New Higgses at the Electroweak Scale

Les Rencontres de Physique de la Vallée d'Aoste

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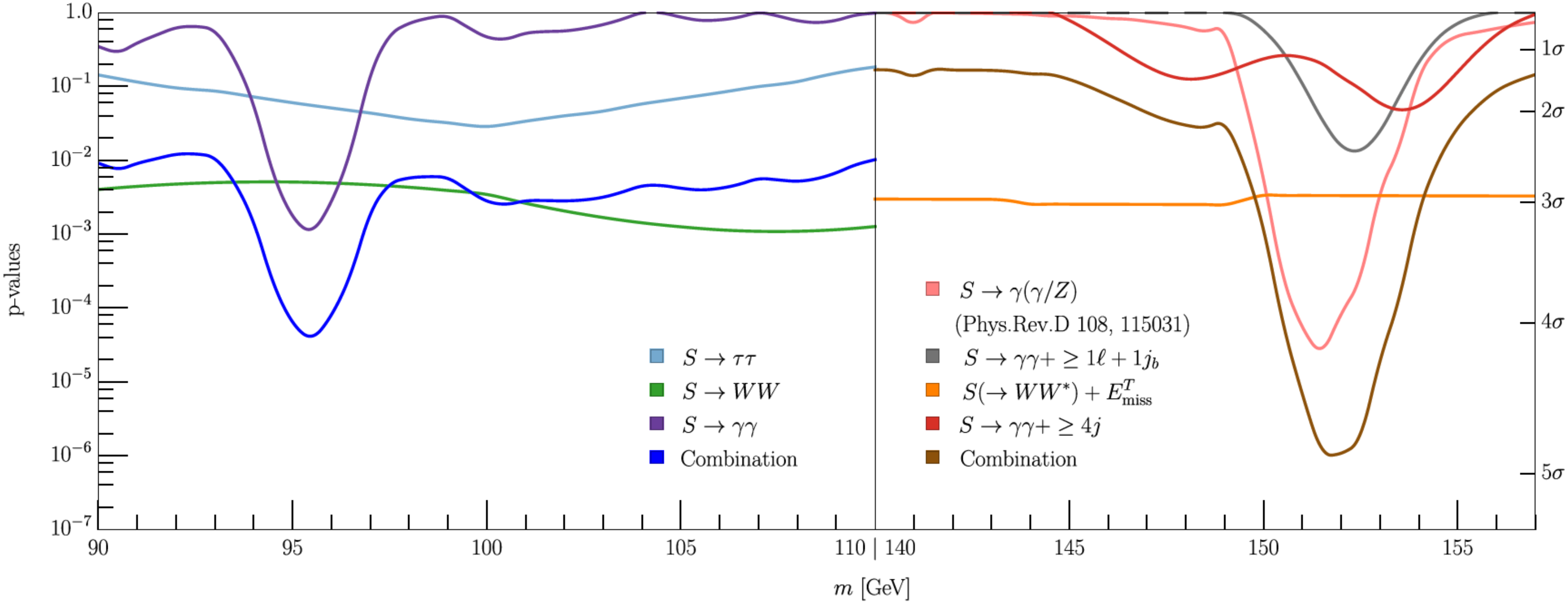
Outline

1. The 95 GeV and 151.5 GeV candidates
2. Is the 151.5 GeV scalar a real Higgs triplet?
3. Anomalies in $t\bar{t}$ differential distributions
4. The Δ2HDMS

Direct hints

[S. Bhattacharya, GC, A. Crivellin et al.]

- Several channels have excess at 95 GeV and 151.5 GeV
- Significance of 3.8σ and 4.7σ (global) respectively
- **For 151.5 GeV, associated production is required**



A 151.5 GeV triplet?

- Fields: neutral Δ^0, charged $\Delta^\pm$
- Parameters: $\langle\Delta\rangle = v_\Delta,\ \alpha_\Delta$
- Weak flavor bounds

	$SU(2)_L$	$U(1)_Y$
Δ	3	0

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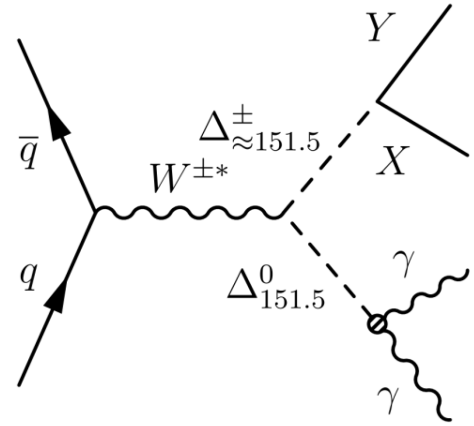

151.5 GeV mostly produced in associated production (AP) ⟷ Produced in AP via Drell-Yan (DY)

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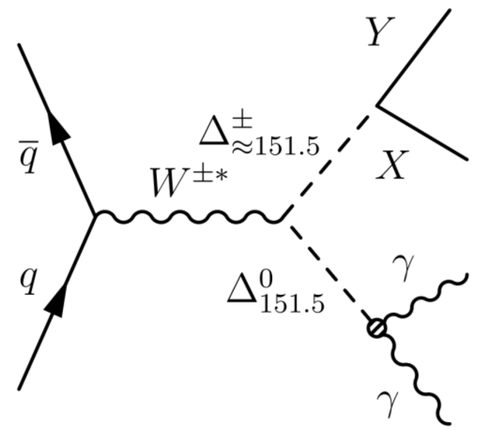

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No excess at 151.5 GeV in ZZ but in WW ⟷ Δ^0 couples to WW but not ZZ (at tree level and with $\alpha_\Delta = 0$)

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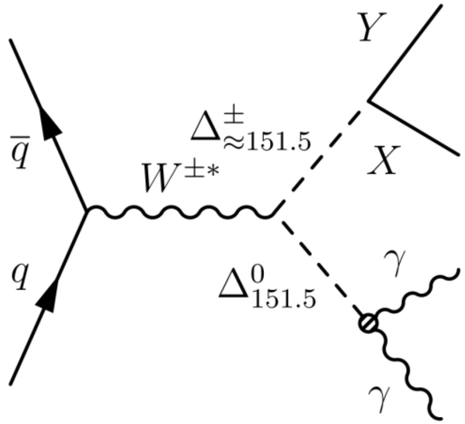

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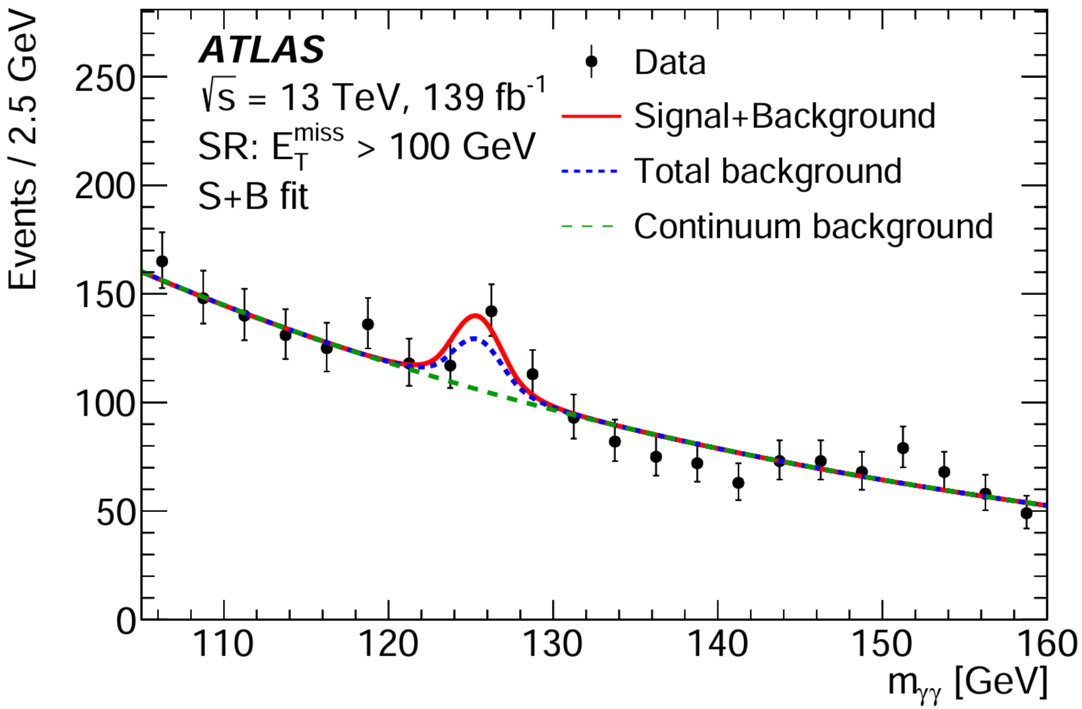
No excess at 151.5 GeV in ZZ but in WW ⟷ Δ^0 couples to WW but not ZZ (at tree level and with $\alpha_\Delta = 0$)

W mass (2.2/3.7σ above SM w/w.o CDFII) ⟷ $\langle\Delta\rangle = v_\Delta \approx O(\text{GeV})$ (therefore: $m_{\Delta^0} \approx m_{\Delta^\pm}$)

