Extended Scalars

Tania Robens

Rudjer Boskovic Institute

on behalf of WG3 Extended Higgs Sector conveners:

M. d'Alfonso, S. Laurila, TR, N. Rompotis, R. Santos, L. Zivkovic

The 20th Workshop of the LHC Higgs Working Group
CERN
13. November '23

Facts

- **conveners:** L. Zivkovic (Belgrade), N. Rompotis (Liverpool), ATLAS; M. d'Alfonso (MIT), S. Laurila (CERN), CMS; T. Robens (Zagreb), R. Santos (Lisbon), Theory
- **Twiki:** https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX
- **Email (conveners/ all):** lhc-higgs-neutral-extended-scalars-convener_at_cern.ch/ lhc-higgs-neutral-extended-scalars_at_cern.ch
- **egroup:** lhc-higgs-neutral-extended-scalars

Recent activities

- reinstated regular meetings, focus on

A) Overlooked signatures
B) Width and interference effects in BSM searches
C) Recasts
D) CPV
E) ...

- **more than 60 talks over 8 days**

see https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX#Meetings for details

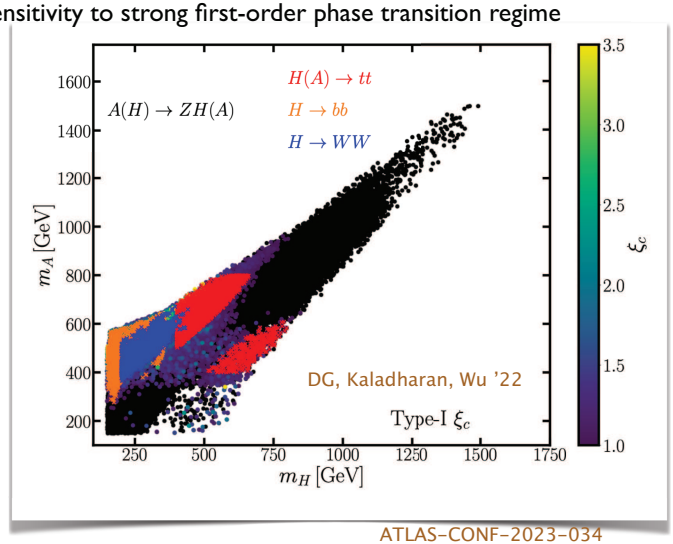
WG3 extended scalars meeting 31.10.23

extremely lively discussions ! [HiggsDays style...]
can only show selection $\Rightarrow$ **recording for details**

Example: D. Goncalves, *Resonant top pair searches at the LHC: a window to electroweak phase transition* [Phys.Rev.D 105 (2022) 9, 095041, Phys.Rev.D 107 (2023) 7, 075040]

Top Pair Resonant Searches via pp→ZH/A

- pp→ZH/A searches mostly account for H/A→bb and H→WW (sensitivity $m_{H,A} < 350$ GeV)
  See e.g., arXiv:2011.05639 and arXiv:1911.03781
- Above top-quark pair threshold the H/A → tt is typically dominant decay, leading to strong limits, and extending the sensitivity to strong first-order phase transition regime

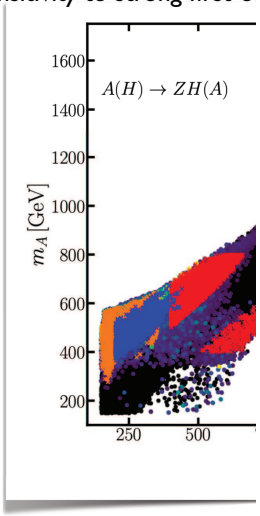


ATLAS-CONF-2023-034
Biekotter, Heinemeyer, No, Radchenko, Romacho, Weiglein '23

Example: D. Goncalves, *Resonant top pair searches at the LHC: a window to electroweak phase transition* [Phys.Rev.D 105 (2022) 9, 095041, Phys.Rev.D 107 (2023) 7, 075040]

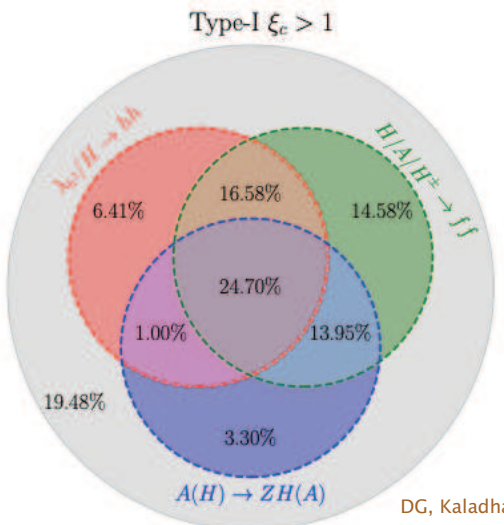
Top Pair Resonant Searches via pp→ZH/A

- pp→ZH/A searches mostly account for H/A→bb and H→WW (sensitivity $m_{...} < 350$ GeV)
  See e.g., arXiv:2011.05639 and arXiv:1911.037
- → Above top-quark pair threshold the H/A
  extending the sensitivity to strong first-o



Combined results

- Complementarity of the Higgstrahlung searches with other relevant classes of searches at the HL-LHC

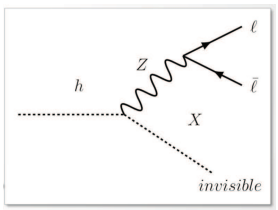


DG, Kaladharan, Wu '22

$$\tan\beta \in (0.8, 25)\,, \quad m_{12}^2 \in (10^{-3}, 10^5)\,\text{GeV}^2\,, \quad m_H \in (150, 1500)\,\text{GeV}\,,$$
$$\cos(\beta-\alpha) \in (-0.3, 0.3)\,, \quad m_A \in (150, 1500)\,\text{GeV}\,, \quad m_{H^\pm} \in (150, 1500)\,\text{GeV}.$$

Example: J.M. No, *Semi-invisible $h \to Z X$ Higgs decays: Extended scalar windows into dark matter* [PRD106 115023]

BSM Higgs boson decay $h \to ZX$ ($X \to$ *invisible*)



Decay channel previously unexplored in literature...

