Searches for light scalars at LHC and interpretation of the findings

F. Richard

In the name of the Calcutta-Orsay-Montpellier collaboration

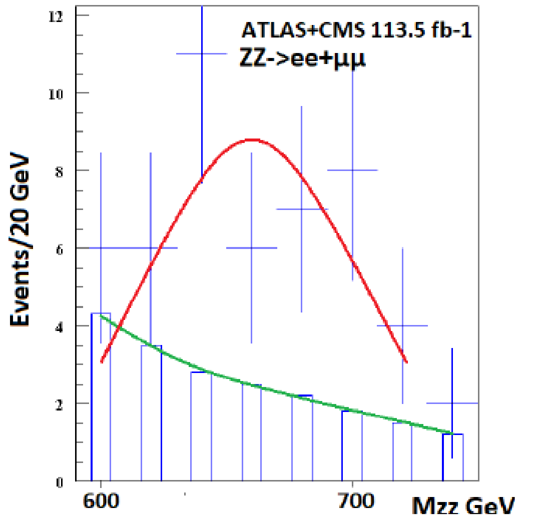
CosPT Workshop II/2022

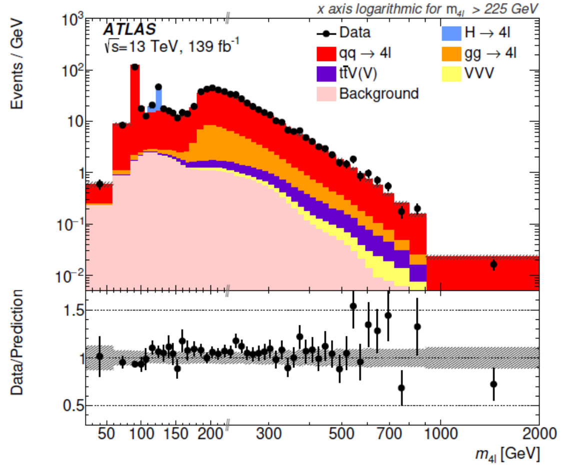
Introduction

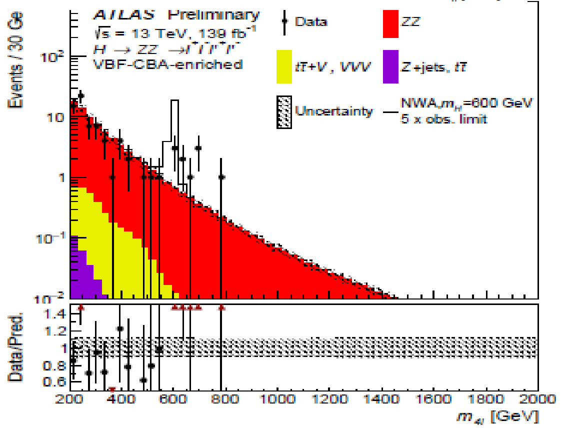
- Before the HEP community can choose between the proposed e+e- colliders, a valid question to ask is: which energy is needed to observe **directly** BSM physics ?
- In other words, which are the masses of the lightest BSM particles ?
- If there are such particles, they should already appear **in LHC present data** as was the case for h(125) at Tevatron
- My prejudice, to avoid "**blind searches**": as for the Higgs in the SM and the pions in QCD, the lightest objects are scalars residuals from a **symmetry breaking mechanism**
- With the help of experts listed at the end of this talk, I have carried such an investigation and tried to interpret consistently **several indications from LHC** by extending the usual **2HD** models to **triplets** (**Georgi Machacek** model GM)
- Given the short time allocated, I will only very partially cover this vast topic and concentrate on one channel, **H(650),** of major relevance for our future

1st indication : H->ZZ into 4 leptons

- The cleanest channel for discoveries
- From a combination of published histograms done in 1806.04529 with 113.5 fb^{-1} from **CMS (2/3) and ATLAS (1/3)** one observes a peak at M_H~660 GeV Γ_H~100 GeV, ~90 fb with s/b=42/14 ~3.75 s.d. local significance
- With 139 fb-1 ATLAS a ~3.5 s.d. effect at the same mass 2103.01918
- With 139 fb-1, with **sequential cuts**, an excess is observed at the same mass, s/b=9/2 ~2.1 s.d., for VBF->H(660)->ZZ ~30 fb 2009.14791
- The corresponding cross section is below the inclusive cross section ~90fb implying a **significant ggF contribution**
- CMS analyses in four leptons, inclusive+VBF, are not yet published
- These results call for a combination of both analyses before one can draw a valid conclusion
- Could stop here but…



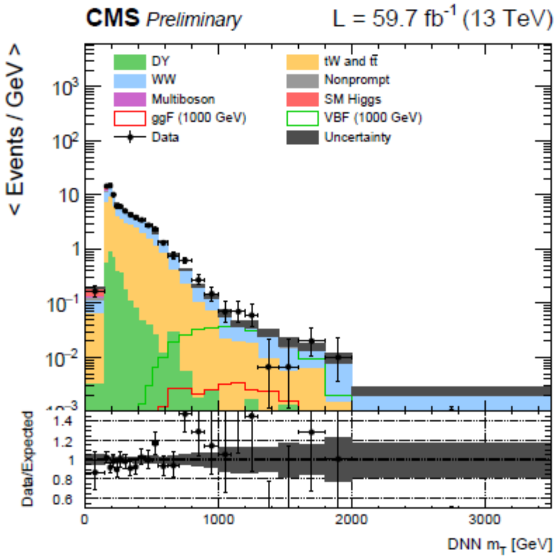




Evidence for VBF->H(650)->W+W- ->ℓℓνν

CMS PAS HIG-20-016

- Large top background even after b-jet vetoing (NB: plot for 60 fb-1 for μe)
- **Wide signal** predicted ±50% mass resolution
- **VBF->H(650)->ℓℓνν** (μμ ee and μe) observed with 3.8 s.d. local (2.6 global) significance
- The **VBF** cross section ~**160±50 fb**, close to SM, is 5 times larger than ZZ, **inconsistent with GM** which predicts for the scalar **H5 WW/ZZ=0.5** !
- Within 2HD, h(125)WW from CMS gives **sin²(α–β)~0.97±0.09** meaning that **H(650)WW~(0.03± 0.09)SM**
- **2 s.d. upper limit in blue**
- Both interpretations are inconsistent !
- An attempt from ATLAS does not reach the same sensitivity (only μe) ATLAS-CONF-2022-066



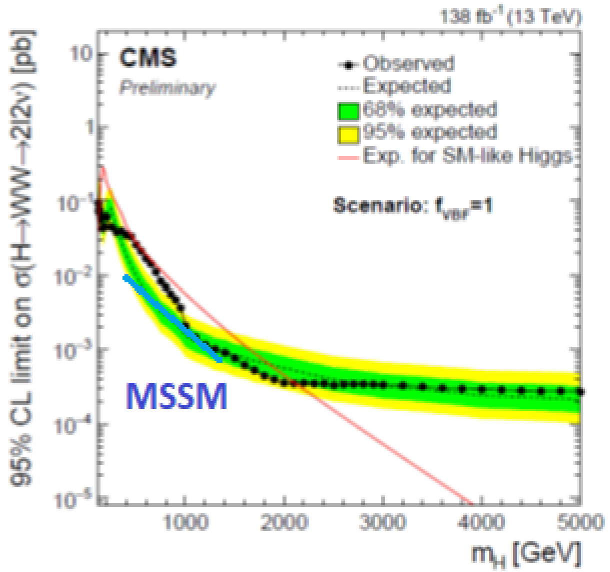
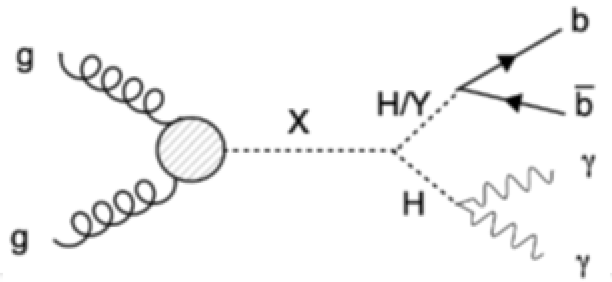


