Constraining sterile neutrinos from the Higgs

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29th November 2018

Higgs Couplings 2018

大阪大学
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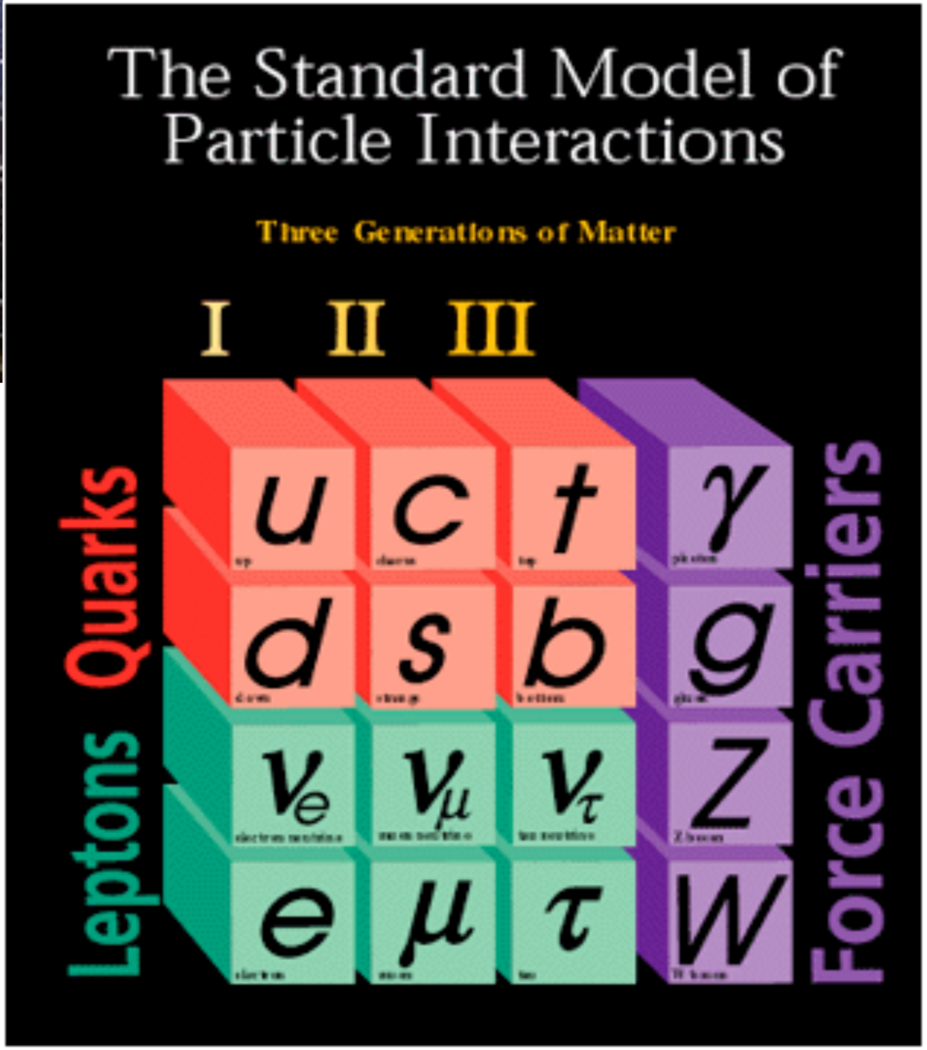
Building Blocks of Nature

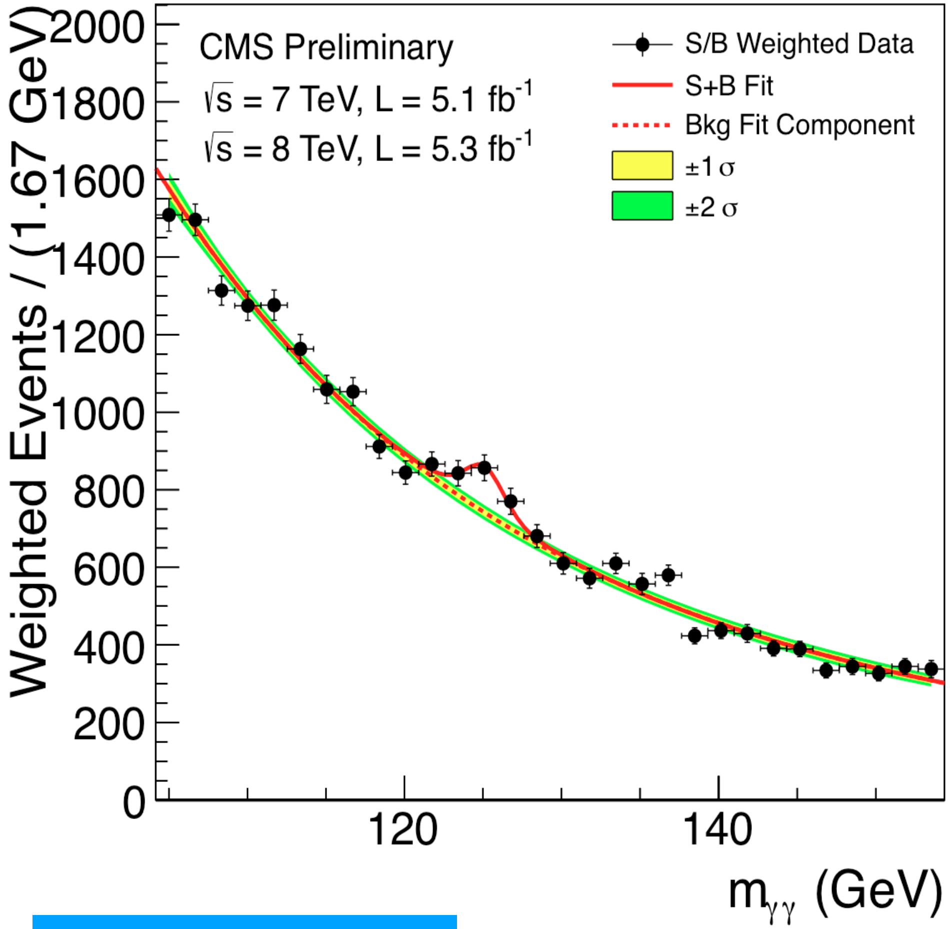
SM = $SU(3)_C \times SU(2)_L \times U(1)_Y$

