M. Biglietti (INFN Roma3) on behalf of ATLAS CDF
CMS and D0 collaborations

MEASUREMENTS OF HIGGS BOSON COUPLINGS

Frontiers in Particle Physics: From Dark Matter to the LHC and Beyond

18-24 January 2014

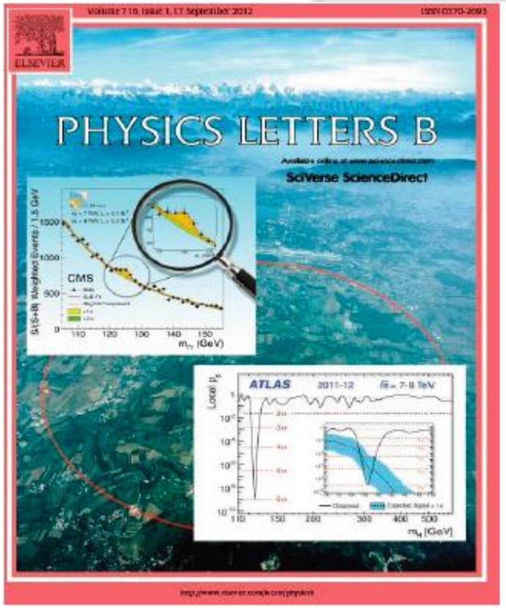
Aspen Center for Physics

After the discovery...

- Is the new boson responsible for the electroweak symmetry breaking?
  - Does it provide masses to the fermions and bosons?
  - Is it the Higgs boson predicted by the SM?

- Transition towards the measurements of the particle's properties
  - Rates and **couplings**
  - Spin and Parity

- Compatibility with SM couplings
  - Fermion/bosons
  - Custodial symmetry
- Presence of BSM particles
  - can contribute to loop-induced processes
  - can contribute to the Higgs boson width



THE BEH-MECHANISM,
INTERACTIONS WITH SHORT RANGE FORCES
AND
SCALAR PARTICLES

Channels Investigated

Almost full luminosity used in almost all channels

LHC Run I : ~5fb^{-1} @ 7TeV + ~20fb^{-1} @ 8TeV

Tevatron Run II : ~9.5fb^{-1} @1.96TeV

	ATLAS				CMS			
	ggF	VBF	VH	ttH	ggF	VBF	VH	ttH
$\gamma\gamma$	✔	✔	✔	✔	✔	✔	✔	✔
ZZ→4l	✔	✔	✔		✔	✔		✔
WW→lνlν	✔	✔	✔		✔	✔	✔	✔
$\tau\tau$	✔	✔	✔		✔	✔	✔	✔
bb			✔	✔		✔	✔	✔

ggF, ttH : Fermion couplings

VBF, VH: EW Vector Boson couplings

☛Productions disentangled from other activities in candidate events

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CDF

Channel			Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels	4×(5 b-tag categories)	$H \to b\bar{b}$	9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels	3×(2 b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$	(3 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels	2×(4 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels	2×(4 b-tag categories)		9.45	90–150
$WH + ZH \to jjb\bar{b}$	(2 b-tag categories)		9.45	100–150
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$	(4 jets,5 jets,≥6 jets)×(5 b-tag categories)		9.45	100-150
$H \to W^+W^-$	2×(0 jets)+2×(1 jet)+1×(≥2 jets)+1×(low-$m_{\ell\ell}$)	$H \to W^+W^-$	9.7	110–200
$H \to W^+W^-$	(e-$\tau_{\rm had}$)+(μ-$\tau_{\rm had}$)		9.7	130–200
$WH \to WW^+W^-$	(same-sign leptons)+(tri-leptons)		9.7	110–200
$WH \to WW^+W^-$	(tri-leptons with 1 $\tau_{\rm had}$)		9.7	130–200
$ZH \to ZW^+W^-$	(tri-leptons with 1 jet,≥2 jets)		9.7	110–200
$H \to \tau^+\tau^-$	(1 jet)+(≥2 jets)	$H \to \tau^+\tau^-$	6.0	100–150
$H \to \gamma\gamma$	1×(0 jet)+1×(≥1 jet)+3×(all jets)	$H \to \gamma\gamma$	10.0	100–150
$H \to ZZ$	(four leptons)	$H \to ZZ$	9.7	120–200

DØ

Channel			Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$	(4 b-tag categories)×(2 jets, 3 jets)	$H \to b\bar{b}$	9.7	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$	(2 b-tag categories)		9.5	100–150
$ZH \to \ell^+\ell^- b\bar{b}$	(2 b-tag categories)×(4 lepton categories)		9.7	90–150
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$	(0 jets,1 jet,≥2 jets)	$H \to W^+W^-$	9.7	115–200
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{\rm had}\nu$			7.3	115–200
$H \to W^+W^- \to \ell\bar{\nu}jj$	(2 b-tag categories)×(2 jets, 3 jets)		9.7	100–200
$VH \to e^\pm\mu^\pm + X$			9.7	100–200
$VH \to \ell\ell\ell + X$			9.7	100–200
$VH \to \ell\bar{\nu}jjjj$	(≥4 jets)		9.7	100-200
$VH \to \tau_{\rm had}\tau_{\rm had}\mu + X$		$H \to \tau^+\tau^-$	8.6	100-150
$H+X \to \ell^\pm\tau^\mp_{\rm had}jj$			9.7	105–150
$H \to \gamma\gamma$			9.6	100-150

