Heavy Neutrinos and (Safe) Jet Vetoes [1]

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13 June 2018

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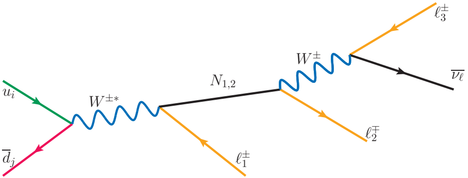
[1] with Silvia Pascoli and Cedric Weiland [1805.09335, 180X.YYYYY]

[2] IPPP → CP3, Universite Catholique de Louvain, Belgium (Fall '18)

The Challenge

Brief history: 2 years ago asked if possible to improve LHC searches for leptonic decays of heavy neutrinos, $N \to \ell_1 W \to \ell_1 \ell_2 \nu$

- "improve" $\neq$ MVA or BDT but a qualitatively new pheno analysis



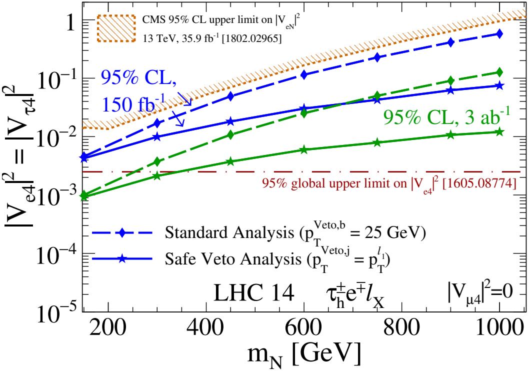
The impetus: new channels ($W\gamma$ fusion), new technology (automated NLO+PS), unclear if lepton number violating $\ell_1^\pm \ell_2^\pm + nj$ is observable

An idea: heavy N events typically contain fewer jets than backgrounds

The question: can jet activity be used to improve heavy N searches?

Money Plot: Pushing the reach of the LHC

The result:



[1805.09335]

Plotted: LHC 14 sensitivity to active-sterile neutrino mixing (coupling) vs heavy neutrino mass in the $\tau_h^\pm e^\mp \ell_X \quad (\ell_X = e, \mu, \tau_h)$ final state

- Dash = standard search with b-jet veto (mirrors 13 TeV CMS for e/μ)
- Solid = "improved" analysis with special type of jet veto

Improved sensitivity up to $10 - 11\times$ with $\mathcal{L} = 3$ ab^{-1}. Now for the details!

Heavy Neutrinos and (Safe) Jet Vetoes

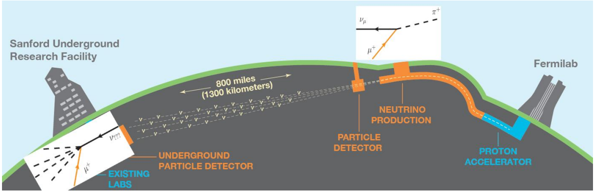
A philosophically new approach to heavy N searches at colliders has increased LHC sensitivity by an order of magnitude (in coupling space)

- New channels, new tools/machinery, new understanding of jets

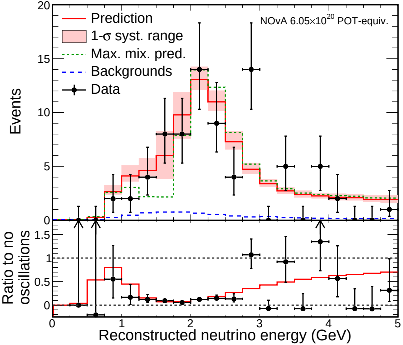
Today:

1. Why heavy neutrinos?
2. Heavy neutrino production at colliders
3. Safe Jet Vetoes
4. Monte Carlo Campaign (an ongoing fight!)
5. Results✓
6. Outlook for future colliders

Motivation for new physics from ν physics



In neutrino fixed-target experiments, ν_μ beams are prepared from $\pi^\pm$, then studied at near and far detectors (reminiscent of early SLAC DIS expts)



Deficit/disappearance of expected ν_μ (+apperance of ν_e/ν_τ) interpreted successfully as $\nu_{\ell_1} \to \nu_{\rm mass} \to \nu_{\ell_2}$ transitions/oscillations [E.g. NOνA ν_μ disapp., 1701.05891]

$\implies$ ν have mass!

