

Is the 2HDM still interesting ?

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Particle Physics after the Higgs discovery

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- 1 Introduction
- 2 2HDMs
- 3 Interplay between different constraints
- 4 With DM
- 5 Cosmo connection
- 6 Summary

Disclaimer

- never worked on 2HDMs myself $\Rightarrow$ also an interesting question for me
- apart from models with dark matter candidates...
- so lets go !

Historically

- 2HDMs important e.g. in the context of SUSY
- needed to be able to give masses to fermions w/o SUSY breaking
- additionally allow e.g. for CP violation, etc...
- see review by Branco et al, *Phys.Rept.* 516 (2012) 1-102

After Higgs discovery: Open questions

Higgs discovery in 2012 $\Rightarrow$ last building block discovered

? Any remaining questions ?

- Why is the SM the way it is ??
 $\Rightarrow$ search for **underlying principles/ symmetries**
- find **explanations for observations not described by the SM**
 $\Rightarrow$ e.g. dark matter, flavour structure, ...
- ad hoc approach: Test **which other models still comply with experimental and theoretical precision**

for all: **Search for Physics beyond the SM (BSM)**

$\Rightarrow$ **main test ground for this: particle colliders** $\Leftarrow$

Special role of the scalar sector

- Higgs potential in the SM**

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2, \quad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

⇒ **mass** for Higgs Boson and Gauge Bosons

$$m_h^2 = 2\lambda v^2, \quad m_W = g \frac{v}{2}, \quad m_Z = \sqrt{g^2 + (g')^2} \frac{v}{2}$$

where v : Vacuum expectation value of the Higgs field, g, g' : couplings in $SU(2) \times U(1)$

⇒ **everything determined in terms of gauge couplings, v , and λ**

**form of potential determines minimum,
electroweak vacuum structure**

⇒ stability of the Universe, electroweak phase transition, etc

- full test requires checks of hhh , $hhhh$ couplings**

⇒ **so far: only limits; possible only at future machines** [HL-LHC:
constraints on $hhhh$]

Models

- new scalars $\Rightarrow$ **models with scalar extensions**
- many possibilities: introduce new $SU(2) \times U(1)$ **singlets, doublets, triplets, ...**
- unitarity $\Rightarrow$ important **sum rule***

$$\sum_i g_i^2(h_i) = g_{SM}^2$$

for coupling g to vector bosons

- many scenarios $\Rightarrow$ **signal strength poses strong constraints**

* modified in presence e.g. of doubly charged scalars, see Gunion, Haber, Wudka, PRD 43 (1991) 904-912.

What about extensions ?

- in principle: **no limit**

can add more singlets/ doublets/ triplets/ ...

⇒ consequence: **will enhance particle content**

additional (pseudo)scalar neutral, additional charged, doubly charged, etc particles

- common feature:

new scalar states, which can now also be produced/ decay into each other/ etc

Particle content

typical content:
singlet extensions $\Rightarrow$ additional CP-even/ odd
mass eigenstates
2HDMs, 3HDMs: add additional charged scalars

- e.g. 2 real scalars $\Rightarrow$ **3 CP-even neutral scalars**
- 2HDM $\rightarrow$ **2 CP-even, one CP odd neutral scalar, and charged scalars**
- ...

How can we see new physics ?

Different ways to see new physics effects

- **Option 1:** see a **direct deviation**, in best of all cases a bump, and/ or something similar $\Rightarrow$ **clear enhanced rates for certain final states, mediated by new physics**
- **Option 2:** observe **signatures that do not exist in SM**, e.g. events with large missing energy (hint of model containing DM)
- **Option 3:** observe **deviations in SM-like quantities which are small(ish)**: $\Rightarrow$ loop-induced deviations, requiring precision measurements
- NB: **these can in principle also be large !!** $\Rightarrow$ all models floating around to explain m_W^{CDF}

Current (large) collider landscape

[<https://europeanstrategy.cern/home>]

pp colliders: **LHC, FCC-hh**

LHC: center-of-mass energy: 8/ 13/ 13.6 TeV, since 2009/ ongoing

HL-LHC: 14 TeV, high luminosity (2027-2040)

FCC-hh: 100 TeV, under discussion

e^+e^- colliders: **ILC/ CLIC/ FCC-ee, CePC**

in plan, high priority in Europe, various center-of-mass energies discussed, priority $\sim 240 - 250$ GeV "Higgs factories"

$\mu^+\mu^-$ colliders

under discussion, early stages [EU-funded design study MuCol started 1.3.23]

Two Higgs Doublet Models

a popular extension: **Two Higgs Doublet models**

- extend SM scalar sector by **one additional doublet**
- a priori: can lead to flavour changing neutral currents
- way to prevent this: **introduce additional symmetries in potential**

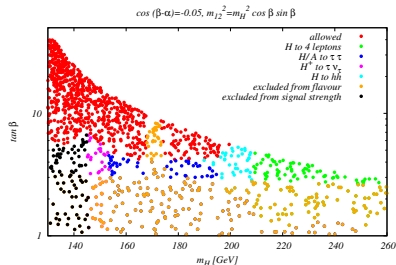
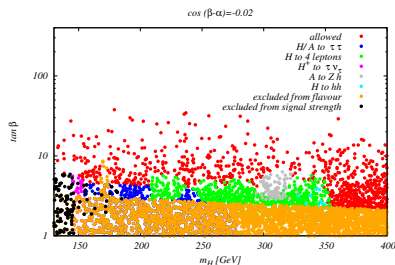
particle content: $\underbrace{h, H}_{\text{CP-even}}, \underbrace{A}_{\text{CP-odd}}, H^\pm$

parameters: **masses**, $+\tan\beta$, $\cos(\beta - \alpha)$, m_{12}

- also subject to various constraints: **B-physics, direct searches, signal strength, ...**
- different types of Yukawa couplings $\Rightarrow$ different effects of constraints

2HDM parameter space for fixed $\cos(\beta - \alpha)$, Type I

TR, EPJ Web Conf. 315 (2024) 01025



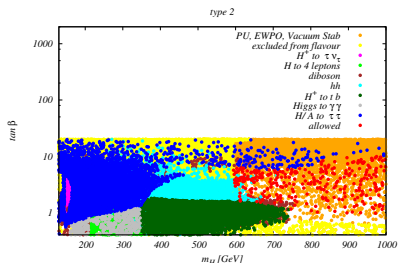
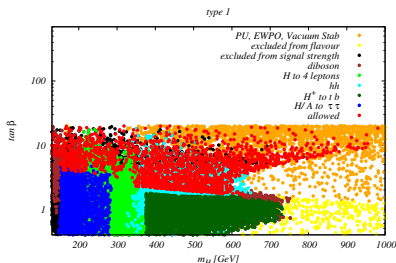
$$m_H = m_A = m_{H^\pm}$$

