Constraints on new phenomena through Higgs coupling measurements and invisible decays with the ATLAS detector

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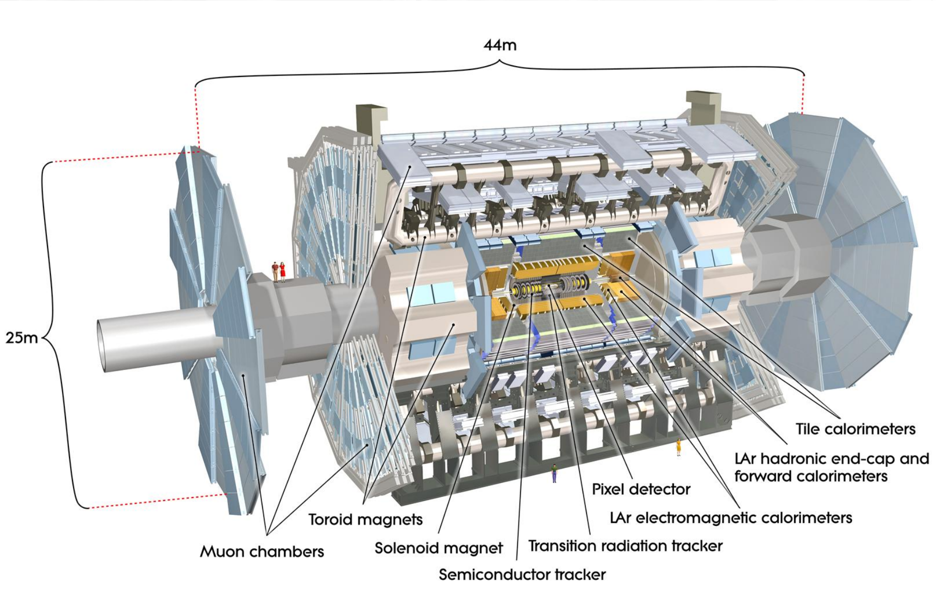
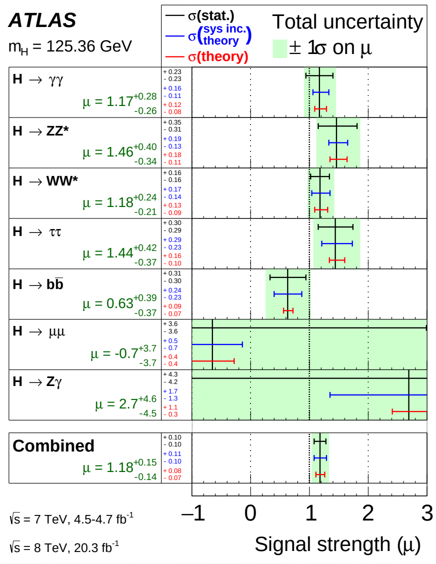
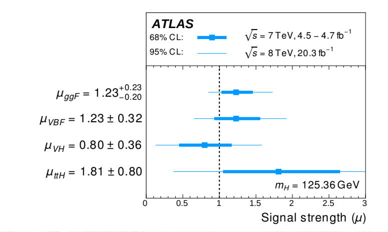
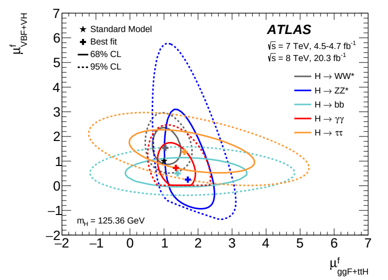
NEW https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2015-03



Combination of Higgs Measurements (now with *ttH*!!!)





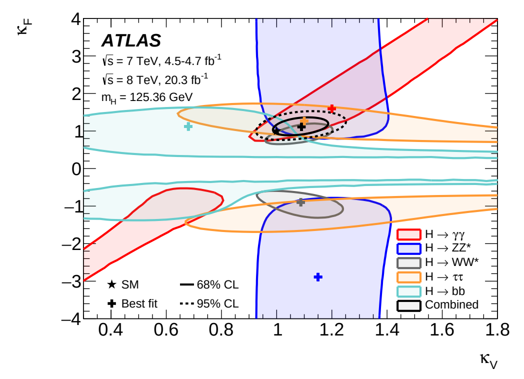


arXiv:1507.04548

Higgs boson Coupling measurements (κ-framework)

- Disentangle individual couplings from production and decays
- Assumptions (LO-inspired benchmark) arxiv:1307.1427):
  - Higgs $\rightarrow$ single resonance
  - Narrow width approximation $\sigma \times BR(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$
  - No modification on the Tensor structure of the couplings (only absolute values are modified)
  - Acceptance unchanged
- Factors κ_i such as

$$\frac{\sigma \times BR(gg \rightarrow H \rightarrow \gamma\gamma)}{(\sigma_{gg} \times BR(H \rightarrow \gamma\gamma))_{SM}} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_h^2}$$



this plot, no invisible/undetected decays assumed

Note that κ_g^2 and κ_γ^2 are loop-induced depending on (κ_t, κ_b and κ_W).

