New Higgses at the Electroweak Scale

Guglielmo Coloretti
University of Zurich and Paul Scherrer Institut
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Outline

1. The 95 GeV and 151.5 GeV scalar candidates

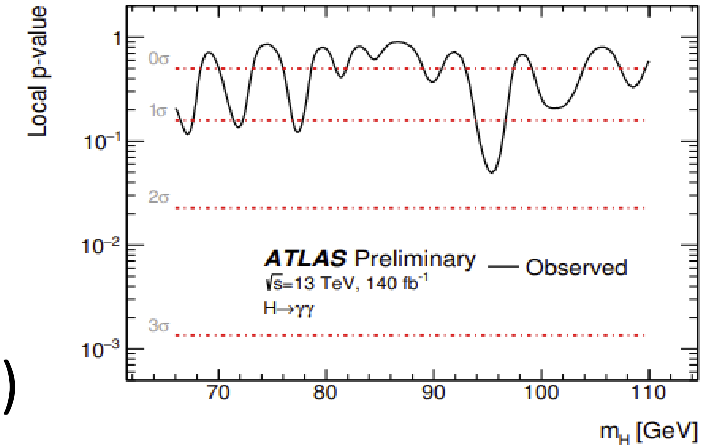
2. A real Higgs triplet at 151.5 GeV?

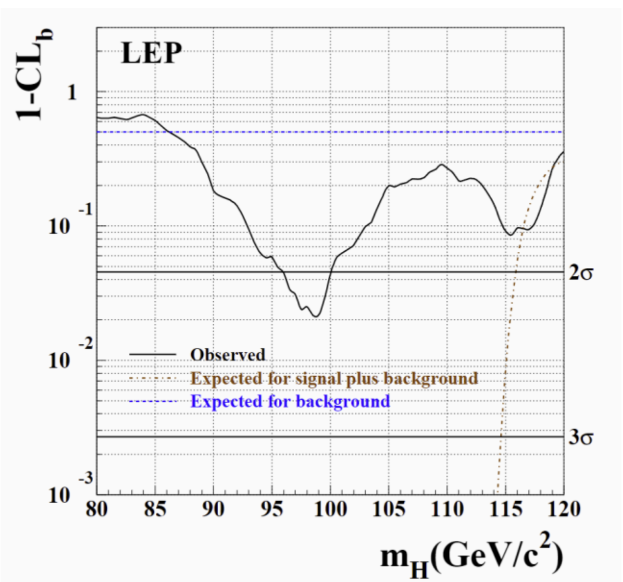
3. Multi-lepton anomalies
   (WW and $t\bar{t}$ differential distributions)

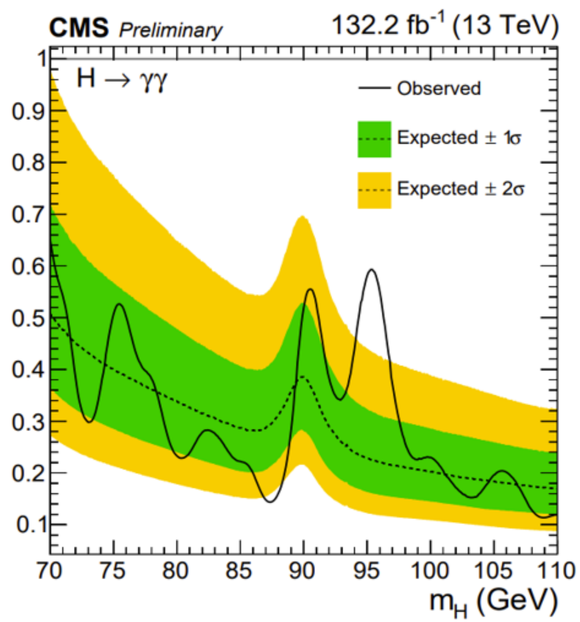
4. The Δ2HDMS

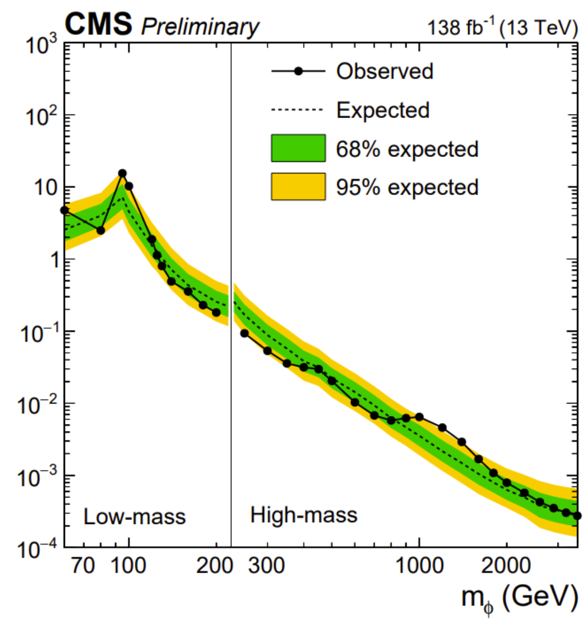
Direct hints at 95 GeV

- LEP: $Z + bb$ (2.3 σ)
- ATLAS: $\gamma\gamma$ (1.7 σ)
- CMS: $\gamma\gamma$ (2.9 σ)
- CMS: $\tau\tau$ (2.4 σ)
  but not seen by ATLAS (1.7 σ)



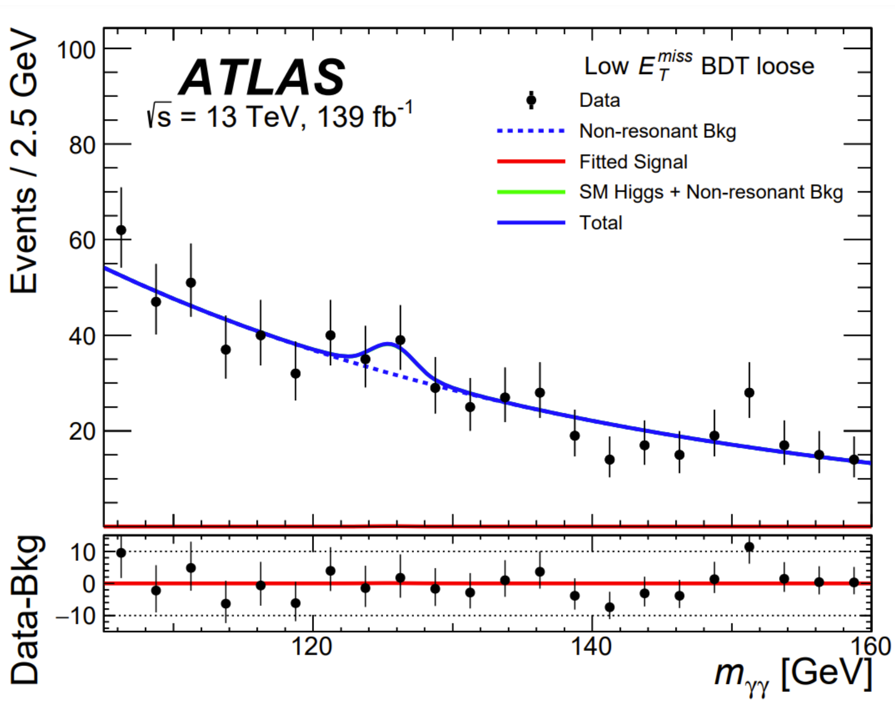


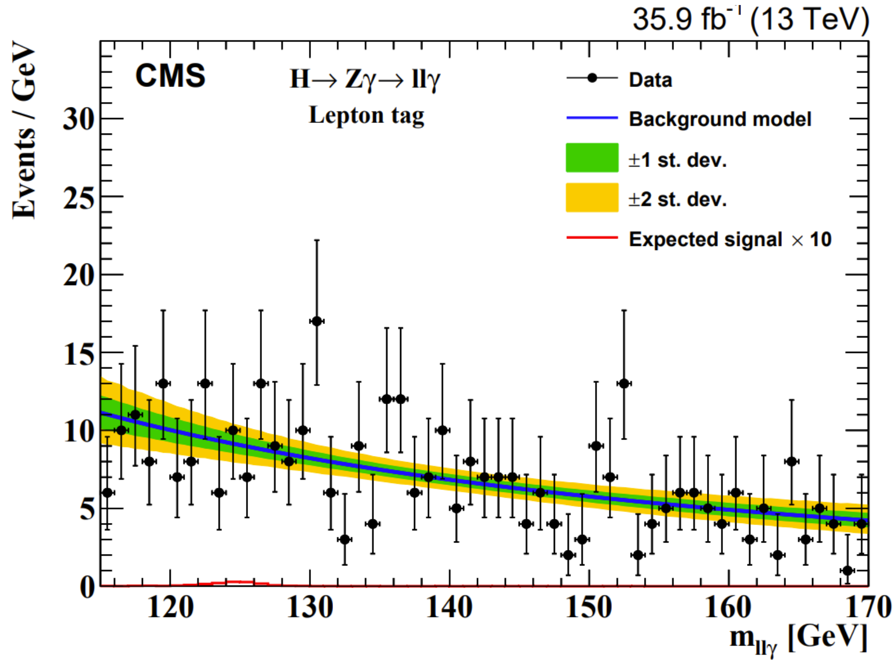




Direct hints at 151.5 GeV

- Hints for a resonance decaying to $\gamma\gamma$, $Z\gamma$
- **Production mechanism favors associated production**

