Heavy Dark Matter in the Three Higgs Doublet Model

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with V. Keus, S. King and S. Moretti

The Standard Model

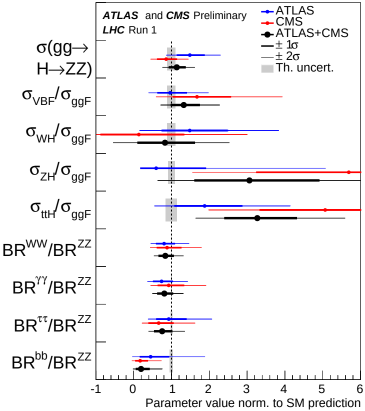
A rigorously tested Theory of Fundamental Interactions

From the LHC:

- a Higgs particle found in 2012
- no significant deviation from the SM
- no sign of New Physics

But no explanation for:

- Dark Matter
- neutrino masses
- baryon asymmetry and baryogenesis
- extra source of CP violation
- vacuum stability
- ...



ATLAS-CONF-2015-044

Dark Matter

Evidence for Dark Matter at diverse scales:

- galaxy scales: rotational speeds of galaxies
- cluster scales: gravitational lensing at galaxy clusters
- horizon scales: anisotropies in the CMB

⇒ **around 25 % of the Universe is**:

- cold
- non-baryonic
- neutral
- very weakly interacting

⇒ **W**eakly **I**nteracting **M**assive **P**article

- stable due to the discrete symmetry

$$\underbrace{\text{DM DM} \to \text{SM SM}}_{\text{pair annihilation}}, \quad \underbrace{\text{DM} \not\to \text{SM}, \ldots}_{\text{stable}}$$

- annihilation cross-section $\langle \sigma v \rangle \propto$ EW interaction
- thermal evolution of DM density – a fixed value after freeze-out

Higgs-portal DM

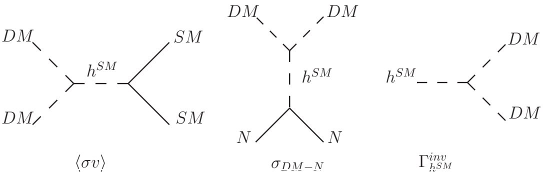
Simplest realisation: the SM with Φ_{SM} + Z_2-odd scalar S:

$$S \to -S, \quad \text{SM fields} \to \text{SM fields}$$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial S)^2 - \frac{1}{2}m_{DM}^2 S^2 - \lambda_{DM} S^4 - \lambda_{SSh}\Phi_{SM}^2 S^2$$

Higgs-portal interaction:

$$\text{SM sector} \overset{\text{Higgs}}{\longleftrightarrow} \text{DM sector}$$



given by the same coupling

Strong constraints from relic density + direct detection + Higgs decays

⇒ modified Higgs-portal-type DM candidates in multi-scalar models

3HDM

Three-Higgs Doublet Models:

- three $SU(2)$ doublets, ϕ_1, ϕ_2, ϕ_3
- richer symmetry groups than the 2HDMs
- richer particle spectrum
- possible update to 6HDMs
- in this talk:

  3HDM with Two Inert and One Higgs doublet i.e. I(2+1)HDM

  focus on **Heavy DM candidate** in the I(2+1)HDM

  more collider phenomenology $\rightarrow$ S. Moretti's talk on Monday

I(2+1)HDM

Z_2-symmetry in I(2+1)HDM:

$$\phi_1 \to -\phi_1, \ \phi_2 \to -\phi_2, \quad \phi_3 \to \phi_3, \ \text{SM fields} \to \text{SM fields}$$

Z_2-invariant potential:

$$V = \sum_{i}^{3} \left[-|\mu_i^2|(\phi_i^\dagger \phi_i) + \lambda_{ii}(\phi_i^\dagger \phi_i)^2 \right] + \sum_{ij}^{3} \left[\lambda_{ij}(\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij}(\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \right]$$
$$+ \left(-\mu_{12}^2(\phi_1^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_2)^2 + \lambda_2(\phi_2^\dagger \phi_3)^2 + \lambda_3(\phi_3^\dagger \phi_1)^2 + h.c. \right)$$
$$+ \left(\lambda_4(\phi_3^\dagger \phi_1)(\phi_2^\dagger \phi_3) + \lambda_5(\phi_1^\dagger \phi_2)(\phi_3^\dagger \phi_3) + \lambda_6(\phi_1^\dagger \phi_2)(\phi_1^\dagger \phi_1) \right.$$
$$\left. + \lambda_7(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_2) + \lambda_8(\phi_3^\dagger \phi_1)(\phi_3^\dagger \phi_2) + h.c. \right)$$

