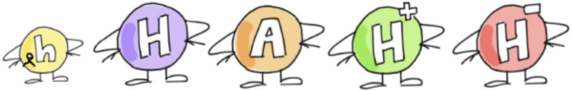
Searches for extra Higgs bosons and the 95 GeV excess(es)

Roadmap of Dark Matter models for Run 3 at CERN

May 16th 2024

Thomas Biekötter

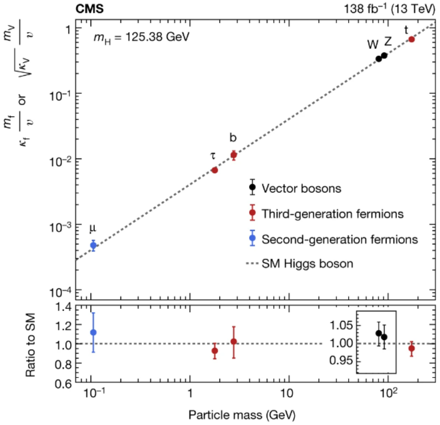


The SM Higgs sector

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

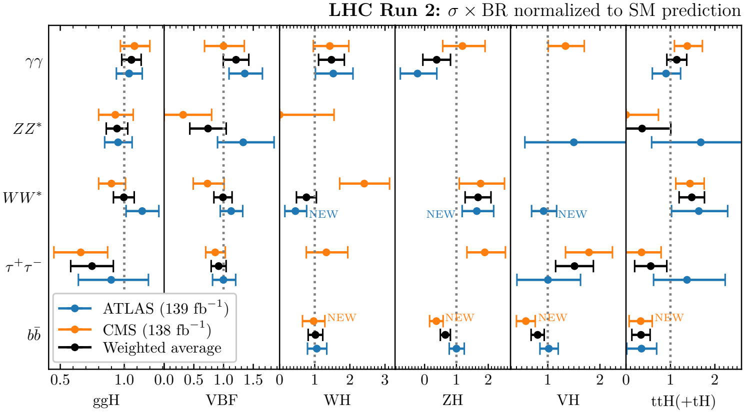


[CMS, 2207.00043]

Any modifications from these predictions → BSM physics

The LHC Run 2 legacy

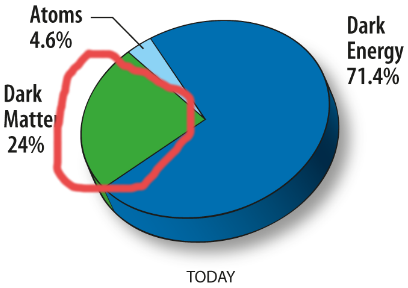
"It is the simple hypotheses of which one must be most wary; because these are the ones that have the most chances of passing unnoticed." – Henri Poincaré

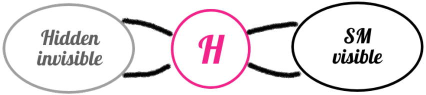


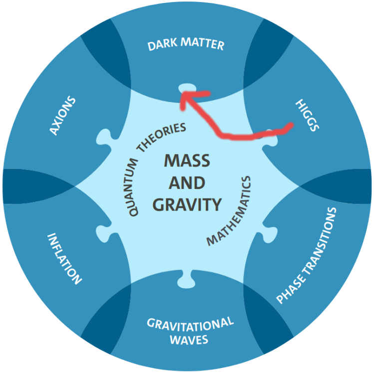
New: After the **10 year anniversary papers**

[CMS: 2103.06956, 2204.12957, **2207.00043**, CMS-HIG-20-001, CMS-PAS-HIG-19-011; ATLAS: 2007.02873, **2207.00092**, ATLAS-CONF-2022-067]

Higgs-portal dark matter



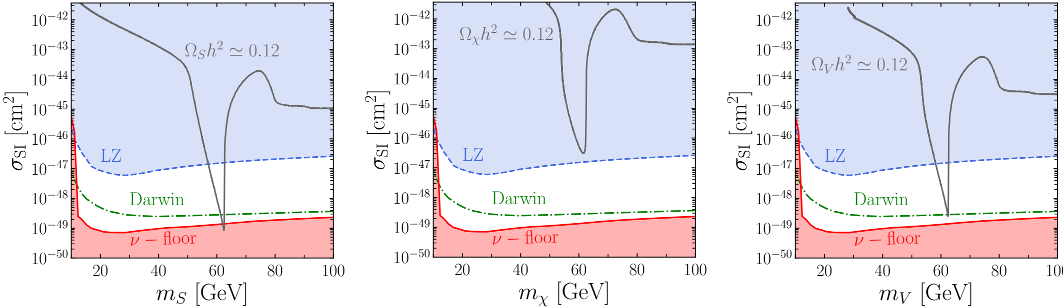




$\dim(\Phi^\dagger\Phi) = \mathrm{GeV}^2 \quad \rightarrow$ 1 of two 2 possible ways for renormalizable portal

