Some BSM physics opportunities of lepton colliders

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Outline

1) **The seesaw mechanism**

2) **Testing the type-II seesaw @ lepton colliders**

3) **Testing the Left-Right Symmetric Model @ lepton colliders**

4) **Discussion and outlook**

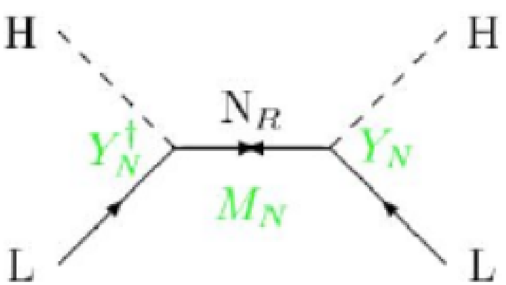
The seesaw mechanism

The SM has no $\nu_R \rightarrow$ no tree-level neutrino mass, but…

- **Weinberg operator:** $\mathcal{O}_5 \sim \frac{1}{\Lambda} l l \phi \phi$
  (S. Weinberg, 1980)
- **After SSB:** $m_\nu \sim \frac{\langle \phi \rangle^2}{\Lambda}$

The (high scale) seesaw mechanism

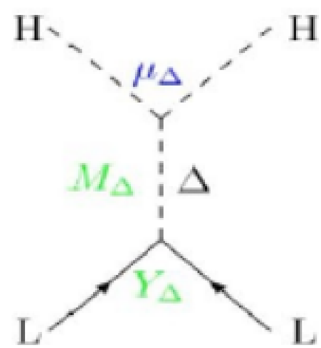
Right-handed singlet:
(type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkowski; Gellman, Ramon, Slansky; Yanagida;Glashow; Mohapatra, Senjanovic Schechter, Valle

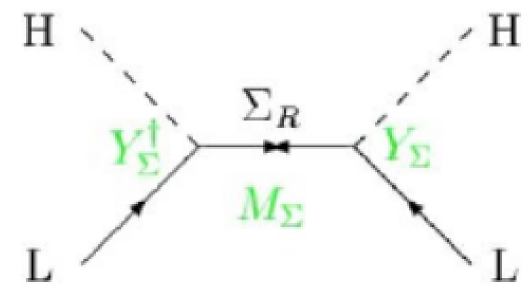
Scalar triplet:
(type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle

Fermion triplet:
(type-III seesaw)



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

Foot, Lew, He, Joshi; Ma; Ma, Roy;T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

Type-II seesaw model

Type-II seesaw

- **Add a scalar triplet:**

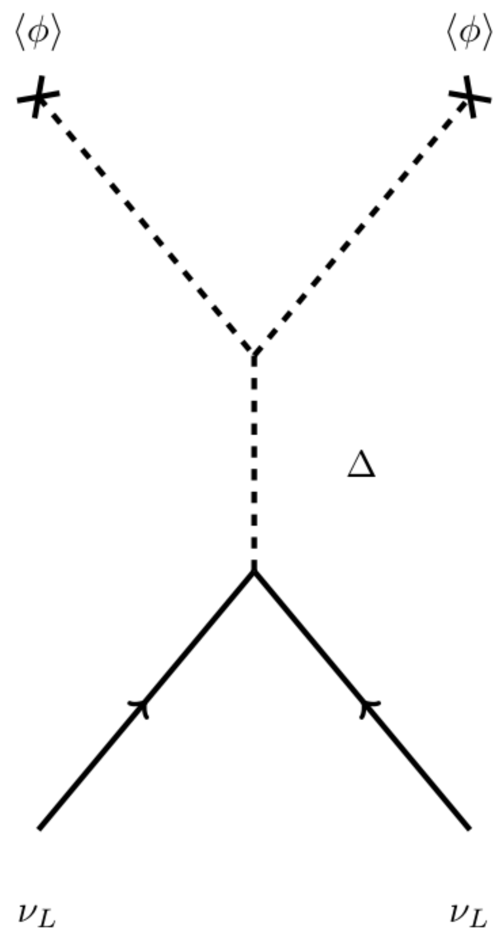
$$\Delta \sim (\mathbf{1}, \mathbf{3}, 2) \sim \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

- **New Yukawa interaction with SM fermions:**

$$-\mathcal{L}_Y = y_\Delta \bar{l}_L^c i\sigma_2 \Delta l_L$$

- **Neutrino mass generation:**

$$m_\nu = \sqrt{2} y_\Delta v_\Delta = y_\Delta \frac{\mu_\Delta}{\sqrt{2}} \frac{v^2}{M_\Delta^2}$$