- 21 parameters in V
- all parameters real – no CP violation
- Yukawa interaction: "Model I"-type (only ϕ_3 couples to fermions)
- explicit Z_2-symmetry

Parameters of V

- $\mu_3^2 = v^2\lambda_{33} = m_h^2/2$ fixed from extremum conditions
- "dark democracy": $\mu_1^2 = \mu_2^2,\ \lambda_{13} = \lambda_{23},\ \lambda'_{13} = \lambda'_{23},\ \lambda_3 = \lambda_2$, e.g.

$$\lambda_2(\phi_2^\dagger\phi_3)^2 + \lambda_3(\phi_3^\dagger\phi_1)^2 + h.c. \to \lambda_2\left((\phi_2^\dagger\phi_3)^2 + (\phi_3^\dagger\phi_1)^2 + h.c.\right)$$

- $\left(\lambda_4(\phi_3^\dagger\phi_1)(\phi_2^\dagger\phi_3) + \lambda_5(\phi_1^\dagger\phi_2)(\phi_3^\dagger\phi_3) + ...\right)$: no new phenomenology

$$\Rightarrow \lambda_{4-8} = 0$$

- $\lambda_1, \lambda_{11,22,12}, \lambda'_{12}$ – self-interactions of inert doublets

21 parameters → 5 important parameters

- μ_2^2 – mass scale of inert particles
- μ_{12}^2, λ_2 – mass splittings; λ_2 lifts degeneracy between H_i and A_i!
- $\lambda_2, \lambda_{23}, \lambda'_{23}$ – DM-Higgs coupling

DM in I(2+1)HDM

Z_2-invariant vacuum state:

$$\phi_1 = \begin{pmatrix} H_1^+ \\ \frac{H_1^0 + iA_1^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} H_2^+ \\ \frac{H_2^0 + iA_2^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}$$

- ϕ_3 – SM-like doublet with SM-like Higgs h
- Z_2-odd doublets ϕ_1 and ϕ_2 mix:

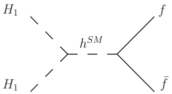
$$H_1 = \cos\alpha_H H_1^0 + \sin\alpha_H H_2^0, \quad H_2 = \cos\alpha_H H_2^0 - \sin\alpha_H H_1^0$$

  (similar for A_i and $H_i^\pm$)
- 4 neutral and 4 charged Z_2-odd particles (double the IDM)
- H_1 – **DM candidate**, other dark particles heavier
- X_1 from the 1st generation is lighter than X_2 from the 2nd generation:

$$M_{X_1} < M_{X_2}$$

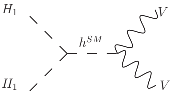
Dark Matter Annihilation

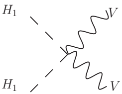
- annihilation through Higgs into fermions



depends on $g_{H_1 H_1 h}$ coupling; dominant channel for $M_{DM} < M_h/2$

- annihilation into gauge bosons (also into virtual states)





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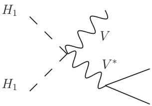
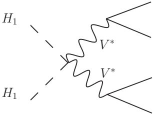
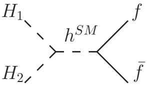
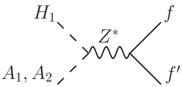


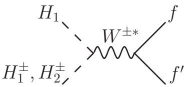


crucial for heavy masses; non-negligible for $M_h/2 < M_{DM} < M_W$

- coannihilation







very important when particles have similar masses

DM Annihilation Scenarios

- Viable scenarios for $M_{H_1} < M_W$:

(A) **no coannihilation effects**: $M_{H_1} < M_{H_2,A_1,A_2,H_1^\pm,H_2^\pm}$

(D) **coannihilation** with H_2, A_1, A_2:

$$M_{H_1} \approx M_{A_1} \approx M_{H_2} \approx M_{A_2} < M_{H_1^\pm,H_2^\pm}$$

See **JHEP 1411 (2014) 016** for details.

