Collider signals for a Universal Seesaw Model

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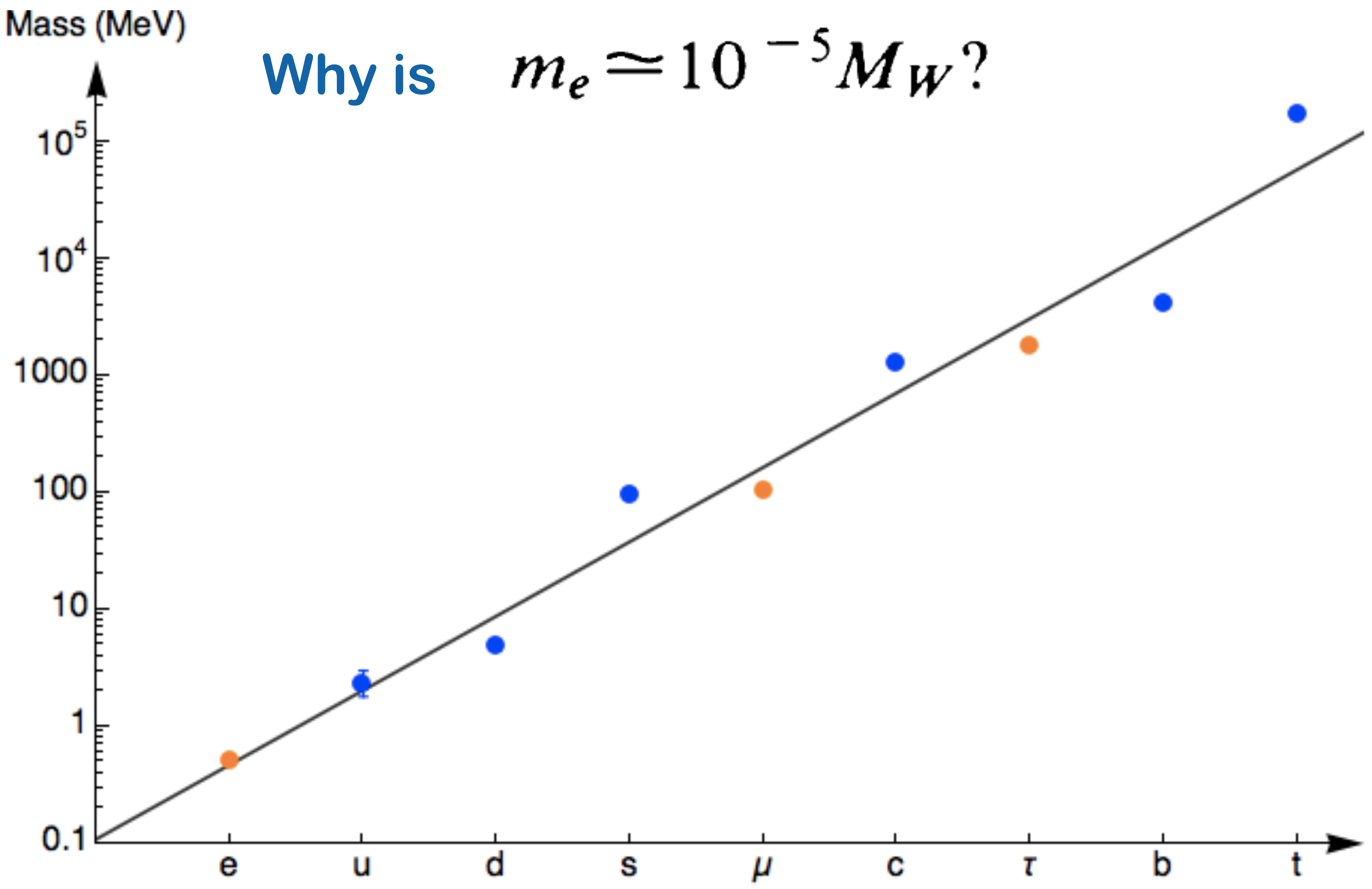
Overview

- **Fermion mass hierarchy in SM leads to a huge spread in the Yukawa coupling values.**

$$\mathscr{L} \sim Y_{ij}\, \bar{f}_{iL}\, \phi\, f_{jR}$$

- **Still a puzzle that drives several BSM ideas….**

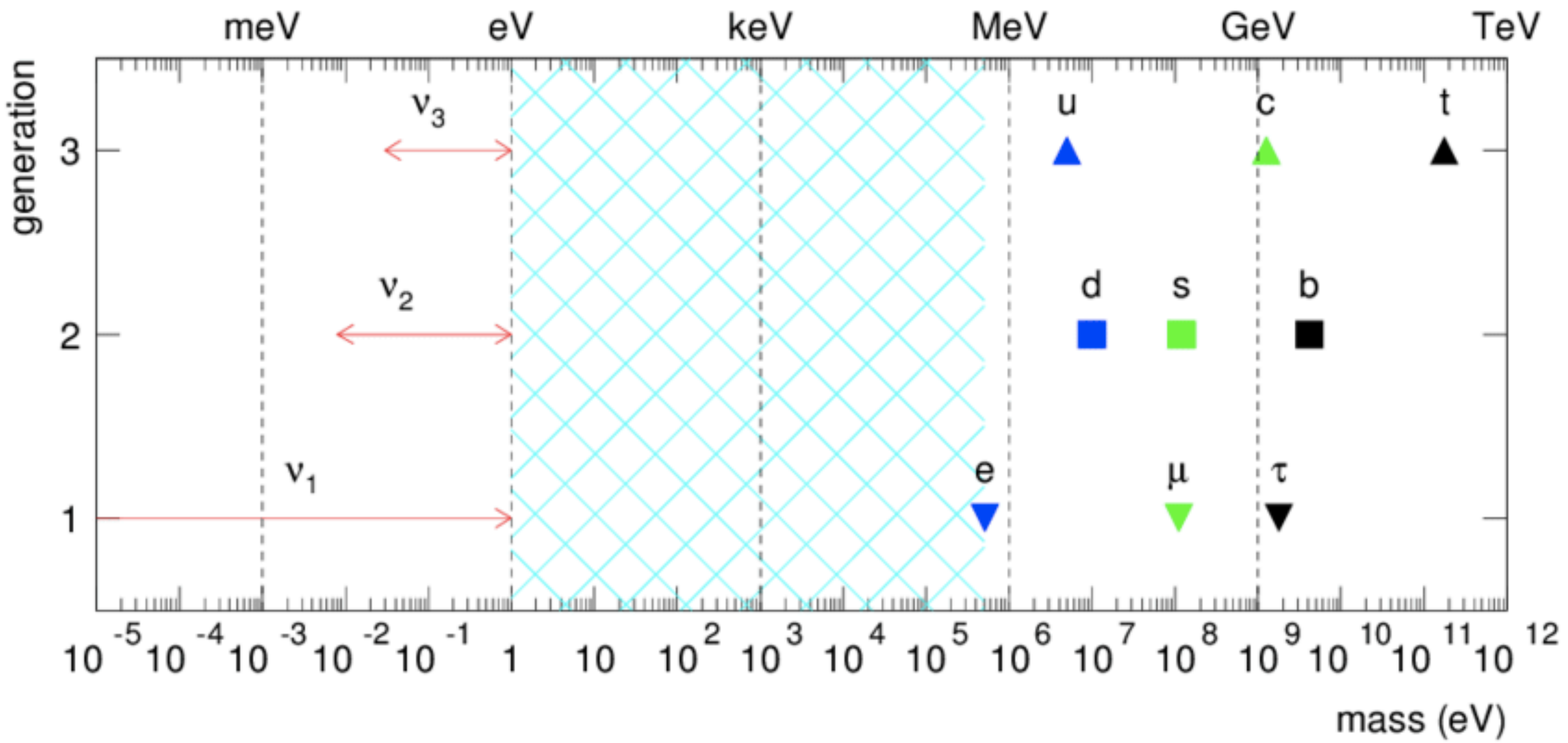
Why is $m_e \simeq 10^{-5} M_W$?



- Neutrinos were happy to be massless in SM but not experimentally.
- Simplest extension would be to add a right-handed singlet (ν_R) like all SM fermions, for them to get mass.
- Introduces a bigger spread in Yukawa couplings $Y_\nu \sim 10^{-11}$ - $Y_t \sim 1$

$$m_{\nu_e} \lesssim 10^{-5} m_e$$

$$\mathscr{L} \sim Y_{\nu_{ij}} \bar{\ell}_{iL} \phi \nu_{jR}$$



- Simply adding the singlet is not very interesting phenomenologically.
- Seesaw mechanisms of tiny neutrino mass generation spiced up matters

$$\mathscr{L} \sim Y_{\nu_{ij}}\ \bar{\ell}_{iL}\ \phi\ \nu_{jR} + \frac{1}{2}\ \overline{\nu^c}_{iR}\ M_{ij}\ \nu_{jR}$$

- Seesaw seen in many avatars with $Y_\nu \sim 10^{-10} - \mathcal{O}(1)$
- New exotic scalars and fermions led to rich phenomenology
- Can we reverse the narration for all fermion masses? Seesaw for all fermion masses?

Berezhiani PLB (1983), Davidson, Wali PRL (1987, 1988)
Chang, Mohapatra PRL (1987), Babu, Mohapatra PRL (1989)

- Universal seesaw models based on $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ gauge symmetries - add VL singlet fermions and scalar doublets

Minimal?

Berezhiani PLB (1983), Davidson, Wali PRL (1987, 1988)
Chang, Mohapatra PRL (1987), Babu, Mohapatra PRL (1989)

$$\mathcal{Q}_{L,i}\left(3,2,1,+\frac{1}{3}\right)=\begin{pmatrix}u_L\\ d_L\end{pmatrix}_i,\quad \mathcal{Q}_{R,i}\left(3,1,2,+\frac{1}{3}\right)=\begin{pmatrix}u_R\\ d_R\end{pmatrix}_i,\qquad U_a\left(3,1,1,+\frac{4}{3}\right),\quad D_a\left(3,1,1,-\frac{2}{3}\right)$$

$$\psi_{L,i}\left(1,2,1,-1\right)=\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}_i,\qquad \psi_{R,i}\left(1,1,2,-1\right)=\begin{pmatrix}\nu_R\\ e_R\end{pmatrix}_i.\qquad E_a\left(1,1,1,-2\right),\quad N_a\left(1,1,1,0\right)$$

Higgs sector $$\chi_L\left(1,2,1,+1\right)=\begin{pmatrix}\chi_L^+\\ \chi_L^0\end{pmatrix},\quad \chi_R\left(1,1,2,+1\right)=\begin{pmatrix}\chi_R^+\\ \chi_R^0\end{pmatrix}$$

$$\mathscr{L}_Y \sim Y_F \overline{D}_F\, \chi\, F + M_F\, \overline{F} F$$

generic seesaw type mass relations: $$m_{q_a} \simeq \frac{Y_a^2 v_L v_R}{2M_a}\,.$$

v_L, v_R fixed!
trade off
$Y_a \leftrightarrow M_a$?