- Model-independent sensitivity analysis for HL-LHC
- BSM model interpretations:

  Extended Higgs sector portal to DM
  Axion-like particles (ALPs)

Example: J.M. No, *Semi-invisible h → Z X Higgs decays: Extended scalar windows into dark matter* [PRD106 115023]

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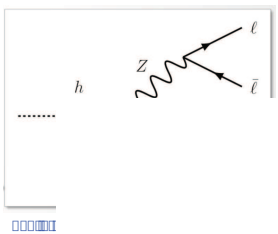


$h \to Z\,(\ell\ell) + invisible$

Decay channel prev

○ Which Higgs production mode @LHC?

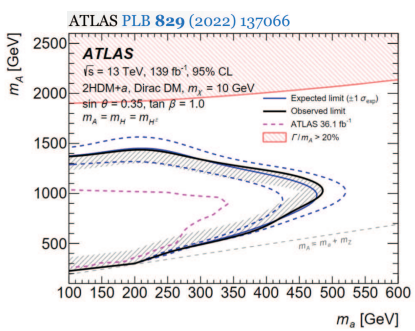
ggF ($pp \to 2\ell + \text{MET}$) ✗ Too much background

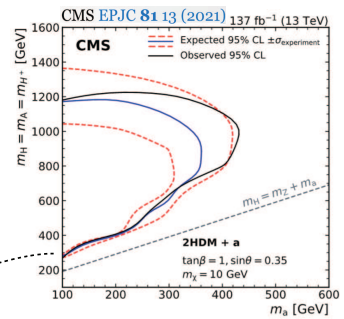
e.g. Seen explicitly in ATLAS/CMS searches for "mono-Z"

- Model-independent sensi
- BSM model interpretatio

Extended H
Axion-like p

ggF $\to H,\ H \to Z + a$ *(invisible)*





$E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV
$m_{\mathrm{T}} > 200$ GeV
insensitive to $m_H = m_h = 125$ GeV

Example: J.M. No, *Semi-invisible h → Z X Higgs decays: Extended scalar windows into dark matter* [PRD106 115023]

BSM Higgs boson decay $h \to ZX$ ($X \to$ *invisible*)

Decay channel p

- Model-independent se
- BSM model interpreta

Extended
Axion-like

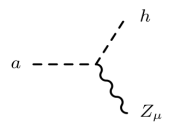
BSM Models

Axion-like particles (ALPs)

- ALP may have:

ALP - Higgs interactions

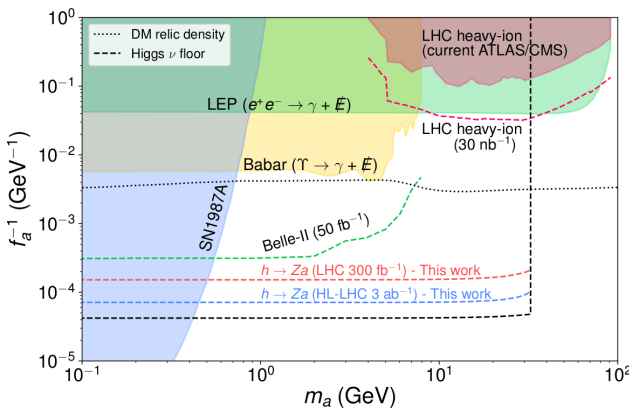
Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz, EJPC 77 (2017) 8, 572
Bauer, Neubert, Thamm, JHEP 12 (2017), 044



ALP - Dark sector interactions

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, JHEP 12 (2017) 094

(dark decay of ALP) "ALP portal to DM"



($y_\chi = 1,\ c_{aZh} = 1,\ m_\chi = 0.45\, m_a$)

BSM ALP setup

$\Gamma(h \to Za) = (m_h^3/16\pi f_a^2)\, c_{aZh}^2\, \lambda^{3/2}$

ALP-DM: $y_\chi\, \bar{\chi}\gamma^\mu\gamma^5\chi\, \partial_\mu a/f_a$

ALP-Photons: $c_{a\gamma\gamma}/f_a\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$

$c_{a\gamma\gamma} \sim \alpha_{\rm EM}$

[plot from Phys.Rev.D 106 (2022) 11, 115023]

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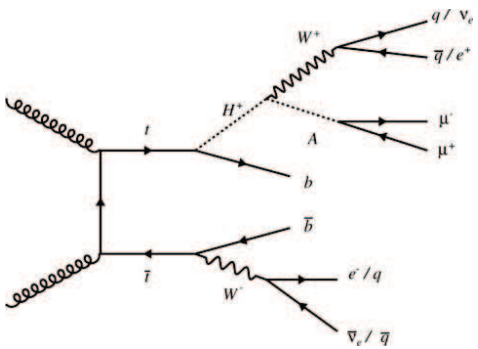
ATLAS EXPERIMENT

