Experimental signals for a heavy scalar resonance in the ATLAS 4-lepton data

(as well as in other ATLAS + CMS data)

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Abstract

1) Theoretical arguments+lattice simulations → a 2nd Higgs resonance of mass

$$(M_H)^{THEOR} = 690 \pm 10\ (stat) \pm 20\ (sys)\ GeV \quad (*)$$

2) In spite of its large mass, it would couple to longitudinal W's with the same typical strength of the lower resonance **m_h =125 GeV.** A relatively narrow resonance produced mainly via gluon-gluon Fusion (**ggF)**

3) But many new decay channels: **H→hh**, **H→hhh, H→hWW**, **H→hZZ**… Hard to estimate **Γ(H→all).** Only a lower bound **Γ(H→all) > 32 GeV**

4) An experimental test which does **NOT** require to know **Γ(H→all)**: search for **H in the "golden" 4-lepton channel**

5) Present **ATLAS** data, for **M(4l) = 620 ÷740 GeV,** indicate an excess which can be interpreted as a new state of mass **$(M_H)^{EXP}$= 670 (15) GeV** consistently with **(*).** The total width estimated **Γ(H→all) = 60(15) GeV**

6) Furthermore, **m_h =125 GeV** and the new **$(M_H)^{EXP}$** are **correlated** as expected if the latter were indeed the 2nd resonance of the Higgs field

7) A quick look at the **ATLAS 2-photon data** and **other CMS data**

(*) M.Consoli and L.Cosmai - Int.J.Mod.Phys.A**37**(2022) 2250091, arXiv:2111.08962v3 [hep-ph]

Presently accepted view: the spectrum of the Higgs field consists of a single narrow resonance of mass $\mathbf{m_h = 125}$ **GeV**

At present, the excitation spectrum of the Higgs field is described in terms of a single narrow resonance of mass $m_h = 125$ GeV associated with the quadratic shape of the effective potential at its minimum. In a description of Spontaneous Symmetry Breaking (SSB) as a second-order phase transition, this point of view is well summarized in the review of the Particle Data Group [1] where the scalar potential is expressed as

$$V_{\rm PDG}(\varphi) = -\frac{1}{2}m^2_{\rm PDG}\varphi^2 + \frac{1}{4}\lambda_{\rm PDG}\varphi^4 \qquad (1)$$

By fixing $m_{\rm PDG} \sim 88.8$ GeV and $\lambda_{\rm PDG} \sim 0.13$, this has a minimum at $|\varphi| = \langle\Phi\rangle \sim 246$ GeV and a second derivative $V''_{\rm PDG}(\langle\Phi\rangle) \equiv m^2_h = (125 \text{ GeV})^2$.

However…

- SSB in **cutoff Φ^4** (weak) 1st–order phase transition (P.H. Lundow and K. Markström, PRE **80**(2009)031104; NPB **845**(2011)120; S. Akiyama et al. PRD **100** (2019) 054510)
- In **cutoff Φ^4**,known approximations to $\mathbf{V_{eff}(\phi)}$ giving a 1st–order transition have TWO mass scales

  i) a smaller mass $\mathbf{m_h}$ from the quadratic shape of $\mathbf{V_{eff}(\phi)}$ at the minima

  ii) a larger mass $\mathbf{M_H}$ from the zero-point energy which determines its depth

  (M.C., L. Cosmai, Int. J. Mod. Phys. A**35** (2020) 2050103; M.C.,in Veltman Memorial Volume, Acta Phys. Pol. B**52** (2021) 763; hep-ph/2106.06543)
- Our simulations on **76^4** lattice (the largest ever considered) support a two-mass structure of the propagator (M.C., L. Cosmai, Int. J. Mod. Phys. A**35** (2020) 2050103)

Then, by computing m_h^2 from the $p \to 0$ limit of $G(p)$ and M_H^2 from its behaviour at higher p^2, the lattice data are consistent with a transition between two different regimes and were well described in the full momentum region by the model form

$$G(p) \sim \frac{1 - I(p)}{2} \frac{1}{p^2 + m_h^2} + \frac{1 + I(p)}{2} \frac{1}{p^2 + M_H^2} \qquad (29)$$

with an interpolating function $I(p)$ which depends on an intermediate momentum scale p_0 and tends to $+1$ for large $p^2 \gg p_0^2$ and to -1 when $p^2 \to 0$. Most notably, the lattice data were also consistent with the expected increasing logarithmic trend $M_H^2 \sim m_h^2 \ln(\Lambda_s/M_H)$ when approaching the continuum limit.

Phenomenology of the heavier Higgs resonance

- From analytic calculations + lattice simulations → theoretical prediction

  $(M_H)^{THEOR}$ **= 690 ± 10 (stat) ± 20 (sys) GeV**

  With such large M_H → top-quark, W, Z… irrelevant for vacuum stability
- This heavier **H** couples to longitudinal W's and Z's with the same strength as **h(125)**
- In fact**, the small m_h** measures the (observable) **interactions of the fluctuations around the minimum of the potential**
- Instead, M_H measures the (unobservable) **interactions within the vacuum condensate**
- **H** = relatively narrow resonance **produced at LHC mainly via gluon-gluon-Fusion (ggF)**
- $\Gamma^{conv}(H \rightarrow WW)$, $\Gamma^{conv}(H \rightarrow ZZ) \approx M_H (G_F M^2_H)$
- $\Gamma(H \rightarrow WW)$, $\Gamma(H \rightarrow ZZ) \approx M_H (G_F m^2_h)$

The widths **Γ(H→WW)** and **Γ(H→ZZ)** much smaller than their conventional values. However, many new channels **…**

- **H→hh**
- **H→hhh**
- **H→hWW**
- **H→hZZ**
- **H→hhhh**
- **H→hhWW**
- **H→hhZZ**
- **………**
- Hard to estimate the total width **Γ(H→all)**
- Hence a test which does **NOT** require to know **Γ(H→all)**
- **This is possible in the 4-lepton channel**

(M.C., L. Cosmai, Int.J.Mod.Phys.A**37**(2022) 2250091, arXiv:2111.08962v3 [hep-ph])

The process pp→ H→ 4-leptons

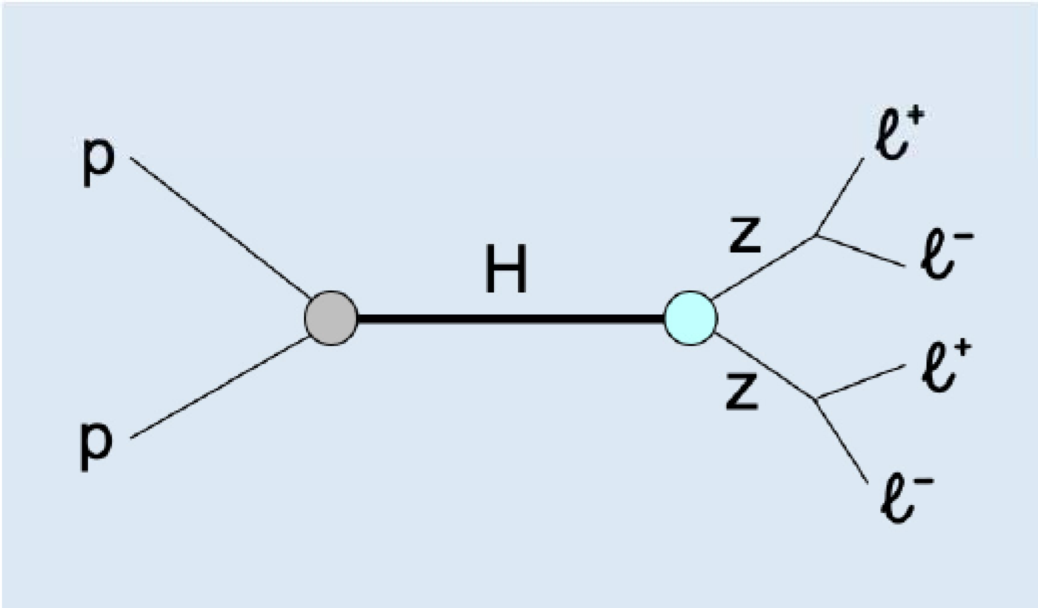


Figure 1: *The 4-lepton production through the chain* $H \rightarrow ZZ \rightarrow 4l$.

