Pheno for ANUBIS

Progress + plans

Anna Mullin
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Starting point with FIPs Physics Centre

“For most of the FPC benchmarks, it is not possible to generate events using conventional methods (i.e. loading UFO model files into Madgraph), for example because the FIPs are produced in meson decays, which need to be simulated first.

We currently do not have any central repository to collect tools and techniques for all the benchmarks, so your best chance is to contact the representatives of the experiments that are most similar to ANUBIS.

This would be Michele Papucci for CODEX-b and Jonathan Feng for FASER2, who should be able to point you to the respective experts for the different models. If you don't want to start all the way at the top, you could try contacting Simon Knapen for CODEX-b and Felix Kling for FASER2, and maybe also David Curtin for MATHUSLA.”

Recent focus

Event generation since July:

1. Madgraph studies of HNLs
   - Series of UFOs based on FeynRules model database → generating samples → comparing kinematics
   - (despite some production mechanisms for HNLs not possible via MG5)
2. Acceptance studies with ANUBIS geometry
   - New isolation cuts, cavern ceiling geometry → increased importance of Drell-Yan decays via W/Z, decreased importance of B/D meson decays (due to hadronic radiation effects)
3. Madgraph studies of other portal models
   - Made UFOs for scalar + vector portal models based on FeynRules → generating samples
   - Easy to continue this, but paused to focus on HNLs because they're the hardest

Pythia attempts

1. Various Pythia attempts at generating B, D meson production of HNLs
    - Some gitlab setups publicly available, generated samples of B meson decays
        - Jan https://github.com/janhajer/hnl/tree/master
        - Other one (brief summary and link git repo)
2. FairShip: publicly available HNL generation framework using Pythia designed by SHiP experiment
    - Ongoing studies with Theo in Lyon
3. Now have local help with Pythia stand-alone event generation
    - Recently joined by Paul

Other leads

- LLP website: https://longlivedparticles.web.cern.ch/node/25 and the link there goes to this dropbox with a huge amount of model files: https://www.dropbox.com/s/0k9oa9s5s4gdvpv/Library.tar.gz?file_subpath=%2FLibrary

- ATLAS setup of UFOs for HNL generation (and Pythia implementation?)
  - Athena frameworks notoriously complicated, but functional

HNL UFOs

1. "Effective HeavyN Dirac/Majorana"
    a. Model description: https://link.springer.com/article/10.1140/epjc/s10052-021-08861-y
    b. One additional heavy neutrino, user-input mass and couplings
    c. Option to remove the quarks and replace them with mesons, which introduces low-energy effective operators
        i. Not applicable to our high-energy case
        ii. I switched "mesons = False" → restores SM quark content and HNL interactions with W and Z bosons

2. "HeavyN Dirac/Majorana" by Richard Ruiz
    a. Model and instructions for production: https://arxiv.org/abs/1602.06957
    b. 3 additional RH neutrinos, singlets under SM gauge symmetry
    c. Can optionally contain dim-6 SMEFT operators

Considerations

1. How does MG5 approach decays when decay width = 0?
    a. Seeing problems with HNL decays when HNL mass is higher than intermediate boson mass.
    b. MG5 told by "DECAY 18000 0.000000e+00" that HNL is stable, but I ask for on-shell decay.
    c. Is MG5 using zero width approximation to restrict intermediate W or Z to be on-shell?
    d. Check: reconstruct the mass by plotting invariant mass at truth level.
    e. Does the W offshell need to be enabled in MG5?
2. What about tiny decay width?
    a. Doesn't always work, but possible to pass a very small non-zero width
3. Generating s-channel vs. t-channel decays?
4. Compare parton-level and hadron-level tests: what products do we expect from the showered events?

HeavyN models

Strategy:

- Investigate alternative set of FeynRules UFOs: Majorana and Dirac “HeavyN” models
- Compare decays of 3 neutrinos of different masses/widths/couplings
- Compare 3 different production modes (W+, W-, Z) of the same neutrinos
- Generate sample sizes = 10,000 events to check plots

Contents:

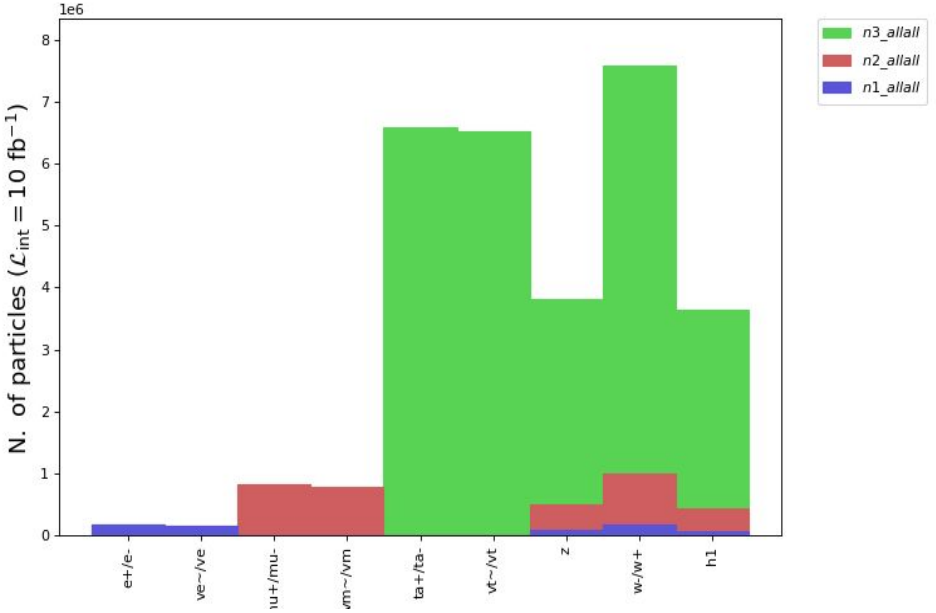
A. 3 types of neutrinos
B. 3 modes of production
C. 2 types of model: Dirac and Majorana
D. Showered and unshowered with Pythia

3 types of neutrinos

1. N1 (ID: 9900012)
    1. mass = 300 GeV
    2. VeN1 = 1. (mu = ta = 0) (model assumes diagonal CKM)
    3. width = 0.303 GeV
2. N2 (ID: 9900014)
    1. mass = 500 GeV
    2. VmuN2 = 1. (e = ta = 0)
    3. width = 1.5 GeV
3. N3 (ID: 9900016)
    1. mass = 1 TeV
    2. VtaN3 = 1. (e = mu = 0)
    3. width = 12.3 GeV

MG5 syntax: e.g. “generate n1 > all all”
then compare with n2 > all all, n3 > all all

Majorana model used to decay neutrinos



Outgoing particle IDs

After being produced, a HNL of several GeVs, but still lighter than M_W, will decay dominantly via off-shell W or Z bosons to a 3-body final state

$$N \to \ell^{\pm}_{\alpha} jj\,, \tag{2}$$
$$N \to \ell^{\pm}_{\alpha} \ell^{\mp}_{\beta} \nu_{\beta}\,, \tag{3}$$
$$N \to \nu_{\alpha} jj\,, \tag{4}$$
$$N \to \nu_{\alpha} \ell^{\pm}_{\beta} \ell^{\mp}_{\beta}\,, \tag{5}$$
$$N \to 3\nu\,. \tag{6}$$

