

BSM benchmarks for the LHC

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based on work with

G.M. Pruna (PRD 88 (2013) 115012), D. Lopez-Val (PRD 90 (2014) 114018), T. Stefaniak (EPJC 75 (2015) 3,105, Eur.Phys.J. C76 (2016) no.5, 268)

A. Ilnicka, M. Krawczyk (Phys.Rev. D93 (2016) no.5, 055026)

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Why benchmarks ??

- ⇒ for theorists: good for **comparison of calculations** (e.g. higher orders), and/ or **search strategies**
- ⇒ for experimentalists: **"know where to start"**
 - **especially important for models with large number of free parameters**
 - desirable: pick benchmarks that **display "typical" features of models**
 - ... **different for each benchmark**
 - ... and **still in LHC discovery range**

now: benchmarks for **singlet extension of SM and Inert Doublet Model**

Higgs Singlet extension (aka The Higgs portal)

The model

- Singlet extension:
simplest extension of the SM Higgs sector
 - add an **additional scalar**, singlet under SM gauge groups
 (further reduction of terms: impose additional symmetries)
- ⇒ potential (H doublet, χ real singlet)

$$\mathbf{V} = -\mathbf{m}^2 \mathbf{H}^\dagger \mathbf{H} - \mu^2 \chi^2 + \lambda_1 (\mathbf{H}^\dagger \mathbf{H})^2 + \lambda_2 \chi^4 + \lambda_3 \mathbf{H}^\dagger \mathbf{H} \chi^2,$$

- **collider phenomenology studied by many authors:** Schabinger, Wells; Patt, Wilzcek; Barger ea; Bhattacharyya ea; Bock ea; Fox ea; Englert ea; Batell ea; Bertolini/ McCullough; ...
- our approach: **minimal:** no hidden sector interactions
- equally: **Singlet acquires VeV**

Phenomenology (in the following: focus on $m_h \sim 125$ GeV)

- SM-like couplings of **light/ heavy** Higgs:
rescaled by $\sin \alpha, \cos \alpha$
- in addition: **new physics channel:** $H \rightarrow hh$

$$\Gamma_{\text{tot}}(H) = \sin^2 \alpha \Gamma_{\text{SM}}(H) + \Gamma_{H \rightarrow hh},$$

- **SM like decays** parametrized by

$$\kappa \equiv \frac{\sigma_{\text{BSM}} \times \text{BR}_{\text{BSM}}}{\sigma_{\text{SM}} \times \text{BR}_{\text{SM}}} = \frac{\sin^4 \alpha \Gamma_{\text{tot,SM}}}{\Gamma_{\text{tot}}}$$

- **new physics channel** parametrized by

$$\kappa' \equiv \frac{\sigma_{\text{BSM}} \times \text{BR}_{H \rightarrow hh}}{\sigma_{\text{SM}}} = \frac{\sin^2 \alpha \Gamma_{H \rightarrow hh}}{\Gamma_{\text{tot}}}$$

Theoretical and experimental constraints on the model

our studies: $m_{h,H} = 125.09 \text{ GeV}$, $0 \text{ GeV} \leq m_{H,h} \leq 1 \text{ TeV}$

- ① limits from **perturbative unitarity**
- ② limits from EW precision observables through S , T , U
- ③ special: **limits from W-boson mass** as precision observable
- ④ **perturbativity** of the couplings (up to certain scales*)
- ⑤ **vacuum stability and minimum condition** (up to certain scales*)
- ⑥ **collider limits** using HiggsBounds
- ⑦ measurement of **light Higgs signal rates** using HiggsSignals and ATLAS-CONF-2015-044 [signal strength combination]