Phenomenology in the 4-lepton channel

- **For $M_H \approx 700$ GeV the conventional $\Gamma(H \rightarrow ZZ)$ width is $G_F M^3_H \approx 56.7$ GeV while here**

$$\Gamma(H \to ZZ) \sim \frac{M_H}{700\ \mathrm{GeV}} \cdot \frac{m_h^2}{(700\ \mathrm{GeV})^2}\, 56.7\ \mathrm{GeV} \qquad (14)$$

Therefore, by defining $\gamma_H = \Gamma(H \to all)/M_H$, we find a fraction

$$B(H \to ZZ) = \frac{\Gamma(H \to ZZ)}{\Gamma(H \to all)} \sim \frac{1}{\gamma_H} \cdot \frac{56.7}{700} \cdot \frac{m_h^2}{(700\ \mathrm{GeV})^2} \qquad (15)$$

- **For a relatively narrow resonance (whose virtuality effects should be small) approximate the cross section by a chain of on-shell branching ratios**

$$\sigma_R(pp \to H \to 4l) \sim \sigma(pp \to H) \cdot B(H \to ZZ) \cdot 4B^2(Z \to l^+ l^-) \qquad (16)$$

- **so that we find a γ_H - σ_R correlation mainly determined by the low-mass m_h**

$$\gamma_H \cdot \sigma_R(pp \to H \to 4l) \sim \sigma(pp \to H) \cdot \frac{56.7}{700} \cdot \frac{m_h^2}{(700\ \mathrm{GeV})^2} \cdot 4B^2(Z \to l^+ l^-) \qquad (17)$$

$$\gamma_H \cdot \sigma_R(pp \to H \to 4l) \sim \sigma(pp \to H) \cdot \frac{56.7}{700} \cdot \frac{m_h^2}{(700\ \mathrm{GeV})^2} \cdot 4B^2(Z \to l^+l^-) \quad (17)$$

- **for σ(pp→H) ≈ σ^{ggF}(pp→H) ≈ 1180(180) fb**

Table 1: *We report the ggF cross section in fb to produce a heavy Higgs resonance at $\sqrt{s}$ = 8 and 13 TeV. The ratios of the two cross sections, respectively 4.311, 4.393 and 4.477, for M_H = 660, 680 and 700 GeV, and the 8 TeV values were taken from the updated Handbook of Higgs cross sections in the CERN yellow report [26]. No theoretical uncertainty is reported.*

M_H[GeV]	σ_{gg}(8 TeV)	σ_{gg}(13 TeV)
660	315.3	1359.26
680	268.2	1178.20
700	229.0	1025.23

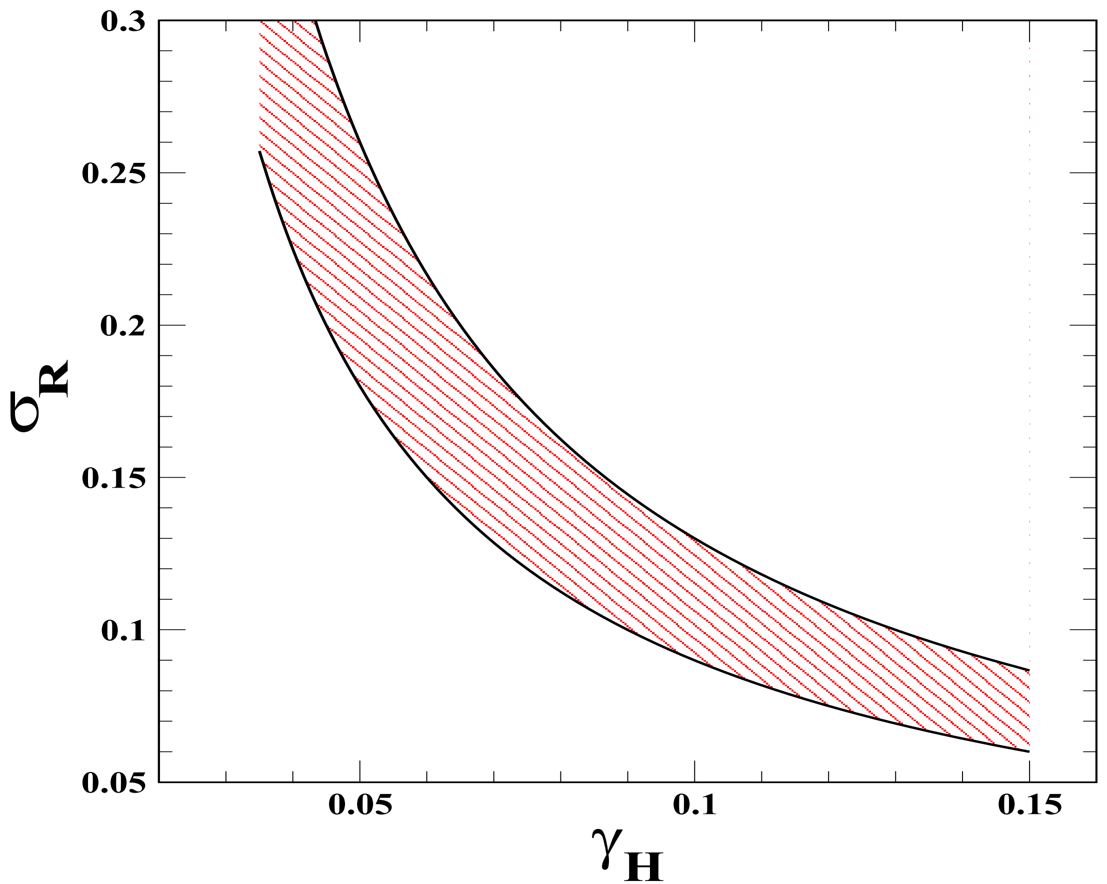
- **m_h = 125 GeV**

$$[\gamma_H \cdot \sigma_R(pp \to H \to 4l)]^{\mathrm{theor}} \sim (0.0137 \pm 0.0021)\ \mathrm{fb} \quad (18)$$

$$\gamma_H = \Gamma_H / M_H$$

$$\sigma_R(pp \to H \to 4l) \sim \sigma(pp \to H) \cdot B(H \to ZZ) \cdot 4B^2(Z \to l^+l^-) \quad (16)$$

$$[\gamma_H \cdot \sigma_R(pp \to H \to 4l)]^{\mathrm{theor}} \sim (0.0137 \pm 0.0021)\ \mathrm{fb} \quad (18)$$



3. Analysis of the ATLAS 4-lepton events (Eur. Phys. J. C 81 (2021) 332)

To check the precise correlation in Eq.(18), we have considered the full ATLAS sample [16] of 4-lepton data for luminosity 139 fb^{-1} and in the region of invariant mass $\mu_{4l} = 620 \div 740$ GeV ($l = e, \mu$) which extends about $\pm$ 60 GeV around our mass value $M_H = 690 \pm 10\,(\mathrm{stat}) \pm 20\,(\mathrm{sys})$ GeV.