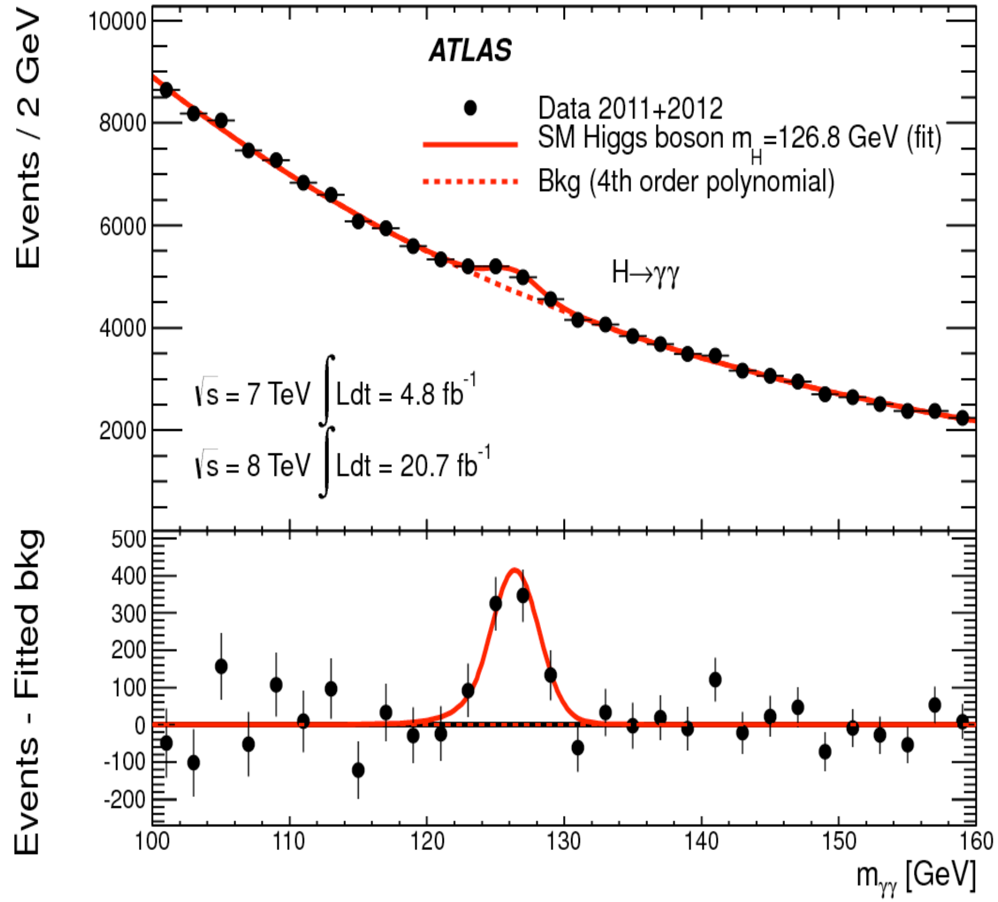


Solved many things and having unsolved issues such as gauge hierarchy problem, existence of tiny neutrino mass

Our point of interest today

Discovery of Higgs boson





Nobel Prize in 2012

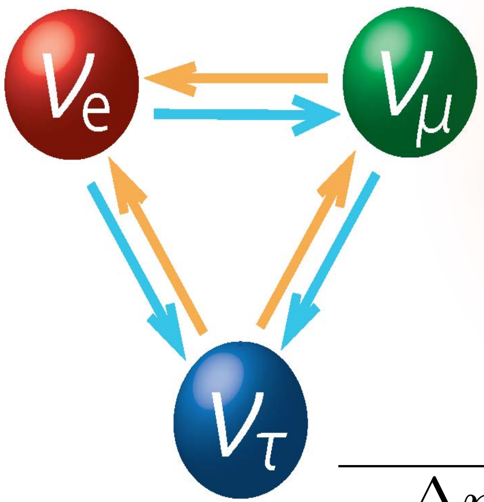
Role in future

Higgs boson mass around 125 GeV

Results in the neutrino Sector

Super- Kamiokande, Sudbury Neutrino Observatory 1999 ,
Neutrino oscillation between mass and flavor eigenstates

Neutrinos are very special



Physics Nobel Prize 2015

ν

Neutrino oscillation data

Δm_{21}^2	$7.6 \times 10^{-5} \mathrm{eV}^2$	SNO
$\lvert \Delta m_{31} \rvert^2$	$2.4 \times 10^{-3} \mathrm{eV}^2$	Super – K
$\sin^2 2\theta_{12}$	0.87	KamLAND, SNO
$\sin^2 2\theta_{23}$	0.999	T2K
	0.90	MINOS
$\sin^2 2\theta_{13}$	0.084	DayaBay2015
	0.1	RENO
	0.09	DoubleChooz

Unsolved questions are there

There are many unsolved questions regarding the nature of the conversion between the flavor and mass mixings

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

(Non-)Unitary ?

How do the neutrinos get mass : seesaw mechanism is the simplest idea. Apart from that there are many other (next-to) simple models like inverse seesaw, linear seesaw etc.

These models describe different natures (Majorana/ Dirac) of neutrino mass. However, yet to be fixed.

Seesaw Mechanism

Gell-Mann, Glashow, Minkowski, Mohapatra, Ramond, Senjanovic, Slansky, Yanagida

Extending the SM with SM-singlet heavy neutrino

$$\mathcal{L} \supset -\sum_{i=1}^{3}\sum_{j=1}^{2} Y_D^{ij}\overline{\ell_L^{\,i}} H N_R^j - \frac{1}{2}\sum_{k=1}^{2} m_N^k \overline{N_R^{kC}} N_R^k + \text{H.c.}$$

Dirac Mass term

Majorana Mass term

Neutrino mass matrix

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix}$$

$$m_D = \frac{Y_D}{\sqrt{2}} v$$

diagonalizing

$$m_\nu \simeq -m_D m_N^{-1} m_D^T.$$

Flavor eigenstate can be expressed in terms of the mass eigenstate

$$\nu_\ell \simeq U_{\ell m}\nu_m + V_{\ell n} N_n$$

PMNS matrix

$M_D M_N^{-1}$

Charged Current interaction

$$\mathcal{L}_{\mathrm{CC}} = -\frac{g}{\sqrt{2}} W_\mu \bar{\ell} \gamma^\mu P_L \underbrace{[U_{\ell m}\nu_m + V_{\ell n} N_n]}_{\nu_\ell} + \mathrm{H.c.},$$

Neutral Current interaction **Expanding ν_ℓ (twice)**

$$\mathcal{L}_{\mathrm{NC}} = -\frac{g}{2\cos\theta_w} Z_\mu [(U^\dagger U)_{mn} \bar{\nu}_m \gamma^\mu P_L \nu_n + (U^\dagger V)_{mn} \bar{\nu}_m \gamma^\mu P_L N_n + (V^\dagger V)_{mn} \bar{N}_m \gamma^\mu P_L N_n] + \mathrm{H.c.},$$

The interaction between the heavy right handed neutrinos and the SM gauge bosons are suppressed by the powers of the mixing (V) parameter.

