νTools for the LHC and Beyond

Tools 2020 - Lyon

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what is this talk about?

LHC 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

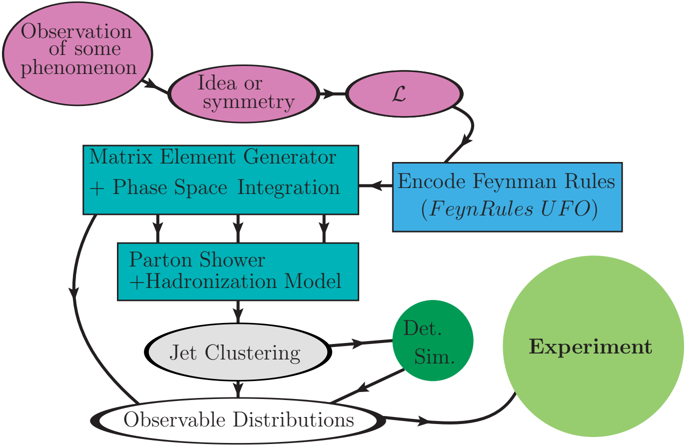
- New channels, e.g., VBF, GF, $W/Z/h/\gamma$ associated production
- New kinematic limits, e.g., off-shell portals, boosted topologies
- Predictions for **both** Dirac and Majorana particles w/ LNV and cLFV
- Quantitatively reliable descriptions of jets, kinematics, and rates

Part of this driven by improved MC support!

simulating LHC collisions

To simulate LHC collisions and model new physics, we follow a chain

- "νTools" denotes the many UFO libraries that interface mainstream Monte Carlo event generators, e.g., MadGraph5, HERWIG, SHERPA



motivation for new physics from ν physics

Nu Masses and New Particles

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

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

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

$$m_\nu^L = y\langle\Delta\rangle \text{ or strong dynamics} \qquad\qquad m_\nu^D = y\langle\Phi_{\text{SM}}\rangle$$

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

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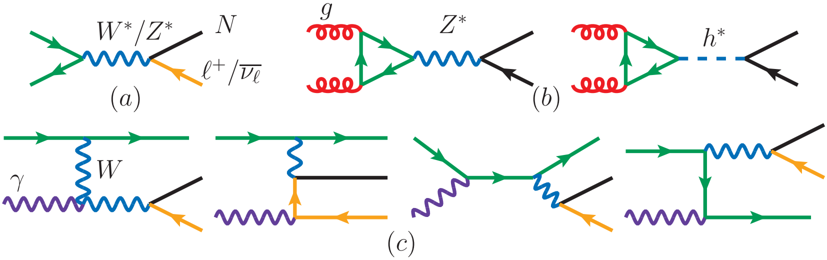
- New particles might be charged under new or old gauge symmetries
- Manifests as processes that violate LNV and/or cLFV at colliders

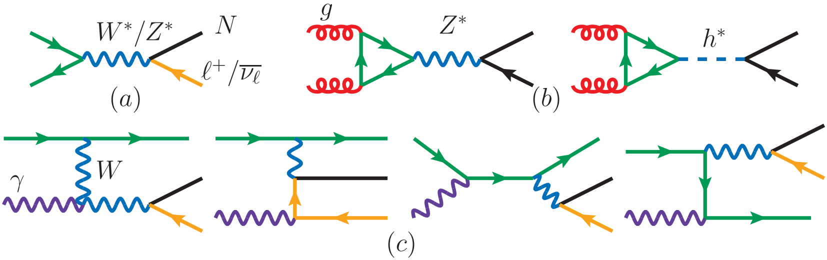
HeavyN@NLO[1]