Minimal Higgs-portals

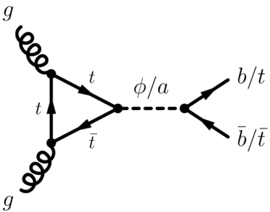
Real scalar DM	Dirac fermion DM	Vector boson DM
$\mathcal{L}_S = -\frac{1}{4}\lambda_S \lvert H\rvert^2 S^2$	$\mathcal{L}_\chi = -\frac{1}{4}\frac{\lambda_\chi}{\Lambda}\lvert H\rvert^2 \bar{\chi}\chi$	$\mathcal{L}_V = -\frac{1}{4}\lambda_V \lvert H\rvert^2 V^\mu V_\mu$



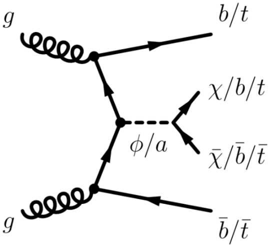
[TB, Mathias Pierre, 2208.05505]

Evading DD constraints → Non-minimal/extended Higgs sectors

Extended Higgs-portals

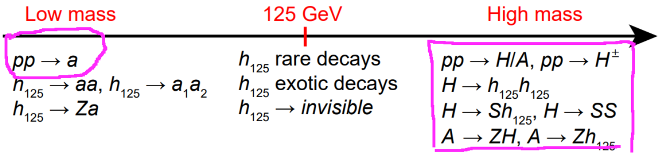


Visible final states



Semi-invisible final states

I will focus mainly on the visible decays



[ATLAS, 2405.04914]

Exotic/invisible decays of h_{125} covered in other talks

Topics

Karlsruher Institut für Technologie

1) `HiggsTools` software

2) Multi-scalar signatures

3) Low-mass searches and h_{95}

1) HiggsTools software

Many new results from Run 2

Karlsruher Institut für Technologie

Decay channel	Production mode	Mass [GeV]	Significance local	Significance global	L [fb^{-1}]	Ref.
$H \to \tau\tau$	b-associated	400	2.7σ	n.a.	139	[48]
$H \to \tau\tau$	ggF	400	2.2σ	n.a.	139	[48]
$H \to \mu\mu$	b-associated	480	2.3σ	0.6σ	36	[49]
$H \to t\bar{t}$	ggF	800	2.3σ	n.a.	140	[51]
$H \to t\bar{t}/tq$	qq and qg	900	2.8σ	n.a.	139	[53]
$H \to ZZ \to 4\ell/2\ell 2\nu$	ggF	240	2.0σ	0.5σ	139	[72]
$H \to ZZ \to 4\ell/2\ell 2\nu$	VBF	620	2.4σ	0.9σ	139	[72]
$H \to \gamma\gamma$	ggF	684	3.3σ	1.3σ	139	[73]
$H \to \gamma\gamma$	ggF	95.4	1.7σ	n.a.	140	[74]
$H \to Z(\ell\ell)\gamma$	ggF	420	2.3σ	n.a.	140	[75]
$H \to Z(q\bar{q})\gamma$	ggF	3640	2.5σ	n.a.	139	[76]
$A \to Zh_{125}(b\bar{b})$	ggF	500	2.1σ	1.1σ	139	[81]
$A \to Zh_{125}(b\bar{b})$	b-associated	500	1.6σ	n.a.	139	[81]
$A \to ZH \to \ell\ell b\bar{b}$	ggF	610 (A), 290 (H)	3.1σ	1.3σ	139	[82]
$A \to ZH \to \ell\ell b\bar{b}$	b-associated	440 (A), 220 (H)	3.1σ	1.3σ	139	[82]
$A \to ZH \to \ell\ell WW$	ggF	440 (A), 310 (H)	2.9σ	0.8σ	139	[82]
$A \to ZH \to \ell\ell t\bar{t}$	ggF	650 (A), 450 (H)	2.9σ	2.4σ	140	[83]
$A \to ZH \to Zh_{125}(b\bar{b})h_{125}(b\bar{b})$	VH	420 (A), 320 (H)	3.8σ	2.8σ	139	[87]
$H^+ \to cb$	$t\bar{t}$ decay	130	3.0σ	2.5σ	139	[90]
$H^+ \to Wa(\mu\mu)$	$t\bar{t}$ decay	120–160 (H^+), 27 (a)	2.4σ	n.a.	139	[92]
$H^+ \to WZ$	VBF	375	2.8σ	1.6σ	139	[93]
$H^{++} \to WW$	VBF	450	3.2σ	2.5σ	139	[95]
$H \to h_{125}h_{125} \to 4b$	ggF	1100	2.3σ	0.4σ	126–139	[108]
$H \to h_{125}h_{125} \to 4b$	VBF	550	1.5σ	n.a.	126	[109]
$H \to h_{125}h_{125} \to b\bar{b}\tau\tau$	ggF	1000	3.1σ	2.0σ	139	[110]
$H \to h_{125}h_{125}$ combination	ggF	1100	3.3σ	2.1σ	126–139	[113]
$X \to Sh_{125} \to b\bar{b}\gamma\gamma$	ggF	575 (X), 200 (S)	3.5σ	2.0σ	140	[118]
$h_{125} \to Z_d Z_d \to 4\ell$	ggF	28	2.5σ	n.a.	139	[129]
$h_{125} \to ZZ_d \to 4\ell$	ggF	39	2.0σ	n.a.	139	[129]
$h_{125} \to aa \to b\bar{b}\mu\mu$	ggF, VBF, VH	52	3.3σ	1.7σ	139	[131]
$h_{125} \to aa \to 4\gamma$	ggF	10–25	1.5σ	n.a.	140	[136]
$h_{125} \to e\tau$ and $h_{125} \to \mu\tau$	ggF, VBF, VH	125	2.1σ	n.a.	138	[144]

