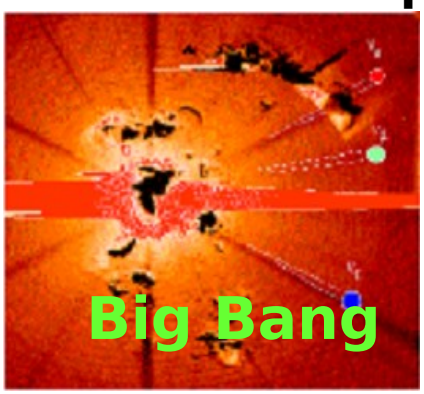
**They travel almost at the speed of light;**

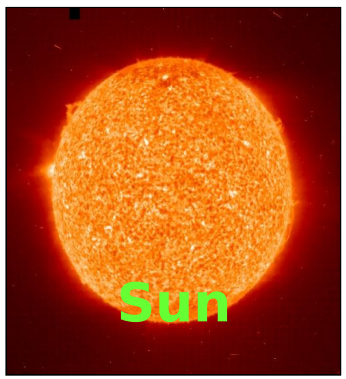


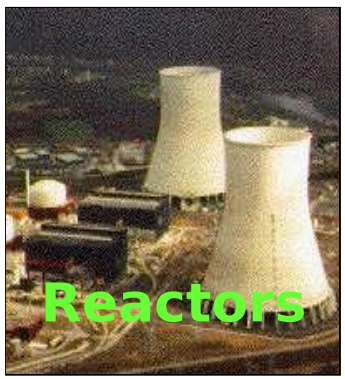




LHC


**Origin of non-zero neutrino masses confirmed by Atmspheric, Solar and Reactor Neutrino Oscillation Experiments**



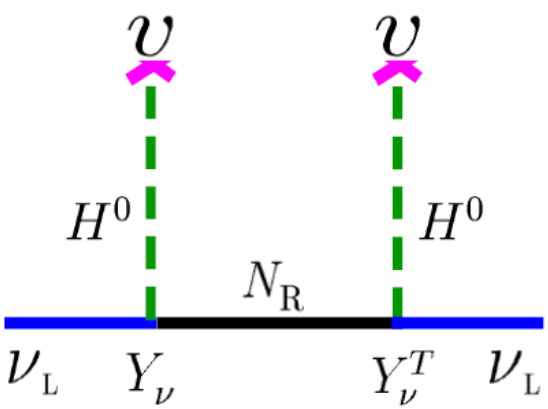

# Origin of ν-mass ? Seesaw Mechanism

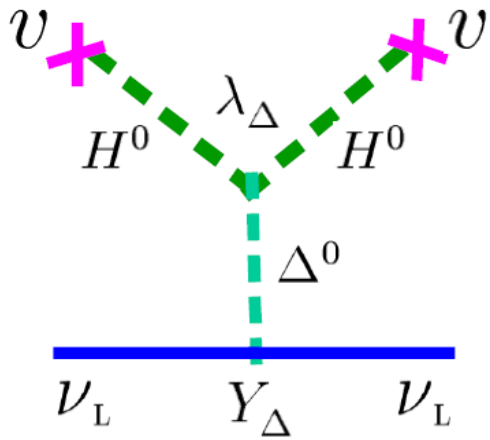


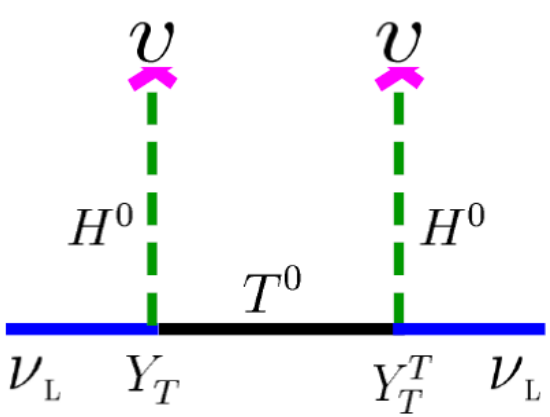
**Natural theoretical way to understand why 3 ν-masses are small**

**Type-I: SM + 3 right-handed Majorana ν's**

**(Minkowski 77; Mohapatra, Senjanovic 79)**




$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T$$

$$M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$

$$M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T$$

**Type-II: SM + 1 Higgs triplet**

Lazarides, Shafi, Wetterich ; Schechter, Valle (1980)

**Type-III: SM + 3 triplet fermions (R. Foot et al 89)**

**Other Testable Seesaw Variants:**

[Mohapatra '86; Mohapatra, Valle '86]

**Inverse, Linear Seesaw**

Malinsky, Romao, Valle (2005)

**Extended Inverse/Linear (SP, Parida, Awasthi 2013..)**

# Why TeV Seesaws?

★ **In Canonical Seesaw Mechanism with Singlet Fermion**

- ★ The Light Neutrino mass formula

$$m_\nu^I \simeq -m_D M_R^{-1} m_D = y_\nu v^2/M_R$$

- ★ In order to be compatible with the neutrino oscillation data, i.e, $|m_\nu| \simeq \sqrt{\Delta m^2_{\rm atm}} = 0.0495$ eV, one requires $M_N \simeq 10^{14-15}$ GeV taking the Yukawa couplings in their natural values i.e, $\mathcal{O}(1)$.

