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

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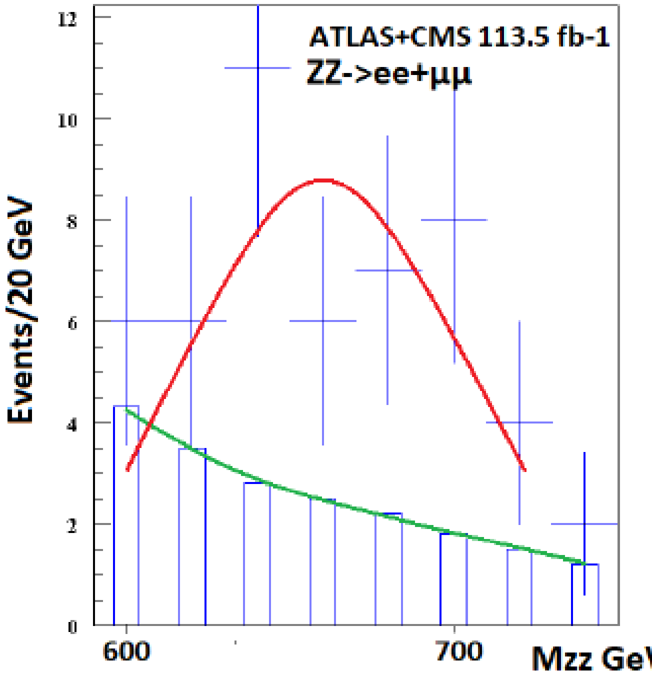
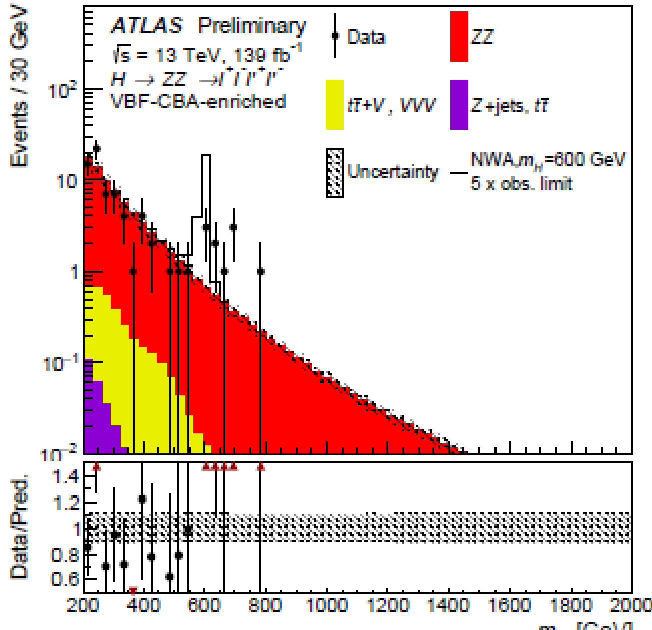
Introduction

- General mood in HEP is that we should expect no direct discovery and be content with precision measurements at HL-LHC, followed by a Higgs factory
- If so, LEP3, the cheapest solution, seems sufficient
- The selling argument for a LC is it's **expandability in energy,** to cope with unforeseen discoveries from LHC
- If these discoveries are to occur, there should already be **some indications** in the present data
- In a '**bottom-up approach**', free of theoretical prejudices, I have looked into the LHC searches for new scalars (**lightest particles** in most composite models as for pions in QCD)
- This talk will briefly recall my findings and give a '**top-bottom interpretation**' of such effects within the **Georgi-Machacek model** (1985 !)
- It will also give an evaluation of the **rates at an e+e- LC**

1st finding : ZZ into four leptons

- Paolo Cea from Bari *1806.04529* had a look at the data from CMS (2/3) and ATLAS (1/3) and found coincidental fluctuations at ~700 GeV
- I did the same and found the following result, **~5 s.d.** , which indeed suggests a bump at 660 GeV, with a ~100 GeV width
- Also seen by ATLAS with **enriched VBF** with ~1/2 the efficiency **ATLAS-CONF-2020-032**
- Not seen in **WW** which is incompatible with WW/ZZ=2 predicted in MSSM





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

- A **ttbar** paper from CMS claims a 3.5 s.d. at ~400 GeV
- CMS took into account interference with the QCD background (major handicap of LHC)
- Signals were observed by ATLAS in $\tau\tau$, $\tau\tau$+b and in **hZ** + b
- Signals at ~3 s.d., giving **>6 s.d.** when combined
- Does not fit with **MSSM** which would predict ~zero for A->hZ

