Constraints on New Phenomena via Higgs Coupling Measurements with the ATLAS Detector

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Introduction

- **The Higgs boson**, the last missing piece of Standard Model, **has been discovered at a mass around 125.5 GeV** and is compatible with 0^{++}

- **Nevertheless, questions remains** : Hierarchy problem, dark matter, new interactions or particles → Imply deviations with respect to Standard Model

- In the Higgs couplings combination :
  → Measure **deviation of the number of signal events** with respect to the expected one :

$$n = s + b = \mu \sigma_{SM} BR_{SM} \mathcal{L} \mathcal{A} \epsilon + b$$

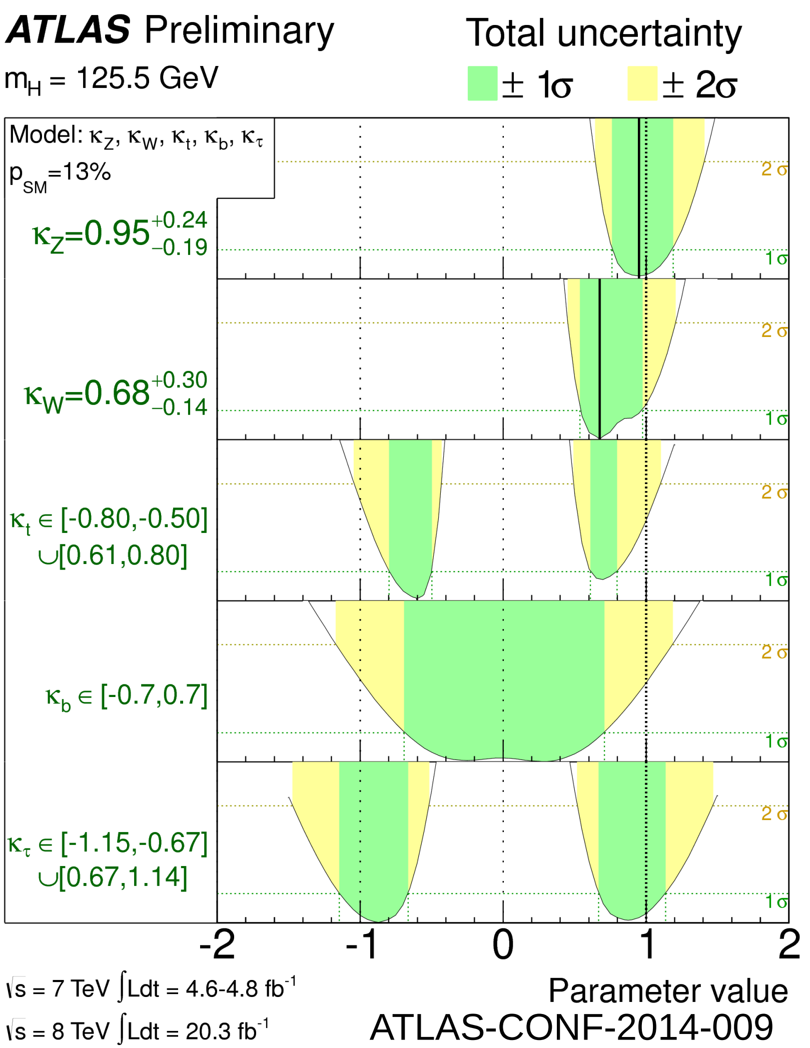
  → **Assume perfect understanding of experimental conditions and analysis** (Luminosity, efficiency background…)
  → Interpret results as a **deviation with respect to Standard Model** (cross section, branching ratio, couplings …)
  → No informations on the origins of the deviations

- In ATLAS-CONF-2014-010**, deviations are used to constrain BSM theories,** results are not final and will be updated

- Results use the h → 4l, h → 2l2ν, h → bb, h →γγ , h →ττ analysis at 7 TeV with up to 4.6-4.8 fb^{-1} and 8 TeV with 20.3 fb^{-1}

Deviation coupling modifiers

- **Define the deviation coupling modifiers κ :**
  → ratio of the Higgs boson coupling over the Standard Model coupling
  → κ = 1 corresponds to Standard Model



- **Determination is based on the maximization of an unbinned likelihood function**

- Use **Narrow width approximation :**
  → Decouple production and decay
  → Example for qq → Zh → $b\bar{b}$:

$$s \propto \kappa_Z^2 \frac{\kappa_b^2}{\kappa_h^2}$$

→ With : $\kappa_h^2 = \dfrac{\Gamma_h}{\Gamma_{h,SM}}$

- If assume Standard Model decays only :

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

Additionnal comments

- **Photons and gluons are not massive but interact with the Higgs boson via a loop**

- **Two treatments** are possible :
  →**Keep the modifiers** and consider an effective coupling : **sensitive to new particles in the loops** (charged for the photons, colored for the gluons)
  →Resolved couplings : **Express as a function of the modifiers of the massive particle**, assume standard model content in the loop

- 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)

- Assume asymptotic distributions for the two tests

Probing the mass dependence (1/2)

- **Check the mass dependence of the Higgs boson couplings with respect to the Standard Model** (linear for the fermions, quadratic for the W, Z bosons)

- Introduce a **phenomenological parametrization** of couplings, or equivalently, of the coupling constant modifiers (arXiv:1303.3879) :

  → 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 $\kappa_V = v\frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$

