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

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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

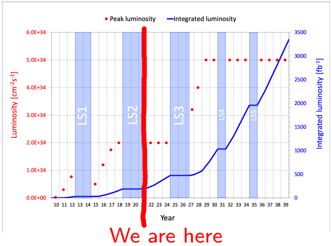
New physics at the LHC?

Nat. hist. Museum Rotterdamm

Theory: Susy, inflation, baryogenesis, . . .
$\Rightarrow$ Non-minimal scalar sectors
$\Rightarrow$ Presence of more than one Higgs boson

Colliders: Excesses at $\sim 3(2)\sigma$ locally(globally)
$\Rightarrow$ Are the excesses consistent with each other?
$\Rightarrow$ Can they have a common origin?
$\Rightarrow$ 10 times more LHC data "around the corner"

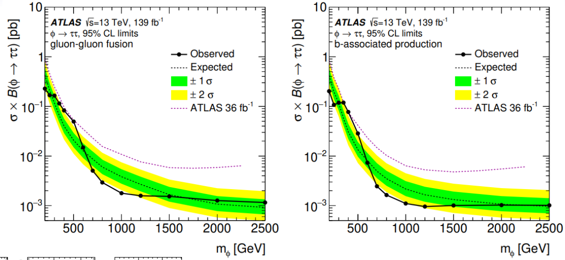
[hilumilhc.web.cern.ch]



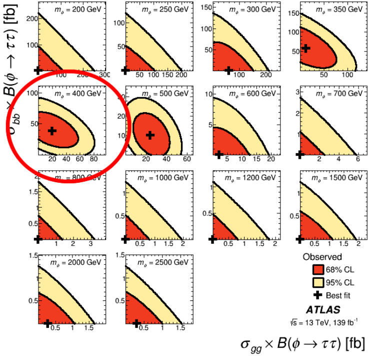
[lhc-commissioning.web.cern.ch]

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

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



[ATLAS: 2002.12223]



[ATLAS: 2002.12223]

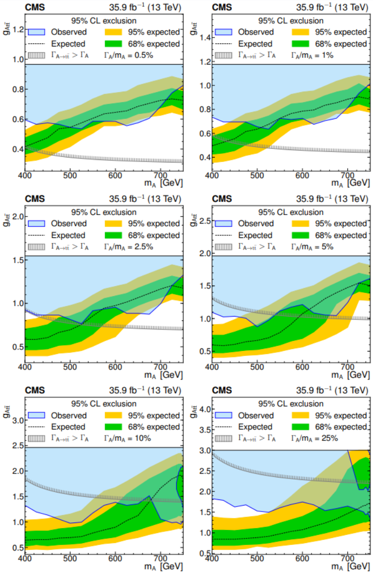
Local excess of 3σ at $\sim$ 400 GeV
Global significance below 2σ

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

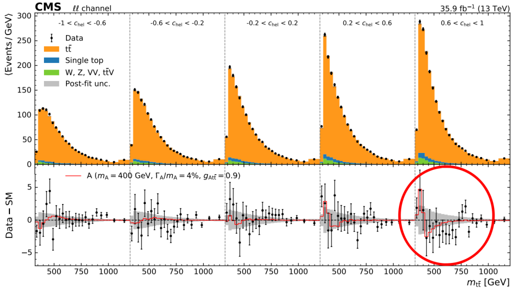
Both prodution modes relevant:
$\Rightarrow \sigma_{bb} \sim 2\sigma_{gg}$

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

“The $t\bar{t}$ excess” at ~ 400 GeV



[CMS: 1908.01115]



[CMS: 1908.01115]

Local excess of $\gtrsim 3\sigma$ at ~ 400 GeV
Global significance below 2σ

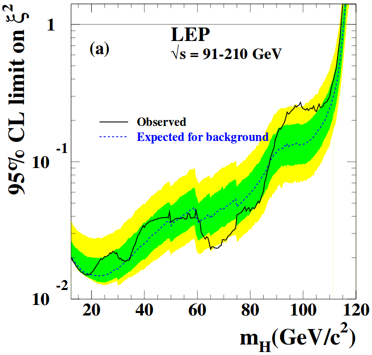
Consistent with a pseudoscalar Higgs boson at ~ 400 GeV

