Possible indications for new Higgs bosons in the reach of the LHC: N2HDM and NMSSM interpretations

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[2109.01128]

HiggsDays 2021 [in person! :)], Santander, Spain

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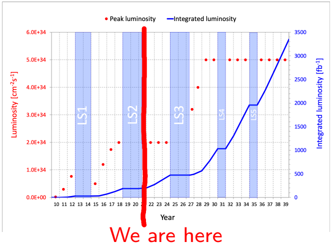
DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

New physics at the LHC?

Usually, BSM models contain an extended Higgs sector,
but so far no clear evidence for BSM physics at the LHC

Not the end of the story:



[lhc-commissioning.web.cern.ch]

Hints as to where new physics could be hiding?

Several Higgs-boson searches show excesses at roughly 400GeV

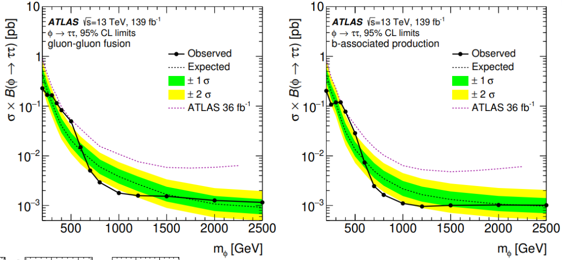
In addition: "CMS and LEP excesses" at 96GeV

A common origin of the excesses at 96/400GeV?

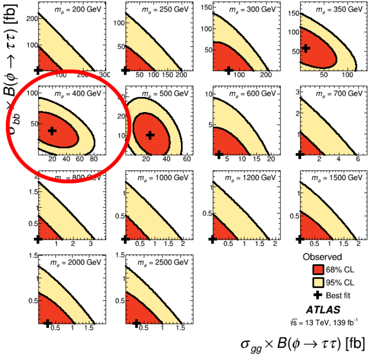
Two concrete model realizations:
Higgs bosons at 400 GeV and 96 GeV in the N2HDM and the NMSSM

Experimental anomalies at about 400GeV

"The $\tau^+\tau^-$ excess" at ~ 400 GeV



[ATLAS: 2002.12223]



[ATLAS: 2002.12223]

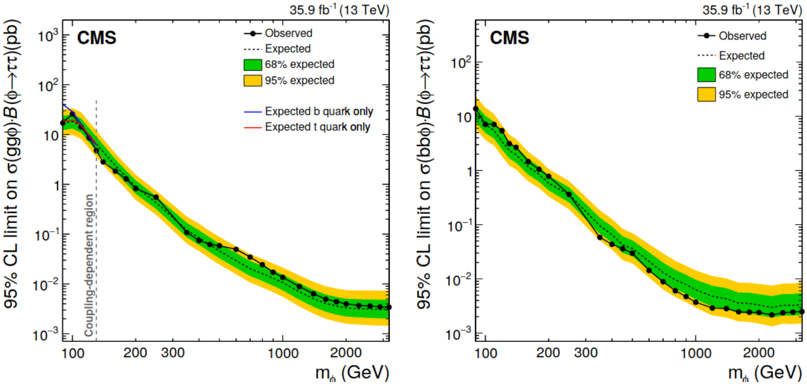
Local excess of 2.7σ at ~ 400 GeV
Global significance below 2σ

Here: $\chi^2_{\tau^+\tau^-}(\sigma_{gg} \times B_{\phi\to\tau^+\tau^-}, \sigma_{bb} \times B_{\phi\to\tau^+\tau^-})$
for $m_\phi = 400$ GeV

