Has LHC observed a tensor resonance ?

ECFA WG1-SRCH

Third workshop on e+e- Higgs/Electroweak/Top factories

Campus des Cordeliers, Paris

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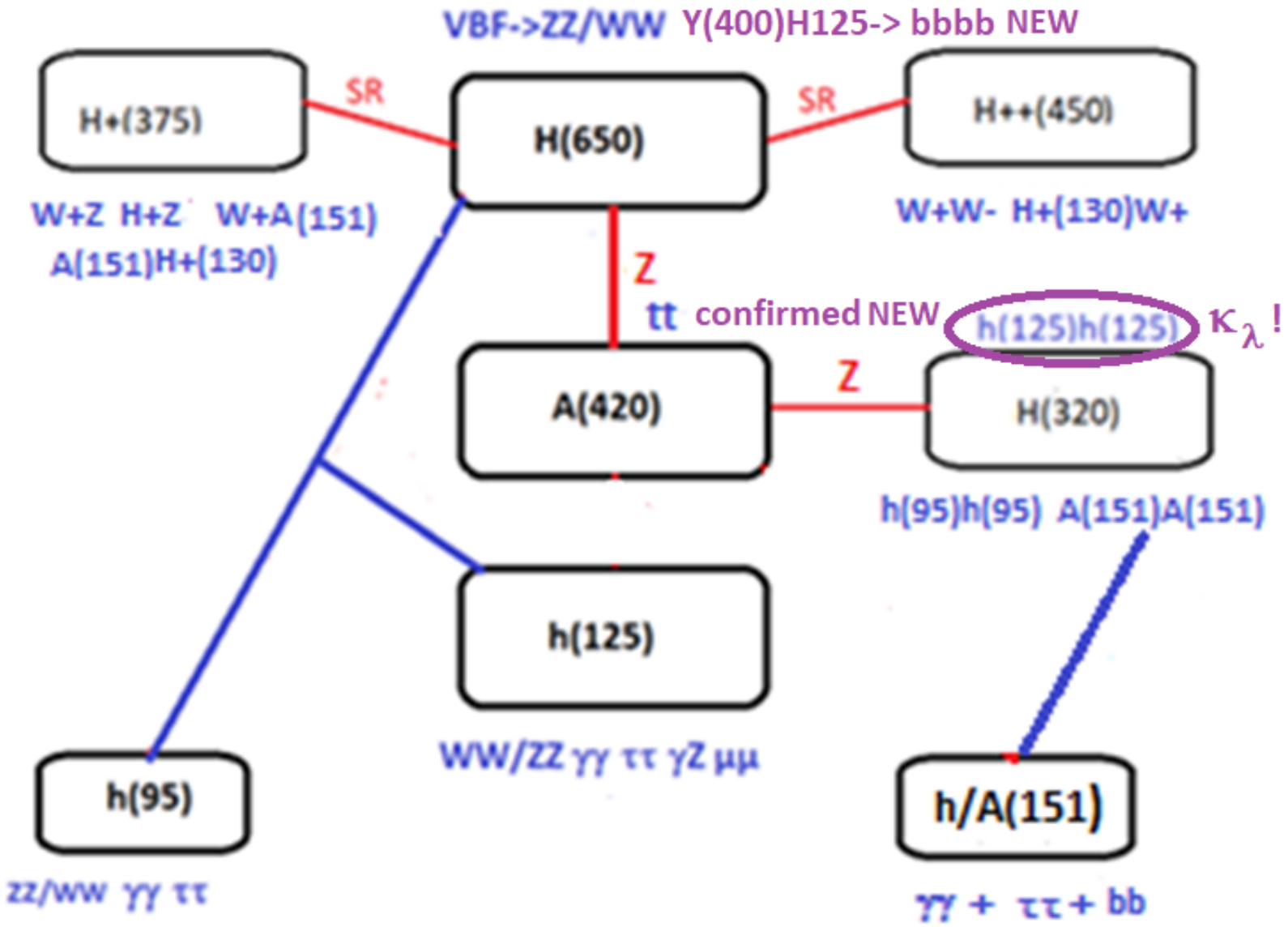
Introduction

- An essential question for choosing among the various options for future colliders is the following: **does LHC show some convincing proof of resonances below a TeV ?**
- Intoxicated by the H125 discovery, we tend to ignore that some of these scalar candidates could well be **tensor candidates** since both types share some final states like ZZ, WW, HH and can only be distinguished through an **angular analys**is, not yet performed in this preliminary phase
- The **strongest candidates X(650)** is now indicated in **five final states** ZZ/WW/bb(95)H125/tt(400)Z/bb(400)H125 New
- Its interpretation seems incompatible with most extensions of the SM: MSSM, NMSSM, TRIPLET models (Georgi Machacek with H++)
- Recently CMS has updated its search of **H(650)->ZZ** New and concluded to an absence of signal for a scalar hypothesis
- We intend to show that this result and the incompatibility of X(650) with available models can be interpreted as an evidence that this particle is a **tensor**

SUMMARY OF BSM SCALAR CANDIDATES

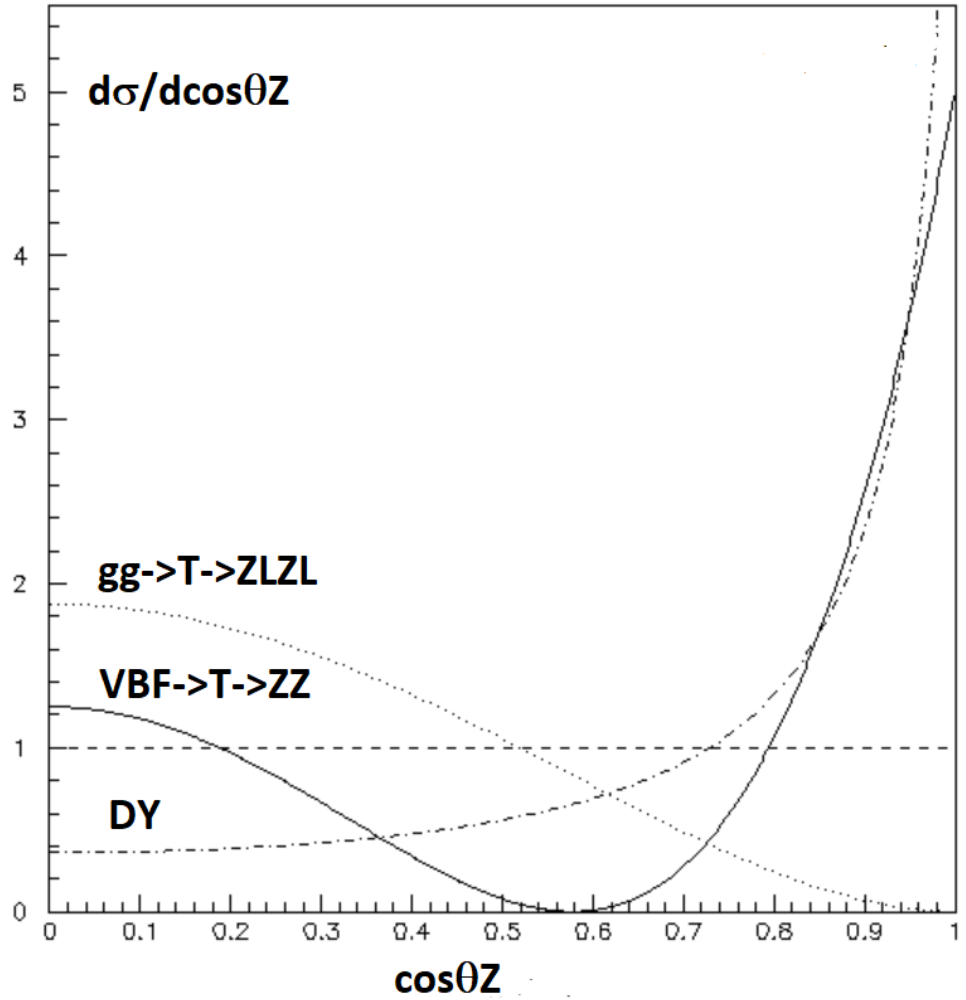


References

[1]X650->ZZ/WW/H125H95/A450Z -- scalar, tensor or both ?
Alain Le Yaouanc(IJCLab, Orsay), (IJCLab, Orsay), François Richard(IJCLab, Orsay(Aug 22, 2024
Contribution to: 3rd ECFA workshop on e+e- Higgs, Electroweak and Top Factories
e-Print: 2408.12178
[2]Triple Higgs coupling
Alain Le Yaouanc(IJCLab, Orsay), (IJCLab, Orsay), François Richard(IJCLab, Orsay)(Apr 15, 2024)
Contribution to LCWS24
e-Print: 2404.09827
[3]As a consequence of H(650)->W+W-/ZZ, one predicts H++->W+W+ and H+->ZW+, as indicated by LHC data
Alain Le Yaouanc(IJCLab, Orsay), François Richard(IJCLab, Orsay) (Aug 23, 2023)
Contribution to: 2nd ECFA Workshop on e+e- Higgs/EW/Top Factories
e-Print: 2308.12180
[4] 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

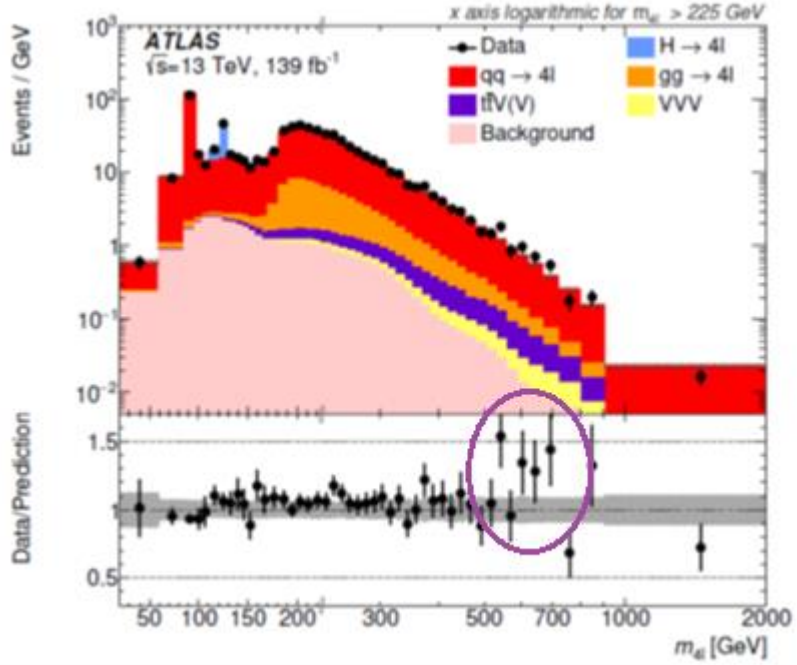
Expectations for T(650)->ZZ

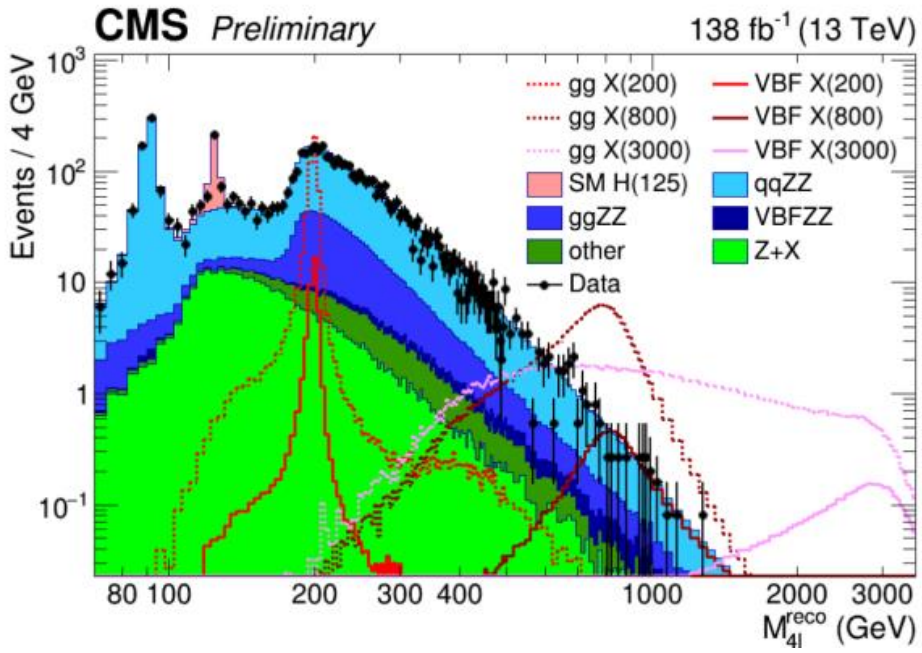
- Final states WW/ZZ/HH are in agreement with observation
- The expected ratio WW/ZZ=2 is compatible with observation (0.5 for GM)
- If VBF->T(650)->ZZ is the dominant mechanism, as suggested by the WW channel, its angular distribution is **almost indistinguishable from the Drell Yan background** and could be missed by applying an angular selection valid for scalar decays
- In the $\ell+\ell-\nu\nu$ analysis ATLAS selects **ETMiss>150 Ge**V which is also incompatible with a tensor distribution