ATLAS analysis: $H \to \gamma\gamma + X$

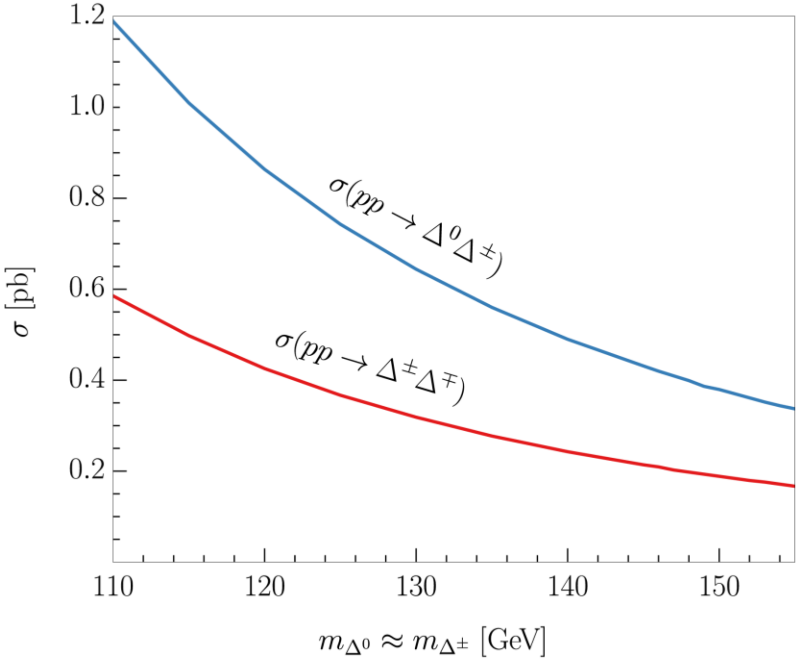
[ATLAS]

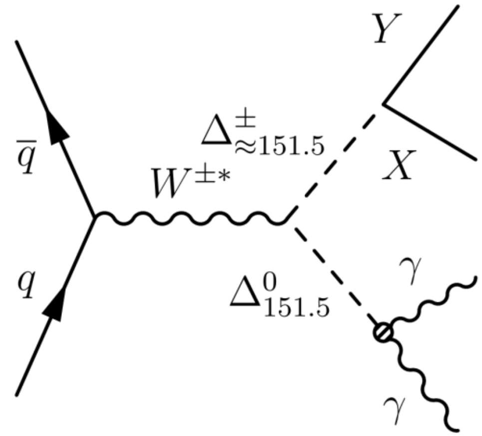
- ATLAS model independent search for AP of SM $H \to \gamma\gamma + X$ covering the 105-160 GeV range
- Multiple categories ($X = l, j, j_b, E_T^{miss}$ ...)
- **Reduced SM background and enhanced NP sensitivity**

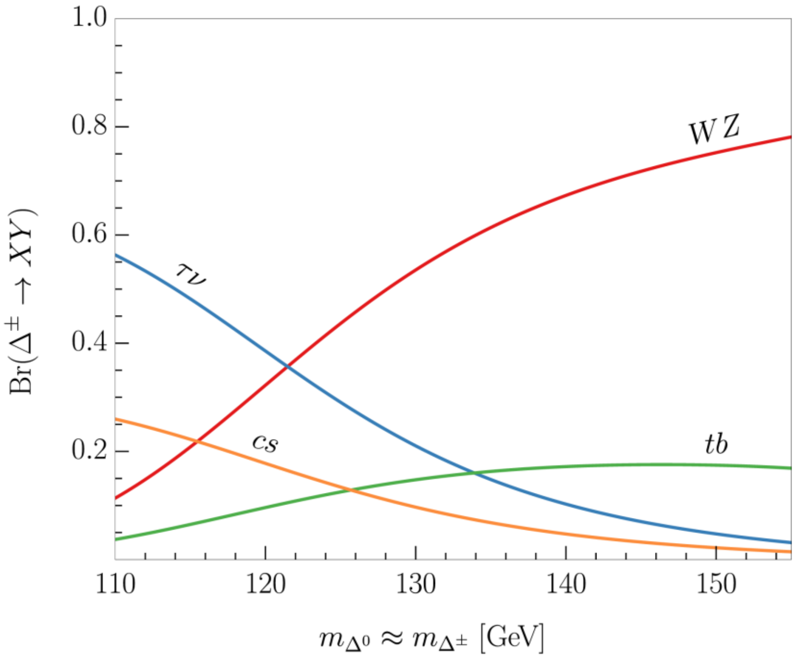


Results: $H \to \gamma\gamma + X$

[S. Banik, GC, A. Crivellin et al.]



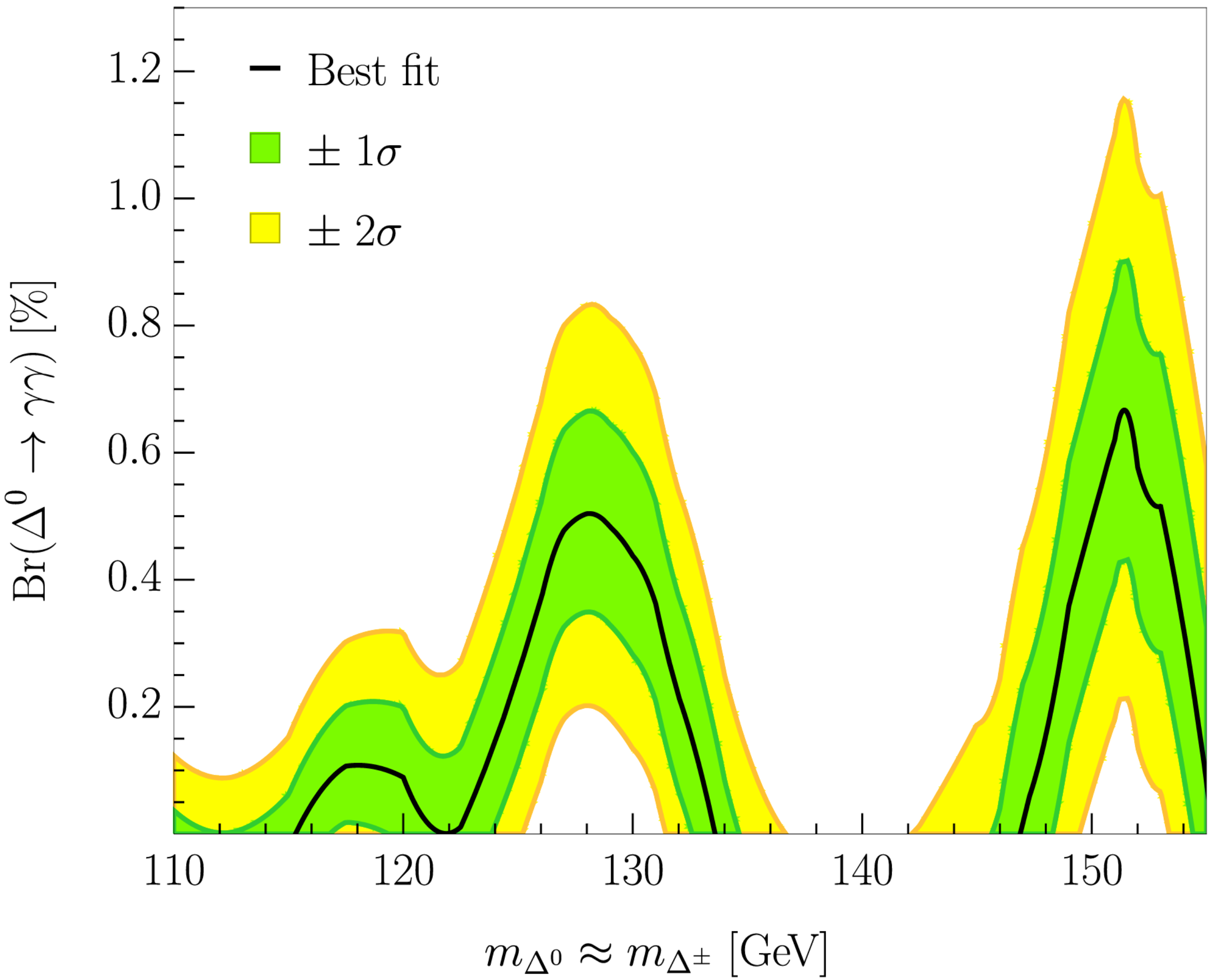




- All relevant parameters are fixed except $m_{\Delta^0,\,\Delta^\pm}$ and $\mathrm{Br}(\Delta^0 \to \gamma\gamma)$

Results: $H \to \gamma\gamma + X$

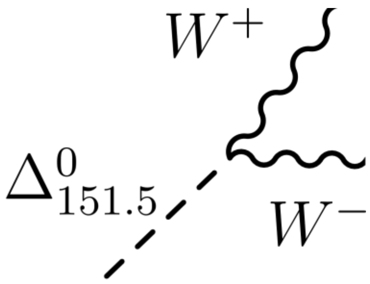
[S. Banik, GC, A. Crivellin et al.]



