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

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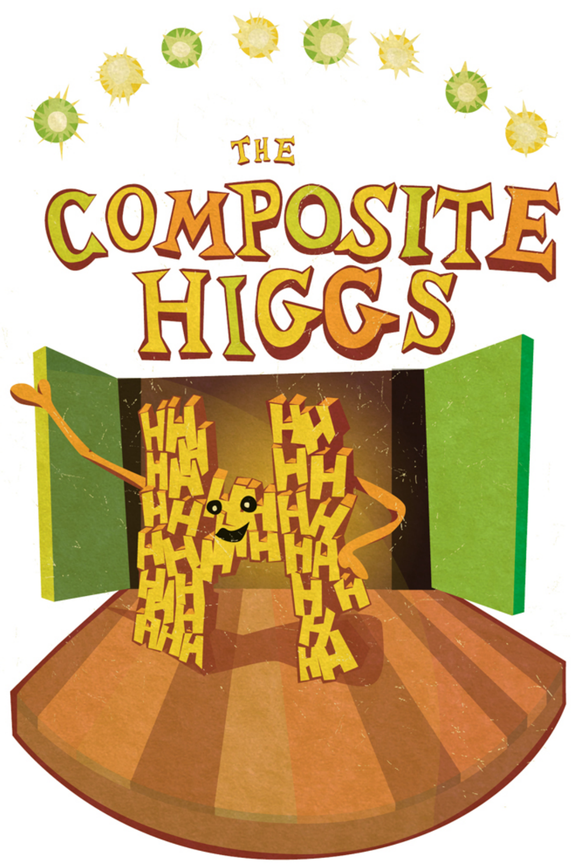
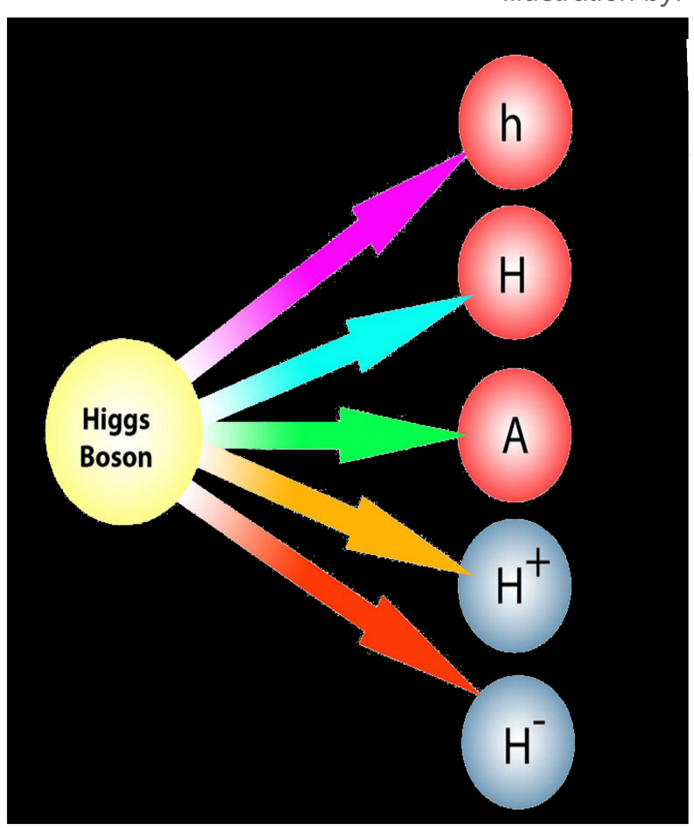
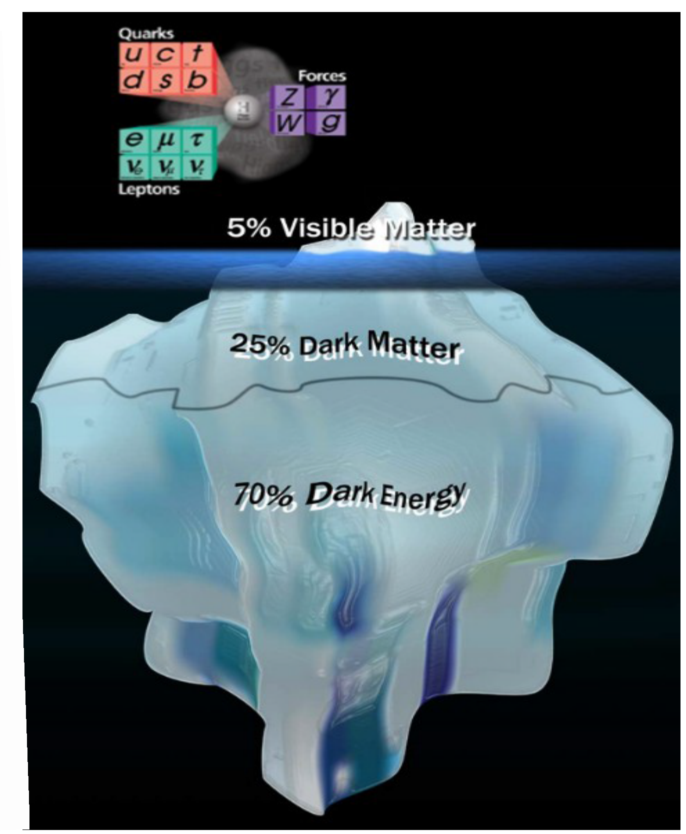
After discovery of Higgs Boson at 125 GeV

Illustration by: Sandbox Studio, Chicago



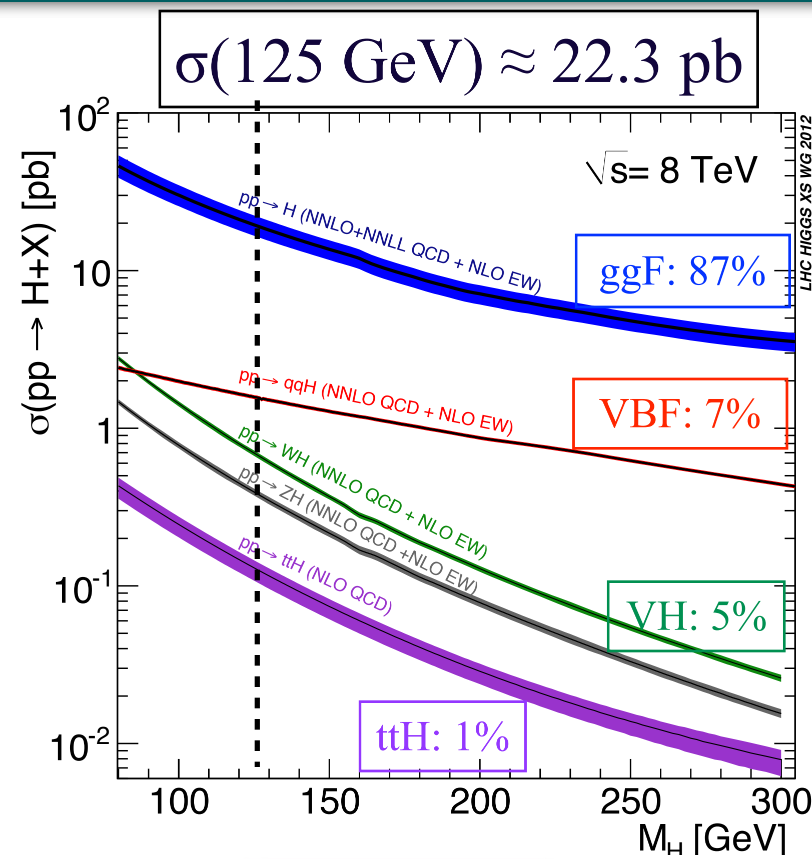


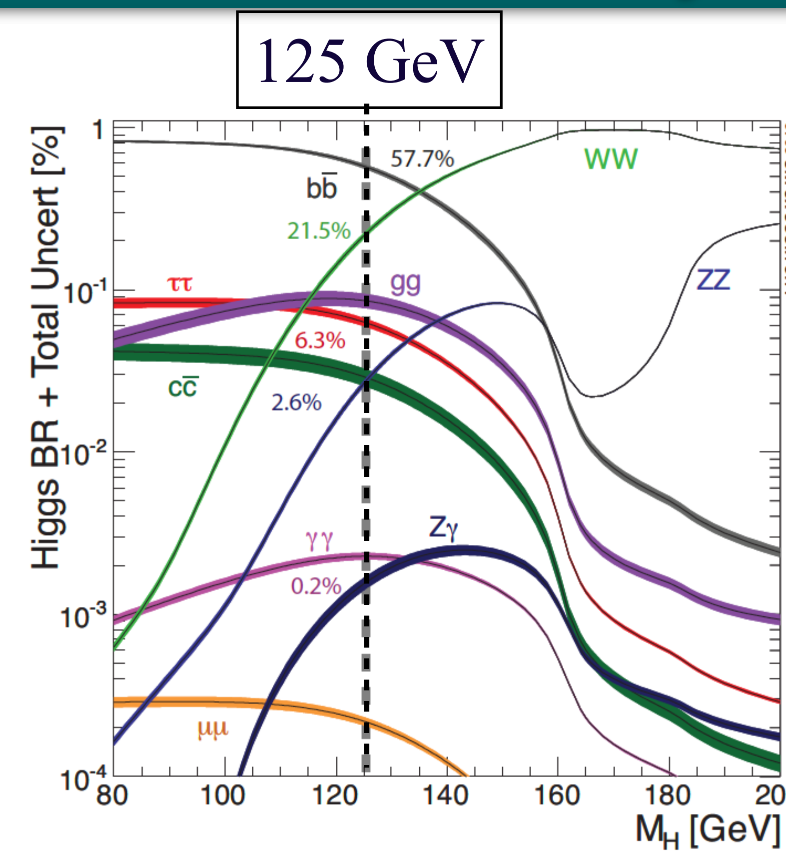


Outline

- Coupling constants in Higgs production and decay
- Multi-channel inputs in Higgs combination
- Probe new physics in loops, invisible width:
  - Higgs Compositeness
  - Additional electro-weak singlet
  - 2 Higgs Doublet Models (Supersymmetric Higgs)
  - Higgs Portal to Dark Matter
- Summary of new Physics constraints