★ **Type-II Seesaw mechanism with Higgs scalar triplet**

- ★ The Type II seesaw formula for light Neutrino mass $m_\nu^{II} \simeq f\, v_L$, where $v_L = \mu_\Delta v^2/M_\Delta^2$ is the VEV of triplet scalar.
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- ★ An obvious setting would be $f \simeq \mathcal{O}(1)$ and $\mu \sim M_\Delta \simeq 10^{14-15}$ GeV in order to explain sub-eV scale of light neutrino masses

★ **Although these seesaw mechanisms look promising while explaining neutrino oscillation data, they lack the direct experimental testability in the ongoing experiments like Large Hadron Collider (LHC) or any future experiment like International Linear Collider.**

★ **This motivates to think of TeV Scale Seesaw and other Low scale Seesaw Variants which can be probed at LHC**

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# Low scale Seesaw Variants and SM Extensions



**Small ν-masses can be generated from slight deviation from this complete "structural cancellation", by deforming *M*_D or *M*_R . (Within Type-I)**

**Kersten, Smirnov 07) + Bhupal and others.....**

★ SM($\nu$)+ Additional singlet fermions (N,S)

Inverse Seesaw

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

Linear Seesaw

$$\begin{pmatrix} 0 & m_D & m_L \\ m_D^T & 0 & M \\ m_L & M^T & 0 \end{pmatrix}$$

★ Extended Inverse Seesaw

$$\begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & M \\ 0 & M^T & \mu \end{pmatrix}$$

Extended Linear Seesaw

$$\begin{pmatrix} 0 & m_D & m_L \\ m_D^T & M_R & M \\ m_L & M^T & 0 \end{pmatrix}$$

# Testability of Seesaw Variants



★ In Generic Inverse/Linear Seesaw Mechanism

[Mohapatra '86; Mohapatra, Valle '86]

★ Malinsky, Romao, Valle (2005)

$$m_\nu \sim \left(\frac{m_D}{M}\right)^2 \mu\,; \quad \text{inverse} \quad \text{or,} \quad m_\nu \sim \left(\frac{m_D}{M}\right) m_L\,; \quad \text{Linear}\,,$$

★ While Heavy neutrinos form a pseudo-Dirac pair. Thus LNV effects from heavy neutrinos are suppressed.

★ In Extended Inverse/Linear Seesaw Mechanism

TeV scale $M_N$ even with large $M_D \sim m_t$ for $\mu \sim$ keV.

Smallness of $\mu$ is *natural* in 't Hooft sense.

$$m_{\rm int} \sim \frac{M^2}{M_R}\,,$$
$$m_{\rm heavy} \sim M_R$$

★ LNV $0\nu\beta\beta$ parameter is given as

$$\eta_\nu = \frac{1}{m_e}\left(\sum_{i=1}^{3} U_{ei}^2 m_i\right) \approx \frac{m_{ee}}{m_e}\,,$$

$$\eta_N = -m_p\left(\sum U_{ei}^2 \frac{1}{\ } + \sum U_{ei}^2 \frac{1}{\ }\right) \equiv -\frac{m_p}{\ }\,.$$

# Neutrinoless Double beta decay



Double beta decay can happen in two processes

$(A,Z) \rightarrow (A,Z+2)+2e+2\nu - (2\nu\beta\beta)$

$(A,Z) \rightarrow (A,Z+2)+2e$ $(0\nu\beta\beta)$

While $(2\nu\beta\beta)$ is already observed,

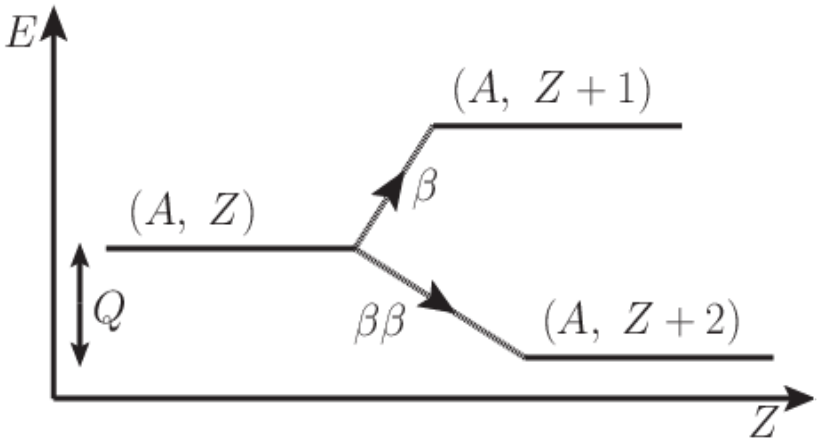
Expts. Like GERDA, EXO, KAMLAND are designed to observe $(0\nu\beta\beta)$

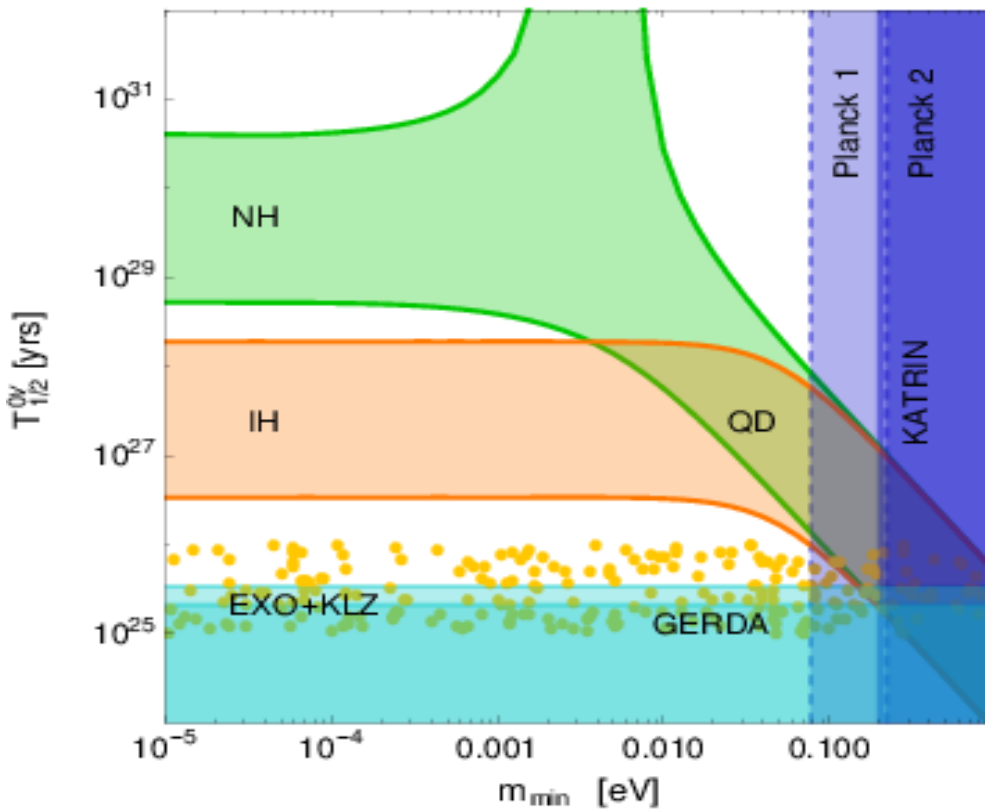
The $(0\nu\beta\beta)$ is sought for in special isotopes with even-even nuclei in which single beta decay is energetically forbidden.