- Viable scenarios for $M_{H_1} > M_W$:

(G) **coannihilation** with $A_1, H_1^\pm, H_2, A_2, H_2^\pm$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_1^\pm} \approx M_{H_2} \approx M_{A_2} \approx M_{H_2^\pm}$$

(H) **coannihilation** with $A_1, H_1^\pm$:

$$M_{H_1} \approx M_{A_1} \approx M_{H_1^\pm} < M_{H_2,A_2,H_2^\pm}$$

This talk; based on **JHEP 1511 (2015) 003**

No proper relic density for other possible mass assignments:

(B) $M_{H_1} \approx M_{H_2} < M_{A_1,A_2,H_1^\pm,H_2^\pm}$ (C) $M_{H_1} \approx M_{A_1} < M_{H_2,A_2,H_1^\pm,H_2^\pm}$

(E) $M_{H_1} \approx M_{H_1^\pm} < M_{H_2,A_1,A_2,H_2^\pm}$ (F) $M_{H_1} \approx M_{H_1^\pm} \approx M_{H_2} < M_{A_1,A_2,H_2^\pm}$

Heavy mass regime

Useful parametrisation:

$$M_{H_2} = M_{H_1} + \Delta, \quad M_{A_1, H_1^\pm} = M_{H_1} + \delta_{A,C}$$

- $\delta_{A,C} \sim \lambda_i \lesssim 15\,\mathrm{GeV}$: ΔM within one generation must be small
- $\Delta \sim \mu_{12}^2$: ΔM between generations can be large

Annihilation scenarios for heavy DM:

(G) Small Δ

two semi-degenerated doublets – 8 coannihilating particles

(H) Large Δ

2nd doublet decoupled – the IDM-like case

Range of parameters considered:

$$M_{H_1} > M_W, \quad 100\mathrm{keV} \lesssim \delta_{A,C} \lesssim 15\,\mathrm{GeV}, \quad 100\mathrm{keV} \lesssim \Delta \lesssim 100\,\mathrm{GeV}$$

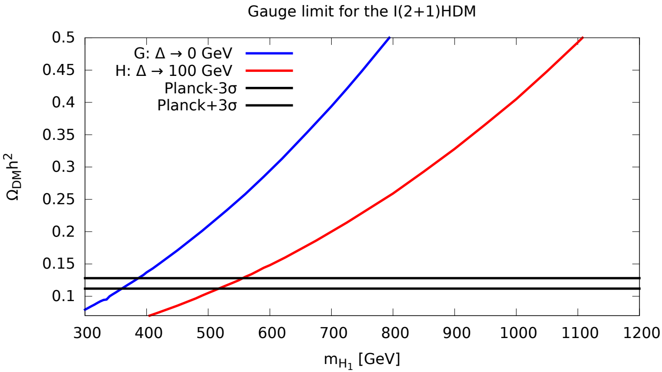
"Gauge limit"

M. Cirelli et al, hep-ph/0512090

Gauge limit = no scalar couplings ($\lambda_i = 0$)

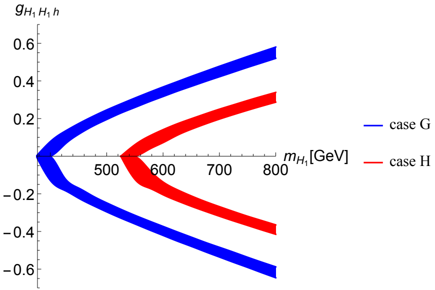
DM annihilates just through gauge processes

σ_{ann} increases for $\lambda_i \neq 0$



Case G : $M_{H_1} \gtrsim 370\,\mathrm{GeV}$, Case H : $M_{H_1} \gtrsim 525\,\mathrm{GeV}$,

