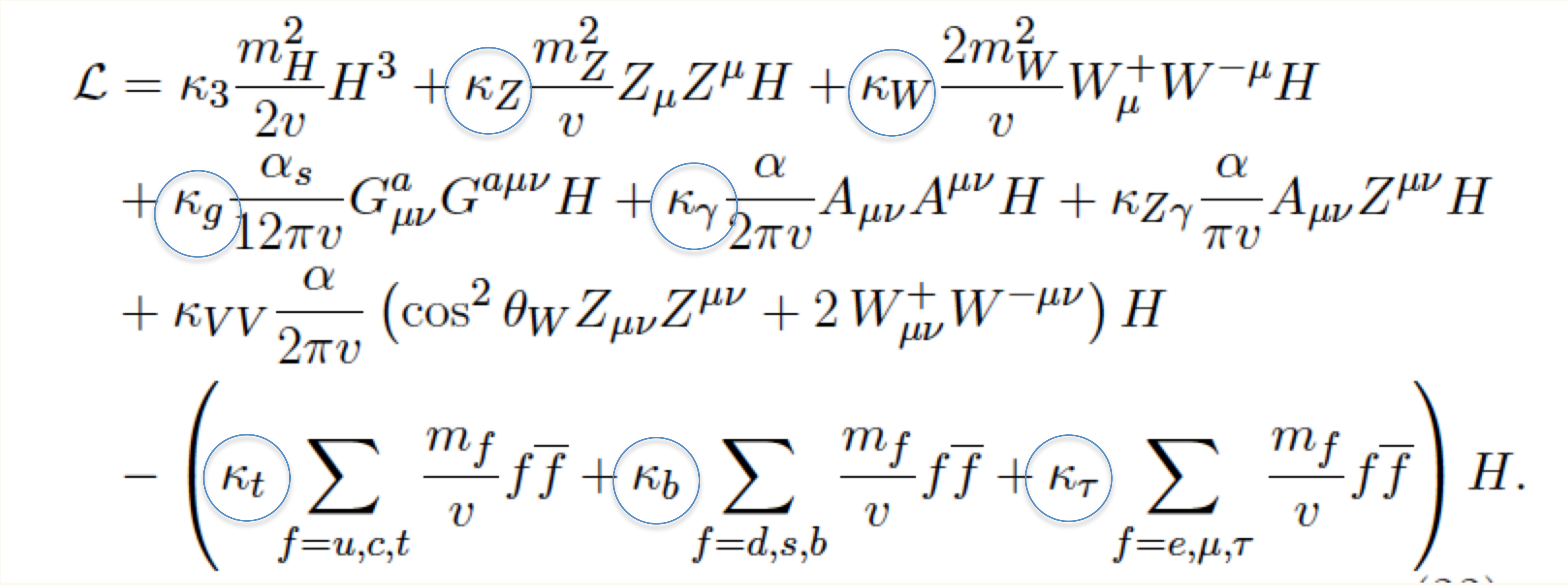


$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$+ \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W^+_{\mu\nu} W^{-\mu\nu}\right) H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H.$$

Eilam Gross, Weizmann Institute of Science

HIGGS HIGGS HIGGS HIGGS HIGGS HIGGS

Acknowledgements : Marumi Kado, Liron Barak

Preface and Outline

The discovery of the Higgs Boson (July 4th 2012) is already starring in movies and books.

We now celebrate two years to Higgs discovery.

This talk is about the distance we have all gone since the declaration of Higgs Hunters' independence…

Searches →**Precision** measurements

Mass

Signal Strengths (cross section X BR)

Couplings

Off-shellness and width

Rare decays

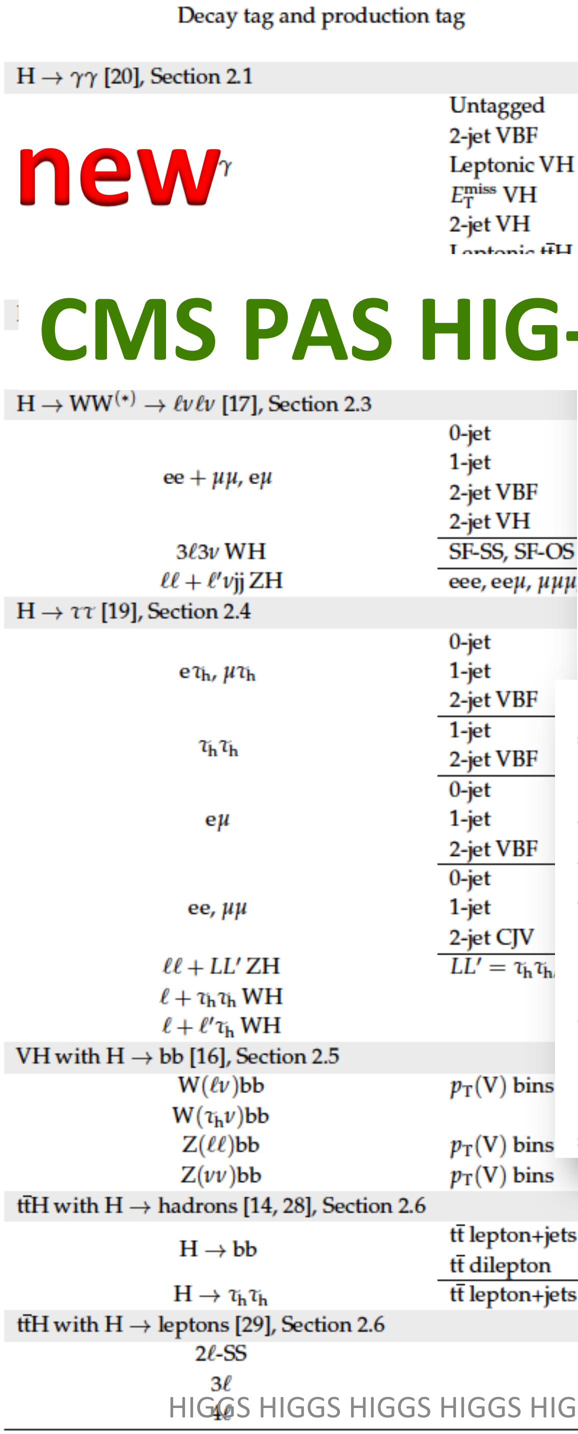
La Combinaison

ATLAS CMS ....not just yet..... but it's coming...

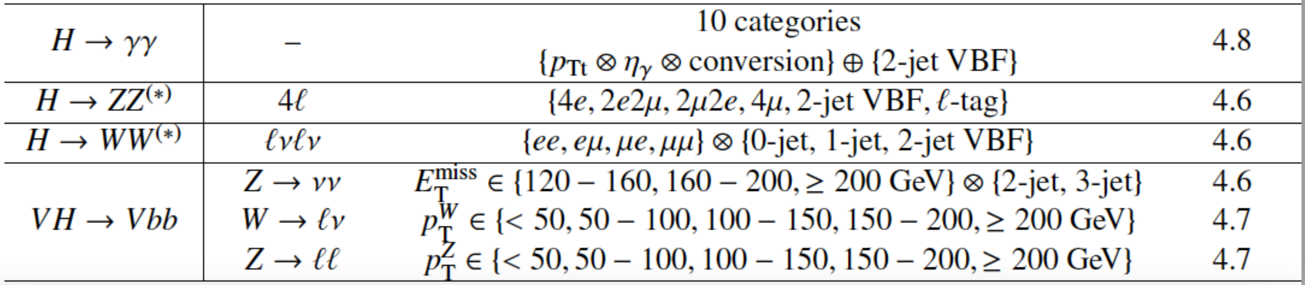
new

CMS PAS HIG-14-009

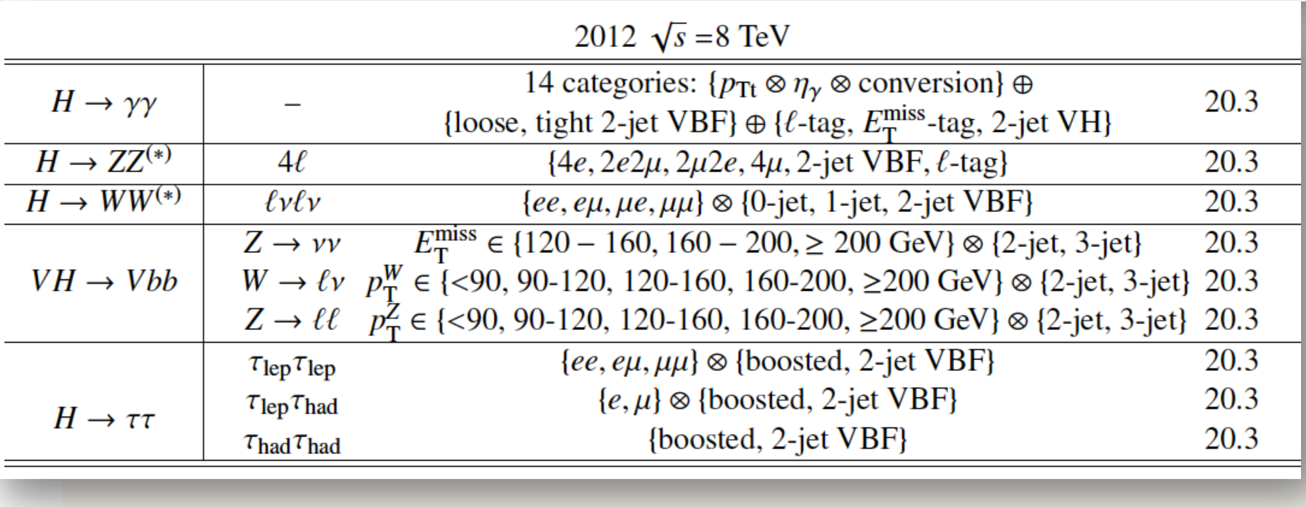
ATLAS-CONF-2014-009



Decay tag and production tag	
$H \to \gamma\gamma$ [20], Section 2.1	
γ	Untagged 2-jet VBF Leptonic VH E_T^{miss} VH 2-jet VH Leptonic $t\bar{t}$H
$H \to WW^{(*)} \to \ell\nu\ell\nu$ [17], Section 2.3	
ee + $\mu\mu$, eμ	0-jet 1-jet 2-jet VBF 2-jet VH
$3\ell3\nu$ WH	SF-SS, SF-OS
$\ell\ell + \ell'\nu jj$ ZH	eee, eeμ, $\mu\mu\mu$
$H \to \tau\tau$ [19], Section 2.4	
eτ_h, $\mu\tau_h$	0-jet 1-jet 2-jet VBF
$\tau_h\tau_h$	1-jet 2-jet VBF
eμ	0-jet 1-jet 2-jet VBF
ee, $\mu\mu$	0-jet 1-jet 2-jet CJV
$\ell\ell + LL'$ ZH	$LL' = \tau_h\tau_h$,
$\ell + \tau_h\tau_h$ WH	
$\ell + \ell'\tau_h$ WH	
VH with $H \to bb$ [16], Section 2.5	
W($\ell\nu$)bb	p_T(V) bins
W($\tau_h\nu$)bb	
Z($\ell\ell$)bb	p_T(V) bins
Z($\nu\nu$)bb	p_T(V) bins
$t\bar{t}$H with $H \to$ hadrons [14, 28], Section 2.6	
$H \to bb$	$t\bar{t}$ lepton+jets $t\bar{t}$ dilepton
$H \to \tau_h\tau_h$	$t\bar{t}$ lepton+jets
$t\bar{t}$H with $H \to$ leptons [29], Section 2.6	
2ℓ-SS	
3ℓ	
4ℓ	



$H \to \gamma\gamma$	–	10 categories $\{p_{Tt} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet VBF}\}$	4.8
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu, \text{2-jet VBF}, \ell\text{-tag}\}$	4.6
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet VBF}\}$	4.6
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	4.6
	$W \to \ell\nu$	$p_T^W \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	4.7
	$Z \to \ell\ell$	$p_T^Z \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	4.7



		2012 $\sqrt{s}$ =8 TeV	
$H \to \gamma\gamma$	–	14 categories: $\{p_{Tt} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus$ $\{\text{loose, tight 2-jet VBF}\} \oplus \{\ell\text{-tag}, E_T^{miss}\text{-tag}, \text{2-jet VH}\}$	20.3
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu, \text{2-jet VBF}, \ell\text{-tag}\}$	20.3
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet VBF}\}$	20.3
$VH \to Vbb$	$Z \to \nu\nu$	$E_T^{miss} \in \{120-160, 160-200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	20.3
	$W \to \ell\nu$	$p_T^W \in \{<90, 90\text{-}120, 120\text{-}160, 160\text{-}200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	20.3
	$Z \to \ell\ell$	$p_T^Z \in \{<90, 90\text{-}120, 120\text{-}160, 160\text{-}200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	20.3
$H \to \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{ee, e\mu, \mu\mu\} \otimes \{\text{boosted, 2-jet VBF}\}$	20.3
	$\tau_{lep}\tau_{had}$	$\{e, \mu\} \otimes \{\text{boosted, 2-jet VBF}\}$	20.3
	$\tau_{had}\tau_{had}$	$\{\text{boosted, 2-jet VBF}\}$	20.3

Mass of the Newly Discovered Scalar

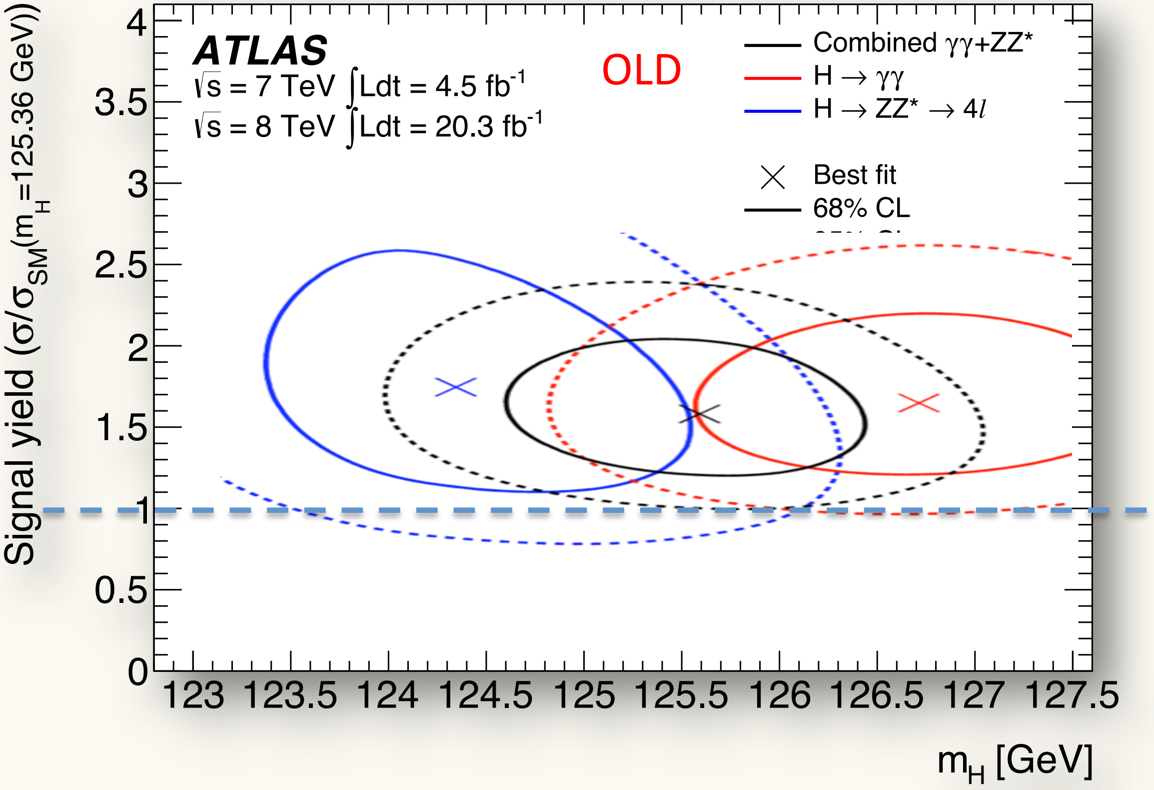
Mass of the Newly Discovered Scalar

ATLAS
OLD

$$\mu^{ZZ}(125.5) = 1.5 \ \pm 0.4$$

OLD

$$\mu^{\gamma\gamma}(125.5) = 1.6 \ \pm 0.30$$



OLD

OLD $m_H^{ZZ} = 124.3 \ ^{+0.6}_{-0.5} \ \text{(stat)} \ ^{+0.5}_{-0.3} \ \text{(syst)} \ \text{GeV}$ $m_H^{\gamma\gamma} = 126.8 \ \pm 0.2 \ \text{(stat)} \ \pm 0.7 \ \text{(syst)} \ \text{GeV}$

OLD ATLAS old $m_H = 125.5 \pm 0.2\text{(stat)}^{+0.5}_{-0.6}(\text{syst}) \ \text{GeV}$

$$\Delta m = 2.3 \pm 0.9$$

$$\text{Compatibility } 2.4\sigma$$

Mass of the Newly Discovered Scalar

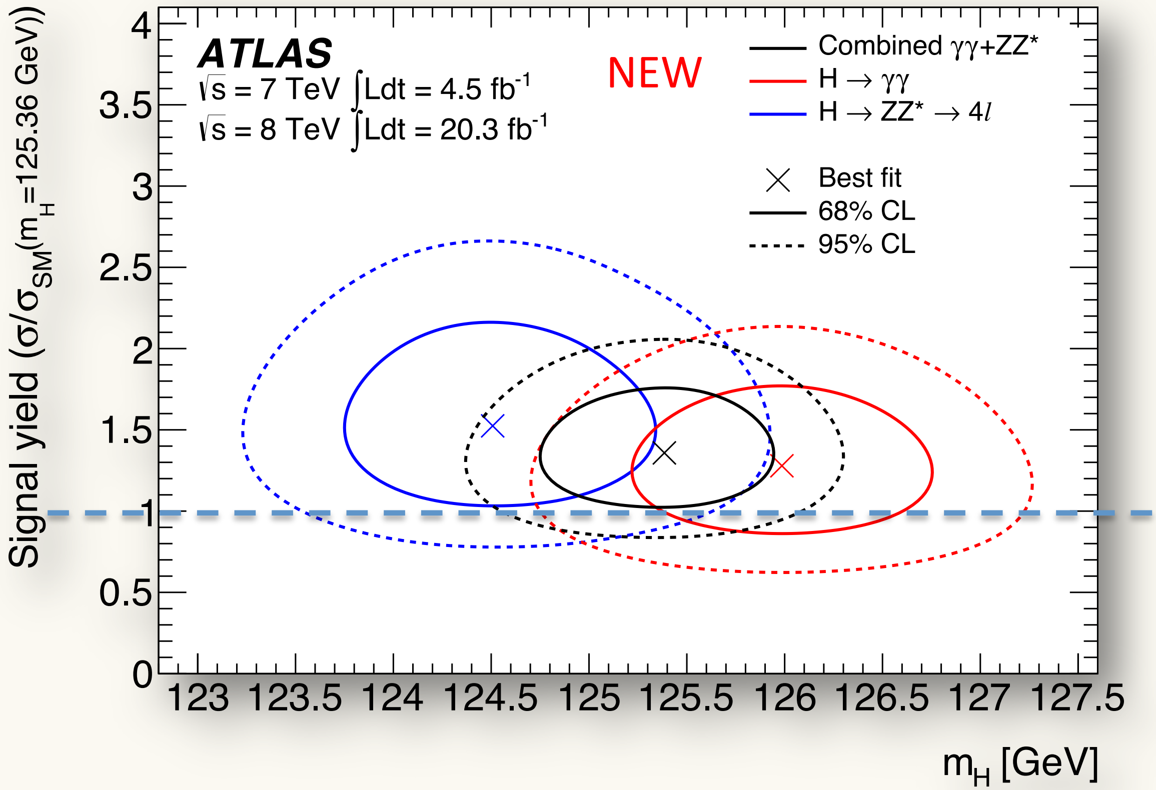
ATLAS

OLD

$$\mu^{ZZ}(125.5) = 1.5 \ \pm 0.4$$

OLD

$$\mu^{\gamma\gamma}(125.5) = 1.6 \ \pm 0.30$$



OLD $m_H^{ZZ} = 124.3 \ ^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV $m_H^{\gamma\gamma} = 126.8 \ \pm 0.2$ (stat) ± 0.7 (syst) GeV

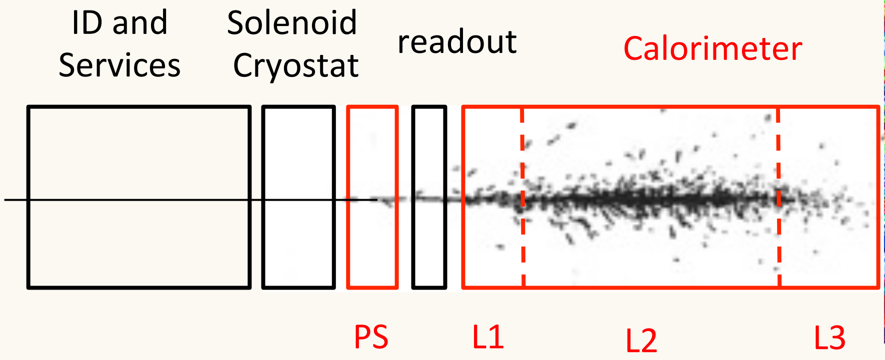
OLD ATLAS old $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})$ GeV

$$\Delta m = 2.3 \pm 0.9$$

Compatibility 2.4σ

Understanding the Detector → IMPROVED SYSTEMATICS

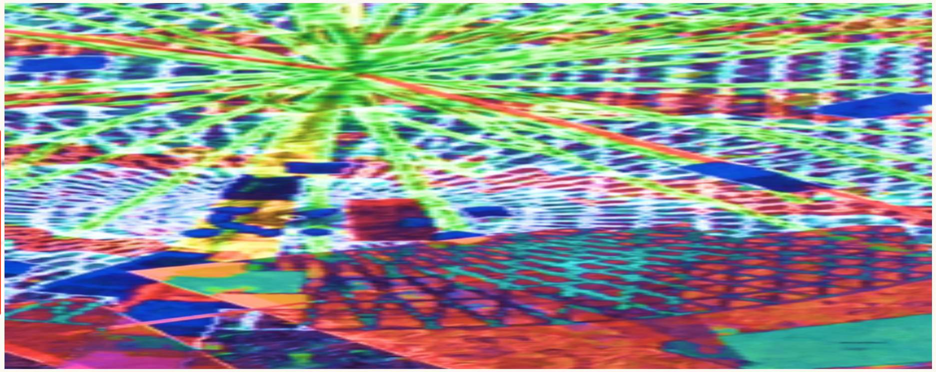
ATLAS $H \to \gamma\gamma, 4\ell$

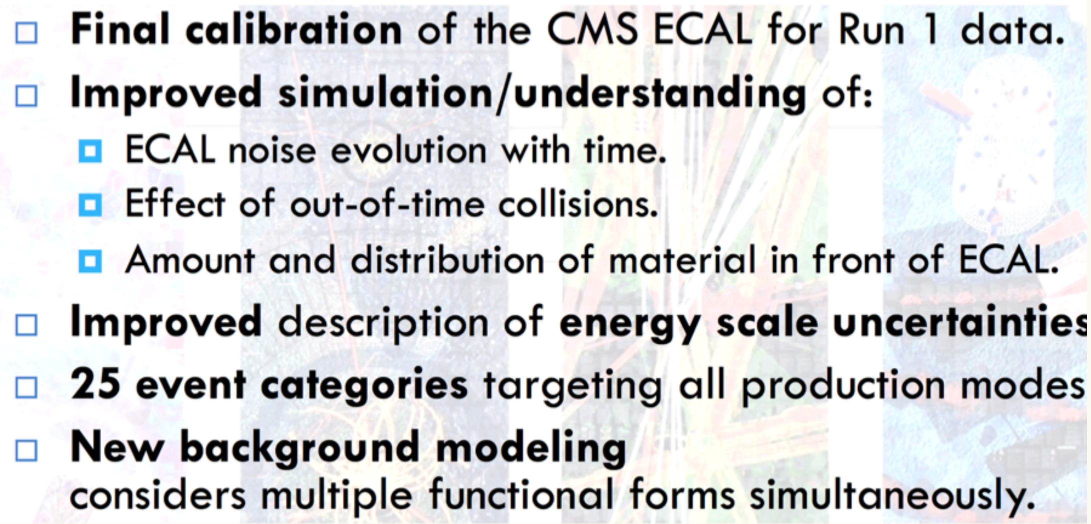


- Recalibration of Layers and gains
- Muon momentum calibration
- Electron and Photon energy calibration
- Better and more accurate material description

- Categories for mass in the diphoton
- FSR recovery & corrections
- BDT-ZZ & per event errors

CMS $H \to \gamma\gamma$





- **Final calibration** of the CMS ECAL for Run 1 data.
- **Improved simulation/understanding** of:
  - ECAL noise evolution with time.
  - Effect of out-of-time collisions.
  - Amount and distribution of material in front of ECAL.
- **Improved** description of **energy scale uncertainties**
- **25 event categories** targeting all production modes
- **New background modeling** considers multiple functional forms simultaneously.

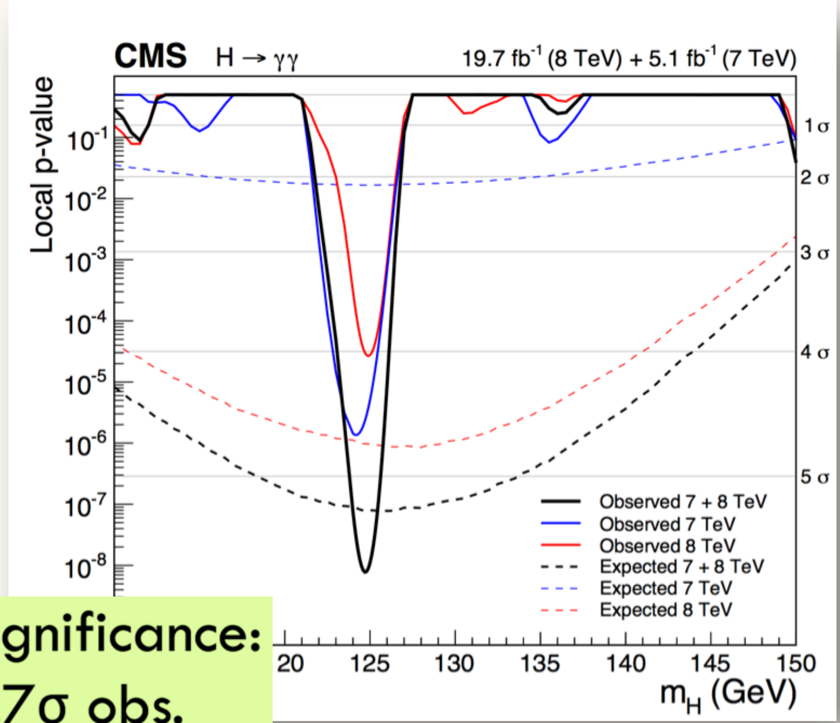
A. David ICHEP 2014

CMS di-photon shines

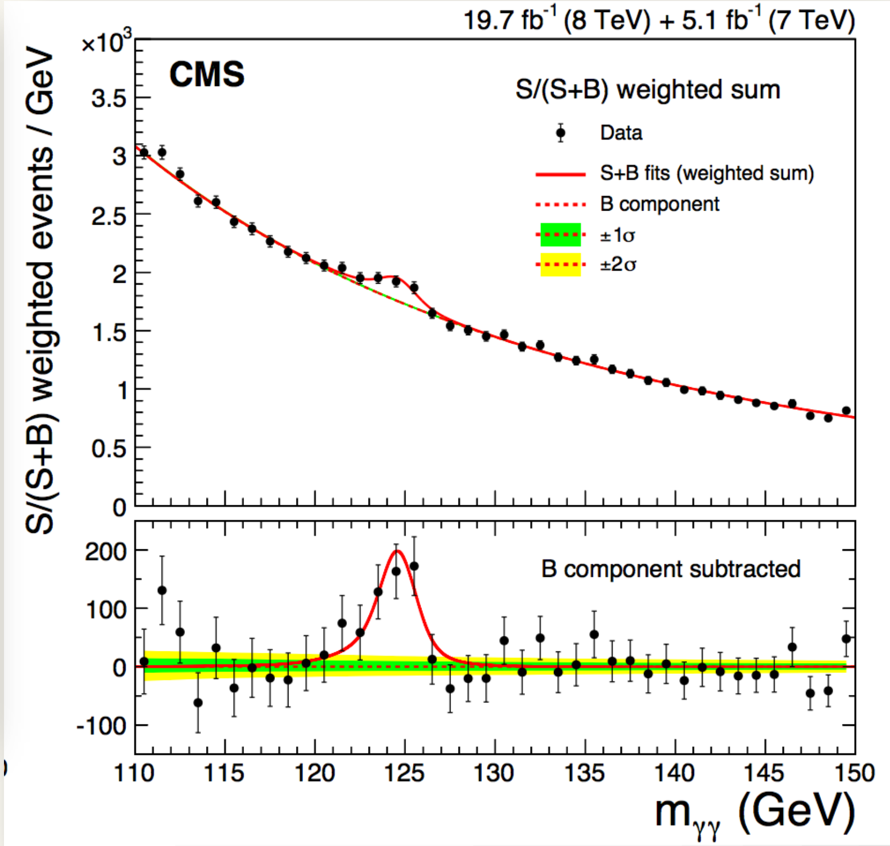
$$\sigma/\sigma_{SM} = 1.14^{+0.26}_{-0.23}\left[{}^{+0.21}_{-0.21}(\mathrm{stat.})^{+0.09}_{-0.05}(\mathrm{syst.})^{+0.13}_{-0.09}(\mathrm{th.})\right]$$

$$m_H = 124.70^{+0.35}_{-0.34}\left[0.31\ (\mathrm{stat}) \pm 0.15\ (\mathrm{syst})\right]\ \mathrm{GeV}$$

http://arxiv.org/pdf/1407.0558.pdf



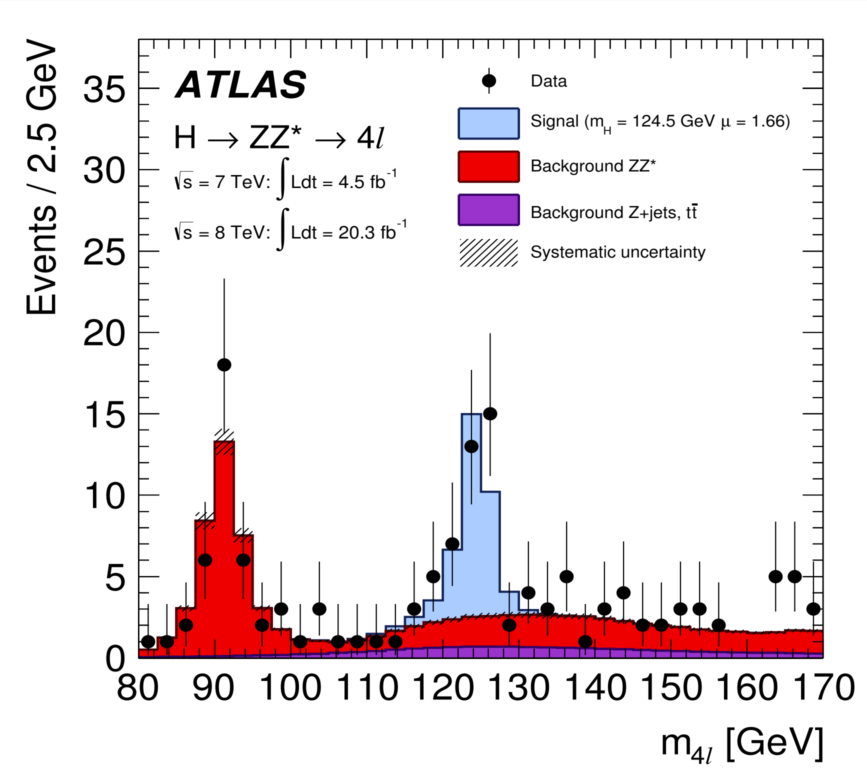
Significance:
5.7σ obs.
(5.2σ exp.)