Testing the type-II seesaw @ lepton colliders

- $H^{\pm\pm}$ **has unique signatures at colliders:** (P.Argawal, et al.; 1803.00677)

$$\Gamma(H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}) = \frac{M_{H^{\pm\pm}}}{(1+\delta_{ij})8\pi}\left(\frac{M_{\nu ij}}{v_\Delta}\right)^2$$

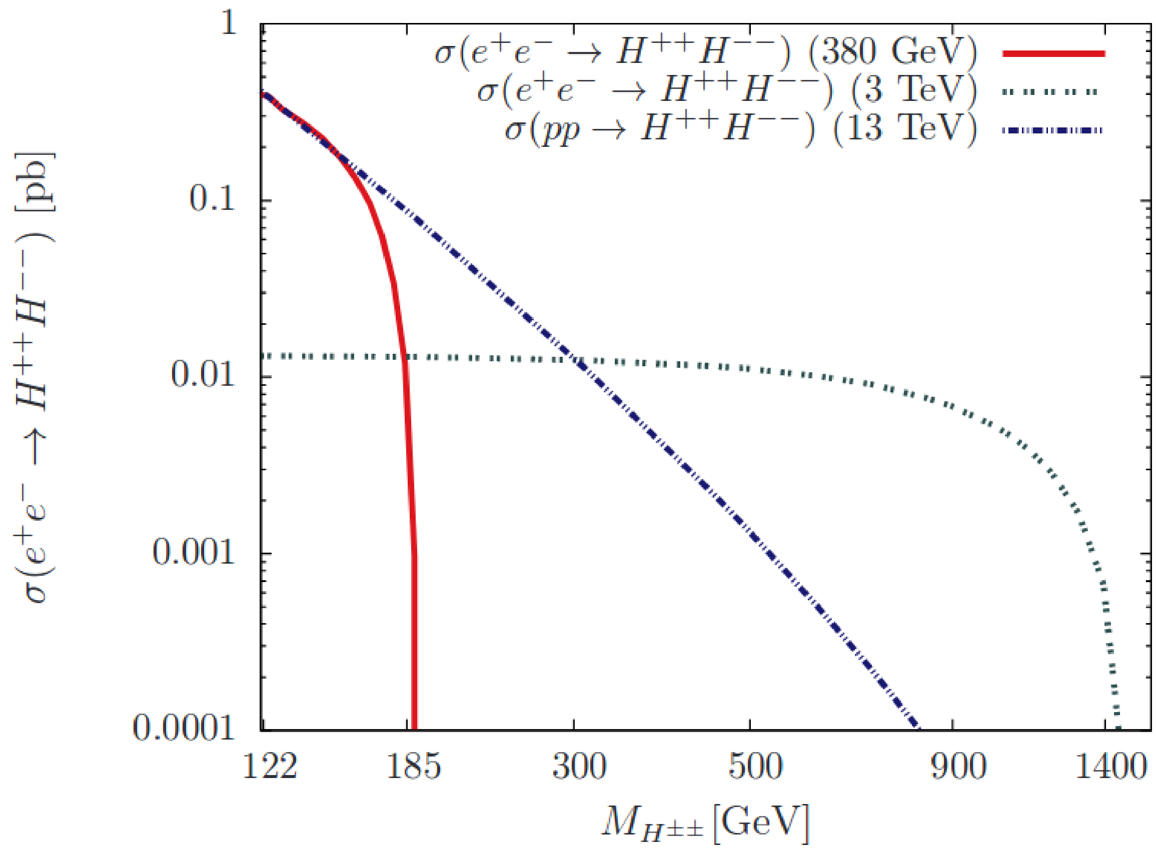
$$\Gamma(H^{\pm\pm} \to W^{\pm}W^{\pm}) = \frac{g^2 v_\Delta^2}{8\pi M_{H^{\pm\pm}}}\sqrt{1-\frac{4M_W^2}{M_{H^{\pm\pm}}^2}}\left(2+\left(\frac{M_{H^{\pm\pm}}^2}{2M_W^2}-1\right)^2\right)$$

- **For** $v_\Delta \geq 10^{-4}$ GeV, $H^{\pm\pm} \to W^{\pm}W^{\pm}$ **becomes dominant.**
- **CMS & ATLAS constraint (dilepton channel):** $M_{H^{\pm\pm}} > 820, 870\,\text{GeV}$ **does not apply. LEP-II does:** $M_{H^{\pm\pm}} > 97.3$ GeV
- **Lepton collider (cleaner environment) more suitable to look for** $H^{\pm\pm} \to W^{\pm}W^{\pm}$ **and hadronic final states!**

Complementarity between hadron and lepton colliders!

