Constraints on new phenomena via Higgs coupling measurements

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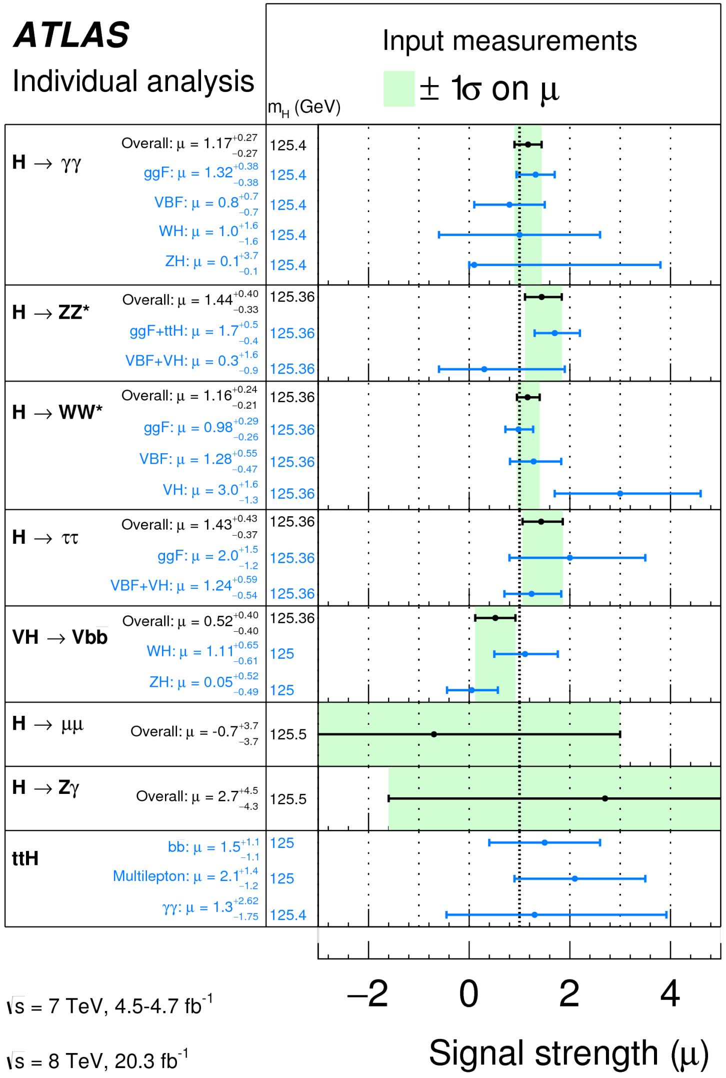
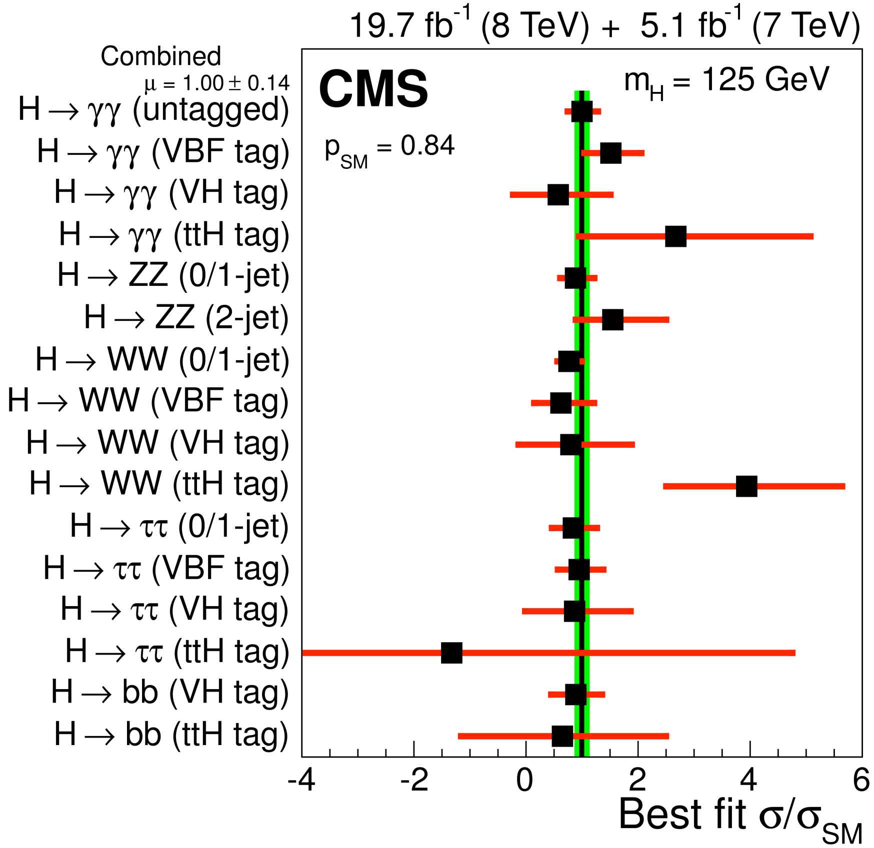
on behalf of the ATLAS & CMS collaborations

Higgs property measurements - couplings strengths

- Signal strengths $\mu(i \rightarrow f)$ as measured by ATLAS & CMS





arXiv:1507.04548

Eur. Phys. J. C 75 (2015) 212

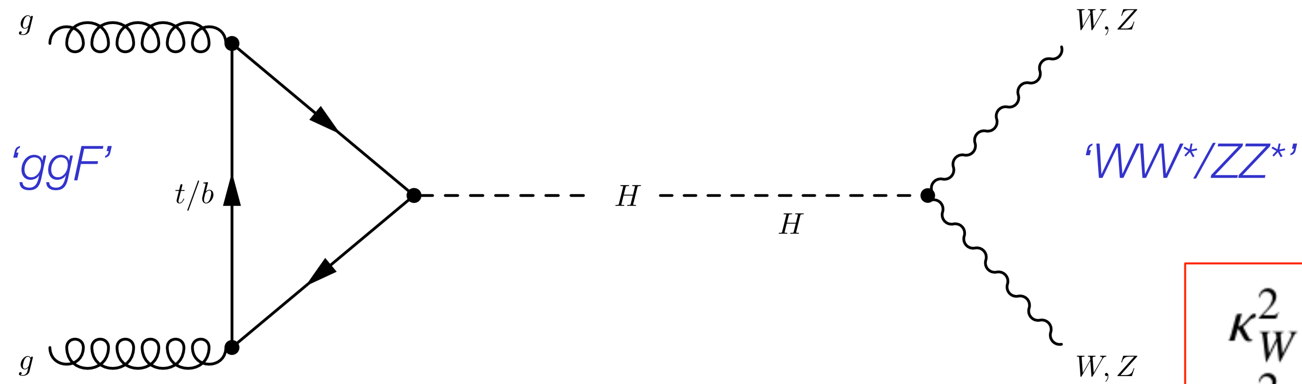
(See also Marco's talk on Tuesday)

From signal strengths to couplings – the κ framework

- How to interpret observed signal strength $\mu(i \rightarrow f)$ in terms of (modified) Higgs boson coupling strenghts?
- Narrow Width Approximation allows factorization of σ as follows

$$\sigma(i \rightarrow H \rightarrow f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

- Parametrize σ_i and Γ_f in modified couplings strengths κ_i w.r.t. SM couplings, assuming the LO degrees of freedom, e.g.



$$\boxed{\kappa_g^2 \sim \quad 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b}$$

$$\boxed{\begin{array}{c} \kappa_W^2 \\ \kappa_Z^2 \end{array}}$$

Expression assumes only SM contributions to loop

The κ framework – the total width

- Note that total *H* width scales all observed cross-sections

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

- Since Γ_H is not yet directly measured with a meaningful precision, must make an assumption on Γ_H to interpret cross-sections in terms of Higgs couplings.
- In absence of *H* decay to invisible particles, can assume SM width, adjusted by effect of k-rescaled couplings

$$\Gamma_H(\kappa_j) = \kappa_H^2(\kappa_j) \cdot \Gamma_H^{SM}$$

$$\kappa_H^2 \sim \begin{array}{l} 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$

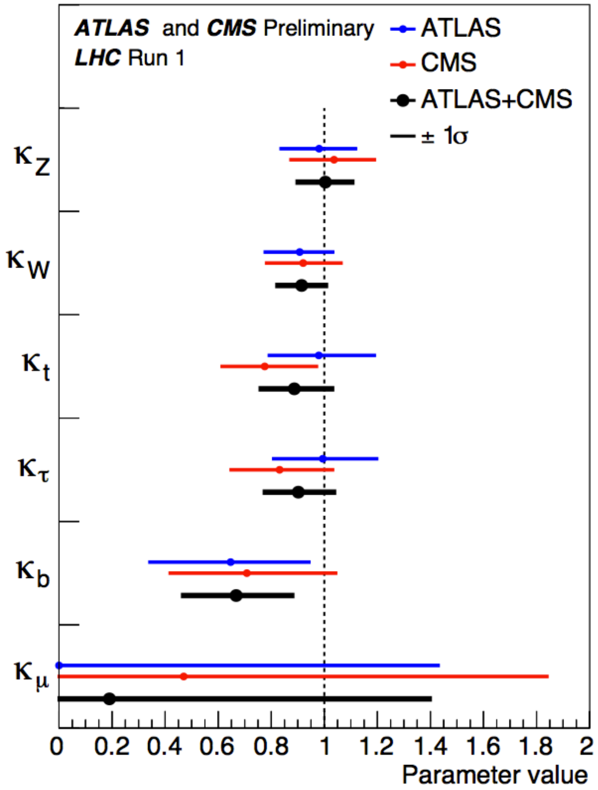
The κ framework – results

- Current LHC data allows to fit for six tree-level Higgs couplings (to Z, W, t, b, τ, μ) probing vector bosons, leptons, and up/down quarks
- Alternatively assume universal scaling for fermions and bosons, for improved precision (at the expense of additional assumptions)

