Heavy neutrino search from the Higgs decay

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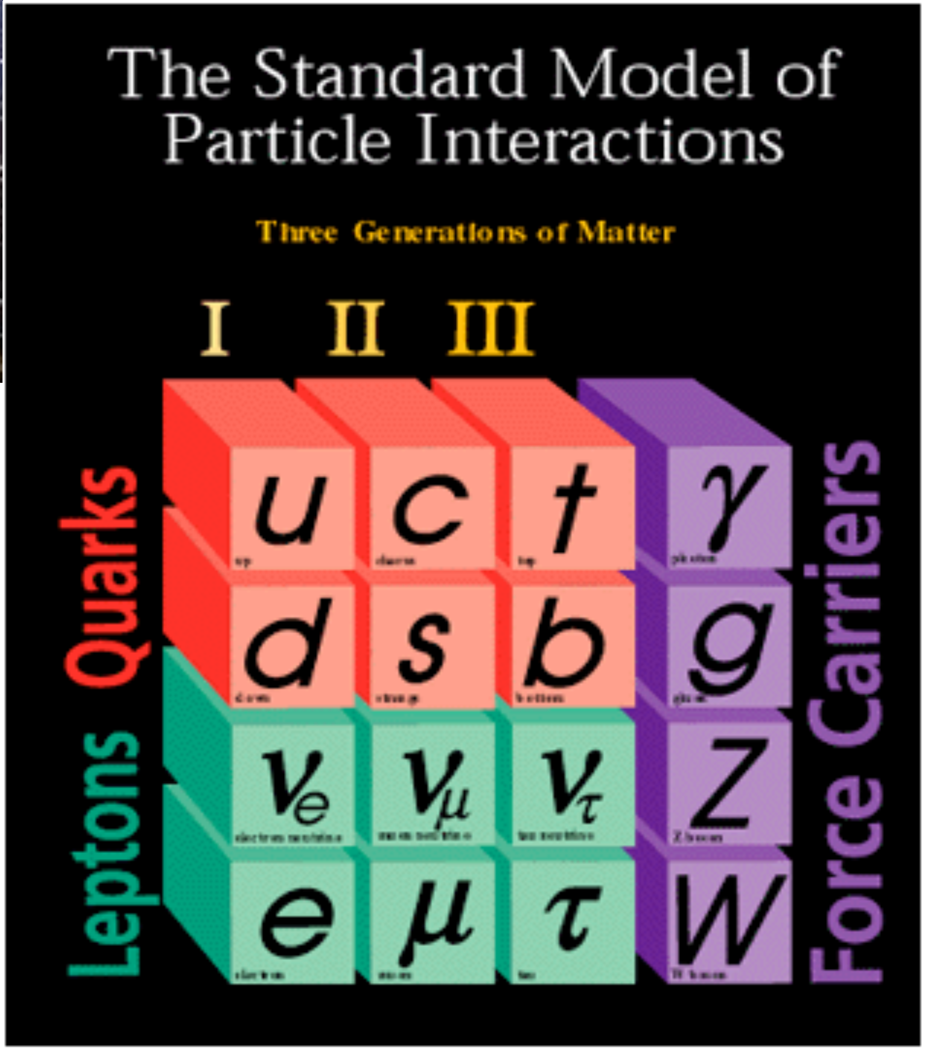
Building Blocks of Nature

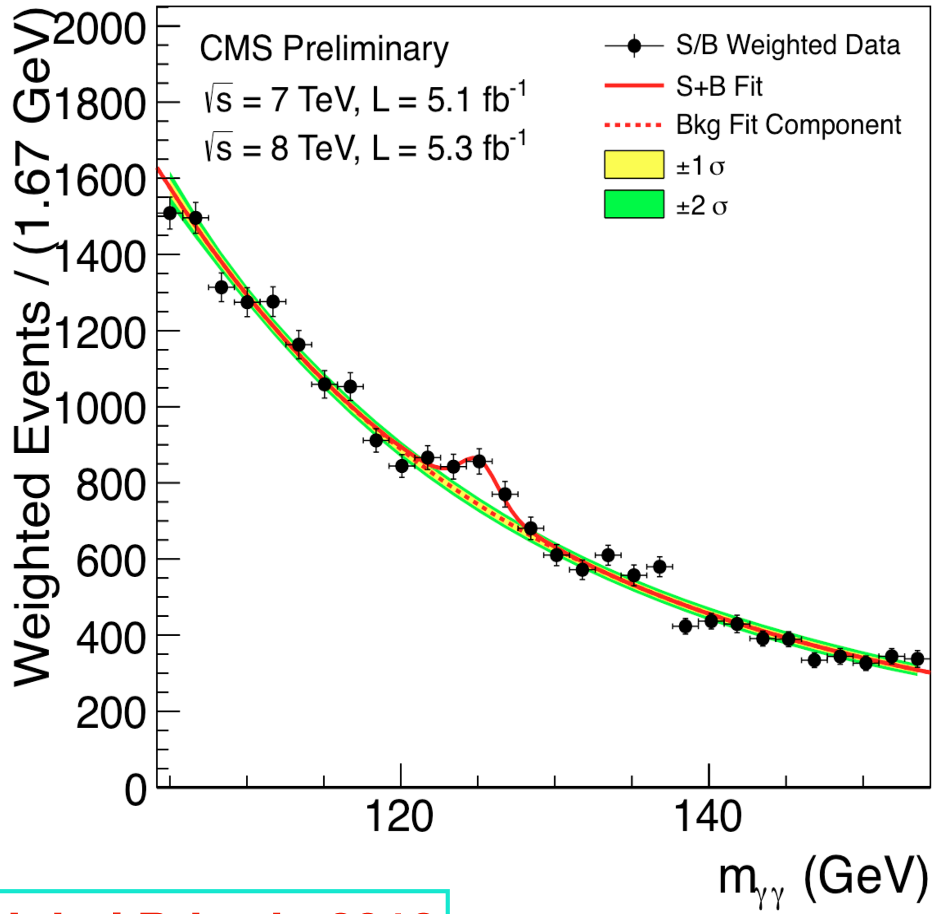
$SM = SU(3)_C \times SU(2)_L \times U(1)_Y$

