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

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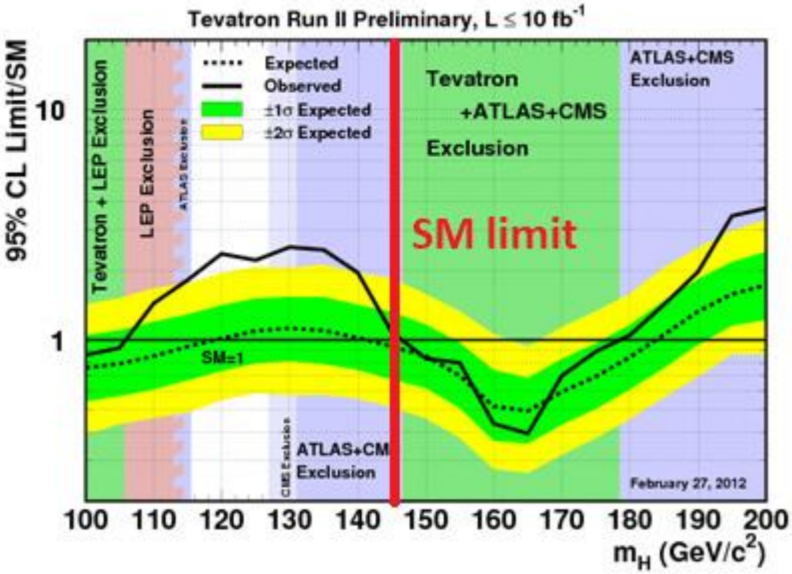
Introduction



- The SM Higgs discovery has relied on the following ingredients:

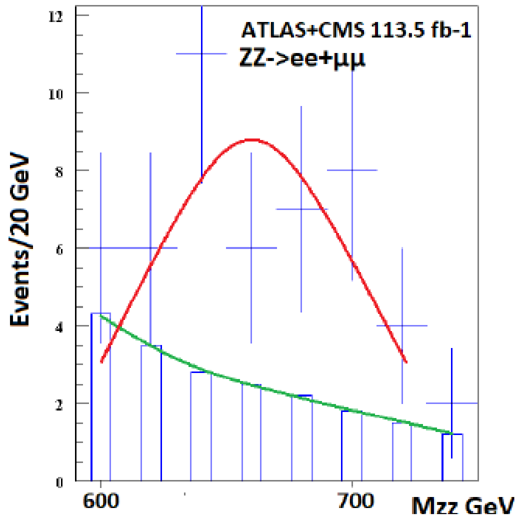
  - A well tested "**effective theory**", the SM, that predicted the mass and the couplings of the Higgs particle

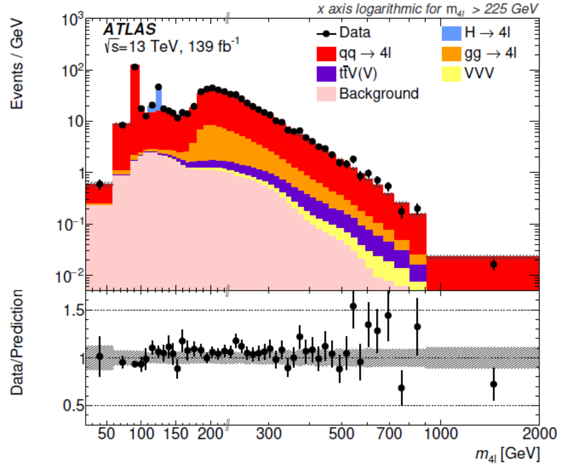
  - A > 5 s.d. evidence for 2 signals **coincidentally** observed by ATLAS and CMS for this particle (Tevatron started with a ~3 s.d. indication + Mh<145 GeV from Mw)

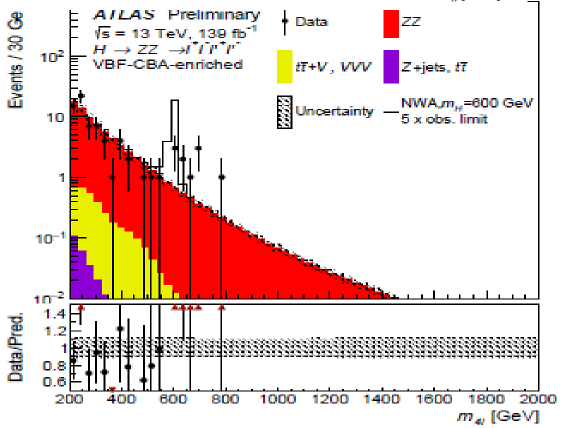
- The following question therefore arises: will LHC meet a similar scenario ?
- Here I will restrict to searches for scalars resulting from **broken symmetries** which, in a large class of BSM models, are the lightest objects in similitude with **pions of QCD**, the **SM h** being one of them
- The dominant phenomenological BSM framework assumes that these scalars belong to doublets and singlets but this can also comprise triplets in an extension proposed in 1985 by **Georgi and Machacek** which is consistent with the **parameter ρ** being very close to 1
- I will show that while not yet reaching 5 s.d. – although not so far from it – there are several **indications** close to that level, which do not seem to match the two doublet models but can be accommodated within reasonable extensions of **GM**
- Some of these indications are not "far fetched" and belong to the gold plated channels of LHC which led to the Higgs discovery

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 ~650 GeV with s/b=42/14 ~4.3 s.d. local significance
- With 139 fb-1 ATLAS sees a much smaller effect but at the same mass 2103.01918
- The VBF channel from ATLAS provides a better s/b, but with about 50% less efficiency
- With 139 fb-1, with **sequential cuts**, an excess is observed at the same mass, s/b=9/2 ~3 s.d., for VBF->H(650)->ZZ ATLAS-CONF-2020-032
- **Machine learning search** does not confirm (see T. Lagouri talk)
- The CMS analyses, 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…



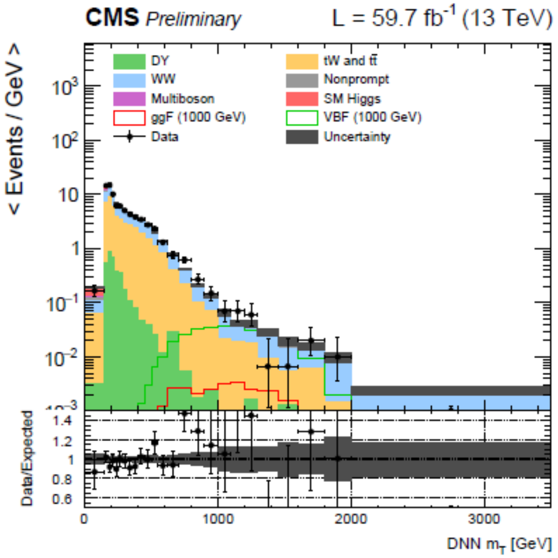




Evidence for VBF->H(650)->W+W- ->eμ$\nu\nu$

CMS PAS HIG-20-016

- 3 samples were analysed by CMS reaching 138 fb-1
- Has a large top background even after b-jet vetoing
- The best evidence reaches 3.8 s.d. is for **VBF->H(650)->eμνν**
- This result does not suffer from the "look elsewhere" downgrading
- The VBF cross section ~160 fb
- Awaiting for the same analysis from ATLAS before reaching any quantitative interpretation of this resonance
- See [2205.12234](2205.12234) for an alternate interpretation of these signals



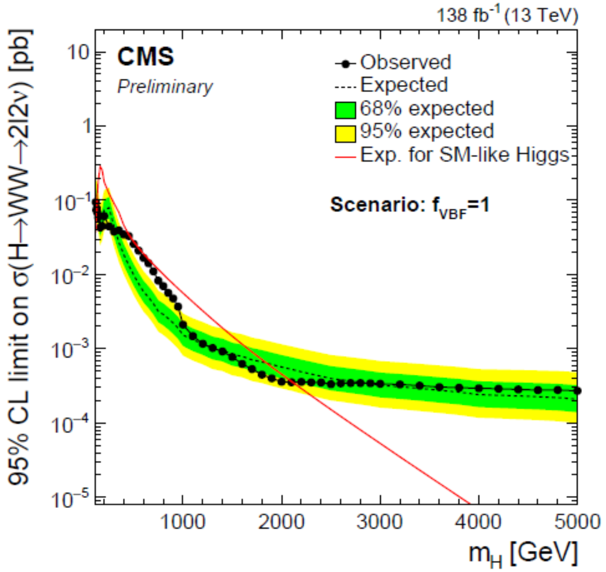
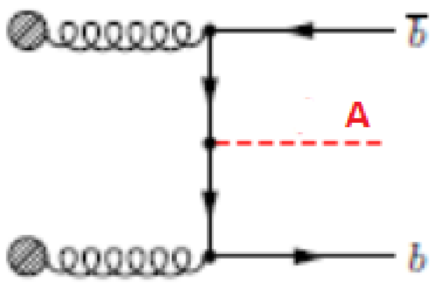


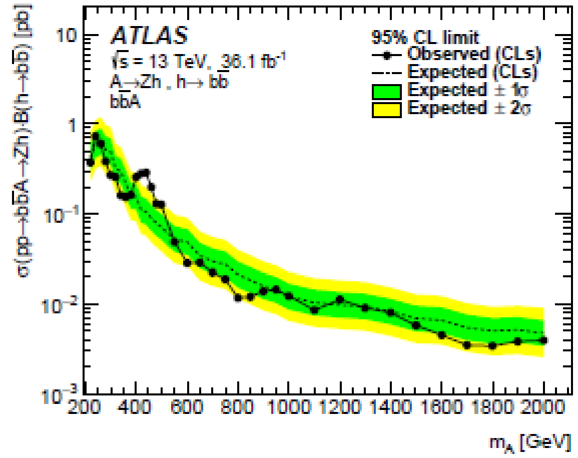
Table 3: Summary of the signal hypotheses with highest local significance for each f_{VBF} scenario. For each signal hypothesis the resonance mass, production cross sections, and the local and global significances are given.

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

2d indication : a resonance at 400 GeV seen in various modes

- CMS sees 3.5 s.d. for ttbar at ~400 GeV $\Gamma/M=4\%$
- CMS took into account **interference** with the QCD background (major issue at LHC)
- Signals were observed by **ATLAS** in ττ, ττ+**b** and in **hZ**+**b** (CP-odd) at ~400 GeV
- ττ, ττ+**b** not confirmed by **CMS**-PAS-HIG-21-001
- ATLAS signals at ~3 s.d. local, but giving **~6 s.d. global** when combined
- Caveat: hZ+b not completed by ATLAS with full stat
- Does not fit with **MSSM** which predicts decoupling for **A->hZ** *1802.09122*
- **-> Try an other model !**





- https://arxiv.org/abs/2001.04770
- https://arxiv.org/abs/2003.07112

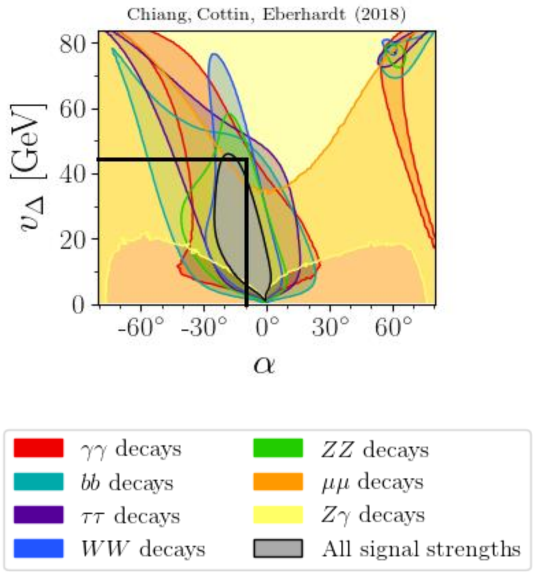
Reaction	Mass GeV	Nb of s.d.	Ref ArXiv
X(400)->tt	400	3.5	*1908.01115*
X(400) ->ττ	400	2.2	*2002.12223*
X(400)->ττ+b	400	2.7	*2002.12223*
A(400)->h(125)Z+b	440	3.6	*1712.06518*
X(400) + high pt e/μ	400	3	*2002.11325*