- Mass scaling : ε and "vacuum expectation value" : M

- **Standard Model** is found for **(ε → 0, M → *v* ≈ 246 GeV)**

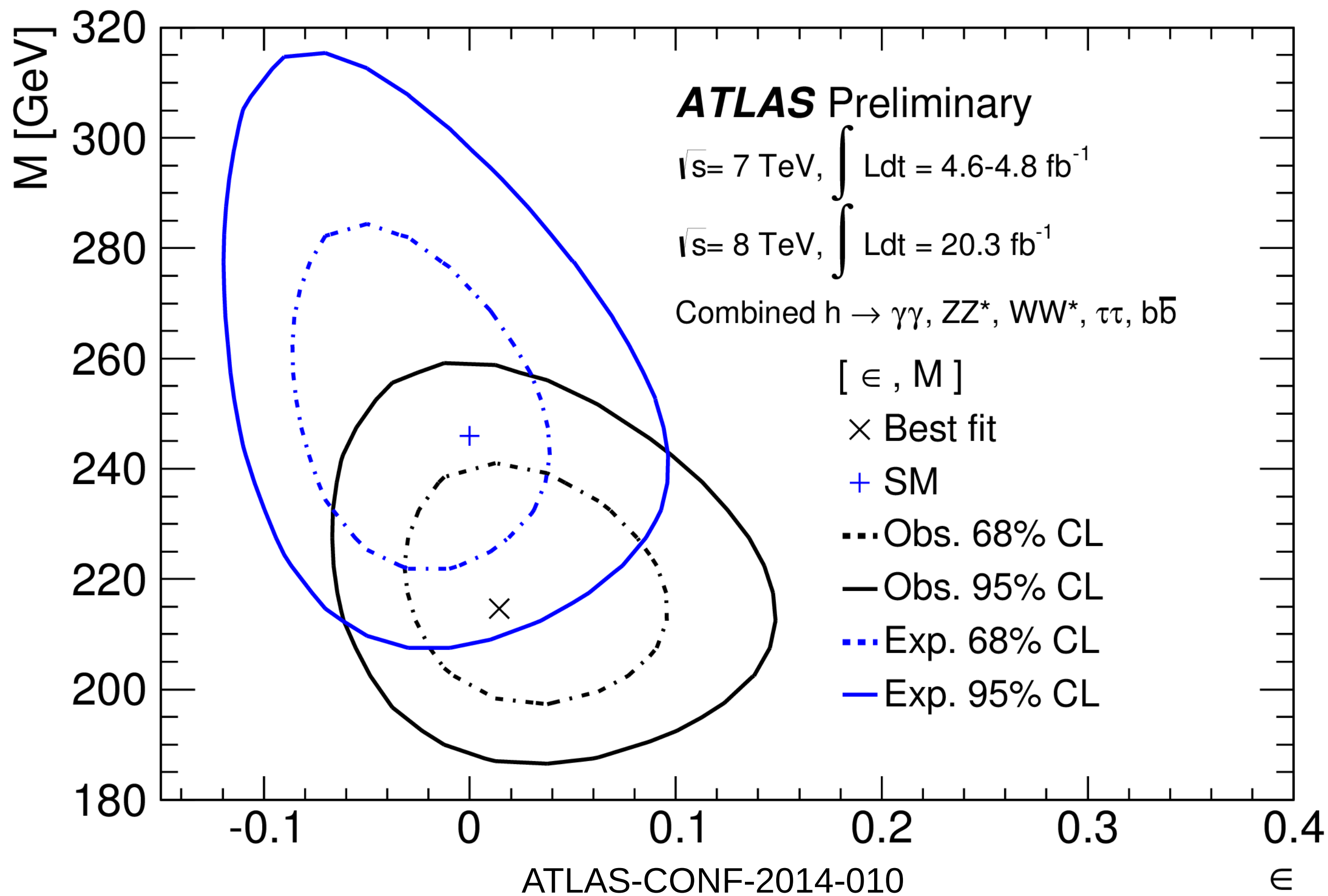
- Consider only Standard Model particles

- Except ε = 0 (Standard Model), others values have no interpretation

Probing the mass dependence (2/2)

- Plot the 2D contours in the plan (ε, M) which correspond to :
  $\rightarrow -2ln(\Lambda(\epsilon, M)) = 2.3$ corresponds to 68 % confidence level
  $\rightarrow -2ln(\Lambda(\epsilon, M)) = 6$ corresponds to 95 % confidence level

- **Standard Model is compatible with data within 1.5 σ**



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Higgs Compositeness (1/2)

- **Possible solution of the hierarchy problem : Higgs boson is a composite particle**

- Introduce a **compositeness scale f** : f → ∞ corresponds to Standard Model

- The Higgs coupling are modified, two models have been tested :

  → 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)

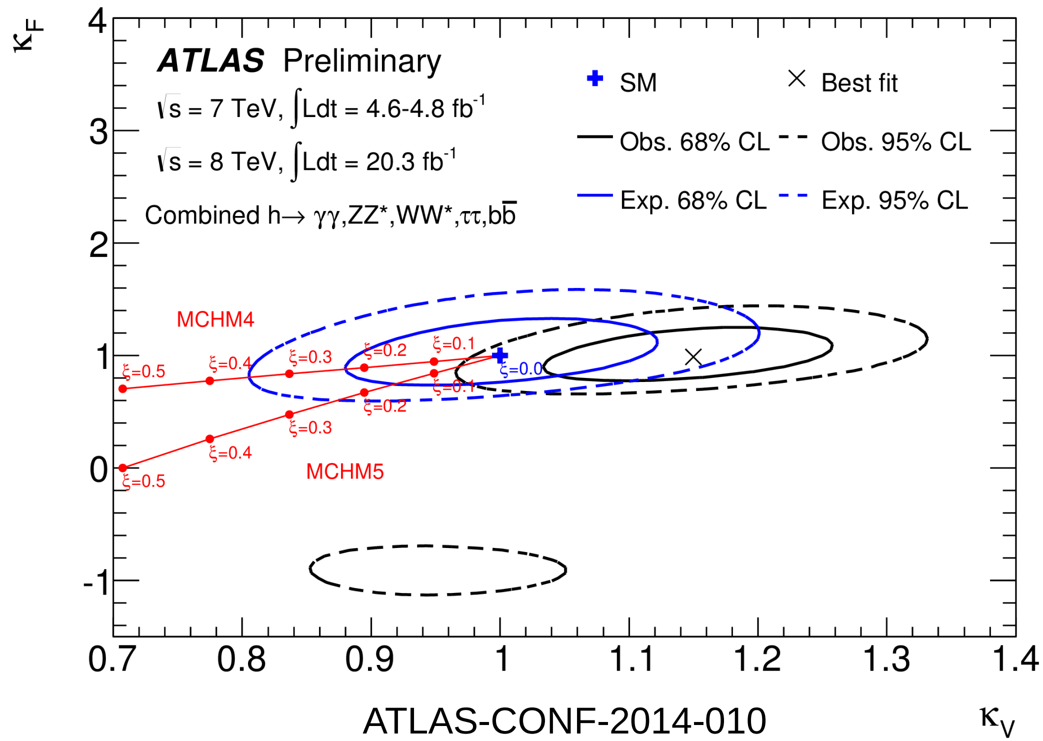
where $\xi = v^2/f^2$ and **ξ → 0 is the Standard Model case**

- Assume **decays and particle content for the loops of standard model**

- Limits on ξ can be deduced and convert into a limit on f
  → **Physical boundary at ξ = 0**

Higgs Compositeness : Results (2/3)

- (1) and (2) define a parametric equation in the plan (κ_V , κ_F)



