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Global interpretation of LHC indications within the Georgi-Machacek Higgs model

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Following various LHC indications for new scalars, an interpretation of these is given in terms of the Georgi-Machacek (GM) model. On top of the confirmed SM Higgs boson, there are indications for a light Higgs at 96 GeV, for a CP-odd boson at 400 GeV and for a heavy Higgs boson at 660 GeV. Potentially interesting deviations are also observed in the ttW cross-section measurement, which naturally fit into this picture. None of them crosses the fatidic five s.d. evidence but the addition of these effects, consistent with GM, suggest that there are good hopes for solid discoveries at HL-LHC, which should boost the motivation for future machines. The GM model also provides a useful framework to estimate the rates expected for various channels at an e+e- collider, together with the range of energies needed. ILC performances are used for a quantitative estimate of these rates for the prominent channels.

Introduction

A collection of indications for BSM physics from ATLAS and CMS was described in two previous notes [1, 2]. The present note provides an updated version of this analysis and an attempt to find a **consistent theoretical interpretation** of these effects.

It is well understood that the SM cannot be the last word since, among many examples, it is unable to provide the necessary inputs to understand our world, in particular to understand baryogenesis. (N)MSSM with CPV, could remedy to this situation but it seems that, in spite of its apparent triumph

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in predicting the Higgs mass, it has lost its basic motivation, which is SUSY, insuring an appropriate cancellation of the quartic mass divergences for **elementary scalars**. A possible way out is to move to **compositeness** which also provides motivations for light scalars, as PNGB (Pseudo Nambu-Goldstone Bosons) particles of an unknown broken symmetry with no precise predictions for the mass spectrum of the new particles. Composite models also require structuring the new scalars into weak isospin multliplets, similar to what does MSSM within SUSY. This allows passing the precision test for the S,T,U variables.

Both the MSSM framework and its composite extensions predict isodoublets and isosinglets and we have seen [1,2] that they enter in conflict with some of the indications provided by LHC results.

At variance with these ideas, Georgi and Machacek (GM) [3] have offered a radically different group structure for the Higgs isomultiplets, quote: "*The possibility that representations containing double charged scalars may participate in the spontaneous breakdown of the SU(2)xU(1) symmetry of electroweak interactions*".

The usual dogma, usually assumed for the Higgs sector, states that to satisfy the identity $\mathbf{M_Z\cos\theta_W/M_W=1}$ (up to loop corrections), one can only allow for isosinglets and isodoublets. The GM model allows for higher isospin states, in such a way as keeping above identity at the tree level, hence the possibility of accommodating exotic scalars with double charge. This result can be achieved without fine-tuning by imposing the custodial symmetry to the Higgs potential [4].

It turns out, as will be shown in this note, that this model offers viable solutions for most inconsistencies between LHC findings and the orthodox extensions of the SM. Examples of this are:

- Absence of signal for H(660)->WW, only observed in the ZZ mode, while MSSM predict HWW/HZZ~2
- Predominant production of H(660) through VBF fusion, ZZ/WW->H(660), in the absence of coupling to heavy fermions which forbids gluon-gluon fusion ggF
- Indication for a CP-odd scalar, with A(400)->Zh, while MSSM predict a decoupling of this mode
- Indication for a 50% excess in ttW, which naturally emerges within this model through the VBF process WZ->H+(660)->A(400)W+ with A(400)->tt
- A less significant excess in ttZ is understood as coming from the smaller production rate for ZZ->H(660)->A(400)Z

One may object to this model an absence of doubly charged signals into the W+W+ mode, but, as will become clear, this can be interpreted as a dominance of complex decay modes like H+(400)W+, much harder to detect at LHC.

Could h(96), indicated by LEP2 and CMS, belong to this GM structure? This seems a priori plausible since the model predicts a second isosinglet together with h(125), but we will see that in such a case one should observe the transition A(400)->h(96)Z with a rate incompatible with LHC findings. I will therefore assume that the second isosinglet is heavier, presumably heavy enough that the decay into h(125)h(125) becomes dominant.

Section II, after recalling these **LHC anomalies**, gives their interpretation within the GM model, with more details in an Appendix. Recently ATLAS has updated its search for H->ZZ and observes an indication in the VBF channel at the relevant mass. The absence of any indication into WW favours the RM model that predicts WW/ZZ~0.5 for a 5-plet scalar instead of ~2 in the usual MSSM case.

Section III is about **cascade decays predicted** by the GM model and possible signals at LHC. A 50% excess in the ttW channel, observed by ATLAS and CMS, is interpreted within the same model. Possibilities offered by lepton tagging are also discussed and illustrated by an ATLAS search. Various anomalies observed in **multileptonic states**, in some cases accompanied by b-jets, are recalled which may, at the qualitative level, lead to a similar interpretation.

Section IV examines what can be hoped for at **HL-LHC** within the GM model.

Section V does the same for **future e+e- colliders**.

II. A Georgi-Machacek interpretation of LHC anomalies

II.1 LHC anomalies

Let me briefly recall what are these anomalies:

- Indications for a scalar into two photons at 96 GeV from CMS
- Several indications (top pairs, tau pairs, Zh(125)) for a pseudo scalar at 400 GeV . When combined statistically, these indications amount to >6 s.d.
- A ~5 s.d. excess at ~660 GeV in the golden mode ZZ into four leptons, obtained by combining CMS and ATLAS data
- No signal in the WW mode, seemingly incompatible with the ratio WW/ZZ~2 predicted by MSSM

Recall that it is not trivial to interpret the various indications for a resonance at 400 GeV:

- gg->A(400)->tt interferes strongly with the QCD background, which renders the extraction of the cross-section delicate
- For A(400), a top Yukawa coupling close to 1 can explain the 3.5 s.d. effect seen in CMS, implying, within MSSM, a negligible coupling to b quarks and taus, which does not seem the case since one has evidence for associated production A+bjet in the Zh and $\tau\tau$ channels

As already stated in my previous notes, these observations do not fit into the usual MSSM scheme. This was also emphasized in [5] for the channel hZ. So far, I had refrained from giving an alternate explanation for these observations, interpreting these inconsistencies as due to the composite origin of these scalars. Here, I will indicate why the GM gives a natural framework for some of these observations, even suggesting additional observations, called generically “cascades”, which naturally emerge in such a phenomenology.

GM naturally includes A(400) and H5(660). It cannot include h(96) as the second singlet, since it would imply a large A(400)->h(96)Z BR (Branching Ratio), not supported by the data. I will therefore assume that the second singlet, hereafter called h’, is heavy. h’ cannot explain the ZZ bump at 660 GeV since it decays dominantly into hh and has a BR into ZZ at the % level (see figure 10).

Recently ATLAS [6] has published an update of the 4 leptons search, with the full sample (139 fb-1) analysed. In figure 1, one observes an excess in the mass region of interest.

Figure 2 shows the result obtained by ATLAS for the VBF search, with a **cut-based** analysis for the 4-lepton case, suggestive of an excess around 660 GeV. This analysis shows that a VBF selection allows reaching a good signal/background ratio. It was only available in ATLAS-CONF-2020-032 and not reported in the final publication. This measurement allows extracting the partial width ΓZZ~15 GeV knowing that the observed total width, see [1], is ~100 GeV.