On the other hand, if M_N is above the EW scale, the dominant decays will be to on-shell W, Z and H bosons, i.e. $N \to \ell^{\pm} W^{\mp}, \nu Z, \nu H$. These 2-body decays will be followed by the decay of the heavy bosons, leading at the end to the same final states as before. Nevertheless, it is important to keep in mind that the kinematics in these two mass regimes will be different.

https://link.springer.com/article/10.1140/epjc/s10052-022-11011-7
(Collider searches for HNLs, 2022)

E.g. from Madgraph: N1 decaying to higgs

n1 > ve h

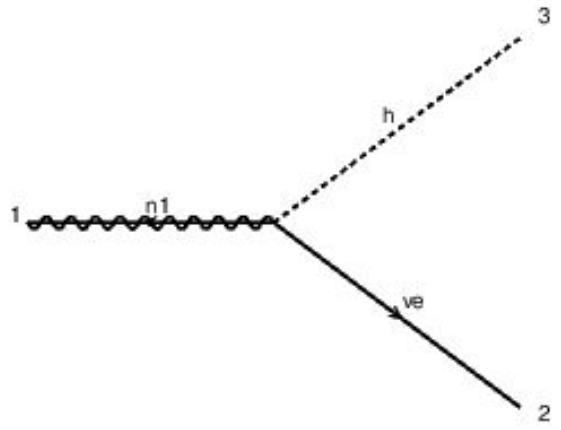


diagram 1 QCD=0, QED=1

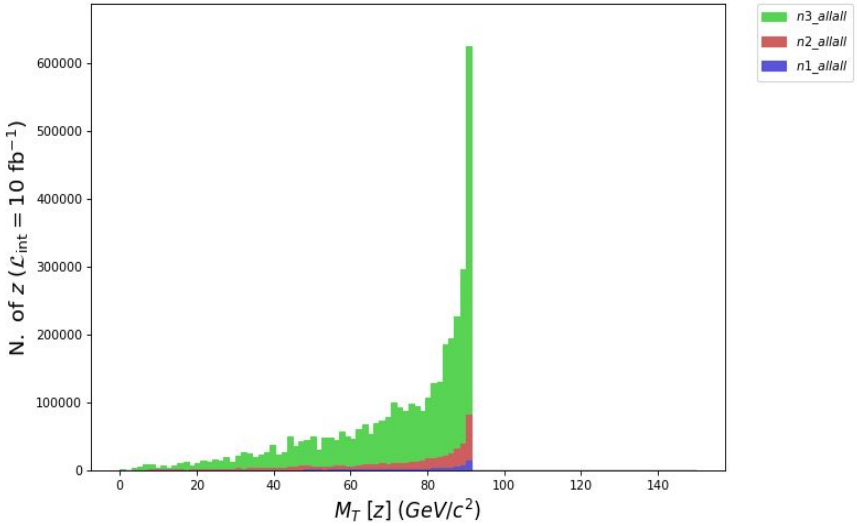
Most of the LHC searches focused on the *smoking gun* signature for Majorana neutrinos, the same sign (SS) dilepton final state:

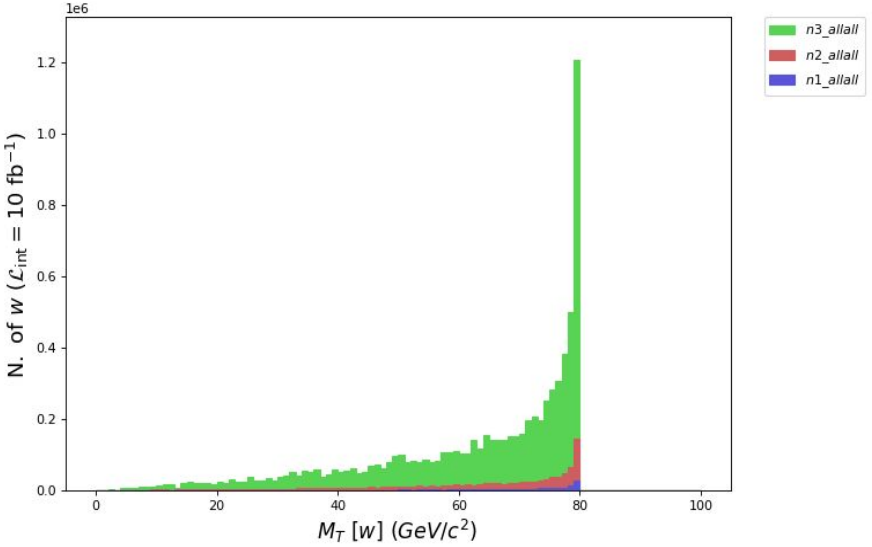
$$pp \to \ell^{\pm}_{\alpha} N \to \ell^{\pm}_{\alpha} \ell^{\pm}_{\beta} + nj\,. \tag{7}$$

Here, the lepton pair is accompanied by at least two jets (see Fig. 1), unless M_N is much lighter or much heavier than M_W, which leads to boosted objects and collimated jets that are reconstructed as a single one.