Yukawa Interaction

$$\mathcal{L}_Y \supset -Y_{D_{\ell m}} \bar{L}_\ell \phi N_m + \text{H.c.}$$

$SU(2)_L$ lepton doublet

$SU(2)_L$ Higgs doublet

$\langle \phi^0 \rangle = v$ $\quad M_D = v Y_D \quad Y_D = V M_N / v$, which is also suppressed by V

$N \to \ell^- W^+, \nu_\ell Z, \nu_\ell h$

Mixing

SM Higgs boson, physical remnant of ϕ

Decay Widths

$$\Gamma(N \to \ell^- W^+) = \frac{g^2 |V_{\ell N}|^2}{64\pi} \frac{M_N^3}{M_W^2} \left(1 - \frac{M_W^2}{M_N^2}\right)^2 \left(1 + \frac{2M_W^2}{M_N^2}\right)$$

$$\Gamma(N \to \nu_\ell Z) = \frac{g^2 |V_{\ell N}|^2}{128\pi} \frac{M_N^3}{M_W^2} \left(1 - \frac{M_Z^2}{M_N^2}\right)^2 \left(1 + \frac{2M_Z^2}{M_N^2}\right)$$

$$\Gamma(N_1 \to \nu_\ell h) = \frac{|V_{\ell N}|^2}{128\pi} \frac{M_N^3}{M_W^2} \left(1 - \frac{M_h^2}{M_N^2}\right)^2$$

Das, Konar, Majhi: 1604.00608

$$M_N < M_W$$

All three body decays

$N \to \ell^- W^+$ → **leptons**

$$\Gamma(N \to \ell_1^- \ell_2^+ \nu_{\ell_2}) \simeq \frac{|V_{\ell_1 N}|^2 G_F^2 M_N^5}{192\pi^3}$$

$$\Gamma(N \to \nu_{\ell_1} \ell_2^+ \ell_2^-) \simeq \frac{|V_{\ell_1 N}|^2 G_F^2 M_N^5}{96\pi^3}(g_L g_R + g_L^2 + g_R^2)$$

$N \to \nu_\ell Z$ → **leptons**

Gorbunov and Shaposhnikov: arXiv:0705.1729
Atre, Han, Pascoli and Zhang: arXiv: 0901.3589
Dib and Kim : arXiv: 1509.05981

$$\Gamma(N \to \nu_\ell \ell^+ \ell^-) \simeq \frac{|V_{\ell N}|^2 G_F^2 M_N^5}{96\pi^3}(g_L g_R + g_L^2 + g_R^2 + 1 + 2g_L)$$

$$\Gamma(N \to \nu_{\ell_1} \nu_{\ell_2} \bar{\nu}_{\ell_2}) \simeq \frac{|V_{\ell_1 N}|^2 G_F^2 M_N^5}{96\pi^3}$$

$N \to \ell^- W^+$ → **hadrons**

$$\Gamma(N \to \ell^- jj) \simeq 3\frac{|V_{\ell N}|^2 G_F^2 M_N^5}{192\pi^3}$$

Das, Dev, Kim: arXiv:1704.0880
Das, Gao, Kamon: arXiv:1704.00881

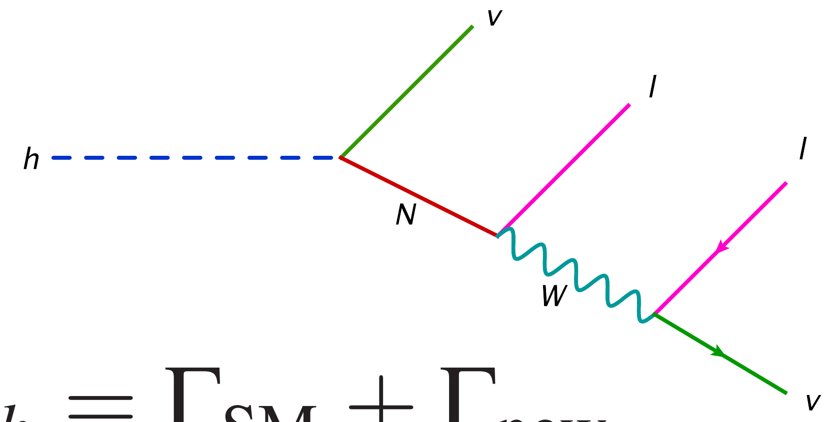
$N \to \nu_\ell Z$ → **hadrons**

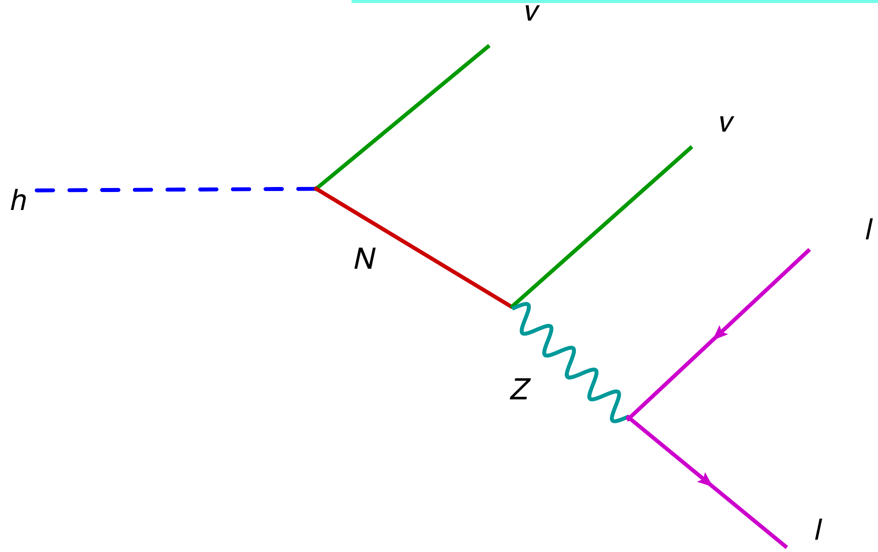
$$\Gamma(N \to \nu_\ell jj) \simeq 3\frac{|V_{\ell N}|^2 G_F^2 M_N^5}{96\pi^3}(g_L g_R + g_L^2 + g_R^2)$$

