Jet substructure shedding light on Heavy Neutrino at the LHC

14 Dec, 2017

SUSY'17, Mumbai

Partha Konar

Physical Research Laboratory

Ahmedabad, India

Collaborators:
Arindam Das,
Arun Thalapillil,
Akanksha Bhardwaj

ArXiv:1709.09712

Neutrino puzzle

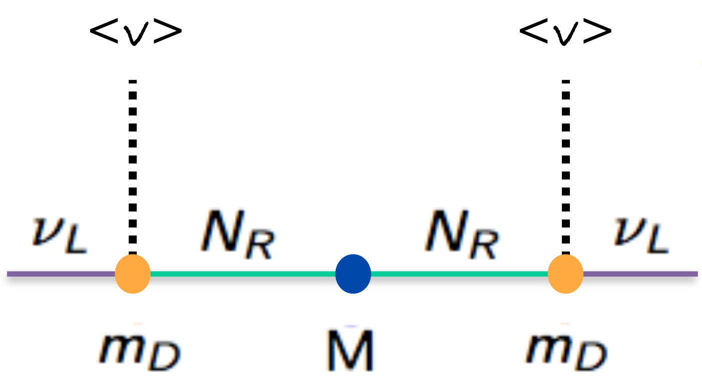
- SM neutrino is massless
  - No right handed counter part for Dirac term
  - Lepton no violation/ Guage invariance with both neutrino, Higgs from doublet => No Majorana term
  - Accidental B-L symmetry prevent mass term in all order

- But, (already) confirmed BSM signatures from neutrino oscillation => Having tiny but non-zero mass and mixing

- Extended Standard Model

Seesaw

- *Simple choice - Seesaw mechanism : Dim 5 operator*
  - *Adding right handed singlet Majorana neutrino*



$$\mathcal{L} \supset -Y_D^{\alpha\beta}\overline{\ell_L^\alpha} H N_R^\beta - \frac{1}{2} M_N^{\alpha\beta} \overline{N_R^{\alpha C}} N_R^\beta + H.c.$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \quad M_D = \frac{Y_D v}{\sqrt{2}}$$

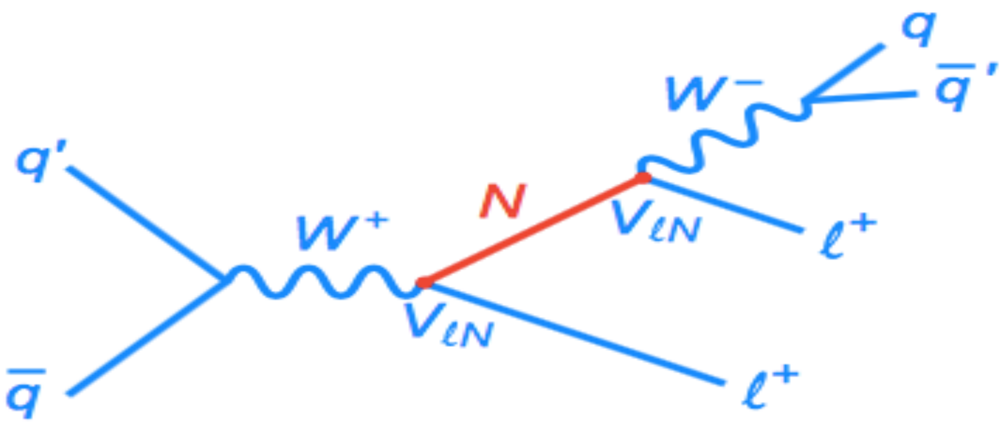
$$m_\nu \simeq -M_D M_N^{-1} M_D^T$$

- *Small Yukawa/ heavy-light mixing* $(M_D M_N^{-1})$ *< = > sub-TeV `heavy neutrino'*
- *Cases-Ibarra parameterisation Yukawa coupling expressed in terms of a orthogonal matrix which remains completely arbitrary and hence can be large.*

