Karlsruher Institut für Technologie

Institute for Theoretical Physics

h95 in GM

HiggsDays in Santander

September 10th 2024

Thomas Biekötter

h95 in GM,2HDM,NMSSM,$\mu\nu$SSM,S2HDM,MRSSM,...

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The SM Higgs sector

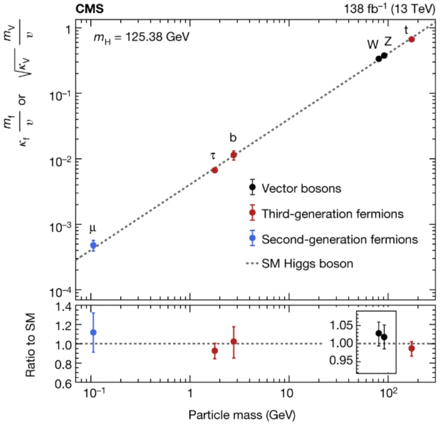
Minimal parametrization of EW symmetry breaking

Predictions:

→ One fundamental scalar particle

→ Couplings $\sim m_f$ or m_V^2

→ No CP violation in Higgs potential

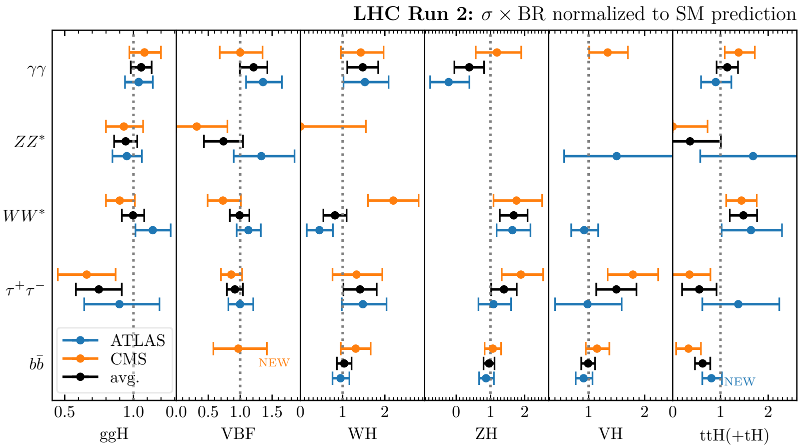


[CMS, 2207.00043]

Any modifications from these predictions → BSM physics

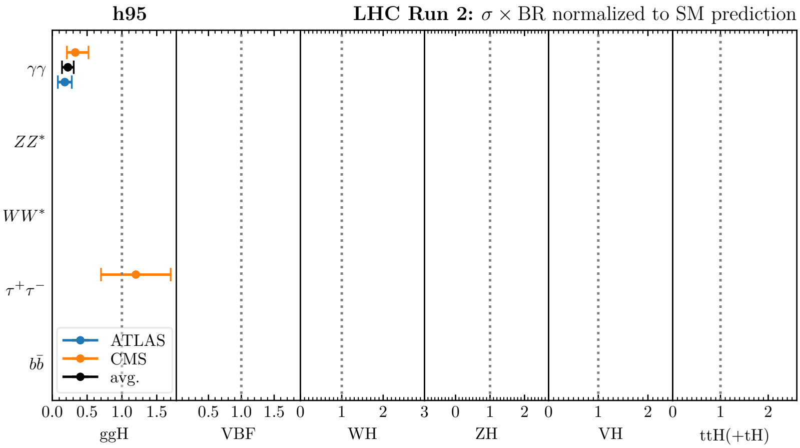
h125 after Run 2

“C’est même des hypothèses simples qu’il faut le plus se défier,
parce que ce sont celles qui ont le plus de chances de passer inaperçues.” – Henri Poincaré



https://gitlab.com/thomas.biekoetter/h125summaryplot

h95 after Run 2



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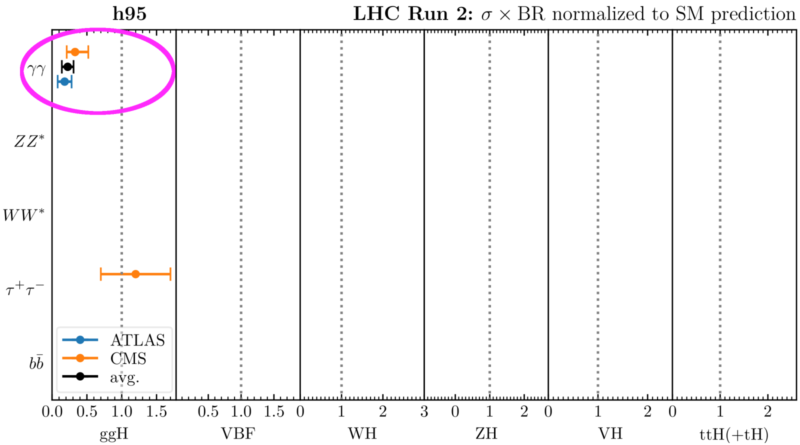
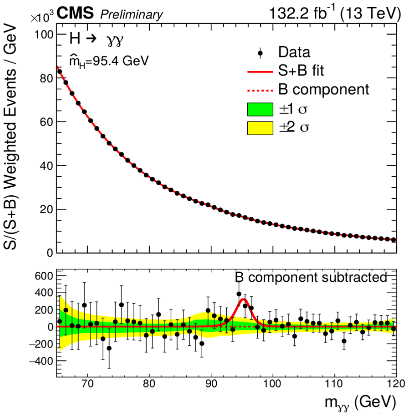
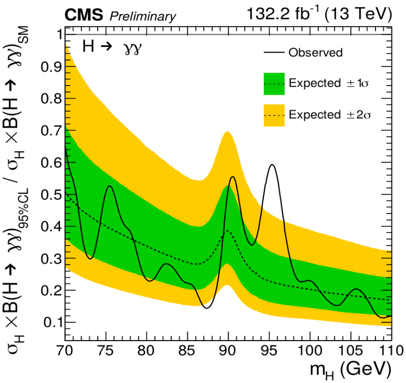


CMS: low-mass $\gamma\gamma$





[CMS-HIG-20-002]

CMS saw excess of events at 95 GeV at 7, 8 and 13 TeV

Final Run 2 results:

$$\mu_{\gamma\gamma}^{\mathrm{CMS}} = 0.33^{+0.19}_{-0.12}$$

- Refined analysis regarding $Z \to e^+e^-$ background
- The excess from Run 1 and 1st-year Run 2 persists!
- $2.9/1.3\sigma$ local/global significance, but signal strength reduced compared to previous result

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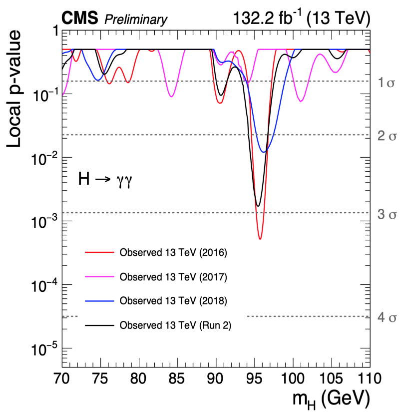

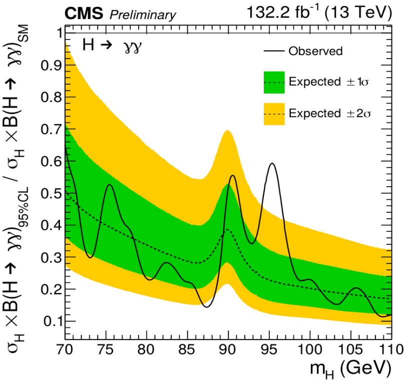

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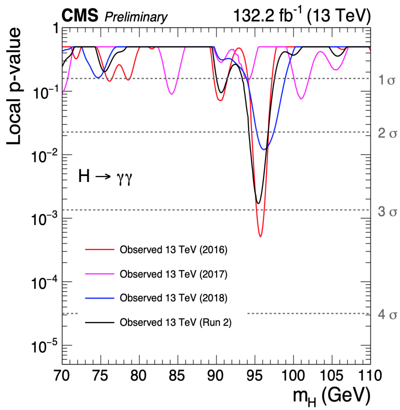