$$g_L = -\tfrac{1}{2} + \sin^2\theta_w, \; g_R = \sin^2\theta_w$$

Heavy Neutrino Production from Higgs Decay

Dev, Franceschini, Mohapatra: 1207.2756@8TeV LHC





$$\Gamma_h = \Gamma_{\rm SM} + \Gamma_{\rm new}$$

$$\Gamma_{\rm SM} \simeq 4.1 \text{ MeV for } M_h = 125 \text{ GeV} \qquad \Gamma_{\rm new} = \frac{Y_D^2 M_h}{8\pi}\left(1 - \frac{M_N^2}{M_h^2}\right)^2$$

$$h \to WW^* \to 2\ell 2\nu \qquad h \to \nu N \to 2\ell 2\nu$$

Region	Mass range
1	$M_N < M_W$
2	$M_W < M_N < M_Z$
3	$M_Z < M_N < M_h$
4	$M_N > M_h$

$$pp \to h \to \nu N \to 2\ell 2\nu.\ \ell = e, \mu$$

Final States: OSSF $\mu\bar{\mu}\nu\bar{\nu}$ and $e\bar{e}\nu\bar{\nu}$

OSOF $\mu\bar{e}\nu\bar{\nu}$ and $e\bar{\mu}\nu\bar{\nu}$

We consider all sorts of charge combinations as Higgs can decay into heavy and anti-heavy neutrinos for Dirac type heavy neutrino or for a Majorana type case the heavy neutrino can decay into both positively and negatively charged leptons

Selection Cuts

ATLAS Phys. Rev. D 92, 012006

$\boxed{\mu\bar{\mu}}$ $p_T^{\ell_2,\text{sub-leading}} > 10$ GeV $p_T^{\ell_1,\text{leading}} > 22$ GeV. $p_T^j > 25$ GeV

$|\eta^{\ell_{1,2}}| < 2.4$ $|\eta^j| < 2.4$ $\Delta R_{\ell\ell} > 0.3$ $\Delta R_{\ell j} > 0.3$ $\Delta R_{jj} > 0.3$

$m_{\ell\ell} > 12$ GeV $\not{E}_T > 40$ GeV

Dilepton transverse momentum is away from the MET $\Delta\phi^{\ell\ell,\text{MET}} > \frac{\pi}{2}$

$p_T^{\ell\ell} > 30$ GeV

$\boxed{e\bar{e}}$ **Same as the previous slide except** $|\eta^{\ell_{1,2}}| < 2.47$

$\boxed{\mu\bar{e}(e\bar{\mu})}$ $|\eta^{e}| < 2.47,\ |\eta^{\mu}| < 2.4$ $m_{e\mu} > 10$ GeV and $\not{E}_T > 20$ GeV

The transverse mass cut is common in the three cases

$$m_T\colon \tfrac{3}{4}M_h < m_T < M_h.$$

$$m_T = \sqrt{(E^{\ell\ell} + p_T^{\nu\nu})^2 - |\vec{p_T}^{\ell\ell} + \vec{p_T}^{\nu\nu}|^2} \qquad E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + (m_{\ell\ell})^2}$$

$\vec{p_T}^{\nu\nu}(\vec{p_T}^{\ell\ell})$ = **Vector sum of the neutrino (lepton) transverse momenta**

$p_T^{\nu\nu}(p_T^{\ell\ell})$ **is the magnitude**

For more detailed analysis of the backgrounds and separation techniques, see Refs. [111-114] of arXiv:1704.0880.

Limits on the mixing angle

After applying the cuts from ATLAS we calculate the yield

$$\mathcal{N}(M_N, |V_{\ell N}|^2) = L \cdot \sigma_h^{\rm SM} \left[\epsilon^{\rm SM} \frac{\Gamma(h \to WW^* \to \ell\bar{\ell}\nu\bar{\nu})}{\Gamma_{\rm SM} + \Gamma_{\rm New}} + \sum_{j,k} \epsilon_{jk} \frac{\Gamma(h \to \bar{\nu}N + \text{c.c.} \to \ell_j \bar{\ell}_k \nu\bar{\nu})}{\Gamma_{\rm SM} + \Gamma_{\rm New}} \right]$$

L **= Integrated luminosity** $\sigma_h^{\rm SM}(pp \to h)$ **= SM Higgs production cross section**

$\epsilon_{\rm SM}$, ϵ_{jk} **= efficiencies for the decays mediated by SM and in presence of heavy neutrino, respectively**

e and μ

Calculated using cuts of ATLAS

$\Gamma(h \to WW^* \to \ell\bar{\ell}\nu\bar{\nu})$, $\Gamma_{\rm SM}$ S. Heinemeyer *et al.* (LHC Higgs Cross Section Working Group), arXiv:1307.1347.

$\sigma_h^{\rm SM}$ **8 TeV** https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV.

14 TeV, 100 TeV https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy.

$$|V_{\ell N}|^2 \xrightarrow[\text{Maximal values}]{} \mathcal{N}(M_N, |V_{\ell N}|^2) < \mathcal{N}_{\text{expt}}$$

$\mathcal{N}_{\text{expt}} = 169$

G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. D **92**, 012006 (2015).

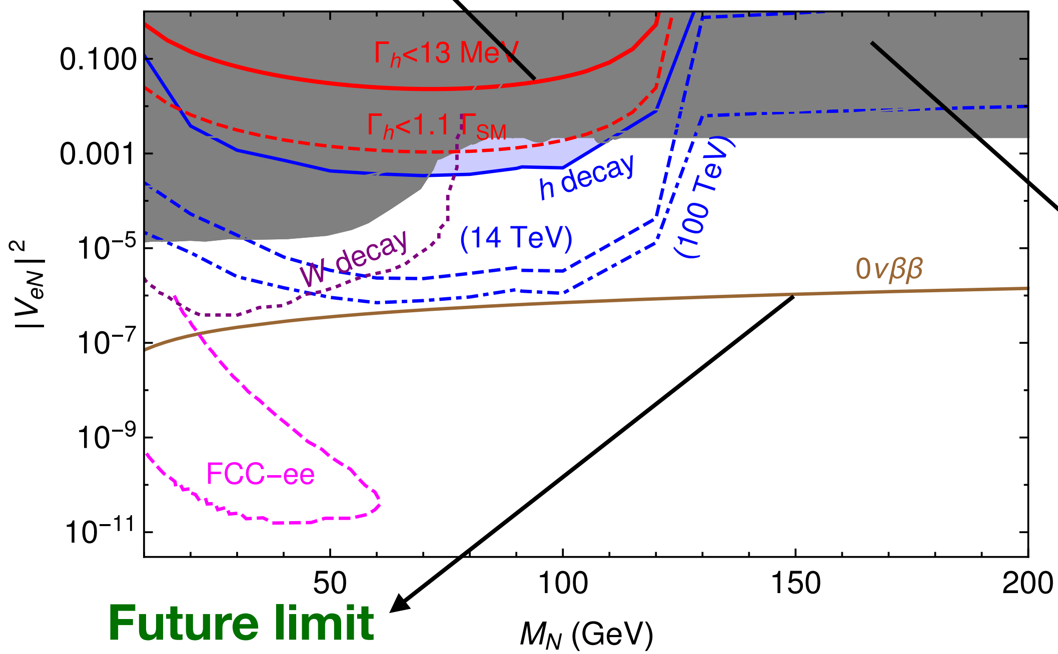
for $M_h = 125$ GeV at $\sqrt{s} = 8$ TeV with $L = 20.3\ \text{fb}^{-1}$

