TeV-scale type-I+II seesaw mechanism and its collider signatures at the LHC

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Outline

- Brief overview of neutrino mass models.
- Introduction to a TeV-scale type-I+II seesaw model.
- EW precision data constraints and collider signatures.
- Concluding remarks .

TeVPA08

Chao, Si, Xing and Zhou, PLB 2008; Chao, arXiv:0806.0889[hep-ph]

Neutrinos are massive!

The first evidence for new physics beyond the SM

$$\Delta m^2_{21} = 7.67\,^{+0.22}_{-0.21}\,\left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2\,,$$

$$\Delta m^2_{31} = \begin{cases} -2.37 \pm 0.15\,\left(^{+0.43}_{-0.46}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(inverted hierarchy)}\,, \\ +2.46 \pm 0.15\,\left(^{+0.47}_{-0.42}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(normal hierarchy)}\,, \end{cases}$$

$$\theta_{12} = 34.5 \pm 1.4\,\left(^{+4.8}_{-4.0}\right)\,,$$

$$\theta_{23} = 42.3\,^{+5.1}_{-3.3}\,\left(^{+11.3}_{-7.7}\right)\,,$$

$$\theta_{13} = 0.0\,^{+7.9}_{-0.0}\,\left(^{+12.9}_{-0.0}\right)\,,$$

$$\delta_{\mathrm{CP}} \in [0,\ 360]\,.$$

Gonzalez Garcia and Maltoni, Phys. Rept. 460, 1(2008).

1. There are no right-handed neutrinos.
2. There is only one Higgs doublet of the SU(2)_L.
3. There are only renormalizable terms.

To generate non-zero neutrino masses one must relax 1 and (or) 2 (or) 3!

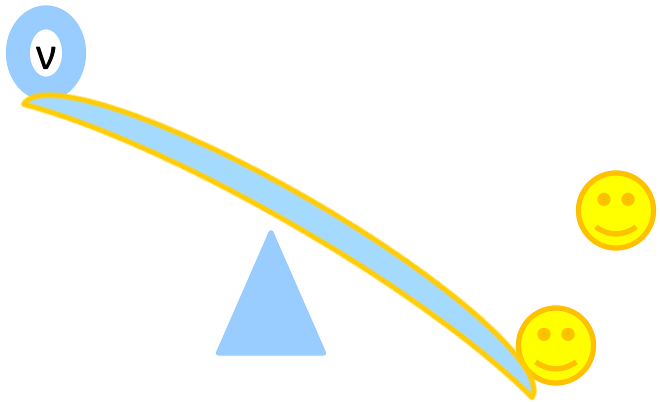
Y_ν~10^{-12}
Unnatural!

Dirac $\Leftrightarrow$ Majorana

- **Seesaw mechanisms**
- **Radiative corrections**
- **RPV SUSY**

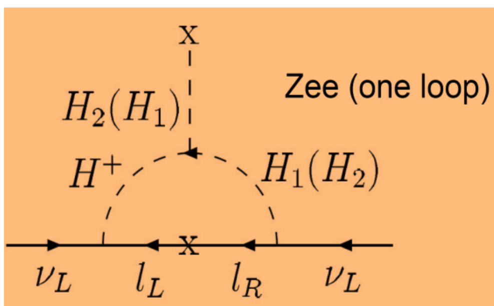
Neutrino mass models

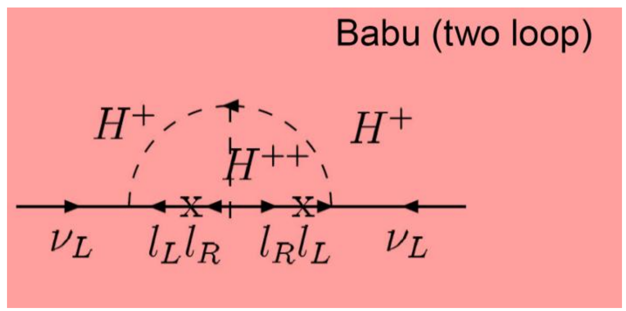
- Seesaw mechanisms, SM+ super-heavy particles

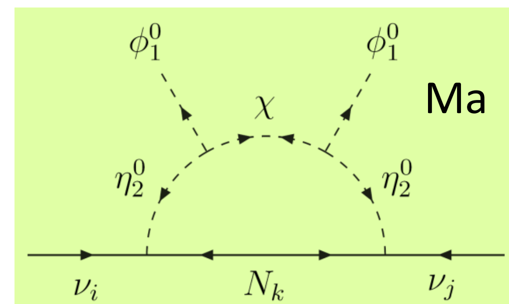


:
- Type-I : Right-handed Majorana neutrinos.
- Type-II : Triplet boson.
- Type-III : Triplet fermions.