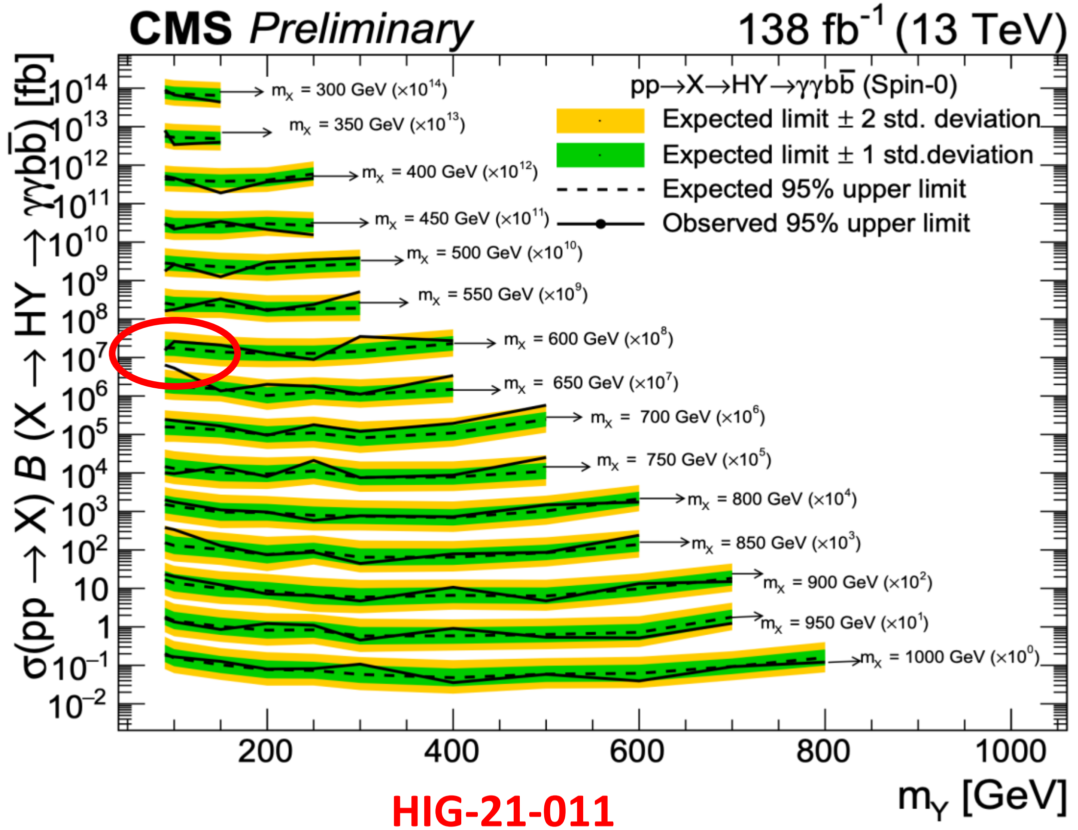
Table 3: Summary of the signal hypotheses with highest local significance for each f_{VBF} scenario. For each signal hypothesis the resonance mass, production cross sections, and the local and global significances are given.

Scenario	Mass [GeV]	ggF cross sec. [pb]	VBF cross sec. [pb]	Local signi. [σ]	Global signi. [σ]
SM f_{VBF}	800	0.16	0.057	3.2	1.7 ± 0.2
$f_{VBF} = 1$	650	0.0	0.16	3.8	2.6 ± 0.2
$f_{VBF} = 0$	950	0.19	0.0	2.6	0.4 ± 0.6
floating f_{VBF}	650	2.9×10^{-6}	0.16	3.8	2.4 ± 0.2

Evidence for gg+VBF->H(650)->Y(90)+h(125)->bb+γγ

- 3.8 s.d. at mH=650 GeV and mY=90 GeV at ICHEP22
- Mass resolution on Y does not allow to distinguish between Z and h(95) 2203.13180
- CP says that bb cannot come from Z->bb but could be h(95)
- The cross section is dominant over other processes ~200 fb
- Could come from a different resonance

