Hints of new physics from multi-lepton anomalies at the LHC

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Motivations:

The SM is clearly incomplete (both theoretically…)

- Dark Matter
- Flavour puzzle
- Hierarchy problems
- Strong CP problem

And many candidates have been proposed as unifications theories

Motivations:

… and experimentally (?)

- Recently, anomalies have been encountered in high energies experiments
- Both ATLAS and CMS cannot give reasons to invariant transverse mass inconsistencies
- Leptonic channels are well understood and the detecting apparatuses well established

Bottom-up approach:

1. Come up with independent model responsible for each different anomalies

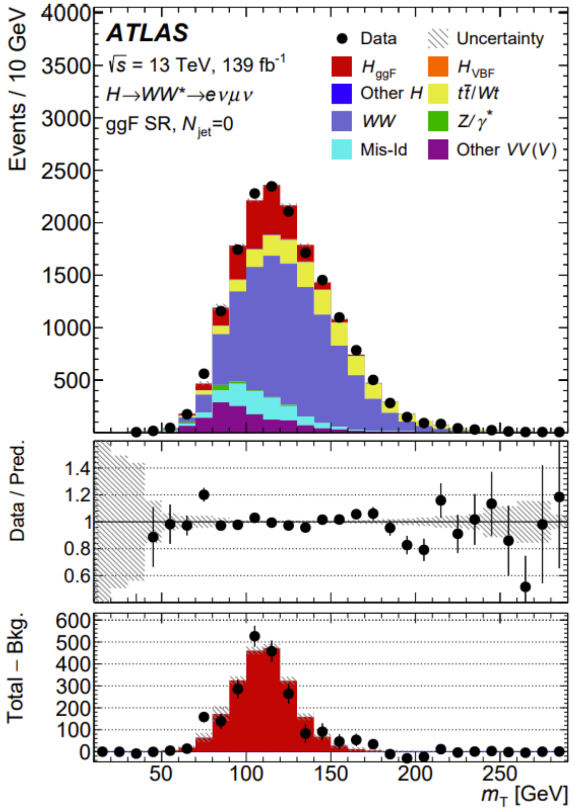
2. Adding the minimal content to the SM (conservative)

3. Carefully test the signature (via simulation and statistical analyses)

4. Combine them in a single unified model

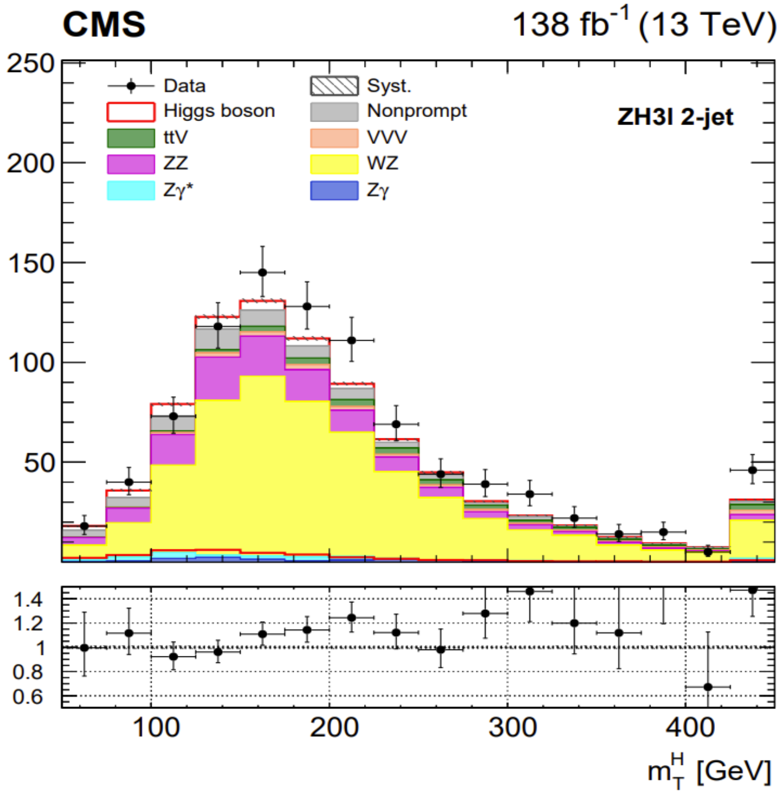
Examples:

gg-fusion, WW decays
DFOS leptons



ATLAS: arXiv:2207.00338v1 [hep-ex] 1 Jul 2022

gg-fusion, ZW decays
SFOS leptons



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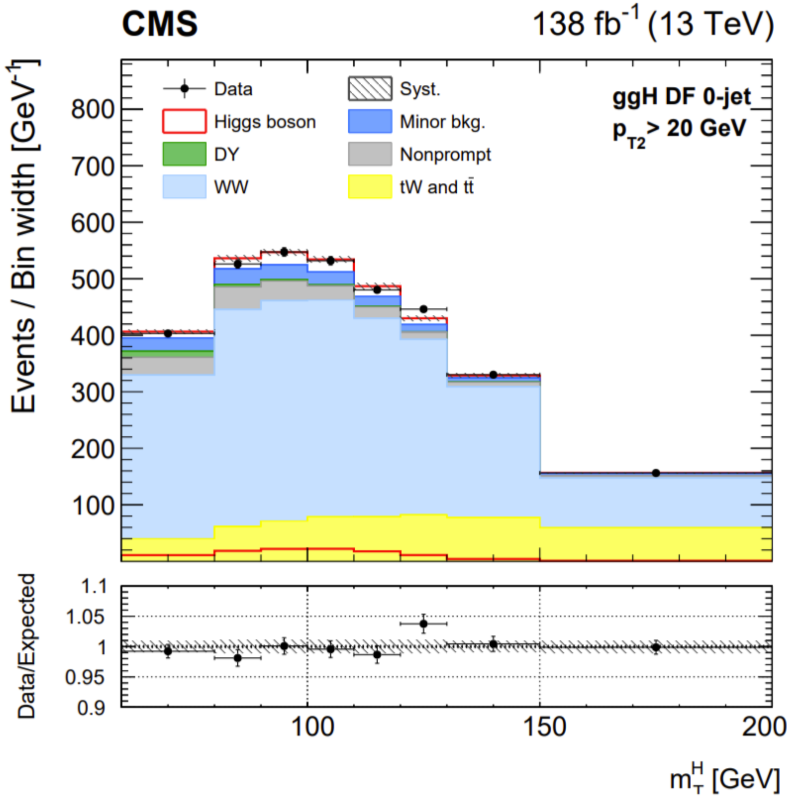

CMS:arXiv:2206.09466v1 [hep-ex] 19 Jun 2022

adapted from Bruce Garcia Mellado
https://indico.cern.ch/event/1216277/timetable/#20230111

Anatomy of the multi-lepton anomalies

Final state	Characteristic	Dominant SM process	Significance
l^+l^- + jets, b-jets	m_{ll}<100 GeV, dominated by 0b-jet and 1b-jet	tt+Wt	>5σ
l^+l^- + full-jet veto	m_{ll}<100 GeV	WW	~3σ
$l^\pm l^\pm$ & $l^\pm l^\pm l$ + b-jets	Moderate H_T	ttW, 4t	>3σ
$l^\pm l^\pm$ & $l^\pm l^\pm l$ et al., no b-jets	In association with h	Wh, (WWW)	4.2σ
$Z(\to l^+l^-)+l$	p_{TZ}<100 GeV	ZW	>3σ

Anomalies cannot be explained by mismodelling of a particular process, e.g. ttbar production alone.

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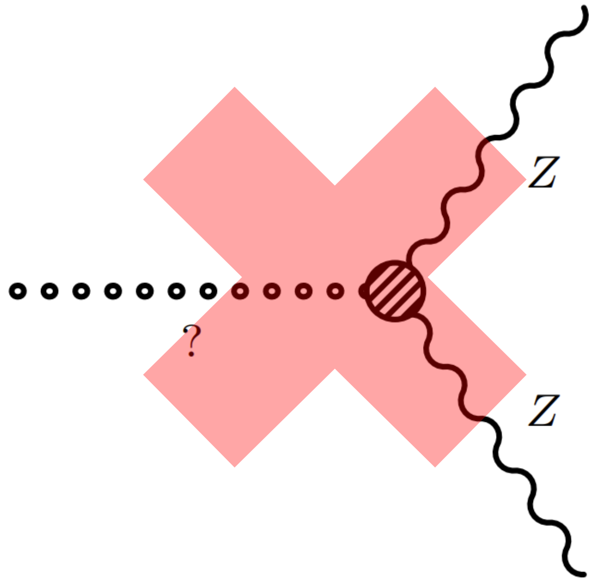
$Z(\rightarrow l^+l^-)+l$	p_{TZ}<100 GeV	ZW	>3σ