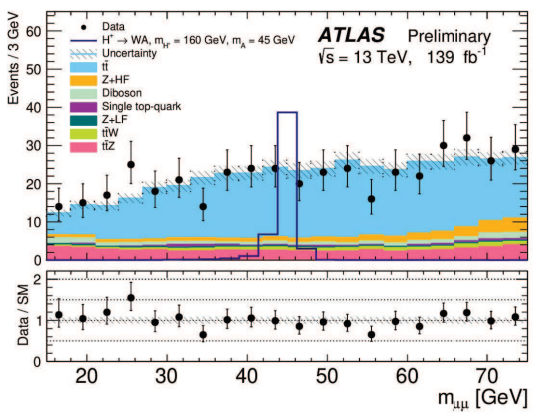
Some recent ATLAS results

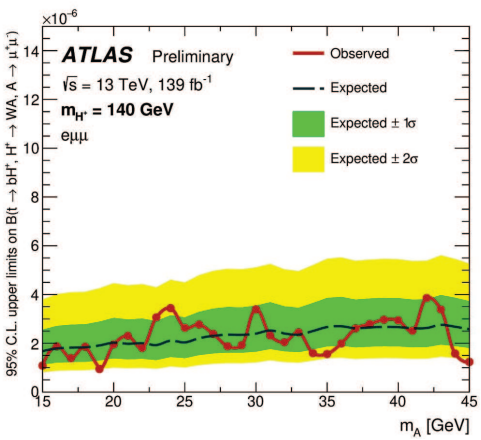
- This is only a flavour of some ATLAS results since our last workshop that are related to Extended Higgs sectors: see the linked public documents for more details

- Charged Higgs: pp → tt with t → H+ A in eμμ final state



ATLAS-CONF-2021-047





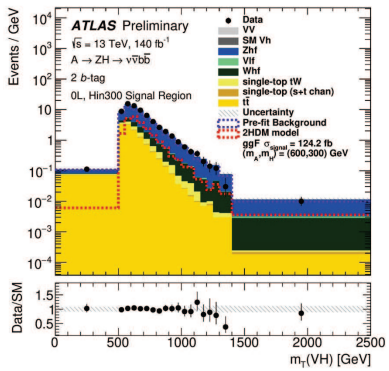
Lidija Zivkovic
Nikolaos Rompotis

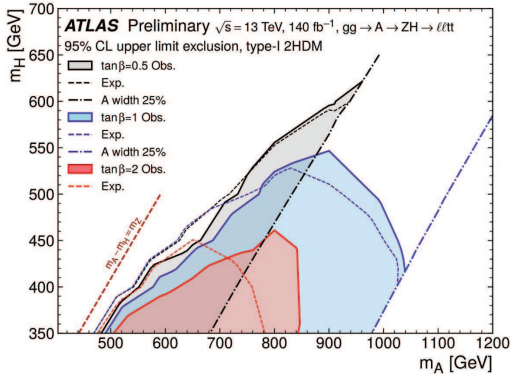
Some recent ATLAS results

- A → ZH → ll tt / vvbb

To journal soon, will be updated

ATLAS-CONF-2023-034

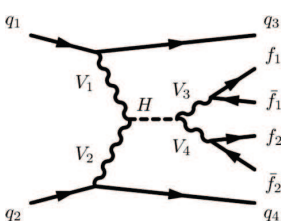


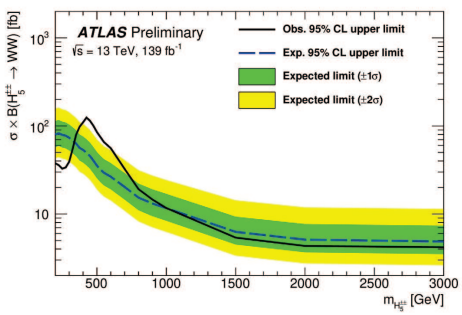


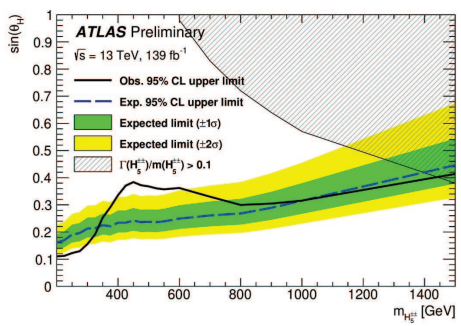
- Same sign W boson pair production

ATLAS-CONF-2023-023

Georgi-Machacek triplet model + other interpretations







[H is here doubly charged; sin $= 0$ puts EWSB into doublet only]

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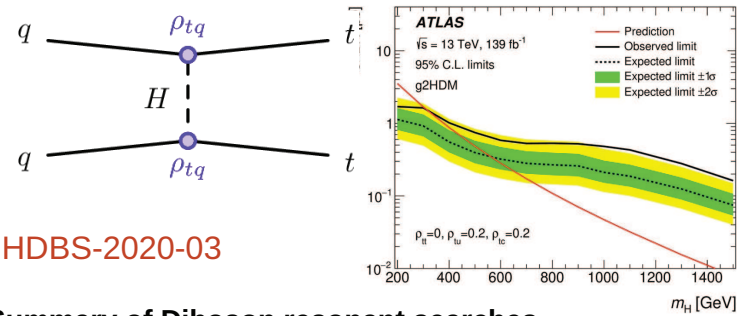
ATLAS EXPERIMENT

