νTools for future (lepton) colliders

LCWS 2021 - Zoom National Laboratory

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what is this talk about?

the ability to simulate neutrino mass models[1]

(about six or so FeynRules UFOs)

with mainstream event generators

(e.g., `MadGraph5`, `Whizard`, `SHERPA`)

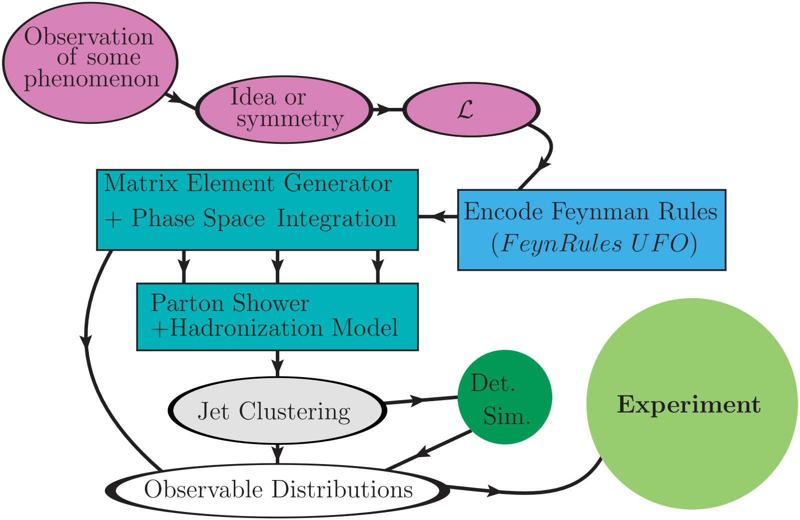
[1] This talk but aimed at those ready to start a new analysis!

anatomy of simulating

$ee/\mu\mu/\ell X/pp/AA$ **collisions**

To simulate new physics in high-p_T collisions, we follow a standard chain:

- UFO libraries encode Feynman rules (.py) and interface with mainstream event generators, e.g., MadGraph5, Whizard, SHERPA



motivation for new physics from ν physics

Nu Masses and New Particles

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

$$m_\nu \neq 0 + \text{left} - \text{handed (LH) Weak currents}$$

$(renormalizability)$

LH Majorana Mass : $m_\nu^L \overline{\nu_L} \nu_L^c$

Dirac Mass : $m_\nu^D \overline{\nu_L} \nu_R$

$(gauge\ invariance)$

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

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

$m_\nu \neq 0$ **+ renormalizability + gauge inv.** $\implies$ **new particles!**

$m_\nu \neq 0$ **+ renormalizability + SM gauge inv.** $\Longrightarrow$ **new particles!**

[Ma'98]

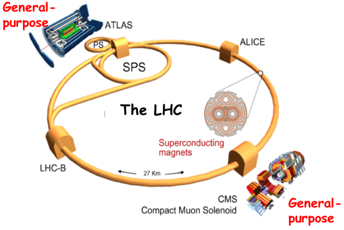
Incredibly powerful but also incredibly vague since new particles:

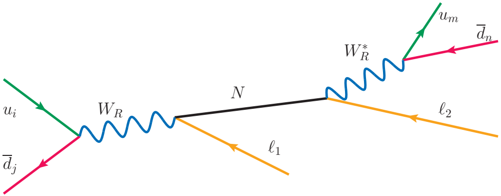
- ... can be light ☺ or heavy ☹
- ... can have SM gauge interactions, e.g., $H^{\pm\pm}$ in Type II Seesaw
- ... can have new gauge interactions, e.g. ν_R and Z_{B-L} in $U(1)_{\mathrm{B-L}}$
- ... must couple to Φ_{SM} and L, often inducing collider processes that do not conserve **lepton number (LNV)** and/or **lepton flavor (LFV)**