- Inherits all the good things of left-right symmetry models:

  Parity symmetry, no strong CP problem, naturally generates light neutrino mass

- Seesaw mechanism is extended to the charged fermion sector
- No need for a more exotic triplet scalar sector
- Yukawa couplings range can be much smaller $Y_\nu \sim 10^{-3} - \mathcal{O}(1)$
- We focus on a lepton specific universal seesaw model based on

$$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

A. Patra, S.K. Rai, 1711.00627

MODEL AND LAGRANGIAN

- Quarks and leptons are all doublets $Q_{L/R}$, $l_{L/R}$
- Higgs doublets under $SU(2)_L$, $SU(2)_R$:

  for leptons $H_{l_L L}, H_{l_R R}$ and for quarks $H_{Q_L L}, H_{Q_R R}$

- No bidoublet - new fermion singlets are needed to generate their masses

  Fermion singlet leptons $E_{L/R}, N_{L/R}$ and singlet quarks $U_{L/R}, D_{L/R}$

- A discrete symmetry to prevent $H_{l_L L}, H_{l_R R}$ from coupling to quarks

All fermions get their masses through seesaw mechanism.

Field	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	Z_2
$Q_{L(R)} = \begin{pmatrix} u \\ d \end{pmatrix}_{L(R)}$	3	2 (1)	1 (2)	$\frac{1}{3}$	+
$l_{L(R)} = \begin{pmatrix} \nu \\ e \end{pmatrix}_{L(R)}$	1	2 (1)	1 (2)	-1	+
U_L, U_R	3	1	1	$\frac{4}{3}$	+
D_L, D_R	3	1	1	$-\frac{2}{3}$	+
E_L, E_R	1	1	1	-2	-
N_L, N_R	1	1	1	0	-
$H_{L(R)Q} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}_{L(R)Q}$	1	2 (1)	1 (2)	1	+
$H_{L(R)l} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}_{L(R)l}$	1	2 (1)	1 (2)	1	-

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

$$\frac{Y}{2} = T_{3R} + \frac{B-L}{2}$$

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Non-zero VEVs are given as

$$\langle H^0_{RQ} \rangle = v_{RQ}, \ \langle H^0_{Rl} \rangle = v_{Rl}, \ \langle H^0_{LQ} \rangle = v_{LQ}, \ \langle H^0_{Ll} \rangle = v_{Ll}$$

with $v_{RQ}, v_{Rl} >> v_{LQ} > v_{Ll}$.

v_{RQ}, v_{Rl} responsible for $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$.

v_{LQ}, v_{Ll} breaks EW symmetry.

Charged gauge boson masses

$$v_{LQ}^2 + v_{Ll}^2 = v_{\rm EW}^2.$$

$$M^2_{W_R^\pm} = \frac{1}{2} g_R^2 (v_{RQ}^2 + v_{Rl}^2), \quad M^2_{W^\pm} = \frac{1}{2} g_L^2 (v_{LQ}^2 + v_{Ll}^2).$$

Neutral gauge boson masses

$v_{RQ}, v_{Rl} >> v_{LQ} > v_{Ll}$

$$M_Z^2 \simeq \frac{1}{2}(g_L^2 + g_Y^2)(v_{LQ}^2 + v_{Ll}^2)$$

$$M_{Z_R}^2 \simeq \frac{1}{2}\left[(g_R^2 + g_V^2)(v_{RQ}^2 + v_{Rl}^2) + \frac{g_V^4(v_{LQ}^2 + v_{Ll}^2)}{g_R^2 + g_V^2}\right]$$

where $g_Y = \frac{g_L g_V}{\sqrt{g_L^2 + g_V^2}}.$

effective SM $U(1)_Y$ gauge coupling

$$\begin{bmatrix} \frac{1}{4}g_R^2(v_{RQ}^2 + v_{Rl}^2) & 0 & -\frac{1}{4}g_R g_V(v_{RQ}^2 + v_{Rl}^2) \\ 0 & \frac{1}{4}g_L^2(v_{LQ}^2 + v_{Ll}^2) & -\frac{1}{4}g_L g_V(v_{LQ}^2 + v_{Ll}^2) \\ -\frac{1}{4}g_L g_V(v_{LQ}^2 + v_{Ll}^2) & -\frac{1}{4}g_R g_V(v_{RQ}^2 + v_{Rl}^2) & \frac{1}{4}g_V^2(v_{RQ}^2 + v_{Rl}^2 + v_{LQ}^2 + v_{Ll}^2) \end{bmatrix}.$$

The Yukawa Lagrangian is given as $(\widetilde{H}_{L/R} = i\tau_2 H^*_{L/R})$

$$
\begin{aligned}
\mathscr{L}_Y \quad = \quad & \Big(Y_{uL}\overline{Q}_L \widetilde{H}_{LQ} U_R + Y_{uR}\overline{Q}_R \widetilde{H}_{RQ} U_L + Y_{dL}\overline{Q}_L H_{LQ} D_R + Y_{dR}\overline{Q}_R H_{RQ} D_L \\
+ \quad & Y_{\nu L}\bar{l}_L \widetilde{H}_{Ll} N_R + Y_{\nu R}\bar{l}_R \widetilde{H}_{Rl} N_L + Y_{eL}\bar{l}_L H_{Ll} E_R + Y_{eR}\bar{l}_R H_{Rl} E_L \\
+ \quad & M_U \overline{U}_L U_R + M_D \overline{D}_L D_R + M_E \overline{E}_L E_R + M_N \overline{N}_L N_R + h.c.\Big) \\
+ \quad & \boxed{M_L N_L^T C N_L + M_R N_R^T C N_R}
\end{aligned}
$$

↑

Majorana mass

Seesaw and fermion masses

Quark and charged lepton masses arise through Type-I seesaw like matrix.

$$\mathcal{L}_u = (\bar{u} \;\; \bar{U})(M_u P_L + M_u^T P_R)\begin{pmatrix} u \\ U \end{pmatrix}$$

These are 6X6 matrices

Quark mass : $M_u = \begin{pmatrix} 0 & Y_{uR} v_{RQ} \\ Y_{uL}^T v_{LQ} & M_U \end{pmatrix}$

bi-unitary transformation

$M_u^{diag} = U_{uL} M_u U_{uR}^\dagger, \quad U_L^{CKM} = U_{uL} U_{dL}^\dagger.$

$V_R^{CKM} = U_{uR} U_{dR}^\dagger$

- Y_{uR} and Y_{uL} are kept diagonal, CKM are generated with off-diagonal Y_{dL}.

Charged lepton mass : $M_e = \begin{pmatrix} 0 & Y_{eR} v_{Rl} \\ Y_{eL}^T v_{Ll} & M_E \end{pmatrix}$

- $Y_{e(L/R)}$ are diagonal.

Neutrino mass matrix in the basis $(\nu_L^*, N_R, \nu_R, N_L^*)$

$$\begin{pmatrix} 0 & Y_{\nu L} v_{Ll} & 0 & 0 \\ Y_{\nu L}^T v_{Ll} & M_R & 0 & M_N^T \\ 0 & 0 & 0 & Y_{\nu R}^T v_{Rl} \\ 0 & M_N & Y_{\nu R} v_{Rl} & M_L \end{pmatrix}$$

- $Y_{\nu R}$ is diagonal, symmetric off-diagonal $Y_{\nu L}$ generates Pontecorvo-Maka-Nakagawa-Sakata (PMNS) mixing matrix.

Depending on M_N two possible cases

Small mixing

1. Majorana case with $M_N \neq 0$: 3 light neutrinos satisfying mass-squared relations and PMNS mixings, 3 neutrinos in the EW breaking scale, 6 heavy neutrinos of TeV scale.
2. Pseudo-Dirac case with $M_N = 0$: Pseudo-Dirac like 3 light neutrinos, 3 heavy neutrinos.

The scalar potential is

$$V(H)=\sum_{i=1}^{4}\mu_{ii}H_i^\dagger H_i+\sum_{\substack{i,j=1\\ i\le j}}^{4}\lambda_{ij}H_i^\dagger H_i H_j^\dagger H_j+\left(\alpha_1 H_{LQ}^\dagger H_{Ll}H_{RQ}^\dagger H_{Rl}\right.$$

$$\left.+\alpha_2 H_{LQ}^\dagger H_{Ll}H_{Rl}^\dagger H_{RQ}+\mu_{12}^2 H_{LQ}^\dagger H_{Ll}+\mu_{34}^2 H_{RQ}^\dagger H_{Rl}+H.C.\right)$$

where $H_1 = H_{LQ}$, $H_2 = H_{Ll}$, $H_3 = H_{RQ}$, $H_4 = H_{Rl}$.

- The Higgs boson spectrum consists of four CP-even states, two CP-odd states, and two charged Higgs bosons..

The terms μ_{12} and μ_{34} break the discrete Z_2 symmetry softly

Snapshot of the Higgs composition

Particle	Mass (GeV)	Eigenstate
H_1	125.5	$0.996\ \mathrm{Re}(H^0_{LQ}) - 0.010\ \mathrm{Re}(H^0_{RQ}) + 0.080\ \mathrm{Re}(H^0_{Ll}) + 0.027\ \mathrm{Re}(H^0_{Rl})$
H_2	2543.9	$-0.0289\ \mathrm{Re}(H^0_{LQ}) - 0.381\ \mathrm{Re}(H^0_{RQ}) + 0.001\ \mathrm{Re}(H^0_{Ll}) + 0.924\ \mathrm{Re}(H^0_{Rl})$
H_3	4229.0	$0.001\ \mathrm{Re}(H^0_{LQ}) - 0.924\ \mathrm{Re}(H^0_{RQ}) + 0.005\ \mathrm{Re}(H^0_{Ll}) - 0.381\ \mathrm{Re}(H^0_{Rl})$
H_4	7127.5	$0.080\ \mathrm{Re}(H^0_{LQ}) - 0.005\ \mathrm{Re}(H^0_{RQ}) - 0.997\ \mathrm{Re}(H^0_{Ll}) + 0.003\ \mathrm{Re}(H^0_{Rl})$
A_1	217.0	$0.001\ \mathrm{Im}(H^0_{LQ}) - 0.707\ \mathrm{Im}(H^0_{RQ}) - 0.008\ \mathrm{Im}(H^0_{Ll}) + 0.707\ \mathrm{Im}(H^0_{Rl})$
A_2	7127.7	$-0.080\ \mathrm{Im}(H^0_{LQ}) - 0.006\ \mathrm{Im}(H^0_{RQ}) + 0.997\ \mathrm{Im}(H^0_{Ll}) + 0.006\ \mathrm{Im}(H^0_{Rl})$
H_1^+	225.8	$-0.707 H^+_{RQ} + 0.707 H^+_{Rl}$
H_2^+	7127.5	$0.080 H^+_{LQ} - 0.997 H^+_{Ll}$

← lighter $H^\pm$ → V_R^{CKM}

$$\alpha_1 = -0.3,\ \alpha_2 = 0.1,\ \lambda_{11} = 0.172,\ \lambda_{12} = 0.8,\ \lambda_{13} = 0.05,\ \lambda_{14} = -0.1,\ \lambda_{22} = 0.5,\ \lambda_{23} = 0.1,$$
$$\lambda_{24} = 0.1,\ \lambda_{33} = 0.2,\ \lambda_{34} = 0.1,\ \lambda_{44} = 0.1,\ \mu_{12}^2 = 2.5\times10^4,\ \mu_{34}^2 = 2.5\times10^4$$

Unlike SM Yukawa couplings range can be much smaller, here from 10^{-3} to 1.