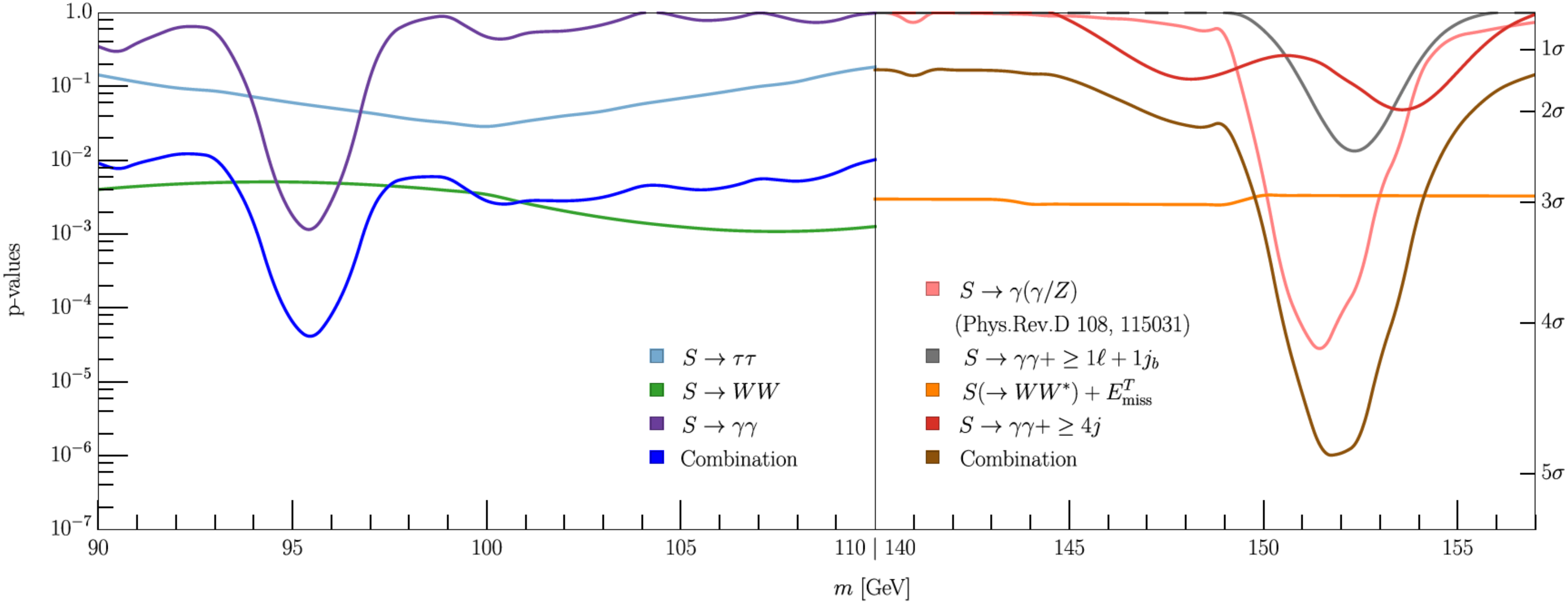




Direct hints

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

- Several channels have excess at 95 GeV and 151.5 GeV
- More than 3σ and 4σ 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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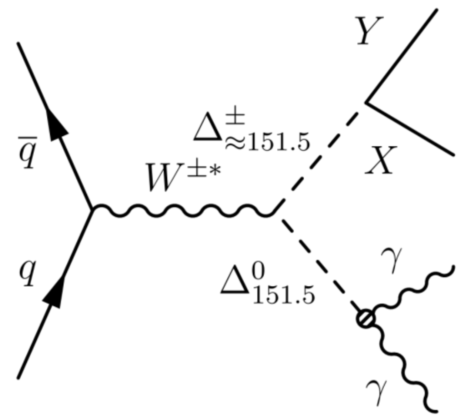

151.5 GeV mostly produced in associated production (AP) ⟷ Produced in AP via Drell-Yan (DY)

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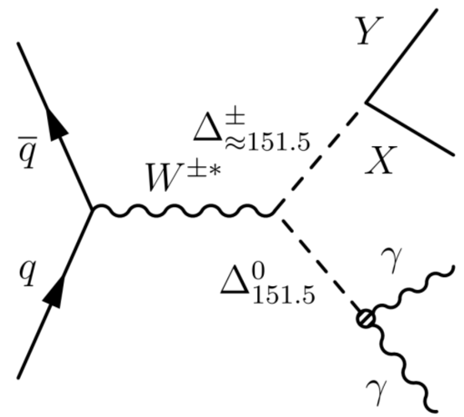

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No excess at 151.5 GeV in ZZ but in WW ⟷ $\Delta^0 WW$ but no $\Delta^0 ZZ$ (tree level and $\alpha_\Delta = 0$)

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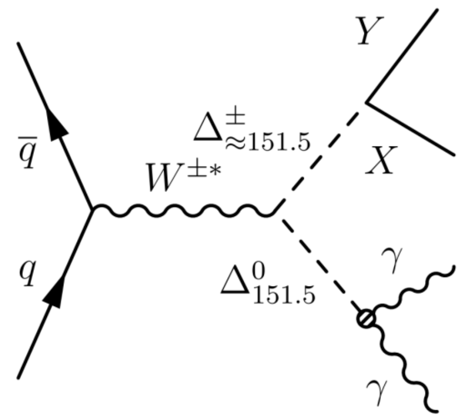

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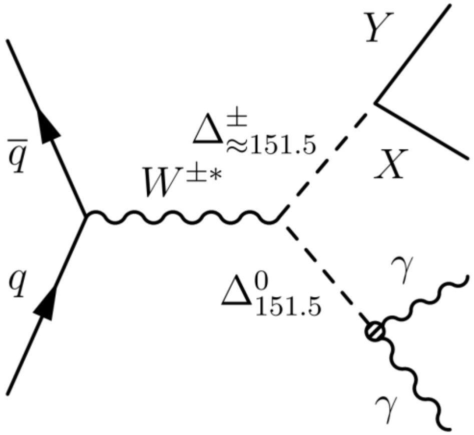
No excess at 151.5 GeV in ZZ but in WW ⟷ $\Delta^0 WW$ but no $\Delta^0 ZZ$ (tree level and $\alpha_\Delta = 0$)

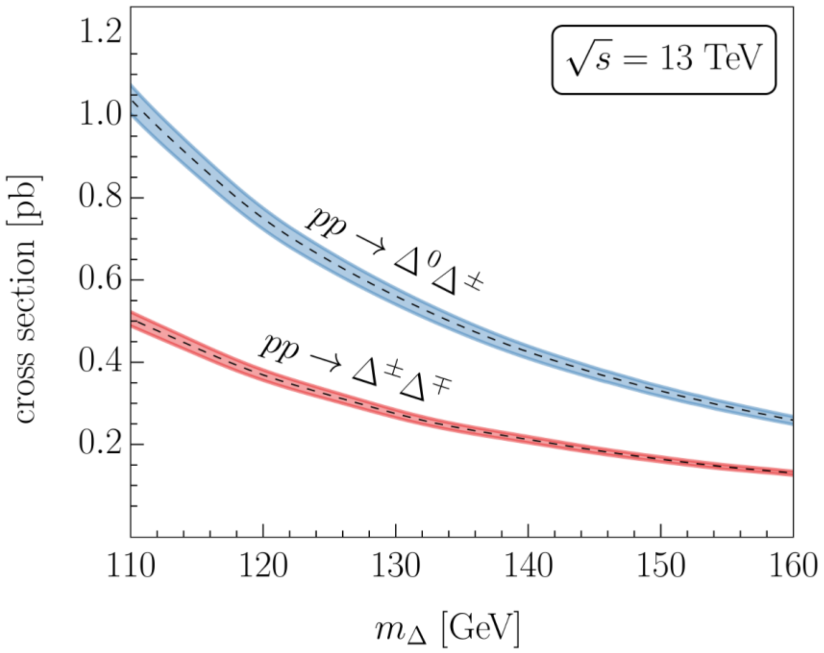
W mass (2.2/3.7σ above SM w/.o CDFII) ⟷ $\langle\Delta\rangle = v_\Delta \approx O$(GeV) (therefore: $m_{\Delta^0} \approx m_{\Delta^\pm}$)