Now, Eq.(18) accounts only for production through the ggF mechanism and ignores the VBF-production mode which plays no role in our picture. Therefore, we should compare with that subset of data that, for their typical characteristics, admit this interpretation. To this end, the ATLAS experiment has performed a Multivariate analysis (MVA) of the ggF production mode which combines a multilayer perceptron (MLP) and one or two recurrent neural networks (rNN). The outputs of the MLP and rNN(s) are concatenated so as to produce an event score. In this way, depending on the score, the ggF events are divided into four mutually exclusive categories: ggF-MVA-high-4μ, ggF-MVA-high- 2e2μ, ggF-MVA-high-4e, ggF-MVA-low. The four sets of events were extracted from the corresponding HEPData file [27] and are reported in Table 2.

Table 2: *At the various 4-lepton invariant mass $\mu_{4l} \equiv E$, we report the ATLAS events for the four different categories of the ggF production mode and their total number.*

E[GeV]	MVA-high-4μ	MVA-high-2e2μ	MVA-high-4e	MVA-low	ToT
635(15)	2	0	1	7	10
665(15)	0	2	2	17	21
695(15)	1	0	1	9	11
725(15)	0	1	0	3	4

▪Fitting the ATLAS 4-lepton data in the range 620÷740 GeV

As in refs.[17, 7], by defining $\mu_{4l} = E$ and $s = E^2$, these 4-lepton events will be described by the interference of a resonating amplitude $A^R(s) \sim 1/(s - M_R^2)$ with a slowly varying background $A^B(s)$. For a positive interference below peak, setting $M_R^2 = M_H^2 - iM_H\Gamma_H$, this gives a total cross section

$$\sigma_T = \sigma_B - \frac{2(s - M_H^2)\,\Gamma_H M_H}{(s - M_H^2)^2 + (\Gamma_H M_H)^2}\sqrt{\sigma_B \sigma_R} + \frac{(\Gamma_H M_H)^2}{(s - M_H^2)^2 + (\Gamma_H M_H)^2}\,\sigma_R \qquad (19)$$

where, in principle, both the average background σ_B, at the central energy 680 GeV, and the resonating peak cross-section σ_R can be treated as free parameters.

Fit to ATLAS data for different $\gamma_H = \Gamma_H/M_H$

Table 3: *For each γ_H we report the values of M_H, the resonating cross section σ_R and the corresponding product $k = \gamma_H \cdot \sigma_R$ which are obtained from a fit with Eq.(19) to the total number of ATLAS events in Table 2.*

γ_H	M_H [GeV]	σ_R [fb]	$k = \gamma_H \cdot \sigma_R$ [fb]
0.05	678(6)	0.218(39)	0.0109(20)
0.06	676(7)	0.191(30)	0.0115(18)
0.07	673(10)	0.174(26)	0.0122(18)
0.08	669(20)	0.161(24)	0.0129(19)
0.09	668(16)	0.151(22)	0.0136(20)
0.10	668(15)	0.141(21)	0.0141(21)
0.11	669(15)	0.133(21)	0.0146(23)
0.12	670(16)	0.125(22)	0.0150(26)
0.13	672(17)	0.118(23)	0.0153(30)
0.14	673(19)	0.112(26)	0.0157(36)
0.15	674(20)	0.106(29)	0.0159(43)

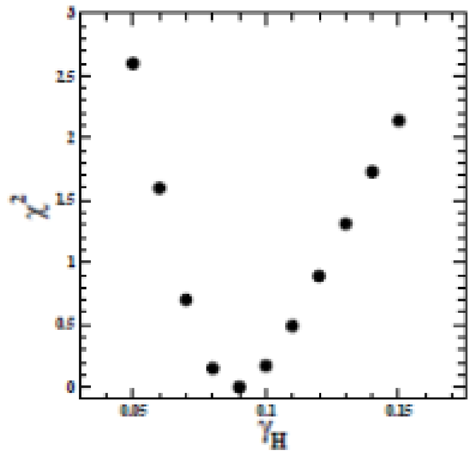


Figure 1: *At the various values of* γ_H, *we report the chi-square of the fit with Eq.(19) to the ATLAS data.*

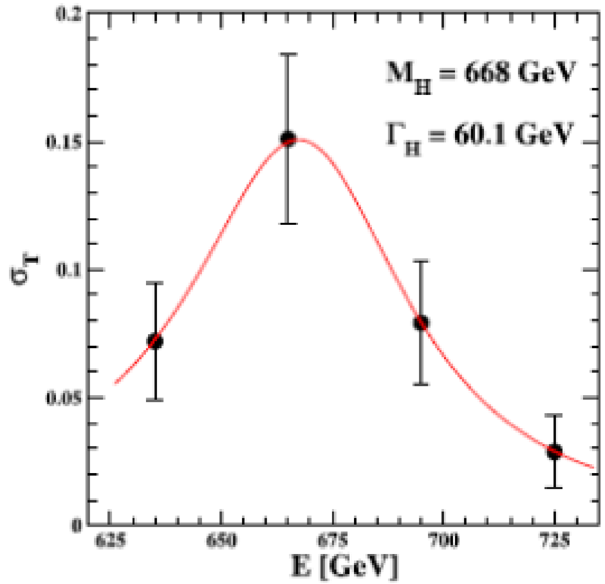


Fig. 2. For $\gamma_H = 0.09$, we show the fit with Eq. (19) to the ATLAS cross-sections in fb.

Correlation reproduced very well: excess unlikely to be a statistical fluctuation

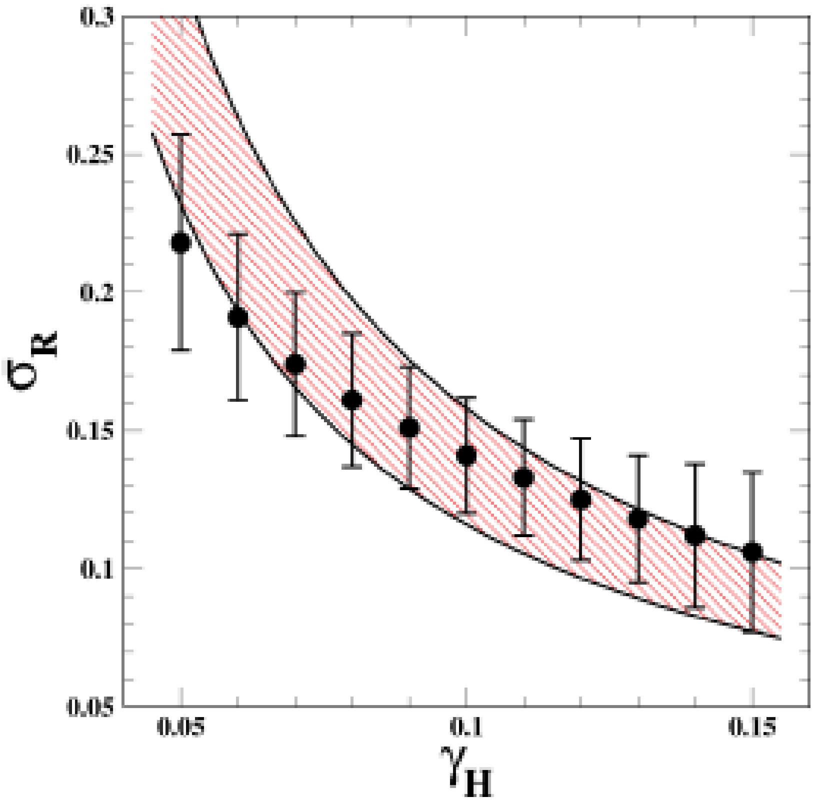


Fig. 3. The σ_R's of Table 3 are compared with our theoretical prediction equation (18) represented by the shaded area enclosed by the two hyperbolae $\sigma_R = (0.0137 \pm 0.0021)/\gamma_H$.