Seesaw at LHC

- If heavy neutrino is `light' enough
  & heavy-light mixing 'large' enough

- Resonant production of heavy Majorana neutrino



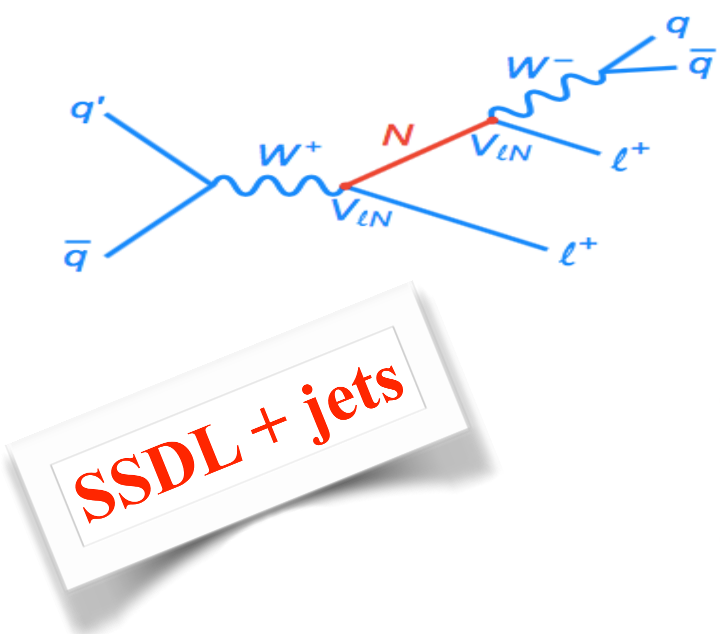
- Produces multi-lepton signature at the LHC

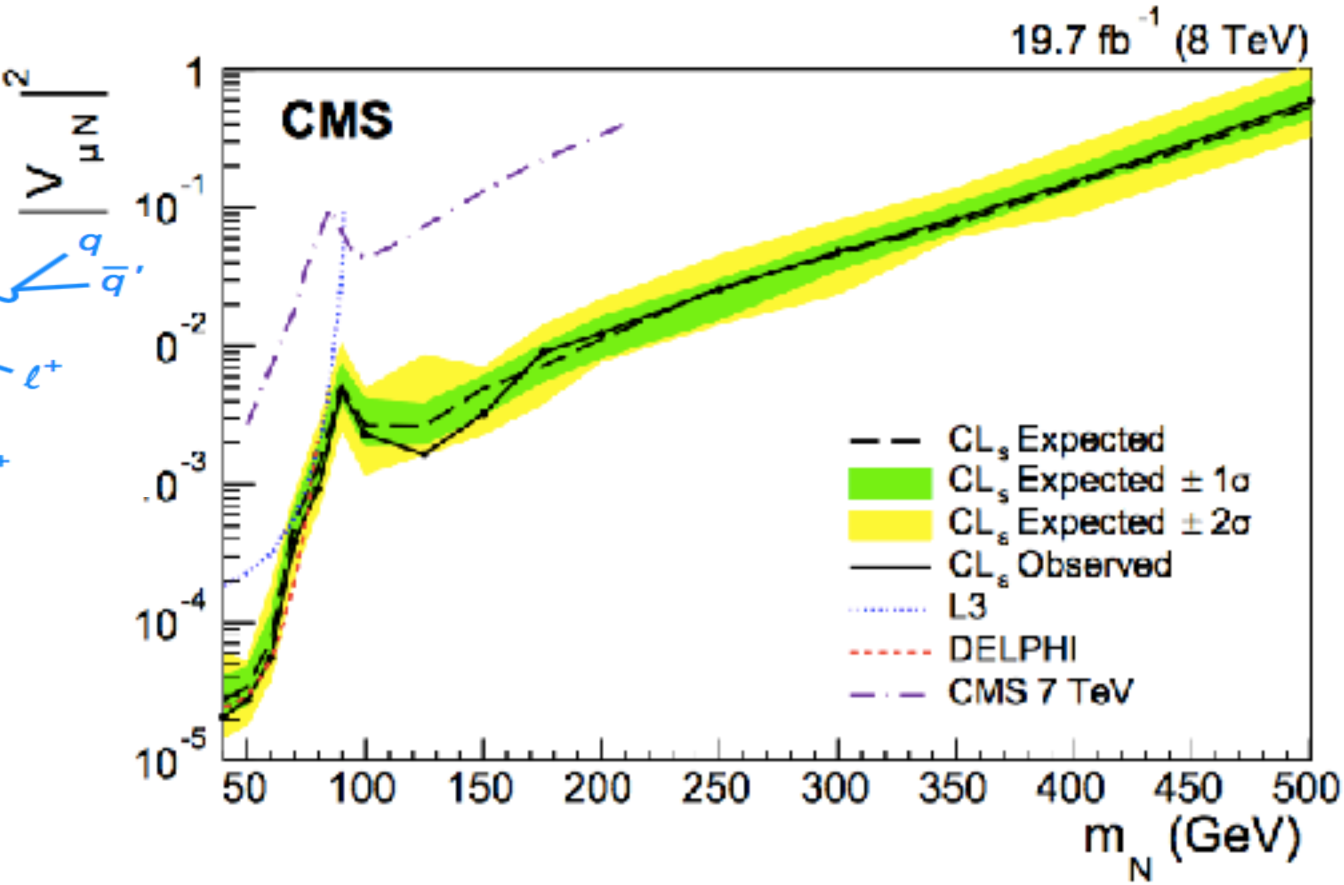
$$pp \to \ell_1^+ N, \quad N \to \ell_2^+ W^-$$
$$pp \to \ell_1^- \overline{N}, \quad \overline{N} \to \ell_2^- W^+$$

