Jet substructure shedding light on heavy Majorana neutrinos at the LHC

Arindam Das

Korea Institute for Advanced Study

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Recent Discoveries and future

Neutrino oscillations experiments confirm the existence of the tiny neutrinos mass and flavor mixing

Standard Model (SM) can not explain such observation

Extension of the SM is necessary through an SM singlet Right Handed Neutrino

Seesaw mechanism

Explains the tiny neutrino mass

Discovery of Higgs

INVISIBLE DECAY

Beyond the SM signature

Can relate

Can be tested @LHC in future

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

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

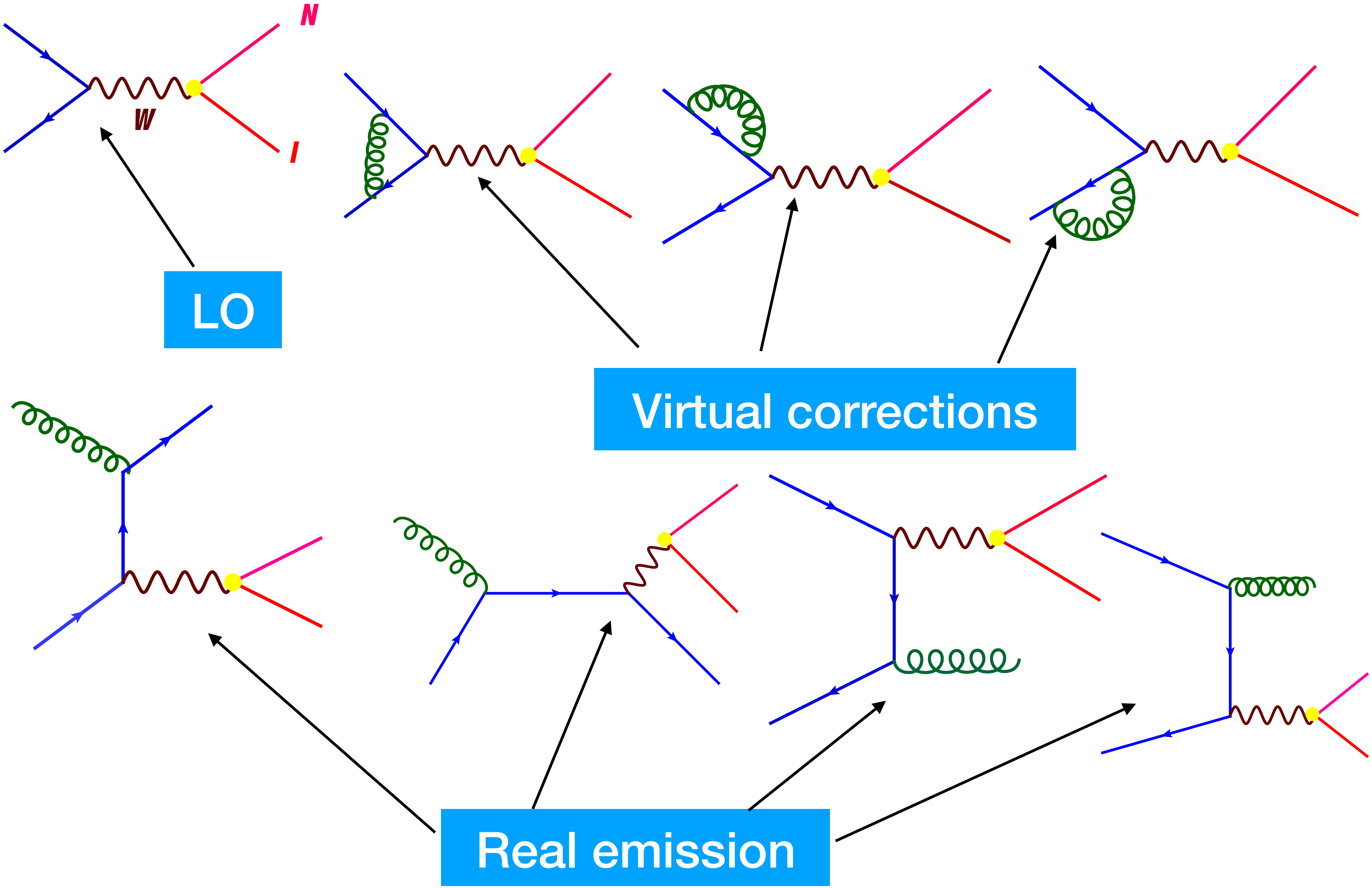
Neutral Current interaction

Expanding ν_ℓ (twice)