ggF+VBF->ZZ

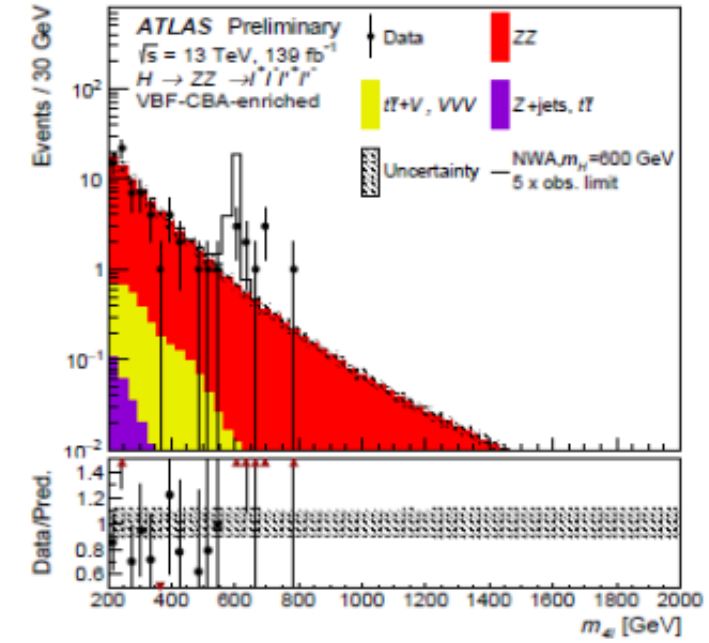
- In a **cut based analysis**, the presence of this resonance is indicated for ggF+VBF but absent in an **MVA** analysis which assumes that X(650) is a **scalar resonance**
  2009.14791
- CMS has also produced an analysis assuming a **scalar resonance**
  CMS-PAS-HIG-24-002
- This **absence of signal in CMS was anticipated from ATLAS** results as due to the selection assuming that X(650) is a scalar to reject the DY background

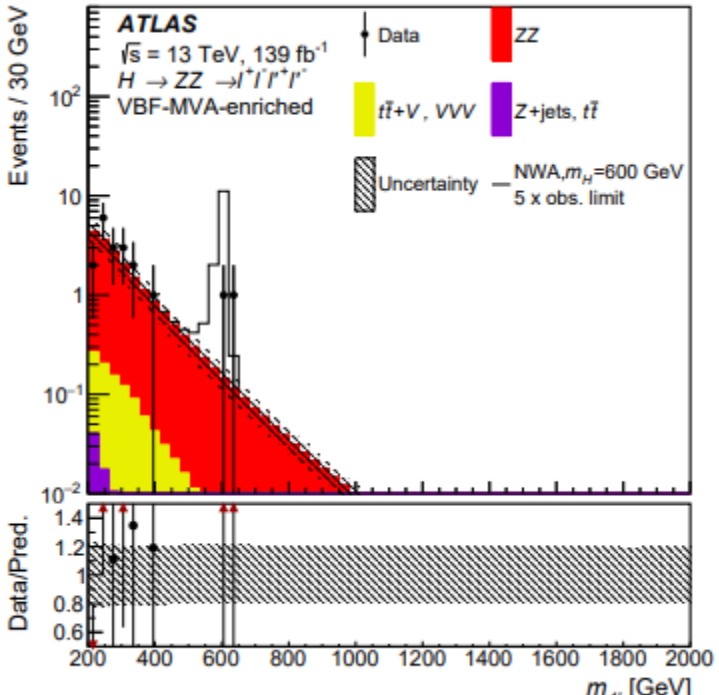




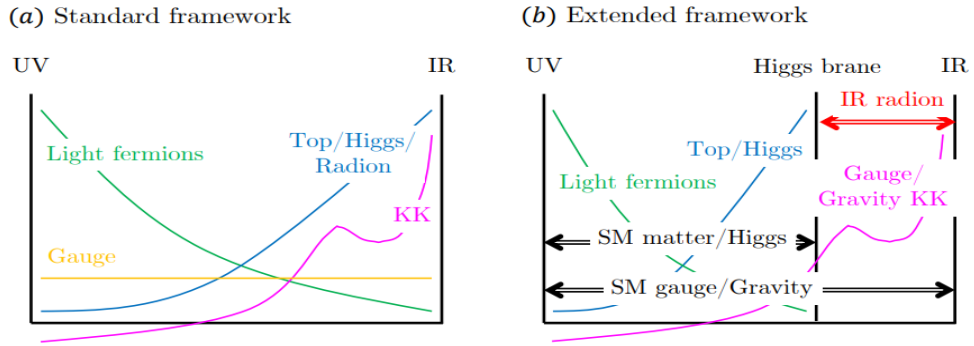
VBF->ZZ

- The ATLAS **cut based analysis** again shows indications around 650 GeV
- The ATLAS MVA analysis *2103.01918* tuned for a scalar reduces this indication while one predicts almost no reduction for a scalar
- This behaviour is simply interpreted assuming that X(650) is a tensor
- If, for instance, one selects against DY $|\cos\theta|<0.8$, one keeps 80 % for a scalar, but only 40 % for a tensor





Possible origin of T(650)



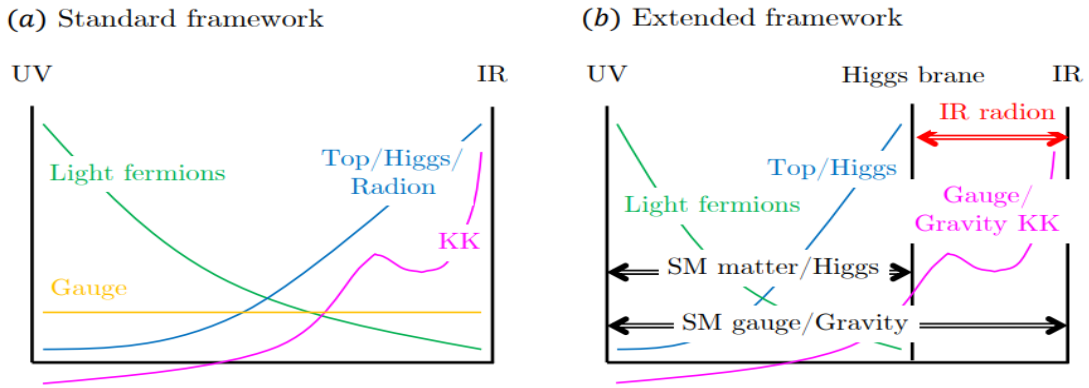
- The familiar **Randall Sundrum** model provides a mechanism to understand the coexistence of the two vastly different scales occurring in our field : the **electroweak scale** and the **Planck scale** by adding an 'warped' extra dimension of size R where on has Mweak=exp(-πkR)MPL with k~MPL and kR of order 11.
- With an extra dimension one expects that ordinary light particles will have Kaluza Klein type excited heavy states with masses of order 1 TeV which can be observed at LHC
- There should be **tensor particles associated to the graviton Gkk**
- T(650) could be one of them
- There are many versions of this model…

Is T(650) the only tensor candidate ?

- The anwser is uncertain and one should re-analyse the various scalar candidates
- For instance, one could speculate that T++(450)→W+W+, T+(375)→ZW+ and T(320)→bbbb->H(125)H(125) belong to a **tensorial isofiveplet**
- This could be proven by sorting out angular distributions
- H++ or T++ are a **model independent prediction** of the Gunion, Haber, Wudka sum rule which is required to satisfy unitarity in the **W+W-→W+W-** process

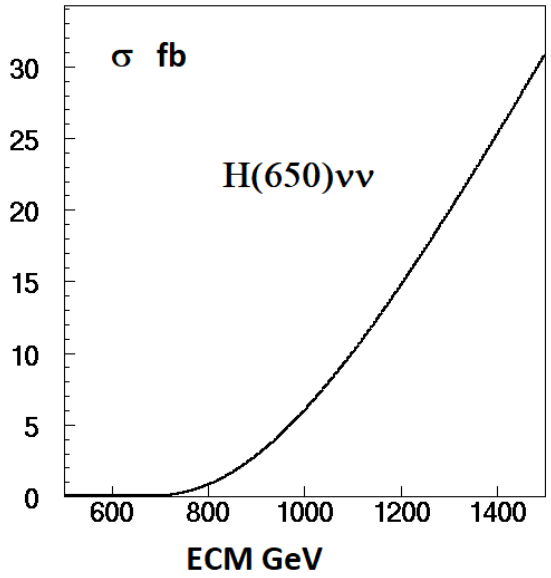
$$g^2(4m_W^2 - 3m_Z^2 c_W^2) \overset{\rho\simeq 1}{\simeq} g^2 m_W^2 = \sum_k g^2_{W^+W^-H_k^0} - \sum_l g^2_{W^+W^+H_l^{--}}$$

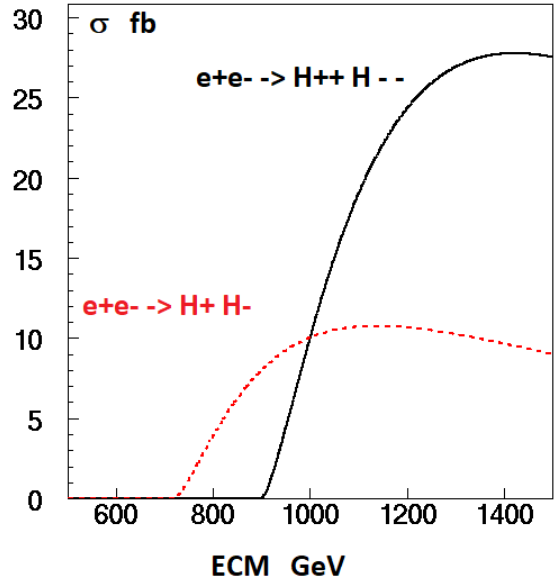
Issues



- KK graviton particles can in principle be produced through **ggF**, either through top loops or through direct coupling, apparently contradicting observations for X(650)->W+W- which conclude that VBF is dominating
- There are however various versions of RS models which might solve this issue as, for instance, when the top quarks are "sequestered" from KK graviton *2008.06480*
- One would also expect that heaky **KK vectors** Zkk/Wkk which, from PM, are expected to be much heavier > 4 TeV
- Consulted experts – K. Agashe and R. Sundrum – do not conclude that these issues kill this interpretation but worry about it

e+e- collider reach





- **ILC** should provide **8000 fb-1 at 1 TeV** needed to reach H++, H(650) and H(320)
- **H(650)** is expected through VBF (beam polarisation allows a factor ~2 gain, not included in above cross sections)
- It can benefit from an increased energy provided by **CLIC**
- Using an **e-e- collider** one could also produce H^{--} through VBF with polarized beams, giving ~100 fb at 1 TeV

