Heavy Neutrinos with Dynamic Jet Vetoes [1]

#Pheno19

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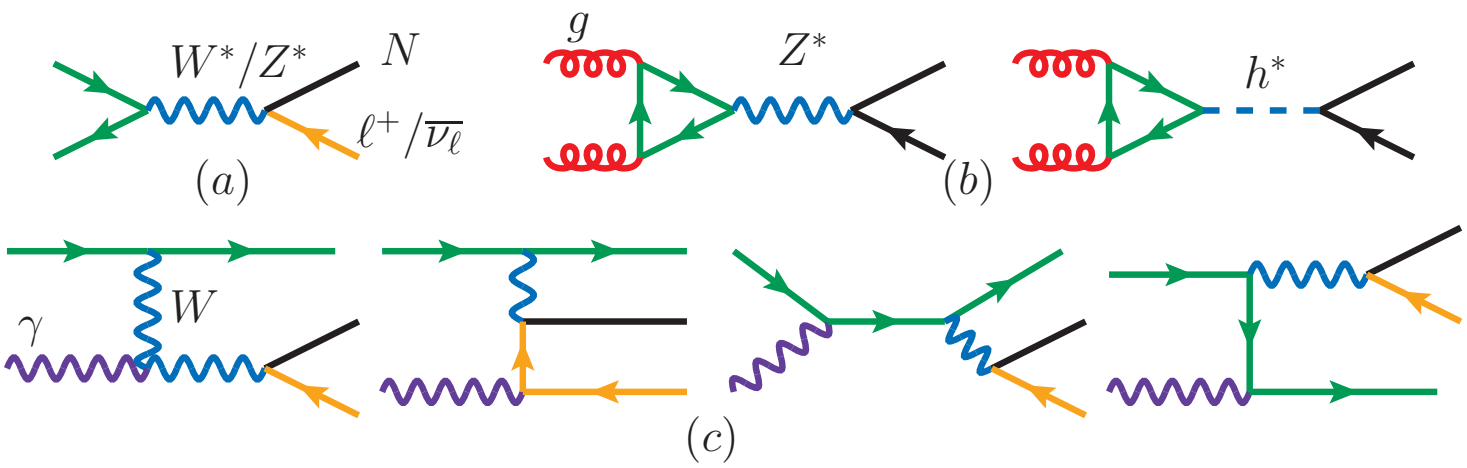
[1] w/ S. Pascoli, et al., [1805.09335, 1812.08750]

Heavy N are a great (though not only) explanation for tiny ν masses

- N couple to Standard Model particles through mass-mixing

$$\underbrace{\nu_{\ell L}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell m'=4}N_{m'=4}}_{\text{mass basis}}$$

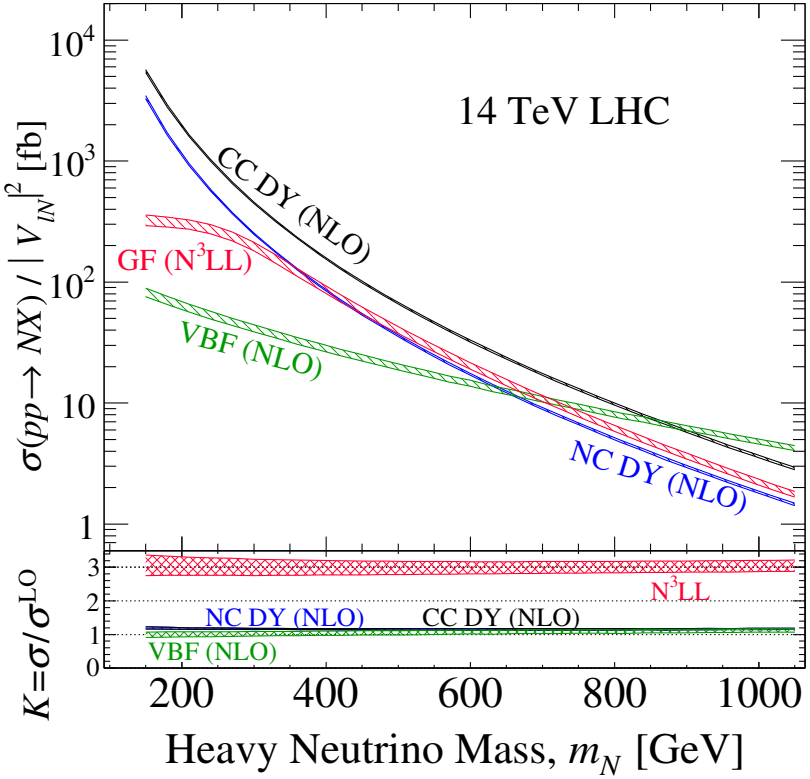
and hence can be produced through a variety of mechanisms

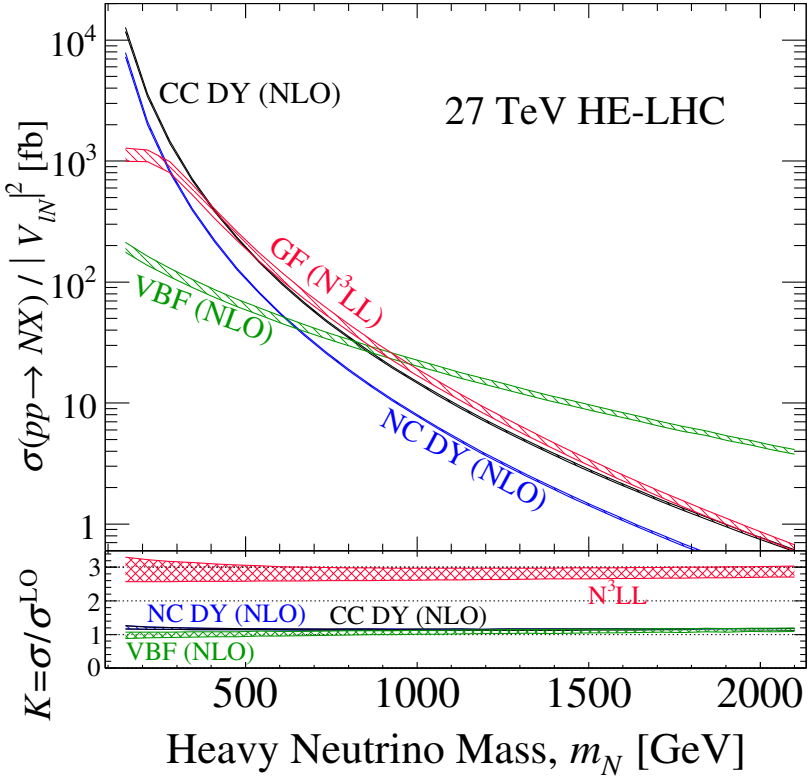


In fact, a surge of new calculations in recent years[2]