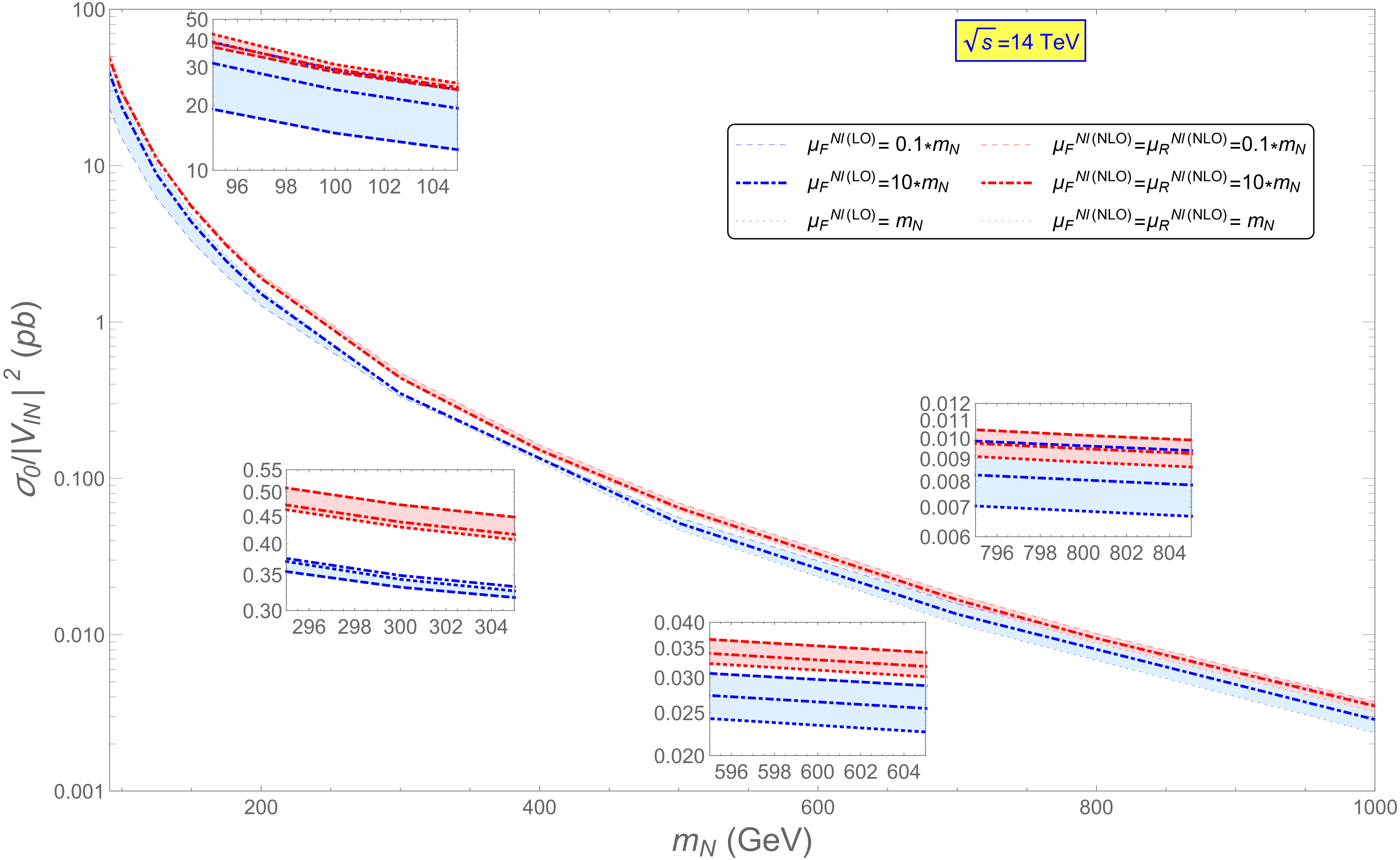
$$\mathcal{L}_{\rm NC} = -\frac{g}{2\cos\theta_w} Z_\mu [(U^\dagger U)_{mn}\bar{\nu}_m\gamma^\mu P_L \nu_n + (U^\dagger V)_{mn}\bar{\nu}_m\gamma^\mu P_L N_n + (V^\dagger V)_{mn}\bar{N}_m\gamma^\mu P_L N_n] + \text{H.c.},$$

The interaction between the heavy Right Handed Neutrinos (RHNs) and the SM gauge bosons are suppressed by the powers of the mixing (V) parameter.