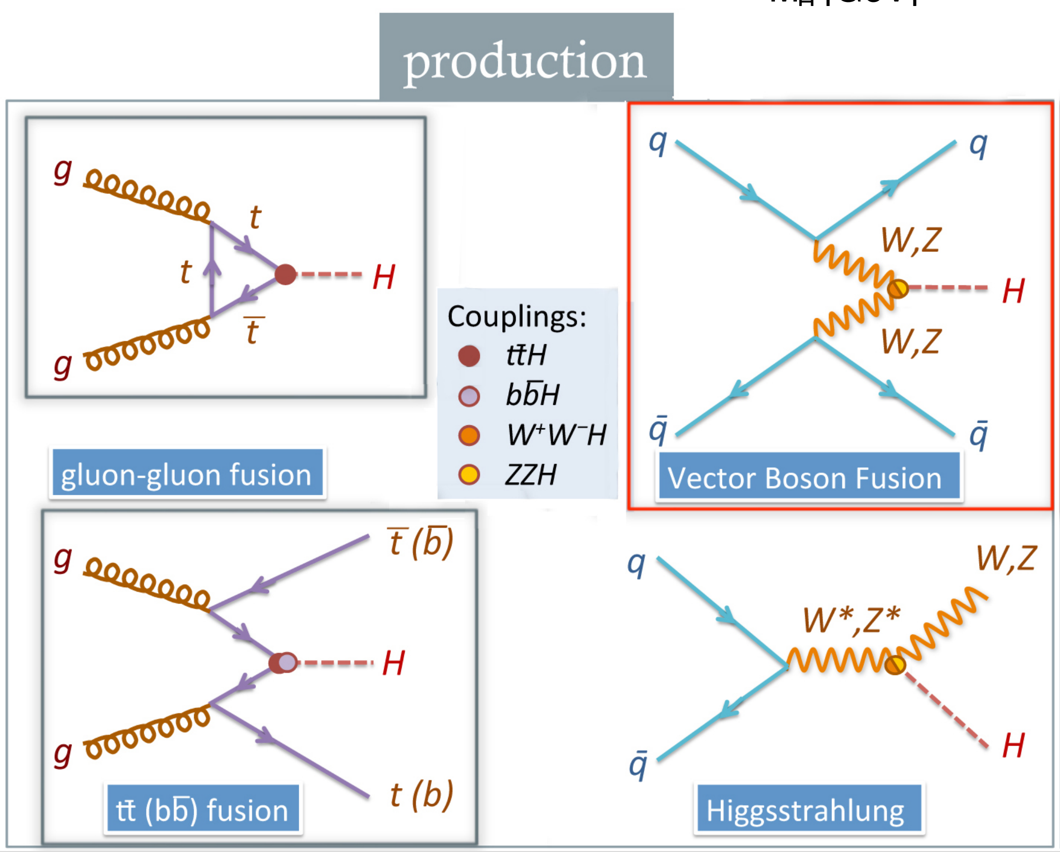
Higgs production and decay

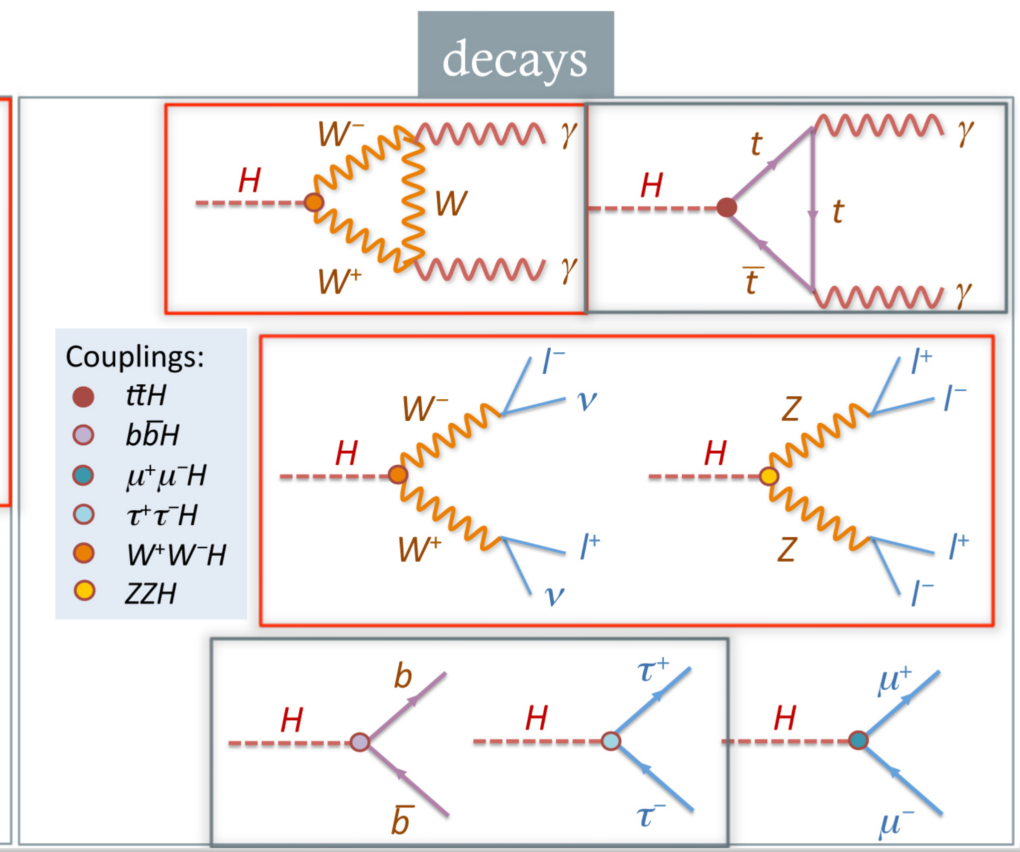




LHC Higgs Cross Section Working Group (2012-2013)

Same Coupling constants affect both in similar manner.





Coupling Fit Framework

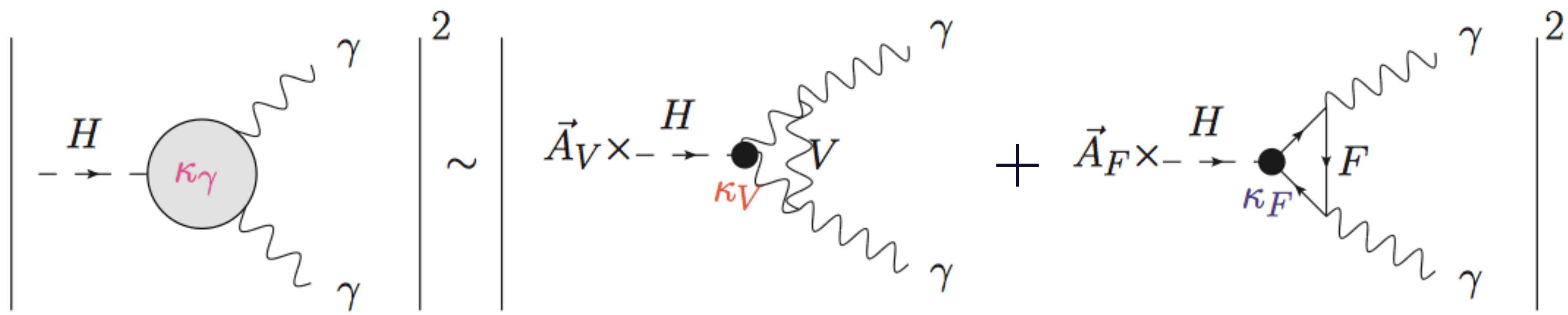
- Assuming the Higgs Boson is a single, narrow, CP-even scalar resonance at 125.5 GeV, production cross-section times branching ratio is: $(\sigma \cdot BR)(i \to H \to f) = \dfrac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$
- Measure deviations from SM in terms of multiplicative coupling scale factors (κ)

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}} \qquad \kappa_H^2 = \frac{\sum \kappa_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

production decay width

- For example, the gluon-gluon fusion production of $H \to \gamma\gamma$ mode is written as:

$$\frac{\sigma \cdot \mathrm{B}\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$



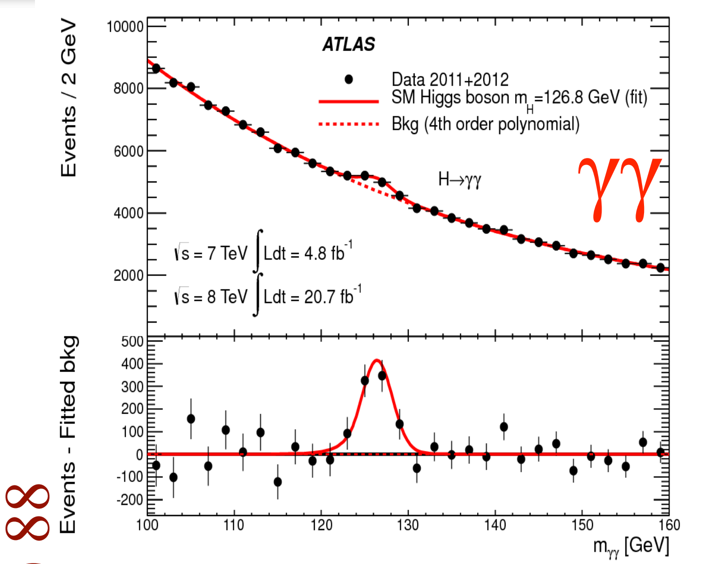
$\Rightarrow \kappa_\gamma^2 = 1.59\,\kappa_W^2 - 0.66\,\kappa_W\,\kappa_t + 0.07\,\kappa_t^2$. Also, $\kappa_g^2 = 1.06\,\kappa_t^2 - 0.07\,\kappa_t\,\kappa_b + 0.01\,\kappa_b^2$.