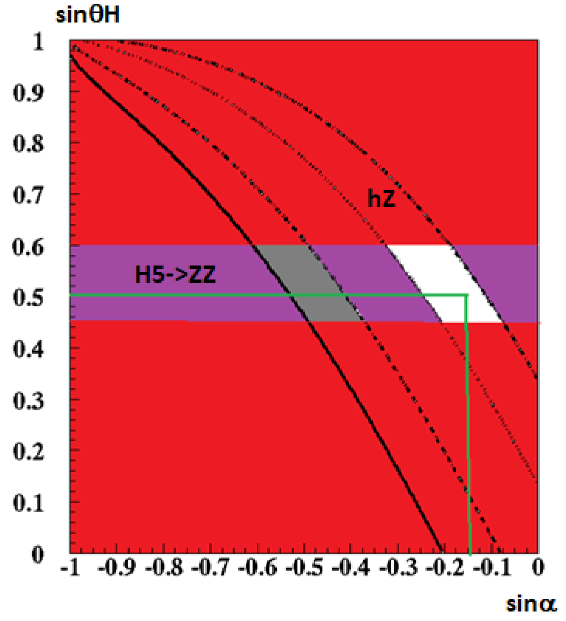
1802.09122

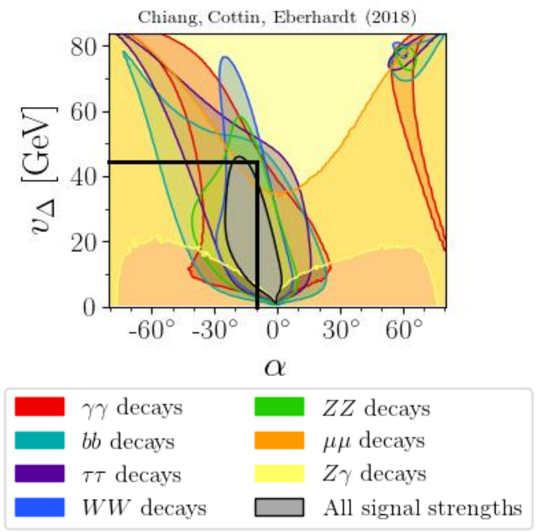
- Have a look to my two ArXiv preprints about anomalies:
- https://arxiv.org/abs/2001.04770
- https://arxiv.org/abs/2003.07112

Reaction	Mass GeV	Nb of s.d.	Ref ArXiv
X(400)->tt	400	3.5	*1908.01115*
X(400) ->$\tau\tau$	400	2.2	*2002.12223*
X(400)->$\tau\tau$+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>1/2 without violating **Mzcosθw/Mw=1**
- Is achieved w/o F.T. by imposing **custodial symmetry**
- Predicts **5-plet** H++ H+ H0 H- H-- degenerate in mass
- **Fermiophobic**, only produced by **VBF**
- H5+ -> WZ is allowed, H5-> ZZ/WW with **ZZ/WW=2** (instead ½ in MSSM)
- 3-plet H3+ H0 (CP odd A) H3- degenerate in mass
- 2 **singlets** h(125) and h'(?) **mixing angle α**
- Present indications from LHC fix the masses except for h'
- Couplings depend on 2 mixing angles constrained by LHC observations : **sinα~-0.15 and sinθH~0.5**

