Deep Learning Searches for Vector-Like Leptons at the LHC and Electron/Muon Colliders

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Vector-like leptons (VLLs) → Both left and right-handed components transform identically under $\mathrm{SU}(2)_\mathrm{L}$.

Predicted by various **GUT and string models** based on non-chiral groups and extensively studied from the phenomenological POV e.g. Gudrun Hiller et. al Phys. Rev. D 102, 071901 (2020); Stefan Bißmann et. al Eur.Phys.J.C 81 (2021) 2, 101

- Lepton flavour universality violation;
- Anomalous magnetic moment of leptons;

However, there has been **limited searches** at colliders

- **CMS**, only one direct search has been made, assuming dominant tau couplings CMS Collaboration Phys. Rev. D 100, 052003 (2019);
- **LEP** searches in the channel $L^\pm \to W^\pm \nu$. **Low limits** at $m_L > 100.8$ GeV L3 Collaboration Phys.Lett.B517:75-85,2001.

Field	$\mathbf{SU(3)}_\mathsf{C}$	$\mathbf{SU(2)}_\mathsf{L}$	$\mathbf{U(1)}_\mathsf{Y}$
$E_{\mathrm{L,R}}$	**1**	**2**	$1/2$
$\mathcal{E}_{\mathrm{L,R}}$	**1**	**1**	1
ν_{R}	**1**	**1**	0

Analysis based on **two** simplified models

- $E_{\mathrm{L,R}}$ (**doublet**) + right-handed neutrino;
- $\mathcal{E}_{\mathrm{L,R}}$ (**singlet**) + right-handed neutrino.

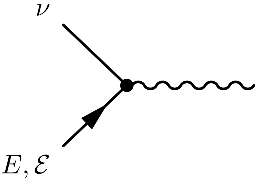
Some considerations

- Inspired by GUT model. Right-handed neutrino in the **keV mass range** António P. Morais et.al Eur.Phys.J.C 80 (2020) 12, 1162; Felipe F. Freitas et. al JHEP 01 (2021) 076.
- Considering a **global flavour** symmetry $\mathrm{U}(1)^3$, allowing couplings **only to muons.**

$$U_L^e = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & 0 & -\sin\alpha \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\alpha & 0 & -\cos\alpha \end{bmatrix}.$$

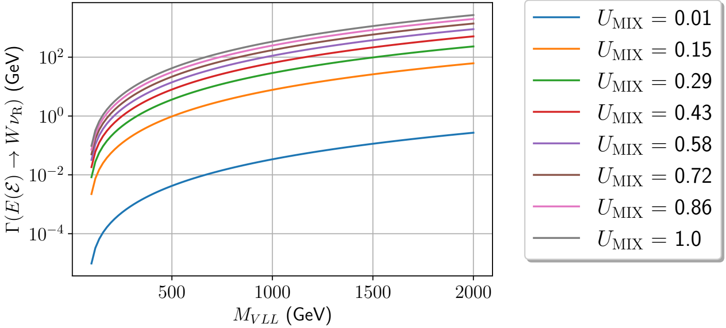
- Neutrino mixing fixed by the PMNS matrix.

Dominant decays via $W\nu E(\mathcal{E})$ vertex,

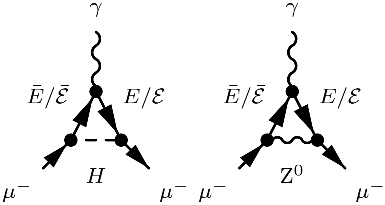


$$\mathrm{W}^+ \propto \; i\frac{g}{\sqrt{2}}U_{\mathrm{MIX}}\mathrm{P_L},$$

- **Doublet case**: $U_{\mathrm{MIX}} \sim \cos(\alpha) \sim \mathcal{O}(1)$
- **Singlet case**: $U_{\mathrm{MIX}} \sim \sin(\alpha) \sim \mathcal{O}(0.01 - 0.001)$