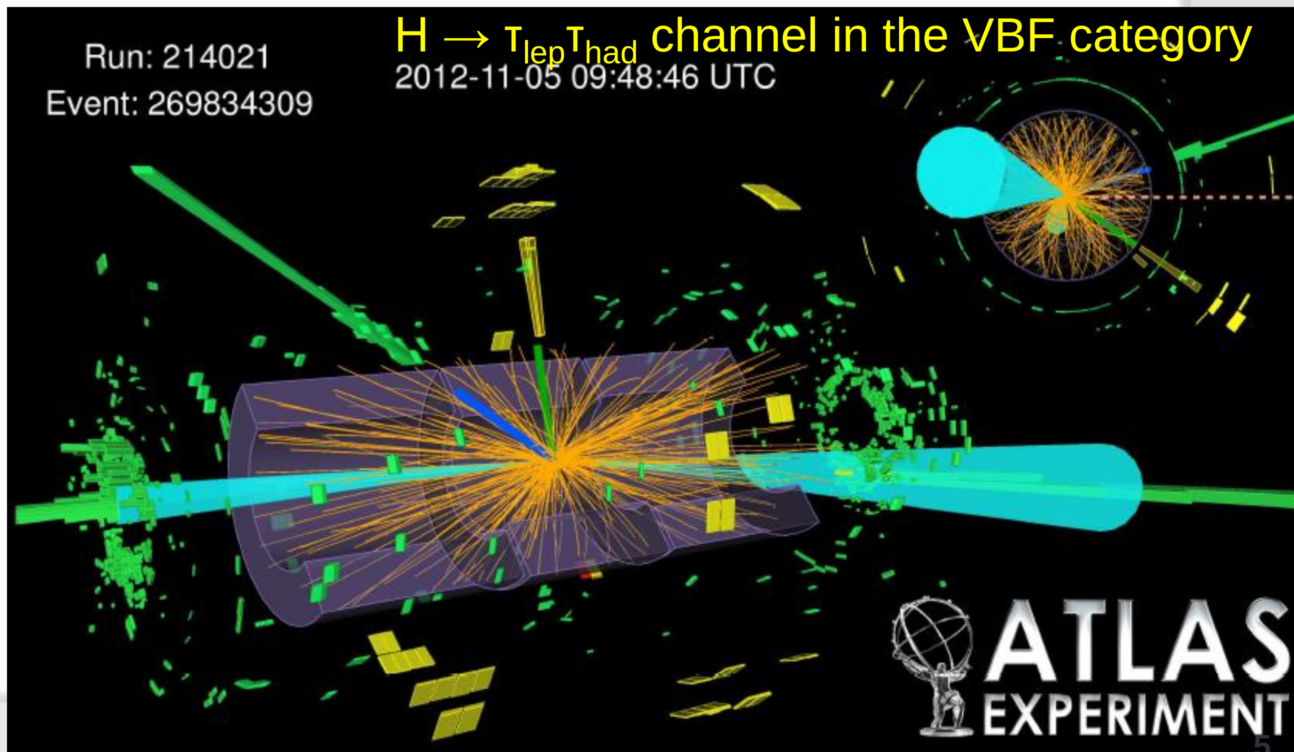
ATLAS-CONF-2013-108

CMS-HIG-13-004

Observation of H→ττ

NEW

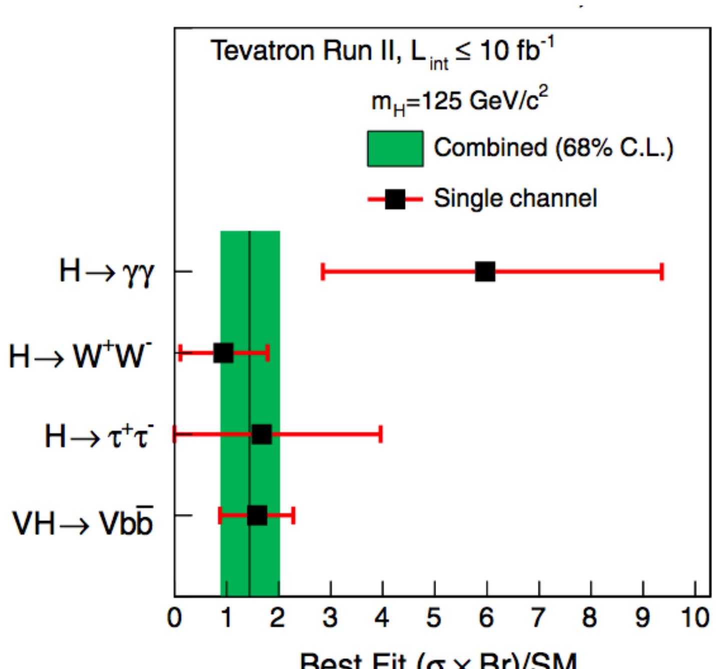
- ATLAS and CMS announce the results of their searches in the ττ channel
- Unambiguous observation of coupling of the Higgs particle to fermions
- Observed (expected) signal significance:
  - ATLAS : 4.1σ (3.2σ)
  - CMS : 3.4σ (3.6σ)

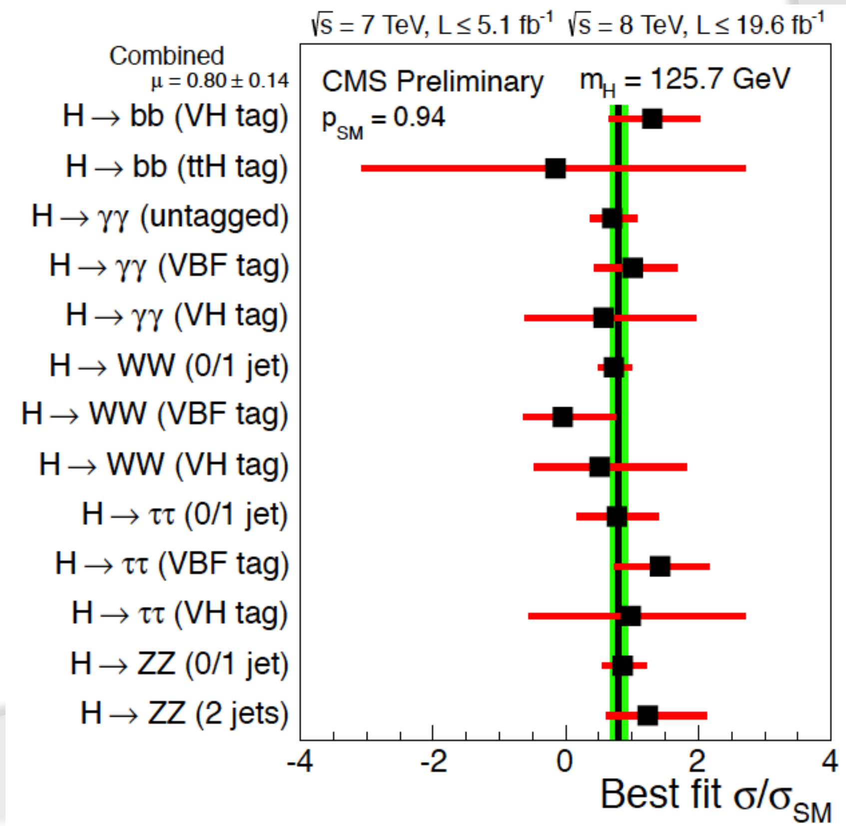


Phys. Lett. B 726 (2013) 88
CMS-HIG-13-005
PRD 88, 052014 (2013)

Probe Production Rate

- $\mu=\sigma/\sigma_{SM}$ determined with a profile likelihood ratio fit with a fixed mass hypothesis
- ATLAS : **μ =1.23± 0.18**, CMS : **μ = 0.80± 0.14**
  - not including latest results in fermionic decay channels
- Tevatron : **$\mu = 1.44^{+0.59}_{-0.56}$**
- additional tags to select preferentially events from a particular production mode.
  - overlaps exist, purity depends on the channel itself (20-50% gg→H contamination in VBF)
- used to test the relative strengths of the couplings to vector bosons and top





Coupling Measurements

- Several production and decay mechanisms contribute to signal rate → interpretation is difficult
- A better option: measure deviations of couplings from the SM prediction (*LHCXSWG YR3: arxiv:11307.1347*)
  - series of benchmark parametrizations
- Basic assumptions:
  - there is only one underlying state at m_H=125.5 GeV
  - width of the Higgs boson is neglected (narrow-width approximation) for decoupling production and decay

$$(\sigma \cdot \mathrm{BR})(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

  - same tensor structure of the SM Higgs boson : $J^{CP} = 0^{++}$ (tested independently by ATLAS/CMS/Tevatron)
    - only allow for modification of coupling strengths
- Under these assumptions all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings

$$\Gamma_H = \kappa_H^2 \cdot \Gamma_H^{SM}\ ;\ \ \Gamma_f = \kappa_f^2 \cdot \Gamma_f^{SM}\ ;\ \ \sigma_i = \kappa_i^2 \cdot \sigma_i^{SM}$$

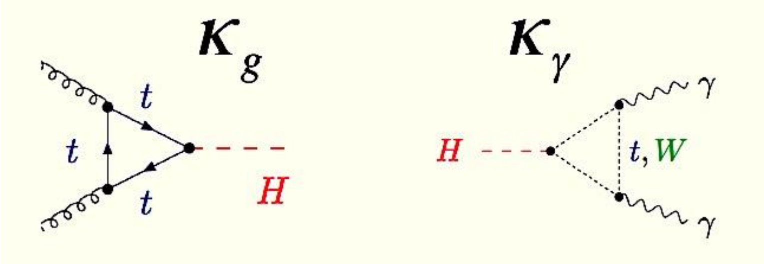
- Example:

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

Coupling Modifiers

- universality of k's for fermions and gauge bosons $k_F = k_b = k_t = k_\tau$, $k_V = k_W = k_Z$ can be assumed

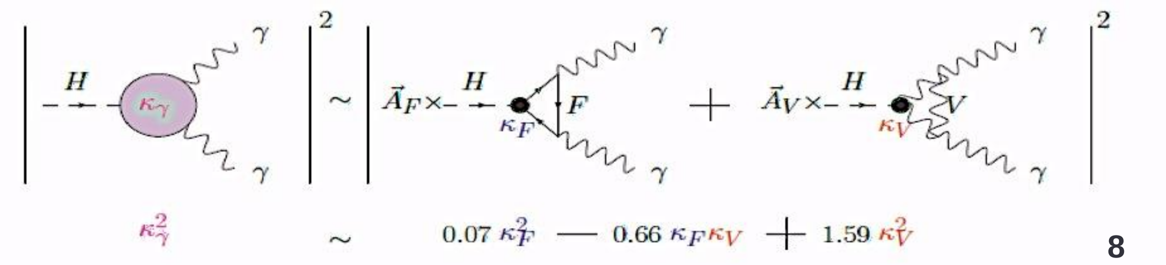
- scale factors of loop induced couplings (k_g, k_γ) and the total width k_H can be treated effectively (allowing for possible additional particles)



$\kappa_H(\kappa_W, \kappa_Z, \kappa_b, \ldots)$ $\kappa_g(\kappa_t, \kappa_b)$ $\kappa_\gamma(\kappa_t, \kappa_W, \ldots)$