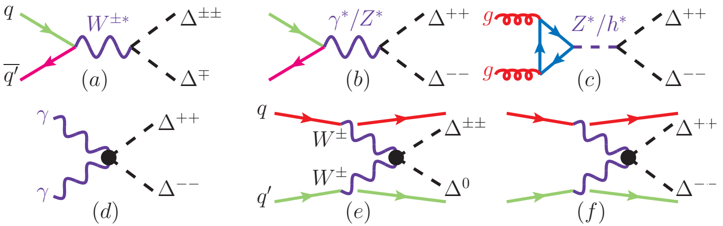
models that explain tiny neutrino masses (Seesaw models)

are testable, especially at colliders, through a variety of mechanism

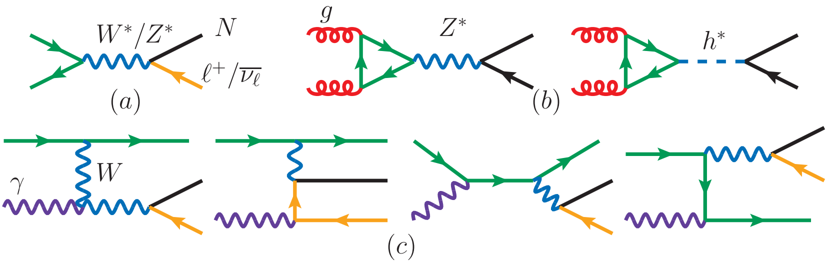
for reviews, see w/ Y. Cai, T. Li, T. Han [1711.02180], and w/ S. Pascoli, C. Weiland [1812.08750]







HeavyN UFO library [2]



[2] with C. Degrande, O. Mattelaer, and J. Turner [1602.06957], feynrules.irmp.ucl.ac.be/wiki/HeavyN

For ***discovery purposes***, take agnostic/pheno. approach with **generic mixing $V_{\ell N}$** and Dirac or Majorana N mass eigenstates

Atre, Han, Pascoli, Zhang [0901.3589]

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

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

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W^-_\mu \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \nu_\ell\right] + \text{H.c.}, \qquad \text{where } P_L = \frac{1}{2}(1-\gamma^5)$$

For ***discovery purposes***, take agnostic/pheno. approach with **generic mixing** $V_{\ell N}$ and Dirac or Majorana N mass eigenstates

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$\Longrightarrow$ SM W coupling to N and charged **leptons** in the **mass basis is**

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

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

HeavyN: URL feynrules.irmp.ucl.ac.be/wiki/HeavyN

- TypeIISeesaw, EffLRSM, WZPrime, SMWeinberg

  also available from feynrules.irmp.ucl.ac.be/wiki/NLOModels!

HeavyN: The Standard Model + Heavy Neutrinos at NLO in QCD

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In collaboration with: Daniel Alva and Tao Han [1]; Celine Degrande, Olivier Mattelear, and Jessica Turner [2]; and Silvia Pascoli and Cedric Weiland [3, 4].

For detailed instructions and examples on using the HeavyN UFO libraries, see C. Degrande, et al, arXiv:1602.06957 and S. Pascoli, et al, arXiv:1812.08750

- For studies of heavy Majorana neutrinos, please consider citing [5] for the Lagrangian and [1, 2] for the Majorana FR/UFO files.
- For studies of heavy Dirac neutrinos, please consider citing [2, 4].

Model Description

Majorana

This effective/simplified model extends the Standard Model (SM) field content by introducing three right-handed (RH) neutrinos, which are singlets under the SM ga
or weak hypercharge charges). Each RH neutrino possesses one RH Majorana mass. After electroweak symmetry breaking, the Lagrangian with three heavy Majora
[5]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_N + \mathcal{L}_{N\ \rm Int}. \quad (1$$

The first term is the Standard Model Lagrangian. In the mass basis, i.e., after mixing with active neutrinos, the heavy Majorana neutrinos' kinetic and mass terms a

$$\mathcal{L}_N = \frac{1}{2}\overline{N_k} i \not\partial N_k - \frac{1}{2} m_{N_k} \overline{N_k} N_k, \quad k = 1, \ldots, 3, \quad (1$$

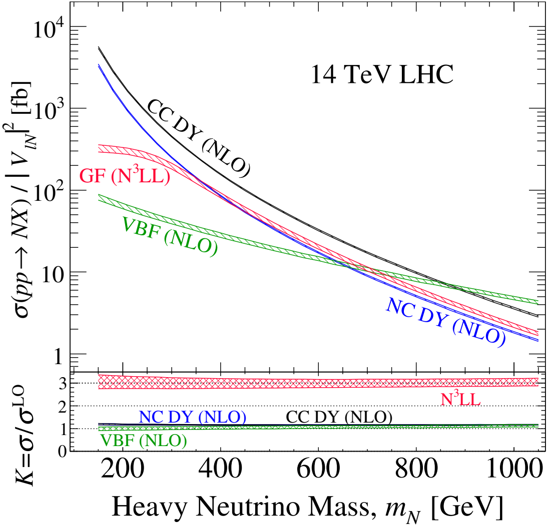
and its interactions with the Weak gauge and Higgs bosons are given by

