Extended scalar sectors at future colliders

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based on work with

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Ruder Boskovic Institute

XXVII Cracow Epiphany Conference on Future of particle physics

IFJ PAN
Cracow, 8.1.21

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)**

$\Longrightarrow$ **main test ground for this: particle colliders** $\Longleftarrow$

Extending the scalar sector

- A priori: **no limit to extend SM scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at** $\sim\, 125\,\mathrm{GeV}$
  - 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
  - ...

Models with extended scalar sectors

Extend SM with additional scalars:
gauge singlet(s), doublet(s), triplet(s), ...

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)

tools used:

`HiggsBounds`, `HiggsSignals`, `2HDMC`, `micrOMEGAs`, `ScannerS`, ...

In this talk...

$\Longrightarrow$ **Models:** Inert Doublet Model, 2 real singlet extension

$\Longrightarrow$ **Colliders:** CLIC, HL-LHC, FCC, $\mu\mu$ collider

References:

Phys.Rev. D93 (2016) no.5, 055026; Mod.Phys.Lett. A33 (2018) no.10n11, 1830007; JHEP 1812 (2018) 081; JHEP 1907 (2019) 053; Eur.Phys.J. C80 (2020) no.2, 151; arXiv:2012.14818; ...

Inert doublet model: The model

- idea: take **two Higgs doublet model, add additional Z_2 symmetry**

$$\phi_D \;\to\; -\phi_D, \phi_S \;\to\; \phi_S, \text{SM} \;\to\; \text{SM}$$

(⇒ implies CP conservation)

⇒ obtain a **2HDM with (a) dark matter candidate(s)**

- potential

$$V = -\frac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S)+m_{22}^2(\phi_D^\dagger\phi_D)\right] + \frac{\lambda_1}{2}(\phi_S^\dagger\phi_S)^2+\frac{\lambda_2}{2}(\phi_D^\dagger\phi_D)^2$$
$$+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D)+\lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger\phi_D)^2+(\phi_D^\dagger\phi_S)^2\right],$$

- only one doublet acquires VeV v, as in SM
  (⇒ implies analogous EWSB)

Number of free parameters

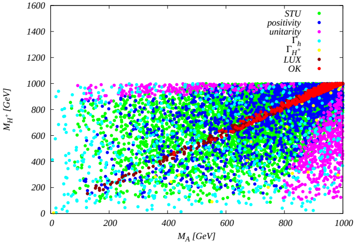
Model has 7 free parameters

- choose e.g.

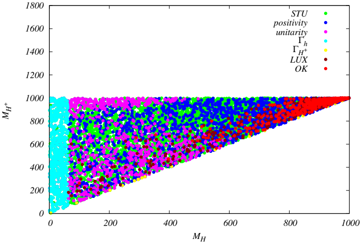
$$\mathbf{v},\ \mathbf{M_h},\ \mathbf{M_H},\ \mathbf{M_A},\ \mathbf{M_{H^\pm}},\ \lambda_2,\ \lambda_{345}\,[=\ \lambda_3+\lambda_4+\lambda_5]$$

- v, M_h fixed $\Rightarrow$ left with **5 free parameters**
- **choosing** M_H as dark matter: $M_H\ \leq\ M_A,\ M_{H^\pm}$

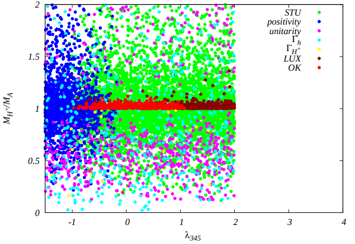
Results of generic scan [arXiv:1508.01671,arXiv:1809.07712]



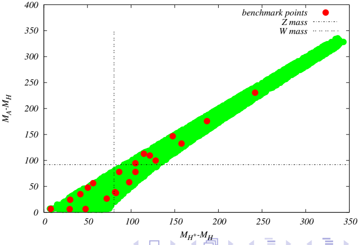
M_A vs $M_{H\pm}$



M_H vs $M_{H\pm}$



λ_{345} vs $M_{H\pm}/M_A$

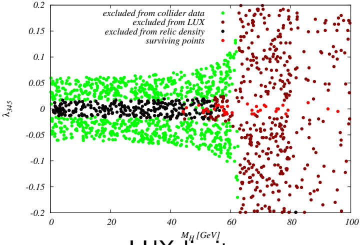


mass differences

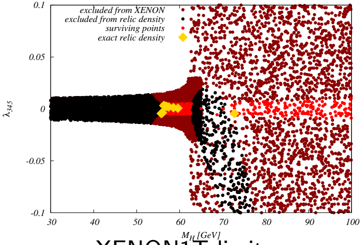
Cases where $M_H \leq M_h/2$

- **discussion so far:** decay $h \rightarrow H\,H$ kinematically not accessible
- for these cases, discussion along different lines

$\Rightarrow$ **extremely strong constraints from signal strength, and dark matter requirements**



LUX limits



XENON1T limits

- additional constraints from combination of W, Z decays and recasted analysis at LEP

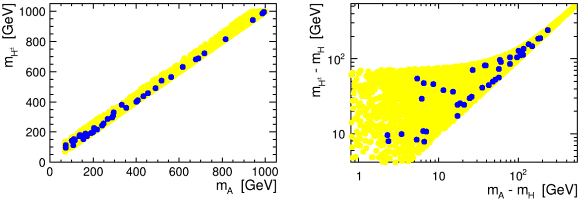
lower limit $M_H \sim 50\,\text{GeV}$

IDM Benchmarks [slide from A.F.Zarnecki, CLICdp meeting, 08/18]

Benchmark points: JHEP 1812 (2018) 081; Analysis: JHEP 1907 (2019) 053 [J. Kalinowski, W. Kotlarski, TR, D. Sokolowska, A.F. Zarnecki]

IDM benchmark points

Out of about 15'000 points consistent with all considered constraints, we chose 43 benchmark points (23 accessible at 380 GeV) for detailed studies:



The selection was arbitrary, but we tried to

- cover wide range of scalar masses and the mass splittings
- get significant contribution to the relic density

For list of benchmark point parameters, see backup slides

Production and decay

- Z_2 symmetry:

only pair-production of dark scalars $H, A, H^{\pm}$

- production modes:

$$\mathbf{p\,p} \rightarrow \mathbf{HA},\, \mathbf{HH^{\pm}},\, \mathbf{AH^{\pm}},\mathbf{H^{+}H^{-}},\, \mathbf{A\,A}\ (+\text{dijet})$$

$$\ell^{+}\,\ell^{-} \rightarrow \mathbf{HA},\, \mathbf{H^{+}H^{-}},\, \mathbf{A\,A}\ (+\nu_{\ell}\,\bar{\nu}_{\ell})$$