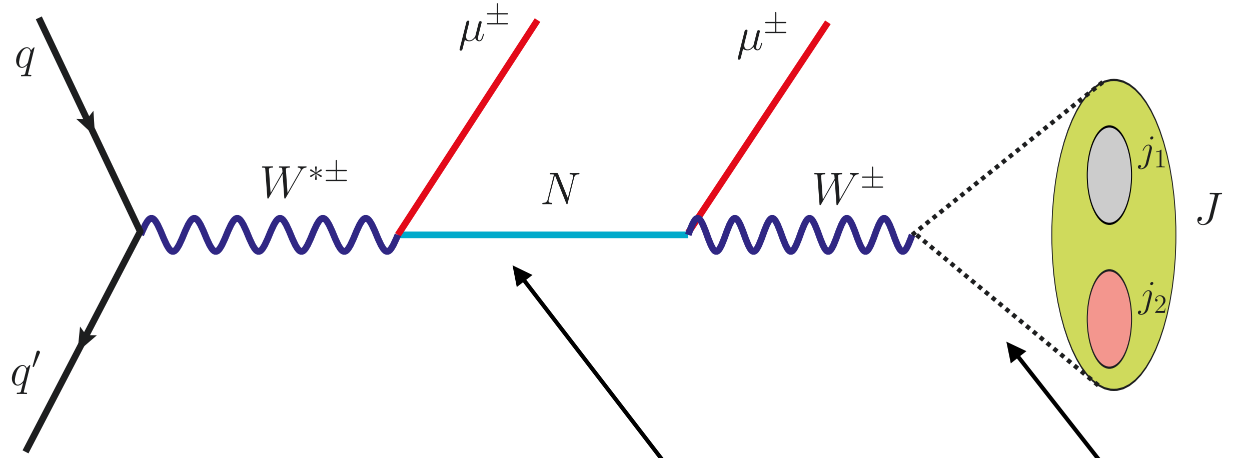
NLO-QCD production of the RHNs @LHC



Production cross section of the RHNs @LHC



New search strategy for the RHNs (Majorana type)



Heavy RHN, makes the W boosted

Boosted W forms a Fat jet

$$p_T^W \sim M_N - \frac{M_W^2}{M_N}$$

Separation between the hadronic decay products of W scale as $\sim M_W/P_T^W$

Same sign dilepton plus a fat jet signal

W tagging

$$N \to W\ell \to J\ell$$

W can be boosted
if the RHN is heavy

Fat Jet

Such a technique could be powerful to distinguish the signal from the SM backgrounds

$\longrightarrow$ We use **N-subjettiness** and **Fat jet mass** to tag the W efficiently

N-subjettiness Inclusive jet-shape variable $\tau_N = \frac{1}{\mathcal{N}_0} \sum_i p_{i,T} \min\{\Delta R_{i1}, \Delta R_{i2}, \cdots, \Delta R_{iN}\}$

$$\mathcal{N}_0 = \sum_i \boxed{p_{i,T}} R \,, \qquad \boxed{\Delta R_{i\alpha}} = \sqrt{(\Delta\eta)^2_{i\alpha} + (\Delta\phi)^2_{i\alpha}}$$

Transverse momenta of the constituent particles inside the jets (i)

Jet radius

Distance between a candidate α-subjet and a constituent particle (i)

τ_N $\longrightarrow$ Suggests the presence of max. N daughters in the original jet

$\longrightarrow$ Used for the N prong hadronic decay

$\longrightarrow$ Better discriminant to tag N-prong hadronic decay $\boxed{\frac{\tau_N}{\tau_{N-1}}}$

Two collimated sub jets are provided for the W tagging hence we concentrate on the variable

$\boxed{\tau_{21}^J = \frac{\tau_2}{\tau_1}}$

Fat jet mass

Fat jet mass M_J

$\rightarrow$ At each iteration in a sequential recombination of the jet algorithm, in the E-scheme, the mother proto jet 4-momentum is the vector sum of the daughter proto jet 4-momenta

$\rightarrow$ Jet algorithm at the end of the iteration provides P_T^J for the full fat-jet

M_J^2 is computed as the invariant mass square of the fat-jet 4-momentum

$\rightarrow$ To reconstruct the candidate fat-jet, Delphes 3. 3. 2 hadron calorimeter outputs are clustered using FastJet 3. 1. 3.

$\rightarrow$ τ_{21}^J is computed with the aid of the N-subjettiness extension, available as part of the Fast Jet-contrib

$\rightarrow$ W-tagging, we use Cambridge- Achen algorithm with jet cone radius R=0.8 along with that we use cuts for the Fat-jet related variables.