Given a *Universal FeynRules Object* (UFO) file, run `mg5amc` out of the box

```
 $ ./bin/mg5_aMC
> import model SM_HeavyN_NLO
> define p = g u c d s
u  c  d  s  a
> define ell = mu+ mu-
> generate p p > n2 ell [QCD]
> output PP_Nmu_NLO
> launch PP_Nmu_NLO
> order=NLO
> fixed_order=ON
> set vmun2 1.0
> set mn2 scan:range(5,1001,25)
> set ww auto
```

$\mathcal{O}(10)$ lines to get each curve →

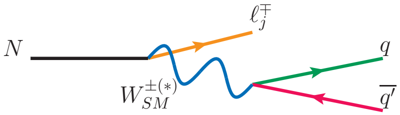
Pascoli, RR, Weiland [1812.08750]



mg5amc+MadSpin+Parton Shower

If the narrow width approximation holds ($\Gamma_N / m_N \ll 1$), efficient generation of $pp \rightarrow W \rightarrow N\ell^\pm \rightarrow \ell^\pm\ell^\pm q\overline{q'}$ possible with `MadSpin`:

Spin-correlation fully treated, RR [2008.01092]



In `madspin_card.dat`, write:

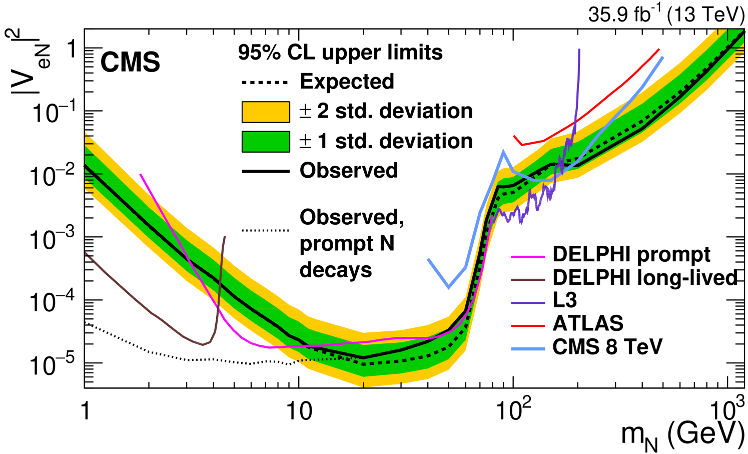
```
set spinmode onshell
define  q = u c d s u~ c~ d~ s~
define ee = e+ e-
decay  n1 > ee q q
launch
```

Parton showering with `PY8` or `HERWIG` straightforward

Fun Fact: possible to steer entire process with a script $\rightarrow$

```
rruiz@mac-1R0-359:~/Scripts/MG5aMC$ more runEffLRSMnlo_pp_Ne_Update.txt
launch EffLRSMnlo_pp_wr_Ne_NLO
order=NLO
shower=PY8
madspin=ON
done
set mwr 4000
set mn1 100
compute_widths wr+
compute_widths n1
set no_parton_cut
set nevents 100k
set LHC 13
set shower_card nsplit_jobs 100
set shower_card ue_enabled true

launch EffLRSMnlo_pp_wr_Ne_NLO
order=LO
shower=ON
```

Plotted: LHC 13 limits in search for $pp \to 3\ell + MET \quad (\ell_X = e, \mu)$



- HeavyN used in CMS trilepton [1802.02965] and dilepton [1806.10905] searches
- ATLAS is currently adopting software!

what about e^+e^- or $\mu^+\mu^-$ collisions?[3]

[3] Also see talk by Krzysztof Mękała!

Making LO(+PS) events for planned lepton colliders as easy as for LHC!

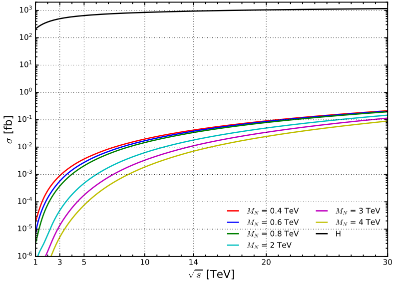
```
 $ ./bin/mg5_aMC
import model SM_HeavyN_NLO
define vv = ve ve
define ell = e+ e-
generate e+ e- > z > N1 vv
        QCD=0 QED=2, n1 > ell j j
output Test_FCCee_ee_Nv_XLOPS
launch
shower=py8
set mz 92.0
set VeN1 1e-4
set mN1 scan:range(10,61,10)
set wn1 auto
set nevents 1k
set ebeam 46.0
set time_of_flight 0.0
set no_parton_cut

done
```

output from cmds on the left!