Up-type Quark (TeV)	Down-type Quark (TeV)	Charged Lepton (TeV)	Neutrino (GeV)	Neutrino (TeV)
$m_U = 11.94$, $m_C = 11.96$, $m_T = 30.0$	$m_D = 16.0$, $m_S = 20.1$, $m_B = 30.0$	$m_{E_1} = 1.17$, $m_{E_2} = 2.0$, $m_{E_3} = 2.56$	$m_{\nu_4} = 186.0$, $m_{\nu_5} = 404.8$, $m_{\nu_6} = 689.7$,	$m_{\nu_7} = 5.14$, $m_{\nu_8} = 5.30$, $m_{\nu_9} = 5.50$, $m_{\nu_{10}} = 15.05$, $m_{\nu_{11}} = 15.11$, $m_{\nu_{12}} = 15.19$

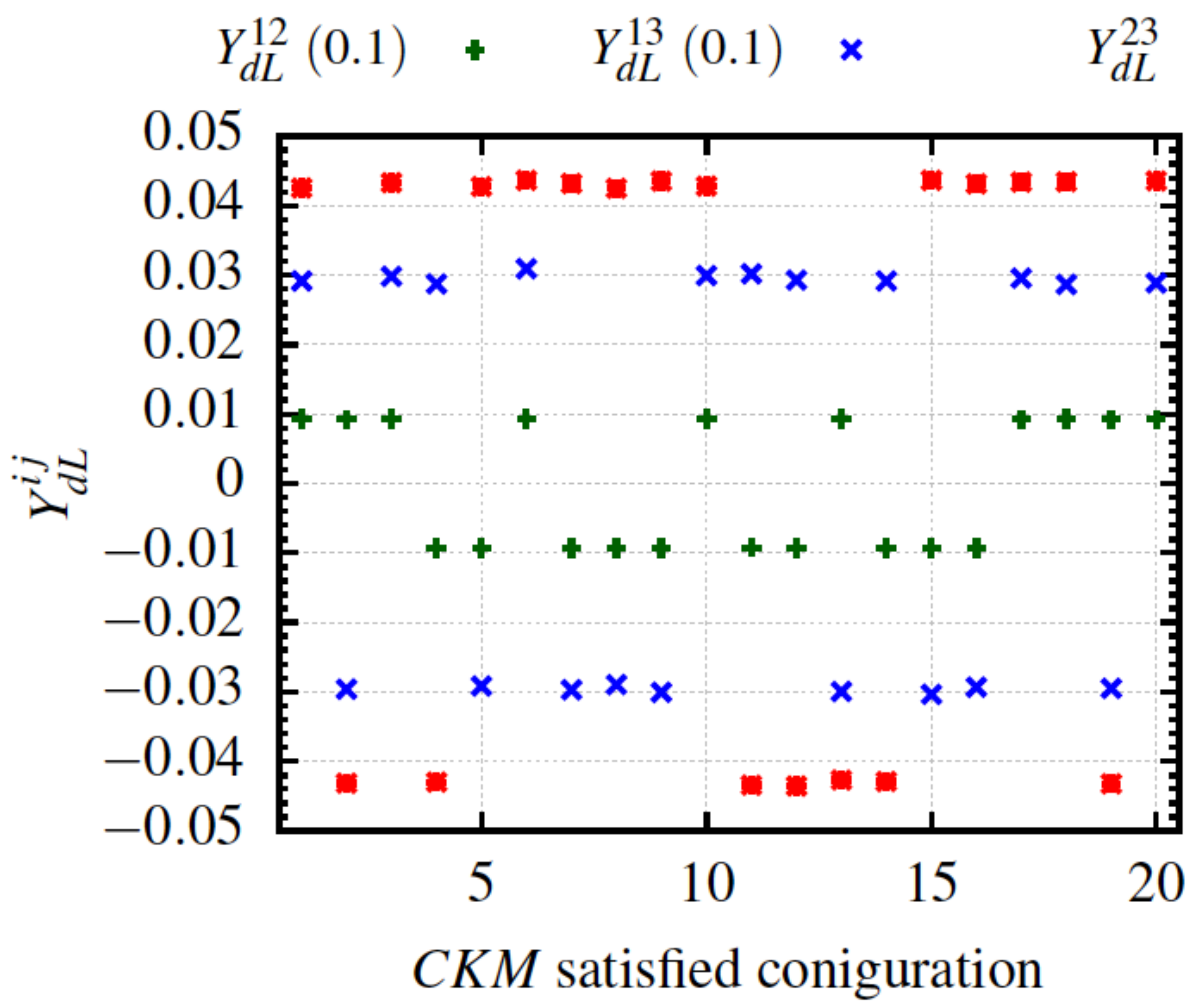
$M_U = \mathrm{Diag}(30.0, 11.93, 6.6) \times 10^3$ $\quad M_D = \mathrm{Diag}(1.6, 2.0, 3.0) \times 10^4$ $\quad M_E = \mathrm{Diag}(0.8, 1.0, 1.0) \times 10^3$

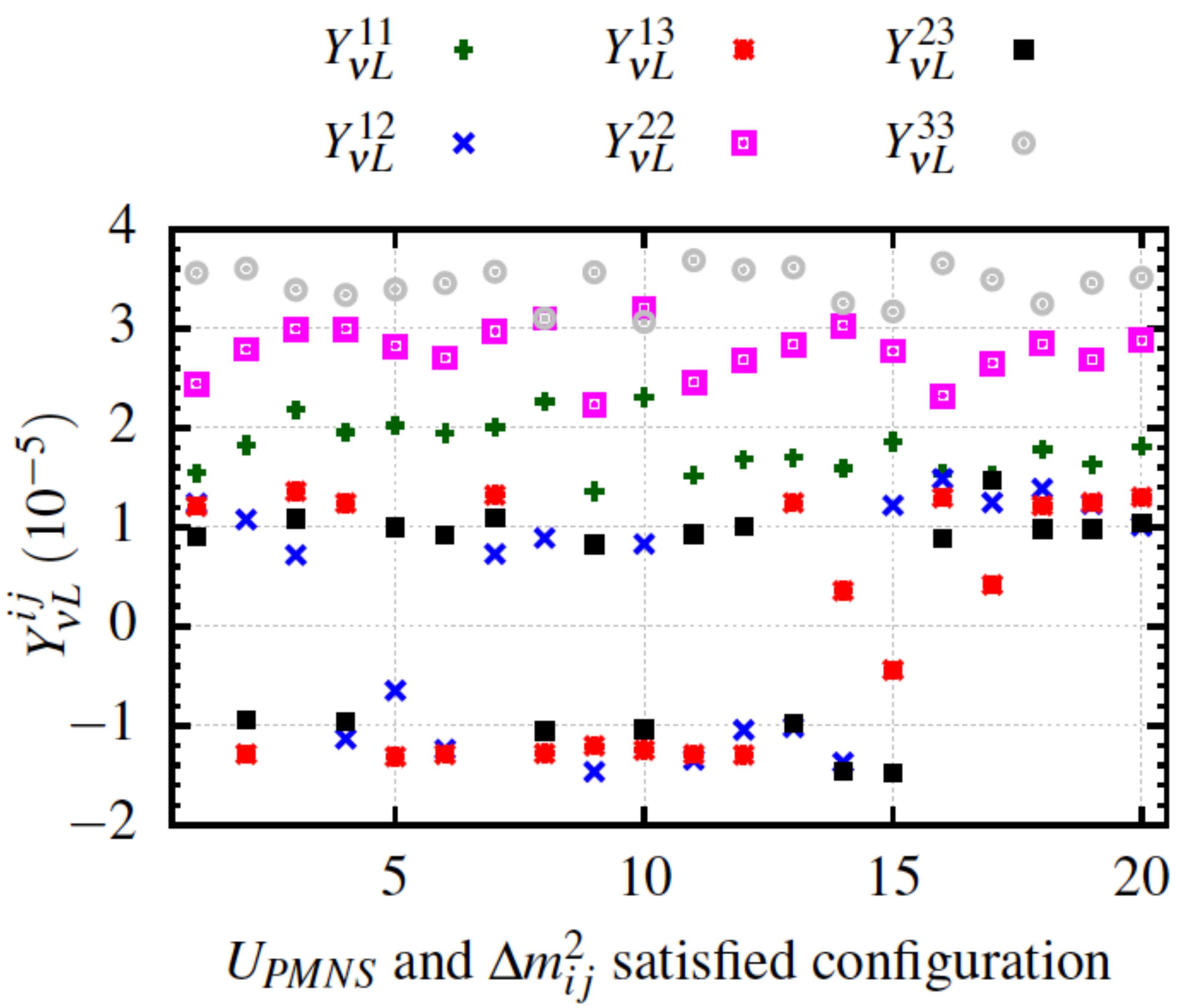
$M_R = M_L = \mathrm{Diag}(1.0, 1.0, 1.0) \times 10^4$ $\quad M_N = \mathrm{Diag}(1.0, 1.0, 1.0) \times 5 \times 10^3$ $\quad$ Off-diagonal elements $Y_{dL}^{ij} \sim 10^{-3}$.

$$Y_{u(L,R)}^{11} \sim Y_{d(L,R)}^{11} \sim Y_{e(L,R)}^{11} \simeq 10^{-2},\ Y_{u(L,R)}^{22} \sim Y_{dR}^{22} \sim Y_{e(L,R)}^{22} \simeq 10^{-1},\ Y_{u(L,R)}^{33} \sim Y_{dL}^{33} \sim Y_{eR}^{33} \simeq 1.0.$$

require $Y_{dR}^{33} \simeq 0.078$ $\quad Y_{eL}^{33} \simeq 0.146$ $\quad$ to keep the third generation fermion masses heavy.

