Light mesons from light heavy neutrinos at colliders

NuFact 23, Seoul National University

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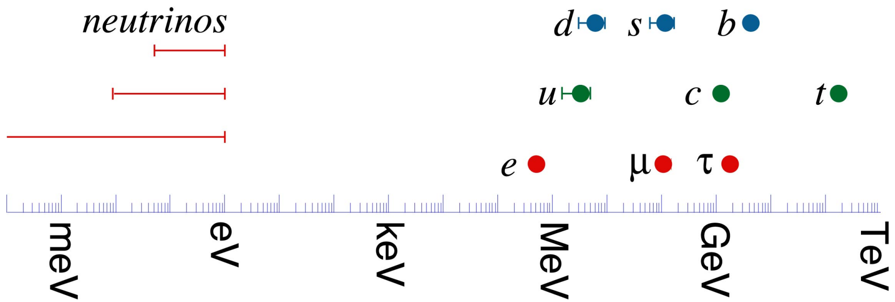
[1] [w/ Jeon†, Fernandez-Martinez, et al (*in progress*)]

Thank you for the invitation!

Problem: according to the SM, $m_\nu = 0$. (Not enough ingredients but data obviously disagree!)

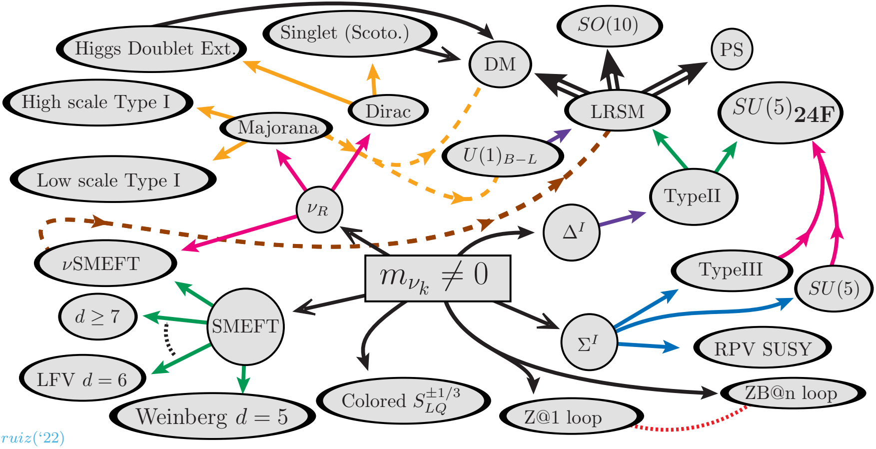


Discovery of neutrino masses $\Longrightarrow$ several open questions:

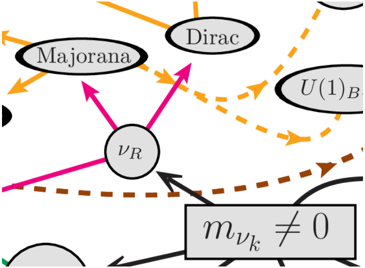
- ν have mass. What is generating m_ν?
- ν masses are *tiny*. What sets the scale of m_ν?
- m_ν are nearly degenerate. What sets the pattern of m_ν?
- ν carry no QCD/QED charge. Are $\nu, \overline{\nu}$ the same (Majorana)?

These core ideas can be realized in ***many*** ways!

Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + *many* others



right-handed neutrinos at the LHC[2]



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[2] For reviews at colliders, see Cai, Han, Li, RR [1711.02180] and Pascoli, RR, Weiland [1812.08750]

adding ν_R to the SM

To generate Dirac masses for ν like other SM fermions, we need ν_R

$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\nu \overline{L}\tilde{\Phi}\nu_R + H.c. = -y_\nu \begin{pmatrix}\overline{\nu_L} & \overline{\ell_L}\end{pmatrix}\begin{pmatrix}\langle\Phi\rangle + h \\ 0\end{pmatrix}\nu_R + H.c.$$

$$= \underbrace{-y_\nu\langle\Phi\rangle}_{=m_D}\overline{\nu_L}\nu_R + H.c. + \ldots$$