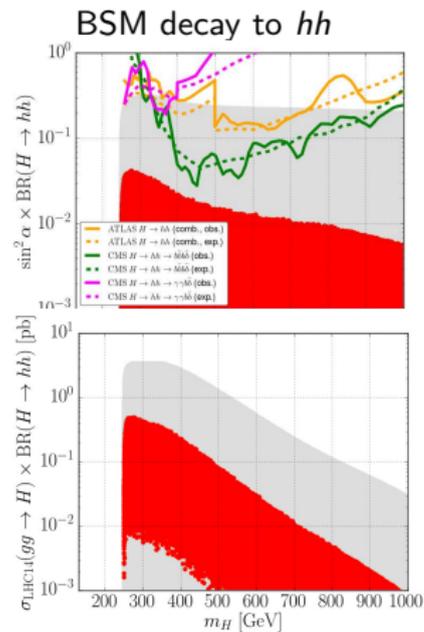
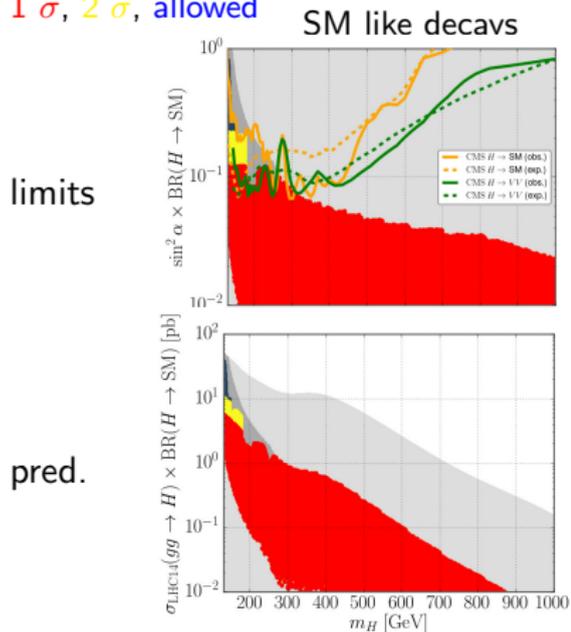
(debatable: minimization up to arbitrary scales, \Rightarrow perturbative unitarity to arbitrary high scales [these are common procedures though in the SM case])

(*): only for $m_h = 125.09 \text{ GeV}$

Benchmark planes for LHC 14

(TR, T. Stefaniak, Eur.Phys.J. C76 (2016) no.5, 268)

1 σ , 2 σ , allowed



Inert doublet model: The model

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

$$\phi_D \rightarrow -\phi_D, \phi_S \rightarrow \phi_S, \text{SM} \rightarrow \text{SM}$$

(\Rightarrow implies **CP conservation**)

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

Number of free parameters here: 7

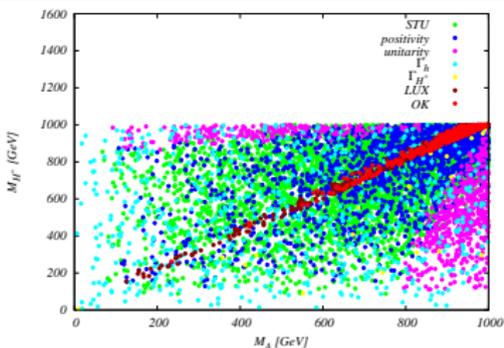
- e.g.

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

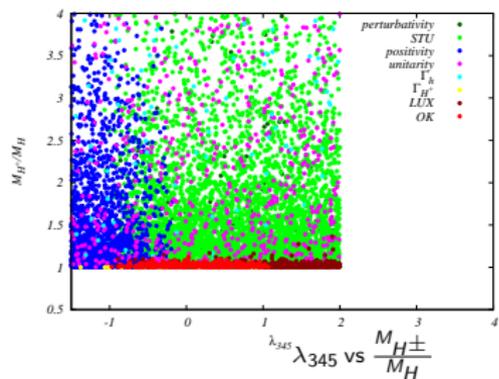
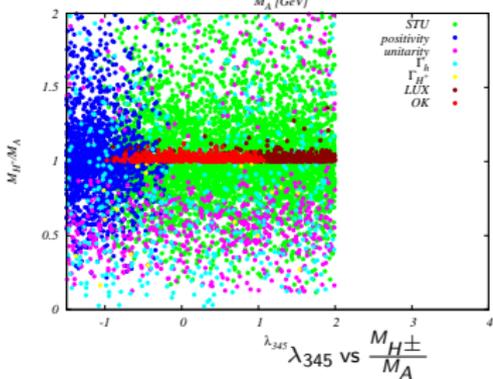
- v, M_h fixed \Rightarrow left with **5 free parameters**

Results after experimental and theoretical constraints

(A. Ilnicka, M. Krawczyk, TR, Phys.Rev. D93 (2016) no.5, 055026)



M_A vs M_{H^\pm} after all constraints



Benchmark selection for current LHC run

- ⇒ points need to **have passed all bounds**
- ⇒ total cross sections calculated using **Madgraph5, IDM model file from Goudelis ea**, 2013 (LO)