Results in the SM_HeavyN_NLO for e+ e- > z > N1 vv QCD=0 QED=2, n1 > ell j j

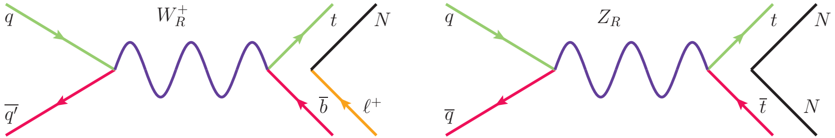
Available Results

Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action	
run_01	e+ e- 46.0 x 46.0 GeV	tag_1	5.136e-05 ± 2.8e-07	1000	parton madevent	LHE	remove run	launch detector simulation
					pythia8	LOG HEPMC	remove run	launch detector simulation
run_02	e+ e- 46.0 x 46.0 GeV	tag_1	4.855e-05 ± 3.7e-07	1000	parton madevent	LHE	remove run	launch detector simulation
					pythia8	LOG HEPMC	remove run	launch detector simulation
run_03	e+ e- 46.0 x 46.0 GeV	tag_1	4.38e-05 ± 3.6e-07	1000	parton madevent	LHE	remove run	launch detector simulation
					pythia8	LOG HEPMC	remove run	launch detector simulation
run_04	e+ e- 46.0 x 46.0 GeV	tag_1	3.776e-05 ± 3e-07	1000	parton madevent	LHE	remove run	launch detector simulation
					pythia8	LOG HEPMC	remove run	launch detector simulation
run_05	e+ e- 46.0 x 46.0 GeV	tag_1	3.037e-05 ± 1.8e-07	1000	parton madevent	LHE	remove run	launch detector simulation
					pythia8	LOG HEPMC	remove run	launch detector simulation
run_06	e+ e- 46.0 x 46.0 GeV	tag_1	2.137e-05 ± 1.3e-07	1000	parton madevent	LHE	remove run	launch detector simulation
					pythia8	LOG HEPMC	remove run	launch detector simulation



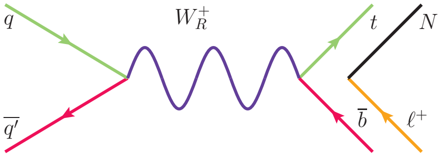
$W^+W^- \to \ell_i^+ \ell_j^-$ possible at muon colliders! [2005.10289]

Effective LRSM@NLO[4]



[4] with O. Mattelaer and M. Mitra [1610.08985], feynrules.irmp.ucl.ac.be/wiki/EffLRSM

In the minimal LRSM: Top (t) and bottom (b) quarks, charged leptons ($\ell^\pm$), and heavy neutrinos (N) all couple to RH gauge bosons ($W_R^\pm$)



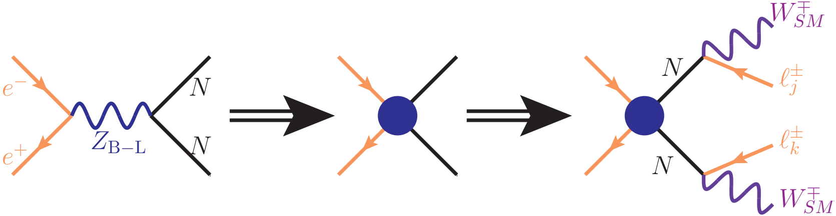
W_R coupling to quarks is analogous to SM W_{SM} couplings:

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W^-_{R\mu} \sum_{q=u,d,...} [\overline{d_j}\ V_{ij}^{CKM'}\ \gamma^\mu P_R u_i] + \text{H.c.}$$

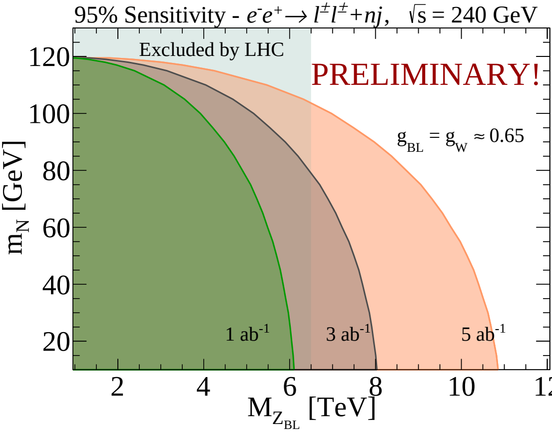
In **mass** basis, coupling to leptons can be generically parametrized as:

Atre, Han, Pascoli, Zhang [0901.3589]; Han, Lewis, RR, Si [1211.6447]

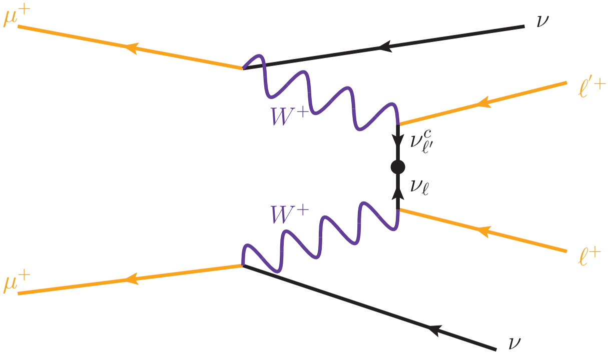
$$\mathcal{L} \approx -\frac{g}{\sqrt{2}} W^-_{R\mu} \sum_{\ell=e}^{\tau} \sum_{m'=4}^{6} [\overline{\ell}\gamma^\mu P_R Y_{\ell m'} N_{m'}] + \text{H.c.}$$



- If ν are Majorana, is (B-L) broken spontaneously?
- If Z_{BL} gauge boson of $U(1)_{B-L}$ is too heavy, LNV is still accessible
- For $g_{BL} = g_W \approx 0.65$, LNV territory beyond LHC reach accessible at Higgs factory!



NEW! `SMWeinberg` UFO library [5]



[5] w/ Fuks, Neundorf, Peters, Saimpert [2012.09882], feynrules.irmp.ucl.ac.be/wiki/SMWeinberg

Weinberg operator is the only SMEFT operator at $d = 5$: Weinberg('79)

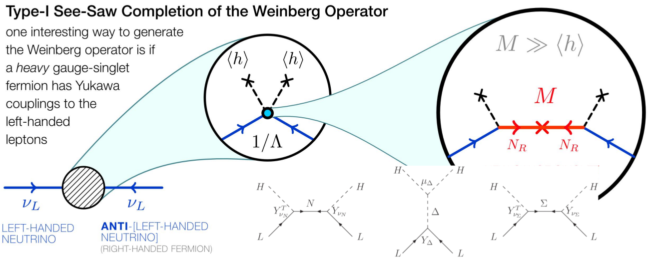
$$\mathcal{L} = \frac{C_5^{\ell\ell'}}{\Lambda}[\Phi \cdot \overline{L}_\ell^c][L_{\ell'} \cdot \Phi]$$

Importantly, after EWSB, generates a Majorana mass matrix for ν

$$m_{\ell\ell'} = C_5^{\ell\ell'} \langle\Phi\rangle^2 / 2\Lambda$$

Can be generated in **many** ways at tree- and loop-level

Eg. Ma ('98), Bonnet, et al [1204.5862]



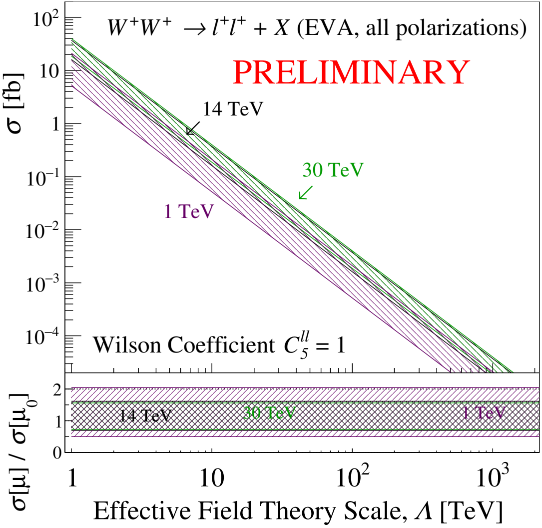
F. Tanedo

Difficult to simulate events since Weinberg op. modifies propagator of ν_ℓ

modern Monte Carlo tools work in mass basis and do not like the idea of modifying $\langle 0|\overline{\nu_{\ell'}}\nu_\ell|0\rangle$

```
 $ ./bin/mg5_aMC
set group_subprocesses false
import model SMWeinbergNLO
generate w+ w+ > mu+ mu+ QED=2
output EVA_ww_mm_XLO
launch
set Lambda 1e7
set Cmm 1
set no_parton_cut
set etal 3
set nevents 100k
set ebeam 5e3
set lpp1 -4
set lpp2 -4
set pdlabel=eva
set nhel 1
set use_syst true
```

$\mathcal{O}(10)$ lines to get each curve



Effective $W/Z/A$ approximation (Dawson'84) for lepton colliders in MadGraph will be released early summer '21!

so what is available?

