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Higgs triplets at the LHC

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Introduction

Motivations:

- W-mass (3.7σ tension)
- Narrow resonances ($\gamma\gamma, WW, \tau\tau, Z + bb$) at 95 and 152 GeV (3.8$\sigma$ and 4.9σ) (2306.17209)
- Multi-lepton anomalies (2109.06065): deviations from SM in processes with W-like signature
  1. $t\bar{t}W, 4t, Wh, WWW$
  2. **Hints for low mass WW resonances ($\geq 2\sigma$)**
  3. **Tension in $t\bar{t}$ differential distributions ($\geq 5.8\sigma$)**

Real $SU(2)_L$ scalar triplet

$$\Delta = \frac{1}{2}\begin{pmatrix} \delta^0 & \sqrt{2}\delta^+ \\ \sqrt{2}\delta^- & -\delta^0 \end{pmatrix}$$

New physical fields :

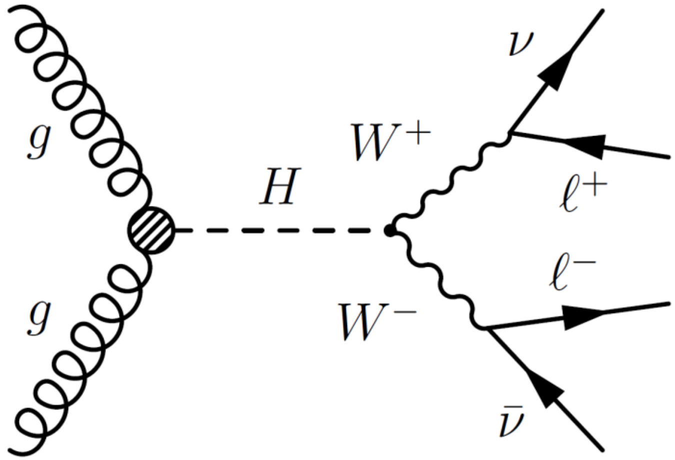
- CP-even scalar H
- Charged scalar $H^{\pm}$

Parameters :

- α: mixing angle with SM-higgs
- v_Δ: vev of δ^0

WW analysis

- **No dedicated BSM search for a resonance (H) decaying to WW** (i.e. $gg \to H \to WW$) with full luminosity and scanning down to 90 GeV for m_H
- CMS (2206.09466) and ATLAS (2207.00338) analyses available for **SM Higgs (135 fb^{-1})**



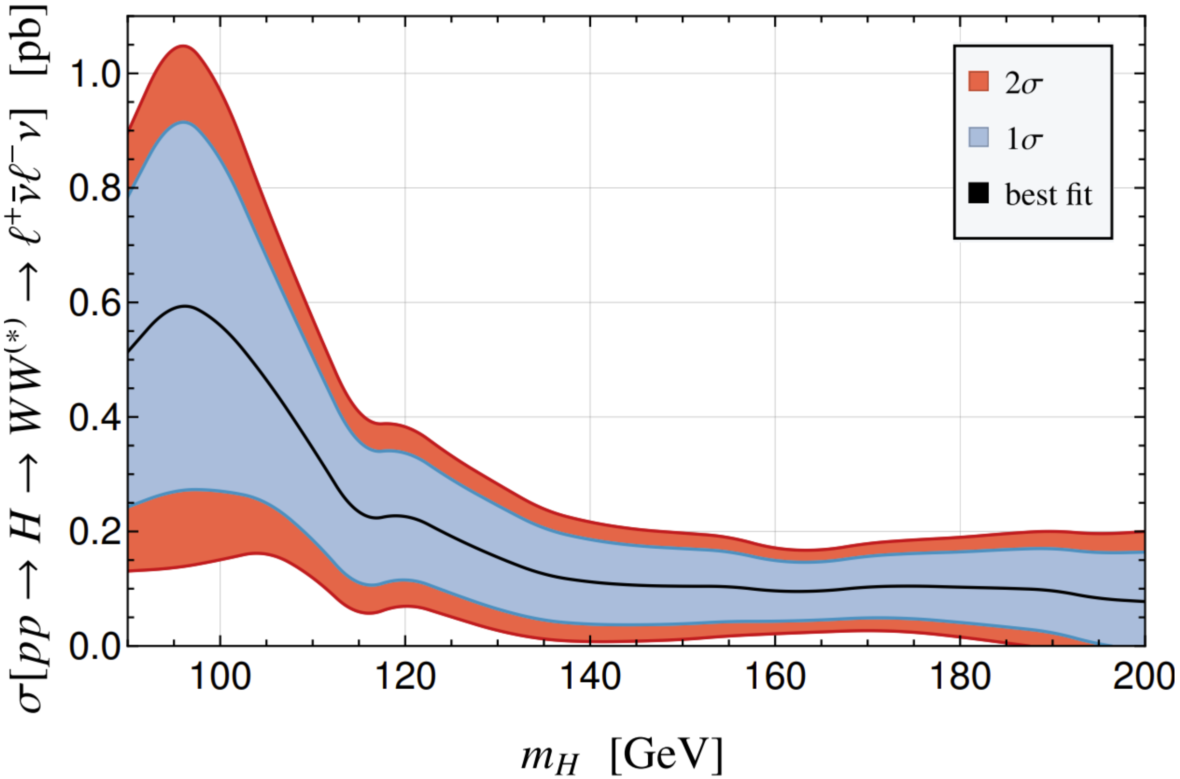
- Re-cast CMS and ATLAS SM Higgs analyses to search **for new scalars**
- **Simulation with MadGraph5 (Pythia8, Delphes3)**