[using thdmTools, Biekötter et al, JHEP 01 (2024) 107]

Recent 2HDM scan using thdmttools

[code reference: Biekotter ea, JHEP 01 (2024) 107]

all new scalar masses set equal, rest is floating



type 1: all couplings from Φ_2 ; type 2: down-type from Φ_1

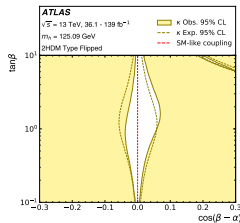
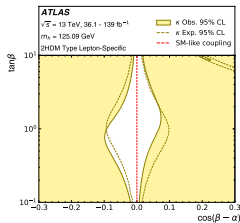
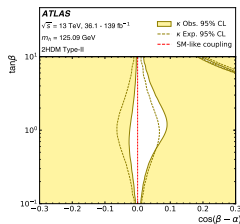
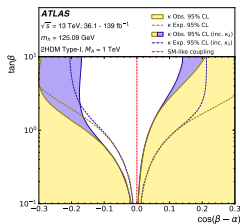
Many signatures

- 2HDMs come with **4 additional particles: $H, A, H^\pm$**
- in principle **opens up room for many signatures not realized in SM**
- production and decay of new particles, with various processes
- **extensive search program from experiments...**

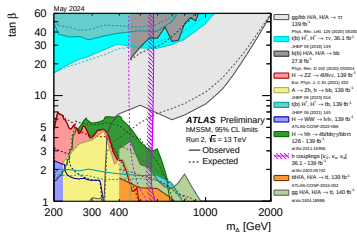
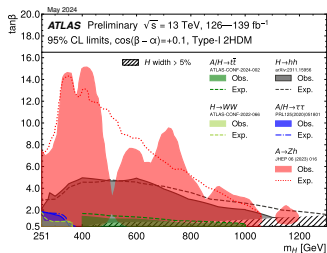
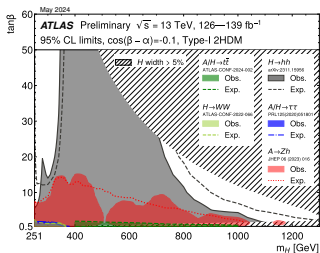
Analyses for 2hdm constraints (older list)

- $A \rightarrow Zh$: CMS, Phys.Lett.B 748 (2015) 221-243, Run 1, 20 fb^{-1} ; CMS, Eur. Phys. J. C 79 (2019) 564, early Run 2;
- H to 4 leptons: ATLAS, Eur.Phys.J.C 81 (2021) 4, 332, full Run 2;
- diboson: ATLAS, Phys. Rev. D 98, 052008 (2018), early Run 2; CMS, HEP 06 (2018) 127, early Run 2; ATLAS, Eur.Phys.J.C 80 (2020) 12, 1165, full Run 2
- hh: ATLAS, ATLAS-CONF-2021-030, full Run 2; CMS, Phys.Rev.Lett. 122 (2019) 12, 121803, early Run 2
- $H^+ \rightarrow t \bar{b}$: ATLAS, JHEP 06 (2021) 145, full Run 2; CMS, JHEP 07 (2020) 126, early Run 2
- $H \rightarrow \tau^+ \tau^-$: CMS, JHEP 07 (2023) 073, full Run 2; CMS, JHEP 09 (2018) 007, early Run 2; ATLAS, Phys.Rev.Lett. 125 (2020) 5, 051801, full Run 2; CMS, CMS-PAS-HIG-14-029, Run 1 combination
- h to 4 leptons: CMS, Phys. Rev. D 89 (2014) 092007, early Run 1
- $H^+ \rightarrow \tau^+ \nu_\tau$: ATLAS, JHEP 09 (2018) 139, early Run 2
- $H \rightarrow \gamma\gamma$: ATLAS, Phys.Lett.B 822 (2021) 136651, full Run 2

ATLAS signal strength fits [JHEP 11 (2024) 097]



ATLAS Type I summary plots
[ATLAS-PHYS-PUB-2024-008]



Consequences of combining constraints: flavour, electroweak precision, and signal strength

- non-singlet scenarios: **also strong constraints from flavour**
- typical example: **2HDMs, constraints in the $(m_{H^\pm}, \tan \beta)$ plane**
- ⇒ **sets lower limit on charged mass**
- ⇒ **strongly correlated to other additional masses via electroweak precision measurements (S, T, U)**

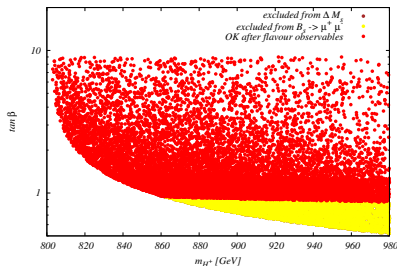
Lower mass bound on additional scalars

- Consequence: "typical" channels at e^+e^- colliders [e.g. HA] require higher center of mass energies [e.g. TeV range]
- example here: **THDMa (2HDM+ singlet)** [TR, Symmetry 13 (2021) 12, 2341]

Example: B- physics constraints [TR, PoS ICHEP2022 176]

Constraints from $B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$, ΔM_s

- $B \rightarrow X_s \gamma$: use fit from updated calculation of Misiak ea, [JHEP 2006 (2020) 175, Eur.Phys.J. C77 (2017) no.3, 201], $\Rightarrow \tan \beta_{\min}(m_{H^\pm})$
- $B_s \rightarrow \mu^+ \mu^-$, ΔM_s : via SPheno, compare to PDG value, HFLAV value [Eur.Phys.J.C 81 (2021) 3, 226]



$$R_{\gamma}^{\text{exp}} \equiv \frac{\mathcal{B}(s+d)\gamma}{\mathcal{B}_{\text{c}\ell\nu}} = (3.22 \pm 0.15) \times 10^{-3},$$

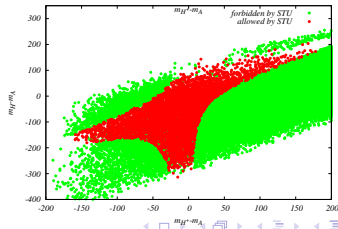
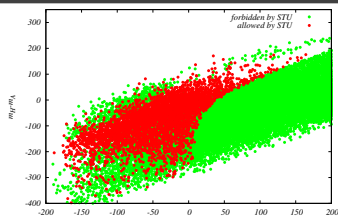
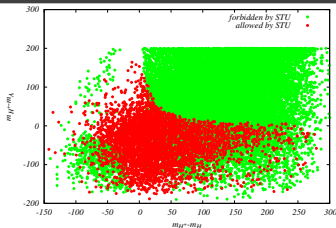
$$\Delta M_s (\text{ps}^{-1}) = 17.757 \pm 0.020 \pm 0.007,$$

$$(B_s \rightarrow \mu^+ \mu^-)^{\text{PDG}} = [3.01 \pm 0.35] \times 10^{-9}$$

Oblique parameters via SPheno, compare to GFitter [Eur. Phys. J., C78(8):675]

Constraints on mass differences

$$m_{H^\pm} - m_H, m_{H^\pm} - m_A, m_A - m_H$$



compare to THDM $\Rightarrow$

In this particular case: ...

