Science & Technology Facilities Council
Rutherford Appleton Laboratory

Measurements of Higgs Boson Properties in ATLAS

Tim Adye
Rutherford Appleton Laboratory
on behalf of the ATLAS Collaboration

Moriond QCD
14th March 2013

Higgs Boson Properties in ATLAS

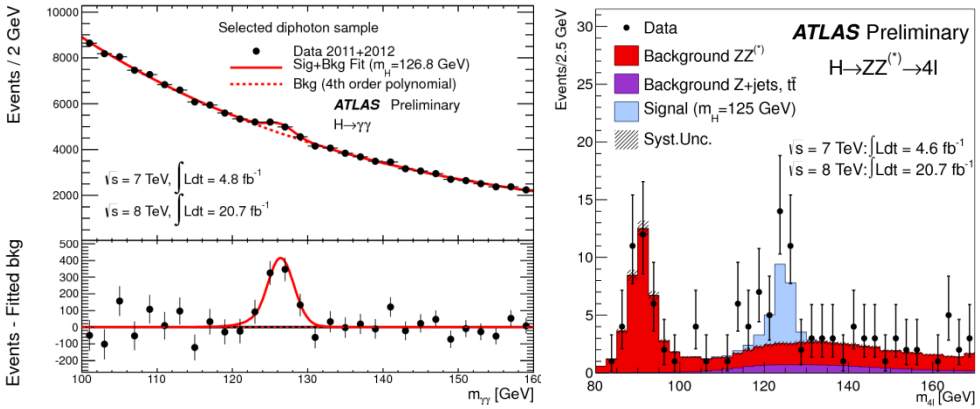
- "Observation of a new particle" in July 2012
- Update in December 2012 with additional luminosity
- Today: updates for the full 2011-2012 dataset in decays to $\gamma\gamma$, ZZ, WW
  - 4.6 fb^{-1} @ 7TeV, 20.7 fb^{-1} @ 8TeV

1. Higgs mass measurement from $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^{(*)}\rightarrow 4l$
2. Signal strength of production and decay
3. Comparison of vector boson fusion (VBF) and gluon fusion (ggF) production modes
4. Comparison of Higgs decay rates
5. Higgs couplings
6. (Higgs spin and parity)

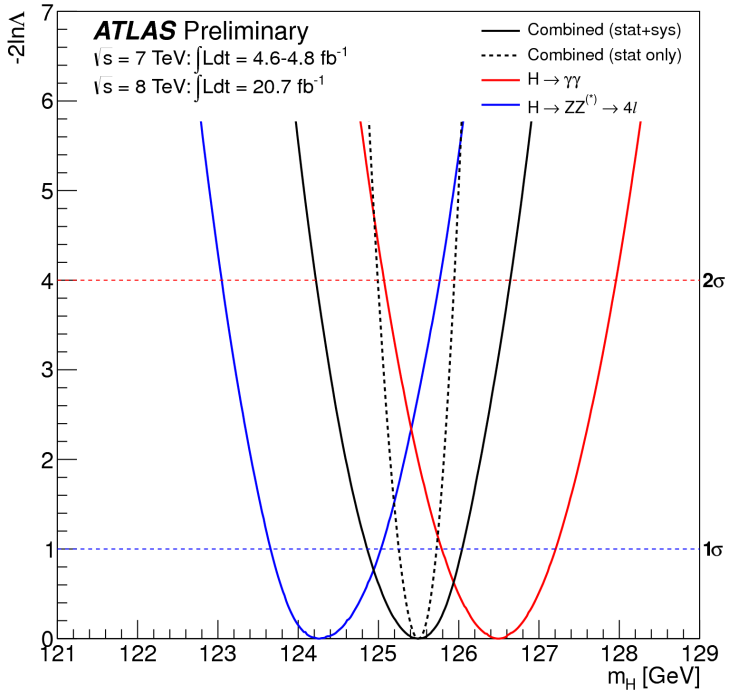
Update last week

Higgs mass

- High resolution mass measurements from $H\to\gamma\gamma$ and $H\to ZZ^{(*)}\to 4l$ spectra



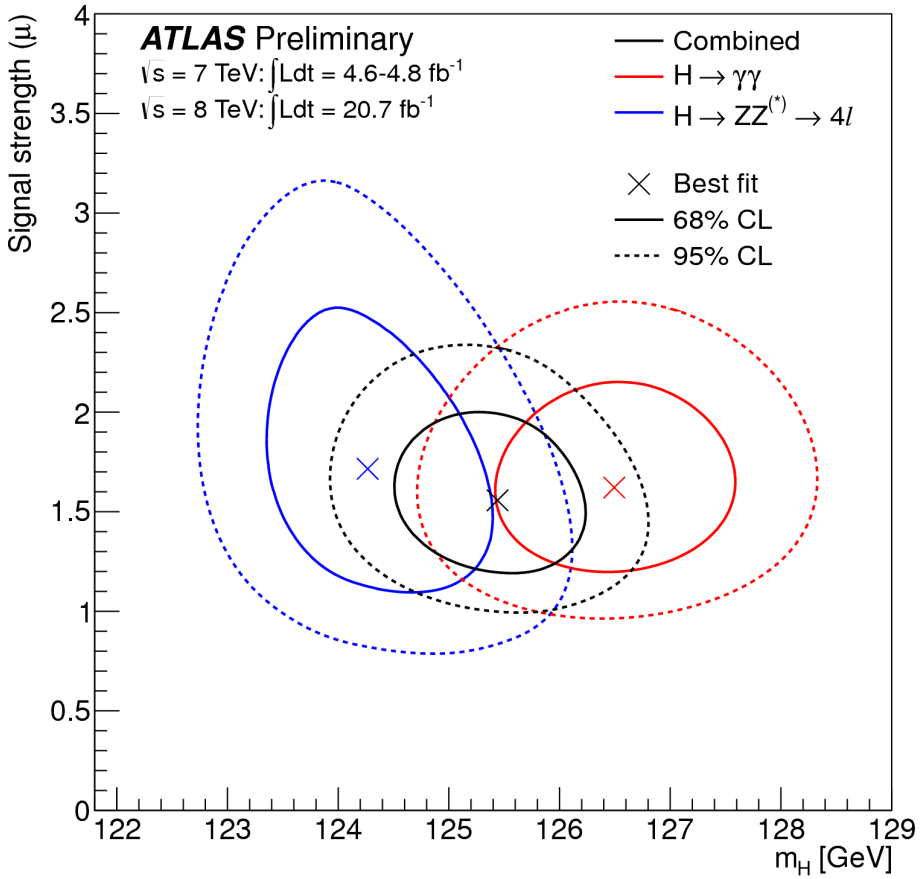
- Combine $\gamma\gamma$ and $4l$ mass measurements
  - Signal strengths, $\mu_{\gamma\gamma}$ and μ_{4l}, allowed to vary independently
    → Don't assume SM couplings
- $m_H = 125.5 \pm 0.2\ (\text{stat})\ ^{+0.5}_{-0.6}\ (\text{sys})$ GeV
  (4.8 fb^{-1} + 20.7 fb^{-1})
- Previous measurement, Dec 2012:
  - $m_H = 125.2 \pm 0.3\ (\text{stat}) \pm 0.6\ (\text{sys})$ GeV
    (4.8 fb^{-1} + 13 fb^{-1})



- Use profile likelihood ratio
  $\Lambda(m_H) = \frac{L(m_H,\hat{\hat{\theta}}(m_H))}{L(\hat{m}_H,\hat{\theta})}$ to quantify m_H confidence intervals with nuisance parameters, θ ($\mu_{\gamma\gamma}$, μ_{4l}, theory, experimental systematics)
- Asymptotically, -2lnΛ distributed as a χ^2

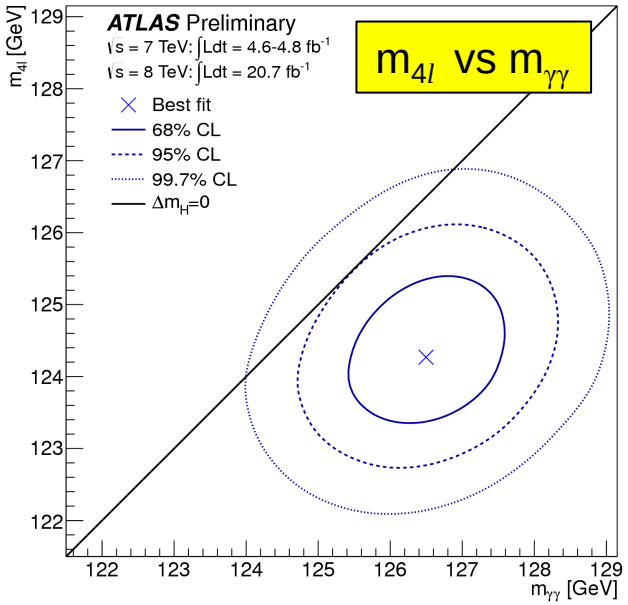
Signal strength vs mass for $\gamma\gamma$ and ZZ