Recent summary of searches for extra Higgs bosons:

[ATLAS, 2405.04914]

So far no evidence for new Higgs boson,
but so many new limits!

How do I know if my model is still allowed?

→ HiggsTools

HiggsTools

The new software package `HiggsTools` incorporates `HiggsBounds` and `HiggsSignals`

[H. Bahl, TB, S. Heinemeyer, C. Li, S. Paasch, G. Weiglein, J. Wittbrodt: 2210.09332]

History of `HiggsBounds` and `HiggsSignals`

Former members: Philip Bechtle, Oliver Brein, Karina E. Williams, Oscar Stal,
Tim Stefaniak, Daniel Dercks, Tobias Klingl, Jonas Wittbrodt

`HiggsBounds` confronts models with cross-section limits from collider searches

- 02/2009, v.1 LEP and Tevatron limits
- 08/2010, v.2 Added support for charged scalars
- 05/2011, v.3 LHC 7 TeV limits included
- 05/2013, v.4 LHC 8 TeV limits included
- 03/2017, v.5 LHC 13 TeV limits included
- 10/2022 Incorporation in HT

`HiggsSignals` confronts models with cross-section and mass measurements of h_{125}

- 05/2013, v.1 Tevatron and LHC 7/8 TeV data
- 03/2017, v.2 LHC 13 TeV data included
- 10/2022 Incorporation in HT

HiggsBounds

Compares the predicted signal rates to experimental 95% CL limits:

For each Higgs boson H_i: $r_i = \dfrac{\sigma_i^{\text{pred}}}{\sigma_{\text{obs}}^{95\%\text{CL}}}$, If $r_i < 1$ for all $H_i \Rightarrow$ parameter point is allowed.

The "r-ratios" r_i are computed only for the most sensitive search based on the expected limit

```
import Higgs.predictions as HP
import Higgs.bounds as HB

pred = HP.Predictions()
H = pred.addParticle(HP.NeutralScalar("H", "even"))
H.setMass(95.0)
HP.effectiveCouplingInput(H, HP.smLikeEffCouplings)
bounds = HB.Bounds("/Path/To/HBDataSet")
res = bounds(pred)
print(res)
```

HiggsBounds

Compares the predicted signal rates to experimental 95% CL limits:

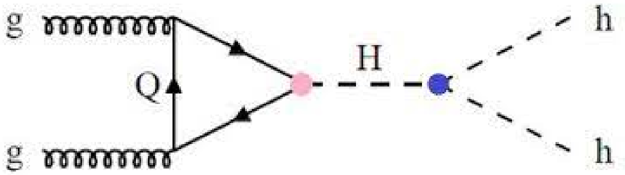
For each Higgs boson H_i: $r_i = \dfrac{\sigma_i^{\text{pred}}}{\sigma_{\text{exp}}^{95\%\text{CL}}}$, If $r_i < 1$ for all $H_i \Rightarrow$ parameter point is allowed.

