Indications for a 150 GeV Triplet Higgs at the LHC

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Oct 8, Higgs@Capri2025

- Based on 2402.00101, 2404.14492, 2411.18618, 2509.07094 with Andreas Crivellin, Siddharth Maharathy, Sumit Banik, Guglielmo Coloretti, Bruce Mellado.

(Going beyond) the Standard Model

A tale of theoretical and phenomenological success

- Several predictions confirmed by experiments at a persuasive level of accuracy: **neutral weak currents, massive vector bosons, Higgs boson**

Theoretical issues:

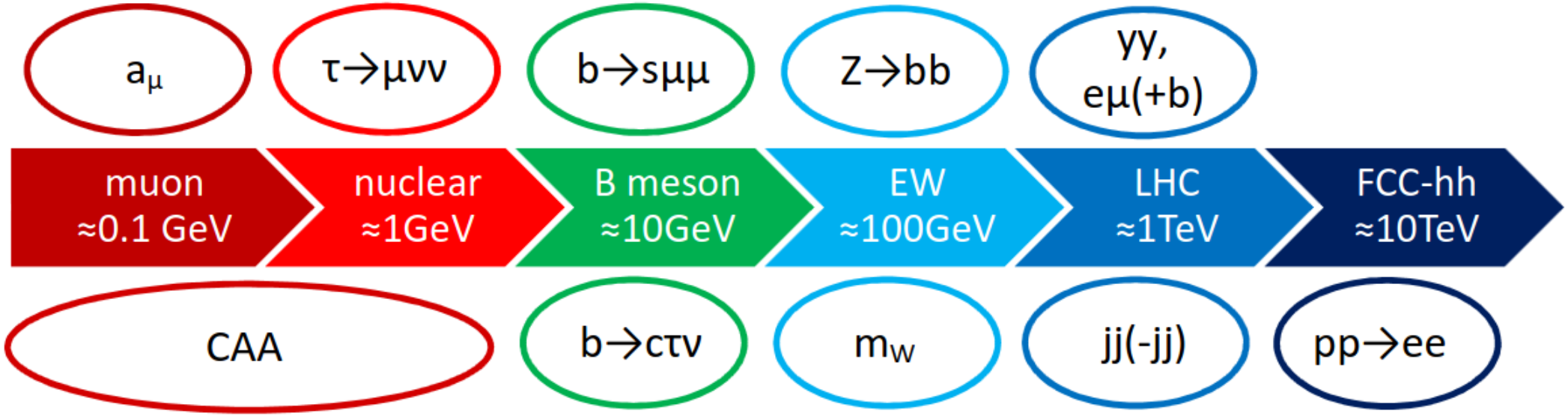
- Fermion mass and mixing hierarchies
- Electroweak vacuum instability
- Strong CP problem
- Naturalness problem

Experimental inconsistencies:

- Neutrino masses and mixings
- Anomalous magnetic moments of the electron and the muon
- B-anomalies
- Baryon asymmetry in the Universe
- Dark matter

Anomalies

- Extensive test of the SM: no discovery of any BSM particles yet
- Several (“Anomalies") : hints for new physics



[stolen from 2309.03870 by Crivellin & Mellado]

- Diphoton, ditau anomalies (95 GeV), Multilepton anomalies at the LHC, ...

  It is very unlikely that all these anomalies will be confirmed in the future, but it is ALSO unlikely that all of them are just statistical flukes.

  Therefore, it is important to assess these anomalies.

Extension of the Standard Model

- Measured properties of the 125 GeV Higgs are consistent with the SM.
- No guiding principle or symmetry forbids the extension of the Higgs sector.
- Several anomalies can be explained by extending the SM Higgs sector.
  $\Rightarrow$ provided their role in electroweak symmetry breaking is minute.
- A plethora of such models: SM + $SU(2)_L$ singlets/doublets/triplets, etc.
- Why a real Higgs triplet?

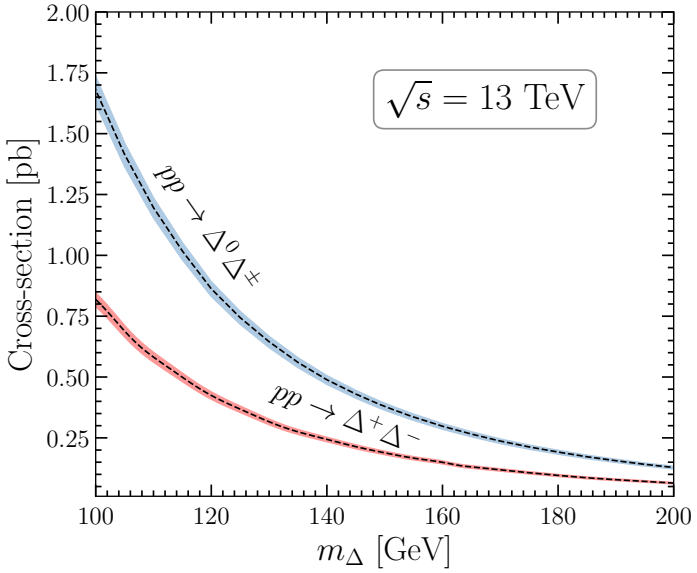
1. **"Multilepton anomalies": compatible with the production of a heavier Higgs decaying into a pair of ≈ 150 GeV Higgses which dominantly decay to WW. 1606.01674, 1711.07874, 1901.05300, 1912.00699, 2009.00032, 2302.07276, 2308.07953, 2312.17374**
2. **There is no excess in the $H \to ZZ^* \to 4\ell$ channel. ATLAS 2004.03447**
3. **Leads to a positive shift in the W-mass at tree-level, as preferred by the CDF-II measurement. (Optional!)**