Testing the type-II seesaw @ lepton colliders

- **Prod. cross section comparison.**
- **CLIC beam polarization of (+80,-30).**
- **Doubly-charged scalar with masses as high as $M_{H^{\pm\pm}} \sim 1400$ GeV can be discovered with $\sqrt{s} = 3$ TeV**



(P.Argawal, et al.; 1803.00677)

Minimal Left-Right Symmetric Model

The Left-Right Symmetric Model

- **Extend the EW gauge group to** $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
  (Mohapatra & Senjanovic, 1980)

- **Parity restoration:**
$$(\mathbf{1},\mathbf{2},\mathbf{1},-1)_L \leftrightarrow (\mathbf{1},\mathbf{1},\mathbf{2},-1)_R$$
$$(\mathbf{3},\mathbf{2},\mathbf{1},1/3)_L \leftrightarrow (\mathbf{3},\mathbf{1},\mathbf{2},1/3)_R$$

- **RH neutrinos are predicted** $\longrightarrow$ **seesaw mechanism!** $m_\nu \sim \dfrac{v^2}{V_R}$

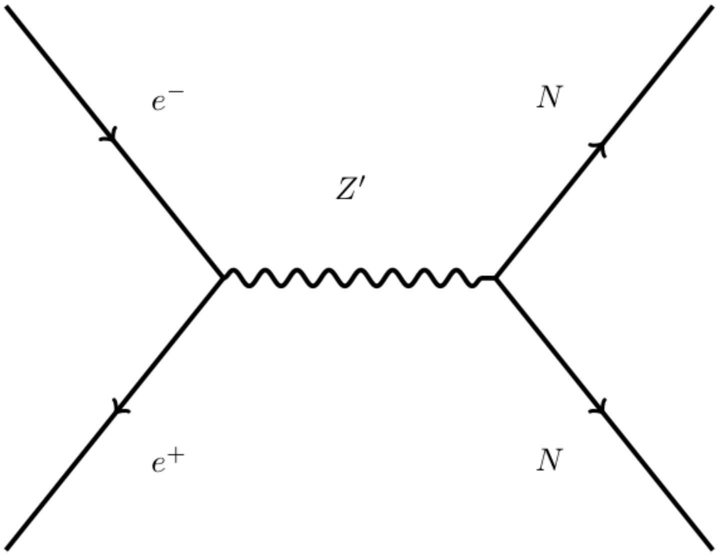
- **New scalars & new gauge bosons:** W_R & Z'

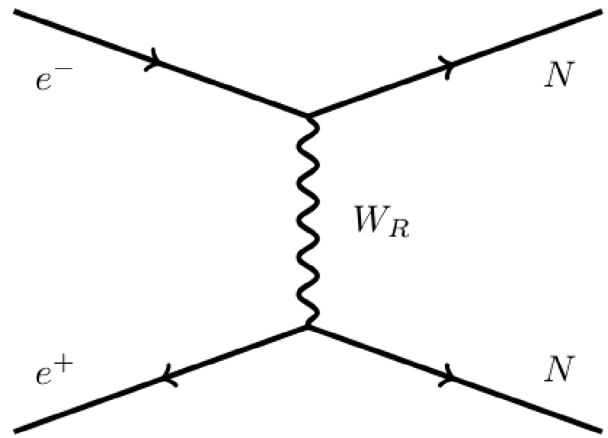
$$\boxed{\textbf{Rich phenomenology!!}}$$

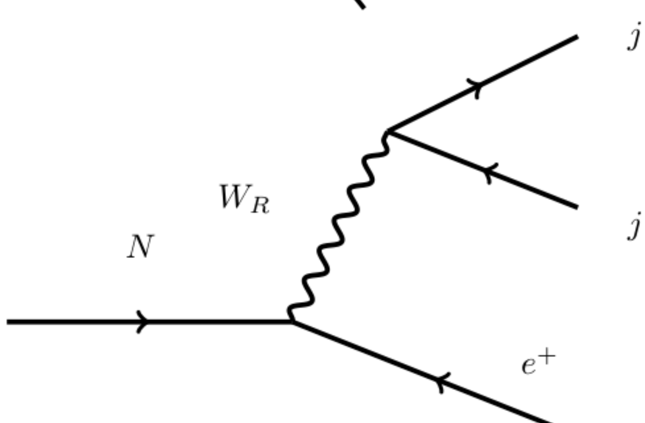
Testing the Left-Right Symmetric Model @ lepton colliders