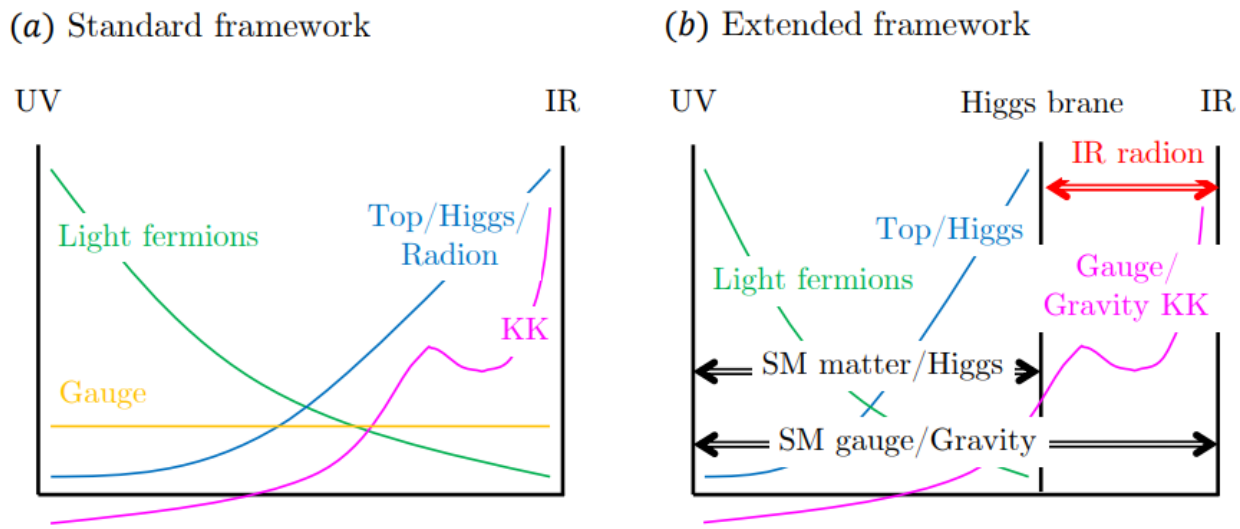
CONCLUSION

- We should not ignore the possibility of tensor candidates in searches for BSM scalar resonances
- To select T(650)->ZZ, it is therefore important to apply a genuine **cut based** method to CMS data, separating VBF from ggF
- The RS scenario seems able to accommodate the tensor T(650) candidate but also implies **Kaluza Klein heavy vectors** which require our attention
- **T(650)** is a fascinating object which can be fully elucidated with an e+e- machine reaching 1 TeV
- This could also be true for the **fiveplet** comprising **T(450)++**
- We await with great hopes a reanalysis of X(650)->ZZ and conclusive results from RUN3, **3.5 sd true signals could then become 5 sd**

Additional slides

Extended RS

- RS models allow a variety of predictions
- In the standard version, the KK graviton overlaps with **Top/Higgs/radions**
- This generates a **large ggF component** through the top loop contribution
- One can modify the locations of top quarks in a "**sequestered**" sector avoiding Gkk->tt coupling
- Gkk->HH can occur through H-radion mixing

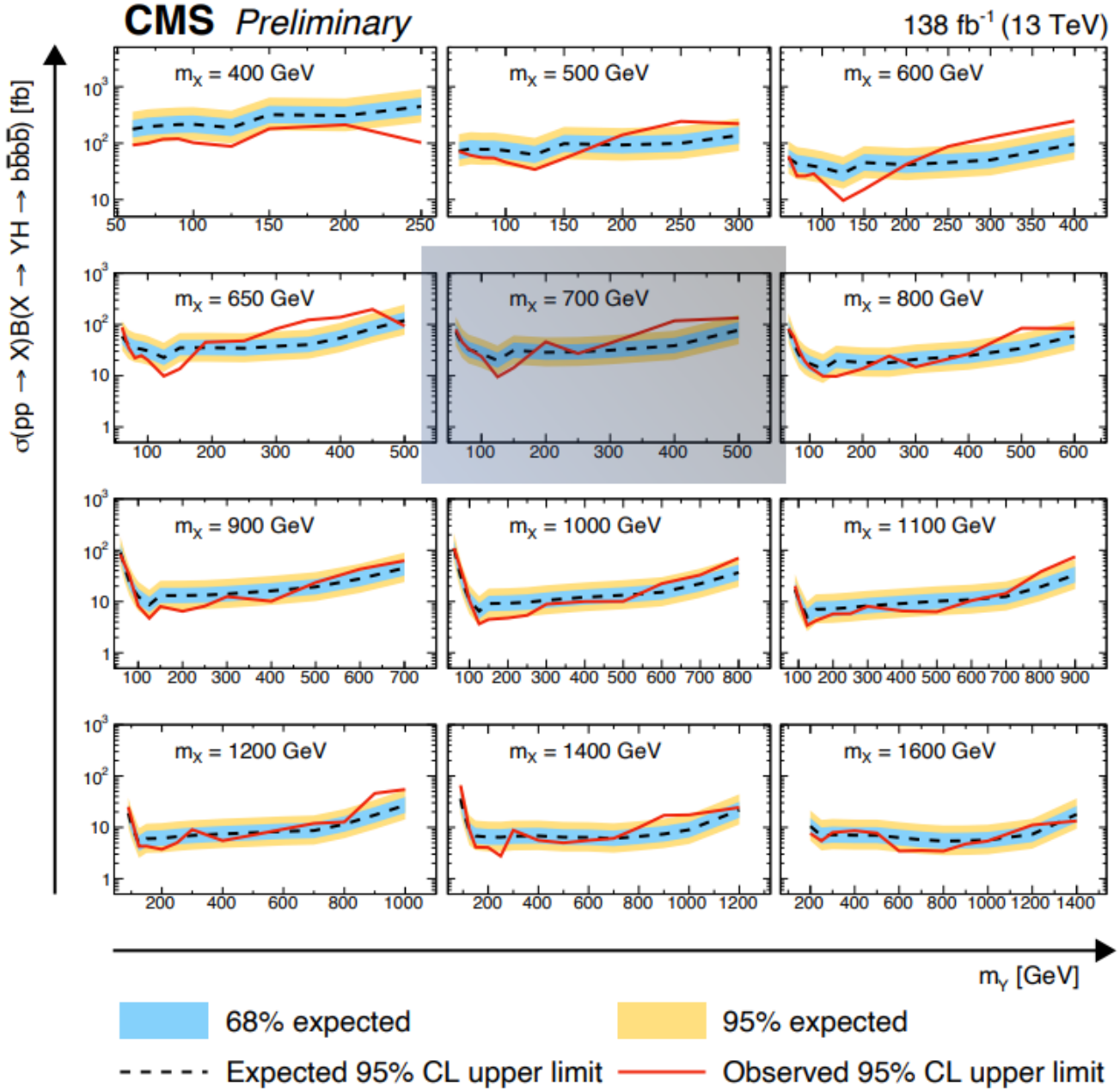


2008.06480

$X \to Yh_{125} \to 4b$

CMS-PAS-HIG-20-012 NEW

- Largest excess at $m_X^{reco} = 700$ GeV, $m_Y^{reco} = 400$ GeV with $4.1(2.5)\sigma$ local(global).
  - Local significance is highly reduced by the look-elsewhere-effect because of high number of mass points.



$A/H \rightarrow t\bar{t}$

NEW

CMS-PAS-HIG-22-013

$> 5\sigma$ deviation.
More pronounced for A

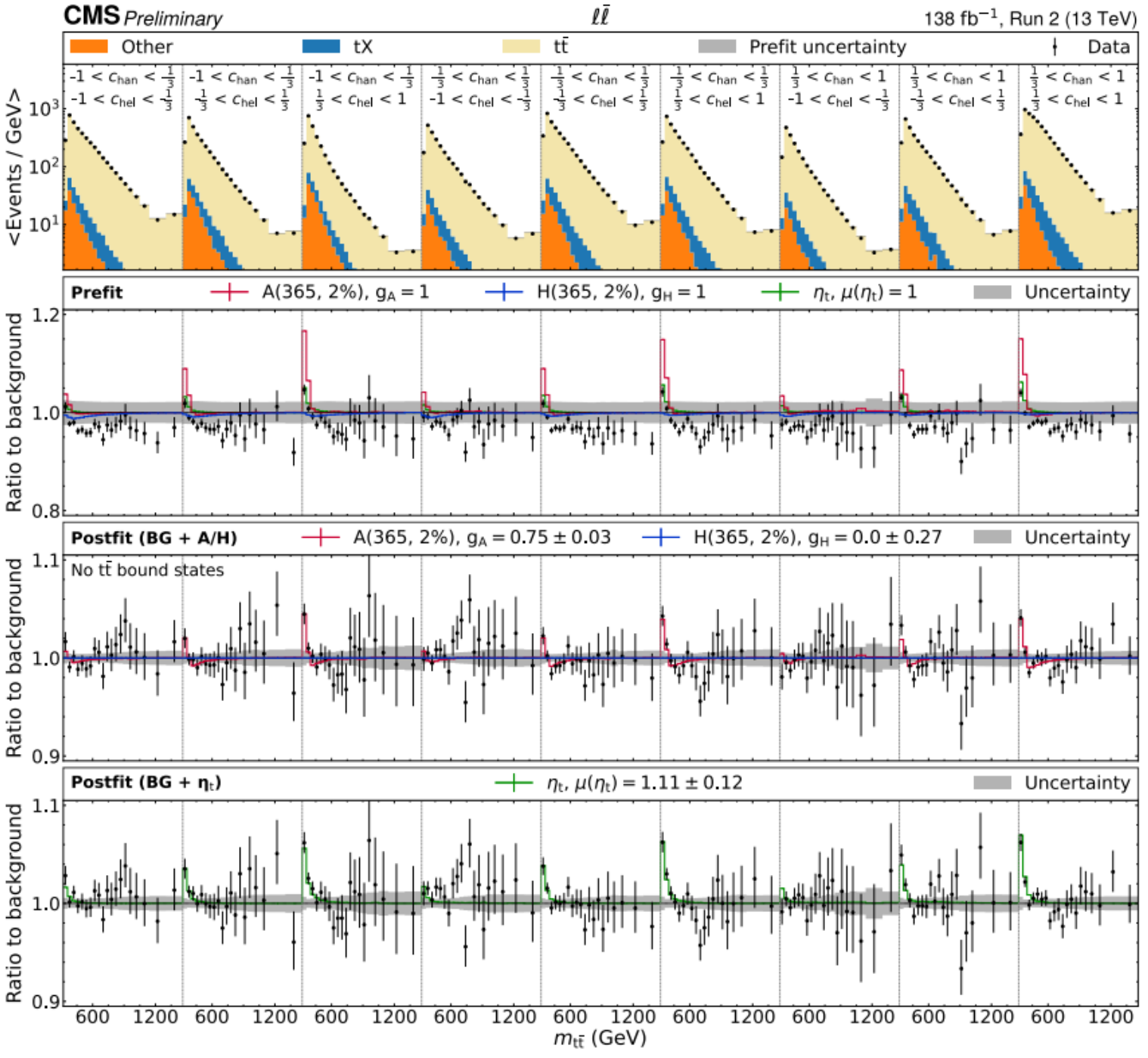
Pseudoscalar $^1S_0^{[1]}$ $t\bar{t}$ bound state:

—> Consistent with the simplified model prediction in arXiv:2102.11281.

—> $\sigma(\eta_t)^{CMS} = 7.1$ pb $(\delta \sim 11\%)$ assuming a bkg. model of resonant $t\bar{t}$ production at NLO pQCD.

Including η_t, stringent constraints on A, H, and A+H covering $m_{A/H}$ = 365-1000 GeV and rel. widths 0.5-25% excluding coupling values as low as 0.4 (0.6) for A and H.

More details in Samuel Baxter's talk.