The "r-ratios" r_i are computed only for the most sensitive search based on the expected limit

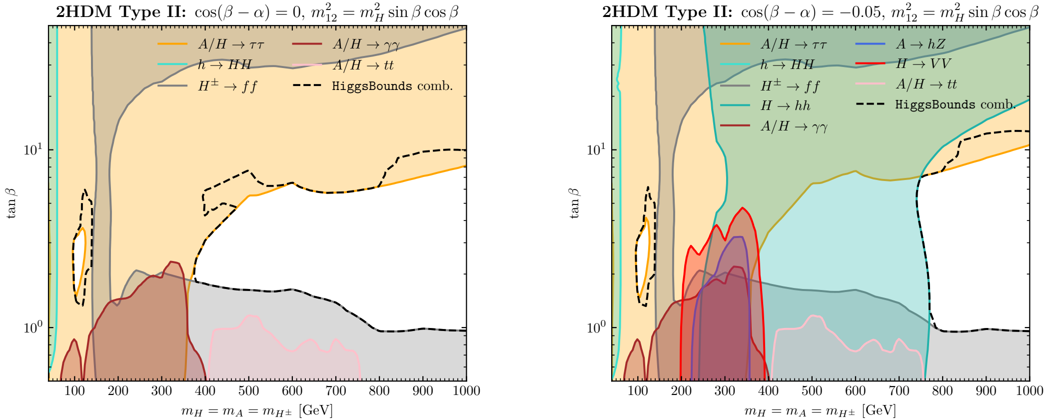
```
HiggsBounds result: excluded
particle | obsRatio | expRatio | selected limit description
---------|----------|----------|--------------------------
    H    |   3.839  |   7.232  | LEP [eeHZ>bb] from hep-ex/0306033 (LEPC
```

2) Multi-scalar signatures

2HDM Type II: $H \to hh$



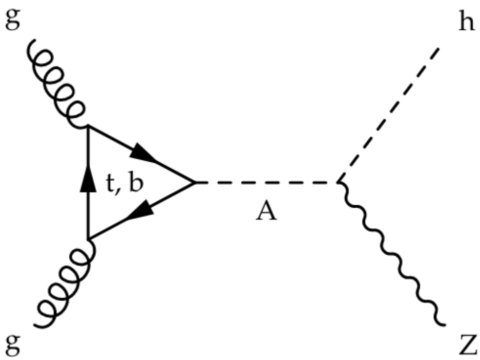
2HDM Type II: $\mathrm{H} \to \mathrm{hh}$



$H \to hh$ searches probe the **"wedge"** even for very small departures from the alignment limit

[`HiggsTools` + `thdmTools`: you can easily make such plots in a small (interactive) python script]

