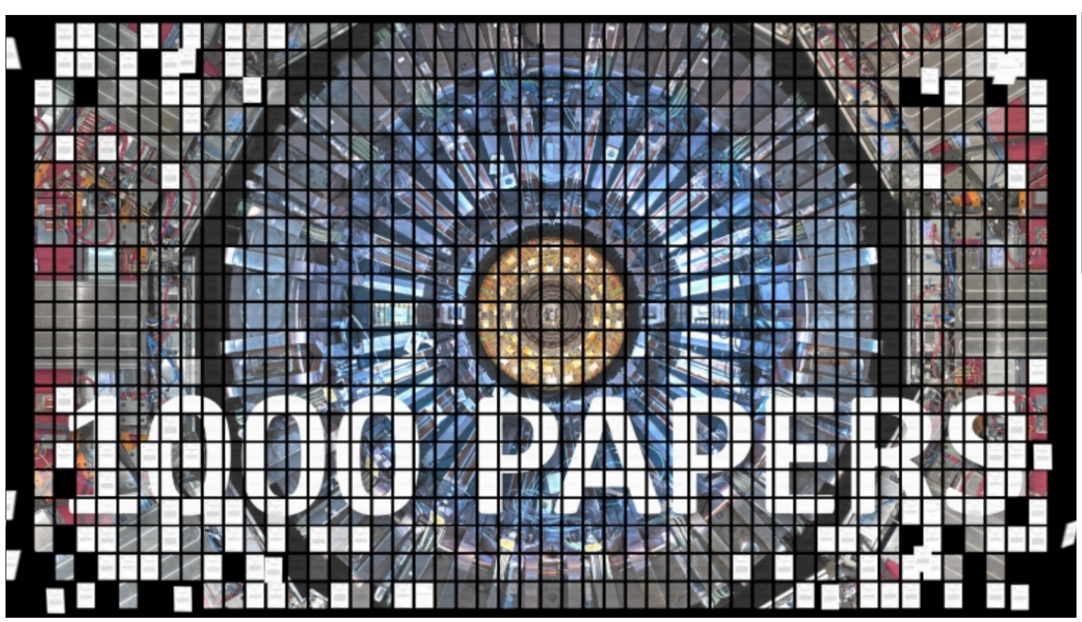
EFT Analysis of the VVV process: a Letter of Interest for Snowmass 2021

Saptaparna Bhattacharya[1], Claudius Krause[2], Stefan Höche[3], Michael Schmitt[1]
[1]Northwestern University
[2]Rutgers University
[3]Fermi National Accelerator Laboratory

November 6th, 2020

Observation of Heavy Tribosons with Run II data

Major milestone in Standard Model physics!



PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About Staff

Featured in Physics | Editors' Suggestion | Open Access

Observation of the Production of Three Massive Gauge Bosons at $\sqrt{s} = 13$ TeV

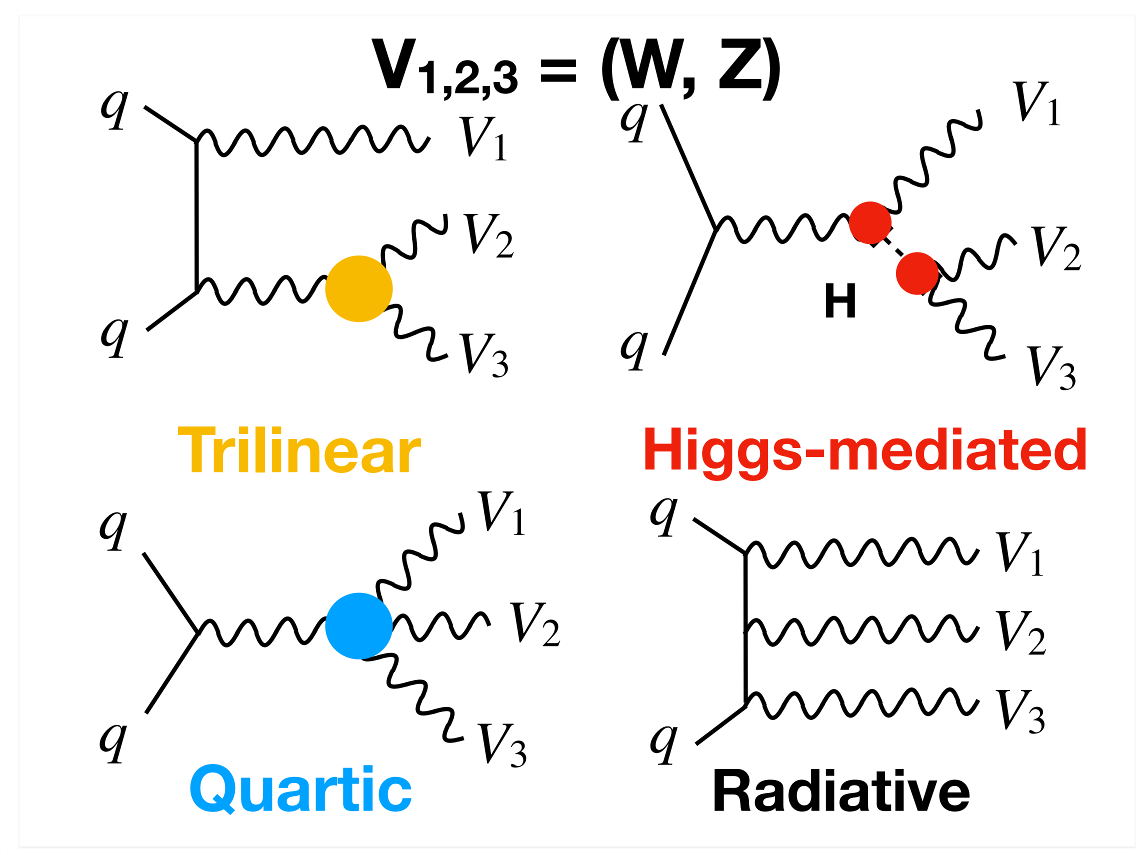
A. M. Sirunyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **125**, 151802 – Published 5 October 2020