Some recent ATLAS results

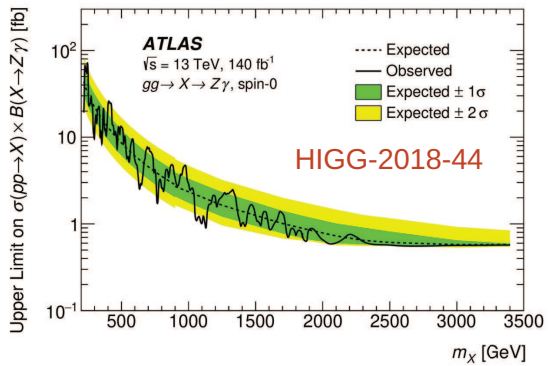
Heavy Higgs with FV in multi-lepton + b-jets

same-sign top-quark pair, three top-quarks, or four top-quarks



HDBS-2020-03

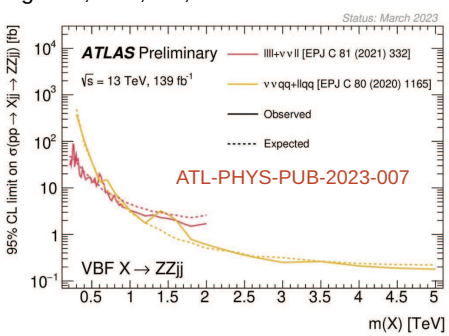
Heavy Higgs to Zγ



HIGG-2018-44

Summary of Diboson resonant searches

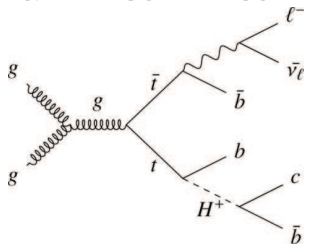
Including: WZ, WW, ZH, WH

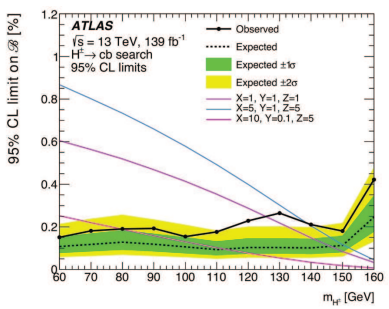


ATL-PHYS-PUB-2023-007

Charged Higgs to cb

HDBS-2019-24
arXiv:2302.11739

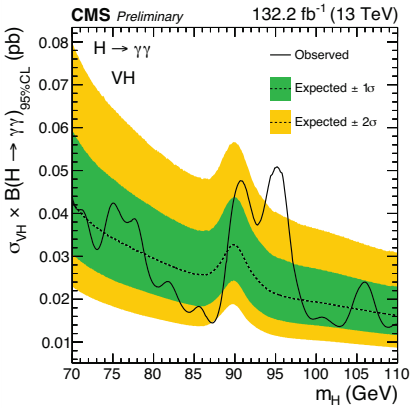


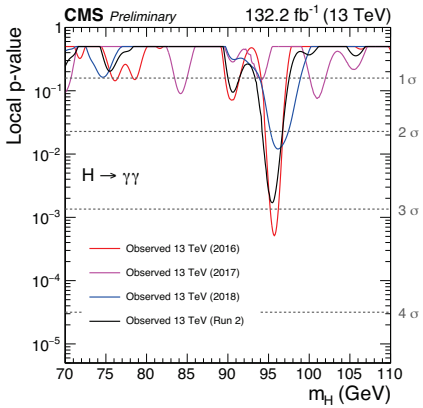


[BR is production times decay; X, Y, Z are coupling modifies in quark/ lepton sector, Phys.Rev.D 98 (2018) 11, 115024]

CMS Highlights: Light Scalar Searches

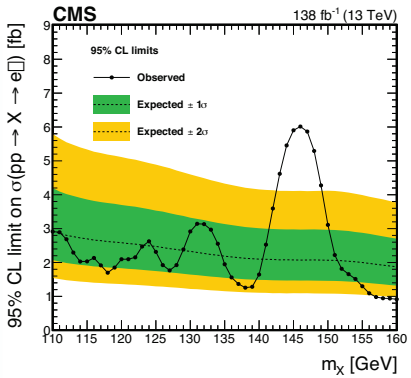
- **Search for ϕ→γγ** arXiv:2311.00130

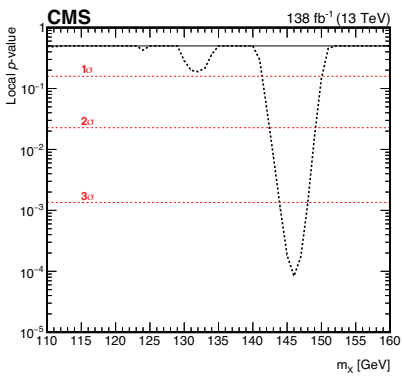




- Search for γγ resonance in 70–110 GeV mass range
- Intriguing **2.9σ** (**1.3σ** global) excess at **95.4 GeV**
  - Similar to the previous CMS result at 8+13 TeV, with 2.8σ (1.3σ global) at 95.3 GeV (arXiv:1811.08459)
  - ATLAS reports 1.7σ at 95 GeV (ATLAS-CONF-2023-035)
  - Mild excess seen also in LEP (arXiv:hep-ex/0306033)