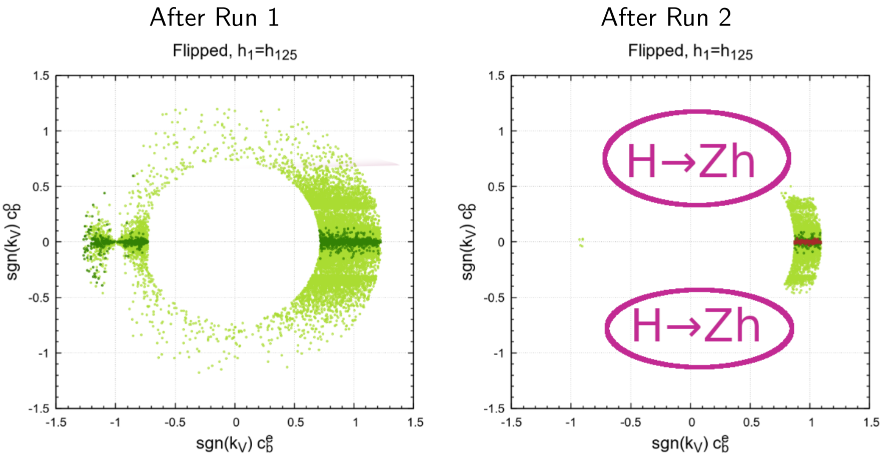
2HDM and CP violation



2HDM and CP violation

Multi-scalar searches probe the CP nature of h_{125}

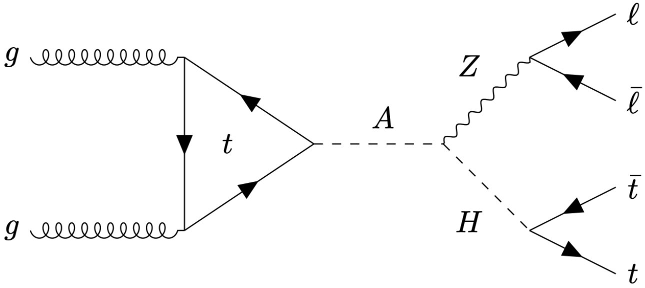
$pp \to H \to Zh \to \ell^+ \ell^- b\bar{b}$ [ATLAS, 1804.01126], [CMS, 1903.00941]



[TB, Fontes, Mühlleitner, Romão, Santos, Silva, 2403.02425]

Crucial information for viability of EW baryogenesis

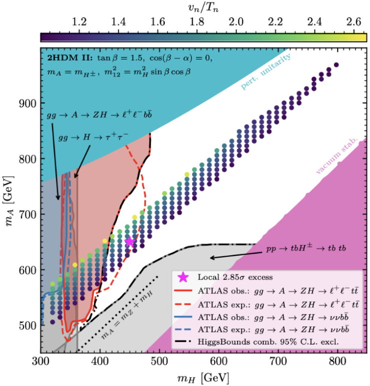
2HDM and a 1st-order EW PT

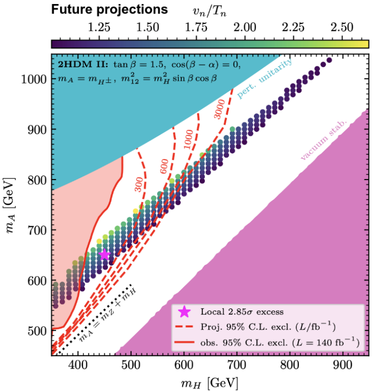


2HDM and a 1st-order EW PT

Multi-scalar searches involving 2 BSM scalars: the smoking gun $gg \to A \to ZH \to \ell^+\ell^- t\bar{t}$

[Dorsch, Huber, Konstandin, No, 2014] [ATLAS, 2311.04033], [CMS, PAS-B2G-23-006]





[TB, Heinemeyer, Olea-Romacho, No, Radchenko, Weiglein, 2309.17431]

Probes so far unexplored region above $t\bar{t}$ threshold (red) favoured by 1st-order EW PT

LHC shapes expectation for GW signals at LISA (Excess at $m_A/m_H = 650/450$ GeV not confirmed by CMS)

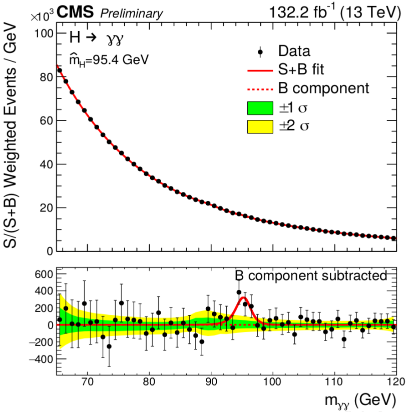
Topics

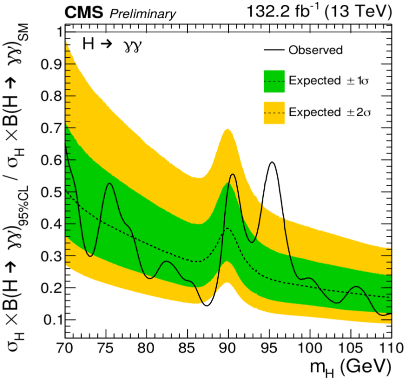
Karlsruher Institut für Technologie

3) Low-mass searches and h_{95}

A dark Higgs boson at 95 GeV?