> - 0-jet
> - Different flavour opposite sign lepton pair

WW results

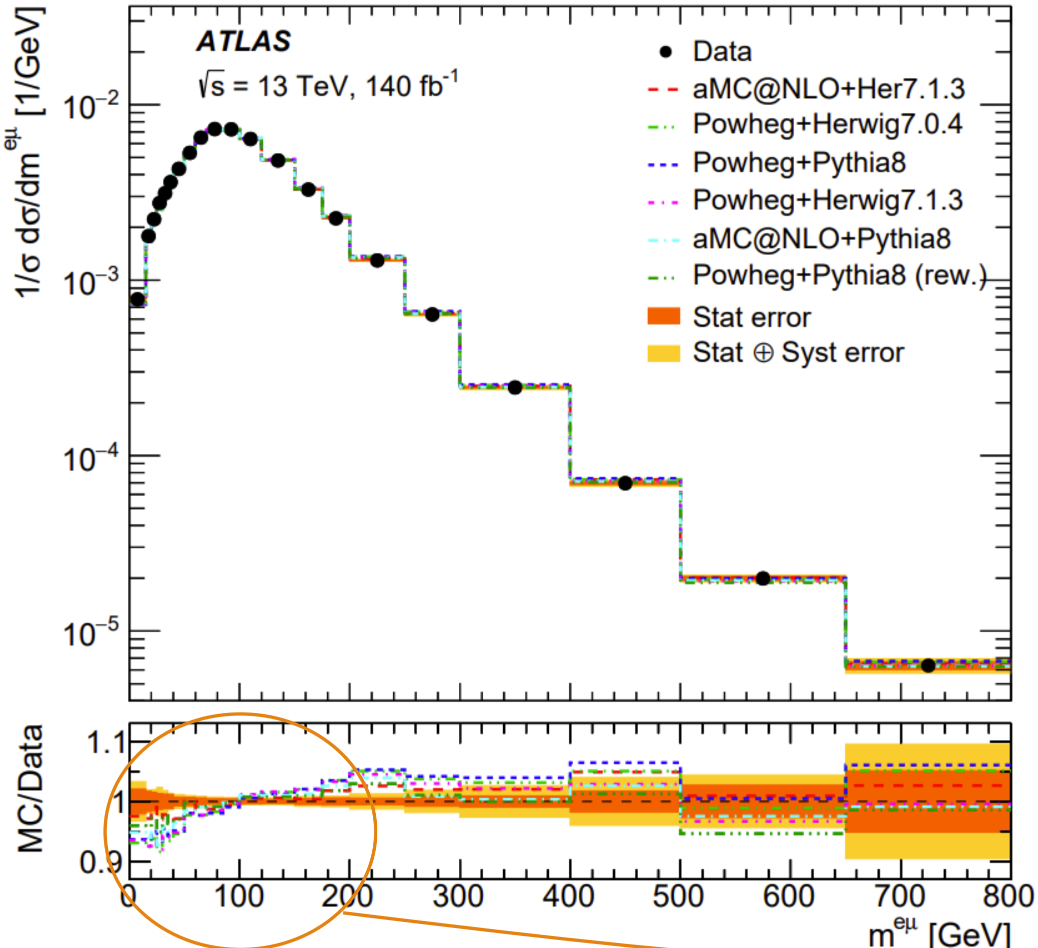
2302.07276 (Coloretti, Crivellin, Bhattacharya, Mellado)

- Observed limit is weaker than expected over the whole mass range (**preference for BSM $\geq 2\sigma$**) in line with the $\gamma\gamma$ indications for resonances at **95 and 152 GeV**



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

- Several distributions analyzed for the lepton pair
- We focus on the invariant mass $m^{e\mu}$



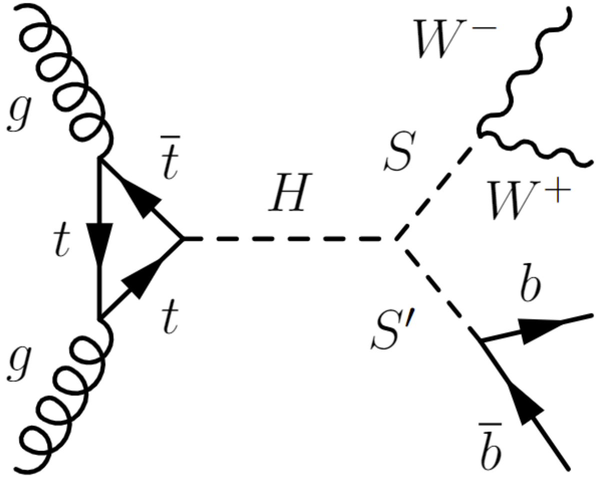
"No model can describe all measured distributions within their uncertainties."
ATLAS 2303.1534

Mismodelling of SM at the LHC or new physics effects?

The binning for low values of $m^{e\mu}$ is relatively thin. For the sake of visibility, we will display the data with equal size for all bins

NP in $pp \to t\bar{t}$ differential distribution

2308.07953 (Banik, Coloretti, Crivellin, Mellado)



- **NP must have $t\bar{t}$-like ($WWl\bar{l}$) signature**
- Masses of S and S' **fixed by the hints for 152 and 95 GeV resonances** (respectively)
- Mass of H large enough to produce S and S' on-shell (**no effects by varying m_H** between 250-320 GeV)

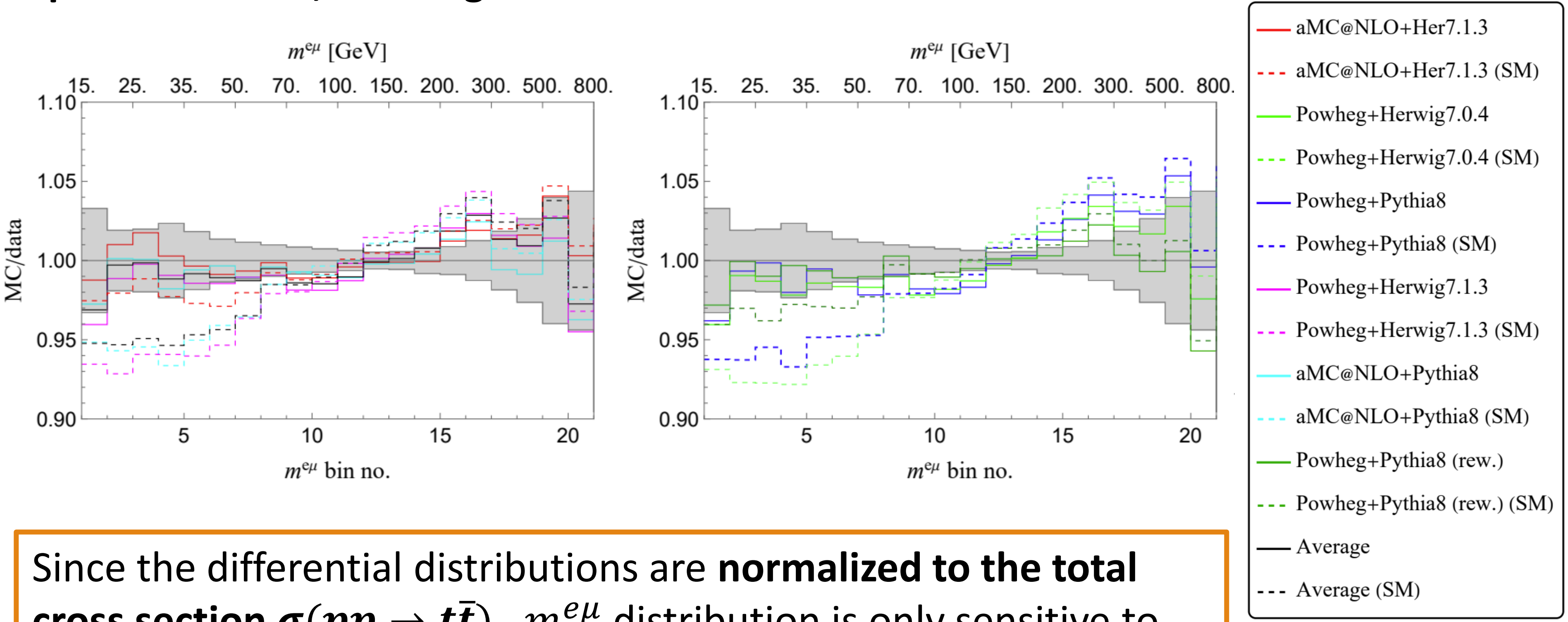
1. $H(270)$:
   - $SU(2)_L$ doublet

2. $S'(95)$:
   - $SU(2)_L$ real singlet
   - Mainly decaying to $b\bar{b}$
   - **Could explain $\gamma\gamma$ signal**

