Predicted e+e- cross sections for neutral scalars from LHC indications

A. Kundu, A. Le Yaouanc, P. Mondal, G. Moultaka, F. Richard
Calcutta-Orsay-Montpellier collaboration

Direct discovery potential working group (WG1-SRCH)
of the ECFA Higgs Factory Study

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Introduction

- The choice of the **next e+e- machine** heavily relies on LHC results, in particular on the presence or absence of **extra scalars**
- So far, no single analysis has provided for a 5 s.d. evidence, but there are however several indications at the ~3 s.d. local level with compatible masses which reveal significant indications
- Can we understand these results and predict the cross sections in e+e- ?
- The answer seems to be yes, but this requires **extending the available phenomenology**

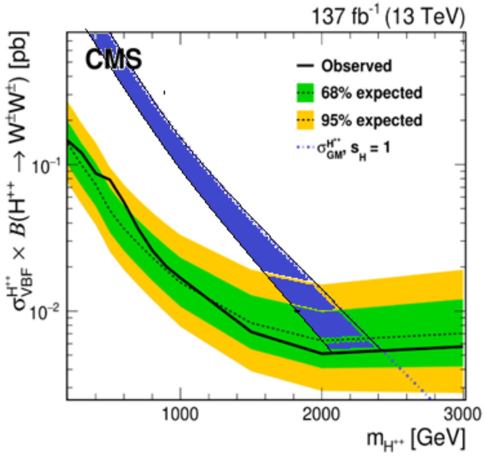
LHC inputs for our work

- We choose to select **> 4 s.d. global significance** with the exception of h151 which results from an **unofficial combination** of CMS & ATLAS data
- This keeps 4 neutral scalars and one pseudo scalar
- No change of significance after a CMS update of h(95)->2γ with RUN1 and RUN2 after some cleaning against Z->e+e-

Process	Channels	References	# s.d. glob.	Michelin
h125	WW/ZZ ggF/VVF $\gamma\gamma$ $\tau\tau$ bb		>6.9	***
H650	WW/ZZ ggF/VVF h95h125	2009.14791 2103.01918 CMS PAS HIG-20-016 CMS-PAS-HIG-21-011	6.7	**
A400	tt ZH320->Zh125h125	1908.01115 ATLAS-CONF-2022-043	5	*
h(95)	$\gamma\gamma$ $\tau\tau$ bb (LEP)	0306033 1811.08159 1803.06553 CMS-PAS-HIG-20-002	4.3	*
h151	$\gamma\gamma$ +ETmiss	2109.02650	4.8	?
H+375	ZW	ATLAS-CONF-2022-005 2104.04762	3.5	
h146	μe	CMS-PAS-HIG-22-002	2.8 (3.8)	

The unitarity constraint

- The large VBF cross section **H(650)->WW** observed by CMS is violating a **general rule** which is imposed by the **preservation of unitarity** for **$W^+ W^- \to W^+ W^-$**
- Haber et al. in *P.R.D* 43 (1991) 904-912 have shown a way to **restore unitarity** by introducing a cancelling **u-channel exchange** of a **doubly charged H - -** (see also 1202.1532)



$$g^2(4m_W^2 - 3m_Z^2 c_W^2) \overset{\rho\simeq 1}{\simeq} g^2 m_W^2 = \sum_k g^2_{W^+W^-H_k^0} - \sum_l g^2_{W^+W^+H_l^{--}}$$

- From the measured WW couplings of h125 ~SM=gmw and H650 ~0.9gmw, one predicts a **large $g_{W+W+H--}$ coupling**
- In absence of a signal in W+W+ at LHC, one predicts a heavy **mH++** but one should take into account the possible opening of **H+W+** which could reduce BR(W+W+) well below 1

The Georgi Machacek model ?

- This model has one iso-doublet plus two iso-triplet and passes the ρ **~1 rule** at tree level
- It predicts **H++** as belonging to a custodial **5-plet H5,H5+,H5++ ,** not necessarily mass degenerate in an extended GM, **e-GM1** 2111.14195
- The neutral H5 component of GM does not allow to interpret the **pattern of decays followed by H(650)** which dominantly decays into W+W-
- We have therefore elaborated a further extension of GM, **e-GM2**, with an **additional doublet** which does the job, H(650) becoming a mixed state of the two doublets
- This extension also allows to include **H(320)**, an additional scalar observed by ATLAS in the reaction **A(420)->H(320)Z**

The neutral sector in an e-GM

- e-GM comprises two doublet fields $\phi 1$, $\phi 2$ with **v1 and v2** and two triplet fields χ, ξ with the same v.e.v. **u**
- For the neutral sector one writes:

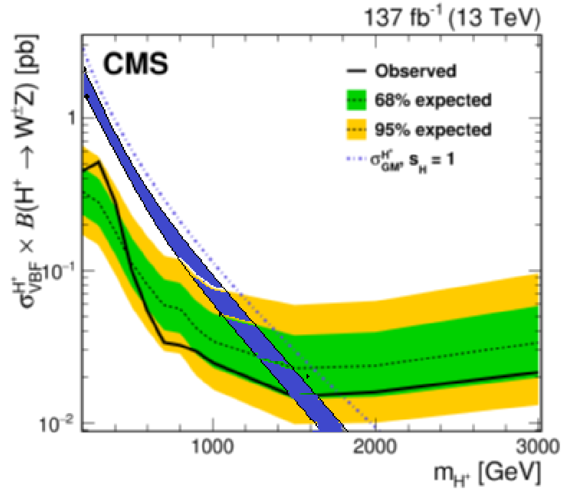
$$\begin{pmatrix} h_{95} \\ h_{125} \\ H_{320} \\ H_{650} \end{pmatrix} = \mathscr{X}_{4\times 4} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \\ \chi^0 \\ \xi^0 \end{pmatrix}$$

where the matrix is 4X4 unitary **real** (no CPV) with 16-4-6=**6 free parameters** requiring the **unitary vectors** to be **orthogonal**

- In total there are 6+3 (v1, v2, u) free parameters and 14 observables from LHC measurements
- One needs to choose between various **Yukawa coupling patterns** and we find that **type I** (all fermions having the same coupling) gives an agreement with the data

Type I result

	1	2	3	4	htt/SM	ZZ/SM	WW/SM
	$\phi 1$	$\phi 2$	χ	ξ			
H95	**0.08**	**-0.56**	**0**	**0.82**	**- 0.96**	**- 0.34**	**0.59**
H125	**0.58**	**0.58**	**0.47**	**0.33**	**0.99**	**0.99**	**1.1**
H320	**0.31**	**0.30**	**-0.88**	**0.17**	**0.52**	**- 1.29**	**- 0.38**
H650	**0.74**	**-0.52**	**0**	**-0.43**	**- 0.90**	**- 0.43**	**- 0.91**



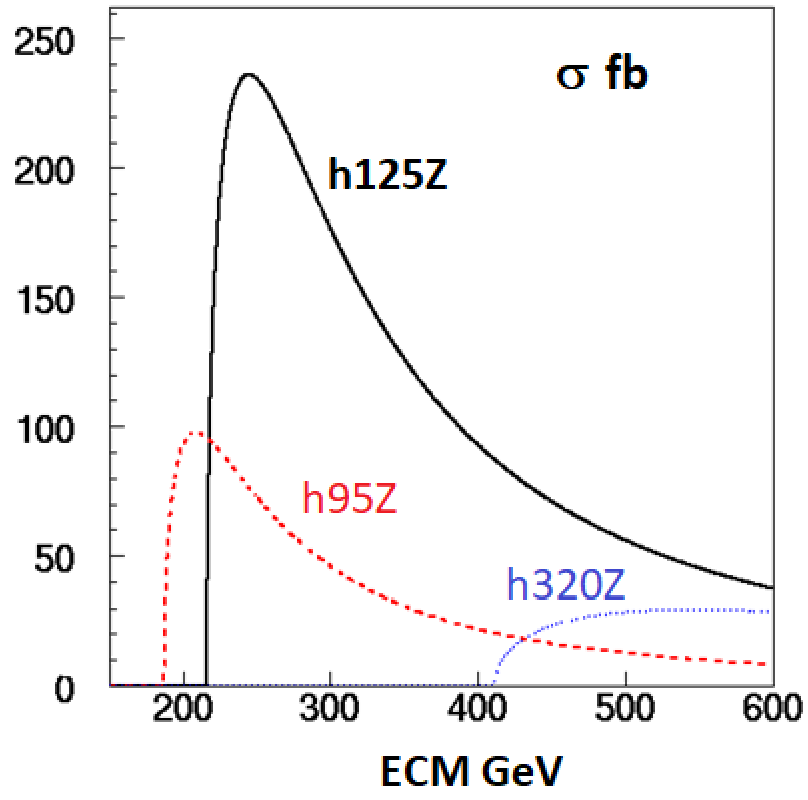
- Non-trivial result since it allows to predict **5 couplings** and **all ZZ/WW signs** relevant for the second sum rule