Sum Rule I

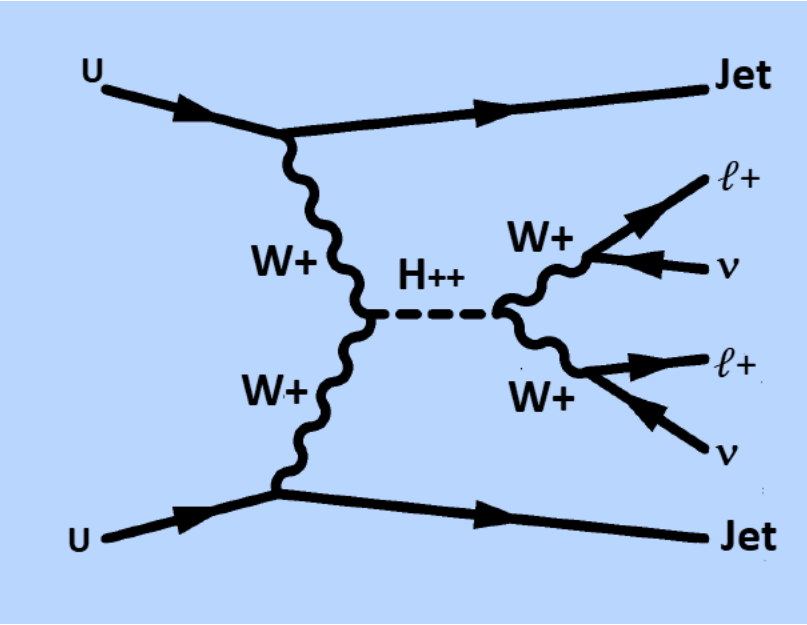
- **W+W- ->W+W-** Haber et al. in *P.R.D* 43 (1991) 904-912

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

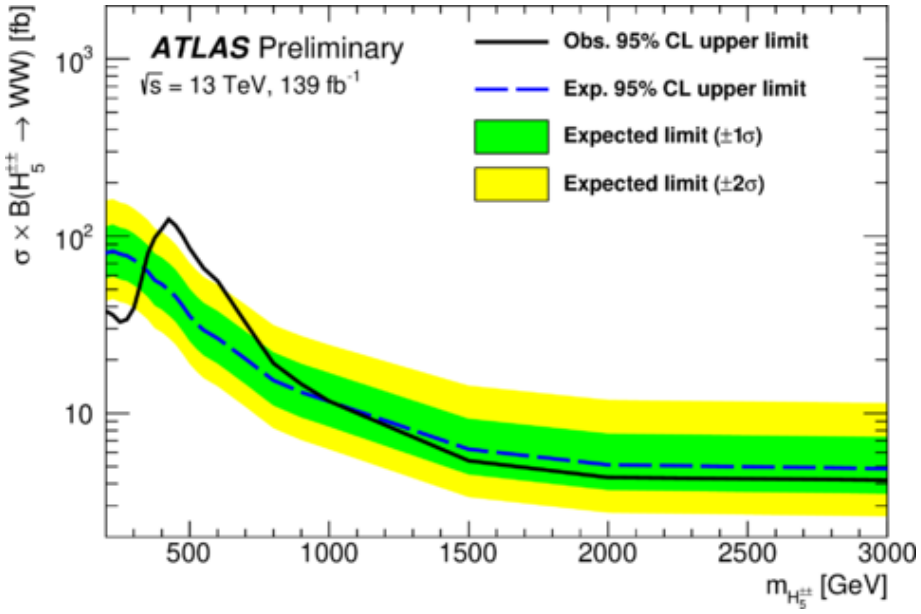
- So-far we have been able to measure H(650)W+W- and (*2302.07276*) h(95)W+W-
- There are other candidates like h(151) and H(330) where these measurements are unavailable, but we have ideas on how to deal with them (**2308.12180** and ***https://indico.cern.ch/event/1253605/***
- H(650) alone forces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



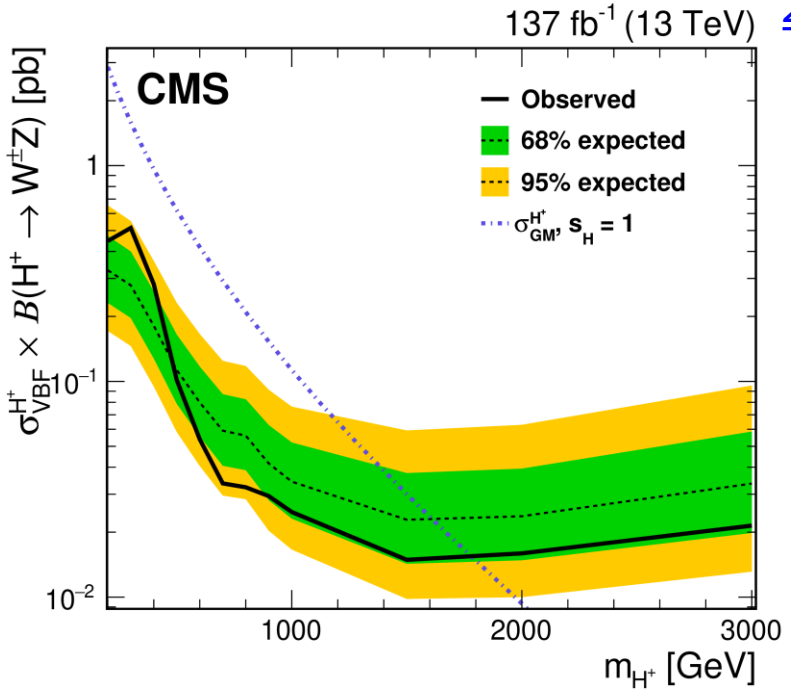
Sum Rule II

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

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

- 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+



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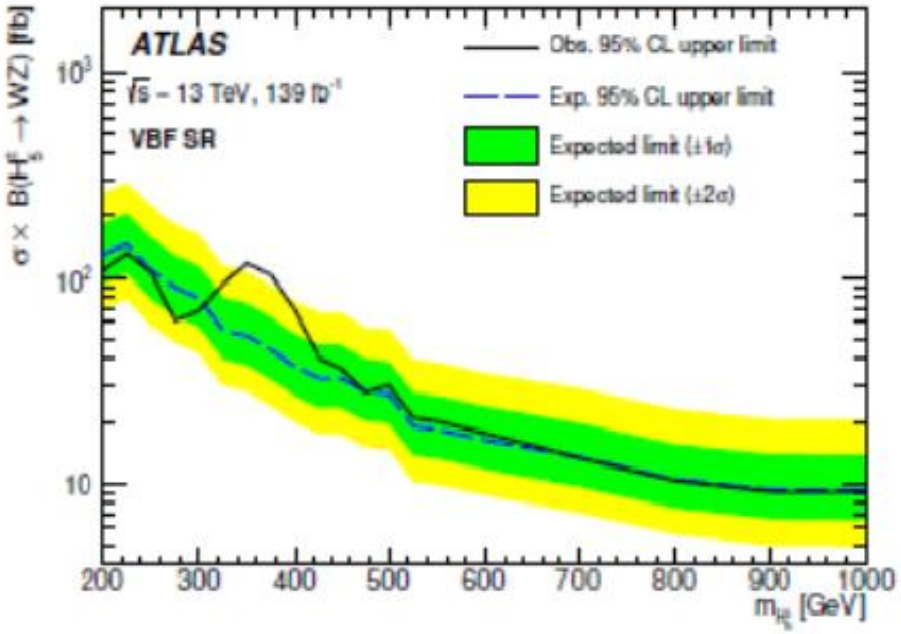


- Coincident excesses at mH5+~375 GeV for ATLAS & CMS
- **ATLAS** claims 2.8 s.d. local
- In GM H5++ and H5+ are mass degenerate which is almost true (see for e-GM [2111.14195](2111.14195))
- H(650) cannot fulfil the requirements of a neutral candidate of H5 but H(320) is more appropriate

Model independent results

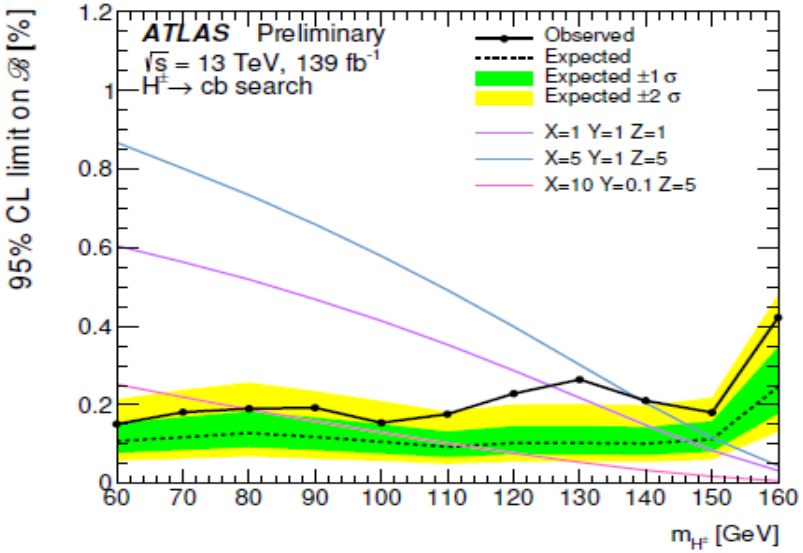
- From these and the SR, one can deduce the total cross section, the elastic BR and the total widths as given in the following table:

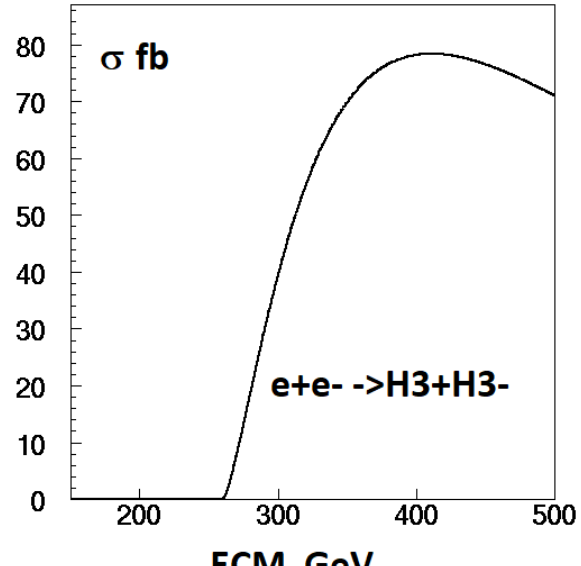
Channel	σ_{VBF} fb	σ_{VBF} VV fb	BR(VV) %	Γtot GeV
H++(450)	830	75	9±4	160
H+(375)	810	125	15±8	80

- 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

A light H'+ ?

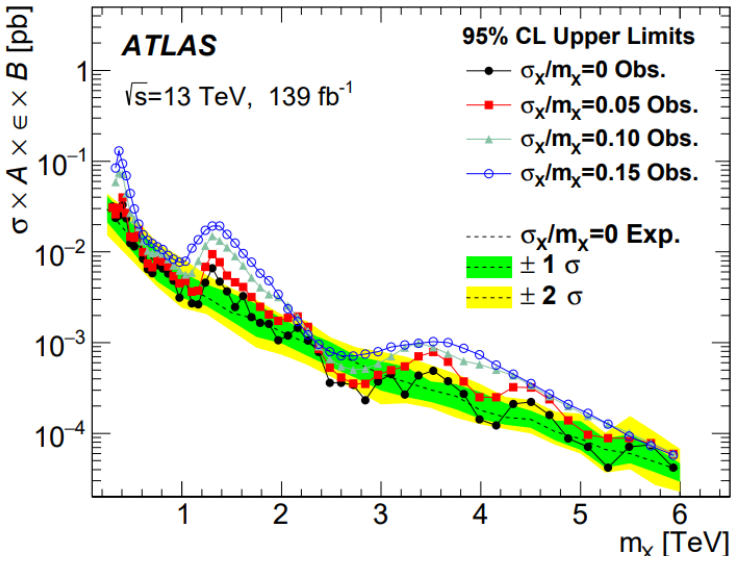
- There are few indirect hints for this
- B decays into Dτ and Λτ are reduced by 1.6 and 1.4 s.d. 2305.00614 suggesting mH+~200 GeV
- ATLAS has searched for t->bH+->bbc and found a 3 s.d. local (2.5 global) excess around 130 GeV 2302.11739
- Not allowed in 2HD models for type II 1702.04571 but allowed 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

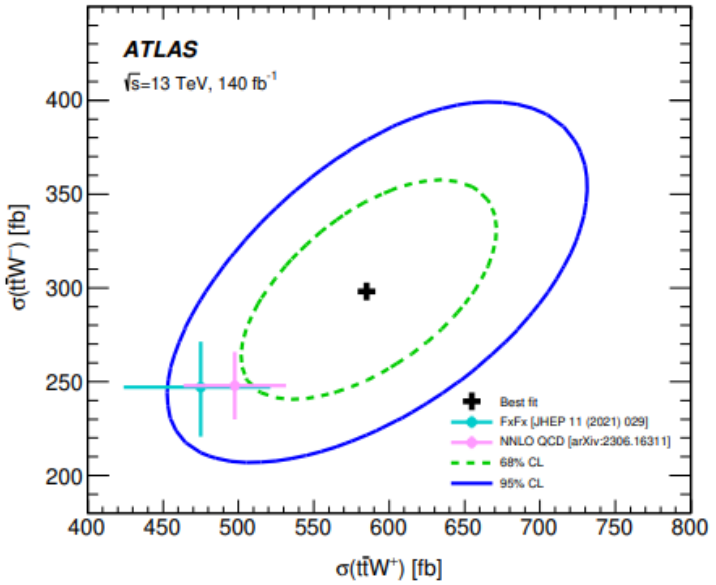




An extra heavy H+ ?