3. $S(152)$:
   - $SU(2)_L$ real triplet ($Y = 0$)
   - Mainly decaying to WW
   - **Natural explanation of W mass anomaly** if neutral component acquires a small vacuum expectation value $v_\Delta \approx O(1\text{GeV})$

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

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



Since the differential distributions are **normalized to the total cross section $\boldsymbol{\sigma(pp \rightarrow t\bar{t})}$**, $m^{e\mu}$ distribution is only sensitive to the shape of NP

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

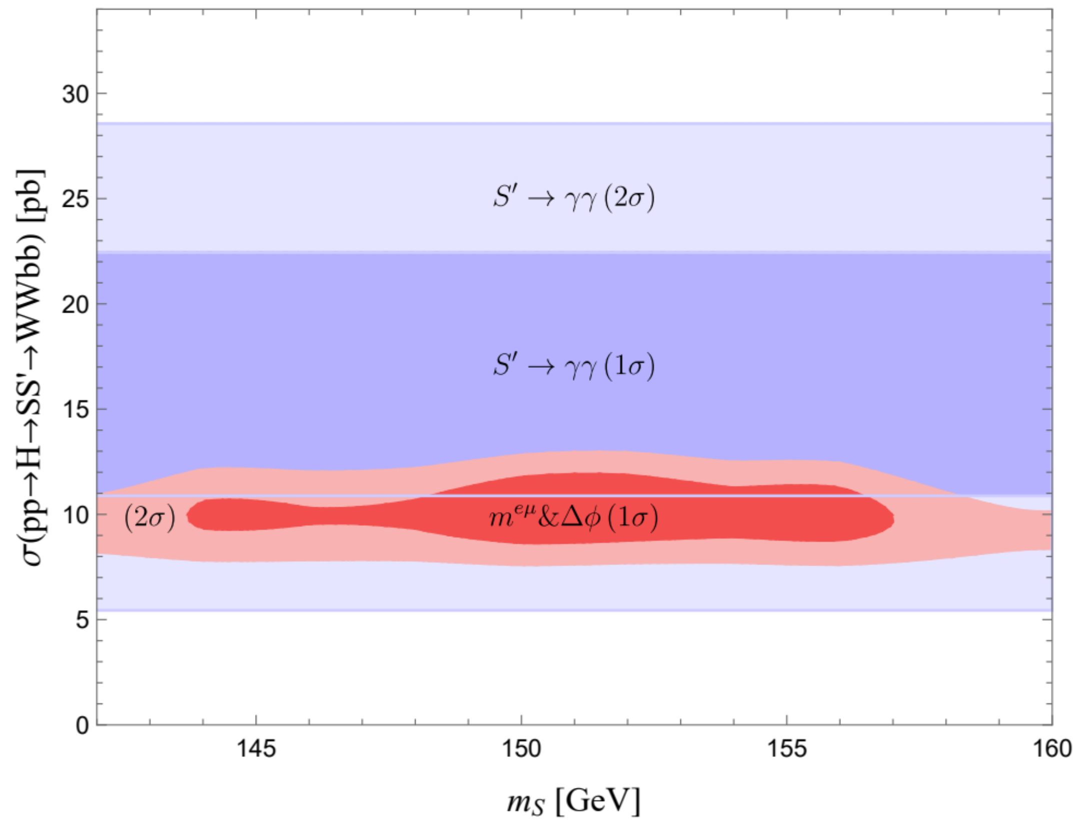
$pp \to t\bar{t}$ and $S'(95) \to \gamma\gamma$

- Assumptions: **S(152) is a triplet and S'(95) is a singlet** in the decay chain $pp \to H \to S(152)\, S'(95) \to WWb\bar{b}$

- Red is preferred region from the $t\bar{t}$ **differential distributions**

- Blue is preferred region from the **$\gamma\gamma$ signal strength at 95 GeV**

- **The regions nicely overlaps**



Triplet $H(95) \to \gamma\gamma$: results

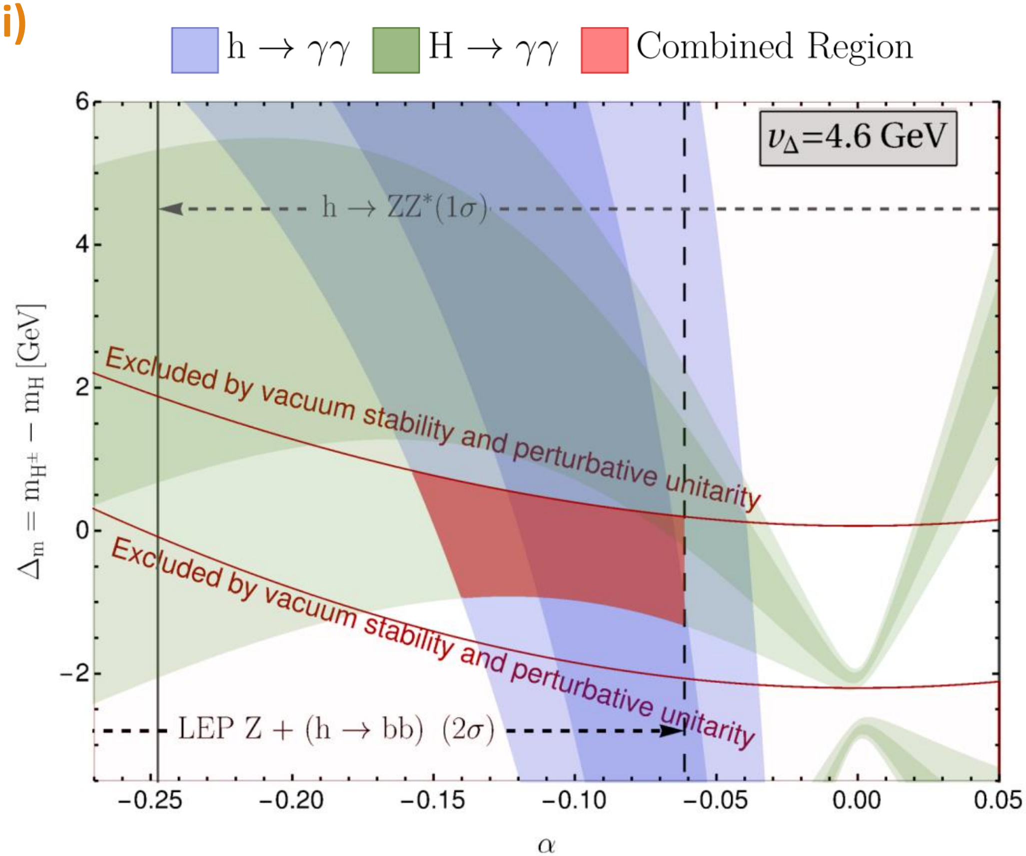
2306.15722 (Ashanujjaman, Banik, Coloretti, Crivellin, Mellado, Mulaudzi)