- decays:

$$\mathbf{A} \rightarrow \mathbf{Z\,H} :\ \mathbf{100\%},\, \mathbf{H^{\pm}} \rightarrow \mathbf{W^{\pm}H} :\ \text{dominant}$$

signature: **electroweak gauge boson(s) + MET**

Parameters tested at colliders: mainly masses

- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **relevant couplings follow from ew parameters (+ derivative couplings)**
- hXX **couplings:** determined by λ_{345} (constrained from direct detection), and **mass differences** $M_X^2 - M_H^2$ $\left(X \in \left[A,\, H^{\pm}\right]\right)$

important interplay between astroparticle physics and collider searches

in the end kinematic test

(holds for $M_H \geq \frac{M_h}{2}$)

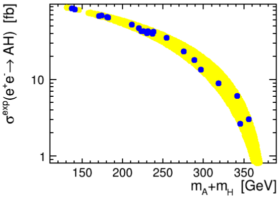
IDM at CLIC [slide from A.F.Zarnecki, CLICdp meeting, 08/18]

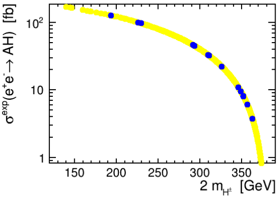
Analysis strategy

Production of IDM scalars at CLIC dominated by two processes:

$e^+e^- \to A \ H$ $\qquad$ $e^+e^- \to H^+H^-$

Leading-order cross sections for inert scalar production processes at 380 GeV:

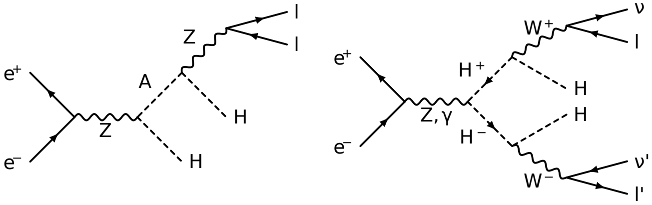




Beam luminosity spectra not taken into account

Leptonic production modes

$$e^+ e^- \rightarrow HA^{(*)} \rightarrow HZ^{(*)}H \rightarrow HH\mu^+\mu^-,$$
$$e^+ e^- \rightarrow H^{+(*)}H^{-(*)} \rightarrow W^{+(*)}W^{-(*)}\,H\,H$$
$$\rightarrow HH\mu^+e^-\,\nu_\mu\,\bar{\nu}_e, \qquad (+e \longleftrightarrow \mu)$$

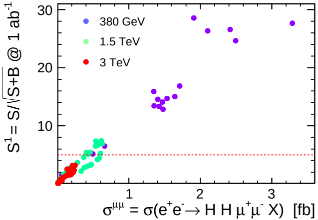


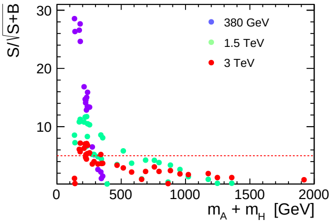
in reality: simulate ***everything* leading to** $\mu^+\mu^- + \not{E}, \mu^\pm e^\mp + \not{E}$

Results for CLIC studies [JHEP 1812 (2018) 081; JHEP 1907 (2019) 053]

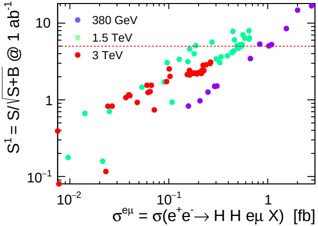
For selected benchmark points...

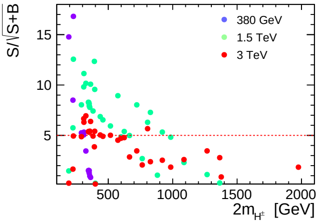
HA **production**





H^+H^- **production**





Semi-leptonic channel at CLIC

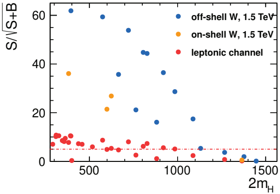
[slide from A.F.Zarnecki, Snowmass meeting, 07/20]

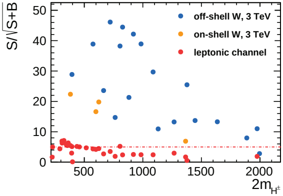
IDM scalars: semi-leptonic analysis

Results

Summary of results obtained for the semi-leptonic channel

compared with leptonic channel results for high mass benchmarks @ CLIC





Huge increase of signal significance!

Discovery reach extended up to $m_{H^\pm} \sim 1$ TeV for CLIC @ 3 TeV

"Sensitivity" comparison, based on simple criterium

production cross sections for BPs at 13, 27, 100 TeV for *pp* collisions, $10, 30\,\mathrm{TeV}$ for $\mu\mu$

- simple counting criterium: **1000 events with design luminosity, comparison of mass reach**

! **processes differ:** pair-production for all but *AA* final states from electroweak processes (Drell-Yan)

- *AA*: mediated via coupling $\bar{\lambda}_{345} = \lambda_{345} - 2\frac{M_H^2 - M_A^2}{v^2}$
$\Rightarrow$ **strong constraints from direct detection and electroweak precision observables**

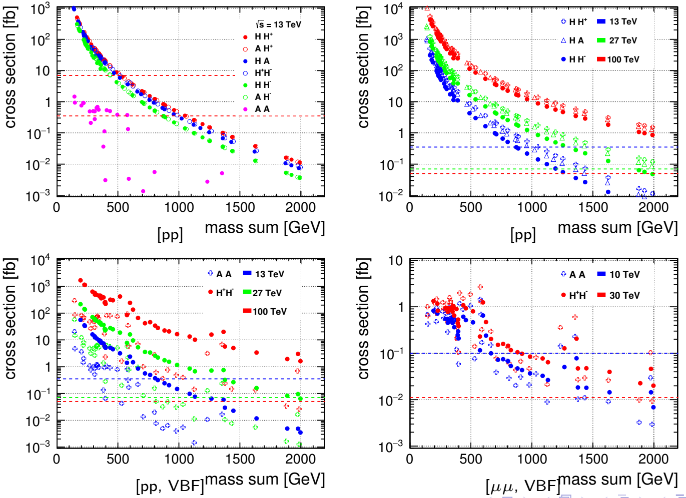
$\Rightarrow$ **include VBF-type topologies: VBF starts playing role**, especially at $\mu\mu$ colliders

