

# Triple Higgs couplings at LHC



Alain Le Yaouanc<sup>1</sup>, François Richard<sup>2</sup>

Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

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## Abstract

*A global interpretation of several significant indications of scalar resonances observed at LHC is achieved using the **Georgi Machacek model**. Among many other consequences, one predicts large cross sections for the processes  $ggF \rightarrow H(320) \rightarrow h(125)h(125)$  and  $A(151)A(151)$  and  $ggF \rightarrow A(420) \rightarrow H(320)Z$ , where **H(320)** has been observed in  $A(420) \rightarrow H(320)Z \rightarrow bbbb\ell\ell$  and where **A(151)** is observed into two photons accompanied by a  $b$  jet, a lepton or missing transverse energy. We predict that  $ggF \rightarrow H(320)$  has a cross section of about 2000 fb with a BR into  $h(125)h(125)$  of 17% and into  $A(151)A(151)$  of 45%. Henceforth we predict that  $ggF \rightarrow H(320) \rightarrow hh$  will dominate over the **SM process**  $h^* \rightarrow hh$ , where  $h$  is the SM  $h(125)$  scalar. One expects that  $H(320) \rightarrow A(151)A(151)$  can be observed into  $bbbb$ , becoming one of the most significant **BSM** phenomena identified so far. Arguments in favor of a SUSY version of GM are provided.*

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<sup>1</sup> Alain Le Yaouanc <alain.le-yaouanc@ijclab.in2p3.fr>

<sup>2</sup> Francois Richard <francois.richard@ijclab.in2p3.fr>

# I. Introduction

Measuring the triple Higgs coupling  $h^* \rightarrow hh$  has been identified as a major goal of our field, our ‘holy grail’, a direct exploration of the Higgs potential. The SM model process has a very small cross section and can be affected if there are resonances decaying into  $hh$ . In this note we will describe a scenario where there is such resonance and how it can be discovered with an optimized strategy. We will show that this resonance provides an interpretation of the pseudo-scalar  $A(151)$ , which is seen into two photons with an additional activity such as extra  $b$  jets, leptons and missing energy.

Recall that several indications for light scalars have been observed in a recent past. Relying on the **Georgi Machacek** model, GM, and on Haber et al. **sum rules**, an attempt for a global interpretation has been presented in [1].

Here we focus on a promising aspect of this work concerning the scalar **H(320)** observed in the cascade  $A(420) \rightarrow H(320)Z \rightarrow bbbb\ell+\ell-$  [2], interpreted as coming from  $H(320) \rightarrow h(125)h(125)$ . This result is shown and interpreted in the appendix. This mechanism constitutes a **source of bbbb events** which can be tagged using the  $Z$  decays into leptons and neutrinos. [2] provides an upper limit of about 70 fb for this process assuming that only  $hh$  contributes.

Interpreting  $H(320)$  as the companion of  $H^+(375)$  and  $H^{++}(450)$  in a five-plet representation of the GM model, we find that  $ggF \rightarrow H(320)$  has a cross of 2000 fb. This interpretation relies on our ability to predict the coupling  $g_{H(320)tt}$  using the ‘matrix method’ described in [1]. Our result says that the **Yukawa coupling**  $Y_{H(320)tt}$ , normalized to the SM value, is  $\sim 0.52$ .

GM predicts that  $H(320)$  will decay into  $A(151)A(151)$  with a BR of 45%. We interpret the origin of the various signatures accompanying the scalar **A(151)** observed into  $2\gamma$  [3] as coming either from the decays into  $bb$  and  $\tau\tau$  of the spectator  $A(151)$  or from  $Z$  decays in the process  $A(420) \rightarrow H(320)Z$ .

There are therefore two sources of  $A(151)A(151)$  (and  $h(125)h(125)$ ):

- One originating from the cascade  $A(420) \rightarrow H(320)Z \rightarrow A(151)A(151)Z$  which provides tagging of the  $2\gamma$  decays either from  $A(131) \rightarrow bb, \tau\tau$  or from  $Z \rightarrow bb, \ell+\ell-, \nu\nu$
- The other originating from  $ggF \rightarrow A(151)A(151)$  with tagging from  $bb, \tau\tau$

We predict that  $H(320)$  will decay into  **$h(125)h(125)$**  with a BR of 17.5%, the later result showing that the present SM searches for di-Higgs will be dominated by the contribution of this resonance, a **critical result**.

Given its large coupling to scalars,  $H(320)$  is very wide,  $\Gamma_{\text{tot}}=220$  GeV. One also predicts  $\Gamma_{ZZ}=5$  GeV, meaning that with such a small BR, this mode has not been detected at LHC.

## II. Impact on the searches for $hh \rightarrow 4b$

Let us first recall that present searches for  $hh$  combine final states like  $\gamma\gamma/WW/bb/\tau\tau$ . The  $4b$  final state has the highest BR but with a large QCD background.

The following bi-dimensional plot [5] indicates the distribution of the background for the observed  $bb$  sub-masses. This background peaks closely to the region of the  $h(125)h(125)$  signal region defined by the SR contour, rendering the detection challenging. This is even more the case for  $A(151)A(151)$  which will be centered on the maximum background but, as we will see below, with an expected cross section two orders of magnitude larger than the SM process.

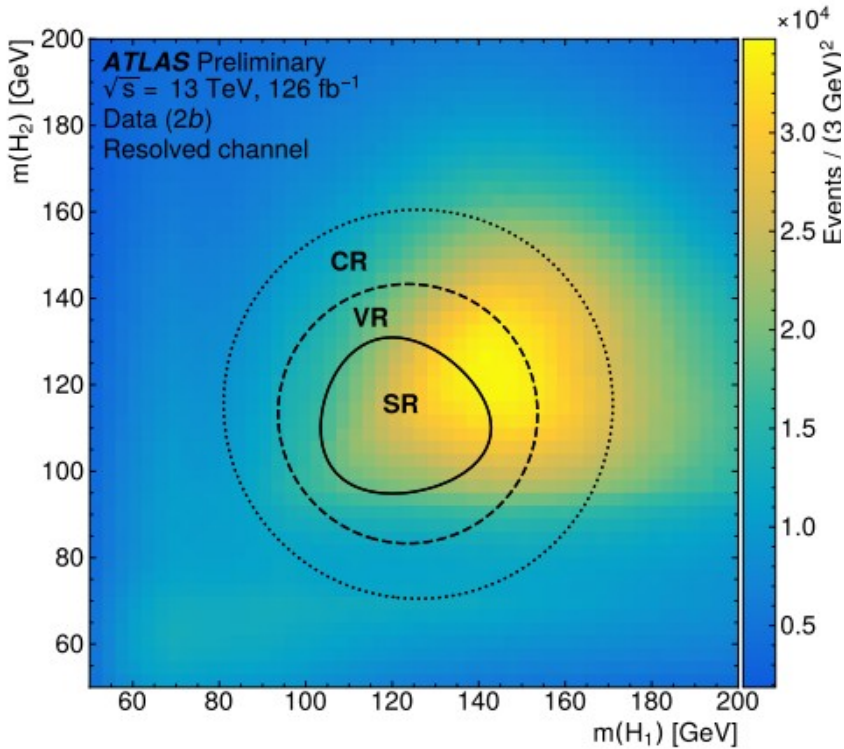


Figure 1:  $mH_1$  and  $mH_2$  are the reconstructed masses of the Higgs bosons candidates in  $4b$  final states, sorted by  $p_T$ .