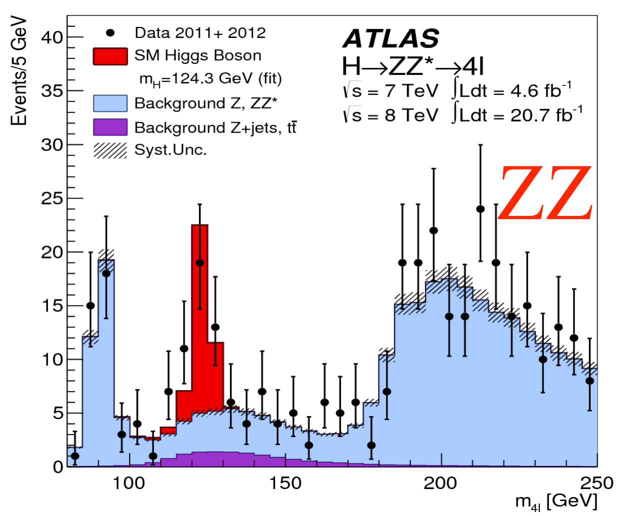
- Probe contributions that change vector(κ_V) or fermion(κ_F) coupling or width(κ_H).

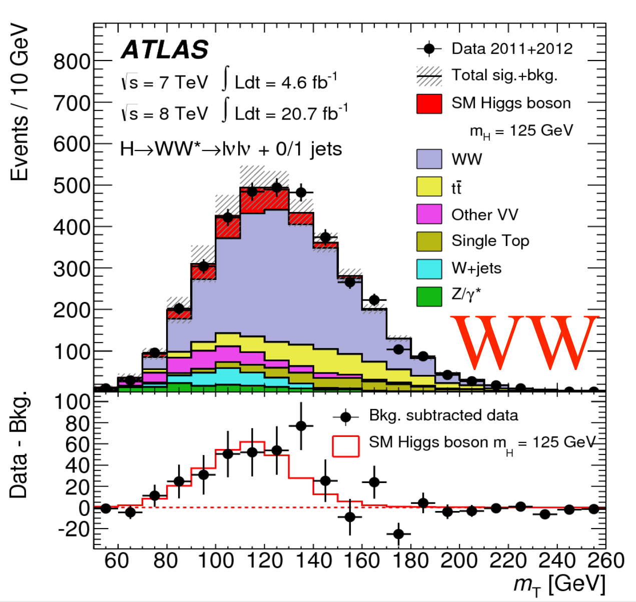
Inputs to Coupling Fit

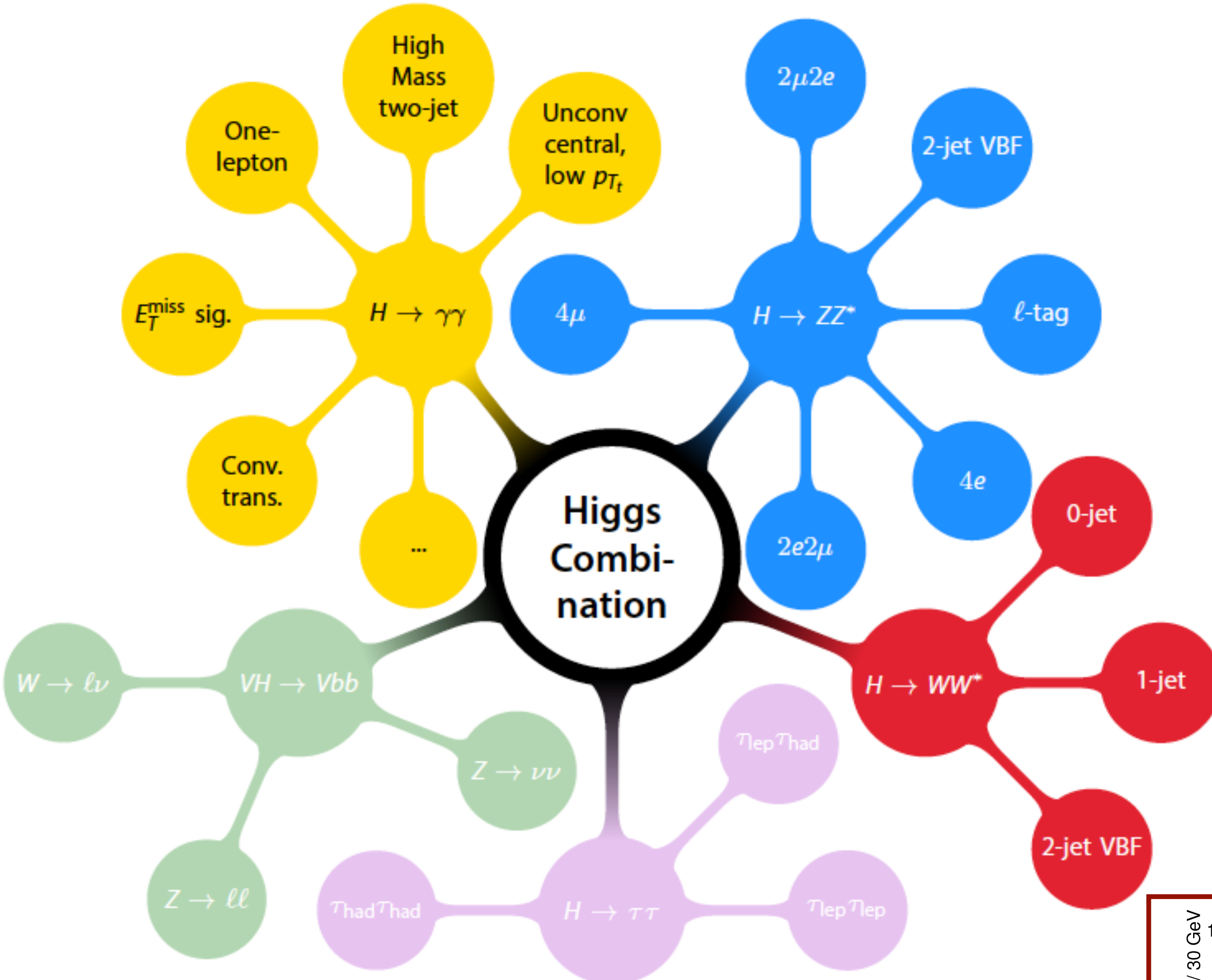
4.8 fb^{-1} at 7 TeV & 20.3 fb^{-1} at 8 TeV

Phys. Lett. B726 (2013) 88









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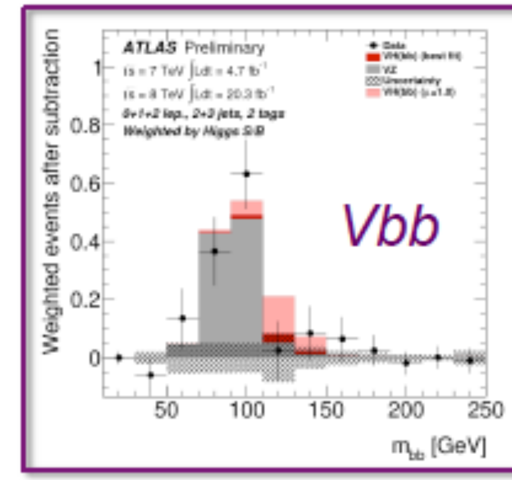

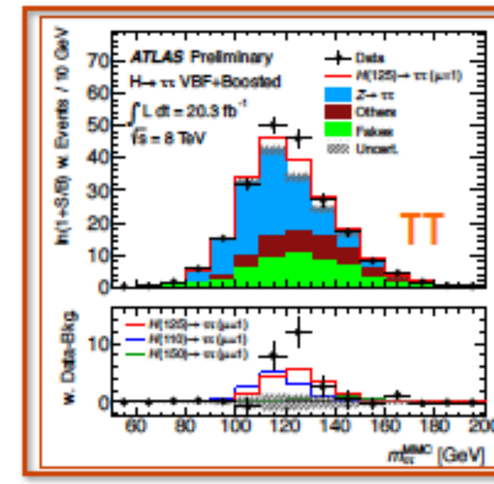

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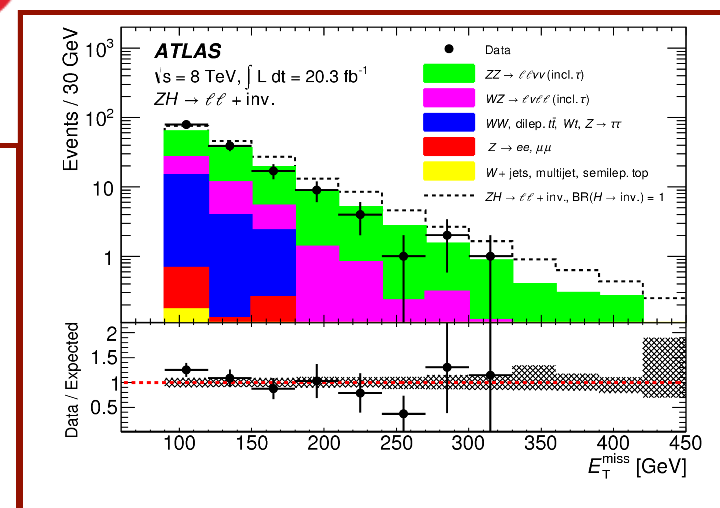
Additional Input:

Constrain invisible width of Higgs using Missing Transverse Energy spectrum from Zh → ℓℓ + E_T^{miss} channel:

Phys. Rev. Lett. 112 (2014) 201802



Coupling Fits and Mass scale dependence

Results of Coupling fit:

κ_Z	Z boson coupling	$0.95^{+0.24}_{-0.19}$
κ_W	W boson coupling	$0.68^{+0.30}_{-0.14}$
κ_t	t quark coupling	$[-0.80, -0.50] \cup [0.61, 0.80]$
κ_b	b quark coupling	$[-0.7, 0.7]$
κ_τ	τ lepton coupling	$[-1.15, -0.67] \cup [0.67, 1.14]$