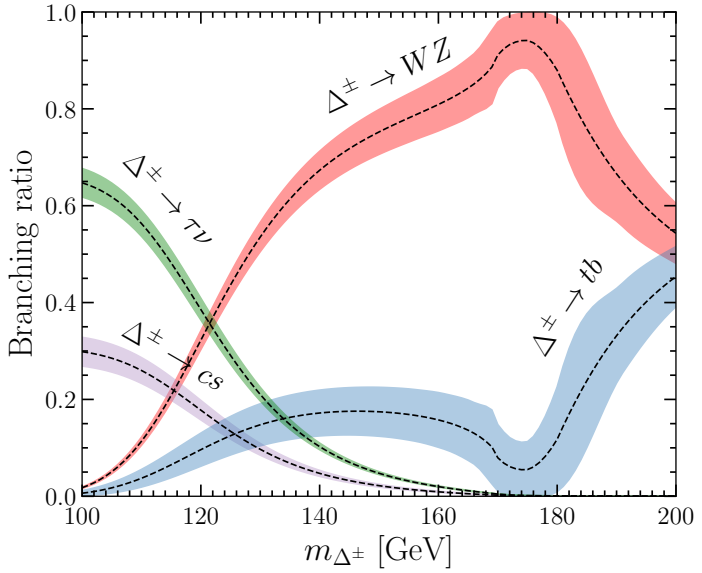
A real Higgs triplet model

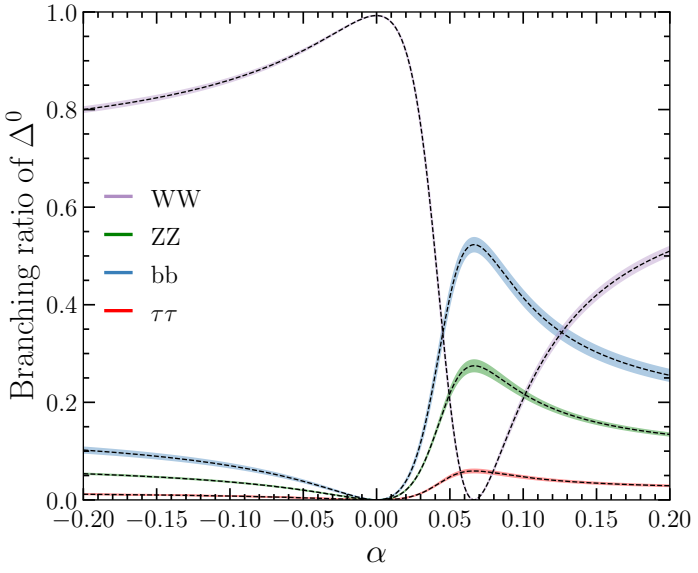
- SM + a $SU(2)_L$ triplet scalar with $Y = 0$

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

- **New states:** a neutral (Δ^0) and a charged Higgs ($\Delta^\pm$).
- Δ^0 procures a non-zero VEV $\Rightarrow$ a positive shift in m_W at tree-level, **EWPD** $\Rightarrow v_\Delta \lesssim \mathcal{O}(1)$ GeV.
- (vacuum stability + perturbative unitarity + EWPD) $\Rightarrow$ Δ^0 and $\Delta^\pm$ are nearly mass-degenerate
- **Production & Decays of the Triplet Higgses:** Drell-Yan production ($W^*/\gamma^*/Z^*$ mediated)

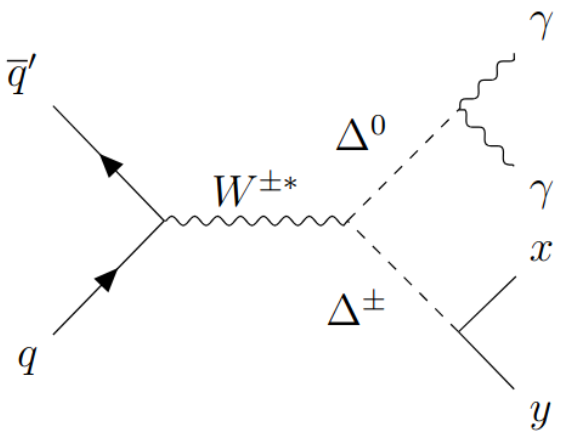






Where to look for the evidence of a Triplet Higgs?

- **Final state:** diphoton + additional particles / missing p_T ($\gamma\gamma + X$)



- **Why $\gamma\gamma + X$?**
  1. smaller SM background
  2. Δ^0 can be reconstructed from the diphoton invariant mass
  3. experimental resolution for the reconstructed resonance mass is better
- **The most recent $\gamma\gamma + X$ searches by ATLAS/CMS**
  1. 2301.10486: 22 $\gamma\gamma + X$ signal regions (SRs), mild excesses in a few SRs
  2. 2405.20040: 3 $\gamma\gamma + X$ SRs

  They provide $m_{\gamma\gamma}$ distributions in the 105–160 GeV range, thereby covering part of the mass range of our interest.

