Combined results, part I: mass, signal strengths, scalar couplings

ATLAS CONF 2013-014
ATLAS CONF 2013-034
CMS PAS HIG 13-005

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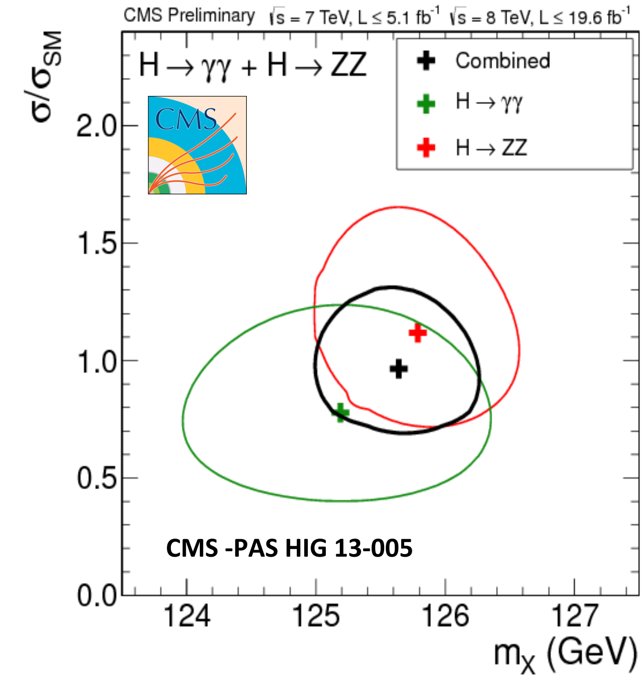
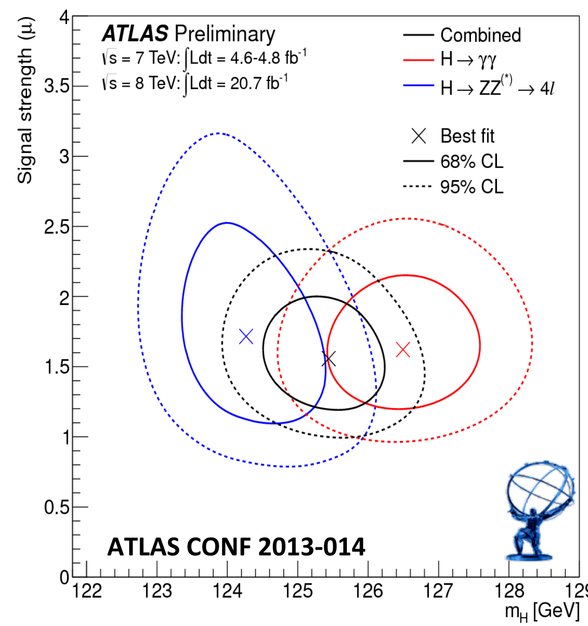
Mass measurement

- The mass is the most directly accessible property of the new Higgs boson:
  - Very little model dependency, only from the calibration of the signal model from simulations.
  - For a narrow width, as predicted in most models, no theoretical issues in the measurement.
- Individual ZZ, γγ results presented in previous talks, just a few words on combination here.

ZZ vs γγ compatibility

- Larger ZZ-γγ tension in ATLAS, so a quantitative evaluation of the consistency between the two results was done
- p-value of Δm=0 hypothesis depends on the assumptions for energy scale systematics:
  - 1.5% for Gaussian systematics
  - 8% for flat systematics





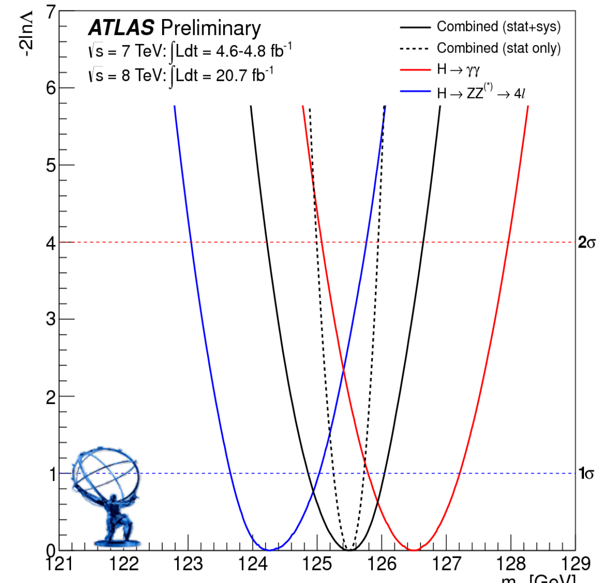
Mass combination

- Mass combination done with relaxed assumptions on the expected signal yields
  - ATLAS: floating μ(ZZ), μ(γγ)
  - CMS: μ(ZZ), $\mu_{VBF+VH}(\gamma\gamma)$, $\mu_{ggH}(\gamma\gamma)$
- Quite compatible results:

ATLAS: $125.5 \pm 0.2 \,^{+0.5}_{-0.6}$ GeV

CMS: $125.7 \pm 0.3 \pm 0.3$ GeV

(stat) (syst)



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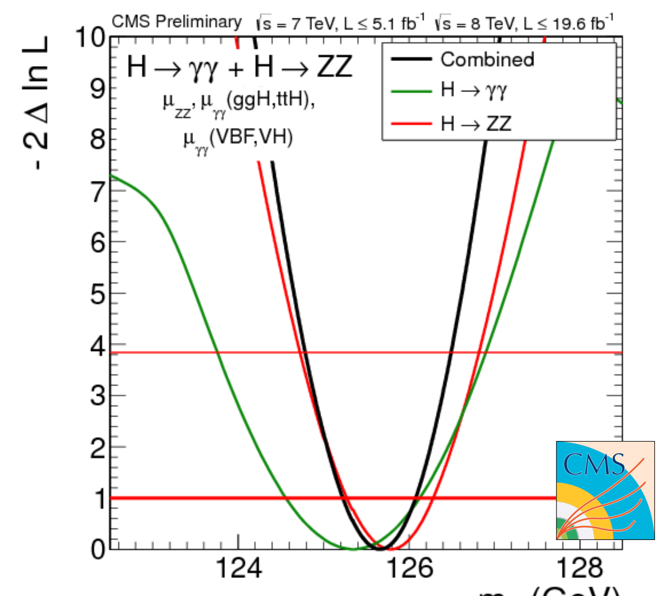

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Signal strength compatibility tests

- A simple and direct way to pitch the observed data against the SM Higgs predictions is by measuring signal strengths in different modes.
- Can be made quantitative by computing a χ^2-like quantity from the likelihood ratio between the SM fit a the fit with relaxed constraints (e.g. with free signal yields in each mode)