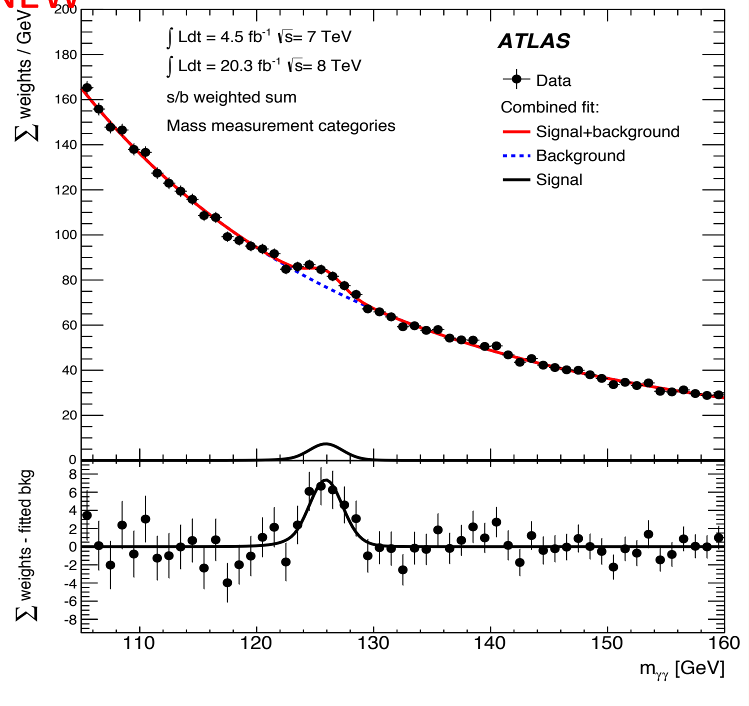
Mass of the Newly Discovered Scalar

ATLAS NEW

Submitted to PRD arXiv:1406.3827



ATLAS NEW



$$m_H^{ZZ} = 124.51 \pm 0.52 \text{ (stat) } \pm 0.06 \text{ (syst)}$$

$$m_H^{\gamma\gamma} = 125.98 \pm 0.42 \text{ (stat) } \pm 0.28 \text{ (syst)}$$

$$m_H = 125.36 \pm 0.37 \text{ (stat) } \pm 0.18 \text{ (syst) GeV}$$

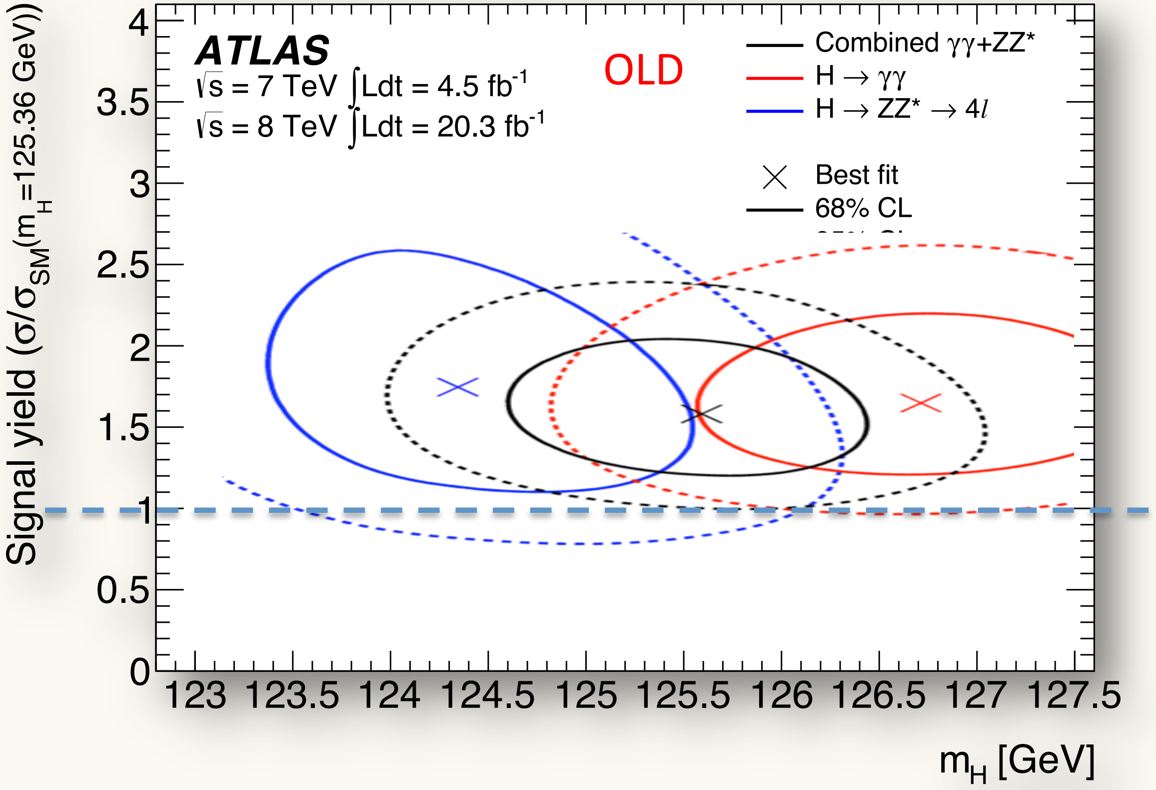
$$\Delta m = 1.47 \pm 0.72$$

Compatibility 1.97σ

Mass of the Newly Discovered Scalar

ATLAS
OLD

$$\mu_{ZZ}(124.3) = 1.7^{+0.5}_{-0.4}$$



OLD

$$\mu_{\gamma\gamma}(125.5) = 1.6 \pm 0.3$$

OLD $m_H^{ZZ} = 124.3\ ^{+0.6}_{-0.5}\ \text{(stat)}\ ^{+0.5}_{-0.3}\ \text{(syst) GeV}$ $m_H^{\gamma\gamma} = 126.8\ \pm 0.2\ \text{(stat)}\ \pm 0.7\ \text{(syst) GeV}$

OLD ATLAS old $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})$ GeV

$$\Delta m = 2.3 \pm 0.9$$

Compatibility 2.4σ

Mass of the Newly Discovered Scalar

ATLAS
OLD

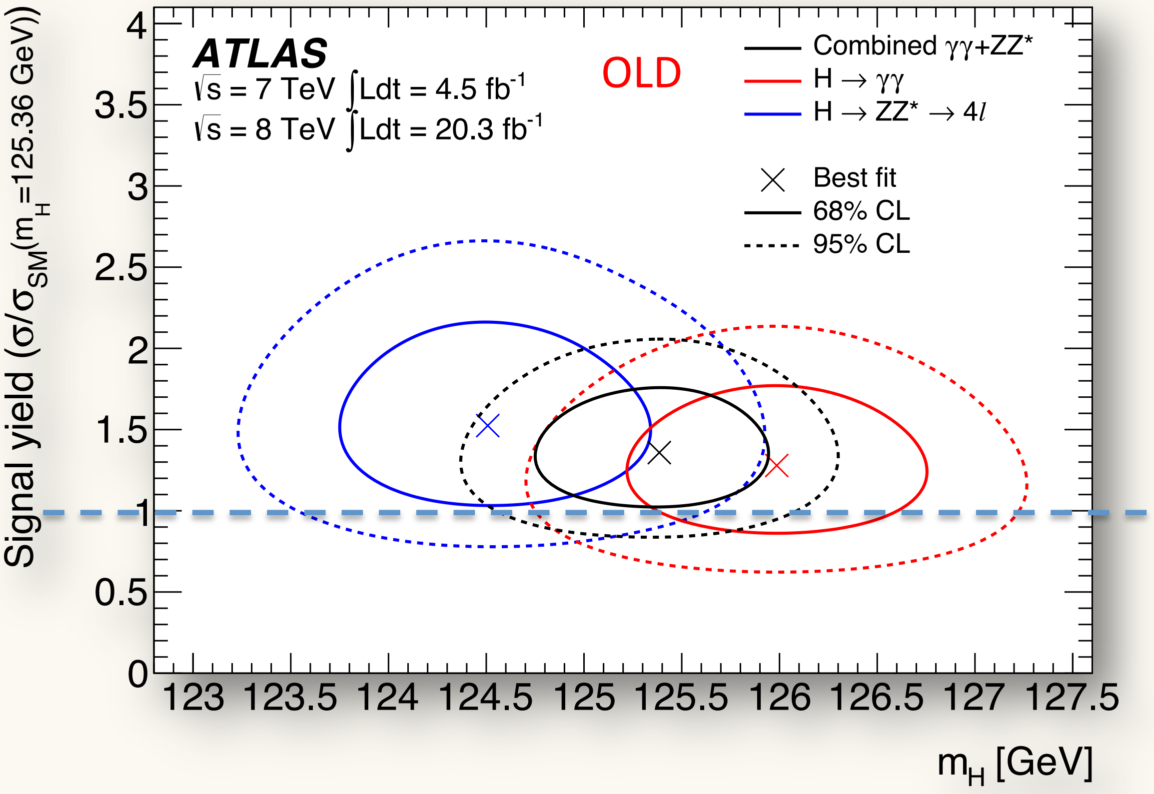
$$\mu_{ZZ}(124.3) = 1.7^{+0.5}_{-0.4}$$

N $\mu^{ZZ}(124.5) = 1.66\ ^{+0.45}_{-0.38}$

OLD

$$\mu_{\gamma\gamma}(125.5) = 1.6 \pm 0.3$$

N $\mu^{\gamma\gamma}(125.98) = 1.3\ \pm 0.30$



OLD $m_H^{ZZ} = 124.3\ ^{+0.6}_{-0.5}\ \text{(stat)}\ ^{+0.5}_{-0.3}\ \text{(syst)}\ \text{GeV}$ $m_H^{\gamma\gamma} = 126.8\ \pm 0.2\ \text{(stat)}\ \pm 0.7\ \text{(syst)}\ \text{GeV}$

N $m_H^{ZZ} = 124.51\ \pm 0.52\ \text{(stat)}\ \pm 0.06\ \text{(syst)}$ $m_H^{\gamma\gamma} = 125.98\ \pm 0.42\ \text{(stat)}\ \pm 0.28\ \text{(syst)}$

OLD ATLAS old $m_H = 125.5 \pm 0.2\text{(stat)}^{+0.5}_{-0.6}(\text{syst})\ \text{GeV}$

$$\Delta m = 2.3 \pm 0.9$$

Compatibility 2.4σ

N $m_H = 125.36\ \pm 0.37\ \text{(stat)}\ \pm 0.18\ \text{(syst)}\ \text{GeV}$

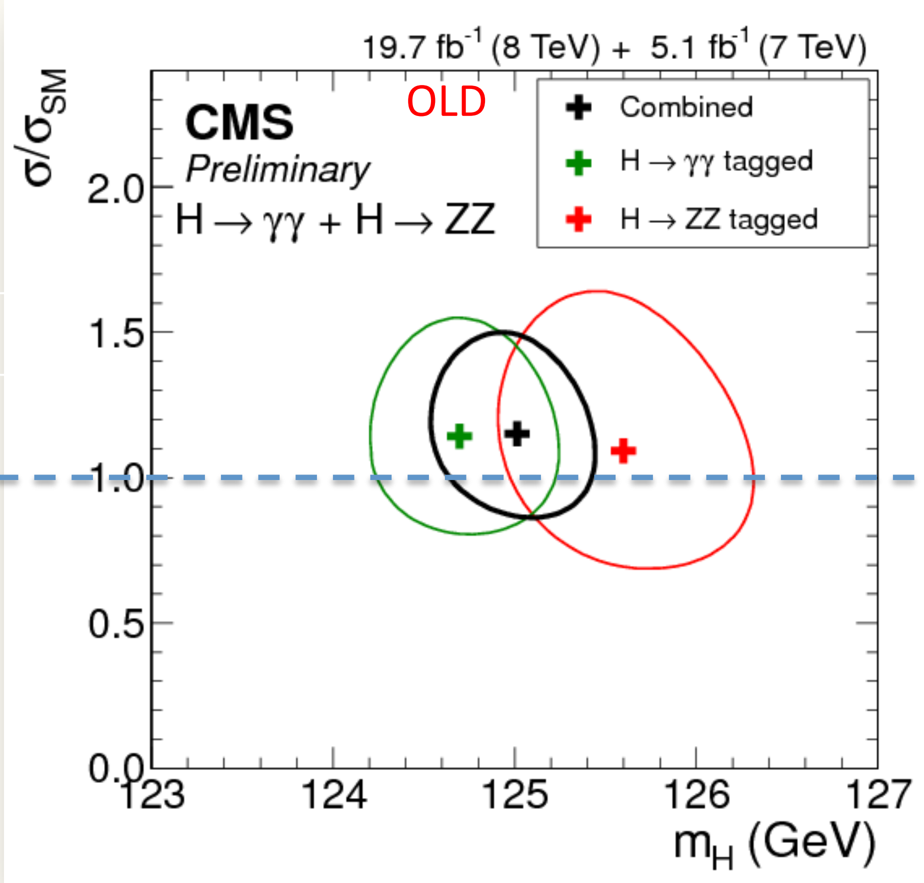
$$\Delta m = 1.47 \pm 0.72$$

Compatibility 1.97σ

Mass of the Newly Discovered Scalar

$$m_H^{ZZ} = 125.6\ \pm 0.4\ \text{(stat)} \pm 0.2\ \text{(syst)}\ \text{GeV}$$

N $m_H^{\gamma\gamma} = 124.7\ \pm 0.31\ \text{(stat)}\ \pm 0.15\ \text{(syst)}$



ATLAS

N $m_H = 125.36\ \pm 0.37\ \text{(stat)}\ \pm 0.18\ \text{(syst)}\ \text{GeV}$

$\Delta m = 1.47 \pm 0.72$

Compatibility 1.97σ

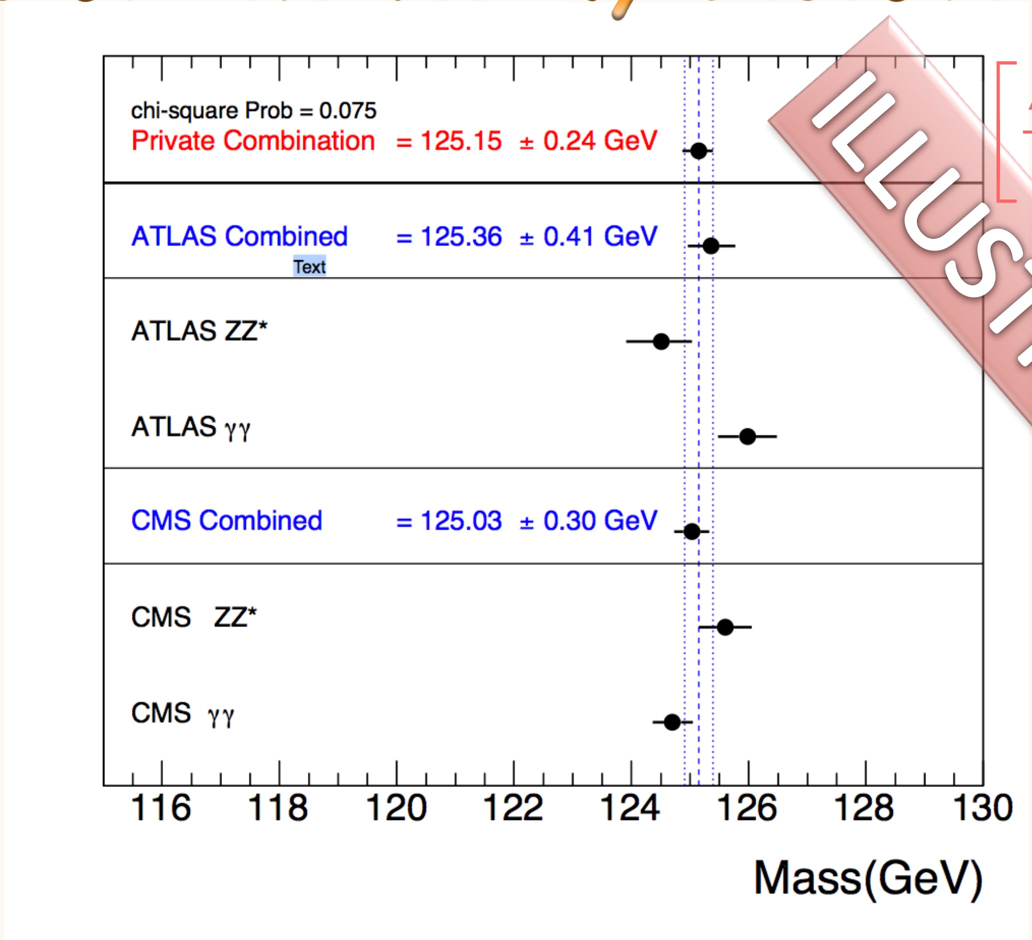
CMS

N $m_H = 125.03\ {}^{+0.26}_{-0.27}\ \text{(stat)}\ {}^{+0.13}_{-0.15}\ \text{(syst)}\ \text{GeV}$

$\Delta m = -0.87^{+0.54}_{-0.59}$

Compatibility 1.6σ

Mass of the Newly Discovered Scalar



$$\left[\frac{\Delta m}{m} = 0.2\%\right]$$

ATLAS

N $m_H = 125.36\ \pm 0.37\ \text{(stat)}\ \pm 0.18\ \text{(syst) GeV}$

$$\Delta m = 1.47 \pm 0.72$$

Compatibility 1.97σ

CMS

N $m_H = 125.03\ ^{+0.26}_{-0.27}\ \text{(stat)}\ ^{+0.13}_{-0.15}\ \text{(syst) GeV}$

$$\Delta m = -0.87^{+0.54}_{-0.59}$$

Compatibility 1.6σ

HIGGS Signal Strengths

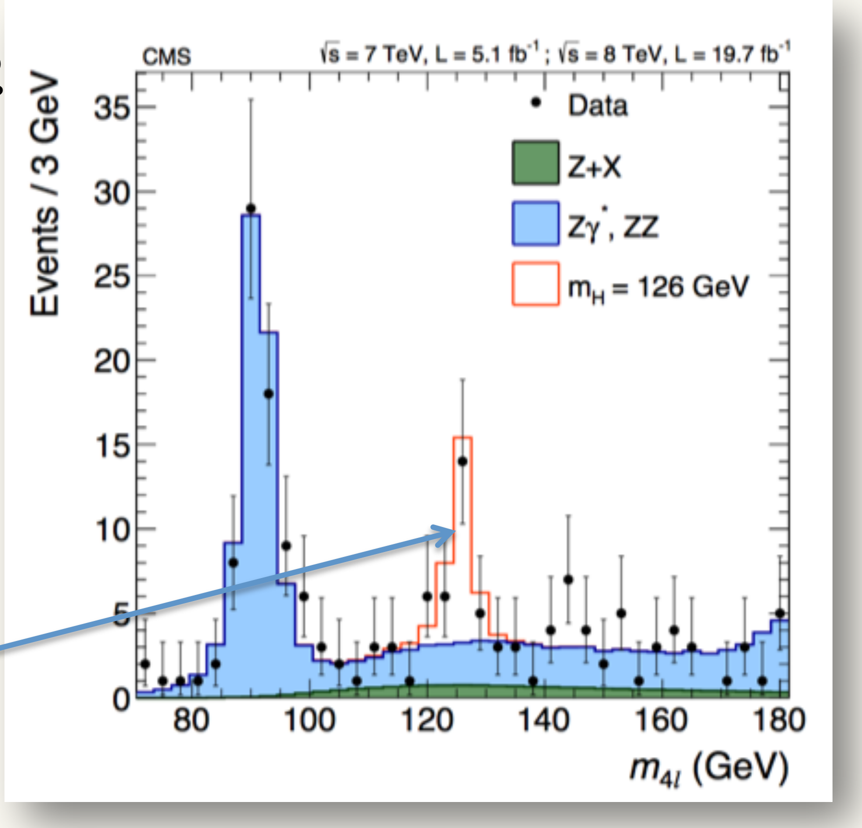
What do we measure

We measure event yields

We want to derive couplings and signal strengths

The first thing we want to measure is the the "signal strength" per channel

The analysis is using discriminators (usually reconstructed mass related) to increase S/B



$$n_s^i = \mu^i \times \sum\nolimits_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

$\mu_{ZZ}(@m_H = 125.5) = 1.44^{+0.40}_{-0.35}$ $6.6\sigma(4.4\sigma exp)$ *ATLAS*

$\mu_{ZZ}(@m_H = 124.5) = 1.66^{+0.45}_{-0.38}$ *ATLAS* mass analysis

$\mu_{ZZ}(@m_H = 124.7) = 0.93^{+0.26+0.13}_{-0.23-0.09}$ $6.8\sigma(6.7\sigma \exp)$ *CMS*

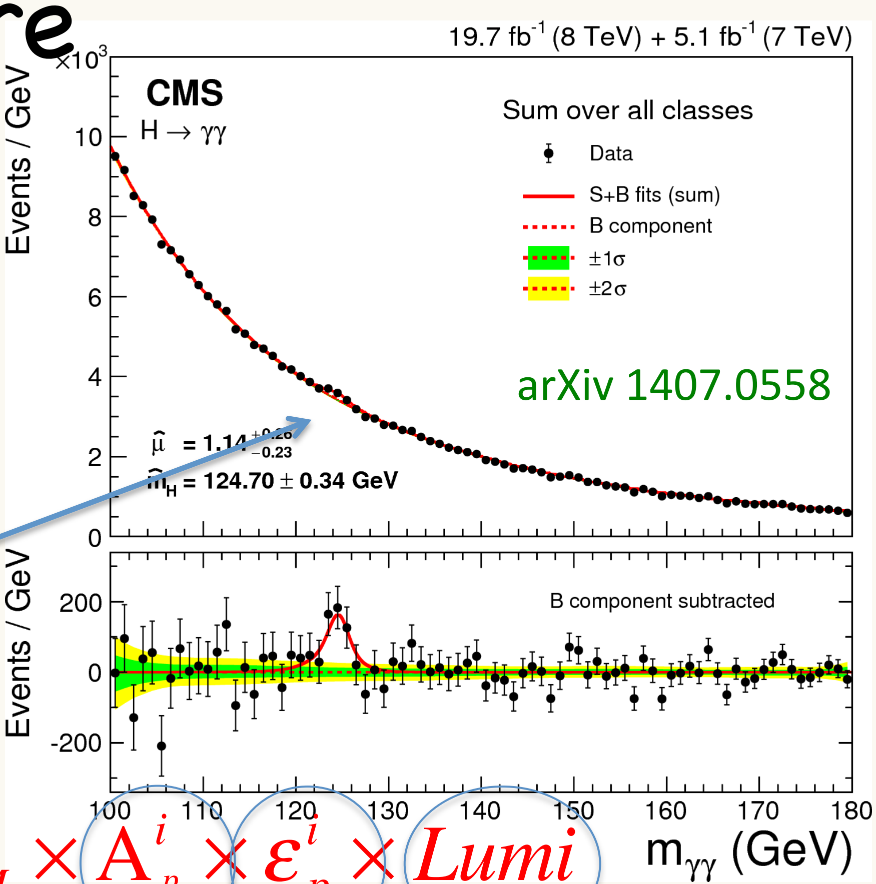
What do we measure

We measure event yields

We want to derive couplings and signal strengths

The first thing we want to measure is the the "signal strength" per channel

The analysis is using discriminators (usually reconstructed mass related) to increase S/B



$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

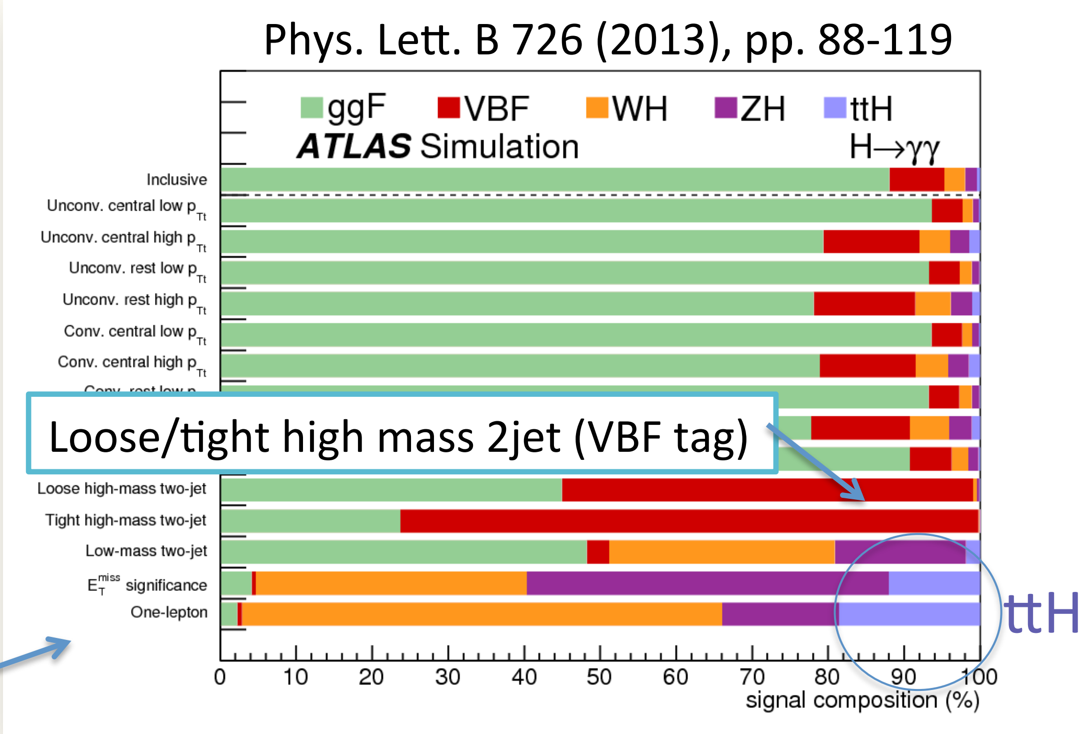
$\mu_{\gamma\gamma}(@m_H = 125.5) = 1.57^{+0.33}_{-0.28}$ $7.4\sigma(4.3\sigma\, exp)$ *ATLAS*

$\mu_{\gamma\gamma}(@m_H = 125.98) = 1.29^{+0.3}_{-0.3}$ *ATLAS* mass analysis

$\mu_{\gamma\gamma}(@m_H = 125.0) = 1.14^{+0.27}_{-0.23}$ $5.7\sigma(5.2\sigma\,\mathrm{exp})$ *CMS*

What do we measure

We increase sensitivity by classifying the events via categories and measure the signal strength per category and then combining them taking all the sytematic and statistical uncertainties into account


Phys. Lett. B 726 (2013), pp. 88-119

Loose/tight high mass 2jet (VBF tag)

ttH

The categories are also sensitive to different production modes, allowing the measurement of the couplings

$$n_s^{c,i} = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

Probe the Production Modes

Define

$$\mu_p^i \equiv \left[\mu_p \mu_{BR}^i\right] \qquad \mu_{BR}^i \equiv \frac{BR^i}{BR_{SM}^i}$$

Parameterize with explicit production modes and decays

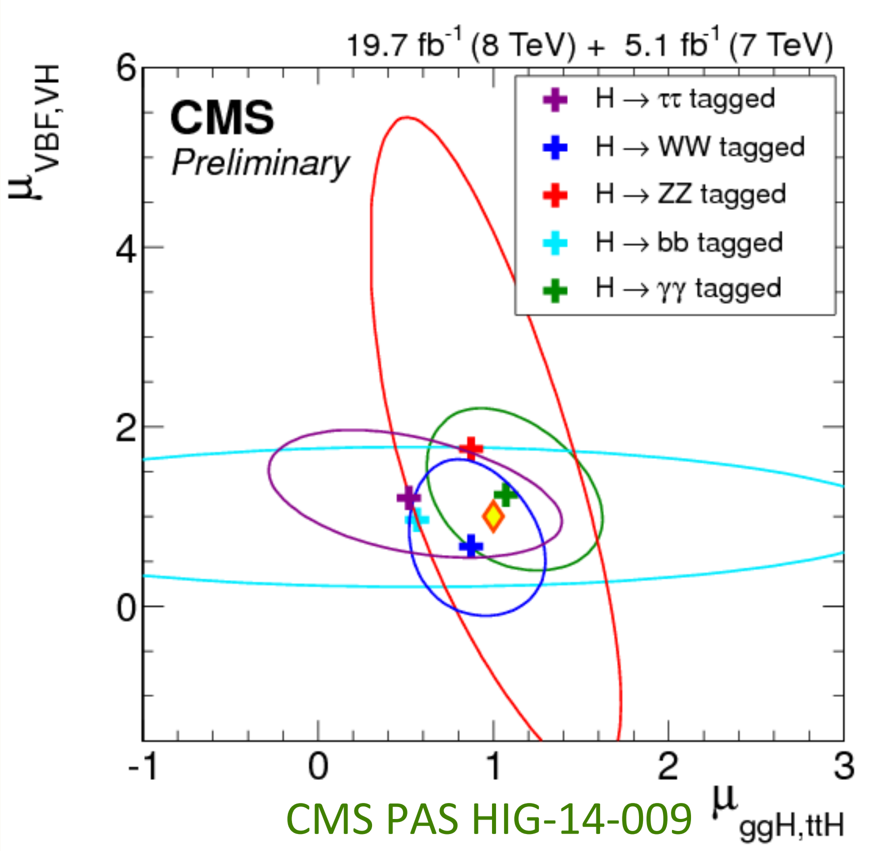
$$n_s^{c,i} = \sum_p \left[\mu^p \mu_{BR}^i\right] \times (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

Note: ONE CAN ONLY FIT THE PRODUCT $[\mu_p \mu_{BR}^f]$

We cannot fit simultaneously the cross section and the BR

→No full Higgs width fit is possible to high accuracy at the LHC (from the signal rates)

The categories allow us to fit specific production modes but **no combination is possible unless we make assumptions on the BR**



CMS PAS HIG-14-009

Probing VBF production mode

We fitted

$$\mu^{i}_{VBF+VH} \equiv \left[\mu_{VBF+VH} \times \mu^{i}_{BR} \right]$$

$$\mu^{i}_{ggF+ttH} \equiv \left[\mu_{ggF+ttH} \times \mu^{i}_{BR} \right]$$

Here we assume

$$\mu^{f}_{VBF+VH} = \mu^{f}_{VBF} = \mu^{f}_{VH} \quad \sim g^{2}_{VVH}$$

$$\mu^{f}_{ggF+ttH} = \mu^{f}_{ggF} = \mu^{f}_{ttH} \quad \sim g^{2}_{ttH}$$

Taking one decay mode at a time we can go one step further and fit the ratio per channel

$$\frac{\mu^{i}_{VBF+VH}}{\mu^{i}_{ggF+ttH}} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$$