Constraints:

- Br[$h \to \gamma\gamma/ZZ$]
- Perturbative unitarity
- Vacuum stability

Hints for 95 GeV scalar:

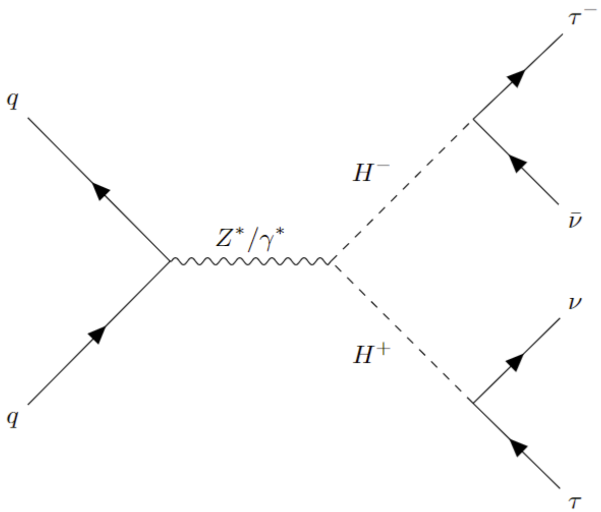
- $H \to \gamma\gamma$ (CMS and ATLAS)
- $Z + (H \to b\bar{b})$ (LEP)
- W mass



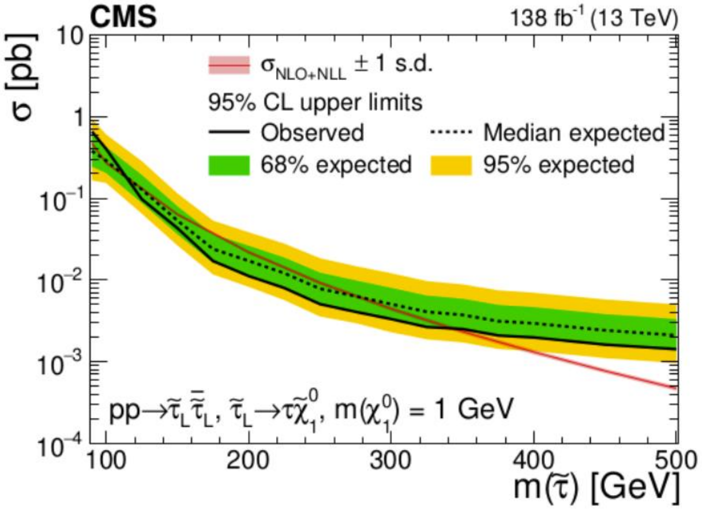
Since effects in W mass are small, v_Δ are required to be small $v_\Delta \approx O(1\text{GeV})$, thus a small mass splitting $m_{H^\pm} \approx m_H \approx 95$ GeV

Triplet $H^{\pm}(95) \to \tau\nu$: stau searches

- Drell-Yan production $pp \to H^{\pm} \to \tau\nu$ **has same signature as stau decays**



- $\sigma(pp \to H^{\pm} \to \tau\nu)$ borderline with existent CMS and ATLAS stau searches limits



- Although $m_{H^{\pm}} \approx m_H$, the maximum mass splitting is $\approx 4(v_\Delta/v_{SM})^2$
- This **opens the channel $H^{\pm} \to HW^*$ and reduces the branching ratios of $H^{\pm} \to \tau\nu$**
- Alternative solution: Vector Like Quarks to enhance $H^{\pm} \to cs$

Conclusions

- Electro-weak scale NP poorly constrained by the LHC
- Several hints motivate existence of new scalars at 95 and 152 GeV
- **Real $SU(2)_L$ scalar triplet can naturally explain W mass excess**

Triplet at **95 GeV**
- WW excess

or

- Resonant $\gamma\gamma$ signal (95 GeV)
- **Tension with the bound on $\sigma(pp \to H^{\pm} \to \tau\nu)$ from stau searches**

Triplet at **152 GeV**
- WW excess
- **$t\bar{t}$ differential distribution anomaly with $H \to S(152)\, S'(95) \to WWb\bar{b}$**
- Resonant $\gamma\gamma$ signal (95 GeV) if **$S(152)$ is a triplet and $S'(95)$ is a singlet**

- **Emergence of a model with multiple scalars in a singlet(95)-doublet(125)-doublet(270)-triplet(150) pattern** (work in progress…)

Thanks for your attention!

Back-up slides

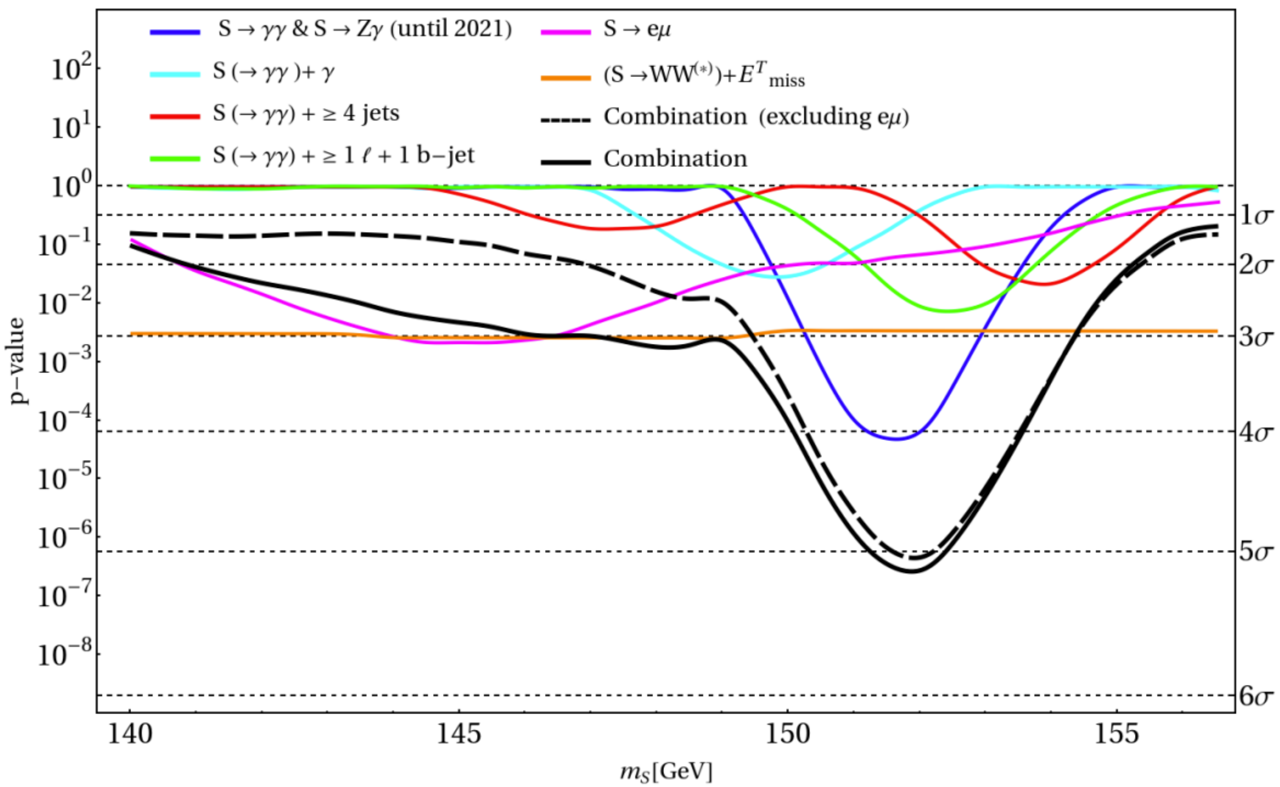
Multi-lepton anomalies: summary

(2109.06065)

