Beyond the Standard Model Higgs bosons in the reach of the LHC

[2103.xxxxx]

Thomas Biekötter

in collaboration with Alexander Grohsjean, Sven Heinemeyer, Victor Lozano,
Christian Schwanenberger and Georg Weiglein

HPNP2021, Osaka, Japan

March 25th 2021

DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

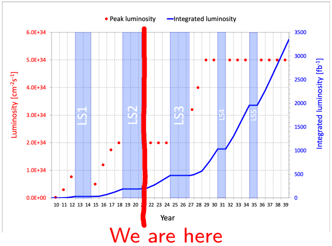
New physics at the LHC?

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”

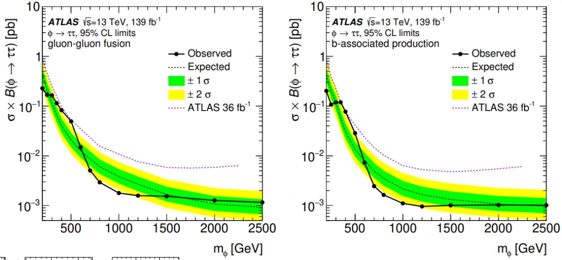
[hilumilhc.web.cern.ch]



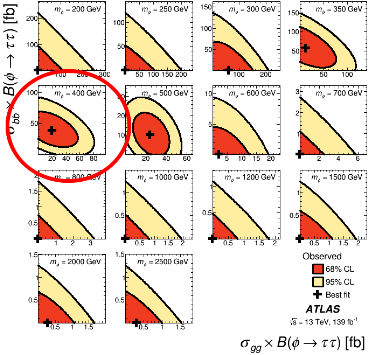
[lhc-commissioning.web.cern.ch]

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

"The $\tau\bar{\tau}$ excess" at ~ 400 GeV



[ATLAS: 2002.12223]



[ATLAS: 2002.12223]

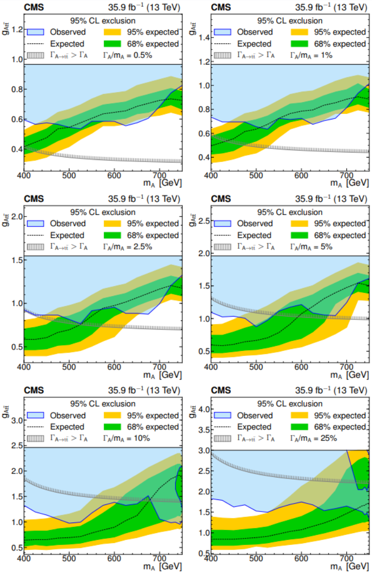
Local excess of 3σ at ~ 400 GeV
Global significance below 2σ

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

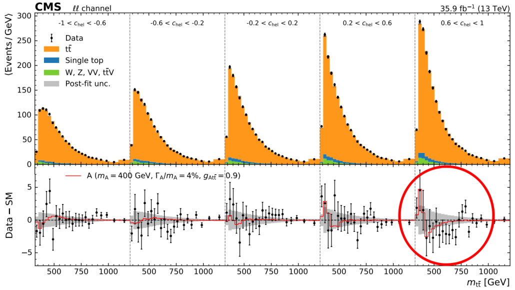
Both prodution modes relevant:
$\Rightarrow \sigma_{bb} \sim 2\sigma_{gg}$

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

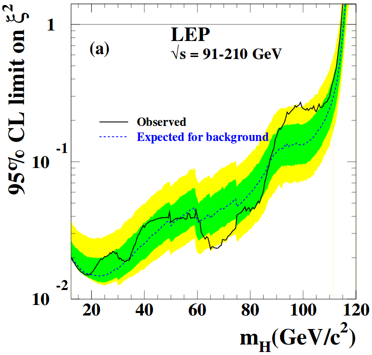
Consistent with a pseudoscalar Higgs boson at ~ 400 GeV

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

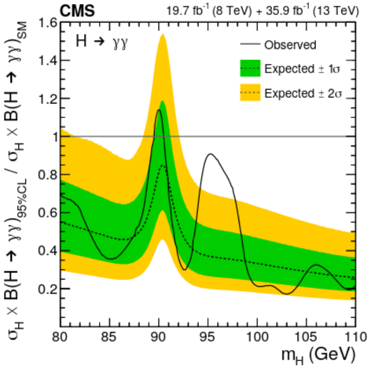
Corresponding ATLAS limits only for $m_A > 500$ GeV and only 8 TeV data

[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:
$\mu_{\rm LEP}\ (e^+e^- \to Zh \to Zb\bar{b}) = 0.117 \pm 0.057$
[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 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 $\tau\bar{\tau}$ excesses at $\sim 400\ \mathrm{GeV}$

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

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	$1/\tan\beta$	$1/\tan\beta$	$\tan\beta$

$\tau\bar{\tau}$ 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 $\sim 96\ \mathrm{GeV}$?