- **In a general scan** [letting 10 parameters float]:

heavy scalar masses $\gtrsim 500$ GeV

Consequence

- channels as e.g. HA **only accessible for $\gtrsim 1$ TeV**
"partonic" center of mass energies

[statement different for other Yukawa structures]

Recasting example: Inert Doublet Model

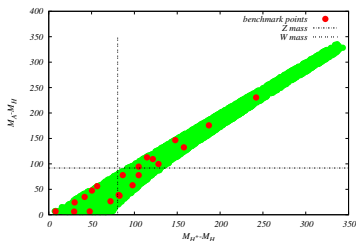
2 Higgs Doublet Model: 4 new scalars $H, A, H^\pm$

Z_2 symmetry $\rightarrow$ **DM candidate(s)** (here: choose H)

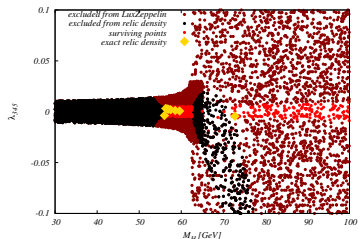
free parameters: **masses**, λ_2, λ_{345} (couplings in V)

signatures: EW gauge boson(s) + MET

$\Rightarrow$ so far: no LHC analysis $\Leftarrow$



Masses highly constrained from electroweak precision
[Kalinowski, Kotlarski, TR, Sokolowska,
Zarnecki, JHEP 1812 (2018)]



... and also from signal strength and
astrophysical constraints ...

[update of Ilnicka, TR, Stefaniak,
Mod.Phys.Lett. A33 (2018) no.10n11, 1830007]

Number of free parameters and constraints

Model has 7 free parameters

- choose e.g.

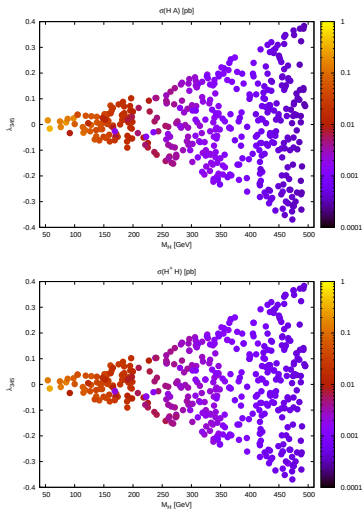
$$\underbrace{\nu, M_h}_{246 \text{ GeV}, 125 \text{ GeV}}, M_H, M_A, M_{H^\pm}, \lambda_2, \lambda_{345} [= \lambda_3 + \lambda_4 + \lambda_5]$$

Constraints

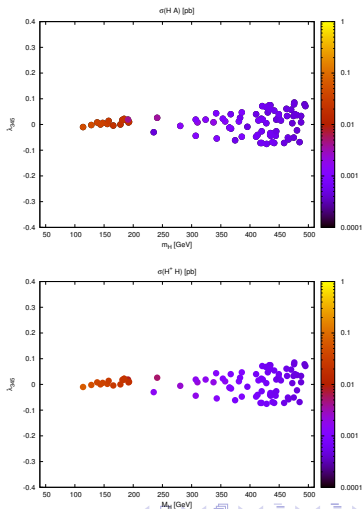
- Theory constraints:** vacuum stability, positivity, constraints to be in inert vacuum, perturbative unitarity, perturbativity of couplings, choosing M_H as dark matter: $M_H \leq M_A, M_{H^\pm}$
- Experimental constraints:** total width of $h W, Z$; collider constraints from signal strength/ direct searches; electroweak precision through S, T, U ; unstable $H^\pm$; reinterpreted/ recastet LEP/ LHC SUSY searches (Lundstrom ea 2009; Belanger ea, 2015); dark matter relic density (upper bound); dark matter direct search limits (LUX-ZEPLIN)

Updated constraints [LUX-ZEPLIN] [Phys.Rev.Lett. 131 (2023) 4, 041002]

LUX



LUX-ZEPLIN



Recast of LHC Run II results

(in collaboration w D. Dercks, Eur.Phys.J.C 79 (2019) 11, 924))

- so far:

no dedicated searches at the LHC (yet)

- however, dominant final states:

jet(s) + MET, EW gauge boson(s) + MET

⇒ **same final states appear in other BSM searches** ⇐

- idea: **use recasting methods** to give (preliminary) exclusion limits if feasible
- many tools around; here: **CheckMATE**
[Drees ea '13, Dercks ea '16]

IDM recast

- considered a long list of processes at 13 TeV
- most sensitive:

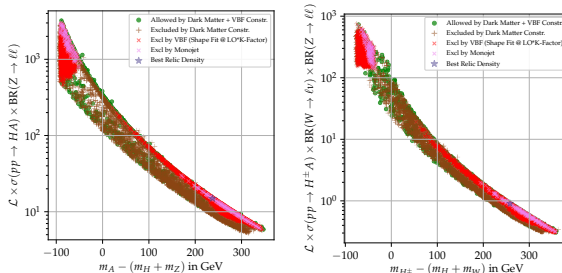
VBF + invisible Higgs decay (by far), Monojet

- ⇒ implemented in CheckMATE [currently: private version]
- ⇒ applied to IDM

VBF: Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at $\sqrt{s} = 13$ TeV, CMS, Phys.Lett.B 793 (2019) 520-551, $[35.9\text{fb}^{-1}]$

Monojet: Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector, ATLAS, JHEP 01 (2018) 126, $[36.1\text{fb}^{-1}]$

Brief comments on null-results for dilepton final states



- **high $\cancel{E}_\perp \Rightarrow$ low σ and vice versa**

experiments need to venture into low $\cancel{E}_\perp$ region

(first discussions: The 15th Workshop of the LHC Higgs Cross Section Working Group, CERN, 12/18; cf

e.g. summary talk by D. Sperka)

Recasting $\ell\ell + \cancel{E}_\perp$ using full Run 2 results

(w. J. Lahiri/ K. Rolbiecki)