ν_R do not exist in the SM, so pretend that they do and $\nu_R = \nu_R^c$:

$$\implies \mathcal{L}_{\text{mass}} = \frac{-1}{2}\underbrace{\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}}_{\text{chiral state}}\quad \underbrace{\begin{pmatrix}0 & m_D \\ m_D & \mu_{\not{L}}\end{pmatrix}}_{\text{mass matrix (chiral basis)}}\quad \begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix}$$

adding ν_R to the SM

To generate Dirac masses for ν like other SM fermions, we need ν_R

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

ν_R do not exist in the SM, so pretend that they do and $\nu_R = \nu_R^c$:

$$\implies \mathcal{L}_{\text{mass}} = \frac{-1}{2} \underbrace{\left(\overline{\nu_L} \quad \overline{\nu_R^c}\right)}_{\text{chiral state}} \underbrace{\begin{pmatrix} 0 & m_D \\ m_D & \mu_{\not{L}} \end{pmatrix}}_{\text{mass matrix (chiral basis)}} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

After diagonalizing the mass matrix, identify ν_L (chiral eigenstate) in the SM as a linear combination of mass eigenstates:

$$\underbrace{|\nu_L\rangle}_{\text{chiral state}} = \cos\theta \underbrace{|\nu\rangle}_{\text{light mass state}} + \sin\theta \underbrace{|N\rangle}_{\text{heavy mass state (this is a prediction!)}}$$

For the experts (1 slide)

Generically paramerize active-sterile neutrino mixing via Atre, et al [0901.3589]

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

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

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

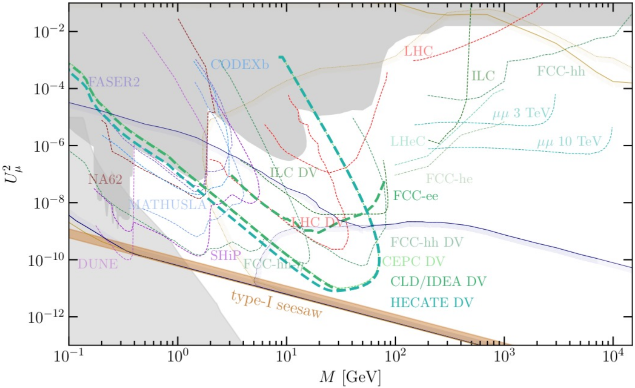
$\implies$ W coupling to N in the **mass basis** is

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

$\implies$ N is **accessible through** $W/Z/h$ bosons

Outlook for low-mass heavy neutrinos (N)

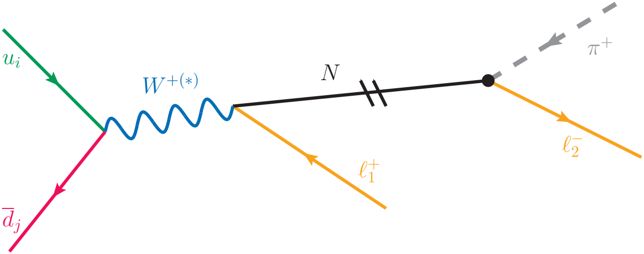
Community Message: Current + next-gen. facilities can probe *simplest* ($m_{\nu_1} = 0$) leptogenesis scenario w/ ν_R Abdullahi, et al [2203.08039]; w/ Alimena, et al [2203.05502]



Note: **LHC picture evolving with new strategies and channels**

Cottin, Helo, Hirsch [1806.05191]; Abada, Bernal, Losada, Marcano [1812.01720]; K. Cheung, H. Ishida, et al [2004.11537]