So, neutrinos have masses $\lesssim \mathcal{O}(0.1)$ eV.

Is this a problem?

Yes.

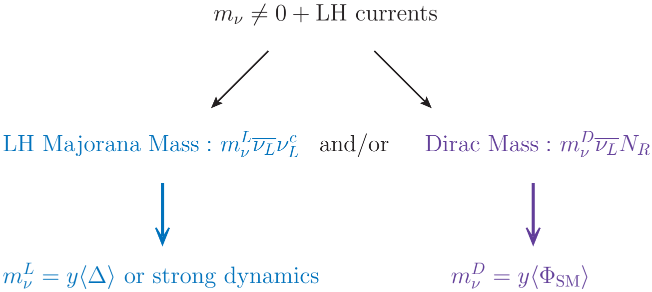
Neutrinos Masses and the Standard Model (SM)

To generate ν masses similar to other SM fermions, we need N_R

$$\mathcal{L}_{\nu~\text{Yuk.}} = -y_\nu \overline{L}\tilde{\Phi} N_R + H.c. = -y_\nu \begin{pmatrix}\overline{\nu_L} & \overline{\ell_L}\end{pmatrix} \begin{pmatrix}\langle\Phi\rangle + h \\ 0\end{pmatrix} N_R + H.c.$$

$\implies m_D \overline{\nu_L} N_R$, where $m_D = y_\nu \langle\Phi\rangle$ and y_ν is the neutrino's Higgs Yukawa coupling. However, ${N_R}^i$ do not exist in the SM, implying $m_D = 0$

Nonzero neutrino masses implies new degrees of freedom exist [Ma'98]:



$m_\nu \neq 0 + \text{LH currents}$

LH Majorana Mass : $m_\nu^L \overline{\nu_L} \nu_L^c$ and/or Dirac Mass : $m_\nu^D \overline{\nu_L} N_R$

$m_\nu^L = y\langle\Delta\rangle$ or strong dynamics

$m_\nu^D = y\langle\Phi_{\text{SM}}\rangle$

Collider Connection to Neutrino Mass Models[3]

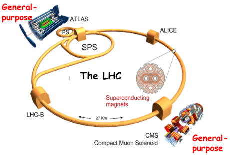
Neutrino mass models (aka Seesaw models) hypothesize new particles of all shapes, spins, charges, and color:

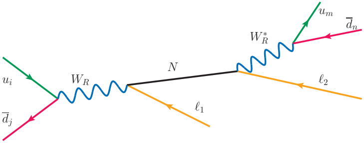
N (Type I), $T^{0,\pm}$ (Type III), Z_{B-L}, $H_R^{\pm,\pm\pm}$ (Type I+II), ...

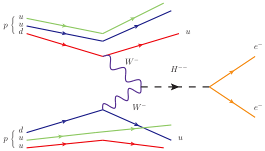
Through gauge couplings and mixing, production in $ee/ep/pp$ collisions

DY : $q\overline{q} \to \gamma^*/Z^* \to T^+T^-$ and $q\overline{q'} \to W_R^\pm \to N\ell^\pm$

WBF : $W^\pm W^\pm \to H^{\pm\pm}$ **GF** : $gg \to h^*/Z^* \to N\nu_\ell$







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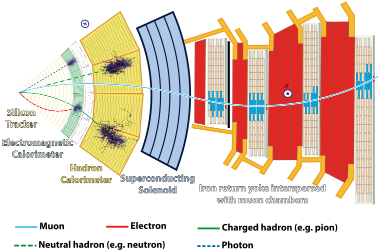
[3] Review on ν mass models at colliders, Y. Cai, T. Li, T. Han, **RR** [1711.02180]

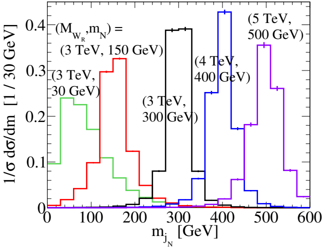
Collider Connection to Low-Scale Neutrino Mass Models[4]

Seesaw particles then decay to SM particles that are observed/inferred by detector subsystems

$$T^{\pm} \to W^{\pm}\nu,\ Z\ell^{\pm},\ h\ell^{\pm} \quad \text{and/or} \quad W_R^{\pm} \to N\ell^{\mp} \to \ell_1^{\pm}\ell_2^{\pm} + nj,$$