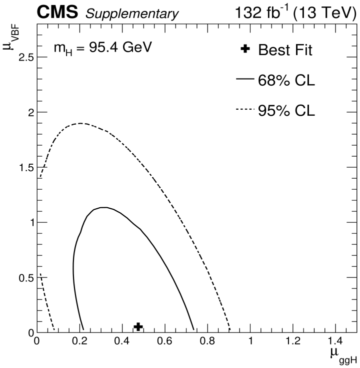

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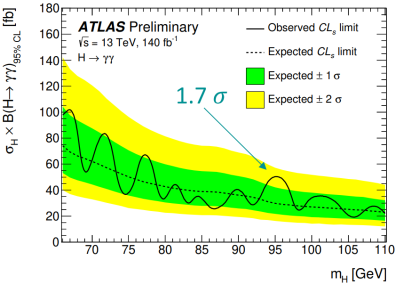
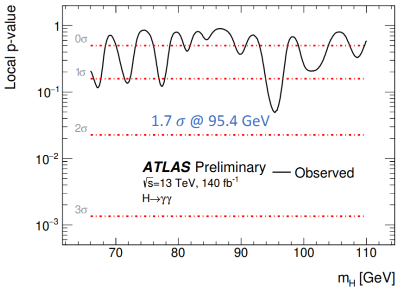
ATLAS: low-mass $\gamma\gamma$

[ATLAS-CONF-2023-035]





Most significant excess at 95 GeV

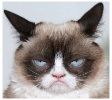
$\mu_{\gamma\gamma}^{\mathrm{ATLAS\ Run\ 2}} \approx$

$$0.18 \pm 0.10$$

[TB, S. Heinemeyer, G. Weiglein, 2306.03889]

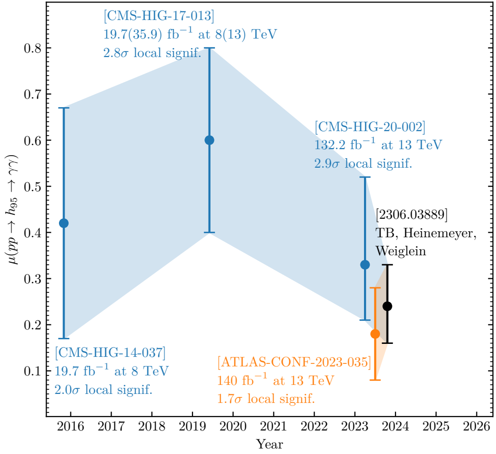
Local 1.7σ excess at **95 GeV**

Local 1.7σ excess at 95 GeV



ATLAS+CMS: low-mass $\gamma\gamma$

$$\mu_{\gamma\gamma}^{\mathrm{CMS+ATLAS}} = 0.24^{+0.09}_{-0.08}$$



Theory:

If this is real, what would we learn about the underlying physics and its implications for phenomena beyond the Standard Model?

Experiment:

How to confirm or exclude? How to measure its couplings?

ATLAS+CMS: low-mass $\gamma\gamma$

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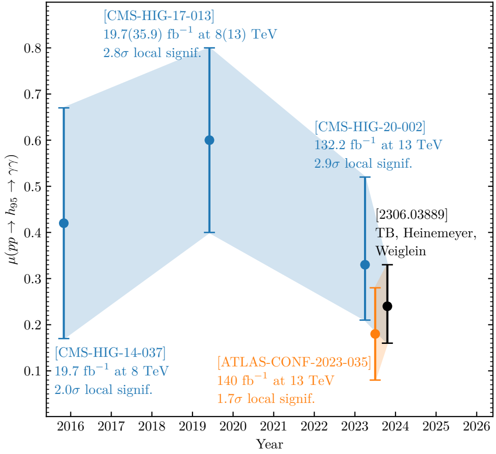
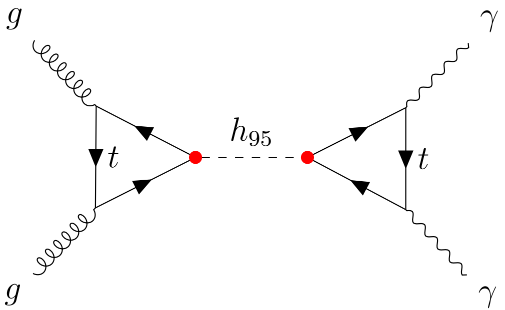
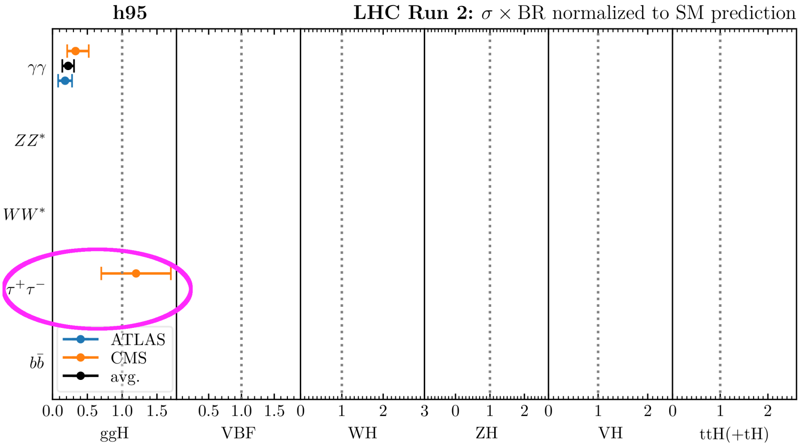




If one only considers the diphoton excess, the only certain coupling is the $h_{95}t\bar{t}$-coupling

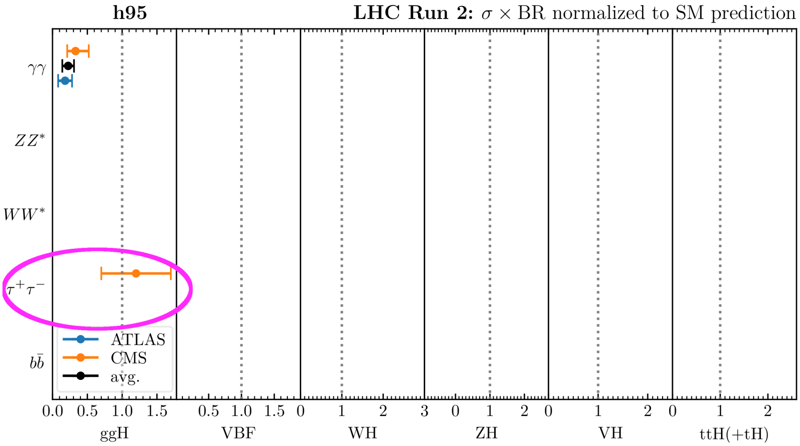
Or extra quarks, but difficult (impossible?) to reconcile with h_{125} signal rates

h95 after Run 2

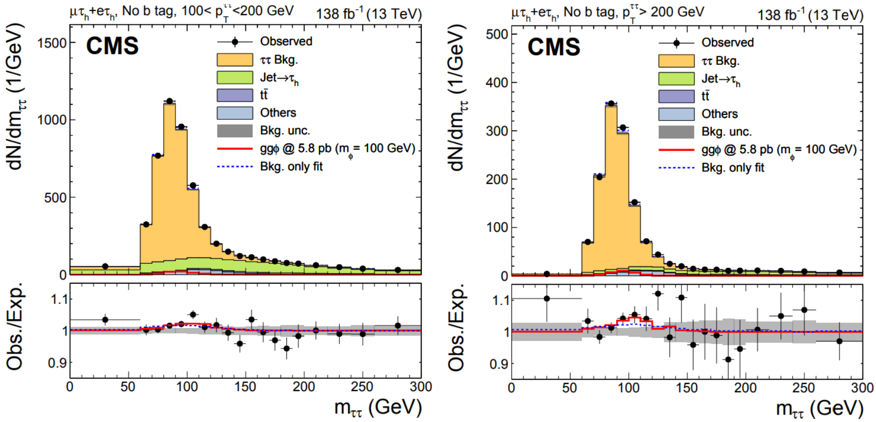


h95 after Run 2

From the "Higgs-hunter perspective" $H \to \tau^+\tau^-$ would be something you search for first
So far no low-mass 13 TeV ATLAS result



CMS: low-mass $\tau^+\tau^-$



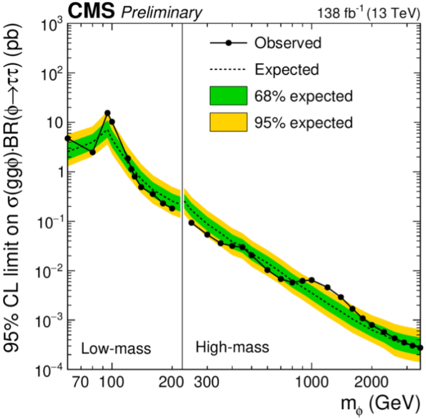
Excess in gluon-fusion production channel:

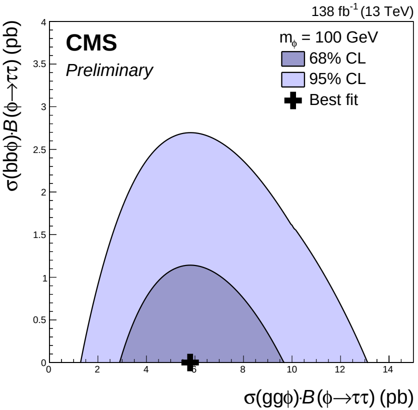
$$\mu_{\tau\tau}^{\rm CMS} \approx 1.2 \pm 0.5$$