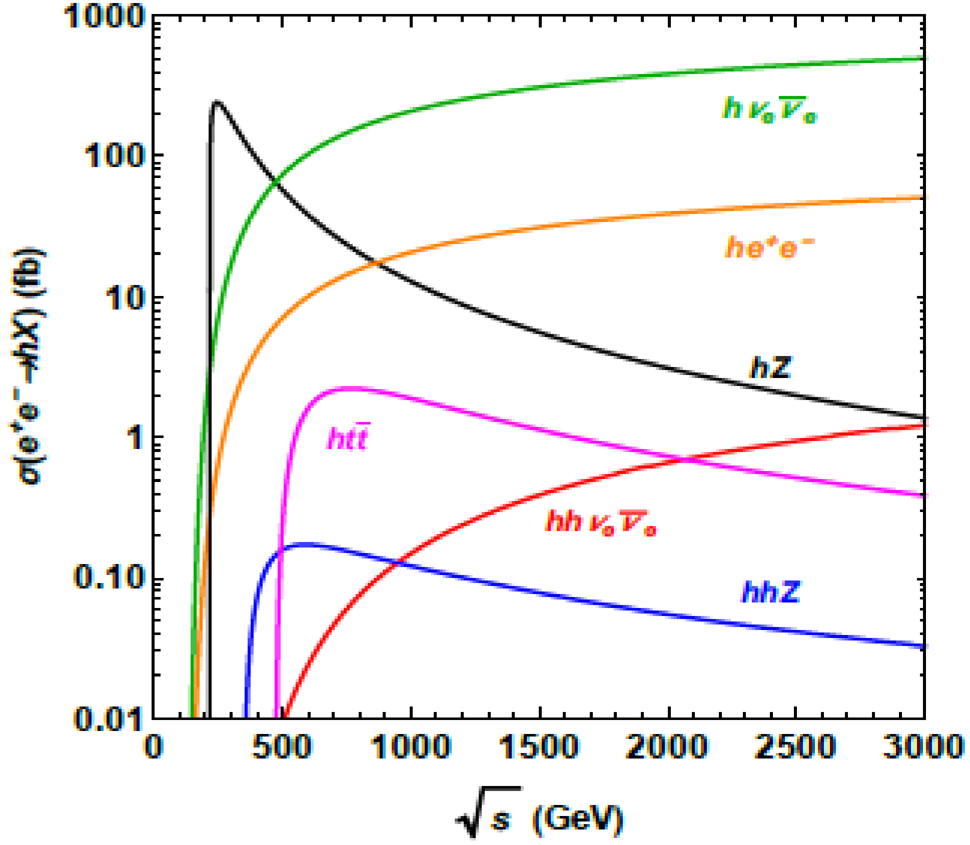
W^+W^- -> Z Z

$$\frac{g^2 m_Z^4 c_W^2}{m_W^2} \overset{\rho\simeq 1}{\simeq} g^2 m_Z^2 = \sum_k g_{W^+W^-H_k^0}\, g_{ZZH_k^0} - \sum_l g^2_{W^+ZH_l^-}$$

- There is a **cancellation** which allow to ~accommodate mH5+=375 GeV
- Predicts $\Gamma_{H320\to ZZ}$~10 GeV, excluded by the 4 lepton search unless Γ_{tot}**~100 GeV**
- Appears plausible if H(320) is predominantly coupled to hh as indicated by the ATLAS result A->ZH(320)->Zbbbb

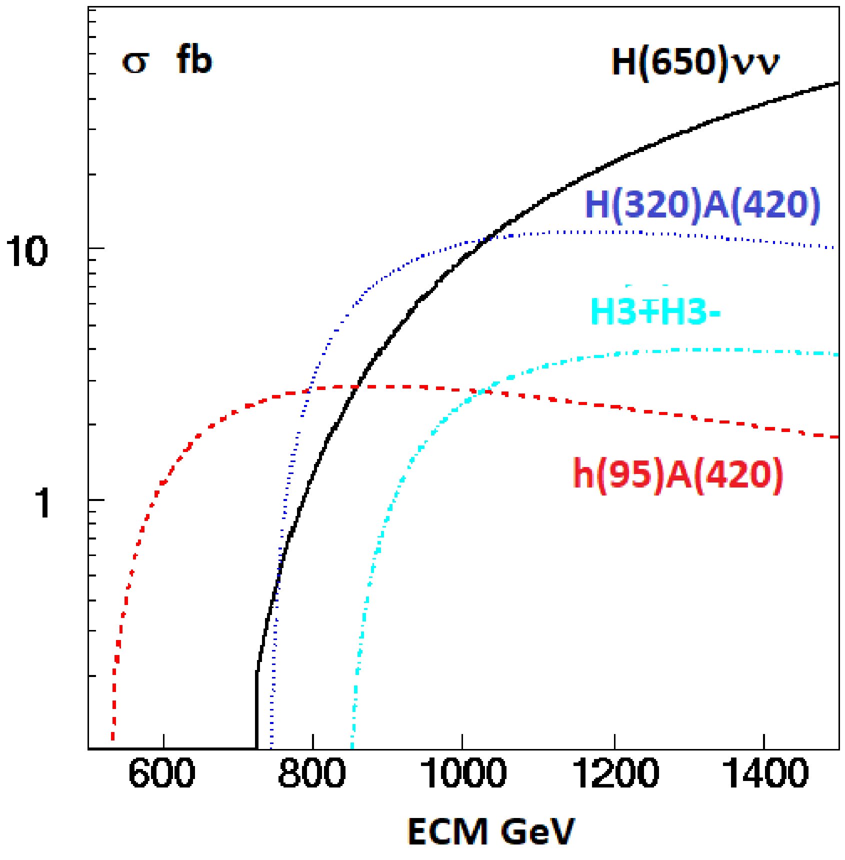
Predicted cross sections

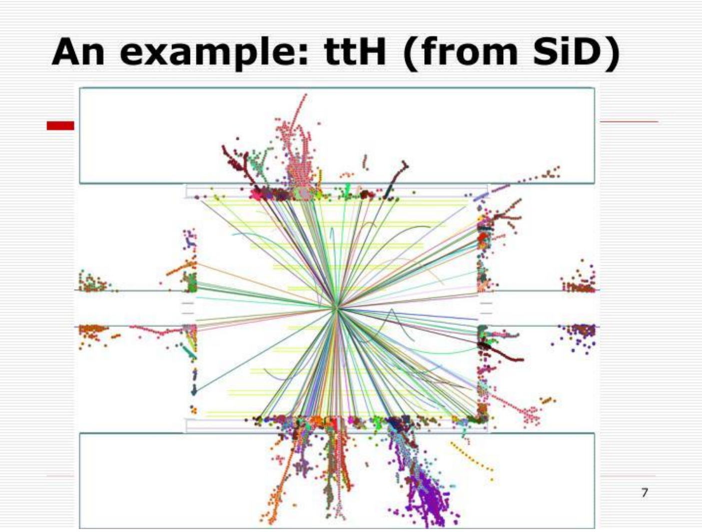




- **Large x-sections allowing very precise measurements**
- **Access to H(320)hh self-coupling 'easy' ~200 times larger than SM hhZ**

