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

Eilam Gross, Weizmann Institute of Science

HIGGS COUPLINGS

Acknowledgements : Marumi Kado, Yossi Nir, Michael Duehrssen,
Marco Pieri, Pierre Savard, Liron Barak

Higgs Ringing Down the Years (Moriond)

2000 SM neutral Higgs search

2001 Higgs in OPAL,DELPHI,ALEPH

2002 LEP Higgs boson searches

2003

2004

2005

2006

2007 Higgs searches in Tevatron

2008

2009 Low mass SM Higgs (Tevatron)

2010 Session: The Higgs at the Tevatron. Review: Higgsless Universe

2011 Higgs Boson Searches with ATLAS based on the 2010 Data

2012 Results from ATLAS, CMS

2013 Study of BEH Production in Bosonic decay channels in CMS, BEH detection to boson pairs in ATLAS

2014 Higgs Properties, Higgs Couplings (this talk)

Bibliography of this Talk

ATLAS

Combinations (and refs therein)

Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC,
PLB 726 (2013) 88–119

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

new Constraints on New Phenomena via Higgs Coupling Measurements with the ATLAS Detector ATLAS-CONF-2014-010

Differential cross sections of the Higgs boson measured in the diphoton decay channel using 8 TeV pp collisions, ATLAS-CONF-2013-072

Zgamma -Search for Higgs boson decays to a photon and a Z boson…
arXiv:1402.3051v1 (hep-ex)

Bibliography of this Talk –CMS

Combinations (refs therein)

Measurements of the properties of the new boson with a mass near 125 GeV, CMS-PAS-HIG-13-005, July 2013

Evidence for the direct decay of the 125 GeV Higgs boson to ferminos arXiv:1401.6527v1 [hep-ex]

Individual channels (published)

HZZ http://arxiv.org/pdf/1312.5353.pdf

HWW http://arxiv.org/pdf/1312.1129.pdf J. High Energy Phys. 01 (2014) 096

Hbb http://arxiv.org/pdf/1310.3687.pdf Phys. Rev. D 89 (2014) 012003

Htautau http://arxiv.org/pdf/1401.5041.pdf

Zgamma http://arxiv.org/pdf/1307.5515.pdf Phys. Lett. B 726 (2013) 587-609

Decay to fermions http://arxiv.org/pdf/1401.6527.pdf

new Search for a Higgs boson decaying to $\gamma^{*}\gamma \rightarrow \mu\mu\gamma$ with dilepton mass below 20 GeV in pp collisions at 8 TeV, CMS PAS HIG-14-003

La Combinaison

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

2011 $\sqrt{s}$ =7 TeV

$H \to \gamma\gamma$	–	
$H \to ZZ^{(*)}$	4ℓ	
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	
$VH \to Vbb$	$Z \to \nu\nu$	E_T^{miss}
	$W \to \ell\nu$	$p_T^W \in$
	$Z \to \ell\ell$	$p_T^Z \in$

new

ATLAS-CONF-2014-009

2012 $\sqrt{s}$ =8 TeV

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

CMS PAS HIG-13-005

H decay	Prod. tag	Analyses: Exclusive final states	No. of channels	m_H resolution	Lumi (fb^{-1}) 7 TeV	Lumi (fb^{-1}) 8 TeV
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4 + 4	1-2%	5.1	19.6
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$ (two dijet classes for 8 TeV)	1 + 2	<1.5%	5.1	19.6
	VH-tag	$\gamma\gamma$ + (e, μ, MET)	3	<1.5%		19.6
$ZZ \to 4\ell$	$N_{jet} < 2$	4e, 4μ, $2e2\mu$	3 + 3	1-2%	5.1	19.6
	$N_{jet} \geq 2$		3 + 3			
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) × (0 or 1 jets)	4 + 4	20%	4.9	19.5
	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 + 2	20%	4.9	12.1
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	2 + 2		4.9	19.5
$\tau\tau$	0/1-jet	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$) × (low or high p_T^τ)	16 + 16	15%	4.9	19.6
	1-jet	$\tau_h\tau_h$	1 + 1			
	VBF-tag	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$) + $(jj)_{VBF}$	5 + 5			
	ZH-tag	(ee, $\mu\mu$) × ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8 + 8		5.0	19.5
	WH-tag	$\tau_h\mu\mu$, $\tau_h e\mu$, $e\tau_h\tau_h$, $\mu\tau_h\tau_h$	4 + 4			
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, eν, $\mu\nu$ with 2 b-jets) × (low or high $p_T(V)$ or loose b-tag)	10 + 13	10%	5.0	12.1
	ttH-tag	(ℓ with 4, 5 or ≥6 jets) × (3 or ≥4 b-tags);	6 + 6		5.0	5.1
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or ≥3 b-tagged jets)	3 + 3			

Introduction

A Higgs Boson has been observed not by 1, but by 6000 physicists (and if you still do not believe me see next slides)…

Is this the missing piece of the SM, or is it a tip of some huge iceberg?

We can try to answer this by measuring the properties of the newly discovered particle

The Higgs is the generator of the elementary Fermion masses. Its Yukawa coupling is proportional to mass.

The BEH mechanism allows the W and the Z to acquire mass without explicitly breaking the symmetry

It dictates the couplings of the Higgs to the gauge Bosons, We would like to verify that.

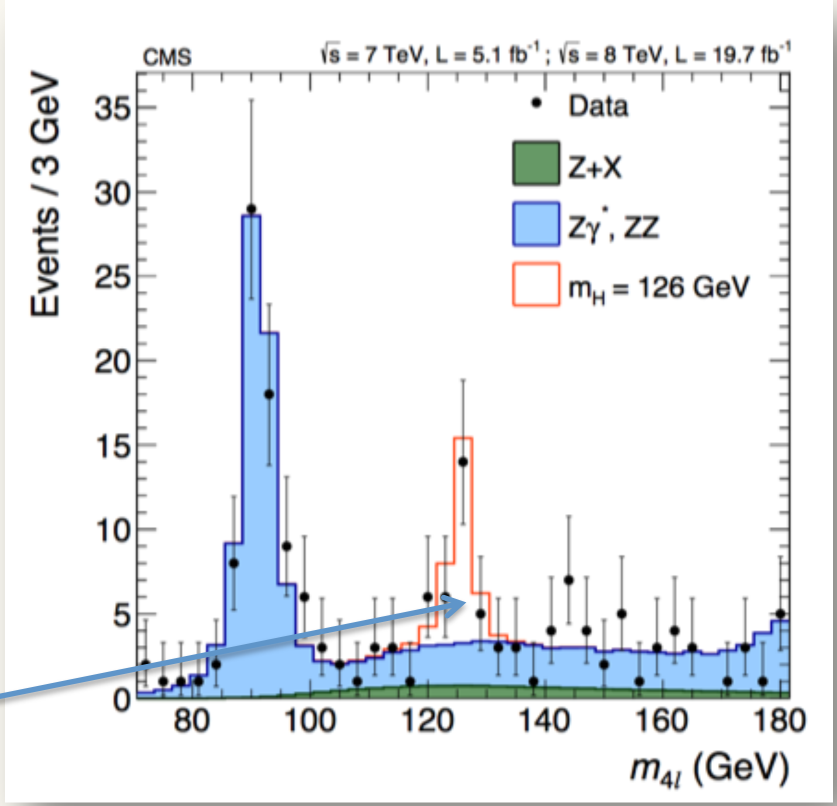
What do we measure

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



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

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

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

$$\mu_{ZZ}(@m_H = 125.6) = 0.93^{+0.26+0.13}_{-0.23-0.09} \qquad 6.8\sigma(6.7\sigma\ \exp)\quad CMS$$

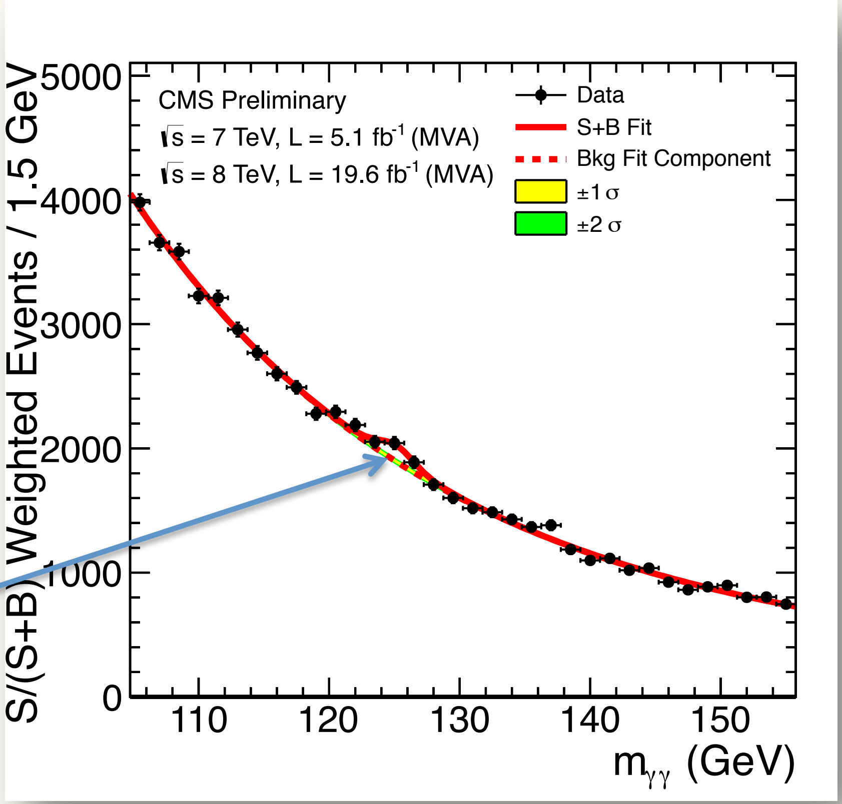
What do we measure

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

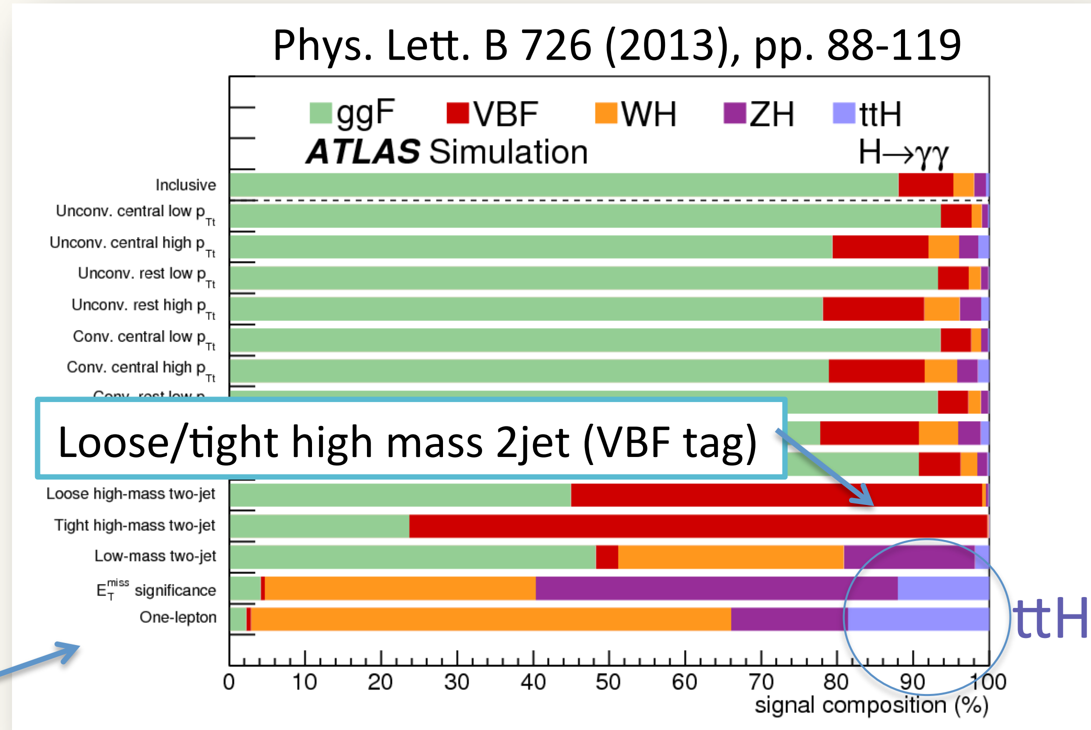


$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

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

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 errors uncertainties into account



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

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

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

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

$$\mu_{\gamma\gamma}(@m_H = 125.7) = 0.77^{+0.29}_{-0.26} \quad 3.2\sigma(3.9\sigma\, \exp)\ \ CMS$$

Probe the Production Modes

Define

$$\mu_p^i \equiv [\mu_p \mu_{BR}^i] \quad \mu_{BR}^i \equiv \frac{BR^i}{BR_{SM}^i}$$

Parameterize with explicit production modes and decays

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

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

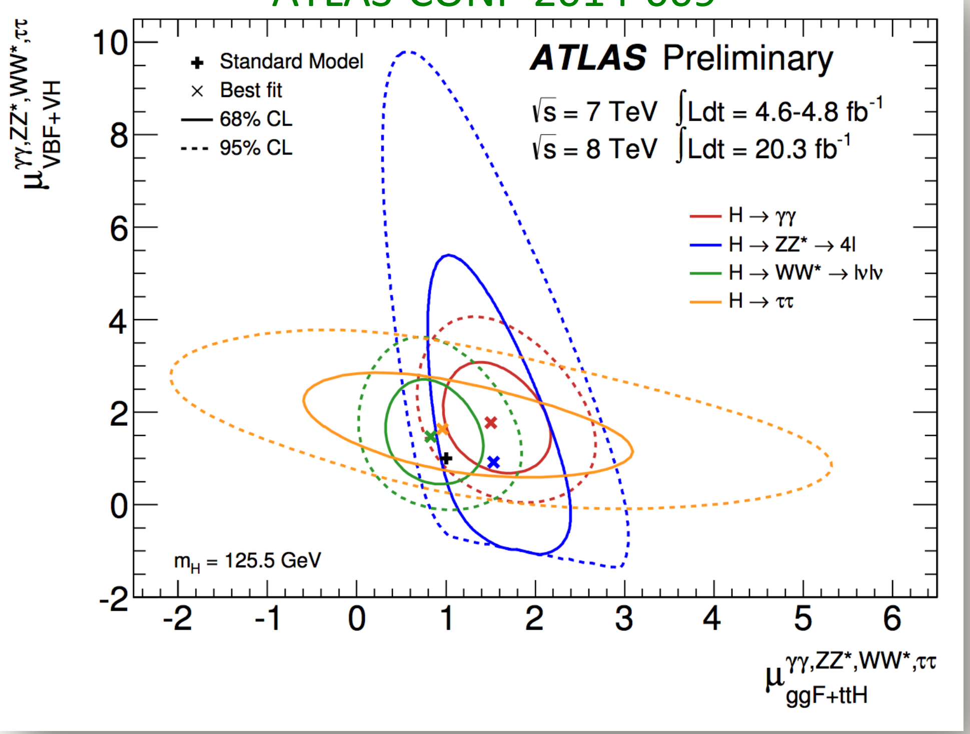
We cannot fit simultaneously the cross section and the BR

→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

ATLAS-CONF-2014-009



Probing VBF production mode

We fitted

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

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

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

	$\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$	*Significance*
ATLAS	$1.4^{+0.7}_{-0.5}$	
CMS	$1.54^{+1.16}_{-0.74}$	3.2σ

CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13005TWiki#Ratio_of_production_modes_not_in