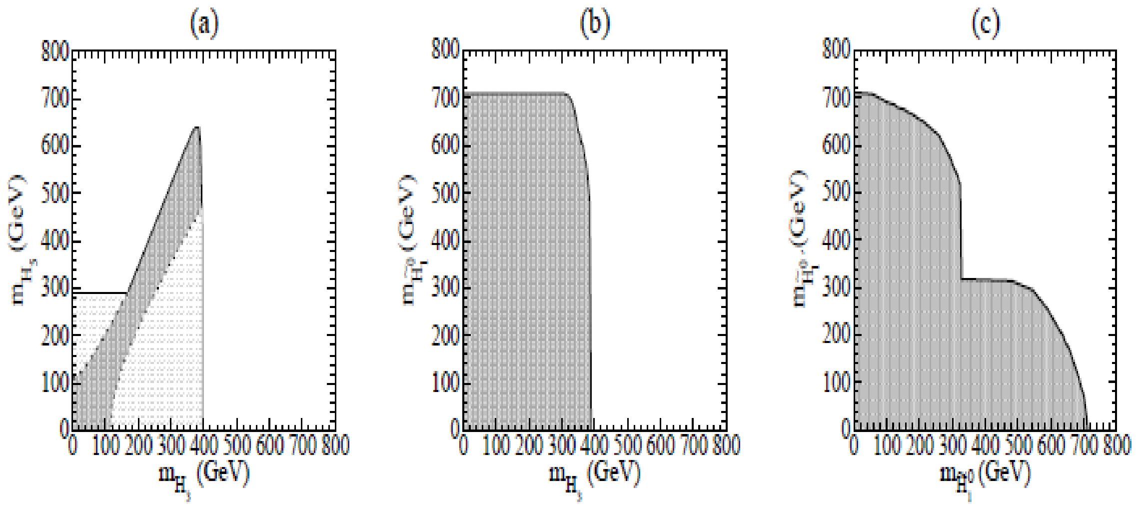




1807.10660

Predicted mass spectrum

- **Unitary bounds** were derived by Aoki and Kanemura:
- mA<400 GeV
- mH5<650 GeV
- mh'<700 GeV
- Zbb suggests that **mH5~√3mA,** in **striking agreement** with LHC present indications

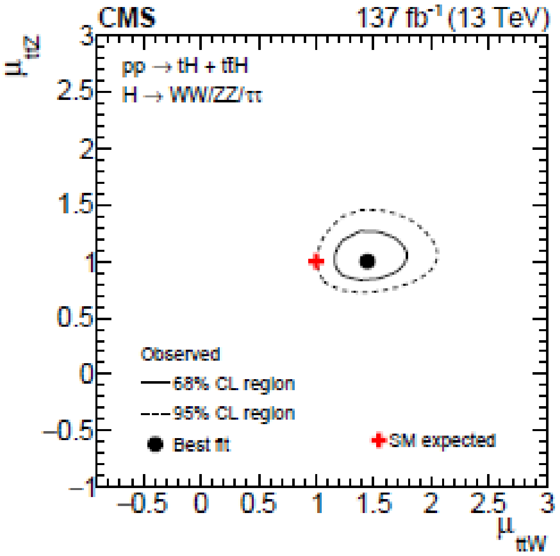


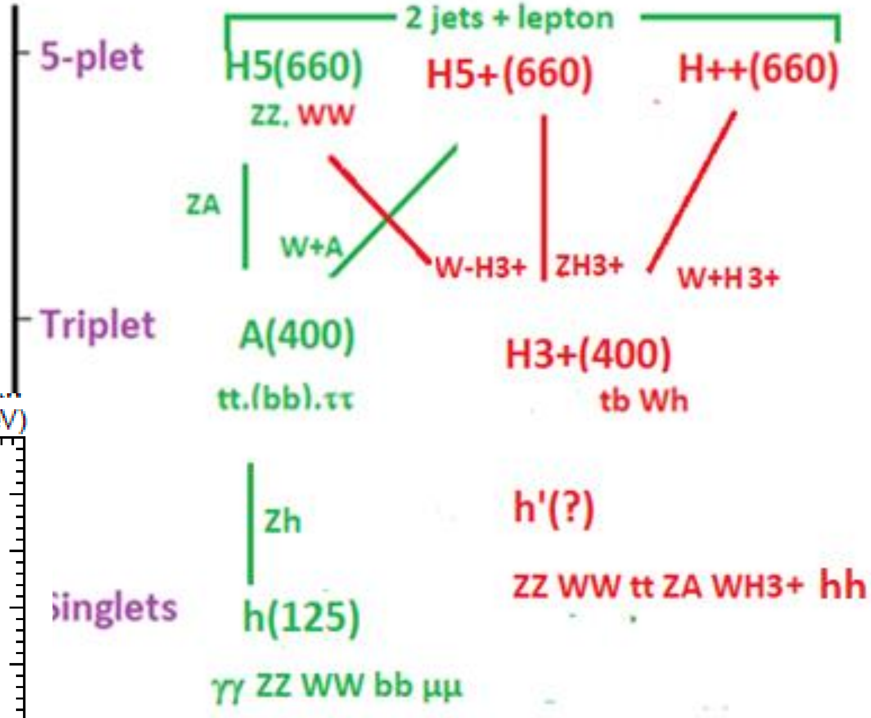
Mayumi Aoki (Tokyo U., ICRR), Shinya Kanemura (Toyama U.)
(Dec 27, 2007)
Published in: Phys.Rev.D 77 (2008) 9, 095009, Phys.Rev.D 89 (2014) 5, 059902 (erratum)
e-Print: 0712.4053