TeV collider reach





- ILC provides 8000 fb-1 at 1 TeV
- Mass degeneracy inside GM triplet mH3+=mA=400 GeV was assumed
- The final states are complex modes (~ttH) requiring the **highest $\mathcal{L}$** and an **almost ideal detector**
- **H(650)** mainly produced through VBF (beam polarisation allows a factor ~2 gain, not included)
- Using a e-e- collider one could also produce H $^{--}$ through VBF

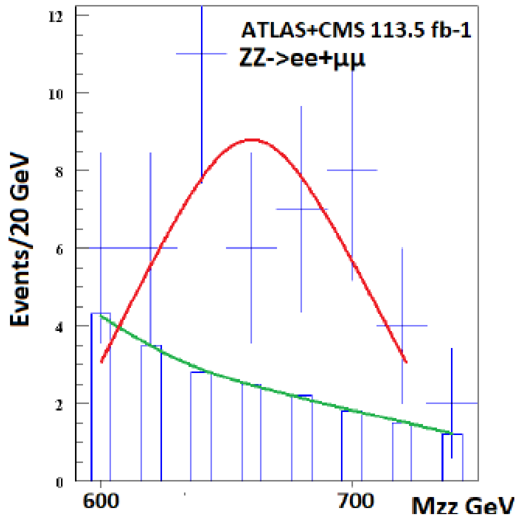
CONCLUSIONS

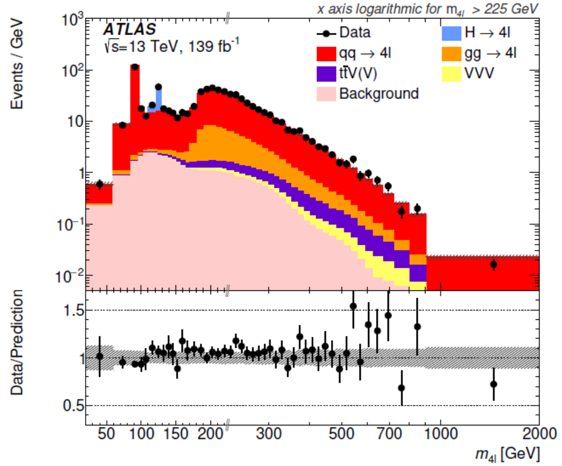
- We propose a **consistent description** for the most significant observations of neutral scalars at LHC with a simple extension of the **GM model**, referred to as **e-GM2**
- This allows for a plausible, but not unique, prediction for the **e+e- cross sections** at future colliders
- At a LC reaching a centre of mass energy of **~1 TeV**, almost all these states are measurable, except perhaps **H++** which should be observed at HL-LHC, illustrating the **complementarity** of the two colliders
- An e+e- LC would allow to probe the **triple scalar couplings**, an essential ingredient to establish the model
- The complexity of the heavier final states and their low cross-section will be **challenging** even for an e+e- machine operating in an easy environment
- Within this scenario, **HL-LHC and a TeV LC** offer a great discovery potential

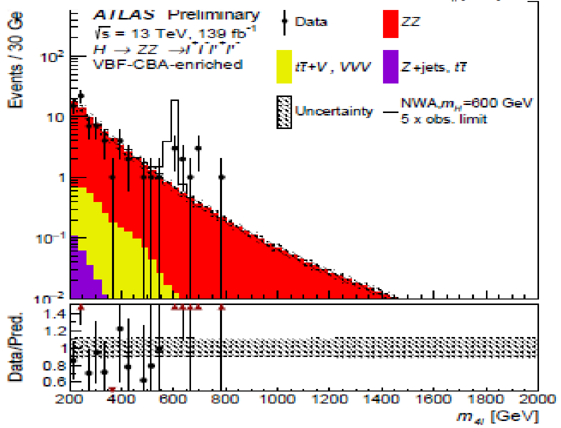
Previous presentation

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 (~2 times smaller with a **MVA analysis** less contaminated by ggF) [2009.14791]
- The VBF cross section is below the inclusive cross section ~90fb implying a **dominant ggF contribution**
- CMS analyses into four leptons, ggF nor 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…



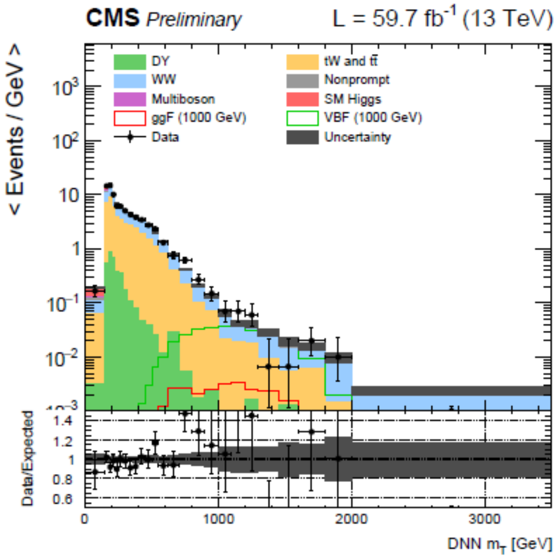




Evidence for VBF->H(650)->W+W- ->ℓℓνν

CMS PAS HIG-20-016

- Large top background even after b-jet vetoing
- **Wide signal** with ±50% mass resolution
- **VBF->H(650)->ℓℓνν** (μμ, ee and μe) favoured 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 **$\sin^2(\alpha-\beta)$~0.97±0.09** meaning that **H(650)WW~$\cos^2(\alpha-\beta)$~(0.03± 0.09)SM**
- **2HD 2 s.d. upper limit shown by the blue line**
- Both interpretations are inconsistent !
- An attempt from ATLAS does not reach the same sensitivity (only μe) ATLAS-CONF-2022-066



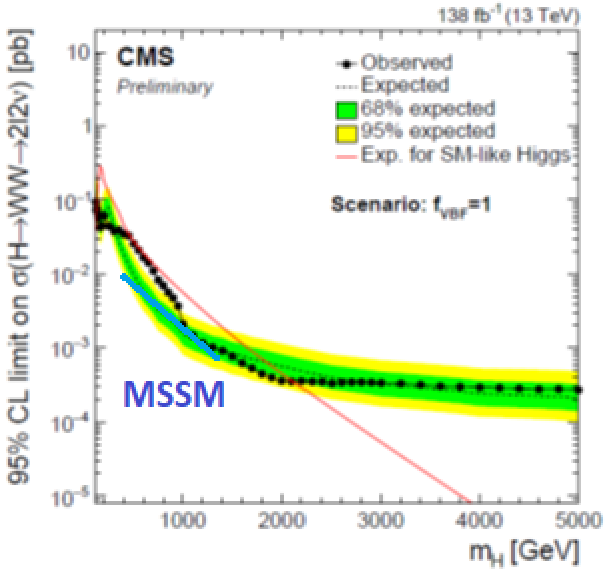
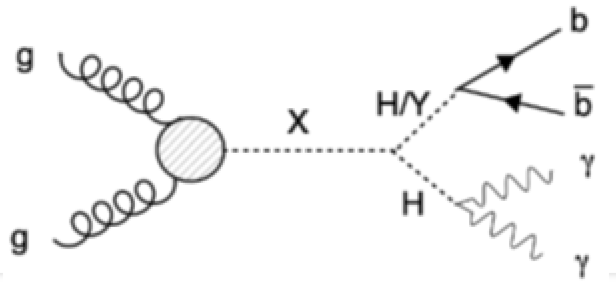