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

Heavy Neutrinos (N) at Hadron Colliders

... can be produced via mixing through a number of mechanisms



Since 2014, active program to systematically compare channels

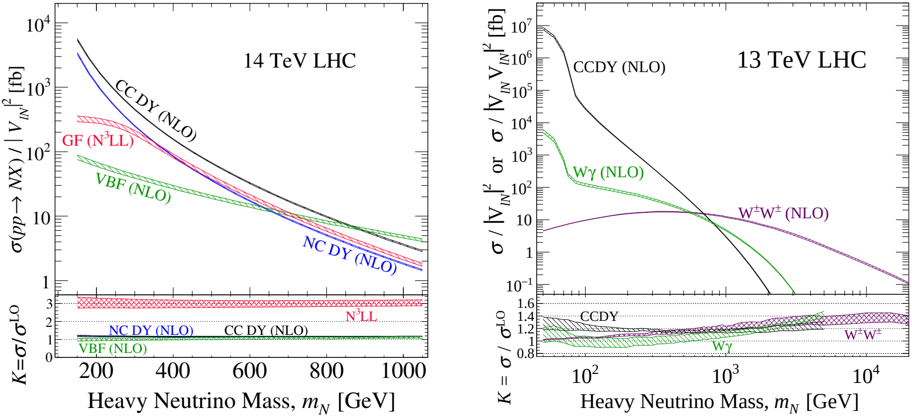
For overview, see review: [1711.02180]

- Clarity needed on $m_N, \sqrt{s}$ **dependence** and **fill gaps in lit.**
- Explore **how new techniques can improve** analyses from 90's-00's

$\Longrightarrow$ better sensitivity, more robust analyses, new public tools

Across $\sqrt{s}$, wild interplay of PDF and matrix elements

w/ Pascoli, et al [1812.08750]; w/ Fuks, et al [2011.02547]

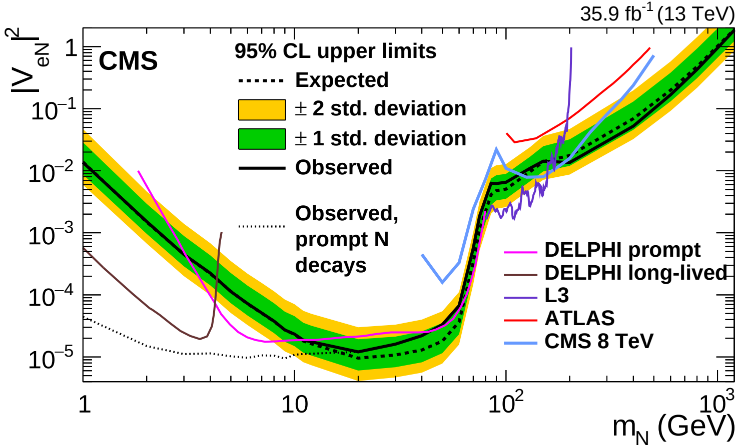


Plotted: Flavor-independent heavy N production rate ($\sigma/|V|^2$) vs mass

- **GF** and **VBF** dominate at larger $\sqrt{s}$, m_N
- At $\sqrt{s} = 100$ TeV and $|V_{\ell N}|^2 \sim 10^{-3}$, about one $N(10\text{ TeV})/\text{ab}^{-1}$

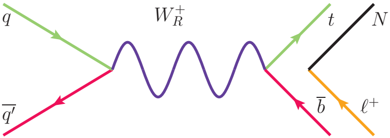
  If roughly BR$\times\varepsilon\times\mathcal{A}\times\mathcal{L}\sim\frac{1}{3}\times 30$ ab^{-1}, then $\sqrt{N_{Obs.}} > 3\sigma$

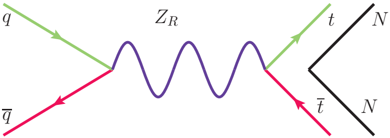
Plotted: LHC 13 limits in search for $pp \to 3\ell + MET \quad (\ell_X = e, \mu)$



- HeavyN used in CMS trilepton [1802.02965] and dilepton [1806.10905] searches
- ATLAS is now adopting software
- Available for both Majorana and Dirac N!