3 types of neutrinos

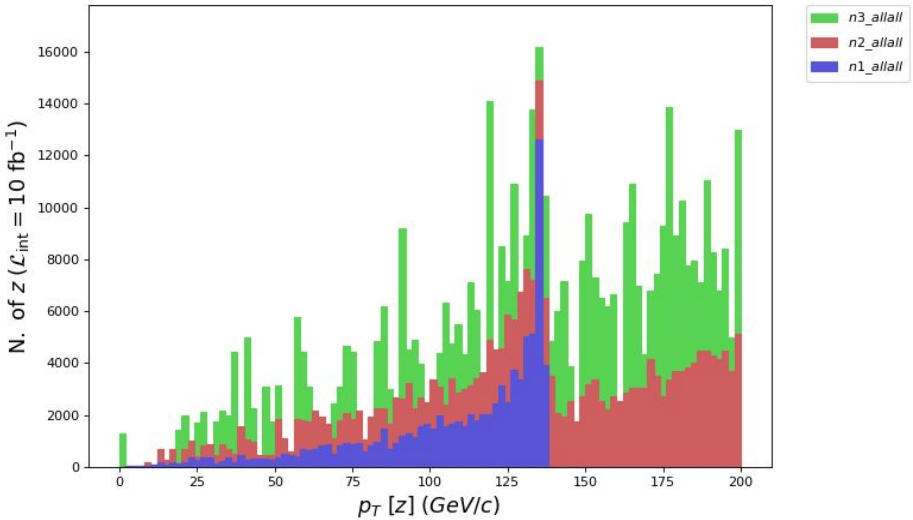
Transverse mass of Zs and Ws

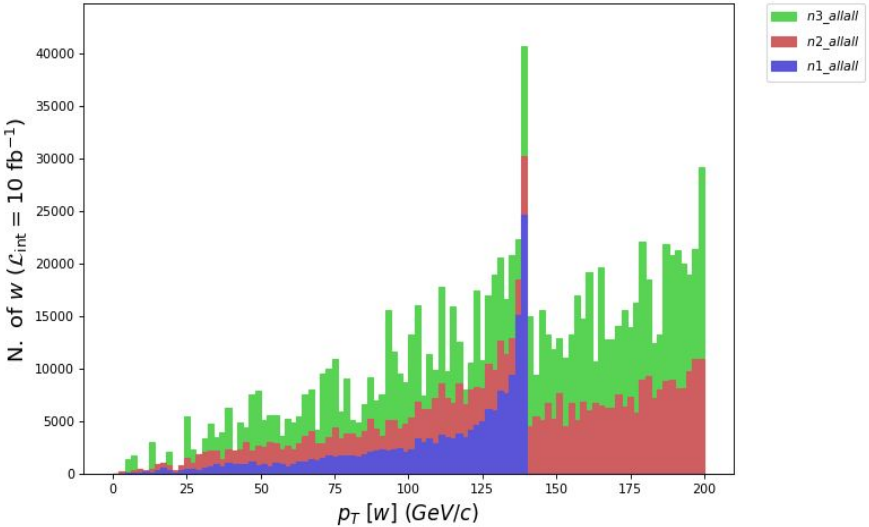




3 types of neutrinos

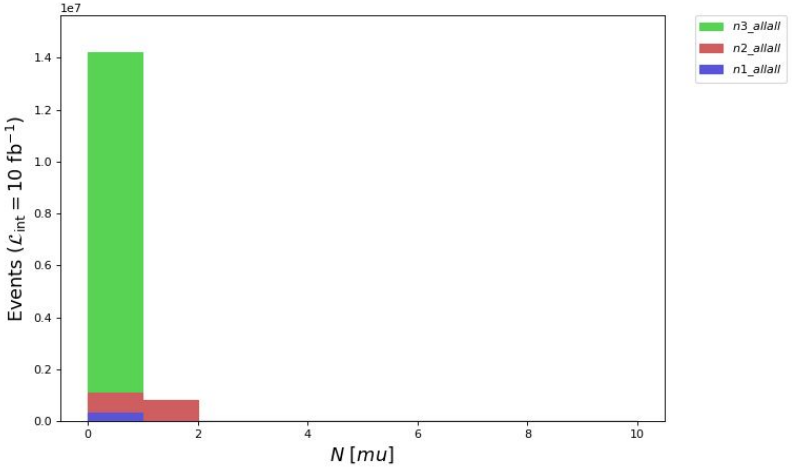
Transverse momentum of Zs and Ws

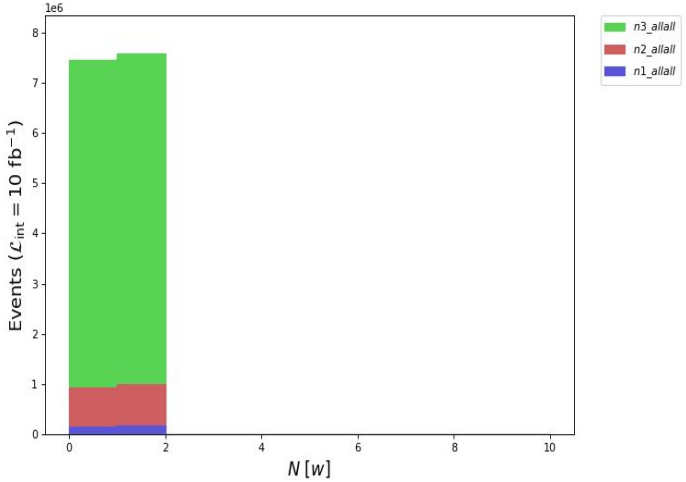




3 types of neutrinos

Multiplicity of muons and Ws



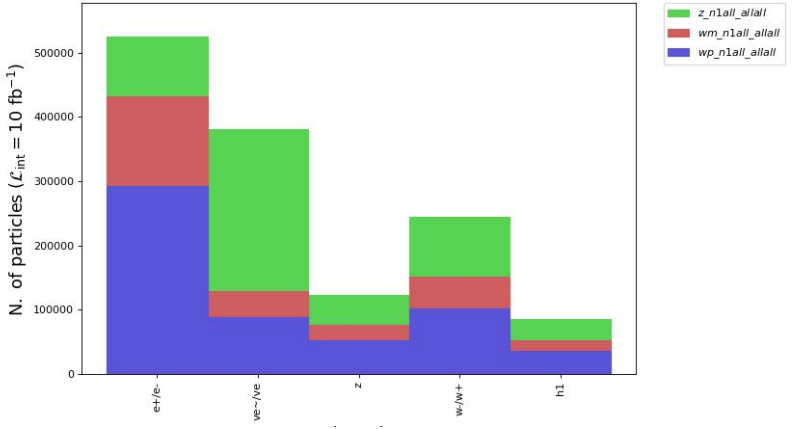


3 production mechanisms

Filename: wp_wm_z_n1all_allall

- Comparing W+, W- and Z modes of production of HNLs on same plots
- All HNLs here are N1 type:
  - Couple only to electrons
  - Mass =300 GeV
  - Width = 0.303 GeV
- 3 samples generated separately with same Majorana model
- All samples include decays of N1 to all possible decay products
- No Pythia showering here

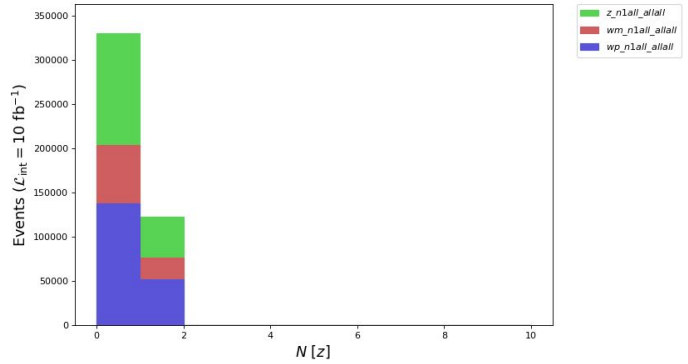
MG5 syntax: e.g. “generate p p > w+ > n1 all, (n1 > all all)”, then replace w+ with w-, z.