Benchmark Points



Case G : $\Delta = 1\,\text{GeV}, \delta_{A,C} = 1\,\text{GeV}$

Case H : $\Delta = 100\,\text{GeV}, \delta_{A,C} = 1\,\text{GeV}$

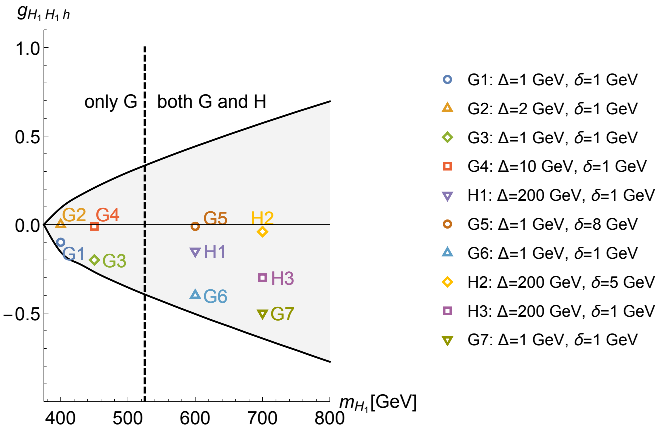
$g_{H_1 H_1 h}$ in Case G > Case H

The same behaviour in both cases

Lower M_{H_1} for Case G

Tools used in calculation: LanHEP, arXiv:1412.5016 [physics.comp-ph]; CalcHEP 3.4, Comput. Phys. Commun. **184** (2013) 1729; micrOMEGAs 3.5.5, Comput.Phys.Commun.185 (2014) 960

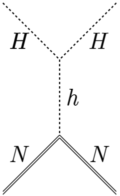
Heavy DM in 3HDM

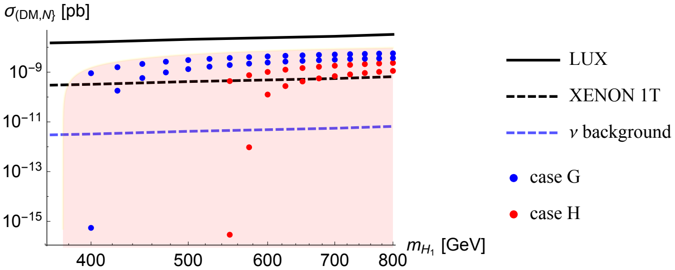


Lower masses and larger couplings – different detection prospects

Direct Detection

$$\sigma_{DM,N} \propto \frac{g^2_{H_1 H_1 h}}{(M_{H_1}+M_N)^2}$$

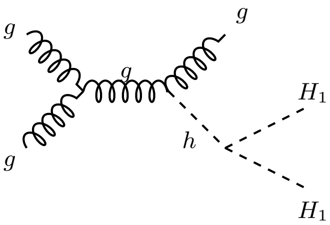




- $\Delta = 100\,\text{GeV}, \delta_{A,C} = 1\,\text{GeV}$ • $\Delta = 1\,\text{GeV}, \delta_{A,C} = 1\,\text{GeV}$

- in agreement with LUX
- within the reach of XENON-1T
- case G (bigger couplings) easier to see/exclude than case H (smaller couplings)

Monojet



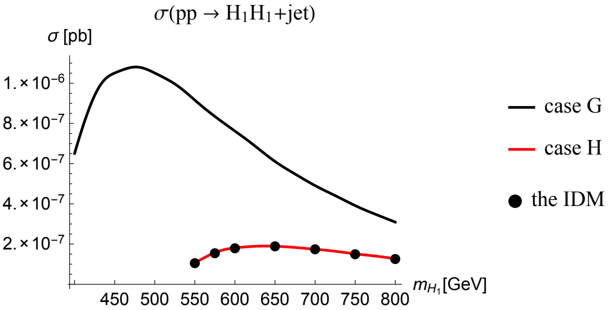
Monojet signature: jet + $\not{E}_T$

Considered diagrams:

$gg \to gH_1H_1$,
$q\bar{q} \to gH_1H_1$,
$qg \to qH_1H_1$

All depend on $g_{H_1H_1h}$

Cuts: $p_T^j > 20\,\text{GeV}, |\eta^j| > 2.5$



Conclusions

- **3HDM** with Z_2 symmetry: I(2+1)HDM
- viable DM candidate
- large dark sector: important coannhilation effects in $\Omega_{DM} h^2$
- Heavy DM candidate – new mass region with respect to the IDM