- 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

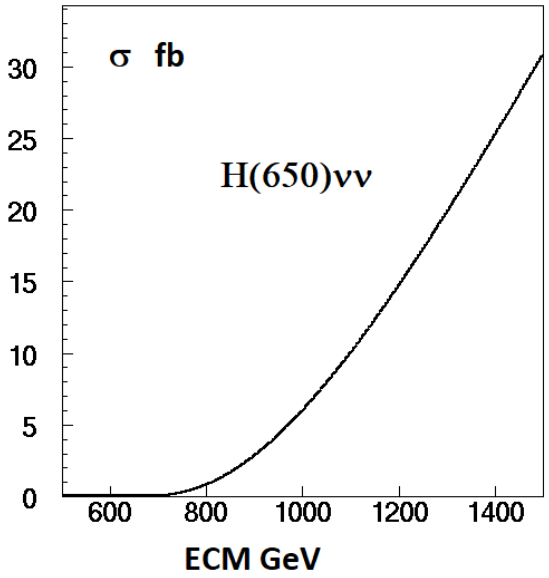


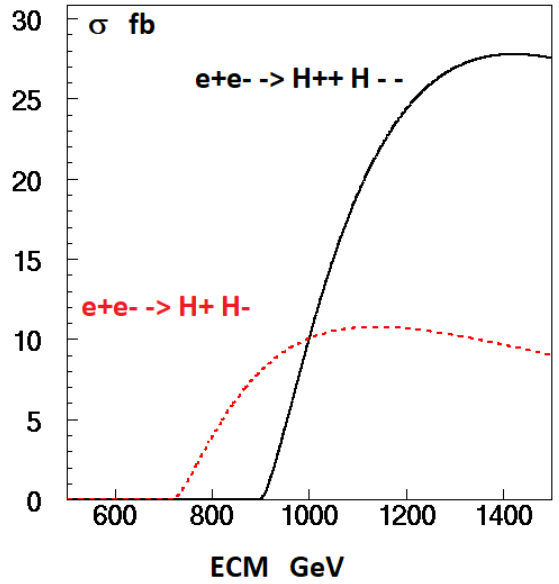


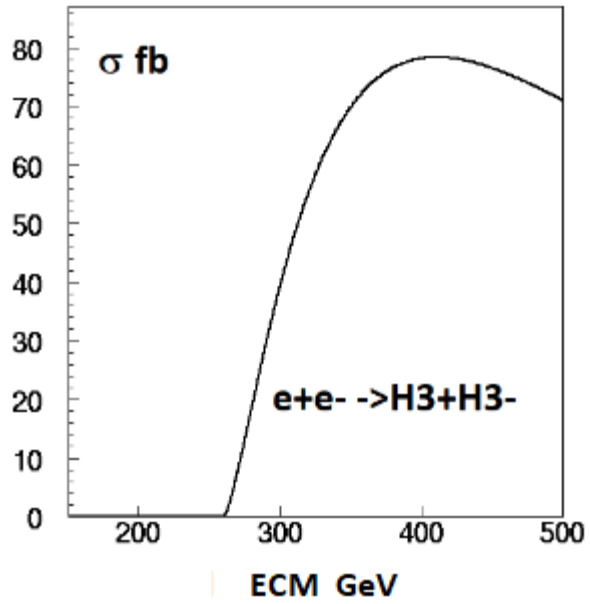
H(320) as a partner of H++ ?

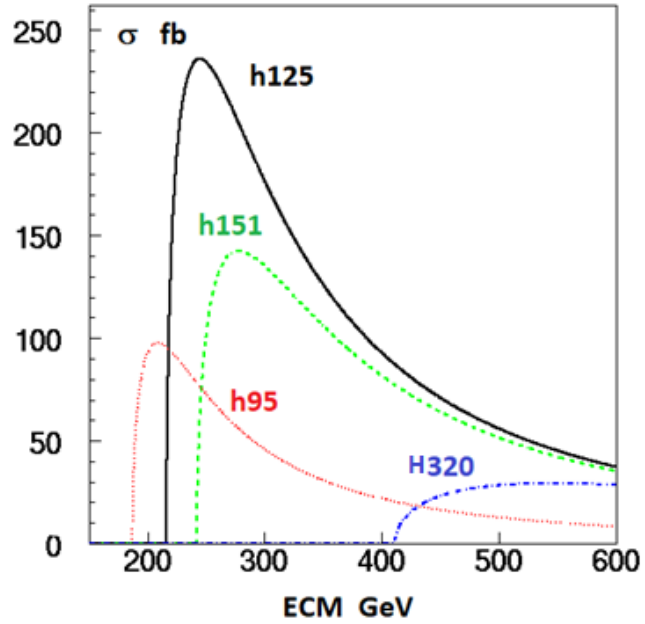
- The **H5 multiplet** containing H++ needs to be completed by a neutral scalar, which cannot be H(650) which is doublet dominated
- Given its mass, H(320) seems appropriate and its dominant content in triplet fields (see matrix) reinforces this hypothesis
- However, its decay into bbbb interpreted as 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) can decay into **A(151)A(151)** which feeds into bbbb, experimentally hardly distinguishable from hh

Collider reach







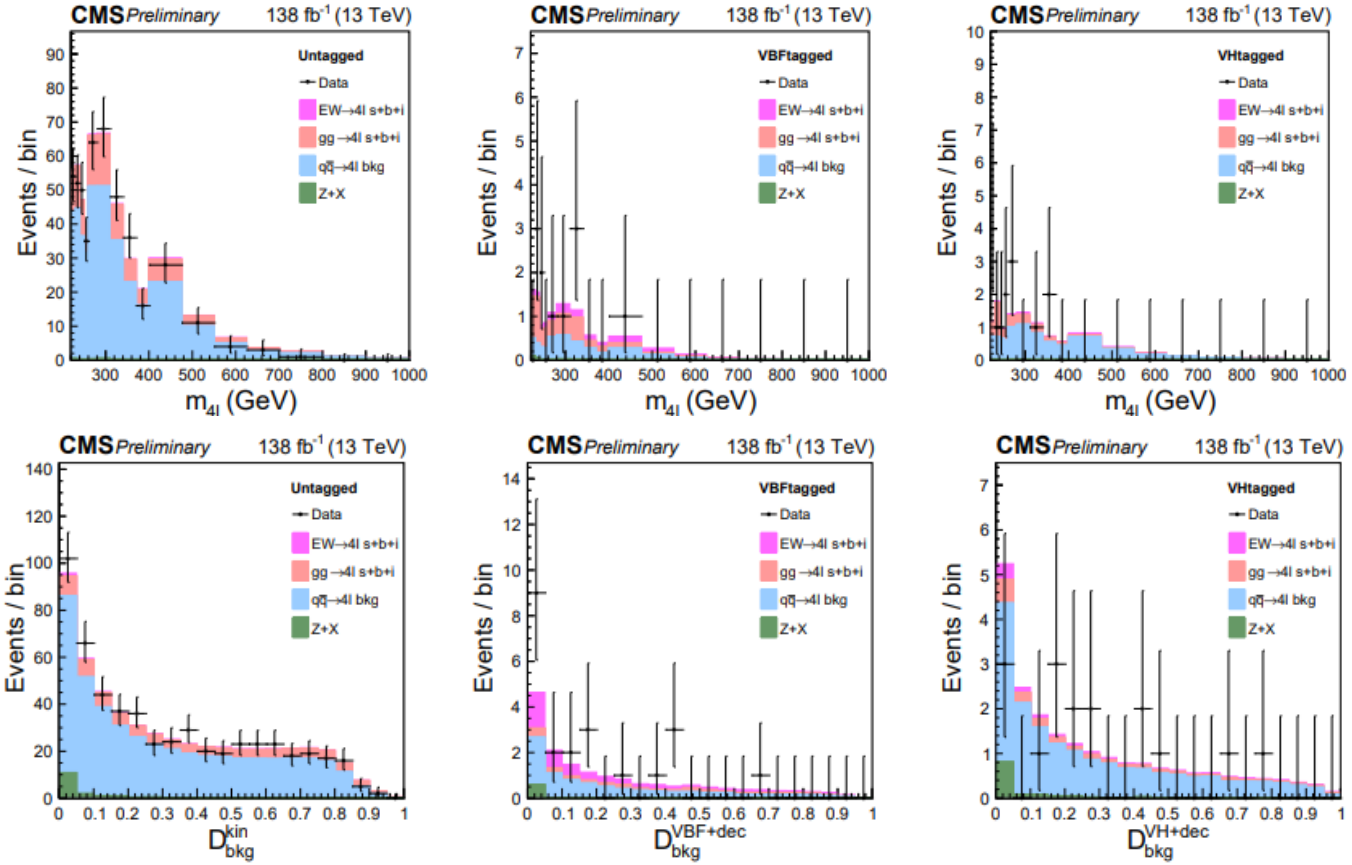


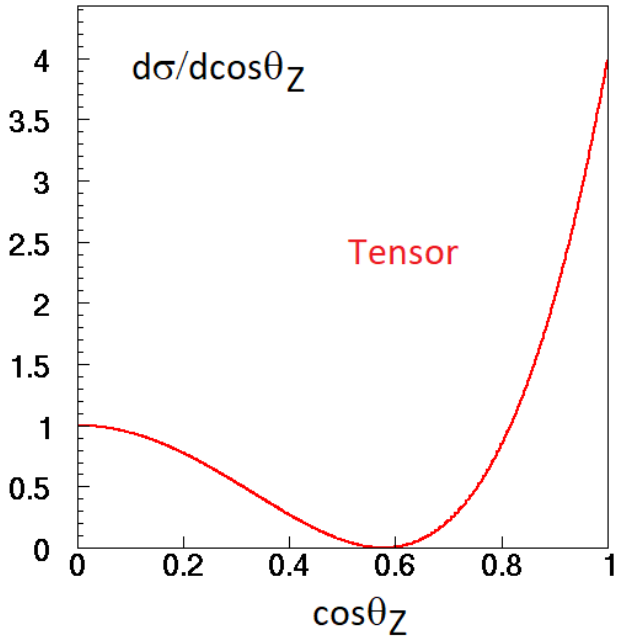
- Final states are complex modes (~ SM ttH) requiring the **highest** $\mathcal{L}$ and an **almost ideal detector with forward coverage for b jet ID**
- ILC would provide **8000 fb-1 at 1 TeV**
- **H(650)** mainly produced through VBF (beam polarisation allows a factor ~2 gain, not included) benefits from an increased energy
- A(420) and A(130) can be seen through cascades like H(650)->ZA(420) 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 ?

