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

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26.08.2014
PANIC2014

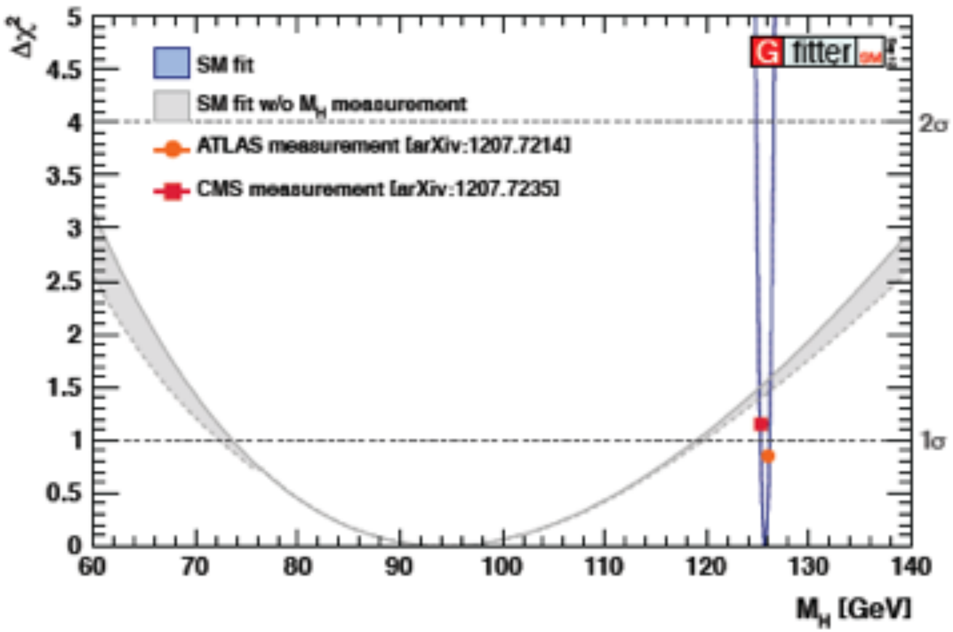
Saclay

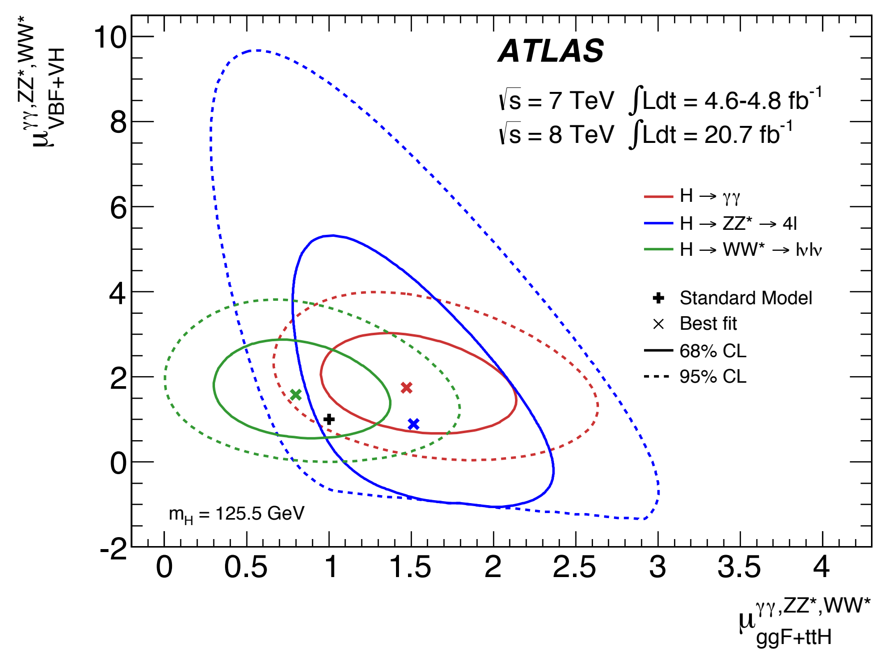
http://atlas.ch

State-of-the-Art

- ★ Higgs-like particle discovered in summer 2012 by ATLAS and CMS [1-2]
- ★ Mass of the new-found particle about 125.5 GeV [3-4]
- ★ Spin-parity compatible with a $J^P = 0^+$ particle [5-7]
- ★ Couplings measurement consistent with SM expectations [3-4]

compatible with SM Higgs





Physics Motivation

The new-found particle is compatible with a SM Higgs

↓

Is the Higgs sector extended?

the presence of a family of Higgs bosons may help answering a number of fundamental open questions:

- ★ Hierarchy problem: why is the Higgs boson mass unnaturally small?
- ★ Dark Matter: looking for DM candidates via the “Higgs portal”

→ **indirect searches** for BSM models (Higgs compositeness, Higgs singlet, **2H-doublet**, **MSSM**, **dark matter**) with the Higgs coupling measurements[8]

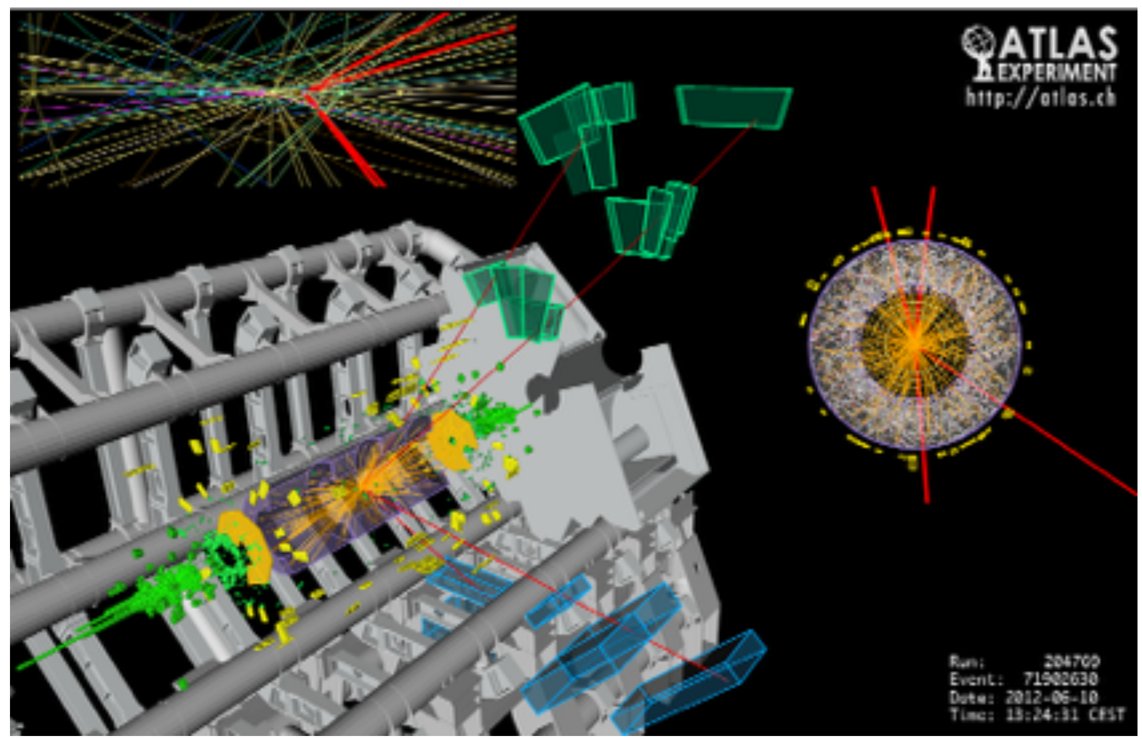
→prospects of such searches at HL-LHC[9]