From this figure one may infer that the SR selection only keeps about 1% (crude estimate) of the  $A(151)A(151)$  population which explains that in spite of its much higher rate, there is no significant excess with respect to the background as shown in figure 2 describing the limit achieved by ATLAS [5].

For the SM, one expects  $\sigma_{ggF}^{hh} = 31$  fb for  $\kappa_\lambda \sim 1$ . Taking into account the BR into  $bb$ , one expects a 10 fb cross section in  $4b$ . For low  $hh$  masses the efficiency in  $4b$  is of order 1%, meaning a negligible amount of events with respect to the huge QCD background.

Within GM, one may expect [1] significant deviations of  $\kappa_\lambda$  from the SM. Figure 3 indicates how the  $m(hh)$  distribution varies, showing that for the predicted value [1]  $\kappa_\lambda \sim 5$ , this distribution peaks in the region of the  $H(320)$  resonance but, again, with a much smaller cross section.

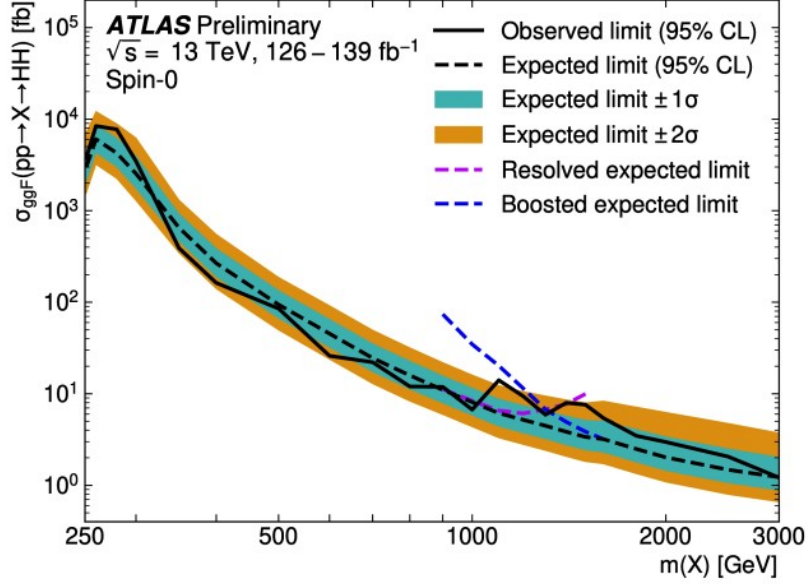


Figure 2: Expected (dashed black lines) and observed (solid black lines) 95% CL upper limits on the cross section times branching ratio of spin zero resonant  $X \rightarrow hh$  production.

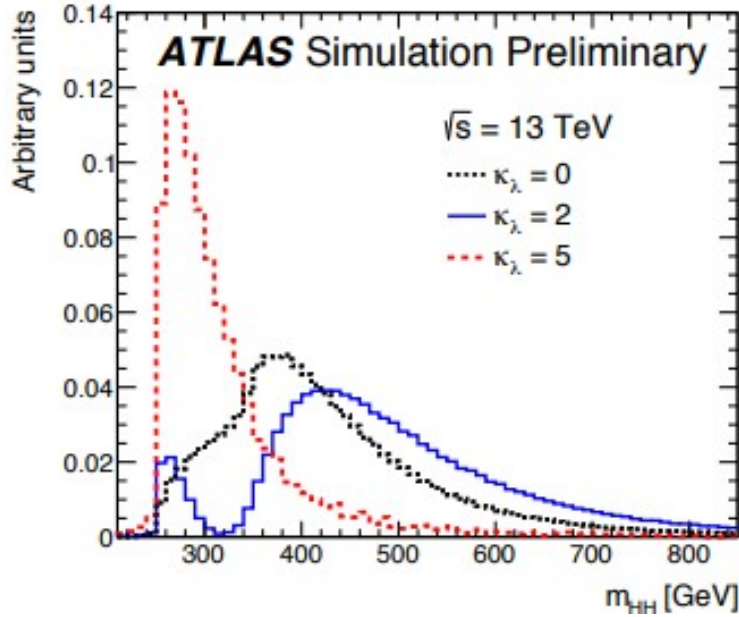


Figure 3 : Mass distribution of the  $hh$  final state for various values of the parameter  $\kappa_\lambda$ .

For  $ggF \rightarrow H(320) \rightarrow hh \rightarrow 4b$  the situation is much more favorable. One expects  $\sigma_{ggF} \sim 300$  fb. Adding  $A(420) \rightarrow H(320)Z$  and including the BR into  $4b$  (see appendix) this gives 140 fb. With 1% eff, one expects 170 events over a background of  $\sim 20000$  events, which should result in a 1.2 s.d. effect, barely visible in figure 2. Figure 3 suggests that an excess around 300 GeV due to  $H(320) \rightarrow hh$  could lead to a misinterpretation as due to a  $\kappa_\lambda$  anomaly.

This excess could be reinforced and made fully significant by adding a mass selection of  $A(151)A(151)$  which would keep a total number of 700 events, providing a  $\sim 5$  s.d. excess.

Given the huge QCD background involved in this analysis, it is essential to estimate this background with a reliable procedure, preferably using **data based methods**. This issue has been addressed by LHC collaborations and seems to be under control [7].