Signal strength by decay mode

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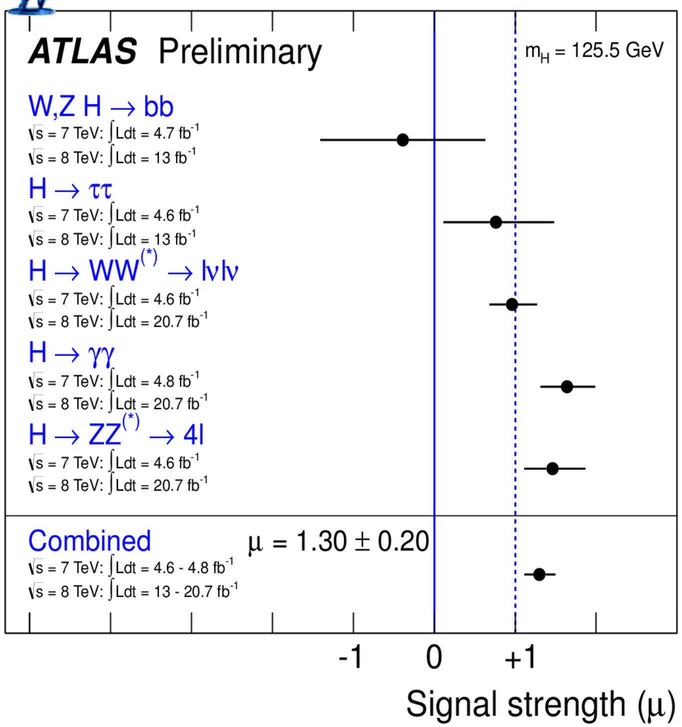
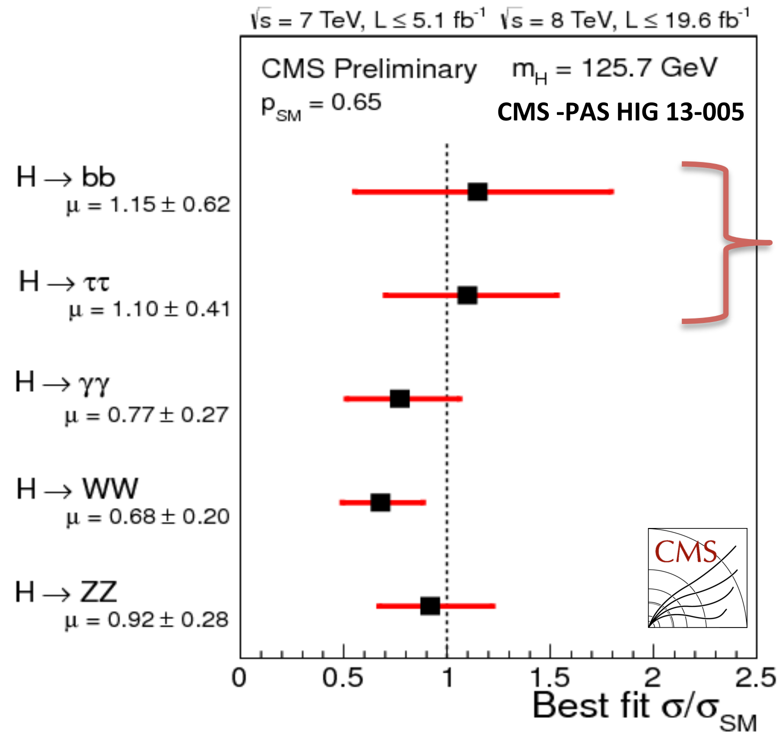
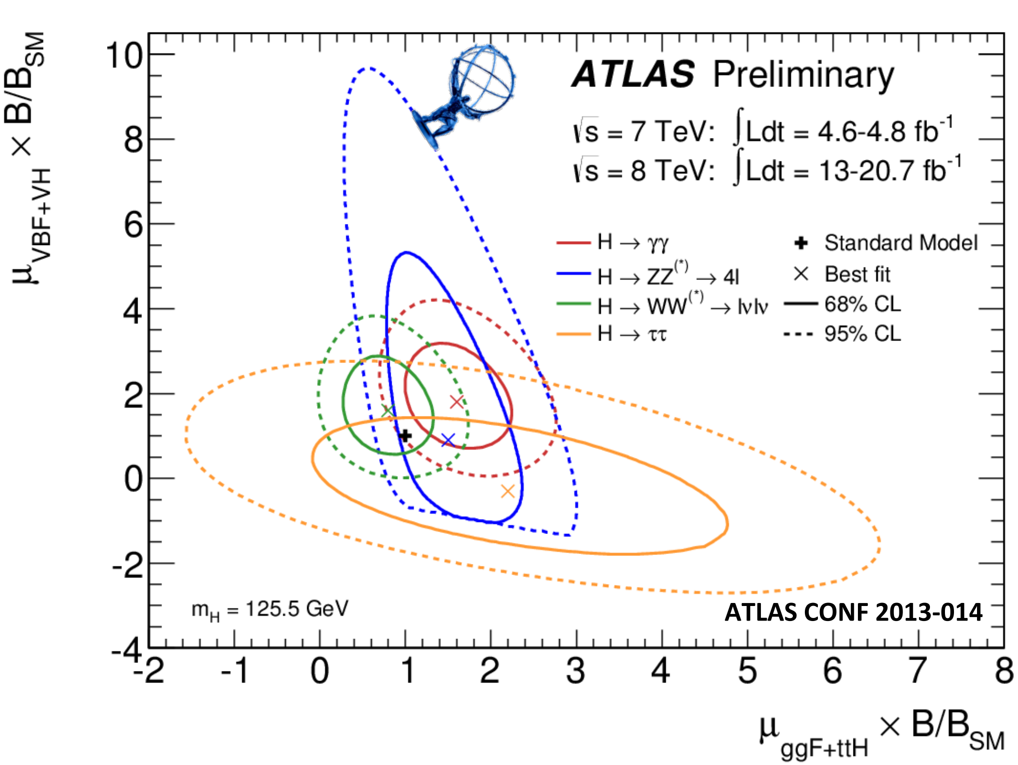


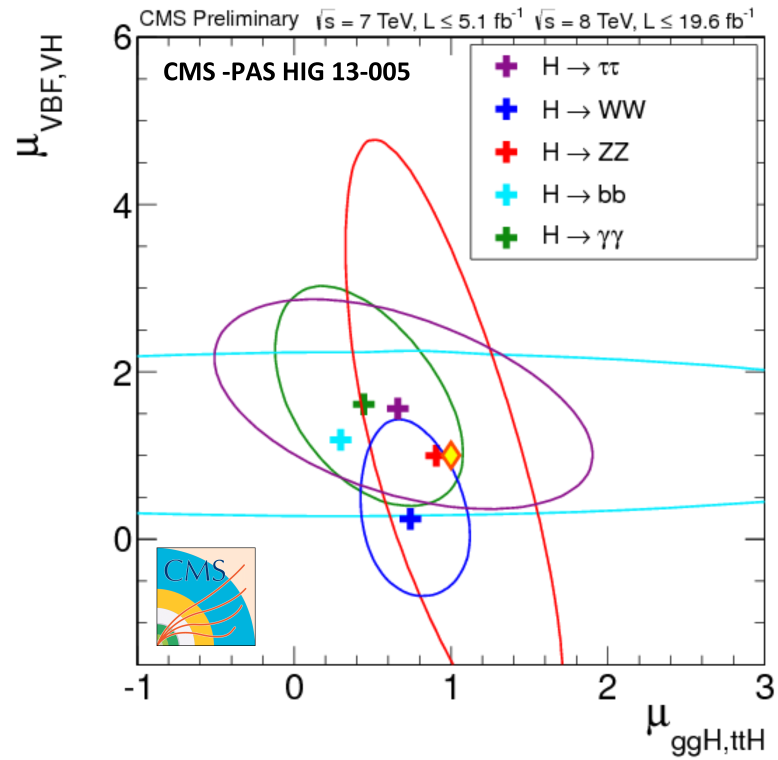


3.4σ signif. for H->ff comb.

- Fair compatibility between the different channels.
- Lower p-value in ATLAS result, 8% mostly driven by overall μ value $\mu = 1.3 \pm 0.2$.