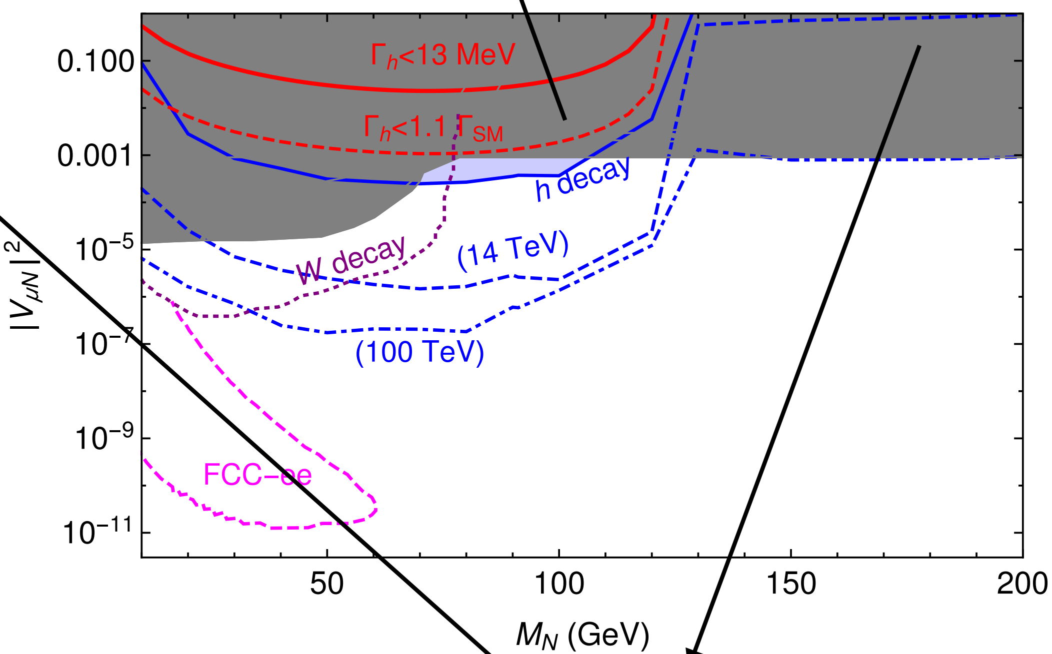
Assuming the same $\mathcal{N}_{\text{expt}}$ for $\sqrt{s} = 14$ and 100 TeV colliders, but with an integrated luminosity of 3000 fb^{-1},

we also show the corresponding future limits

CMS, JHEP 09 (2016) 051: 7&8 TeV combined $H \longrightarrow W W^*$, upper limit on Yukawa as well as mixing

Future sensitivity can go down to 10%precise result at pp collider: arXiv:1606.09408