Analyzed Data

- Full Run-1 ATLAS data sample used **~25 fb^{-1}**
- Combination of the couplings is used to constrain BSM parameters
- Rates measured in all decay channels:
  - $h \rightarrow \gamma\gamma$
  - $h \rightarrow ZZ^* \rightarrow 4\ell$
  - $h \rightarrow WW^* \rightarrow \ell\nu\ell\nu$
  - $h \rightarrow \tau\tau$
  - $h \rightarrow b\bar{b}$
  - + $Zh \rightarrow \ell\ell E_T^{miss}$ limits

[Higgs portal to DM]

- Other direct searches are **not** considered

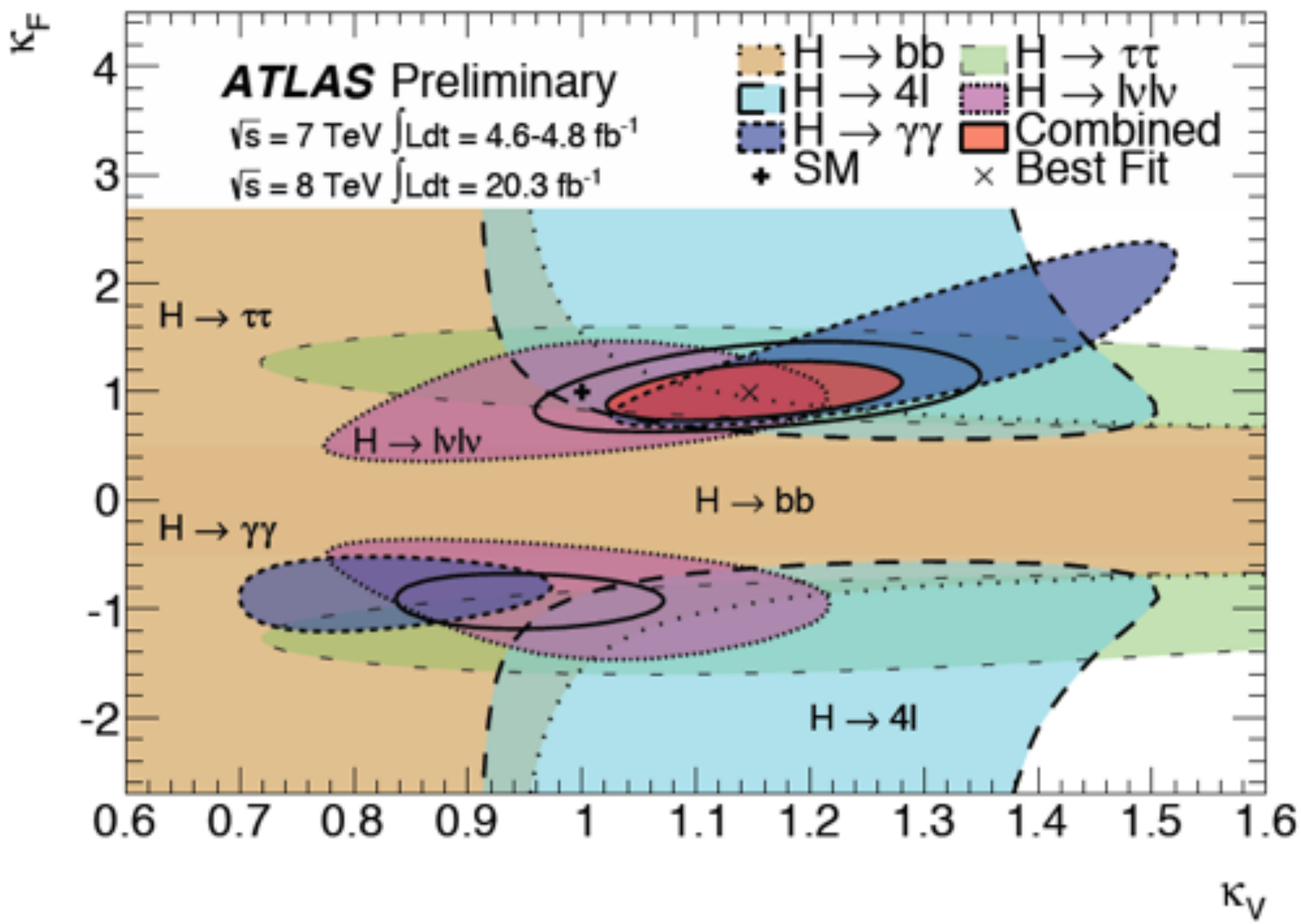


event display of $h \rightarrow ZZ^* \rightarrow 4\mu$

Coupling Measurements

★ Measured couplings to vector-bosons, fermions

→ **compatible with the SM within ~1.5σ**



STATISTICAL TREATMENT

★ Confidence intervals are based on the profile likelihood ratio test statistic **t_α = -2 ln Λ(α)**

