Triboson Excesses in light of a Real Higgs Triplet Model

Srimoy Bhattacharya
School of Physics and Institute for Collider Particle Physics
University of the Witwatersrand, Johannesburg, South Africa

An Ongoing Work in collaboration with
Siddharth P. Maharathy, Mukesh Kumar, Andreas Crivellin, Rachid Mazini, Bruce Mellado

Professor Yaquan Fang

Renowned Physicist & Esteemed Collaborator

(1974 - 2025)

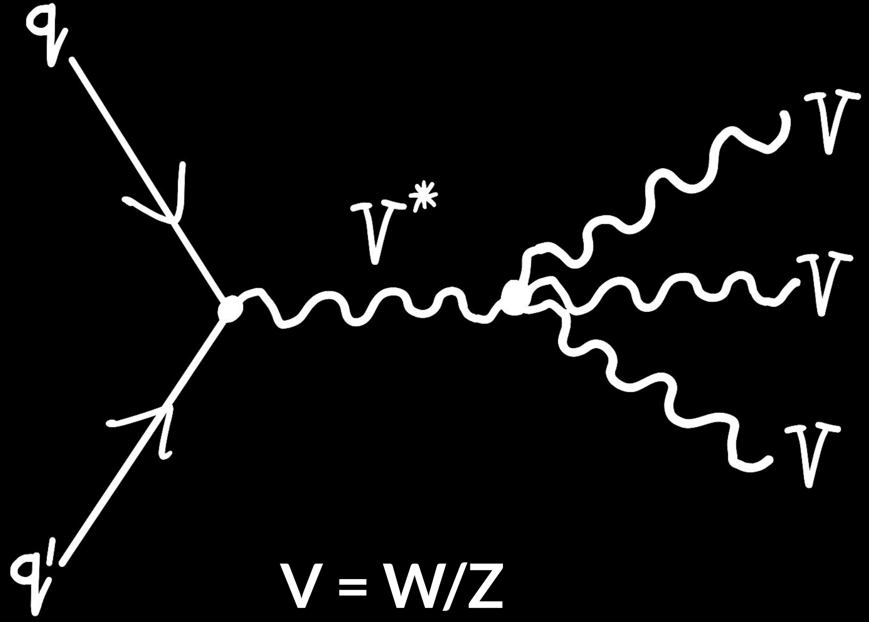
It is with deep sadness that we acknowledge the passing of our collaborator and friend, Prof. Yaquan Fang.

We gratefully remember Prof. Fang's invaluable contributions to our ongoing research on the 152 GeV scalar excess. His deep insights, collaborative spirit, and scientific excellence continue to inspire us. Beyond the science, he will be remembered for his kindness, humility, and dedication.

In memory and gratitude.

Outline

- Introduction
- Motivation
- Model
- Analysis
- Conclusion



Introduction

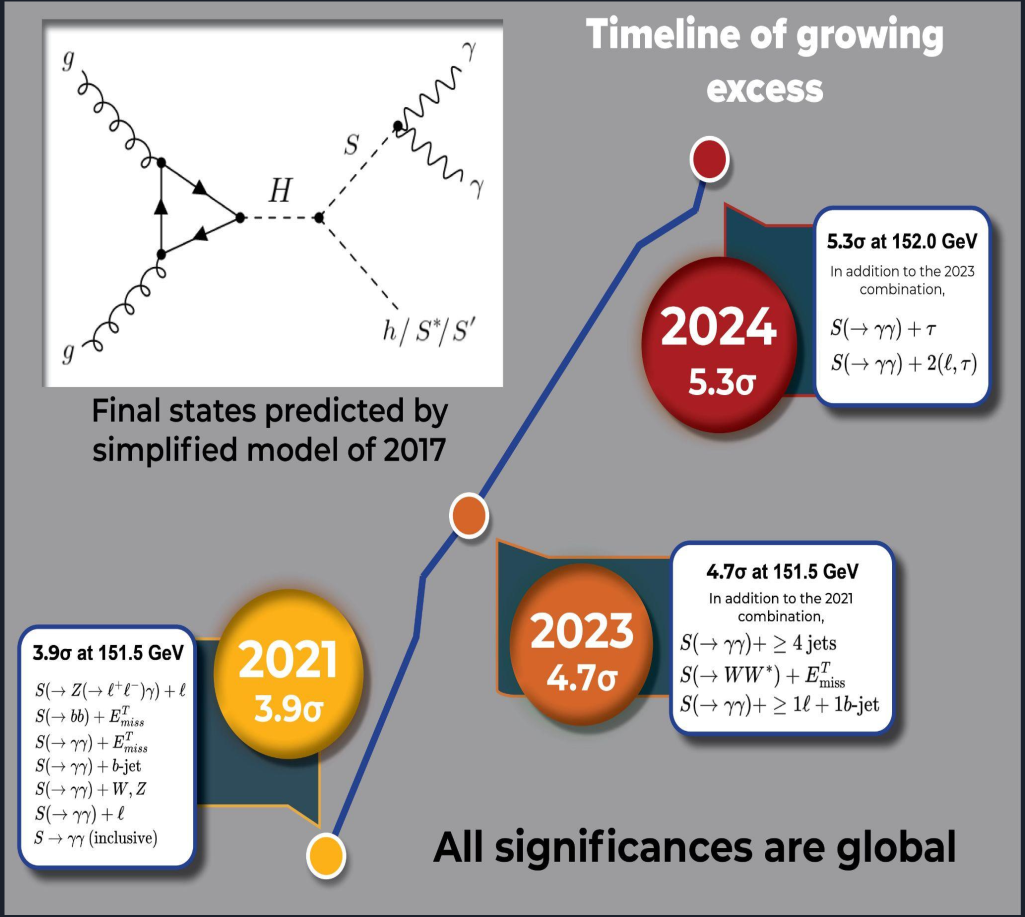
- The discovery of the Brout-Englert-Higgs boson at the LHC by ATLAS and CMS has opened a new chapter in particle physics.
- Does not exclude the existence of additional scalar bosons.
- "Multi-lepton anomalies" emerged as deviations from the SM predictions in several analyses of multi-lepton final states from ATLAS and CMS.
- These Multi-lepton anomalies consistently predict a possible new resonance with a mass around **150 ± 5 GeV**.
- Recent measurements have reported excesses in diphoton, Zγ, and WW final states, suggesting the presence of a new Higgs-like scalar particle S with a mass around 152±1 GeV.

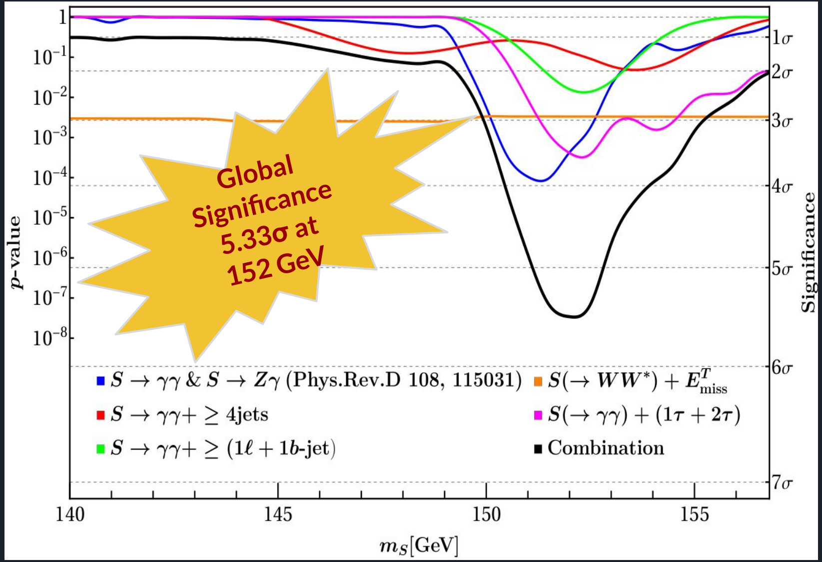
Anatomy of Multi-lepton Anomalies (2024)

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, ttZ/tWZ	>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

Ref. Anomalies in particle physics and their implications for physics beyond the standard model (**Nature Reviews Physics volume 6, pages 294–309 (2024)**) by Andreas Crivellin & Bruce Mellado)