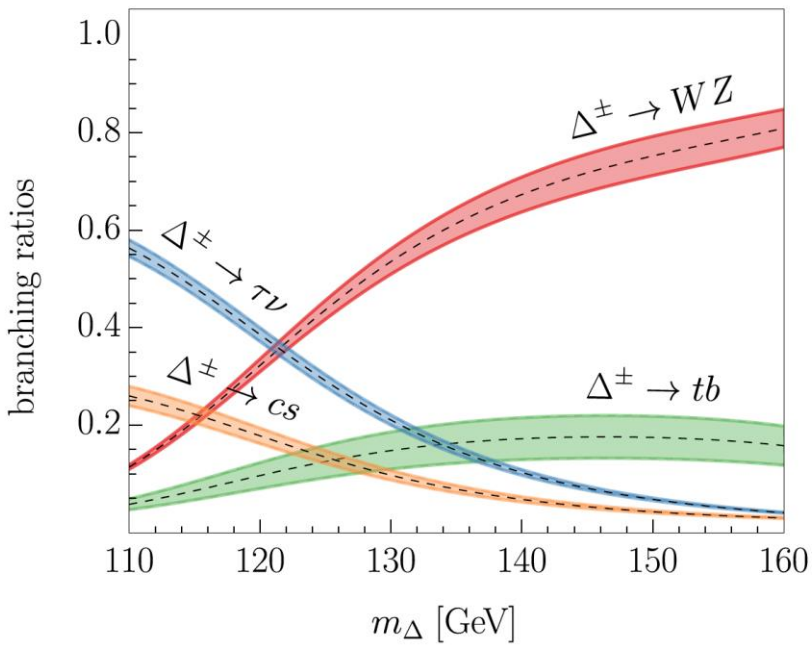
Model: $H \to \gamma\gamma + X$

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

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



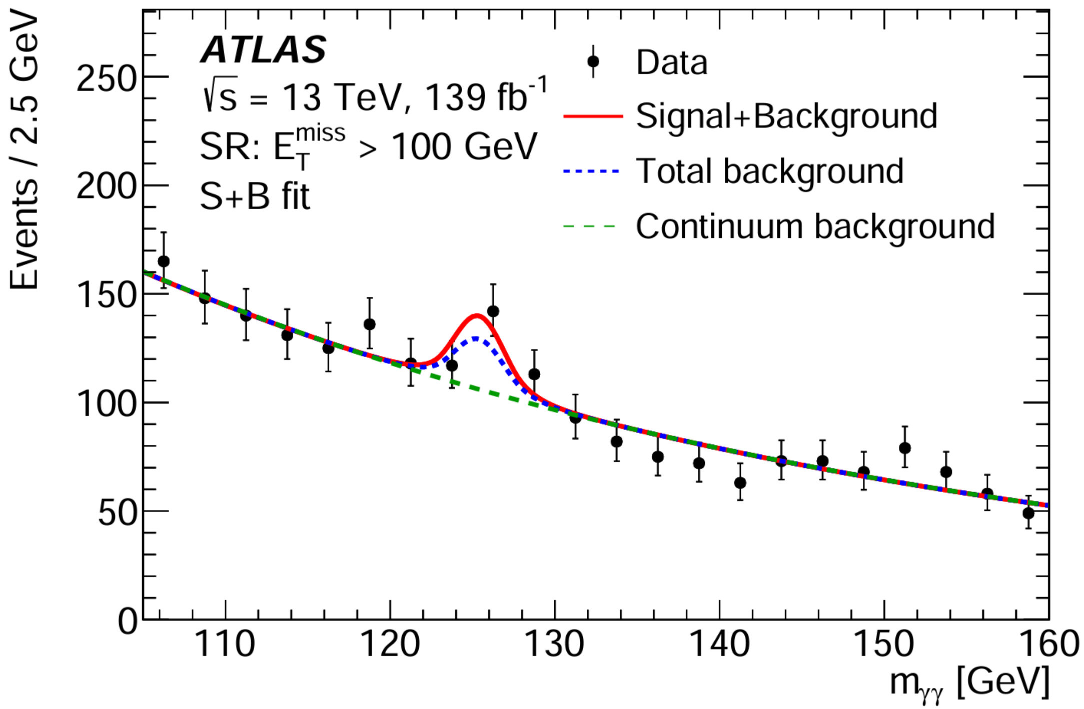




ATLAS analysis: $H \rightarrow \gamma\gamma + X$

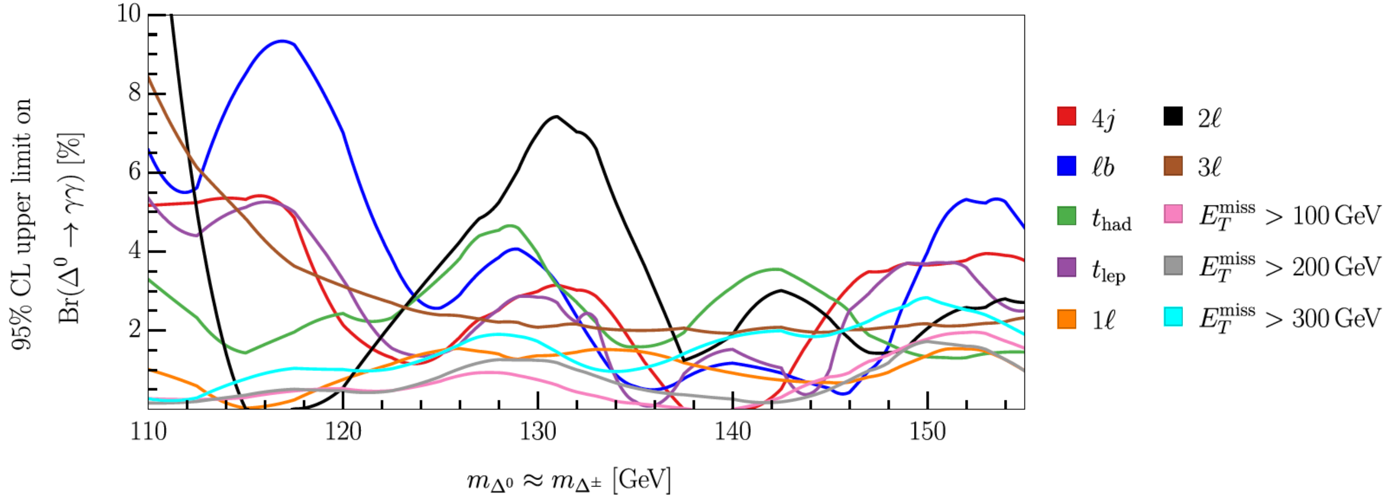
[ATLAS]

- ATLAS model independent search for AP with Run2 data
- SM $H \rightarrow \gamma\gamma + X$ covering the 105-160 GeV range
- Multiple categories ($X = l, j, j_b, E_T^{miss}$ ...)
- **Reduced SM background and enhanced NP sensitivity**



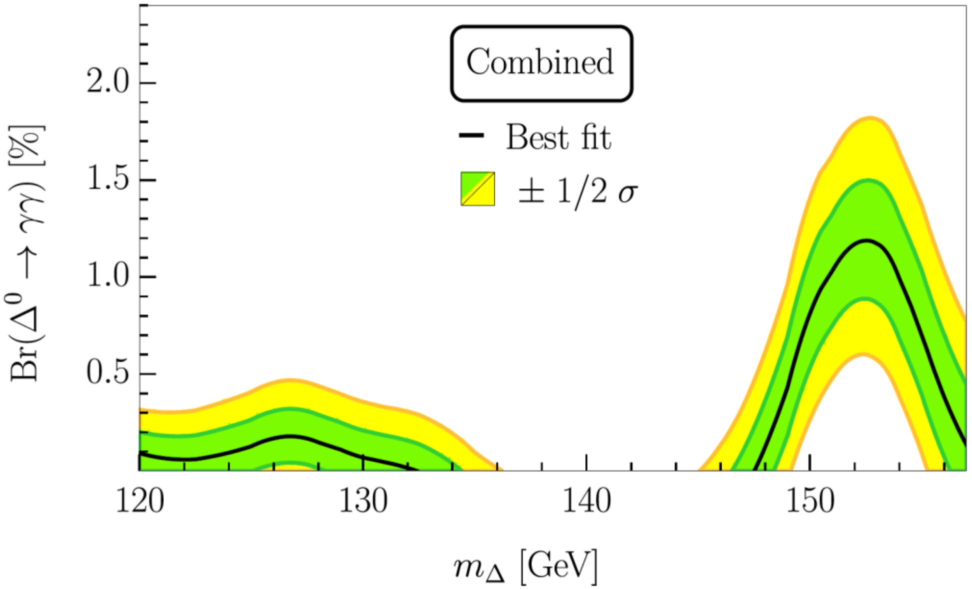
Results: $H \to \gamma\gamma + X$

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

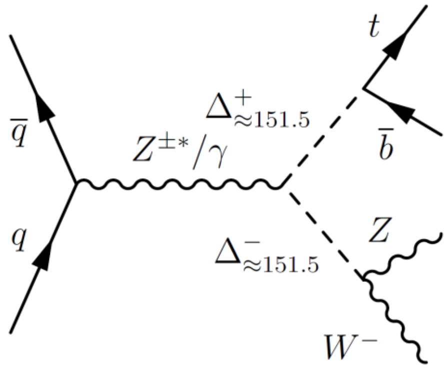


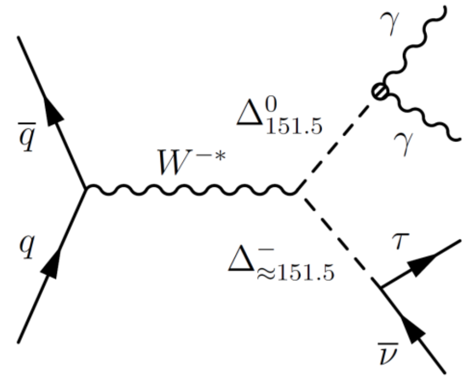
- 22 channels analyzed by ATLAS
- 10 relevant for a real triplet
- 8 of them show excesses

- **Br($\Delta^0 \to \gamma\gamma$) preferred value over SM by $\approx 3\sigma$**

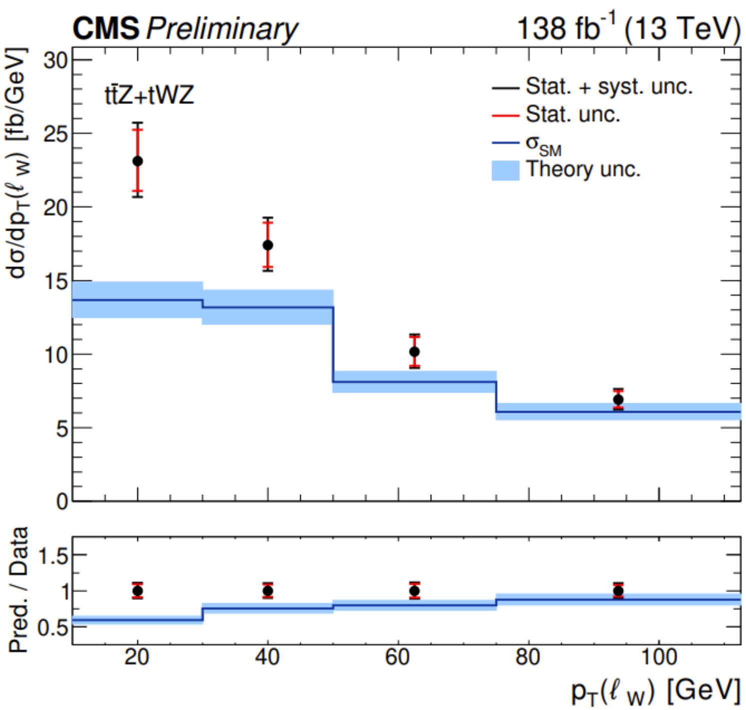


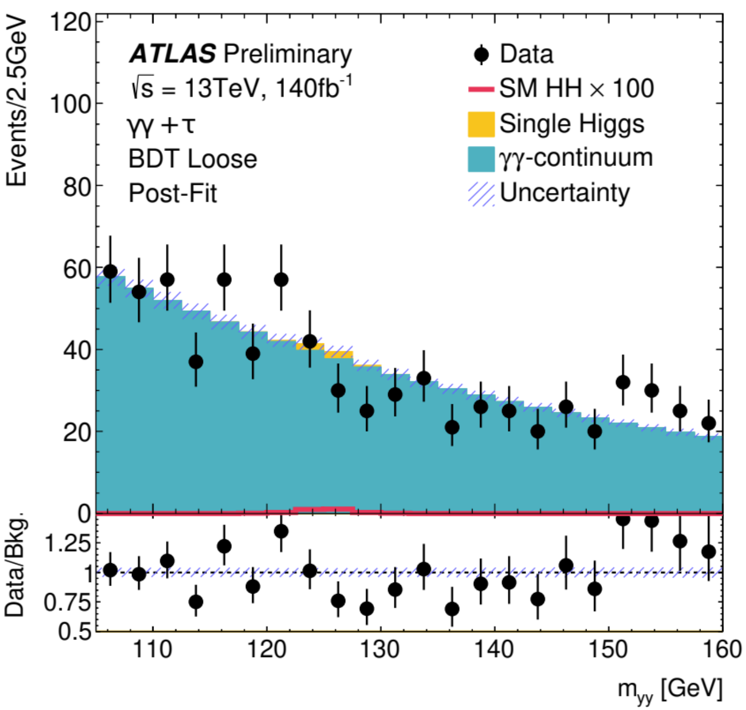
New Moriond results!