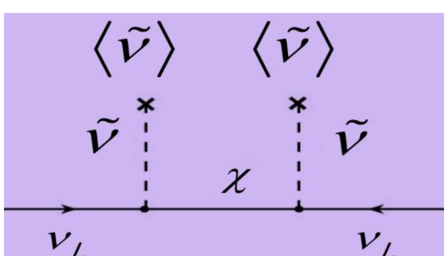
- Loop models, neutrino masses are radiatively induced







- RPV, sneutrinos get vevs , inducing mixing between ν and χ



$$M_\nu \approx \frac{\langle\tilde{\nu}\rangle^2}{M_\chi} \approx \frac{\mathrm{MeV}^2}{\mathrm{TeV}} \approx \mathrm{eV}$$

New physics @ the TeV scale

- Unitarity violation in WW scattering
- Cold dark matter
- Hierarchy problem
- Muon g-2

String, …

EW scale

TeV

GUT

Planck

EW precision observables
ν masses and oscillations
0νββ decays
….

SUSY
Extra dimensions
Little Higgs
Twin Higgs doublet
…..
Seesaw?

Gauge couplings unification
Flavor symmetry
SO(10), SU(5)…

naturalness

testability

Type-I +II seesaw model: SM+3 N_R+ 1Δ_L

$$-\mathcal{L}_{\rm lepton} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2}\overline{N^c_{\rm R}} M_{\rm R} N_{\rm R} + \frac{1}{2}\overline{l_{\rm L}} Y_\Delta \Delta i\sigma_2 l^c_{\rm L} + {\rm h.c.}$$

$$-\mathcal{L}_{\rm mass} = \overline{e_{\rm L}} M_l E_{\rm R} + \frac{1}{2}\overline{(\nu_{\rm L} \quad N^c_{\rm R})} \begin{pmatrix} M_{\rm L} & M_{\rm D} \\ M^T_{\rm D} & M_{\rm R} \end{pmatrix} \begin{pmatrix} \nu^c_{\rm L} \\ N_{\rm R} \end{pmatrix} + {\rm h.c.}$$

$$M_\nu = v_\Delta Y_\Delta - M_D M_R^{-1} M_D^T$$

$$v_\Delta = \lambda_\xi v^2 / M_\xi \;, \quad v = \sqrt{\mu^2/(\lambda - 2\lambda^2_\xi)}$$

$$V(H,\Delta) = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \frac{1}{2} M^2_\xi {\rm Tr}\left(\Delta^\dagger \Delta\right) - \left[\lambda_\xi M_\xi H^T i\sigma_2 \Delta H + {\rm h.c.}\right]$$

Seven Higgs bosons : doubly charged Higgs bosons $\Delta^{++}$and Δ^{--}; singly charged Higgs bosons δ^{+} and δ^{-}; CP-odd A^0; CP-even H^0 ; SM Higgs h^0.

Higgs sector in detail:

$$H \equiv \begin{pmatrix} \varphi^+ \\ (\varphi_1 + i\varphi_2)/\sqrt{2} \end{pmatrix} ,$$

$$\Delta = \begin{pmatrix} \xi^- & -\xi_1 - i\xi_2 \\ \sqrt{2}\xi^{--} & -\xi^- \end{pmatrix} .$$

$$\begin{aligned} \Delta^{++} &= \xi^{++} \\ \delta^+ &= c_\theta \xi^+ + s_\theta \varphi^+ \approx \xi^+ + \kappa\varphi^+ \\ A^0 &= c_\theta \xi_2 + s_\theta \varphi \approx \xi_2 + \kappa\varphi_2 \\ H^0 &= c_\alpha \xi_1 - s_\alpha \varphi_1 \\ h^0 &= s_\alpha \xi_1 + c_\alpha \varphi_1 \end{aligned}$$

$$M^2_{\Delta^{\pm\pm}} = M^2_\Delta , \quad M^2_{\delta^\pm} = M^2_\Delta (1+\kappa^2) , \quad M^2_{A^0} = M^2_\Delta (1+2\kappa^2) , \quad M^2_{H^0} = M^2_\xi \left(c^2_\alpha + s^2_\alpha \varrho^2 + 2\sqrt{2} s_\alpha c_\alpha \kappa \right)$$

$$\tan\theta = \kappa , \quad \tan 2\alpha = 2\sqrt{2}\kappa/(1-\rho^2) , \quad \kappa = \sqrt{2} v_\Delta / v , \quad \rho = \sqrt{2}/M_\xi .$$