Analysis and Simulation

$$pp \to \ell_1^+ N, \quad N \to \ell_2^+ W^-, \quad W^- \to J$$
$$pp \to \ell_1^- \overline{N}, \quad \overline{N} \to \ell_2^- W^+, \quad W^+ \to J.$$

$$\ell_1 = \ell_2 = \mu$$

Dominant background is coming from $W^{\pm}W^{\pm} + jets$

Other backgrounds are : $WZ + jets$ and $WWZ + jets$

According to arXiv: 1501.05566 (CMS Collaboration, RHN search at 8 TeV), the top quark decays can be controlled effectively by rejecting the events where at least one jet had been identified as originating from the b-quark. Additional veto affects the signal and other backgrounds at 5%-7% level.

Event generator: MadGraph5-aMC@NLO.

Hadronization : PYTHIA6.4

Matching : MLM scheme based on Shower- kT algorithm with p_T ordered showers

SM backgrounds : Matching scale QCUT is set between 20 GeV - 30 GeV

Showered events are passed through Delphes with the CMS card in it

Basic selection criteria for the signal event $(\mu^{\pm}\mu^{\pm} + J)$

- Muons $\mu^{\pm}$ are identified with a minimum transverse momentum $p_T^{\mu} > 10\,\mathrm{GeV}$ and rapidity range $|\eta^{\mu}| < 2.4$, with a maximum efficiency of 95%. Efficiency decreases for p_T^{μ} above 1 TeV.

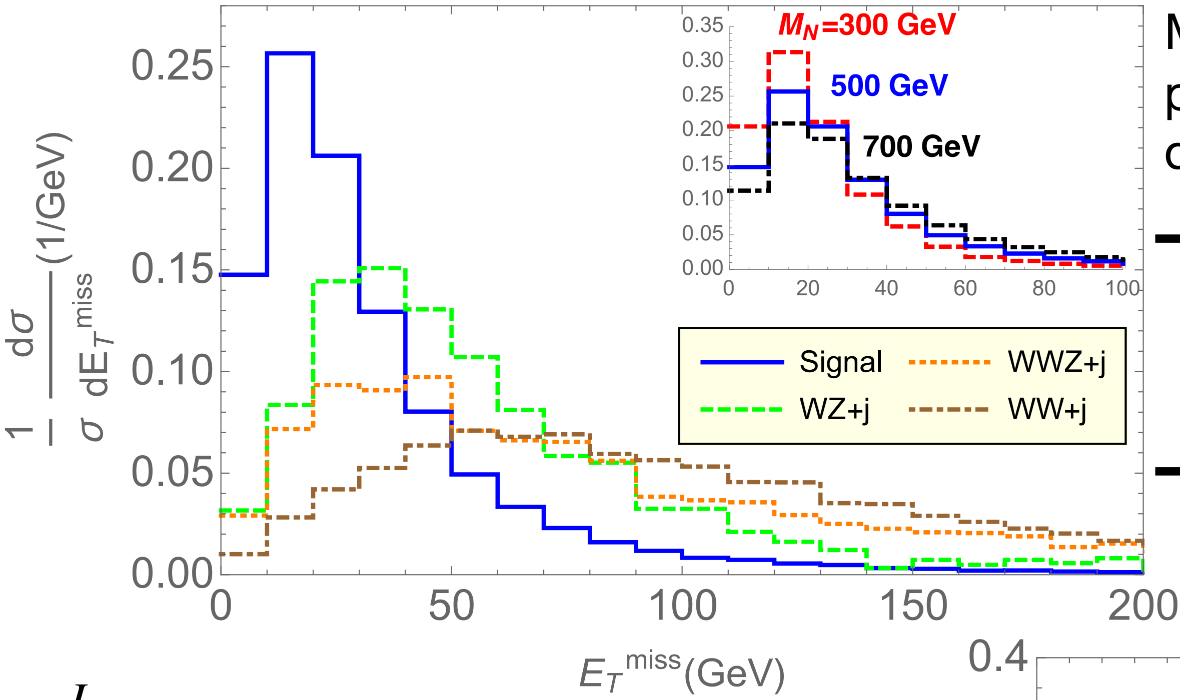
- Only events with reconstructed di-muons having same sign are selected for further analysis.

- Hard jets having at least $p_T^{j} > 10\,\mathrm{GeV}$ and $|\eta^{j}| < 2.4$ are identified.