Probing VBF production mode

ATLAS-CONF-2014-009

We fitted

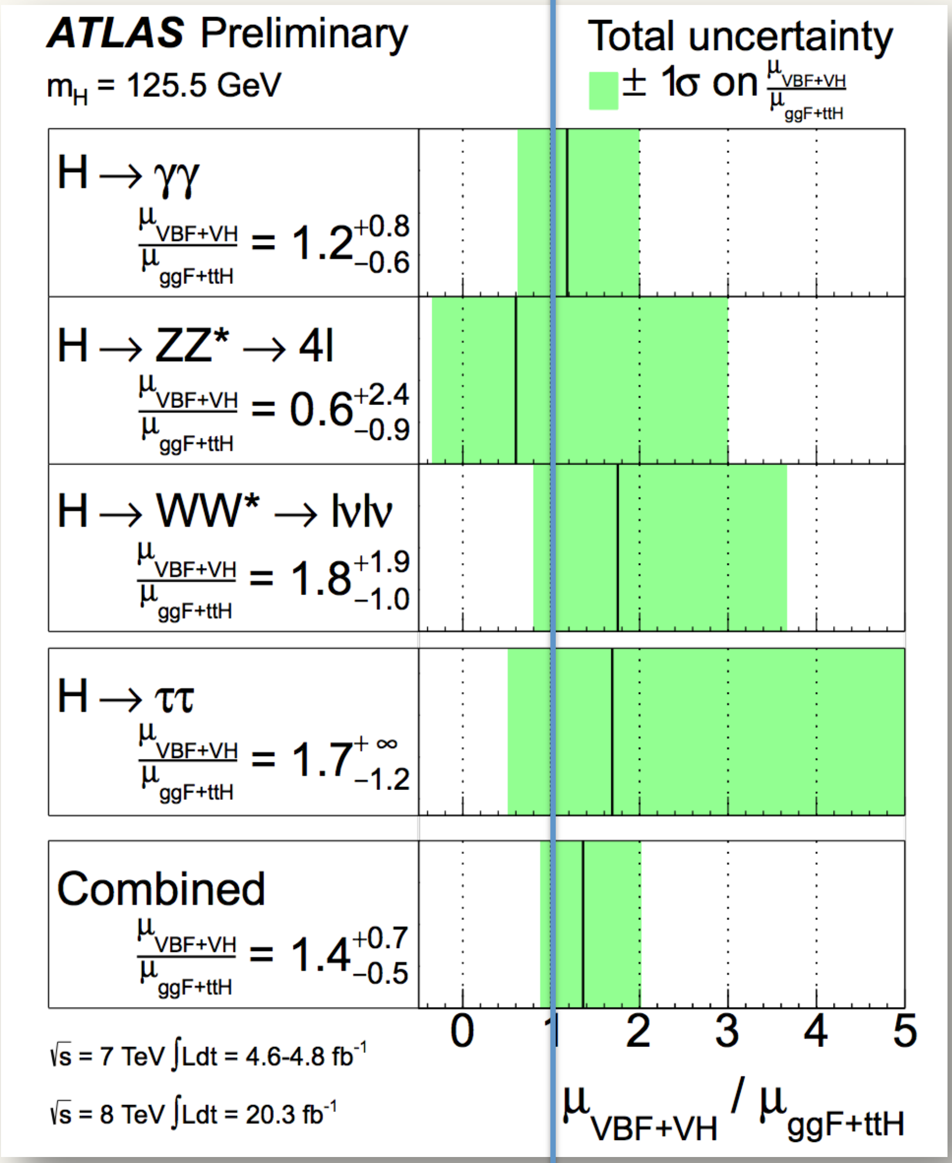
$$\mu^i_{VBF+VH} \equiv \left[\mu_{VBF+VH} \times \mu^i_{BR}\right]$$

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

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



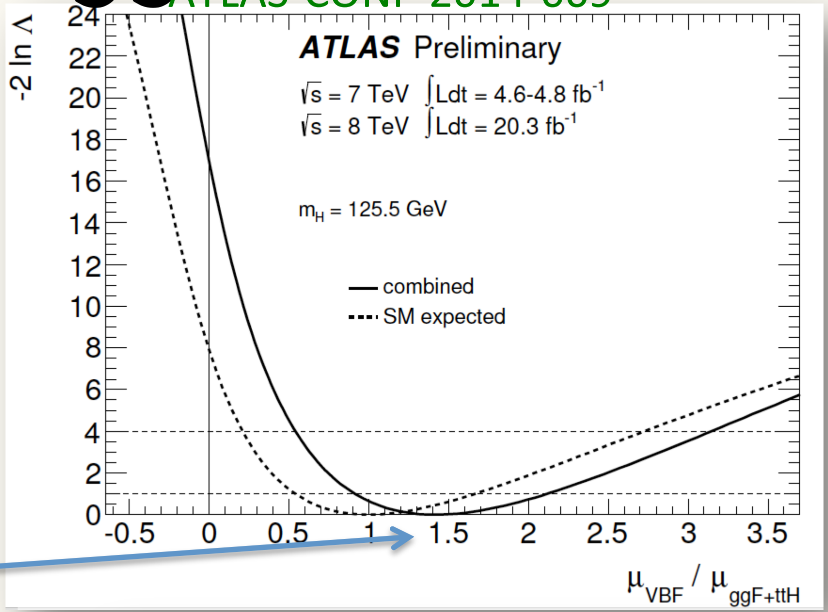
Evidence for VBF Higgs Production

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

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

evidence for VBF Higgs production

ATLAS-CONF-2014-009



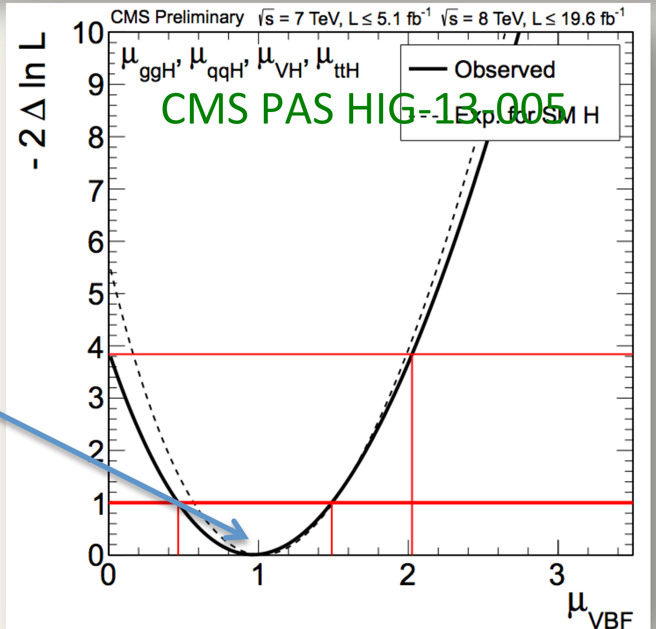
$$\frac{\mu_{VBF}}{\mu_{ggF+ttH}} = 1.4 \pm 0.3(stat)^{+0.6}_{-0.4}(sys) \text{ ATLAS}$$

ATLAS Conf Comb

CMS profile VH,ggF and ttH

$$\mu_{VBF} = 0.95 \pm 0.5 \text{ CMS}$$

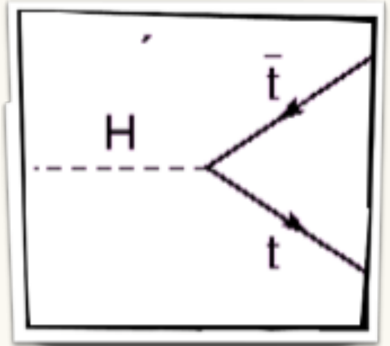
CMS PAS HIG-13-005



μ_{VBF}=0 is excluded at 4.1σ (ATLAS)

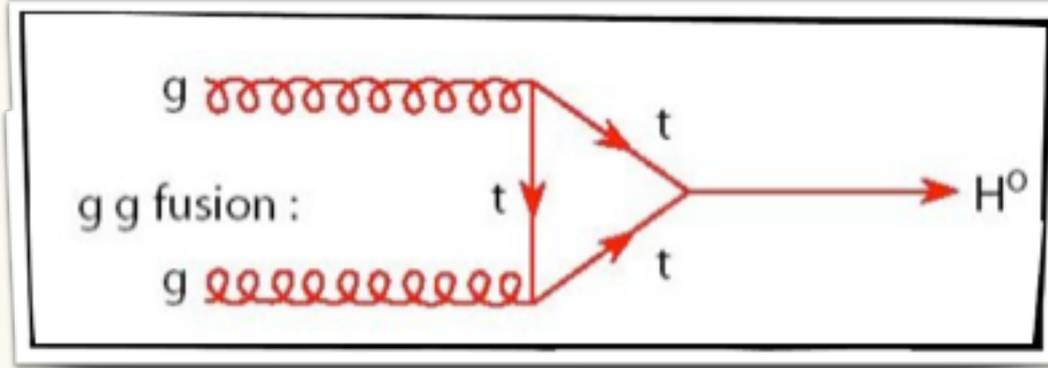
μ_{VBF}=0 is excluded at 2.0σ (assuming SM BRs) (CMS)

Indirect Sensitivity to Fermion Couplings



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

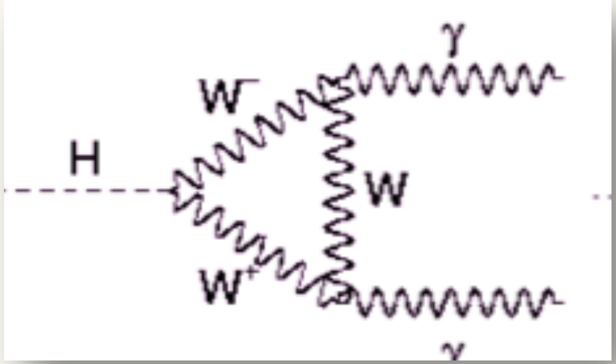
$$k_t^2 = \frac{g_t^2}{g_{t.SM}^2}$$



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

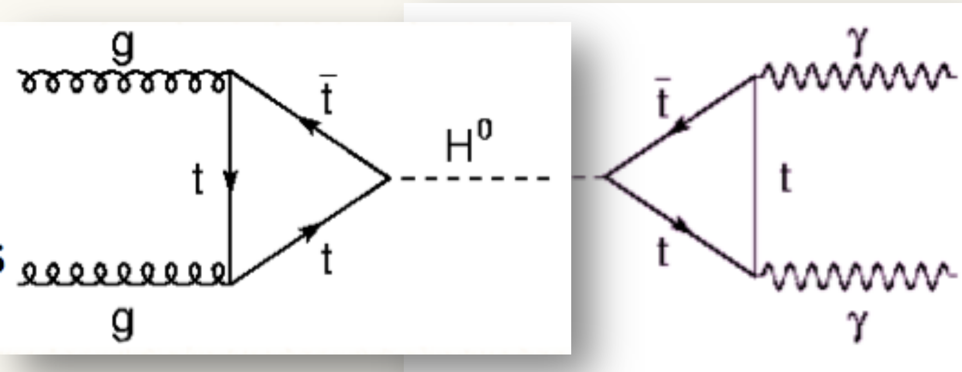
Note that if all fermion couplings are set to be equal, $k_g^2 = k_F^2$

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



Direct observation of H→bb and H→ττ

The Bosonic channels (γγ,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 ττ 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.

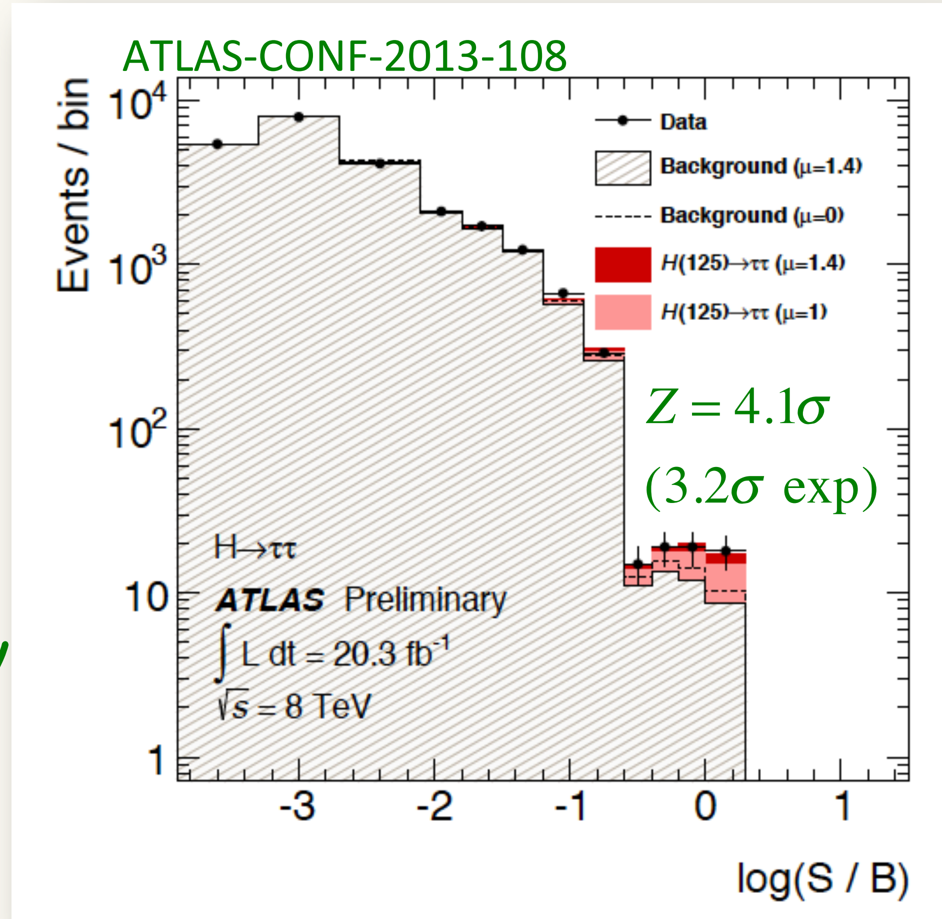
With a SM BR of over 6% and a relatively clean signal in VBF and Boosted categories, H→ττ is even more important then the bb (with the current luminosity and analysis status) in order to establish the Higgs direct coupling to fermions.

Fermions Direct: H→ττ

Discriminator is not necessarily mass (CMS)

Here it's a BDT score (ATLAS)

(see talks in YSF by Niels Ruthmann & Riccardo Manzoni)

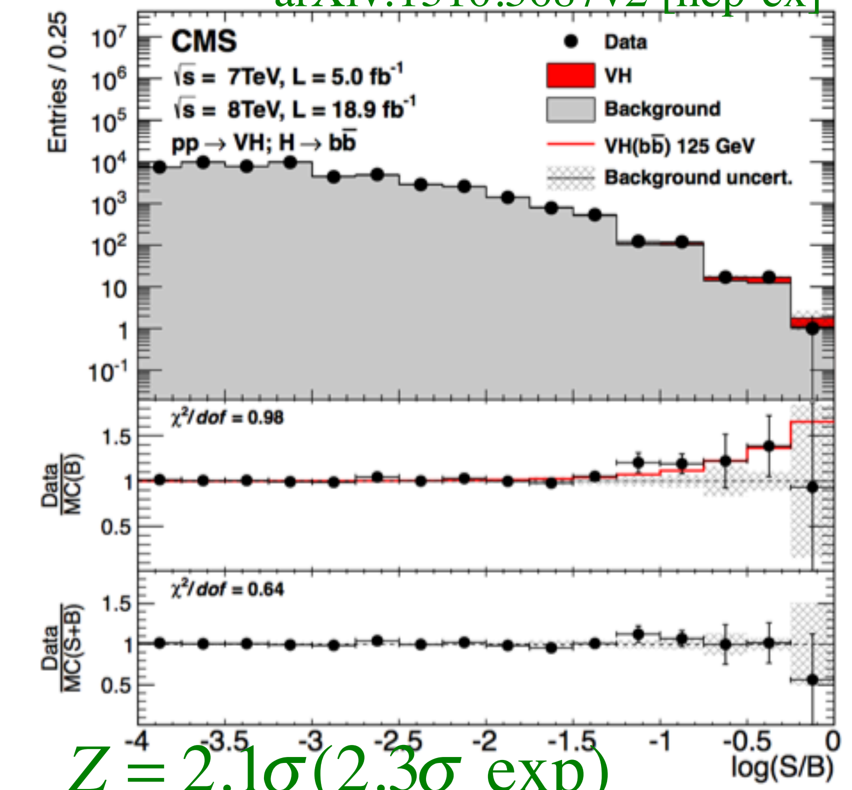


H→ττ	CMS	ATLAS
Signal Strength	μ=0.78±0.27	$\mu=1.4^{+0.5}_{-0.4}$
Excess	3.2σ (exp 3.7σ)	4.1σ (exp 3.2σ)

