Searching for Low-Mass Resonances at the LHC (and beyond)

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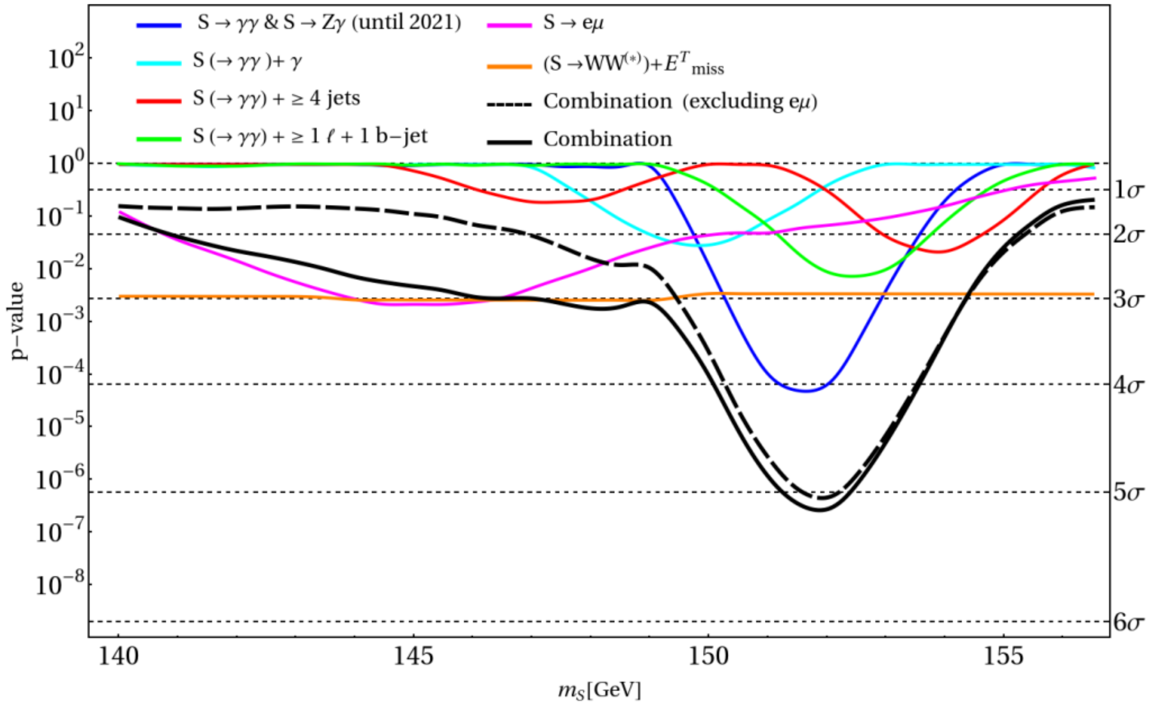
Structure of the talk

1. Motivations
2. WW leptonic excess at 95 GeV
3. $\gamma\gamma$ excess at 95 GeV
4. Scalar $SU(2)_L$ real triplet as a NP candidate
5. CEPC foreseen studies

Overview and Motivations

- Multi-lepton anomalies (MLA) are excess related to muon and electrons as final states
- **MLA are rising more and more at the LHC** and motivates the existence of new scalars at the weak scale
- **Low mass energy range still not-so-well scrutinized at the LHC**
- In addition: **152 GeV (and 95 GeV)** in $\gamma\gamma, \tau\tau, WW$ and bb channels



2306.17209v1: Bhattachara, G.C., Crivellin, Mellado

WW to leptons

based on 2302.07276: G.C., Crivellin, Bhattacharya, Mellado

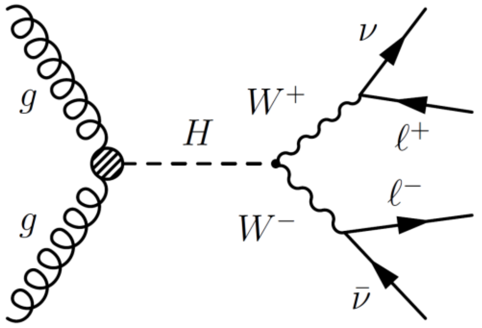
- MLA suggests decays of scalar resonance to a pair of W bosons
- **No available dedicated resonant BSM searches for $gg \to H \to WW$** with full luminosity and scanning down to 95 GeV for a scalar H
- CMS and ATLAS analyses available for **SM higgs in $gg \to h \to WW$ with full luminosity 135 fb^{-1}**

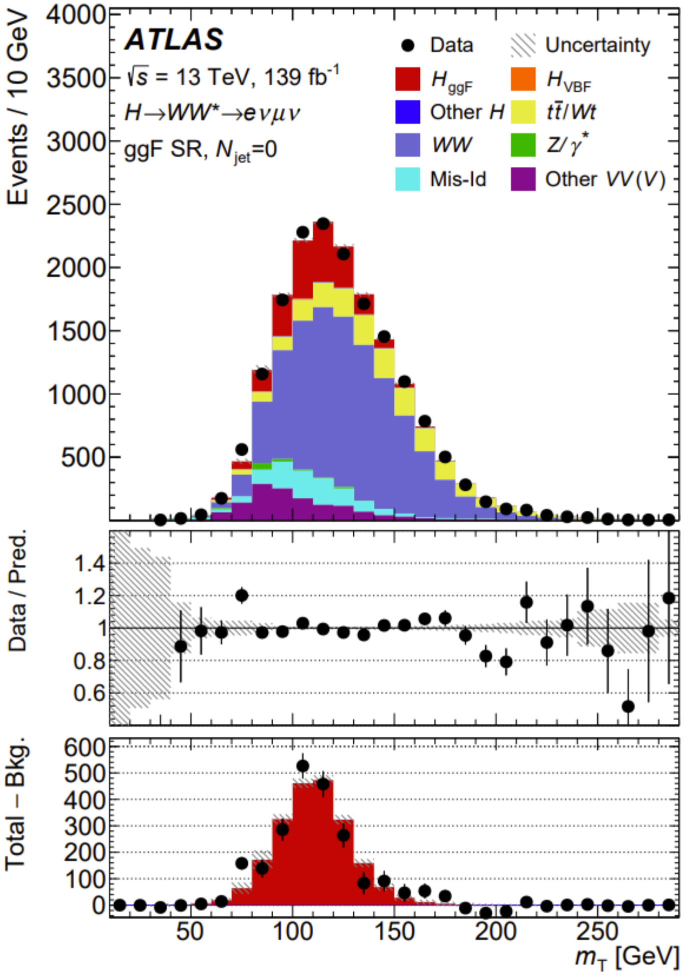
→ We re-cast CMS and ATLAS SM Higgs analyses to search **for new scalars**