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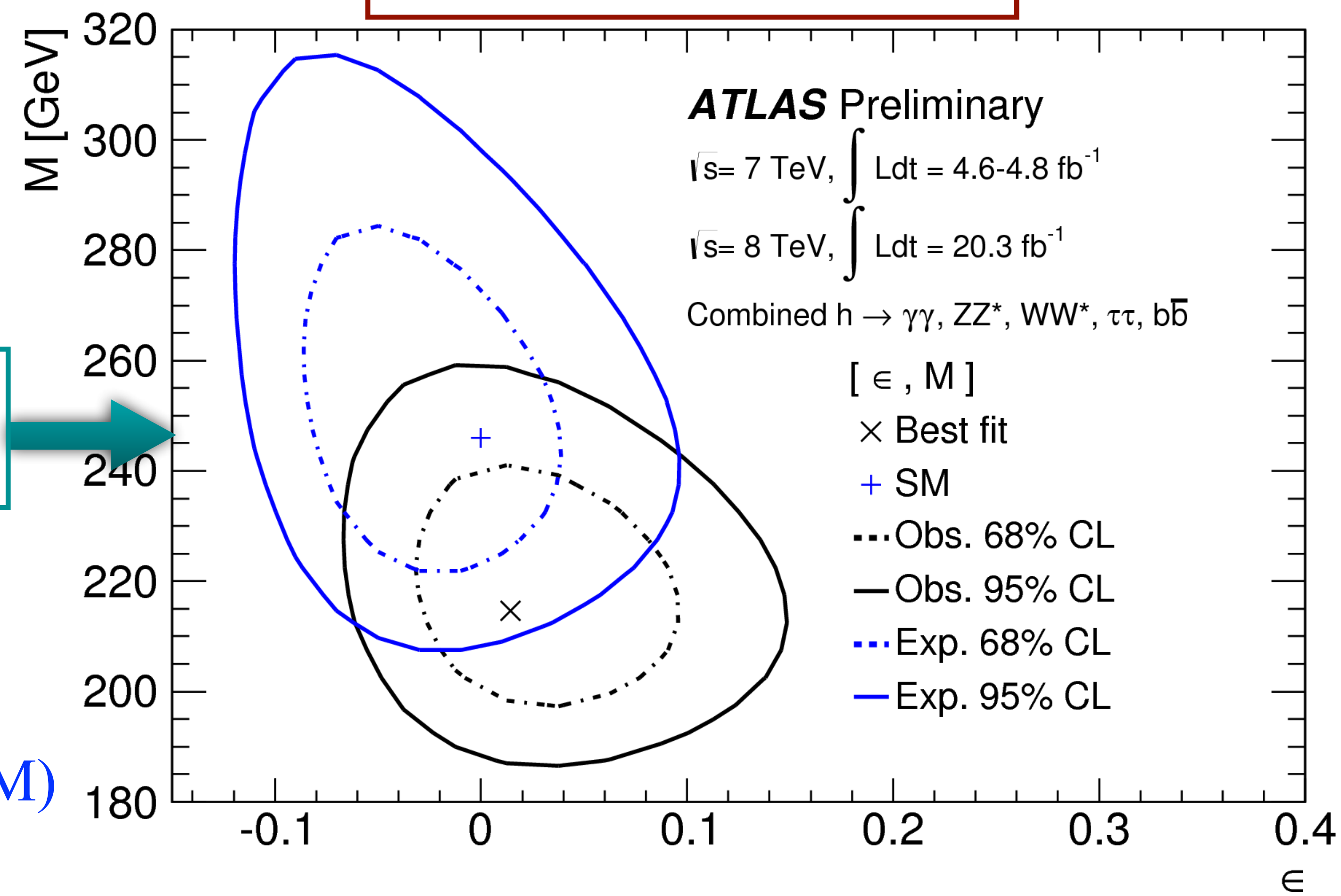
Mass scale parameterization

J. Ellis & T. Hou, JHEP 1306 (2013) 103

Linear: $$\kappa_{f,i} = \upsilon \frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}}$$

Quadratic: $$\kappa_{V,j} = \upsilon \frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$

246 GeV



ϵ: mass scaling parameter (= 0 in SM)
M: vacuum expectation value parameter
v: vacuum expectation value (= 246 GeV in SM)

Measured coupling mass dependence and vacuum expectation value are consistent with SM within 1.5 σ

Higgs compositeness

Minimal Composite Higgs Models (MCHM) represent another possible explanation for the scalar naturalness problem, wherein the Higgs is a composite, pseudo-Nambu-Goldstone boson.

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

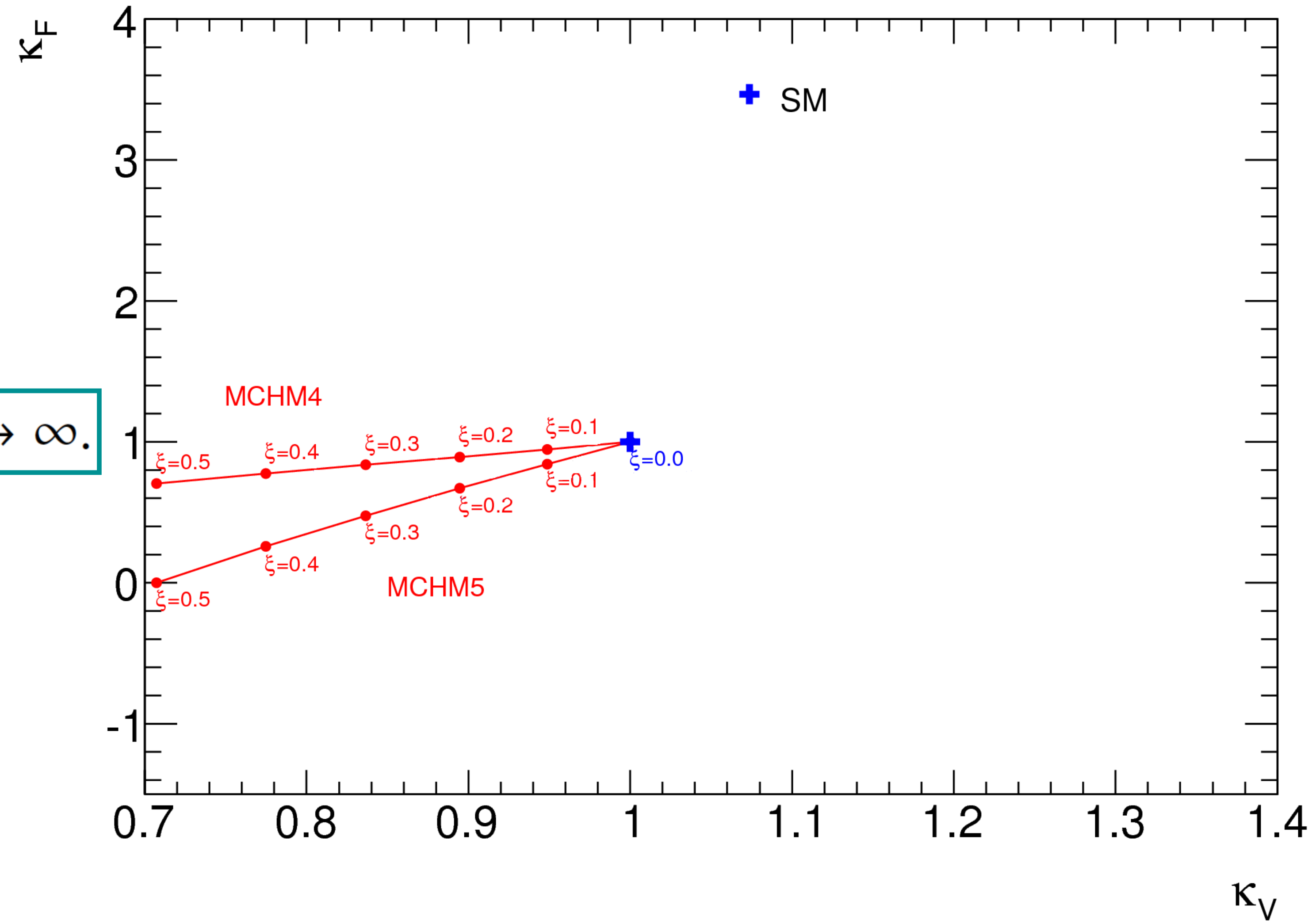
MCHM5 : $\kappa_V = \sqrt{1-\xi} \quad \kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$

where $\xi = v^2/f^2$ is a scaling parameter and f is the compositeness scale

$\kappa_V = \kappa_W = \kappa_Z$

$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

SM is recovered in the limit $\xi \to 0$, namely $f \to \infty$.



K.Agashe, et.al. Nucl.Phys.B719 (2005) 165; R.Contino, Phys.Rev.D75 (2007) 055014; M.Carena, et. al. Phys.Rev.D76 (2007) 035006.