- 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)

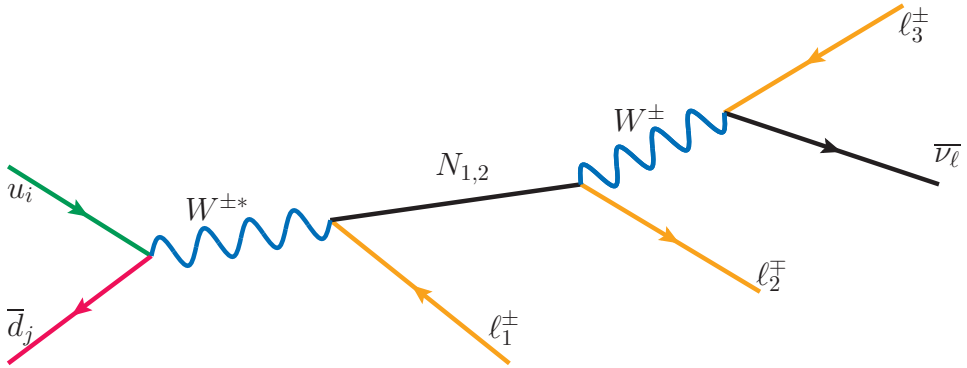
- For $\sqrt{s} = 14$ TeV, **DY** and **VBF** dominate at low- and high-mass
- For $\sqrt{s} \gtrsim 25 - 27$ TeV **GF** greater than **DY** due to gg luminosity

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

A Challenge

3 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 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?

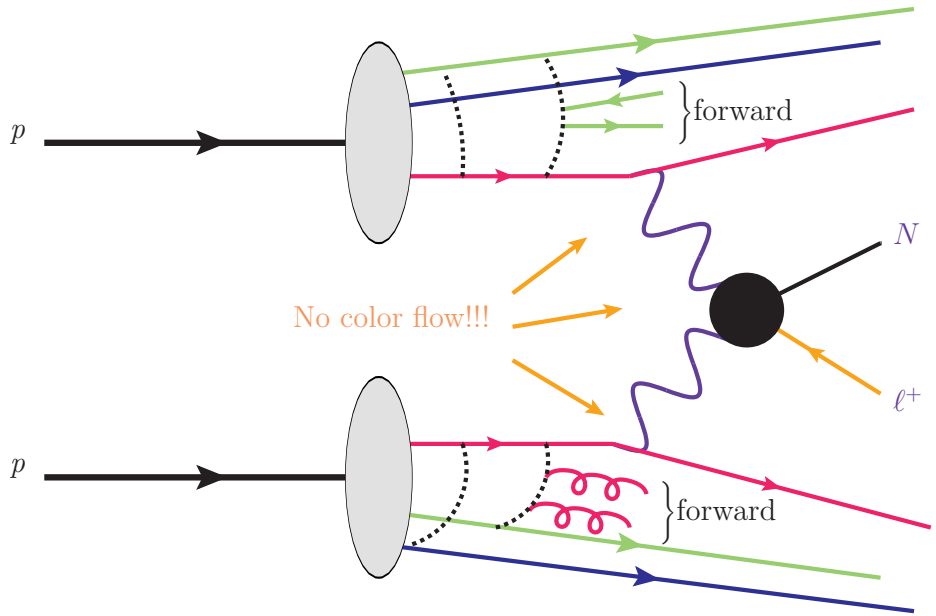
Specialness of

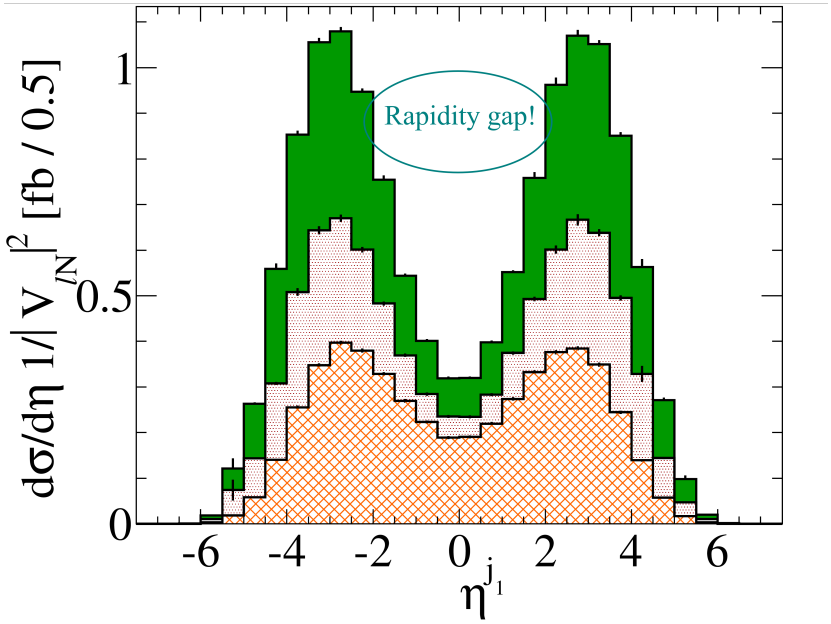
Vector Boson Fusion (VBF) and Drell-Yan (DY)

In high-p_T / high-Q^2 pp collissions, there is color *everywhere*...