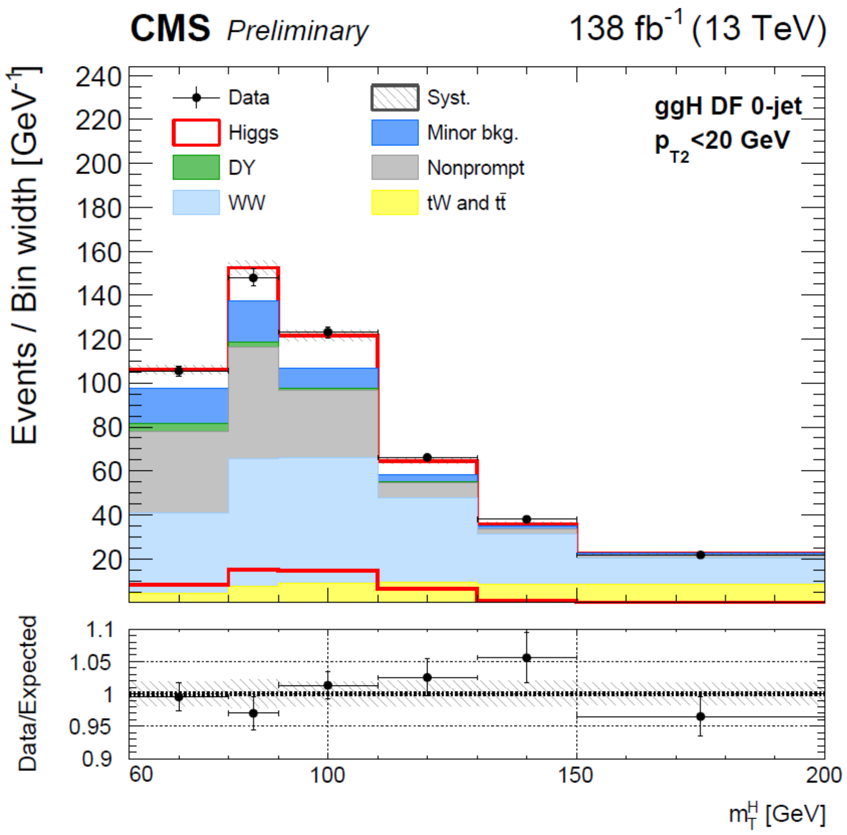
SM *WW* searches

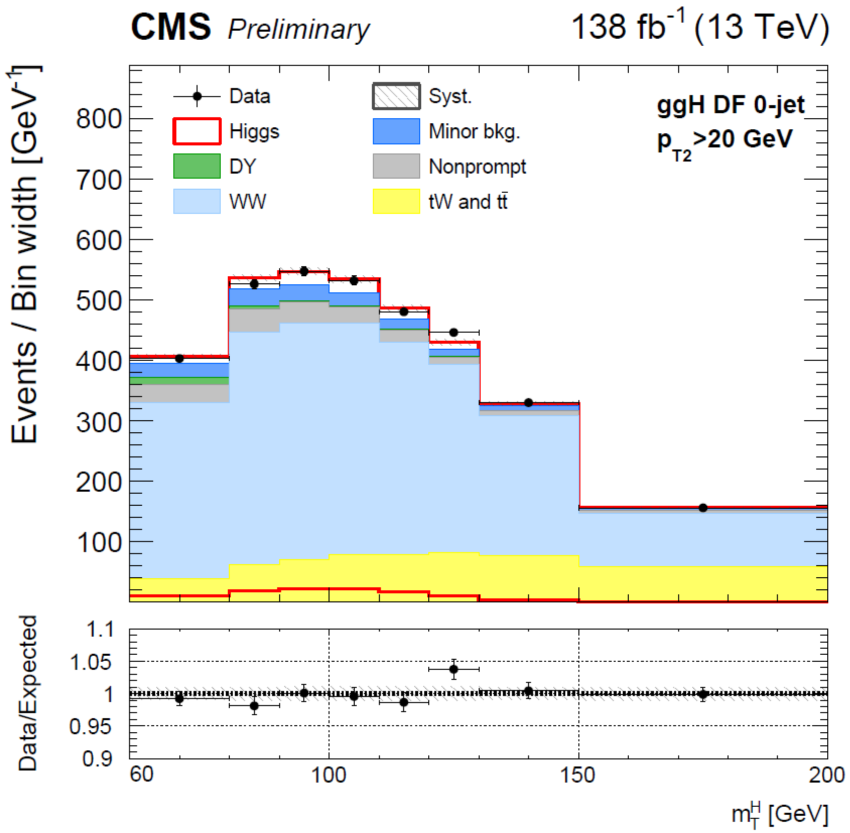
CATEGORY

1. 0-jets
2. Gluon fusion (ggH)
3. Different flavour opposite sign (DFOS) lepton pair



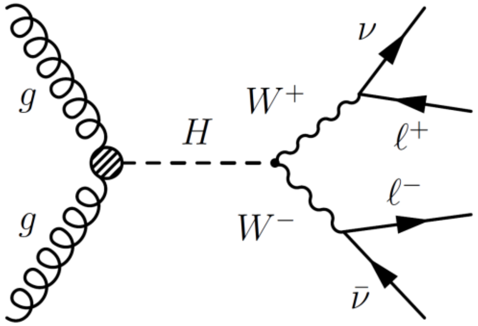






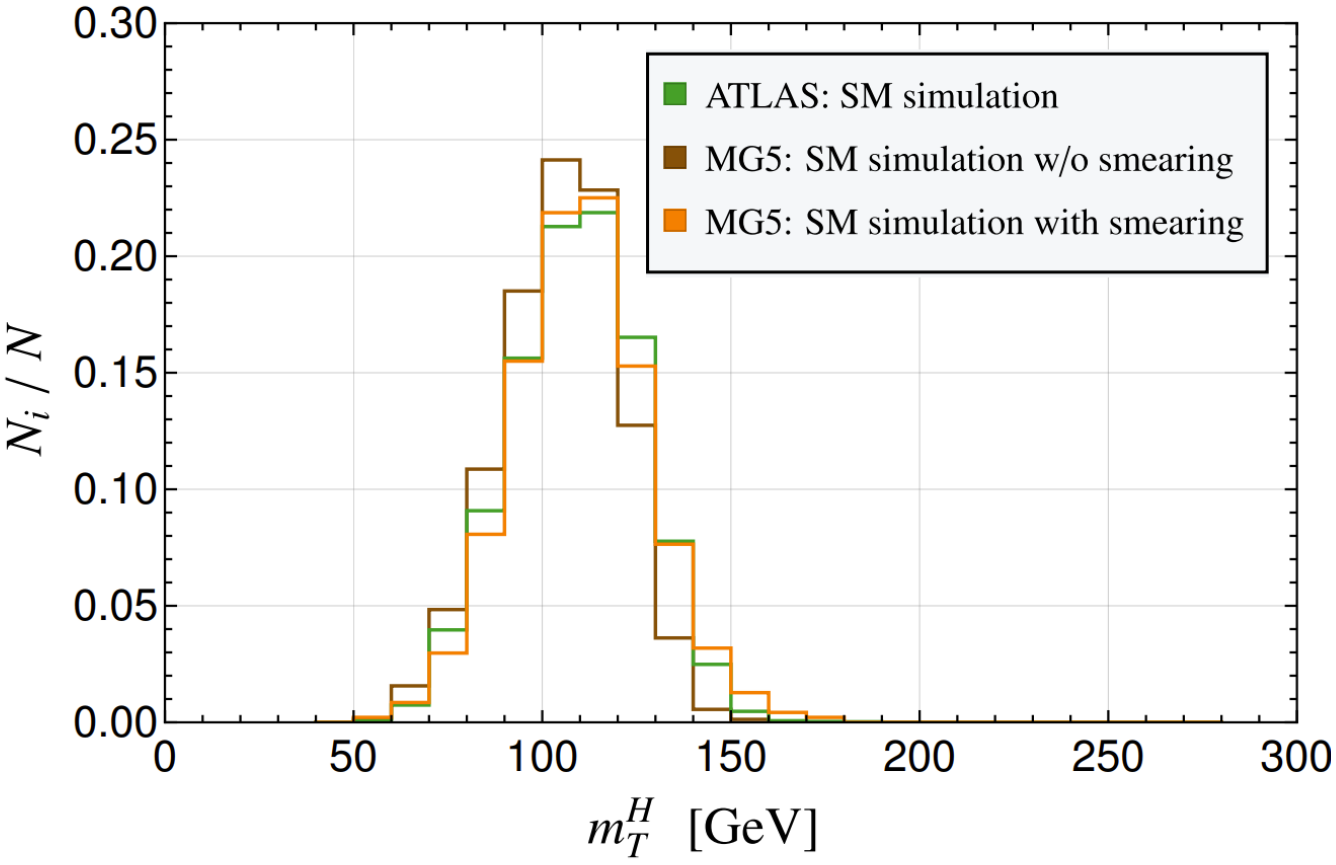
Simulation

HEP tools:
→ **MadGraph5_aMC@NLO**
→ Pythia8 (showering)
→ Delphes (detector)