Content

1 Higgs couplings and internal structure
- Mass scaling
- Minimal Composite Higgs Model

2 Constrains on Multiple Higgs bosons
- Real Electroweak Singlet
- 2HDM
- Simplified MSSM

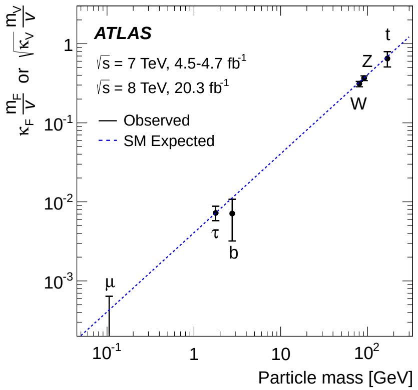
3 Probing Invisible Higgs boson decays
- Direct (Invisible) searches
- Combination of indirect (visible channels) and direct (invisible searches)

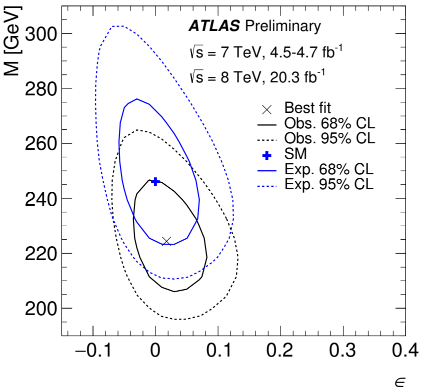
“Mass scaling” of couplings

- Each coupling in terms of vev ($v \approx 246$ GeV) and ϵ (note that SM: $\epsilon \to 0$)

$$\kappa_{f,i} = v\frac{m^{\epsilon}_{f,i}}{M^{1+\epsilon}} \qquad \kappa_{V,j} = v\frac{m^{2\epsilon}_{V,j}}{M^{1+2\epsilon}}$$

$\varepsilon : 0.018 \pm 0.039, M : 224^{+14}_{-12}$ **GeV**



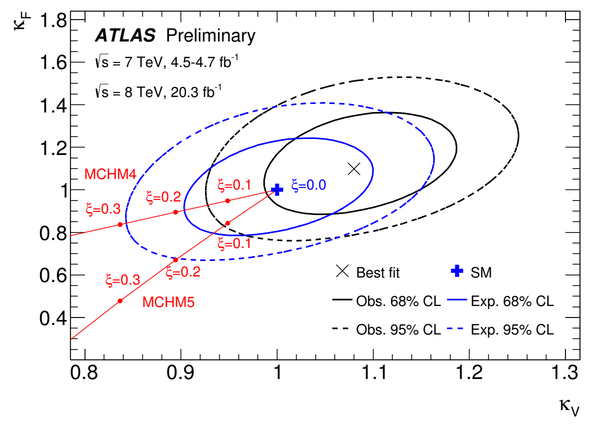


arXiv:1507.04548 HIGGS-2015-03

Minimal Composite Higgs Model

- Scalar Naturalness: Higgs $\rightarrow$ composite pseudo Nambu-Goldstone boson
  95% CL obs (exp): **MCHM4:** $f > 710$**(510) GeV;** **MCHM5:** $f > 780$**(600) GeV**
- Higgs couplings modified as function of compositeness scale f
  $\xi = v^2/f^2$

- MCHM4:
  $\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$
- MCHM5:
  $\kappa_V = \sqrt{1-\xi}$
  $\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$



- SM recovered in the limit $\xi \rightarrow 0$, namely $f \rightarrow \infty$.