Abscence of central color flow in VBF

$\Longrightarrow$ absence of central, high-p_T jets ("rapidity gap"[3])





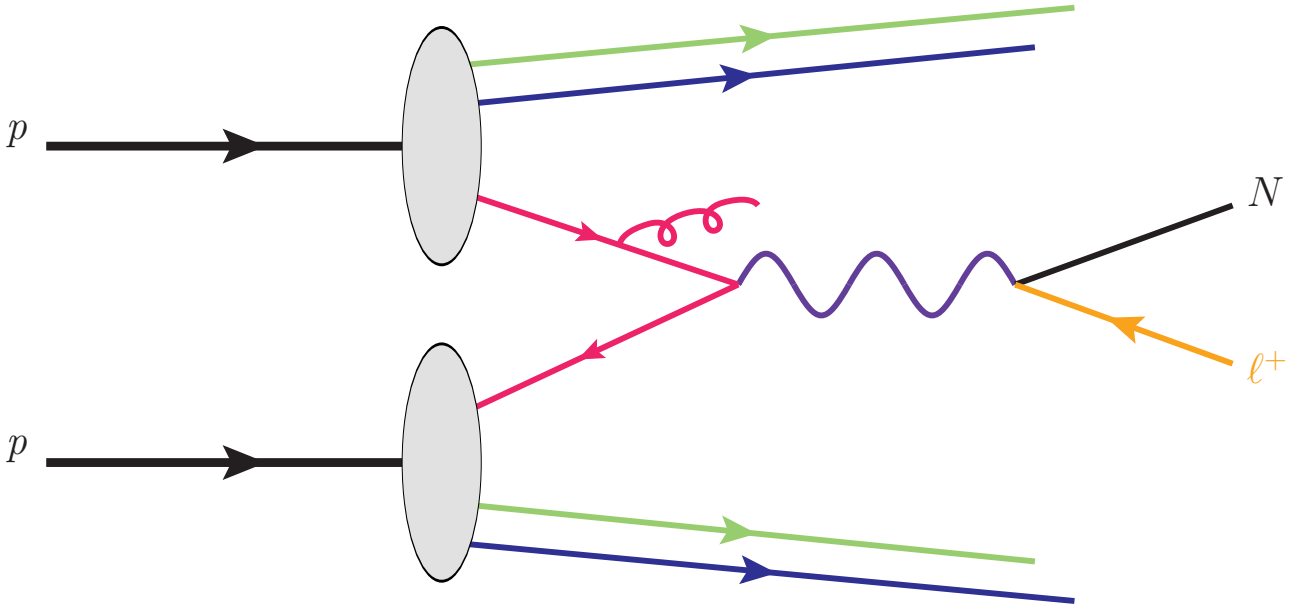
Basis for Central Jet Veto[4]:

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

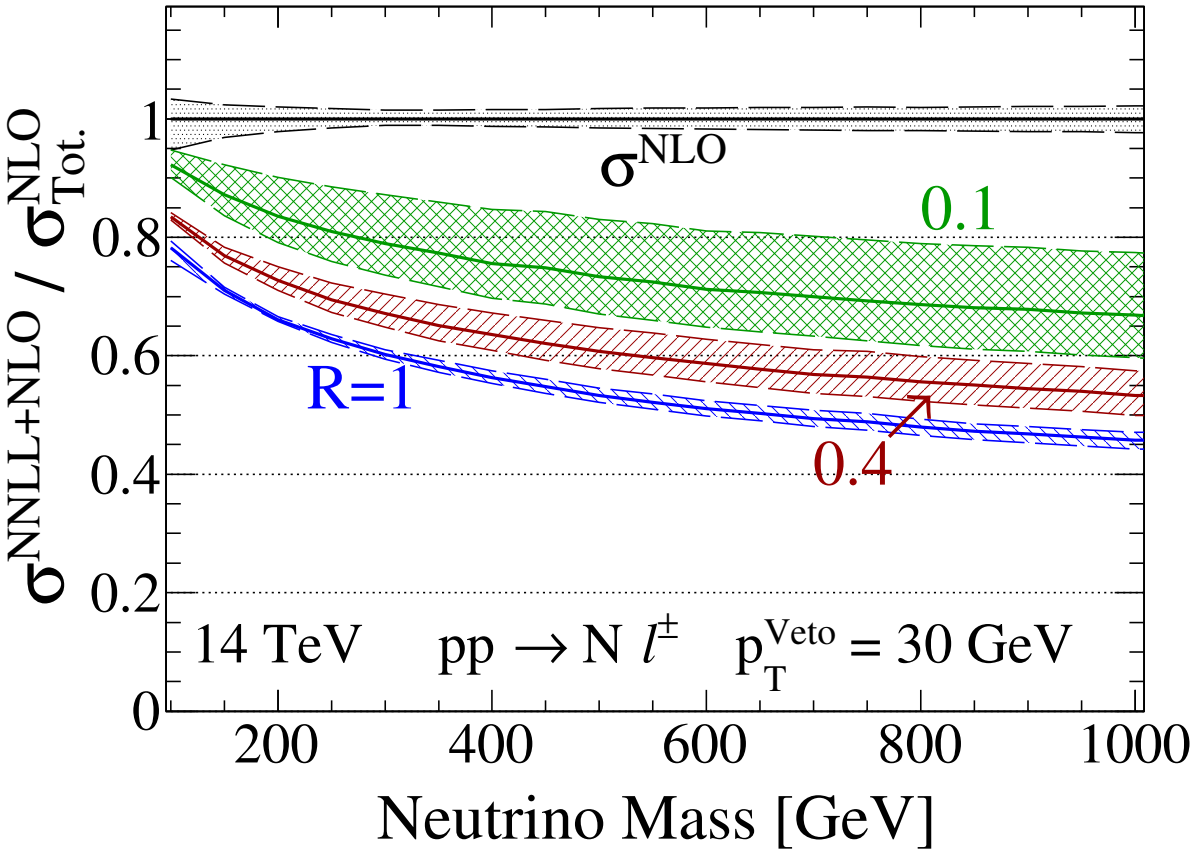
[3] Dokshitzer, Khoze, Troyan ('86)

[4] Barger, et al, PRD44, 2701 ('91) + PLB346, 106 ('95); Bjorken ('94)