Equivalently **one can fit m_h** from the ATLAS 4-lepton data in the high-mass range 620 ÷ 740 GeV

γ_H	M_H [GeV]	σ_R [fb]	$k = \gamma_H \cdot \sigma_R$ [fb]
0.05	678(6)	0.218(39)	0.0109(20)
0.06	676(7)	0.191(30)	0.0115(18)
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0.15	674(20)	0.106(29)	0.0159(43)

$$\gamma_H \cdot \sigma_R(pp \to H \to 4l) \sim \sigma(pp \to H) \cdot \frac{56.7}{700} \cdot \frac{m_h^2}{(700\ \mathrm{GeV})^2} \cdot 4B^2(Z \to l^+l^-) \quad (17)$$

$$[\gamma_H \cdot \sigma_R(pp \to H \to 4l)]^{\mathrm{theor}} \sim (0.0137 \pm 0.0021)\ \mathrm{fb}$$

→

$$[\gamma_H \cdot \sigma_R(pp \to H \to 4l)]^{\mathrm{fit}} = k \sim (0.0137 \pm 0.0008)\ \mathrm{fb}$$

→

$$(m_h)^{\mathrm{fit}} \sim (125 \pm 13)\ \mathrm{GeV}$$

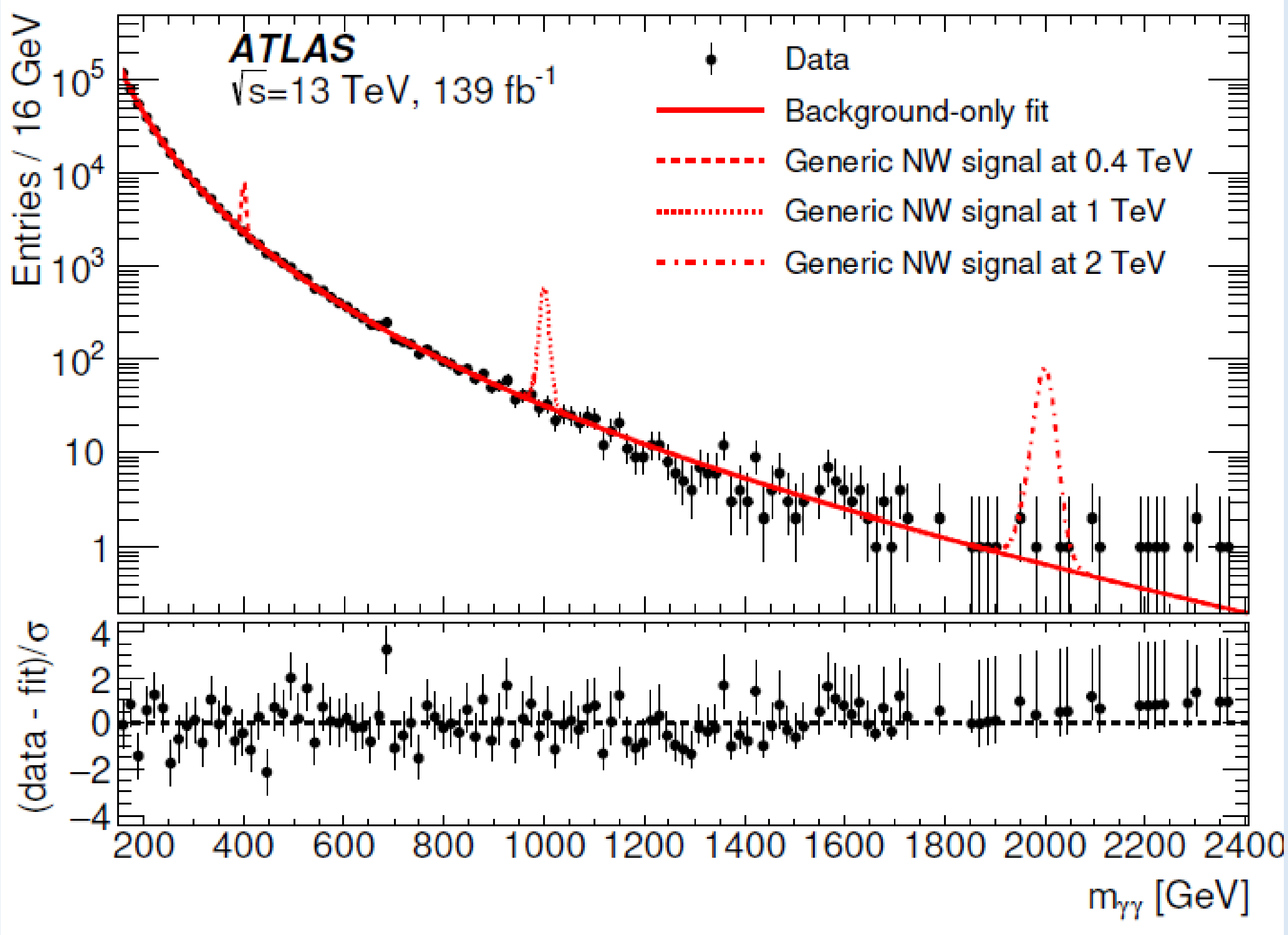
Moreover…

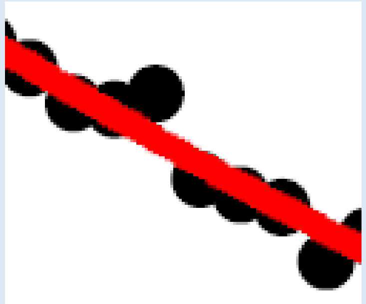
- The ATLAS 4-lepton data show no sizeable VBF contribution to the **H** resonance **as expected** (in the relevant region **only 2 VBF events vs. 46 ggF events**)

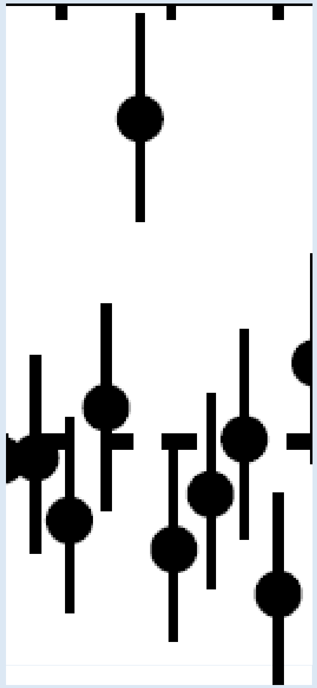
- For **M_H ≈ 680 GeV** the ATLAS selection criteria of ggF events and the total cross-section **$\sigma^{ggF}(pp \rightarrow H) \approx 1180(180)$ fb** are consistent to an extraordinary level of accuracy

- The sharp **γ_H - σ_R** correlation becomes a guiding principle to trust in other excesses → the **ATLAS 2-photon channel**