Collider parameters

collider	cm energy [TeV]	$\int \mathcal{L}$	1000 events [fb]
HL-LHC	13/ 14	$3\,\mathrm{ab}^{-1}$	0.33
HE-LHC	27	$15\,\mathrm{ab}^{-1}$	0.07
FCC-hh	100	$20\,\mathrm{ab}^{-1}$	0.05
ee	3	$5\,\mathrm{ab}^{-1}$	0.2
$\mu\mu$	10	$10\,\mathrm{ab}^{-1}$	0.1
$\mu\mu$	30	$90\,\mathrm{ab}^{-1}$	0.01

Sensitivity in figures [arXiv:2012.14818]

lines: 1000 events for design luminosity



Sensitivity in numbers

after HL-LHC: in general **mass scales** ($\sum M_i$ for pair-production) **up to 1 TeV**, in AA **channel 200-600 GeV** (500-600 including VBF)

collider	all others	AA	AA +VBF
HE-LHC	2 TeV	400-1400 GeV	800-1400 GeV
FCC-hh	2 TeV	600-2000 GeV	1600-2000 GeV
CLIC, 3 TeV	2 TeV$^{1),2)}$	- $^{3)}$	300-600 GeV
$\mu\mu$, 10 TeV	2 TeV$^{1)}$	-	400-1400 GeV
$\mu\mu$, 30 TeV	2 TeV$^{1)}$	-	1800-2000 GeV

1) only HA, H^+H^-;

2) detailed investigation including background, beam strahlung, etc [arXiv:1811.06952, arXiv:1812.02093]

3) also including Zh mediation

IDM: Summary

- **Inert Doublet model: Intriguing new physics model**

$\Rightarrow$ can provide **dark matter candidate**

$\Rightarrow$ mediated via electroweak processes
(leads to ew gauge boson(s) + $\not{E}$ final state)

- **at e^+e^-: detailed studies available, mass reach $\sim 1\,\mathrm{TeV}$**
- specific channel: AA, **pair-production mediated via suppressed coupling $\bar{\lambda}_{345}$**
- **accessibility increased including VBF-type topologies**
"simple" criterium:

> **10 (30) TeV $\mu\mu$ similar reach to 27 (100) TeV pp**

- in reality: probably higher reach due to cleaner environment...

stay tuned...

LHC: Multi scalar production modes

[Eur.Phys.J. C80 (2020) no.2, 151; arXiv:2101.00037]

Adding two real scalar singlets

Scalar potential (Φ: $SU(2)_L$ doublet, S, X: $SU(2)_L$ singlets)

$$\mathcal{V} = \mu_\Phi^2 \Phi^\dagger \Phi + \mu_S^2 S^2 + \mu_X^2 X^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_S S^4 + + \lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2.$$

Imposed $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetry, which is spontaneously broken by singlet vevs.

$\Rightarrow$ three $\mathcal{CP}$-even neutral Higgs bosons: h_1, h_2, h_3

Two interesting cases:

Case (a): $\langle S \rangle \neq 0, \langle X \rangle = 0 \Rightarrow X$ is DM candidate;

Case (b): $\langle S \rangle \neq 0, \langle X \rangle \neq 0 \Rightarrow$ all scalar fields mix.

Again, Higgs couplings to SM fermions and bosons are *universally reduced by mixing*.

Tim Stefaniak (DESY) | BSM Higgs physics | ALPS 2019 | 27 April 2019 10

[some material stolen from T. Stefaniak, Talk at ALPS 2019, April '19]

singlet = singlet under SM gauge group

Possible production and decay patterns

$$M_1 \leq M_2 \leq M_3$$

Production modes at *pp* and decays

$$pp \to h_3 \to h_1\, h_1; \quad pp \to h_3 \to h_2\, h_2;$$
$$pp \to h_2 \to h_1\, h_1; \quad pp \to h_3 \to h_1\, h_2$$

$$h_2 \to \text{SM};\; h_2 \to h_1\, h_1;\; h_1 \to \text{SM}$$

$\Rightarrow$ **two scalars with same or different mass decaying directly to SM, or $h_1\, h_1\, h_1$, or $h_1 h_1 h_1 h_1$**

[h_1 decays further into SM particles]

[BRs of h_i into $X_{\text{SM}} = \frac{\kappa_i \Gamma^{\text{SM}}_{h_i \to X}(M_i)}{\kappa_i \Gamma^{\text{SM}}_{\text{tot}}(M_i) + \sum_{j,k} \Gamma_{h_i \to h_j\, h_k}}$; κ_i: rescaling for h_i]

Benchmark points/ planes [ASymmetric/ Symmetric]

AS **BP1:** $h_3 \to h_1 h_2$ **(**$h_3 = h_{125}$**)**

SM-like decays for both scalars: $\sim$ 3 pb; h_1^3 final states: $\sim$ 3pb

AS **BP2:** $h_3 \to h_1 h_2$ **(**$h_2 = h_{125}$**)**

SM-like decays for both scalars: $\sim$ 0.6 pb

AS **BP3:** $h_3 \to h_1 h_2$ **(**$h_1 = h_{125}$**)**

(a) SM-like decays for both scalars $\sim$ 0.3 pb; **(b)** h_1^3 **final states:** $\sim$ 0.14 pb

S **BP4:** $h_2 \to h_1 h_1$ **(**$h_3 = h_{125}$**)**

up to 60 pb

S **BP5:** $h_3 \to h_1 h_1$ **(**$h_2 = h_{125}$**)**

up to 2.5 pb

S **BP6:** $h_3 \to h_2 h_2$ **(**$h_1 = h_{125}$**)**

SM-like decays: up to 0.5 pb; h_1^4 **final states: around 14 fb**

Benchmarks and decay patterns [Eur.Phys.J. C80 (2020) no.2, 151]

suggested benchmark points for symmetric $h_X \rightarrow h_Y\, h_Y$ and assymetric $h_3 \rightarrow h_1\, h_2$ scenarios
h_{125} can be either $h_1,\, h_2,\, h_3$

- **SM couplings inherited through mixing**, $\propto \kappa_i$, such that

$$g_{h_i \rightarrow X\,Y} = \kappa_i\, g^{\text{SM}}_{h_i \rightarrow X\,Y}.$$

- **additional onshell decays**

$$h_3 \rightarrow h_1\, h_2,\; h_3 \rightarrow h_1\, h_1,\; h_3 \rightarrow h_2\, h_2,\; h_2 \rightarrow h_1\, h_1$$