Constraints from EW precision data:

$$M^2_{h^0} = M^2_\xi \left(c^2_\alpha \varrho^2 + s^2_\alpha - 2\sqrt{2} s_\alpha c_\alpha \kappa \right)$$

$$M^2_W = \frac{1}{4} g^2_2 \left(v^2 + 2v^2_\xi \right) , \quad M^2_Z = \frac{1}{4} \left(g^2_1 + g^2_2 \right) \left(v^2 + 4v^2_\xi \right)$$

$$\rho \equiv \frac{M^2_W}{M^2_Z \cos^2\theta_W} = \frac{v^2 + 2v^2_\xi}{v^2 + 4v^2_\xi} , \qquad \rho = 1.0002^{+0.0007}_{-0.0004} \qquad \Longrightarrow \qquad \frac{v_\xi}{v} \lesssim 0.01$$

Neutrino sector:

Diagonalization (flavor basis $\Rightarrow$ mass basis):

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

$$V^{\dagger}V + S^{\dagger}S = VV^{\dagger} + RR^{\dagger} = 1$$

$$\nu_L = V\hat{\nu}_i + R\hat{N}_i$$

V is not unitary

$$R \approx M_{\rm D} / M_{\rm R}$$

$$V \approx \left(1 - \frac{1}{2}RR^{\dagger}\right) V_{\rm unitary}$$

The interactions of heavy Majorana neutrinos with SM particles:

$$\begin{aligned}
\mathcal{L}_{\rm W} &= -\frac{g}{\sqrt{2}}\overline{l_{\rm L}}R\gamma^{\mu}P_L N_i W_{\mu}^{-} + \text{h.c.} \ , \\
\mathcal{L}_{\rm Z} &= -\frac{g}{2c_{\rm W}}\overline{\nu_{\rm L}}R\gamma^{\mu}P_L N_i Z_{\mu} + \text{h.c.} \ , \\
\mathcal{L}_{\rm H} &= -\frac{g}{2}\frac{M_i}{M_{\rm W}}\overline{\nu_{\rm L}}RP_R N_i h^0 + \text{h.c.} \ .
\end{aligned}$$

A TeV-scale type-I+II seesaw scenario

- N_R and Δ are O(1) TeV or close to the EW scale.
- M_D is O(10) GeV to generate large UV and LNV signatures for N.
- M_L is O(1) GeV to generate large LNV signatures for Δ.

$$M_\nu = M_L - M_D M_R^{-1} M_D^T = Y_\Delta v_\Delta - v^2 Y_\nu M_R^{-1} Y_\nu^T \approx 0$$

1 GeV

10 GeV

100GeV

O(1)

O(1)

$$Y_\Delta = \frac{R \widehat{M}_{\mathrm{N}} R^T}{v_\Delta}$$

Some questions:

- How to generate small but non-zero neutrino masses?
- Does this model conflict with EW precision measurement?
- What about the collider signatures of N_R and Δ ?

① Neutrino masses

Discrete flavor symmetry can be used to guarantee the "structure cancellation" ---- Chao, Luo, Xing and Zhou PRD 08

Small neutrino masses can be generated from slight deviation from this complete "structure cancellation"

The relevant perturbation parameters are mainly responsible for those neutrino masses and contribute little to possible collider signatures ---- decoupling between collider physics and the neutrino mass generation.

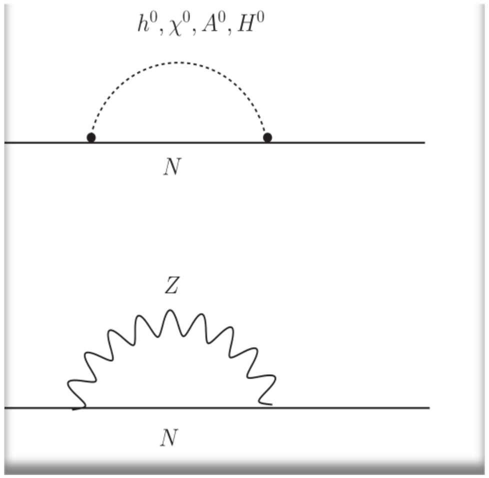
Dangerous radiative corrections

$$\delta M_I = \frac{\alpha_w}{16\pi M_W^2} R_{ik} M_k R^T_{kj} \left[M_k^2 F(M_k^2, M_Z^2) - M_k^2 F(M_k^2, M_{h^0}^2) - 4 M_Z^2 F(M_k^2, M_Z^2) \right]$$

$$\delta M_L = -\frac{1}{32\pi^2} (Y_\Delta R^*)_{ik} M_k (R^\dagger Y_\Delta)_{kj} \left[c_\alpha^2 F(M_k^2, M_{H^0}^2) - c_\theta^2 F(M_k^2, M_{A^0}^2) \right]$$

$$M_\nu = M_L - M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T + \delta M_L + \delta M_I \approx M_L(1 - \delta_{II}) - M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T (1 - \delta_I)$$

$$\delta_{II} \ll \delta_I \precsim 10^{-3} \quad \Rightarrow \quad (Y_\Delta)_{\alpha\beta} = \frac{(M_{\rm L})_{\alpha\beta}}{v_\Delta} \approx \sum_{i=1}^{3} \frac{R_{\alpha i} R_{\beta i} M_i}{v_\Delta}$$



