Triple Higgs couplings

ECFA WG1-SRCH

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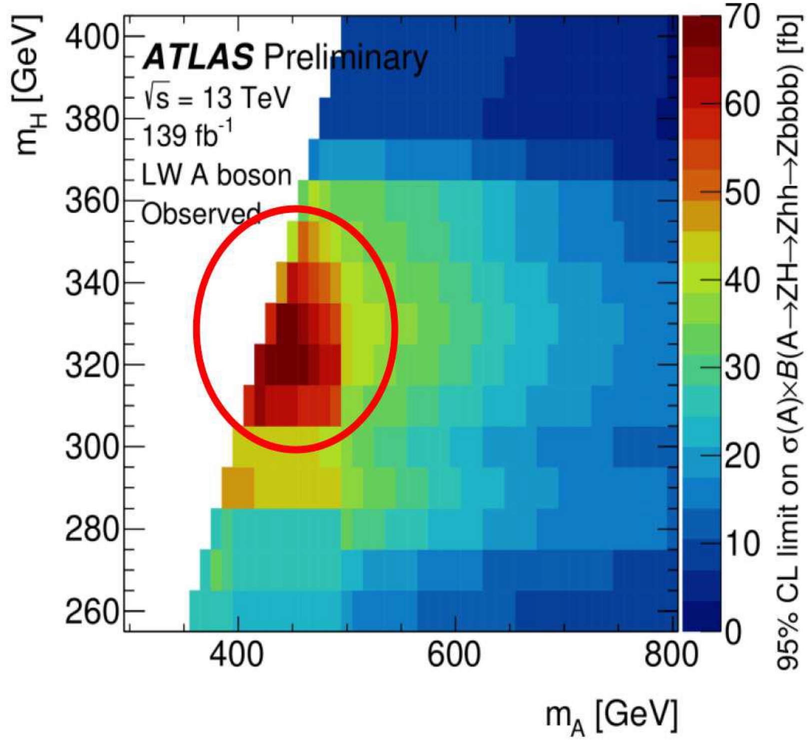
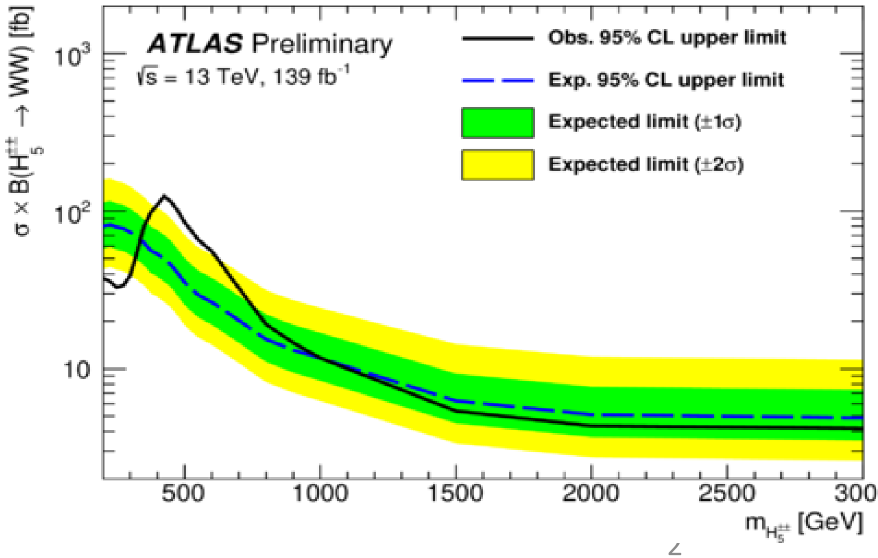
Calcutta-Orsay-Montpellier collaboration

Introduction

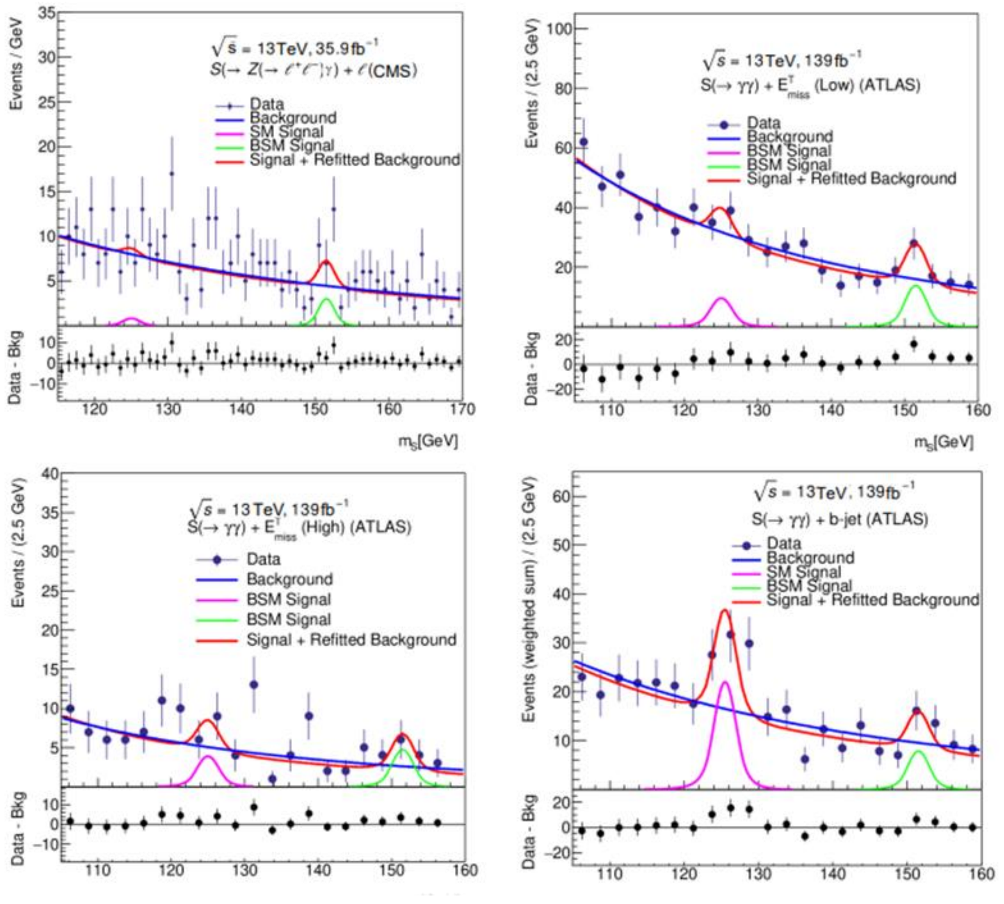
- Measuring h*->hh appears as a high priority of our field
- A very low SM x-section, 30 fb, with very large backgrounds makes this a formidable task
- Much easier if there are **resonances H->hh**
- Direct evidence, 3.8 sd : **A(420)->H(320)->hh->bbbb** [2210.05415](2210.05415)
- BR(W+W+) ~10% using Haber et al. SR implies light charged Higgs H+(130) [2312.00420](2312.00420) and a dominant BR(H+H+)
- These results naturally fit into **Georgi Machacek** model
- This model associates to **H+(130),** seen in [2302.11739](2302.11739) a light **CP-odd A** with similar mass





A(151)

- There is a candidate A(151)-> γγ at 4.8 s.d. when asking +b or Etmiss or leptons [2404.1492](https://arxiv.org/abs/2404.1492)
- CP odd suggested by non observation in ZZ
- GM predicts that **A(420)->H(320)Z->A(151)A(151)Z**
- Could easily be found using the same technique usec for h(125)h(125)
- Gives a cross section in bbbb 4 times larger than h(125)h(125)
- Should provide the most convincing (>>5 sd) BSM LH signal so far !
- **Three discoveries** at a time : A(420), H(320), A (151) .



e-GM summary

- All but one among the **10 e-GM scalars** have a candidate indicated by LHC data

GM	**Isosinglet**	**h95**	**h125**
	Isotriplet	**A151**	**H+130**
	Isofiveplet	**H320**	**H+375 H++450**
E-GM	**Extradoublet**	**A420**	**H650 H+ ?**

- Physical states differ substantially from the GM Isospin states (see below)
- There is a candidate **H+->A(420)W+ -> ttW+**

Example of a matrix solution

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

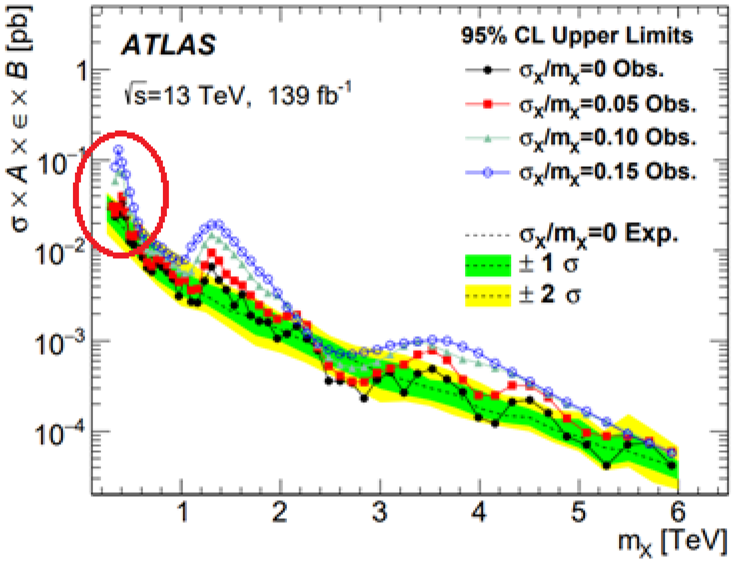
$$H_5^0 = \sqrt{\frac{2}{3}}\xi^0 - \sqrt{\frac{1}{3}}\chi^{0,r},$$

	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

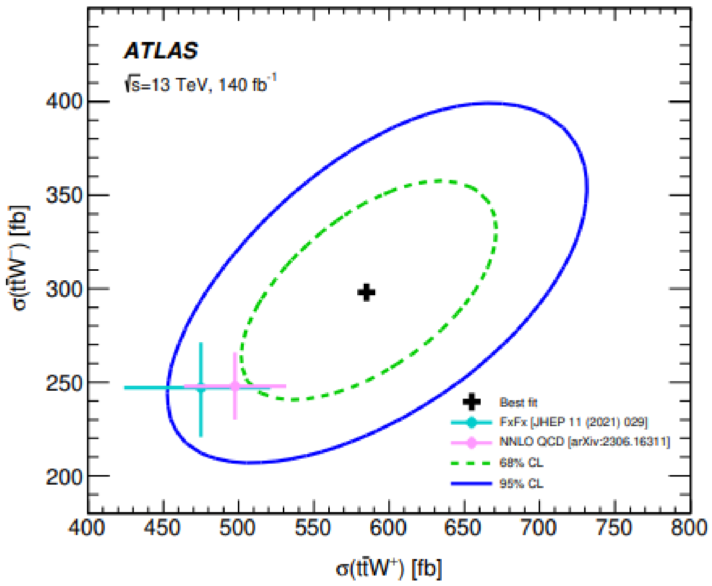
- h(125)=0.58(ϕ1+ϕ2)+0.58H'1
- v1 =-30 v2=102 u=70 GeV   v=174 GeV
- Type I Yukawa Yi/SM=xi2*mt/v2
- Hi_{WW}/SM=(xi1v1+xi2v2)/v+(2xi3+2√2xi4)u/v
- Neutral scalars do not coincide with GM isospin states H1, H3 and H5
- Coloured squares have unmeasured couplings which can be **predicted** by this method
- **H125** has a **large mixing with H^{0}'1** as predicted by PM of *1807.10660*
- **H650** dominated by **doublets** does not belong to fiveplet
- **H320** belongs to fiveplet but differs from H05 therefore couples to h125h125
- H320->ZZ has a width ~5 GeV subdominant to $\Gamma_{H320\text{->}AA}$ ~ 100 GeV
- Predicts μ95γγ and μ125~1 while ATLAS+ CMS measure **μ95γγ=0.27±0.1** *2302.07276* and μ125~1 implying that **charged scalar** contributions act very differently

An extra H+ ?