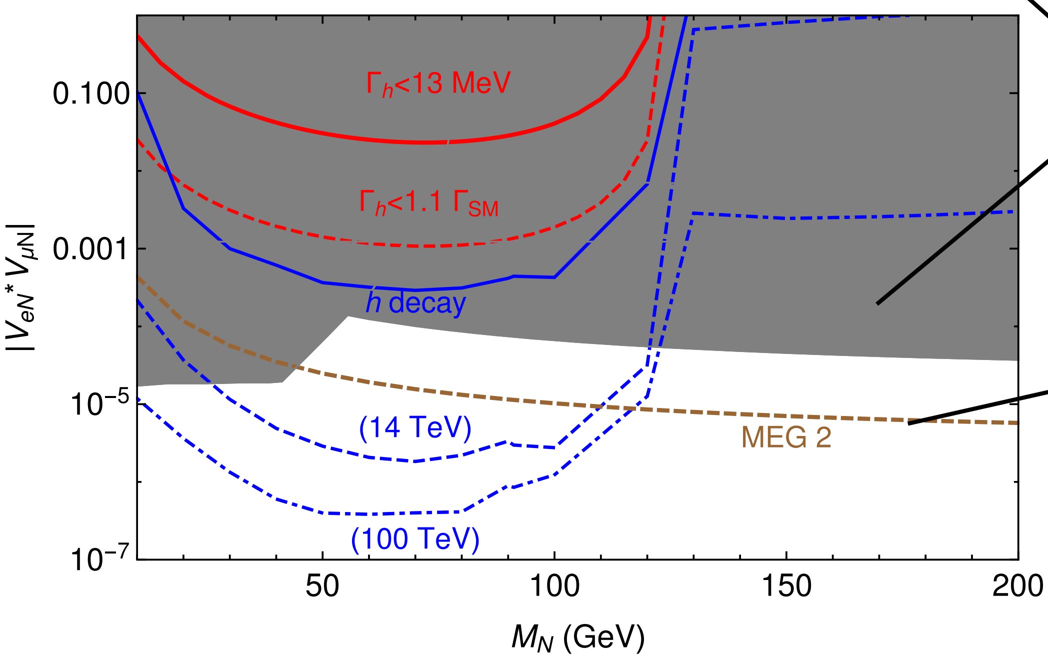




Future limit considering Majorana heavy neutrinos only

Excluded by LEP LHC,EWPD,

LFV limits from CMS is also included in the lower panel



FCC-ee : Limits from Z decay

W-decay @LHC

Future limits

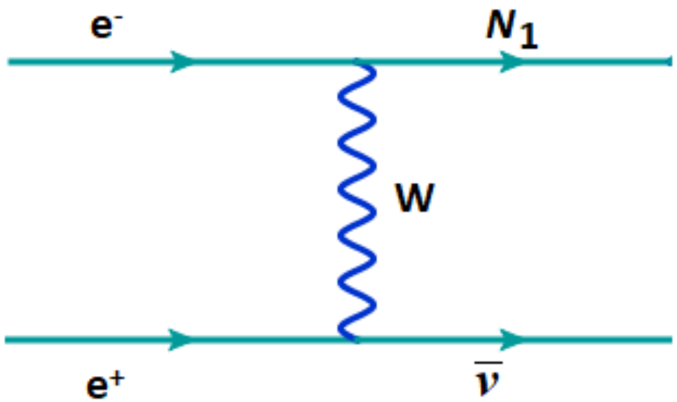
$\mu \rightarrow e\gamma$

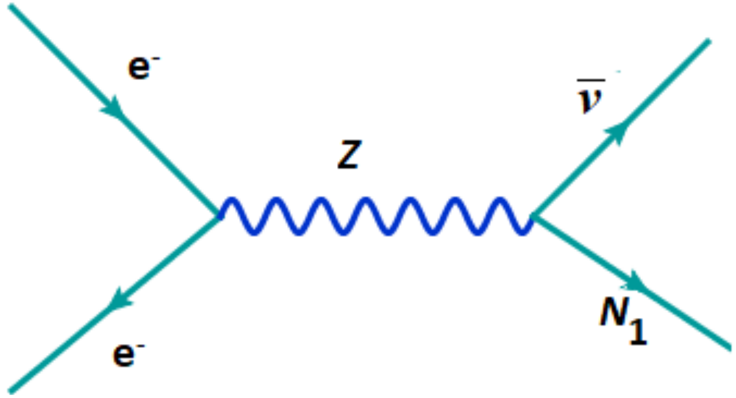
~ future branching ratio O(10 -15)

arXiv:1704.0880

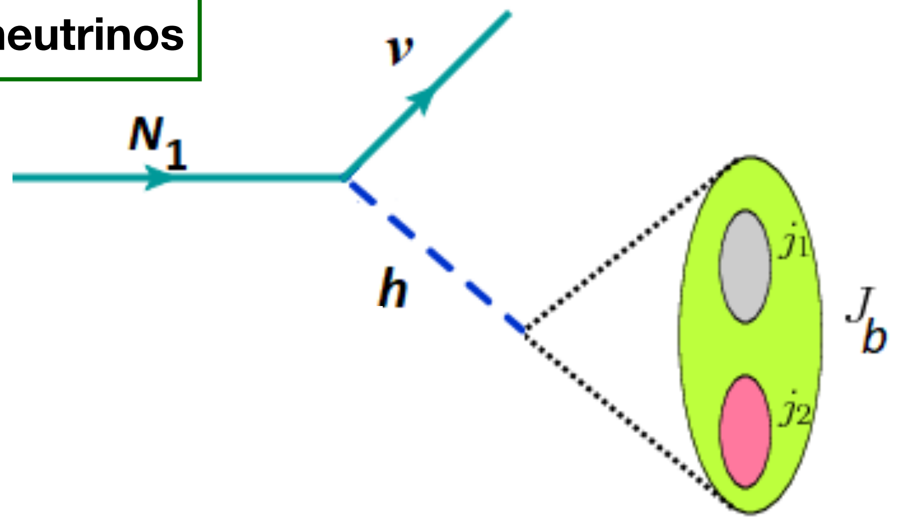
Right handed neutrino production at the linear collider

See also: 1008.2257, 1207.3734, 1502.05915,1503.05491, 1512.06035, 1604.02420, 1612.02728, 1810.08970, 1811.04291, etc.





Higgs production from right handed neutrinos



Basic cuts

1. Electrons in the final state should have the following transverse momentum (p_T^e) and pseudo-rapidity ($|\eta^e|$) as $p_T^e > 10$ GeV, $|\eta^e| < 2.5$.

2. Jets are ordered in p_T, jets should have $p_T^j > 10$ GeV and $|\eta^j| < 2.5$.

3. Photons are counted if $p_T^\gamma > 10$ GeV and $|\eta^\gamma| < 2.5$.

4. Leptons should be separated by $\Delta R_{\ell\ell} > 0.2$.

5. The leptons and photons are separated by $\Delta R_{\ell\gamma} > 0.3$.

6. The jets and leptons should be separated by $\Delta R_{\ell j} > 0.3$.

7. Fat Jet is constructed with radius parameter $R = 0.8$.

Advanced Cuts

- *Advanced cuts for $M_N = 400\ GeV$- $900\ GeV$ at the $\sqrt{s} = 1\ TeV$ linear collider*

- Transverse momentum for J_b, $p_T^{J_b} > 250$ GeV.
- Fat-b mass, $M_{J_b} > 115$ GeV.
- Missing energy, $p_T^{miss} > 150$ GeV.

Benchmark : 700 GeV and 800 GeV

- *Advanced cuts for the $M_N = 1\ TeV$ -2.9 TeV for the $\sqrt{s} = 3\ TeV$ linear collider*

- Transverse momentum for fat-b (J_b), $p_T^{J_b} > 350$ GeV.
- Fat-b mass, $M_{J_b} > 115$ GeV.
- Missing energy, $p_T^{miss} > 175$ GeV.