- recently: **a lot of interest has gone into the THDMa**
[THDM+ additional pseudoscalar + fermionic dm candidate]

[see Ipek ea, Phys. Rev., D90(5):055021, 2014; No, Phys. Rev., D93(3):031701, 2016; Goncalves ea, Phys. Rev. D95(5):055027, 2017; Bauer ea, JHEP, 05:138, 2017; Tunney ea, Phys. Rev., D96(9):095020, 2017; also TR, Symmetry 13 (2021) 12, 2341]

shares $Z + \cancel{E}_\perp$ as a dominant channel

- what about a recast there ??**
- tool of choice: **CheckMATE**

[Drees ea, Comput.Phys.Commun. 187 (2015) 227-265; Dercks ea, Comput.Phys.Commun. 221 (2017) 383-418]

Search for associated production of a Z boson with an invisibly decaying Higgs boson or dark matter candidates at $\sqrt{s} = 13\text{TeV}$ with the ATLAS detector, Phys. Lett. B 829 (2022) 137066

- used in TR, Symmetry 13 (2021) 12, 2341 to constrain $Z + \cancel{E}_\perp$ channel
- cut out 9% of the THDMa parameter space¹
- maybe also useful for IDM ?

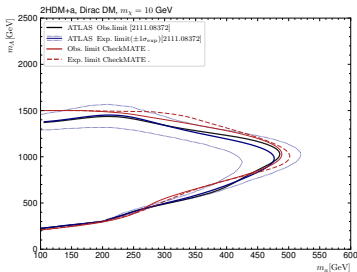
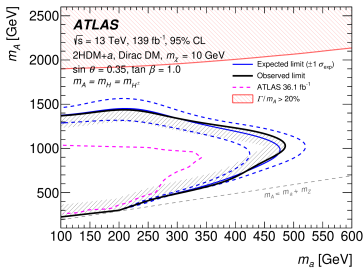


Fig from Phys. Lett. B 829 (2022) 137066

¹ Scan dependent statement

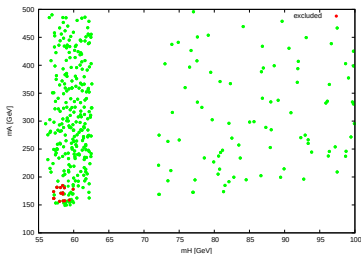
Validation within CheckMATE, thanks to I. Lara

First results

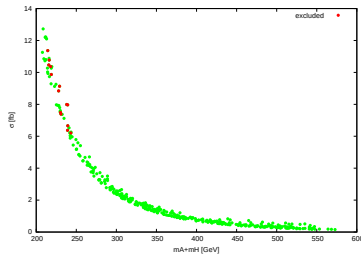
specific sample, concentrates on low $m_H \leq 100$ GeV

dominant production: $pp \rightarrow Z^* \rightarrow HA, A \rightarrow H\ell^+\ell^-$

In principle: only m_A, m_H should matter



allowed and excluded points, (m_H, m_A) plane



allowed and excluded points $(m_H + m_A, \sigma_{HA}^{\text{cuts}})$ plane

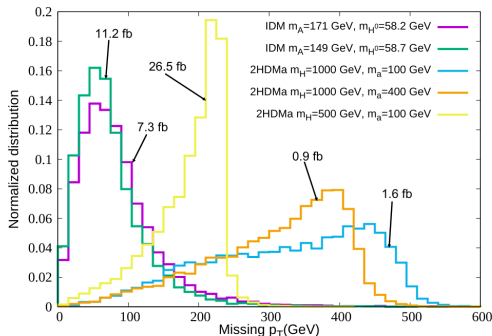
in practise:

contamination from $pp \rightarrow H^\pm A$ with hadronic W decays

Kinematic distributions

nota bene: **cross sections for THDMA typically much smaller, still excluded !**

reason: **differences in kinematic distributions**; here: **missing $p_{\perp}$**

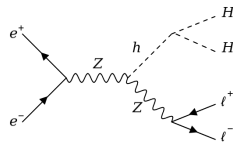
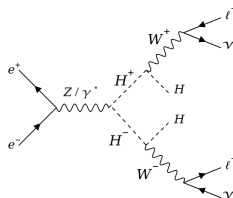
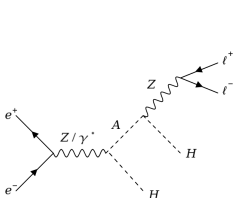


Cut in analysis: $\cancel{E}_{\perp} \geq 90$ GeV

IDM: Leptonic production modes

(M. Benedikt et al., Eur. Phys. J. C (2025) 85:891)

$$\begin{aligned}
 e^+ e^- &\rightarrow HA^{(*)} \rightarrow HZ^{(*)} H \rightarrow H H \ell^+ \ell^-, \\
 e^+ e^- &\rightarrow H^{+(*)} H^{-(*)} \rightarrow W^{+(*)} W^{-(*)} H H \\
 &\rightarrow H H \ell^+ \ell^- \nu_e \bar{\nu}_e,
 \end{aligned}$$



in reality: simulate ***everything*** leading to $\ell^+ \ell^- + \cancel{E}$

Search strategy

- consider **3 scenarios**

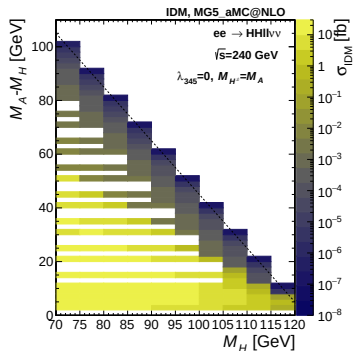
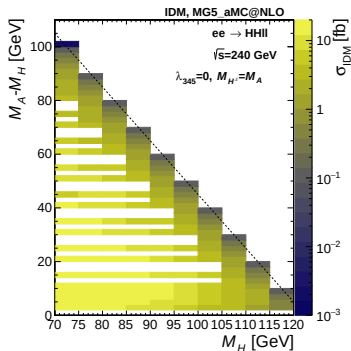
$$(S1) \quad M_{H^\pm} = M_A, \lambda_{345} = 0;$$

