Constraints on new phenomena via Higgs boson couplings and the search for invisible decays with the ATLAS detector

David Delgove (LAL-Orsay)

Introduction

- In 2012, the **Higgs boson was discovered**
- The properties of the Higgs boson were measured :

→ Mass: 125.36 ± 0.37 (stat.) ± 0.18 (syst.) GeV (ATLAS only)

→ Spin/CP: compatible with 0^+ while the others values are excluded : 0^-, $1^\pm$, $2^\pm$

→ Couplings

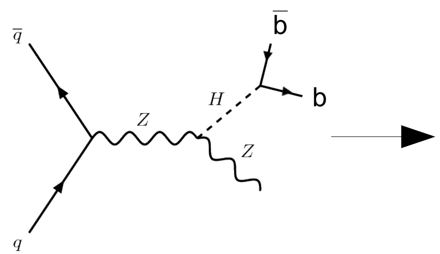
- **These measurements are compatible with Standard model (SM) expectations but there is however still room for new physics :** hierarchy problem, dark matter, new interactions or particles

Coupling modifiers

- The **coupling modifiers κ** are defined as the **ratio of the Higgs boson coupling over the SM value : κ = 1 means SM Higgs boson**
- Expressions of the measured production cross sections and partial width of the Higgs boson :

$$\sigma(i \to h) = \kappa_i^2 \sigma_{SM}(i \to h) \qquad \Gamma(h \to f) = \kappa_f^2 \Gamma_{SM}(h \to f)$$

- **The narrow width approximation allows decoupling of production and decay.** For qq → Zh → bb, the number of signal events *s* is :



$$s = \kappa_Z^2 \frac{\kappa_b^2}{\kappa_h^2} \sigma_{SM}(qq \to Zh) BR_{SM}(h \to bb) \mathcal{L}\mathcal{A}\epsilon \text{ with } \kappa_h^2 = \frac{\Gamma}{\Gamma_{SM}}$$

- **The determination of the κ is based on the maximization of a likelihood function**
- All the presented models are a parametrization of the coupling modifiers

Comments

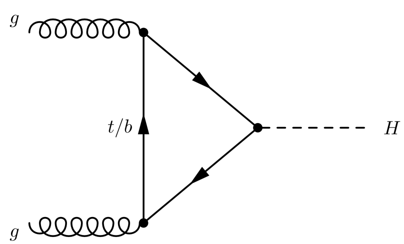
- **An assumption is required to have an absolute determination of the couplings,** if only Standard Model Higgs decays are considered :

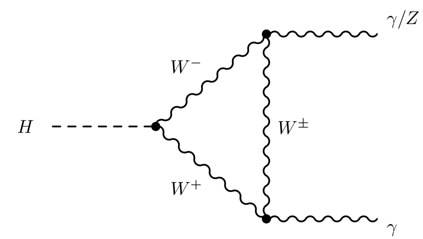
$$\kappa_h^2 = \sum_i \kappa_i^2 BR_{i,SM}$$

- Photons and gluons interact with the Higgs boson via a loop, two treatments are possible :

  → **Resolved couplings : assume no NP in the loops,** only the potentially modified couplings to SM particles.

$$\kappa_{gluon}^2 = 1.06\kappa_t^2 - 0.07\kappa_b\kappa_t + 0.01\kappa_b^2 \qquad \kappa_\gamma^2 = 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$$



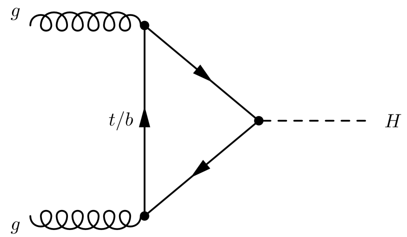


  → **Effective couplings to photons and gluons** (no assumptions on NP in the loops)

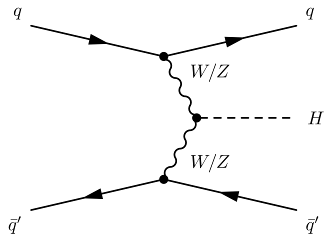
Inputs to the combination

- The following channels are used :
  - $h \to ZZ$, $h \to WW$, $h \to \gamma\gamma$, $h \to Z\gamma$
  - $h \to \tau\tau$, $h \to bb$, $h \to \mu\mu$