- … or can be expressed in terms of fundamental factors k_W, k_Z, k_t… (assuming the SM contents)
- total width $\Rightarrow \kappa_H^2 \approx 0.75\kappa_F^2 + 0.25\kappa_V^2$

- photon vertex loop H→γγ mediated by W and fermions (mainly top)
→sensitivity to relative sign between k_V and k_F from the interference $k_V k_F$ term
  - → k_V assumed positive
  - → two minima

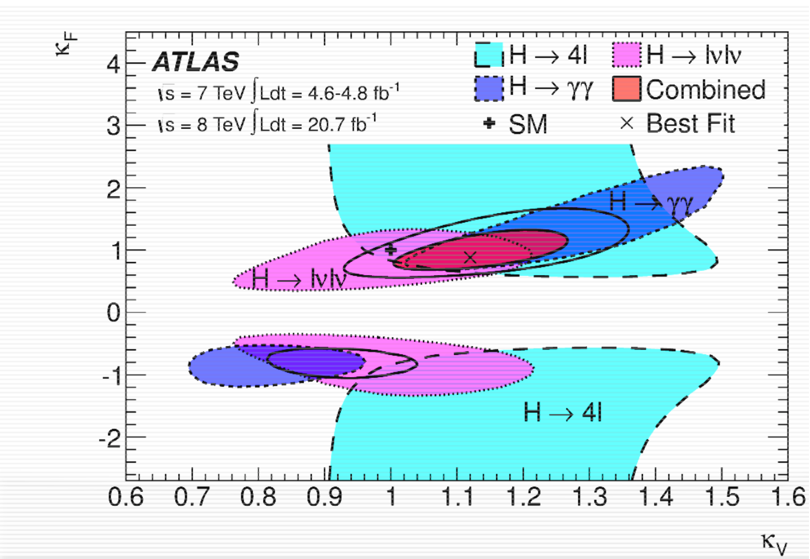


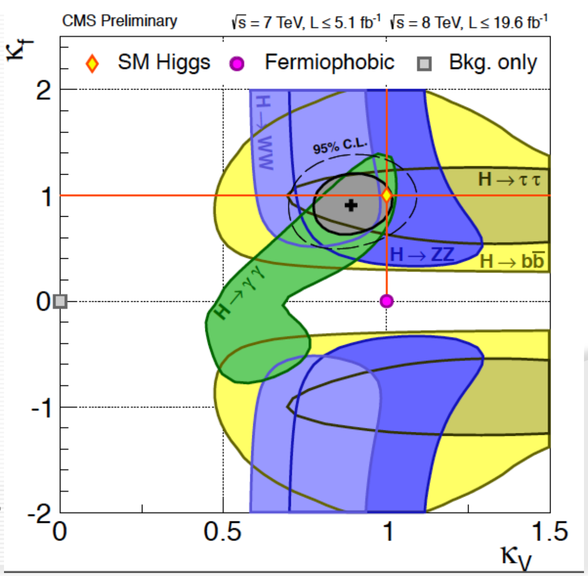
Fermion versus Vector Boson couplings

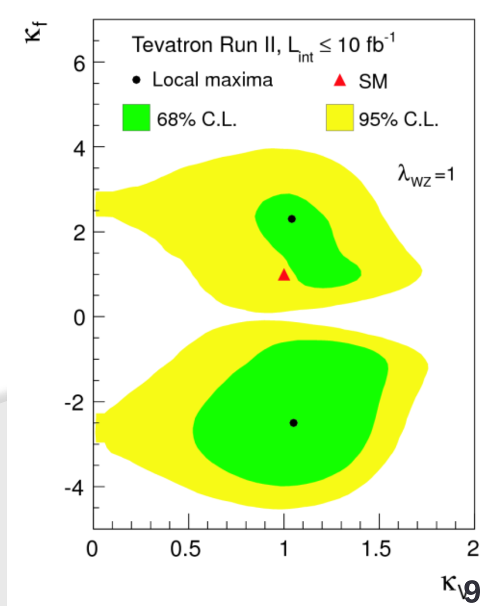
Phys. Lett. B 726 (2013) 88
CMS-HIG-13-005
PRD 88, 052014 (2013)

- Assume no BSM contributions to the total decay width and photon/gluon vertex loops
  - Interpret gluon and photon loops in terms of tree-level couplings to top, bottom, W …

Best fit prefers positive couplings, good compatibility with SM seen

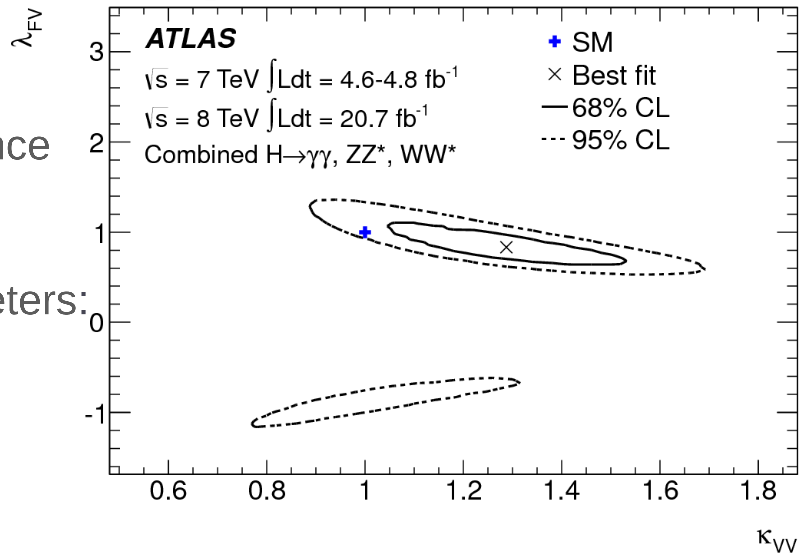




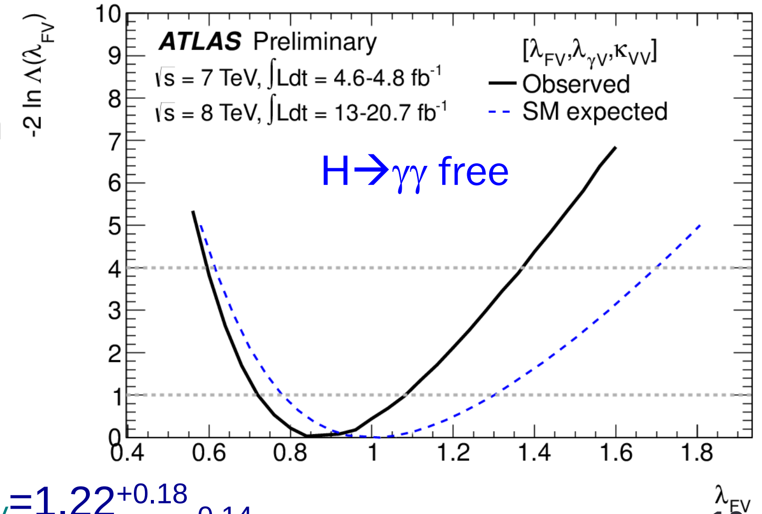


Fermion/Vector Boson couplings with looser assumptions

- no assumptions on the total width Γ_H
  - gives strong constraints on the fermion coupling k_F since dominated in the SM by the sum of fermion terms
  - ratios of coupling scale factors measured, free parameters: $\boldsymbol{\kappa_{VV}}=\kappa_V\kappa_V/\kappa_H$, $\boldsymbol{\lambda_{FV}}=\kappa_F/\kappa_V$
  - 68% CL intervals : , $\boldsymbol{\lambda_{FV}}$=[0.70,1.01] $\boldsymbol{\kappa_{VV}}$= [1.13,1.45]
  - λ_{FV} = 0 (no fermion couplings) strongly disfavored



- no assumptions on Γ_H and on H→γγ content
  - H→γγ loop can be a sensitive probe of BSM physics and account for possible different interference between vector bosons and fermions
  - free parameters $\boldsymbol{\kappa_{VV}}$, $\boldsymbol{\lambda_{FV}}$, $\boldsymbol{\lambda_{\gamma V}}=\kappa_\gamma/\kappa_V$
  - no sensitivity to the relative sign between fermion and vector boson couplings



