# Heavy Neutrinos from Vector Boson Fusion

## IPPP VBF Workshop


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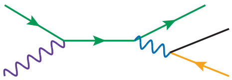
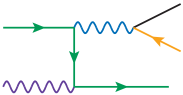
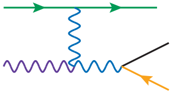
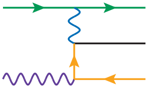
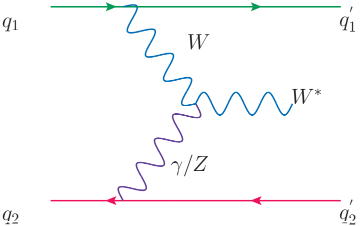





## Anatomy of $W\gamma$ Scattering

# VBF: Great for Probing High-Mass Scales

In weak boson scattering, $t$-channel propagators give rise to logarithms that scale with the hard scattering process




$$\int_0^{E^2} \frac{dQ_V^2}{Q_V^2 - M_V^2} \to \log \frac{E_V^2}{M_V^2} \sim \log \frac{\hat{s}}{M_V^2}$$

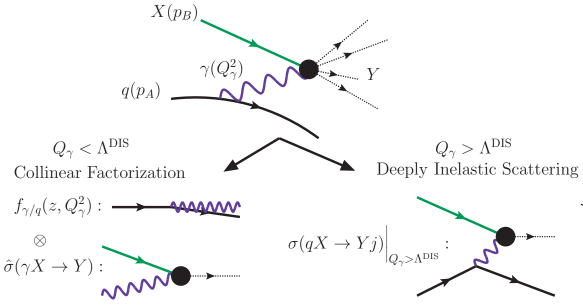
Logs are regulated by weak boson **masses**.

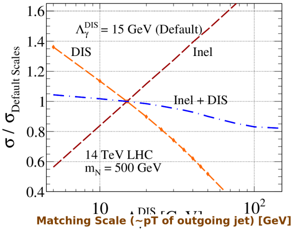
In principle (and in nature), logs for $t$-channel **photons** are regulated by fermion masses. In practice:

1. Introduce a cutoff, e.g., $\eta$, $p_T$ cuts on associated jet
2. Collinearly factorize to obtain a $\gamma$ PDF
3. Combine the two via some matching scheme

# Scattering with $t$-Channel Photons

(a) collinear photon radiation and (b) wide-angle photon radiation



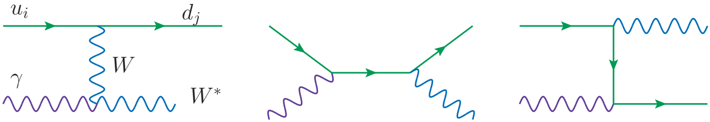

Recognize that the logs appearing in each expression are the same!

$$f_{\gamma/p}(Q_\gamma^2) \sim \log \frac{Q_\gamma^2}{\Lambda^{\mathrm{El}\ 2}} \longleftarrow \text{same log} \longrightarrow \frac{d\sigma(qX)}{dQ_\gamma^2} \propto \frac{1}{Q_\gamma^2}$$

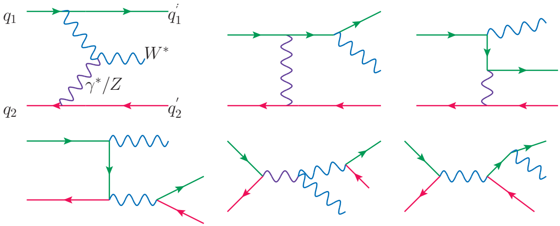
Evolve $f_{\gamma/p}(Q_\gamma)$ in **up to** and integrate (b) **from** same scale $\Lambda^{DIS}$

# A Look at Different Phase Space Regions

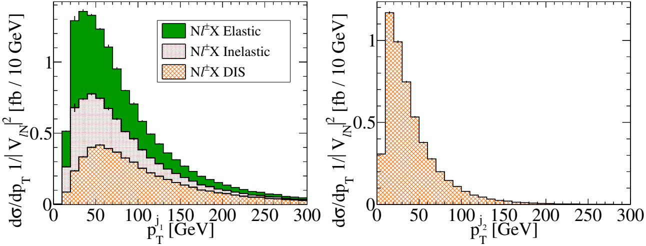
Region (a): $q\gamma \to qW^*$ given by VBF + Compton diagrams