likelihood ratio

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

parameter of interest: μ, m_h, κ, Θ

systematic uncertainties → **nuisance parameters Θ**

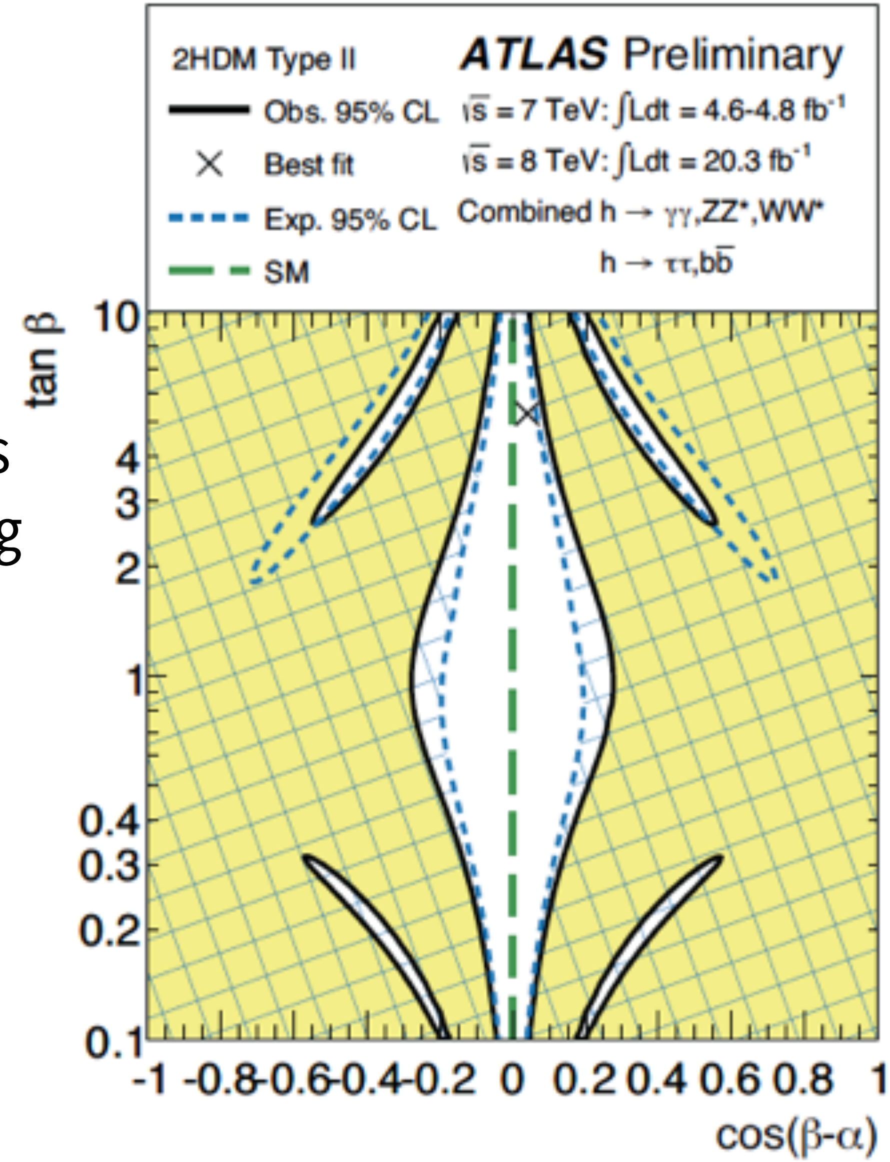
★ L(α, Θ(α)) → product of the likelihoods in each channel

★ In each channel → likelihood is the sum of the signal and background pdfs for the signal/background discriminating variable

★ signal pdf → MC simulation, background pdf → data and MC

Two-Higgs-Doublet Models

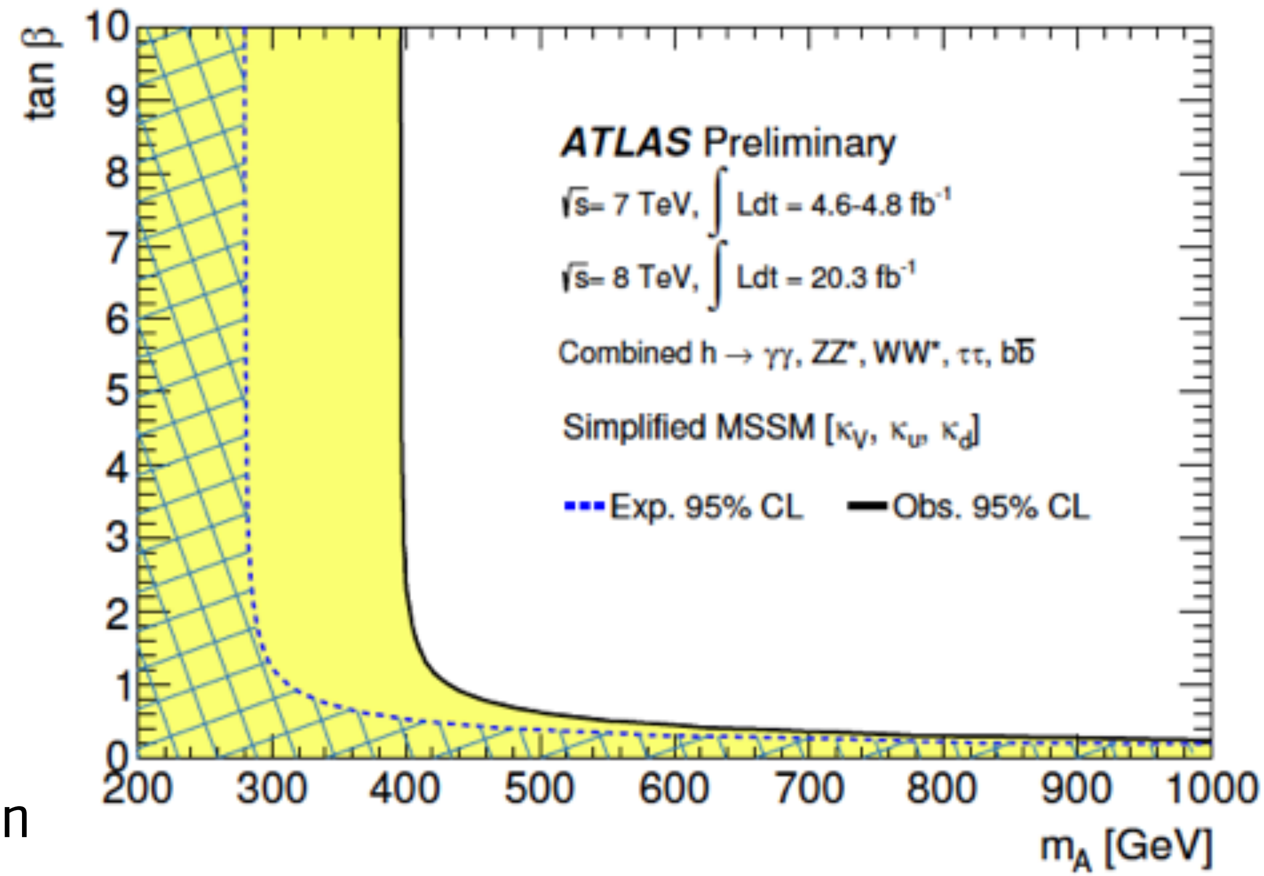
- Extension where the Higgs sector is extended by an additional doublet:
  - two neutral CP-even → h and H
  - one neutral CP-odd → A
  - two charged bosons → $H^{\pm}$
- Different couplings to vector bosons and fermions are tested all satisfying the Glashow-Weinberg condition
  - ex: type II (MSSM-like) → one doublet couples to up-type quarks, the other to down-type quarks and leptons.



