Experimental signals for a second resonance of the Higgs field

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References:

M.C., L. Cosmai, Int. J. Mod. Phys. A35 (2020) 2050103; hep-ph/2006.15378

M.C., L. Cosmai, Symmetry 12 (2020) 2037; doi:103390/sym12122037

M.C. , in Veltman Memorial Volume, Acta Phys. Pol. B52 (2021) 763; hep-ph/2106.06543

M.C., L. Cosmai, arXiv:2111.08962 [hep-ph], November 2021

Abstract

A) Today, at the end of RUN2, there are the following indications (slides 1-15)

i) ATLAS+CMS(50% statistics) 4-lepton data in the range of invariant mass 650÷710 GeV, give a **3-sigma excess** over the estimated background. It indicates a new (relatively narrow) resonance of mass $\mathbf{m_{4l}=(M_H)^{EXP} \approx 670 \div 680}$ **GeV**

ii) ATLAS 2-gamma data also indicate **a 3-sigma excess** for $\mathbf{m_{\gamma\gamma} = (M_H)^{EXP} \approx 680}$ **GeV**

iii) With **two 3-sigma effects** in two different channels → probability of accidental coincidence is now at 4-sigma level

B) This mass range is consistent with the prediction of a second resonance of the Higgs field $\mathbf{(M_H)^{THEOR} = 690 \pm 10}$ **(stat)** $\pm$ **20 (sys) GeV** **(slides 16-27)**

C) By refining the analysis of the ATLAS 4-lepton data, the hypothetical new

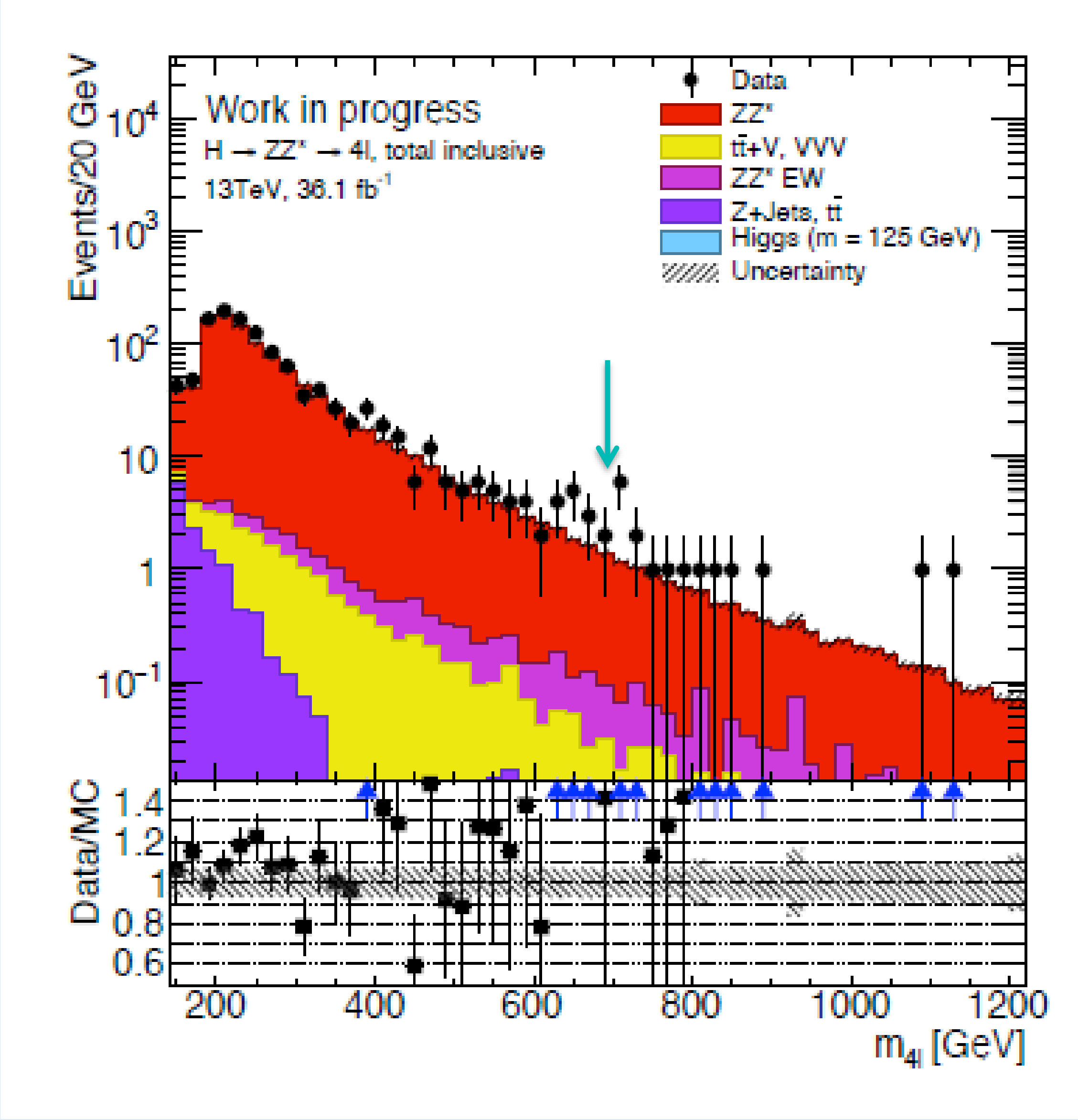
$\mathbf{M_H \approx 680}$ **GeV and the mass** $\mathbf{m_h}$ **=125 GeV are further correlated as expected** if M_H were the second resonance of the Higgs field **(slides 28-39).** This correlation eliminates the spin-zero vs. spin-2 ambiguity

D) CONCLUSION: **with the present 100% CMS 4-lepton events**, the issue could be settled now (5-sigma level), **before the start of RUN3** **(slide 40)**

P.S. A final remark on the effect of a two-mass structure on radiative corrections **(slides 41-46)**

ATLAS 4-lepton events : Lum= 36.1 fb$^{(-1)}$

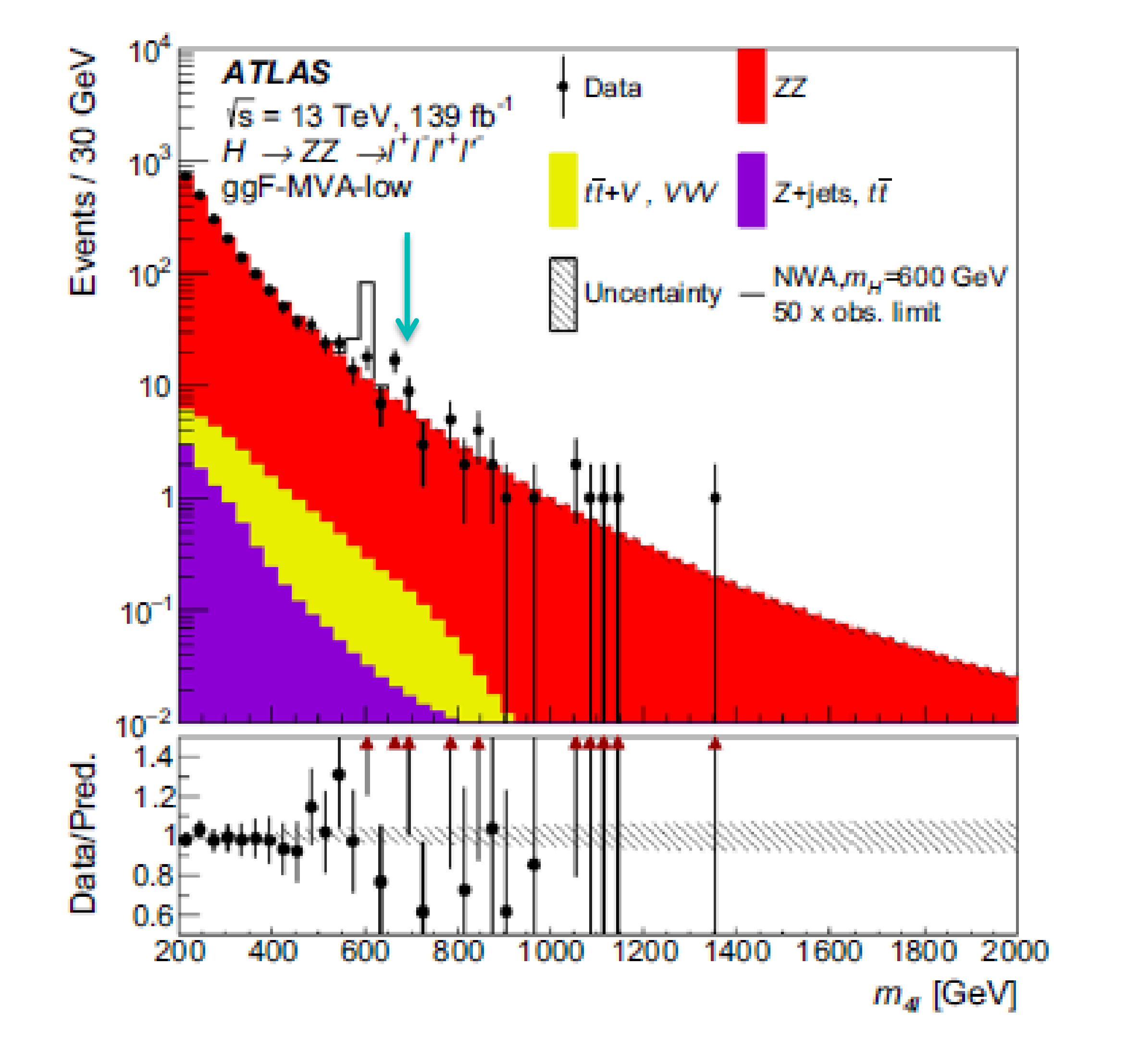
Local p0 → 3.6 σ excess around 700 GeV: D. Denysiuk's 2017 PhD thesis, https://tel.archives-ouvertes.fr/tel-01681802v2.



ATLAS 4-lepton events: LUM=139 $fb^{(-1)}$

$\langle N_{meas}\rangle$= 26(5) for E=650÷710 GeV vs. $N_B \approx 13$ → 2.6 σ excess

Relatively narrow resonance at 680 GeV (fast decrease of number of events)



CMS 4-lepton data: full LUM=137 fb$^{(-1)}$

- Relevant data in a single bin 600÷800 GeV.
- No hint on a localized effect near 680 GeV
- Look at lower-statistics samples