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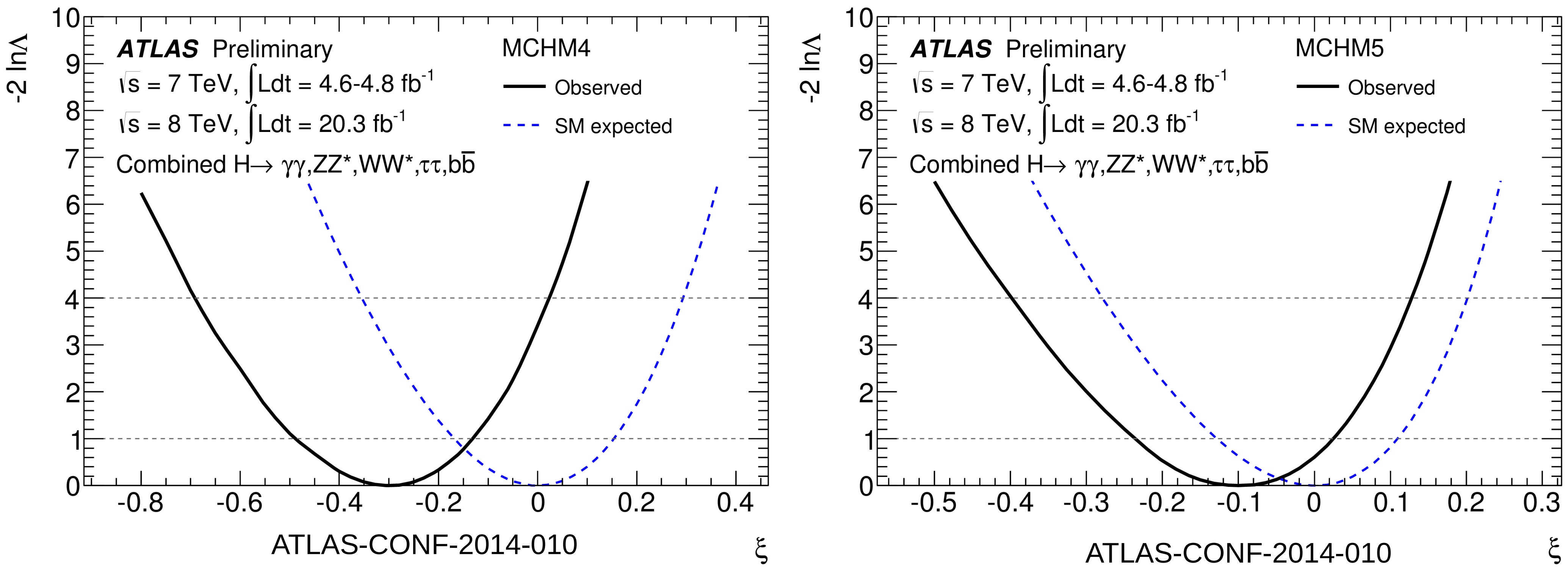
- Easy visualization of the probed region in the plan (κ_V , κ_F)
  → Composite models are disfavoured

Higgs Compositeness : Results (3/3)

- Profiled likelihood for the two models :



- **Current Limits at 95 % CL (Alternative procedure) :**
  - → **MCHM 4 : f > 710 GeV (exp. : f > 460 GeV)**
  - → **MCHM 5 : f > 640 GeV (exp. : f > 550 GeV)**

Additional Electroweak singlet (1/3)

- **Simplest extension of the Standard Model Higgs Sector :**
  → Additional Electroweak Singlet
  → Possible solution to dark matter problem
  → **Two Higgs Boson h (Standard Model) and H**

- **Coupling of h/H are the standard model prediction for the mass of the considered Higgs Boson decreased by a factor κ/κ'** such that :

$$\kappa^2 + \kappa'^2 = 1$$ **(unitarity constraint)**

- For the lightest Higgs boson, consider only Standard Model particles :

$$\sigma_h = \kappa^2 \sigma_{h,SM}, \Gamma_h = \kappa^2 \Gamma_{h,SM}, BR_{h,i} = BR_{h,SM,i}$$

- Consider the **possibility for the heaviest Higgs boson to decay into new particles with no charge and no color** (resolved couplings for photons and gluons) :
  → For instance, if allowed, H → hh
  → Introduce a branching ratio : $BR_{H,new}$

Additionnal Electroweak singlet (2/3)

- For the heaviest Higgs boson :

$$\sigma_H = \kappa'^2 \sigma_{H,SM},\ \Gamma_H = \frac{\kappa'^2}{1 - BR_{H,new}} \Gamma_{H,SM},\ BR_{H,i} = \frac{\kappa'^2}{1 - BR_{H,new}} BR_{H,i,SM}$$

- Using the unitarity constraint, the likelihood (initially a function of κ) can be expressed as a function of κ' :
  → Possible to deduce a limit on κ'

  → Observed : $\kappa'^2 = -0.30^{+0.17}_{-0.18}$

  → Expected : $\kappa'^2 = -0.00^{+0.15}_{-0.17}$

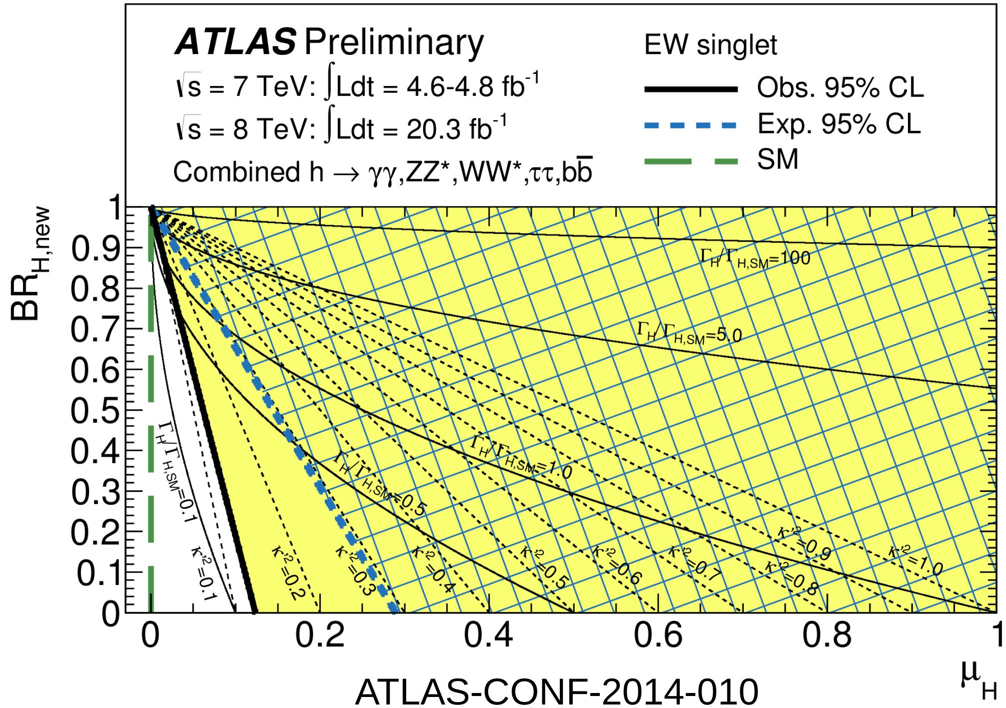
- **Applying alternative Procedure at 95 % CL :**
  → the limit is $\kappa'^2 < 0.12$ (0.29 for exp.)