A better approach to observe this signal is to search for  $A(420) \rightarrow H(320) + Z$ . We already know [2] that a 3.8 s.d. excess has been reached without including  $A(151)A(151)$ . Even taking into account an increased background one therefore expects an excess **above  $\sim 10$  s.d.**

### III. Cross sections in $e^+e^-$

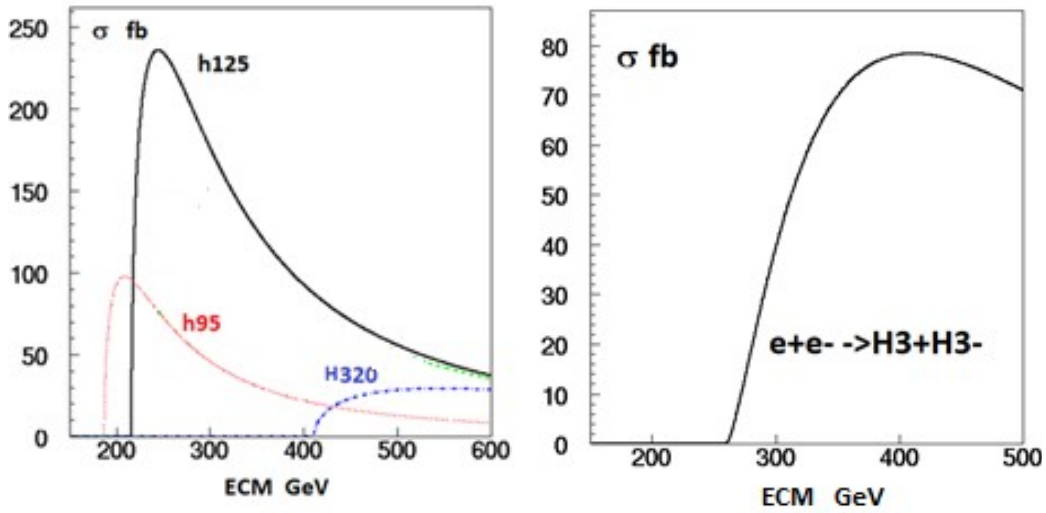


Figure 4: Predicted cross sections for the lightest scalars.

These curves are from [1]. The coupling of  $H(320)$  to  $ZZ$  is sufficiently large that the process  $e^+e^- \rightarrow H(320)Z$  has a substantial cross section as indicated in figure 4, where the lightest GM states are reported. An ILC operating at 500 GeV will collect  $\sim 4000 \text{ fb}^{-1}$ , producing more than  $10^5$  such events.

An  $e^+e^-$  machine should be able to separate the contributions of  $A(151)A(151)$  and  $h(125)h(125)$  in  $bbbb$ , benefiting from kinematical constraints. It would presumably also isolate the  $h(95)h(95)$  channel.

### IV A road to discoveries

What to do next ? It seems that the best strategy would be to update the  $A \rightarrow ZH \rightarrow bbbbZ$  analysis by including a mass selection for the  $A(151)A(151)$  contribution. One would kill 3 birds with the same bullet since the analysis would:

1. Confirm  $H(320)$
2. Confirm  $A(420)$
3. Confirm  $A(151)$

One could also try discovering  $A(420) \rightarrow H(130)H(130)Z \rightarrow bcbcZ$ , recalling that 36% of  $H(320)$  decays go into  $H+H^-$ .

The road to di-Higgs inclusive discovery into bbbb is also opened but perhaps more arduous.

## IV. Summary and conclusions

This brief analysis shows that the bbbb topology is likely to provide a proof of the presence of **triple Higgs couplings** like  $H(320) \rightarrow A(151)A(151)$  and  $h(125)h(125) \rightarrow bbbb$ , which would constitute the strongest evidence for BSM physics at LHC, a first step in exploring the properties of the Higgs potential within the GM model. An other access to such couplings would be the direct identification of  $H^{++}(450) \rightarrow H^{+}(130)H^{+}(130)$  which is dominant according to our analysis [1].

We have identified two potential sources providing  $H(320)$ :

- The cascade  $A(420) \rightarrow H(320)Z$  which gave the first evidence for  $H(320)$ , with a cross section of about 700 fb
- The gluon fusion process  $ggF \rightarrow H(320)$  with a cross section of 2000 fb

These two channels need therefore to be analysed with the assumption that the bbbb final state can also originate from  **$A(151)A(151)$** .

For what concerns the channel  **$A(420) \rightarrow H(320)Z$** , adding  $h(125)h(125)$  and  $A(151)A(151)$  a very convincing proof of the resonances  $A(420)$ ,  $H(320)$  and  $A(151)$  should be reached in the **bbbbZ final state**.

**We threfore predict that by adding  $h(125)h(125)$  and  $A(151)A(151)$  contributions, the di-Higgs search should deliver a fully significant signal for  $H(320)$ , well above 5 s.d., which would constitute the most convincing signal for proving BSM physics at LHC.**

Note that these results do not require the HL-LHC phase but can be reached with the RUN2 data.

It is however fair to add a word of caution since this prediction is based on results coming from several indications which may vanish and from a chain of reasoning which is quite involved. Recall, in particular that our evaluation of  $ggF \rightarrow H(320)$  relies on an indirect evaluation of the top Yukawa coupling of  $H(320)$  through the ‘matrix method’ developed in in [1].

We also rely on an indirect derivation of the triple scalar coupling  $H(320) \rightarrow A(151)A(151)$  which follows from an estimate of the BR of  $H^{++}(450)$  into  $W+W+$  provided by the unitarity sum rules.

It is however fair to say that these predictions rely on a large set of **direct observations** provided by LHC data which are consistently described within a **solid phenomenological framework** which should guide future searches.

This framework may however still require further extensions, as suggested by a tension between the value of the **vacuum expectation u** deduced from the SR and the indirect determination of this quantity from the B physics constraints. The SUSY version of GM, **SGM**, described in section V of the appendix, is a potential candidate to remedy to this tension. It contains a larger number of scalars to be discovered with HL-LHC.

## Acknowledgments

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*Thanks to Mioaran Lu from ATLAS for following closely this work.*

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# Appendix

## I. Inputs for H(320)

Figure 5 from [2] shows the evidence for the cascade  $A(420) \rightarrow H(320)Z \rightarrow bbbb\ell + \ell^-$ . The local significance reaches 3.8 s.d. Recall [1] that  $A(420)$  is also observed in top pairs and through the transition  $H(650) \rightarrow A(420)Z \rightarrow t\bar{t}\ell + \ell^-$ . Based on an MSSM interpretation which predicts  $m_A > m_H$ , this analysis assumes, without proof,  $A(650) \rightarrow H(420)Z$ , at variance with our interpretation within the GM model.

