Searches for light scalars at LHC and interpretation of the findings

F. Richard

IJCLab Orsay

WG1: joined HTE & SRCH session

October 2022

First ECFA WORKSHOP.

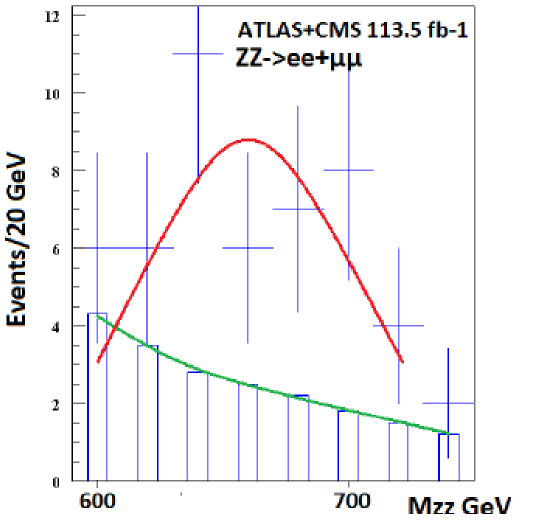
[**on e+e- Higgs/EW/Top Factories, October 5-7, 2022, in Hamburg**]

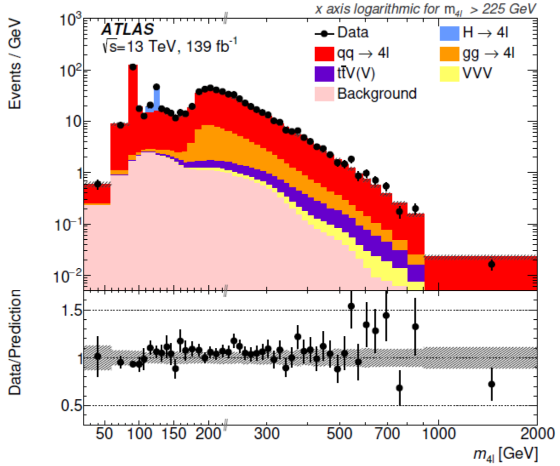
Introduction

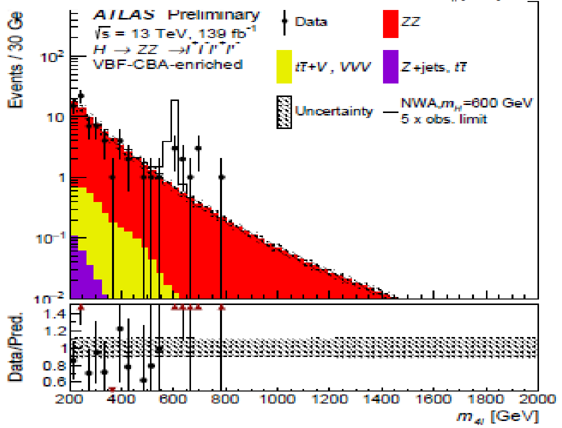
- Before the HEP community can choose between the proposed e+e- colliders, a valid question to ask is: which energy is needed to observe **directly** BSM physics ?
- In other words, which are the masses of the lightest BSM particles ?
- If there are such particles, they should already appear **in LHC present data** as was the case for h(125) at Tevatron
- If they don't, there is little hope for a firm discovery in a near future
- My prejudice : 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 the various indications from LHC in terms of the **Georgi Machacek** model GM
- Given the short time allocated, I will only very partially cover this topic and concentrate on only one indication

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 1806.04529 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…



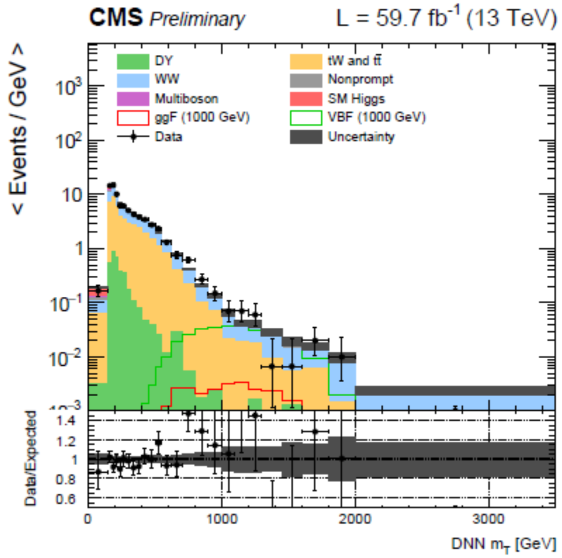




Evidence for VBF->H(650)->W+W- ->eμνν

CMS PAS HIG-20-016

- Has a large top background even after b-jet vetoing
- 3.8 s.d. evidence for **VBF->H(650)->eμνν**
- 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 MSSM h(125)WW from CMS gives $\sin^2(\alpha-\beta)$~0.97±0.09 meaning that H(650)WW~0.03± 0.09SM
- Both models are inconsistent !
- See [2208.00920]() and [2112.00921]() for alternate interpretations of these indications