- **Search for ϕ→eμ** arXiv:2305.18106





- Search for lepton-flavor violating decays, forbidden in the SM but predicted e.g. in **Type III 2HDM**
  - Analysis covers the 110–160 GeV mass range
- Most stringent limits to date
  - **3.8σ** (**2.8σ** global) excess at **146 GeV**

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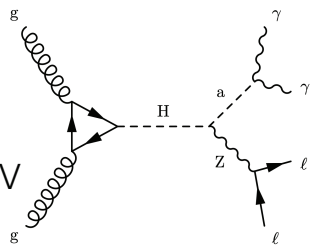
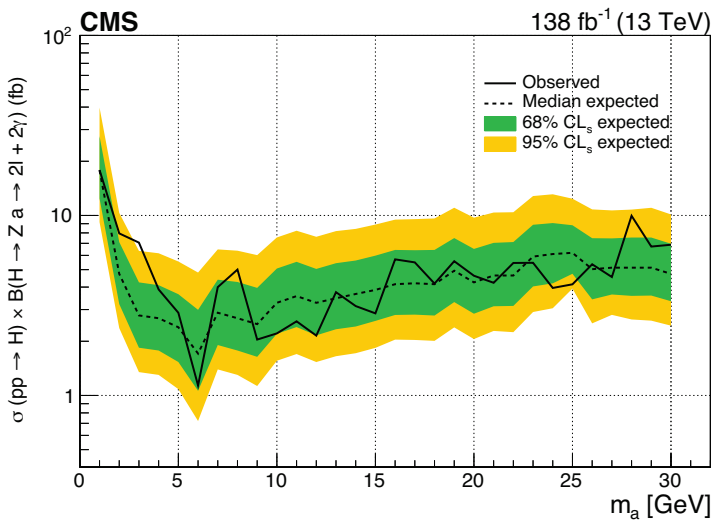
CMS Highlights: Pseudoscalar Searches

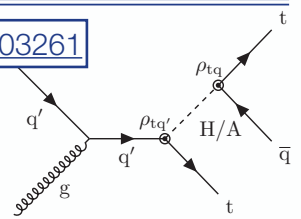
- **Search for H→Za→llγγ**
  - Covering m_a range 1–30 GeV
  - No significant excess, but 2.6σ (1.3σ global) at $m_a = 3$ GeV

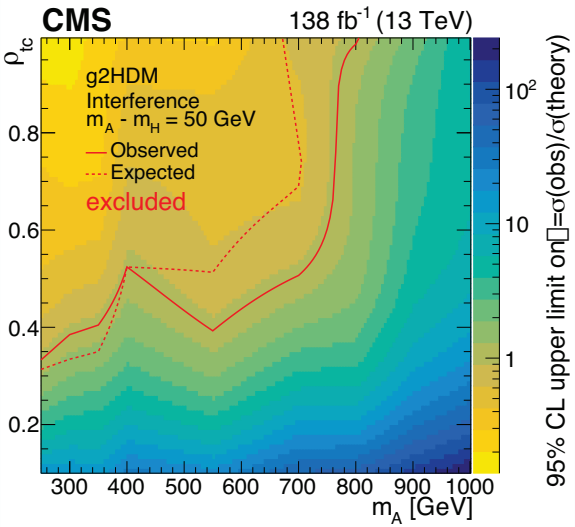
  arXiv:2311.00130





- **Search for tA→ttq** arXiv:2311.03261
  - Motivated by **gH2DM**
  - No significant excess
  - Various coupling and H/A interference scenarios considered





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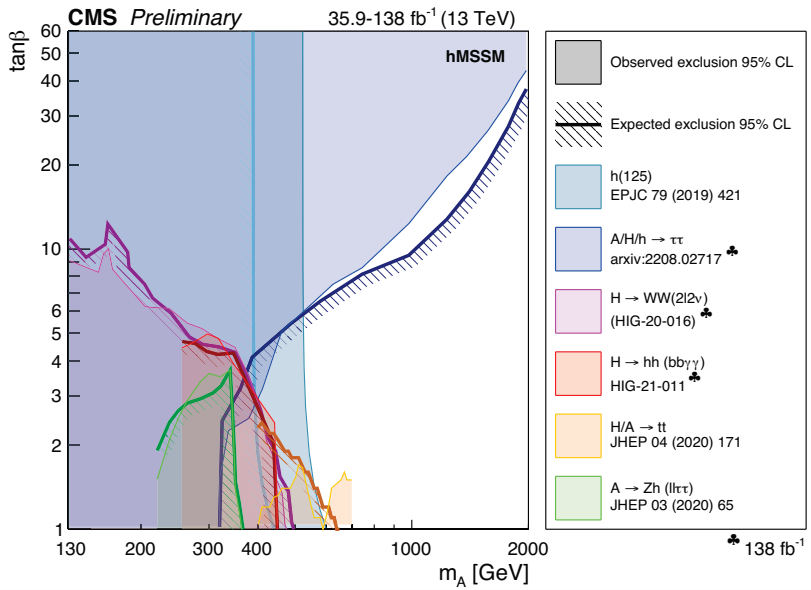
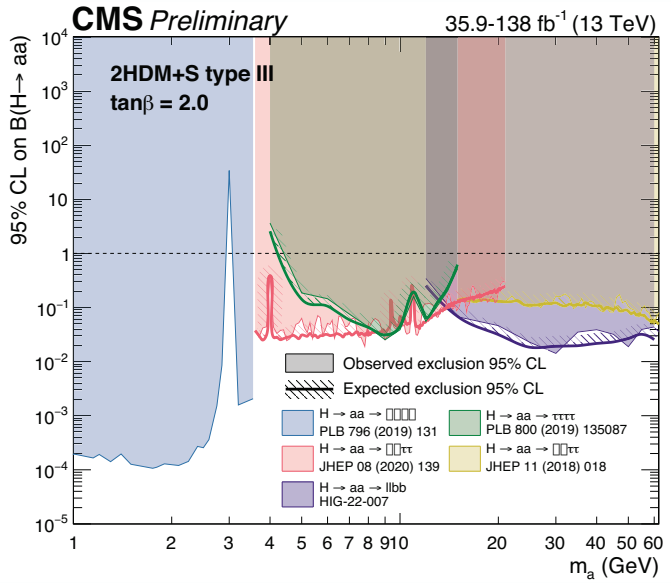
CMS Highlights: Summary Plots