Type II and IV can realize the $96\ \mathrm{GeV}$ excesses

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

$\to$ Simultaneously also the $t\bar{t}$ or (and) the $\tau\bar{\tau}$ excess

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

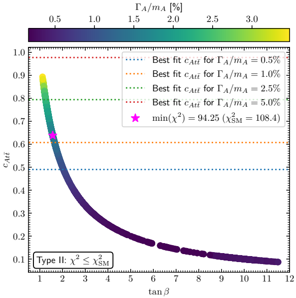
Codes: `ScannerS`, `N2HDECAY`, `SusHi`, `HiggsBounds`, `HiggsSignals`

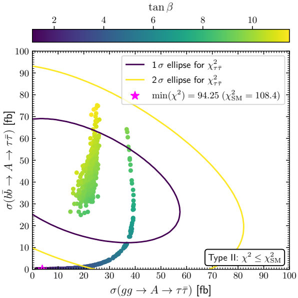
A 400 GeV pseudoscalar in the type II N2HDM

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

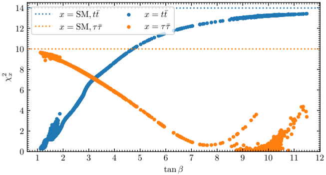
$$20 \text{ GeV} \leq m_{h_{a,c}} \leq 1000 \text{ GeV} , \quad m_{h_b} = 125.09 \text{ GeV} , \quad m_A = 400 \text{ GeV} ,$$

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





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



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

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

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

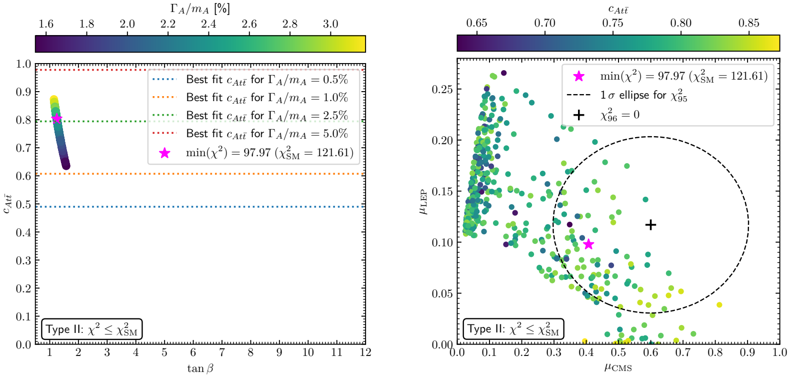
$$\chi^2 = \chi^2_{125} + \chi^2_{t\bar{t}} + \chi^2_{\tau\bar{\tau}} + \chi^2_{96}$$, we demand: $\chi^2 \leq \chi^2_{\mathrm{SM}}$

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 $\tau\bar{\tau}$ excess

(1)



In the N2HDM type II the pseudoscalar A can give rise to the $t\bar{t}$ excess at 400 GeV in combination with a scalar h_1 at ~ 96 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

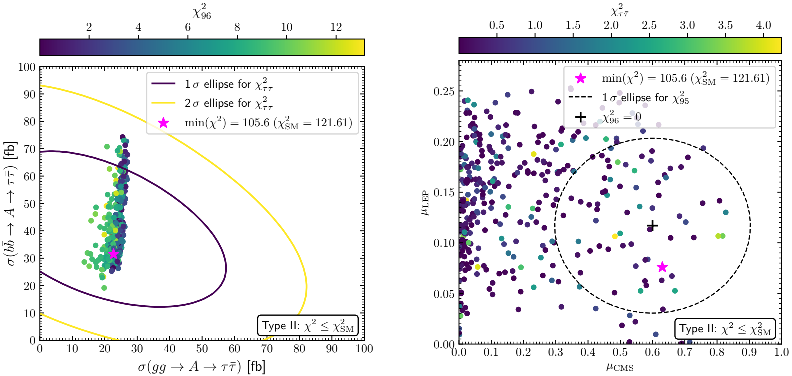
$$\chi^2 = \chi^2_{125} + \chi^2_{t\bar{t}} + \chi^2_{\tau\bar{\tau}} + \chi^2_{96}$$, we demand: $\chi^2 \leq \chi^2_{\rm SM}$

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 $\tau\bar{\tau}$ excess

(2)



In the N2HDM type II the pseudoscalar A can give rise to the $\tau\bar{\tau}$ 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

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

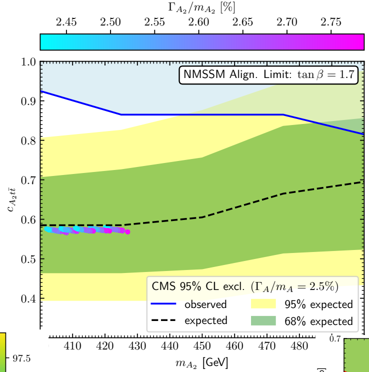
$t\bar{t}$ excess $\to$ low $\tan\beta$

Alignment without decoupling

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

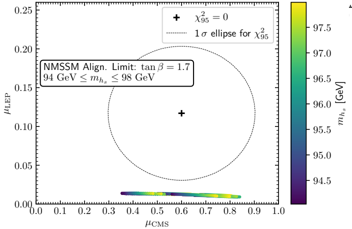
$$\frac{M_A^2 \sin^2 2\beta}{4\mu^2} + \frac{\kappa \sin 2\beta}{2\lambda} = 1$$