CKM satisfied Y_{dL}; U_{PMNS} and Δm^2_{ij} satisfied $Y_{\nu L}$





- $Y^{21}_{dL} = Y^{32}_{dL} = Y^{31}_{dL} = 0$.
- $Y_{\nu R} = \text{Diag}(0.2, 0.3, 0.4)$, $Y^{ij}_{\nu L} = Y^{ji}_{\nu L}$ with

6.82×10^{-5} eV$^2 < \Delta m^2_{21} < 8.04 \times 10^{-5}$ eV^2,
2.43×10^{-3} eV$^2 < \Delta m^2_{31} < 2.60 \times 10^{-3}$ eV^2 and U_{PMNS}
[I. Esteban *et. al.* 2007.14792]

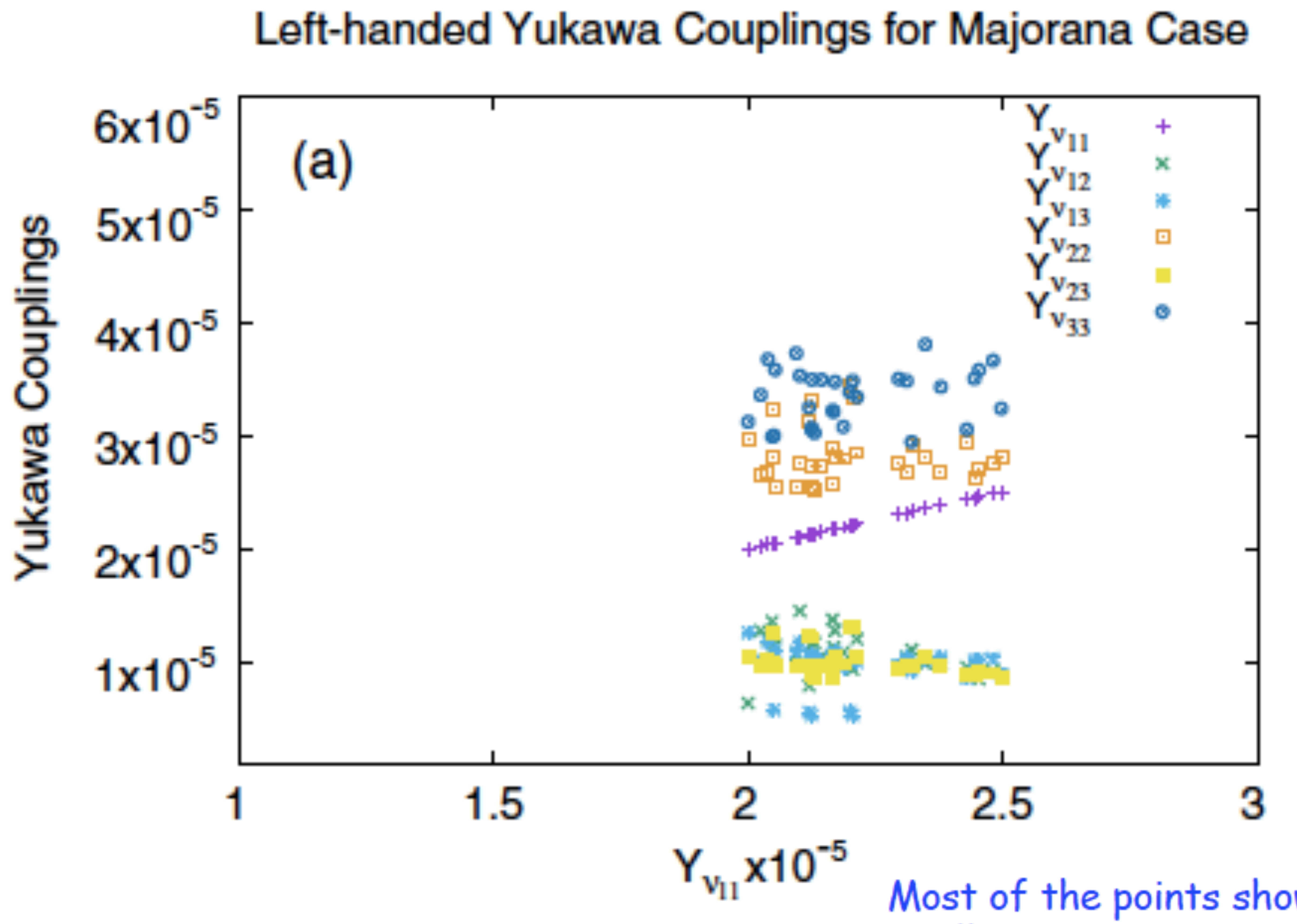
Majorana neutrino case

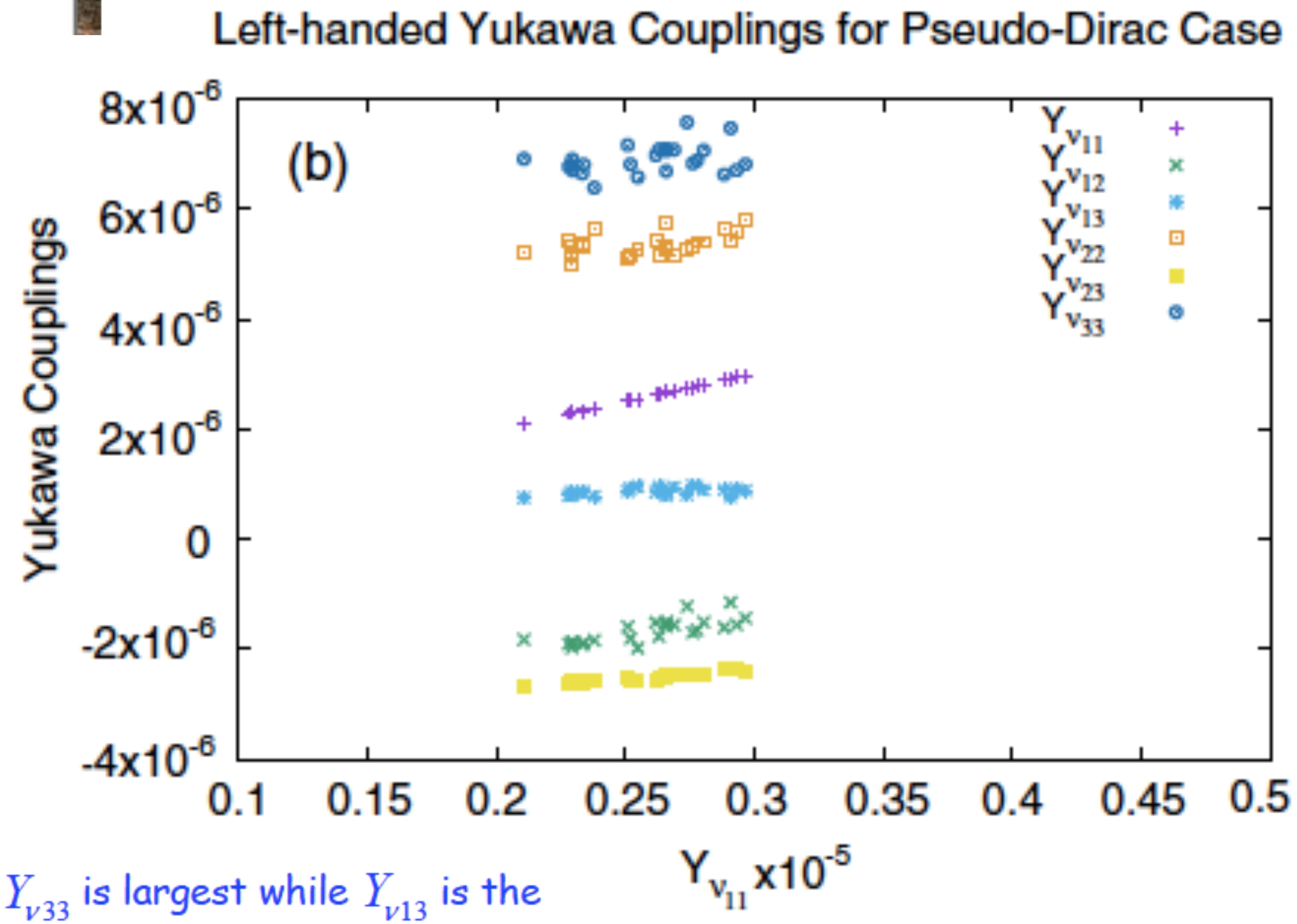
$$M_R = M_L = Diag(10^4, 10^4, 10^4),\ M_N = Diag(10^3, 10^3, 10^3),\ Y_{\nu R_{ii}} \sim 0.1,\ Y_{\nu L_{ij}} \sim 10^{-5}$$

Pseudo-Dirac neutrino case

$$M_R = M_L = Diag(200, 300, 400),\ M_N = 0,\ Y_{\nu R_{ij}} = \frac{v_{Ll}}{v_{Rl}} Y_{\nu L_{ij}}$$

Correct light neutrino mass $Y_{\nu L_{ij}} \sim 10^{-6}$ which leads to $Y_{\nu R_{ij}} \sim 10^{-9}$.