CMS-PAS-TOP-23-004





ATLAS-CONF-2024-005

Multi-lepton anomalies (MLA)

- Multi-lepton anomalies (MLA): deviations from SM in processes with W- like signature (e/μ + MET)

Final state	SM backgrounds
→ $\ell^+\ell^-$ + (b-jets)	$t\bar{t}, Wt$
→ $\ell^+\ell^-$ + (no jet)	W^+W^-
$\ell^\pm\ell^\pm, 3\ell$ + b-jets	$t\bar{t}W^\pm, t\bar{t}t\bar{t}$
$\ell^\pm\ell^\pm, 3\ell$ + (no b-jet)	$W^\pm h(125), WWW$
$Z(\to \ell\ell)\ell$ + (no b-jet)	$ZW^\pm$

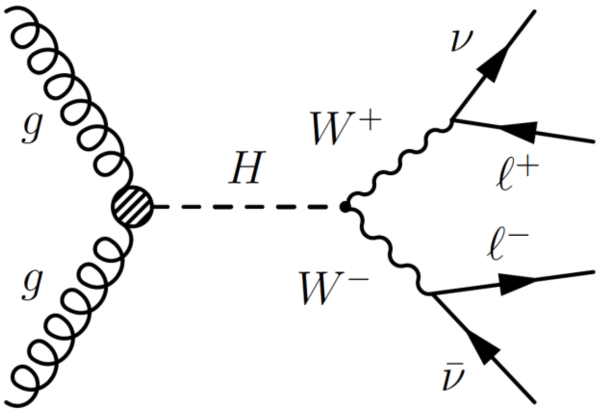
- The EW scale NP is not yet fully explored at the LHC (**associated production**)

- **LHC Run3 data, FCC and CEPC** will be able to scrutinize BSM scenarios at this scale

WW analysis

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

- **No dedicated BSM search for $gg \to H \to WW$** with full luminosity and scanning over m_H
- CMS (2206.09466) and ATLAS (2207.00338) analyses available for **SM Higgs (135 $\mathbf{fb^{-1}}$)**

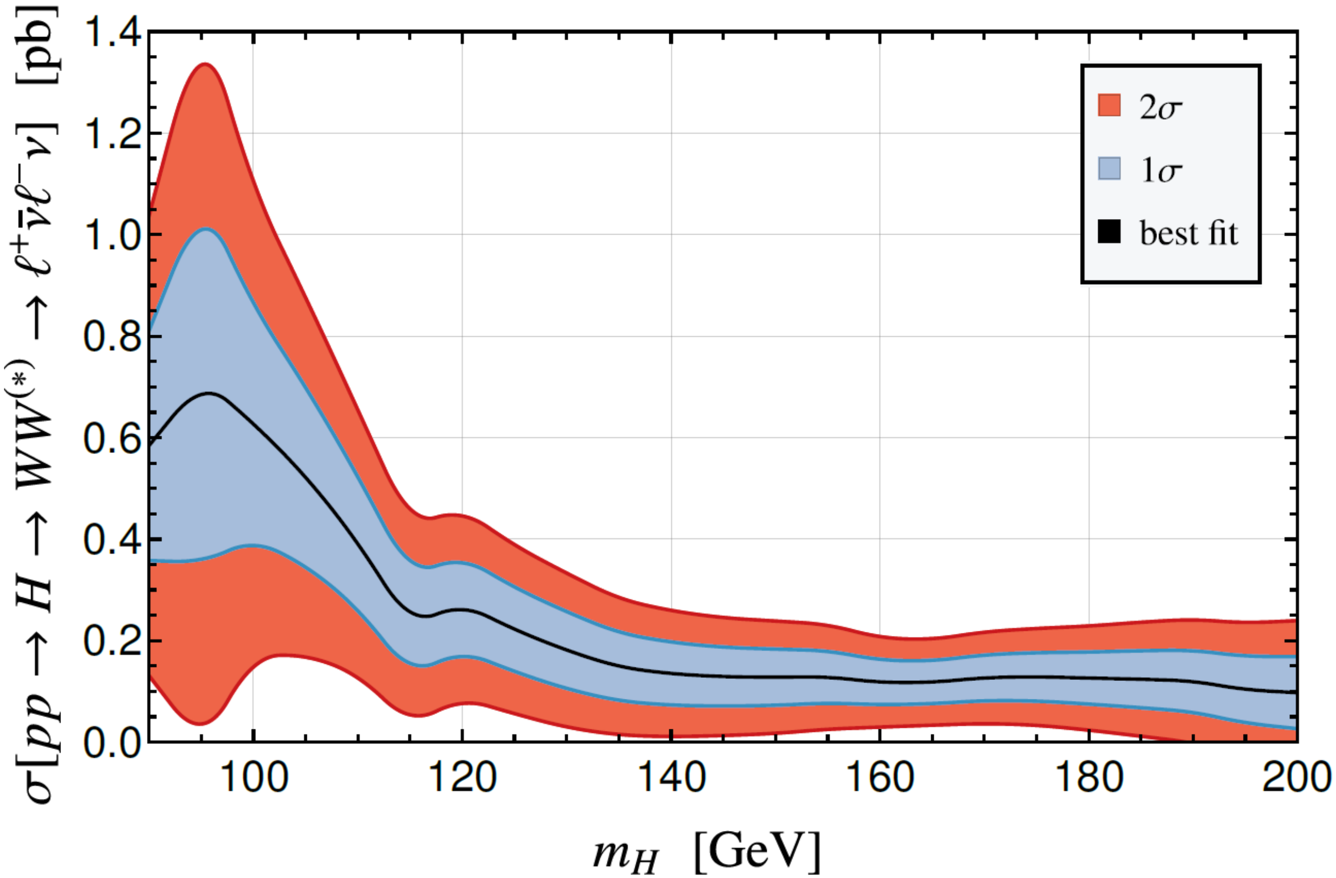


- Re-casting analyses to search **for new scalars**
- **Simulation with MadGraph5_aMC@NLO (Pythia8, Delphes)**

- 0-jet
- Different flavour opposite sign lepton pair

WW results

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



Connecting 95 and 151.5 GeV?

- Δ^0 at 151.5 GeV mainly decays to WW
- What if produced in association with another particle?
- Which possible signatures would it manifest?

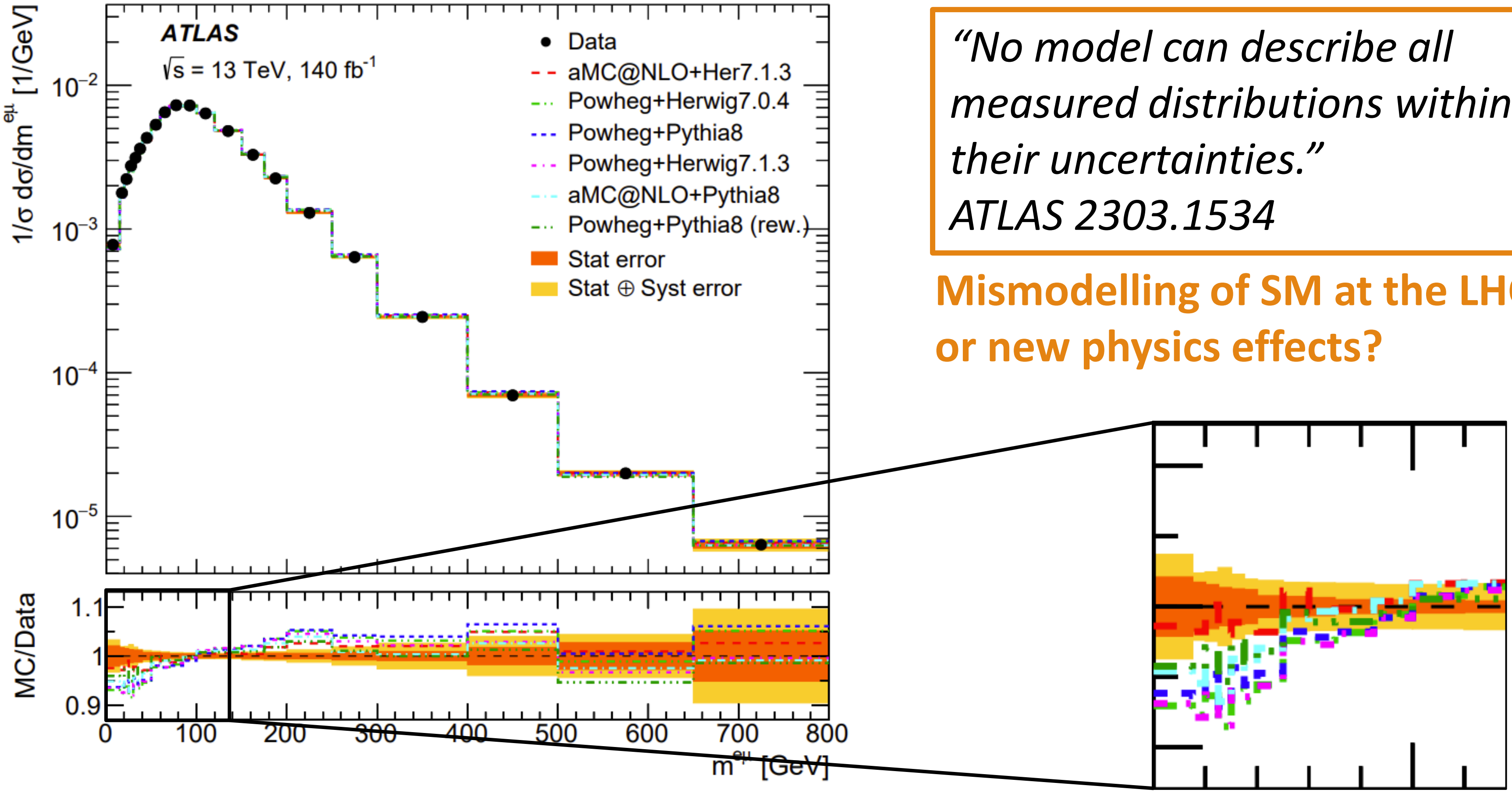
Is there a way to connect the 95 GeV and 151.5 GeV hints for NP?