Final state	Characteristics	SM backgrounds	Significance
$\ell^+\ell^-$+(b-jets)[51,54,55]	$m_{\ell\ell} < 100$ GeV, $(1b, 2b)$	$t\bar{t}, Wt$	$> 5\sigma$
$\ell^+\ell^-$+(no jet)[50,56]	$m_{\ell\ell} < 100$ GeV	W^+W^-	$\approx 3\sigma$
$\ell^\pm\ell^\pm, 3\ell$ + b-jets[53,57,58]	Moderate H_T	$t\bar{t}W^\pm, t\bar{t}t\bar{t}$	$> 3\sigma$
$\ell^\pm\ell^\pm, 3\ell$, (no b-jet)[52,59,60]	In association with h	$W^\pm h(125), WWW$	$\gtrsim 4\sigma$
$Z(\to \ell\ell)\ell$, (no b-jet)[51,61]	$p_T^Z < 100$ GeV	$ZW^\pm$	$> 3\sigma$

- Summary of all channels with multi-lepton anomalies
- ℓ being a muon or an electron

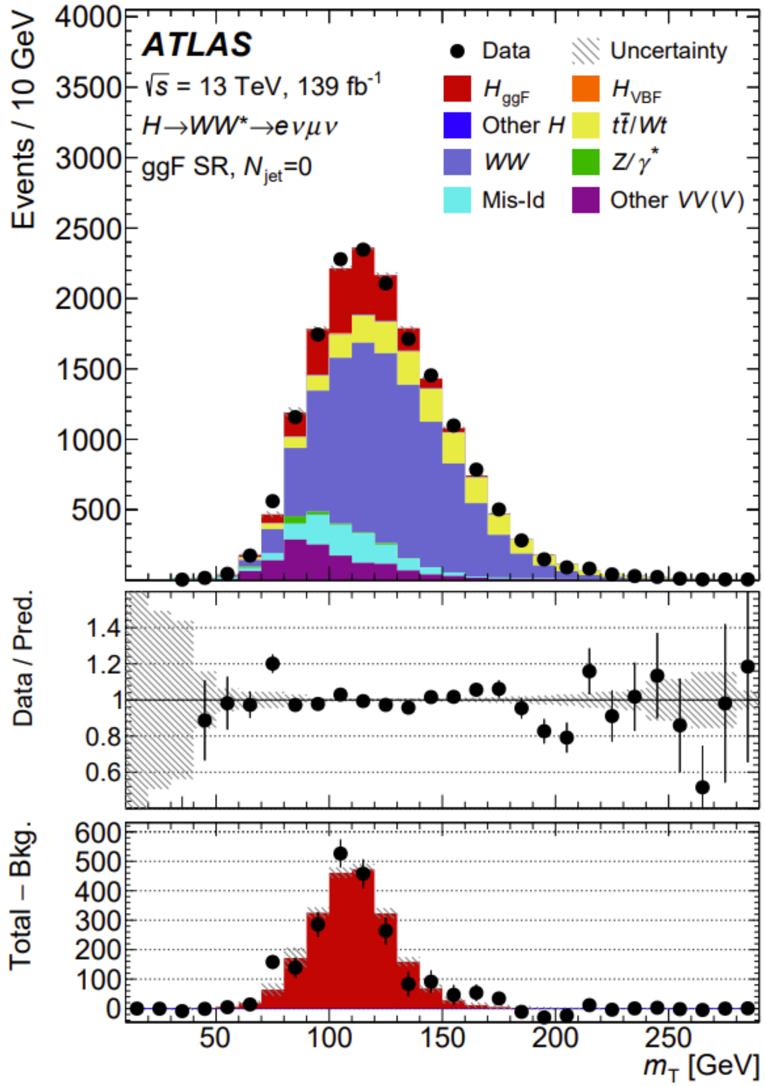
95 and 152 excess: summary



2109.06065

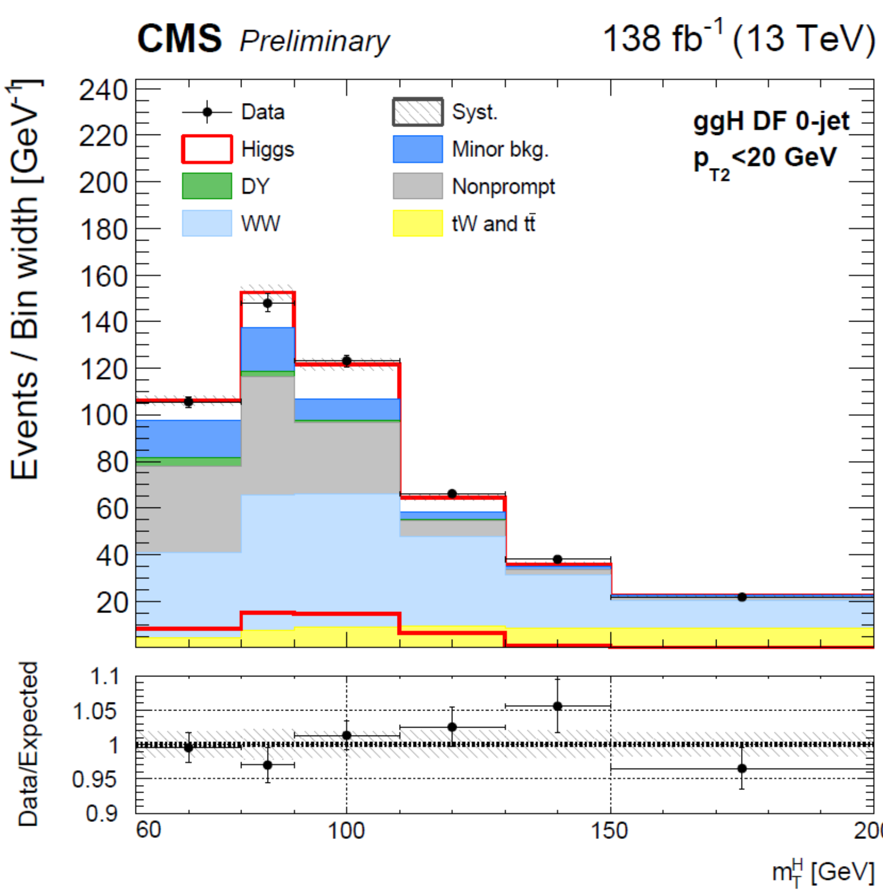
- The p-values of the individual high mass channels as well as their combination, both including and excluding the μe signal