Testing production and decay modes

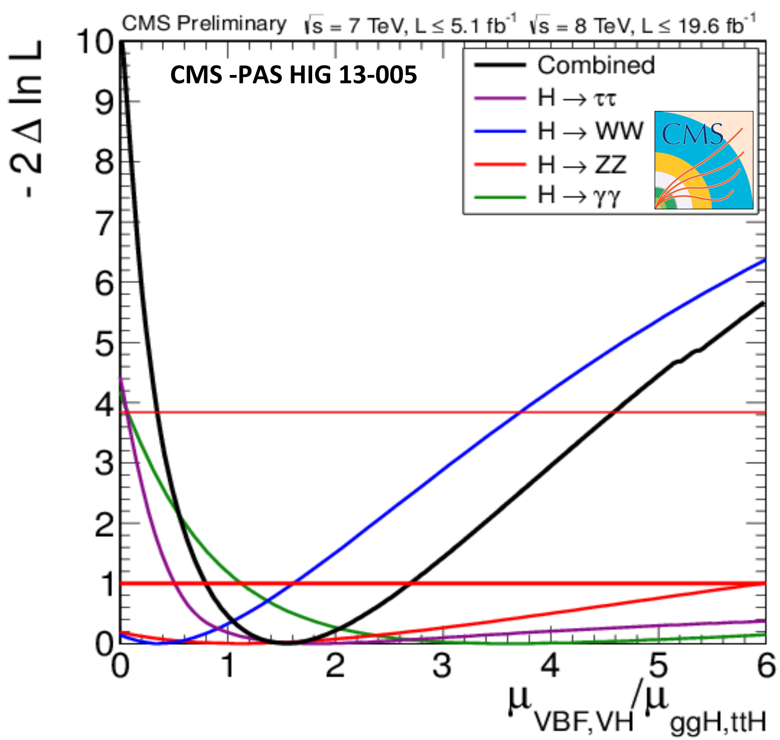


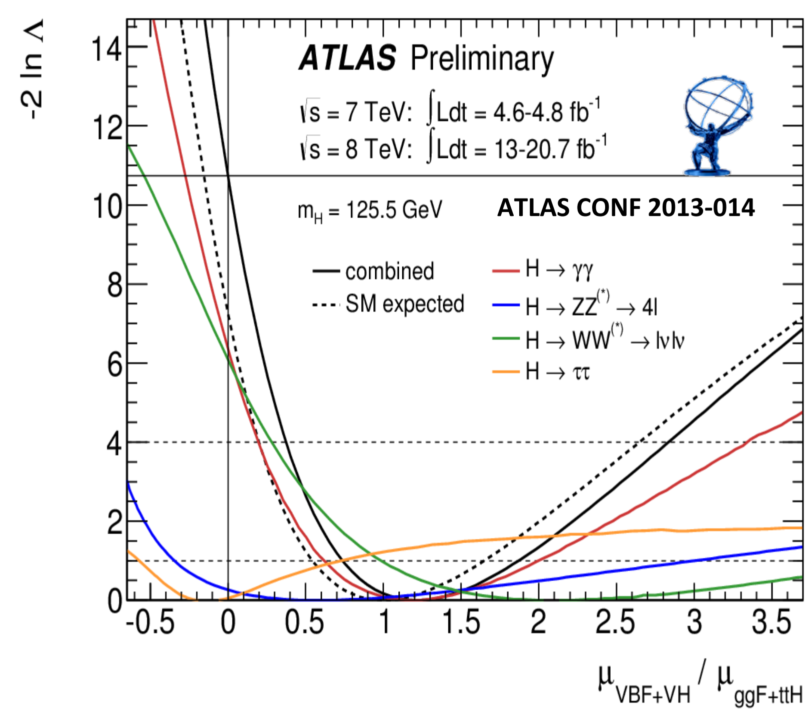


- Simultaneous fit for the signal strengths in VBF+VH and ggH+ttH production modes.
- Shows complementarity of different channels.

Testing production modes from ratios

- In the ratio μ(VBF,VH)/μ(ggH,ttH), the decay BRs drop out, so a combination is possible.
- ATLAS: 3.1σ evidence of VBF from μ(VBF)/μ(ggH,ttH)



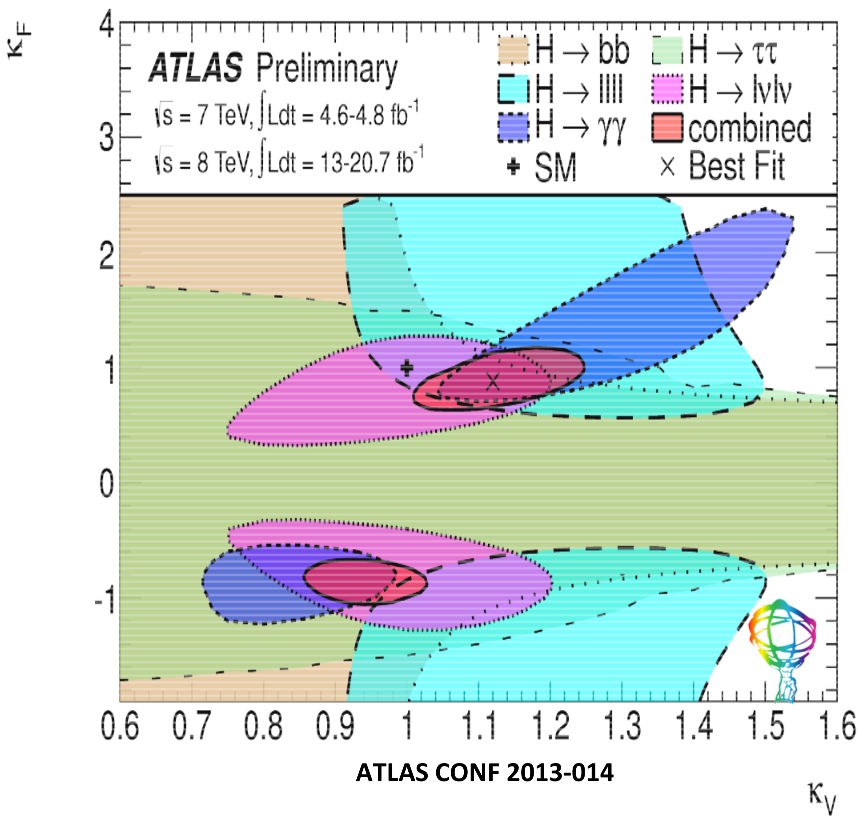


Coupling

- Performing a real measurement of the Higgs couplings requires a theoretical framework to compute accurate predictions beyond the SM.
- In the meantime, rely on ad-hoc prescription for **parameterizing deviations from the SM** from LHC Higgs XS WG (arXiv:1209.0040)
- Fundamental assumptions of the method:
  - Same tensor structure as SM Higgs ($J^{CP} = 0^{+}$).
  - Narrow width (to factorize production & decay)
- Experimentally, assume all signal shape variations negligible with respect to signal yield variations.

κ_V, κ_f benchmark model

- Simple benchmark model with 2 universal coupling modifiers: to W/Z and to fermions.