UFO	NLO	Spin	M or D	#	V'	LNV	LFV	arXiv
HeavyN	✓	✓	M	3		✓	✓	[1602.06957]
HeavyN_Dirac	✓	✓	D	3			✓	[1812.08750]
EffLRSM	✓	✓	M	3	✓	✓	✓	[1610.08985]
WZPrime	✓	✓			✓		✓	[1701.05263]
TypeIISeesaw	✓	✓			✓	✓	✓	[1912.08975]
SMWeinberg	✓	✓				✓	✓	[2012.09882]

Legend:

- "NLO" = simulations at LO and NLO in QCD possible
- "Spin" = spin correlation fully described

for details, see RR [2008.01092]

- "M or D" = Majorana or Dirac N
- "#" = number of N in the model file
- "V'" = new gauge, scalar, or pseudoscalar bosons

(other new particles can be long-lived!)

Happy to make more public, just ask!

summary (impact)

Collider tests and searches of **lepton number violation (LNV)** and **charged lepton flavor violation (cLFV)**, i.e., ν mass models, have *vastly* improved over the past several years

This includes:

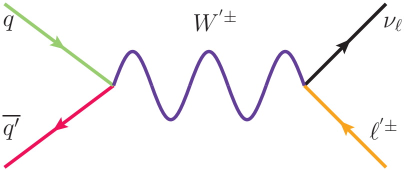
- Predictions for Dirac and Majorana particles w/ LNV and cLFV
- New kinematic limits, e.g., off-shell portals, long-lived topologies
- New channels, e.g., VBF, $W/Z/h/\gamma$ associated production, GF
- Quantitatively reliable descriptions of jets, kinematics, and rates

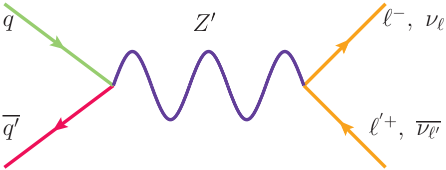
Improved sensitivity driven by improved MC support!

... with more in development (collaborators and friends are welcome!)

Thank you.

vprime@NLO[6]





6 with B. Fuks [1610.08985], feynrules.irmp.ucl.ac.be/wiki/WZPrimeAtNLO

Neutrino mass models with more generic W'/Z' boson that couple to SM fermions, e.g., Universal Extra Dimensions and $U(1)_{B-L}$, also supported

available at feynrules.irmp.ucl.ac.be/wiki/WZPrimeAtNLO

The companion article for this model file is arXiv:1701.05263 [hep-ph].

(Note: NLO UFO models can also be used for LO computations.)

Model Description

This effective model extends the Standard Model (SM) field content by introducing the massive vector fields $W'^{+/-}$ and Z' bosons, which are electrically cha
model independent, couplings to SM gauge bosons and scalars are omitted.

Following Refs. [1, 2], the Lagrangian parameterizing the new vector bosons' couplings to up-type and down-type quark fields u_i and d_j is given by

$$\mathcal{L}^q = -\frac{g}{\sqrt{2}}\sum_{i,j}\left[\overline{u}_i V_{ij}^{\text{CKM}}\ W_\mu'^{+}\ \gamma^\mu\left(\kappa_L^q P_L + \kappa_R^q P_R\right)\ d_j + \text{H.c}\right] \quad (1$$

$$-\frac{g}{\cos\theta_W}\sum_{q=u,d}\sum_i\left[\overline{q}_i\ Z_\mu'\gamma^\mu\left(\zeta_L^q P_L + \zeta_R^q P_R\right)q_i\right]\ ,+\text{H.c.} \quad (2$$