- Candidate fat-jets are to be identified, $R = 0.8$, CA jet with $|\eta^{J}| < 2.4$

- We identify the hardest fat-jet with the $W^{\pm}$ candidate jet (J), and this is required to have $p_T^{J} > 100\,\mathrm{GeV}$.

Signal and background distributions (Basic selection+ $p_T^J > 100$ GeV)



MET: Calculated from isolated leptons, photons and jets along with unclustered deposites.

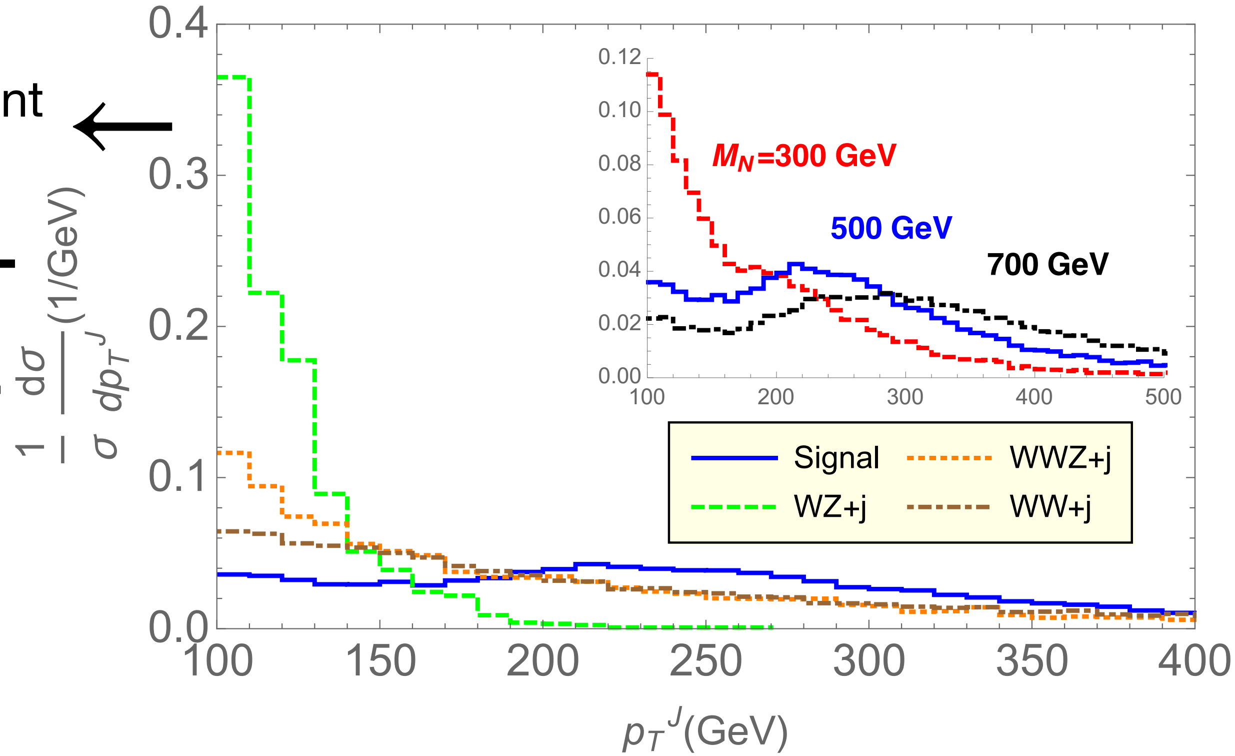
→ Mismeasurememts of hard jets in the signal, in SM backgrounds, $W \to \ell\nu$