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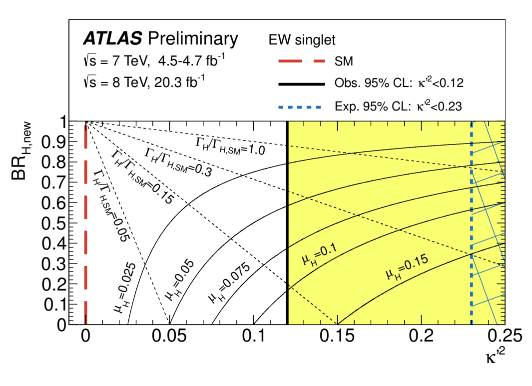
Additional Real Electroweak Singlet

- Simplest extension: additional real EW singlet, m_H heavier than 125 GeV
- Couplings $\rightarrow$ mixing gives: $\kappa^2 + \kappa'^2 = 1$
- Coupling (and signal strength as predicted by heavier SM-like Higgs) modified by allowing new decays $\text{BR}_{H,new}$, like $H \rightarrow hh$



95%CL: $\kappa'^2 < 0.12(0.23)$

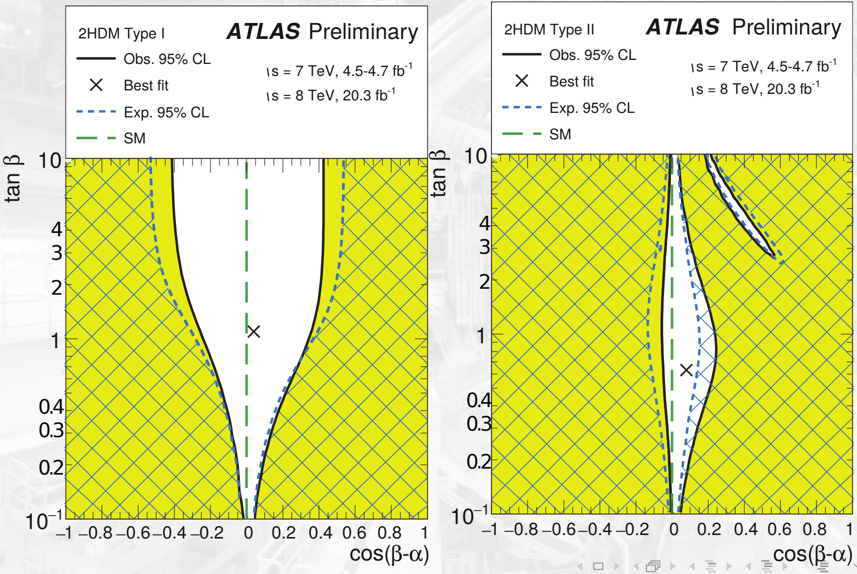
Two Higgs Doublet Model

- Two identical complex scalar fields($SU(2)$)
- The 2HDM scalar potential $\rightarrow Z_2$ broken symmetry
- In the CP-conserving case, parameters can be reduced to 6: 4 masses $m_h, m_H, m_{H\pm}, m_A$, and 2 angles α, β
- $\tan\beta = v_1/v_2$: ratio of vevs (satisfying $v_1^2 + v_2^2 = v^2 \approx (246\text{ GeV})^2$
  α: mixing angle between h and H

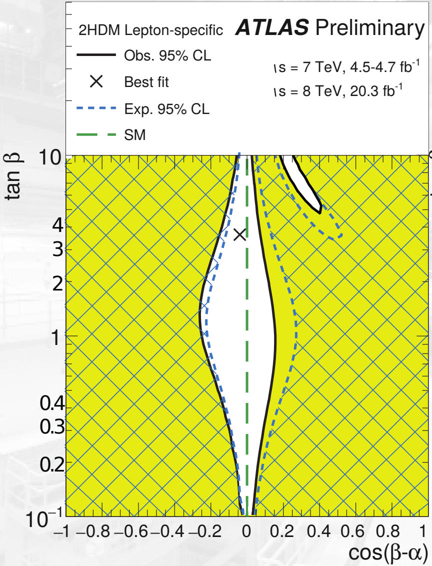
Coupling scale factor	Type I (fermiophobic)	Type II (MSSM-like)	Type III (lep. specific)	Type IV (flipped)
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

