Higgs Boson Couplings Measurements by ATLAS

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LHCP 2013

Introduction

- "Observation of a new particle" in July 2012!
- Is it compatible with the SM?

  VBF production mechanism? YES!

  Probe Lagrangian structure

  1. *Boson & Fermion couplings*
  2. *Custodial symmetry*
  3. *Loop induced couplings to gluons and photons: non-SM particles*
- Other ATLAS talks in this conference

  A. Mehta, L. Kashif & D. Jamin

Including $\gamma\gamma$, ZZ, WW updated to full 2011-2012 dataset

4.6/fb @ 7TeV, 20.7/fb @ 8TeV

$\tau\,\tau$ & bb results

4.6/fb @ 7TeV, 13/fb @ 8TeV

A word about the procedure

- Construct a likelihood of Poisson probabilities

$$L(\mu, \boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k} \ .$$

- signal and background parameterized as

$$s_i = s_{\text{tot}} \int_{\text{bin}\, i} f_s(x; \boldsymbol{\theta}_s)\, dx \ ,$$

$$b_i = b_{\text{tot}} \int_{\text{bin}\, i} f_b(x; \boldsymbol{\theta}_b)\, dx \ .$$

"nuisance parameters"
represent lack of knowledge
examples below

- For couplings measurement the signal is represented as

$$n^k_{\text{signal}} = \left(\sum_i \mu_i \sigma_{i,\text{SM}} \times A^k_{if} \times \varepsilon^k_{if} \right) \times \mu_f \times B_{f,\text{SM}} \times \mathcal{L}^k$$

cross section scale

acceptance

efficiency

branching ratio scale

luminosity

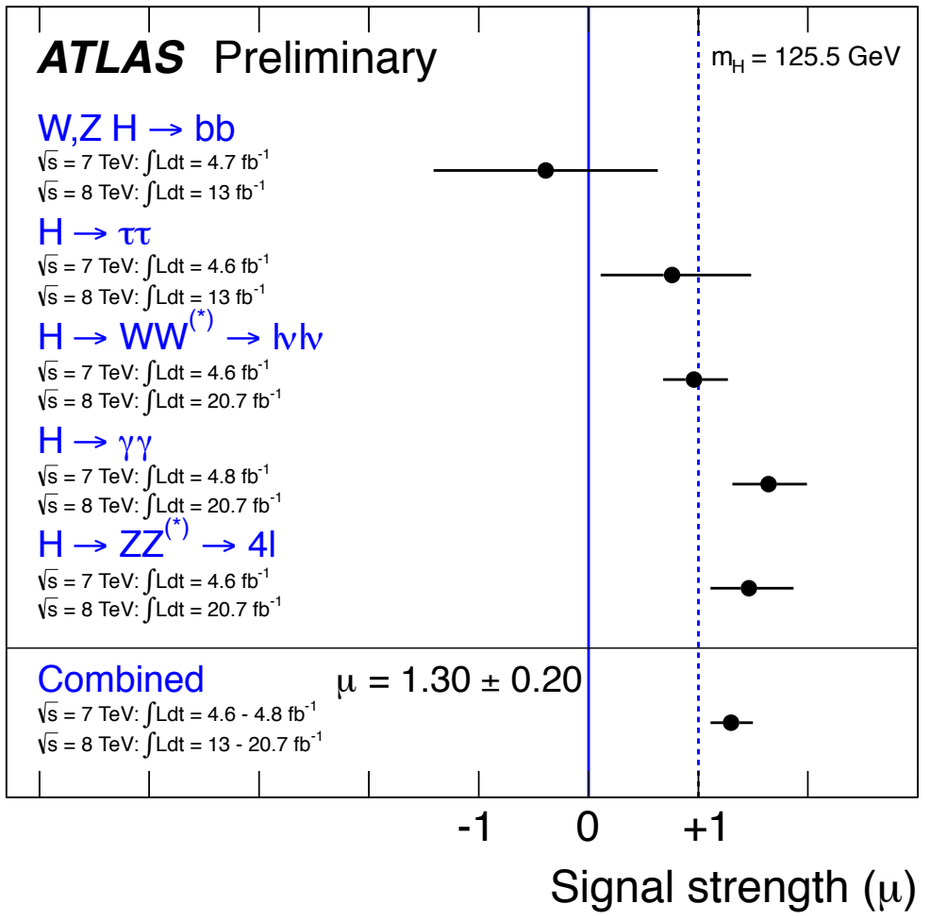
- Test hypothesized values of mu with a test statistics

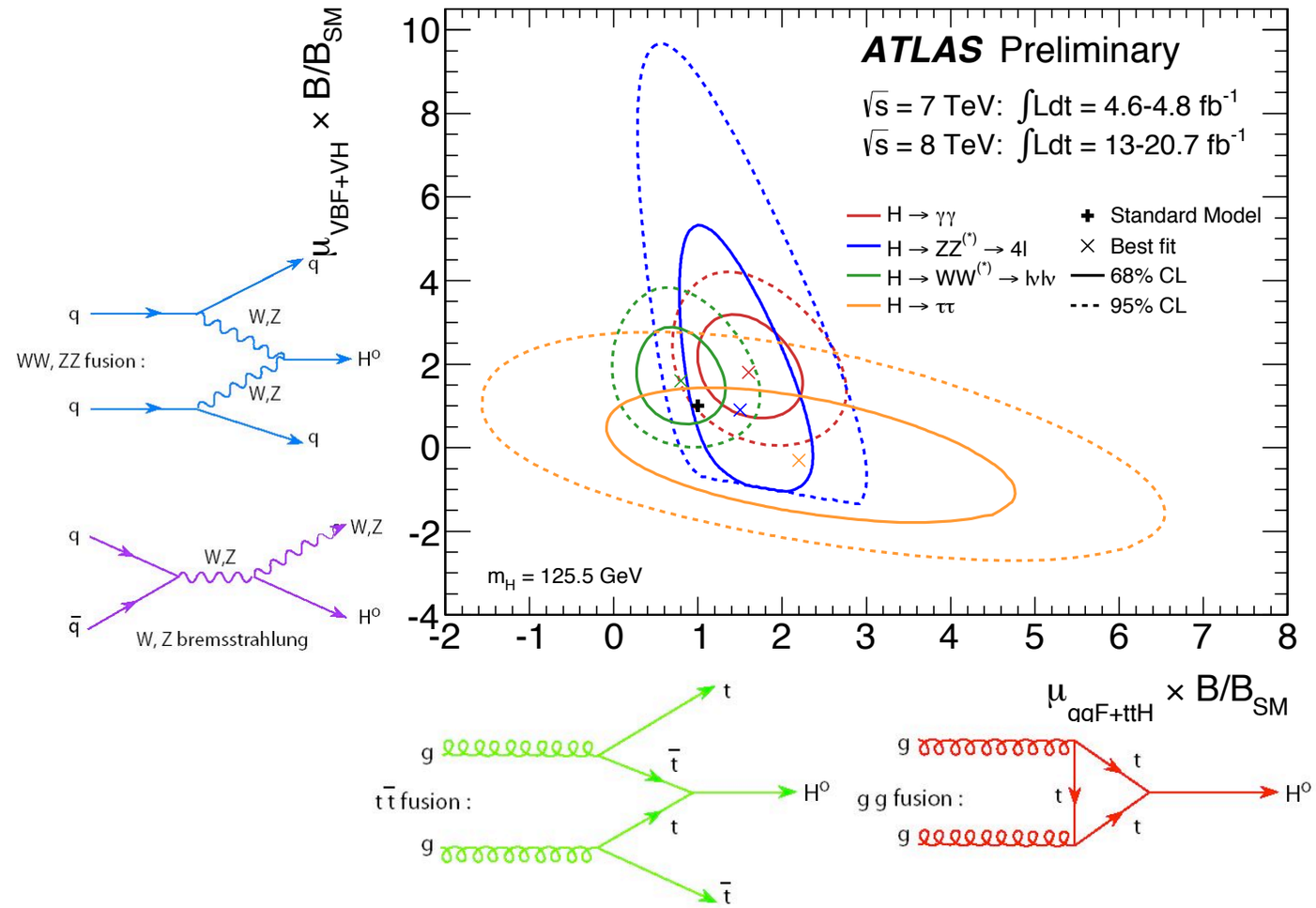
maximize likelihood for fixed mu

$$\Lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(\hat{\mu}, \hat{\theta})}$$