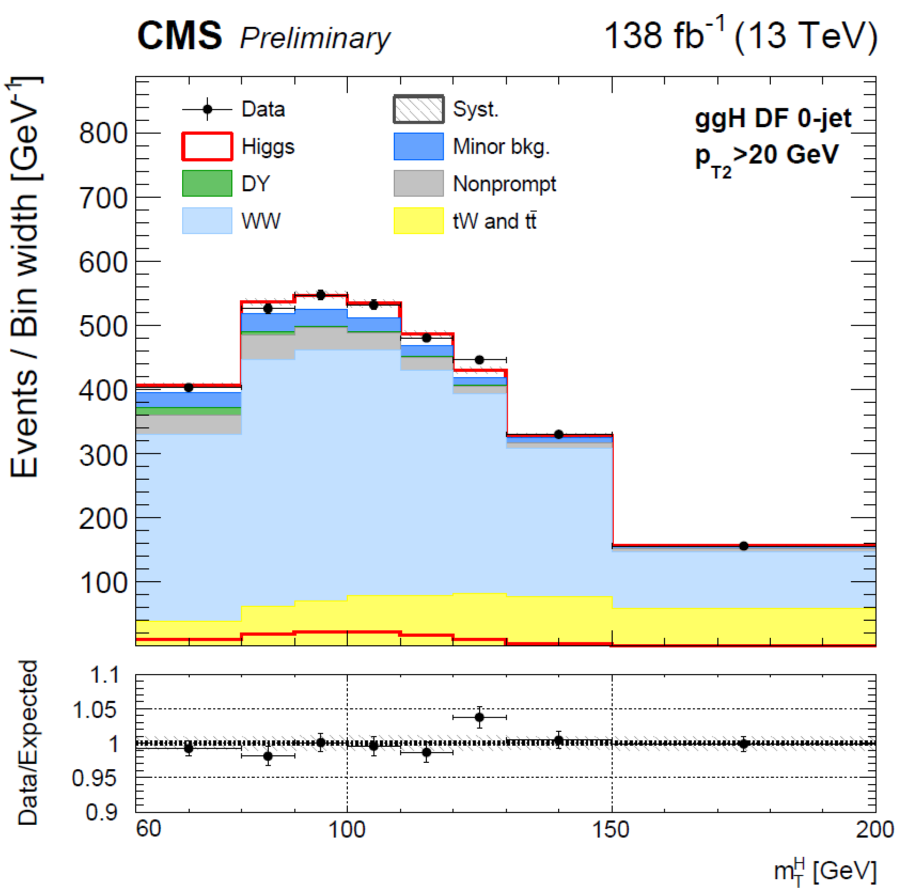
SM WW searches: ATLAS 2207.00338



- ATLAS reports the postfit data
- Only SM contribution is rescaled by a factor of 1.21

SM WW searches: CMS 2206.09466





- CMS performs a simultaneous fit of SM+background

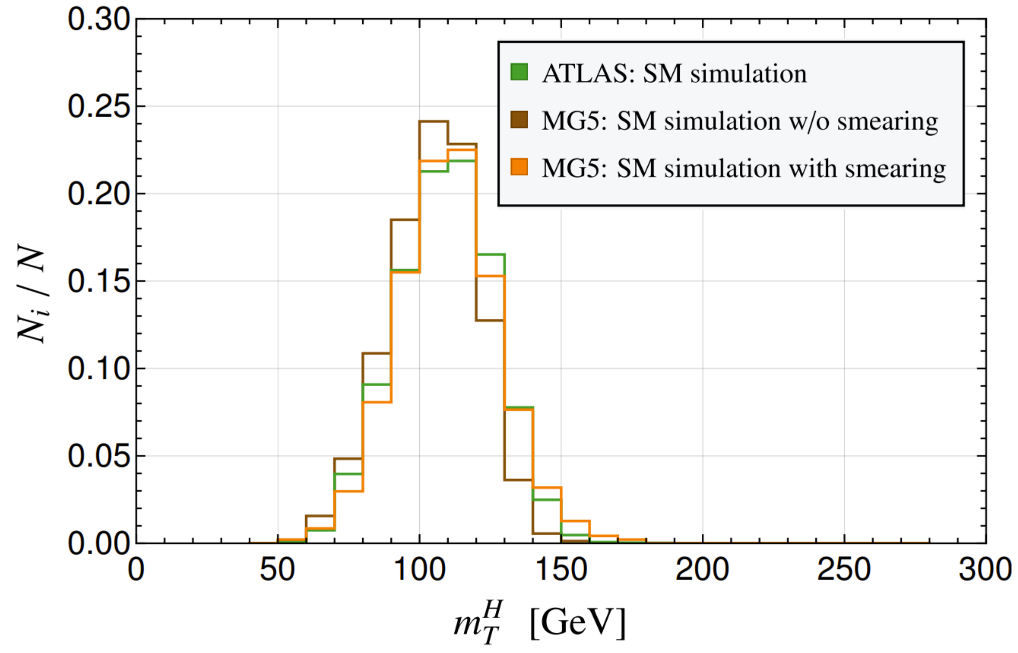
Simulation

HEP tools: **MadGraph5_aMC@NLO (Pythia8, Delphes)**

Limitations of fast simulation

- SM-simulation VS ATLAS one
- **Smearing and shifts**
- Corrected **for efficiency (energy dependence)**
- Corrected for **QCD NNLO effect in production cross section**

Checks over SM-samples:
ATLAS full-simulation VS **MG5 fast-simulation**



Uncertainties

ATLAS

- **ATLAS scaled SM theory prediction by 1.21**
- Strong anti-correlations among the different background signals (including the SM Higgs)
- Mis-Id background is least correlated and the total uncertainty matches total one
  → Mis-Id uncertainty chosen as the total experimental systematic uncertainty
- **Theory uncertainty (systematic):**
  7% uncertainty on the SM Higgs signal