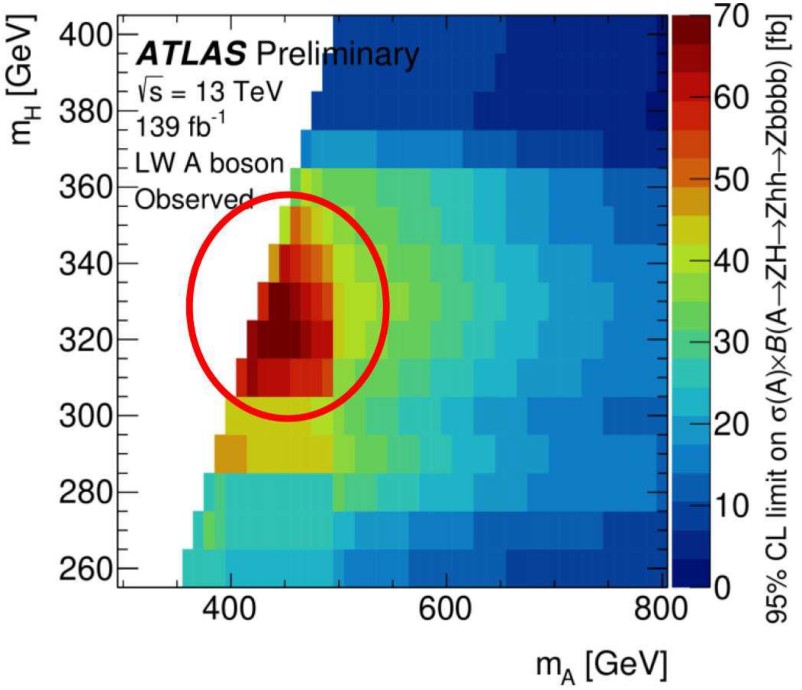




HIG-21-011

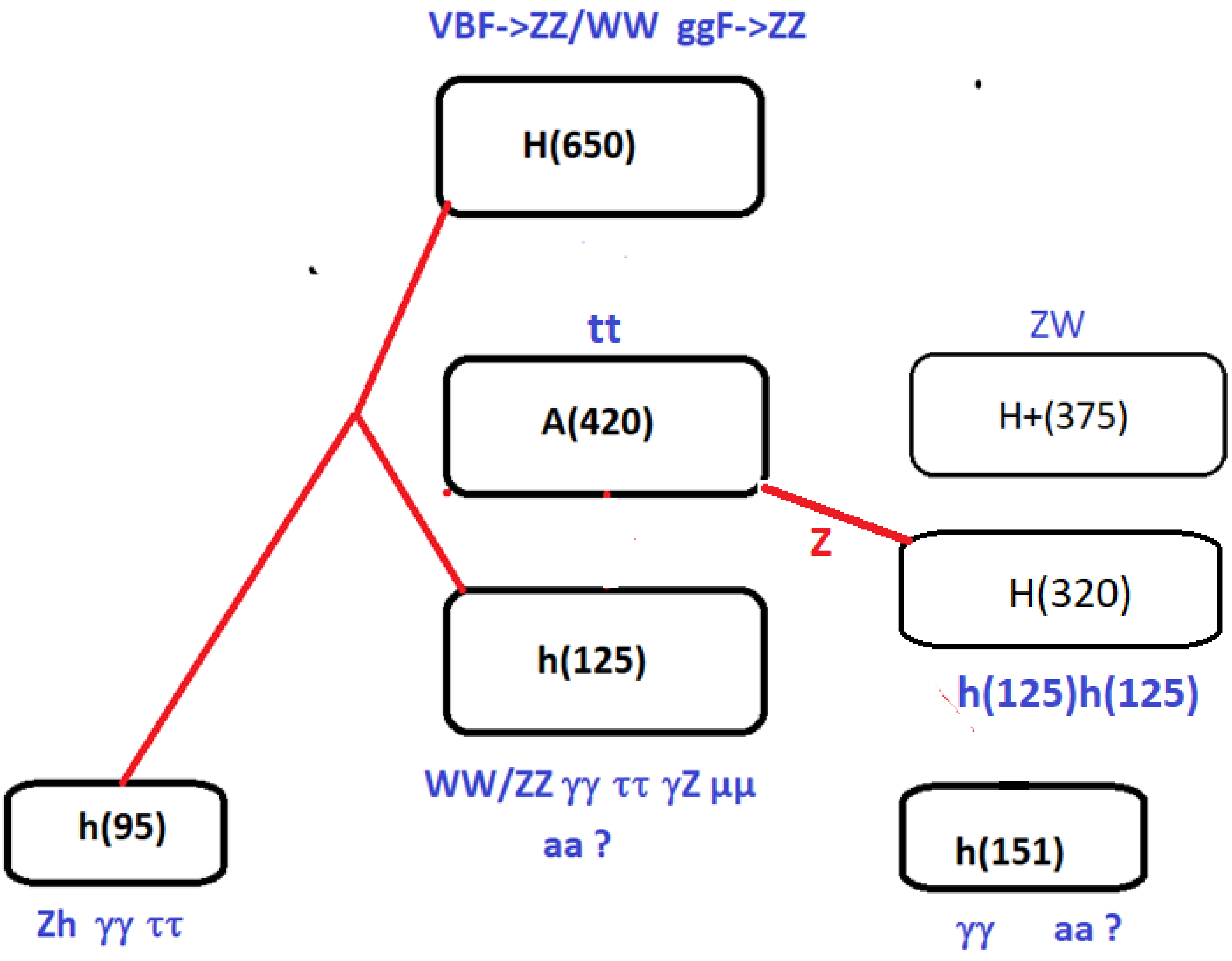
Interpretation of findings

- H(650) cannot be accommodated within 2HD nor H5 from GM (ggF contribution and ZZ/WW)
- Would require an extension of GM which are under investigation (see Gilbert Moultaka talk)
- Adding previous evidences for H(650), one gets **> 7 s.d. global** (assuming h(125)h(95) **comes from the same scalar**)
- Reinforced evidence for h(95) 2204.05975
- Evidences for A(400)->ττ and Zh from ATLAS not confirmed
- New evidence for **A->ZH(330)->Zhh** from ATLAS at 3.8 s.d. ATLAS-CONF-2022-043
- See *2208.00920* and *2112.00921* for alternate interpretations of H(650)



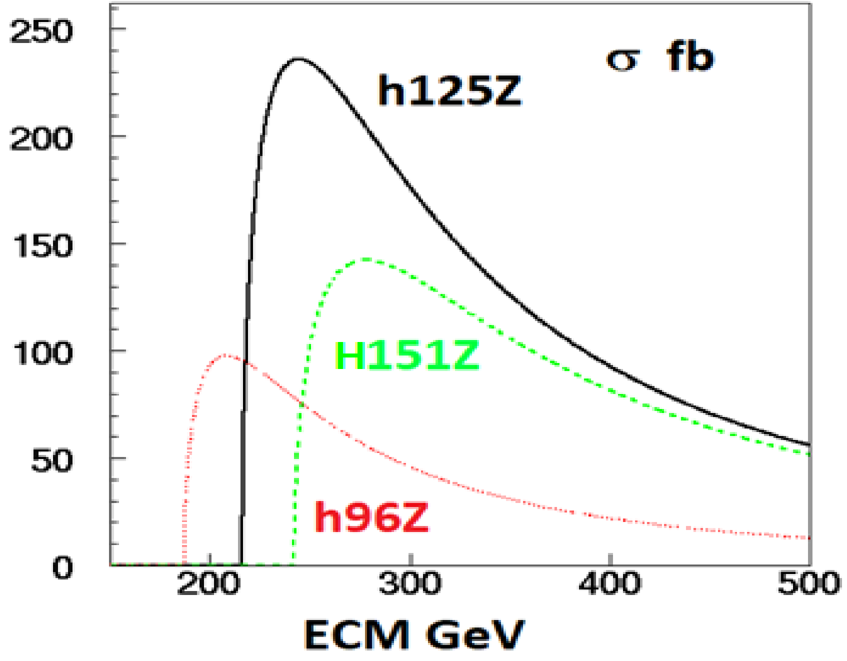
Reaction	# channels/expts	# σ global (loc)	Michelin rating
pp->h(125)	>2/2	6.9	***
pp->H(650)	2/2	7.5	**
pp->A(400)	3/2	5	*
h(95) LHC+LEP2	3/2	4.3	*
pp->H(151)+Z	1/2	4.8	*
pp->H5+(375)->WZ	1/2	3.5	
h(125)->a(52)a(52)	1/1	1.7 (3.3)	
pp->H3+(130)->bc	1/1	1.6	

SUMMARY ON BSM CANDIDATES



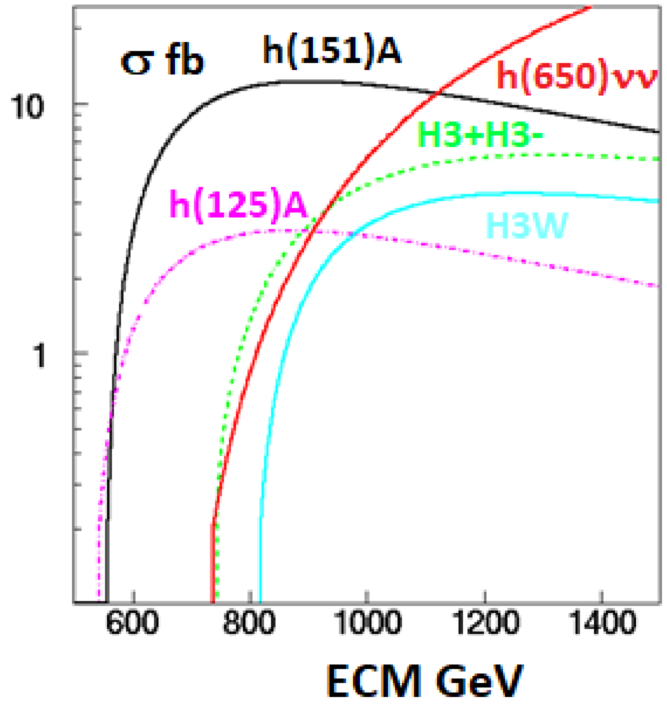
GM cross sections in e+e-

- Higgs factories



- Large x-sections allowing very precise measurements

- TeV linear colliders



- Assumes mass degeneracy inside multiplets : mH3+=mA
- These are complex modes requiring the **highest** $\mathcal{L}$ and **almost ideal reconstruction efficiency**

Conclusions

- Growing evidence for **H(650)** observed by CMS into **WW** and into **h(95)h(125)**
- ATLAS has not yet searched h(95)h(125) nor CMS released ZZ into 4 leptons
- VBF->H(650)->WW is inconsistent with **two doublet models**
- The pattern of decays of H(650) into ZZ/WW calls for an extension of the **GM model**
- This is also true for the recent ATLAS observation of **A(420)->H(330)Z**
- Before believing we still need **understanding** : major role of theory
- These observations offer a rich and new landscape for HEP, in particular for future for e+e- colliders under discussion and motivate a **linear e+e- collider reaching no less than 1 TeV**
- **Complex final states** implied by GM will have a **critical impact in the design of future LC detectors**

BBC: Large hadron collider: A revamp that could revolutionise physics

References

- Global interpretation of LHC indications within the Georgi-Machacek Higgs model,
  Talk presented at the International Workshop on Future Linear Colliders (LCWS2021).
  François Richard (IJCLab, Orsay)(Mar 22, 2021)
  e-Print: 2103.12639 and ref therein
- Searches for scalars at LHC and interpretation of the findings Anirban Kundu (Calcutta U.),
  Alain Le Yaouanc (IJCLab, Orsay), Poulami Mondal (Calcutta U.), François Richard (IJCLab, Orsay)
  Contribution to 2022 ECFA Workshop on e+e- Higgs/EW/TOP factories
  e-Print: 2211.11723

Acknowledgements

Contributions from Gilbert Moultaka are gratefully acknowledged.

This work has benefitted from discussions with Sven Heinemeyer and Howard Haber through various workshops.