Effective LRSM@NLO[2]





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

Left-Right Symmetric Models (LRSM) postulate that the SM's $V-A$ structure originates from the spontaneous breakdown of parity symmetry:

$$\mathcal{G} = \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \underbrace{\mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L}}$$ After scalar

Δ_R acquires a vev $\langle \Delta_R \rangle \gg \langle \Phi_{\mathrm{SM}} \rangle$: $\hookrightarrow \mathrm{U}(1)_Y$

Higgs field Φ then breaks down the EW group $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \to \mathrm{U}(1)_{EM}$

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With N_R, all SM fermions can be grouped in $\mathrm{SU}(2)_L$ *and* $\mathrm{SU}(2)_R$ doublets. Dirac masses generated in (mostly) usual way with Φ, i.e., $\Delta\mathcal{L} \ni \overline{Q}_L \Phi Q_R$

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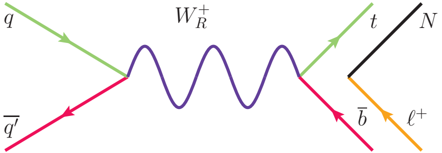
Neutrinos obtain LH (RH) Majorana masses from triplet scalar Δ_L (Δ_R):

$$m^{\nu}_{\mathrm{light}} = \underbrace{y_L \langle \Delta_L \rangle}_{\text{Type II}} - \underbrace{\left(y_D {y_R}^{-1} y_D^T \right) \langle \Phi \rangle^2 \langle \Delta_R \rangle^{-1}}_{\text{Type I a la Type II}} \sim \mathcal{O}(0) + \text{symm.-breaking}$$

Major pheno: heavy N, W'/Z' ($\approx W_R/Z_R$), and $H_i^{\pm\pm}$, $H_j^{\pm}$, H_k^0

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:

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

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

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

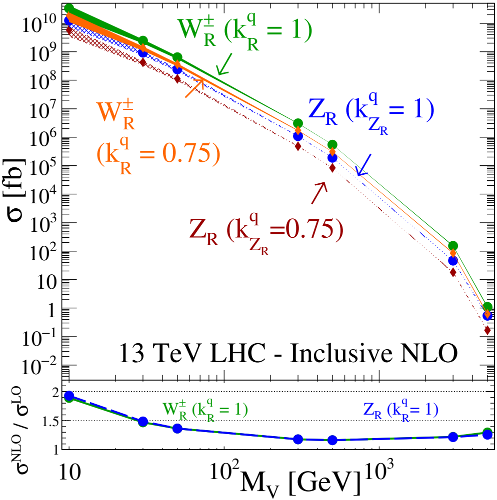
$$\mathcal{L} \approx -\frac{g}{\sqrt{2}} W_{R\mu}^- \sum_{\ell=e}^{\tau} \sum_{m'=4}^{6} [\overline{\ell}\gamma^\mu P_R Y_{\ell m'} N_{m'}] + \mathrm{H.c.}$$

FeynRules to MadGraph5aMC@NLO

Given an effective FeynRules@NLO model file, one can run mg5amc

(See Oliver's and HS's Lectures!)

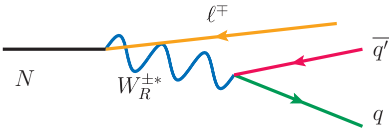
```
> import model EffLRSM_NLO
> define p  = u c d s b u~ c~ d~ s~ b~ g
> define j  = p
> define wr = wr+ wr-
> generate p p > wr [QCD]
> output PP_WR_NLO; launch
> order=NLO
> fixed_order=ON
> set MWR scan:range(1000,6001,1000)
> set dynamical_scale_choice 3
```



mg5amc+MadSpin+Parton Shower

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

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
```

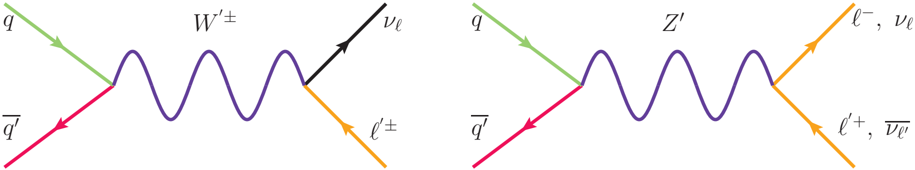
Parton showering with `PY8` or `HERWIG` straightforward

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