Towards the Δ2HDMS

[S. Banik, GC, A. Crivellin, B. Mellado]

- **151.5 GeV: real triplet $\Delta^0_{151.5}$ (Δ)**
  ⇒ mainly decays to WW



Towards the Δ2HDMS

[S. Banik, GC, A. Crivellin, B. Mellado]

- **151.5 GeV: real triplet $\Delta^0_{151.5}$ (Δ)**
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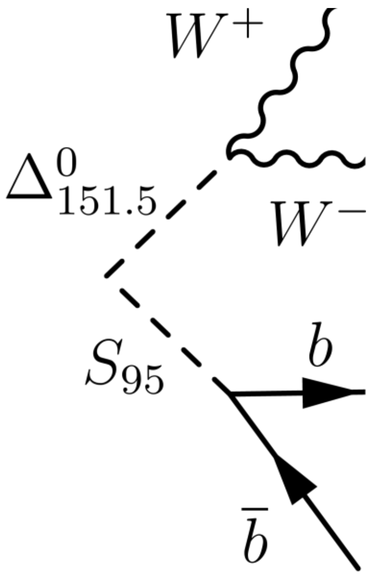
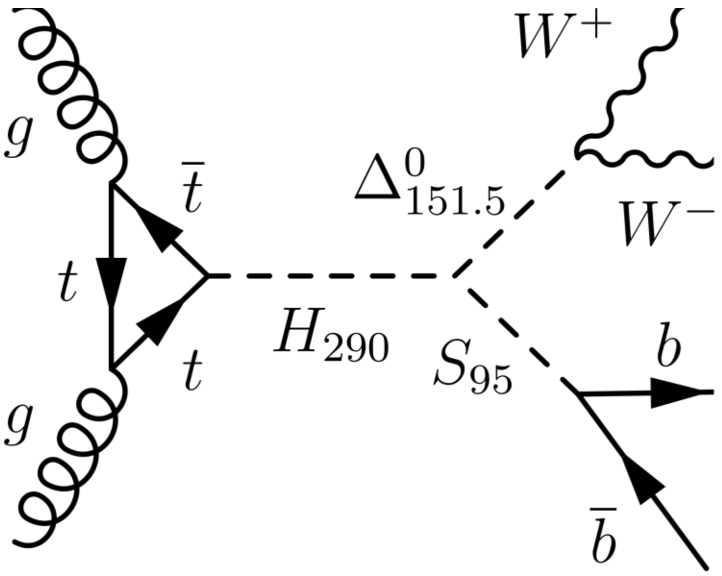
- **95 GeV: real singlet S_{95} (φ_s)**
  ⇒ mainly decays to $\boldsymbol{b\bar{b}}$



Towards the Δ2HDMS

[S. Banik, GC, A. Crivellin, B. Mellado]

- **151.5 GeV: real triplet $\Delta^0_{151.5}$ (Δ)**
  ⇒ mainly decays to WW
- **95 GeV: real singlet S_{95} (φ_s)**
  ⇒ mainly decays to $b\bar{b}$
- m_{Δ^0}, m_S fixed by hints at 151.5 GeV, 95 GeV (resp.)
- H contained in a second Higgs doublet φ_1 with
  $m_H > m_{\Delta^0} + m_S$



$$\mathcal{L} = -\lambda_0 \phi^\dagger_{\rm SM} \Delta \phi_1 \phi_{\rm s} + {\rm h.c.}$$

Towards the Δ2HDMS

[S. Banik, GC, A. Crivellin, B. Mellado]

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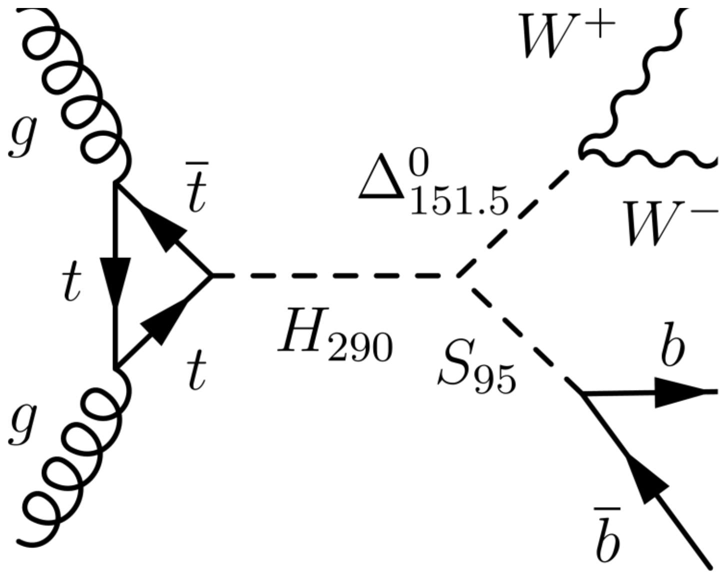


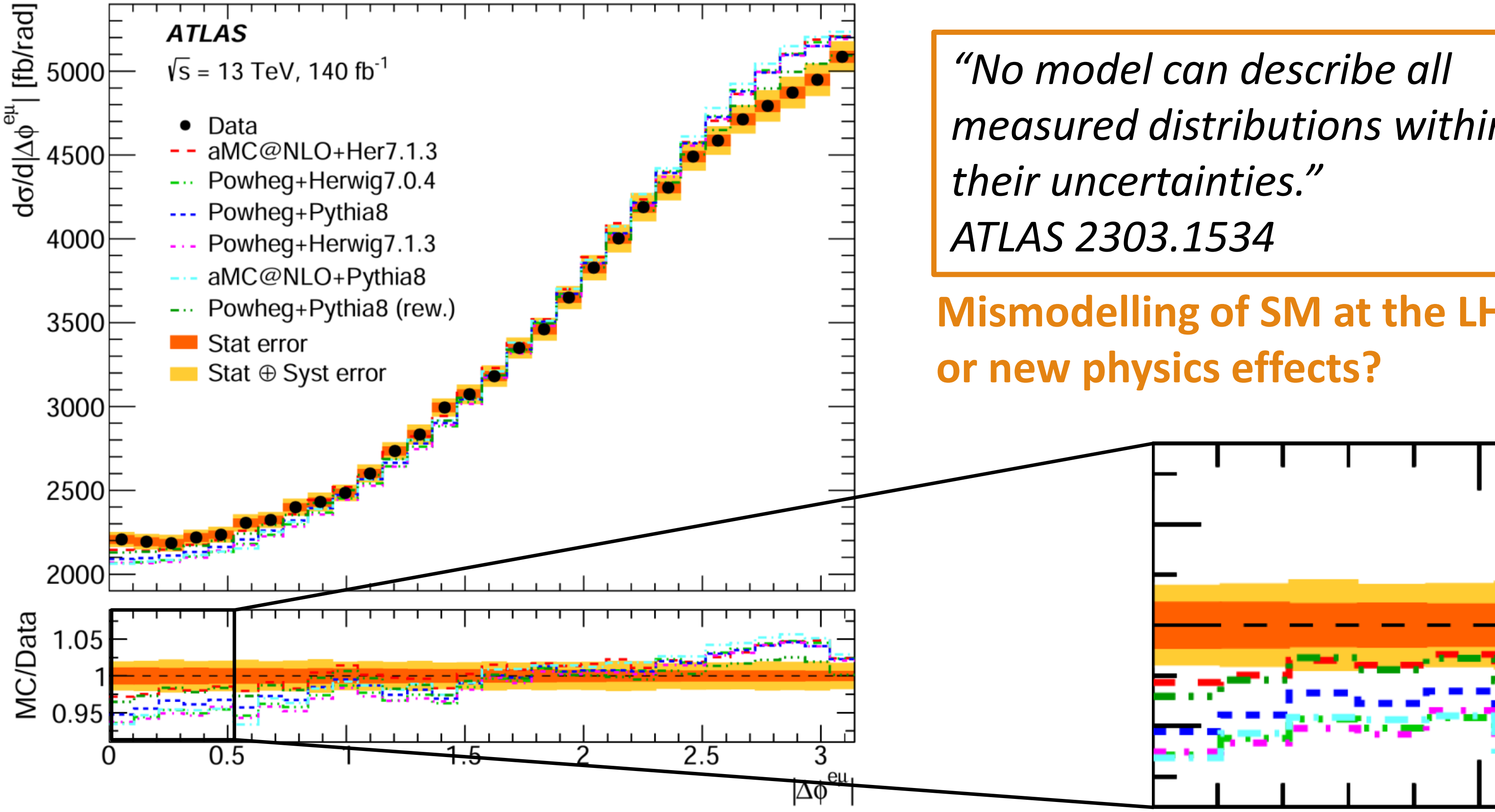
Has $t\bar{t}$-like ($WWb\bar{b}$) signature

$$\mathcal{L} = -\lambda_0 \phi^\dagger_{\mathrm{SM}} \Delta \phi_1 \phi_{\mathrm{s}} + \mathrm{h.c.}$$

$pp \to t\bar{t}$ differential distributions

[ATLAS]

- Several distributions analyzed for the lepton pair
- **Example: angle between the two final leptons $|\Delta\varphi^{e\mu}|$**