limits consistent with SM expectations

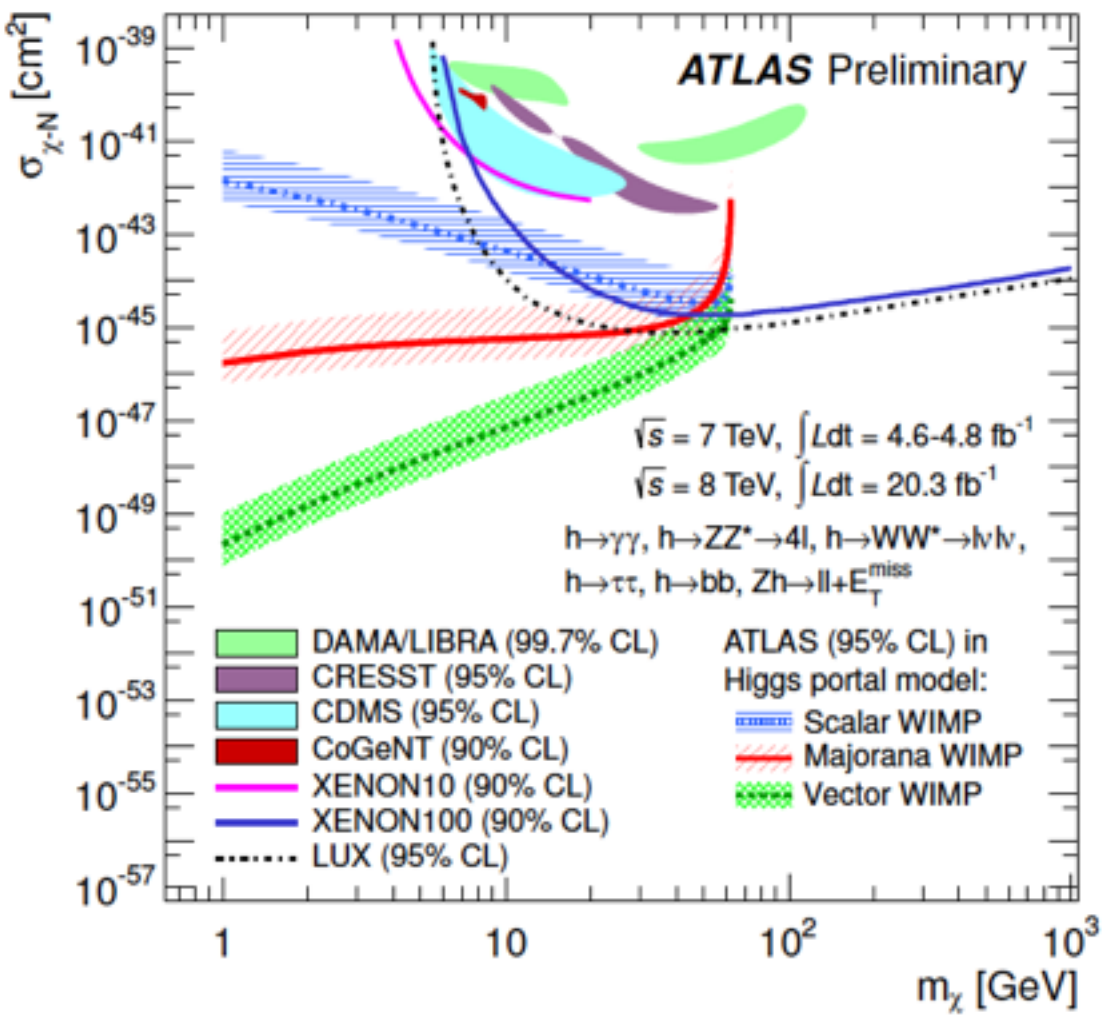
Simplified MSSM

- ★ A simplified Minimal Supersymmetric SM (MSSM) is probed via Higgs couplings to:
  - ★ vector bosons (W, Z)
  - ★ up-type fermions (mainly top)
  - ★ down-type fermions (mainly bottom and τ)
- ★ For tanβ›2, lower limit on CP-odd Higgs mass is: m_A › 400 GeV obs. (290 GeV exp.)



still large unexplored region for tanβ › 1

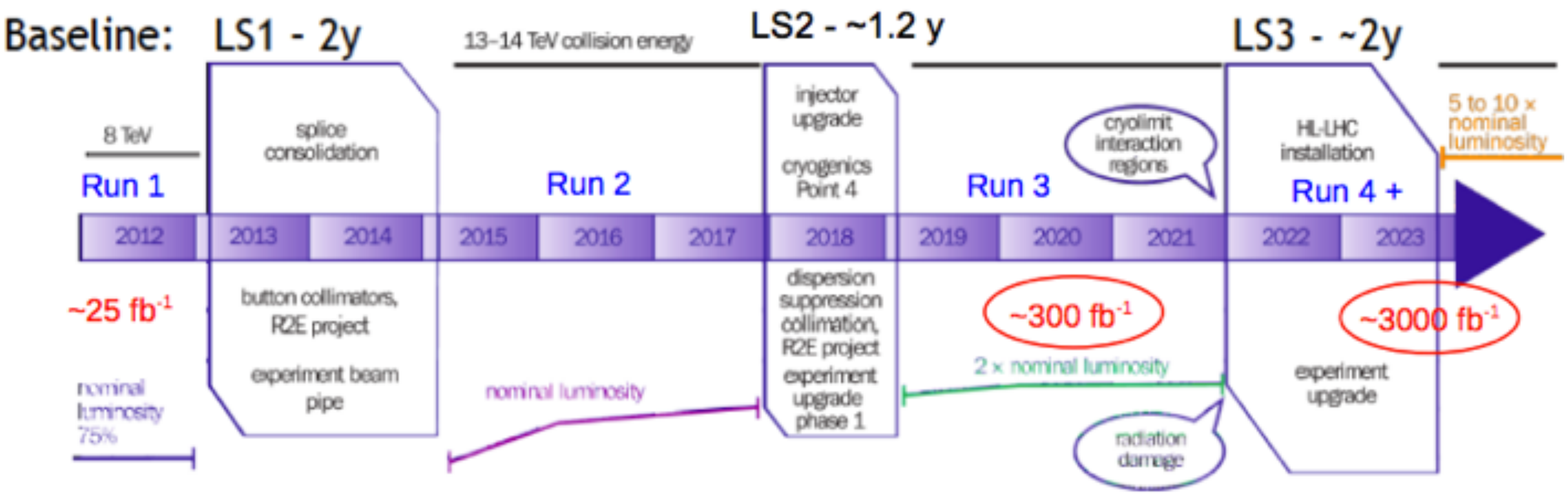
Higgs Portal to Dark Matter



- The Higgs boson may decay invisibly to new particles: $\chi \to m_\chi < m_h/2$
- Upper limit set on the Higgs invisible branching ratio:

  BR_{inv} < 0.37 obs. (0.39 exp.)
- WIMP-nucleon scattering cross-section → ATLAS dominates in the **low mass region**

THE LHC PROGRAM



Broad physics program in the Higgs sector:

- ★ **Couplings and rare decays (H→μμ, Zγ, J/ψγ ?)**
  - **→ test of the SM and indirect searches for new physics**
- ★ Direct searches for BSM
- ★ Search for CP violation in the Higgs sector

Measurements Perspectives

Couplings

★ Experimental precisions of ~1.5% on κ_V and ~3% on κ_f are expected with 3000 fb^{-1} (3.5% and 8.5% with current theoretical uncertainties)

★ ~2.5%on κ_V and 7% on κ_f are expected with 300 fb^{-1} (3.5% and 8.5% with current theoretical uncertainties)

ATLAS-PHYS-PUB-2013-014/15/16

Higgs to invisible

Expected limits with 95% CL on the invisible branching ratio of the Higgs boson

	300 fb^{-1}	3000 fb^{-1}
From ZH→ll+invisible	[23,32]%	[8,16]%
From coupling measurements	[25,28]%	[12,15]%

Conclusions

★ The measured Higgs boson couplings and their mass dependence, invisible BR and vacuum expectation value are compatible with the SM expectation

★ Limits are set on new physics phenomena by using the Higgs coupling measurements extracted with the full ATLAS data sample in all decay channels available → no hints for new physics up to now

★ Still a lot of margin for new physics to be discovered at the HL-LHC !

Bibliography

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- [2] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B 716 (2012) 30, arXiv:1207.7235 [hep-ex];
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- [5] ATLAS Collaboration, *Evidence for the spin-0 nature of the Higgs boson using ATLAS data*, Phys. Lett. B 726 (2013) 120, arXiv:1307.1432 [hep-ex];
- [6] CMS Collaboration, *Study of the Mass and Spin-Parity of the Higgs Boson Candidate Via Its Decays to Z Boson Pairs*, Phys. Rev. Lett. 110 (2013) 081803, arXiv:1212.6639 [hep-ex];
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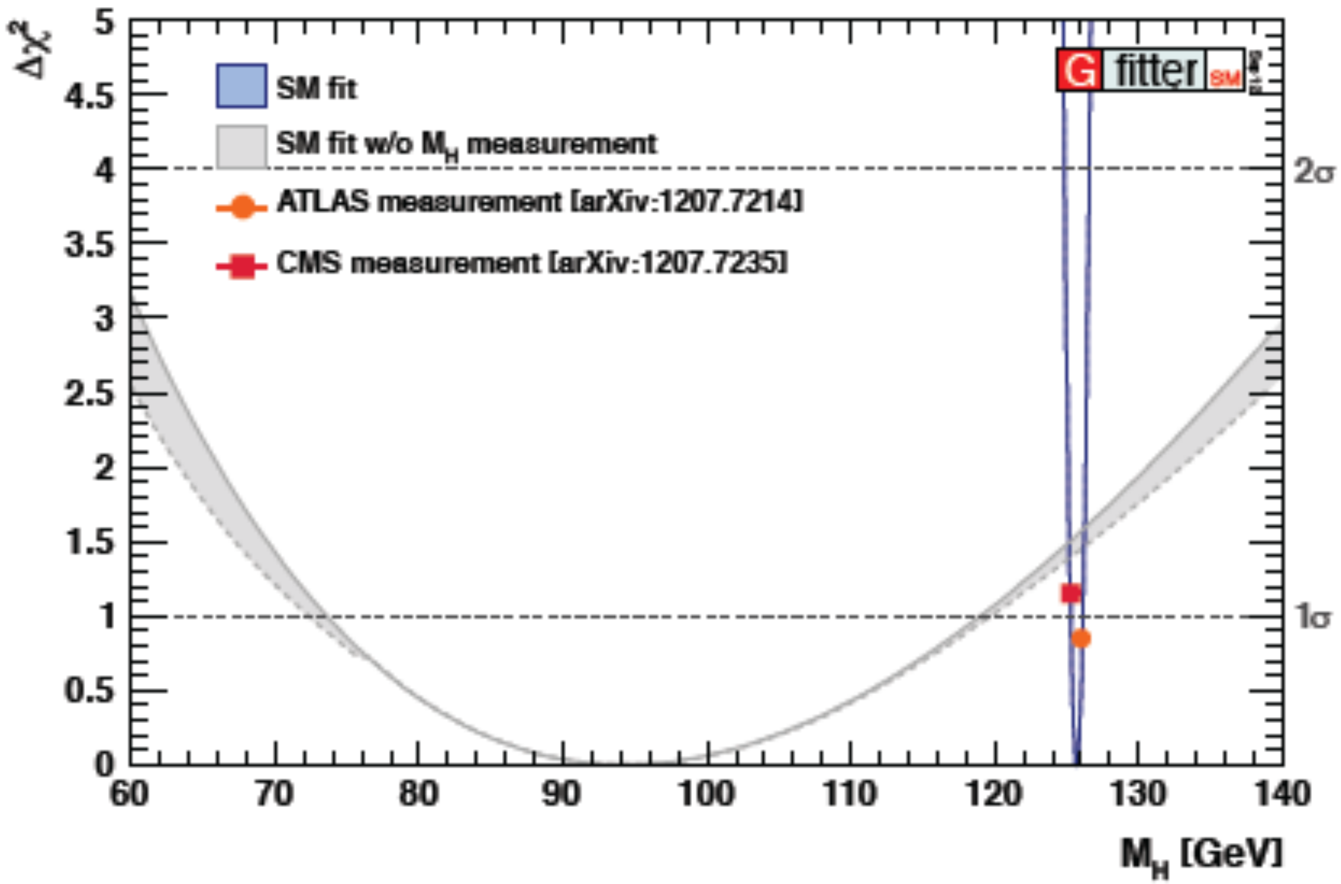
Backup Slides