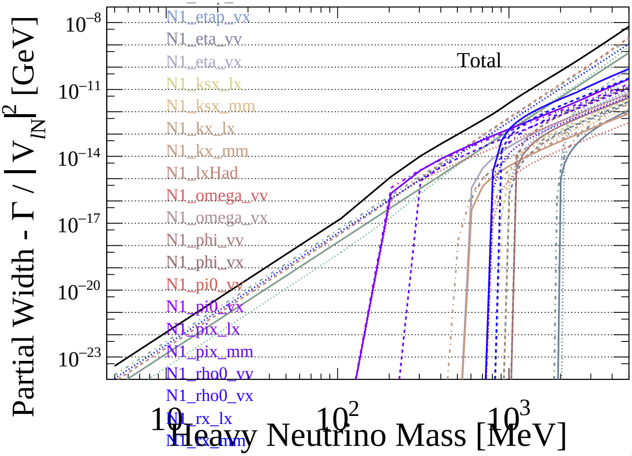
what about low, low-mass *N*?



Decays of sub-GeV N

For $m_N \lesssim 2$ GeV, $N \to \ell^\pm + n$Had. decays disappear (no phase space)

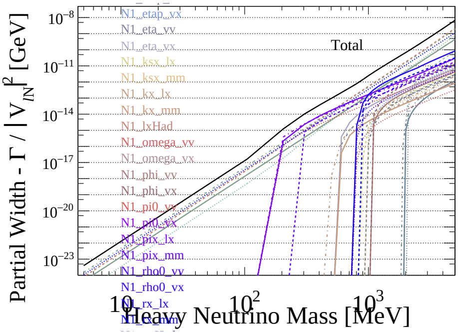
– however, single-meson modes remain: $N \to \ell^\pm M^\mp$ or νM^0



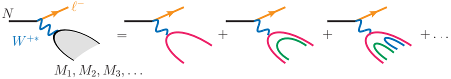
This plot is interesting→

$N \to \ell^\pm M^\mp$ and $N \to \nu M^0$ decay rates were computed with `HeavyN_Meson+MadGraph5_aMC@NLO`

`mg5amc` is a flagship event generator for collider experiments:
- up to NLO in QCD for (B)SM
- up to NLO in EW for SM
- BSM possible if Feynman rules are known (`FeynRules` "UFO" plugin)

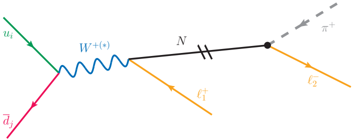


[w/ Jeon†, Fernandez-Martinez, Kulkarni, et al (*in progress*)]



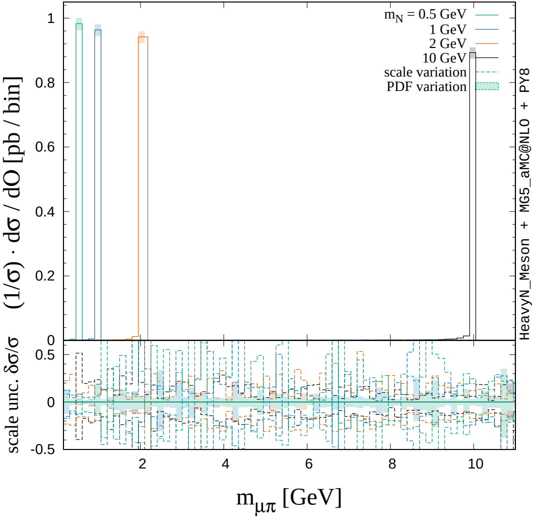
New: `HeavyN_Meson` UFO combines two things:
- `HeavyN` UFO: Feynman rules for Type I Seesaw — Degrand, RR, et al 1602.06957
- Low-energy EFT for N-M-ℓ/ν — Coloma, Fernandez-Martinez, et al 2007.03701

Light mesons from light N at the LHC



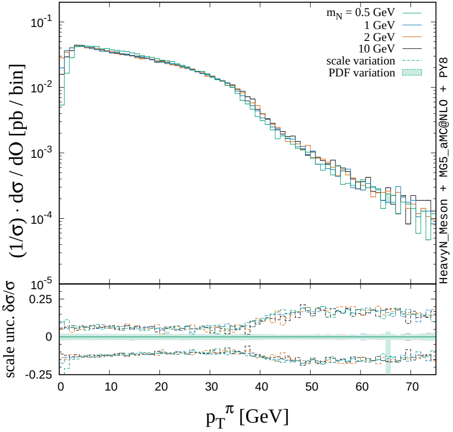
Proof-of-concept:

1. $pp \to W^{(*)} \to Ne^{\pm}$ at NLO in QCD at $\sqrt{s} = 13$ TeV LHC
2. $N \to \mu^{\pm}\pi^{\mp}$ decay with full spin correlation
3. full parton shower (PY8)
4. basic reconstruction

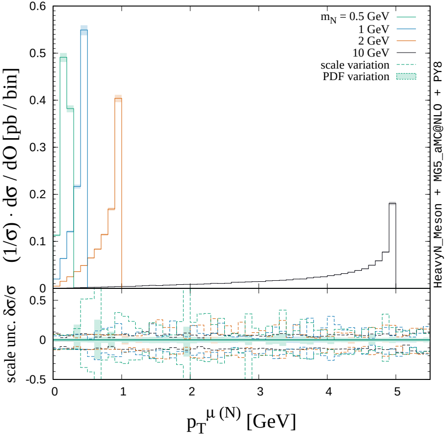


Light mesons from light *N* at the LHC

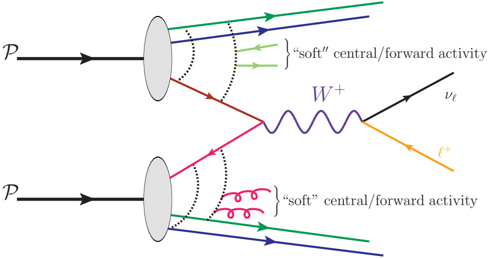
lab frame



N's frame



challenges of a low-mass analysis



Challenge: at $\sqrt{s} = 13/14$ TeV, lots of GeV-scale mesons

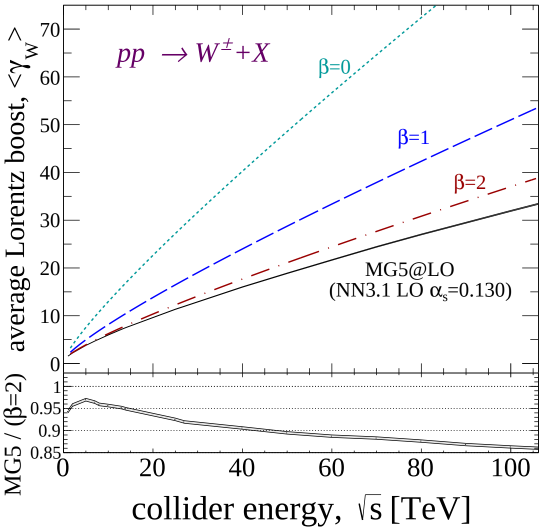
interesting resolution can be realized by approximating PDF: $f_{i/p}(\xi) \approx \frac{\text{const.}\times(1-\xi)^{\beta}}{x^{1+\delta}}$

for $\beta = 2$, $\langle \gamma_W^{(\text{lab})} \rangle = \frac{-1-9\tau_0+9\tau_0^2+\tau_0^3-6\tau_0(1+\tau_0)\log(\tau_0)}{3\sqrt{\tau_0}[3-3\tau_0^2+(1+4\tau_0+\tau_0^2)\log(\tau_0)]}$, where $\tau_0 = M_W^2/s$

first take away: varying β shows importance of $\xi = 1$ and large y (rapidity) regions

Plotted: avg. Lorentz boost of W

$(\langle \gamma_W^{(\text{lab})} \rangle = \langle E_W^{(\text{lab})} \rangle / M_W)$