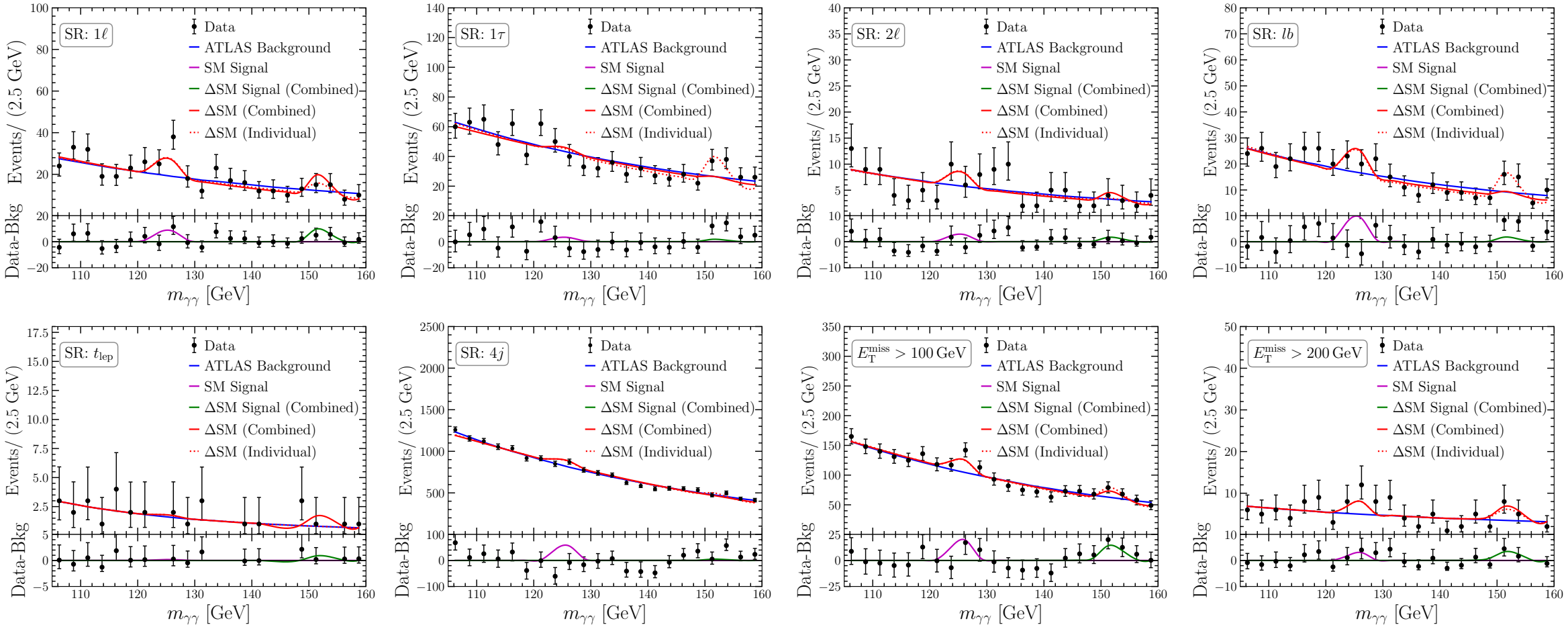
Analysing the $\gamma\gamma + X$ searches by ATLAS: Relevant SRs

- out of 25 SRs, only 10 SRs are relevant for our model

Target	Signal region	Detector level selections	Correlation
High jet activity [83]	$4j$	$n_{\text{jet}} \geq 4$, $\lvert\eta_{\text{jet}}\rvert < 2.5$	–
Top [83]	ℓb	$n_\ell \geq 1$, $n_{b\text{-jet}} \geq 1$	–
	t_{lep}	$n_{\ell=e,\mu} = 1$, $n_{\text{jet}} = n_{b\text{-jet}} = 1$	
Lepton [83, 133]	2ℓ	$ee, \mu\mu$ or $e\mu$	$< 26\%$
	1ℓ	$n_\ell = 1$, $n_{\tau_{\text{had}}} = 0$, $n_{b\text{-jet}} = 0$, $E_{\text{T}}^{\text{miss}} > 35$ GeV (only for e-channel)	
Tau [133]	$1\tau_{\text{had}}$	$n_\ell = 0$, $n_{\tau_{\text{had}}} = 1$, $n_{b\text{-jet}} = 0$, $E_{\text{T}}^{\text{miss}} > 35$ GeV	–
$E_{\text{T}}^{\text{miss}}$ [83]	$E_{\text{T}}^{\text{miss}} > 100$ GeV	$E_{\text{T}}^{\text{miss}} > 100$ GeV	29%
	$E_{\text{T}}^{\text{miss}} > 200$ GeV	$E_{\text{T}}^{\text{miss}} > 200$ GeV	

Analysing the $\gamma\gamma + X$ searches by ATLAS: $m_{\gamma\gamma}$ spectra

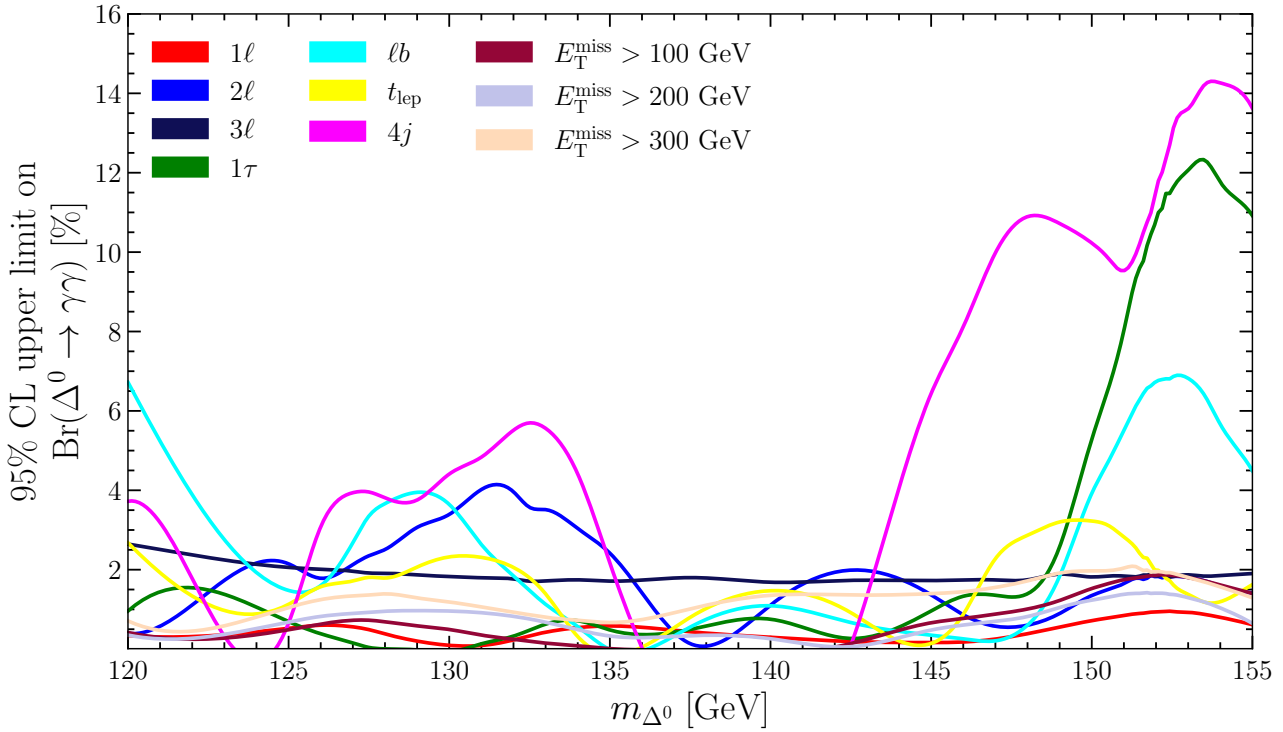
Refitting the continuum background: $\left(1 - \frac{m_{\gamma\gamma}}{\sqrt{s}}\right)^{b} \left(\frac{m_{\gamma\gamma}}{\sqrt{s}}\right)^{a_0 + a_1 \log(m_{\gamma\gamma}/\sqrt{s})}$