But not ZZ

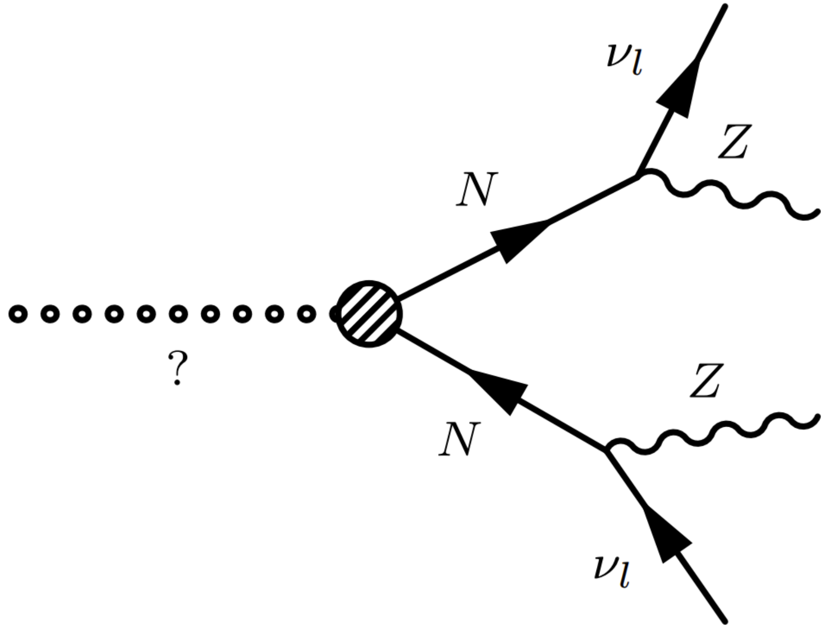
Anomalies cannot be explained by mismodelling of a particular process, e.g. ttbar production alone.

1st idea:

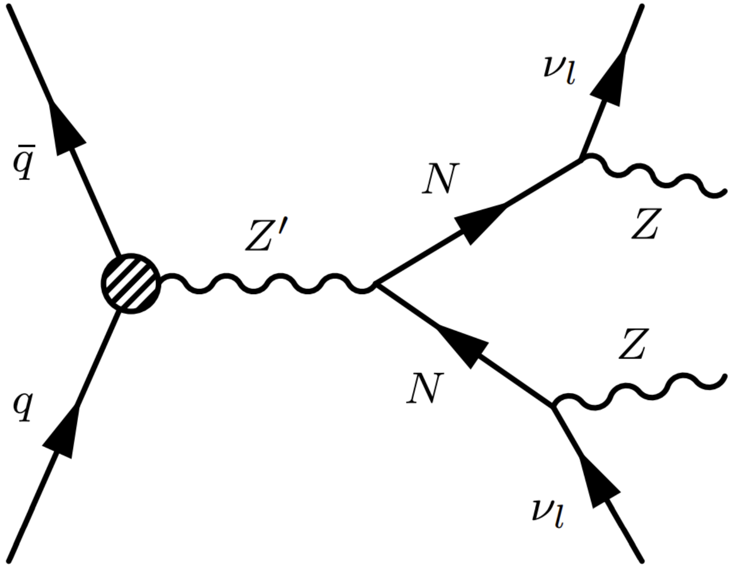
Mechanism to avoid mass reconstruction of the particle decaying to two Z bosons