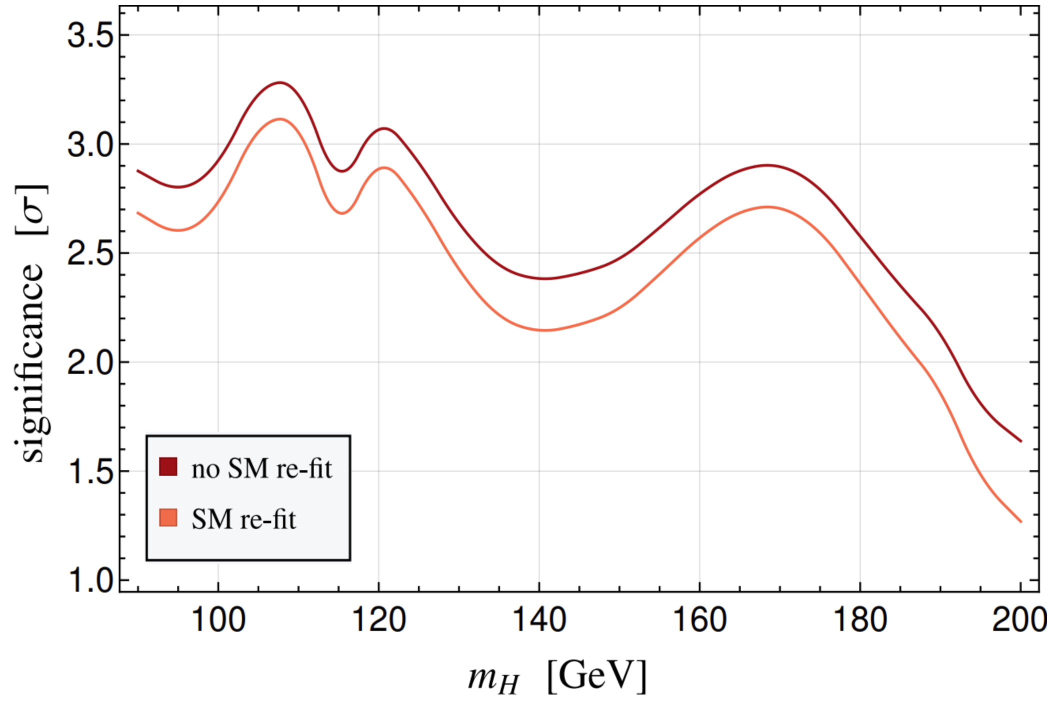
- **Limitations of fast simulation**
  - → SM-simulation VS ATLAS one
  - → **Smearing and shifts**
  - → Corrected **for efficiency (energy dependence)**
  - → Corrected for **QCD NNLO effect in production cross section**

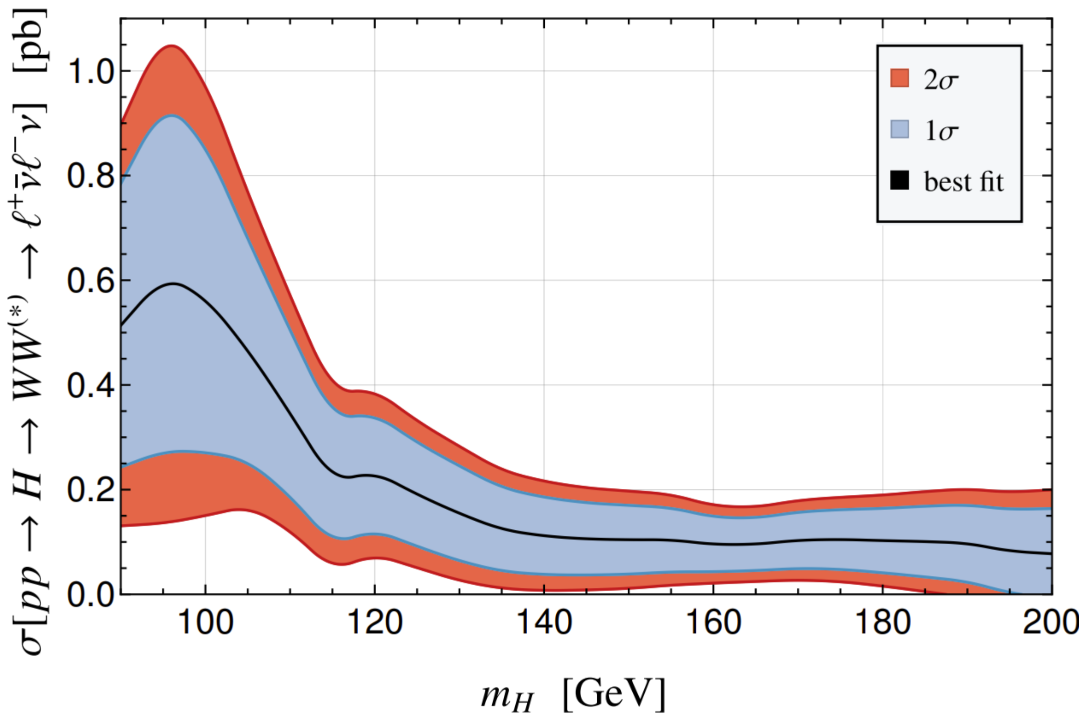
Checks over SM-samples:
ATLAS full-simulation VS **MG5 fast-simulation**



Results

- Observed limit is weaker than the expected one over the whole range (**preference for BSM contribution**)
- Allowed cross section is **largest around 95 GeV**