Cascades I

- The picture suggest the presence of many **cascades** which allow various strategy of signature
- ttW and ttZ seem the most promising channels
- ttW shows a 50% exces… in both experiments which ca… attributed to these cas…

2011.03652





Cascades II

- Cascades could also explain the various anomalies recorded by **Budenbrock et al** *1901.05300* in ATLAS and CMS
- They propose **additional scalars** which tend to cascade into each other but with no direct evidence for these scalars
- **No obvious contradiction**
- A thorough analysis in terms of GM needed

- H5->ttW/Z ->bbWWW/Z
- H5->(hW,tb)W/Z->bbW+W-/Z
- H5++->(hW,tb)W+->bbW+W+

JHEP 1910 (2019) 157

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

The simplidied model seems to describe the discrepancies in different corners of the phase-space with large differences in cross-sections, eg, OS and SS di-leptons

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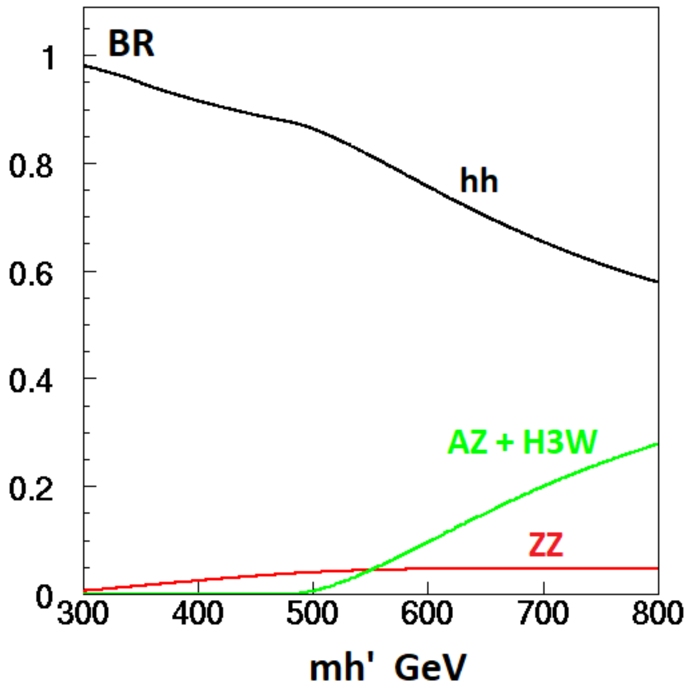
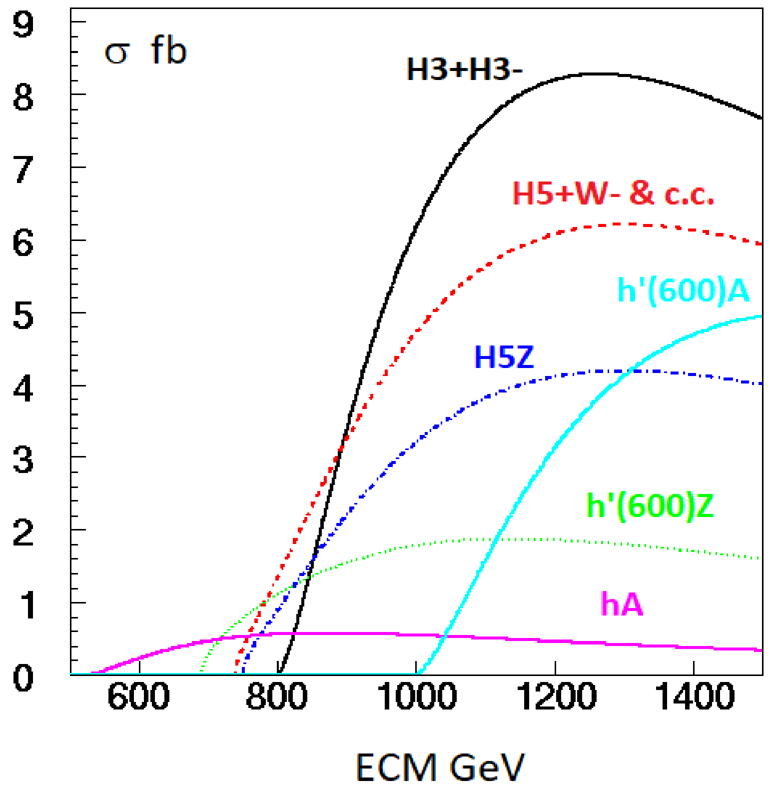
Prospects at HL-LHC