Adding missing energy to ZZ decays



1st model (building): vector 2HDM + S * + $U(1)'$ gauged



$SU(3) \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)'$

$$\Phi_1 \in (\ 1,\ 2,\ \frac{1}{2}, \boxed{-1})$$
$$\Phi_2 \in (\ 1,\ 2,\ \frac{1}{2}, \boxed{0})$$
$$\Phi_s \in (\ 1,\ 1,\ 0, \boxed{1})$$
$$N \in (\ 1,\ 1,\ 0, \boxed{-1})$$

$$\mathcal{L}_N = \overline{N} i \not{D} N - M_N \overline{N} N - Y_\nu \overline{L}\, \widetilde{\Phi}_1\, N_R$$

$$\begin{aligned} V_{pot} = & -\mu_1 \Phi_1^\dagger \Phi_1 + \lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 - \mu_2 \Phi_2^\dagger \Phi_2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 \\ & - \mu_s \Phi_s \Phi_s^* + \lambda_s \left(\Phi_s \Phi_s^*\right)^2 \\ & + \lambda_d \left(\Phi_2^\dagger \Phi_2\right)\left(\Phi_1^\dagger \Phi_1\right) + \lambda_m \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) \\ & + \lambda_{1s} \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_s \Phi_s^*\right) + \lambda_{2s} \left(\Phi_2^\dagger \Phi_2\right)\left(\Phi_s \Phi_s^*\right) + \mathcal{A} \left(\Phi_1^\dagger \Phi_2 \Phi_s^* + \text{h.c.}\right) \end{aligned}$$

1st model (building): field content

$SU(3)\otimes SU(2)_L\otimes U(1)_Y\otimes U(1)'$

$$\Phi_1 \in (\ 1,\ \ 2,\ \ \frac{1}{2},\ -1\ )$$

$$\Phi_2 \in (\ 1,\ \ 2,\ \ \frac{1}{2},\ \ 0\ )$$

$$\Phi_s \in (\ 1,\ \ 1,\ \ 0,\ \ 1\ )$$

$$N \in (\ 1,\ \ 1,\ \ 0,\ -1\ )$$

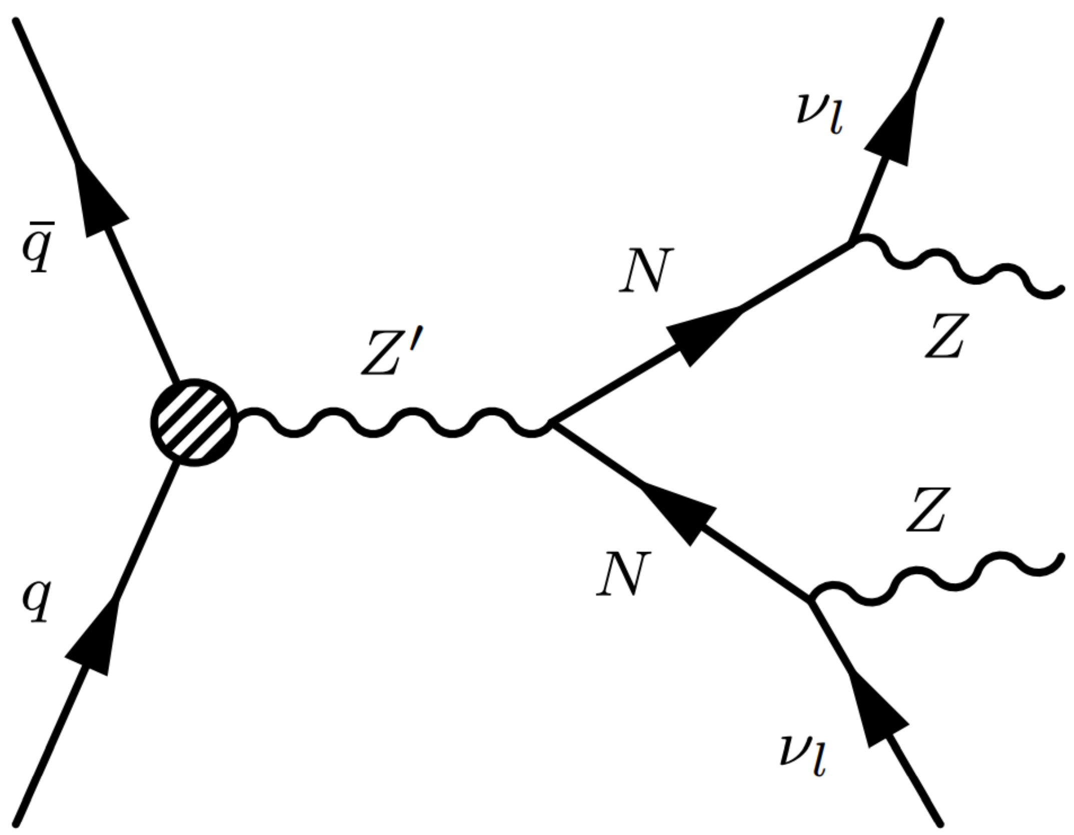
→ 2 massive charged scalars: **H+/H-**
1 CP-odd massive scalar **A**
1 CP-even massive scalar (heavy higgs): **H**