  → $M_{H_1} \gtrsim 370\,\text{GeV}$ for small mass splittings

  → $M_{H_1} \gtrsim 525\,\text{GeV}$ for large mass splitting

  → both scenarios can be realised in the TeV mass range
- Region with larger couplings:

  → in agreement with LUX

  → within the reach of XENON1T
- Larger couplings with smaller M_{H_1}:

  → improved detection prospects at the LHC

References

- Higgs-portal DM models

  [B. Patt and F. Wilczek, hep-ph/0605188, X. Chu, T. Hambye, and M. H. Tytgat, JCAP 1205 (2012) 034, A. Djouadi, O. Lebedev, Y. Mambrini, and J. Quevillon, Phys.Lett. B709 (2012) 65–69]

- 3HDM

  [V. Keus, S. King, S. Moretti JHEP 1401 (2014) 052, V. Keus, S. King, S. Moretti arXiv:1408.0796]

- Experimental constraints

  [ATLAS-CONF-2015-044, LUX Collaboration, Phys. Rev. Lett. **112** (2014) 091303, XENON1T Collaboration, Springer Proc. Phys. **148** (2013) 93]

- Numerical Tools

  [LanHEP, arXiv:1412.5016 [physics.comp-ph]; CalcHEP 3.4, Comput. Phys. Commun. **184** (2013) 1729; micrOMEGAs 3.5.5, Comput.Phys.Commun.185 (2014) 960]

BACKUP SLIDES

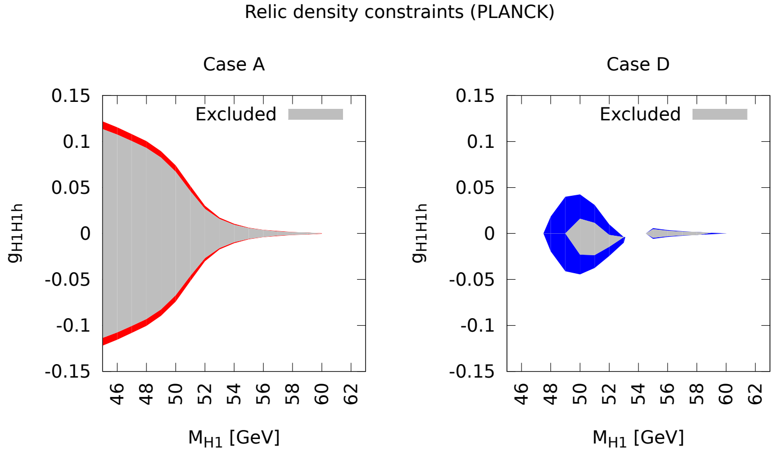
Mass formulas

$$
\begin{aligned}
m_{H_1}^2 &= -\mu_2^2 + \Lambda_{\phi_2} - \mu_{12}^2, & m_{H_2}^2 &= m_{H_1}^2 + 2\mu_{12}^2,\\
m_{H_1^\pm}^2 &= -\mu_2^2 + \Lambda'_{\phi_2} - \mu_{12}^2, & m_{H_2^\pm}^2 &= m_{H_1^\pm}^2 + 2\mu_{12}^2,\\
m_{A_1}^2 &= -\mu_2^2 + \Lambda''_{\phi_2} - \mu_{12}^2, & m_{A_2}^2 &= m_{A_1}^2 + 2\mu_{12}^2.
\end{aligned}
$$

$$
\begin{aligned}
\lambda'_{23} &= \frac{1}{v^2}(m_{H_1}^2 + m_{A_1}^2 - 2m_{H_1^\pm}^2),\\
\lambda_2 &= \frac{1}{2v^2}(m_{H_1}^2 - m_{A_1}^2),\\
\lambda_{23} &= g_{H_1 H_1 h} - \frac{2}{v^2}(m_{H_1}^2 - m_{H_1^\pm}^2),
\end{aligned}
$$