arXiv:1401.5041v1 [hep-ex] ATLAS-CONF-2013-108

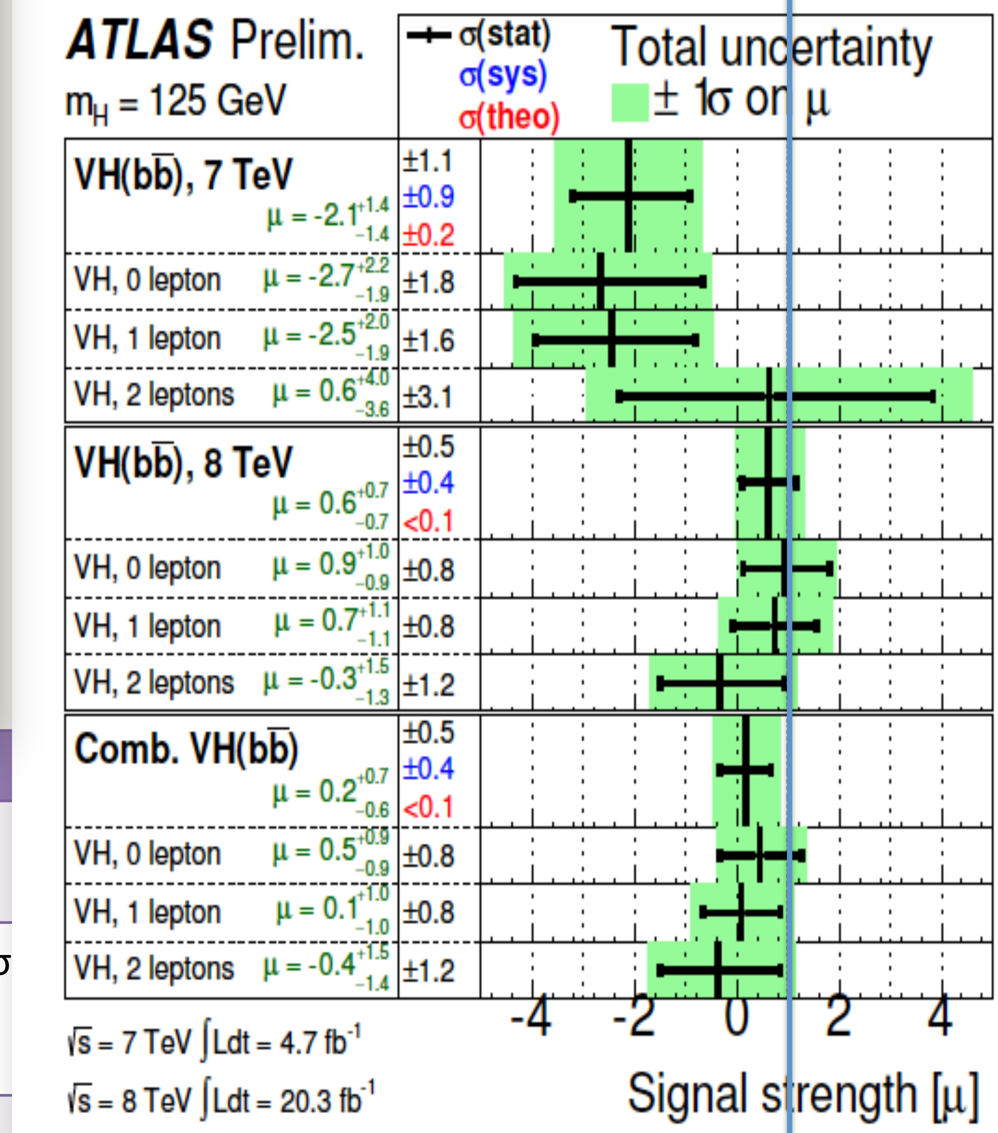
Fermions Direct: H→bb

arXiv:1310.3687v2 [hep-ex]



$Z = 2.1\sigma (2.3\sigma \text{ exp})$

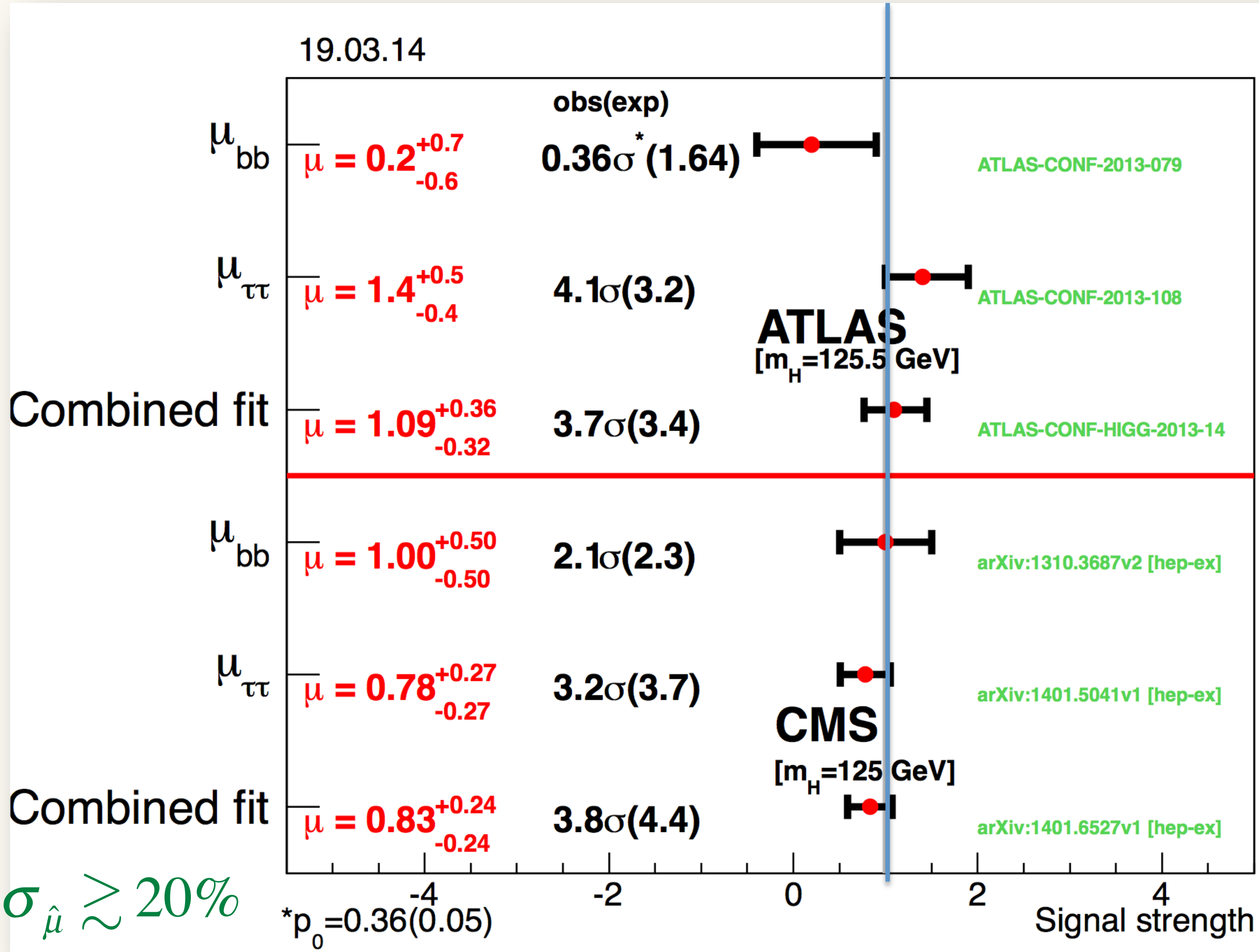
ATLAS-CONF-2013-079



	CMS	ATLAS
Signal Strength	μ=1.0±0.5	μ=0.2±0.5(stat) ±0.4(syst)
Excess	2.1σ (exp 2.3σ)	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)

Direct Evidence for H→Fermions

Combining bb and ττ



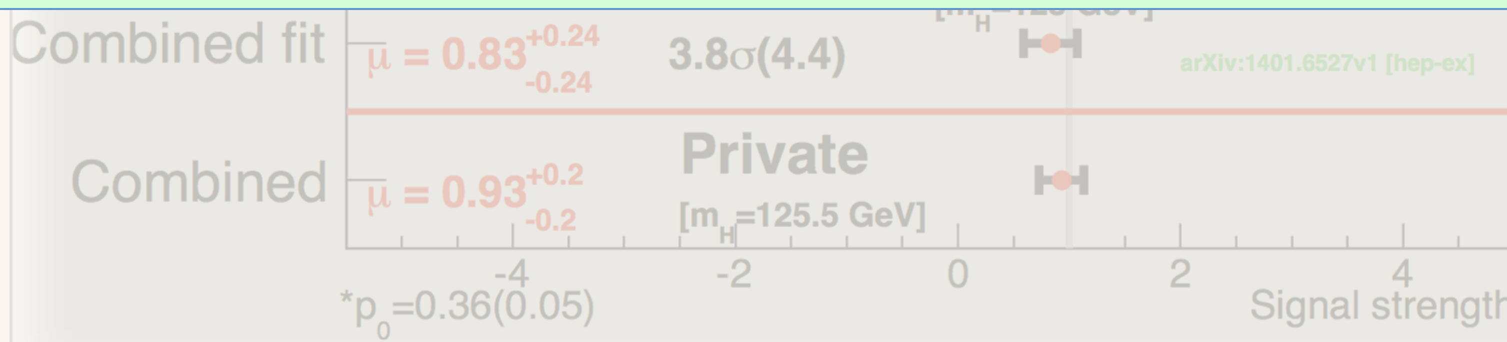
$\hat{\mu} \sim 0.93, \sigma_{\hat{\mu}} \gtrsim 20\%$

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

ttH, H→bb

The final state is extremely difficult for it contains 4 b-quarks and suffers from an extremely difficult to control tt+HF BG.

(see talks on ttH by Cristina Botta and Eve Le Menedeu)

Measuring Higgs Couplings

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

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

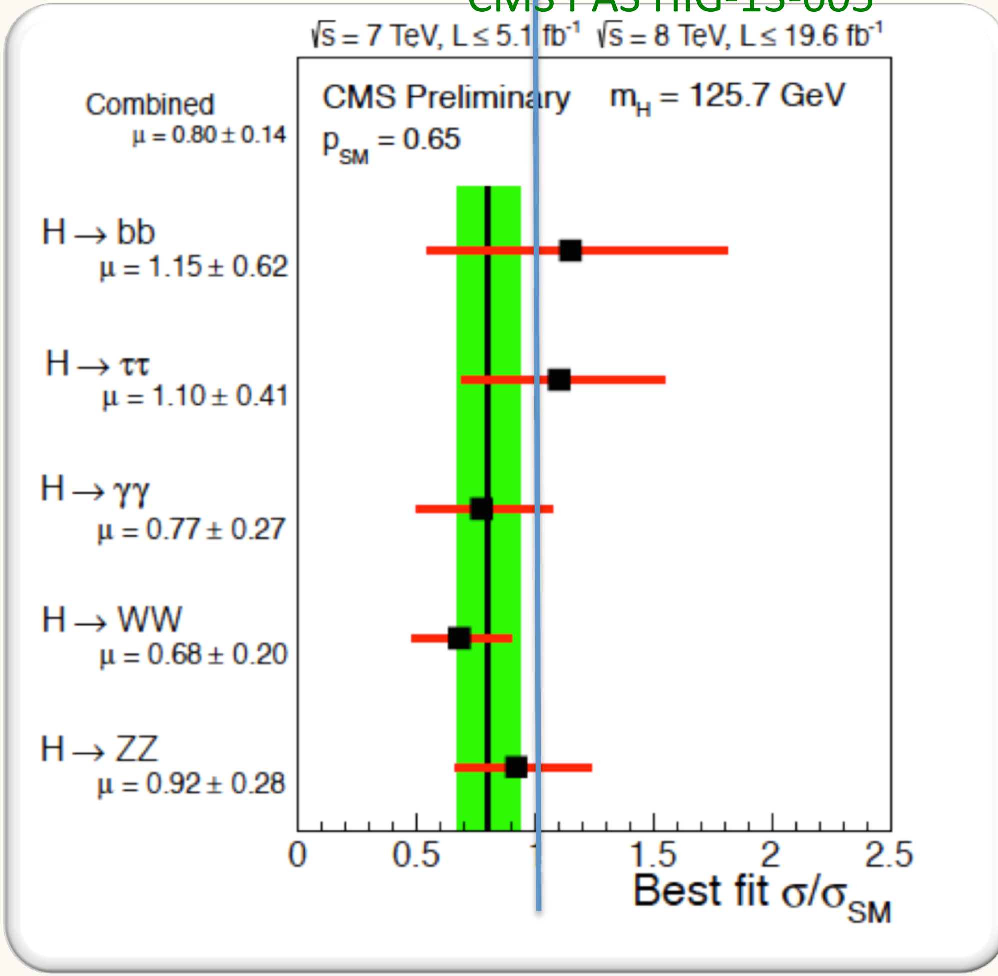
$$n_s^{c,i} = \sum_p \left[\mu^p \mu_{BR}^i\right] \times (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

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

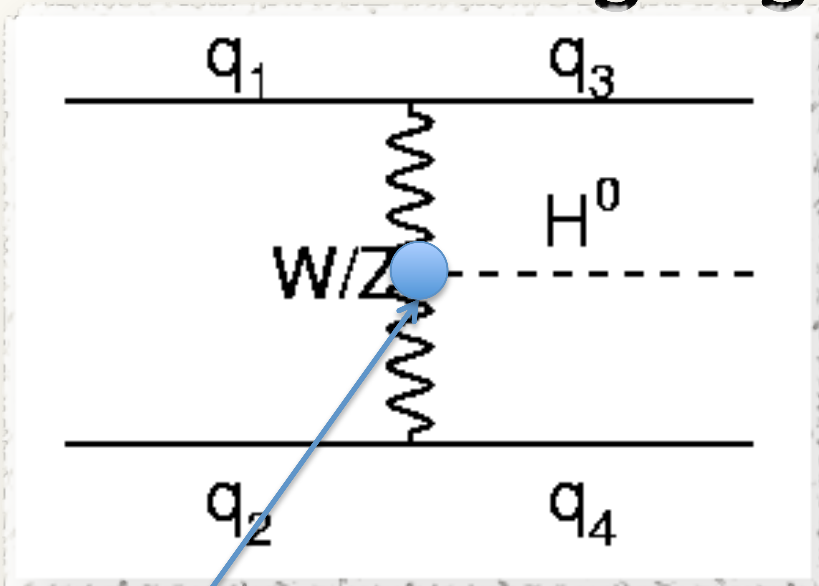
The degeneracy can be broken by parameterize the strength parameters with couplings and introduce constraints which reduce the number of p.o.i. and allow reasonable fits.

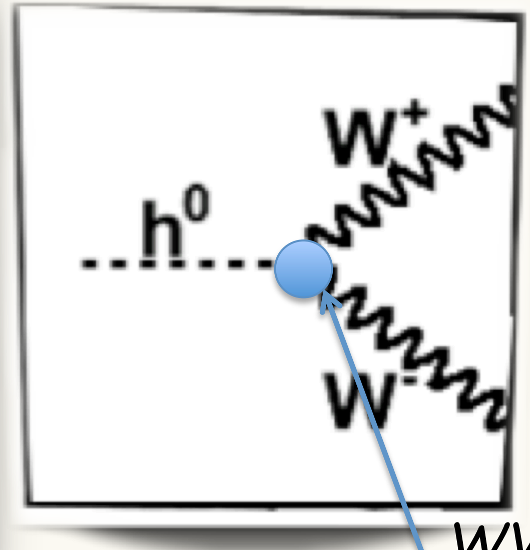
$$k_i^2 = \frac{\Gamma_i}{\Gamma_I^{SM}} \quad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

CMS PAS HIG-13-005



Disentangling The Couplings





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

$$\mu^{WW}_{BR} = \frac{k^2_W}{k^2_H}$$

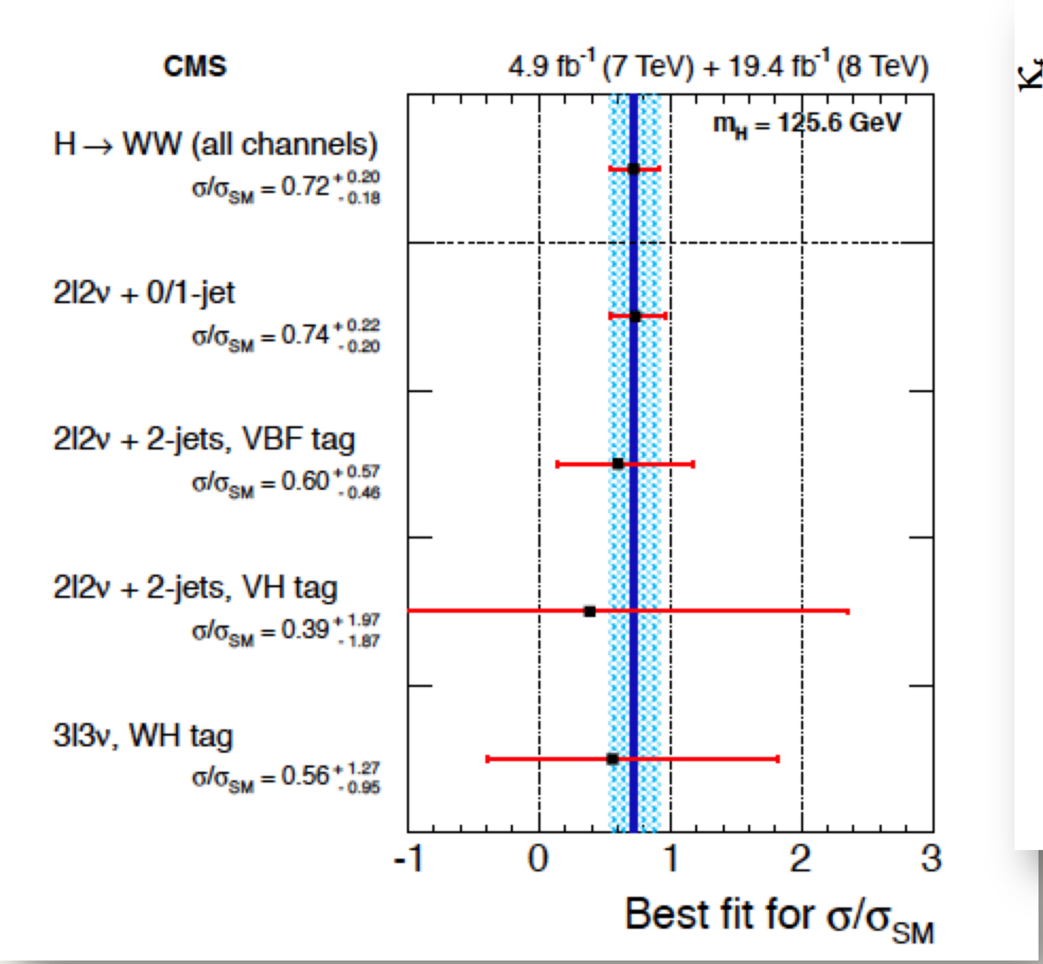
$$\mu_{VBF} = k^2_{VBF} = k^2_w BR^{WW}_{SM} + k^2_Z BR^{ZZ}_{SM}$$