Heavy Neutrinos and Central Jet Vetoes



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



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 $p_T^{\rm Veto}$ $\Longrightarrow$ increasing top quark background

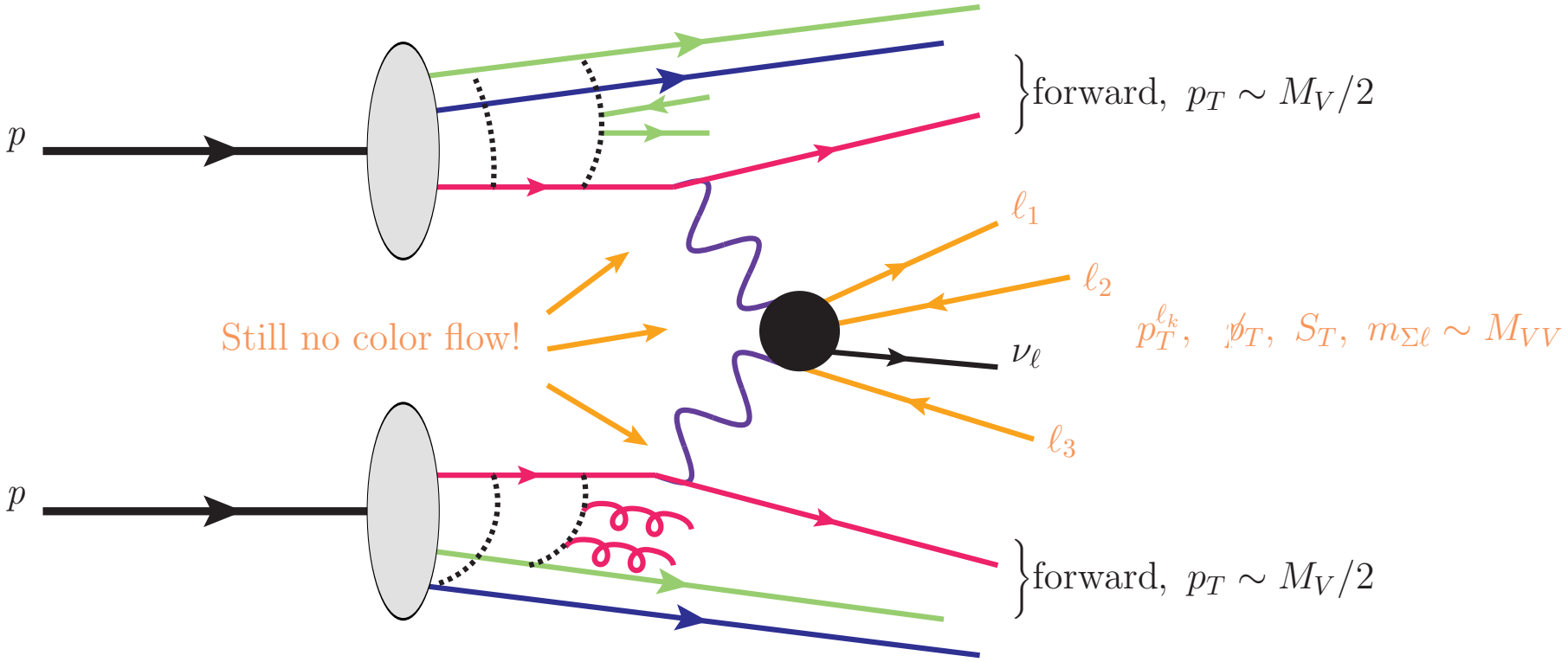
[5] Ditto for sleptons [Tackmann, et al, 1603.03052] and W' [w/ Fuks, 1701.05263]

Dynamic Jet Vetoes[6]:

Reenvisioning the Jet Veto

[6] w/ Pascoli, et al, 8pg letter [1805.09335], 97~(101)pg analysis [1812.08750]

For production of leptons in VBF: $p_T^{\ell_k},\ S_T\ \sim M_{VV} \gg p_T^{j_{VBS}} \sim M_V/2$



[7] Inspired by CMS using the ratio $r_j^\ell = (p_T^\ell / p_T^j)$ for lepton isolation [1701.06940]

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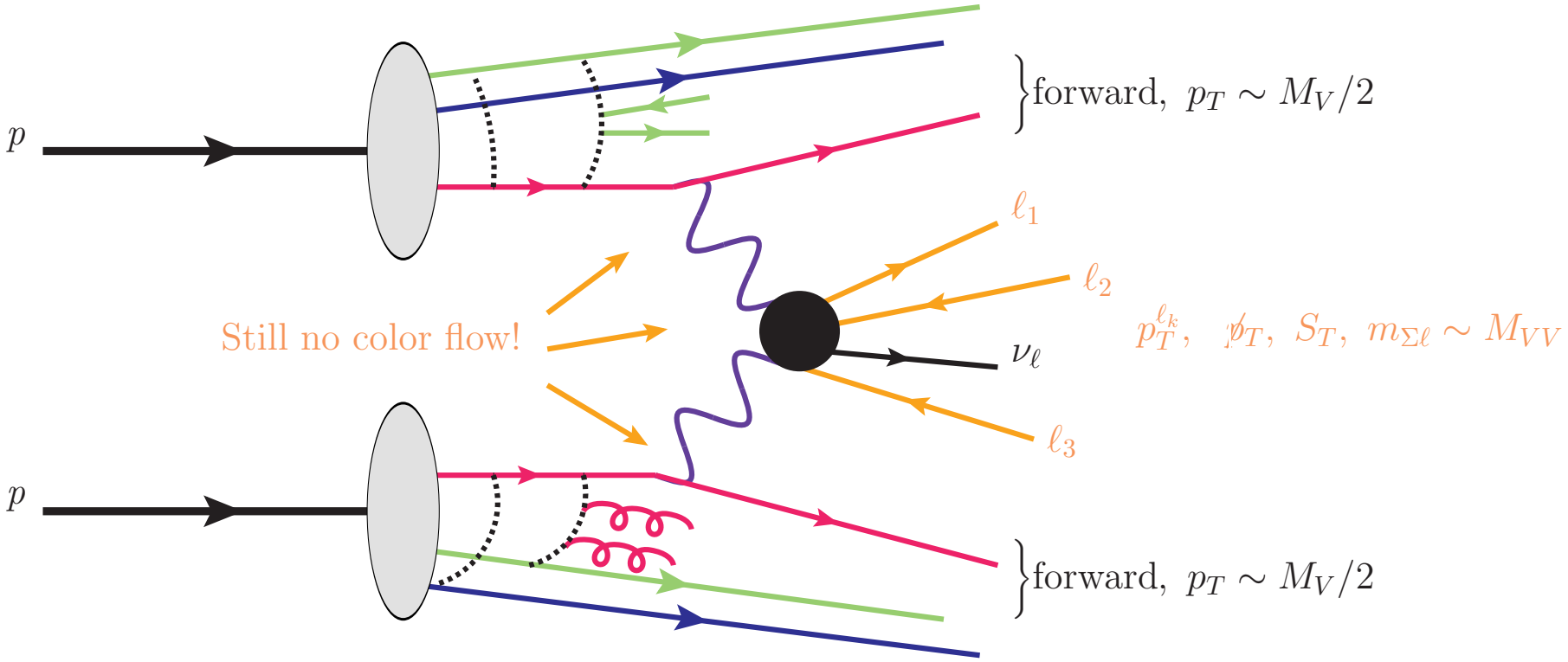