- Confirm H(660)->ZZ and A->hZ,$\tau\tau$
- Search for the second singlet h'
- Presumably heavy with h'->hh
- Search for H+->WZ in VBF
- Select VBF and try to reconstruct complex final states from ttZ and ttW
- …

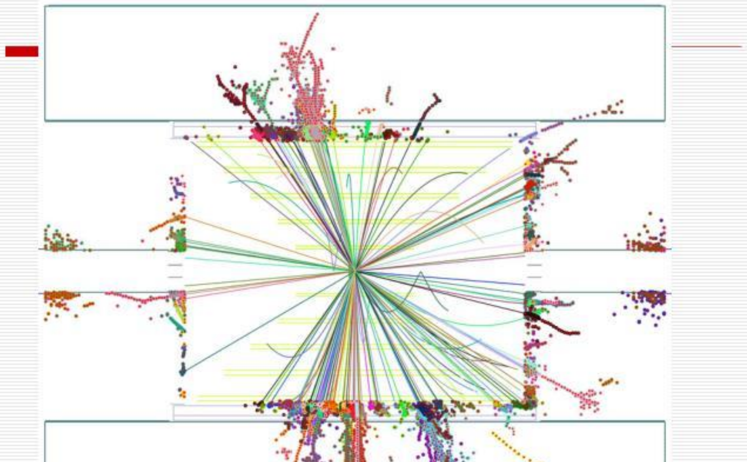


Prospects for a LC

- ~1 TeV is needed to observe this spectrum
- >1.5 TeV to pair produce H5++ H5 - -
- Requires highest possible **luminosity** ~8000 fb-1 with ILC at 1 TeV *1903.01629*
- Excellent **“hermeticity”** for jet reconstruction and b tagging needed for these complex modes $\varepsilon \sim \Omega^n$ n~8
- **Recoil mass techniques** using Z/W/h with their *hadronic decays* (recoil mass is wide due to the resonance widths) to be tried
- Backgrounds are small (Zhh ~0.5 fb at 1 TeV)



An example: ttH (from SiD)



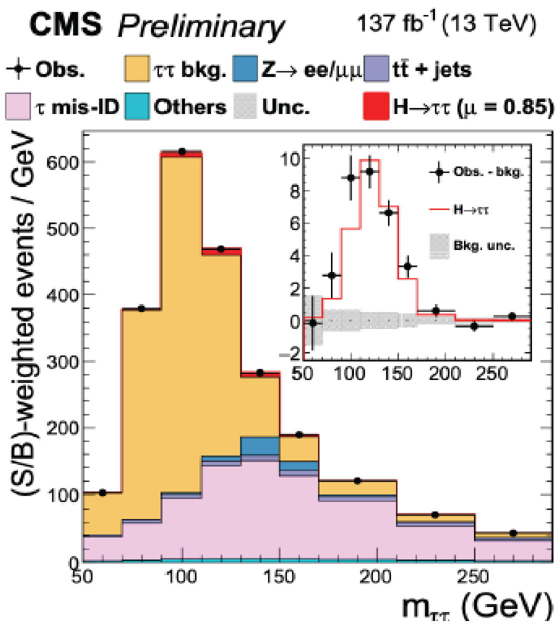
Conclusions

- There is life in LHC data and one is eagerly awaiting for a full analysis and professional data combinations between ATLAS and CMS e.g. for ZZ
- The **Giorgi-Machacek** model seems to provide the best interpretation for the various anomalies, both **spectroscopic** **A(400) & H(660)** and **topologic** **multi-leptons + b jets**, each at the ~8 s.d. level
- Almost all ingredients are now available to test at LHC the **precise predictions** of this model on a large set of observables
- Measuring precisely the parameters of these scalars should be possible at an **e+e- collider reaching at least 1 TeV**, preferably **>1.5 TeV**
- **Critical impact on future LC detectors**
- Suggestions, criticisms welcome
- Paper available http://hal.in2p3.fr/in2p3-03162150 and arXiv:2103.12639

APPENDIX

What about h(96) ?