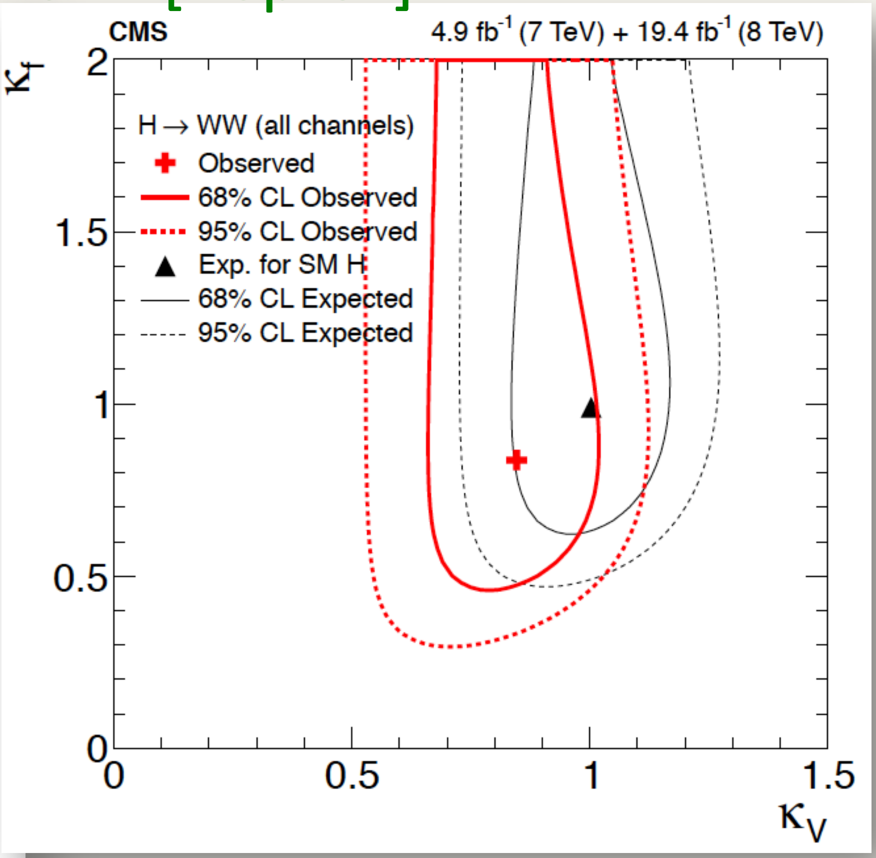
The simplest non-trivial model is (k_{F}, k_V) where all Fermion couplings are set to k_F and all Boson couplings to k_V

$$\frac{\sigma^{WW}_{VBF}}{\sigma^{WW}_{VBF}(SM)} = \frac{k^2_V \cdot k^2_V}{0.75k^2_F + 0.25k^2_V}$$

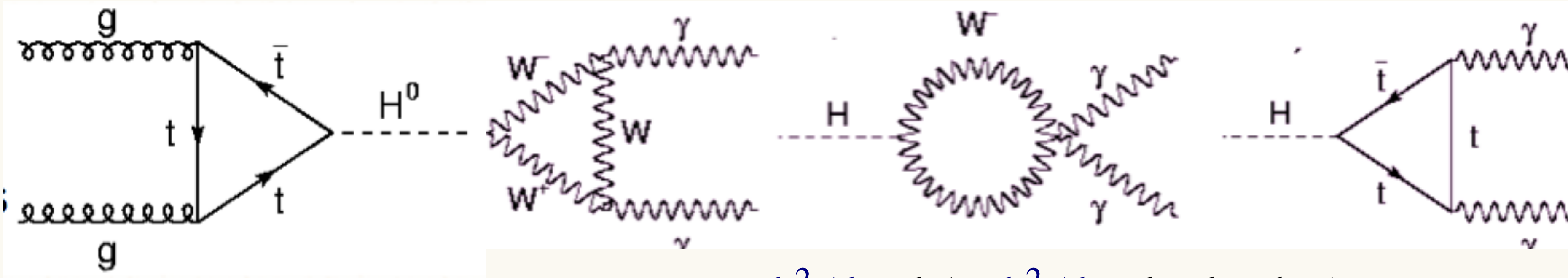
Disentangling The Couplings

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

In the (k_F, k_V) benchmark:

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

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

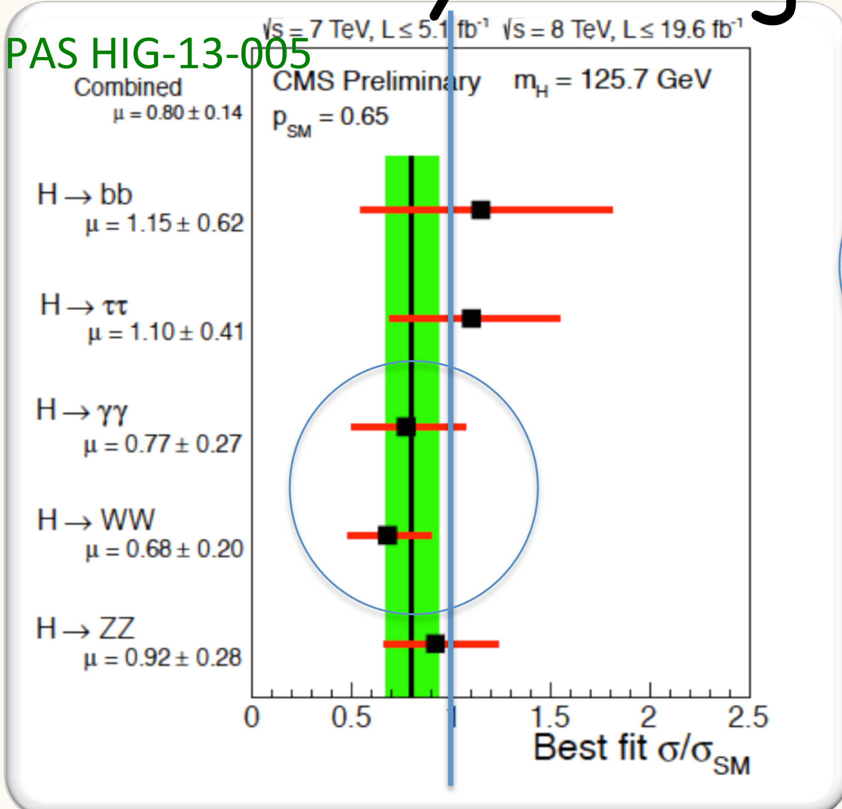
$$\sigma(ggF) \times BR(H \to WW, ZZ) \sim \frac{k_F^2 \cdot \mathrm{k}_V^2}{0.75 k_F^2 + 0.25 k_V^2}$$

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

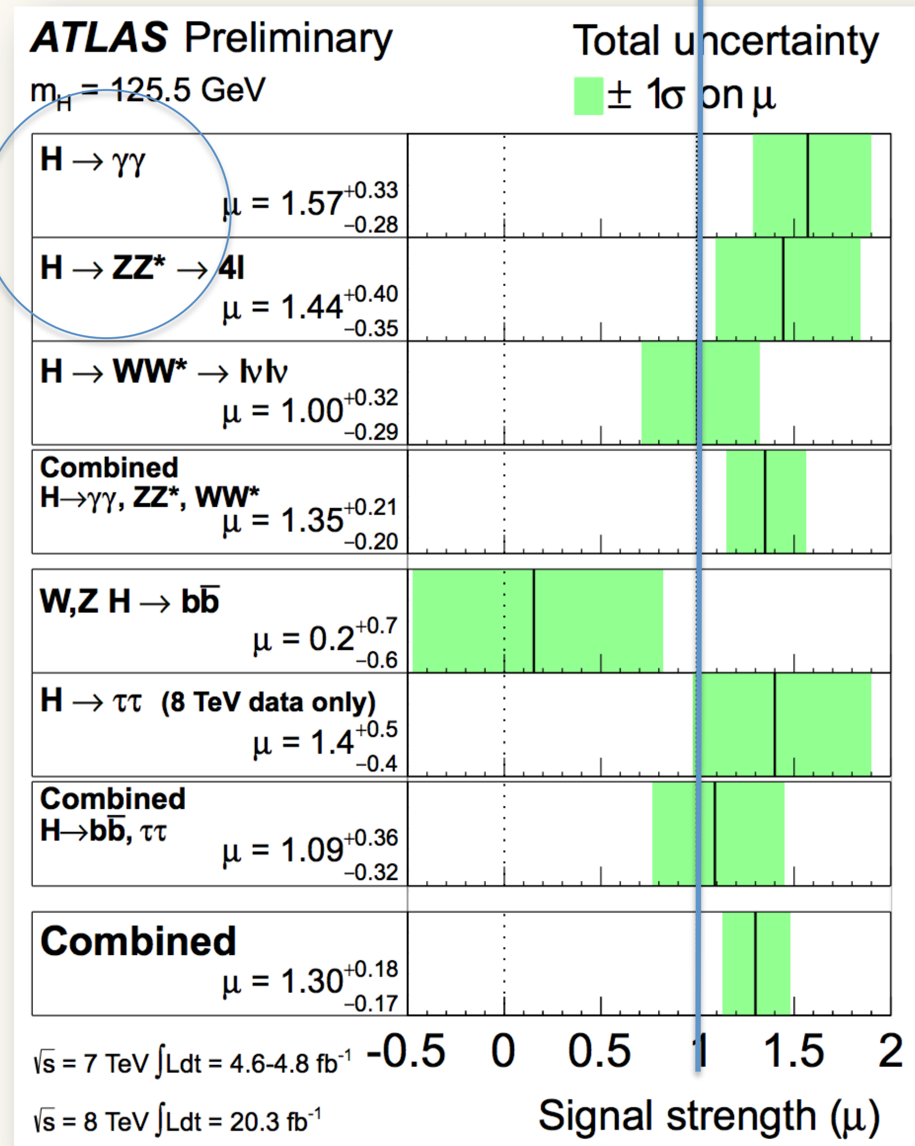
$$\sigma(VBF, VH) \times BR(H \to \tau\tau, bb) \sim \frac{k_V^2 \cdot \mathrm{k}_F^2}{0.75 k_F^2 + 0.25 k_V^2}$$

Summary of Signal Strength

CMS PAS HIG-13-005



ATLAS-CONF-2014-009

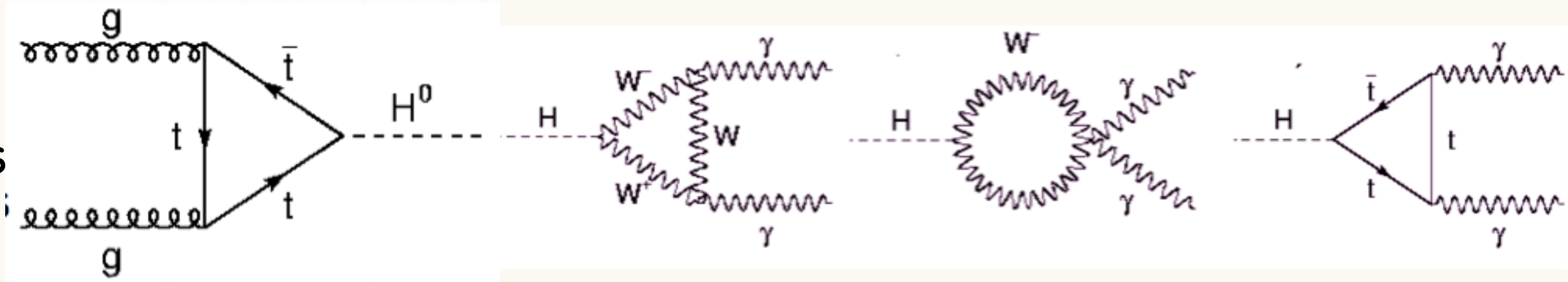


ATLAS bb is low but with large error.

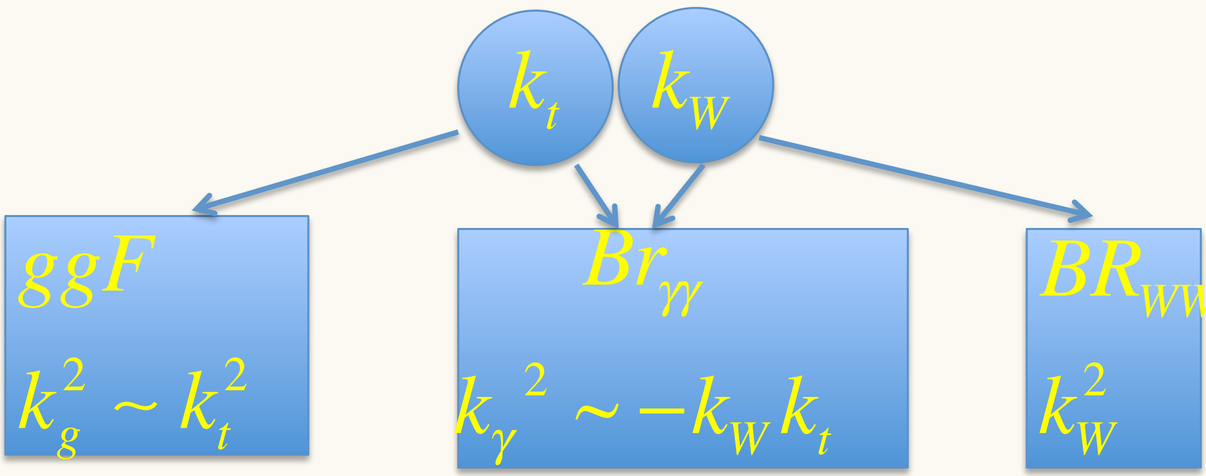
$$k_\gamma^2 = |1.28 k_W - 0.28 k_t|^2$$

A comment on Interference

is



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



If k_t=-1 ggF slightly affected

WW unaffected

$\gamma\gamma$ 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.

$$k_H^2 = \frac{\sum_{j=Z,W,t,b,\tau} k_j^2 \Gamma_j^{SM} + k_\gamma^2 \Gamma_\gamma^{SM} + k_g^2 \Gamma_g^{SM}}{\Gamma_H^{SM}}$$

$$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$$

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

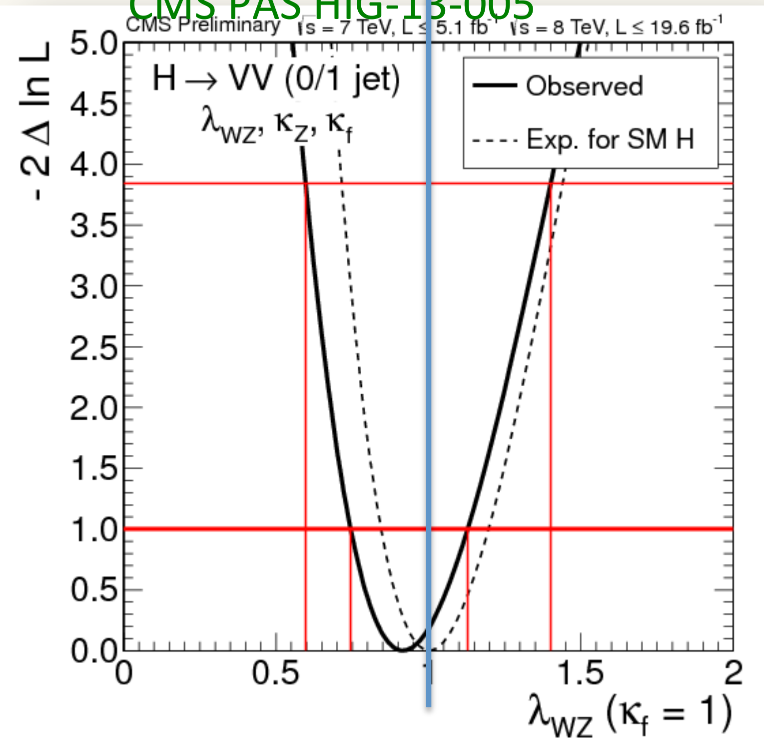
λ_{WZ} is expected to be protected and consistent with unity