②EW precision measurement constraint--- $(g-2)_\mu$

The current experimental data

E821 - Final Report: hep-ex/0602035

$$a_\mu^{\rm exp} = (11659208 \pm 6) \times 10^{-10}$$

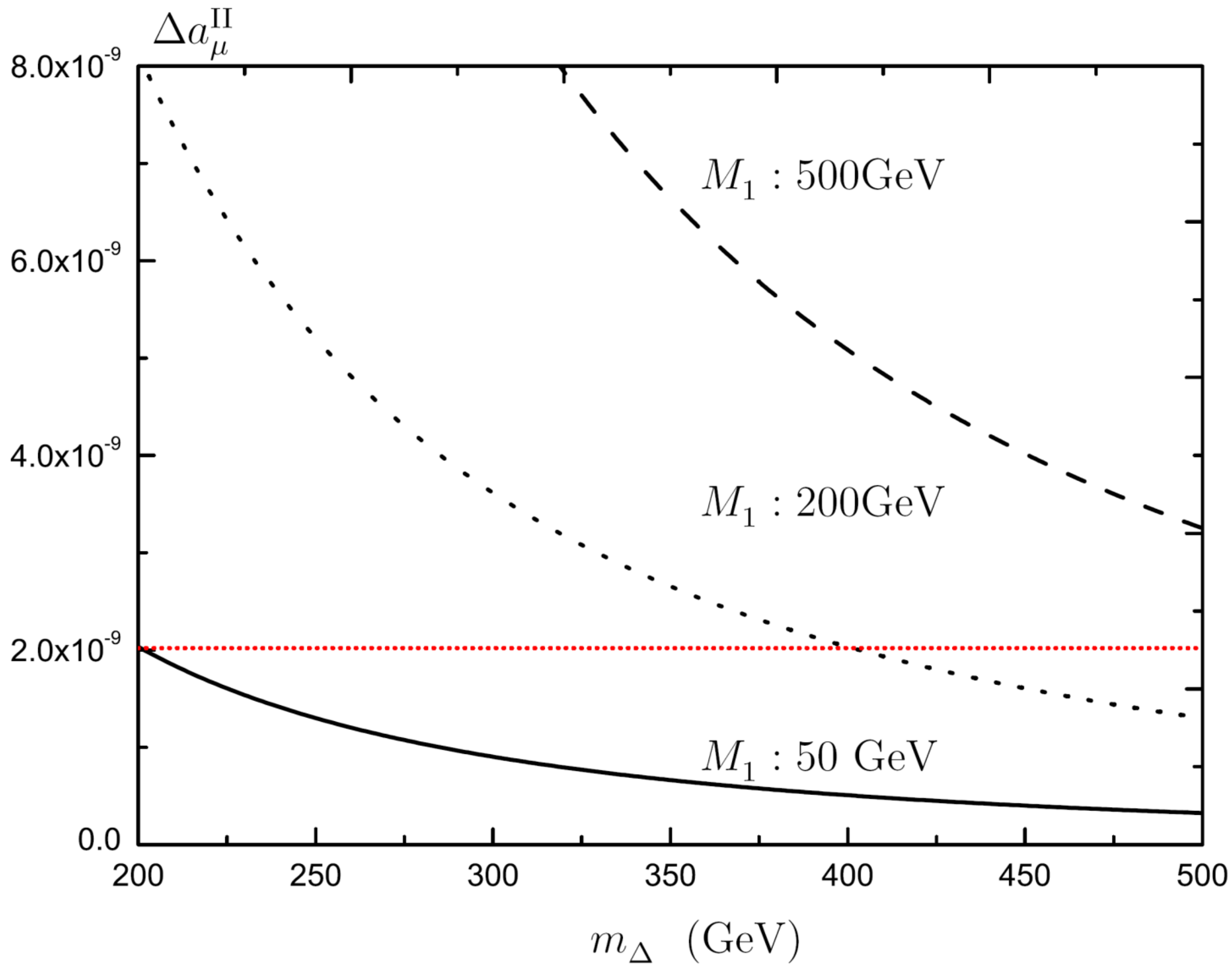
$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 22(10) \times 10^{-10}$$