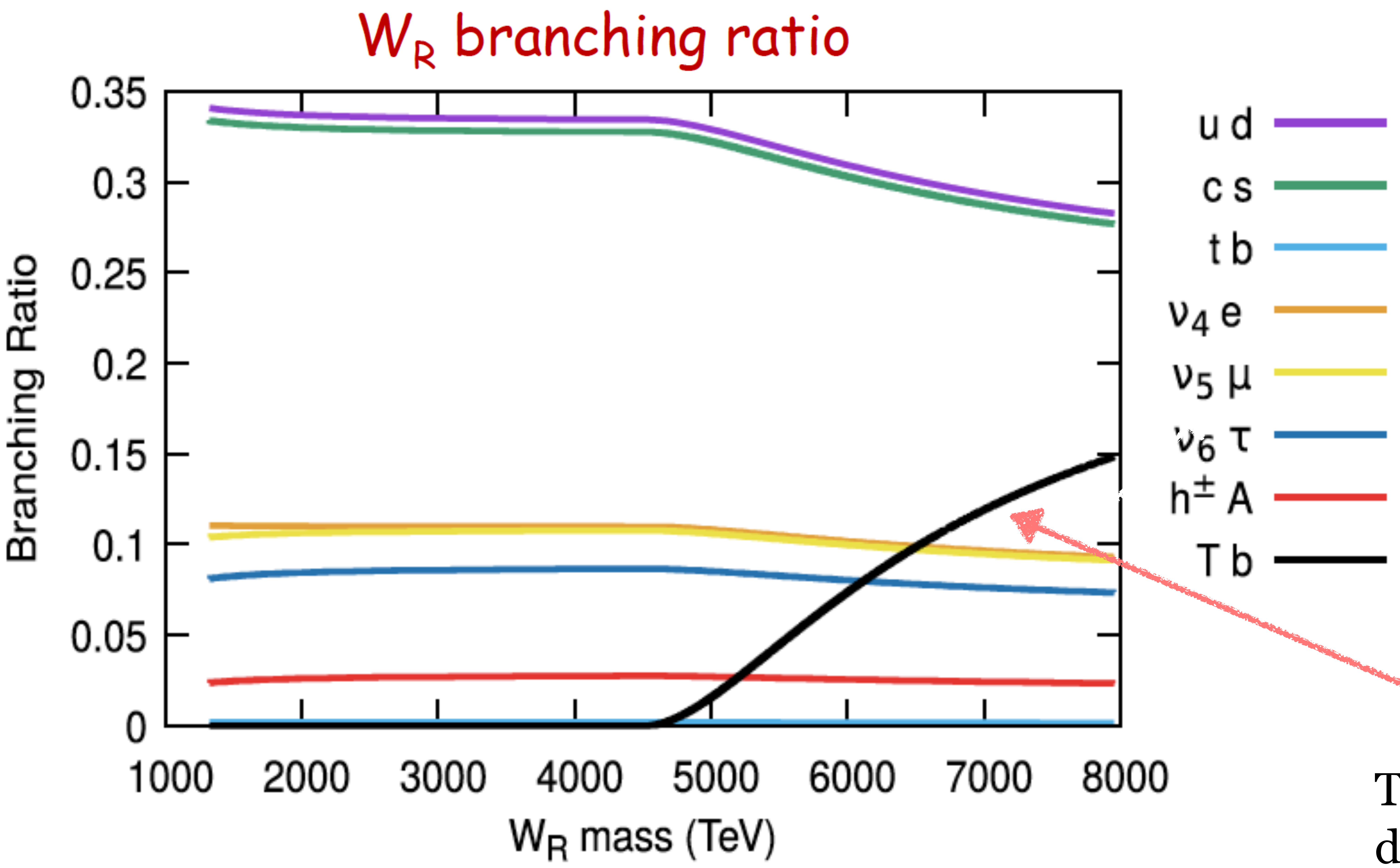




Most of the points show $Y_{\nu 33}$ is largest while $Y_{\nu 13}$ is the smallest.

$v_{RQ} = v_{Rl} = 6.0\,\text{TeV}, \quad v_{LQ} = 173.4\,\text{GeV}, \quad v_{Ll} = 14\,\text{GeV}.$

Mixing between SM and heavy states very small except top quark. $(\lesssim 1\%)$

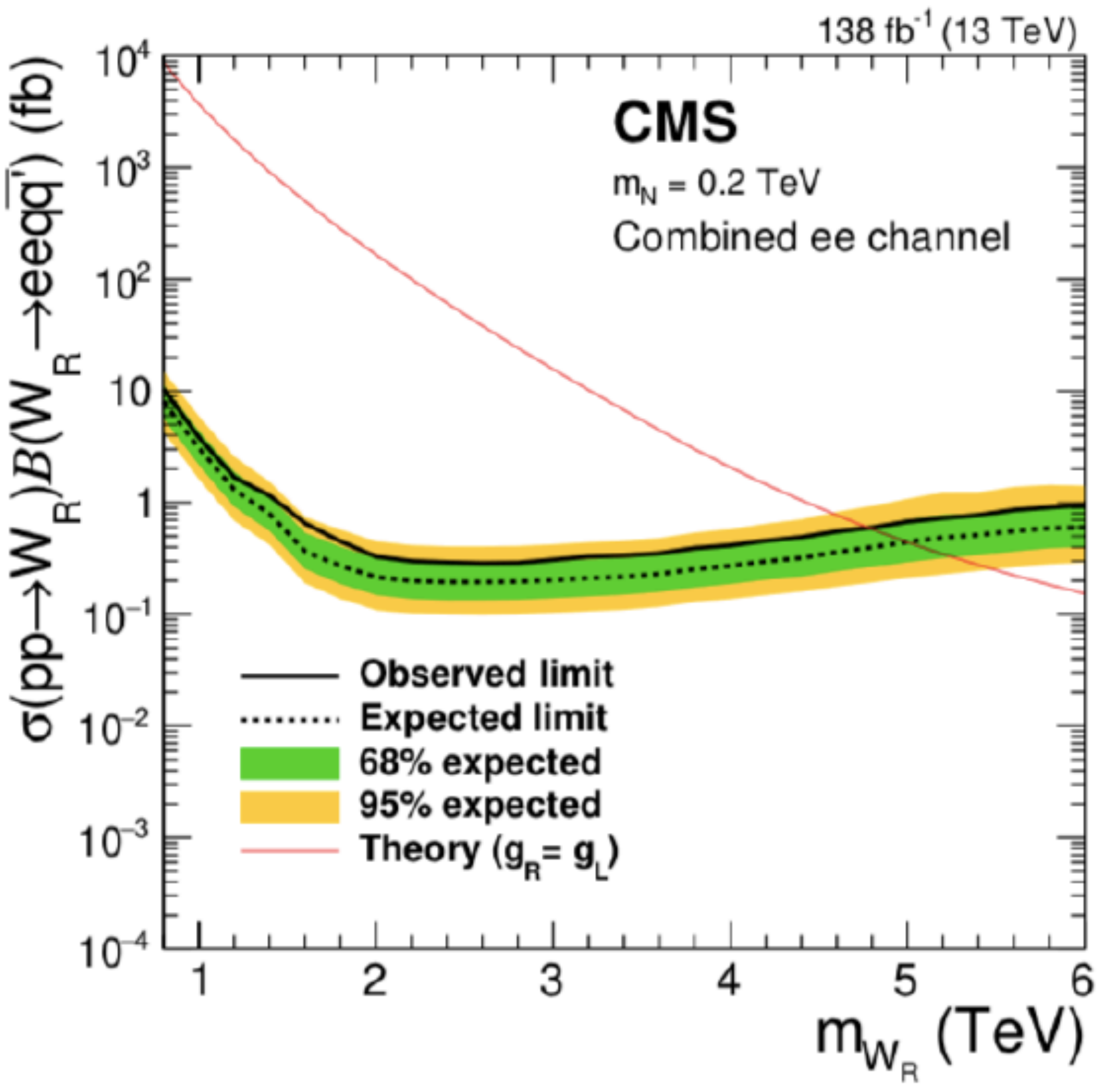


Right-handed component of top quark almost entirely from singlet.

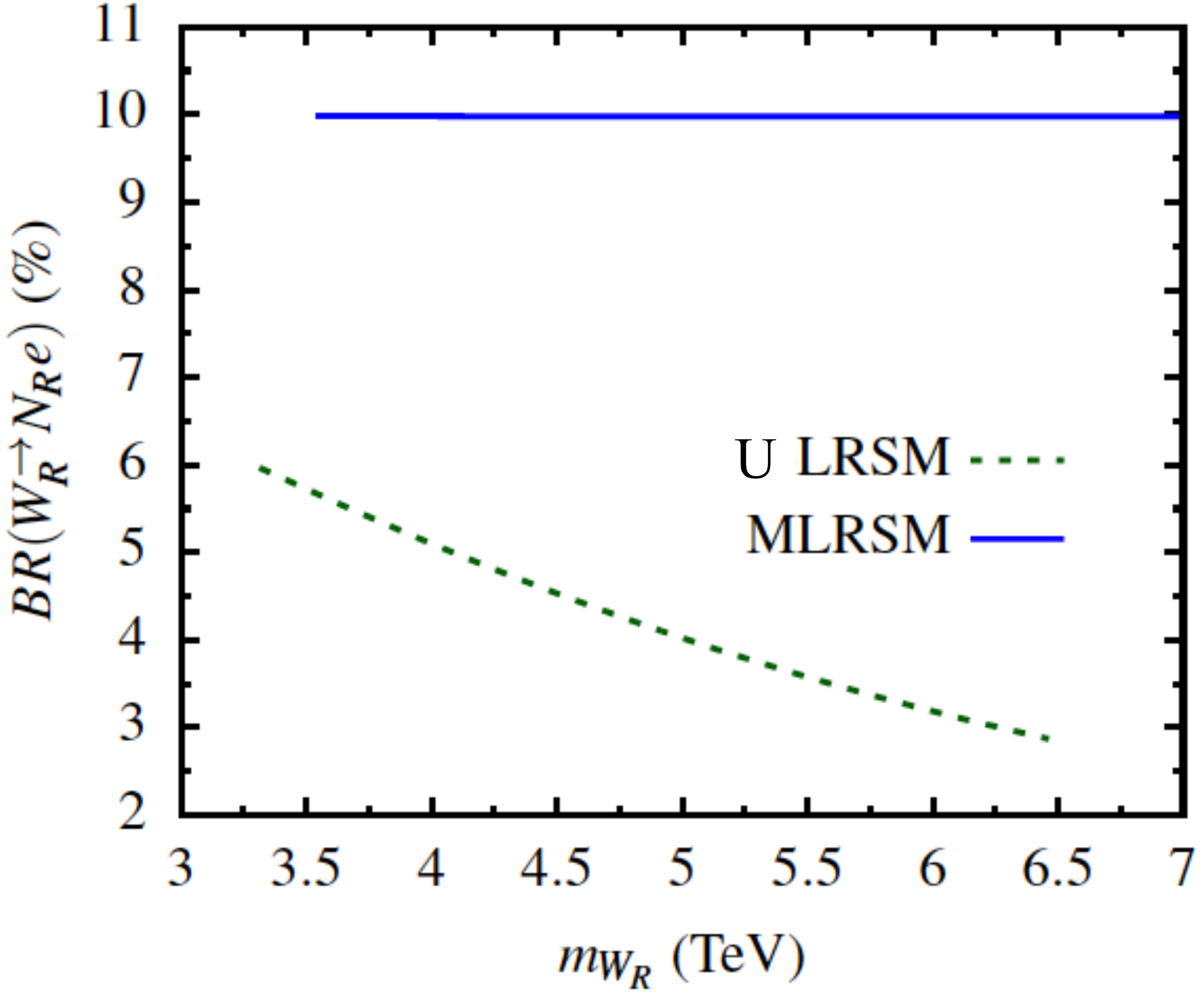
$$M_u^{33} \sim 400\ GeV$$

The heavier top-partner which is singlet dominated can contribute to W_R decay due to it being lighter than the other exotics and the right CKM mixing structure