(whenever kinematically feasible)

$\Rightarrow$ **relative ratio for SM final states as in SM at mass M_i**

$$\text{BR}_{h_i \rightarrow \text{SM}}(M_i) = \frac{\kappa_i^2\, \Gamma^{\text{SM}}_{h_i \rightarrow \text{SM}}(M_i)}{\kappa_i^2\, \Gamma^{\text{SM}}_{h_i \rightarrow \text{SM}}(M_i) + \sum_{j,k} \Gamma_{h_i \rightarrow h_j\, h_k}}$$

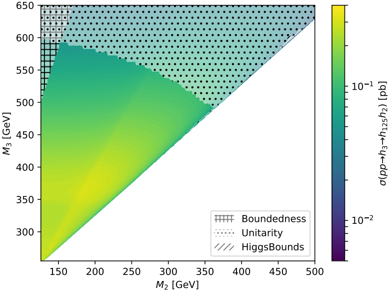
BP3: $h_3 \to h_1 h_2$ $(h_1 = h_{125})$ [up to 0.3 pb]

BP3

$\sigma(pp \to h_3) \simeq 0.06 \cdot \sigma(pp \to h_{SM})|_{m=M_3}$
$\mathrm{BR}(\mathrm{h}_3 \to \mathrm{h}_{125}\mathrm{h}_2)$ mostly $\sim 50\%$.
if $M_2 < 250\,\mathrm{GeV}$: $\Rightarrow h_2 \to$ SM particles.
if $M_2 > 250\,\mathrm{GeV}$:
$\Rightarrow \mathrm{BR}(\mathrm{h}_2 \to \mathrm{h}_{125}\mathrm{h}_{125}) \sim 70\%$,

$\Rightarrow$ spectacular triple-Higgs signature

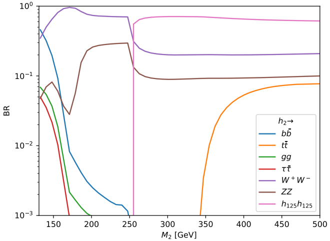
[up to 140 fb; maximal close to thresholds]

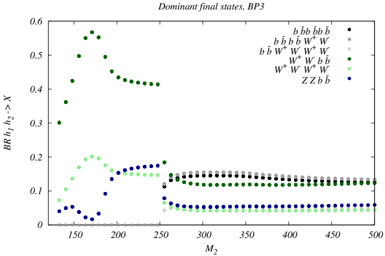


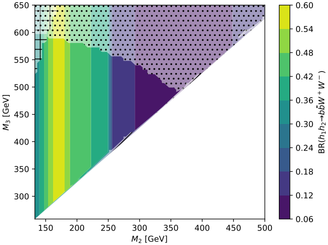
$[\kappa_3 = 0.24]$ $[\Gamma_3/M_3 \leq 0.05]$

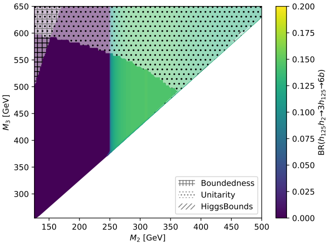
[relevant searches: $36\,\mathrm{fb}^{-1}$ searches for $h_3 \to V\,V$]

BP3: $h_3 \to h_1 h_2 \; (h_1 = h_{125})$ [up to 0.3 pb]









up to 0.18 pb

up to 30 fb

Exploration of $h_1 h_1 h_1$ final state at HL-LHC

[A. Papaefstathiou, TR, G. Tetlalmatzi-Xolocotzi, arXiv:2101.00037]

concentrate on $p\,p \rightarrow h_1\,h_1\,h_1 \rightarrow b\,\bar{b}\,b\,\bar{b}\,b\,\bar{b}$

$\Rightarrow$ **select points** on BP3 which might be **accessible at HL-LHC**

$\Rightarrow$ perform detailed analysis including SM background, hadronization, ...

- tools: implementation using **full t, b mass dependence, leading order** [UFO/ Madgraph/ Herwig] [analysis: use K-factors]

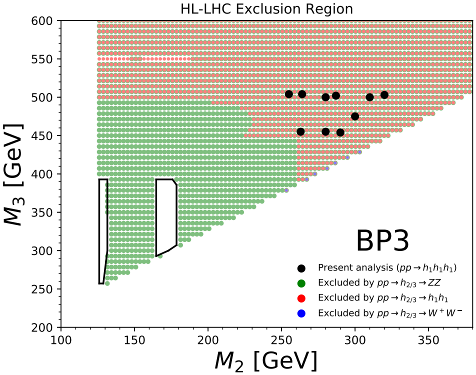
Benchmark points and results

(M_2, M_3) [GeV]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]	$\sigma(pp \to 3b\bar{b})$ [fb]	$\text{sig}\|_{300\text{fb}^{-1}}$	$\text{sig}\|_{3000\text{fb}^{-1}}$
$(255, 504)$	32.40	6.40	2.92	9.23
$(263, 455)$	50.36	9.95	4.78	15.11
$(287, 502)$	39.61	7.82	4.01	12.68
$(290, 454)$	49.00	9.68	5.02	15.86
$(320, 503)$	35.88	7.09	3.76	11.88
$(264, 504)$	37.67	7.44	3.56	11.27
$(280, 455)$	51.00	10.07	5.18	16.39
$(300, 475)$	43.92	8.68	4.64	14.68
$(310, 500)$	37.90	7.49	4.09	12.94
$(280, 500)$	40.26	7.95	4.00	12.65

discovery, exclusion

$\Rightarrow$ at HL-LHC, all points within reach $\Leftarrow$

What about other channels ?



[extrapolation of 36 fb^{-1} and HL projections]

⇒ model can be tested from various angles ⇐

[Phys. Rev. Lett. 122 (2019) 121803; Phys. Lett. B800 (2020) 135103; JHEP 06 (2018) 127; CERN Yellow Rep. Monogr. 7 (2019) 221; Eur. Phys. J. C78 (2018) 24; ATL-PHYS-PUB-2018-022]

2 real singlets: Summary

- **3 scalars with different masses:**

rich phenomenology

- either **asymmetric** $(h_1\, h_2)$ or **symmetric** $(h_x h_x)$ final states

$\Rightarrow$ production **cross sections up to 3 pb (AS)/ 60 pb (S)**

- interesting **multi-scalar final states** $(h_1 h_1 h_1,\ h_1 h_1 h_1 h_1)$
- decays typically involve $b\bar{b}$, $W^+ W^-$, $\tau^+\tau^-$ pairs that reconstruct to scalars
- detailed investigation:

$h_1\ h_1\ h_1$ **already accessible at** $300\,\mathrm{fb}^{-1}$

Stay tuned...