Both prodution modes relevant:
$\Rightarrow \sigma_{bb} \sim 2\sigma_{gg}$

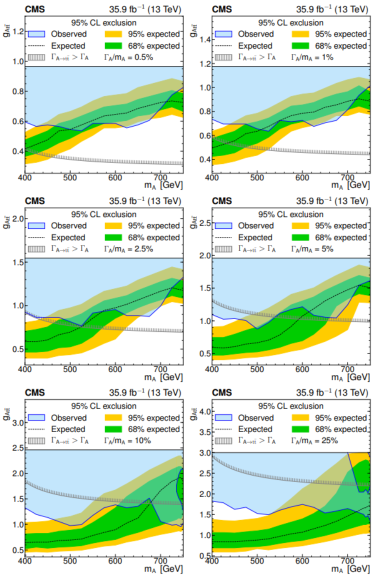
No excess in CMS analyses, but only $35.9\mathrm{fb}^{-1}$
[CMS: 1803.06553]

"The $\tau^+\tau^-$ excess" at $\sim$ 400 GeV

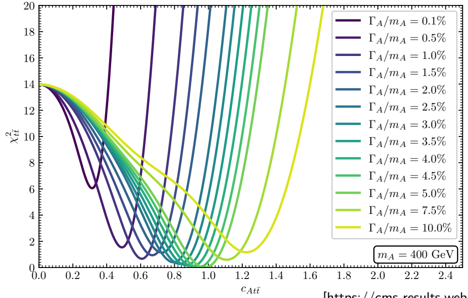


[CMS: 1803.06553]

"The $t\bar{t}$ excess" at $\sim$ 400 GeV



[CMS: 1908.01115]



[https://cms-results.web.cern.ch]

Local excess of 3.5σ at $\sim$ 400 GeV
Global significance below 2σ

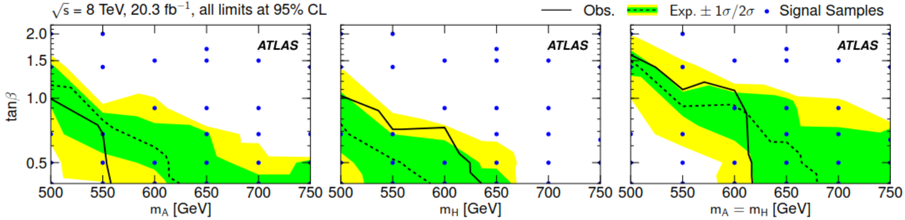
Consistent with a pseudoscalar Higgs boson at $\sim$ 400 GeV

Most significant for $\Gamma_A/m_A = 4\%$ and $c_{At\bar{t}} \sim 1$, but also consistent with slightly different m_A and Γ_A/m_A $\rightarrow \chi^2_{t\bar{t}}(m_A, \Gamma_A/m_A, c_{At\bar{t}})$

Corresponding ATLAS limits only for $m_A > 500$ GeV and only 8 TeV data

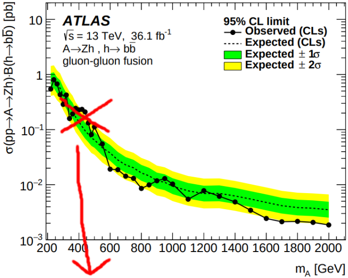
[ATLAS: 1707.06025]

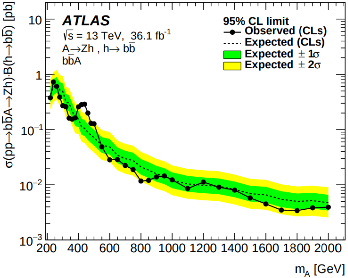
“The $t\bar{t}$ excess” at ~ 400 GeV



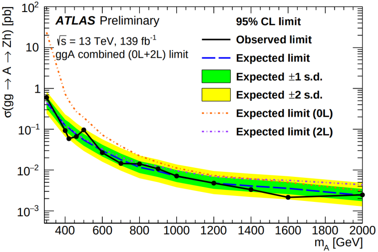
[ATLAS: 1707.06025]

“The Zh excess” at ~ 400 GeV





[ATLAS: 1712.06518]



[ATLAS-CONF-2020-043]

ATLAS 36fb^{-1}:

- Local excess (3.6σ) in $b\bar{b} \to A \to Zh$:)
- Local excess ($\sim 2\sigma$) in $gg \to A \to Zh$:)

CMS 36fb^{-1}:

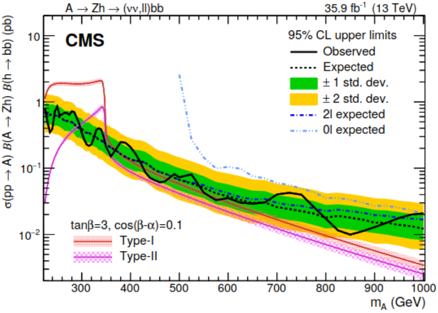
- Small local excess (2σ) in $b\bar{b} \to A \to Zh$:I
- No excess in $gg \to A \to Zh$:([CMS: 1903.00941]

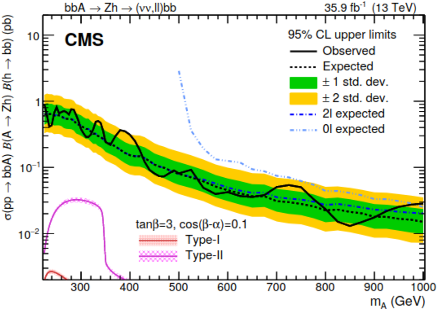
ATLAS 139fb^{-1}:

- No excess in $gg \to A \to Zh$:(

Excess in $b\bar{b}$ still alive, but no clear picture...

"The Zh excess" at ~ 400 GeV

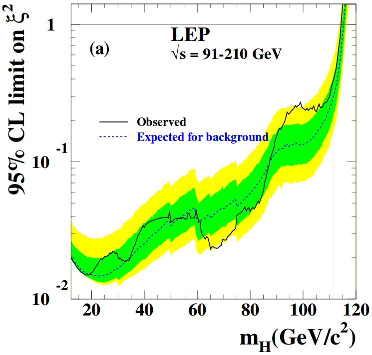




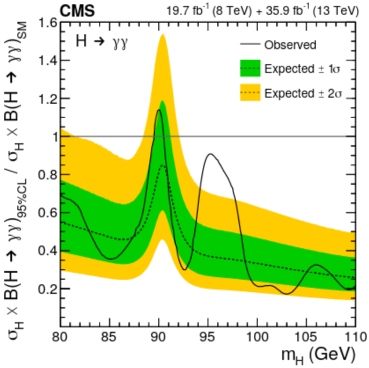
[CMS: 1903.00941]

Experimental anomalies at about 96GeV

"The 96GeV excesses" (LEP and CMS)



[LEP: hep-ex/0306033]



[CMS: 1811.08459]

$\sim 2\sigma$ local excess at 96 - 98GeV

Extracted signal strength:
$\mu_{\rm LEP}\ (e^+e^- \to Zh \to Zb\bar{b}) = 0.117 \pm 0.057$
[1612.08522]

Run I/II data: Local excess of $\gtrsim 3\sigma$

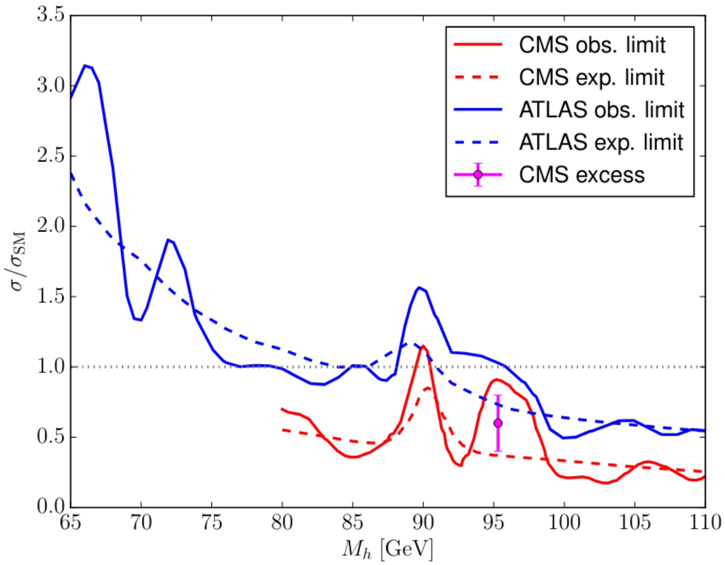
Extracted signal strength:
$\mu_{\rm CMS}\ (gg \to h \to \gamma\gamma) = 0.6 \pm 0.2$