Lepton Number Violation within Conformal Inv. Inverse Seesaw

Pascal, Manfred, SP, J. Smirnov

ArXiv:1505.07453 [hep-ph]



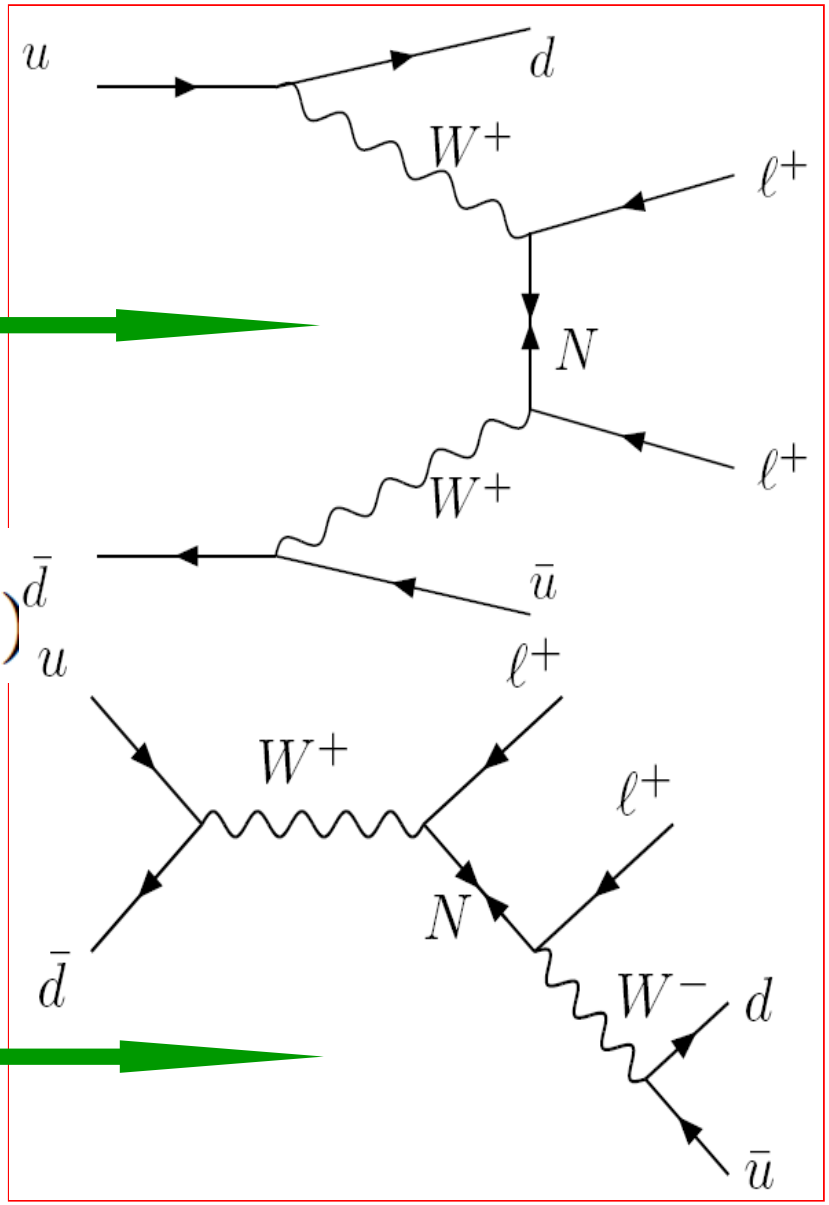



# Collider Signature



**Lepton number violation:**

**Same like-sign dilepton events at hadron colliders, such as Tevatron (~2 TeV) and LHC (~14 TeV).**




**collider analogue to 0νββ decay**

See Martin Hirsch's Talk
or Citation credits therein)