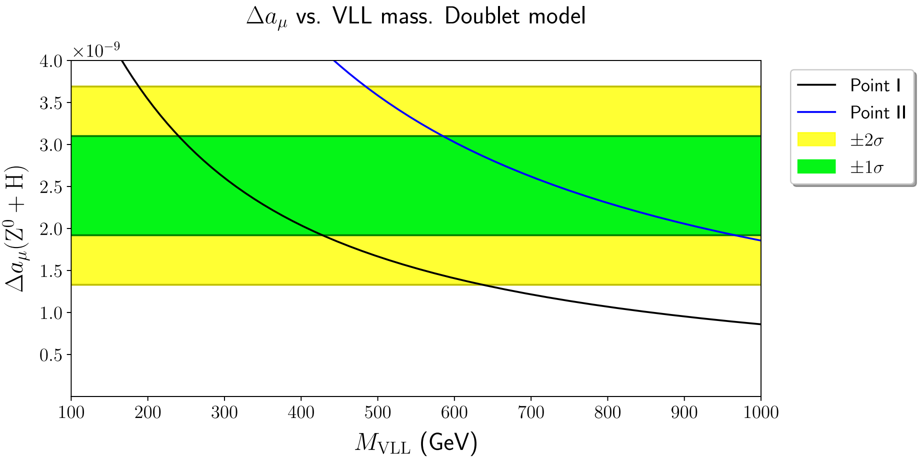


As mentioned, we consider scenarios where **VLLs couple to muons** → One-loop diagrams with Z^0/Higgs Kristjan Kannike et. al JHEP 02 (2012) 106, JHEP 10 (2012) 136 (erratum)



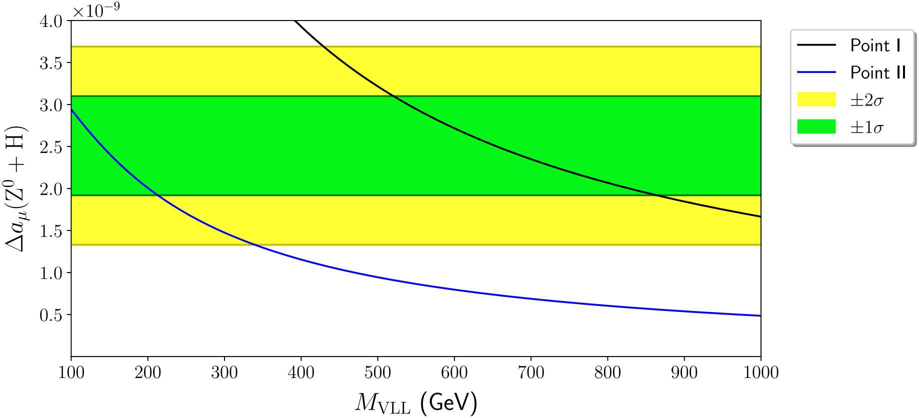
- Z^0 contribution: $\Delta a_\mu^{\mathrm{Z}^0} \propto -m_\mu^2 \left|g^Z_{L,R}\right|^2$
  Negative and subleading
- H contribution: $\Delta a_\mu^{\mathrm{H}} \propto m_\mu M_{\mathrm{VLL}}(g^H_R g^H_L)$
  Dominant

Non-zero mixings with VLLs induce **lepton flavour violating** (LFV) vertices are **generated** (mainly involving μ decays) → Model implemented in `SARAH`. `Spheno` and `flavio` to compute LFV observables.

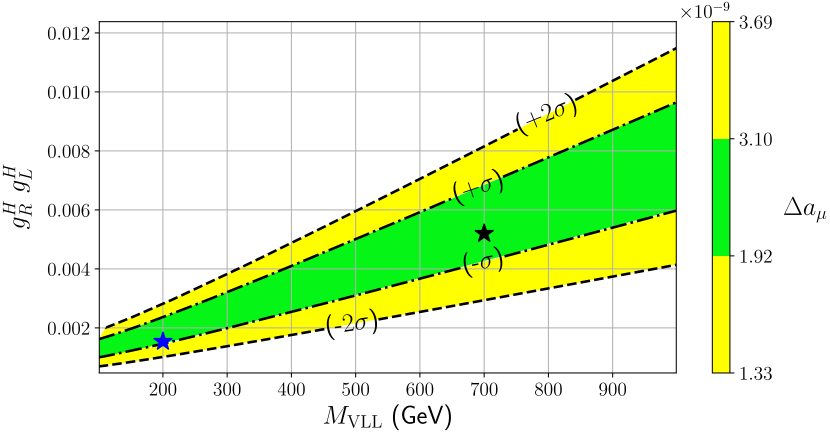


- **Blue line (Point I)**: $g_L^Z = 0$, $g_R^Z = -0.023$, $g_L^H = g_R^H = 0.076$;
- **Black line (Point II):** $g_L^Z = 0$, $g_R^Z = -0.039$, $g_R^H = g_L^H = 0.052$.