Identification of particles and properties through reconstruction of final-state kinematics, e.g., invariant mass peaks and angular distributions





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[4] Review on ν mass models at colliders, Y. Cai, T. Li, T. Han, **RR** [1711.02180]

II: Heavy Neutrinos and Colliders

(Heavy) Neutrino Mixing for Non-experts

After EWSB, ν_ℓ and N_R are singlets under $\mathrm{SU}(3)_c \otimes \mathrm{U}(1)_{\mathrm{EM}} \implies$ mixing!

- Neutrino oscillations already tell us mass states $\neq$ flavor states

Example: In a two-state system, mixing between chiral eigenstates and mass eigenstates is given by unitary transformation/rotation

$$\underbrace{\begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}}_{\text{chiral basis}} = \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix} \underbrace{\begin{pmatrix} \nu_1 \\ N_2 \end{pmatrix}}_{\text{mass basis}}$$

Decompose chiral states in an interaction theory into mass states by making the replacement:

$$|\nu_L\rangle = \cos\varphi|\nu_1\rangle + \sin\varphi|N_2\rangle \overset{\varphi\ll 1}{\approx} (1 - \tfrac{1}{2}\varphi^2)|\nu_1\rangle + \varphi|N_2\rangle$$

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Simplify: Like CKM, messy for $n > 1$ gen., so parameterize [0901.3589]:

- Large active-light as $|U_{\ell\nu_m}|^2 \sim 1 - (m_\nu/m_N)$
- Small active-heavy/active-sterile as $|V_{\ell N_{m'}}|^2 \sim (m_\nu/m_N)$

High-Scale vs Low-Scale Type I Seesaw

Realistic mixing is complicated[5]:

- ≥ 2 light mass eigenstates $\implies$ multiple singlet neutrinos needed
- Mass matrix sensitive to number of states and Dirac vs Majorana
- Size of Dirac/Majorana masses $\implies$ size of m_ν
- Off-diagonal entries $\implies$ lepton flavor violation
- Majorana mass (μ_M) $\Leftrightarrow$ lepton number violation

Nonetheless, two limits:

- High-scale seesaw: $\mu_M \gg \langle \Phi_{SM} \rangle$ and $m_\nu \sim m_D(m_D/\mu_M), \quad m_N \sim \mu_M$
- Low-scale seesaw: $\mu_M \ll \langle \Phi_{SM} \rangle$ and $m_\nu \sim \mu_M(m_D/m_R)^2, \quad m_N \sim m_R$

For ***discovery purposes***, no need to complicate life. Take agnostic/pheno. approach with generic $V_{\ell N}$ parametrization and one N state

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[5] See for example, C. Weiland's thesis, [1311.5860]

Heavy Neutrino Charged Currents

Consider left-handed (LH) $SU(2)_L$ doublets (**gauge basis**):

$$L_{aL} = \begin{pmatrix} \nu_a \\ l_a \end{pmatrix}_L, \quad a = 1, 2, 3.$$

The SM W chiral coupling to **leptons** in **flavor basis** is given by

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W^+_\mu \sum_{\ell=e}^{\tau} \left[\overline{\nu_{\ell L}} \gamma^\mu P_L \ell^- \right] \quad + \quad H.c.$$

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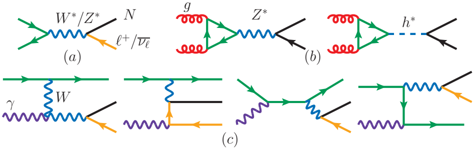
The SM W chiral coupling to **leptons** in the **mass basis**

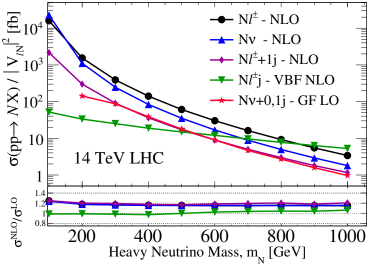
$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} \left[\sum_{m=1}^{3} \overline{\nu_m} U_{m\ell}^* + \overline{N^c} V_{N\ell}^* \right] \gamma^\mu P_L \ell^- \quad + \quad H.c.$$