[effective ggh vertex implemented by hand]

- highest production cross sections: HA ; $H^\pm H$; $H^\pm A$; $H^+ H^-$
- decay $A \rightarrow HZ$ always 100 %
- decay $H^\pm \rightarrow HW^\pm$ usually dominant

$$pp \rightarrow HA : \leq 0.03 \text{ pb,}$$

$$pp \rightarrow H^\pm H : \leq 0.03 \text{ pb,}$$

$$pp \rightarrow H^\pm A : \leq 0.015 \text{ pb,}$$

$$pp \rightarrow H^+ H^- : \leq 0.01 \text{ pb.}$$

Summary

- **LHC run II in full swing** \Rightarrow **exciting times (still) ahead of us**
- one important question: **test Higgs sector**, especially wrt **extensions/ additional matter content**
- from current **LHC and astrophysical data: models already highly constrained**
- discussion here: 2 models: , **singlet; 2HDM with dark matter (IDM)**
- **identified viable regions in parameter space**
- from these: **predictions for current LHC run**
!! stay tuned, and thanks for listening !!

Appendix

Comments on constraints (1) - Perturbativity issues

Perturbative unitarity:

- tests combined system of all (relevant) $2 \rightarrow 2$ scattering amplitudes for $s \rightarrow \infty$
- we considered:

$$WW, ZZ, HH, Hh, hh \rightarrow WW, ZZ, HH, Hh, hh$$

- makes sure that the largest eigenvalue for the "0"-mode partial wave of the diagonalized system ≤ 0.5
- "crude" check that unitarity is not violated
(Literature: Lee/ Quigg/ Thacker, Phys. Rev. D 16, 1519 (1977))
(in the end: all "beaten" by perturbativity of running couplings)

Singlet

Comments on constraints (2) - running couplings and vacuum

- ① **perturbativity:** $|\lambda_{1,2,3}(\mu_{run})| \leq 4\pi$
- ② **potential bounded from below:** $\lambda_1, \lambda_2 > 0$
- ③ **potential has local minimum:** $4\lambda_1\lambda_2 - \lambda_3^2 > 0$

\Rightarrow need (2), can debate about (1), (3) at all scales \Leftarrow

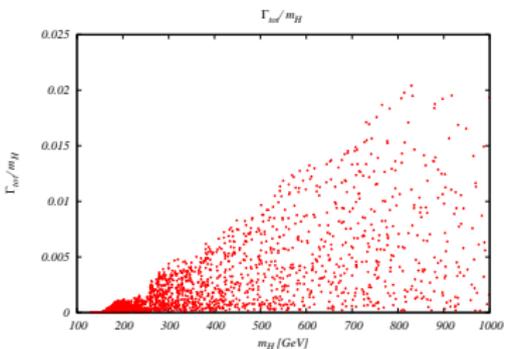
RGE running: variation of input parameters

- especially in sensitive cases, but also otherwise:
check robustness against input parameters
 - here: especially important in decoupling (ie SM-like) case
(cf. various discussions in the literature...)
 - our check:
vary $\alpha_s(m_Z)$, $y_t(m_t)$ for 1σ around central values
 - main impact: **on vacuum stability**, ie $\lambda_1 > 0$ condition
 - **no significant change in $\kappa_{\max}(m_H)$, ...**
- ⇒ **not relevant for collider studies** (at this stage...)

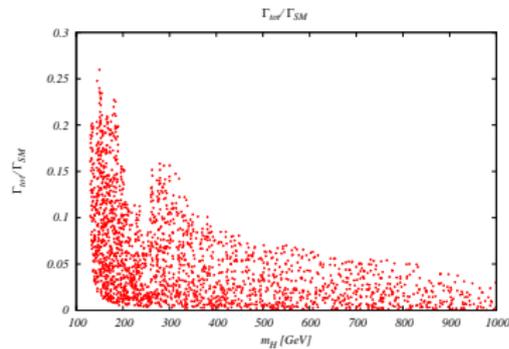
Singlet

Interim comment on total width

- Total width greatly reduced



width over mass



suppression factor of width

Benchmarks in Yellow Report IV

all benchmarks: $A \rightarrow ZH = 100\%$

- **Benchmark I: low scalar mass**

$$M_H = 57.5 \text{ GeV}, M_A = 113.0 \text{ GeV}, M_{H^\pm} = 123 \text{ GeV}$$

$$HA : 0.371(4)\text{pb}, H^+ H^- : 0.097(1)\text{pb}$$

- **Benchmark II: low scalar mass**

$$M_H = 85.5 \text{ GeV}, M_A = 111.0 \text{ GeV}, M_{H^\pm} = 140, \text{ GeV}$$