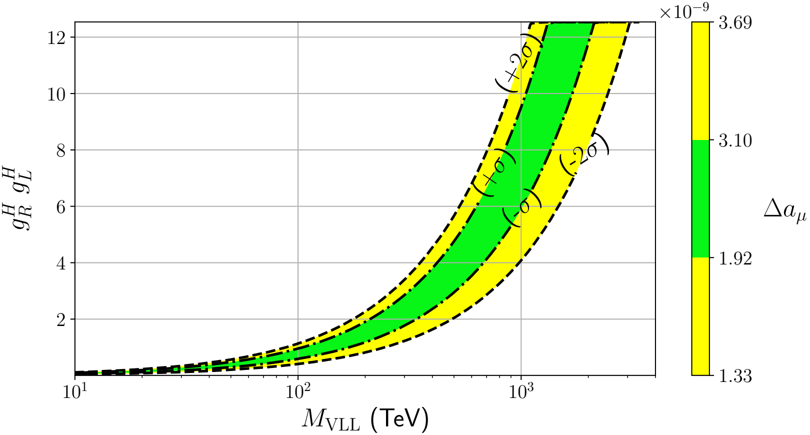
Δa_μ vs. VLL mass. Singlet model



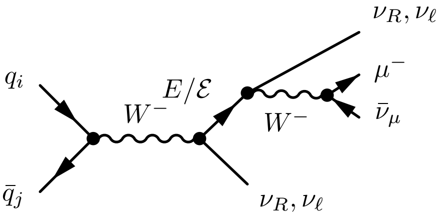
- **Blue line (Point I)**: $g_L^Z = -0.036$, $g_R^Z = 0.0$, $g_L^H = g_R^H = -0.039$;
- **Black line (Point II):** $g_L^Z = -0.023$, $g_R^Z = 0.0$, $g_R^H = g_L^H = -0.072$.



- Dominant contributions for the Higgs. Can **constraint coupling product.**
- $g_L^H g_R^H \in [6.93\times10^{-4}, 2.01\times10^{-3}]$ for 100 GeV.
  $g_L^H g_R^H \in [4.14\times10^{-3}, 1.15\times10^{-2}]$ for 1 TeV.



- **Extended** mass range. Up to the perturbative limit, $\max(g) = \sqrt{4\pi}$.
- Can still **accommodate** the anomaly up to **1200 TeV**;
- Again, valid for **both** singlet and doublet models.



Using benchmark points consistent with g-2 to perform collider phenomenology.

At LHC

- **Single-production of VLLs:** One charged lepton (muon) plus missing energy;
- Simple selecion criteria

$$p_T(\mu^-) > 25 \text{ GeV},$$
$$\text{MET} > 15 \text{ GeV and}$$
$$\left|\eta(\mu^-)\right| \leq 2.5$$

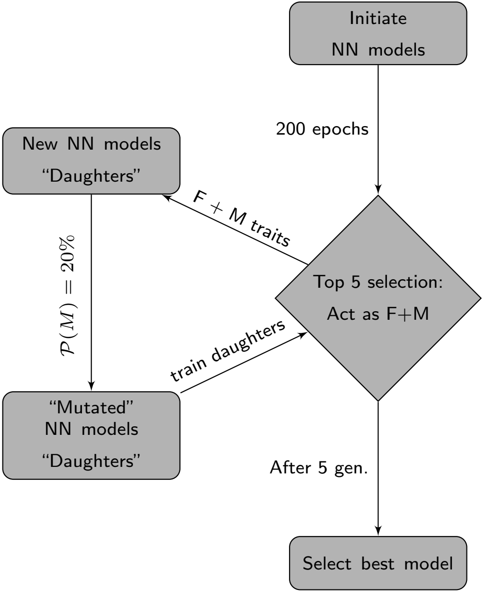
- **Genetic algorithm** Felipe F. Freitas et. al JHEP 01 (2021) 076 for neural network construction and optimization. **Maximizes** significance Adam Elwood and Dirk Krücker arXiv:1806.003226.

Algorithm:

- Randomly generate N models, by pooling a list of hyper-parameters;
- Train: Top 5 models are used to breed daughter networks;
- Add mutation probability. Train daughters and iterate the cycle.