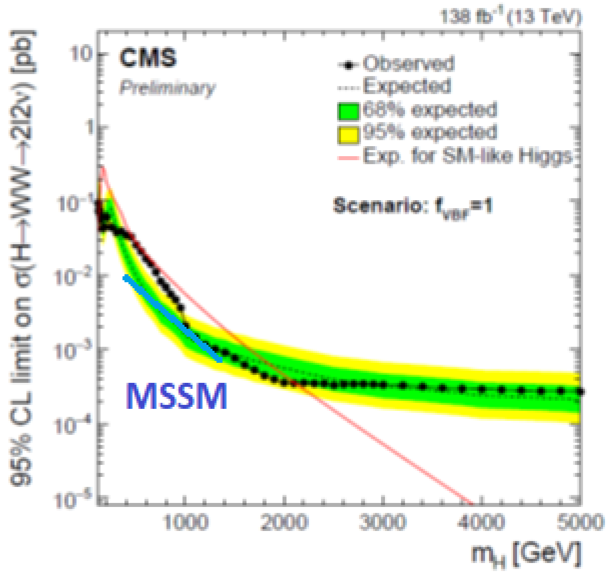
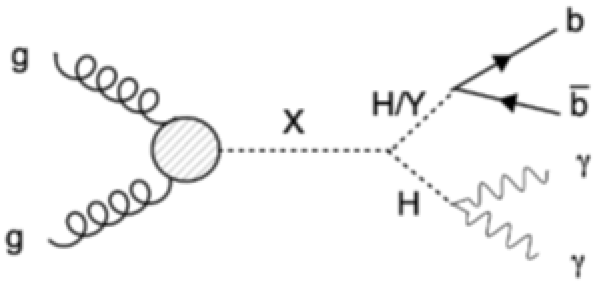


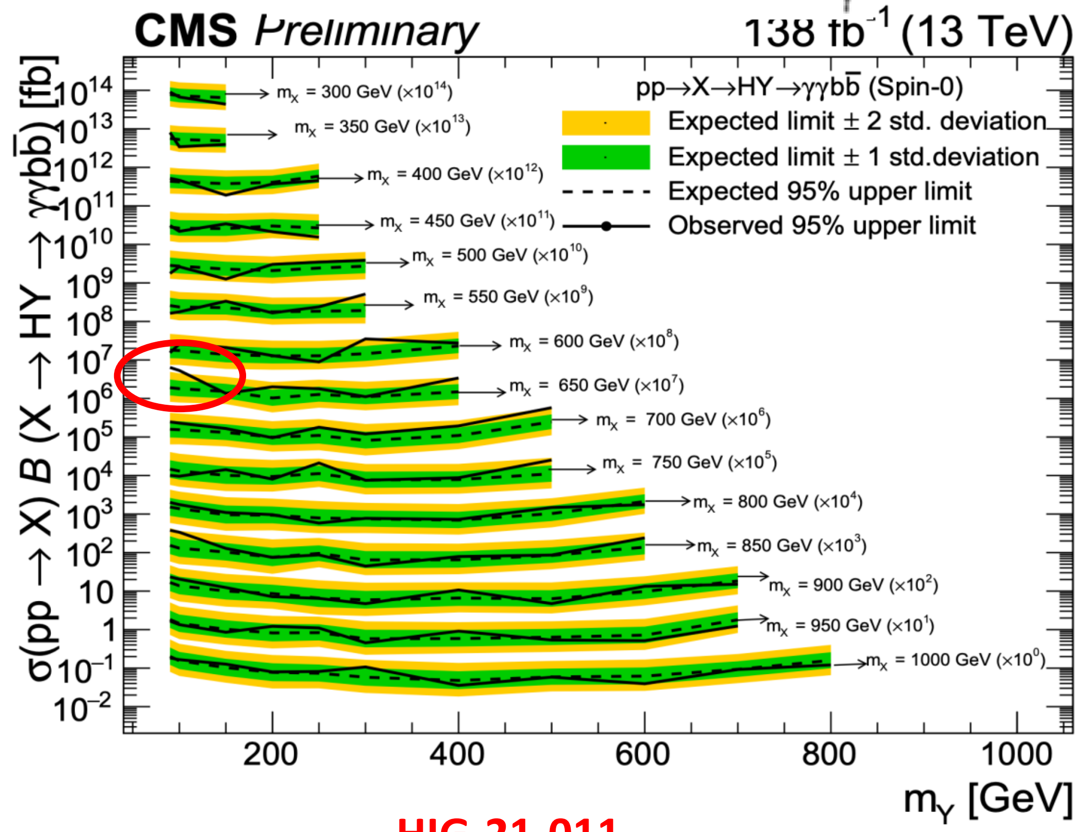
Table 3: Summary of the signal hypotheses with highest local significance for each f_{VBF} scenario. For each signal hypothesis the resonance mass, production cross sections, and the local and global significances are given.