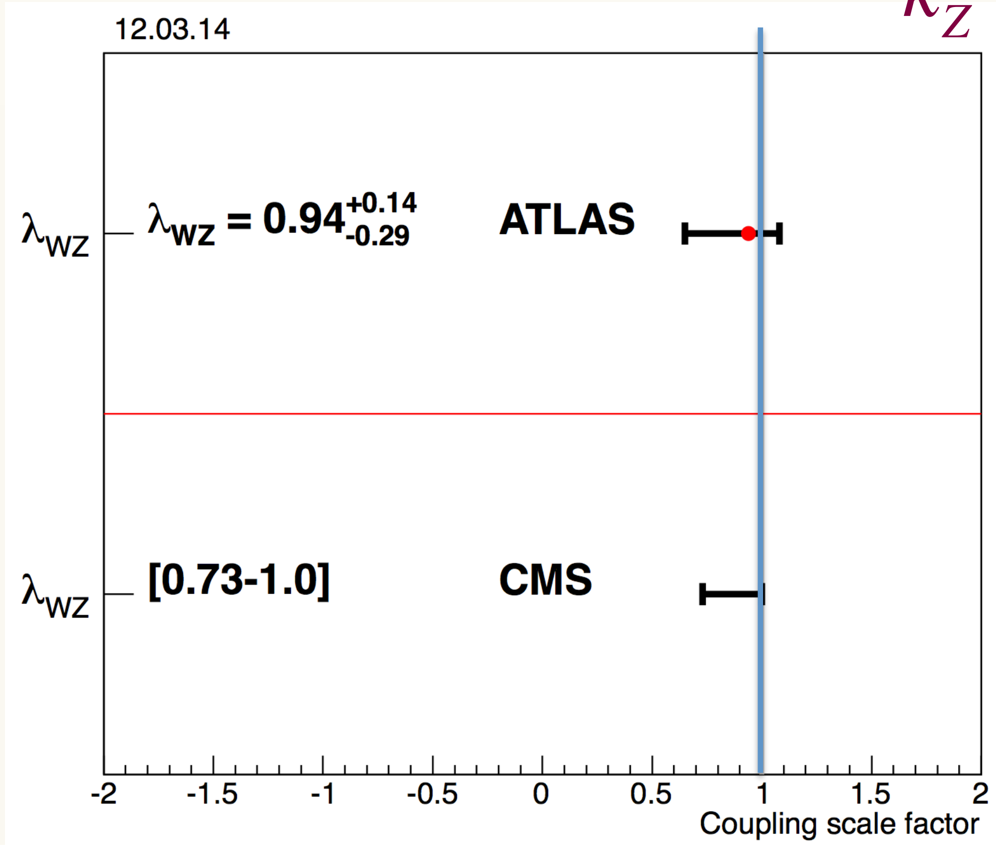
Large deviations from 1 indicate new physics.

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

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

CMS PAS HIG-13-005





The Full Monty I : SM

Generic Model I (ATLAS)

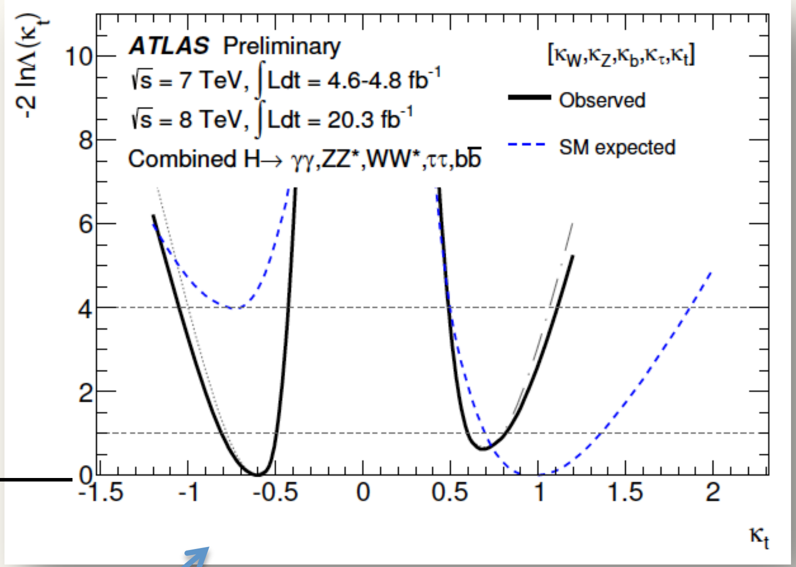
All couplings to SM particles are fitted independently

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

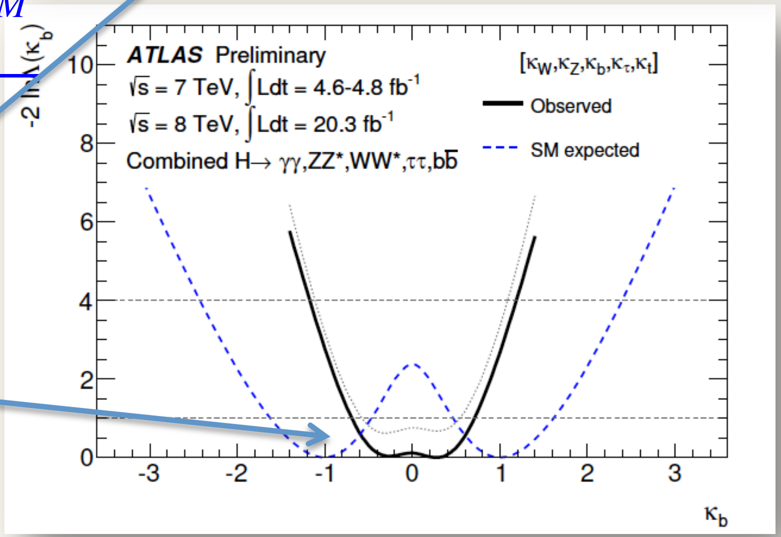
p.o.i $\quad k_W, k_Z, k_b, k_\tau, k_t$

Loop & Width Constrains $\quad k_g(k_b, k_t) \quad k_\gamma(k_b, k_t, k_\tau, k_W)$

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



ATLAS-CONF-HIGG-2013-14



-High γγ rate prefers negative k_t

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

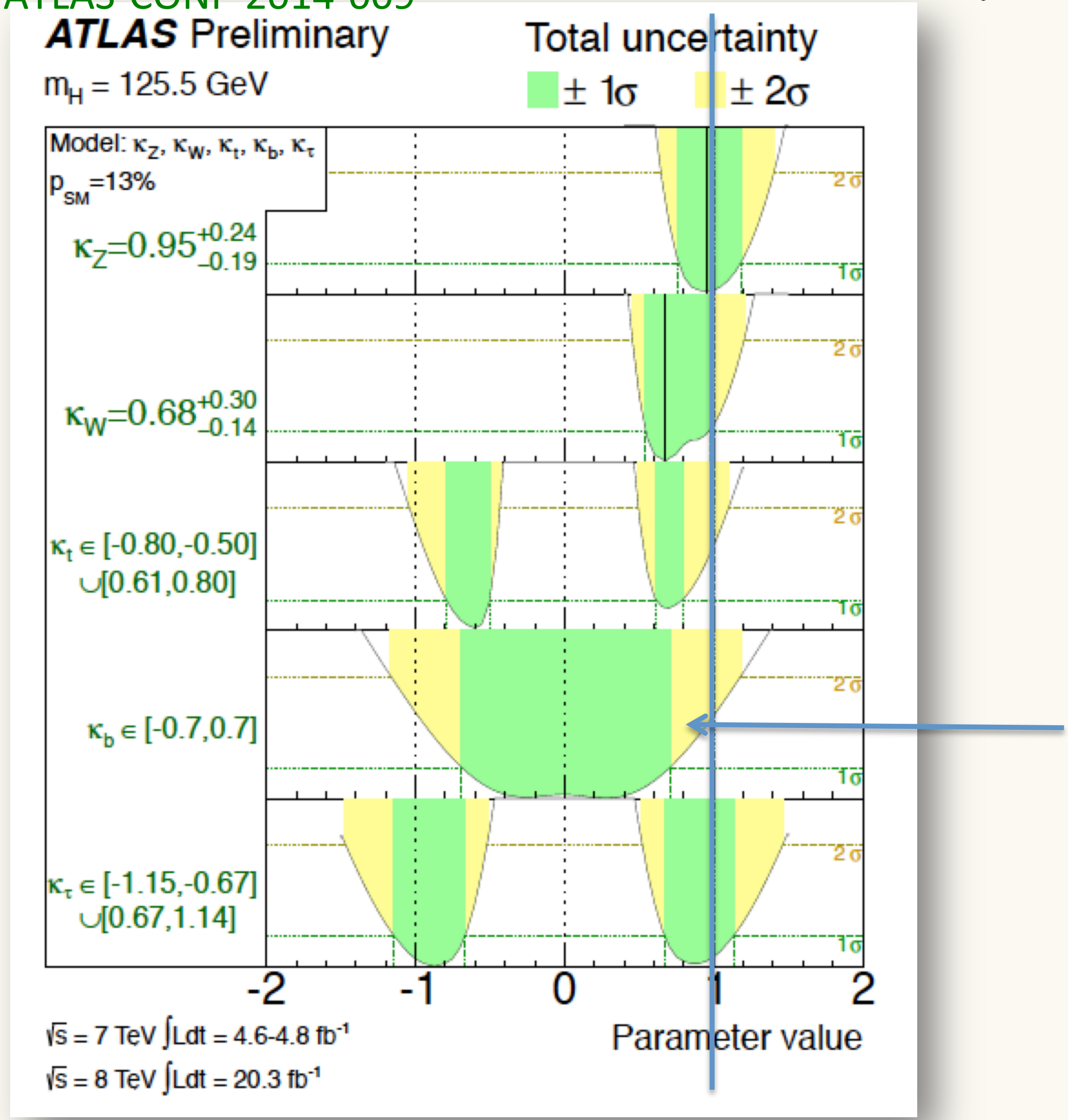
-The low measured bb rate does not reflect the sensitivity for k_b

ATLAS were unlucky

-The 5D compatibility with SM is 14%

The Full Monty I : SM

ATLAS-CONF-2014-009



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

Vector and Fermion Couplings

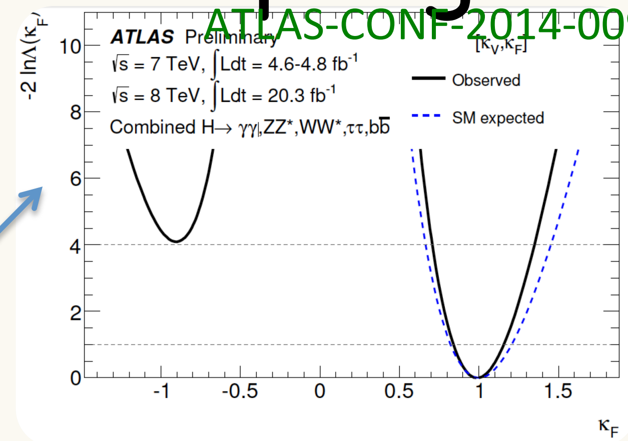
The $\gamma\gamma$ loop induces some sensitivity to the relative sign between k_t and k_W

The high observed H→ZZ pulls k_W up,

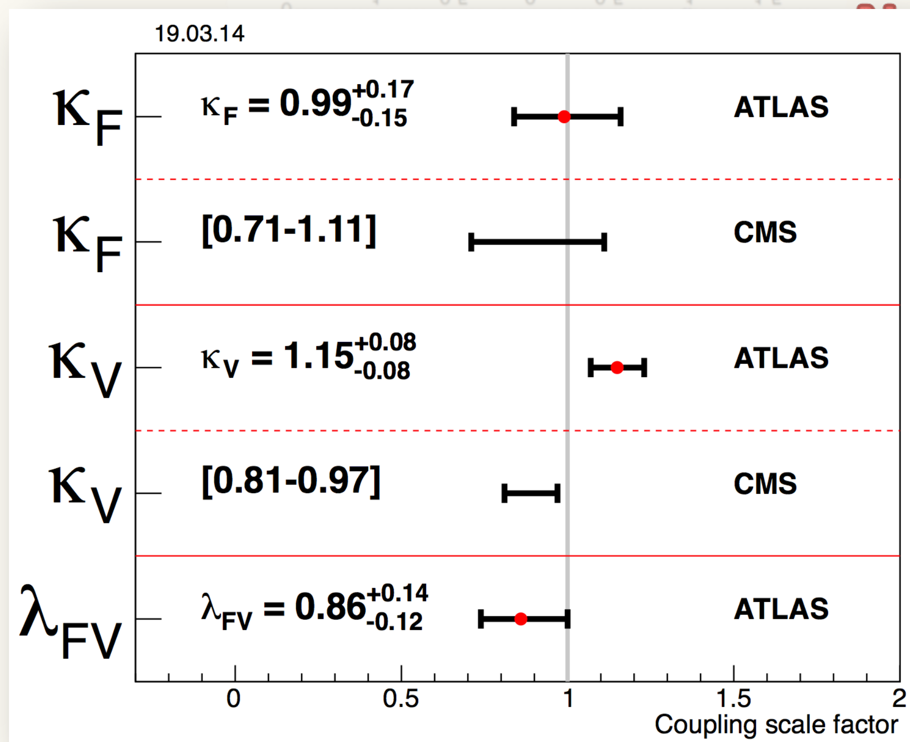
allowing high $\gamma\gamma$ rate and keeps k_t positive

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

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	$\Gamma_{i,u}=0$	[0.81,0.97]
(SM)	k_F	$k_H{}^2(k_j)$	[0.71,1.11]
ATLAS (NP_{NL})	λ_{FV}	k_{VV} profiled	$0.86^{+0.14}_{-0.12}$



