The excess at 690 GeV: theory and experiment

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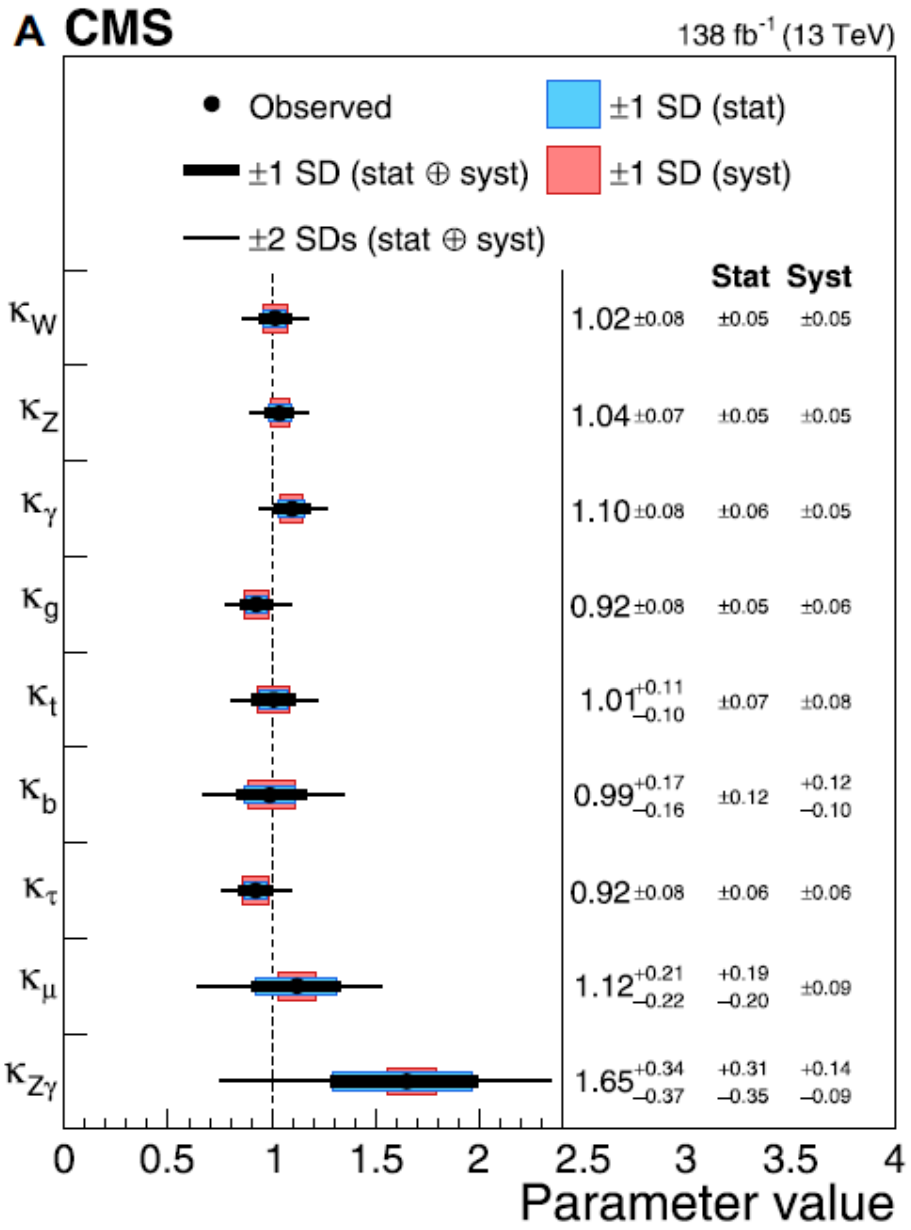
Abstract

1) Theoretical arguments + lattice simulations indicate that, besides the known resonance with $\mathbf{m_h = 125\ GeV}$, the SM Higgs field $\mathscr{H}$ may exhibit a second resonance with mass $\mathbf{(M_H)^{Theor} = 690(30)\ GeV}$

2) The expected phenomenology should correspond to a relatively narrow resonance mainly produced at LHC by the gluon-gluon Fusion (ggF) process. There should also be a rescaling of the $\mathscr{H}^3$ coupling by $\kappa_\lambda = (M_H/m_h) \approx 5.5$

3) Around 690 GeV, there is some excess of events over the background in various LHC data. There are also several excess/defect sequences that may indicate a change of sign of the interference between a new resonance and background. The combined statistical significance of all such deviations is far from negligible. A value $\kappa_\lambda \approx 5.5$ is also well consistent with the data

Note: an addendum on radiative corrections (not to be discussed but reported in the last 4 slides)



Interactions of the Higgs boson with all other particles

(in units of the expected values)

Theory → κ=1

- **G. Ortona, Frontiers in Physics, September 2023**

Remarkable agreement but still some uncertainty

- Uncertainty about the effective potential $V(\phi)$ at large $|\phi|$→ the absolute minimum of the perturbative potential is not at $v \approx 246$ GeV, leading to the possibility of a metastable vacuum (not discussed any further here)
- Also uncertainty about the behaviour of $V(\phi)$ near $\phi=0$→ is SSB a second-order or weak first-order phase transition?
- The latter uncertainty seems irrelevant for phenomenology. Any form of the potential, with a minimum at $v \approx 246$ GeV and quadratic shape fixed by $m_h = 125$ GeV, should be phenomenologically equivalent at the Fermi scale
- But is it really that simple?

SSB in cutoff Φ^4 is a weak first-order phase transition

(NOT second-order as with $V_{pert}(\phi)$)

- In the traditional picture (classical double-well potential + perturbative quantum corrections) SSB is a 2nd-order phase transition
- But lattice simulations of Φ^4 give instead a (weak) 1st-order phase transition
- Magnetization depending on the temperature, from Akiyama et al. PRD 100, (2019) 054510 for the Ising limit (volumes up to 1024^4)
- Later on, the same authors, see PRD 104, 034507 (2021), also confirmed the result at finite lattice coupling (volumes up to 1024^4)
- By assuming this framework, let us exploit possible implications

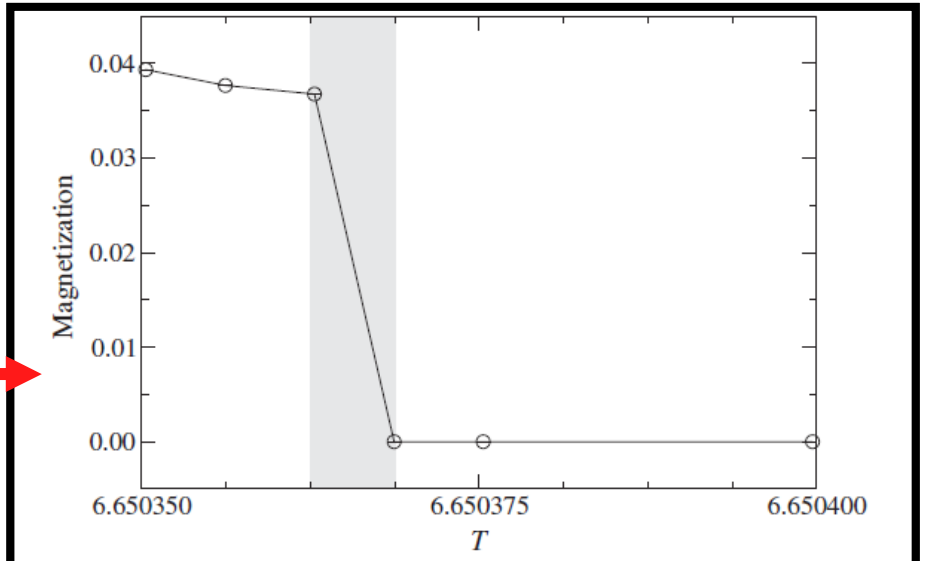


FIG. 7. Spontaneous magnetization in the thermodynamic limit with $D_{cut} = 13$. Error bars, provided by extrapolation, are within symbols. $T_c(D_{cut} = 13)$ estimated by $X^{(n)}$ of Eq. (15) is within the gray band.

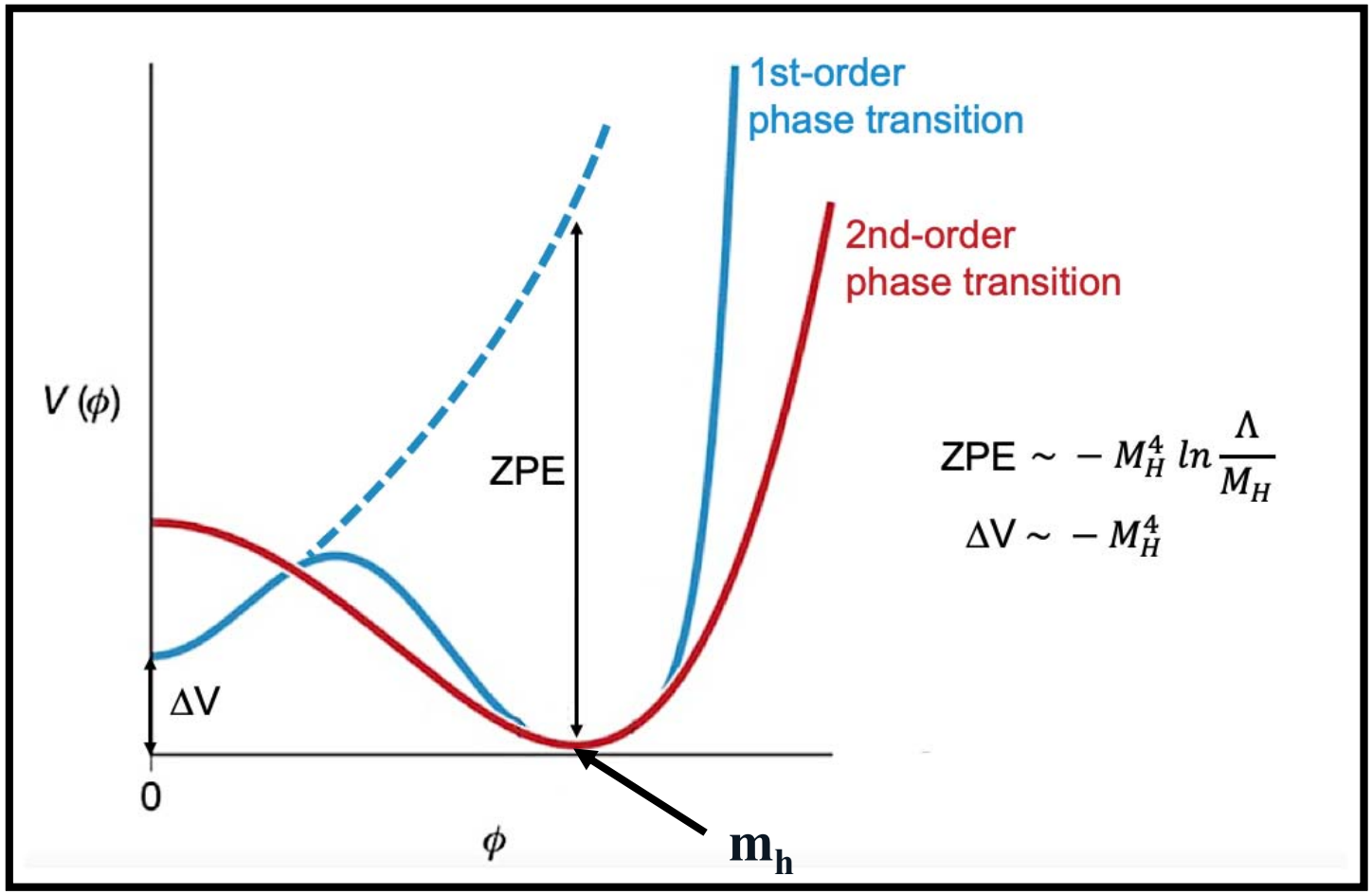
SSB in Φ^4: 2nd-order vs. 1st-order:

The role of Zero-Point-Energy (ZPE)

1st-order scheme

m_h = 125 GeV

M_H = ?