Giorgi-Machacek for pedestrians

- Allows I=3/2, H++, without violating ρ=**$M^2_w/M_z^2\cos^2\theta_w$=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 $v_\chi = v_\xi$

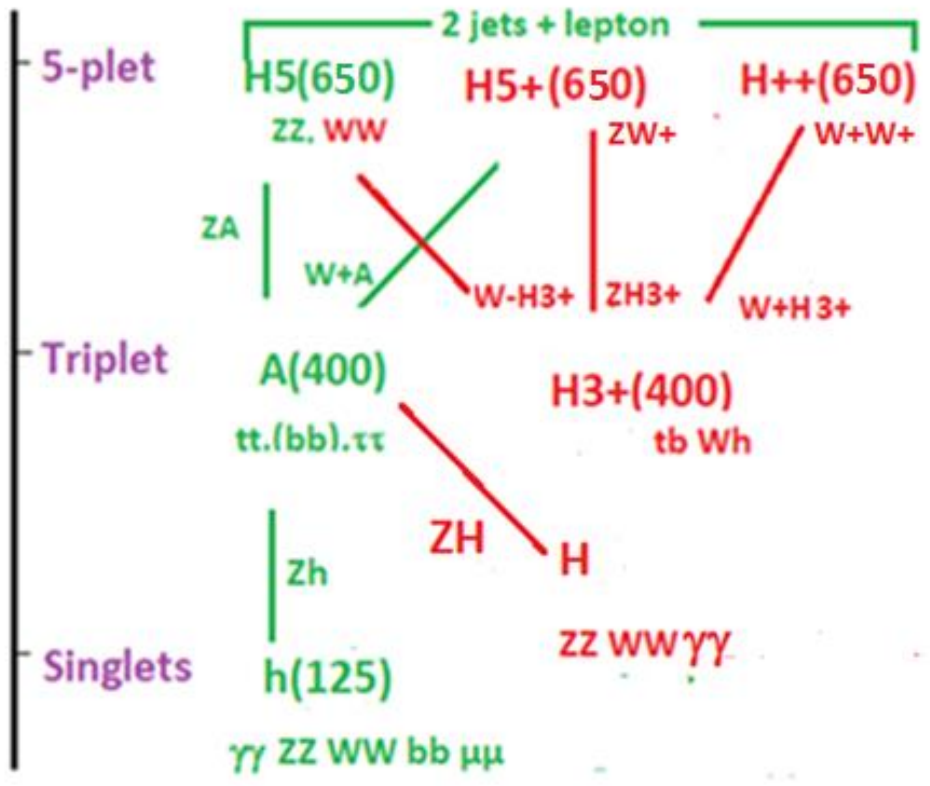


1807.10660

- Predicts a **Quintet** H5++ H5+ H50 H5- H5-- **Fermiophobic**, only produced by **VBF** for which H(650) could be a candidate
- **+ Triplet Gaugephobic** H3+ H30 (CP-odd) H3- -> **A(400)**
- Mass degeneracy inside multiplets usually assumed but unnecessary for $\rho=1$ 2111.14195
- + **Singlets h(125)** and H1 **mixing angle α**
- **Unitarity constraints** impose mH<700 GeV and fixing m5 and m3, that mH1<250 GeV
- Allows A(400)->hZ but A(400)->H1Z ~25 times larger if mH1~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

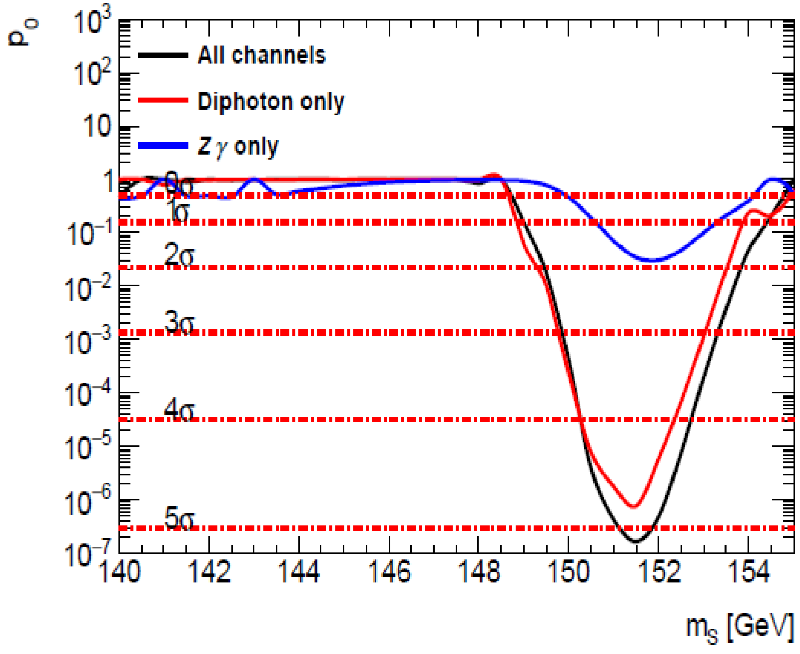
3d indication: cascades

- The GM picture suggests the presence of many **cascades** which allow various strategies of signature: like sign leptons, leptons + b jets, ttW etc…
- Cascades could explain the various topological anomalies recorded by **Budenbrock et al** [1901.05300](1901.05300) in ATLAS and CMS with an overall significance ~ **8 s.d.**
- Similar analysis performed by CMS in [2202.08676](2202.08676)
- 2 **additional scalars H(270) S(150)** were predicted by Budenbrock et al which tend to cascade into each other H->SS* and H->Sh(125)

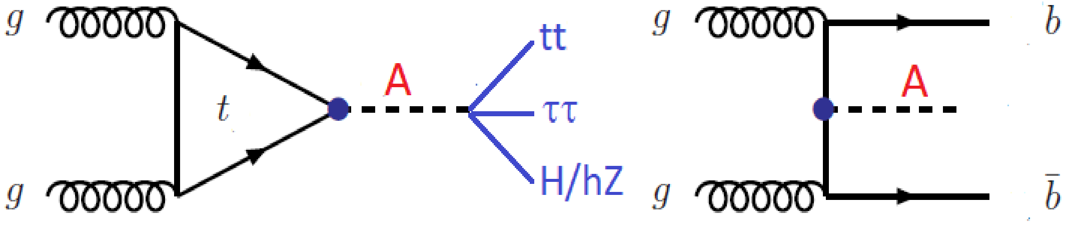


4th indication H(151)->2γ + Etmiss + …

- Following *1901.05300*, signal observed by Crivellin et al. *2109.02650* asking ETMiss or presence of additional leptons and b jets (global **4.8 s.d.)**



- GM interpretation:



- 1st mechanism has σ~6000 fb
- ETMiss comes from Z->νν **without invoking other particles**
- The second mechanism allows to understand Zh(125)+bjets observed by ATLAS

ZWW: a paradox ?

- GM predicts for BR(A->HZ)=54%
- For H, in MeV: Γtot_{SM}=5 Γ(WW)=4.5 Γ(ZZ)=0.5 $\Gamma(\gamma\gamma)$=0.025
- **Γ_{BSM}=? Visible and invisible**
- Predicts $\delta\sigma$(ZWW) ~3000 fb if **Γ_{BSM}=0**
- Excluded by CMS limit $\delta\sigma$(ZWW)<400 fb *2006.11191*
- Would require Γ_{BSM} ~ 40 MeV to lower BR(WW)
- BRinv <30% deduced from h(125) favours Γ_{BSMvis}
- If H->BSM visible, it is likely that this happens also for h(125)

H(151)->aa ?

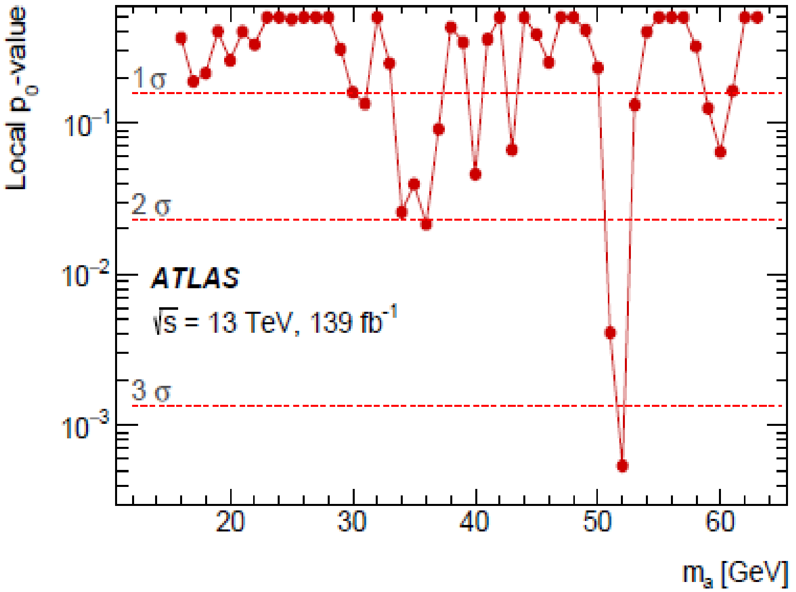
2110.00313

- ATLAS observes an evidence **3.3σ local 1.7σ global** for **h(125)->aa** scalar or pseudo-scalar ma=52 GeV
- Such an object is well motivated (DM, EW phase transition, g-2…)
- BR(h->μμbb) ~2 10^{-4} μμbb/bbbb~1/1300 hence Γ(h->aa)~1 MeV
- Could be much larger for H in the GM model

h=cosαH1 –sinαH1’ H=sinαH1 +cosαH1’

assuming a(52) couples to the H1’ component

Γ(H->aa)=Γ(h->aa)/$\sin^2\alpha$=44 MeV !



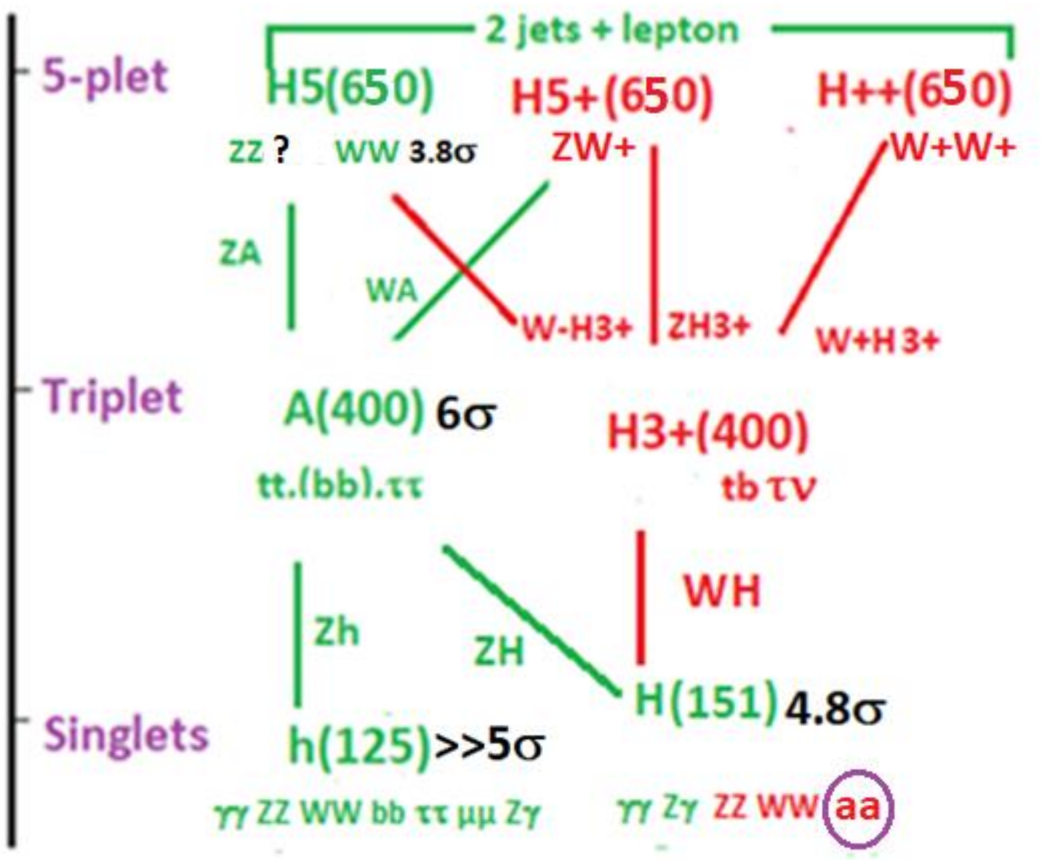
Final evaluation

ΓHtot MeV	ΓWW MeV	ΓZZ MeV	$\Gamma\gamma\gamma$ MeV	Γaa MeV	Γinv MeV
5-50	4.5	0.5	0.025	45	<2-20

ΓAtot GeV	Γtt GeV	ΓhZ GeV	ΓHZ GeV	ΓA BSM GeV
16	6.4	0.4	8	?

