Triboson Excesses in light of a Real Higgs Triplet Model at the LHC

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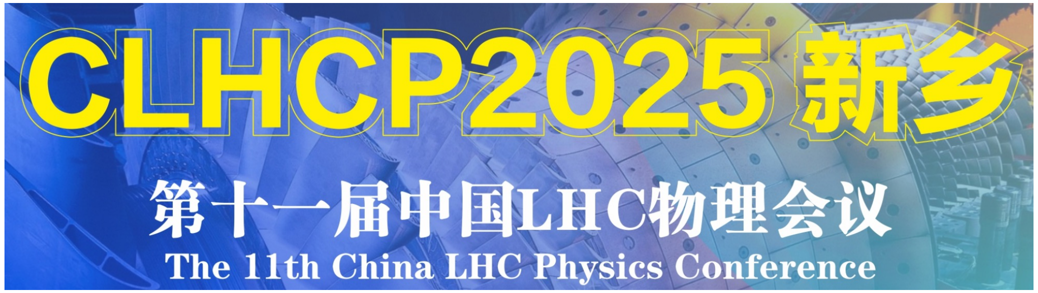
IHEP, Wits University, University of Zurich, IHEP



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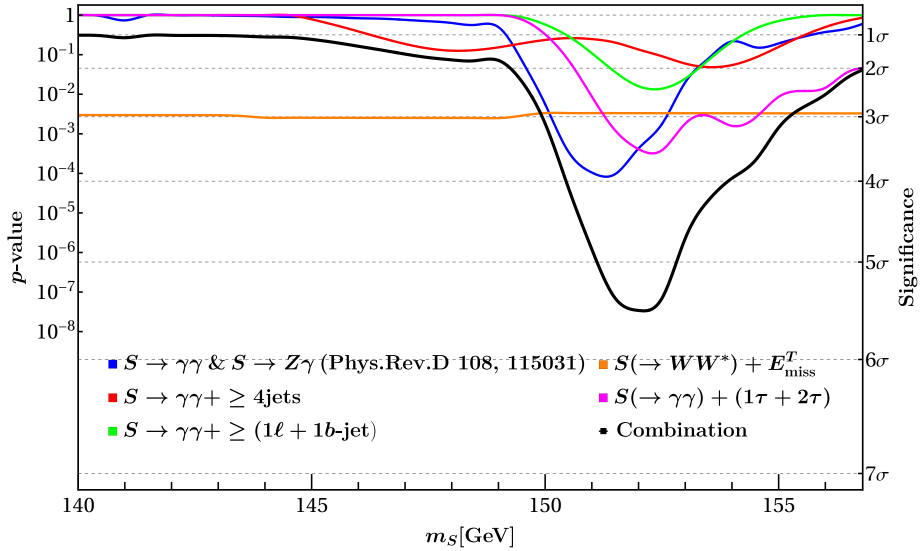
Outline

- ❑The Timeline
- ❑The S(152) candidate
- ❑Is it a Triplet?
- ❑VVV excesses
- ❑Impact on e⁺e⁻



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

The Timeline

2015
Run 1 excesses
Motivating asymm.
Diboson final states

2016
Simplified di-boson model
predicting multi-lepton excesses
Eur.Phys.J.C 76 (2016) 10, 580

2017/2018
Multi-lepton anomalies in Run 1
Prediction of m_S=150$\pm$5 GeV
in association with leptons/jets/MET
J.Phys.G 45 (2018) 11, 115003

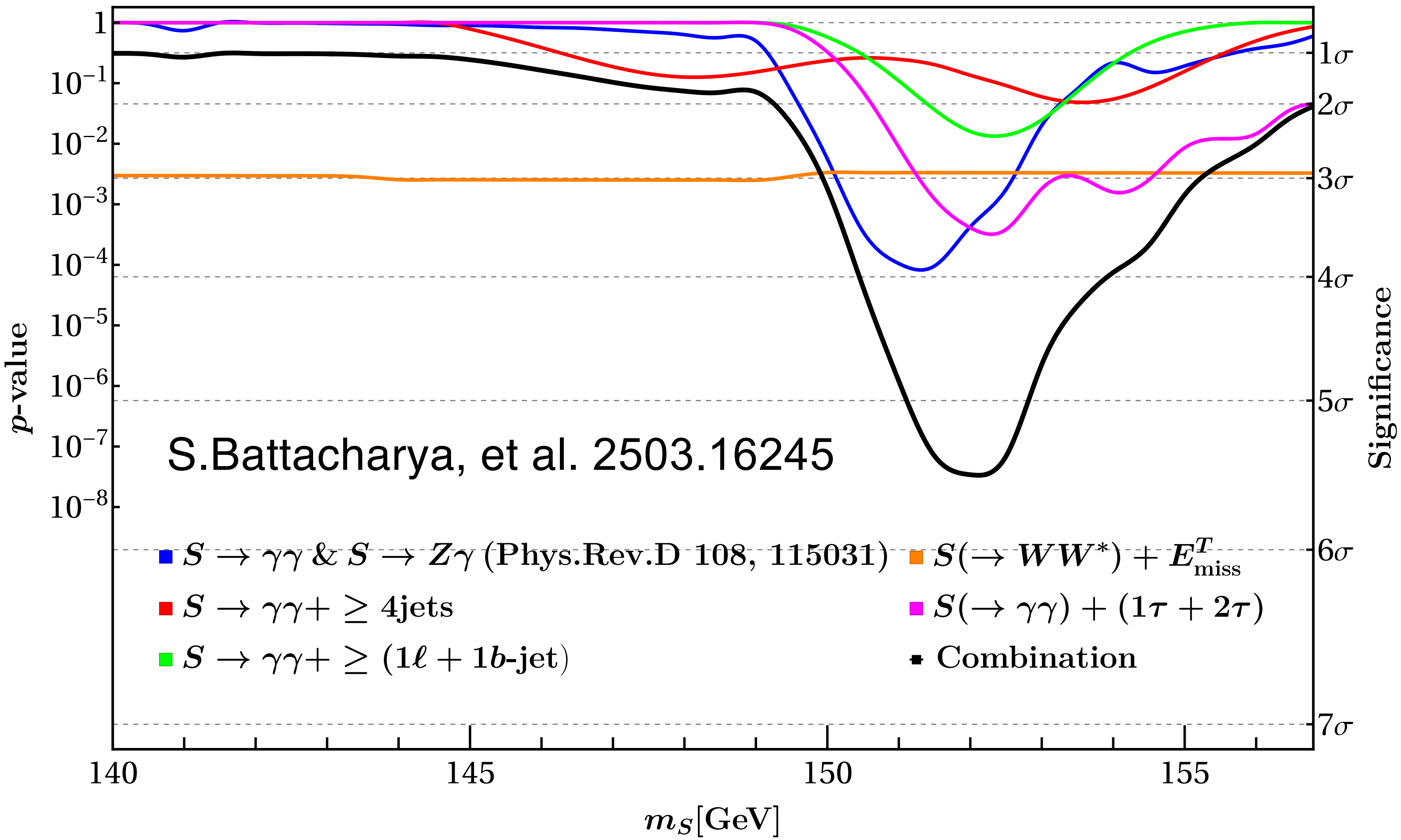
2019
Multi-lepton anomalies
verified in Run 2
JHEP 10 (2019) 157

2021
First narrow excess at 151.5$\pm$1
GeV with jets/leptons/MET
reaching 3.9$\boldsymbol{\sigma}$
Phys.Rev.D 108 (2023) 11, 115031

2025
Narrow excess at
152$\pm$1 GeV with 5.3$\boldsymbol{\sigma}$
with leptons/jets/MET
2503.16245

Currently, continue to accumulate excesses at 152$\pm$1 GeV and exploring Triplet Y=0 leading to triboson excesses

Current status of the combination, based on the Fischer method with 5 n.d.o.f yields largest global significance of a narrow structure beyond the SM at the LHC



Is the S(152) a part of a Triplet?