Additionnal Electroweak singlet (3/3)

- Define the signal strength factor :

$$\mu_H = \frac{\sigma_H BR_H}{(\sigma_H BR_H)_{SM}} = \kappa'^2(1 - BR_{H,new})$$

- From the limit on κ' : deduce excluded region in the plan (μ_H ,$BR_{H,new}$)



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Two Higgs doublet models (1/3)

- Other extension of the Standard Model Higgs Sector :
  → Additional Higgs doublet such as MSSM (5 Higgs Bosons)
  → Motivated by hierarchy problem and dark matter

- **Couplings described by two parameters :**
  → tan β : the ratio of the vev's of the two Higgs doublets
  → α : the mixing angle between the two CP-even Higgs states

- Assume the discovered Higgs boson is the lightest CP-even states
  → Standard model particles content for the loops and decays

- In the models, **b-quark coupling** to the light Higgs boson can **become important :**
  → Need to **take in account the bbH production mode**
  → Done for all the two Higgs doublet models
  → **Rescale the fusion gluon cross section with the prediction of SUSHI and 2HDMC**
  → **Corrections below 10 % for the region compatible at 95 % confidence level**

Two Higgs doublet models : Type I and II (2/3)

	κ_V	κ_u	κ_d	κ_l
Type 1	sin(β-α)	cos α / sin β	cos α / sin β	cos α / sin β
Type 2	sin(β-α)	cos α / sin β	- sin α / cos β	- sin α / cos β

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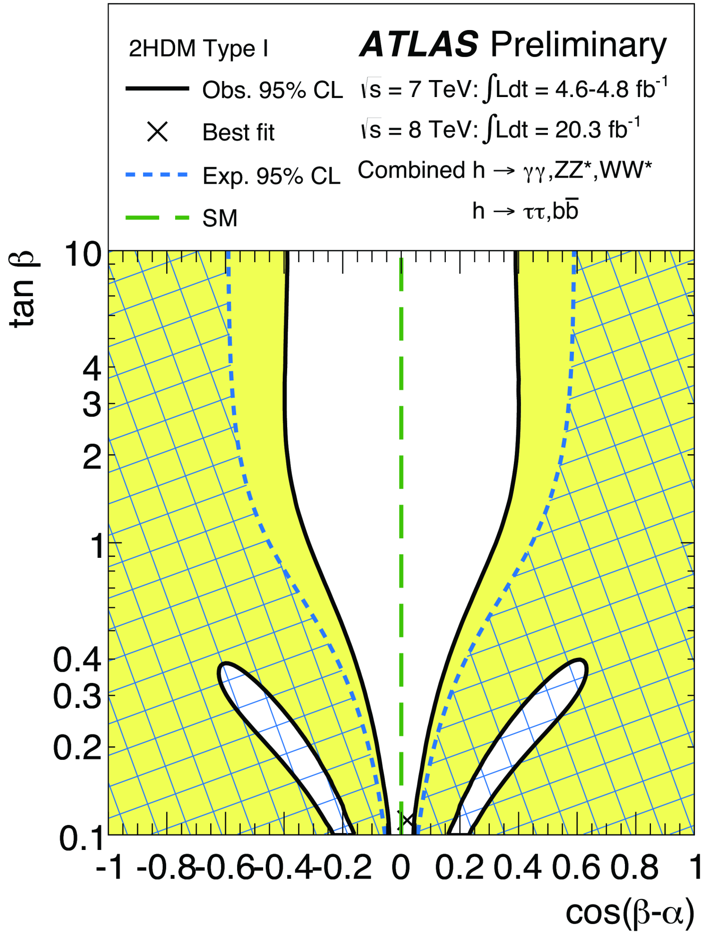

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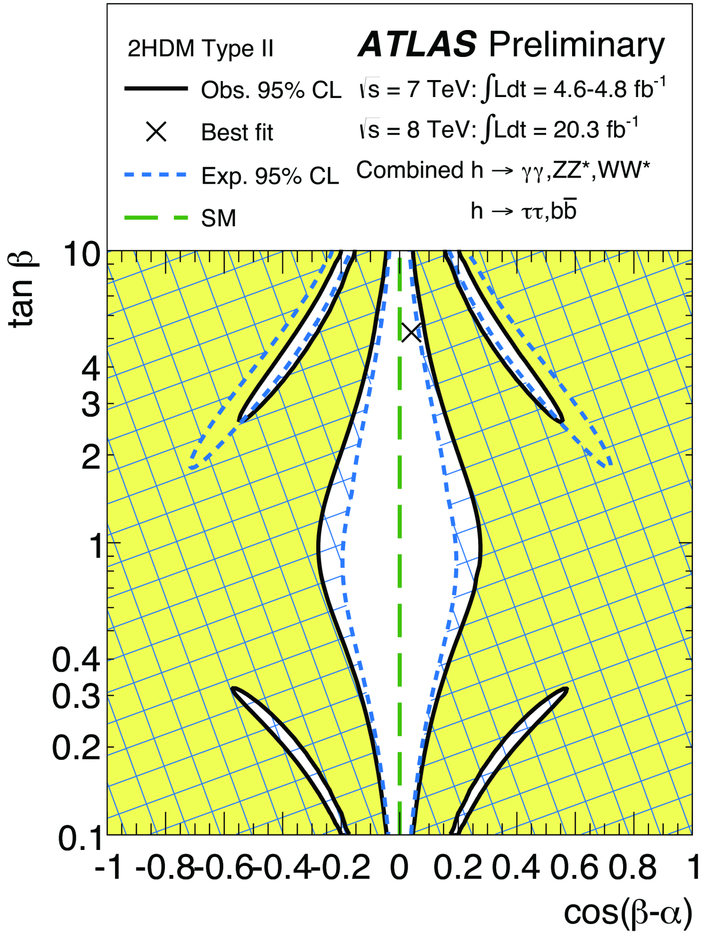

Two Higgs doublet models Type III and IV (3/3)

	κ_V	κ_u	κ_d	κ_l
Type 3	sin(β-α)	cos α / sin β	cos α / sin β	- sin α / cos β
Type 4	sin(β-α)	cos α / sin β	- sin α / cos β	cos α / sin β