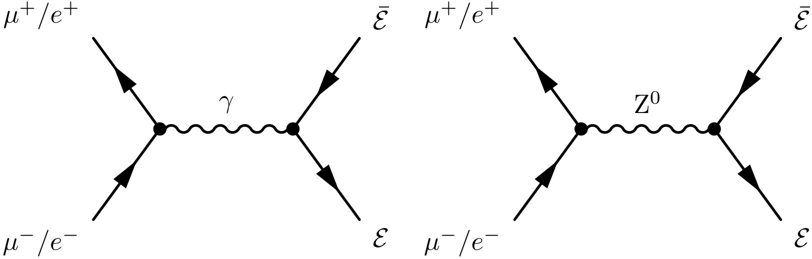
Nice **advantages**:

- Simplifies network construction. Simple way to find the best hyperparameters;
- Straightforward way to maximize distinct metrics.

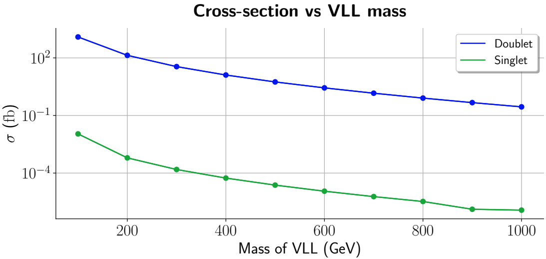


LHC → proton/proton collider → **Favours** production of **coloured particles** !

VLLs are colour singlets, can only be produced via **electroweak processes** → **Favoured** at lepton colliders.



Considering **pair-production** topologies. Analysis for **singlet** model, due to low mixing values, U_{MIX} and a physics-case for lepton colliders.

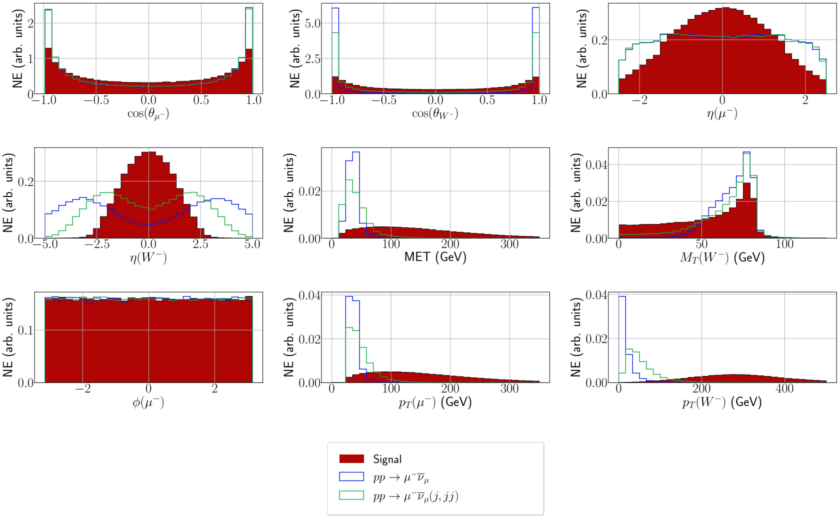


$\mathbf{M_{VLL}}$ = 700 GeV

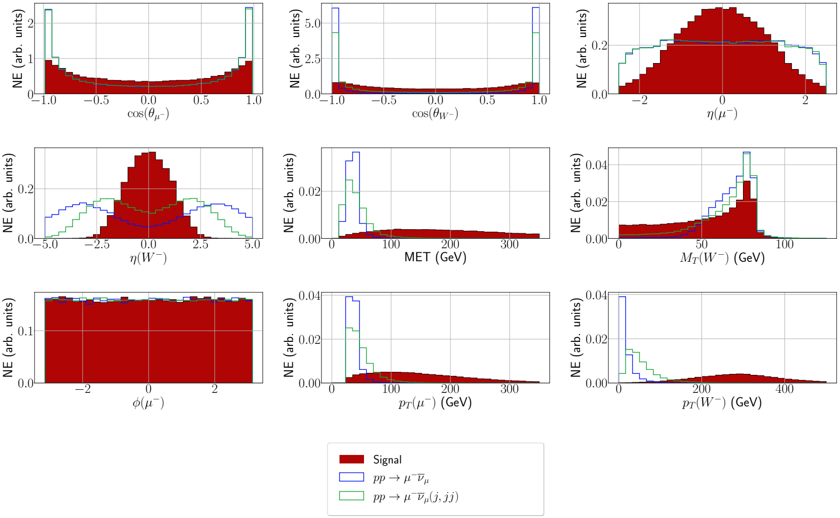
- $\boxed{\textbf{Doublet}: 0.39 \text{ fb},}$
- $\boxed{\textbf{Singlet}: 5.94\times10^{-6} \text{ fb},}$
- $pp \to \mu^-\bar{\nu}_\mu$: 3.45×10^6 fb,
- $pp \to \mu^-\bar{\nu}_\mu(j, jj)$: 4.79×10^6 fb.