Motivated by the lack of ZZ signal, where excess is seen in $\gamma\gamma$, $Z\gamma$ and WW

JHEP 04 (2025) 003

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

SM SU(2)$_L$ Doublet

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

BSM Scalar Triplet with Y=0, with a VeV

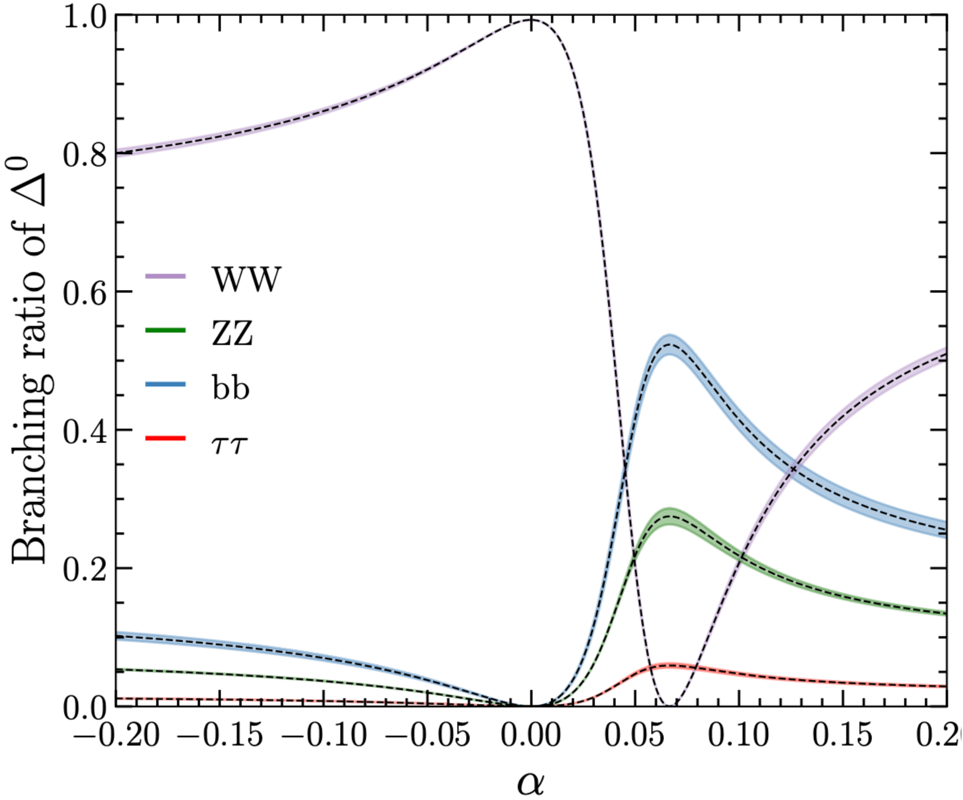
$$\begin{pmatrix} h \\ \Delta^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_\Phi^0 \\ h_\Delta^0 \end{pmatrix}$$

Mixing of the neutral sector

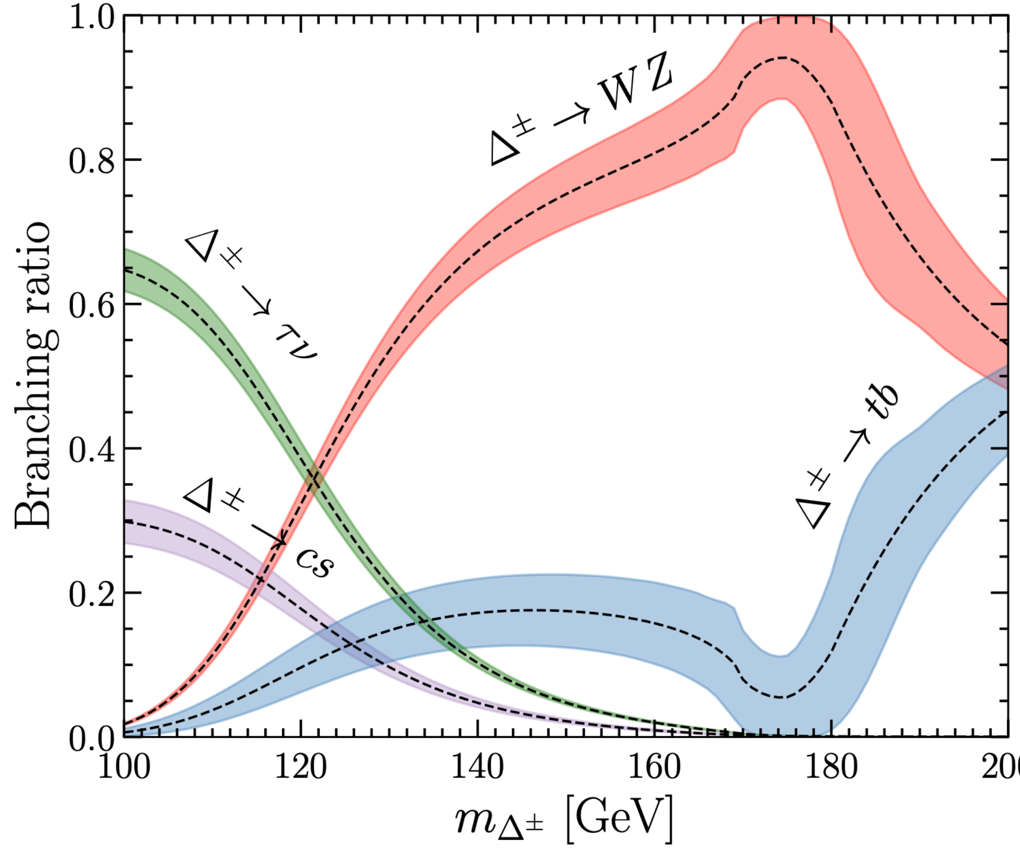
Charged and neutral scalars nearly degenerate for low mixing and VeV

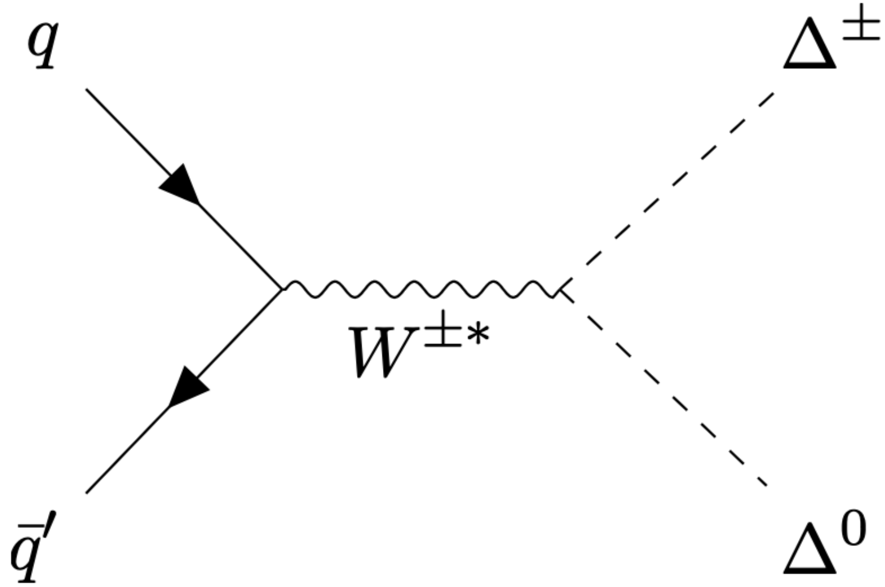
$$m_{\Delta^\pm}^2 - m_{\Delta^0}^2 = Av_\Delta - \frac{\lambda_\Delta v_\Delta^2}{2} + \tan\alpha\left(\lambda_{\Phi\Delta}v_\Delta - \frac{A}{2}\right)v_\Phi$$

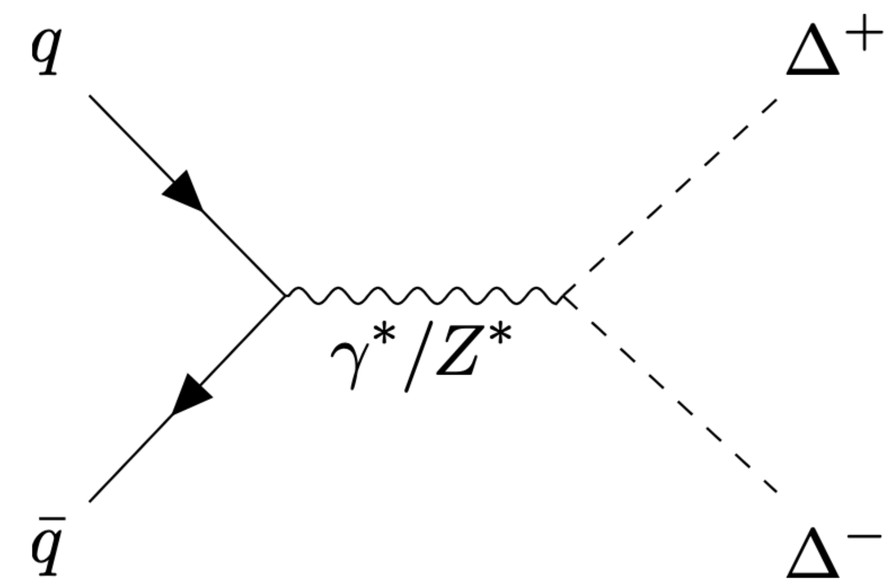
At low values of mixing, decay to ZZ is suppressed