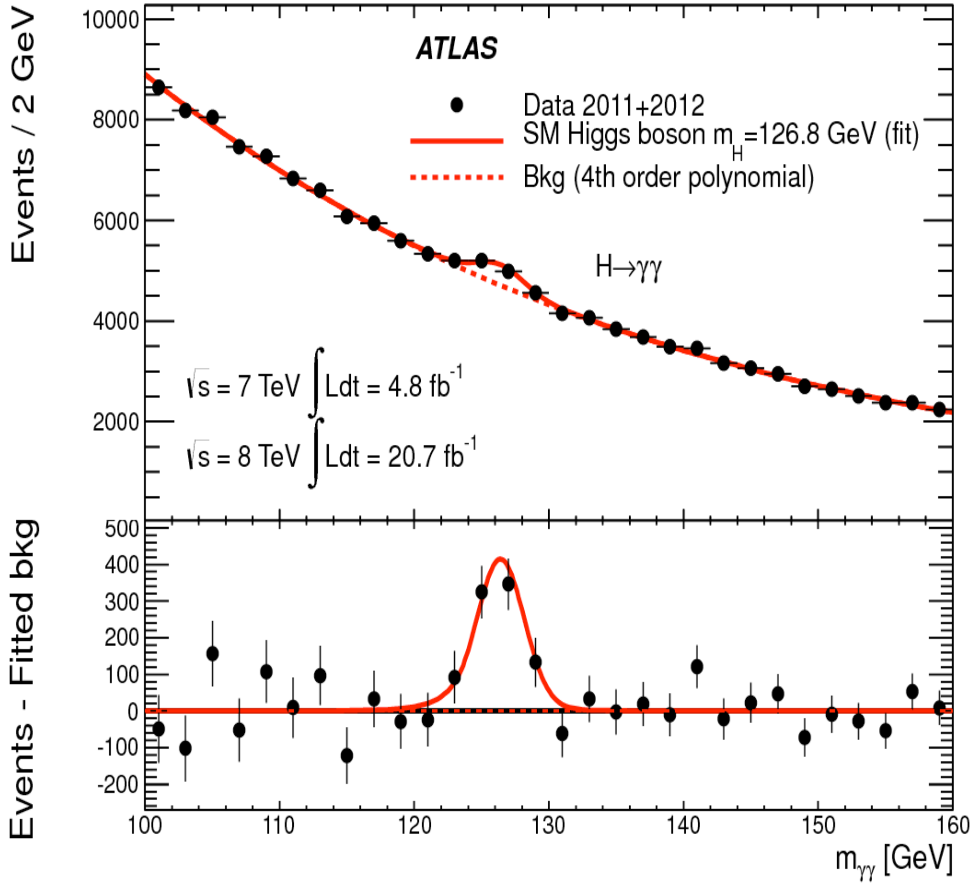


Solved many things and having unsolved issues such as gauge hierarchy problem, existence of tiny neutrino mass

Our point of interest today

Discovery of Higgs boson





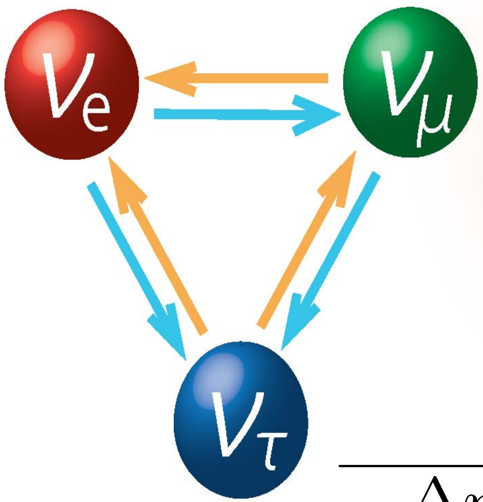
Nobel Prize in 2012

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^2_{21}	$7.6 \times 10^{-5}\mathrm{eV}^2$	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 ?