- Previous results allow to fix the widths of A & H
- CMS indicates **ΓAtot ~16 GeV**, leaving few MeV for BSM
- **H(151)** decays are dominantly BSM, not necessarily aa but visible, from the LHC measurements of WW
- BR(Z->$\nu\nu$)σ(A->HZ)BR(H->2γ)=0.2*3000(0.025/ΓHtot)
  0.42±0.13 fb in Crivellin et al. suggesting ΓHtot~40 MeV
- σ(4ℓ)=σ(A->HZ)BR(H->ZZ)BR(ZZ->4ℓ)= 3000(0.5/ΓHtot)0.07^2=0.18 fb
  compatible with <0.28 fb in Crivellin et al.

The GM+a picture

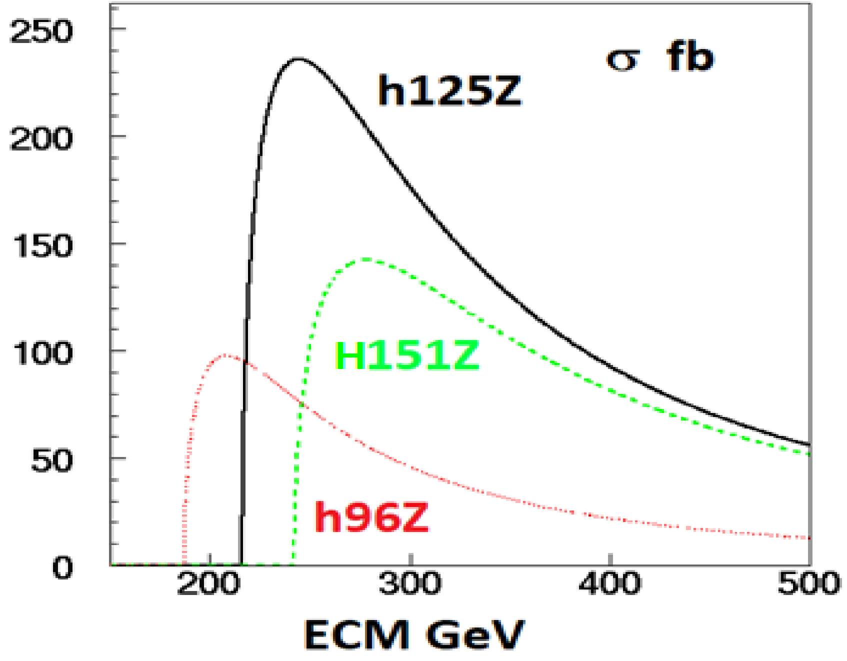


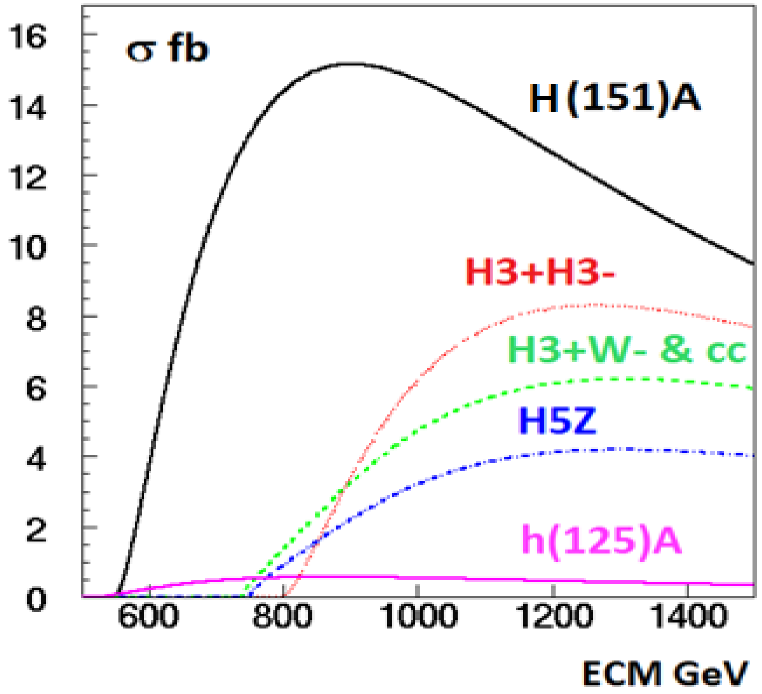
- GM predicts the mass and couplings of H(151) with a BSM final state **aa**
- **A->H(151)Z with H(151)->aa and a->bb** with **σ ~ 5000 fb** offers a major new topology for discoveries
- This topology is **similar to h(125)Z with h->bb**, which could explain the apparent large cross section for “hZ” seen by ATLAS which could be a fake

GM cross sections in e+e-

- At 1 TeV

- At 250 GeV



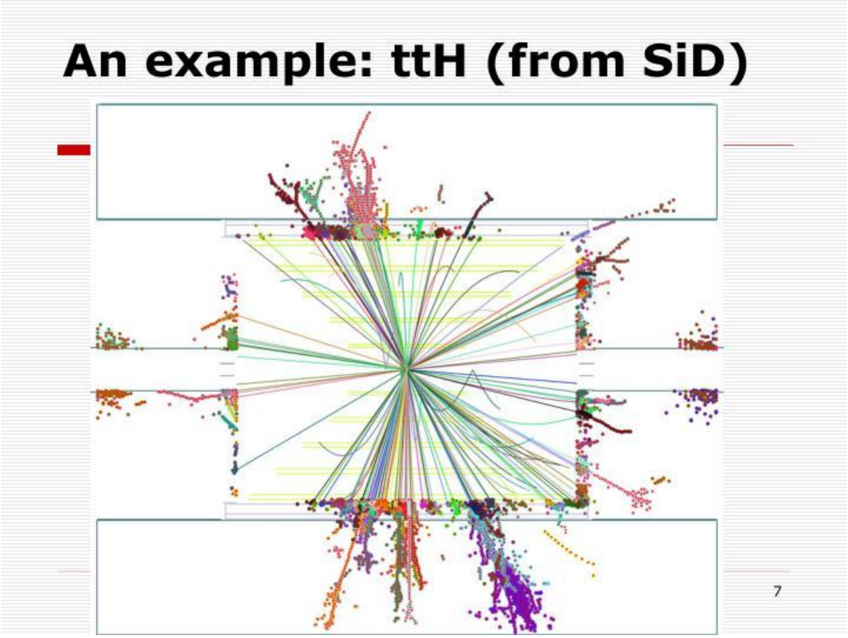


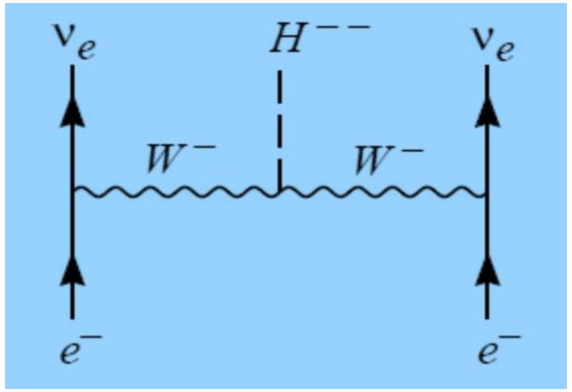
- Large xsections allowing very precise measurements

- Assumes mass degeneracy inside multiplets
- H5Z is a only a guess and needs confirmation
- Complex modes which requires highest $\mathcal{L}$ and reconstruction efficiency

Prospects for a LC

- ECM=1 TeV is sufficient to observe the full GM scalar spectrum
- Requires highest possible **luminosity,** ~8000 fb-1 with ILC at 1 TeV *1903.01629*
- $\Omega > 0.9$ is needed for jet reconstruction and b tagging for these complex modes $\varepsilon ff \sim \Omega^n$ n~8





- >1.5 TeV to pair produce H5++ H5 - - in e+e-

but 1 TeV enough in **VBF** **e-e- ->W-W-νν->H5- - νν** ~few fb for single production

Conclusions

- Evidence is building up at LHC for the presence of a rich scalar spectroscopy in the framework of the **GM model** which predict scalars lighter than 700 GeV therefore **fully testable at LHC**
- An indication coming from Crivellin et al. suggests that **H(151)** could have a **BSM dominant decay**, a scenario comforted by ATLAS observing h(125)->aa, with ma=52 GeV
- There are a few concerns, e.g. about H(650) into WW and ZZ which would benefit from an official **combination of ATLAS and CMS analyse**s
- These results potentially open good prospects for HL-LHC discoveries/confirmations, with the following message: **do not assume that BSM physics necessarily means masses > 1 TeV**
- All neutral scalars of GM have been observed while the absence of **H3+, H5+ and H5++** can still be understood (see Appendix)
- GM offers an entirely new landscape for e+e- colliders under discussion and motivates a **linear e+e- collider reaching no less than** **1 TeV**
- Complex final states will have a **critical impact on the design of future LC detectors**

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

APPENDIX

Missing slides (lack of lime)

GM constraints on MH and BR(H(151)->2γ)

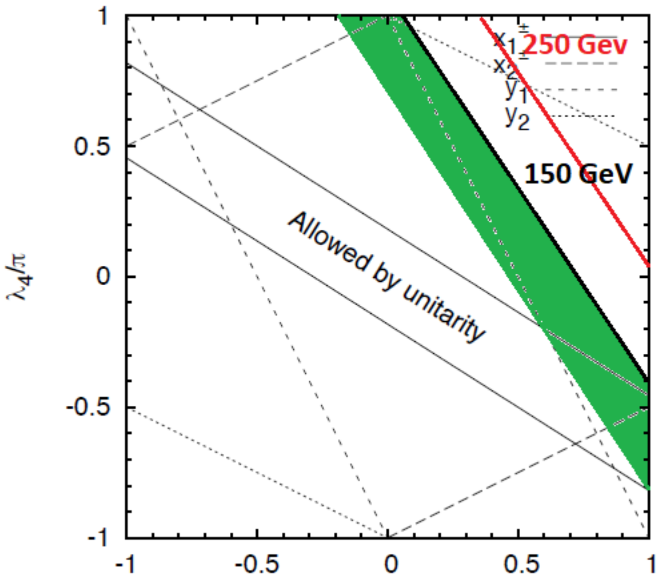
- The GM model gives strict **unitary limits** on the scalar masses and on the coefficient of the scalar potential:

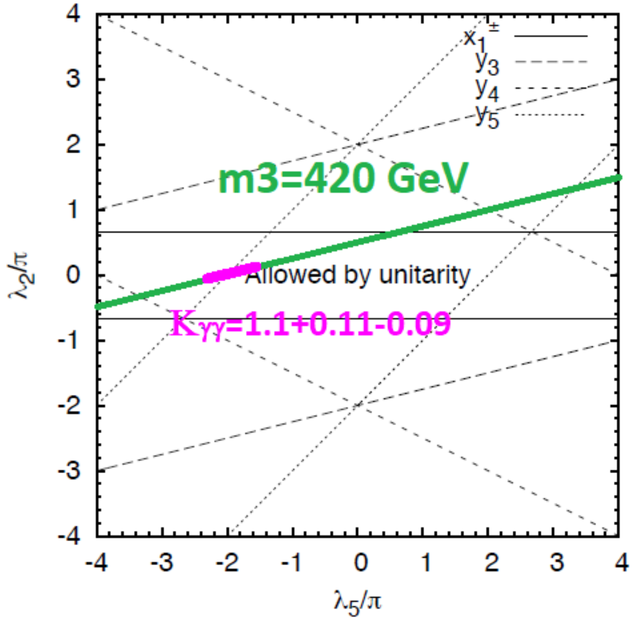
$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{+*} & \phi^{0} \end{pmatrix},$$

$$X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix}$$

$$\begin{aligned} V(\Phi, X) = & \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 + \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) \\ & + \lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) \\ & - M_1\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab}. \end{aligned}$$