Heavy neutrinos, doubly and singly charged Higgs contribute to g-2

$$\begin{aligned}
a_\mu^N &= \frac{G_{\rm F} m_\mu^2}{8\sqrt{2}\pi^2} \sum_i R_{\mu i} R_{i\mu}^\dagger \left[I\left(M_{\rm W}^2, M_i^2\right) - 10/3 \right] \ , \\
a_\mu^\Delta &= \frac{1}{16\pi^2} \sum_{\alpha=e,\mu,\tau} |(Y_\Delta)_{\mu\alpha}|^2 \left[I_1(m_\alpha^2, m_\Delta^2) + I_2(m_\alpha^2, m_\Delta^2) \right] \ , \\
a_\mu^\delta &= \frac{1}{16\pi^2} \sum_\alpha |(Y_\Delta)_{\mu\alpha}|^2 (VV^\dagger)_{\alpha\alpha} I_3(m_\mu^2, m_\delta^2) \ ,
\end{aligned}$$

$$\Delta a_\mu = a_\mu^\Delta + a_\mu^\delta + a_\mu^N .$$

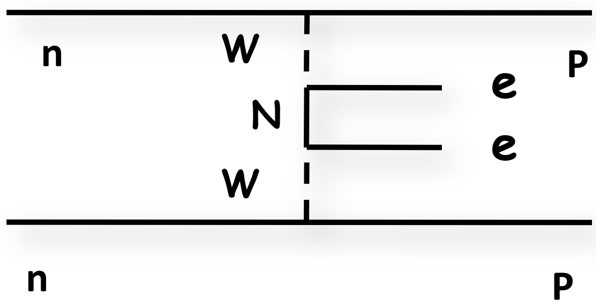
For details, see, Chao, arXiv:0806.0889

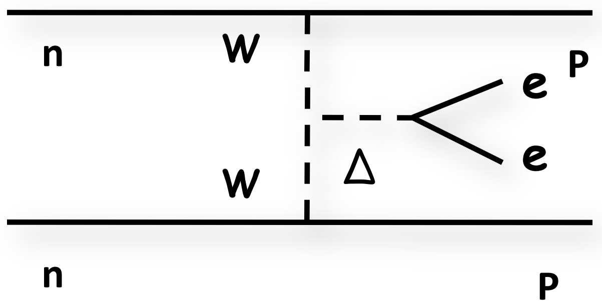


A. R_{ei}~0, $R_{\mu i}$~ $R_{\tau i}$~0.1 in our chosen parameter space.
B. Δa_μ is proportional to M_N.
C. Given 200 GeV < M_Δ< 500 GeV, the upper bound for M_N is 310.5 GeV.

③ EW precision measurement constraint---LNV

I. Neutrinoless double beta decay





$$\left|\sum_i R_{ei}^2/M_i + (M_\mathrm{L})_{ee}/M_\xi^2\right| < 5\times 10^{-8} \quad \mathrm{GeV}^{-1}$$

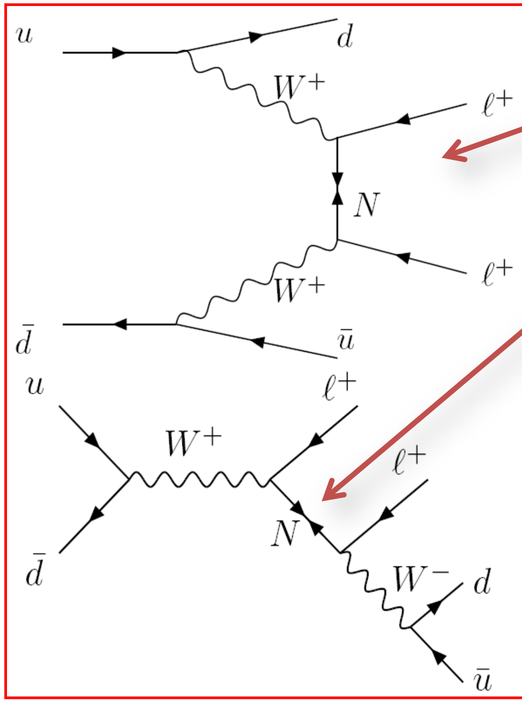
II. LNV rare meson decays $M \longrightarrow M' + l_\alpha + l_\beta$

$$\Gamma_{\alpha\beta} = \frac{G_\mathrm{F}^4 m_M^7}{128\pi^3} f_M^2 f_{M'}^2 |K_V|^2 \langle R_{\alpha i}R_{\beta i}/M_i + (M_\mathrm{L})_{\alpha\beta}/M_\xi^2\rangle^2 \Phi_{\alpha\beta}$$