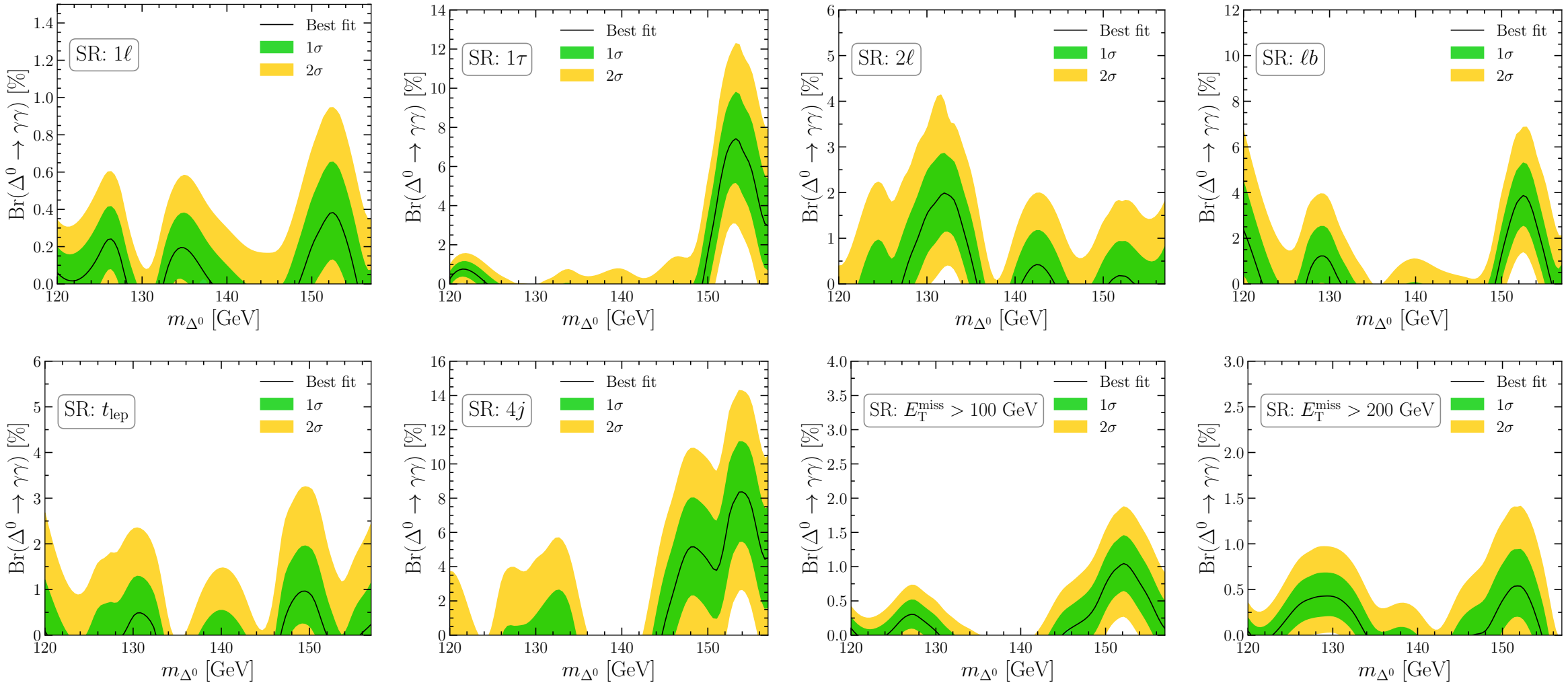
Analysing the $\gamma\gamma + X$ searches by ATLAS: Upper limits on diphoton BR

Assuming the bins as independent number-counting experiments $\mathcal{L}_{\rm SR}(\mu) = \prod_i \text{Poiss}\left(n^i|\mu s^i + b^i\right)$

Profile likelihood ratio test statistics $\Lambda_\mu = -2\log\left(\frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})}\right)$