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



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

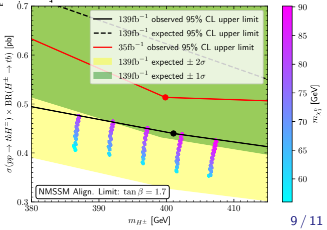
Code: `NMSSMTools`



Side effects:

$\leftarrow \quad \rightarrow$

$\kappa < \lambda \qquad m_{H^\pm} \sim m_A$



A pseudoscalar at ~ 400 GeV in the NMSSM

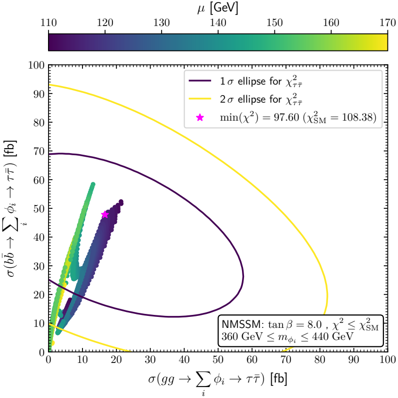
$\tau\bar{\tau}$ **excess** $\rightarrow$ moderate $\tan\beta = 8$

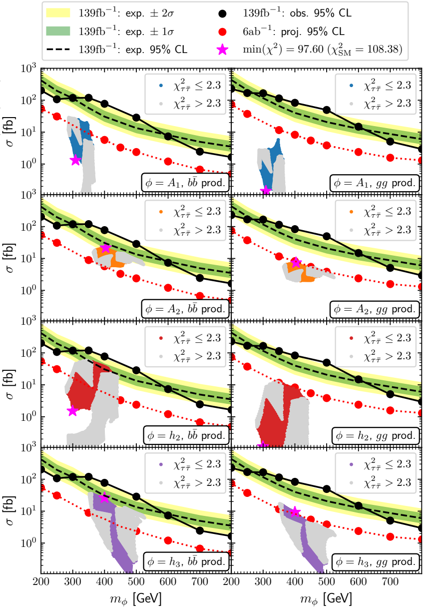
Alignment via decoupling:

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

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

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





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 can give rise to either the $t\bar{t}$ or the $\tau\bar{\tau}$ excesses

$\rightarrow$ In addition, the excesses at 96 GeV can be accommodated with a singlet-like scalar h_1

$m_{h_1} \sim 96~\mathrm{GeV}$, $m_{h_2} = 125~\mathrm{GeV}$, $m_A \sim 400~\mathrm{GeV}$ and $m_{h_3} \sim m_{H^\pm} \gtrsim 550~\mathrm{GeV}$

$\rightarrow$ Very predictive

- An NMSSM pseudoscalar A_2 can be the origin of the $t\bar{t}$ excess

$\rightarrow$ Theory: *Natural* NMSSM: alignment without decoupling

$\rightarrow$ In addition, a singlet-like h_1 can give rise to the CMS excess

- For larger values of $\tan\beta$ the NMSSM can realize the $\tau\bar{\tau}$ excess

$\rightarrow$ Alignment only via decoupling

$\rightarrow$ Large radiative corrections in Higgs sector

Outlook: How to probe?

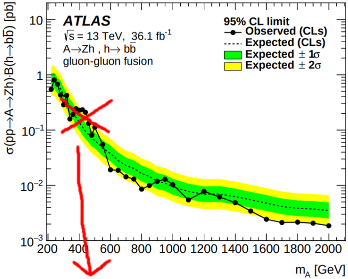
$t\bar{t}$ **scenarios:** $gg \rightarrow \phi \rightarrow t\bar{t}$, $pp \rightarrow H^\pm \rightarrow tb$ (SUSY), $gg \rightarrow A \rightarrow Zh$, $gg \rightarrow H \rightarrow ZA$ (✓)

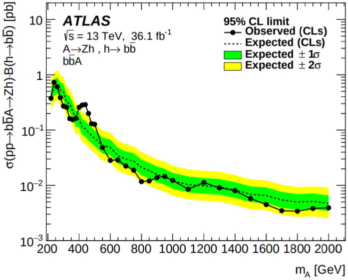
$\tau\bar{\tau}$ **scenarios:** CMS/HL-LHC searches for $\phi \rightarrow \tau\bar{\tau}$ with $139\mathrm{fb}^{-1}/3000\mathrm{fb}^{-1}$ ✓

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

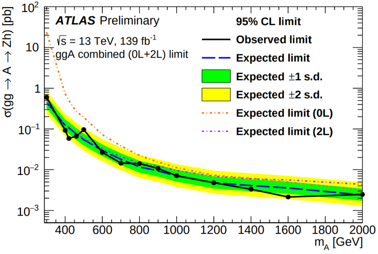
THANKS!

“The Zh excess” at ∼ 400 GeV





[ATLAS: 1712.06518]



[ATLAS-CONF-2020-043]