Approximations where SSB is weakly first-order

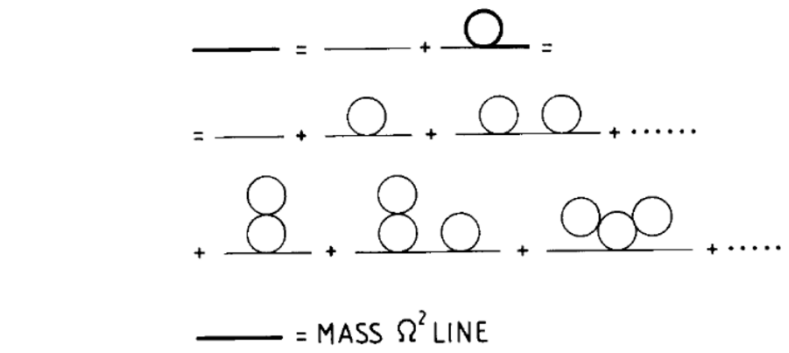
- The simplest approximation where SSB is weakly first-order is the Coleman-Weinberg one-loop potential. This is the prototype of «Gaussian-like» approximations where

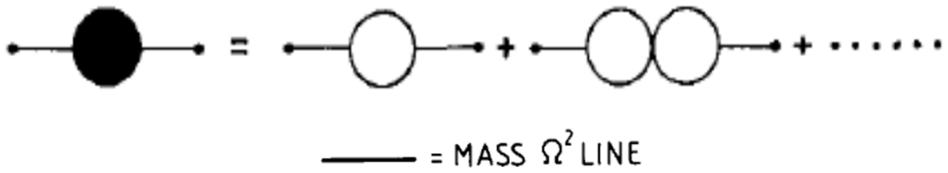
  $\mathbf{V_{eff}(\phi)}$ = some classical background + **ZPE** of free-field-like quantum fluctuations

- By minimizing these (non-perturbative) potential structures, residual interactions of field fluctuations vanish, in the continuum limit, as expected from «triviality»
- A new mass scale M_H » 125 GeV emerges. Its interplay with m_h = 125 GeV requires, however, to determine the p-dependence of the scalar propagator. This cannot be obtained from the effective potential itself but it requires the corresponding **Gaussian Effective Action**

Propagator from Gaussian Effective Action (GEA) in Φ^4

(in terms of diagrams, it can be represented as a 2-step procedure)





$$\Omega^2(\phi) = m_B^2 + \frac{\lambda\phi^2}{2} + \frac{\lambda}{2} I_0[\Omega(\phi)],$$

where

$$I_0(\Omega) = \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 + \Omega^2}.$$

$$\Omega^2(\phi_v) = \lambda\phi_v^2/3 \equiv M_H^2$$

and an inverse scalar propagator

$$G^{-1}(p) = p^2 + M_H^2 A(p, M_H),$$

$$A(p, M_H) = \frac{1 - J(p, M_H)}{1 + \frac{J(p, M_H)}{2}}$$

$$J(p, M) = \lambda \int \frac{d^4k}{(2\pi)^4} \frac{1}{(k^2 + M^2)[(k+p)^2 + M^2]}.$$

The Gaussian potential gives $\Delta V \approx -(M_H)^4$ and $A(0, M_H) \approx \varepsilon \approx L^{-1}$ where $\varepsilon = \lambda/(16\pi^2)$ and $L = \mathrm{Ln}(\Lambda/M_H)$ → **$G^{-1}(p=0) = (m_h)^2 \approx L^{-1}(M_H)^2 \ll (M_H)^2$** .

But in units of v= 246 GeV, one finds **$(m_h)^2 \approx L^{-1} v^2$** → **$M_H = K v$.** Therefore, in the $\varepsilon \to 0$ limit, M_H and v=246 GeV scale uniformly while $(m_h/v) \to 0$. This means that, in a correct $\varepsilon \to 0$ limit, G(p) must become free-field with mass M_H, the only exception being the zero-measure set p=0.

Instead, in the cutoff theory, there would be two regions: $G^{-1}(p) \approx p^2 + (m_h)^2$ for $p \to 0$

$G^{-1}(p) \approx p^2 + (M_H)^2$ at larger p^2

Gaussian Effective Action in Φ^4 : O(N) theory

- In the O(N) theory, one introduces two variational parameters Ω and ω, respectively for the shifted and unshifted fields, and 3 coupled equations, see A. Okopinska PLB 375 (1996) 213

$$\Omega^2 = m_B^2 + \frac{\lambda\phi^2}{2} + \frac{\lambda}{2} I_0(\Omega) + \frac{\lambda}{6}(N-1) I_0(\omega),$$

$$\omega^2 = m_B^2 + \frac{\lambda\phi^2}{6} + \frac{\lambda}{6} I_0(\Omega) + \frac{\lambda}{6}(N+1) I_0(\omega),$$

$$B \equiv m_B^2 + \frac{\lambda\phi^2}{6} + \frac{\lambda}{2} I_0(\Omega) + \frac{\lambda}{6}(N-1) I_0(\omega) \; = \; 0.$$

- The ω is just a variational parameter. Upon diagonalization of the propagator matrix, one finds (N-1) fields with $\mathcal{G}^{-1}(p) = p^2 + B$ that become exactly massless at the minimum of the effective potential where B=0

$$G^{-1}(p) \; = \; p^2 + M_H^2 A(p, \Omega, \omega),$$

where now[8]

$$A(p, \Omega, \omega) \; = \; \frac{1 - J(p, \Omega) + \frac{J(p,\omega)}{3} - \frac{N+2}{9} J(p, \Omega) J(p, \omega)}{1 + \frac{J(p,\Omega)}{2} + \frac{N+1}{6} J(p, \omega) + \frac{N+2}{18} J(p, \Omega) J(p, \omega)}.$$

- For the singlet field, the propagator has the same previous structure. Only, A(p,Ω,ω) is now more complicated due to the sequence of Ω-ω loops.

$$A(0, \Omega, \omega) \; \sim \; \epsilon \; \sim \; L^{-1},$$

so that

$$m_h^2 \; \equiv \; M_H^2 \, A(0, \Omega, \omega) \; \sim \; M_H^2 \, L^{-1} \; \ll \; M_H^2 \, .$$

- By denoting again as $\mathbf{M_H}$ the parameter Ω at that values of ϕ where B=0, one finds the same 2-mass structure $(\mathbf{m_h})^2 \approx (\mathbf{M_H})^2 \; L^{-1}$ as for the one-component theory

2-mass structure? Check with lattice simulations of G(p)

- Fit the lattice data to free-field propagator and extract $\mathbf{m_h}$ from $[G(p)]_{latt}$ for $p \to 0$ and $\mathbf{M_H}$ from $[G(p)]_{latt}$ at larger p^2. Then rescale the data and compare with a straight line
- First check with the symmetric phase (straight line everywhere → only one mass, as it should be…)
- A difference in the broken-symmetry phase. One cannot fit all data with the same mass. Good fits in different momentum regions with two different masses M_H and m_h
- Lattice simulations are also needed because the slope of the Ln(Λ) trend between M_H and m_h is different in the various Gaussian-like approximations to the effective potential (different classes of diagrams being resummed). We have thus extracted the slope parameter $\mathbf{c_2}$

$$\mathbf{M_H \approx m_h \, L^{½} \, c_2^{-1/2} \qquad [c_2^{-1/2}]_{latt} = 0.67(3)}$$

κ	lattice	M_H	m_h	$[\ln(\Lambda_L/M_H)]^{-1/2}$	$(c_2)^{-1/2}$
0.07512	32^4	0.2062(41)	0.1857(8)	0.606(2)	0.673(14)
0.0751	48^4	~ 0.200	0.1796(5)	~ 0.603	~ 0.671
0.07504	32^4	0.1723(34)	0.1507(7)	0.587(2)	0.671(14)
0.0749	76^4	0.0933(28)	0.0769(8)	0.533(2)	0.647(22)
0.0749	76^4	0.096(4)	0.0769(8)	0.535(3)	0.668(31)
0.0749	76^4	0.100(6)	0.0769(8)	0.538(4)	0.700(42)

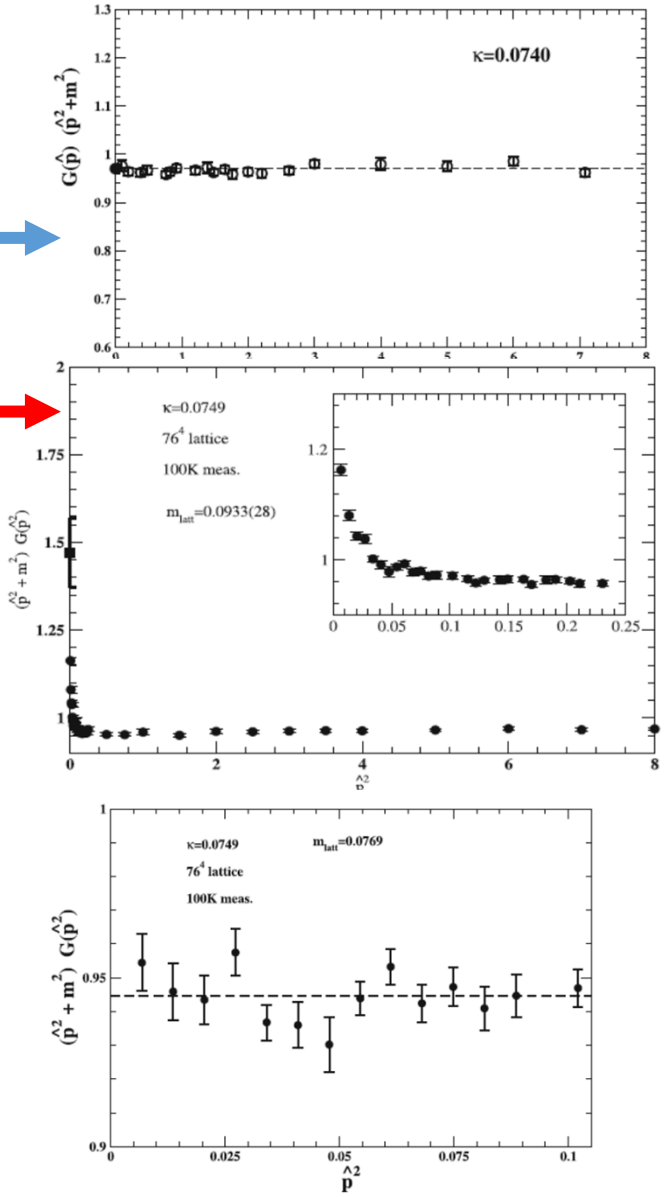


Fig. 4 The propagator data from Ref. [10] at $\kappa = 0.0749$ for $\hat{p}^2 < 0.1$. The lattice data were rescaled here with zero-momentum mass $m_h = 0.0769\,(8)$

The prediction $M_H = 690(30)$ GeV

- After checking the logarithmic scaling and having extracted the coefficient $\mathbf{c_2}$

$$\mathbf{M_H \approx m_h\, L^{½}\, c_2^{-1/2}} \qquad \mathbf{[c_2^{-1/2}]_{latt} = 0.67 \pm 0.03}$$

combine with $\mathbf{(m_h)^2 = \lambda\, v^2/3}$ and the leading-order relation $\mathbf{\lambda \approx (16\,\pi^2/3)\cdot L^{-1}}$. Then, for v ≈ 246 GeV, this gives

$$\mathbf{m_h \approx (4\,\pi v/3)\cdot L^{-½} \approx 1.03\ TeV \cdot L^{-½}}$$

$$\mathbf{M_H \approx K \cdot v} \qquad \text{with} \quad K = (4\,\pi/3)\,[c_2^{-1/2}]_{latt} \approx (8\,\pi/9)$$

or

$$\mathbf{(M_H)^{Theor} \approx 690\ (30)\ \ GeV}$$

- This prediction is remarkably consistent with the old theoretical bounds on the cutoff-dependent m_h , say $m_h < (m_h)^{max}$ from lattice simulations of the O(4) theory, (C. B. Lang 670(80) GeV and U. Heller 710(60) GeV, 1994)

$$\mathbf{(m_h)^{max} \approx 690\ (50)\ \ GeV} \qquad \text{Lang + Heller 1994}$$

So that, from $\mathbf{m_h \approx 1.03\ TeV \cdot L^{-½}}$ and $\mathbf{(m_h)^{max} = 690(50)\ GeV \rightarrow (L^{1/2})_{min} = 1.5(1)}$

we find

$$\mathbf{(M_H)^{Theor} \approx (m_h)^{max}\,(L^{1/2})_{min}}\ (0.67 \pm 0.03) = \mathbf{(m_h)^{max}} \cdot (1.00 \pm 0.08)$$

- Conclusion: if a second resonance exists, its mass can only be in a narrow window around 690 GeV. But, in the real world, $\mathbf{m_h = 125\ GeV}$. Therefore, if such a second resonance exists the ultraviolet cutoff Λ of the scalar sector must be extremely large.