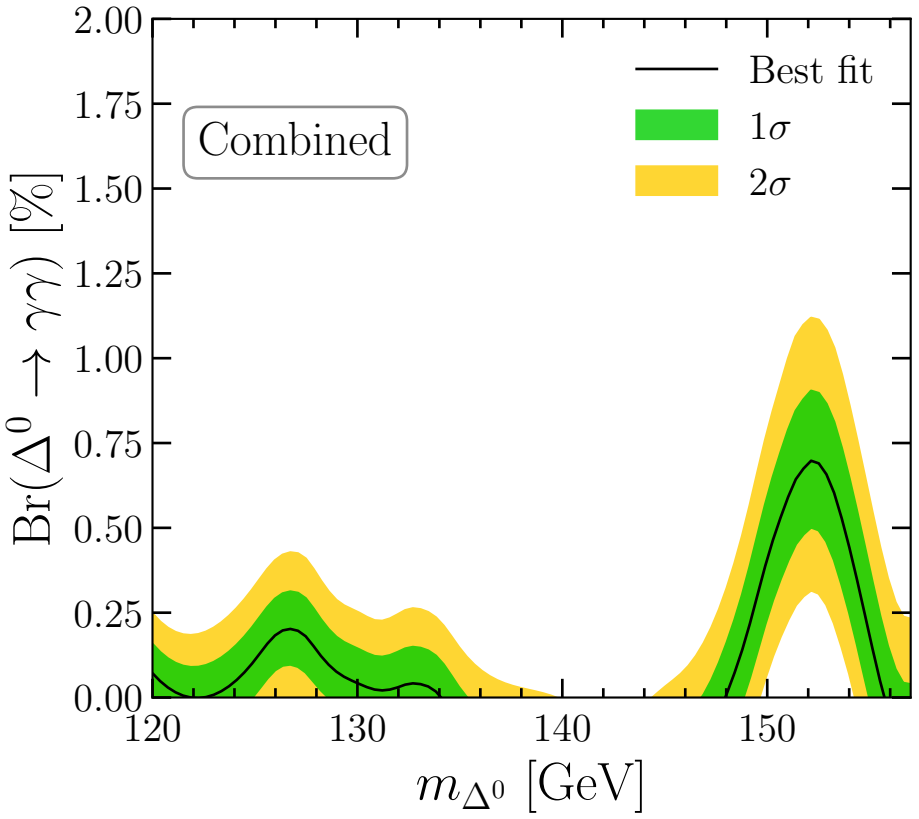


Analysing the $\gamma\gamma + X$ searches by ATLAS: Preferred diphoton BR



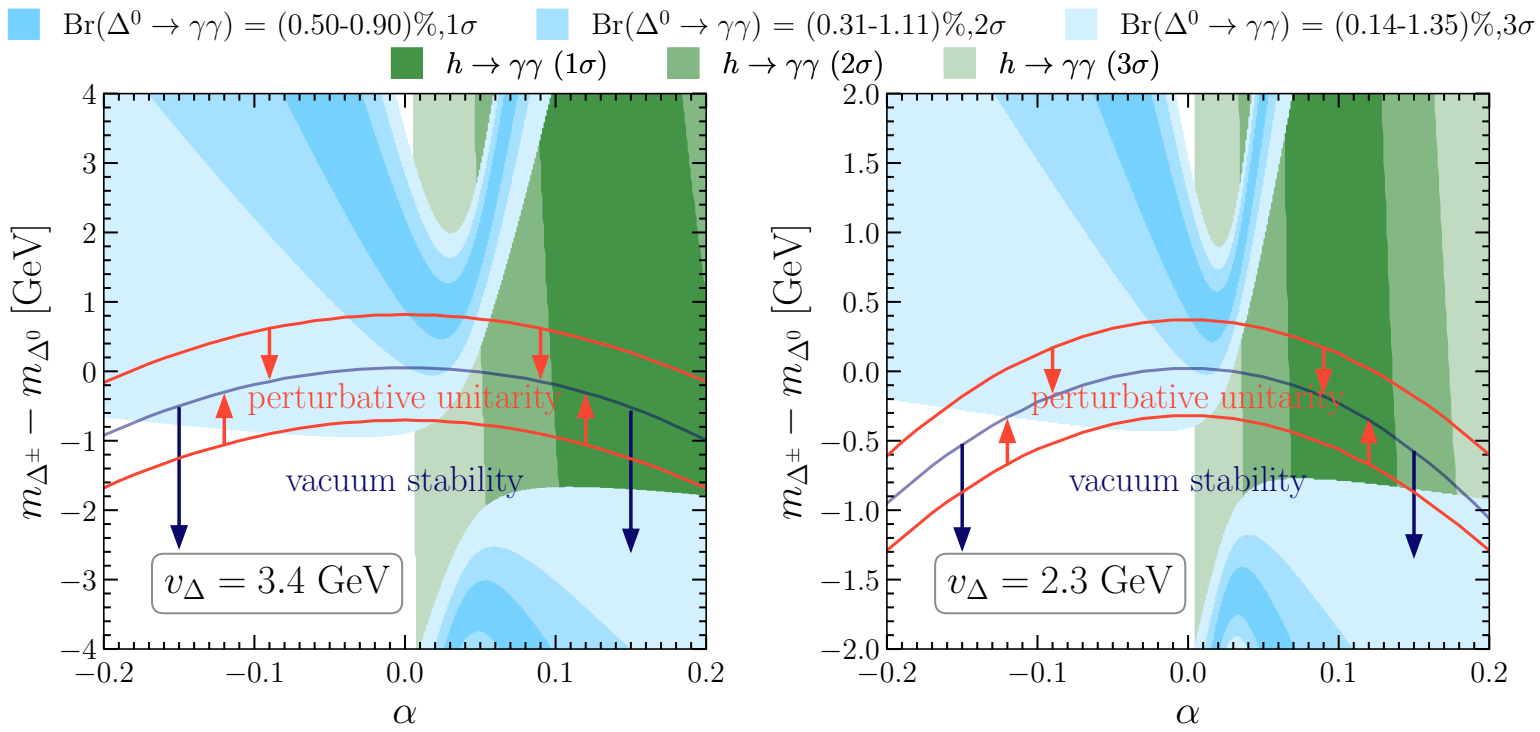
Analysing the $\gamma\gamma + X$ searches by ATLAS: Combinig all SRs

Combining all the relevant Signal Regions: $\mathcal{L}_{\rm SR}(\mu) = \prod_i \text{Poiss}\left(n^i|\mu s^i + b^i\right)$



The ATLAS $\gamma\gamma + X$ data favors a Br$(\Delta^0 \to \gamma\gamma) \approx 0.7\%$ at $m_{\Delta^0} \approx 152$ GeV with a significance of $\approx 4\sigma$

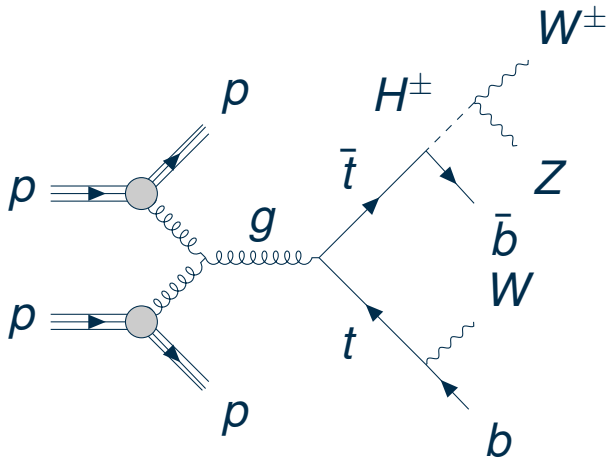
How well does this fit in the Higgs triplet model?



