New Production Mechanism for Heavy Neutrinos at the LHC

P. S. Bhupal Dev

Consortium for Fundamental Physics,
The University of Manchester, United Kingdom

PSBD, A. Pilaftsis and U. K. Yang, Phys. Rev. Lett. **112**, 081801 (2014) [arXiv:1308.2209];
A. Das, PSBD and N. Okada, Phys. Lett. B **735**, 364 (2014) [arXiv:1405.0177];
and ongoing.

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Outline

- Introduction
- Direct Collider Searches
- A New Production Mechanism
- Improving the Collider Sensitivity
    - Majorana Case
    - (Pseudo)-Dirac Case
- Conclusion

Introduction

- Neutrino Oscillations $\Longrightarrow$ Non-zero neutrino masses and mixing.
- First (and so far only) conclusive 'experimental' evidence of BSM Physics.
- LH neutrinos massless in the SM because
  - No RH counterpart (i.e. no Dirac mass, unlike charged fermions).
  - ν_L part of $SU(2)_L$ doublet $\Rightarrow$ No Majorana mass term $\nu_L^T C^{-1} \nu_L$.
  - Accidental $(B-L)$-symmetry. Non-perturbative effects cannot induce neutrino mass.
- Simply adding RH neutrinos (N) requires tiny Yukawa coupling $y_\nu \lesssim 10^{-12}$.
- A more natural way is by breaking $(B-L)$.
- Within the SM, parametrized through dimension-5 operator $\lambda_{ij}(L_i^T\Phi)(L_j^T\Phi)/\Lambda$.
  [S. Weinberg, PRL **43**, 1566 (1979)]
- Three tree-level realizations: Type I, II, III Seesaw mechanism.
- A pertinent question in the LHC era:

  Can the seesaw mechanism be tested at the LHC?

- Profound implications for Leptogenesis, Dark Matter, Lepton Flavor Violation, Neutrinoless Double Beta Decay, EDM, Vacuum Stability, etc.
  [see e.g., parallel talks by Harz, Ilakovac, Mitra, Morisi, Niro, Teresi, Weiland,....]

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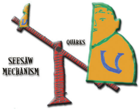
Type-I Seesaw

- Seesaw messenger: SM-singlet fermions (RH neutrinos).
- Have a Majorana mass term $M_N N^\mathsf{T} C^{-1} N$, in addition to the Dirac mass $M_D = v y_\nu$.
- In the flavor basis $\{\nu_L^C, N\}$, leads to the general structure

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^\mathsf{T} & M_N \end{pmatrix}$$

[Minkowski '77; Mohapatra, Senjanović '79; Yanagida '79; Gell-Mann, Ramond, Slansky '79; Schechter, Valle '80]

- In the seesaw approximation $||\xi|| \ll 1$, where $\xi \equiv M_D M_N^{-1}$ and $||\xi|| \equiv \sqrt{\mathrm{Tr}(\xi^\dagger \xi)}$,
  - $M_\nu^{\rm light} \simeq -M_D M_N^{-1} M_D^\mathsf{T}$ is the light neutrino mass matrix.
  - $\xi \equiv M_D M_N^{-1}$ is the heavy-light neutrino mixing.



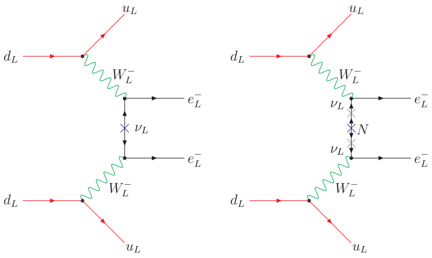
- In a bottom-up approach, no prediction for the seesaw scale.
- Wide range of possibilities over 20 orders of magnitude (keV - 10^{14} GeV)!
- A concrete UV-completion, such as LRSM or $SO(10)$ GUT, could fix this.
  [see plenary talk by R. N. Mohapatra]

Two Testable Aspects of Seesaw

Majorana Mass

⇓

LNV: Neutrinoless Double Beta Decay

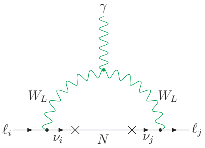


- Mixed diagram sub-dominant if small mixing or due to cancellation effects.
- Does not necessarily probe the heavy-light mixing.