- **MSSM**



- **2HDM+S**



- These are just a couple of examples; all the latest summary plots are available at: *https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG*

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Update of recommended cross sections for 13.6 TeV: charged scalars

Current focus:
production of charged scalars in standard production mode, i.e. $p\,p \to H^+\,t\,\bar{b}$ production

- **split into 3 mass ranges:**

$$m_{H^+} \leq 150\,\mathrm{GeV},\ m_{H^+} \in [150;\,200]\ \mathrm{GeV},\ m_{H^+} \geq 200\,\mathrm{GeV}$$

- **low mass range:** available in the mHmax-scenario;
  however, this is type II $\Rightarrow$ **basically ruled out by flavour+ electroweak !**
  current plan: **provide rates for type I in a grid**
  input: up-to-date $t\bar{t}$ cross sections

[see https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO#Updated_reference_cross_sections for numbers and references]

Update of recommended cross sections for 13.6 TeV: charged scalars

- **intermediate mass range:** follow 4FS as discussed in C. Degrande ea, Phys.Lett. B772 (2017) 87-92 using Madgraph **(nearly) done for type II, type I will be obtained using conversion formula**
- **high mass range:** work in progress:
  - first **reproduction of [some] previous numbers for 13 and 14 TeV using both 4FS and 5FS**, using Prospino (5FS), and private code from M. Spira (4FS)
  - **grids will be extended to masses of 2 TeV**
  - **13.6 TeV numbers are derived using interpolation**

Update of recommended cross sections for 13.6 TeV: charged scalars: credits

- **people involved: N. Rompotis** (low mass range), **E. Bagnaschi**, with help from **M. Zaro** (intermediate mass range), **E. Bagnaschi, M. Spira** (high mass range)

⇒ see dedicated talk by Emanuele ⇐

Update of recommended cross sections for 13.6 TeV: neutral scalars

urgently needed from WG1: production cross sections for SM-like scalars of a different mass at 13.6 TeV!

$\Rightarrow$ **we hope to resolve this during this meeting** (or, if not feasible, asap) **!**

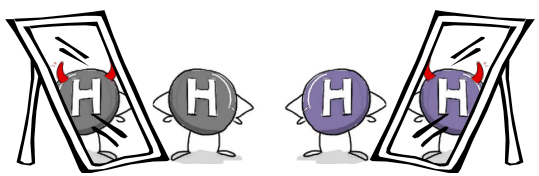
important input for many new physics scenario predictions and tools

Joint activities with WG2: CP violation and Higgs Sector
[see more detailed talk on Wednesday]

three meetings over the last 2 years, $\sim$ 20 talks

CPV in Higgs interactions:
WG2/WG3 (extended Higgs) joint meeting

WG3: Mariarosaria d'Alfonso, Santeri Laurila, Tania Robens, Nikos Rompotis, Rui Santos, Shufang Su & Lidija Zivkovic
WG2: Nicolas Berger, Mauro Donega, Ken Mimasu & Daniele Barducci



23rd June 2022

1

Joint WG2/WG3 activity

Todays meeting!

- Received several kick-off meeting contributions that overlapped with WG3 (extended Higgs sector) interests
- Many interesting signatures of spontaneous/explicit CPV in extended Higgs sectors
- From mixing of would-be CP-even/odd eigenstates

Discovery of BSM Higgs in multiple decay channels ⇒ CPV

Classes	C_1	C_2	C_3	C_4	C_5
Decays	$h_3 \to h_2 Z$	$h_2 \to h_1 Z$	$h_3 \to h_1 Z$	$h_3 \to h_2 Z$	$h_3 \to ZZ$
	$h_2 \to h_1 Z$	$h_1 \to ZZ$	$h_1 \to ZZ$	$h_2 \to ZZ$	$h_2 \to ZZ$
	$h_3 \to h_1 Z$	$h_2 \to ZZ$	$h_3 \to ZZ$	$h_3 \to ZZ$	$h_1 \to ZZ$

WG3 Proposal for CP violating benchmarks in the C2HDM ~ 2015
[Fontes et al.; PRD 92 (2015) 055014]

h_{125}-style CP properties study for BSM scalars ⇒ CPV

Decay angular distributions etc.

6

[Slides from K. Mimasu, https://indico.cern.ch/event/1173518/]

goal:
study CPV in models with extended Higgs sectors
will result in whitepaper/ report/ ...

Open topics...

Recently happened...