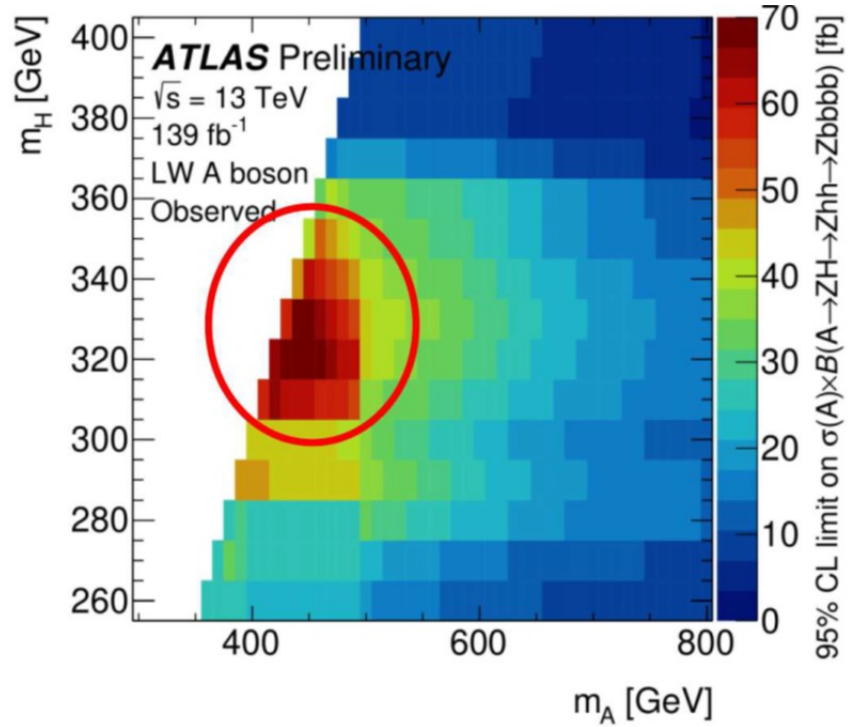


Figure 5: Observed upper bounds at 95% CL on  $\sigma(A) \times BR(A \rightarrow ZH \rightarrow Zh h \rightarrow Zbbbb)$  in the  $(m_A, m_H)$  plane for a large width  $A(420)$  boson.

If one assumes that  $H(320)$  is identified to  $H_5$  from the GM fivetuple of GM, it decays into  $A(151)A(151)$  and  $H^+(130)H^-(130)$  and it decouples from singlet states. Mixing deeply modifies this picture, as will see in section 3, allowing decays into  $h(125)h(125)$  and, to a lesser degree, into  $h'(95)h'(95)$ . One predicts  $AA/H+H-/hh/h'h'=45\%/36\%/17.5\%/0.5\%$  with  $\Gamma_{tot}=220$  GeV.

It is likely that the mass and the width deduced from  $A(420) \rightarrow HZ$ , are underestimated given the constraints of this decay which is close to the kinematical limit.

Assuming  $H(320) \rightarrow hh$ , [2] sets a limit  $\sigma(A)B(A \rightarrow H(320)Z \rightarrow bbbb) < 70 \text{ fb with 95\% CL}$ . The excess above background suggests that this cross section is  $\sim 35 \text{ fb}$ . Taking into account the BR into  $hh$  and the BR of  $hh$  into  $4b$ , this amounts to a cross section  $\sigma_{A \rightarrow H(320)Z} \sim 700 \text{ fb}$ , to be compared to  $\sigma_{ggF \rightarrow H(320)} = 2000 \text{ fb}$ .

If  $A(420)$  couples maximally to the top quark, one expects  $\sigma_{gg \rightarrow A(420)} \sim 40 \text{ pb}$  and a width into top pairs  $\sim 10 \text{ GeV}$ . This means that  $\text{BR}(A(420) \rightarrow HZ) = 2\%$ . This small value does not come as a surprise given that the reaction  $A(420) \rightarrow H(320)Z$  is close to the kinematical limit. One may speculate that  $A(420) \rightarrow h(125)Z$  is likely to be observable given the more favourable phase space. There were indeed indication for such a reaction [15].

## II. Indications for $A(151) \rightarrow \gamma\gamma + \text{tags}$

[3] has collected the various indications for a resonance in two photons which can be observed using various tagging signatures as shown in figure 6. The combination of these observations reaches **4.8 s.d.**