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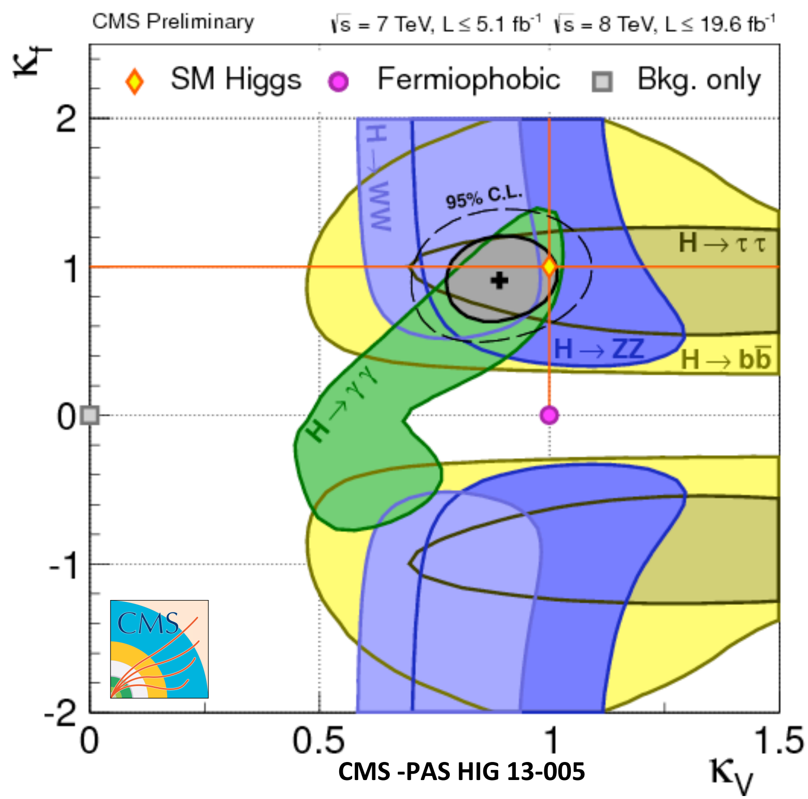

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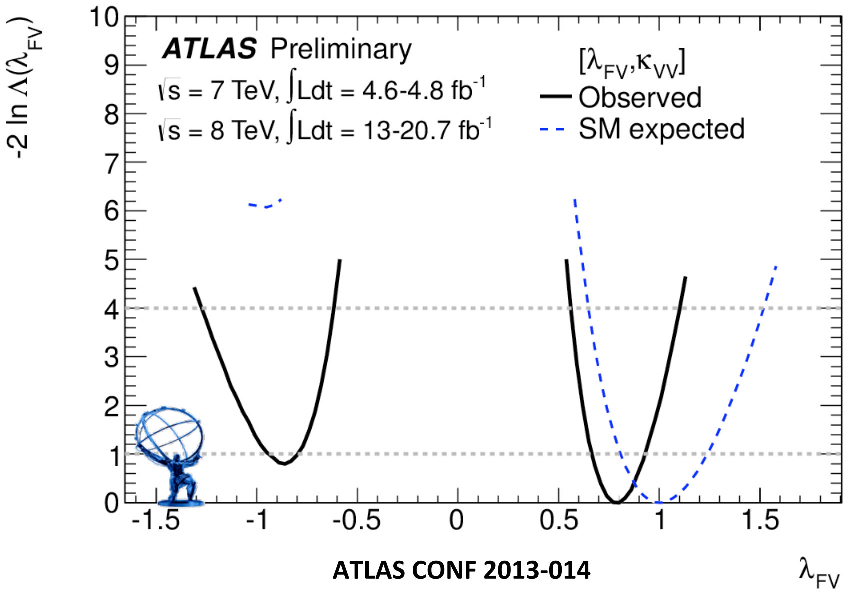
κ_V, κ_f variation: λ_{FV}, κ_{VV}

- κ_V, κ_f model assumes total width as in SM but for the rescaling of the couplings with κ_V, κ_f
- This assumption can be relaxed redefining them:

$\lambda_{FV} := \kappa_f / \kappa_V$ **$\kappa_{VV} := \kappa_V^2 / (\Gamma/\Gamma_{SM})$**



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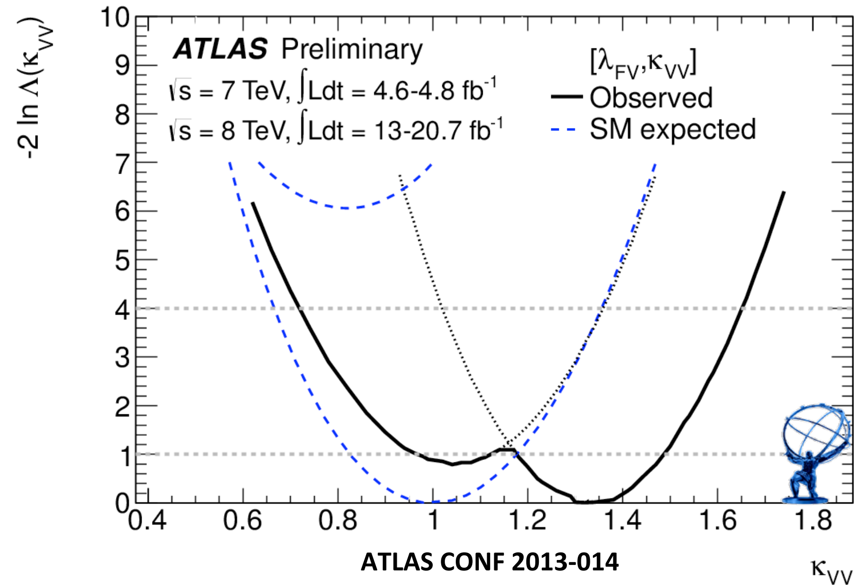

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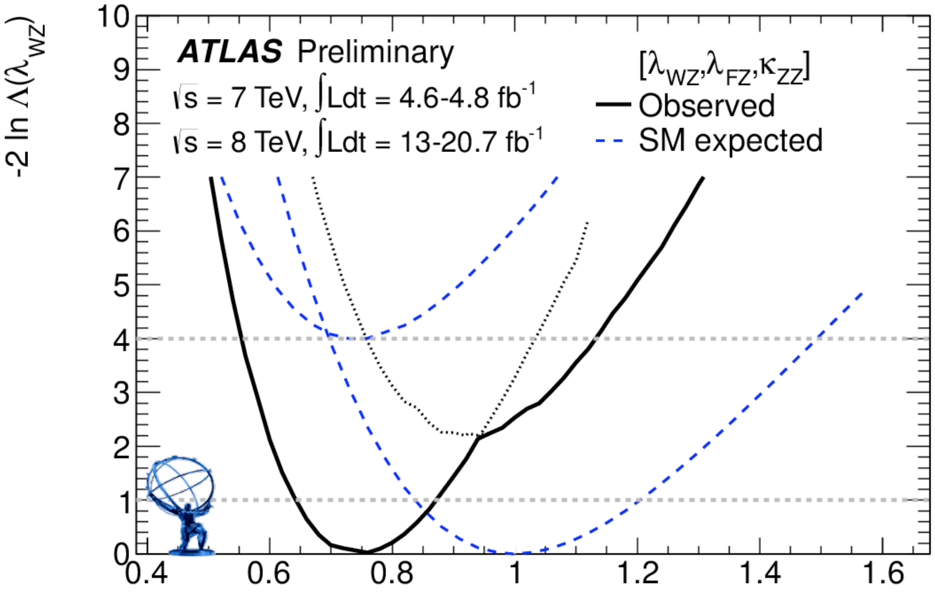
Custodial symmetry

- The ratio of couplings to W and Z bosons is predicted to be SM-like in many scenarios.
- Probed in a fit with 3 parameters κ_f, κ_Z, λ_{WZ}, the third being the ratio of W/Z couplings.