SSDL + jets

CMS8: 1501.05566, 1603.02248
ATLAS8: 1506.06020

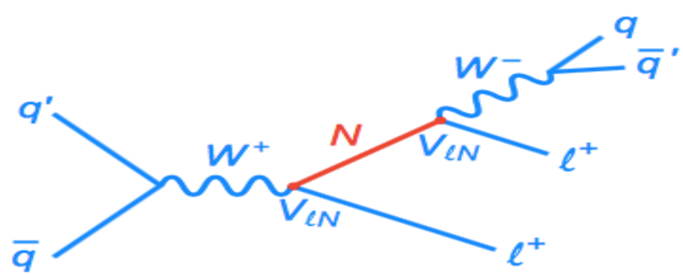
Seesaw at LHC



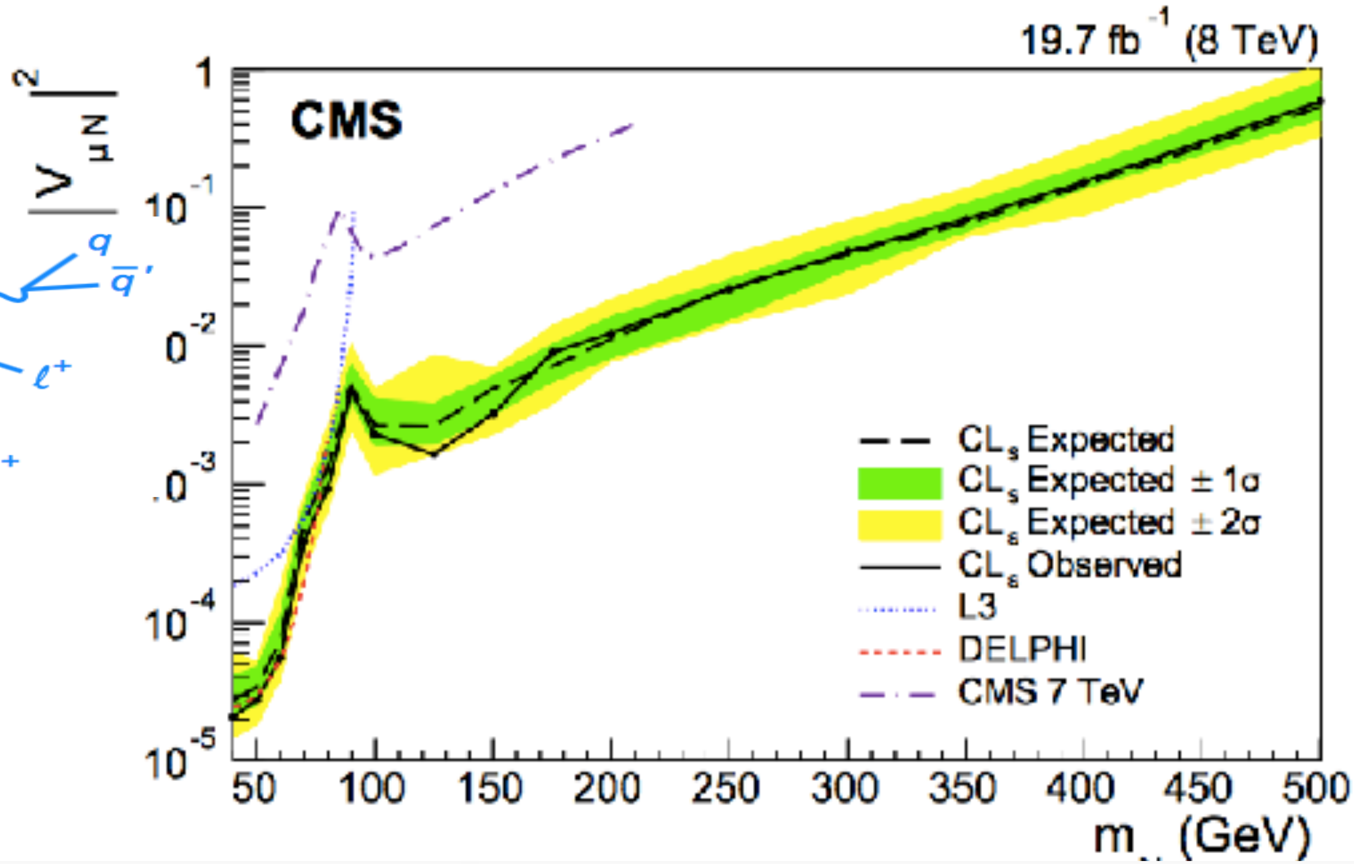


CMS8: 1501.05566, 1603.02248
ATLAS8: 1506.06020

Seesaw at LHC



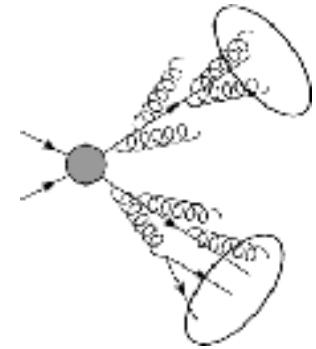
SSDL + jets



If we could use the internal feature of these additional jets, to deduce:

- **'W'-jets**
- **Production topology**
- **Control background**

"New" jets @ LHC



- Increased energy of hadron collider
- Exploration for intermediate to very heavy resonance

  : if PT<2TeV ~ 100 GeV splitting is distinguishable with cell size 0.1

- Calorimeters have enough finer resolution & improving

  : ~ 50 E_cell of .1 in R=0.4

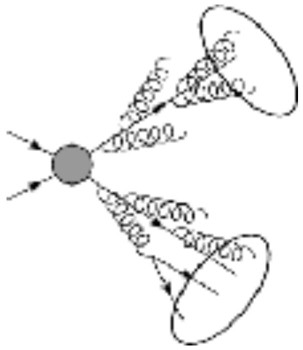