$\Longrightarrow$ N is **accessible through** $W/Z/h$ currents

Heavy Neutrino Production At Hadron Colliders

Heavy *N* can be produced through a variety of mechanisms in *pp* collisions





In fact, a resurgence of calculations in recent years[6]

- Clarity needed on (i) conflicting claims and (ii) $m_N, \sqrt{s}$ dependence

$\Longrightarrow$ more physical collider definitions + public tools [1602.06957]

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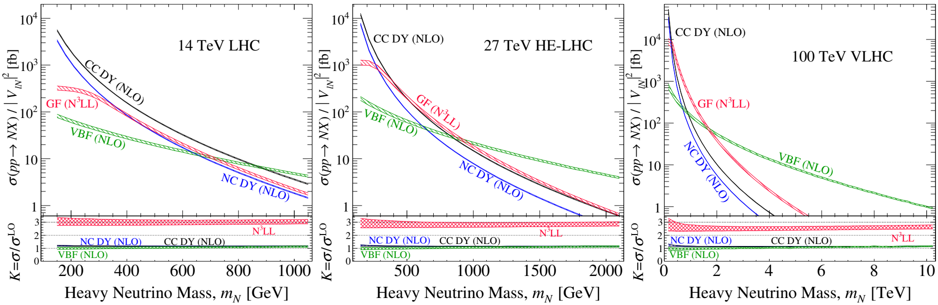
[6] DY@NLO [*1509.06375,]; VBF [1308.2209, *1411.7305, *1602.06957]; GF [1408.0983, *1602.06957] @NNNLL [*1706.02298]; DY,VBF Automation@NLO [*1602.06957]; Review: [*1711.02180]; (*) = Pittsburgh/IPPP

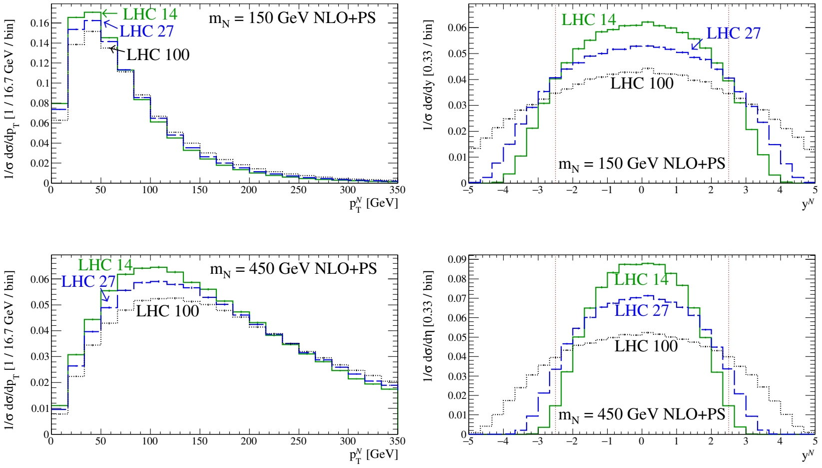
Across different colliders, wild interplay of PDF and matrix elements



Plotted: Normalized production rate ($\sigma/|V|^2$) vs heavy N mass (m_N)

- For $\sqrt{s} \gtrsim 25 - 27$ TeV GF greater than DY due to gg luminosity
- For $m_N \gtrsim 1 - 2$ TeV, VBF dominant due to large Yukawa couplings
- A 100 TeV, for $|V_{\ell N}|^2 \sim 10^{-3}$ and $\mathcal{L} = 30$ ab^{-1}, one has $\mathcal{O}(30)$ events if $m_N = 10$ TeV! If BR$\times\varepsilon \sim \times\mathcal{A}\frac{1}{3}$, then $\sqrt{N_{Obs.}} > 3\sigma$

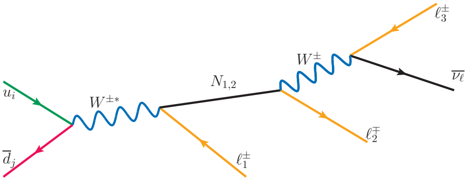
Heavy N Kinematics vs $\sqrt{s}$ (1/2)