Current Status

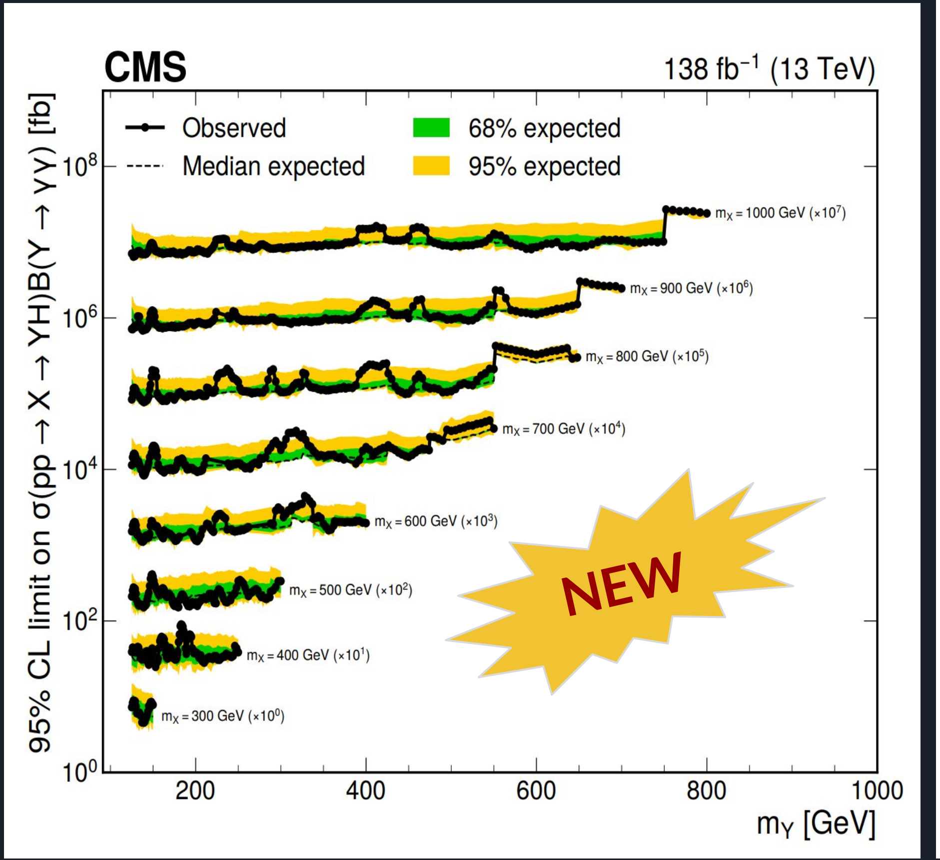




Selected References :

- J.Phys. G46 (2019) no.11, 115001
- JHEP 1910 (2019) 157
- Chin.Phys.C 44 (2020) 6, 063103
- Physics Letters B 811 (2020) 135964
- Eur.Phys.J.C 81 (2021) 365
- PhysReVD.108.115031 (2023)
- Phys.Rev.D 108 (2023) 3, 035026
- Nature Reviews Physics, Volume 6. P-294-309 (2024)

New Result from CMS (2506.23012)



arXiv:2506.23012v1 [hep-ex] 28 Jun 2025

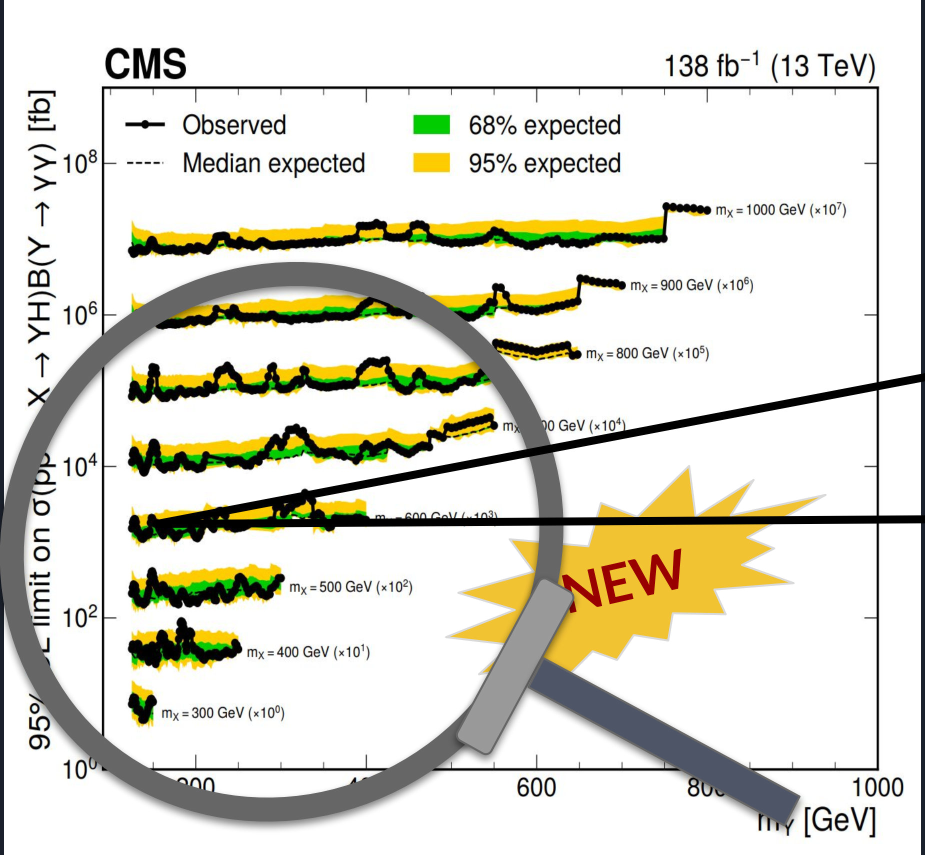
Search for the nonresonant and resonant production of a Higgs boson in association with an additional scalar boson in the $\gamma\gamma\tau\tau$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

The results of a search for the production of two scalar bosons in final states with two photons and two tau leptons are presented. The search considers both nonresonant production of a Higgs boson pair, HH, and resonant production via a new boson X which decays either to HH or to H and a new scalar Y. The analysis uses up to 138 fb^{-1} of proton-proton collision data, recorded between 2016 and 2018 by the CMS experiment at the LHC at a center-of-mass energy of 13 TeV. No evidence for signal is found in the data. For the nonresonant production, the observed (expected) upper limit at 95% confidence level (CL) on the HH production cross section is set at 930 (740) fb, corresponding to 33 (26) times the standard model prediction. At 95% CL, HH production is observed (expected) to be excluded for values of κ_λ outside the range between −12 (−9.4) and 17 (15). Observed (expected) upper limits at 95% CL for the X → HH cross section are found to be within 160 to 2200 (200 to 1800) fb, depending on the mass of X. In the X → Y($\tau\tau$)H($\gamma\gamma$) search, the observed (expected) upper limits on the product of the production cross section and decay branching fractions vary between 0.059–1.2 fb (0.087–0.68 fb). For the X → Y($\gamma\gamma$)H($\tau\tau$) search the observed (expected) upper limits on the product of the production cross section and Y → $\gamma\gamma$ branching fraction vary between 0.69–15 fb (0.73–8.3 fb) in the low Y mass search, tightening constraints on the next-to-minimal supersymmetric standard model, and between 0.64–10 fb (0.70–7.6 fb) in the high Y mass search.

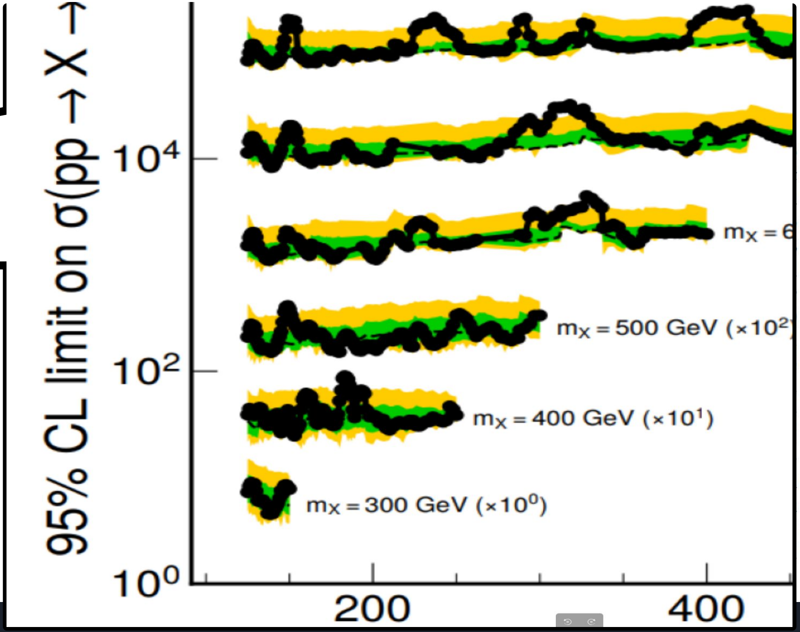
New Result from CMS (2506.23012)