This ratio is INDEPENDENT of the decay channel so we can combine

	$\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$
ATLAS	$1.4^{+0.7}_{-0.5}$
CMS	$1.25^{+0.63}_{-0.45}$

CMS PAS HIG-14-009

ATLAS-CONF-2014-009

Probing VBF production mode

We fitted

$$\mu^{i}_{VBF+VH} \equiv \left[\mu_{VBF+VH} \times \mu^{i}_{BR}\right]$$

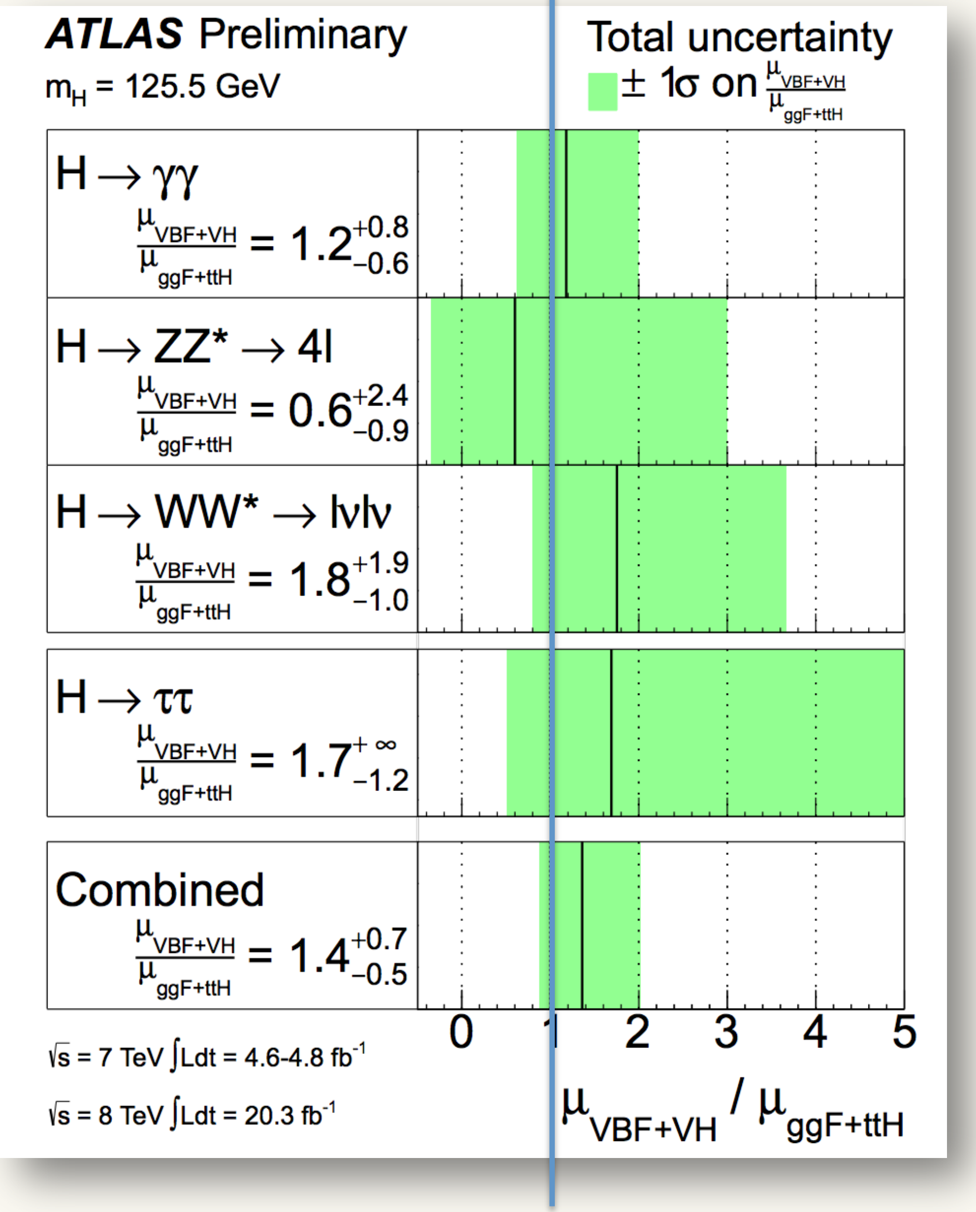
$$\mu^{i}_{ggF+ttH} \equiv \left[\mu_{ggF+ttH} \times \mu^{i}_{BR}\right]$$

Taking one decay mode at a time we can go one step further and fit the ratio per channel

$$\frac{\mu^{i}_{VBF+VH}}{\mu^{i}_{ggF+ttH}} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$$

This ratio is INDEPENDENT of the decay channel so we can combine

ATLAS-CONF-2014-009



Evidence for VBF Higgs Production

PROFILING $\frac{\mu_{VH}}{\mu_{ggF+ttH}}$ we can

Fit $\frac{\mu_{VBF}}{\mu_{ggF+ttH}}$ and find an

evidence for VBF Higgs production

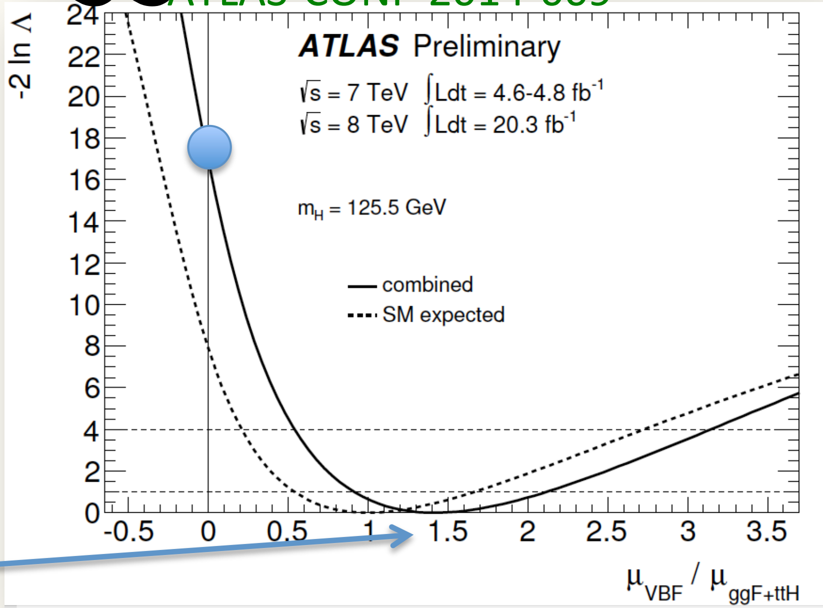
$$\frac{\mu_{VBF}}{\mu_{ggF+ttH}} = 1.4 \pm 0.3(stat)^{+0.6}_{-0.4}(sys) \quad \text{ATLAS}$$

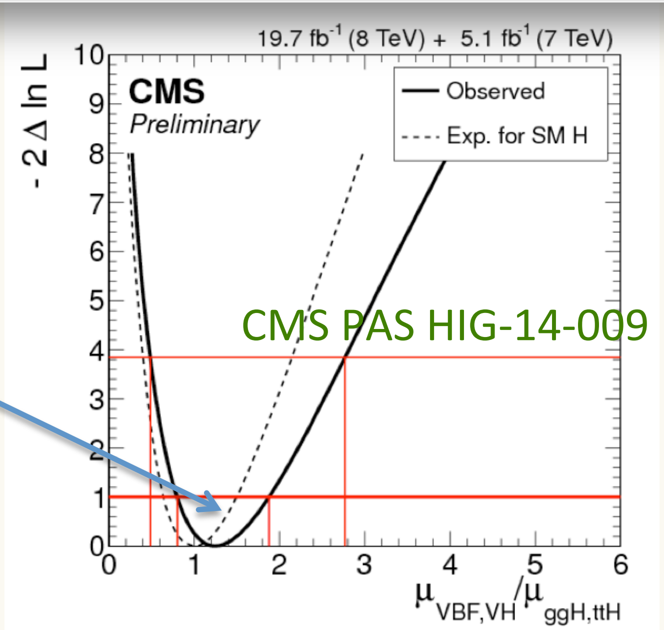
$$\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}} = 1.25^{+0.63}_{-0.45} \quad \text{CMS}$$

μ_{VBF}=0 is excluded at 4.1σ (ATLAS)

μ_{VBF}=0 is excluded at 3.6σ (CMS)

ATLAS-CONF-2014-009



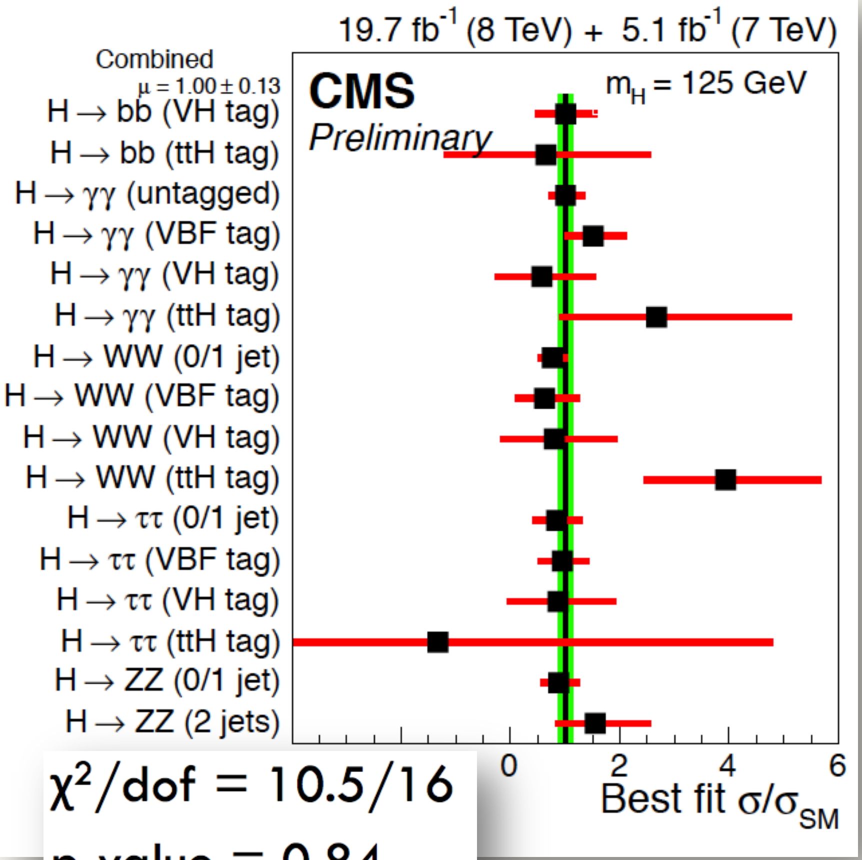


CMS PAS HIG-14-009

Probe the Production Modes

CMS performs a new analysis with a global fit to all production (and decay) modes. Profiling all the other decay modes, assuming SM BRs, they find

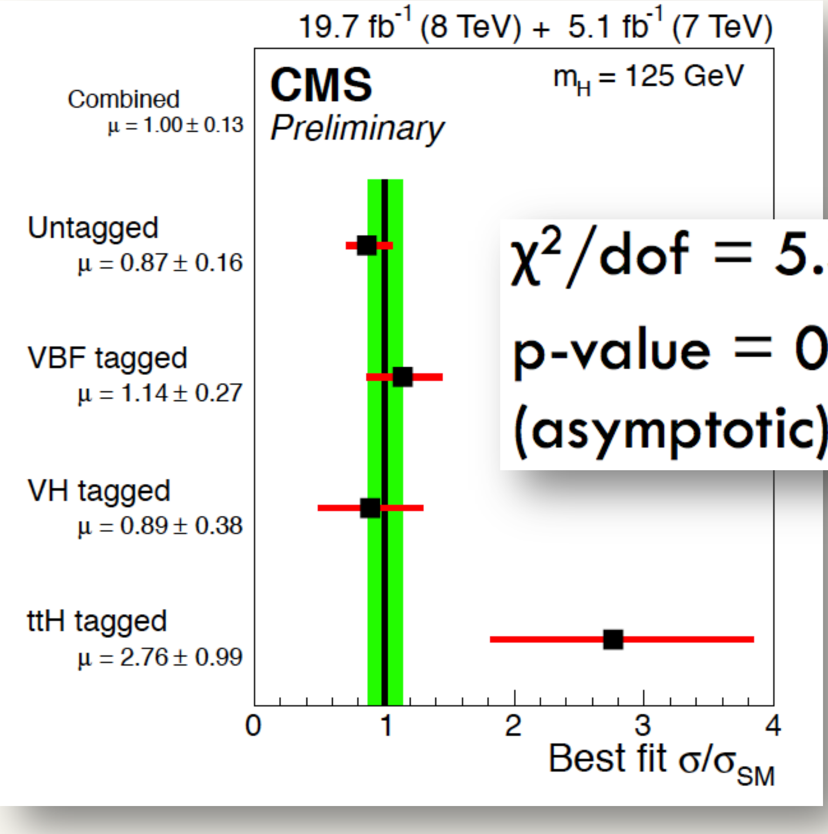
CMS PAS HIG-14-009



χ^2/dof = 10.5/16

p-value = 0.84

(asymptotic)

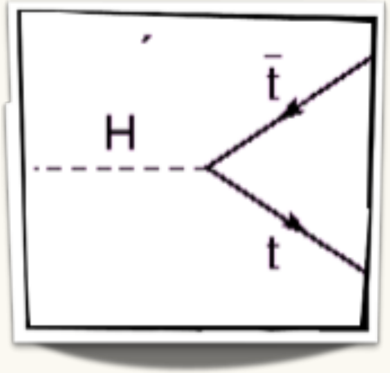


χ^2/dof = 5.3/4

p-value = 0.26

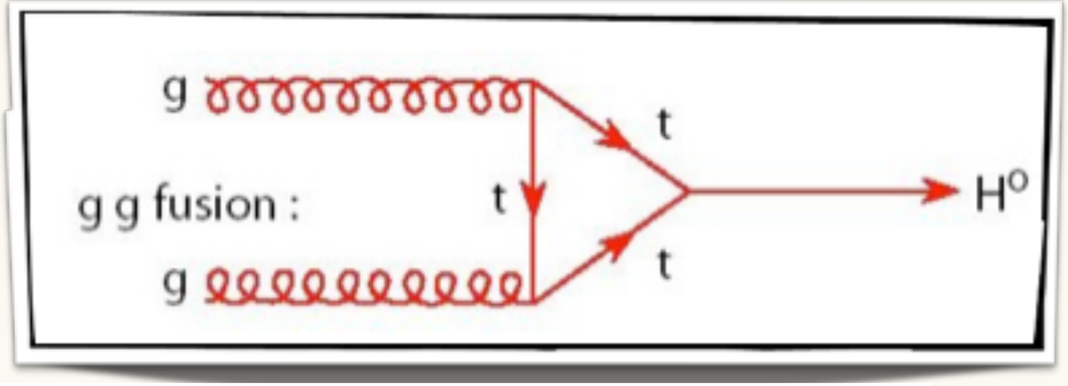
(asymptotic)

Indirect Sensitivity to Fermion Couplings



$$k_t^2 = \frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}}$$

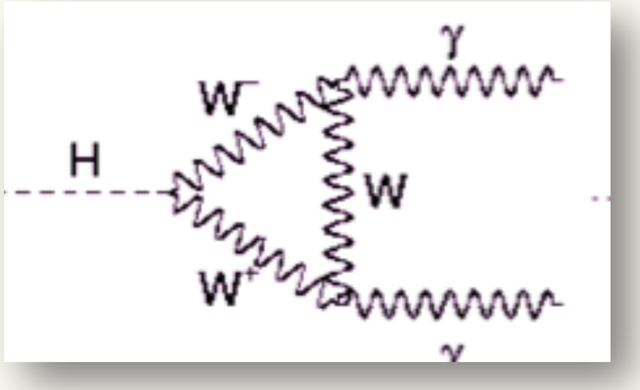
$$k_t^2 = \frac{g_t^2}{g_{t.SM}^2}$$



$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

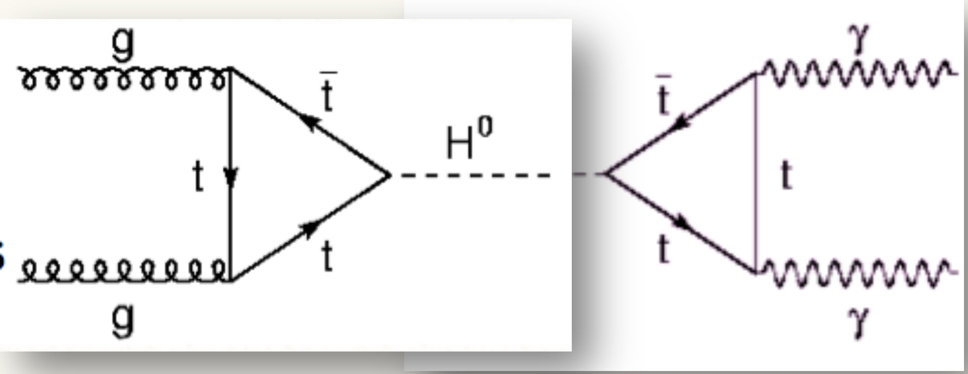
Note that if all fermion couplings are set to be equal, $k_g^2 = k_F^2$

$$k_\gamma^2 = \left|1.28 k_W - 0.28 k_t\right|^2$$



Direct observation of H→bb and H→$\tau\tau$

The Bosonic channels ($\gamma\gamma$,ZZ,WW) provide indirect evidence about the fermion couplings to Higgs via loops



But the direct evidence came with the observation of the bb and the $\tau\tau$ by (first) CMS and (then) ATLAS

H->bb dominates the Higgs total width (BR~58%)

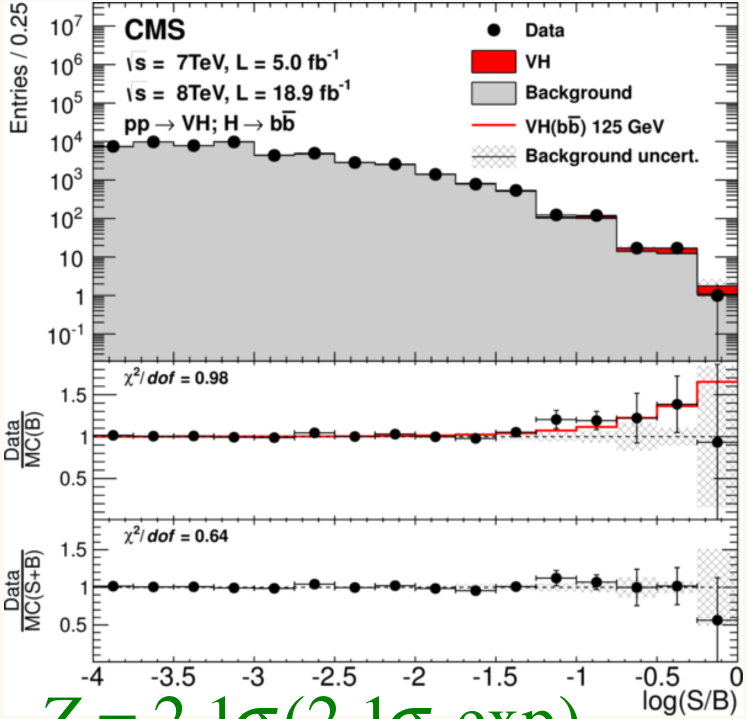
ggF,H→bb is saturated with overwhelming direct production of bb from QCD background

The handle is given by a Vector Boson produced in association with the H→bb in the VH,H→bb process.

With a SM BR of over 6% and a relatively clean signal in VBF and Boosted categories, H→$\tau\tau$ is even more important then the bb (with the current luminosity and analysis status) in order to establish the Higgs direct coupling to fermions.

Fermions Direct: H→bb

VH,H→bb results:

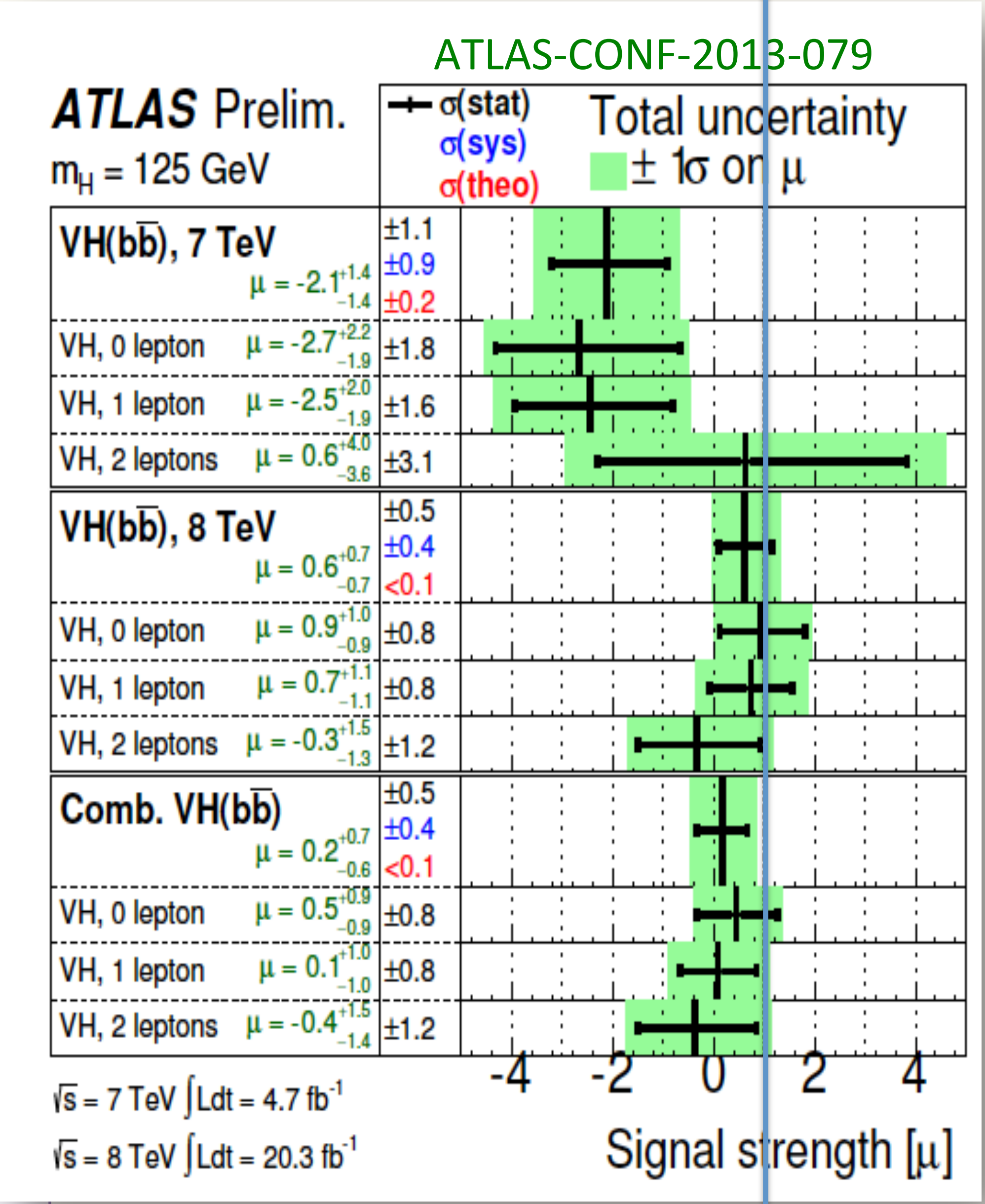


arXiv:1310.3687v2 [hep-ex]

$$Z = 2.1\sigma (2.1\sigma\ \exp)$$

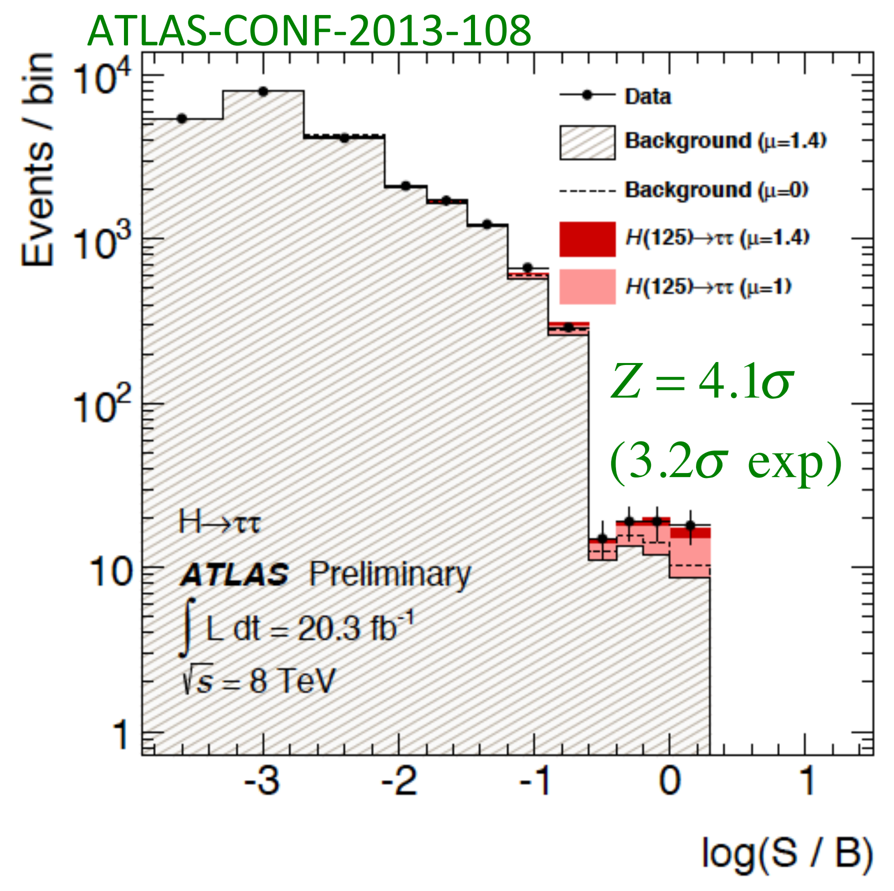
	CMS	ATLAS
Signal Strength	μ=1.0±0.5	μ=0.2±0.5(stat) ±0.4(syst)
Excess	2.1σ (exp 2.1σ)	0.36σ (exp 1.64σ [p_0=0.36 (exp 0.05)]
Upper Limit on μ	μ<1.89 (exp 0.95)	μ<1.4 (exp 1.3)

ATLAS-CONF-2013-079



Fermions Direct: H→$\tau\tau$

Discriminator is not necessarily mass



ATLAS-CONF-2013-108

$Z = 4.1\sigma$

$(3.2\sigma \text{ exp})$

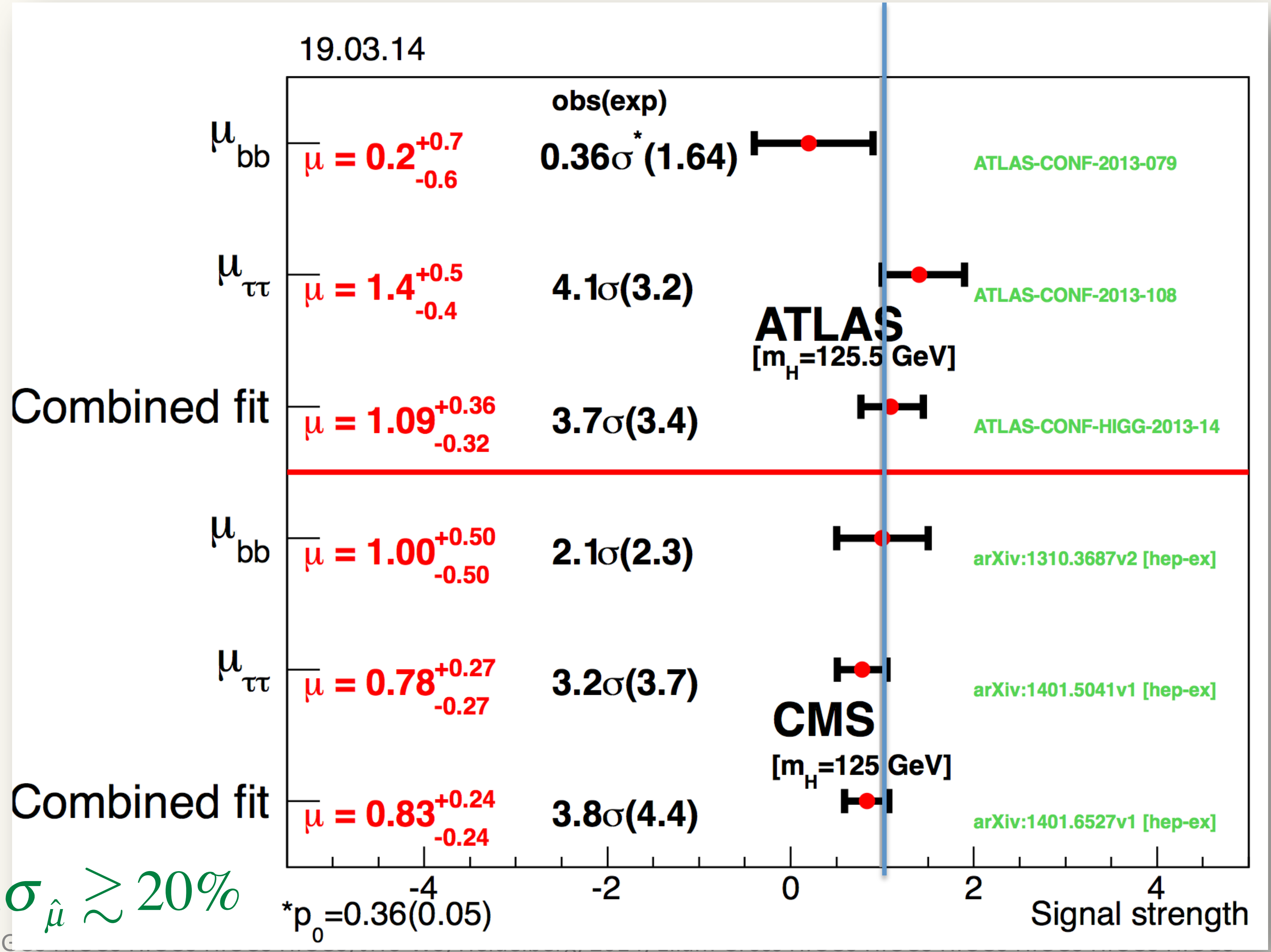
H→$\tau\tau$	CMS	ATLAS
Signal Strength	μ=0.78±0.27	$\mu=1.4^{+0.5}_{-0.4}$
Excess	3.2σ (exp 3.7σ)	4.1σ (exp 3.2σ)

arXiv:1401.5041v1 [hep-ex]