- Computations in fast sequential algorithms

  : fast jet algorithm

=> production and analysis of boosted objects & fat jet

Decay & fragmentation of boosted object Produce a collimated spray of hadron, standard Algorithm consider it as single jet

"New" jets @ LHC

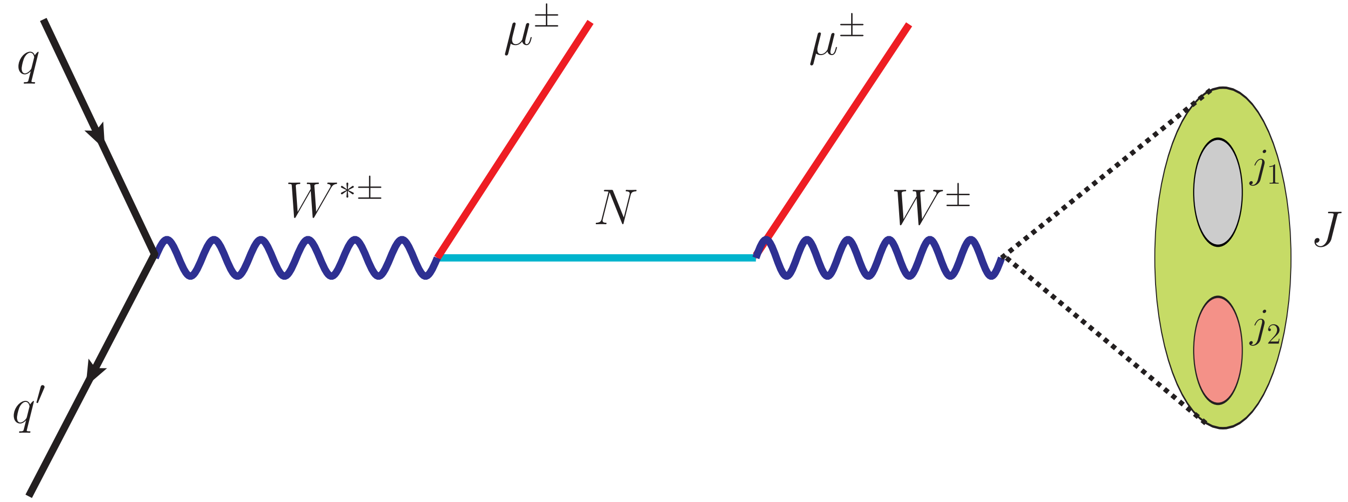


- With same jet mass, boosted hadronic objects have a fundamentally different energy pattern VS to QCD jets
- Clean up smearing effect of jet contamination from IRS, UE, Pileups
- In this work, we exploit the characteristics and kinematic properties for these Boosted W-jets

=> production and analysis of boosted objects & fat jet

Decay & fragmentation of boosted object Produce a collimated spray of hadron, standard Algorithm consider it as single jet