floats to maximize likelihood

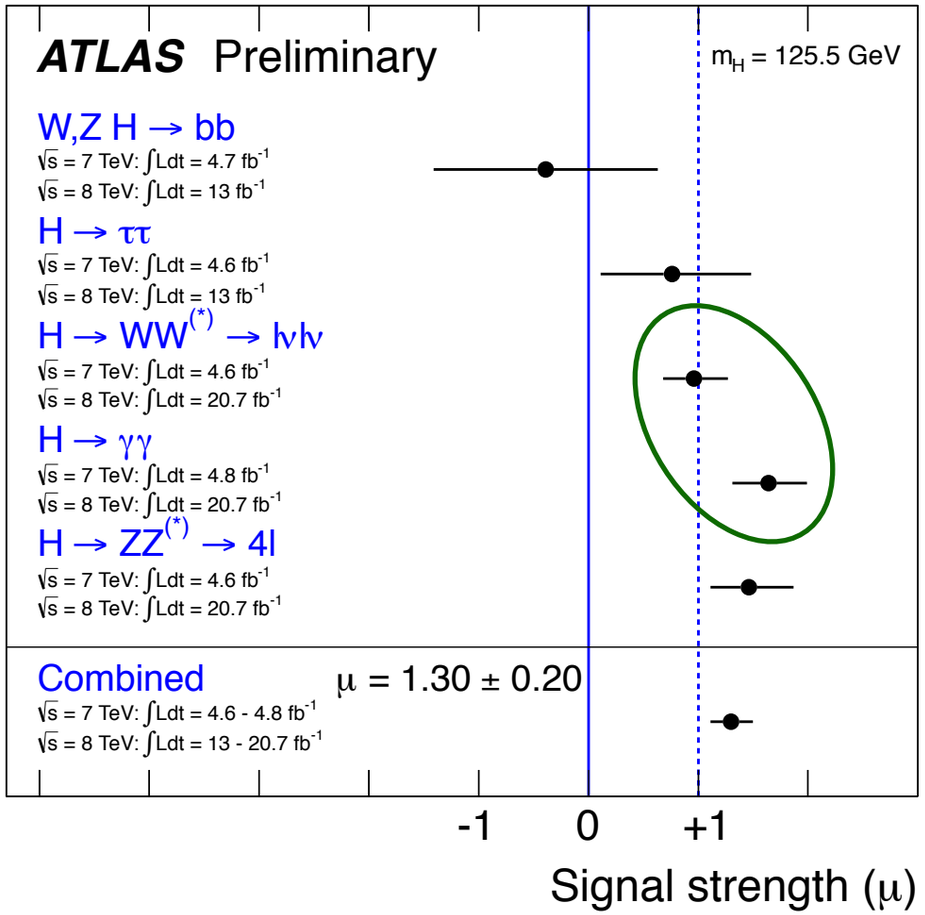
All the information is here

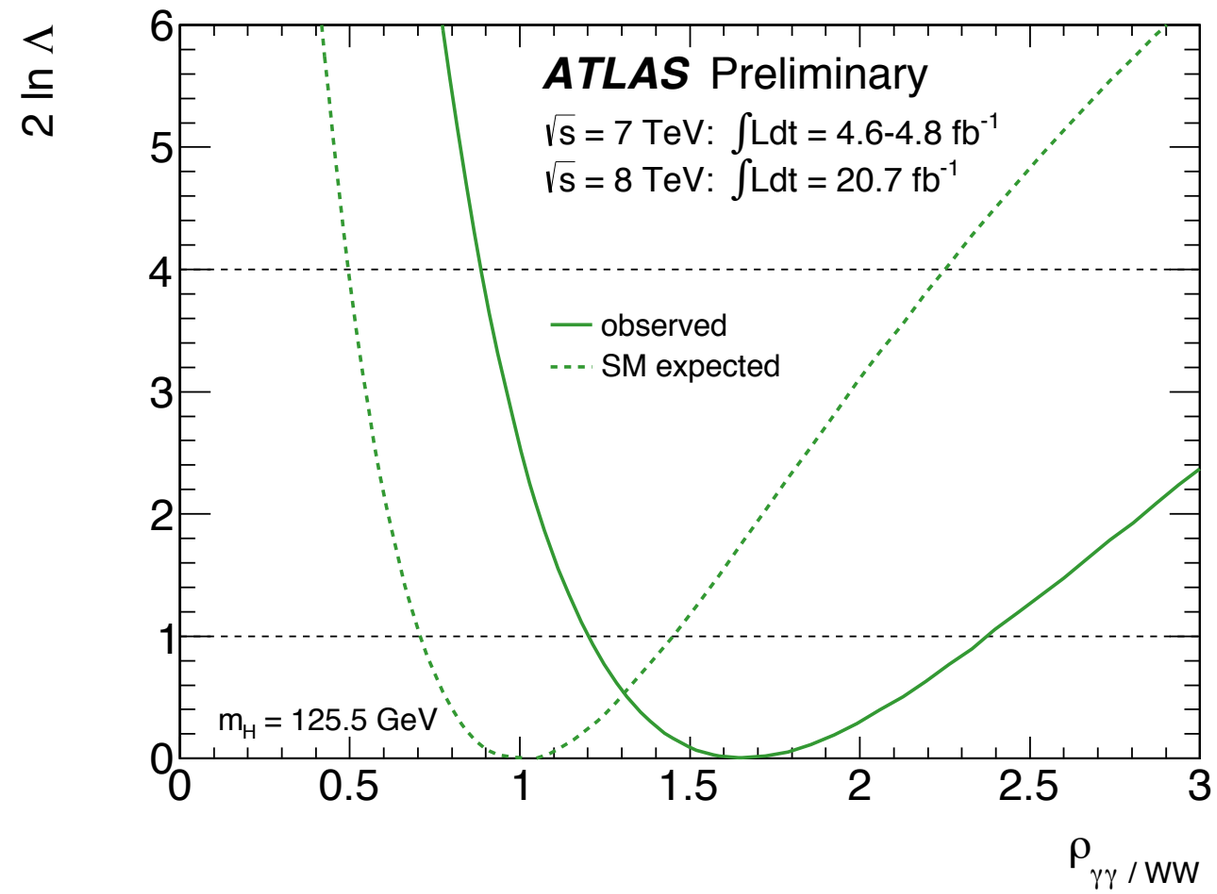




Recast this information in different physically interesting scenarios to look for a coherent deviation from the SM

Example





ratio of BR(γγ)/BR(WW) is > 1

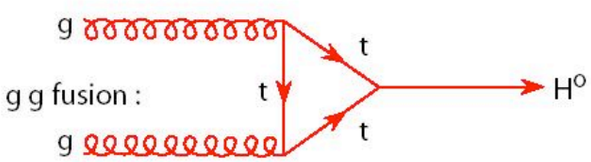
$\mu_{\gamma\gamma}$ is measured high

μ_{WW} is at SM expectation

Couplings

Working Assumptions of LO tree level motivated framework:

- single narrow resonance with a mass near 125.5 GeV
- zero-width approximation - $\sigma \times BR(ii \to \mathrm{H} \to ff) = \dfrac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$,
- only modifications to couplings strength is considered
  - assume tensor structure of a CP-even scalar (SM)



Production modes

$$\frac{\sigma_{\mathrm{ggF}}}{\sigma_{\mathrm{ggF}}^{\mathrm{SM}}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_W^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_Z^2$$

$$\frac{\sigma_{\mathrm{ttH}}}{\sigma_{\mathrm{ttH}}^{\mathrm{SM}}} = \kappa_t^2$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

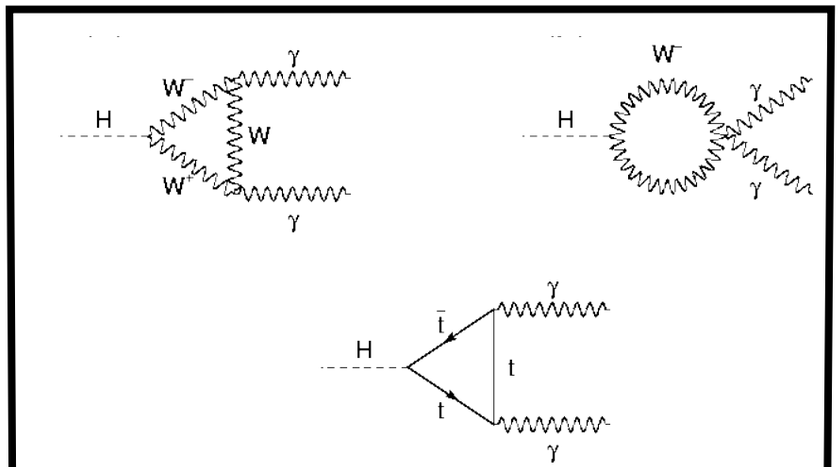
Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}}}{\Gamma_{\mathrm{WW}}^{\mathrm{SM}}} = \kappa_W^2$$

$$\frac{\Gamma_{\mathrm{ZZ}}}{\Gamma_{\mathrm{ZZ}}^{\mathrm{SM}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{\mathrm{SM}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau\tau}}{\Gamma_{\tau\tau}^{\mathrm{SM}}} = \kappa_\tau^2$$



$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

An example: $\sigma \cdot \mathrm{BR}\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \dfrac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$

1. Fermion versus Vector Couplings

Currently bb and ττ modes are compatible with both Higgs boson signal and SM background hypothesis at 95%CL

Free Parameters
$\kappa_F (= \kappa_t = \kappa_b = \kappa_\tau = \kappa_g)$
$\kappa_V (= \kappa_W = \kappa_Z)$

Test ***Fermion vs Vector*** couplings under various assumptions

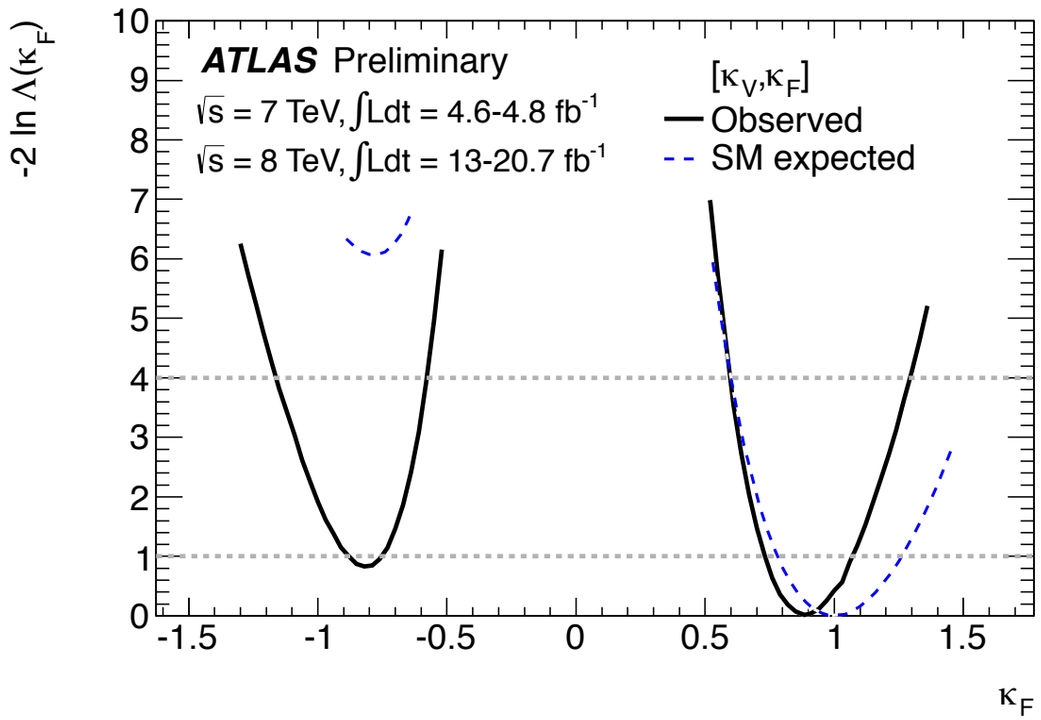
Simplest - assume only SM particles & total Width

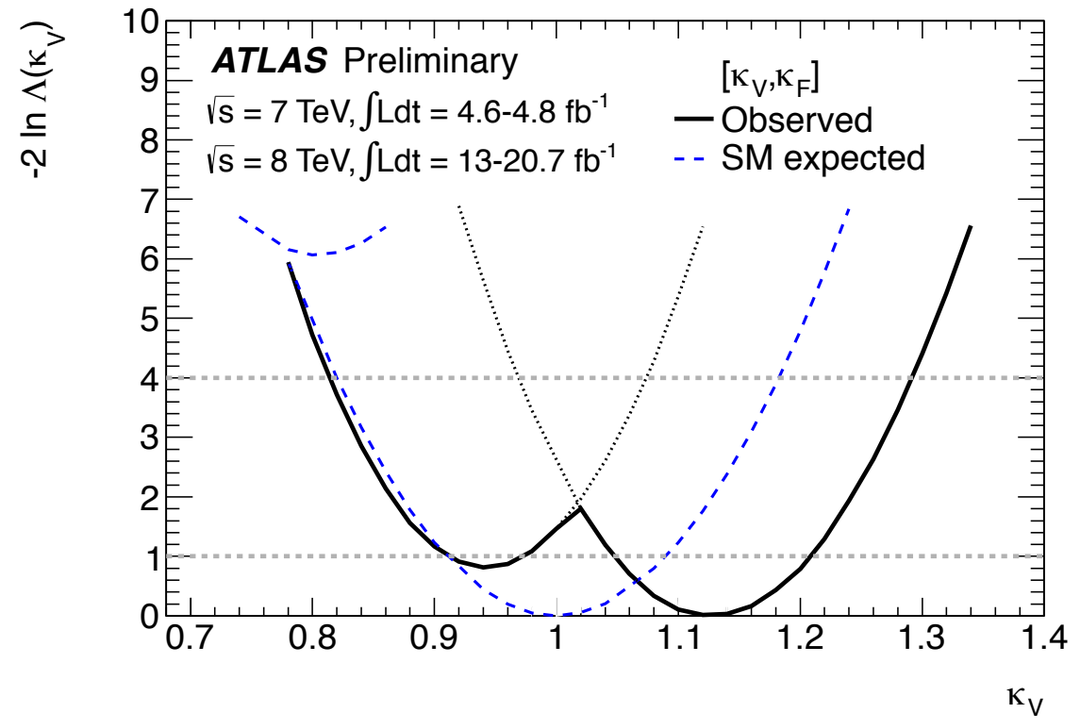
Then - release total width assumption

Finally - release H→γγ loop content assumption

Fermion versus Vector Couplings

Assume ***only SM particles*** enter total width and $\gamma\gamma$ decay loop





Example→ $\sigma(gg \to H) \cdot \mathcal{B}(H \to VV^{(*)}) \sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$