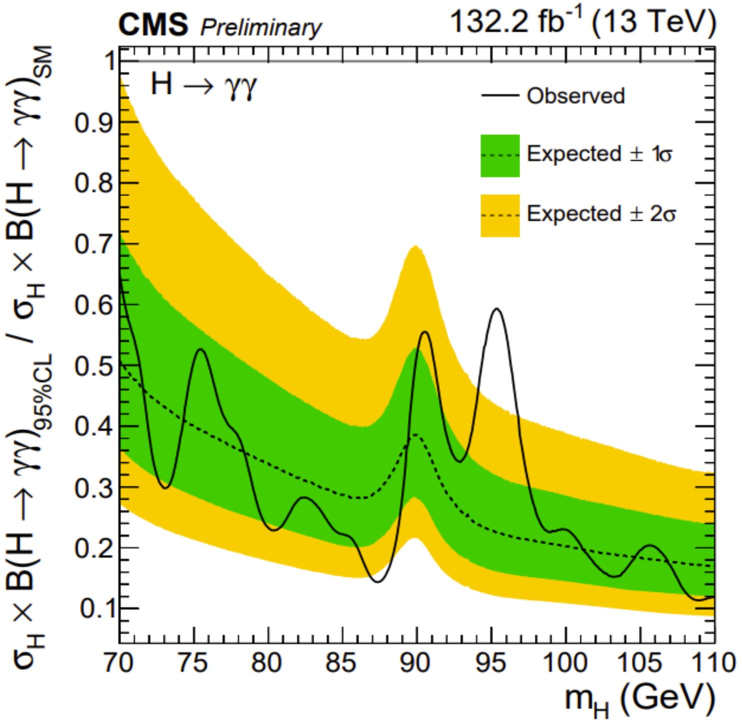


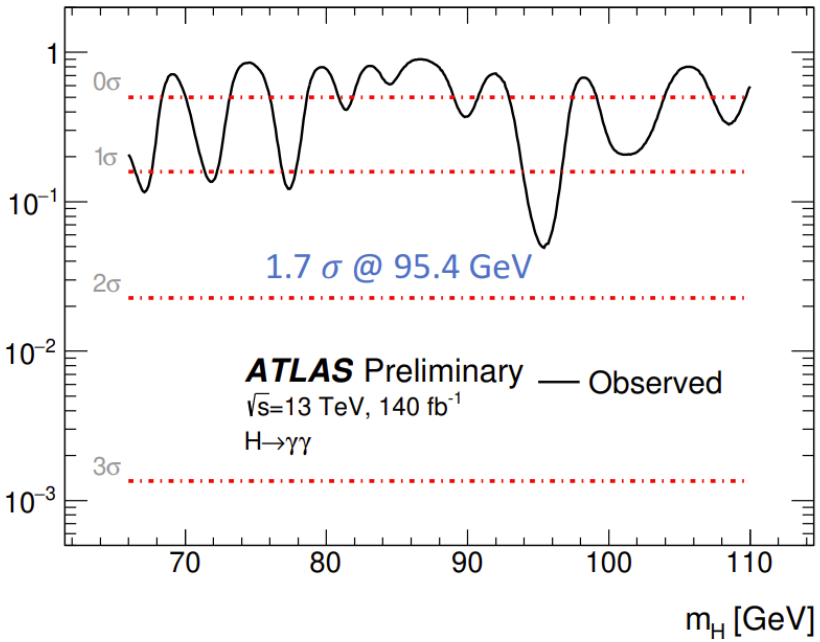
- **Global significance is only below ≈ 2 σ**
- Considering the existing hints for a scalar at 95 GeV **i.e. removing the look-elsewhere effect**
→ significance of >~ 2.5 σ.

$\gamma\gamma$ signal at 95 GeV

based on 2306.15722: Ashanujjaman, Banik, G.C, Crivellin, Mellado, Mulaudzi

- Recent CMS and ATLAS excess at 95 GeV in $\gamma\gamma$
- Already existing hint at LEP in bb
- **Excess in $H \rightarrow WW$ but not in $H \rightarrow ZZ \rightarrow 4l$**





Possible solution: scalar $SU(2)_L$ real triplet?

The model: ΔSM

Real scalar $SU(2)_L$ triplet with $Y = 0$

$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
1	2	0

$$\Delta = \frac{1}{2}\begin{pmatrix} \delta^0 & \sqrt{2}\delta^+ \\ \sqrt{2}\delta^- & -\delta^0 \end{pmatrix}, \quad \langle\delta^0\rangle = v_\Delta$$

Living in the adjoint rep. of SU(2), it couples only to WW and WZ and not to ZZ (at least at tree level and for no mixing with the SM higgs)

Two new mass eigenstates:

- Neutral CP-even scalar $\boldsymbol{H}$
- Charged Higgs $\boldsymbol{H^\pm}$
- **Small mass splitting (of the same order of the vev of the triplet v_Δ)**

Choice of independent parameters:

- $M_H, M_{H^\pm}$: masses of $H, H^\pm$
- v_Δ: vacuum expectation value of the triplet
- α: CP-even mixing angle $(H - h)$

W mass

- Since the triplet Δ does not couple to ZZ, it only produces a **shift in the W mass**, proportional to the vacuum expectation of the neutral component v_Δ

$$\Delta = \frac{1}{2}\begin{pmatrix} \delta^0 & \sqrt{2}\delta^+ \\ \sqrt{2}\delta^- & -\delta^0 \end{pmatrix}, \quad \langle \delta^0 \rangle = v_\Delta$$

Living in the adjoint rep. of SU(2), it naturally couples to WW and not to ZZ (at least at tree level and for no mixing with the SM higgs)

With a value for $\boldsymbol{v_\Delta}$ **of about few GeV**:

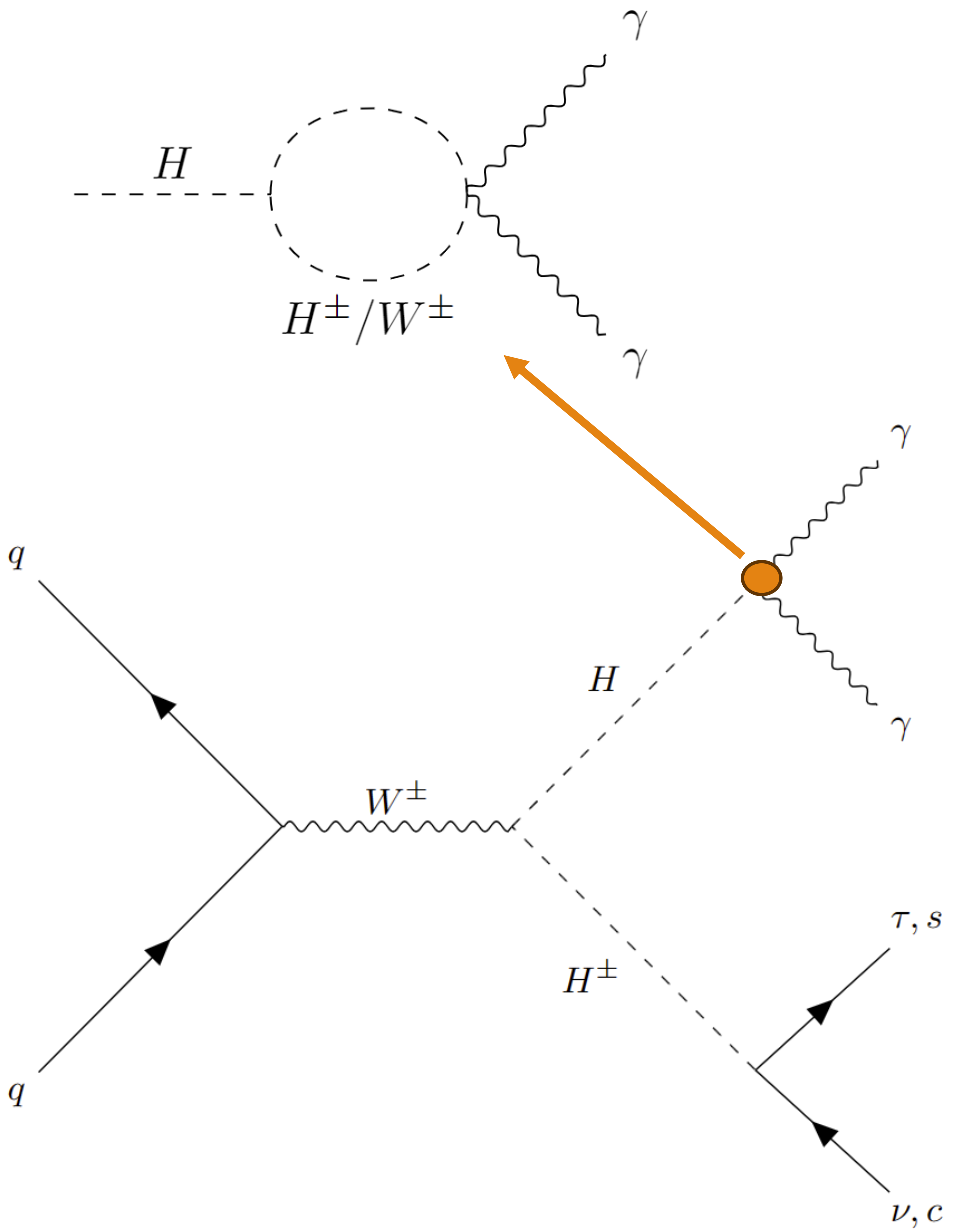
- Explanation of the tension between SM prediction and world average measurement of the W mass (≈ **2.2 σ**)
- Tension rises when including CDF II measurement (≈ **3.7 σ**)

$$M_Z^2 = \frac{g_2^2 + g_1^2}{4} v^2 = M^2_{Z(SM)}$$

$$M_W^2 = \frac{g_2^2}{4}(v^2 + 4v_\Delta^2) = M^2_{W(SM)} + g_2^2\, v_\Delta^2$$