Thanks to Pawel Jan Klimek for providing useful infos about ATLAS results.

APPENDIX

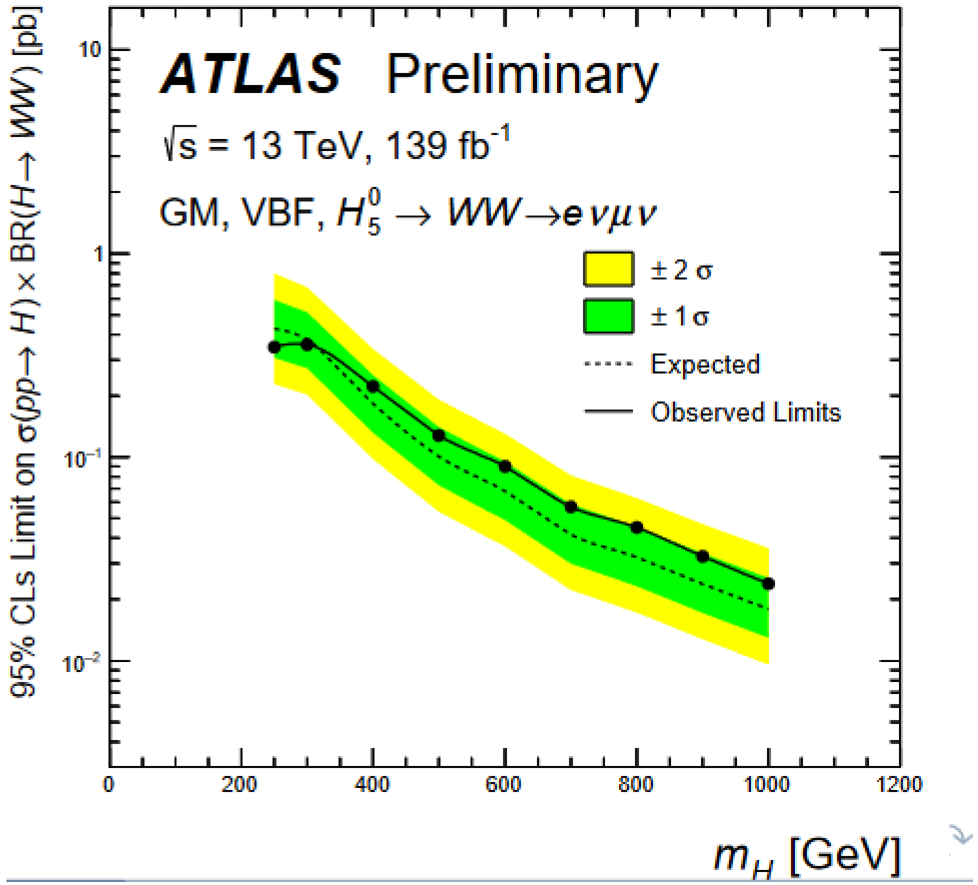
Missing slides & additional slides

(lack of lime)

H->WW->μe$\nu\nu$ from ATLAS

- ATLAS has provided a **preliminary result** (PISA) on VBF->H5->WW in μe$\nu\nu$ (not μμ nor ee) [ATLAS-CONF-2022-066]
- Like CMS, ATLAS sees a wide excess around 650 GeV but with only at the 1 s.d. level
- ATLAS can set a 200 fb 2 s.d. limit for

  σ(pp->H)xBR(H->WW)
- This limit is **compatible** with the observation of CMS 160±50 fb
- ATLAS has a smaller efficiency as compared to CMS (retain only **μe**)

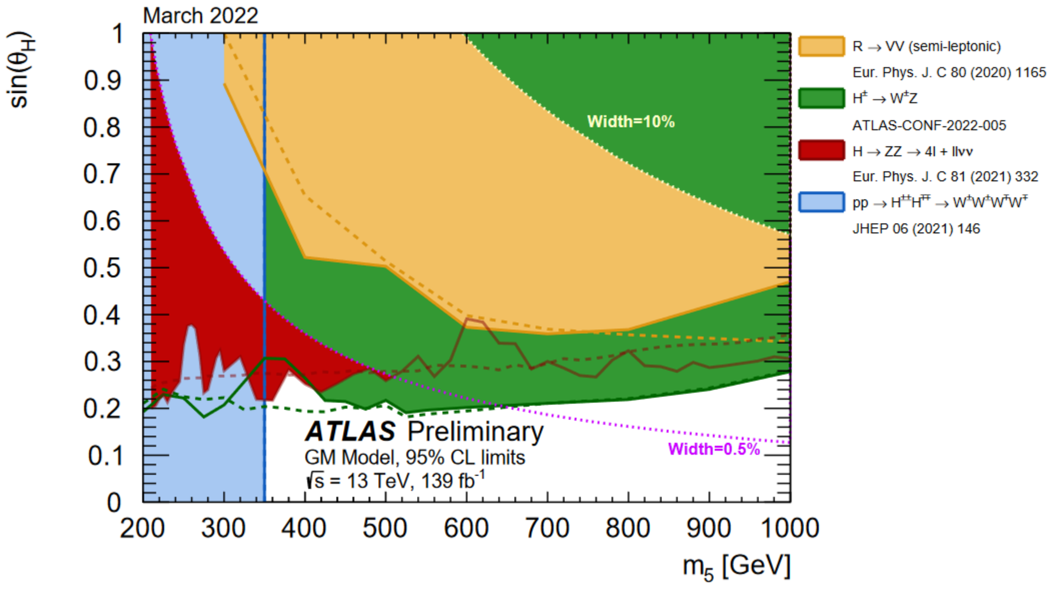


Charged Higgs searches

- ATLAS has attempted to combine the searches for H5 into **ZZ->ℓ⁺ℓ⁻ℓ'⁺ℓ'⁻, H+->ZW+** and **H++->W+W+** , assuming a common mass m5 for these particles and varying the mixing parameter sin(θ_H)

- They have also searched for the DY process **pp->H5++ H5- - ->W+W+W-W-** which allows to eliminate the dependence on sin(θ_H).

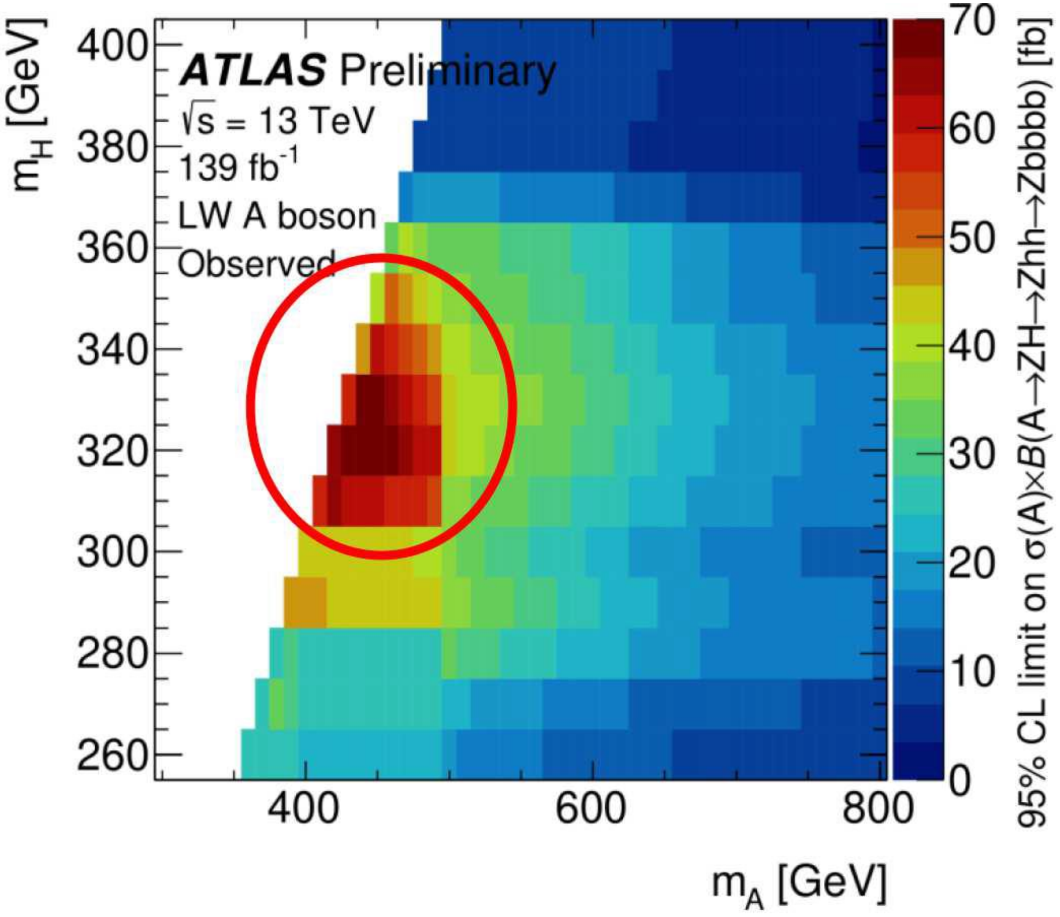
- These exclusions however do not consider the potential **cascades** of these particles into the triplets H3+ and A, like for instance H5++ ->H3+W+ which could weaken these limits assuming 100% W+W+