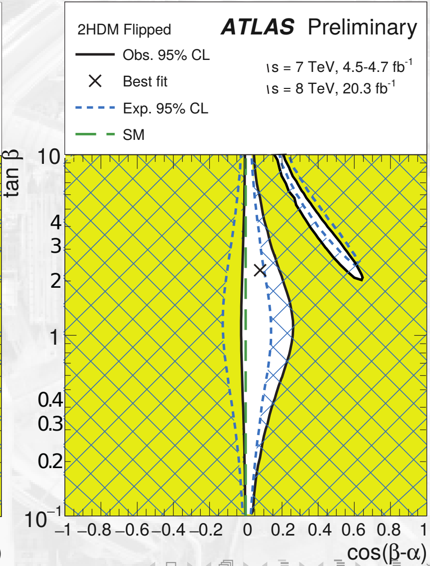
- Assumptions (for interpretations): 125 GeV is the light higgs, no radiative corrections, only SM decays. Convention: $\sin(\beta-\alpha) \geq 0$
- SM-like alignment limit retrieved at $\cos(\beta-\alpha) = 0$

Two Higgs Doublet Model, Type I and II



2HDM, Lepton Specific & Flipped



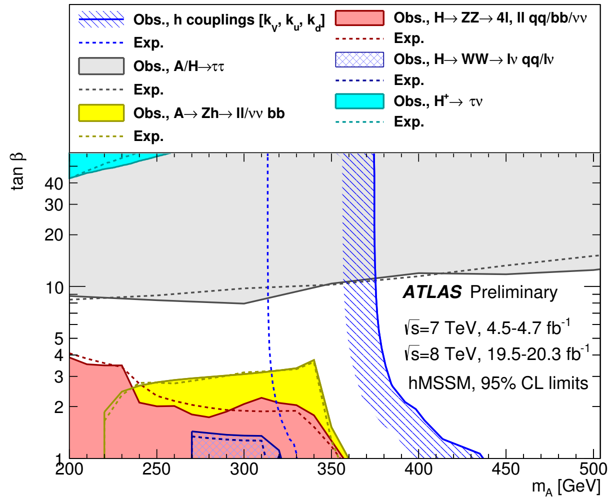


Simplified MSSM, (hMSSM)

Assumptions:

- *h* production and decay modes as in the SM
- stops in ggF and $\gamma\gamma$ not included
- Same for light staus and charginos
- Decays to SUSY or heavy-to-light Higgs decays not included

for $\tan\beta > 1$:
$m_A > 370$ **(310) GeV**



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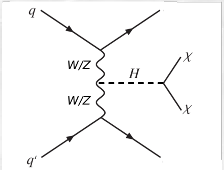
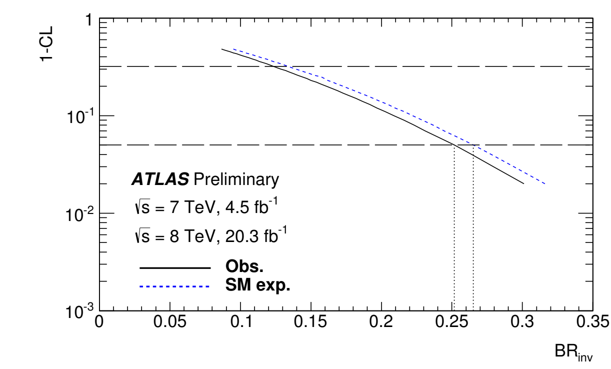
Higgs to invisible searches

More details in Philippe Calfayan talk!



- Tag events with large missing energy → use particles produced together with the Higgs
- Assume productions (& acceptance) as in SM
- $h \to ZZ \to 4\nu$: 1.2×10^{-3} (no sensitivity)

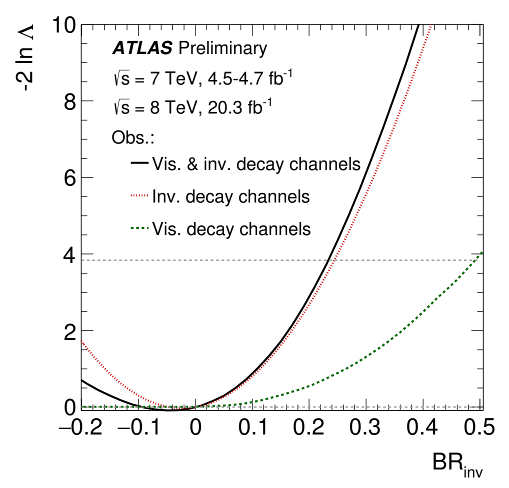


- $ZH \to (\ell\ell)$ INV: Phys. Rev. Lett. 112, 201802 (2014)
- $VH \to (jj)$ INV: Submitted to EPJC (2015)
- VBF $H \to$ INV: HIGGS-2015-YY