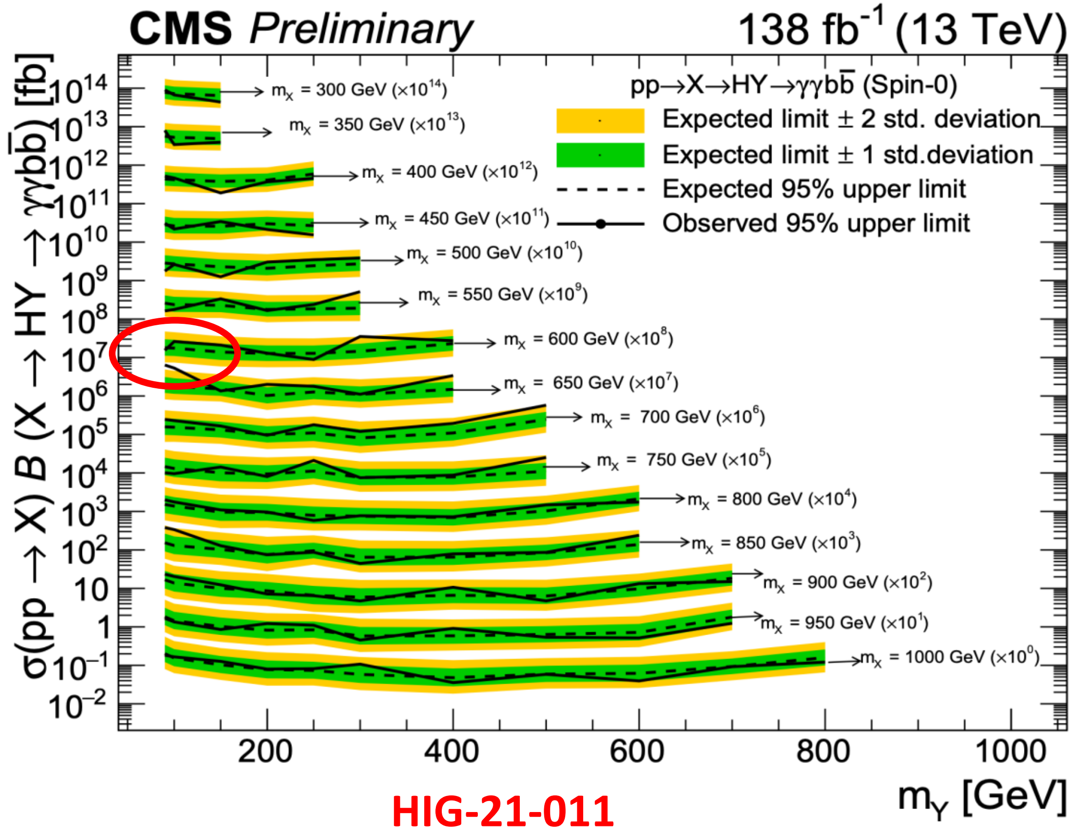
Table 3: Summary of the signal hypotheses with highest local significance for each f_{VBF} scenario. For each signal hypothesis the resonance mass, production cross sections, and the local and global significances are given.

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. for mH=650 GeV and mY=90 GeV shown at ICHEP22
- Mass resolution on Y does not allow to distinguish between Z and h(95) which is by now a "good old friend"
- CP says that bb cannot come from Z->bb but could be h(95) which is another strong candidate seen in 3 channels 2203.13180 +1 (2302.07276)
- The cross section is dominant over all other indications **~200 fb**