Benchmark : 1.5 TeV and 2.0 GeV

Cut flow for the linear colliders

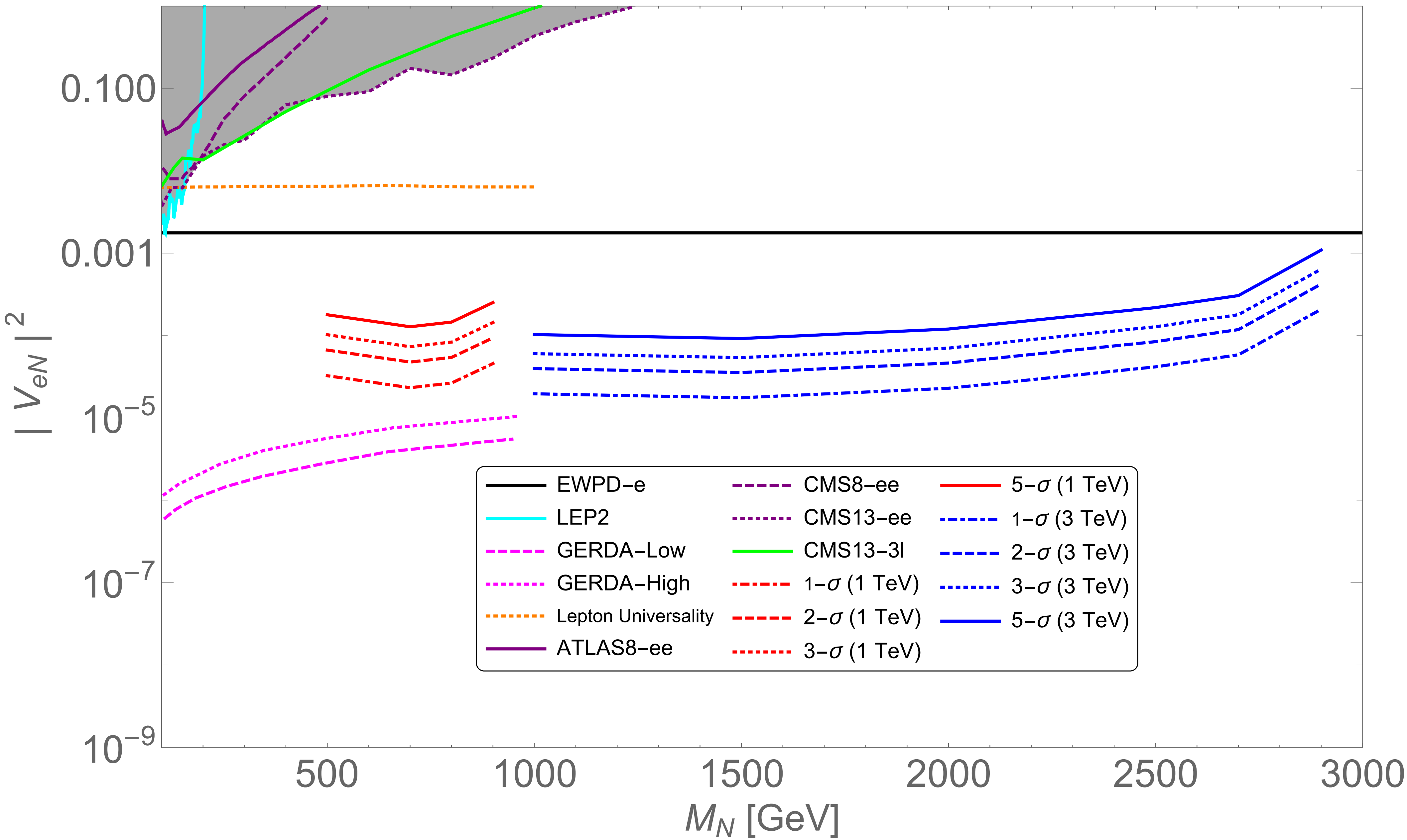
1 TeV

Cuts	Signal		Background
	$M_N = 700$ GeV	$M_N = 800$ GeV	
Basic Cuts	3,710,000	2,600,000	159,740
$p_T^{miss} > 150$ GeV	3,162,849	2,306,928	24,903
$p_T^{J_b} > 250$ GeV	1,050,634	991,978	3,172
$M_{J_b} > 115$ GeV	924,000	811,000	446

3 TeV

Cuts	Signal		Background
	$M_N = 1.5$ TeV	$M_N = 2$ TeV	
Basic Cuts	5,910,000	4,380,000	371,420
$p_T^{miss} > 175$ GeV	5,538,438	4,224,334	72,284
$p_T^{J_b} > 350$ GeV	3,206,529	2,457,662	11,798
$M_{J_b} > 115$ GeV	2,490,000	1,910,000	1,870

Limits on the mixing angle



See,1811.04291 for the references regarding the bounds

Conclusions

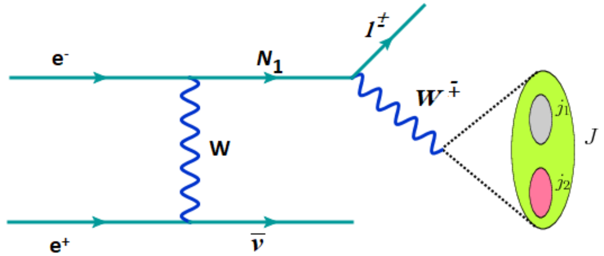
We have studied the production processes of the heavy neutrinos from Higgs at the LHC and future colliders.

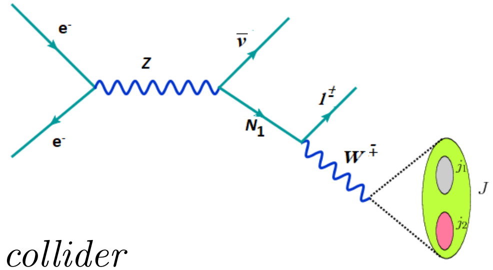
We have studied dilepton plus MET final state and constrained it from the recent ATLAS search ($h \longrightarrow WW^*$) at the 8 TeV to put current and prospective (14 TeV and 100 TeV) upper limits on the mixing angles.

We have studied the production process of the RHNs at the linear collider where a heavy RHN can be tested. Such RHNs can sufficiently boost the daughter particles to study the fat jet signature. We consider Higgs as an example such that a fat-b jet plus missing momentum can constrain the light-heavy mixings at the linear collider.


Thank you for your attention

Backup slides





Advanced cuts for $M_N = 400$ *GeV-900 GeV at the* $\sqrt{s} = 1$ *TeV linear collider*

- Transverse momentum for fat-jet $p_T^J > 150$ GeV for M_N mass range 400 GeV-600 GeV and $p_T^J > 250$ GeV for M_N mass range 700 GeV-900 GeV.
- Transverse momentum for leading lepton $p_T^{e^\pm} > 100$ GeV for M_N mass range 400 GeV-600 GeV and $p_T^{e^\pm} > 200$ GeV for M_N mass range 700 GeV-900 GeV.
- Polar angle of lepton and fat-jet $|\cos\theta_e| < 0.85$, $|\cos\theta_J| < 0.85$.
- Fat-jet mass $M_J > 70$ GeV.

500 GeV @ 1 TeV linear collider

Cuts	Signal	Background				Total
		$\nu_e eW$	WW	ZZ	$t\bar{t}$	
Basic Cuts	27,560,000	2,306,000	344,000	69,500	332,800	3,052,000
$\lvert\cos\theta_J\rvert \leq 0.85$	14,741,800	218,400	66,800	1,560	19,005	306,020
$\lvert\cos\theta_e\rvert \leq 0.85$	14,590,000	69,360	34,220	555	17,480	121,620
$p_T^J > 150$ GeV	13,314,236	62,360	34,024	411	17,447	114,243
$M_J > 70$ GeV	10,482,000	54,350	30,530	366	16,580	101,820
$p_T^\ell > 100$ GeV	10,250,000	49,270	27,960	12	7,780	85,020

800 GeV @ 1 TeV linear collider

Cuts	Signal	Background				Total
		$\nu_e eW$	WW	ZZ	$t\bar{t}$	
Basic Cuts	12,560,000	2,306,000	344,000	69,500	332,800	3,052,000
$\lvert\cos\theta_J\rvert \leq 0.85$	9,184,800	218,400	66,800	1,560	19,005	306,020
$\lvert\cos\theta_e\rvert \leq 0.85$	9,110,000	69,360	34,220	555	17,480	121,620
$p_T^J > 250$ GeV	7,918,577	61,756	34,020	502	15,720	111,998
$M_J > 70$ GeV	7,260,000	45,880	30,500	344	15,380	92,100
$p_T^\ell > 200$ GeV	7,170,000	31,940	21,920	10	3,010	56,880