For LFV in LR @ LHC see: (S.P.Das, et al., 1206.0256)

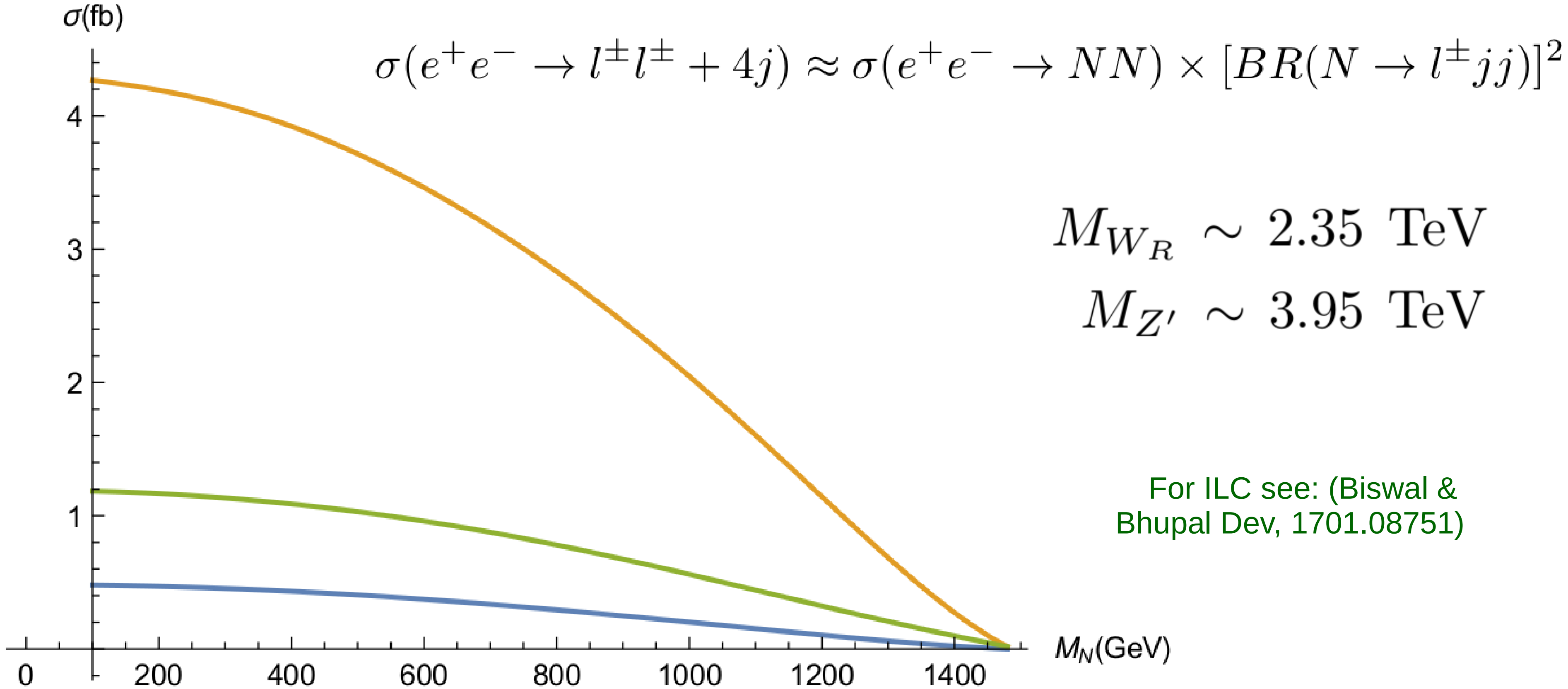
- **Goal:** $e^+e^- \to l^\pm l^\pm + 4j$, **implies** $\Delta L = 2$