Physics See synopsis: Hat Trick Observation for Bosons

Observation of Heavy Tribosons with Run II data

Combined observed significance at 5.7 σ
Observed significance for WWW and WWZ at 3.3 σ and 3.4 σ

- Rich physics content in triboson final states
- Access to various couplings
- Recent result explored leptonic final states, primarily geared toward:
  - **WWW:** same-signed dilepton and trilepton
  - **WWZ:** four leptons
  - **WZZ:** five leptons
  - **ZZZ:** six or more leptons
- Current plan is to explore semi-leptonic final states (at least one gauge boson decays to jets) in CMS



Search for WWW, WWZ, WZZ and ZZZ

EFT Framework

The EFT framework provides a convenient tool to characterize the potential impact of new physics that could exist at scales beyond our current reach

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\lambda^4}\mathcal{O}_j + \cdots$$

- **Trilinear operators are of the form:**

$$\mathcal{O}_W = \epsilon^{abc} W_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{a\mu} \qquad \mathcal{O}_{HD} = \left|\Phi^\dagger (D_\mu \Phi)\right|^2 \qquad \mathcal{O}_{HWB} = \Phi^\dagger \sigma^a \Phi W^a_{\mu\nu} B^{\mu\nu}$$

- **Quartic operators are of the form:**

$$\mathcal{L}_{\text{S},0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi\right] \times \left[(D_\mu \Phi)^\dagger D_\nu \Phi\right]$$

Longitudinal operators

$$\mathcal{L}_{\text{M},0} = Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi\right]$$

Mixed operators

$$\mathcal{L}_{\text{T},0} = Tr\left[W_{\mu\nu}W^{\mu\nu}\right] \times Tr\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$

Transverse operators

Dim-6 operators in SMEFT

- In the most restrictive flavor scenario, there are 59 operators (The SMEFTsim package, theory and tools: Ilaria Brivio et al.)
- Madgraph implementation includes 82 parameters, annotated here: http://nuhep.northwestern.edu/~sapta/param_card.dat
- However, what is relevant for us?
- J. Baglio et al. "An NLO QCD effective field theory analysis of W^+W^- production at the LHC including fermionic operators" have explored the following operators (note includes fermionic operators):

In the past in CMS/ATLAS only gauge boson self interaction operators have been explored

$$\mathcal{O}_{3W} = \epsilon^{abc} W_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{a\mu} \tag{1.6}$$

$$\mathcal{O}_{HD} = |\Phi^\dagger (D_\mu \Phi)|^2 \tag{1.7}$$

$$\mathcal{O}_{HWB} = \Phi^\dagger \sigma^a \Phi W_{\mu\nu}^a B^{\mu\nu} \tag{1.8}$$

$$\mathcal{O}_{HF}^{(3)} = i \left(\Phi^\dagger D_\mu \sigma^a \Phi - (D_\mu \Phi^\dagger) \sigma^a \Phi\right) \bar{f}_L \gamma^\mu \sigma^a f_L \tag{1.9}$$

$$\mathcal{O}_{HF}^{(1)} = i \left(\Phi^\dagger D_\mu \Phi - (D_\mu \Phi^\dagger) \Phi\right) \bar{f}_L \gamma^\mu f_L \tag{1.10}$$