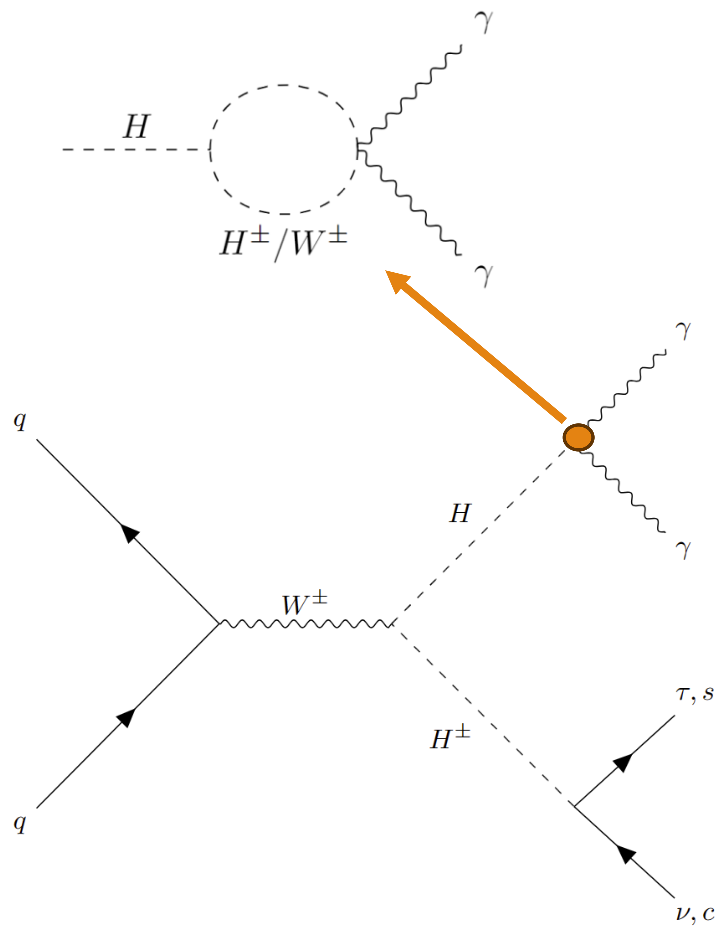
CMS

- CMS uses a combined fit to signal and background to account for systematic uncertainties
  → **re-fit background (including SM signal) when including new physics**
- **Theory uncertainty (systematic):**
  7% uncertainty on the SM Higgs signal

Systematics uncertainties correlations included

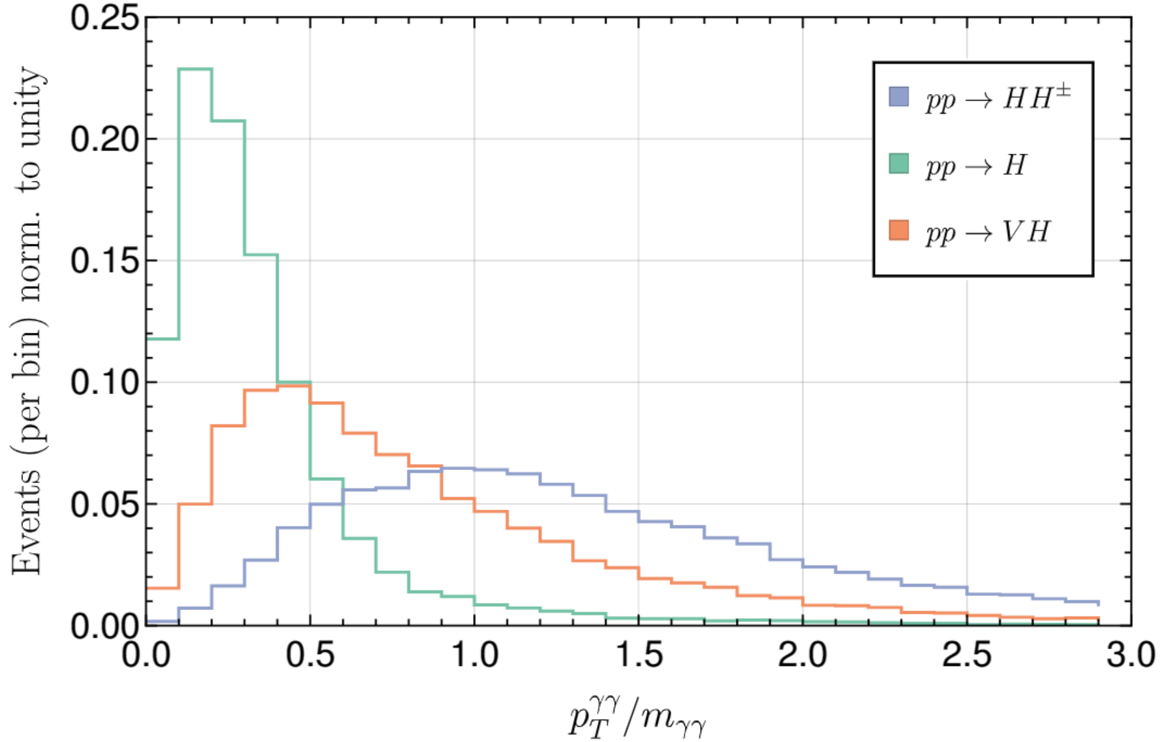
Drell-Yan production

- Drell-Yan production leading to the $\gamma\gamma$ excess (in addition to gluon fusion (GF) via mixing with the SM higgs)
- **Br[$H \to \gamma\gamma$] sizable as a function of the mixing CP-even angle α and the mass splitting $H^{\pm} - H$**
- Although $H \to \gamma\gamma$ produced in association with $H^{\pm} \to$ jets, **the signal does not fall in the vector boson fusion (VBF) category** (due to the angular distributions of the jets)



Predictions for p_T of $H \to \gamma\gamma$

- H produced in association with $H^{\pm}$:
  $pp \to H^{\pm}\,(H \to \gamma\gamma)$
- p_T spectrum not gluon fusion (GF) – like:
  $pp \to H \to \gamma\gamma$
- p_T spectrum not VH – like:
  $pp \to V\,(H \to \gamma\gamma)$



- Model built at NLO in QCD with Feynrules
- Signals generated at NLO in QCD via MadGraph5 with CMS cuts
- **Shape of p_T of the photon pair with strong predictivity**

FCCC mediated by $\boldsymbol{H^{\pm}}$

- Coupling of Δ to fermions happens **only via mixing** with the SM higgs doublet