→ **Top quark differential distributions**

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

[ATLAS]

- Several distributions analyzed for the lepton pair
- **Example: invariant mass of the two final leptons $m_{e\mu}$**



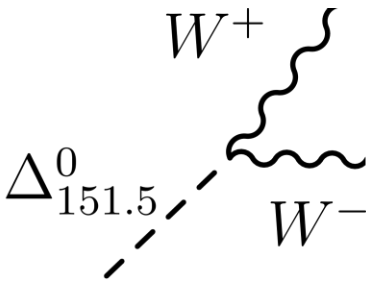
"No model can describe all measured distributions within their uncertainties."
ATLAS 2303.1534

Mismodelling of SM at the LHC or new physics effects?

Towards the Δ2HDMS

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

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



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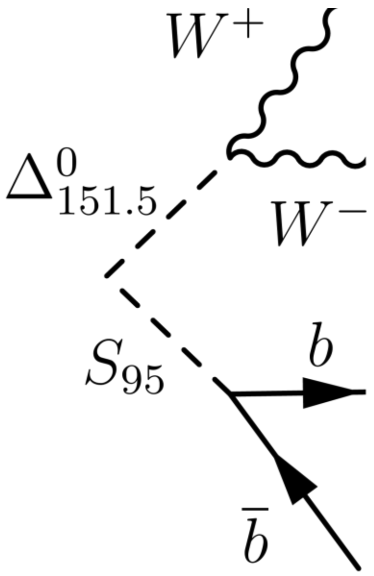
- **95 GeV: real singlet S_{95} (φ_s)**
  ⇒ mainly decays to $b\bar{b}$



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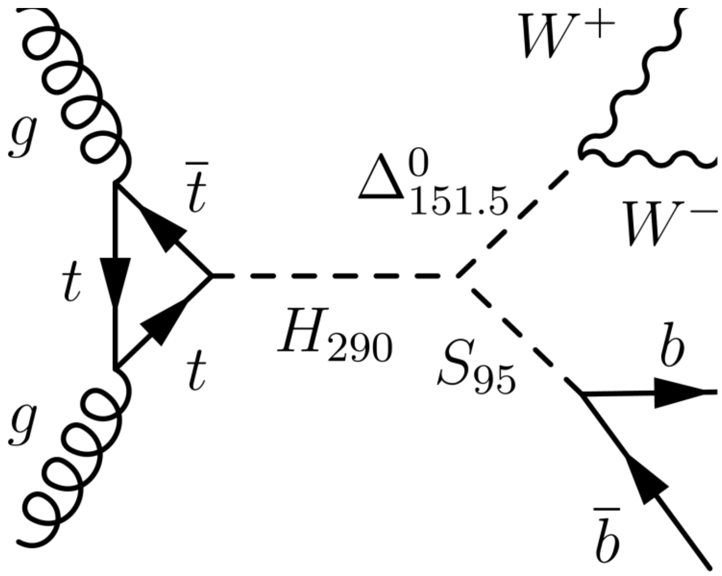
- **95 GeV: real singlet S_{95} (φ_s)**
  ⇒ mainly decays to $b\bar{b}$
- m_{Δ^0}, m_S fixed by hints at 151.5 GeV, 95 GeV (resp.)
- H contained in a second Higgs doublet φ_1 with
  $m_H > m_{\Delta^0} + m_S$



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

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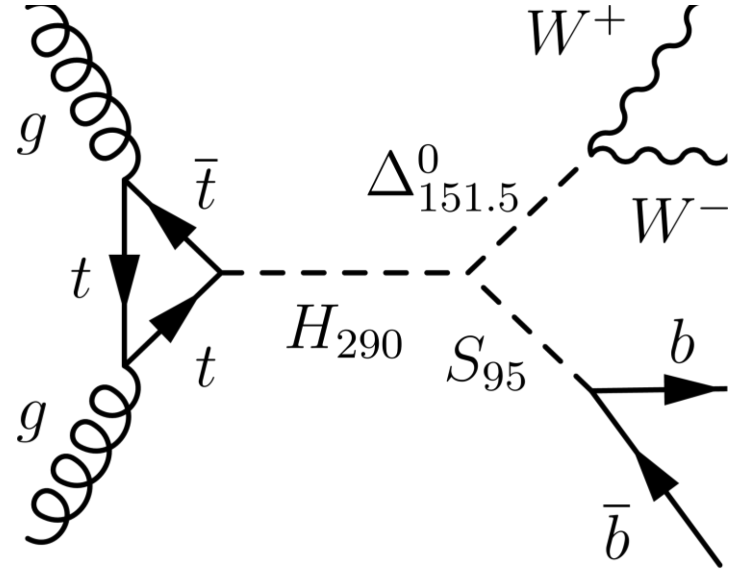


Has $t\bar{t}$-like ($WWb\bar{b}$) signature

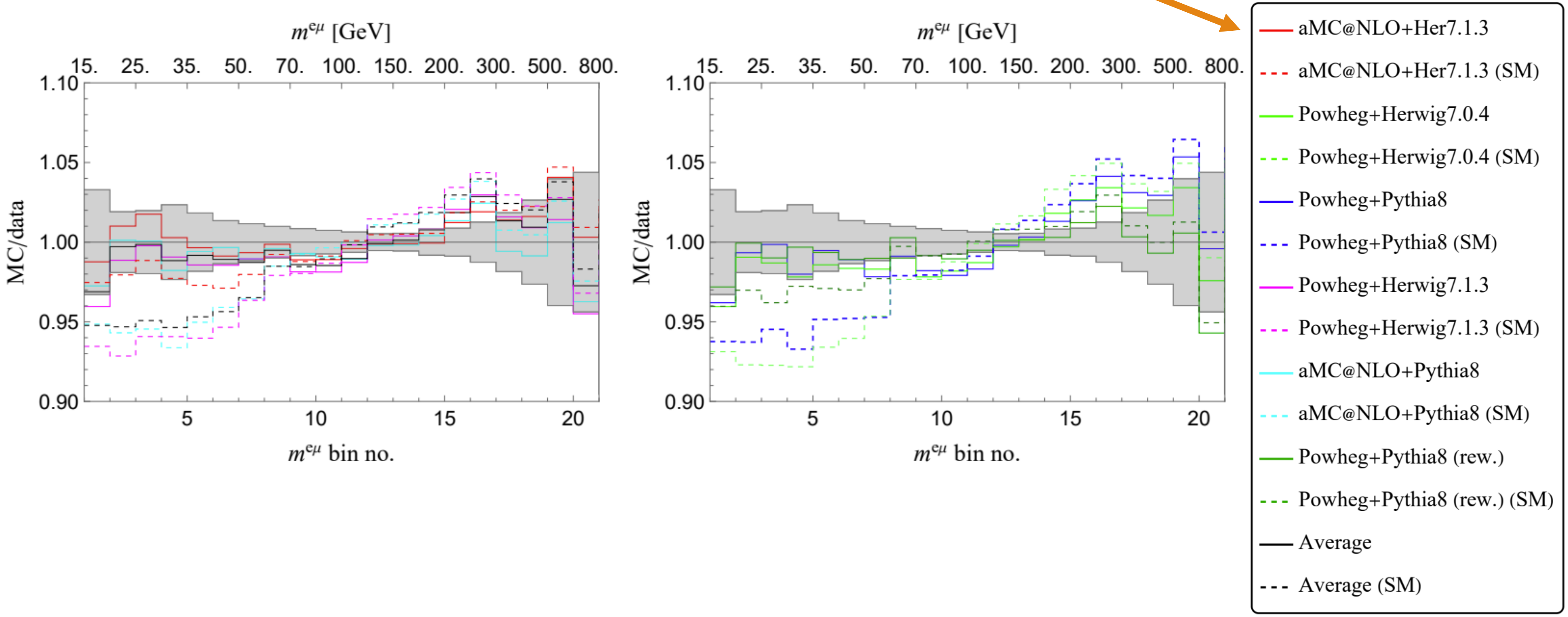
NP shape independent from m_H

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

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



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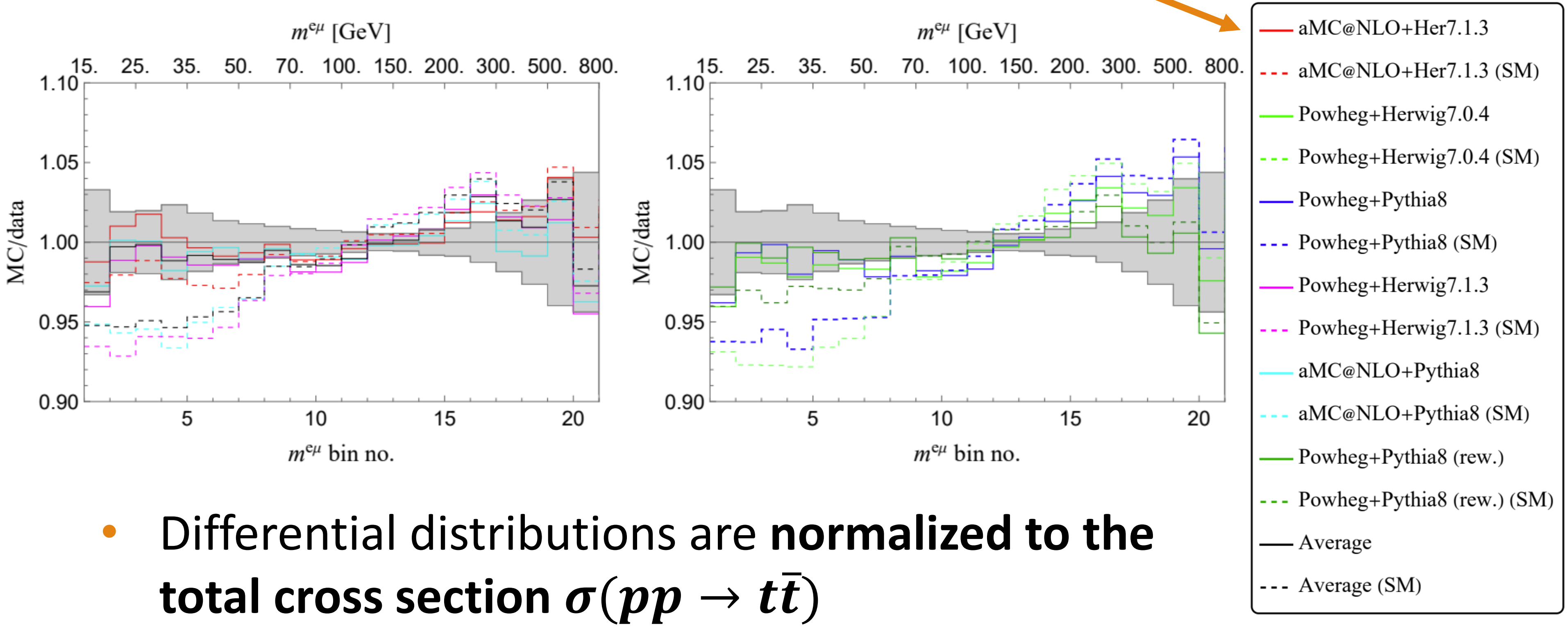