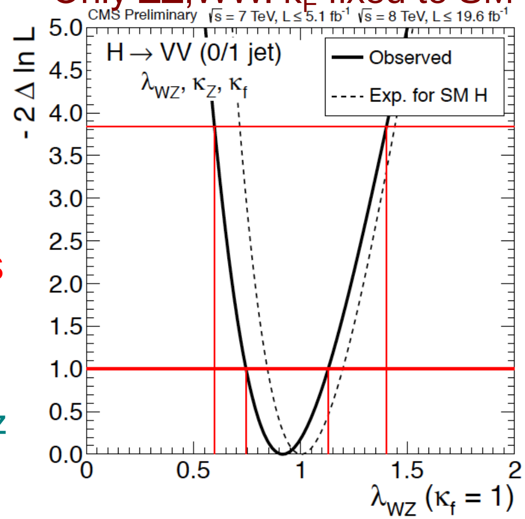
- 68% CL results : , $\boldsymbol{\lambda_{FV}}=0.85^{+0.23}_{-0.13}$ $\boldsymbol{\kappa_{VV}}$=1.15± 0.21 , $\boldsymbol{\lambda_{\gamma V}}=1.22^{+0.18}_{-0.14}$

Probing the W to Z ratio (custodial symmetry) - I

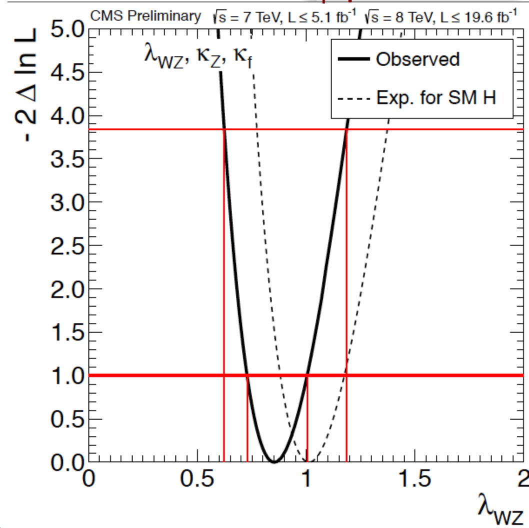
- SM requires $\kappa_W = \kappa_Z$
- Free parameters:

  $\lambda_{WZ}=\kappa_W/\kappa_Z$, κ_Z, κ_F
- CMS
  - only H→ZZ, WW in 0/1 jet categories
    - ratio $\lambda_{WZ}=\kappa_W/\kappa_Z$ model independent, production dominated by gg→H
    - account small VBF contribution → κ_Z treated as nuisance parameter, $\kappa_F=1$
    - λ_{WZ} = [0.60,1.40] @95% CL
  - all channels
    - Assuming SM content in the $\gamma\gamma$ loop and using VBF+VH production, κ_F profiled
    - λ_{WZ} = [0.62,1.19] @95% CL

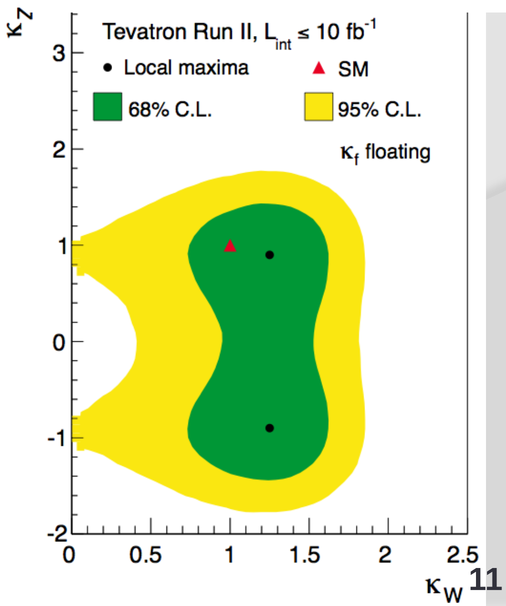
Only ZZ,WW. κ_F fixed to SM



All channels. κ_F profiled



- Tevatron
  - allow both κ_W and κ_Z to vary independently
  - $\lambda_{WZ}=1.24^{+2.34}_{-0.42}$ @68% CL
  - (κ_W, κ_Z) = (0, 0) corresponds to no Higgs production/decay in the most sensitive search modes not included in the 95% C.L. region due to the significant excess of events @125 GeV



Probing the W to Z ratio (custodial symmetry) - II

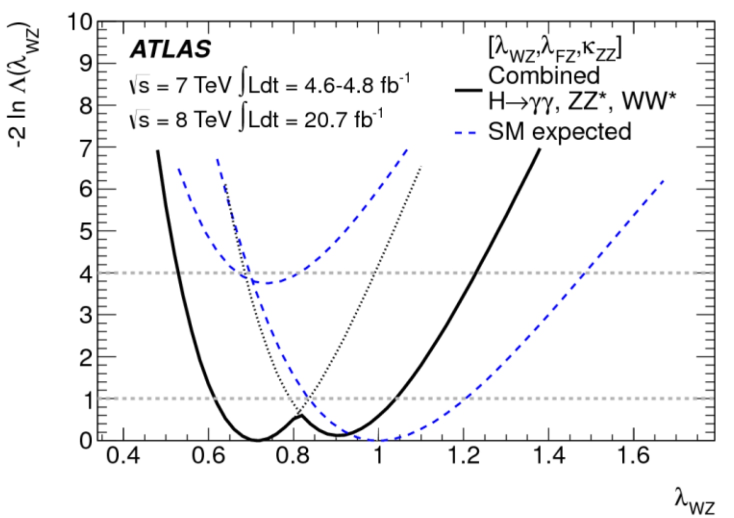
- Three or four free parameters
  - $\lambda_{\gamma Z}$ absorbs BSM effects in H→γγ loop
  - no assumptions on the total width Γ_H

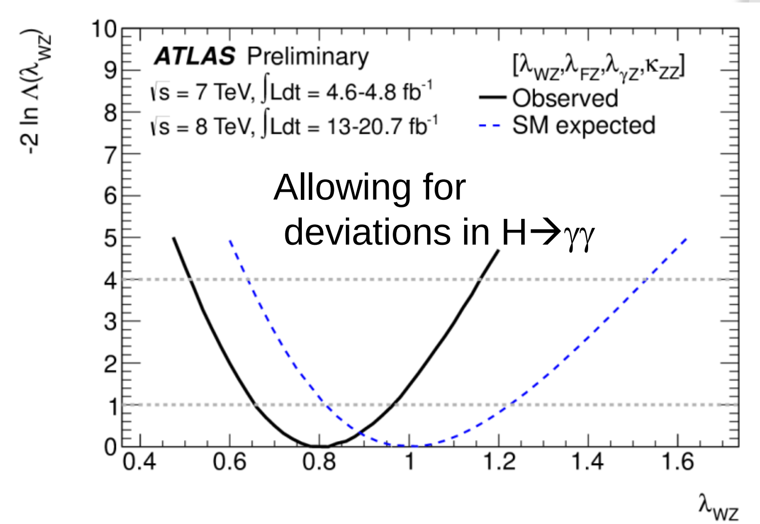
$$\begin{aligned} \kappa_{ZZ} &= \kappa_Z \cdot \kappa_Z / \kappa_H \\ \lambda_{WZ} &= \kappa_W / \kappa_Z \\ \lambda_{\gamma Z} &= \kappa_\gamma / \kappa_Z \\ \lambda_{FZ} &= \kappa_F / \kappa_Z \quad . \end{aligned}$$

- ATLAS
  - 68% CL results
    - non-SM local minimum preferred for λ_{FZ} but the other local minimum is compatible with SM at ~1.5σ level

$$\begin{aligned} \lambda_{WZ} &\in [0.64, 0.87] \\ \lambda_{FZ} &\in [-0.89, -0.55] \\ \kappa_{ZZ} &\in [1.20, 2.08] \end{aligned}$$

$$\begin{aligned} \lambda_{WZ} &= 0.80 \pm 0.15 \\ \lambda_{\gamma Z} &= 1.10 \pm 0.18 \\ \lambda_{FZ} &= 0.74^{+0.21}_{-0.17} \\ \kappa_{ZZ} &= 1.5^{+0.5}_{-0.4} \end{aligned}$$