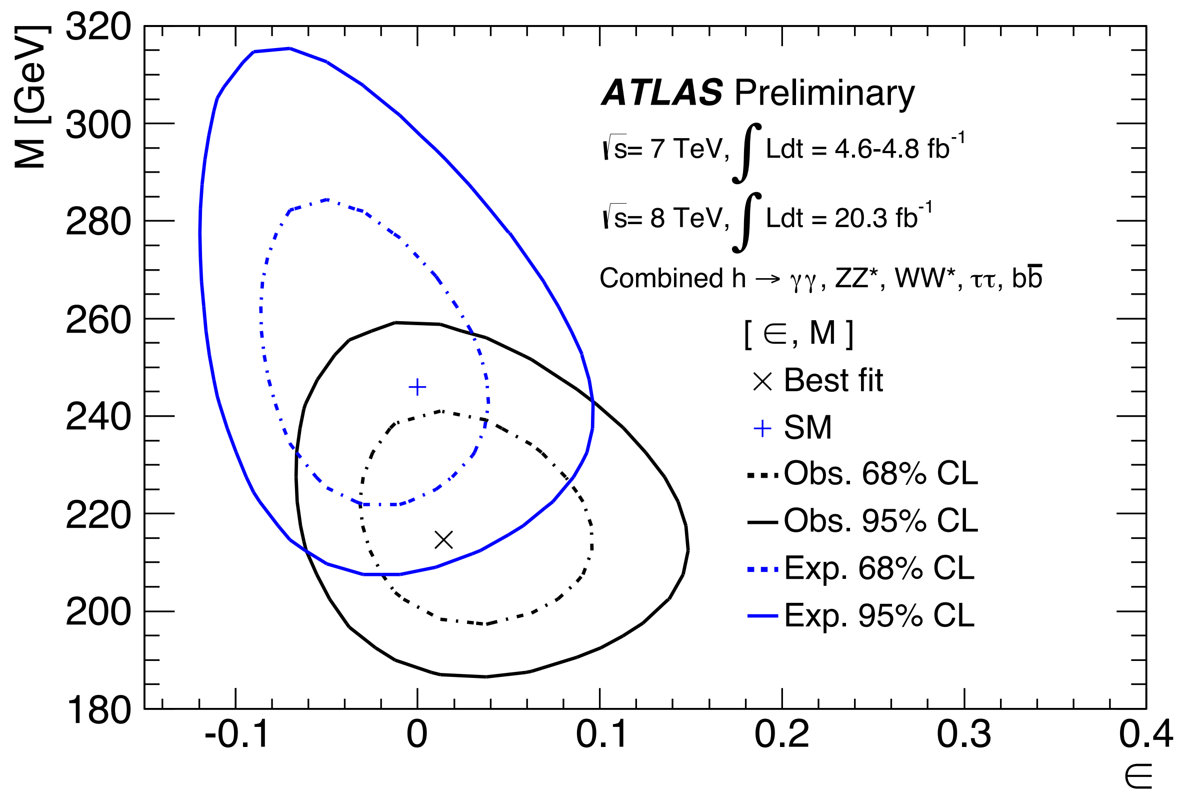
Electroweak Fit With GFitter



- **blue line:** full SM fit
- **grey band:** fit without M_H measurement included → gives $M_H = 94^{+25}_{-22}$ GeV, 1.3σ from the measured value

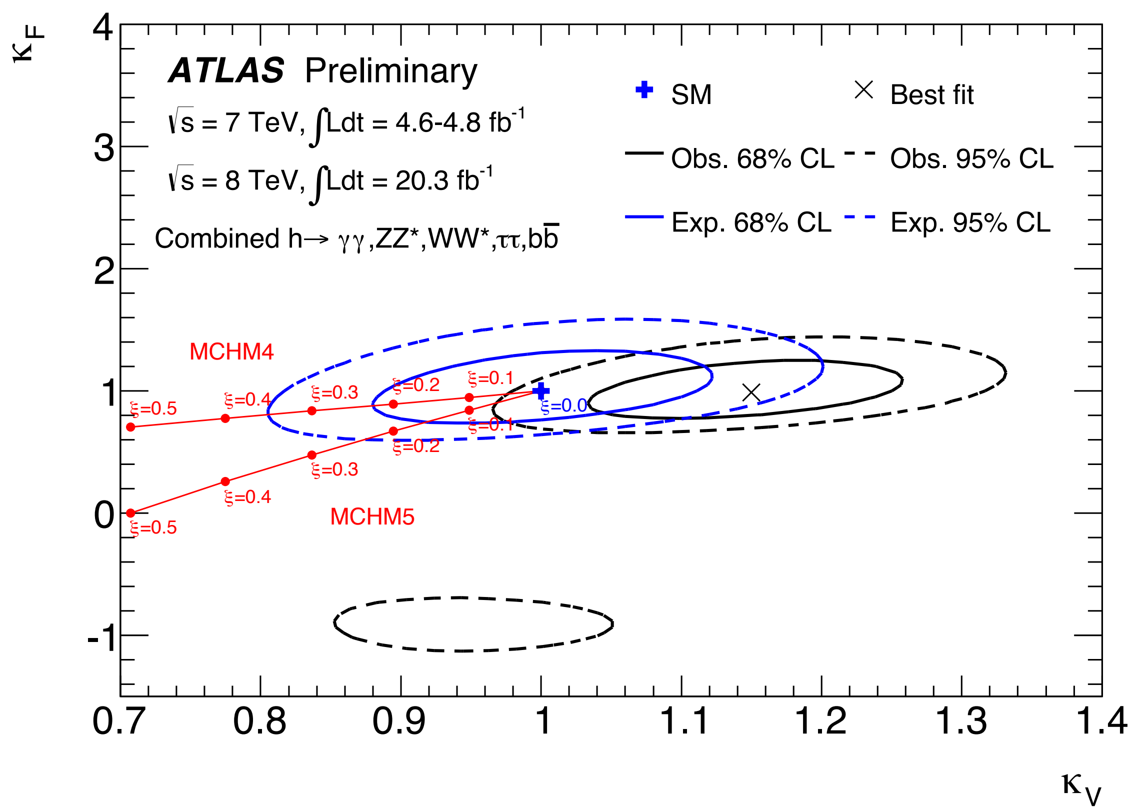
Mass Scaling and Vacuum Expectation

★ The couplings mass dependence and the vacuum expectation value are also consistent with the SM[8]