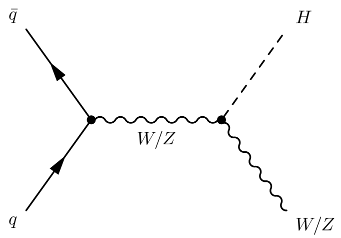
- Main production modes considered :



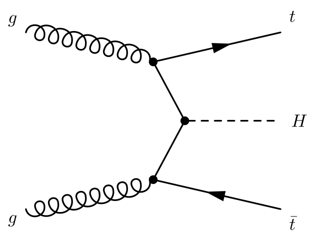
gluon fusion



VBF



Z/Wh



tth

- The full run 1 dataset is used which represents up to 4.7 fb^{-1} at 7 TeV and up to 20.3 fb^{-1} at 8 TeV

Higgs compositeness

- A **composite Higgs boson could solve the hierarchy problem** :

  ➡ Introduction of a compositeness scale : f

- In these models, the Higgs boson couplings to V (= W/Z) bosons (κ_V) and to fermions (κ_F) are modified as follows :

  → MCHM 4 : $\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}\ (1)$

  → MCHM 5 : $\kappa_V = \sqrt{1-\xi}$ and $\kappa_F = \dfrac{1-2\xi}{\sqrt{1-\xi}}\ (2)$

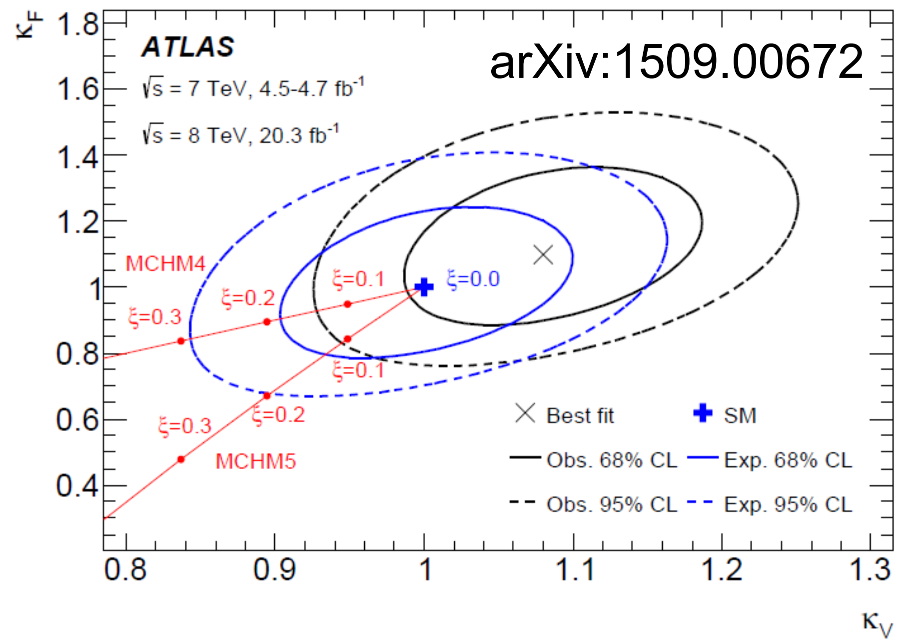
  where $\xi = v^2/f^2$ and **ξ → 0 (f →∞) recovers the Standard Model case**

- The couplings to photons and gluons are resolved
- Only the standard model decays are considered

Probed regions in (κ_V, κ_F) plane

- The equations (1) and (2) on the previous slide define a parametric equation in the plane (κ_V , κ_F)

- Visualization of the probed region :
  → Composite models are disfavoured



- Limits on f at 95% CL :

Model	Lower limit on f	
	Obs.	Exp.
MCHM4	710 GeV	510 GeV
MCHM5	780 GeV	600 GeV

Two Higgs doublets models (2HDM)

- Other extension of the Standard Model Higgs Sector :

  → Additional Higgs doublet such as in the MSSM (5 Higgs Bosons : 2 CP-even, 1 CP-odd, 2 charged Higgs boson)