Heavy-light Mixing

⇓

- LFV (e.g., $\mu \to e\gamma$, $\mu^- \to e^- e^+ e^-$, $\mu - e$ conv in nuclei)

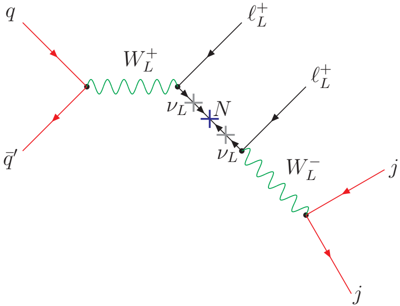


- Non-unitarity of the PMNS mixing matrix.
- Sizable contribution to EW precision observables.
- Do not necessarily prove the Majorana nature since a Dirac neutrino can also give large LFV and non-unitarity effects.

Low-energy tests of Seesaw at the intensity frontier require *synergy* between the two aspects.

Direct Test of Seesaw

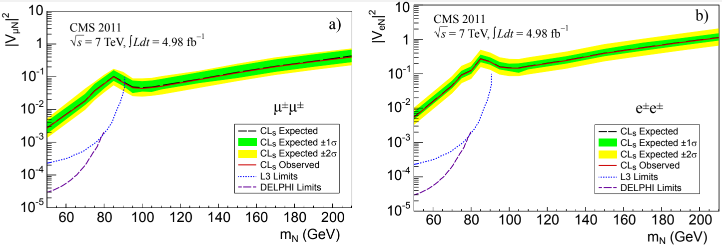
- A direct test of *both* aspects of type-I seesaw at the *Energy Frontier*.
- 'Smoking gun' signal: $pp \to W_L^* \to \ell_\alpha^\pm N \to \ell_\alpha^\pm \ell_\beta^\pm W_L^\mp \to \ell_\alpha^\pm \ell_\beta^\pm jj$ with no $\not{E}_T$.
(Note: LFV for $\alpha \neq \beta$.)

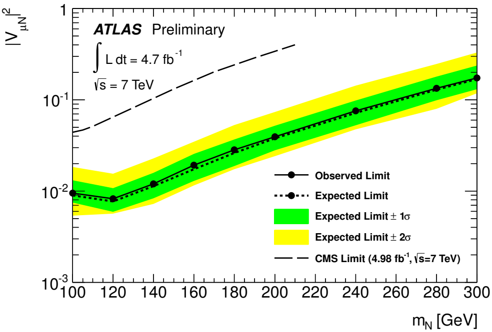


- Requires *both* Majorana nature of *N* at (sub-)TeV scale and 'large' heavy-light mixing to have an observable effect at the LHC.

[A. Pilaftsis, ZPC **55**, 275 (1992); A. Datta, M. Guchait and A. Pilaftsis, PRD **50**, 3195 (1994); T. Han and B. Zhang, PRL **97**, 171804 (2006); F. del Aguila, J. A. Aguilar-Saavedra and R. Pittau, JHEP **0710**, 047 (2007)]

Direct Search Limits from LHC 7

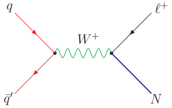




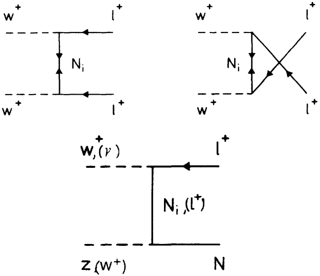
[CMS Collaboration, PLB **717**, 109 (2012); ATLAS Collaboration, ATLAS-CONF-2012-139; see the next talk by Un-ki Yang.]

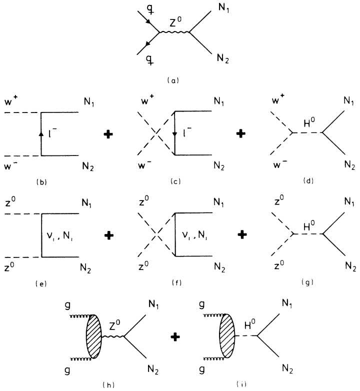
Heavy Neutrino Production at the LHC

- LHC searches so far considered only the *s*-channel process



- Many other production modes, but most of them turn out to be negligible.