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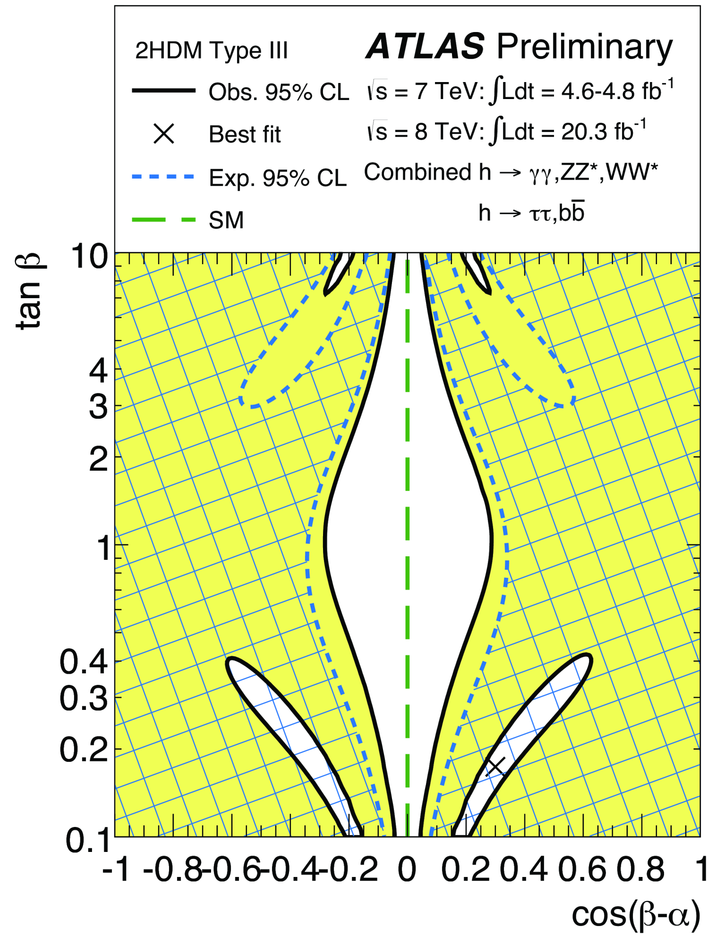

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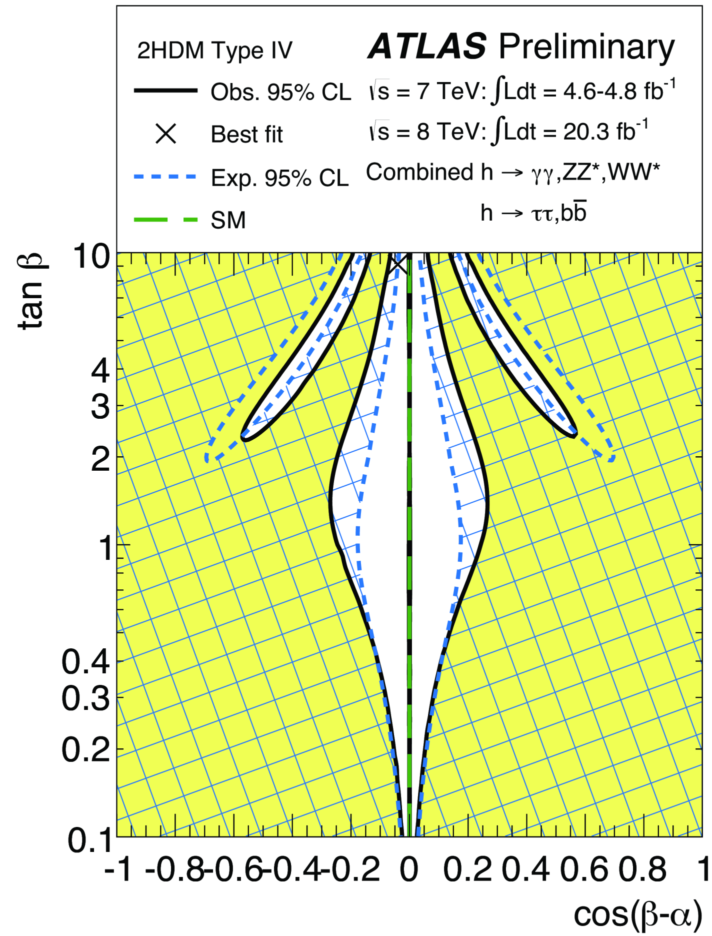


Simplified MSSM (1/2)

- MSSM provides a possible solution to the hierarchy problem and dark matter

- Simplification of MSSM (arxiv:1307.5205) :
  → **Radiative corrections involving top quark and stops are fixed by the mass of the standard model Higgs boson**
  → **Loops corrections from stops in ggF and diphoton decays are neglected** (expected less than 5%)
  → **Corrections which break universality of down type fermions** ($\kappa_b \neq \kappa_\tau$) are **negleted**
  → **Deviation coupling modifiers for boson (κ_V), up type-fermion (κ_u), down type-fermion (κ_d) depend only on tan β and m_A the mass of the pseudo scalar Higgs boson**

- **Take in account the bbh production** mode by modifying the deviation coupling modifier of gluons only in the case of gluons fusion production :

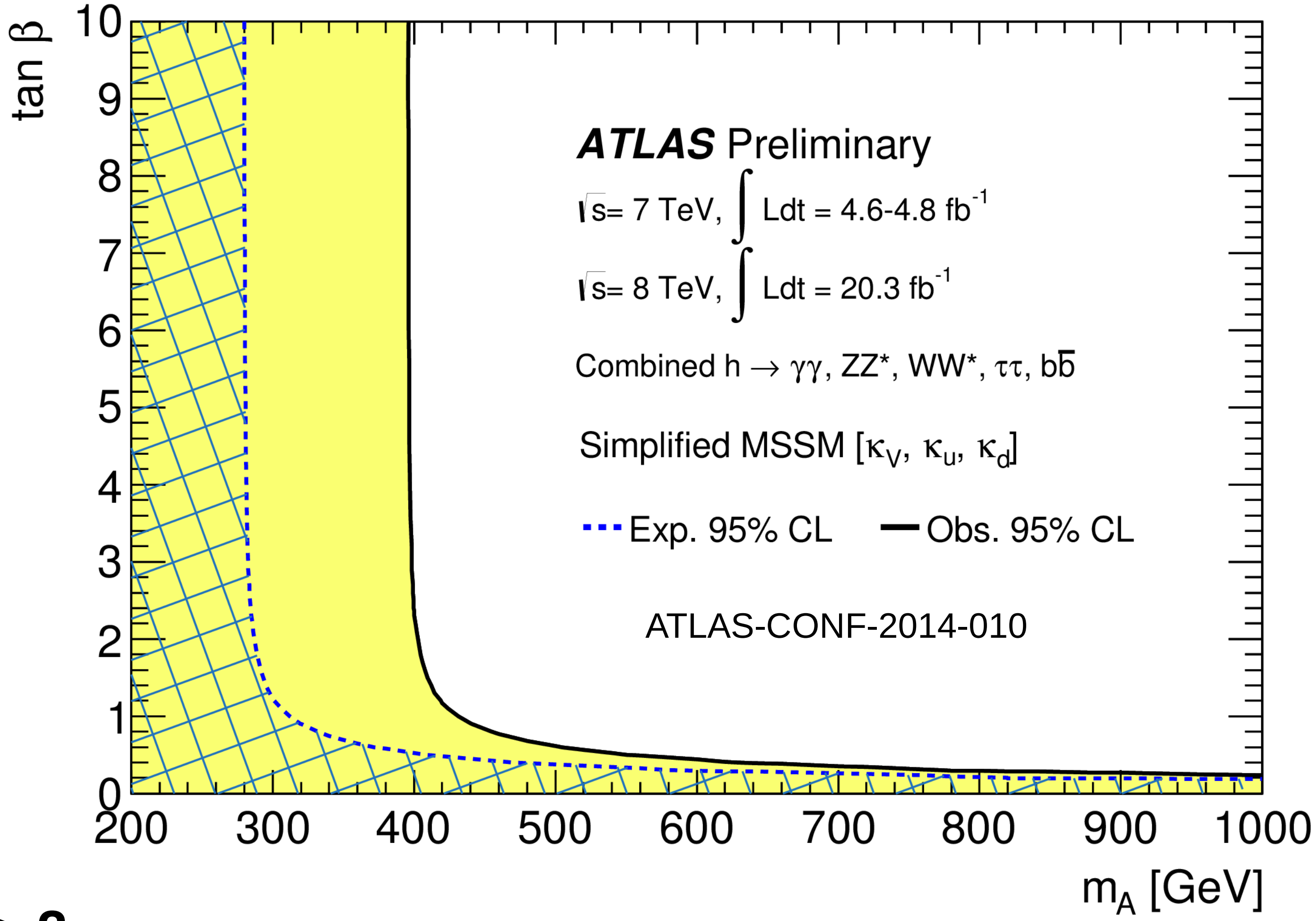
$$1.06\kappa_t^2 - 0.07\kappa_b\kappa_t + 0.01\kappa_b^2 + 0.011\kappa_b^2$$