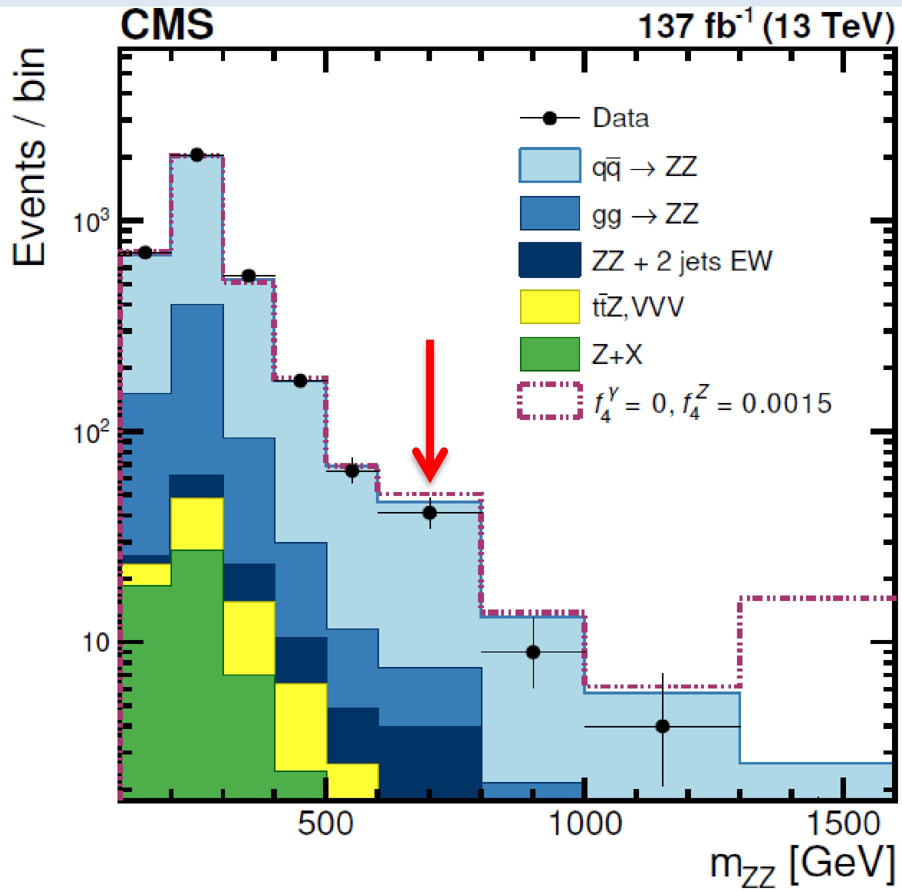
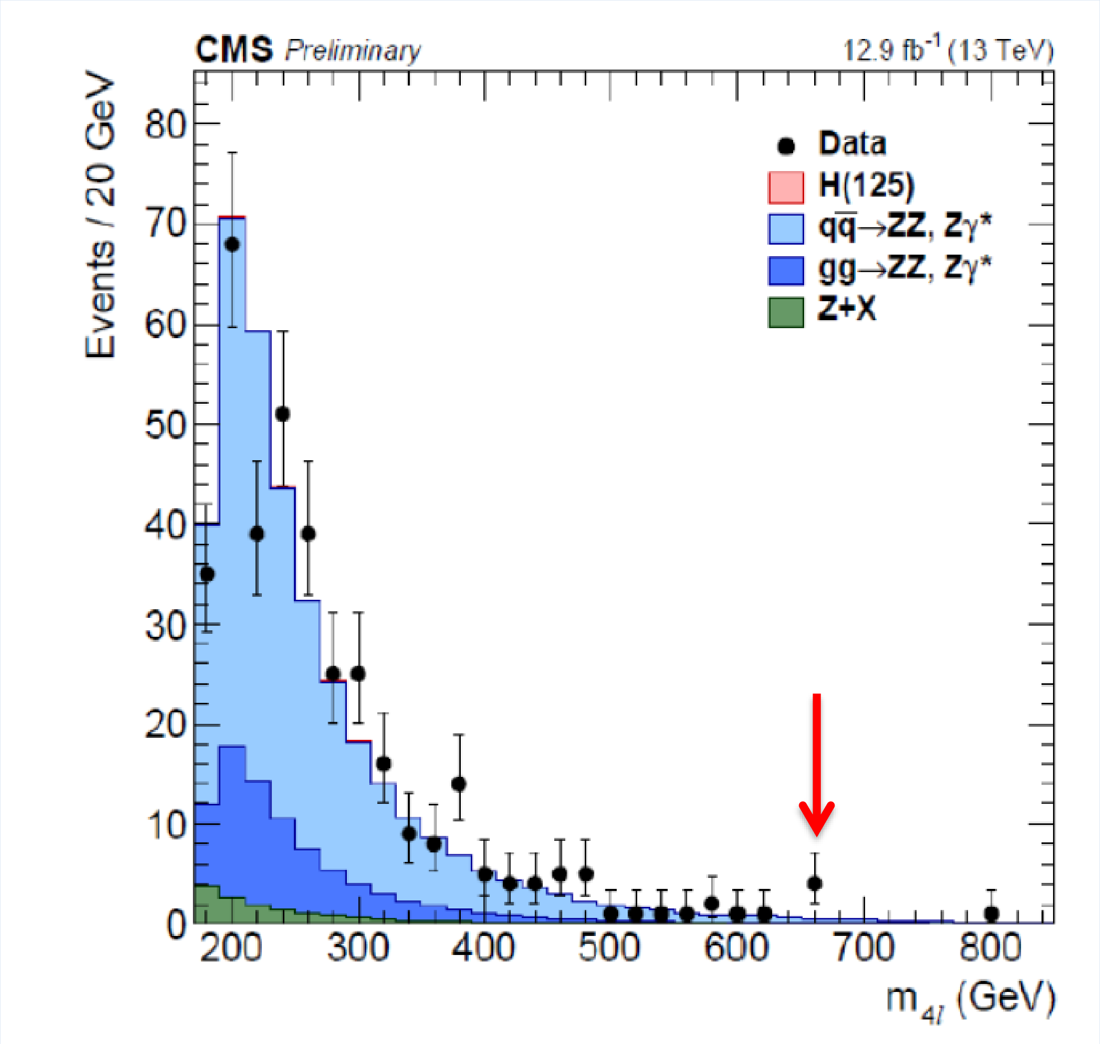


Figure 7: Distribution of the reconstructed ZZ mass for the combined 4e, 2e2μ, and 4μ channels. Points represent the data with error bars showing the statistical uncertainties, the shaded histograms represent the SM prediction including signal and irreducible background from simulation, and the reducible background estimate from data. Dashed histogram represents an example of the aTGC signal. The last bin includes contribution from all events with mass above 1300 GeV.

First CMS sample showing an excess of 4-lepton events at 660(10) GeV → $\langle N_{meas} \rangle = 4$ vs. $N_B \approx 0.45$



- In spite of its small statistics this picture will be useful to compare ATLAS and CMS background estimates

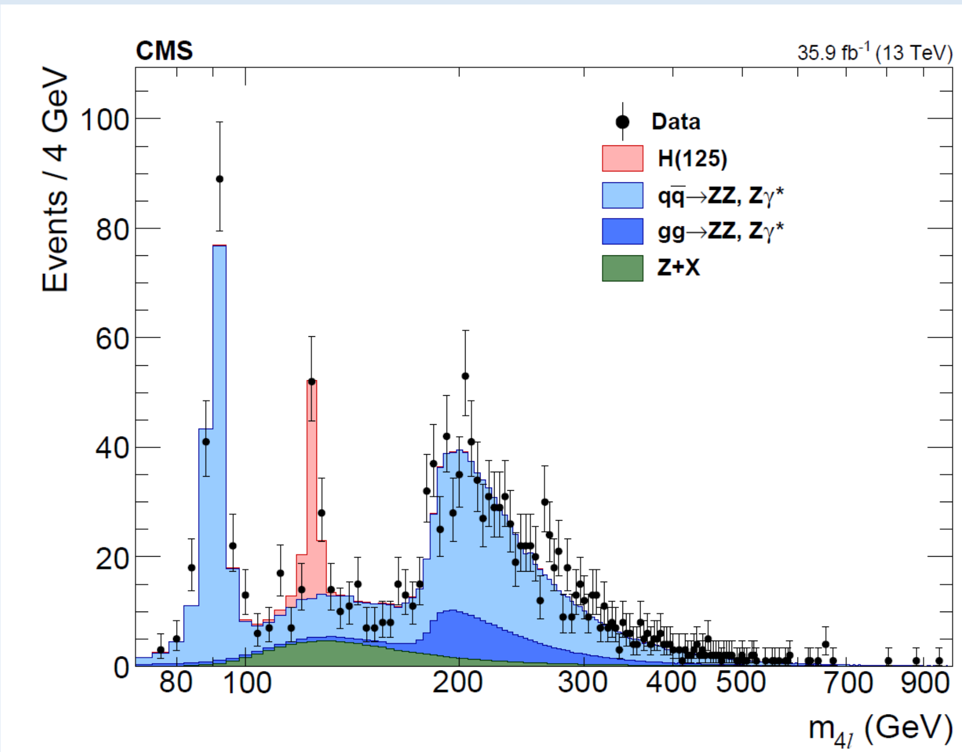
- At that energy, for 12.9 $fb^{(-1)}$ and 20 GeV bin, it implies $N_B \approx 7.3$ for 139 $fb^{(-1)}$ and a 30 GeV bin, in excellent agreement with ATLAS value $N_B \approx 7.2$

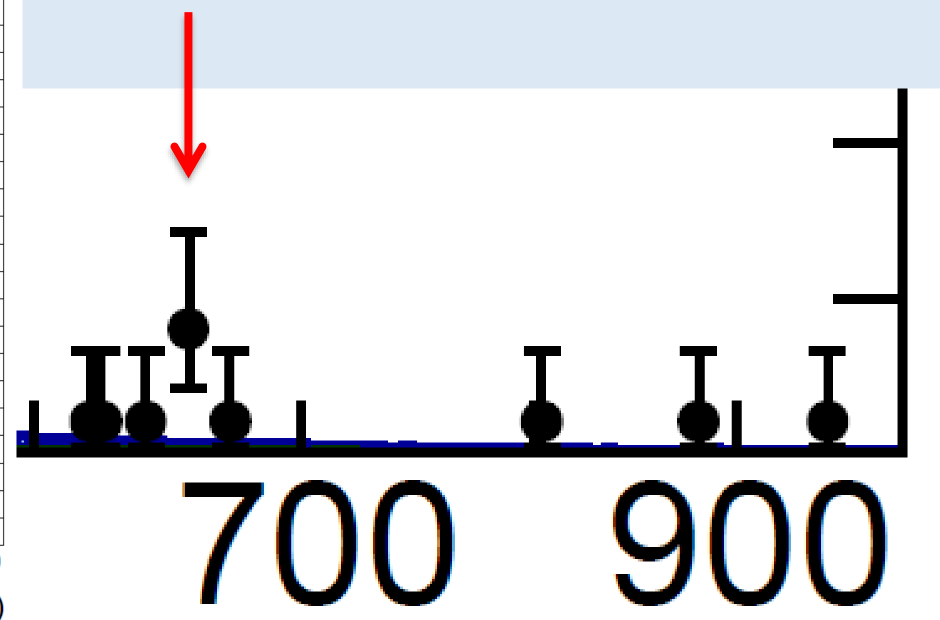
JHEP11(2017)047;arXiv:1706.09936[hep-ex]