Results	Obs.	Exp.
VBF h	0.30	0.35
$Z(\to \ell\ell)h$	0.75	0.62
$V(\to jj)h$	0.78	0.86
Combined	**0.25**	**0.27**

Combining indirect (visible channels) & direct (invisible searches)

- The partial widths for Higgs decays to undetectable (e.g. $h \to gg$) assumed to be negligibly
- With the **visible channels** alone (and $\kappa_V \leq 1$): $\mathrm{BR_{inv}} < 0.49(0.48)$ obs (exp)
- Combination **visible channels** and **invisible searches** one can remove restrictions of ($\kappa_V \leq 1$)
- Physical boundary $\mathrm{BR_{inv}} > 0$
- The most general result with independent parameters: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g, \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR_{inv}}$ 95%CL limit of: **0.23 (0.24) obs (exp)**



Higgs Invisible, alternative parametrisations

95% CL

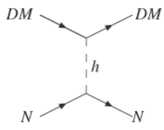
	Observed	Expected	Assumptions
Direct (invisible searches)	0.25	0.27	Productions as SM ($\kappa_i = 1$)
Indirect (visible channels)	0.49	0.48	$\kappa_{Z,W} \leq 1$
Combination[*]	**0.23**	**0.24**	**None**[**]
Comb. (alt. parametrisation)	0.23	0.23	$\kappa_{Z,W} \leq 1$
Comb. (alt. parametrisation)	0.18	0.24	one κ_F, and one κ_V
Comb. (alt. parametrisation)	0.16	0.23	one κ_F, and one $\kappa_V \leq 1$

90% CL

	Observed	Expected	Assumptions
Combination	0.22	0.23	**None**[**]

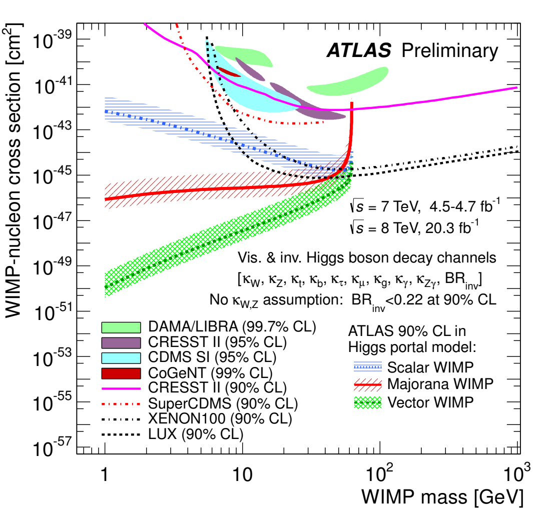
[*] Except $VH \rightarrow (jj)$inv, overlapping phase-space
[**] Except for undetectable

Higgs Portal Interpretation

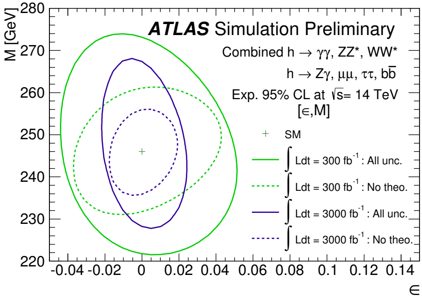


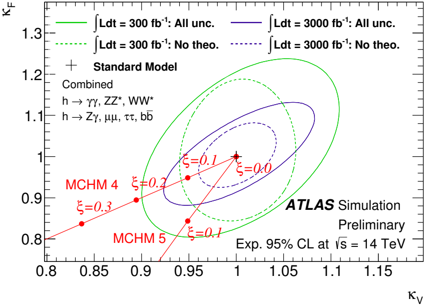
- Used 90%CL instead of 95%
- WIMP $< m_h/2$
- Higgs only mediator...