- Signal strength $\mu = \sigma/\sigma_{SM}$ vs m_H contours for $\gamma\gamma$ and ZZ and their combination

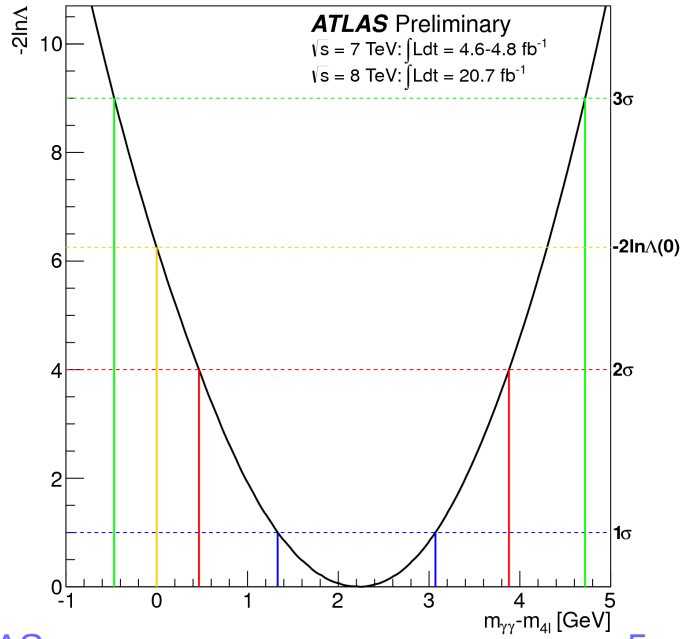


Comparison of masses from $H\to\gamma\gamma$ and $H\to ZZ^{(*)}\to 4l$

- The individual mass measurements, $m_{\gamma\gamma}$ and m_{4l}, are slightly correlated due to the common EM scale systematic (for photons in $m_{\gamma\gamma}$ and electrons in m_{4l})
  - Pulls $m_{\gamma\gamma}$ down by 350 MeV in combined fit

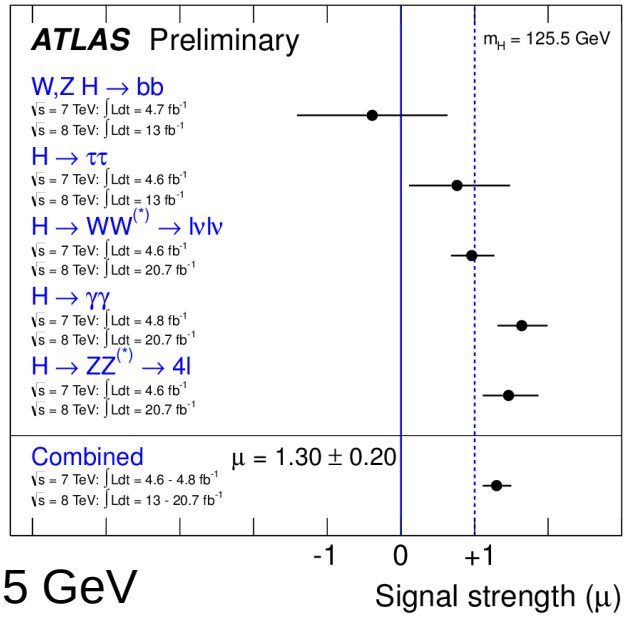


- Test assumption that both decays come from a common mass
  - $\Delta m_H = m_{\gamma\gamma} - m_{4l}$
    $= 2.3^{+0.6}_{-0.7}\ (\mathrm{stat}) \pm 0.6\ (\mathrm{sys})$ GeV
- Consistency Δm_H=0:
  - p-value = 1.5% (2.4σ)
  - More conservative E scale model: allow systematics to vary without constraint ±1σ (rectangular PDF): p-value = 8% (1.7σ)



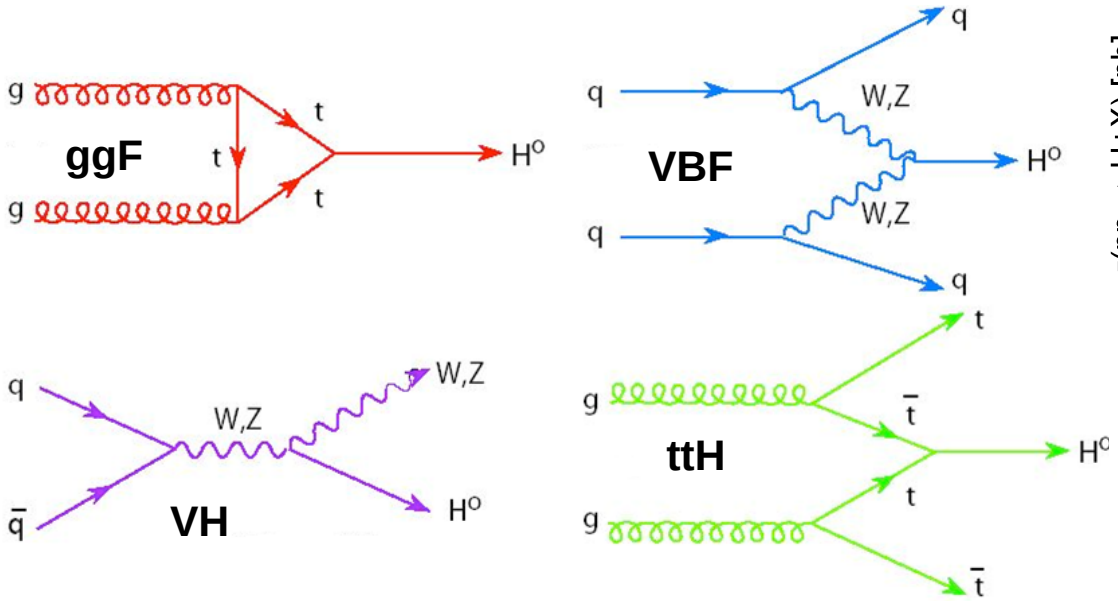
- Previous measurement, Dec 2012:
  - $\Delta m_H = 3.0 \pm 0.8\ (\mathrm{stat})^{+0.7}_{-0.6}\ (\mathrm{sys})$ GeV

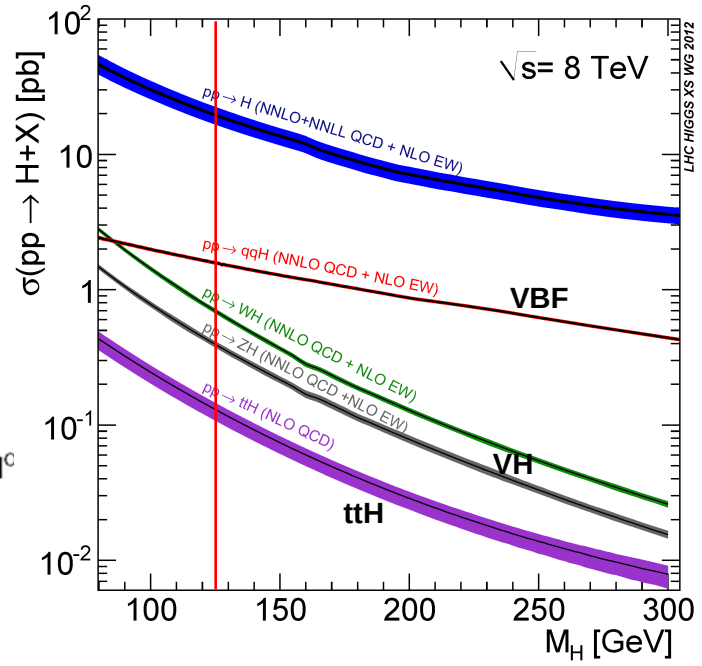
Signal strength



- Combination of
  - W,Z H → bb (4.7 fb^{-1} + 13 fb^{-1})
  - H → ττ (4.6 fb-1 + 13 fb-1)
  - H → WW$^{(*)}$ → *lνlν* (4.6 fb-1 + 20.7 fb-1) **Update today!**
  - H → γγ (4.8 fb-1 + 20.7 fb-1) **Update last week!**
  - H → ZZ$^{(*)}$ → 4*l* (4.6 fb-1 + 20.7 fb-1) **Update last week!**
- Signal strength $\mu = \sigma/\sigma_{SM}$ measured assuming m_H=125.5 GeV
  - Only ±4% change to combined μ for ±1 GeV
- Combined $\mu = 1.30 \pm 0.13\,(stat) \pm 0.14\,(sys)$
- Compatibility between measurements and SM (μ=1)
  - Common μ vs SM: 9%
  - with rectangular QCD scale/PDF constraints: 40%
  - All μ_{bb}, $\mu_{\tau\tau}$, μ_{WW}, $\mu_{\gamma\gamma}$, μ_{ZZ} vs μ=1: 8% (5 d.o.f)
  - All μ_{bb}, $\mu_{\tau\tau}$, μ_{WW}, $\mu_{\gamma\gamma}$, μ_{ZZ} vs μ=1.30: 13% (4 d.o.f)
- ATLAS also sets limits (95%CL; not used in combination):
  - H → μμ: μ<9.8 (20.7 fb-1) **New last week!**
  - H → Zγ: μ<18.2 (4.6 fb-1 + 20.7 fb-1) **New last week!**