Winter's talk in Plenary,
Mohapatra's talk in Plenary
Future prospects: Marfatia
New Physics: Irina Mocioiu
GeV Neutrinos : Rasmussen
Bounds on type-I : Das

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

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

Dirac Mass term

Majorana Mass term

Neutrino mass matrix

plenary talks by Winter (19th June), Mohapatra (21st June)

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

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

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

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

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

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

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

Antusch, Atre, Chen, Deppisch, Dev, Drewes, Franceschini, Gao, Kamon, Kim, Mohapatra, Fischer, Han, Pascoli, Pilaftsis, Senjanovic

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

$SU(2)_L$ 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, Okada; Das, Konar, Majhi; Deppisch, Dev, Pilaftsis: Review arXiv:1502.06541

$M_N < M_W$

All three body decays

$N \to \ell^- W^+ \to$ **leptons**

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

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

$N \to \nu_\ell Z \to$ **leptons**

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

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

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

$N \to \ell^- W^+ \to$ **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

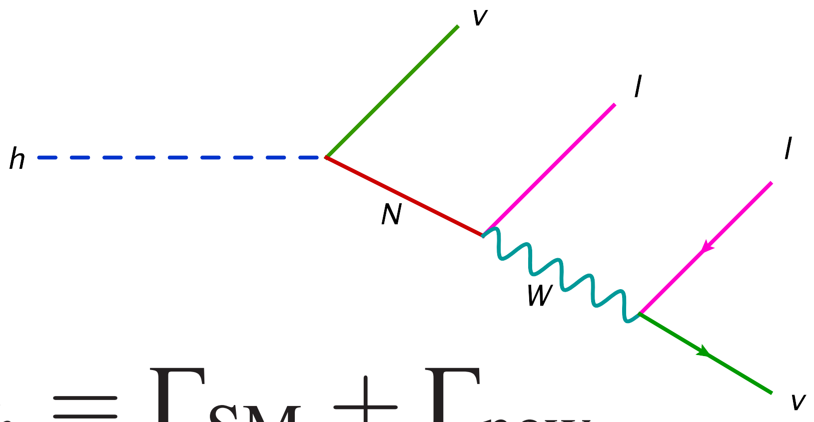
$N \to \nu_\ell Z \to$ **hadrons**

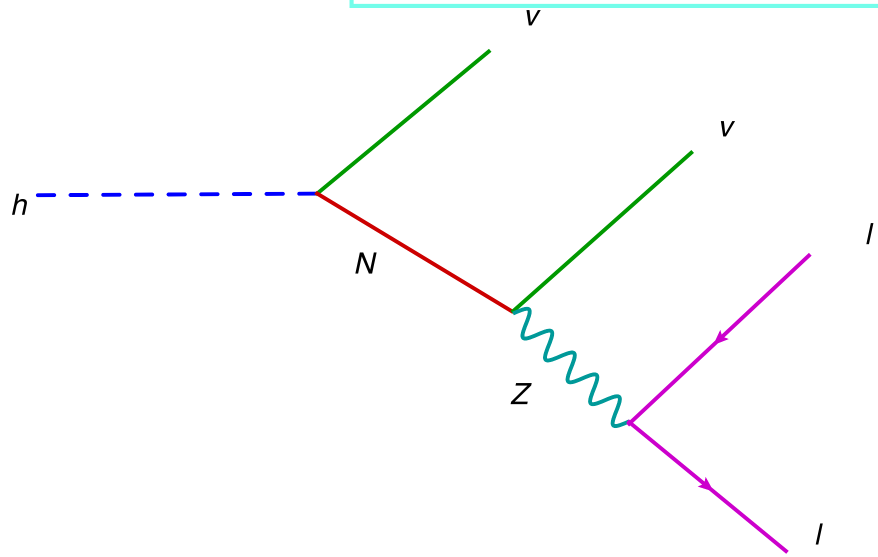
$$\Gamma(N \to \nu_\ell jj) \simeq 3\frac{|V_{\ell N}|^2 G_F^2 M_N^5}{96\pi^3}(g_L g_R + g_L^2 + g_R^2)$$

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

Heavy Neutrino Production from Higgs Decay

Dev, Franceschini, Mohapatra: PRD86,093010(2012)@8TeV LHC





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

$$\Gamma_{\rm SM} \simeq 4.1 \text{ MeV for } M_h = 125 \text{ GeV}$$

$$\Gamma_{\rm new} = \frac{Y_D^2 M_h}{8\pi}\left(1 - \frac{M_N^2}{M_h^2}\right)^2$$

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

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

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

Higgs and new physics in the EW section:
CMS-ATLAS: Aeikens, Bortignon, Chakraborty, Herde, Ismail, Maksimovic, Rossin, Varol,
Plenary by Fan

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 $\quad p_T^{\ell_1,\text{leading}} > 22$ GeV. $\quad p_T^j > 25$ GeV