An idea[7]: on event-by-event basis, set $p_T^{\rm Veto} = p_T^{\ell_1}$

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

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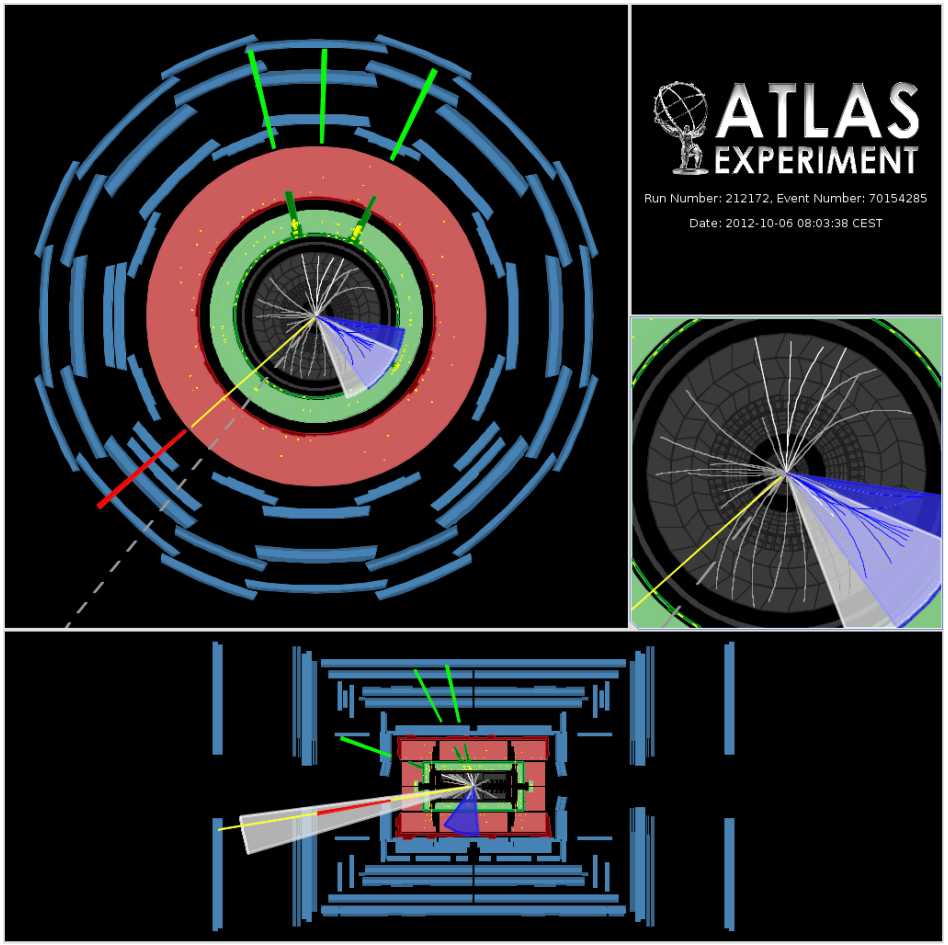
Top Quark Background vs Dynamic Jet Vetoes



$pp \to t\bar{t}Z \to 1\mu + 3e + 2j_b + \not{E}_T$
candidate event [1509.05276]
Textbook kinematics:
- $m_{ee} = 93$ GeV
- $\not{E}_T = 57$ GeV