The residual Higgs-field interactions

- $\mathbf{V_{int}(\mathscr{H}) = \frac{1}{2}\,\varepsilon_1\,(M_H)^2/v\,\mathscr{H}^3 + \frac{1}{8}\,\varepsilon_2\,(M_H/v)^2\,\mathscr{H}^4}$

$(M_H)^2/v = K^2 v$ and $(M_H/v)^2 = K^2$ cannot describe residual couplings that should vanish when $\Lambda \rightarrow \infty$. In fact, by minimizing the Gaussian potential one finds

- $\mathbf{\varepsilon_1 = (m_h/M_H) \approx L^{-1/2}} \qquad \mathbf{\varepsilon_2 = (\varepsilon_1)^2 \approx L^{-1}}$

Equivalently, the same potential can also be expressed as

- $\mathbf{V_{int}(\mathscr{H}) = \frac{1}{2}\,\kappa_\lambda\,(m_h)^2/v\,\mathscr{H}^3 + \frac{1}{8}\,(m_h/v)^2\,\mathscr{H}^4}$

with $\kappa_\lambda = (M_H/m_h) = (\varepsilon_1)^{-1}$

(Effective) Lagrangian of the Higgs field

The previous results can be summarized in the Lagrangian structures :

$$\mathscr{L}(\mathscr{H}) = \tfrac{1}{2}\,\mathscr{H}\,G^{-1}\mathscr{H} - \kappa_\lambda(\lambda v/3!)\,\mathscr{H}^3 - (\lambda/4!)\,\mathscr{H}^4$$

1-component Φ^4

$$\mathscr{L}(\mathscr{H}, \chi^a) = \tfrac{1}{2}\,\mathscr{H}\,G^{-1}\mathscr{H} + \tfrac{1}{2}\,\chi^a\partial^2\chi^a - \kappa_\lambda(\lambda v/3!)\mathscr{H}(\mathscr{H}^2 + \chi^a\chi^a) - (\lambda/4!)\,(\mathscr{H}^2 + \chi^a\chi^a)^2$$

O(N) theory

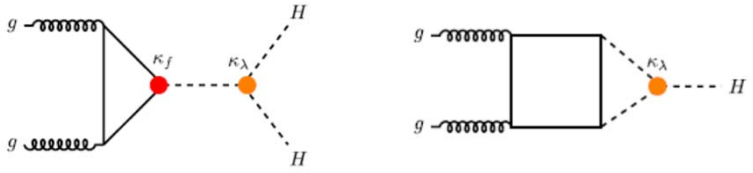
with $\kappa_\lambda = (M_H/m_h) \approx 5.5$

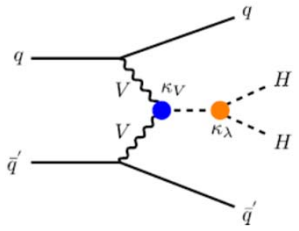
and $\lambda = 3\,(m_h/v)^2$

New aspects: i) the rescaling $\kappa_\lambda \neq 1$

ii) a second resonance around 690 GeV

$\kappa_\lambda \approx 5.5$ is well consistent with the present data





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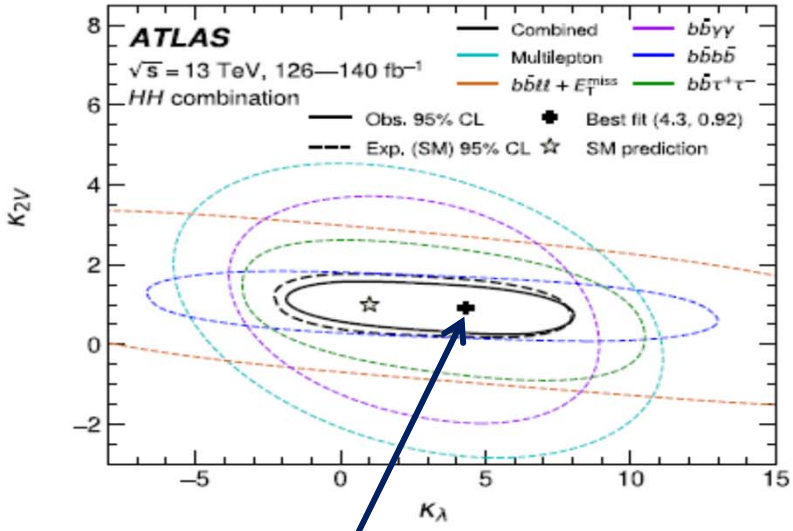
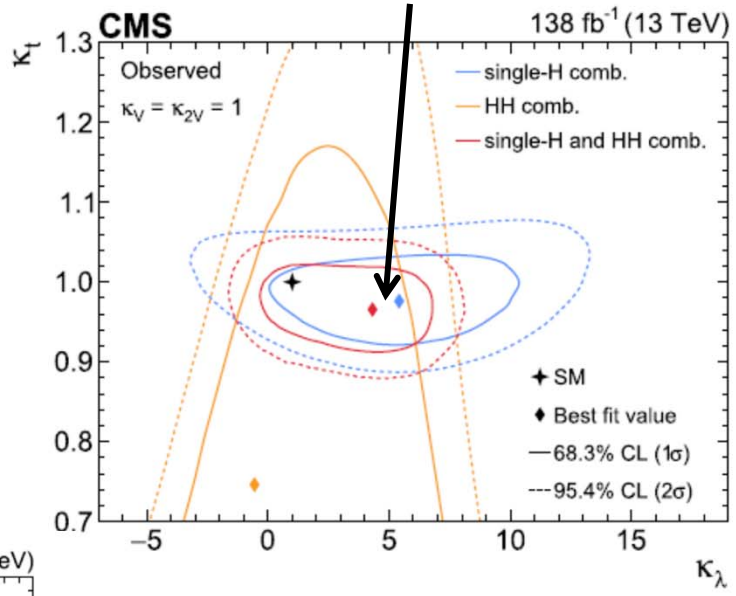
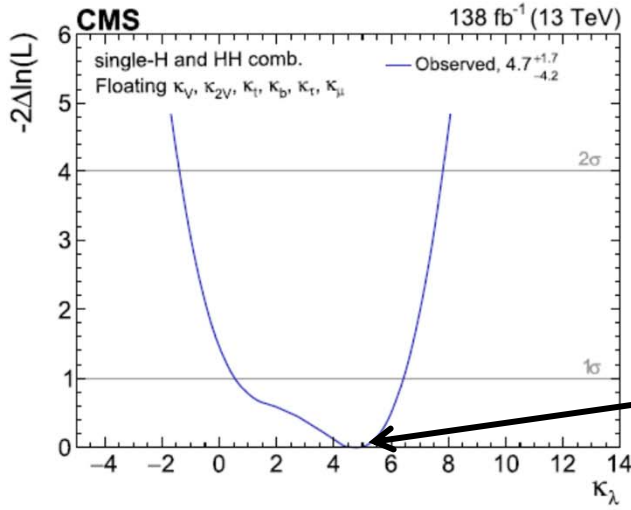
Best fit **H** and **HH combined**



Best fit





Best fit with all other κ parameters floating

The theory at $g_{gauge} \neq 0$

- To obtain the Lagrangian at non-zero gauge couplings, one should simply replace in the SM Lagrangian
- 1) $\frac{1}{2}\,\mathcal{H}\,[\partial^2 - (m_h)^2]\,\mathcal{H} \rightarrow \frac{1}{2}\,\mathcal{H}\,G^{-1}\,\mathcal{H}$

  2) $(m_h)^2/v \rightarrow \kappa_\lambda \cdot (m_h)^2/v$ with $\kappa_\lambda = (M_H/m_h) \approx 5.5$
- These replacements implement the infinite resummations of one-loop bubbles, in the pure scalar sector. The resulting structure is then consistent with the assumed exact «triviality» of Φ^4 theory and with a description of SSB as a weak first-order transition.
- In this way, the scalar sector is treated non perturbatively while the effects of the gauge couplings can be added perturbatively. This different treatment of the two sectors is in the spirit of an effective Lagrangian and consistent with the content of the Equivalence Theorem in renormalizable gauges
- With $M_H \approx 690$ GeV, fermion and gauge fields give small corrections to vacuum energy. In fact, logarithmically divergent ZPE is proportional to the fourth power of the mass so that $12(m_t/M_H)^4 < 0.05$ and $[6(M_w)^4 + 3(M_z)^4]/(M_H)^4 \approx 0.002$
- Note a crucial aspect: the trilinear term $3(m_h M_H/v)$ is larger than $3(m_h)^2/v$ but smaller than $3(M_H)^2/v$ by the inverse amount. For this reason, the decay width into longitudinal Ws of the 690 GeV resonance, as compared to the conventional width for a Higgs boson of the same mass, would be suppressed by the factor $(m_h/M_H)^2 \approx 0.033$