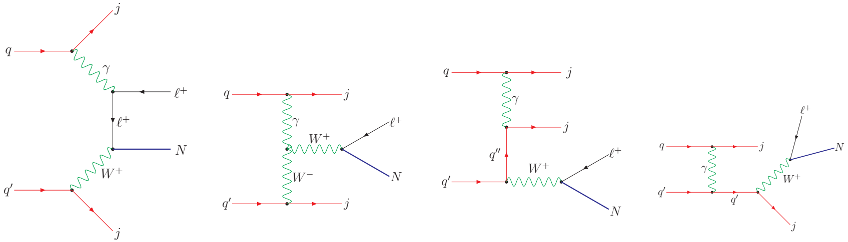
[A. Datta, M. Guchait and A. Pilaftsis, PRD **50**, 3195 (1994)]

New *Dominant* Production Channel: $N\ell^{\pm} + nj$

- EW processes involving *t*-channel virtual photons give rise to *diffractive* processes, e.g.

$$pp \;\to\; W^{*}\gamma^{*}jj \;\to\; \ell^{\pm}Njj \;,$$

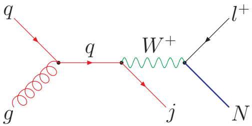
which are *not* negligible, but infrared enhanced. [PSBD, A. Pilaftsis, U. K. Yang, PRL **112**, 081801 (2014)]

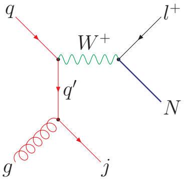


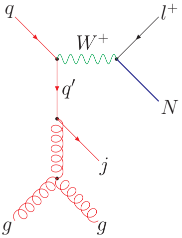
- Divergent 'inclusive' cross section due to collinear singularity.
- A non-zero minimum p_T^j required to make the production cross section finite.
- Low-p_T^j regime can be accounted for by an effective photon structure function of the proton (analogous to the Weizsäcker-Williams EPA for electrons). [V. M. Budnev, I. F. Ginzburg, G. V. Meledin and V. G. Serbo, Phys. Rept. **15**, 181 (1974); B. A. Kniehl, PLB **254**, 267 (1991); S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, PLB **319**, 339 (1993); M. Drees, R. M. Godbole, M. Nowakowski and S. D. Rindani, PRD **50**, 2335 (1994); M. Glück, C. Pisano and E. Reya, PLB **540**, 75 (2002); C. Pisano, EPJC **38**, 79 (2004).]

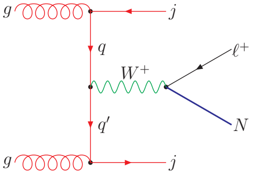
New *Dominant* Production Channel: $N\ell^{\pm} + nj$

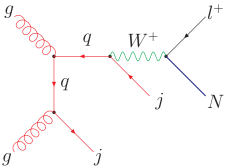
- For tagged n-jets (with $n \geq 1$), must also include QCD processes involving virtual quarks and gluons in the t-channel.
- gg-fusion diagrams give the dominant contribution due to large gluon content of the proton.



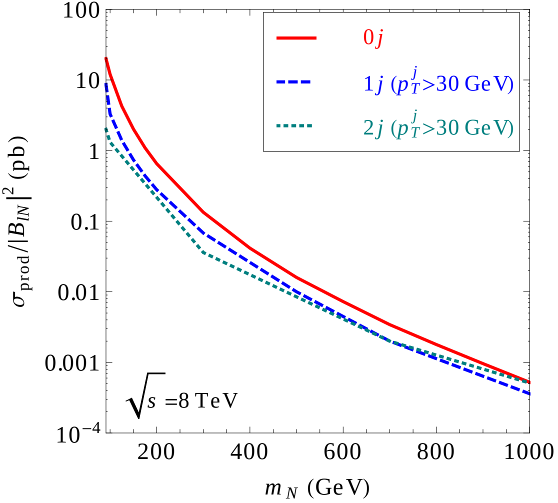








Comparison of the Cross Sections for $pp \to N\ell^{\pm} + nj$



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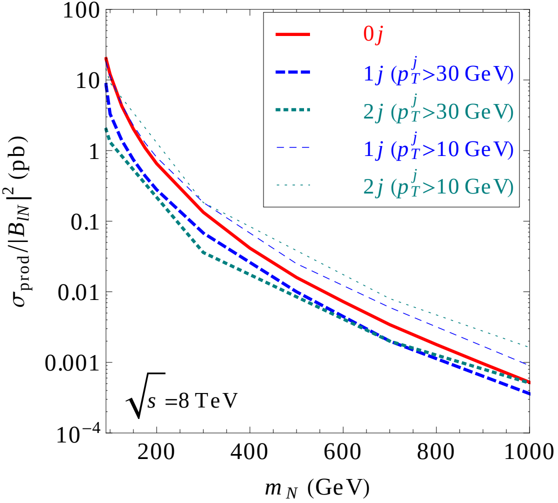
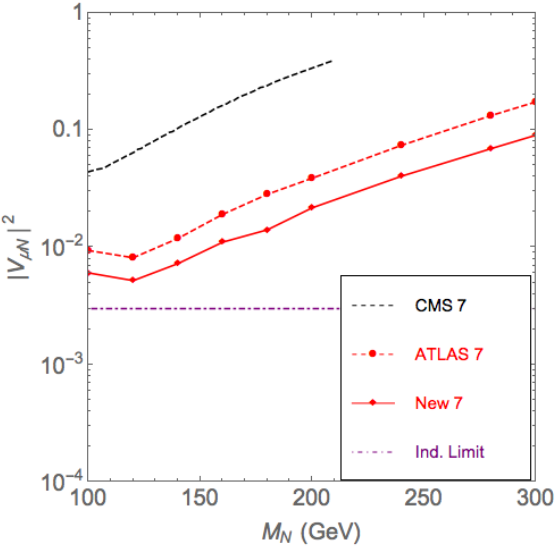