Appendix

Number of free parameters and theory constraints

Model has 7 free parameters

- choose e.g.

$$\mathbf{v},\ \mathbf{M_h},\ \mathbf{M_H},\ \mathbf{M_A},\ \mathbf{M_{H^\pm}},\ \lambda_2,\ \lambda_{345}\,[=\lambda_3+\lambda_4+\lambda_5]$$

- v, M_h fixed $\Rightarrow$ left with **5 free parameters**

Constraints: Theory

- **vacuum stability, positivity, constraints to be in inert vacuum**
- **perturbative unitarity, perturbativity of couplings**
- **choosing** M_H as dark matter: $M_H \leq M_A,\ M_{H^\pm}$

Constraints: Experiment

$$M_h = 125.1\,\mathrm{GeV},\; v = 246\,\mathrm{GeV}$$

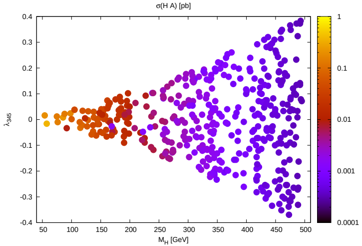
- total width of M_h ($\Gamma_h < 9\,\mathrm{MeV}$) (CMS, $80\,\mathrm{fb}^{-1}$) [Phys. Rev. D 99, 112003 (2019)]
- total width of W, Z
- collider constraints from signal strength/ direct searches;
- electroweak precision through S, T, U
- unstable $H^{\pm}$
- reinterpreted/ recastet LEP/ LHC SUSY searches

  (Lundstrom ea 2009; Belanger ea, 2015)
- dark matter relic density (upper bound)
- dark matter direct search limits (XENON1T)

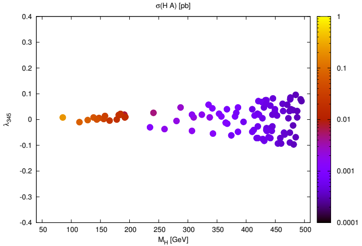
$\Rightarrow$ **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

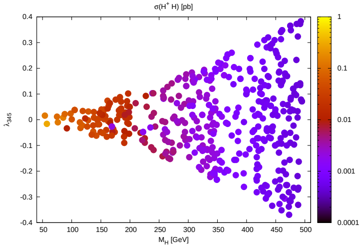
Updated constraints [XENON1T] [Phys.Rev.Lett. 121 (2018) no.11, 111302]

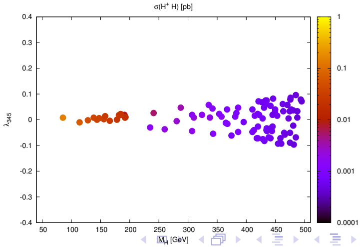
LUX



XENON







Benchmark planes for LHC [XENON/ Signal rates improved] [YREP 4]

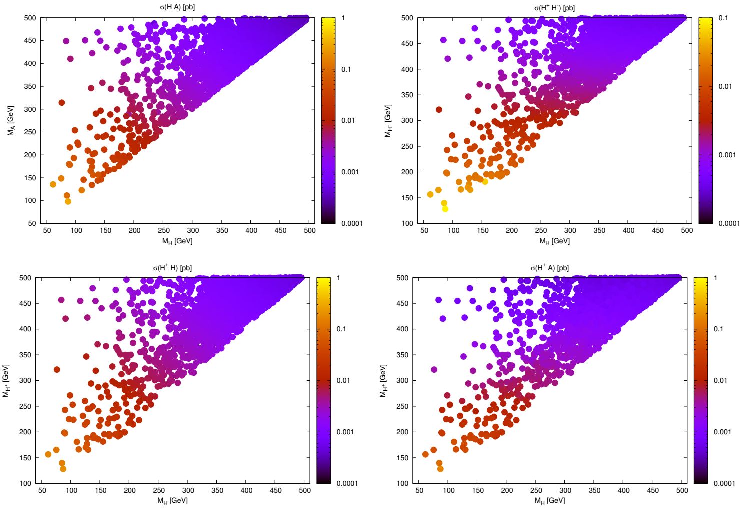


Figure : Production cross sections in pb at a 13 TeV LHC

Total widths in IDM scenario [old]

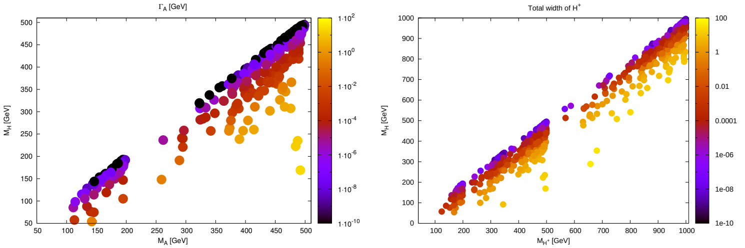
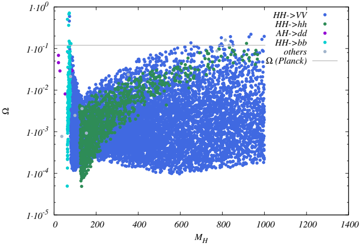
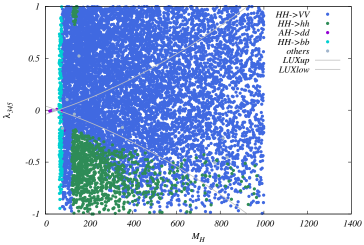


Figure : Total widths of unstable dark particles: A and $H^{\pm}$ in plane of their and dark matter masses.