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

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

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

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

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

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

The transverse mass cut is common in the three cases

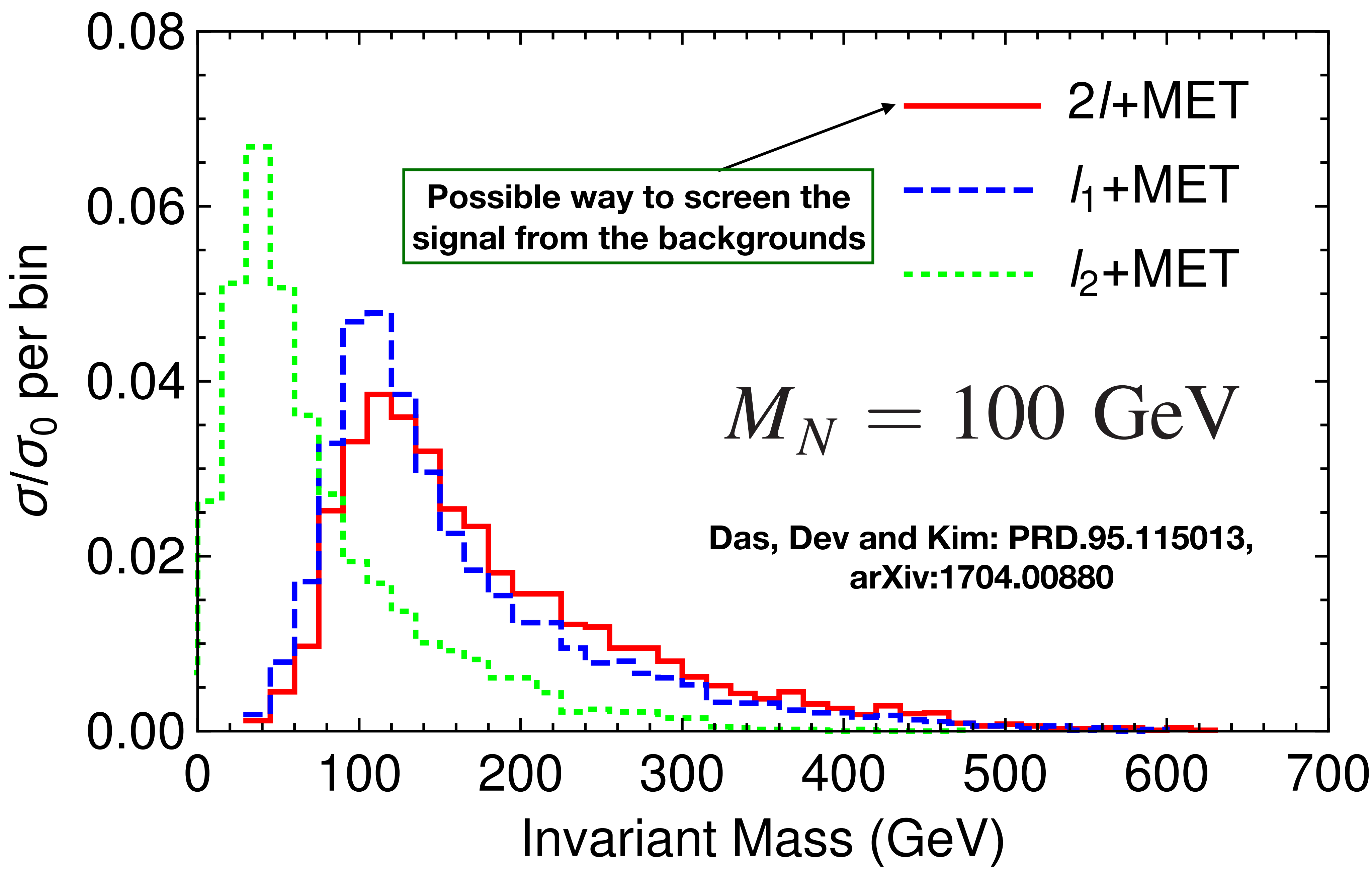
$$m_T\colon \tfrac{3}{4} M_h < m_T < M_h.$$

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

$\vec{p_T}^{\nu\nu}(\vec{p_T}^{\ell\ell})$ **= 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.


0.08
0.06
0.04
0.02
0.00
σ/σ_0 per bin
0
100
200
300
400
500
600
700
Invariant Mass (GeV)
2l+MET
l_1+MET
l_2+MET
Possible way to screen the signal from the backgrounds
$M_N = 100$ GeV
Das, Dev and Kim: PRD.95.115013, arXiv:1704.00880

Limits on the mixing angle

After applying the cuts from ATLAS we calculate the yield

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

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.