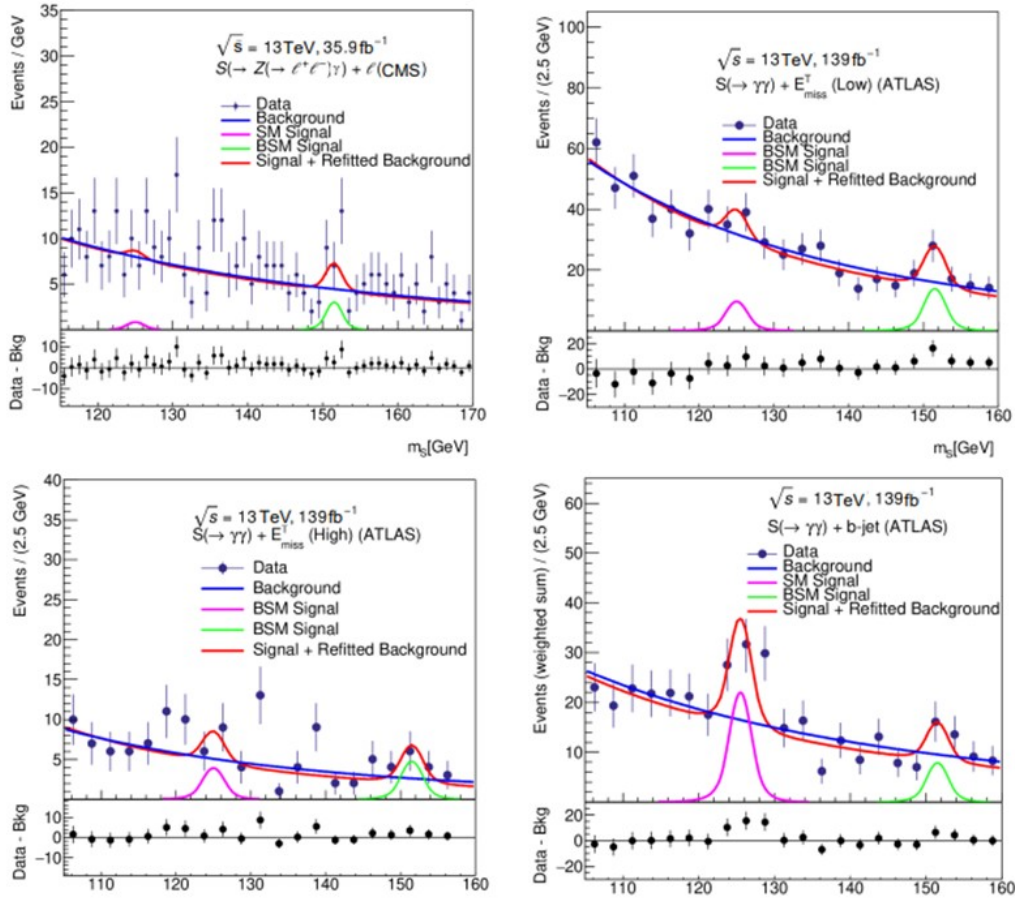


Figure 6:  $\gamma\gamma$  mass distributions observed by ATLAS in CMS when adding a tagging requirement.

These observations appear compatible with the processes:

$$H(320)(Z) \rightarrow A(151)A(151) \rightarrow \gamma\gamma + \tau\tau \text{ or } bb \text{ (bb, } \nu\nu, e+e-) \text{}$$

A recent indication [7] for the  $\tau\tau$  interpretation is shown in figure 7.

A back of the envelope estimate including the following table derived from GM, allows to quantitatively comfort our interpretation of the origin of these tagged events.

| Channel    | bb | $\tau\tau$ | cc  | gg | $\gamma\gamma$ |
|------------|----|------------|-----|----|----------------|
| BR(A151) % | 74 | 8          | 3.7 | 15 | 0.13           |

Note the difference with respect to h(125) where the BR in bb is below 60% given the ZZ/WW contributions.

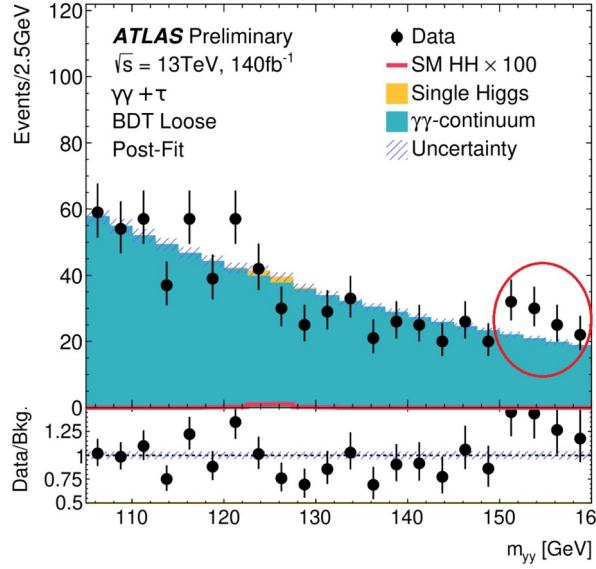


Figure 7:  $\gamma\gamma$  mass distribution observed in [7] when requiring the presence of a  $\tau$  particle.

Since A(151) has not been observed in the ZZ mode, it seems reasonable to assume that it is a **CP odd scalar**. This fits perfectly to the GM description where H+(130) and A(151) pertain to the same triplet.

It was suggested [3] that this resonance is also observed in the WW mode. However one should not forget that the mass resolution for this mode, observed in leptonic modes with neutrinos, is poor and that there is no clear mass separation with the SM mode. Therefore this interpretation remains an open question.

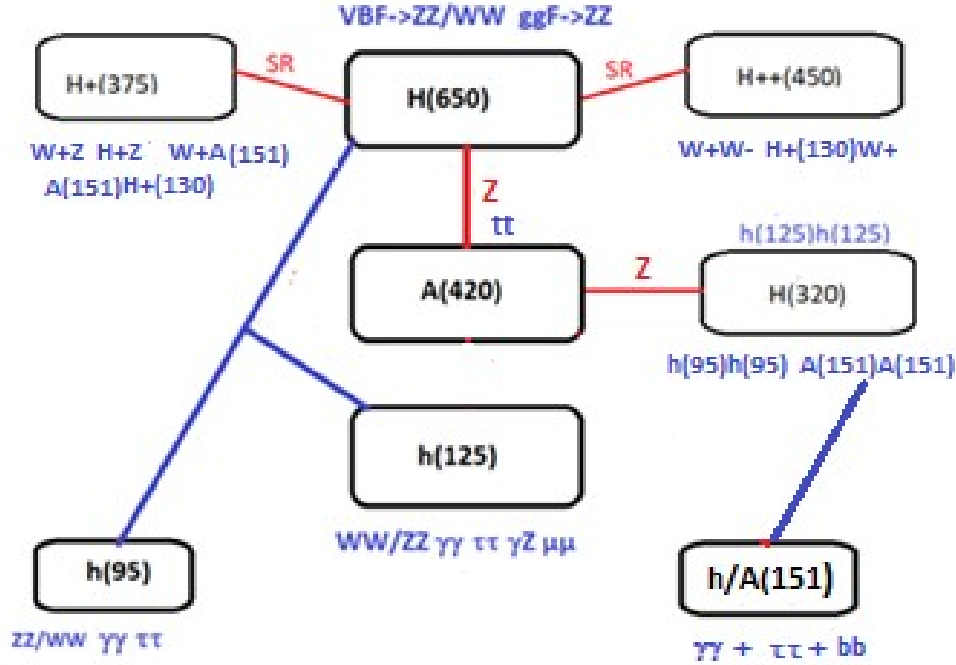
### III. A global interpretation of LHC indications for scalars

This section intends to collect and summarize inputs from [1] which are needed for the present analysis.

The diagram below summarizes our present list of significant LHC findings [1]. This reference also gives the list of papers providing the various indications and their significance with a marked emphasis on H(650) which is the driving input for the sum Haber et al. rules.

The table below summarizes a global interpretation of the various indications collected in terms of an **extended Georgi Machacek model**. One is able to identify all states predicted by the original GM model.