- Differential distributions are **normalized to the total cross section $\sigma(pp \to t\bar{t})$**
- Only sensitive to the shape of NP

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

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ATLAS generated $t\bar{t}$ samples with **several different** matrix element

Monte Carlo	χ^2_{SM}	χ^2_{NP}	σ_{NP}	Sig.	m_S[GeV]
Powheg+Pyhtia8	213	102	9pb	10.5σ	$143-156$
aMC@NLO+Herwig7.1.3	102	68	5pb	5.8σ	$--$
aMC@NLO+Pythia8	291	163	10pb	11.3σ	148-157
Powheg+Herwig7.1.3	261	126	10pb	11.6σ	149-156
Powheg+Pythia8 (rew)	69	35	5pb	5.8σ	$--$
Powheg+Herwig7.0.4	294	126	12pb	13.0σ	149-156
Average	182	88	9pb	9.6σ	143-157

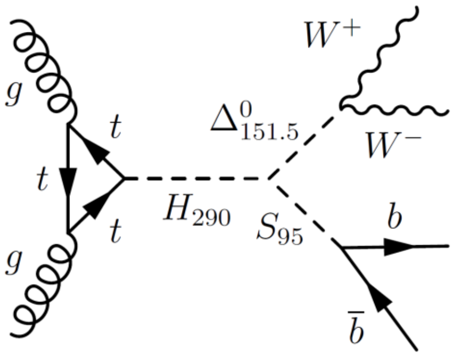
total cross section $\sigma(pp \to t\bar{t})$

NP hypothesis is preferred over the SM by $\geq 5.8\sigma$

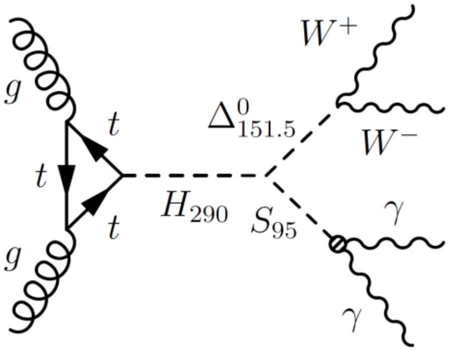
Towards the Δ2HDMS (continued)

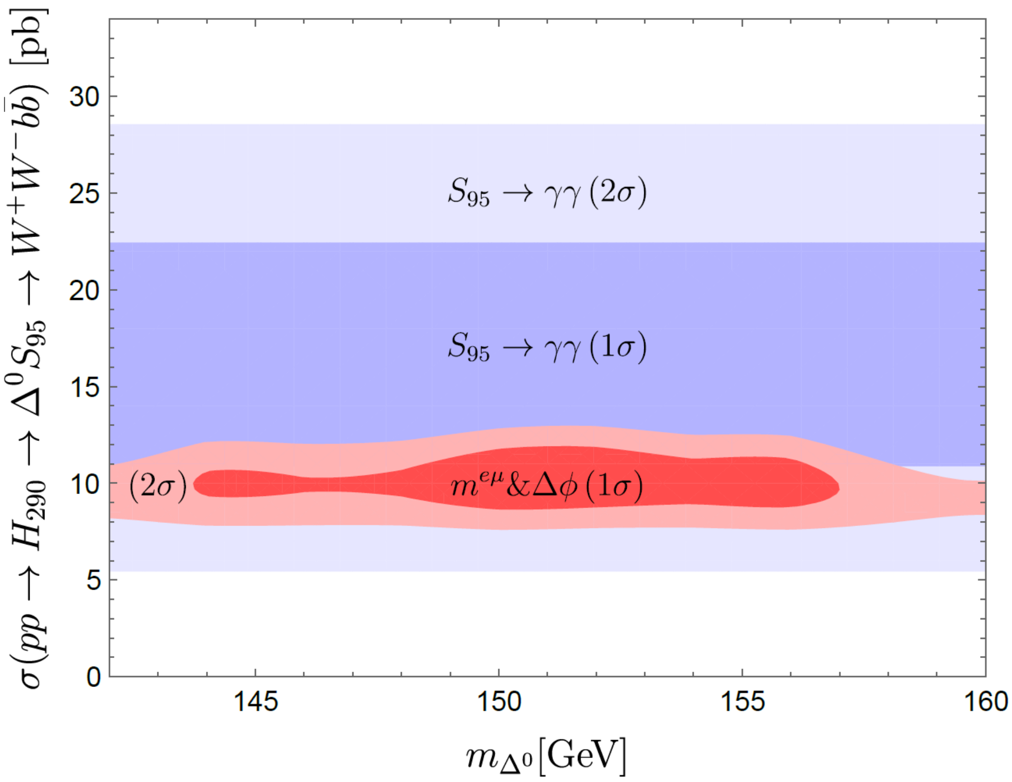
[S. Banik, GC, A. Crivellin, B. Mellado]

- $t\bar{t}$ **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

The Δ2HDMS

[GC, A. Crivellin, B. Mellado]

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

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Δ	3	0	$-/+$	$\Delta^0_{151.5}, \Delta^{\pm}_{\approx 151.5}$

- No trilinear couplings (CP conserving)
- Only a term allowed with odd number of any field

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

(necessary to explain top quark differential distributions)

The Δ2HDMS

[GC, A. Crivellin, B. Mellado]

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Direct hints

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Direct hints

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

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WW excess

Direct hints

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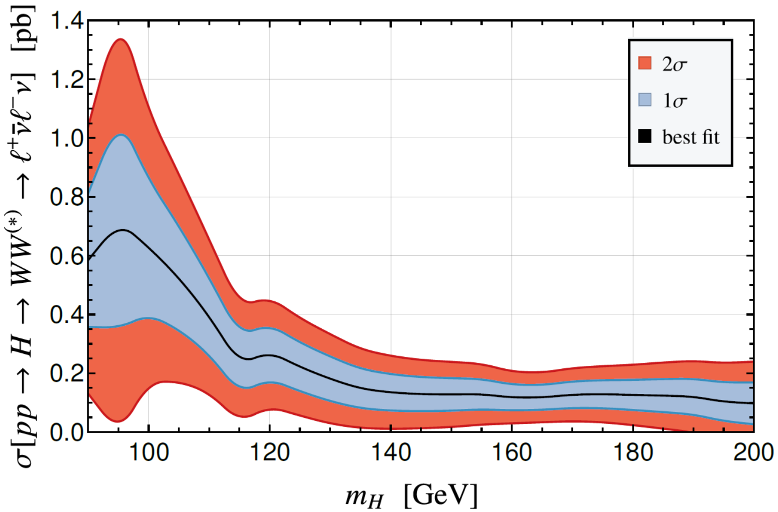
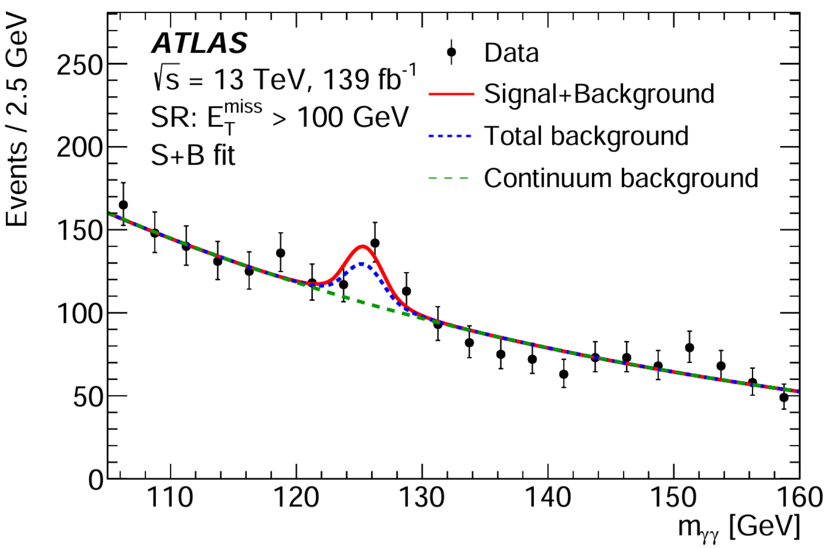
WW (reminder)

[GC, A. Crivellin, B. Mellado]

- WW excess ($\approx 2\sigma$) **requires more than a real Higgs triplet** (strictly 2 leptons opposite charge/flavor - jet veto)



- **The $\gamma\gamma$ signal for 151.5 GeV (ATLAS) is mostly in association with additional E_T^{miss}**