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

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

$$\downarrow$$

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

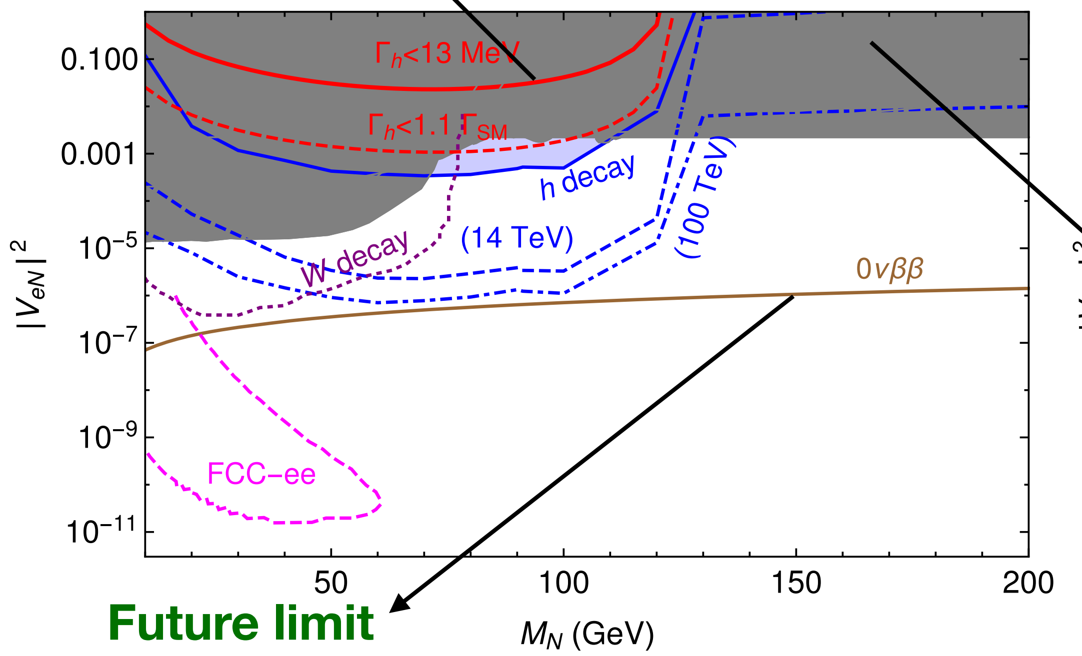
for $M_h = 125$ GeV at $\sqrt{s} = 8$ TeV with $L = 20.3\ \mathrm{fb}^{-1}$

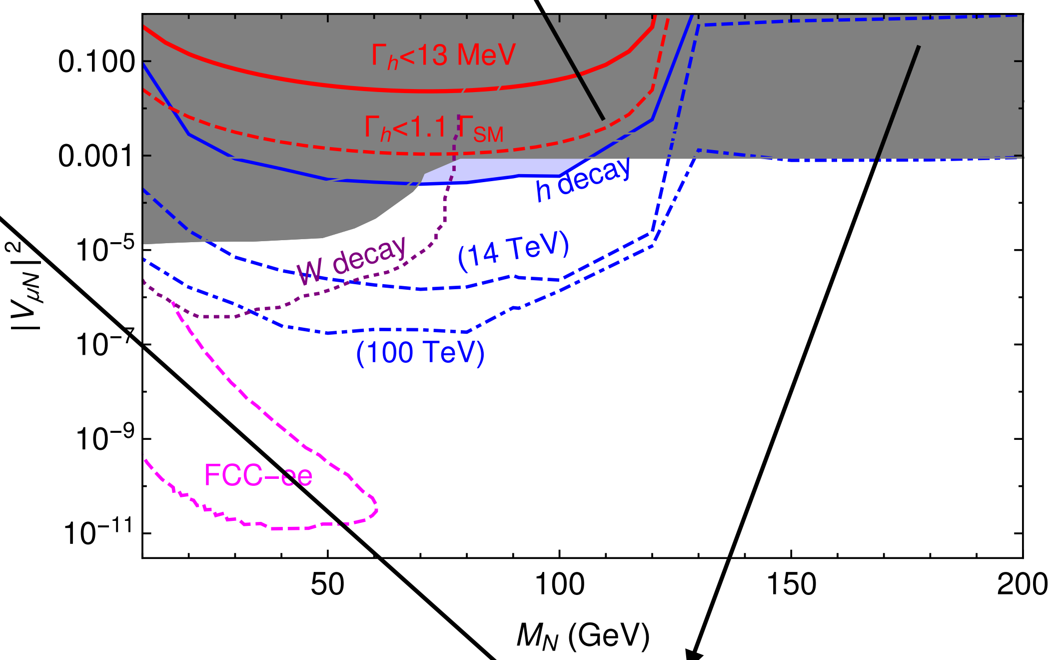
Assuming the same $\mathcal{N}_{\rm expt}$ for $\sqrt{s} = 14$ and 100 TeV colliders, but with an integrated luminosity of 3000 fb^{-1},

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 @100 can go down to 10%precise result at 100 TeV pp collider: arXiv:1606.09408