To interpret H(650) properties, one has to add an extra doublet to this model, predicting 3 additional states, two of them fitting nicely in this extension, while there is no direct evidence for the predicted extra charged scalar **H+(x)**. We further discuss this issue in section IV.



| GM   | Isosinglet   | h95  | h125         |
|------|--------------|------|--------------|
|      | Isotriplet   | A151 | H+130        |
|      | Isofiveplet  | H320 | H+375 H++450 |
| E-GM | Extradoublet | A420 | H650 H+ ?    |

One has four CP even scalars and the following table, derived as explained in [1], indicates that the physical states are mixtures of the doublets and triplet fields, including the SM h(125).

|      | 1              | 2              | 3     | 4     | Y <sub>tt</sub> /SM | ZZ/SM | WW/SM |
|------|----------------|----------------|-------|-------|---------------------|-------|-------|
|      | φ <sub>1</sub> | φ <sub>2</sub> | χ     | ξ     |                     |       |       |
| H95  | 0.10           | - 0.56         | 0     | 0.80  | - 0.96              | -0.34 | 0.60  |
| H125 | 0.58           | 0.58           | 0.47  | 0.33  | ~1                  | ~1    | ~1    |
| H320 | 0.27           | 0.34           | -0.80 | 0.35  | 0.50                | -1.20 | -0.40 |
| H650 | 0.79           | -0.50          | -0.1  | -0.34 | -0.90               | -0.60 | -0.90 |

$v_1=-30$  GeV,  $v_2=102$  GeV are vacuum expectations for the for the two doublets,  $u=70$  GeV for the triplets. One has  $v=174$  GeV= $\sqrt{v_1^2+v_2^2+4u^2}$ . With a **type I solution** assumed for the Yukawa couplings, one has  $Y_i/SM=x_i 2mt/v$ . For the HiWW coupling normalised to the SM value, one has:

$$H_{iWW}/SM=(x_{i1}v_1+x_{i2}v_2)/v+(2x_{i3}+2\sqrt{2}x_{i4})/v$$

Missing quantities concerning H(320) and h(95) (see the colored squares above) can be predicted, in particular for what concerns H(320).

Above matrix gives critical informations about the four neutral candidates. Generally speaking their properties **markedly differ from the isospin proper states of GM** which has very important experimental consequences. As an example if H(320) would strictly behave as a proper state of H5, it would not couple to h(125) and H(320) would not have been discovered ! Few additional comments:

- H650 is dominated by the two doublet components, and therefore is not a likely candidate for the 5-plet H5 which in GM is a pure triplet state
- H320 is dominated by the triplet components hence naturally fits into H5, with a mass compatible with H+(375) and H++(450)
- The SM scalar h125 contains a large fraction of triplet components which have, so far, not induced significant deviations from the SM.
- h95 is dominated by a triplet component

In the **charged sector**, the **unitarity sum rules from** [8] relate W+W- and ZZ couplings of the neutral scalars to those of the **charged scalars**. One derives:

$$g^2_{H^{++}WW}/SM=1.3\pm0.4 \quad g^2_{H^{+}ZW}/SM=0.8\pm0.2$$

hence the partial width of elastic modes:

$$\Gamma_{H^{++}WW(450)}=15\pm5 \text{ GeV} \quad \Gamma_{H^{+}ZW(375)}=12\pm4 \text{ GeV}.$$

From these and the SR, one can deduce the total VBF cross section, the elastic BR and the total widths as given in the following table:

| Channel  | $\sigma_{VBF}$ fb | $\sigma_{VBF}$ VV fb | BR(VV) %   | $\Gamma_{tot}$ GeV |
|----------|-------------------|----------------------|------------|--------------------|
| H++(450) | 830               | 75                   | 9 $\pm$ 4  | 160                |
| H+(375)  | 810               | 125                  | 15 $\pm$ 8 | 80                 |

**These are model independent results** derived from measurements [1]. BR into W+W+ and ZW+ are below 20%, implying dominant contributions of HV and HH final states. Indications for H+(130)->bc and A(151)-> $\gamma\gamma$  which likely belong to the GM triplet comfort this interpretation.

Within GM, one can deduce the vacuum expectation of the two triplets constituents, called hereafter **u** and the related quantity **s<sub>H</sub>**. This allows to estimate BR(VH) which turns out to be of the same order as BR(VV), therefore not solving the problem, as summarized in the following table.

| Channel | u GeV       | s <sub>H</sub> | BR(VV) % | BR(VH) % |
|---------|-------------|----------------|----------|----------|
| H++     | 70 $\pm$ 12 | 0.80 $\pm$ 0.1 | 9        | 12.5     |
| H+      | 80 $\pm$ 13 | 0.90 $\pm$ 0.2 | 15       | 17       |

One can then adjust the GM parameters such that the HH contributions complete the missing BR. Together with the observed properties of h(125) and h(95), this allows a **full extraction** of the other parameters of this model [1], a way to **fully reconstruct the Higgs potential** in the GM model.

This results in the following GM parameters<sup>3</sup>:

| u GeV | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | $\lambda_4$ | $\lambda_5$ | M1 GeV | M2 GeV |
|-------|-------------|-------------|-------------|-------------|-------------|--------|--------|
| 70    | 0.07        | -1.4        | -1.06       | 1.25        | -6.3        | 950    | 400    |

Note that the large **values of the parameters M1 and M2** originate from the requirement that  $H^{++} \rightarrow H+H$  is dominant over  $W+W$ . They naturally induce **large triple Higgs couplings**.

To determine the loop contributions for  $\gamma\gamma$  and  $Z\gamma$ , an additional parameter governing the **mixing** between the two lightest scalars, h95 and h125, is needed. This parameter is adjusted such that  $\mu h125\gamma\gamma=1$ , compatible with LHC measurements. As expected, one observes, through the loops, significant effects on:

- $\mu125Z\gamma=2.3$  as compared to  $\mu125Z\gamma=2.2\pm0.7$  [9]
- $\mu95\gamma\gamma=0.3$  (instead of 1 w/o the charged scalars) as compared to  $\mu95\gamma\gamma=0.24\pm0.09$  from [10].

One can also extract the triple h125 coupling, normalized to the SM  $\kappa_\lambda=5$ . This result is compatible with expectation as shown in figure 8.