ATLAS: 2D compatibility with SM 10%

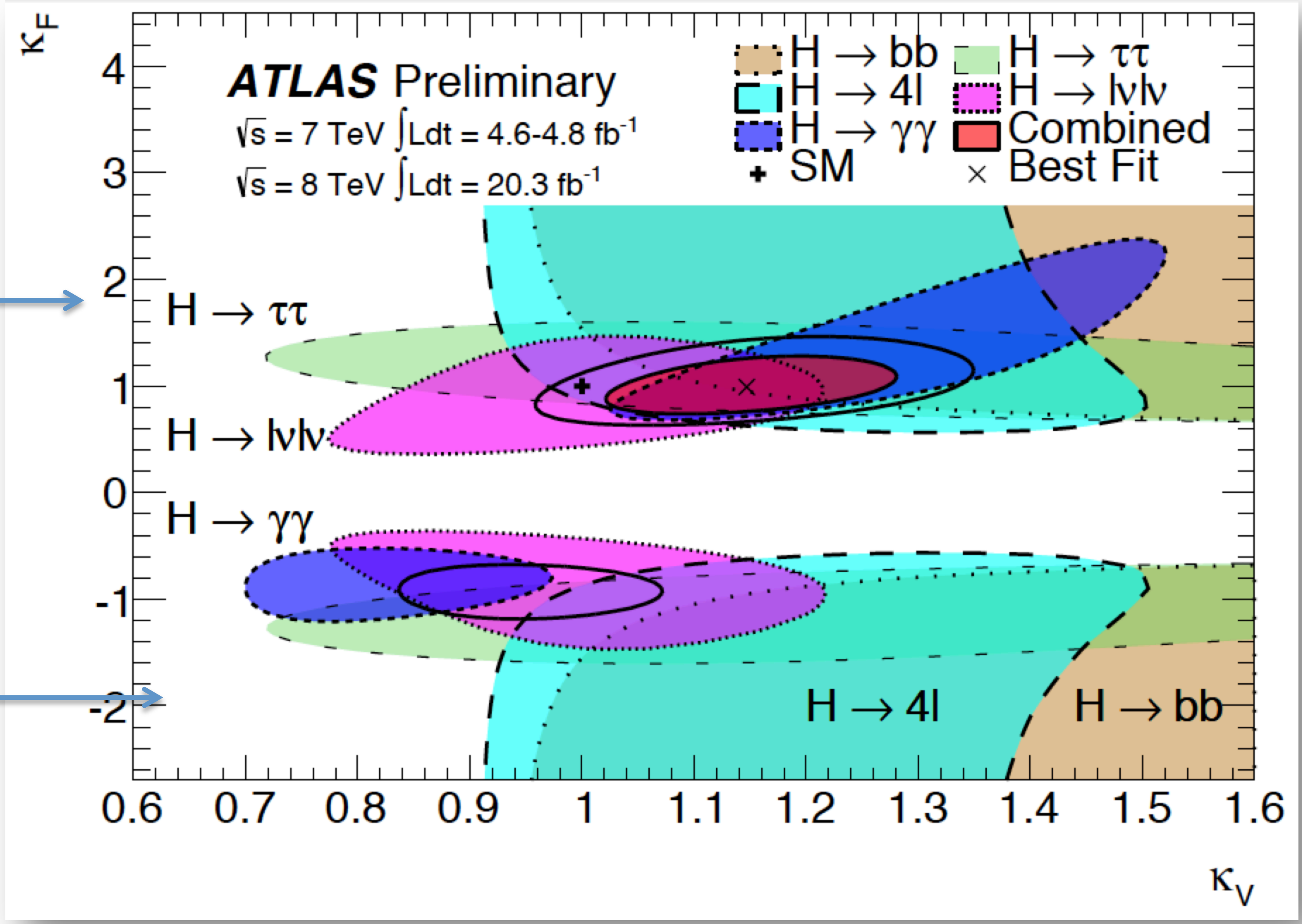
Vector and Fermion Couplings

This plot tells a story:

ATLAS-CONF-2014-009

SM –
No Tension

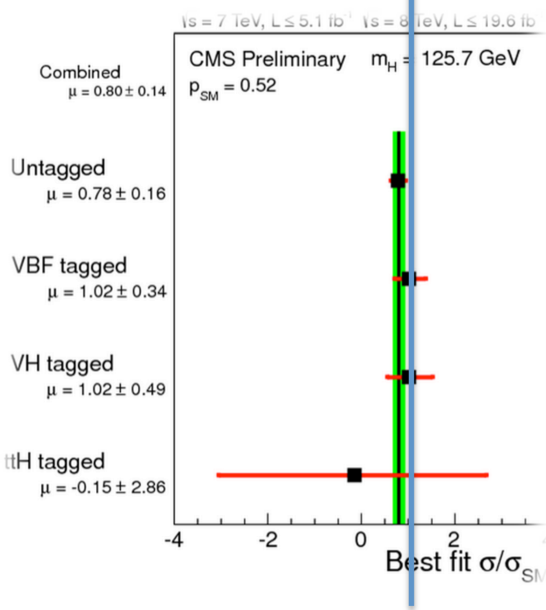
Tension
Drifting
apart



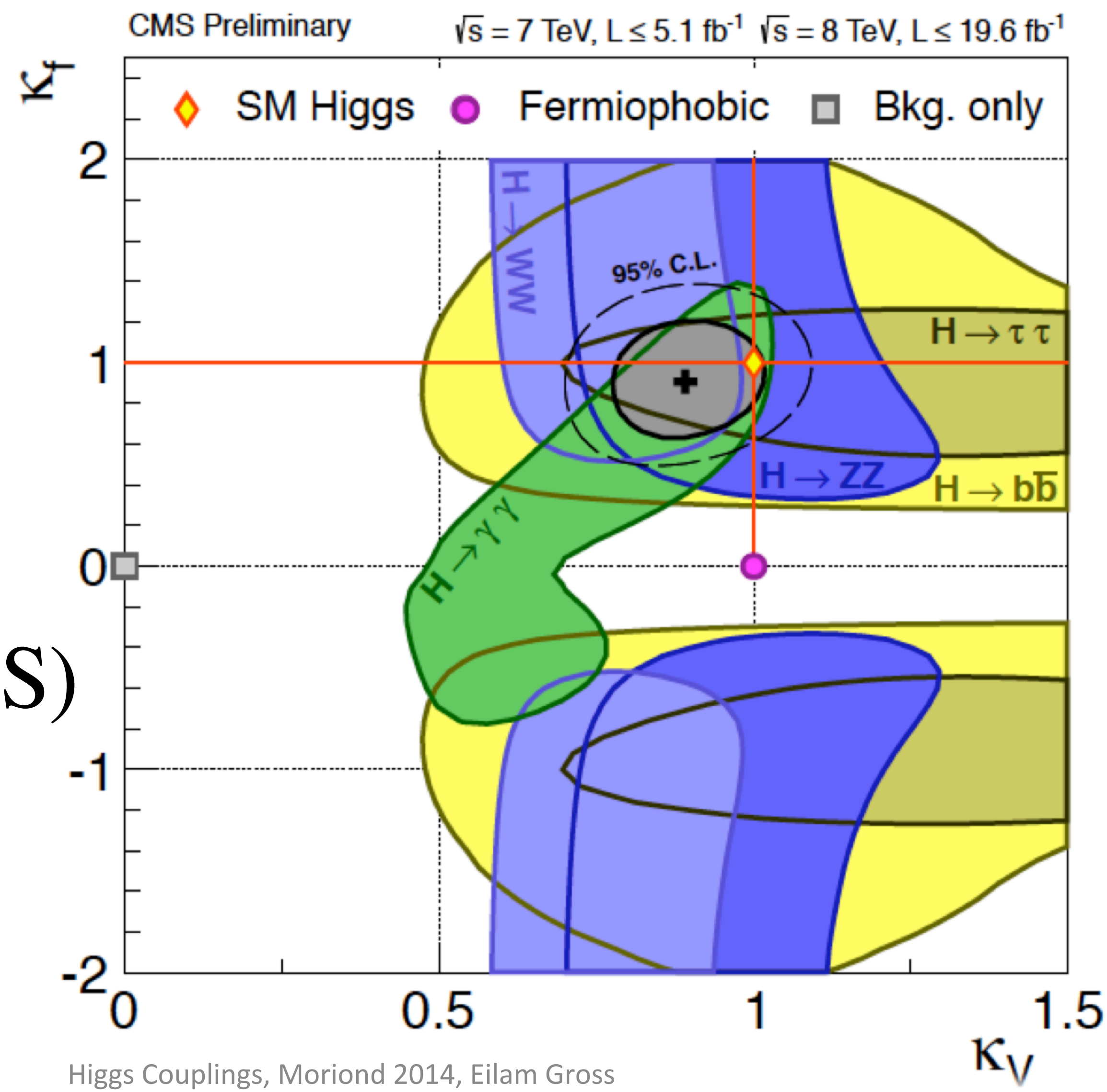
Vector and Fermion Couplings

This plot tells a story:

CMS PAS HIG-13-005



CMS PAS HIG-13-005



$\gamma\gamma$ is low (CMS)

$$\mu_{ggF} = k_F^2$$

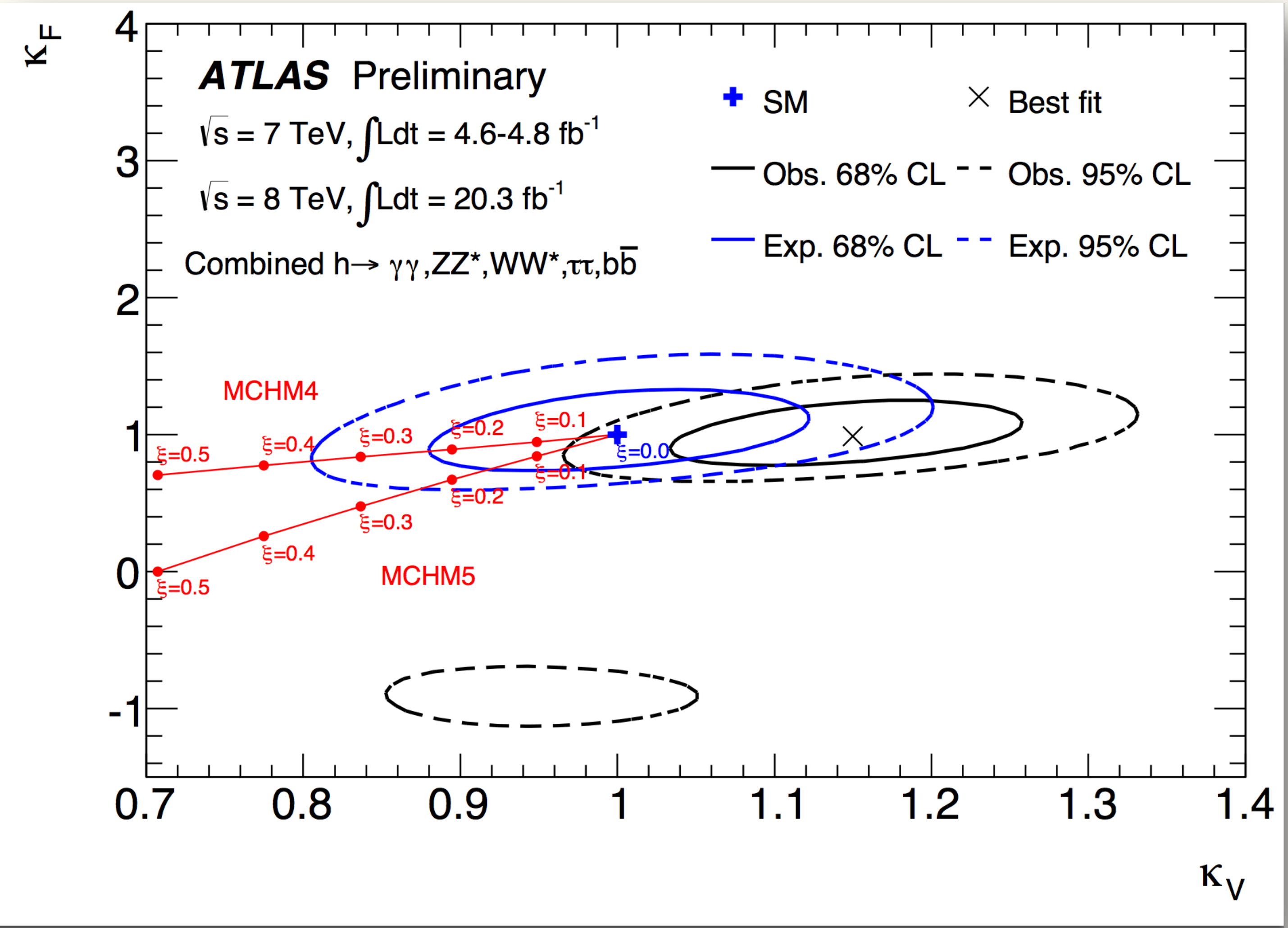
$$\mu_{VBF} = k_{VBF}^2$$

Minimal Composite Higgs Model

$$MCHM4 \quad k_V = k_F = \sqrt{(1-\epsilon)} \quad \epsilon = \frac{v^2}{f}$$

$$MCHM5 \quad k_F = \frac{1-2\epsilon}{\sqrt{(1-\epsilon)}} \quad \epsilon = \frac{v^2}{f}$$

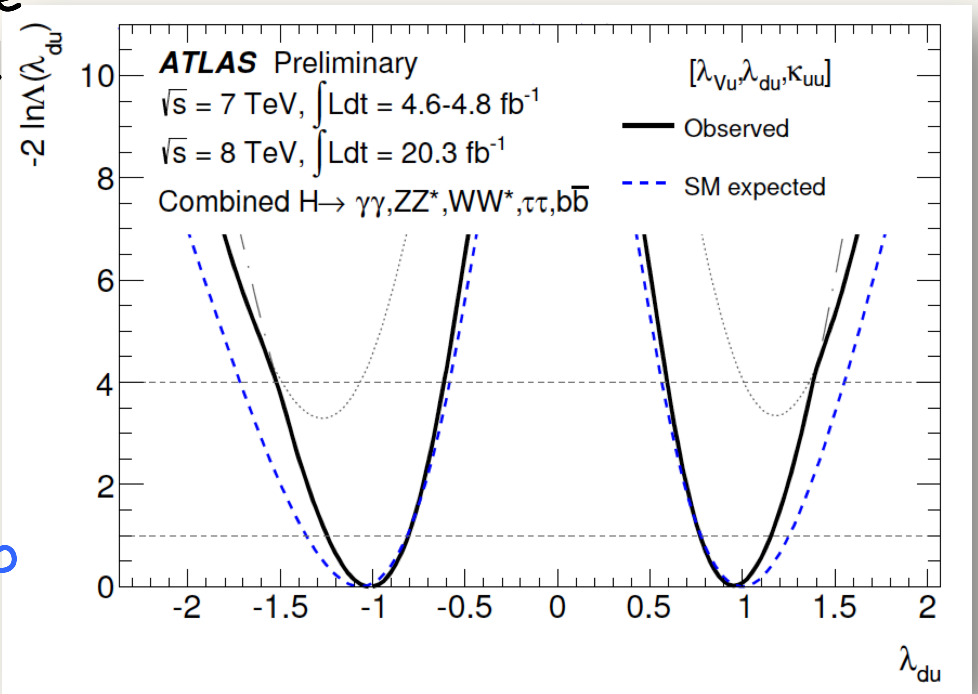
ATLAS-CONF-2014-010



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 small asymmetry is from b and t interference in ggH loop

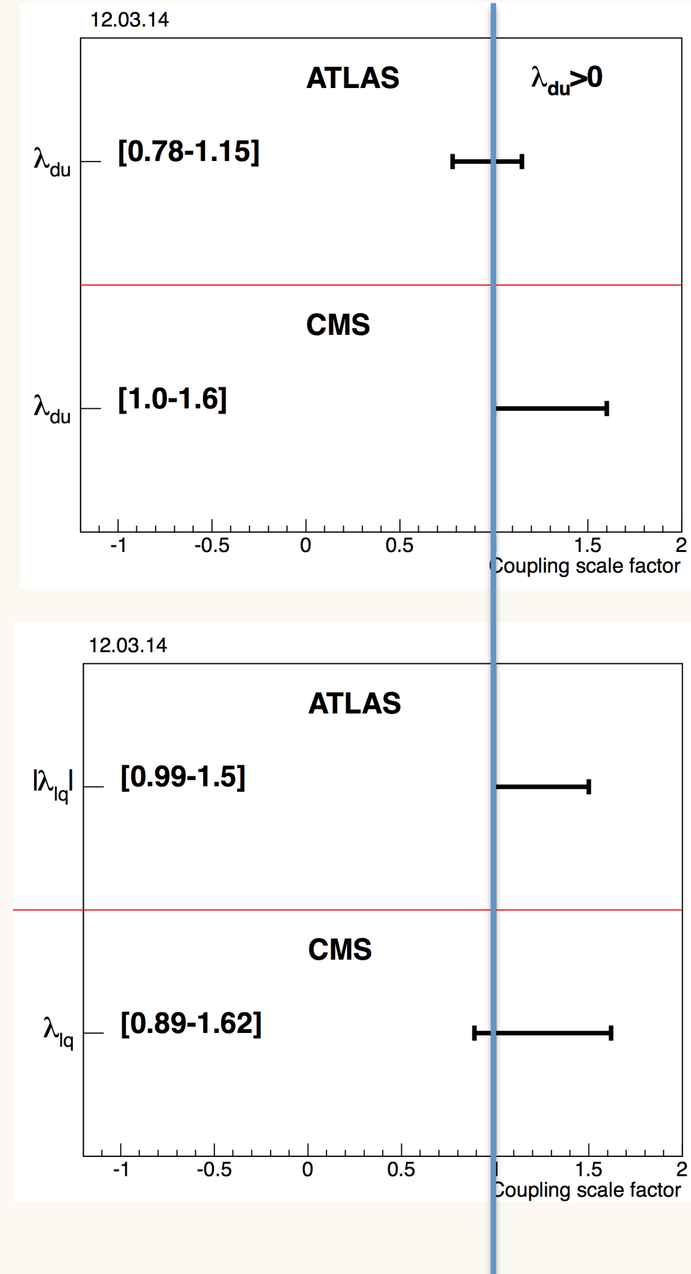
A vanishing coupling to downtype fermions is excluded at the ~3.6σ(~4σ) ATLAS(CMS)