Fit with 6 fundamental couplings,

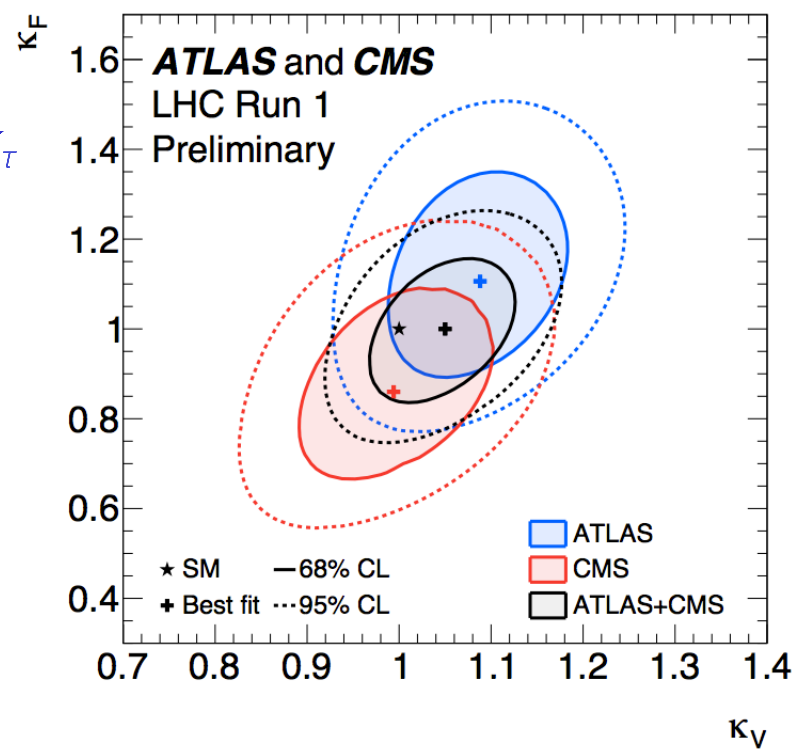
loops resolved in SM content,

no invisible decays



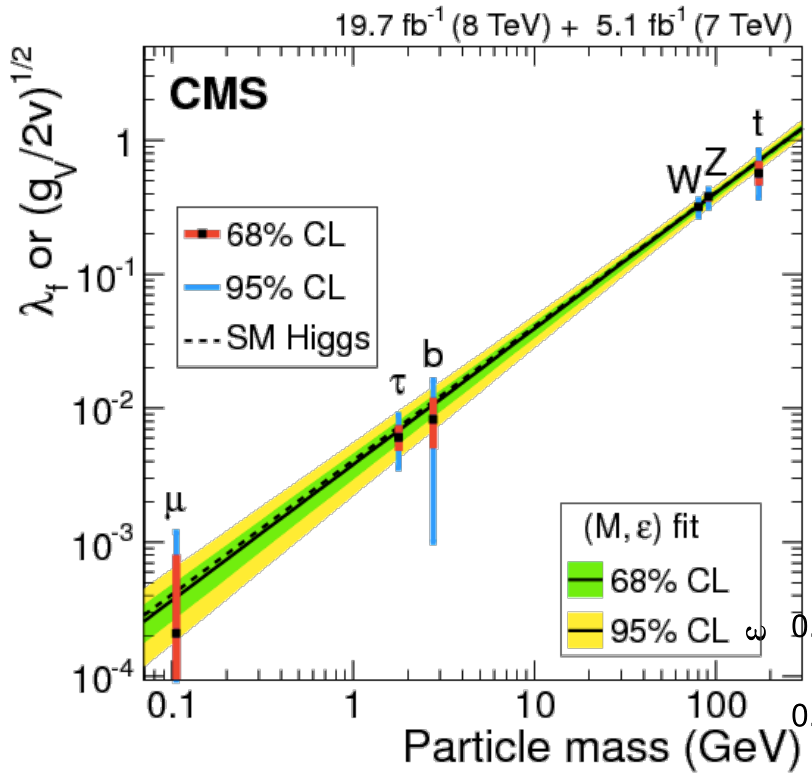
$\boldsymbol{k_F}=k_t=k_b=k_\mu=k_\tau$

$\boldsymbol{k_V}=k_W=k_Z$



Mass scaling - Does h(125) behave like a Higgs boson?

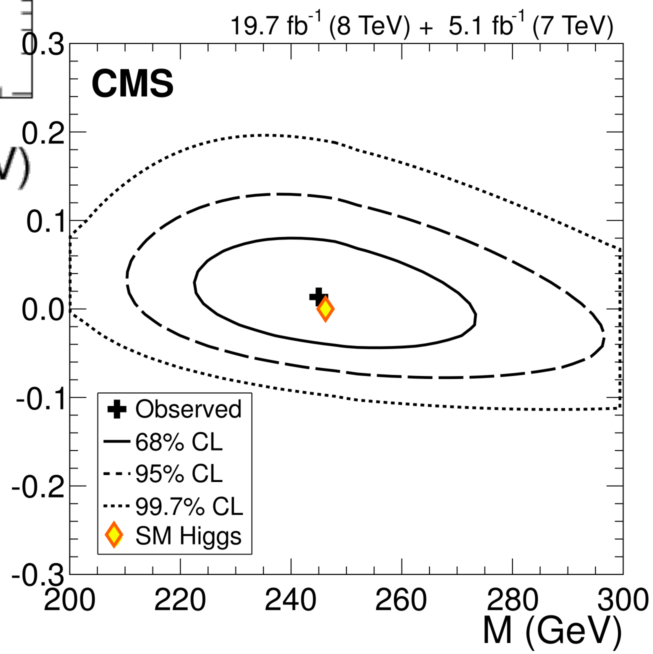
- For SM Higgs boson coupling strength related to mass of particle

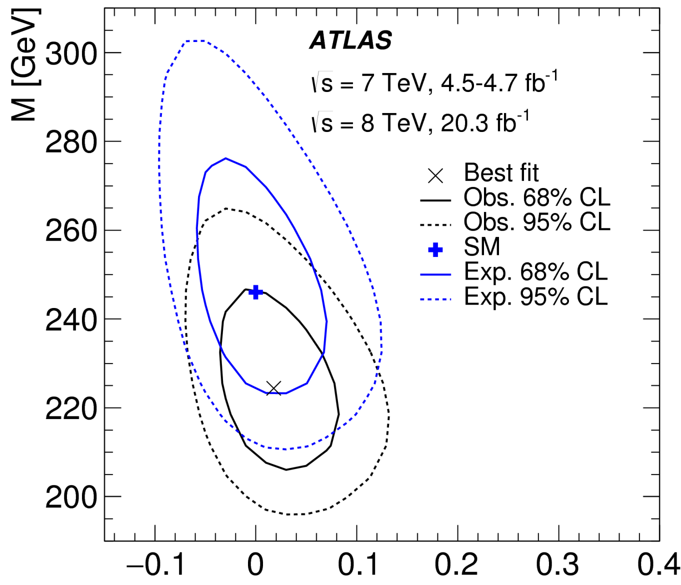


Test this relation with parametrization that allows deviation in slope and curvature of the relation between mass and λ_f / g_V

$$k_{F,i} = v\frac{m_{f,i}^{\varepsilon}}{M^{1+\varepsilon}} \qquad k_{V,j} = v\frac{m_{V,j}^{2\varepsilon}}{M^{1+2\varepsilon}}$$

CERN-PH-EP-2015-191 (arXiv 1509.00672)





Curvature (ε) and slope (M) consistent with SM values

Minimal Composite Higgs models: MCHM

- A possible solution for scalar hierarchy problem is that H is not elementary particle, but pseudo Nambu Goldstone boson arising from a higher energy theory (a SO(5)/SO(4) model)
  - MCHM4: SM fermions embedded in spinorial representations of SO(5)
  - MCHM5: SM fermions embedded in fundamental representations of SO(5)
- Attractive feature of these models is that Higgs couplings are modified in a simple form w.r.t. SM and relate to compositeness scale

MCHM4:

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

MCHM5:

$$\kappa_V = \sqrt{1-\xi}$$

$$\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}} \quad ,$$

$\xi = v^2/f^2$ is a scaling parameter

SM: $\xi=0$, $f=\infty$

MCHM compositeness scale

Minimal Composite Higgs models: MCHM

MCHM4

ξ<0.12 (95% C.L.)
SM exp: <0.23

f>710 GeV
SM exp: >510 GeV

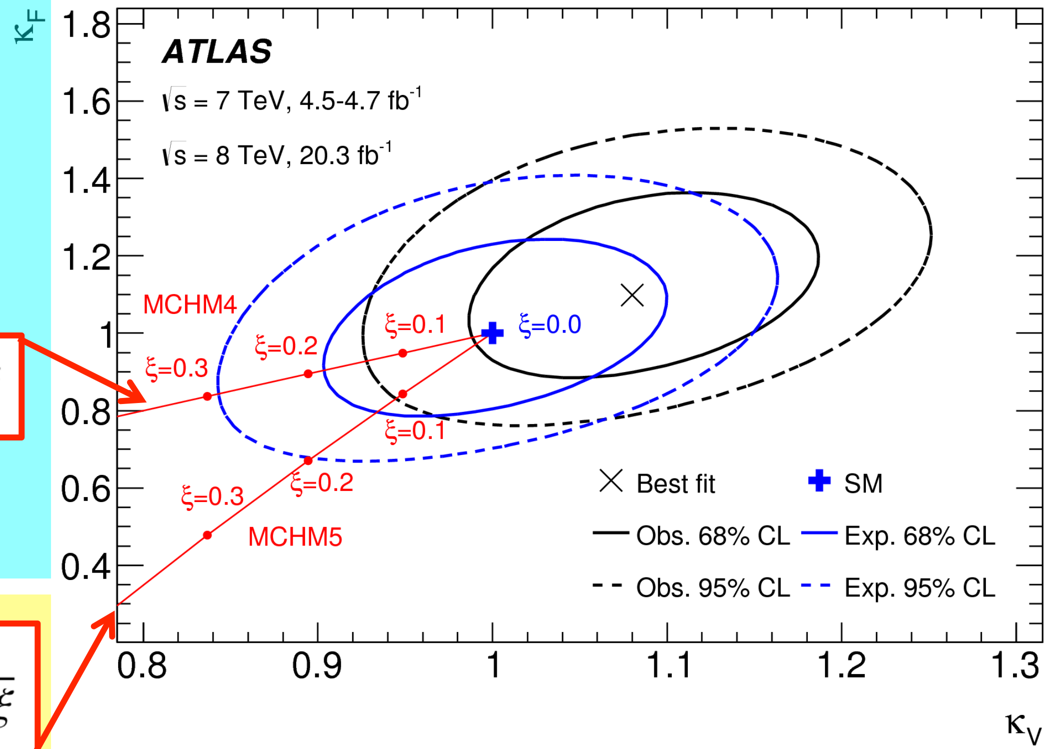
$$\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$$