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

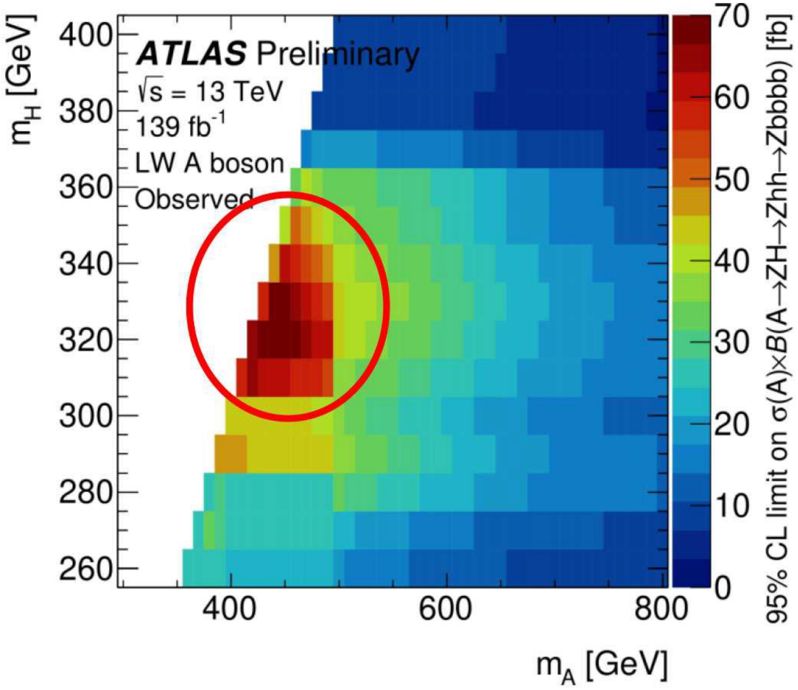
- 3.8 s.d. at mH=650 GeV and mY=90 GeV at ICHEP22
- Mass resolution on Y does not allow to distinguish between Z and h(95) [2203.13180]
- CP says that bb cannot come from Z->bb but could be h(95)
- The cross section is dominant over other processes ~200 fb





HIG-21-011

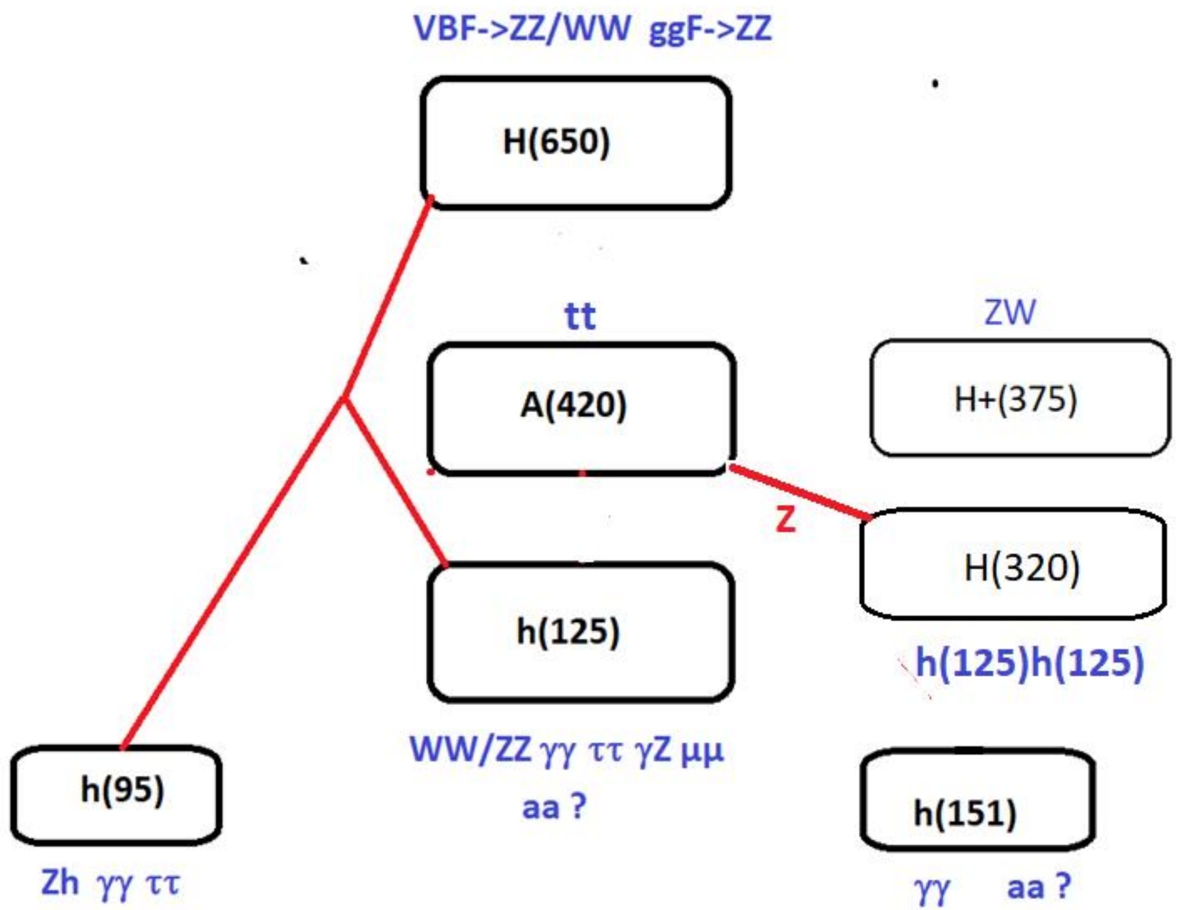
Interpretation of H(650) et al.