Search for the nonresonant and resonant production of a Higgs boson in association with an additional scalar boson in the $\gamma\gamma\tau\tau$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

arXiv:2506.23012v1 [hep-ex] 28 Jun 2025



Experimental Inputs

Center of Mass Energy	Process	Observed Cross section (fb)	Expected Cross section (fb)
$\sqrt{s} = 13$ TeV	WWZ	$442 \pm 94(\text{stat.})^{+60}_{-52}(\text{syst.})$ [1] $300^{+120}_{-100}(\text{stat.})^{+50}_{-40}(\text{syst.})$ [2] $280^{+120}_{-110}(\text{stat.})^{+40}_{-30}(\text{syst.})$ [3]	329.0 [1] 354.0 [2] 373.0 [3]
	WZZ	$200^{+111}_{-91}(\text{stat.})^{+65}_{-37}(\text{syst.})$ [1] $200^{+160}_{-110}(\text{stat.})^{+70}_{-20}(\text{syst.})$ [2]	93.1 [1] 91.6 [2]
	WWW	$820 \pm 100(\text{stat.}) \pm 80(\text{syst.})$ [4]	511.0 ± 18 [4]
	tWZ	$248 \pm 38(\text{stat.}) \pm 35(\text{syst.})$ [5]	136.0^{+9}_{-8} [5]
$\sqrt{s} = 13.6$ TeV	WWZ	$700^{+270}_{-230}(\text{stat})^{+90}_{-60}(\text{syst})$ [3]	402 [3]
	tWZ	$242 \pm 62(\text{stat.}) \pm 46(\text{syst.})$ [5]	147.8^{+10}_{-9} [5]

[1] ATLAS Collaboration, G. Aad et al. arXiv:2412.15123 [hep-ex].
[2] CMS Collaboration, A. M. Sirunyan et al., Phys. Rev. Lett. 125 no. 15, (2020) 151802, arXiv:2006.11191 [hep-ex].
[3] CMS Collaboration, arXiv:2505.20483 [hep-ex].
[4] ATLAS Collaboration, G. Aad et al.Phys. Rev. Lett. 129 no. 6,(2022) 061803, arXiv:2201.13045 [hep-ex].
[5] CMS Collaboration, “Observation of tWZ production at the CMS experiment,”. CMS-PAS-TOP-24-009

Motivation

- **Interestingly, no excess has been observed in the ZZ channel**, despite clear hints in **diphoton, Zγ, and WW** final states near **m_S≈152±1 GeV**.

- This **pattern is difficult to accommodate** within models involving only **Higgs doublet extensions**, where a scalar typically couples to both WW and ZZ at tree level.

In contrast, the **Real Higgs Triplet Model (RHT)** — featuring a **triplet scalar with hypercharge Y=0 - naturally explains the absence** of a signal in the ZZ channel:

- The scalar S (triplet-like) **does not couple to a pair of Z bosons at tree level**, due to the structure of the custodial symmetry.

- Leads to positive shift in the W-mass at tree-level, as preferred by the CDF-II measurement.

Ref :CDF Collaboration, T. Aaltonen et al., "High-precision measurement of the W boson mass with the CDF II detector," Science 376 no. 6589, (2022) 170–176.

Description of the Real Higgs Triplet Model

- The Higgs sector of the real Higgs triplet model (RHT) is composed of the SM Higgs $SU(2)_L$ doublet (Φ) with Y = 1/2 (in our convention).

- The Higgs triplet (Δ) with Y = 0 transforming in the adjoint representation of $SU(2)_L$

$$\Phi = \begin{pmatrix} h_\Phi^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + h_\Phi^0 + iG^0) \end{pmatrix}$$

$$\Delta = \frac{1}{2}\begin{pmatrix} v_\Delta + h_\Delta^0 & \sqrt{2}h_\Delta^+ \\ \sqrt{2}h_\Delta^- & -(v_\Delta + h_\Delta^0) \end{pmatrix}$$

- The most general scalar potential of the RHT model is (all couplings can be assumed to be real)

$$V = -\mu_\phi^2\,\Phi^\dagger\Phi + \frac{\lambda_\phi}{4}(\Phi^\dagger\Phi)^2 - \mu_\Delta^2\,\mathrm{Tr}(\Delta^\dagger\Delta) + \frac{\lambda_\Delta}{4}[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + A\,\Phi^\dagger\Delta\Phi + \lambda_{\phi\Delta}\,\Phi^\dagger\Phi\cdot\mathrm{Tr}(\Delta^\dagger\Delta),$$

Ref: Anatomy of real Higgs Triplet model
JHEP 04 (2025) 003
arXiV: 2411.18618[hep-ph]

Description of the Real Higgs Triplet Model

- The Higgs sector of the real Higgs triplet model (RHT) is composed of the SM Higgs $SU(2)_L$ doublet (Φ) with Y = 1/2 (in our convention).

- The Higgs triplet (Δ) with Y = 0 transforming in the adjoint representation of $SU(2)_L$

v_Φ and v_Δ are the respective vacuum expectation values (VEVs)

$h^0_{\Phi,\Delta}$ are real scalar fields

$$\Phi = \begin{pmatrix} h_\Phi^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + h_\Phi^0 + iG^0) \end{pmatrix} \qquad \Delta = \frac{1}{2}\begin{pmatrix} v_\Delta + h_\Delta^0 & \sqrt{2}h_\Delta^+ \\ \sqrt{2}h_\Delta^- & -(v_\Delta + h_\Delta^0) \end{pmatrix}$$

- The most general scalar potential of the RHT model is (all couplings can be assumed to be real)

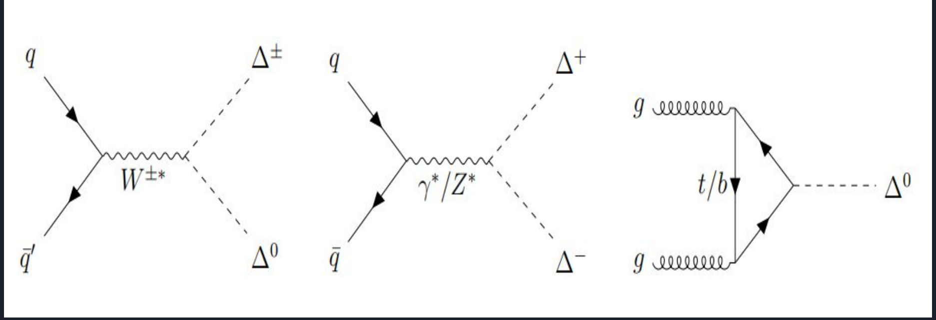
$$V = -\mu_\phi^2\,\Phi^\dagger\Phi + \frac{\lambda_\phi}{4}(\Phi^\dagger\Phi)^2 - \mu_\Delta^2\,\mathrm{Tr}(\Delta^\dagger\Delta) + \frac{\lambda_\Delta}{4}[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + A\,\Phi^\dagger\Delta\Phi + \lambda_{\phi\Delta}\,\Phi^\dagger\Phi\cdot\mathrm{Tr}(\Delta^\dagger\Delta),$$

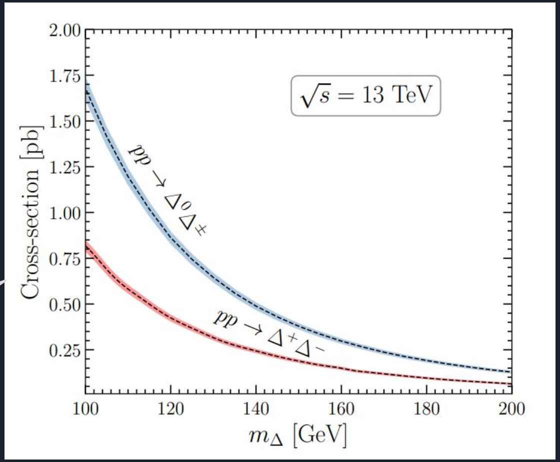
Ref: Anatomy of real Higgs Triplet model
JHEP 04 (2025) 003
arXiV: 2411.18618[hep-ph]

- Note that in the limit A → 0, the potential possesses a global $O(4)_\Phi \times O(3)_\Delta$ symmetry and the discrete $Z_{2,\Delta}$ ($\Delta \to -\Delta$) symmetry. Therefore, a non-zero A leads to a soft breaking of this symmetry

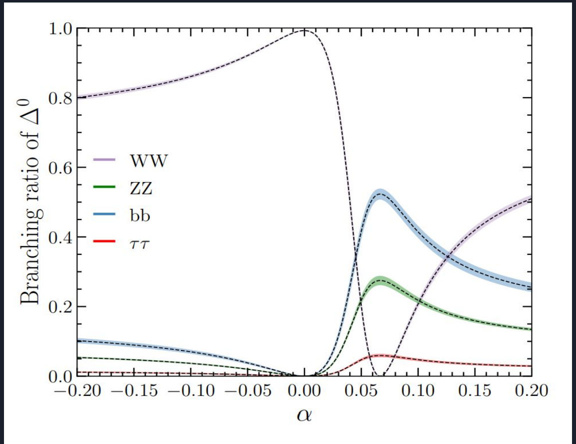
Production Mechanism

- Example Feynman diagrams showing the production of the triplet-like Higgs at the LHC: Drell-Yan (left and middle) and ggF (right).