Fat jet from Heavy Neutrino

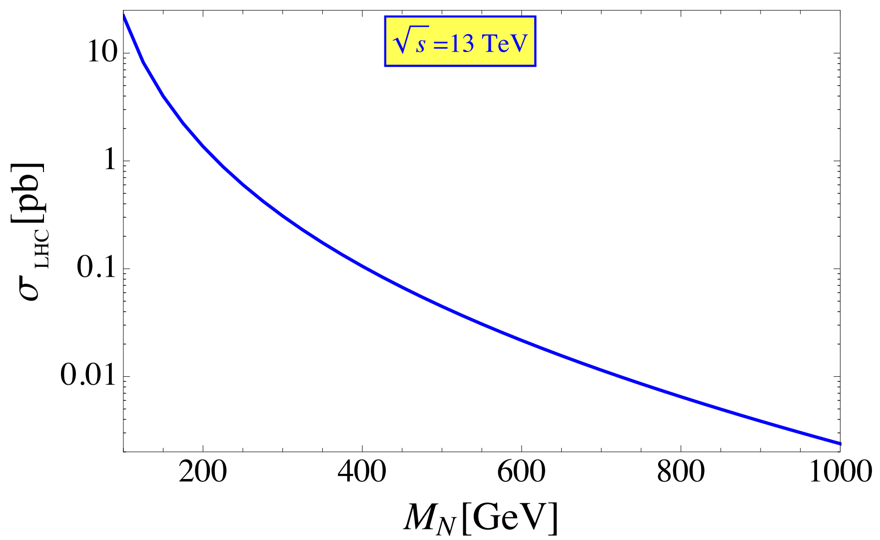


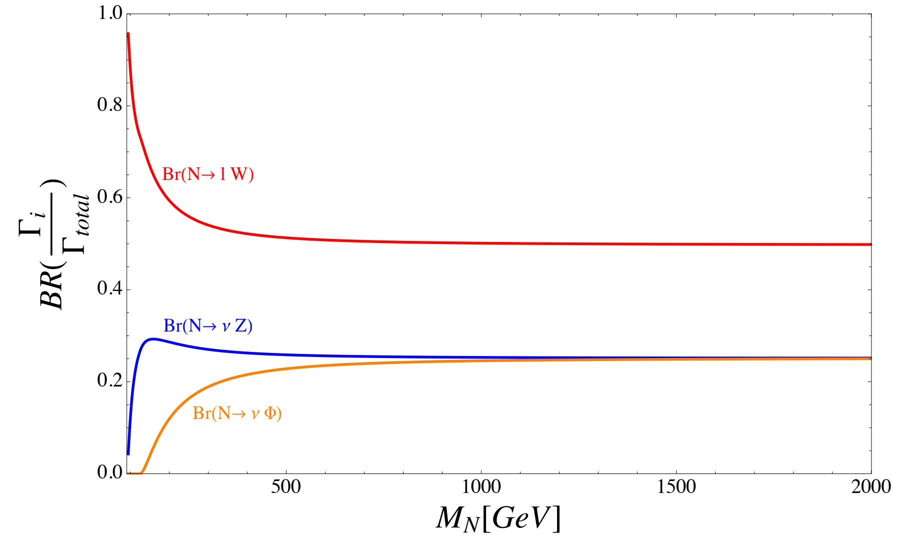
$$pp \to \ell_1^+ N, \quad N \to \ell_2^+ W^-$$
$$pp \to \ell_1^- \overline{N}, \quad \overline{N} \to \ell_2^- W^+$$

$$W^- \to J$$
$$W^+ \to J$$

Features of these boosted fat-jets are prominent for large M_N ~ 300 GeV and above

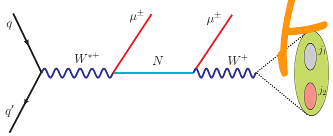
Heavy Neutrino at LHC





Total production cross-section and branching ratios of heavy Majorana neutrino as a function of its mass at the LHC with $\sqrt{s}$ = 13 TeV and normalised by the $|V_{\mu N}|^2$.

$$BR(N \to \ell W) : BR(N \to \nu Z) : BR(N \to \nu H) \simeq 2:1:1.$$



Fat jet from Heavy Neutrino

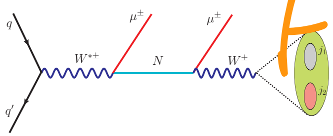
- A simplified model - Only light-heavy mixing for the Muons.
- Backgrounds for Same-sign-di-muon + fat-jet :