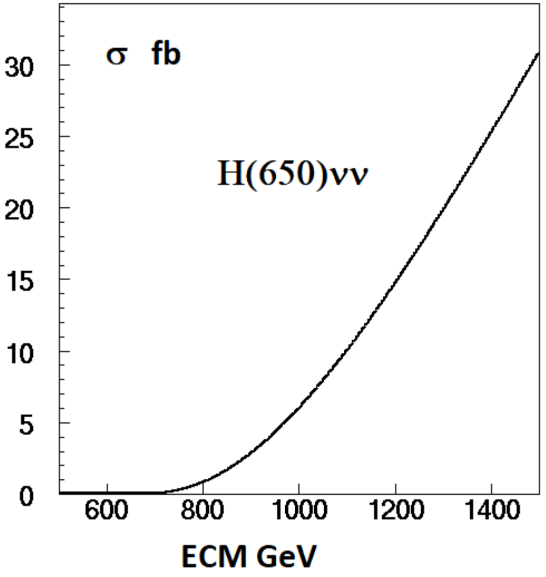
- An e-GM scheme requires an extra H+ related to H(650)
- By analogy with H(650)->A(420)Z->ttZ, one expects that **H+->A(420)W+->ttW+**
- An inclusive search for heavy jet-jet masses associated to a high pT lepton provides such a candidate [2001.04770](2001.04770)

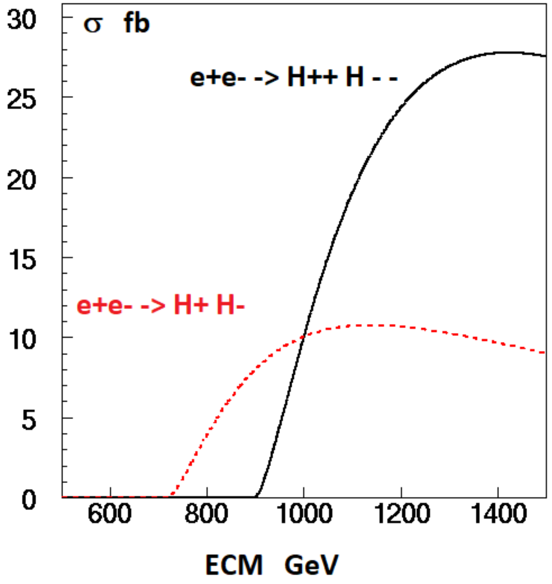


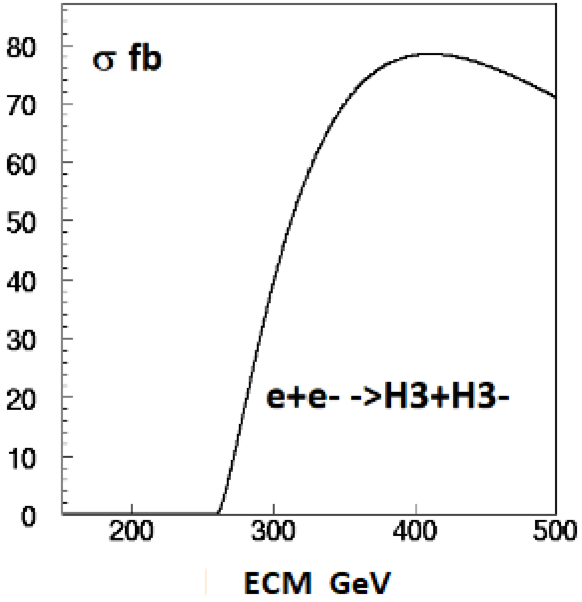
- ATLAS and CMS observe an excess in the inclusive measurement of ttW+/- [2401.05299](2401.05299)
- Seems to proceed through ZW fusion to explain the charge asymmetry (p->u->W+ : factor 2)
- One should therefore observe H+->ZW
- No such effect in ttZ, which is not yet understood

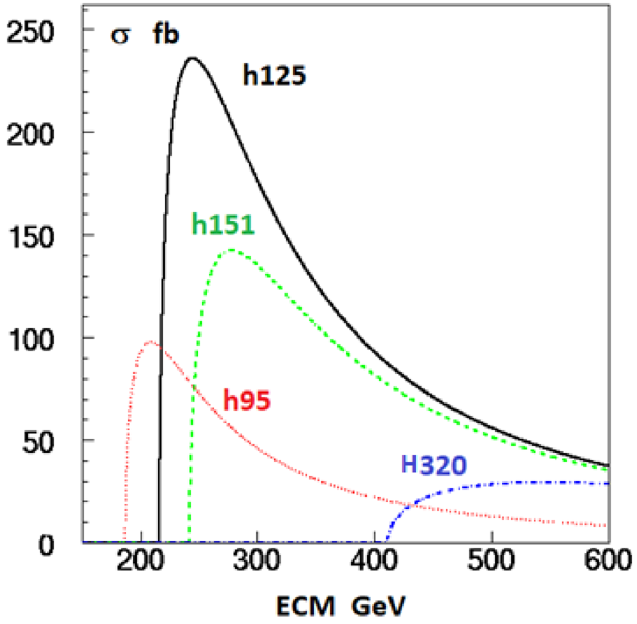


e+e- collider reach









- Final states are complex modes (~ SM ttH) requiring the **highest $\mathcal{L}$** and an **almost ideal detector with forward coverage for b jet ID**
- ILC would provide **8000 fb-1 at 1 TeV**
- **H(650)** mainly produced through VBF (beam polarisation allows a factor ~2 gain, not included) benefits from an increased energy
- A(420) and A(130) can be seen through cascades like H(650)->ZA(420), H+(375)->A(130)W+, H(320)->A(131)A(131)
- Using an **e-e- collider** one could also produce H^{--} through VBF with polarized beams ~100 fb at 1 TeV
- Circular machine can access to h95, h151 and H+(130)

Conclusions

- H(320)->h(125)h(125) should contribute to the h*->hh SM measurements
- A global interpretation based on GM+SR predicts an immediate **triple discovery** for A(420), A(151), H(320)
- The table of **e-GM isospin states** can be filled with the various indications provided by LHC
- The **matrix method** shows that the neutral candidates, including h(125), strongly differ from the isospin pure states predicted by GM
- Evidence for a **third H+** in H+->ttW+ as expected in e-GM
- Read our papers : 2404.09827 the most recent
- **2211.11723** and ***https://indico.cern.ch/event/1253605/***
- **2308.12180** **constantly updated**
- Stay tuned !

Additional slides

Sum Rule I

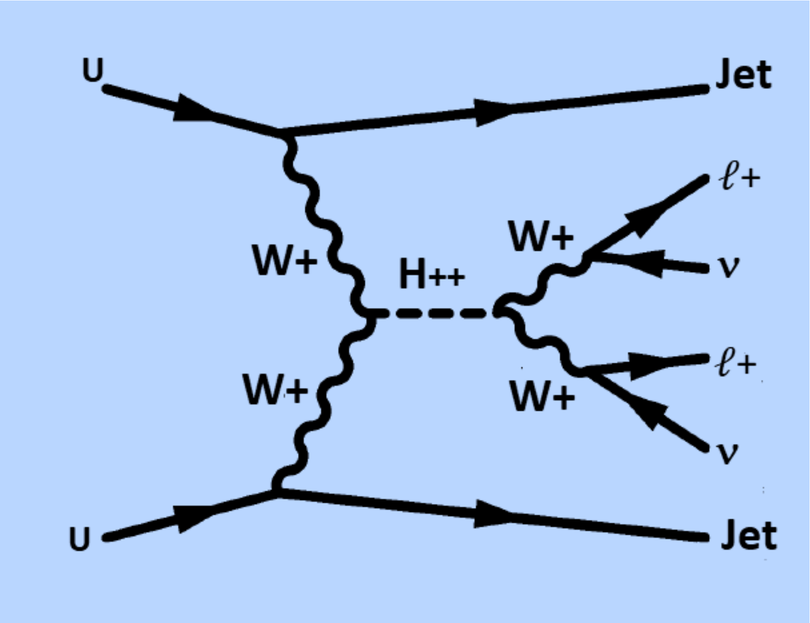
- **W+W- ->W+W-** Haber et al. in *P.R.D* 43 (1991) 904-912

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

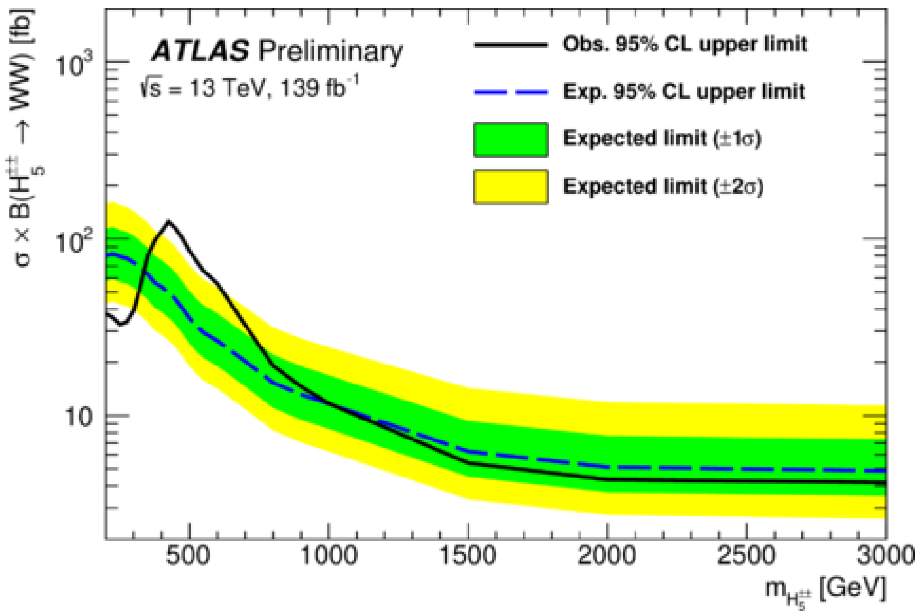
- So-far we have been able to measure H(650)W+W- and (*2302.07276*) h(95)W+W-
- There are other candidates like h(151) and H(330) where these measurements are unavailable, but we have ideas on how to deal with them (**2308.12180** and ***https://indico.cern.ch/event/1253605/***
- H(650) alone forces to have a contribution of H++->W+W+ with a coupling ~ SM=gmW

First hint for H++

- Recently at the Belgrade ATLAS meeting: **H++(450)->W+W+**
- LHC is ideally suited for this measurement:



- 3.2 s.d. local, 2.5 s.d. global
- The reconstruction efficiency of CMS is a factor 2 below that of ATLAS [2312.00420]



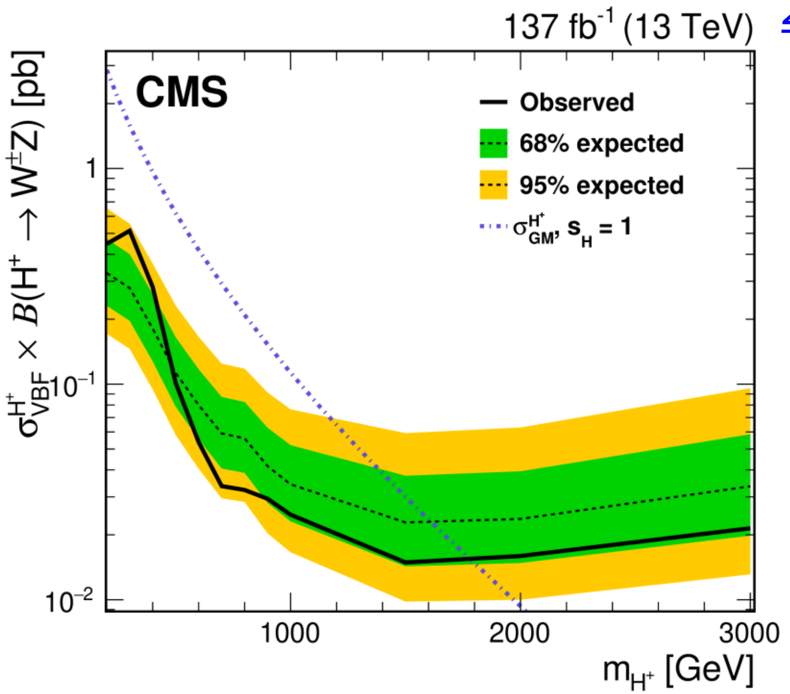
Sum Rule II

- **W+W- -> ZZ** allows a similar SR

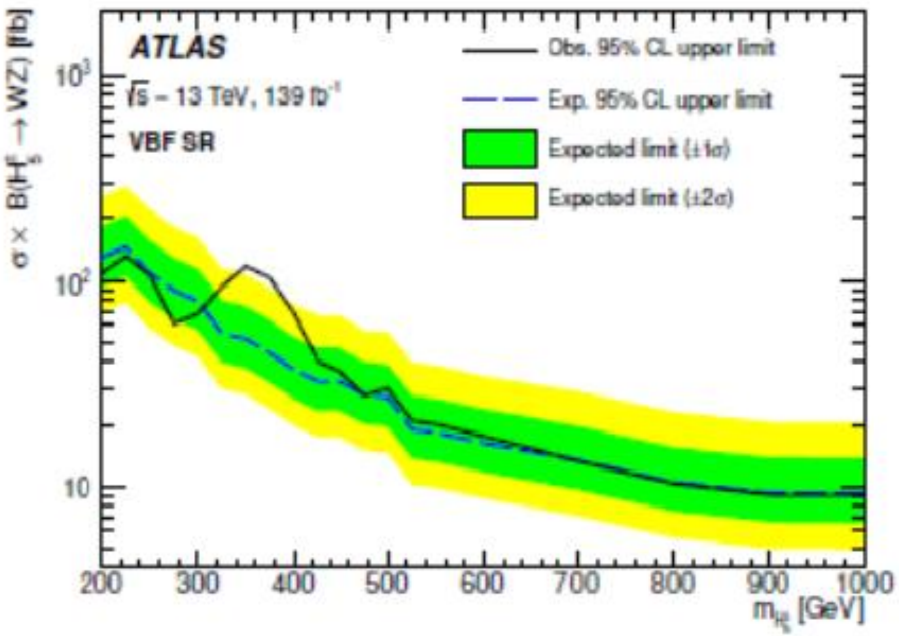
$$\frac{g^2 m_Z^4 c_W^2}{m_W^2} \overset{\rho\simeq 1}{\simeq} g^2 m_Z^2 = \sum_k g_{W^+W^-H_k^0} g_{ZZH_k^0} - \sum_l g^2_{W^+ZH_l^-}$$

- This forces a strong coupling for **H+->ZW+** which should be observed at LHC
- Note that this result depends on the **signs** of the coupling constants which are not known from present measurements
- h95ZZ is known from LEP2 (but not its sign !)