Exp : Dear theorist, can you provide us with **sample cross sections for XYZ** in your model ?

Th : sure. [sits down and works on this for a couple of weeks]

Exp : Thanks.

time passes...

Exp$^{(\prime)}$: ah, by the way, **we had some questions but not the time to resolve them. Your results will not be included after all.**

! Not OK ! [NB: also theorists time is time...]

$\Rightarrow$ things like this need to be handled differently $\Leftarrow$

Suggestions ?

Summary

- **ongoing activities: regular meetings, including WG2/ 3 interaction**
- so far: **no clear discovery** [although a couple of excesses around]
- **13.6 TeV cross sections: on their way**

$\Rightarrow$ **we do have open issues that need to be discussed**

Recent activities

Meetings in the last 2 years

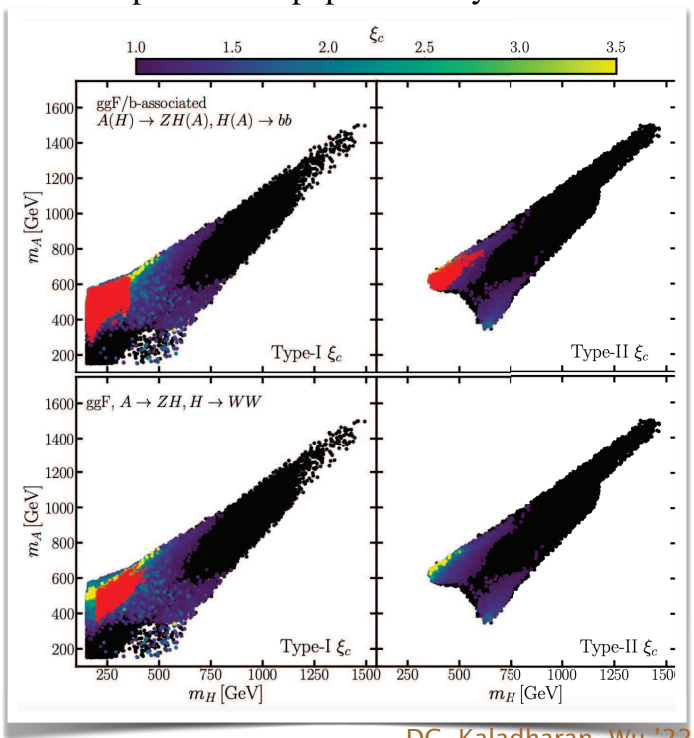
- **6./7.7.21: https://indico.cern.ch/event/1050919/**
- **5.11.21: https://indico.cern.ch/event/1091117/**
- **23.6.22*: https://indico.cern.ch/event/1173518/**
- **16.11.22: https://indico.cern.ch/event/1217666/**
- **11.1.23*: https://indico.cern.ch/event/1230456/**
- **26.9.23*: https://indico.cern.ch/event/1327545/**
- **31.10.23: https://indico.cern.ch/event/1339704/**
- more than 60 talks over the 8 days

[* denotes joint WG2/ WG3 meetings]

Searches via pp→ZH/A: HL-LHC projection

- A(H)→ZH(A): widely discussed channel in the context of EWPT Dorsh, Huber, No 13'

Until last year, theoretical and experimental papers mostly focus on H/A→bb and H→WW searches



DG, Kaladharan, Wu '22
ATLAS-CONF-2023-034
Biekotter, Heinemeyer, No, Radchenko, Romacho, Weiglein '23

Example: M. Menen, *Classifying the CP properties of the ggH coupling in H+2j production* [arXiv:2309.03146]

BSM framework

Free parameters:

- Higgs characterisation model: Higgs H assumed to be mixed CP state
- Effective Higgs-gluon coupling:

Artoisenet et al. ´13

$$\mathcal{L}_{ggH} = -\frac{1}{4v}\left(-\frac{\alpha_s}{3\pi} c_g G^a_{\mu\nu} G^{\mu\nu,\alpha} + \frac{\alpha_s}{2\pi} \tilde{c}_g G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}\right) H$$

- Effective CP-even (c_g) and CP-odd ($\tilde{c}_g$) coupling modifiers
- SM obtained for $c_g = 1$, $\tilde{c}_g = 0$

- Higgs-gluon coupling corresponds to top-Yukawa in the heavy top limit and if there are no low-mass BSM particles in the ggF loop ⇒ $c_g = c_t$, $\tilde{c}_g = \tilde{c}_t$
- We impose a cut $p_T^H < 200\text{GeV}$ to remain in the heavy top limit

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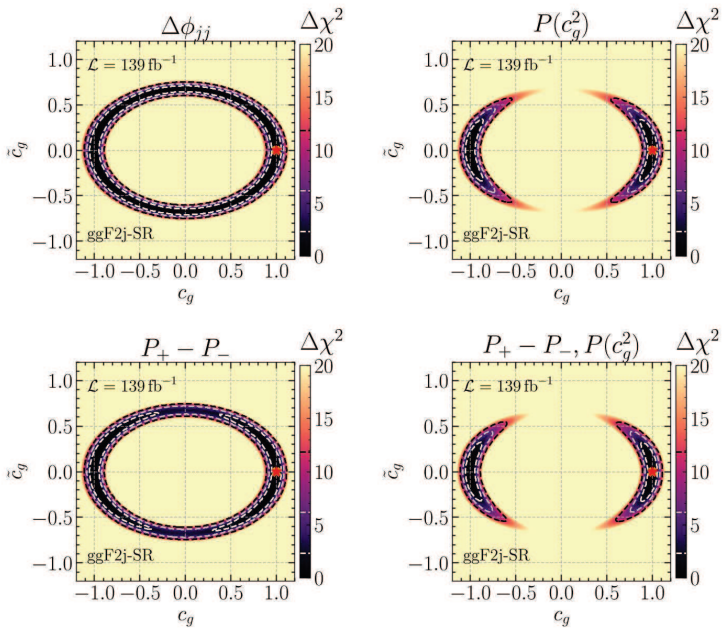
26.09.2023 Marco Menen