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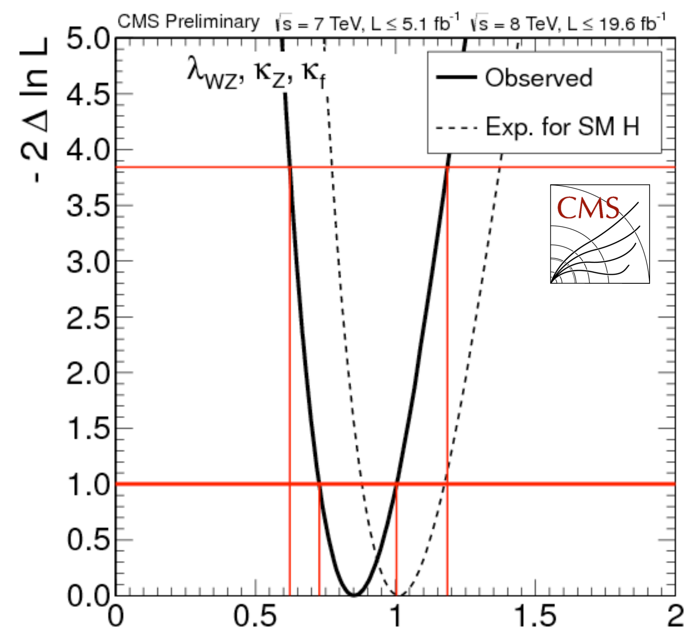

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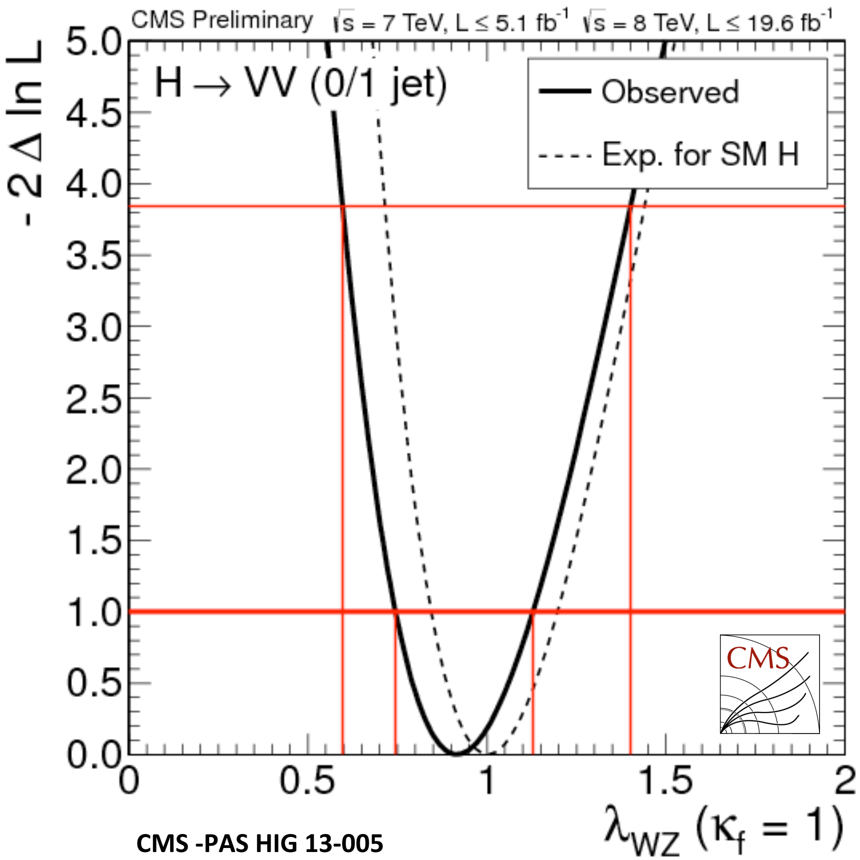
Custodial symmetry: variations

- The result from the full combination contains information from multiple sources: BR's of WW, ZZ; ratio of VH-tagged modes, BR(γγ), …
- To disentangle results, alternative fits have been performed:
  - CMS: use only WW, ZZ modes with 0-1 jet (dominated by gluon fusion production)
  - ATLAS: leave γγ effective coupling free in the fit, to allow for possible BSM effects there.

Custodial symmetry: variations

Only 0/1 jet ZZ, WW.
(κ_f fixed to SM value)



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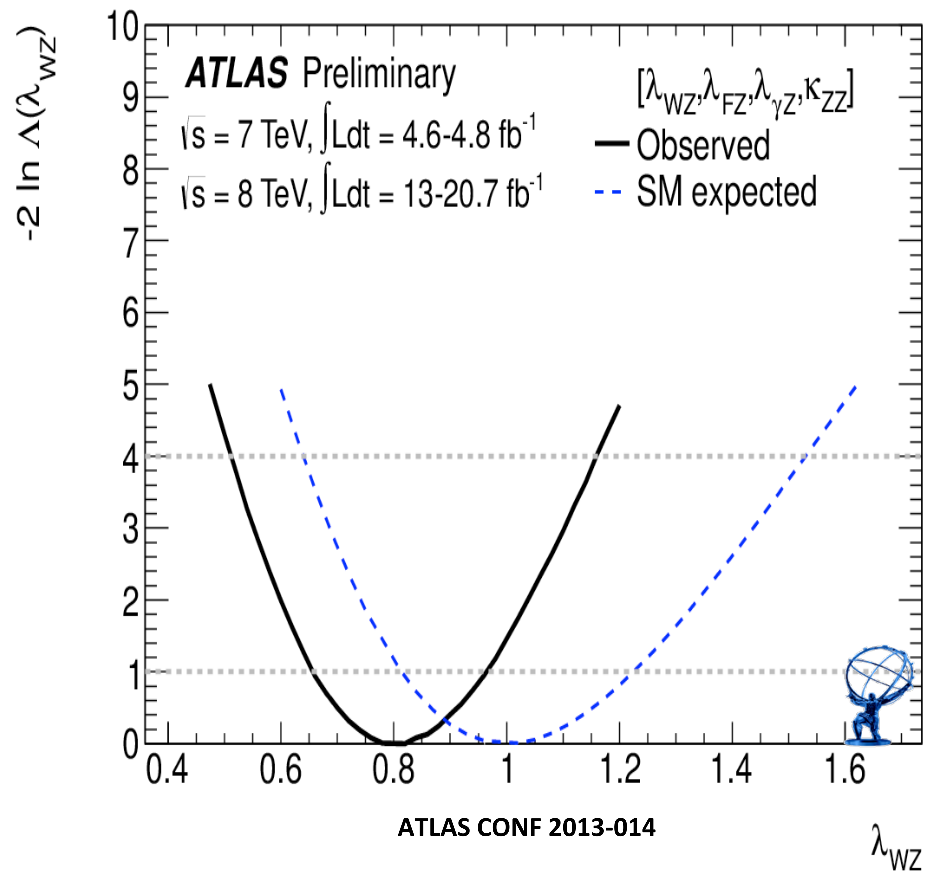
All channels, with extra degree of freedom for γγ



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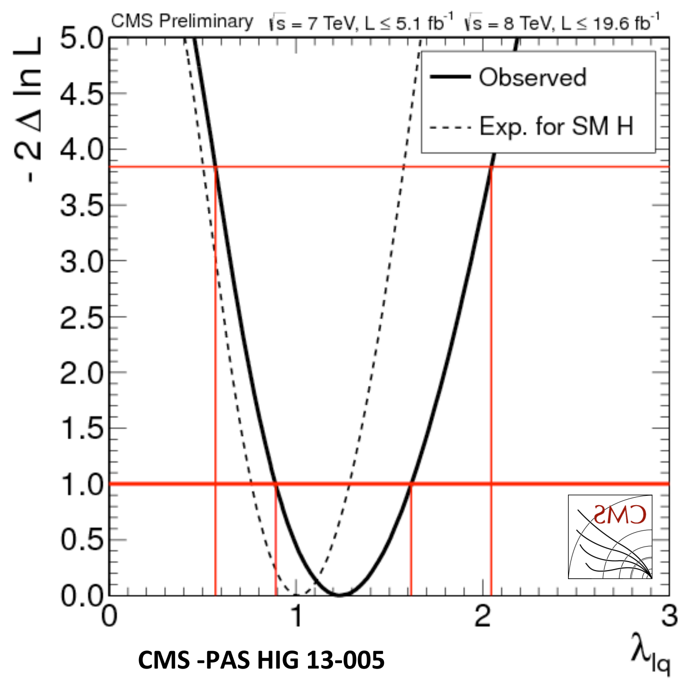
Probing couplings to fermions

- Test for non-universality allowing for different couplings between different kinds of fermions, as expected e.g. in SUSY or 2HDM models.