Resonant production $pp \to W_R^* \to T\bar{b}$



138 fb^{-1} (13 TeV)
CMS
m_N = 0.2 TeV
Combined ee channel
Observed limit
Expected limit
68% expected
95% expected
Theory ($g_R = g_L$)
$\sigma(pp \to W_R)\mathcal{B}(W_R \to eeq\bar{q}')$ (fb)
m_{W_R} (TeV)

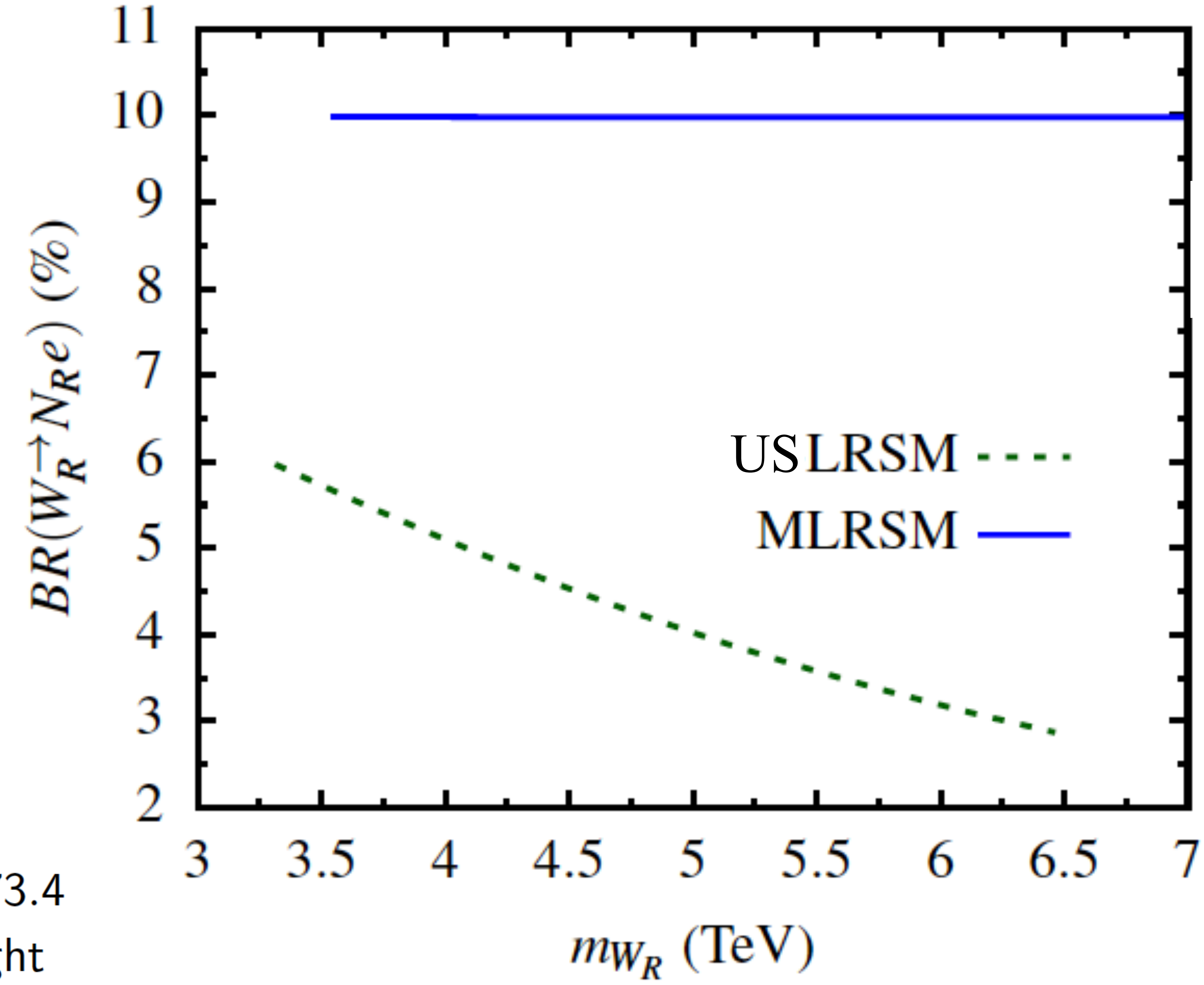


U LRSM
MLRSM
$BR(W_R \to N_R e)$ (%)
m_{W_R} (TeV)

Particle	Mass
W_R	5.0 TeV
Z_R	5.93 TeV
H_1	125.0 GeV
H_2	7.4 TeV
H_3	8.15 TeV
H_4	14.31 TeV
A_1	8.15 TeV
A_2	13.52 TeV
H_1^+	8.15 TeV
H_2^+	13.52 TeV

Input parameters: $v_{LQ}/\sqrt{2} = 173.4$ GeV, $v_{Ll}/\sqrt{2} = 14$ GeV. The right handed VEVs are $v_{RQ} = 12.48$ TeV and $v_{Rl} = 8.4$ TeV.

W_R branching ratio



$W_R^+ \to jj$	67%
$W_R^+ \to t\bar{b}$	10.37%

$W_R^+ \to E_4^+ \nu_4$	5.09 %
$W_R^+ \to E_5^+ \nu_6$	4.48 %
$W_R^+ \to E_6^+ \nu_5$	3.59 %

additional decay modes

COLLIDER SIGNALS

- The light charged Higgs is linear combination of right-handed doublets.
- Majorana neutrinos of mass at the EW scale are part of the right-handed doublet and decay mainly into charged Higgs and leptons.
- They can be pair produced through the Z_R exchange DY processes leading to a very interesting final state

$$pp \to \nu_4 \nu_4 \to e^- \, e^- \, H^+ \, H^+ \to 2e^- + 2t + 2\bar{b}$$

- If charged Higgs is heavier than the heavy neutrinos we get an entirely different signature

$$pp \to H^+ \, H^- \to \nu_j \nu_j \ell_i^+ \ell_i^-$$

$$pp \to H_1^+ H_1^- \to \nu_4 e^+ \nu_4 e^- \to 2e^\pm + 4j + e^+ e^- .$$

Small rates!
not much help
from Kinematics!

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COLLIDER SIGNALS

Particle		Width (GeV)	Important decay channels
BP1	$M_{\nu_4} = 136.4$ GeV	7.12×10^{-9}	$\nu_4 \to e^{\pm} jj \sim 99.3\%$
	$M_{\nu_5} = 258.3$ GeV	4.57×10^{-4}	$\nu_5 \to \mu^{\pm} H_1^{\mp} \sim 100\%$
	$M_{\nu_6} = 317.0$ GeV	2.97×10^{-3}	$\nu_6 \to \tau^{\pm} H_1^{\mp} \sim 100\%$
	$M_{H_1^{\pm}} = 224.7$ GeV	4.6×10^{-4}	$H_1^{\pm} \to \nu_4 e^{\pm} \sim 99\%$
BP2	$M_{\nu_4} = 317.0$ GeV	2.11×10^{-3}	$\nu_4 \to e^{\pm} H_1^{\mp} \sim 100\%$
	$M_{\nu_5} = 550.9$ GeV	3.03×10^{-2}	$\nu_5 \to \mu^{\pm} H_1^{\mp} \sim 100\%$
	$M_{\nu_6} = 837.6$ GeV	1.04×10^{-1}	$\nu_6 \to \tau^{\pm} H_1^{\mp} \sim 100\%$
	$M_{H_1^{\pm}} = 224.7$ GeV	5.78×10^{-6}	$H_1^{+} \to t\bar{b} \sim 92.9\%$

$$pp \to \nu_5 \nu_5 \to \mu^{\pm}\mu^{\pm} H_1^{\mp} H_1^{\mp} \to 2\mu^{\pm} + 2e^{\mp} + 4j.$$

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Up-type Quark (TeV)	Down-type Quark (TeV)	Charged Lepton (TeV)	Neutrino (GeV)	Neutrino (TeV)
$m_U = 11.94$, $m_C = 11.96$, $m_T = 30.0$	$m_D = 16.0$, $m_S = 20.1$, $m_B = 30.0$	$m_{E_1} = 1.17$, $m_{E_2} = 2.0$, $m_{E_3} = 2.56$	$m_{\nu_4} = 186.0$, $m_{\nu_5} = 404.8$, $m_{\nu_6} = 689.7$,	$m_{\nu_7} = 5.14$, $m_{\nu_8} = 5.30$, $m_{\nu_9} = 5.50$, $m_{\nu_{10}} = 15.05$, $m_{\nu_{11}} = 15.11$, $m_{\nu_{12}} = 15.19$

Decay	Br
$W_R^+ \to jj$	67%
$W_R^+ \to t\bar{b}$	10.37%
$W_R^+ \to e^+\nu_4$	5.12 %
$W_R^+ \to \mu^+\nu_5$	1.6 %
$W_R^+ \to \tau^+\nu_6$	2.45 %
$W_R^+ \to E_4^+\nu_4$	5.09 %
$W_R^+ \to E_5^+\nu_6$	4.48 %
$W_R^+ \to E_6^+\nu_5$	3.59 %

Decay	Br
$Z_R \to q\bar{q}$	70%
$Z_R \to \nu_4\nu_4$	7.2%
$Z_R \to \nu_5\nu_5$	6.5%
$Z_R \to E_4\bar{E}_4$	2%
$Z_R \to E_5\bar{E}_5$	1%