Evidence for H+ -> ZW+



2207.03925



- Coincident excesses at mH5+~375 GeV for ATLAS & CMS
- **ATLAS** claims 2.8 s.d. local
- In GM H5++ and H5+ are mass degenerate which is almost true (see for e-GM 2111.14195)
- H(650) cannot fulfil the requirements of a neutral candidate of H5 but H(320) is more appropriate

Model independent results

- From these and the SR, one can deduce the total cross section, the elastic BR and the total widths as given in the following table:

Channel	**σ_{VBF} fb**	**σ_{VBF} VV fb**	**BR(VV) %**	**Γtot GeV**
H++(450)	830	75	9±4	160
H+(375)	810	125	15±8	80

- These predictive results only rely on the validity of the sum rule approach, which seems legitimate given that VV final states at the LHC energy scale agree with the SM predictions
- They call for lighter charged scalers to provide VH and HH contributions

GM interpretation

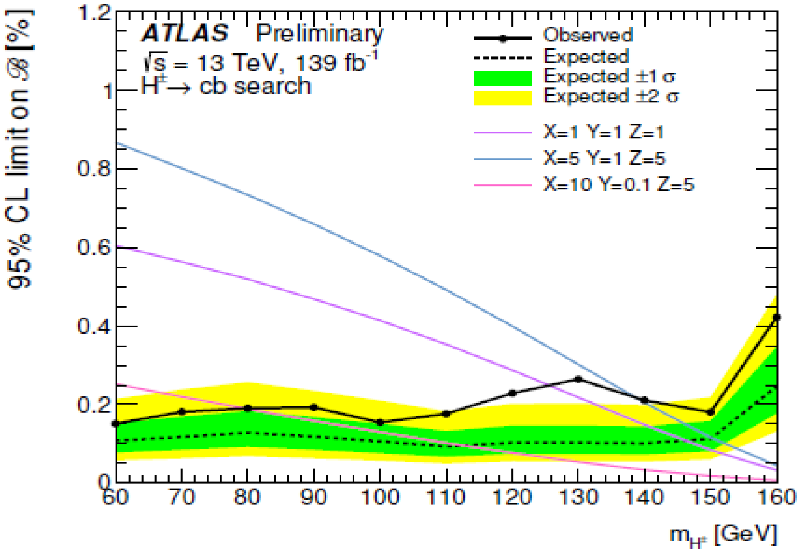
- Quantitatively, SR predicts $\Gamma_{\mathbf{H{+}{+}\text{->}W{+}W{+}}}$ and the measured cross section allows to deduce the BR(W+W+) and the total width $\Gamma_{\mathbf{H{+}{+}\text{->}W{+}W{+}}}$/BR(W+W+)

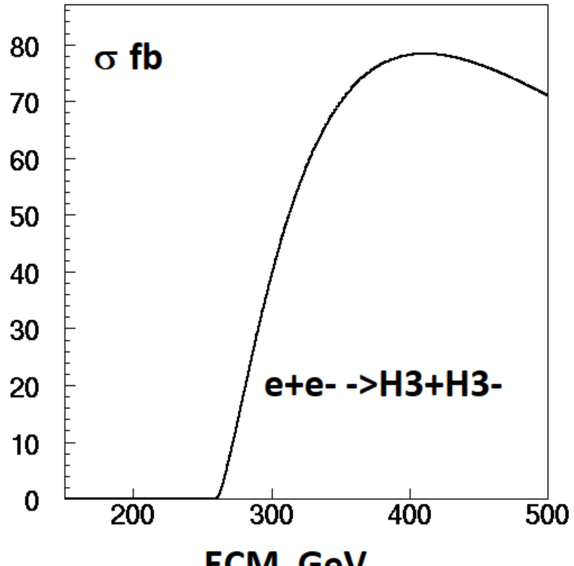
Channel	u GeV	s_H	BR(VV) %	BR(VH) %
H++	70±12	0.80±0.1	9	12.5
H+	80±13	0.90±0.2	15	17

- **u=70 GeV** comes as a surprise: usual lore is BR(W+W+)=1 and u<25 GeV
- This large value is inconsistent with models with only one triplet (*2312.17314*) requiring u much smaller to fulfill **ρ~1**
- BR(W+W+)~10% requires other modes like H'+W+ or even **H'+H'+** (ZH'+ for H+)
- **A light (or several) H'+ predicted**

A light H'+ ?

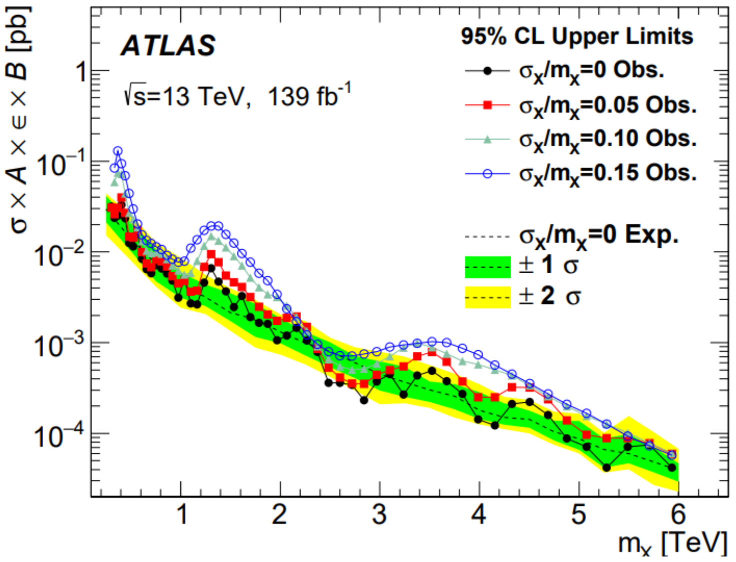
- There are few indirect hints for this
- B decays into Dτ and $\Lambda\tau$ are reduced by 1.6 and 1.4 s.d. 2305.00614 suggesting mH+~200 GeV
- ATLAS has searched for t->bH+->bbc and found a 3 s.d. local (2.5 global) excess around 130 GeV 2302.11739
- Not allowed in 2HD models for type II 1702.04571 but allowed for tanβ>2 in type I
- One predicts A mass degenerate which can feed into H+(375)->AW+ (could be A(151) seen into 2γ)
- Works quantitatively to explain the observed BR of H++ and H+(375) into H'+H'+ and H'+A
- Good news for circular colliders

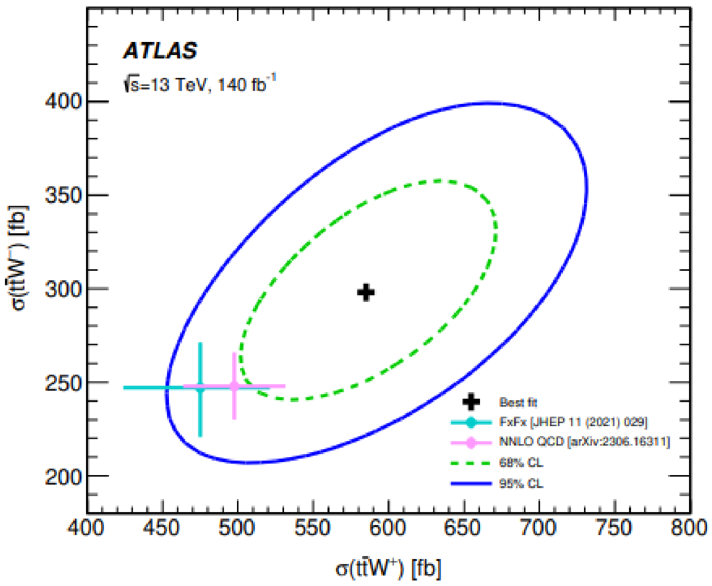




An extra H+ ?

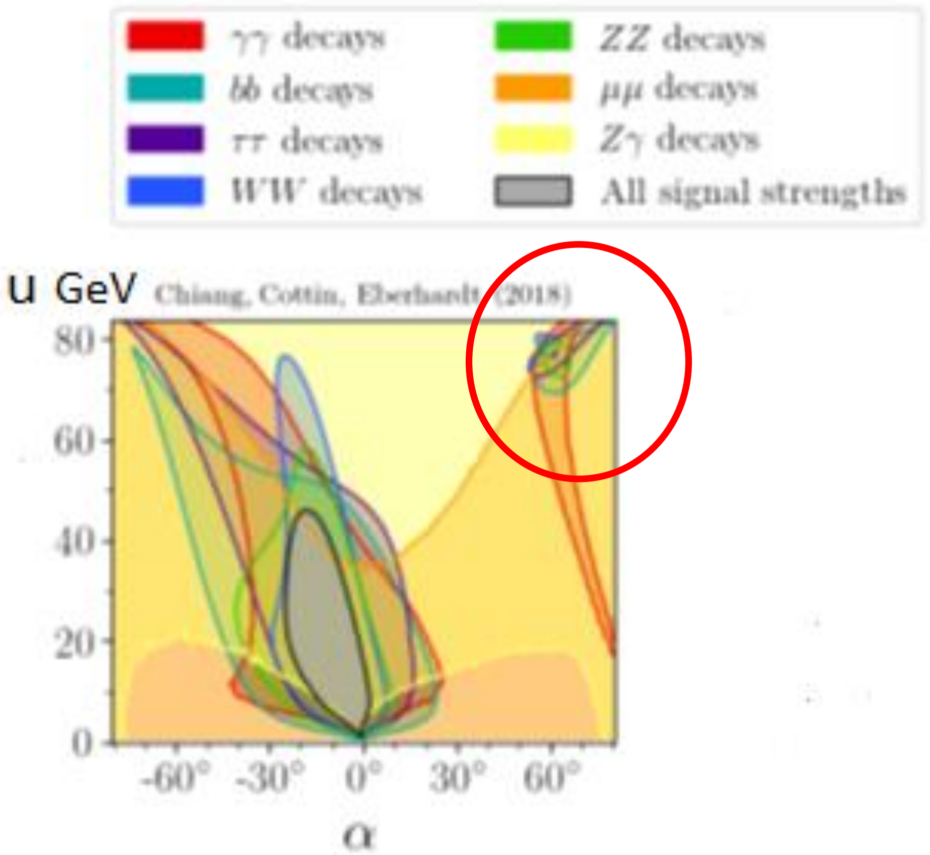
- An e-GM scheme requires an extra H+ related to H(650)
- By analogy with H(650)->A(420)Z->ttZ, one expects that **H+->A(420)W+->ttW+**
- An inclusive search for heavy jet-jet masses associated to a high pt lepton provides such a candidate [2311.04033]
- This reaction could be indirectly observed by ATLAS and CMS as an excess in the inclusive measurement of ttW+ [2401.05299]
- However no sign of an excess in ttZ





Precision Measurements

- **u~70 GeV** deduced from the sum rules seems incompatible with PM
- There is however a GM solution with **large α~60°** and u=v_ξ=v_χ=75 GeV which satisfies PM for h(125)
- Implies that h can have a **large triplet component** still passing PM
- Not necessarily true for **h->hh** or **Zγ**
- **μ95γγ~0.3** differs from the matrix prediction ~1, perhaps due to the charged Higgs sector while μ125γγ~1 could be due to an accidental cancellation



1807.10660

The neutral sector in e-GM

- e-GM comprises two doublet fields $\phi1$, $\phi2$ with vev **v1 and v2** and two triplet fields χ, ξ with the same vev **u**
- For the neutral sector one writes:

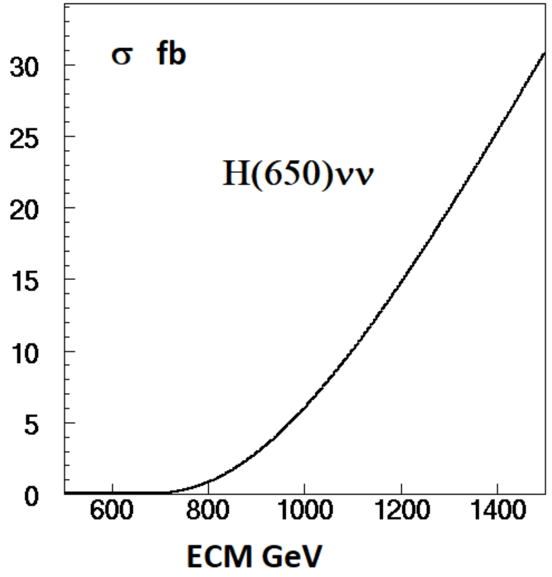
$$\begin{pmatrix} h_{95} \\ h_{125} \\ H_{320} \\ H_{650} \end{pmatrix} = \mathscr{X}_{4\times4} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \\ \chi^0 \\ \xi^0 \end{pmatrix}$$

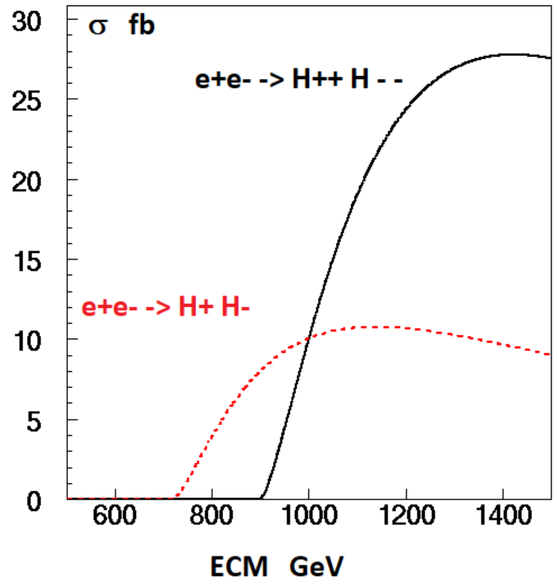
- where the matrix is 4X4 unitary **real** (no CPV) with 16-4-6=**6 free parameters** requiring the **unitary vectors** to be **orthogonal**
- In total there are 6+3 (v1, v2, u) free parameters and 7 observables from LHC measurements, u from SR + constraint $v1^2+v2^2+4u^2=(174\ \text{GeV})^2$
- One needs to choose between various **Yukawa coupling patterns** and we find that **type I** (all fermions having the same coupling) gives a reasonable agreement with the data

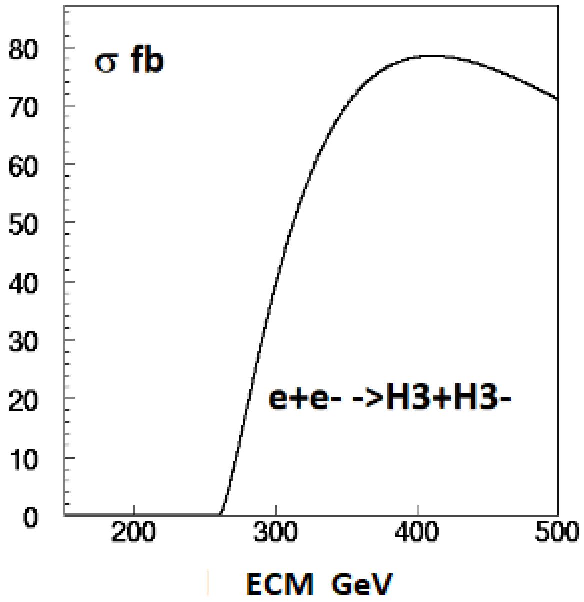
H(320) as a partner of H++ ?