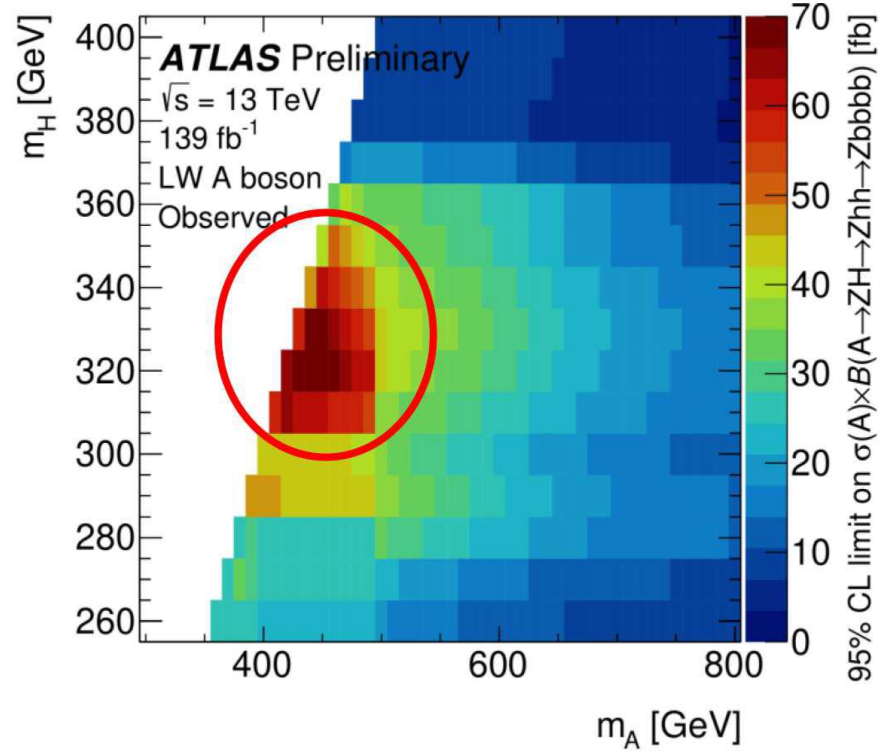




HIG-21-011

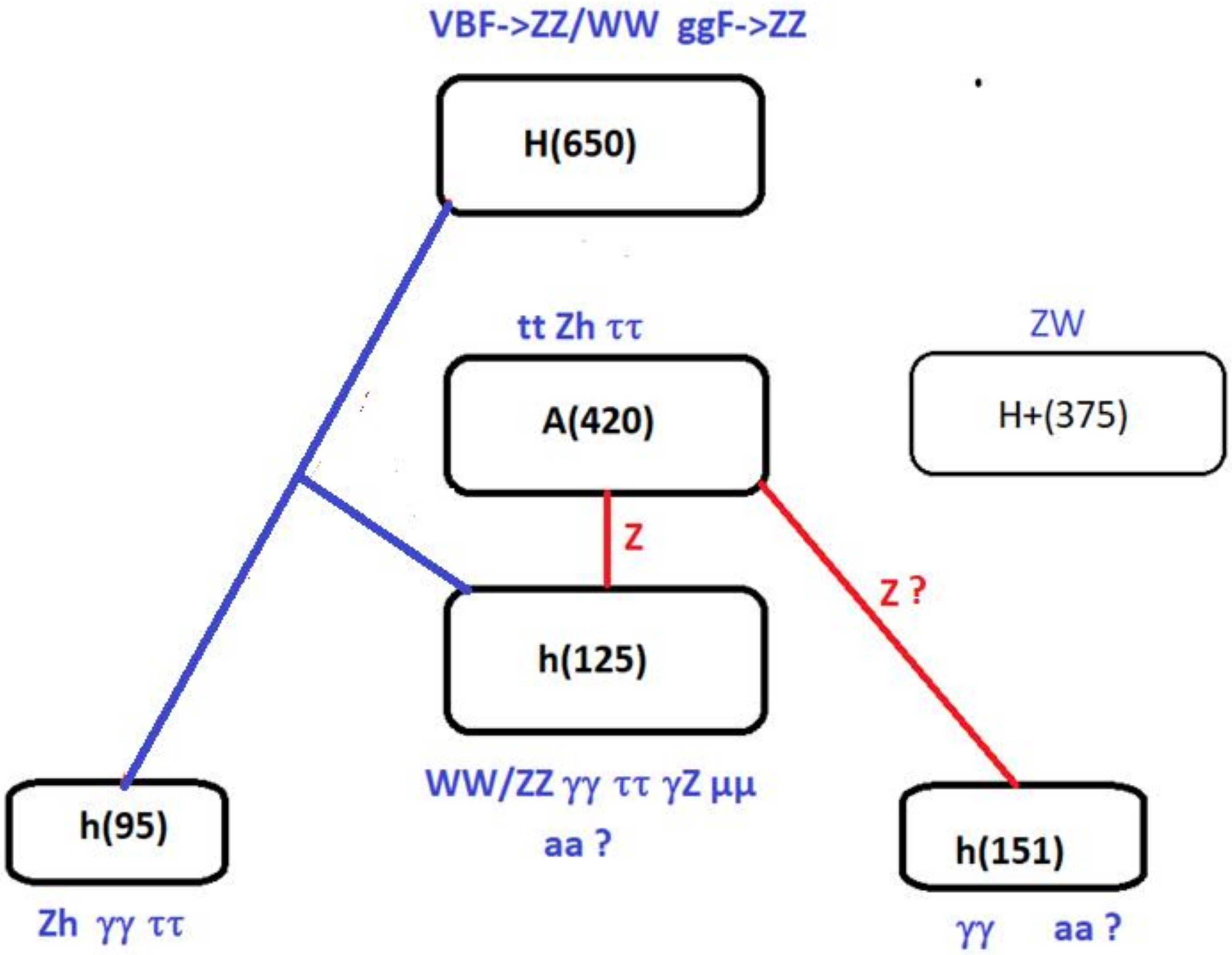
Interpretations

- H(650) cannot be accommodated within 2HD nor the genuine GM model
- Requires an extension of GM with an extra doublet where H(650) is **a mixed state of doublets and triplets**, under construction by our group
- Combining indications from H(650), one gets **6.7 s.d.** using **P=Nbins*∏ Pi and 5.8 s.d. with a conservative approach**
- The channel H(650)->h(95)h(125) provides a reinforced evidence for h(95) 2204.05975
- Initial evidences for A(400)->ττ and Zh from ATLAS not confirmed, nor progress on A->tt from CMS
- But new evidence for **A->ZH(320)->Zhh->Zbbbb** from ATLAS at 3.8 s.d. ATLAS-CONF-2022-043 which also requires **e-GM**
- See *2208.00920* and *2112.00921* for alternate interpretations of H(650)



Reaction	# channels/expts	# σ ∏Pi (loc)	# σ Frequ..	Michelin rating
pp->h(125)	>2/2	>6.9	**6.7**	***
pp->H(650)	3/2	6.7	5.8	**
pp->A(400)	3/2	5	4.5	*
h(95) LHC+LEP2	3/2	4.3	4	*
pp->H(151)+Z	1/2	4.8	4.8	*
pp->H5+(375)->WZ	1/2	3.5	3	
h(125)->a(52)a(52)	1/1	1.7 (3.3)	1.7	
pp->H3+(130)->bc	1/1	1.6	1.6	

SUMMARY OF BSM CANDIDATES



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

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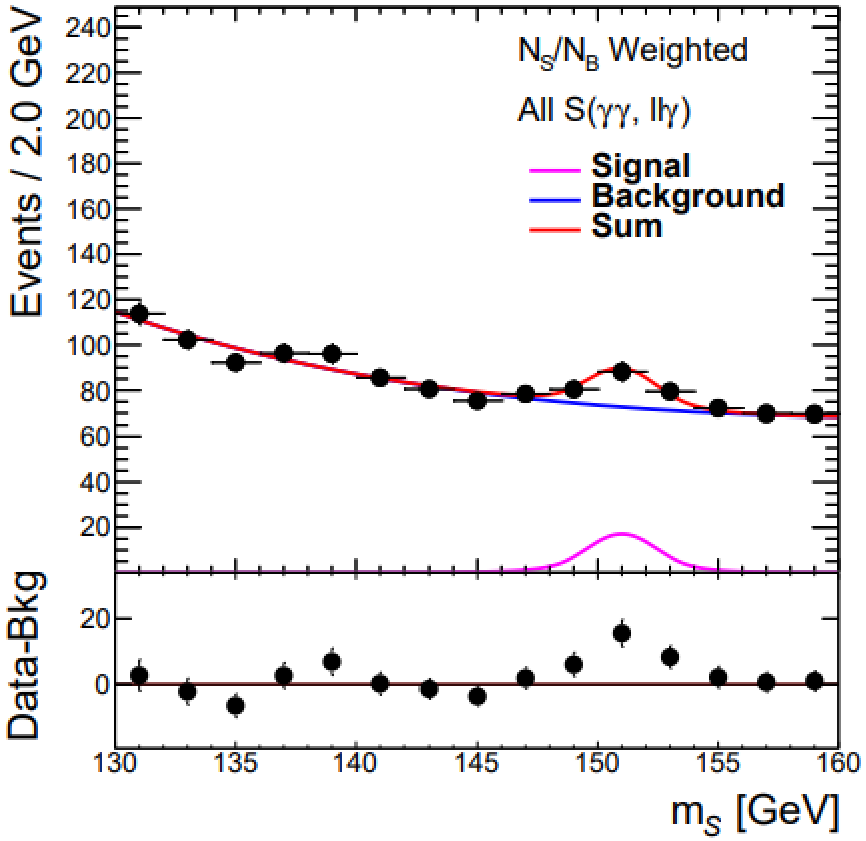
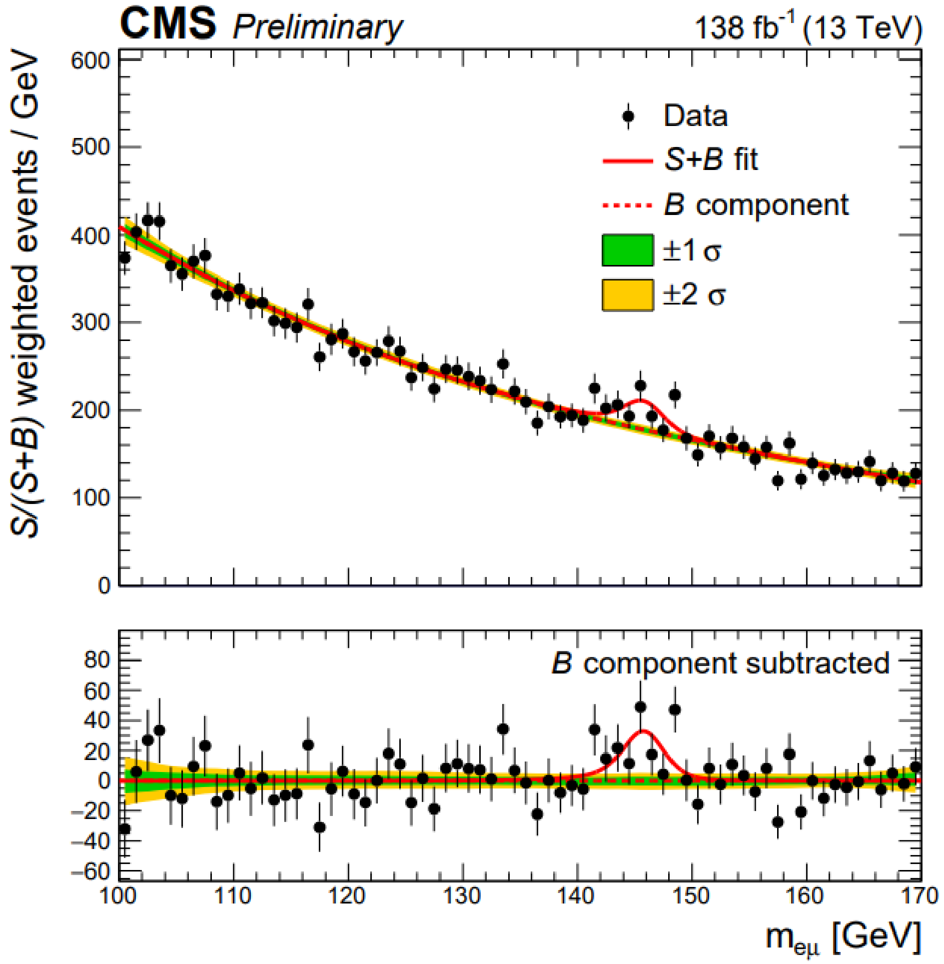
Thanks to Pawel Jan Klimek for providing useful infos about ATLAS results.