- h(96)->2γ by CMS, not by ATLAS which however does not reach the same sensitivity
- Could it be the h' ?
- If so one would expect A->h'(96)Z ~30*A->h(125)Z, which is not the case
- Could be an additional singlet, for instance, the Radion expected within Randall Sundrum phenomenology *1712.06410*
- Difficult to observe at LHC in the fermionic modes given the contamination from ZZ
- Ideal for an e+e- collider h(96)->bb ττ gg



CMS-PAS-HIG-19-010

Georgi-Machacek Couplings

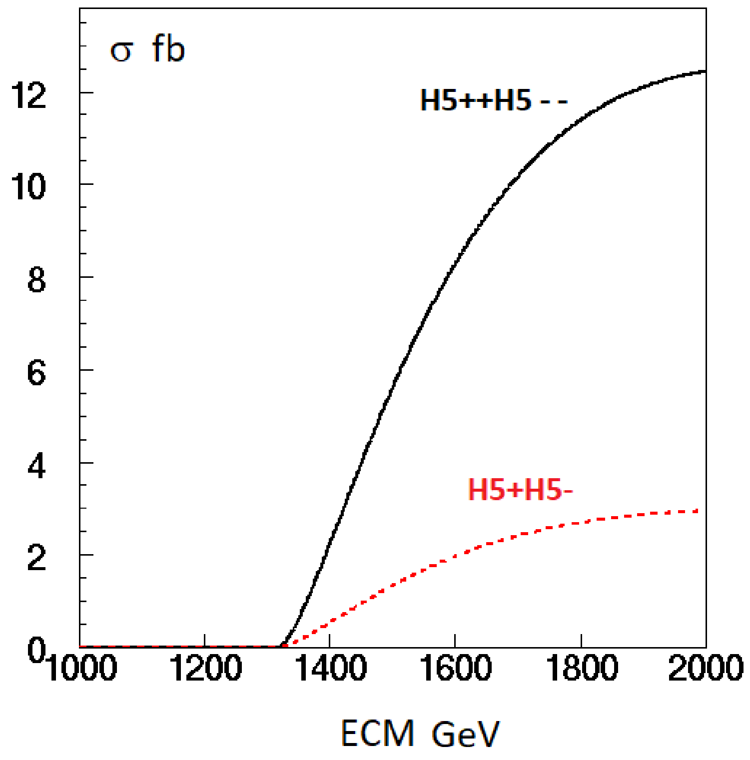
Type	coupling /SM, MSSM	Numerically	σee fb@1 TeV	e+e- Eth GeV
h(125)WW/ZZ	cαcH- 1.63sαsH	0.98	12.0	216
h'(600)WW/ZZ	sαcH+1.63cαsH	0.68	1.5	mh'+mz
h(125)tt,bb	cα/cH	1.14		
h'tt,bb	sα/cH	0.17		
Att,bb,ττ	tanH	0.58		
H5WW, H5ZZ	1.15sH,-2.31sH	0.57,1.16	3	751
H5AZ,H5H3+W-	1.16cH	1	0	1060
H5+H3+Z,H5+AW+	cH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

