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

[2106.xxxxx]

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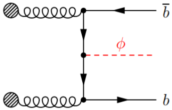
June 24th 2021

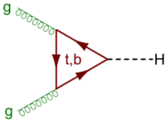
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

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

Look for a peak in $\sigma(pp \to \phi \to \tau^+\tau^-)$ as function of m_ϕ

Here: Narrow-width approximation and two different production mechanisms considered: ggF and $b\bar{b}$





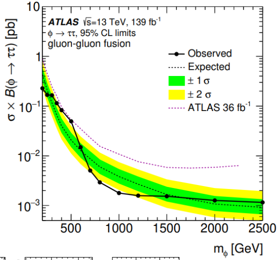
$$\times$$

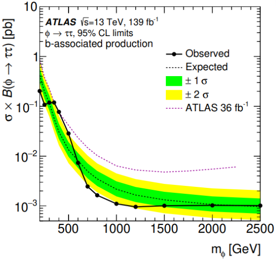
$$\mathrm{BR}(\phi \to \tau^+\tau^-)$$

$$\Rightarrow \chi^2_{\tau^+\tau^-}\left(\sigma(gg \to \phi \to \tau^+\tau^-), \sigma(b\bar{b} \to \phi \to \tau^+\tau^-)\right)$$

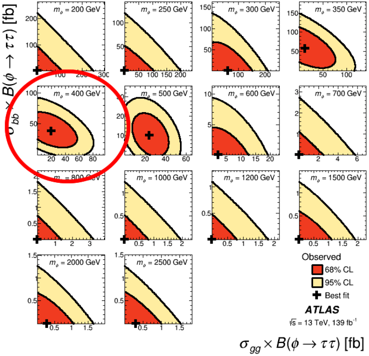
for different m_ϕ

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





[ATLAS: 2002.12223]



[ATLAS: 2002.12223]

Local excess of 3σ at $\sim 400\ \mathrm{GeV}$
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 $m_\phi = 400\ \mathrm{GeV}$

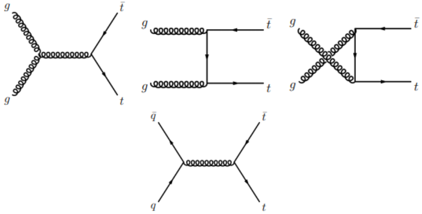
Both prodution modes relevant:
$\Rightarrow \sigma_{bb} \sim 2\sigma_{gg}$

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

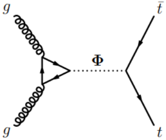
"The $t\bar{t}$ excess" at $\sim$ 400 GeV

Search in $t\bar{t}$ finalstate more complicated:
(1) Width effects are important
(2) Interference with SM background is important

SM:

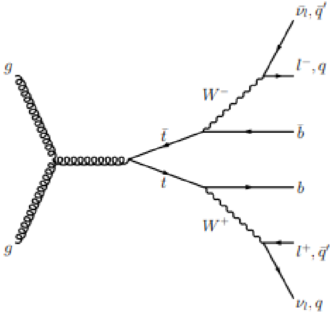


BSM state:



$\Rightarrow$ Peak-dip structure in $m_{t\bar{t}}$ distribution

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



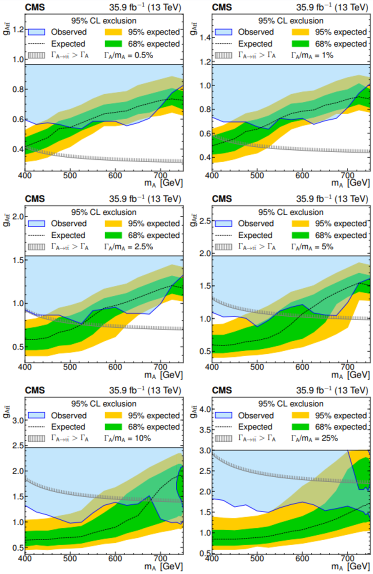
Angular distribution of leptons in finalstate provides further information:

(1) Can help to discrimnate between SM background and BSM contribution

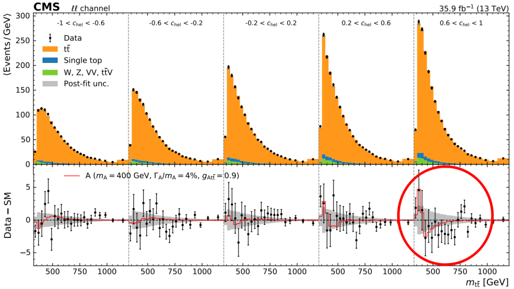
(2) Is sensitive to CP-properties of ϕ, here
$\rightarrow$ Scalar H and pseudoscalar A interpretation

$$\Rightarrow \chi^2_{t\bar{t}}(m_\phi, \Gamma_\phi/m_\phi, c_{\phi t\bar{t}}) \text{ with } \phi = H, A$$

"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

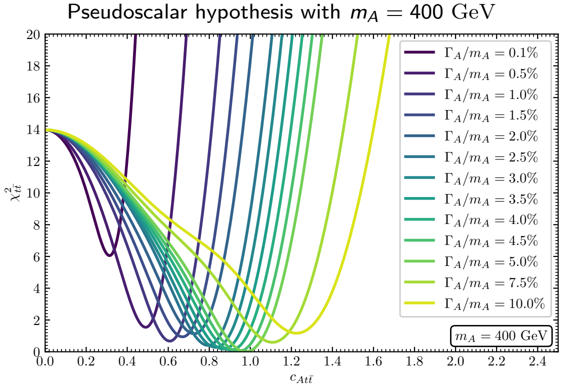
Consistent with a pseudoscalar Higgs boson at ~ 400 GeV

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

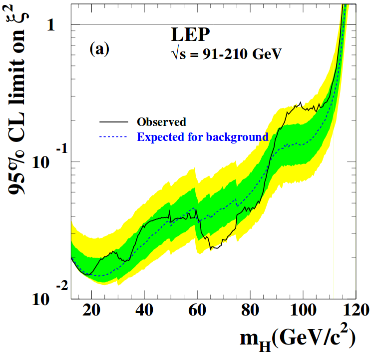
[ATLAS: 1707.06025]

“The $t\bar{t}$ excess” at ~ 400 GeV

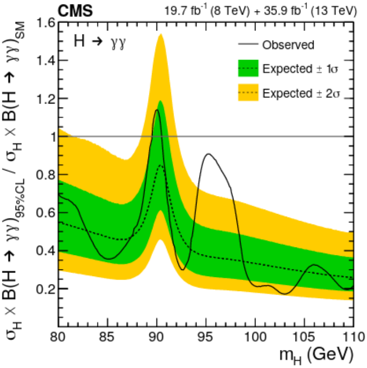


The whole $\chi^2_{t\bar{t}}$ now available publicly at
`http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-027/index.html`

"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 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

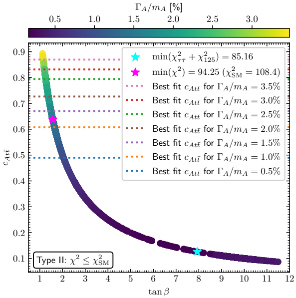
Codes: `ScannerS`, `N2HDECAY`, `SusHi`, `HiggsBounds`, `HiggsSignals`

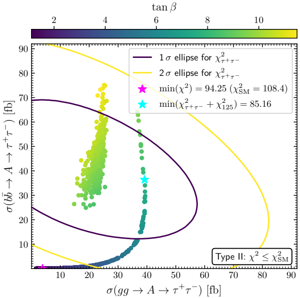
A 400 GeV pseudoscalar in the type II N2HDM

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

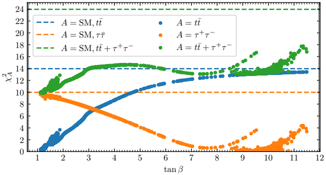
$$20\ \text{GeV} \leq m_{h_{a,c}} \leq 1000\ \text{GeV}\ , \quad m_{h_b} = 125.09\ \text{GeV}\ , \quad m_A = 400\ \text{GeV}\ ,$$