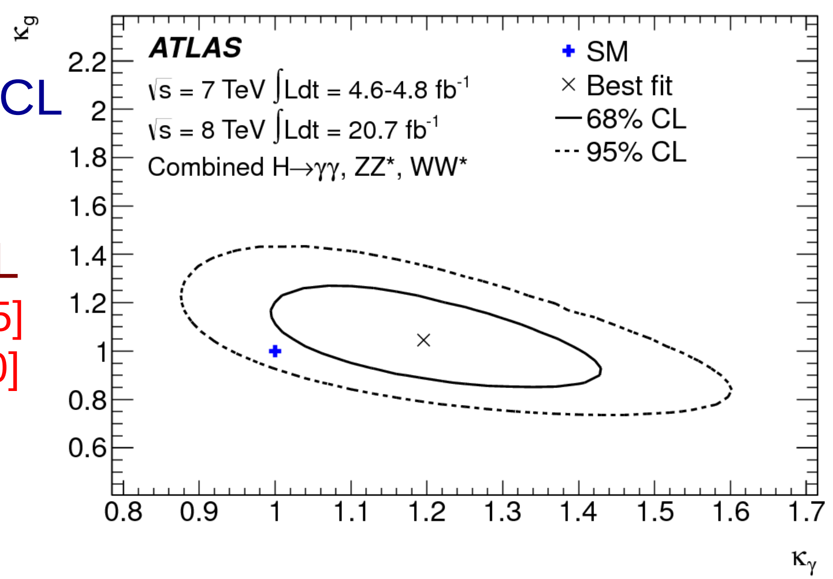


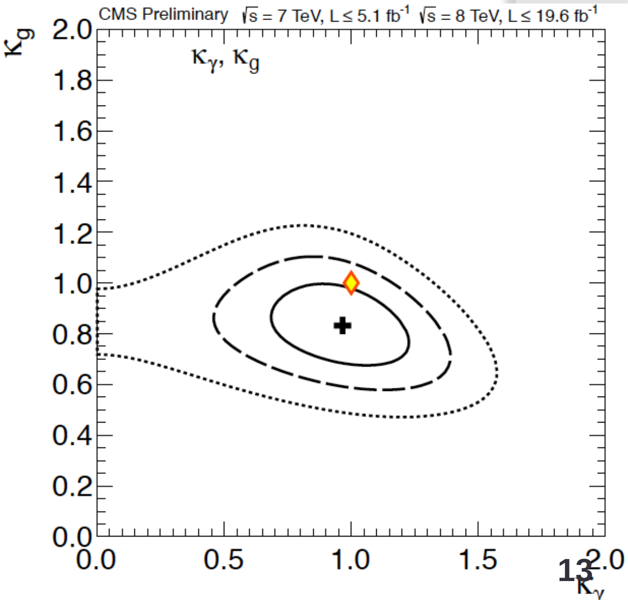
Phys. Lett. B 726 (2013) 88
CMS-HIG-13-005

Test for BSM Physics in Loops

- SM processes at 1-loop particularly sensitive to anomalous new physics effects
- Two options to probe BSM contributions:
  1. release assumption of only-SM content in Higgs production loop
     - fit effective coupling κ_γ , κ_g but fix other tree level parameters to SM (k_j=1)
     - assume no BSM contributions to the total decay width
  2. release assumption of only-SM contributions to Higgs width **Γ_H (next slide)**
- Effective couplings to gluons and photons in good agreement with SM

- ATLAS @68% CL
  - k_g = 1.04±0.14
  - k_γ = 1.20±0.14
- CMS @95% CL
  - k_g = [0.63, 1.05]
  - k_γ = [0.59, 1.30]



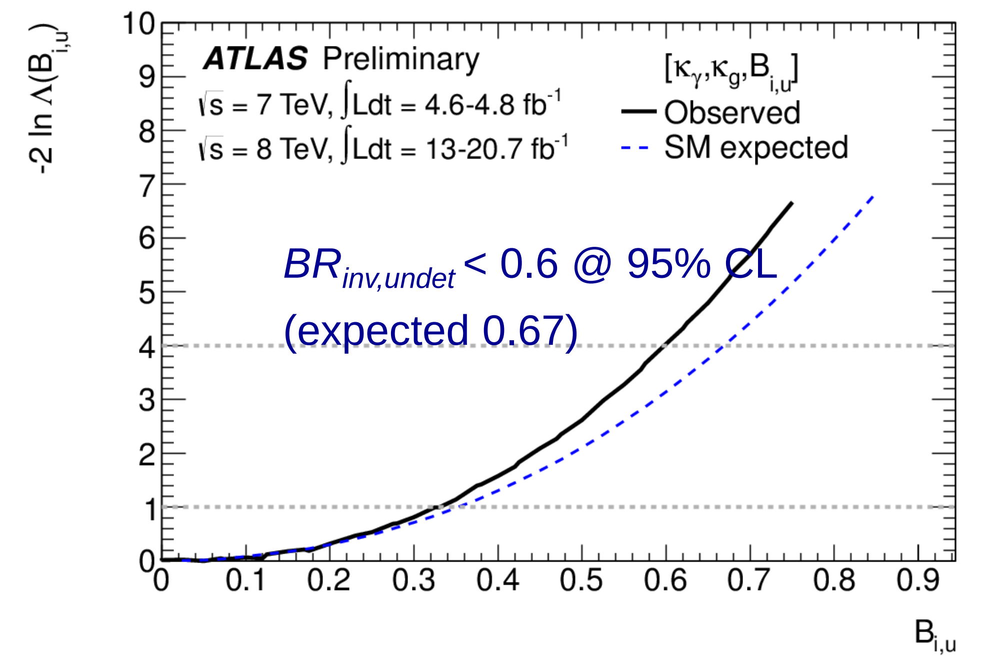


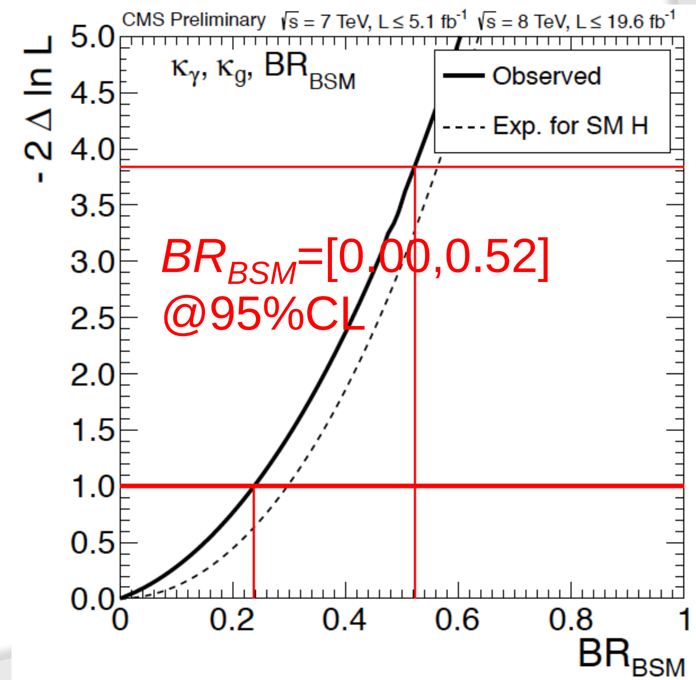
Test for BSM Physics in Decays

- direct invisible decays or decays into final states that cannot be distinguished from background
- the total width Γ_H is parameterized with additional $BR_{inv,undet}$
- free parameters κ_γ , κ_g, $BR_{inv,undet}=BR_{BSM}$
- BSM Γ_H contribution constrained