- Cannot be accommodated within MSSM nor GM
- Would require several extensions of these models which are under investigation
- Reference 1908.08554 proposes adding only **isosinglets** which would be insufficient to interpret other observations like A(400)
- Adding previous evidences for H(650) one gets **> 7 s.d. global**
- Evidence for A(400)->ττ and Zh from in ATLAS not confirmed
- Evidence for A->ZH(330)->Zhh from ATLAS at 3.8 s.d. ATLAS-CONF-2022-043

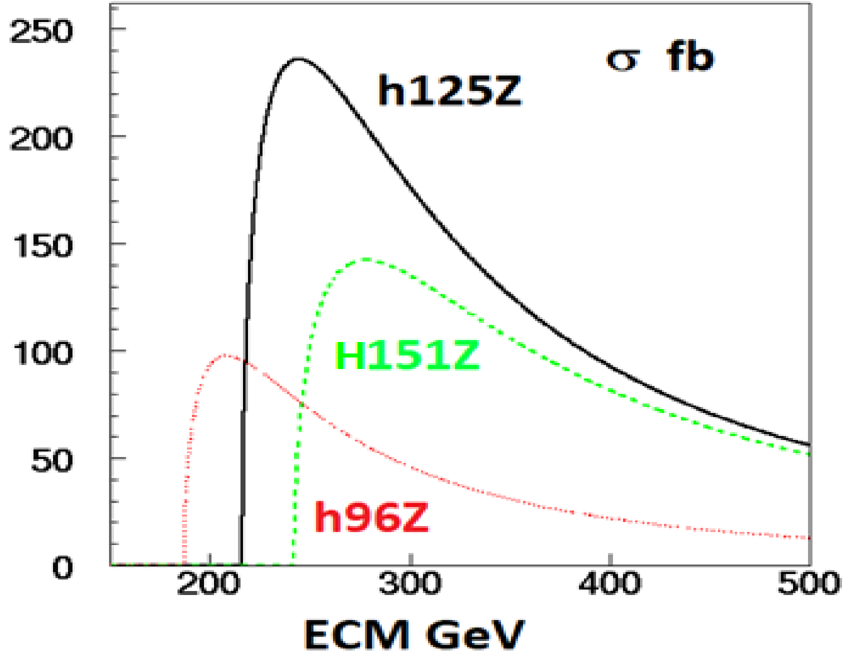
Reaction	# channels/expts	# σ global (loc)	Michelin rating
pp->h(125)	>2/2	6.9	***
pp->X(750)	1/2	4.3 (dead)	*
pp->A(400)	3/2	5	*
pp->H(650)	2/2	7.5	**
pp->SSℓ,ℓ+b,…	>2/2	8	*
pp->H(151)+Z	1/2	4.8	*
h(95) LHC+LEP2	3/2	4.3	*
pp->H5+(375)->WZ	1/2	3.5	
h(125)->a(52)a(52)	1/1	1.7 (3.3)	
pp->H3+(130)->bc	1/1	1.6	

SUMMARY ON BSM CANDIDATES



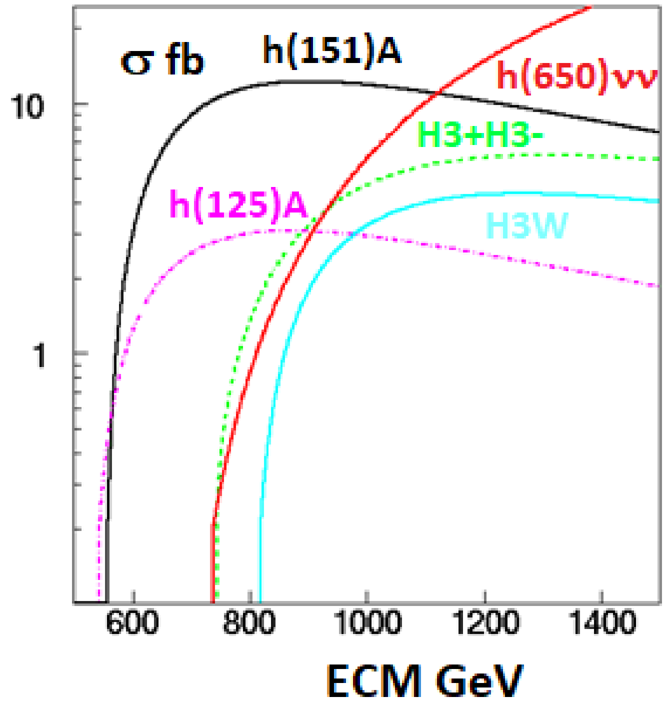
GM cross sections in e+e-

- 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

- There are various evidences for BSM scalars
- There has been recent progress on the evidence for **H(650)** observed by CMS into **WW** and into **h(95)h(125)**
- VBF->H(650)->WW is inconsistent with MSSM
- 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
- It firmly confirms the presence of this resonance (> 5s.d. global)
- Before believing we still need understanding
- These observations offer an entirely 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

Acknowledgements

Contributions from*:*

- A. Kundu, P. Mondal and P.B. Pal from Calcutta University
- G. Moultaka from Université de Montpellier L2
- A. Le Yaouanc from IJCLab-Orsay

are gratefully acknowledged

Reference

Global interpretation of LHC indications within the Georgi-Machacek Higgs model, Talk presented at the International Workshop on Future Linear Colliders (LCWS2021), 15-18 March 2021. C21-03-15.1
François Richard (IJCLab, Orsay)(Mar 22, 2021) Contribution to: LCWS 2021
e-Print: 2103.12639 and ref therein