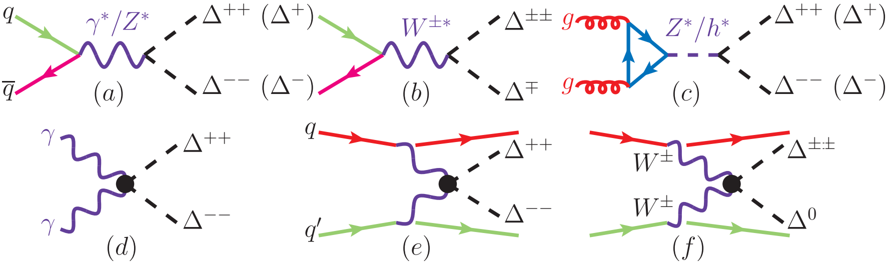
Here, `i` and `j` denote flavor indices, $P_{L/R}$ are the usual left/right-handed chirality projectors, V^{CKM} is the CKM matrix, and `g` and `\theta_W` are the we
respectively. We choose coupling normalizations facilitating the mapping to the reference Sequential Standard Model (SSM) Lagrangian `{\cal L}_{\rm S`
`\kappa_{L,R}^q` and `\zeta_{L,R}^q` serve as overall normalization of the new interactions relative to the strength of the weak coupling constant.

The interactions involving charged lepton \ell and massless neutrino \nu_\ell fields are parametrized by

$$\mathcal{L}^\ell = -\frac{g}{\sqrt{2}}\sum_i\left[\overline{\nu}_{\ell_i} W_\mu'^{+}\ \gamma^\mu \kappa_L^\ell P_L \ell_i^- + \text{H.c}\right] \quad (1$$

$$-\frac{g}{\cos\theta_W}\sum_{f=\ell,\nu_\ell}\sum_i\left[\overline{f}_i\ Z_\mu'\gamma^\mu\left(\zeta_L^f P_L + \zeta_R^f P_R\right)f_i\right]\ .+\text{H.c.} \quad (2$$

TypeIISeesaw@NLO[7]



[7] with B. Fuks, O. Mattelaer, and M. Nemevšek [1912.08975], feynrules.irmp.ucl.ac.be/wiki/TypeIISeesaw

Type II Seesaw Mechanism for Neutrino Masses

Hypothesize a **scalar** $SU(2)_L$ triplet with **lepton number** $L = -2$

Konetschny and Kummer ('77); Schechter and Valle ('80); Cheng and Li ('80); Lazarides, et al ('81); Mohapatra and Senjanovic ('81)

$$\hat{\Delta} = \frac{1}{\sqrt{2}}\begin{pmatrix} \Delta^{+} & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^{0} & -\Delta^{+} \end{pmatrix}, \quad \text{with} \quad \mathcal{L}_{\Delta\Phi} \ni \mu_{h\Delta}\left(\Phi^{\dagger}\hat{\Delta}\cdot\Phi^{\dagger} + \text{H.c.}\right)$$

The mass scale $\mu_{h\Delta}$ breaks lepton number, and induces $\langle\Delta\rangle \neq 0$:

$$\sqrt{s}\langle\hat{\Delta}\rangle = v_{\Delta} \approx \frac{\mu_{h\Delta} v_{\text{EW}}^2}{\sqrt{2}m_{\Delta}^2}$$

which leads to **left-handed Majorana masses** for neutrinos

$$\Delta\mathcal{L} = -\frac{y_{\Delta}^{ij}}{\sqrt{2}}\overline{L^{c}}\hat{\Delta}L = -\frac{y_{\Delta}^{ij}}{\sqrt{2}}\begin{pmatrix}\overline{\nu^{jc}} & \overline{\ell^{jc}}\end{pmatrix}\begin{pmatrix} 0 & 0 \\ v_{\Delta} & 0 \end{pmatrix}\begin{pmatrix}\nu^{i} \\ \ell^{i}\end{pmatrix}$$

$$\ni -\frac{1}{2}\underbrace{\left(\sqrt{2}y_{\Delta}^{ij}v_{\Delta}\right)}_{=m_{\nu}^{ij}}\overline{\nu^{jc}}\nu^{i}$$

Generates light ν_m masses via vev **WITHOUT** invoking sterile N_k!

The lack of Monte Carlo support for $\Delta^{\pm\pm}, \Delta^{\pm}$ was an oversight

- Universal FeynRules Object (UFO) libs exist for many other models

See FeynRules database feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

After a request by hep-ex'ers, we wrote `TypeIISeesaw@NLO` UFO libraries

available at feynrules.irmp.ucl.ac.be/wiki/TypeIISeesaw

```
> import model TypeII_NLO_UFO
> generate p p > d++ d-- [QCD]
> output TypeIInlo_DYX_DxxDxx_NLO
> launch
> order=NLO
> fixed_order=ON
> set mdpp scan1:range(100,2001,50)
> set dynamical_scale_choice -1
> set no_parton_cut
> set jetalgo    -1
> set jetradius 0.4
```

TypeIISeesaw : Canonical type II Seesaw at NLO in QCD

Contact Information

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In collaboration with Miha Nemevšek and Richard Ruiz. See arXiv:1911.NNNNN [hep-ph].