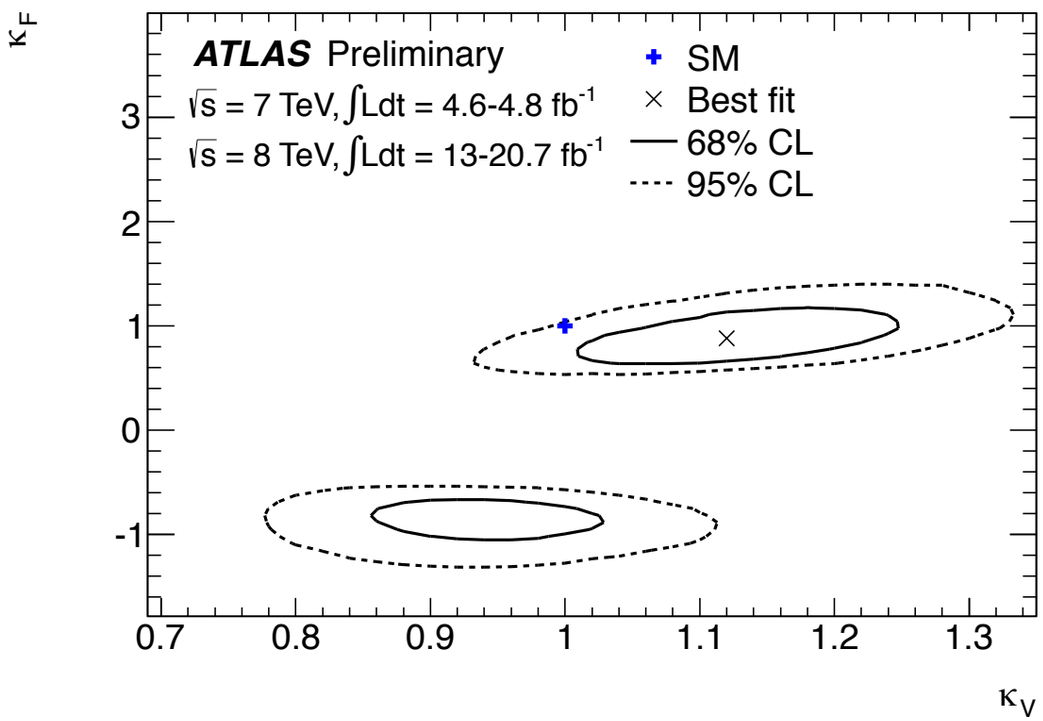
68% CL:

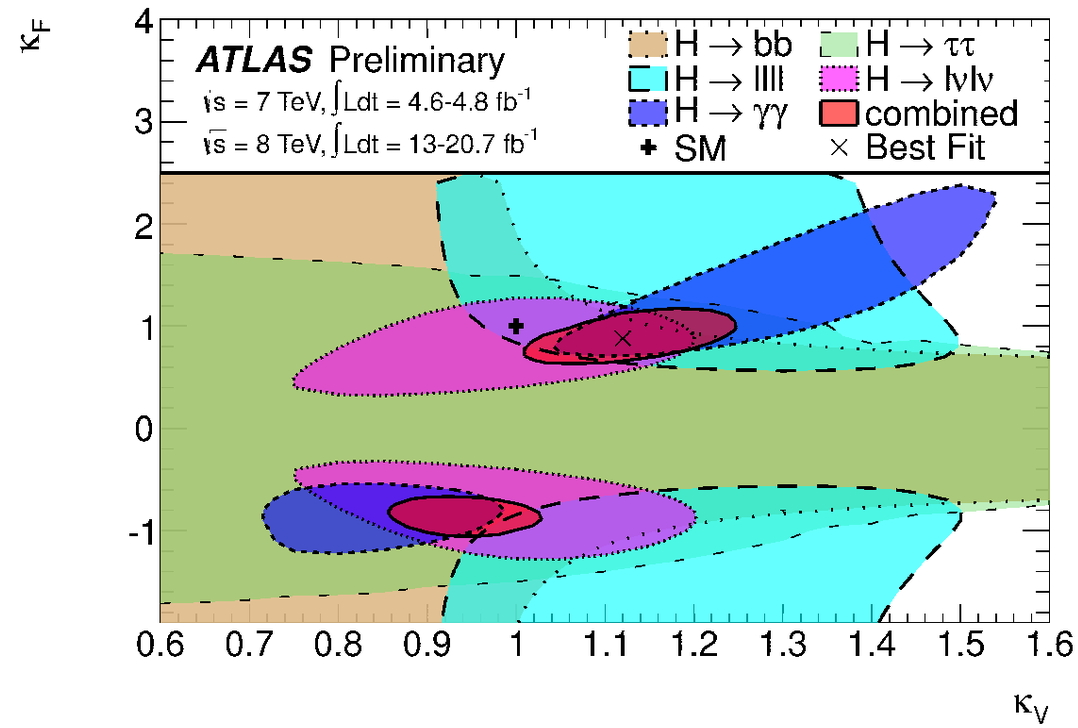
$K_F \in [-0.88,-0.75] \cup [0.73,1.07]$ - **incompatible with zero!**

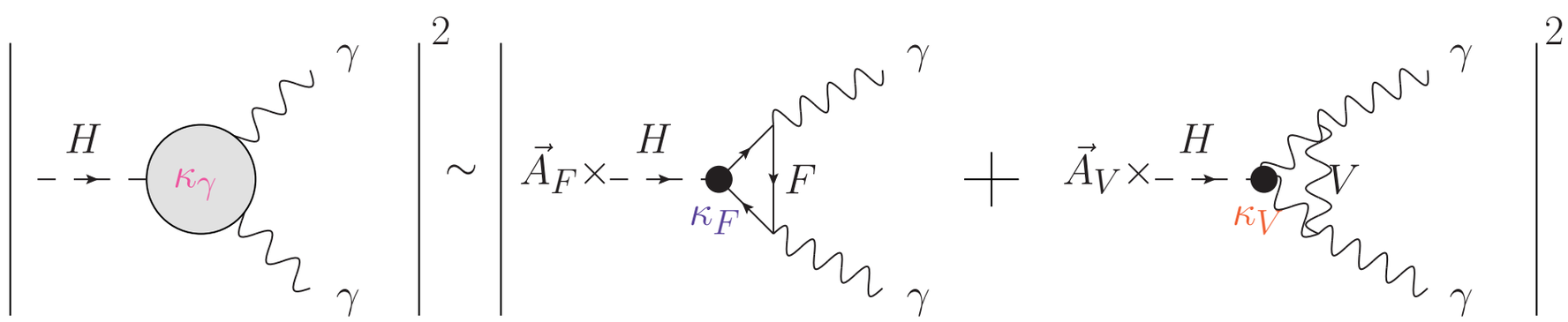
$K_V \in [0.91,0.97] \cup [1.05,1.21]$

Interference

Assume ***only SM particles*** enter total width and γγ decay loop





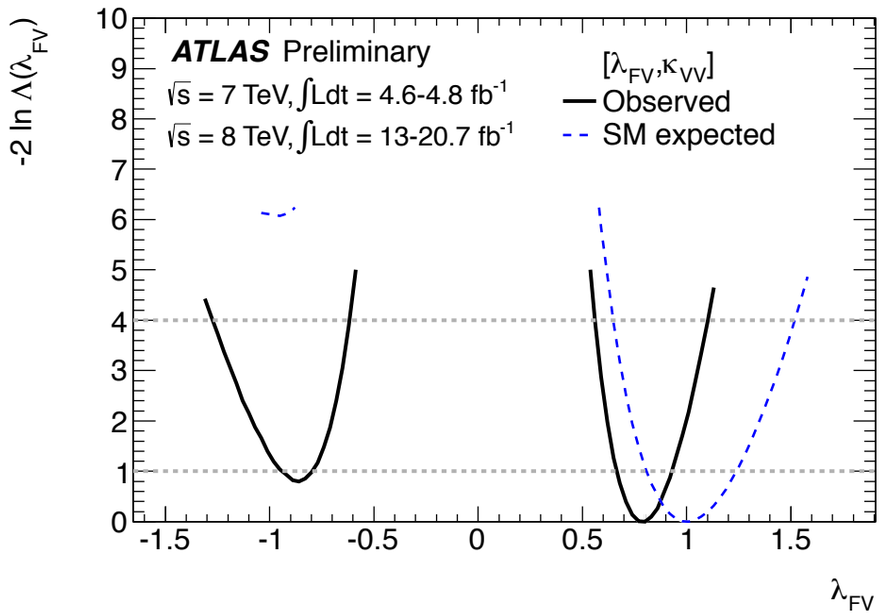


$$\kappa_\gamma^2 \sim 0.07\,\kappa_F^2 - 0.66\,\kappa_F\kappa_V + 1.59\,\kappa_V^2$$

V/F interference in γγ decay loop - sensitivity to relative sign

Relaxing Assumptions

Previous model assumed $K_H^2 = 0.75\ K_F^2 + 0.25\ K_V^2$



Free Parameters

$$\lambda_{FV} = \frac{\kappa_F}{\kappa_V}$$

$$\kappa_{VV} = \frac{\kappa_V^2}{\kappa_H}$$

$\lambda_{FV} \in [-0.94,-0.80] \cup [0.67,0.93]$ (68% C.L.)

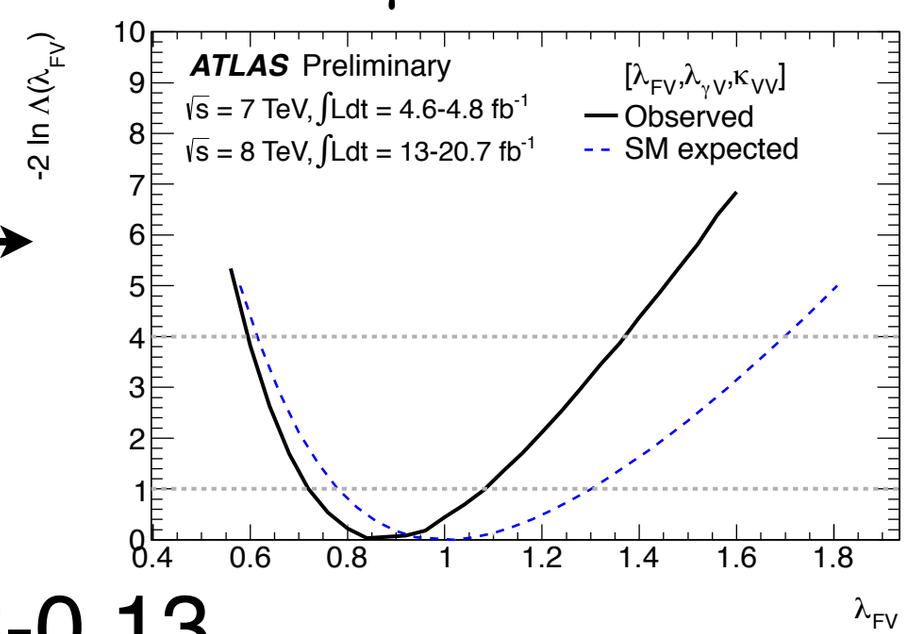
Relax *assumption of contributions* to K_γ

Free Parameters

$$\lambda_{FV} = \frac{\kappa_F}{\kappa_V}$$

$$\kappa_{VV} = \frac{\kappa_V^2}{\kappa_H}$$

$$\kappa_{\gamma V} = \frac{\kappa_\gamma}{\kappa_V}$$



$\lambda_{FV} = 0.85^{+0.23}_{-0.13}$

2. Custodial Symmetry

Free Parameters

$$\boxed{\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}}$$

$$\kappa_{ZZ} = \frac{\kappa_Z^2}{\kappa_H}$$

$$\lambda_{FZ} = \frac{\kappa_F}{\kappa_Z}$$

Custodial Symmetry : Identical coupling for W and Z

Has strong theoretical and experimental bounds

Can now be vetted in the Higgs sector!