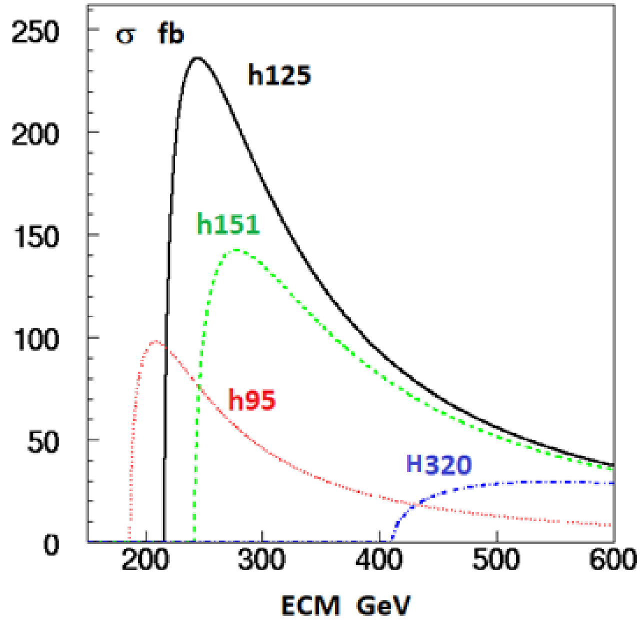
- The **H5 multiplet** containing H++ needs to be completed by a neutral scalar, which cannot be H(650) which is doublet dominated
- Given its mass, H(320) seems appropriate and its dominant content in triplet fields (see matrix) reinforces this hypothesis
- However, its decay into bbbb interpreted as h(125)h(125) seems to violate GM
- Note that h(125) and h(95) also carry triplet components which allows H(320)->hh
- H(320) most probably decays into **A(151)A(151)** which feeds into bbbb, experimentally indistinguishable from hh
-

Collider reach









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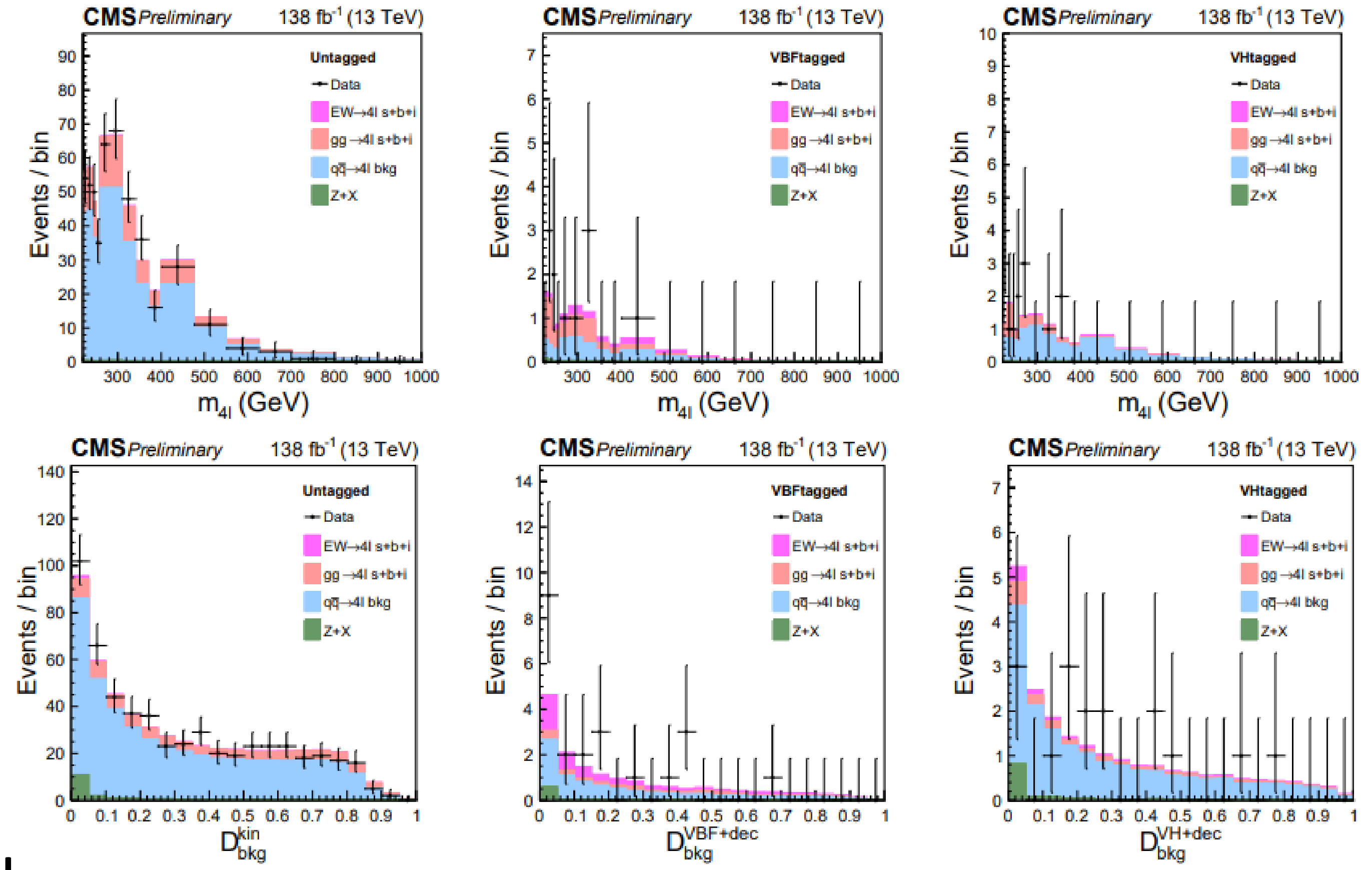
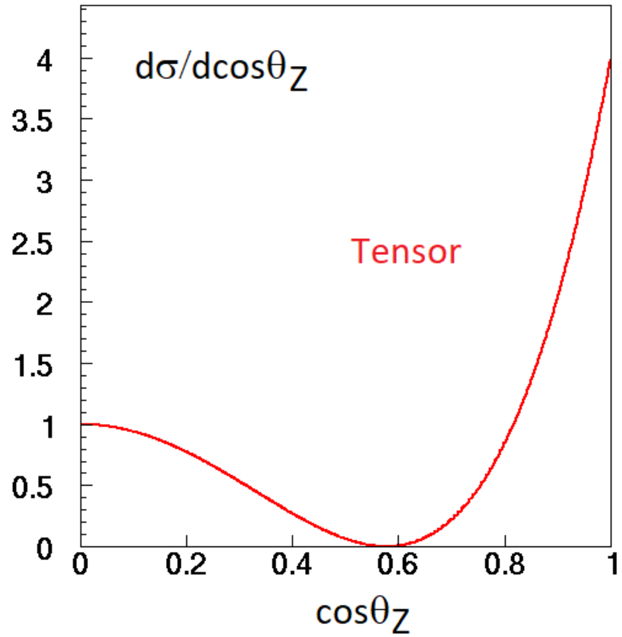
- A(420) and A(130) can be seen through cascades like H(650)->ZA(420) and H+(375)->A(130)W+
- Using an **e-e- collider** one could also produce H^{--} through VBF with polarized beams ~100 fb at 1 TeV
- Circular machine can access to h95, h151 and H+(130)

Results from CMS

[CMS-PAS-HIG-21-019]

- Selecting a scalar solution in ZZ->4l , D_{bkg}>0.6, CMS finds:



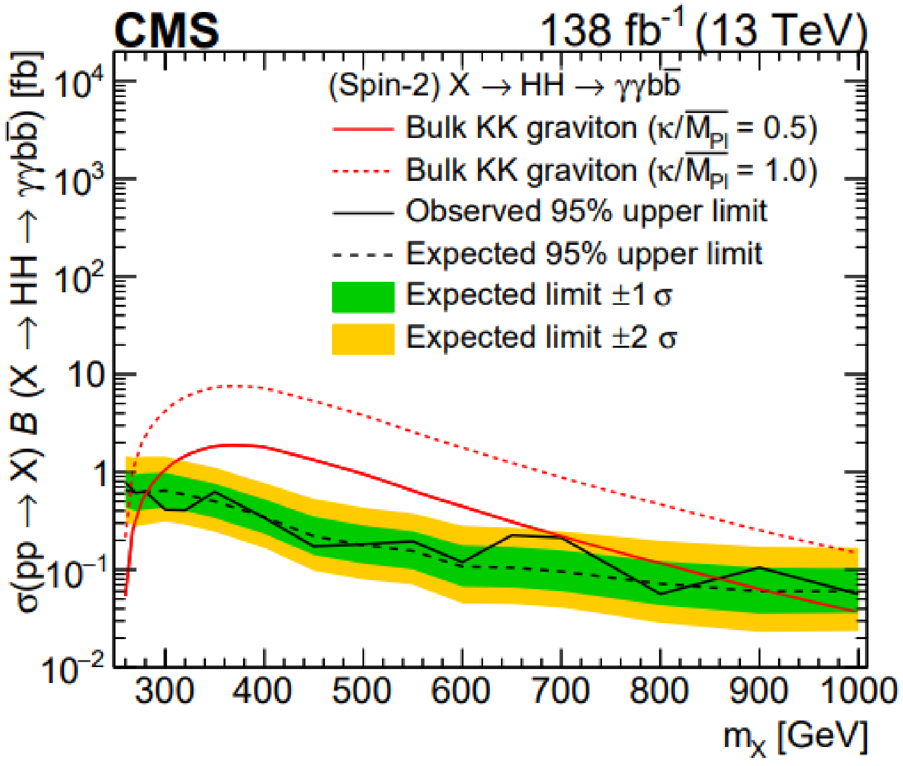


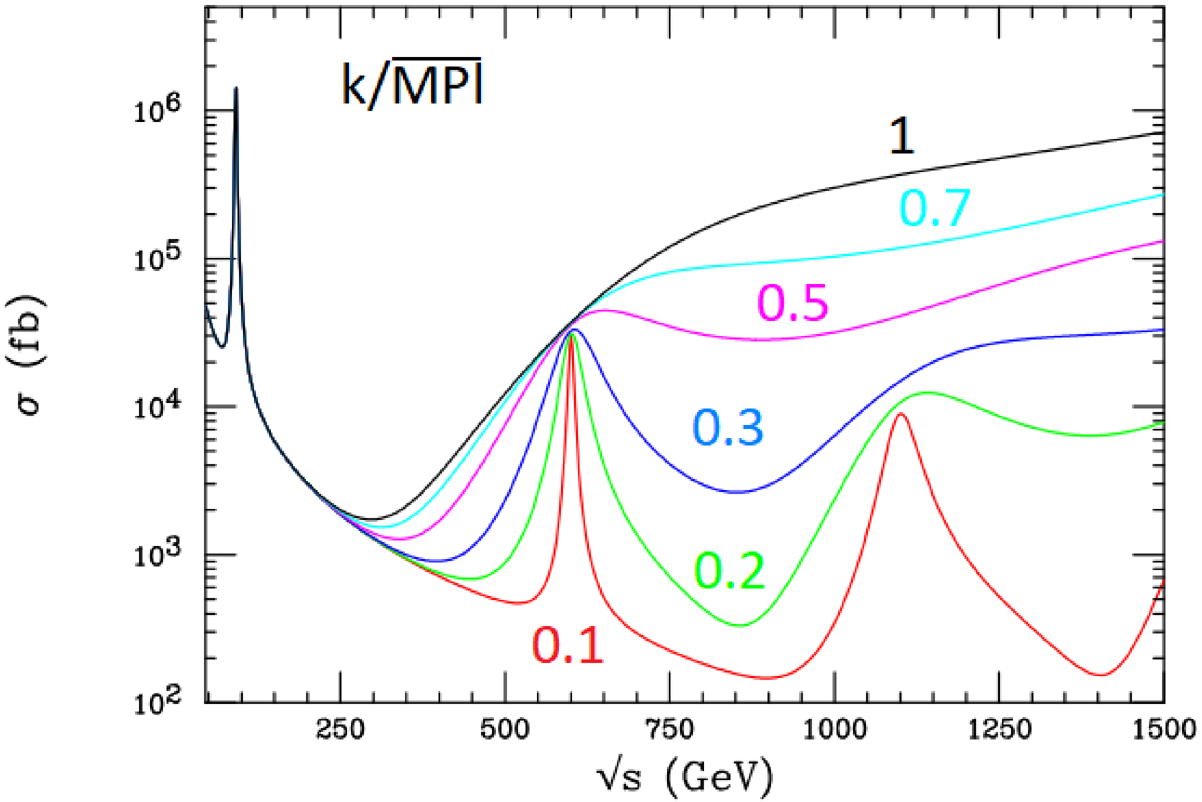
Tensor decay in ZZ

-
- No sign of an excess at ~650 GeV in this subsample
- A tensor resonance, fwd peaked, removed by this selection ?

Bulk KK graviton ?