Higgs production modes



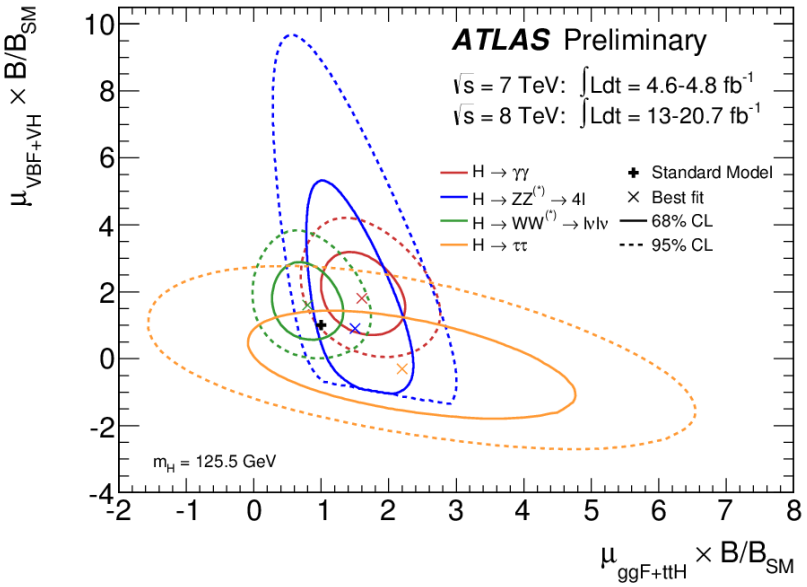


- Dominant Higgs production modes expected from the SM at m_H=125 GeV:
  - 19.5 pb: gg fusion (ggF)
  - 1.6 pb: vector boson fusion (VBF) – tagged with 2 jets in $\gamma\gamma$, ZZ, and WW analyses
  - 1.1 pb: W,Z + H (VH) – W,Z tagged in $\gamma\gamma$, ZZ, and bb analyses
  - 0.1 pb: tt + H (ttH)
- Group together production signal strengths:
  - Fermion-mediated: $\mu_{ggF+ttH} \equiv \mu_{ggF} = \mu_{ttH}$
  - Boson-mediated: $\mu_{VBF+VH} \equiv \mu_{VBF} = \mu_{VH}$

– ttH,VH rates subdominant

VBF and ggF production modes

- μ_{VBF+VH} vs $\mu_{ggF+ttH}$
  - Measured yields in different production modes could be modified by B/B_{SM}
    - May be different for each decay mode

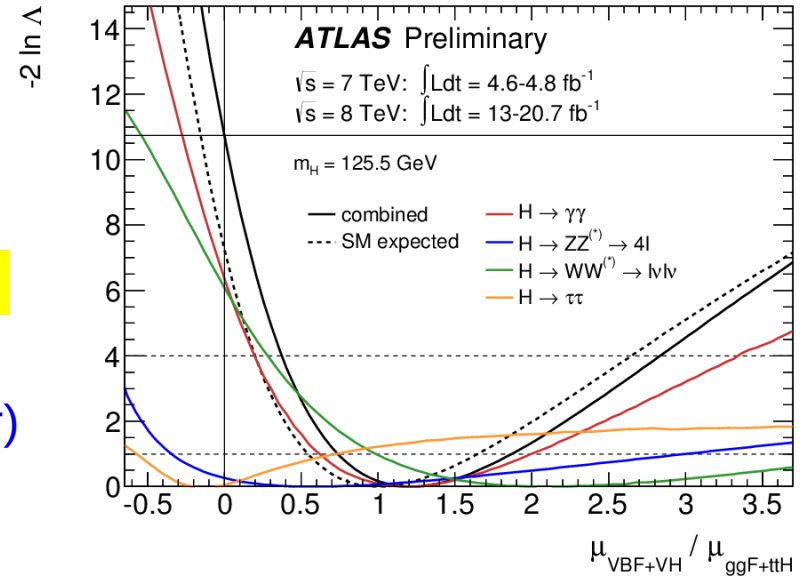


- Ratio μ_{VBF+VH} / $\mu_{ggF+ttH}$
  - B/B_{SM} cancels out in each decay mode
    - Can compare / combine different modes
  - μ_{VBF+VH} / $\mu_{ggF+ttH} = 1.2^{+0.7}_{-0.5}$

Compatible with SM

- Also test for VBF alone (profile μ_{VH}):
  - p-value of μ_{VBF} / $\mu_{ggF+ttH}$=0: 0.09% (3.1σ) (1-sided)

Evidence for VBF



Higgs decays

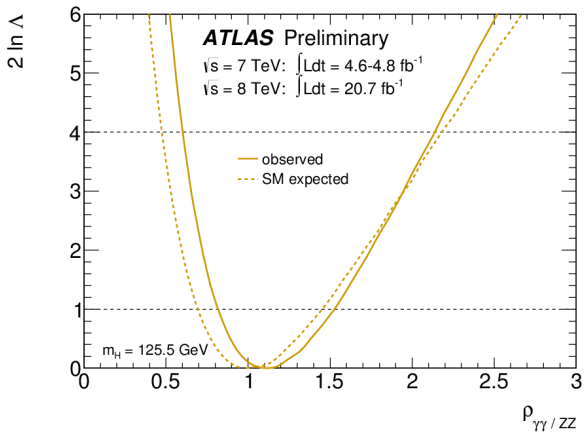
- Can also test decays in a fairly model-independent way
  - Relative ratios of branching ratios, eg. $\rho_{\gamma\gamma/ZZ} = \frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to ZZ^{(*)})} \times \frac{\mathrm{BR}_{\mathrm{SM}}(H\to ZZ^{(*)})}{\mathrm{BR}_{\mathrm{SM}}(H\to\gamma\gamma)}$

- $\rho_{\gamma\gamma/\mathrm{ZZ}} = 1.1^{+0.4}_{-0.3}$
- $\rho_{\gamma\gamma/\mathrm{WW}} = 1.7^{+0.7}_{-0.5}$
- $\rho_{\mathrm{ZZ/WW}} = 1.6^{+0.8}_{-0.5}$