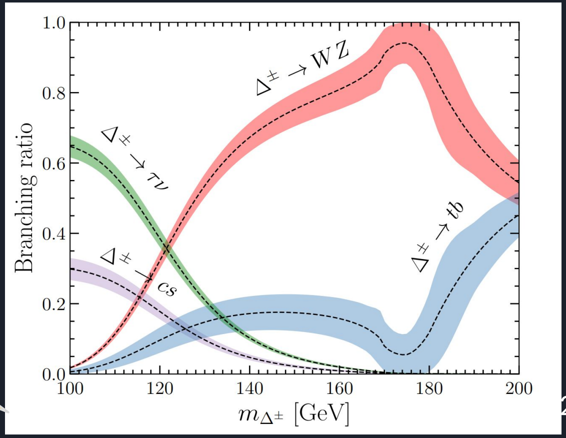
Drell-Yan production cross-sections for the triplet-like Higgses (including the NLO+NNLL QCD corrections)



Dominant branching ratios of Δ^0

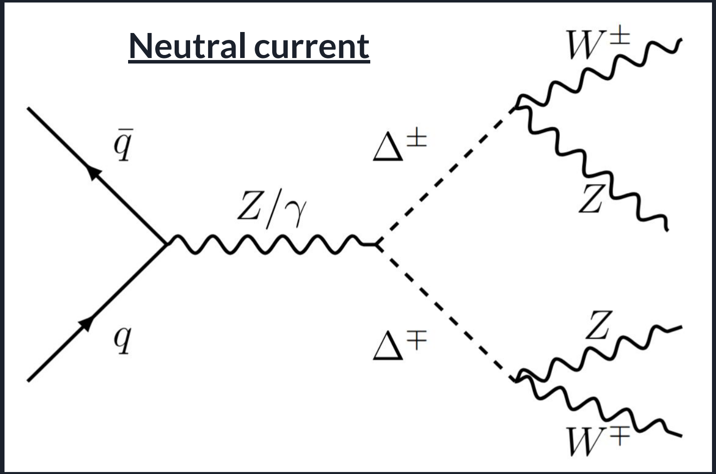
Ref: Anatomy of real Higgs Triplet model
JHEP 04 (2025) 003
arXiV: 2411.18618[hep-ph]

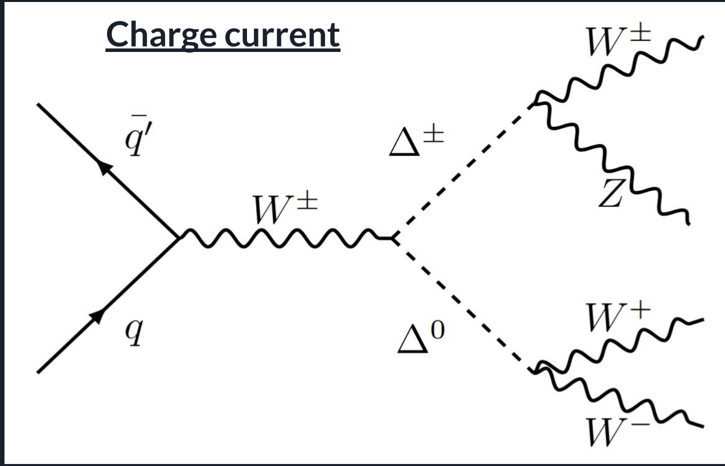
Dominant branching ratios of $\Delta^{\pm}$



Phenomenology of Triplet Scalars at the LHC

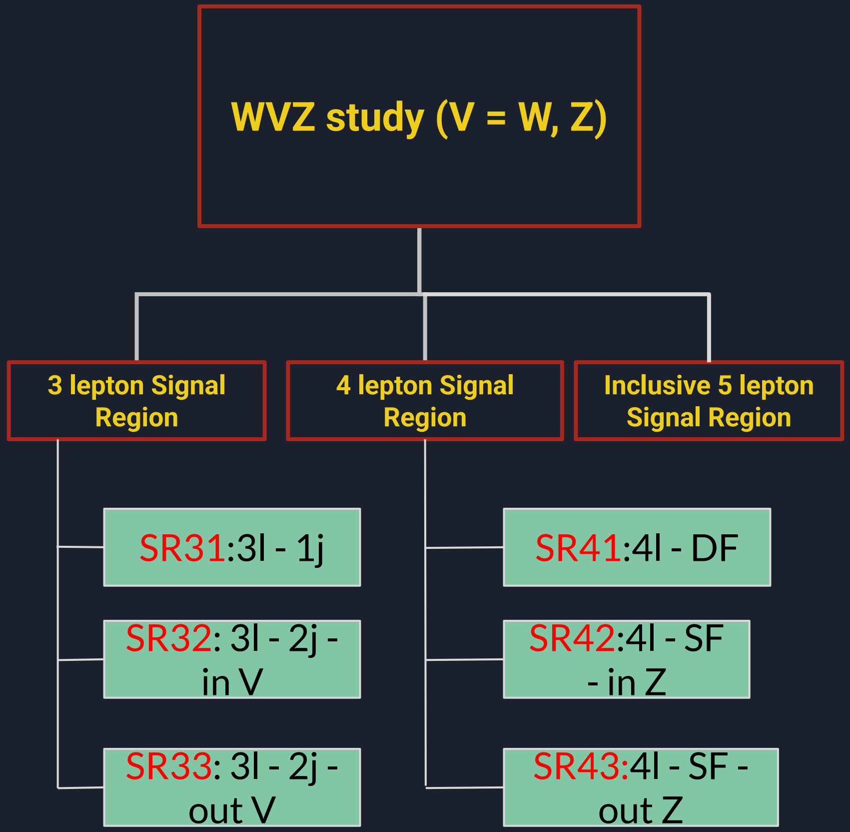
- Drell-Yan production of the triplet-like Higgs bosons, pp $\rightarrow \Delta^0\Delta^\pm$ and pp $\rightarrow \Delta^+\Delta^-$, with their decays $\Delta^0 \rightarrow W^+W^-$ and $\Delta^\pm \rightarrow W^\pm Z$ lead to final states with multiple charged leptons.





- The model can be explored to understand if it can account for excesses observed in tri-boson production at the LHC, which could be evidence for physics beyond the Standard Model.

WVZ (V=W/Z) Study (ATLAS)