The signal acceptance, defined as the ratio of the number of reconstructed events after all selection requirements to the total number of simulated events, is found between 30% (15%) and 46% (22%) in the ggF(VBF)-enriched category for the ggF(VBF) production mode depending on the signal mass hypothesis. This means that a large fraction, if not all, of the signal observed in figure 1 could come from VBF.

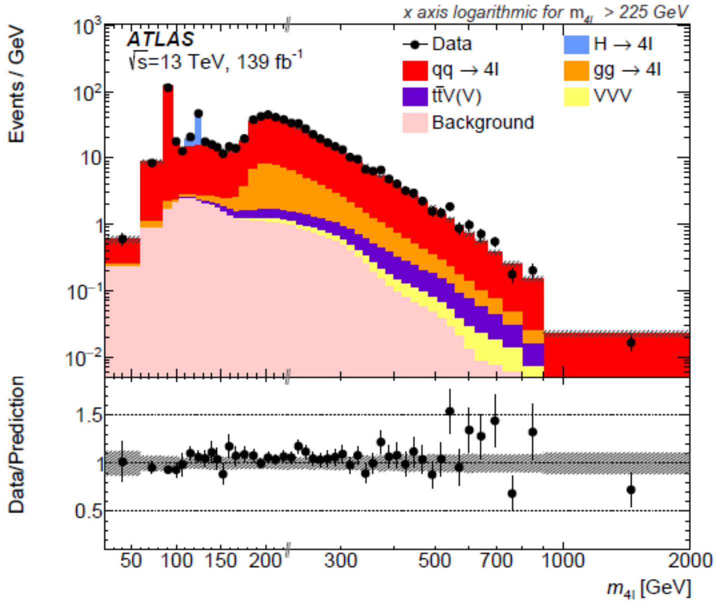


Figure 1: ATLAS results for the 4 leptons analysis with an integrated luminosity of 139 fb-1 at 13 GeV.

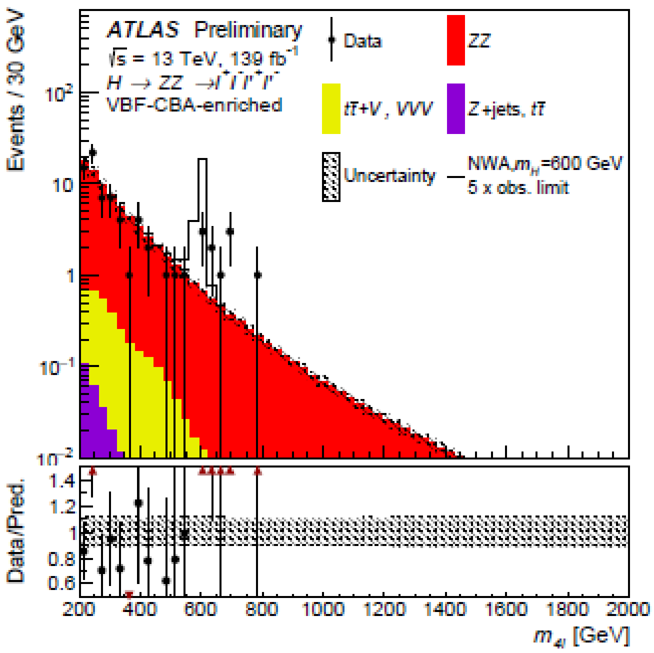


Figure 2: Cut based analysis of ATLAS for the VBF->ZZ channel into 4 leptons. The predicted signal indicated in the figure is narrower than the expected signals for H5.

Note that the two resonances h' and H5(660) could very well overlap and eventually interfere. This effect is however expected to be weak since, as discussed in the Appendix, h'(600) will decay dominantly into h(125)h(125).

II.2 Indication for a charged Higgs?

In contrast to MSSM, GM predicts a tree-level coupling of H5+ into ZW, which allows **VBF production** of such a particle. The two figures below [7,8] – not considered in my previous notes – provide weak but coincident evidence, at similar masses, for such a mechanism but, contrary to expectations, at a mass clearly below H5(660). ATLAS observes, for the VBF category, a 2.9 standard deviation for mH+=450 GeV. Recall that, in GM, mH3+=mA=400 GeV with no coupling to ZW.

The analysed samples, respectively 15.2 fb-1 and 36.1 fb-1, correspond to a small fraction of the presently available luminosity and should be updated.

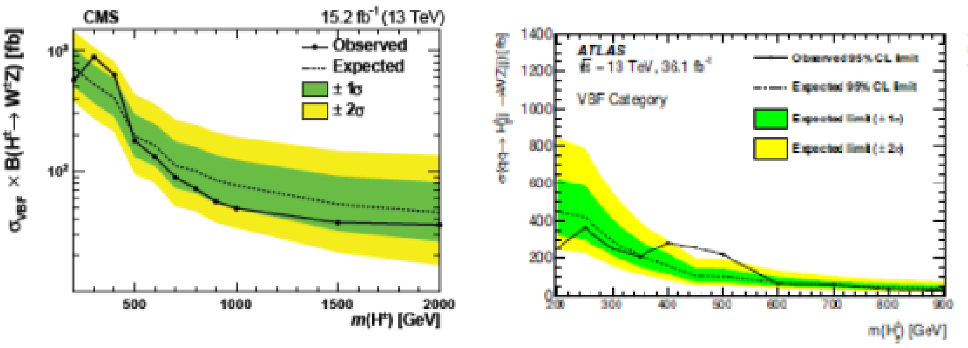


Figure 3: CMS and ATLAS results on ZW->H+->ZW search.

II.3 Quantitative treatment of the GM model

The formalism and the details of the derivation of GM parameters are explained in the Appendix. In the present section, I will summarize the line of reasoning and the conclusions.

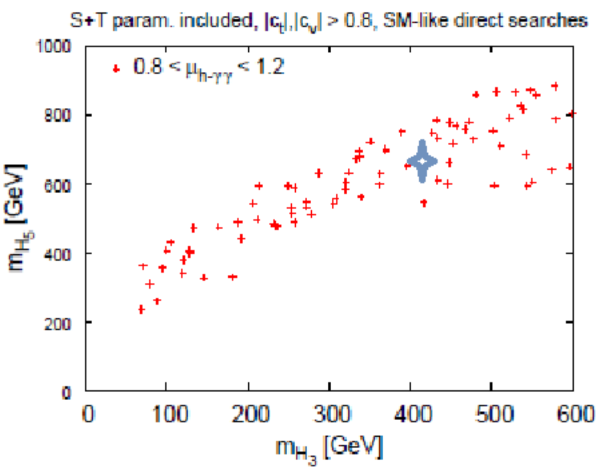


Figure 4: GM solutions fulfilling S+T and h(125)->2photons constraints. Signal is marked by a cross.

The GM couplings depend on two mixing angles α and θ_H and, given the various constraints that need to be fulfilled to describe LHC data, the retained solution is:

sH=0.50 cH=0.87 sα=-.15 cα=0.99 with the vacuum expectations **vχ=43 GeV** and **vϕ=214 GeV**.

This solution follows from existing constraints coming from the SM scalar h(125), which is an isosinglet of the GM solution. Masses from the 3-plet and 5-plet suggested by LHC data also fulfil the S,T parameters as can be seen from figure 4 from [9]. Figure 15 of the Appendix shows that this choice is quite tight. The only missing parameter, as already mentioned, is the mass of the second scalar singlet labelled h'.