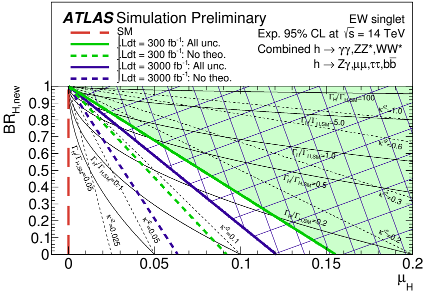
- Higgs Portal
  → spin dependent!
- **Vector/Fermion(Majorana) are even more EFT dependent...**

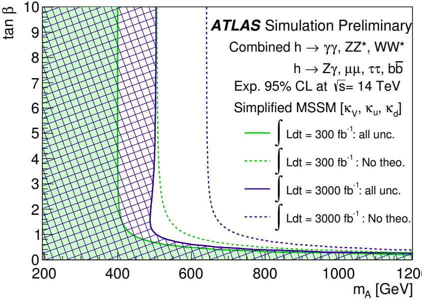


14 TeV prospects









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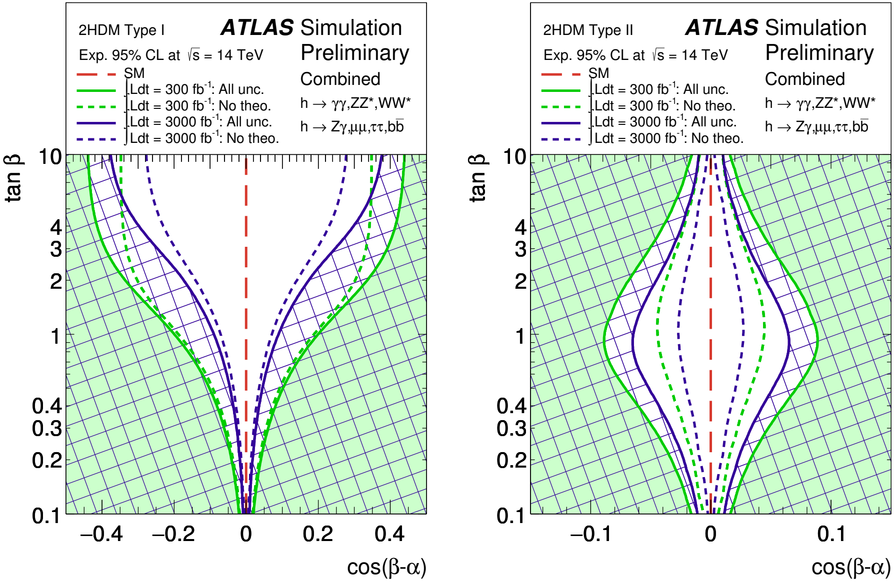
14 TeV prospects - 2HDM



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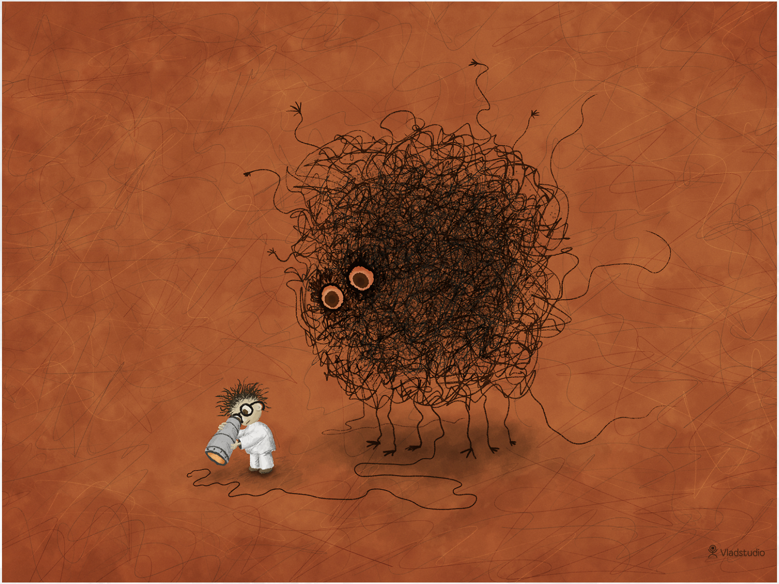
Outlook

- Higgs discovery, great achievement of the LHC program...
- Precise measurements of the **Higgs boson** couplings let us to constrain new phenomena
- Understanding of the real nature of the Electroweak Symmetry Breaking $\rightarrow$ tool to explore new physics!
  - Mass scaling (ε : 0.018 $\pm$ 0.039, M : 224^{+14}_{-12} GeV)
  - Minimal Composite Higgs models ($f >$ 710(780) GeV MCHM4(5))
  - Additional Electroweak Singlets ($\kappa'^2 < 0.12$)
  - Two Higgs Doublet Models (Alignment limit within 1σ)
  - Simplified versions of MSSM ($m_A >$ 370 GeV)
  - Anomalous Higgs to invisible decays ($\mathrm{BR_{inv}}$ <0.23)

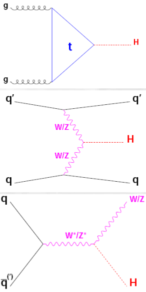
THANKS!!!