Beam polarization effect @ CLIC

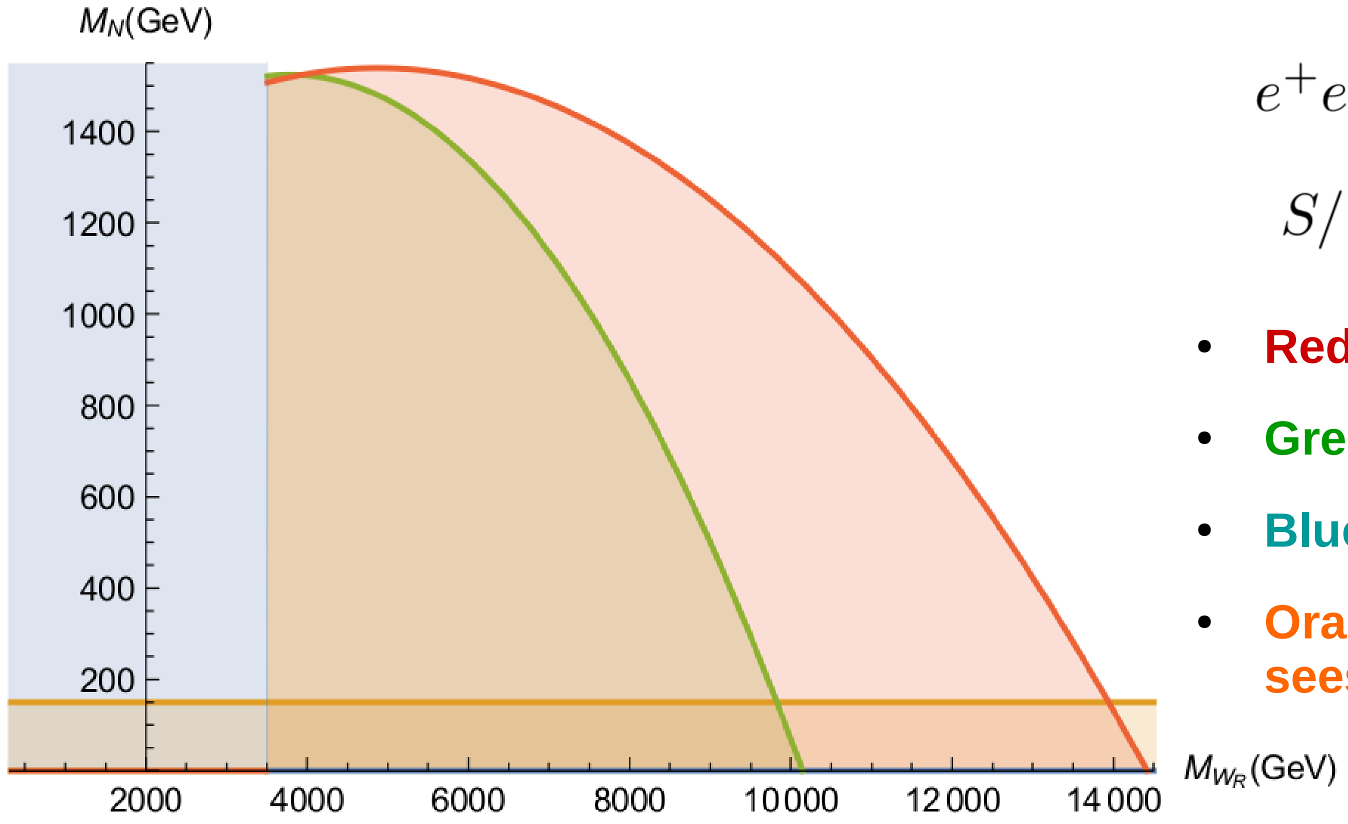


For ILC see: (Biswal & Bhupal Dev, 1701.08751)

- **Orange: (+100,-100)**
- **Green: unpolarized**
- **Blue: (-100,+100)**

BEAM POLARIZATION ALLOW US TO DISTINGUISH THE CHIRALITY OF THE CURRENT!! INTERESTING TO APPLY ALSO TO 331 THEORY

Discovery potential for right handed charged current @ CLIC



$$e^+e^- \to l^\pm l^\pm + 4j$$

$$S/\sqrt{S+B} \sim 5$$

- **Red: completely polarized.**
- **Green: unpolarized.**
- **Blue: excluded by LHC.**
- **Orange: excluded by seesaw consistency**

CLIC can explore energies up to 14 TeV!

CONCLUSIONS

- **Complementarity between hadron & lepton colliders.**

- **Tools like beam polarization make lepton colliders very powerful machines.**

BACK UP

Rho parameter

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = \frac{1 + \frac{2v_t^2}{v_d^2}}{1 + \frac{4v_t^2}{v_d^2}}$$

$$\rho \; = \; 1.0004^{+0.0003}_{-0.0004}$$

$$v_t \; < \; 5 \; \mathrm{GeV}$$

H++ production diagram