Higgs compositeness

Results of Coupling fit:

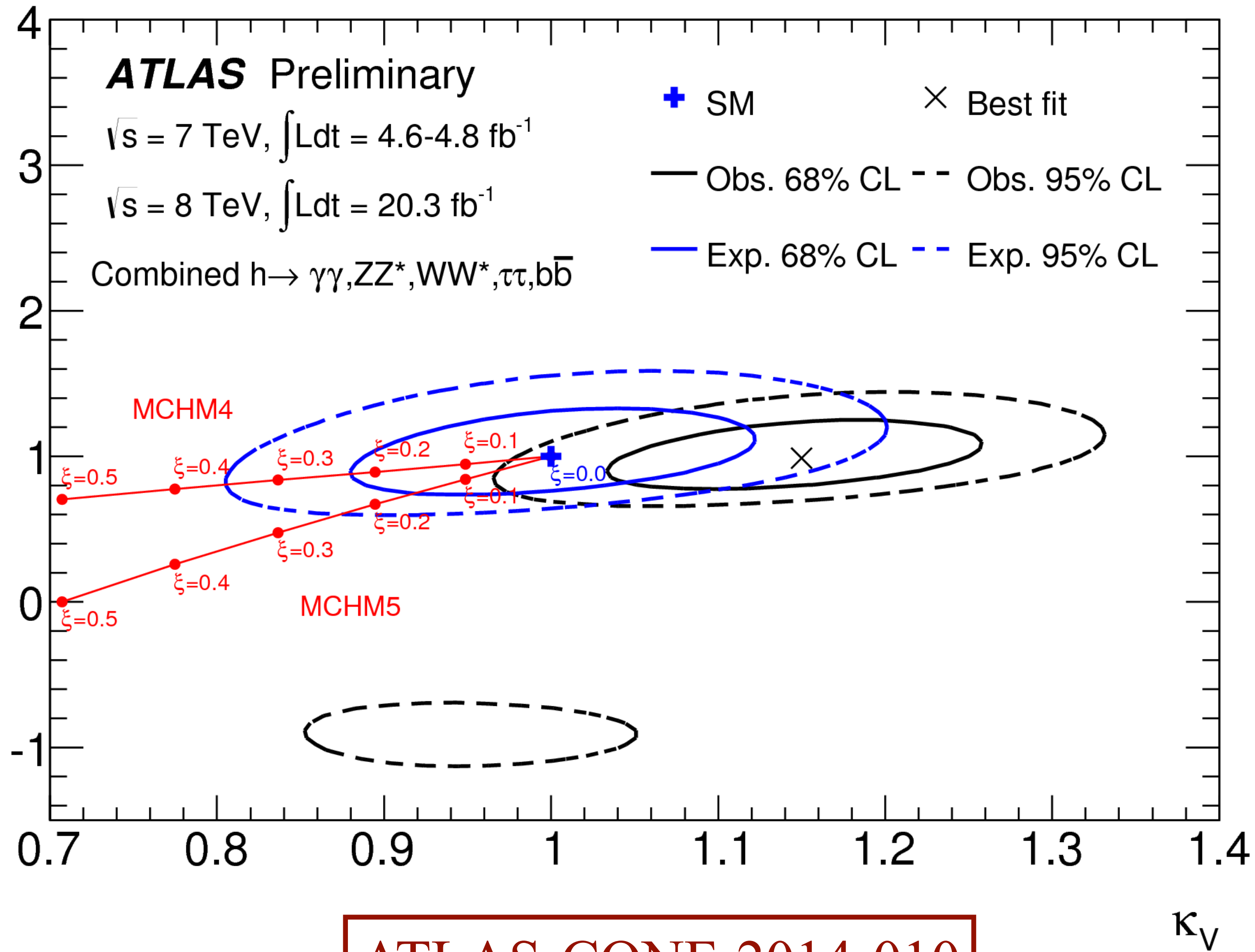
MCHM4 :	$\kappa = \sqrt{\mu_h}$	Universal coupling	$1.14^{+0.09}_{-0.08}$
MCHM5 :	κ_V	Vector boson (W, Z) coupling	1.15 ± 0.08
	κ_F	Fermion $(t, b, \tau, \ldots)$ coupling	$0.99^{+0.17}_{-0.15}$

Accounting for physical boundary $\xi \geq 0$, lower limits are set at 95% CL

	Observed	Expected
MCHM4	f > 710 GeV	f > 460 GeV
MCHM5	f > 640 GeV	f > 550 GeV

Observed limits are stronger than expected ones, because measured Higgs signal strength $\mu_h > 1$ which corresponds to $\xi < 0$.

A secondary minima in the likelihood exists at $\kappa_F < 0$ due to primarily large measured $h \to \gamma\gamma$ rate in Phys. Lett. B726 (2013) 88.



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Additional EW singlet

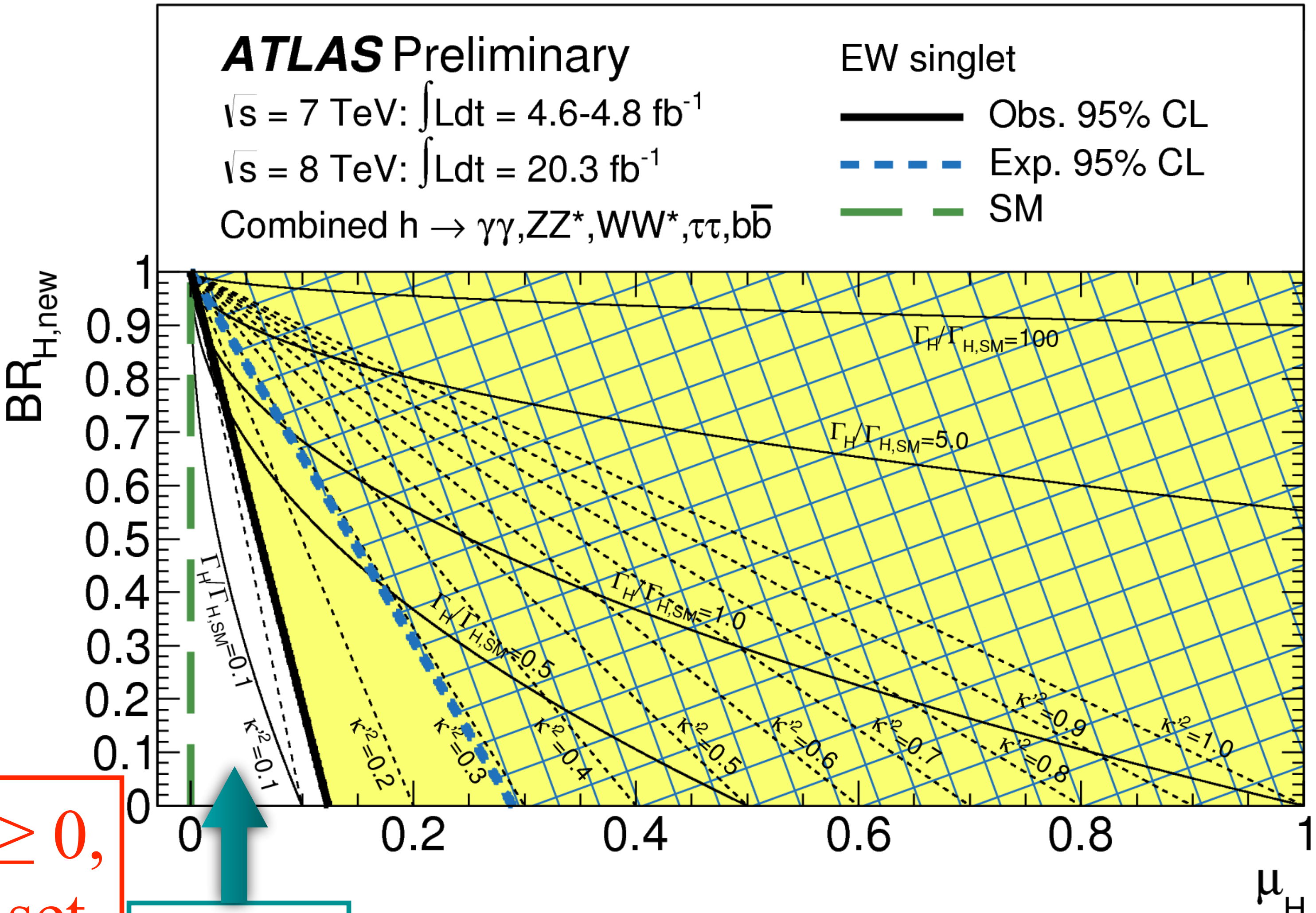
Addition of an extra electroweak singlet field to the doublet Higgs field of SM provides a possible answer to the dark matter problem.
Spontaneous symmetry breaking ⇒ 2 CP-even bosons: h (light) & H (heavy), both of which couple to SM fermions & vectors bosons but with modified coupling: κ and κ′ for h and H respectively, satisfying the unitarity constraint $\kappa^2 + \kappa'^2 = 1$.

$$\mu_h = \frac{\sigma_h \times \mathrm{BR}_h}{(\sigma_h \times \mathrm{BR}_h)_{\mathrm{SM}}} = \kappa^2$$

$$\mu_H = \frac{\sigma_H \times \mathrm{BR}_H}{(\sigma_H \times \mathrm{BR}_H)_{\mathrm{SM}}} = \kappa'^2\,(1 - \mathrm{BR}_{H,\mathrm{new}})$$

where $\mathrm{BR}_{H,\mathrm{new}}$ is the branching ratio of all new non-SM kinematically allowed decay modes of H that open up as μ_H increases.

LHC Higgs XS WG YR3, arXiv: 1307.1347 [hep-ph]



allowed region

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Accounting for physical boundary $\kappa'^2 \geq 0$, observed (expected) upper limits are set to be $\kappa'^2 < 0.12\ (0.29)$ at 95% CL.

2 Higgs Doublet Models

- 5 Higgs Bosons: 2 CP-even neutral bosons: h (light) & H (heavy),
  1 CP-odd neutral boson (A) and 2 charged bosons ($H^{\pm}$).
- 6 parameters: m_h, m_H, m_A, $m_{H\pm}$, α: mixing between h & H, and
  tanβ = <vev>$_u$/<vev>$_d$ satisfying <vev>$_u^2$ + <vev>$_d^2$ = $(246\ \text{GeV})^2$.
- Evade existing experimental bounds by satisfying Glashow-Weinberg condition:
  - **Type I:** one doublet couples only with vector bosons **[Fermiophobic]**, other only with fermions
  - **Type II:** one doublet couples with up-type quarks, other with down-type quarks and leptons **[MSSM-like]**
  - **Type III:** one doublet couples with quarks as in Type I, other with leptons as in Type II **[lepton-specific]**
  - **Type IV:** one doublet couples with quarks as in Type II, other with leptons as in Type I **[Flipped]**

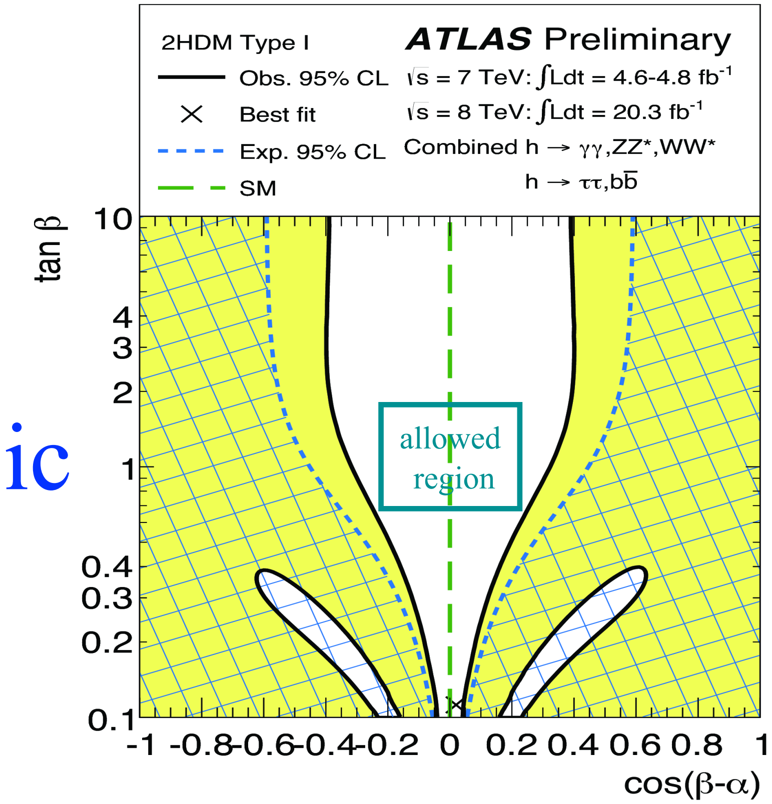
G. Branco et, al. Phys. Rept. 516 (2012) 1.