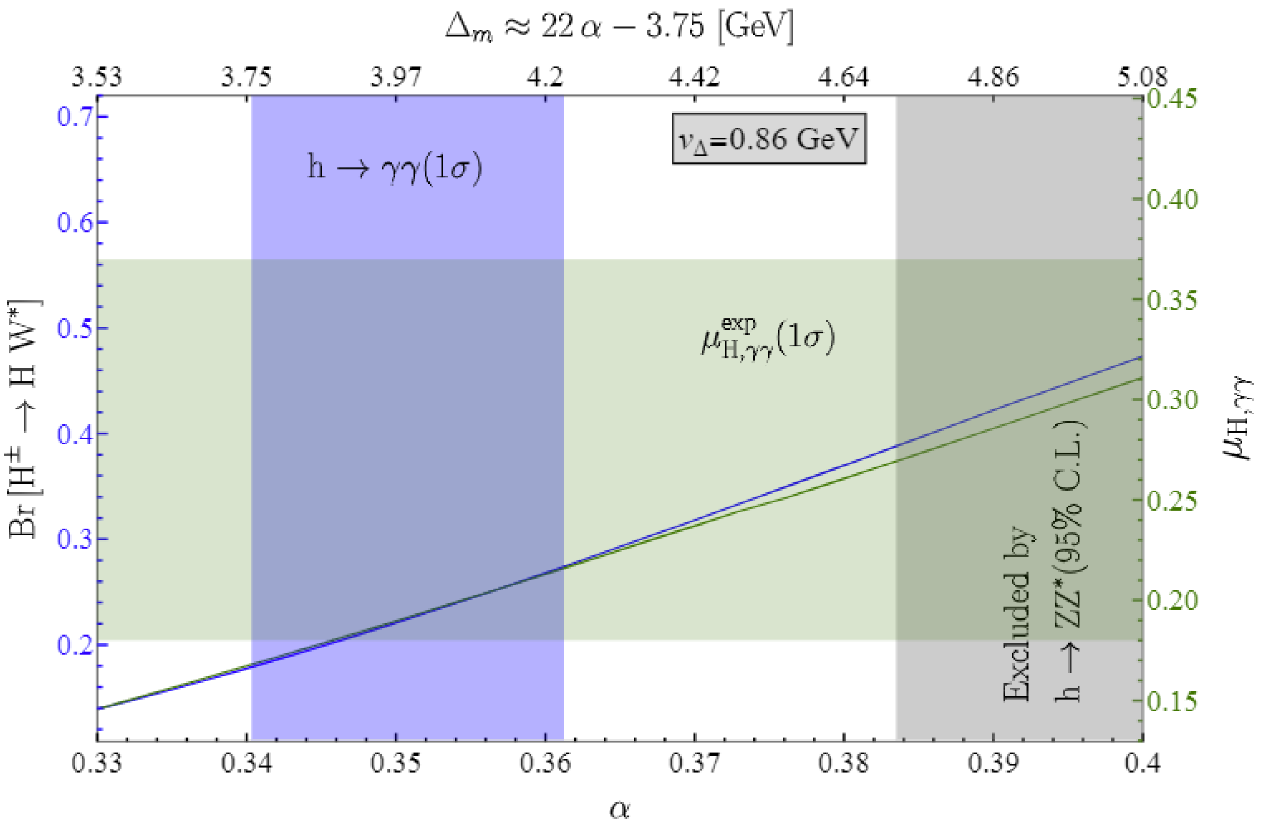
- Couplings of $H^{\pm}$ to fermions are proportional to $\boldsymbol{Sin(\epsilon)} \approx \frac{\boldsymbol{v_{\Delta}}}{\sqrt{\boldsymbol{v_{\Delta}^2 + v_{SM}^2}}}$

  with ϵ being the mixing angle among the charged component of the triplet and the SM charged Goldstone boson

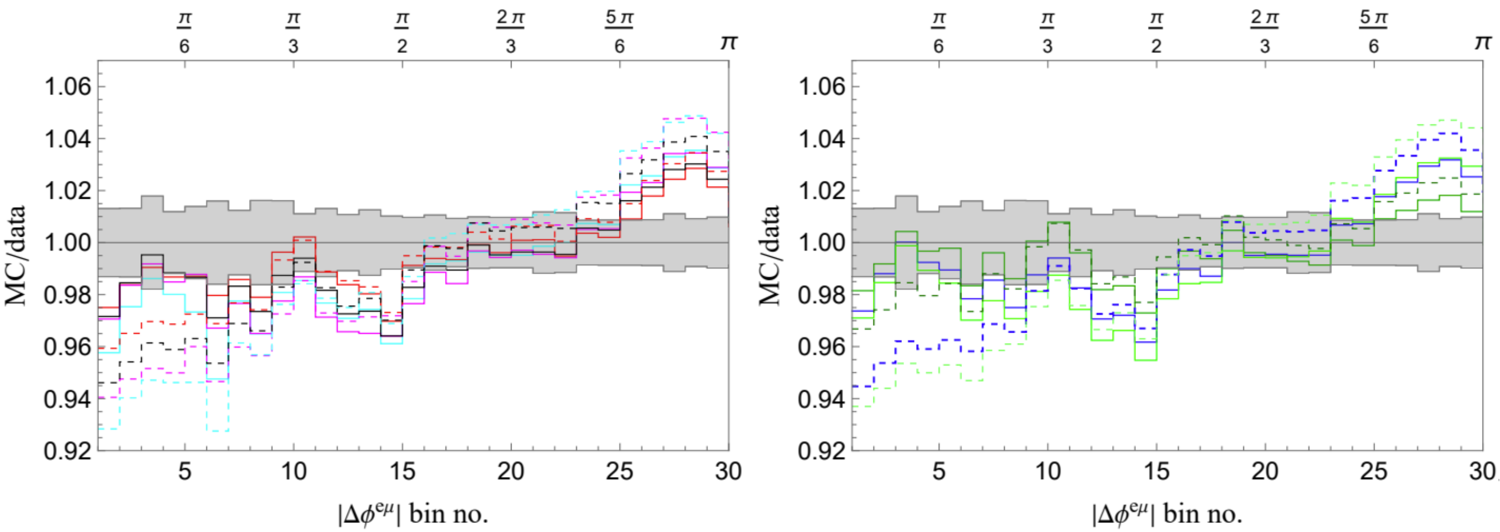
- **Since $\boldsymbol{v_{\Delta}}$ is small ($\boldsymbol{m_W}$ only slightly enhanced), effects related to FCCC mediated by $\boldsymbol{H^{\pm}}$ are negligible**

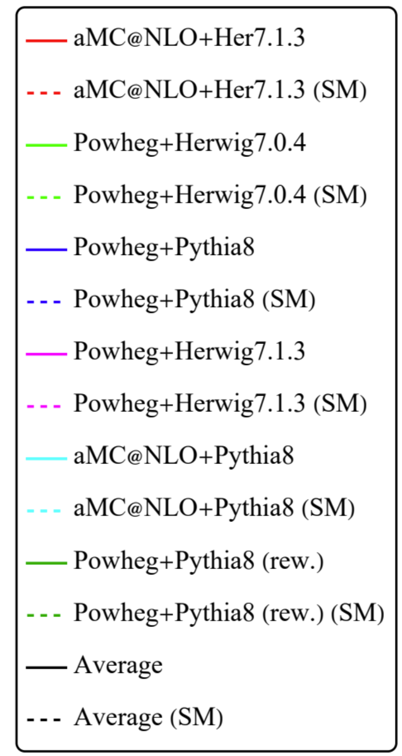
Reduction of Br[$H^{\pm} \to \tau\nu$]

- Although $m_{H^{\pm}} \approx m_H$, opening of the channel $H^{\pm} \to HW^*$
- Reducing the decay rate $H^{\pm} \to \tau\nu$
- **Alternative solution: Vector Like Quarks to enhance $H^{\pm} \to cs$**



$pp \to t\bar{t} : |\Delta\varphi|$





$|\Delta\varphi|$ distribution normalized to the total cross section $\sigma(pp \to t\bar{t})$

$\to$ **in average, NP hypothesis is preferred over the SM by 10.4σ**

$pp \to t\bar{t}$: $|\Delta\varphi|$, $m^{e\mu}$ and combination

	$m^{e\mu}$				$\Delta\phi^{e\mu}$				$m^{e\mu} + \Delta\phi^{e\mu}$				
	$\chi^2_{\rm SM}$	$\chi^2_{\rm NP}$	$\sigma_{\rm NP}$	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