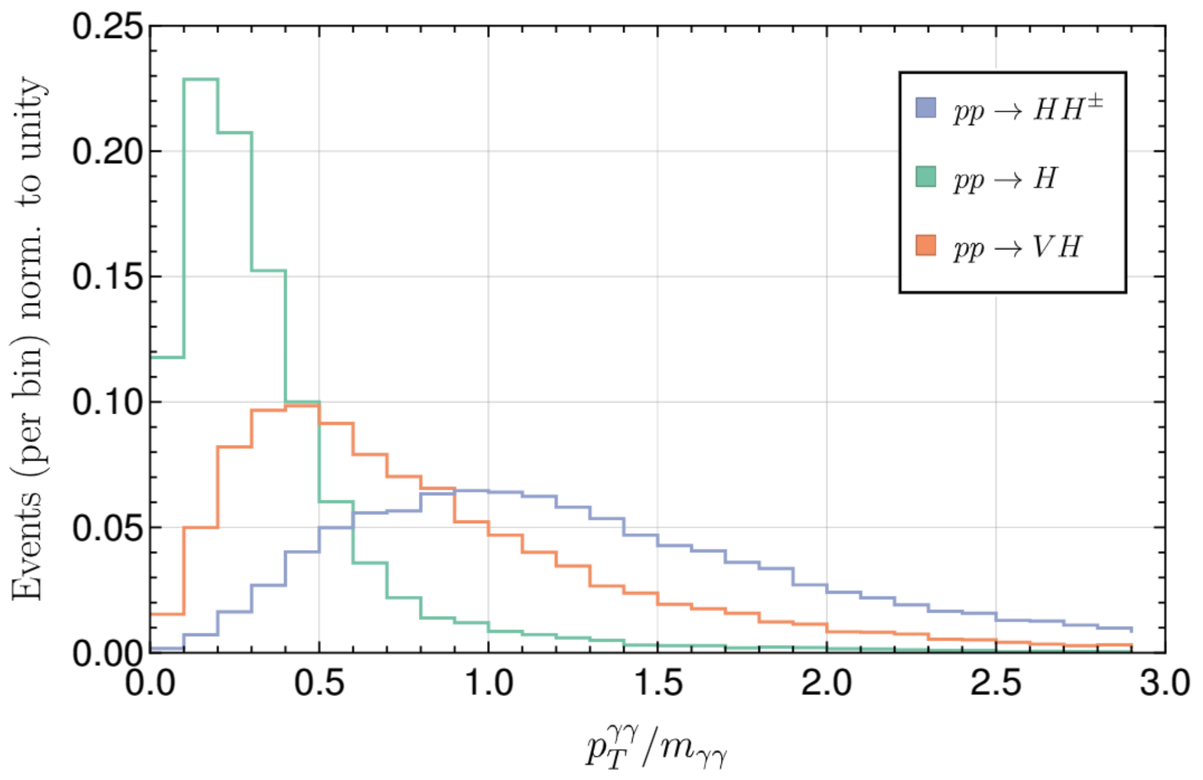
DY production

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



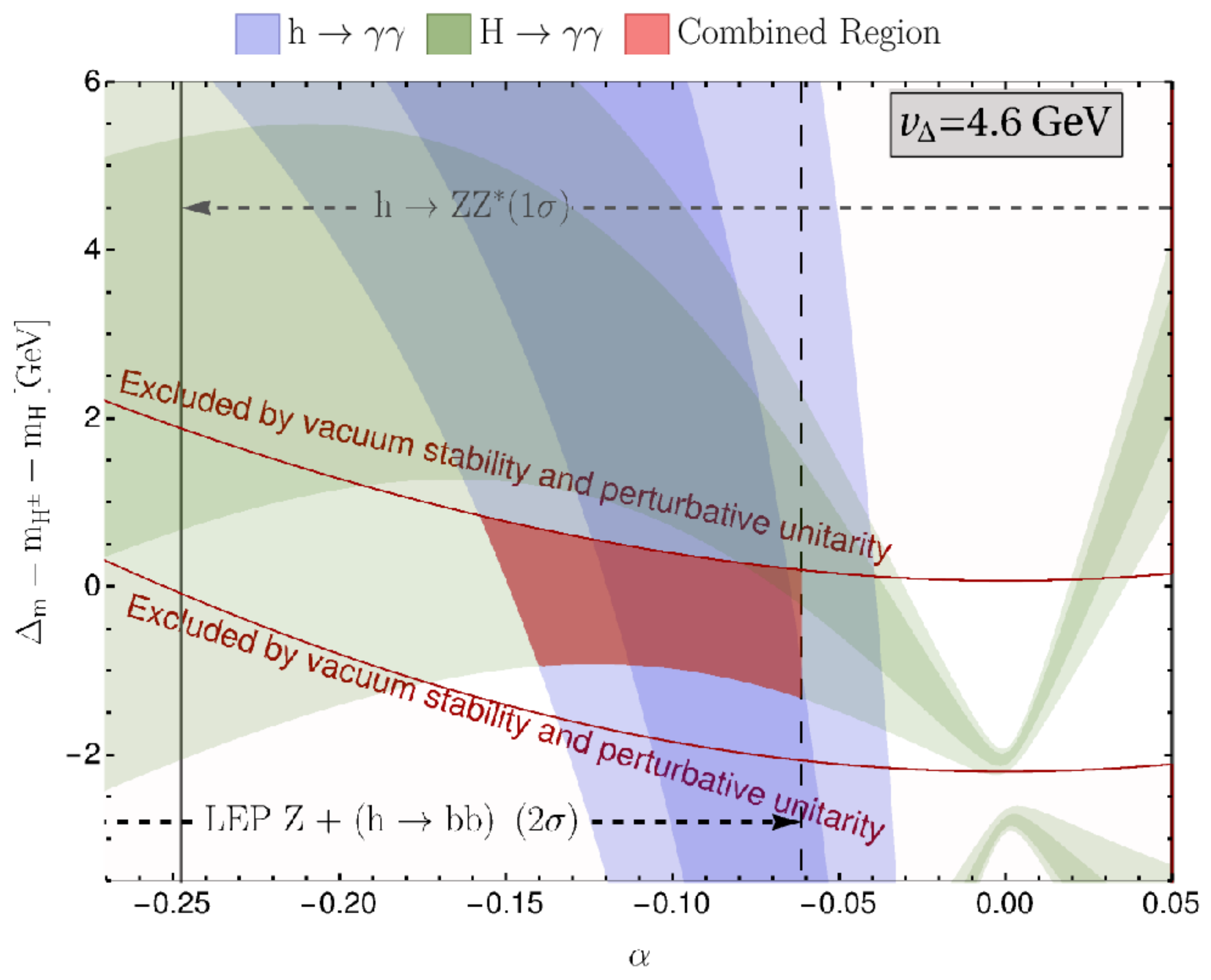
Predictions for p_T of $H \to \gamma\gamma$

- H produced in association with $H^{\pm}$ in the ΔSM: $pp \to H^{\pm} (H \to \gamma\gamma)$
- 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_aMC@NLO with CMS cuts
- **Shape of p_T of the photon pair with strong predictivity**

Results



Hints:

- $H \to \gamma\gamma$ at 95 GeV (CMS and ATLAS)
- $Z + (H \to bb)$ at 95 GeV (LEP)
- W mass (CDF II)