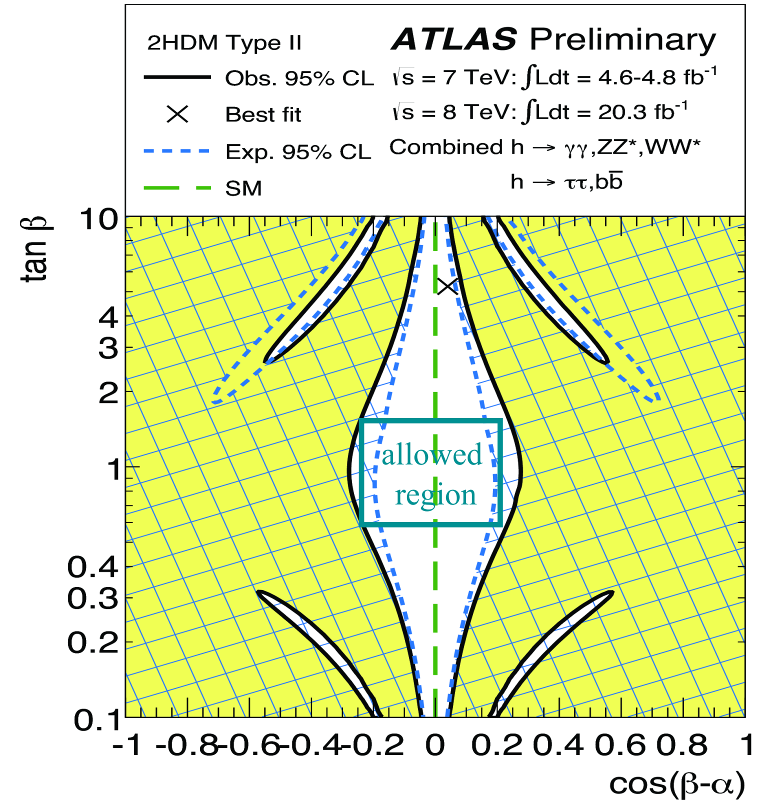
Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

- Assume 125.5 GeV particle is the light CP-even Higgs boson in these 2HDMs.

2 Higgs Doublet Models

Type I: Fermiophobic





Type II: MSSM-like

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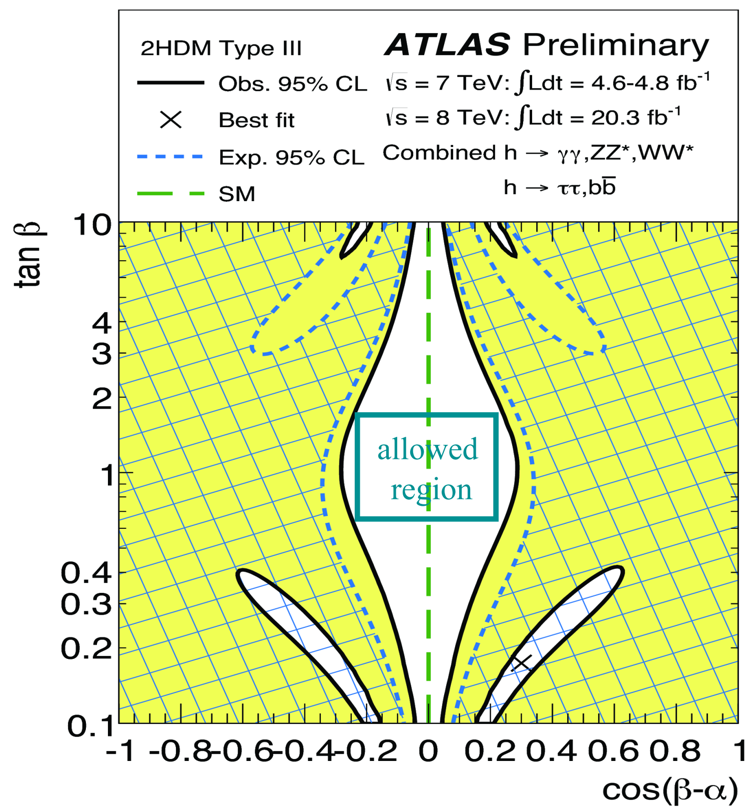
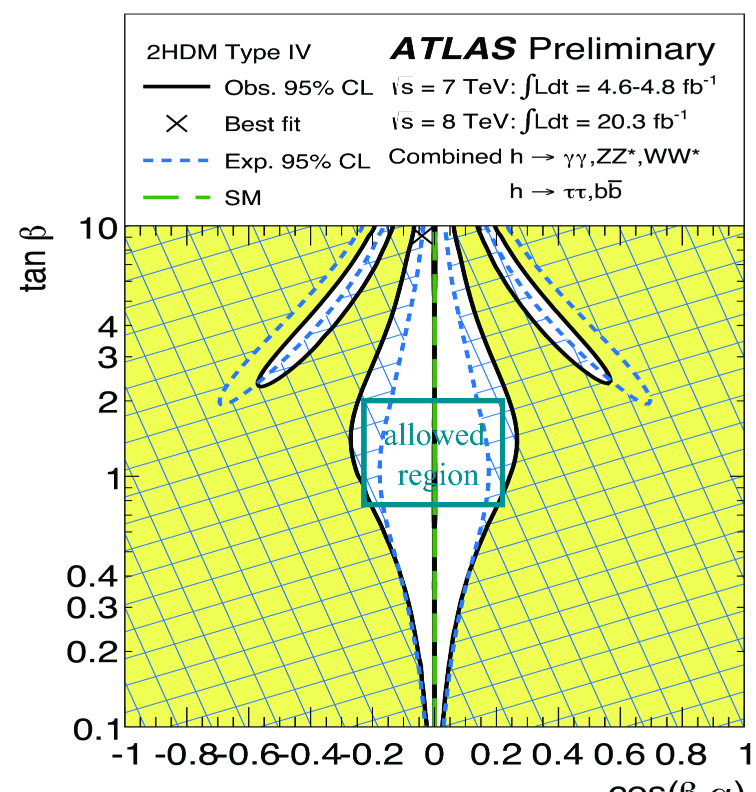
Type III: Lepton-specific





Type IV: Flipped

Simplified MSSM

- In a simplified MSSM scenario, coupling scale factors for light CP-even Higgs [m_h = 125.5 GeV] can be written as function of CP-odd Higgs mass m_A & tanβ

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

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

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

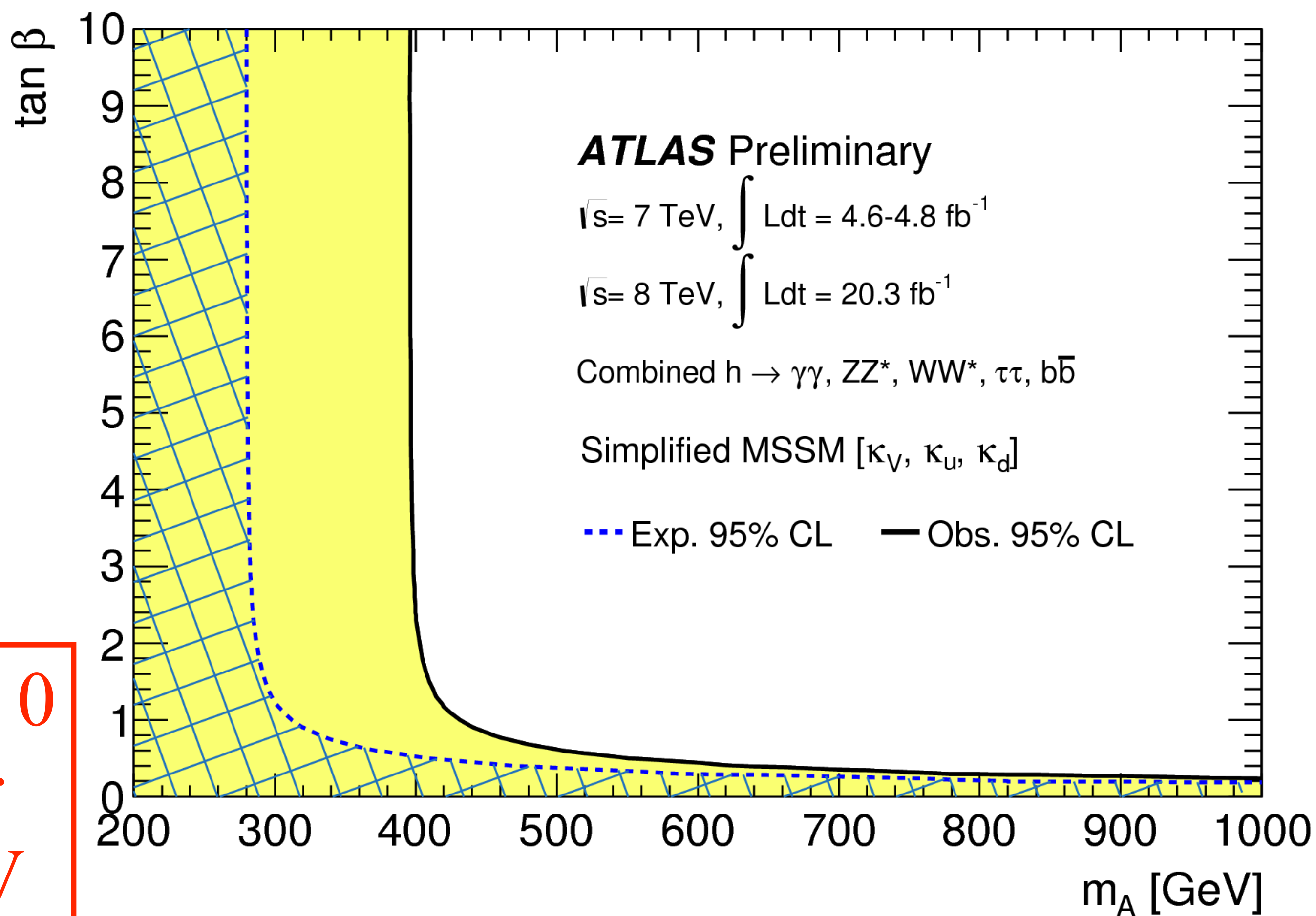
$$s_u = \frac{1}{\sqrt{1+\frac{\left(m_A^2+m_Z^2\right)^2\ \tan^2\beta}{\left(m_Z^2+m_A^2\ \tan^2\beta-m_h^2\left(1+\tan^2\beta\right)\right)^2}}}$$