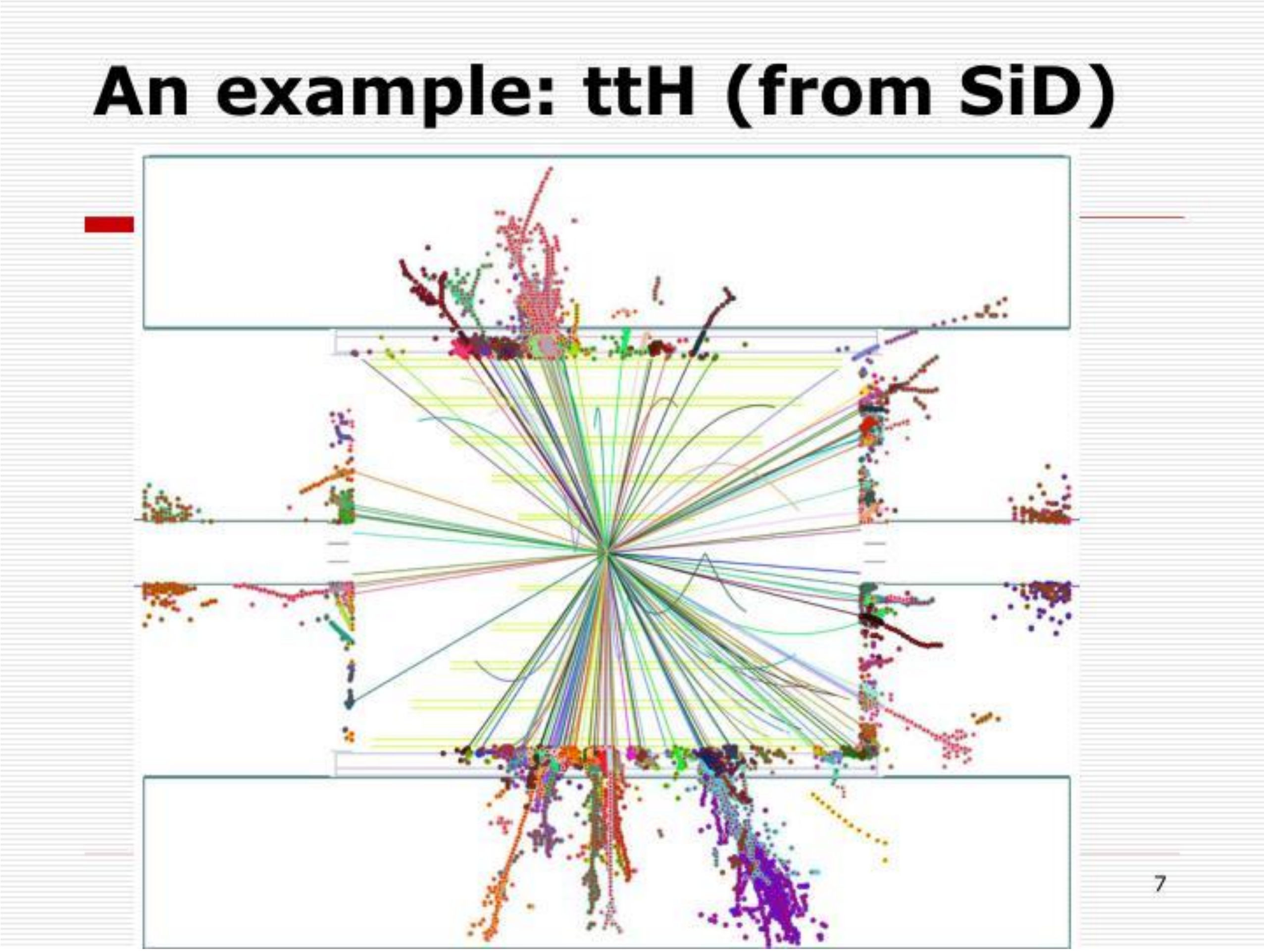
ATL-PHYS-PUB-2022-008

A(420)->ZH(320)->Zh(125)h(125)

- Great ingenuity !
- local (global) significance of **3.8σ (2.8σ)**
- hh into 4b using mass constrain to improve resolution
- [ATLAS-CONF-2022-043]
- Second appearance of triple Higgs coupling !
- No interpretation in minimal GM
- Calls for an extra doublet

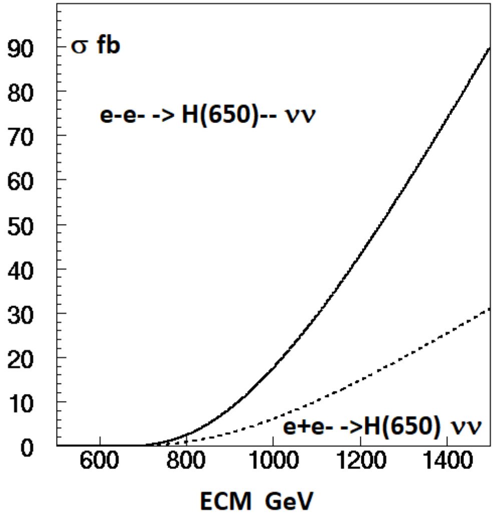


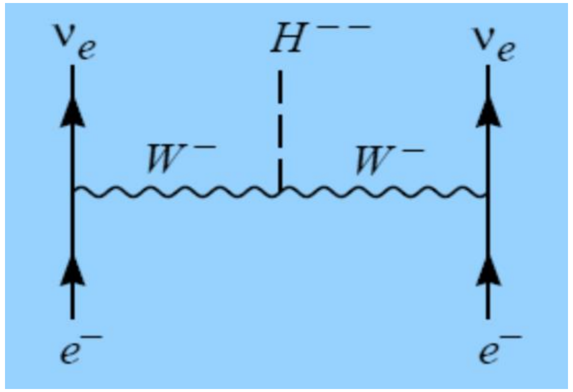
Complex events



VBF at a LC

- ECM=1 TeV is sufficient to observe the full GM scalar spectrum provided one can use VBF
- Requires highest possible **luminosity,** ~8000 fb-1 with ILC at 1 TeV *1903.01629*





- >1.5 TeV to produce H5++ H5 - - in e+e- but 1 TeV enough in **VBF** **e-e- ->W-W-νν->H5- - νν**