[CMS, 2208.02717]

- Broad excess compatible with a mass of 95 GeV
- Most significant at 100 GeV: $3.1/2.7\ \sigma$ local/global
- Significance at 95 GeV: $2.6/2.3\ \sigma$ local/global

CMS: low-mass $\tau^+\tau^-$





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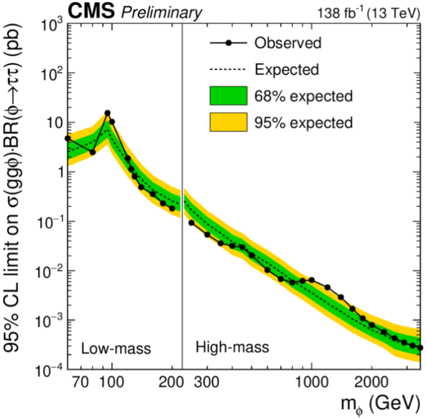

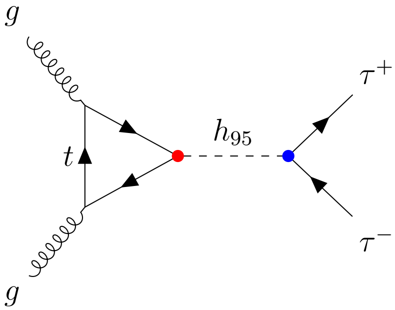

The ditau excess requires a $h_{95}\tau^+\tau^-$-coupling

- Broad excess compatible with a mass of 95 GeV
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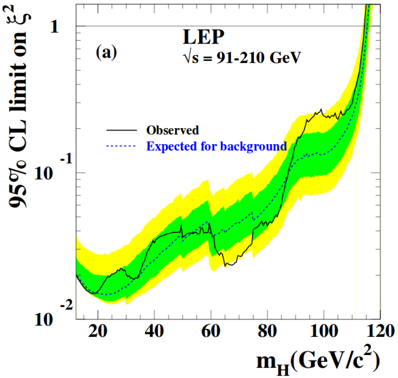
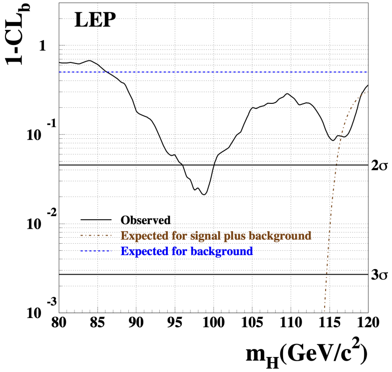
LEP: $e^+e^- \to Zh \to Zb\bar{b}$

[LEP, hep-ex/0306033]





LEP combination shows local $2\ \sigma$ excess at 95 GeV: $\mu_{bb}^{\text{LEP}} = 0.1 \pm 0.05$ [Cao et al.,1612.08522]

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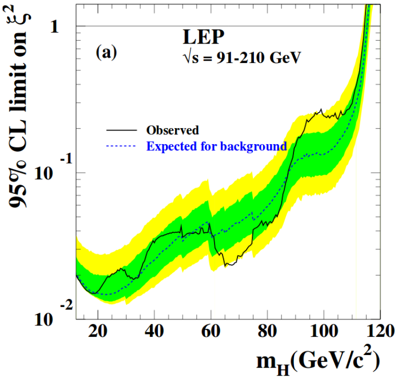
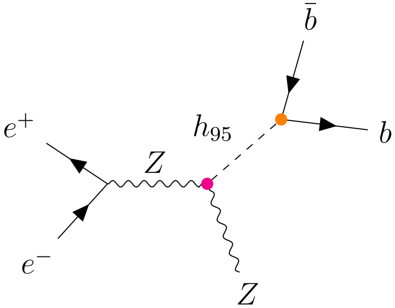
[LEP, hep-ex/0306033]





Only the LEP excess requires a $h_{95}ZZ$-coupling

LEP combination shows local $2\ \sigma$ excess at 95 GeV: $\mu_{bb}^{\text{LEP}} = 0.10 \pm 0.05$ [Cao et al.,1612.08522]

Two b or not two b?

Recent paper claims that signal hypothesis is excluded by 1999–2000 data alone [P. Janot, 2407.10948].

> A similar, though less quantitative, statement had already been made by the LEP experiments and the LEP Higgs working group in Ref. [52]: "*In the 189 GeV data, an excess had been observed [...] compatible with the dominant* $e^+e^- \to ZZ$ *background. [...] There is no evidence for a systematic effect at threshold in the data collected above 189 GeV.*".

[P. Janot, 2407.10948]

It is worth reading what was left out:

> In the 189 GeV data, an excess at $m = 97$ GeV has indeed been observed [25] (see the large negative value of $-2\ln Q$ close to the signal+background prediction) which was due mainly to small excesses in ALEPH and OPAL data compatible with $e^+e^- \to ZZ$, the dominant background in the vicinity of that mass. This excess still has a significance of about two standard deviations when LEP data from all energies are combined, and one cannot exclude a physics interpretation beyond the SM (e.g. MSSM with several neutral Higgs bosons). However, there is no evidence for a systematic effect at threshold in the data collected at the other energies below 206 GeV.

[LEP, hep-ex/0107029]

Two b or not two b?

Karlsruher Institut für Technologie

A 95 GeV Higgs boson at LEP ?

- From https://arxiv.org/abs/hep-ex/0107029

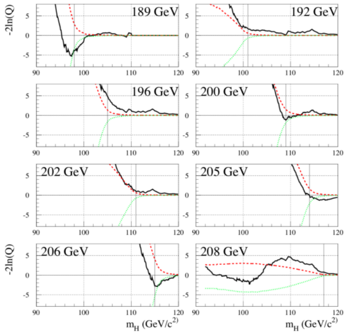


Figure 11: Behaviour of $-2\ln Q$ in subsets collected at different c.m. energies. In each plot, the full curve shows the observed behaviour, the dashed/dotted lines show the expected behaviour for background/signal+background, and the vertical line indicates the test-mass $m = E_{cm} - M_Z$ GeV, just at the kinematic limit. (The subset labelled 208 GeV has very low statistics.)

- A plot rarely shown (why?)
  - The excess shows only at $\sqrt{s}$ = 189 GeV
    - With the SM ZH cross section
      - ➔ Note: 98+91 = 189 : kinematic limit !
  - Expect many more events at large $\sqrt{s}$
    - Just with the phase space increase
      - ➔ As shown by the green curves
  - Excess excluded by $\sqrt{s}$ = 192 to 206 GeV
    - Where 99% of the integrated luminosity has been delivered
      - ➔ The bottom right plot is essentially with zero statistics
- Conclusion
  - LEP cannot be claimed to support the interpretation of an excess at LHC as a second Higgs boson around m_H = 95 GeV
  - In case, FCC-ee would be best to study this new particle (and the 125 GeV Higgs too!)

CCT Meeting
14 Sept 2023 2

[Slide by P. Janot, CCT Meeting 2023]

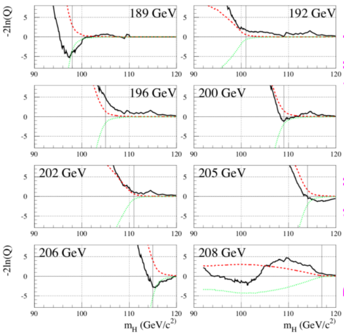
Two b or not two b?

Karlsruher Institut für Technologie

A 95 GeV Higgs boson at LEP ?

- From https://arxiv.org/abs/hep-ex/0107029

Likelihood ratio for a SM Higgs boson



Because the lines are not displayed at 95 GeV in the most relevant plots

Figure 11: Behaviour of $-2\ln Q$ in subsets collected at different c.m. energies. In each plot, the full curve shows the observed behaviour, the dashed/dotted lines show the expected behaviour for background/signal+background, and the vertical line indicates the test-mass $m = E_{cm} - M_Z$ GeV, just at the kinematic limit. (The subset labelled 208 GeV has very low statistics.)