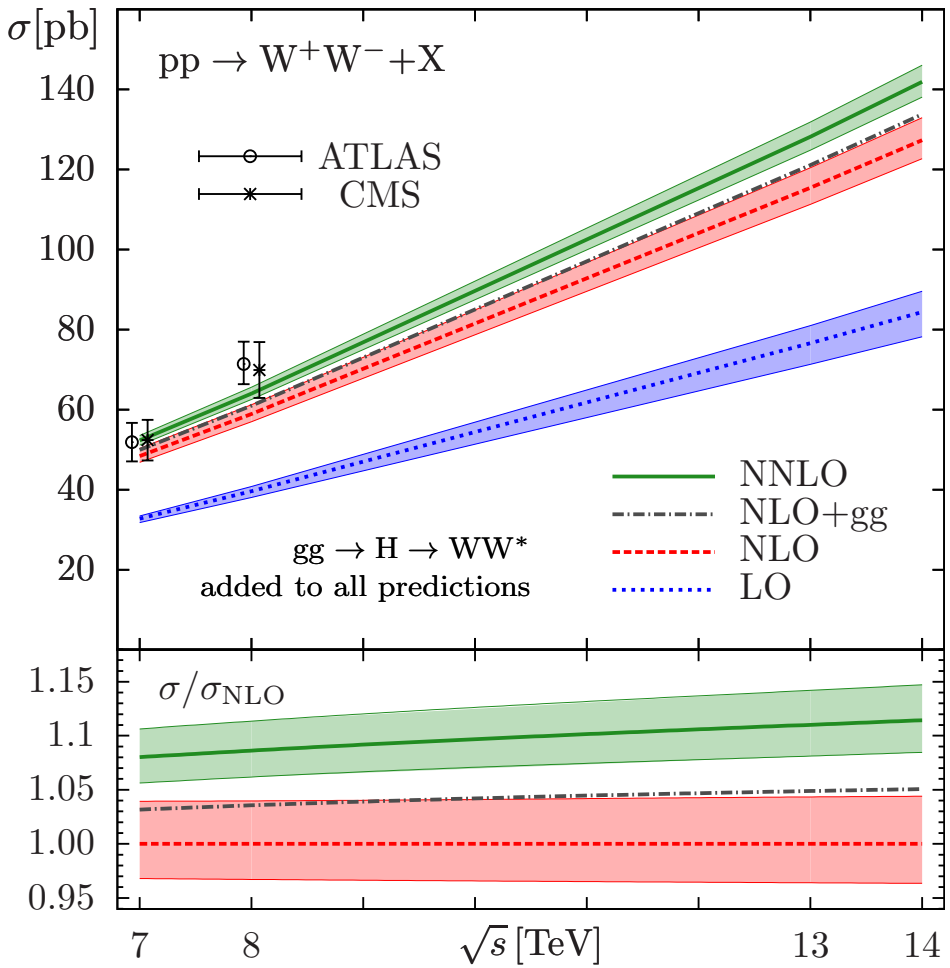
Typically,

- $p_T^{e_3} \sim \frac{M_Z}{2} \sim 45$ 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 $p_T^{\rm Veto} = p_T^{\ell_1}$ can cut top background ***without*** b-jet tagging!

Irreducible Backgrounds vs Dynamic Jet Vetoes

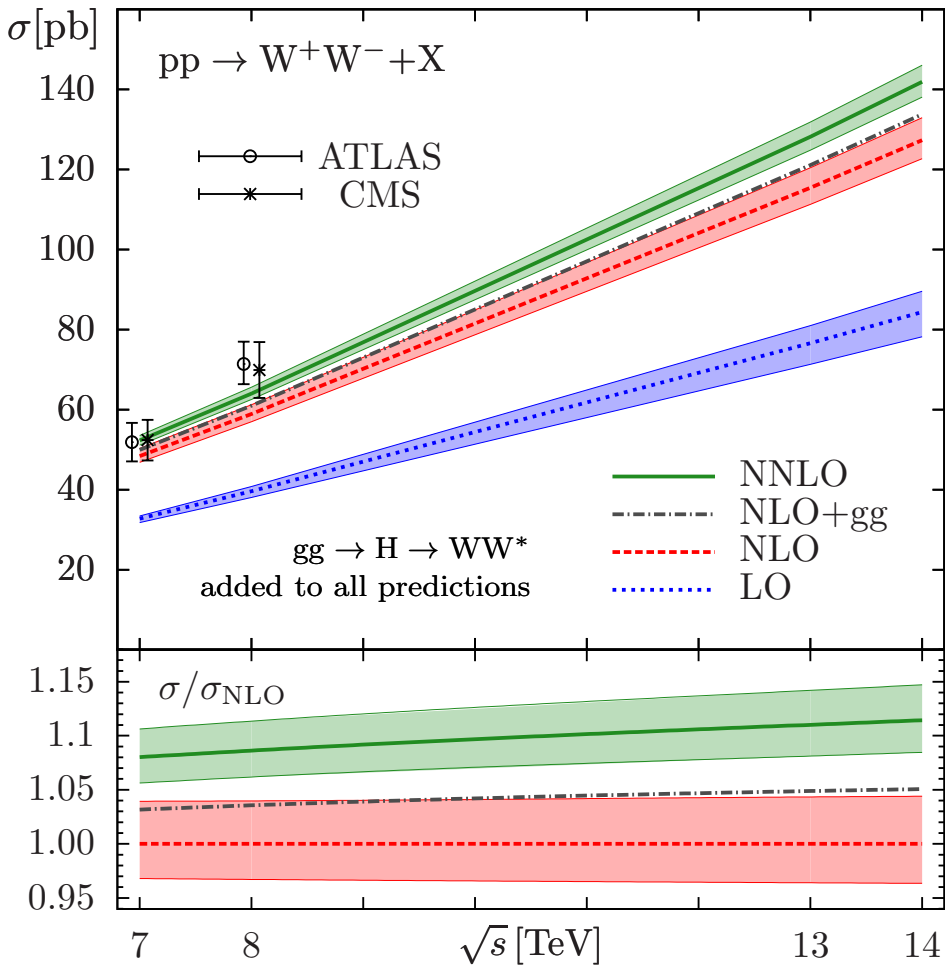


Inclusive diboson production possesses *large* QCD corrections, e.g., $pp \to W^+W^-$ at NNLO [1408.5243]

- Driven by $pp \to W^+W^-j$
- $p_T^\ell \sim \frac{M_V}{2} + \frac{p_T^j}{2n_b}$ ($n_b = \#$ bosons)