→ SM: masses of SU(2) bosons, higgs

→ 1 massive CP-odd real scalar **S**
Mass of **Z'**

→ Vector-like neutrinos **N** (both chirality charged the same under U(1))

1^{st} model: analyses



- MadGraph simulation (FeynRules, Pyhtia8, Delphes ….)
- Performing the cuts in C++ (ROOT, MadAnalysis)
- Post-processing (smearing, shift ….)
- Statistical analyses to extract the significance (likely-hood ratio, chi squared ….)

Possible extension?

Extending the symmetry from $U(1)'$ to $SU(2)'$ → Additional W^+/W^- bosons

- Left-Right symmetric model
- Recover CP-symmetry at higher energies
- Insight in V-A weak structure
- Possible stage of other UV-completion

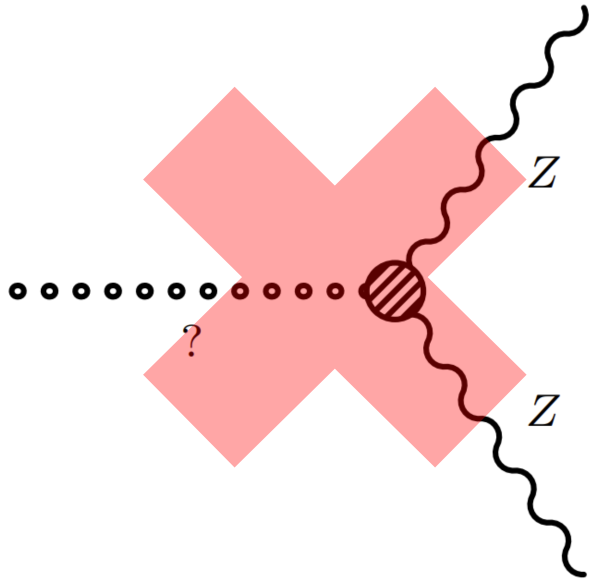
$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

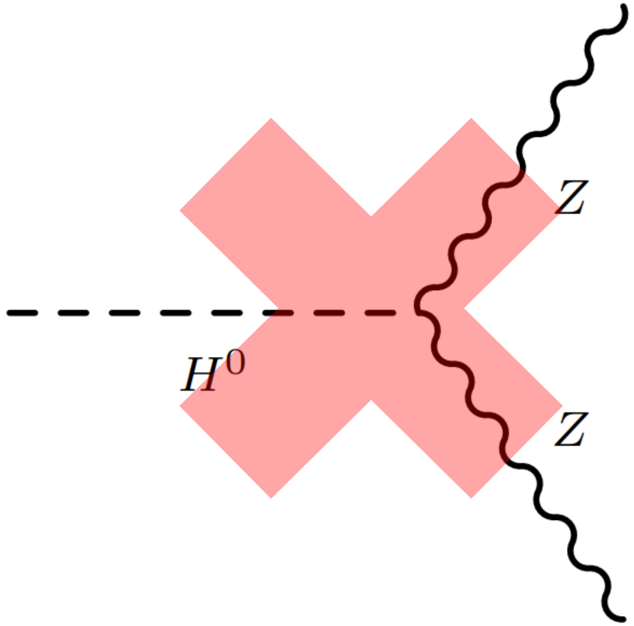
↓

$$SU(2)_L \otimes U(1)_Y$$

2nd idea:

Mechanism to avoid mass reconstruction of the particle decaying to two Z bosons → Avoiding this decay at tree level

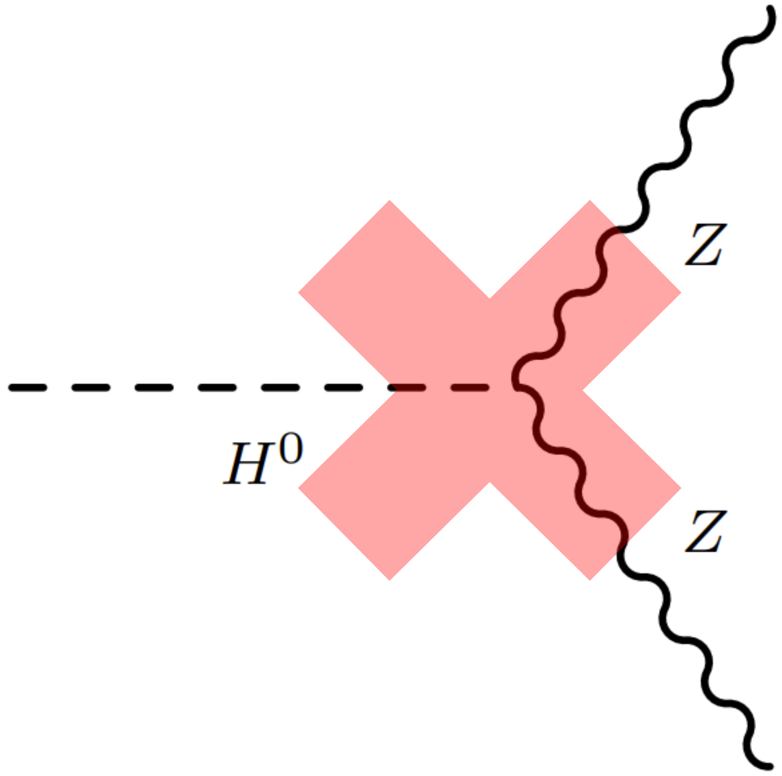




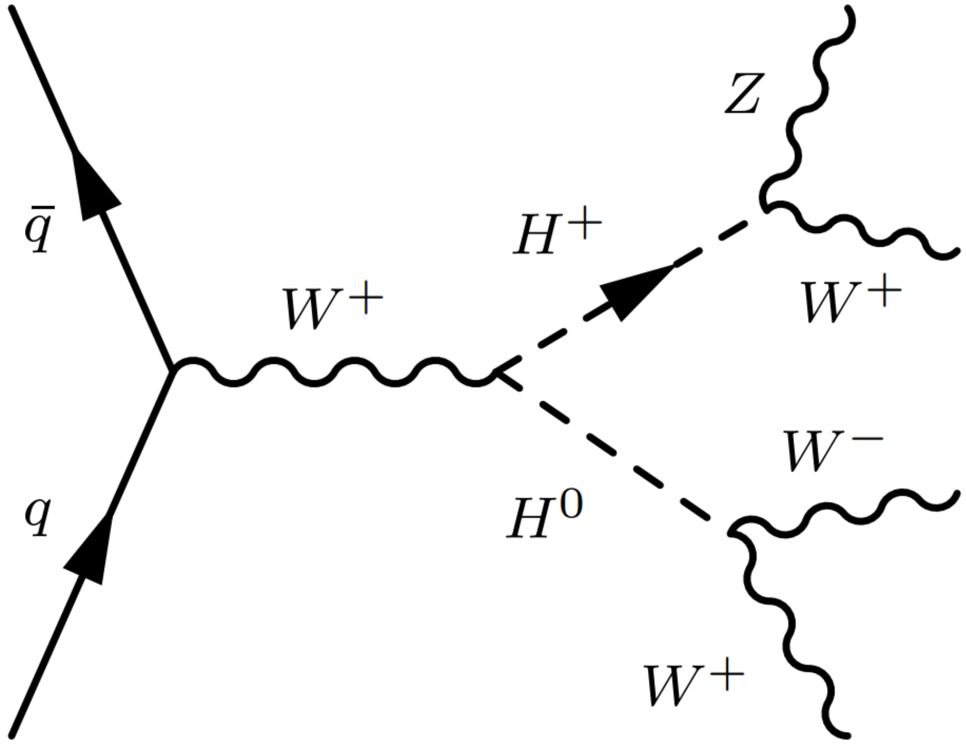
2^{nd} model: scalar scalar triplet with Y=0