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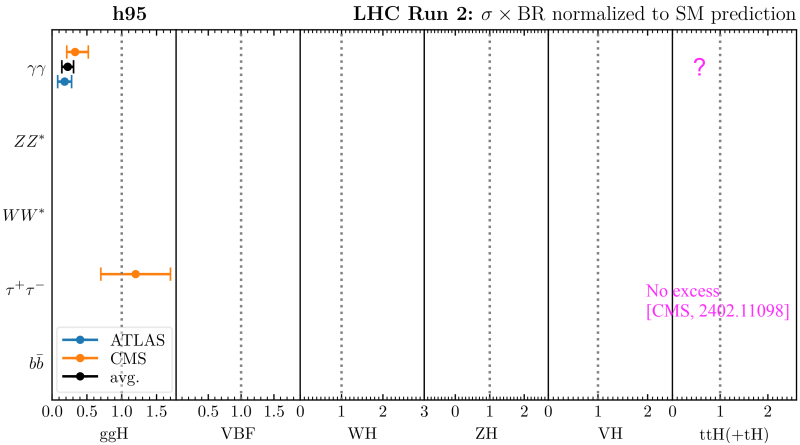
CCT Meeting 14 Sept 2023 2

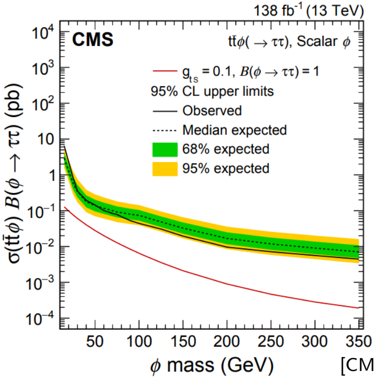
[Slide by P. Janot, CCT Meeting 2023]

h95 after Run 2

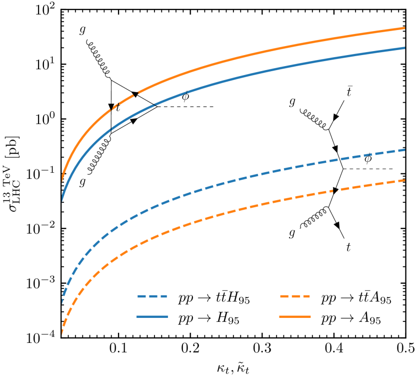
Other relevant channels taking only couplings supported by LHC excesses?
$pp \to t\bar{t}h_{95}$ with $h_{95} \to \tau^+\tau^-$ and $h_{95} \to \gamma\gamma$ look most promising.



CMS: tth with $h \to \tau^+\tau^-$



[CMS, 2402.11098]



$\Rightarrow$ For scalar: $\mu_{\tau\tau} \lesssim 0.5$ $\Rightarrow$ Excludes the $\tau^+\tau^-$ excess at about 2σ

For pseudoscalar: $\mu_{\tau\tau} \lesssim 4.0$ $\Rightarrow$ No constraints

h95: UV-complete models

Authors	Model	arXiv	Excesses	Comments
Cao, Guo, He et al.	nNMSSM	1612.08522	$bb + \gamma\gamma$	
Fox, Weiner	2HDM	1710.07649	$bb + (\gamma\gamma)$	
Haisch, Malinauskas	2HDM	1712.06599	$bb + (\gamma\gamma)$	
TB, Heinemeyer, Muñoz	$\mu\nu$SSM	1712.07475	$bb + \gamma\gamma$	EW seesaw
Liu, Liu, Wagner, Wang	$U(1)_{L_\mu - L_\tau}$	1805.01476	$bb + \gamma\gamma$	B-anomalies
Domingo, Heinemeyer, Paßehr, Weiglein	NMSSM	1807.06322	$bb + \gamma\gamma$	
Hollik, Liebler, Moortgat-Pick et al.	μNMSSM	1809.07371	$bb + \gamma\gamma$	Inflation
TB, Chakraborti, Heinemeyer	N2HDM	1903.11661	$bb + \gamma\gamma$	
Cline, Toma	pNG + squarks	1906.02175	$bb + \gamma\gamma$	DM
Choi, Hui Im, Sik Jeong et al.	gNMSSM	1906.03389	$bb + \gamma\gamma$	
Cao, Jia, Yue et al.	nNMSSM	1908.07206	$bb + \gamma\gamma$	Type-I seesaw
Aguilar-Saavedra, Joaquim	SM + $U(1)_{Y'}$	2002.07697	$bb + \gamma\gamma$	
TB, Olea-Romacho	S2HDM	2108.10864	$bb + \gamma\gamma$	DM, GC excess
TB, Grohsjean, Heinemeyer et al.	NMSSM	2109.01128	$\gamma\gamma$	400 GeV excess
Heinemeyer, Lika, Moortgat-Pick et al.	2HDM+s	2112.11958	$bb + \gamma\gamma$	
TB, Heinemeyer, Weiglein	N2HDM	2203.13180	$bb + (\tau\tau) + \gamma\gamma$	
TB, Heinemeyer, Weiglein	N2HDM	2204.05975	$bb + (\tau\tau) + \gamma\gamma$	CDF M_W
Benbrik, Boukidi, Moretti et al.	A2HDM-III	2204.07470	$bb + \gamma\gamma$	LFV

Green: 2HDM(+X), blue: Susy, red: Extra charged fields

h95: UV-complete models

Authors	Model	arXiv	Excesses	Comments
TB, Heinemeyer, Weiglein	S2HDM	2303.12018	$bb + (\tau\tau) + \gamma\gamma$	DM
Azevedo, TB, Ferreira	C2HDM	2305.19716	$bb + \tau\tau + \gamma\gamma$	
Bonilla, Carcamo, Kovalenko et al.	Left-Right model	2305.11967	$\gamma\gamma$	DM
TB, Heinemeyer, Weiglein	S2HDM	2306.03889	$bb + (\tau\tau) + \gamma\gamma$	DM
Escribano, Martín Lozano, Vicente	Scotogenic	2306.03735	$bb + \gamma\gamma$	DM, ν masses
Belyaev, Benbrik, Boukidi et al.	A2HDM	2306.09029	$bb + (\tau\tau) + \gamma\gamma$	
Ashanuman, Banik, Coloretti et al.	$Y = 0$ triplet	2306.15722	$\gamma\gamma$	CDF M_W
Aguilar-Saavedra, Camara et al.	UN2HDM	2307.03768	$(\tau\tau)$, $\gamma\gamma$	
Dutta, Lahiri, Li et al.	2HDMS	2308.05653	$bb + \gamma\gamma$	
Ellwanger, Hugonie	NMSSM	2309.07838	$bb + (\gamma\gamma)$	
Cao, Jia, Lian et al.	gNMSSM	2310.08436	$bb + \gamma\gamma$	DM
Borah, Mahapatra Paul et al.	2HDM+$U(1)_{L_\mu - L_\tau}$	2310.11953	$\gamma\gamma$	DM, gm2, CDF
Arcadi, Busoni, Cabo-Almeida et al.	2HDM+s/a	2311.14486	$(bb) + \gamma\gamma + (\tau\tau)$	
Ahriche	GM	2312.10484	$bb + \gamma\gamma + (\tau\tau)$	
Coloretti, Crivellin, Mellado	2HDM+S+triplet	2312.17314	$\gamma\gamma$	h_{151}, h_{400}
Cao, Lian	gNMSSM	2402.15847	$bb + \gamma\gamma$	DM, gm2
Kalinowski, Kotlarski	MRSSM	2403.08720	$bb + \gamma\gamma$	DM

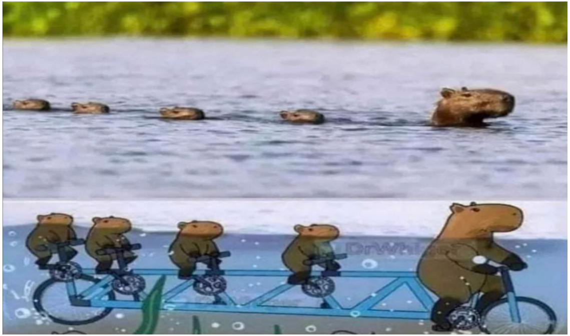
Green: 2HDM(+X), blue: Susy, red: Extra charged fields

h95: UV-complete models

Authors	Model	arXiv	Excesses	Comments
Ellwanger, Hugonie	NMSSM	2403.16884	$bb + \gamma\gamma$	DM, gm2
Ellwanger, Hugonie, King, Moretti	NMSSM	2404.19338	$bb + \gamma\gamma$	DM, $\chi^0\chi^\pm$ excess
Benbrik, Boukidi, Moretti	A2HDM	2405.02899	$bb + \gamma\gamma + \tau\tau$	$h_{95} + A_{95}$
Arhrib, Phan, Tran, Yuan	gauged 2HDM	2405.03127	$bb + (\gamma\gamma)$	$h_{125} \to Zy$ excess
Lian	NMSSM	2406.10969	$bb + \gamma\gamma$	DM
Gao, Ma, Xu	2HDM+S	2408.03705	$bb + \gamma\gamma$	BAU

Green: 2HDM(+X), blue: Susy, red: Extra charged fields

h95: UV-complete models



Two generic lessons:

1. The 95 GeV Higgs boson is not alone
2. Many possible but no direct relation to new-physics questions

   Could come from an SU(2) doublet or triplet, a DM portal, a Majoron, a right-handed sneutrino, ...

Classes of models

1. h_{95} is a component of an SU(2) multiplet
   - 2HDM
   - C2HDM
   - A2HDM
   - $Y = 0$ triplet
   - Georgi-Machacek model
   - ...