Problem with fermionic couplings

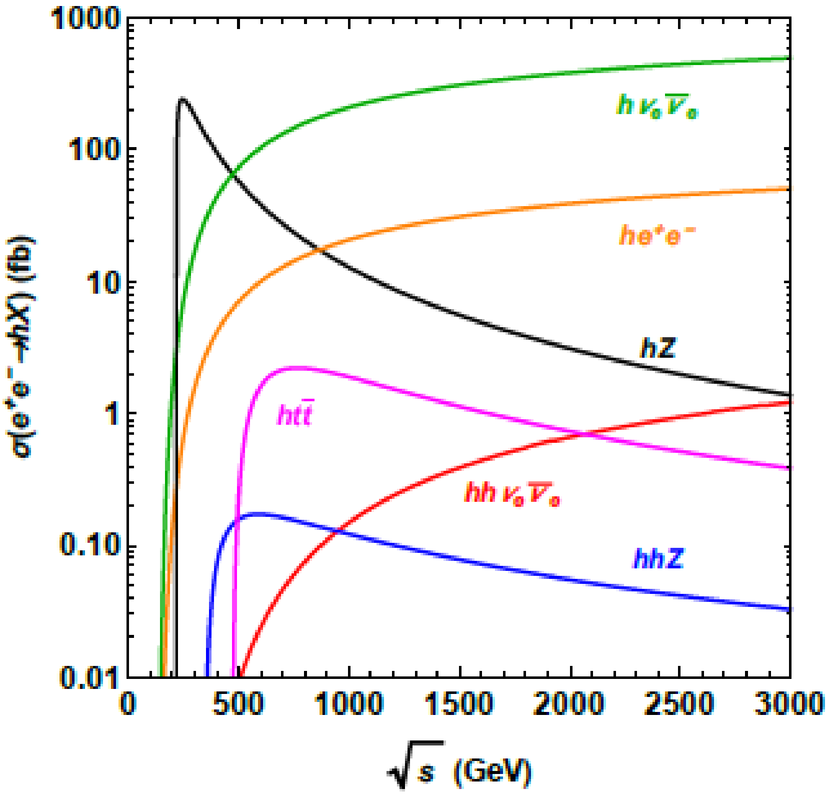
- A(400) is observed into $\tau\tau$ with a BR inconsistent with MSSM
- While the Yukawa coupling is close to the SM in tt it is 10 to 20 times larger in $\tau\tau$
- This cannot be fixed as in MSSM by having a large **tanβ** since the tt coupling goes like **1/ tanβ**
- Additional issue: h(125)Z and $\tau\tau$ are reinforced by asking a **spectator b** jet which implies a large Abb coupling
- In GM fermion couplings for A(400) all Yukawa couplings are affected by $\tan\theta_M$, also inconsistent

High energy cross-sections

- Access to H++(660)



- SM h(125) cross-sections



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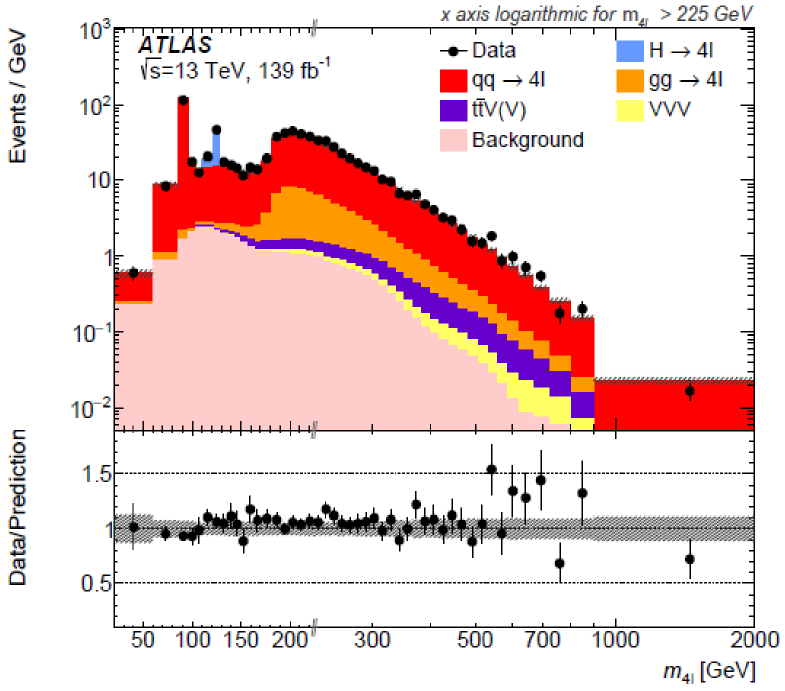
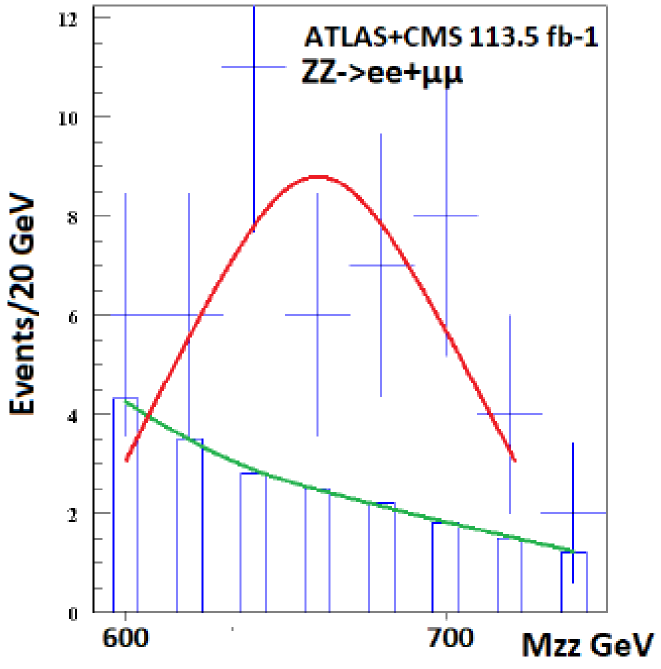
Update from ATLAS