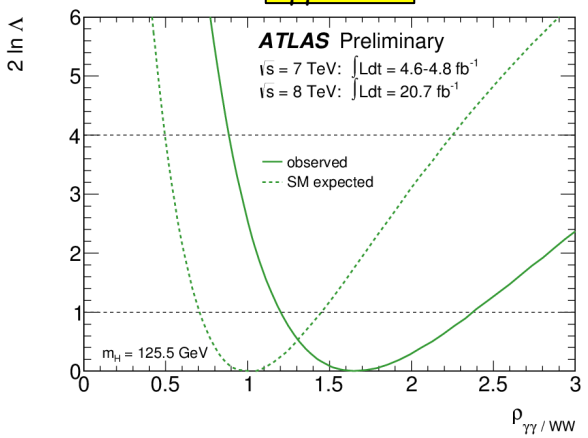
All compatible with SM

Note: only two ratios independent

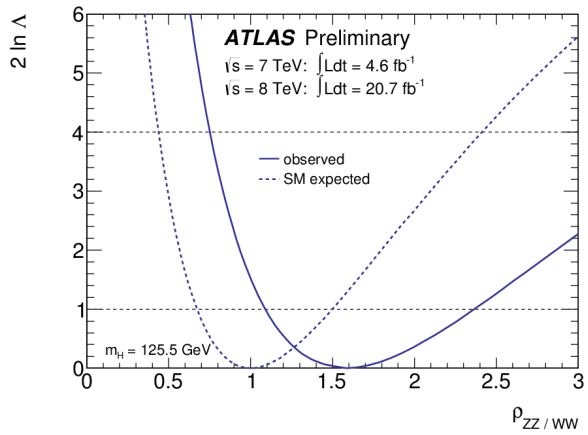
γγ/ZZ



γγ/WW



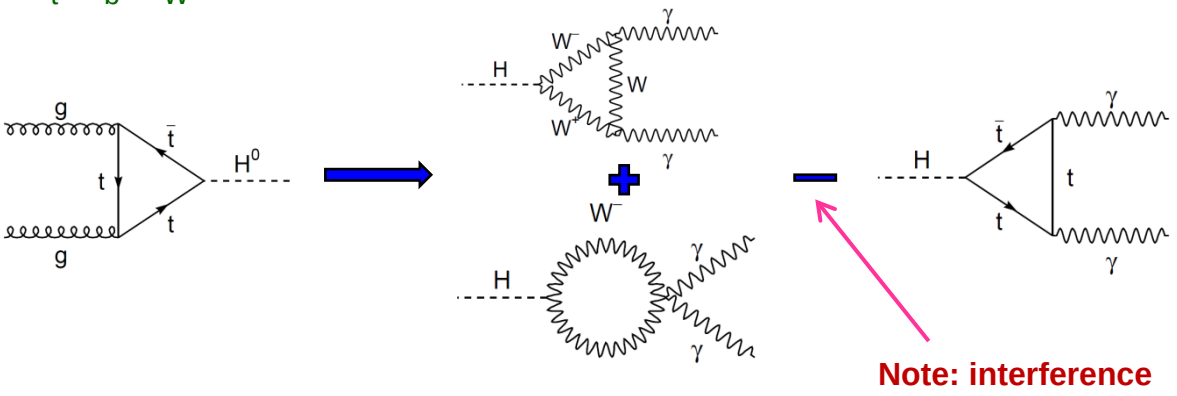
ZZ/WW



Higgs couplings

- For each observed final state, production and decay involve several couplings
- Test SM by applying scale factors κ_i to each coupling and fitting for κ_is
  - Assume a single resonance with a mass near 125 GeV
    - Test at 125.5 GeV (varying mass hypothesis is a small effect)
  - Assume narrow resonance ($\sigma \cdot BR(ii \to H \to ff) \approx \sigma_{ii} \cdot \Gamma_{ff} / \Gamma_H$)
  - Only test modifications to the magnitude of the couplings (=> CP even scalar)
- Not all couplings accessible with current data, so test specific scenarios
  - Benchmark models defined by the LHC-XS-WG

- Eg. $H \to \gamma\gamma$: $(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$
  - where κ_g and κ_γ are effective scale factors on the loop couplings
    - functions of κ_t, κ_b, κ_W,...



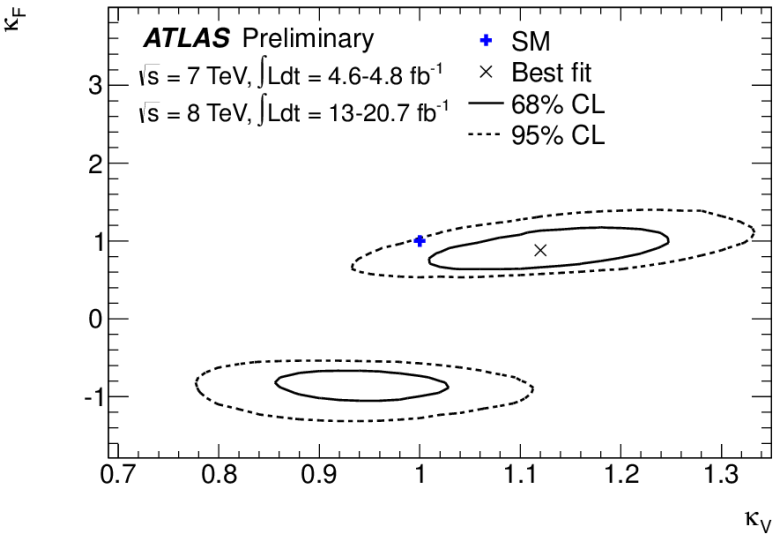
Fermion vs Vector couplings

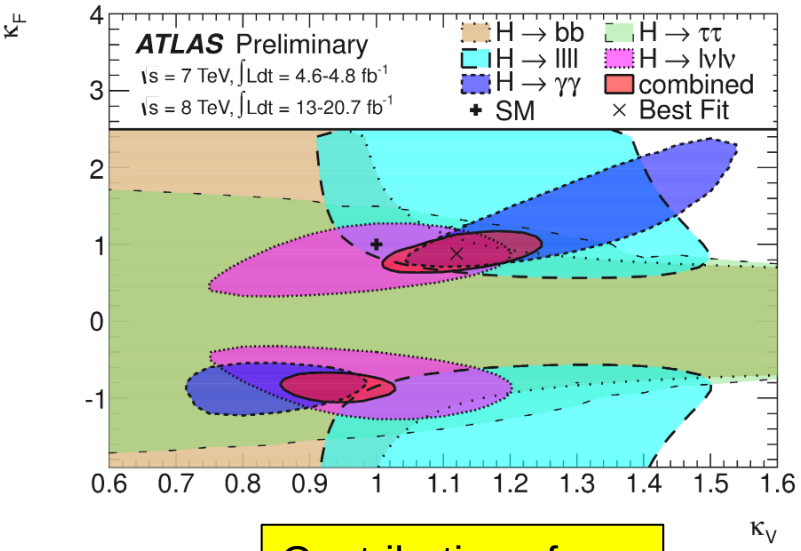
- Model:
  - Vector and fermion couplings grouped together
  - $\kappa_V \equiv \kappa_W = \kappa_Z$ [SM: $\kappa_V=\kappa_F=1$]
  - $\kappa_F \equiv \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$
  - Assume only SM particles contribute to κ_g ($gg\rightarrow H$, via fermion loop) and κ_γ ($H\rightarrow\gamma\gamma$)
    - This assumption can be relaxed – see backup slides
- Some sensitivity to relative sign due to $H\rightarrow\gamma\gamma$ interference term

- κ_V = [0.91, 0.97] and [1.05, 1.21] (68% CL)
- κ_F = [-0.88, -0.75] and [0.73, 1.07]

- 2D Compatibility with SM: 8%

κ_F VS κ_V





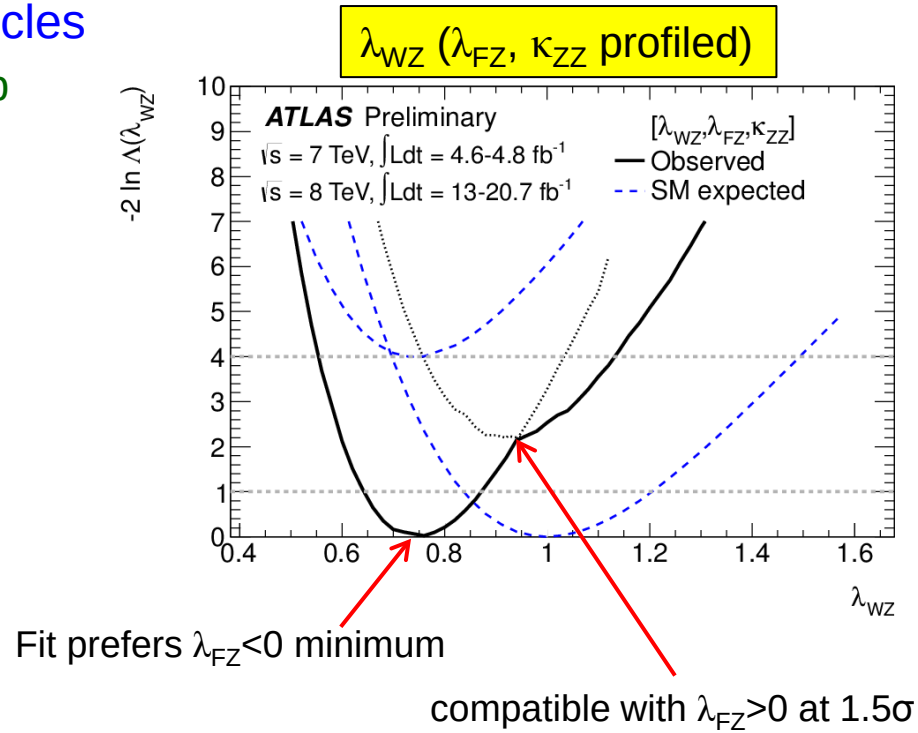
Contribution of individual channels

Custodial symmetry: W vs Z couplings

- Model:
  - Ratio of W/Z couplings, fermion couplings grouped together, total width left free
  - $\lambda_{WZ} \equiv \kappa_W / \kappa_Z$ [SM: $\lambda_{WZ}=\lambda_{FV}=\kappa_{ZZ}=1$]
  - $\lambda_{FZ} \equiv \kappa_F / \kappa_Z$ (profiled in fit)
  - $\kappa_{ZZ} \equiv \kappa_Z\kappa_Z / \kappa_H$ (profiled in fit)
  - Assume loops contain only SM particles
    - Can relax assumption on $H\rightarrow\gamma\gamma$ loop content – see backup slides

- λ_{WZ} = [0.64, 0.87] (68% CL)