Basic phenomenology of the 690 GeV resonance

- As compared to a conventional Higgs boson of 700 GeV, the large width Γ^{conv} (H→WW+ZZ) ≈ 150 GeV is reduced to about Γ(H→WW+ZZ) ≈ 5 GeV.
- Altogether, for $(M_H)^{Theor}$ = 690 (30) GeV , the total width is expected in the range Γ(H→all) ≈ 25 ÷ 35 GeV with a main branching ratio into top-quark pairs ≈ 75÷80 % and the other main decay modes B(H→ZZ) = 0.053(12), B(H→WW) = 0.11(2), B(H→hh) = 0.05(1)
- Due to its weak coupling to longitudinal Ws and Zs, H-production at LHC through Vector-Boson Fusion (VBF) would be much smaller than gluon-gluon-Fusion (ggF) with typical cross section σ^{ggF}(pp→H)= 1000(200) fb.
- Example) σ^{peak}(pp→H→4l)= 1000(200) x 0.053(12) x 0.0045 **≈ 0.25(10) fb.**
- Thus for σ^{BKG}(pp→H→4l)≈ 0.214 fb (E= 665 ÷ 720 GeV) (ATLAS)

  one finds $\langle \sigma_{peak} / \sigma_{BKG} \rangle = 0.7 \div 1.6$

Background + resonance: difference with the 125 GeV resonance

We have adopted the model of a resonance interfering with a background $\sigma_B(E)$.
This produces a total cross section ($s = E^2$ and $\Gamma_H = \Gamma(H \to \text{all})$)

$$\sigma_T(E) = \sigma_B(E) + \sigma_{\rm BW}(E) + \sigma_{\rm int}(E) \,,$$

where

$$\sigma_{\rm int}(E) = 2\sqrt{\sigma_B(E)\sigma_{\rm peak}}\,\frac{(M_H^2 - s)}{\Gamma_H M_H}\,R(E)$$

and

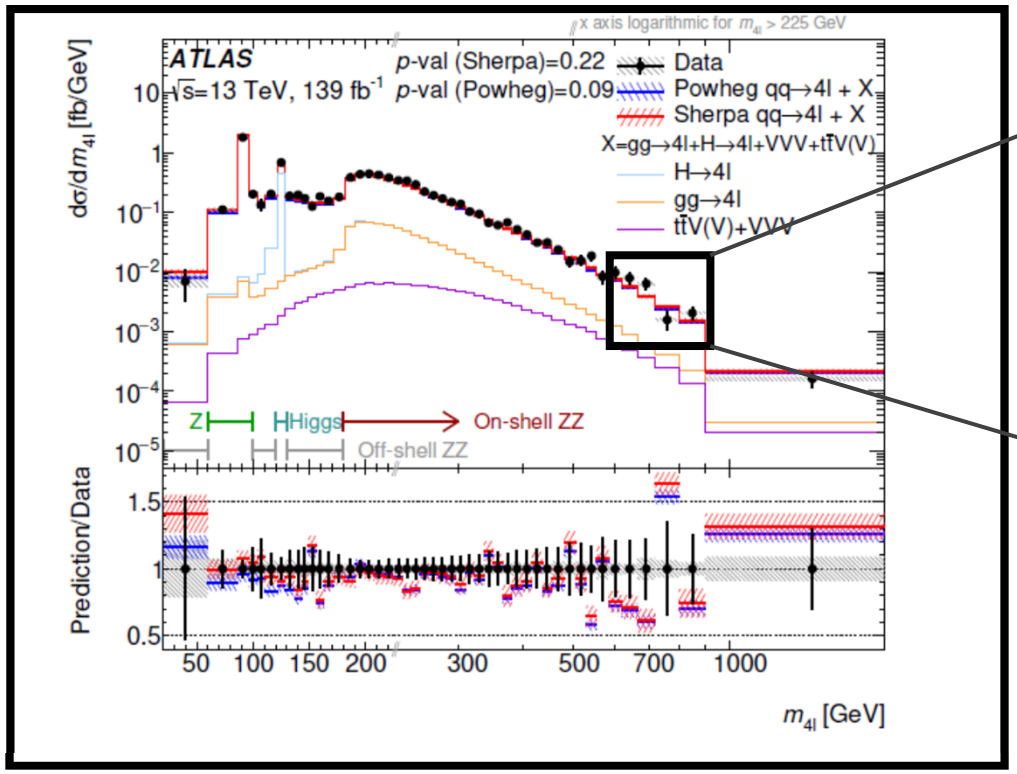
$$\sigma_{\rm BW}(E) = \sigma_{\rm peak}\cdot R(E)$$

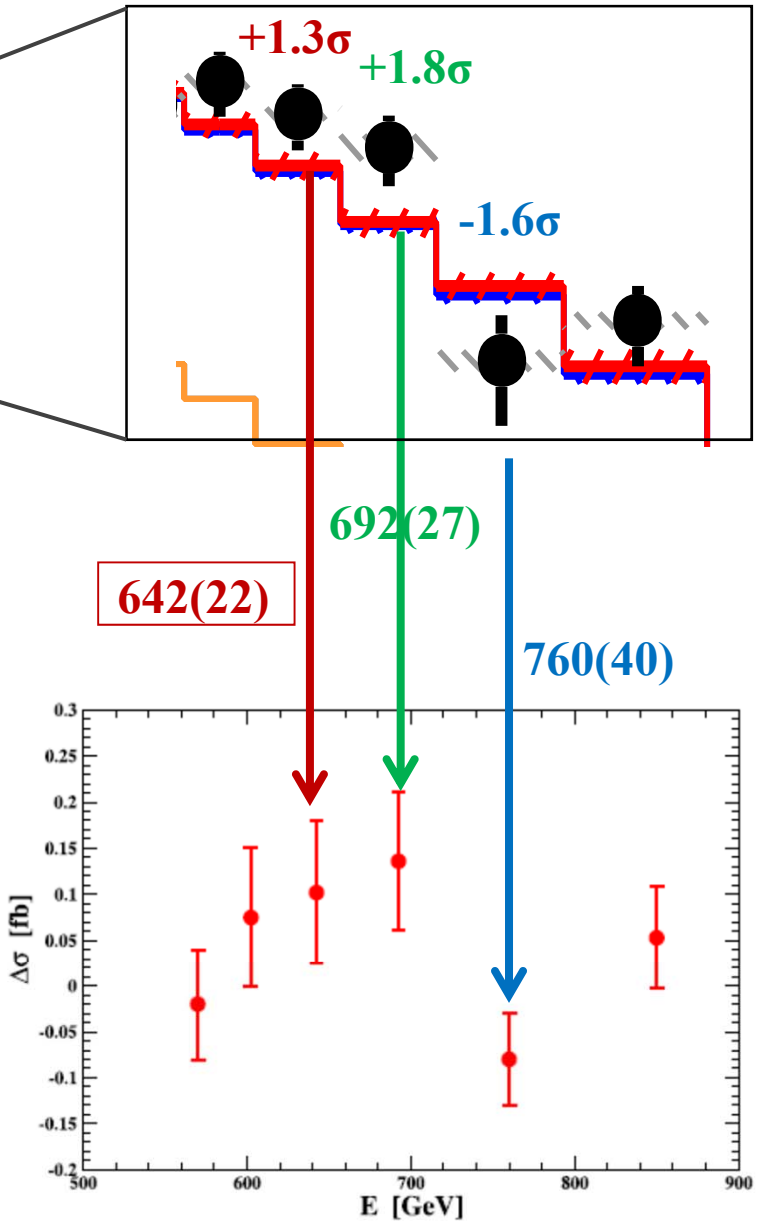
$$R(E) = \frac{(\Gamma_H M_H)^2}{(s - M_H^2)^2 + (\Gamma_H M_H)^2}\,.$$

- In many channels : Breit-Wigner peak comparable to (or smaller than) BKG
- Sizeable interference effects. Data binning may produce a signal with no excess in the bin including the mass... Example: bins of size ≈ 2Γ and ‹ σ_{peak} / σ_{BKG} › = **0.7**
- M - 5/2Γ ‹ E ‹ M – Γ/2 → **S/B = σ_T /σ_B ≈ 1.6**
- M – Γ/2 ‹ E ‹ M + 3Γ /2 → **S/B = σ_T /σ_B ≈ 1.0**
- M + 3Γ/2 ‹ E ‹ M + 7Γ /2 → **S/B = σ_T /σ_B ≈ 0.6**
- Definite experimental signal **:** search for **excess/defect sequences**
- Example of statistical significance with a ≈ 25% accuracy: S/B= 1.60 ± 0.40; 1.05 ± 0.25; 0.60 ± 0.15 → combined 3σ deviation (not just 1.5σ as from excess only)

ATLAS charged 4-lepton cross-section m_{4l} = 600÷900 GeV

see Fig.5 of JHEP 07(2021)005; arXiv:2103.01918v1 [hep-ex]





Bin [GeV]	σ_{EXP} [fb]	σ_B [fb]	$(\sigma_{EXP} - \sigma_B)$ [fb]
555–585	0.252 ±0.056	0.272 ± 0.023	−0.020 ± 0.060
585–620	0.344 ± 0.070	0.259 ± 0.021	+0.085 ± 0.075
620–665	0.356 ± 0.075	0.254 ± 0.023	+0.102 ± 0.078
665–720	0.350 ± 0.073	0.214 ± 0.019	+0.136 ± 0.075
720–800	0.126 ± 0.047	0.206 ± 0.018	−0.080 ± 0.050
800–900	0.205 ± 0.052	0.152 ± 0.017	+0.053 ± 0.055

ATLAS 4-lepton categories : combined ≈ 4.5σ deviation

Table 3: The ATLAS [22] ggF-like 4-lepton events for the various categories (see text) with, in parentheses, the expected background. The error bars in the S/B ratio reflect the $\sqrt{N}$ statistical uncertainty of the observed events.

E [GeV]	high-4μ	high-2e2μ	high-4e	low	Total	S/B
560 (30)	4 (3.6)	3 (6.2)	5 (2.7)	38 (32.0)	50 (44.5)	1.13 ± 0.16
620 (30)	3 (2.3)	2 (3.9)	4 (1.7)	25 (20.0)	34 (27.9)	1.22 ± 0.21
680 (30)	1 (1.5)	2 (2.5)	3 (1.1)	26 (13.0)	32 (18.1)	1.77 ± 0.31
740 (30)	0 (1.0)	1 (1.6)	0 (0.7)	3 (8.7)	4 (12.0)	0.33 ± 0.17
800 (30)	1 (0.7)	2 (1.1)	0 (0.5)	7 (6.0)	10 (8.3)	1.21 ± 0.38

+ 2.4σ

- 3.9σ !

For further comparison with CMS 4-lepton data, note

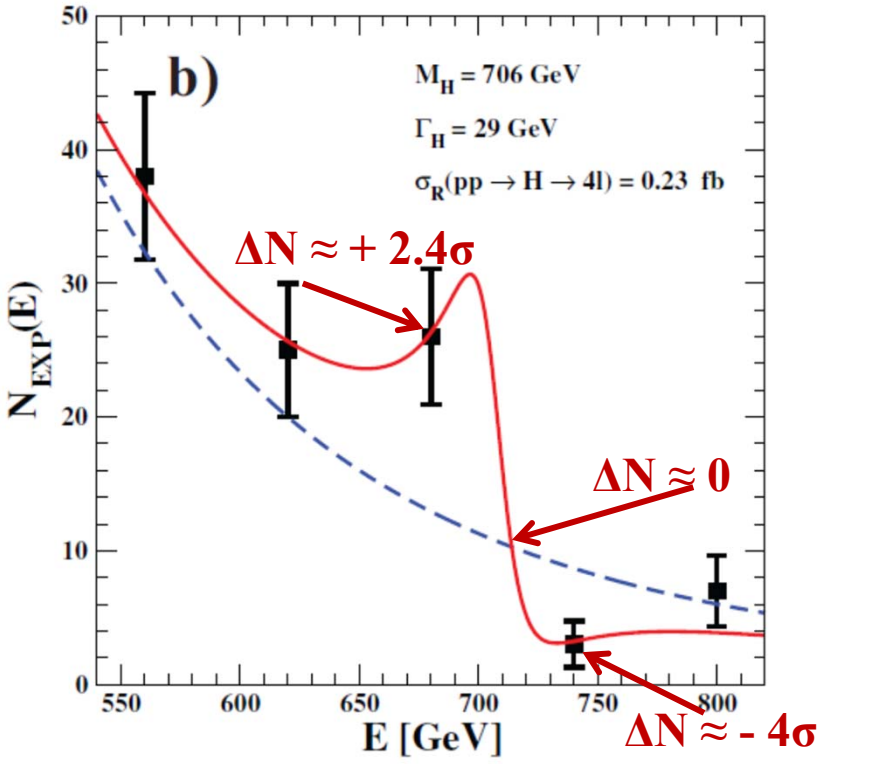
‹S/B› = 0.69 ± 0.18 ATLAS E = 710 ÷ 830 GeV (14 obs. events vs. 20.3 expected)

ATLAS «ggF-low» charged 4-lepton events

EPJC **81** 332 (2021)

- The dominant ATLAS ggF-low events grouped in bins of 60 GeV
- Fitted mass and width :
- **M= 706(25) GeV** and **Γ = 29(20) GeV**
- **Γ/M ≈ 0.04 ± 0.03**
- Full red curve and blue dashed background coincide for E ≈ M

- From cross section data (symmetric error bars):
- **M=677(22) GeV** and **Γ ≈ 21(16) GeV**
- **Γ/M ≈ 0.03 ± 0.02**