**dominant channel**

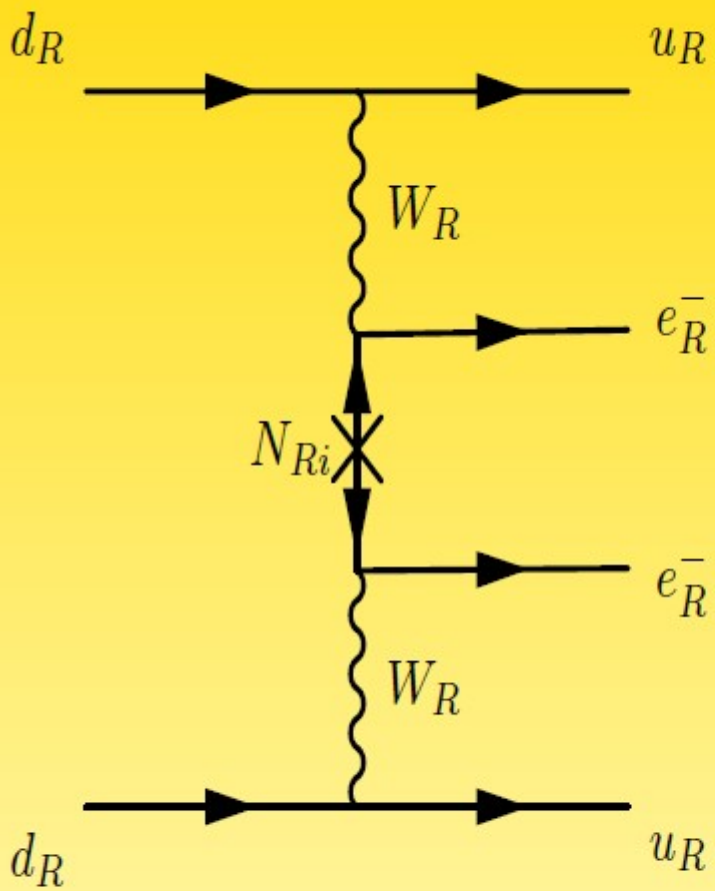
***N* can be produced on resonance**

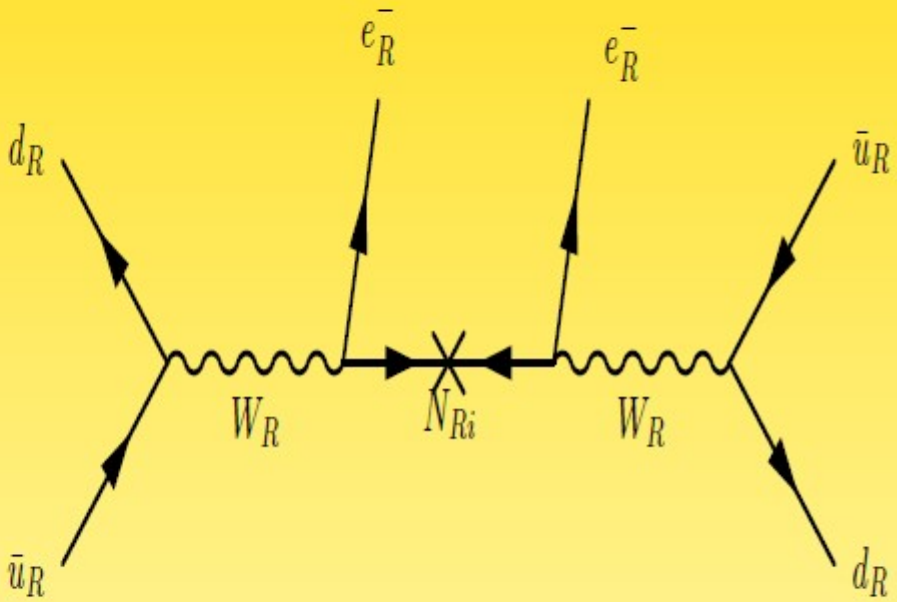
# Left-Right Theory and Sizable Effects



## Left-right symmetry

Mohapatra, Pati 74)
Senjanovic 75)