MCHM5

ξ<0.10 (95% C.L.)
SM exp: <0.17

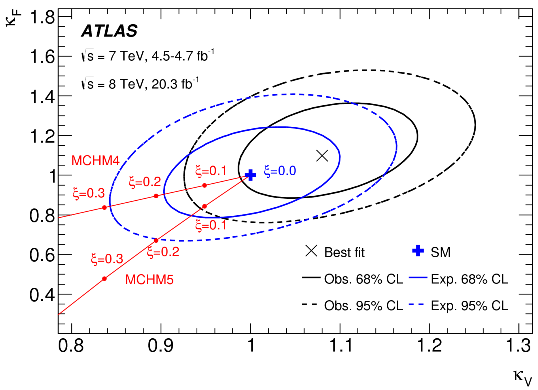
f>780 GeV
SM exp: >600 GeV

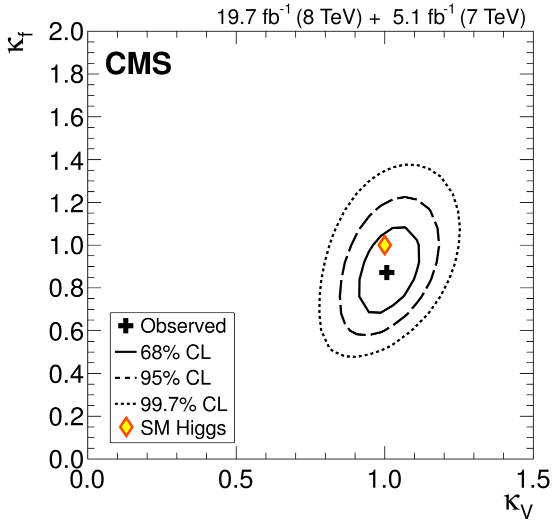
$$\kappa_V = \sqrt{1-\xi} \qquad \kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}},$$

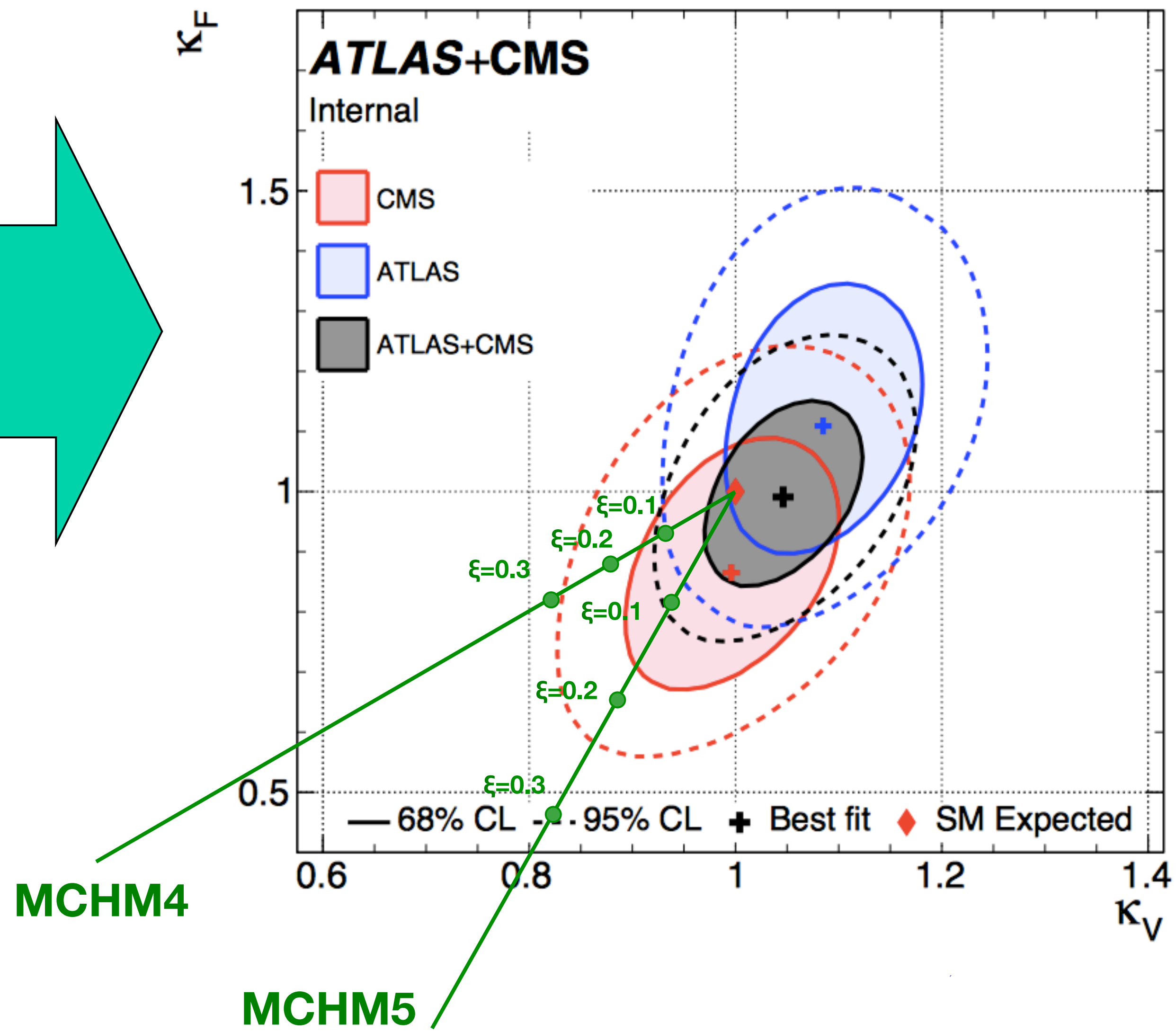


Physics motivated SM extensions – Composite Higgs models

- MCHM4/5 trajectories (manually) overlaid on new ATLAS/CMS combined measurement of (k_V,k_F)







SM extensions with additional H fields – Electroweak Singlet

- The simplest extension of the SM Higgs sector adds a single EW scalar field to SM doublet field,
  - Both have non-zero VEV, Mixing between singlet state and surviving doublet state
  - Two CP-even Higgs bosons *h* and *H*, assumed to have different masses
- Coupling properties of h(125) in EWS different from that in SM

$$\left.\begin{aligned} \mu_h &= \frac{\sigma_h \times \mathrm{BR}_h}{(\sigma_h \times \mathrm{BR}_h)_{\mathrm{SM}}} = \kappa^2 \\ \mu_H &= \frac{\sigma_H \times \mathrm{BR}_H}{(\sigma_H \times \mathrm{BR}_H)_{\mathrm{SM}}} = \kappa'^2 \left(1 - \mathrm{BR}_{H,\mathrm{new}}\right) \end{aligned}\right\} \quad \kappa^2 + \kappa'^2 = 1$$

SM: k=1, k'=0

ATLAS

$$\mu_h = 1.18^{+0.15}_{-0.14}$$

ATLAS

$$\kappa'^2 < 0.12 \quad (95\%\ \mathrm{C.L.}) \quad \exp < 0.23$$

(new ATLAS+CMS combined: $\mu_h = 1.09 \pm 0.11$)

SM extensions with additions H fields – 2 Higgs doublets

- Models with 2 Higgs Doublet fields
  have 5 Higgs bosons h,H,A, H^+,H^-, with 6 theory parameters
  - 4 masses $m_h, m_H, m_A, m_{H\pm}$
  - Ratio of VEVs: **tan(β)** = v_1/v_2 [with $v_1^2 + v_2^2 = (246\ \text{GeV})^2$]
  - Mixing angle ***α*** between h, H:
- What limits can we set on α,β assuming
  observed $h(125)$ is light CP-even Higgs of the 2HDM model?
- Gauge invariants imposes relation between α,β
  and 2HDM h,H couplings to bosons and fermions relative to SM

$$
\begin{aligned}
g_{hVV}^{\text{2HDM}} / g_{hVV}^{\text{SM}} &= \sin(\beta - \alpha) \\
g_{HVV}^{\text{2HDM}} / g_{HVV}^{\text{SM}} &= \cos(\beta - \alpha)
\end{aligned}
$$

SM extensions with additions H fields – 2 Higgs doublets

- Imposing Glashow-Weinberg condition to suppress FCNCs, four solutions are obtained for Higgs boson couplings to vector bosons (k_V), up/down-type quarks (k_u,k_d) and leptons (k_l)

$$g_{hVV}^{2\mathrm{HDM}} / g_{hVV}^{\mathrm{SM}} = \sin(\beta - \alpha)$$
$$g_{HVV}^{2\mathrm{HDM}} / g_{HVV}^{\mathrm{SM}} = \cos(\beta - \alpha)$$