ggF2j signal region

- Ellipse from total rate
- $\Delta\phi_{jj}$ alone is not able to resolve the ellipse
- 2D-limits dominated by the $P(c_g^2)$ classifier (low interference contribution)
- $|\tilde{c}_g| \leq 0.32$ @ 1σ



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Example: R. Capucha, *Search for an invisible scalar in tt final states at the LHC* [arXiv:2308.00819]

DM Lagrangian and CP-observables

- Analysis performed within the context of **simplified models of DM production** at the LHC. The **DMsimp** model was used.

$$\mathcal{L}_{SM}^{Y_0} = \frac{y_{33}^t}{\sqrt{2}}\bar{t}(g_{u33}^S + ig_{u33}^P\gamma^5)tY_0$$

Backovic et al. – 1508.05327

$$\mathcal{L}_{X_D}^{Y_0} = \bar{X}_D(g_{X_D}^S + ig_{X_D}^P\gamma_5)X_D\,Y_0$$

- **CP-even:** $g_{u33}^S = 1$, $g_{u33}^P = 0$. **CP-odd:** $g_{u33}^S = 0$, $g_{u33}^P = 1$. **CP-mixed:** $g_{u33}^{S/P} \neq 0$ (**CP-violating interaction**).
- $t\,(\bar{t}) \rightarrow W^+b\,(W^-\bar{b})$ and $W^+(W^-) \rightarrow l^+\upsilon_l(l^-\bar{\upsilon}_l)$: **dileptonic final state**, with $l = e, \mu$.
- $\mathbf{BR}\,(\mathbf{Y_0} \rightarrow \mathbf{X_D}\bar{\mathbf{X}}_\mathbf{D}) \approx \mathbf{1}$. We focus only on the tops and mediator interaction.

- **Several observables** have been proposed to **probe the CP-nature of the Higgs** in the Higgs-top couplings. To illustrate our findings, we considered the **azimuthal angle difference of the charged leptons** from the tops decay, $\boldsymbol{\Delta\phi_{l^+l^-}}$, and the $\mathbf{b_4}$ **variable** in the laboratory frame (LAB)

$$b_4 = (p_t^z.p_{\bar{t}}^z)/(|\vec{p}_t|.|\vec{p}_{\bar{t}}|)$$

Gunion, He - hep-ph/9602226, Buckley, Gonçalves - 1511.06451

- In order to evaluate this variable, the kinematic reconstruction of the $t\bar{t}$ system needs to be accomplished.

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DM Lagrangian and CP-observables

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$\mathcal{L}_S^Y$

$\mathcal{L}_\chi^Y$

- **CP-even:** g^S_{u33}= 1, g^P_{u33}= 0. **CP-odd:** g^S_{u33}= 0, g
- t ($\bar{t}$) → W^+b ($W^-\bar{b}$) and W^+(W^-) → $l^+\upsilon_l$(l^-i
- **BR** $(\mathbf{Y_0 \to X_D \bar{X}_D}) \approx \mathbf{1}$. We focus only on the tc

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- In order to evaluate this variable, the kinematic

Results – heavier masses

- Results extended to a **massive DM mediator**, with m_{Y_0}= 1, 10, 125 GeV. As expected, **exclusion limits worsen as masses increase** in both scenarios, since the $t\bar{t}Y_0$ production cross section decreases for heavier Y_0 masses.

- The observable choice can have some impact on the exclusion limits, even in scenario 1, for heavier masses, because of the cross section decrease.

Scenario 1

Exclusion Limits from $\Delta\phi_{l^+l^-}$		$L = 200$ fb^{-1} (68% CL)	$L = 200$ fb^{-1} (95% CL)	$L = 3000$ fb^{-1} (68% CL)	$L = 3000$ fb^{-1} (95% CL)
$m_{Y_0} = 1$ GeV	$g^S_{u33} \in$	[-0.073, +0.073]	[-0.142, +0.142]	[-0.038, +0.038]	[-0.068, +0.068]
	$g^P_{u33} \in$	[-0.89, +0.89]	[-1.65, +1.65]	[-0.43, +0.43]	[-0.83, +0.83]
$m_{Y_0} = 10$ GeV	$g^S_{u33} \in$	[-0.198, +0.198]	[-0.368, +0.372]	[-0.098, +0.098]	[-0.188, +0.188]
	$g^P_{u33} \in$	[-0.87, +0.87]	[-1.65, +1.65]	[-0.44, +0.44]	[-0.83, +0.83]
$m_{Y_0} = 125$ GeV	$g^S_{u33} \in$	[-0.328,+0.322]	[-0.608, +0.612]	[-0.162, +0.162]	[-0.308, +0.308]
	$g^P_{u33} \in$	[-1.48, +1.49]	[-2.77, +2.78]	[-0.75, +0.75]	[-1.41, +1.41]