- The region preferred by the ATLAS $\gamma\gamma + X$ data is in tension with the theoretical constraints.
- While we have growing indications for a 152 GeV triplet-like Higgs, the model should be superseded with additional fields.

Part 2: Searching for low-mass charged Higgs bosons in top decays

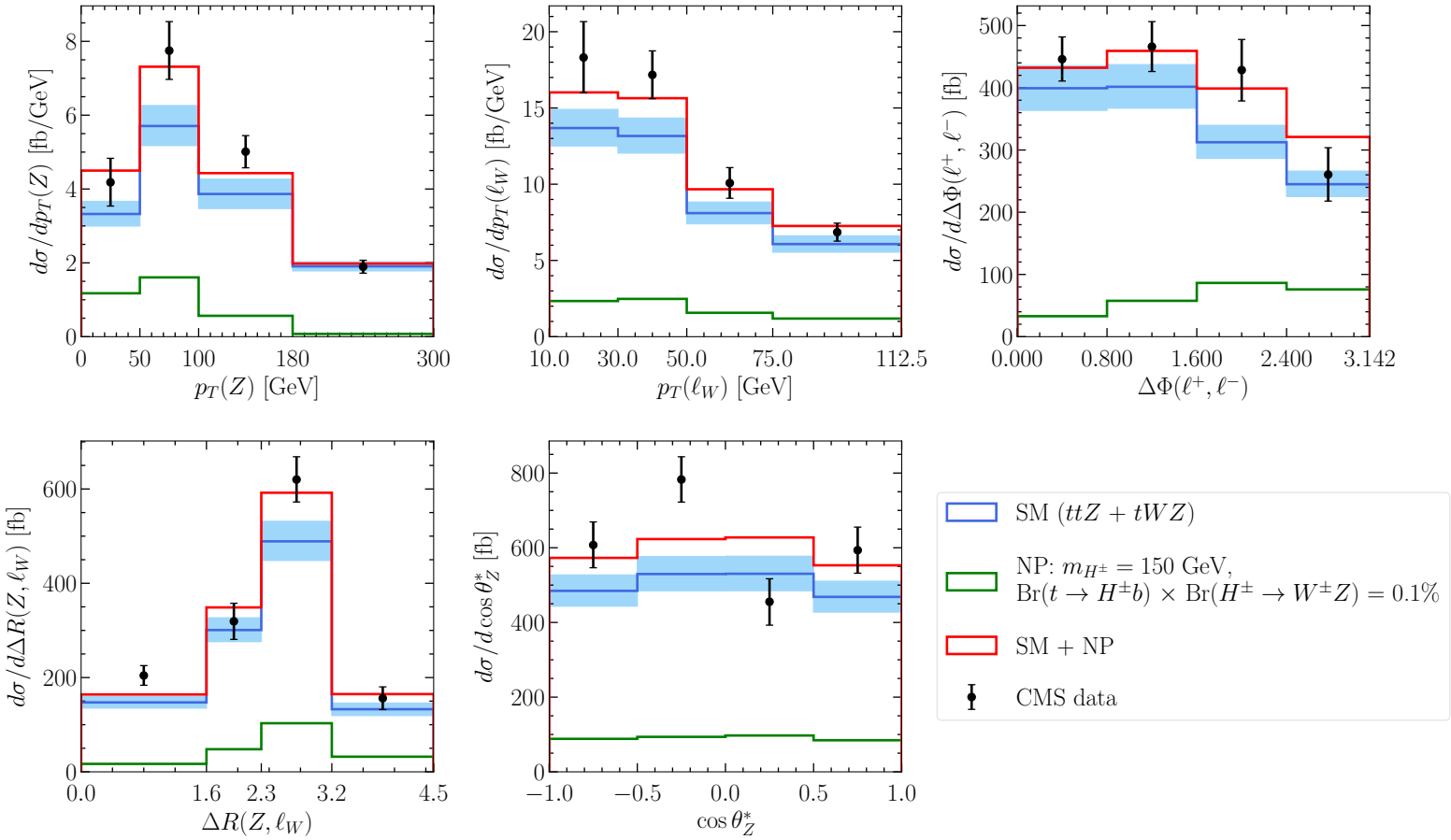
- Top-quark decays: a promising avenue for searching light charged Higgs bosons.
- CMS/ATLAS have searched for charged Higgs bosons decaying into *cs* [2005.08900, 2407.10096], *cb* [2302.11739] and $\tau\nu$ [1903.04560, 2412.17584], and put stringent limits on $\mathrm{Br}(t \to H^{\pm} b) \times \mathrm{Br}(H^{\pm} \to XY)$.
- But there is no search for the $H^{\pm} \to W^{\pm} Z$ mode. This mode can be dominant in $SU(2)_L$-triplet scenarios [Georgi 85, Chanowitz 8, Gunion 89, Cheung 94, Cheung 02, Asakawa 05]



- This leads to $t\bar{t}Z$-like signature: 3/4 leptons + *b*-jets. Therefore, we can constrain light charged Higgs by recasting existing $t\bar{t}Z$ analyses [ATLAS 2312.04450, CMS 2410.23475].