ATLAS 2-photon data PLB 822(2021) 136651

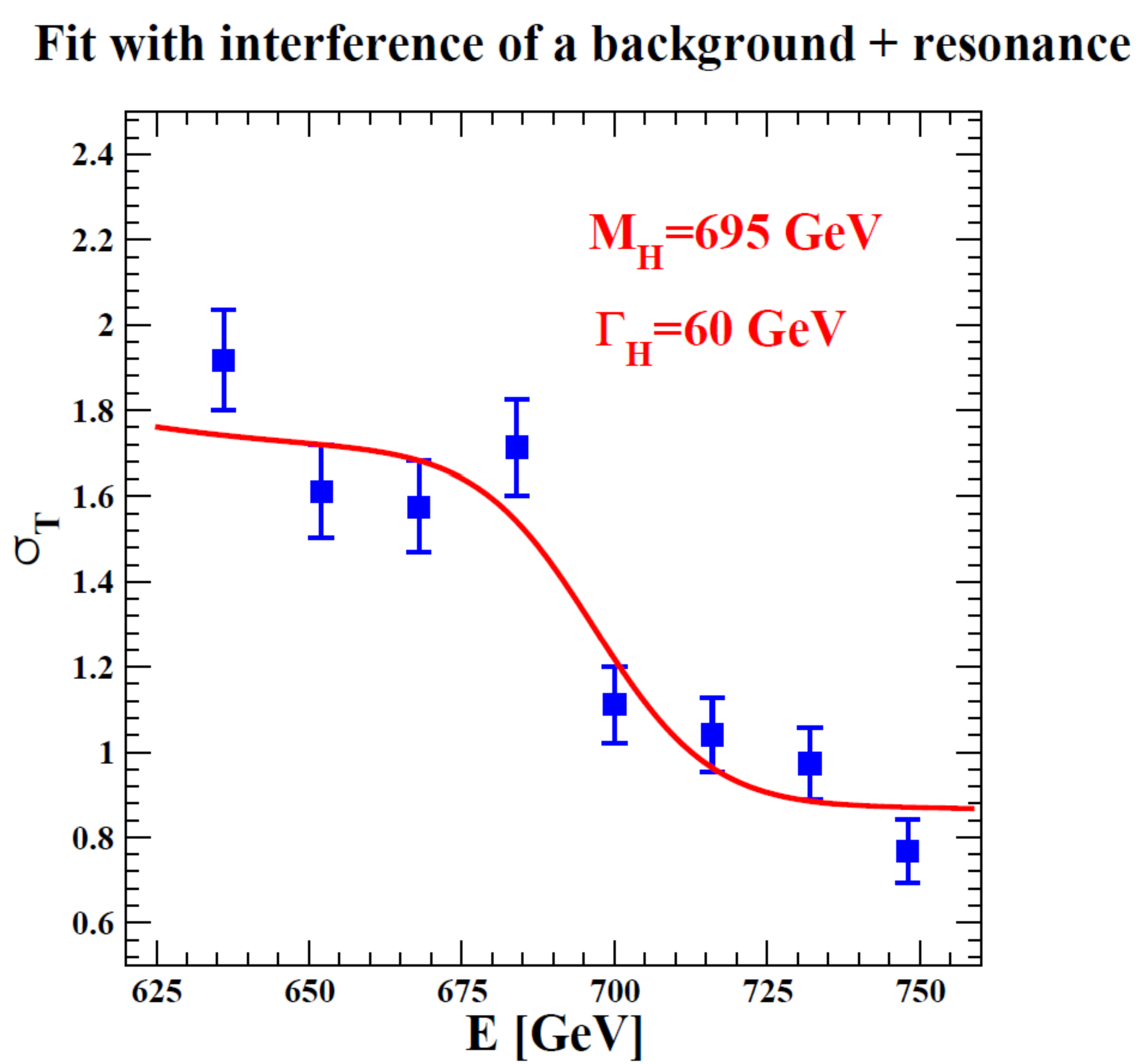






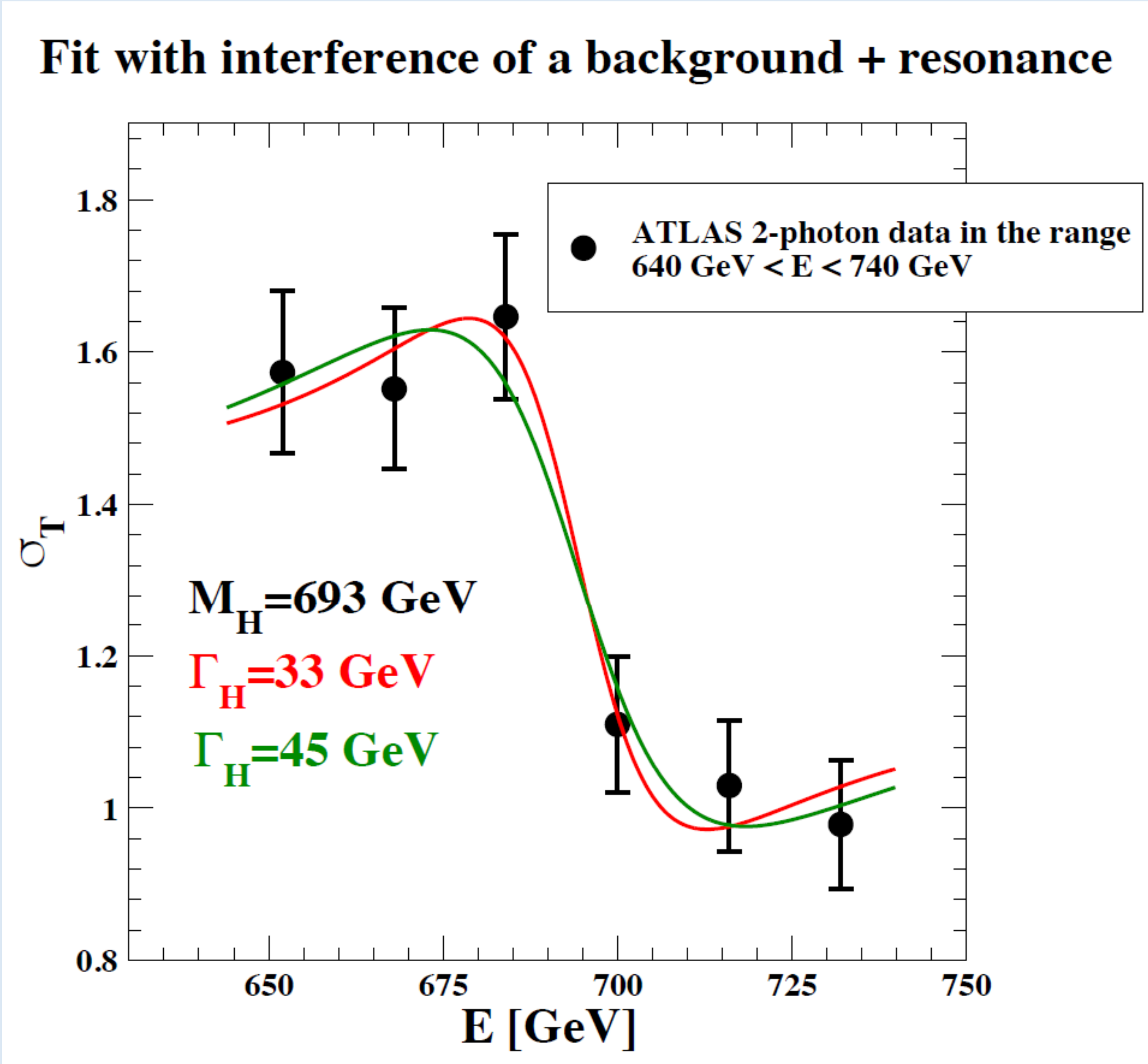
- Fit to 630 ÷750 GeV ATLAS 2-photon data

