Heavy Neutrinos from Heavy Bosons with MadGraph5_aMC@NLO

#LHCLLP9 - Zoom National Accelerator Laboratory

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the case for ν physics

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

[Ma ('98)]

Incredibly powerful but also incredibly vague since new particles:

- ... can be light ☺ or heavy ☹
- ... can be short-lived ☺ or long-lived ☺
- ... 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)**

the case for sterile neutrinos

The case for sterile neutrinos

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

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

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

However, ν_R^k do not exist in the SM, implying $m_D = 0$

The case for sterile neutrinos

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

However, ν_R^k do not exist in the SM, implying $m_D = 0$

A solution: The Type I Seesaw mechanisms generate m_ν by hypothesizing right-handed neutrinos ν_R^k with Majorana mass $m_R^k = \Lambda_{LNV}$

- depending on assumptions, $m_\nu \sim \Lambda_{LNV}$ or v^2/Λ_{LNV}

After EWSB, ν_ℓ and ν_R have same quantum numbers $\implies$ mixing!

In practice?

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

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

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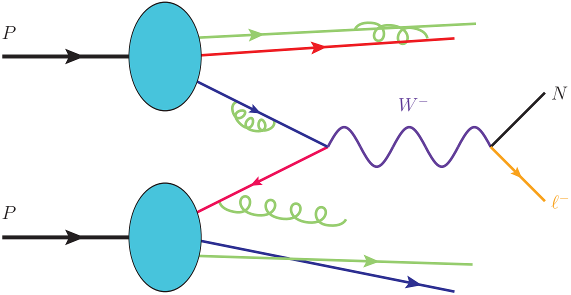
$\Longrightarrow$ SM W coupling to N and charged **leptons** in the **mass basis is**

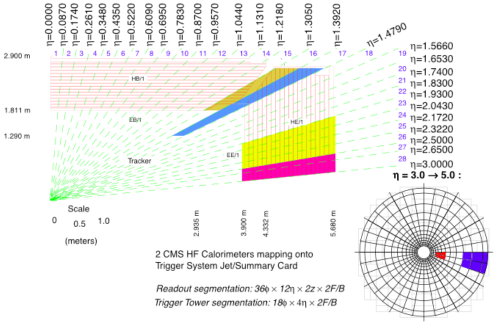
$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \left(\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell N} N\right)\right] + \text{H.c.}$$

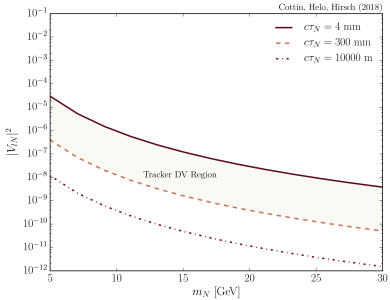
$\Longrightarrow$ N is **accessible through** $W/Z/H$ currents

searching for long-lived heavy neutrinos at colliders[1]



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





Decays of light N through SM weak currents can be very long-lived:

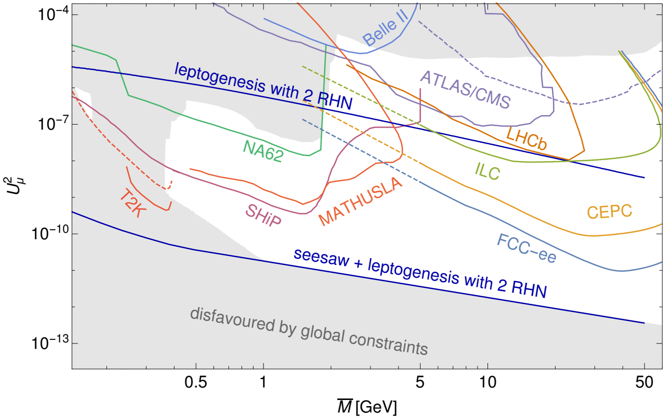
$$\Gamma_{\text{Tot.}} \sim G_F^2 m_N^5 \sum |V|^2 \ (\text{small } |V| \implies \text{long lifetime!})$$

$$\implies d_0 = \beta c \tau = \frac{\beta c \hbar}{\Gamma_{\text{Tot.}}} \sim \frac{1.45 \ m}{\sum |V|^2} \left(\frac{1 \text{ GeV}}{m_N} \right)$$

(Near) detectors have *finite* detector volume, with radius $< \mathcal{O}(10)$ m

- N may decay in ECAL (1-2m), HCAL (2-3m), μChamber (>5m)

Community Message: Current and next-gen. facilities can directly test *simplest* resonant leptogenesis scenarios with high-scale Type I Seesaw



Update of Drewes, et al [1609.09069]

Note: LHC picture evolving with better strategies and add'l channels

Cottin, Helo, et al [1806.05191]; Abada, Bernal, et al [1812.01720]; Cheung, Ishida, et al [2004.11537]

“Just how can I do this great physics?”