CMS: low-mass $\gamma\gamma$ searches





[CMS: CMS HIG-20-002]

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

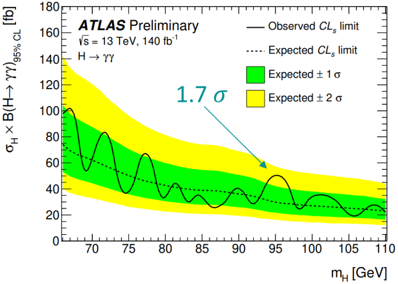
Final Run 2 results:

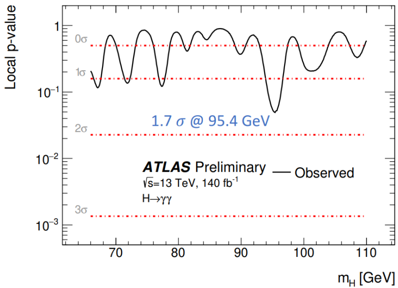
$\mu_{\gamma\gamma}^{\mathrm{CMS}} = 0.33^{+0.19}_{-0.12}$

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

ATLAS: low-mass $\gamma\gamma$ searches

[ATLAS-CONF-2023-035]





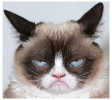
Most significant excess at 95 GeV

$$\mu_{\gamma\gamma}^{\text{ATLAS Run 2}} \approx 0.18 \pm 0.10$$

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

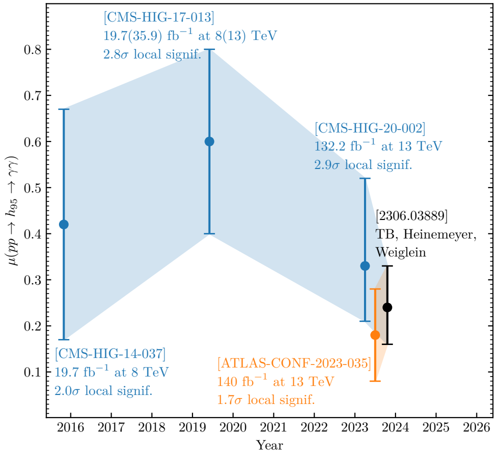
Local 1.7σ excess at **95 GeV**

Local 1.7σ excess at 95 GeV

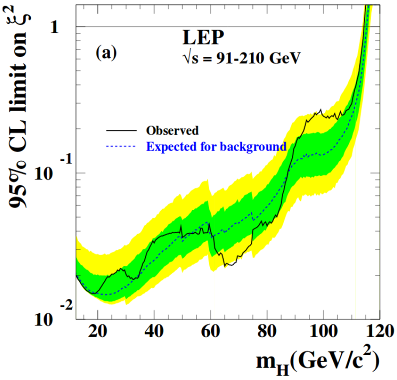


h95: The current picture

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



Further excesses at 95 GeV:

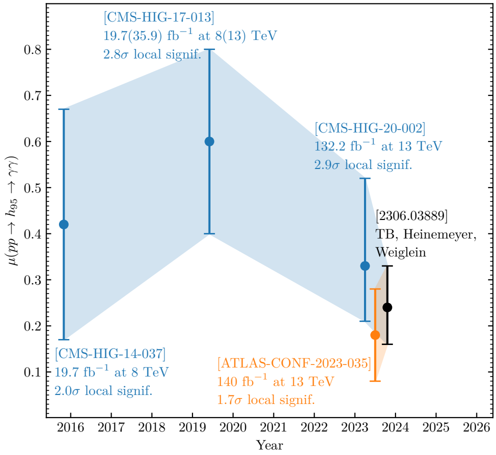


[LEP, hep-ex/0306033]

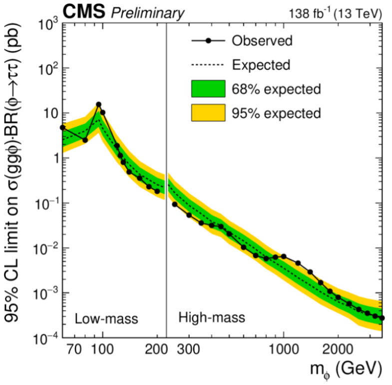
$$\mu_{bb}^{\text{LEP}}(e^+e^- \to Z \to Zh_{95} \to Zb\bar{b}) \approx 0.11 \pm 0.05$$

h95: The current picture

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



Further excesses at 95 GeV:



[CMS, 2208.02717]

$\mu_{\tau\tau}^{\text{CMS}}(gg \to h_{95} \to \tau^+\tau^-) \approx 1.2 \pm 0.5$

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 M_W
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	$\gamma\gamma$	151/400 GeV excesse
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