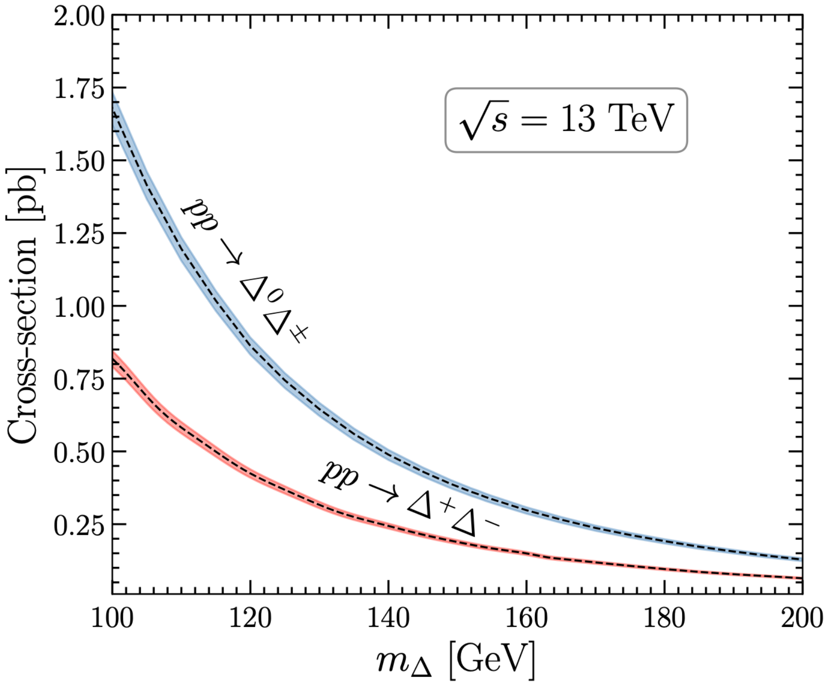


Branching ratio of the charged scalar at ~150 GeV is dominated by ZW

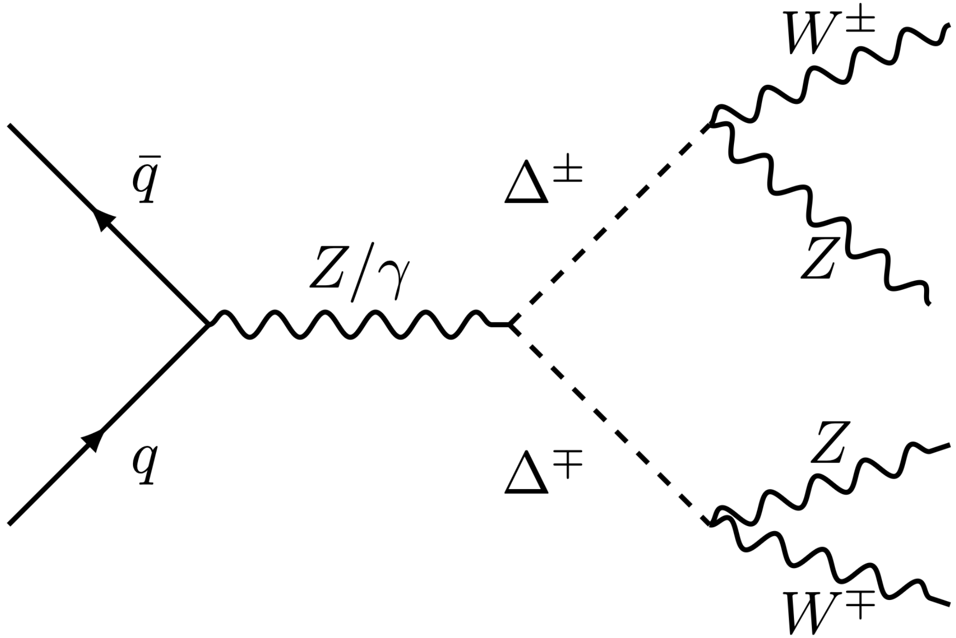


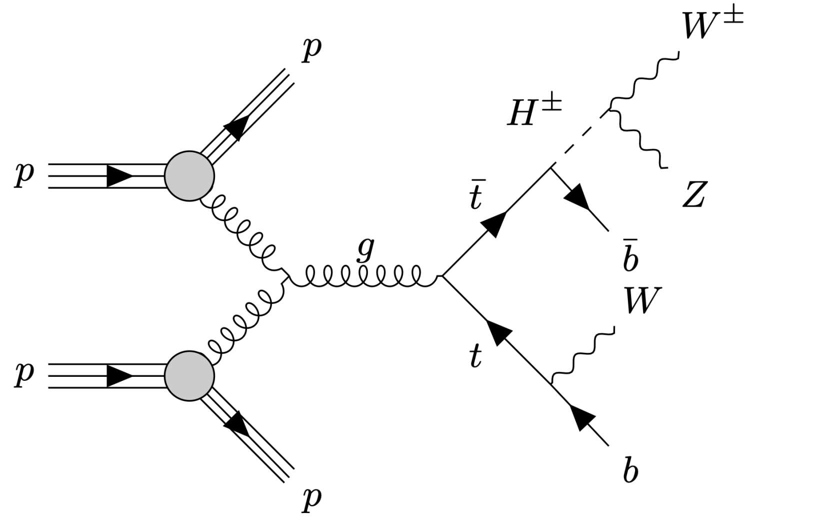




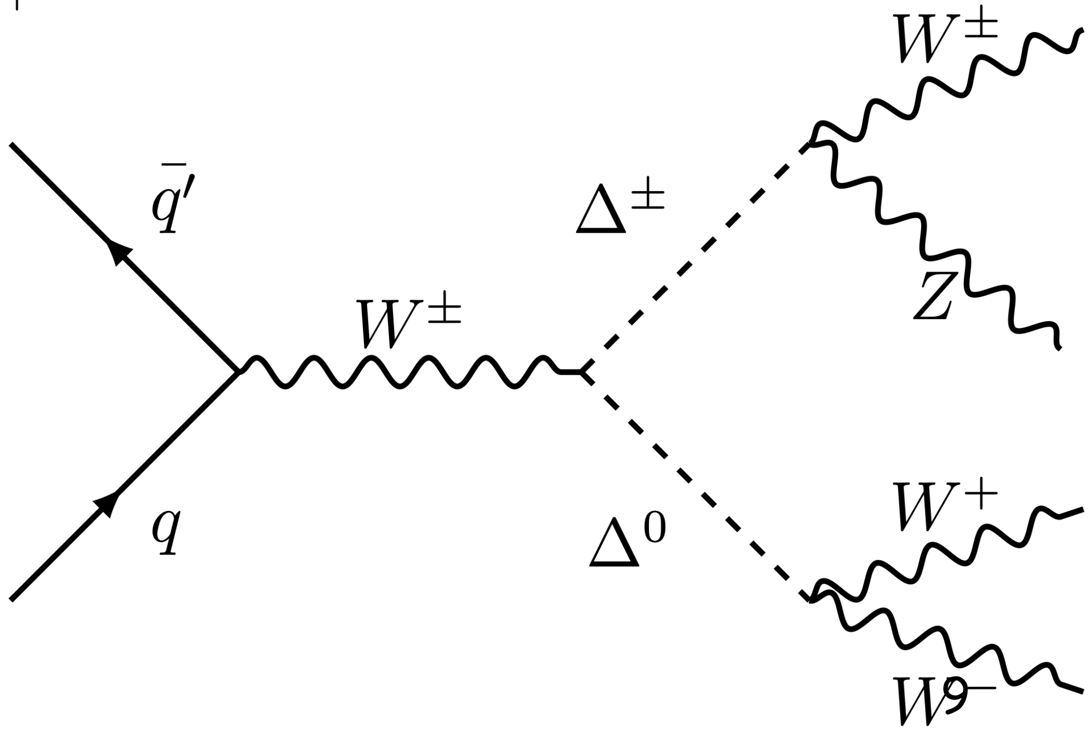


For a scalars of mass ~150 GeV, produce sufficient VVV, (V=W,Z) to generated excesses at the LHC





Predicts the emergence of VVV signatures with and without b-jets.