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

Irreducible Backgrounds vs Dynamic Jet Vetoes



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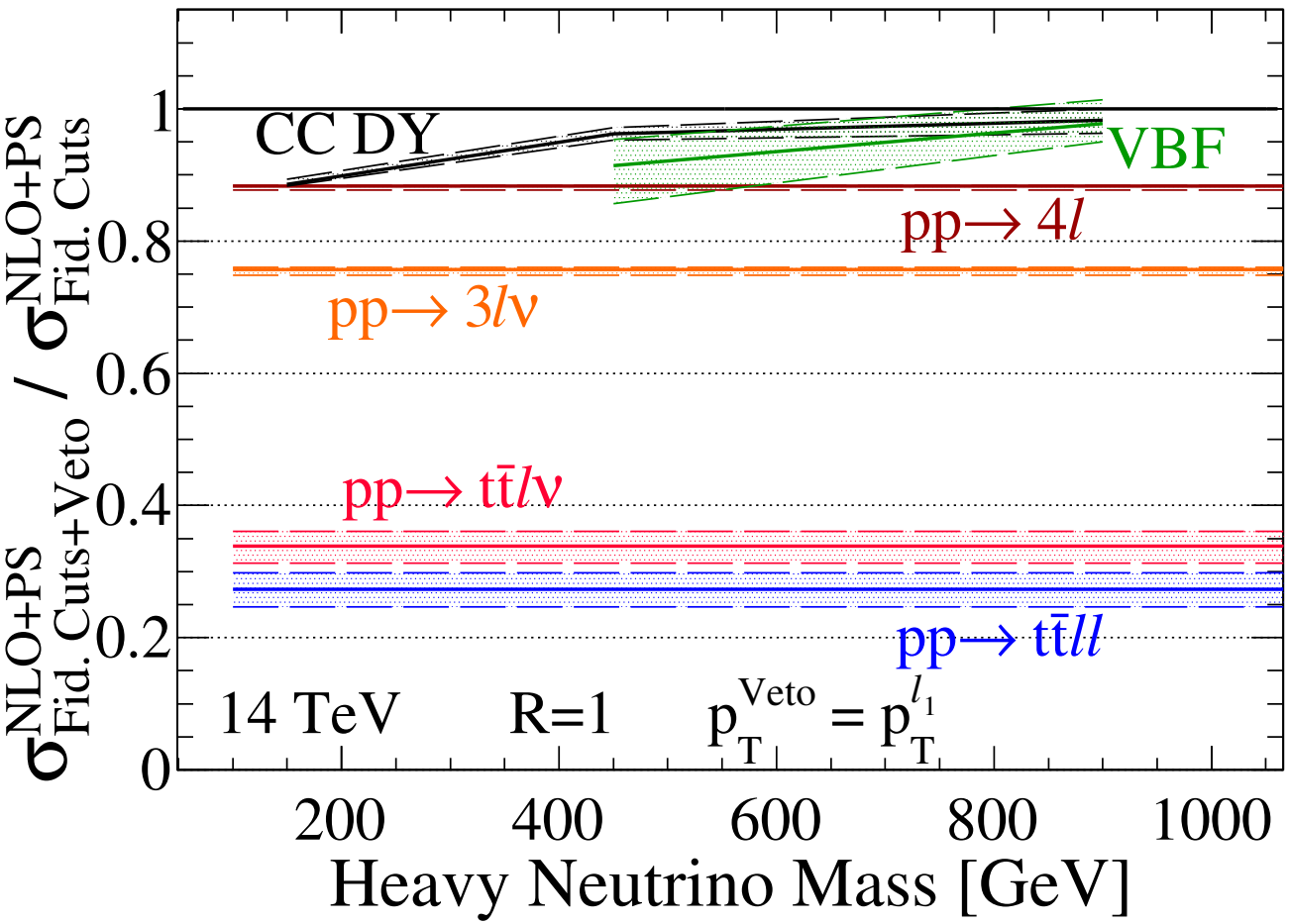
Jets mistagged/IDed as τ_h/e, i.e., "fake leptons," major irreducible bkg:

- E.g., $pp \to W^+W^-j$
- Subleading jets more likely to be mis-IDed than leading jet

Setting $p_T^{\rm Veto} = p_T^{\ell_1}$ can **reduce** irreducible backgrounds

Plotted: veto efficiency $\varepsilon(p_T^j < p_T^{\rm Veto}) = \sigma^{\rm NLO+PS}_{\rm Fid.\ Cuts+Veto} \ / \ \sigma^{\rm NLO+PS}_{\rm Fid.\ Cuts}$