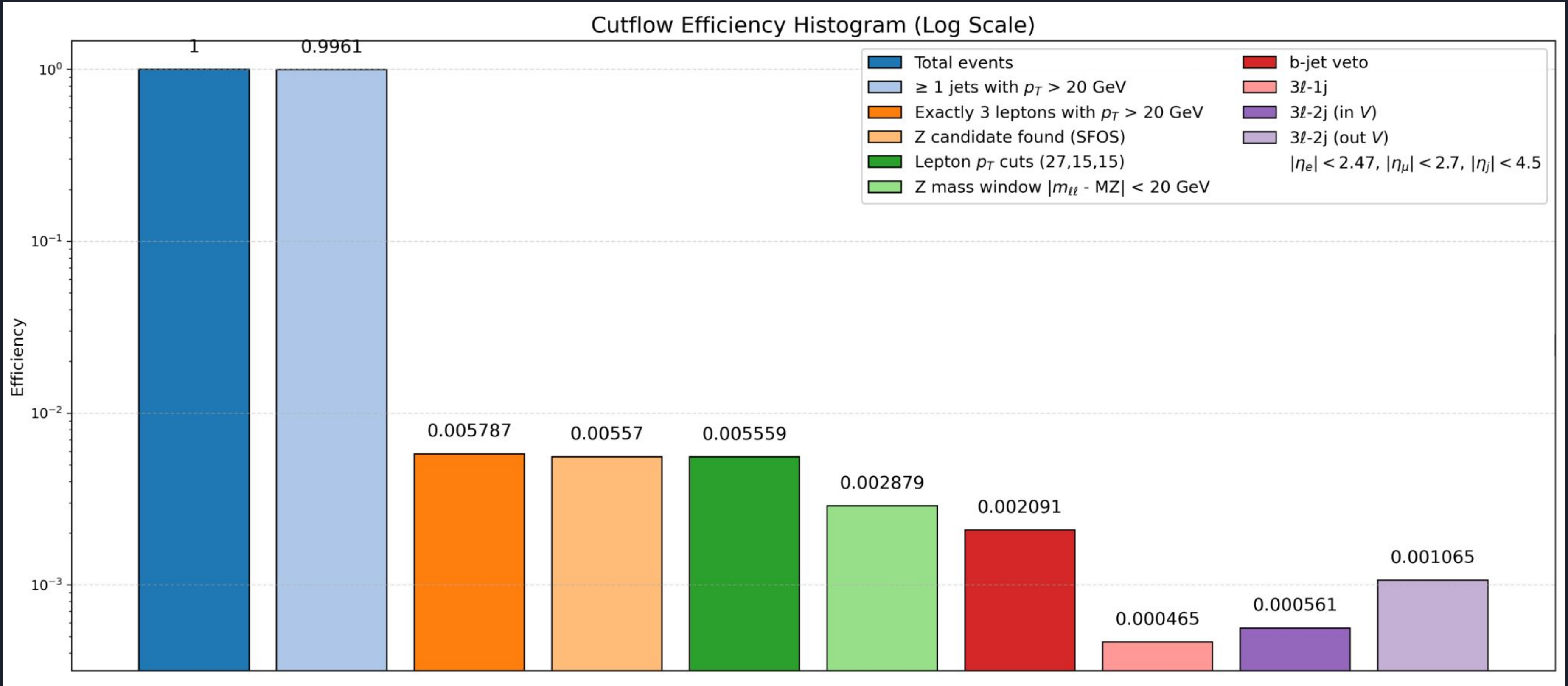


Inclusive 3ℓ event selection			
Satisfy preselection criteria	✓		
Lepton	$p_T > 15$ GeV and at least one lepton with $p_T > 27$ GeV		
Lepton from the Z decays	"Loose_VarRad" isolation for electrons and "PFLow_Loose_VarRad" isolation for muons		
Lepton from the W decays	"Tight" identification and "PLImprovedTight" isolation		
Invariant mass of any SFOS dilepton pairs	> 12 GeV		
Invariant mass of the Z boson	$\|m_{\ell\ell} - m_Z\| < 20$ GeV		
Number of leptons	$= 3$		
Number of b-jets	$= 0$		
3ℓ signal regions			
	3ℓ-1j	**3ℓ-2j-inV**	**3ℓ-2j-outV**
Satisfy inclusive 3ℓ selection criteria	✓	✓	✓
BDT score > 0.42	✓	✓	✓
Number of jets	$= 1$	≥ 2	≥ 2
m_{jj}	–	> 60 GeV and < 110 GeV	< 60 GeV or > 110 GeV

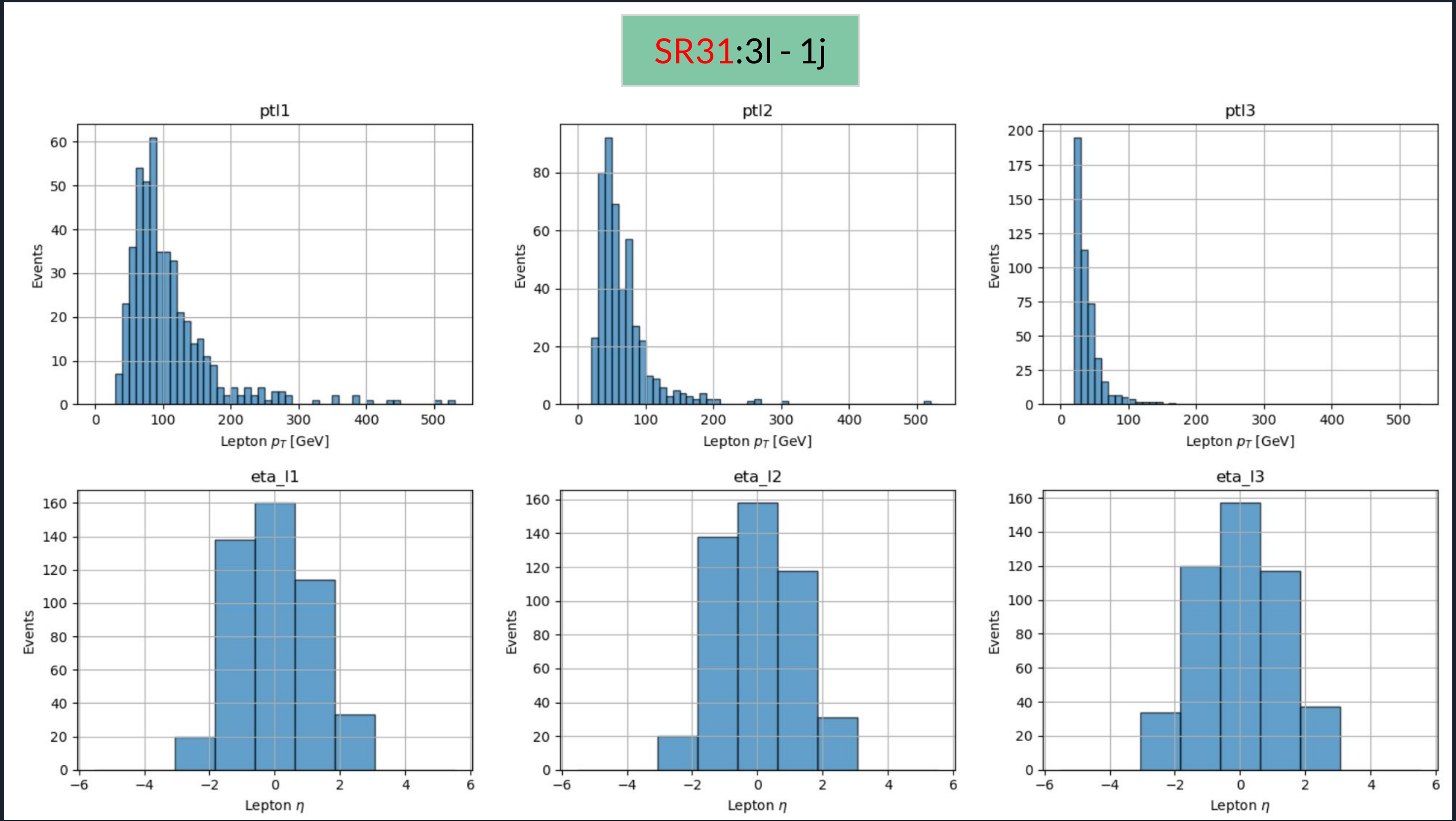
Inclusive 4ℓ event selection			
Satisfy preselection criteria	✓		
Lepton	Exactly four leptons with $p_T > 30, 15, 8, 6$ GeV		
Lepton from the Z decays	"Loose_VarRad" isolation for electrons and "PFLow_Loose_VarRad" isolation for muons		
Leptons from the W decays	"Medium" identification and "PLImprovedTight" isolation		
Invariant mass of any SFOS dilepton pairs	> 12 GeV		
Invariant mass of the Z boson	$\|m_{\ell\ell} - m_Z\| < 20$ GeV		
Minimum angular distance between any lepton pairs	> 0.1		
E_T^{miss}	> 10 GeV		
Number of b-jets	$= 0$		
4ℓ signal regions			
	4ℓ-DF	**4ℓ-SF-inZ**	**4ℓ-SF-outZ**
Satisfy inclusive 4ℓ selection criteria	✓	✓	✓
Flavour for lepton from the W decays	$e\mu$	same-flavour	same-flavour
$m_{\ell\ell}$ for the two $W-$leptons	–	$\|m_{\ell\ell} - m_Z\| < 20$ GeV	$\|m_{\ell\ell} - m_Z\| > 20$ GeV

Ref: ATLAS Collaboration, G. Aad et al. arXiv:2412.15123 [hep-ex].