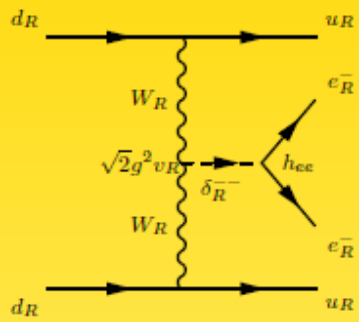


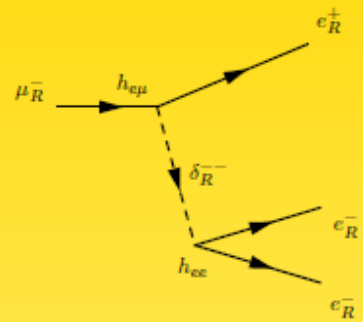



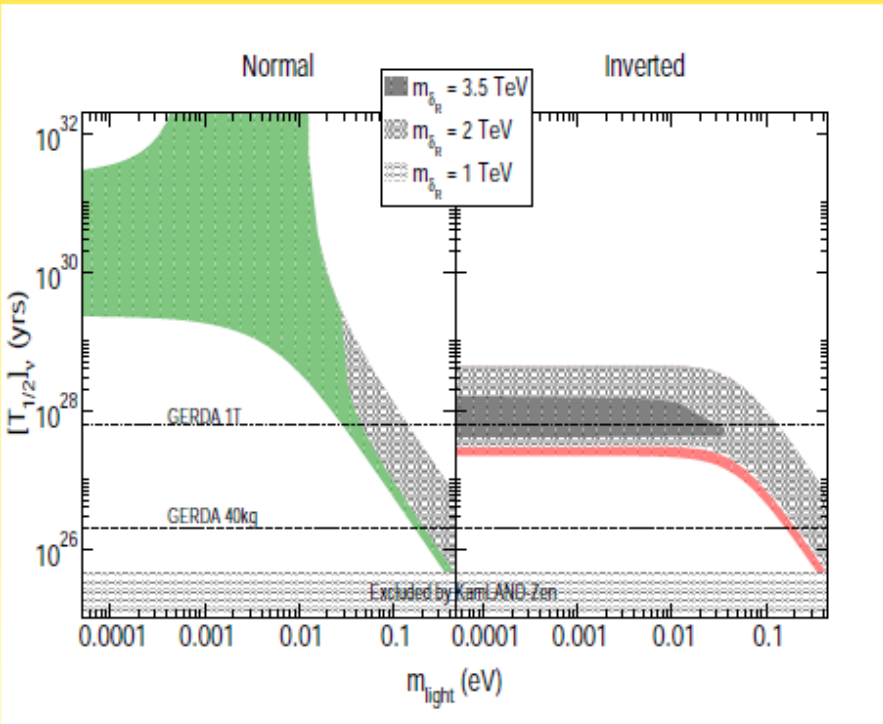

Senjanovic, Keung, 1983; Tello *et al.*; Nemevsek *et al.*

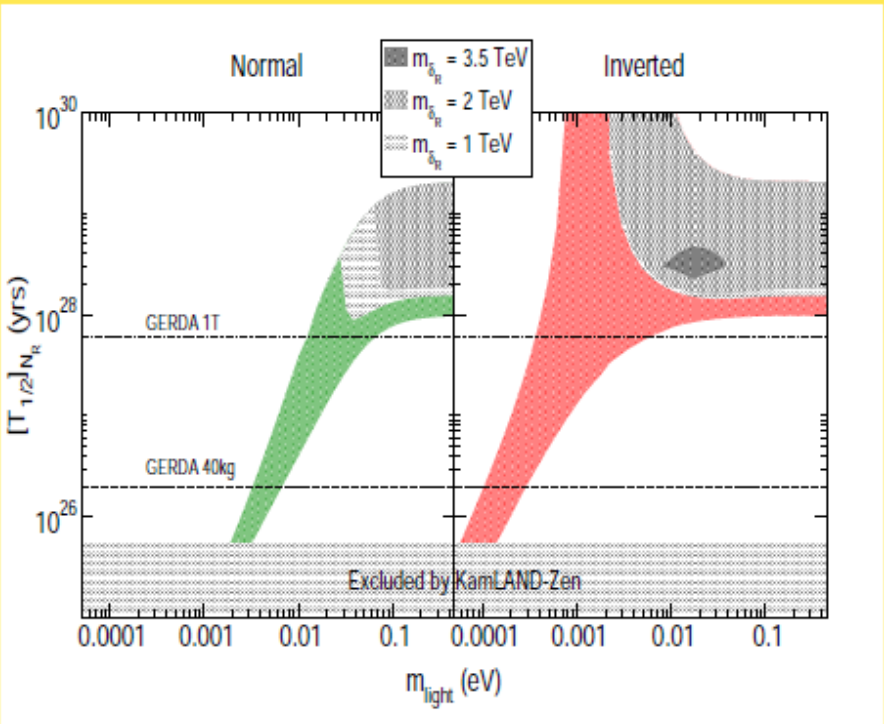
(LNV at colliders: Deppisch)

# Constraints from Lepton Flavor Violation



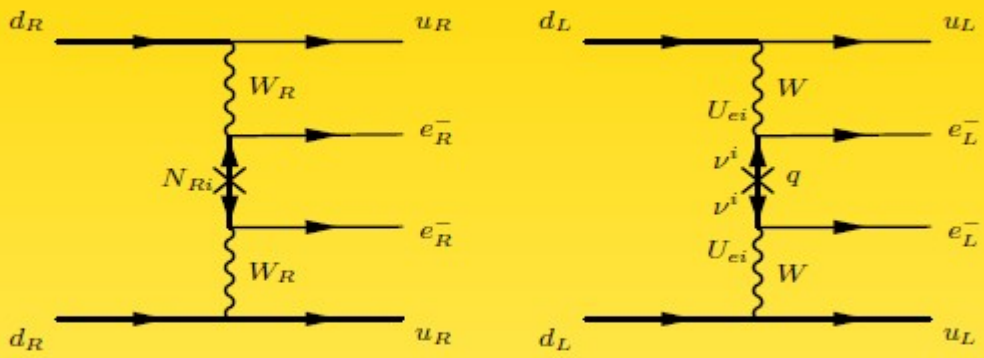



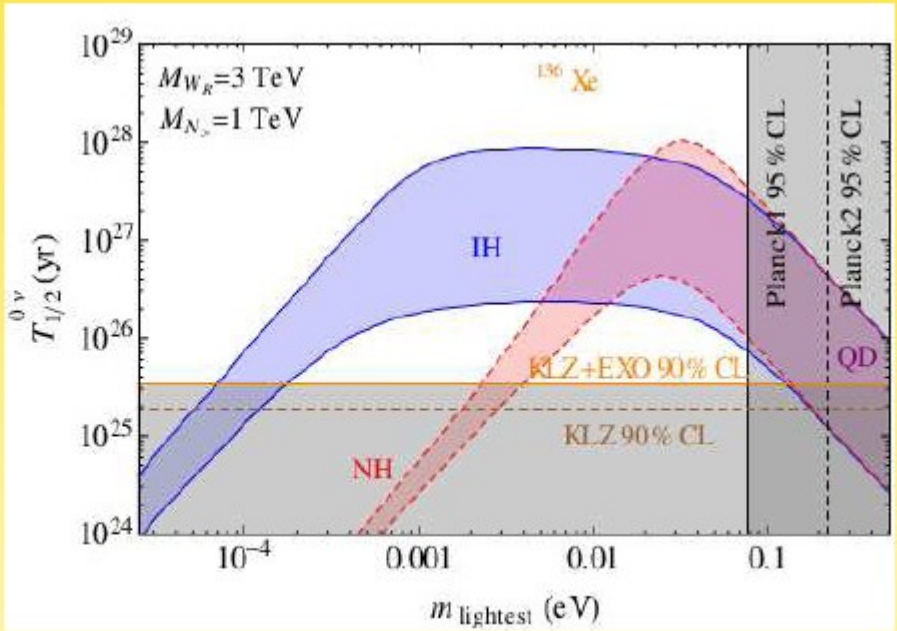




RODEJOHANN JHEP **1309**

# Adding diagrams

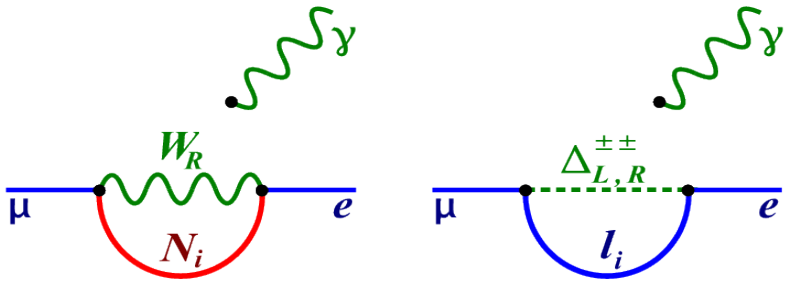


# Lepton Flavor Violation



**Neutrino Oscillation gives the phenomena of Lepton Flavor Violation. The contributions from light neutrinos are suppressed.**