  → MSSM is motivated by hierarchy problem and dark matter

- **The discovered Higgs boson is assumed to be the lightest CP-even state**

- **The couplings are described by two parameters :**

  → tan β : ratio of the vev's of the two Higgs doublets

  → α : mixing angle between the two CP-even Higgs states

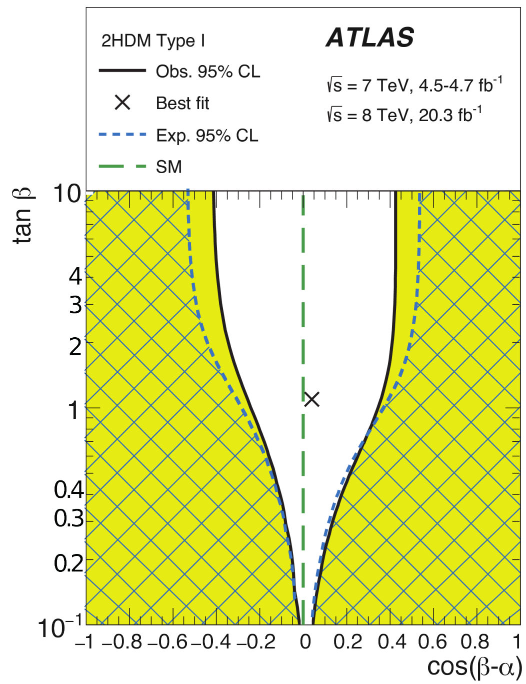
- The couplings of the Higgs to photons and gluons are resolved

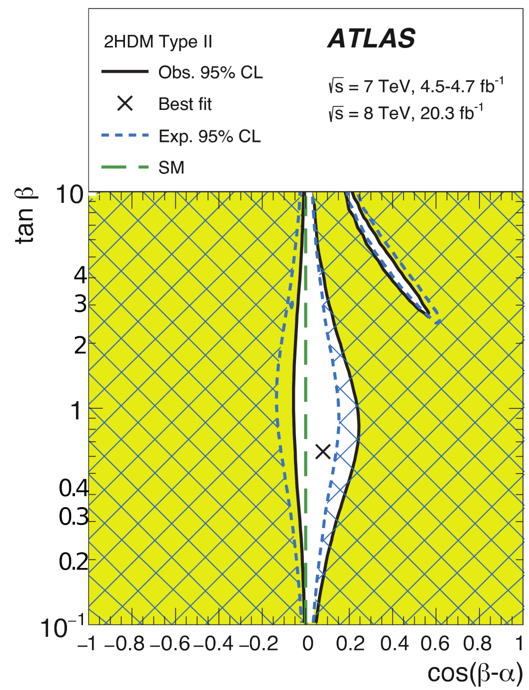
- Only the standard model decays are considered

Type 1 and Type 2

- Results for type 1 and type 2 in the plane (cos β - α , tan β) :

<table>
<tr><th></th><th>K_V</th><th>K_u</th><th>K_d</th><th>K_l</th></tr>
<tr><td>Type 1</td><td rowspan="2">sin(β-α)</td><td rowspan="2">cos α / sin β</td><td>cos α / sin β</td><td>cos α / sin β</td></tr>
<tr><td>Type 2</td><td>- sin α / cos β</td><td>- sin α / cos β</td></tr>
</table>





arXiv:1509.00672

- Compatible with SM alignment limit : type 3 and 4 are in backup

Simplified MSSM : hMSSM

- Simplification of the MSSM, a 2HDM of type 2 :

  → The radiative corrections (ΔM_{22}) involving the top quark and stops are fixed by the mass of the standard model Higgs boson :

$$\Delta\mathcal{M}_{22}^2 = \frac{M_h^2(M_A^2 + M_Z^2 - M_h^2) - M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}$$

  → The loop corrections from stops in gluon fusion production and diphoton decays are neglected (expected less than 5%)

  → The corrections which break universality of down type fermions ($\kappa_b \neq \kappa_\tau$) are neglected

The coupling modifiers for bosons (κ_V), up type fermions (κ_u), down type fermions (κ_d) depend only on tan β and mA the mass of the pseudo-scalar Higgs boson

Limits in the (m_A ,tan β) plane

- The couplings to photons and gluons are resolved
- Only the standard model decays are considered