Fit with interference of a background + resonance

CMS 4-lepton data: S/B ratio

(CMS PAS HIG-24-002 - July 2024)

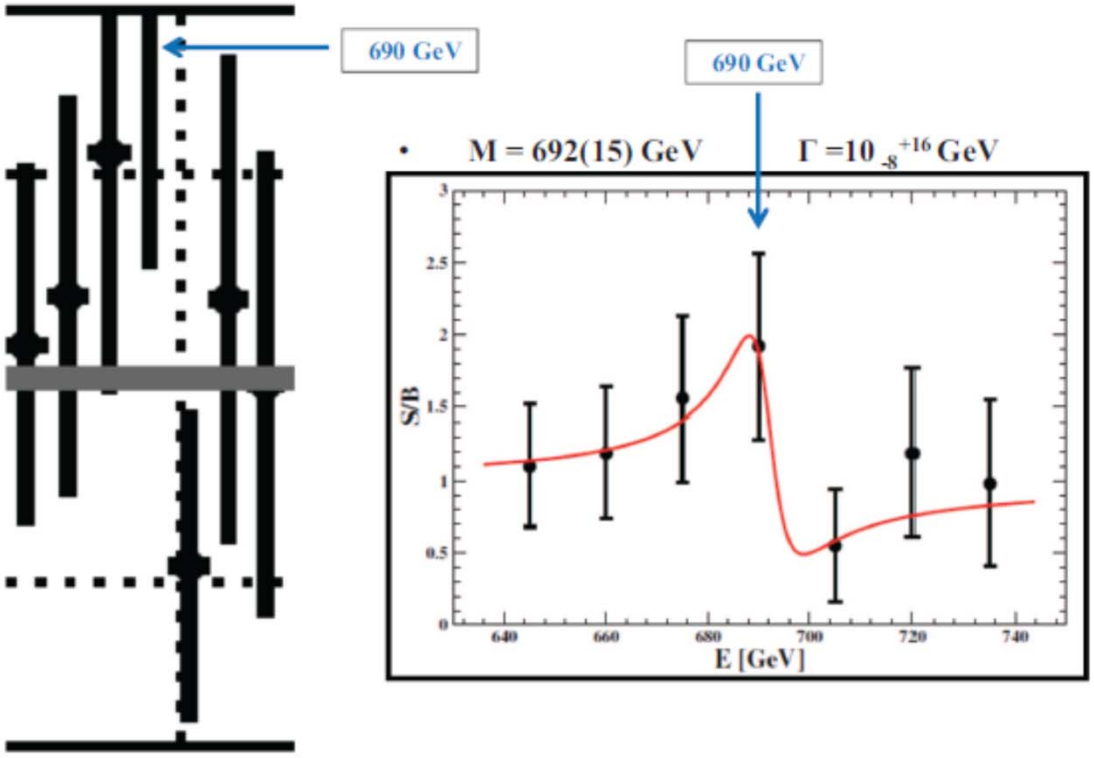
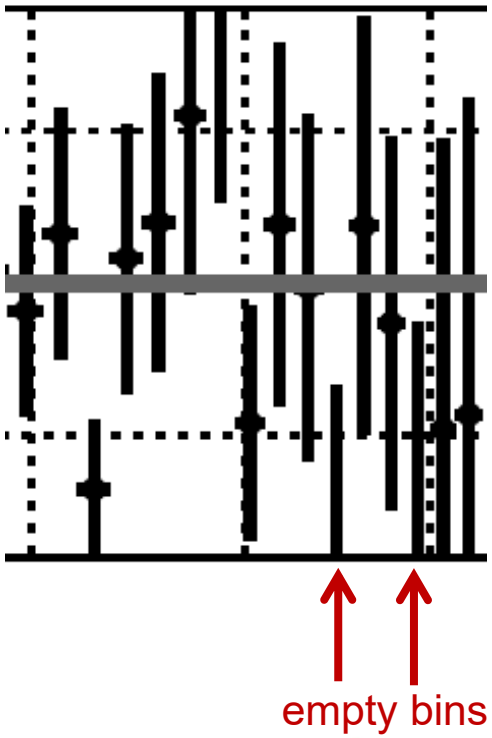


Figure 4: The CMS 4-lepton data [23] for S/B at E= 640÷740 GeV and our fit with Eq. (9).

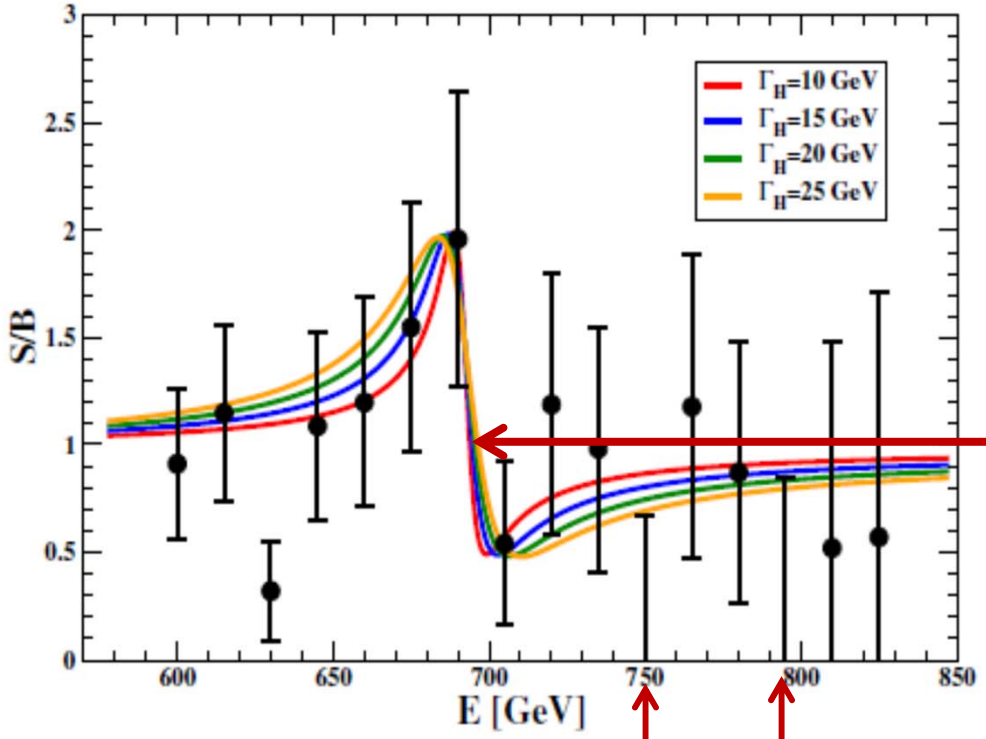
CMS 4-lepton data: S/B ratio

(CMS PAS HIG-24-002 - July 2024)

$M_H \approx 692$ GeV (and various widths)



empty bins



S/B = 1
E= M_H

empty bins

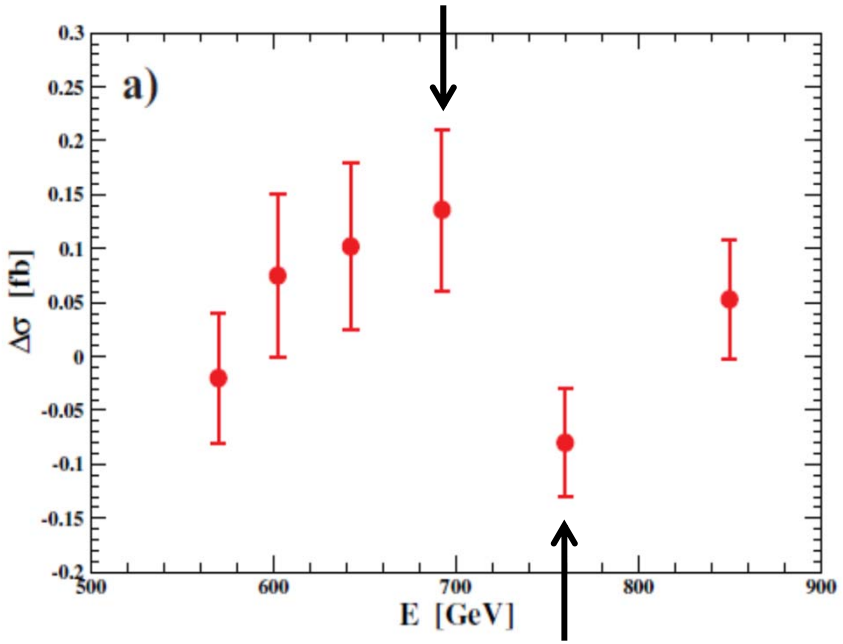
Figure 4. Comparing the CMS S/B ratios to eq. (5.2), for $M_H = 692$ GeV, $N_R = 0.55$, and four different widths.

4-lepton channel: ATLAS + CMS

ATLAS 4-lepton cross section

JHEP **07**(2021)005

- $\Delta\sigma(E) = \sigma^{exp}(E) - \sigma^{bkg}(E)$
- 692(27) GeV ‹S/B› = 1.64 ± 0.34