Constraints from LNV decays of mesons

Decay modes	Experimental constraints	$\Phi_{\alpha\beta}$	$\langle R_{\alpha i}R_{\beta i}/M_i + (M_{\rm L})_{\alpha\beta}/M_\xi^2\rangle$ GeV^{-1}
$B^+ \to \pi^- e^+ e^+$	1.6×10^{-6}	0.0499	3.82×10^4
$B^+ \to \pi^- \mu^+ \mu^+$	1.4×10^{-6}	0.0495	3.58×10^4
$B^+ \to \pi^- e^+ \mu^+$	1.3×10^{-6}	0.0995	2.43×10^4
$B^+ \to K^- e^+ e^+$	1.0×10^{-6}	0.0491	1.07×10^5
$B^+ \to K^- \mu^+ \mu^+$	1.8×10^{-6}	0.0487	1.43×10^5
$B^+ \to K^- e^+ \mu^+$	2.0×10^{-6}	0.0977	1.07×10^5
$D^+ \to \pi^- e^+ e^+$	3.6×10^{-6}	0.0494	4.53×10^4
$D^+ \to \pi^- \mu^+ \mu^+$	4.8×10^{-6}	0.0464	5.39×10^4
$D^+ \to \pi^- e^+ \mu^+$	5.0×10^{-5}	0.0957	1.21×10^5
$D^+ \to K^- e^+ e^+$	4.5×10^{-6}	0.0394	5.17×10^4
$D^+ \to K^- \mu^+ \mu^+$	1.3×10^{-5}	0.0365	9.14×10^4
$D^+ \to K^- e^+ \mu^+$	1.3×10^{-4}	0.0758	2.00×10^5
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	0.0377	8.00×10^2
$K^+ \to \pi^- \mu^+ \mu^+$	3.0×10^{-9}	0.0108	3.40×10^3
$K^+ \to \pi^- e^+ \mu^+$	5.0×10^{-10}	0.0367	8.00×10^2

④ Signatures of N and Δ at the LHC

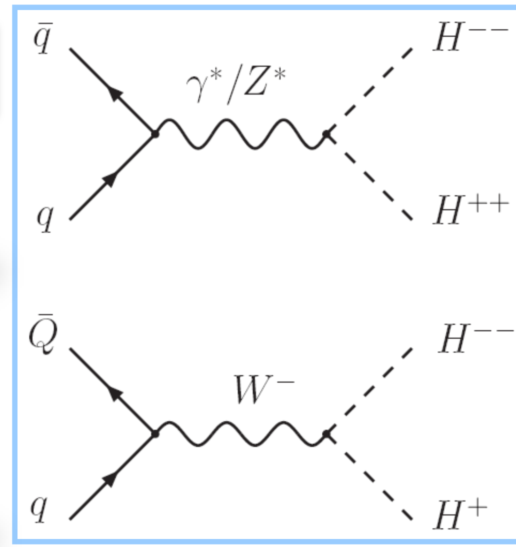


σ∝ $|R|^4$, highly suppressed

σ ∝ $|R|^2$ ·BR, N Produced on resonance

$$\sigma(pp \to l_\alpha^+ l_\beta^+ W^- X) \approx \sigma_N \cdot \frac{|R_{\alpha 1}|^2 |R_{\beta 1}|^2}{4 \sum_\gamma |R_{\gamma 1}|^2}$$

$$\sigma(pp \to l_\alpha^+ N_1 X)/|R_{\alpha 1}|^2$$



$$\sigma(pp \to l_\alpha^+ l_\beta^+ H^- X) = \sigma_H \cdot \mathrm{Br}(H^{++} \to l_\alpha^+ l_\beta^+),$$

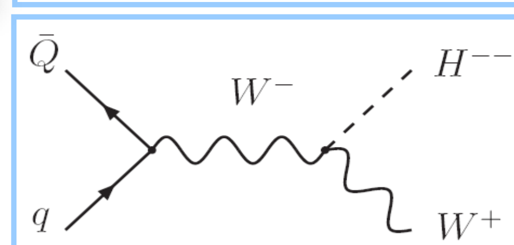
$$\sigma(pp \to l_\alpha^+ l_\beta^+ W^- X) = \sigma_W \cdot \mathrm{Br}(H^{++} \to l_\alpha^+ l_\beta^+),$$

$$\sigma(pp \to l_\alpha^+ l_\beta^+ H^{--} X) = \sigma_{\mathrm{pair}} \cdot \mathrm{Br}(H^{++} \to l_\alpha^+ l_\beta^+),$$

$$\sigma_{\mathrm{pair}} \equiv \sigma(pp \to H^{++} H^{--} X)$$

$$\sigma_H \equiv \sigma(pp \to H^{++} H^- X)$$

$$\sigma_W \equiv \sigma(pp \to H^{++} W^- X)$$



Numerical results (A minimal case with only 1 N and 1 Δ)

Gu, Zhang and Zhou PRD 06

3·1 complex matrix R can be parameterized by 3 rotation angles and 3 phases ---Xing, PLB 2008

$$R = \begin{pmatrix} s_{14}^* \\ c_{14} s_{24}^* \\ c_{14} c_{24} s_{34}^* \end{pmatrix} = \begin{pmatrix} s_{14}^* \\ s_{24}^* \\ s_{34}^* \end{pmatrix} + \mathcal{O}\left(s_{ij}^3\right)$$