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

about 3 times more events than expected at 660(15) GeV

$\langle N_{BKG}\rangle \approx 1.9$ $\langle N_{meas}\rangle = 6$

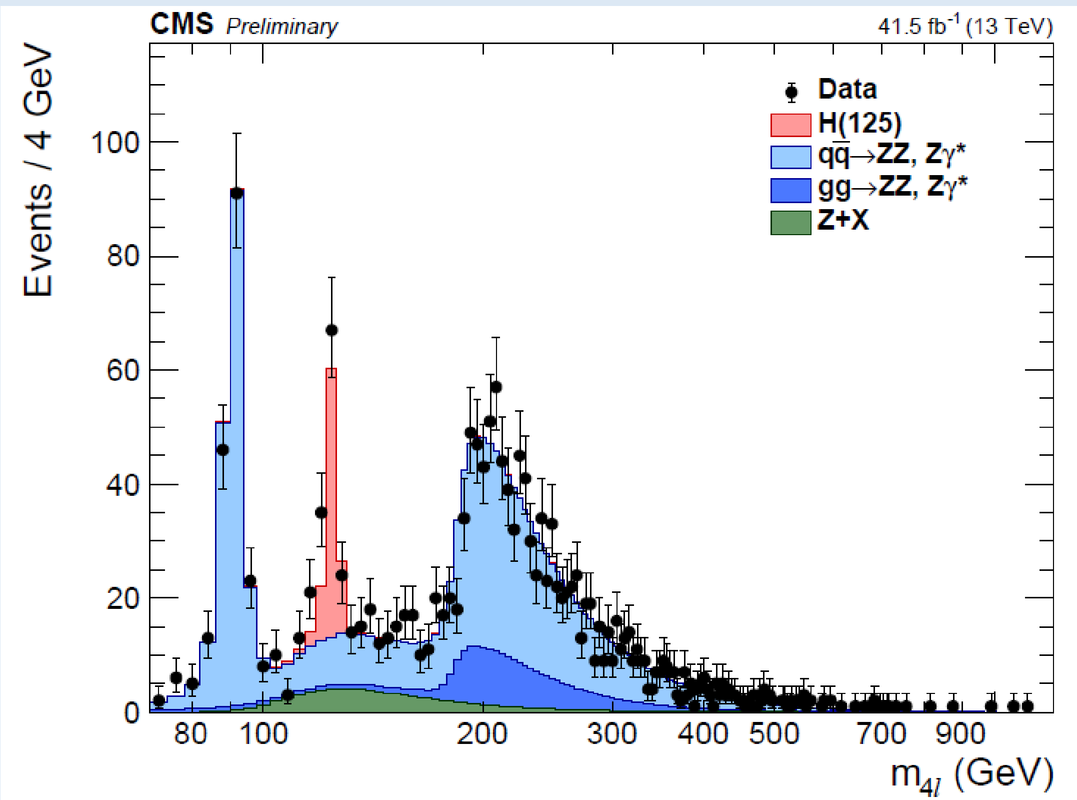


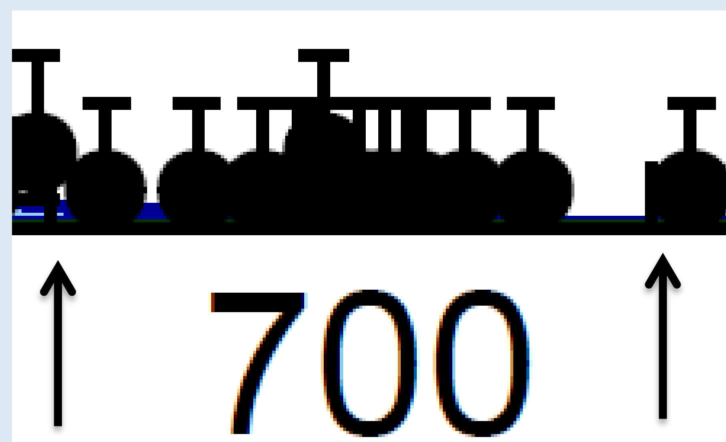


CMS PAS HIG-18-001, 2018/06/03

CMS 2017 data: Lum = 41.5 fb$^{(-1)}$

(inset 600÷800 GeV)

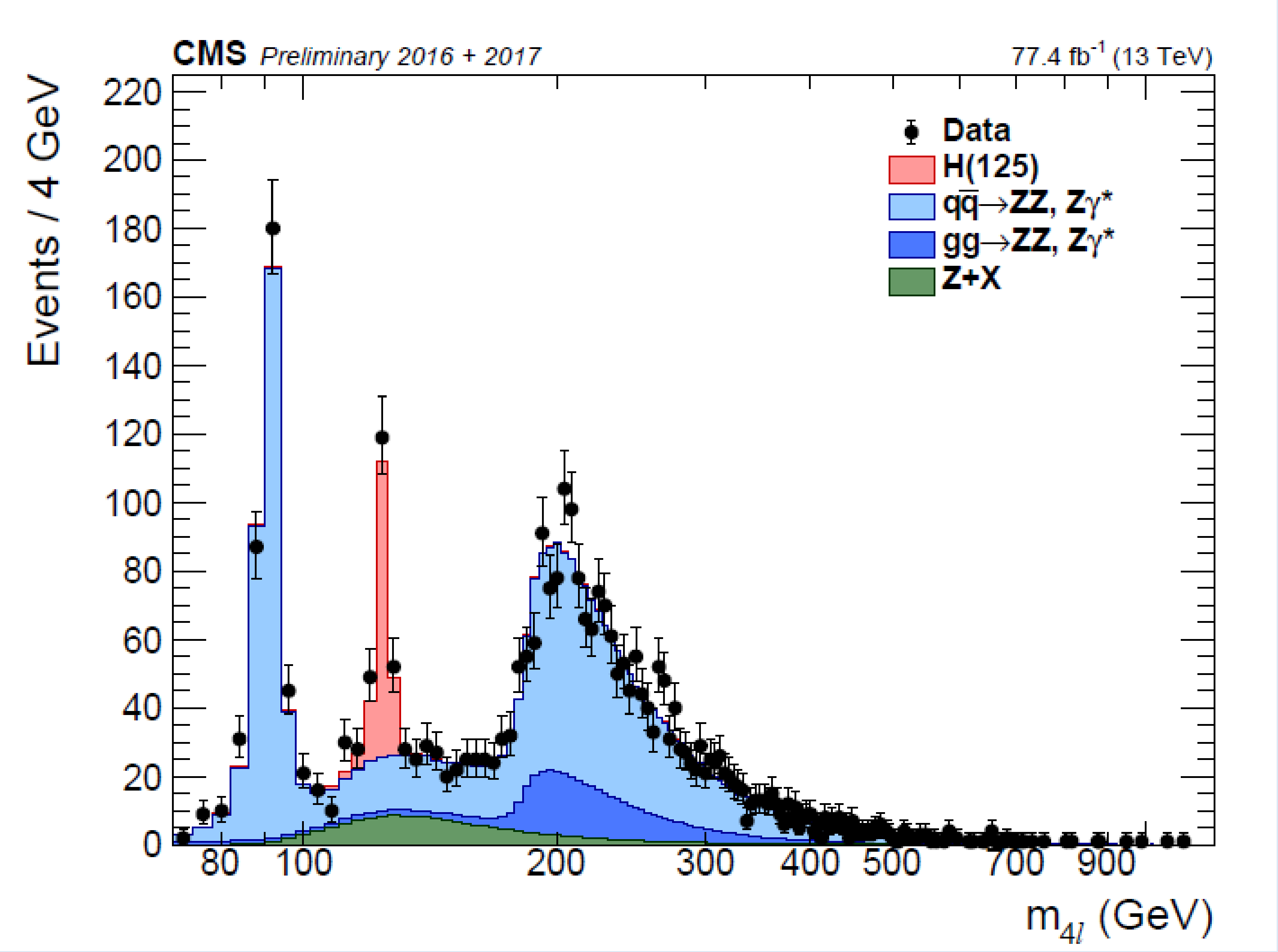




CMS PAS HIG-18-001,2018/06/03

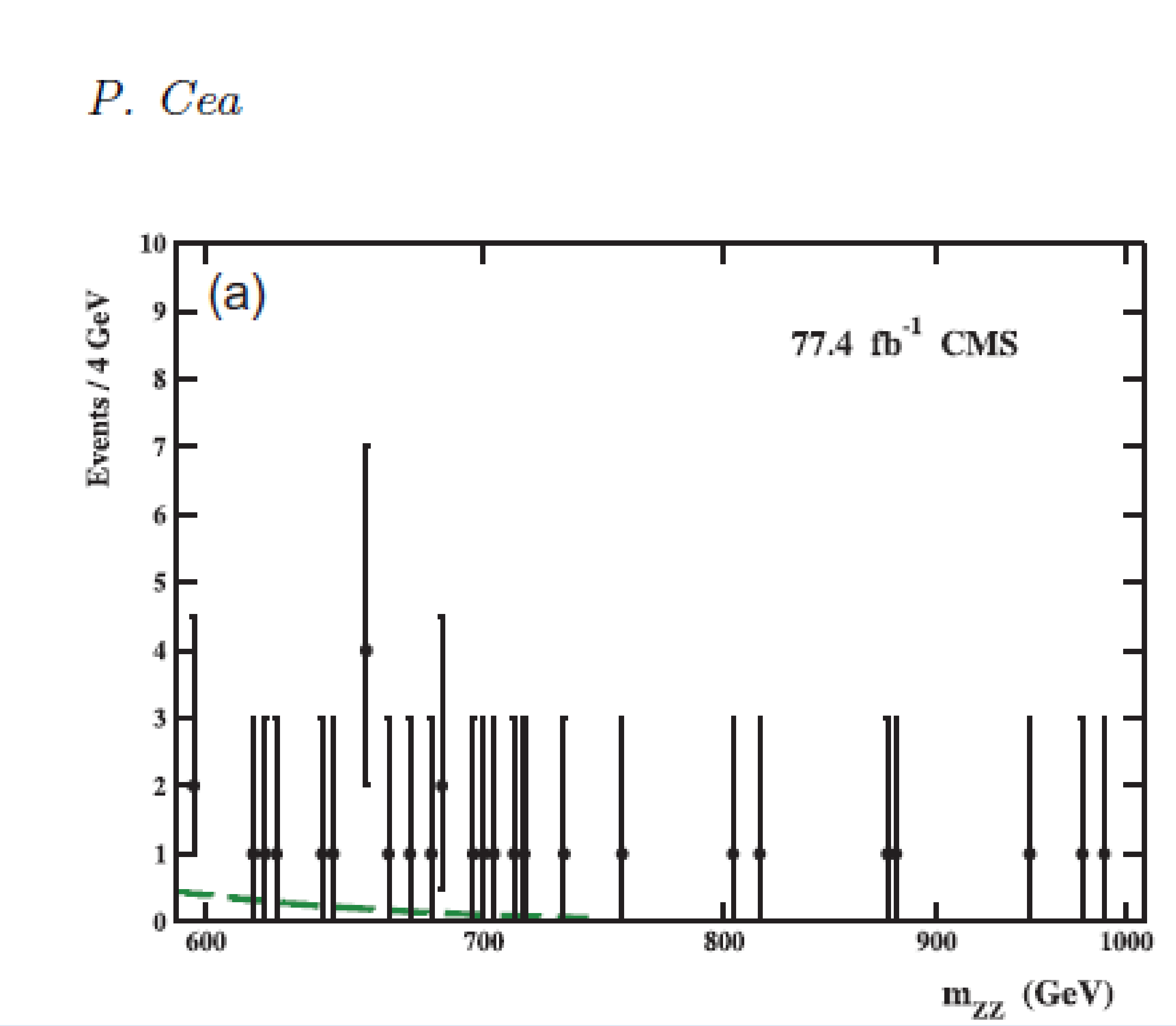
4-lepton CMS 2016+2017 Lum = 77.4 fb$^{(-1)}$

Largest CMS sample scanning around 680 GeV but … how to read it?



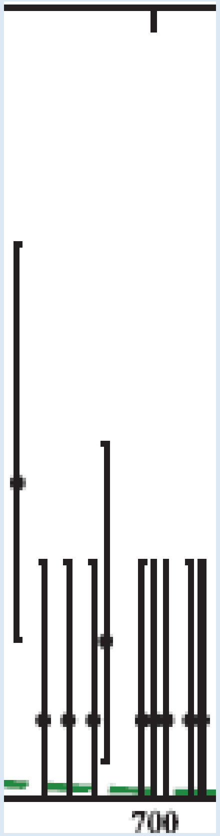
Cea’s extraction of the 2016+2017 CMS data