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





(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

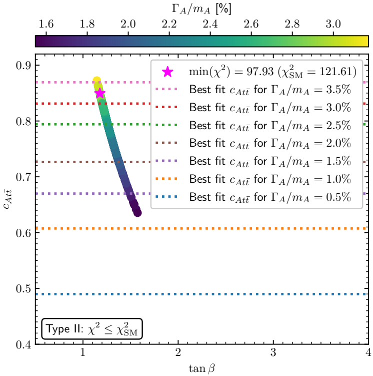
$$\chi^2 = \chi^2_{125} + \chi^2_{t\bar{t}} + \chi^2_{\tau\bar{\tau}} + \chi^2_{96}$$, we demand: $\chi^2 \leq \chi^2_{\mathrm{SM}}$

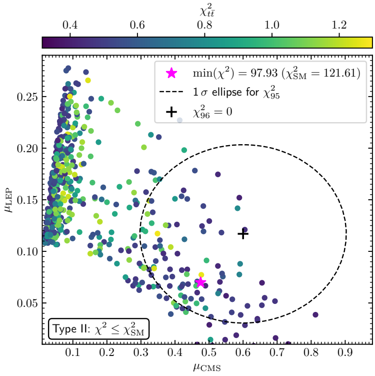
Parameters as before, except: $95\ \mathrm{GeV} \leq m_{h_1} \leq 98\ \mathrm{GeV}$, and

(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

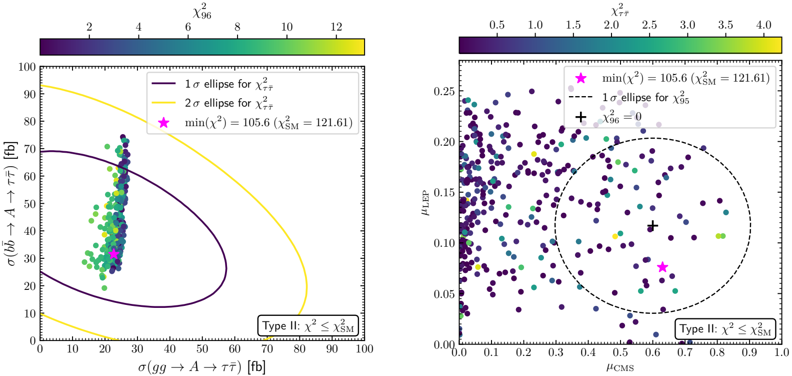
$$\chi^2 = \chi^2_{125} + \chi^2_{t\bar{t}} + \chi^2_{\tau\bar{\tau}} + \chi^2_{96} \text{ , we demand: } \chi^2 \leq \chi^2_{\mathrm{SM}}$$

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

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

(2) $6 \leq \tan\beta \leq 12.5$ for $\tau\bar{\tau}$ 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

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

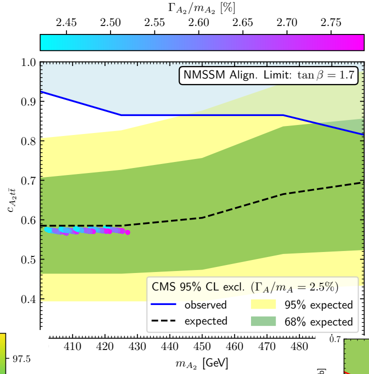
$t\bar{t}$ excess $\to$ low $\tan\beta$

Alignment without decoupling

$$\lambda = \frac{m_{h_{125}}^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2\beta}$$

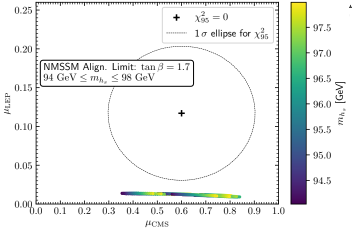
$$\frac{M_A^2 \sin^2 2\beta}{4\mu^2} + \frac{\kappa \sin 2\beta}{2\lambda} = 1$$

[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

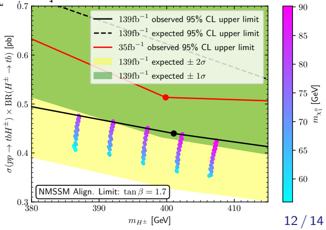
Code: `NMSSMTools`



Side effects:

$\leftarrow$ $\rightarrow$

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

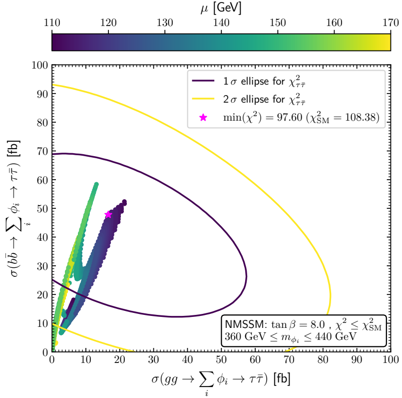


A pseudoscalar at ~ 400 GeV in the NMSSM

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

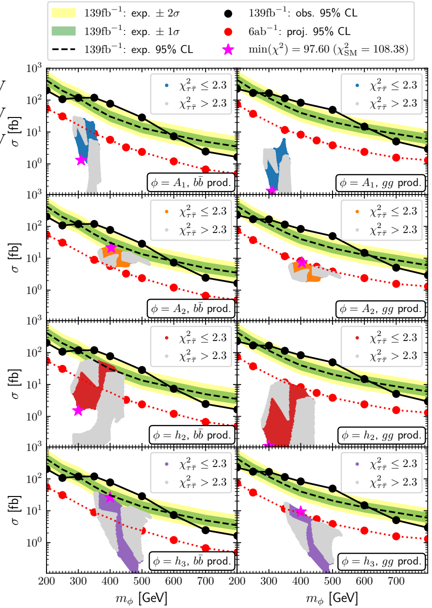
Alignment via decoupling:

$\tan\beta = \mathbf{8}$, $\lambda = 0.36$, $\kappa = 0.58$, $110\text{ GeV} \leq \mu \leq 170\text{ GeV}$
$360\text{ GeV} \leq M_A \leq 560\text{ GeV}$, $A_\kappa = -200\text{ GeV}$, $A_t = 6\text{ TeV}$
$m_{\tilde{t}} = 2.5\text{ TeV}$, $M_3 = 2.7\text{ TeV}$, $M_1 = 1\text{ TeV}$, $M_2 = 2\text{ TeV}$



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 $\tau^+\tau^-$ excesses

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

$m_{h_1} \sim 96$ GeV, $m_{h_2} = 125$ GeV, $m_A \sim 400$ GeV and $m_{h_3} \sim m_{H^\pm} \gtrsim 550$ 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 $\tau^+\tau^-$ excess

$\rightarrow$ Alignment only via decoupling

$\rightarrow$ Large radiative corrections in Higgs sector

Outlook: How to probe?

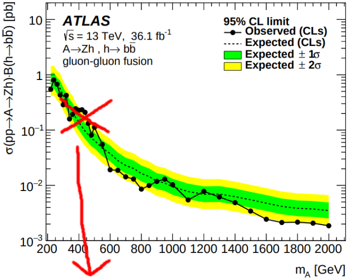
$t\bar{t}$ **scenarios:** $gg \to \phi \to t\bar{t}$, $\sigma(tH, ttH, Wh) \times \mathrm{BR}(H \to t\bar{t})$, $pp \to H^\pm \to tb$ (SUSY),
$gg \to A \to Zh$, $gg \to H \to ZA$ (✓)

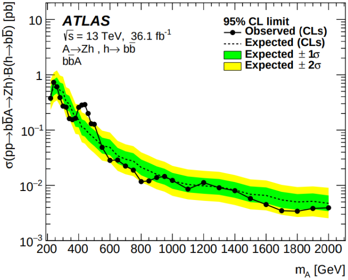
$\tau^+\tau^-$ **scenarios:** CMS/HL-LHC searches for $\phi \to \tau\bar{\tau}$ with $139\mathrm{fb}^{-1}/3000\mathrm{fb}^{-1}$ ✓

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

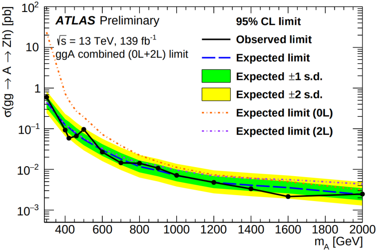
Thanks!

"The Zh excess" at ~ 400 GeV





[ATLAS: 1712.06518]



[ATLAS-CONF-2020-043]