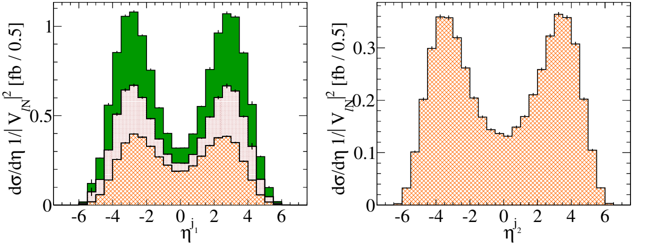

Region (b): At larger momentum transfers ($Q^2 \gg m_p^2$), we recover the deeply inelastic scattering (DIS) contribution of $qq \to W^* q' q'$



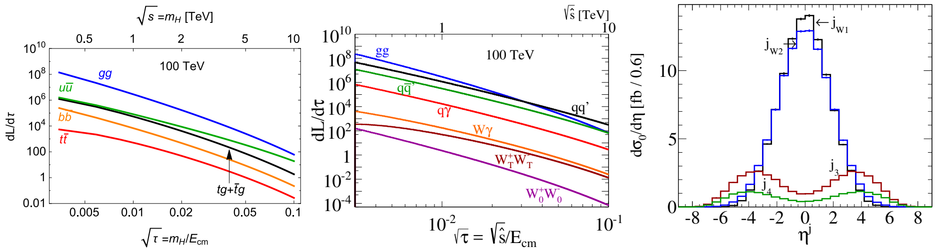
For $M_{W\gamma} > 300$ GeV $- 1$ TeV, only ~40% (50%) of events have a second jet with $p_T > 15$ (25) GeV at 14 (100) TeV [1411.7305]




Most $W\gamma$ events have a second jet outside fiducial volume of ATLAS/CMS.



# $W\gamma$ Scattering at 100 TeV (1 slide)[1]

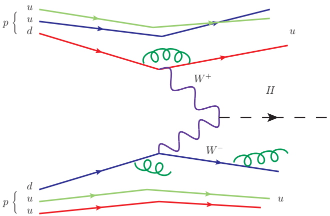


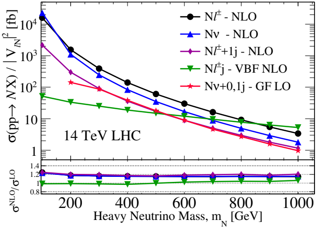

- Central region extends to $|\eta| \sim 3 - 4$, so very challenging.
- Forward region extends to $|\eta| \sim 4 - 8$, so comically difficult.
- Kinematics of decay products scale with $\langle\Phi\rangle_{BSM} \gg \langle\Phi_{EW}\rangle, \Lambda_{QCD}$
  Helps with trigger/selection.
- LHC VBF tagging will not work at VLHC.
  Perhaps high-$p_T$, central jet veto as new VBF tag?

[1] Many 100 TeV plots in Han, et al [1411.2588]; Arkani-Hamed, et al [1511.06495]; AH**RR** [1411.7305]

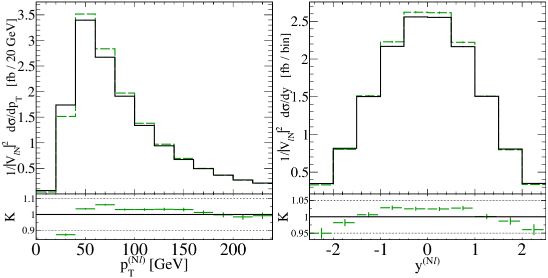
# QCD Corrections to $W\gamma$ Scattering (1 slide)

VBF is a color-singlet process (zero color flow): QCD corrections largely included in PDF definition, so little impact on total cross section



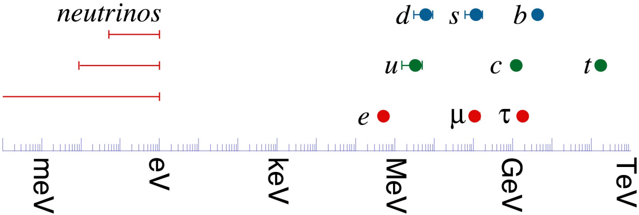

Larger change to NLO+PS kinematics, but numerically small [DMRT, 1602.06957]



## Using VBF to probe New Physics

# Motivation for New Physics from Neutrinos

The SM, via the Higgs Mechanism, explains *how* elementary fermions obtain mass, i.e., the $m_f = y_f\langle\Phi\rangle$, **not** the values of $m_f$.