- [2310.01643](2310.01643) [*9909255*](9909255) e+e- -> $\mathcal{G}_{KK}$(600) -> μ+μ- versus k/Mplanck
- (just for illustration since e+e- is unlikely to couple to $\mathcal{G}_{KK}$)





b->sγ constraint on mH+

- Light H+ excluded for 2HDM II, not for 2HDM I with tanβ>2 1702.04571

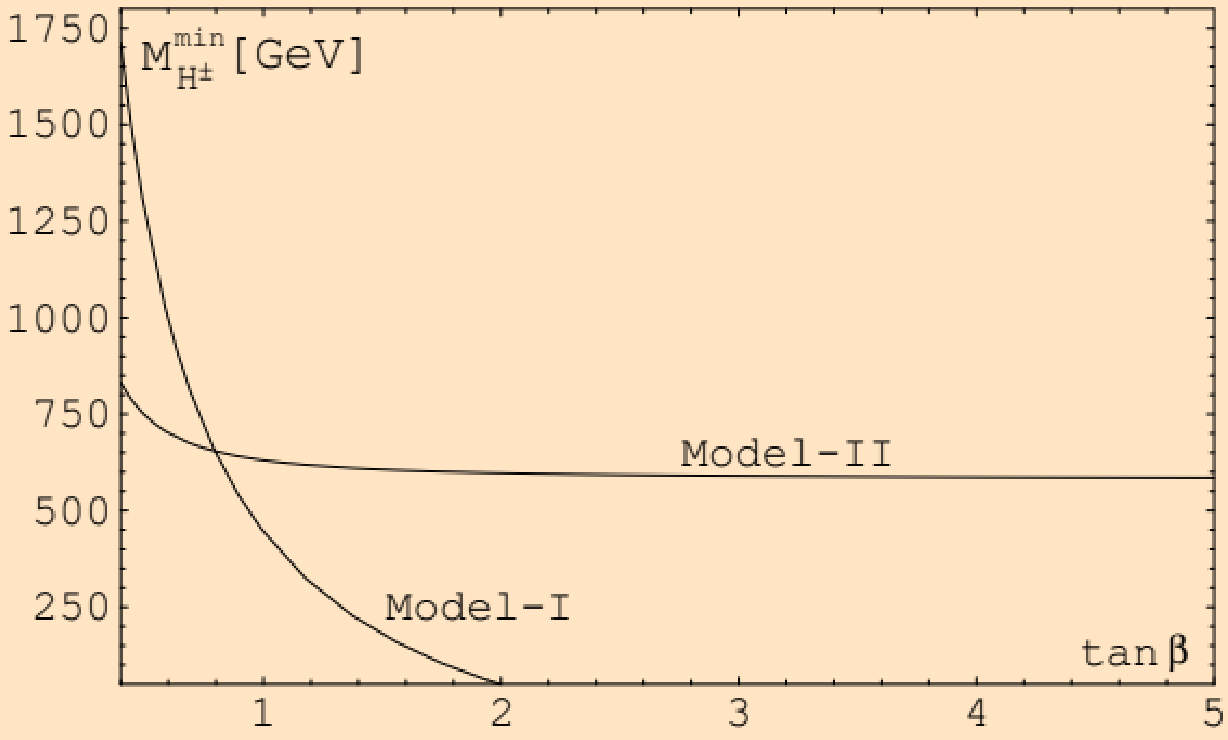


Figure 4: 95% C.L. lower bounds on $M_{H^\pm}$ as functions of $\tan\beta$.

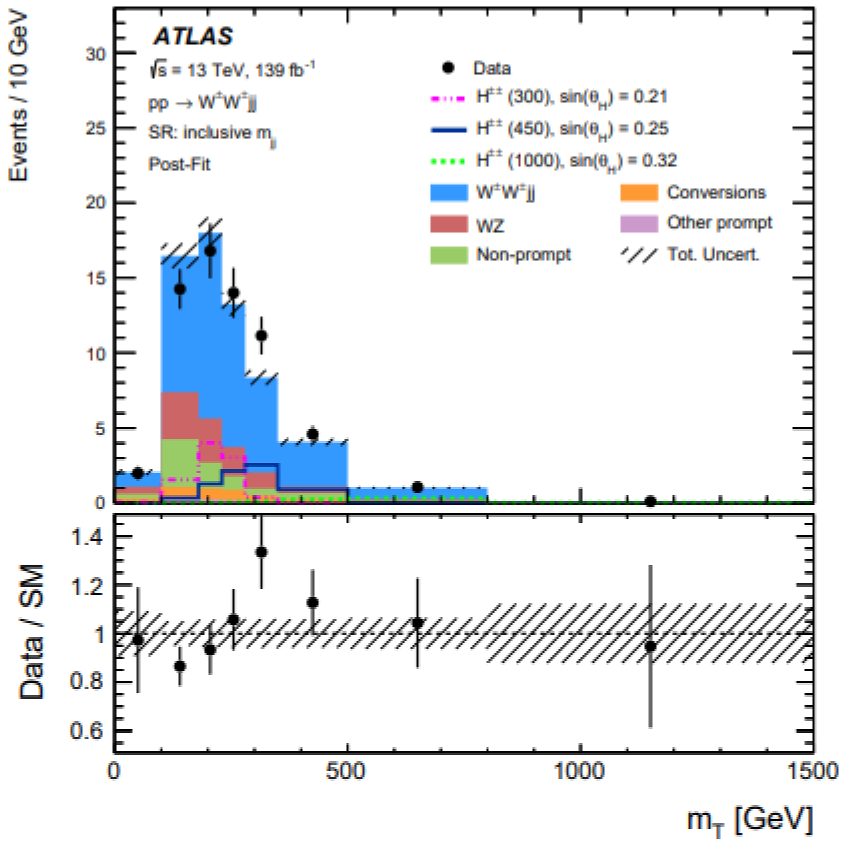
How to derive the missing couplings ?

- There are indications for several neutral scalars candidates on the market, with unknown couplings to WW/ZZ
- Can one derive them taking into account the present measurements ?
- The answer seems positive assuming there is no CP violation and using available measurements

Process	Channels	References	# s.d. glob. (local)	Michelin
H650	WW/ZZ ggF/VBF h95h125	1806.04429 2009.14791 2103.01918 CMS PAS HIG-20-016 2310.01643	6.1	**
A420	tt ZH320->Zh125h125	1908.01115 2210.05415	5	*
h95	$\gamma\gamma$ $\tau\tau$ bb (LEP)	0306033 1811.08159 1803.06553 CMS-PAS-HIG-20-002 ATLAS-CONF-2023-035	3.9	~*
h151	$\gamma\gamma$ +ETmiss	2109.02650	4.8	?
H+375	ZW	ATLAS-CONF-2022-005 2104.04762	(3.5)	
H++450	W+W+	ATLAS-CONF-2023-023 2104.04762	(3.9)	
H+160	bc	*EPS-HEP2021, 631*	(3)	
h146	μe	CMS-PAS-HIG-22-002	(3.8)	

W+W- with b jet veto > 50 times larger W+W+ due to tt background

2312.00420



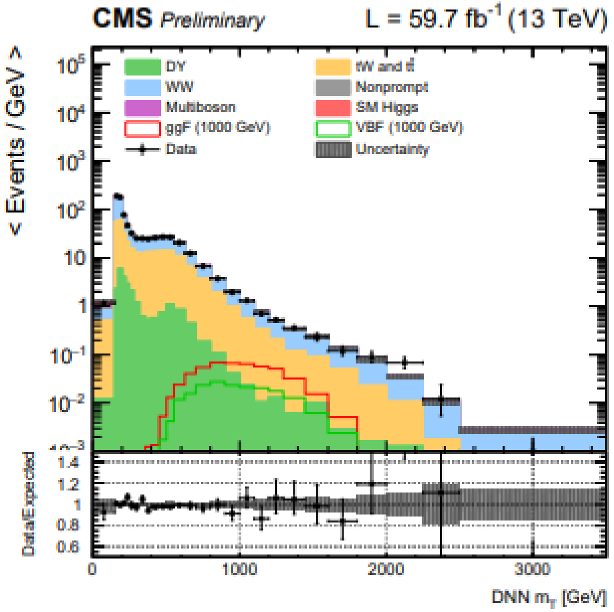
VBF W+W+

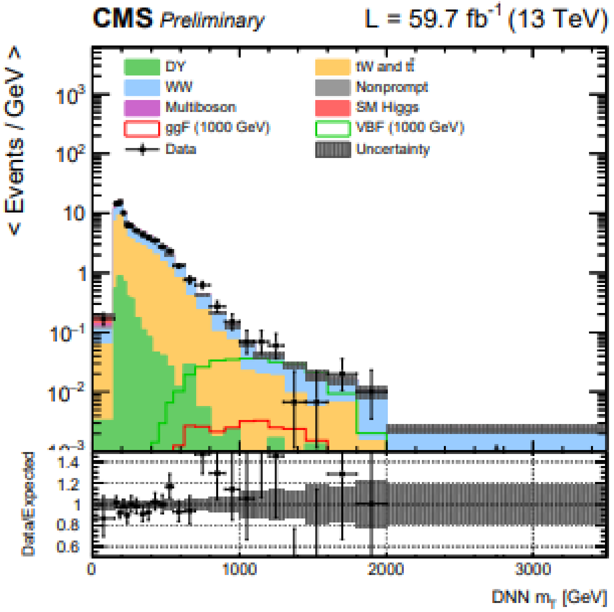
μe

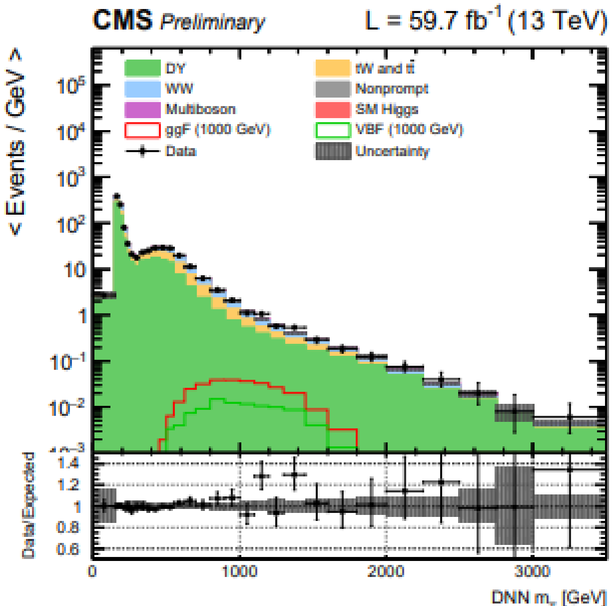
μ+μ-

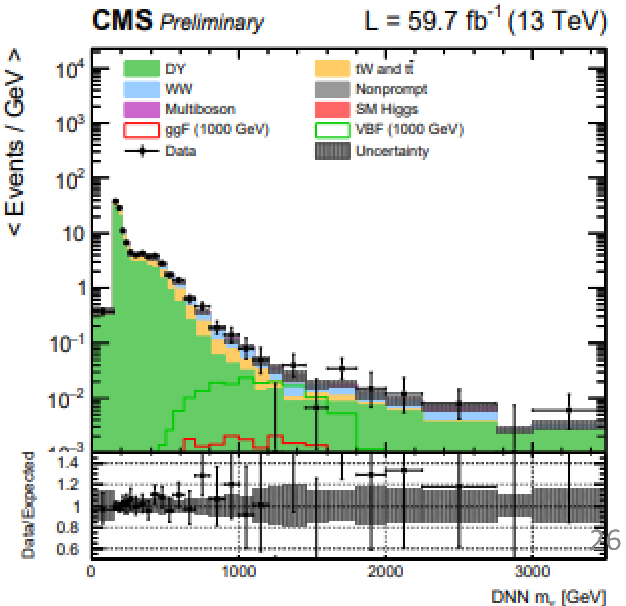
ggF W+W-

VBF W+W-







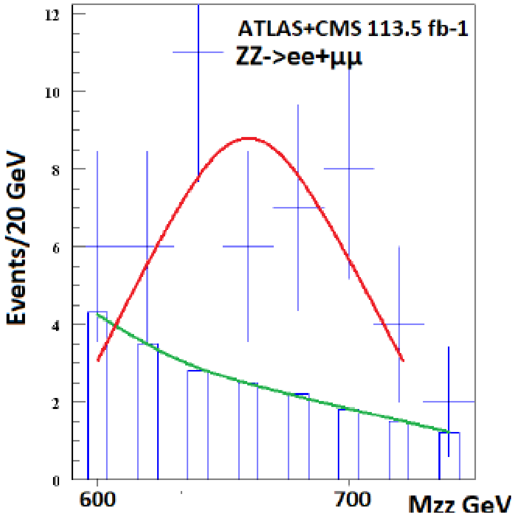


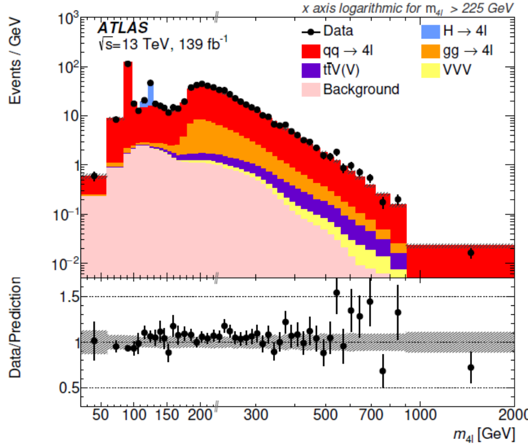
Scalars for sum rules

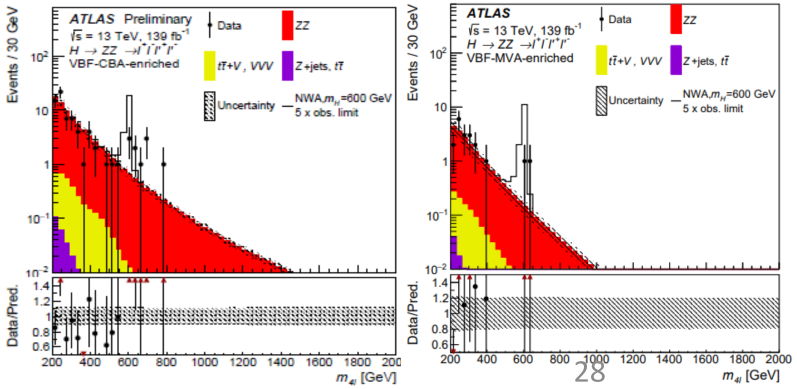
Scalar	Channels	References	# s.d. glob.
H650	WW/ZZ ggFVBF h95h125	1806.04529 2009.14791 2103.01918 CMS-PAS-HIG-20-016 CMS-PAS-HIG-21-011	6.1
h95	$\gamma\gamma$ $\tau\tau$ bb (LEP2)	0306033 1811.08159 1803.06553 CMS-PAS-HIG-20-002 ATLAS-CONF-2023-035	3.9
H++450	W+W+	ATLAS-CONF-2023-023 2104.04762	2.6
H+375	ZW	2207.03925 2104.04762	2.7
H++ & H+			4.3