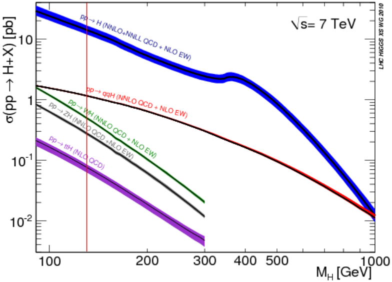


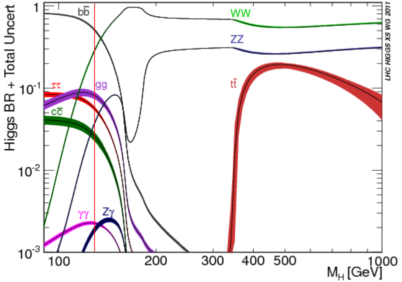
BACKUP SLIDES ...

The SM Higgs boson

NNLO, NNLL, EW corrections, uncertainties inclusive & exclusive P_T^H, line-shape, interference, BR, etc... [link]







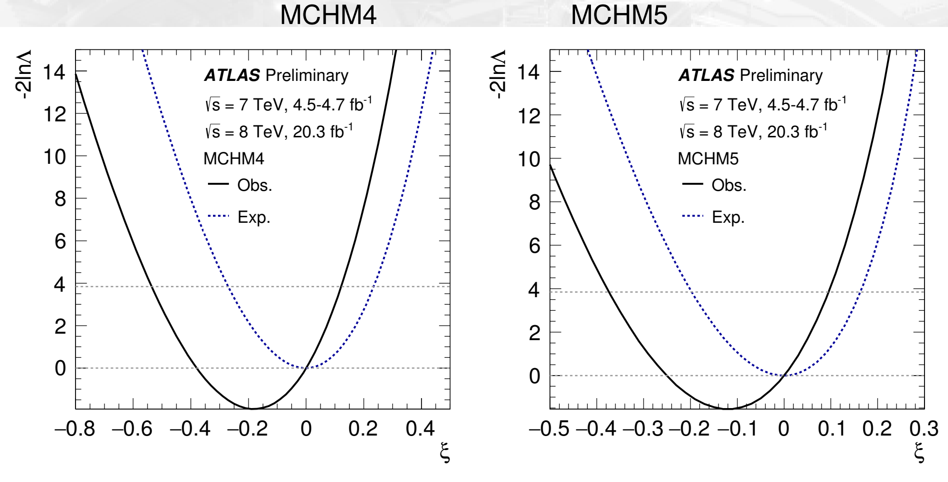
Nature is very kind... $m_H = 125.09$ GeV

→ although not easy, many modes to study at the LHC...

$\sqrt{s}$ [TeV]	7	8	13
$\sigma_{pp\to H}$ [pb]	17.352	22.097	50.471
σ_{ggF} [pb]	15.11 (QCD)$^{+7.1\%}_{-7.8}$ PDF$^{+7.6\%}_{-7.1\%}$	19.24 (QCD)$^{+7.2\%}_{-7.8\%}$ PDF$^{+7.5\%}_{-6.9\%}$	43.87 (QCD)$^{+7.5\%}_{-7.9\%}$ PDF$^{+7.1\%}_{-6.0\%}$
σ_{VBF} [pb]	1.222 (QCD)$^{+0.3\%}_{-0.3\%}$ PDF$^{+2.5\%}_{-2.1\%}$	1.579 (QCD)$^{+0.2\%}_{-0.2\%}$ PDF$^{+2.6\%}_{-2.8\%}$	3.744 (QCD)$^{+0.7\%}_{-0.7\%}$ PDF$^{+3.2\%}_{-3.2\%}$
σ_{VH} [pb]*	0.934 (QCD)$^{+0.9\%}_{-0.9\%}$ PDF$^{+2.6\%}_{-2.6\%}$	1.149 (QCD)$^{+1.0\%}_{-1.0\%}$ PDF$^{+2.3\%}_{-2.3\%}$	2.350 (QCD)$^{+0.7\%}_{-1.5\%}$ PDF$^{+2.2\%}_{-2.2\%}$
σ_{ttH} [pb]	0.0861 (QCD)$^{+3.2\%}_{-9.3\%}$ PDF$^{+8.4\%}_{-8.4\%}$	0.129 (QCD)$^{+3.8\%}_{-9.3\%}$ PDF$^{+8.1\%}_{-8.1\%}$	0.507 (QCD)$^{+5.7\%}_{-9.3\%}$ PDF$^{+8.8\%}_{-8.8\%}$