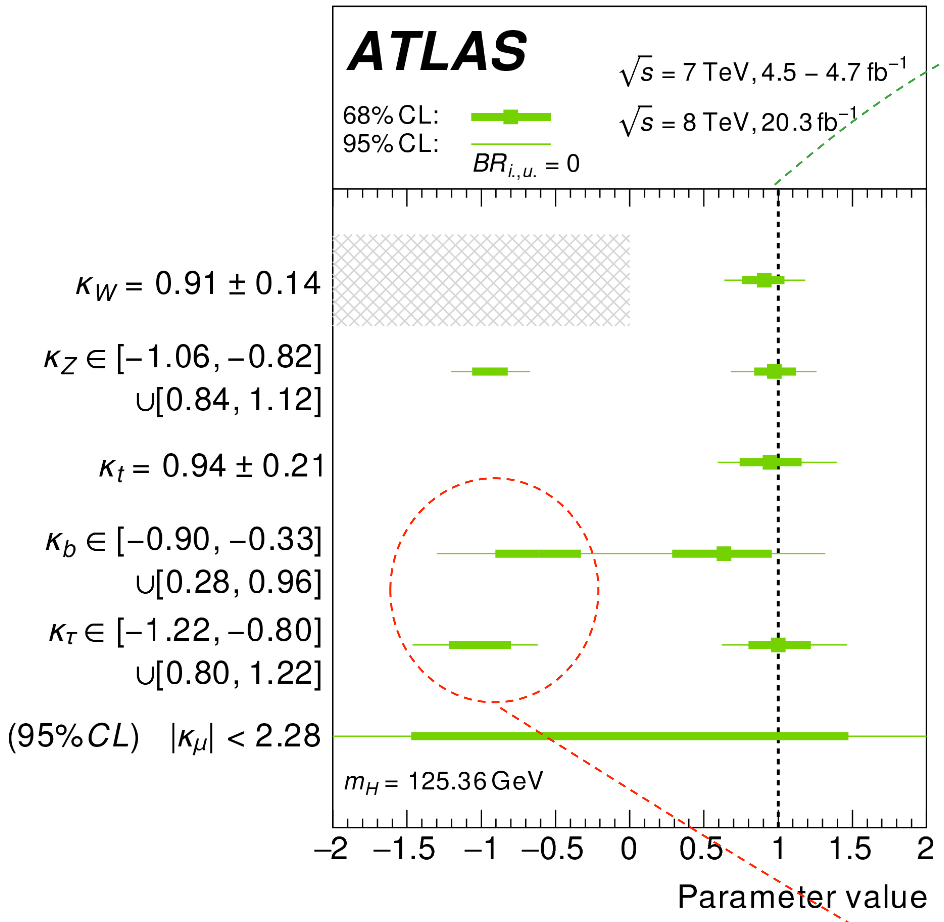
Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$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

"fermiophobic" "MSSM-like"

SM extensions with additions H boson – 2 Higgs doublets

- Results – 2HDM type 2

Measured fundamental couplings



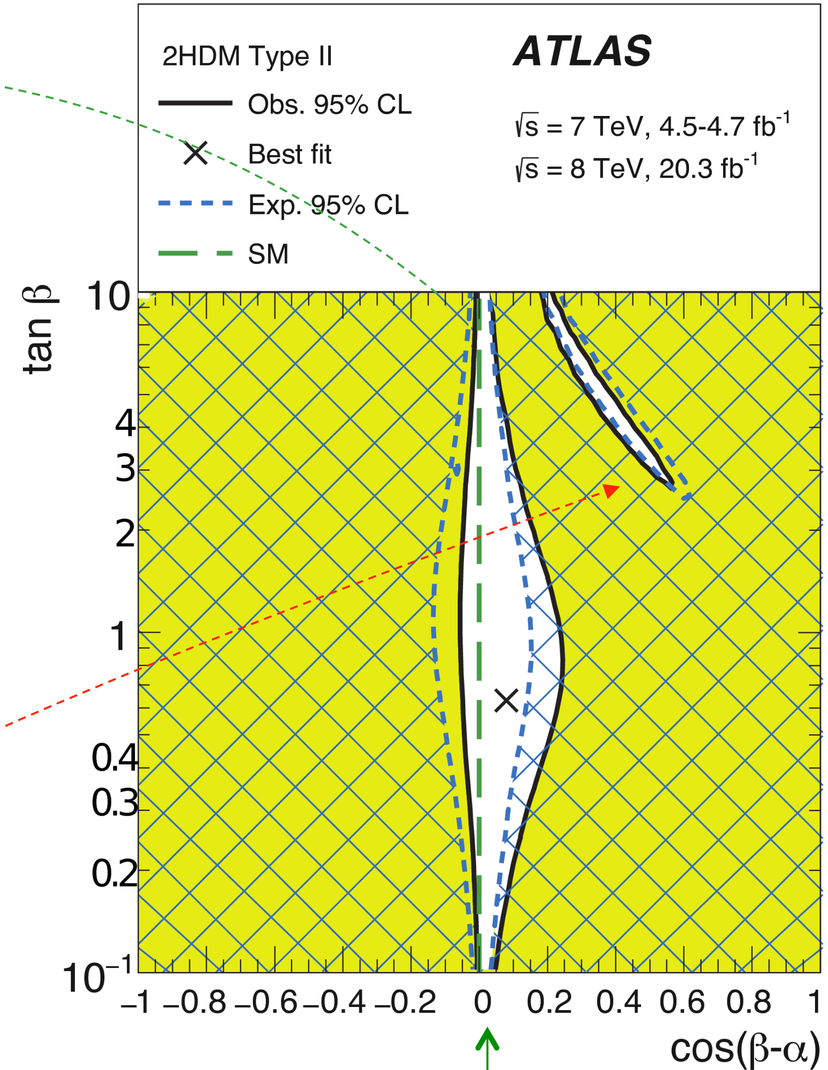
$\kappa_V = \sin(\beta - \alpha)$

$\kappa_u = \cos(\alpha)/\sin(\beta)$

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

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

Remapped to 2HDM-Type 2

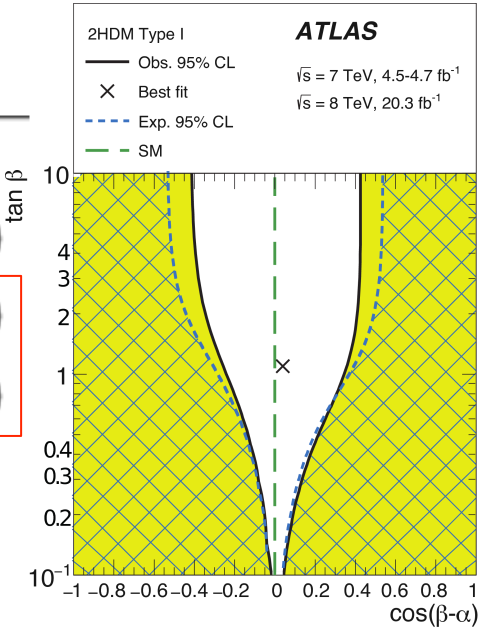


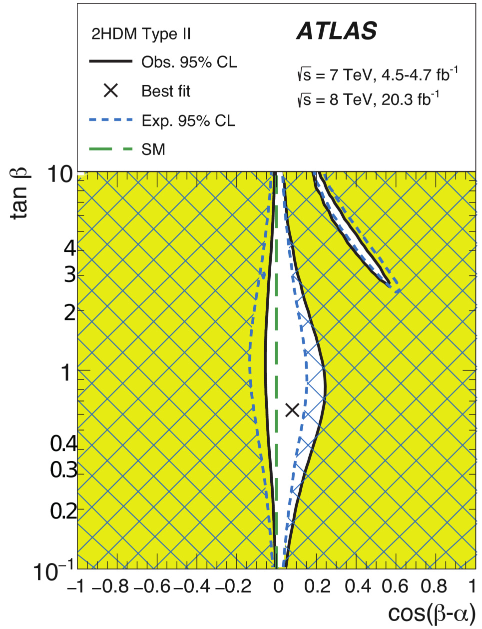
SM alignment limit cos(β-α)=0

SM extensions with additions H boson – 2 Higgs doublets

Type 1

κ_V	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$



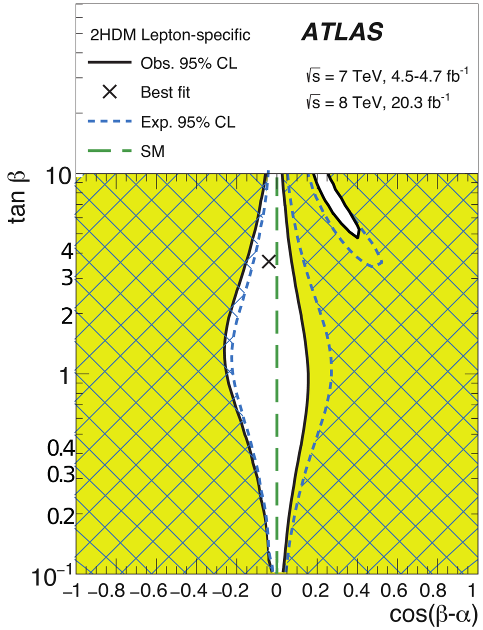


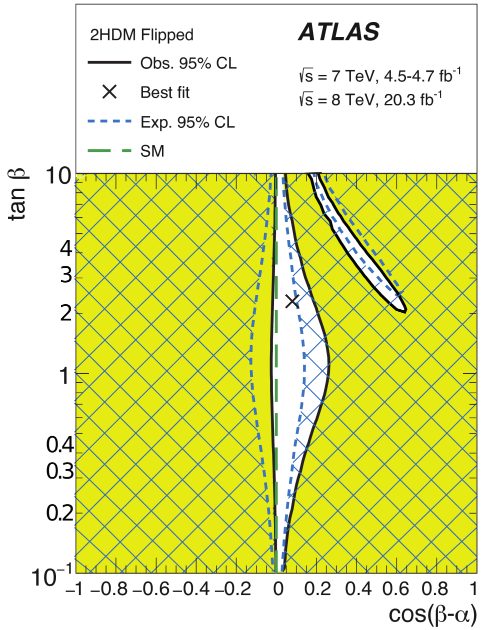
Type 2

κ_V	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$
κ_d	$-\sin(\alpha)/\cos(\beta)$
κ_l	$-\sin(\alpha)/\cos(\beta)$