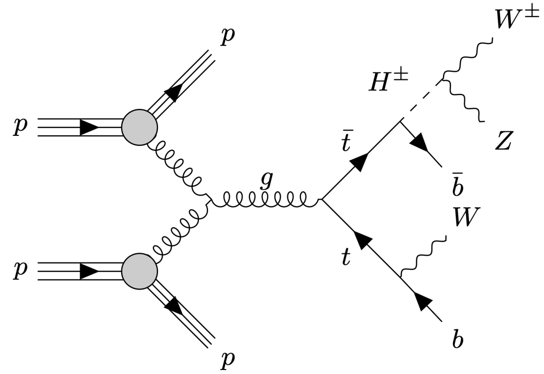


Seven out of eight measurements are elevated.
The most accurate measurements are anomalous

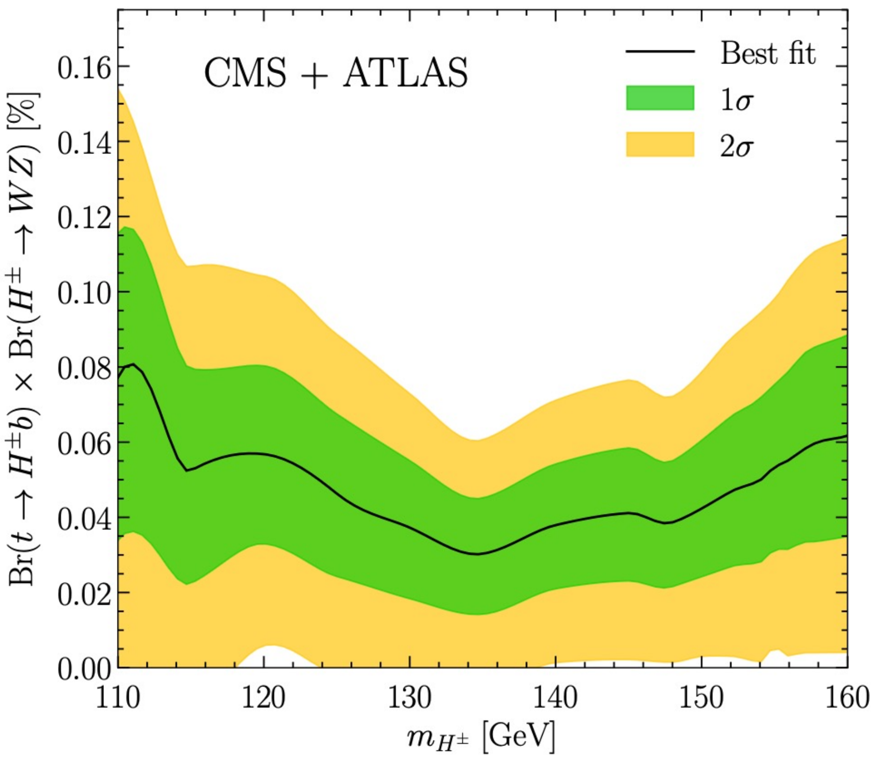
Center of Mass Energy	Process	Observed Cross section (fb)	Expected Cross section (fb)
$\sqrt{s} = 13$ TeV	WWZ	$442 \pm 94(\text{stat.})^{+60}_{-52}(\text{syst.})$ [9]	329.0 [9]
		$280^{+120}_{-110}(\text{stat.})^{+40}_{-30}(\text{syst.})$ [10]	373.0 [10]
	WZZ	$200^{+111}_{-91}(\text{stat.})^{+65}_{-37}(\text{syst.})$ [9]	93.1 [9]
		$200^{+160}_{-110}(\text{stat.})^{+70}_{-20}(\text{syst.})$ [11]	91.6 [11]
	WWW	$820 \pm 100(\text{stat.}) \pm 80(\text{syst.})$ [12]	511.0 ± 18 [12]
	tWZ	$248 \pm 38(\text{stat.}) \pm 35(\text{syst.})$ [13]	136.0^{+9}_{-8} [13]
$\sqrt{s} = 13.6$ TeV	WWZ	$700^{+270}_{-230}(\text{stat})^{+90}_{-60}(\text{syst})$ [10]	402[10]
	tWZ	$242 \pm 62(\text{stat.}) \pm 46(\text{syst.})$ [13]	147.8^{+10}_{-9} [13]

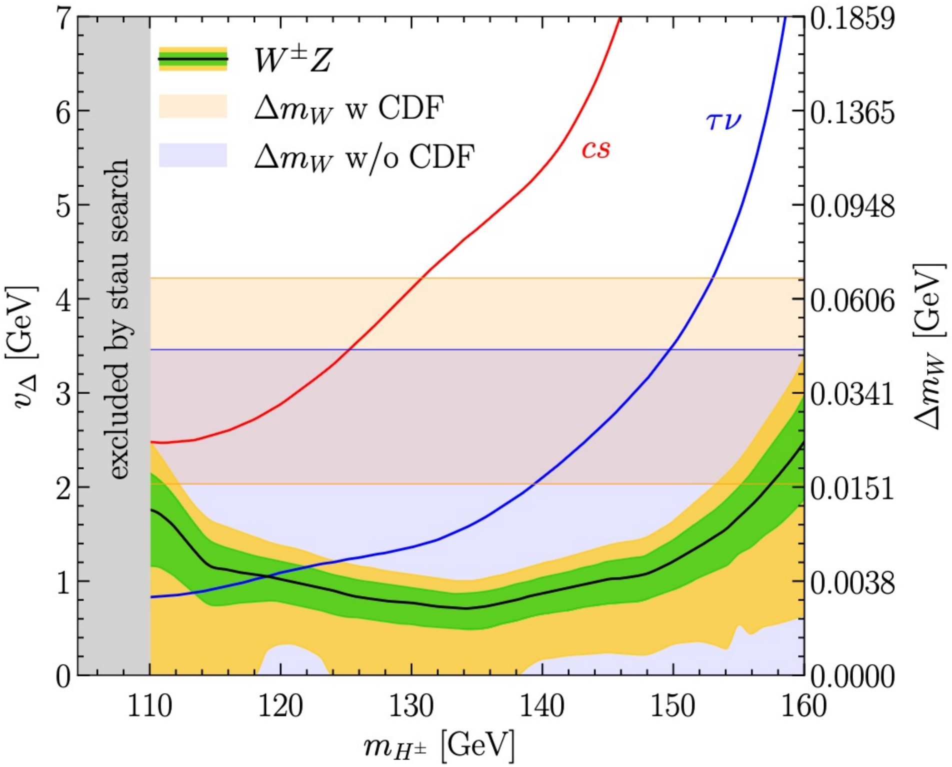
First attempt to interpret the excesses in VVV production. Here we focus in the ttZ+tWZ production.

https://arxiv.org/abs/2509.07094



Triplet interpretation does not seem to contradict EW data and existing constraints by charged scalar searches. Complete interpretation of all VVV excesses is next the next step.