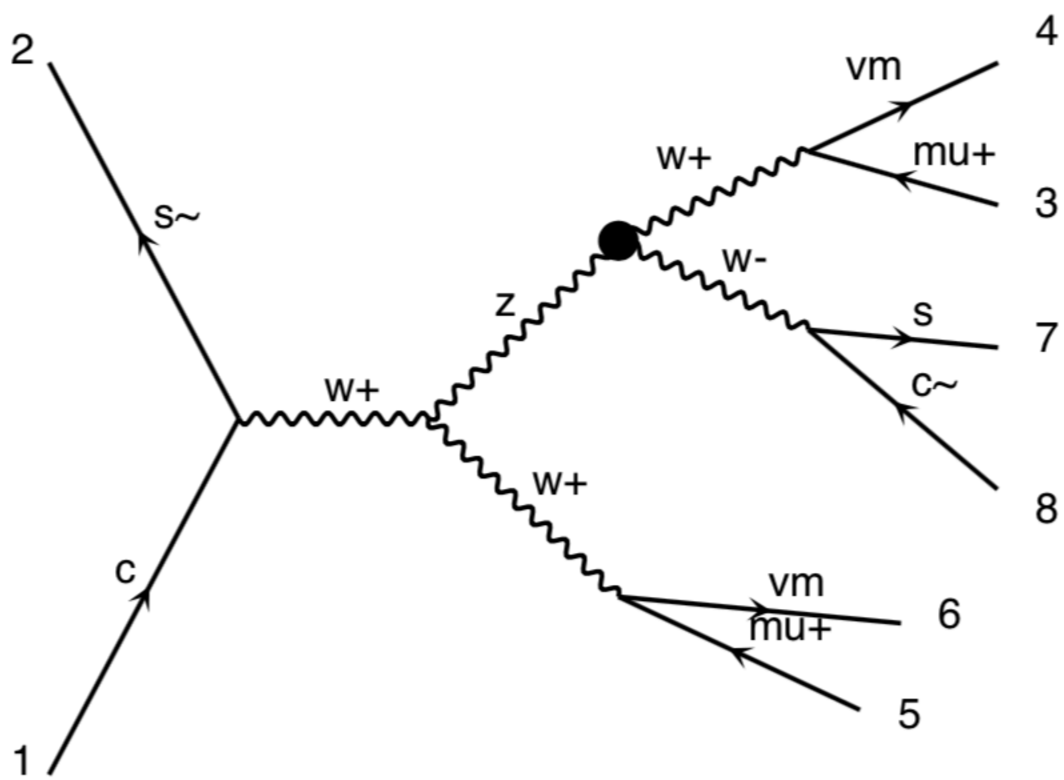
$$\mathcal{O}_{Hf}^{(1)} = i \left(\Phi^\dagger D_\mu \Phi - (D_\mu \Phi^\dagger) \Phi\right) \bar{q}_R \gamma^\mu q_R \tag{1.11}$$