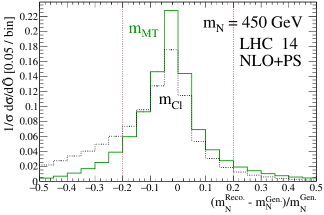


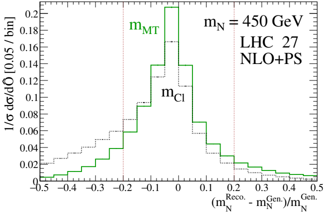
Interestingly, p_T-based observables retain shape across $\sqrt{s}$

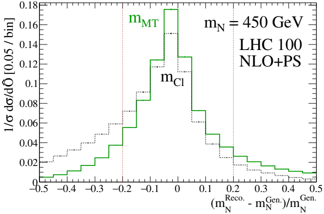
- **Important**: for DY $pp \to N\ell$, one has $p_T^\ell \sim m_N/3$

Heavy N Kinematics vs $\sqrt{s}$ (2/2)







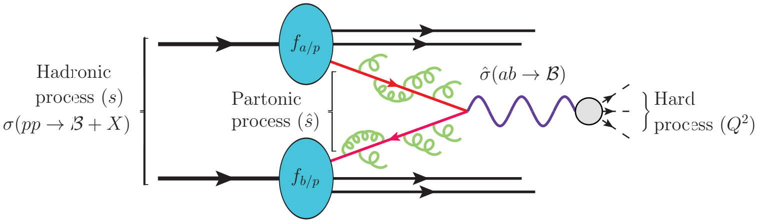


Shape retention across $\sqrt{s}$ also holds for more complex variables

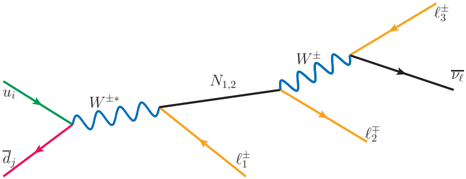
- Multi-body and cluster mass is a proxy for inv. mass of $N \rightarrow 2\ell\nu$

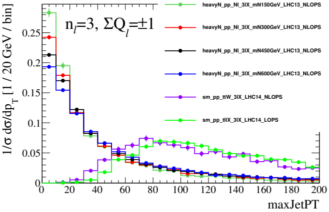
III: Heavy Neutrinos and Jet Vetoes

Jets in Heavy Neutrino Production



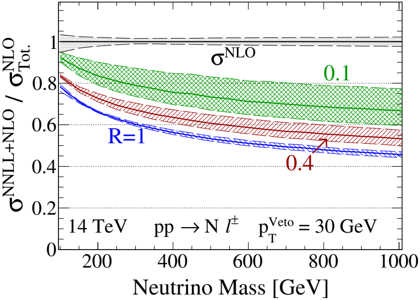
Well-known that QCD radiation (jets!) in Drell-Yan and color-singlet processes are typically forward (high η) or soft (low p_T), unlike QCD ($t\overline{t}$)





Heavy Neutrinos and Jet Vetoes

Unfortunately, also known that for Drell-Yan and color-singlet processes, there is more/harder QCD radiations (jets!) as the system gets heavier



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[7] Disclosure: discovered basis of idea in an unrelated CMS paper on $WW + 0j$

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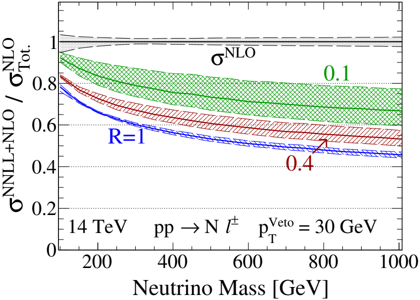

Then a thought[7]: What if we relaxed p_T^{Veto} with increasing m_N?

- No-go due to top quark background

New thought: What if we relaxed p_T^{Veto} with increasing $m_{\ell\ell\ell}$?

- For $t\bar{t}W \rightarrow 3\ell X$, $m_{\ell\ell\ell} \sim 3M_W/2$ and no change for increasing m_N
- For $pp \rightarrow N\ell \rightarrow 3\ell X$, $m_{\ell\ell\ell} \sim m_N$ and changes for increasing m_N

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Heavy Neutrinos and Safe Jet Vetoes

New thought: how about p_T of the leading charged lepton in the event?