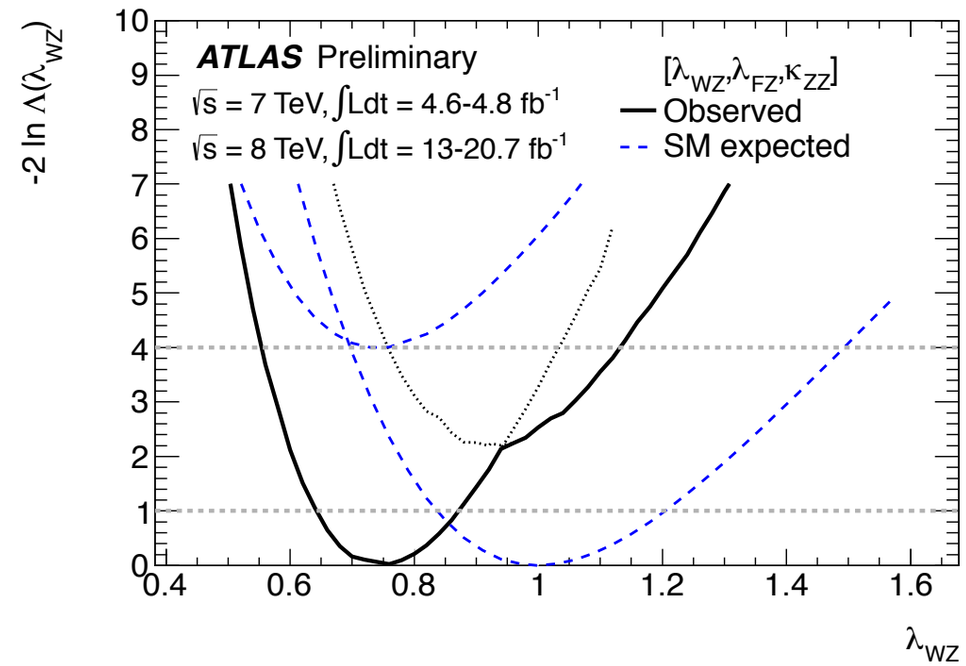
(No assumption on total width)

Custodial Symmetry

Previously assumed $K_H^2 = 0.75\ K_F^2 + 0.25\ K_V^2$

Assume only SM particles enter $\gamma\gamma$ loop

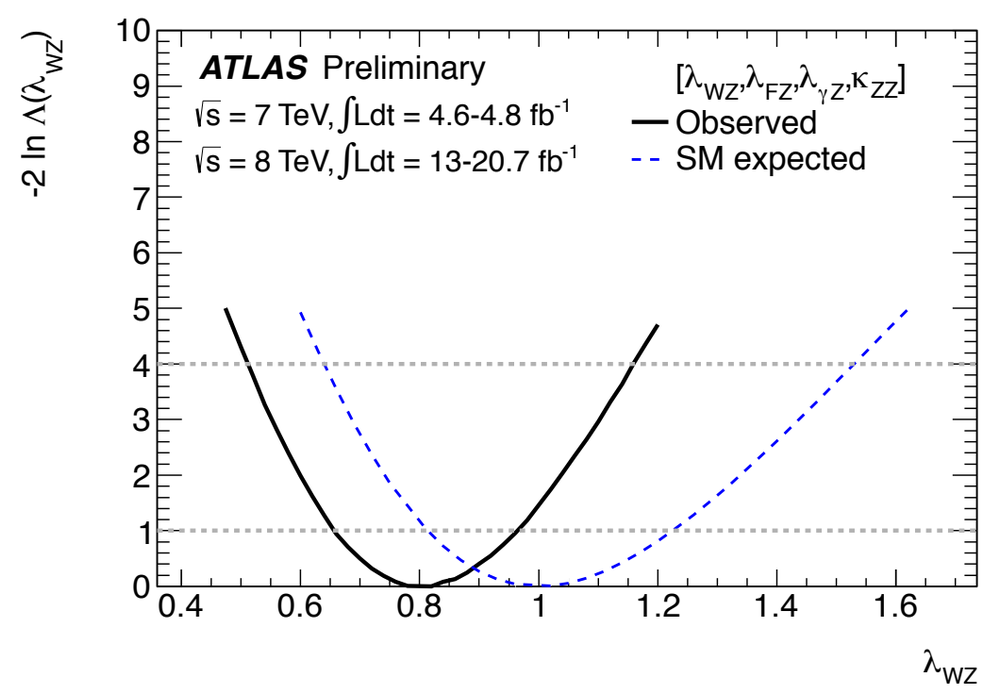
$\lambda_{WZ} \in [0.64, 0.87]$



No assumptions on $\gamma\gamma$ loop content

include $\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$

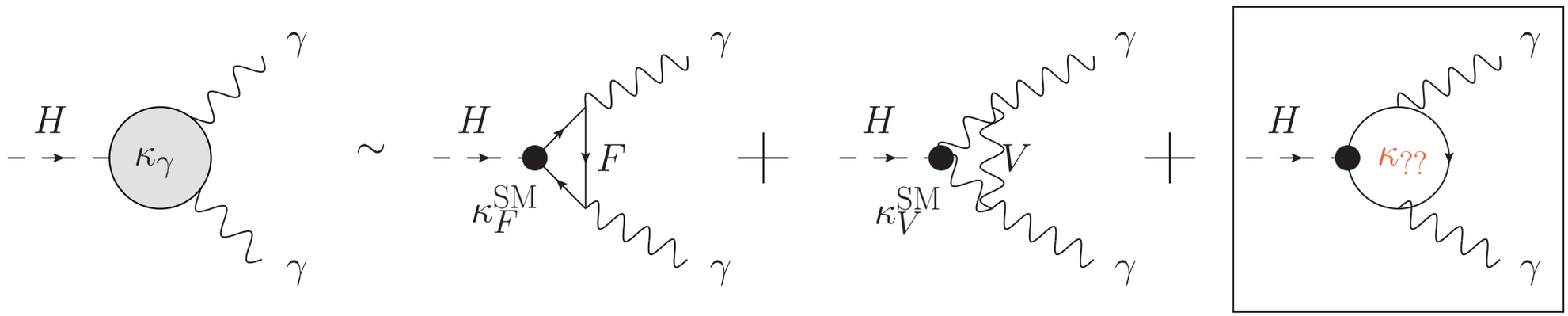
$\lambda_{WZ} = 0.80 \pm 0.15$



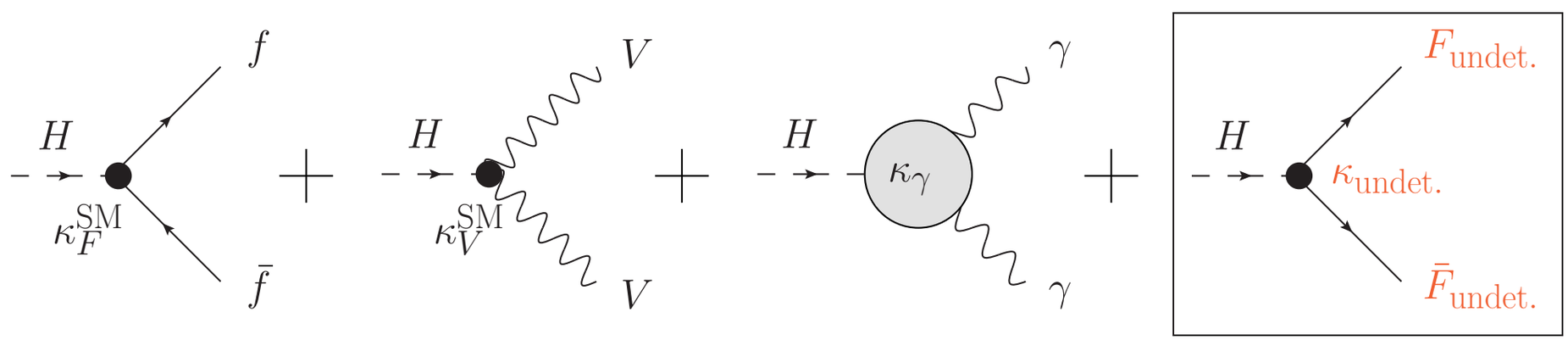
3. Probing Non-SM Loop Contributions

Fix all non-loop K_i to SM value of 1

Directly measure effective couplings-test non-SM contributions



$K_g = 1.08 \pm 0.14$ $K\gamma = 1.23 + 0.16 - 0.13$

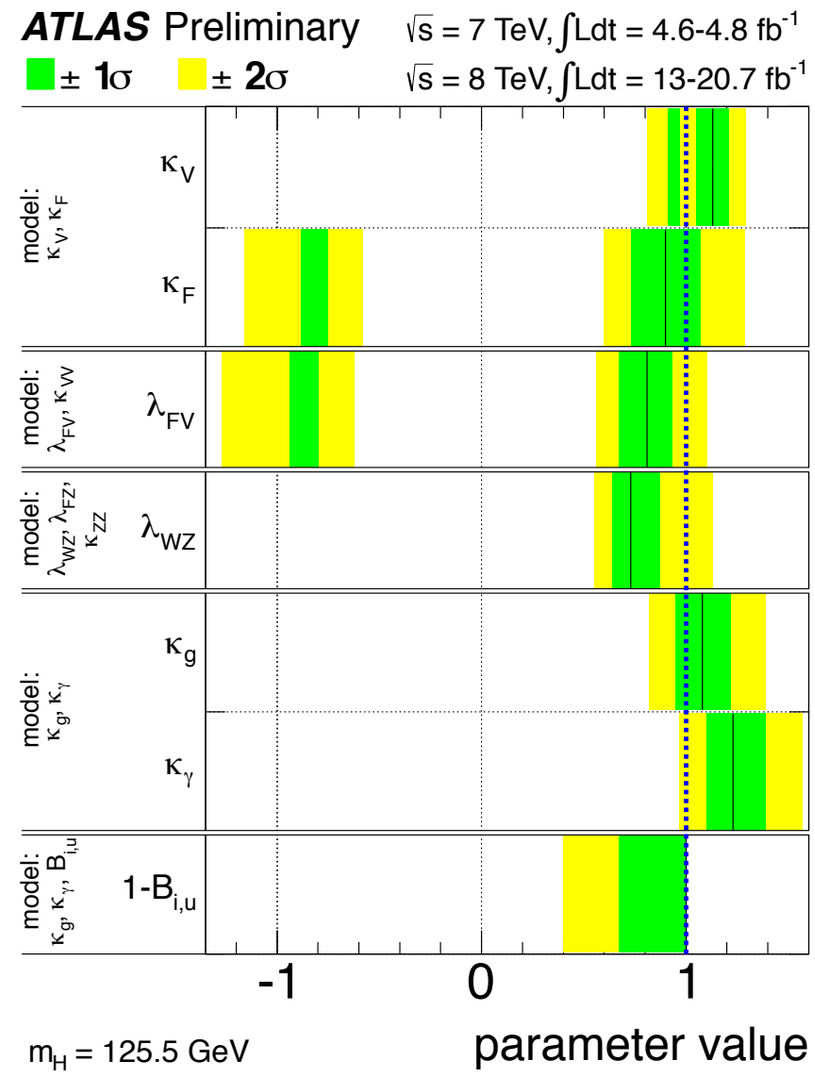


$BR_{invis/undet} < 0.33$ @ 68% CL

Summary

Global	Production	Decay
$\hat{m}_H = 125.5^{+0.5}_{-0.6}$ GeV	$Z_{VBF+VH} = 3.3$ (2.7 exp)	$\rho^{\gamma\gamma}_{ZZ} = 1.1^{+0.4}_{-0.3}$
$\hat{\mu} = 1.3 \pm 0.2$	$Z_{VBF} = 3.1$ (2.5 exp)	$\rho^{\gamma\gamma}_{WW} = 1.7^{+0.7}_{-0.5}$
$Z = X$ (Y exp)		$\rho^{WW}_{ZZ} = 1.6^{+0.8}_{-0.5}$

Couplings		
Vector/Fermion	SM Particles	$\kappa_V \in [-0.88, -0.75] \cup [0.73, 1.07]$
		$\kappa_F \in [0.91, 0.97] \cup [1.05, 1.21]$
	+Free Γ_H	$\lambda_{VF} \in [-0.94, -0.8] \cup [0.67, 0.93]$
	+Free $\Gamma_{\gamma\gamma}$	$\lambda_{VF} = 0.85^{+0.23}_{-0.13}$
Custodial Sym	Free Γ_H	$\lambda_{WZ} \in [0.64, 0.87]$
	+Free $\Gamma_{\gamma\gamma}$	$\lambda_{WZ} = 0.80 \pm 0.15$
Loop Vertices	Non-loop $\kappa_i = 1$	$\kappa_g = 1.08 \pm 0.14$
		$\kappa_\gamma = 1.23^{+0.16}_{-0.13}$
	Inv./Undet. Decays	$\mathrm{BR}^{\mathrm{undet.}}_{\mathrm{inv.}} < 0.33$ (68% CL)



Evidence has stacked up to drop the “like” in Higgs-like

Bonus

Summary Table

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,\mathrm{d}t$ (fb^{-1})
		2011 $\sqrt{s}$ =7 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	4.6
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \mathrm{conversion}\} \oplus$ {2-jet VBF}	4.8
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes$ {0-jet, 1-jet, 2-jet VBF}	4.7
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes$ {0-jet} $\oplus \{\ell\ell\} \otimes$ {1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, VH}	4.6
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes$ {0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet}	4.6
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	{1-jet, 2-jet}	4.6
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes$ {2-jet, 3-jet}	4.6
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7
		2012 $\sqrt{s}$ =8 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu, 2-\mathrm{jet\ VBF}, \ell-\mathrm{tag}\}$	20.7
$H \to \gamma\gamma$	–	14 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \mathrm{conversion}\} \oplus$ {2-jet VBF} $\oplus$ {ℓ-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$-tag, 2-jet VH}	20.7
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes$ {0-jet, 1-jet, 2-jet VBF}	20.7
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes$ {1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, VH}	13
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes$ {0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet}	13
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	{1-jet, 2-jet}	13
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes$ {2-jet, 3-jet}	13
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13

12 minutes - no time for details!