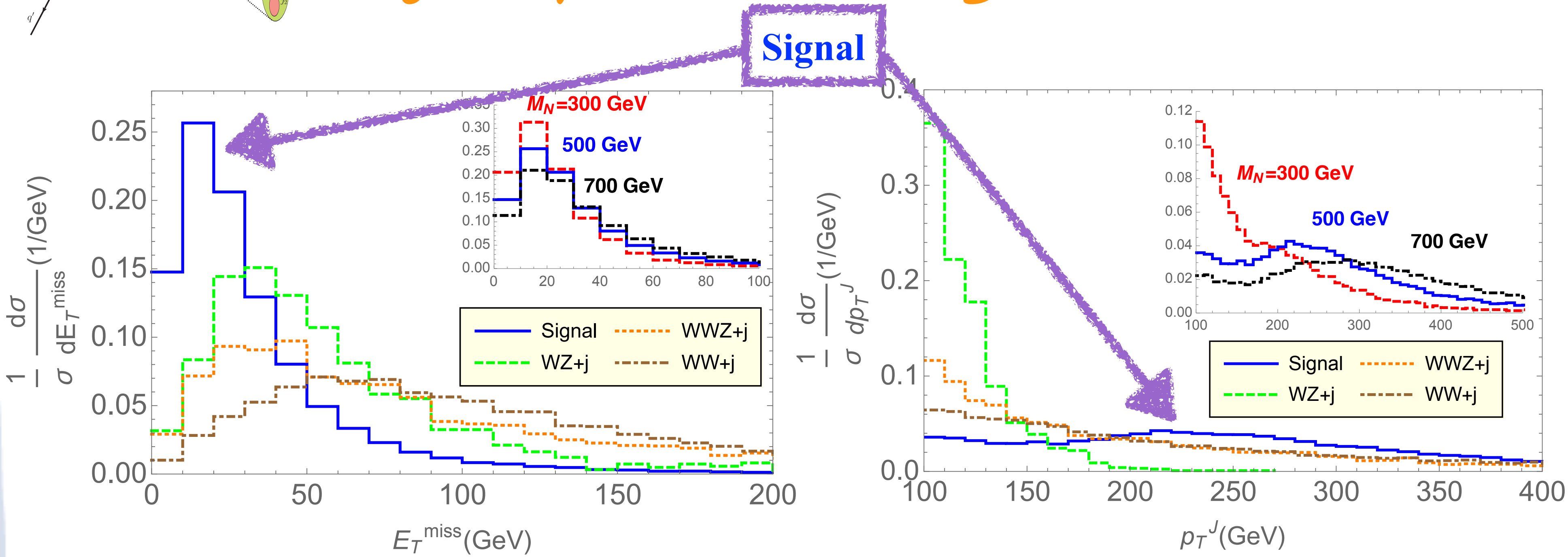
  Electroweak gauge boson decay (Di-boson+j, Tri-boson+j)

  + "fat-jet" - from a W boson OR mimicked from QCD jets
- MadGraph5-aMC@NLO => Pythia => Delphes
- MLM matching on a shower-kT algorithm with pT-ordered showers

- Same sign $\mu^{\pm}$ with $p^{\mu}_{T} > 10$ GeV, $|\eta^{\mu}| < 2.4$
- Candidate fat-jets are identified - R = 0.8 CA jet with $|\eta^{J}| < 2.4$
- Hardest fat-jet ~ $W^{\pm}$ candidate jet (J) having $p^{J}_{T} > 100$ GeV