1^{st} indication : H->ZZ into 4 leptons

- The **cleanest channel** for discoveries
- From a combination of published histograms [1806.04529](1806.04529) with 113.5 fb^{-1} from **CMS (2/3) and ATLAS (1/3)** one observes a peak with M_H~660 GeV Γ_H~100 GeV, σ~90±25 fb with s/b=46/20 ~3.8 s.d. local significance (5.8 Bayesian), 2.8 s.d. global
- With 139 fb-1, with **sequential cuts**, an excess is observed at the same mass, s/b=9/2 ~2.1 s.d., for VBFBR(ZZ)->H(660)->ZZ ~34±20 fb (~2 times smaller with a **MVA analysis**) [2009.14791](2009.14791) and 3 sd 150±60 fb for ggFBR(ZZ)
- The MVA analysis gives ggFBR(ZZ)<50 fb MVA + **ℓ+ℓ-νν**
- CMS analyses into four leptons are not yet published
- These results call for a combination of both analyses before one can draw a valid conclusion
- Could stop here but…

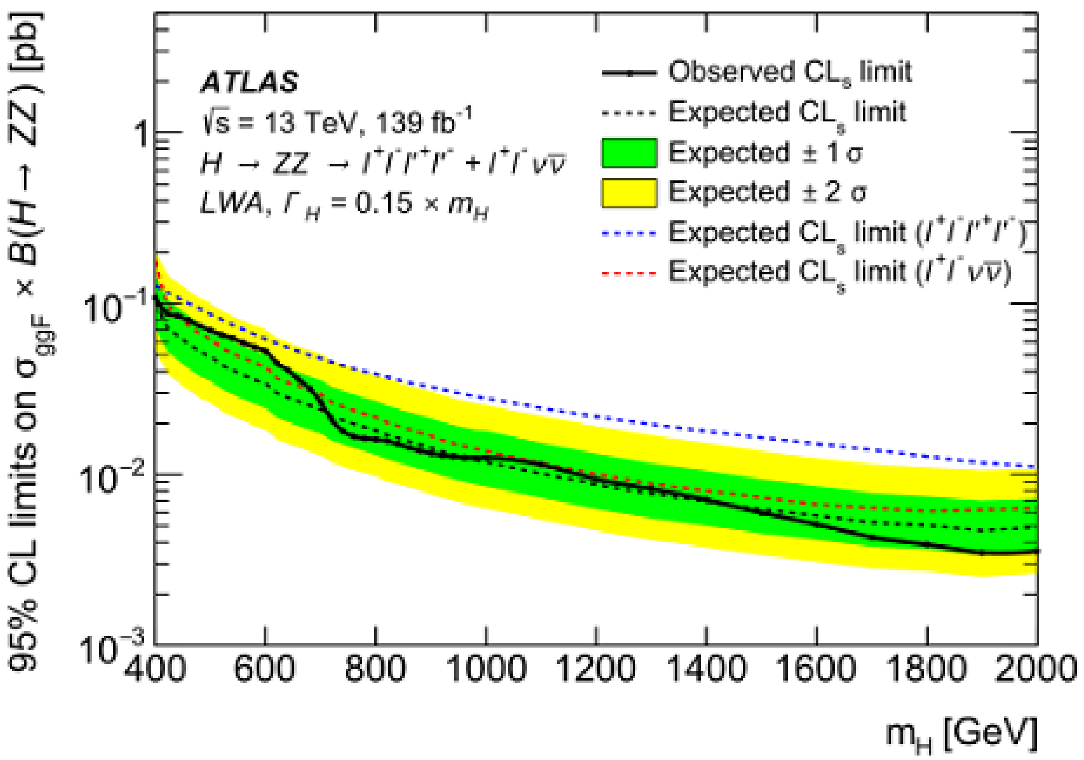






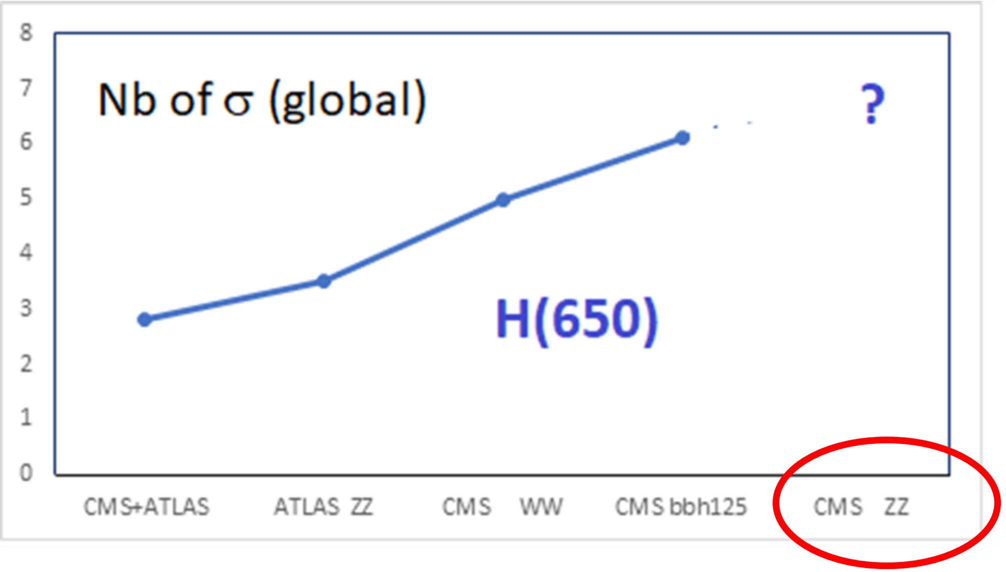
CAVEAT on H(650)->ZZ

- CBA with 4 leptons indicates an excess ~3.5s d combining ggF and VBF
- This translates (guesswork) into ggF(BR(ZZ)~150+-60 fb
- Adding **ℓ+ℓ-νν** one sets an upper limit ggF(BR(ZZ)<50fb assuming a 100 GeV width
- In "tension" with above result



Historical progress of H(650)

Steps	Mode	Origin	Local sd	Remark	Global sd
0	ZZ->4ℓ	ATLAS+CMS from [7]	3.8	ATLAS+CMS 113.5 fb-1 Defines mass & width	2.8
1	ZZ->4ℓ	From ATLAS	3.5	From histogram	3.5
2	WW->ℓνℓν	From CMS	3.8	Official statement	5
3	h(95)h(125)->bbγγ	From CMS	3.8	Official statement	6.1



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

ggF has a large top background even after b-jet vetoing and using **μe** (against DY)

Wide signal with ±50% mass resolution

VBF->H(650)->$\ell\ell\nu\nu$ allows to see a signal

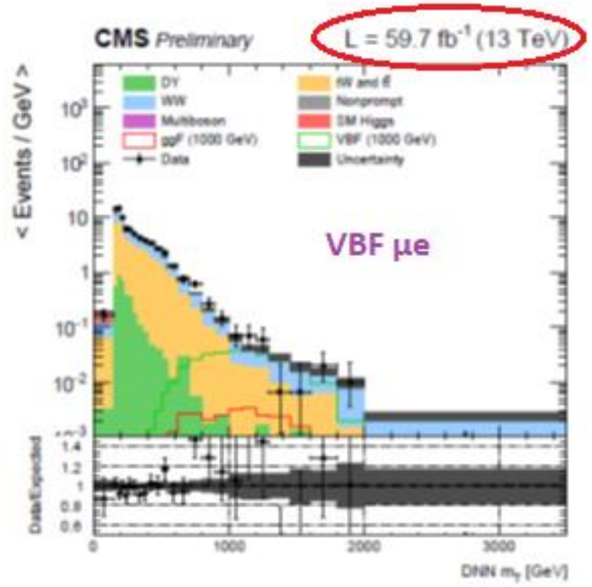
This **VBF** cross section ~**160±50 fb**, close to SM, is ~3 times larger than VBF->ZZ, inconsistent with **GM** which predicts for the scalar **H5 WW/ZZ=0.5**

2 HD excluded (bue line) h(125)WW predicts **sin²(α–β)~0.97±0.09** meaning that **H(650)WW~cos²(α–β)~(0.03± 0.09)SM**

Both GM and 2HD excluded !

An attempt from ATLAS does not reach the same sensitivity (only μe) ATLAS-CONF-2022-066

μe



CMS PAS HIG-20-016

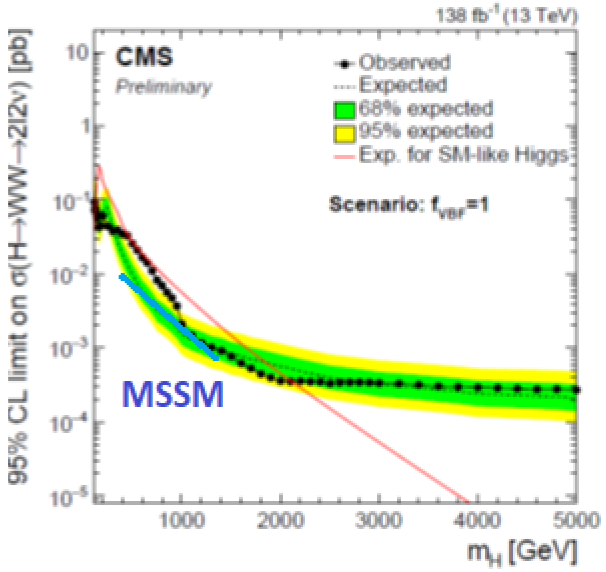
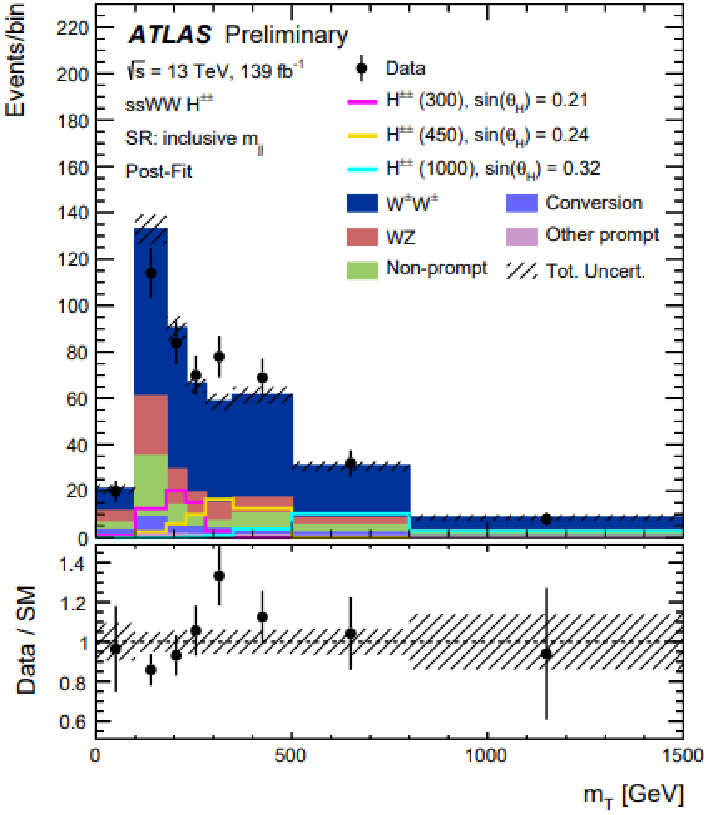


Table 3: Summary of the signal hypotheses with highest local significance for each f_{VBF} scenario. For each signal hypothesis the resonance mass, production cross sections, and the local and global significances are given.