- For $t\bar{t}W \to 3\ell X$, $p_T^\ell \sim M_W/2$ and no change for increasing m_N
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Heavy Neutrinos and Safe Jet Vetoes

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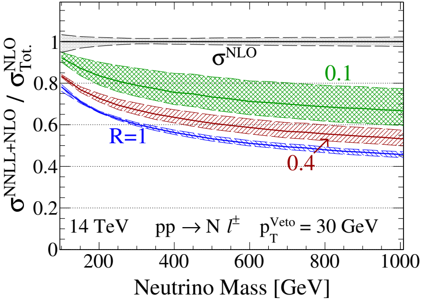

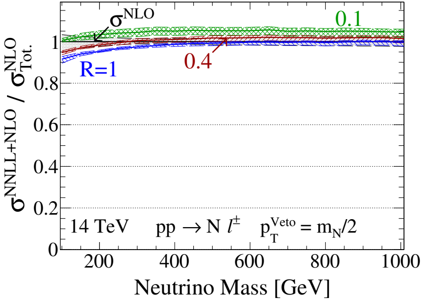

A final thought (I think a lot): does this actually work? Such a veto cannot just be applied in tandem with "standard" cuts due to correlations.

IV: The Monte Carlo (MC) Campaign

Jet vetoes are nonstandard selection cuts and make MC generation tricky

- Need reliable description of *leading* jet at high and low p_T for both (color-singlet) signal and (color-singlet) background processes
- Veto requires resummation/parton shower and jet definition $\implies$ cannot apply veto at same time as other cuts
- Major bkg have add'l $\ell^{\pm}$ outside fid. volume $\implies$ inclusive samples

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[8] C. Degrande, O. Mattelaer, **RR**, Jessica Turner [1602.06957]

[9] See W'+jet veto analysis, Fuks, **RR** [1701.05263]

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Moto: "We start at NLO"

- Event Generation: HeavyN@NLO UFO[8] + MadGraph5_aMC@NLO
    - Bare-bones gen-level cuts on leptons + MadSpin for decay
- Shower: Pythia8.2 (w/ QED shower + recoil + Monash* Tune)
- Particle-level Reco (lhe output): MadAnalysis5 + anti-k_T with[9] $R = 1$
- Smearing + offline analysis: private ROOT code

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The Monte Carlo Campaign: Modeling Heavy N

Dirac vs Majorana nature has major impact on spin correlation[10]

Avoid this outright and drop Narrow Width Approximation for N

- DY: $q\overline{q'} \to \ell_1 \ell_2 W$ at NLO in QCD, then decay $W \to \ell_3 \nu$
- VBF: $q\gamma \to \ell_1 \ell_2 W q'$ at NLO in QCD, then decay $W \to \ell_3 \nu$

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[10] "Confusion Theorem," B.~Keyser [**PRD26**, 1662 ('82); Moriond 2018]; T. Han, I. Lewis, **RR**, ZG Si [1211.6447]

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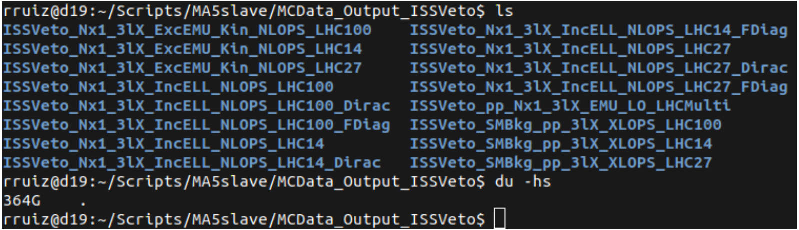

```
rruiz@d19:~/Scripts/MA5slave/MCData_Output_ISSVeto$ ls
ISSVeto_Nx1_3lX_ExcEMU_Kin_NLOPS_LHC100    ISSVeto_Nx1_3lX_IncELL_NLOPS_LHC14_FDiag
ISSVeto_Nx1_3lX_ExcEMU_Kin_NLOPS_LHC14     ISSVeto_Nx1_3lX_IncELL_NLOPS_LHC27
ISSVeto_Nx1_3lX_ExcEMU_Kin_NLOPS_LHC27     ISSVeto_Nx1_3lX_IncELL_NLOPS_LHC27_Dirac
ISSVeto_Nx1_3lX_IncELL_NLOPS_LHC100        ISSVeto_Nx1_3lX_IncELL_NLOPS_LHC27_FDiag
ISSVeto_Nx1_3lX_IncELL_NLOPS_LHC100_Dirac  ISSVeto_pp_Nx1_3lX_EMU_LO_LHCMulti
ISSVeto_Nx1_3lX_IncELL_NLOPS_LHC100_FDiag  ISSVeto_SMBkg_pp_3lX_XLOPS_LHC100
ISSVeto_Nx1_3lX_IncELL_NLOPS_LHC14         ISSVeto_SMBkg_pp_3lX_XLOPS_LHC14
ISSVeto_Nx1_3lX_IncELL_NLOPS_LHC14_Dirac   ISSVeto_SMBkg_pp_3lX_XLOPS_LHC27
rruiz@d19:~/Scripts/MA5slave/MCData_Output_ISSVeto$ du -hs
364G    .
rruiz@d19:~/Scripts/MA5slave/MCData_Output_ISSVeto$ 
```