Improved Upper Limit on light-heavy Neutrino Mixing



[PSBD, Pilaftsis and Yang, PRL **112**, 081801 (2014)]

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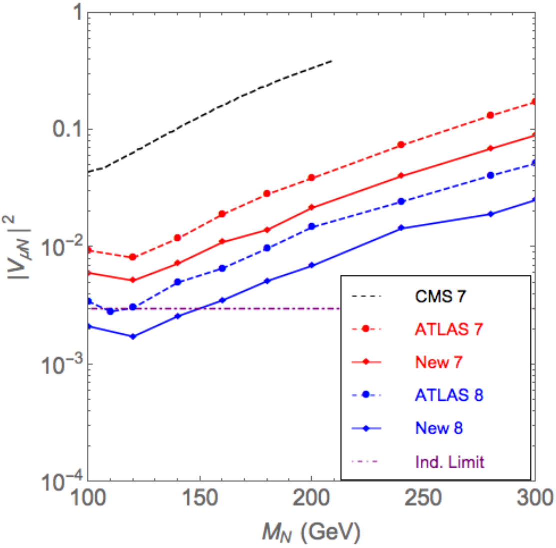

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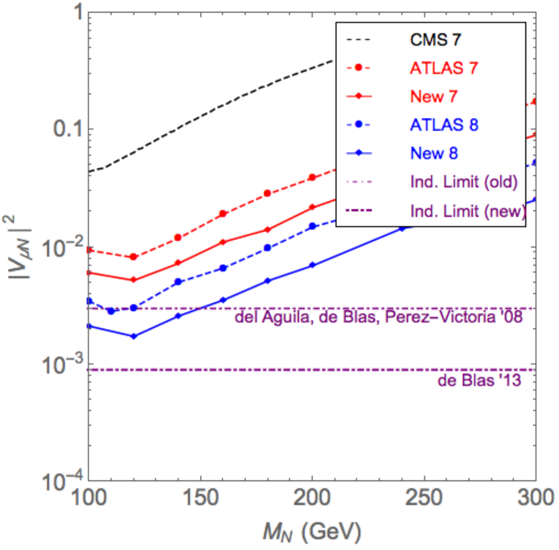

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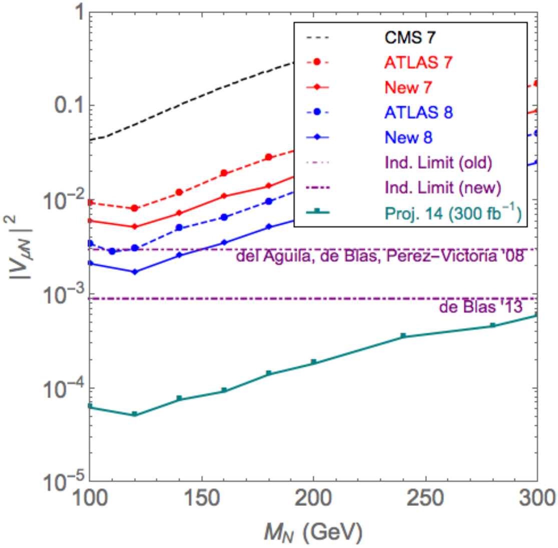

Large Mixing with TeV-scale M_N

- In 'vanilla' seesaw, for $M_N \gtrsim$ TeV, we expect $\xi \sim M_D M_N^{-1} \simeq (M_\nu M_N^{-1})^{1/2} \lesssim 10^{-6}$.
- Suppresses all mixing effects to an unobservable level.
- Need special textures of M_D and M_N to have 'large' mixing effects with TeV-scale M_N. [Pilaftsis, Underwood '04; Kersten, Smirnov '07; Xing '09; He, Oh, Tandean, Wen '09; Ibarra, Molinaro, Petcov '10; Deppisch, Pilaftsis '10; Mitra, Senjanović, Vissani '11]
- One example: [Kersten, Smirnov '07]

$$M_D = \begin{pmatrix} m_1 & \delta_1 & \epsilon_1 \\ m_2 & \delta_2 & \epsilon_2 \\ m_3 & \delta_3 & \epsilon_3 \end{pmatrix} \quad (\text{with } \epsilon_i, \delta_i \ll m_i), \qquad M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix}.$$