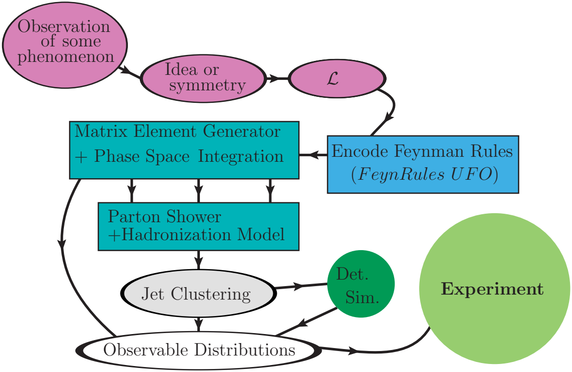
- Anonymous audience member

Searching for heavy Majorana and (pseudo)Dirac neutrinos N at LHC experiments follows any other analysis chain

- BIG PROBLEM (neutrino masses!)✓
- BIG SOLUTION (sterile neutrinos!) / model / Lagrangian✓
- Signal simulation with favorite generator ☹
  e.g., `MadGraph5`, `Whizard`, `SHERPA`
- Background simulation with favorite generator✓
- Design long-lived particle analysis ☺
- Collect data, control regions, unblind, do some statistics ☺

Major effort over past five-six years to make it possible to simulation Seesaw models with your favorite generator

- Universal FeynRules Object (UFO) libraries encode Feynman rules (.py) that plug into mainstream event generators, e.g., `MadGraph5`, `Whizard`, `SHERPA` Alloul, Christensen, Duhr, Degrande, and Fuks feynrules.irmp.ucl.ac.be



HeavyN: 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]

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

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 a

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

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

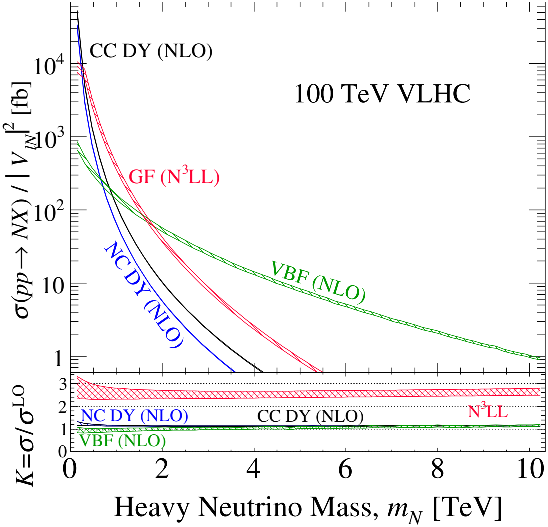
time for some plots

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 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]



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

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

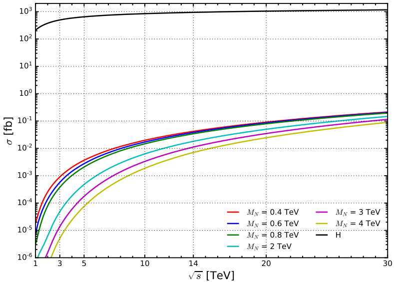
```
 $ ./bin/mg5_aMC
import model SM_HeavyN_NLO
define vv = ve ve~
define ell = e+ e-
generate e+ e- > z > N1 vv
         QCD=0 QED=2, n1 > ell j j
output Test_FCCee_ee_Nv_XLOPS
launch
shower=py8
set mz 92.0
set VeN1 1e-4
set mN1 scan:range(10,61,10)
set wn1 auto
set nevents 1k
set ebeam 46.0
set time_of_flight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

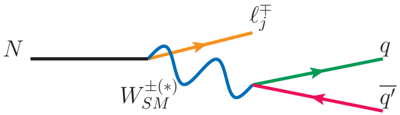


$W^+W^- \rightarrow \ell_i^+ \ell_j^-$ possible at muon colliders! [2005.10289]

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
```

