Heavy Neutrinos with Dynamic Jet Vetoes

#Pheno19

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\(^1\text{w/ S. Pascoli, et al., [1805.09335, 1812.08750]}\)
Heavy $N$ are a great (though not only) explanation for tiny $\nu$ masses

- $N$ couple to Standard Model particles through mass-mixing

$$\nu_{\ell L} \approx \sum_{m=1}^{3} U_{\ell m} \nu_{m} + V_{\ell m'=4} N_{m'=4}$$

and hence can be produced through a variety of mechanisms

In fact, a surge of new calculations in recent years$^2$

- Clarity needed on (i) $m_N$, $\sqrt{s}$ dependence and (ii) conflicting claims
- Across different colliders, wild interplay of PDF and matrix elements

$^2$For extensive details, see the review w/ Y. Cai, T. Li, and T. Han [1711.02180]
Plotted: Normalized production rate \( \sigma / |V|^2 \) vs heavy \( N \) mass \( (m_N) \)
- For \( \sqrt{s} = 14 \) TeV, DY and VBF dominate at low- and high-mass
- For \( \sqrt{s} \gtrsim 25 - 27 \) TeV GF greater than DY due to \( gg \) luminosity

Note: For \( m_N = 10 \) TeV and \( |V_{\ell N}|^2 \sim 10^{-3} \), then at 100 TeV, one has \( O(30) \) VBF events after 30 ab\(^{-1}\)! If \( BR \times \epsilon \times A \sim \frac{1}{3} \), then \( \sqrt{N_{\text{Obs}}} > 3\sigma \)
A Challenge

3 years ago asked if possible to improve LHC searches for leptonic decays of heavy neutrinos, $N \rightarrow \ell_1 W \rightarrow \ell_1 \ell_2 \nu$

- “improve” $\neq$ MVA or BDT but a qualitatively new search strategy

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 bkg events

The question: Can jet observables be used to improve heavy $N$ searches?
Specialness of

Vector Boson Fusion (VBF) and Drell-Yan (DY)
In high-$p_T$ / high-$Q^2$ $pp$ collisions, there is color everywhere...

Absence of central color flow in VBF

$\Longrightarrow$ absence of central, high-$p_T$ jets ("rapidity gap")

Basis for Central Jet Veto$^4$:

- Reject events with any jet satisfying $p_T^j > 25 - 30$ GeV, $|\eta^j| < 2 - 3$
- Crucial to Higgs physics but not perfect...

$^3$Dokshitzer, Khoze, Troyan (‘86)

$^4$Barger, et al, PRD44, 2701 (’91) + PLB346, 106 (’95); Bjorken (’94)
Heavy Neutrinos and Central Jet Vetoes

$p

N

ℓ^+

N

ℓ^+

p

p
Plotted: veto efficiency \( \varepsilon(p_T^{Veto}) = \frac{\sigma_{NLO+NNLL}^{NLO}(p_T^{Veto})}{\sigma_{DY}^{NLO}(\text{No Cuts})} \)

Jet vetoes applied to heavy \( N \) production fail *spectacularly*\(^5\)

- Significant dependence on mass scale and jet radius \( R = 0.1, 0.4, 1 \)
- Relaxing \( p_T^{Veto} \Rightarrow \) increasing top quark background

\(^5\)Ditto for sleptons [Tackmann, et al, 1603.03052] and \( W' \) [w/ Fuks, 1701.05263]
Dynamic Jet Vetoes\textsuperscript{6}:

Reenvisioning the Jet Veto

\textsuperscript{6}w/ Pascoli, et al, 8pg letter [1805.09335], 97~(101)pg analysis [1812.08750]
For production of leptons in VBF: $p_T^{\ell_k}, S_T \sim M_{VV} \gg p_T^{j_{VBS}} \sim M_V/2$

Still no color flow!

An idea

7 Inspired by CMS using the ratio $r_j^\ell = (p_T^\ell/p_T^j)$ for lepton isolation [1701.06940]
For production of leptons in VBF: $p_T^{l_k}, S_T \sim M_{VV} \gg p_T^{jVBS} \sim M_V/2$

An idea\(^7\): on event-by-event basis, set $p_T^{Veto} = p_T^{l_1}$

- VBF events pass by construction; ditto for DY and GF processes.
- Since $(m_N/p_T^{Veto}) \sim 1$, jet veto logarithms under control
- What about other background processes, e.g., top quarks?