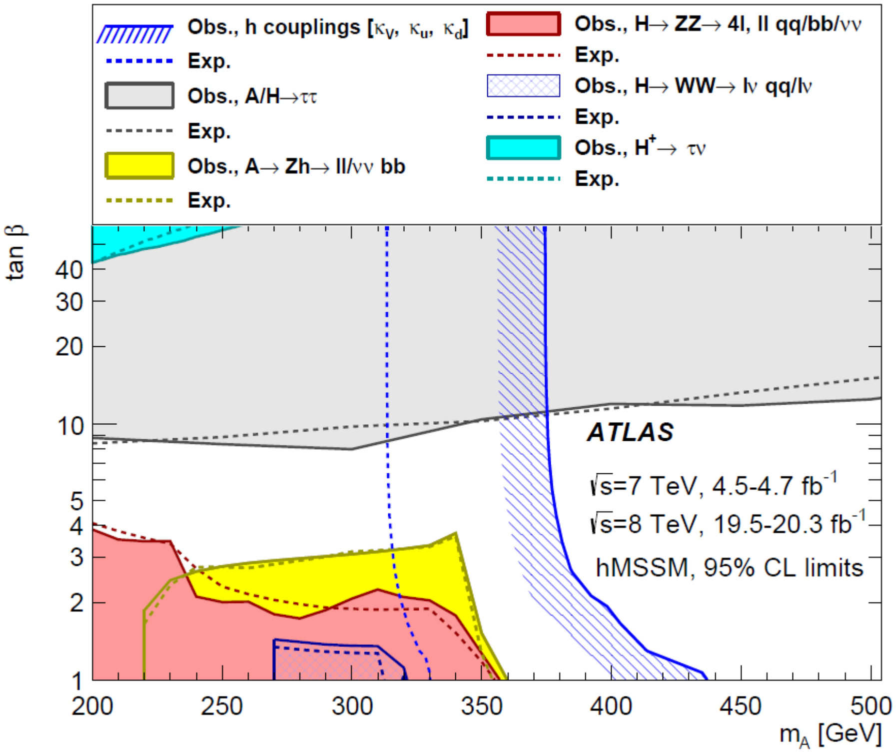
- Excluded regions by direct and indirect searches :

  → **Complementarity and redundancy of the searches**

- For tan β > 2, at 95% CL :

  mA > 370 GeV (obs.)

  mA > 310 GeV (exp.)



arXiv:1509.00672

Higgs invisible branching ratio

- **The Higgs boson could decay into Wimps, if the wimps are not too heavy**

- **The searches with visible decays products can probe such models.**

  → Effective couplings for photons and gluons

  → Modified expression for $\kappa_H^2 = \frac{\sum_i \kappa_i^2 BR_{i,SM}}{1 - BR_{inv}}$

- **But assumptions on the couplings are required to make the fit converging,** for example : $\kappa_V < 1$ and $BR_{und} = 0$.

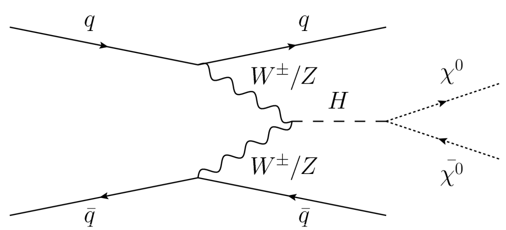
  → The (expected) limit on BR_{inv} is 0.49 (0.48) at 95 % CL

Searches of invisible Higgs decay

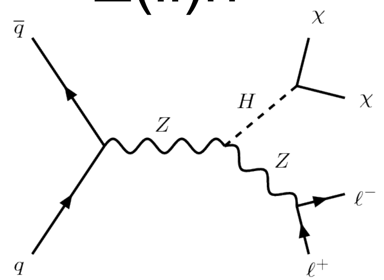
- The final states with high missing transverse energy and with leptons or jets give the possibility to search for directly invisible decays of the Higgs boson

- Three channels have been used :

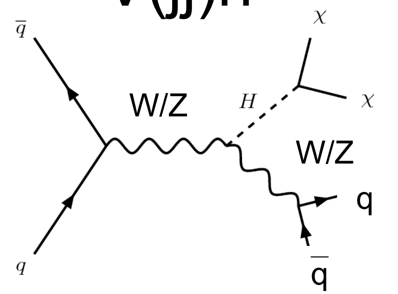
VBF



Z(ll)h



V(jj)h



- The number of signal event is parametrized as follows :

$$s = BR_{inv}\,\sigma_{SM}\mathcal{L}\mathcal{A}\epsilon$$

- **Assuming the SM rates for the production modes, the combined (expected) limit on the invisible branching ratio of the Higgs boson is 0.25 (0.27) at 95% CL**