$$HA : 0.226(2)\text{pb}, H^+ H^- : 0.0605(9)\text{pb}$$

- **Benchmark III: intermediate scalar mass**

$$M_H = 128.0 \text{ GeV}, M_A = 134.0 \text{ GeV}, M_{H^\pm} = 176.0, \text{ GeV}$$

$$HA : 0.0765(7)\text{pb}, H^+ H^- : 0.0259(3)\text{pb};$$

Benchmark: high masses

- **Benchmark IV: high scalar mass, mass degeneracy**

$$M_H = 363.0 \text{ GeV}, M_A = 374.0 \text{ GeV}, M_{H^\pm} = 374.0 \text{ GeV}$$

$$H, A : 0.00122(1)\text{pb}, H^+H^- : 0.00124(1)\text{pb}$$

- **Benchmark V: high scalar mass, no mass degeneracy**

$$M_H = 311.0 \text{ GeV}, M_A = 415.0 \text{ GeV}, M_{H^\pm} = 447.0 \text{ GeV}$$

$$H, A : 0.00129(1)\text{pb}, H^+H^- : 0.000553(7)\text{pb}$$

Constraints: Theory

⇒ **consider all current constraints on the model** ⇐

- Theory constraints: **vacuum stability, positivity, constraints to be in inert vacuum**
⇒ **limits on (relations of) couplings**, e.g.

$$\lambda_1 > 0, \lambda_2 > 0, \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0, \lambda_{345} + \sqrt{\lambda_1 \lambda_2} > 0$$

- **perturbative unitarity, perturbativity of couplings**
- **choosing** M_H as dark matter:

$$M_H \leq M_A, M_{H^\pm}$$

Constraints: Experiment

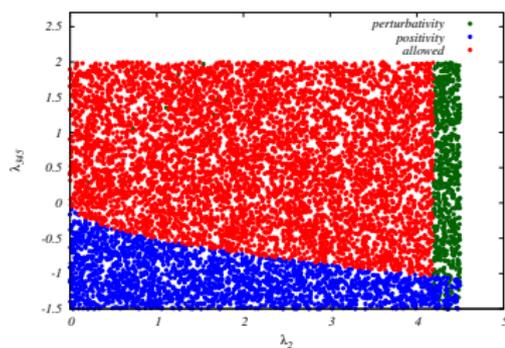
$$M_h = 125.1 \text{ GeV}, v = 246 \text{ GeV}$$

- total width of $M_h^{(*)}$
 - 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 $(*)$ (LUX)
- ⇒ **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

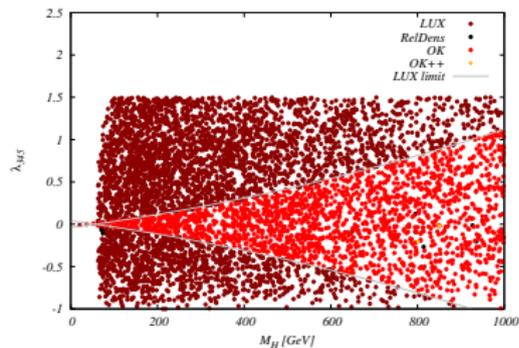
$(*)$ updates not yet included

Obvious/ direct constraints on couplings

- some constraints \Rightarrow direct limits on couplings
- examples: limit on λ_2 from $HHHH$ coupling, limit on $\lambda_{345}(M_H)$ from direct detection



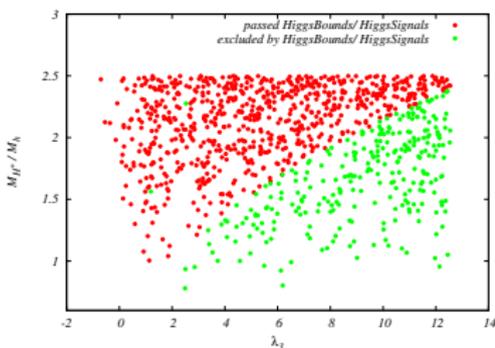
λ_2, λ_{345} plane and limits from perturbativity, positivity