Event Selection compilation for VVZ measurements

Selection Type	**ATLAS**	**CMS**
	Object Selection Criteria	
Electron	$p_T > 7$ GeV, $\|\eta\| < 2.47$	$p_T > 10$ GeV, $\|\eta\| < 2.5$
Muon	$p_T > 5$ GeV (> 15 GeV for calo-tag), $\|\eta\| < 2.7$	$p_T > 10$ GeV, $\|\eta\| < 2.4$
Jet	$p_T > 20$ GeV, $\|\eta\| < 4.5$	$p_T > 25$ GeV, $\|\eta\| < 2.4$, anti-k_T ($R = 0.4$)
b-jets	$= 0$	$= 0$
	Event Preselection Criteria	
Trigger	Single-, di-, tri-, quad-lepton triggers	Same
Lepton Multiplicity	≥ 3 charged leptons	≥ 2 leptons (channel-dependent)
Z boson mass window (if applicable)	$\|m_{\ell\ell} - m_Z\| < 40$ GeV	Prompt lepton selection, tight ID/isolation
	Inclusive 3ℓ Event Selection	
Preselection	✓	✓
Lepton p_T	> 15 GeV, at least one > 27 GeV	≥ 3 leptons: one > 25 GeV, others > 20 GeV (or all > 25 GeV if 0 SFOS)
SFOS dilepton mass	> 12 GeV; $\|m_{\ell\ell} - m_Z\| < 20$ GeV	> 20 GeV; $\|m_{\ell\ell} - m_Z\| > 20$ GeV for SFOS
Jet and b-jet	No b-jets; SRs based on 1 or 2 jets	No jets (1 allowed if 0 SFOS); no b-jets
Kinematic variables	—	$m_T^{3\text{rd}} > 90$ GeV, $\|\vec{p}_T^{3\ell}\| > 50$ GeV, $\Delta\phi > 2.5$, $\|m_{3\ell} - m_Z\| > 10$ GeV
	3ℓ Signal Regions	
Region definitions	**3ℓ**-1j : 1 jet **3ℓ**-2j-inV : ≥ 2 jets, $60 < m_{jj} < 110$ GeV **3ℓ**-2j-outV : ≥ 2 jets, $m_{jj} < 60$ or > 110 GeV	**3ℓ**-0SFOS **3ℓ**-1SFOS **3ℓ**-2SFOS
	Inclusive 4ℓ Event Selection	
Preselection	✓	✓
Lepton p_T	Exactly four: 30, 15, 8, 6 GeV	Exactly four: Z pair > 25, 10 GeV; others > 25, 10 GeV
SFOS dilepton mass	> 12 GeV, $\|m_{\ell\ell} - m_Z\| < 20$ GeV	Z1: $\|m_{\ell\ell} - m_Z\| < 10$ GeV, Z2: $\|m_{\ell\ell} - m_Z\| > 10$ GeV
$\Delta R_{\ell\ell}$	> 0.1	—
E_T^{miss}	> 10 GeV	—
b-jets	$= 0$	$= 0$
	4ℓ Signal Regions	
Common categories	**4ℓ-DF**: different-flavour W leptons ($e\mu$) **4ℓ-SF-inZ**: same-flavour W leptons, $\|m_{\ell\ell} - m_Z\| < 20$ GeV **4ℓ-SF-outZ**: same-flavour W leptons, $\|m_{\ell\ell} - m_Z\| > 20$ GeV	
	Inclusive 5ℓ Event Selection	
Preselection	✓	✓
Leptons	≥ 5 leptons	≥ 5 leptons; leading two > 25 GeV, others > 10 GeV
Z boson candidates	≥ 2 SFOS pairs with $\|m_{\ell\ell} - m_Z\| < 20$ GeV	≥ 2 SFOS pairs with $\|m_{\ell\ell} - m_Z\| < 15$ GeV
Other cuts	—	$m_T > 50$ GeV
b-jets	$= 0$	$= 0$

ATLAS VVZ (3l)

Cut	$\Delta^0\Delta^\pm$ [fb]	$\Delta^\mp\Delta^\pm$ [fb]
Production Cross section	379.5	188.6
≥ 3 leptons	3.84	2.30
Exactly 3 leptons and 1 jet	3.07	1.69
Lepton p_T cuts (27,15,15)	2.34	1.29
≥ 1 OSSF pair	2.07	1.25
All OSSF $m_{\ell\ell} \geq 12$GeV	1.98	1.20
Z mass window $\|m_{\ell\ell} - M_Z\| < 20$ GeV	0.94	0.62
$1.37 < \|\eta_\ell\| < 1.52$	0.94	0.62
≥ 1 jet with $p_T > 20$ GeV, b-jet veto	0.79	0.45
3ℓ-1j	0.18	0.10
3ℓ-2j (in V)	0.23	0.15
3ℓ-2j (out V)	0.38	0.20

ATLAS VVZ (5l)

Cut	$\Delta^0\Delta^\pm$ [fb]	$\Delta^\mp\Delta^\pm$ [fb]
Production Cross section	379.5	188.6
≥ 5 leptons	0.03	0.02
≥ 2 OSSF pair	0.03	0.02
b-jet veto	0.01	0.01

ATLAS VVZ (4l)

Cut	$\Delta^0\Delta^\pm$ [fb]	$\Delta^\mp\Delta^\pm$ [fb]
Production Cross section	379.5	188.6
$= 4$ leptons	0.41	0.24
Lepton p_T cuts (30,15,8,6)	0.40	0.23
≥ 1 OSSF pair	0.39	0.23
All OSSF $m_{\ell\ell} \geq 12$GeV	0.37	0.22
Z mass window $\|m_{\ell\ell} - M_Z\| < 20$ GeV	0.22	0.14
$p_T^{miss} > 10$ GeV, b-jet veto	0.19	0.11
4ℓ-DF	0.09	0.04
4ℓ-SF (in V)	0.02	0.02
4ℓ-SF (out V)	0.08	0.05

Event Selection for WWW measurement

Selection Type	**ATLAS**
	Object Selection Criteria
Electron	$p_T > 20$ GeV, $\|\eta\| < 2.47$ (excluding $1.37 < \|\eta\| < 1.52$)
Muon	$p_T > 20$ GeV, $\|\eta\| < 2.5$
Jet	$p_T > 20$ GeV (central: $\|\eta\| < 2.5$), $p_T > 30$ GeV (forward: $2.5 < \|\eta\| < 4.5$),
b-jets	Vetoed
	Inclusive 2ℓ Event Selection
Lepton Multiplicity	Exactly two same-sign leptons: $e^\pm e^\pm$, $e^\pm \mu^\pm$, or $\mu^\pm \mu^\pm$
Leading Lepton p_T	> 27 GeV
Dilepton Mass	$40 < m_{\ell\ell} < 400$ GeV
Jets	≥ 2 central jets; $m_{jj} < 160$ GeV, $\|\Delta\eta_{jj}\| < 1.5$
b-jets	Vetoed
Extra Leptons	Events with additional e ($p_T > 7$ GeV) or μ ($p_T > 4.5$ GeV) are rejected
E_T^{miss} (only $e^\pm e^\pm$)	$S(E_T^{\text{miss}}) > 3$ if $80 < m_{\ell\ell} < 100$ GeV is avoided
	Inclusive 3ℓ Event Selection
Lepton Multiplicity	Exactly three leptons: $e^\pm e^\pm \mu^\mp$ or $\mu^\pm \mu^\pm e^\mp$
Leading Lepton p_T	At least one lepton with $p_T > 27$ GeV
SFOS Pair Veto	No same-flavor opposite-sign (SFOS) lepton pairs allowed
Jets	No requirement, but events with additional leptons are vetoed
b-jets	Vetoed
Extra Leptons	Events with extra e ($p_T > 7$ GeV) or μ ($p_T > 4.5$ GeV) rejected

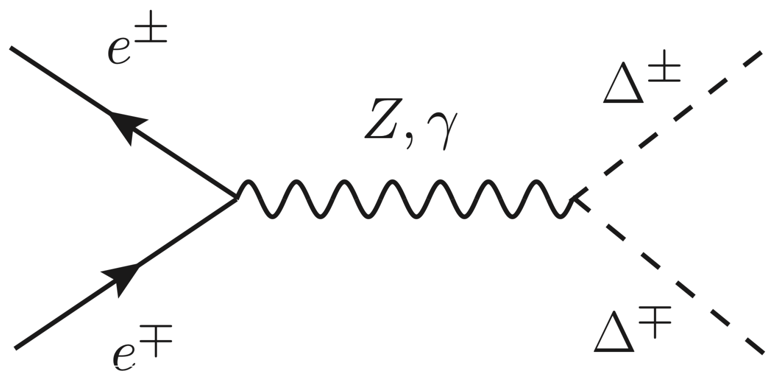
ATLAS WWW (SS2l)