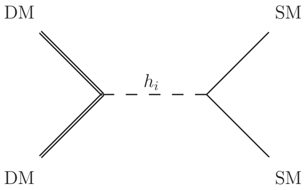
h95: UV-complete models

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
Arhrib, Phan, Tran, Yuan	gauged 2HDM	2405.03127	$bb + (\gamma\gamma)$	$h_{125} \to Zy$ excess

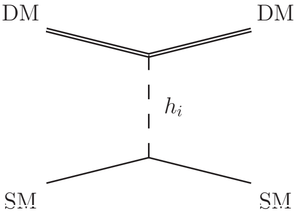
Green: 2HDM(+X), blue: Susy, red: Extra charged fields

The singlet-extended 2HDM

Relic abundance:
DM annihilation



Direct detection:
DM scattering



Can we have one without the other?

The singlet-extended 2HDM

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S: Complex field charged under a softly-broken global U(1)

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

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

On-shell χ interactions with Higgs sector proportional to momentum of s

Vanishing DM-nucleon scattering at classical level
in limit of zero-momentum exchange

Pseudo Nambu-Goldsone Dark Matter

[Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy, 0811.0393]

The singlet-extended 2HDM

S2HDM = **2HDM**(ϕ_1, ϕ_2) + complex singlet Φ_S [TB, M.O. Olea Romacho, 2108.10864]

Higgs potential

$$V = V_{\text{2HDM}}(\Phi_1, \Phi_2)|_{\mathbb{Z}_2} + m_{12}^2 \left(\Phi_1 \Phi_2^\dagger + \text{h.c.}\right) + V_{\text{portal}}(\Phi_1, \Phi_2, \Phi_S)|_{U(1)} - \frac{\mu_\chi}{4} \left(\Phi_S^2 + \text{h.c.}\right)$$

13 free parameters (2 fixed by experiment):

$$m_{H_1} = 125 \text{ GeV},\ m_{H_2},\ m_{H_3},\ m_A,\ m_{H^\pm},\ m_\chi,\ \alpha_{1,2,3},\ \tan\beta,\ m_{12}^2,\ v = 246 \text{ GeV},\ v_S$$

EW vacuum:

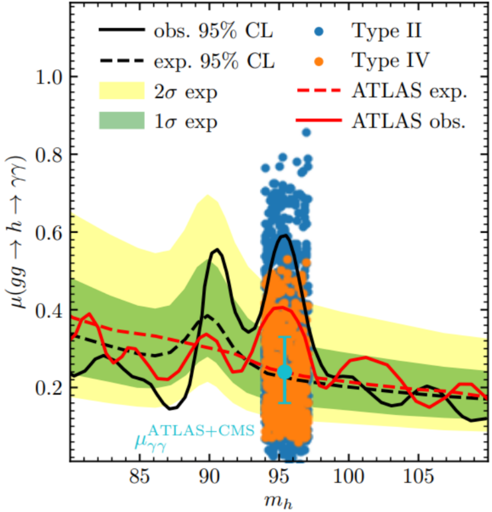
$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}, \quad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix}, \quad \langle \Phi_S \rangle = v_S/\sqrt{2} \quad \in \mathbb{R} \quad \tan\beta := v_2/v_1$$

Visible sector:

3 CP-even scalars $h_1 = h_{95}$, $h_2 = h_{125}$, h_3 1 CP-odd scalar A 2 charged scalars $H^\pm$

Dark sector: Scalar pseudo-Nambu-Goldstone (pNG) dark matter state χ $\rightarrow$ **Faint to DD**

h95 in the S2HDM



Scan in S2HDM type II and type IV (flipped) using genetic algorithm

Code: `s2hdmTools`

[TB, O. Olea Romacho, 2108.10864]