\(^7\)Inspired by CMS using the ratio $r_j^\ell = (p_T^\ell/p_T^j)$ for lepton isolation [1701.06940]
$pp \rightarrow t\bar{t}Z \rightarrow 1\mu + 3e + 2j_{b+} \not{E}_T$

candidate event [1509.05276]

Textbook kinematics:
- $m_{ee} = 93$ GeV
- $\not{E}_T = 57$ GeV

Typically,
- $p_T^{e_3} \sim \frac{M_Z}{2} \sim 45$ GeV
- $p_T^{e_1} \sim \frac{m_t}{4}(1 + \frac{M_W^2}{m_t^2}) \sim 50$ GeV
- $p_T^{b_1} \sim \frac{m_t}{2}(1 - \frac{M_W^2}{m_t^2}) \sim 60$ GeV

$p_T^{b_1} > p_T^{\ell_k} \implies$ event vetoed!

Setting $p_T^{Veto} = p_T^{\ell_1}$ can cut top background without $b$-jet tagging!
Inclusive diboson production possesses large QCD corrections, e.g., $pp \rightarrow W^+W^-$ at NNLO [1408.5243]

- Driven by $pp \rightarrow W^+W^-j$
- $p_T^\ell \sim \frac{M_W}{2} + \frac{p_T^j}{2n_b} \ (n_b = \# \ bosons)$
  $\implies$ large $p_T^j > p_T^\ell$ tail
Irreducible Backgrounds vs Dynamic Jet Vetoes

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$\Rightarrow$ large $p_T^j > p_T^\ell$ tail

Jets mistagged/IDed as $\tau_h/e$, i.e., “fake leptons,” major irreducible bkg:
- E.g., $pp \rightarrow W^+ W^- j$
- Subleading jets more likely to be mis-IDed than leading jet

Setting $p_T^{Veto} = p_T^{\ell_1}$ can reduce irreducible backgrounds
Plotted: veto efficiency \( \varepsilon(p_T^j < p_T^{\text{Veto}}) = \frac{\sigma_{\text{NLO+PS Fid. Cuts+Veto}}}{\sigma_{\text{NLO+PS Fid. Cuts}}} \)

- Static jet vetoes \(\rightarrow\) poor signal efficiency for high-mass BSM
- Setting \(p_T^{\text{Veto}} = p_T^{l_1}\) can alleviate this
Discovery Prospects?
**Plot:** LHC 14 sensitivity to \((\text{coupling})^2\) vs heavy neutrino mass

**Signal I:** \(pp \rightarrow \mu^\pm e^\mp \ell_X + \text{MET}\)

**CMS 95% CL upper limit on \(|V_{e4}|^2\)**
- 13 TeV, 35.9 fb\(^{-1}\) [1802.02965]

- 95% CL, 35.9 fb\(^{-1}\) [1805.09335]
- 95% CL, 3 ab\(^{-1}\)

**Improved sensitivity up to 10 – 11× with \(\mathcal{L} = 3\ \text{ab}^{-1}\).**
**Conclusion:** LHC can compete with dedicated flavor experiments

- See [1812.08750] for various flavor channel comparisons, etc
Summary and Next Steps

A class of jet vetoes has been developed for high-mass, multi-ℓ searches, one based on comparing lepton vs hadronic activities, e.g., $H_T^{\text{Veto}} = p_T^{\ell_1}$

- New scheme reveals $> 90 – 95\%$ signal acceptance with little-to-no dependence on mass scales (contrary to previous schemes)
- Substantial reduction in QCD theory uncertainty $\implies$ less need for high-precision resummation
- Redesigned search analysis gives better reduction of background

Application to new physics searches appears very promising:
- Sterile neutrinos: improved sensitivity $\sim 10 – 11 \times$
- Sleptons: Relative improvement of $p_T^{\text{Veto}}, H_T^{\text{Veto}} = p_T^{\ell_k}, S_T$, depends on mass spectrum $\implies$ veto can be tuned accordingly [1901.09937]
- In progress: lots! machine learning/NN, impact of higher jet multiplicities (FxFx), underlying event/MPI, add’l uncertainties
Thank you.