- Low production cross-sections for singlet VLL;
- At $\mathcal{L} = 3000 \text{ fb}^{-1}$: $N_{\text{exp}} = 1170$ events for **doublet**, $N_{\text{exp}} = 0.01782$ events for **singlet**;
- Significance only computed for $N_{\text{exp}} > 1$ events.

Single production of doublet VLL with mass M = 700 GeV



Single production of singlet VLL with mass M = 700 GeV



LHC

Mass of VLL (GeV)	300 fb^{-1} (RUN III)			3000 fb^{-1} (HL-LHC)			
	$s/\sqrt{s+b}$	$\mathcal{Z}(<1\%)$	$\mathcal{Z}_A$	$s/\sqrt{s+b}$	$\mathcal{Z}(<1\%)$	$\mathcal{Z}_A$	Δa_μ
100	604.49	899.31	570.48	1911.55	2858.26	652.44	5.19×10^{-9}
200	201.86	285.55	150.83	638.33	902.98	181.21	3.54×10^{-9}
300	102.57	145.18	52.98	324.37	459.09	66.18	2.60×10^{-9}
400	43.37	87.71	11.20	137.16	277.36	14.42	2.04×10^{-9}
500	36.78	57.93	8.17	116.31	183.20	10.57	1.67×10^{-9}
600	15.24	21.55	1.44	48.20	68.16	1.88	3.03×10^{-9}
700	10.81	15.29	0.1	34.20	48.36	0.96	2.62×10^{-9}
800	7.37	10.64	0.34	23.30	33.66	0.45	2.30×10^{-9}
900	6.11	8.64	0.24	19.33	27.34	0.31	2.06×10^{-9}
1000	4.70	6.65	0.14	14.86	21.02	0.18	1.86×10^{-9}
100	5.45	9.52	0.13	17.24	30.09	0.16	2.94×10^{-9}
200	1.49	2.10	0.010	4.70	6.65	0.012	2.01×10^{-9}

- For doublet, we can probe VLLs up to 1 TeV (Run III and HL-LHC). For singlet, we can only exclude them for 100 GeV (Run-III) or 200 GeV (HL-LHC);
- Assuming the more conservative metric, $\mathcal{Z}_A$, the doublet can be excluded up to 500 GeV.

Lepton colliders

	200 GeV	700 GeV	1200 GeV	1700 GeV	2200 GeV	2700 GeV	3200 GeV	3700 GeV
$E_{\rm CM} = 1.5$ TeV	19.18 fb	5.51 fb	–	–	–	–	–	–
$E_{\rm CM} = 3$ TeV	5.00 fb	4.21 fb	2.49 fb	–	–	–	–	–
$E_{\rm CM} = 10$ TeV	0.46 fb	0.45 fb	0.44 fb	0.41 fb	0.39 fb	0.35 fb	0.31 fb	0.26 fb
$E_{\rm CM} = 14$ TeV	0.23 fb	0.23 fb	0.23 fb	0.22 fb	0.21 fb	0.21 fb	0.19 fb	0.18 fb
$E_{\rm CM} = 14$ TeV ($e^+e^-\gamma\gamma$)	17.95 fb	0.54 fb	0.095 fb	0.027 fb	0.0095 fb	0.0037 fb	0.001585 fb	0.00069 fb
$E_{\rm CM} = 14$ TeV ($\mu^+\mu^-\gamma\gamma$)	9.10 fb	0.26 fb	0.045 fb	0.012 fb	0.0043 fb	0.0017 fb	0.00070 fb	0.00030 fb

- **Greater cross-sections** can be obtained. Allowing higher mass ranges to be probed;
- **Maximal values** shortly after $E_{\rm CM} \sim 2M_{\rm VLL}$;
- Photon fusion processes grow with $\ln\left(s/m^2_{e,\mu}\right)$. Can play important role in high-energies and in the low mass regime;
- Relevant for singlet VLLs.