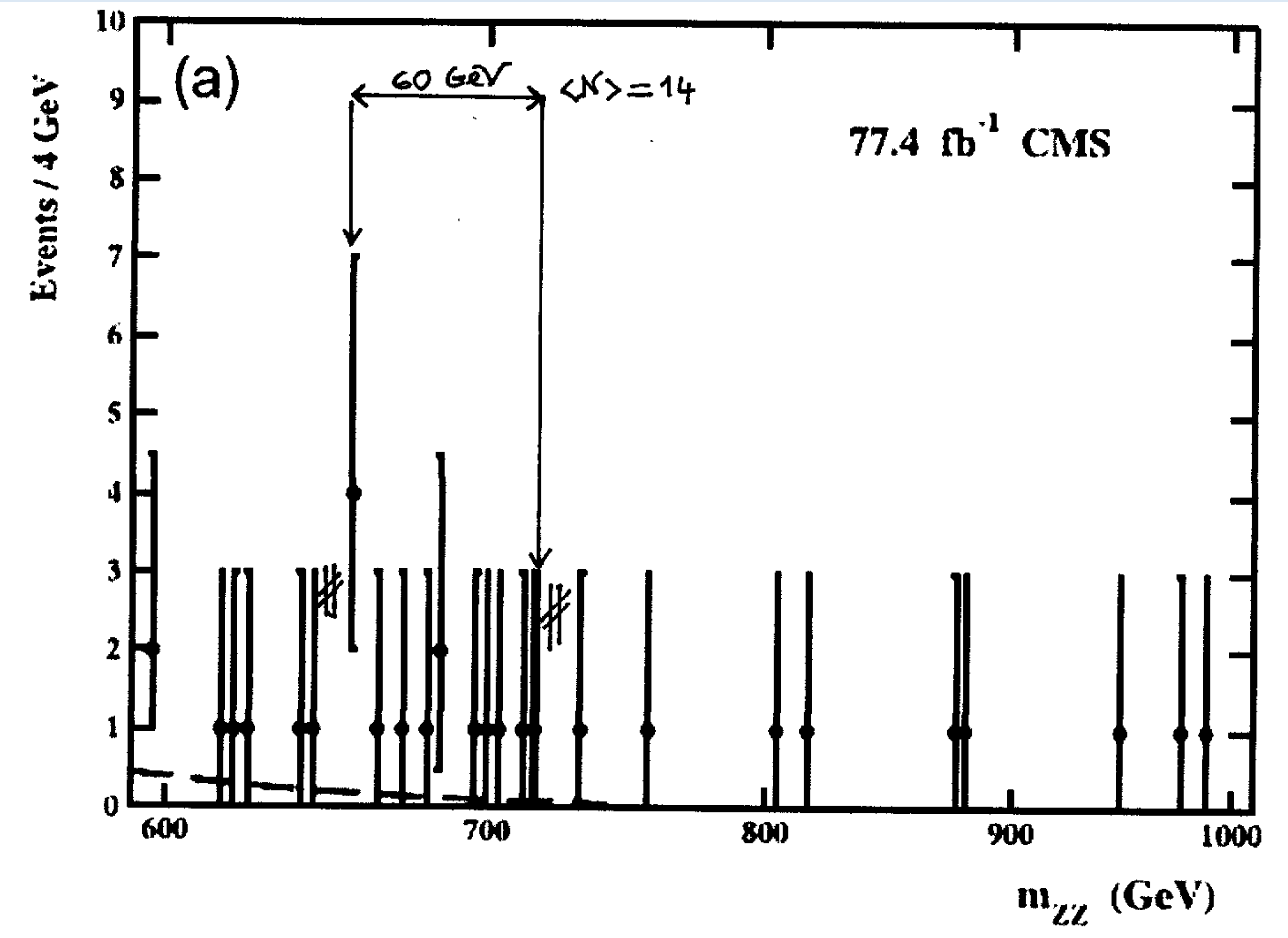
MPLA 34(2019)1950137



CMS 77.4 $fb^{(-1)}$: bin of 60 GeV as for ATLAS

(for **E ≈ 685(30) GeV** the value ‹N(4l)› **=14** → no overlap with neighboring points)





Consistency of ATLAS vs. CMS 4-lepton data

(for the central region of 60 GeV exhibiting the excess of events)

Table 2: *We report the total number of 4-lepton events, observed by ATLAS and CMS, for two central regions of 60 GeV corresponding to an excess of events. The CMS bin was obtained from Fig.9 of [29] by using the expanded picture reported in Fig.1a) of [30]. This bin choice eliminates any uncertainty due to possible overlap with neighboring points. Notice the very good agreement when re-scaling the CMS events by the ratio (139/77.4)=1.8.*

	E[GeV]	LUM[fb^{-1}]	$N_{obs}(4l)$
ATLAS	680(30)	139	26(5)
CMS	685(30)	77.4	14(4)

Comparison: DATA (ATLAS+CMS) Vs. Background

ATLAS	$E \approx 680(30)$ GeV	$N(4l) = 26\ (5)$
CMS	$E \approx 685(30)$ GeV	$N(4l) = 14\ (4)$

i) Comparison with ATLAS **Expected** Background for 139 fb^{-1}

$$(N_B)^{Expected} \approx 7.19 \rightarrow 665(15)\ \text{GeV}$$
$$(N_B)^{Expected} \approx 5.85 \rightarrow 695(15)\ \text{GeV}$$

ii) Comparison with CMS **Expected** Background for 77.4 fb^{-1}

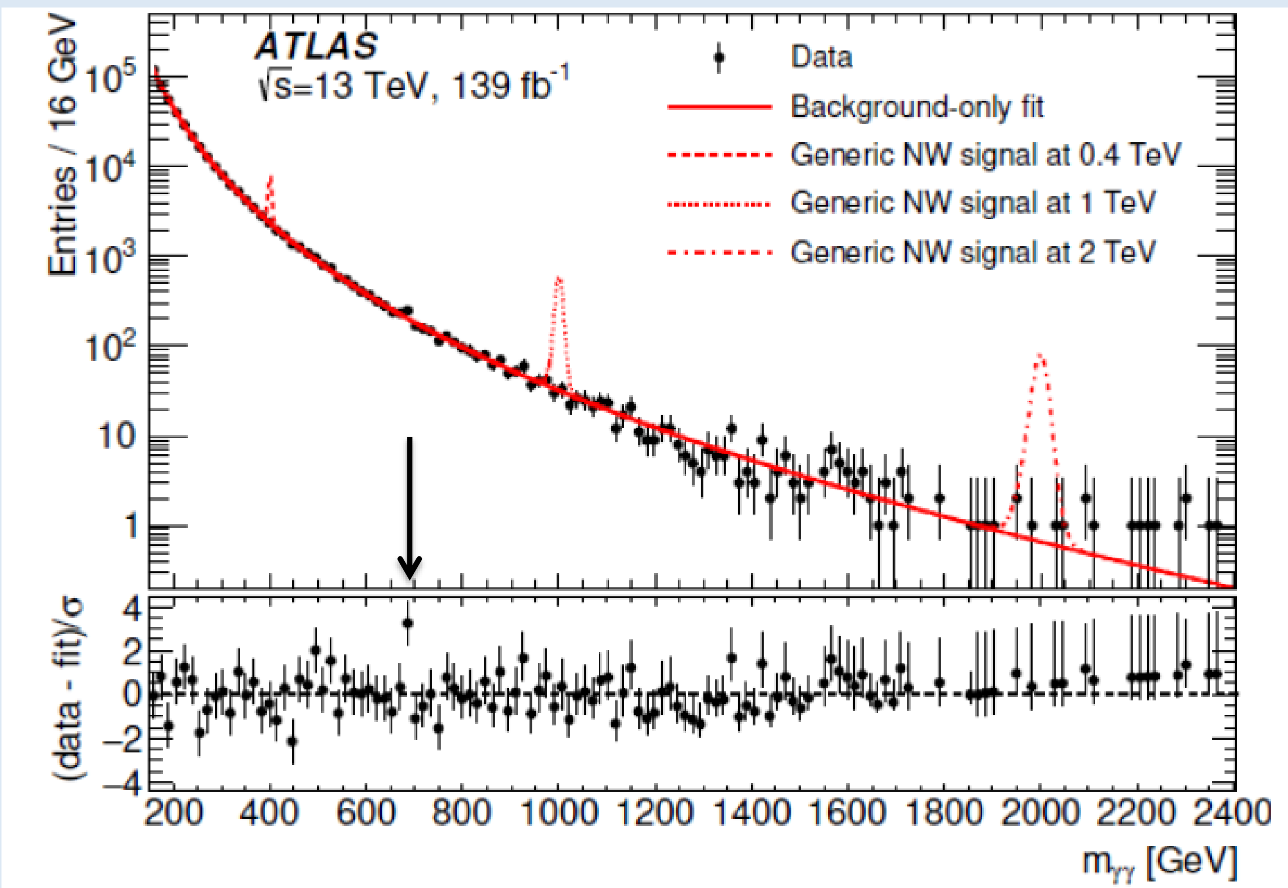
$$(N_B)^{Expected} \approx 4.00 \rightarrow 670(15)\ \text{GeV}$$
$$(N_B)^{Expected} \approx 3.26 \rightarrow 700(15)\ \text{GeV}$$

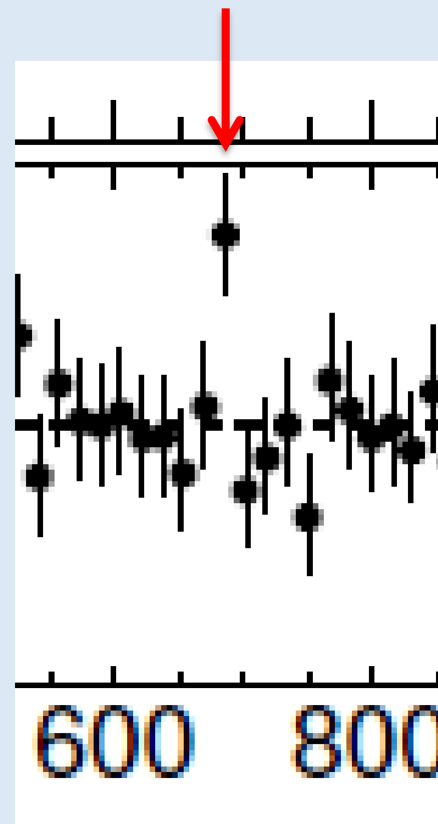
Total LUM=ATLAS 139 fb^{-1} + CMS 77.4 fb^{-1} = 216.4 fb^{-1}

N^{meas}(ATLAS+CMS)	N_B(Expected)	Excess(σ)
40(6.4)	**20.3**	**3.1**

ATLAS 2-gamma spectrum:

again a 3σ excess at E=680 GeV





Results of this first phenomenological analysis

- **TWO 3σ effects** in the 4-lepton and 2-gamma channels point toward a new (relatively narrow) resonance with mass of about 680 GeV

- Probability of an accidental fluctuation at the 4-sigma level

- Consistency with the prediction of a (relatively narrow) **second resonance of the Higgs field with mass $M_H = 690 \pm 10 \pm 20$ GeV**

- Check with a more refined analysis if the hypothetical new resonance around 680 GeV **shows the expected correlation with the small $m_h = 125$ GeV mass**

- Some theoretical background about: i) the existence of the second resonance

  ii) its basic phenomenology

Presently accepted view: the mass spectrum of the Higgs field consists of a single narrow resonance of mass **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

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

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

A new 700 GeV resonance of the Higgs field? → SSB induced by the pure scalar sector (W,Z, top-quark irrelevant)

With gauge bosons, SSB is a weak first-order phase transition (Coleman-Weinberg)

But from lattice simulations of pure Φ^4 → SSB is also a weak first-order phase transition

Imposing a first-order transition: known forms of $V_{eff}(\varphi)$ have 2 mass scales:

$\mathbf{m_h}$ and $\mathbf{M_H}$

$\mathbf{m_h}$ from $V''_{eff}(\varphi= \pm v)$ is a low-p mass. $\mathbf{M_H}$ from zero-point energy is a higher-p mass. Scaling different with cutoff $\boldsymbol{\Lambda}$

$$\mathbf{M^2_H \approx m^2_h \ln (\Lambda/ M_H) >> m^2_h}$$

$\mathbf{m_h \neq M_H}$ → the propagator G(p) has not a simple one-pole form

But for $\Lambda\to\infty$ a one-pole G(p): "triviality" ($\mathbf{M_H}$ decouples for finite $\mathbf{m_h}$ or, for finite $\mathbf{M_h}$, the vanishingly small $\mathbf{m_h}$ describes only the zero-measure set p=0)

Lattice simulations of G(p) support the two-mass structure and the expected scaling law

$$\mathbf{M^2_H \approx m^2_h \ln (\Lambda/ M_H)}$$

Thus, for $\Lambda\to\infty$, differently from $\mathbf{m_h}$, $\mathbf{M_H}$ remains finite in unit of $\langle\boldsymbol{\Phi}\rangle \approx 246$ GeV → $\mathbf{M_H= K \langle\Phi\rangle}$

Combining the leading order $\mathbf{m_h} - \langle\boldsymbol{\Phi}\rangle$ relation with the lattice data for the ratio $\mathbf{m_h / M_H}$ → K=2.80±0.04±0.08 or $\mathbf{M_H}$ = 690±10±20 GeV

SSB in **cutoff Φ^4** → weak first-order phase transition (see P.H. Lundow and K. Markstroem, PRE80(2009)031104; NPB845(2011)120) picture below from S. Akiyama et al. PRD100(2019)054510)