The following table summarizes the couplings deduced from this solution and, when relevant, the predicted cross-sections for an e+e- operating at 1 TeV. In section IV, I will give the energy dependence of the rates expected at ILC.

Type	coupling /SM, MSSM	Numerically	σee fb@1 TeV	e+e- Eth GeV
h(125)WW/ZZ	cαcH- 1.63sαsH	0.98	12.0	216
h'(600)WW/ZZ	sαcH+1.63cαsH	0.68	1.5	mh'+mz
h(125)tt,bb	cα/cH	1.14		
h'tt,bb	sα/cH	0.17		
Att,bb,$\tau\tau$	tanH	0.58		
H5WW, H5ZZ	1.15sH,-2.31sH	0.57,1.16	3	751
H5AZ,H5H3+W-	1.16cH	1	0	1060
H5+H3+Z,H5+AW+	cH	0.87	0	1060
Zh(125)A	1.63(sαcH+0.6cαsH)	0.28	0.4	525
Zh'(600)A	1.63(cαcH- 0.6sαsH)	1.48	0	mh'+mA
h'(600)H3+W-	1.63(cαcH- 0.6sαsH)	1.48		
ZH5+W-	2sH	1.0	2*2.2	740
ZH3+H3-	1	1	5.7	800

The following table gives the partial widths for some relevant channels.

Channel	ΓWW/ZZ GeV	Γtt GeV	ΓZh(125) GeV	ΓAZ GeV	ΓH3W GeV	Γtot GeV
A(400)	-	11.1	0.38	-	-	11.5
H5(660)	6/15.7	-	-	27	41	90

The isosinglet h' decays mainly into hh (see Appendix and figure 10).

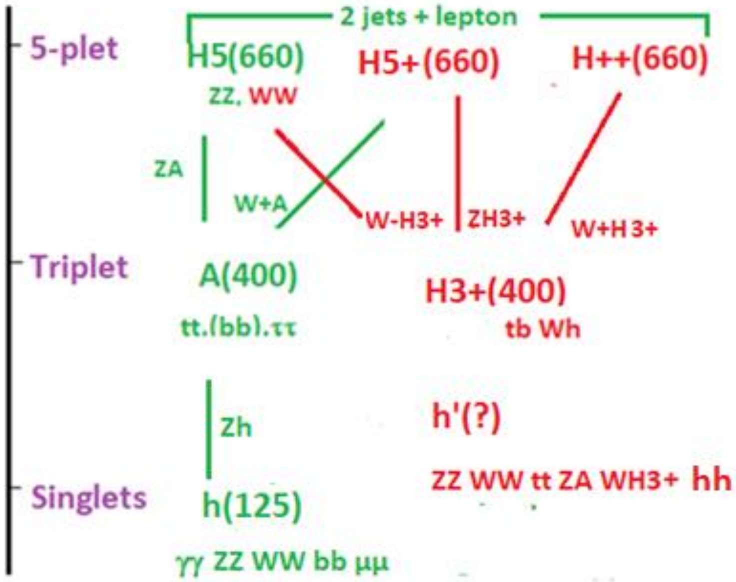
Few remarks are of order:

- The coupling of A(400) to h'Z is ~5 times larger than for h(125)Z which excludes the hypothesis that h(96) could be the missing singlet
- For H5(660), the predicted width comes quite close to the observed width [1,2], ~100 GeV
- Loop contributions (gg, $\gamma\gamma$, $Z\gamma$) are ignored but should not affect the total width result

III. Cascades at LHC

In the GM model, one expects that the heavier scalars which, according to our analysis, belong to the 5-plet, will **cascade** into lighter scalars from the triplet and could populate the **topologies ttZ and ttW** studied at LHC. This is also true for the singlet h', but to a lesser degree given the prominent decay h'->2h. The cascade mechanism is pictorially described in the following picture, recalling that particles of the 5-plet are mass degenerate at ~660 GeV. Accordingly, H5 and H5+ will cascade into ZA and WA, which will contribute to ttZ and ttW final states. ttW receives a contribution from H5+ and H5- which are produced by VBF with stronger couplings than the neutral H5.

In the picture below, green is used for particles and processes which are already identified from LHC data.



III.1 ttW and ttZ measurements at LHC

An excess in ttW, was observed, both by ATLAS and CMS, at 8 TeV and confirmed at 13 TeV. Figure 5 shows a 2 s.d. significance for CMS [10].

A similar effect should be observed for ttZ, noting however that the SM cross-section for this process being larger and the expected signal being lower, this effect is harder to observe.

The most recent CMS measurement CMS-PAS-TOP-18-009:

σ(ttZ)=1.00+0.06-0.05(stat)+0.07-0.06(syst) pb

agrees with ATLAS-CONF-2020-028:

σ(ttZ)=1.05+0.05-0.05(stat)+0.09-0.09(syst) pb

which therefore show the same excess, ~20%, with respect to the NLO+NNLL prediction:

σ(ttZ)SM=0.863+0.07-0.09(scale)±0.03 pb

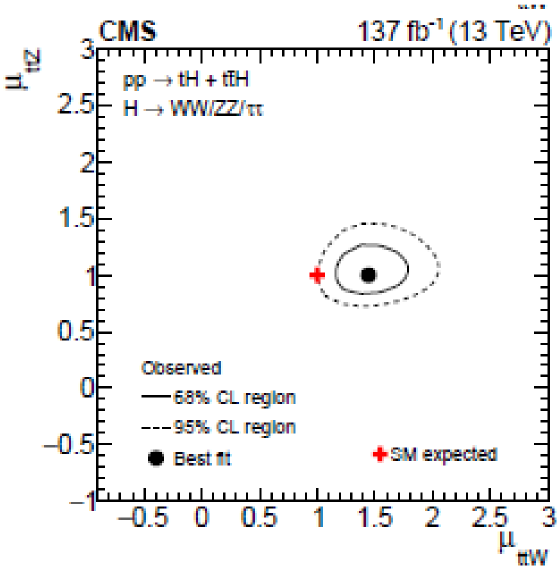


Figure 5: CMS ttZ and ttW measurements normalized to expectations.

Given present uncertainties, ttW and ttZ measurements are compatible with this GM interpretation.

An essential point to achieve progress and establish the origin of this mechanism is to realize that the 5-plet is produced by the VBF mechanism, while the SM component comes from ggF. **Selecting the VBF topology** should therefore eliminate most of the SM part and confirm this interpretation. To my knowledge, **this measurement has not yet been performed**. Once this selection is operated, one should observe that the top pair masses cluster around 400 GeV. One should also observe a **charge asymmetry** in the selected ttW events produced by ZW fusion which simply reflects the ratio u/d~2 for the valence quarks of the parent protons.

Finally, the ttZ topology, with Z into lepton pairs, allows to reconstruct the parent H5 resonance. These statements are true in case one uses fully hadronic top decays since leptonic decays contain unmeasured neutrinos.

III.2 ATLAS search for cascades using lepton tagging

In [11], an attempt has been made to reconstruct resonances decaying hadronically which are accompanied by a lepton with large pT. The cascade mechanisms:

- H5,h'->AZ,H3+W-
- H5+->AW+,H3+Z
- H5++->H3+W+

can provide such a high pT lepton, which originates from Z/W accompanying an H3 decaying hadronically. The pT selection will be easily fulfilled given that, in the centre of mass of H5, the W/Z energy is E*~210 GeV, which provides a boost to Z/W particles.