Lepton-specific

κ_V	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$
κ_l	$-\sin(\alpha)/\cos(\beta)$





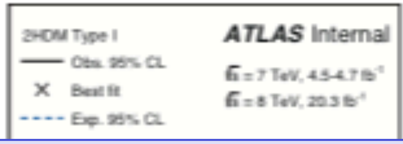
Flipped

κ_V	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$
κ_d	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$

SM extensions with additions H boson – 2 Higgs doublets

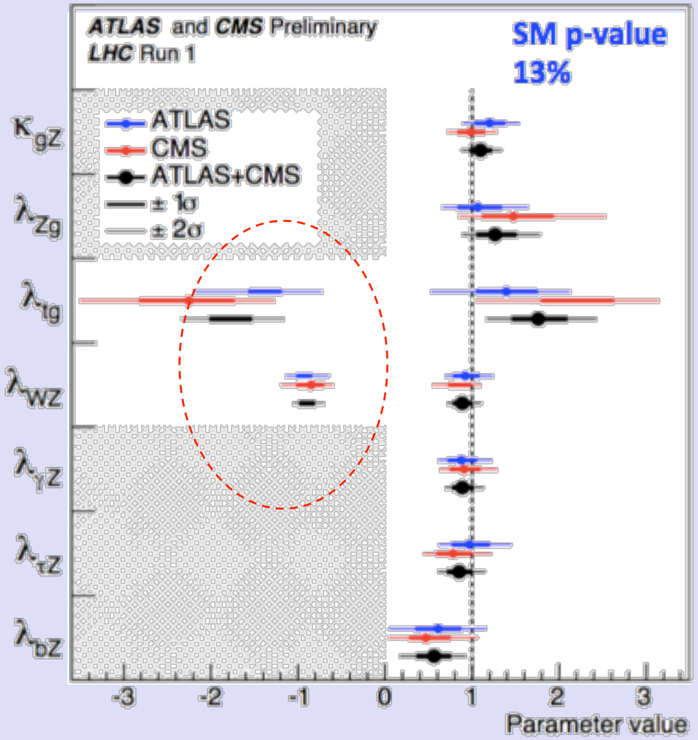
Type 1

κ_V	$\sin($
κ_u	$\cos(\alpha$
κ_d	$\cos(\alpha$
κ_l	$\cos(\alpha$



Type 2

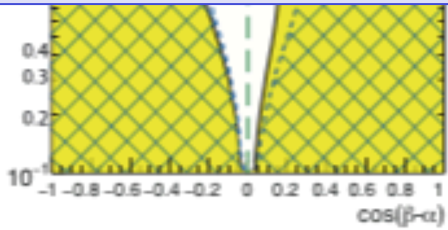
κ_V	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$
κ_d	$-\sin(\alpha)/\cos(\beta)$
κ_l	$-\sin(\alpha)/\cos(\beta)$



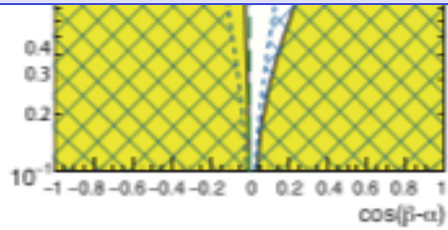
NB: New ATLAS+CMS combined result does not yet eliminate negative sign solutions

Lepton-s

κ_V	$\sin(\beta$
κ_u	$\cos(\alpha)/$
κ_d	$\cos(\alpha)/$
κ_l	$-\sin(\alpha)/\cos(\beta)$



(c) Lepton-specific



(d) Flipped

Flipped

κ_V	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$
κ_d	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$

Beyond 2HDM-Type 2 – A simplified MSSM (hMSSM)

- In MSSM mixing between *h* and *H* is described by

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

Radiative corrections (primarily involving top/stop quarks)

If sub-leading correction δ_1 is ignored → can express M_S fully in m_A, tanβ
→ can express coupling scale factors for $\kappa_V, \kappa_u, \kappa_d$ in m_A and tanβ

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

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

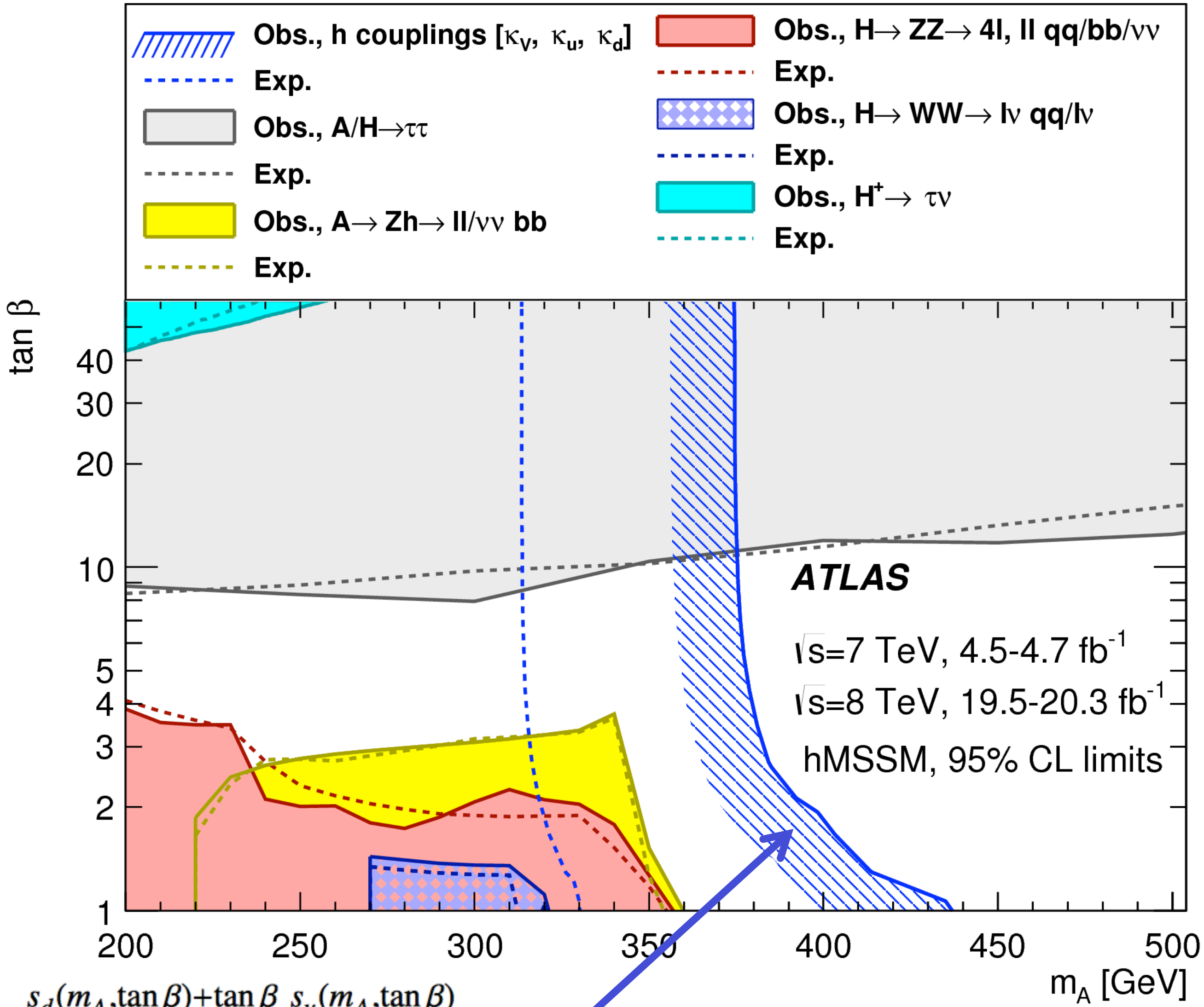
$$\kappa_u = s_u(m_A, \tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

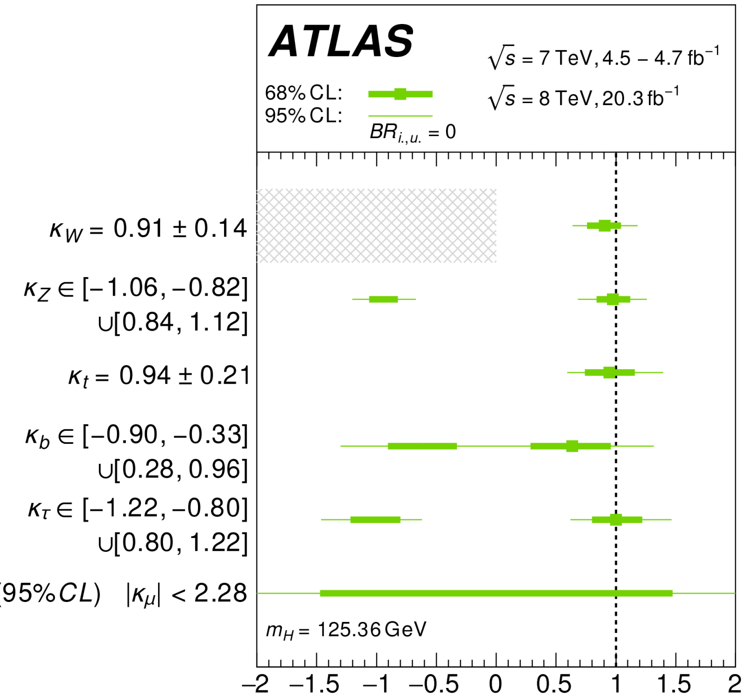
$$s_d = \frac{(m_A^2 + m_Z^2)\tan\beta}{m_Z^2 + m_A^2\tan^2\beta - m_h^2(1+\tan^2\beta)}\, s_u$$