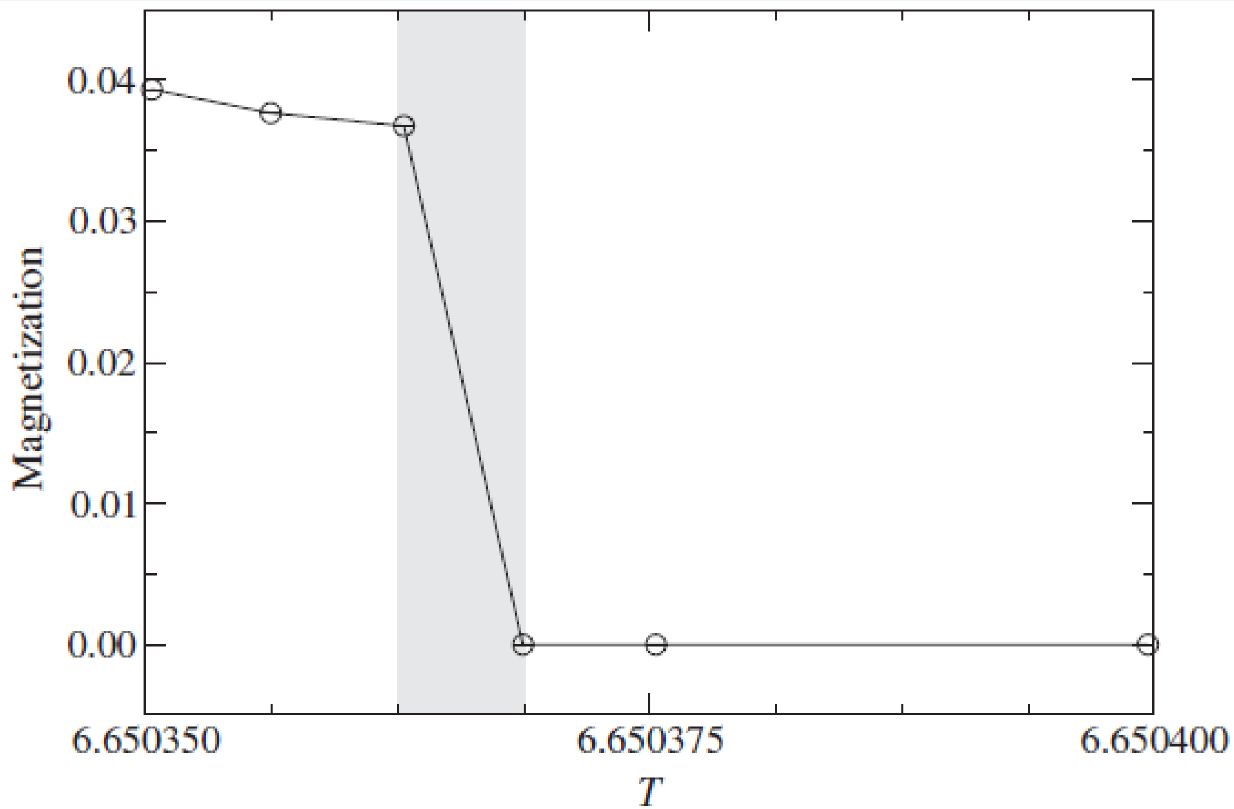


FIG. 7. Spontaneous magnetization in the thermodynamic limit with $D_{\mathrm{cut}} = 13$. Error bars, provided by extrapolation, are within symbols. $T_{\mathrm{c}}(D_{\mathrm{cut}} = 13)$ estimated by $X^{(n)}$ of Eq. (15) is within the gray band.

Simplest approximations to (pure) Φ^4 where SSB is weakly 1st-order: 1-loop and Gaussian potential → 2 mass scales:

$\mathbf{m_h}$ from quadratic shape of $\mathbf{V_{eff}(\varphi = \pm v)}$ and $\mathbf{M_H}$ from zero-point energy

By introducing the mass-squared parameter $M^2(\varphi) \equiv \frac{1}{2}\lambda\varphi^2$, the 1-loop potential can be expressed as a classical background + zero-point energy of a particle with mass $M(\varphi)$, i.e.

$$V_{1-\text{loop}}(\varphi) = \frac{\lambda\varphi^4}{4!} - \frac{M^4(\varphi)}{64\pi^2}\ln\frac{\Lambda_s^2\sqrt{e}}{M^2(\varphi)} \qquad (9)$$

Thus, non-trivial minima of $V_{\text{eff}}(\varphi)$ occur at those points $\varphi = \pm v$ where

$$M_H^2 = \frac{\lambda v^2}{2} = \Lambda_s^2 \exp(-\frac{32\pi^2}{3\lambda}) \qquad (10)$$

with a quadratic shape

$$m_h^2 \equiv V''_{1-\text{loop}}(\pm v) = \frac{\lambda^2 v^2}{32\pi^2} = \frac{\lambda}{16\pi^2}M_H^2 \sim \frac{M_H^2}{L} \ll M_H^2 \qquad (11)$$

where $L \equiv \ln\frac{\Lambda_s}{M_h}$. Notice that the energy density depends on M_h and *not* on m_h, because

$$\mathcal{E}_{1-\text{loop}} = V_{1-\text{loop}}(\pm v) = -\frac{M_H^4}{128\pi^2} \qquad (12)$$

therefore the critical temperature at which symmetry is restored, $k_B T_c \sim M_H$, and the stability of the broken phase depends on the larger M_H and not on the smaller m_h.

$$V_G(\varphi) = \frac{\hat\lambda\varphi^4}{4!} - \frac{\Omega^4(\varphi)}{64\pi^2}\ln\frac{\Lambda_s^2\sqrt{e}}{\Omega^2(\varphi)}$$

$$\hat\lambda = \frac{\lambda}{1 + \frac{\lambda}{16\pi^2}\ln\frac{\Lambda_s}{\Omega(\varphi)}}$$

$$\Omega^2(\varphi) = \frac{\hat\lambda\varphi^2}{2}$$

$$M_H^2 = \Omega^2(v)$$

$$\mathcal{E}_G = V_G(\pm v) = -\frac{M_H^4}{128\pi^2}$$

In both approximations

$$m_h^2 \equiv V''_{\text{eff}}(\pm v) \sim \frac{M_H^2}{L} \ll M_H^2$$

$m_h \neq M_H$ → propagator G(p) has not a single-pole structure

m_h^2, being $V''_{\rm eff}(\varphi)$ at the minimum, is directly the 2-point, self-energy function $|\Pi(p=0)|$.

On the other hand, the Zero-Point Energy (ZPE) is (one-half of) the trace of the logarithm of the inverse propagator $G^{-1}(p) = (p^2 - \Pi(p))$. After subtracting constant terms and quadratic divergences, matching the 1-loop zero-point energy at the minimum gives the relation

$$ZPE \sim -\frac{1}{4}\int_{p_{\rm min}}^{p_{\rm max}} \frac{d^4p}{(2\pi)^4}\frac{\Pi^2(p)}{p^4} \sim -\frac{\langle \Pi^2(p)\rangle}{64\pi^2}\ln\frac{p^2_{\rm max}}{p^2_{\rm min}} \sim -\frac{M_H^4}{64\pi^2}\ln\frac{\Lambda_s^2}{M_H^2} \qquad (3)$$

This shows that M_H^2 effectively refers to some average value $|\langle \Pi(p)\rangle|$ at larger p^2.

→ Therefore, if $m_h \neq M_H$, there must be a non-trivial momentum dependence of $\Pi(p)$ ←

Check with lattice simulations of the scalar propagator.

Lattice simulations of the scalar propagator

Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Nuclear Physics B 729 [FS] (2005) 542–557
NUCLEAR PHYSICS B

Comparison of perturbative RG theory with lattice data for the 4d Ising model

P.M. Stevenson

$$S = \sum_x \left[-2\kappa \sum_{\mu=1}^{4} \phi(x)\phi(x+\hat{\mu}) + \phi(x)^2 + \lambda\big(\phi(x)^2 - 1\big)^2 \right], \tag{1}$$

which is equivalent to the more traditional expression

$$S = \sum_x \left[\frac{1}{2} \sum_{\mu=1}^{4} \big(\partial_\mu \phi_0(x)\big)^2 + \frac{1}{2} m_0^2 \phi_0(x)^2 + \frac{g_0}{4!}\phi_0^4 \right], \tag{2}$$

where $\partial_\mu \phi_0(x) = \phi_0(x+\hat{\mu}) - \phi_0(x)$. The translation between the two formulations is given by

$$\phi_0 = \sqrt{2\kappa}\,\phi, \qquad m_0^2 = \frac{(1-2\lambda)}{\kappa} - 8, \qquad g_0 = \frac{6\lambda}{\kappa^2}. \tag{3}$$

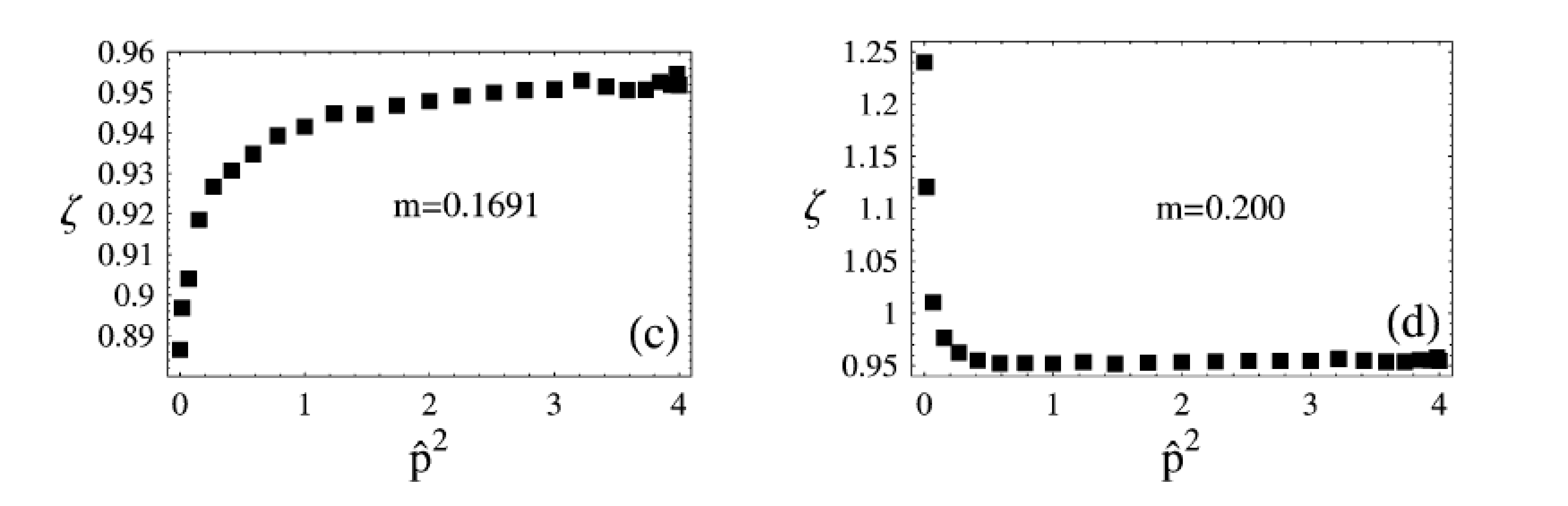
Stevenson's analysis of the lattice propagator
(data from Balog, Duncan, Willey, Niedermeyer, Weisz NPB714(2005)256)

For κ=0.0751 in the broken phase, he reports the rescaled propagator.

$$\zeta \equiv (\hat{p}^2 + m^2)G(p)$$

Standard one-pole propagator → ζ has a flat profile

Left: re-scaling with the mass 0.1691 from the p=0 limit
Right: re-scaling with the mass giving a flat profile at larger p^2



Lattice Checks

(M.C. and Leonardo Cosmai, Int. J. Mod. Phys. A35 (2020) 2050103; hep-ph/2006.15378