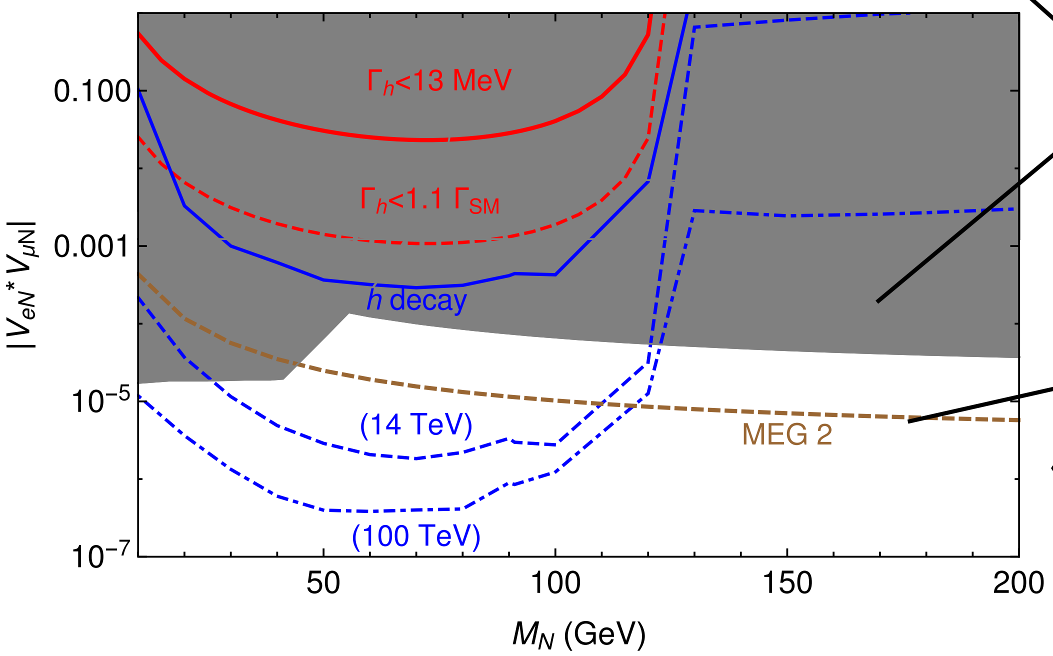




Future limit considering Majorana heavy neutrinos only

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

$\mu \rightarrow e\gamma$

~ future branching ratio O(10^{-15})

Future limits

Heavy neutrino production from $\ell\nu jj$

W boson produced in the Higgs decay to $\nu N \to \nu\ell W$

$$\boxed{\ell\nu jj}$$

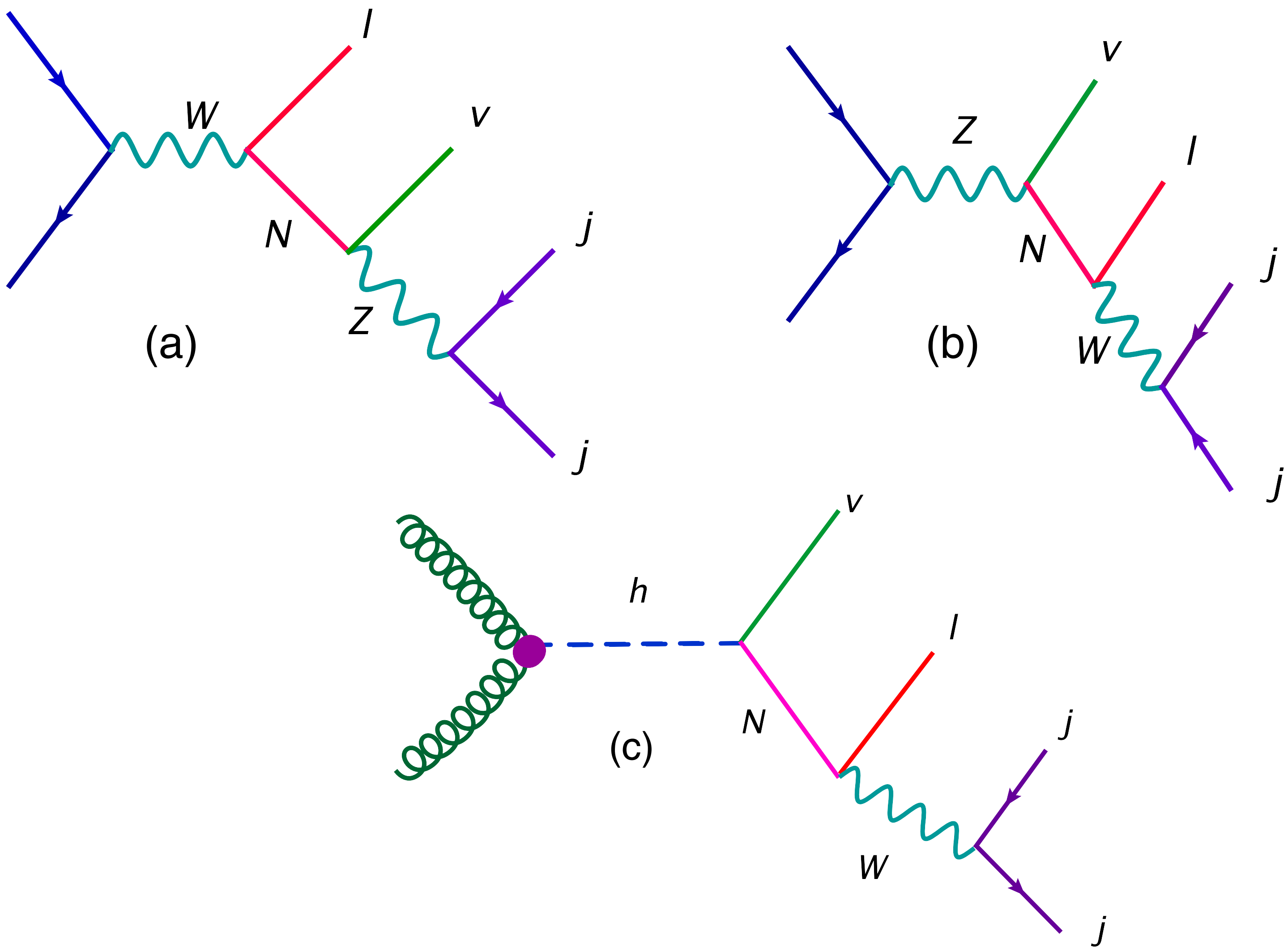
W $\longrightarrow$ Br(lv) : 22%, $\ell = e, \mu$