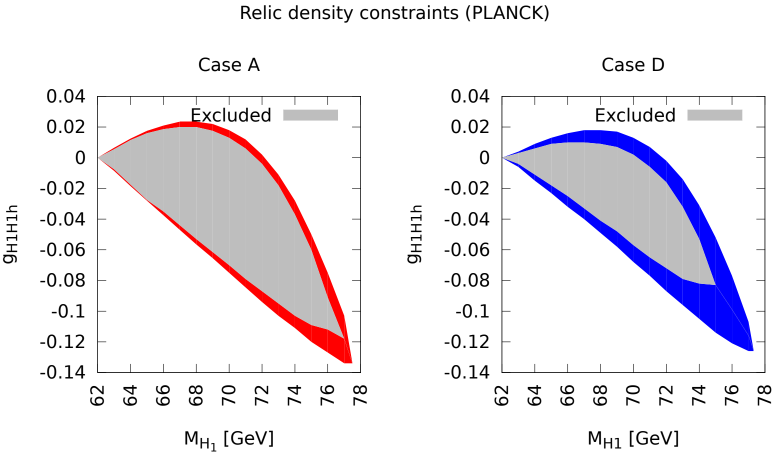
with $g_{H_1 H_1 h} = \lambda_{23} + \lambda'_{23} + 2\lambda_2$.

Planck constraints: $M_{DM} < M_h/2$

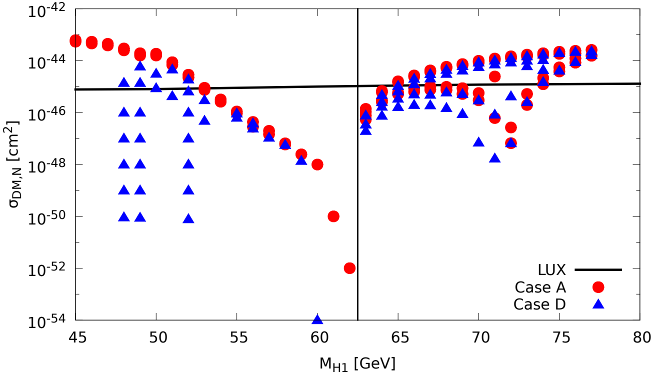


Case A (no coannhilation) – coupling bigger than in Case D (with coannihilation)

Planck constraints: $M_{DM} > M_h/2$



Case A and Case D slightly different

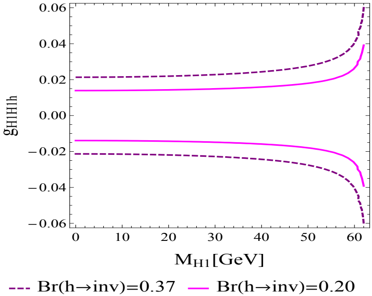


Case D: new region in agreement with LUX with respect to Case A

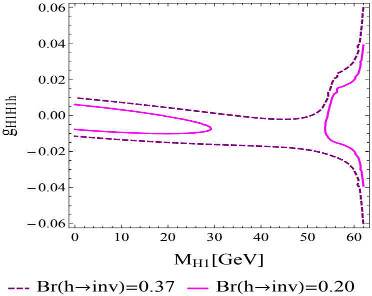
sign of coannhilation effects

LHC constraints

$$Br(h \to inv) \approx \frac{\sum_{i,j} \Gamma(h \to X_i X_j)}{\Gamma^{SM}(h) + \sum_{i,j} \Gamma(h \to X_i X_j)}$$



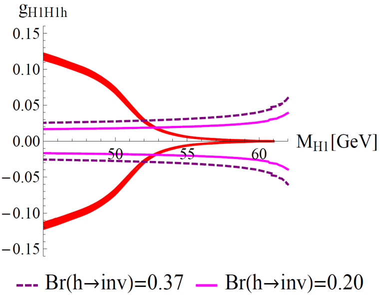
case A



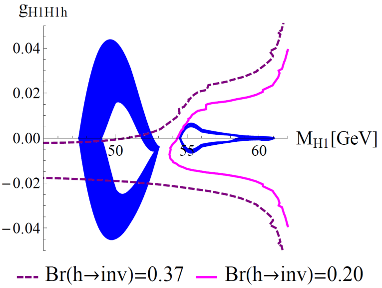
case D

- $Br(h \to inv) < 37\% \Rightarrow$
  - $|g_{H_1 H1h}| \lesssim 0.02$ for Case A
  - $-0.015 \lesssim g_{DMh} \lesssim 0$ for Case D
- $Br(h \to inv) < 20\% \Rightarrow$
  - $|g_{H_1 H1h}| \lesssim 0.015$ for Case A
  - strong constraints for Case D!