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
$\to \chi^2_{t\bar{t}}(m_A, \Gamma_A/m_A, c_{At\bar{t}})$

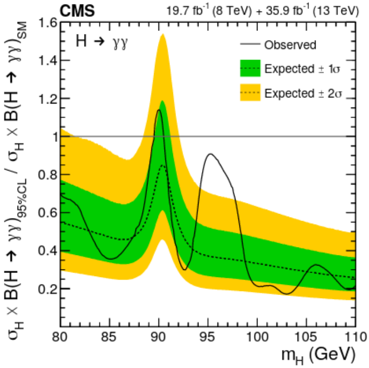
Corresponding ATLAS limits only for $m_A > 500$ GeV and only 8 TeV data

[ATLAS: 1707.06025]

"The 96GeV excesses" (LEP and CMS)



[LEP: hep-ex/0306033]



[CMS: 1811.08459]

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

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

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

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

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

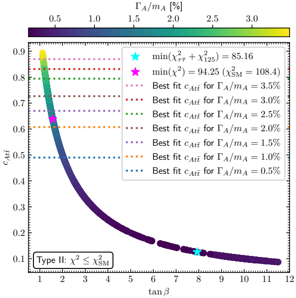
Codes: `ScannerS`, `N2HDECAY`, `SusHi`, `HiggsBounds`, `HiggsSignals`

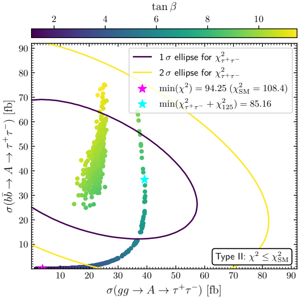
A 400 GeV pseudoscalar in the type II N2HDM

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

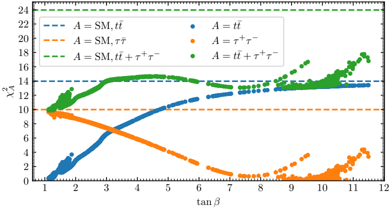
$$20 \text{ GeV} \leq m_{h_{a,c}} \leq 1000 \text{ GeV} , \quad m_{h_b} = 125.09 \text{ GeV} , \quad m_A = 400 \text{ GeV} ,$$

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





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



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

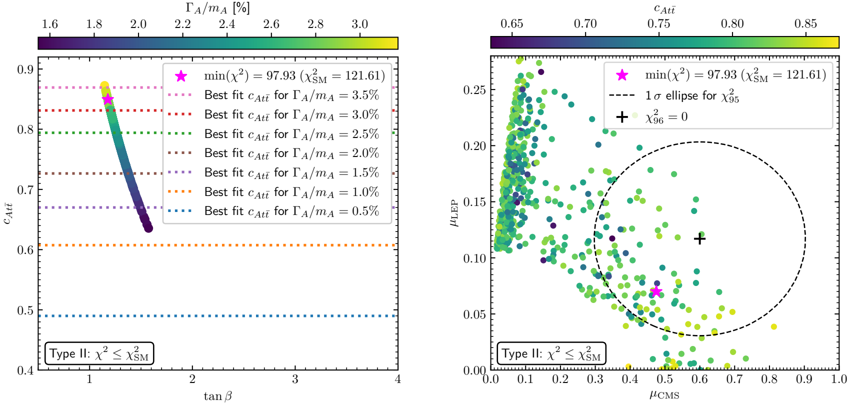
$$\chi^2 = \chi^2_{125} + \chi^2_{t\bar{t}} + \chi^2_{\tau^+\tau^-} + \chi^2_{96}\text{ , we demand: } \chi^2 \leq \chi^2_{\mathrm{SM}}$$