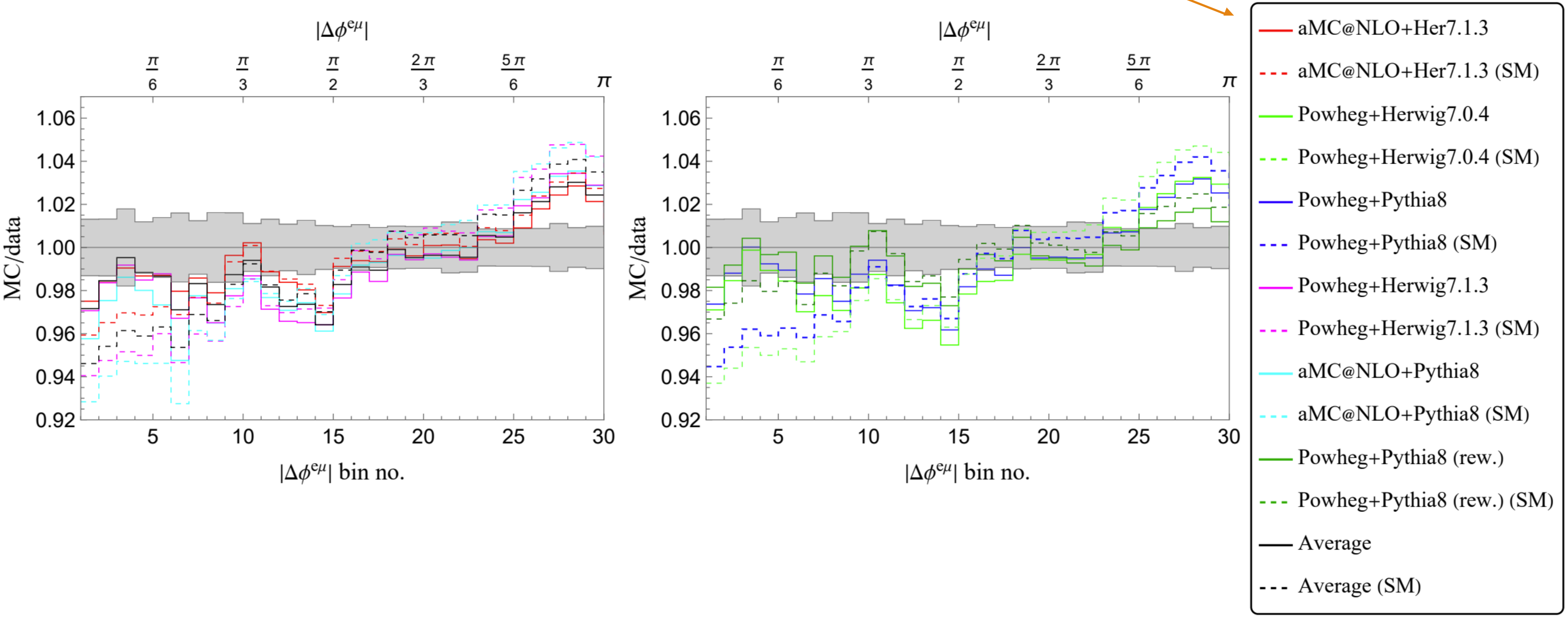
"No model can describe all measured distributions within their uncertainties."
ATLAS 2303.1534

Mismodelling of SM at the LHC or new physics effects?

$pp \to t\bar{t}$: results

[S. Banik, GC, A. Crivellin, B. Mellado]

ATLAS generated $t\bar{t}$ samples with **several different** matrix element generators, parton shower, and fragmentation simulation

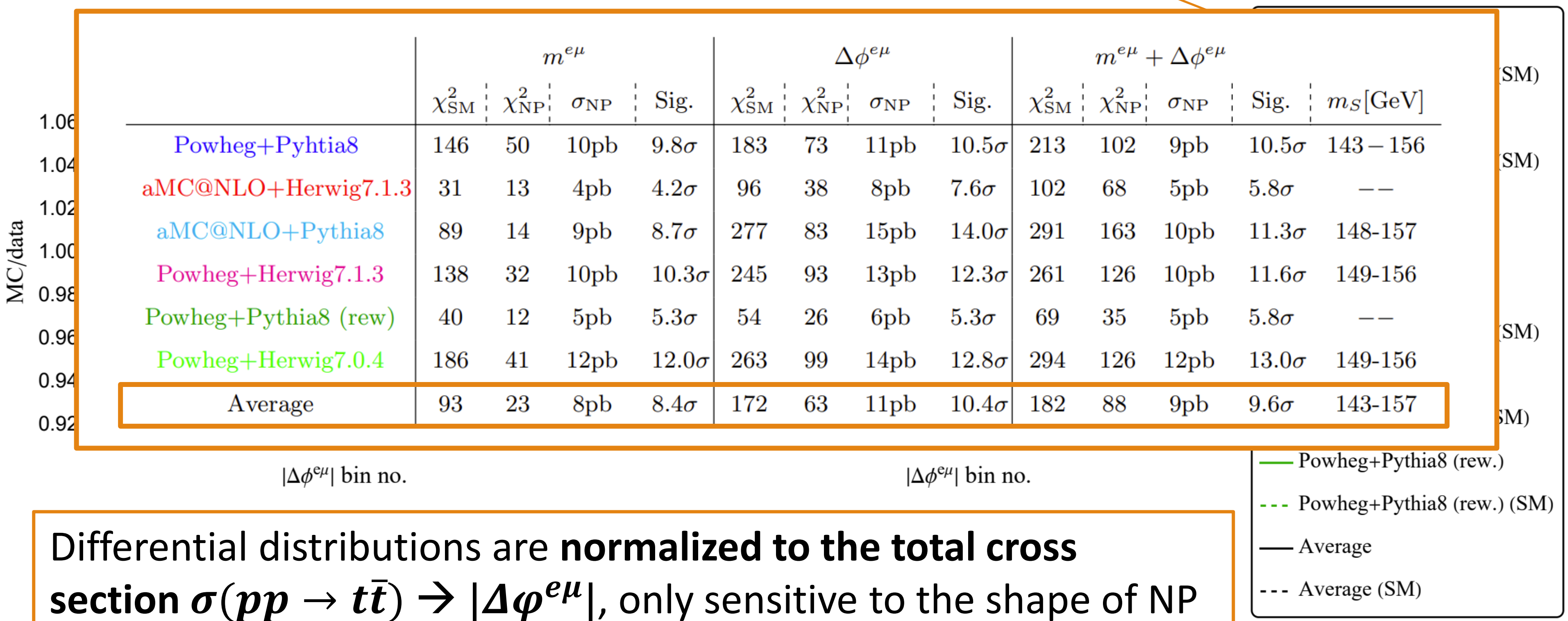


$pp \to t\bar{t}$: results

[S. Banik, GC, A. Crivellin, B. Mellado]

ATLAS generated $t\bar{t}$ samples with **several different** matrix element generators, parton shower, and fragmentation simulation

	$m^{e\mu}$				$\Delta\phi^{e\mu}$				$m^{e\mu} + \Delta\phi^{e\mu}$				
	$\chi^2_{\rm SM}$	$\chi^2_{\rm NP}$	$\sigma_{\rm NP}$	Sig.	$\chi^2_{\rm SM}$	$\chi^2_{\rm NP}$	$\sigma_{\rm NP}$	Sig.	$\chi^2_{\rm SM}$	$\chi^2_{\rm NP}$	$\sigma_{\rm NP}$	Sig.	m_S[GeV]
Powheg+Pyhtia8	146	50	10pb	9.8σ	183	73	11pb	10.5σ	213	102	9pb	10.5σ	$143-156$
aMC@NLO+Herwig7.1.3	31	13	4pb	4.2σ	96	38	8pb	7.6σ	102	68	5pb	5.8σ	$--$
aMC@NLO+Pythia8	89	14	9pb	8.7σ	277	83	15pb	14.0σ	291	163	10pb	11.3σ	148-157
Powheg+Herwig7.1.3	138	32	10pb	10.3σ	245	93	13pb	12.3σ	261	126	10pb	11.6σ	149-156
Powheg+Pythia8 (rew)	40	12	5pb	5.3σ	54	26	6pb	5.3σ	69	35	5pb	5.8σ	$--$
Powheg+Herwig7.0.4	186	41	12pb	12.0σ	263	99	14pb	12.8σ	294	126	12pb	13.0σ	149-156
Average	93	23	8pb	8.4σ	172	63	11pb	10.4σ	182	88	9pb	9.6σ	143-157

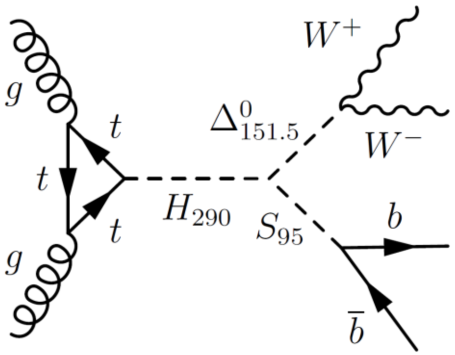


Differential distributions are **normalized to the total cross section $\sigma(pp \to t\bar{t})$** → $|\Delta\varphi^{e\mu}|$, only sensitive to the shape of NP
→ **NP hypothesis is preferred over the SM by $\geq 5.8\sigma$**

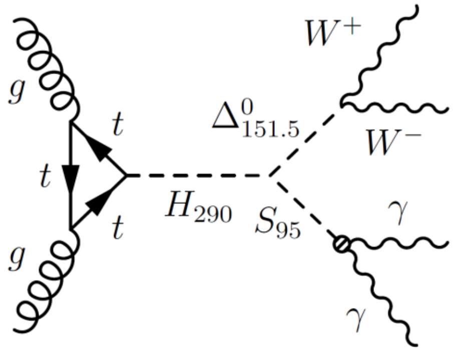
Towards the Δ2HDMS (continued)