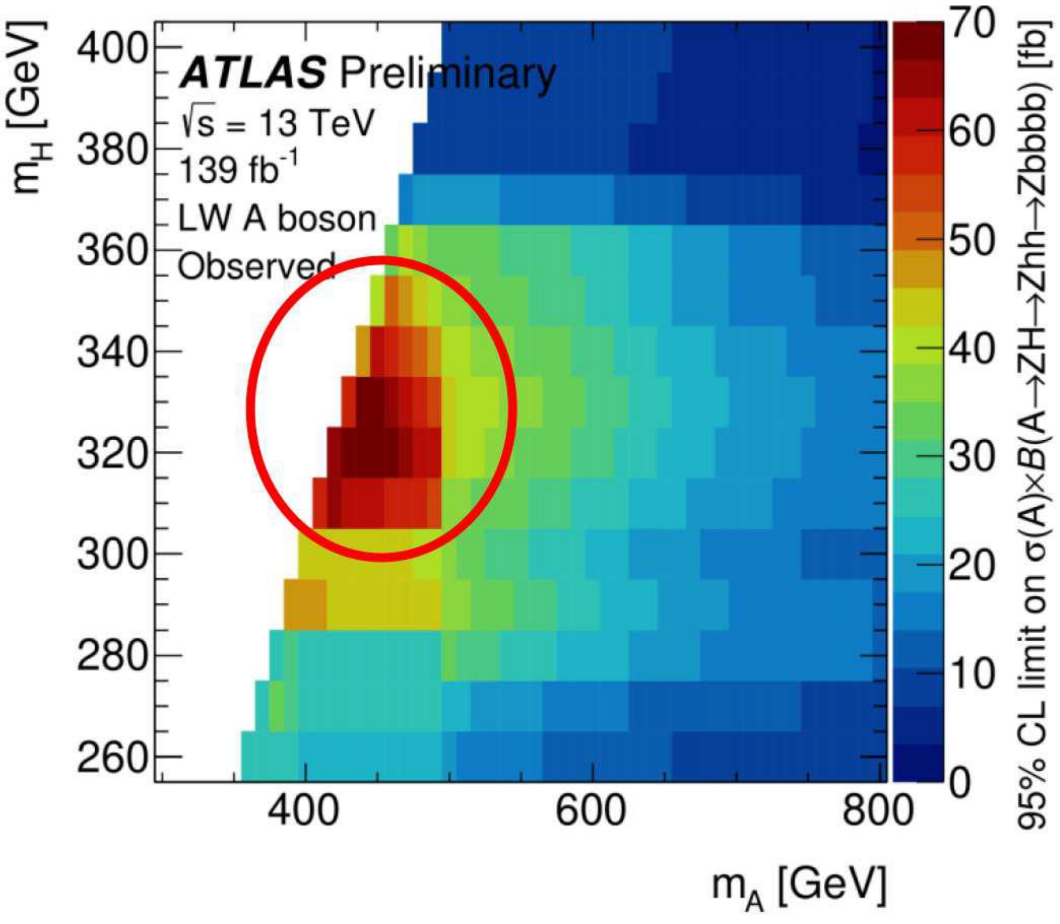
APPENDIX

Missing slides & additional slides

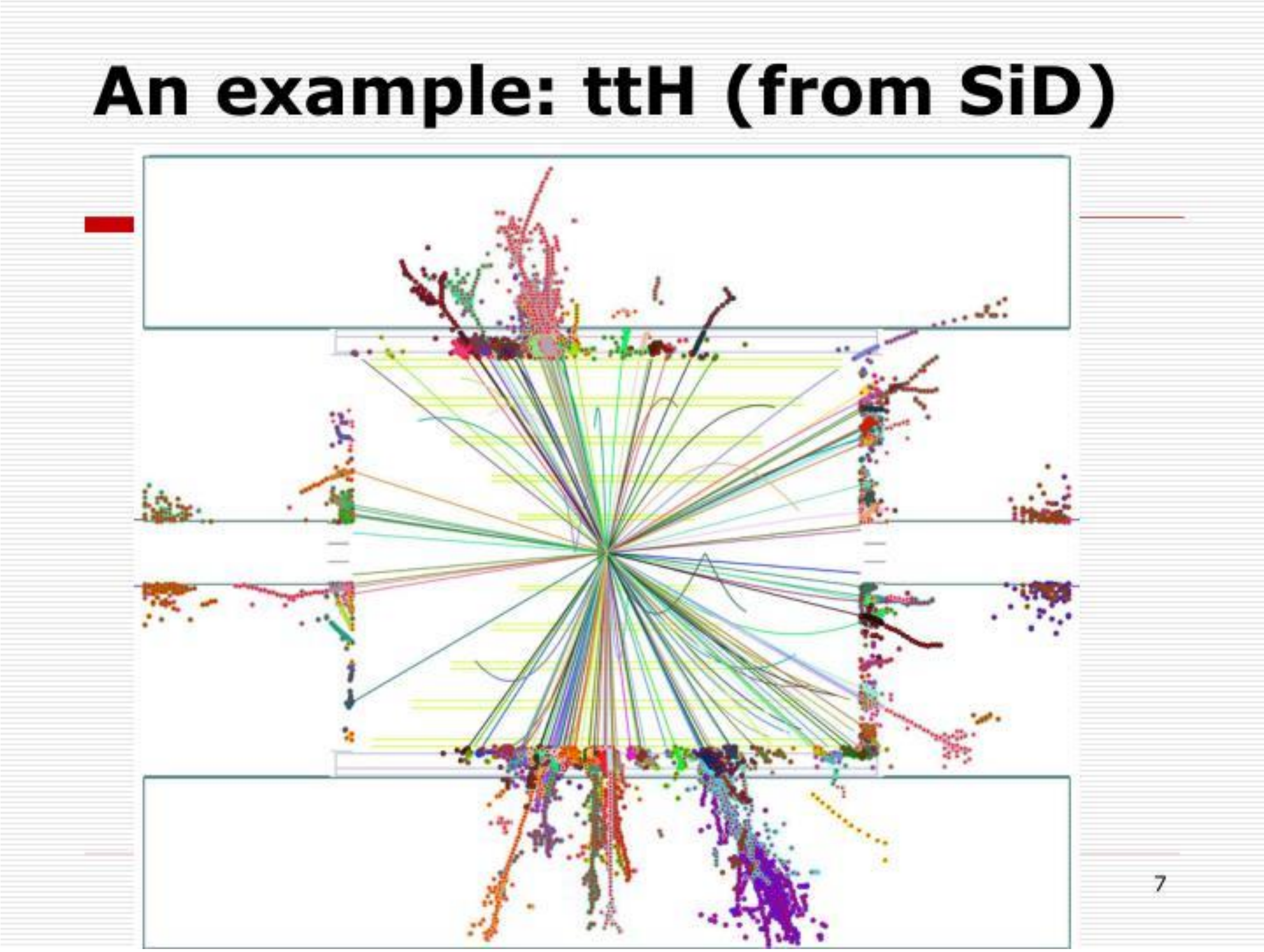
(lack of lime)

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

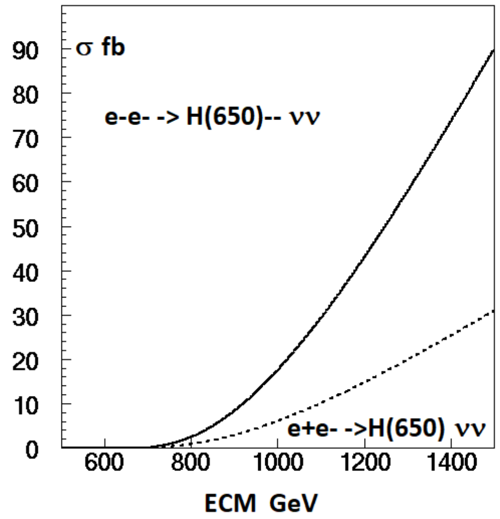


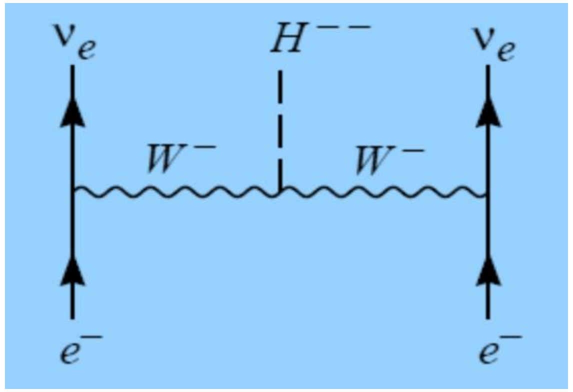
Complex events



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**

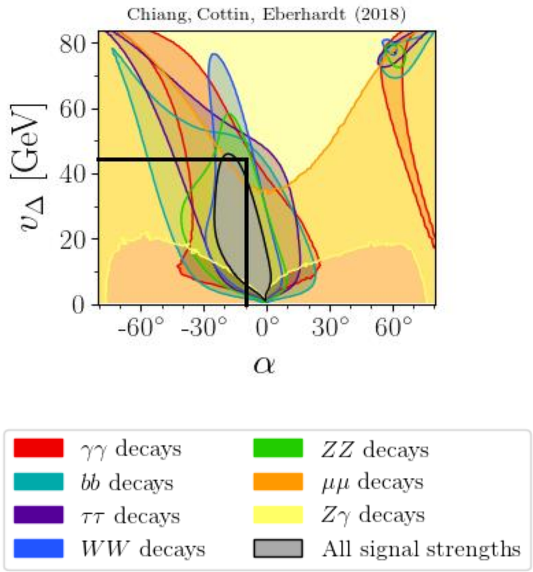
GM model issues

Giorgi-Machacek for pedestrians

- Allows I=2, H++, without violating ρ=**M²w/Mz²cos²θw=1** at tree level
- Is achieved by combining 1 isospin doublet (v_ϕ) + 2 triplets 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 **Fiveplet** of physical states H5++ H5+ H50 H5- H5–
Fermiophobic only produced by **VBF**
- **+ Triplet** H3+ H30 (CP-odd) -> **A(400)**
- **Mass degeneracy** inside multiplets usually assumed but **unnecessary** for ρ=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 $v\phi$ Y=1 T=1 $v\chi$ Y=0 T=1 $v\xi$