$\to \chi^2_{96}(\mu_{\rm LEP}, \mu_{\rm CMS})$ assuming no correlation between $\mu_{\rm LEP}$ and $\mu_{\rm CMS}$

Many model interpretations with common origin of both excesses, including N2HDM and NMSSM

see [T.B, M. Chakraborti, S. Heinemeyer: 2003.05422] for a list models

"The 96GeV excesses" (LEP and CMS)



[1812.05864]

N2HDM

The Next-to 2 Higgs Doublet Model: N2HDM

N2HDM $=$ 2HDM-I/II/III/IV(ϕ_1, ϕ_2) $+$ Real Scalar Singlet(ϕ_s), $\mathbb{Z}_2'$: $\phi_s \to -\phi_s$

$\mathbb{Z}_2'$ spontaeusly broken when $\langle \phi_s \rangle = v_s \neq 0$ $\Rightarrow \phi_{1,2,s}$ are mixed

Higgs sector

CP-even Higgs bosons $h_{1,2,3}$, pseudoscalar A, charged Higgs bosons $H^\pm$

1. Pseudoscalar A as the origin of the $t\bar{t}$ and the $\tau^+\tau^-$ excesses at ~ 400 GeV

$\tan\beta = \frac{v_1}{v_2}$

Yukawa type	$\lvert c_{At\bar{t}} \rvert$	$\lvert c_{A\tau\bar{\tau}} \rvert$	$\lvert c_{Ab\bar{b}} \rvert$
I	$1/\tan\beta$	$1/\tan\beta$	$1/\tan\beta$
II	$1/\tan\beta$	$\tan\beta$	$\tan\beta$
III	$1/\tan\beta$	$\tan\beta$	$1/\tan\beta$
IV	$1/\tan\beta$	$1/\tan\beta$	$\tan\beta$

$\tau^+\tau^-$ can only be realized in type II

In combination with $t\bar{t}$ excess?

2. Pseudoscalar A at 400 GeV and in addition a scalar h_1 at ~ 96 GeV?

Type II and IV can realize the 96 GeV excesses

[T.B, M. Chakraborti, S. Heinemeyer: 1903.11661]

$\rightarrow$ Simultaneously also the $t\bar{t}$ or (and) the $\tau^+\tau^-$ excess

Constraints: Vacuum stability, tree-level perturbative unitarity, collider searches, h_{125} signal rates, flavour physics observables, electroweak precision observables

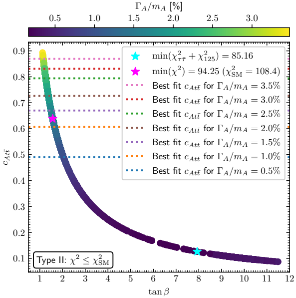
Codes: `ScannerS`, `N2HDECAY`, `SusHi`, `HiggsBounds`, `HiggsSignals`

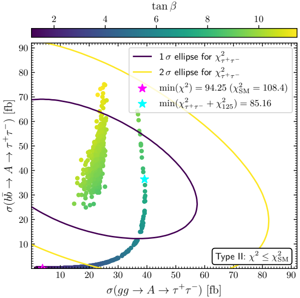
A 400 GeV pseudoscalar in the type II N2HDM

$$\chi^2 = \chi^2_{125} + \chi^2_{t\bar{t}} + \chi^2_{\tau^+\tau^-} \text{ , we demand: } \chi^2 \leq \chi^2_{\rm SM}$$

$$20\ \text{GeV} \leq m_{h_{a,c}} \leq 1000\ \text{GeV}\ , \quad m_{h_b} = 125.09\ \text{GeV}\ , \quad m_A = 400\ \text{GeV}\ ,$$

$$550\ \text{GeV} \leq m_{H^\pm} \leq 1000\ \text{GeV}\ , \quad 10\ \text{GeV} \leq v_S \leq 1500\ \text{GeV}\ , \quad 0.5 \leq \tan\beta \leq 12.5$$