$$(S2) \quad M_{H^\pm} = M_A, \lambda_{345} = \lambda_{345}^{\max};$$

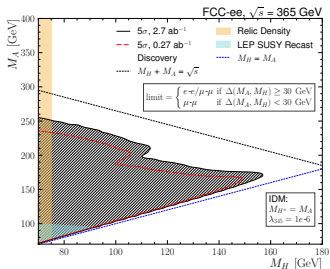
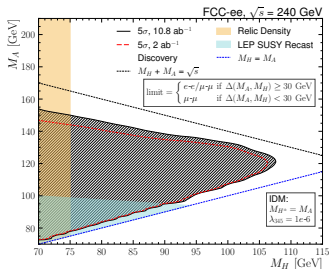
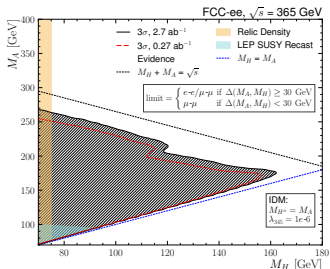
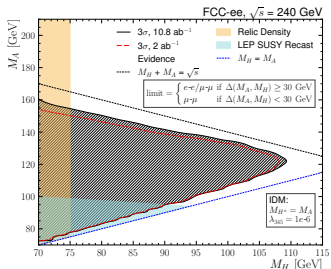
$$(S3) \quad M_{H^\pm} = M_{H^\pm}^{\max}, \lambda_{345} = \lambda_{345}^{\max}$$

- idea: **switch on/ off various contributions**
- other parameters: M_H **free**, $\lambda_2 = 0.1$

Sample cross sections



Results [exclusion and discovery], scen 1, including pNN



Investigate VBF-type production of AA at muon collider (10 TeV) (w. J. Braathen, M. Gabelmann, P. Stylianou; arXiv:2411.13729)

- main target

$$\mu^+ \mu^- \rightarrow AA \nu_\mu \bar{\nu}_\mu$$

with $A \rightarrow HZ$ and semileptonic decay modes for Z s.

- typical cross sections [after some basic cuts]
 $\lesssim 0.05 \text{ fb}$ **at 10 TeV center of mass energy**

Why muon collider ?

- **AA production only mediated via h_{125}**

- coupling

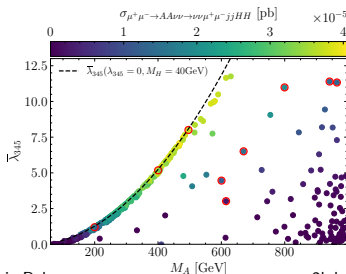
$$\bar{\lambda}_{345} = \lambda_{345} + \frac{2(m_A^2 - m_H^2)}{v^2}$$

- λ_{345} typically small from DM constraints

- mass difference can also not be too large

[although we found counterexamples]

- large com energies $\Rightarrow$ **log-enhanced VBF type production**

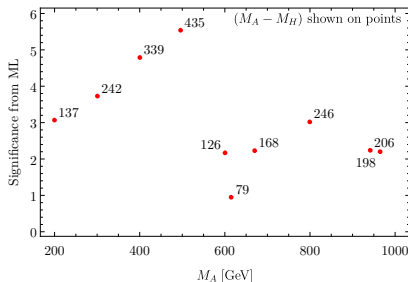


upper limit on $\bar{\lambda}_{345}$
pert. limit at 4 π

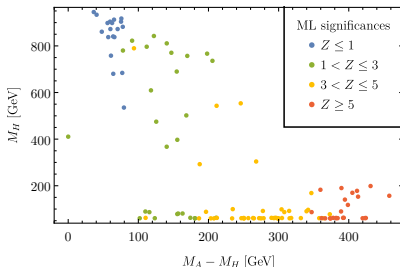
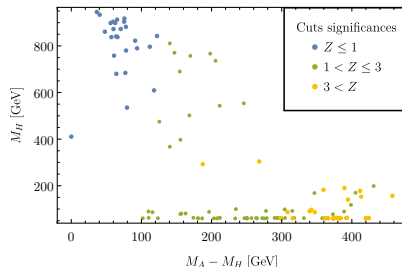
benchmark points (red circles)

Strategy

- generate $\mu^+ \mu^- \rightarrow AA \nu_\mu \bar{\nu}_\mu$ with $A \rightarrow H \ell^+ \ell^-$, $A \rightarrow H jj$
- 2 approaches: **cut based vs machine learning** (XGBoost)
- main result: **ML supersedes the cut based method, significances $\geq 3/5$ possible**



Results



$$Z = \sqrt{2 \left[(S + B) \ln \left(1 + \frac{S}{B} \right) - S \right]}$$

- IDM should be **testable at 10 TeV muon collider**, using ML analysis (similar to ours)
- **lower limit on cross sections** (w precuts) **of about 0.07 (0.05)fb for exclusion (discovery)**
- **systematic uncertainties need to be well under control**;
best $\leq 5\%$ for systematic uncertainties

Cosmo connection

- currently hot topic: **connection of new physics scenarios to evolution of the universe**
- **modified potential leads to additional contributions to effective vacuum**
- also often: **connection to modified self couplings, often at higher order**

⇒ very active field, but I am no expert...

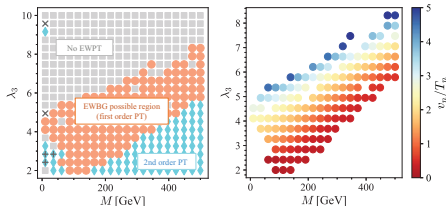
(slide from S. Kanemura, HiggsDays 25)

Electroweak phase transition

(Used Cosmotransitions)

Wainwright (2011)

- Several fates of the vacuum



- For successful EWBG, at least,
 - $O(1)$ large λ_3 coupling
 - Satisfying $v_n/T_n > 1$ are needed.

$$\text{c.f.) } m_{H^\pm}^2 = M^2 + \frac{1}{2}\lambda_3 v^2$$

and

$$m_{H_2} = m_{H_3} = m_{H^\pm}$$

M. Endo, M. Aiko, S.K., Y. Mura, arXiv: JHEP 07 (2025) 236

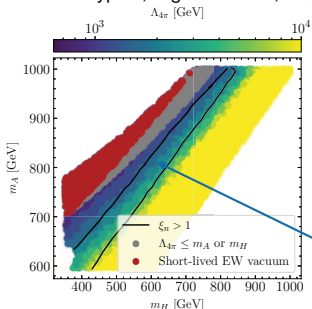
23

(slide from G. Weiglein, HiggsDays 25)

Correlation of strong first-order EWPT with splitting between BSM Higgs masses of extended Higgs sector

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '22]
 2HDM, N2HDM, ... : the parameter region giving rise to a **strong first-order EWPT**, which may cause a detectable gravitational wave signal, yields an **enhancement of the trilinear Higgs self-coupling** and “**smoking gun**” signatures at the LHC

2HDM of type II, alignment limit, $\tan\beta = 3$:

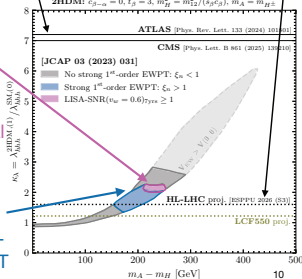


region with potentially observable gravitational wave (GW) signal

region with strong first-order EWPT

current bound

HL-LHC sensitivity

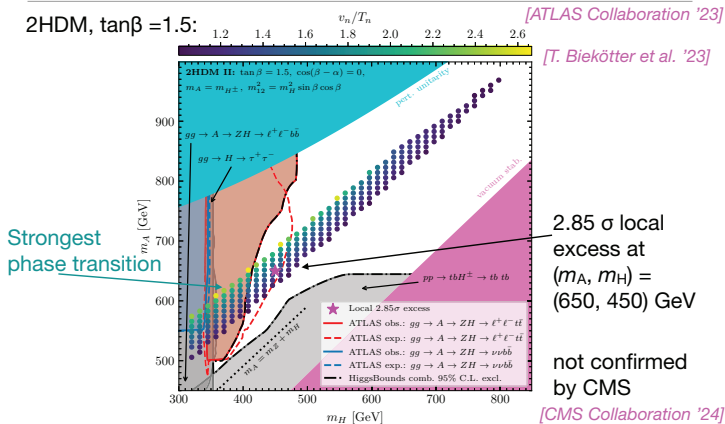


the nature of Higgs physics, Georg Weiglein, Higgs Days at Santander 2025, Santander, 09 / 2025

(slide from G. Weiglein, HiggsDays 25)

ATLAS “smoking gun” search $pp \rightarrow A \rightarrow ZH \rightarrow Zt\bar{t}$
vs. preferred region for strong first-order EWPT

2HDM, $\tan\beta = 1.5$:



$\Rightarrow$ LHC searches start to probe the region giving rise to a strong FOEWPT

The future of Higgs physics, Georg Weiglein, Higgs Days at Santander 2025, Santander, 09 / 2025

Summary

Models with extended scalar sectors provide an interesting setup to introduce new scalar particles, with different CP/ charge quantum numbers

⇒ leads to many **new interesting signatures**, some of which are not yet covered by current searches

some of these: also interesting connections of electroweak phase transitions/ gravitational waves/ etc

Next steps

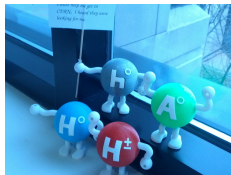
- **(re) investigate models with extended scalar sectors at e^+e^- colliders** [ECFA effort ongoing]

Many things to do

Appendix

Other possible extensions

- A priori: **no limit to extend scalar sector**
- **make sure you**
 - have a **suitable ew breaking mechanism**, including a **Higgs candidate at ~ 125 GeV**
 - can explain **current measurements**
 - are **not excluded by current searches** and precision observables
- **nice add ons:**
 - can **push vacuum breakdown to higher scales**
 - can **explain additional features**, e.g. dark matter, or hierarchies in quark mass sector
 - ...
- Multitude of models out there
- adding ew gauge singlets/ doublets/ triplets...
 $\Rightarrow$ **new scalar states** $\Leftarrow$



Models with extended scalar sectors

Constraints

- **Theory**

minimization of vacuum (tadpole equations), vacuum stability, positivity, perturbative unitarity, perturbativity of couplings

- **Experiment**

provide viable candidate @ 125 GeV (coupling strength/ width/ ...);
agree with null-results from additional searches and ew gauge boson measurements (widths);
agree with electroweak precision tests (typically via S,T,U);
agree with astrophysical observations (if feasible)

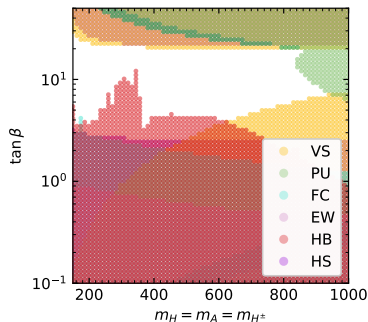
Limited time $\Rightarrow$ next slides highly selective...

[long list of models, see e.g. <https://twiki.cern.ch/twiki/bin/view/LHCPHysics/LHCHXSWG3>]

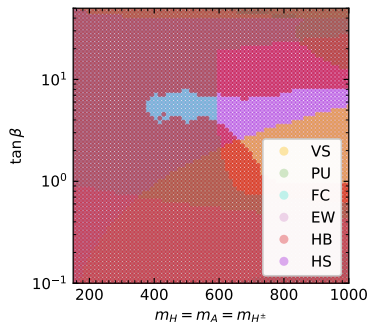
tools used: HiggsBounds, HiggsSignals, 2HDMC, micrOMEGAs, ...

2HDM parameter space, previous plots w all constraints

[thanks to K. Radychenko, tool presented in 2309.17431]



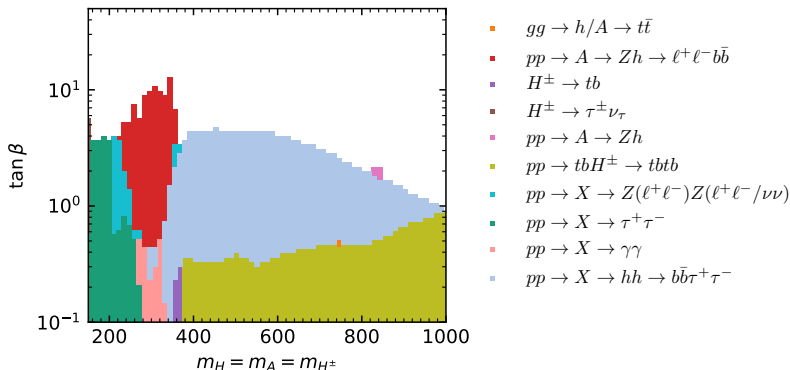
Type I, $\cos(\beta - \alpha) = 0.1$



Type II, $\cos(\beta - \alpha) = 0.05$

Most up-to-date search constraints for 2HDM type I

[thanks to K. Radychenko, tool presented in 2309.17431]