ATLAS-CONF-2013-108

Direct Evidence for H→Fermions

Combining bb and ττ



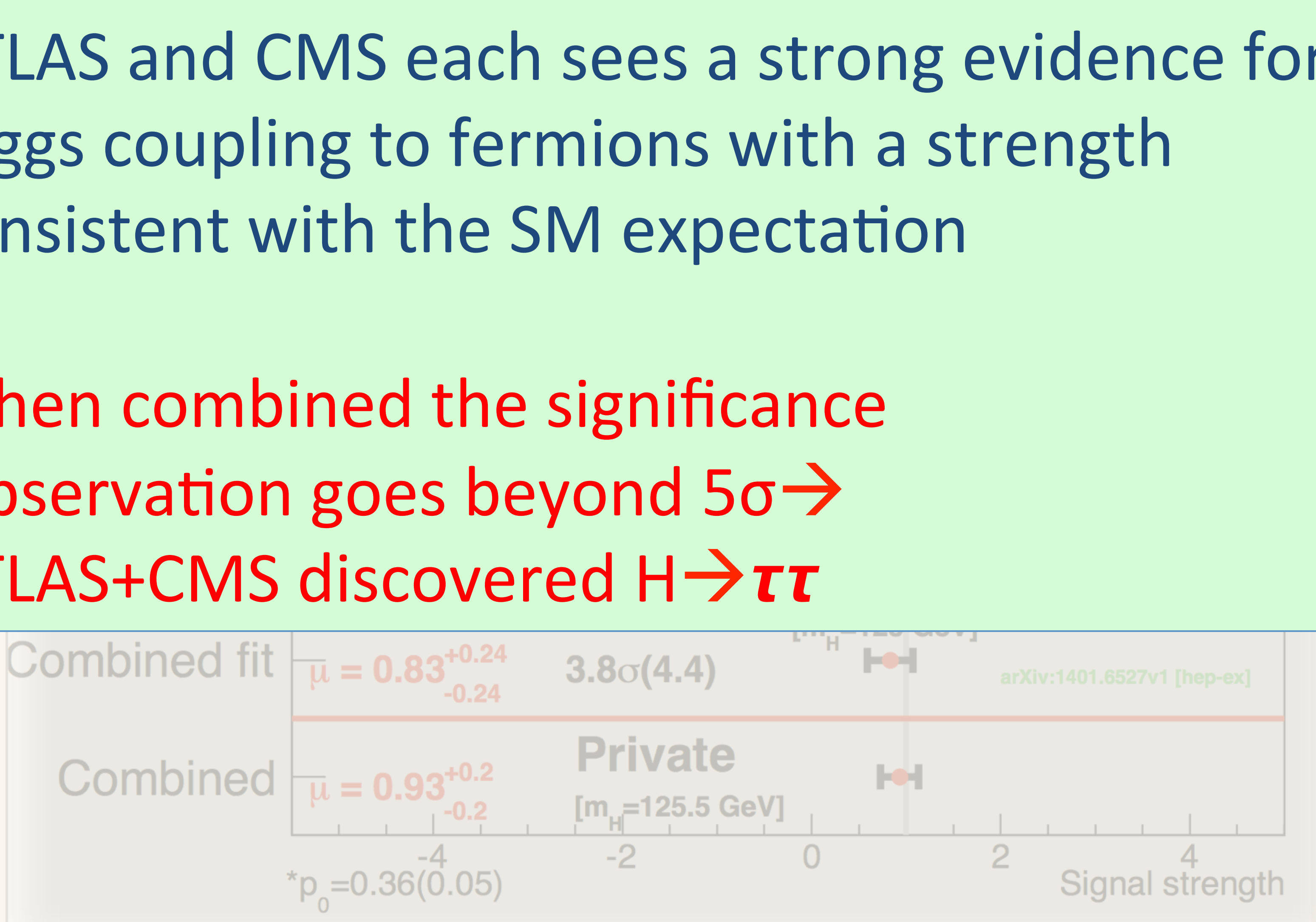
$$\hat{\mu} \sim 0.93, \sigma_{\hat{\mu}} \gtrsim 20\%$$

Direct Evidence for H→Fermions

Combining bb and ττ

ATLAS and CMS each sees a strong evidence for Higgs coupling to fermions with a strength consistent with the SM expectation

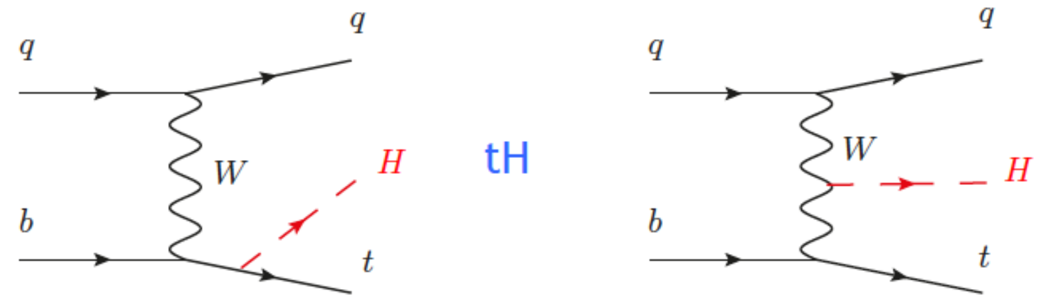
When combined the significance
observation goes beyond 5σ→
ATLAS+CMS discovered H→***ττ***



Comment: Fermions Direct: ttH

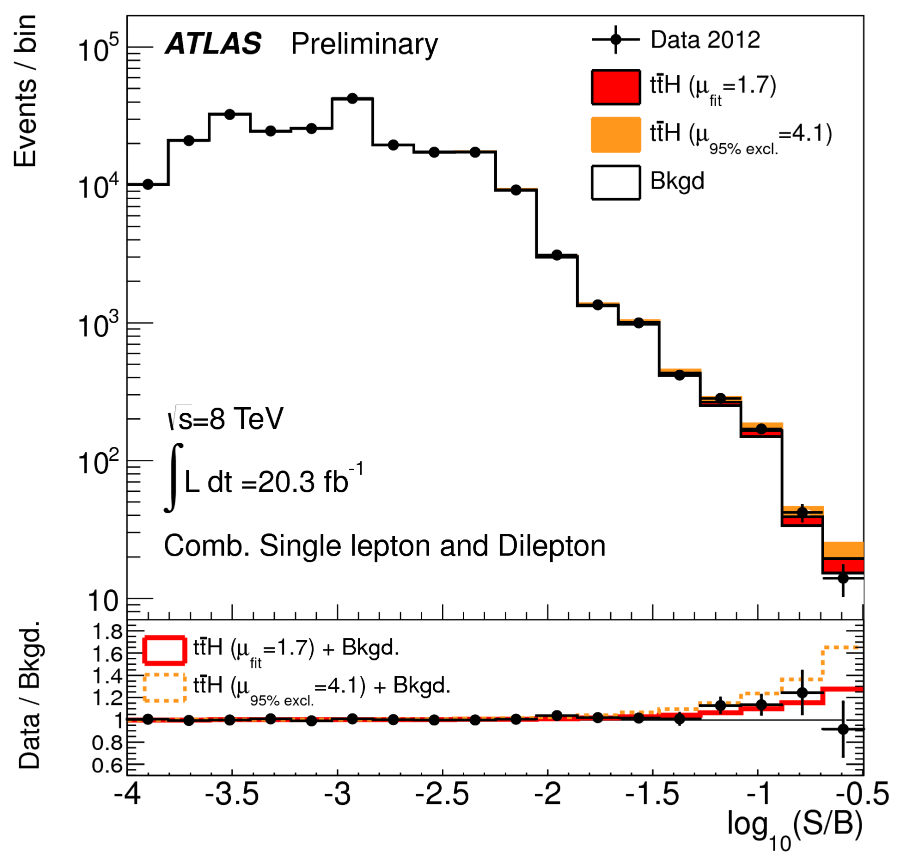
Probing the Higgs Yukawa coupling to top is of an ultimate importance. $m_{top}/v \sim 1$. Higgs won't decay to tt, but one can probe directly the ttH coupling by the Higgsstrahlung of Higgs off top or tt fusion to Higgs, or single top production.

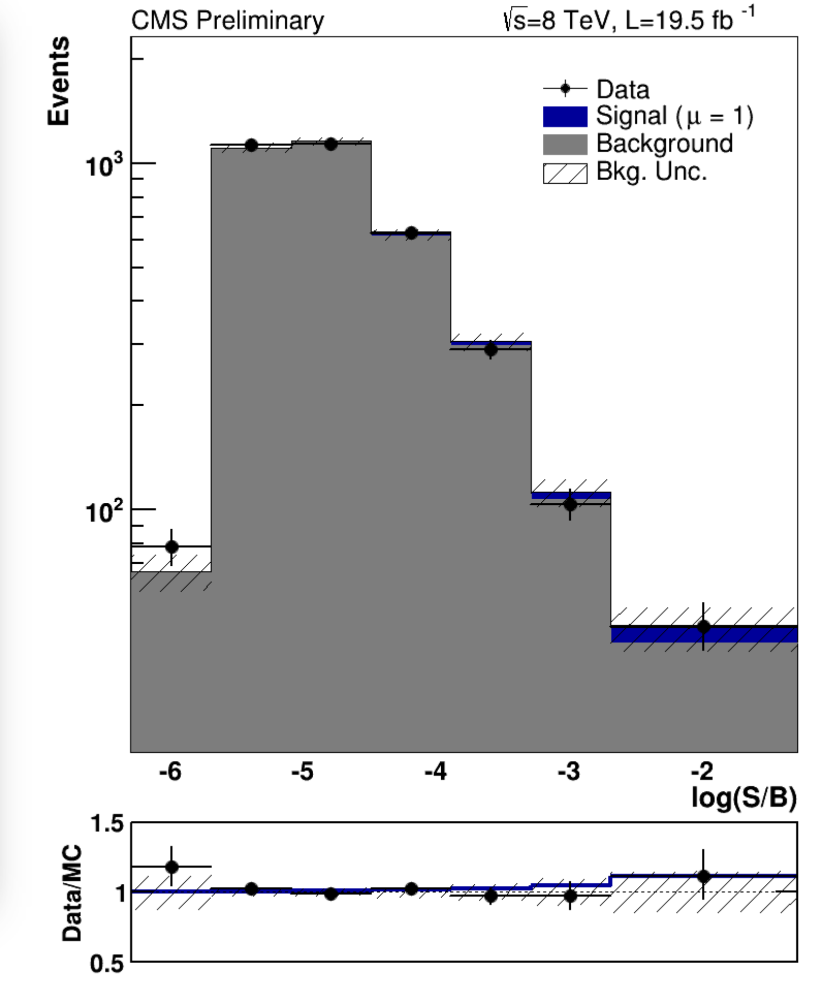
The Higgs then decays to bb, $\tau_h\tau_h$ or multileptons (from ZZ,WW or ττ) with extremely small $\sigma \times BR$.



$$\propto 3.3 \times \kappa_W^2 - 5.1 \times \kappa_t \kappa_W + 2.8 \times \kappa_t^2$$

ttH, H→bb





$$ttH\,, H \to bb$$

CMS using ME $\mu < 2.9\ (exp\ \ 3.3)\quad \mu = 0.67^{+1.35}_{-1.33}$

ATLAS $\mu < 4.1\ (exp\ \ 2.6)\quad \mu = 1.7 \pm 1.4$

HIGGS Couplings

Measuring Higgs Couplings

$$\begin{aligned}
\mathcal{L} = {} & \kappa_3 \frac{m_H^2}{2v} H^3 + \enclose{circle}{\kappa_Z} \frac{m_Z^2}{v} Z_\mu Z^\mu H + \enclose{circle}{\kappa_W} \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\
& + \enclose{circle}{\kappa_g} \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \enclose{circle}{\kappa_\gamma} \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\
& + \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu}\right) H \\
& - \left(\enclose{circle}{\kappa_t} \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \enclose{circle}{\kappa_b} \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \enclose{circle}{\kappa_\tau} \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H.
\end{aligned}$$

Define the normalized coupling constants (w.r.t. the SM couplings)

$$k_i^2 = \frac{\Gamma_i}{\Gamma_I^{SM}} \qquad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

Measuring Higgs Couplings

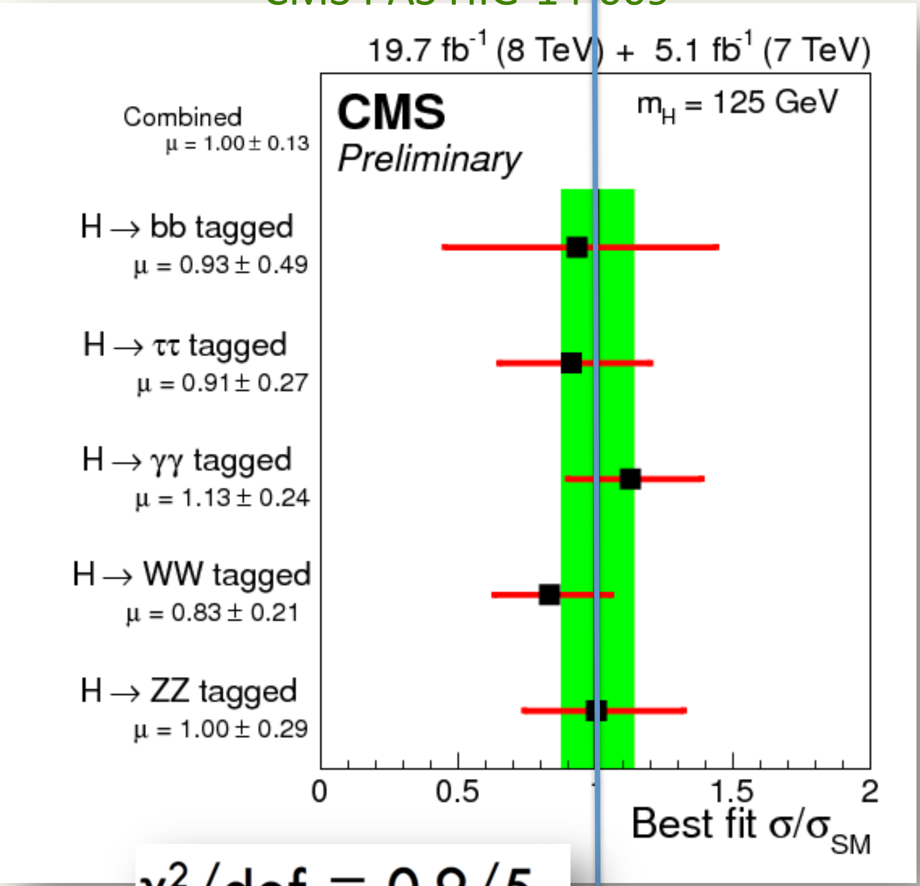
$$n_s^{c,i} = \sum_p \left[\mu^p \mu_{BR}^i\right] \times (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

Can we resolve the degeneracy, disentangle $\left[\mu^p \mu_{BR}^{WW}\right]$

The degeneracy can be broken by parameterize the strength parameters with couplings and introduce constraints which reduce the number of p.o.i. and allow reasonable fits.

$$k_i^2 = \frac{\Gamma_i}{\Gamma_I^{SM}} \qquad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

CMS PAS HIG-14-009

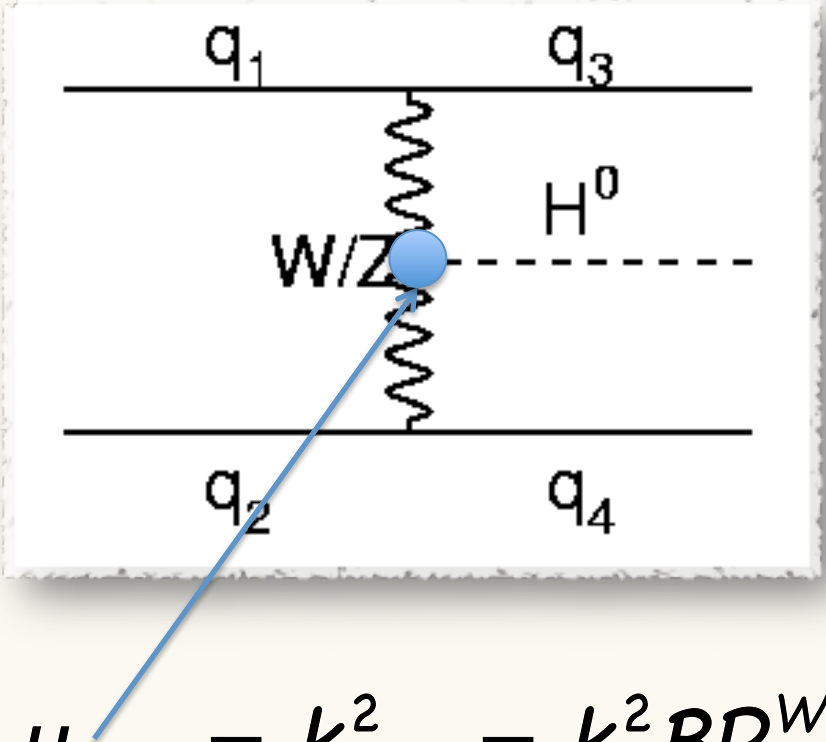


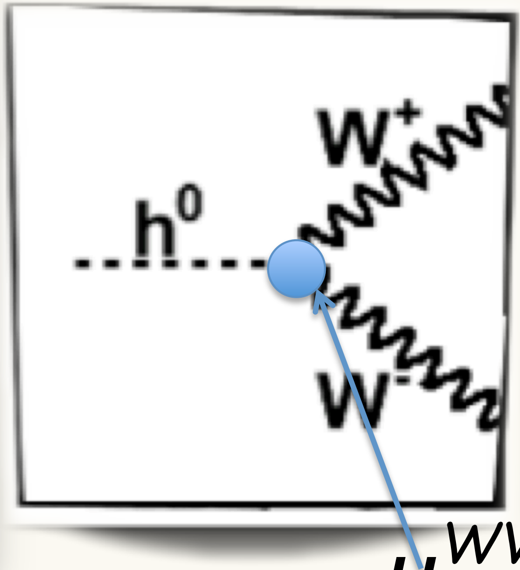
$\chi^2/\text{dof} = 0.9/5$

p-value = 0.97

(asymptotic)

Disentangling The Couplings





$$\mu_{VBF}^{WW} = [\mu_{VBF}\mu_{BR}^{WW}]$$

$$\mu_{BR}^{WW} = \frac{k_W^2}{k_H^2}$$

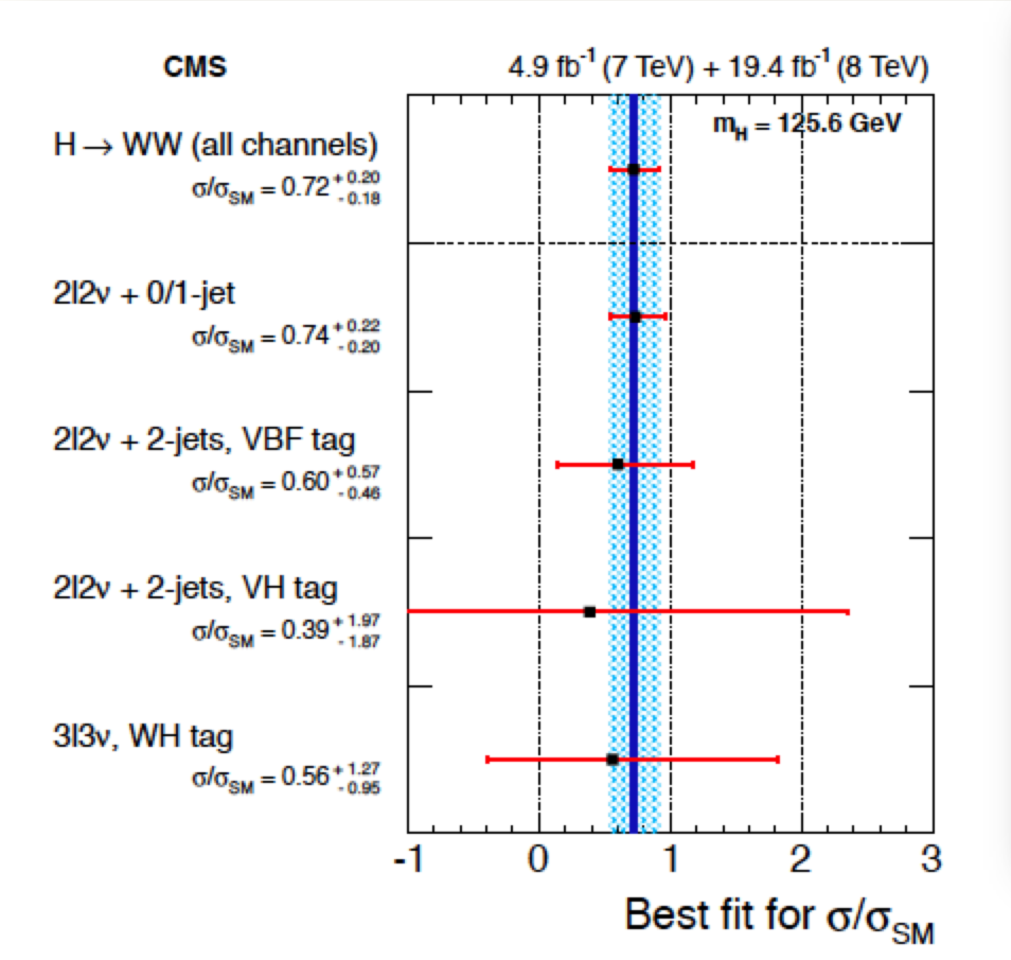
$$\mu_{VBF} = k_{VBF}^2 = k_w^2 BR_{SM}^{WW} + k_Z^2 BR_{SM}^{ZZ}$$

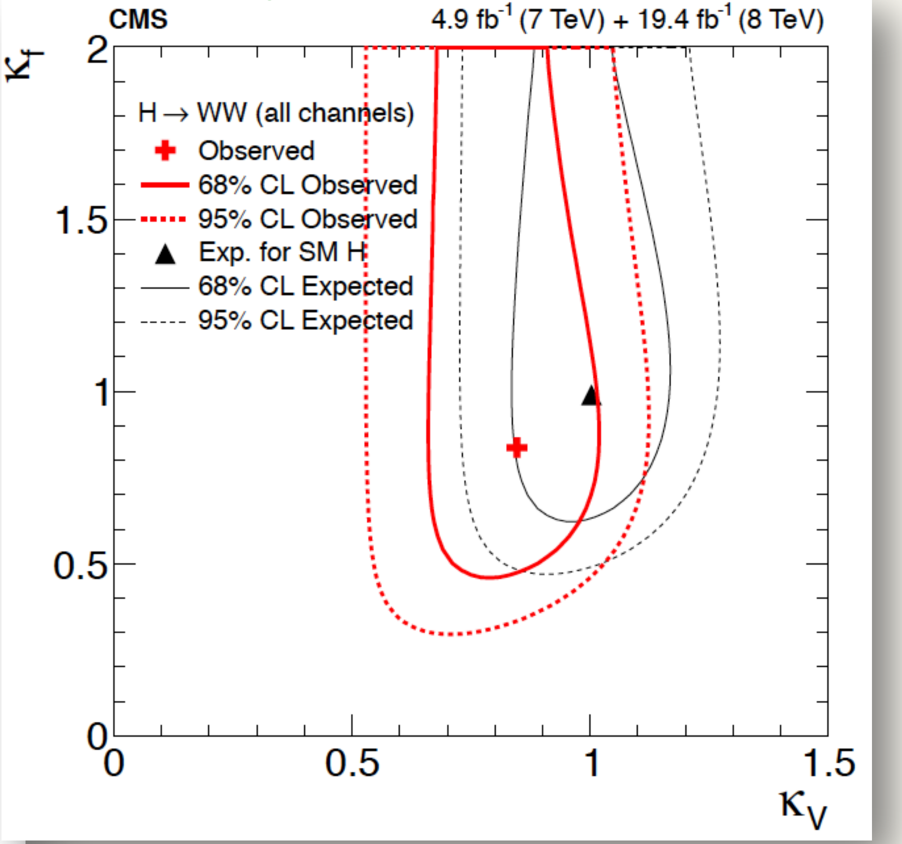
The simplest non-trivial model is (k_F, k_V) where all Fermion couplings are set to k_F and all Boson couplings to k_V

$$\frac{\sigma_{VBF}^{WW}}{\sigma_{VBF}^{WW}(SM)} = \frac{k_V^2 \cdot k_V^2}{0.75k_F^2 + 0.25k_V^2}$$

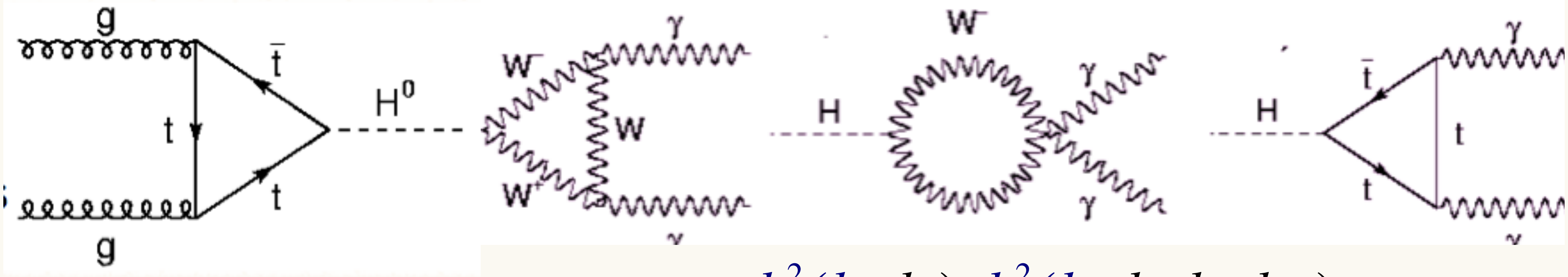
Disentangling The Couplings

arXiv:1312.1129v1 [hep-ex]





Disentangling The Couplings



$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) \sim \frac{k_g^2(k_b,k_t)\cdot k_\gamma^2(k_b,k_t,k_\tau,k_W)}{k_H^2(k_Z,k_W,k_\tau,k_t,k_b)}$$

Note, couplings are dependent on the Higgs mass

$$\sigma(ggF)\times BR(H\to\gamma\gamma) \sim \frac{k_F^2\cdot \mathrm{k}_\gamma^2(k_F,k_F,k_F,k_V)}{0.75k_F^2+0.25k_V^2}$$

$$\sigma(VBF)\times BR(H\to\gamma\gamma) \sim \frac{k_V^2\cdot \mathrm{k}_\gamma^2(k_F,k_F,k_F,k_V)}{0.75k_F^2+0.25k_V^2}$$

In the (k_F, k_V) benchmark:

$$\sigma(ggF)\times BR(H\to WW,ZZ) \sim \frac{k_F^2\cdot \mathrm{k}_V^2}{0.75k_F^2+0.25k_V^2}$$

$$\sigma(VBF)\times BR(H\to WW,ZZ) \sim \frac{k_V^2\cdot \mathrm{k}_V^2}{0.75k_F^2+0.25k_V^2}$$

$$\sigma(VBF,VH)\times BR(H\to \tau\tau,bb) \sim \frac{k_V^2\cdot \mathrm{k}_F^2}{0.75k_F^2+0.25k_V^2}$$

Summary of Signal Strength

ATLAS bb is low but with large error.

$$k_\gamma^2 = \left|1.28 k_W - 0.28 k_t\right|^2$$

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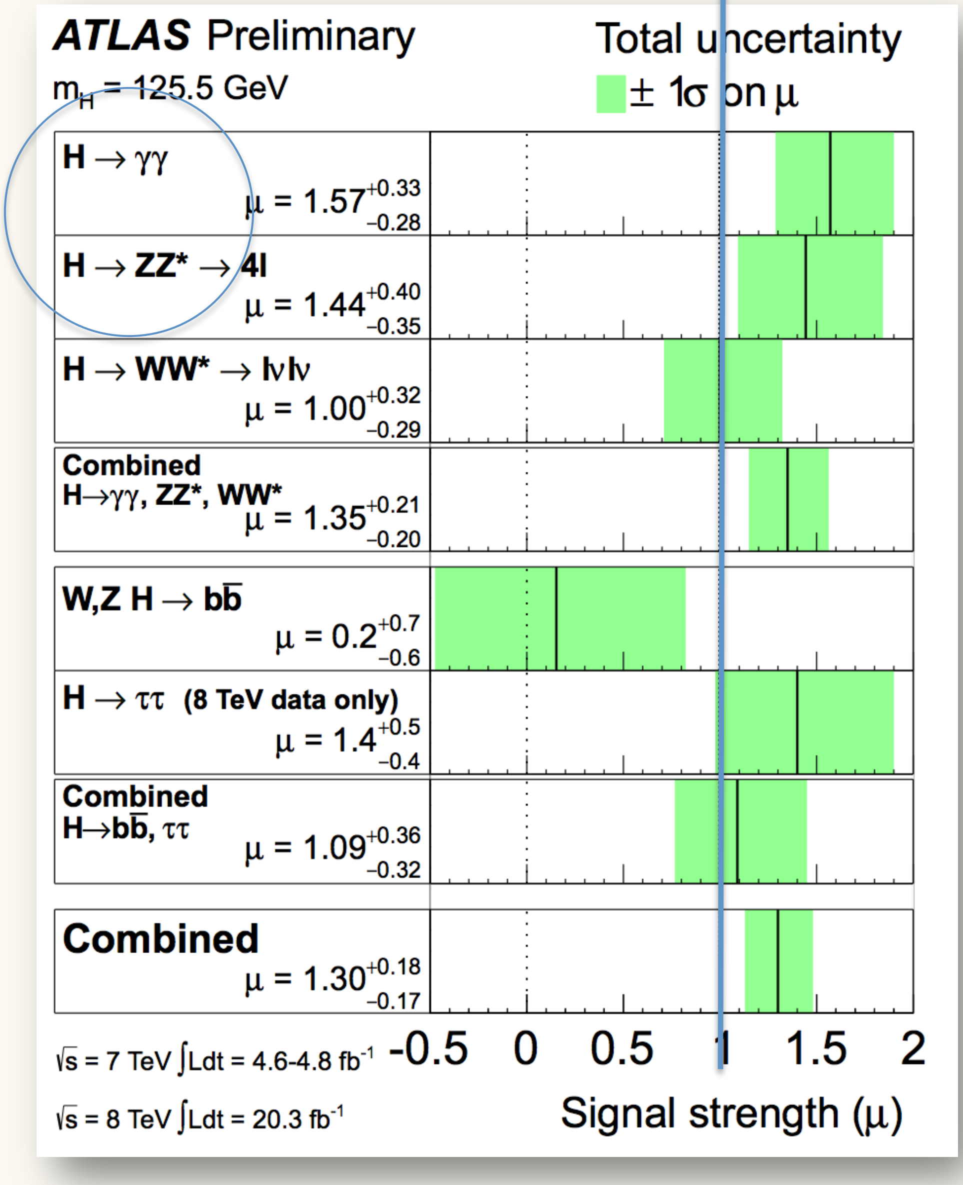
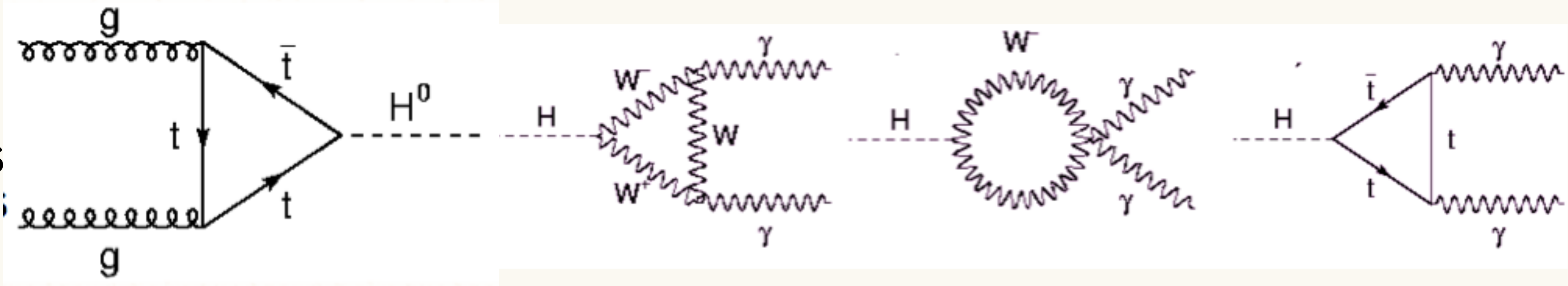
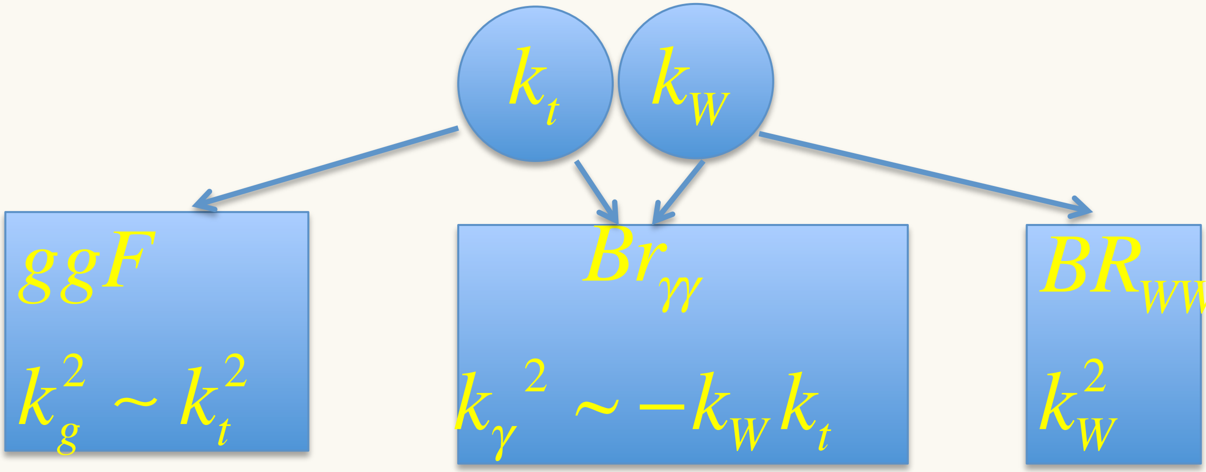


A comment on Interference

is



$$n_s^{\gamma\gamma} \sim k_g^2(k_t, k_b) \times k_\gamma^2(k_t, k_W) \quad k_\gamma^2 = |1.28 k_W - 0.28 k_t|^2$$



k_t k_W

ggF

$k_g^2 \sim k_t^2$

$Br_{\gamma\gamma}$

$k_\gamma{}^2 \sim -k_W k_t$

BR_{WW}

k_W^2

If k_t=-1 ggF slightly affected
WW unaffected
γγ increases

Allowing negative k_t is extremely important

Can be probed with tH

Coupling Benchmarks

To make reasonable fits we introduce physics motivated scenarios.