Plotted: avg. Lorentz boost of N

$$(\langle\gamma_N^{(\rm lab)}\rangle = \langle E_N^{(\rm lab)}\rangle/m_N)$$

Challenge: at $\sqrt{s} = 13/14$ TeV, lots of GeV-scale mesons

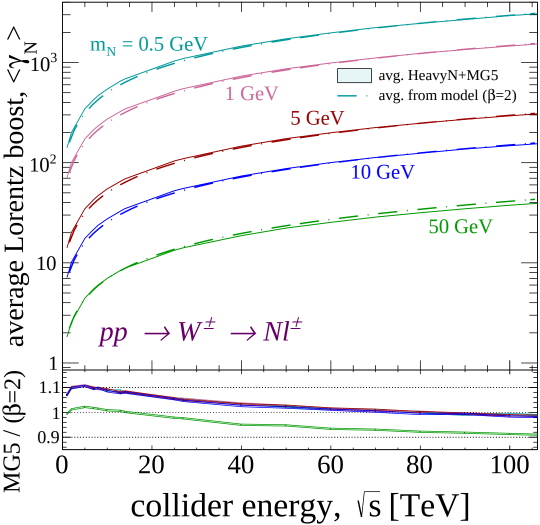
interesting resolution can be realized by approximating

$$\langle\gamma_N^{(\rm lab)}\rangle = \langle\gamma_W^{(\rm lab)}\rangle|_{\beta=2} \times E_N^{(W)}$$

where

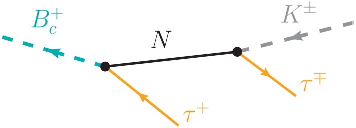
$$E_N^{(W)} = \frac{M_W}{2}\left(1 + \frac{m_N^2}{M_W^2} - \frac{m_l^2}{M_W^2}\right)$$

second take away: ultra light N (and decay products) are still very energetic!

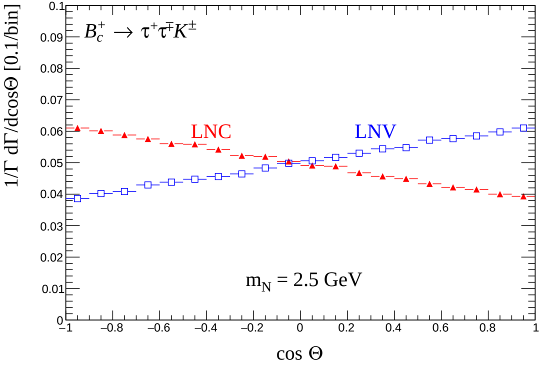


$\mathcal{B}$ factories

For $m_N \ll M_W$, N can appear in $\mathcal{B}_c^+ \to \tau^+\tau^\mp K^\pm$ decays (or similar)



PRELIMINARY: polar angle of $K^\pm$ w.r.t. N's propagation direction

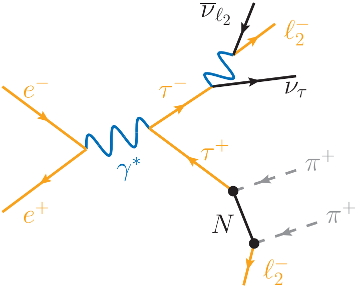


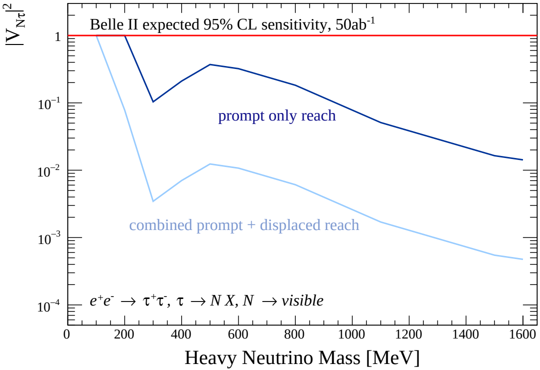
Take away: angular distributions encode differences between LNV ($\tau^+\tau^+K^-$) and LFC ($\tau^+\tau^-K^+$)

Han, Lewis, RR, et al [1211.6447]

☺ reconstructed from evts using `HeavyNMeson+MG5` →

For $m_N \ll M_W$, N can appear in decays of $\tau^\pm$





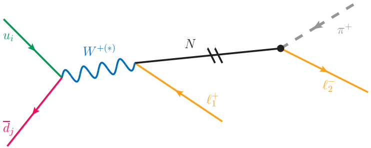
LHC is not the only collider looking for N

- **PRELIMINARY:** **Belle 2**'s sensitivity to LNV and LFV from $\tau^\pm$ decays show promise, but numbers need finalizing

Summary and conclusion

ν have mass and discoverying their origin motivates searches at colliders!

for reviews, see Cai, Han, Li, RR [1711.02180] and Pascoli, RR, Weiland [1812.08750]



- the existence of (sub-)GeV sterile N is a well-motivated solution

(but not only solution!)