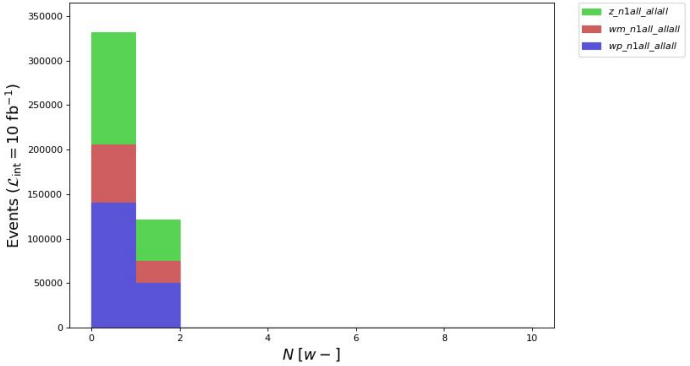


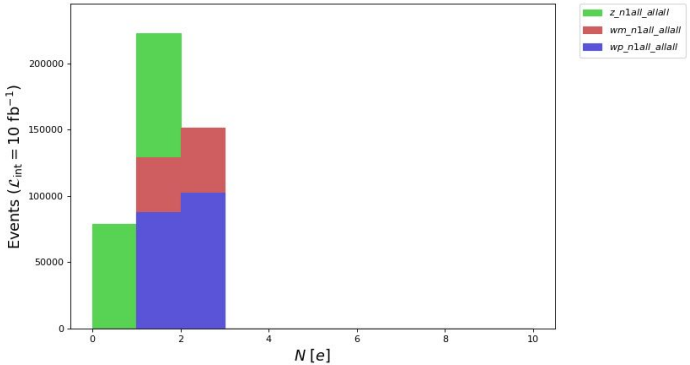
Breakdown of outgoing particle by ID

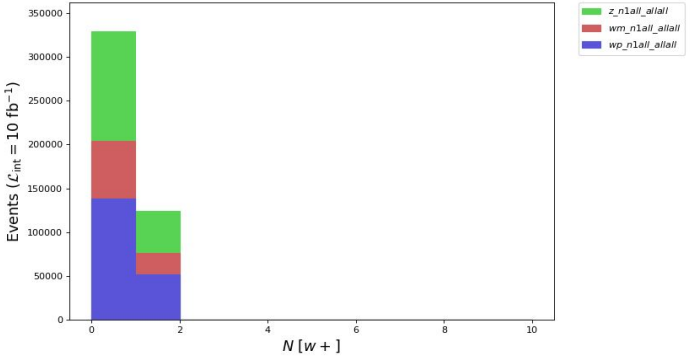
3 production mechanisms

Multiplicity of Zs, electrons, Ws



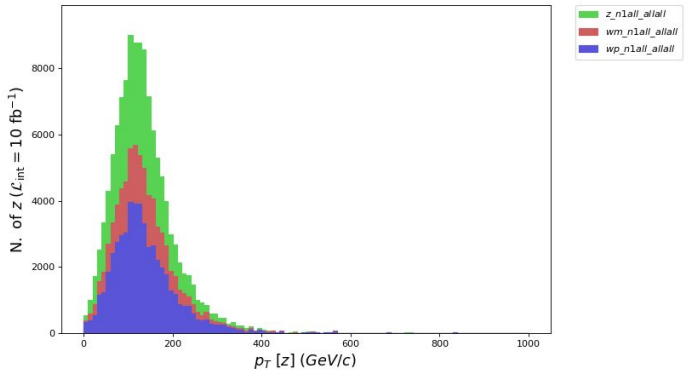


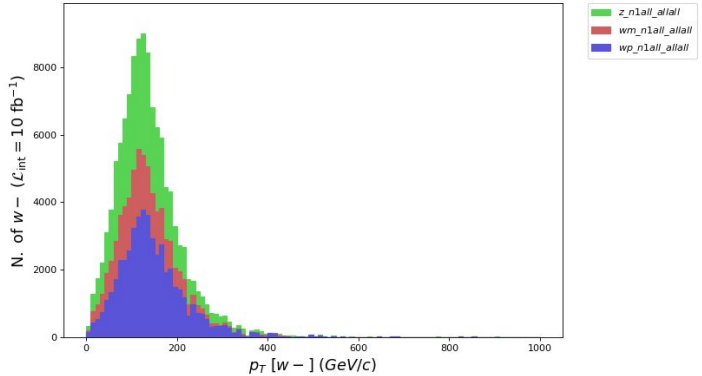


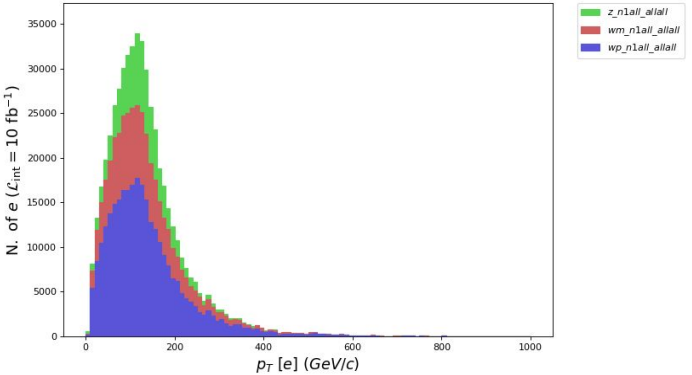


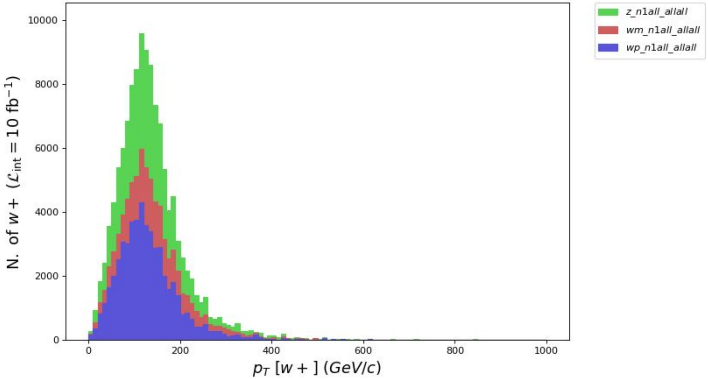
3 production mechanisms

Transverse momentum of Zs, electrons, Ws



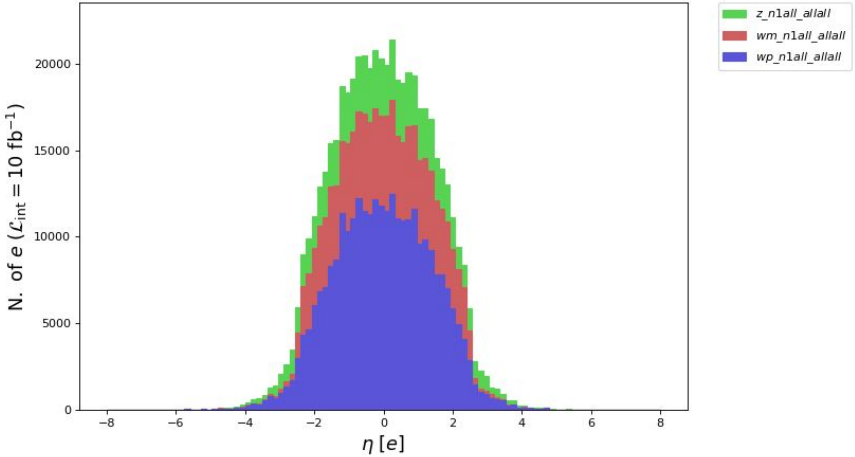


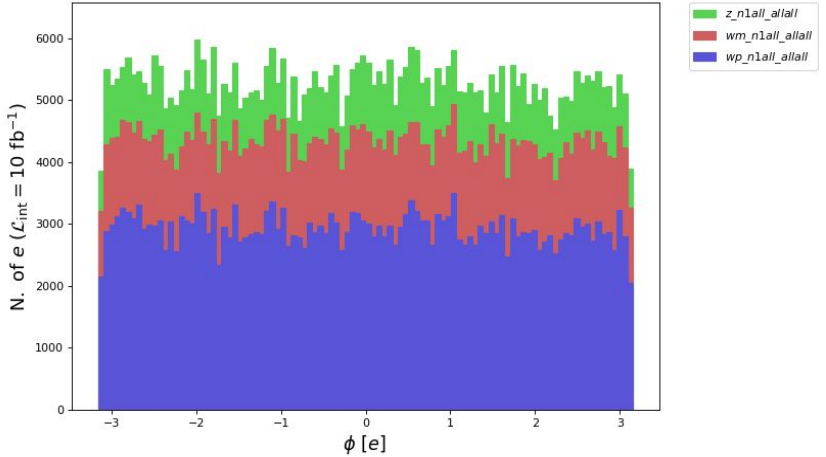