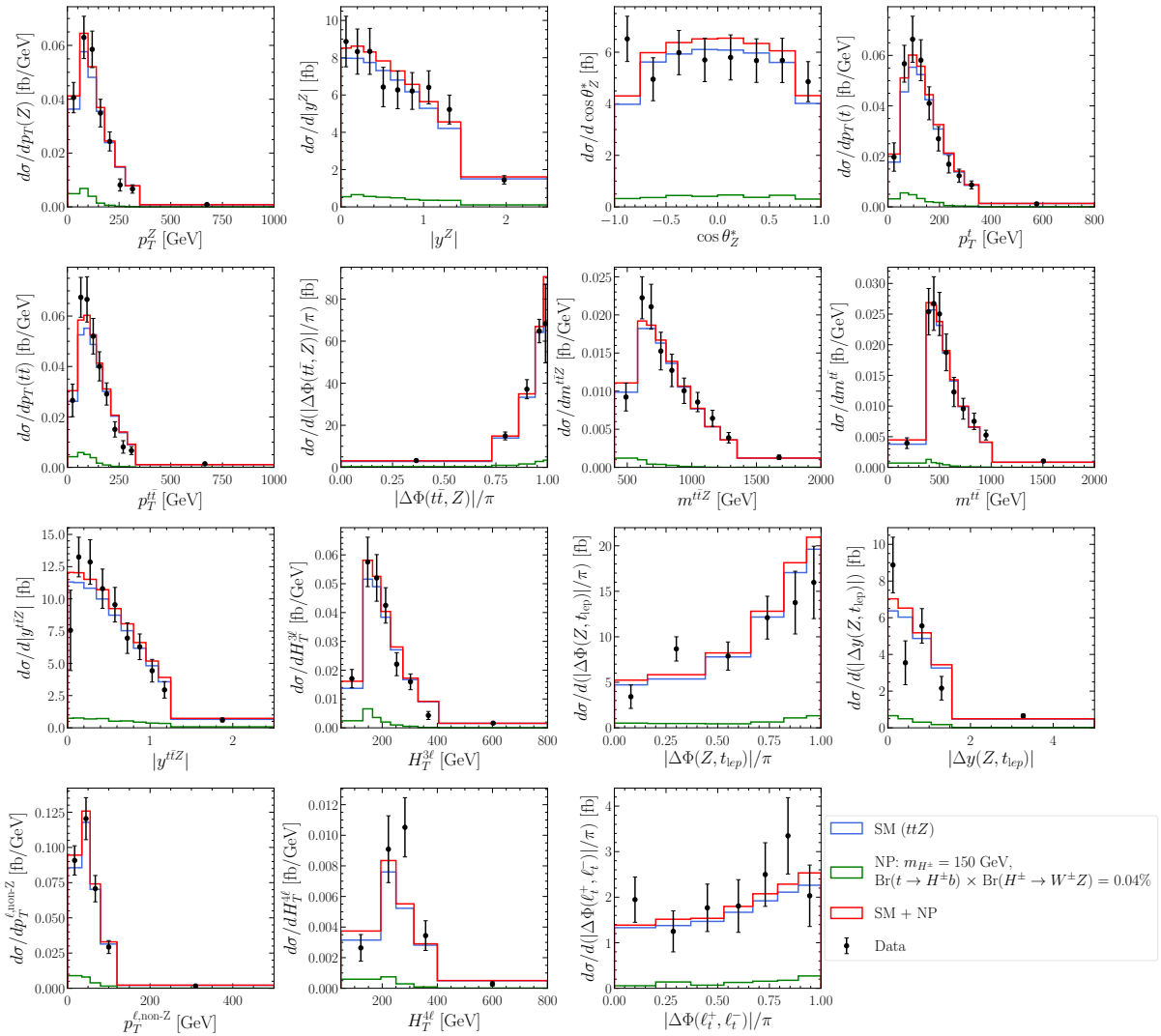
Recasting $t\bar{t}Z$ analyses [ATLAS 2312.04450, CMS 2410.23475]

- **Validation of our recast**: simulating the SM processes $pp \to t\bar{t}Z$ and tWZ using `MadGraph5_v3.5.3`, `Pythia 8.3`.
- For reconstruction/selection of physics objects, and event selection, we closely follow the CMS and ATLAS analyses.
- CMS provides differential cross sections for the sum of $t\bar{t}Z$ and tWZ production (within the SM), unfolded to the parton level, as functions of 5 kinematic variables.



Recasting $t\bar{t}Z$ analyses [ATLAS 2312.04450, CMS 2410.23475]

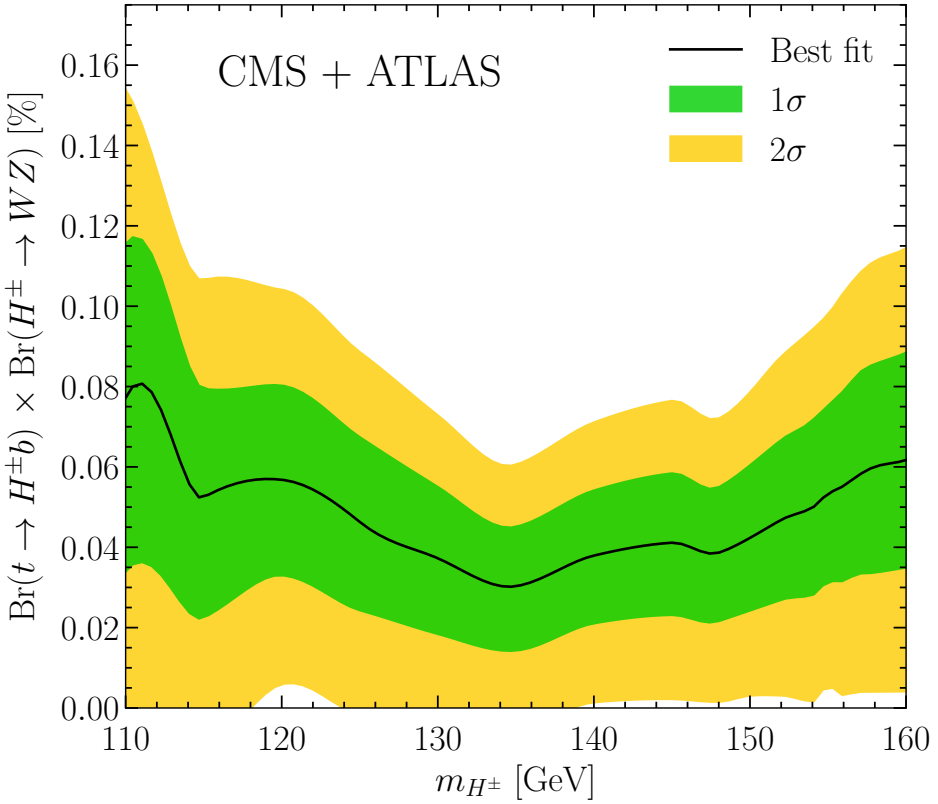
- ATLAS provides differential cross sections for $t\bar{t}Z$ production (within the SM), unfolded to both particle and parton levels, as functions of 15 kinematic variables.