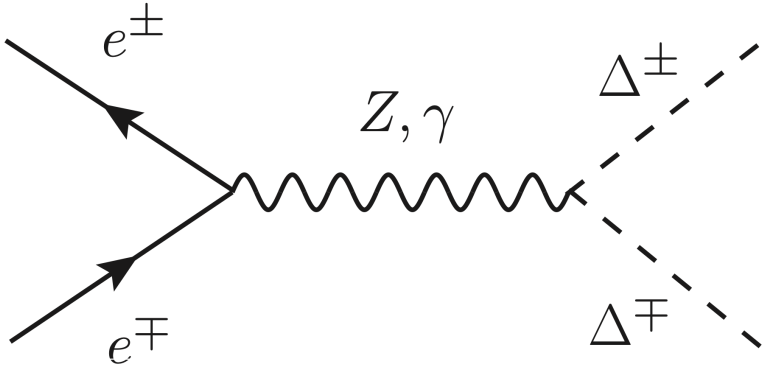
Cut	$\Delta^0\Delta^\pm$ [fb]	$\Delta^\mp\Delta^\pm$ [fb]
Production Cross section	379.5	188.6
$= 2$ leptons	16.64	6.23
Leptons with Same charge	4.64	1.03
≥ 1 jet , b-jet veto	2.64	0.58
$p_T(\ell_1) > 27$ and 40 GeV $< m_{\ell\ell} <$ 400 GeV	2.32	0.45
$m_{jj} <$ 160 GeV	1.31	0.27
$ee - mode$	0.12	0.02
$e\mu - mode$	0.65	0.12
$\mu\mu - mode$	0.43	0.09

ATLAS WWW (3l)

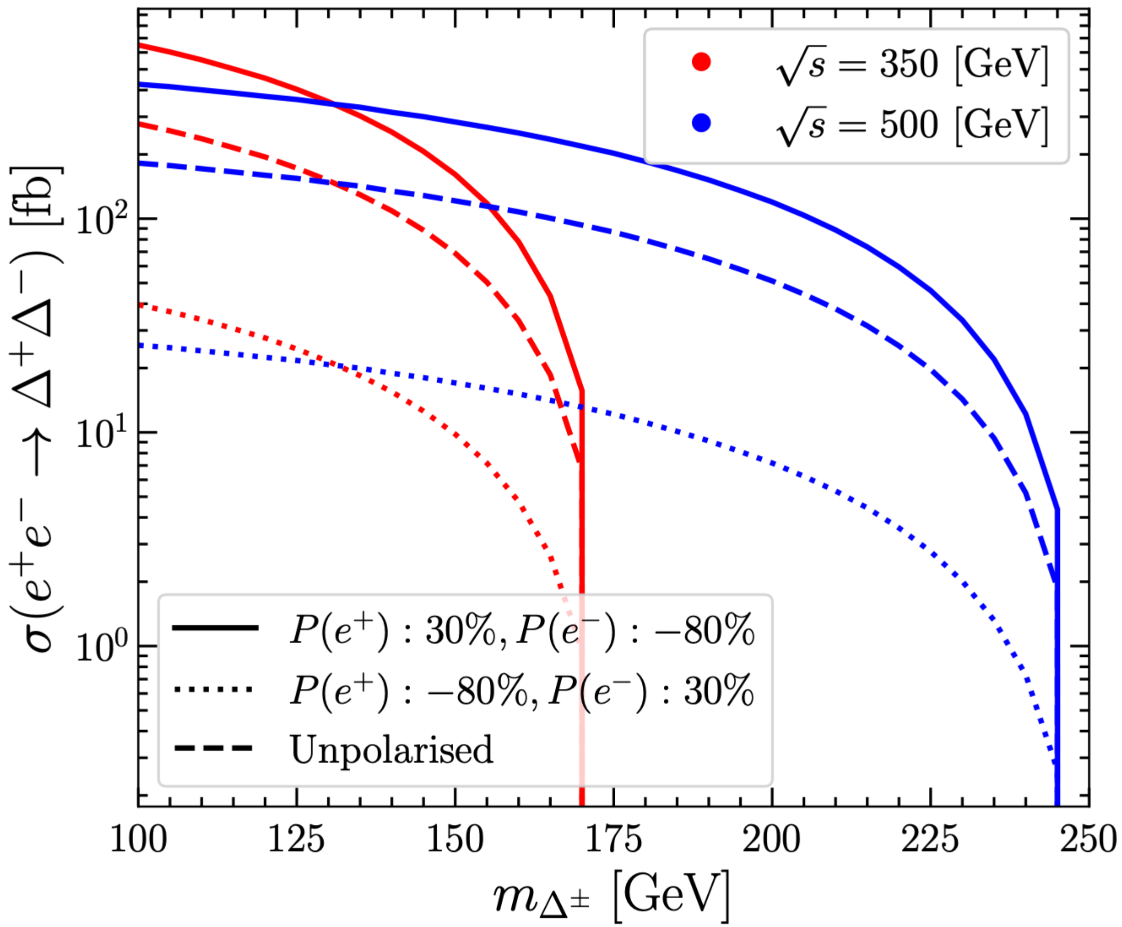
Cut	$\Delta^0\Delta^\pm$ [fb]	$\Delta^\mp\Delta^\pm$ [fb]
Production Cross section	379.5	188.6
$= 3$ leptons	2.20	1.20
$p_T(\ell_1) > 27$	2.20	1.20
b-jet veto and no-OSSF leptons	0.27	0.03

Impact on e^+e^- Colliders





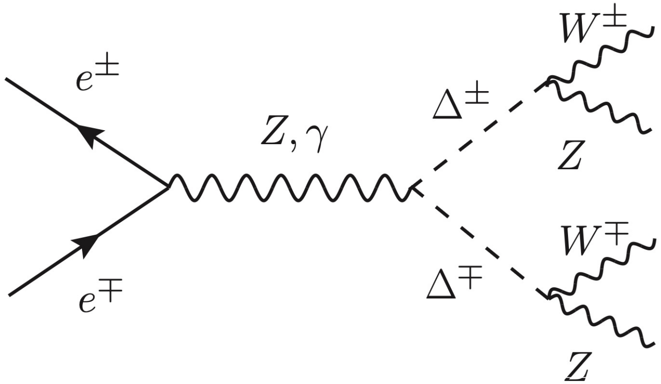
https://arxiv.org/abs/2509.14378



Define three representative signal regions.

More comprehensive study to come in the future.

Signal Region		ℓ and j selection criteria
SR1:	$3j + 1\ell$	$n_{\text{jet}} \geq 3$, $n_{\ell=e,\mu} \geq 1$, $p_T(j) > 20$ GeV, $p_T(\ell) > 10$ GeV, $\theta_{j,\ell} < 9.38°$
SR2:	$3\ell + \tau_{\text{had}}$	$n_{\ell=e,\mu} \geq 3$, $n_{\tau_{\text{had}}} \geq 1$, $p_T(\ell) > 10$ GeV, $p_T(\tau_{\text{had}}) > 20$ GeV, $\theta_{\ell,\tau_{\text{had}}} < 9.38°$
SR3:	$4j + \tau_{\text{had}}$	$n_{\text{jet}} \geq 4$, $n_{\tau_{\text{had}}} \geq 1$, $p_T(j) > 10$ GeV, $p_T(\tau_{\text{had}}) > 10$ GeV, $\theta_{j,\tau_{\text{had}}} < 9.38°$



Signal Region 1

$\geq$ 3j+1l

Implemented a DNN based on features below

Variables	Definition
$E(\ell_1)$	Energy of the leading lepton (ℓ_1)
H_{T}	Scalar sum of the hadronic p_{T}
E_{eff}	Effective energy ($= E(\text{jets}) + E(\text{leptons}) + p_{\mathrm{T}}^{\mathrm{miss}}$)
$p_{\mathrm{T}}(\ell_1)/L_{\mathrm{T}}$	Ratio of the leading lepton p_{T} over the scalar sum of all leptonic p_{T}
$\Delta\phi(j_1, \ell_1)$	Angular separation between the leading jet (j_1) and the leading lepton (ℓ_1)
$E(j_2)$	Energy of the sub-leading jet (j_2)
$p_{\mathrm{T}}(j_1)$	p_{T} of the leading jet (j_1)
$p_{\mathrm{T}}(j_1)/H_{\mathrm{T}}$	Ratio of the leading jet p_{T} and the scalar sum of hadronic p_{T}
$E(j_3)$	Energy of the third leading jet (j_3)
$E(j_1)$	Energy of the leading jet (j_1)
M_{eff}	Effective mass ($= H_{\mathrm{T}} + p_{\mathrm{T}}^{\mathrm{miss}}$)
$\Delta\phi(j_{123}, \ell_1)$	Angular separation between the 3-jet system (j_{123}) and the leading lepton (ℓ_1)
$\Delta\phi(j_2, \ell_1)$	Angular separation between the sub-leading jet (j_2) and the leading lepton (ℓ_1)
m_{j_2, j_3}	Invariant mass of the 2$^{\text{nd}}$ and 2$^{\text{rd}}$ leading jets (j_2, j_3)
$m(j_1, j_2, j_3)$	Invariant mass of the leading 3-jet system (j_{123})