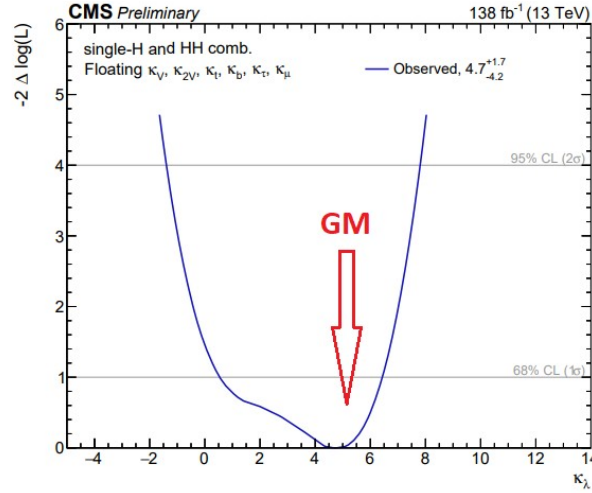


Figure 8 : A recent compilation from CMS [11] on the self-coupling parameter  $\kappa_\lambda$  normalised to the SM. Observed likelihood scans of  $\kappa_\lambda$  assuming  $\kappa_V$ ,  $\kappa_{2V}$ ,  $\kappa_t$ ,  $\kappa_b$ ,  $\kappa_\tau$ , and  $\kappa_\mu$  as unconstrained nuisance parameters.

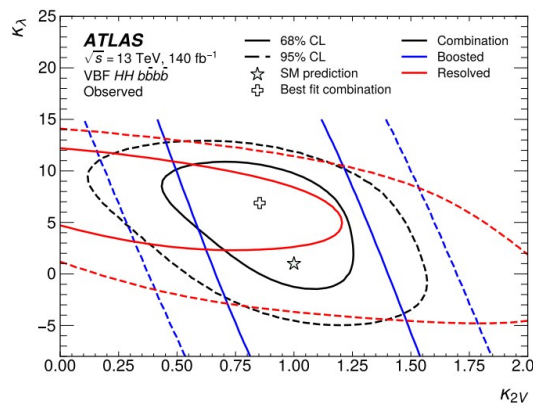


Figure 9: Observed likelihood contours in the  $\kappa_\lambda$   $\kappa_{2V}$  plane. The black ellipse is the result of a combination of resolved and unresolved VBF  $bbbb$  analyses.

<sup>3</sup> Beware that these parameters follow the conventions from [1] while other authors use the mass parameters M1 & M2 with opposite signs and reverse  $\lambda_2$  and  $\lambda_4$ .

Finally, CMS has issued a new analysis on  $HHV \rightarrow bbbbV$  and  $HH$  channels [16], without a search for resonances. Some excess, at  $\sim 2$  s.d. level, is present for  $\kappa_\lambda=1$  on the measured cross sections, both for  $HHV$  and  $HH$  channels, as shown in figure 10. These excesses correspond to the predicted cross sections  $350+120$  fb for  $H(320) \rightarrow hh$ , and 120 fb for  $A \rightarrow ZH(320) \rightarrow Zhh$ .

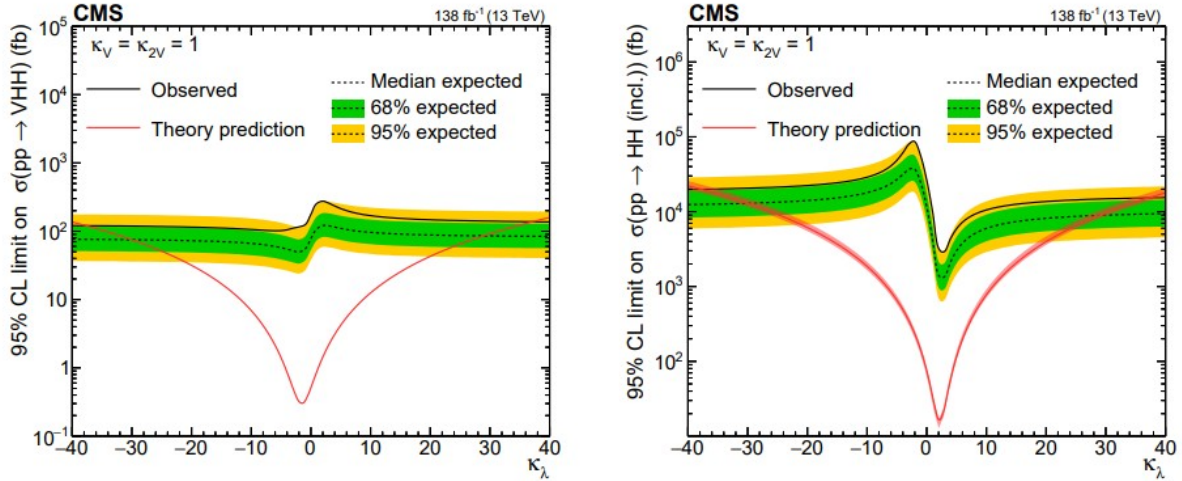


Figure 10: 95% CL limit on  $VHH$  (left) and  $HH$  (right) cross sections for SM couplings for  $\kappa_V=\kappa_{2V}=1$ .

#### IV The missing $H^\pm$

In [12] there is a candidate for  $H^\pm \rightarrow ttW^\pm$  provided by an inclusive search for heavy resonances decaying into two jets accompanied by a high  $pt$  lepton interpreted as coming from a  $W^\pm$ . The reconstructed mass of the two jets is compatible with  $A(420) \rightarrow tt$  and therefore is a candidate for:

$$H^\pm \rightarrow A(420)W^\pm$$

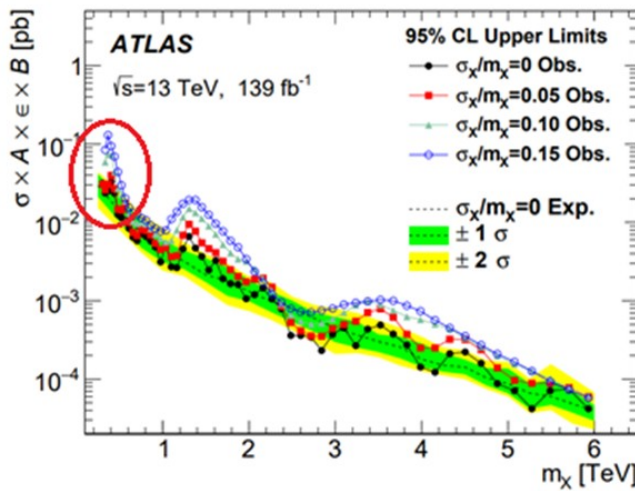


Figure 11: Jet-Jet mass recoiling to a large  $pt$  lepton.

Figure 11 shows the largest effect for large values of  $\sigma_X/m_X$  implying that A(420) has a total width of order 100 GeV. This width could also be due to a poor mass resolution.