Missing slides & additional slides

(lack of lime)

Compatibility h->μe and h->γγ

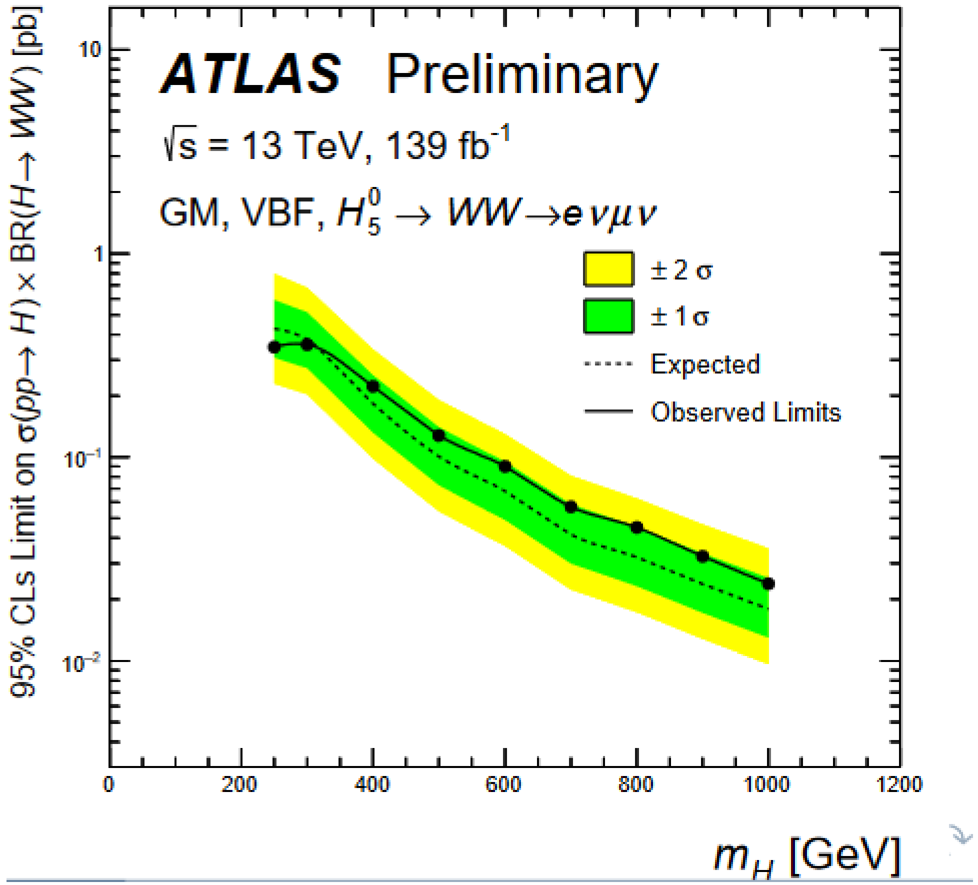




H->WW->μe$\nu\nu$ from ATLAS

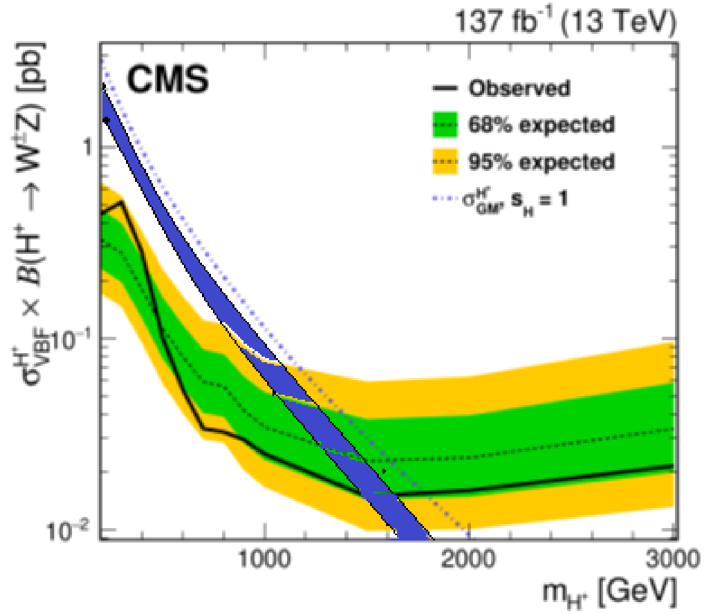
- ATLAS has provided a **preliminary result** (PISA) on VBF->H5->WW in μe$\nu\nu$ (not μμ nor ee) ATLAS-CONF-2022-066
- Like CMS, ATLAS sees a wide excess around 650 GeV but with only at the 1 s.d. level
- ATLAS can set a 200 fb 2 s.d. limit for

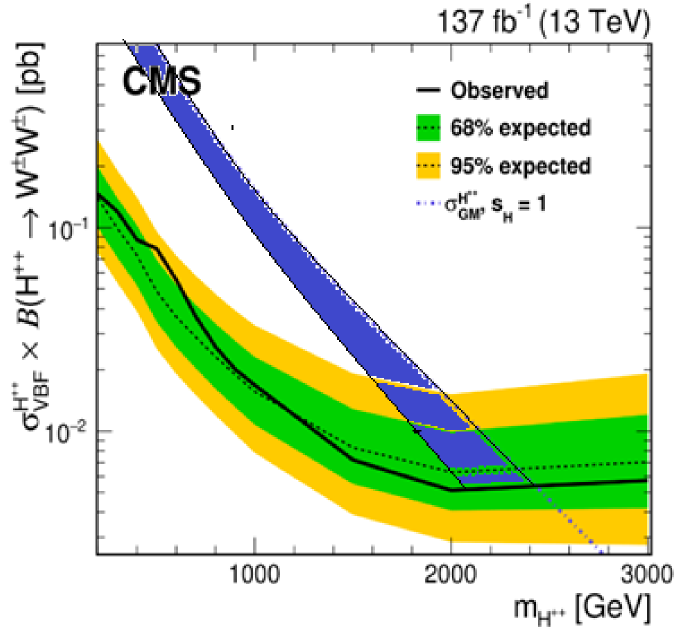
  σ(pp->H)xBR(H->WW)
- This limit is **compatible** with the observation of CMS 160±50 fb
- ATLAS has a smaller efficiency as compared to CMS (retain only **μe**)



Predictions from the sum rules

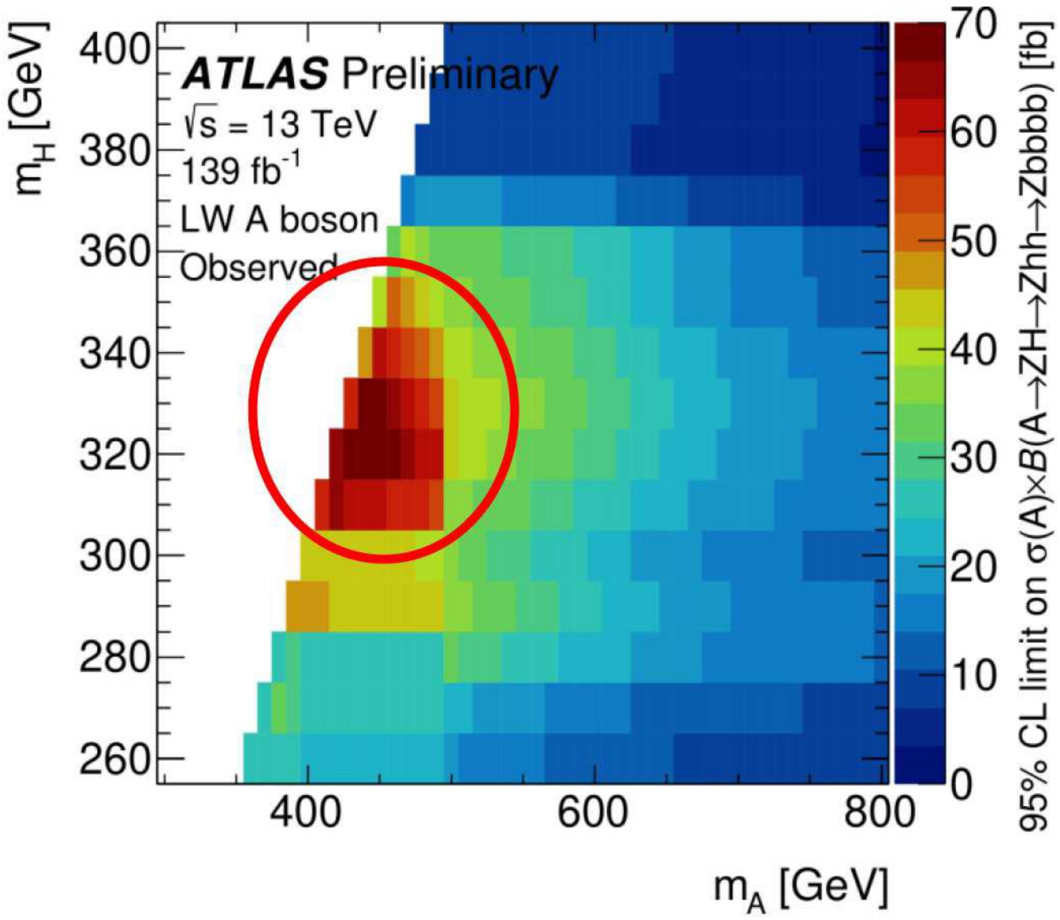
- For H+5->WZ the blue band is closer to the limit from CMS and one cannot exclude mH5+=375 GeV, as indicated by ATLAS and CMS
- The blue band, obtained assuming BR(W+W+)=1, will decrease with the opening of H++-> H3+W+, H3+H3+ and H5+W