A typical input : s_{14} =0, s_{24}=s_{34}=0.1

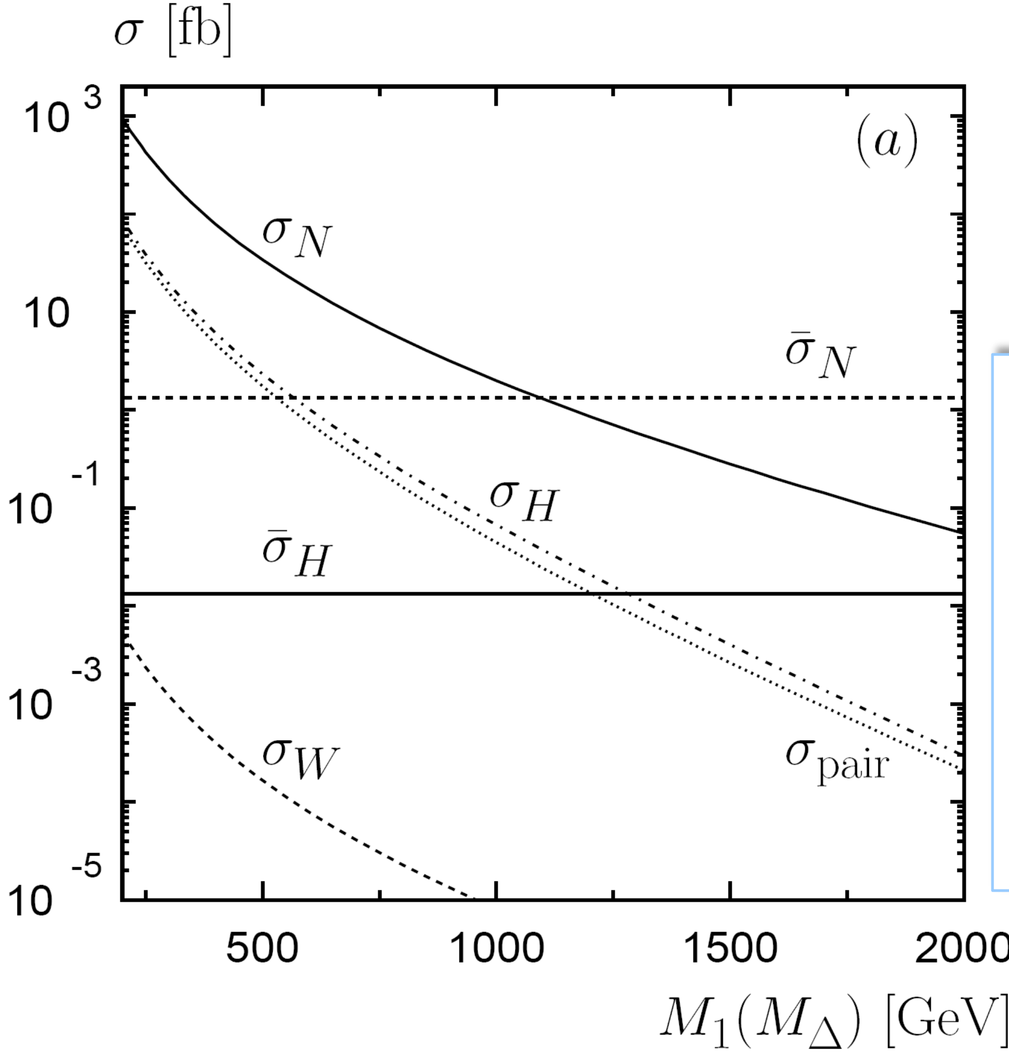
$$|RR^\dagger| = \begin{pmatrix} s_{14}^2 < 1.1\times10^{-2} & s_{14}s_{24} < 7.0\times10^{-5} & s_{14}s_{34} < 1.6\times10^{-2} \\ s_{14}s_{24} < 7.0\times10^{-5} & s_{24}^2 < 1.0\times10^{-2} & s_{24}s_{34} < 1.0\times10^{-2} \\ s_{14}s_{34} < 1.6\times10^{-2} & s_{24}s_{34} < 1.0\times10^{-2} & s_{34}^2 < 1.0\times10^{-2} \end{pmatrix}$$

Antush, et al JHEP 06

$$\Gamma(H^{\pm\pm} \to l_\alpha^\pm l_\beta^\pm) = \frac{M_1^2 M_\Delta}{8\pi(1+\delta_{\alpha\beta})v_\Delta^2} |R_{\alpha 1}|^2 |R_{\beta 1}|^2$$

$$\mathrm{Br}(H^{\pm\pm} \to \mu^\pm\mu^\pm) \approx \frac{s_{24}^4}{(s_{24}^2 + s_{34}^2)^2} ,$$

$$\mathrm{Br}(H^{\pm\pm} \to \mu^\pm\tau^\pm) \approx \frac{2 s_{24}^2 s_{34}^2}{(s_{24}^2 + s_{34}^2)^2} ,$$