LHC vs Planck



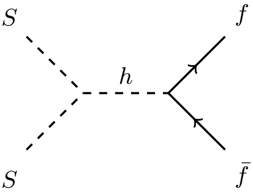
case A



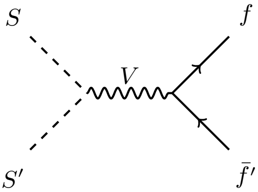
case D

- $Br(h \to inv) < 37\%\ \ \&\ \ \Omega_{DM} h^2 \Rightarrow$
  - $M_{DM} \gtrsim 53\,\text{GeV}$ for Case A
  - almost all masses ok for Case D
- $Br(h \to inv) < 20\%\ \ \&\ \ \Omega_{DM} h^2 \Rightarrow$
  - $M_{DM} \gtrsim 53\,\text{GeV}$ for Case A
  - $M_{DM} \gtrsim 53\,\text{GeV}$ for Case D

Light DM annihilation:

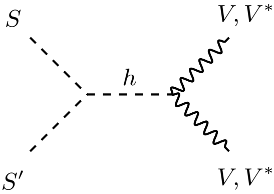


(a)

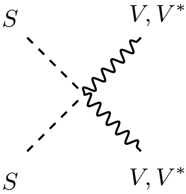


(b)

Virtual gauge bosons:



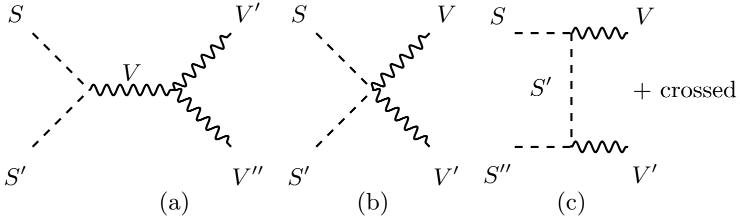
(a)



(b)

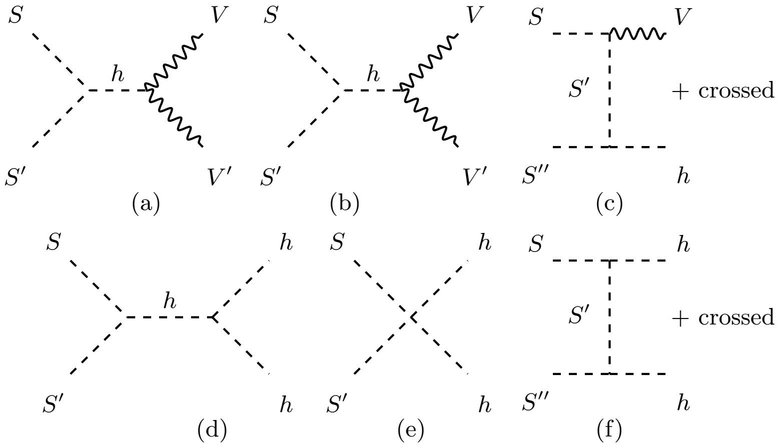
DM annihilation diagrams - gauge limit

Heavy DM (co)annihilation diagrams with pure gauge boson final states:

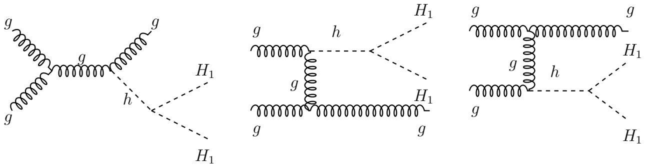


DM annihilation diagrams

Heavy DM (co)annhilation channels involving the SM-like Higgs boson:

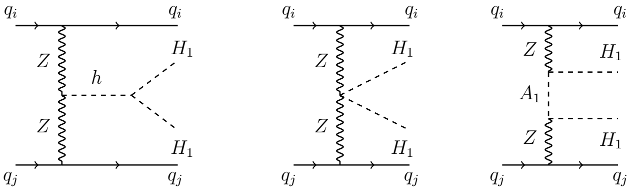


Monojet - dominant diagrams

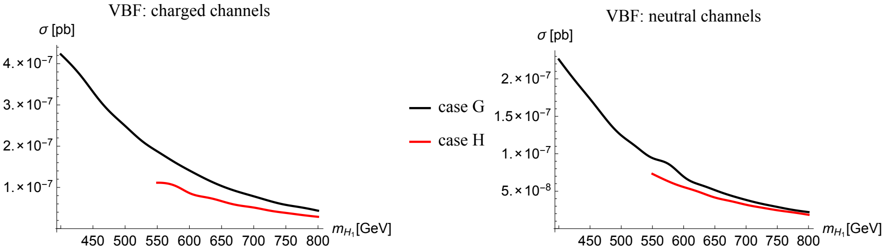


1. $gg \to gH_1H_1$ via a triple gluon and a hgg effective vertex.
2. $q\bar{q} \to gH_1H_1$, where $q = u, d, c, s, b$. The dominant contribution comes from the s-channel via the $gq\bar{q}$ tree-level vertex and the hgg effective coupling.
3. $qg \to qH_1H_1$, where $q = u, d, c, s, b$. The dominant contributions here come from $gb \to H_1H_1b$ with the Higgs boson radiated off of the b quark legs and $qg \to qH_1H_1$ t-channel via a $gq\bar{q}$ tree-level vertex and the hgg effective coupling.

Di-jet VBF

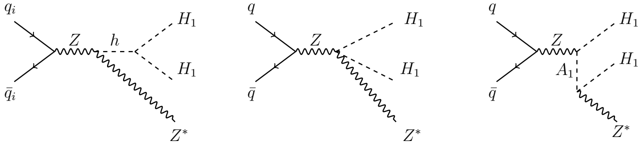


q_i
q_i
Z
h
H_1
Z
H_1
q_j
q_j
q_i
q_i
Z
H_1
Z
H_1
q_j
q_j
q_i
q_i
Z
H_1
A_1
Z
H_1
q_j
q_j

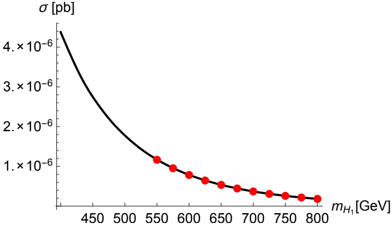


VBF: charged channels
σ [pb]
$4.\times10^{-7}$
$3.\times10^{-7}$
$2.\times10^{-7}$
$1.\times10^{-7}$
450 500 550 600 650 700 750 800
m_{H_1}[GeV]
case G
case H
VBF: neutral channels
σ [pb]
$2.\times10^{-7}$
1.5×10^{-7}
$1.\times10^{-7}$
$5.\times10^{-8}$
450 500 550 600 650 700 750 800
m_{H_1}[GeV]

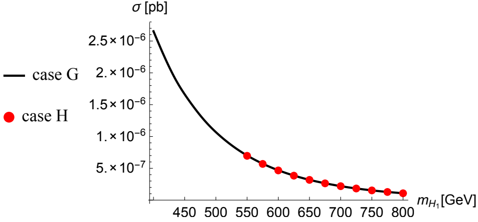
HS



HS: charged channels



HS: neutral channels



Vacuum instability

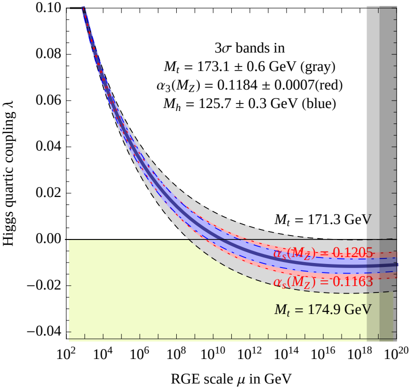
[Butazzo et al (arXiv:1307.3536)]

For the SM:

$$V = \lambda \phi^4$$

$$\beta_\lambda \sim (\lambda^2 - y_t^4 + \ldots) \Rightarrow$$

λ negative at large scales



Additional scalar states $\Rightarrow$
additional **positive** contributions to β_λ
help to stabilize the SM vacuum

[see e.g.: SM + singlet, arXiv:0910.3167]