Combined VBF vs ggF measurement

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}}$$

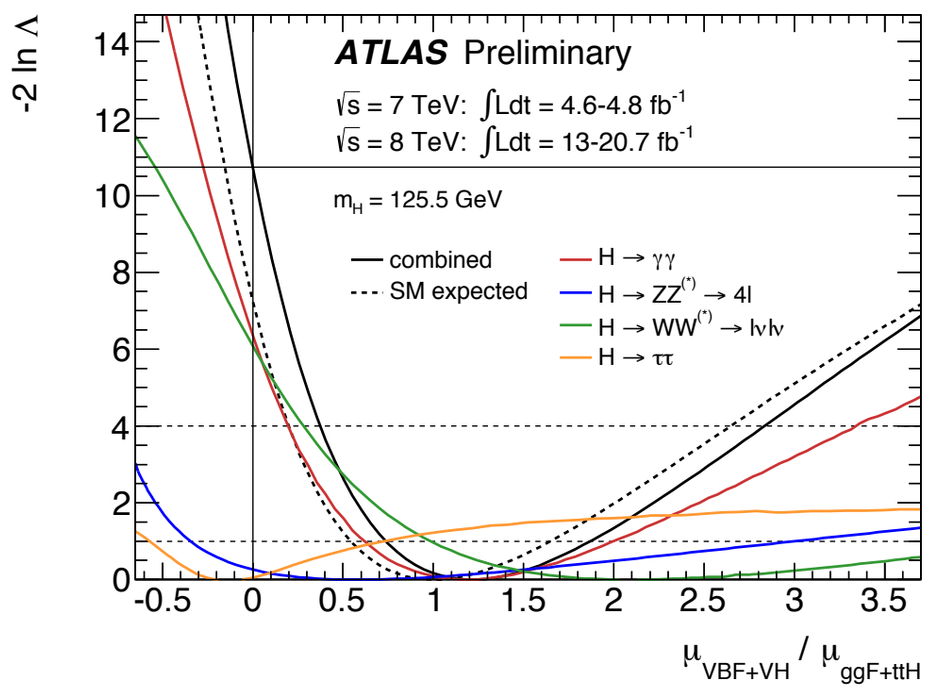
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$$

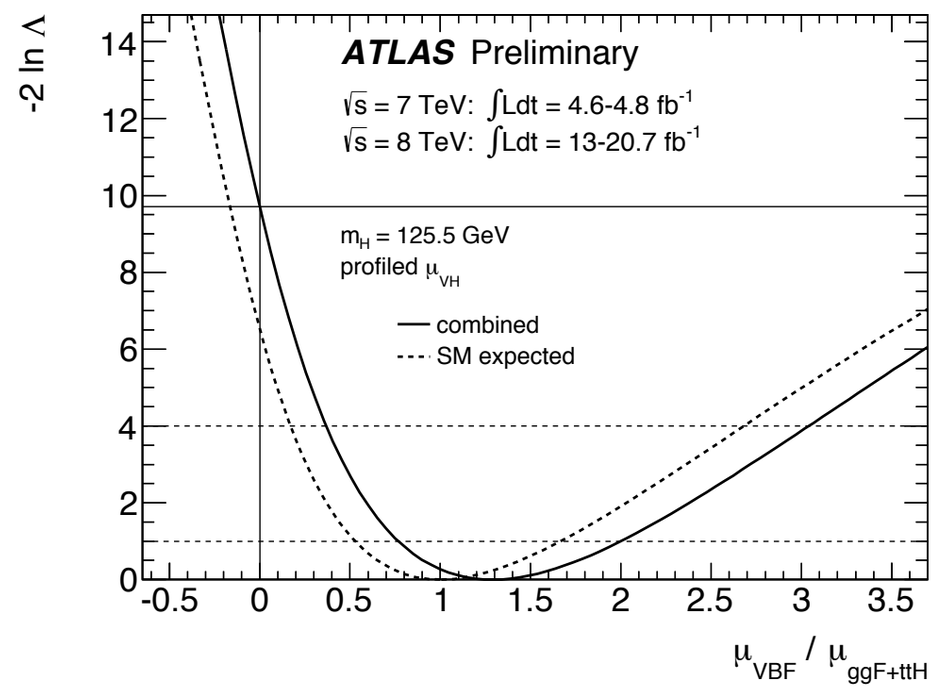
$$\sigma(gg \to H) * \mathrm{BR}(H \to WW^{(*)}) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to WW^{(*)}) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$$

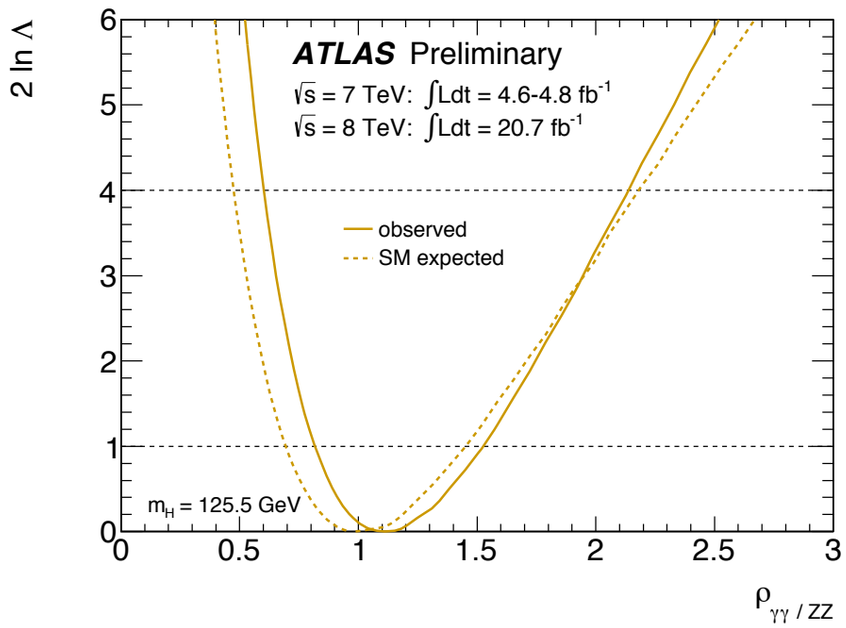
$$\sigma(gg \to H) * \mathrm{BR}(H \to \tau\tau) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \tau\tau) \sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}$$

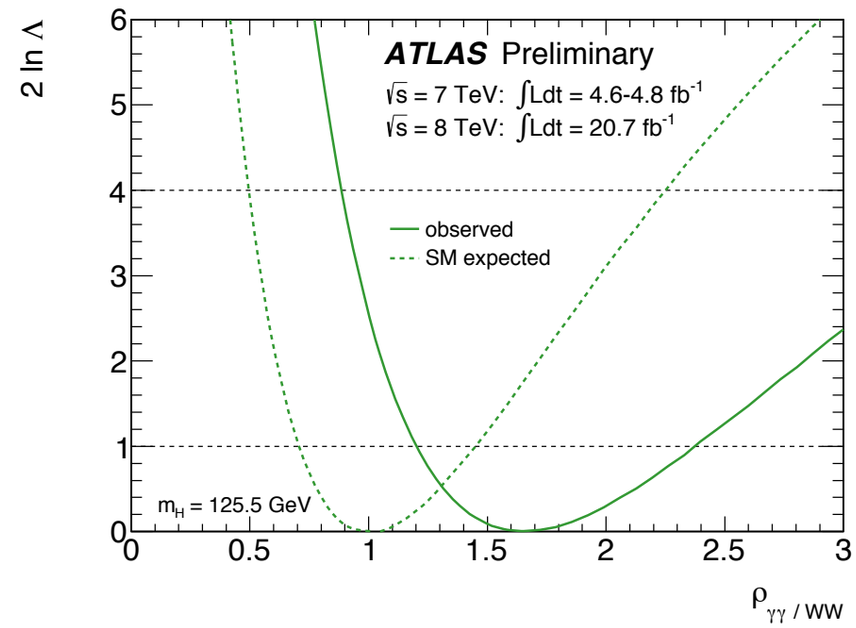




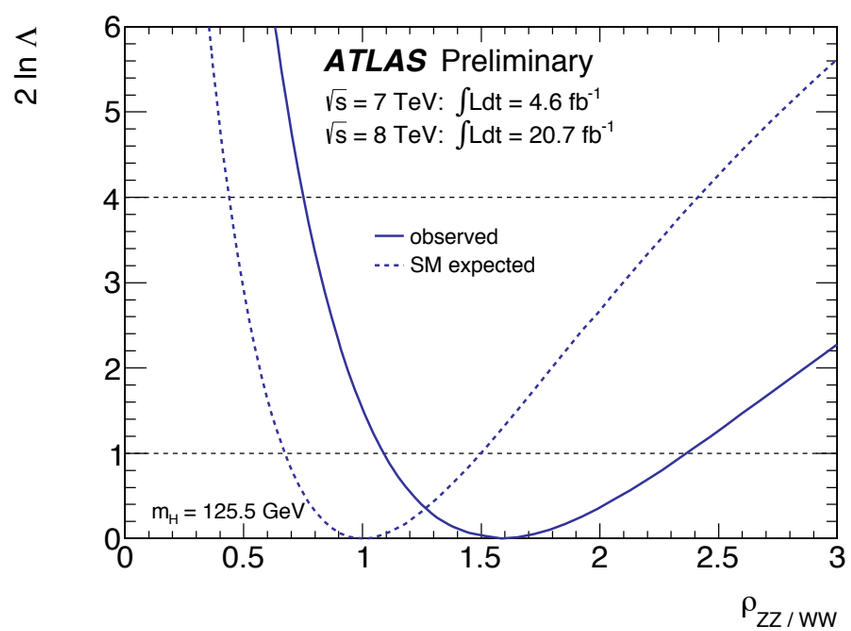
Ratio of Branching Ratios



(a)



(b)



$$\rho_{\gamma\gamma/ZZ} = \frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to ZZ^{(*)})} \times \frac{\mathrm{BR}_{\mathrm{SM}}(H\to ZZ^{(*)})}{\mathrm{BR}_{\mathrm{SM}}(H\to\gamma\gamma)}$$