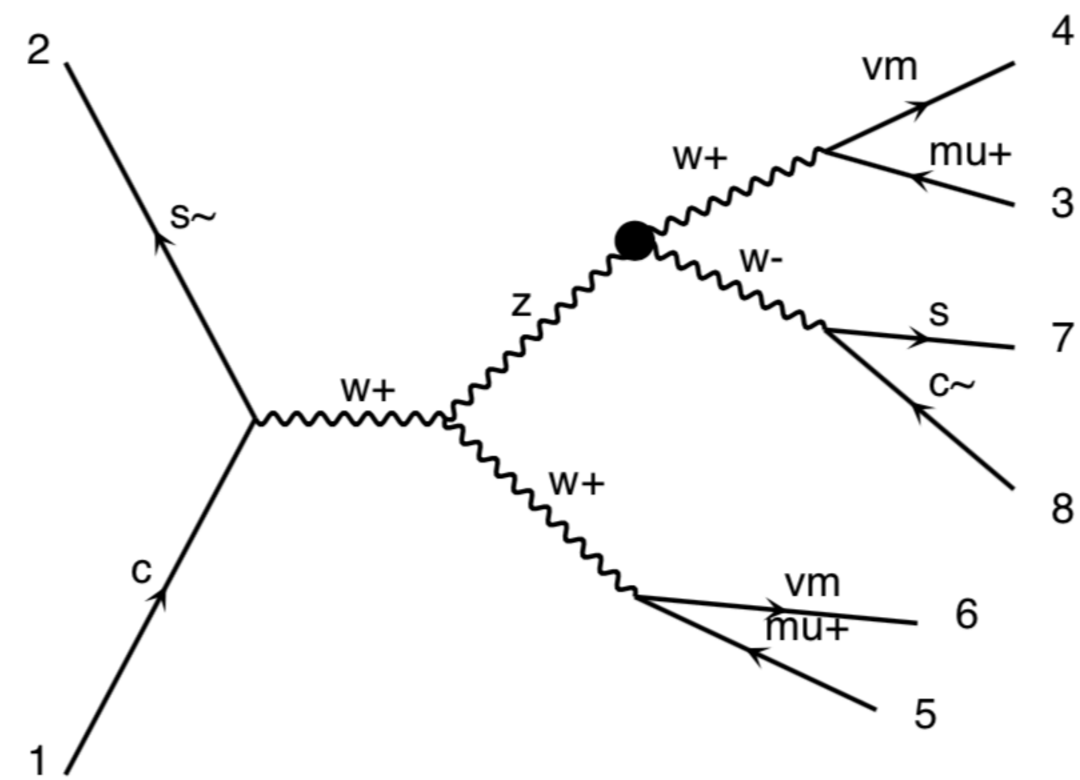
$$\mathcal{O}_{Hud}^{(1)} = i \left(\tilde{\Phi}^\dagger D_\mu \Phi\right) \bar{u}_R \gamma^\mu d_R \tag{1.12}$$

$$\mathcal{O}_{ll} = (\bar{l}_L \gamma^\mu l_L)(\bar{l}_L \gamma_\mu l_L) \tag{1.13}$$

Study was extended to include WZ, ZH and ZZ and extends this set with a few additional operators (http://nuhep.northwestern.edu/~sapta/Dim6Operators.pdf)

A first exploration of dim-6 in triboson final states using SMEFT: Analysis pipeline I