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

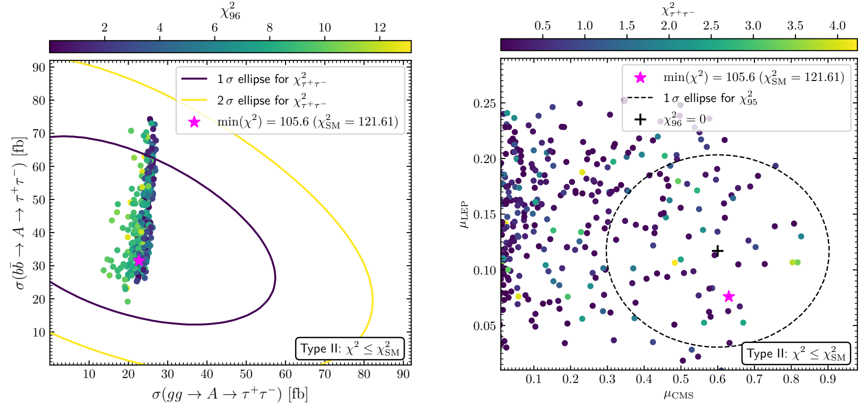
$$\chi^2 = \chi^2_{125} + \chi^2_{t\bar{t}} + \chi^2_{\tau^+\tau^-} + \chi^2_{96}\ \text{, we demand: } \chi^2 \leq \chi^2_{\text{SM}}$$

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 ~ 96 GeV giving rise to the LEP and CMS excesses

(Type IV doesn't work)

A pseudoscalar at ~ 400 GeV in the NMSSM

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

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

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

Alignment without decoupling

$$\lambda = \frac{m^2_{h_{\mathrm{SM}}} - M_Z^2 \cos 2\beta}{v^2 \sin^2 \beta}$$

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

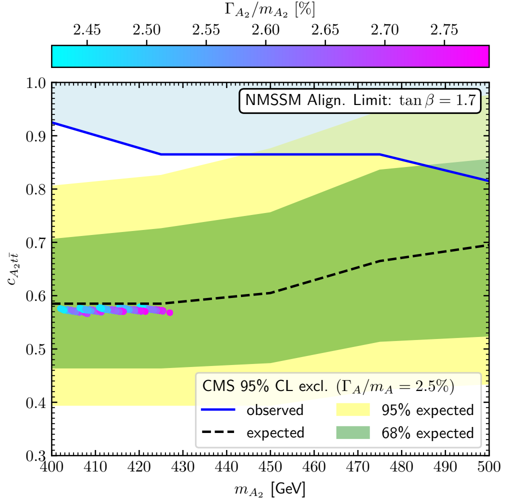
[Carena, Haber, Low, Shah, Wagner 1510.09137]

$$M_A = [410.0, 430.0]\ \mathrm{GeV}\ , \quad \lambda = 0.66\ ,$$
$$\mu = [182, 202]\ \mathrm{GeV}\ , \quad \kappa = [0.043, 0.204]\ ,$$
$$A_\kappa = [-517, 65]\ \mathrm{GeV}\ , \quad M_1 = 140\ \mathrm{GeV}\ ,$$
$$M_2 = 180\ \mathrm{GeV}\ , \quad M_3 = 3000\ \mathrm{GeV}\ ,$$
$$m_{\tilde{t}} = 1200\ \mathrm{GeV}\ , \quad A_t = 0\ \mathrm{GeV}$$

Code: `NMSSMTools`

Also μ_{CMS} can be explained

$\to$ Appendix/questions



A pseudoscalar at ~ 400 GeV in the NMSSM

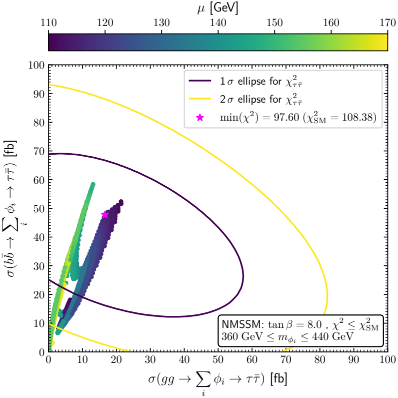
$\tau^+\tau^-$ **excess** $\rightarrow$ moderate $\tan\beta = 8$