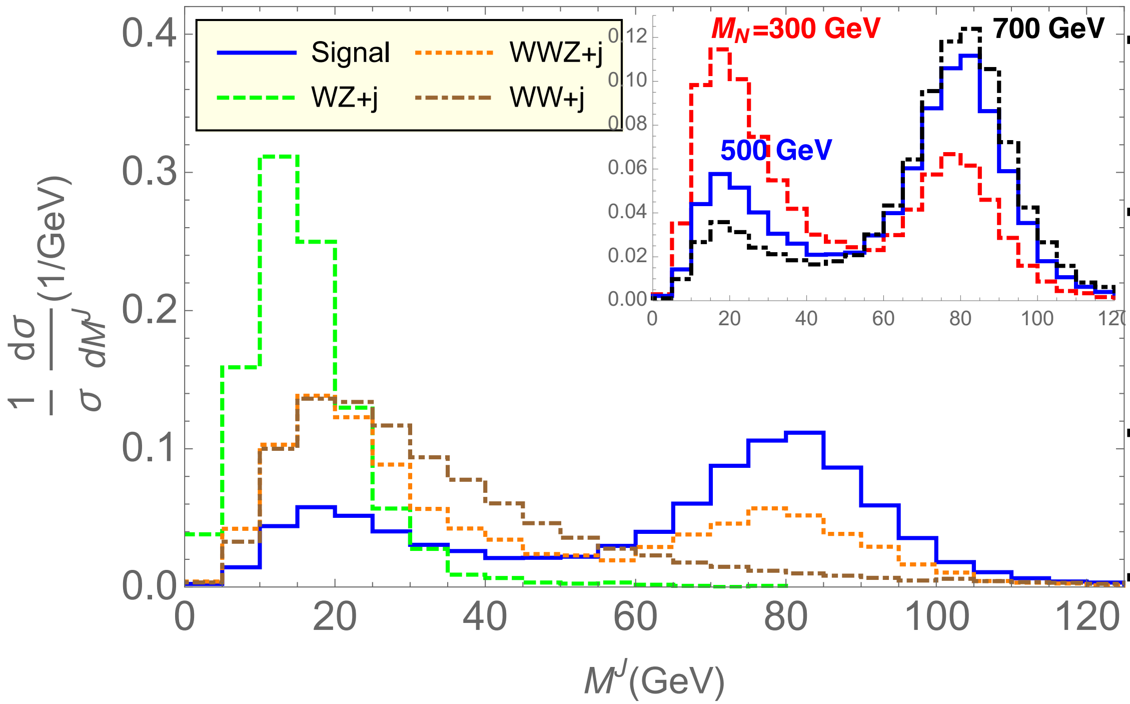
→ Large MET contributions are coming from the backgrounds

p_T^J is the vector sum of all constituent 4-momenta in J

Signal is harder compared to the backgrounds

Heavier RHN produces harder J candidates.





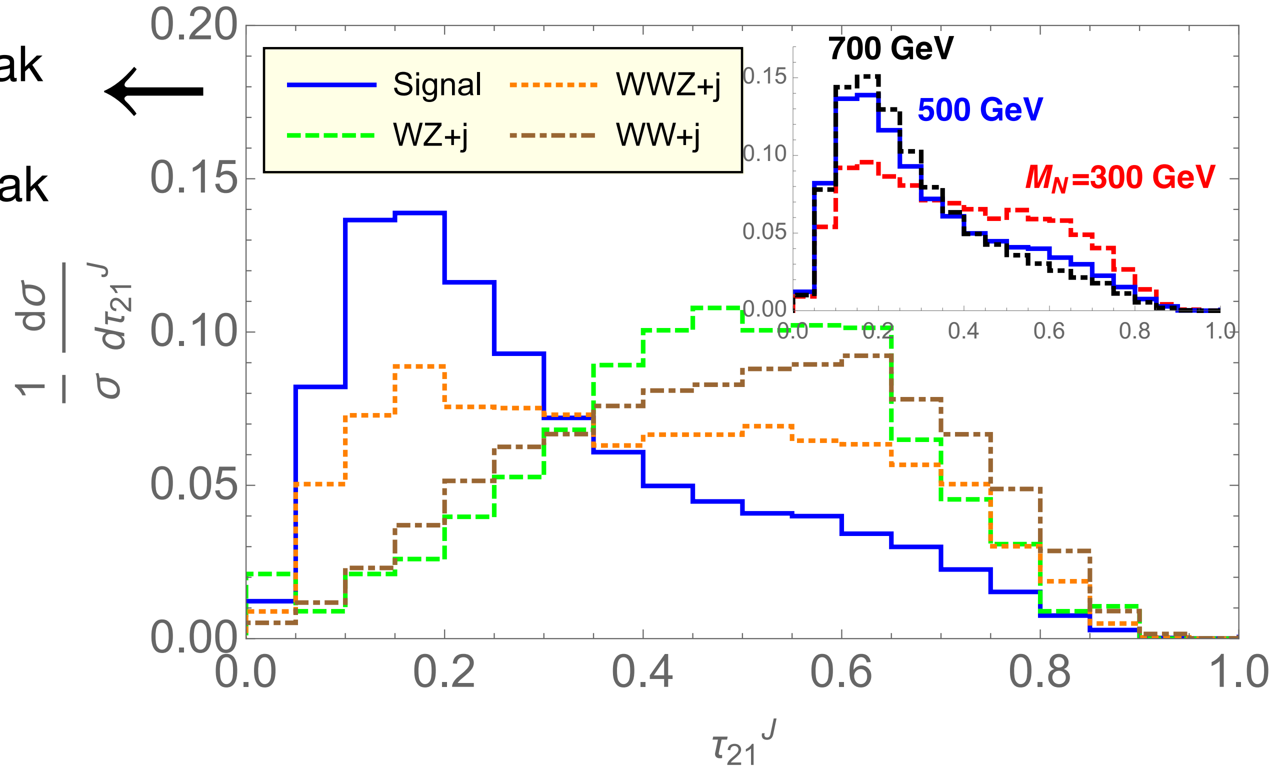
Peak at 80 GeV reflects the jet mass of W like fat-jet. In the backgrounds, this peak is absent.