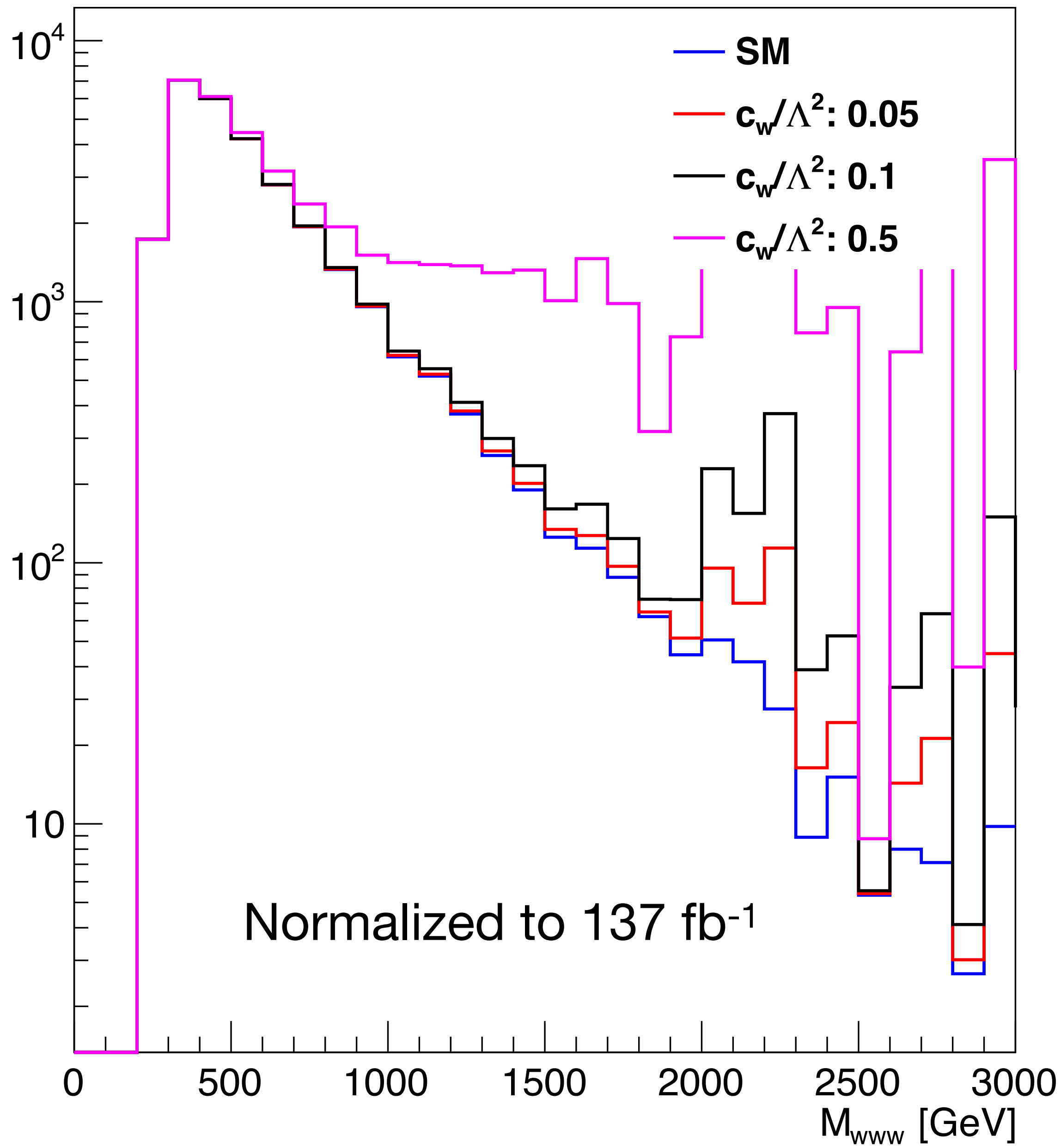


- Generated the following process:

```
generate p p > w+ w+ w- NPcW=1 NP=1, w+ > l+ vl, w- > j j
```

- Madgraph produces diagrams with explicit reference to relevant vertices
- Produced a toy MC sample with the BWCutOff set to 15.0 for the time being (Higgs mediated process absent)
- Can change values in the param card ($\mathbf{c_W}$) (current best limit is at ~1.0, source SMP-18-008) and LambdaSMEFT = 1 TeV

A first exploration of dim-6 in triboson final states using SMEFT: Analysis pipeline II



LHE level study

$$\mathcal{O}_W = \epsilon^{abc} W_{\mu}^{a\nu} W_{\nu}^{b\rho} W_{\rho}^{a\mu}$$

- Started exploration of dim-6 operators with C_w
- Operator mediates gauge boson self interactions (can generate 3 W's on mass shell)
- Used invariant mass of 3 bosons to characterize EFT enhancement
- Plan to extend similar study for operators of interest

RUTGERS UNIVERSITY | NEW BRUNSWICK

Questions we plan on addressing

- How does the VVV process constrain anomalous triple and quartic gauge couplings?
  - Sensitivity to one SMEFT operator assuming others vanish?
- How does the VVV process contribute to the global SMEFT fit?
- Sensitivity to dim-8 operators, given no dim-6 contributions?
- Dim-6 squared contributions versus dim-8?
- Range of EFT validity
- Best observables to characterize impact of EFTs

Similar questions are also being discussed at the LHC EFT Working Group

LOI with some degree of overlap: Global SMEFT Fits Including Theory Uncertainties (J. Gu, H. Kim, I. Lewis, A. Martin, and W. Shepherd)

Additional Material

RUTGERS UNIVERSITY | NEW BRUNSWICK

Open questions

NORTHWESTERN UNIVERSITY

- Which SMEFT scheme to use for our purposes:
  - M_W or α?
  - For reference currently using $U(3)^5$ flavor symmetric case
- Is it correct to specify processes like this:
  - generate p p > w+ w+ w- NPcW=1 NP=1, w+ > l+ vl, w- > j j
  - Will this work for all relevant operators?
- How should one treat purely BSM contributions versus the interference with the SM?
- The full dim-8 bases paper posted on arXiv; generate dim-6 and dim-8 separately?
- Using SMEFT@LO: is this sufficient?
- How does one assess EFT validity?

Open questions with answer based on the discussion with Ilaria

- Which SMEFT scheme to use for our purposes:
  - M_W or α? Use the M_W scheme
  - For reference currently using $U(3)^5$ flavor symmetric case : simplest case, fine to use for now
- Is it correct to specify processes like this:
  - generate p p > w+ w+ w- NPcW=1 NP=1, w+ > l+ vl, w- > j j

Yes because generating something like this: generate p p > w+ w+ w- NPcW==1 NP==1, w+ > l+ vl, w- > j j would not work

Important to remember that Madgraph includes new physics contributions only in the production part of the diagrams. The decay vertices are untouched by the EFT operators.