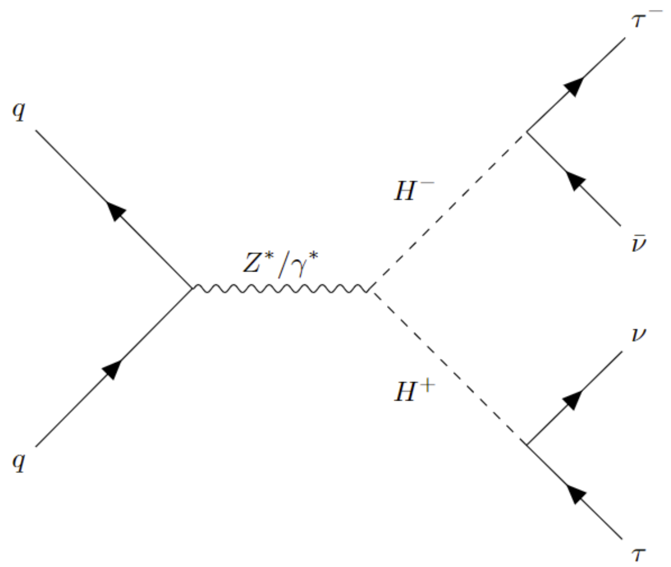
Constraints:

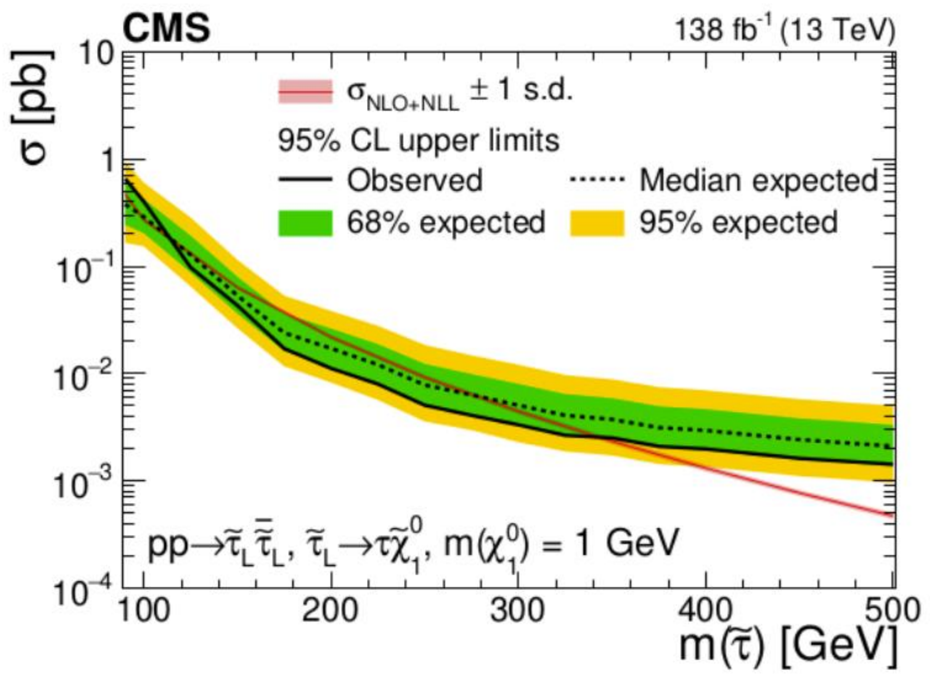
- SM Br$[h \to \gamma\gamma]$
- SM Br$[h \to ZZ]$
- Perturbative unitarity
- Vacuum stability

Allowed red region respects constraints and give reason to the measured hints

Limits Br[$H^{\pm} \approx$ 95 GeV]

- Drell-Yan production of $H^{\pm}$
- **Same signature as stau decays**
- **Recasting of the stau searches**
- Br[$H^{\pm} \rightarrow \tau\, \nu$] $\approx 60\%$, borderline with existent CMS and ATLAS stau search limits

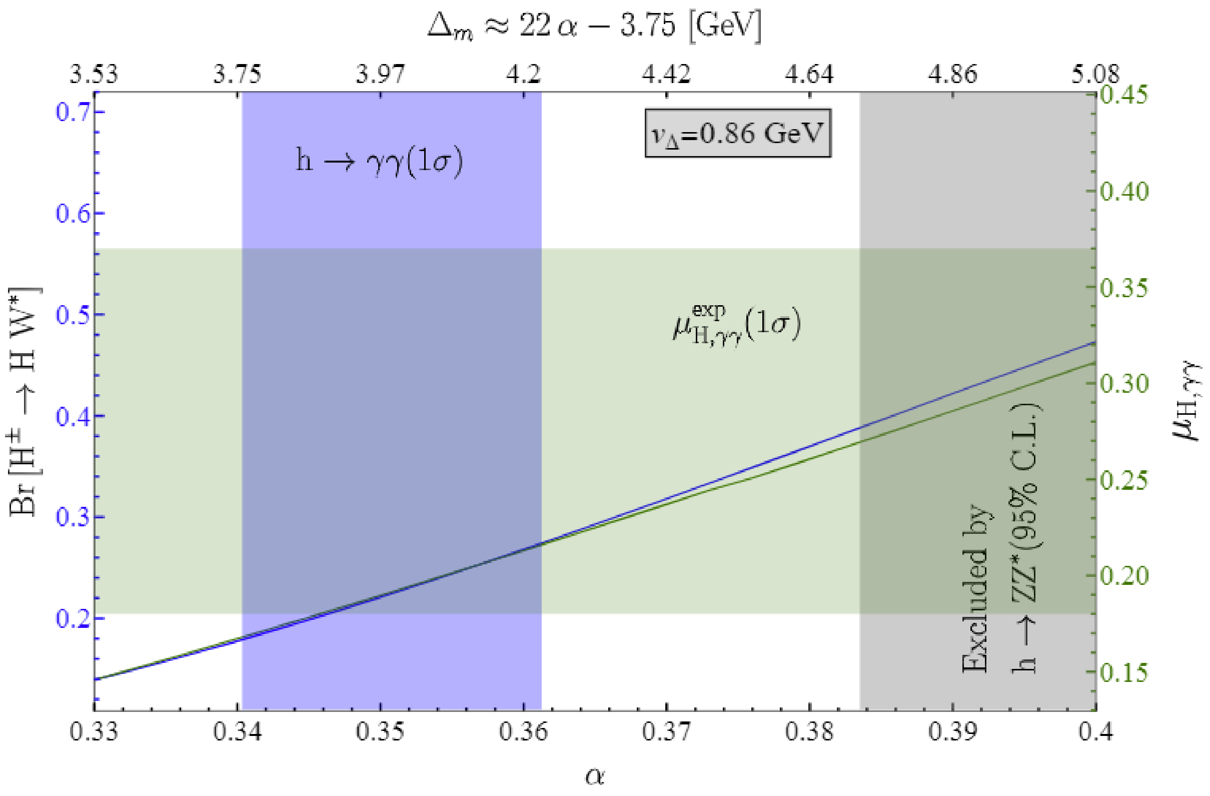




Reduction of Br[$\boldsymbol{H^{\pm} \to \tau\nu}$]