Cutflow for 3 leptons Signal Region

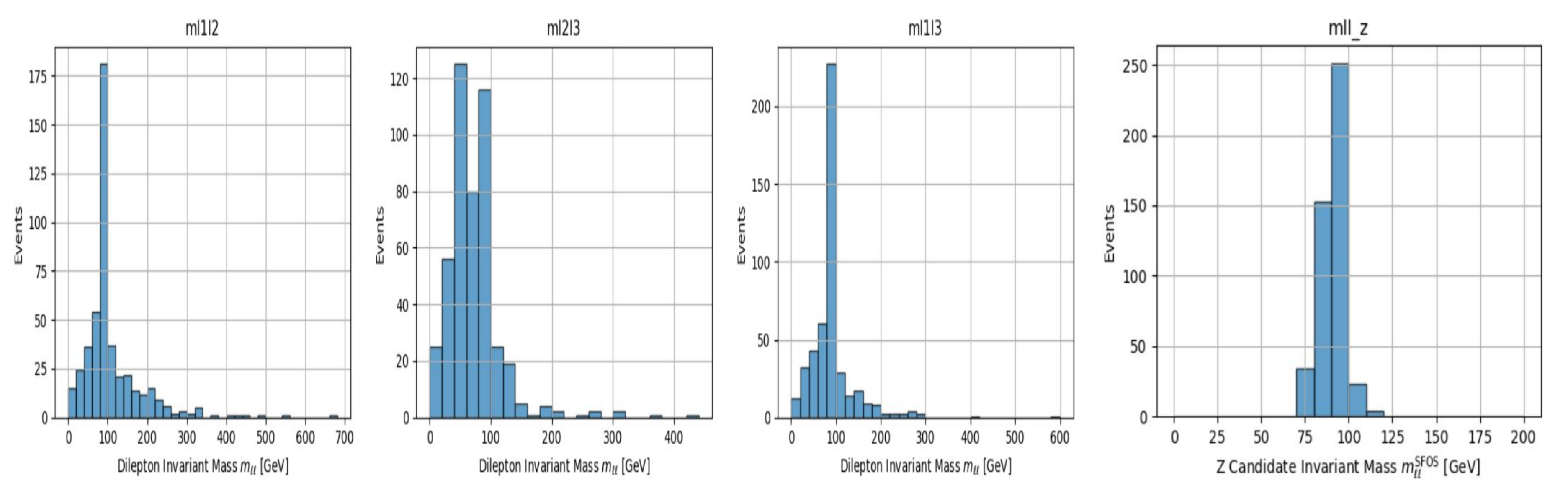


SR31 : p_T and η distributions of 3 leptons



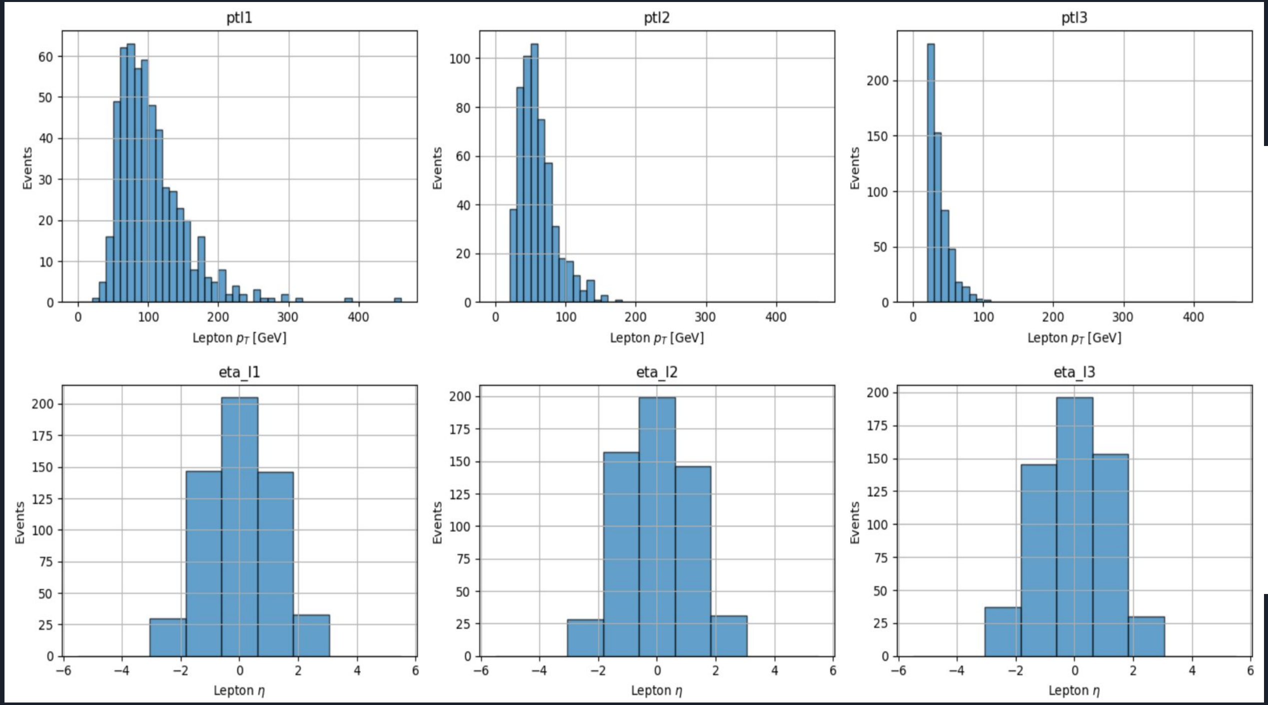
SR31 : di-lepton mass distribution

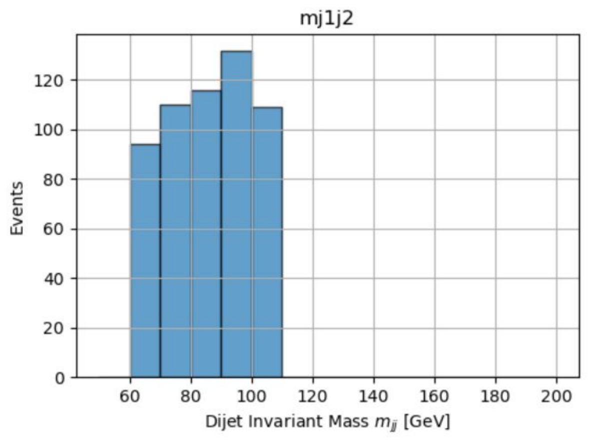
SR31:3l - 1j



SR32 : p_T and η distributions of 3 leptons

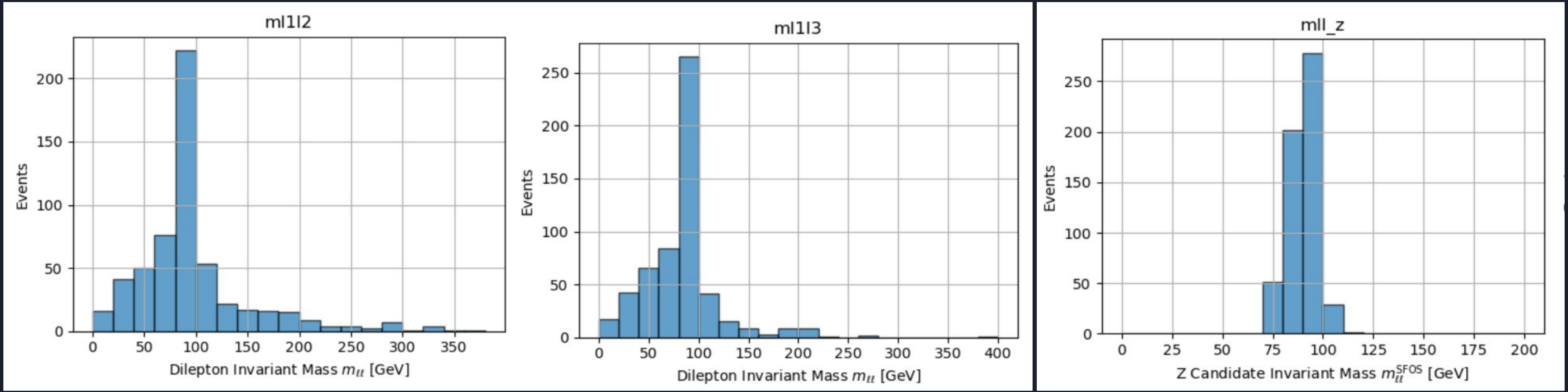
SR32: 3l - 2j - in V





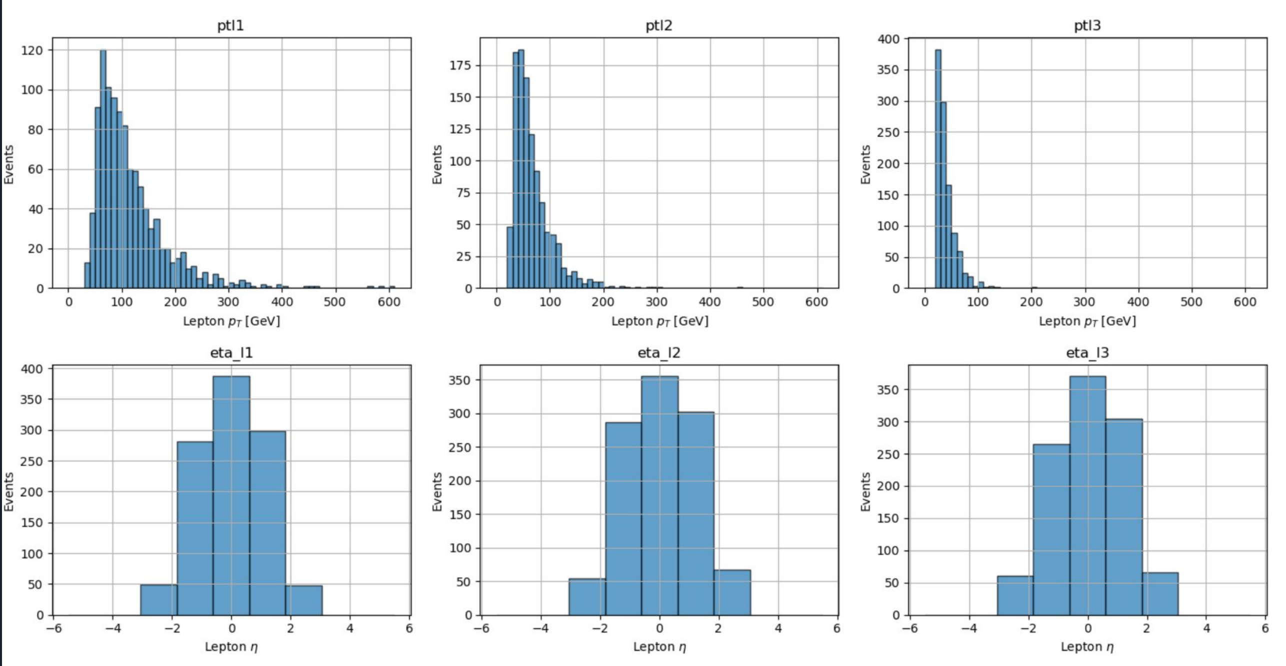
SR32 : di-lepton mass distribution

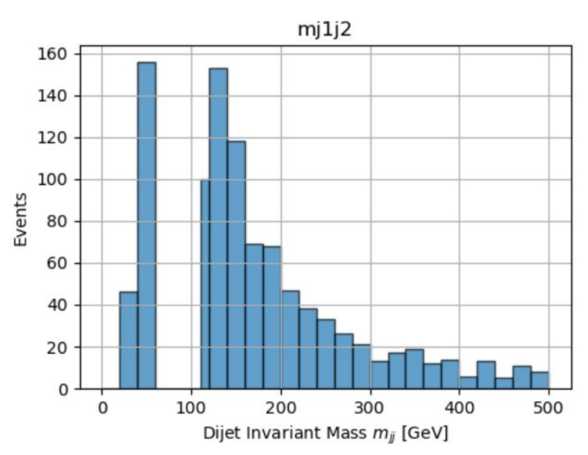
SR32: 3l - 2j - in V



SR33 : p_T and η distributions of 3 leptons

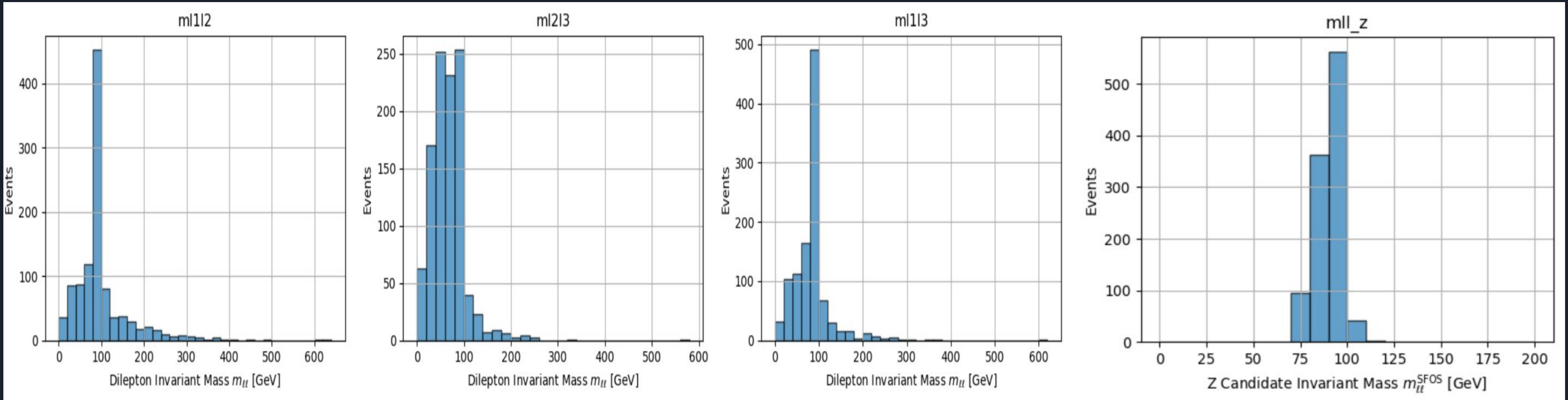
SR33: 3l - 2j - out V



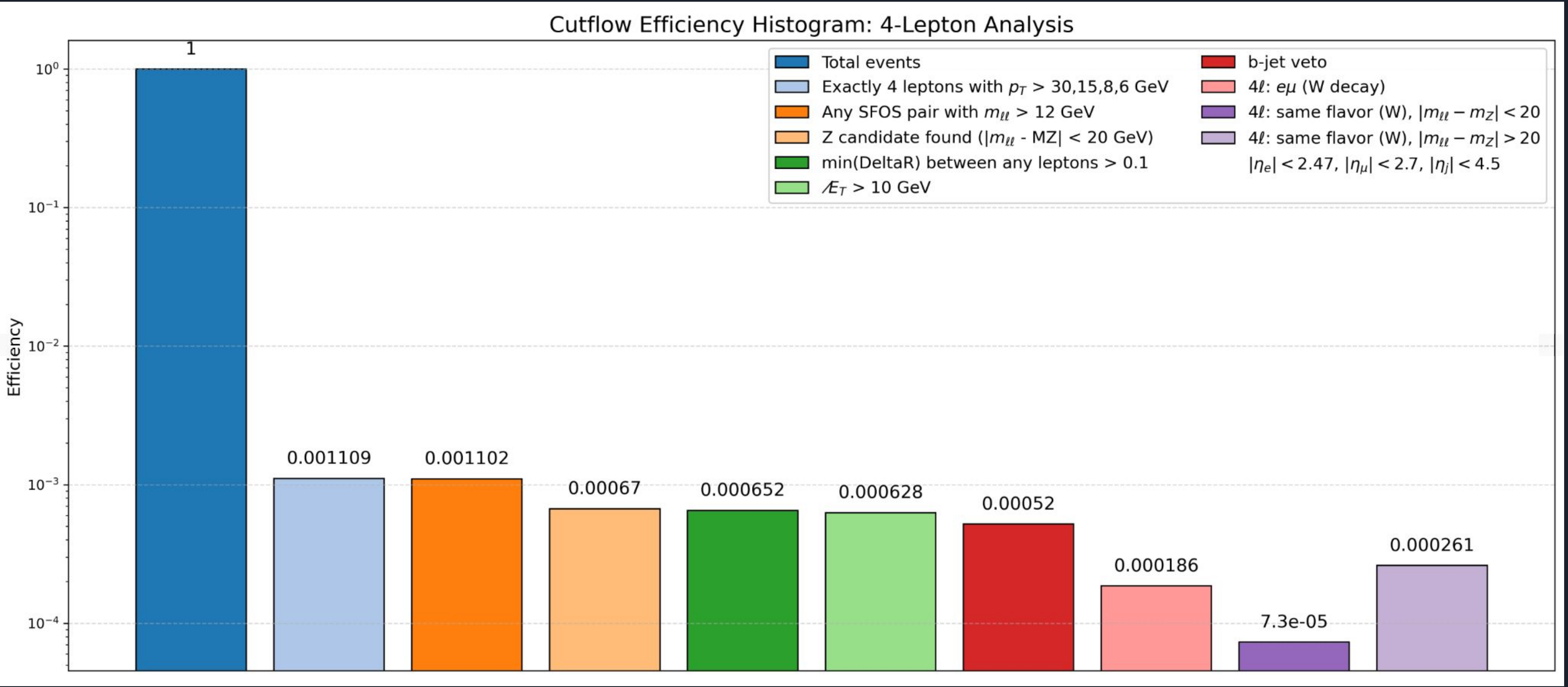


SR33 : di-lepton mass distribution

SR33: 3l - 2j - out V

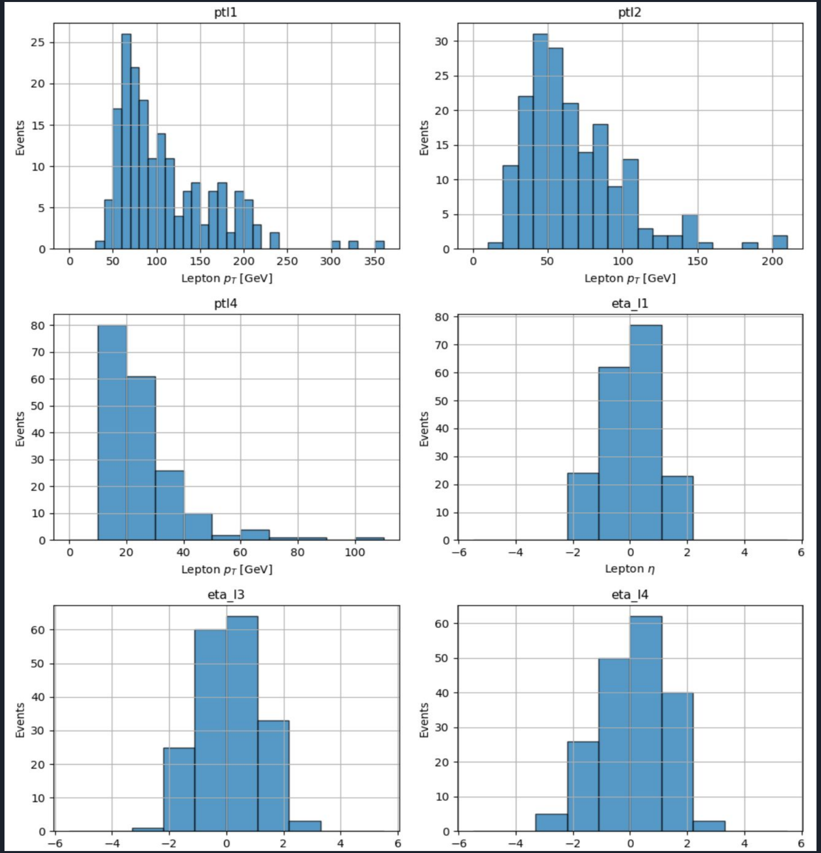


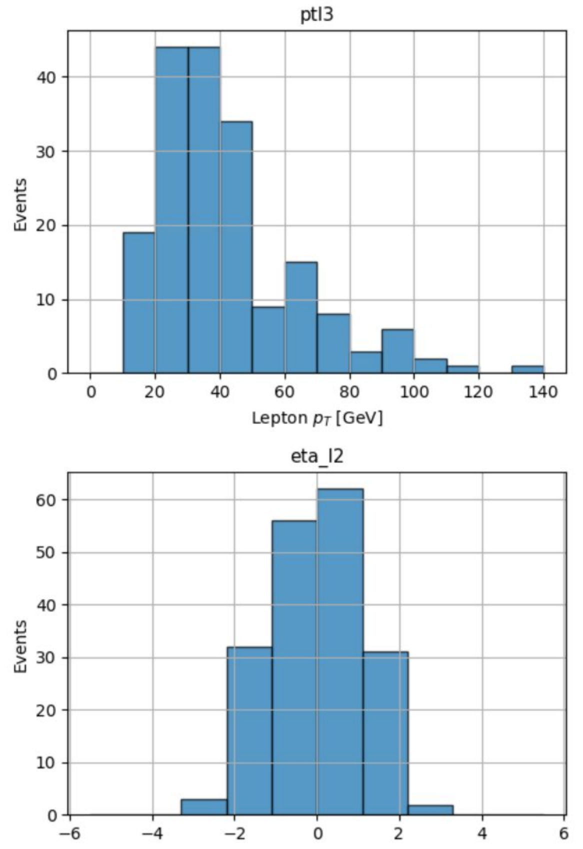
Cutflow for 4 leptons Signal Region



SR41 : p_T and η distributions of 4 leptons

SR41:4l - DF





Background Processes

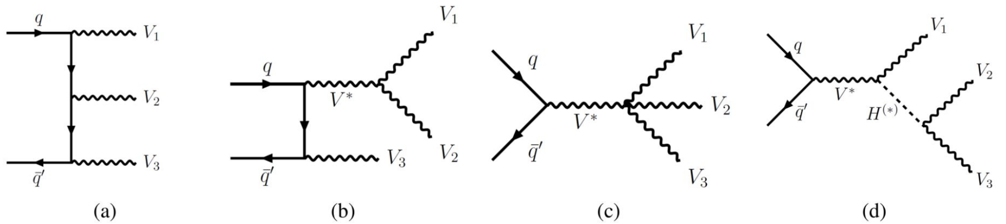


Figure 1: Representative Feynman diagrams for the production of three massive vector bosons, including diagrams with (a) mono boson vertices, diagrams sensitive to (b) triple and (c) quartic gauge boson couplings, and (d) the Higgsstrahlung process.

ATLAS Collaboration, G. Aad et al. arXiv:2412.15123 [hep-ex].

Table 5: Data and post-fit predicted yields for all SRs. Uncertainties in the predictions include both statistical and systematic uncertainties added in quadrature; correlations among systematic uncertainties are taken into account in the calculation of the total uncertainties.