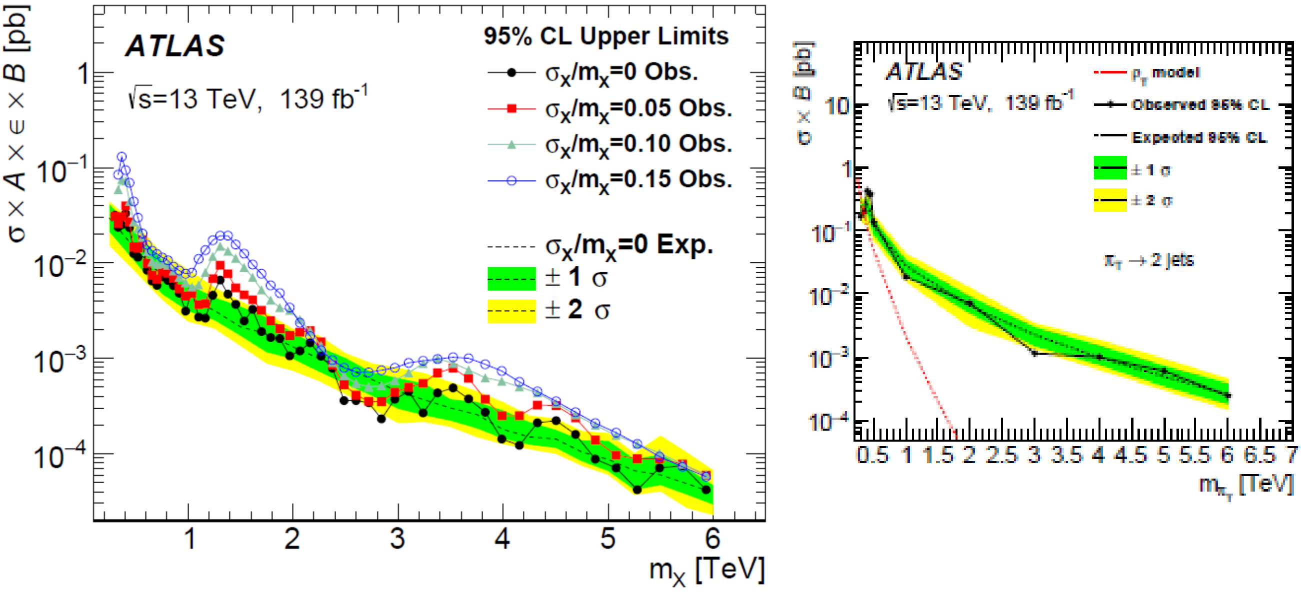


Figure 6, left: upper limit on the cross-section times acceptance, times BR for an inclusive search of a resonance tagged by a high pT lepton. Right : upper limit for the cross-section times BR for a scalar resonance decaying into two jets.

This search covers not only ttZ and ttW final states coming from AZ and AW but also from H3+W-, H3+Z and H3+W+ (and their complex conjugate states). One can try to combine the Z particle to the hadronic part to reconstruct exclusive decays of H5 and H5+ resonances. A **VBF selecti**on should enhance this signal as mentioned in the previous section.

The excess at 400 GeV in figure 6 (left) appears optimal for a wide resonance assumption. This may be due to a mixture of several contributions with differing masses. The excess of π_T–>2 jets events observed in figure 6 (right) corresponds to a cross-section of a few 100 fb, compatible with what one would expect from the contribution of the parent 5-plet.

III.3 Alternate interpretation of these excesses

In [12], a Randall Sundrum mechanism, deduced from the AFBb anomaly observed at LEP1, is predicting a possible enhancement of the ttZ coupling. In this interpretation, there is simply a larger cross-section for ttZ but with no significant alteration of the kinematical distributions with respect to the SM. This is radically different from the GM cascade interpretation, where one would expect that, for instance, the **average transverse momentum** distribution of Z/W could be larger than for the SM.

Reference [13] has analysed anomalies for **multi-leptonic states accompanied (or not) by b-jets** and has interpreted them as due to the occurrence of new scalars, H(270) and S(150), with H decaying into S+h(125). Once these masses are fixed, the result depends on one parameter, $\beta^2 g$.

The table below shows a detailed description of these anomalies observed with ATLAS and CMS. The claim is that combining all these discrepancies, there is an **overall 8 s.d. effect**, incompatible with a statistical fluctuation.

This approach is complementary to the one used to establish the presence of the **A(400)** resonance in [2] where, by combining several exclusive channels, one reaches a similar statistical significance **beyond 6 s.d.** If one takes into account the H5(660)->ZZ excess, the ttW excess, one also reaches an overall ~8 s.d. effect. These two observations are clearly independent and reinforce the case for promising discoveries at HL-LHC.

One can ask whether the two approaches are **contradictory**. This does not seem the case since [13] does not claim to have observed exclusively heavy scalars but is just using the decay products of these hypothetical scalars to feed the various categories for which excesses were observed by ATLAS and CMS.

Selection	Best-fit β_g^2	Significance
ATLAS Run 1 SS $\ell\ell$ and $\ell\ell\ell$ + b-jets	6.51 ± 2.99	2.37σ
ATLAS Run 1 OS $e\mu$ + b-jets	4.09 ± 1.37	2.99σ
CMS Run 2 SS $e\mu$, $\mu\mu$ and $\ell\ell\ell$ + b-jets	1.41 ± 0.80	1.75σ
CMS Run 2 OS $e\mu$	2.79 ± 0.52	5.45σ
CMS Run 2 $\ell\ell\ell + E_T^{miss}$ (WZ)	9.70 ± 3.88	2.36σ
ATLAS Run 2 SS $\ell\ell$ and $\ell\ell\ell$ + b-jets	2.22 ± 1.19	2.01σ
ATLAS Run 2 OS $e\mu$ + b-jets	5.42 ± 1.28	4.06σ
ATLAS Run 2 $\ell\ell\ell + E_T^{miss}$ (WZ)	9.05 ± 3.35	2.52σ
Combination	2.92 ± 0.35	8.04σ

The same can be done in the case of GM and the following table shows that the various cascades described at the beginning of this section can do the job. Remarkably, GM predicts that these excesses have a **VBF origin,** which offers a discriminating test of the two hypotheses.

Another discrimination comes from the measurements of ttW and ttZ, which is only affected in the GM case.

In the meanwhile, I would be tempted to conclude that the two approaches could just be **two ways to look at the same phenomenon**.

Type/ Channel	A(tt)Z	A(tt)W	H3+(tb,Wh)W-	H3+(W+h)W+	H3+(tb)Z
ATLAS R1 SS ℓℓ and 3ℓ + b	X	X		X	X
ATLAS R1 OS eμ +b	X	X	X		X
CMS R2 SS eμ, μμ, 3ℓ +b	X	X	X	X	X
CMS R2 OS eμ	X	X	X		X
CMS R2 3ℓ +ETmiss	X	X			X
ATLAS R2 SS ℓℓ and 3ℓ + b	X	X		X	X
ATLAS R2 OS eμ + b	X	X	X		X
ATLAS R2 3ℓ +ETmiss	X	X			X

IV. An open problem: the fermion sector

From the previous sections, one would tend to conclude that all goes well within the GM. This is not so in the **fermion sector**, as pointed out in the Appendix. How can one understand why A(400) is accompanied by b jets at a level which allows to tag efficiently A->Zh and A->ττ ? One can partly attribute the appearance of b jets as due to the cascades from H5->ZA, but the cross-sections for ZA is clearly insufficient to explain quantitatively the phenomenon. Even then, one is left with the ratio A->ττ/A->tt~0.8% [2] that is two orders of magnitude larger than allowed in the GM model where it goes like $m\tau^2/3mt^2$. In the MSSM scheme, the Yukawa coupling for b and τ is enhanced by tanβ, requiring tanβ~10–20 to explain observations. This requires that the top coupling is decreased by 1/tanβ, leading to a contradiction since one needs an almost SM Yukawa coupling for A(400)->tt to reproduce the observed cross-section [2].