Dark matter relic density

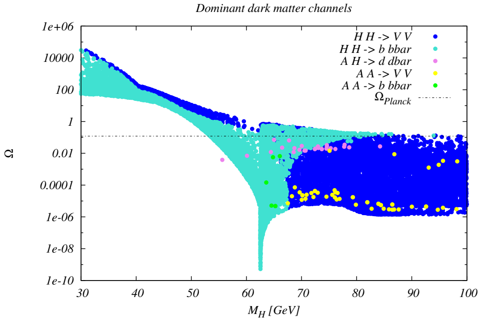


all but DM constraints



all but DM constraints

Dominant annihilation channels for the IDM



- dominant = **largest contribution** can be 51 % vs 49 %...
- as obtained from **MicroMegas 4.3.5**
- interesting/ promising: $A\,H \to d\,\bar{d}$;
  needs further investigation

Backup slide

Low mass IDM benchmark points

No.	M_H	M_A	$M_{H^\pm}$	λ_2	λ_{345}	$\Omega_c h^2$
BP1	72.77	107.8	114.6	1.445	-0.004407	0.1201
BP2	65	71.53	112.8	0.7791	0.0004	0.07081
BP3	67.07	73.22	96.73	0	0.00738	0.06162
BP4	73.68	100.1	145.7	2.086	-0.004407	0.08925
BP5	55.34	115.4	146.6	0.01257	0.0052	0.1196
BP6	72.14	109.5	154.8	0.01257	-0.00234	0.1171
BP7	76.55	134.6	174.4	1.948	0.0044	0.0314
BP8	70.91	148.7	175.9	0.4398	0.0051	0.124
BP9	56.78	166.2	178.2	0.5027	0.00338	0.08127
BP10	76.69	154.6	163	3.921	0.0096	0.02814
BP11	98.88	155	155.4	1.181	-0.0628	0.002737
BP12	58.31	171.1	173	0.5404	0.00762	0.00641
BP13	99.65	138.5	181.3	2.463	0.0532	0.001255
BP14	71.03	165.6	176	0.3393	0.00596	0.1184
BP15	71.03	217.7	218.7	0.7665	0.00214	0.1222
BP16	71.33	203.8	229.1	1.03	-0.00122	0.1221
BP17	55.46	241.1	244.9	0.289	-0.00484	0.1202
BP18	147	194.6	197.4	0.387	-0.018	0.001772
BP19	165.8	190.1	196	2.768	-0.004	0.002841
BP20	191.8	198.4	199.7	1.508	0.008	0.008494
BP21	57.48	288	299.5	0.9299	0.00192	0.1195
BP22	71.42	247.2	258.4	1.043	-0.00406	0.1243
BP23	62.69	162.4	190.8	2.639	0.0056	0.06404

And what about LHC ?

[TR, *IDM benchmarks for the LHC at 13 and 27 TeV*, Talk at Higgs Cross Section Working group WG3 submeeting, 24.10.18]

No.	M_H	M_A	$M_{H^\pm}$	HA	$H\,H^+$	AH^+	H^+H^-	AA	onshell
BP1	72.77	107.803	114.639	322	304	169	132	0.4	
BP2	65	71.525	112.85	1022	363	322	140	0.1	
BP3	67.07	73.222	96.73	909	504	444	242	0.1	
BP4	73.68	100.112	145.728	377	165	115	55.1	0.3	
BP6	72.14	109.548	154.761	314	144	88.9	45.1	0.4	W
BP7	76.55	134.563	174.367	173	99.0	50.8	29.2	0.4	W
BP8	70.91	148.664	175.89	144	103	42.7	28.3	0.5	W
BP9	56.78	166.22	178.24	125	116	34.4	27.1	0.6	W, Z
BP10	76.69	154.579	163.045	120	119	46.4	37.3	0.5	W
BP11	98.88	155.037	155.438	87.7	101	50.4	43.8	0.2	
BP12	58.31	171.148	172.96	113	125	34.5	30.3	0.6	W, Z
BP13	99.65	138.484	181.321	113	68.8	44.7	25.2	0.3	W
BP14	71.03	165.604	175.971	106	103	35.5	28.3	0.5	W, Z
BP15	71.03	217.656	218.738	46.9	54.6	14.2	12.8	0.4	W, Z
BP16	71.33	203.796	229.092	57.3	47.3	14.6	10.8	0.4	W, Z
BP18	147	194.647	197.403	29.6	34.0	21.3	17.9	0.1	
BP19	165.8	190.082	195.999	25.5	28.6	22.5	18.3	0.03	
BP20	191.8	198.376	199.721	17.9	21.4	20.1	16.9	0.03	
BP21	57.475	288.031	299.536	20.6	21.8	4.02	4.04	0.3	W, Z
BP22	71.42	247.224	258.382	31.3	32.5	8.05	6.90	0.4	W, Z
BP23	62.69	162.397	190.822	125	88.9	31.3	21.1	0.5	W, Z

Production cross sections in fb, at 13 TeV [UFO+Madgraph]

$\gtrsim$ 1000 events in Run II for each process: all but BPs 21 and 22

Backup slide

High mass IDM benchmark points

No.	M_H	M_A	$M_{H\pm}$	λ_2	λ_{345}	$\Omega_c h^2$
HP1	176	291.4	312	1.49	-0.1035	0.0007216
HP2	557	562.3	565.4	4.045	-0.1385	0.07209
HP3	560	616.3	633.5	3.38	-0.0895	0.001129
HP4	571	676.5	682.5	1.98	-0.471	0.0005635
HP5	671	688.1	688.4	1.377	-0.1455	0.02447
HP6	713	716.4	723	2.88	0.2885	0.03515
HP7	807	813.4	818	3.667	0.299	0.03239
HP8	933	940	943.8	2.974	-0.2435	0.09639
HP9	935	986.2	988	2.484	-0.5795	0.002796
HP10	990	992.4	998.1	3.334	-0.051	0.1248
HP11	250.5	265.5	287.2	3.908	-0.1501	0.00535
HP12	286.1	294.6	332.5	3.292	0.1121	0.00277
HP13	336	353.3	360.6	2.488	-0.1064	0.00937
HP14	326.6	331.9	381.8	0.02513	-0.06267	0.00356
HP15	357.6	400	402.6	2.061	-0.2375	0.00346
HP16	387.8	406.1	413.5	0.8168	-0.2083	0.0116
HP17	430.9	433.2	440.6	3.003	0.08299	0.0327
HP18	428.2	454	459.7	3.87	-0.2812	0.00858
HP19	467.9	488.6	492.3	4.122	-0.252	0.0139
HP20	505.2	516.6	543.8	2.538	-0.354	0.00887

Backup slide

Signal processes for $\mu^+\mu^-$ final state

$$\begin{aligned} e^+e^- &\rightarrow \mu^+\mu^- \, HH, \\ &\rightarrow \mu^+\mu^-\nu_\mu\bar{\nu}_\mu \, HH, \\ &\rightarrow \tau^+\mu^-\nu_\tau\bar{\nu}_\mu \, HH, \;\; \mu^+\tau^-\nu_\mu\bar{\nu}_\tau \, HH, \\ &\rightarrow \tau^+\tau^- \, HH, \;\; \tau^+\tau^-\nu_\tau\bar{\nu}_\tau \, HH. \\ & \quad \text{with} \tau^\pm \rightarrow \mu^\pm\nu\nu \end{aligned}$$