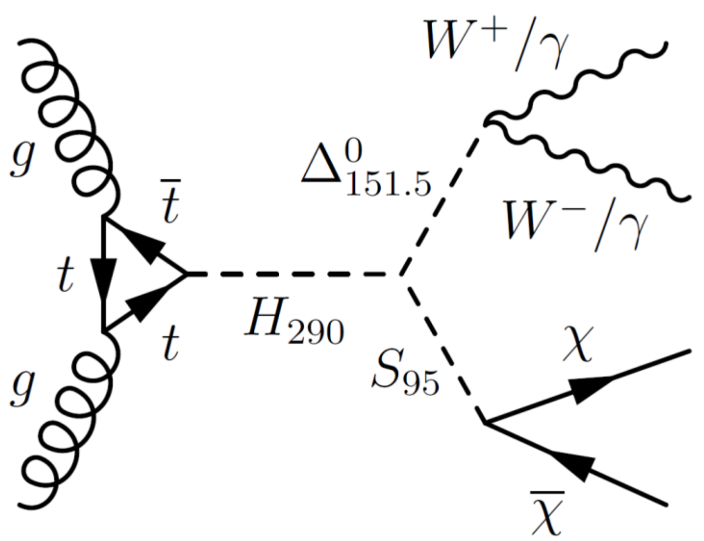


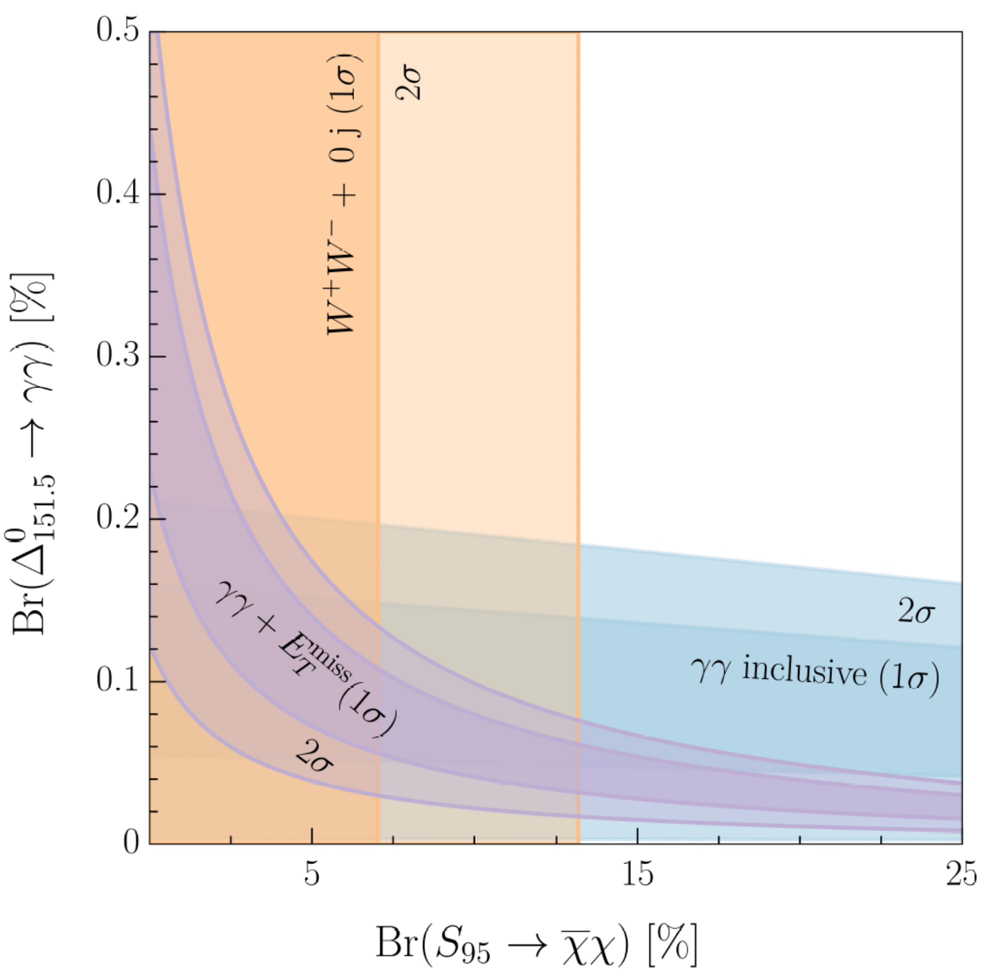
$$WW \,/\, \gamma\gamma \;+\; E_T^{miss}$$

The Δ2HDMS: WW

[GC, A. Crivellin, B. Mellado]

- 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

[GC, A. Crivellin, B. Mellado]

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- Right-handed quarks are odd under Z_2 symmetry
- Other fields are even under the Z_2/Z_2' symmetry

→ only ϕ_2 has Yukawa couplings

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[GC, A. Crivellin, B. Mellado]

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ϕ_2	2	$1/2$	$+/-$	SM
ϕ_1	2	$1/2$	$-/+$	$H_{290}, H^{\pm}_{400}, A_{400}$
Δ	3	0	$-/+$	$\Delta^0_{151.5}, \Delta^{\pm}_{\approx 151.5}$

- Right-handed quarks are odd under Z_2 symmetry
- Other fields are even under the Z_2/Z_2' symmetry

$$-\mathcal{L}_Y^{\not{Z}_2} = \mu_t \sqrt{2}\frac{m_t}{v}\bar{Q}_3\tilde{\phi}_1 u_3 \,.$$

→ only ϕ_2 has Yukawa couplings

The Δ2HDMS

[GC, A. Crivellin, B. Mellado]

Field	$SU(2)_L$	$U(1)_Y$	Z_2/Z_2'	Physical fields
ϕ_s	1	0	$+/-$	S_{95}
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- $pp \to A \to t\bar{t}$
- $pp \to At\bar{t} \to t\bar{t}t\bar{t}$

The Δ2HDMS

[GC, A. Crivellin, B. Mellado]

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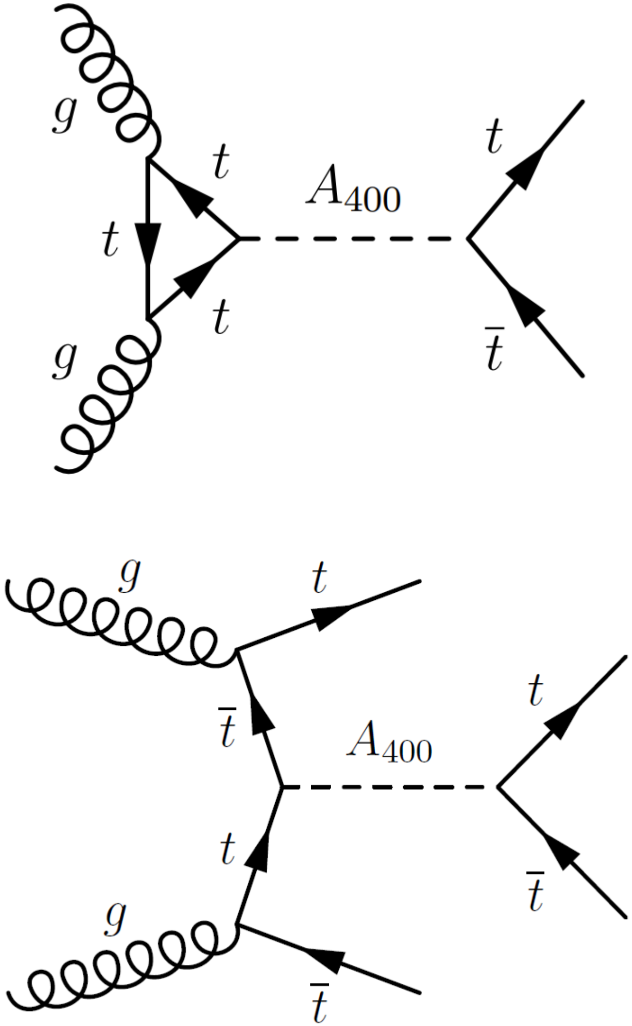
Δ	3	0	$-/+$	$\Delta^0_{151.5}, \Delta^{\pm}_{\approx 151.5}$

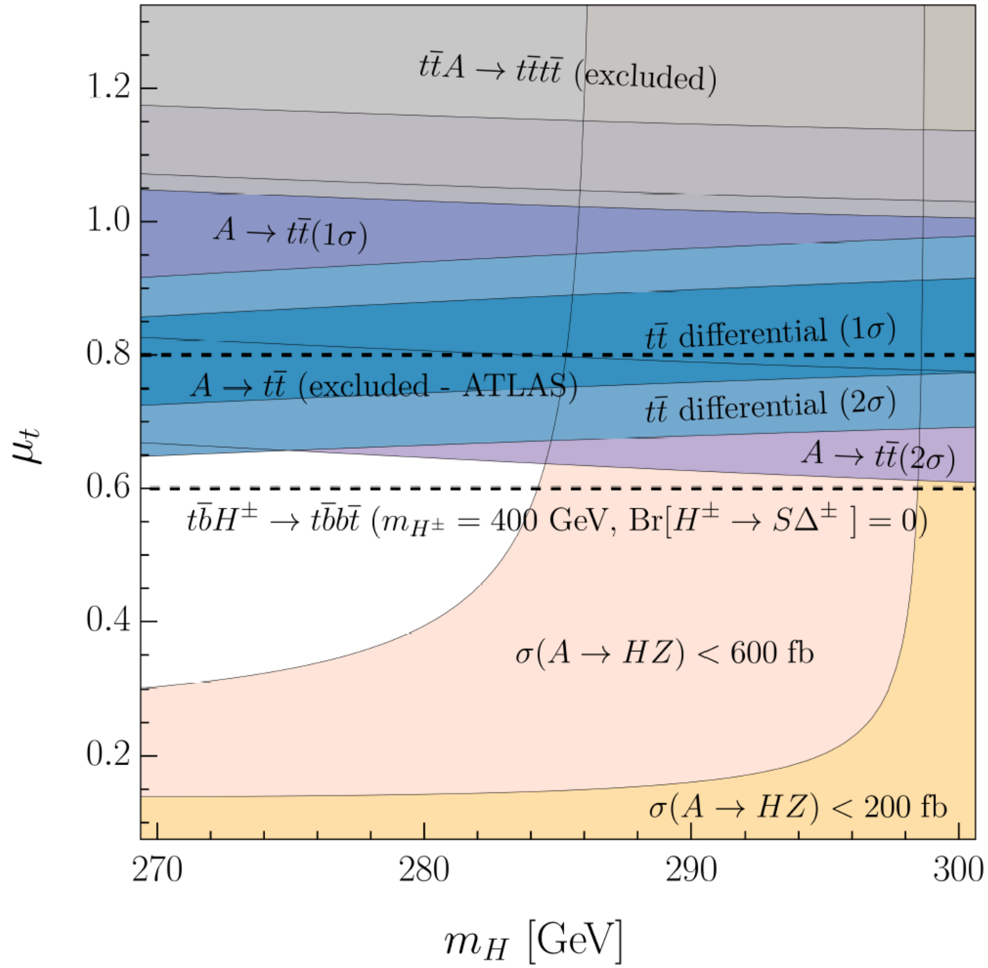
- CP-odd scalar mainly decays to $t\bar{t}$
- $t\bar{t}$ shape similar to SM

- $pp \to A \to t\bar{t}$
- $pp \to At\bar{t} \to t\bar{t}t\bar{t}$

The Δ2HDMS: A_{400}

[GC, A. Crivellin, B. Mellado]





The Δ2HDMS

[GC, A. Crivellin, B. Mellado]