Testing the compatibility of the discovered Higgs with the SM is to test also where is it NOT compatible, spotting where NP might sneak in.

NP can appear in either the Higgs width and/or in the loops.

$$k_H^2 = \frac{\sum\limits_{j=Z,W,t,b,\tau} k_j^2 \Gamma_j^{SM} + k_\gamma^2 \Gamma_\gamma^{SM} + k_g^2 \Gamma_g^{SM}}{\Gamma_H^{SM}} \qquad \Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$$

Γ_H	k_γ	k_g	Scenario	Comments
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	SM	only SM particles in loops
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	k_γ	k_g	$NP<$	m_{NP} could be $< \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	k_γ	k_g	$NP>$	$m_{NP} > \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	NP_{NL}	NP (not in the loops) neither charged nor coloured

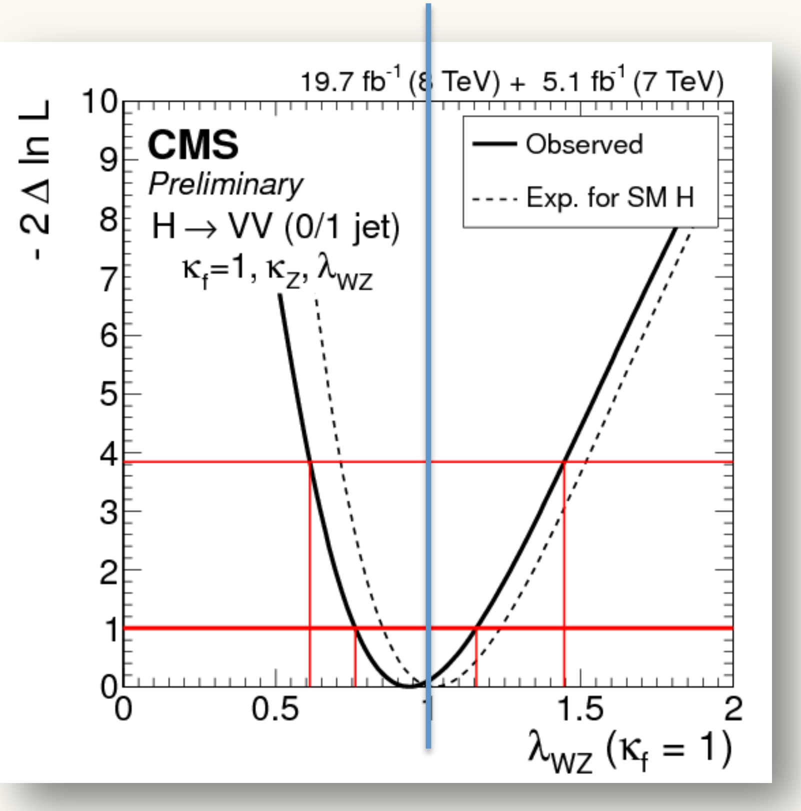
Probing Custodial Symmetry

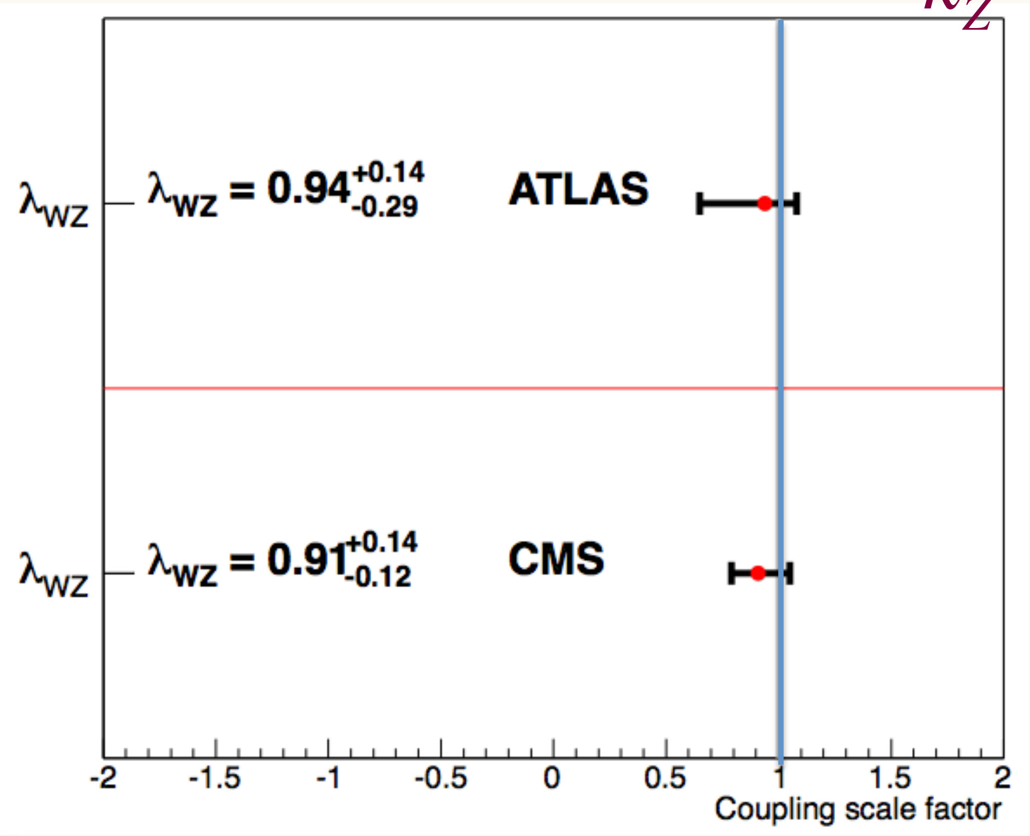
λ_{WZ} is expected to be protected and consistent with unity

Large deviations from 1 indicate new physics.

ATLAS (NP_{NL})	**Overall λ_{fZ}, k_{zz} profiled**
CMS (SM)	Overall k_Z,K_f profiled

$$\lambda_{WZ} = \frac{k_W}{k_Z}$$





The Full Monty I : SM

Generic Model I (ATLAS, CMS)

All couplings to SM particles are fitted independently

k_Z and k_W assumed positive, fit is sensitive to sign of k_t/k_W

p.o.i $k_W, k_Z, k_b, k_\tau, k_t$

Loop & Width Constrains

$$k_g(k_b, k_t) \quad k_\gamma(k_b, k_t, k_\tau, k_W)$$

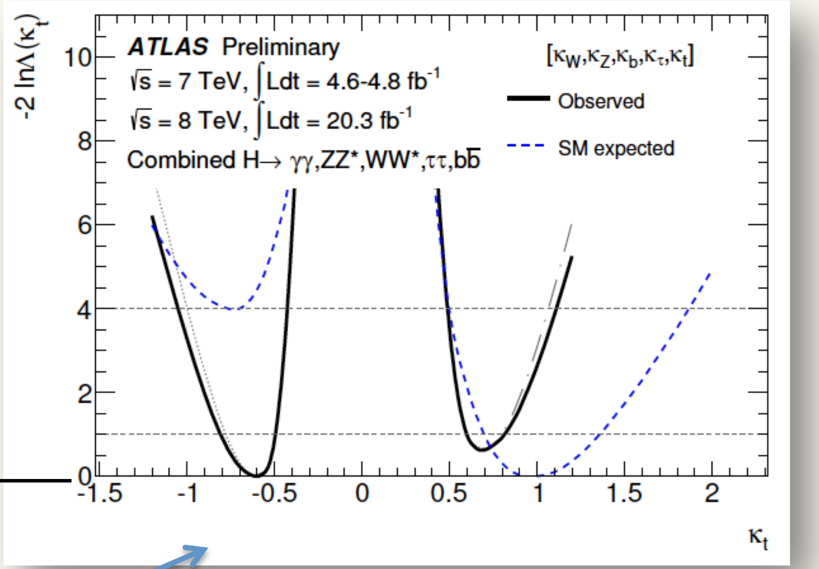
$$k_H^2(k_b, k_t, k_\tau, k_W, k_Z) = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

-High $\gamma\gamma$ rate prefers negative k_t

$$k_\gamma^2 = |1.28 k_W - 0.28 k_t|^2$$

-The low measured bb rate does not reflect the sensitivity for k_b
ATLAS were unlucky

-The 5D compatibility with SM is 14%



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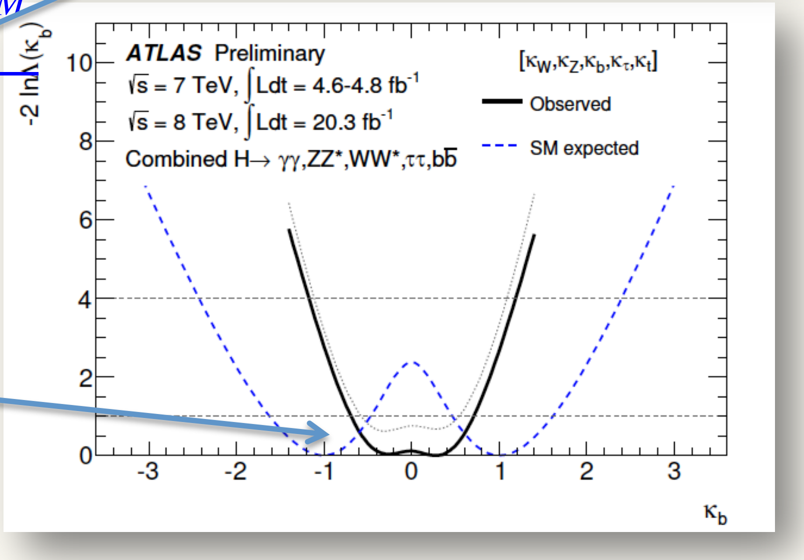

The Full Monty I : SM

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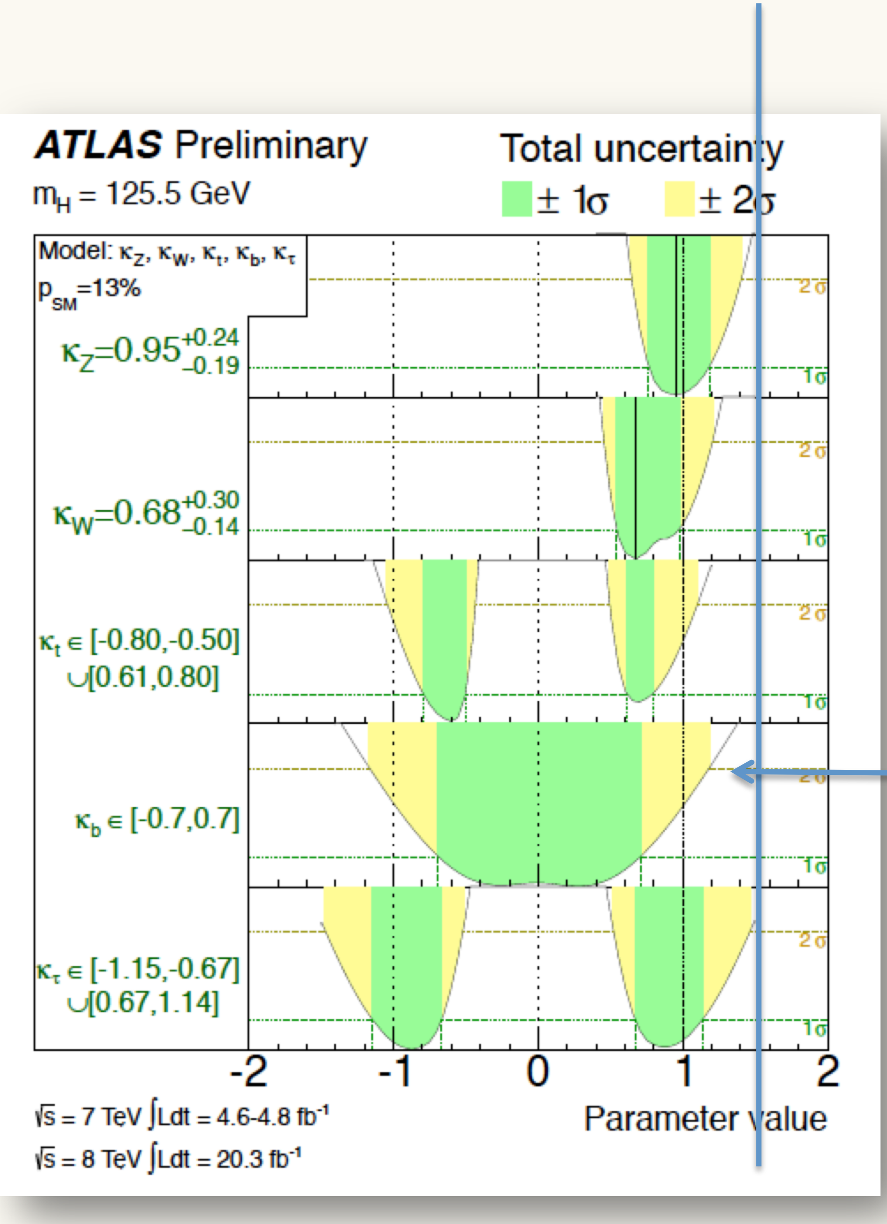
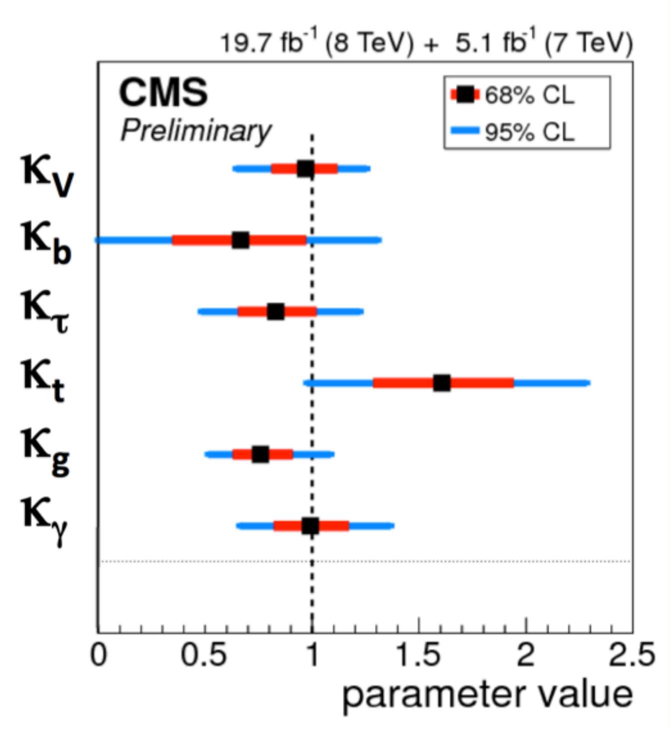


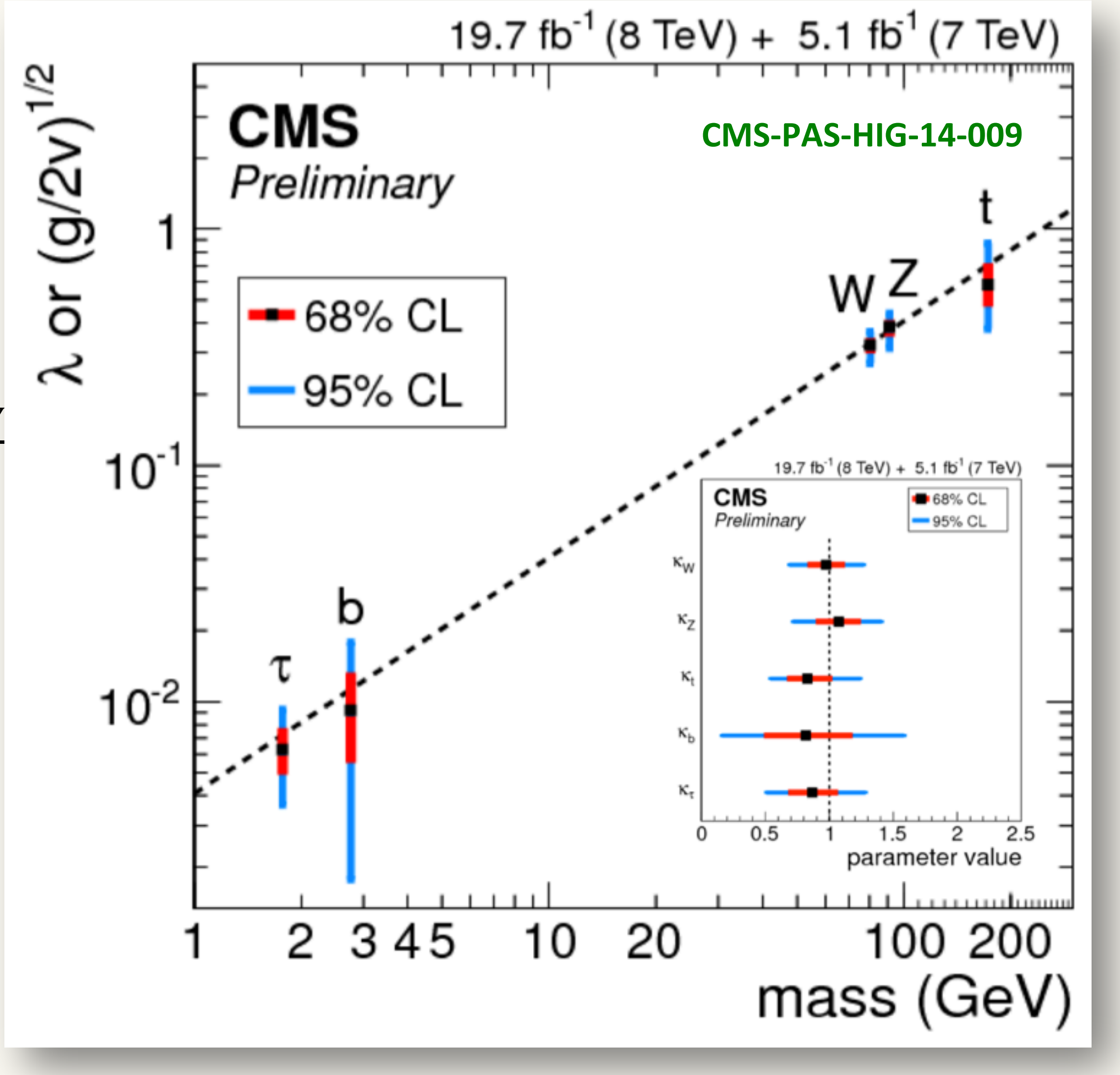


bb makes 58% of the Higgs width, bb rate measured low, pulls all couplings down

HIGGS PR

$$\lambda_f \equiv k_f \cdot \frac{m_f}{v}$$

$$\lambda_V \equiv \left(g_V / 2v\right)^{1/2} = k_v^{\,1/2} \cdot \frac{m_V}{v}$$



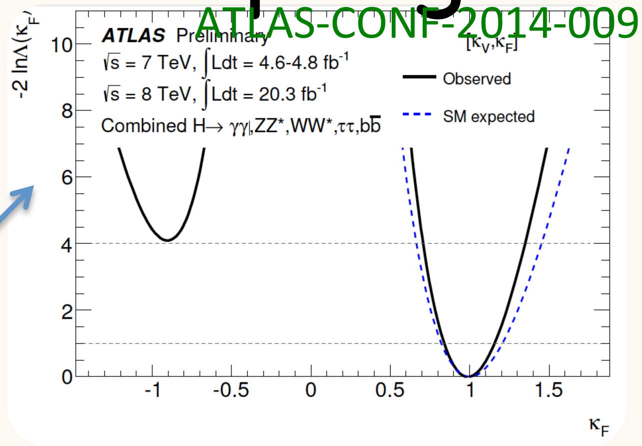
Vector and Fermion Couplings

The $\gamma\gamma$ loop induces some sensitivity to the relative sign between k_t and k_W

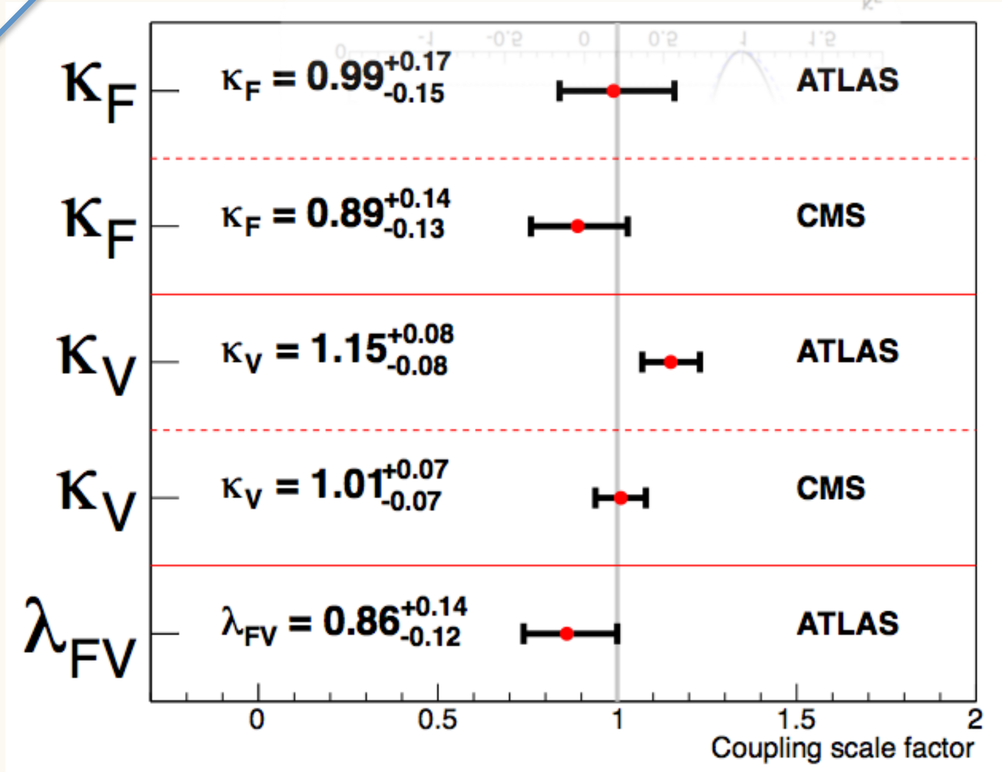
The high observed H→ZZ pulls k_W up,

allowing high $\gamma\gamma$ rate and keeps k_t positive

$$k_\gamma^2 = \left|1.28k_W - 0.28k_t\right|^2$$


ATLAS-CONF-2014-009

	fitted	comments	
ATLAS	k_V	$\Gamma_{i,u}=0$	1.15 ± 0.08
(SM)	k_F	$k_H{}^2(k_j)$	$0.99^{+0.17}_{-0.15}$
CMS	k_V	$\Gamma_{i,u}=0$	$0.89^{+0.14}_{-0.13}$
(SM)	k_F	$k_H{}^2(k_j)$	$1.01^{+0.07}_{-0.07}$
ATLAS (NP_{NL})	λ_{FV}	k_{VV} profiled	$0.86^{+0.14}_{-0.12}$

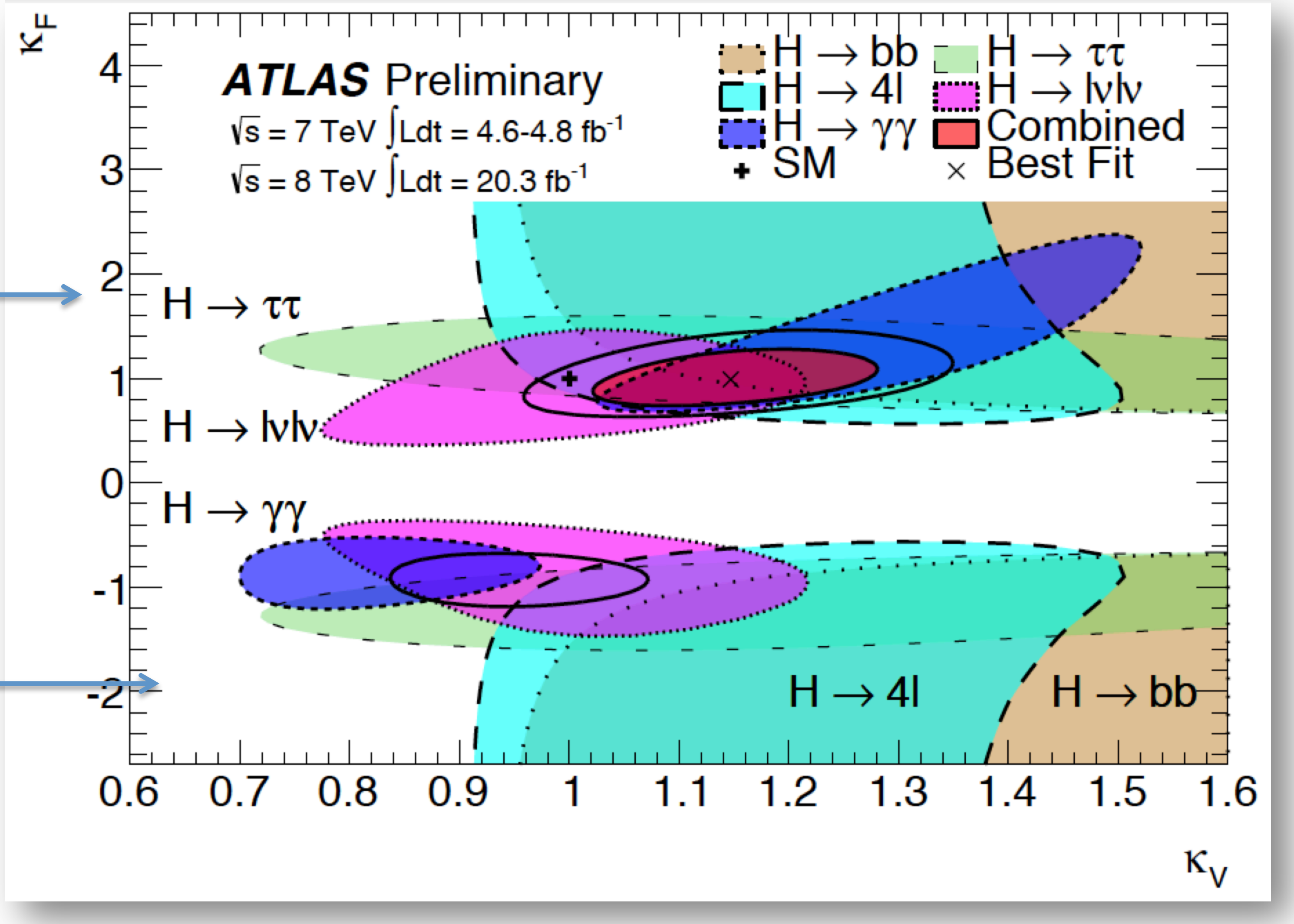


ATLAS: 2D compatibility with SM 10%

Vector and Fermion Couplings

This PR plot tells a story:

ATLAS-CONF-2014-009

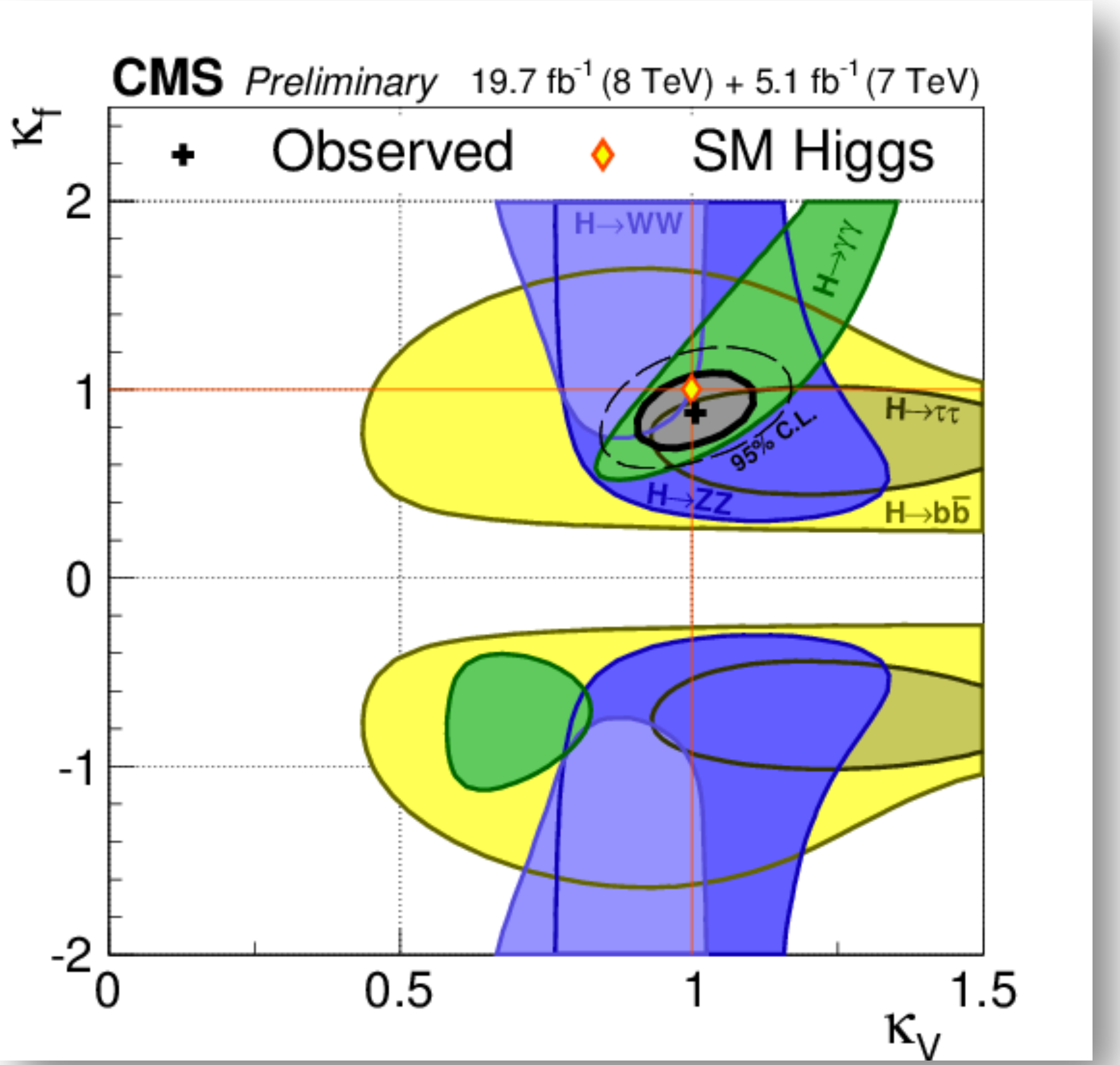


SM – No Tension

Tension Drifting apart

Vector and Fermion Couplings

This PR plot tells a story:

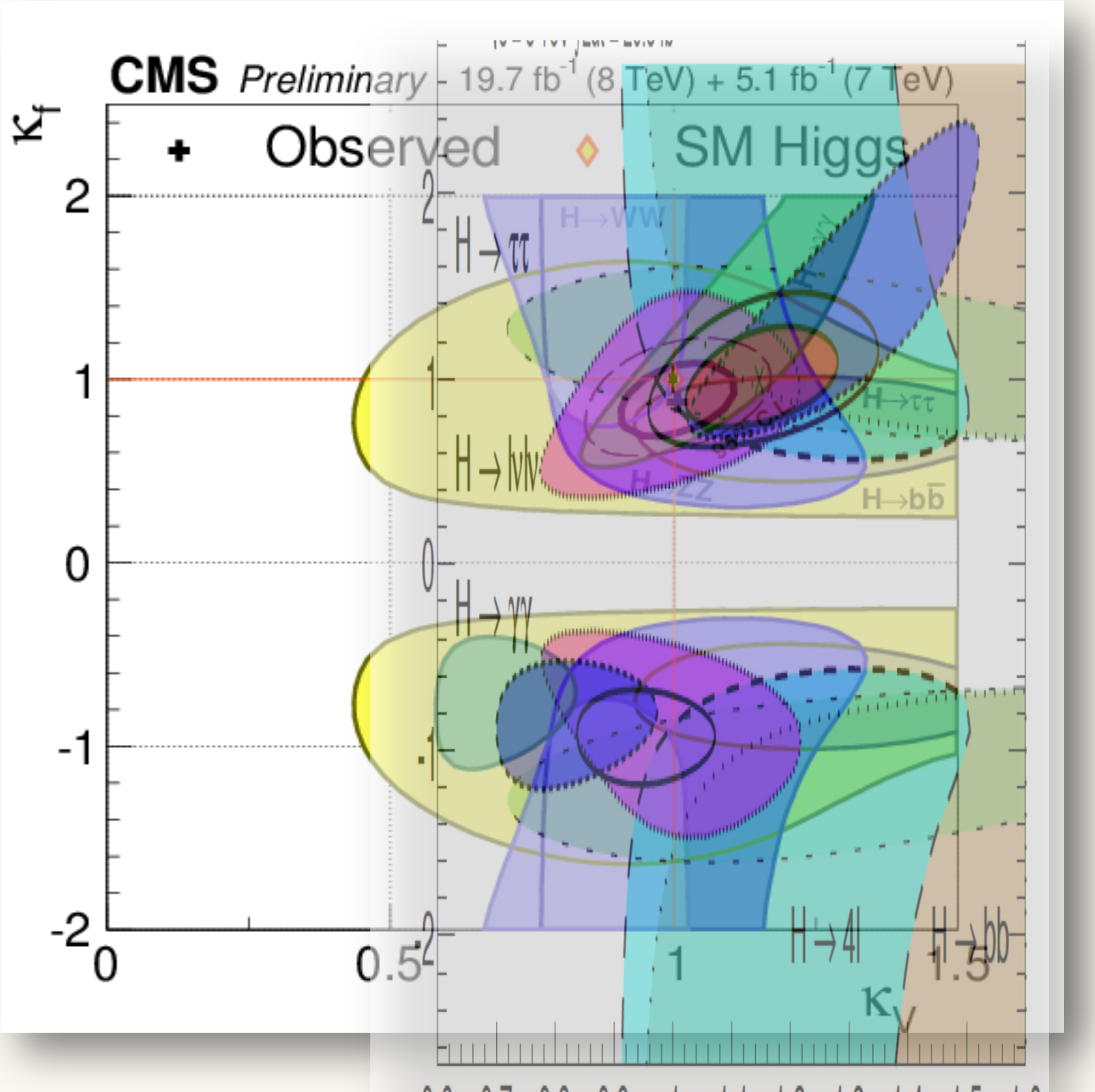


SM – No Tension

Tension Drifting apart

Vector and Fermion Couplings

This plot tells a story:



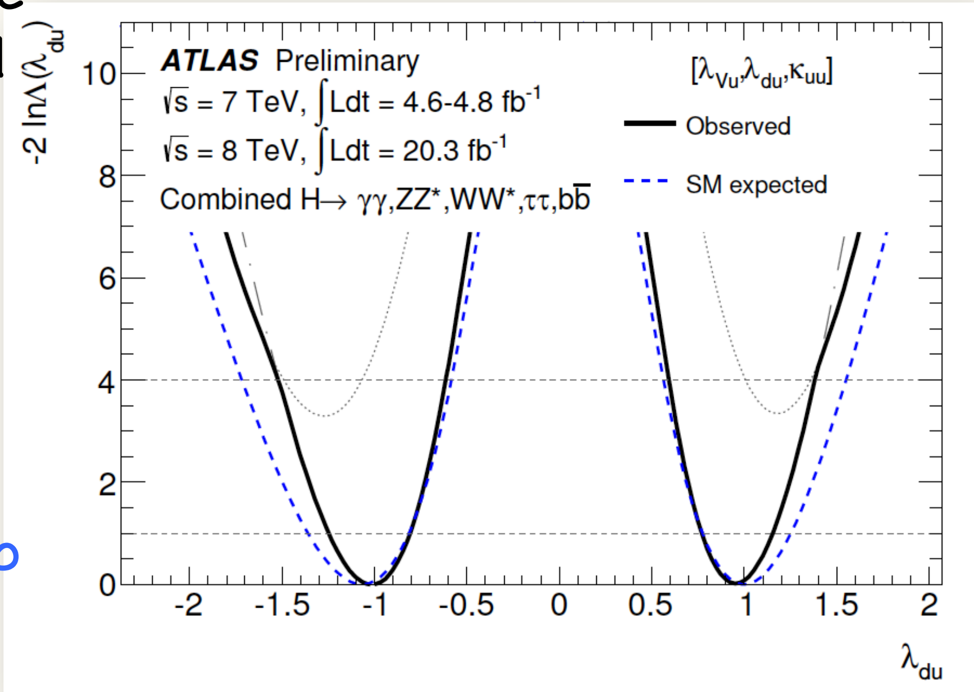
SM –
No Tension

Tension
Drifting
apart

Probing the Fermion Couplings Asymmetry

In models BSM (e.g. 2HDM) there is an asymmetry between k_u and k_d (u=c,t; d=b, τ) or k_ℓ and kq

ATLAS-CONF-2014-009



The direct measurement of the Higgs couplings to b and τ together with the direct (ttH) and loops induced coupling to top allows to measure λ_{du}

Measurement of the coupling to τ allows a measurement of $\lambda_{\ell q}$

The future will bring the Muons and better ttH into the game and improve the measurement

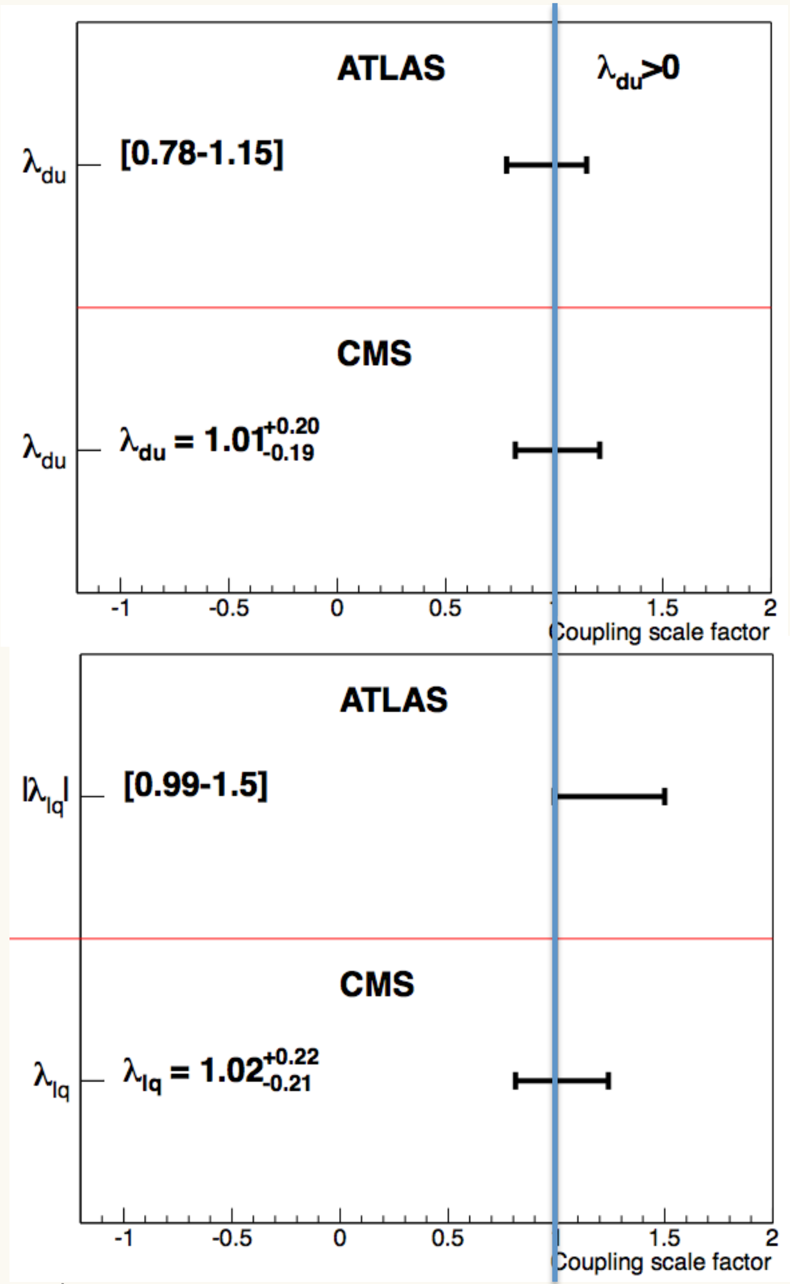
The small asymmetry is from b and t interference in ggH loop

A vanishing coupling to downtype fermions is excluded at the ~3.6σ(~4σ) ATLAS(CMS)

Asymmetries in Fermion Sector

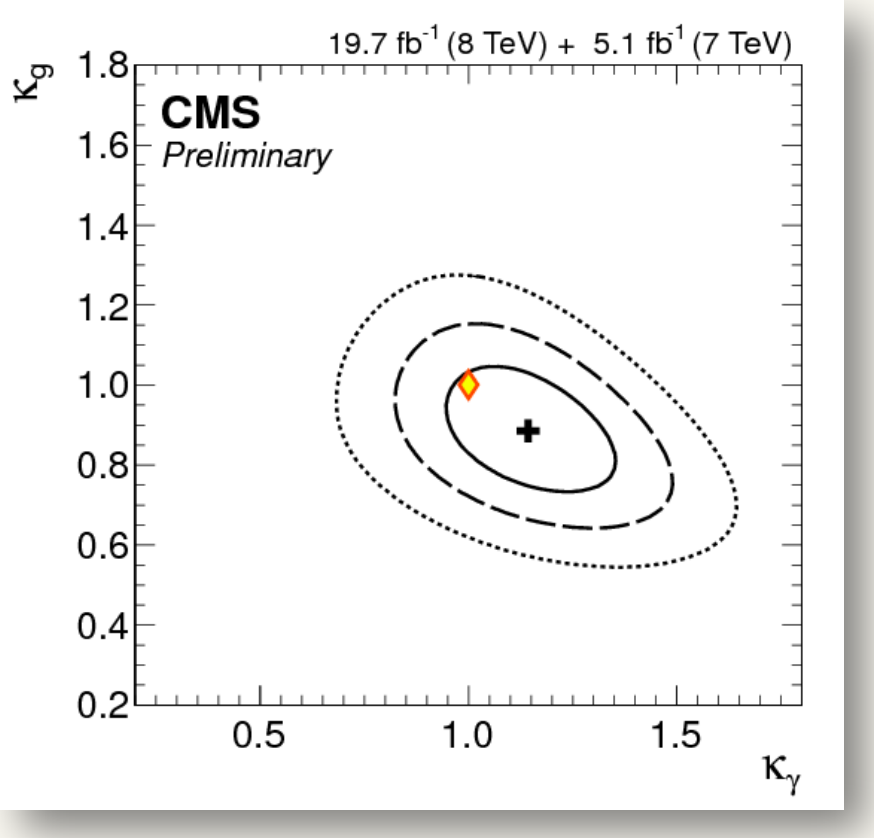
CMS are using a SM-like model while ATLAS are using an NP_{NL} model

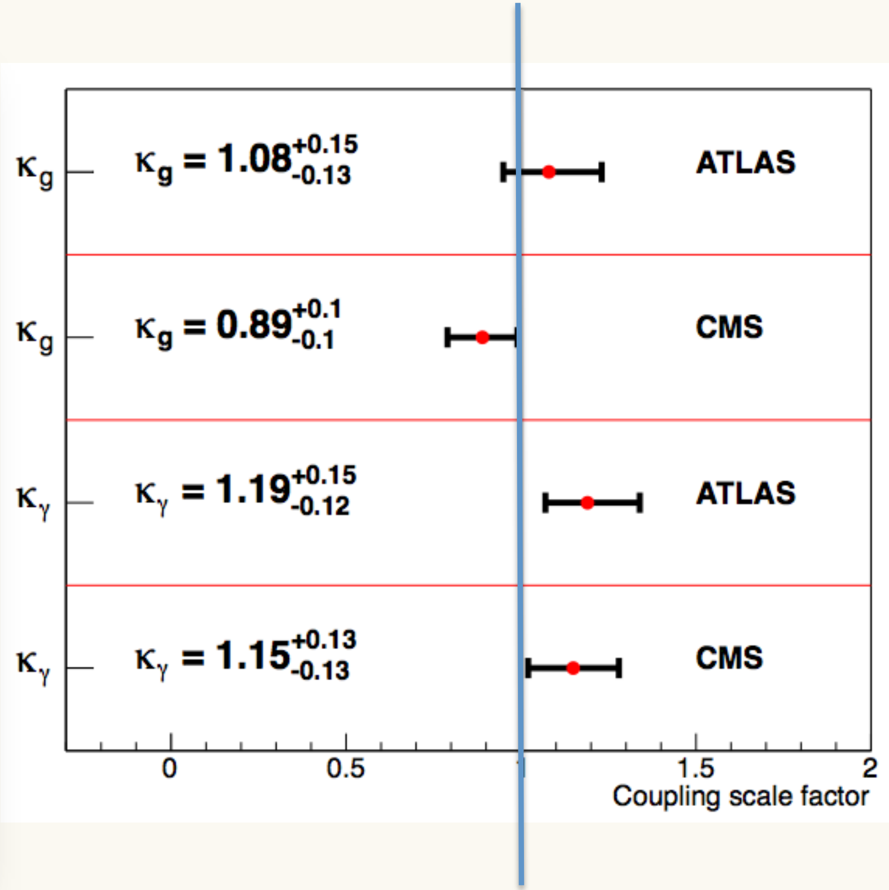
	fitted	68% positibe C.I.	p.o.i
ATLAS	λ_{du}	[0.78,1.15]	$\lambda_{du}, \lambda_{Vu}, k_{uu}$
(SM_{NL})	$\lambda_{\ell q}$	[0.99,1.5]	$\lambda_{\ell q}, \lambda_{Vq}, k_{qq}$
CMS	λ_{du}	$1.01^{+0.2}_{-0.19}$	λ_{du}, k_V, k_u
(SM)	$\lambda_{\ell q}$	$1.02^{+0.22}_{-0.21}$	$\lambda_{\ell q}, k_V, k_q$



Probing the Beyond (kg,kγ)

Scenario	$k_H(k_j)$	$k_\gamma(k_t,k_W)$	$k_g(k_t,k_b)$	k_F	k_V	p.o.i	
(k_g,k_γ) (NP>)	√	×	×	$=1$	$=1$	k_g,k_γ	A,C

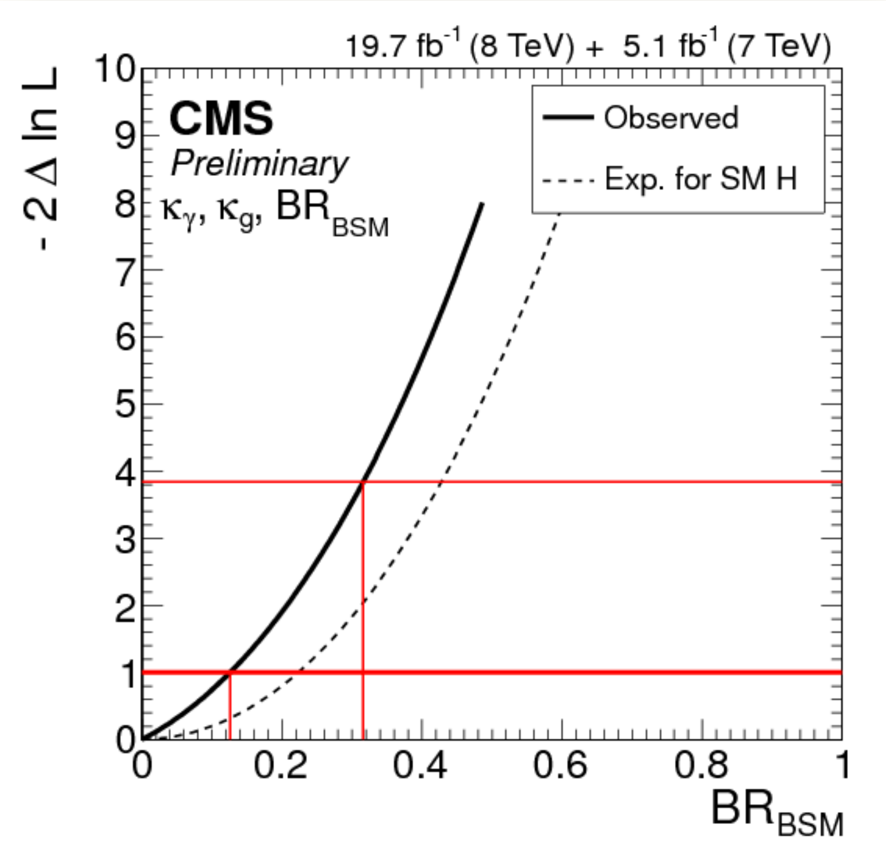




Probing the Beyond ($kg,k\gamma,Br_{i,u}$)

Scenario	$k_H(k_j)$	$k_\gamma(k_t,k_W)$	$k_g(k_t,k_b)$	k_F	k_V	p.o.i	
(k_g,k_γ) (NP<)	$\surd^*$	×	×	$=1$	$=1$	$k_g,k_\gamma,BR_{i,u}(*)$	A,C

	fitted	$k_g,k_\gamma,BR_{i,u}$
ATLAS	k_g	$1.10^{+0.17}_{--0.13}$
	k_γ	$1.19^{+0.14}_{-0.13}$
	$BR_{i,u}$	$BR_{i,u} < 0.41(\exp 0.55)$
CMS	k_g	
	k_γ	
	$BR_{i,u}$	$BR_{i,u} < 0.32$



The Full Monty II (C6)

Generic Model II (C6) (CMS)

Replace loop induced couplings by effective couplings, k_g,k_γ

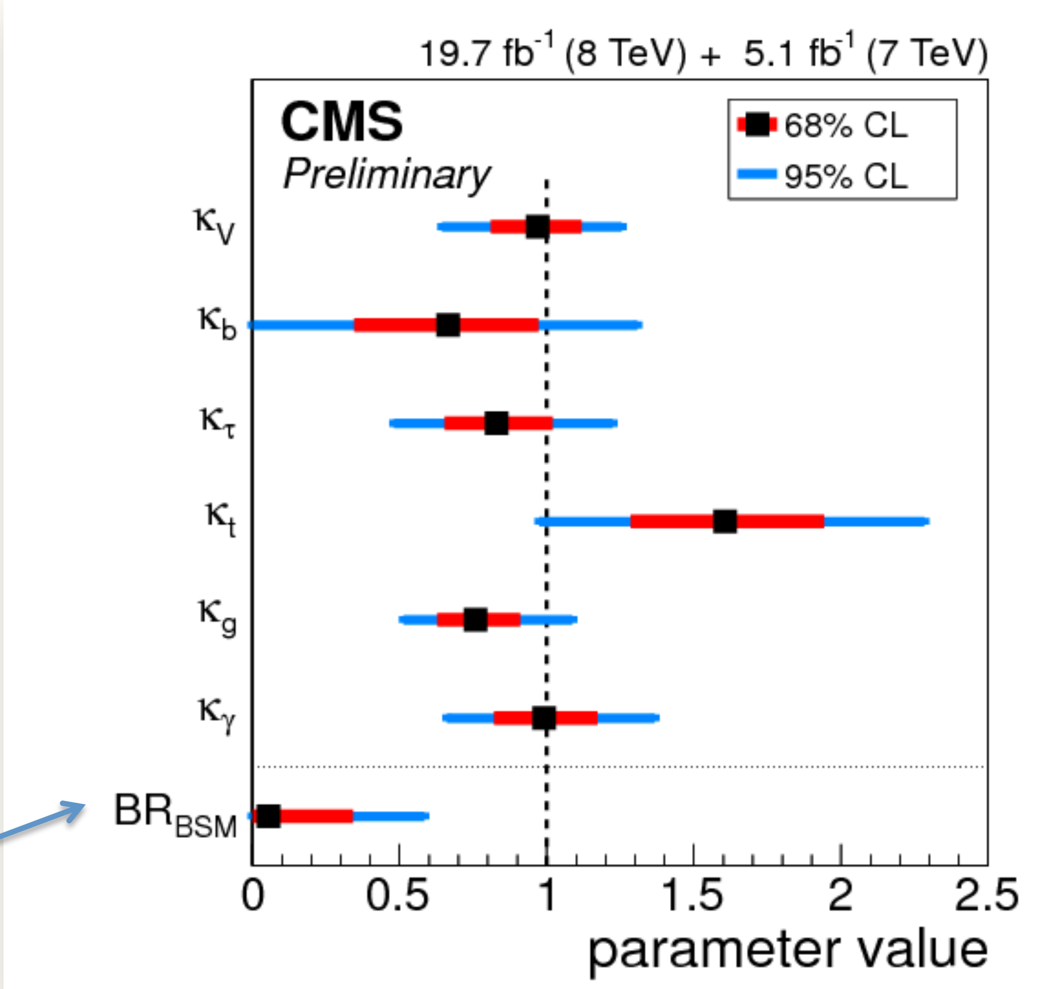
All couplings are fitted independently

The width is not allowed to have BSM contributions (NP>)

$$\text{p.o.i:}\quad k_V, k_b, k_\tau, k_t, k_g, k_\gamma$$

Generic Model III (CMS)

Allowing BR_{BSM} in the loop



https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig14009TWiki

The Full Monty IV (C7,The Mother of All Models)

Generic Model IV (ATLAS,CMS)

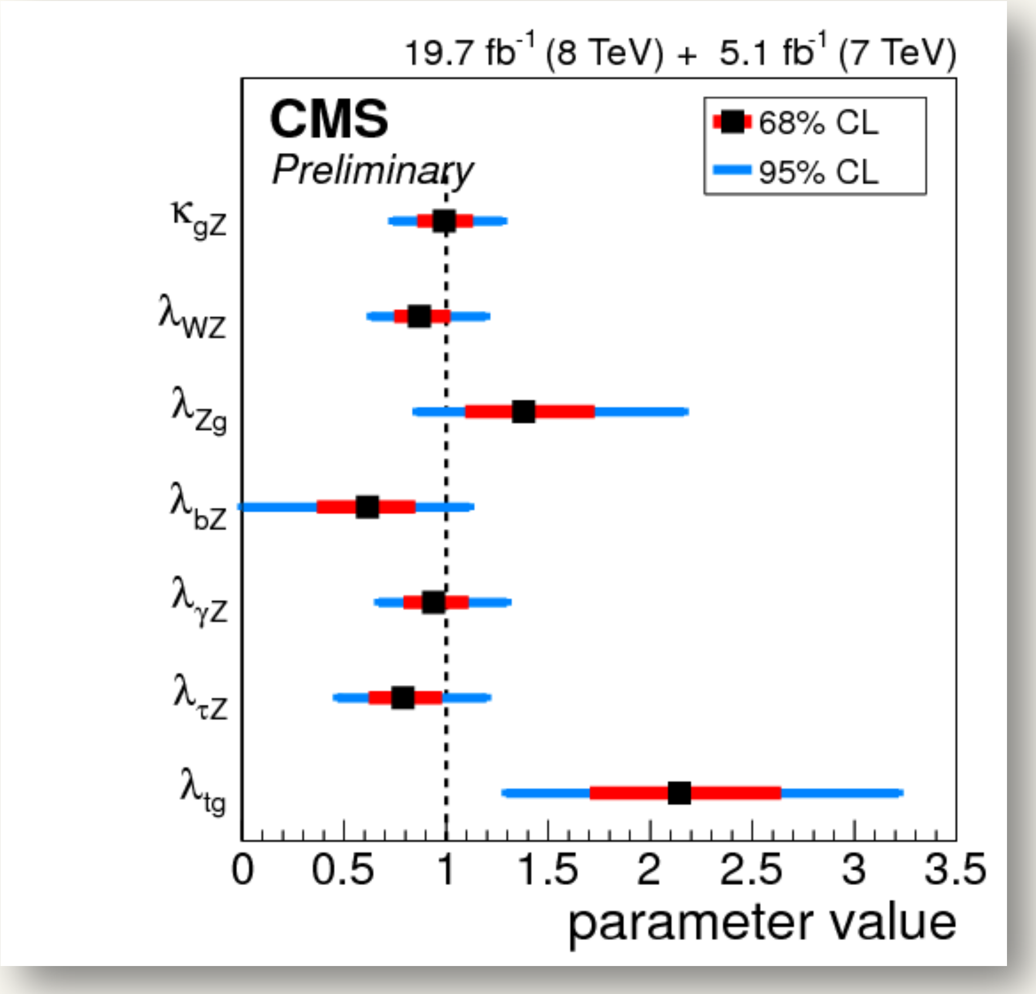
Release constrain in SM width to allow BSM contributions.