Combination : direct + indirect searches

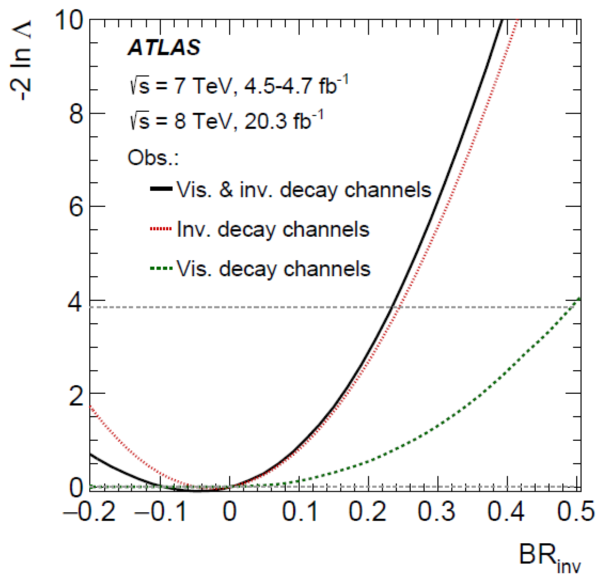
- The indirect+direct constraints can be combined which removes :
  - → Assumption on the rates of production modes
  - → Assumption on the couplings ($\kappa_V < 1$)
- The V(jj)h channel is not included in the combination due to overlap of the event selection with Vh(bb)

arXiv:1509.00672

- **The (expected) observed limit is**

  BR_{inv} < 0.23 (0.24) at 95% CL

- The limit is dominated by direct searches



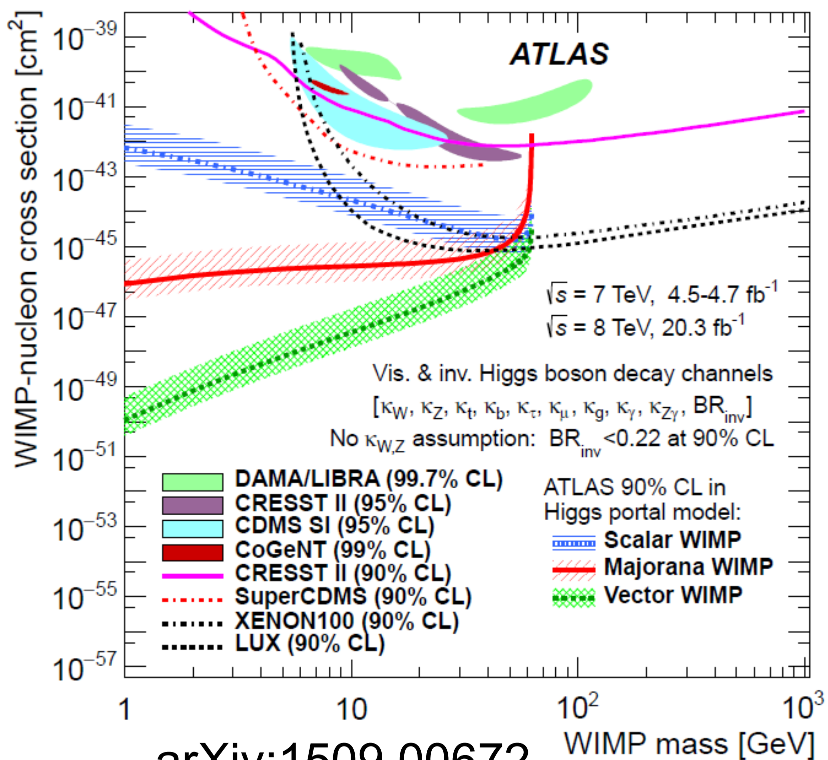
Higgs portal to dark matter

- The Higgs portal to dark matter model assumes that only the Higgs boson couples to dark matter particles :

  ➡ Possible to convert the invisible branching ratio into a scattering cross section of dark matter on a nucle**i**

- The conversion depends on the nature of dark matter (scalar, fermionic, bosonic)

- **The limits at low mass from ATLAS in the Higgs Portal model are significantly better than those from direct detection searches**



arXiv:1509.00672

Summary

- All the results are compatible with the Standard Model
- Higgs compositeness :

  → MCHM 4 : f > 710 GeV (exp. : f > 510 GeV)

  → MCHM 5 : f > 780 GeV (exp. : f > 600 GeV)

  → **Disfavored by current measurements**
- **2HDM : consistent with SM alignment limit**
- Simplified MSSM (hMSSM) :