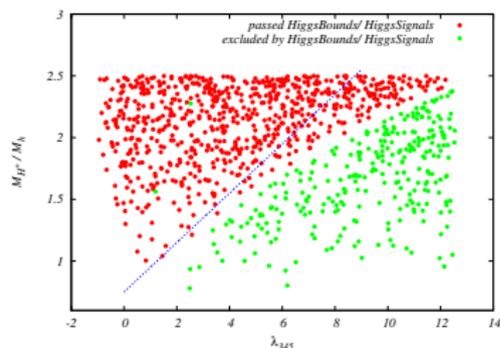
M_H, λ_{345} plane, limits from LUX(*)

More direct constraints on couplings

- constraints on **combination of M_H^\pm/M_h and λ_3** from **one-loop corrected rate of $h \rightarrow \gamma\gamma$** (constraints: ratio too low !!)



limits on λ_3 , M_H^\pm/M_h , plane



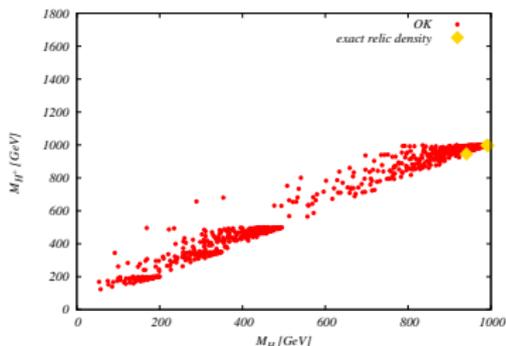
... translated to λ_{345} , M_H^\pm/M_h

... and what if I want exact DM relic density ??

[preliminary results]

E.g. **this means**

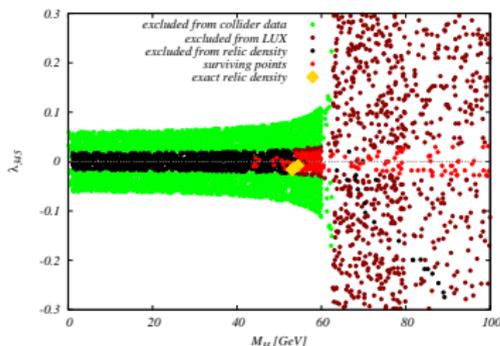
- $m_{H^\pm} \in [100 \text{ GeV}; 620 \text{ GeV}]$ or $> 840 \text{ GeV}$
- $m_H \notin [75 \text{ GeV}; 120 \text{ GeV}]$ or $\sim 54 \text{ GeV}$
- ...



sample plot, M_H vs. M_{H^\pm}

Last comment: cases where $M_H \leq M_h/2$

- **discussion so far:** decay $h \rightarrow HH$ kinematically not accessible
 - for these cases, **discussion along different lines**
- ⇒ **extremely strong constraints from signal strength, and dark matter requirements**



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

no allowed point with $M_H < 45$ GeV

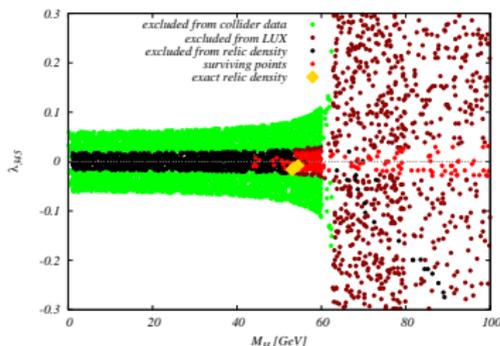
Parameters tested at LHC: masses

- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
 - **LHC@13 TeV** does not depend on λ_2 , only marginally on λ_{345}
 - all **relevant couplings follow from ew parameters (+ derivative couplings)** \Rightarrow in the end a kinematic test
 - only in exceptional cases λ_{345} important; did not find such points
- \Rightarrow **high complementarity between astroparticle physics and collider searches**

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

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

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Last comments: publications where scan has been used