Replace loop induced couplings by effective couplings, k_g,k_γ

All couplings are fitted independently

p.o.i $\lambda_{WZ},\lambda_{tg},\lambda_{bZ},\lambda_{\tau Z},\lambda_{gZ},\lambda_{\gamma Z},\kappa_{gZ}$

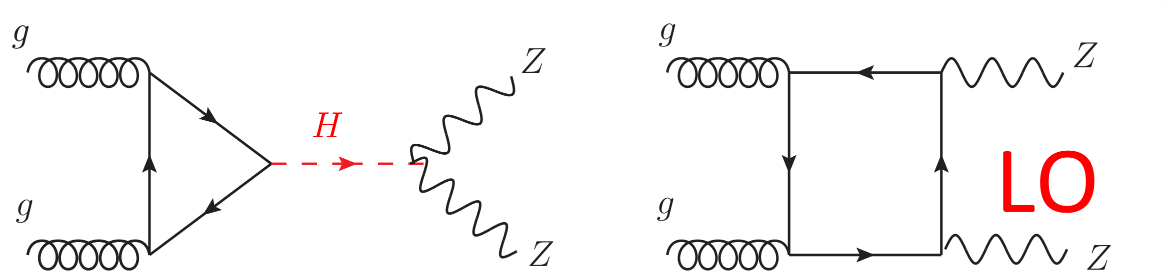
-Poor sensitivity to top coupling



https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig14009TWiki

Off-Shell HIGGS
or
HIGGS WIDTH

Higgs off-shell Physics



STRONG INTERFERENCE

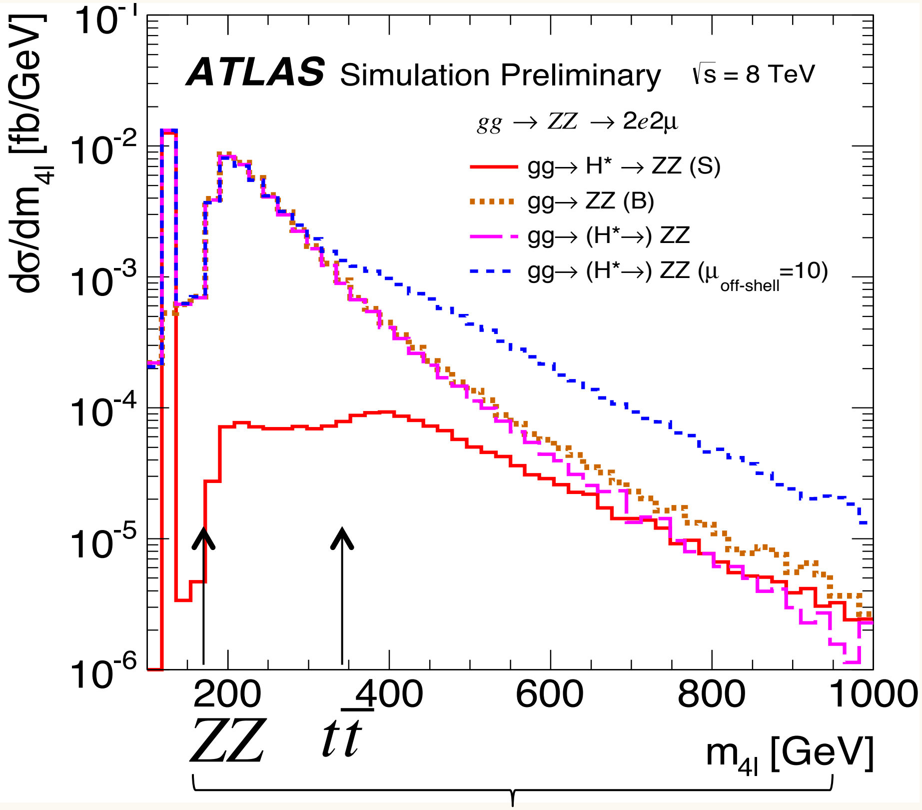
$$\frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{V,\text{off-shell}}$$

$$\frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

Interf. $\sqrt{\mu_{\text{off-shell}}} = \kappa_{g,\text{off-shell}} \cdot \kappa_{V,\text{off-shell}}$

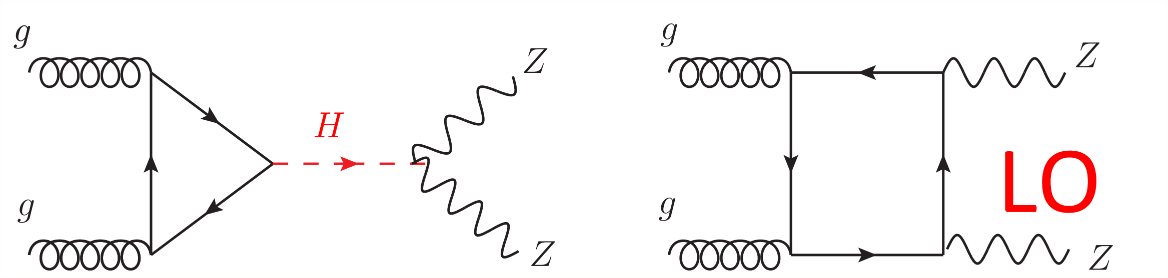
$$\boxed{\frac{\mu_{off-shell}}{\mu_{on-shell}} = \frac{\Gamma_H}{\Gamma_H^{SM}}}$$

Interference can resolve sign of k_t



Far Off Shell domain

Higgs off-shell Physics



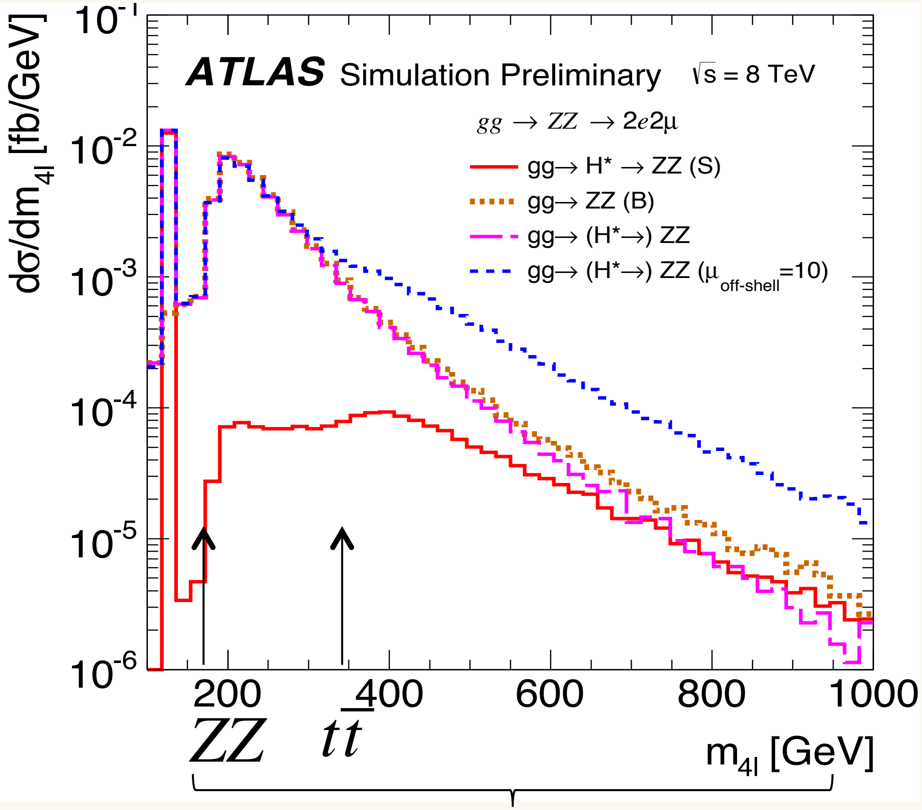
STRONG INTERFERENCE

$$\boxed{\frac{\mu_{off-shell}}{\mu_{on-shell}} = \frac{\Gamma_H}{\Gamma_H^{SM}}}$$

Assumptions

- No NP that affects Higgs couplings but not the continuum
- Higgs couplings off shell = on shell

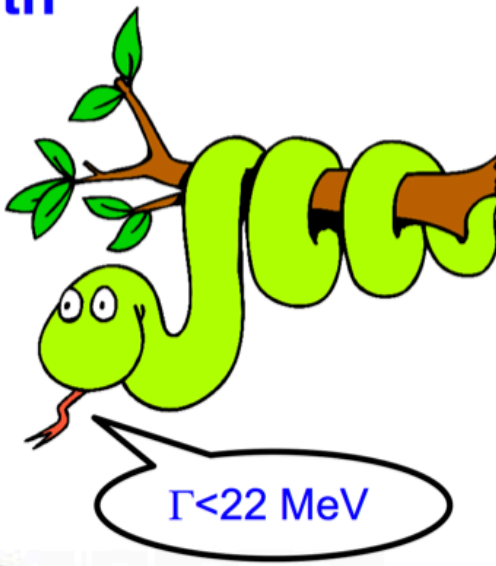
$$R^b_{H^*} = \frac{k_{gg\to ZZ}}{k_{gg\to H^*\to ZZ}}$$ **(=1 in CMS)**



Far Off Shell domain

Higgs off-shell Physics

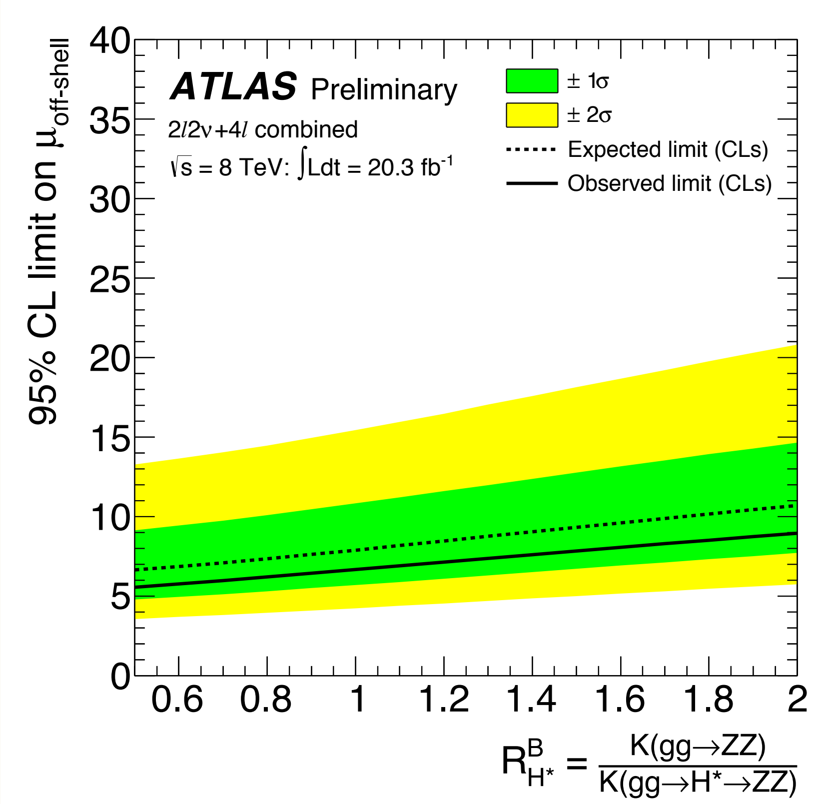
L. Quertenmont

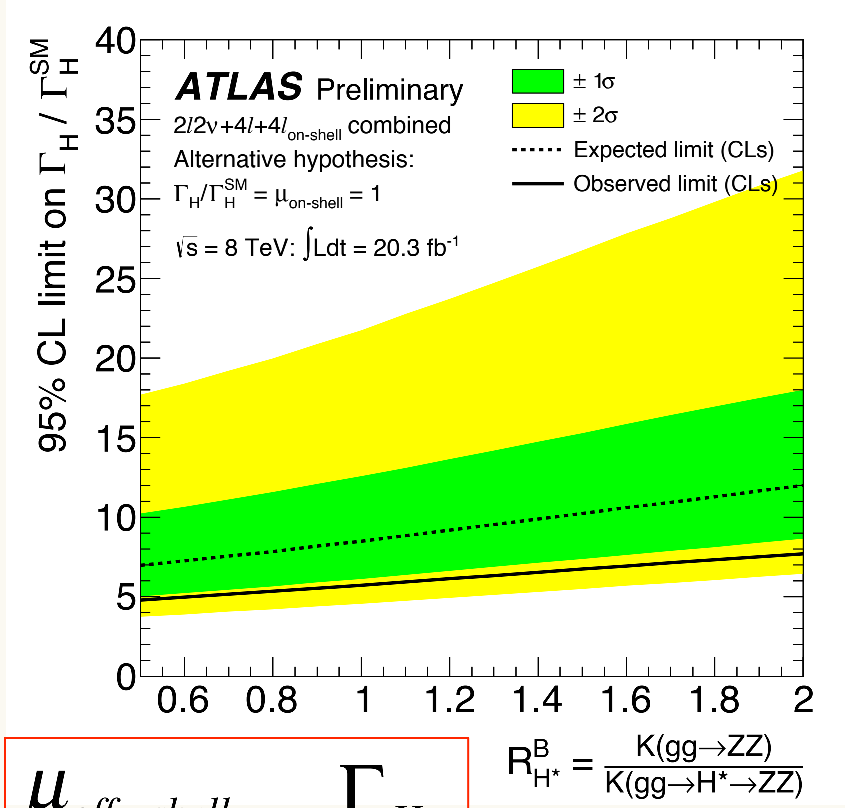


- **First experimental constraint on Higgs total width using off-shell H(125) production**
- ZZ→4l and ZZ→2l2nu channels considered
- Mild model-dependence
- 95% C.L. Limit:
  - **$\Gamma/\Gamma_{SM} < 5.4$** (8.0 expected)
  - **$\Gamma < 22$ MeV** (33 expected)
- Measurement :
  - $\Gamma_H = 4.2^{+13.5}_{-4.2}$ MeV (expected)
  - $\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV (observed)
- **Accepted for publication in PLB**

CMS use same K factors for signal and gg continuum
CMS do not use CLs

Higgs off-shell Physics





$$\frac{\mu_{off-shell}}{\mu_{on-shell}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

CLs 95% CL limit obs. (exp.)

$m_{OffShell} < 6.7\ (7.9)$

For $R_H^{BG} = 1$

$$\frac{\Gamma_H}{\Gamma_H^{SM}} < 5.7(8.5) \text{ at the 95\% CL}$$

Wondering: Can we do triple Higgs coupling using off-shell Higgs Physics?

HIGHLIGHTS

Some (still) Rare Decay Channels

	$Z\gamma$	$\gamma\gamma^{*} \to \gamma\mu\mu$	$\mu\mu$
ATLAS	$\mu_{up} < 11(9)$		$\mu_{up} < 7(7.2)$
CMS	$\mu_{up} < \ \sim 10(10)$	$\mu_{up} < \ \sim 11(8)$	$\mu_{up} < 7.4(5.1)$

ATLAS-CONF-2013-010

CMS-PAS-HIG-13-007

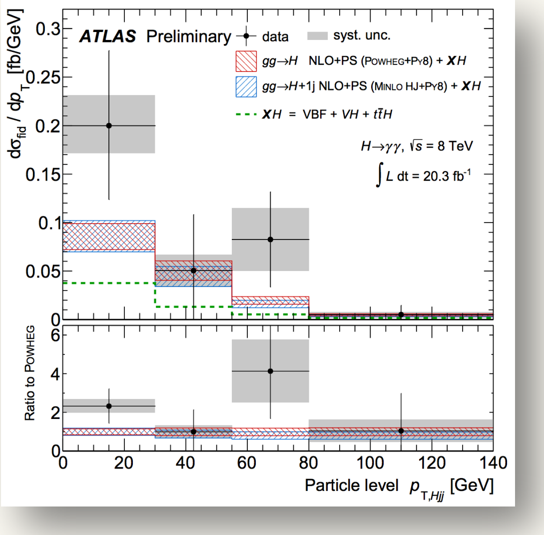
$$BR(H \to \mu\tau) < 0.0157 \ (\exp \ 0.0075) \ @\text{the } 95\% CL$$

CMS-PAS-HIG-14-005

Differential Cross Sections

$$H \to \gamma\gamma$$

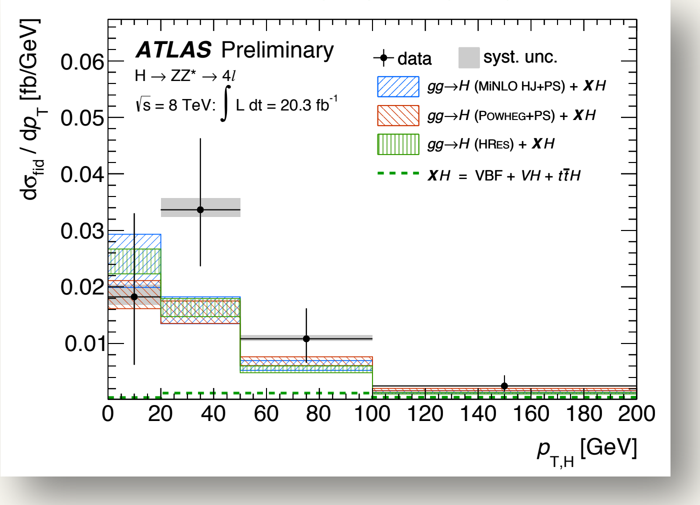
ATLAS-CONF-2013-072



$$\frac{d\sigma}{d^{Hjj}_{p_T}}$$

$$H \to 4l$$

ATLAS-CONF-2014-044

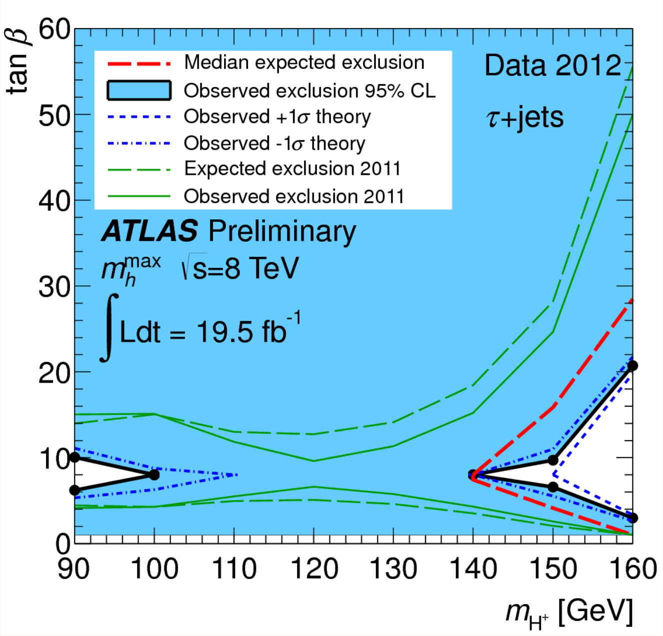


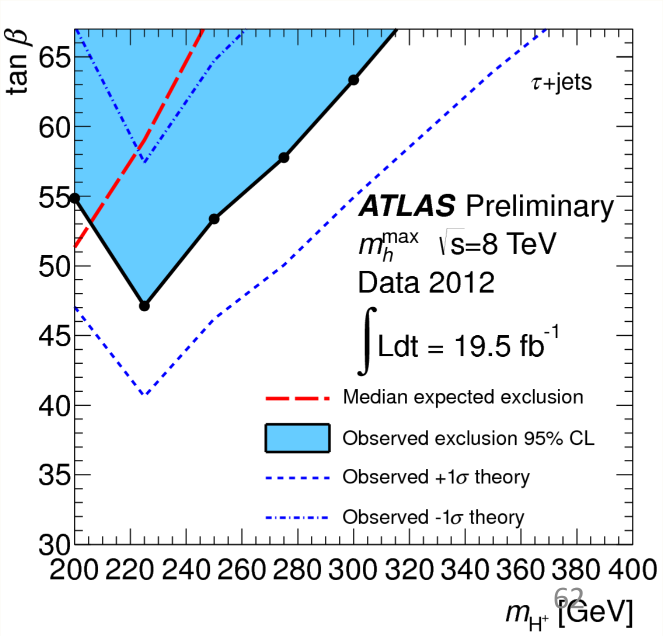
Charged Higgs, the new holy grail?

ATLAS-CONF-2013-090

Charged Higgs search

$$H^\pm \to \tau^\pm \nu$$

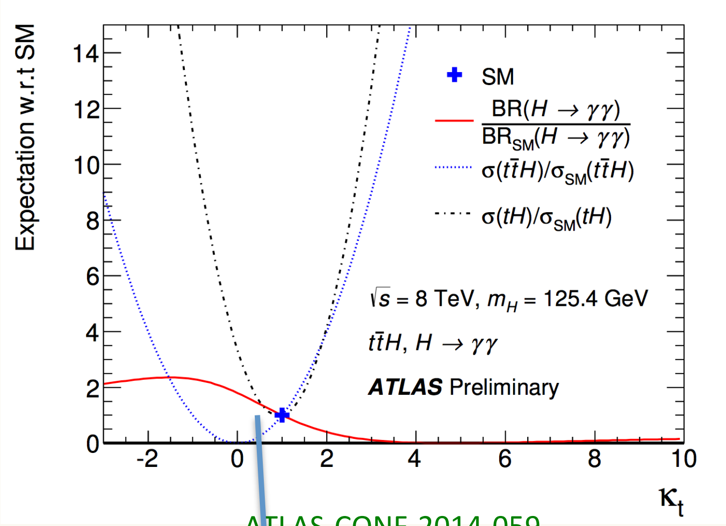


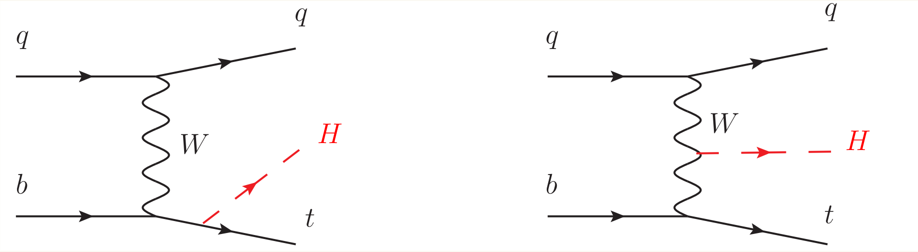


RUN 2
emphasis

$$H^\pm \to tb$$

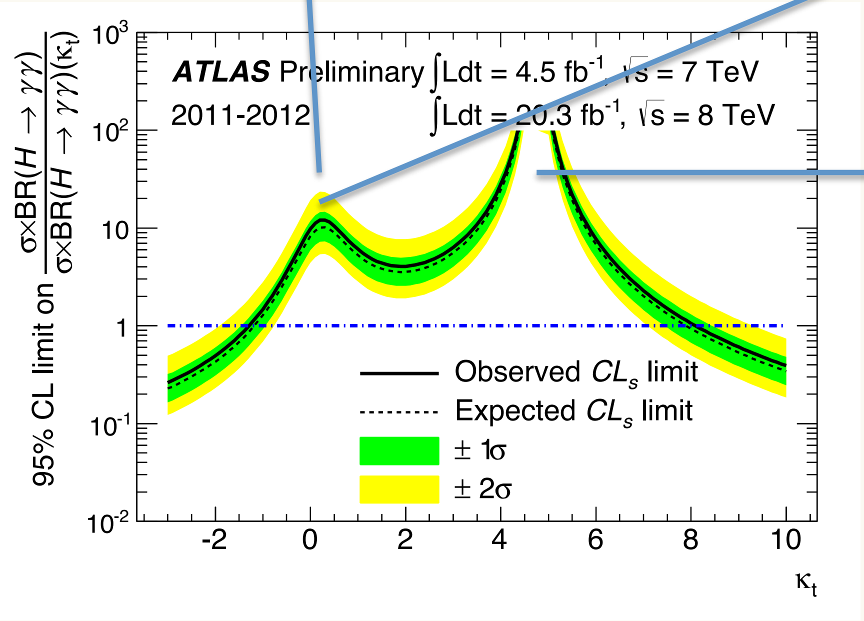
Highlight t(t)H→t(t)γγ





ATLAS-CONF-2014-059

$$\propto 3.3\times\kappa_W^2 - 5.1\times\kappa_t\kappa_W + 2.8\times\kappa_t^2$$



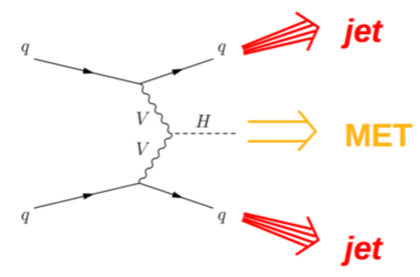
Accidental cancellation of W and t in the di-photon production loop

DM – the new Holy Grail?

PRL 112, 201802 (2014)

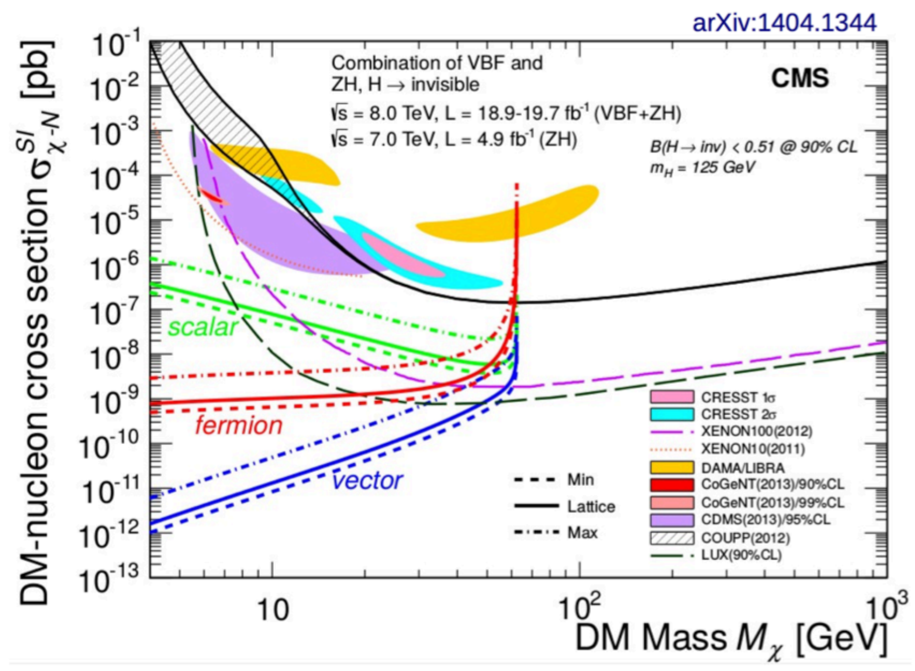
arXiv:1404.1344

	ATLAS	CMS
Channels	$qq \to ZH \to \ell\ell + MET$	VBF $qq \to qq(H) \to jj + MET$ $qq \to ZH \to \ell\ell, bb + MET$
Limit	$BR_{inv} < 0.75(\exp 0.62)$	$BR_{inv} < 0.58(\exp 0.44)$

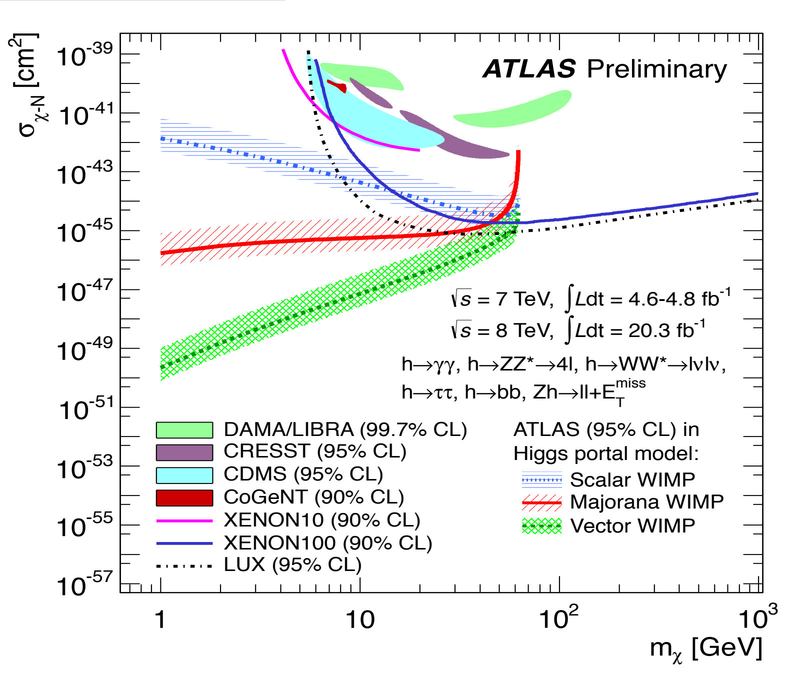


DARK MATTER

Pure Higgs portal interpretation

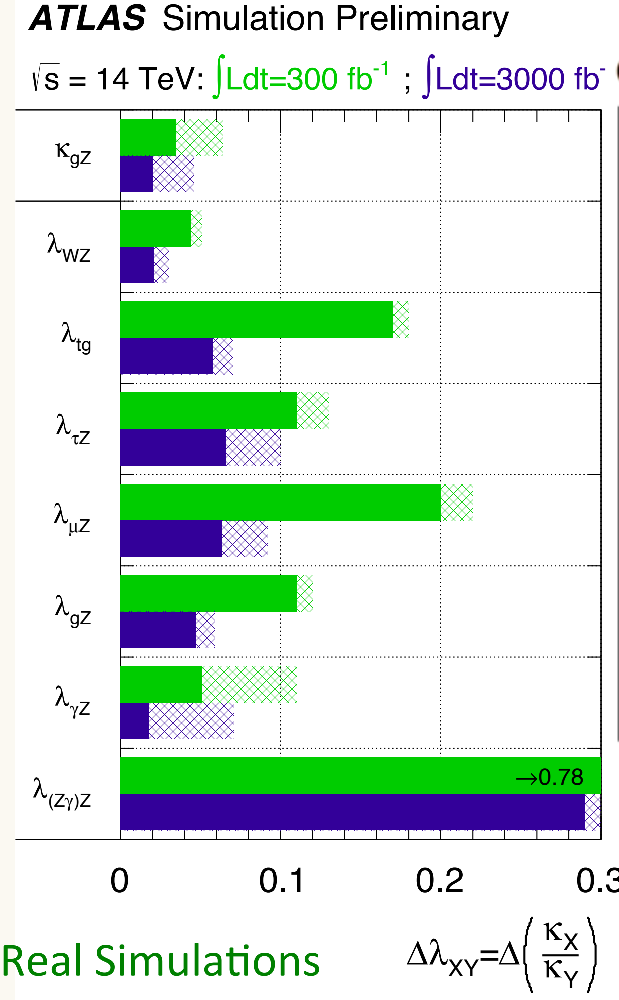


ATLAS-CONF-2014-010

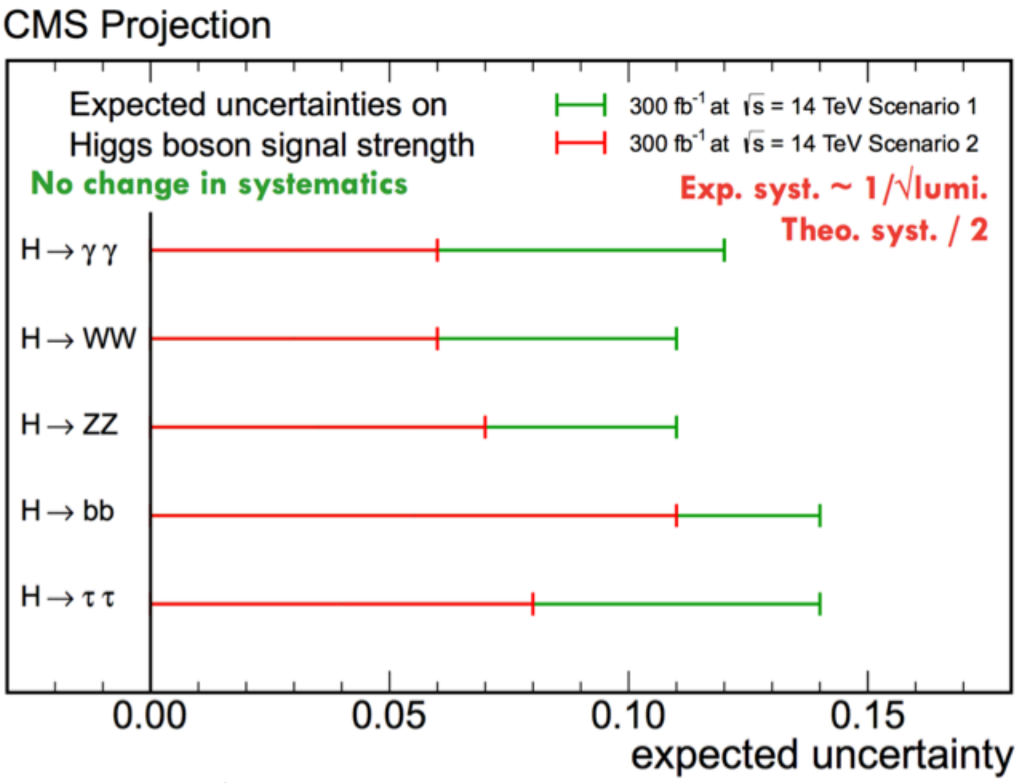


(Pessimistic) Prospects

ATL-PHYS-PUB-2013-014



Real Simulations



Extrapolations

We will do (much) better

The H^0IGGS Landscape

Based on
M. Kado
ICHEP 2014

Legend

❤ My Favorites
✔ ✔ictory
(More or less done)
✻ Under work
(one way or another)

Precision

- ✔ Mass
- ✔ Coupling properties
- ✔ Quantum numbers Spin
- ✻ Quantum numbers CP
- ✻ Differential cross sections
- ❤ Off Shell couplings and width
- ❤ Interferometry

Is the SM minimal?