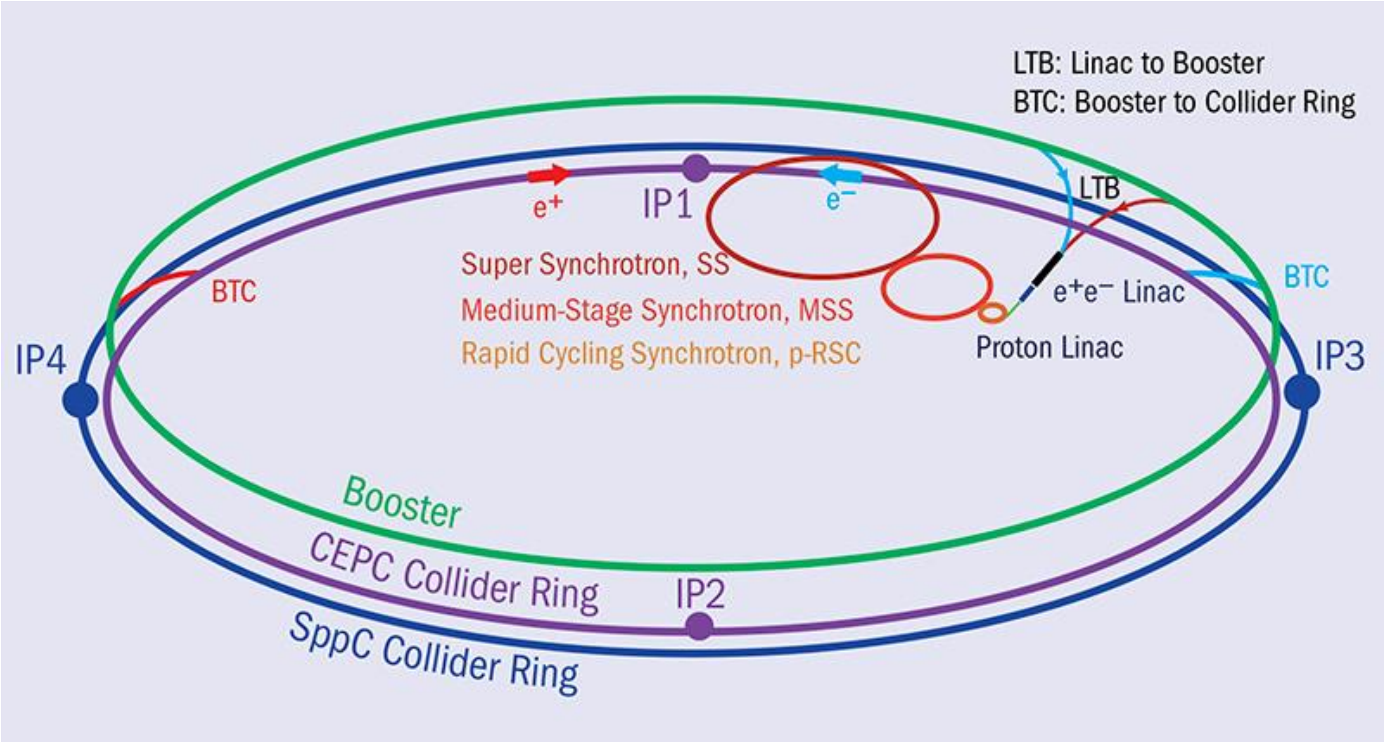
- **Enhancement of the mass splitting (requires care: perturbative unitarity and vacuum stability)**

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



CEPC prospects

- **Mass of $H^{\pm}$ and H would lie around 100 GeV**
- **LHC suffers from pile-up at these energy scales** (especially after the high-lumi upgrade)
- CEPC with $e^{+}e^{-}$ could measure the properties of the ΔSM with **unprecedent precision**
- **Necessary precise determination of the branching ratios** for the charged $H^{\pm}$



Conclusions and outlook

- We re-casted CMS and ATLAS searches of a SM-scalar decaying to WW finding **hints for new physic resonances decaying to WW** (around 95 GeV and 150 GeV)

- We **minimally extended the SM** with a scalar $SU(2)_L$ real triplet to account for the 95 GeV excess (WW and $\gamma\gamma$) with the following **predictions:**

1. Positive shift in the W mass (CDF II)
2. $\gamma\gamma$ produced in association with leptons and jets (not vector boson fusion - like)
3. p_T of $\gamma\gamma$ has spectrum different from gluon fusion and VH
4. A low mass charged higgs H^+ (study-case at CEPC) leading to a stau-like excess in LHC Run 3

- Potentially **studied at the LHC and more precisely at the CEPC**

- **$3W$ and $4W$ signals to be scrutinize as further constraints**

Thanks for the attention!

Back-up slides

Statistical analyses

covariance matrix (statistic and systematic)

- Significance computed via a χ^2 test $\chi^2 = [N_i^{\text{data}} - N_i^{\text{theory}}] \Sigma_{ij}^{-1} [N_j^{\text{data}} - N_j^{\text{theory}}]$

BSM signal

$$N_i^{\text{theory}} = p_{\text{BKG}}(N_i^{\text{SM}} + N_i^{\text{BKG}}) + p_{\text{BSM}} N_i^{\text{BSM}}$$

SM signal

CMS re-fit the background and SM-signal: we can therefore either float this contribution or take the nominal values of the paper

$$N_i^{\text{theory}} = p_{\text{BKG}}(N_i^{\text{SM}} + N_i^{\text{BKG}})$$

$$N_i^{\text{theory}} = N_i^{\text{SM}} + N_i^{\text{BKG}}$$

→ **both cases included in the fit**

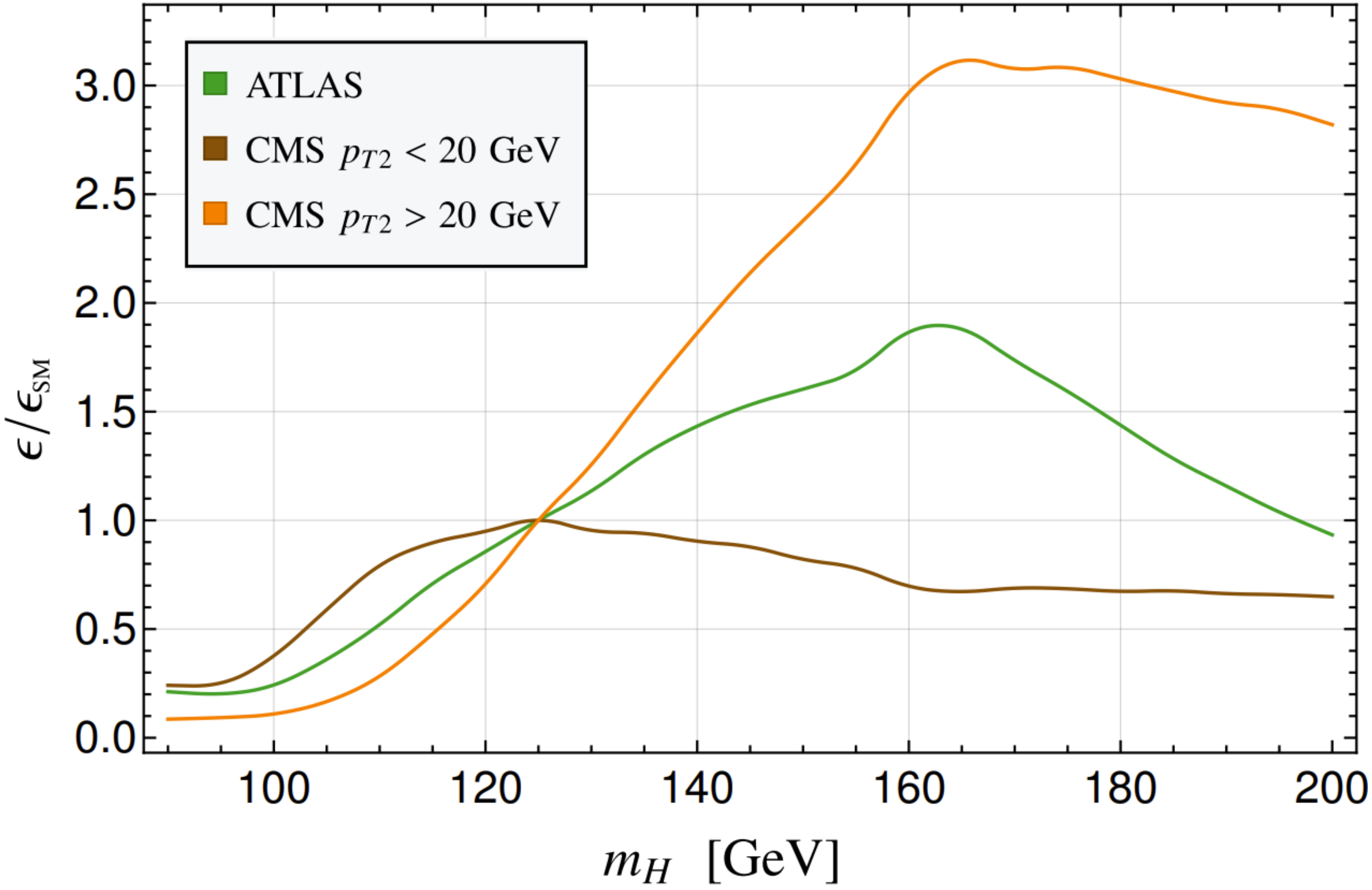
- **BSM signal strength w.r.t. SM**: $\mu_{\text{BSM}} = \dfrac{\sigma[pp \to H \to WW^{(*)} \to \ell^+\bar{\nu}\ell^-\nu]}{\sigma[pp \to h \to WW^* \to \ell^+\bar{\nu}\ell^-\nu]}$