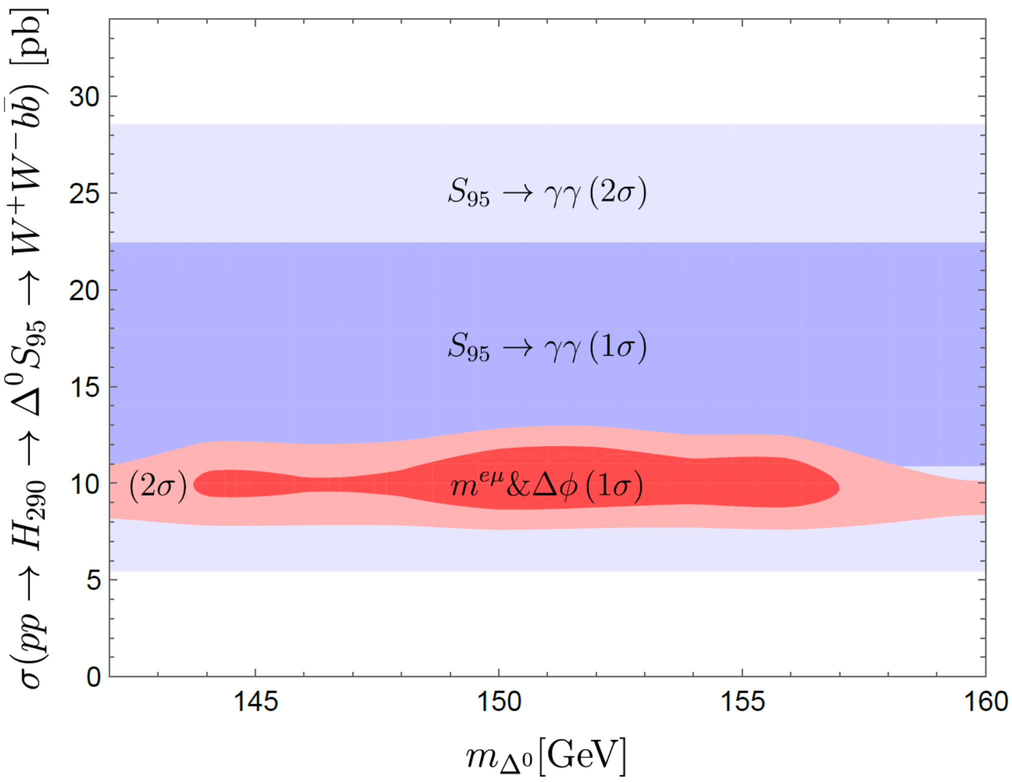
[S. Banik, GC, A. Crivellin, B. Mellado]

- $t\bar{t}$ **differential distributions fixes** $pp \to H_{290} \to \Delta_{151.5}\, S_{95}$



- $\gamma\gamma$ **strength at 95 GeV with Br fixed by the model**





The preferred regions nicely overlap

Conclusions

- **Hints for NP at 95 GeV and 151.5 GeV** (3.8σ and 4.9σ global)
- Associated production is crucial for the explanation of the 151.5 GeV excesses
- $\gamma\gamma + X$ excess at 151.5 GeV explained by **a real triplet produced via Drell-Yan**
- Anomalies in $t\bar{t}$ differential distributions ($\geq$ 5.8σ) explained combining the 95 GeV and the 152 GeV scalars
- **Δ2HDMS model provides a consistent explanation** (and more: resonant $t\bar{t}$ excess at 400 GeV - 3.5σ local, WW....)

Thanks for your attention!

Back-up slides

Is there NP at the EW scale?

EW scale NP is not fully explored at the LHC (**associated production**)
$\rightarrow$ **Run3 data (and FCC/CEPC)** will scrutinize different NP scenarios

- Multi-lepton anomalies (MLA): deviations from SM in processes with W- like signature ($e/\mu + E_T^{miss}$)

Final state	SM backgrounds	Significance
$\ell^+\ell^- +$ (b-jets)	$t\bar{t}, Wt$	$> 5\sigma$
$\ell^+\ell^- +$ (no jet)	W^+W^-	$\approx 3\sigma$
$\ell^\pm\ell^\pm, 3\ell +$ b-jets	$t\bar{t}W^\pm, t\bar{t}t\bar{t}$	$> 3\sigma$
$\ell^\pm\ell^\pm, 3\ell +$ (no b-jet)	$W^\pm h(125), WWW$	$\gtrapprox 4\sigma$
$Z(\rightarrow \ell\ell)\ell +$ (no b-jet)	$ZW^\pm$	$> 3\sigma$

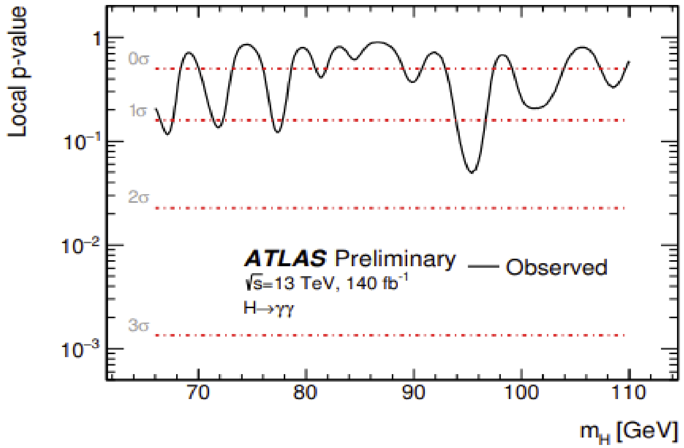
[O. Fischer, B. Mellado, A. Bagnasci, A. Crivellin et al.]

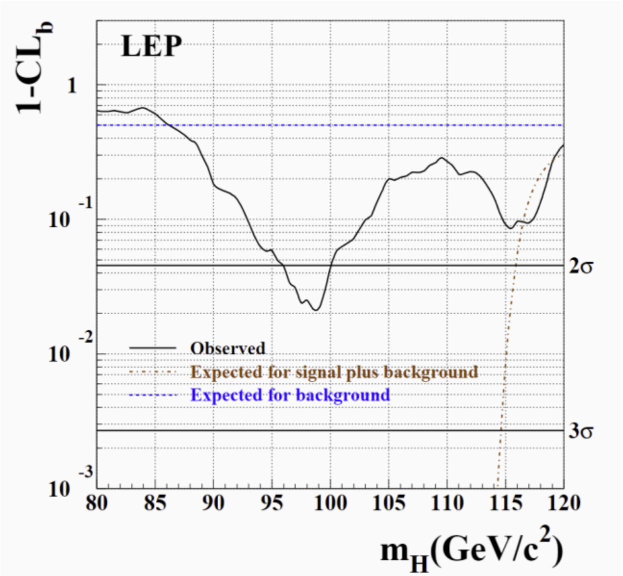
- W mass (2.2/3.7σ tension exl/in-cluding CDF II) $\rightarrow$ Custodial Symmetry

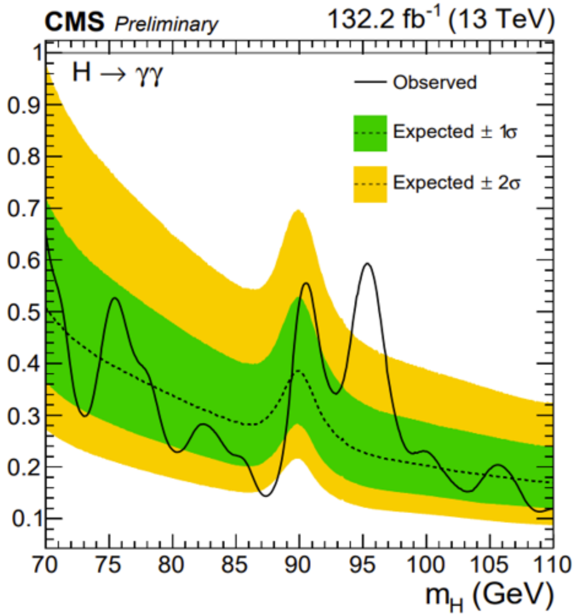
- Narrow resonances ($\gamma\gamma, Z\gamma, \tau\bar{\tau}, Z + b\bar{b}$) at 95 and 152 GeV (3.8$\sigma$ and 4.9σ) $\rightarrow$ Direct hints

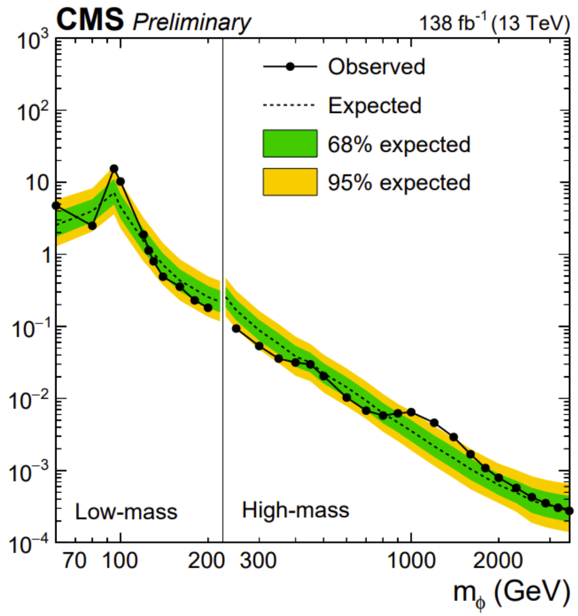
Direct hints at 95 GeV

- LEP: $Z + bb$ (2.2 σ)
- ATLAS: $\gamma\gamma$ (1.7 σ)
- CMS: $\gamma\gamma$ (2.9 σ)
- CMS: $\tau\tau$ (2.4 σ)