W $\longrightarrow$ Br(jj) : 67% $\longrightarrow$ **Chance of a gain due to > 3 times Br. into leptons**

Large irreducible backgrounds WW and WZ.

Practically, the purely leptonic modes are more clean turning out the signal sensitivity better than those with the jets, however, reconstruction is easier due to one neutrino in the final state.

Apart from the Higgs decay, the heavy neutrino can display the same final states through the CC and NC interactions. Finally after the decays of the W, Z bosons hadronically, we can get same final states.



Selection cuts

$$\sqrt{s} = 8 \text{ TeV}$$

$$p_T^{\ell} > 20 \text{ GeV} \qquad p_T^{j_{1,2}} > 30 \text{ GeV}$$

$$|\eta_{\ell}| < 2.5 \qquad |\eta^{j_{1,2}}| < 2.5$$

$$\Delta R_{\ell j} > 0.3$$

$$\Delta R_{jj} > 0.4.$$

$$m_i - 20 < m_i < m_i + 20, \quad m_i = M_N, m_W \text{ or } m_Z$$

Depending upon the process

$$\sqrt{s} = 14 \text{ TeV}$$

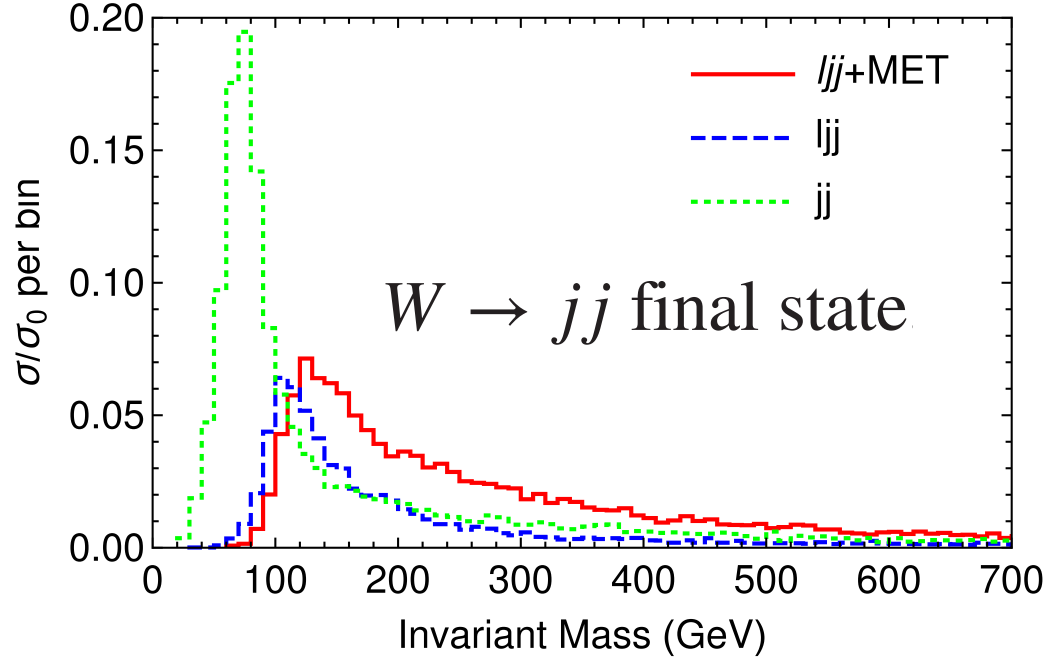
$$p_T^{\ell} > 30 \text{ GeV and } p_T^{j_{1,2}} > 32 \text{ GeV}$$