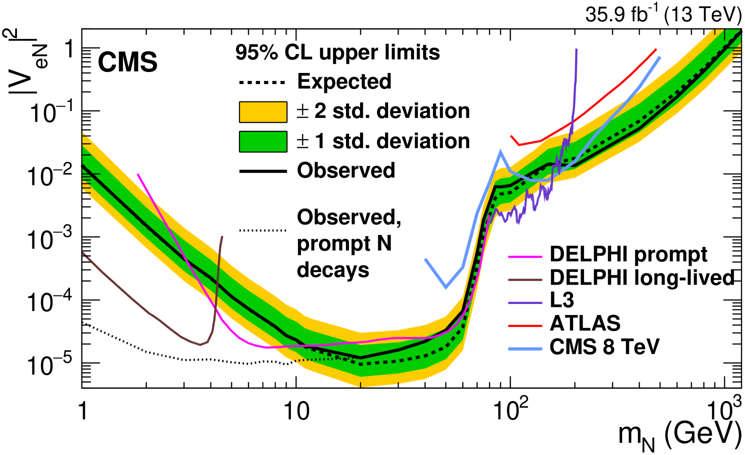
Parton showering with `PY8` or `HERWIG` straightforward

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
```

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

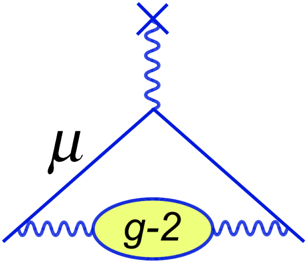


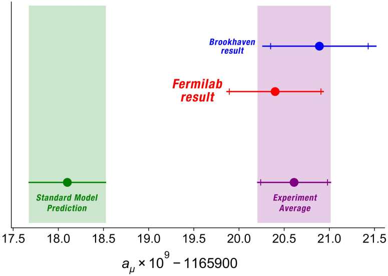
- HeavyN used in CMS trilepton [1802.02965] and dilepton [1806.10905] searches
- ATLAS is currently adopting software (JobOptions already available!)

NEW:[2] sterile neutrinos N and Δa_μ

[2] V. Cirigliano, W. Dekens, J. de Vries, K. Fuyuto, E. Mereghetti [2105.11462]

Anomalous magnetic moment of the μ





Fermilab's Muon g-2 has *confirmed* that $a_\mu = (g_\mu - 2)/2$ is *a bit* large

[2104.03281]

$$a_\mu^{\rm average} = (116\,592\,061 \pm 41) \cdot 10^{-11}$$

$$a_\mu^{\rm SM} = (116\,591\,810 \pm 43) \cdot 10^{-11}$$

The difference? Large enough to start taking BSM solutions seriously.

$\Delta a_\mu = (251 \pm 59) \cdot 10^{-11}$ or about 4.2σ!

Can new N interactions account for this?

Yes, in a surprisingly succinct manner.

ν**SMEFT** is the Standard Model Effective Field Theory extended by ν_R

$\psi^2 H^3$		$\psi^2 H^2 D$		$\psi^2 HX$(+H.c.)	
$\mathcal{O}_{L\nu H}$(+H.c.)	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$	$\mathcal{O}_{H\nu}$	$(\bar{\nu}_R\gamma^\mu\nu_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{\nu B}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$
		$\mathcal{O}_{H\nu e}$(+H.c.)	$(\bar{\nu}_R\gamma^\mu e)(\tilde{H}^\dagger iD_\mu H)$	$\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I\tilde{H}W^{I\mu\nu}$
$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R)$(+H.c.)	
$\mathcal{O}_{\nu\nu}$	$(\bar{\nu}_R\gamma^\mu\nu_R)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu}$	$(\bar{L}\gamma^\mu L)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Le}$	$(\bar{L}\nu_R)\epsilon(\bar{L}e)$
$\mathcal{O}_{e\nu}$	$(\bar{e}\gamma^\mu e)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{Q\nu}$	$(\bar{Q}\gamma^\mu Q)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Qd}$	$(\bar{L}\nu_R)\epsilon(\bar{Q}d)$
$\mathcal{O}_{u\nu}$	$(\bar{u}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu\nu_R)$			$\mathcal{O}_{LdQ\nu}$	$(\bar{L}d)\epsilon(\bar{Q}\nu_R)$
$\mathcal{O}_{d\nu}$	$(\bar{d}\gamma^\mu d)(\bar{\nu}_R\gamma_\mu\nu_R)$				
$\mathcal{O}_{du\nu e}$(+H.c.)	$(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$				
$(\bar{L}R)(\bar{R}L)$		$(\not{L}\cap B)$(+H.c.)		$(\not{L}\cap\not{B})$(+H.c.)	