Search references

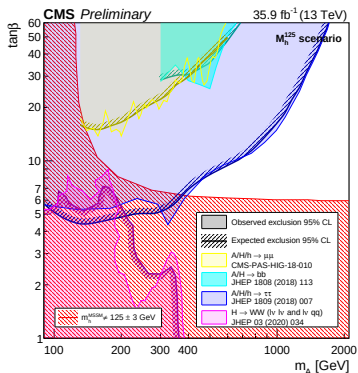
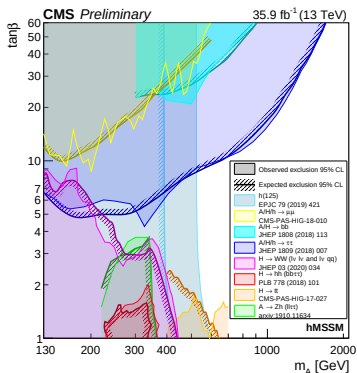
- CMS, 36 fb^{-1} , JHEP 04 (2020) 171, JHEP 03 (2022) 187 (erratum)
- ATLAS, 36 fb^{-1} , Phys.Lett.B 783 (2018) 392-414
- CMS, 36 fb^{-1} , JHEP 07 (2020) 126
- ATLAS, 36 fb^{-1} , JHEP 09 (2018) 139
- CMS, 36 fb^{-1} , Eur.Phys.J.C 79 (2019) 7, 564
- ATLAS, 139 fb^{-1} , JHEP 06 (2021) 145
- ATLAS, 139 fb^{-1} , Eur.Phys.J.C 81 (2021) 4, 332
- CMS, 138 fb^{-1} , JHEP 07 (2023) 073
- ATLAS, 139 fb^{-1} , Phys.Lett.B 822 (2021) 136651
- ATLAS, 139 fb^{-1} , ATLAS-CONF-2021-030

Analyses for 2hdm constraints

- $A \rightarrow Z h$: CMS, Phys.Lett.B 748 (2015) 221-243, Run 1, 20 fb^{-1} ; CMS, Eur. Phys. J. C 79 (2019) 564, early Run 2;
- H to 4 leptons: ATLAS, Eur.Phys.J.C 81 (2021) 4, 332, full Run 2;
- diboson: ATLAS, Phys. Rev. D 98, 052008 (2018), early Run 2; CMS, HEP 06 (2018) 127, early Run 2; ATLAS, Eur.Phys.J.C 80 (2020) 12, 1165, full Run 2
- hh : ATLAS, ATLAS-CONF-2021-030, full Run 2; CMS, Phys.Rev.Lett. 122 (2019) 12, 121803, early Run 2
- $H^+ \rightarrow t \bar{b}$: ATLAS, JHEP 06 (2021) 145, full Run 2; CMS, JHEP 07 (2020) 126, early Run 2
- $H \rightarrow \tau^+ \tau^-$: CMS, JHEP 07 (2023) 073, full Run 2; CMS, JHEP 09 (2018) 007, early Run 2; ATLAS, Phys.Rev.Lett. 125 (2020) 5, 051801, full Run 2; CMS, CMS-PAS-HIG-14-029, Run 1 combination
- h to 4 leptons: CMS, Phys. Rev. D 89 (2014) 092007, early Run 1
- $H^+ \rightarrow \tau^+ \nu_\tau$: ATLAS, JHEP 09 (2018) 139, early Run 2
- $H \rightarrow \gamma\gamma$: ATLAS, Phys.Lett.B 822 (2021) 136651, full Run 2

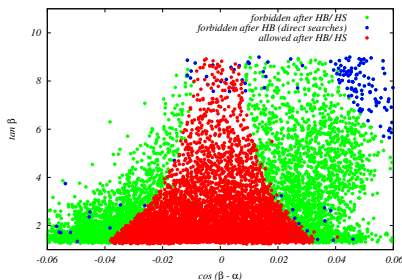
CMS MSSM summary plots, early Run II

[<https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG>]



Direct searches and signal strength

Via HiggsBounds/ HiggsSignals



$\cos(\beta - \alpha) > 0.04$:

$h_{125} \rightarrow ZZ$

[CMS Run I, Phys. Rev. D

89 (2014) 092007]

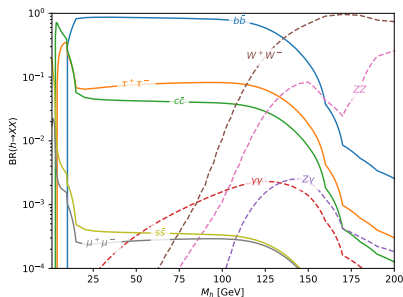
Relevant BSM searches:

$H/A \rightarrow \tau\tau$ [ATLAS Run II, Phys.Rev.Lett. 125 (2020) no.5, 051801],

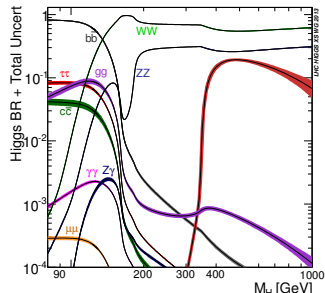
$H \rightarrow h_{125}h_{125}$ [ATLAS 2018 data, JHEP 1901 (2019) 030],

$A \rightarrow H/h_{125}Z$ [ATLAS 2018/ full Run 2 data, Phys.Lett. B783 (2018) 392-414, ATLAS-CONF-2020-043]

Reminder: decays of a SM-like Higgs of mass $M \neq 125 \text{ GeV}$

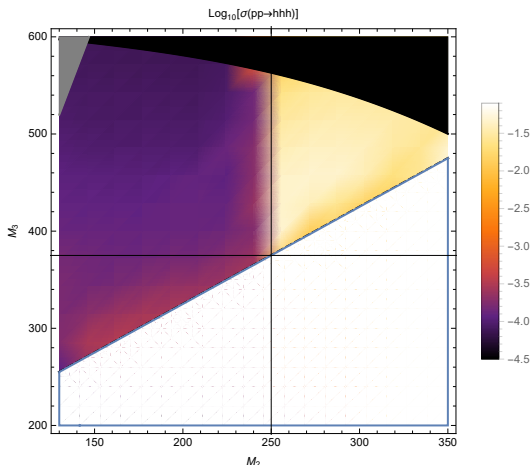


(using HDecay, courtesy J.Wittbrodt)



(<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGCrossSectionsFigures>)

$h_1 h_1 h_1$ production cross sections, leading order [pb]



highest values: $\sim 50\text{fb}$ for $M_2 \sim 250\text{ GeV}$, $M_3 \sim 400 - 450\text{ GeV}$

Current back of the envelope accuracy estimates

[for triple couplings, from M. Selvaggis talk at Higgs Pairs mini-workshop 09/21, and Snowmass WPs arXiv:2203.07622 (ILC)/ arXiv:2203.07646 (C^3)]

- HL-LHC/ ILC₂₅₀/ CLIC₃₈₀/ CEPC₂₄₀/ $C^3_{250} \sim 50\%$
- FCC-ee_{240/365}, ILC₅₀₀, $C^3_{550} \sim 20 - 27\%$
- ILC_{500-1000GeV}, CLIC_{3TeV} $\sim 8 - 11\%$
- FCC-hh $\sim 3.5 - 8\%$
- $\mu\mu_{30TeV} \sim 2 - 3\%$

[HH / single H ; recent updates not included]

? What about quartic couplings ?