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

Results of Coupling fit:

$\lambda_{Vu} = \kappa_V/\kappa_u$	Ratio of vector boson & up-type fermion ($t, c, \ldots$) couplings	$1.21^{+0.24}_{-0.26}$
$\kappa_{uu} = \kappa_u^2/\kappa_h$	Ratio of squared up-type fermion coupling & total width scale factor	$0.86^{+0.41}_{-0.21}$
$\lambda_{du} = \kappa_d/\kappa_u$	Ratio of down-type fermion ($b, \tau, \ldots$) & up-type fermion couplings	$[-1.24, -0.81] \cup [0.78, 1.15]$

Accounting for physical boundary $m_A > 0$ & tanβ > 0, observed (expected) lower limits are set to be $m_A > 400$ (280) GeV at 95% CL for 2 < tanβ < 10



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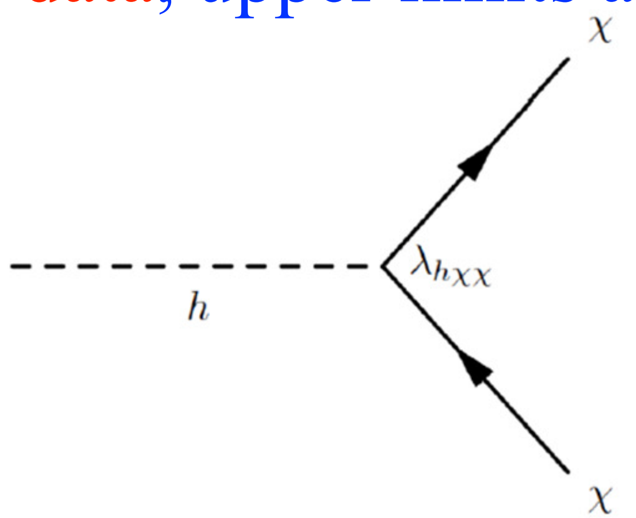
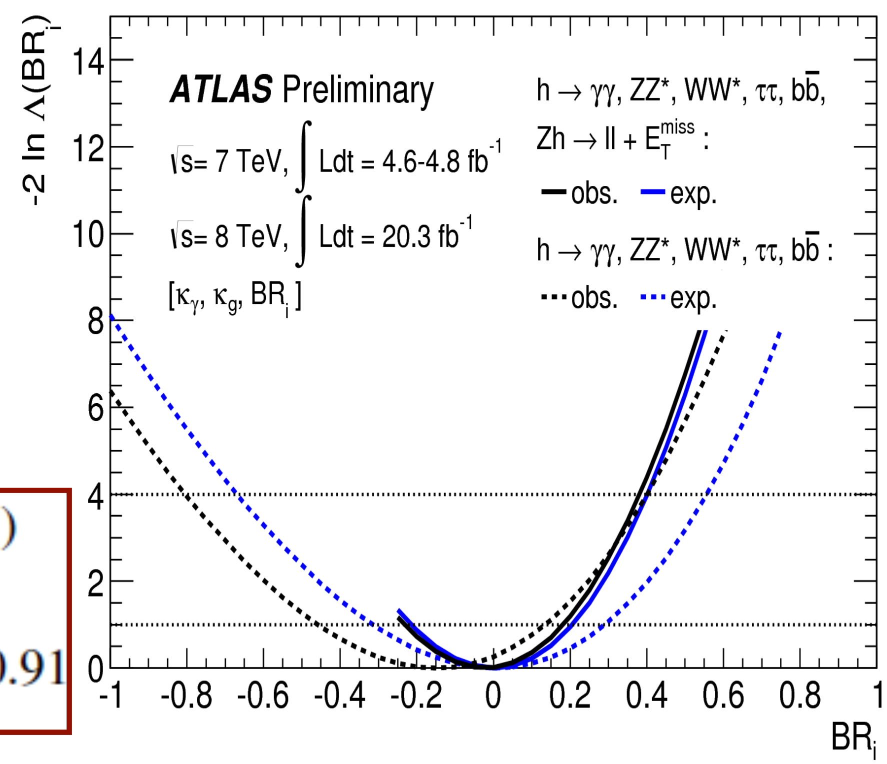
Invisible decay of Higgs Boson

- Invisible SM Higgs decay width is small (BR = 1.2×10^{-3}) from $H\rightarrow ZZ^*\rightarrow 4\nu$(s).
- Search for invisible-decaying Higgs Boson produced in association with Z Boson with 4.5+20.3 fb^{-1} at 7+8 TeV data sets observed (expected) 95% CL upper limit on invisible branching ratio $BR_i < 0.75$ (0.62). **Phys. Rev. Lett. 112 (2014) 201802.**
- Portal model: Higgs Boson may decay invisibly to Dark Matter candidates like weakly interacting massive particles (WIMP) **B.Patt & F. Wilczek, arXiv: hep-ph/0605188.**
- Using up to 4.8+20.3 fb^{-1} at 7+8 TeV from $\gamma\gamma$, WW, ZZ, $\tau\tau$, bb without/with Zh data, upper limits at 95% CL are set accounting for physical boundary at $BR_i \geq 0$.



$$\kappa_h^2 = \Gamma_h/\Gamma_{h,SM} = \sum_i \kappa_i^2/(1-BR_i)$$

$$\sum_i \kappa_i^2 = 0.0023\,\kappa_\gamma^2 + 0.085\,\kappa_g^2 + 0.91$$

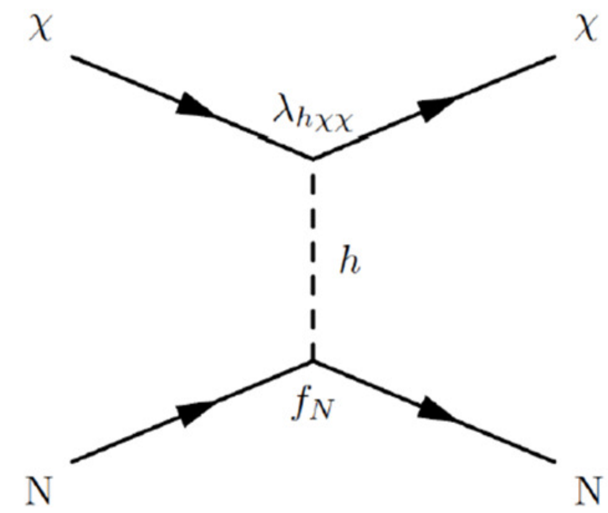


Zh → ℓℓ + Missing Transverse Energy	With	Without
Obs. 95% CL Upper Limit on BR	0.37	0.41
Exp. 95% CL Upper Limit on BR	0.39	0.55