  → For tan β > 2, mA > 370 (310) GeV obs. (exp.) @ 95% CL

  → **A pseudo scalar Higgs below 1 TeV is still possible**
- The (expected) observed limit on invisible branching ratio :

  → BR_{inv} < 0.23 (0.24) at 95% CL

Thanks

Backup

Alternative procedure : Test Statistic

Determination of the confidence interval uses the profiled likelihood ratio :

$$\Lambda(\alpha) = \frac{\mathcal{L}(\alpha, \hat{\hat{\theta}}(\alpha))}{\mathcal{L}(\hat{\alpha}, \hat{\theta})}$$

α : parameters of interest

θ : nuisance parameters

If the studied parameter has a physical boundary (for instance $BR_{inv}>0$), an **alternative test statistic is defined** (similar to the Feldmans and Cousins procedure)

Alternative test statistic for a boundary at zero:

$$\tilde{t_\mu} = \begin{cases} \frac{\mathcal{L}(\alpha,\hat{\hat{\theta}}(\alpha))}{\mathcal{L}(0,\hat{\hat{\theta}}(0))} & \hat{\mu} < 0 \\ \frac{\mathcal{L}(\alpha,\hat{\hat{\theta}}(\alpha))}{\mathcal{L}(\hat{\alpha},\hat{\theta})} & \hat{\mu} > 0 \end{cases}$$

Probing the mass dependence : model

- This model **checks the mass dependency of the Higgs boson couplings** with the following parametrization :

  → For the couplings : $g_f = \sqrt{2}\frac{m_f^{1+\epsilon}}{M^{1+\epsilon}}$ and $g_V = 2\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}$

  → For the modifiers : $\kappa_f = v\frac{m_f^{\epsilon}}{M^{1+\epsilon}}$ and $\kappa_V = v\frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$

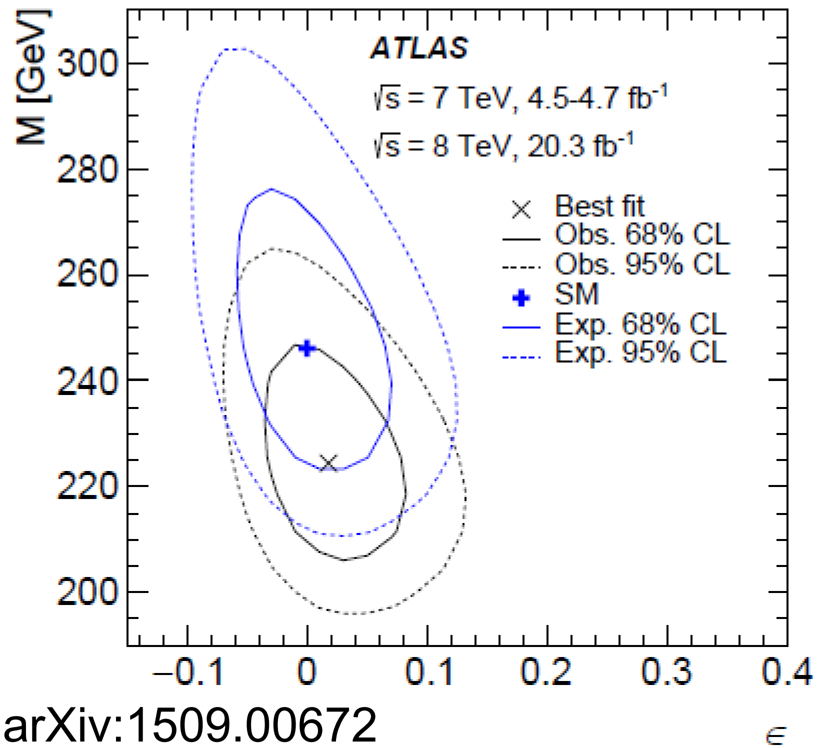
- **ε is a mass scaling factor, M the vaccum expectation value :**

  → Standard Model : (ε, M) → (0, v = 246 GeV)

- The couplings to photons and gluons are resolved

Probing the mass dependence : result

- Two dimensional confidence region in the plane (ε, M) :



arXiv:1509.00672

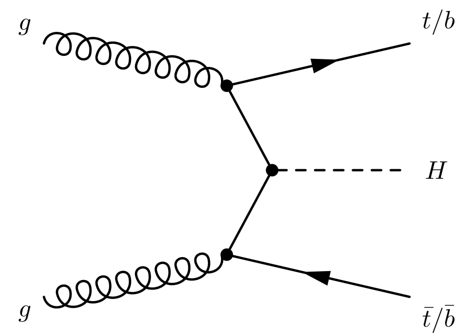
Best fit values :