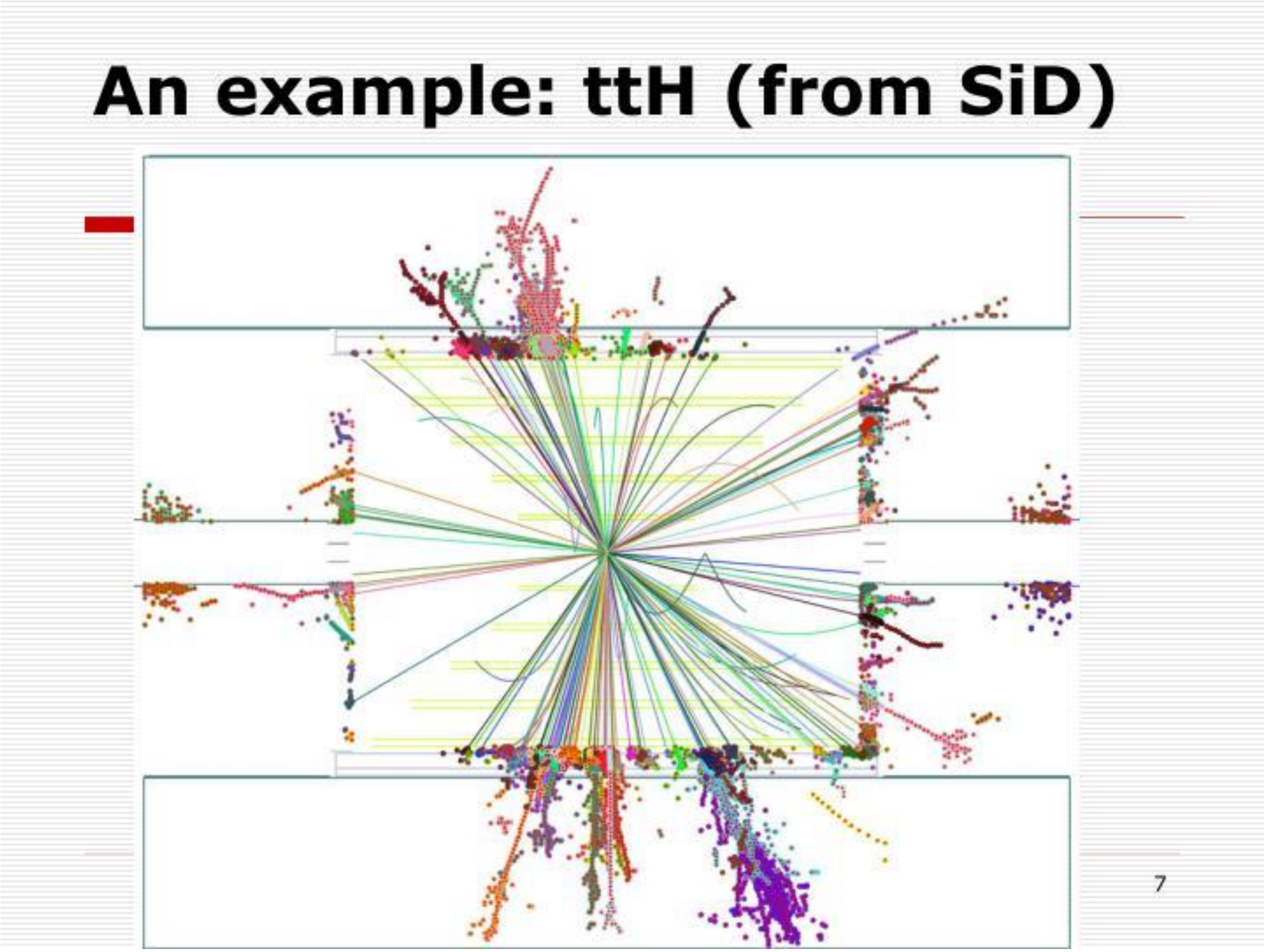
A(420)->ZH(320)->Zh(125)h(125)

- Local (global) significance of **3.8σ (2.8σ)**
- hh into 4b using mass constraint to improve resolution
- Requires e-GM for H(320)
- Note that A(420)->ZH(320) is close to threshold, meaning that the true width of H(320) could be larger than indicated by the plot



ATLAS-CONF-2022-043

Complex events



GM model issues

Georgi-Machacek for pedestrians

- Allows I=2, H++, without violating **$\rho = M^2_W / M_Z^2 \cos^2\theta_W = 1$** at tree level
- Is achieved by combining 1 isospin doublet (v_ϕ) + 2 triplets, 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 $v_\chi = v_\xi = u$

- 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**

Yukawa coupling schemes in 2HDM

- Yukawa couplings in 2HDM offer a wide range of possibilities 2104.03275
- In most 2HDM models each type of fermion (u,d,ℓ) is **coupled to only one scalar doublet** ϕ_1 or ϕ_2 hence no FLV
- In **type III** they can be coupled to both hence **FLV at tree level** 1612.01644
- The preferred mass region is for mh<2Mw

	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	×	×	×	×	×	×	$\frac{\xi_u - t_\beta}{1+\xi_u t_\beta}$	$\frac{\xi_d - t_\beta}{1+\xi_d t_\beta}$	$\frac{\xi_\ell - t_\beta}{1+\xi_\ell t_\beta}$

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](1308.4025)

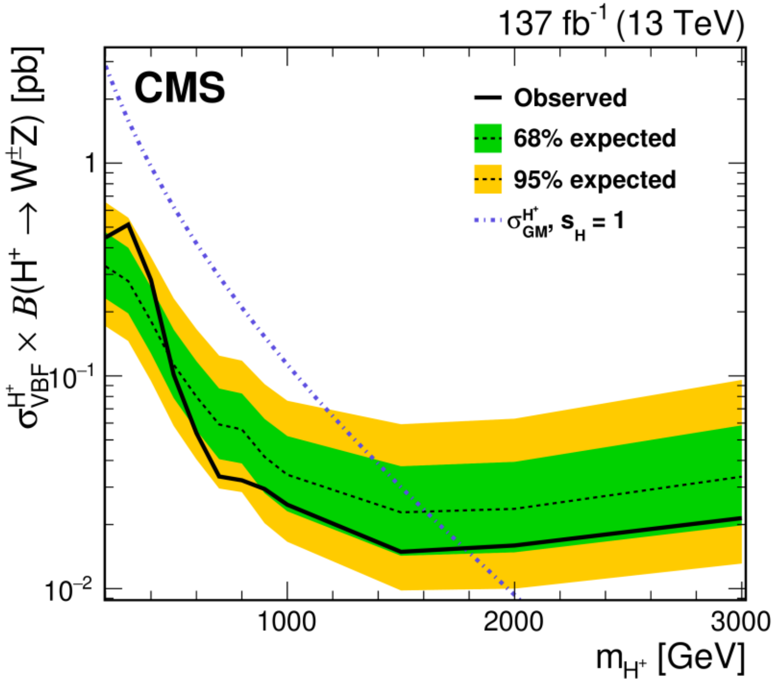
$$\Sigma_{-1} = \begin{pmatrix} \frac{\chi^-}{\sqrt{2}} & \chi^0 \\ \chi^{--} & -\frac{\chi^-}{\sqrt{2}} \end{pmatrix}, \quad \Sigma_0 = \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix}, \quad \Sigma_1 = \begin{pmatrix} \frac{\psi^+}{\sqrt{2}} & \psi^{++}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

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

- 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
- Two doublets as needed to interpret H320 and the ZZ/WW decays of H(650)
- DM candidate
- Complex/rich world with ~20 Higgs scalars

What about H5+ and H5++ ?