- A priori **m<700 GeV for all scalars** *1404.2640*
- Knowing m3 and m5 one finds **mH<250 MeV** for the missing scalar
- From LHC observations and **h(125)->2γ** one can extract all parameters and compute **Γ(H(151)->2γ)=0.025 MeV** *1708.08753*





Higgs self coupling predictions

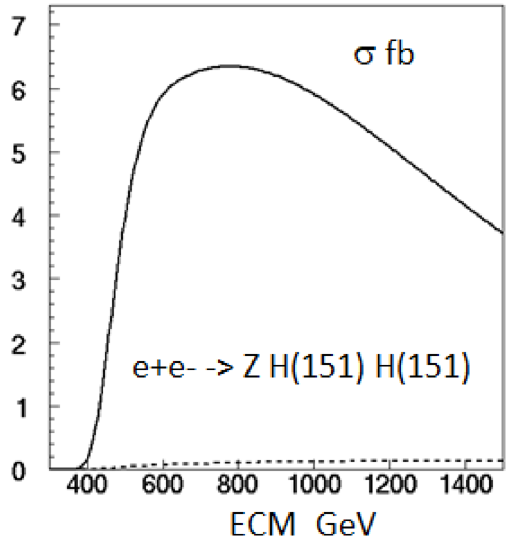
m3 GeV	m5 GeV	sα	sH	λ1/π	λ2/π	λ5/π	λ3/π	λ4/π	M1 GeV	M2 GeV
420	660	-0.15	0.5	0.02	0.01	-1.7+0.2-0.6	0.6	-0.2	1000	1000

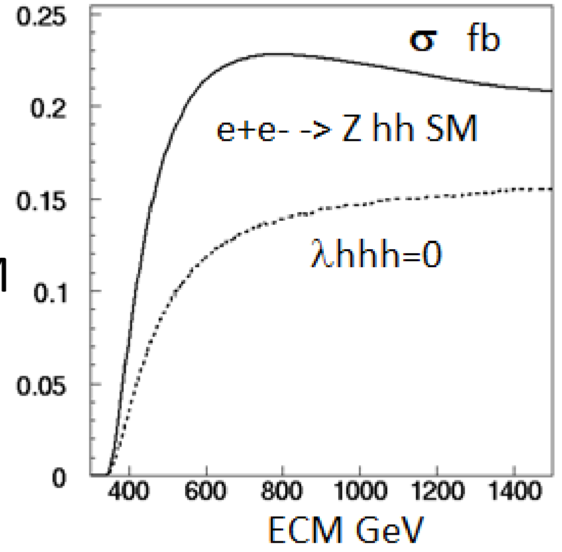
- Fixing the GM parameters of the scalar potential from LHC observables, one can deduce the self couplings

λ_{HHH}/SM~22 λ_{hHH}/ ~3.36 λ_{hhH}/SM~1.6 λ_{hhh}/SM~0.14

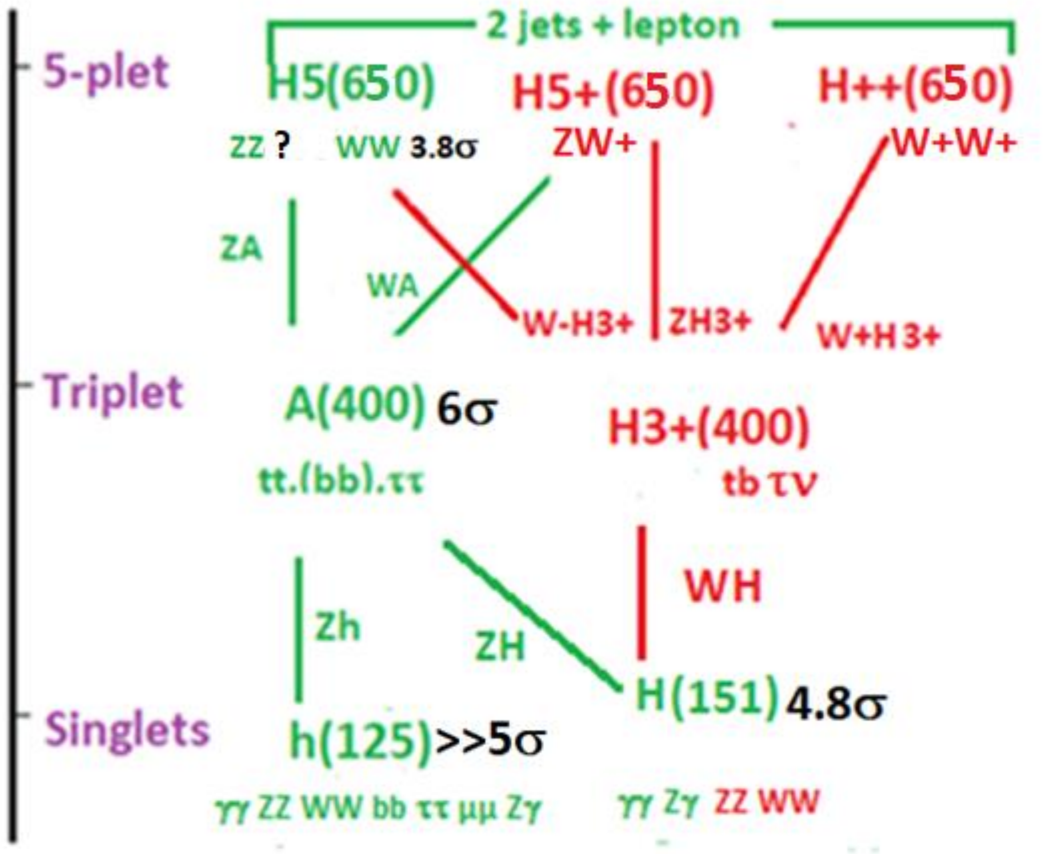
- **e+e- ->ZHH** reaches ~**4 fb at √s~600 GeV** ~27 times Zhh SM
- **e+e- -> Zhh** almost unchanged /SM from the contribution of H->hh
- Recalling that H should decay in ~90% of the cases into BSM modes, presumably into a pair of CP-odd light scalars **H->aa**
- At LHC one expects that final states with HH originate either from a Higgsstrahlung, VBF or from the cascade **A->H*Z->HHZ**
- The Z spectator can be used as a **tagger**
- These measurements are sensitive to the two parameters M1 and M2 of the GM potential recalling that

$$g_{HHH} = 24\lambda_1 s_\alpha^3 v_\phi + 6 s_\alpha c_\alpha \left(\sqrt{3} s_\alpha v_\chi + c_\alpha v_\phi\right)(2\lambda_2 - \lambda_5) + 8\sqrt{3} c_\alpha^3 v_\chi (\lambda_3 + 3\lambda_4) - \frac{3\sqrt{3}}{2} M_1 s_\alpha^2 c_\alpha - 4\sqrt{3} M_2 c_\alpha^3 ,$$





The new GM+a picture



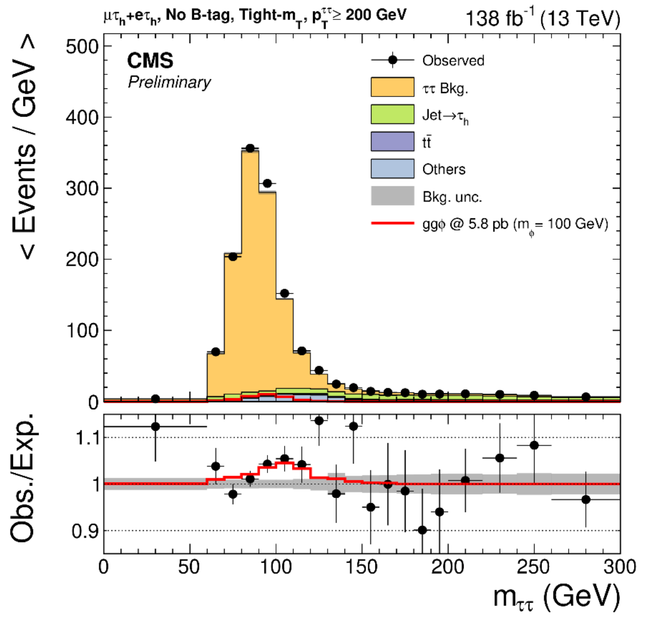
- GM predicts correctly the mass and couplings of H(151)
- All neutrals scalars are indicated
- Charged Higgs absent but **H3+** not searched into **WH(151)** which can dominate (also aW)

Type	coupling /SM, MSSM	sα=-0.15 sH=0.5
h(125)WW/ZZ	cαcH- 1.63sαsH	0.98
H(151)WW/ZZ	sαcH+1.63cαsH	0.68
h(125)tt,bb	cα/cH	1.14
H(151)tt,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
H(151)AZ,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

What about h(96) ?

(see also S. Heinemeir at this WS)

- h(96)->2γ by CMS, not by ATLAS which however does not reach the same sensitivity
- Could it be the singlet H ?
- One would expect A->H(96)Z ~30*A->h(125)Z, which does not seem to be the the case
- Could be an additional isosinglet embedded in an EGM or be the Radion expected within Randall Sundrum phenomenology *1712.06410*
- A 3.1 s.d. indication of h(100)->$\tau\tau$ is seen by CMS after substraction (see *2205.03187* for a CP-odd interpretation)
- Ideal for an e+e- collider h(96)->bb $\tau\tau$ gg



CMS-PAS-HIG-21-001

GM model issues

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

A GM interpretation of the Mw excess?

- Recall that

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

- From the CDF recent measurement of M_W which implies a deviation from 1 of this parameter one may wonder if GM could provide the simplest explanation ?
- See 3 GM references: 2204.12898 2204.07844 2204.05760
- In *2204.12898* it is shown that this is indeed possible provided the scalar potential is modify to avoid generating unwanted effects (a bit technical, sorry)

Top-down approach to GM

- The GM model does not pronounce on the **origin of symmetry breaking** and is therefore **incomplete**
- In a **UV complete scenarios**, one assumes a symmetry breaking mechanism from extended symmetries to a group containing the SM SU(2)XU(1), accompanied by **pseudo Nambu-Goldstone bosons** in addition to the SM Higgs doublet which can result in GM
- A recent reference 1703. 06064 shows how this mechanism can naturally generate **Higgs triplets**
- Some of these theories are **strongly interacting** and therefore constraints are extracted by lattice calculations
- In any case the GM model can be easily tested since in predicts scalars with masses below 700 GeV which can be ruled out at LHC

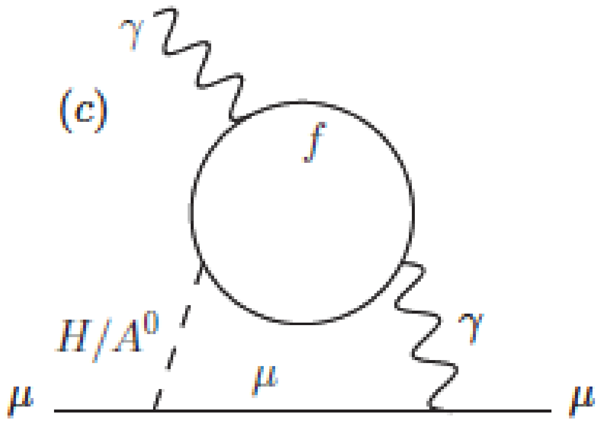
GM and LHC precision measurements on h(125)