3 production mechanisms

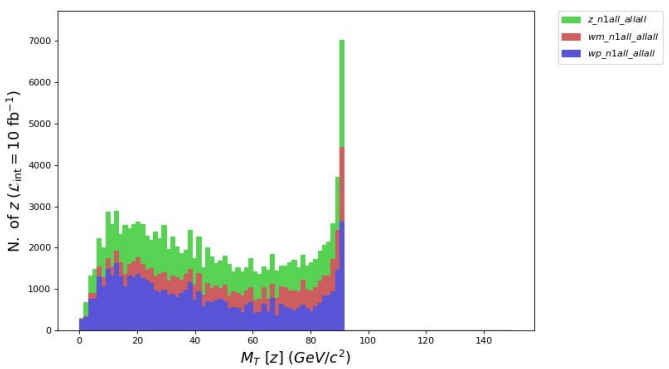
Angular information for electrons

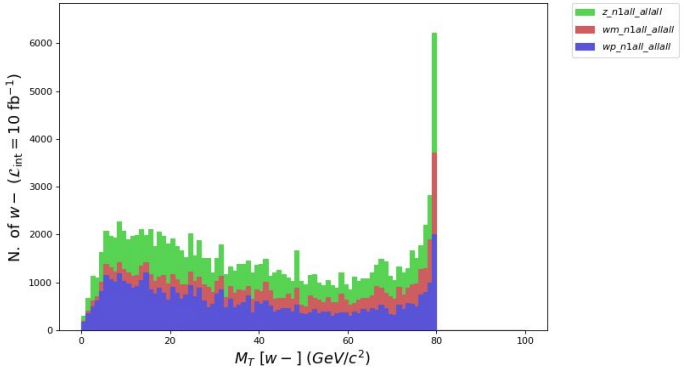


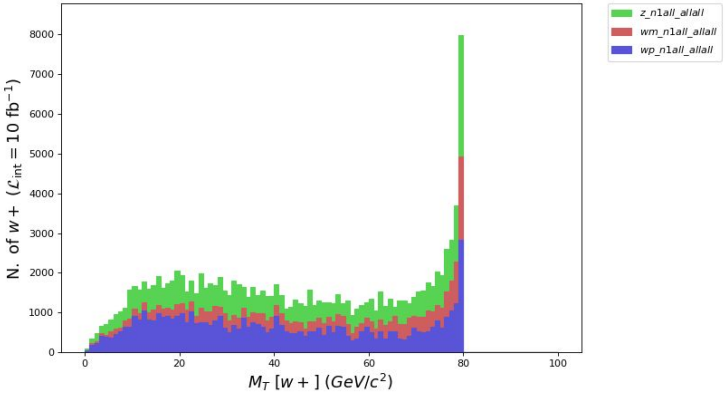


3 production mechanisms

Transverse mass of Zs and Ws







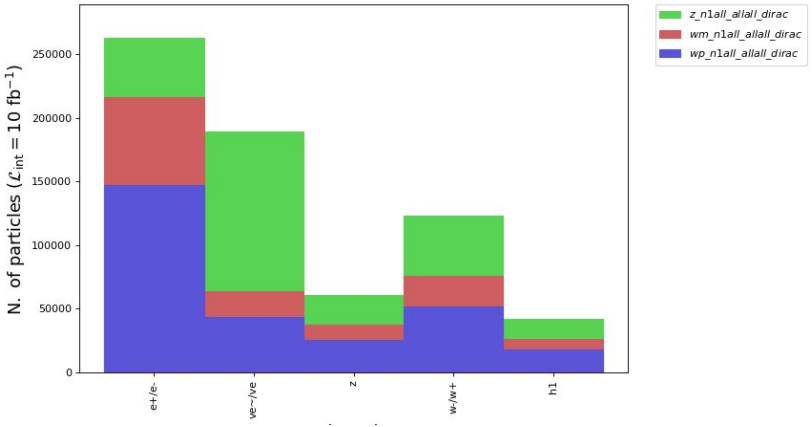
2 types of model: Dirac vs Majorana

Dirac UFO defines separate anti-particle HNL - check here that consistent results generated in Dirac model,

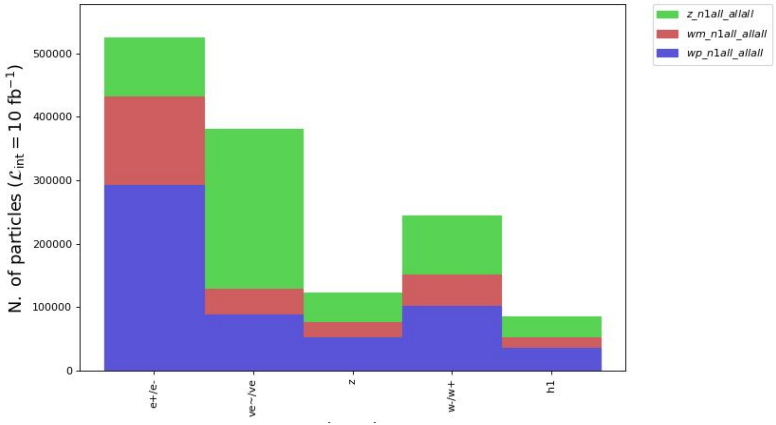
e.g: generate p p > z > n1 all, (n1 > all all)

add process p p > z > n1~ all, (n1~ > all all)