Contribution of bbh

- Standard Model corresponds to $m_A \rightarrow \infty$

Simplified MSSM (2/2)

- 2D contours in the plan (m_A , tan β) :



- **For tan β > 2 :**
  → mA > 400 GeV @ 95% CL (obs.)
  → mA > 290 GeV @ 95% CL (exp.)

Higgs invisible branching ratio (1/2)

- Models introduce weakly interacting particles (Wimps) to solve the dark matter problem

- **Interact weakly with all the standard model particles except the Higgs Boson**, if the mass of the particle is lower than m_h /2 :
  → Higgs Boson could decay in these particles (BR_{inv})

- Possibility to probe this model with the visible searches using the following **model (κ_{gluon}, κ_γ , BR_{inv})** :
  → **Sensitive to new particles in loops and decays**
  → Formula of κ_h is modified :

$$\kappa_H^2 = \frac{0.085\kappa_{gluon}^2 + 0.0023\kappa_\gamma^2 + 0.91}{1 - BR_{inv}}$$

  → **Others : κ_b, κ_t, κ_W, κ_Z, κ_τ are fixed to 1**
  → **Assume BR_{und} = 0**

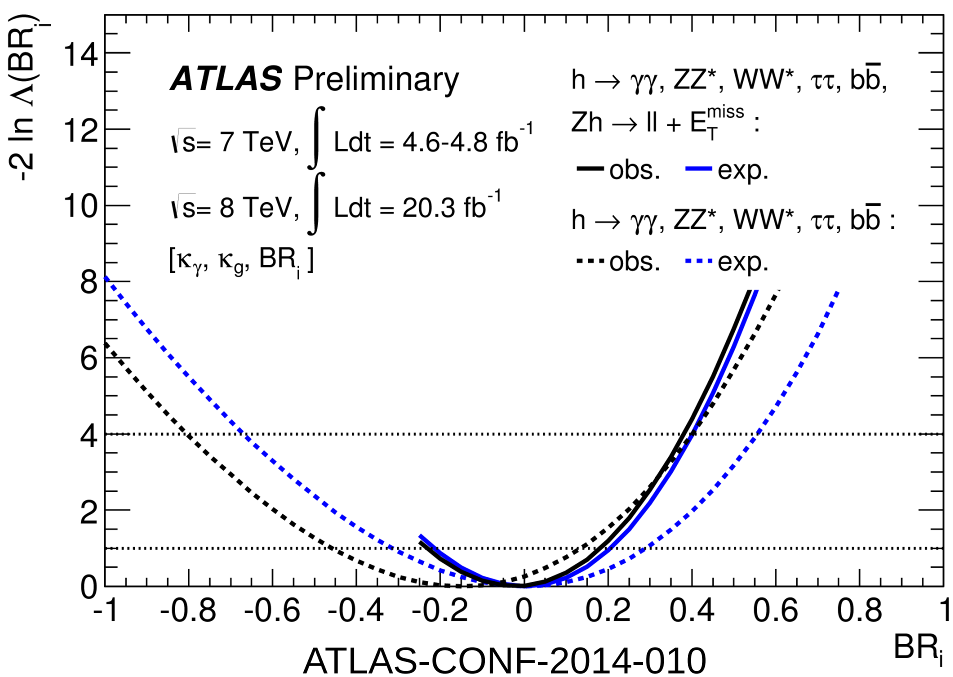
- For this model only : **Combine the Zh → ll + Etmiss (arxiv :1402.3244) with the 5 visible searches (referred as 6 channels)**

Higgs invisible branching ratio (2/2)

- **6-channels :** Ignoring physical boundary → alternative procedure :
  - → Obs. : $BR_{inv} = -0.02 \pm 0.20$ → **BR_{inv} < 0.37 @ 95 % CL**
  - → Exp. : $BR_{inv} = 0.00 \pm 0.21$ → **BR_{inv} < 0.39 @ 95 % CL**

- **5-channels results :** Ignoring physical boundary → alternative procedure :
  - → Obs. : $BR_{inv} = -0.16^{+0.28}_{-0.30}$ → **BR_{inv} < 0.41 @ 95 % CL**
  - → Exp. : $BR_{inv} = 0.00^{+0.29}_{-0.32}$ → **BR_{inv} < 0.55 @ 95 % CL**

- Continuous curves stop at -0.3 due to negative pdfs



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Higgs portal to Dark matter

- **Possible to convert the invisible branching ratio into scattering cross section of dark matter on a nuclei**