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

- 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, $v\phi$=213 GeV for the doublet, $v\xi$=$v\chi$=43.5 GeV for the triplets

SGM: a SUSY version of GM

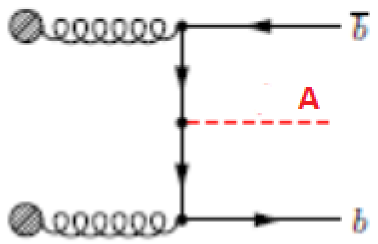
1308.4025

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

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

- 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

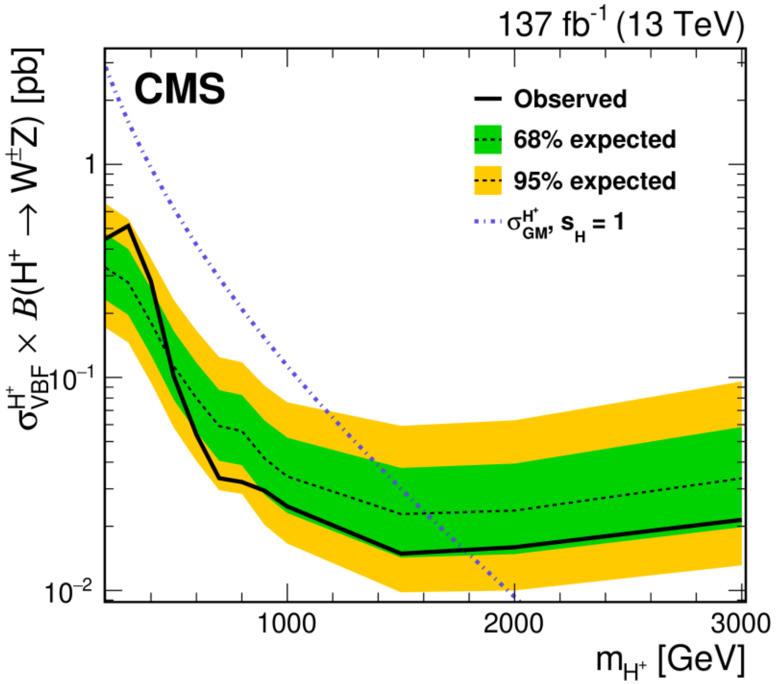
Need for extending GM



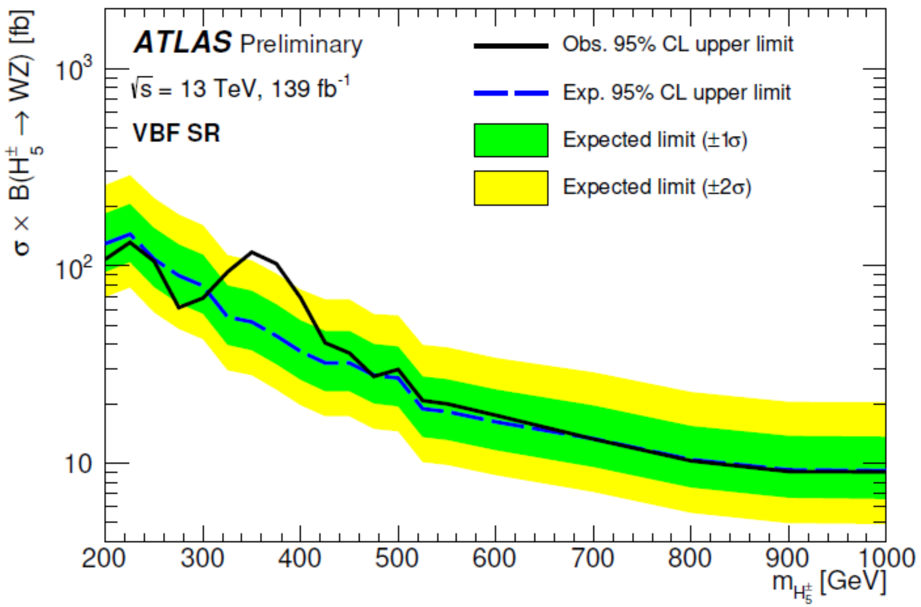
- Is GM satisfying the various observations ?
- The answer is NO
- This is the case for H(650) ZZ/WW
- The **fermionic couplings** of A(400) which tell us that **Yt~SM** while **Yb,τ >> SM and GM** but this needs confirmation
- The remedy for fermions is to add an **extra doublet** and benefit from an 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*