- In the limit $\epsilon_i, \delta_i \to 0$, the neutrino masses given by $M_\nu \simeq -M_D M_N^{-1} M_D^\mathsf{T}$ vanish, although the heavy-light mixing $\xi_{ij} \sim m_i/M_j$ can be large.
- Such structures can be naturally guaranteed by some symmetries. [PSBD, Lee, Mohapatra '13]
- However, requires quasi-degenerate heavy neutrinos.
- Naively expect the LNV signal to be always suppressed.
- Exceptions: (i) Resonant enhancement when $\Delta m_N \sim \Gamma_N$. [Bray, Lee, Pilaftsis '07]; (ii) in presence of RH gauge currents [PSBD, Mohapatra '13; PSBD, Lee, Mohapatra '13].

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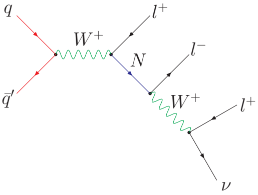
Another Natural Low-scale Seesaw

- Inverse seesaw mechanism. [Mohapatra, PRL **56**, 561 (1986); Mohapatra and Valle, PRD **34**, 1642 (1986)]
- Two sets of singlet fermions (N, S) with opposite lepton numbers.
- In the flavor basis $\{\nu^C_{L,l}\,, N_{R,\alpha}\,, S^C_{L,\beta}\}$,

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D & \mathbf{0} \\ M_D^\mathsf{T} & \mathbf{0} & M_N^\mathsf{T} \\ \mathbf{0} & M_N & \mu_S \end{pmatrix} \quad \text{and} \quad M_\nu = M_D M_N^{-1} \mu_S\, {M_N^{-1}}^\mathsf{T} M_D^\mathsf{T} + \mathcal{O}(\mu_S^3)$$

- Smallness of μ_S natural in the 't Hooft sense, since L-symmetry restored for $\mu_S \to \mathbf{0}$.
- Allows for large mixing $V_{lN} \simeq M_D M_N^{-1}$ without invoking cancellations.
- Rich phenomenological implications. [a few PhD Theses!]

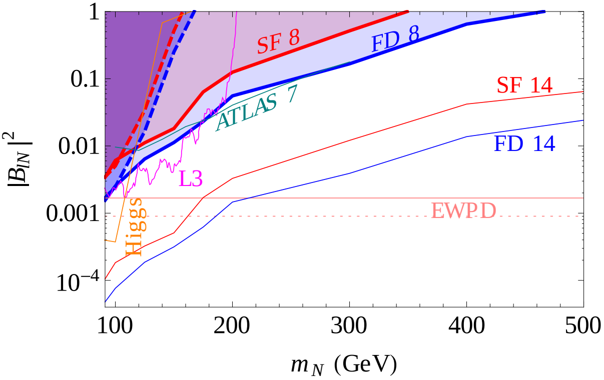
- LNV signal of same-sign dileptons suppressed due to small μ_S.
- Opposite-sign dilepton signal swapmed with large SM background (such as $pp \to Z + nj$).
- Golden channel is the trilepton signal: [del Aguila, Aguilar-Saavedra '09; Chen, PSBD '11]



Same infrared enhancement effects in the production cross section for $pp \to N\ell^\pm + nj$

Direct Limits on Heavy Dirac Neutrinos

- Used the CMS model-independent search for anomalous production of multi-lepton events using the 19.5 fb^{-1} data at $\sqrt{s} = 8$ TeV LHC. [CMS Collaboration, arXiv:1404.5801 [hep-ex]]
- Simulated signal events for $pp \to \ell^{\pm}\ell^{\mp}\ell^{\pm} + nj$ (with n =0–4) using the same CMS selection criteria.
- Put direct constraints on the heavy Dirac neutrino parameter space.



[A. Das, PSBD and N. Okada, PLB **735**, 364 (2014)]

Conclusion

- A simple paradigm for neutrino masses: Type-I Seesaw.
- Two key aspects: Majorana neutrino mass and Heavy-light neutrino mixing.
- Can be tested individually at the Intensity Frontier and/or simultaneously at the Energy Frontier.