- A consistency check: no two-mass structure in the symmetric phase

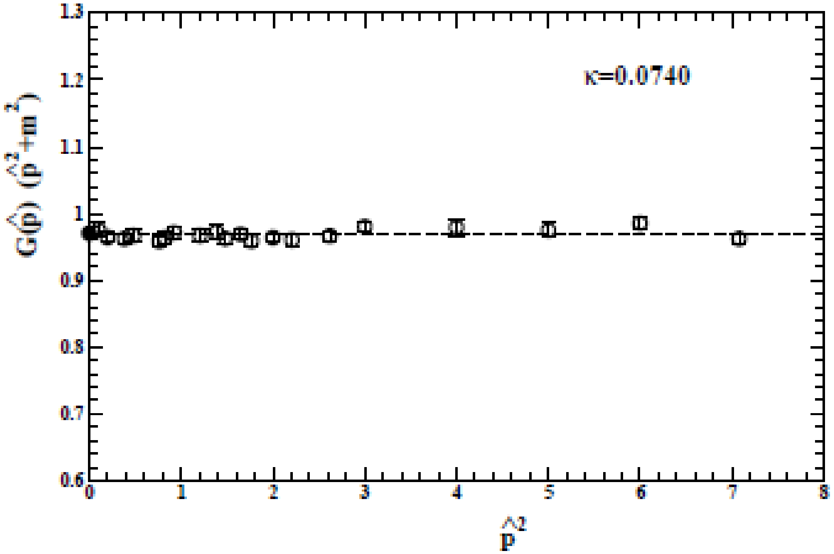
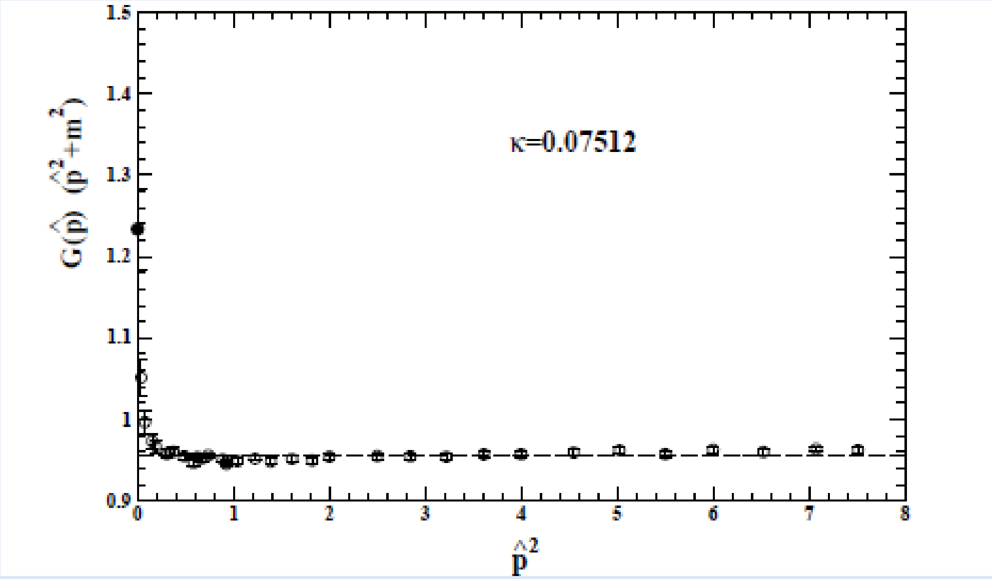
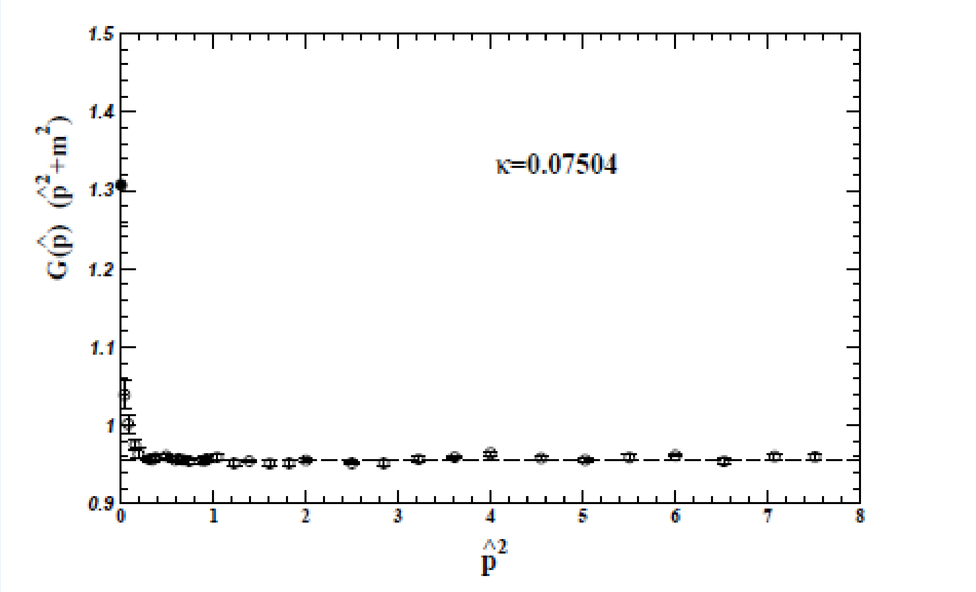


Figure 1: *The lattice data of ref.[8] for the re-scaled propagator in the symmetric phase at* $\kappa = 0.074$ *as a function of the square lattice momentum* $\hat{p}^2$. *The fitted mass from high* $\hat{p}^2$, $m_{\rm latt} = 0.2141(28)$, *describes well the data down to* $\hat{p} = 0$. *The dashed line indicates the value of* $Z_{\rm prop} = 0.9682(23)$ *and the* $\hat{p} = 0$ *point is* $2\kappa\chi m^2_{\rm latt} = 0.9702(91)$.

Lattice propagator in the broken phase

(P.Cea., M.C, L.Cosmai, P.M.Stevenson, MPLA14(1999)1673





Propagator on a 76^4 lattice: 2 flat ranges→2 mass-shell regions

(M.C. and L.Cosmai, IJMP A35 (2020) 2050103; hep-ph/2006.15378

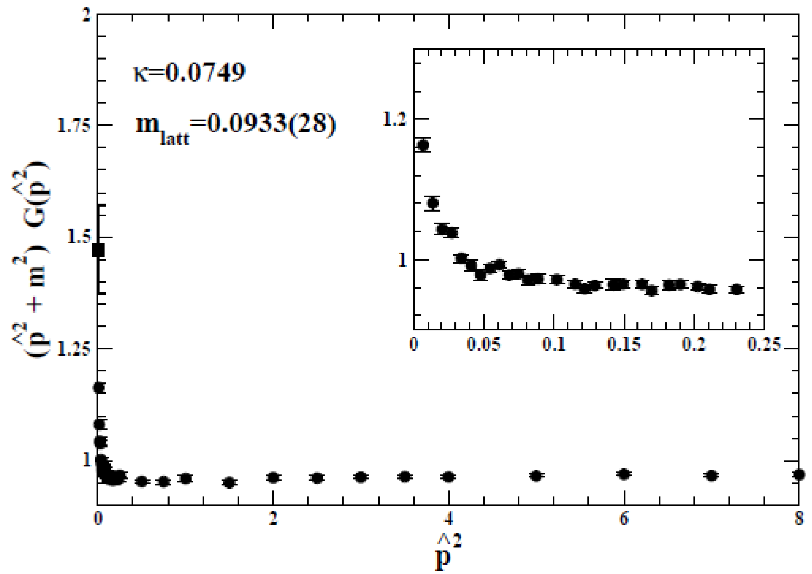


Figure 2: *The propagator data of ref.[8], for* $\kappa = 0.0749$, *rescaled with the lattice mass* $M_H \equiv m_{\rm latt} = 0.0933(28)$ *obtained from the fit to all data with* $\hat{p}^2 > 0.1$. *The peak at* $p = 0$ *is* $M_H^2/m_h^2 = 1.47(9)$ *as computed from the fitted* M_H *and* $m_h = (2\kappa\chi)^{-1/2} = 0.0769(8)$.

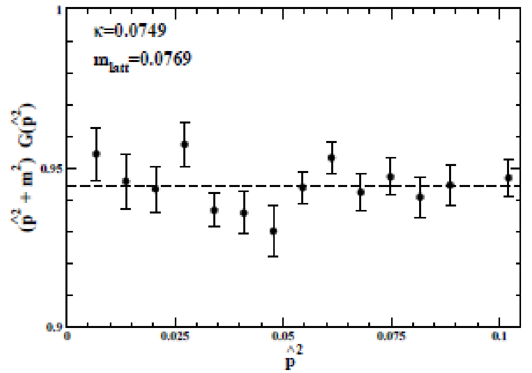


Figure 3: *The propagator data of ref.[8] at* $\kappa = 0.0749$ *for* $\hat{p}^2 < 0.1$. *The lattice mass used here for the rescaling was fixed at the value* $m_h = (2\kappa\chi)^{-1/2} = 0.0769(8)$.

Two-mass structure of the lattice propagator

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. By analogy with superfluid He-4, where the observed energy spectrum arises by combining the two quasi-particle spectra of phonons and rotons, the lattice data were well described in the full momentum region by the model form [7]

$$G(p) \sim \frac{1 - I(p)}{2} \frac{1}{p^2 + m_h^2} + \frac{1 + I(p)}{2} \frac{1}{p^2 + M_h^2} \tag{4}$$

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 $M_H^2 \sim L m_h^2$ when approaching the continuum limit [3].

Estimating M_H from lattice simulations of the propagator

The relation $M_H^2 \sim m_h^2 L$ means that, differently from m_h, the larger M_H would remain finite in units of the weak scale $\langle\Phi\rangle \sim 246.2$ GeV for an infinite ultraviolet cutoff. Thus one can derive their proportionality relation. To this end, let us express M_H^2 in terms of $m_h^2 L$ through some constant c_2, say

$$M_H^2 = m_h^2 L \cdot (c_2)^{-1} \tag{5}$$

and replace the leading-order estimate $\lambda \sim 16\pi^2/(3L)$ in the relation $\lambda = 3m_h^2/\langle\Phi\rangle^2$. Then M_H and $\langle\Phi\rangle$ are related through a cutoff-independent constant K

$$M_H = K\langle\Phi\rangle \tag{6}$$

with $K \sim (4\pi/3) \cdot (c_2)^{-1/2}$. Since, from a fit to the lattice propagator [5], we found $(c_2)^{-1/2} = 0.67 \pm 0.01$ (stat) $\pm\, 0.02$ (sys) this gives the estimate

$$M_H = 690 \pm 10 \text{ (stat)} \pm 20 \text{ (sys) GeV} \tag{7}$$

Basic phenomenology of the (hypothetical) 700 GeV Higgs resonance

With a Higgs resonance $\mathbf{M_H = K\langle\Phi\rangle} \approx 700$ GeV one usually expects strong interactions governed by the large coupling $\lambda_0=3K^2$

This reflects tree-level calculations in the unitary gauge where $W_L W_L$ scattering is like $\chi\chi$ scattering with the same contact coupling at all momentum scales

But beyond tree-level, in $\chi\chi$ scattering the contact coupling $\lambda_0=3K^2$, at a scale Λ, becomes, at a scale μ, $\lambda(\mu)$ with evolution determined by the β-function

Namely, at the scale μ, $\mathbf{A(\chi\chi\rightarrow\chi\chi) \approx \lambda(\mu)}$

with $\mathbf{\lambda(\mu) \approx 1/L}$ and $\mathbf{L=\ln(\Lambda/\mu)}$. By the Equivalence Theorem, the same applies to $W_L W_L \rightarrow W_L W_L$

Therefore, one finds $A(W_L W_L\rightarrow W_L W_L)=$ $A(\chi\chi\rightarrow\chi\chi)[1+O(g^2)]\approx\lambda(\mu)$

This is also consistent with the "triviality" of Φ^4 : the constant $3K^2$ **cannot** be a measure of observable interactions. For $\mu\approx \mathbf{M_H}$

$$\boldsymbol{\lambda(M_H) = 3K^2(m_h/M_H)^2} \approx G_F \mathbf{m^2_h}$$

The same holds true for other observable quantities of the scalar sector, in particular for the heavy $\mathbf{M_H}$ width $\Gamma(\mathbf{M_h}\rightarrow W_L W_L) \approx \mathbf{M_H}(G_F\mathbf{m^2_h})$

The heavy $\mathbf{M_H}$ if it exists, would be a relativel narrow resonance

With a relatively small decay width into longitudinal W's, main $\mathbf{M_H}$ -production at LHC via Gluon-Gluon-Fusion

Basic phenomenology of the heavy resonance. I

A heavy Higgs resonance H, with mass $M_H = K\langle\Phi\rangle \sim 700$ GeV, is usually believed to be a broad resonance due to the strong interactions in the scalar sector. This view derives from the original Lee-Quigg-Tacker calculation in the unitary gauge showing that, with a mass M_H in the scalar propagator, high-energy $W_L W_L$ scattering is indeed similar to $\chi\chi$ Goldstone boson scattering with a large contact coupling $\lambda_0 = 3K^2$. The same coupling would also enter the $H \to W_L W_L$ decay width.