Signal processes for $e^\pm\mu^\mp$ final state

$$\begin{aligned} e^+e^- &\rightarrow \mu^+\nu_\mu \, e^-\bar{\nu}_e \, HH, \;\; e^+\nu_e \, \mu^-\bar{\nu}_\mu \, HH, \\ &\rightarrow \mu^+\nu_\mu \, \tau^-\bar{\nu}_\tau \, HH, \;\; \tau^+\nu_\tau \, \mu^-\bar{\nu}_\mu \, HH, \\ &\rightarrow e^+\nu_e \, \tau^-\bar{\nu}_\tau \, HH, \;\; \tau^+\nu_\tau \, e^-\bar{\nu}_e \, HH, \\ &\rightarrow \tau^+ \, \tau^- \, HH, \;\; \tau^+\nu_\tau \, \tau^-\bar{\nu}_\tau \, HH, \end{aligned}$$

Analysis strategy

We consider two possible final state signatures:

- moun pair production, $\mu^+\mu^-$, for AH production
- electron-muon pair production, μ^+e^- or $e^+\mu^-$, for H^+H^- production

Both channels include contributions from AH and H^+H^- production!
In particular due to leptonic tau decays.

Signal and background samples were generator with WHizard 2.2.8
based on the dedicated IDM model implementation in SARAH,
parameter files for benchmark scenarios were prepared using SPheno 4.0.3

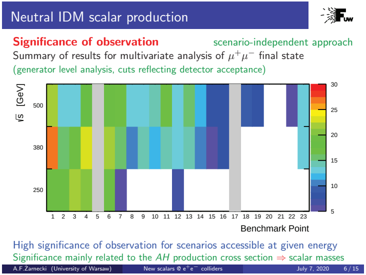
CLIC luminosity spectra taken into account (1.4 TeV scaled to 1.5 TeV)

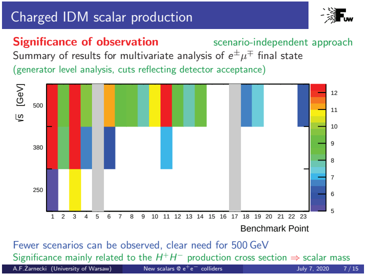
Generator level cuts reflecting detector acceptance:

- require lepton energy $E_l > 5\,\text{GeV}$ and lepton angle $\Theta_l > 100\,\text{mrad}$
- no ISR photon with $E_\gamma > 10\,\text{GeV}$ and $\Theta_\gamma > 100\,\text{mrad}$

Results for ILC-type energies

[slides from A.F.Zarnecki, Snowmass meeting, 07/20]





lesson: **sum of masses determine reach !** roughly:

$$230\,\text{GeV}@250\text{GeV},\ \sim\ 300\,\text{GeV}@380\,\text{GeV},\ \sim\ 380\text{GeV}@500\,\text{GeV}$$

[for points we considered]

Production cross sections at 100 TeV [pb]

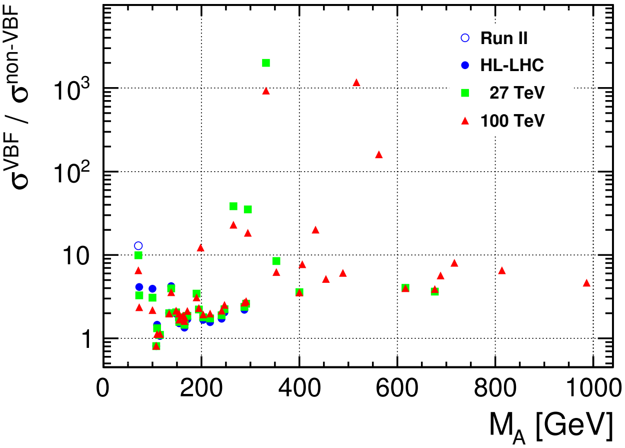
[naive estimate: AH^+ best channel]

No.	M_H	M_A	$M_{H^\pm}$	HA	$H\,H^+$	$H\,H^-$	AH^+	$A\,H^-$	H^+H^-	AA
BP1	72.77	107.803	114.639	4.00	3.47	2.65	2.06	1.55	1.85	0.0337
BP2	65	71.525	112.85	11.2	4.07	3.12	3.67	2.80	1.94	0.0380
BP3	67.07	73.222	96.73	10.1	5.47	4.22	4.88	3.75	3.09	0.0249
BP4	73.68	100.112	145.728	4.61	2.02	1.52	1.47	1.10	0.901	0.0260
BP6	72.14	109.548	154.761	3.91	1.79	1.34	1.17	0.871	0.763	0.0336
BP7	76.55	134.563	174.367	2.31	1.29	0.957	0.722	0.529	0.530	0.0215
BP8	70.91	148.664	175.89	1.97	1.33	0.992	0.622	0.453	0.533	0.0238
BP9	56.78	166.22	178.24	1.74	1.47	1.10	0.517	0.375	0.517	0.0359
BP10	76.69	154.579	163.045	1.67	1.51	1.13	0.668	0.488	0.641	0.0241
BP11	98.88	155.037	155.438	1.28	1.31	0.975	0.718	0.525	0.715	0.0137
BP12	58.31	171.148	172.96	1.58	1.57	1.18	0.519	0.376	0.550	0.0299
BP13	99.65	138.484	181.321	1.60	0.937	0.691	0.647	0.472	0.459	0.00938
BP14	71.03	165.604	175.971	1.51	1.33	0.989	0.531	0.385	0.532	0.0341
BP15	71.03	217.656	218.738	0.742	0.763	0.560	0.244	0.173	0.301	0.0341
BP16	71.33	203.796	229.092	0.882	0.674	0.493	0.250	0.177	0.268	0.0341
BP18	147	194.647	197.403	0.499	0.511	0.370	0.343	0.246	0.337	0.00685
BP19	165.8	190.082	195.999	0.441	0.441	0.318	0.361	0.259	0.336	0.00216
BP20	191.8	198.376	199.721	0.329	0.345	0.247	0.327	0.234	0.311	0.000189
BP21	57.475	288.031	299.536	0.367	0.346	0.249	0.0941	0.0646	0.153	0.0319
BP22	71.42	247.224	258.382	0.524	0.487	0.353	0.152	0.106	0.204	0.0296
BP23	62.69	162.397	190.822	1.74	1.17	0.867	0.476	0.344	0.425	0.0327

Production cross sections at 100 TeV [fb]