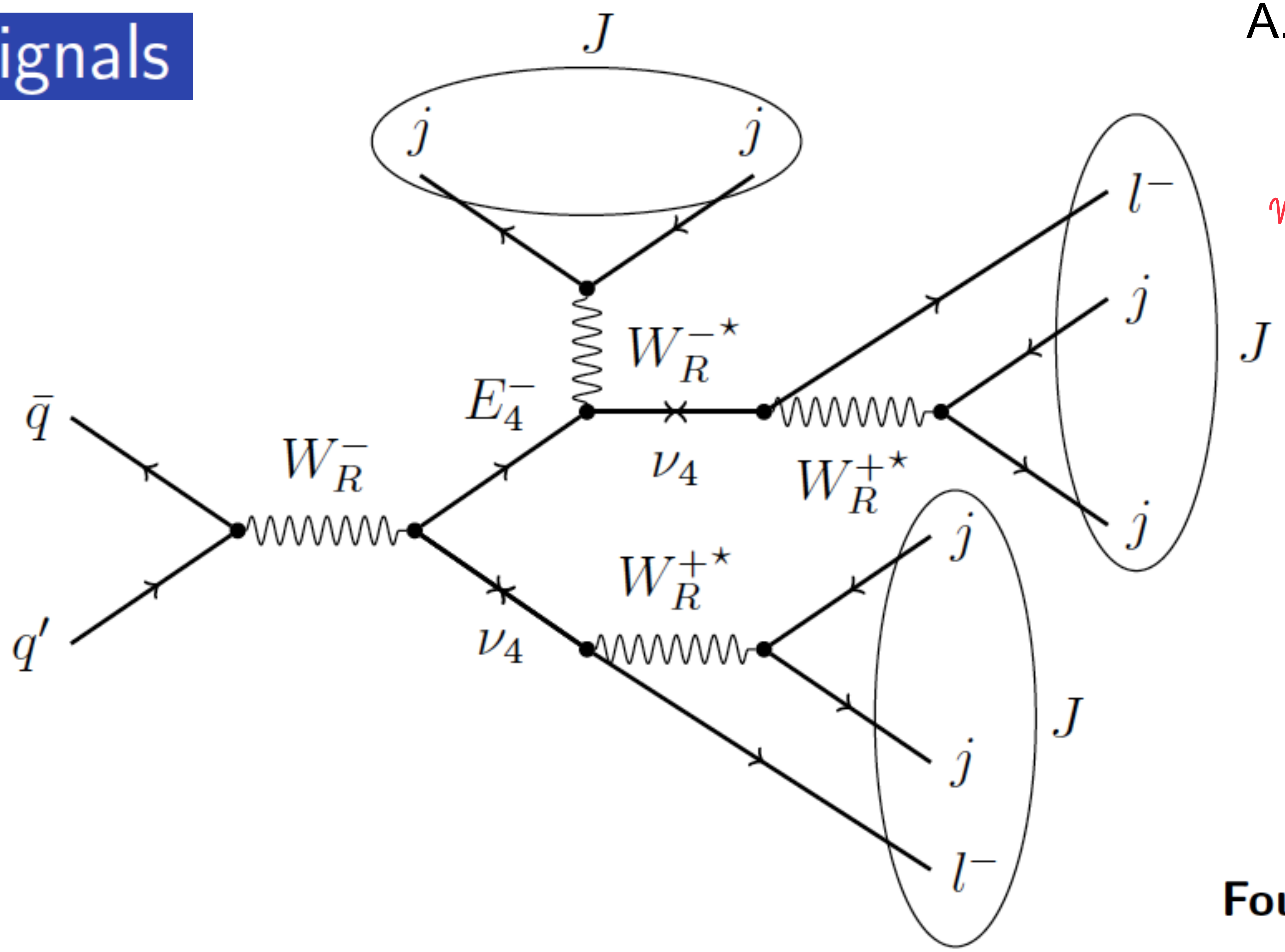
Decay	Br
$E_4 \to \nu_4 jj$	70%
$E_5 \to \nu_6 jj$	13%
$E_6 \to \nu_5 jj$	73.7%
$E_6 \to \mu jj$	3.45%
$\nu_4 \to e^\pm jj$	100%
$\nu_5 \to \mu^\pm jj$	94.5%
$\nu_6 \to \tau^\pm jj$	87.3%

$M_{W_R} \sim 5$ TeV

$M_{Z_R} \sim 6$ TeV

Fatjet Signals

A. Dey, R. Rahaman. SKR (2207.06857)



non-isolated leptons!

2 & 3 fat jet signal!

Four-fatjet: $pp \to Z_R,\ Z_R \to E_4\bar{E}_4,\ E_4 \to \nu_4 jj$

Variables

- p_T and mass of fatjet, p_T of lepton subjets.
- lepton subjet fraction (LSF)
- lepton mass drop (LMD)

C. Brust *et al.* 1410.0362

$$LSF_n = \frac{p_{T\,l_n}}{p_{T\,l_n}^{sj}}.$$

lepton subjet fraction of each lepton is defined as the ratio of the lepton p_T to its associated subjet p_T

$$LMD_n = \frac{m^2_{sj-l_n}}{m^2_{sj}}.$$

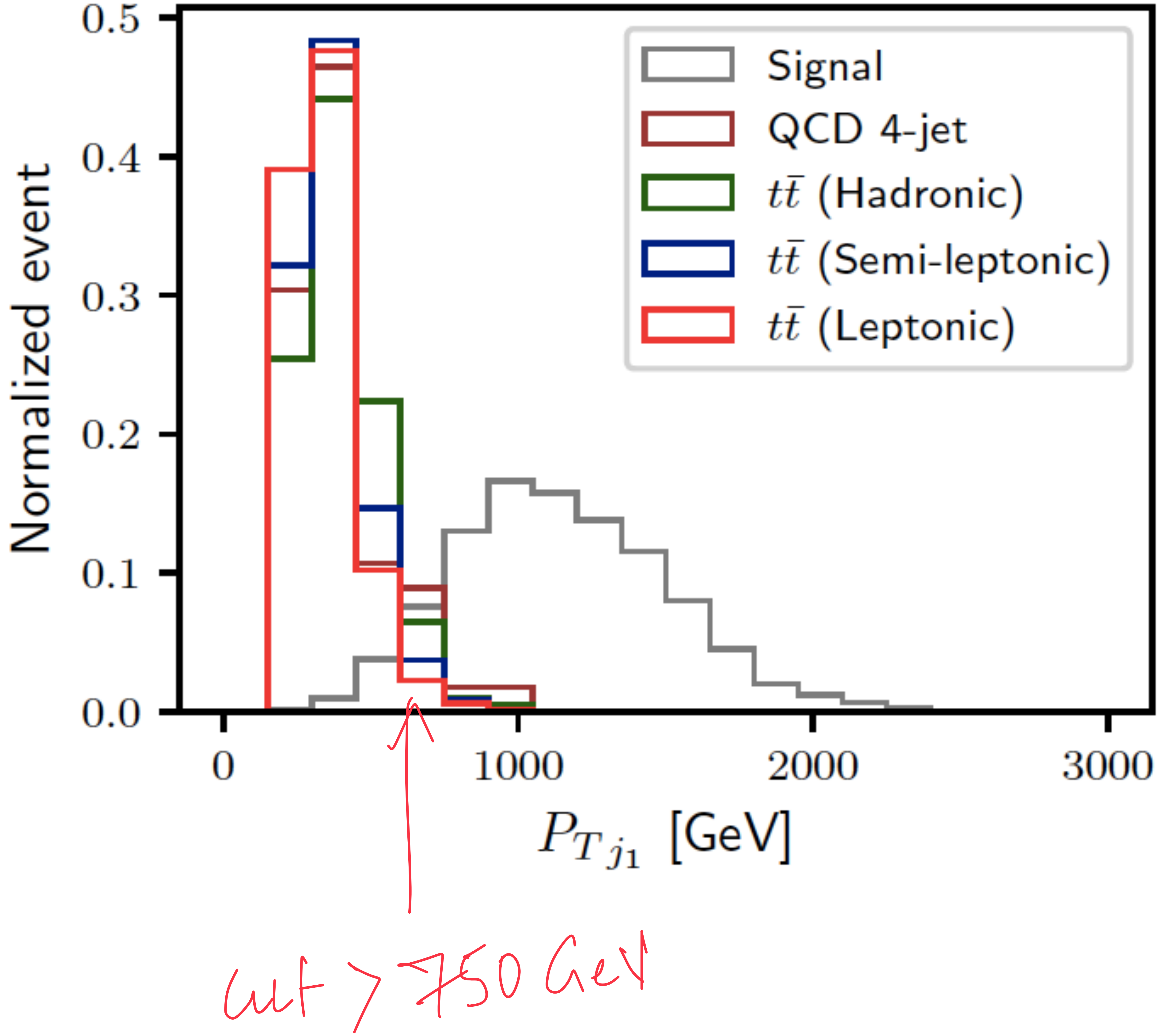
m_{sj} : invariant mass of the subjet including the lepton

m_{sj-l_n}: mass of the hadronic component only

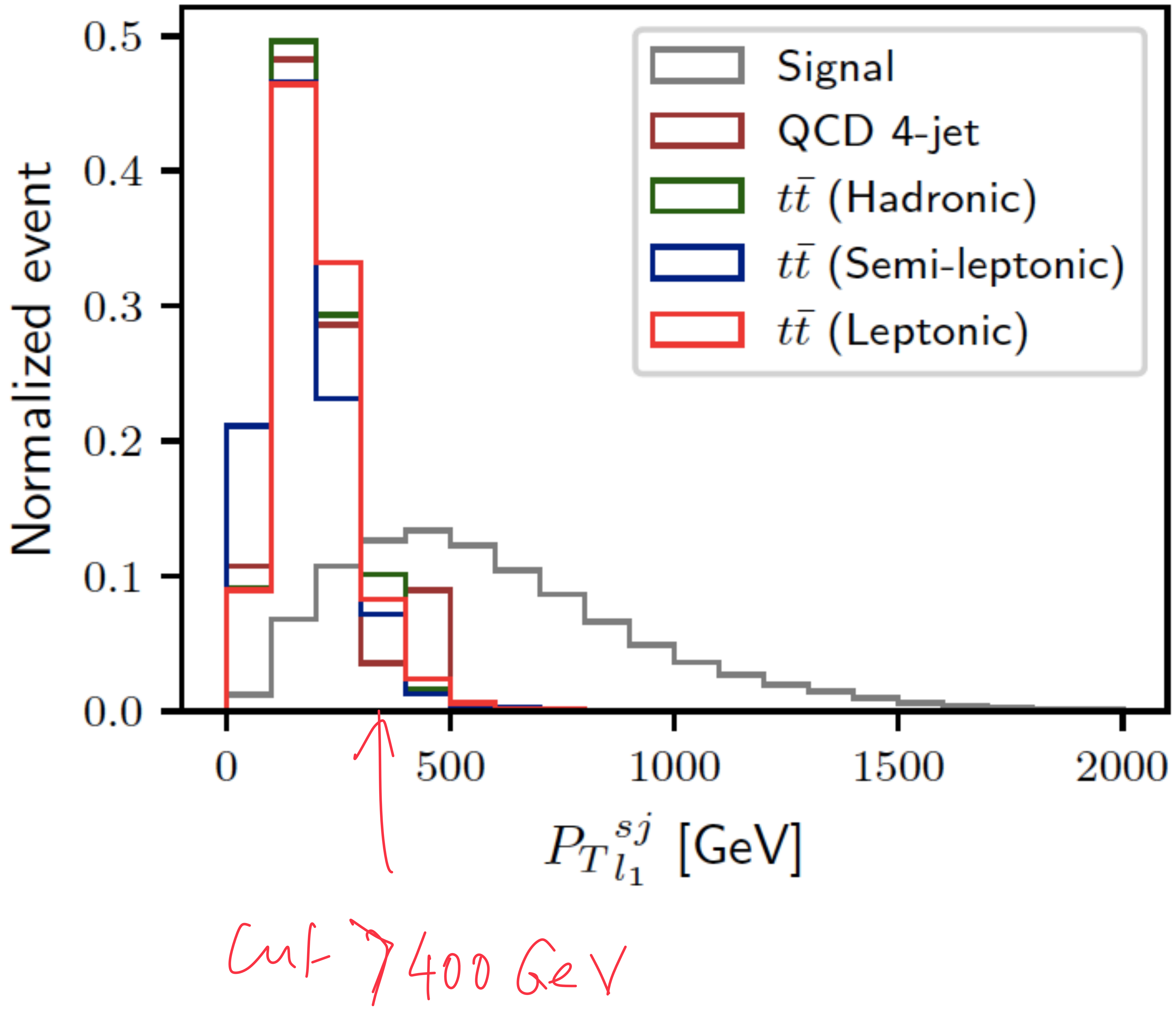
Backgrounds

- **QCD multi-jet:** Major background with huge cross section. We consider up-to 4jet final state.
- $t\bar{t}$ **:** Next dominant background with promt lepton in fatjet.
- W/Z**+jets:** tW cross section very low as compared to $t\bar{t}$.
- tW**:** W/Z+jets with moderate cross section, probability of getting two high p_T leptons in two fatjets is very small compared to $t\bar{t}$.