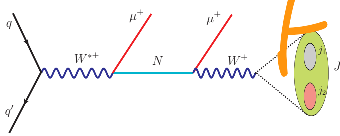
Fat jet from Heavy Neutrino

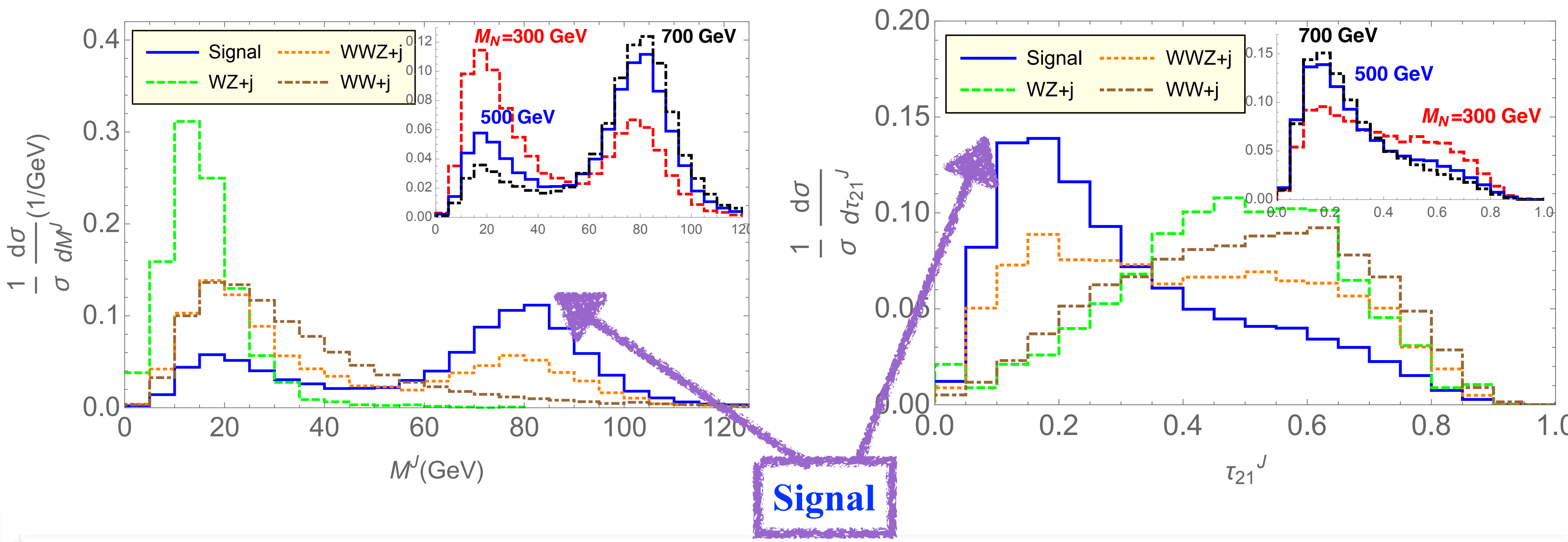




Normalised distribution as a function of MET & p^J_T after the application of the basic selection cuts; including p^J_T > 100 GeV

Fat jet from Heavy Neutrino

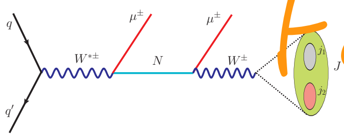




Normalised distribution as a function of invariant-mass M_J & N-subjet ratio τ_2/τ_1 of fat jet after the application of the basic selection cuts; including p^J_T > 100 GeV

$$\tau_N = \frac{1}{\mathcal{N}_0}\sum_i p_{i,T}\min\{\Delta R_{i1}, \Delta R_{i2}, \cdots, \Delta R_{iN}\} \qquad \mathcal{N}_0 = \sum_i p_{i,T}R.$$

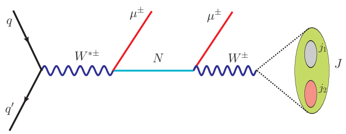
– **Inclusive jet shape variable quantify if the original jet consists of N daughter subjets**