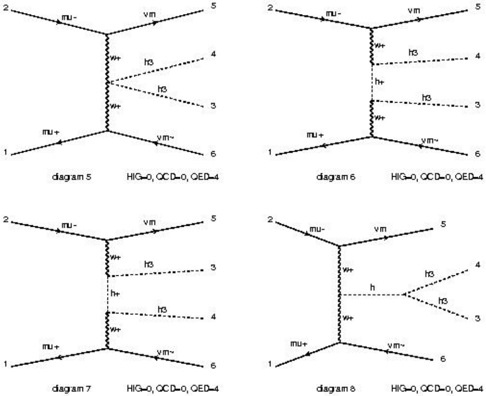
No.	M_H	M_A	$M_{H^\pm}$	HA	$H\,H^+$	$H\,H^-$	AH^+	$A\,H^-$	H^+H^-	AA
HP1	176	291.36	311.96	176	163	114	86.4	59.2	103	12.3
HP2	557	562.316	565.417	9.89	11.1	7.00	10.9	6.88	10.1	-
HP3	560	616.32	633.48	8.32	9.01	5.62	7.72	4.77	9.27	0.781
HP4	571	676.534	682.54	6.76	7.60	4.70	5.79	3.53	9.13	1.76
HP5	671	688.108	688.437	5.02	5.78	3.52	5.54	3.37	5.19	0.0421
HP6	713	716.444	723.045	4.21	4.79	2.89	4.75	2.86	4.39	0.0185
HP7	807	813.369	818.001	2.69	3.11	1.84	3.07	1.81	2.85	0.0210
HP8	933	939.968	943.787	1.59	1.87	1.07	1.85	1.06	1.66	-
HP9	935	986.22	987.975	1.45	1.71	0.978	1.56	0.886	1.72	0.150
HP10	990	992.36	998.12	1.29	1.52	0.863	1.52	0.859	1.36	-
HP11	250.5	265.49	287.226	132	125	86.6	115	79.2	99.1	0.0714
HP12	286.05	294.617	332.457	89.9	79.5	54.3	76.1	51.9	65.6	0.320
HP13	336	353.264	360.568	51.0	54.2	36.4	50.1	33.6	46.7	0.160
HP14	326.55	331.938	381.773	59.4	51.2	34.3	49.9	33.5	42.2	0.00751
HP15	357.6	399.998	402.568	37.2	40.7	27.0	34.1	22.5	33.7	0.781
HP16	387.75	406.118	413.464	31.8	34.3	22.6	31.8	20.9	29.6	0.0805
HP17	430.95	433.226	440.624	23.9	26.0	17.0	25.7	16.8	23.7	0.0180
HP18	428.25	453.979	459.696	22.3	24.4	15.9	22.2	14.4	20.9	0.147
HP19	467.85	488.604	492.329	16.9	18.8	12.1	17.5	11.2	16.5	0.0795
HP20	505.2	516.58	543.794	13.5	14.0	8.87	13.5	8.54	12.1	-

Enhancement *AA* using VBF type topologies, *pp* colliders

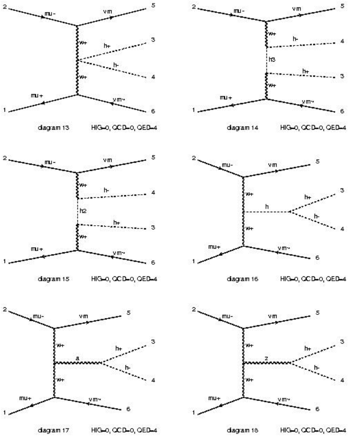


Dominant enhancements e.g. from H^+A production (offshell) / WW fusion diagrams

Main contributions, *AA* VBF, $\mu\mu$

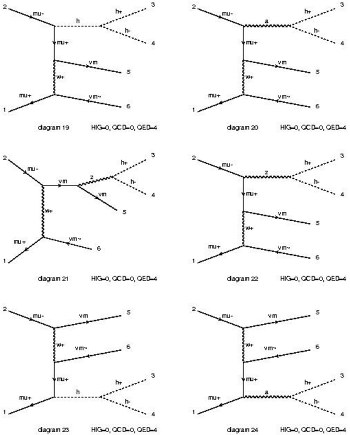


Diagrams via W^+W^- fusion, $\mu\mu$ (GI I)



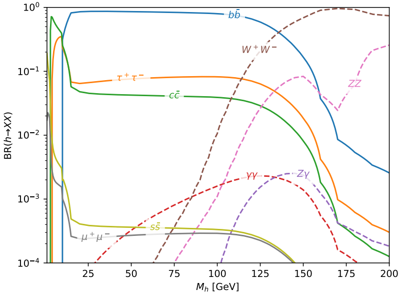
Diagrams made by MadGraph5_aMC@NLO

Diagrams via $W\mu$ fusion, $\mu\mu$ (GI II)

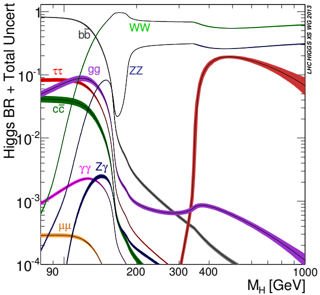


Diagrams made by MadGraph5_aMC@NLO

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



(using HDecay, courtesy J.Wittbrodt)



(https://twiki.cern.ch/twiki/bin/view/LHCPhysics

/LHCHXSWGCrossSectionsFigures)

Cut selection

Label	(M_2, M_3) [GeV]	$< P_{T,b}$ [GeV]	$\chi^{2,(4)} <$ [GeV^2]	$\chi^{2,(6)} <$ [GeV^2]	$m_{4b}^{\rm inv} <$ [GeV]	$m_{6b}^{\rm inv} <$ [GeV]
A	(255, 504)	34.0	10	20	-	525
B	(263, 455)	34.0	10	20	450	470
C	(287, 502)	34.0	10	50	454	525
D	(290, 454)	27.25	25	20	369	475
E	(320, 503)	27.25	10	20	403	525
F	(264, 504)	34.0	10	40	454	525
G	(280, 455)	26.5	25	20	335	475
H	(300, 475)	26.5	15	20	352	500
I	(310, 500)	26.5	15	20	386	525
J	(280, 500)	34.0	10	40	454	525

Table : $|\eta|_b < 2.35$, $\Delta m_{\rm min,\ med,\ max} < [15, 14, 20]$ GeV, $p_T(h_1^i) > [50, 50, 0]$ GeV, $\Delta R(h_1^i, h_1^j) < 3.5$ and $\Delta R_{bb}(h_1) < 3.5$.

χ^2s: variables used in h_1 reconstruction