Fermion and Vector Couplings

Only SM particles

$$\kappa_F (= \kappa_t = \kappa_b = \kappa_\tau = \kappa_g)$$

$$\kappa_V (= \kappa_W = \kappa_Z)$$

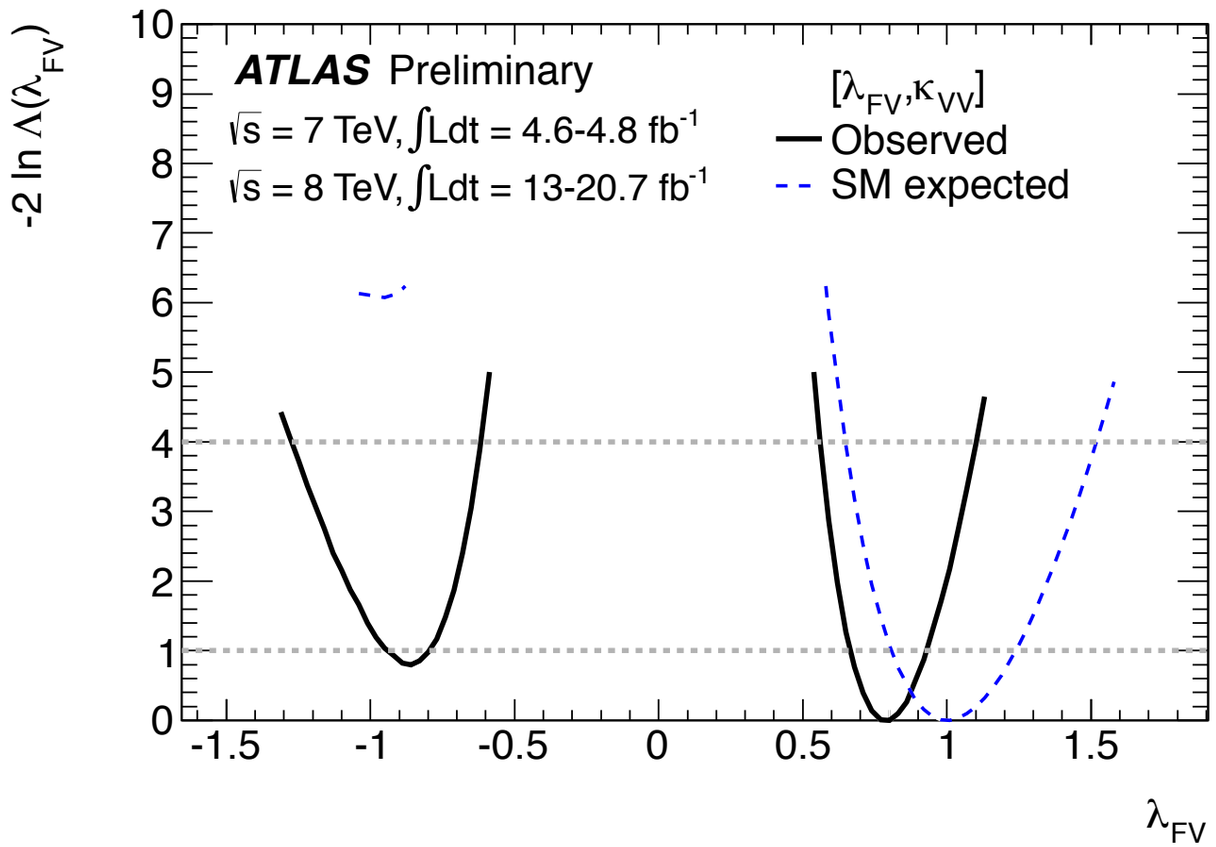
$$\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2} \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \frac{\kappa_V^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2} \\
\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) &\sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2} \quad ,
\end{aligned}$$

Fermion and Vector Couplings

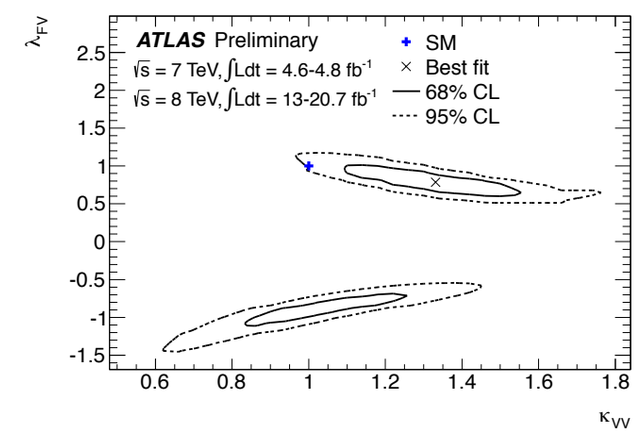
No Total Width Assumption

$$\lambda_{FV} = \kappa_F/\kappa_V$$
$$\kappa_{VV} = \kappa_V \cdot \kappa_V/\kappa_H \quad .$$

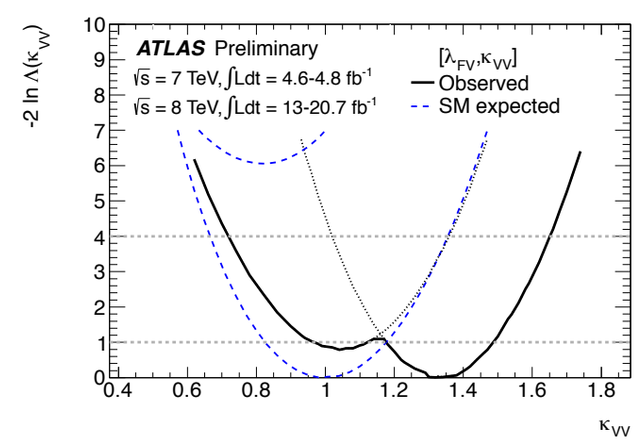
$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \lambda_{FV}^2 \cdot \kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, 1)$$
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, 1)$$
$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \lambda_{FV}^2 \cdot \kappa_{VV}^2$$
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \kappa_{VV}^2$$
$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \kappa_{VV}^2 \cdot \lambda_{FV}^2 \quad ,$$



(a)



(b)



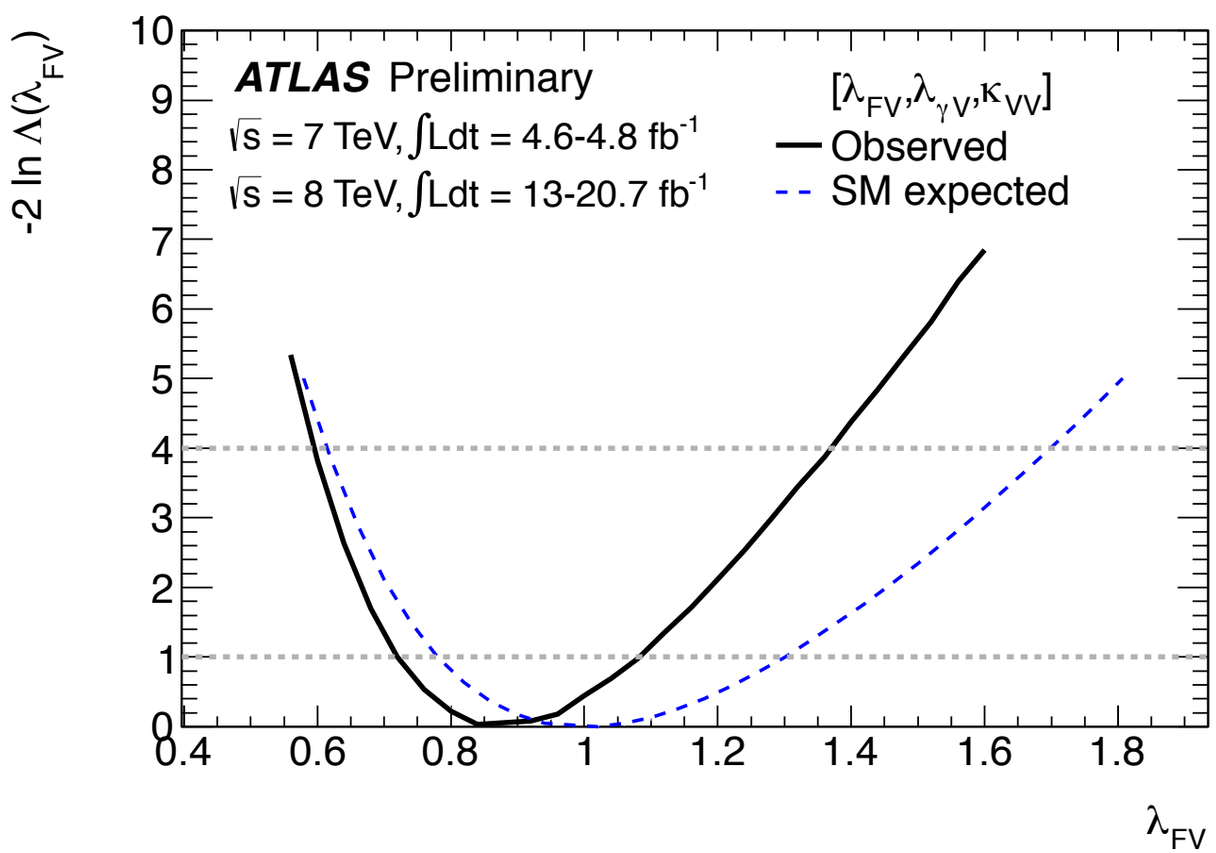
(c)

Fermion and Vector Couplings

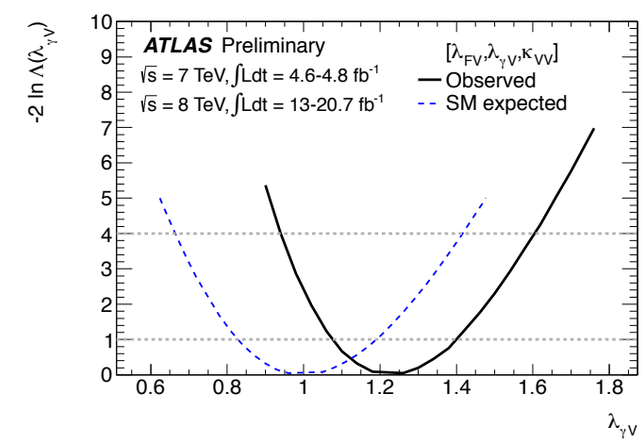
No Total Width Assumption && $\gamma\gamma$ loop content

$$\lambda_{FV} = \kappa_F/\kappa_V$$
$$\lambda_{\gamma V} = \kappa_\gamma/\kappa_V$$
$$\kappa_{VV} = \kappa_V \cdot \kappa_V/\kappa_H$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \lambda_{FV}^2 \cdot \kappa_{VV}^2 \cdot \lambda_{\gamma V}^2$$
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \kappa_{VV}^2 \cdot \lambda_{\gamma V}^2$$
$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \lambda_{FV}^2 \cdot \kappa_{VV}^2$$
$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \kappa_{VV}^2$$
$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \kappa_{VV}^2 \cdot \lambda_{FV}^2 \quad .$$



(a)



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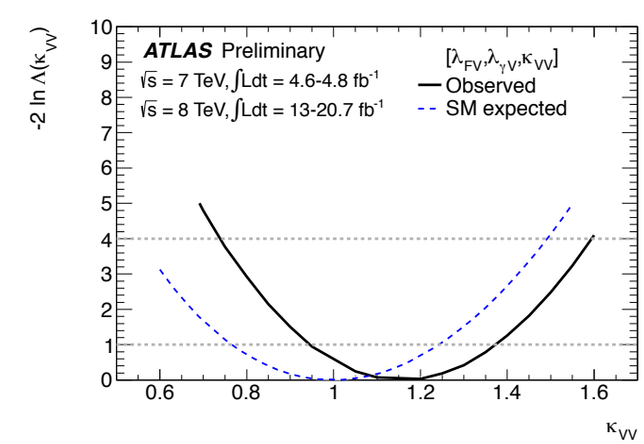