Interference → non resonating background + resonance



Fit to the **ATLAS γγ data in the range 630÷750 GeV**. The background is very large so that here one just sees the interference (and not the Breit-Wigner as in the 4-lepton case)

More on ATLAS γγ events



CONCLUSIONS from ATLAS DATA

- A fit to the ATLAS 4-lepton data points toward a new resonance of mass **$(M_H)^{EXP}$=670 (15) GeV** and width **$(\Gamma_H)^{EXP}$= 60(15) GeV**

- The mass is consistent with our theoretical prediction for the 2nd resonance of the Higgs field **$(M_H)^{THEOR}$ = 690 ± 10 (stat) ± 20 (sys) GeV**
- The width is consistent with our lower bound **$(\Gamma_H)^{THEOR}$ > 33 GeV**

- By assuming a partial width H→ ZZ which scales as

$$\Gamma(H \to ZZ) \sim \frac{M_H}{700\ \mathrm{GeV}} \cdot \frac{m_h^2}{(700\ \mathrm{GeV})^2}\ 56.7\ \mathrm{GeV}$$

the ATLAS data yield a fitted value **$(m_h)^{fit}$ = 125 ± 13 GeV,** which reproduces the direct experimental value **$(m_h)^{exp}$= 125 GeV**

- The ATLAS γγ data suggest a slightly larger experimental mass

$(M_H)^{EXP}$=695(10) GeV

and slightly smaller experimental width

$(\Gamma_H)^{EXP}$= 45(15) GeV

Good consistency within errors

What about CMS data ?

- At present, CMS public results with 4-lepton full statistics (RUN2 2016 - 2018) have a too large binning at high masses

- However, 2016 and 2017 data which were plotted in previous publications with a binning adequate to our purposes also at high masses, show an excess in the same region as for ATLAS

m(4l) = 660(10) GeV

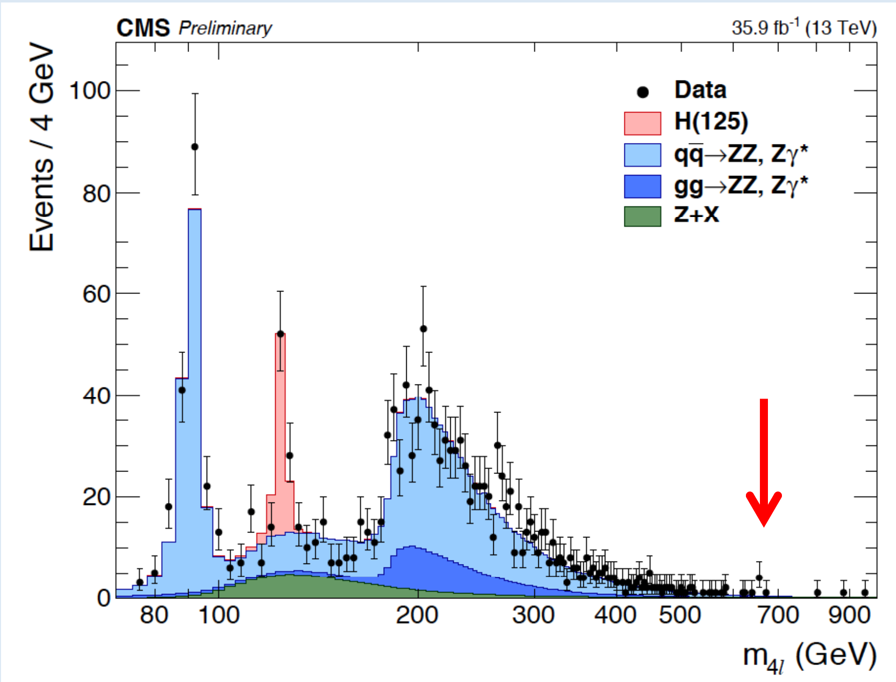
JHEP11(2017)047; arXiv:1706.09936[hep-ex]

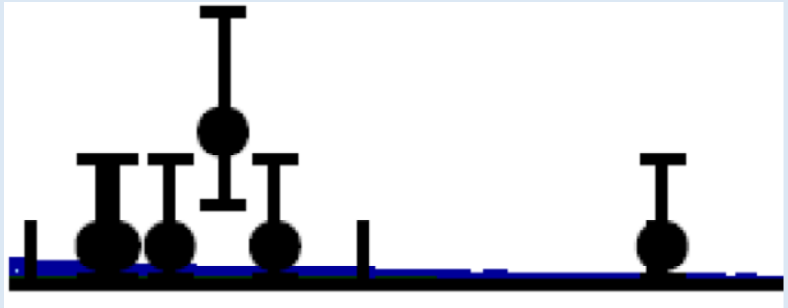
CMS 4-lepton 2016 data: Lum=35.9 fb$^{(-1)}$

Note: on average 8 events for E=600÷700 GeV vs. 1 event at very end 800 GeV

This is very different from the expected slowly decreasing background.

Sizeable peak at m(4l)=660(10) GeV as for ATLAS m(4l)=665(15) GeV





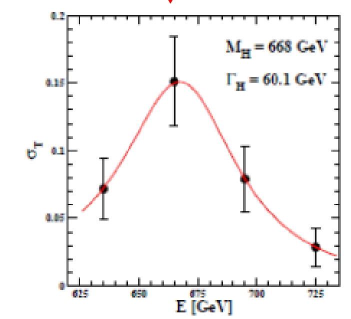


Figure 2: *For $\gamma_H = 0.09$, we show the fit with Eq.(19) to the ATLAS cross sections in fb.*

No events observed above 1 TeV

Other interesting channels to look at

X → W^+W^- → leptons

"Search for high mass resonances decaying into W^+W^- in the dileptonic final state with 138 fb-1 of proton-proton collisions at $\sqrt{s}$ = 13 TeV"
(full RUN2) **CMS PAS HIG-20-016**