Signal region	3ℓ-1j	3ℓ-2j-inV	3ℓ-2j-outV	4ℓ-DF	4ℓ-SF-inZ	4ℓ-SF-outZ	5ℓ
VVZ	104±17	99±15	173±27	26.7±4.6	18.6±2.1	26.8±4.0	3.9±0.6
WZ+jets	4271±91	932±26	2656±81	–	–	–	–
ZZ+jets	547±46	113±14	239±27	19.7±1.2	1447±35	383.2±9.9	–
Z+jets	130±43	35±12	59±18	–	–	–	–
$t\bar{t}Z$	8.2±1.0	35.5±3.1	92.5±7.0	8.3±0.9	1.8±0.2	7.0±0.7	–
Fake	–	–	–	6.5±2.0	14.5±8.5	11.6±4.2	4.9±0.6
Others	219±12	65.1±5.5	221±12	4.5±0.4	12.2±0.4	10.7±0.4	–
Total expected	5280±68	1278±28	3440±54	65.8±5.1	1494±34	439±10	8.9±0.9
Data	5273	1280	3423	65	1513	429	13

Conclusion

- Hints for “multi-lepton anomalies” , accumulated by the analysis of LHC data, pointing towards the existence of BSM Higgs.

- With these anomalies one predicts a scalar, S, with a mass 150±5 GeV from the decay of a heavier H.

- Excesses in diphoton, Zγ, and W W spectra hint at a Higgs-like scalar S with mass mS ≈ 152±1 GeV, while the ZZ channel remains SM-like.

- This pattern aligns with a Real Higgs Triplet (RHT) model with hypercharge Y = 0, where S does not couple to ZZ at tree level.

- Triplet scalars can be Drell–Yan produced and decay to electroweak bosons, enhancing triboson final states such as WWZ, WZZ, and WWW .

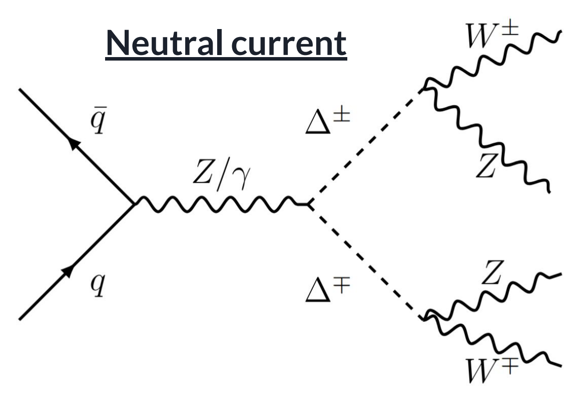
- Intriguingly, both ATLAS and CMS have reported significant excesses in such triboson channels

- We investigate whether the RHT model can account for these triboson excesses through electroweak production and decay of triplet scalars.