leading fat jet



leading lepton in the fat jet



A. Dey, R. Rahaman. SKR (2207.06857)

- 3σ sensitivity with $600\ fb^{-1}$ data in the 2 & 3 fatjet signal.
- Significant improvement over same-sign (isolated) charged lepton searches in left-right symmetry model.
- Resonant production is crucial for the signal rates and therefore signal is sensitive to the scale of right-handed current mediator.
- Role of scalar mediators in the cascades can give more interesting final states.

- Universal seesaw models put all fermion masses under a common umbrella
- The simplest extension that works well is based on a left-right symmetric framework
- Minimal extension includes addition of scalar doublets and singlet vector-like fermions in the spectrum beyond SM
- Interesting signals present at colliders if the new states are kinematically accessible.

T. Ghosh, R. Rahaman. SKR (2308.10314)

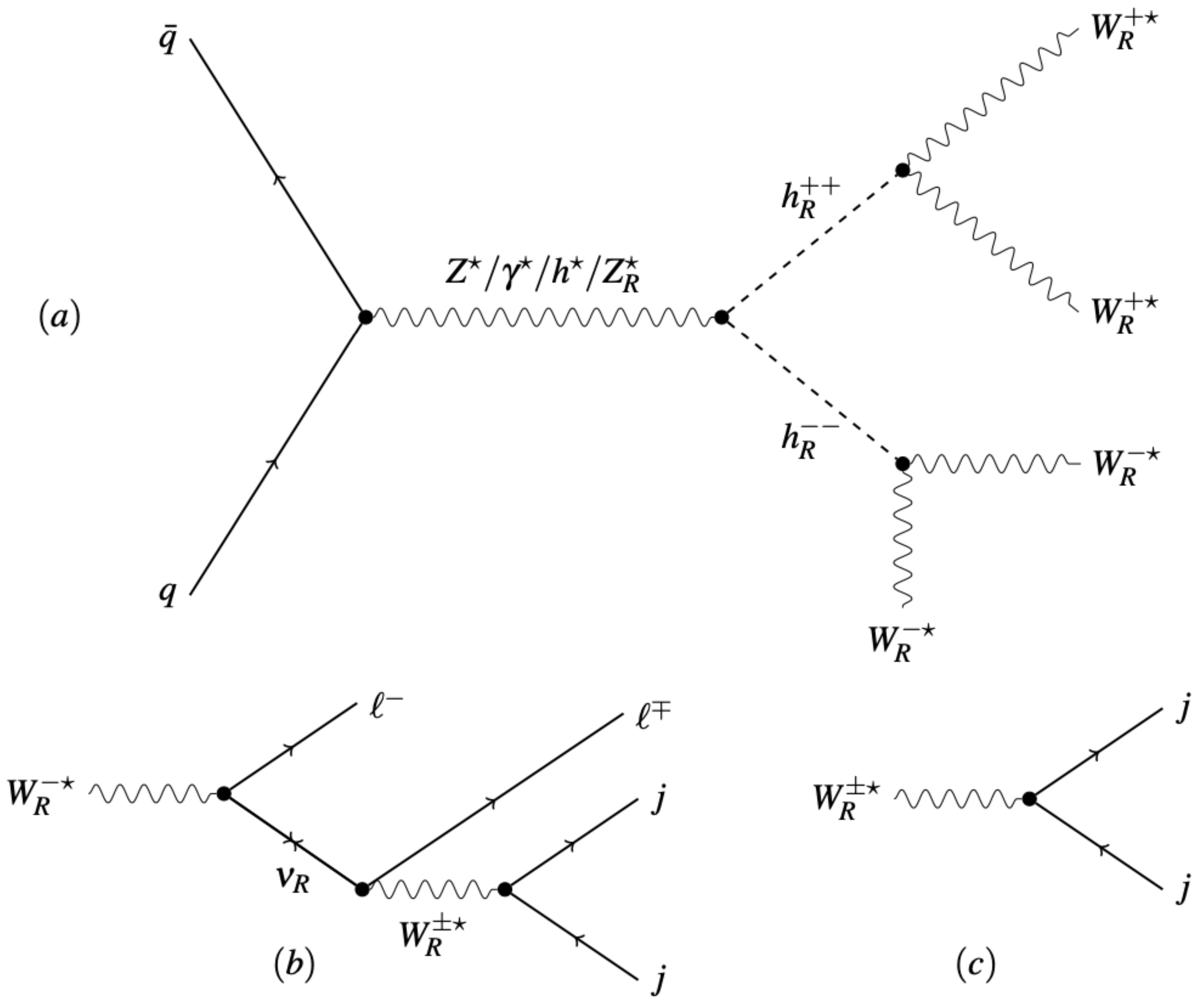
- What if we had a more exotic triplet scalar sector but it turned out to be fermiophobic?
- The neutrino mass is still generated via seesaw

$$\mathcal{O}^{(5)}_{WO} = \frac{\eta_{WO}}{\Lambda} \bar{L}^c_R \tilde{H}^\dagger_R \tilde{H}_R L_R, \qquad M_{\nu_R} \approx \eta_{WO} \frac{v_R^2}{\Lambda}.$$

[S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566–1570]

- We probe a lepto-phobic doubly charged Higgs in multi-lepton final state.
- This model provide exotic signature of SS4l with no background and six-lepton with very low background.

- Four-lepton,
- Six-lepton,
- Eight-lepton, and
- Same-sign four-lepton (SS4L).



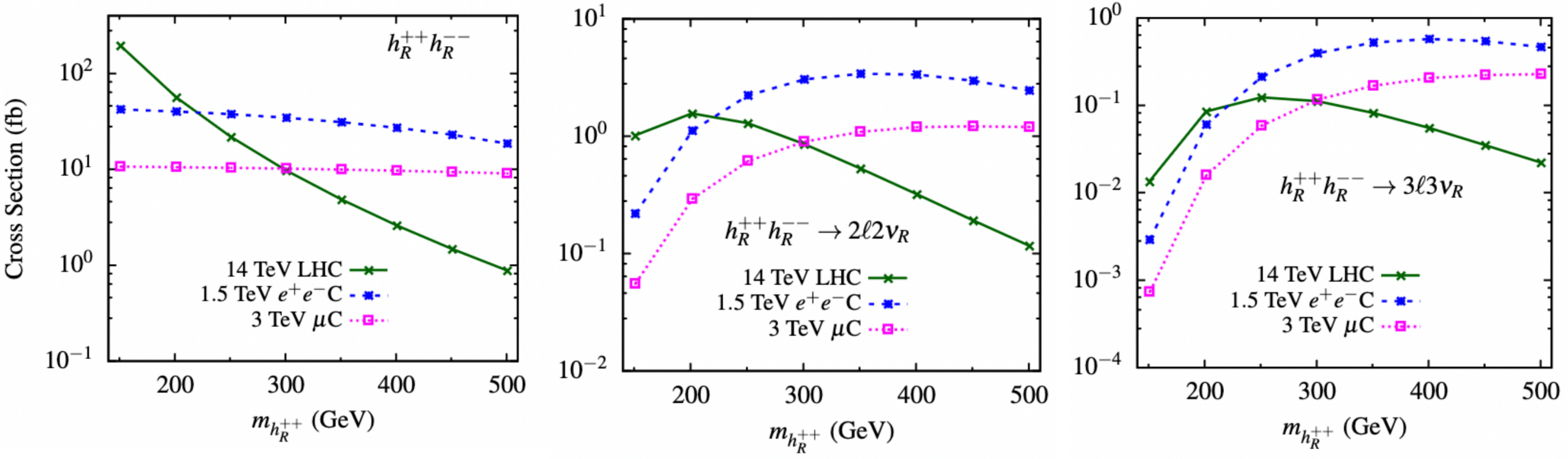
- Four-body decay:

$$\ell^\pm \nu_R 2j: \quad h_R^{++/--} \to W_{R\,1}^{\pm\star} W_{R\,2}^{\pm\star};\; W_{R\,1}^{\pm\star} \to \ell^\pm \nu_R,\; W_{R\,2}^{\pm\star} \to jj,$$

$$2\ell^\pm 2\nu_R: \quad h_R^{++/--} \to W_{R\,1}^{\pm\star} W_{R\,2}^{\pm\star},\; W_{R\,1,2}^{\pm\star} \to \ell^\pm \nu_R,\ \text{and}$$

$$4j: \quad h_R^{++/--} \to W_{R\,1}^{\pm\star} W_{R\,2}^{\pm\star},\; W_{R\,1,2}^{\pm\star} \to jj.$$

PROSPECT AT FUTURE LEPTON COLLIDERS



- The e+e−C and μC will have a significantly improved performance compared to the LHC.
- For the higher masses the LHC sensitivity begins to drop — difficult to observe the 4ℓ and 6ℓ final state at LHC beyond a mass of about 450 GeV.
- The e+e−C and μC on the other hand will be able to observe the h++ for much heavier mass, limited only by the energy reach.
- For example, the e+e−C cross-section is 18.7 times larger than the LHC for mh++ = 500 GeV, and for the μC, it is 10 times larger than the LHC.
- With a cleaner environment in a lepton collider (e+e−C and μC), the number of events in the 4ℓ and 6ℓ final states will be even more than the LHC case with similar integrated luminosity.

Thank you