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

Simplified MSSM

- Limits in m_A,tanβ space from light Higgs couplings in simplified MSSM model





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

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

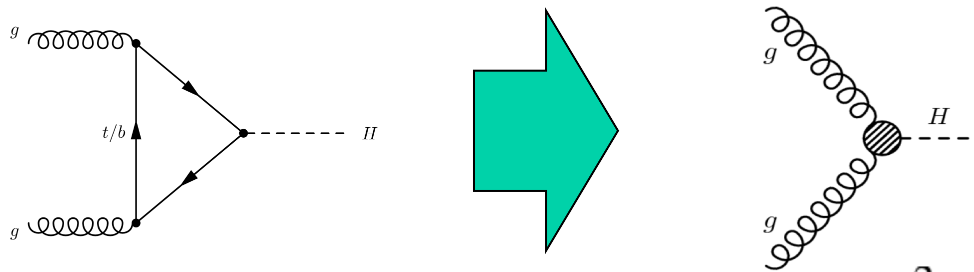
$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta}\quad ,$$

SM decoupling limit at m_A=∞

The κ framework – dealing with invisible decays

- Results shown so far assumed no invisible (BSM) Higgs decays nor BSM contributions to loops. Now drop these assumptions.
- Represent loop processes with effective parameters, rather than assuming SM loop content

'SM resolved'



'effective coupling'

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

$$\kappa_g^2$$

- Allowing invisible decays to contribute to total width

$$\Gamma_H(\kappa_j, \mathrm{BR_{i.,u.}}) = \frac{\kappa_H^2(\kappa_j)}{(1 - \mathrm{BR_{i.,u.}})} \Gamma_H^{\mathrm{SM}}$$

If BR(i.u.) >0 then all observed cross-sections lowered by common factor

$$\sigma(i \to H \to f) = \frac{\sigma_i(\kappa_j) \cdot \Gamma_f(\kappa_j)}{\Gamma_H(\kappa_j)}$$

Limit on invisible Higgs decays from Higgs couplings

- Concept: set limit on BR to invisible or undetected decays $BR_{u.i.}$

$$\Gamma_H(\kappa_j, \mathrm{BR}_{\mathrm{i.,u.}}) = \frac{\kappa_H^2(\kappa_j)}{(1 - \mathrm{BR}_{\mathrm{i.,u.}})} \Gamma_H^{\mathrm{SM}}$$

- When k_H is modeled by 6+3 k_i's it has no strong upper bound
  → BRinv not bounded (Γ_H due to large k_H or to large BR_{iu}?)
  → Must introduce some assumptions to bound k_H

- Scenario 1 – Assume 6 tree-level couplings at SM (k=*1*),
  but leaving effective couplings for loops floating

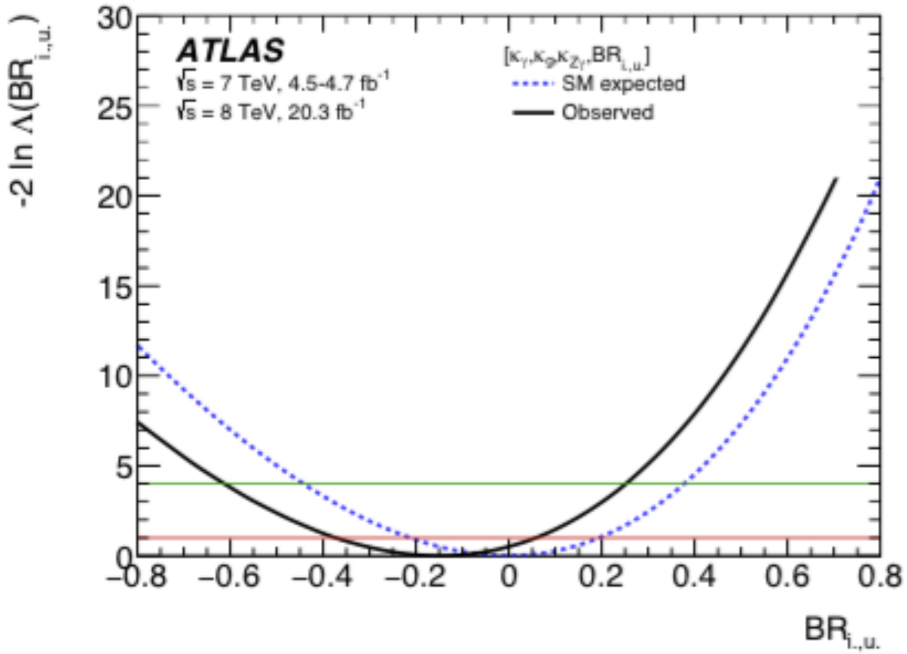
- Scenario 2 – Keep all 6+3 coupling parameters floating,
  but bound vector boson couplings k_W,k_Z<1

  (Bound k_V<1 occurs naturally in many BSM physics models, e.g. EWS, 2HDM, MCHM…)

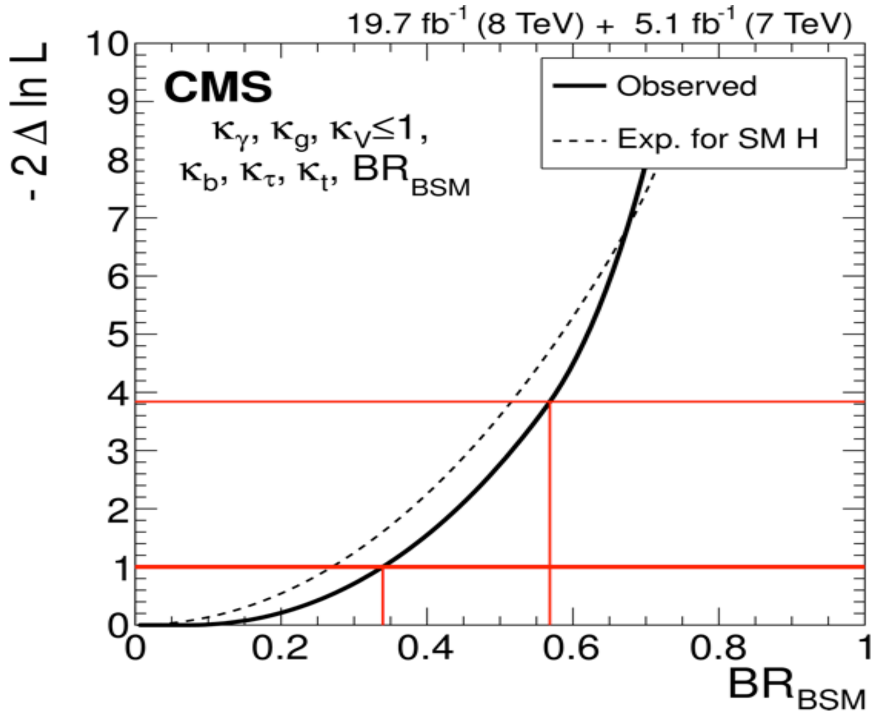
(alternatively, use off-shell coupling strength measurements to constrain Γ_H, albeit with additional assumptions)

Limit on invisible Higgs decays from Higgs couplings

- Assuming SM-like treel-level couplings (loop couplings profiled)



- Assuming kV<1 (loop and fundamental couplings profiled)

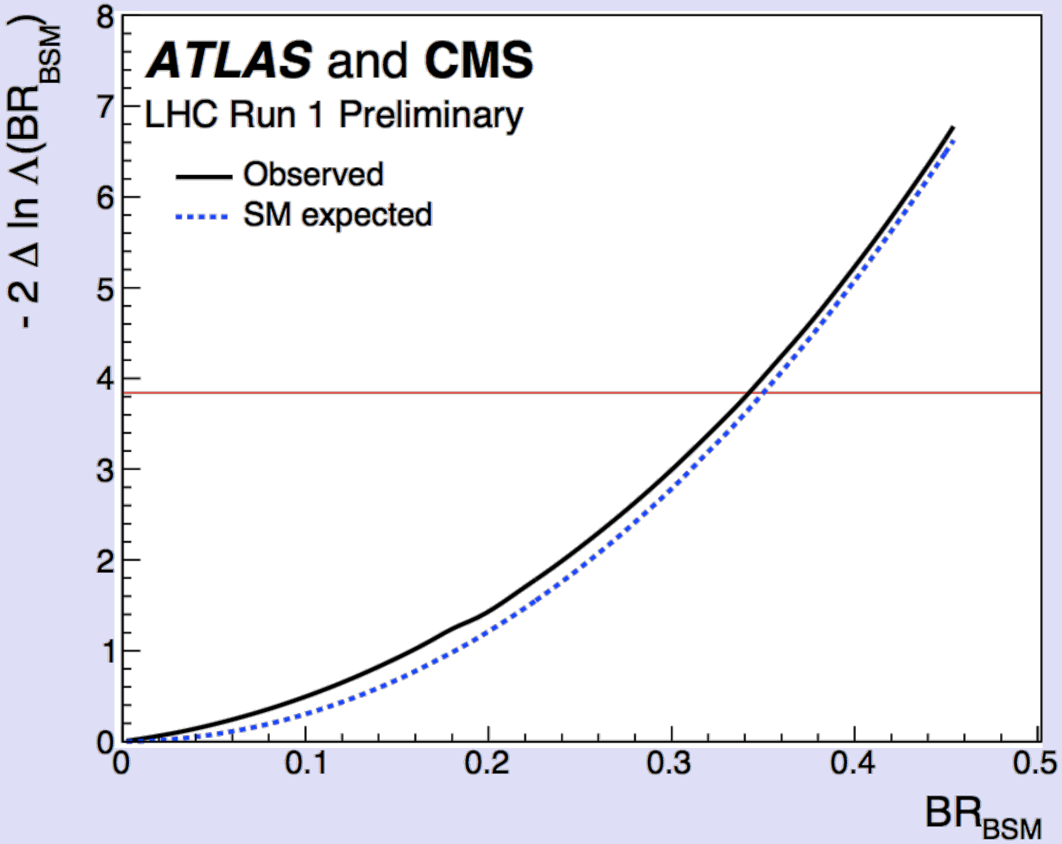


ATLAS $BR_{u.i.}$ <0.27 (95% C.L) exp<0.37
CMS $BR_{u.i.}$ < 0.32 (95% C.L.) exp<0.42