However, by accepting the "triviality" of Φ^4 theories in 4D, the $\Lambda-$independent combination $3M_H^2/\langle\Phi\rangle^2 = 3K^2$ *cannot* represent a coupling entering observable processes. Indeed, the constant $3K^2$ is basically different from the coupling λ governed by the $\beta-$function

$$\ln\frac{\mu}{\Lambda} = \int_{\lambda_0}^{\lambda} \frac{dx}{\beta(x)} \tag{8}$$

For $\beta(x) = 3x^2/(16\pi^2) + O(x^3)$, whatever the contact coupling λ_0 at the asymptotically large Λ, at finite scales $\mu \sim M_H$ this gives $\lambda \sim 16\pi^2/(3L)$ with $L = \ln(\Lambda/M_H)$.

Basic phenomenology of the heavy resonance. II

Therefore, to find the $W_L W_L$ scattering amplitude at some scale μ, one should improve on the Lee-Quigg-Tacker calculation and first use the $\beta-$function to re-sum the higher-order effects in $\chi\chi$ scattering

$$A(\chi\chi \to \chi\chi)\Big|_{g_{\mathrm{gauge}}=0} \sim \lambda \sim \frac{1}{\ln(\Lambda_s/\mu)} \tag{9}$$

and then use the Equivalence Theorem [18, 19, 20] which gives

$$A(W_L W_L \to W_L W_L) = [1 + O(g^2_{\mathrm{gauge}})]\, A(\chi\chi \to \chi\chi)\Big|_{g_{\mathrm{gauge}}=0} = O(\lambda) \tag{10}$$

Thus the large coupling $\lambda_0 = 3K^2$ is actually replaced by the much smaller coupling

$$\lambda = \frac{3m_h^2}{\langle\Phi\rangle^2} = 3K^2\,\frac{m_h^2}{M_H^2} \sim 1/L \tag{11}$$

M_H : heavy but relatively narrow resonance
(produced mainly by GGF mechanism)

For the same reason, the conventional large width into longitudinal vector bosons computed with $\lambda_0 = 3K^2$, say $\Gamma^{\rm conv}(H \to W_L W_L) \sim M_H^3/\langle\Phi\rangle^2$, should instead be rescaled by $(\lambda/3K^2) = m_h^2/M_H^2$. This gives

$$\Gamma(H \to W_L W_L) \sim \frac{m_h^2}{M_H^2}\,\Gamma^{\rm conv}(M_H \to W_L W_L) \sim M_H\,\frac{m_h^2}{\langle\Phi\rangle^2} \qquad (12)$$

where M_H indicates the available phase space in the decay and $m_h^2/\langle\Phi\rangle^2$ the interaction strength. If the heavier state couples to longitudinal W's with the same typical strength of the low-mass state it would represent a relatively narrow resonance.

Due to the suppression of the conventional H-width into longitudinal W's and Z's, the relevant production mechanism in our picture is through the Gluon-Gluon Fusion (GGF) process. In fact, the other production through Vector-Boson Fusion (VBF) plays no role. The point is that the $VV \to H$ process (here $VV = W^+W^-, ZZ$) is the inverse of the $H \to VV$ decay so that $\sigma^{\rm VBF}(pp \to H)$ can be expressed [26] as a convolution with the parton densities of the same Higgs resonance decay width. The importance given traditionally to VBF depends on the conventional large width into longitudinal W's and Z's computed with the $3K^2$ coupling. In our case, where this width is rescaled by the small ratio $(125/700)^2 \sim 0.032$, one finds $\sigma^{\rm VBF}(pp \to H) \lesssim 10$ fb which can be safely neglected.

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**

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

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

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

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

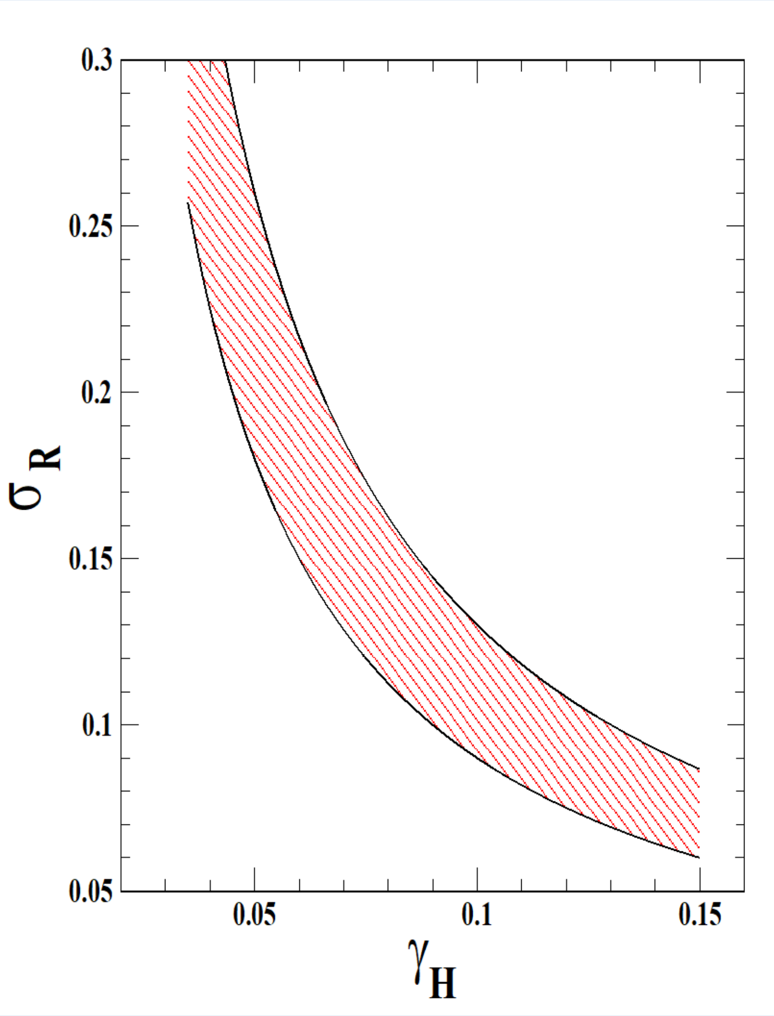
$$\sigma_R(pp \to H \to 4l) \sim \sigma(pp \to H) \cdot B(H \to ZZ) \cdot 4B^2(Z \to l^+l^-) \tag{16}$$

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

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

- **for σ(pp→H) ≈ 950(150) fb** (GGF and 13 TeV) and **m_h = 125 GeV**

$$[\gamma_H \cdot \sigma_R(pp \to H \to 4l)]^{\text{theor}} \sim (0.011 \pm 0.002)\ \text{fb} \tag{18}$$

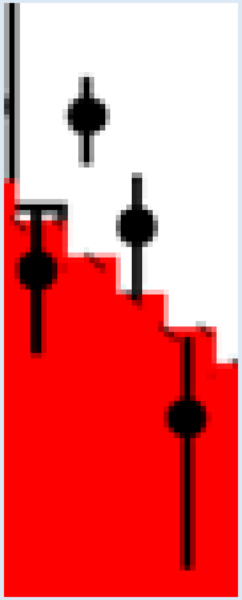


- Fitting the ATLAS 4-lepton data in the range 620÷740 GeV

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 1: *For each γ_H we report the values of M_H and resonating cross section σ_R obtained from a fit with Eq.(19) to the ATLAS data.*

γ_H	M_H [GeV]	σ_R [fb]
0.04	678(5)	0.218(40)
0.05	677(6)	0.176(30)
0.06	675(7)	0.152(26)
0.07	672(11)	0.137(23)
0.08	670(14)	0.126(21)
0.09	670(14)	0.117(19)
0.10	670(15)	0.109(19)
0.11	671(15)	0.102(18)
0.12	672(16)	0.096(19)
0.13	673(18)	0.090(20)
0.14	674(20)	0.085(22)

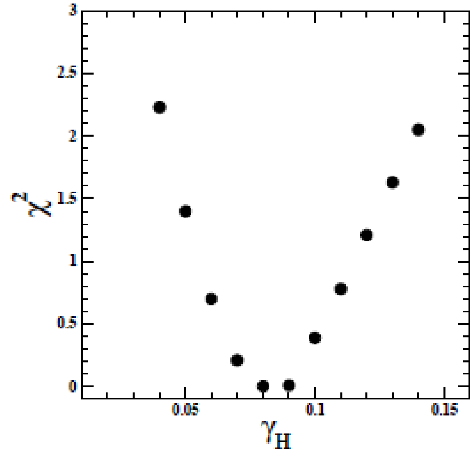


Figure 1: *At the various values of γ_H, we report the chi-square of the fit with Eq.(19) to the ATLAS data.*