Parameter	Obs.	Exp.
ϵ	0.018 ± 0.039	0.000 ± 0.042
M	224^{+14}_{-12} GeV	246^{+19}_{-16} GeV

- **Standard Model compatible within 1.5 standard deviations**

2HDM : bbh production

- Four types of 2HDM can be defined with different expressions for the coupling modifiers
- In 2HDM, **the couplings to b-quarks can become large, thus the bbh production is not negligible**



- The **coupling modifiers of the gluon fusion is adjusted** to take in account this contribution :

$$1.06\kappa_t^2 - 0.07\kappa_b\kappa_t + 0.01\kappa_b^2 + 0.011\kappa_b^2$$

$+ 0.011\kappa_b^2$ → Contribution of bbh

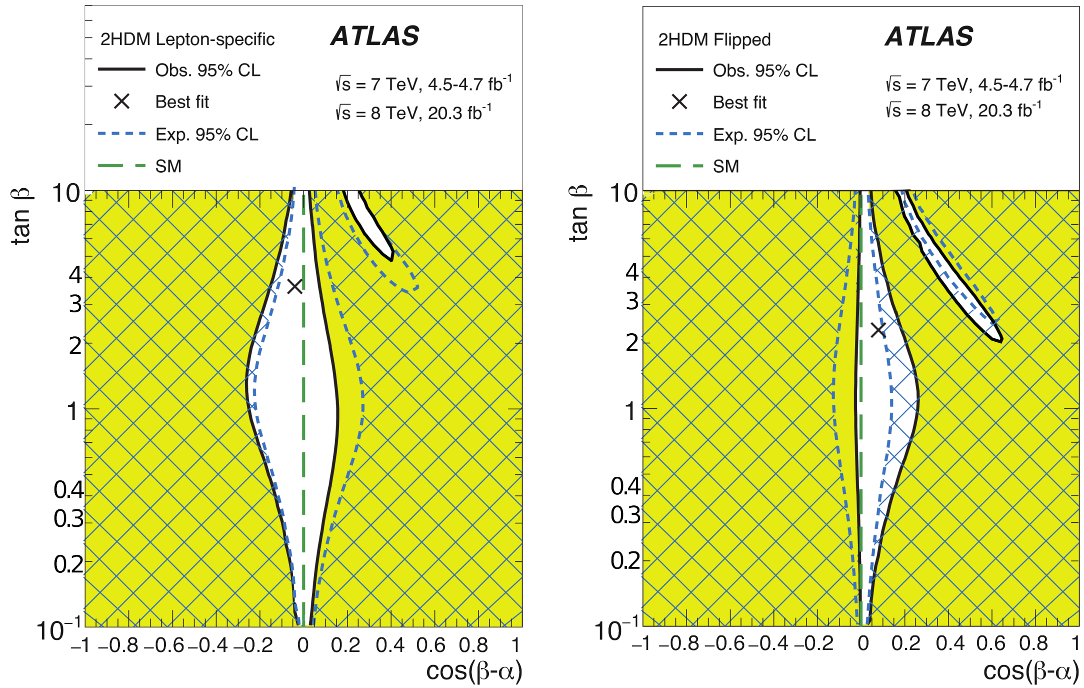
→ The new expression is used only for the cross section of the gluon fusion (ggF)

→ Assume that the bbh differential distributions are the same as those in ggF process

Type 3 and Type 4

- Results for type 3 and type 4 in the plane (cos β - α , tan β) :

	K_V	K_u	K_d	K_l
Type 3 : Lepton specific	sin(β-α)	cos α / sin β	cos α / sin β	- sin α / cos β
Type 4 :Flipped			- sin α / cos β	cos α / sin β



- Compatible with SM alignment limit

arXiv:1509.00672

Simplified MSSM : Mass Matrix

Mass matrix given by :

$$\mathrm{M}_S^2 = \begin{pmatrix} m_Z^2 cos^2\beta + m_A^2 sin^2\beta & -(m_Z^2 + m_A^2) cos\beta sin\beta \\ -(m_Z^2 + m_A^2) cos\beta sin\beta & m_Z^2 sin^2\beta + m_A^2 cos^2\beta \end{pmatrix} + \begin{pmatrix} \Delta M_{11}^2 & \Delta M_{12}^2 \\ \Delta M_{12}^2 & \Delta M_{22}^2 \end{pmatrix}$$