It is however fair to stress that the GM model also does not provide an explanation for the large couplings of A(400) into τ/b and one should therefore invoke another mechanism to interpret the ATLAS-CMS observations. Additional phenomenological inputs are needed to understand such a behaviour that could be due to **compositeness**.

V. Future prospects at LHC

From previous sections, one expects LHC:

- To confirm the existence of A(400) through top pairs, Zh and ττ
- To confirm H5(660) into ZZ/WW through VBF
- To confirm indications for a charged Higgs into ZW through VBF
- To search for h'->2h which is expected to be the dominant decay mode (figure 10)
- To reconstruct H5, H5+ using ttW and ttZ final states
- To discover H3+ by using hadronic final states tagged by a high pT leptons from Z/W decays
- To search for H5++

At LHC, H5++ can be singly produced through VBF. It decay modes are into W+W+ and H3+W+ (and complex conjugate), the latter being predominant with H3+ decaying into tb or hW+. This gives topologies of the type tbW->bbW+W+ and hW+W+->bbW+W+, which can be searched for by selecting the VBF mode. [14] gives a pessimistic prediction for this channel as shown in figure 7.

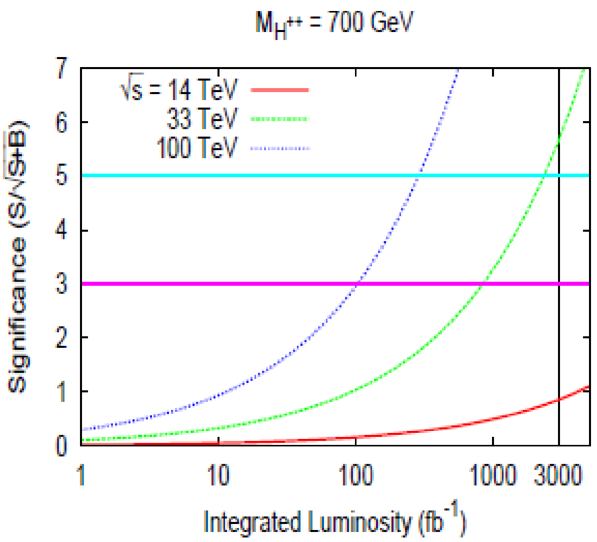


Figure 7: Expected significance for a H++(700) vs. the integrated luminosity delivered by LHC at 14 TeV

To fully assess GM, searching for h' is a priority. From the first table of section II.3, one concludes that:

- ggF->h' cross-section is reduced by a factor 30 with respect to a SM Higgs
- VBF remains the best prospect since it is only reduced by a factor 2 with respect to SM
- For mh'>230 GeV the dominant decay mode is 2h (see Appendix)

For h'(600), the predicted VBF cross-section is ~100 fb plus ~50 fb from ggF, with a dominant decay into 2h (see Appendix and figure 10).

Finally, not to be forgotten, is the clarification of the status of h(96), only observed by CMS. h(96) seems unrelated to the GM model and could open new avenues. It could be interpreted as the RS scalar called **Radion**. As stated in [15], this particle will, through mixing effects, influence the properties of h(125).

VI. Future prospects at e+e- colliders

VI.1 Expected rates at a TeV collider

The various indications from LHC, when interpreted within the GM model, can be consolidated into quantitative predictions for future e+e- colliders with the noticeable exception of the second singlet scalar h', for which the mass is unknown. It is however plausible to assume that such a particle, to escape detection at LHC must be heavy and does not decay dominantly into ZZ (see figure 10).

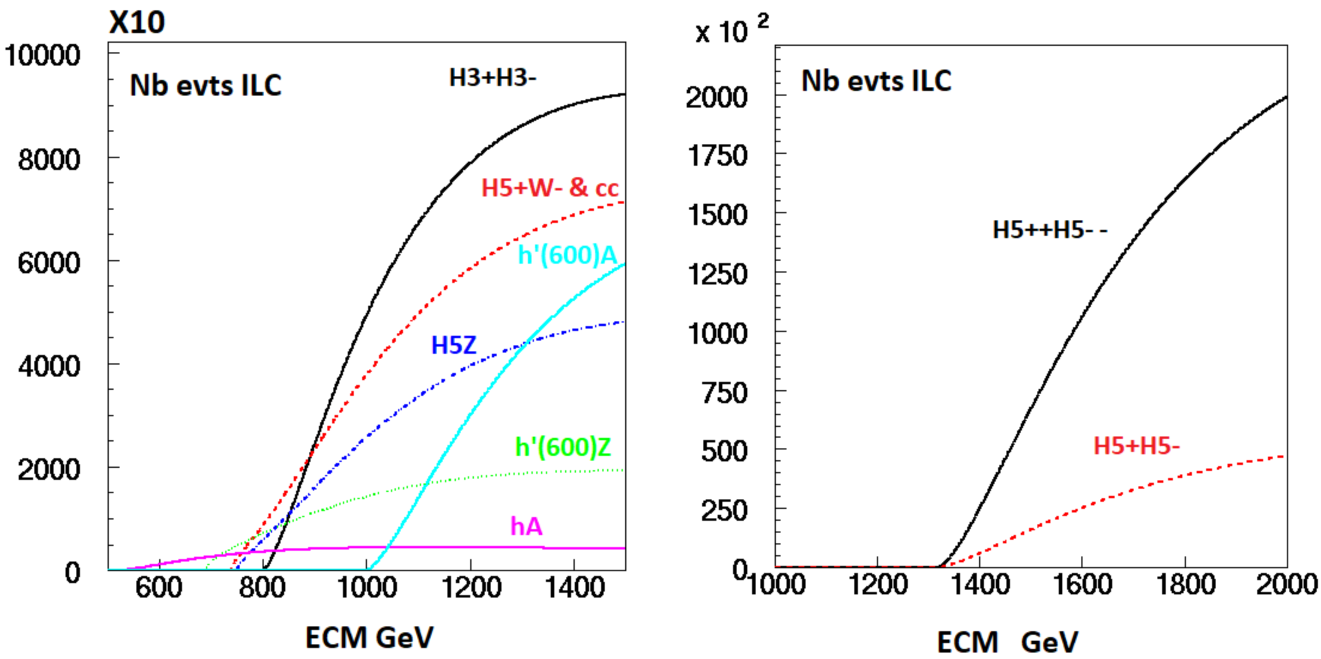


Figure 8: Predicted rates for various GM channels at ILC versus the centre of mass energy ECM in GeV. Mh'=600 GeV.

Figure 8 shows a clear advantage in reaching 1 TeV at a future e+e- collider. All GM final states could then be covered with the exception of doubly charged scalars requiring ECM> 1.4 TeV. H5++ can be singly produced in association with W-W- but the corresponding cross-section falls below 0.1 fb, as predicted in [16].