Incomplete list of papers looking at quartic coupling

- W. Bizon, U. Haisch and L. Rottoli, *Constraints on the quartic Higgs self-coupling from double-Higgs production at future hadron colliders*, JHEP 10 (2019) 267 [1810.04665].
- S. Borowka, C. Duhr, F. Maltoni, D. Pagani, A. Shivaji and X. Zhao, *Probing the scalar potential via double Higgs boson production at hadron colliders*, JHEP 04 (2019) 016 [1811.12366].
- T. Liu, K.-F. Lyu, J. Ren and H.X. Zhu, *Probing the quartic Higgs boson self-interaction*, Phys. Rev. D98 (2018) 093004 [1803.04359].
- J. Alison et al., *Higgs boson potential at colliders: Status and perspectives*, Rev. Phys. 5 (2020) 100045 [1910.00012].
- A. Papaefstathiou and K. Sakurai, *Triple Higgs boson production at a 100 TeV proton-proton collider*, JHEP 02 (2016) 006 [1508.06524].
- C.-Y. Chen, Q.-S. Yan, X. Zhao, Y.-M. Zhong and Z. Zhao, *Probing triple-Higgs productions via $4b2\gamma$ decay channel at a 100 TeV hadron collider*, Phys. Rev. D93 (2016) 013007 [1510.04013].
- D.A. Dicus, C. Kao and W.W. Repko, *Self Coupling of the Higgs boson in the processes $p p \rightarrow ZHHH + X$ and $p p \rightarrow WHHH + X$* , Phys. Rev. D93 (2016) 113003 [1602.05849].
- R. Contino et al., *Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies*, CERN Yellow Rep. (2017) 255 [1606.09408].
- B. Fuks, J.H. Kim and S.J. Lee, *Scrutinizing the Higgs quartic coupling at a future 100 TeV proton-proton collider with taus and b-jets*, Phys. Lett. B771 (2017) 354 [1704.04298].
- A. Papaefstathiou, G. Tetlalmatzi-Xolocotzi and M. Zaro, *Triple Higgs boson production to six b-jets at a 100 TeV proton collider*, Eur. Phys. J. C 79 (2019) 947 [1909.09166]. [-1.7 ; 13]
- F. Maltoni, D. Pagani and X. Zhao, *Constraining the Higgs self-couplings at e^+e^- colliders*, JHEP 07 (2018) 087 [1802.07616]. $CLIC_{3TeV}$ [-5 ; 7]
- M. Chiesa, F. Maltoni, L. Mantani, B. Mele, F. Piccinini and X. Zhao, *Measuring the quartic Higgs self-coupling at a multi-TeV muon collider*, JHEP 09 (2020) 098 [2003.13628]. all $[0; 2]$ best (30TeV) $[0.7; 1.5]$

Finite width: Input and crucial quantities

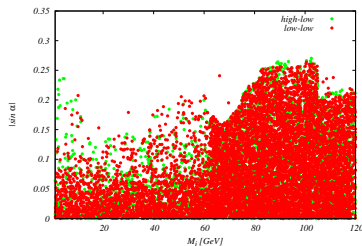
	Benchmark scan no 1	benchmark scan no 2
m_{h_1}	125.09 GeV	125.09 GeV
m_{h_2}	300GeV	600GeV
$\tan \beta$	3.3	1.6
$\sin \theta$	0.17	0.17
Γ_{h_2}	0.5408GeV	4.9802GeV
$\text{BR}_{h_2 \rightarrow h_1 h_1}$	0.5519	0.3396
$\Gamma_{\tilde{h}_2}$	20MeV	20MeV
	Cross Sections	
$pp \rightarrow h_1 h_1$	$(69.858 \pm 0.015)\text{fb}$	$(25.573 \pm 0.101)\text{fb}$
$pp \rightarrow h_2$	$(106.47 \pm 0.003)\text{fb}$	$(23.075 \pm 0.0007)\text{fb}$
$pp \rightarrow h_2 \rightarrow h_1 h_1$	$(58.628 \pm 0.002)\text{fb}$	$(7.8852 \pm 0.0003)\text{fb}$
$pp \rightarrow h_1 h_1 \setminus h_2$	$(14.179 \pm 0.0008)\text{fb}$	$(14.083 \pm 0.0007)\text{fb}$
$pp \rightarrow \tilde{h}_2 \rightarrow h_1 h_1$	$(1588.6 \pm 0.08)\text{fb}$	$(1951.2 \pm 0.05)\text{fb}$

What about different collider reaches ?

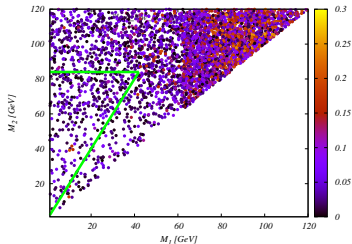
- **many different future colliders are discussed** [past- HL-LHC]
- current focus: **Higgs factories** (e^+e^- , $\sqrt{s} \sim 250$ GeV)
interesting: compare possible reach ?
- will do a _superficial_ comparison for a specific model
- of course more detailed studies called for

Singlet extensions [TR, arXiv:2203.08210 and Symmetry 2023, 15(1), 27]

TRSM: 2 real singlets [TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J.C 80 (2020) 2, 151]



mass and mixing angle



case with two light scalars;
color coding: h_1 rescaling

- **low-low**: both additional scalars below 125 GeV; **high-low**: one new scalar above 125 GeV

Possible model reach

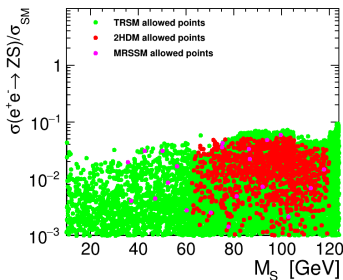
[slide from A.F.Zarnecki, Higgs 2023]

Motivation



Possible scenarios

Benchmark points consistent with current experimental and theoretical bounds



Two-Real-Singlet Model

thanks to Tania Robens

see [arXiv:2209.10996](https://arxiv.org/abs/2209.10996) [arXiv:2305.08595](https://arxiv.org/abs/2305.08595)

Two Higgs-Doublet Model

thanks to Kateryna Radchenko

thdmTool package, see [arXiv:2309.17431](https://arxiv.org/abs/2309.17431)

Minimal R-symmetric Supersymmetric SM

thanks to Wojciech Kotlarski [arXiv:1511.09334](https://arxiv.org/abs/1511.09334)