2. h_{95} is component of a singlet field (mixing with h_{125})
   - N2HDM
   - S2HDM
   - NMSSM
   - $\mu\nu$SSM
   - Left-right model
   - ...

3. $h_{95} \to \gamma\gamma$ requires extra charged/coloured fields
   - $\mathrm{U}(1)_{L_\mu - L_\tau}$ model
   - $\mathrm{U}(1)_{Y'}$ model
   - UN2HDM
   - Scotogenic model
   - Georgi-Machacek model (?)
   - ...

Classification is not perfect (exclusive), but each group represents the three main features of h_{95} to get the required couplings in the various models

Classes of models

1. h_{95} is a component of an SU(2) multiplet
   - 2HDM
   - C2HDM
   - A2HDM
   - $Y = 0$ triplet
   - Georgi-Machacek model
   - ...

2. h_{95} is component of a singlet field (mixing with h_{125})
   - N2HDM
   - S2HDM
   - NMSSM
   - $\mu\nu$SSM
   - Left-right model
   - ...

3. $h_{95} \to \gamma\gamma$ requires extra charged/coloured fields
   - $\mathrm{U}(1)_{L_\mu - L_\tau}$ model
   - $\mathrm{U}(1)_{Y'}$ model
   - UN2HDM
   - Scotogenic model
   - Georgi-Machacek model (?)
   - ...

A95 in the 2HDM Type I

2HDM interpretations had been discarded due to limited di-photon signal rates

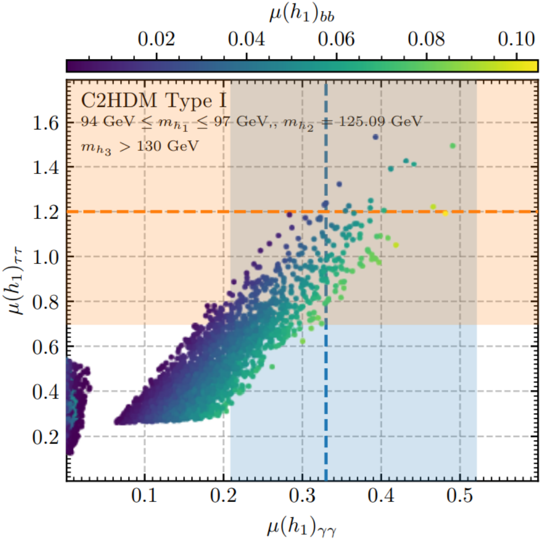
With the updated experimental results the picture has changed

$A_{95} \approx A$ dominantly CP-odd state
$\rightarrow$ LEP excess requires CP violation

Can also describe the di-tau excess, but tensions with indirect constraints from flavour physics and electron EDMs

[D. Azevedo, TB, P. Ferreira, 2305.19716]

ScannerS + HiggsTools



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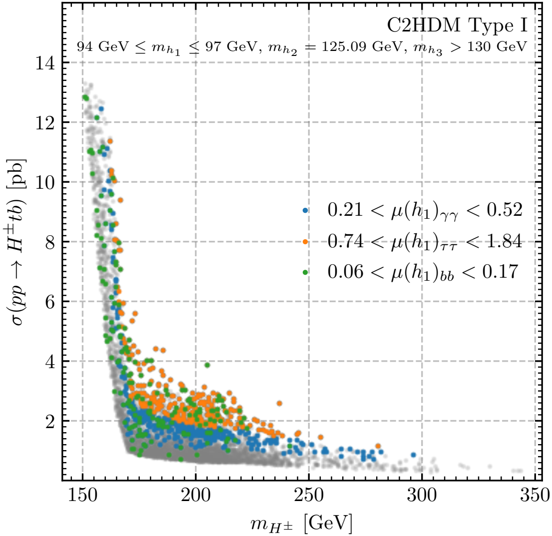
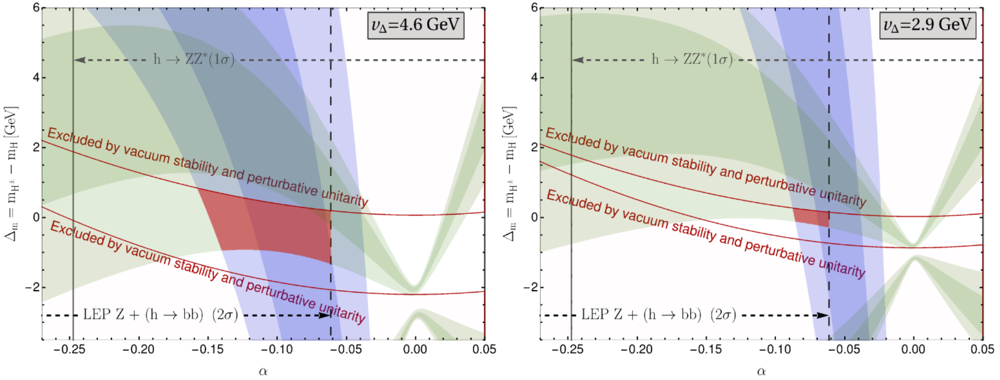


$Y = 0$ Triplet

ΔSM violates custodial symmetry at tree level $\rightarrow$ $M_W^2 = \frac{g_2^2}{4}(v^2 + 4v_\Delta^2)$ (CDF anomaly)



[Ashanuman, Banik, Coloretti, Crivellin, Mellado, Mulaudzi, 2306.15722]

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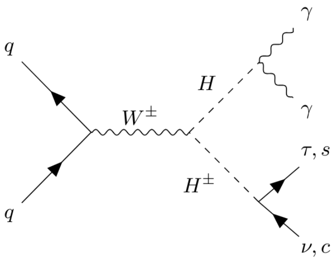

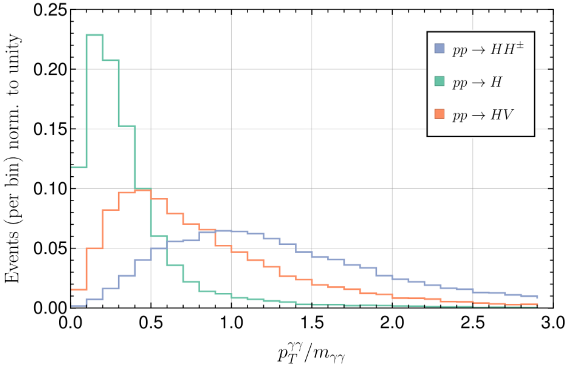

[Ashanuman, Banik, Coloretti, Crivellin, Mellado, Mulaudzi, 2306.15722]

Requires different production mode. Compatible with experimental assumptions?

Classes of models

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- UN2HDM
- Scotogenic model
- Georgi-Machacek model (?)
- ...

The S2HDM

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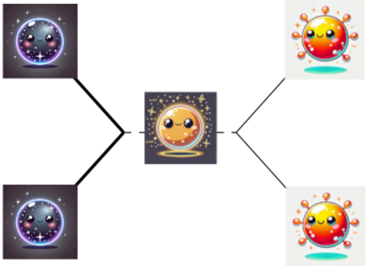
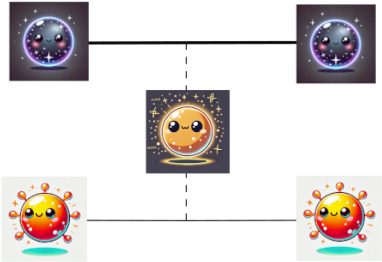
Can we have DM annihilation without scattering?



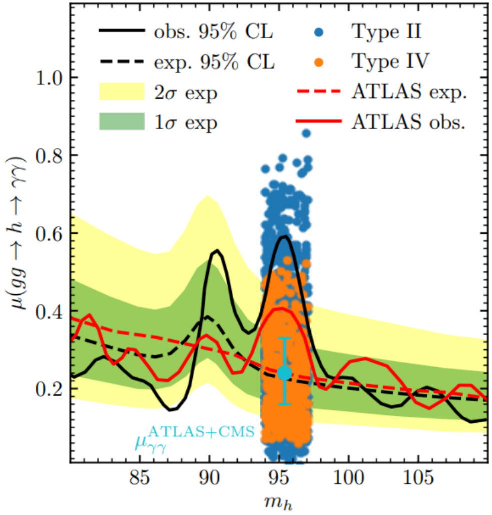


$$\mathcal{L} = \left(\partial_\mu S\right)^* \partial^\mu S - V(\phi_i, S)\big|_{\mathrm{U}(1)} - V(S)\big|_{\cancel{U(1)}-\mathrm{soft}}$$

$$S = \frac{1}{\sqrt{2}}\,(v_S + \phi_S)\,\mathrm{e}^{\mathrm{i}\,\chi/v_S} \quad \Rightarrow \quad \mathcal{L}_{\chi\chi\phi_S} = \frac{1}{2v_s}\left(\partial^2\phi_S\right)\chi\chi - \frac{\phi_S}{v_s}\chi\left(\partial^2 + m_\chi^2\right)\chi$$