VI.2 Mass, width and cross-section measurements

For H5Z and h'Z channels, one can proceed as for h(125)Z, using Z into lepton pairs [17]. This method will also give access to the total width and the invisible width. Optimal centre of mass energy is ~mh'+200 GeV for h'Z and ~1000 GeV for H5Z.

The situation is however quite different from the SM measurements for h(125)Z since there is a negligible ZZ and h(125)Z background for these large masses. The recoil mass width comes from the large width of these heavy resonances, meaning that one can use also hadronic decays of W/Z/h (the later for hA) without a significant degradation. One can further improve the reconstruction accuracy by imposing the Z/W/h mass constraint.

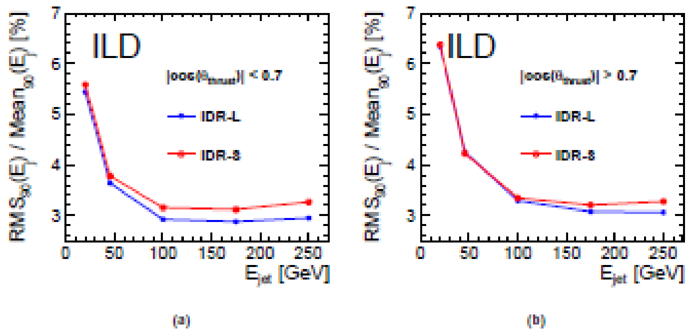


Figure 9: Expected jet resolution at ILD versus jet energy for two versions of the detector. Plot (a) corresponds to the barrel region, while plot b is for the end-cap.

Since H5+ and H5 are **mass-degenerate**, the recoil mass technique is delicate for H5Z and H5+W- modes. One needs to use the ability of the detector to separate W and Z masses. This ability has been thoroughly studied [18] and works quite well with the resolutions of figure 9.

If h' and H5 are mass-degenerate, a discrimination is still possible noticing that they share different final states, h' decaying dominantly into h(125)h(125).

The table below gives an estimate of the expected accuracies for resonances produced in e+e- at ECM=1 TeV.

Mode	δM MeV	δσ/σ %	δΓ/Γ %	δΓinv/Γ
H5Z	280 MeV	0.7%	0.5%	0.02%
h'(600)Z	180 MeV	1%	0.7%	0.03%
A(400)h(125)	460 MeV	2.4%	1.7%	0.2%

Clearly these estimates are too optimistic since they assume a perfect W-Z separation in hadronic modes, while one knows that, due to b semi-leptonic decays, Z->bb can leak into W. One can veto against b quarks with no damage for W decays. A full study with a **realistic simulation** is therefore required. Presently, my intention is to draw the attention on the importance of a **precise particle flow reconstruction** for Z/W/h hadronic decay in the detectors planned for future e+e-colliders and give a crude estimate of the performances that one can expect from an ILD-like detector.

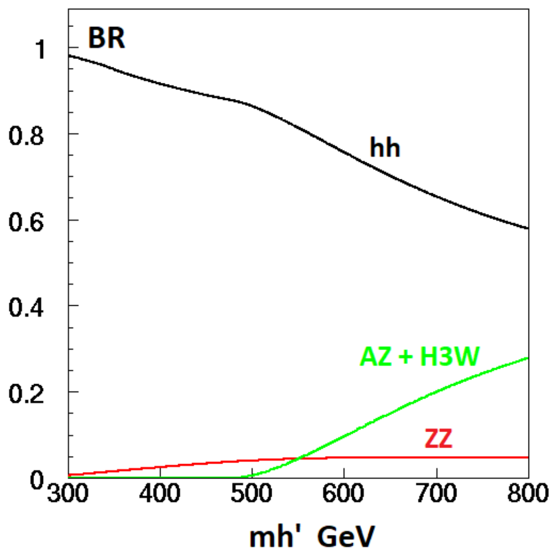


Figure 10: Branching ratio of the main decay modes of h' versus the mass of this particle.

For the channel H3+H3-, the mass can be deduced by measuring the cross-section, given its large cross section and steep dependence with the centre of mass energy.

Figure 10 shows the variation of the BR of h' for the main final states. Details of its derivation can be found in the Appendix. It shows that this particle is best identified in the hh mode. A 1 TeV linear collider should cover this search up to a mass of ~900 GeV in the h'Z channel. Note that, at 1 TeV, the SM background Zhh is an order of magnitude lower than the cross-section for Zh'(600), which allows a very clean measurement of the h' properties.

In conclusion, these examples show how a LC operating up to 1 TeV will be an insuperable instrument to perform the critical measurements needed to disentangle the very rich spectroscopy expected from the GM model.

Conclusions and future prospects

This note has attempted to describe and interpret the great diversity of indications for BSM physics, observed by ATLAS and CMS. Two entirely different approaches, one based on **spectroscopy**, the other on **topology** (multileptonic events associated to b jets, ttW), lead to the conclusion that a **BSM mechanism** is present in LHC data. Provided that phenomenology can provide a **consistent interpretation** of these apparently unrelated evidences, these effects should be taken seriously and drive the search strategy at LHC.

The conclusion of this paper is that they agree quite well with the **Georgi-Machacek** framework, with the exception of the couplings of A(400) to b and τ fermions which seems incompatible to the coupling to top quarks. Using the LHC measurement, one can precisely determine the parameters of this model and forge a useful tool to predict what is left to be measured or discovered both at LHC and at future e+e- machines. These results allow to design a proper strategy for discoveries at LHC avoiding the usual criticisms against open minded searches: the so called "**look elsewhere**" criteria, which inexorably weaken evidences, can be eliminated given that all masses and most couplings are by now determined, with no arbitrariness in the choice of channels. This reminds the situation when LHC was starting its search for the SM Higgs boson.

A major virtue of these findings is avoiding the ongoing blind **race for heavier masses**, with the implicit statement that SUSY is just behind the corner, at the risk of sacrificing genuine signals. One can already witness this dangerous tendency by noticing that, with more analysed luminosity, one does not observe progress for relevant low mass regions. This is true for the searches for A(400) and even more dramatic for h(96) where no real progress is happening.

With an appropriate approach for discoveries at LHC, one will not only be able to confirm/discard such effects but also to design an optimum strategy for improving present searches. A good example of this is the **"cascade" approach** where one tags by a high pT lepton an inclusive search for hadronic decays. One can allow further selections for this search (e.g. b-tag selection) and try to reconstruct the mass of the parent 5-plet heavy resonance.

This also true for the **ttW analysis** where one could try to reconstruct exclusively the resonance producing the 50% excess. Even at the inclusive level, one can observe a more striking deviation from the SM model predictions by applying a **VBF selection** to this channel. If the excess observed is due to H5+, then all these events come from ZW fusion, while the SM events originate mostly from ggF. This feature is a **critical prediction of my analysis**, which should be relatively easy to verify with standard methods. In this way, one would isolate a very pure GM signal and, ultimately, be able to reconstruct the mass of the parent Higgs from the 5-plet. This example beautifully illustrates the importance of **VBF physics** and the request that the detectors can still perform well on forward jet tagging in the HL-LHC phase.

A straightforward issue is clearly to consolidate the **4 leptons analysis for the ZZ** final state and combine the two LHC experiments. Separating ggF from VBF is a crucial issue.