- 3D compatibility with SM: 5%

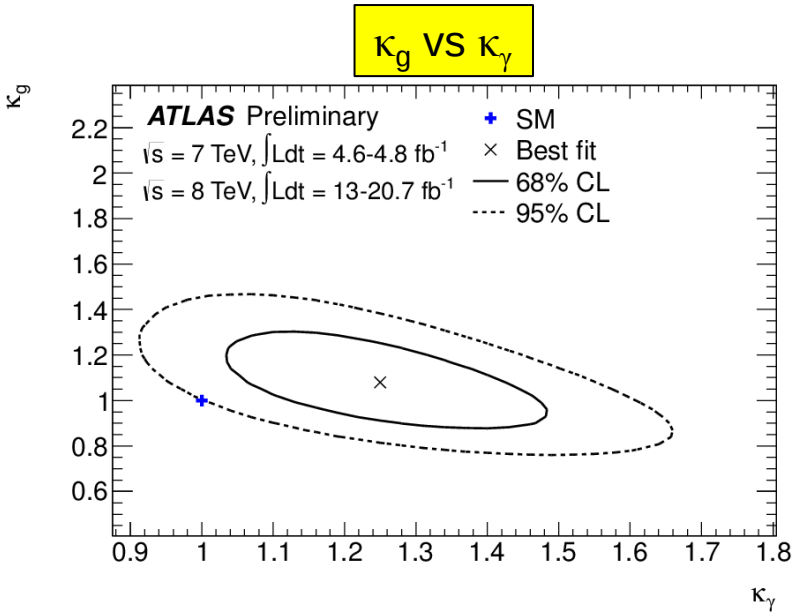


Non-SM particle content in gg→H and H→γγ loops

- Model:
  - Test for non-SM particle content in gg→H (κ_g) and H→γγ (κ_γ) loops
  - Assume all tree-level couplings as in SM ($\kappa_W=\kappa_Z=\kappa_t=...=1$) and no extra SM contributions to the total width (κ_H)
  - Parameters: κ_g and κ_γ [SM: $\kappa_g=\kappa_\gamma=1$]

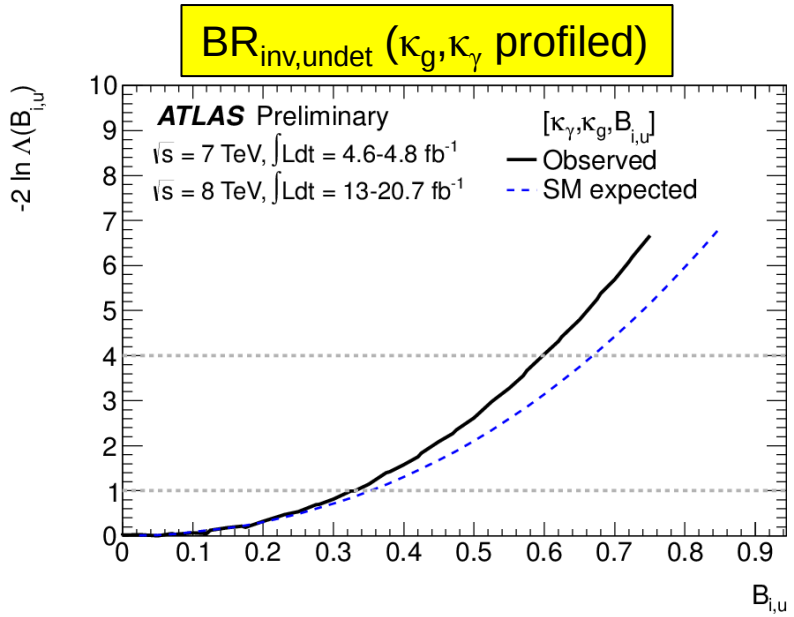
- $\kappa_g = 1.08 \pm 0.14$
- $\kappa_\gamma = 1.23^{+0.16}_{-0.13}$

- 2D compatibility with SM: 5%



Non-SM decay modes

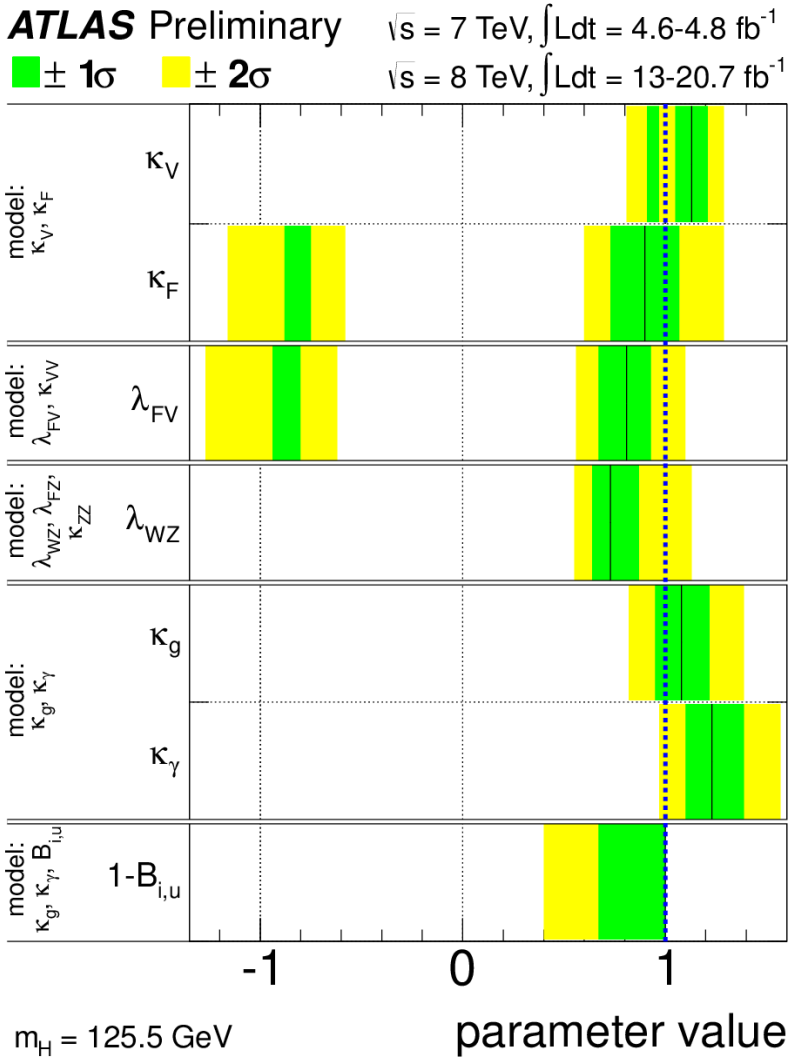
- Model:
  - Assume all SM vertex couplings (κ_i=1) and test for invisible or undetectable non-SM decay modes
  - $BR_{inv,undet} = 1 - \frac{\kappa_H^2}{\Gamma_H/\Gamma_H^{SM}}$ [SM: $\kappa_g=\kappa_\gamma=1$, $BR_{inv,undet}=0$]
  - Profile κ_g and κ_γ



- $BR_{inv,undet} < 0.6$ (95% CL)
- 3D compatibility with SM: 10%
- ATLAS also has a dedicated search for $Z\,H \rightarrow$ invisible (missing E_T):
  - $BR_{inv} < 0.65$ (95% CL) **New last week!**

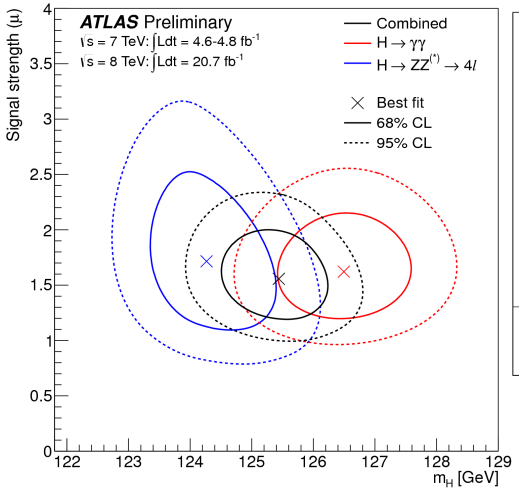
Summary of coupling results

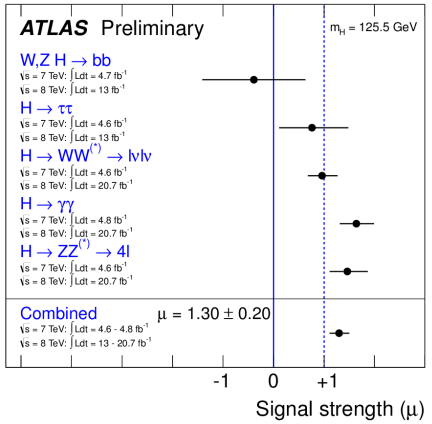
- Overall compatibility with SM: 5-10%
  - No significant deviation from SM
- Note: each model is a different way of fitting the same data
  - correlated, so don't add them up!