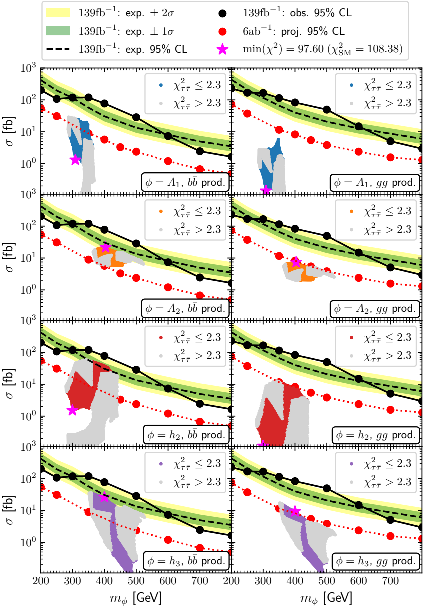
Alignment via decoupling:

$\tan\beta = \mathbf{8}$, $\lambda = 0.36$, $\kappa = 0.58$, $110\ \mathrm{GeV} \leq \mu \leq 170\ \mathrm{GeV}$

$360\ \mathrm{GeV} \leq M_A \leq 560\ \mathrm{GeV}$, $A_\kappa = -200\ \mathrm{GeV}$, $A_t = 6\ \mathrm{TeV}$

$m_{\tilde{t}} = 2.5\ \mathrm{TeV}$, $M_3 = 2.7\ \mathrm{TeV}$, $M_1 = 1\ \mathrm{TeV}$, $M_2 = 2\ \mathrm{TeV}$





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 $\tau^+\tau^-$ 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?

$t\bar{t}$ **scenarios:** $gg \rightarrow \phi \rightarrow t\bar{t}$, $pp \rightarrow H^\pm \rightarrow tb$ (SUSY), $gg \rightarrow A \rightarrow Zh$, $gg \rightarrow H \rightarrow ZA$ (✓)

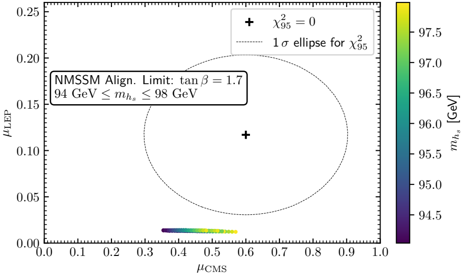
$\tau^+\tau^-$ **scenarios:** CMS/HL-LHC searches for $\phi \rightarrow \tau^+\tau^-$ with $139\mathrm{fb}^{-1}/3000\mathrm{fb}^{-1}$ ✓

96 GeV **scenarios:** Indirect h_{125} constraints, CMS $gg \rightarrow h \rightarrow \gamma\gamma$ with $139\mathrm{fb}^{-1}$, ILC (?)

THANKS!

A Higgs boson at 96 GeV in the alignment-without-decoupling limit of the NMSSM

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

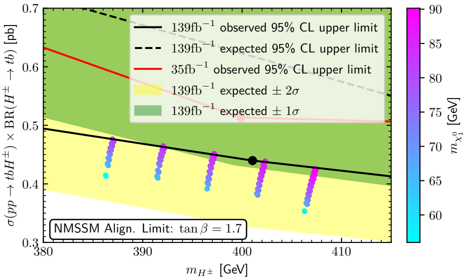


Side effect:

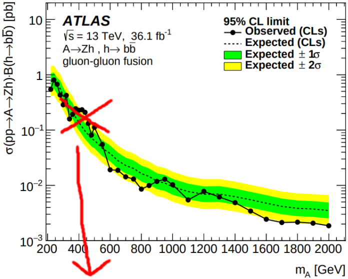
$\leftarrow \quad \kappa < \lambda$

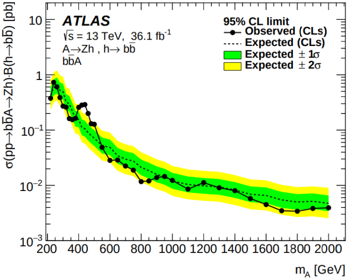
Side effect:

$m_{H^\pm} \sim m_A \quad \rightarrow$

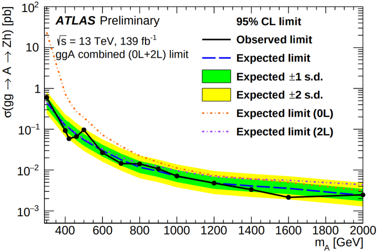


“The Zh excess” at ∼ 400 GeV





[ATLAS: 1712.06518]



[ATLAS-CONF-2020-043]