How should one deal with off-shell components? Is the answer that one needs to generate this process: generate p p > l+ vl l+ vl j j NPcW=1 NP=1

- Will this work for all relevant operators?

Yes, if "activating" each operator one at a time during event generation

Open questions with answer based on the discussion with Ilaria

- How should one treat purely BSM contributions versus the interference with the SM?

Using the reweight feature in Madgraph guarantees that BSM contributions are generated by simple multiplicative factors of the SM expectation. Safe to generate pure BSM vs. interference in Madgraph using the reweighting technique.

- The full dim-8 bases paper posted on arXiv; generate dim-6 and dim-8 separately?

No UFO model that includes both dim-6 and dim-8 operators are expected to arrive anytime soon. Generate the two processes separately because there are two different UFO models.

Open questions with answer based on the discussion with Ilaria

- Using SMEFT@LO: is this sufficient?

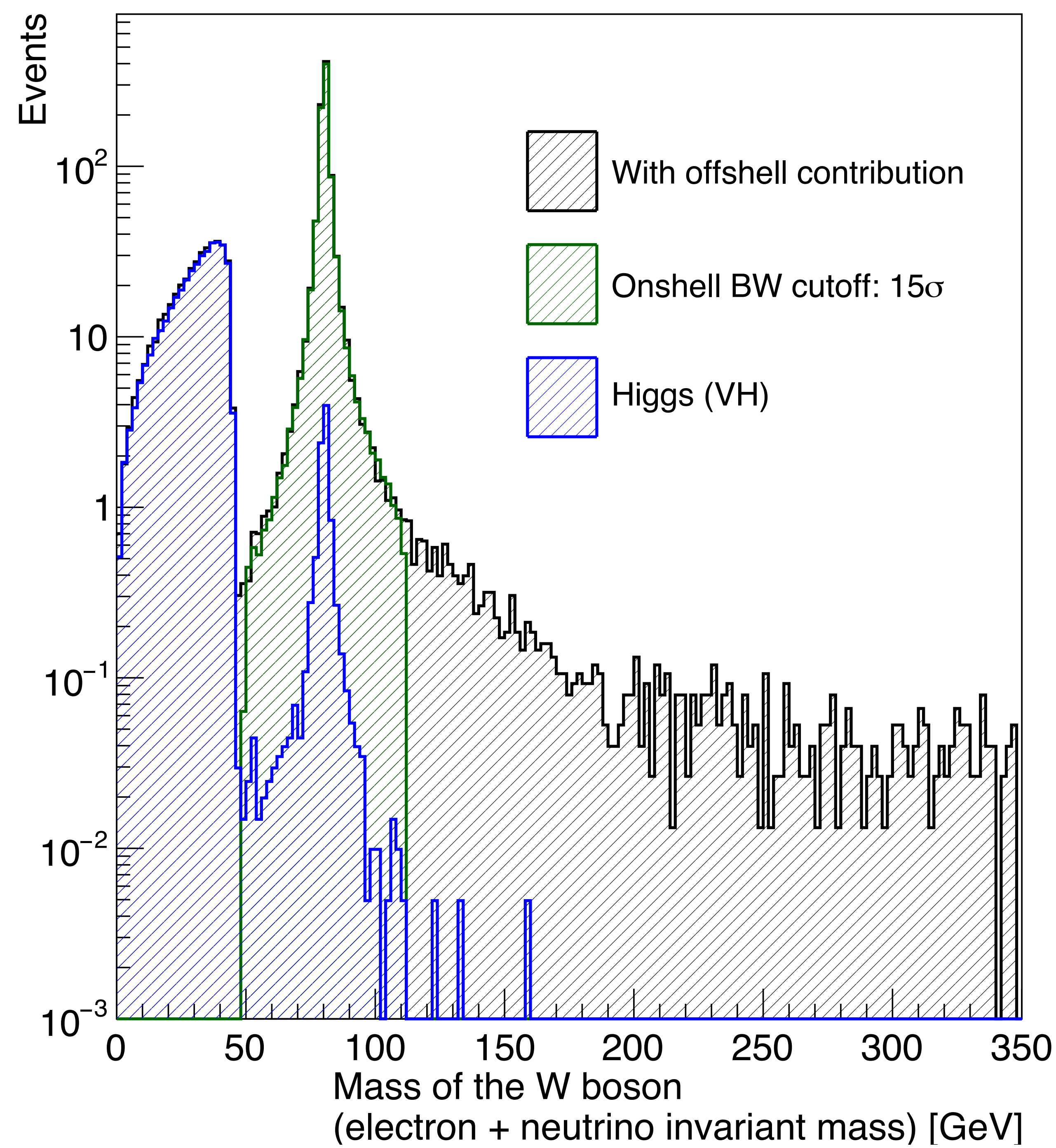
Yes, since triboson physics involves electroweak physics and is not dominated by QCD processes (unlike the top production processes which necessitate the use of SMEFT@NLO)

- How does one assess EFT validity?