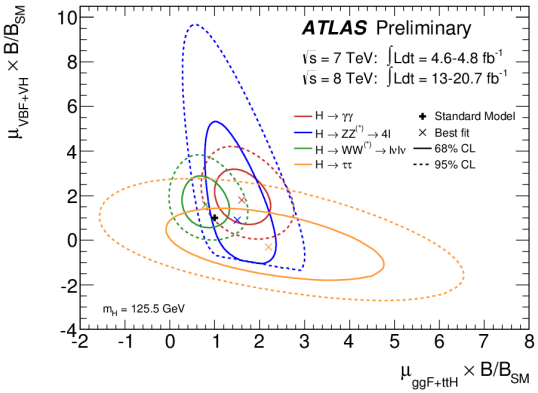


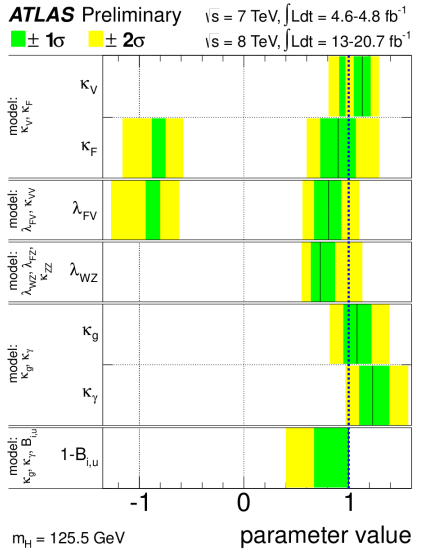
Conclusion

- $m_H = 125.5 \pm 0.2\ (\text{stat})\ ^{+0.5}_{-0.6}\ (\text{sys})$ GeV
- $\mu = 1.30 \pm 0.13\ (\text{stat}) \pm 0.14\ (\text{sys})$
- $\mu_{VBF+VH} / \mu_{ggF+ttH} = 1.2^{+0.7}_{-0.5}$
- 3.1σ evidence for VBF production
- Higgs couplings consistent with SM
- Spin and parity (from Eleni's talk):
  - compatible with 0^+
  - start to exclude 2^+_m in γγ and WW, and 0^-, 1^+ in ZZ









BACKUP

References

- Higgs couplings: ATLAS-CONF-2013-034
- Higgs mass: ATLAS-CONF-2013-014

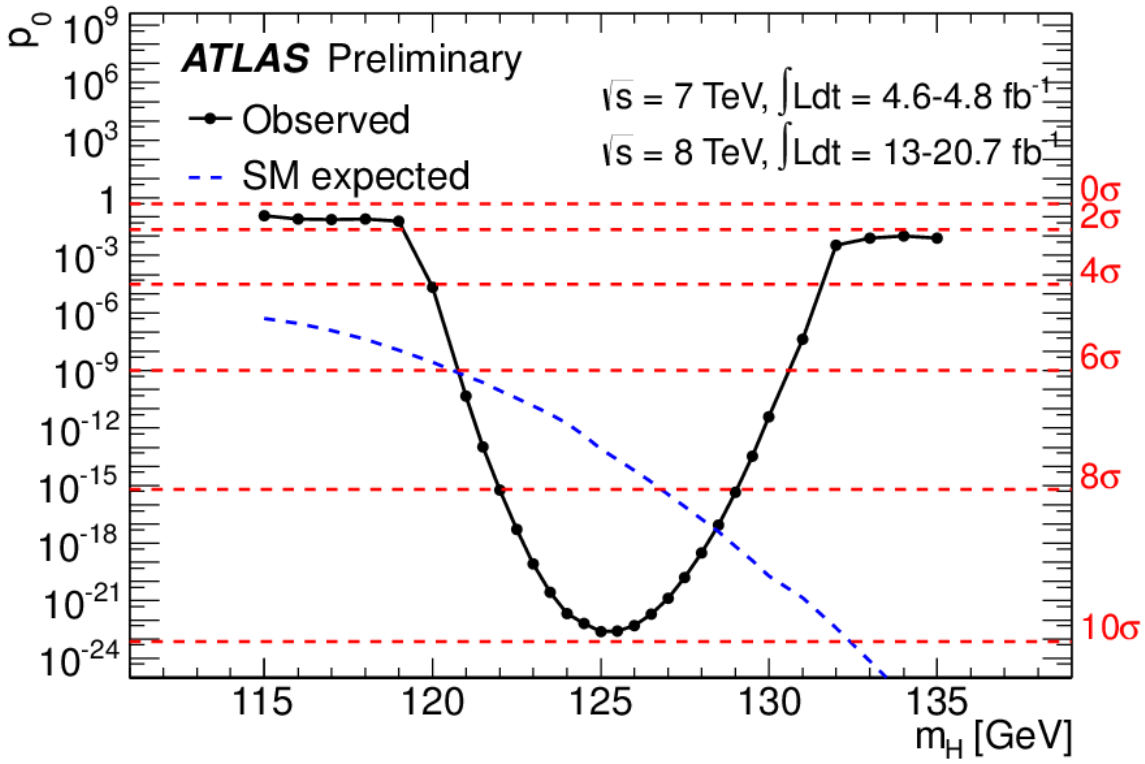
- $\gamma\gamma$: ATLAS-CONF-2013-012, spin: ATLAS-CONF-2013-029
- ZZ: ATLAS-CONF-2013-013
- WW: ATLAS-CONF-2013-030, spin: ATLAS-CONF-2013-031
- $\tau\tau$: ATLAS-CONF-2012-160 (Nov 2012)
- bb: ATLAS-CONF-2012-161 (Nov 2012)
- $\mu\mu$: ATLAS-CONF-2013-010
- $Z\gamma$: ATLAS-CONF-2013-009
- ZH→invisible: ATLAS-CONF-2013-011

- Previous combination: ATLAS-CONF-2012-170 (Dec 2012)
- Previous coupling results: ATLAS-CONF-2012-127 (Sep 2012)
- Observation: Phys. Lett. B 716 (2012) 1-29 (July 2012)

- LHC XS WG coupling recommendations: arXiv:1209.0040

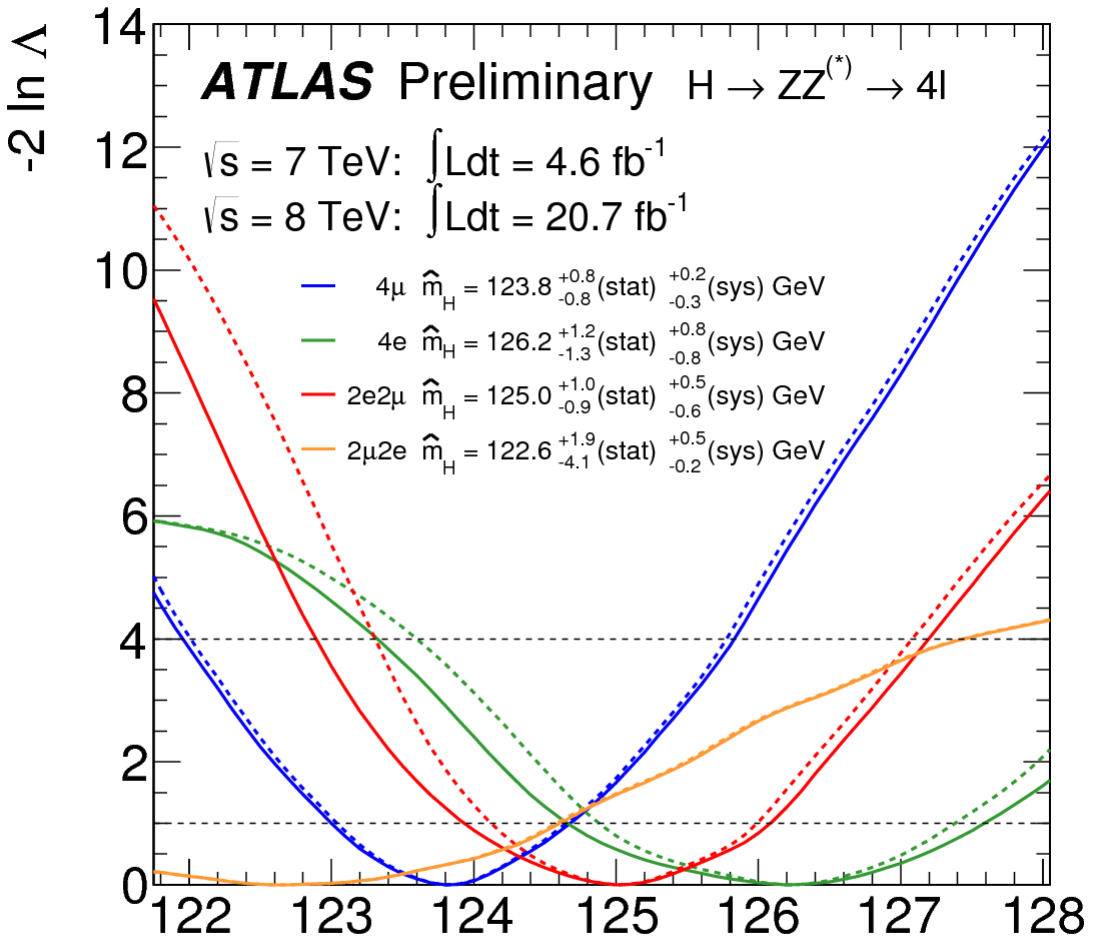
p_0 vs m_H hypothesis

- Update of combined p_0
  - Mass scale systematics taken into account
  - primarily of interest during discovery phase