- New heavy neutrino production mechanism gives improved LHC sensitivity due to *infrared enhancement* effects.
- Improved direct limits on heavy neutrino parameter space, which are (at least) comparable with complementary constraints from indirect searches.
- Similar infrared enhancement effects can also be applied to other exotic searches at the LHC, e.g. charged Higgs searches.

THANK YOU.

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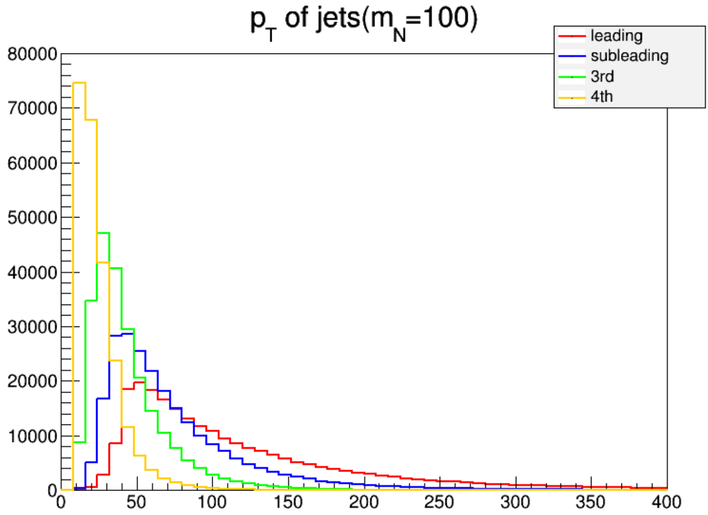

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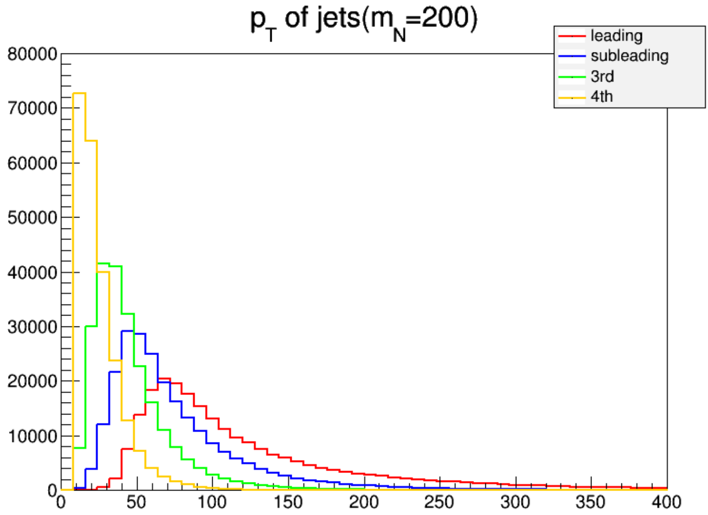

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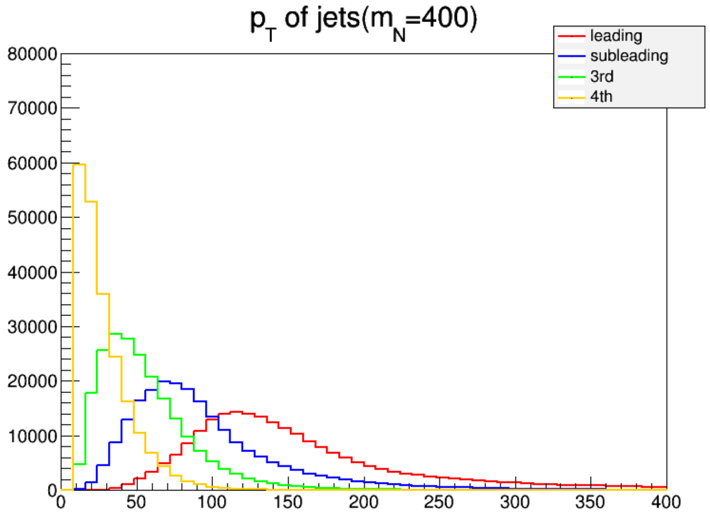