```
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
madspin=ON
rruiz@mac-1R0-359:~/Scripts/MG5aMC$ ./bin/mg5_aMC ./runEffLRSMnlo_pp_Ne_Update.txt
```

vprime@NLO[3]



[3] 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

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

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

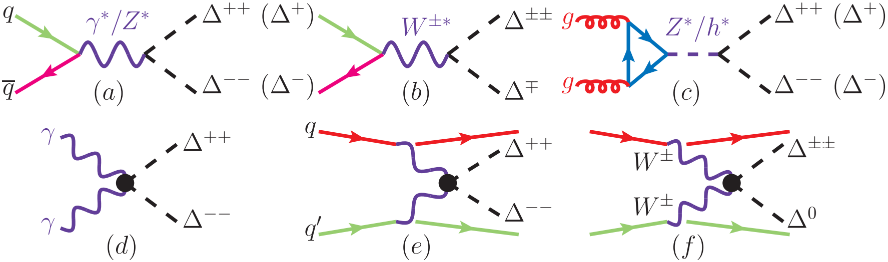
Here, `i` and `j` denote flavor indices, $P_{L/R}$ are the usual left/right-handed chirality projectors, V^{CKM} is the CKM matrix, and `g` and `\theta_W` are the we
respectively. We choose coupling normalizations facilitating the mapping to the reference Sequential Standard Model (SSM) Lagrangian `{\cal 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

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

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

TypeIISeesaw@NLO[4]



[4] 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 $\langle \Delta \rangle \neq 0$:

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

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

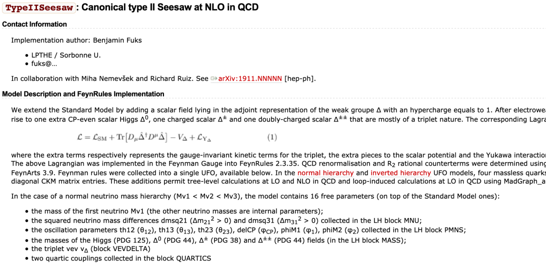
- Universal FeynRules Object (UFO) libs exist for many other models

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

Implementation author: Benjamin Fuks

- LPTHE / Sorbonne U.
- fuks@...

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

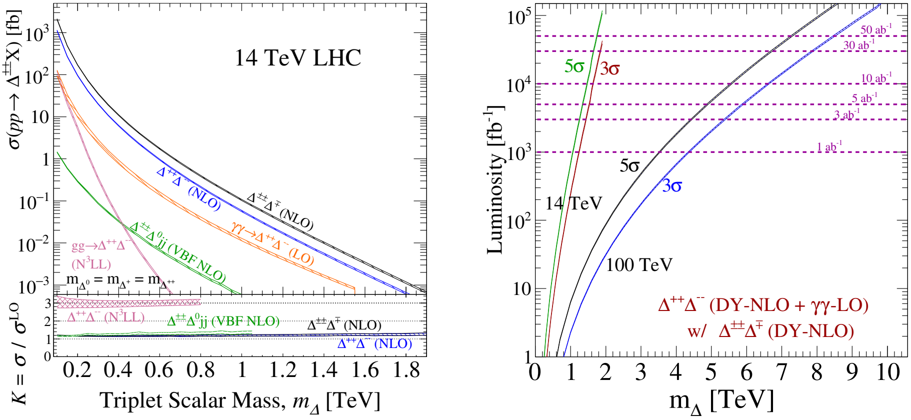
$$\mathcal{L} = \mathcal{L}_{\rm SM} + {\rm Tr}\big[D_\mu \hat{\Delta}^\dagger D^\mu \hat{\Delta}\big] - V_\Delta + \mathcal{L}_{Y_\Delta} \qquad (1)$$

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} $\implies$ $m_\Delta \approx 8 - 9$ TeV
- **LOTS** not covered, e.g., γ PDF, jet vetoes at NLO+NNLL

just check out the paper! [1912.08975]

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- New channels, e.g., VBF, GF, $W/Z/h/\gamma$ associated production
- New kinematic limits, e.g., off-shell portals, boosted topologies
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- Quantitatively reliable descriptions of jets, kinematics, and rates

Part of this driven by improved MC support!

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

Thank you.