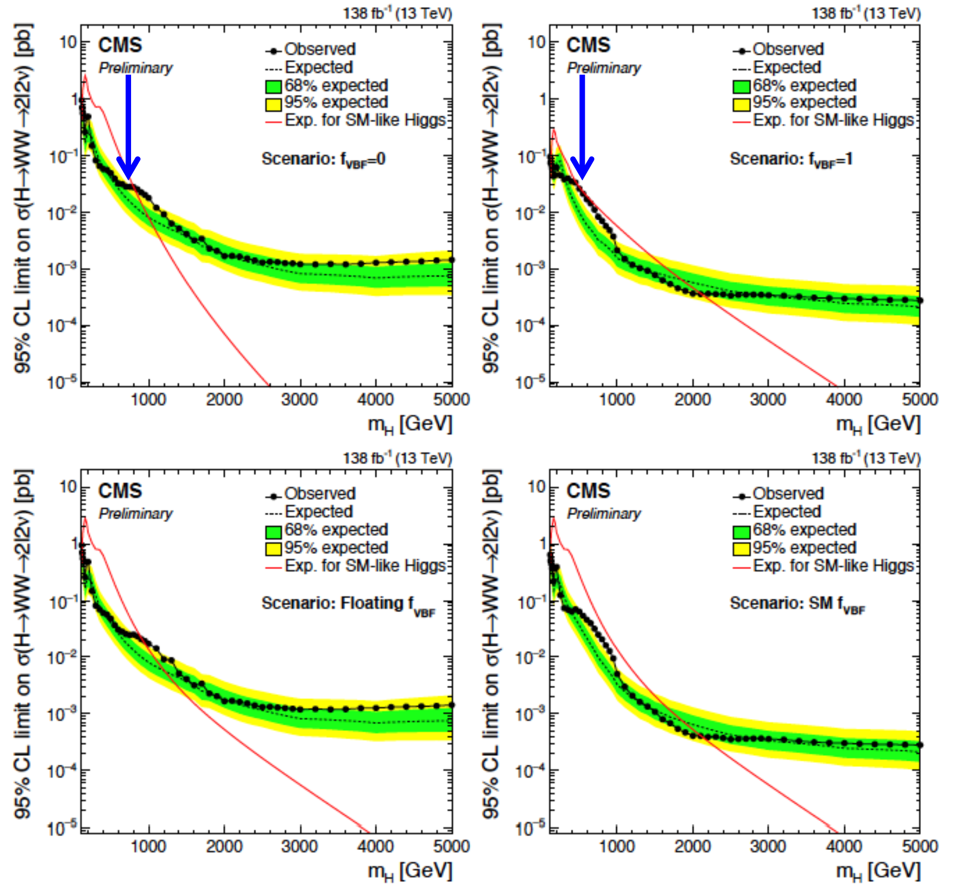


Figure 4: Limits using the combined Run 2 data set for the $f_{VBF} = 0$ (top left), $f_{VBF} = 1$ (top right), floating f_{VBF} (bottom left) and the SM f_{VBF} scenarios (bottom right).

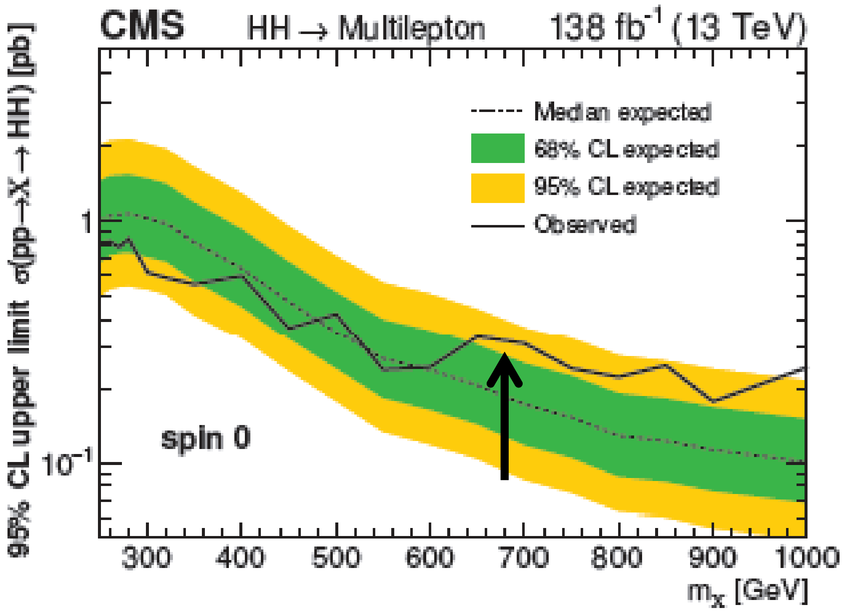
This analysis considered

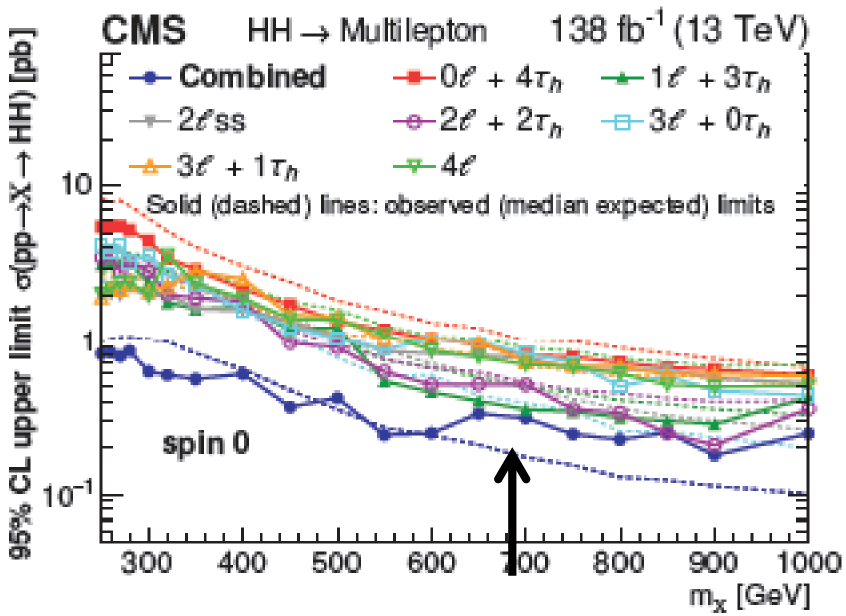
- ★ eμ, μμ, ee (+ neutrinos) final states
- ★ ggF and VBF production processes
- ★ different scenarios

All scenarios show an excess in the region of interest

X ➔ H(125)+H(125) ➔ 4W, 2W+2tau, 4tau ➔ leptons

"Search for Higgs boson pairs decaying to WWWW, WWττ, and ττττ in proton-proton collisions at √s = 13 TeV"
(full RUN2) **CMS PAS HIG-21-002**





Again, a small excess observed in the region of interest

CONCLUSIONS

- A fit to the **ATLAS 4-lepton + γγ data** suggest a new resonance

$$(M_H)^{EXP} = 680(15)\ \text{GeV} \qquad\qquad (\Gamma_H)^{EXP} = 45(15)\ \text{GeV}$$

- The mass is well consistent with our theoretical prediction for the 2nd resonance of the Higgs field