Higgs Boson Compositeness

- A composite Higgs boson is a possible solution to the hierarchy problem
- Limits at 95% CL are set on the **compositeness scale *f***
- Two Minimal Composite Higgs Models (MCHM) are considered:
  - MCHM4 → f > 710 GeV
  - MCHM5 → f > 460 GeV



$\xi = (v/f)^2$

MCHM4 and MCHM5 Parameterisations

In the MCHM4 model [26], the ratio of the predicted couplings to their SM expectations can be written in the particularly simple form:

$$\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}, \tag{7}$$

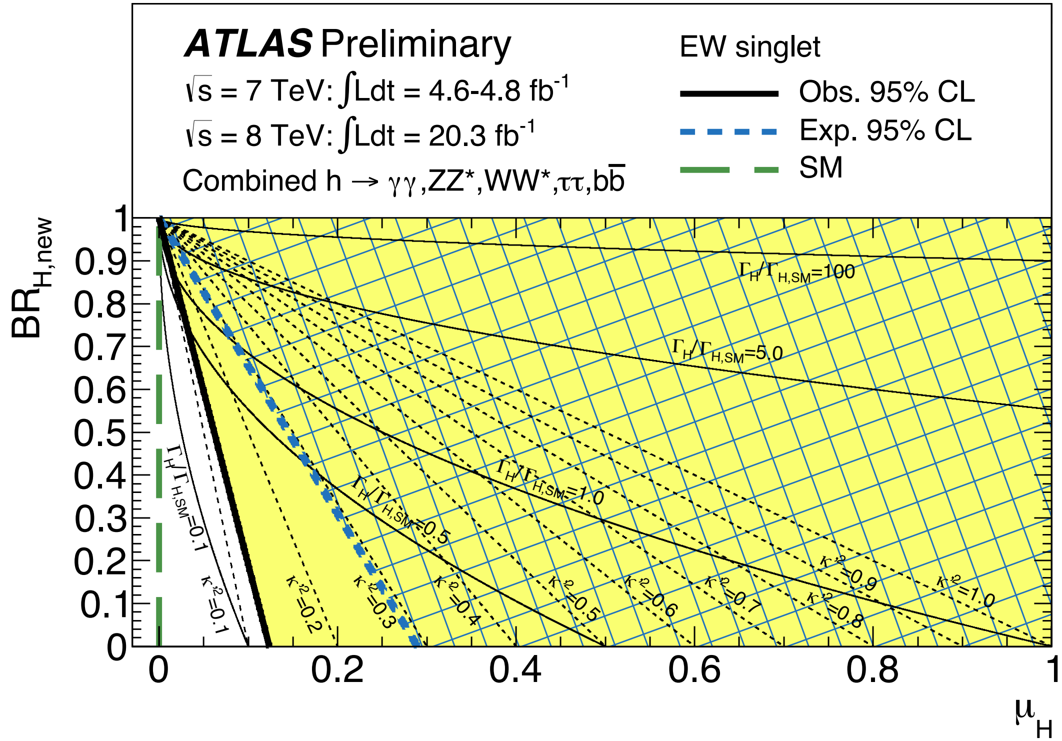
Similarly, in the MCHM5 model [27, 28] the measured rates are expressed in terms of ξ by rewriting the couplings as:

$$\begin{aligned} \kappa_V &= \sqrt{1-\xi} \\ \kappa_F &= \frac{1-2\xi}{\sqrt{1-\xi}}. \end{aligned} \tag{8}$$

(here: $\xi = (v/f)^2$)

Additional EW Real Singlet

- ★ Simplest extension of the SM: additional singlet → two non-degenerate CP-even Higgs bosons (h, H)
- ★ Measuring κ' → H coupling strength reduction factor (κ' = 0 in SM)
- ★ Unitarity is conserved: $\kappa^2+\kappa'^2 = 1$
- ★ **Obs. $\kappa'^2 = 1-\mu_h = -0.30\ {+0.17}\ {-0.18}$** (Exp. $\kappa'^2 = 0\ {+0.15}\ {-0.17}$)
- ★ 95% CL upper limit: $\kappa'^2 < 0.12$ obs. (<0.29 exp.)



2HDM Parameters

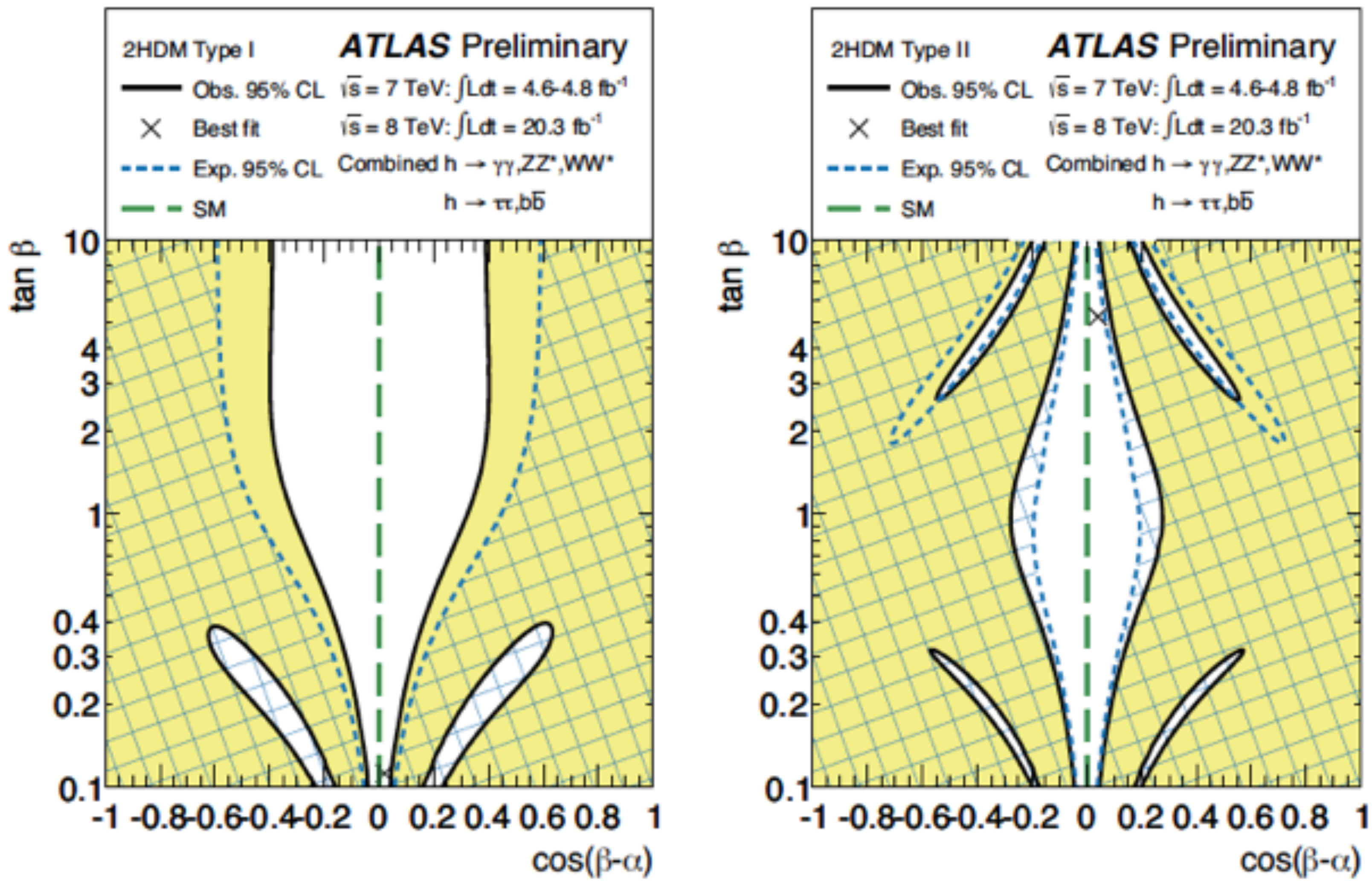
The Glashow-Weinberg condition is satisfied by four types of 2HDMs [38]:

- Type I: One Higgs doublet couples to vector bosons, while the other couples to fermions. The first doublet is "fermiophobic" in the limit of no mixing.
- Type II: This is an "MSSM-like" model, in which one Higgs doublet couples to up-type quarks and the other to down-type quarks and leptons.
- Type III: This is a "lepton-specific" model, where the Higgs bosons have the same couplings to quarks as in the Type I model and to leptons as in Type II.
- Type IV: This is a "flipped" model, where the Higgs bosons have the same couplings to quarks as in the Type II model and to leptons as in Type I.

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	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Table 2: Couplings of the light Higgs boson h to weak vector bosons (κ_V), up-type quarks (κ_u), down-type quarks (κ_d), and leptons (κ_l), expressed as ratios to the corresponding SM predictions in 2HDMs of various types.

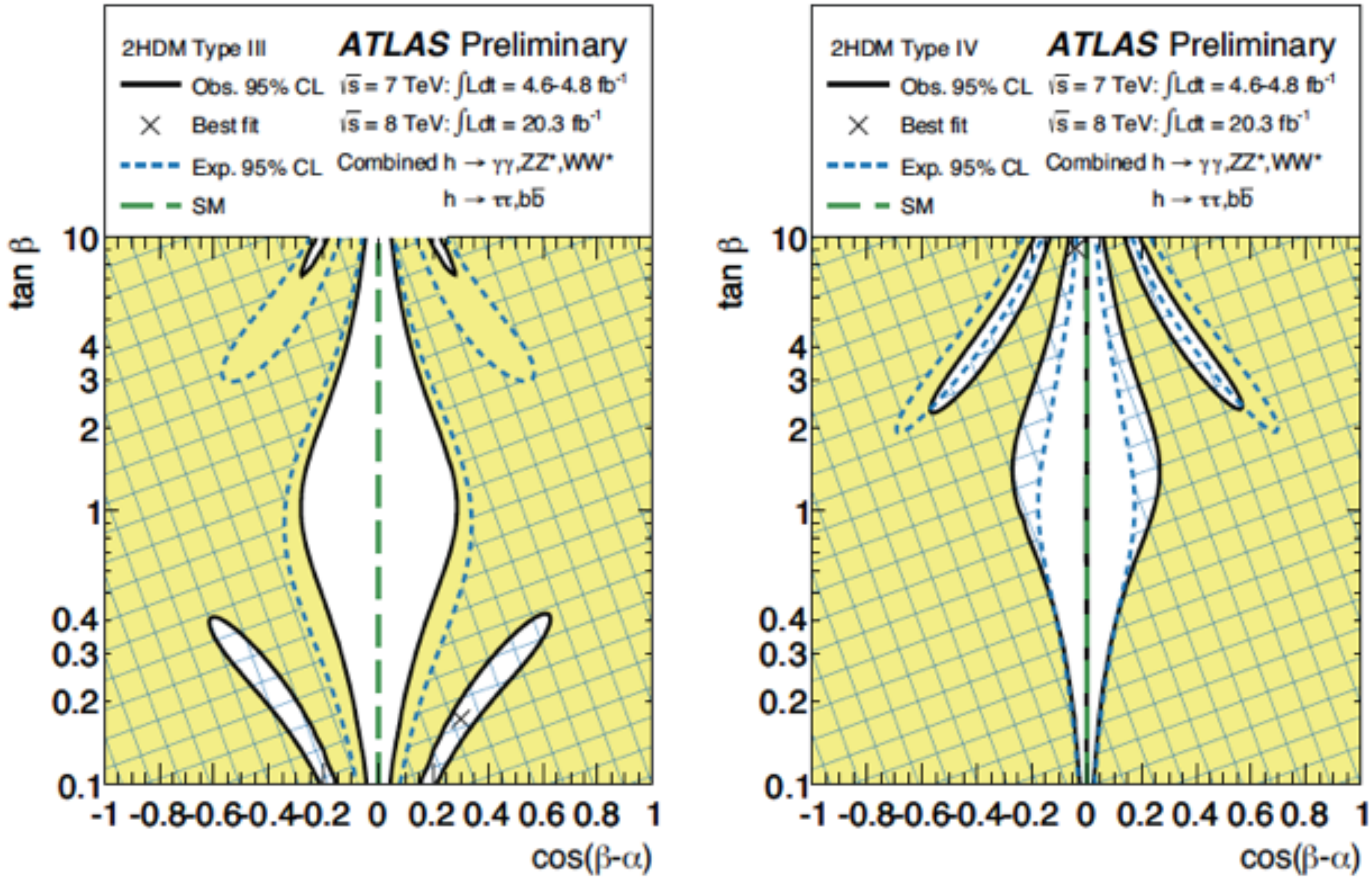
2HDM Results /1



(a) Type I

(b) Type II

2HDM Results /1



(c) Type III

(d) Type IV