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

W+W- with b jet veto > 50 times larger than W+W+ due to tt and DY backgrounds



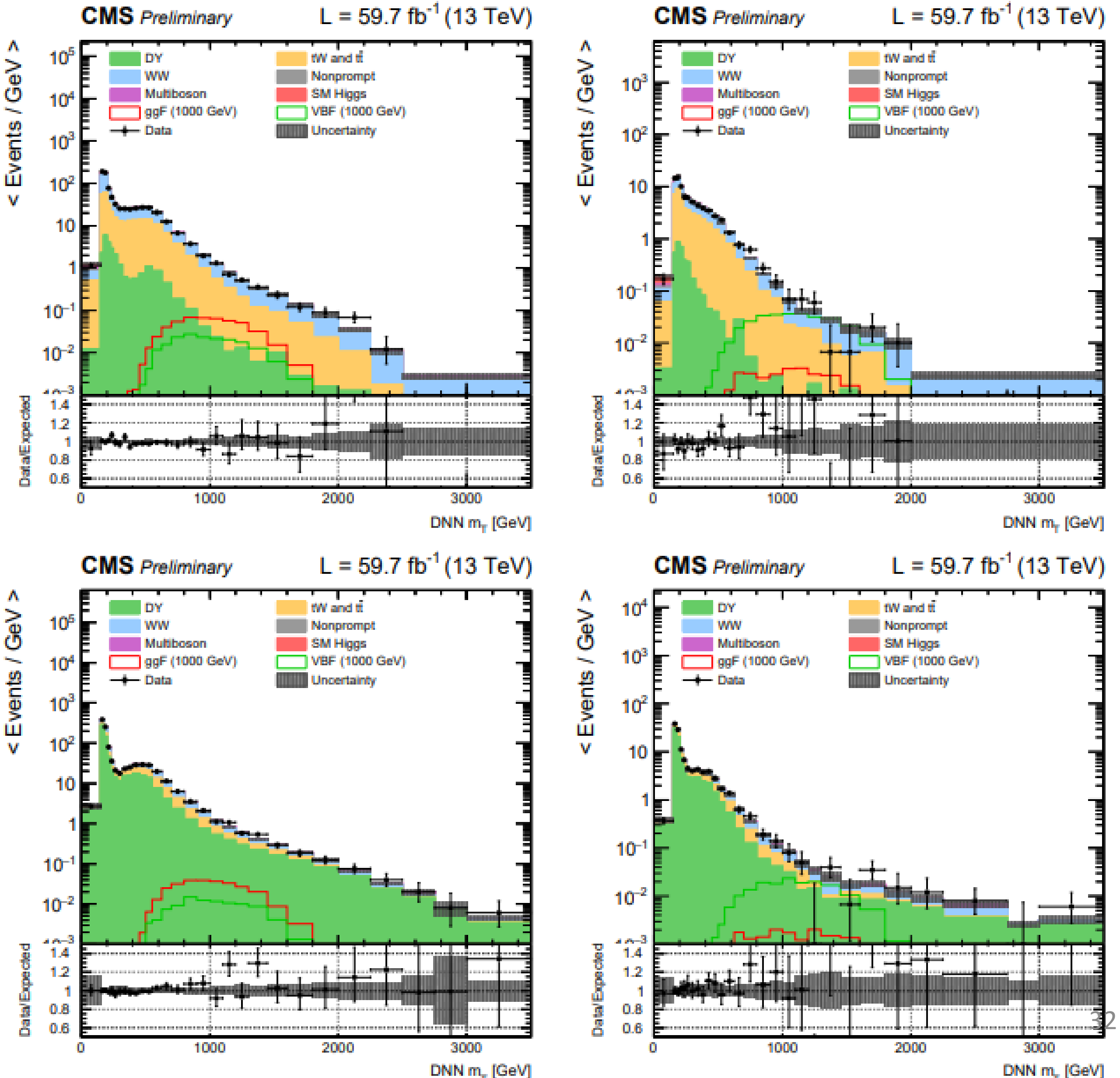
W+W+ much easier

ggF->W+W-

VBF W+W-

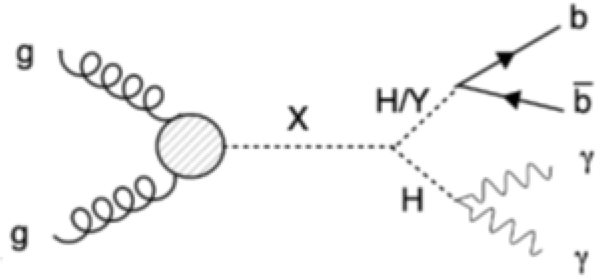
μ+e-

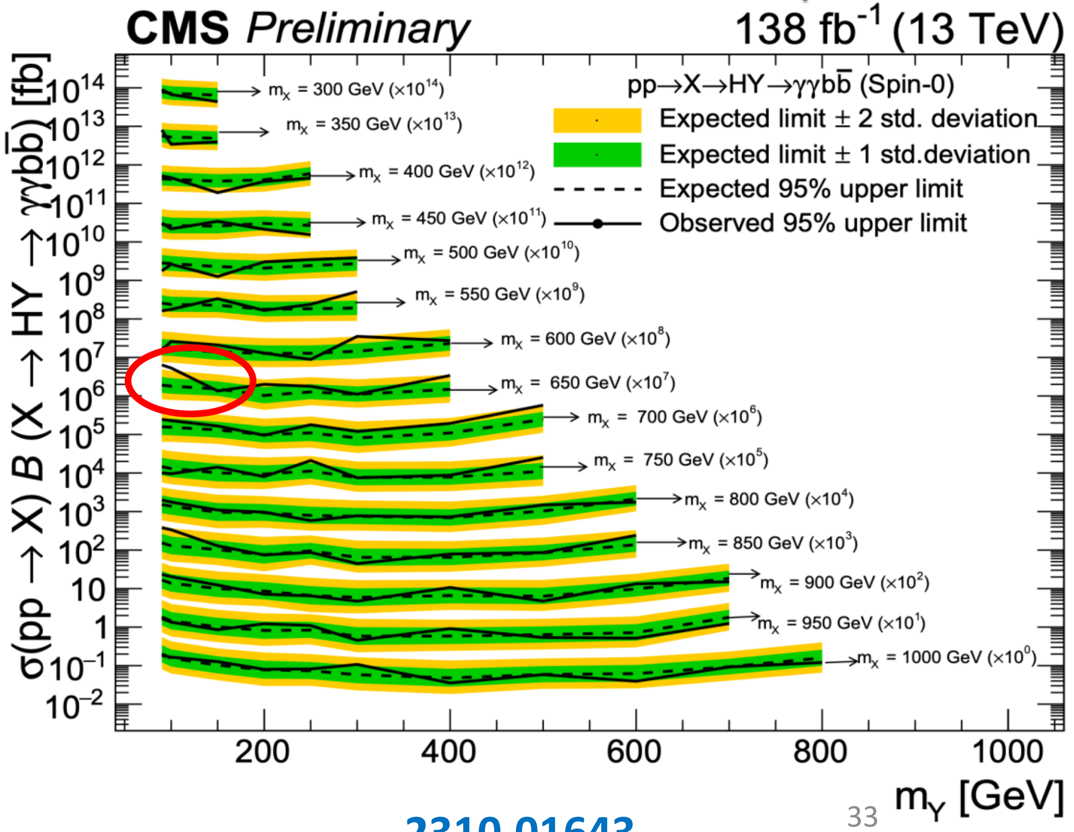
μ+μ-



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 scalar candidate seen in 3 channels [2203.13180](2203.13180) +[2302.07276](2302.07276)
- The cross section is dominant over all other indications **~190+90-70 fb** but it includes ggF+VBF
- Also interpreted by CMS as a **tensor particle**

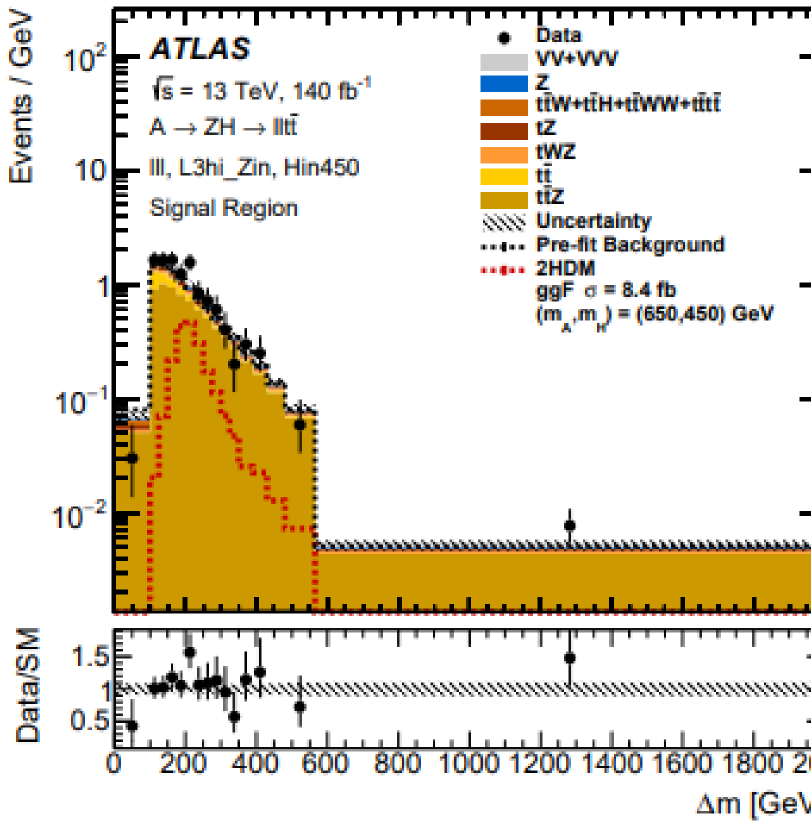




[2310.01643](2310.01643)

Evidence for H(650)->A(450)Z

- ATLAS sees a 2.85 s.d. excess in ttZ in A(650)->H(450)Z->ttℓ+ℓ- [2311.04033]
- Also compatible with **H(650)->A(450)Z->ttℓ+ℓ-**
- Reinforces the case for H(650)
- The CP=-1 candidate A(420)->tt 1908.01115 is compatible given the poor mass resolution
- A third observation was in A(420)->H(320)Z->hhZ [ATLAS-CONF-2022-043]
- In this context, there is no need to invoke the LE criterion which would justify the word 'insignificant' for this new indication easily accommodated within GM



Δm=m(ttℓ+ℓ-)-m(tt)

Scalars for sum rules

Scalar	Channels	References	# s.d. glob.
H650	WW/ZZ ggFVBF h95h125	1806.04529 2009.14791 2103.01918 CMS-PAS-HIG-20-016 CMS-PAS-HIG-21-011	6.1
h95	$\gamma\gamma$ $\tau\tau$ bb (LEP2)	0306033 1811.08159 1803.06553 CMS-PAS-HIG-20-002 ATLAS-CONF-2023-035	3.9
H++450	W+W+	ATLAS-CONF-2023-023 2104.04762	2.6
H+375	ZW	2207.03925 2104.04762	2.7
H++ & H+			4.3

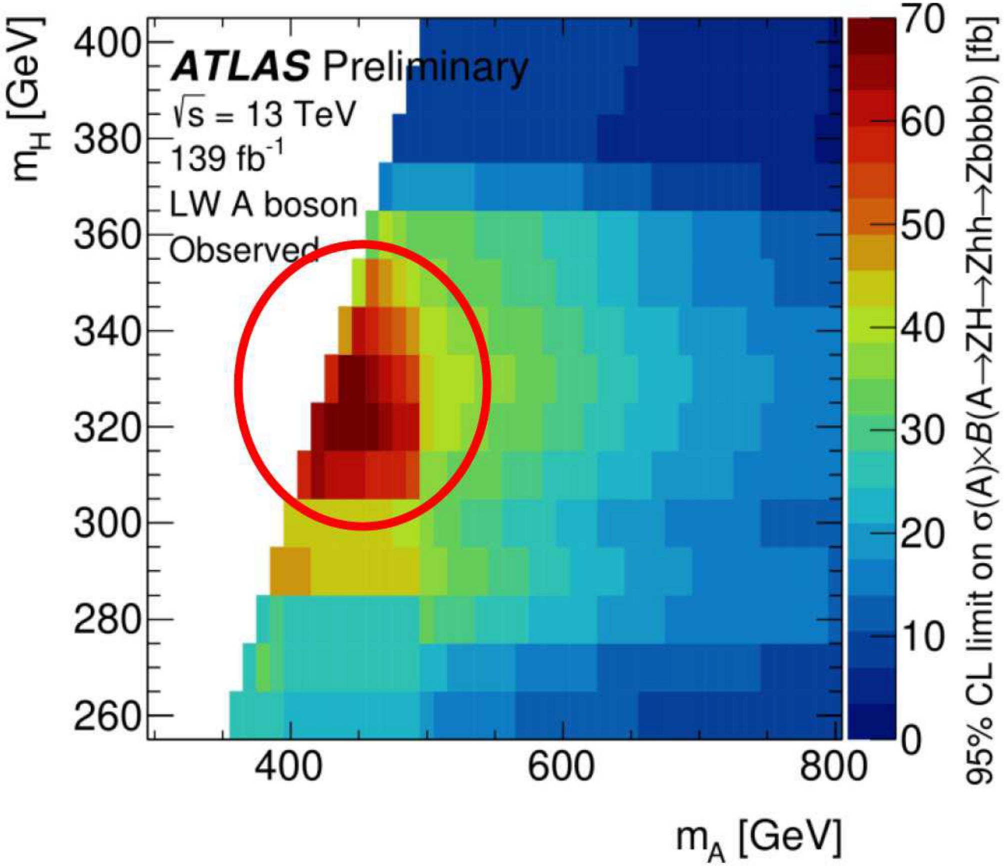
LHC inputs for our work

- We choose to select * combined searches with > **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-
- ATLAS claims 1.7 s.d. on h95->2γ
- Recent progress for H++ from ATLAS

Scalar	Channels	References	# s.d. glob.	Michelin
H(125)	WW/ZZ ggF/VBF γγ ττ bb		>6.9	***
H(650)	WW/ZZ ggF/VBF h95h125 H(650)->A(450)Z	2009.14791 2103.01918 CMS-PAS-HIG-20-016 CMS-PAS-HIG-21-011 2311.04033	6.1	**
A(420)	tt ZH320->Zh125h125 H(650)->A(450)Z	1908.01115 2210.05415 2311.04033	5	*
h(95)	γγ ττ bb (LEP)	0306033 1811.08159 1803.06553 CMS-PAS-HIG-20-002	4.3	*
h(151)	γγ +ETmiss	2109.02650	4.8	?
H++450	W+W+	ATLAS-CONF-2023-023 2104.04762	3.9	
H+375	ZW	2205.03925 2104.04762	3.5	
h146	μe	CMS-PAS-HIG-22-002	2.8 (3.8)	

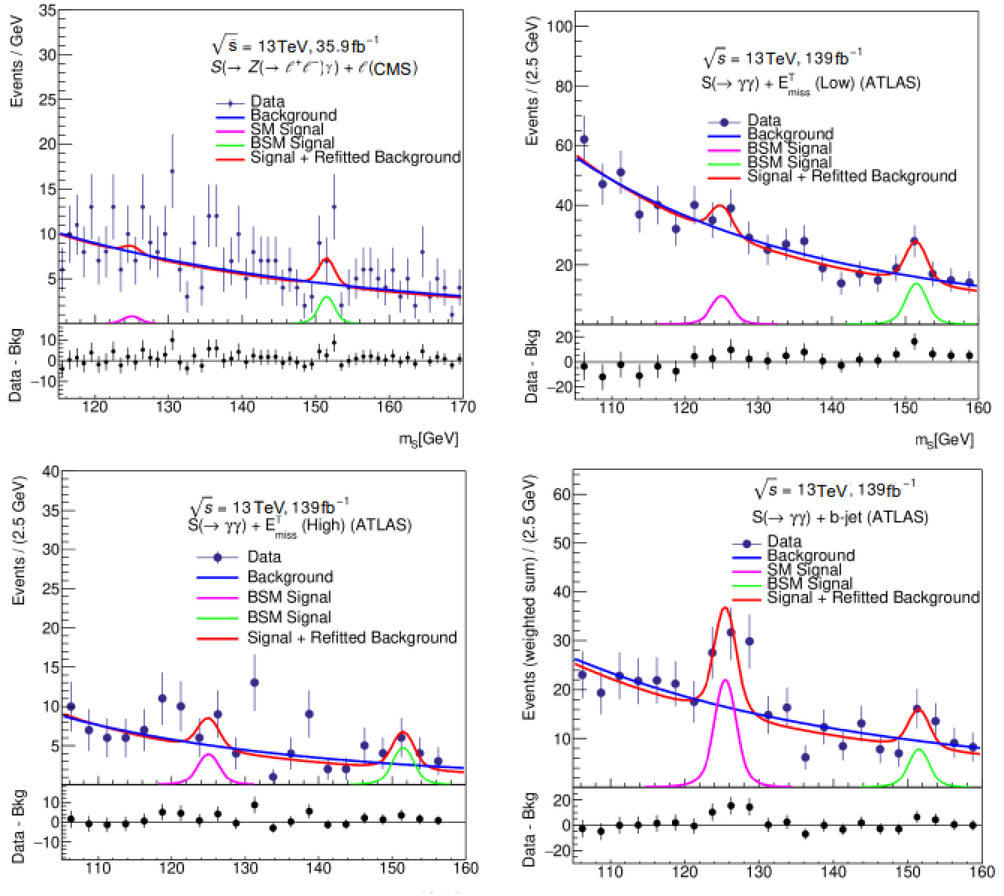
Evidence for H(320) and A(420)