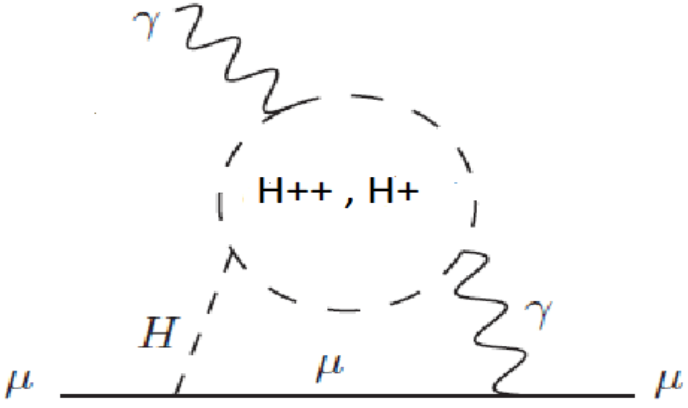
- **σ(gg->h) +28%** from htt in GM
- **Γhtot +25%** due to h->aa and **+16%** from Γbb
- LHC measures σΓx/Γtot hence ~**compensation** ggF/Γtot apparent Γγγ Γww/zz -12% from true values
- Γbb comes from WWF->h and h+Z/W with ~compensation on Γbb -12% from true value
- LHC does not reveal GM due to these compensating effects except for VBF->h->WW* where a -40% effect could become visible with better accuracies
- ATLAS-CONF-2021-014 **μVBF=1.0±0.20**
  CMS PAS HIG-20-013 **μVBF=0.70±0.26**
- Separation and high accuracy will be available in e+e-

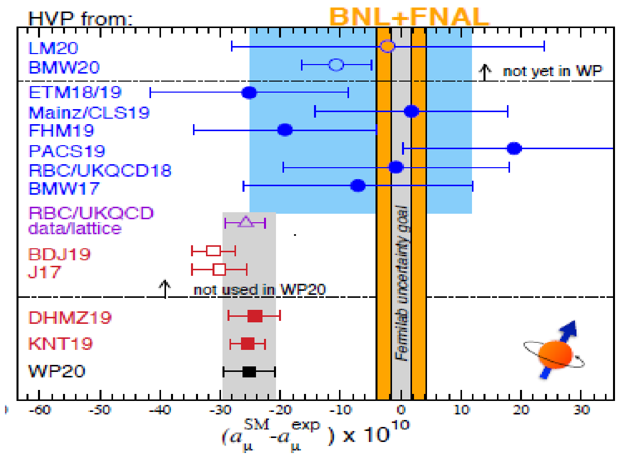
Type	coupling/SM	sα=-0.15 sH=0.5
h(125)WW/ZZ	cαcH- 1.63sαsH	0.99
H(151)WW/ZZ	sαcH+1.63cαsH	0.68
Att,bb,ττ	tanH	0.58
h(125)tt,bb	cα/cH	1.14
H(151)tt,bb	sα/cH	0.17
Zh(125)A	1.63(sαcH+0.6cαsH)	0.28
ZH(151)A	1.63(cαcH- 0.6sαsH)	1.48
Wh(125)$H3^+$	1.63(sαcH+0.6cαsH)	0.28
WH(151)$H3^+$	1.63(cαcH- 0.6sαsH)	1.48

What about g-2 in eGM+a(52) ?

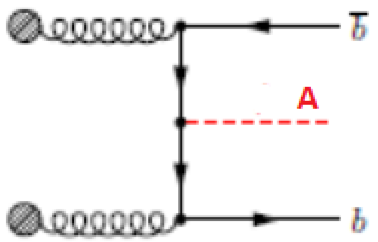
- Usual wisdom is that extra scalars need to be **<100 GeV** to influence g-2
- The two loop contributions (**Barr Zee**) dominate and gives the right sign
- *2104.03275* with 2 doublets+1 triplet predicts a significant ($\geq 10^{-9}$) contribution to aμ provided there is an enhanced μμ coupling (~x100)
- A quantitative prediction for the eGM+a model with 2 doublets + 2 triplets + a(52) seems promising





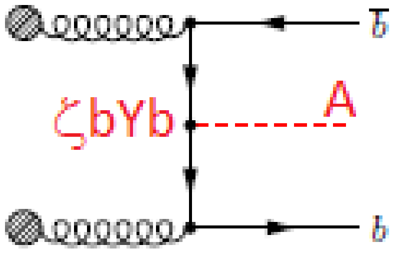


Need for extending GM

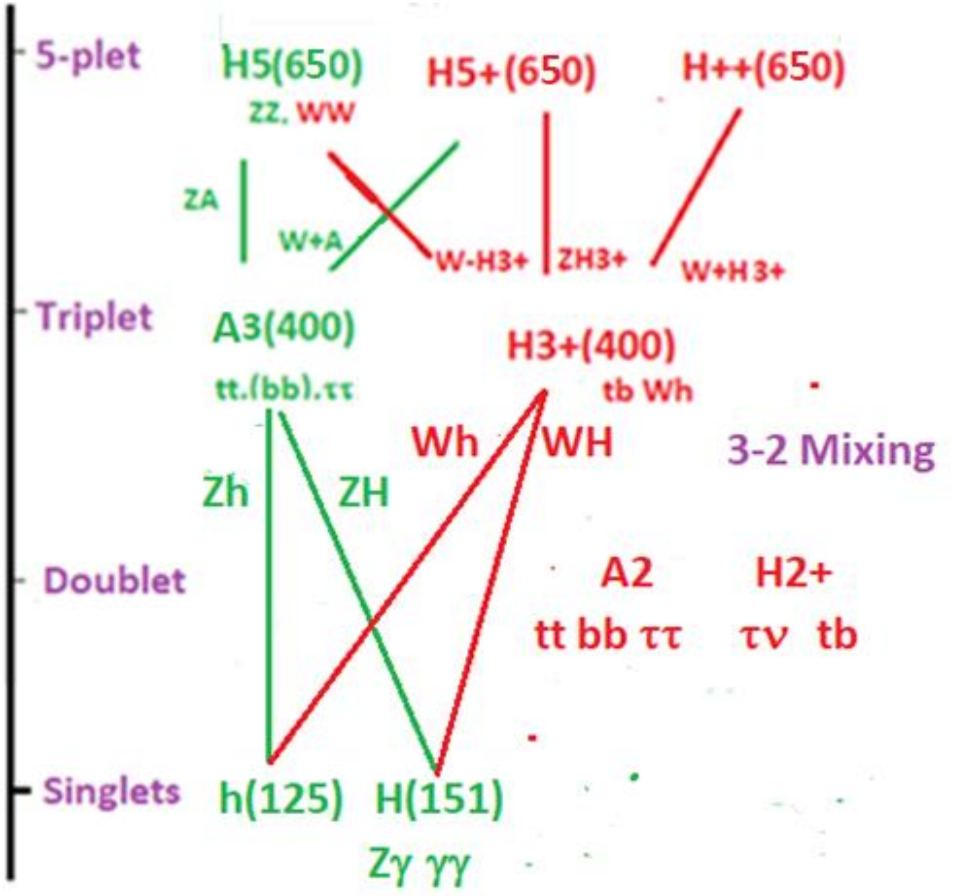


- Is GM satisfying the various observations ?
- The answer is NO, in particular for what concerns the **fermionic couplings** of A(400) which tell us that **Yt~SM** while **Yb,τ >> SM and GM**
- The remedy is to add an **extra doublet** and benefit from an enhancement of **Yb,τ~tanβ~20** 'à la MSSM'. 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**
- 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*

GM+2 doublets model



- Yukawa couplings
- A2HDS ζℓ,d~20   ζu~0.7



	Y_1^d	Y_1^u	Y_1^ℓ	Y_2^d	Y_2^u	Y_2^ℓ	ζ_u	ζ_d	ζ_ℓ
Type I	0	0	0	×	×	×	t_β^{-1}	t_β^{-1}	t_β^{-1}
Type II	×	0	×	0	×	0	t_β^{-1}	$-t_\beta$	$-t_\beta$
Type X	0	0	×	×	×	0	t_β^{-1}	t_β^{-1}	$-t_\beta$
Type Y	×	0	0	0	×	×	t_β^{-1}	$-t_\beta$	t_β^{-1}
A2HDS	×	×	×	×	×	×	$\frac{\xi_u - t_\beta}{1+\xi_u t_\beta}$	$\frac{\xi_d - t_\beta}{1+\xi_d t_\beta}$	$\frac{\xi_\ell - t_\beta}{1+\xi_\ell t_\beta}$

Giving up mass degeneracy in the scalar sector

- **Mass degeneracy** inside H5 and H3 is not necessary to insure the constraint ρ~1 as pointed out in 2111.14195
- This aspect is very important for searches
- This aspect is critical for experimental searches and could explain the absence of charged Higgs scalars in ZW and W+W+ if **mH3+<mA**, in which case H5++->H3+W+ competes with W+W+

$$V(\Phi, X) = \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 + \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X)$$
$$+\lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b)$$
$$-M_1\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab}.$$

$$V(\phi,\chi,\xi) = \bar{\mu}_2^2\phi^\dagger\phi + \bar{\mu}_3'^2\chi^\dagger\chi + \frac{\bar{\mu}_3^2}{2}\xi^\dagger\xi$$
$$+\bar{\lambda}_1(\phi^\dagger\phi)^2 + \bar{\lambda}_2|\tilde{\chi}^\dagger\chi|^2 + \bar{\lambda}_3(\phi^\dagger\tau^a\phi)(\chi^\dagger t^a\chi) + \left[\bar{\lambda}_4(\tilde{\phi}^\dagger\tau^a\phi)(\chi^\dagger t^a\xi) + \mathrm{h.c.}\right]$$
$$+\bar{\lambda}_5(\phi^\dagger\phi)(\chi^\dagger\chi) + \bar{\lambda}_6(\phi^\dagger\phi)(\xi^\dagger\xi) + \bar{\lambda}_7(\chi^\dagger\chi)^2 + \bar{\lambda}_8(\xi^\dagger\xi)^2 + \bar{\lambda}_9|\chi^\dagger\xi|^2 + \bar{\lambda}_{10}(\chi^\dagger\chi)(\xi^\dagger\xi)$$
$$-\frac{1}{2}\left[\bar{M}_1'\phi^\dagger\Delta_2\tilde{\phi} + \mathrm{h.c.}\right] + \frac{\bar{M}_1}{\sqrt{2}}\phi^\dagger\Delta_0\phi - 6\bar{M}_2\chi^\dagger\overline{\Delta}_0\chi.$$

- In 2204.12898 it was shown that with this type of potential one can interpret the result of CDF II by assuming that **vξ ≠ vχ**

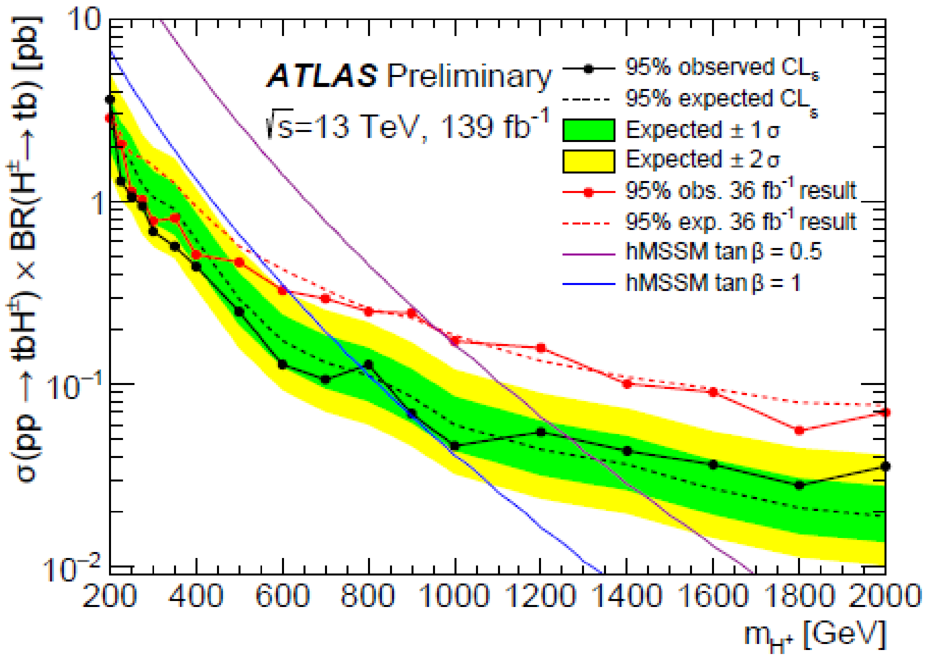
What is meant by eGM+a ?