Advanced cuts for $M_N = 700$ GeV-2.9 TeV at the $\sqrt{s} = 3$ TeV linear collider

- Transverse momentum for fat-jet $p_T^J > 250$ GeV for the M_N mass range 700 GeV-900 GeV and $p_T^J > 400$ GeV for M_N mass range $1 - 2.9$ TeV.
- Transverse momentum for leading lepton $p_T^{e^\pm} > 200$ GeV for M_N mass range $700 - 900$ GeV and $p_T^{e^\pm} > 250$ GeV for M_N mass range $1 - 2.9$ TeV.
- Polar angle of lepton and fat-jet $|\cos\,\theta_e| < 0.85$, $|\cos\,\theta_J| < 0.85$.
- Fat-jet mass $M_J > 70$ GeV.

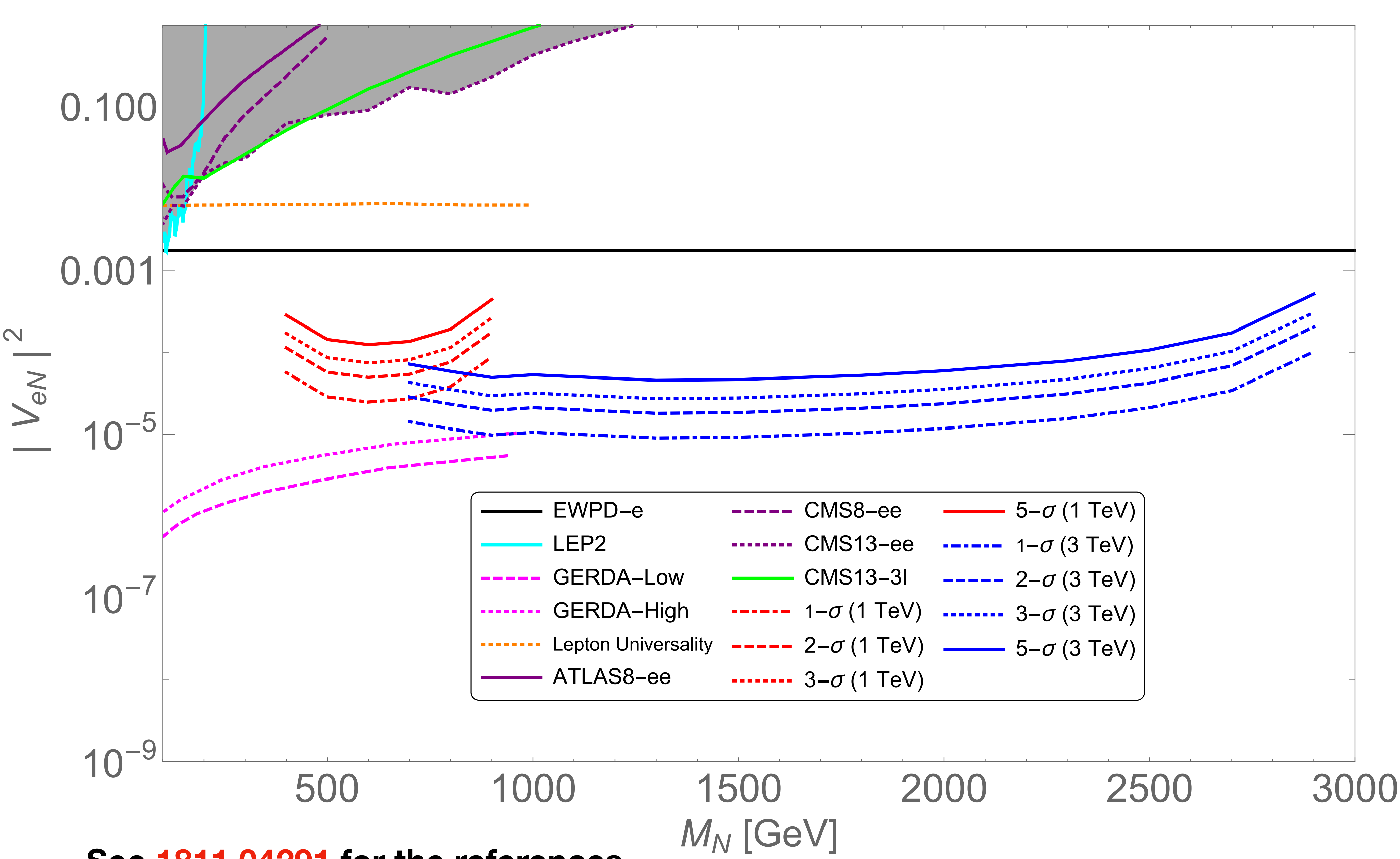
800 GeV @ 3 TeV linear collider

Cuts	Signal	Background				Total
		$\nu_e eW$	WW	ZZ	$t\bar{t}$	
Basic Cuts	34,420,000	3,690,000	55,600	11,720	38,200	3,795,600
$\lvert\cos\,\theta_J\rvert \leq 0.85$	15,757,000	196,640	6,240	143	324	203,348
$\lvert\cos\,\theta_e\rvert \leq 0.85$	14,810,000	37,580	4,720	110.8	220	42,620
$p_T^J > 250$ GeV	13,481,625	26,145	4,640	110	224	31,120
$M_J > 70$ GeV	13,250,600	22,020	4,460	1	220	26,780
$p_T^\ell > 200$ GeV	13,100,000	18,860	4,160	1	144	23,165

2000 GeV @ 3 TeV linear collider

Cuts	Signal	Background				Total
		$\nu_e eW$	WW	ZZ	$t\bar{t}$	
Basic Cuts	20,320,000	3,690,000	55,600	11,720	38,200	3,795,600
$\lvert\cos\,\theta_J\rvert \leq 0.85$	12,382,300	196,640	6,240	143	324	203,348
$\lvert\cos\,\theta_e\rvert \leq 0.85$	12,360,000	37,580	4,720	110.8	220	42,620
$p_T^J > 400$ GeV	12,297,867	19,100	4,689	110	215	24,115
$M_J > 70$ GeV	11,820,000	17,120	4,460	1	220	21,800
$p_T^\ell > 250$ GeV	11,810,000	15,120	4,080	1	128	19,330

Limits on the mixing angle



See, 1811.04291 for the references