Leptons vs Quarks



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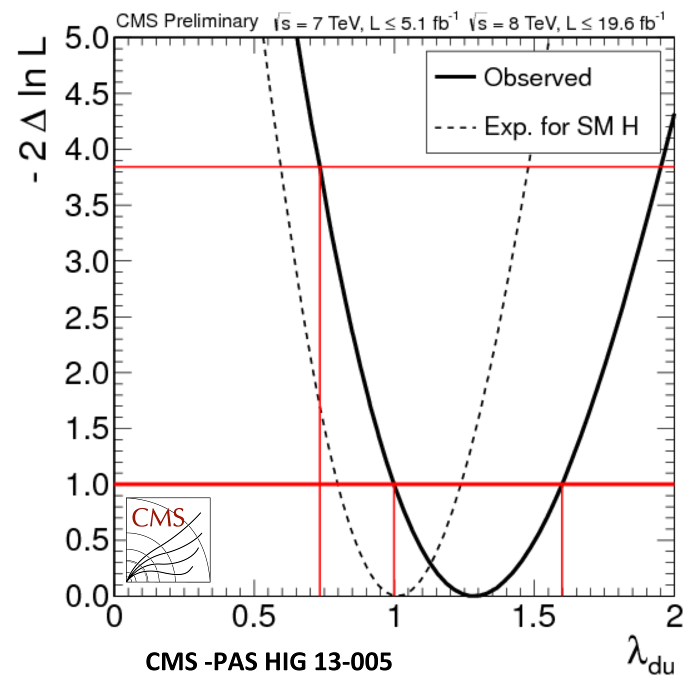
Up- vs Down-type Fermions



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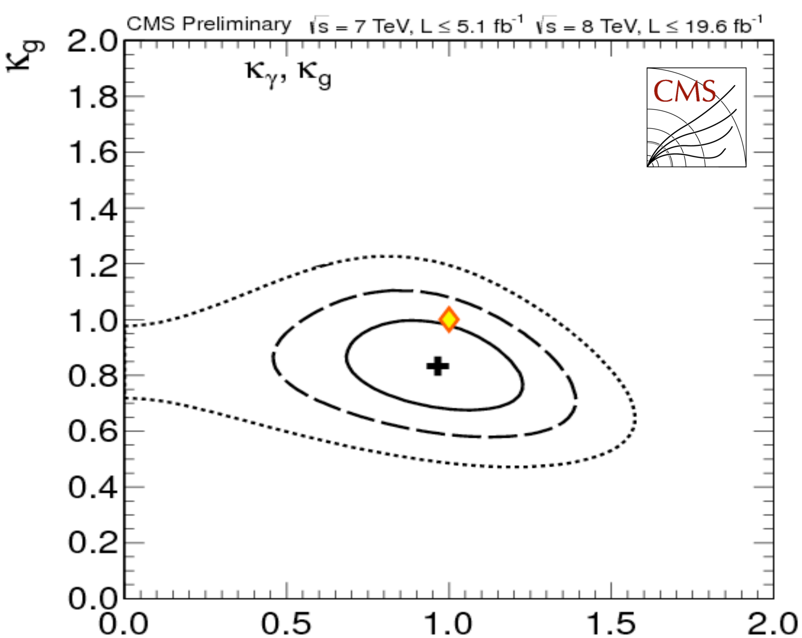
Probing for BSM physics in loops

- Loop-induced couplings are a natural place for deviations from BSM physics to appear.
- Fit data assuming SM tree-level couplings, but with free photon and gluon effective couplings.



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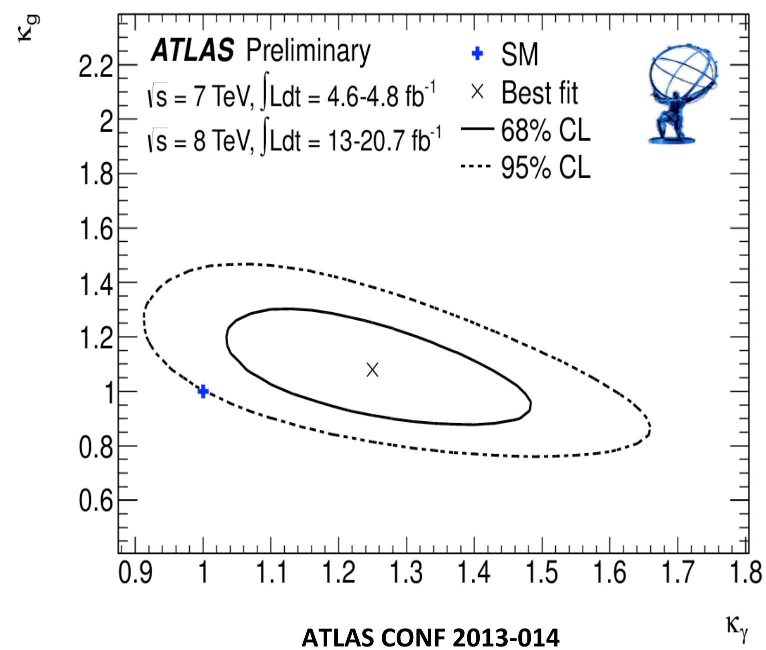

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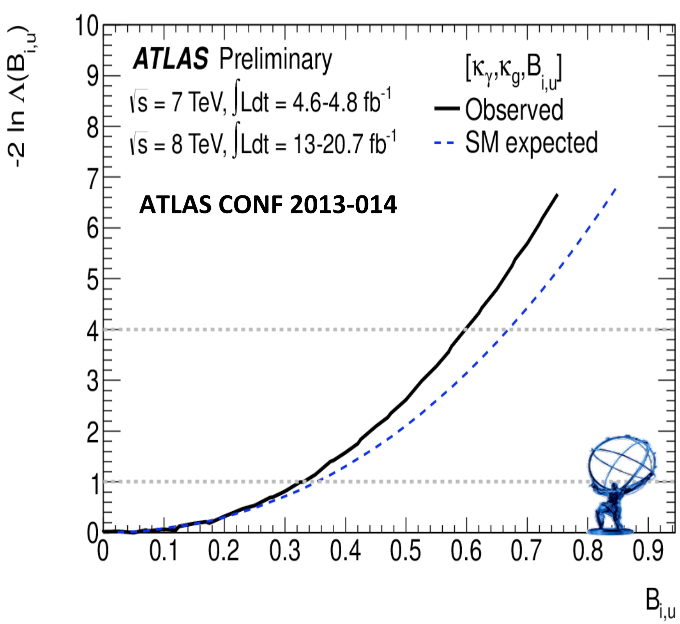
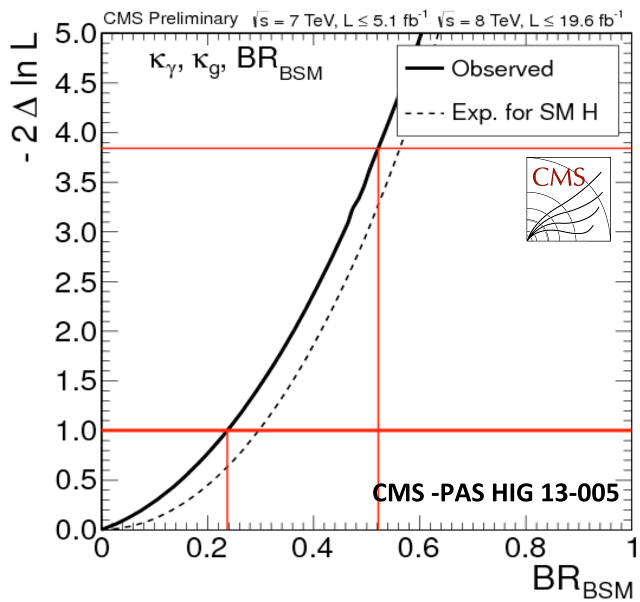
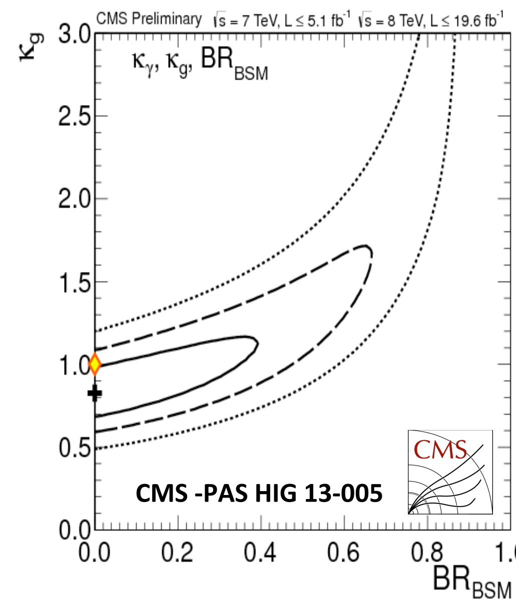
Probing for BSM also in decays