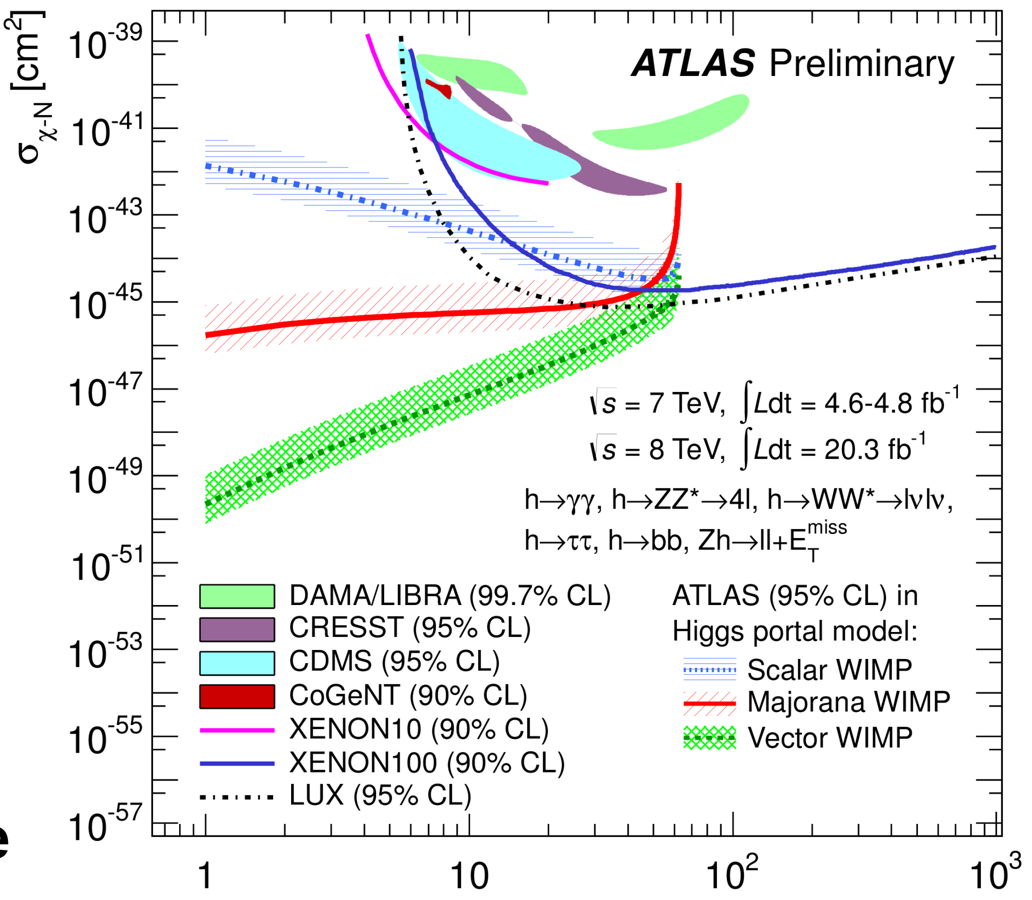
- Depends on the nature (scalar, fermionic, vector) of dark matter

- Allow **comparison with direct searches** (e.g XENON)

- Assume the invisible branching ratio of the Higgs boson only comes from the wimps

- Assume VH production rate of Standard Model

- **Limits from ATLAS in Higgs Portal model at low mass significantly better than those from direct detection limits**



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Conclusion

- All results compatible with Standard Model
- Higgs Imposter : consistent with mass scaling and vev within 1.5σ
- Higgs compositeness :
  → MCHM 4 : f > 710 GeV (exp. : f > 460 GeV)
  → MCHM 5 : f > 640 GeV (exp. : f > 550 GeV)
- Electroweak Singlet : $\kappa'^2 < 0.12$ (0.29) observed (expected)
- 2HDM : consistent with SM alignment limit within 1-2σ
- Simplified MSSM model :
  → for tan β > 2, m_A > 400 (290) Gev obs. (exp.) @ 95% CL
- Higgs Portal to dark matter :
  → BR_{inv} < 0.37 (0.39) observed (expected) @ 95 % CL

Thanks

Questions ?

BACKUP

Input Channels : 7 TeV

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]
2011 $\sqrt{s}$ =7 TeV			
$H \rightarrow \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \mathrm{conversion}\} \oplus$ {2-jet VBF}	4.8
$H \rightarrow ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu$, 2-jet VBF, ℓ-tag$\}$	4.6
$H \rightarrow WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes$ {0-jet, 1-jet, 2-jet VBF}	4.6
$VH \rightarrow Vbb$	$Z \rightarrow \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\ \mathrm{GeV}\} \otimes$ {2-jet, 3-jet}	4.6
	$W \rightarrow \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\ \mathrm{GeV}\}$	4.7
	$Z \rightarrow \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200\ \mathrm{GeV}\}$	4.7

- For the invisible Higgs combination (and Higgs portal to dark matter), use also the Zh → ll + E_t^{miss} :
  - → arxiv:1402.3244

Input Channels : 8 TeV

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]
2012 $\sqrt{s}$ =8 TeV			
$H \to \gamma\gamma$	–	14 categories: $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \mathrm{conversion}\} \oplus$ {loose, tight 2-jet VBF} $\oplus$ {ℓ-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$-tag, 2-jet VH}	20.3
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu$, 2-jet VBF, ℓ-tag$\}$	20.3
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes$ {0-jet, 1-jet, 2-jet VBF}	20.3
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\ \mathrm{GeV}\} \otimes$ {2-jet, 3-jet}	20.3
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{<90$, 90-120, 120-160, 160-200, $\geq$200 GeV$\} \otimes$ {2-jet, 3-jet}	20.3
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{<90$, 90-120, 120-160, 160-200, $\geq$200 GeV$\} \otimes$ {2-jet, 3-jet}	20.3
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{ee, e\mu, \mu\mu\} \otimes$ {boosted, 2-jet VBF}	20.3
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes$ {boosted, 2-jet VBF}	20.3
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	{boosted, 2-jet VBF}	20.3

- For the invisible Higgs combination (and Higgs portal to dark matter), use also the Zh → ll + E_t^{miss} :
  - → arxiv:1402.3244

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:

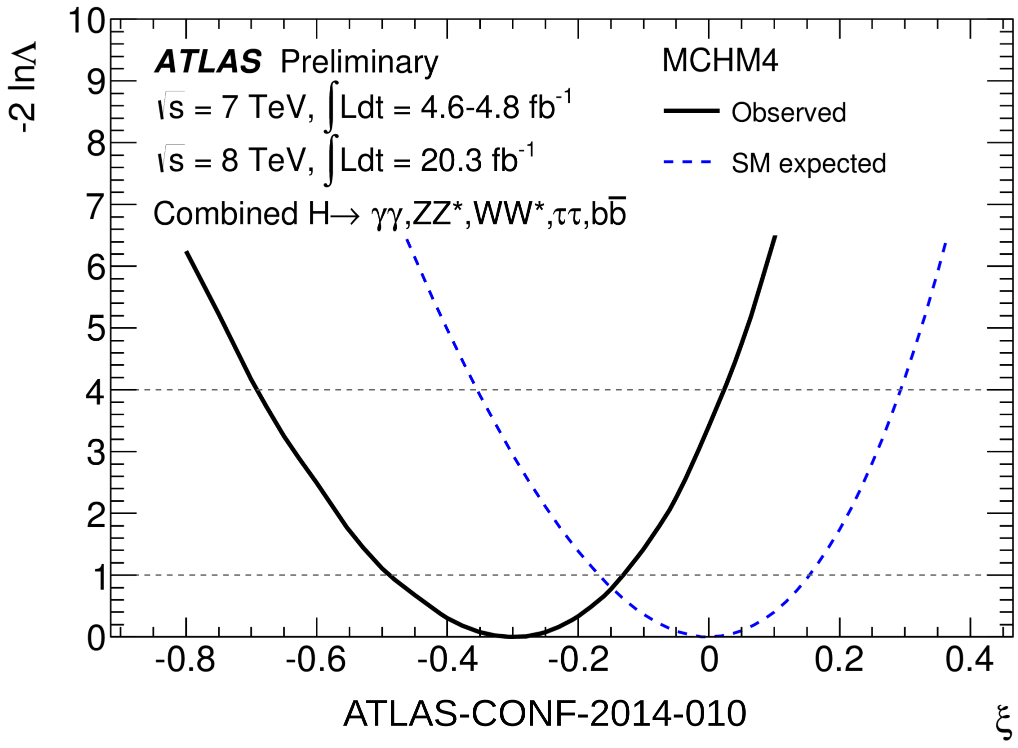
$$\tilde{t_\mu} = \begin{cases} \frac{\mathcal{L}(\alpha, \hat{\hat{\theta}}(\alpha))}{\mathcal{L}(0, \hat{\hat{\theta}}(0))} & \hat{\mu} < 0 \\ \frac{\mathcal{L}(\alpha, \hat{\hat{\theta}}(\alpha))}{\mathcal{L}(\hat{\alpha}, \hat{\theta})} & \hat{\mu} > 0 \end{cases}$$

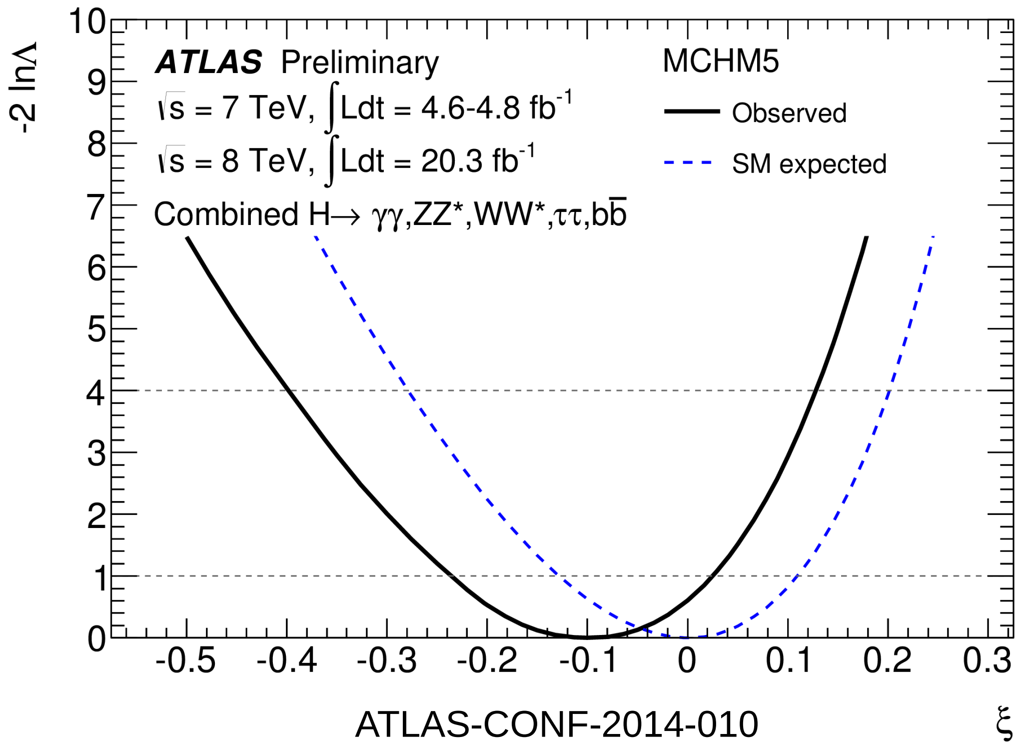
Higgs Compositeness : Results

- Best fit values and errors (Ignoring physical boundary ξ > 0) :

→ MCHM 4 : $\xi = -0.30^{+0.17}_{-0.18}$ (obs.) and $\xi = 0.00^{+0.15}_{-0.17}$ (exp.)

→ MCHM 5 : $\xi = -0.08^{+0.11}_{-0.16}$ (obs.) and $\xi = 0.00^{+0.11}_{-0.13}$ (exp.)





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 :

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

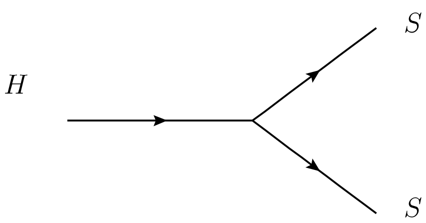
$$\kappa_V = \frac{\frac{1}{\sqrt{1+tan^2\beta}}}{\sqrt{1 + (\frac{m_h^2 - M_Z^2 cos^2\beta - M_A^2 sin^2\beta}{-(M_Z^2 + M_A^2) cos\beta sin\beta})^2}} + \frac{\frac{tan\beta}{\sqrt{1+tan^2\beta}} \frac{m_h^2 - M_Z^2 cos^2\beta - M_A^2 sin^2\beta}{-(M_Z^2 + M_A^2) cos\beta sin\beta}}{\sqrt{1 + (\frac{m_h^2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

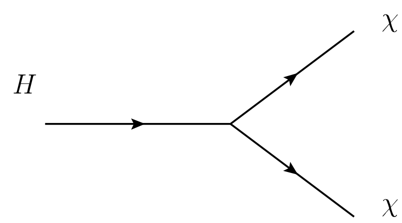
Interpretation in Higgs Portal to DM

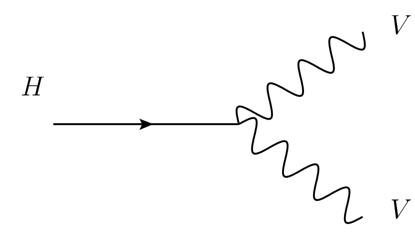
Djouadi, Falkowski, Mambrini, Quevillon

$$H^\dagger H$$

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

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

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

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

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

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

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

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