(Also the "$A \to Zh$" excess can be realized) $\to$ Later

Both the $t\bar{t}$ and the $\tau^+\tau^-$ excesses can be realized, but not simultaneously

$\tan\beta \lesssim 2.5$ for $t\bar{t}$ excess
$\tan\beta \gtrsim 5.5$ for $\tau^+\tau^-$ excess

A 400 GeV pseudoscalar and a 96 GeV scalar in the type II N2HDM

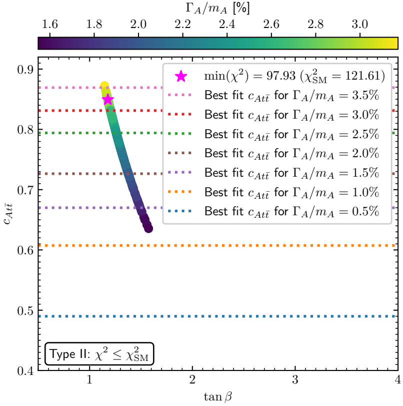
$$\chi^2 = \chi^2_{125} + \chi^2_{t\bar{t}} + \chi^2_{\tau^+\tau^-} + \chi^2_{96} \text{ , we demand: } \chi^2 \leq \chi^2_{\rm SM}$$

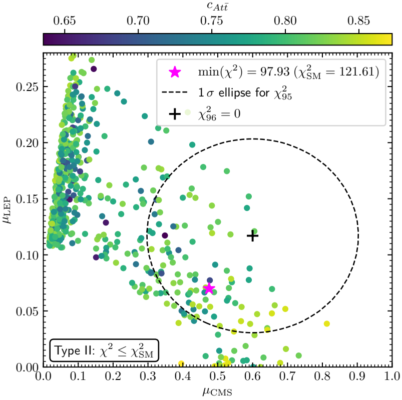
Parameters as before, except: $95\ \mathrm{GeV} \leq m_{h_1} \leq 98\ \mathrm{GeV}$, and

(1) $0.5 \leq \tan\beta \leq 4$ for $t\bar{t}$ excess

(2) $6 \leq \tan\beta \leq 12.5$ for $\tau^+\tau^-$ excess

(1)





In the N2HDM type II the pseudoscalar A can give rise to the $t\bar{t}$ excess at $400\ \mathrm{GeV}$ in combination with a scalar h_1 at $\sim 96\ \mathrm{GeV}$ giving rise to the LEP and CMS excesses

(Type IV also works)

A 400 GeV pseudoscalar and a 96 GeV scalar in the type II N2HDM

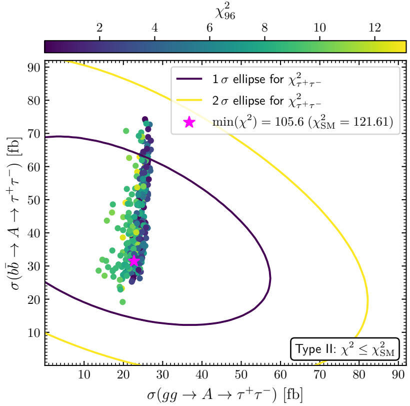
$\chi^2 = \chi^2_{125} + \chi^2_{t\bar{t}} + \chi^2_{\tau^+\tau^-} + \chi^2_{96}$, we demand: $\chi^2 \leq \chi^2_{\rm SM}$

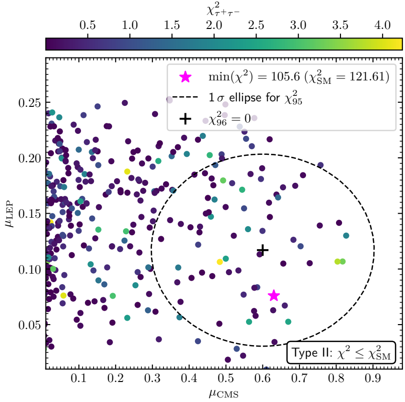
Parameters as before, except: 95 GeV $\leq m_{h_1} \leq$ 98 GeV, and