- **Production of Inert Scalars at the high energy e^+e^- colliders**, M. Hashemi ea, **JHEP 1602 (2016) 187**
- **Exploring the Inert Doublet Model through the dijet plus missing transverse energy channel at the LHC**, P. Poulose ea, **arXiv:1604.03045**
- **Yellow Report IV of the Higgs Cross Section Working Group**, **arXiv:1610.07922**
- S. Moretti ea, *to appear*

Very brief: parameters determining couplings (production and decay)

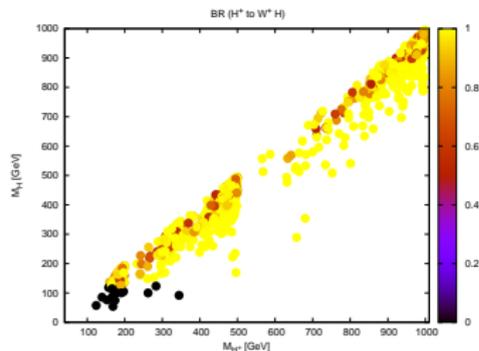
dominant production modes: through Z ; Z, γ, h for AH ; H^+H^-
important couplings:

- ZHA : $\sim \frac{e}{s_W c_W}$
- ZH^+H^- : $\sim e \coth(2\theta_w)$
- γH^+H^- : $\sim e$
- hH^+H^- : $\lambda_3 v$
- H^+W^+H : $\sim \frac{e}{s_W}$
- H^+W^+A : $\sim \frac{e}{s_W}$

!! mainly determined by electroweak SM parameters !!

Aside: typical BRs

- decay $A \rightarrow HZ$ always 100 %
- decay $H^\pm \rightarrow HW^\pm$



second channel $H^\pm \rightarrow AW^\pm$

⇒ collider signature: SM particles and MET ⇐

Total widths in IDM scenario

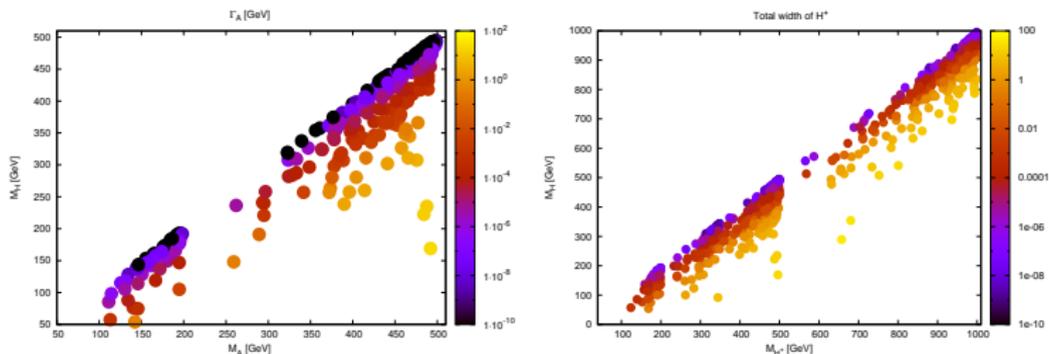
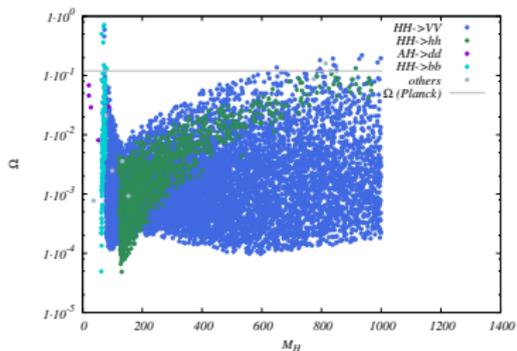


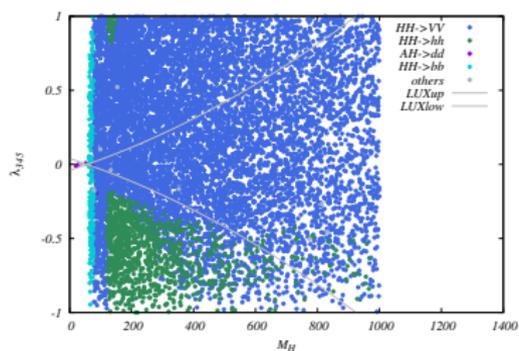
Figure : Total widths of unstable dark particles: A and H^\pm in plane of their and dark matter masses.

IDM

Dark matter relic density



all but DM constraints



all but DM constraints