- Triplet lives in the same representation of the $SU(2)_L$ gauge bosons (adjoint)
- It couples via the structure constant of SU(2), namely ε_{ijk}.
- Diagonal component of the triplet (H^0) couples to the diagonal component of $SU(2)_L$ with two equal indices ($\varepsilon_{i33} = 0$)
- Hence, this coupling is naturally prevented
- $Y = 0$ guarantees no production of doubly charged W^{++}/W^{--}

$$\Phi = \begin{bmatrix} H^- \\ H^0 + \frac{v_T}{\sqrt{2}} \\ H^+ \end{bmatrix}^{SU(3) \otimes SU(2)_L \otimes U(1)_Y} \in (1, 3, 0)$$



2nd model: analysis



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Fine!

1st model (building): vector boson 2HDM + S * + $U(1)'$ gauged

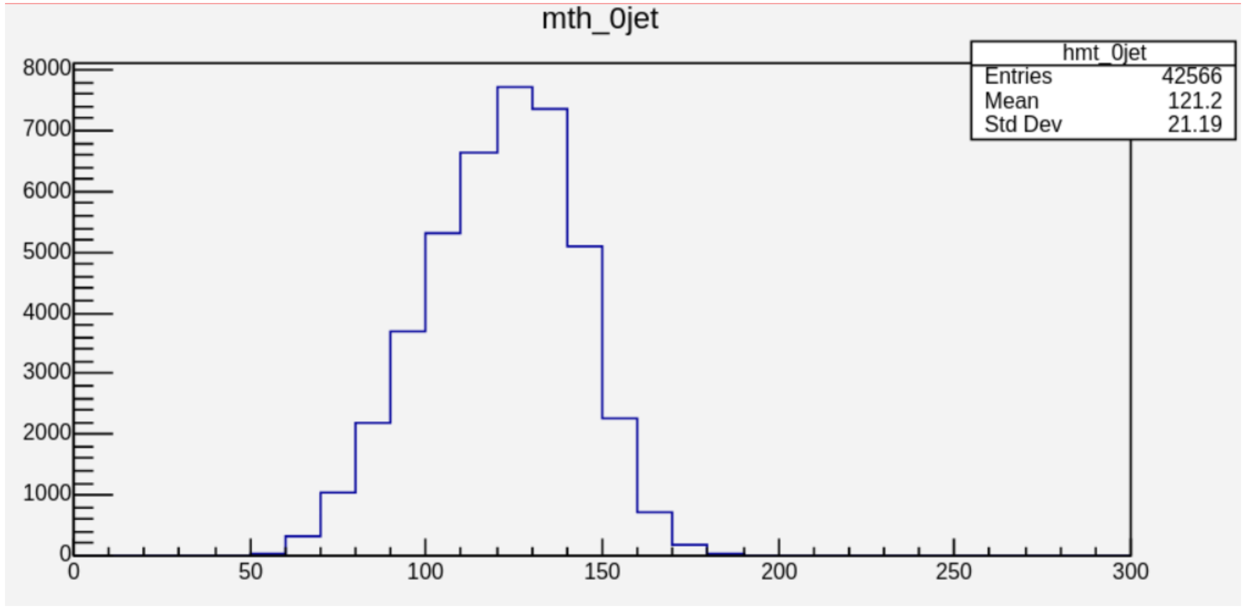
1. Coupling to heavy neutrinos → 1. $U(1)'$ gauged

2. Mixing with neutrinos but not with rest of SM → 2. Interaction with Yukawa sector with another $SU(2)$ scalar doublet

3. Anomalies at specific transverse mass resonance → 3. Massive Z', namely SBB over additional (complex) scalar

Some very preliminary plots

ATLAS, WW search, mS=150 GeV



CMS, WW search, mS=95 GeV