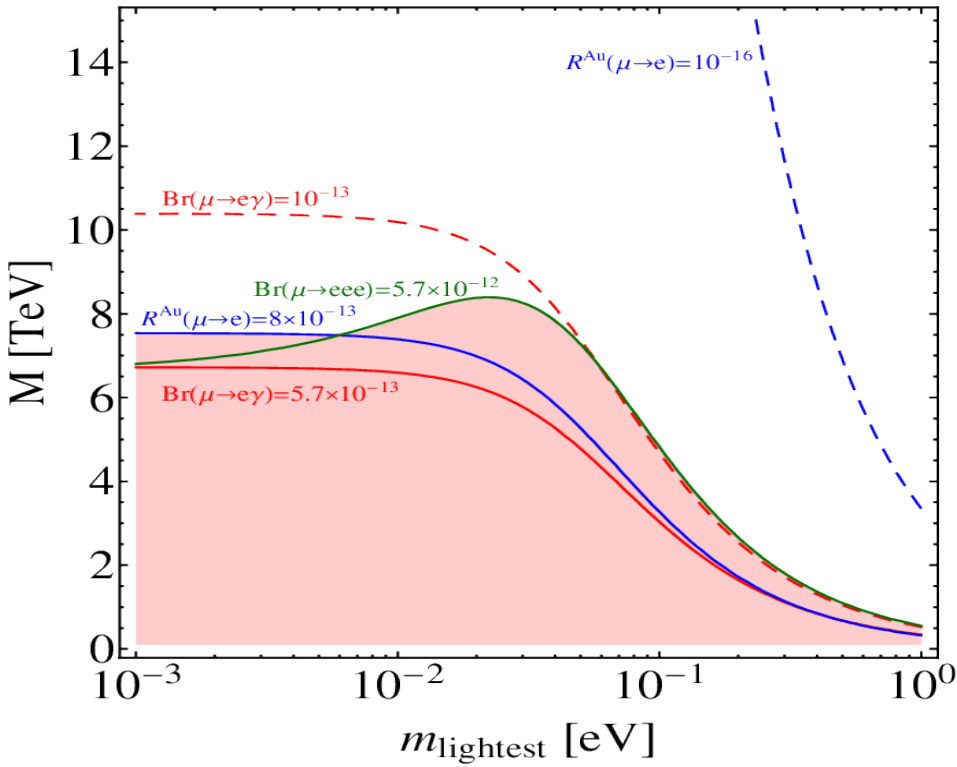

**μ→e+γ,** μ→eee, τ→μee, μ→e

**Indicates new physics contributions**

**currently running MEG experiment:**

**Br.(μ→e+γ)<5.7x10^(-13)**

**MEG Collaboration**



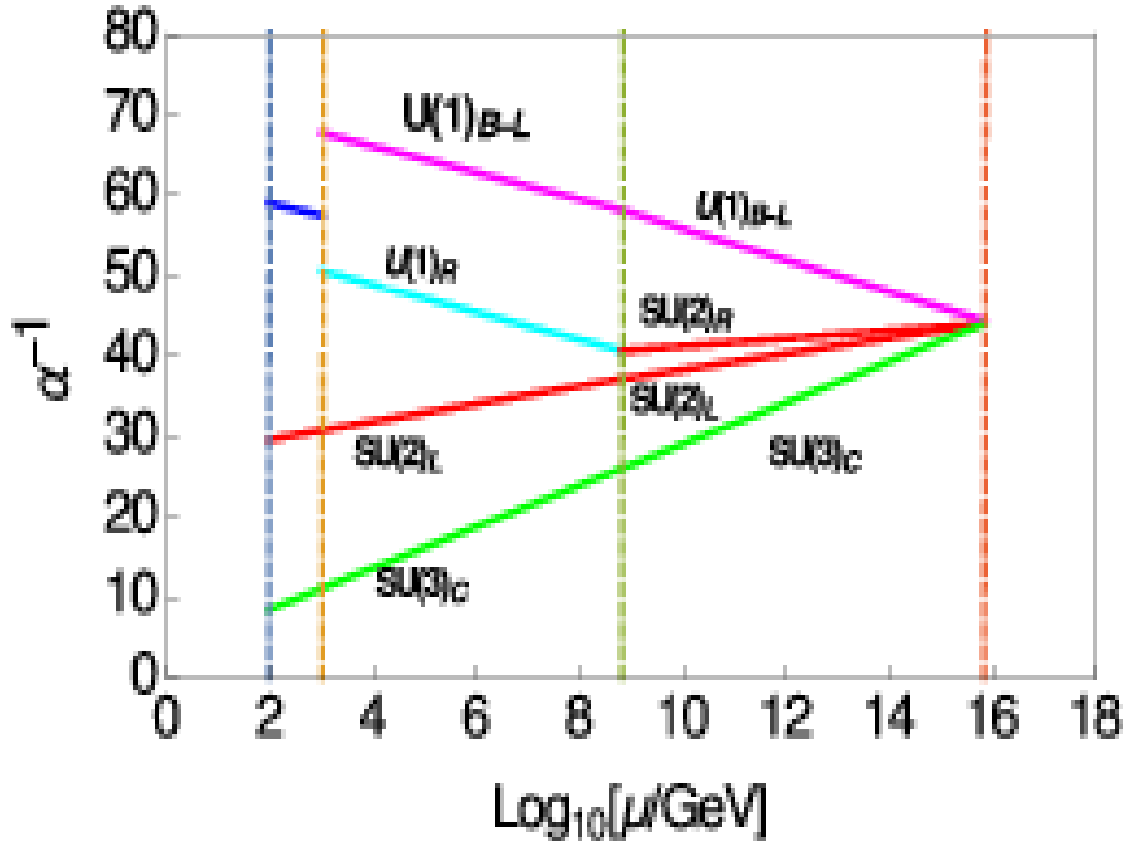

**F.Deppisch, Gonzalo, SP, Sarkar, Sahu**
**Phys.Rev. D91 (2015) 1, 015018**

# Low scale Seesaw and SO(10) GUT



. Provides Large light-heavy neutrino mixing relevant for LHC, LFV and 0nbb process

. We have embedded the idea in SO(10) Model and Study gauge coupling unification and Collider Study.