$$\Gamma_H = \Gamma_H^{SM} + \Gamma_H^{BSM}$$

$$\mathcal{BR}_{\text{inv.,undet.}} = \Gamma_H^{BSM}/\Gamma_H$$





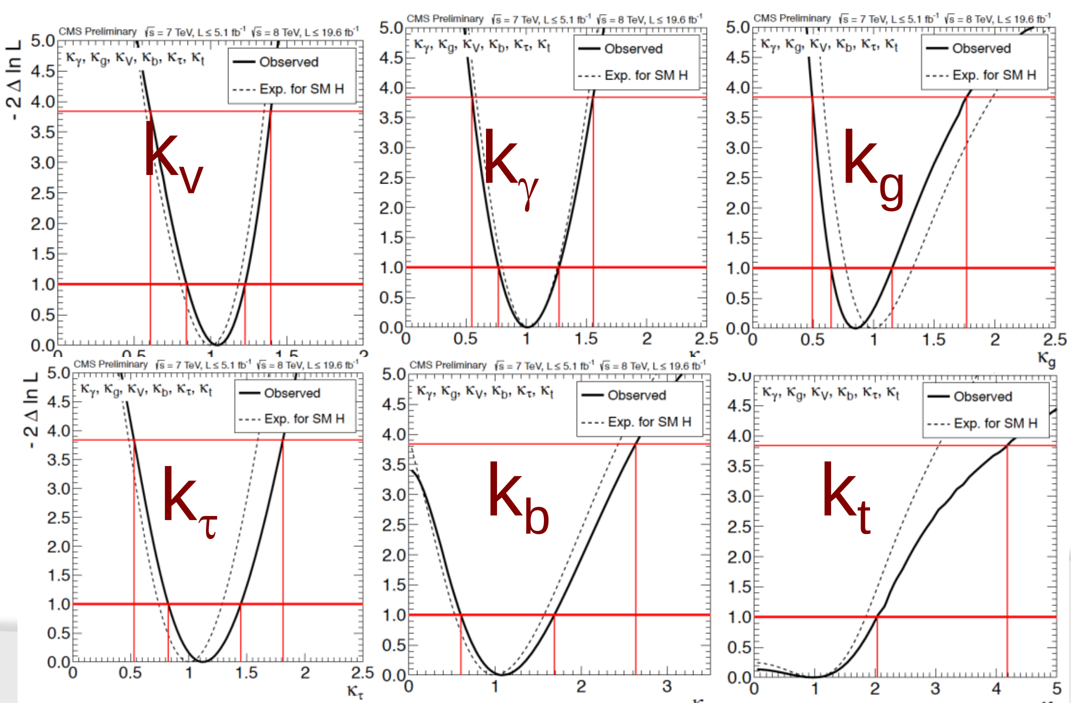
More information on Higgs → invisible in Justin Griffiths' talk

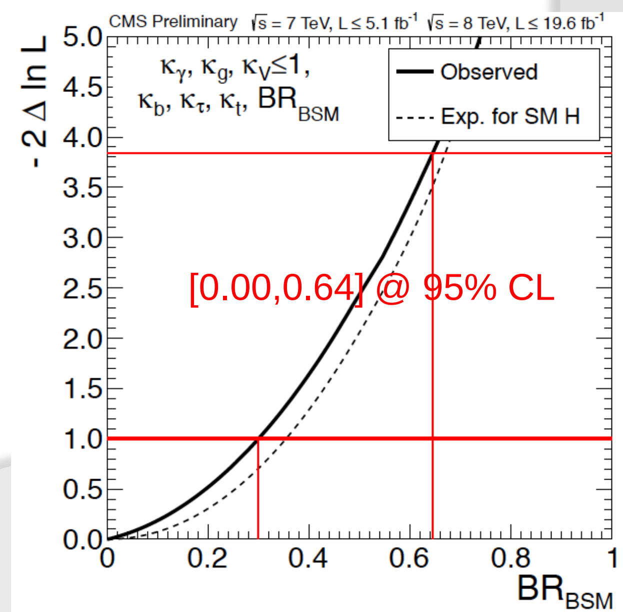
A more general parametrization

CMS-HIG-13-005

- custodial symmetry: $\kappa_W = \kappa_Z = \boldsymbol{\kappa_V}$
- the couplings to third generation fermions are scaled independently by $\mathbf{k_t}$, $\mathbf{k_b}$, $\mathbf{k_\tau}$
- effective couplings to gluons and photons, induced by loops, given by $\mathbf{k_g}$ and $\mathbf{k_\gamma}$
- the partial width can be Γ_{BSM} zero or free → 6 or 7 fitted parameters

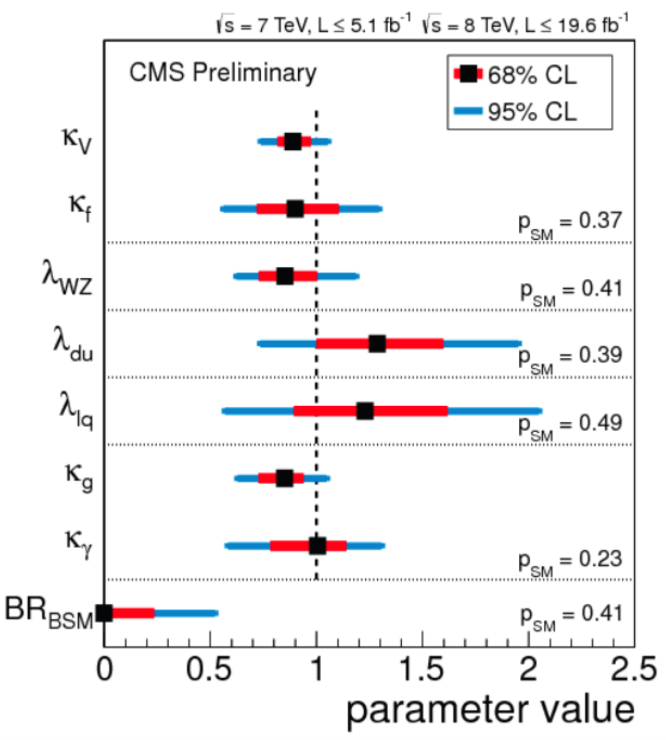
- no statistically significant anomalies with respect to the SM hypothesis

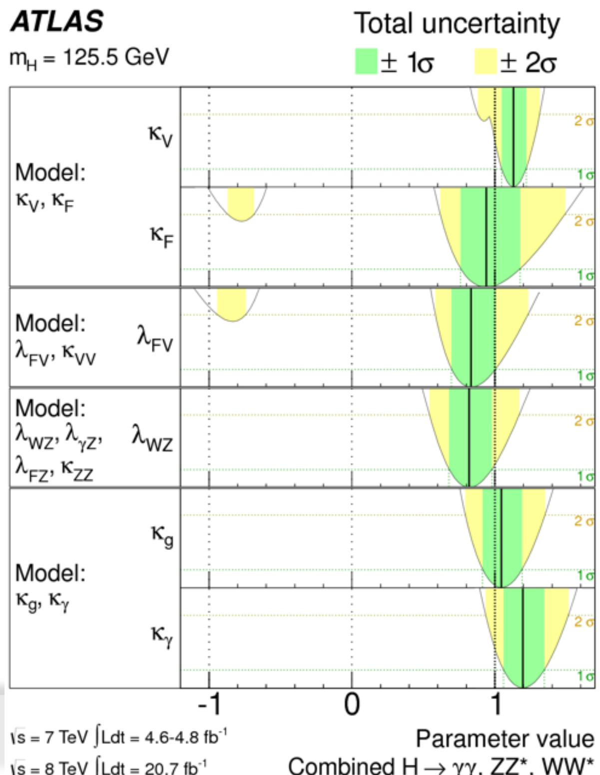


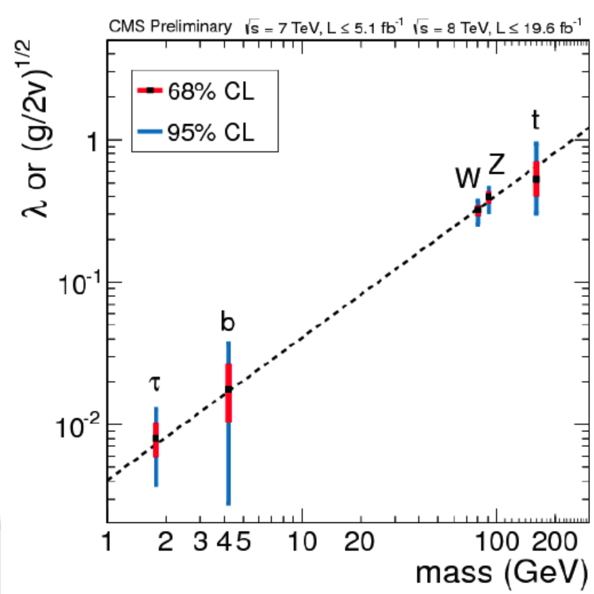


Summary of Coupling Measurements

- different sectors of the new boson couplings tested, all measurements are consistent with the SM Higgs hypothesis, including
  - couplings vs mass
  - fermion universality
    - ratios of the couplings of down/up fermions ($\lambda_{du} = k_d/k_u$) and of leptons/quarks ($\lambda_{lq} = k_l/k_q$)