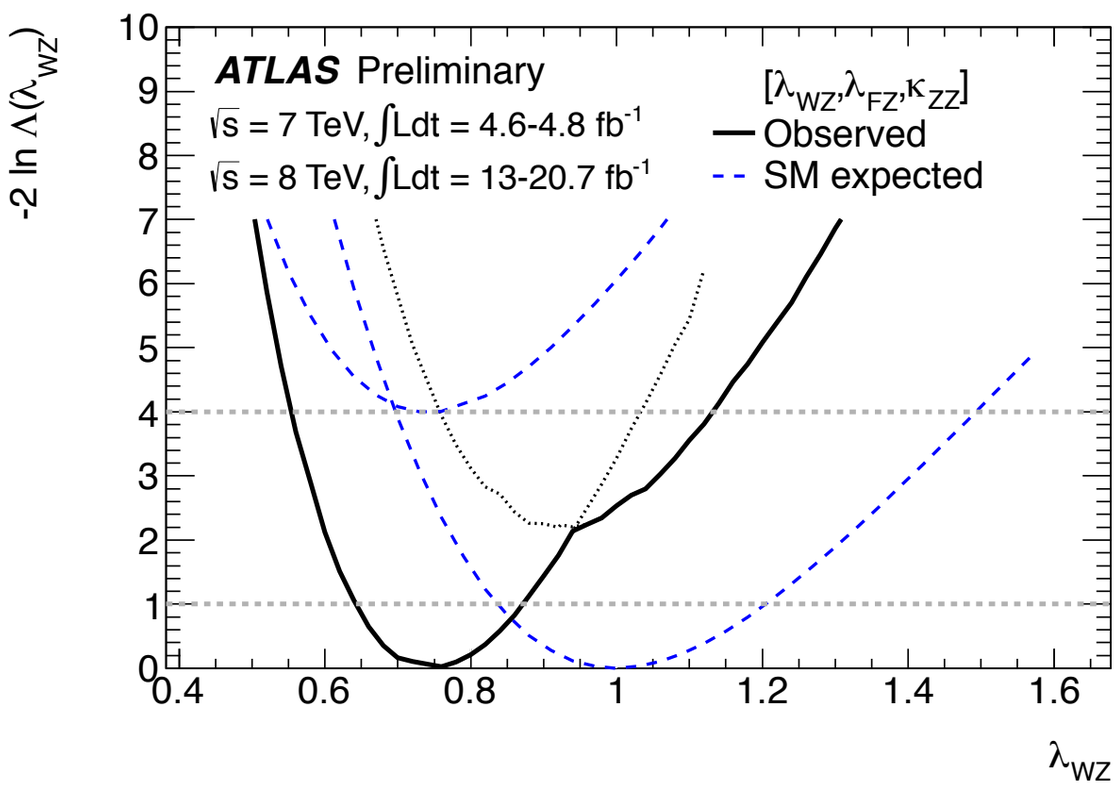
(c)

Custodial Symmetry

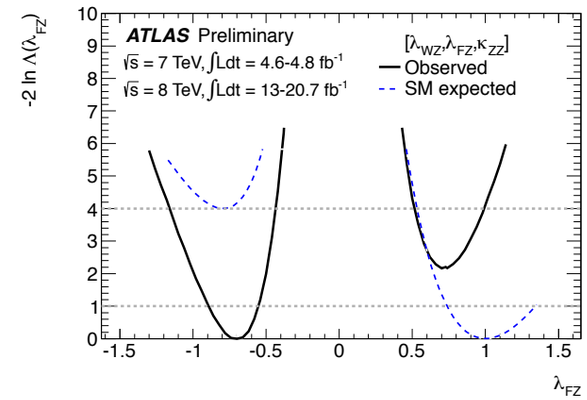
No Total Width Assumption

$$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z / \kappa_H$$
$$\lambda_{WZ} = \kappa_W / \kappa_Z$$
$$\lambda_{FZ} = \kappa_F / \kappa_Z \quad .$$

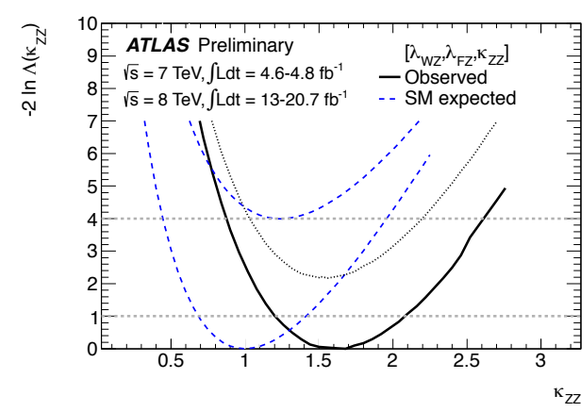
$$\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, 1) \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{\mathrm{WZ}}, 1) \cdot \kappa_{ZZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, 1) \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{\mathrm{WZ}}, 1) \cdot \kappa_{ZZ}^2 \\
\sigma(gg \to H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \cdot \lambda_{\mathrm{WZ}}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{\mathrm{WZ}}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{\mathrm{WZ}}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \tau\tau) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{\mathrm{WZ}}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \quad ,
\end{aligned}$$



(a)



(b)

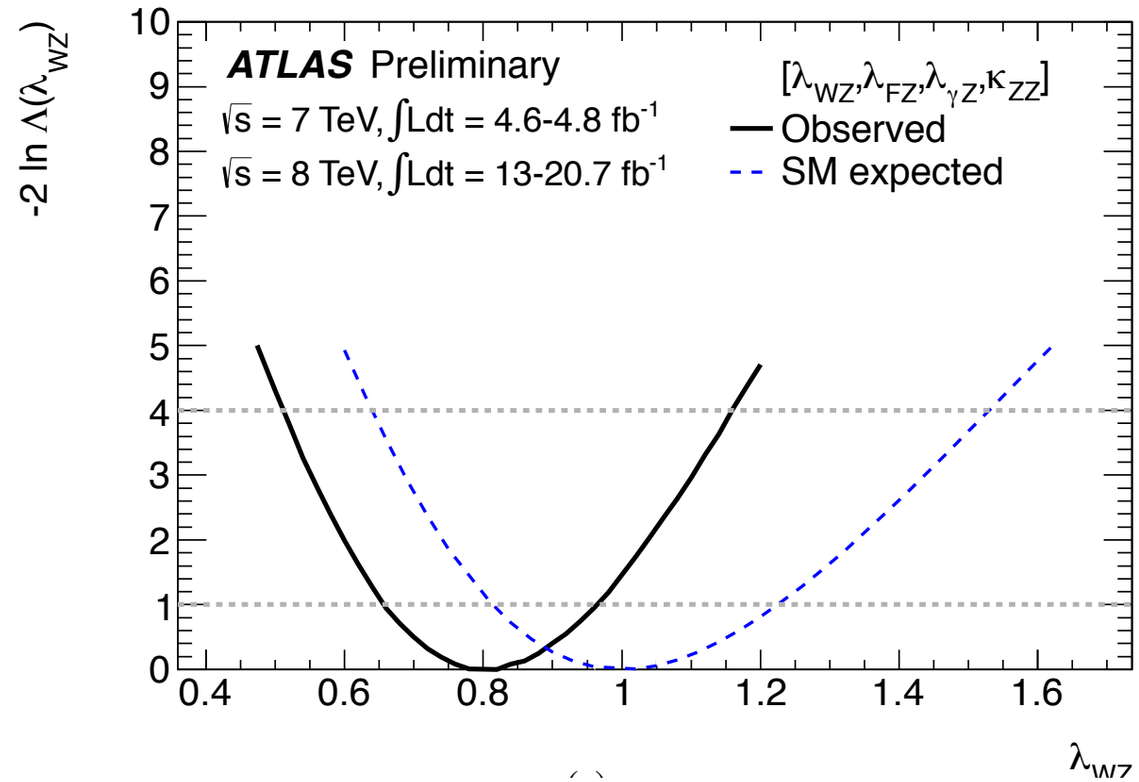


Custodial Symmetry

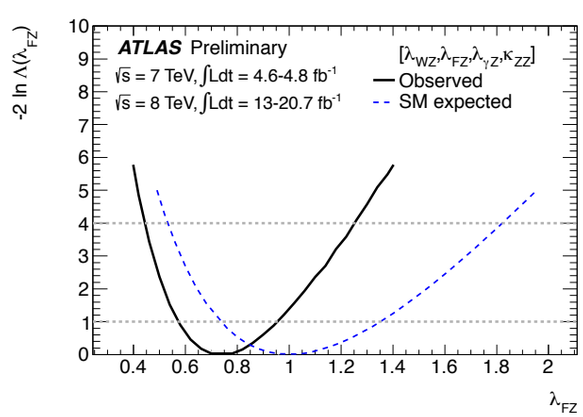
No Total Width Assumption && $\gamma\gamma$ loop content

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

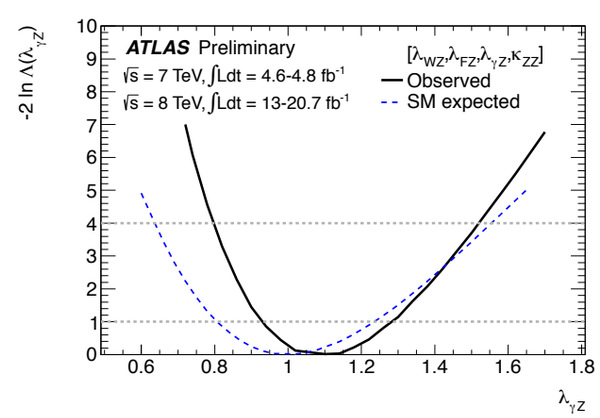
$$\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \cdot \lambda_{\gamma Z}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{\gamma Z}^2 \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \\
\sigma(gg \to H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \lambda_{FZ}^2 \cdot \kappa_{ZZ}^2 \cdot \lambda_{WZ}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{WZ}^2 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \tau\tau) &\sim \kappa_{\mathrm{VBF}}^2(\lambda_{WZ}, 1) \cdot \kappa_{ZZ}^2 \cdot \lambda_{FZ}^2
\end{aligned}$$



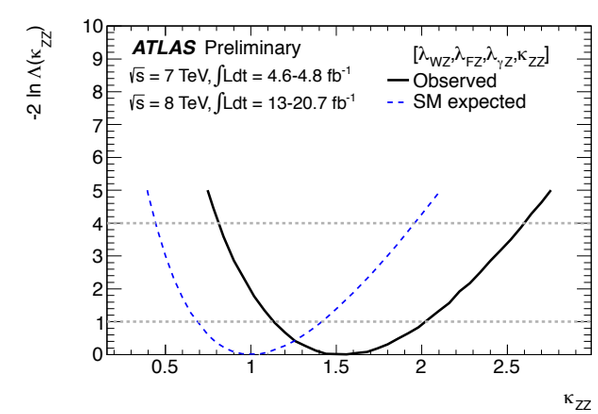
(a)



(b)



(c)