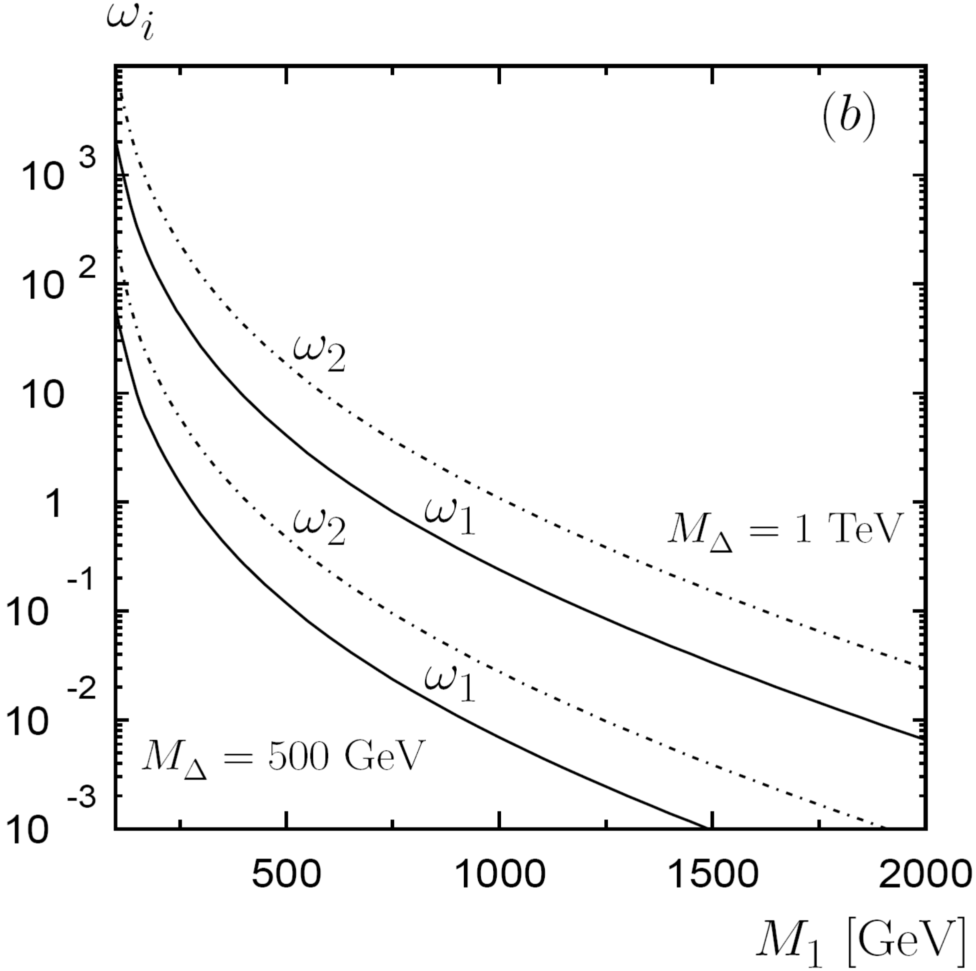


- σ_W is too tiny.
- Single production is larger.
- Ratio of σ_H and σ_{pair} lies in the range [1.1, 1.6].
- Δ should be observed up to 1.2 TeV.
- N should be observed up to 1.1 TeV.

$$\bar\sigma_{N(H)} = \frac{1 \text{ event}}{300 \text{ fb}^{-1}} \frac{1}{B_{N(H)}},$$

$$B_N = \frac{|R_{\alpha 1}|^2 |R_{\beta 1}|^2}{4\sum_\gamma |R_{\gamma 1}|^2}, \qquad B_H = \mathrm{Br}(H^{++} \to \mu^+\mu^+).$$

Correlative signatures of N and Δ



$$\omega_1 \equiv \frac{\sigma(pp \to \mu^+\mu^+W^-X)|_{N_1}}{\sigma(pp \to \mu^+\mu^+H^-X)|_{H^{++}}},$$

$$\omega_2 \equiv \frac{\sigma(pp \to \mu^+\mu^+W^-X)|_{N_1}}{\sigma(pp \to \mu^+\mu^+H^{--}X)|_{H^{++}}}$$

$$\omega_1 \approx \sigma_N(s_{24}^2 + s_{34}^2)/(4\sigma_H)$$

$$\omega_2 \approx \sigma_N(s_{24}^2 + s_{34}^2)/(4\sigma_{\text{pair}})$$

Concluding remarks

- A testable TeV-scale type-I+II seesaw scenario is proposed.
- Constraints from EW precision measurement are considered.
- Collider signatures are discussed.
- Further work is necessary to distinguish LNV signatures of N from those of Δ.

Thank you