BSM signal strength @ 95 and 150

$m_H = 95\,\mathrm{GeV}$	$\mu_{\mathrm{BKG}}^{p_{T2}<20}$	$\mu_{\mathrm{BKG}}^{p_{T2}>20}$	μ_{BSM}	χ^2_{BSM}	$\chi^{2,\text{re-fit}}_{\mathrm{SM}}$	$\sigma^{\text{re-fit}}$	χ^2_{SM}	σ
ATLAS			0.7	49.0	57.7	3.0	57.7	3.0
CMS $p_{T2} < 20\,\mathrm{GeV}$	1.01		0.0	5.5	5.5	0.0	6.8	1.2
CMS $p_{T2} > 20\,\mathrm{GeV}$		1.01	-3.5	6.2	9.0	-	9.1	-
Combined Fit	1.00	1.00	0.5	65.4	72.2	2.6	73.3	2.8
$m_H = 150\,\mathrm{GeV}$	$\mu_{\mathrm{BKG}}^{p_{T2}<20}$	$\mu_{\mathrm{BKG}}^{p_{T2}>20}$	μ_{BSM}	χ^2_{BSM}	$\chi^{2,\text{re-fit}}_{\mathrm{SM}}$	$\sigma^{\text{re-fit}}$	χ^2_{SM}	σ
ATLAS			0.1	54.5	57.7	1.8	57.7	1.8
CMS $p_{T2} < 20\,\mathrm{GeV}$	0.97		0.6	1.5	5.5	2.0	6.8	2.3
CMS $p_{T2} > 20\,\mathrm{GeV}$		0.99	0.2	8.0	9.0	1.0	9.1	1.0
Combined Fit	1.01	0.99	0.1	67.2	72.2	2.2	73.3	2.5

TABLE I. Fit results for the two cases $m_H = 95\,\mathrm{GeV}$ and $m_H = 150\,\mathrm{GeV}$, motivated by the existing hints for new scalars at the LHC. Note that the sizable value of μ_{BSM} in the CMS $p_T > 20\,\mathrm{GeV}$ category for the 95 GeV case is due to the very small efficiency.

Simulation efficiency



Uncertainties

ATLAS	CMS

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

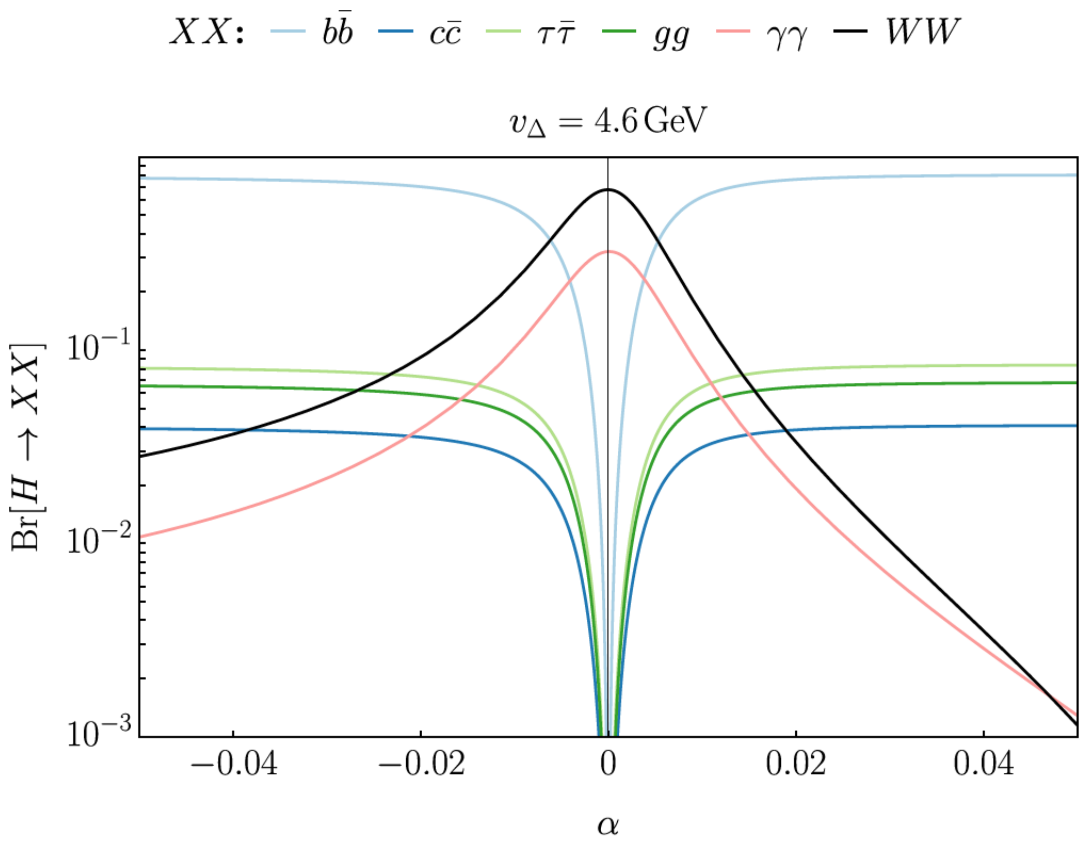
CMS

- 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

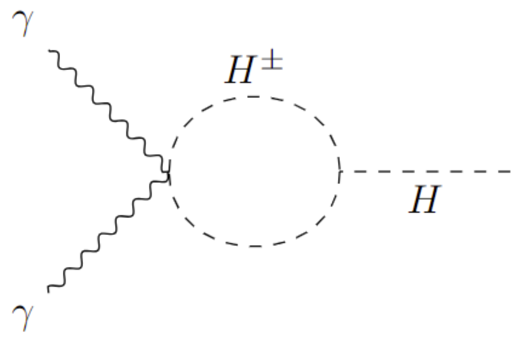
Systematics uncertainties correlations included

Br[H] at 95 GeV

3/4. $\gamma\gamma$ and ΔSM



- **Plot for same masses** $H^\pm - H$
- Dependence on mass splitting $H^\pm - H$



- **Sizable $\gamma\gamma$ branching ratio** due to $H^\pm$ loop
- Bounds due to same effects in branching ratios of SM-h to $\gamma\gamma$
- Dependence on mass splitting $H^\pm - H$