An ultimate proof of the GM model – its **smoking gun** - is to observe a charged scalar. The easiest channel seems to be H3+->h(125)W+. H5+->ZW+ is allowed, contrary to the MSSM case, but dominant decay modes are AW+ and H3+Z, not easy to reconstruct exclusively.

For what concerns **future e+e- HE colliders,** like ILC and CLIC, these indications, when confirmed, will support the need to reach at least 1 TeV, with the highest possible luminosity. A large fraction of the program – h(125)A(400), H5(660)Z, H3+H3-, h'Z – can be performed with energies **reaching ~1 TeV**, while extending this energy above 1.5 TeV, one can observe the scalars with **double charge**. Final states from the 5-plet are **very complex** and will require not only high **luminosity** but also an **almost perfect detector** with best possible angular coverage for jet reconstruction and flavour tagging.

To conclude, there is a fascinating possibility that a model, proposed in 1985, could provide a plausible interpretation or the large set of anomalies observed by ATLAS and CMS.

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APPENDIX

I. The Georgi-Machacek model for pedestrians

This model allows having an exotic spectrum of scalars with double charges, without violating the so-called rho parameter constraint. By having higher isospin representations, it allows to have a direct coupling of H+ to WZ, which in the usual MSSM case is forbidden at the tree level.

One has the following content:

A 5-plet **H5-- H5- H5 H5+ H5++** with mass degeneracy.

These particles are fermiophobic and can only be produced by VBF and not by ggF, through a fermionic loop. H5+ can couples to ZW.

Triplet **H3- CP-odd H3 (called A) H3+** with mass degeneracy.

H3+ does not couple to ZW but couples to fermions and to hW.

Two singlets called **h(125) and h' ,** which can mix with a mixing angle α.

Below are summarized the main LHC observations and the GM interpretations.

H5 is observed in ZZ at 660 GeV, by selecting four leptons and combining, unofficially [1] CMS and ATLAS data. ATLAS, with the full statistics, confirms these findings and, in addition, shows an indication for VBF->ZZ. No signal is observed into WW. GM interpretation of this behaviour: in HWW/HZZ~2 in MSSM/SM, while HWW/HZZ~0.5 in GM.

H5, H5+, H5++ can couple to the Higgs triplet (see below), with the following decay modes:

- H5->AZ, explaining the ~20% excess in ttZ indicated by ATLAS and CMS
- H5+->AW+, explaining the ~50% excess in ttW observed by ATLAS and CMS
- H5+->ZW hint in ATLAS and CMS at ~500 GeV

H5++->W+W+ and W+H3+, the later giving ZW+W+ and tbW+. A limit is set on W+W+ by CMS.

These channels contribute to an inclusive search in 2 jets with lepton tag (from W/Z) in ATLAS, which gives an indication around 400 GeV.

Triplets can couple to a vector boson+h:

- A->Zh(125) observed in $\mu\mu$/ee +bjet-tag in ATLAS
- H3+->W+h(125) not observed

and to heavy fermions:

- A->tt in CMS, $\tau\tau$ +bjet-tag in ATLAS
- H3+->tb, $\tau+\nu$ not observed

The two singlets h(125) and h'(?) have the usual decays:

- h(125)->ZZ*/WW*, $\gamma\gamma$, $\tau\tau$, $\mu\mu$, bb, cc, gg
- h'(?)->WW/ZZ, hh, tt, $\tau\tau$, $\mu\mu$, bb, cc, gg
- h', if heavy enough, goes into AZ, H3+W-

II. Quantitative treatment of the GM model

In this model, the various relevant couplings depend on the following parameters:

- Two vacuum expectations **$v\chi$** and **$v\phi$**, which are related to the SM vacuum expectation v by the formula $v^2=8v\chi^2+v\phi^2$, v~246 GeV.
- Two mixing angles θ_H and α, with **$\cos\theta_H=c_H=v\phi/v$** and **$\sin\alpha=s\alpha$**

The various couplings to bosons and fermions are given in terms of these parameters as shown in the table of section II. I have used primarily [19] and [20] to derive these couplings.

II.1 h(125) constraints

The present conclusion seems to be that the GM model, as it is, gives a qualitative description of the various indications observed at LHC in the bosonic decays. At the quantitative level, it allows to fulfil the constraints imposed by Higgs precision measurements, if the two mixing angles fall within an interval defined in figure 11.

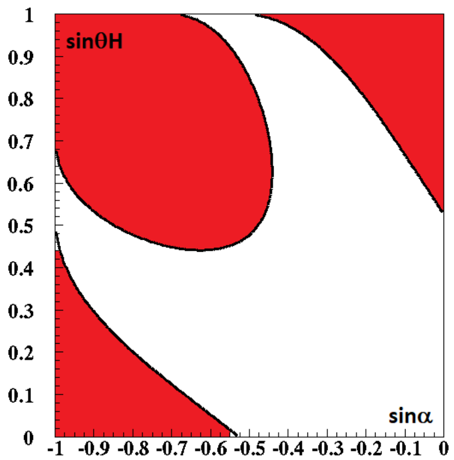

Figure 11: Allowed region for the two mixing angles of the GM.
The two contours correspond to h(125)ZZ/SM (amplitude) between 0.85 and 1.15.

II.2 Unitarity bounds on GM scalar masses

These bounds were derived by [21]. Lets briefly recall these results which can be read from figure 12 :

- mH3<400 GeV
- mH5<650 GeV
- mh'<700 GeV

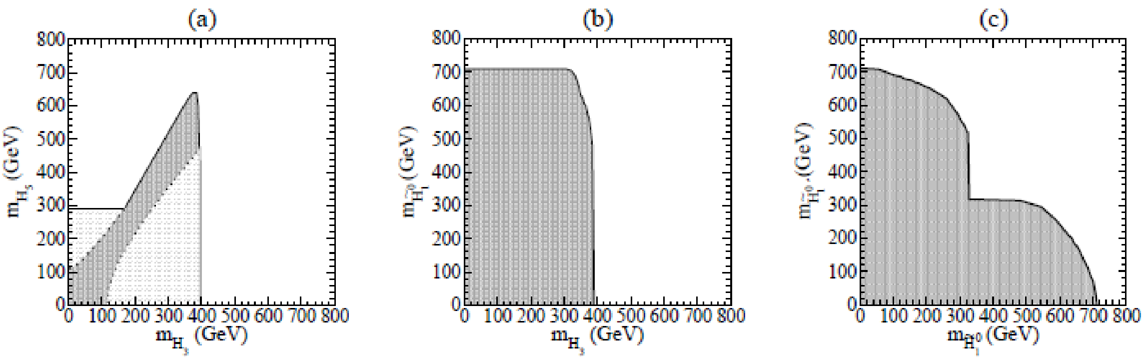

Figure 12: Allowed regions of the masses of the GM Higgs bosons. In figure (a), the light shadowed regions are excluded by Zbb. H01 is the SM boson while H01' is the other singlet.

Precision measurements from LEP1 on Zbb predict that **mH5~√3mH3**, in **striking agreement** with LHC present indications. Zbb also provides a constraint on tanθ_H as shown in figure 13 from [22].