"Pseudo-Namub-Goldstone Dark Matter" [Barger et al., 0811.0393]

h95 in the S2HDM



Parameter scan with `s2hdmTools`

[TB, M. O. Olea Romacho, 2108.10864]

Constraints:

- h_{125} signal rate `HiggsBounds`
- Higgs-boson searches `HiggsSignals`
- EWPO
- Vacuum stability `HOM4PS2`
- Perturb. unitarity
- DM relic abundance `micrOMEGAs`
- DM direct detection

[TB, Gabriel, Olea, Santos, 2207.04973]

Fermi galactic center excess

[TB, M. O. Olea Romacho, 2108.10864]

With $\mu_{\gamma\gamma} \sim 0.3$ no preference anymore for Yukawa type II over Type IV

[TB, M. O. Olea Romacho, 2108.10864], [TB, S. Heinemeyer, G. Weiglein, 2303.12018, 2306.03889]

h95 in the S2HDM Type IV

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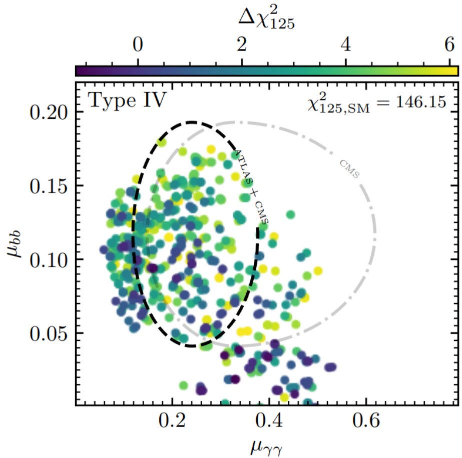
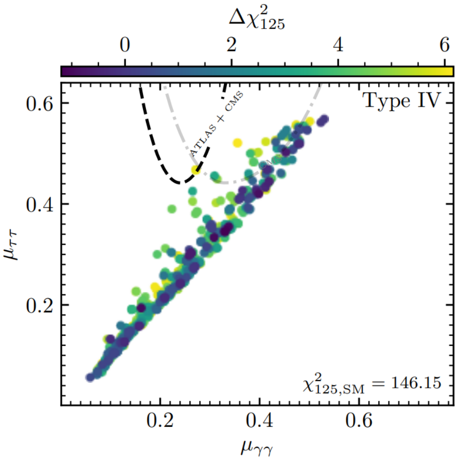




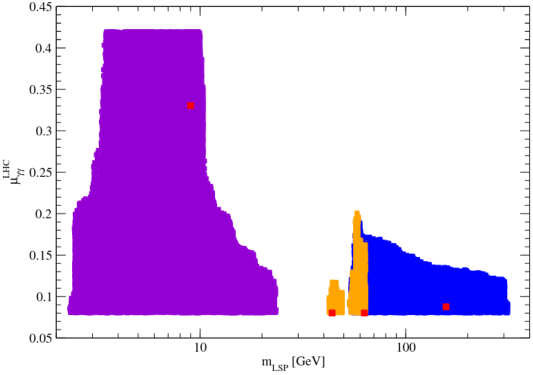
CP-even h_{95}: $\mu_{\tau\tau} \approx \mu^{\mathrm{cms}}_{\tau\tau} = 1.2 \pm 0.5$ in tension with

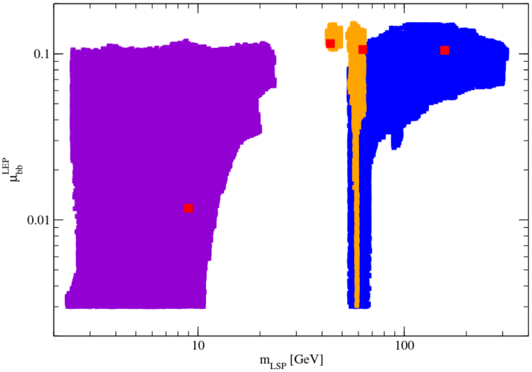
Limits from $pp \to t\bar{t}\phi \to t\bar{t}\tau^+\tau^-$ [CMS, 2402.11098]

[TB, S. heinemeyer, G. weiglein, 2306.03889]

Supersymmetry: NMSSM

The presence of h95 would be a clear indication of beyond-the-MSSM physics





Colours: DM annihilation mechanisms (magenta: A_S-funnel)

[Ulrich Ellwanger, Cyril Hugonie, 2403.16884]

$h_{95} \approx h_S$ mixed with h_{125} to describe $\mu_{\gamma\gamma}$ and μ_{bb}

Singlino LSP $(\Omega h^2 = \Omega h^2|_{\text{Planck}})$

Supersymmetry: NMSSM

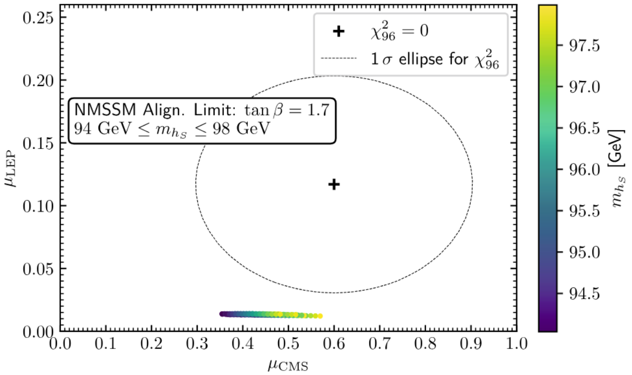
Alignment without decoupling limit

[Carena, Haber, Low, Shah, Wagner, 1510.09137]

Gives $\mu_{\gamma\gamma}$, a SM-like h_{125} and many additional LHC pheno:

- Stops below ≈ 1.5 TeV
- Higgsinos at ≈ 200 GeV
- Singlino below 125 GeV
- H, A and $H^{\pm}$ below ≈ 1 TeV

Prediction: CMS $\tau^+\tau^-$ goes away and LEP $b\bar{b}$ was fluctuation



[TB, Grohsjean, Heinemeyer, Schwanenberger, Weiglein, 2109.01128]

Light NMSSM singlet state with sizable signal rates in $pp \to h_S \to \gamma\gamma$ discussed shortly after the h_{125} discovery

[Barbieri, Buttazzo, Kannike, Sala, Tesi, 1307.4937]

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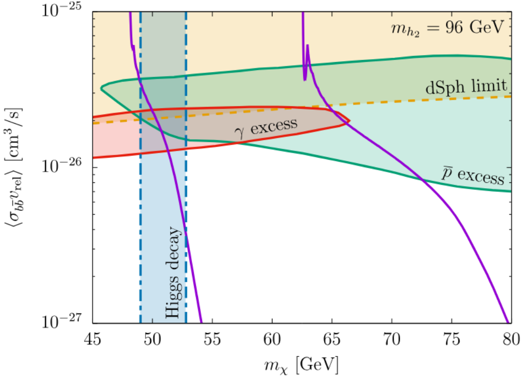
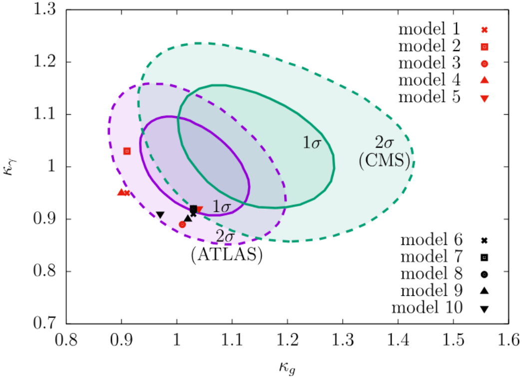
pNG with extra coloured scalar

SM + complex singlet + coloured scalar (pNG dark matter) [J. Cline, T. Toma, 1906.02175]





"γ excess": GCE, purple: $\Omega h^2 = \Omega h^2\big|_{\rm Planck}$

Different models: different charges for coloured scalar

$\mathcal{O}(10\%)$ modifications of h_{125} couplings

Additionally strong limits from LHC searches for coloured scalars

Georgi-Machacek model

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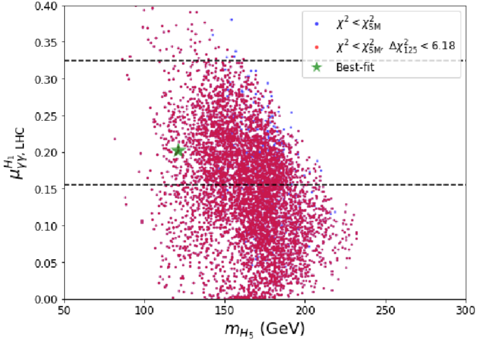
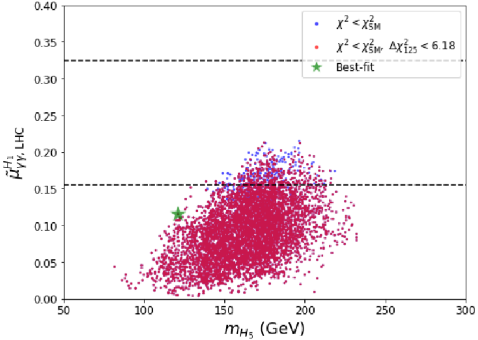
SM + Triplet$_{Y=0}$ + Triplet$_{Y=1}$ with SO(4) $\quad \to \quad \rho^{\text{tree}} = 1$ [Georgi and Machacek, Chanowitz and Golden]

Including $H^{\pm\pm}$-loop



Not including $H^{\pm\pm}$-loop



[Chen, Chiang, Heinemeyer, Weiglein, 2312.13239]

Smoking-gun would be $pp \to H_5^{\pm\pm} \to W^{\pm}W^{\pm}$ with $m_{H_5^{\pm\pm}} \lesssim 200$ GeV

Size of modifications of $h_{125} \to \gamma\gamma$?