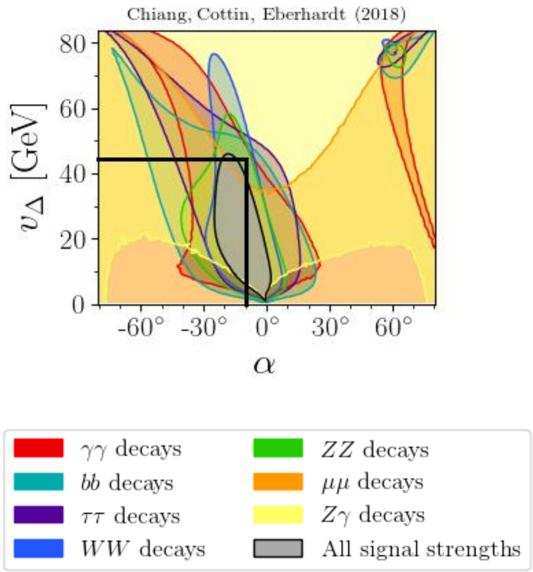
GM model issues

Giorgi-Machacek for pedestrians

- Allows I=2, H++, without violating **$\rho = M^2w/Mz^2\cos^2\theta w = 1$** at tree level
- Is achieved by combining 1 isospin doublet (v_ϕ) + 2 triplets, one real the other imaginary, with the same vacuum expectations :

$$\rho = \frac{\tilde{v}_\phi^2 + 4\tilde{v}_\chi^2 + 4\tilde{v}_\xi^2}{\tilde{v}_\phi^2 + 8\tilde{v}_\chi^2} = \frac{v^2}{v^2 + 4(\tilde{v}_\chi^2 - \tilde{v}_\xi^2)}.$$

=1 with $v_\chi = v_\xi$



1807.10660

- Predicts a **5-plet** of physical states H5++ H5+ H50 H5- H5– **Fermiophobic** only produced by **VBF**
- **+ 3-plet** H3+ H30 (CP-odd) -> **A(400)**
- **Mass degeneracy** inside multiplets usually assumed but **unnecessary** for $\rho=1$ see 2111.14195
- + **Singlets h(125)** and H **mixing angle α**
- Allows A(400)->hZ but A(400)->HZ much larger if mH~mh
- Couplings depend on 2 mixing angles constrained by LHC observations
- Tentative choice: **sinα~-0.15 and sinθH~0.5 (v_χ=43 GeV)** to agree with PM

GM predictions

- h(125)->WW/ZZ SM close to SM OK
- h(125)->tt/bb + 28% /SM
- ZZ/WW~2 for H5 instead of 0.5 in SM

while H(650) has ZZ/WW~1/5

- A(400)->bb,ττ/tt >>1 GM requires 1
- There are two singlet candidates h(95) and h(151) while GM only predicts one singlet
- singlet->ττ bb only through mixing with SM h
- Extensions or alternate to GM badly needed
- A SUSY version of GM already exists

Type	coupling /SM, MSSM	sα=-0.15 sH=0.5
h(125)WW/ZZ	cαcH- 1.63sαsH	0.98
HWW/ZZ	sαcH+1.63cαsH	0.68
h(125)tt,bb	cα/cH	1.14
Htt,bb	sα/cH	0.17
Att,bb,ττ	tanH	0.58
H5WW, H5ZZ	0.57sH,-1.15sH	0.27,-0.58
H5AZ,H5H3+W-	1.16cH	1
H5+H3+Z,H5+AW+	cH	0.87
h(125)AZ,hH3+W-	1.63(sαcH+0.6cαsH)	0.28
HAZ,HH3+W-	1.63(cαcH- 0.6sαsH)	1.48
H5+W-Z,H5++W+W+	-2sH,2.48sH	1.0,1.24
H3+H3-Z	1	1

The GM model for advanced

- GM is constituted by one doublet ϕ and two triplets, one complex χ and one real ξ, with the same vacuum expectations to get **ρ=1**

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^{0*} \end{pmatrix}, \quad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix}$$

Y=1/2 T=1/2 vϕ   Y=1 T=1 vχ   Y=0 T=1 vξ

$$\rho = \frac{\tilde{v}_\phi^2 + 4\tilde{v}_\chi^2 + 4\tilde{v}_\xi^2}{\tilde{v}_\phi^2 + 8\tilde{v}_\chi^2} = \frac{v^2}{v^2 + 4(\tilde{v}_\chi^2 - \tilde{v}_\xi^2)}.$$

- Only ϕ couples to fermions
- They form the following physical states, dominantly triplet

$$H_5^{++} = \chi^{++},$$
$$H_5^+ = \frac{(\chi^+ - \xi^+)}{\sqrt{2}},$$
$$H_5^0 = \sqrt{\frac{2}{3}}\xi^0 - \sqrt{\frac{1}{3}}\chi^{0,r},$$
$$H_3^+ = -s_H\phi^+ + c_H\frac{(\chi^+ + \xi^+)}{\sqrt{2}},$$
$$H_3^0 = -s_H\phi^{0,i} + c_H\chi^{0,i}.$$

- H1 and H1' have following composition

$$H_1^0 = \phi^{0,r},$$
$$H_1^{0\prime} = \sqrt{\frac{1}{3}}\xi^0 + \sqrt{\frac{2}{3}}\chi^{0,r}.$$

- The physical states are

$$h = \cos\alpha\, H_1^0 - \sin\alpha\, H_1^{0\prime},$$
$$H = \sin\alpha\, H_1^0 + \cos\alpha\, H_1^{0\prime}.$$

- The mixing angle α **has to be small** to avoid altering the doublet properties of the SM h(125)
- E.g. sin α=-0.15 & sH=0.5, vϕ=213 GeV for the doublet, vξ=vχ=43.5 GeV for the triplets

Perturbative unitarity

- Works beautifully for SM with h(125) well below the bound ~ 1 TeV
- Very constraining for GM: all within reach of a TeV collider [0712.4053]

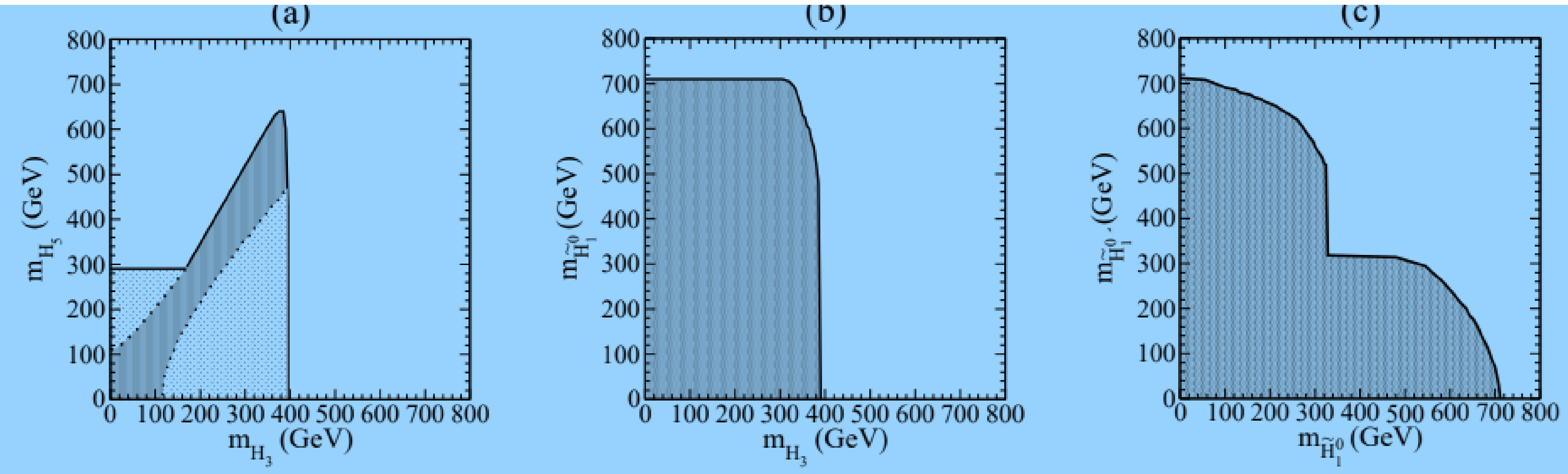


Figure 1: Allowed regions of the masses of the Higgs bosons in the m_{H_3} - m_{H_5} plane (a), in the m_{H_3} - $m_{\tilde{H}_1^0}$ plane (b) and in the $m_{\tilde{H}_1^0}$ - $m_{\tilde{H}_1^{0\prime}}$ plane (c). In Fig. 1(a) the light shadowed regions are excluded by the $Zb\bar{b}$ results.