To set limits on Wilson Coefficients, it is advisable to not use additional form factors. Dim-6 operators will display less of a runaway feature in the tails of distributions than dim-8 and might not need the inclusion of form factors anyway.

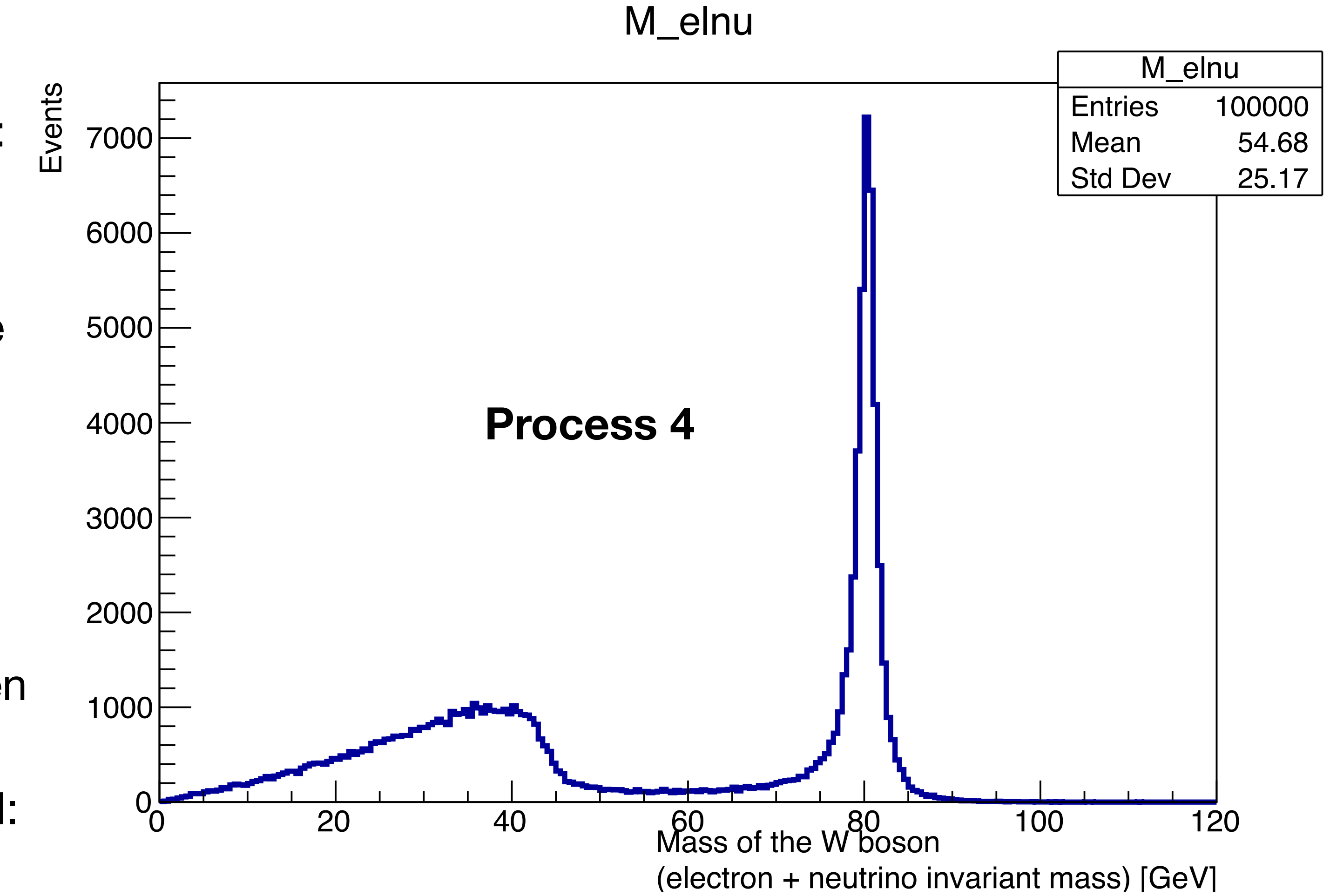
Invariant Mass of $M_{e\nu}$

- `generate p p > w+ w+ w-, w- > e- vl~` **(process 1)**
- `generate p p > w+ w+ e- vl~` **(process 2)**
- `generate p p > w+ h,(h > w+ w-, w- > e- vl~)` **(process 3)**



Why does the invariant mass ($M_{e\nu}$) peak at the lower masses most of the time?