b->sγ constraint on mH+

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

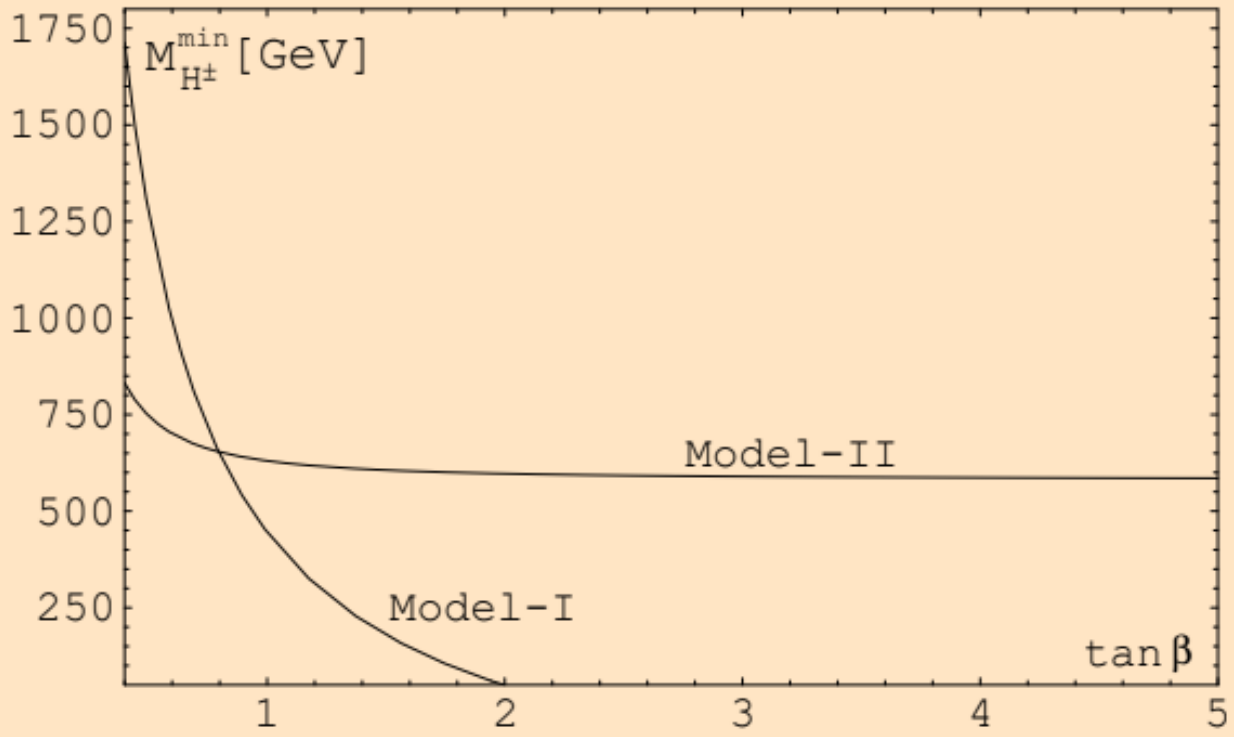
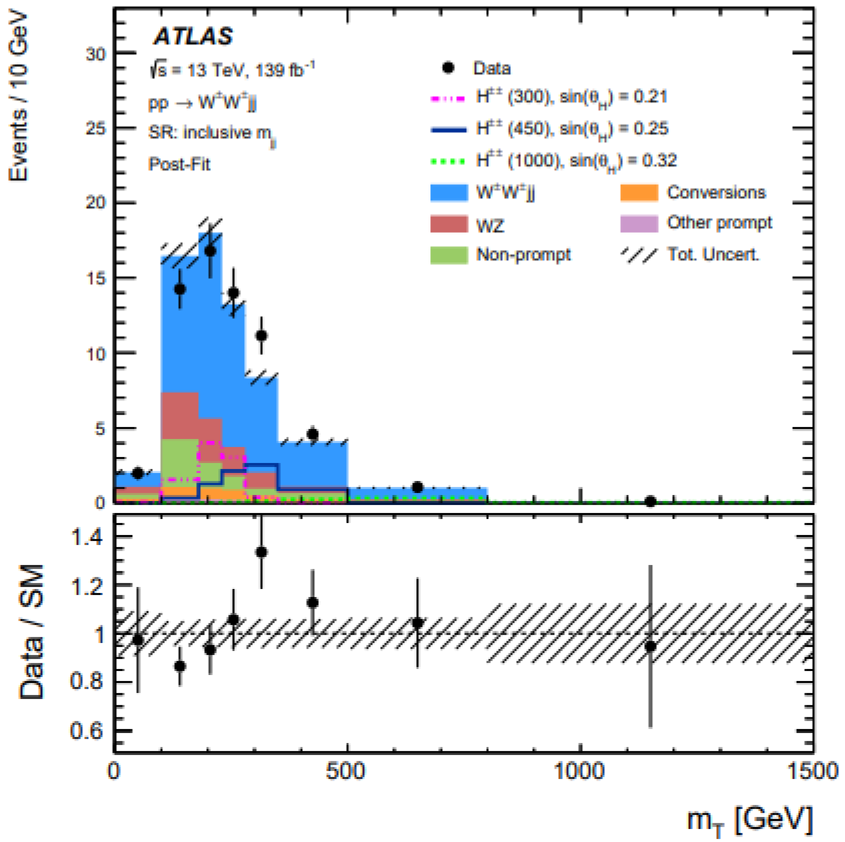


Figure 4: 95% C.L. lower bounds on $M_{H^\pm}$ as functions of $\tan\beta$.

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

2312.00420



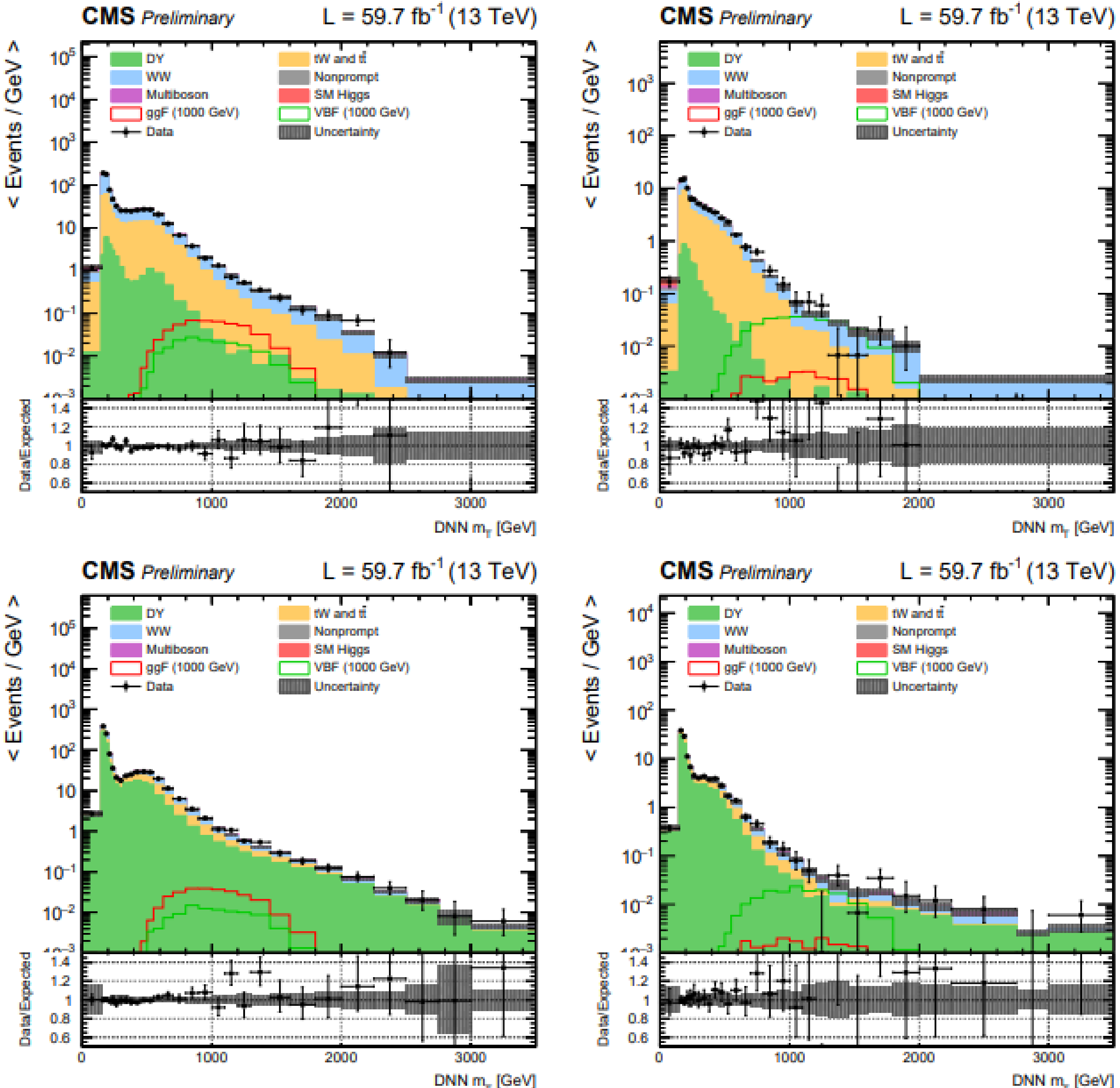
VBF W+W+

ggF W+W-

VBF W+W-

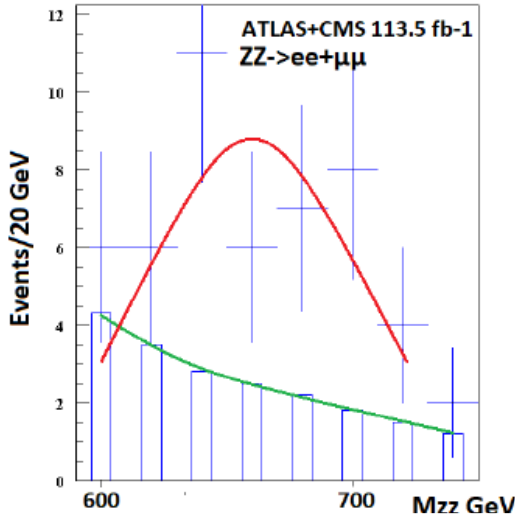
μe

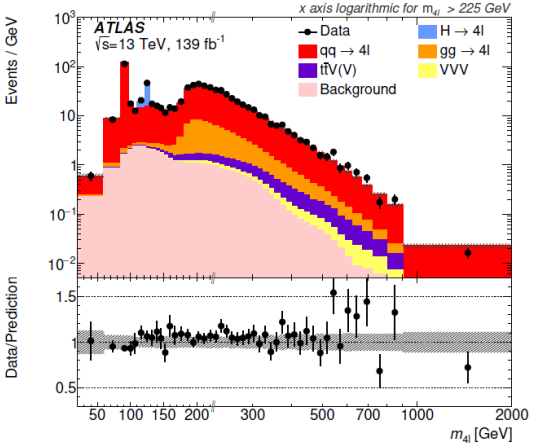
μ+μ-

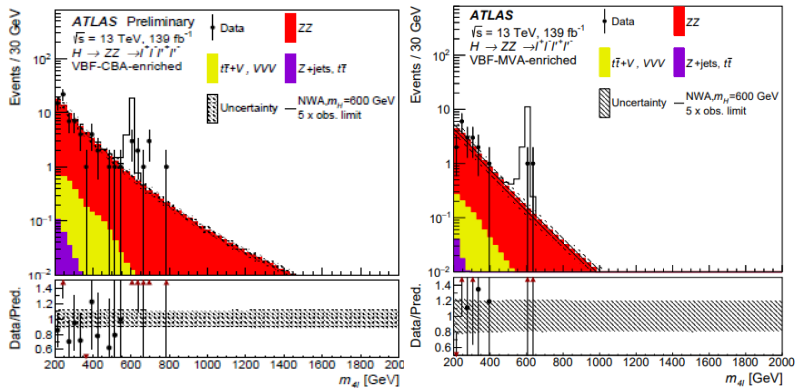


1st indication : H->ZZ into 4 leptons

- The **cleanest channel** for discoveries
- From a combination of published histograms *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* 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…