Thank you

Back up slides

Decays of the triplet-like Higgses Δ^0 and $\Delta^{\pm}$



$$\Gamma(\Delta^{\pm} \to W^{\pm} Z^*) = \frac{9g^2 \lambda^2_{\Delta^{\pm}W^{\mp}Z}}{128\pi^3 \cos^2\theta_w m_{\Delta^{\pm}}} \left(\frac{7}{12} - \frac{10}{9}\sin^2\theta_W + \frac{40}{27}\sin^4\theta_W\right) H\left(\frac{m_W^2}{m_{\Delta^{\pm}}^2}, \frac{m_Z^2}{m_{\Delta^{\pm}}^2}\right)$$

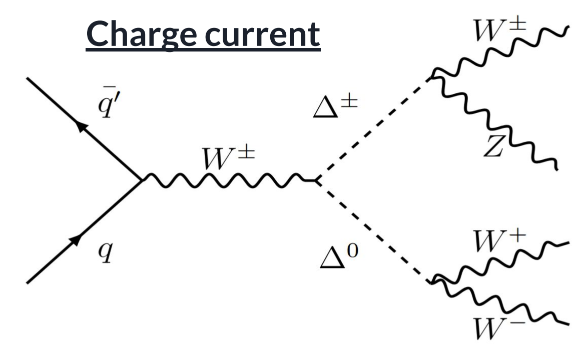
$$\Gamma(\Delta^{\pm} \to W^{\pm *} Z) = \frac{9g^2 \lambda^2_{\Delta^{\pm}W^{\mp}Z}}{256\pi^3 m_{\Delta^{\pm}}} H\left(\frac{m_Z^2}{m_{\Delta^{\pm}}^2}, \frac{m_W^2}{m_{\Delta^{\pm}}^2}\right),$$

where,

$$\lambda_{\Delta^{\pm}W^{\mp}Z} = -\frac{g^2}{2\cos\theta_w}\left(2v_\Delta \cos^2\theta_w \cos\beta - v_\Phi \sin^2\theta_w \sin\beta\right)$$

and

$$H(x,y) = \frac{1}{4x\sqrt{-\beta(x,y)}}\left\{\tan^{-1}\left(\frac{1-x+y}{\sqrt{-\beta(x,y)}}\right) + \tan^{-1}\left(\frac{1-x-y}{\sqrt{-\beta(x,y)}}\right)\right\}\left\{-3x^3 + (9y+7)x^2 - 5(1-y)^2 x + (1-y)^3\right\} + \frac{1}{24xy}\left\{(-1+x)(2+2x^2+6y^2-4x-9y+39xy) - 3y(1-3x^2+y^2-4x-2y+6xy)\log x\right\},$$



$$\Gamma(\Delta^0 \to WW^*) = \frac{3g^6 m_{\Delta^{\pm}}}{2048\pi^3 m_W^2}\left(-v_\Phi \sin\alpha + 4v_\Delta \cos\alpha\right)^2 \beta_V'\left(\frac{m_W^2}{m_{\Delta^0}^2}\right)$$

$$\beta_V'(x) = \frac{3(1-8x+20x^2)}{\sqrt{4x-1}}\cos^{-1}\frac{3x-1}{2x\sqrt{x}} - \frac{(1-x)}{2x}(2-13x+47x^2) - \frac{3}{2}(1-6x+4x^2)\log x$$