- Should there not a 50% occupancy in the lower mass region (the off-shell W) and a 50% occupancy at 80.4 GeV (pole mass of the W)?
- The answer lies in the way the process was generated:
    - `generate p p > w+ h,(h > w+ w-, w- > e- vl~)` **(process 3)**
    - This syntax in Madgraph implies that only one W is off shell (the one that was decayed)
    - The undecayed W is generated at the pole mass
    - In this scenario, given that one W was generated at the pole mass, almost 100% of the time the other W is off-shell as can be seen on the previous slide
- To finally verify that this is indeed the case, I generated:
    - `generate p p > w+ h,(h > w+ w-, w- > e- vl~, w+ > e+ vl)` **(process 4)**
    - In this case, I get back the 50% probabilities of each of the Ws



Integral between 0-50 GeV : 49092

Integral between 50-90 GeV: 50505

Conclusion: to reconstruct the full $M_{e\nu}$ spectrum, the treatment on the previous slide appears correct

Dim-6 Operators

	Warsaw Basis
c_{1W}	$2M_W^2\sqrt{G_F\sqrt{2}}\left\{\frac{v^2}{\Lambda^2}\left(C_{H\Box}-\frac{1}{4}C_{HD}\right)+\frac{\delta M_W^2}{M_W^2}+\frac{\delta G_F}{2G_F}\right\}$
c_{1Z}	$2M_Z^2\sqrt{G_F\sqrt{2}}\left\{\frac{v^2}{\Lambda^2}\left(C_{H\Box}+\frac{3}{8}C_{HD}+s_Wc_WC_{HWB}\right)+\frac{\delta M_Z^2}{M_Z^2}+\frac{\delta G_F}{2G_F}\right\}$
c_{3W}	$\frac{vC_{HW}}{\Lambda^2}$
c_{3Z}	$\frac{v}{\Lambda^2}\left(c_W^2C_{HW}+s_W^2C_{HB}+s_Wc_WC_{HWB}\right)$
d_{1Z}^{Ru}	$\frac{2M_Z}{\Lambda^2}C_{Hu}$
d_{1Z}^{Lu}	$\frac{2M_Z}{\Lambda^2}\left(C_{Hq}^{(1)}-C_{Hq}^{(3)}\right)$
d_{1Z}^{Rd}	$\frac{2M_Z}{\Lambda^2}C_{Hd}$
d_{1Z}^{Ld}	$\frac{2M_Z}{\Lambda^2}\left(C_{Hq}^{(1)}+C_{Hq}^{(3)}\right)$
d_{1W}^{R}	$-\sqrt{2}\frac{M_W}{\Lambda^2}C_{Hud}$
d_{1W}^{L}	$-2\sqrt{2}\frac{M_W}{\Lambda^2}C_{Hq}^{(3)}$

TABLE III: Anomalous Higgs gauge boson couplings in the Warsaw basis .

https://arxiv.org/pdf/2003.07862.pdf

Use https://arxiv.org/pdf/1008.4884.pdf to get explicit form of the operator

Dim-6/8 Operators: Technical challenges

- Samples are often generated with the following syntax:
  - `generate p p > w w w [QCD]`
  - w decayed in Madspin
- The following syntax:
  - `generate p p > l vl l vl j j [QCD]` is extremely computationally intensive
- Model parameter reweighting (aTGC/aQGC) at NLO with Madspin does not work out of the box currently
- Area of active work in GEN
- Currently works for specific cases with aTGCs
- Goal is to enable feature for all cases with aTGCs/aQGCs

RUTGERS UNIVERSITY | NEWARK

Observation of Heavy Tribosons with Run II data

Northwestern University

- Triboson (VVV) production **observed for the first time!**
- Observed significance for **WWW and WWZ at 3.3 σ and 3.4 σ**

Process	Observed (expected) significance
WWW	**3.3** (3.1)
WWZ	**3.4** (4.1)
WZZ	**1.7** (0.7)
ZZZ	**0.0** (0.9)
Combined	**5.7** (5.9)