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

Asymmetries in Fermion Sector

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

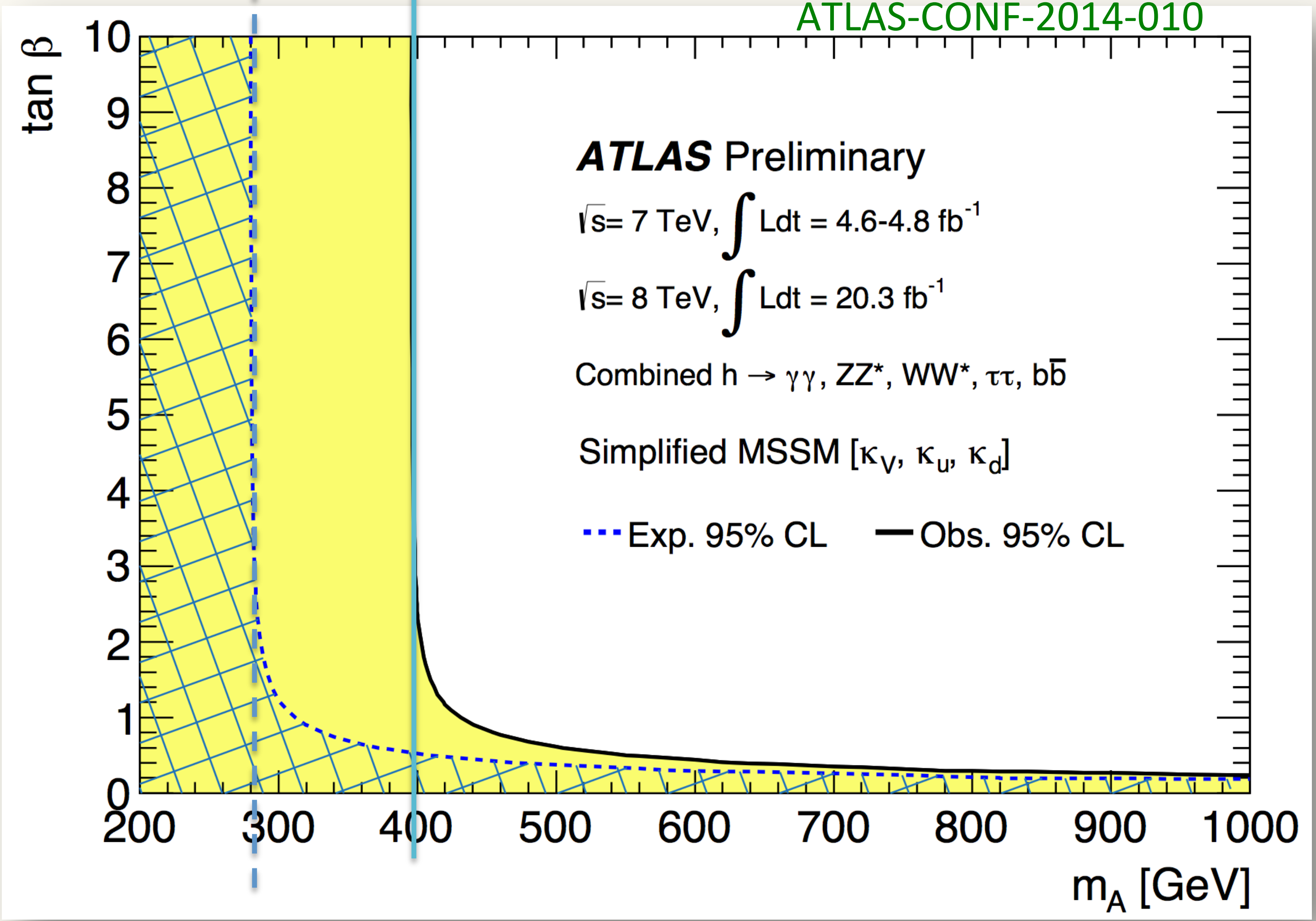
	fitted	68% positibe C.I.	p.o.i
ATLAS	λ_{du}	[0.78,1.15]	$\lambda_{du}, \lambda_{Vu}, k_{uu}$
(SM_{NL})	$\lambda_{\ell q}$	[0.99,1.5]	$\lambda_{\ell q}, \lambda_{Vq}, k_{qq}$
CMS	λ_{du}	[1,1.6]	λ_{du}, k_V, k_u
(SM)	$\lambda_{\ell q}$	[0.89,1.62]	$\lambda_{\ell q}, k_V, k_q$



Simple MSSM Interpretation

$$m_A > 400\ GeV \ \text{for } \mathrm{tg}\beta > 2$$

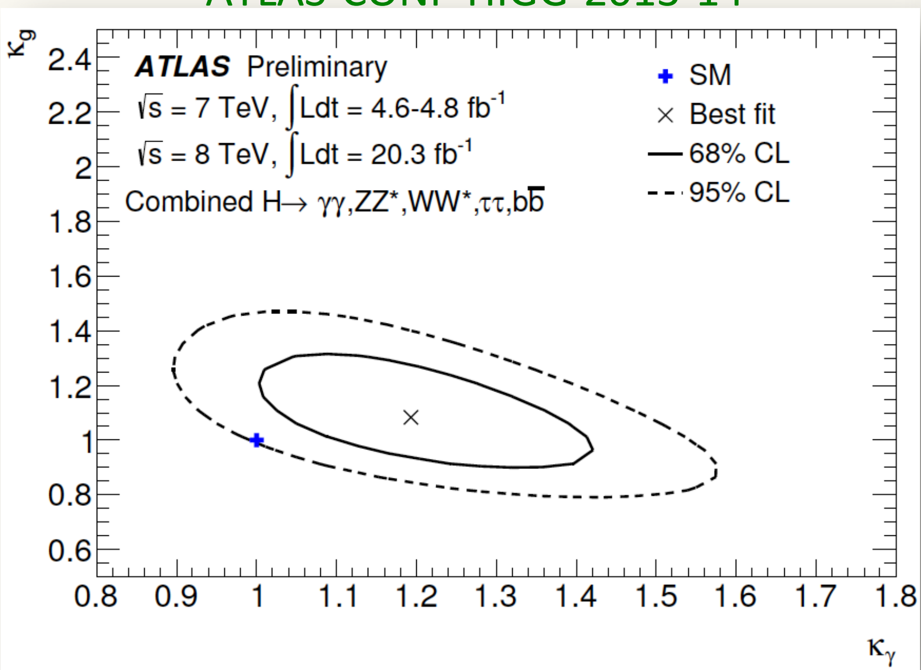
ATLAS-CONF-2014-010

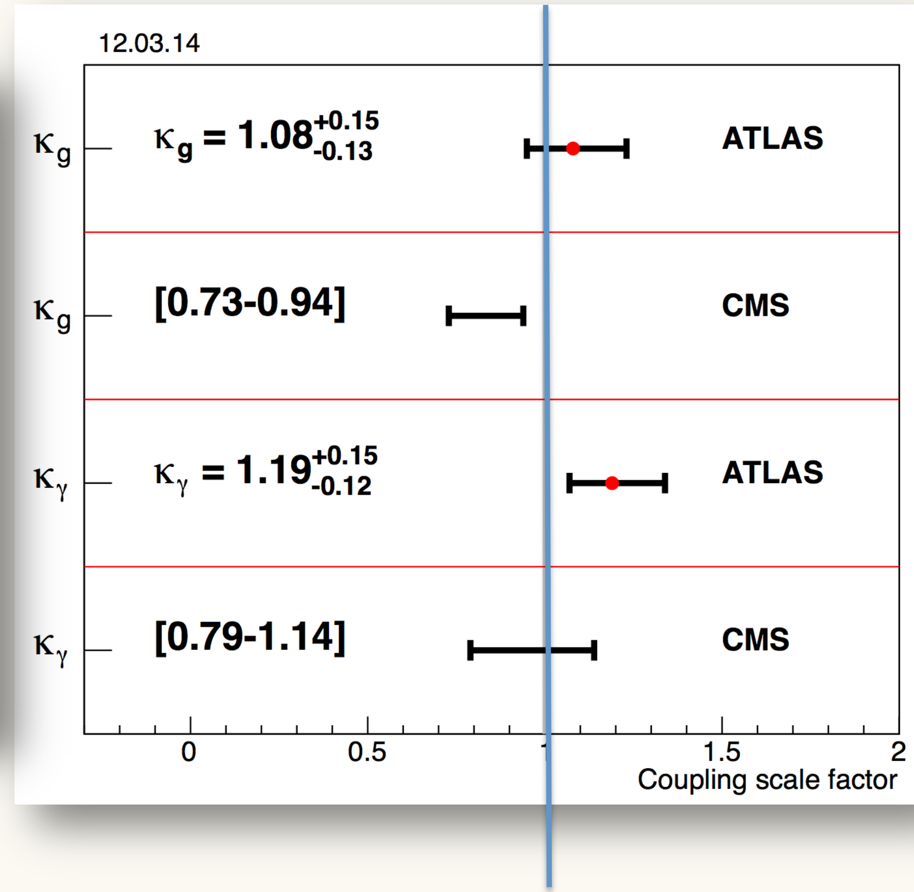


Probing the Beyond (kg,kγ)

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

ATLAS-CONF-HIGG-2013-14

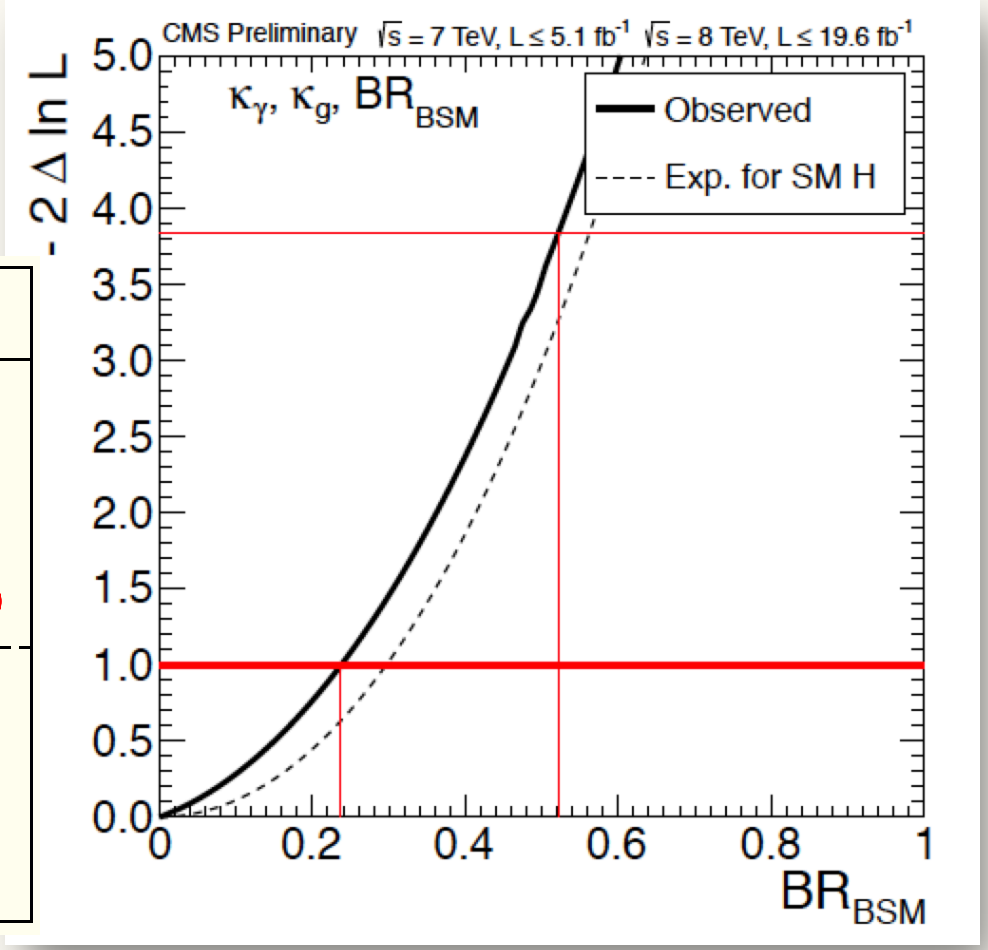




Probing the Beyond ($k_g, k_\gamma, Br_{i,u}$)

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<)	$\surd^*$	$\times$	$\times$	$=1$	$=1$	$k_g, k_\gamma, BR_{i,u}(*)$	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	
	$BR_{i,u}$	$BR_{i,u} < 0.52$



The Full Monty II (The Mother of All Models)

Generic Model II (ATLAS)

Release constrain in SM width to allow BSM contributions.