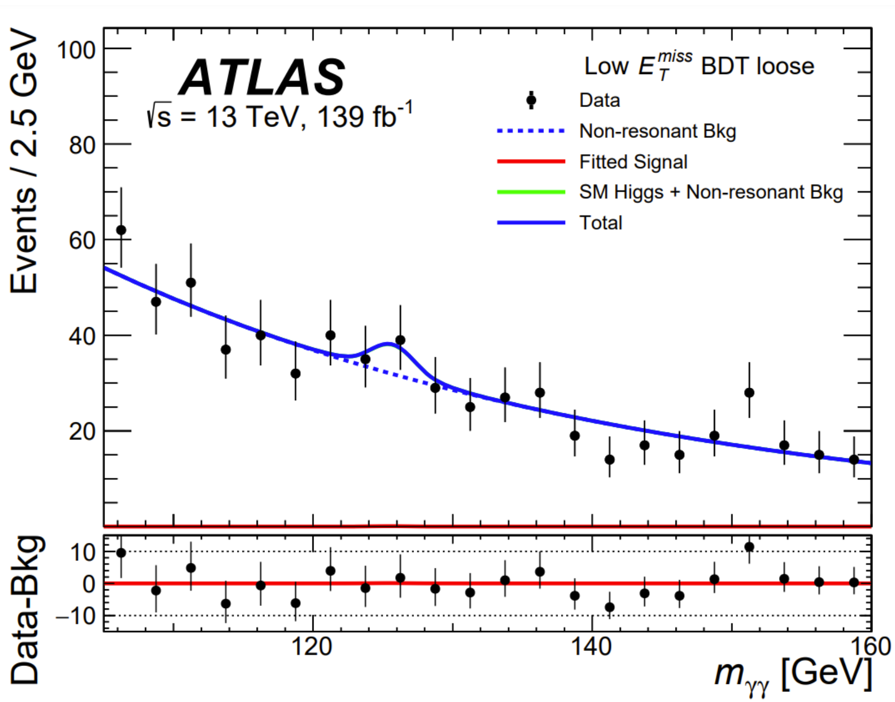


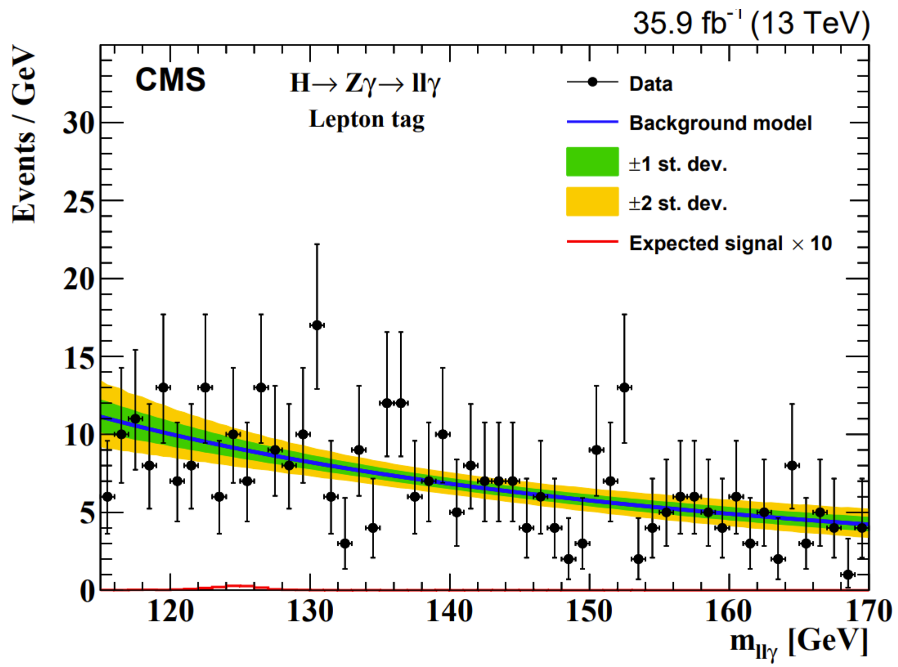




Direct hints at 151.5 GeV

- Hints for a resonance decaying to $\gamma\gamma$, $Z\gamma$ in associated production, **most significant with E_T^{miss}**
- New Scalar (Higgs) boson? **Relation to DM?**





Statistical analysis

NOTE: in the Δ2HDMS
$$\boldsymbol{S' = S_{95}}$$
$$\boldsymbol{S = \Delta^0_{151.5}}$$

[S. Bhattacharya, GC, A. Crivellin et al.]

≈95 GeV (S')

- $\tau\tau$ and WW added on the previous combination using Fisher's combined probability
- LEE included with LEP results (trial factor)

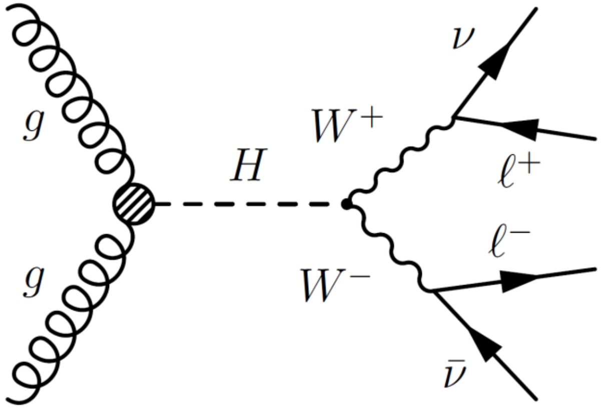
≈ 151.5 GeV (S)

- Simplified model $H \to SS^*$ with S being SM-like (associated production)
- 1 DoF for $\mathrm{Br}(S \to \text{invisible})$ and inclusion of related trial factor
- Since S is SM-like, no chances to have $S \to WW$ while avoiding $S \to ZZ \Rightarrow$ additional 1 DoF for $S \to WW$
- $(S \to \gamma\gamma) + \gamma$ and $(S \to \gamma\gamma) + \geq 1j\ + j_b$ not predicted by the simplified model $\Rightarrow$ additional 2 DoF

WW analysis

[GC, A. Crivellin, B. Mellado et al.]

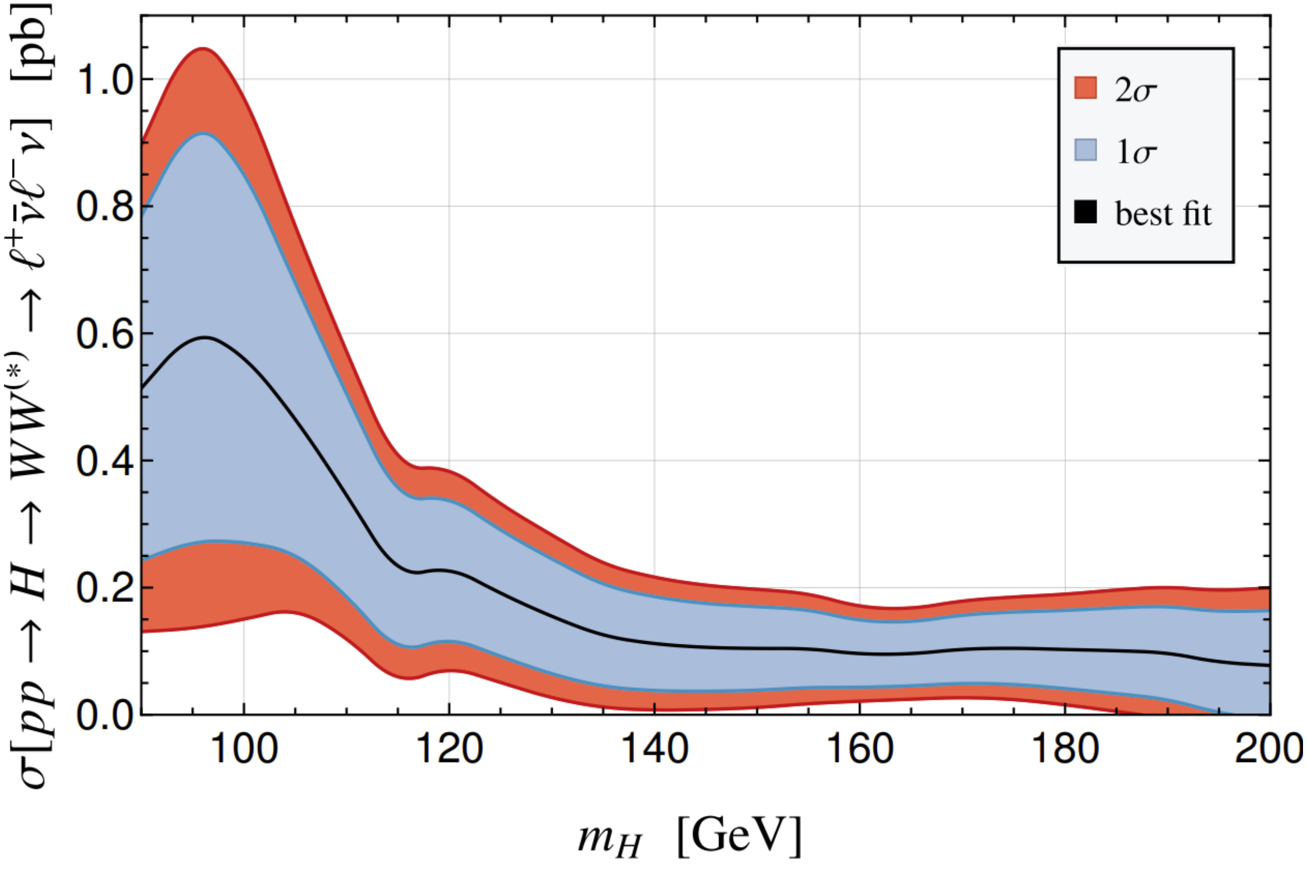
- **No dedicated BSM search for $gg \to H \to WW$** with full luminosity and including 90 GeV for the range of m_H
- CMS (2206.09466) and ATLAS (2207.00338) analyses available for **SM Higgs (135 $\mathbf{fb^{-1}}$)**
- Re-casting analyses to search **for new scalars**
- **Simulation with MadGraph5_aMC@NLO (Pythia8, Delphes)**