Spanning many orders of magnitudes, the relationship of fermion masses is still a mystery. Two observations:

1. Neutrinos have mass (BSM physics and **2015** !)
2. Neutrinos have unusually small mass (new physics?)

# Nonzero Neutrino Masses is BSM Physics

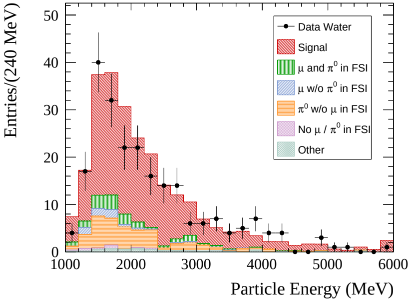
To generate $\nu$ masses similar to other SM fermions, we need $N_R$

$$\mathcal{L}_{\nu \text{ Yuk.}} = -y_\nu \left(\overline{\nu_L} \quad \overline{\ell_L}\right) \begin{pmatrix} 0 \\ \langle \Phi \rangle + h \end{pmatrix} N_R + H.c. \implies -m_D \overline{\nu_L} N_R + H.c.$$

$m_D = y_\nu \langle \Phi \rangle$, and $y_\nu$ is the neutrino's Higgs Yukawa coupling.

Since ${N_R}^i$ do not exist in the SM, **massless neutrinos are predicted.**

Through oscillation expts., the massless neutrino paradigm is now knot to be inaccurate.
[T2K $\nu_e$ appearance, 1503.08815v3]




**Neutrino masses is evidence of physics beyond the SM.**

Seesaw Mechanisms: pathways to naturally small $m_\nu$

# Seesaw Mechanisms: Pathways to Naturally Small $m_\nu$

Spinor/gauge algebra + renormalizability restrict ways to construct $m_\nu$ [Ma'98]

"Type 0": Add SM-singlet $N_R$ with $y_\nu \sim 10^{-12}$ and forbid Majorana mass

- Possible, but tiny $y_\nu$ is theoretically unsatisfying

Type I: Add $N_R$ and keep the Majorana mass term

- $\mathcal{L} \ni -y_\nu \overline{L}\tilde{\Phi} N_R - \frac{m_R}{2}\overline{N_R{}^c} N_R \implies m_\nu \propto m_D^2/m_R, \quad m_D = y_\nu \langle \Phi \rangle$

Type II: Add scalar $SU(2)_L$ triplet ($\Delta^{0,\pm,\pm\pm}$) - **No $N_R$ required**

- $\mathcal{L} \ni y_\Delta \overline{L}(i\sigma_2)\Delta L^c \implies m_\nu \propto y_\Delta \langle \Delta \rangle \overline{\nu^c}\nu, \quad \langle \Delta \rangle <$ few GeV

Type III: Add fermion $SU(2)_L$ triplet ($T^{0,\pm}$)

- $\mathcal{L} \ni y_T \overline{L} T^a \sigma^a (i\sigma^2)\Phi + \frac{m_T}{2}\overline{T^{0c}} T^0 \implies m_\nu \propto m_D^2/m_T$

Less Minimal Models: Hybrid, Inverse, Radiative, ..., all with rich pheno

# TeV-Scale Seesaw Models

"Vanilla seesaws" are only proof-of-principle ideas, not realistic models:

Type I Ex: $\Delta m^2_{sol/atm}$ require at least two nonzero masses (so two $N_R$). Naively, $N_R$ have comparable $m_R$. Naive scaling does not hold.

**Super Important**: **discovery/benchmark** collider pheno, e.g., LFV, LNV, etc., of TeV-scale and vanilla seesaws **are the same**. Straightforward to reinterpret LHC Type I, II, III, etc. results for ***extended or hybrid*** models.

**Ex 1:** TeV-scale Seesaws occur naturally in hybrid models, e.g., Type I+II[2],

$$m_{\rm light} = \underbrace{\tilde{m}_L}_{\rm Type\ II} - \underbrace{\tilde{m}_D \tilde{m}_R^{-1} \tilde{m}_D^T}_{\rm Type\ I} \sim \mathcal{O}(0) + \text{symm.-breaking terms}$$

**Note:** TeV-scale lepton number violation in Type I models is decoupled from tiny neutrino masses [0705.3221]; different from saying no **LNV**.