- LHC observations result into eGM+a: 2 doublets, 2 triplets, 1 CP-odd singlet a, 1CP-even singlet h(96)
- With custodial symmetry breaking terms it can can break **mass degeneracy** of 3-plets and 5-plets usual in GM 2111.14195
- Lifting the triplet vacuum degeneracy it can provide the ρ **parameter** contribution needed for the CDF II Mw excess 2204.12898
- The **additional doublet** allows to cope with A decays, using **Yukawa alignment** to explain fermion couplings
- The **additional singlet CP-odd a(52)** introduced to explain **H(151) decays** can be used in various ways:
- With a large **aμμ coupling enhancement** it can explain the g-2 effect
- *2202.12631* also assume that a(52) can decay into **DM** pairs
- **EW phase transition** is helped by a(52) *0705.2425*
- The role of h(96), left out of eGM+a, is unclear unless one assumes that it is the isoscalar needed to stabilize the brane of RS
- eGM+a would have a very **complex scalar potential** with 12 isoscalars

LHC issues

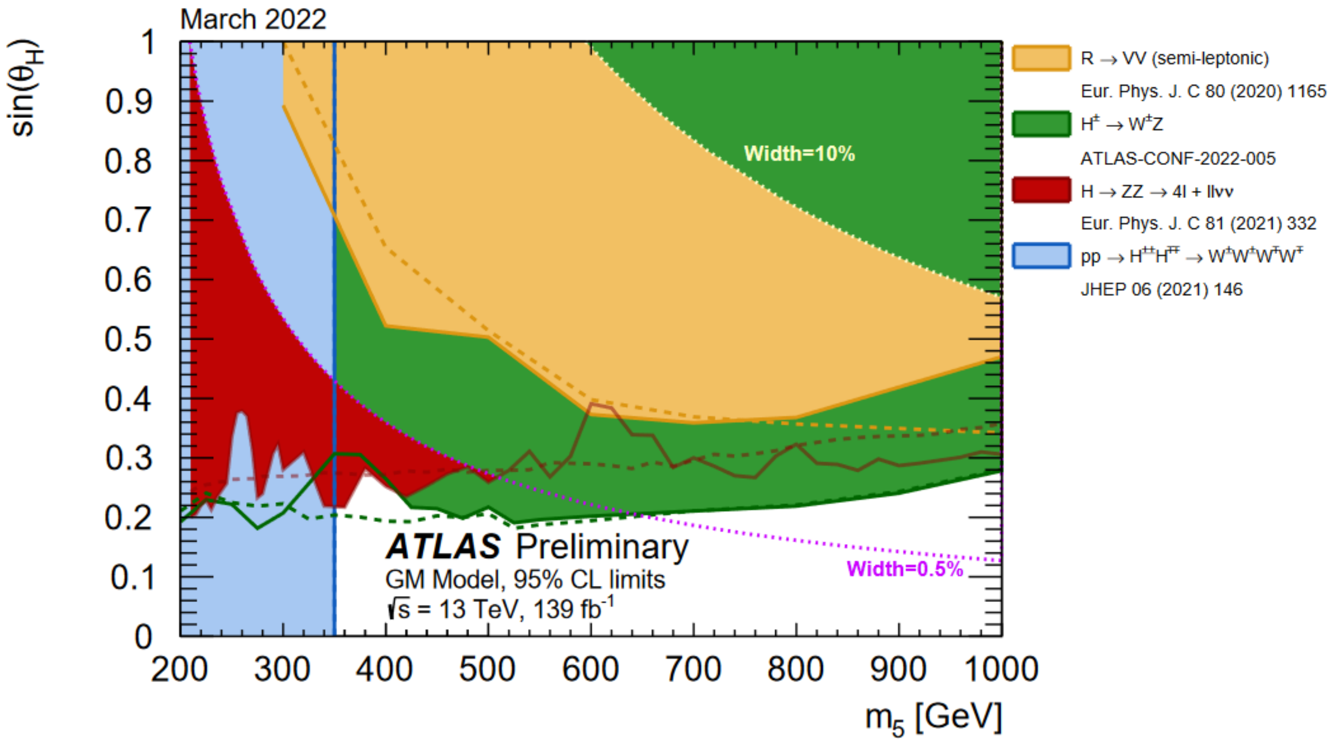
A worry

- How present indications, if real, can progress with increased luminosity ?
- There is a common tendency to expect **massive objects**, hence to optimize the various selections accordingly, in contrast to the strategy used to discover h(125)
- This may result in an absence of progress for relatively light scalars, a concern in the present scenario
- An example of this is shown in the search for H+->tb where progress in luminosity is unclear for masses ~400 GeV which are relevant in our case

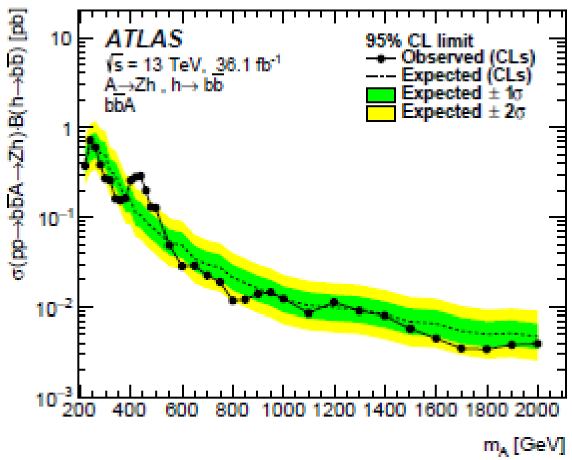


ATLAS GM summary plot

- ATL-PHYS-PUB-2022-008
- The present solution which assumes $\sin\theta_H$=0.5 and m5=650 GeV seems incompatible with this summary plot of ATLAS
- Seems covered by H+->W+Z not dominant when ZH3+ opens up which is the case
- An additional contribution of H5->W+a competing with ZW is also ignored
- H5(650) relative width ~0.5% is invalid in the assumed scenario (100/650=15%)

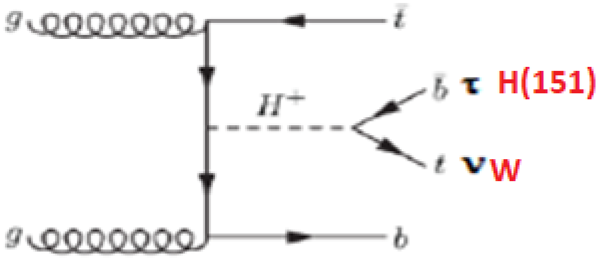


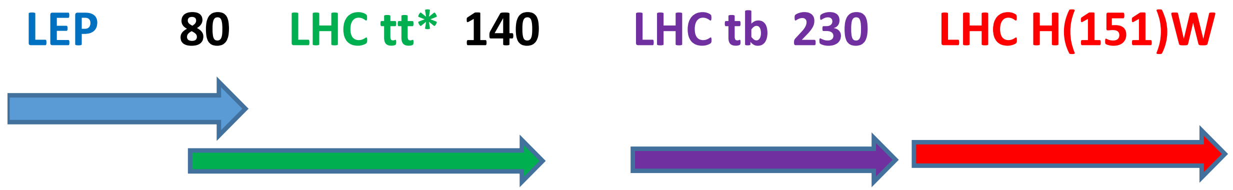
Why does ATLAS observe A->hZ ?



- The A->hZ GM coupling seems too small to explain the ATLAS observation
- gg->A->H(151)Z has a cross section 20 to 30 times larger ~3000 fb
- Assuming H(151)->a(52)a(52) with a->bb in ~90% of cases, which fraction of these events can fake hZ ?
- ATLAS requires two "small R-jets" and restricts the mh range to 110-145 GeV, which implies that a large fraction of H(151)Z events will be lost
- This can explain why the observed excess in ggF is only ~200 fb, implying that ~10% of the HZ decays are accepted by this analysis
- For the bbA topology, the 4b final states could allow accidental selections of the gg->A contribution
- Given the ratio hZ/HZ, one can therefore not exclude that the observed signal is dominantly due to A->HZ
- The reconstruction efficiency of the "hZ" channel depends on the experimental selections and may vary, perhaps explaining apparent contradictory results

What about H3+ ?



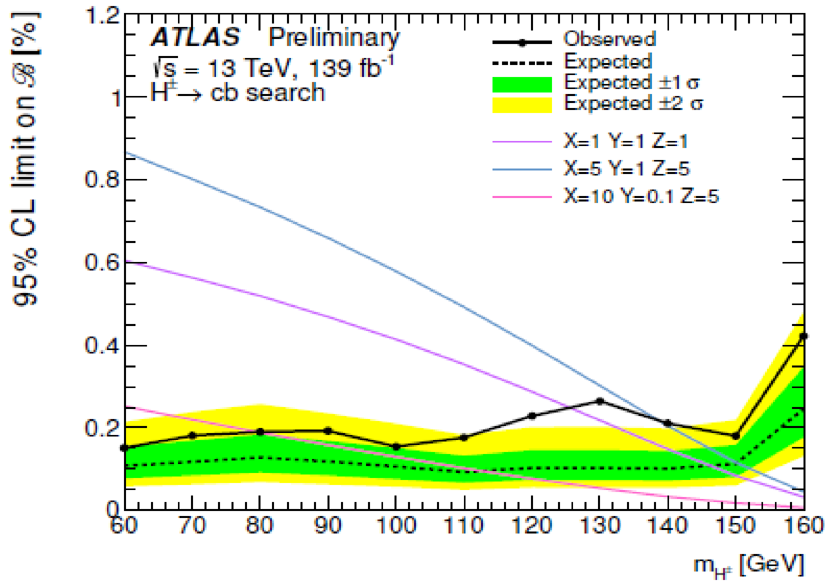


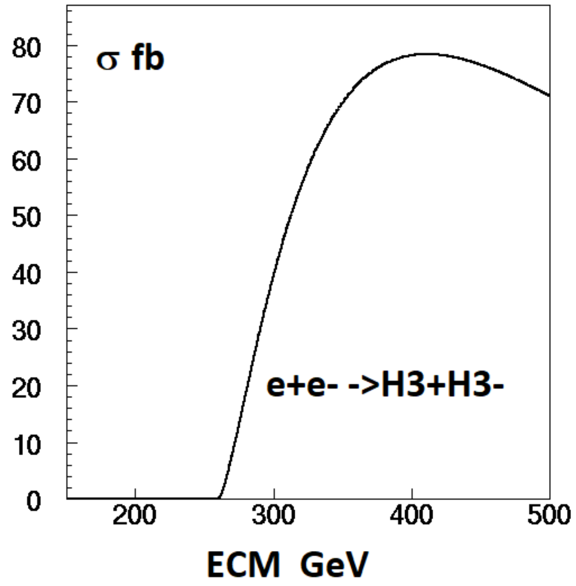
- mH3+=mA=400 GeV is predicted in GM however *2111.14195* tells us that mass degeneracy can be relaxed
- -> Full coverage is needed noting that there is a **blind zone** between 140 and the tb threshold
- The GM dominant decay mode **H3+->H(151)W+** has not been searched for (hW+ subdominant)
- For mH3+=400 GeV GM predicts BR(HW)/BR(tb)~1
- An excess is reported on H+->cb (next slide) with mH+=130 GeV, consistent with the eGM model

ATL-PHYS-PUB-2020-006
23 March 2020

What if mH3+=130 GeV ?