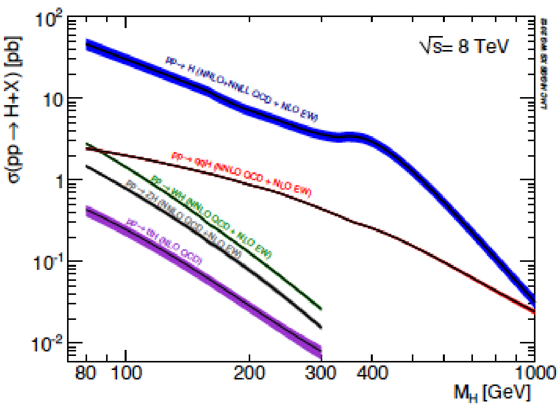


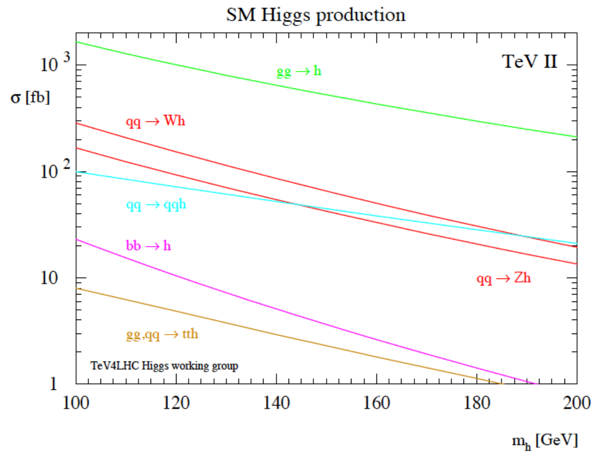
Conclusions

- Outstanding LHC and Tevatron performance allowed to test the fundamental properties of the discovered Higgs boson
- The compatibility of the measured yields for the studied channels with the SM prediction is tested under various benchmark assumptions probing salient features of the couplings
- No significant deviation from the SM prediction is observed in any of the fits performed
- LHC Run-I accuracy achieved is ~20-30%
- LHC Run-II and HL-LHC will bring more statistics to improve the current measurement but also open new channels
  - Top Yukawa direct measurement with ttH
  - Couplings to 2nd generation fermions (**μ**)
  - Higgs self-couplings (HHH)
- → More information on "Future prospects for Higgs measurements" in Hubert Kroha' talk

BACKUP

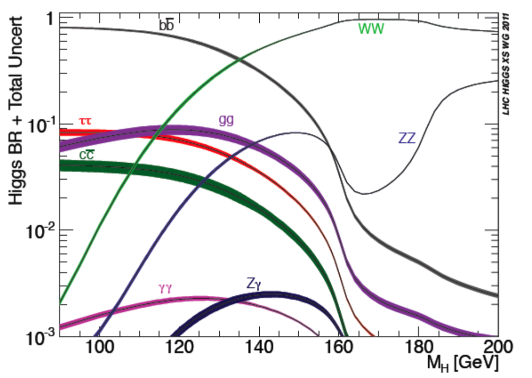
Production/Decay Processes (backup)



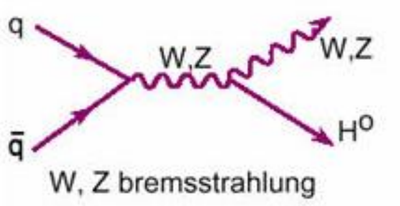


☛Higgs decays :

γγ, ZZ→4l, WW, bb, ττ

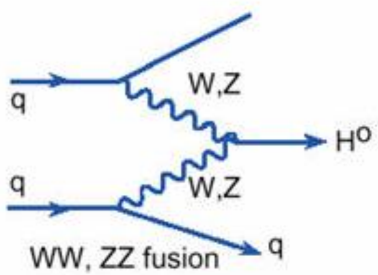


☛Productions disentangled from other activities in candidate events



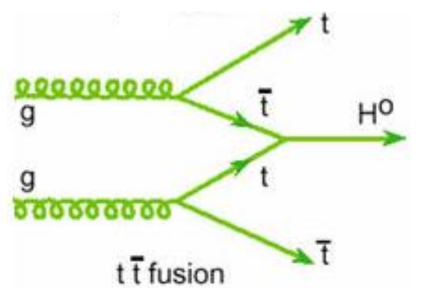
VH

Leptons, missing ET or low-mass dijets from W or Z decays



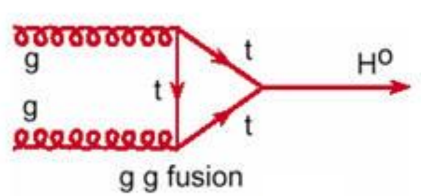
VBF

Two high p_T jets with high-mass and large pseudorapidity separation



ttH

Two top quarks: leptons, missing ET, multijets or b-tagged jets



ggF

the rest

EW Vector Boson couplings

Fermion couplings

Statistical Procedure

Construct likelihood from Poisson probabilities with parameter of interest (signal strength μ in this case):

$$L\left(\text{data}\,|\,\mu,\theta\right)=\text{Poisson}\left(\text{data}\,|\,\mu\cdot s(\theta)+b(\theta)\right)\times p\left(\tilde{\theta}\,|\,\theta\right)$$

μ: signal strength; θ: 'nuisance' parameters (efficiencies...)

Hypothesized value of μ is tested with a test statistic:

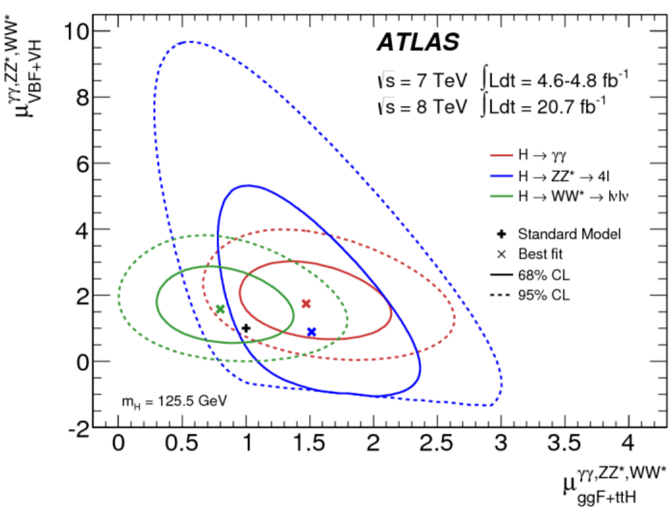
$$q_{\mu}=-2\ln\Lambda(\mu)=-2\ln\left[\frac{L\left(\mu,\hat{\hat{\theta}}(\mu)\right)}{L\left(\hat{\mu},\hat{\theta}\right)}\right]$$

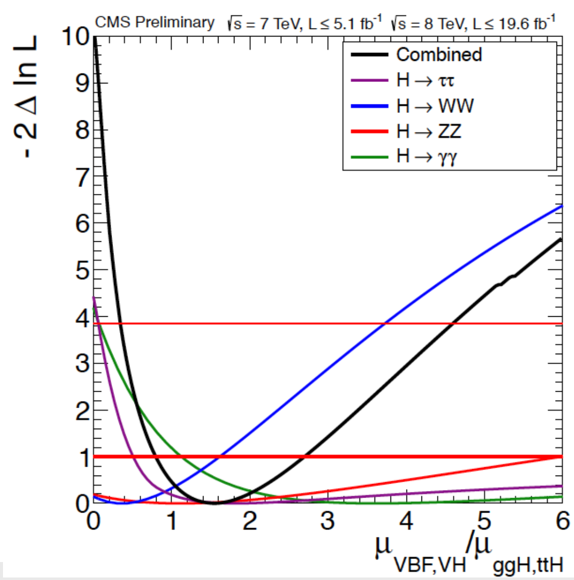
Systematic uncertainties are included as nuisance parameters constrained by chosen pdfs (Gaussian, log-normal, …)