[2] Akhmedov et al [hep-ph/0609046; hep-ph/0612194]; Chao, et al [0907.0935]

# Event Generators (1 slide)

Modern general purpose MC packages[3] are *very* sophisticated

"With great power there must also come - great responsibility"- B. Parker ('62)

- "Black boxes" **very** easy to use but contain lots of physics

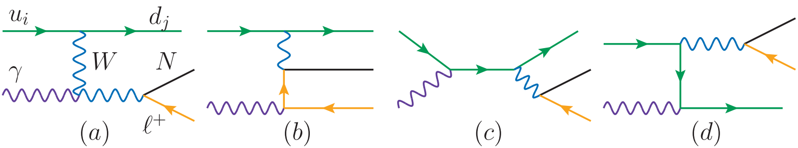
Seesaws have been implemented in mainstream event generators:

- ALPGEN:[4] Type I Seesaw but only Drell-Yan processes
- FeynRules: Translates Lagrangian to "Universal File Output" (**UFO**) for MC packages. Public library[5] contains favorite models:
  - **Type I**: HeavyN@NLO (DM**R**T) - lepton number and flavor violation
  - **Type II**: Scalar Sector @ NLO (Degrande)
  - **B-L and LRSM:** $Z'$ (Christensen), $W'$ (Donini, Fuks), + updates soon
  - **Type III:** (Biggio, Bonnet) - LNV+LFV with heavy+SM leptons
  - Authors are happy to help and answer questions!

[3] Herwig/Herwig++, MadGraph (MG5_aMC@NLO), Sherpa - All take UFO inputs.
[4] del Aguila, et al [hep-ph/0606198], http://mlm.web.cern.ch/mlm/alpgen/
[5] http://feynrules.irmp.ucl.ac.be/wiki/SimpleExtensions

# Lepton Number Violation

# Heavy N from VBF: $pp \to N\ell^{\pm}jj, \quad N \to \ell^{\pm}W^{\mp} \to \ell^{\pm}jj$

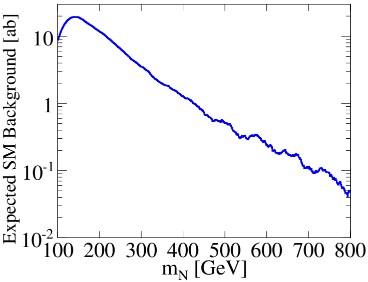



| Lepton Cuts | Jet Cuts | Other Cuts |
|---|---|---|
| $\Delta R_{\ell\ell} > 0.2$<br>$p_T^{\ell}$ $(p_T^{\ell\ \mathrm{Max}}) > 10$ (30) GeV<br>$\lvert\eta^{\ell}\rvert < 2.4$ | $\Delta R_{jj} > 0.4$<br>$p_T^{j}$ $(p_T^{j\ \mathrm{Max}}) > 15$ (40) GeV<br>$\lvert\eta^{j}\rvert < 2.4$<br>$\lvert M_W^{\mathrm{Candidate}} - M_W\rvert < 20$ GeV<br>$\lvert m_{jjj} - m_t\rvert < 20$ GeV (Veto) | $\Delta R_{\ell j}^{\mathrm{Min}} > 0.5$<br>$\not{E}_T < 35$ GeV<br>$\lvert m_N^{\mathrm{Candidate}} - m_N\rvert < 20$ GeV |

**Table 12**. Parton-level cuts on 14 TeV $\mu^{\pm}\mu^{\pm}jjX$ Analysis.

| $\sigma \setminus m_N$ [GeV] | 100 | 200 | 300 | 400 | 500 | 600 | 700 |
|---|---|---|---|---|---|---|---|
| $\sigma_0^{\mathrm{All\ Cuts}}$ [fb] | 576 | 132 | 36.0 | 14.0 | 6.28 | 3.05 | 1.55 |
| $\sigma_{\mathrm{Tot}}^{\mathrm{SM}}$ [ab] | 14.1 | 18.6 | 5.62 | 2.05 | 0.837 | 0.393 | 0.195 |
| $n_{2\sigma}^{b+\delta_{\mathrm{Sys}}}(100\ \mathrm{fb}^{-1})$ | 4 | 4 | 2 | 1 | 1 | 0 | 0 |
| $n_{2\sigma}^{s}(100\ \mathrm{fb}^{-1})$ | 8 | 8 | 6 | 5 | 5 | 4 | 4 |

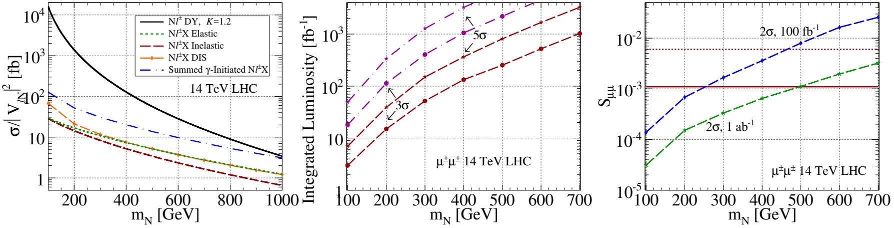
**Table 13**. Same as table 6 for 14 TeV LHC.