Campaign will reach $\sim 500+$ GB since for each collider:
- 100-200K evts per signal hypothesis and 1-10M evts per process
- Will be made public via Zenodo (CERN-supported platform)

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V: Results

Flavor Hypothesis and Signal Definition

As a benchmark flavor mixing scenario we set:

$$|V_{e4}| = |V_{\tau 4}| \neq 0 \quad \text{and} \quad |V_{\mu 4}| = 0$$

Predicting two complementary[11] signal processes ($\ell_X = e, \mu, \tau_h$):

Signal I: $pp \to \tau_h^+ \tau_h^- \ell_X + \text{MET}$ and **Signal II:** $pp \to \tau_h^\pm e^\mp \ell_X + \text{MET}$

Selection Cuts: Standard ID requirements and $m_{2\ell,3\ell}$ cuts

Nonstandard Cuts:

- Require $p_T^{j_1} < p_T^{\ell_1}$ (jet veto) and $S_T^\ell > 120$ GeV
- Given m_N hypothesis, cut on closest multi-body transverse mass $\tilde{M}$

$$\tilde{M}_{T,i}^2 = \left[\sqrt{p_T^2(\ell^{\rm OS}) + m_{\ell^{\rm OS}}^2} + \sqrt{p_T^2(\ell_i^{\rm SS}, \not{\vec{p}}_T) + M_W^2}\right]^2 - \left[\vec{p}_T(\ell^{\rm OS}, \ell_i^{\rm SS}) + \not{\vec{p}}_T\right]^2, \quad i = 1, 2.$$

---

[11] BR($\tau/W \to eX$) are well-measured $\implies$ can falsify no-LFV hypothesis if measured

Backgrounds

Associated Top Quark Production: $pp \to t\bar{t}\ell\ell$, $t\bar{t}\ell\nu$, $tq\ell\ell$ (LO+PS)

- Typical p_T of lepton from t: $p_T^\ell \sim \frac{m_t}{4}(1 + \frac{M_W^2}{m_t^2}) \sim 50$ GeV
- Typical p_T of b from t: $p_T^b \sim \frac{m_t}{2}(1 - \frac{M_W^2}{m_t^2}) \sim 65$ GeV
- $p_T^\ell < p_T^b \implies$ top events vetoed without need of b-tagging

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Electroweak Production: $pp \to 4\ell$, $3\ell\nu$,WWW, $WW\ell\ell$

- Jet veto + multi-boson production $\implies$ EW bosons at rest
- Typical $S_T \equiv \sum_\ell |\vec{p}_T^\ell|$ for $3W$ or WZ: $S_T \sim \frac{3M_V}{2} \sim 120 - 130$ GeV
- Typical S_T for heavy N: $S_T \sim \frac{m_N}{3} + \frac{m_N}{2} + \frac{m_N}{4} = \frac{13m_N}{12}$