SGM: a SUSY version of GM

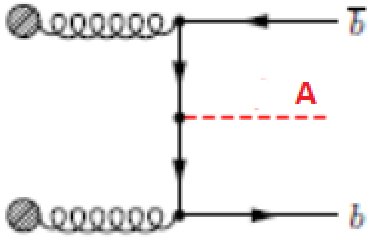
1308.4025

$$\Sigma_{-1} = \begin{pmatrix} \frac{\chi^-}{\sqrt{2}} & \chi^0 \\ \chi^{--} & -\frac{\chi^-}{\sqrt{2}} \end{pmatrix}, \quad \Sigma_0 = \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix}, \quad \Sigma_1 = \begin{pmatrix} \frac{\psi^+}{\sqrt{2}} & \psi^{++} \\ \psi^0 & -\frac{\psi^+}{\sqrt{2}} \end{pmatrix}$$

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

- GM does not necessarily mean compositeness
- SGM provides all the “goodies” of SUSY
- Perturbativity, computability
- EWSB naturally triggered
- Mh predicted with less “tension” on stop masses with extra contributions to RC
- DM candidate
- Complex/rich world with ~20 Higgs scalars + some extra scalars

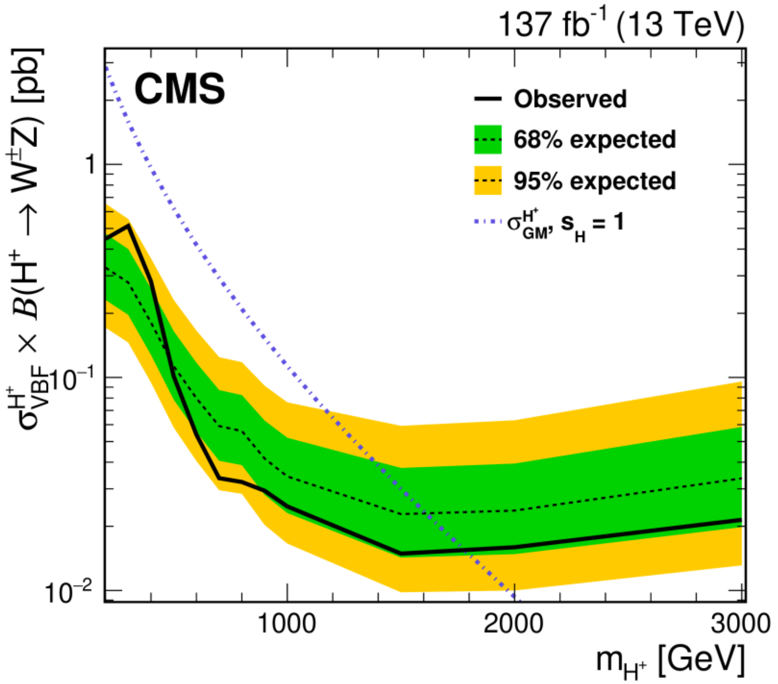
Need for extending GM



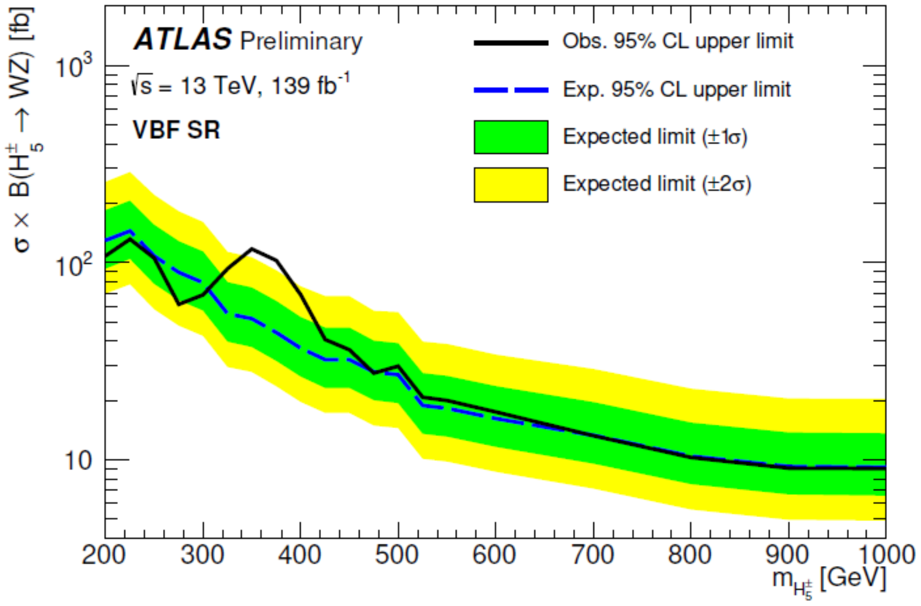
- Is GM satisfying the various observations ?
- The answer is clearly NO
- This is the case for H(650) ZZ/WW<<1 while H5 has 2
- The **fermionic couplings** of A(400) which tell us that **Yt~SM** while **Yb,τ >> SM and GM** but this needs confirmation
- The remedy for fermions is to add an **extra doublet** and benefit from an enhancement of **Yb,τ~tanβ~20** 'à la MSSM'. Too naïve since then **Yt~1/tanβ**
- The **Yukawa alignment mechanism** is a more general scheme sufficient to suppress **FCNC** and allowing an **independent tuning for u,d,ℓ** *0908.1554*
- It assumes that both doublets couple to all fermions requiring **Y2f=ξfY1f** where Y1f and Y2f are the Yukawa couplings to the two doublets ϕ1 and ϕ2, and where **ξf** is an arbitrary constant which can be complex and differ for **u,d,ℓ**
- One can then have **Yb,τ** >> SM even if tanβ ~1 and Yt~SM *0908.1554*
- Note finally that this extension naturally occurs in the SUSY version of GM *1308.4025*

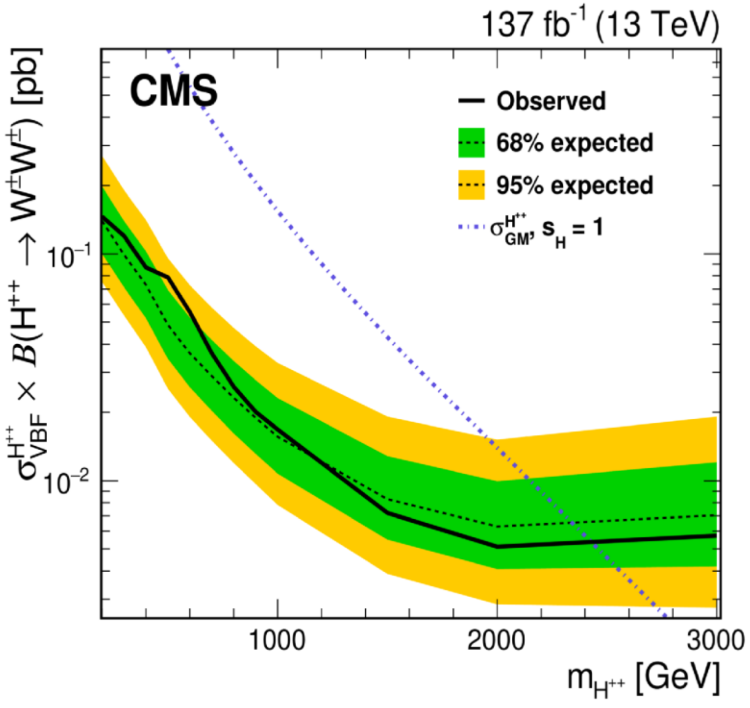
What about H5+ and H5++ ?