$H \to ZZ^{(*)} \to 4l$ individual channel mass measurements

- 4μ
- 4e
- 2e2μ
- 2μ2e



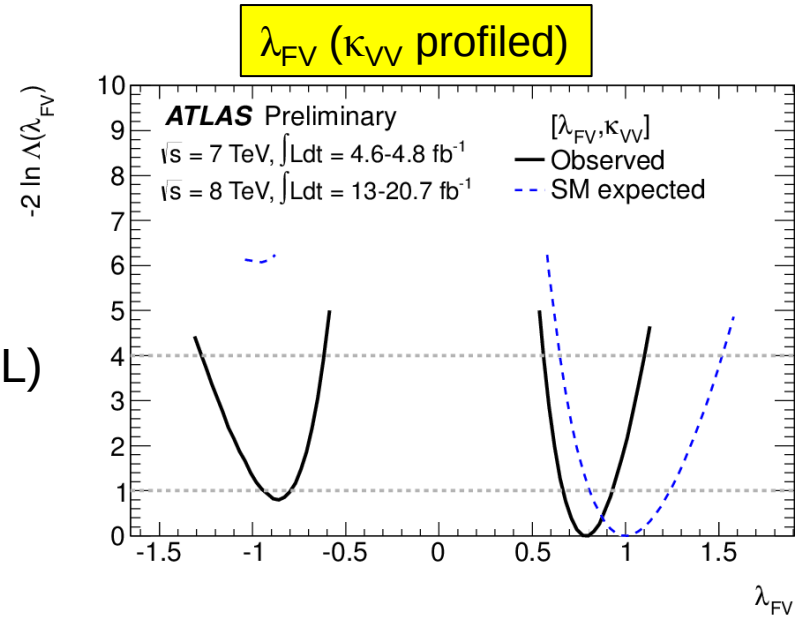
- Solid: with mass scale systematics
- Dashed: without mass scale systematics

Fermion vs Vector couplings
no assumption on total width

- Model:
  - Ratio of fermion/vector couplings with no assumption on the total width
  - $\lambda_{FV} \equiv \kappa_F / \kappa_V$ [SM: $\lambda_{FV}=\kappa_{VV}=1$]
  - $\kappa_{VV} \equiv \kappa_V\kappa_V / \kappa_H$ (profiled in fit)

- λ_{FV} = [-0.94, -0.80] and [0.67, 0.93] (68% CL)

- 2D compatibility with SM: 7%



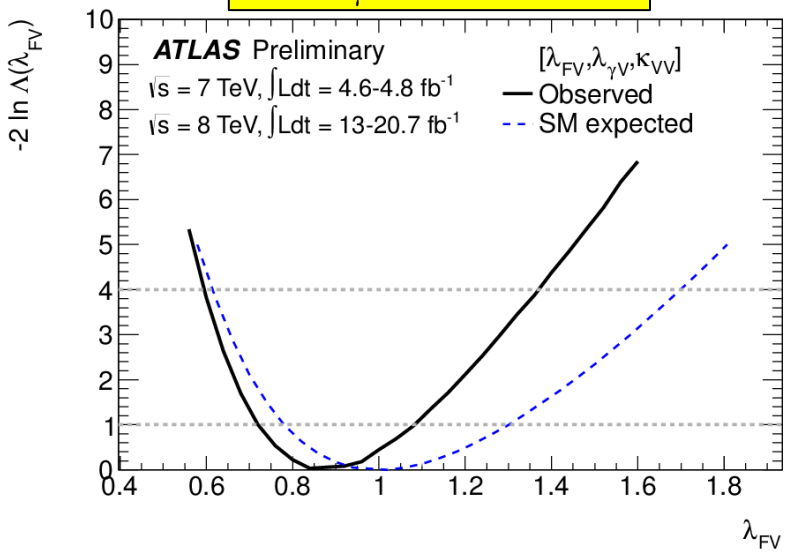
Fermion vs Vector couplings
no assumption on total width or H→γγ loop content

- Model:
  - Ratio of fermion/vector couplings with no assumption on the total width or H→γγ loop content
  - $\lambda_{FV} \equiv \kappa_F / \kappa_V$ [SM: $\lambda_{FV}=\lambda_{\gamma V}=\kappa_{VV}=1$]
  - $\lambda_{\gamma V} \equiv \kappa_\gamma / \kappa_V$ (profiled in fit)
  - $\kappa_{VV} \equiv \kappa_V\kappa_V / \kappa_H$ (profiled in fit)

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

- 3D compatibility with SM: 9%

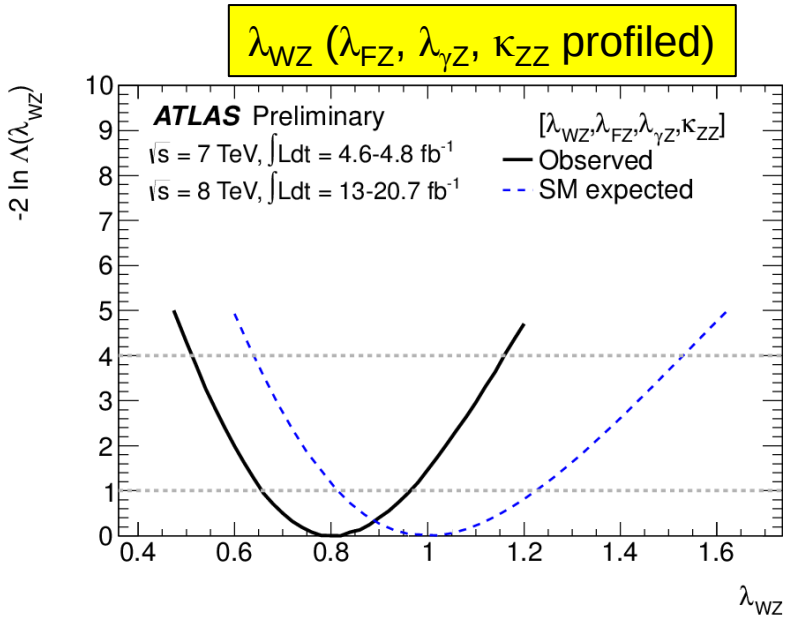
λ_{FV} ($\lambda_{\gamma V}$, κ_{VV} profiled)