- ATLAS has observed **A(420)->ZH(320)** with H(320)->h(125)h(125)->bbbb
- The bb mass resolution is too poor to exclude contributions from h(95) or A(130)
- The significance is 3.8 s.d. local ***2210.05415***
- This decay sits close to the kinematical limit meani that H(320) could be heavier and complete the GM **H5 multiplet**, together with H+(375), H++(450)
- Recall that H(320)->hh is forbidden only if h is a pu singlet and H pure triplet, which is not the case
- Note finally that this indication constitutes the **3d evidence** for a CP odd A, together with A->tt and H(650)->AZ

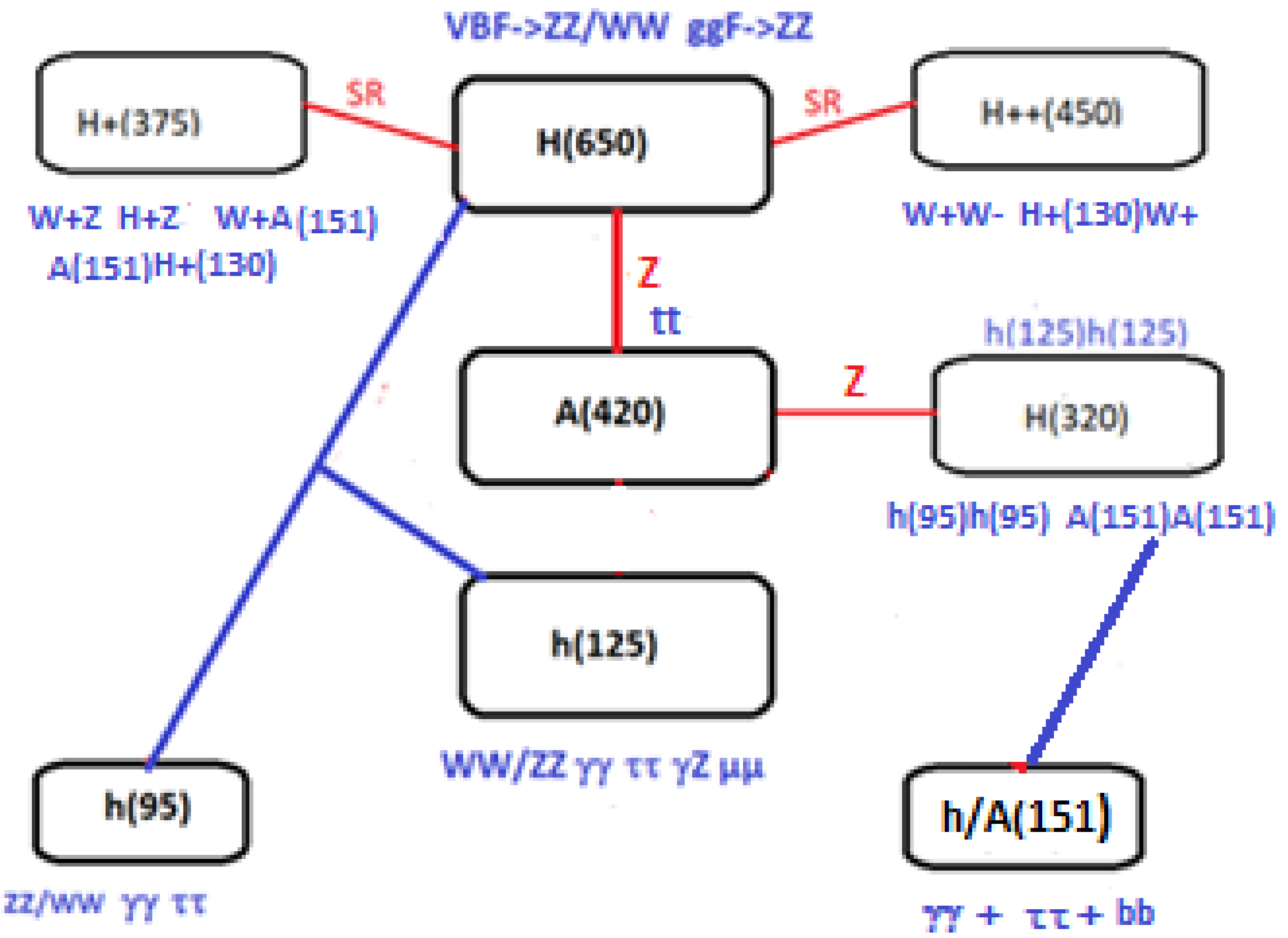


Evidence for h/A(151)->γγ+ **tag**

- A second γγ+Zγ peak appears when requiring extra tag Etmiss or b jet
- 2109.02650 claims ~4 sd by combining ATLAS and CMS data
- GM predicts that ggF->H(320) has a cross cross section of 2000 fb, 2/3 going into A(151)A(151) with **A->bb,** **ττ** providing the tagging ingredient
- One predicts **BR(A(151)->γγ)~1.310-3**



SUMMARY OF BSM CANDIDATES



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** and h' **mixing angle α**

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=vχ ρ=1

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

- Only ϕ
- They form the following physical states, dominantly triplet r
- $s_H=2\sqrt{2}v\chi/v$

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

- 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

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

- Common wisdom: the mixing angle α **has to be small** to avoid altering the doublet properties of the SM h(125)
- Also vξ=vχ are predicted small while SR says that vξ=vχ=70 GeV

SGM: a SUSY version of GM

1308.4025

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

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

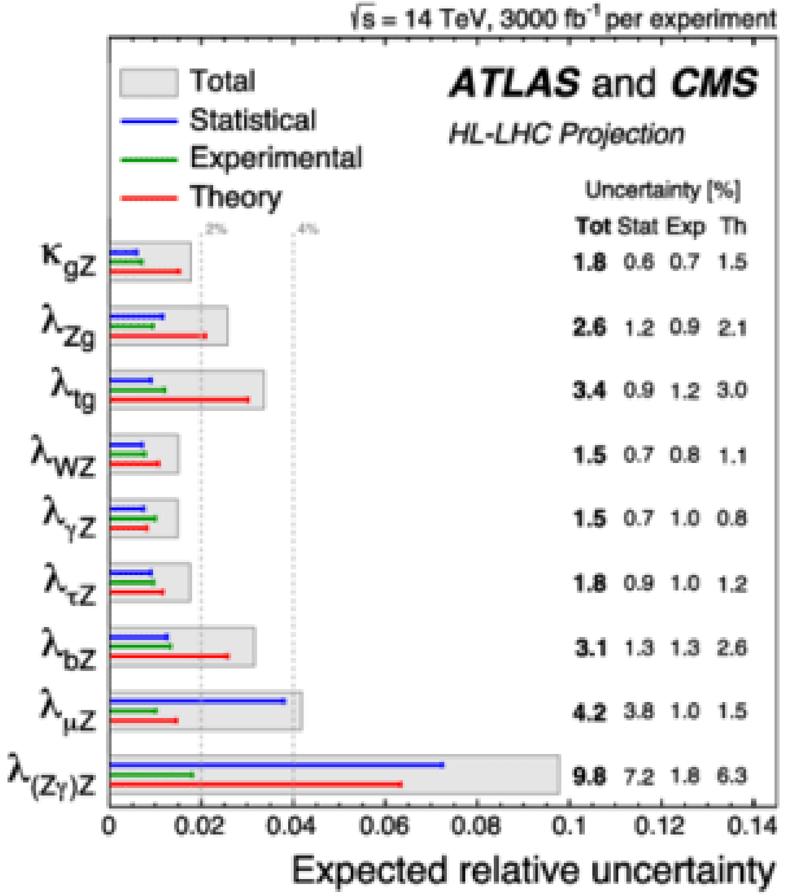
- GM does not necessarily mean compositeness

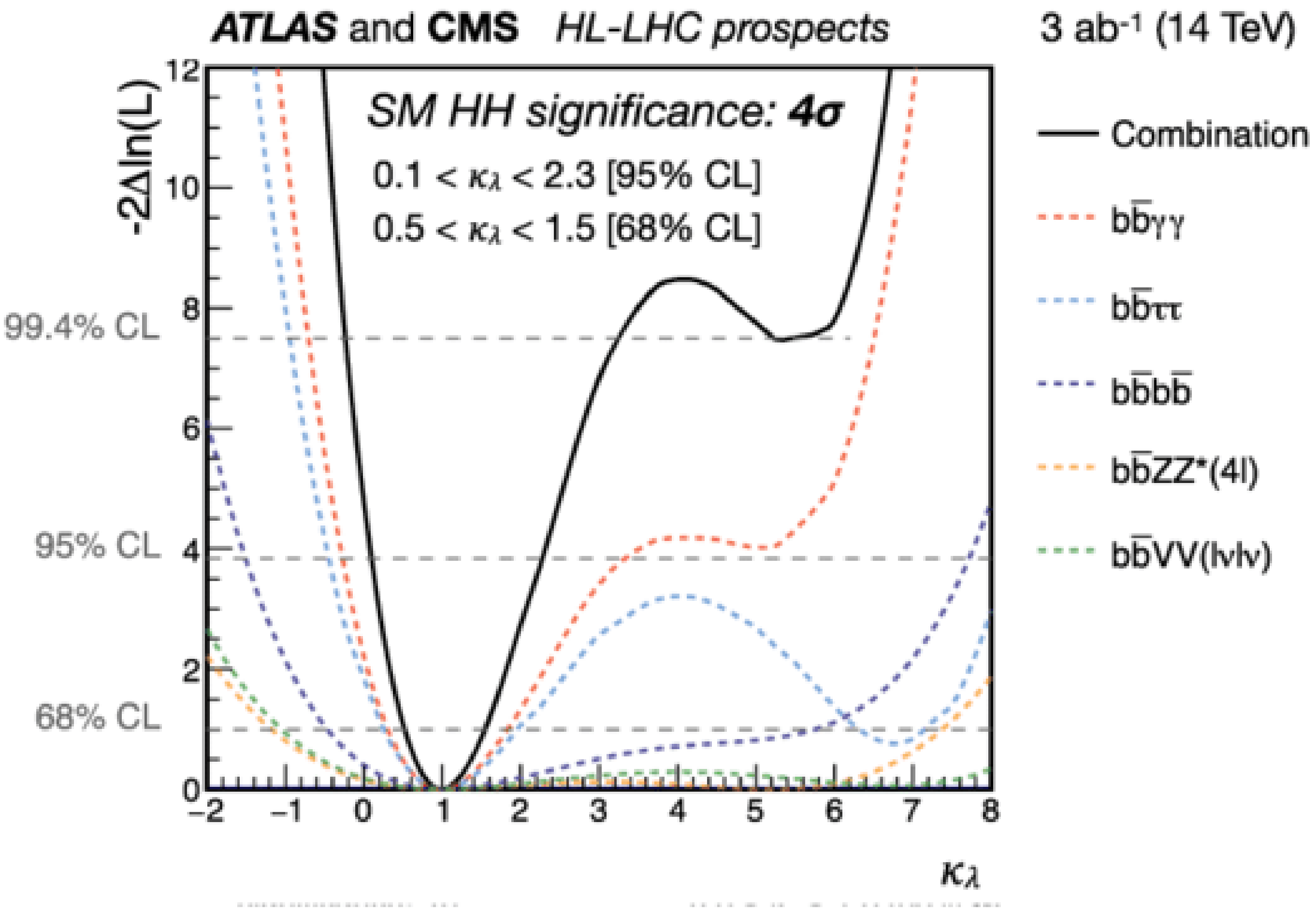
SGM provides all the “goodies” of SUSY:

Perturbativity, computability

- EWSB naturally triggered
- Mh predicted with less “tension” on stop masses with extra contributions to RC
- Two doublets as needed to interpret H320 and the ZZ/WW decays of H(650)
- DM candidate
- Complex/rich world with ~20 Higgs scalars

Expected HL-LHC accuracies





TeV projects

SNOWMASS

D. Schulte
Higgs Hunting 23

+ CEPC-ee 0.24 TeV
SPPC-pp 100 TeV

	CME [TeV]	Lumi per IP [$10^{34}cm^{-2}s^{-1}$]	Years to physics	Cost range [B$]	Power [MW]
FCC-ee	0.24	8.5	13-18	12-18	290
ILC	0.25	2.7	<12	7-12	140
CLIC	0.38	2.3	13-18	7-12	110
ILC	3	6.1	19-24	18-30	400
CLIC	3	5.9	19-24	18-30	550
MC	3	1.8	19-24	7-12	230
MC	10	20	>25	12-18	300
FCC-hh	100	30	>25	30-50	560

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	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	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	$\gamma\epsilon_x$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	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 $5.4 \cdot 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ [26]. *): For operation at the Z-pole additional beam power of 1.94/3.88 MW is necessary for positron production.