Path forward at the LHC

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1. Direct searches for h95

- ATLAS Run 2: $\phi \to \tau^+\tau^-$
- CMS/ATLAS Run 3: $\phi \to \gamma\gamma$
- $pp \to t\bar{t}\phi \to t\bar{t}b\bar{b}$ feasable?

2. Indirectly from h125

- $h_{125} \to VV^*$ (singlet mixing)
- $h_{125} \to \gamma\gamma$ (additional charged fields: $H^\pm, H^{\pm\pm}, \ldots$)

3. Other searches

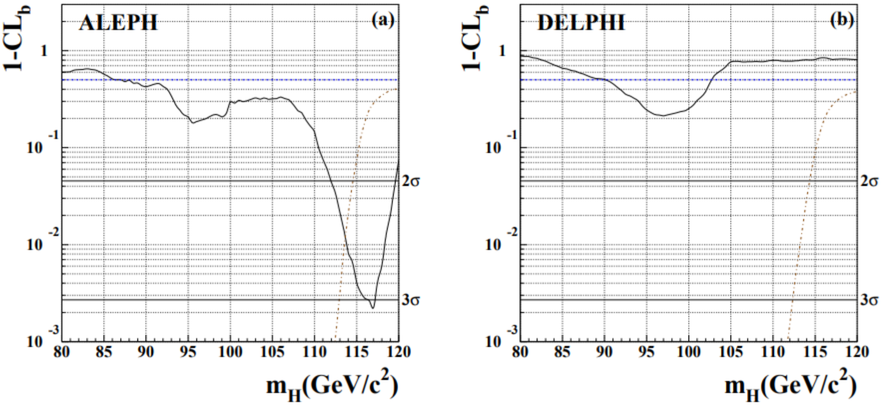
- $H^\pm \to tb/\tau\nu$ for $m_{H^\pm} \sim m_t$
- $H^{\pm\pm} \to W^\pm W^{\pm *} \lesssim 200$ GeV
- Resonant $X \to h_{95}Y$ with with $Y = V/h_{95}/h_{125}$

Other ways to probe h95 with already existing data?

Thanks!

LEP: $e^+e^- \to Zh \to Zb\bar{b}$

Background only confidence across LEP experiments



[LEP, hep-ex/0306033]

LEP: $e^+e^- \to Zh \to Zb\bar{b}$

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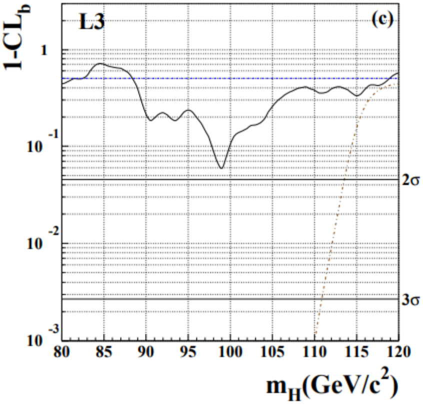

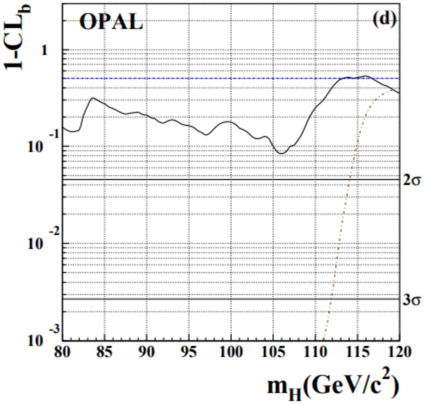

[LEP, hep-ex/0306033]

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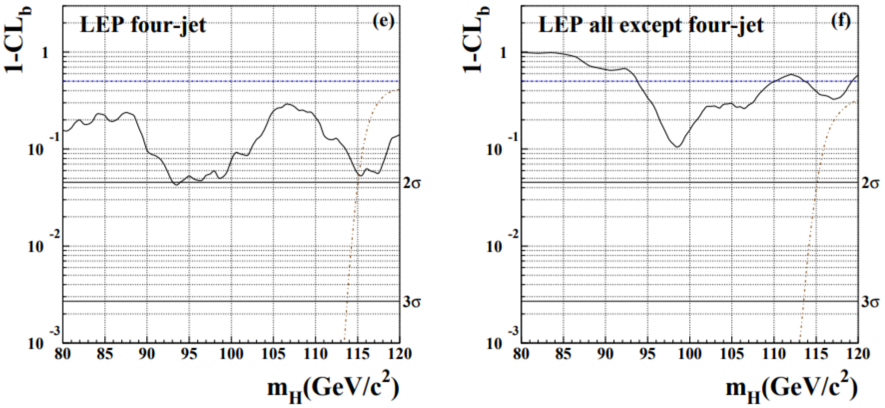

[LEP, hep-ex/0306033]

CMS: low-mass $\gamma\gamma$

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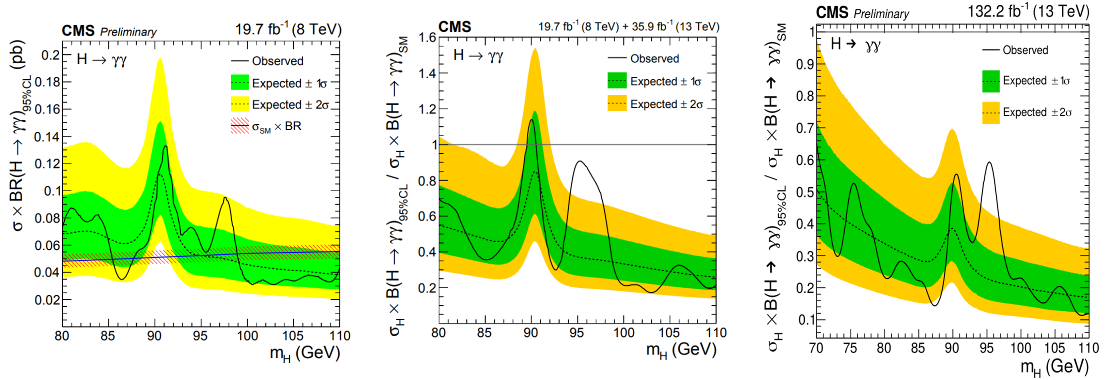
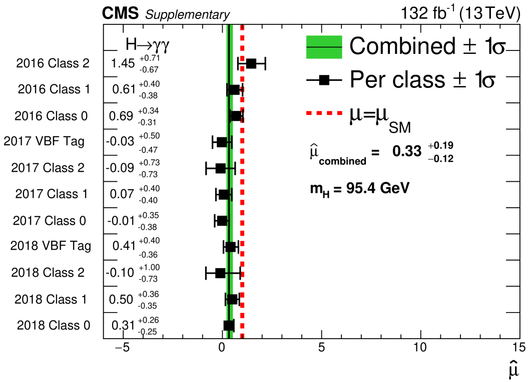
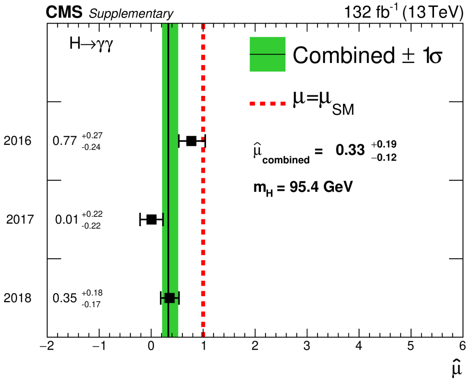
The CMS diphoton excess over time



[CMS-HIG-17-013, CMS-HIG-20-002]