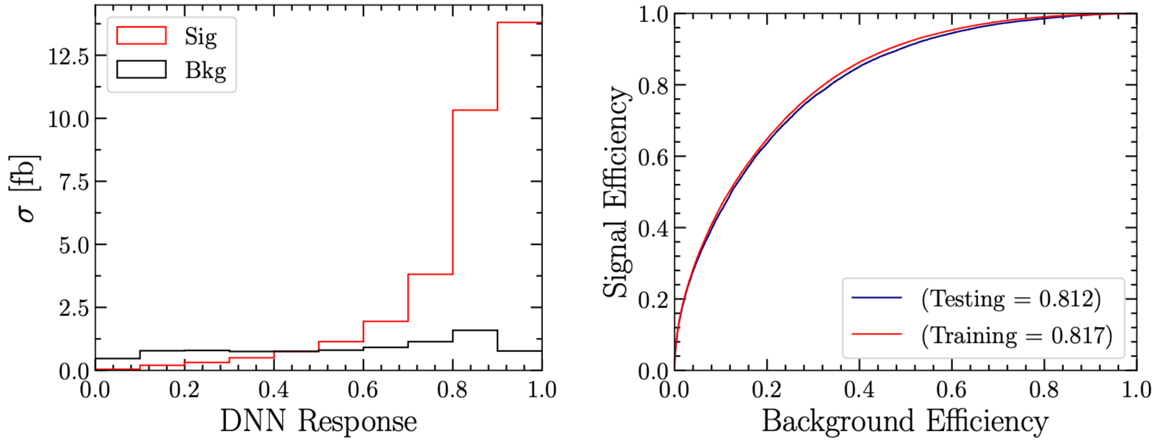


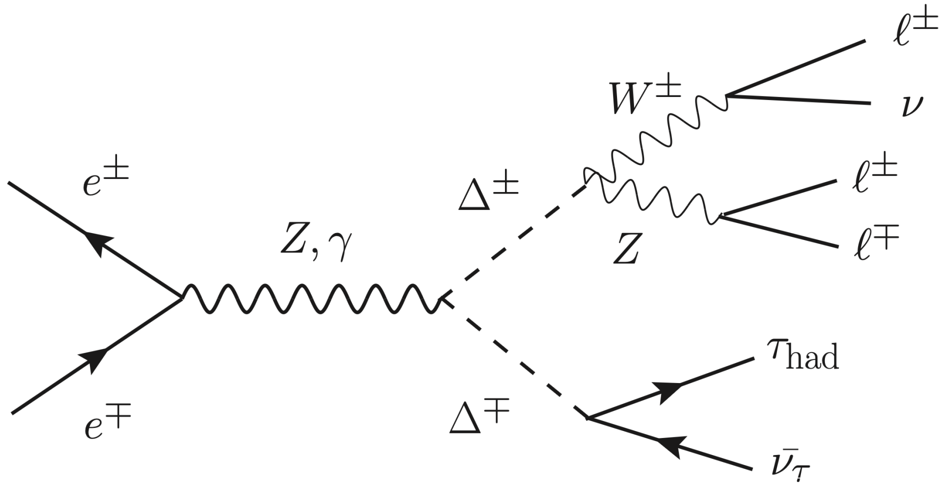
Figure 5. Left: DNN response for signal and background for SR1. Right: ROC-curve for both training and testing samples for SR1.

Process	$\geq 3j + 1\ell$	DNN Response > 0.7
Signal	32.82 fb	28.45 fb
VVV	8.76 fb	3.67 fb

Table 3. Fiducial cross sections of both the signal and background after the preselction and DNN score for SR1, where $V = W^{\pm}, Z$ and h.

Signal Region 2

$\geq$ 3l+1τ_{had}



Implemented a DNN based on features below

Variables	Definition
$m(\ell_1, \ell_2, \ell_3)$	Invariant mass of leading 3-lepton system (ℓ_{123})
$p_{\rm T}(\tau_j)/\sqrt{H_{\rm T}}$	Ratio of tau-tagged jet $p_{\rm T}$ and the square-root of $H_{\rm T}$
$M_{\rm eff}$	Effective mass
$E(\ell_1)$	Energy of leading lepton
$L_{\rm T}$	Scalar sum of all leptonic $p_{\rm T}$
$E(\ell_2)$	Energy of sub-leading lepton
$E_{\rm eff}$	Effective energy ($= E(\text{jets}) + E(\text{leptons}) + p_{\rm T}^{\rm miss}$)
$E(\ell_3)$	Energy of ℓ_3
$E(\tau_j)$	Energy of τ_j
$m(\ell_1, \ell_2)$	Invariant mass of leading 2-lepton system (ℓ_{12})

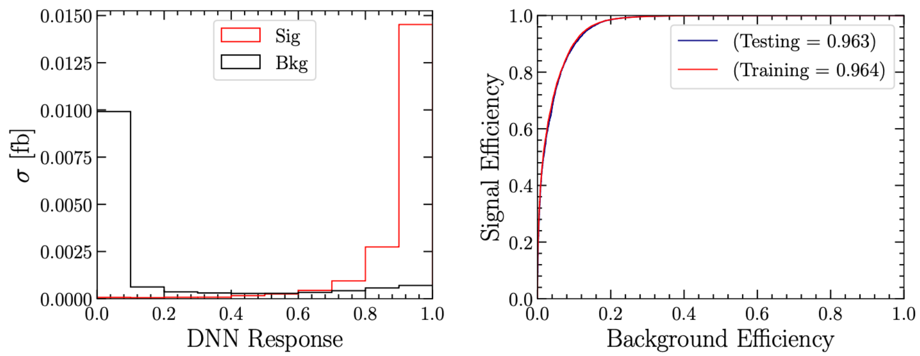
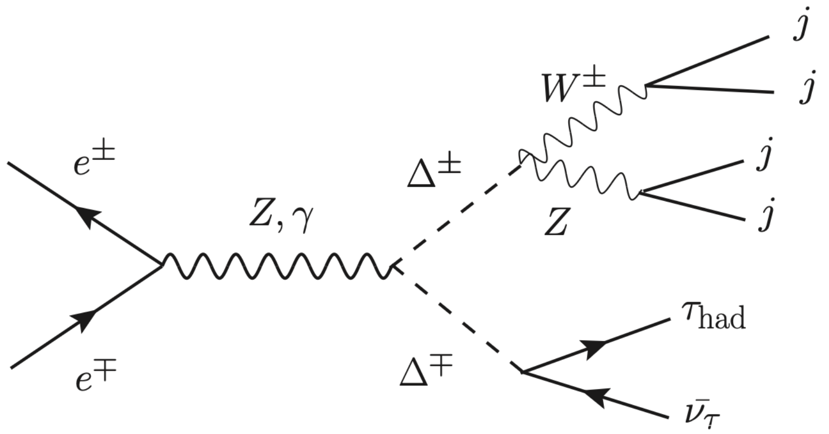


Figure 7. Left: DNN response to signal and background for both training and testing samples, for SR2. Right: ROC-curve for both training and testing samples for SR2.