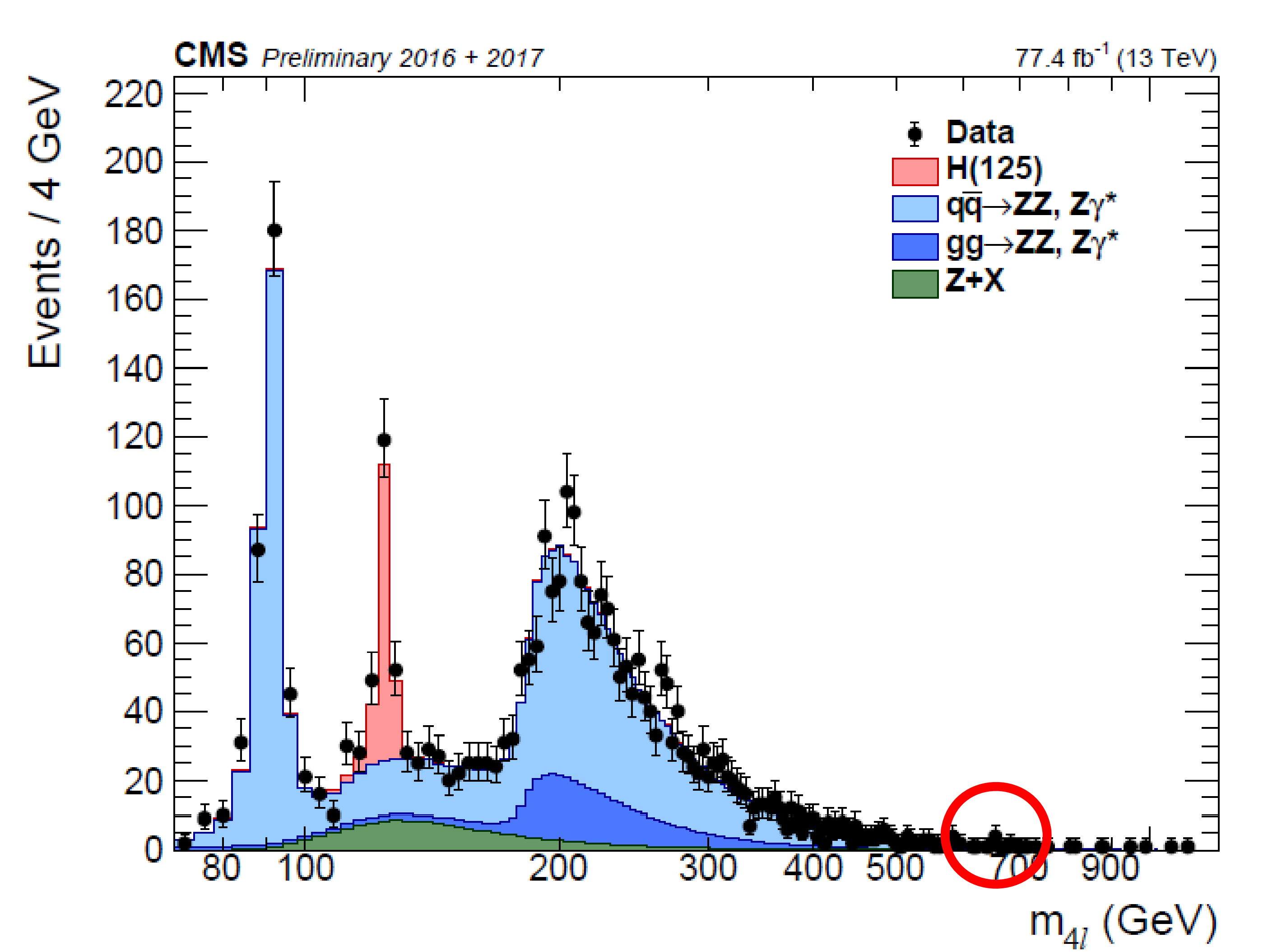
$$(M_H)^{THEOR} = 690 \pm 10\ (\text{stat}) \pm 20\ (\text{sys})\ \text{GeV}$$

- More significantly, the 4-lepton data reproduce the sharp γ_H - σ_R correlation, expected for the 2nd resonance. This correlation is uniquely fixed by $\mathbf{m_h}$
- Thus, equivalently, from the 4-lepton data in the high-mass range 620-740 GeV, one finds a fitted value $\mathbf{(m_h)^{fit} = 125 \pm 13}$ **GeV,** which reproduces the direct experimental value $\mathbf{(m_h)^{exp} = 125}$ **GeV**
- The sharp γ_H - σ_R correlation, becomes a guiding principle to trust in other small excesses which seem to be present also in CMS, in 4-lepton as well as in other final states
- The issue of the second Higgs resonance could thus be settled now with just the present data from **RUN2**

4-lepton CMS 2016+2017 Lum = 77.4 fb^{-1}

CMS PAS HIG-18-001

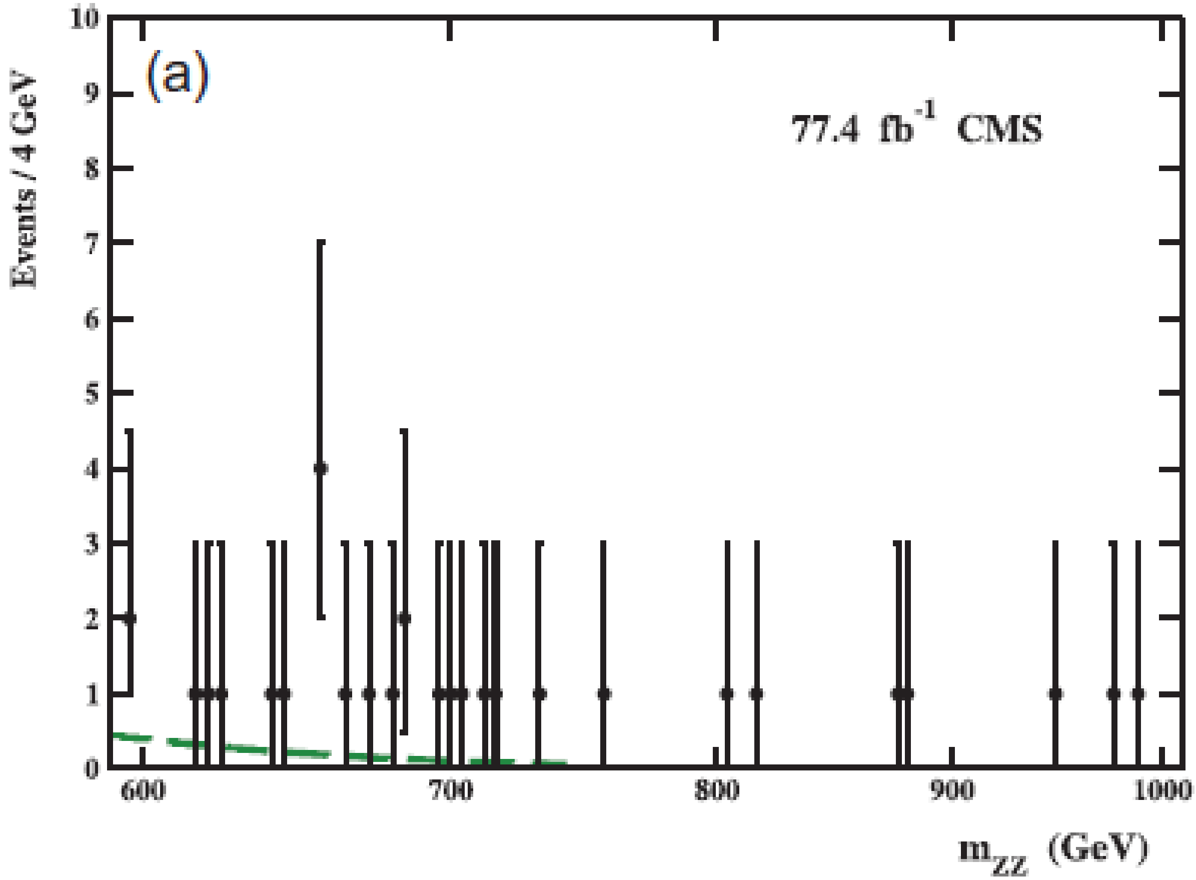
Largest CMS sample with an adequate binning at high mass



P. Cea's extraction of the 2016+2017 CMS data

(Mod. Phys. Lett. A 34 (2019) 1950137)

P. Cea



CMS 77.4 fb^{-1} vs. ATLAS 139 fb^{-1}

- CMS 77.4 fb$^{(-1)}$ E ≈ 685(30) GeV → **‹N(4l)› =14** **Measured**
- CMS 77.4 fb$^{(-1)}$ E ≈ 620÷740 GeV → **‹N(4l)› =19÷20** **Measured**

- CMS 139 fb$^{(-1)}$ E ≈ 685(30) GeV → **‹N(4l)› =25** **Extrapolated**
- ATLAS 139 fb$^{(-1)}$ E ≈ 685(30) GeV → **‹N(4l)› =26** **Measured (*)**

- CMS 139 fb$^{(-1)}$ E ≈ 620÷740 GeV → **‹N(4l)› =34÷36** **Extrapolated**
- ATLAS 139 fb$^{(-1)}$ E ≈ 620÷740 GeV → **‹N(4l)› =36** **Measured (*)**
- **(*) MVA-ggF-low category only**

- **Excellent agreement (the selection of 4-lepton events in ATLAS and CMS are very similar, as well as acceptances and efficiencies)**