In backgrounds the fat-jet is faked by QCD jets. Only in WWZ fat-jet is originated from the hadronic decay of one of the W's.

Significant W like fat-jets are observed for the heavier RHNs.

Spurious peak at 20 GeV comes from the events where some 4-momenta from the hadronically decaying boosted W is missed in the jet clustering. Higher p_T^J cut may reduce it.

$\tau_{21}^J = \frac{\tau_2}{\tau_1}$ for the W-like fat-jets peak around the small values, for heavier RHNs this peak shifts in the lower values of the variable



Final selection criteria

- Leading muon should have $p_T(\mu_1) > 20\,\text{GeV}$ and the next hardest muon must have $p_T(\mu_2) > 15\,\text{GeV}$.

- Minimum invariant mass for the same sign muon pair must satisfy $m_{\mu\mu} > 50\,\text{GeV}$. This is easily satisfied for the signal events, and can control backgrounds with non-prompt muon pairs.

- Lacking any missing particles for our signal, require $E_T^{\text{miss}} < 35\,\text{GeV}$. This can control background events with large MET contributions.

- The hardest, reconstructed fat-jet must have $\boxed{p_T^J > 150\,\text{GeV}.}$

- We also demand the invariant mass of the hardest, reconstructed fat-jet to satisfy $M_J > 50\,\text{GeV}$. In principle one may use a mass window around the $W^\pm$ mass, but we find that a simple lower bound suffices.

- The N-subjettiness ratio corresponding to the reconstructed fat-jet must satisfy $\tau_{21}^J < 0.5$.

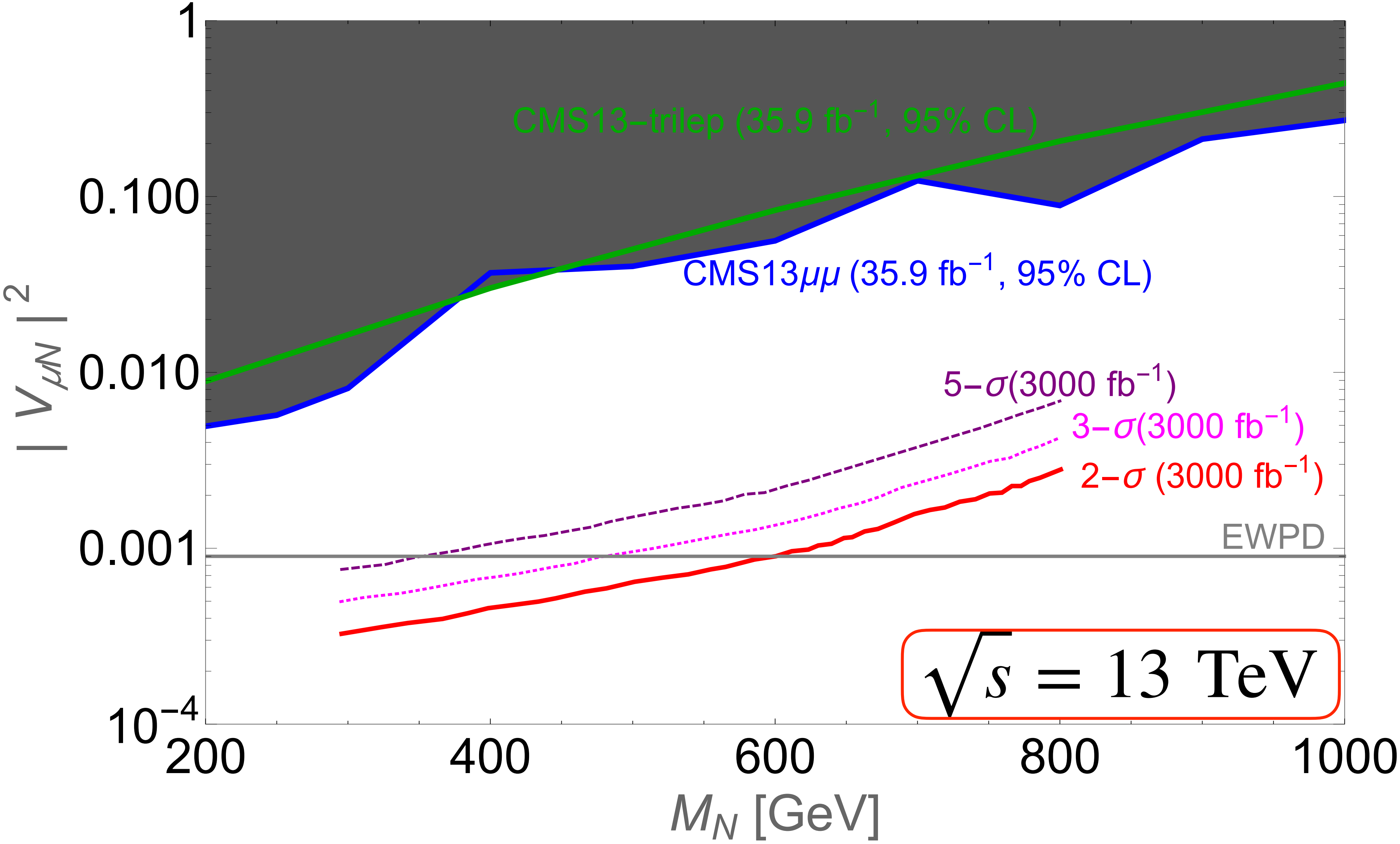
Cut flow of the Signal and background at the LHC