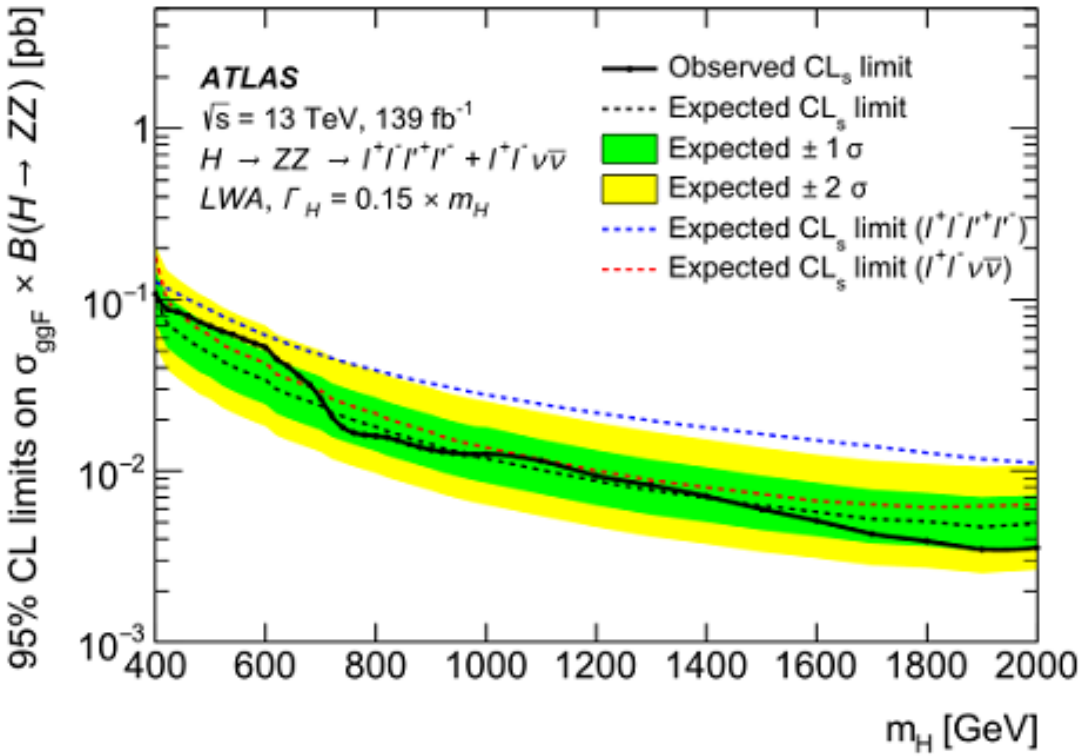






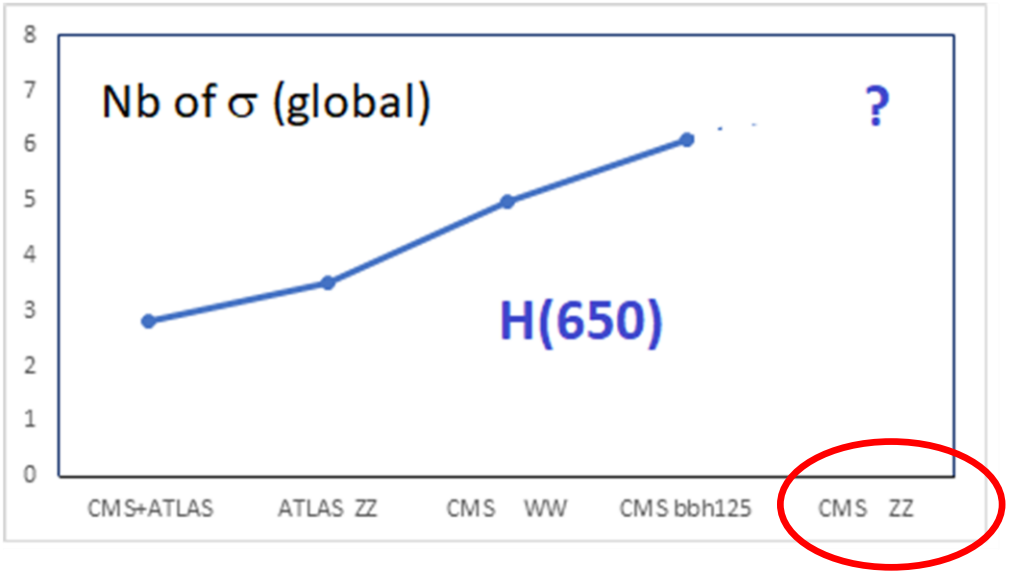
CAVEAT on H(650)->ZZ

- 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 $\ell+\ell-\nu\nu$ 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

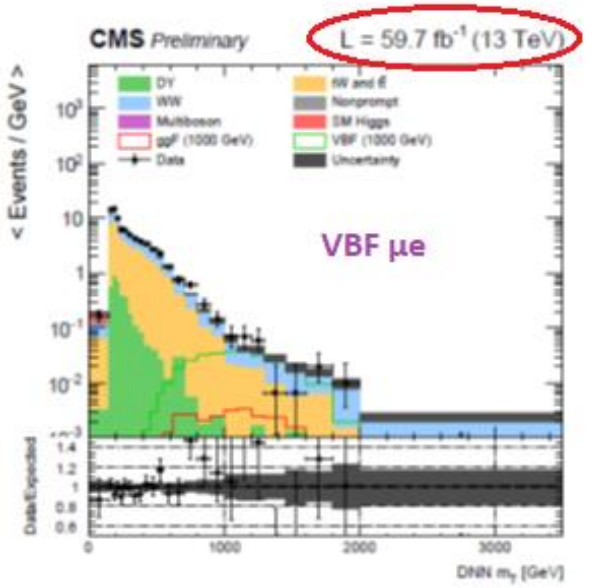
This **VBF** cross section **~160±50 fb**, close to SM, is ~3 times larger than VBF->ZZ, inconsistent with **GM** which predicts for the scalar **H5 WW/ZZ=0.5**

2 HD excluded (bue line) h(125)WW predicts **$\sin^2(\alpha-\beta)$~0.97±0.09** meaning that **H(650)WW~$\cos^2(\alpha-\beta)$~(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

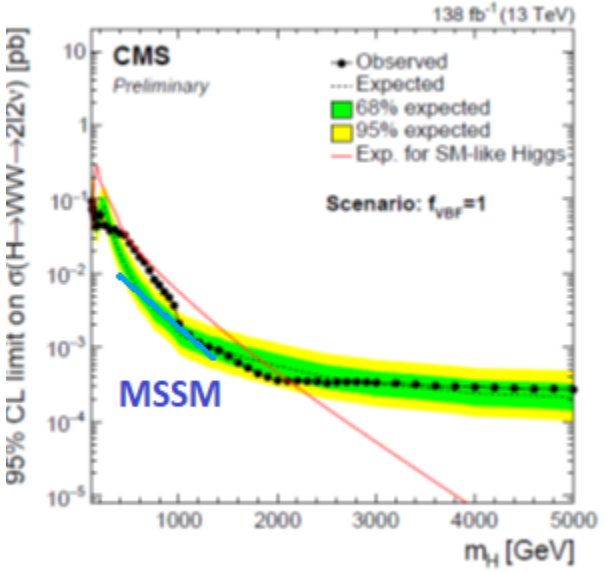
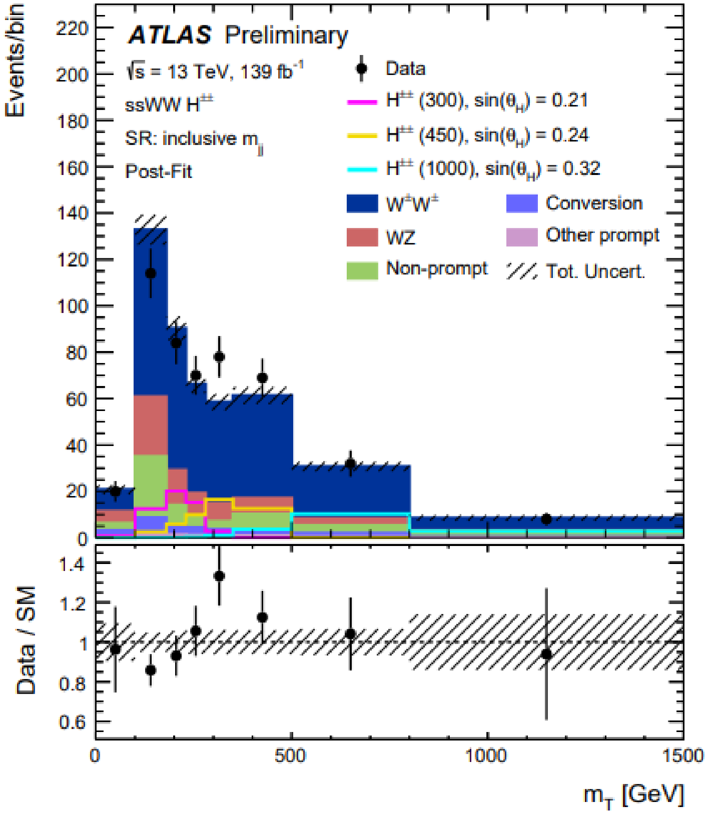


Table 3: Summary of the signal hypotheses with highest local significance for each f_{VBF} scenario. For each signal hypothesis the resonance mass, production cross sections, and the local and global significances are given.