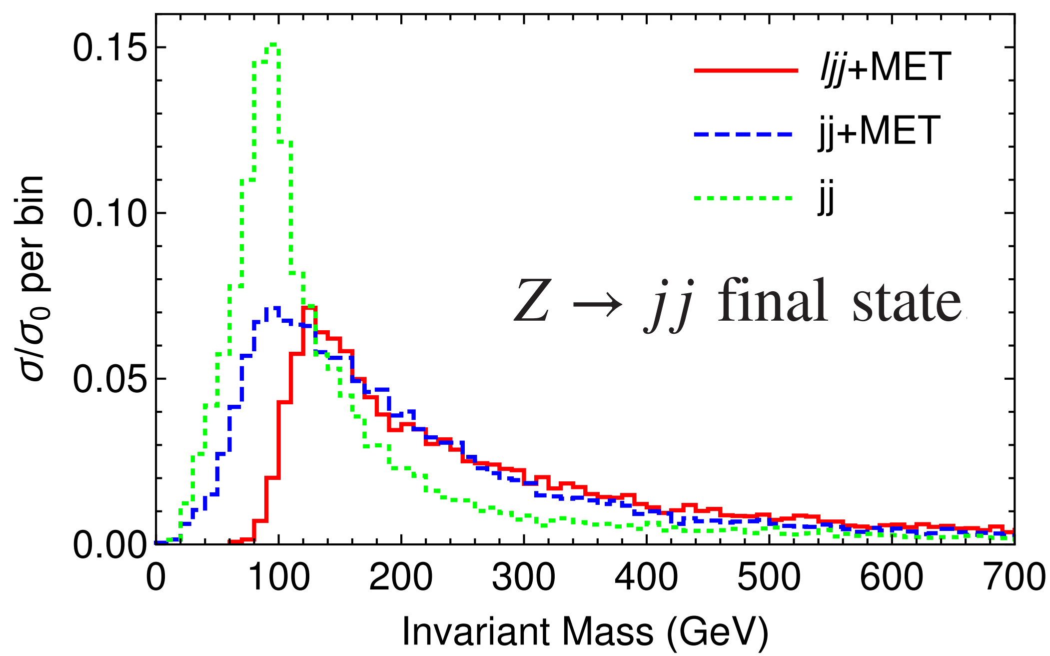
$$\sqrt{s} = 100 \text{ TeV}$$

Other cuts remain the same

$$p_T^{\ell} > 53 \text{ GeV} \quad \text{and} \quad p_T^{j_{1,2}} > 35 \text{ GeV}$$

$M_N = 100$ GeV



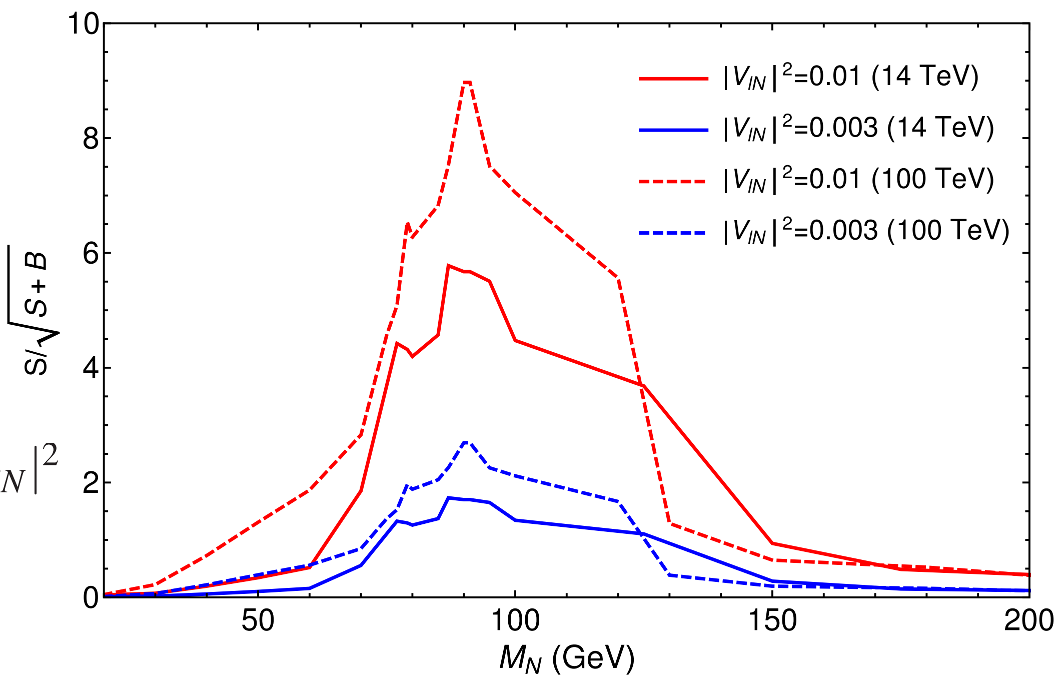


Significance

$\sqrt{s} = 14$ **TeV**

$\sqrt{s} = 100$ TeV

Two different choices of $|V_{\ell N}|^2$



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 ($h \to WW^*$) at the 8 TeV to put current and prospective upper limits on the mixing angles.

We have also studied the single lepton final state with dijet and MET from all possible channels including CC and NC and Higgs. Which can be improved from the Higgs+ISR final state, when Higgs decays into heavy neutrino. (See, Das, Gao, Kamon: arXiv:1704.00881 [hep-ph]).

Thank You