LHCXSEC WG

Minimal Composite Higgs Model



Two Higgs Doublet Model potential

- Natural path to explore $\rightarrow$ two identical complex scalar fields($SU(2)$)
- The 2HDM scalar potential is a Z_2 broken symmetric 2HDM

$$V(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 + (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c})$$
$$+\frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c}]$$

- In the CP-conserving case, parameters can be reduced to:
3 masses $m_h, m_H, m_{H\pm}, m_A,$, 2 angles $\alpha,\ \beta$ and 1 potential parameter m_{12}^2

- For the VV final states $\rightarrow$ type I and II where there are not FCNC

Mass mixing matrix for the neutral, CP-even Higgs bosons:

$$\mathcal{M}_S^2 = (m_Z^2 + \delta_1)\begin{bmatrix} \cos^2(\beta) & -\cos(\beta)\sin(\beta) \\ -\cos(\beta)\sin(\beta) & \sin^2(\beta) \end{bmatrix} + m_A^2 \begin{bmatrix} \sin^2(\beta) & -\cos(\beta)\sin(\beta) \\ -\cos(\beta)\sin(\beta) & \cos^2(\beta) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \frac{\delta}{\sin^2(\beta)} \end{bmatrix}$$

δ_1 and δ are radiative corrections involving top quarks and stops.
The couplings in a simplified MSSM model can be obtained from this mass mixing matrix as follows: The trace of the mass mixing matrix is taken and evaluated at the light Higgs boson mass of $m_h = 125.09$ GeV, allowing the δ_1 and δ corrections to be determined as a function of m_A and $\tan\beta$. Neglecting the sub-leading correction δ_1, then by substituting for δ the mass mixing matrix is fully determined by m_A and $\tan\beta$. This matrix is diagonalised to find the eigenvectors, and in particular those components of the eigenvector corresponding to the light Higgs boson, s_u and s_d. This allows the Higgs boson couplings to be determined as functions of m_A and $\tan\beta$ only:

$$\kappa_V = \frac{s_d(m_A, \tan\beta) + \tan\beta \; s_u(m_A, \tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A, \tan\beta)\,\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

$$\kappa_d = s_d(m_A, \tan\beta)\sqrt{1+\tan^2\beta},$$

where the functions s_u and s_d are given by:

$$s_u = \frac{1}{\sqrt{1+\frac{\left(m_A^2+m_Z^2\right)^2 \tan^2\beta}{\left(m_Z^2+m_A^2\tan^2\beta - m_h^2(1+\tan^2\beta)\right)^2}}}$$

$$s_d = \frac{\left(m_A^2+m_Z^2\right)\tan\beta}{m_Z^2+m_A^2\tan^2\beta - m_h^2(1+\tan^2\beta)}\, s_u.$$

Higgs Portal Dark-Matter interpretation

$$\Gamma^{\text{Majorana}}(h \to \chi\chi) = \frac{\lambda_{h\chi\chi}^{2\ \text{Majorana}} v^2 m_h}{32\pi\Lambda^2} \left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{3/2}$$

$$\Gamma^{\text{Scalar}}(h \to \chi\chi) = \frac{\lambda_{h\chi\chi}^{2\ \text{Scalar}} v^2}{64\pi m_h} \left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2}$$

$$\Gamma^{\text{Vector}}(h \to \chi\chi) = \frac{\lambda_{h\chi\chi}^{2\ \text{Vector}} v^2}{256\pi m_\chi^4 m_h} \left[m_h^4 - 4m_\chi^2 m_h^2 + 12 m_\chi^4\right] \left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2}$$

$$\sigma_{\chi N}^{\text{Majorana}} = \frac{\lambda_{h\chi\chi}^{2\ \text{Majorana}}}{4\pi\Lambda^2 m_h^4} \frac{m_\chi^2 m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

$$\sigma_{\chi N}^{\text{Scalar}} = \frac{\lambda_{h\chi\chi}^{2\ \text{Scalar}}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

$$\sigma_{\chi N}^{\text{Vector}} = \frac{\lambda_{h\chi\chi}^{2\ \text{Vector}}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(m_\chi + m_N)^2}$$