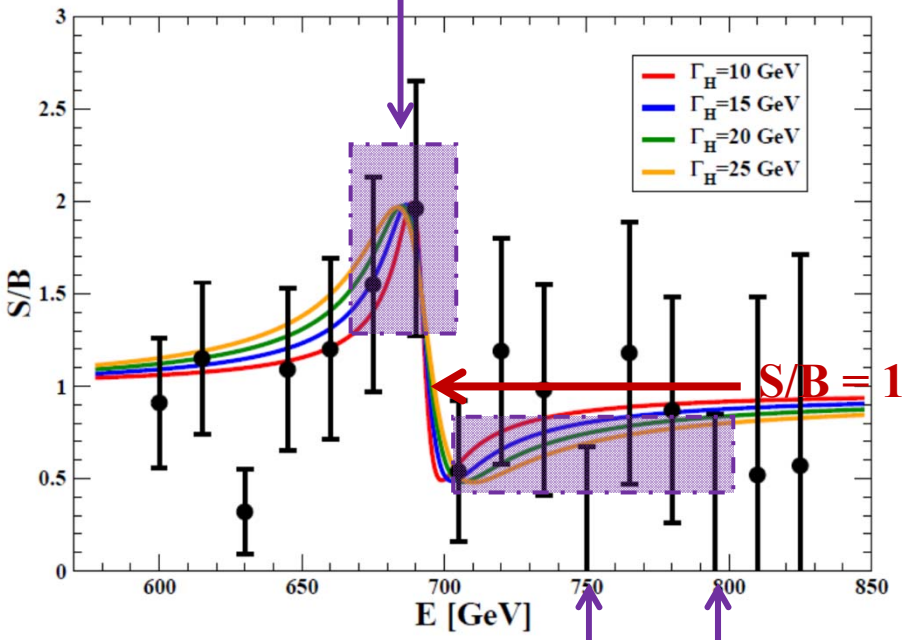


- 760(40) GeV ‹S/B› = 0.61 ± 0.23

CMS 4-lepton data

- E= 682(15) GeV

‹S/B› = 1.74 ± 0.45

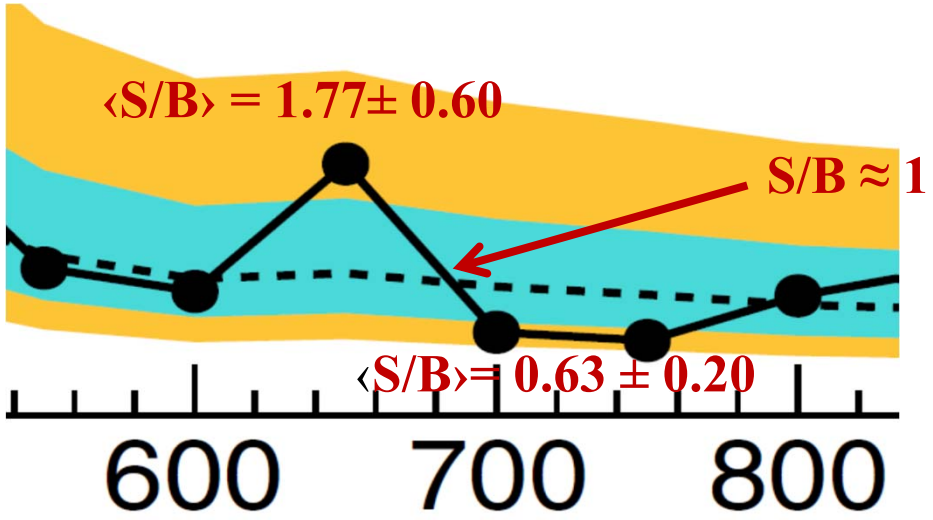


- E=705÷825 GeV ‹S/B› = 0.68 ± 0.17
- 16 observed events vs. 23.5 expected

ATLAS (bb+γγ) data

PRD **106** (2022) 052001

$M_H \approx 675(25)$ GeV → S/B ≈ 1



M_X (GeV)	σ^{obs} [fb]	$\sigma^{expected}$ [fb]
600	73.6 (14.3)	$81.1^{+43.3}_{-22.7}{}^{+119.0}_{-37.6}$
650	149.3 (20.3)	$84.4^{+44.4}_{-23.6}{}^{+120.1}_{-39.1}$
700	49.4 (12.0)	$76.5^{+40.0}_{-21.4}{}^{+109.6}_{-35.4}$
750	44.5 (12.0)	$71.7^{+37.6}_{-20.0}{}^{+103.3}_{-33.2}$
800	71.0 (14.0)	$65.8^{+35.1}_{-18.4}{}^{+98.5}_{-30.5}$

At 650, 700 and 750 GeV, a combined 2.4σ deviation . But…

$\Delta\sigma^{obs} = \sigma^{obs}(650) - \sigma^{obs}(700) = 99.9(23.6)$ fb vs. $\Delta\sigma^{expected} < 18.4$ fb, → 3.4σ effect

To explain this discrepancy, one needs an **asymmetric** effect that increases the number of events with **m(γγjj) around 650 GeV** and decreases the number of events with **m(γγjj) around 700 GeV,** as with a resonance of mass ≈ **675 GeV**

4-lepton (ATLAS & CMS) and (bb+γγ) (ATLAS): same excess/defect pattern

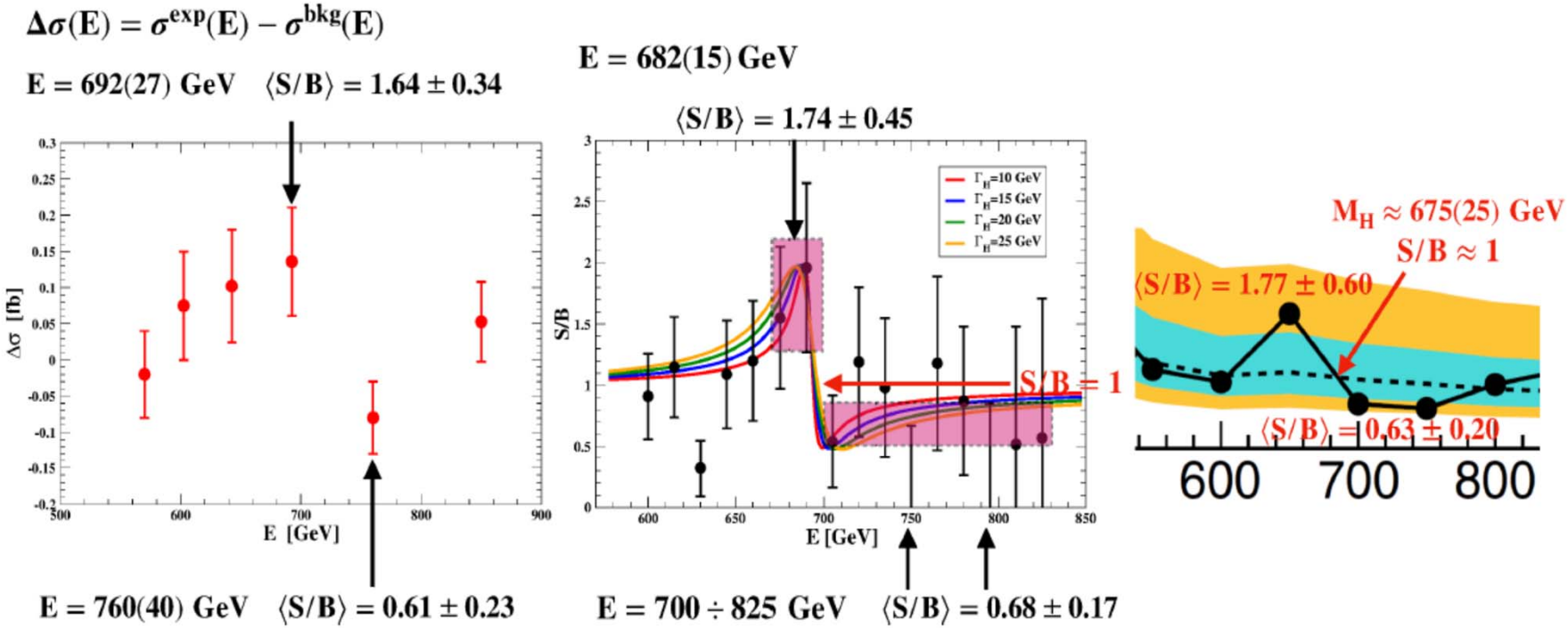


Figure 6: The ATLAS 4-lepton data of Fig. 2 with the CMS data of Fig. 5, and the analogous ATLAS data [24], for $\sigma(pp \to X \to hh)$ from the $b\bar{b} + \gamma\gamma$ final state.

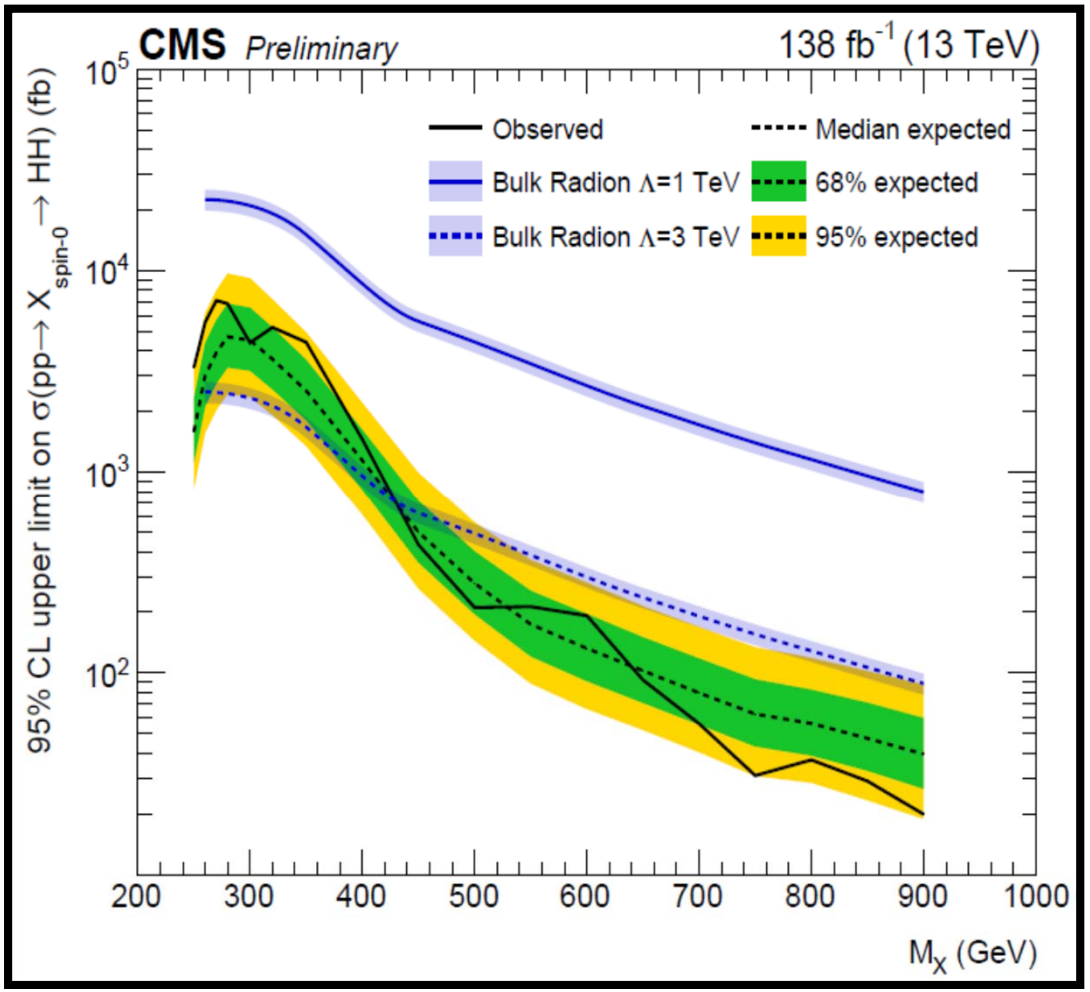
‹S/B› in the 4-lepton channel past BW peak

‹S/B› = 0.68 ± 0.17 CMS E = 705 ÷ 825 GeV (16 obs events vs. 23.5 expected)

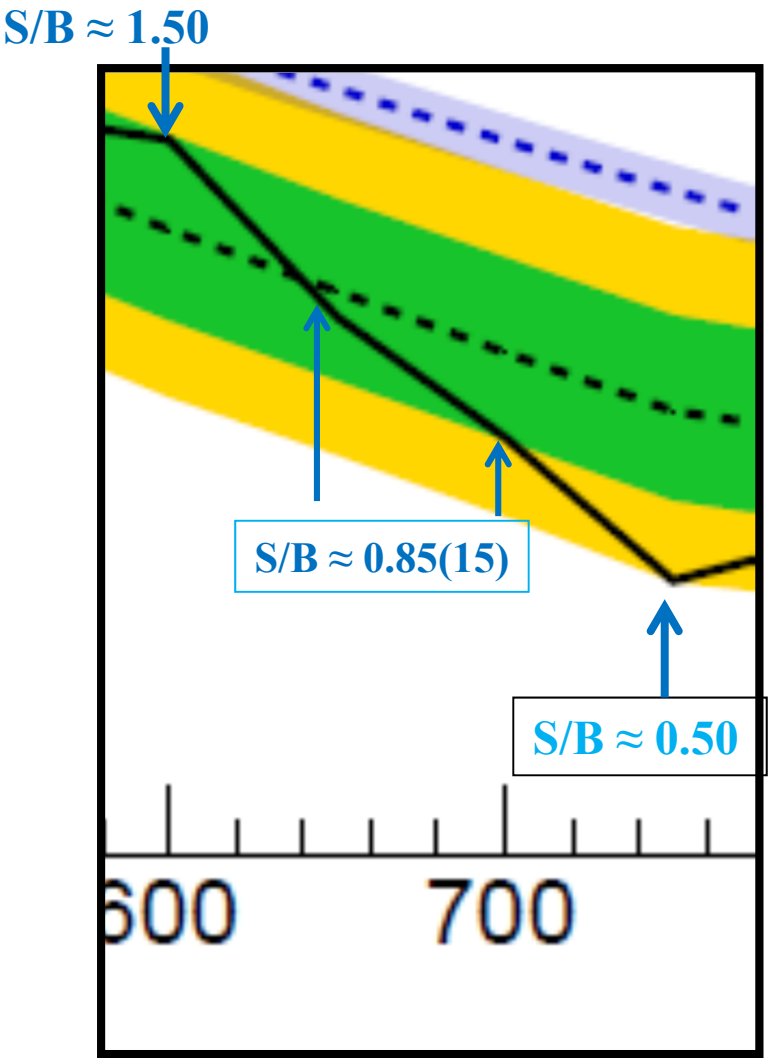
‹S/B› = 0.69 ± 0.18 ATLAS E = 710 ÷ 830 GeV (14 obs events vs. 20.3 expected)