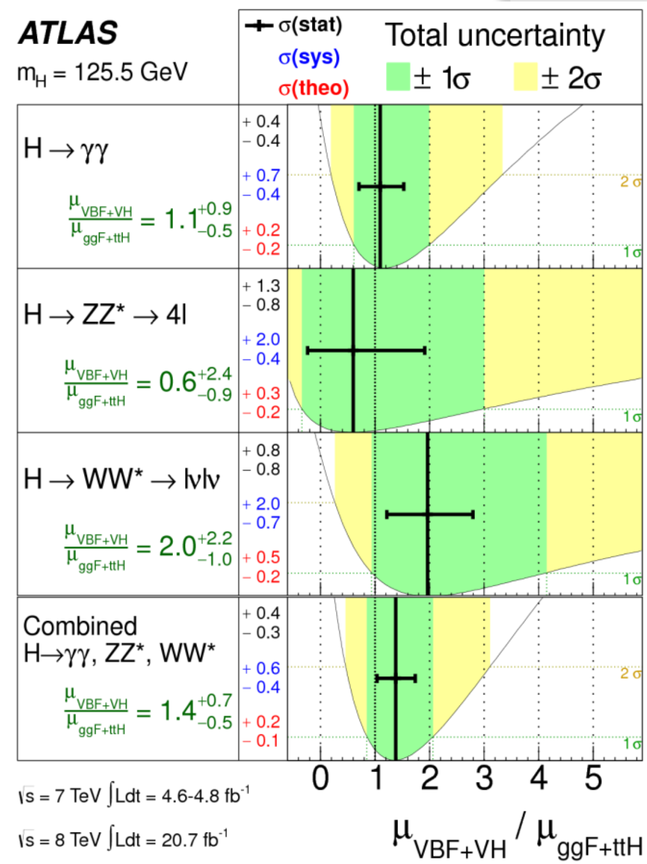
Combination amounts to taking product of likelihoods from different channels: $L\left(\text{data}\,|\,\mu,\theta\right)=\Pi_i\, L_i\left(\text{data}_i\,|\,\mu,\theta_i\right)$

Production Signal Strengths

- data are fitted separating vector bosons mediated (VBF,VH) from gluon mediated processes (ggF, ttH, mainly involving top loops) → Yukawa vs gauge coupling
- two signal strengths (μ_{VBF+VH}, $\mu_{ggF+ttH}$) for each decay channel
- 95% CL contours consistent with SM expectations
- contours for the combination of the decay channels are not meaningful (new physics in the BRs)
- combination is done in a model independent way measuring the ratios for the each production channel and their combination







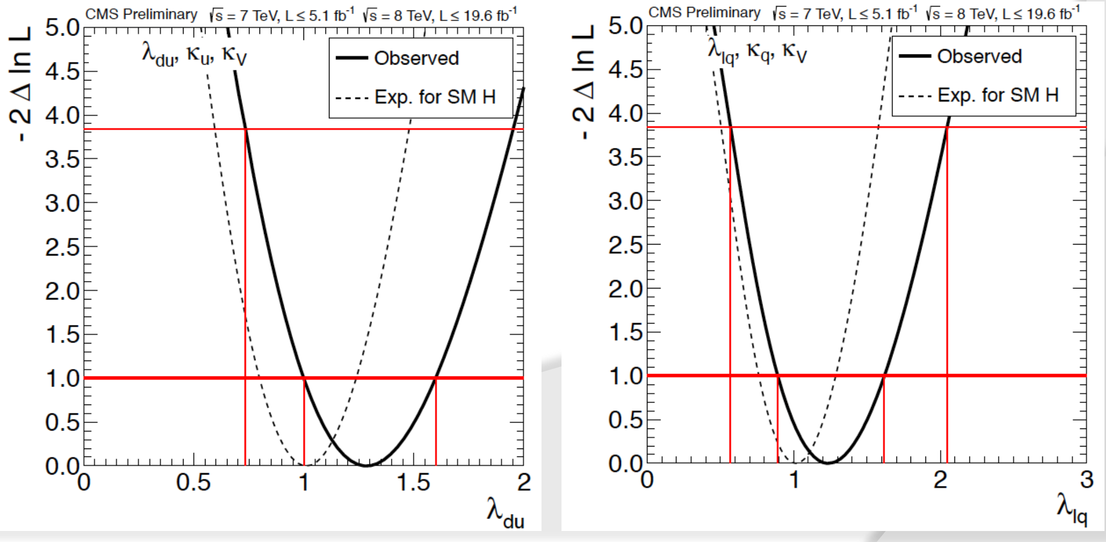
Benchmark Models

- Several models can be tested:
  - couplings to fermions and bosons
  - custodial symmetry:
    - in the SM: $\lambda_{WZ}=\kappa_W/\kappa_Z=1$, extract λ_{WZ} from measured inclusive rates of H→WW and H→ZZ (including VBF and VH production)
  - production and decay loops (testing BSM heavy particles):
    - couplings of the known particles to the Higgs have SM strength ($k_j=1$)
    - new particles can contribute to loop-induced processes (scale factors k_g and k_γ)
    - new particles do not contribute to the Higgs width

Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√

Test for asymmetries in the couplings to fermions

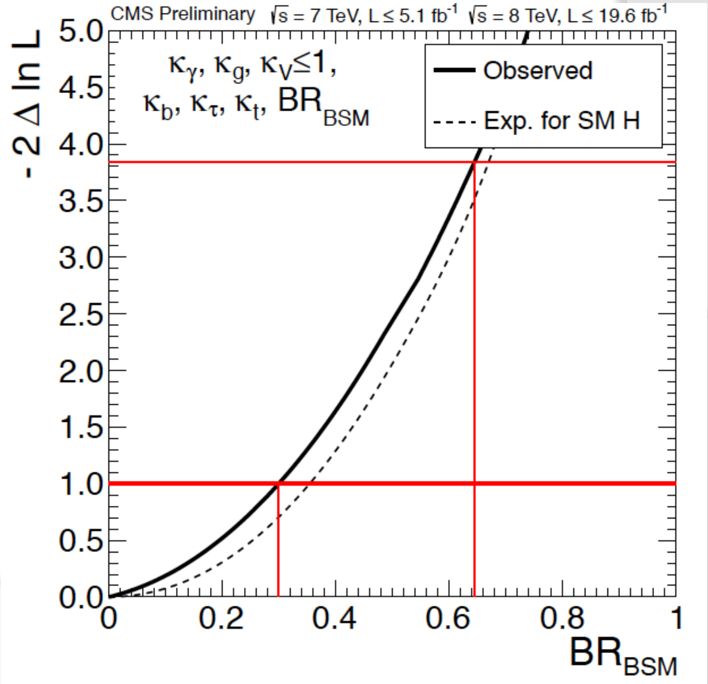
- In 2HDM models the couplings of the neutral Higgs bosons to fermions can be modified wrt the Yukawa couplings of the SM Higgs boson.
  - in MSSM the couplings of neutral Higgs bosons to up-type and down-type fermions are modified
    - the modification are the same for all three generations and for quarks and leptons
  - more in general leptons can decouple from the Higgs boson that behaves in a SM-like way wrt W/Z and quarks
- allow for different ratios of the couplings of down/up fermions (**$\lambda_{du} = k_d/k_u$**) or of leptons/quarks (**$\lambda_{lq} = k_l/k_q$**)
  - up-type fermions=top (from ggF production), down-type fermions =bottom quark, tau lepton (from decays)
- Free parameters:
  - **λ_{du} , k_u, k_V**
  - **λ_{lq} , k_q, k_V**
  - assume $\Gamma_{BSM} = 0$
- 95% CL intervals
  - **λ_{du} = [0.74,1.95]**
  - **λ_{lq} = [0.57,2.05]**
  - Both are constrained to be positive



Constraints on BR_{BSM} in a scenario with free couplings

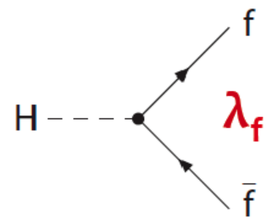
- An alternative more general scenario can be obtained
  - allowing for a non-vanishing Γ_{BSM}
  - 7 fitted parameters: **k_V ,k_t ,k_b ,k_t ,k_γ,k_g** and **BR_{BSM}**
  - constraining $k_V<1$
    - requirement motivated by many EWSB models

- BR_{BSM} derived while profiling all the other parameters
  - in the interval [0.00,0.64] @ 95% CL.

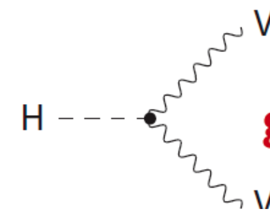


Couplings vs mass

- the Higgs boson couplings are proportional to the masses of the particles



$\lambda_f = m_f / v$



$g_V = 2\, m_V^2 / v$

$\lambda_f = \kappa_f\, m_f / v$

$g_V = 2\, \kappa_V\, m_V^2 / v$

- Perform fit to full CMS combination, resolving gluon and photon loops in terms of tree-level couplings
- Top coupling from ggF
- Redefine couplings with scale factors