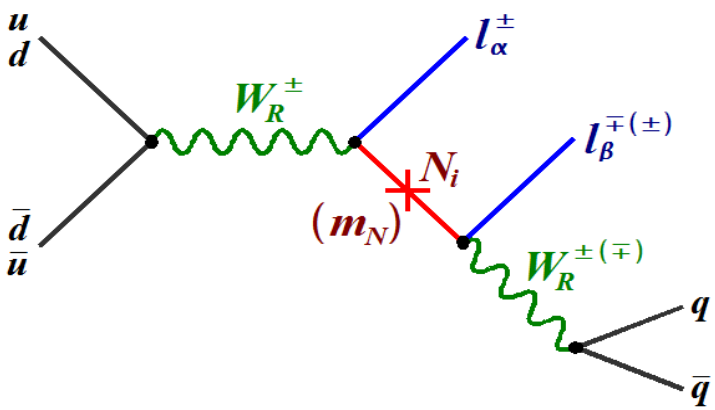

**Low Scale Seesaw Mechanism and their LNV, BNV, LFV and Collider Complementarity within GUT Models.**

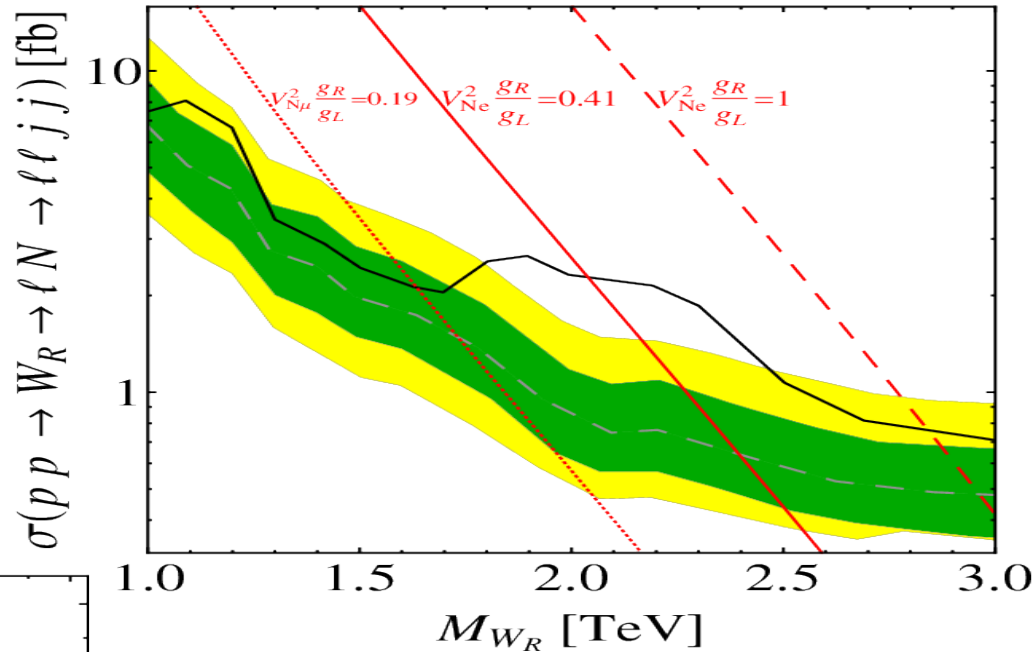
| | |
|---|---|
| SP, Prativa, | Eur.Phys.J. C74 (2014) 10, 3078 |
| Parida, Awasthi, SP | JHEP 1308 (2013) 122 |
| Debasish, SP, Prativa | Nucl.Phys. B881 (2014) 444 |

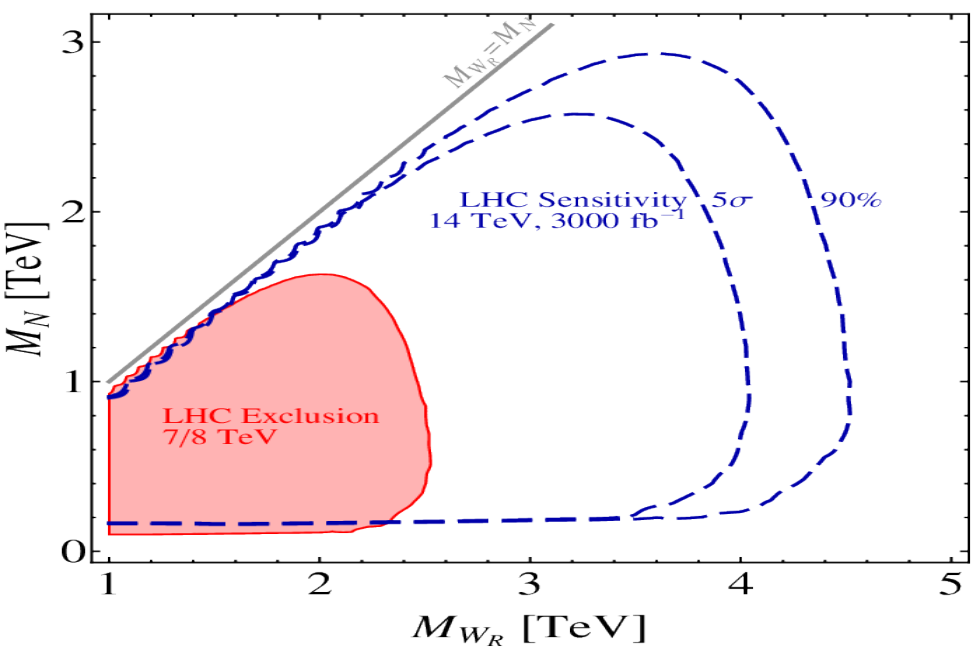
# Signal of WR gauge boson at LHC



F.Deppisch, Gonzalo, SP, Sarkar, Sahu (Phys.Rev. D90 (2014) 5, 053014 )