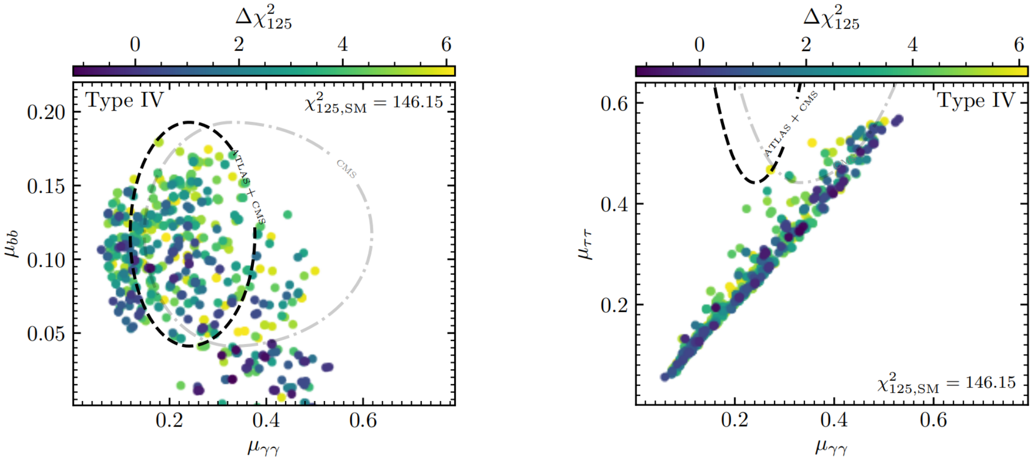
Constraints: h_{125}, searches, EWPO, vacuum stability, perturb. unitarity, DM relic abundance, DM direct detection

Direct detection: [TB, P. Gabriel, O. Olea Romacho, R. Santos, 2207.04973]

Due to reduced signal strength no preference anymore for Yukawa type II

[TB, S. Heinemeyer, G. Weiglein, 2303.12018, 2306.03889]

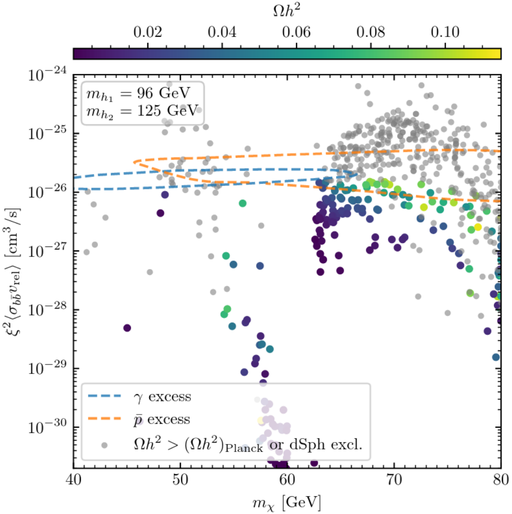
h95 in the S2HDM Type IV/FL



CP-even h_{95}: $\mu_{\tau\tau} \approx \mu_{\tau\tau}^{\text{CMS}} = 1.2 \pm 0.5$ 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]

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]

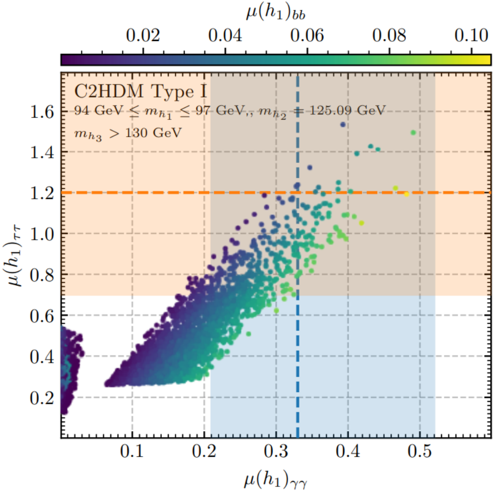
A95 in the 2HDM Type I

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
$\rightarrow$ Enhanced ggA production XS
$\rightarrow$ Smaller $t\bar{t}A$ production XS
$\rightarrow$ LEP excess requires CP violation

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



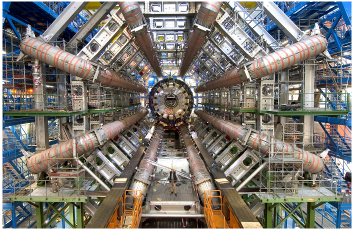
[D. Azevedo, TB, P. Ferreira, 2305.19716]

The end

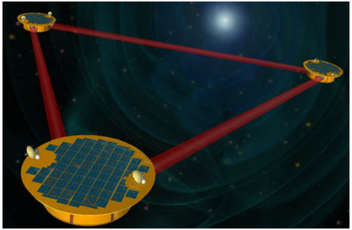
By going from 8 TeV to 13 TeV we do not just get “stronger limits“.

We are able to probe conceptual features of BSM theories that have not been experimentally accessible before!

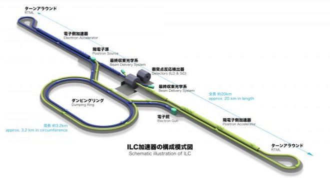
LHC



LISA



Higgs factory (?)



Thanks!