Replace loop induced couplings by effective couplings, k_g,k_γ

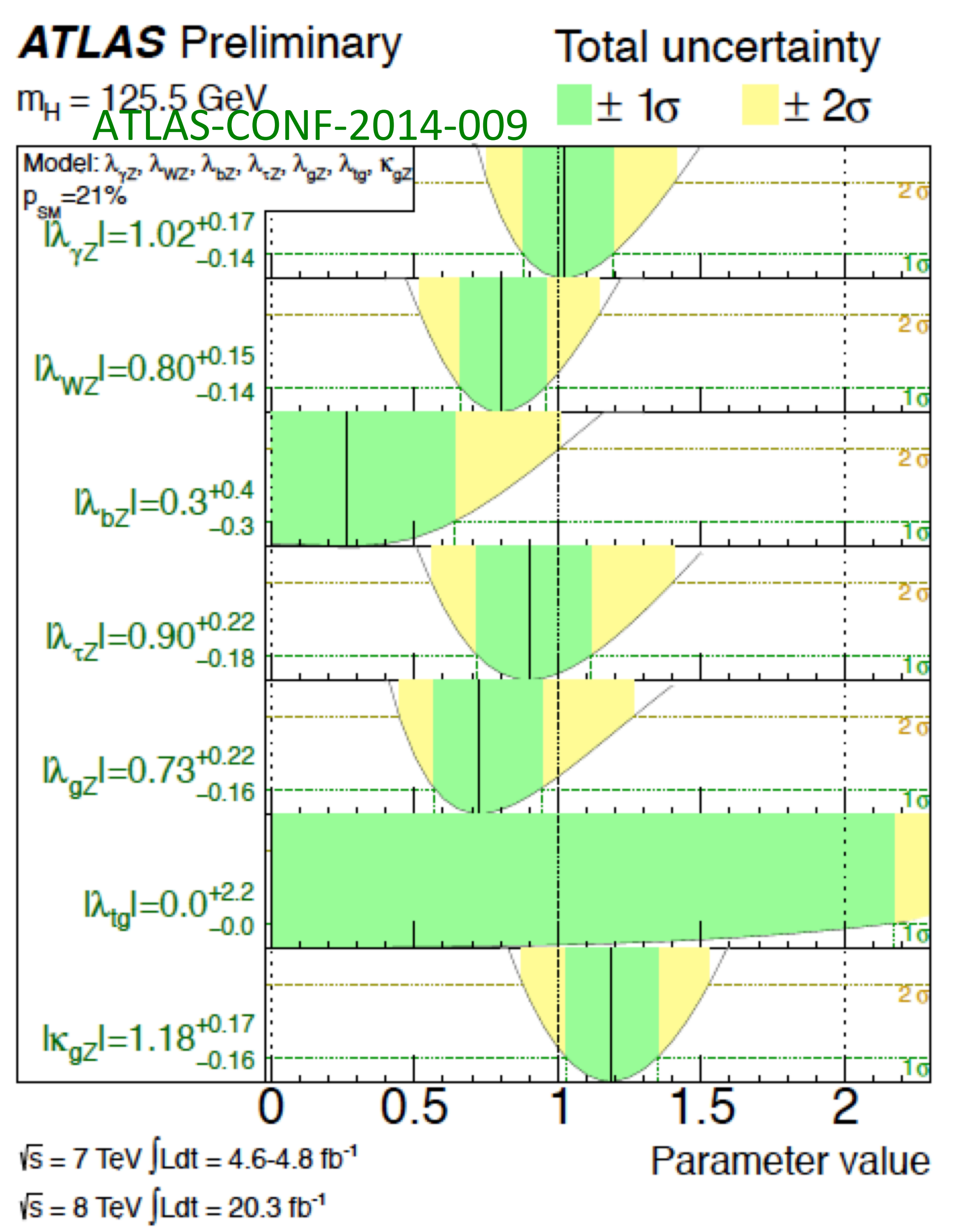
All couplings are fitted independently

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

-No sensitivity to relative sign

-Poor sensitivity to top coupling

-The 7D compatibility with SM is 21%



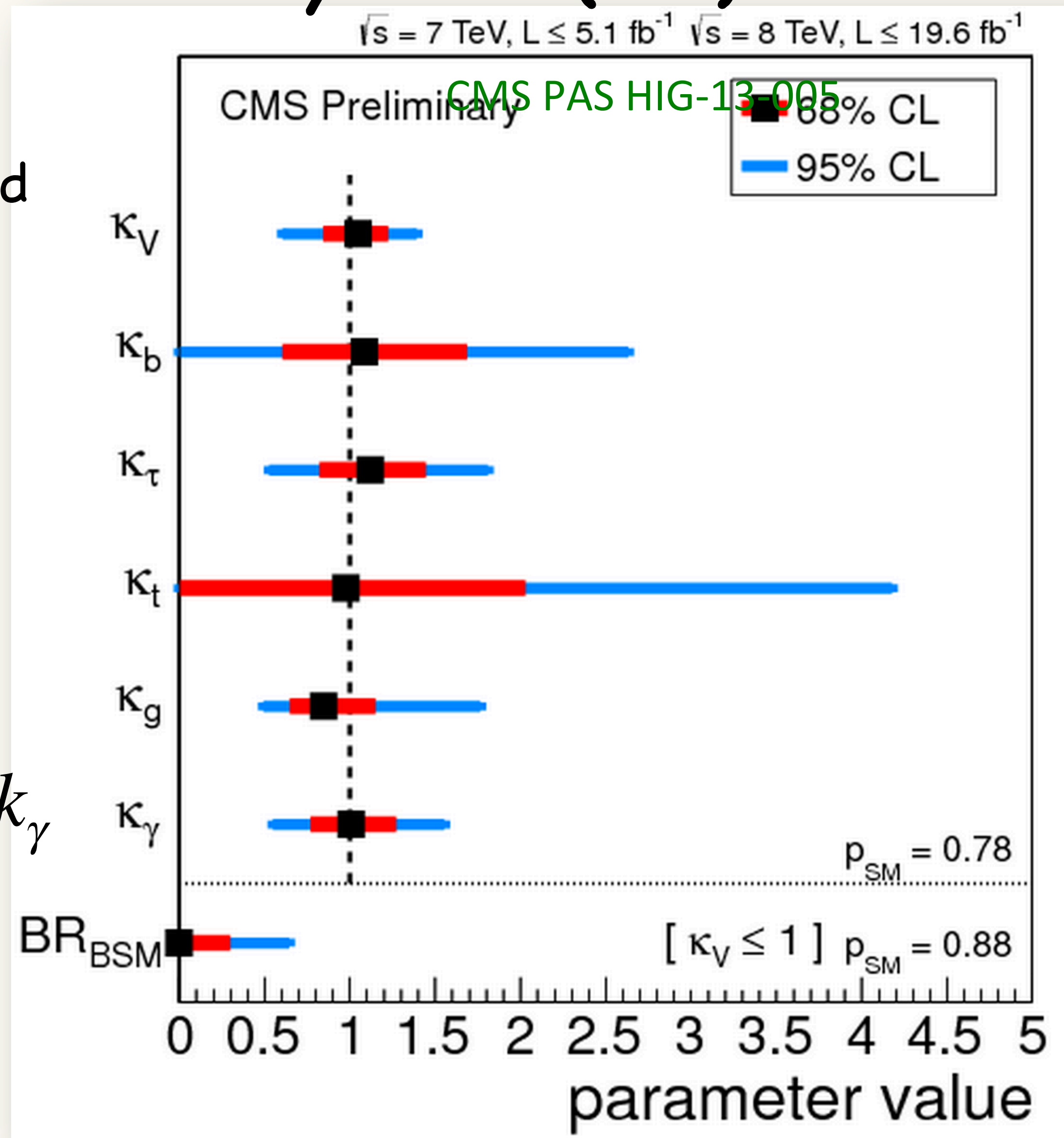
The Full Monty III (C6)

Generic Model III (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)

The C6 model, same as generic model II, but constrain $k_W = k_Z$

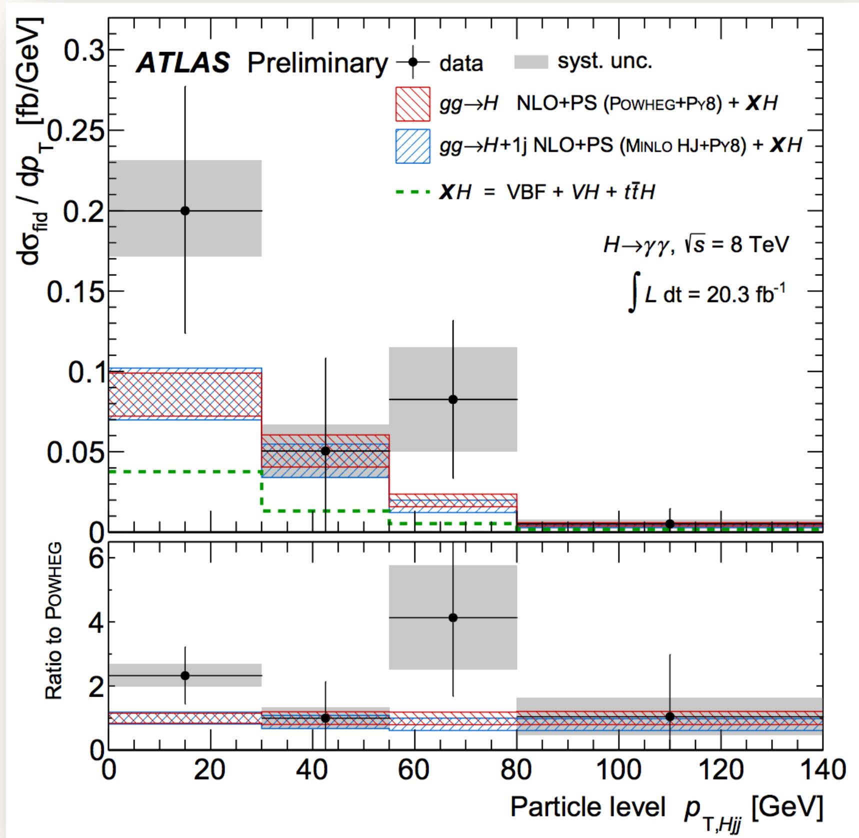
Some (still) Rare Decay Channels

	$Z\gamma$	$\gamma\gamma^* \to \gamma\mu\mu$	$\mu\mu$
ATLAS	$\mu_{up} < 11(9)$		$\mu_{up} < 9.8(8.2)$
CMS	$\mu_{up} < \sim 10(10)$	$\mu_{up} < \sim 11(8)$	$\mu_{up} < 7.4(5.1)$

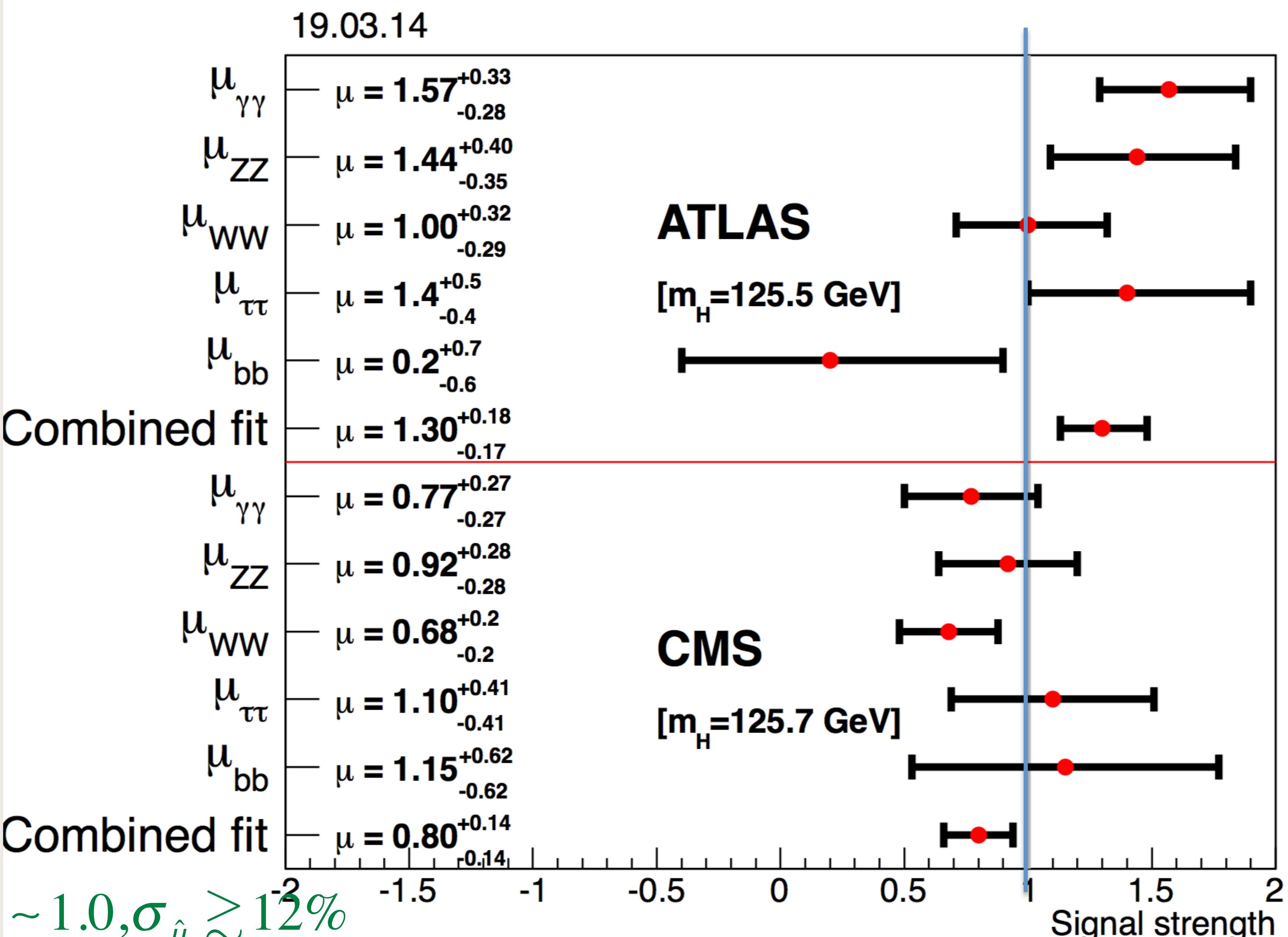
ATLAS-CONF-2013-072

Differential Cross Sections (H→$\gamma\gamma$)

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

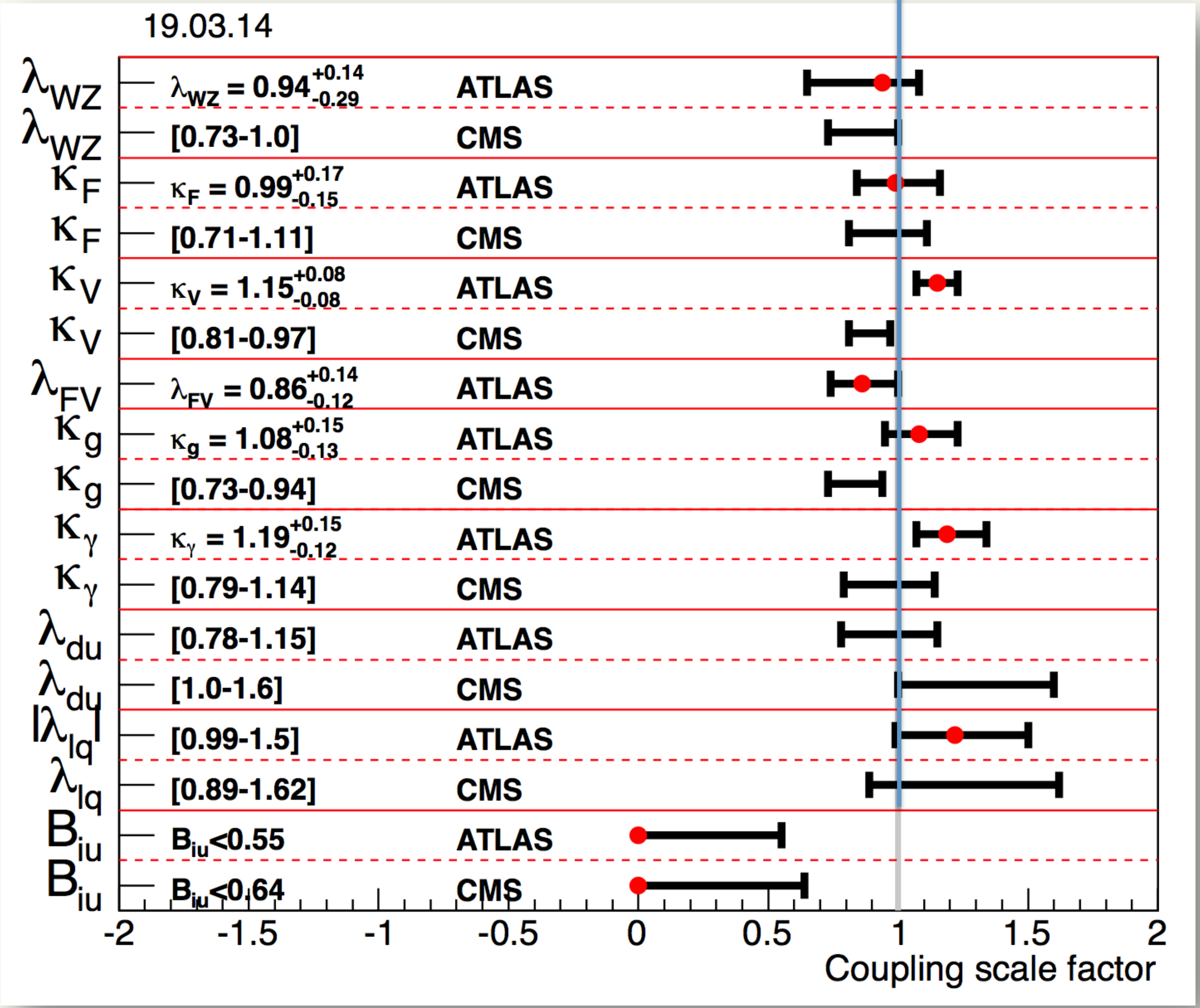


Conclusions I



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

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 more luminosity collected (so far) it does not reveal a new face, it is remarkably compatible with a SM Higgs

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……

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)

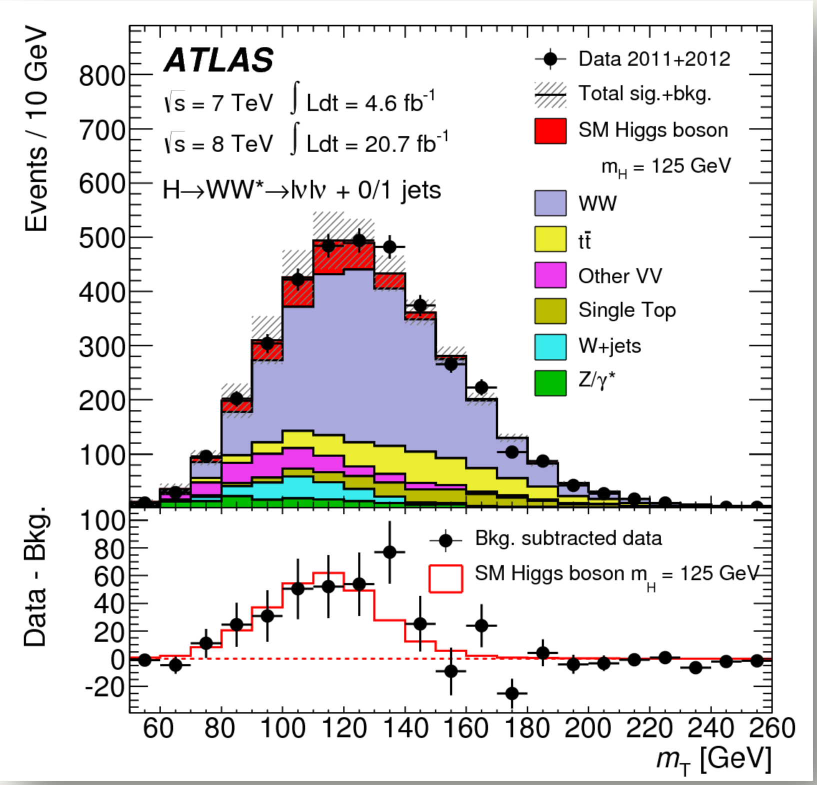
Dominant BG WW and tt

Understanding Etmiss tails crucial

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%)

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

$\mu^{WW} = 0.72^{+0.20}_{-0.18}$ $4.3\sigma(5.8\sigma\, \exp)$ @m_H=125.6 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<)	√*	×	×	$=1$	$=1$	$k_g, k_\gamma, BR_{i,u}(*)$	*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

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

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