Dirac: output particle IDs

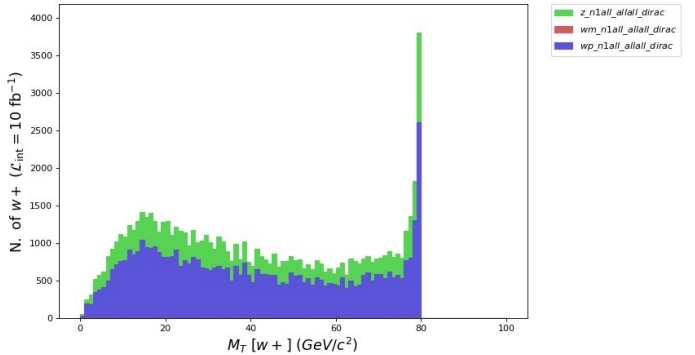


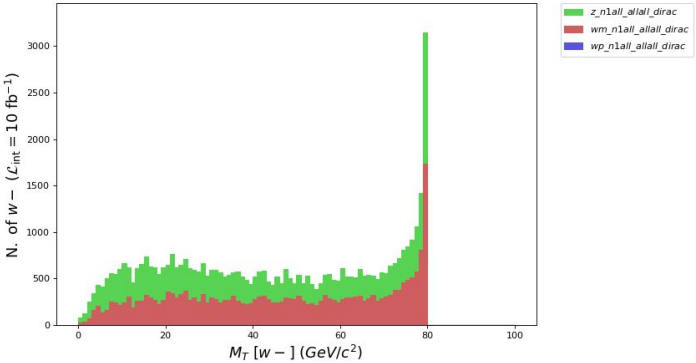
Majorana: output particle IDs



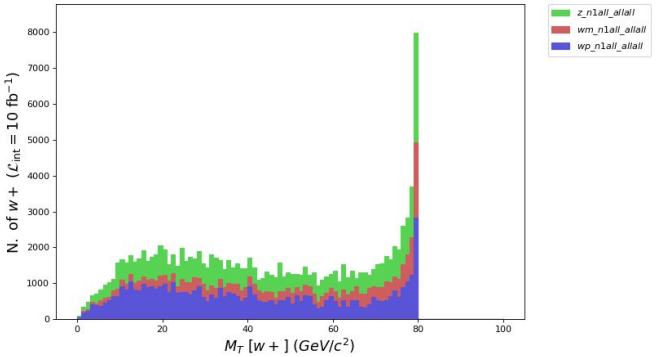
2 types of model: Dirac vs Majorana

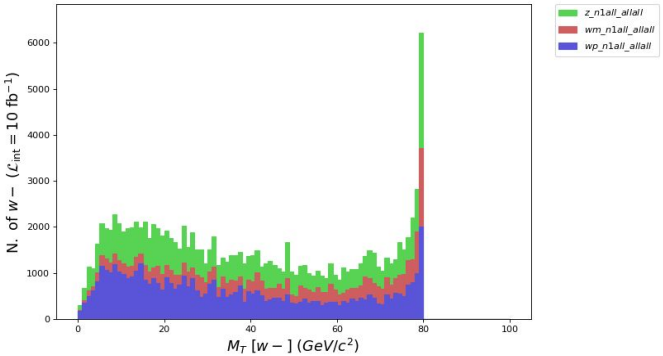
Dirac



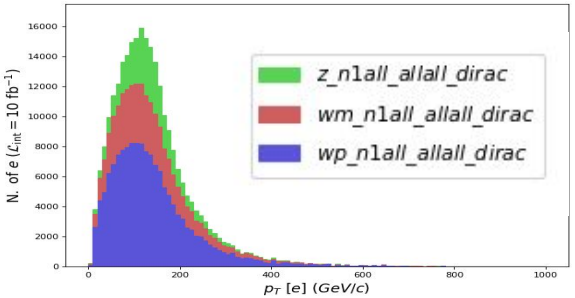


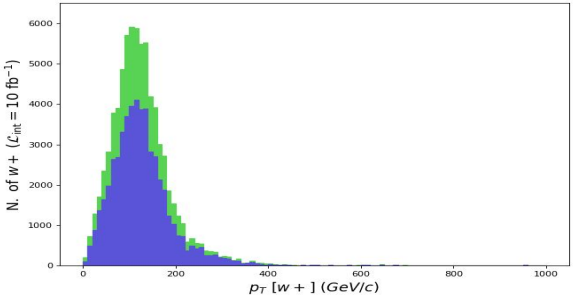
Majorana

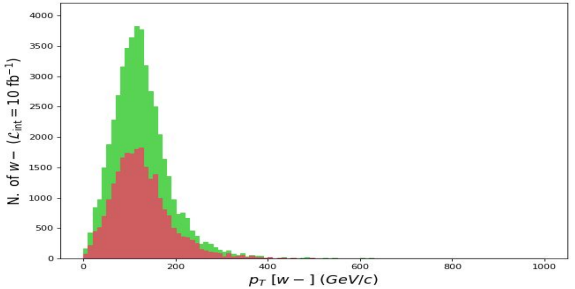