This process mirrors the process observed by [14] with our interpretation:

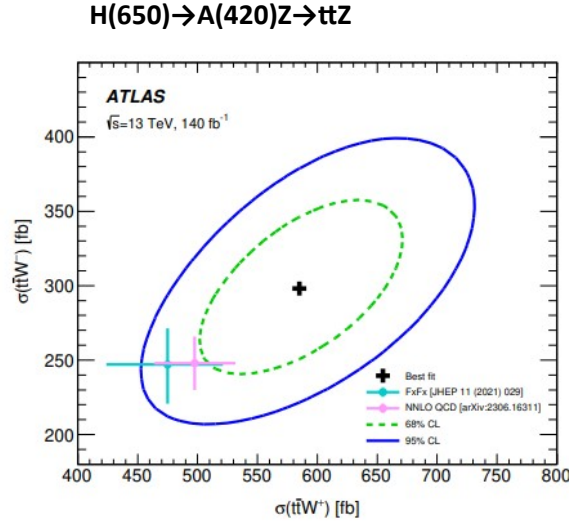


Figure 12: Measurements of  $ttW+$  and  $ttW-$  cross sections [13]

It is likely that these two particles have about the same mass. This finding also provides an interpretation for the excess reported for the  $ttW+$  and  $ttW-$  channels [13] shown in figure 12.

Within GM, a plausible production mechanism is the fusion  $W+Z \rightarrow H+$ . This would explain that the excess is more pronounced for  $ttW+$ , given that energetic  $W$  are emitted by the valence quarks of the incoming proton:

$$p \rightarrow u \rightarrow W+ / p \rightarrow d \rightarrow W- = 2$$

One should therefore also observe  $H+ \rightarrow ZW$  provided that the BR is not too small.

This interpretation has a practical consequence on the SR: this extra  $H+$  should contribute and reduce accordingly the value of the vacuum expectation  $u$ , which would be welcome given the constraints due to B physics (see figure 13 of next section).

The contribution from  $H(650) \rightarrow AZ \rightarrow ttZ$  shows no impact on  $\sigma(ttZ)$  measurements. This difference, still marginally significant, indicates that  $\sigma(H650 \rightarrow AZ)BR(ttZ)$  is smaller than  $\sigma(H+ \rightarrow AW+)BR(ttW+)$  which, to be understood, requires a precise determination of the composition of  $H+$  not yet achieved so far.

## V SUSY extension of GM

Accommodating  $H(650)$  has required adding an extra doublet. Is this sufficient to accommodate present observables ? This does not seem to be the case judging from the B physics constraints shown in figure 13. The value of  $u \sim 80$  GeV derived from the SR seems too large with respect to the upper bounds derived from B physics measurements. In the ZW SR we have not taken into account the contribution from the heavy  $H+$  predicted by e-GM. This particle seems to couple to  $ZW+$  and therefore should also contribute to this SR, therefore reducing the value of  $u$ .

A SUSY version of GM, SGM [18], would predict an extra  $H^{++}$ , which also reduces the value of  $u$  in the WW SR, reestablishing the consistence between the results of the two SR.

It is therefore tempting to predict that SGM could be at work, doubling the number of scalars to be discovered at LHC with respect to GM, not to speak of the SUSY sector itself.

If so, one expects the following isospin content:

- Three singlets  $h \ h' \ a$
- Two doublets  $H^+ \ H^- \ A$
- 1 Triplet  $H^+ \ A$
- 1 Fiveplet scalar  $H^{++} \ H^+ \ H^- \ H$
- 1 Fiveplet pseudo  $H'^{++} \ H'^+ \ A$

**In total 20 states :  $2H^{++} \ 2H^- \ - \ 4 \ H^+ \ 4H^- \ - \ 4A \ 4H$**

Therefore no change in the neutral CP even sector and  $u$  likely to be reduced by SR contributions due to additional charged scalars.

Note that for the WW SR, one may think that only the doublet and scalar fiveplet isospin states contribute but recall that the physical states may substantially differ from the isospin states, therefore the four neutral CP even physical states will contribute as well as the two doubly charged physical states.

SGM is therefore a likely valid extension of GM. It has **20 physical states** a priori distinct from the SGM isospin states.

SR are modified with  **$u$  reduced** in accordance with **B physics**. There are **two  $H^{++}$  physical** states for WW SR but still four neutral scalars. SGM provides all the “goodies” of SUSY:

**Perturbativity, computability, GUT**

**EWSB** naturally triggered

DM candidate

$M_h=125$  GeV is accommodated with less “tension” on **stop masses** (6 TeV in MSSM)

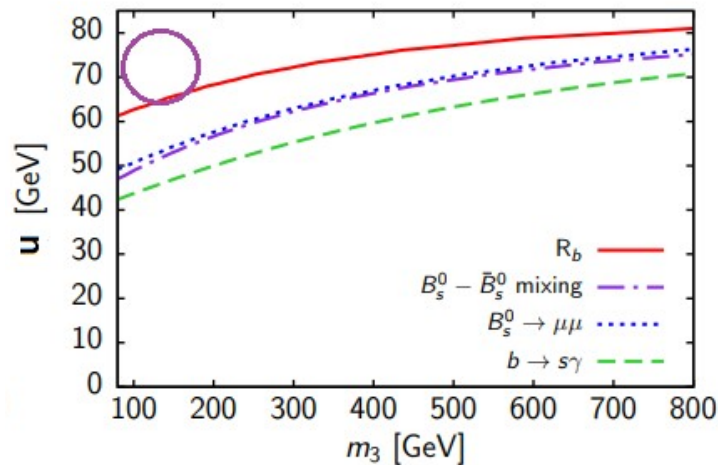


Figure 13: This picture, taken from [18], indicates the upper limits (2 s.d. level) derived on the parameter  $u$  of the GM model from B physics PM. The ellipse shows our prediction.

To summarize, there are indications that e-GM is incomplete and that the GM spectrum could be even richer than suggested by the various indications presently identified in LHC data. SGM predicts that there could be **two additional CP odd scalars, one  $H^+$  and one  $H^{++}$ , to be discovered** and of course renewed motivation to search for the SUSY particles.

The next obvious question is: **where is SUSY** ? As well-known, there are scenarios where SUSY has so far escaped to LHC searches due to mass degeneracies, the so called ‘compressed-spectrum’ case, which explains an absence of signal [20] at LHC. This reference uses an NMSSM interpretation of SUSY which, as in SGM, contains singlets. It recalls that there are weak but coincidental indications from ATLAS and CMS for quasi-degenerate gauginos. This model predicts three neutralinos and one chargino clustering around 250 GeV, a scenario eminently favourable to an ILC collider reaching at least 500 GeV.

Reconciling these apparently independent descriptions is an urgent task for phenomenology.