Process	$\geq 3\ell + \tau_{\rm had}$	DNN Response > 0.7
Signal	0.019 fb	0.016 fb
VV $\tau\nu$	0.013 fb	0.001 fb

Signal Region 3

$\geq$ 4j+1τ_{had}

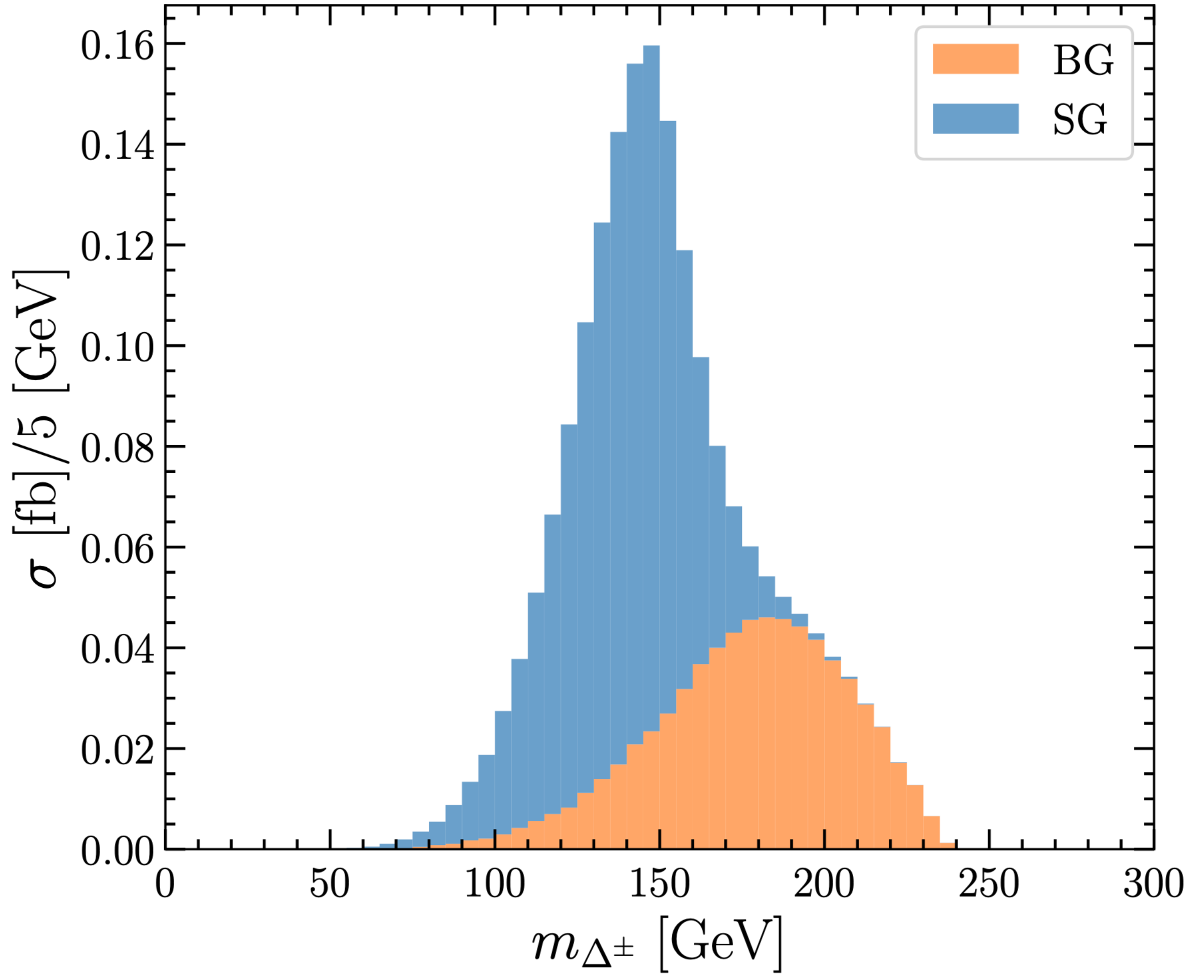


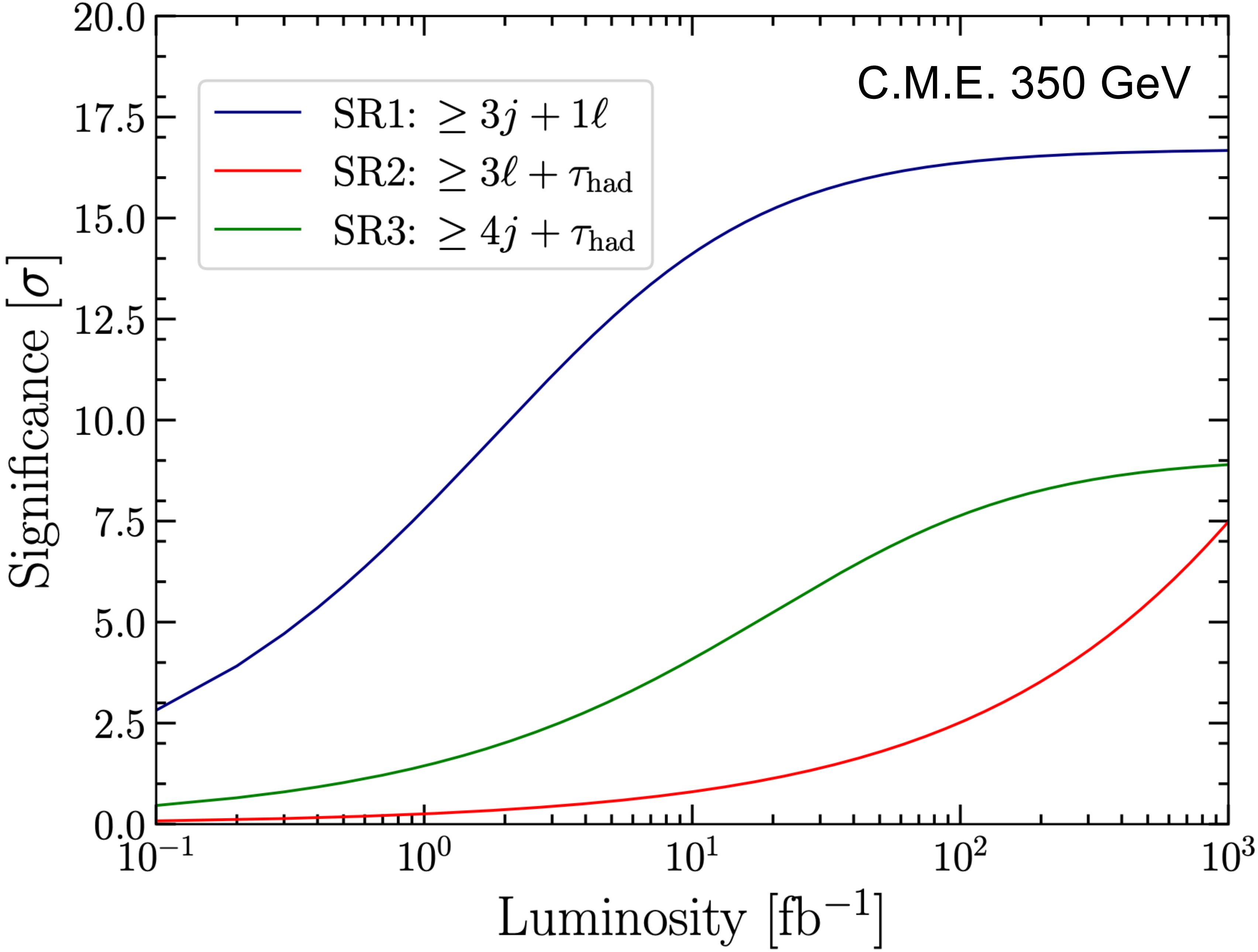
Analysis designed to reconstruct the invariant mass of the charged scalar

Cuts	Signal [fb]	Background [fb]
After preselection	1.3	1.25
10 GeV $< p_{\rm T}(j_1) <$ 100 GeV	1.28	1.17
10 GeV $< p_{\rm T}(j_2) <$ 65 GeV	1.272	1.07
10 GeV $< p_{\rm T}(j_3) <$ 50 GeV	1.27	1.03
$\lvert\Delta\phi(W \text{ or } Z, \Delta^{\pm})\rvert >$ 2.0 rad	1.253	0.92
$E_{\rm eff} <$ 240 GeV	1.252	0.70
$m_{\Delta^{\pm}} <$ 200 GeV	1.25	0.41

Table 7. Cut-flow summary for SR3, showing the signal and background cross sectior femtobarn after each selection cut.

O(1) GeV for 500 fb-1





C.M.E. 350 GeV
SR1: $\geq 3j + 1\ell$
SR2: $\geq 3\ell + \tau_{\mathrm{had}}$
SR3: $\geq 4j + \tau_{\mathrm{had}}$
Significance $[\sigma]$
Luminosity $[\mathrm{fb}^{-1}]$
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Outlook and Conclusions

- Presence of large narrow excess at 152 GeV in the $\gamma\gamma, Z\gamma, WW$ channels but absence in ZZ channel prompts to consider models that alter custodial symmetry without violating constraints
- Consider embedding the 152 GeV neutral scalar into a Triplet with Y=0, Δ^0
- Leads to prediction of degenerate charged scalars, $\Delta^{\pm}$ producing VVV excesses at LHC
  - Excess of VVV production identified
- Direct impact on e^+e^- collisions, with strong discovery potential for C.M.E. 350 GeV and mass measurement of O(1) GeV for 500 fb^{-1}