Other evidences

CMS σ(pp→X→H(125)H(125)→bb+WW)

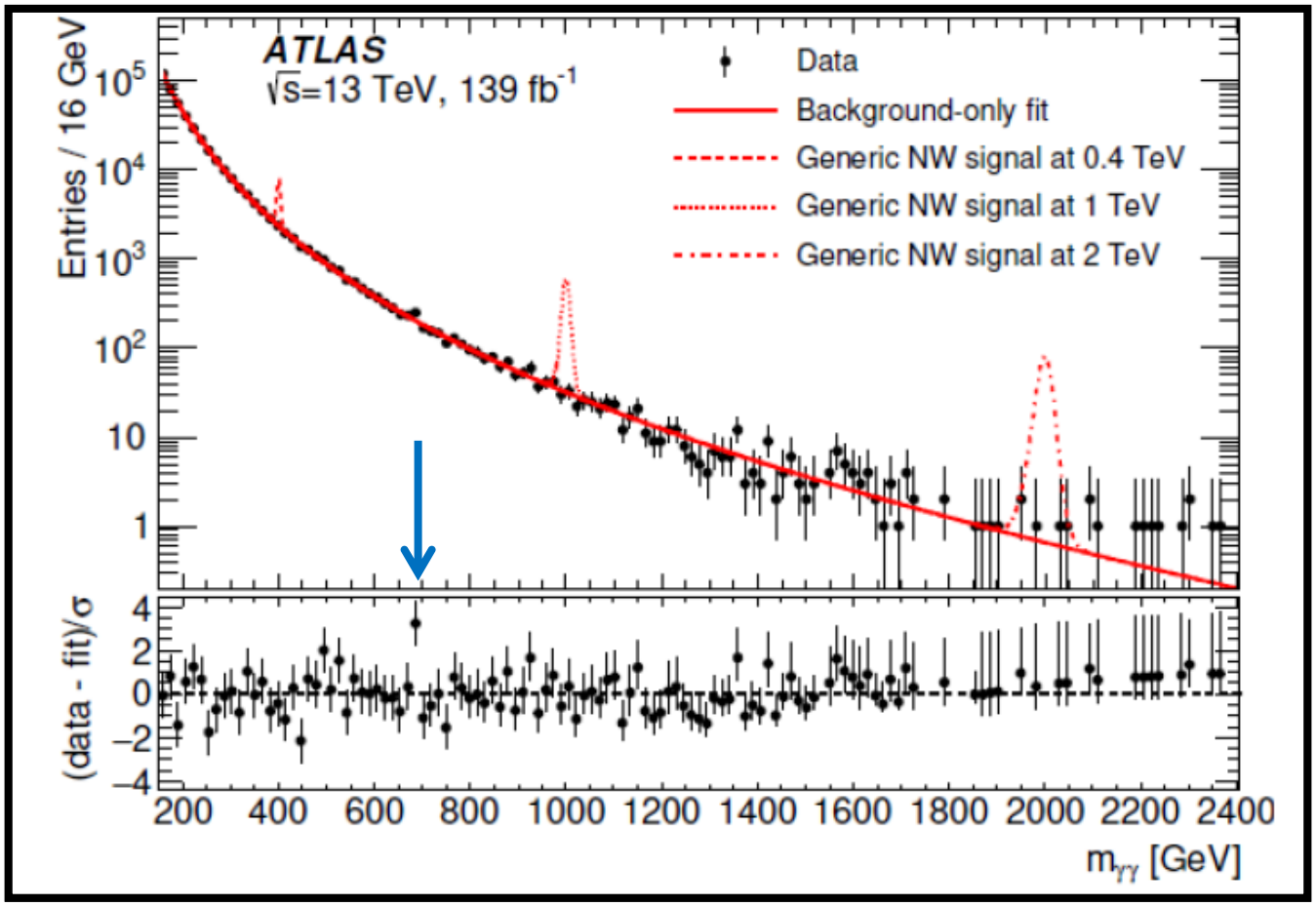


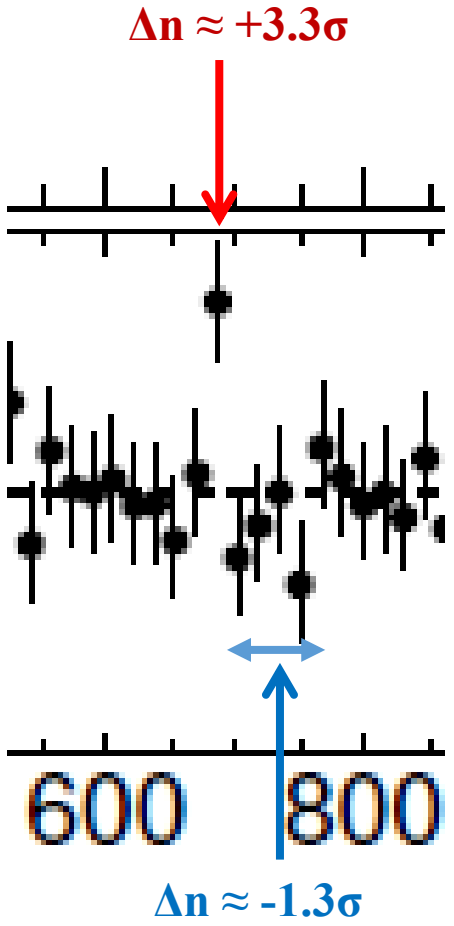
- M - 5/2Γ ‹ E ‹ M – Γ/2 → S/B = $\sigma_T/\sigma_B \approx 1.6$
- M – Γ/2 ‹ E ‹ M + 3Γ /2 → S/B = $\sigma_T/\sigma_B \approx 1.0$
- M + 3Γ/2 ‹ E ‹ M + 7Γ /2 → S/B = $\sigma_T/\sigma_B \approx 0.6$



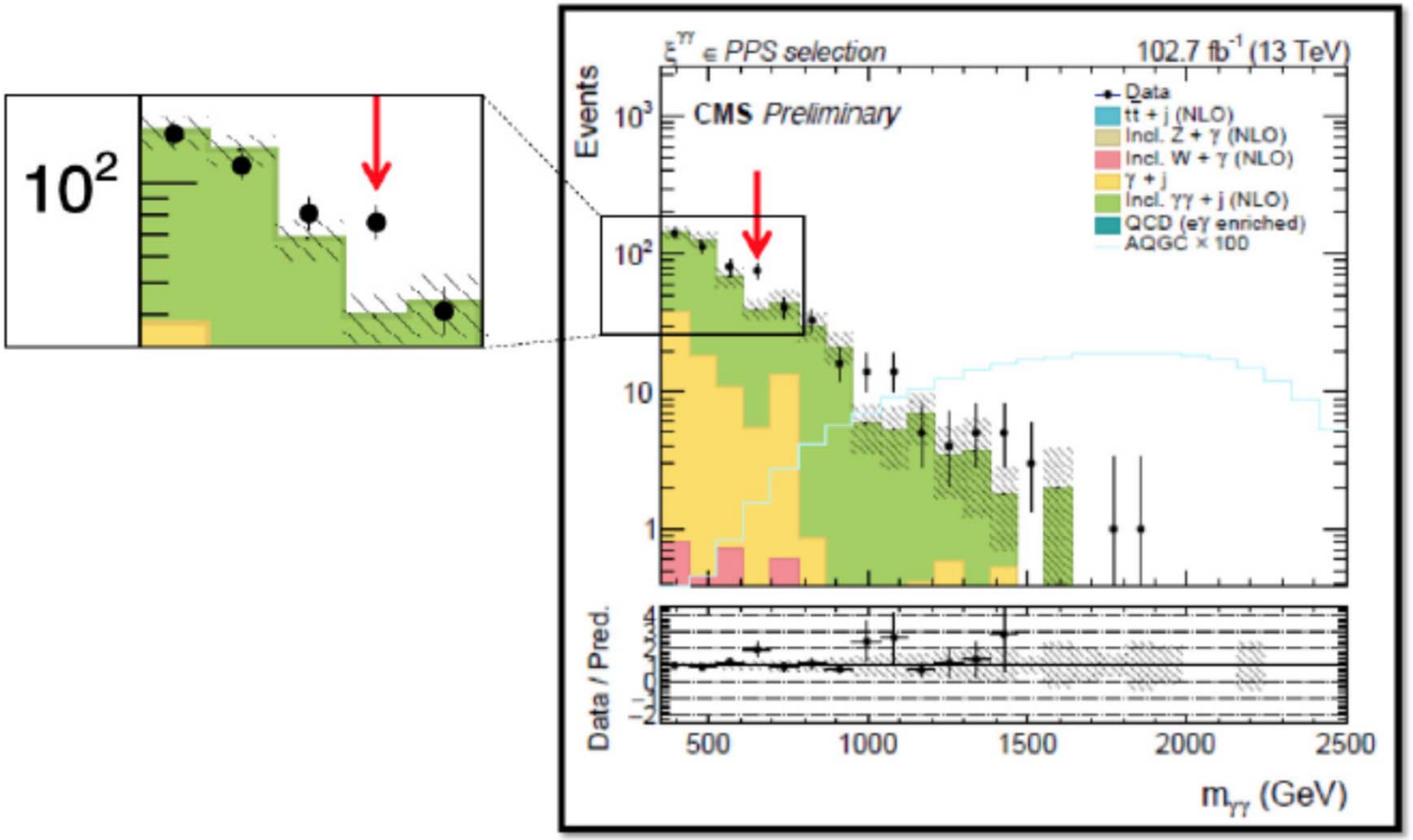
ATLAS γγ spectrum: a (local) 3.3 σ excess at E=684 GeV

see ATLAS Coll. PLB 822 (2021) 136651





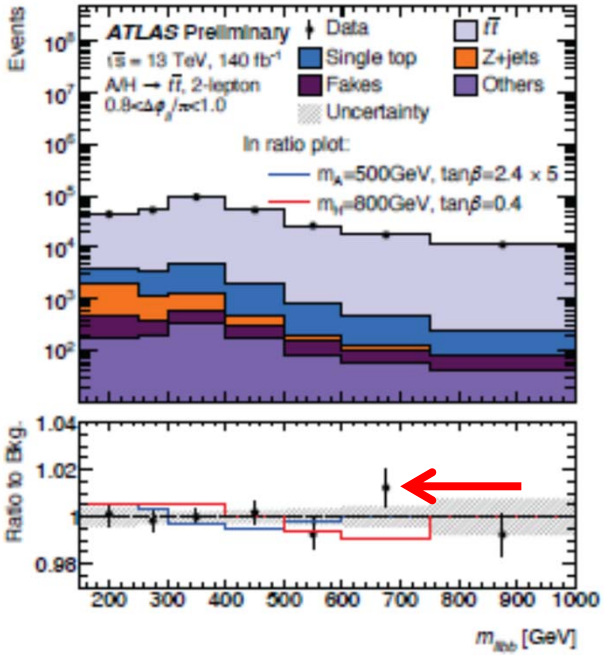
CMS-TOTEM analysis of γγ pairs produced in pp diffractive scattering (PRD 110 (2024)012010)



- For a m(γγ)= 650(40) GeV → N^{obs} = 76(9) vs. N^{Theor} = 40(8)
- This is a +3σ effect (the only significant excess in the plot)

ATLAS top-quark pair production

- Large B(H→t $\bar{t}$) ≈ 75% is expected
- Small +1σ excess observed around 675 GeV
- The effect is minuscule +1% but has exactly **the expected value** for a signal of about **1 pb** on the much larger **background of about 100 pb** (CMS: JHEP 02 (2019) 149)



(e) $0.8 < \Delta\phi_{\ell\ell} < 1.0$

Table 12: The measured differential cross section and bin boundaries for each bin of the normalized and absolute measurements of the $t\bar{t}$ differential cross section at parton level in the full phase space as a function of $m_{t\bar{t}}$ are tabulated.