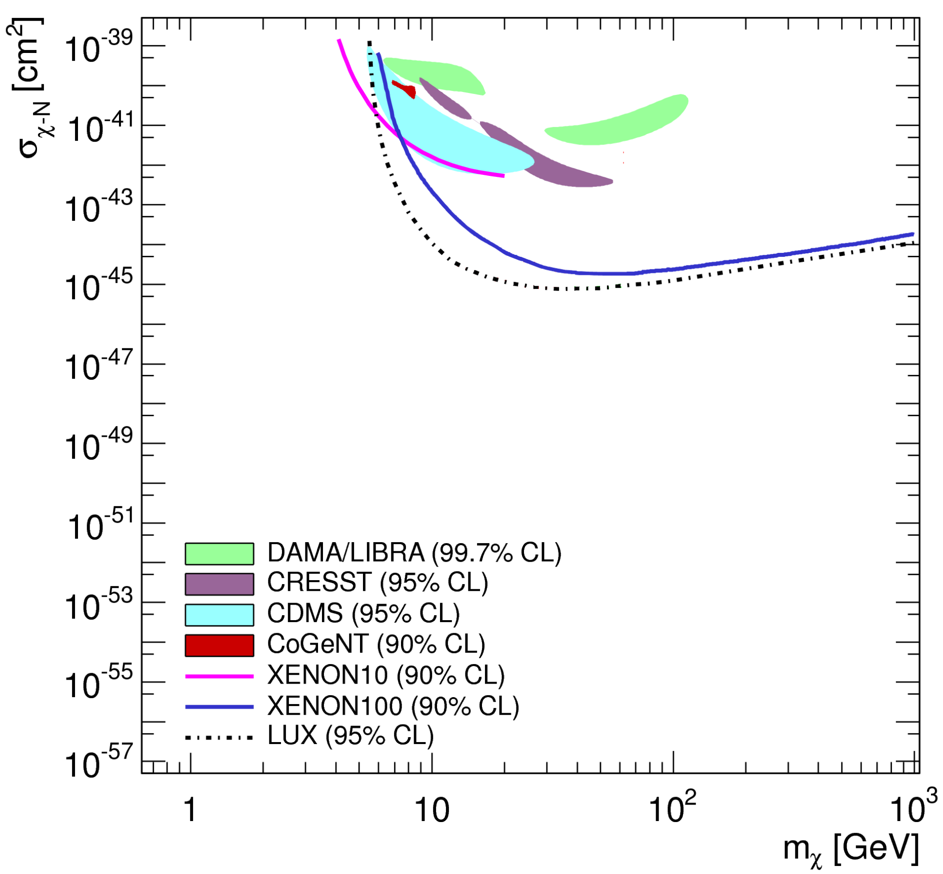
ATLAS-CONF-2014-010

Higgs Portal to Dark Matter

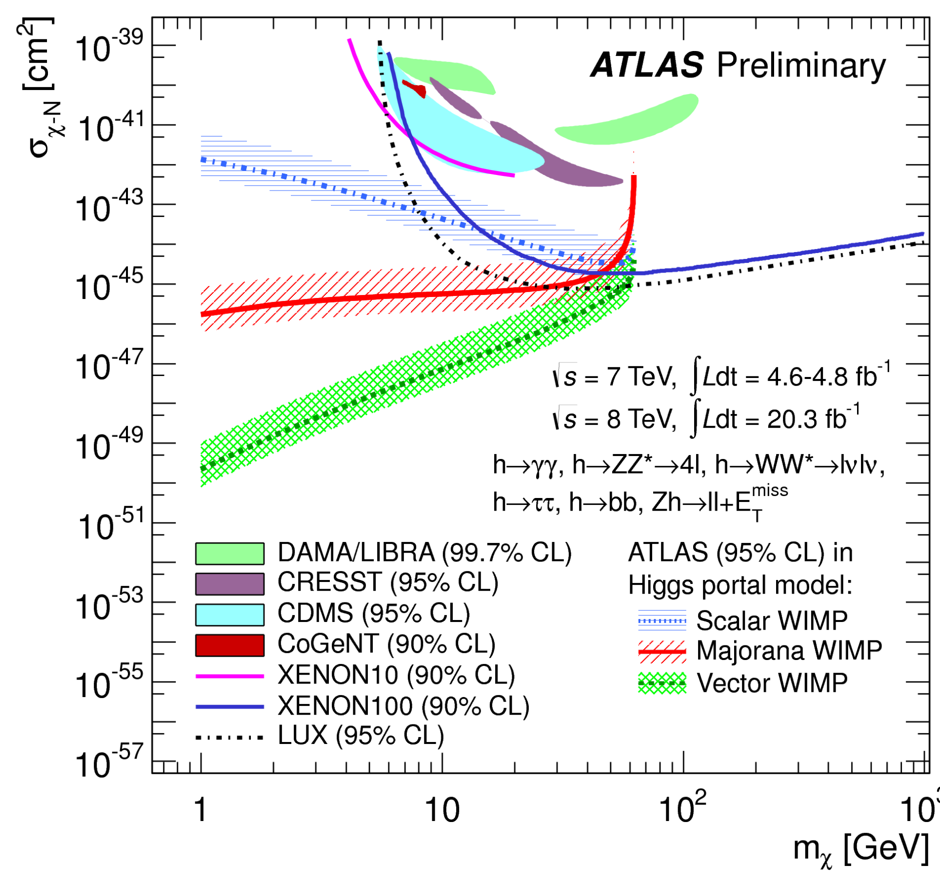
- Assuming Higgs-nucleon coupling $f_N = 0.33\ {+0.30}\ {-0.07}$ from Lattice QCD [A. Djouadi, et. al. Phys. Lett. B709 (2012) 65], limits on invisible Higgs branching ratio can be translated into limits on the WIMP-nucleon scattering cross-section.
- These spin-dependent limits are more stringent than direct detection experiments for low WIMP-mass.



<u>Direct detection constraints</u>



<u>ATLAS constraints superimposed</u>

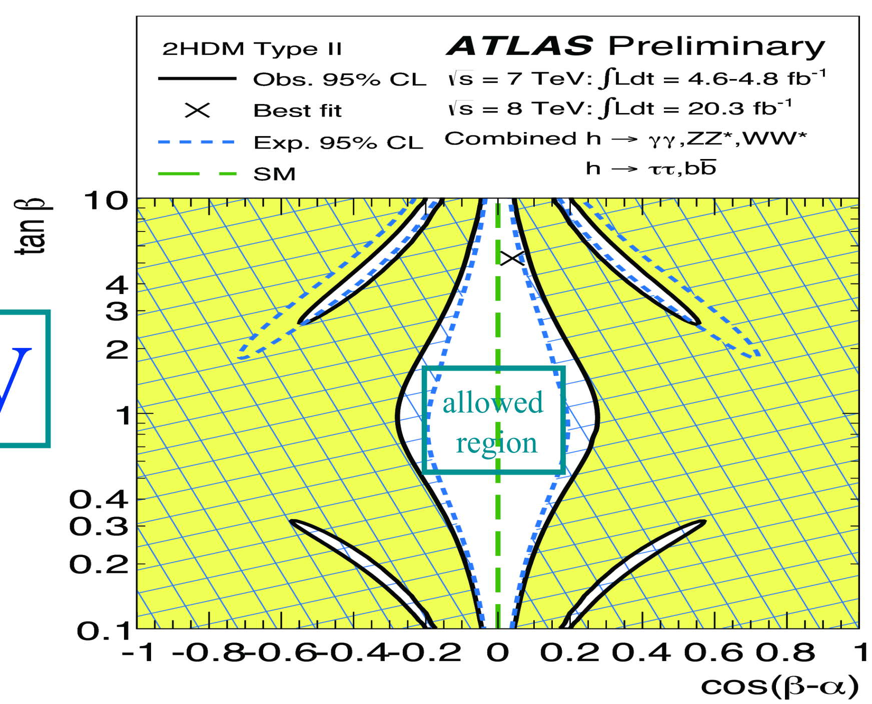


ATLAS-CONF-2014-010

Summary of new Physics constraints

- The measured coupling, their mass dependence, the vacuum expectation value, invisible branching ratio of the Higgs boson are compatible with SM within statistical and systematic uncertainties. No indication of new Physics is observed.
- Compositeness scale f > 710 (640) GeV at 95% CL for MCHM4 (MCHM5).
- Simplified MSSM limits are set to be m_A > 400 GeV at 95% CL for 2 < tanβ < 10.
- Limits on coupling strength of additional EW singlet set to be < 0.12 at 95% CL.
- Limits on WIMP-nucleon scattering are better than direct-detection experiments.
- Run2 data at 13/14 TeV significantly enhance prospects of observing New Physics.

7/8 TeV



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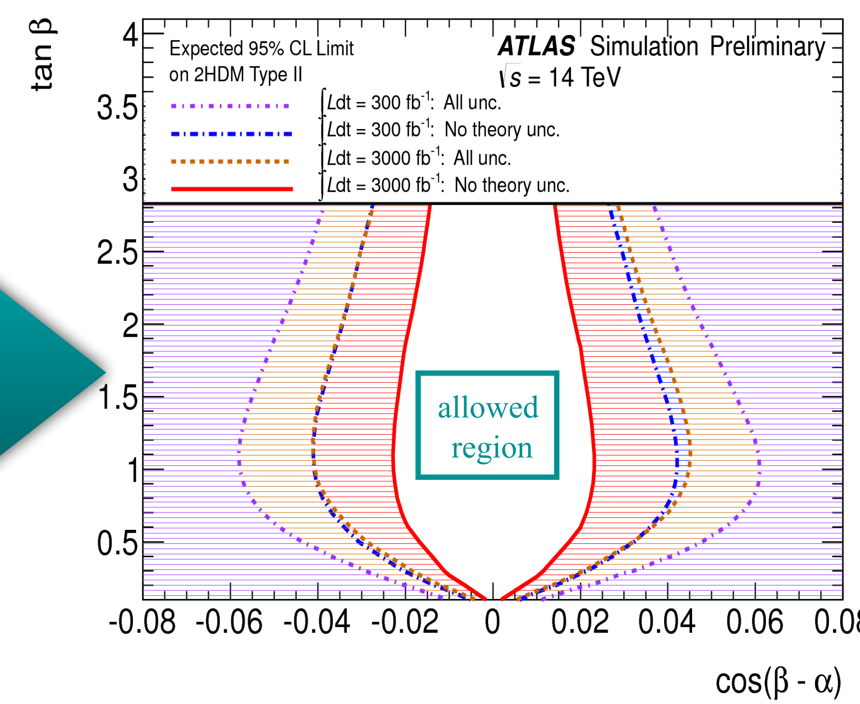

ATLAS-PHYS-PUB-2013-015

13/14 TeV

ATLAS References

1. Measurements of Higgs production and couplings using diboson final states with the ATLAS detector at the LHC. Phys. Lett. B726 (2013) 88.
2. Search for the bb decay of the Standard Model Higgs boson in associated (W/Z)H production with the ATLAS detector. ATLAS-CONF-2013-079.
3. Evidence for Higgs Boson Decays to the $\tau^+\tau^-$ Final State with the ATLAS Detector. ATLAS-CONF-2013-108.
4. Search for Invisible Decays of a Higgs Boson Produced in Association with a Z Boson in ATLAS. Phys. Rev. Lett. 112 (2014) 201802.
5. Updated coupling measurements of the Higgs boson with the ATLAS detector using up to 25 fb^{-1} of proton-proton collision data. ATLAS-CONF-2014-009.
6. Constraints on New Phenomena via Higgs Coupling Measurements with the ATLAS Detector. ATLAS-CONF-2014-010.
7. Sensitivity to New Phenomena via Higgs Couplings with the ATLAS Detector at a High-Luminosity LHC. ATLAS-PHYS-PUB-2013-015.