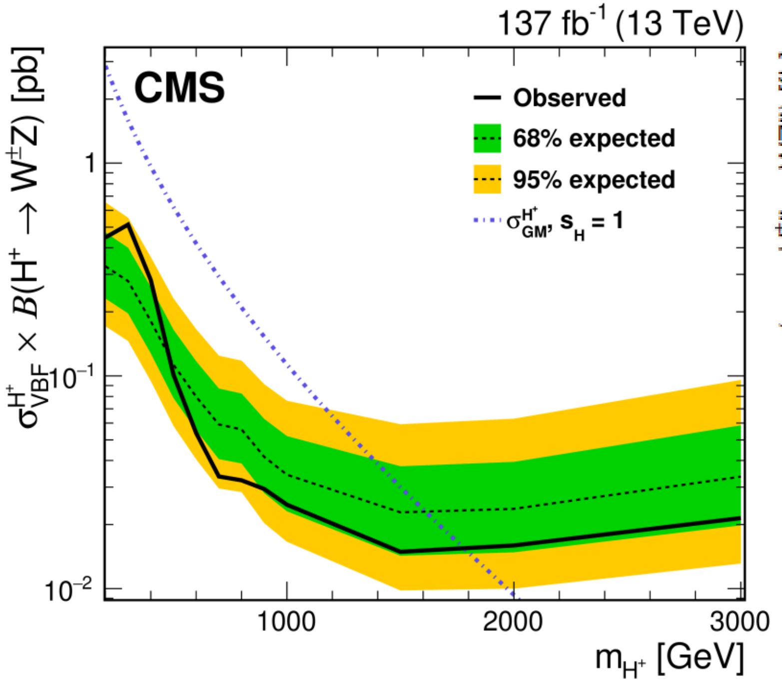
- An excess is reported by ATLAS: a 3 sd deviation in H+->cb with **mH3+=130 GeV** ***EPS-HEP2021, 631***
- Main source is gg->tt*, t*->H+b with a cross section of ~10 µb but a huge background
- $\mathbb{B}$=BR(t->Hb)BR(H->cb)=0.16±0.6%
- Inconsistent with standard GM but acceptable within eGM 2111.14195
- For H++ BR(H3+W+)/BR(W+W+)~(cH/sH)^2~3 could explain why W+W+ is marginally observed at ~500 GeV by CMS
- BR(H3+H3+)/BR(W+W+) non negligible, depends on the details of the scalar potential
- Γ(H50->H3+W)=17 GeV hence ΓH5=130 GeV, still acceptable
- e+e-->H3+H3-, H3±W have large cross sections and good visibility



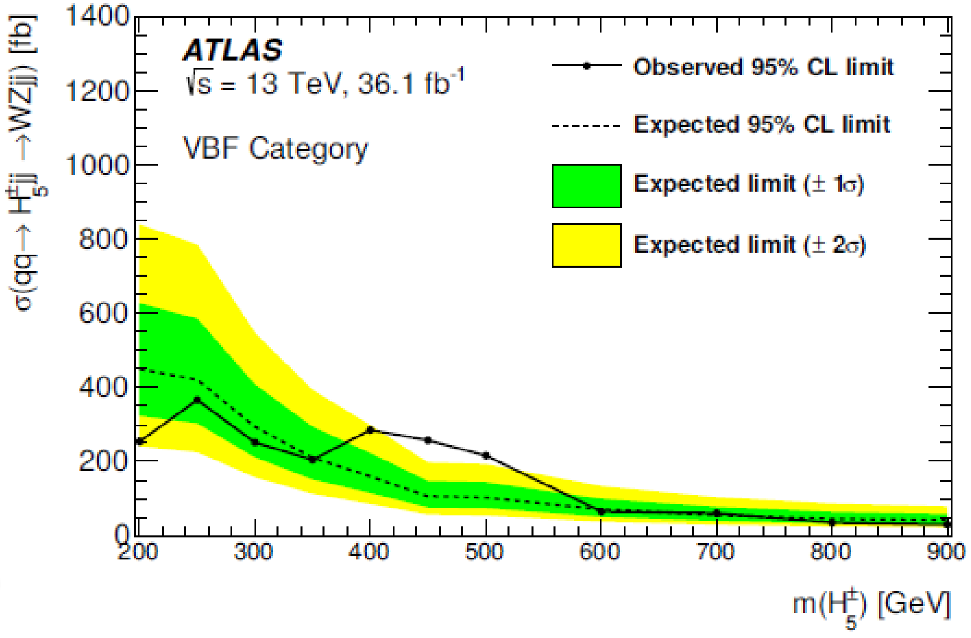


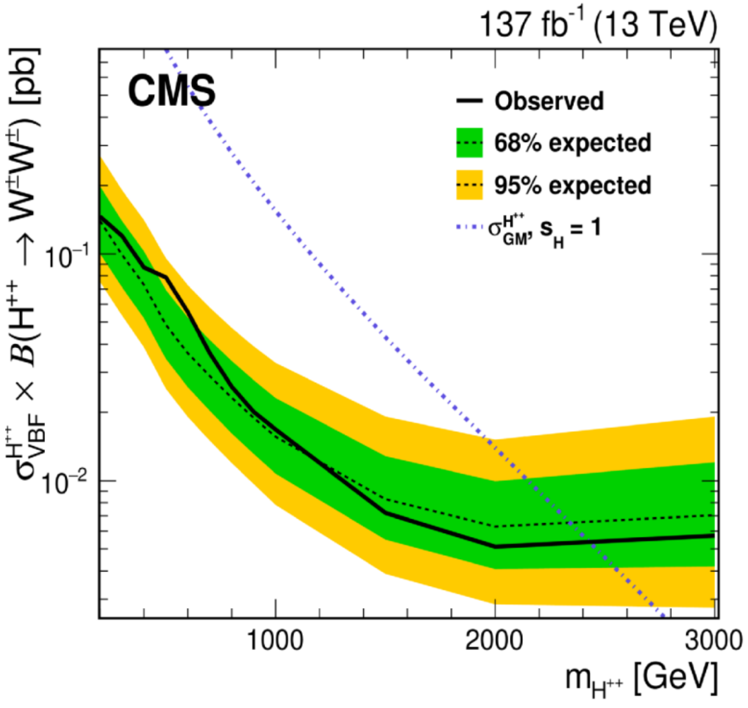
What about H5+ and H5++ ?

2104.04762



1806.01532





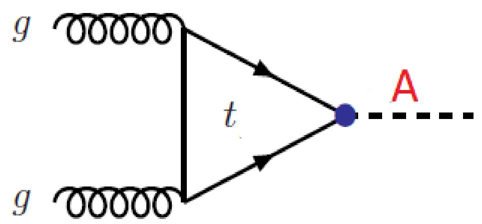
- CMS cross sections assume $\mathbf{s_H=1}$ are divided by 4 for $\mathbf{s_H=0.5}$
- If H3+ is light H3+Z and H3+W+ become dominant and these resonances become wide
- Coincident excess at mH5+~450 GeV for ATLAS (2.9 sd) & CMS while GM predicts 650 GeV
- Not excluded in eGM 2111.14195

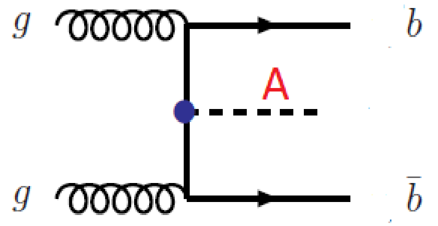
Confusing role of a(52)

- This particle can mix with H30 (and A2 in eGM)
- One can have transitions like H5(650)->Za, H5+->W+a, A->ah/H, H3+->Wa suppressed by $\sin^2\theta$ but kinematically favoured
- Will compete with the dominant modes ZZ/WW, ZW, H(151)Z
- Could perhaps explain the absence of H5+ and H3+ signals
- a(52) decays predominantly into bb (90%) and $\tau\tau$ (10%)
- One expects that A->H(151)Z with H->aa which can be misidentified as A->h(125)Z with h(125)->bb
- These modes can be searched at LHC
- Many models assume that a connects to DM a->$\chi\chi$

Prospects at HL-LHC

- eGM is a gold mine for LHC with a very rich spectrum of scalars with multiple signatures
- LHC has to:
- Confirm simplest topologies H(650)->ZZ->4ℓ,WW->ℓℓνν
H(151)->2γ + Etmiss
- Confirm h(96)->2γ
- Confirm A->tt & A->hZ,ττ + b
- Search for A->H(151)Z & H3+->H(151)W with H->aa->4b
- Confirm H3+(130) -> cb
- Confirm H5+->W+Z H5++->W+W+ with VBF selection
- Select VBF and try to reconstruct complex final states like H5->AZ->ttZ and H5+->AW+->ttW+
- Improve searches on H++ -> W+W+
- …

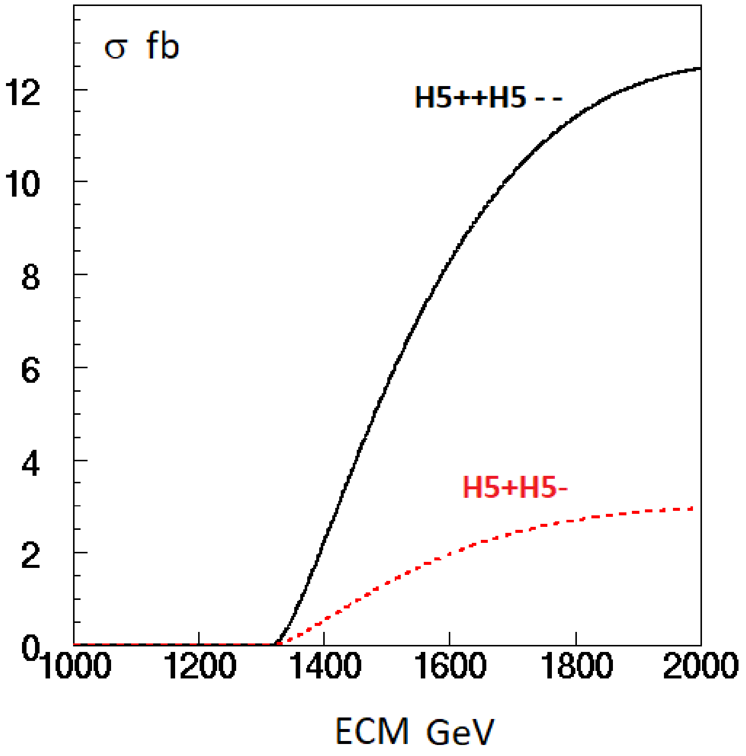




e+e- Colliders

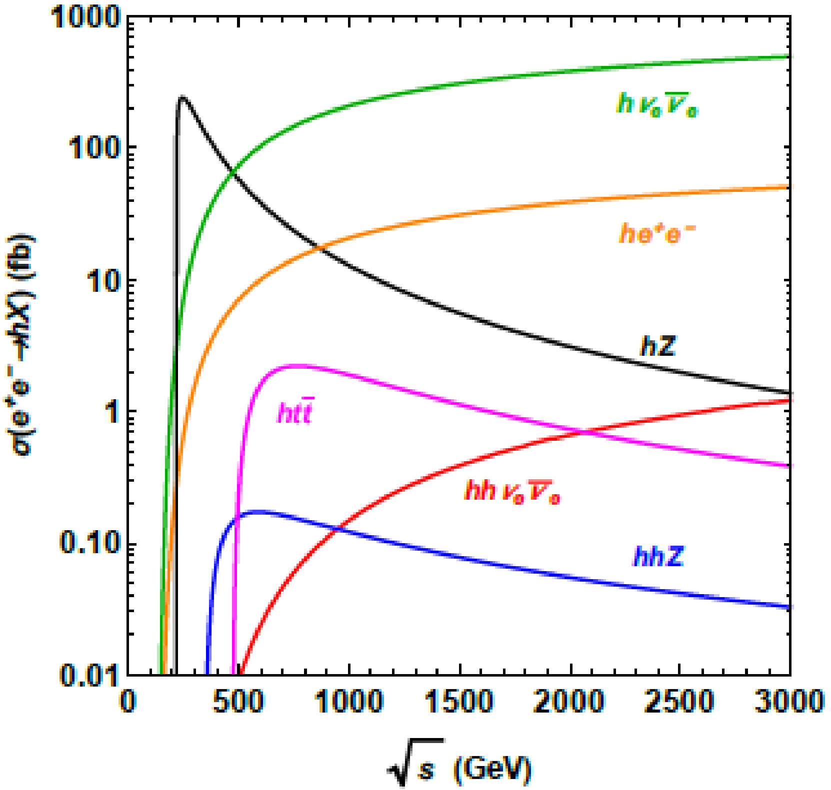
High energy e+e- cross-sections

- H5++(650) and H5+(650) in GM



Could be lighter in eGM

- SM h(125) cross-sections



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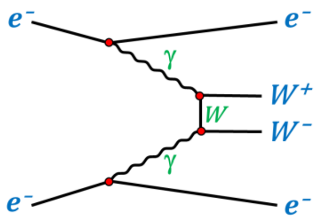
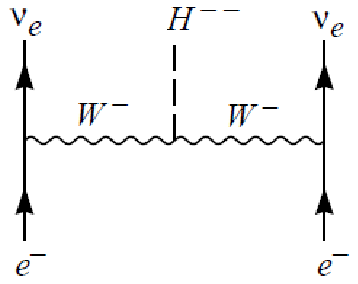