$m_{t\bar{t}}$ [GeV]	$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}}$ [GeV^{-1}]	$\frac{d\sigma}{dm_{t\bar{t}}}$ [pb/GeV]
[300, 380]	$(1.981 \pm 0.036 \pm 0.18) \times 10^{-3}$	$1.664 \pm 0.031 \pm 0.163$
[380, 470]	$(3.992 \pm 0.049 \pm 0.183) \times 10^{-3}$	$3.354 \pm 0.041 \pm 0.324$
[470, 620]	$(2.009 \pm 0.023 \pm 0.057) \times 10^{-3}$	$1.688 \pm 0.019 \pm 0.122$
[620, 820]	$(6.363 \pm 0.108 \pm 0.355) \times 10^{-4}$	$0.535 \pm 0.009 \pm 0.038$
[820, 1100]	$(1.438 \pm 0.041 \pm 0.105) \times 10^{-4}$	$0.121 \pm 0.003 \pm 0.012$
[1100, 1500]	$(2.72 \pm 0.106 \pm 0.206) \times 10^{-5}$	$(2.285 \pm 0.089 \pm 0.21) \times 10^{-2}$
[1500, 2500]	$(2.45 \pm 0.24 \pm 0.464) \times 10^{-6}$	$(2.059 \pm 0.201 \pm 0.383) \times 10^{-3}$

σ ≈ 107 ± 7.6 pb

Remarks (before summarizing the data)

- With a definite mass prediction of 690 (30) GeV, one should look for deviations from the background nearby, say in the region 600 ÷ 800 GeV, so that **local deviations cannot be downgraded** by the so called "Look Elsewhere" Effect (LEE).

- With the present energy and luminosity of LHC, the second resonance is too heavy to be seen unambiguously by both collaborations in all possible channels.

- In view of the characteristic signature of the proposed resonance, statistical significance of the deviations should also consider those excess/defect sequences indicating the change of sign of the interference around a BW peak at 690(30) GeV

Conclusions

M_H values from various data sets, with symmetric error bars. Statistical significance **by combining excess/defects sequences in the expected mass range 690(30) GeV.** LEE downgrade does not apply when having a definite theoretical prediction.

• $(M_H)^{EXP} \approx$ **694 (13) GeV**	ATLAS 4-lepton data	$\approx (3 \div 4.5)\ \sigma$
• $(M_H)^{EXP} \approx$ **696 (12) GeV**	ATLAS inclusive $\gamma\gamma$ events	$\approx 3.3\sigma$
• $(M_H)^{EXP} \approx$ **692 (15) GeV**	CMS 4-lepton data	$\approx$ 2.5 σ
• $(M_H)^{EXP} \approx$ **675 (25) GeV**	ATLAS (bb+$\gamma\gamma$) events	$\approx (2.4 \div 3.4)\ \sigma$
• $(M_H)^{EXP} \approx$ **675 (75) GeV**	ATLAS top-quark pairs	$\approx 1\sigma$
• $(M_H)^{EXP} \approx$ **650 (40) GeV**	CMS-TOTEM $\gamma\gamma$ in pp diffractive	$\approx 3\sigma$

- $(M_H)^{COMB} \approx$ **680 (10) GeV**

compare with

- $(M_H)^{THEOR} =$ **690 (30) GeV**

- Dealing with different final states of two different experiments, one could try to estimate the overall statistical significance from the sum of the squares of the various σ's. The resulting values, (6.3 ÷ 7.6) σ, indicate that **the observed deviations cannot be simple statistical fluctuations**

The issue of radiative corrections

The issue of radiative corrections is discussed in the Conclusions of EPJC (2024), **84:951**; arXiv:2308.01429 [hep-ph]. For compleneless a brief summary is given here.

As an example, let us consider the corrections to the ρ-parameter from the scalar sector. A general analysis requires to separate the contributions where the large mass M_H acts as a mass from those where is traded for a coupling constant, in the 3-and 4-point vertex functions, and that prevent decoupling for very large M_H. By expressing these vertex functions as $g_3 = 3\varepsilon_1 (M_H)^2/v$ and $g_4 = 3\varepsilon_2 (M_H/v)^2$, for $\varepsilon_1 = \varepsilon_2 = 1$ there would be sizeable corrections $(M_H/v)^{2n}$ at the (n+1)-loop level. But, by constraining the scalar sector to be consistent with "triviality", observable effects far below the ultraviolet cutoff Λ will be suppressed by powers of the factor $(\varepsilon_1)^2 = \varepsilon_2 = (m_h/M_H)^2 \approx [\mathrm{Ln}(\Lambda)]^{-1}$. This factor, that would vanish in a true continuum limit, in the real world has the numerical value $(125/690)^2 \approx 0.032$ so that, for instance, the original quadratic 2-loop correction to Δρ becomes completely negligible. The only effect that remains is the 1-loop logarithm. In [2] this was discussed in connection with the works of Van der Bij (see arXiv:1711.03898 [hep-ph] and Acta Phys. Polon. B52(2021) 627) where he had been considering the effect of a Higgs-field propagator with several poles. At one loop, the various poles do not mix up and, thus, one could consider an effective mass parameter m_{eff} that somehow interpolates between the various masses. The resulting mild dependence on $\mathrm{Ln}(m_{eff})$ can then become consistent with present precision data, **provided one takes into account the known positive correlation with $\alpha_s(M_z)$ in the QCD correction, $r_{QCD}(M_z) = 1 + \alpha_s(M_z)/\pi$ …**

This positive correlation implies that if an observable points toward a small (or large) value of the effective Higgs mass, then the fit will also prefer small (or large) values of $\alpha_s(M_z)$, and viceversa. See e.g. the extreme cases in the PDG review where from the experimental set (A_{LR}, M_Z, Γ_Z, m_t) one would predict the pair [$m_{eff} = 38^{+30}_{-21}$ GeV, $\alpha_s(M_z)=0.1182(47)$] while from the other set ($A_{FB}(b,c)$, M_Z, Γ_Z, m_t) the other pair [$m_{eff} = 348^{+187}_{-124}$ GeV, $\alpha_s(M_z)=0.1278(50)$]. Therefore, for a real precision test of the pure electroweak sector, one should try to reduce the strong interaction uncertainty and not just fit $r_{QCD}(M_Z) = 1 + \alpha_s(M_z)/\pi$ …from the data. Instead, one should constrain its value at the Z-peak by extrapolating from below (PETRA, PEP, TRISTAN) and from above (LEP2).

This was done in the careful reanalysis by **P. Janot in Phys. Lett. B 594, 23 (2004),** where the known excesses were considerably reduced to $1+\delta^{low}(M_Z) = 1.0079(52)$, extrapolating from below, and $1+\delta^{high}(M_Z) = +1.015(9)$, extrapolating from above. This gives an average correction $1 + \delta^{extr.}(M_Z) = 1.0097(45)$ to the pure perturbative QCD evolution with a leading strong interaction correction (being the same for γ and Z exchange) which is

$$[r_{QCD}(M_Z)]^{extr.} = 1.0477 \pm 0.0047$$

Therefore from the PDG Z hadronic width $\Gamma(Z \rightarrow hadrons)=1744.4(2.0)$ one finds a Z width in the quark-parton model $\Gamma(Z \rightarrow q\text{-}qbar)=1665(8)$ MeV which is 2-sigma smaller than the value 1681.3 MeV obtained by Huang et al. in EPJC 81 (2021) 291 for the known top-quark mass and a Higgs mass of 125 GeV. As one can check, for the same top-quark mass, this difference of -16(8) MeV, would require an effective Higgs mass which is much larger than 125 GeV. But things are actually worse because the theoretical bare ratio $R^0 = \Gamma(Z \rightarrow q\text{-}qbar) / \Gamma(Z \rightarrow l^+l^-)$ is nearly insensitive to the top-quark and Higgs mass.

Therefore, a smaller bare width of 1665(8) MeV will produce a tension with the PDG Z leptonic width $\Gamma(Z \rightarrow l^+l^-) = 83.984(86)$ MeV which would then be too large. The moral is that if one wants to reduce the strong interaction uncertainty, by constraining $r_{QCD}(M_Z)$ from below and from above the Z peak, testing precisely the pure electroweak sector is no more obvious.

From the PDG review: i) positive M_H- $\alpha_S(M_z)$ correlation ii) vDIS not included

Table 10.7: Values of $\widehat{s}^2_Z$, s^2_W, α_s, m_t and M_H [both in GeV] for various data sets. In the fit to the LHC (Tevatron) data the α_s constraint is from the $t\bar{t}$ production [204] (inclusive jet [205]) cross-section.

Data	$\widehat{s}^2_Z$	s^2_W	$\alpha_s(M_Z)$	m_t	M_H
All data	0.23122(3)	0.22332(7)	0.1187(16)	173.0 ± 0.5	125
All data except M_H	0.23107(9)	0.22310(19)	0.1190(16)	172.8 ± 0.5	$90^{+\ 17}_{-\ 16}$
All data except M_Z	0.23113(6)	0.22336(8)	0.1187(16)	172.8 ± 0.5	125
All data except M_W	0.23124(3)	0.22347(7)	0.1191(16)	172.9 ± 0.5	125
All data except m_t	0.23112(6)	0.22304(21)	0.1191(16)	176.4 ± 1.8	125
M_H, M_Z, Γ_Z, m_t	0.23125(7)	0.22351(13)	0.1209(45)	172.7 ± 0.5	125
LHC	0.23110(11)	0.22332(12)	0.1143(24)	172.4 ± 0.5	125
Tevatron + M_Z	0.23102(13)	0.22295(30)	0.1160(45)	174.3 ± 0.7	$100^{+\ 31}_{-\ 26}$
LEP	0.23138(17)	0.22343(47)	0.1221(31)	182 ± 11	274^{+376}_{-152}
SLD + M_Z, Γ_Z, m_t	0.23064(28)	0.22228(54)	0.1182(47)	172.7 ± 0.5	$38^{+\ 30}_{-\ 21}$
$A^{(b,c)}_{FB}$, M_Z, Γ_Z, m_t	0.23190(29)	0.22503(69)	0.1278(50)	172.7 ± 0.5	348^{+187}_{-124}
$M_{W,Z}$, $\Gamma_{W,Z}$, m_t	0.23103(12)	0.22302(25)	0.1192(42)	172.7 ± 0.5	$84^{+\ 22}_{-\ 19}$
low energy + $M_{H,Z}$	0.23176(94)	0.2254(35)	0.1185(19)	156 ± 29	125

νDIS data not included by PDG

(+3σ discrepancyby NuTeV → +1.5 σ, see P. Coloma et al. JHEP04(2017) 116)

The NuTeV collaboration found $s^2_W = 0.2277 \pm 0.0016$ (for the same reference values), which was 3.0 σ higher than the SM prediction [151]. However, since then several groups have raised concerns about the interpretation of the NuTeV result, which could affect the extracted $g^2_{L,R}$ (and thus s^2_W) including their uncertainties and correlation. These include the assumption of symmetric strange and anti-strange sea quark distributions, the electron neutrino contamination from K_{e3} decays, isospin symmetry violation in the parton distribution functions and from QED splitting effects, nuclear shadowing effects, and a more complete treatment of EW and QCD radiative corrections. A more detailed discussion and a list of references can be found in the 2016 edition of this *Review*. The precise impact of these effects would need to be evaluated carefully by the collaboration, but in the absence of such an effort we do not include the νDIS constraints in our default set of fits.