**LHC:** **recent data from CMS on dilepton + 2jets signal can be explained with 2.4 TeV right-handed charged gauge boson WR**

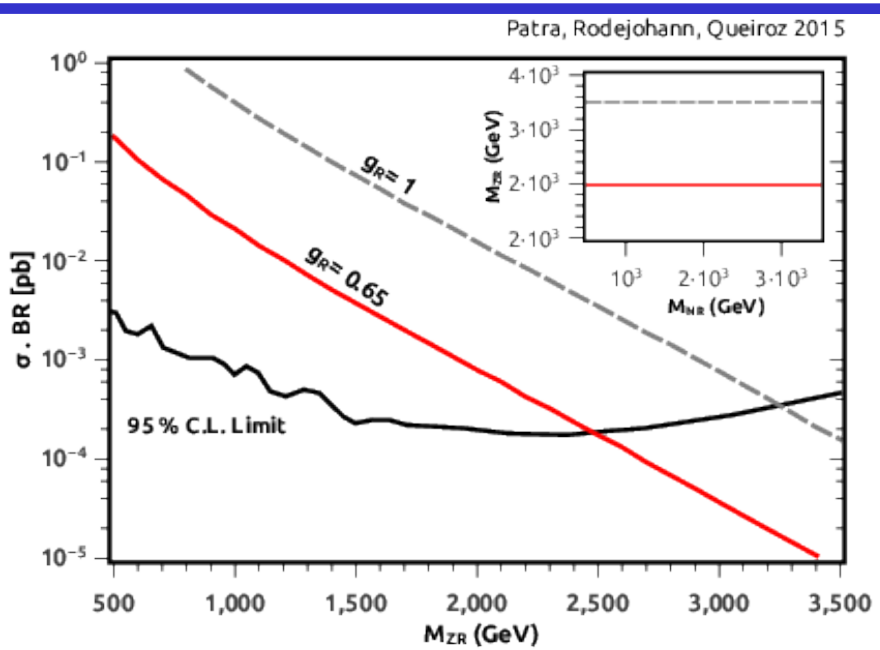
**which arise in a D-parity violating leftright symmetric model.**

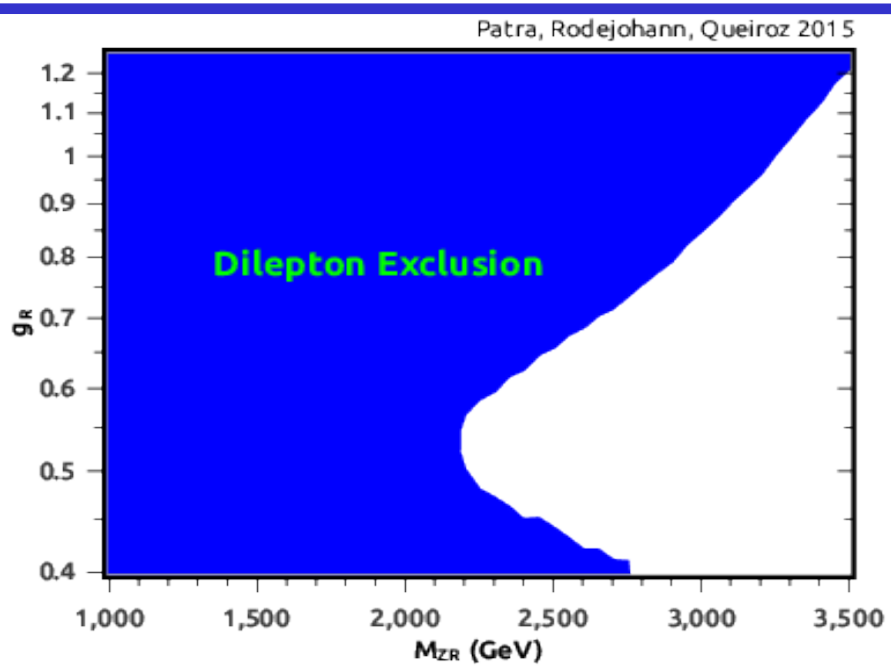
**TeV scale WR would imply B − L violation at the TeV scale**

**(the first evidence for baryon or lepton number violation)**

# Today in ArXiv

## SP, Queiroz, Rodejohann: arXiV:1506.03456




# Stringent Dilepton Bounds on Left-Right Models using LHC data

Sudhanwa Patra[1,2], Farinaldo S. Queiroz[1], Werner Rodejohann[1*]
[1] *Max-Planck-Institut für Kernphysik, Postfach 103980, 69029 Heidelberg, Germany*
[2] *Center of Excellence in Theoretical and Mathematical Sciences, Siksha 'O' Anusandhan University, Bhubaneswar-751030, India*

In canonical left-right symmetric models the lower mass bounds on the charged gauge bosons are in the ballpark of $3-4$ TeV, resulting into much stronger limits on the neutral gauge boson $Z_R$, making its production unreachable at the LHC. However, if one evokes different patterns of left-right symmetry breaking the $Z_R$ might be lighter than the $W_R^{\pm}$ motivating an independent $Z_R$ collider study. In this work, we use the 8 TeV ATLAS 20.3 fb$^{-1}$ luminosity data to derive robust bounds on the $Z_R$ mass using dilepton data. We find strong lower

# SUMMARY



- **Testable Seesaw Variants are important in the context of LNV, LFV and Collider complementarity study and operative at few TeV scale**

- **Low scale extended Inverse/Linear Seesaw is well connected to Neutrino Mass, Matter-antimatter asymmetry, keV Dark Matter, LNV, LFV effects and feasible at LHC**

**Possible extensions of the SM is expected to be detected at LHC, which includes Left-Right Models and Can give Sizable effects**

- **Whatever new physics we observe at LHC Run-II, will lead us to a new era in particle physics !!**