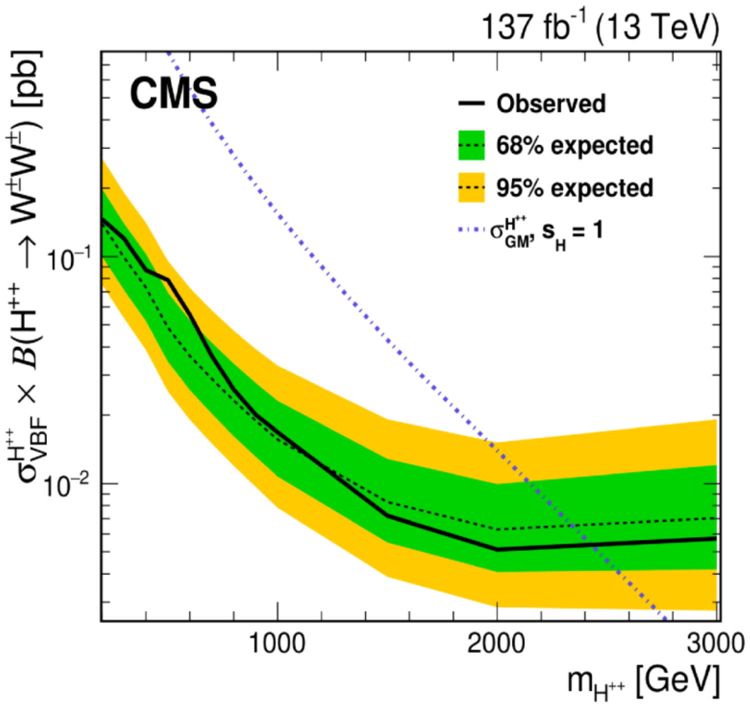
What about H5+ and H5++ ?

2104.04762



ATLAS-CONF-2022-005



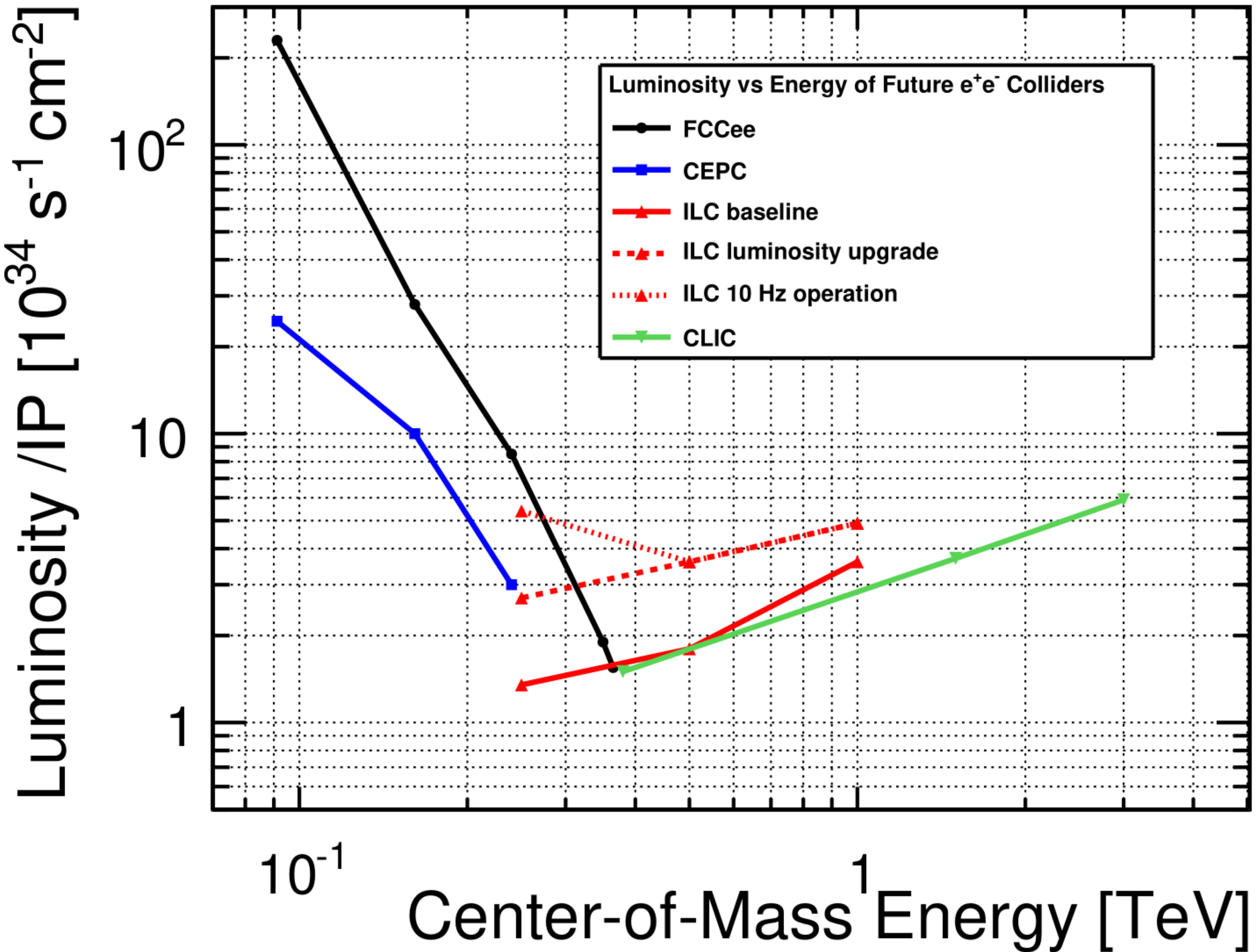


- CMS cross sections assume $\mathbf{s_H=1}$ are divided by 4 for $\mathbf{s_H=0.5}$
- If H3+ is light H3+Z and H3+W+ become dominant and these resonances become wide
- Coincident excess at mH5+~375 GeV for ATLAS (2.8sd) & CMS

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.