- new software (`HeavyN_Meson`) developed to facilitate state-of-the-art simulations for $N \to M\ell/\nu$, $M \to N\ell/\nu$, and $\tau \to NM$ at colliders

- Preliminary results are encouraging; final results out soon!


mechanism
review
impact
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hadron
LRSM
decay
heavy
discovery
test
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Thank you!

backup

Approximating $\langle \gamma_W^{(\text{lab})} \rangle$

The starting point is the **Collinear Factorization Thm**

Collins, Soper, Sterman ('85,'88,'89); Collins, Foundations of pQCD (2011)

$$d\sigma^{\text{LO}}(pp \to W + X) = \sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{\text{LO}}(ab \to W) \quad + \underbrace{\mathcal{O}\left(\frac{\Lambda_{\text{NP}}^p}{Q^{p+2}}\right)}_{\text{part./nucl. boundary}}$$

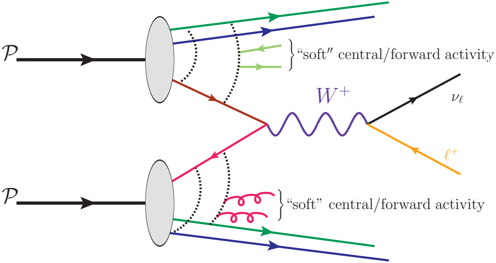
The average of a kinematic observable $\mathcal{O}$ can be obtained from the matrix element:

$$\langle \mathcal{O} \rangle = \frac{1}{\sigma} \times \int d\sigma \times \mathcal{O}$$

$$\implies \langle E_W \rangle = \frac{1}{\sigma} \times \int d\sigma \times E_W$$

$$\implies \langle E_W \rangle \big|_{events} \approx \frac{1}{\sigma} \times \sum_i wgt_i \times E_W$$

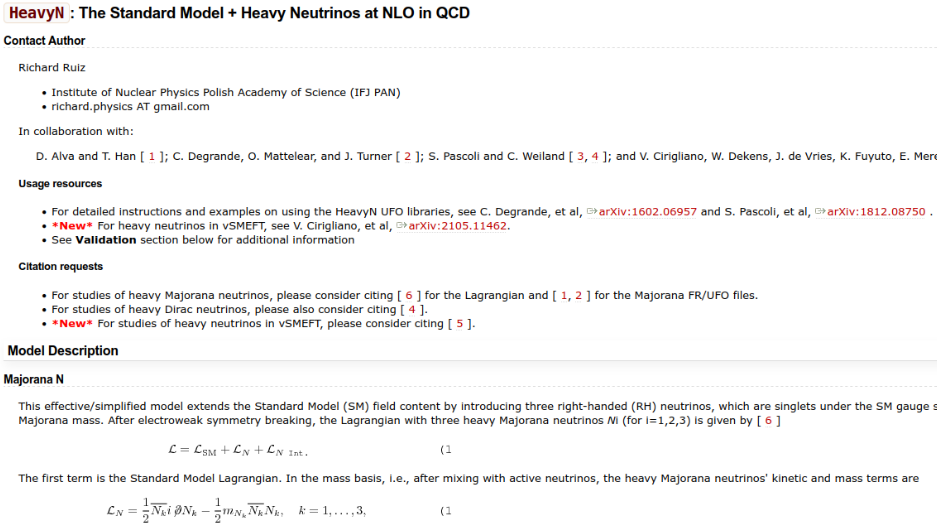
Assuming $f_{i/p}(\xi) \approx \frac{\text{const.} \times (1-\xi)^\beta}{x^{1+\delta}}$, with $\beta = 0, 1, 2, \ldots$, gives a closed form for $\sigma(pp \to W + X)$!