It is possible to show that : $\Delta M_{22}^2 = \frac{\delta}{sin^2\beta} >> \Delta M_{11}^2, \Delta M_{12}^2$

And finally : $M_h^2 = M_Z^2 cos^2(2\beta) + \delta$

The expressions of deviation coupling modifiers are :

$$\kappa_{down} = \frac{\sqrt{1+tan^2\beta}}{\sqrt{1+\left(\frac{m_h^2 - M_Z^2 cos^2\beta - M_A^2 sin^2\beta}{-(M_Z^2+M_A^2) cos\beta sin\beta}\right)^2}} \quad \kappa_{up} = \frac{\frac{\sqrt{1+tan^2\beta}}{tan\beta} \frac{m_h^2 - M_Z^2 cos^2\beta - M_A^2 sin^2\beta}{-(M_Z^2+M_A^2) cos\beta sin\beta}}{\sqrt{1+\left(\frac{m_h^2 - M_Z^2 cos^2\beta - M_A^2 sin^2\beta}{-(M_Z^2+M_A^2) cos\beta sin\beta}\right)^2}}$$

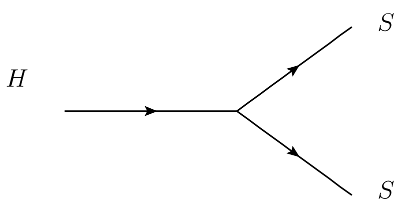
$$\kappa_V = \frac{\frac{1}{\sqrt{1+tan^2\beta}}}{\sqrt{1+\left(\frac{m_h^2 - M_Z^2 cos^2\beta - M_A^2 sin^2\beta}{-(M_Z^2+M_A^2) cos\beta sin\beta}\right)^2}} + \frac{\frac{tan\beta}{\sqrt{1+tan^2\beta}} \frac{m_h^2 - M_Z^2 cos^2\beta - M_A^2 sin^2\beta}{-(M_Z^2+M_A^2) cos\beta sin\beta}}{\sqrt{1+\left(\frac{m_h^2 - M_Z^2 cos^2\beta - M_A^2 sin^2\beta}{-(M_Z^2+M_A^2) cos\beta sin\beta}\right)^2}}$$

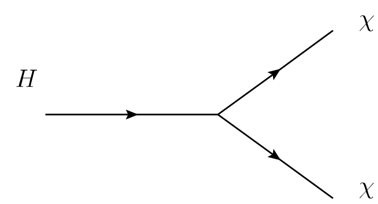
Interpretation in Higgs Portal to DM

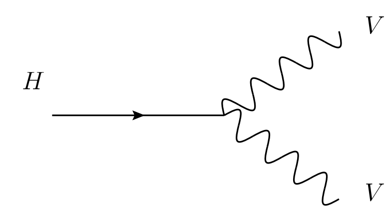
Djouadi, Falkowski, Mambrini, Quevillon

$H^\dagger H$

SM ------------------------- DM







$\mathcal{L}_S \supset -\frac{1}{2} m_S S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2$

$\mathcal{L} \supset -\frac{1}{2} m_f \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi}\chi$

$\mathcal{L} \supset \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu$

Spin Independent (SI) DM-nucleon elastic cross section

$$\sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2} ,$$

$$\sigma^{SI}_{V-N} = \frac{\lambda^2_{hVV}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2} ,$$

$$\sigma^{SI}_{f-N} = \frac{\lambda^2_{hff}}{4\pi \Lambda^2 m_h^4} \frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2}$$

$$\Gamma^{\rm inv}_{h\to SS} = \frac{\lambda^2_{hSS} v^2 \beta_S}{64\pi m_h} ,$$

$$\Gamma^{\rm inv}_{h\to VV} = \frac{\lambda^2_{hVV} v^2 m_h^3 \beta_V}{256\pi M_V^4} \left(1 - 4\frac{M_V^2}{m_h^2} + 12\frac{M_V^4}{m_h^4}\right) ,$$

$$\Gamma^{\rm inv}_{h\to\chi\chi} = \frac{\lambda^2_{hff} v^2 m_h \beta_f^3}{32\pi \Lambda^2} ,$$

$$\beta_X = \sqrt{1 - 4M_X^2/m_h^2}$$