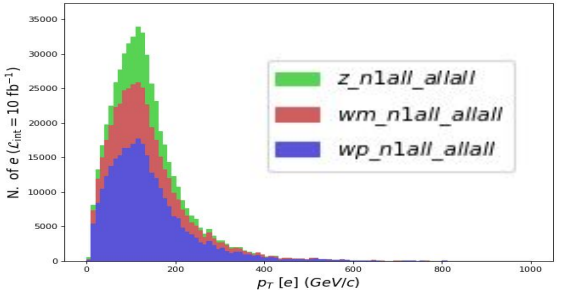
Dirac

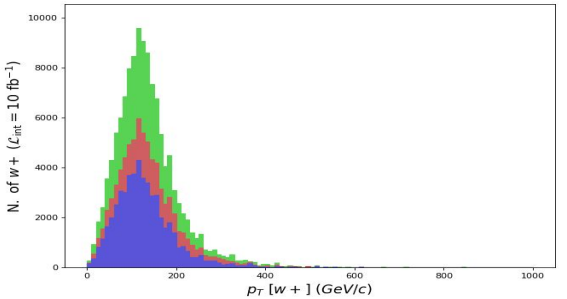


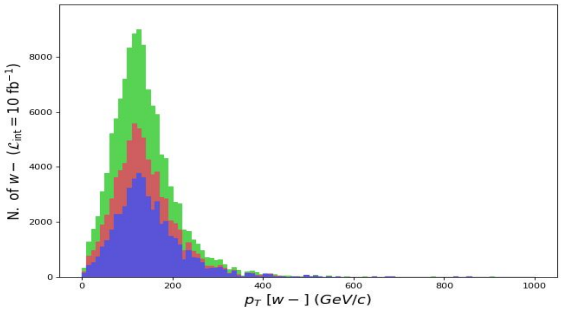




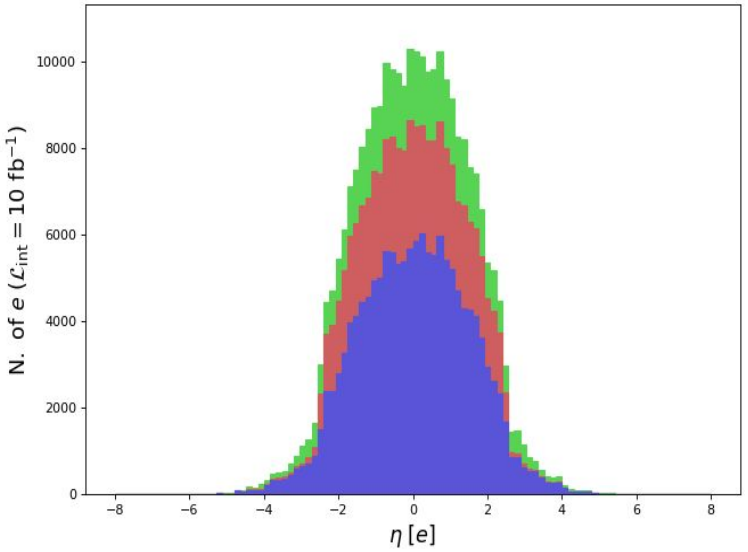
Majorana



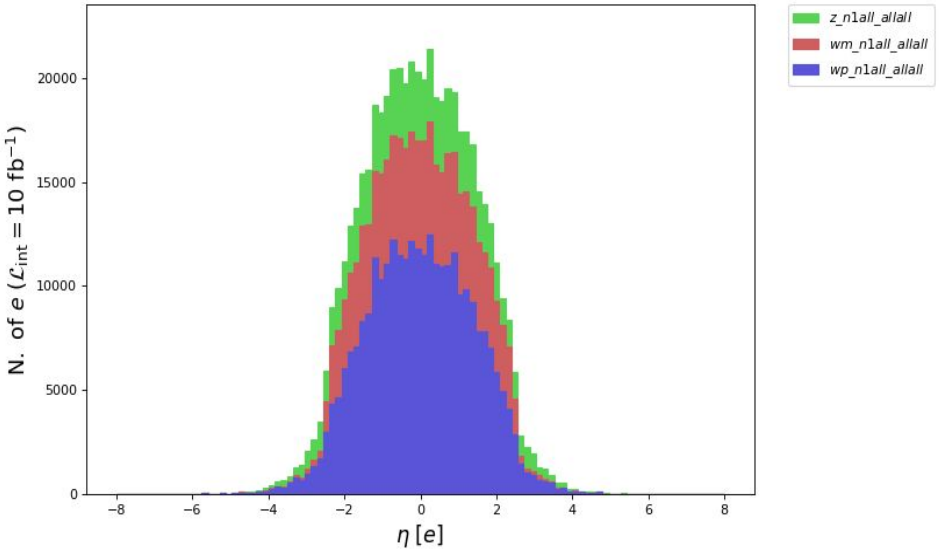




Dirac



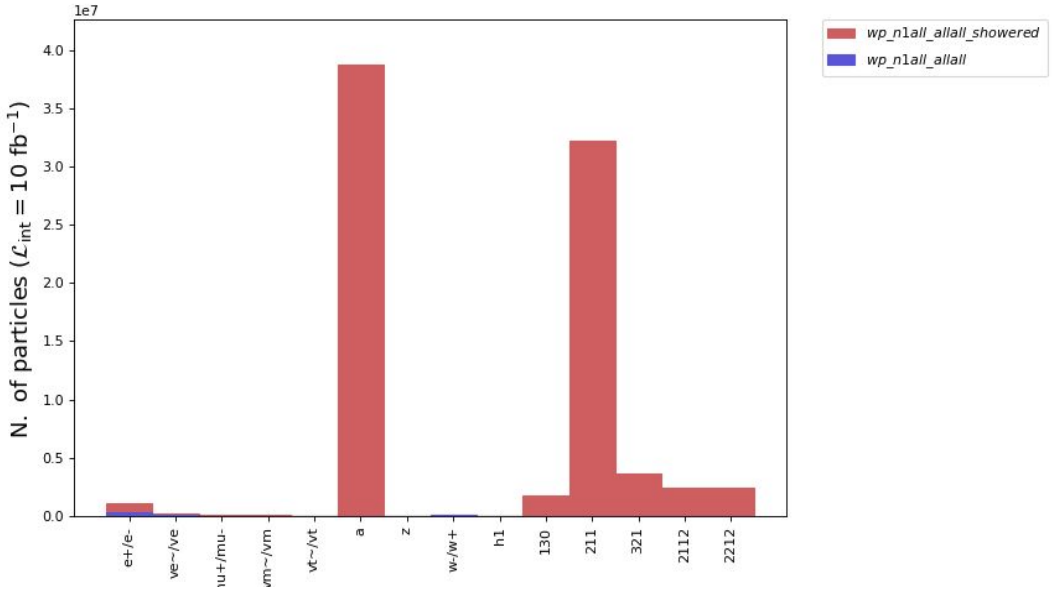
Majorana



Showered with Pythia

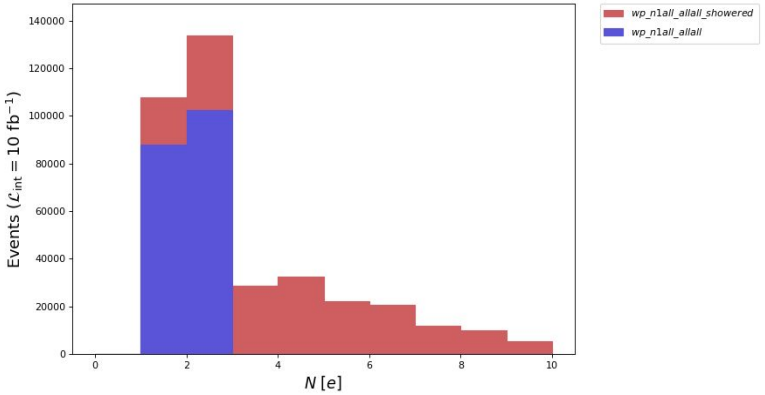
MG5 syntax: “generate p p > w+ > n1 all, (n1 > all all)”