CMS: low-mass $\gamma\gamma$

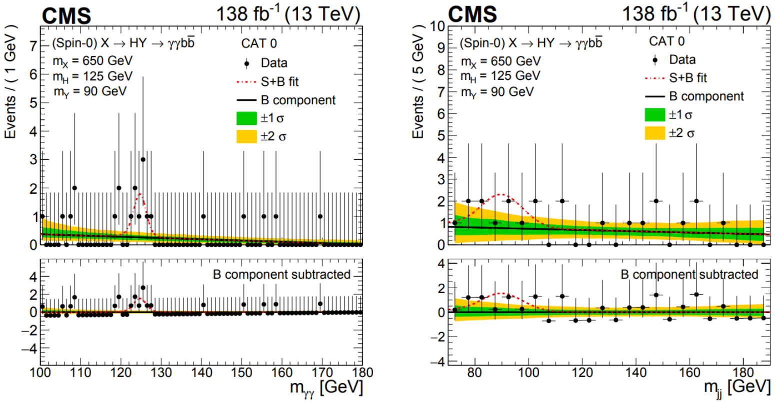




[CMS-HIG-20-002]

CMS: $pp \to X \to YX \to \gamma\gamma b\bar{b}$

$3.8/2.8$ local/global excess: $\sigma(pp \to X_{650} \to H_{125} Y_{90} \to \gamma\gamma b\bar{b}) \sim 0.35$ fb



[CMS, 2310.01643]

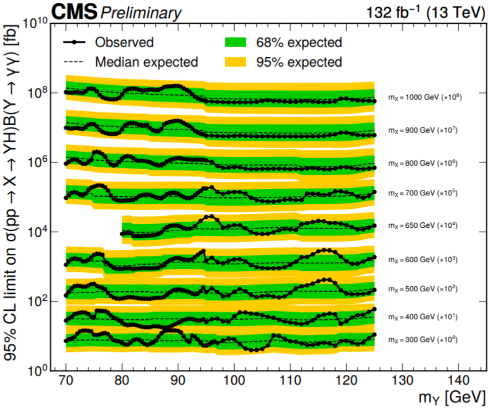
Excluded this year by ATLAS: $\sigma_{95\%\ \mathrm{C.L.}}(pp \to X_{650} \to H_{125} Y_{90} \to \gamma\gamma b\bar{b}) < 0.20$ fb

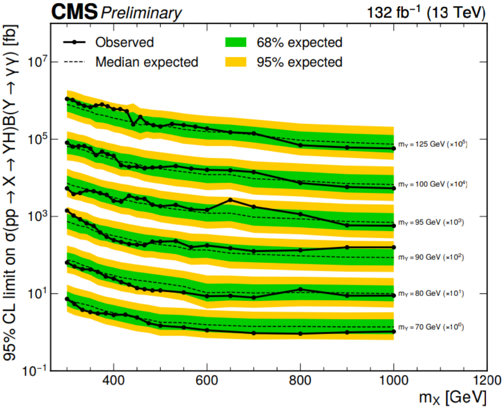
ATLAS should have seen a 2.7σ excess

[ATLAS, 2404.12915]

CMS: $pp \to X \to HY \to \tau^+\tau^-\gamma\gamma$

2.3 local excess: $\sigma(pp \to X_{650} \to H_{125}Y_{95} \to \tau^+\tau^-\gamma\gamma)$

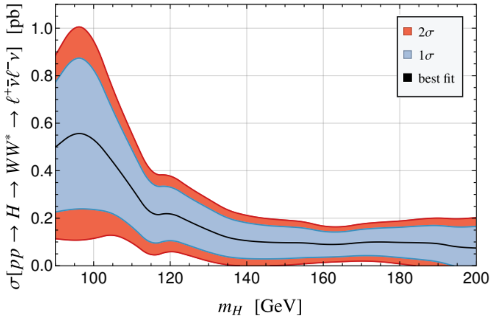


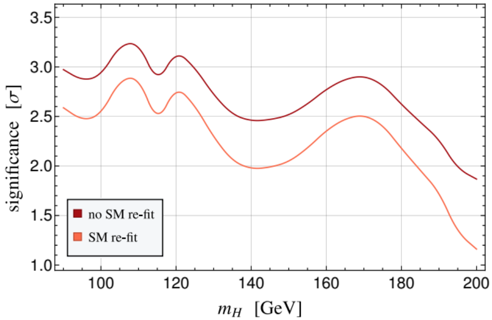


[CMS-PAS-HIG-22-012]

h95 → WW*

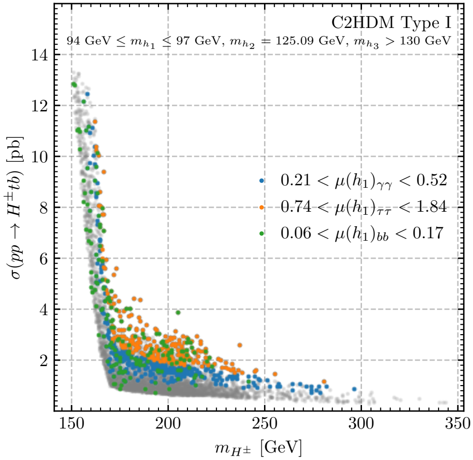
Hints for $h_{95} \to WW^*$ from recasting of $h_{125} \to WW^*$ measurements were reported

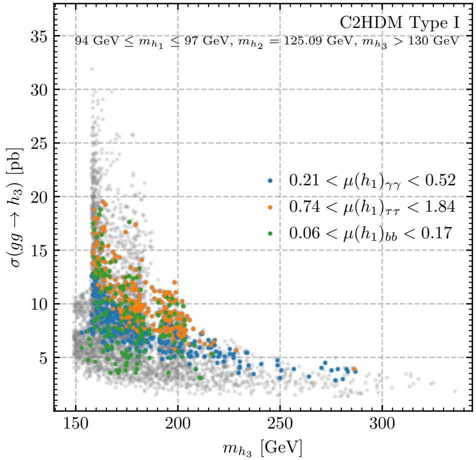




[Coloretti, Crivellin, Bhattacharya, Mellado, 2302.07276]

C2HDM-I: Hide and seek

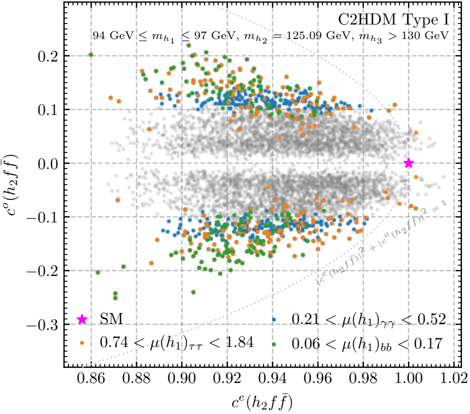




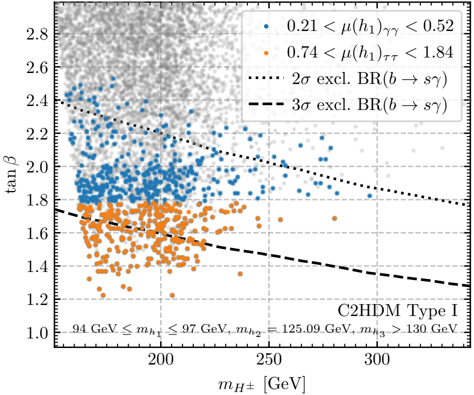
[D. Azevedo, TB, P. Ferreira, 2305.19716]

C2HDM-I: Indirect constraints

CP violation

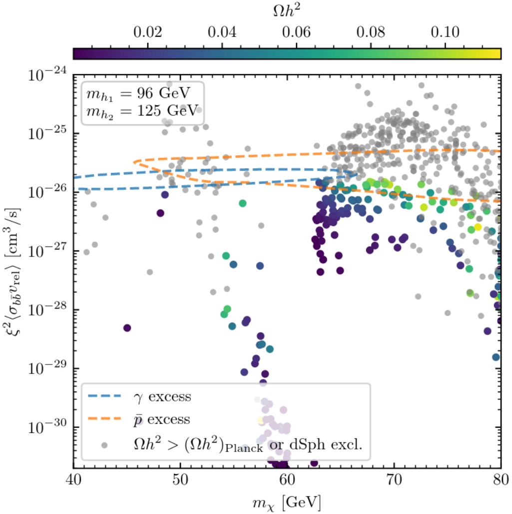


Flavour physics



[D. Azevedo, TB, P. Ferreira, 2305.19716]

h95 in the S2HDM: dark matter



What about dark matter?

Correct relic abundance via "vanilla" freeze-out

DM annihilation: $\chi\chi \to h_{95}/h_{125} \to b\bar{b}$

DM mass: $m_\chi > 62.5$ GeV to describe excesses

$\to$ no $\mathrm{BR}(h_{125} \to \mathrm{inv})$

Today's annihilation cross section and DM mass in the right ballpark for the **galactic-center excess.**

[TB, O. Olea Romacho, 2108.10864]