- As previous model, but introduce an extra parameter for BSM decays, affecting Γ_{tot}
  Set upper limits on BR_{BSM} profiling κ_g, κ_γ





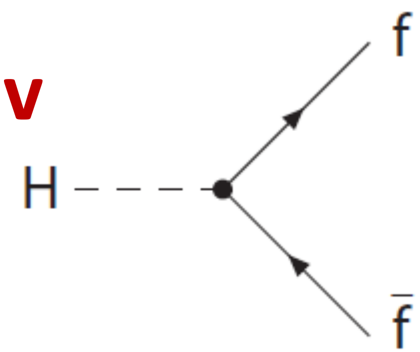


note strong correlation κ_g vs BR_{BSM} from $\mu(gg \rightarrow H \rightarrow VV)$

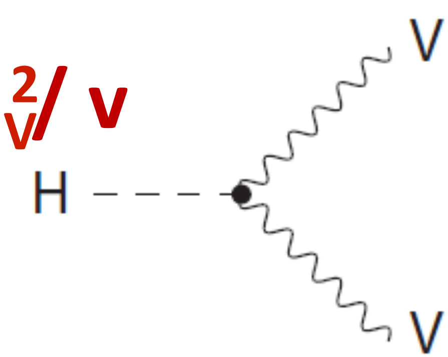
Fit coupling deviations vs mass

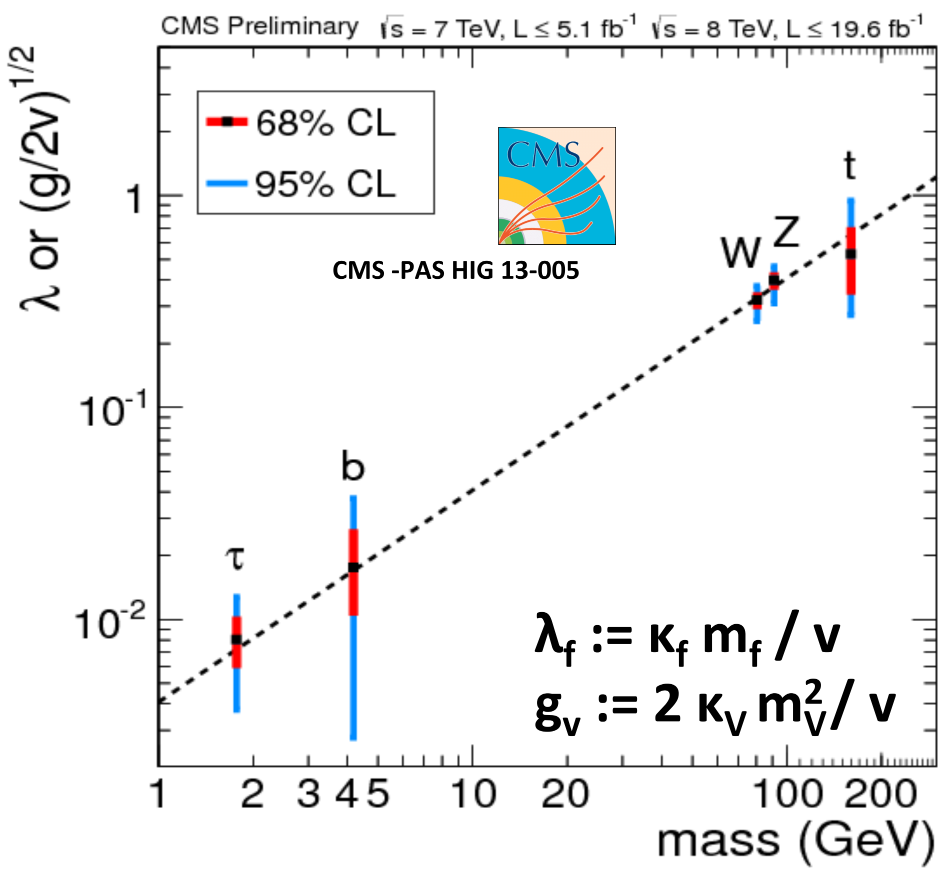
- Fit to all tree-level couplings vs particle mass. $\gamma\gamma$ and gg loops resolved in terms of tree-level couplings as in SM.

$\lambda_f = m_f / v$



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





Couplings, summary

All in all, everything is quite consistent with a SM Higgs.

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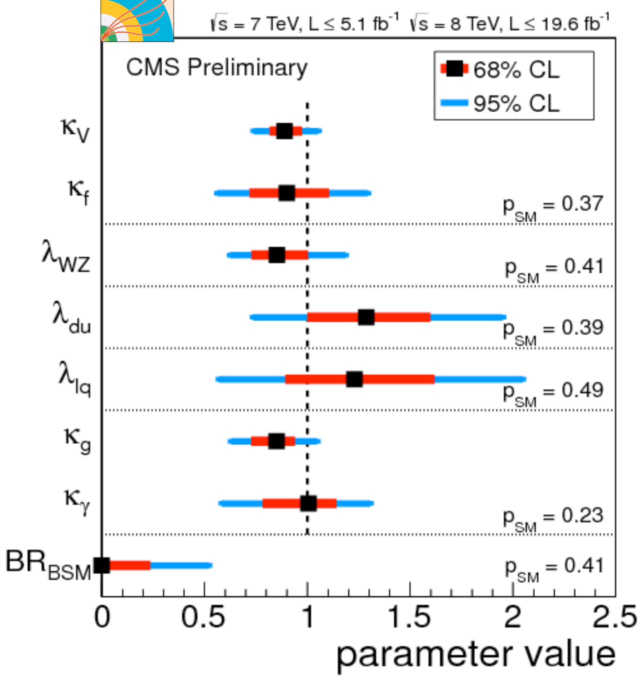
Benchmark models