Model Description and FeynRules Implementation

We extend the Standard Model by adding a scalar field lying in the adjoint representation of the weak groupe Δ with an hypercharge equals to 1. After electrowe
rise to one extra CP-even scalar Higgs Δ^0, one charged scalar $\Delta^{\pm}$ and one doubly-charged scalar $\Delta^{\pm\pm}$ that are mostly of a triplet nature. The corresponding Lagra

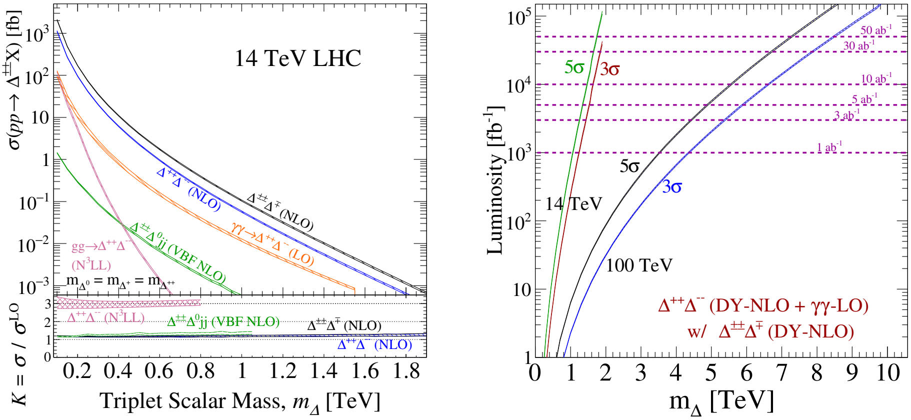
$$\mathcal{L} = \mathcal{L}_{\rm SM} + {\rm Tr}\left[D_\mu\hat{\Delta}^\dagger D^\mu\hat{\Delta}\right] - V_\Delta + \mathcal{L}_{Y_\Delta} \qquad (1)$$

where the extra terms respectively represents the gauge-invariant kinetic terms for the triplet, the extra pieces to the scalar potential and the Yukawa interactio
The above Lagrangian was implemented in the Feynman Gauge into FeynRules 2.3.35. QCD renormalisation and R_2 rational counterterms were determined using
FeynArts 3.9. Feynman rules were collected into a single UFO, available below. In the normal hierarchy and inverted hierarchy UFO models, four massless quarks
diagonal CKM matrix entries. These additions permit tree-level calculations at LO and NLO in QCD and loop-induced calculations at LO in QCD using MadGraph_a

In the case of a normal neutrino mass hierarchy (Mv1 < Mv2 < Mv3), the model contains 16 free parameters (on top of the Standard Model ones):

- the mass of the first neutrino Mv1 (the other neutrino masses are internal parameters);
- the squared neutrino mass differences dmsq21 ($\Delta m_{21}^2 > 0$) and dmsq31 ($\Delta m_{31}^2 > 0$) collected in the LH block MNU;
- the oscillation parameters th12 (θ_{12}), th13 (θ_{13}), th23 (θ_{23}), delCP (φ_{CP}), phiM1 (φ_1), phiM2 (φ_2) collected in the LH block PMNS;
- the masses of the Higgs (PDG 125), Δ^0 (PDG 44), $\Delta^{\pm}$ (PDG 38) and $\Delta^{\pm\pm}$ (PDG 44) fields (in the LH block MASS);
- the triplet vev v_Δ (block VEVDELTA)
- two quartic couplings collected in the block QUARTICS

a revised outlook for both $\sqrt{s} = 14$ TeV and 100 TeV!



- At LHC with $\mathcal{L} = 5$ ab^{-1}, 3σ sensitivity up to $m_\Delta \sim 1.5$ TeV
- At $\sqrt{s} = 100$ TeV with $\mathcal{L} = 30 - 50$ ab^{-1} $\Longrightarrow$ $m_\Delta \approx 8 - 9$ TeV
- **LOTS** not covered, e.g., γ PDF, jet vetoes at NLO+NNLL

just check out the paper! [1912.08975]