ATLAS $BR_{u.i.}$<0.49 (95% C.L.) exp<0.48
CMS $BR_{u.i.}$ <0.57 (95% C.L.) exp<0.52

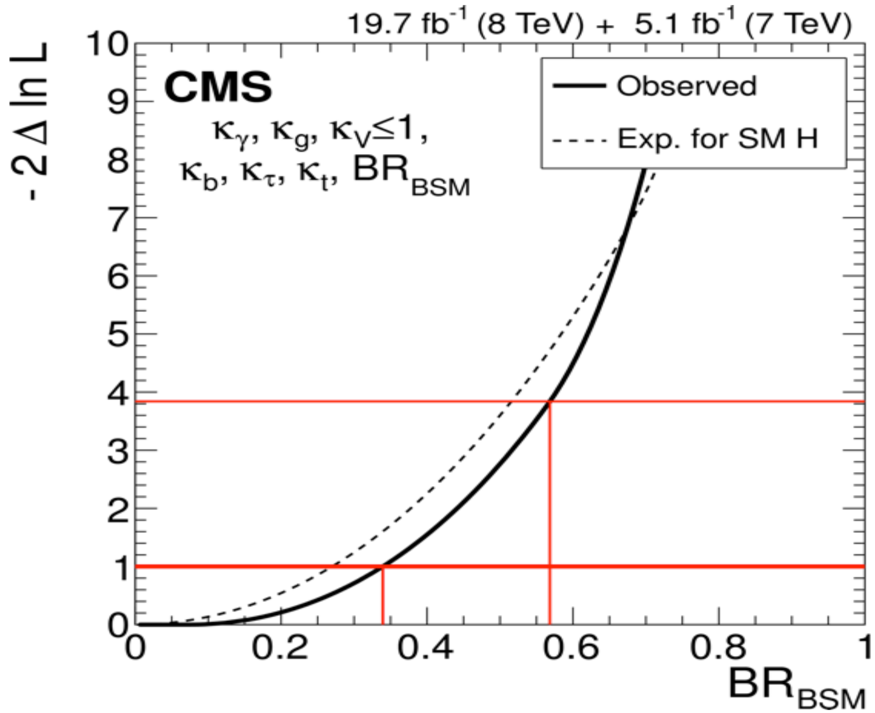
ATLAS observed better than SM expected due to observed global strength > 1

Limit on invisible Higgs decays from Higgs couplings



New combined ATLAS+CMS result
$BR_{u.i.}$ < 0.34 (95% C.L.)
assuming kV<1 (all couplings floating)

- Assuming kV<1 (loop and tree-level couplings profiled)



ATLAS $BR_{u.i.}$<0.49 (95% C.L.) exp<0.48
CMS $BR_{u.i.}$ <0.57 (95% C.L.) exp<0.52

What about direct limits on H→inv decays

- Searches for associated (VH) or VBF Higgs productions with H→invisible decays also set limits on Br_{inv}
  - Experimental signature: associated products plus large missing ET
- Individual ATLAS and CMS searches in ZH, WH and VBF channels set limits between 182% and 28%

Reference	Process	Experiment	Observed limit	Expected limit
PRL 112, 201802 (2014)	Z(-> ll) H	ATLAS	75%	62%
EPJC 74 (2014) 2980	Z(-> ll) H	CMS	83%	86%
EPJC 74 (2014) 2980	Z(-> bbar) H	CMS	182%	199%
EPJC (2015) 75:337	V(W/Z -> jets) H	ATLAS	78%	86%
CMS-PAS-EXO-12-055	V/jet + E_T^{miss}	CMS	53%	62%
CMS-PAS-HIG-14-038	VBF H -> inv	CMS	57%	40%
ATLAS-CONF-2015-004	VBF H -> inv	ATLAS	28%	31%

Direct searches assume SM Higgs production rate!

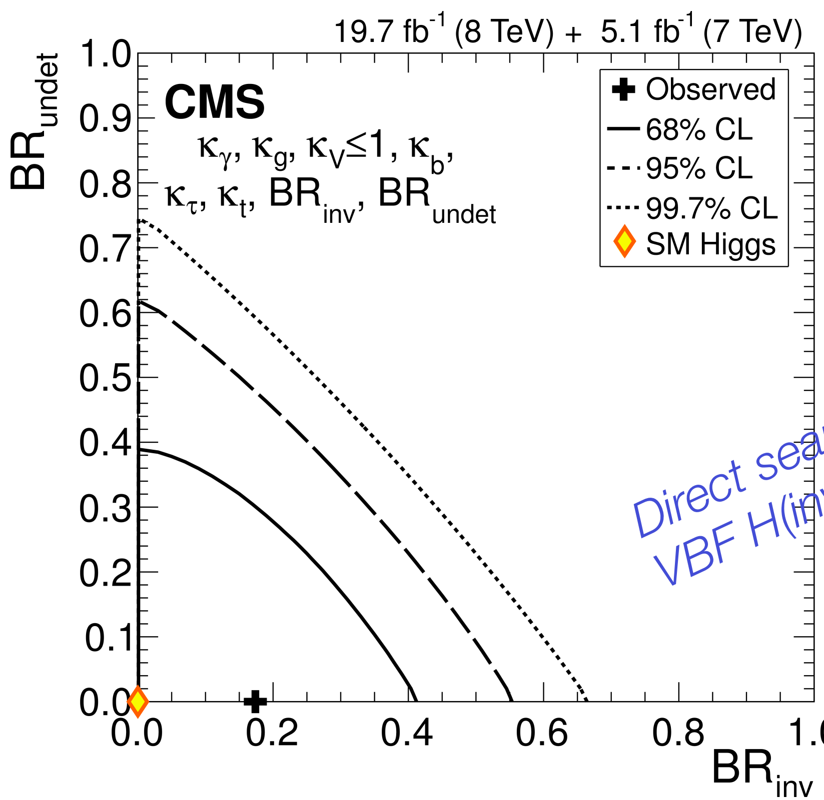
VBF searches most powerful…

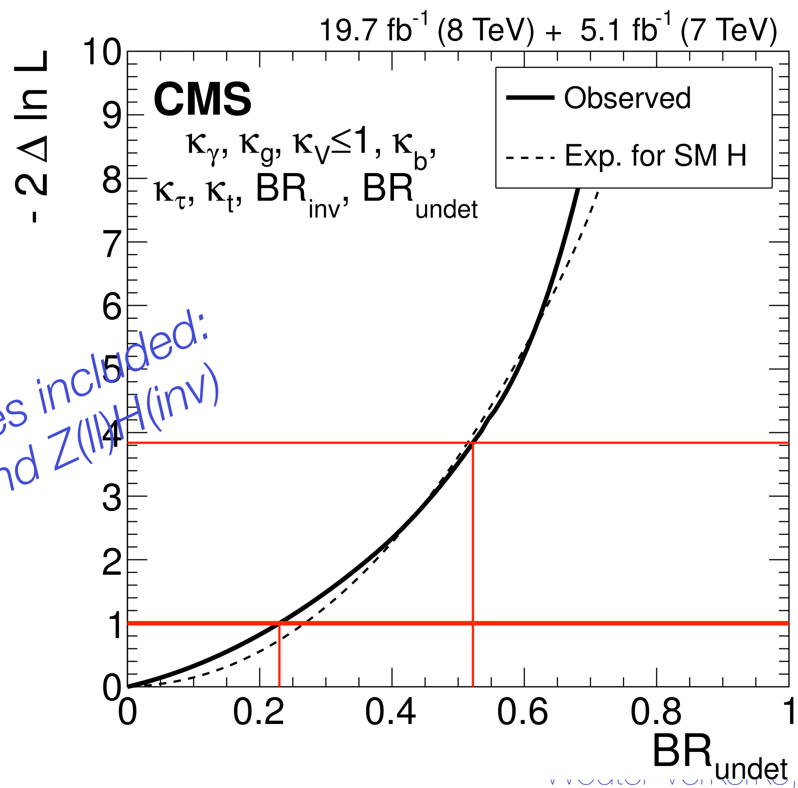
ATLAS HIGG-2015-03 ATLAS Direct Combined result: BR_{inv} < 0.25 at 95% C.L. (<0.27 expected)

CMS PAS HIG-14-038 CMS Direct Combined result: BR_{inv} < 0.46 at 95% C.L. (<0.35 expected)

Combining direct and indirect measurements

- **Indirect** measurements from couplings measure sum of invisible decays (BR_{inv}) and undetected decays (BR_{undet}, e.g. BSM H decays to lepton+jets)
- **Direct** searches requiring MET only constrain invisible decays (BR_{inv})
- Can (weakly) constrain BR_{undet} by combining direct & indirect measurements