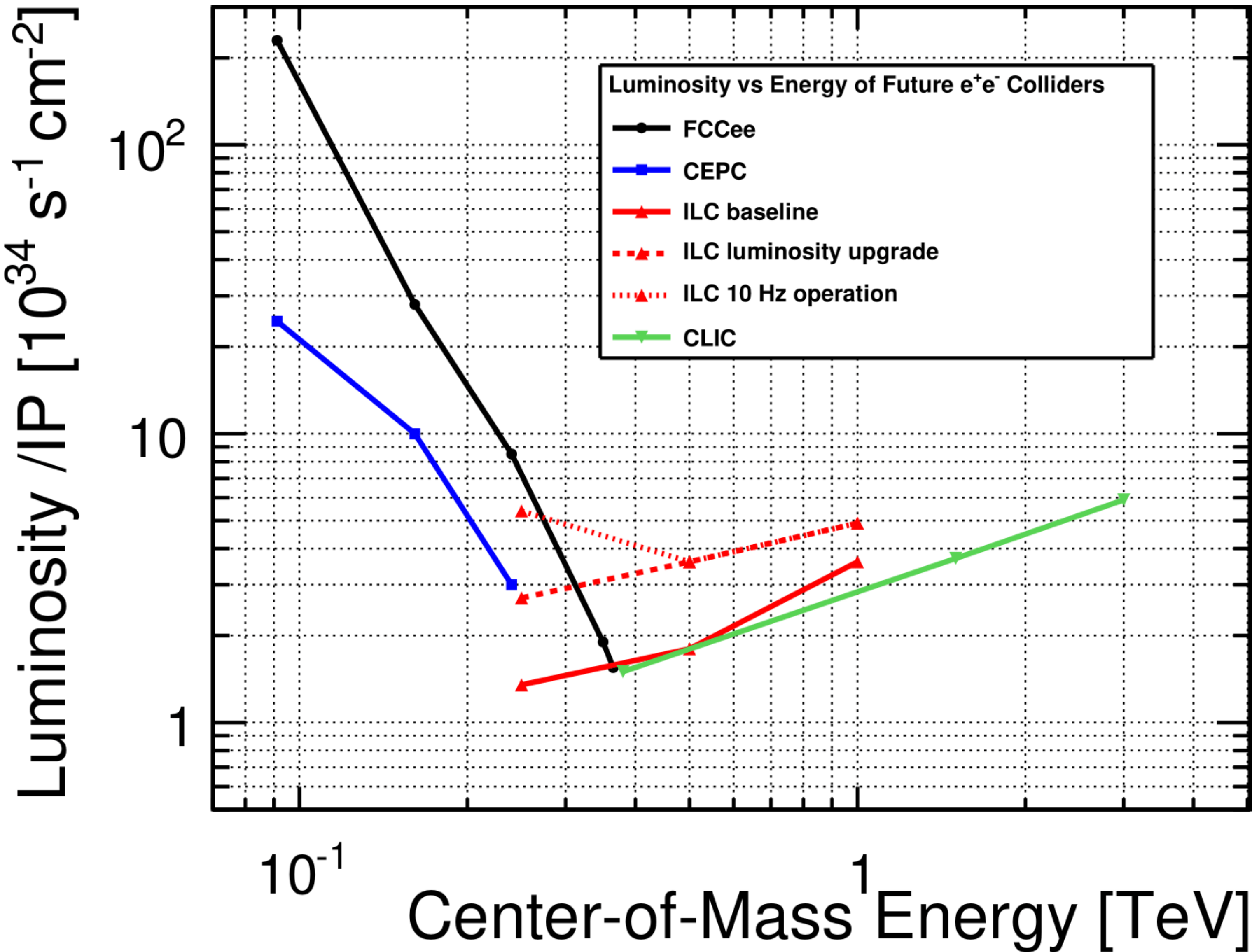
[2103.01918](https://arxiv.org/abs/2103.01918)



14.2 events expected between 630 and 730 GeV with 42 events observed 1/3ATLAS + 2/3CMS

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



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