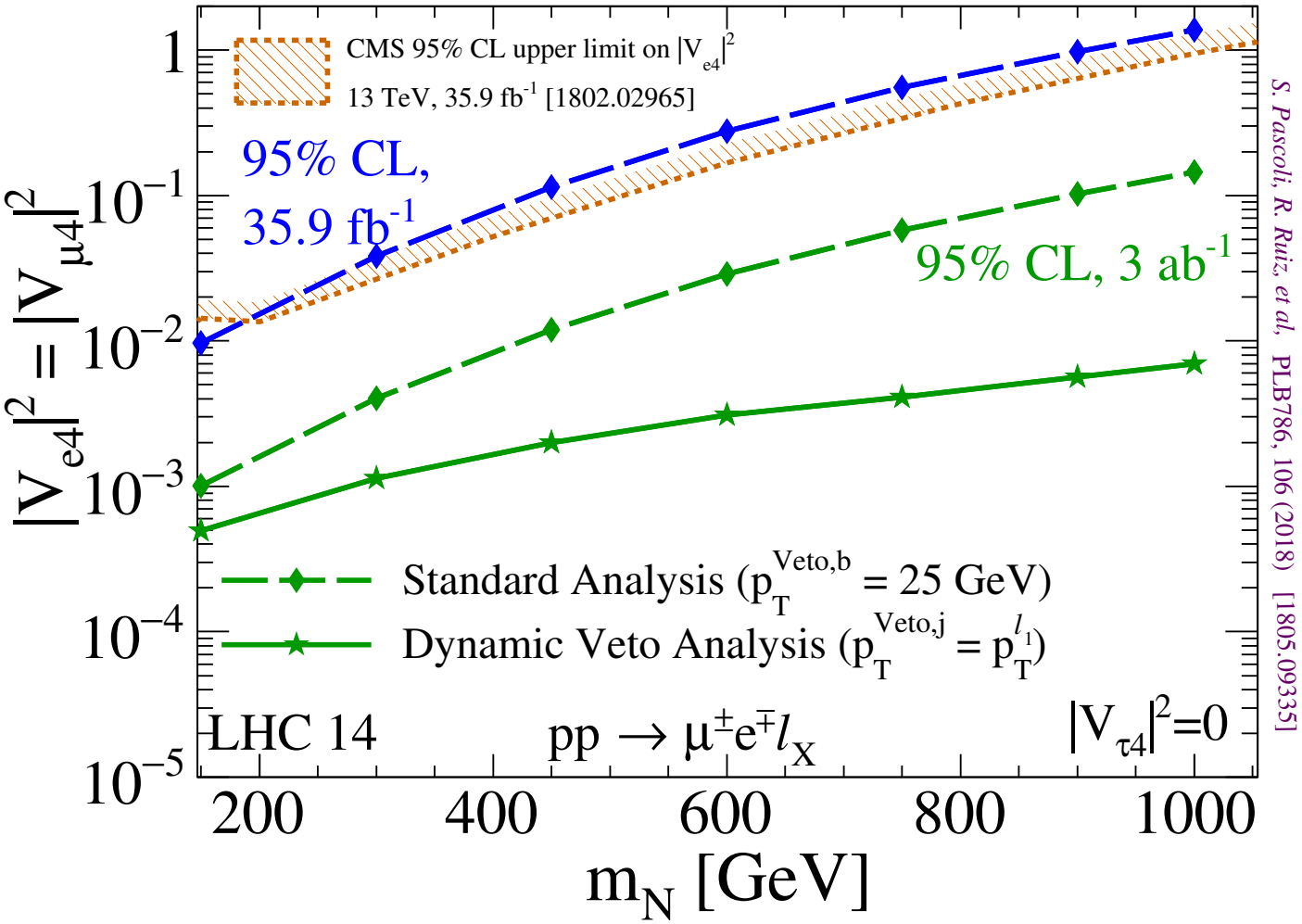


- Static jet vetoes $\Longrightarrow$ poor signal efficiency for high-mass BSM
- Setting $p_T^{\rm Veto} = p_T^{\ell_1}$ can alleviate this

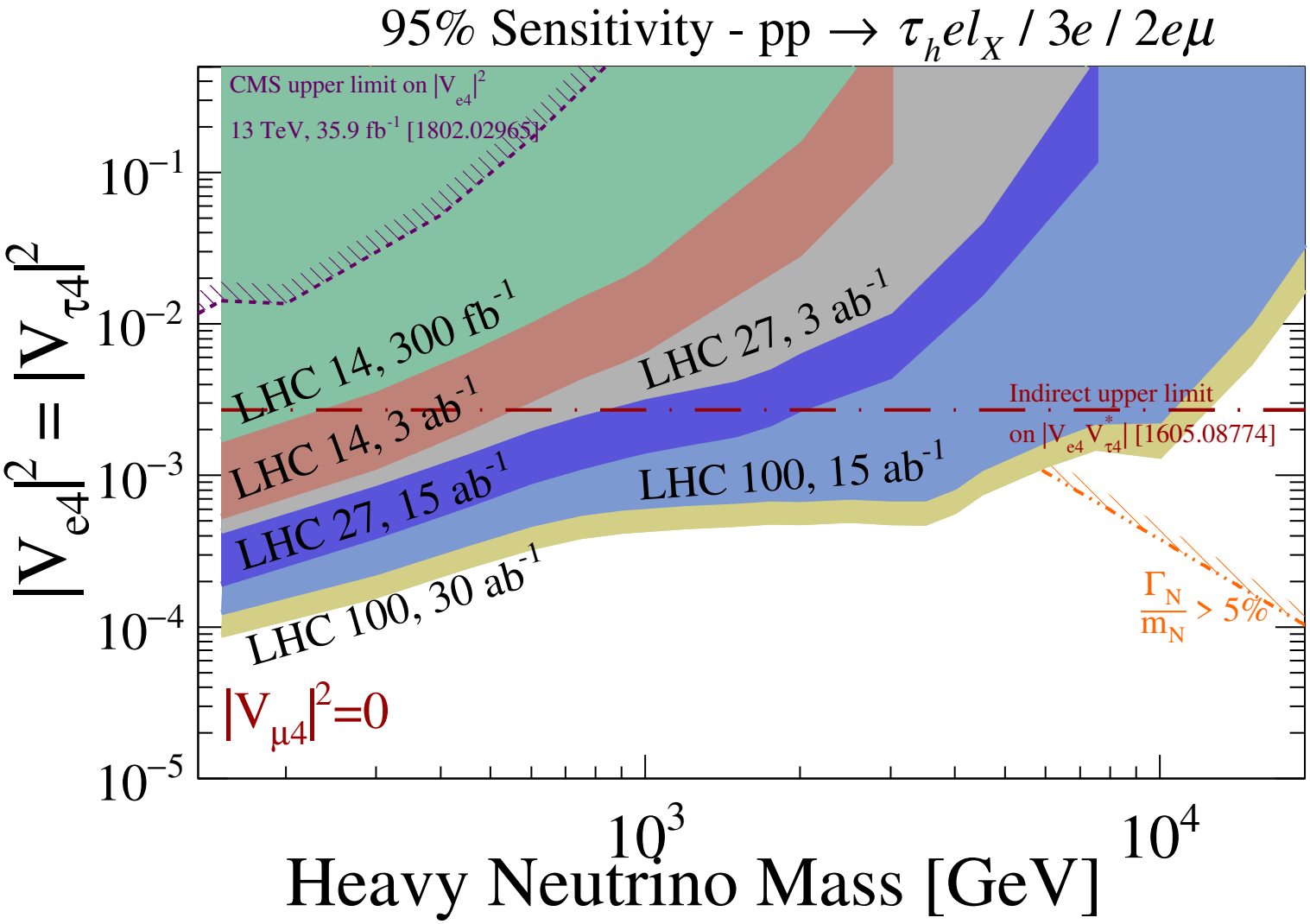
Discovery Prospects?

Plot: LHC 14 sensitivity to (coupling)^2 vs heavy neutrino mass

Signal I: $pp \to \mu^{\pm} e^{\mp} \ell_X$+MET



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



Conclusion: LHC can compete with dedicated flavor experiments

- See [1812.08750] for various flavor channel comparisons, etc
- Euro. Strategy Update, "BSM at the HL- and HE-LHC" [1812.07831]

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., $H_T^{\rm Veto} = p_T^{\ell_1}$

- 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
  $\Longrightarrow$ 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 $p_T^{\rm Veto}$, $H_T^{\rm Veto} = p_T^{\ell_k}, S_T$, depends on mass spectrum $\Longrightarrow$ 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.