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WW excess

Direct hints

$m_W \Rightarrow \langle\Delta\rangle \approx O$(GeV)
$Y = 0 \Rightarrow$ no flavor bounds

- $pp \to t\bar{t}$
- $pp \to At\bar{t} \to t\bar{t}t\bar{t}$

The Δ2HDMS

[GC, A. Crivellin, B. Mellado]

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WW excess

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

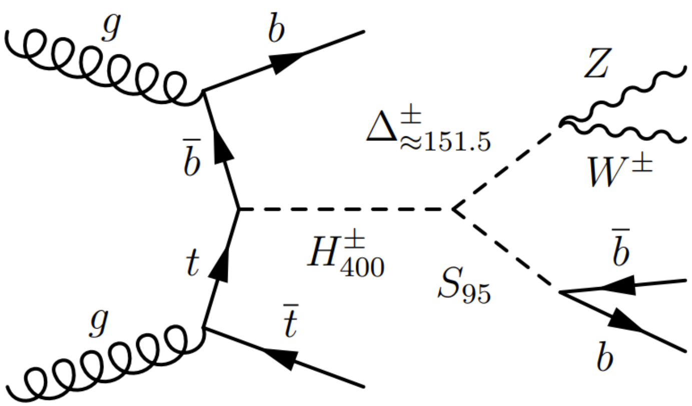
Direct hints

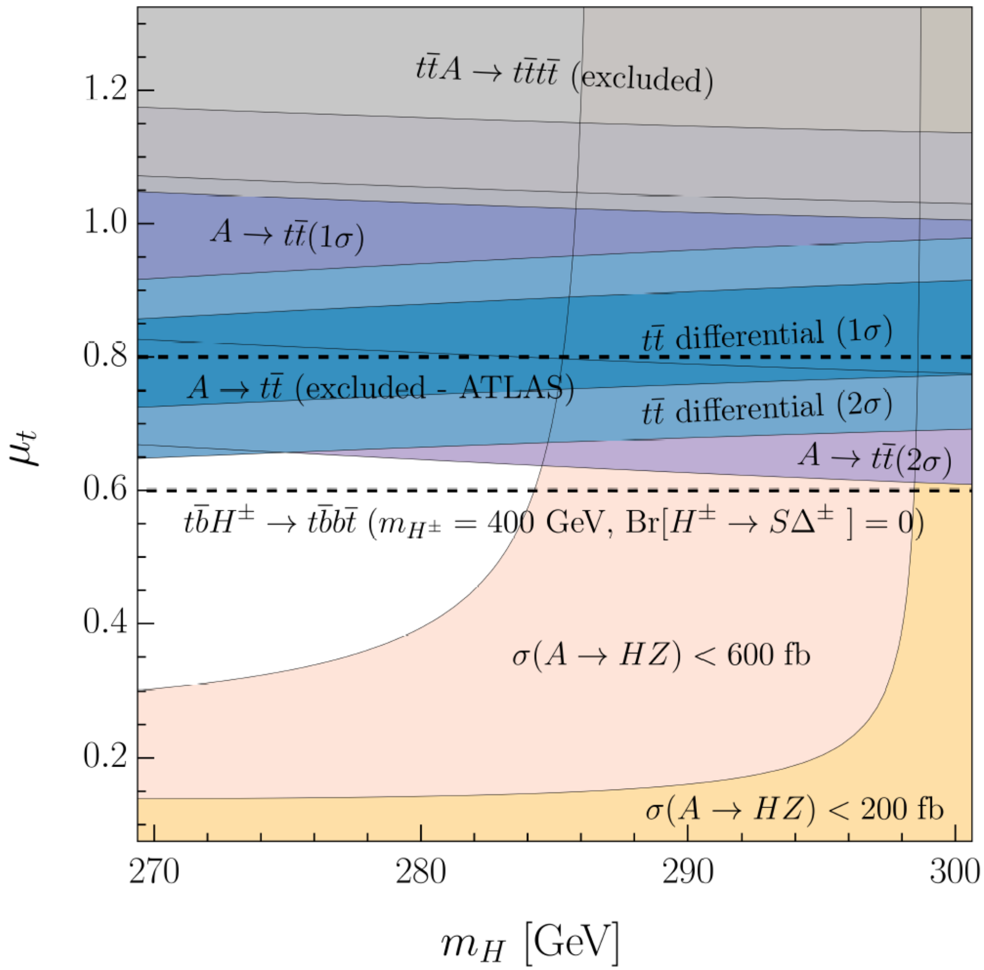
$m_W \Rightarrow \langle\Delta\rangle \approx O(\text{GeV})$
$Y = 0 \Rightarrow$ no flavor bounds

- $pp \to t\bar{t}$
- $pp \to At\bar{t} \to t\bar{t}t\bar{t}$

The Δ2HDMS: $H^{\pm}_{\approx 400}$

[GC, A. Crivellin, B. Mellado]





- Opening the channel
  $$H^{\pm}_{400} \to \Delta^{\pm}_{\approx 151.5}\, S_{95}$$
- Dominant production/decay has $t\bar{t}W$ ($t\bar{t}Z$) signature
- ≈200 fb predicted and 400 fb allowed at the 2σ level

Cosmology

- The $\Delta 2\mathrm{HDMS}$ can be further constrained from cosmological data

- A real triplet is enough for a strong first order EW phase transition
  [Bandyopadhyay et al.]

- The $\Delta 2\mathrm{HDMS}$ can also explain Baryogenesis
  [Ramsey et al.]

Conclusions

- **Hints for NP at 95 GeV and 151.5 GeV** ($\approx 3\sigma$ and $\approx 4\sigma$)
- $\gamma\gamma + X$ excess at 151.5 GeV explained by **a real triplet produced via Drell-Yan**
- Anomalies in $t\bar{t}$ differential distributions ($\geq 5.8\sigma$) explained combining the 95 GeV and the 152 GeV scalars
- **Δ2HDMS model provides a consistent explanation** (and more!)

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**)
→ **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)	$W^\pm h(125), WWW$	$\gtrapprox 4\sigma$
$Z(\to \ell\ell)\ell +$ (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) → 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) → Direct hints

Statistical analysis

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

[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 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 ⇒ additional 2 DoF

$pp \to t\bar{t}$ 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 $m_{\mathrm{T},t}/2$, 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:

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

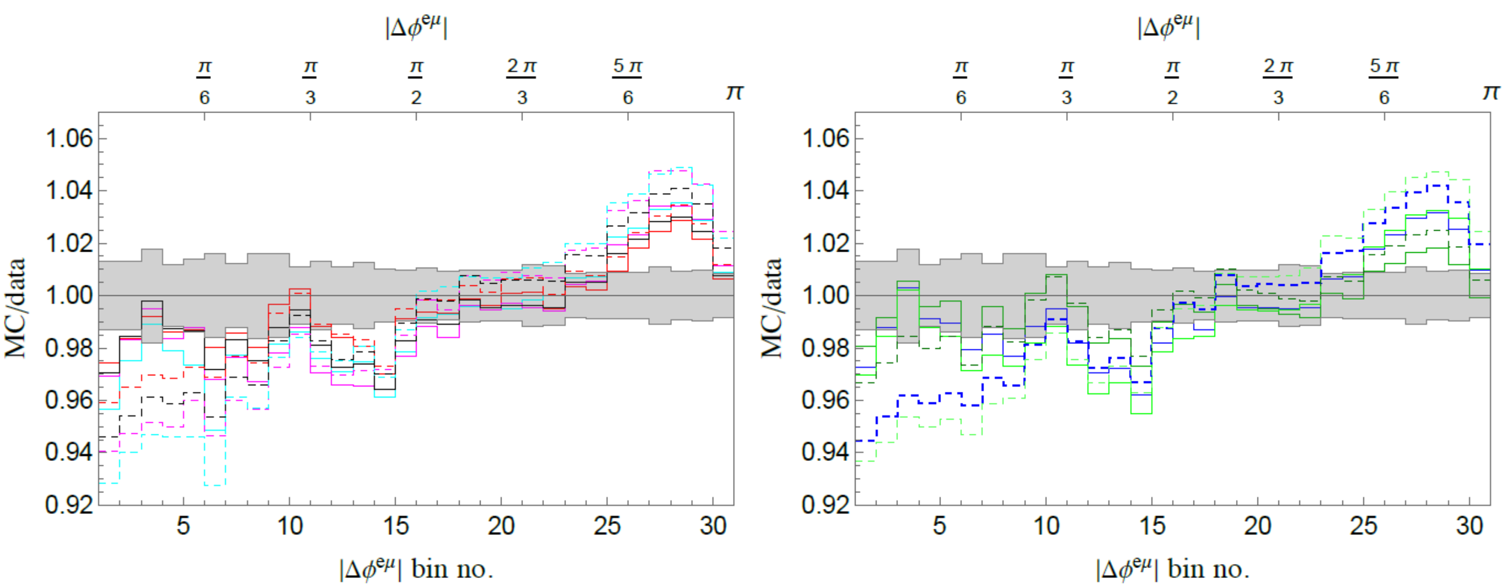
MC/Data

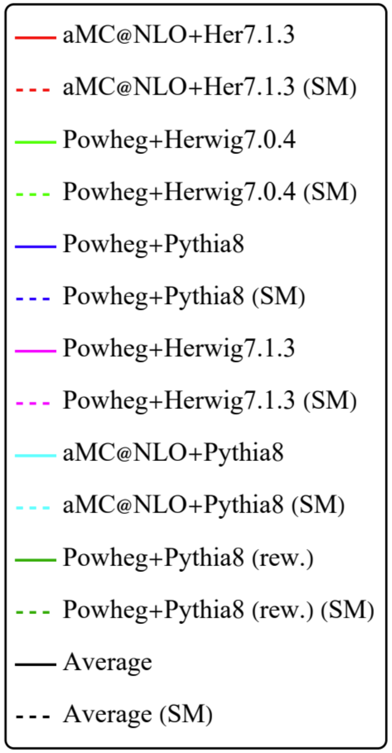
Correlation matrix computed from MG5 simulation

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

NP cross section extracted from fitted signal strength

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





- $|\Delta\phi|$ distribution normalized to $\sigma(pp \to t\bar{t})$
- **NP hypothesis is preferred over the SM by $\geq 5.8\sigma$**

The Δ2HDMS: prediction

- Deviations from SM prediction in $m_{b\bar{b}e\mu}$