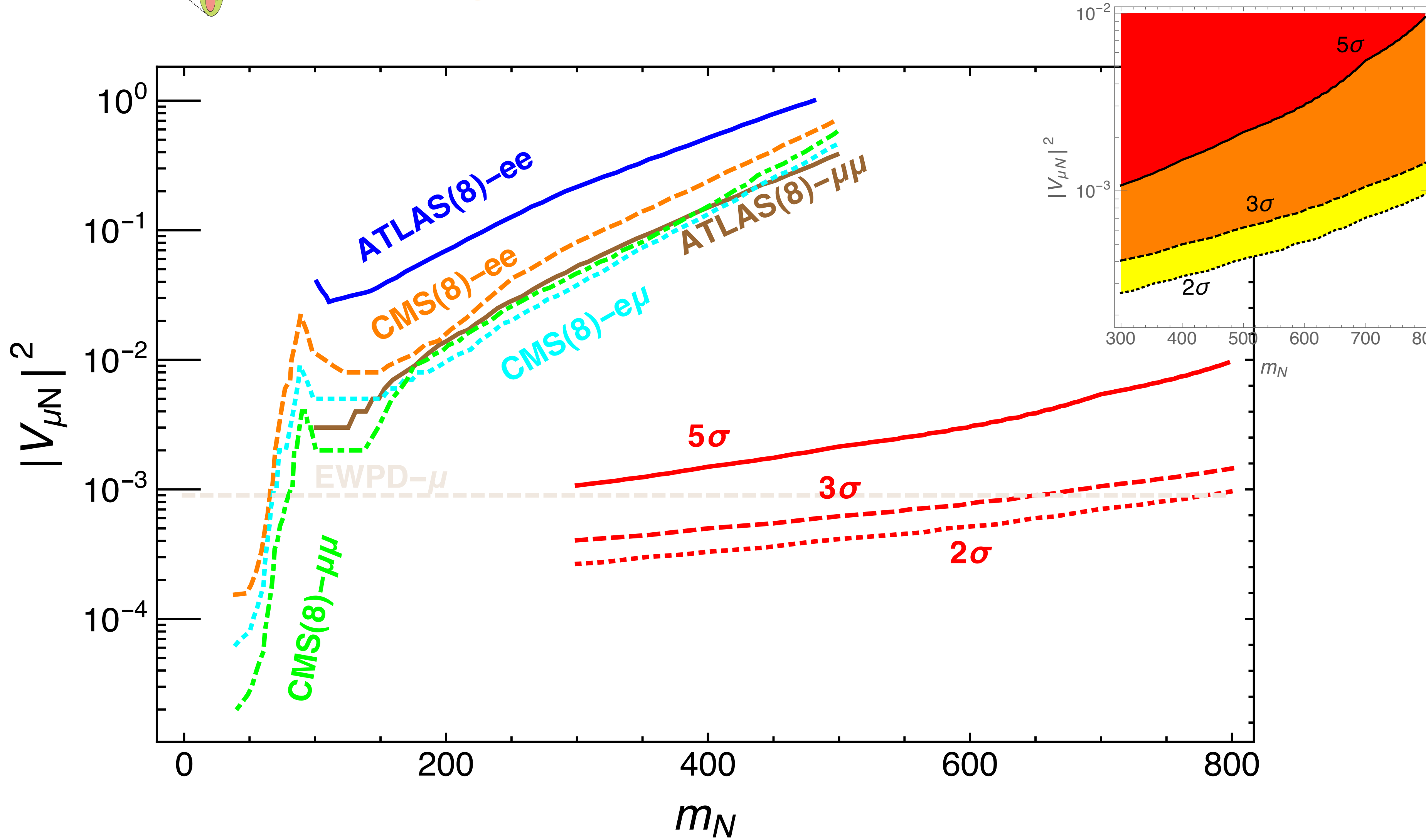
Fat jet from Heavy Neutrino

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	60.0+33.0 [100%]	26.7+17.4 [100%]	14.0+9.5 [100%]	3282.0+3136.5 [100%]	5474.4+4234.5 [100%]	126.05+120.2 [100%]
$p_T(\mu_{1,2}), m_{\mu\mu}$	58.0+ 29.0 [94%]	24.1+ 14.8 [88%]	11.4+6.7 [77%]	2724.30+2575.03 [83%]	3045.2+2796.2 [60%]	104.0+96.7 [82%]
$E_T^{miss} < 35$ GeV	48.34+20.0 [74%]	20.8 +13.2 [77%]	7.3+5.5 [55%]	314.94+197.1 [7.9%]	105.2+104.2 [2.2%]	12.1+ 9.8 [8.9%]
$p_T^J > 150$ GeV	25.6+15.0 [44%]	15.2+ 10.5 [58%]	6.0+4.3 [44%]	184.02+110.4 [4.5%]	20.2+ 15.08 [0.4%]	7.07+6.2 [5.3%]
$M_J > 50$ GeV	21.4+12.3 [36%]	11.2+ 7.4 [42%]	4.8+3.2 [34%]	41.05+32.08 [1.1%]	6.4+4.7 [0.1%]	3.3+2.5 [2.3%]
$\tau_{21}^J < 0.5$	19.5+10.0 [32%]	9.6+5.2 [34%]	3.9+2.0 [25%]	21.1+19.3 [0.6%]	3.3+2.9 [0.06%]	1.5+1.4 [1.2%]

The effectiveness of different variables in minimizing backgrounds is iilustrated in the form a cut flow. The two numbers correspond to expected events in $\mu^+\mu^+$ and $\mu^-\mu^-$ channels. We adopt a typical mixing angle $|V_{\mu N}| = 0.03$. The numbers are for an integrated luminosity of $3000 fb^{-1}$, at the 13 TeV LHC.



Heavy Neutrino at LHC



Exclusion limit in terms of heavy neutrino mass M_N and $|V_{\mu N}|^2$ at the 13 TeV LHC with other available limits.

Outlook

- Non-zero but Tiny neutrino mass can be realised through the simple type-I mechanisms which involves the Majorana type heavy neutrino.
- TeV scale heavy neutrinos can be produced at the LHC through a large mixing angle with the SM light neutrinos
- Such production channel is explored using boosted fat jet substructure which is e=inevitable for probing large heavy neutrino mass.
- Opens up interesting possibility to explore intermediate to heavy masses of RHN

Thank You