(1) $0.5 \leq \tan\beta \leq 4$ for $t\bar{t}$ excess

(2) $6 \leq \tan\beta \leq 12.5$ for $\tau^+\tau^-$ excess

(2)

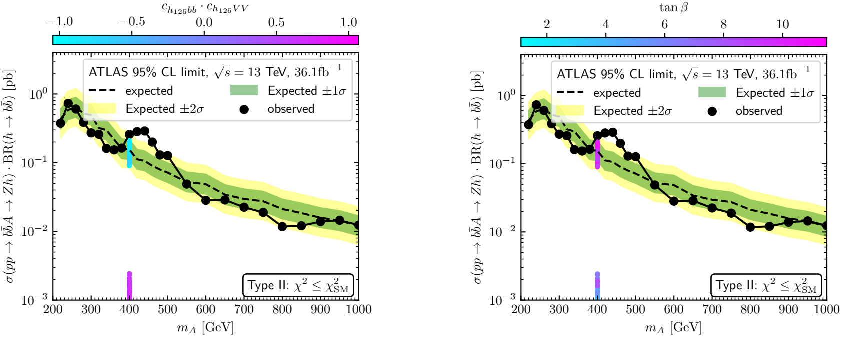




In the N2HDM type II the pseudoscalar A can give rise to the $\tau^+\tau^-$ excess at 400 GeV in combination with a scalar h_1 at $\sim$ 96 GeV giving rise to the LEP and CMS excesses

(Type IV doesn't work)

N2HDM: What about the Zh excess?



Zh excess can be accommodated for tan $\beta \gtrsim 8$ in the wrong-sign Yukawa coupling regime

$\Rightarrow$ In combination with the $\tau^+\tau^-$ excess

$\Rightarrow$ In combination with the excess at 96GeV

NMSSM

A pseudoscalar at ~ 400 GeV in the NMSSM

The Higgs sector of the NMSSM is similar to the one of the N2HDM type II

$$W_{\rm NMSSM} = W_{{\rm MSSM},\not\mu} + \lambda\, \hat{s}\, \hat{H}_u \cdot \hat{H}_d + \frac{1}{3}\, \kappa\, \hat{s}^3$$

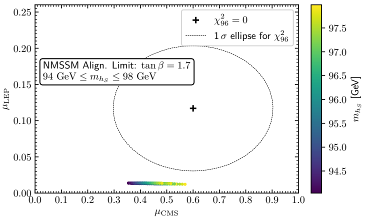
$t\bar{t}$ excess $\rightarrow$ low $\tan\beta$

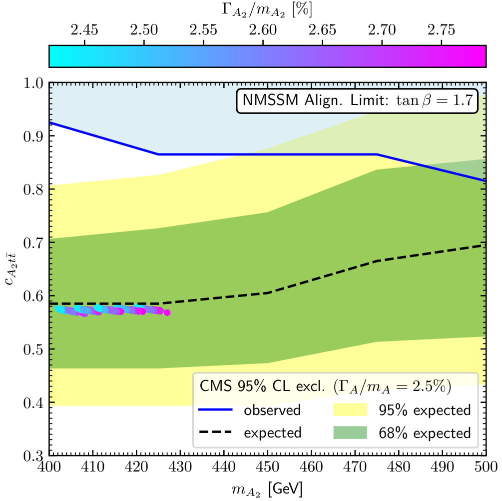
Alignment without decoupling

$$\lambda = \frac{m_{h_{\rm SM}}^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2 \beta}$$

$$\frac{M_A^2 \sin^2 2\beta}{4\mu^2} + \frac{\kappa \sin 2\beta}{2\lambda} = 1$$

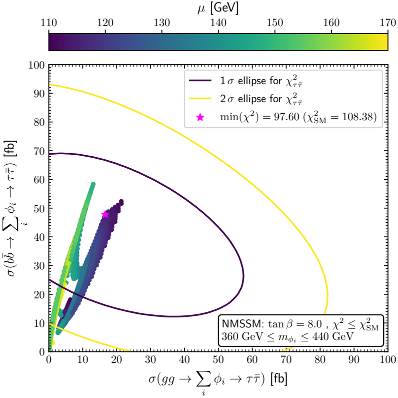
[Carena, Haber, Low, Shah, Wagner 1510.09137]