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

`HeavyN_vSMEFTdim6`, `TypeIISeesaw`, `EffLRSM`, `WZPrime`, `SMWeinberg`, `ZeeBabu`

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



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

Contact Author

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- richard.physics AT gmail.com

In collaboration with:

D. Alva and T. Han [1]; C. Degrande, O. Mattelear, and J. Turner [2]; S. Pascoli and C. Weiland [3, 4]; and V. Cirigliano, W. Dekens, J. de Vries, K. Fuyuto, E. Mere

Usage resources

- 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 .
- ***New*** For heavy neutrinos in vSMEFT, see V. Cirigliano, et al, arXiv:2105.11462.
- See **Validation** section below for additional information

Citation requests

- For studies of heavy Majorana neutrinos, please consider citing [6] for the Lagrangian and [1, 2] for the Majorana FR/UFO files.
- For studies of heavy Dirac neutrinos, please also consider citing [4].
- ***New*** For studies of heavy neutrinos in vSMEFT, please consider citing [5].

Model Description

Majorana N

This effective/simplified model extends the Standard Model (SM) field content by introducing three right-handed (RH) neutrinos, which are singlets under the SM gauge s
Majorana mass. After electroweak symmetry breaking, the Lagrangian with three heavy Majorana neutrinos *Ni* (for i=1,2,3) is given by [6]

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

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 are

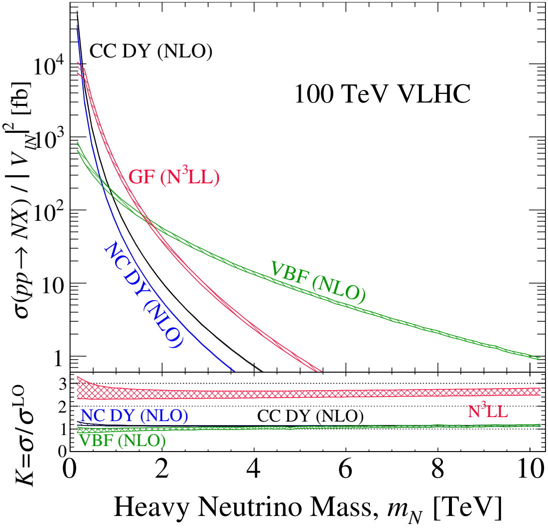
$$\mathcal{L}_N = \frac{1}{2}\overline{N_k} i \partial\!\!\!/ N_k - \frac{1}{2} m_{N_k} \overline{N_k} N_k, \quad k = 1, \ldots, 3, \qquad (1$$

FeynRules to MadGraph5aMC@NLO

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 b u∼ c∼
d∼ s∼ b∼ 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 LHC 100
> set vmun2 1.0
> set mn2 scan:range(5,1001,25)
> set wn2 auto
```

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

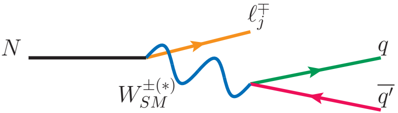


Pascoli, RR, Weiland [1812.08750]

mg5amc+MadSpin+Parton Shower

If the narrow width approximation is justified ($\Gamma_N/m_N \ll 1$), efficient generation of $e^+e^- \to Z \to \nu N \to \nu\ell^\pm q\overline{q'}$ possible with `MadSpin`:

Spin-correlation fully treated, RR [2008.01092]

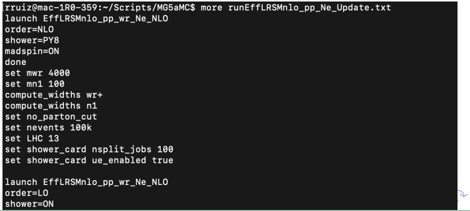


In `madspin_card.dat`, write:

```
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 →



```
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
```