$\mathcal{O}_{Qu\nu L}$(+H.c.)	$(\bar{Q}u)(\bar{\nu}_R L)$	$\mathcal{O}_{\nu\nu\nu\nu}$	$(\bar{\nu}_R^c\nu_R)(\bar{\nu}_R^c\nu_R)$	$\mathcal{O}_{QQd\nu}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(Q_\alpha^i C Q_\beta^j)(d_\sigma C\nu_R)$
				$\mathcal{O}_{udd\nu}$	$\epsilon_{\alpha\beta\sigma}(u_\alpha C d_\beta)(d_\sigma C\nu_R)$

Table 1: The complete basis of dimension-six operators involving ν_R taken from Ref. [24]. The operators are expressed in terms of a column vector of n gauge singlet fields, ν_R, and of SM fields, the lepton and Higgs doublets, L and H, the quark left-handed doublet $Q = (u_L, d_L)^T$, and the right-handed fields e, u, and d.

Unexpectedly, only one νSMEFT can generate the right Δa_μ

$$\mathcal{L}_{H\nu e} \approx \frac{gv^2}{2\sqrt{2}\Lambda^2}\sum_{k=1}^{3}\left[\bar{C}_{H\nu e}\right]_{k\ell}\left(\overline{N_k}\gamma^\mu P_R\,\ell_R\right)W_\mu^+\left(1+\frac{h}{v}\right)^2 + \text{H.c.}$$

This generates Δa_μ of the form

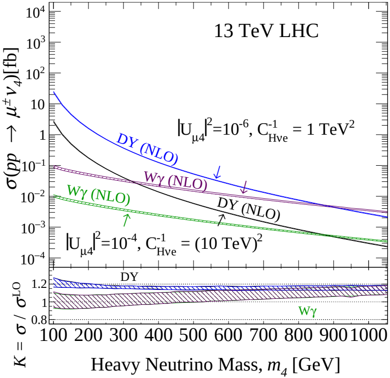
$$\Delta a_\mu \sim -\frac{2m_\mu m_N}{(4\pi)^2\Lambda^2}\mathrm{Re}\left(V_{\mu N}\left[\bar{C}_{H\nu e}\right]_{N\mu}\right)$$

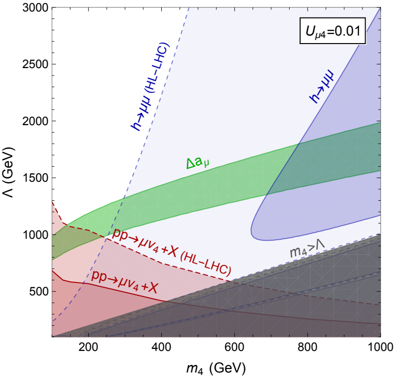
(see [2105.11462] for exact formula!)

Δa_μ at the LHC

We created a new UFO `HeavyN_vSMEFTdim6` containing $\mathcal{O}_{H\nu e}$

Already available from the FeynRules UFO database: feynrules.irmp.ucl.ac.be/wiki/HeavyN





Conclusion: If N are involved in Δa_μ, then expect something in

$$pp \to N\mu^\pm + X \text{ and } H \to \mu^+\mu^-$$

in Run III data and at the HL-LHC (see the paper for more details! [2105.11462])

summary

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

- Available: UFOs with Majorana or Dirac N
- Available: UFOs with full CKM matrix or all quark masses
- Available: LO (XLO) and LO+NLO (NLO) Feynman rules

- NEW: (some) νSMEFT operators at dimension six
- In development: decays to/from vector mesons for $m_N \lesssim 5$ GeV
- In development: more studies on spin-correlation
- In development: more studies on off-shell mediators

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

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- For studies of heavy Dirac neutrinos, please consider citing [2, 4].

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[5]

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

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

UFO	NLO	Spin	M or D	#	V'	LNV	LFV	arXiv
HeavyN	✓	✓	M	3		✓	✓	[1602.06957]
HeavyN_Dirac	✓	✓	D	3			✓	[1812.08750]
HeavyN_vSMEFTdim6	✓	✓	M	3		✓	✓	[2105.11462]
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!

Thank you.