- 0-jet
- Different flavour opposite sign lepton pair

WW results

- Observed limit is weaker than expected over the whole mass range (**preference for BSM $\geq 2\sigma$**)



$pp \to t\bar{t}$ differential distributions

(2303.15340)

The uncertainty associated with the matrix element generation is estimated using MadGraph5_aMC@NLO [36] interfaced with Pythia 8.230 as an alternative generator, with the A14 tune and the NNPDF2.3 set of PDFs for the underlying event, parton shower and fragmentation. Since the 'matrix element correction' (MEC) in Pythia 8.230 is switched off in this simulation [37], a sample of Powheg+Pythia 8.230 events with MEC switched off, with the same PDF sets as the nominal Powheg+Pythia 8.230 generator, was also produced for comparison with MadGraph5_aMC@NLO. In order to estimate the uncertainty associated with the modelling of fragmentation and parton showering, a sample was generated with Powheg interfaced with Herwig 7.0.4 [38, 39] with the H7UE tune [40] and the NNPDF3.0 PDF set.

Additional samples using alternative generators were produced for comparison with data. These include Powheg interfaced with Herwig 7.1.3 [41], MadGraph5_aMC@NLO interfaced with Herwig 7.1.3, and Powheg+Pythia 8.230 with the PDF4LHC15_nnlo_mc set [33, 42]. Finally, a reweighted Powheg+Pythia 8.230 sample was generated. The reweighting is performed on the top-quark p_T variable, using the kinematics of the top quarks in the MC sample after initial- and final-state radiation. The prediction for the top-quark p_T spectrum is calculated to next-to-next-to-leading order (NNLO) in QCD with NLO EW corrections [43, 44] with the NNPDF3.0 QED PDF set using dynamic renormalisation and factorisation scales $m_{T,t}/2$, i.e. half the top-quark transverse mass,[3] for the top-quark p_T as proposed in Ref. [43], with $m_t = 173.3$ GeV. The reweighting was applied such that at the end of the procedure the reweighted MC sample is in good agreement with the higher-order prediction for the reweighted variable [45]. This sample is referred to as being reweighted to the NNLO prediction in the remainder of the document.

$pp \to t\bar{t}$: statistical fit

$$r_i = \frac{\sigma_i^{\rm NP}/\sigma^{\rm NP}}{\sigma_i^{\rm SM}/\sigma^{\rm SM}}$$

NP signal bin by bin normalized to SM (as ATLAS did)

Chi squared fit:

$$\chi^2_{\rm NP} = \sum_{i,j=1} \frac{(a x_i + \varepsilon_{\rm NP} r_i - 1)\,\rho_{ij}\,(a x_j + \varepsilon_{\rm NP} r_j - 1)}{\delta_i \delta_j}$$

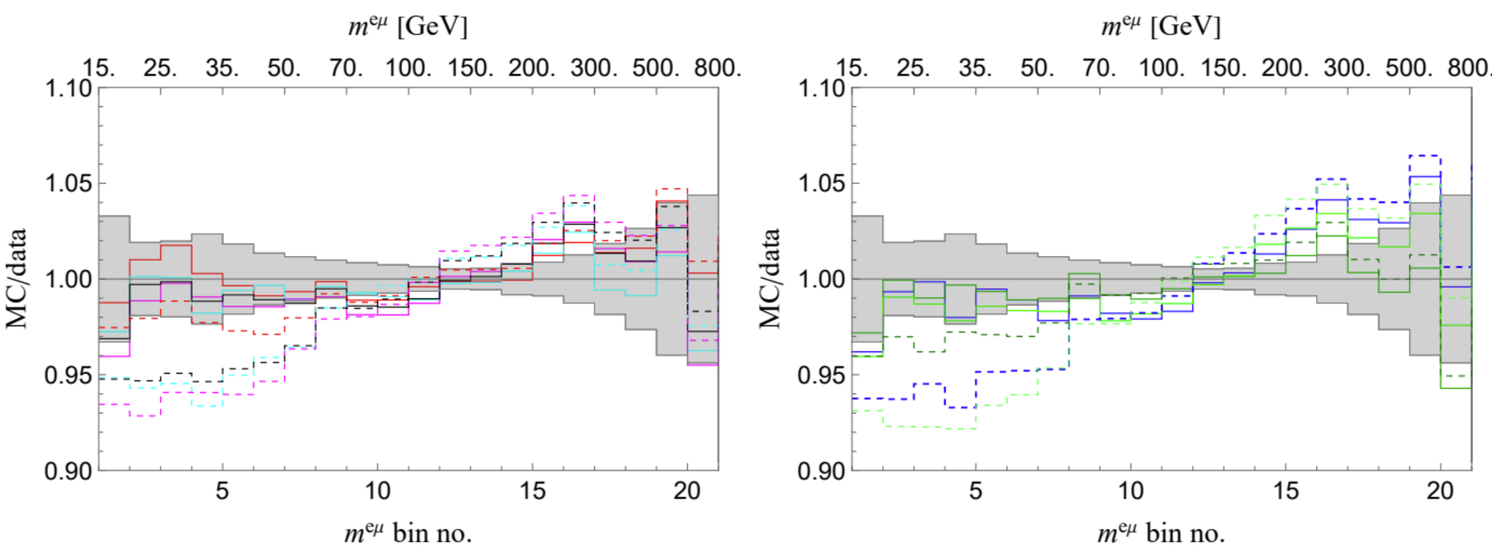
MC/Data

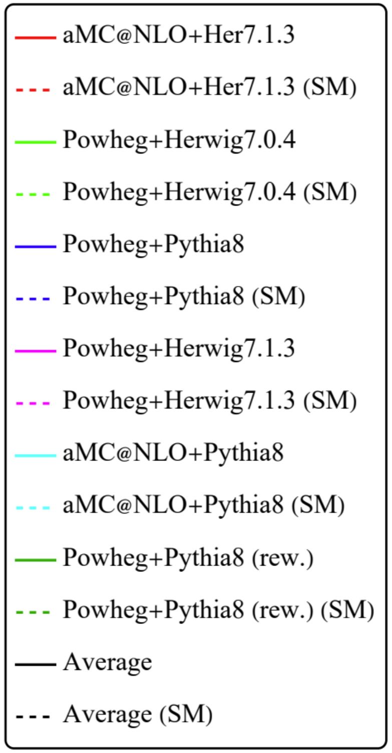
Correlation matrix computed from MG5 simulation

$$\sigma_{\rm NP} \approx \varepsilon_{\rm NP} \sum_i r_i \sigma_i^{\rm EXP}$$

NP cross section extracted from fitted signal strength

$pp \to t\bar{t} : m^{e\mu}$





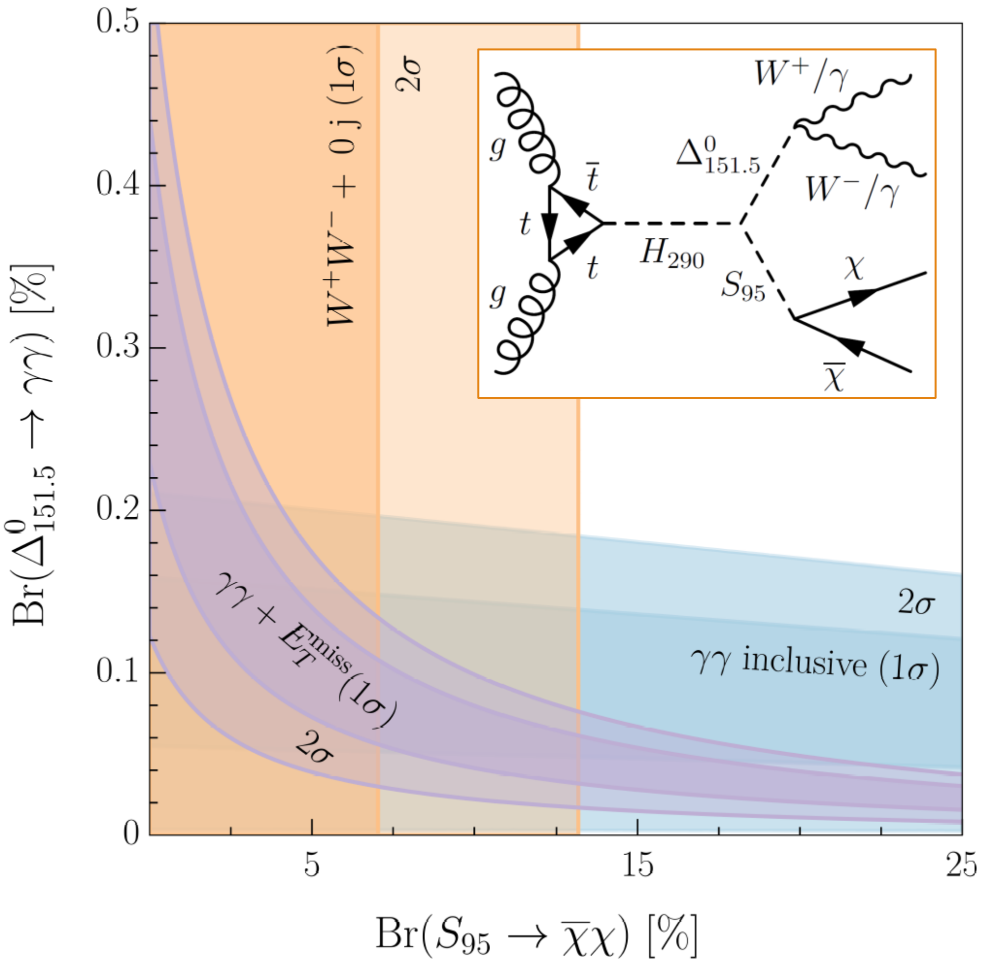
$m^{e\mu}$ distribution normalized to the total cross section $\sigma(pp \to t\bar{t})$