To summarize . . .

- We have analysed two simple extensions to the SM, with a **doublet** and **singlet** VLL in the context of the **LHC** and future **lepton colliders**;
- **Both models** can **successfully accommodate** the observed discrepancy for $(g-2)_\mu$ within 1σ bounds, across a wide range of masses;
- Using **Deep Learning** algorithms, we are caple of excluding VLLs at both **run-III and at HL-LHC**;
- Physics-case is analysed **for lepton colliders**. We find that **greater cross-sections** are obtained, allowing for a much wider range of masses to be probed, relevant for singlet VLLs, whose reach is at LHC is low.

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Thank you for your attention

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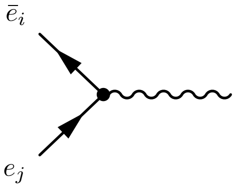
Backup



$$\mathrm{Z}^0 = \; i\big(g_L^Z\gamma_\mu \mathrm{P_L} + g_R^Z\gamma_\mu \mathrm{P_R}\big),$$

$$\begin{aligned} g_L^Z &= \frac{1}{2}(g\cos\theta_W - g'\sin\theta_W)\left[(U_L^e)^*_{j4}(U_L^e)_{i4} + \sum_{a=1}^{3}(U_L^e)^*_{ja}(U_L^e)_{ia}\right], \\ g_R^Z &= -g'\sin(\theta_W)\sum_{a=1}^{3}(U_R^e)^*_{ia}(U_R^e)_{ja} + \frac{1}{2}(U_R^e)^*_{i4}(U_R^e)_{j4}(g\cos\theta_W - g'\sin\theta_W), \end{aligned} \tag{1}$$

$$\begin{aligned} & g_L^Z = \frac{1}{2}(g\cos\theta_W - g'\sin\theta_W)\left[(U_L^e)^*_{44}(U_L^e)_{24} + \sum_{a=1}^{3}(U_L^e)^*_{4a}(U_L^e)_{2a}\right] \Leftrightarrow \\ \Leftrightarrow \quad & g_L^Z = \frac{1}{2}(g\cos\theta_W - g'\sin\theta_W)[\cos\alpha\sin\alpha - \sin\alpha\cos\alpha] \Leftrightarrow g_L^Z = 0. \end{aligned} \tag{2}$$

$$\mathcal{L}_{doublet} = \Big(\Theta_i \bar{E}_{\rm L} e^i_{\rm R}\phi + \Upsilon \bar{E}_{\rm L}\nu_{\rm R}\tilde{\phi} + \Sigma_i \bar{L}^i \nu_{\rm R}\tilde{\phi} + \Omega \bar{E}_{\rm R}\nu_R\tilde{\phi} + \Pi_{ij}\bar{L}^i e^j_{\rm R}\phi + \text{H.c.}\Big) + \\ + M_E \bar{E}_{\rm L} E_{\rm R} + M^i_{LE}\bar{L}_i E_{\rm R} + \frac{1}{2} M_{\nu_{\rm R}} \bar{\nu}_R \nu_R \,, \tag{3}$$

$$\mathcal{L}_{singlet} = \Big(\theta_i \bar{L}^i \mathcal{E}_{\rm R}\phi + \sigma^i \bar{L}_i \nu_{\rm R}\tilde{\phi} + \pi_{ij}\bar{L}^i e^j_{\rm R}\phi + \text{H.c.}\Big) + M_E \bar{\mathcal{E}}_{\rm L}\mathcal{E}_{\rm R} + \frac{1}{2} M_{\nu_{\rm R}} \bar{\nu}_R \nu_R \,, \tag{4}$$

we have

$$\begin{aligned} g_L^{E\nu_\mu W} &= \frac{g}{\sqrt{2}}\sin\alpha\left[U_\nu^{\text{doublet}}\right]_{22}, \\ g_L^{E\nu_R W} &= \frac{g}{\sqrt{2}}\cos\alpha, \\ g_L^{\mathcal{E}\nu_\mu W} &= \frac{g}{\sqrt{2}}\sin\alpha\left[U_\nu^{\text{singlet}}\right]_{22}. \end{aligned} \tag{5}$$

This in turn means that the cross section for the doublet case will be much larger than the one for the singlet case, because the strength of the dominant contribution for the former, in particular the coupling to right-handed neutrinos, is proportional to $\cos\alpha$ while for the latter it is controlled by $\sin\alpha$.