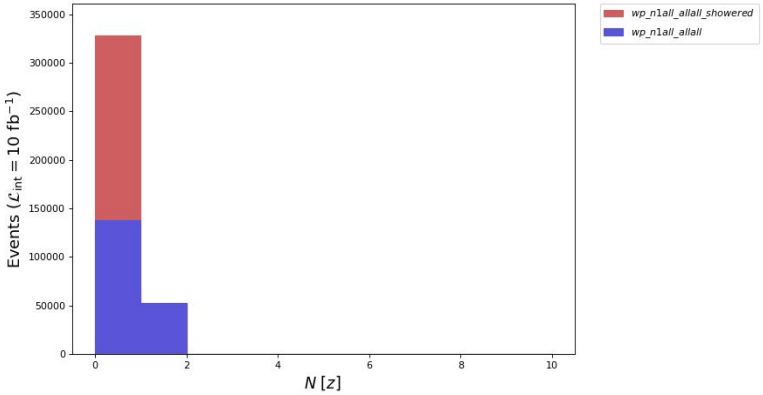
Outgoing particle IDs

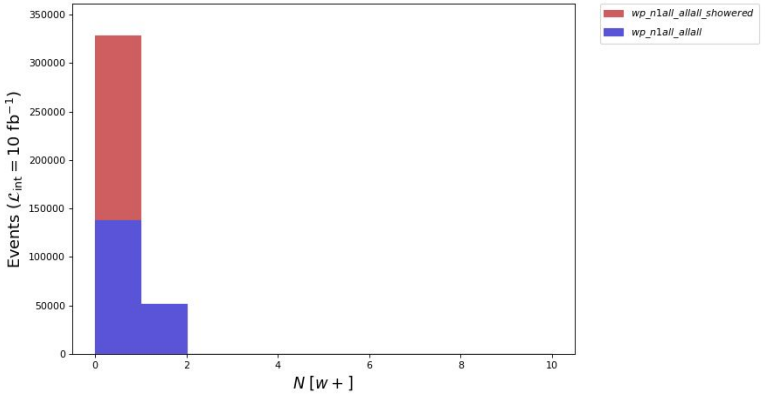


Showered with Pythia

Multiplicities of Zs, electrons, W+

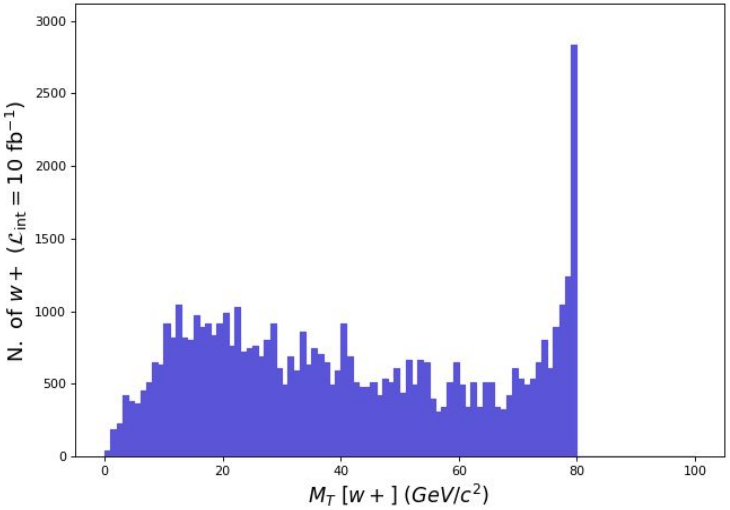


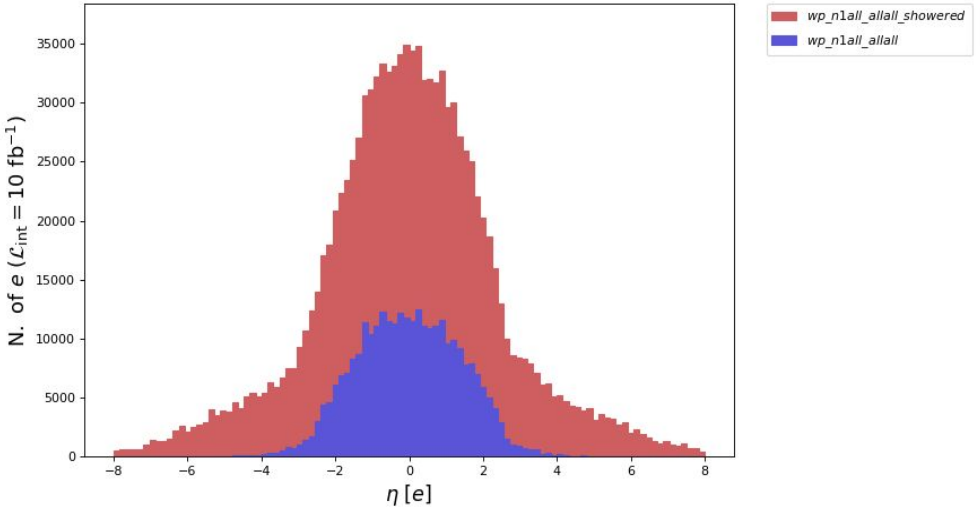




Showered with Pythia

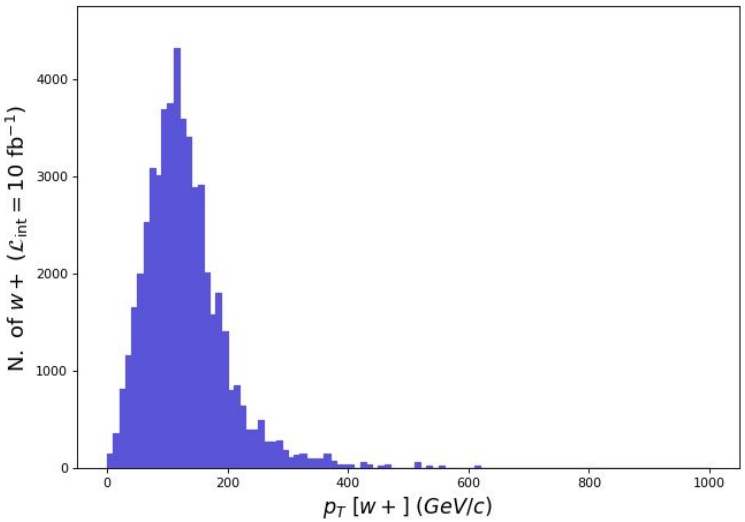
Transverse mass of W+, eta of electrons

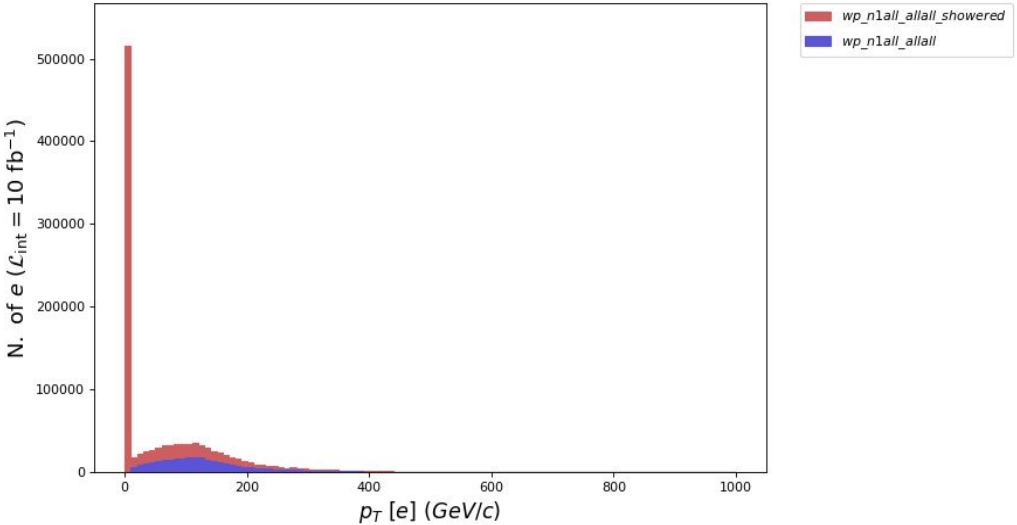




Showered with Pythia

Transverse momentum of W+ and electrons





Production mechanisms

"HeavyN" modes of producing HNLs

Other relevant modes with HeavyN, besides DY

Aim to check:

```
> generate g g > n2 vv [QCD]
```

- The inclusive, unmatched LO gluon fusion rate

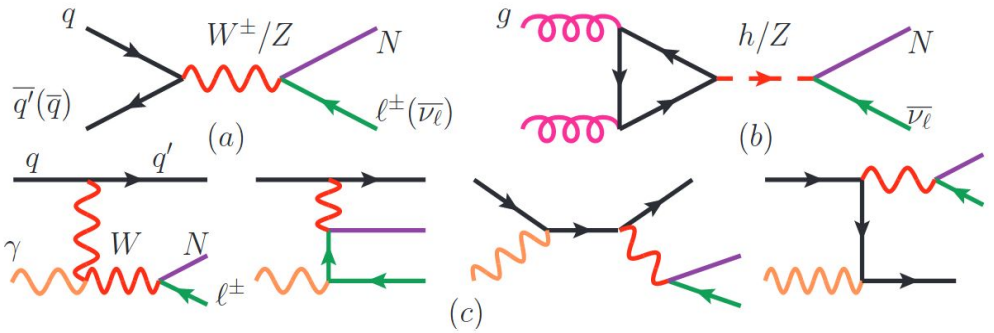


FIG. 1: Heavy neutrino production via (a) charge (neutral) current Drell-Yan, (b) gluon fusion, and (c) $W\gamma$ fusion.

Also check:

```
> define q = u c d s b u~ c~ d~ s~ b~
> generate q a > n2 mu q QED=3 QCD=0 [QCD]
> add process a q > n2 mu q QED=3 QCD=0 [QCD]
> output PP_VBF_NLO; launch;
```

https://arxiv.org/pdf/1602.06957.pdf

- Vector boson fusion

Understand output of Pythia showering

Check what goes into M_T calculation - shape because missing ET (neutrinos)

Short-term plans

1. Particle-level analysis of MG5 samples with Pythia showering
    - Complete checks to fully understand outputs
2. Acceptance study with detector simulation
    - Applying updated cuts for ANUBIS geometry
    - This completes the pipeline for a single model/sample - then straightforward to replace samples with other parameters/models and rerun!

Long-term plans

Possible outline:

1. HNLs paper?
    - Update to the 2020 ANUBIS pheno paper on sensitivity to HNL models
    - Requires combination of production modes (e.g. Madgraph and Pythia)
2. Add ANUBIS to FIPs/PBC plots?
    - HNLs, scalar, vector and axion models
    - 3 additional portal models easily produced in Madgraph with existing UFOs
    - Require knowledge of specific parameters
3. Additional studies/models wrapped into a subsequent paper?