A pseudoscalar at ~ 400 GeV in the NMSSM

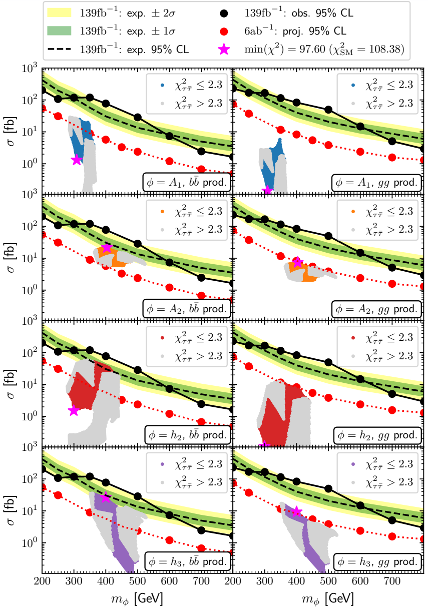
$\tau^+\tau^-$ **excess** $\rightarrow$ moderate $\tan\beta = 8$



Interference effects not important:

$m_{h_3} - m_{h_2} \gg \Gamma_{h_2} + \Gamma_{h_3}$

$m_{A_2} - m_{A_1} \gg \Gamma_{A_1} + \Gamma_{A_2}$



Conclusions

- **Pseudoscalar of the N2HDM type II:** Either the $t\bar{t}$ or the $\tau^+\tau^-$ (+ Zh) excesses

$\rightarrow$ In addition: **Singlet-like scalar** at 96 GeV for LEP and CMS excesses
$m_{h_1} \sim 96\ \mathrm{GeV}$, $m_{h_2} = 125\ \mathrm{GeV}$, $m_A \sim 400\ \mathrm{GeV}$ and $m_{h_3} \sim m_{H^\pm} \gtrsim 550\ \mathrm{GeV}$
$\rightarrow$ Very predictive

- **Pseudoscalar of the NMSSM:** $t\bar{t}$ excess in alignment-without-decoupling limit

$\rightarrow$ In addition: **Singlet-like scalar** at 96 GeV can give rise to the CMS excess

- **NMSSM with** $\tan\beta \sim 8$**:** $\tau^+\tau^-$ excess

Outlook: How to probe? Expiration/discovery date?

$t\bar{t}$ **scenarios:** $gg \rightarrow \phi \rightarrow t\bar{t}$, $pp \rightarrow H^\pm \rightarrow tb$ (SUSY), $gg \rightarrow A \rightarrow Zh$, $gg \rightarrow H \rightarrow ZA$ (✓)
$\tau^+\tau^-$ **scenarios:** CMS/HL-LHC searches for $\phi \rightarrow \tau^+\tau^-$ with $139\mathrm{fb}^{-1}/3000\mathrm{fb}^{-1}$ ✓
Zh **scenarios:** ATLAS/CMS searches for $b\bar{b} \rightarrow A \rightarrow Zh$ with $139\mathrm{fb}^{-1}$ ✓
96 GeV **scenarios:** Indirect h_{125} constraints, CMS $gg \rightarrow h \rightarrow \gamma\gamma$ with $139\mathrm{fb}^{-1}$, ILC (?)

THANKS!

The charged Higgs bosons in the alignment-without-decoupling limit of the NMSSM with 400GeV

$\tan\beta = 1.7$, $\quad M_A \sim 400$ GeV $\quad \Rightarrow \quad \lambda \sim 0.66$, $\quad \mu \gtrsim 100$ GeV