$$|V_{\mu N}| = 0.03,\ \sqrt{s} = 13\text{TeV},\ \text{Luminosity} = 3000\ \text{fb}^{-1}$$

Cut	Signal for M_N			Background		
	300 GeV	500 GeV	700 GeV	WW+j	WZ+j	$WWZ+j$
Pre-selection + $\mu^\pm\mu^\pm + J$ $p_T^J > 100$ GeV	82.2+ 45.2 [100%]	36.6+23.4 [100%]	19.2+13.0 [100%]	2717.5+2597.0 [100%]	9881.3+7639.3 [100%]	252.1+240.4 [100%]
$p_T(\mu_{1,2}), m_{\mu\mu}$	79.5+ 39.8 [94%]	33.02+ 20.3 [88%]	15.6+9.2 [77%]	2255.7+2132.1 [83%]	5496.6+5074.1 [60%]	208.0+193.4 [82%]
$E_T^{\rm miss} < 35$ GeV	66.3+27.4 [74%]	28.5 +18.1 [77%]	10.0+7.6 [55%]	260.8+163.2 [7.9%]	189.9+188.1 [2.2%]	24.2+ 19.6 [8.9%]
$p_T^J > 150$ GeV	35.1+20.6 [44%]	15.2+ 10.5 [58%]	8.3+6.0 [44%]	152.4+91.4 [4.5%]	36.5+ 27.2 [0.4%]	14.14+12.4 [5.3%]
$M_J > 50$ GeV	29.3+16.9 [36%]	20.9+ 10.2 [42%]	6.6+4.4 [34%]	34.0+26.6 [1.1%]	11.6+8.5 [0.1%]	6.6+5.0 [2.3%]
$\tau_{21}^J < 0.5$	26.7+13.7 [32%]	13.2+7.2 [34%]	5.4+2.8 [25%]	17.5+15.9 [0.6%]	5.9+5.2 [0.06%]	3.0+2.8 [1.2%]

Two numbers correspond to the events $\mu^+\mu^+$ and $\mu^-\mu^-$ channels.

Mass versus mixing plot and comparison to the current bounds



CMS 13 tri-lep : 1802.02965, CMS13$\mu\mu$: 1806.10905

Conclusions

We have studied the low scale seesaw model with Majorana type RHNs considering the characteristic signal of SSDL plus a Fat-jet. The massive RHNs are helping to boost the W boson which is a decay product of the RHN. Finally the hadronic decay product of the boosted W forms a Fat-jet.

Studying the signal to background process we have prepared the mass versus mixing plot for the 13 TeV LHC with 3000/fb luminosity. We have compared the $2-\sigma$, $3-\sigma$ and $5-\sigma$ contours.

We have compared our results with the current observations at the LHC with 35.9/fb luminosity at the 95% CL. We have used the SSDL and tri-lepton searches for the Majorana RHNs at the LHC.

We propose that this search strategy can significantly improve the mass versus mixing contours in future.

Thank You