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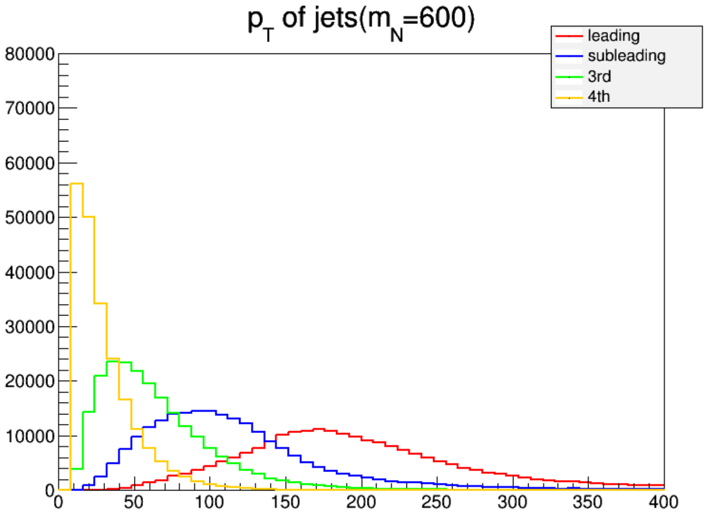

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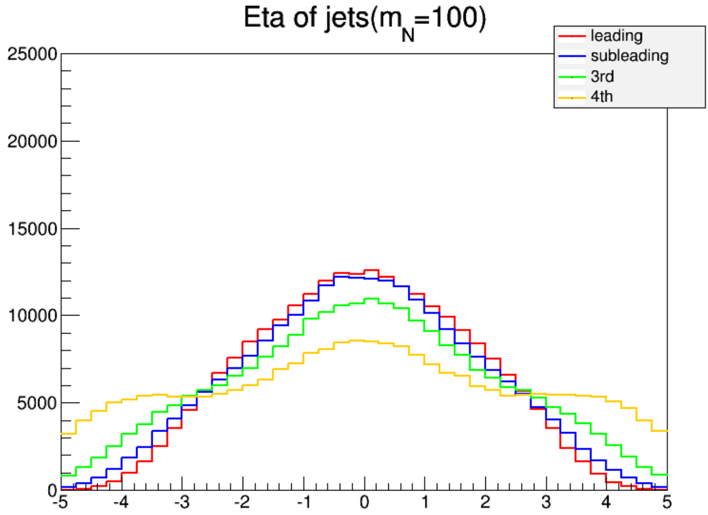
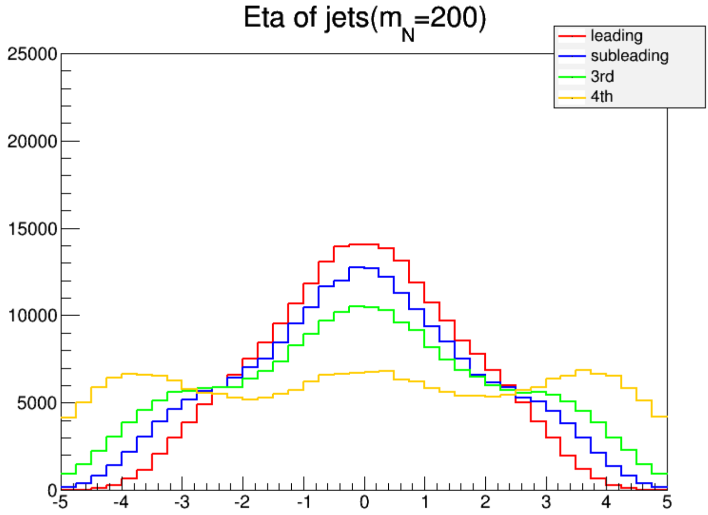
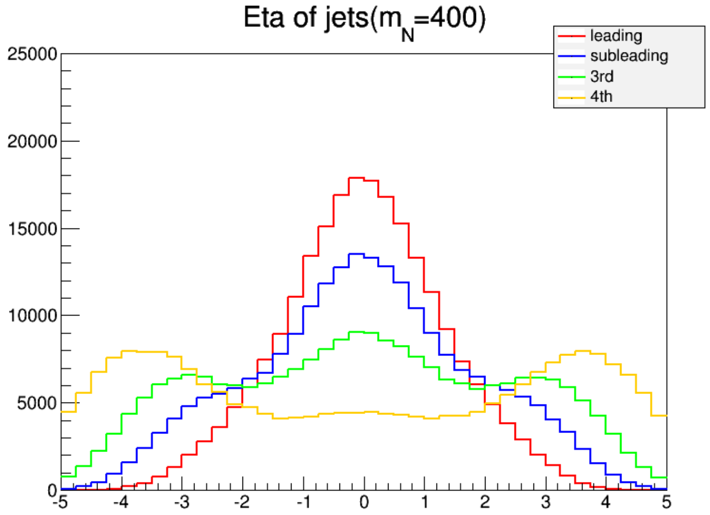