2104.04762



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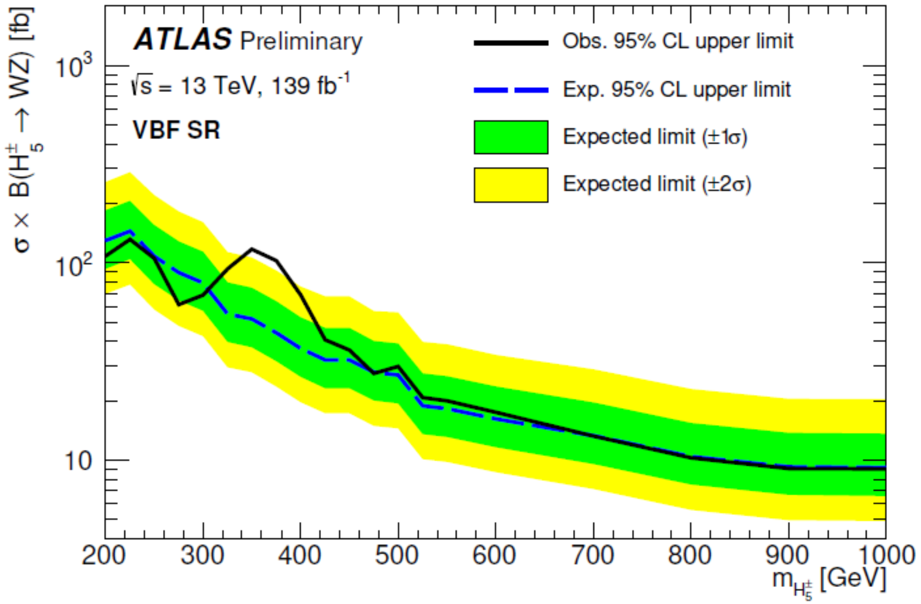
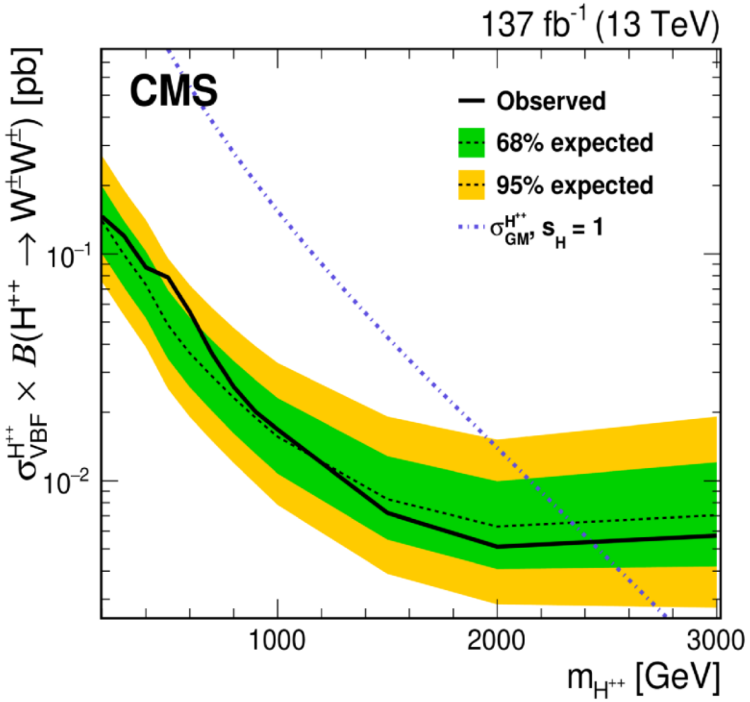


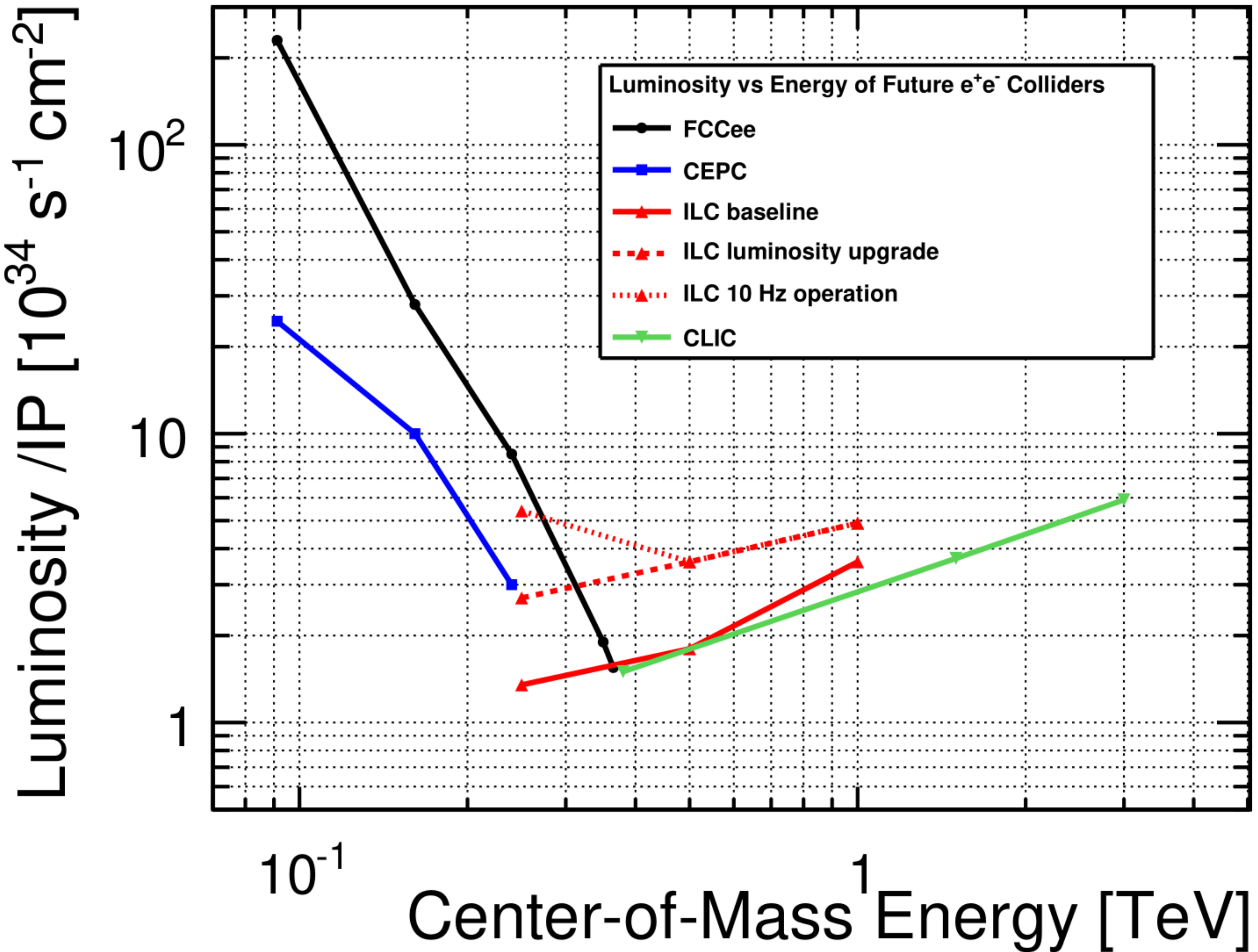


- CMS cross sections assume $\mathbf{s_H=1}$ are divided by 4 for $\mathbf{s_H=0.5}$
- If H3+ is light H3+Z and H3+W+ become dominant and these resonances become wide
- Coincident excess at mH5+~375 GeV for ATLAS (2.8sd) & CMS while naïve GM predicts 650 GeV
- Not excluded in eGM 2111.14195

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.