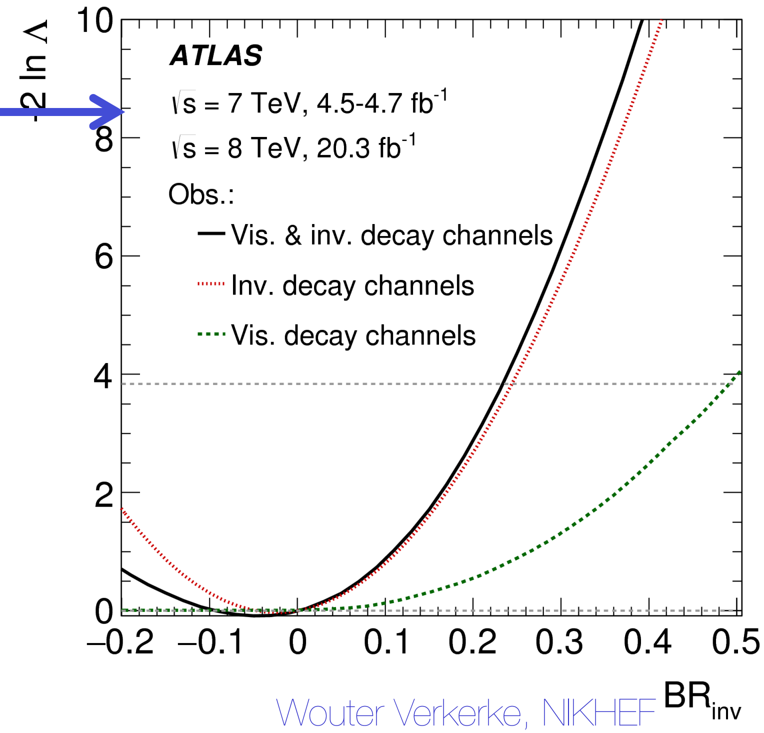


Combining direct and indirect measurements

- Alternatively, (conservatively) assume BR_{undet}=0 → Both direct and indirect searches measure BR_{inv}
- In direct searches can release assumption of SM production rate
  → substitute measured rate from couplings fit
- In coupling fit can release assumption k_V<1
  → direct limit on BR_{inv} is sufficiently strong to bound Γ_H

Includes VBFHinv+ZllHinv

Most general result (assumes only BR_{undet}=0)
ATLAS: **BR_{inv}<0.23 at 95% C.L.** (exp <0.24)
CMS: **BR_{inv}< 0.49 at 95% C.L.** (exp<0.32)
(assumes kV<1)



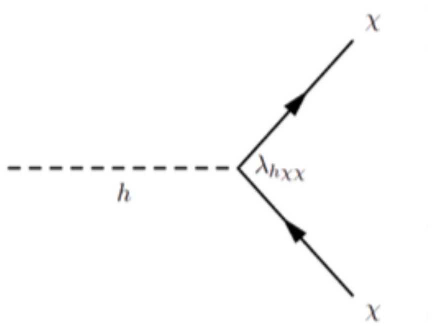
ATLAS

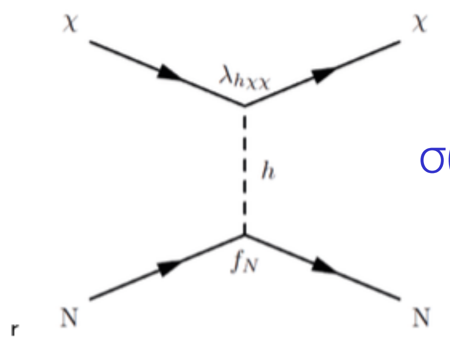
Decay channels	Coupling parameterisation	κ_i assumption	Upper limit on BR_{inv} Obs.	Exp.
Invisible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$	$\kappa_{W,Z,g} = 1$	0.25	0.27
Visible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$	$\kappa_{W,Z} \leq 1$	0.49	0.48
Inv. & vis. decays	$[\boldsymbol{\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}}, \mathbf{BR_{inv}}]$	**None**	**0.23**	**0.24**
Inv. & vis. decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, BR_{inv}]$	$\kappa_{W,Z} \leq 1$	0.23	0.23

Interpreting H→inv as BSM physics: Higgs portal model

- Higgs portal model: *h* decays to invisible WIMP pairs
  → Can map BR(h→WIMP) to WIMP/nucleon cross-section

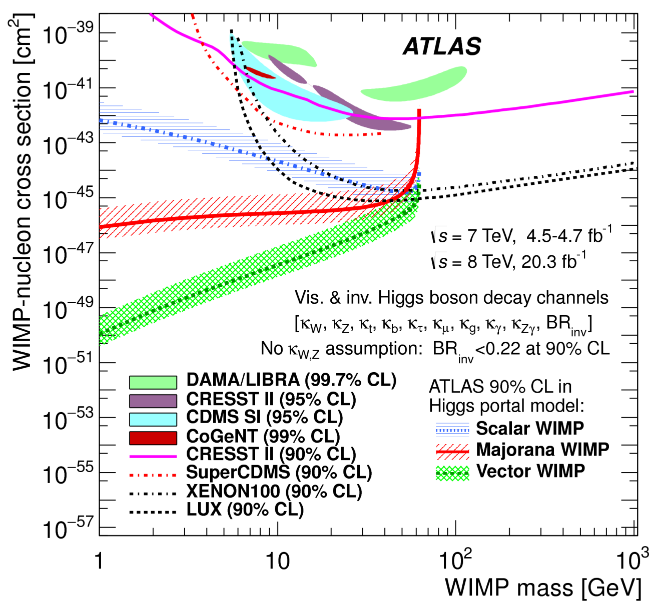
BR(h→χχ)



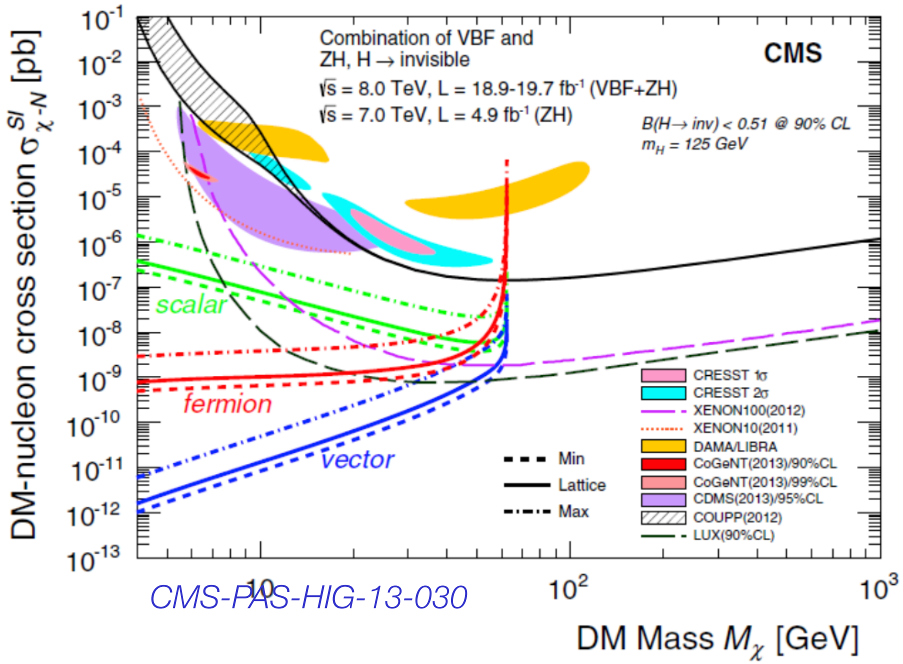


σ(Nχ→Nχ) *NB: σ depends on assumed spin X*

ATLAS: BR_{inv}<0.22 **at 90% C.L**



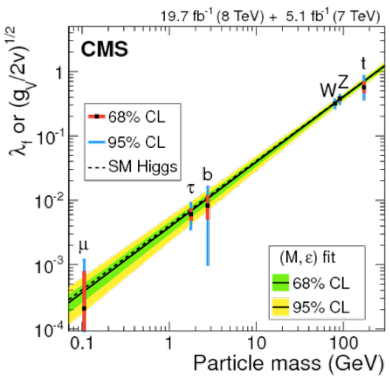
CMS: BR_{inv}<0.51 **at 90% C.L**

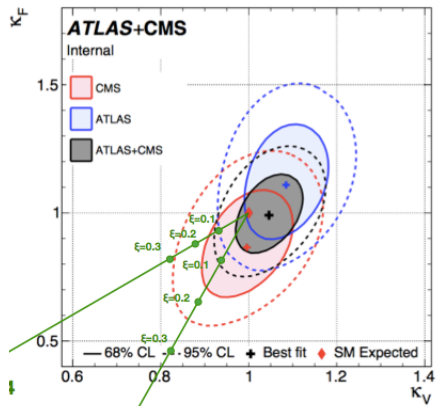


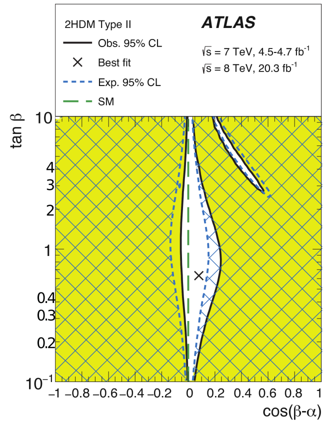
CMS-PAS-HIG-13-030

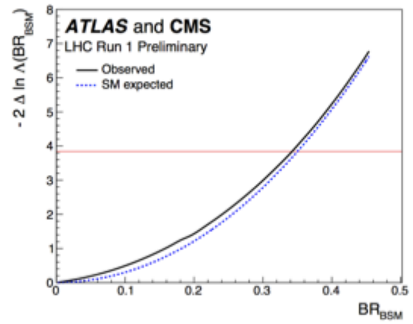
Summary

- Experimental constraints on Higgs couplings from ATLAS/CMS run-1 data strongly restrict parameter space of many BSM models (EW singlet, 2HDM, MCHM, hMSSM, Higgs portal to DM)









- Both coupling fits and direct searches constrain BR(H→inv). A combined limit exploiting both sources makes minimal assumptions and restricts BR(inv)<0.23 at 95% C.L.

- Most (coupling) measurements statistics dominated, additional data of Run-2 data will allow for significant improvement in precision.