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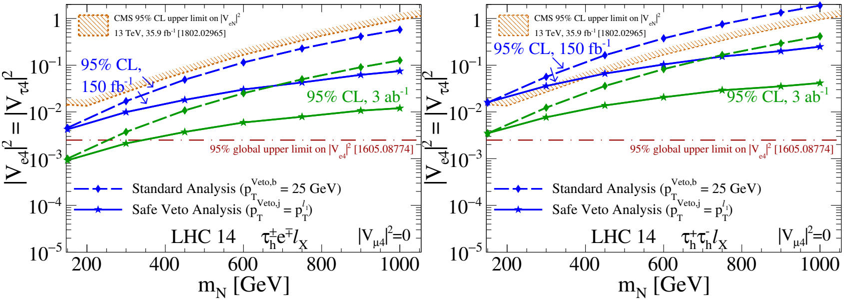
Fake Leptons:

- Fake $e^\pm$: Random j in $t\bar{t}$ reassigned; evts weighted using [1611.05032]
- Fake $\tau^\pm$: (mis)tagging rates from 13 TeV Det. Performance studies
- Color conservation $\implies$ second jet with comparable p_T likely exist

Results for 14 TeV LHC: $e\tau$ Scenario



Plotted: LHC 14 sensitivity to active-sterile neutrino mixing (coupling) vs heavy neutrino mass

- Dash = standard search[12] with b-jet veto (13 TeV CMS for e/μ)
- Solid = "improved" analysis with special type of jet veto

Improved sensitivity up to $10-11\times$ with $\mathcal{L} = 3$ ab^{-1}.

[12] More aggressive cuts on charged leptons: e.g., $p_T^{\ell_1} > 55$ GeV, $m_{3\ell} > 80$ GeV

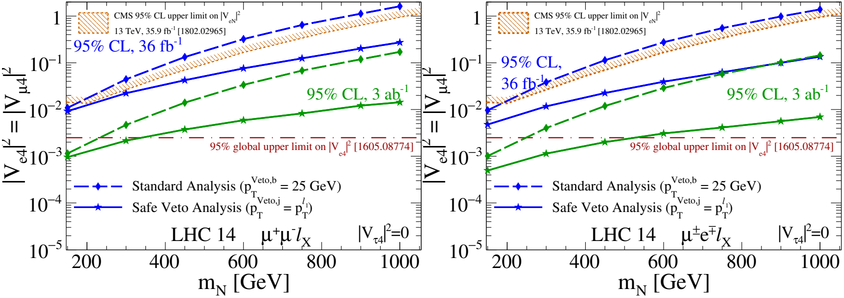
More Results at 14 TeV LHC: $e\mu$ Scenario

Benchmark flavor mixing scenario II:

$$|V_{e4}| = |V_{\mu 4}| \neq 0 \quad \text{and} \quad |V_{\tau 4}| = 0$$

Predicting two complementary signal processes ($\ell_X = e, \mu, \tau_h$):

Signal I: $pp \to \mu^+\mu^-\ell_X$+MET and **Signal II:** $pp \to \mu^\pm e^\mp \ell_X$+MET



Again, improved sensitivity > 10× with $\mathcal{L} = 3$ ab^{-1}.

Preliminary Results at 27 TeV LHC: $e\tau$ Scenario

Benchmark flavor mixing scenario I with $e - \tau$ mixing:

Signal: $pp \rightarrow \tau^{\pm} e^{\mp} \ell_X + \text{MET}$

SURPRISE

(L) 14 TeV vs (R) 27 TeV with $\mathcal{L} = 3, 15, 30$ ab^{-1}

WARNING VERY PRELIMINARY: Missing stats and uses 14 TeV cuts

Summary

Heavy neutrinos remain one of the best (but not the only!) explanations for tiny neutrino masses

We have investigated a new approach to searches for heavy N in pp collisions based on a dynamical jet veto ($p_T^{\rm Veto} = p_T^{\ell_1}$)

- New veto scheme reveals $> 90 - 95\%$ signal acceptance with little-to-no dependence on m_N (contrary to previous methods)
- Substantial reduction in QCD theory uncertainty at NLO+NNLL(Veto) $\implies$ less need for high-precision resummation
- Redesigned search analysis with better reduction of background $\implies$ Improved LHC sensitivity by up to $10\times$ over LHC's lifetime

Remember: "*The LHC is planned to run over the next 20 years, with several stops scheduled for upgrades and maintenance work*" [press.cern]

- High-Luminosity LHC and Belle II goals: 3-5 ab^{-1} and 50 ab^{-1}
- Premature to claim "nightmare scenario" (SM Higgs + nothing else)

Thank you.