- ❤ 2 HDM searches and charged Higgs
- ✻ MSSM, NMSSM searches
- ✻ Doubly charged Higgs bosons

H^0

Rare Decays

- ✻ $Z\gamma$
- ✻ $\mu\mu$
- ✻ LFV $\mu\tau$, $e\tau$

Etc…

…and More!

- ✻ FCNC top decays
- ✻ Di-Higgs production
- ✻ Trilinear couplings (prospects)

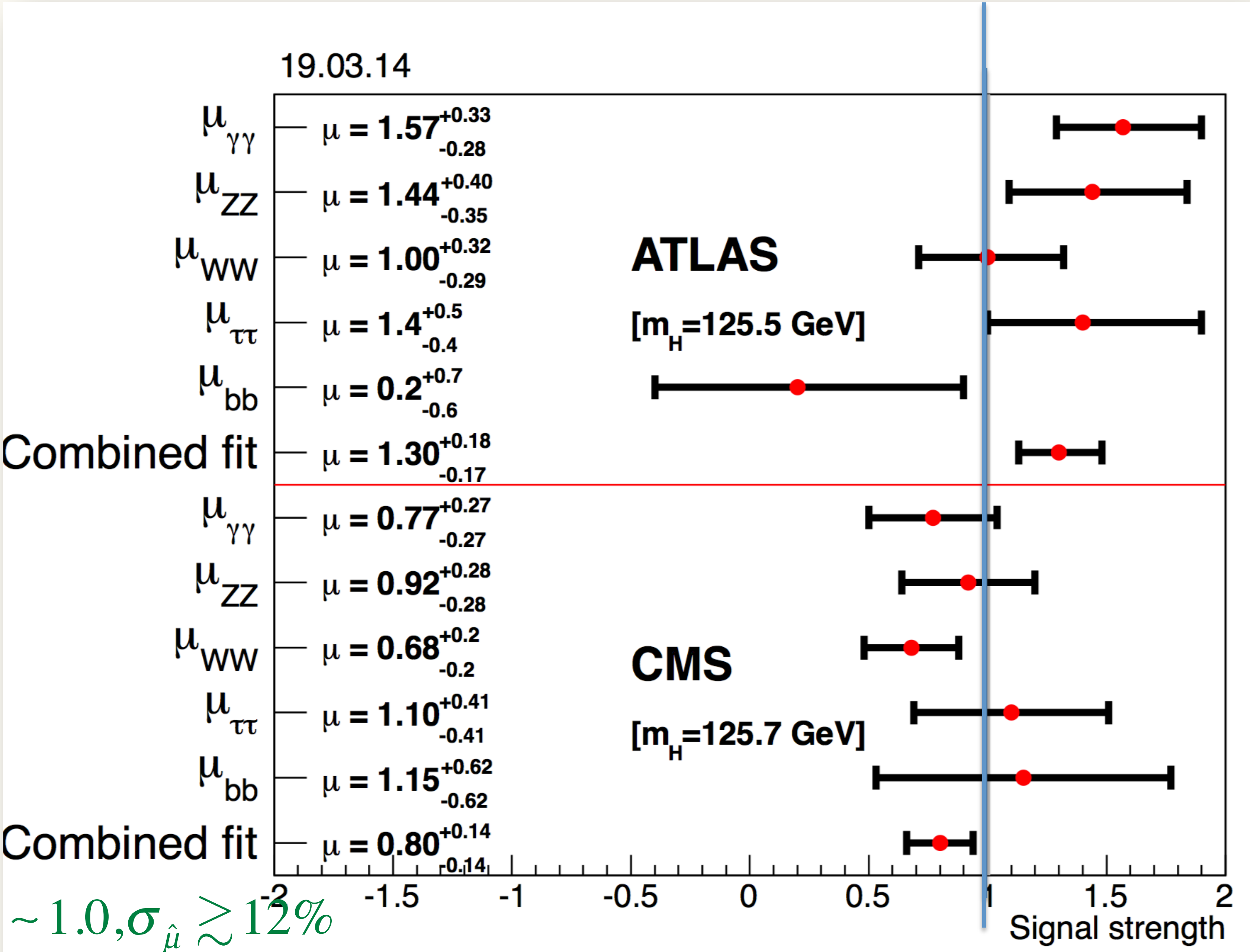
Etc…

Tool for discovery

- ❤ Portal to DM (invisible Higgs)
- ✻ Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

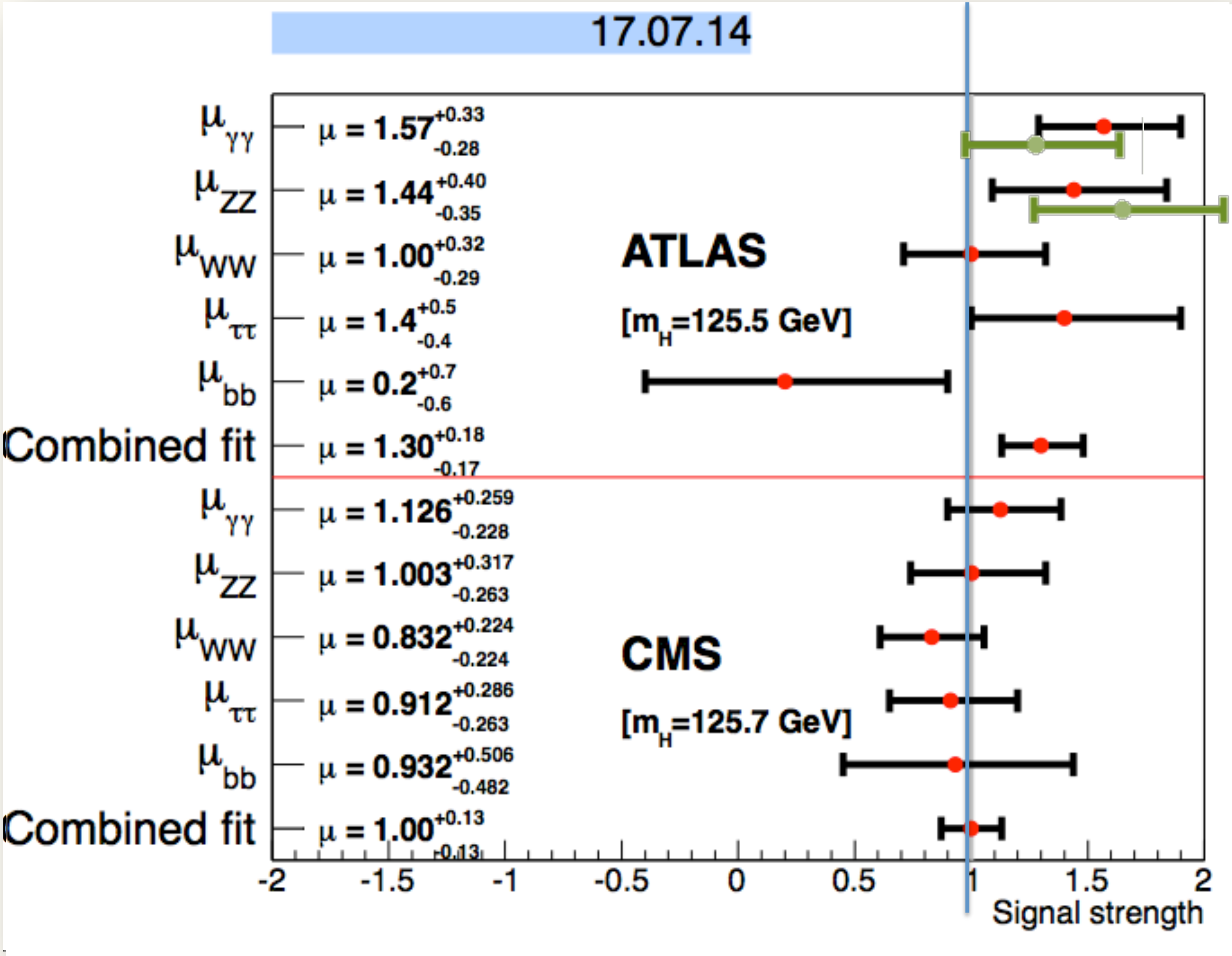
Etc….

Conclusions I



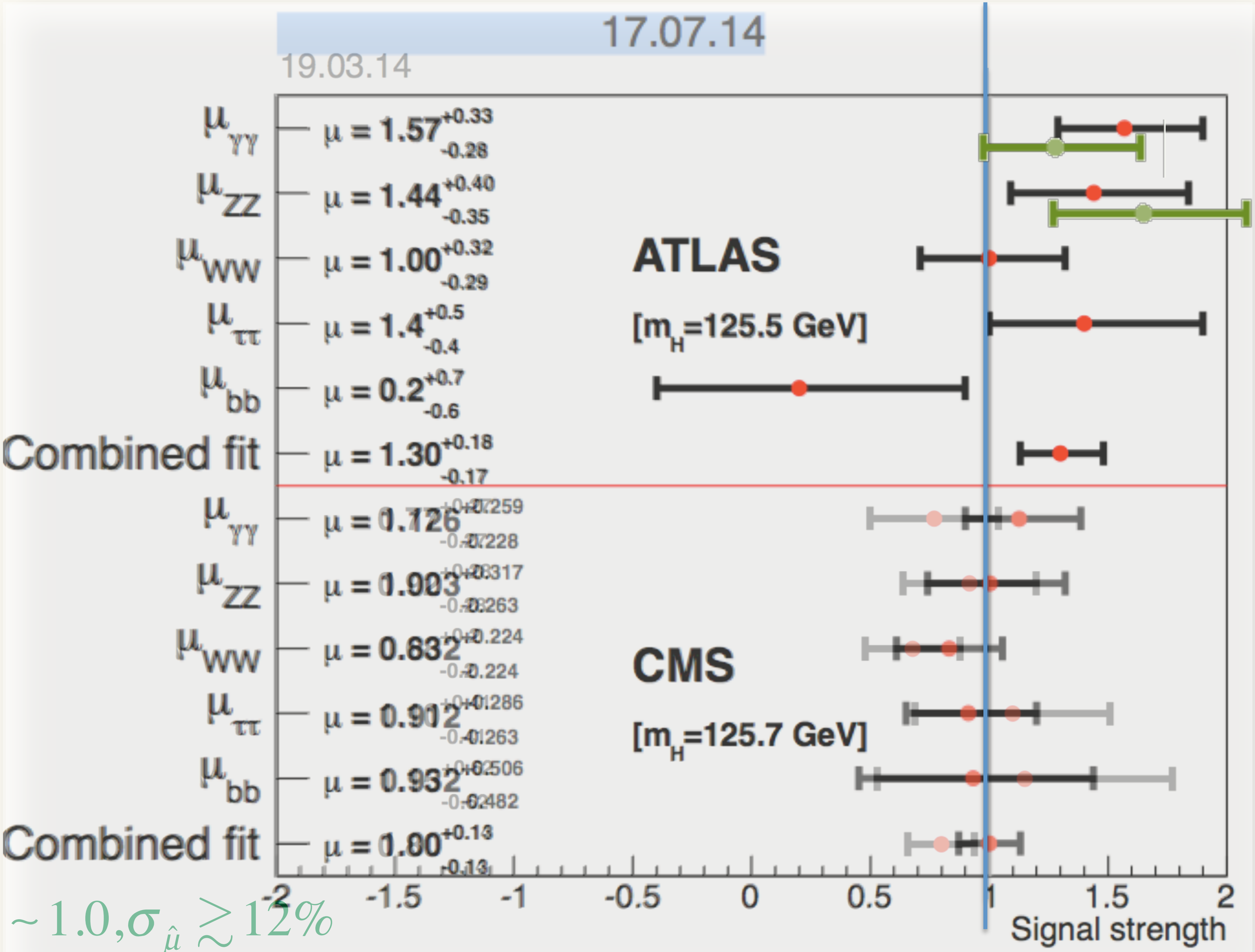
$$\hat{\mu} \sim 1.0, \sigma_{\hat{\mu}} \gtrsim 12\%$$

Conclusions I



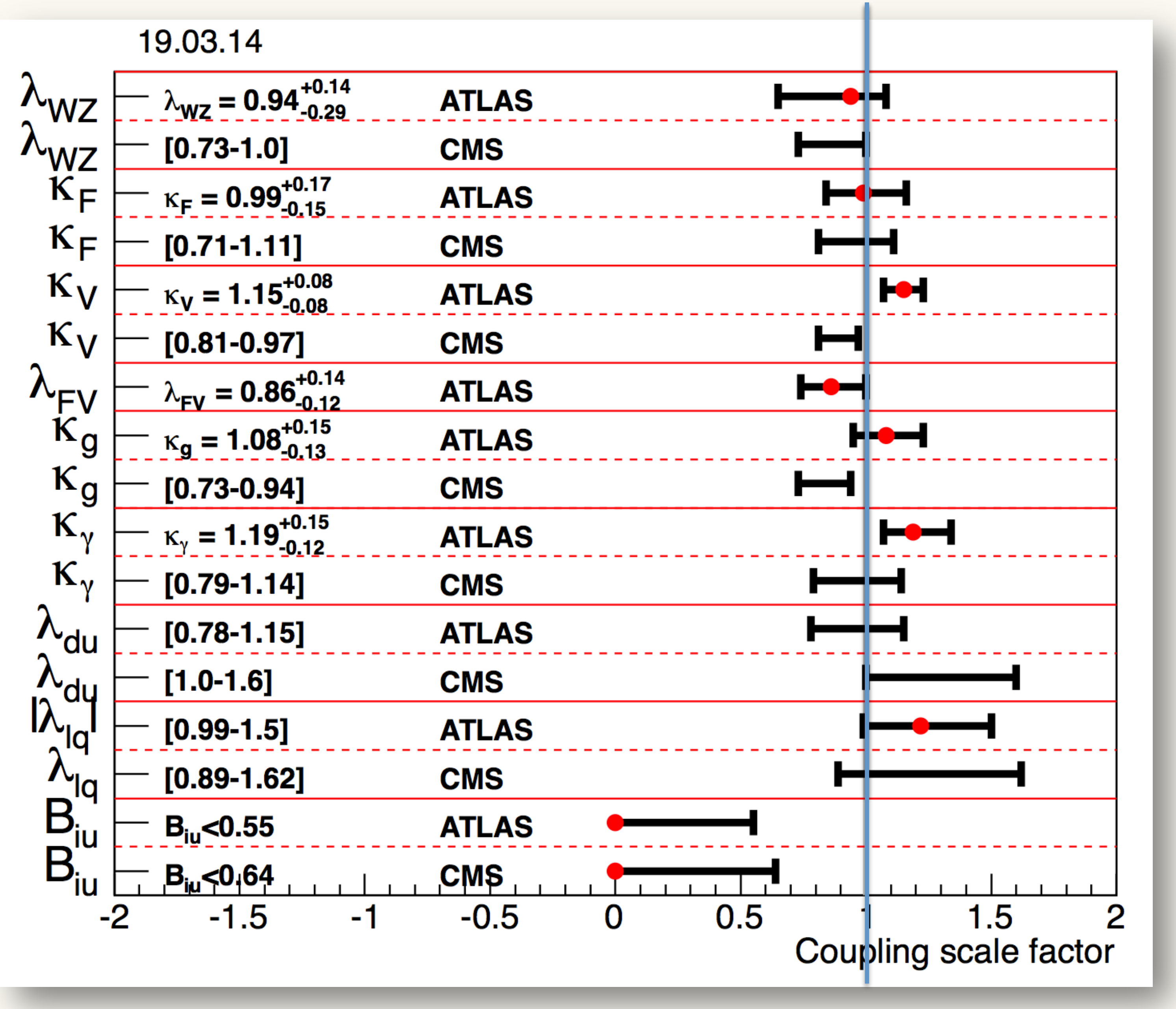
$\hat{\mu}$

Conclusions I

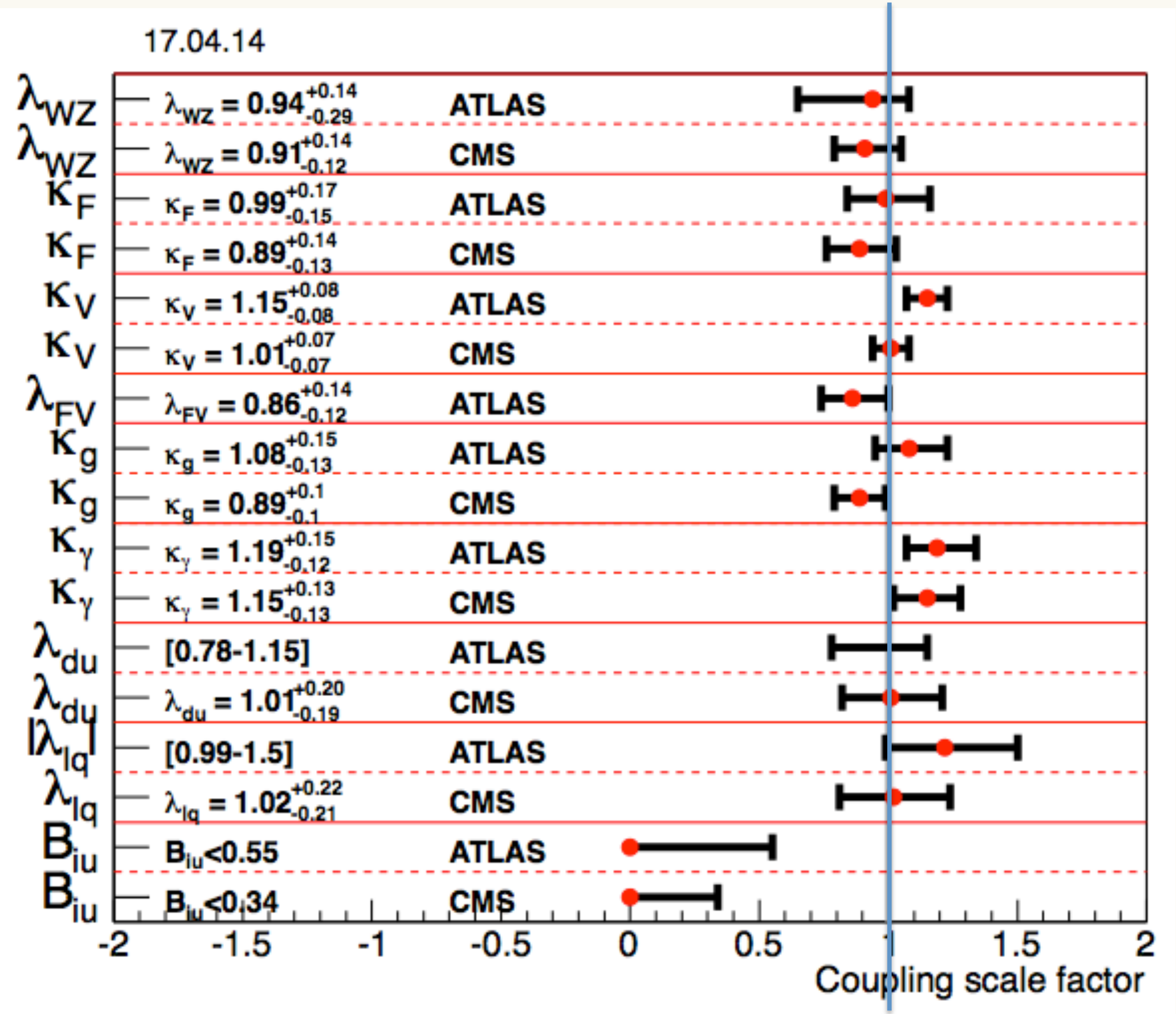


$\hat{\mu} \sim 1.0, \sigma_{\hat{\mu}} \gtrsim 12\%$

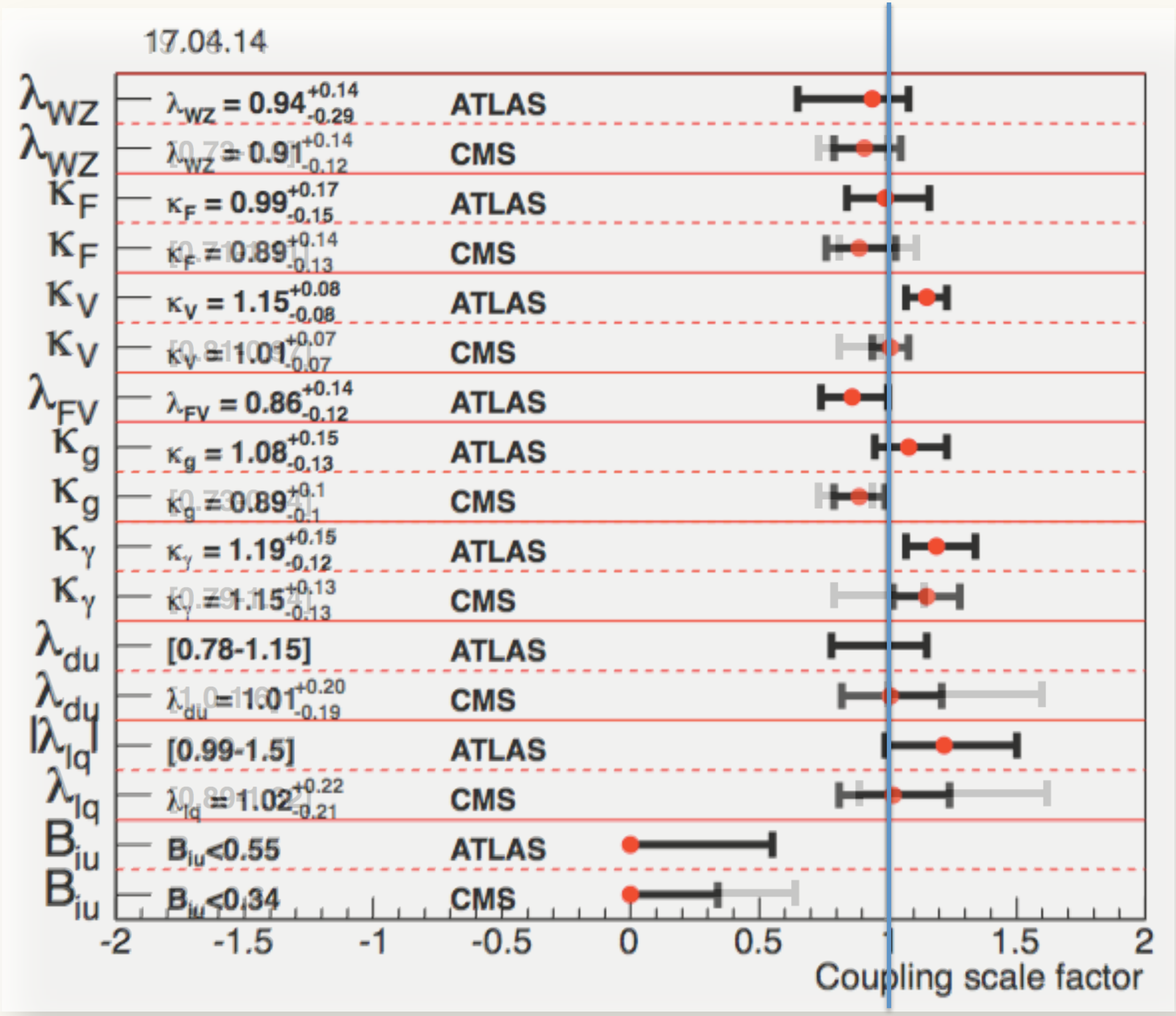
Conclusions II



Conclusions II



Conclusions II



Conclusions III

In two years the "discovery of a scalar particle compatible with a SM Higgs Boson" made a phase transition into "precsion measurements"

The Higgs moved from the "search" regime to the "SM" regime

The last year has proven that reducing the experimental systematics pays

The experiments should focus in understanding the detector and do better calibrations.

IT TAKES TIME!

For now in most important measurements we are statistically limited

Conclusions IV

The Higgs revolution has just begun and we look forward to better measurements and new searches that will reveal hopefully either new particles or significant deviations from the SM. But life is becoming more demanding……

The new holy grails of HEP are probably Dark Matter and Charged Higgs

We thank the LHC machine team that enabled us to experience a once in a physicist's lifetime experience!

BACKUP

Discovery Channel H->WW

H->WW->lvlv

A challenging channel;

No mass reconstruction (mT,mll)

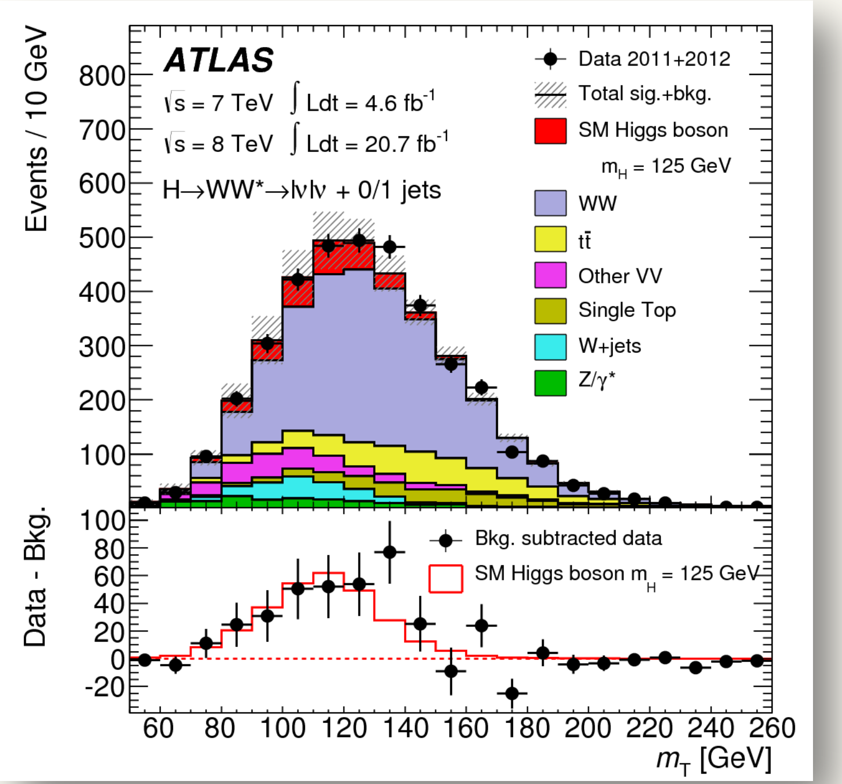
Dominant BG WW and tt

Understanding Etmiss tails crucia

BG from DATA control regions

Analysis in categories:

(0,1,2 jets VBF,VH)X(SF,DF)



Phys. Lett. B 726 (2013), pp. 88-119

Most important systematics from signal cross section (QCD scale, PS and UE, total >10%)

$$\mu^{WW} = 0.99^{+0.31}_{-0.28} \quad 3.8\sigma(3.8\sigma\, exp) \ @ \ m_H\!=\!125 \text{ GeV } ATLAS$$

$$\mu^{WW} = 0.72^{+0.20}_{-0.18} \quad 4.3\sigma(5.8\sigma \text{ exp}) \ @m_H\!=\!125.6 \text{ GeV } CMS$$

CMS: J. High Energy Phys. 01 (2014)

Scenario	$k_H(k_j)$	$k_\gamma(k_t, k_W)$	$k_g(k_t, k_b)$	k_F	k_V	p.o.i	
Custodial (NP_{NL})	–	√	√	√	×	$\lambda_{WZ} .\lambda_{FZ}, k_{ZZ}$	A
Custodial (SM)	√	√	√	√	×	λ_{WZ}, k_Z, k_F	C
(k_F, k_V) (SM)	√	√	√	√	√	k_F, k_V	A,C
(k_F, k_V) (NP_{NL})	–	√	√	√	√	λ_{FV}, k_{VV}	A
Generic I (SM)	√	√	√	×	×	$k_W, k_Z, k_t, k_b, k_\tau$	A
Generic II (NP)	–	×	×	×	×	$\lambda_{WZ}, \lambda_{bZ}, \lambda_{\gamma Z}, \lambda_{gZ}, \lambda_{\tau Z}, \lambda_{tg}$	
u/d (SM)	√	√	√	k_u, k_d	√	λ_{du}, k_V, k_u	C
ℓ/q (SM)	√	√	√	k_ℓ, k_q	√	$\lambda_{\ell q}, k_V, k_q$	
u/d (NP_{NL})	–	√	√	k_u, k_d	√	$\lambda_{du}, \lambda_{Vu}, k_{uu}$	A
ℓ/q (NP_{NL})	–	√	√	k_ℓ, k_q	√	$\lambda_{\ell q}, \lambda_{Vq}, k_{qq}$	
(k_g, k_γ) (NP>)	√	×	×	$=1$	$=1$	k_g, k_γ	A,C
(k_g, k_γ) (NP<)	$\surd^*$	×	×	$=1$	$=1$	$k_g, k_\gamma, BR_{i,u}(*)$	A,C
C6 (NP>)	√	×	×	–	√	$k_\gamma, k_g, k_V, k_t, k_b, k_\tau$	C

Measuring Higgs Couplings

$$n_s^{c,i} = \sum_p \left[\mu^p \mu_{BR}^i\right] \times (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

The degeneracy of $\left[\mu^p \mu_{BR}^i\right]$ can be broken by parameterize the strength parameters with couplings and introduce constraints which reduce the number of p.o.i. and allow reasonable fits.

$$k_i^2 = \frac{\Gamma_i}{\Gamma_I^{SM}} \qquad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

Examples: @ m_H=125.5 GeV

$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 - 0.66 \cdot \kappa_W \kappa_t + 0.07 \cdot \kappa_t^2$$

(t,W) interference

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

(t,b) interference

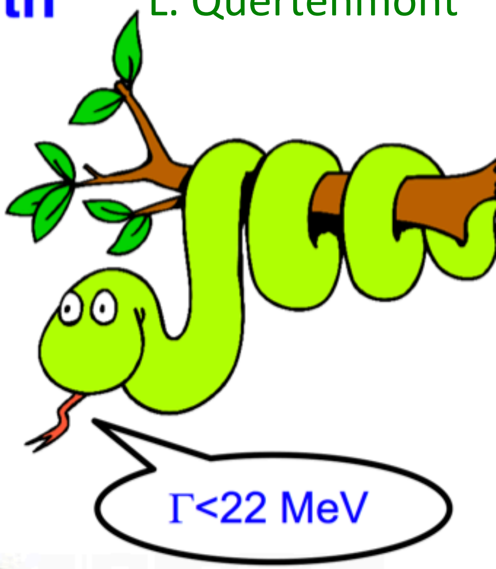
$$\kappa_{VBF}^2 \sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$$

$$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2$$

Uncertainties Width Measurements

- **First experimental constraint on Higgs total width using off-shell H(125) production**

L. Quertenmont



- ZZ→4l and ZZ→2l2nu channels considered
- Mild model-dependence
- 95% C.L. Limit:
  - **$\Gamma/\Gamma_{SM} < 5.4$** (8.0 expected)
  - **$\Gamma < 22$ MeV** (33 expected)
- Measurement :
  - $\Gamma_H = 4.2^{+13.5}_{-4.2}$ MeV (expected)
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- **Accepted for publication in PLB**