Backgrounds: $pp \to W^{\pm}W^{\pm}jj, \quad W^{\pm}W^{\pm}W^{\mp}$

$pp \to t\bar{t}W/Z, \quad t\bar{t}$ (charge mis-ID)

**VBF is sizable contribution to inclusive jet process.**




- $5\sigma$ at LHC for $m_N = 260$ (530) GeV after 100 fb$^{-1}$ (1 ab$^{-1}$)
- $2\sigma$ sensitivity w/ 100 fb$^{-1}$ extends to $m_N =$ 450 GeV!
- $5\sigma$ at VLHC for $m_N = 580$ (1070) GeV after 100 fb$^{-1}$ (1 ab$^{-1}$)

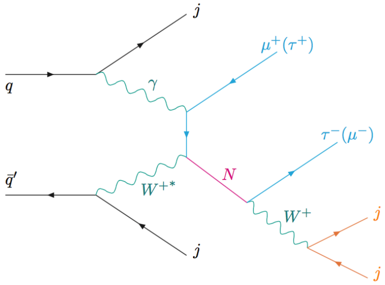
The LHC and High Luminosity LHC programs are taking us to unexplored territory and perhaps (I hope) a new discovery!

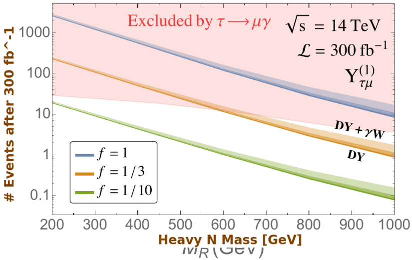
## Lepton Flavor Violation

Due to $\nu_L^a - N_R^b$ mixing, $N$ decays can violate lepton flavor, e.g.,

$$pp \to N\mu^{\pm} j_{VBF} j_{VBF}, \quad N \to \tau^{\mp} W^{\pm}$$

Common in, e.g., Inverse and Linear Seesaw models, where LNV is suppressed for TeV-scale neutrinos [Mohapatra ('86); +Valle ('86); Bernabeu, et al ('87); etc.]



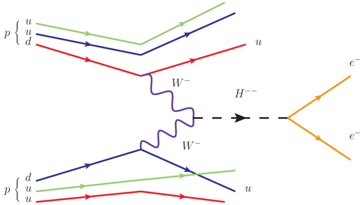

Like LNV case, VBF pushes sensitivity in benchmark models. Arganda, et al [1508.05074]
(Talk to Cedric for more info.)

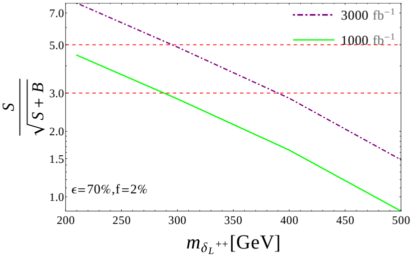
# Doubly Charged Scalars $H^{\pm\pm}$

Same-sign $W$ scattering can produce $H^{\pm\pm}$ in Type II-based Seesaws, i.e.,

$$pp \to H^{\pm\pm} j_{VBF} j_{VBF}, \quad H^{\pm\pm} \to W^{\pm}W^{\pm}/\ell^{\pm}\ell'^{\pm}$$

Good VBF BSM pheno studies by the Texas A&M pheno/CMS group [1210.0964; 1304.7779; 1404.0685; 1411.6043]




$H^{\pm\pm} \to \tau^{\pm}\tau^{\pm}$ (or other pairs) can be probed despite such small couplings

# Outlook and Discussion

The origin of tiny neutrino masses is still a puzzle and may manifest at collider experiments via the production of Seesaw partners.

- Colliders are very complimentary to low energy and oscillation expts.
- VBF is a powerful discovery tool.

Now tell us theory/pheno folk what you need!