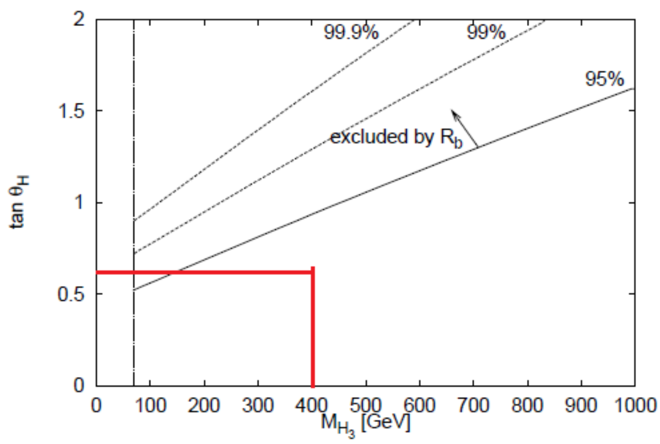

Figure 13: Bounds from Rb for the G-M model with SU(2)c symmetry. Indicated by red coordinates is my solution.

III. Constraints from LHC indications

III.1 Fermion couplings

Recall ATLAS and CMS observations:

- Associated production of A+bjet for hZ and ττ channels
- Yukawa coupling YAtt between 0.3 and 0.7

The first observation requires a large coupling of A to b to generate the proper rate of associated production A+bjet. The second features requires a large coupling of A to τ.

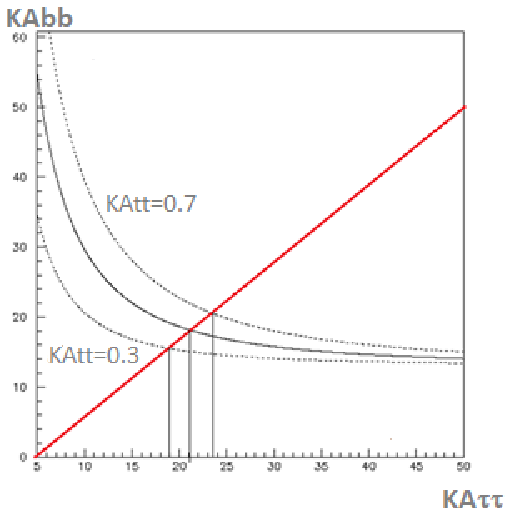

Figure 14: Using ATLAS indications for a 400 GeV resonance into tau pairs + b quarks and the CMS analysis for A(400) into top pairs, this figure shows the solutions for A couplings to tau and b for the KAtt interval deduced from CMS. The red line assumes the MSSM relation between tau and b couplings.

Let us define KAff as the ratio of the Aff coupling to the SM Yukawa coupling. Figure 14 shows the variation of KAττ vs KAbb for 3 values of KAtt: 0.3, 0.5 and 0.7. One sees that for a given value of KAbb, it is possible to adjust KAττ to reproduce the ATLAS data. It is however fair to say that small values of KAbb require unnaturally high values of KA$\tau\tau$. Therefore, the most natural choice is KAbb~20. The red line shows the MSSM relation between KAbb and KA$\tau\tau$, which leads to solution KAbb~20. In MSSM this reads as tanβ=20, which may sound acceptable, unless one notices that this result is **incompatible** with the standard relation KAtt=1/tanβ.

For what concerns GM, one expects KAtt=KAbb=tanθ_H~0.6, clearly also incompatible with LHC observations.

III.3 Bosonic constraints

Three constraints were used:

- The h(125)ZZ coupling constraint from LHC already discussed
- The H5(660)->ZZ constraint
- The A(400)->h(125)Z constraint

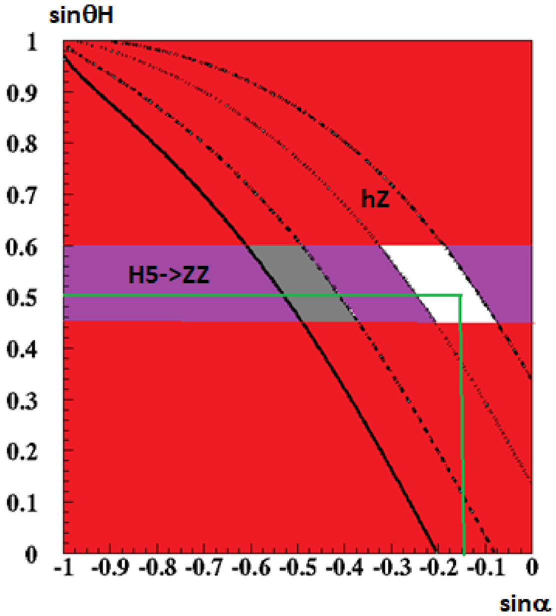

Figure 15: Constraints from A(400)->hZ (4 curves) and from H5->ZZ (magenta band). Defines two squares, the left-handed one (in grey) being rejected by the h(125)ZZ coupling constraint from figure 11.

The overall results in a narrow region, shown in figure 15. I have selected :

s_H=0.50 c_H=0.87 sα=-.15 cα=0.99 with the vacuum expectations **vχ=43 GeV** and **vϕ=214 GeV**.

Note that the search for H++(660)->W+W+ by CMS [23] can be translated into the upper bound sinθ_H<0.32, which seems to contradict the result of figure 15. This interpretation clearly depends on the assumption for mH3. In [24] it was recommended to assume that BR(H5++>W+W+)=100% while, in our case, the dominant decay will occur into H+3W+, hence an increase in the upper bound on sinθ_H.

IV. Isosinglet h’ properties

In GM, a heavy isosinglet h’ can decay into ZZ/WW, tt, ZA, WH3+ and hh. The fermionic decay width, proportional to $\sin^2\alpha$ is negligible. The hh decay is dominant, as shown in figure 10 in the main text. This result is claimed by [25] with some simplifications. Reference [26], more rigorous, reaches similar conclusions. For h’(600), one predicts BR(hh)=75%, BR(ZZ+WW)=15% and BR(H3W+AZ)=10%.

This means that:

- the search for h’ should use the hh final state
- h’(600) contributions to AZ and H3W cascades will be rather modest
- h’ and H5, if they share the same mass, will be easy to separate using hh

Both ATLAS [27] and CMS [28] observe a slight excess at ~600-800 GeV. This excess corresponds to a cross-section ~20±10fb in the VBF mode. The predicted cross-section for pp->h’(600)->hh is ~50 fb, with a large uncertainty.

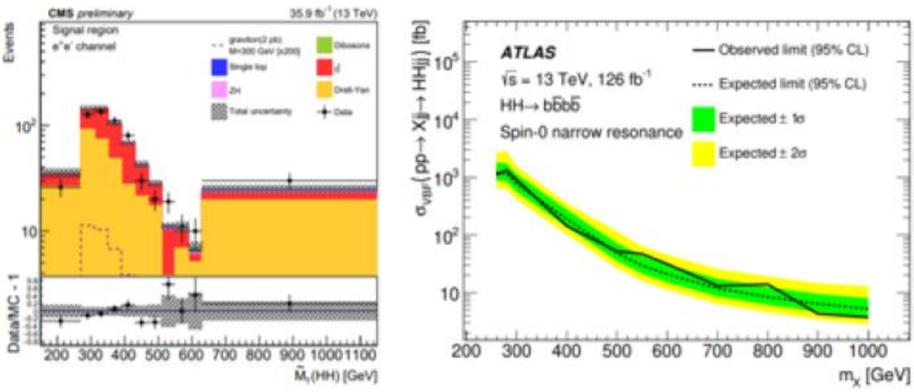

Figure 16 : Search from ATLAS and CMS for resonances decaying into h(125)h(125).