$\to$ **in average, NP hypothesis is preferred over the SM by $\geq 5.8\sigma$**

The Δ2HDMS Model: PHENO

[GC, A. Crivellin, B. Mellado]

- WW excess at 151.5 GeV cannot be explained by only a real Higgs triplet
- **The $\gamma\gamma$ signal for 151.5 GeV is mostly in association with additional E_T^{miss}**
- Adding branching ratios to invisible for S_{95}



If $\mathrm{Br}(S_{95} \to \bar{\chi}\chi) = 0 \Rightarrow$ agrees with ATLAS for $pp \to (\Delta^0_{151.5} \to \gamma\gamma)\Delta^{\pm}_{\approx 151.5}$

The Δ2HDMS Model

[GC, A. Crivellin, B. Mellado]

Field	$SU(2)_L$	$U(1)_Y$	Z_2/Z_2'	Physical fields
ϕ_s	2	0	$+/-$	S_{95}
ϕ_2	2	$1/2$	$+/-$	SM
ϕ_1	2	$1/2$	$-/+$	$H_{290}, H^{\pm}_{400}, A_{400}$
Δ	3	0	$-/+$	$\Delta^0_{151.5}, \Delta^{\pm}_{\approx 151.5}$

WW

$t\bar{t}W\,(t\bar{t}Z)$

Direct hints

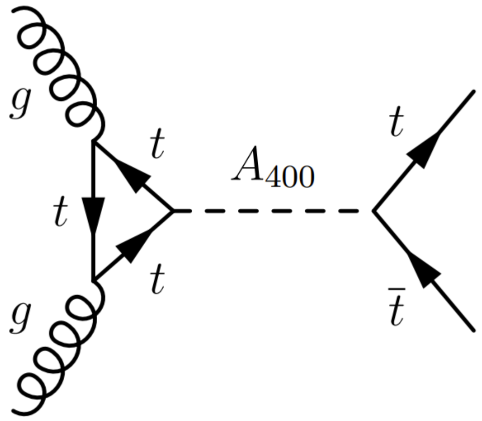
$m_W \Rightarrow \langle\Delta\rangle \approx O(\text{GeV})$
$Y = 0 \Rightarrow$ weak flavor bounds

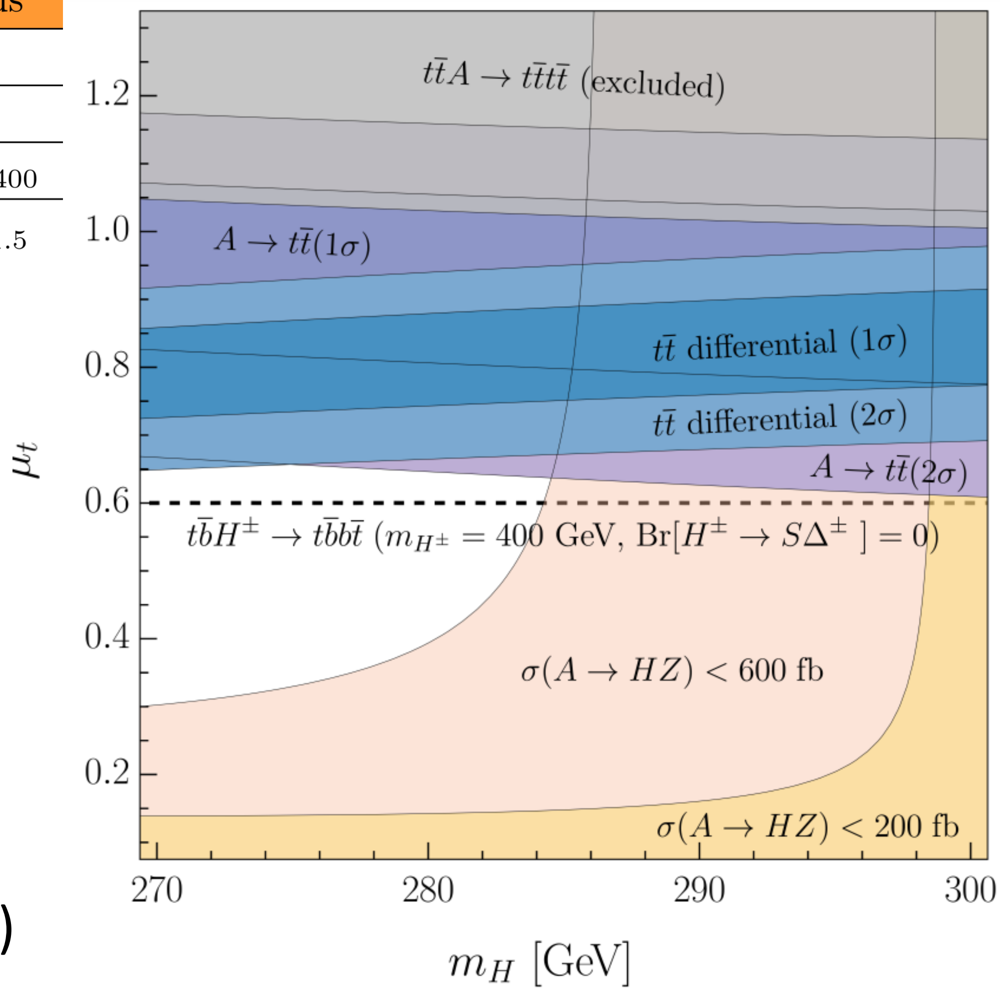
Resonant $t\bar{t}$

The Δ2HDMS: A_{400}

[GC, A. Crivellin, B. Mellado]

Field	$SU(2)_L$	$U(1)_Y$	Z_2/Z_2'	Physical fields
ϕ_s	2	0	$+/-$	S_{95}
ϕ_2	2	1/2	$+/-$	SM
ϕ_1	2	1/2	$-/+$	$H_{290}, H^{\pm}_{400}, A_{400}$
Δ	3	0	$-/+$	$\Delta^0_{151.5}, \Delta^{\pm}_{\approx 151.5}$



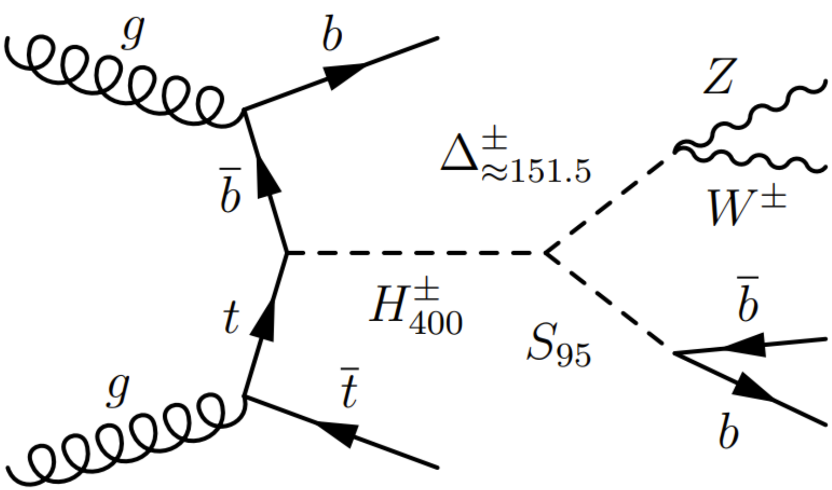


- Explains resonant $t\bar{t}$ excess at 400 GeV (3.5σ local)

The Δ2HDMS Model: $\boldsymbol{H^{\pm}_{\approx 400}}$

[GC, A. Crivellin, B. Mellado]

Field	$SU(2)_L$	$U(1)_Y$	Z_2/Z_2'	Physical fields
ϕ_s	2	0	$+/-$	S_{95}
ϕ_2	2	1/2	$+/-$	SM
ϕ_1	2	1/2	$-/+$	$H_{290}, H^{\pm}_{400}, A_{400}$
Δ	3	0	$-/+$	$\Delta^0_{151.5}, \Delta^{\pm}_{\approx 151.5}$



- Avoiding constraints on $t\bar{b}H^{\pm}_{400} \to t\bar{b}b\bar{t}$ by opening the channel $H^{\pm}_{400} \to \Delta^{\pm}_{\approx 151.5}\, S_{95}$
- 400 fb allowed at the 2σ level for $t\bar{t}W\,(t\bar{t}Z)$