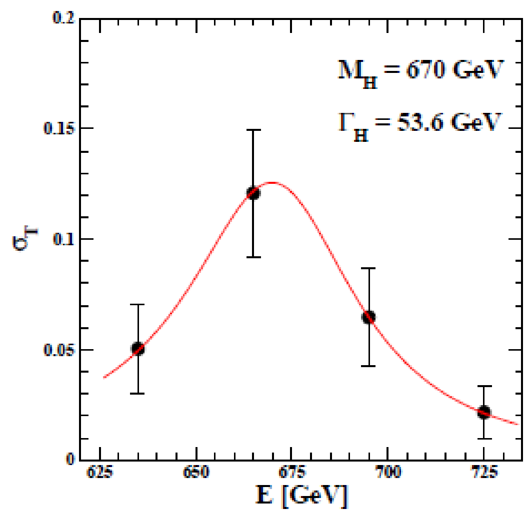
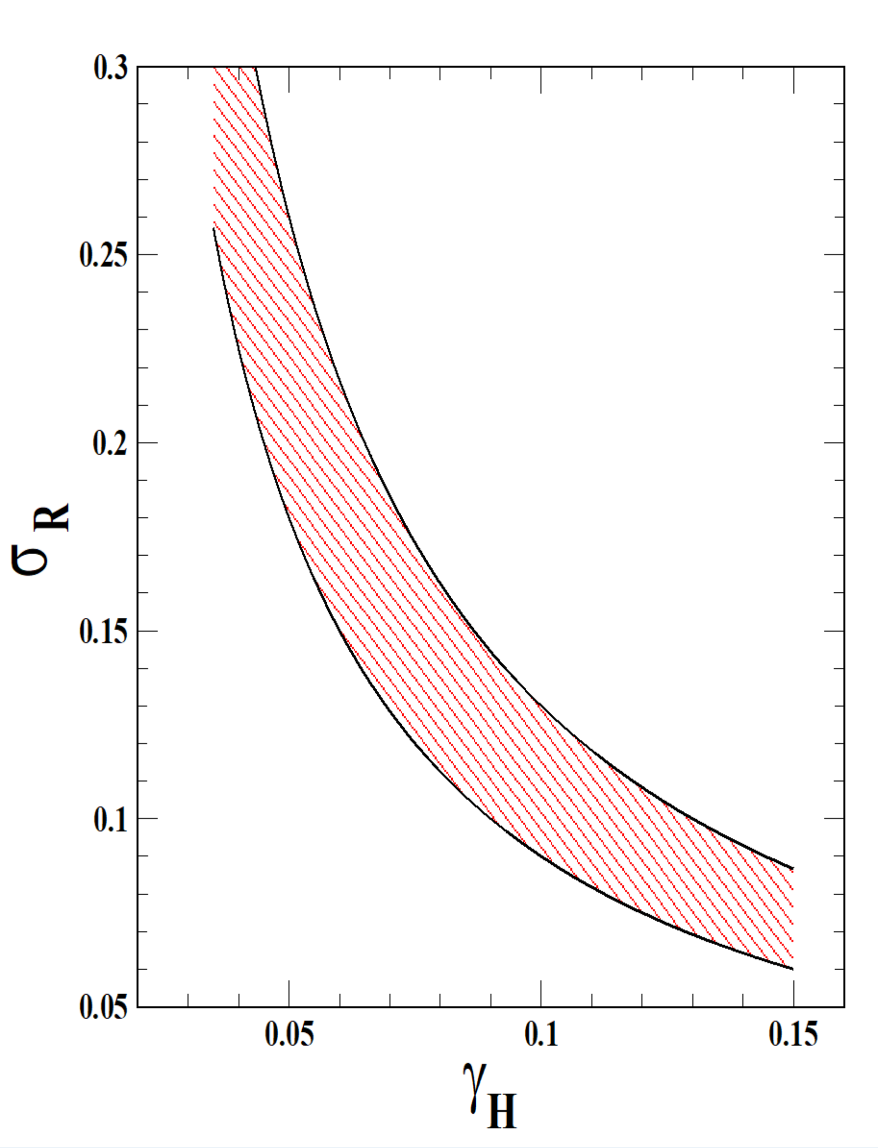
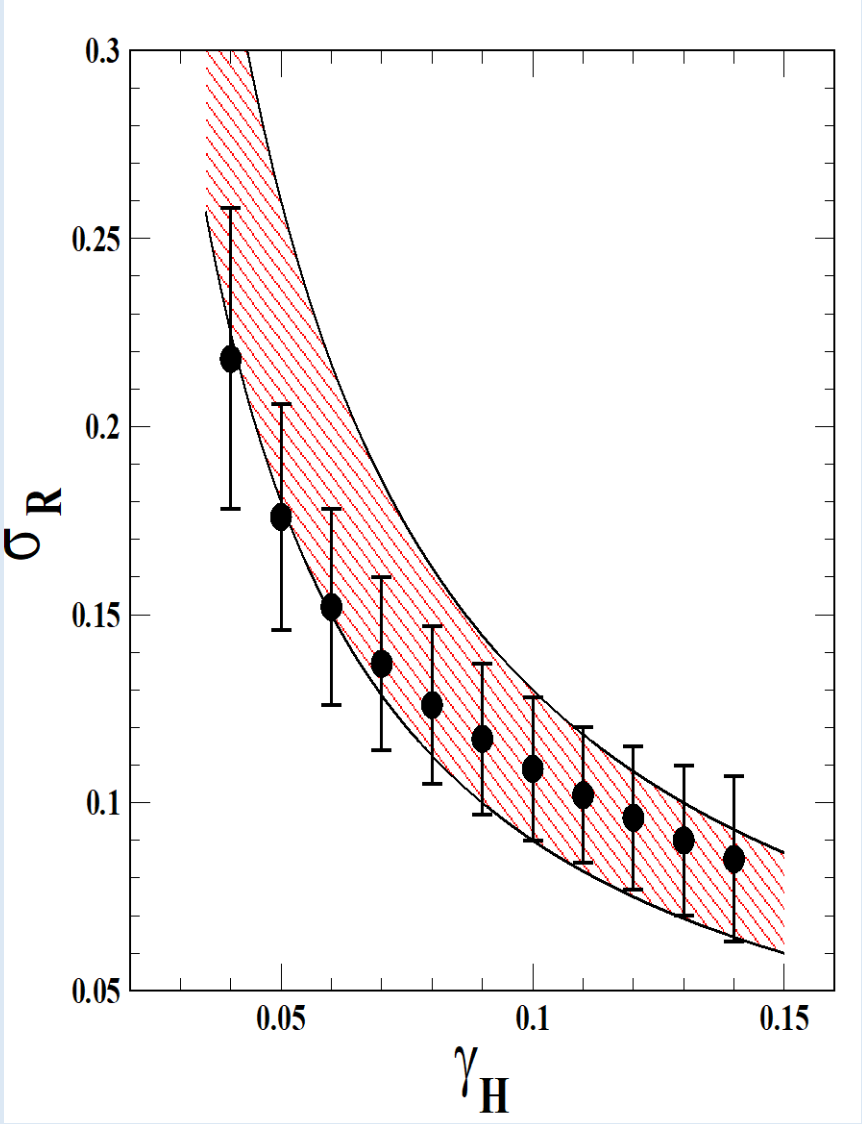


Figure 2: *For $\gamma_H = 0.08$, we show the fit with Eq.(19) to the ATLAS cross sections in fb.*

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



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



Equivalently one can fit m_h from the ATLAS data

Table 1: *For each γ_H we report the values of M_H and resonating cross section σ_R obtained from a fit with Eq.(19) to the ATLAS data.*

γ_H	M_H [GeV]	σ_R [fb]
0.04	678(5)	0.218(40)
0.05	677(6)	0.176(30)
0.06	675(7)	0.152(26)
0.07	672(11)	0.137(23)
0.08	670(14)	0.126(21)
0.09	670(14)	0.117(19)
0.10	670(15)	0.109(19)
0.11	671(15)	0.102(18)
0.12	672(16)	0.096(19)
0.13	673(18)	0.090(20)
0.14	674(20)	0.085(22)

To place this agreement on a more quantitative basis, we have performed a fit with the functional form

$$\sigma_R(pp \to H \to 4l) = k/\gamma_H \quad (21)$$

to the σ_R's of Table 1 by obtaining the average result

$$[\gamma_H \cdot \sigma_R(pp \to H \to 4l)]^{\text{theor}} \sim (0.011 \pm 0.002)\ \text{fb}$$

$$[\gamma_H \cdot \sigma_R(pp \to H \to 4l)]^{\text{fit}} = k \sim (0.0101 \pm 0.0006)\ \text{fb} \quad (22)$$

This value, which is well consistent with Eq.(18), can then be replaced in the left-hand side of Eq.(17) by providing the combined determination

$$[\sigma(pp \to H) \cdot m_h^2]^{\text{fit}} = (1.36 \pm 0.08) \cdot 10^7\ \text{fb} \cdot \text{GeV}^2 \quad (23)$$

Therefore, with the previous estimate $\sigma(pp \to H) \sim \sigma^{\text{GGF}}(pp \to H) \sim 950(150)$ fb, we find the range $m_h \sim (108 \div 134)$ GeV which can be summarized as

$$(m_h)^{\text{fit}} \sim (121 \pm 13)\ \text{GeV} \quad (24)$$

in good agreement with the measured Higgs particle mass.

CONCLUSIONS

- The ATLAS + CMS 4-lepton data indicate a **3σ excess for E=650÷710 GeV**
- A fit to the ATLAS data points toward a new resonance of mass 660÷680 GeV
- The existence of this resonance is also supported by a corresponding **3σ excess at 680 GeV in the invariant mass of the ATLAS γγ events**
- This range of mass values is well consistent with our theoretical prediction for the second resonance of the Higgs field **M_H = 690 ± 10 (stat) ± 20 (sys) GeV**
- Furthermore, by assuming a partial width 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 **$(m_h)^{fit}$ = 121 ± 13 GeV,** well consistent with the direct experimental value **$(m_h)^{exp}$= 125 GeV**

- This present level of consistency requires a final confirmation with a combined ATLAS+CMS analysis. In principle, **with the full CMS 4-lepton statistics, the issue could already be settled now, before the start of RUN3**

A remark on radiative corrections

- With two resonances of the Higgs field, what about radiative corrections?
- Our lattice simulations indicate a propagator structure

$$G(p) \sim \frac{1-I(p)}{2}\frac{1}{p^2+m_h^2} + \frac{1+I(p)}{2}\frac{1}{p^2+M_h^2} \quad (4)$$

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 $p^2 \to 0$.

- This is very close to van der Bij propagator Acta Phys. Polon. B**11** (2018) 397.

$(-1 \leq \eta \leq 1)$

$$G(p) \sim \frac{1-\eta}{2}\frac{1}{p^2+m_h^2} + \frac{1+\eta}{2}\frac{1}{p^2+M_H^2} \quad (49)$$

- In the ρ-parameter at one loop, this is similar to have an effective Higgs mass

$$m_{\text{eff}} \sim \sqrt{m_h M_H}\,(M_H/m_h)^{\eta/2} \quad (47)$$

In our case, this would be between $m_h = 125$ GeV and $M_H \sim 700$ GeV.

- How well, the mass from radiative corrections agree with the direct LHC result 125 GeV?

From the PDG review: positive M_H-$\alpha_S(M_z)$ correlation (Important: NuTeV is not considered→ larger M_H)

Table 10.7: Values of $\hat{s}^2_Z$, 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	$\hat{s}^2_Z$	s^2_W	$\alpha_s(M_Z)$	m_t	M_H
All data	0.23122(3)	0.22332(7)	0.1187(16)	173.0 ± 0.4	$\cancel{125}$
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	$\cancel{125}$
All data except M_W	0.23124(3)	0.22347(7)	0.1191(16)	172.9 ± 0.5	$\cancel{125}$
All data except m_t	0.23112(6)	0.22304(21)	0.1191(16)	176.4 ± 1.8	$\cancel{125}$
M_H, M_Z, Γ_Z, m_t	0.23125(7)	0.22351(13)	0.1209(45)	172.7 ± 0.5	$\cancel{125}$
LHC	0.23110(11)	0.22332(12)	0.1143(24)	172.4 ± 0.5	$\cancel{125}$
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	$\cancel{125}$

First remark: NuTeV not included by PDG

The NuTeV collaboration found $s_W^2 = 0.2277 \pm 0.0016$ (for the same reference values), which was 3.0 σ higher than the SM prediction [89]. However, since then several groups have raised concerns about interpretation of the NuTeV result, which could affect the extracted $g_{L,R}^2$ (and thus s_W^2) including their uncertainties and correlation. These include the assumption of symmetric strange and antistrange 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 a such an effort we do not include the νDIS constraints in our default set of fits.

Second remark: the importance of $\alpha_S(M_z)$

Schmitt→ present most complete analysis

hep-ex/0401034
nuhep-exp/04-01

Apparent Excess in $e^+e^- \to$ hadrons

Michael Schmitt

Northwestern University

January 22, 2004

Abstract

We have studied measurements of the cross section for $e^+e^- \to$ hadrons for center-of-mass energies in the range 20–209 GeV. We find an apparent excess over the predictions of the Standard Model across the whole range amounting to more than 4σ.

Higgs mass from LEP1

TOKUSHIMA 95-02
(hep-ph/9503288)
March 1995

Remarks on the Value of the Higgs Mass
from the Present LEP Data

M. CONSOLI[a)] AND Z. HIOKI[b)]

ABSTRACT

We perform a detailed comparison of the present LEP data with the one-loop standard-model predictions. It is pointed out that for $m_t = 174$ GeV the "bulk" of the data prefers a rather large value of the Higgs mass in the range 500-1000

ALEPH+DELPHI+L3+OPAL

α_s	0.113	0.125	0.127	0.130
m_h(GeV)	100	100	500	1000
TOTAL χ^2	43.6	37.8	36.4	38.2

Table VII. Total χ^2 for the four Collaborations.

α_s	0.113	0.125	0.127	0.130
m_h(GeV)	100	100	500	1000
ALEPH	6.7	8.6	7.6	8.2
DELPHI	7.6	8.8	7.3	7.3
L3	10.3	4.7	5.4	5.9
OPAL	11.4	7.9	5.1	4.1
TOTAL χ^2	36.0	30.0	25.4	25.5

Table VIII. Total χ^2 for the four Collaborations by excluding the data for $A^o_{FB}(\tau)$.