Custodial symmetry: W vs Z couplings no assumption on H→γγ loop content

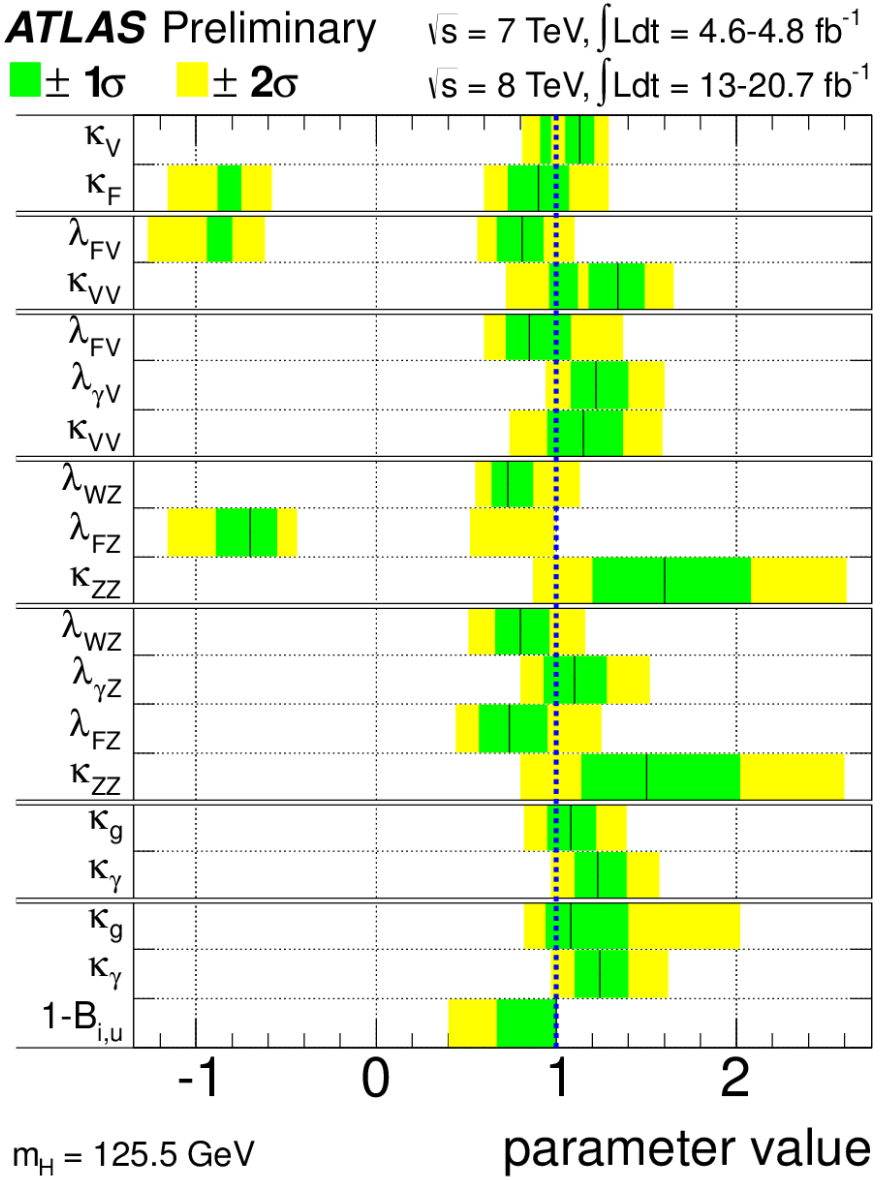
- Model:
  - Ratio of W/Z couplings with no assumption on H→γγ loop content
  - $\lambda_{WZ} \equiv \kappa_W / \kappa_Z$ [SM: $\lambda_{WZ}=\lambda_{FV}=\lambda_{\gamma Z}=\kappa_{ZZ}=1$]
  - $\lambda_{FZ} \equiv \kappa_F / \kappa_Z$ (profiled in fit)
  - $\lambda_{\gamma Z} \equiv \kappa_\gamma / \kappa_Z$ (profiled in fit)
  - $\kappa_{ZZ} \equiv \kappa_Z\kappa_Z / \kappa_H$ (profiled in fit)

- $\lambda_{WZ} = 0.80 \pm 0.15$
- 4D compatibility with SM: 9%



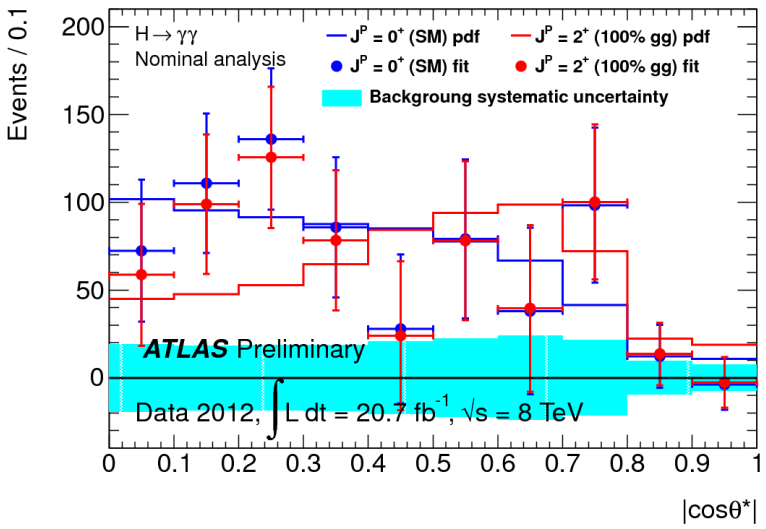
Summary of coupling results - detail

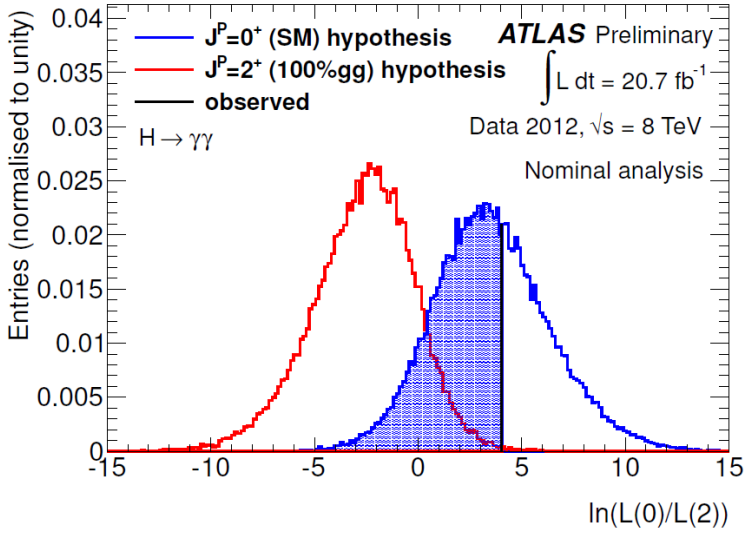
- Overall compatibility with SM: 5-10%
  - No significant deviation from SM
- Note: each model is a different way of fitting the same data
  - correlated, so don't add them up!



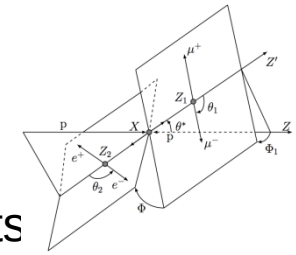
Higgs spin: H → γγ

- Compare spin 0^+ (SM) to a 2^+_m model (graviton-like with minimal couplings)
  - Observation of H→γγ already excludes spin 1
- Use θ* in Higgs rest frame to discriminate
- Compared to 0^+, can exclude 2^+ at 99.3% (assuming 100% gg-production)

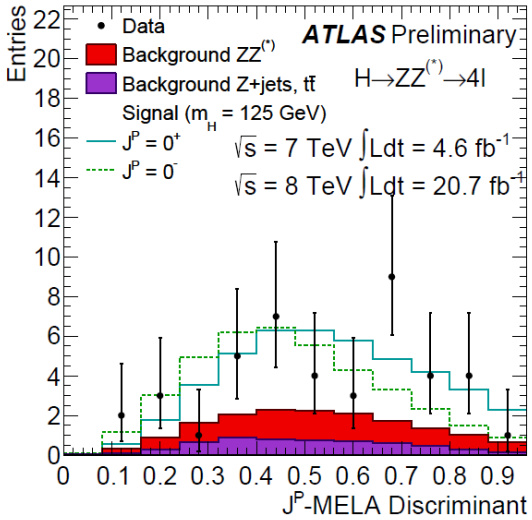


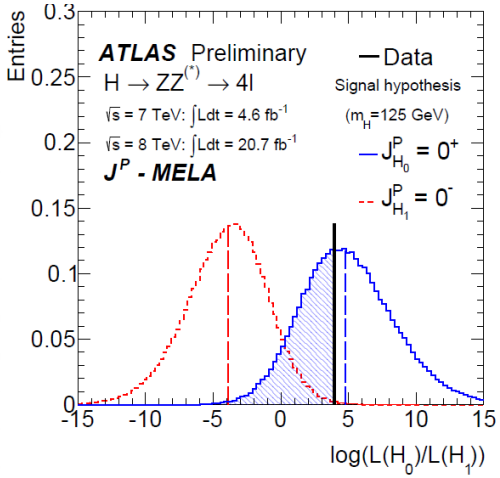


Higgs spin and parity: $H \rightarrow ZZ^{(*)} \rightarrow 4l$



- Compare spin 0^+ (SM) to 0^-, $1^\pm$, $2^\pm$ models
- Use 5 production and decay angles to form two alternative discriminants
  - Multivariate (BDT)
  - Matrix element likelihood ratio (J^P-MELA)
- Spin 0^+ hypothesis favoured over 0^-, 1^+
- Cannot yet distinguish well spin 0^+ from, spin 2





		BDT analysis				J^P-MELA analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S	tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022	0.0011	0.0022	0.40	0.004
1^+	p_0	0.0016	0.001	0.55	0.002	0.0031	0.0028	0.51	0.006
1^-	p_0	0.0038	0.051	0.15	0.060	0.0010	0.027	0.11	0.031
2^+_m	p_0	0.092	0.079	0.53	0.168	0.064	0.11	0.38	0.182
2^-	p_0	0.0053	0.25	0.034	0.258	0.0032	0.11	0.08	0.116

Higgs spin: H → WW$^{(*)}$ → *lvlv*

- Compare spin 0^+ (SM) to a 2^+_m model (graviton-like with minimal couplings)
- Use $m_{\parallel}$, $p^T_{\parallel}$, $\Delta\varphi_{\parallel}$, and m_T to form a BDT discriminant
- Compared to 0^+, can exclude 2^+ at 95-99% (depending on qq production fraction)