Recasting $t\bar{t}Z$ analyses: Result

$$\chi^2 = [\sigma_i^{\text{data}} - \sigma_i^{\text{theory}}]\, \Sigma_{ij}^{-1}\, [\sigma_j^{\text{data}} - \sigma_j^{\text{theory}}]\,, \quad \sigma_i^{\text{theory}} = \mu_{\text{SM}}\, \sigma_i^{\text{SM}} + \mu_{\text{NP}}\, \sigma_i^{\text{NP}}$$

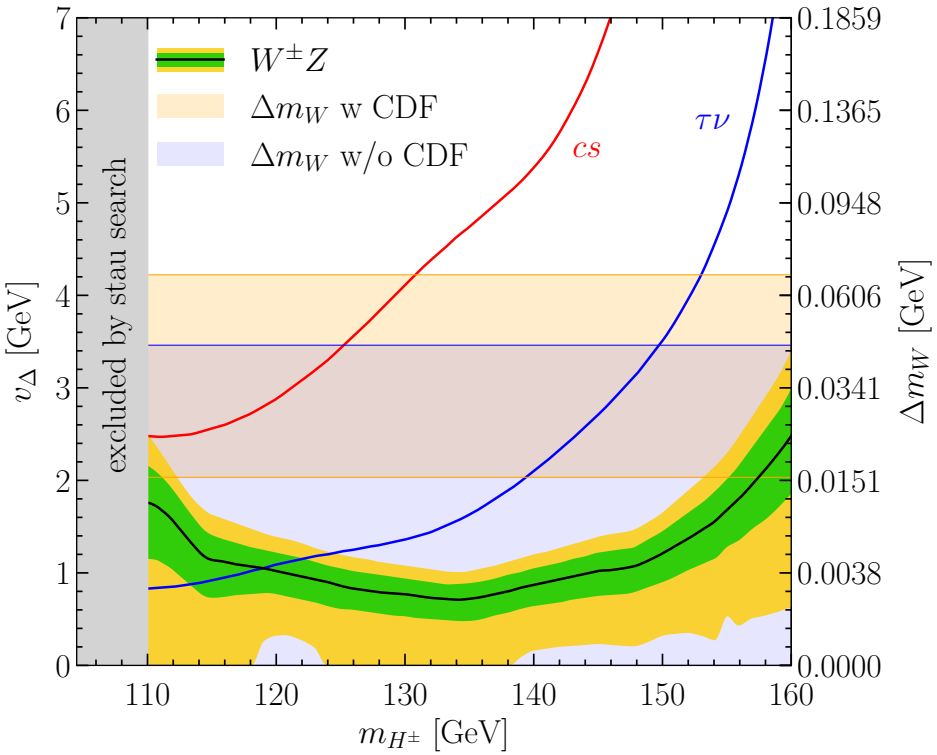
- The NP signal strength μ_{NP} is identified with $\text{Br}(t \to H^\pm b) \times \text{Br}(H^\pm \to W^\pm Z)$.



- Note: the lower edge of the 2σ band lies very close to zero, indicating a mild ($\sim 2\sigma$) preference for NP.

Recasting $t\bar{t}Z$ analyses: Interpretation within the real Higgs triplet model

- The decays of $H^{\pm}$ depend primarily on its mass, with the WZ mode being dominant.
- Moreover, this field remains largely unconstrained by LHC searches [Chabab 18, Butterworth 23, Ashanujjaman 24], as such $H^{\pm}$ can be lighter than the top quark, enabling $t \to H^{\pm} b$.



- The limits estimated here are stronger than those from the dedicated cs and $\tau\nu$ searches and surpass the electroweak precision constraints across the entire mass range.

Summary and Outlook

- ATLAS $\gamma\gamma + X$ data indicates toward a 152 GeV Higgs triplet, with $\mathrm{Br}(\Delta^0 \to \gamma\gamma) \approx 0.7\%$ and a significance of $\approx 4\sigma$.
- That said, the preferred region is in tension with the theoretical constraints; the model, therefore, should be superseded with additional fields.

- Recast of the $t\bar{t}Z$ measurements result in stringent limits on $\mathrm{Br}(t \to H^{\pm} b) \times \mathrm{Br}(H^{\pm} \to WZ)$ at the sub-permille level.
- Interpreted within the real Higgs triplet model, this yields a novel constraint on its VEV of $v_\Delta \lesssim 2\,\mathrm{GeV}$. Intriguingly, our limits are stronger than those from LHC searches in the cs and $\tau\nu$ modes. Furthermore, they surpass the bounds from electroweak precision observables in the entire mass range.
- Moreover, the $t\bar{t}Z$ data exhibit a $\sim 2\sigma$ preference for a NP signal. While not significant in isolation, it strengthens the case for a $152 \pm 1\,\mathrm{GeV}$ Higgs, indicated in diphoton measurements.
- Future HL-LHC runs and dedicated analyses targeting the $H^{\pm} \to WZ$ mode in top decays could decisively test this scenario, potentially uncovering Higgs bosons beyond the SM.

Thanks for your attention. **Any questions?**