2104.04762



ATLAS-CONF-2022-005

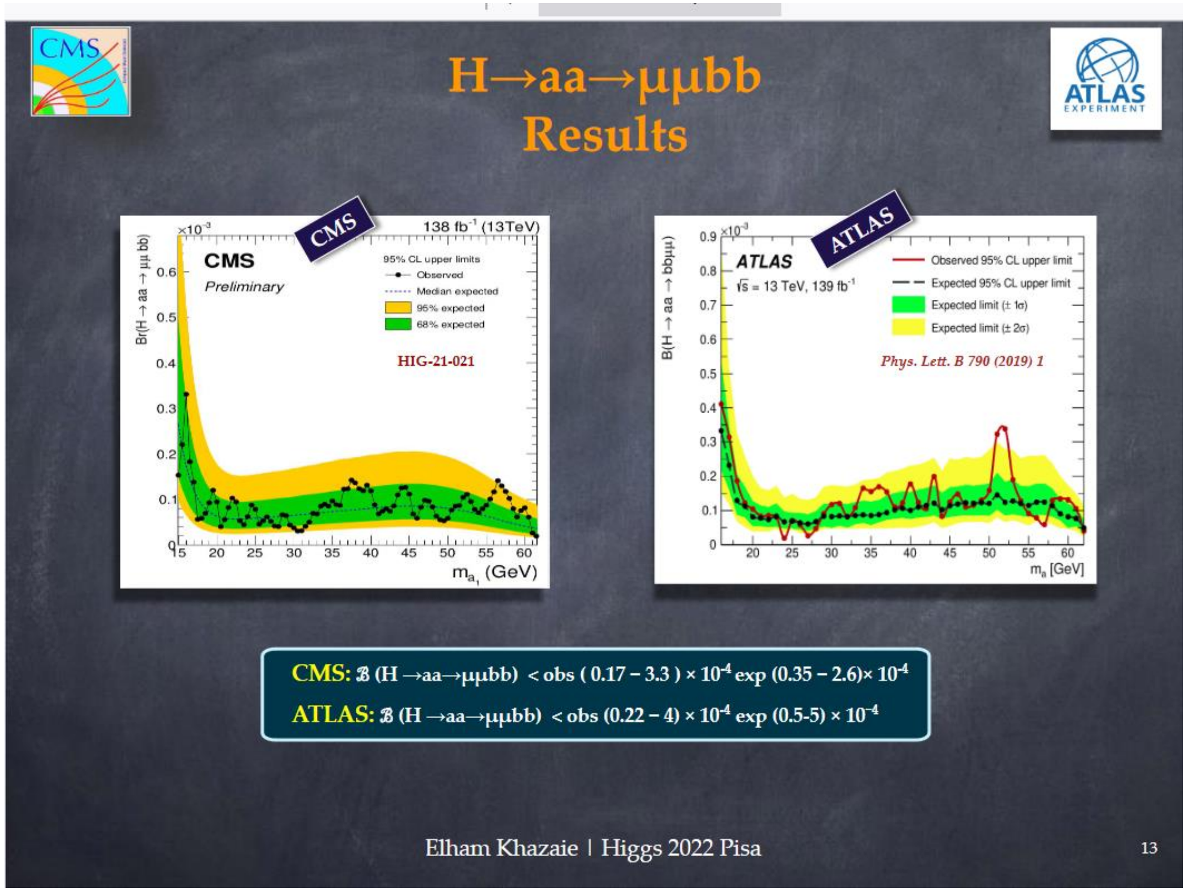




- CMS cross sections assume **s_H=1** are divided by 4 for **s_H=0.5**
- If H3+ is light H3+Z and H3+W+ become dominant and these resonances become wide
- Coincident excess at mH5+~375 GeV for ATLAS (2.8sd) & CMS while naïve GM predicts 650 GeV
- Not excluded in eGM 2111.14195

Update on h(125)->aa

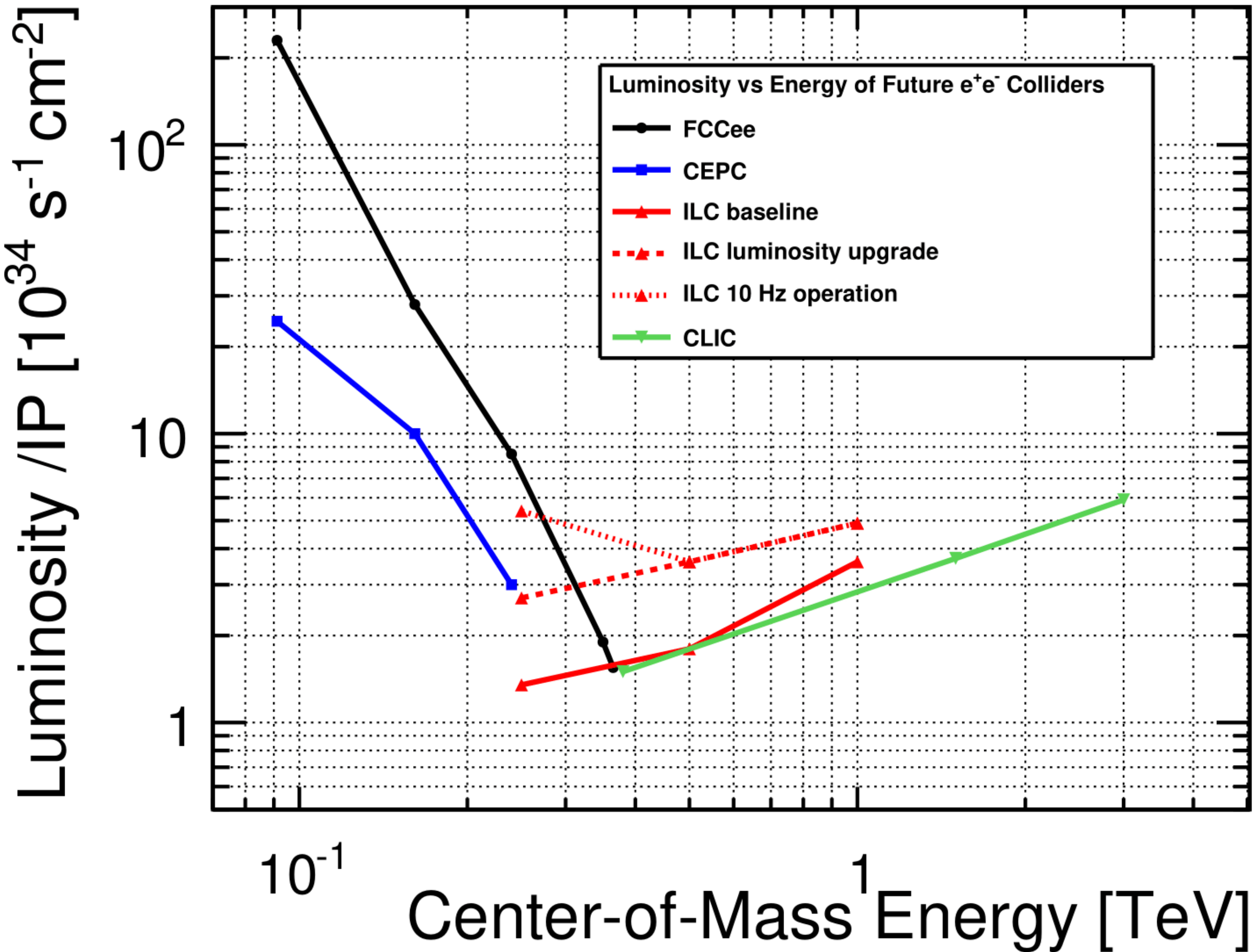
- Result shown at HIGGS22-PISA
- With more sensitivity, CMS does not observe the indication from ATLAS
- It does not exclude it either
- [CMS HIG-21-021]()



e+e- Colliders

LUMINOSITY at 1 TeV

- In reference *1903.01629* a running scenario of ILC at **1 TeV collecting 8000 fb-1** has been envisaged
- Beneficial for **Higgs self-coupling** measurement
- Discoveries at LHC would boost these studies at ILC an CLIC
- Convert ILC into an ERL 2105.11015 and 2203.06476



Snowmass Paper

arXiv:2203.07622

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole		Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ^*_{z}	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

Table 4.1: Summary table of the ILC accelerator parameters in the initial 250 GeV staged configuration and possible upgrades. A 500 GeV machine could also be operated at 250 GeV with 10 Hz repetition rate, bringing the maximum luminosity to $5.4 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [26]. *): For operation at the Z-pole additional beam power of 1.94/3.88 MW is necessary for positron production.