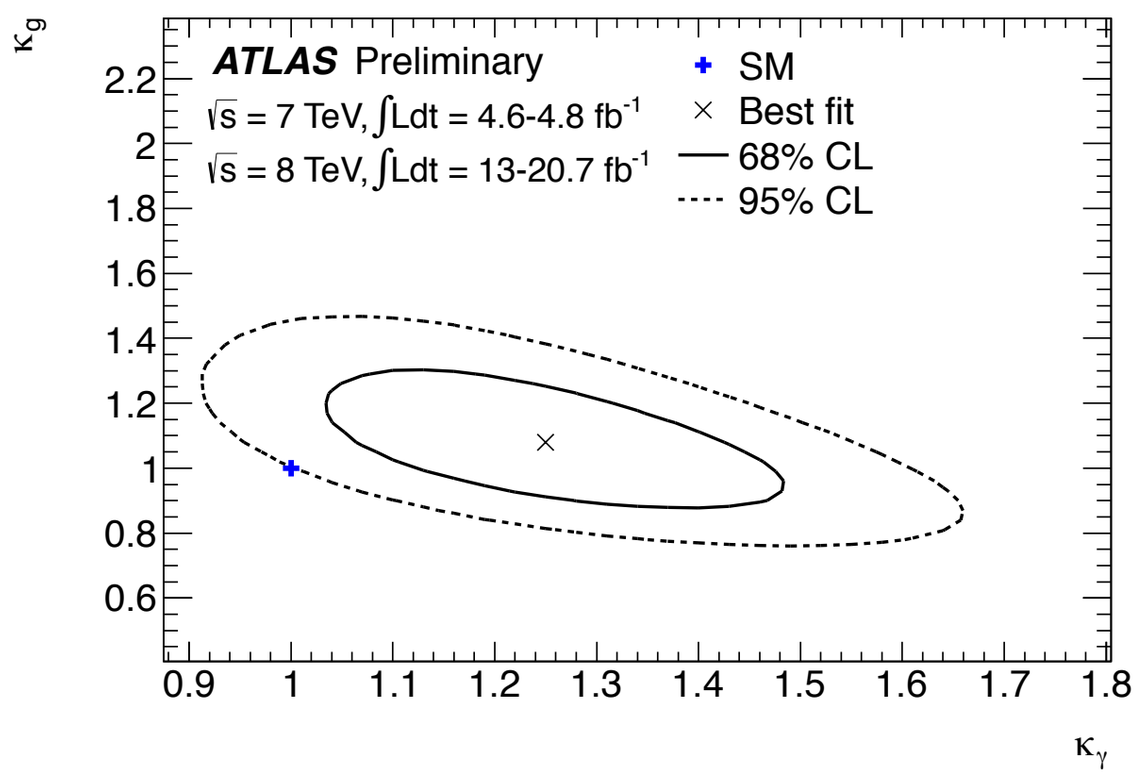


(d)

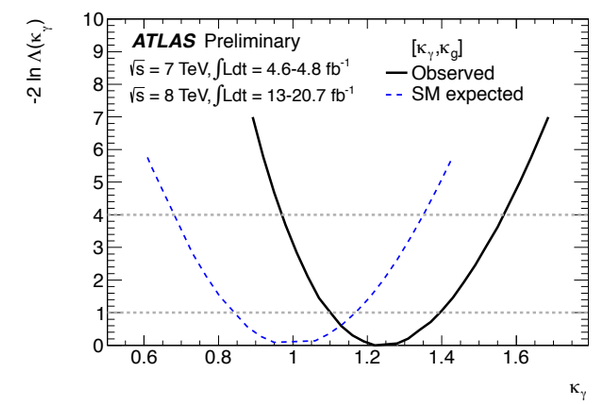
Non-SM contributions

Total Width Fixed

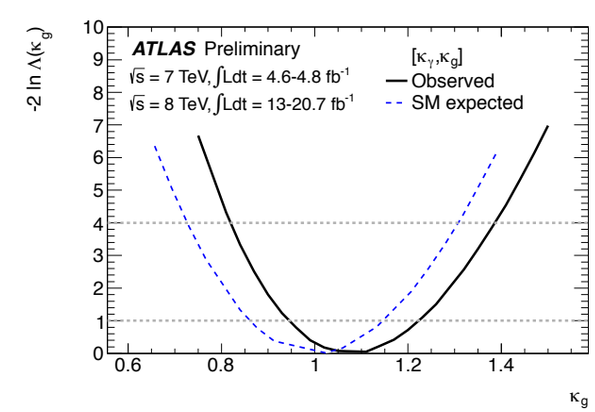
$$
\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \frac{\kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \frac{\kappa_g^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \qquad (4 \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \\
\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) &\sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \quad .
\end{aligned}
$$



(a)



(b)



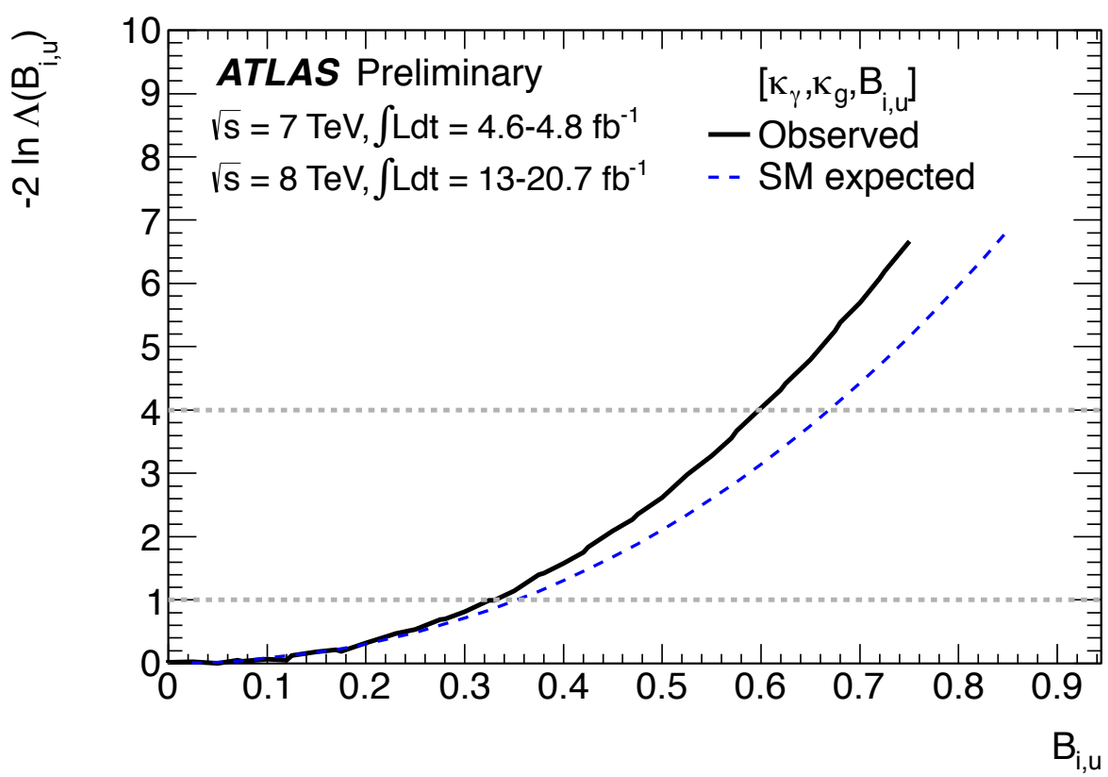
(c)

Non-SM contributions

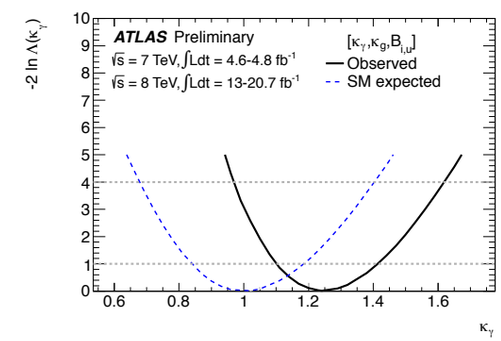
Total Width Free

$$
\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}}) \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \frac{\kappa_\gamma^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}}) \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \frac{\kappa_g^2}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}}) \qquad (48) \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) &\sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}}) \\
\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) &\sim \frac{1}{0.085 \cdot \kappa_g^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.91} \cdot (1 - \mathrm{BR}_{\mathrm{inv.,undet.}}) \quad .
\end{aligned}
$$

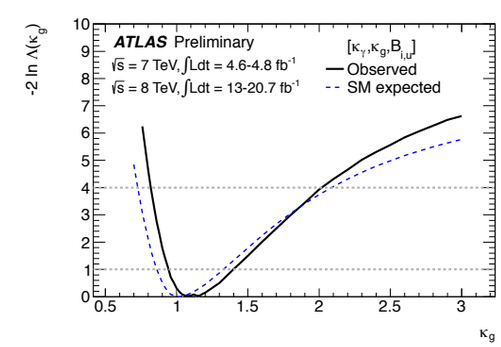
$$
\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - \mathrm{BR}_{\mathrm{inv.,undet.}})} \Gamma_H^{\mathrm{SM}} \quad .
$$

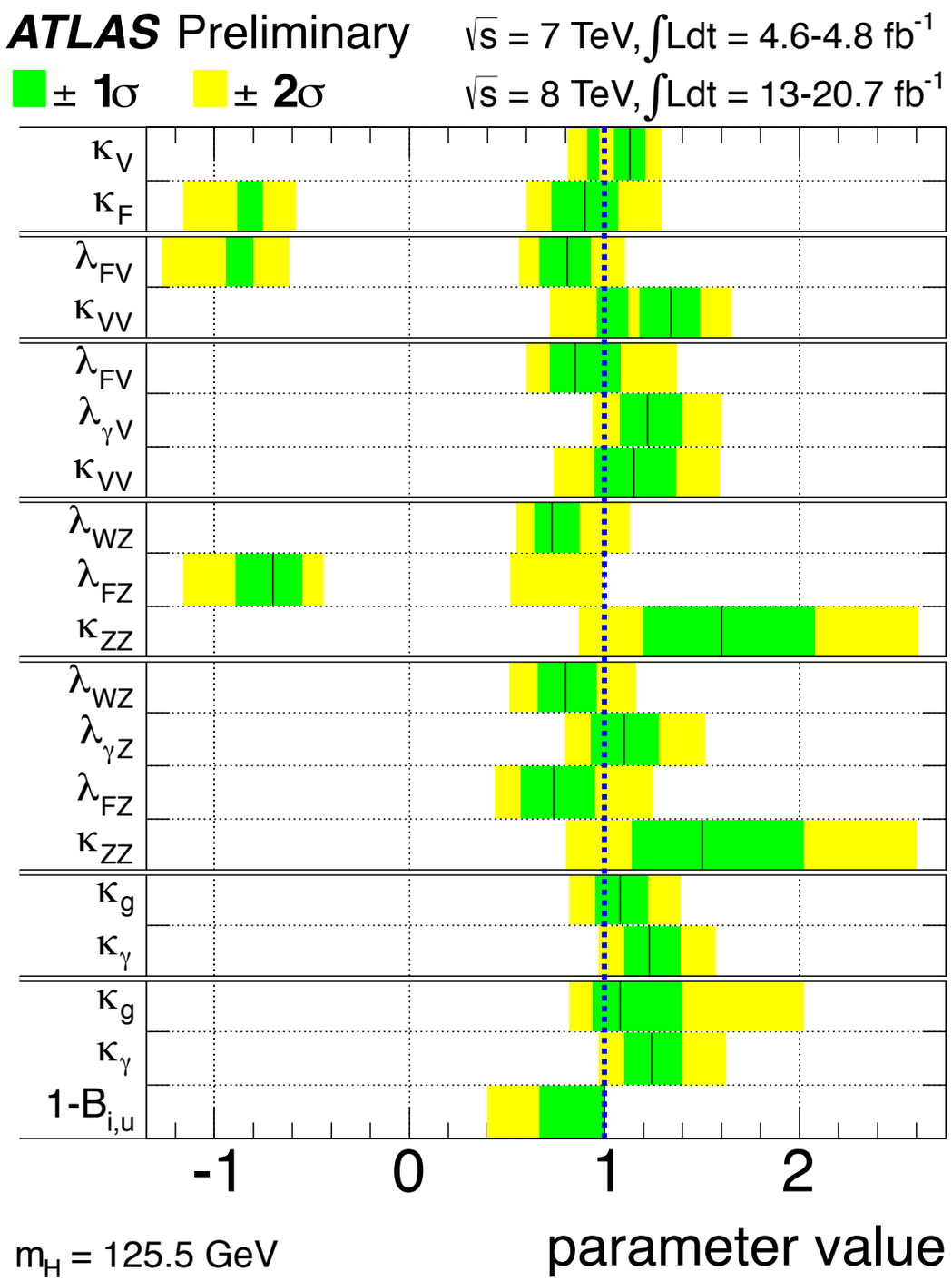


(a)



(b)



(c)

Fully Summary