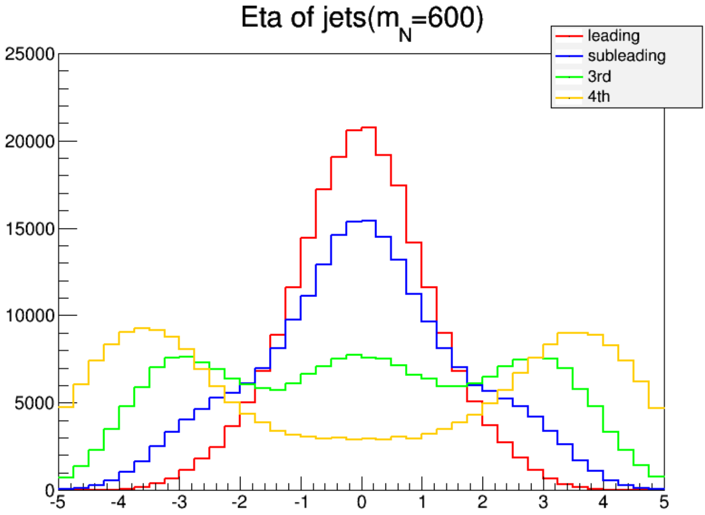
η Distribution of the Jets



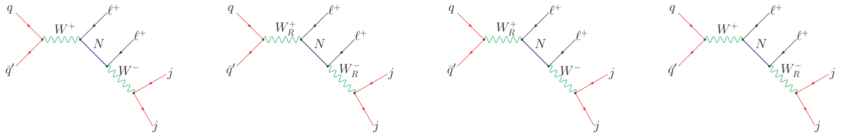
η Distribution of the Jets



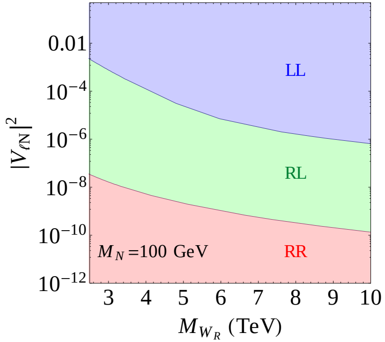
η Distribution of the Jets

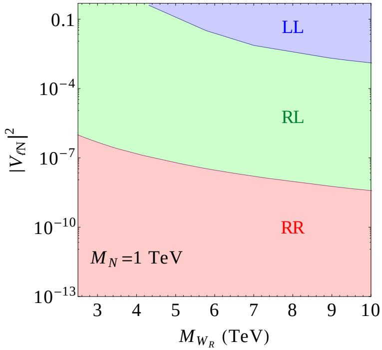


Heavy Neutrino Phase Diagram for LHC



(a) LL (b) RR (c) RL (d) LR

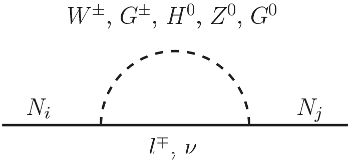




[C.-Y. Chen, PSBD and R. N. Mohapatra, PRD **88**, 033014 (2013)]

Resonant Enhancement of the LNV Signal

- In the limit of degenerate heavy neutrinos, width effects are important.
- Need sophisticated field-theoretic formalism, e.g. resummation of self-energy graphs
  [Pilaftsis, PRD **56**, 5431 (1997); NPB **504**, 61 (1997)]



- Define an one-loop resummed heavy neutrino propagator:

$$\widehat{S}(\not{p}) = \begin{bmatrix} \not{p} - m_1 + i\mathrm{Im}\widehat{\Sigma}_{11}(\not{p}) & i\mathrm{Im}\widehat{\Sigma}_{12}(\not{p}) \\ i\mathrm{Im}\widehat{\Sigma}_{21}(\not{p}) & \not{p} - m_2 + i\mathrm{Im}\widehat{\Sigma}_{22}(\not{p}) \end{bmatrix}^{-1}$$

  where $\mathrm{Im}\widehat{\Sigma}$ is the absorptive part of the heavy neutrino self-energy matrix.
- Resonant enhancement of the LNV signal when $\Delta m_N \sim \Gamma_N$. [Bray, Lee, Pilaftsis '07]
- For instance, for on-shell production of $N_{1,2}$ with $\bar{s} = (m_1^2 + m_2^2)/2$,

$$\mathcal{A}^{\mu\mu}_{\mathrm{LNV}}(\bar{s}) = -V^2_{\mu N}\frac{2\Delta m_N}{\Delta m_N^2 + \Gamma_N^2} + \mathcal{O}(\Delta m_N/m_1) \quad \text{for} \;\; \Delta m_N \lesssim \Gamma_N.$$