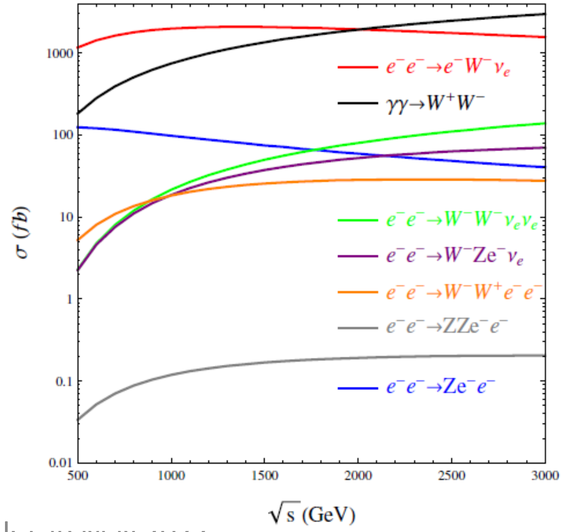
e-e- collider issues for H- - (650)

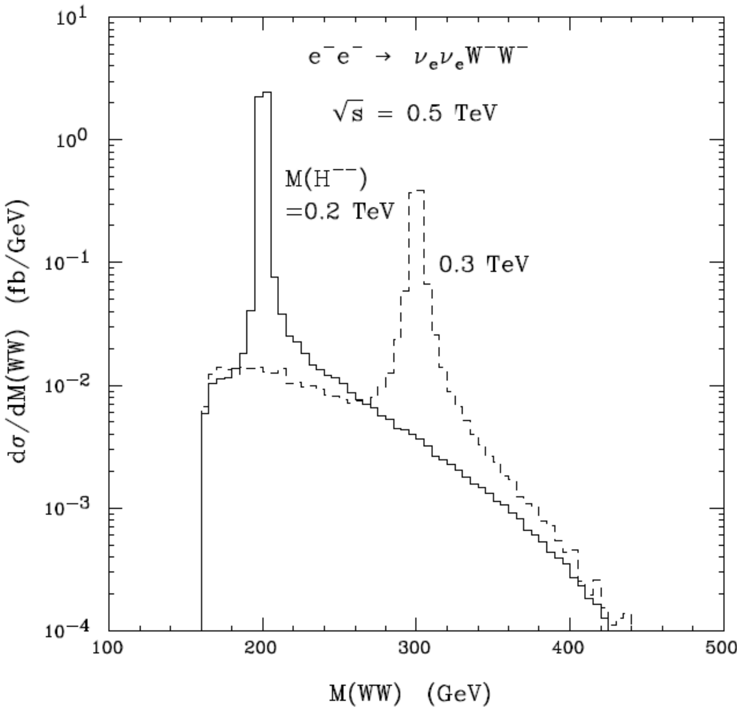
- $\mathcal{L}$e-e-~70%$\mathcal{L}$e+e- seems feasible (Drutskoy at ILCX2021)
- σ_{VBF}(e-e→H- -(650))=3.5 fb at 1 TeV
- With polarized beams, 80% for e-, luminosity gain 1.8² for W-W-
- Switch from e+e- will require changing polarity of many magnets
- Telnov ERL scheme seems feasible
- Ref 9404335 sinθH=0.7 (2 times smaller signal in my case)
- *2109.05855* (sinθH=0.1)

- **H--(650)->H3-(400)W-** with **H3+->tb,HW** easily separated from W-W- using **b-tagging** + multijet cuts
-

9404335

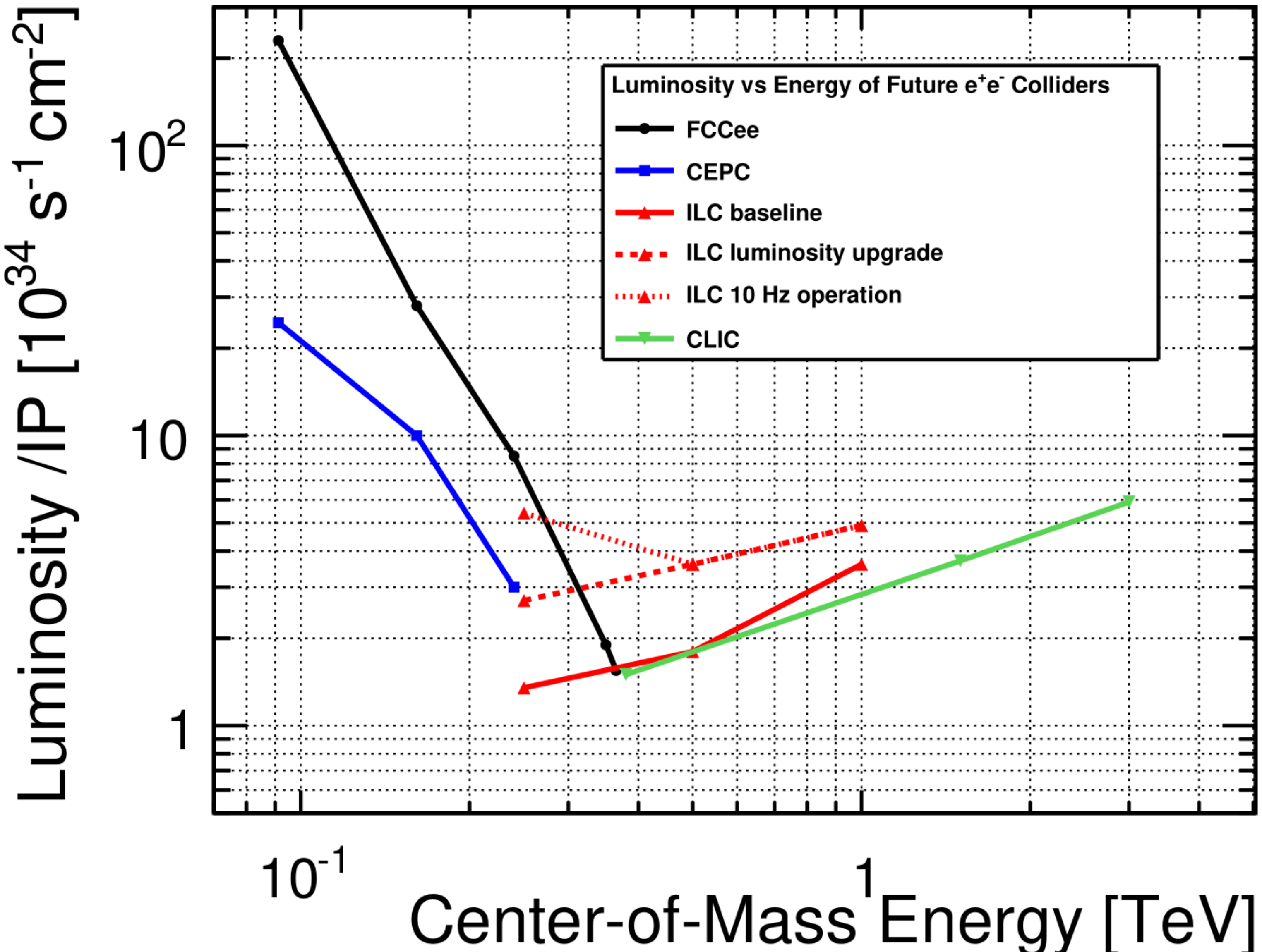


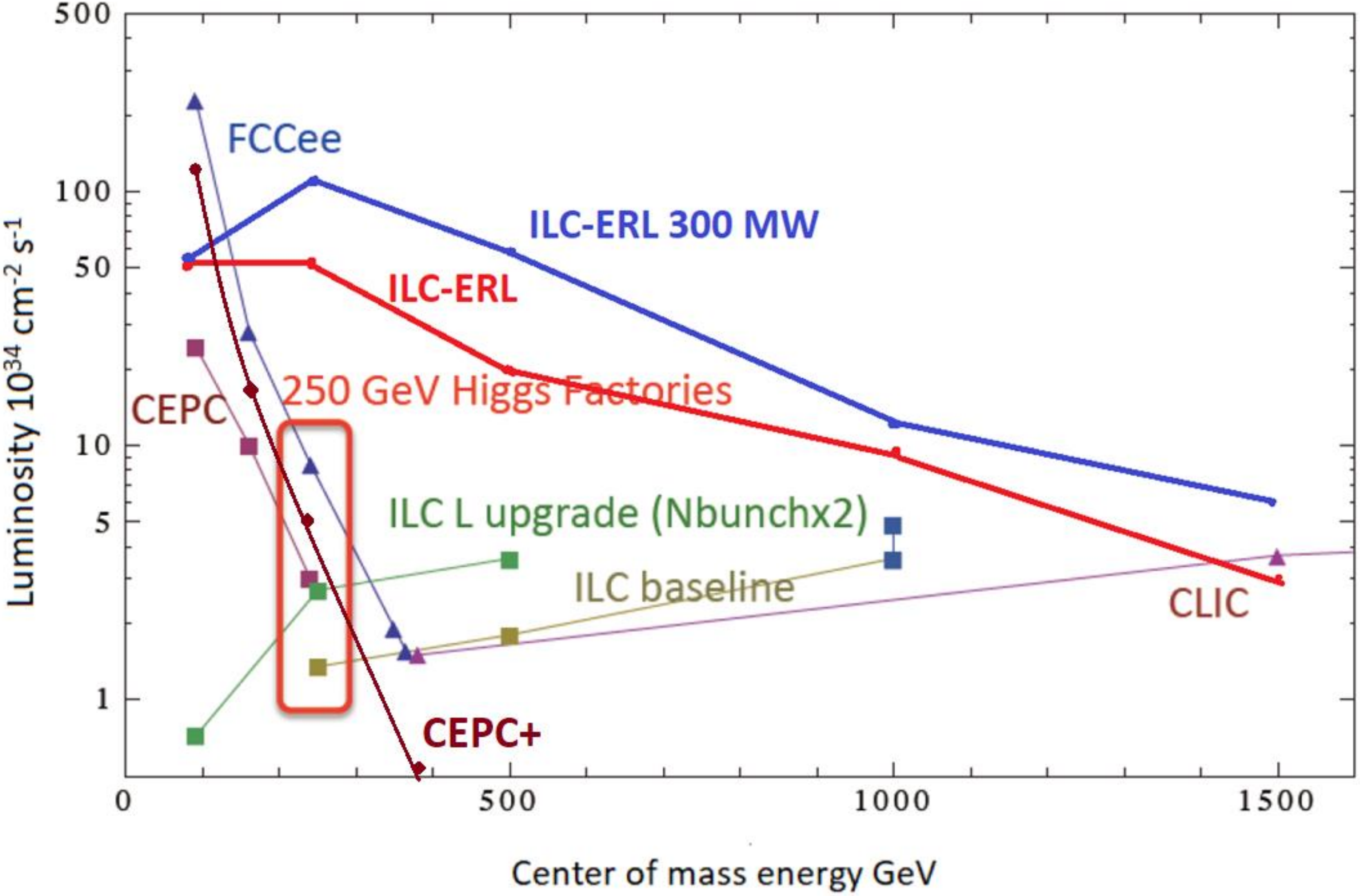




LUMINOSITY at 1 TeV

- 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 and CLIC
- Convert ILC into an ERL 2105.11015 ?




500
100
50
10
5
1
Luminosity 10^{34} cm^{-2} s^{-1}
0
500
1000
1500
Center of mass energy GeV
FCCee
ILC-ERL 300 MW
ILC-ERL
250 GeV Higgs Factories
CEPC
ILC L upgrade (Nbunchx2)
ILC baseline
CLIC
CEPC+

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.