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



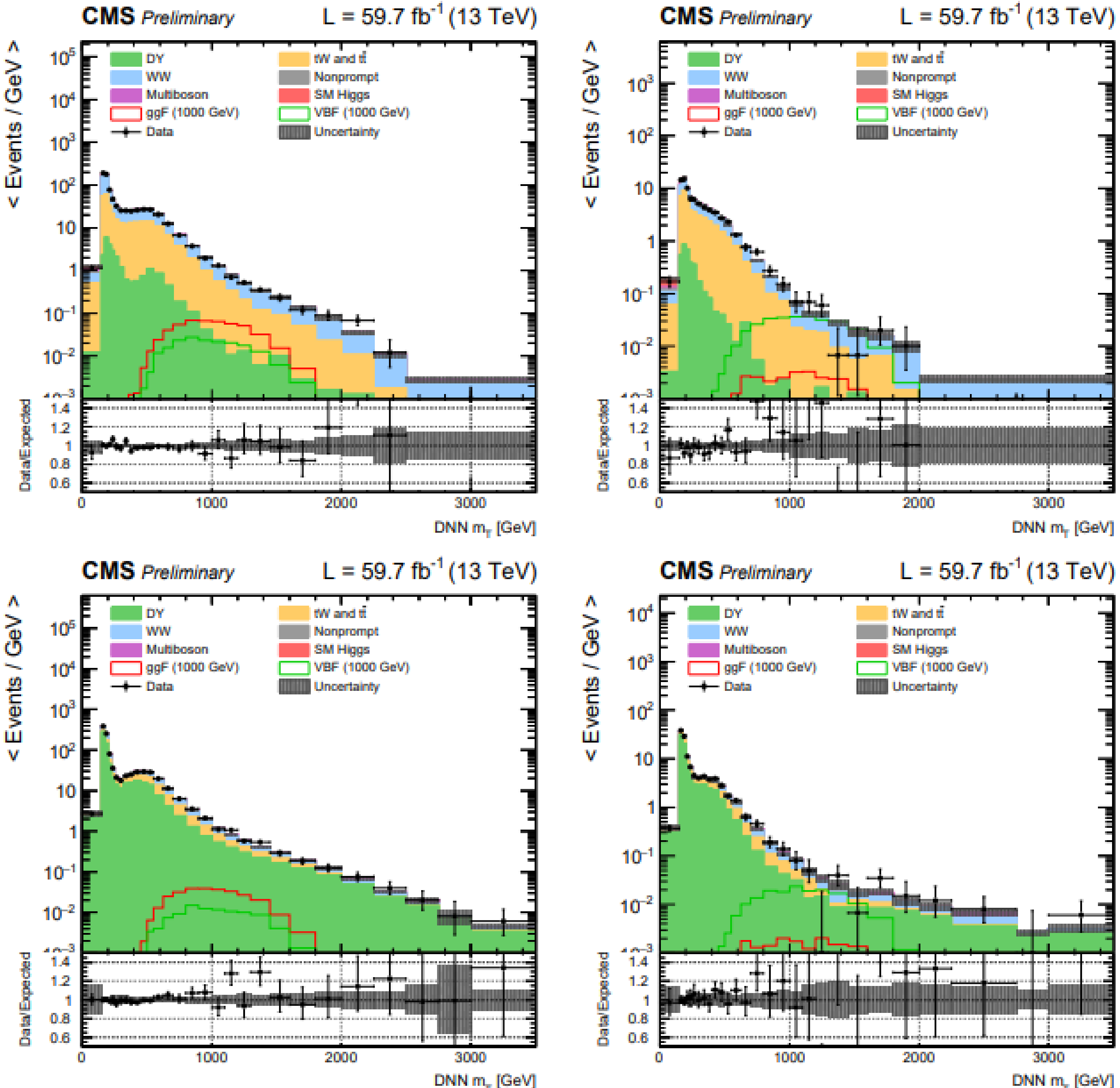
W+W+ much easier

ggF->W+W-

VBF W+W-

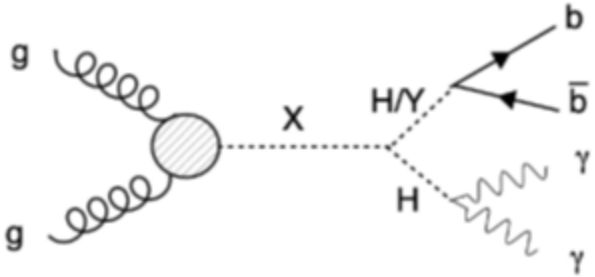
μ+e-

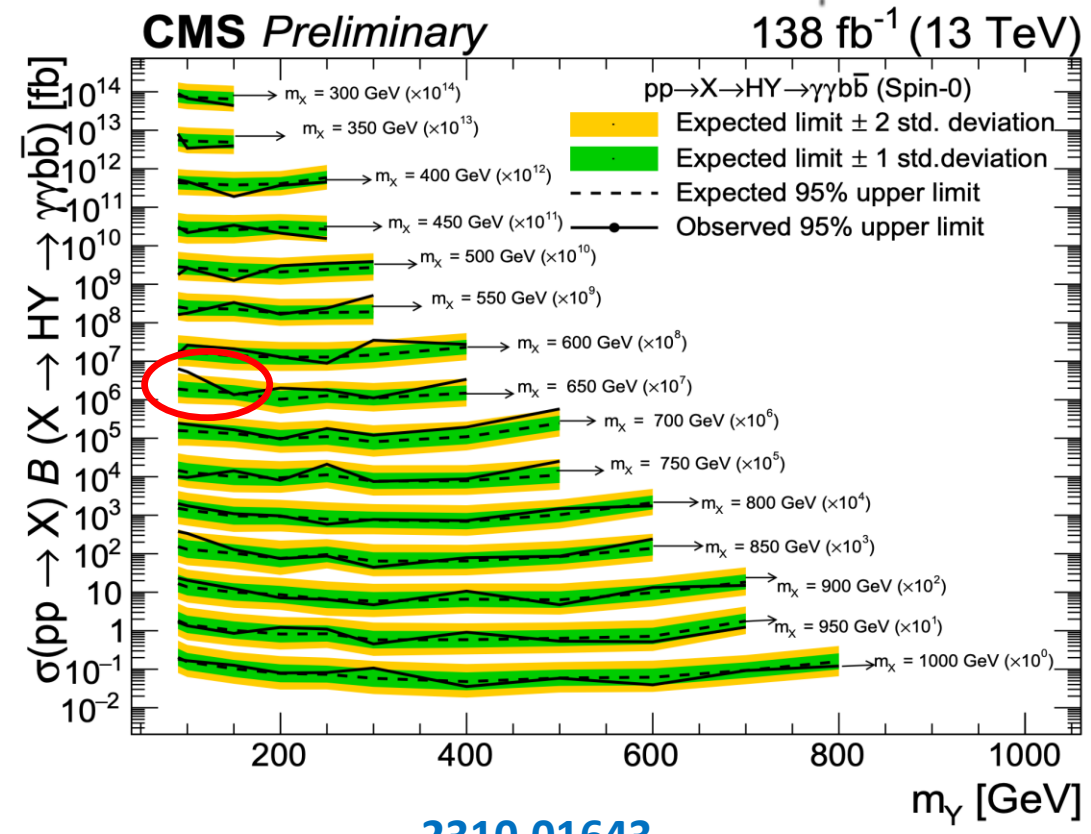
μ+μ-



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**

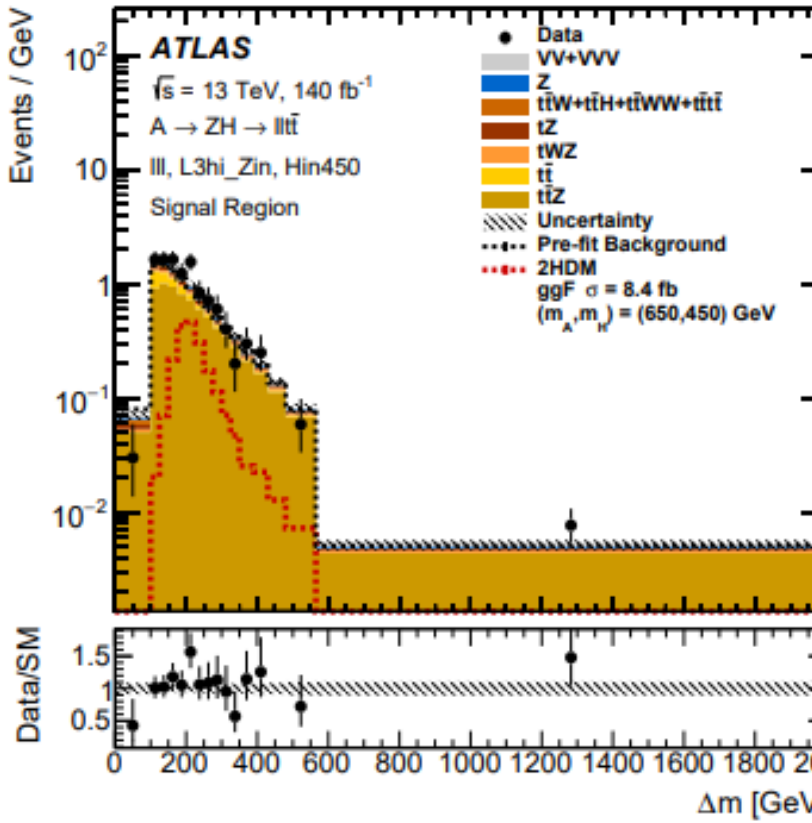




[2310.01643](2310.01643)

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

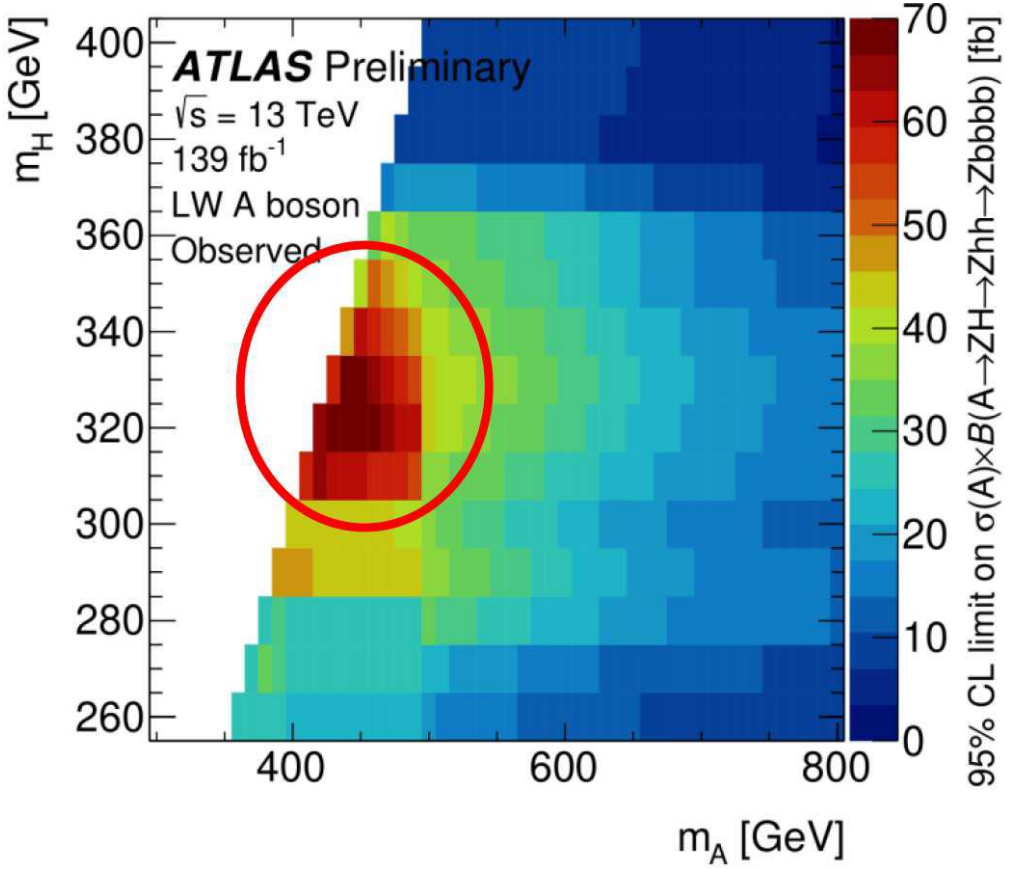
LHC inputs for our work

- 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 $\gamma\gamma$ $\tau\tau$ 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)	$\gamma\gamma$ $\tau\tau$ bb (LEP)	0306033 1811.08159 1803.06553 CMS-PAS-HIG-20-002	4.3	*
h(151)	$\gamma\gamma$ +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)	

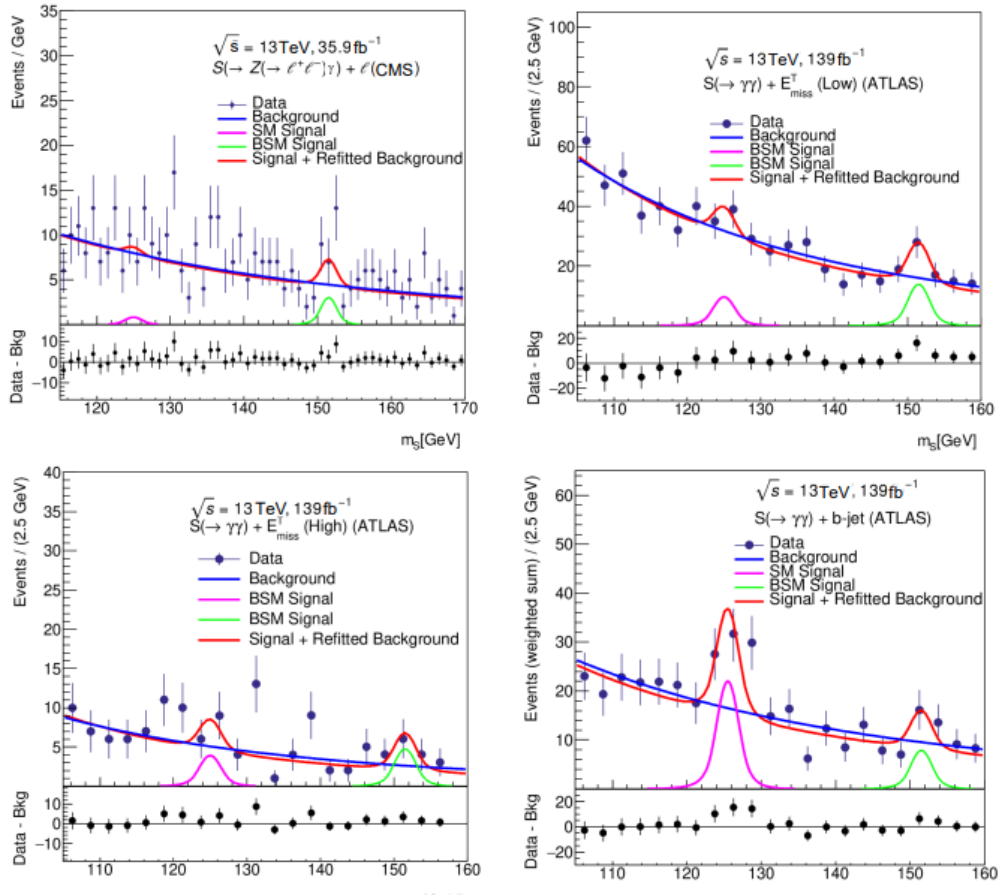
Evidence for H(320) and A(420)

- 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**



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	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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	1312/262	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.