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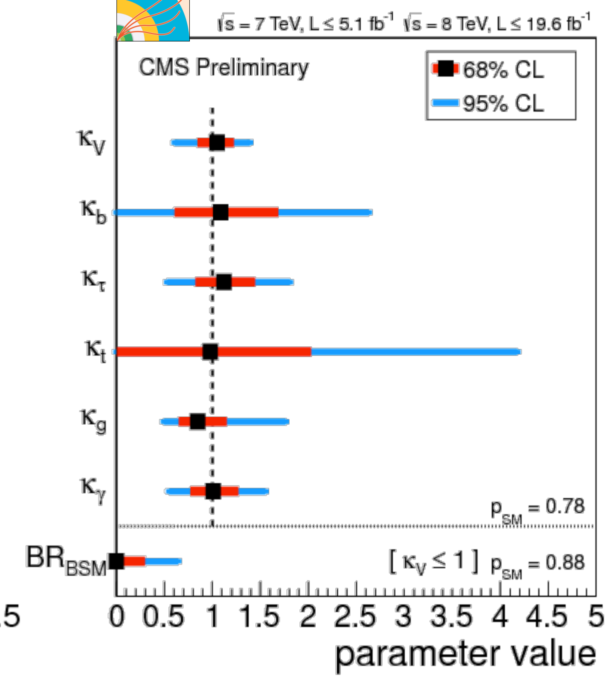
General κ fits



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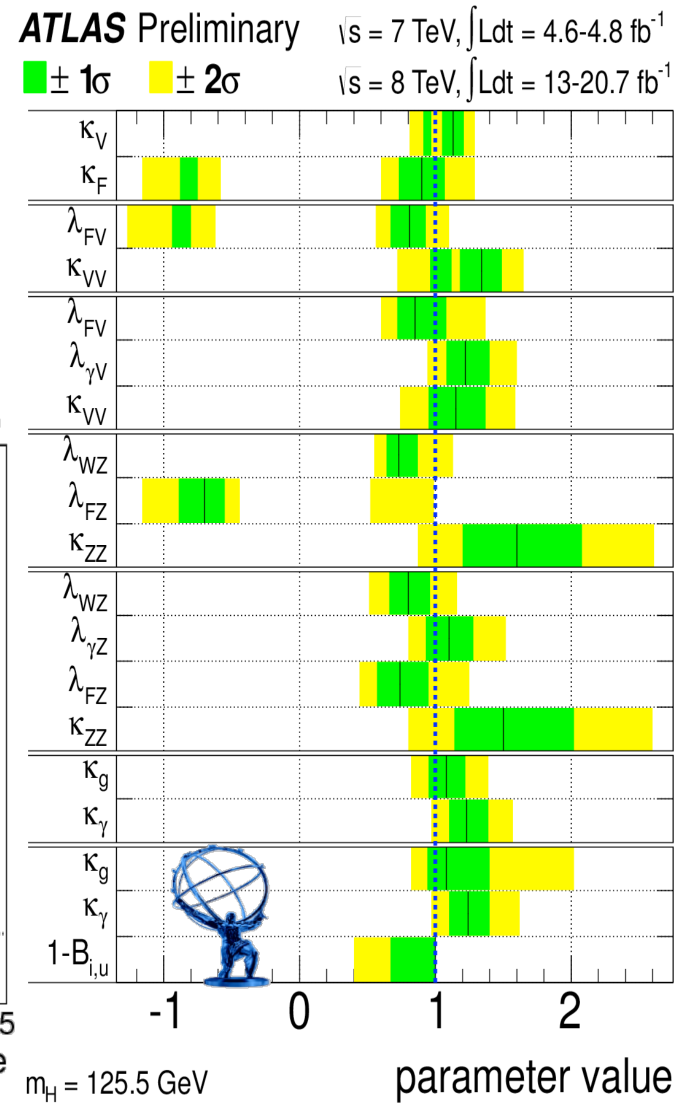

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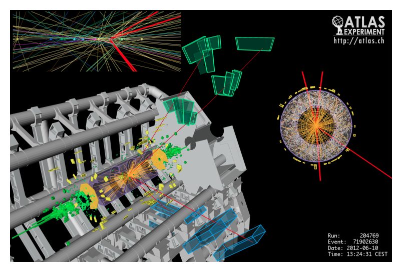
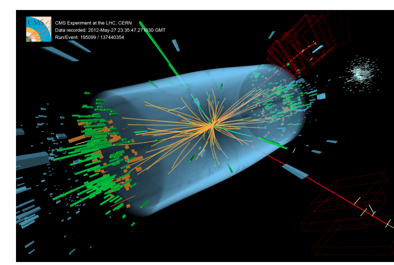
Spin and parity





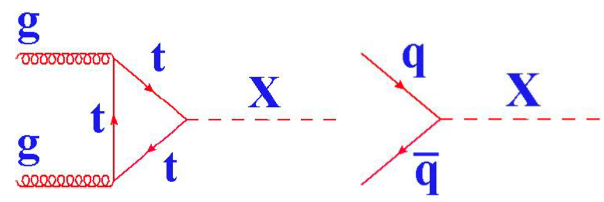
combination:	**ATLAS-CONF-2013-040**	**CMS-PAS-HIG-13-005**
H→γγ:	**ATLAS-CONF-2013-029**	**.**
H→ WW→ lν lν :	**ATLAS-CONF-2013-031**	**CMS-PAS-HIG-13-003**
H→ ZZ→ 4l:	**ATLAS-CONF-2013-013**	**CMS-PAS-HIG-13-002**

Spin and parity of the new resonance

- A new resonance discovered by ATLAS and CMS
- Is this the Standard Model Higgs Boson?
  - Measurement of its quantum numbers necessary in addition to the couplings to fermions and gauge bosons
  - The SM Higgs is a neutral scalar with $J^{CP}=0^{++}$
- The new resonance decay in pairs of gauge bosons with total charge 0
  - Parity to be determined, integer spin
  - Observation of $\gamma\gamma$ decay $\rightarrow$ Spin 1 disfavored (Landau-Yang theorem)

Spin parity measurement

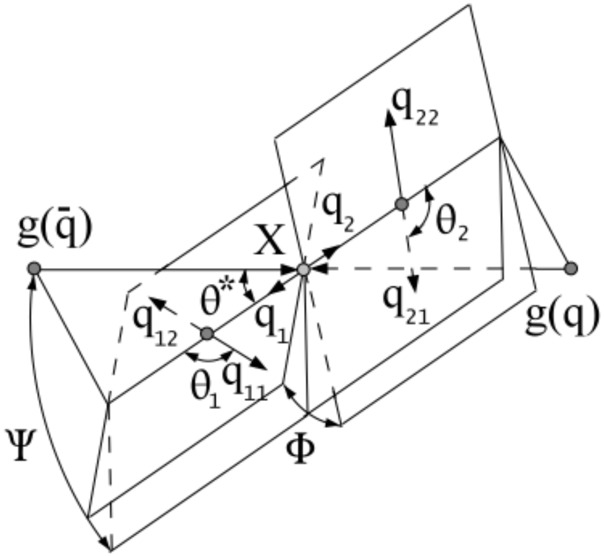
- Production mechanism:
  - Spin 0: gluon gluon fusion
  - Spin 1: qqbar production
  - Spin 2: both gluon gluon fusion and qqbar production
    - Observables sensitive to qqbar production fraction f_{qq} → different polarizations along collision axis selected
    - Exclusion can be studied as function of the f_{qq}



- Most general lagrangian for spin 2 contains many free parameters
  - Impossible to exclude all models → Graviton inspired tensor with minimal couplings to SM particles (2^{+}_{m}) considered
- Different spin parity hypothesis tested against SM $J^P=0^+$
  - $H \to ZZ^* \to 4l$: $J^P = 0^-, 0^+_h, 1^-, 1^+, 2^+_m$
  - $H \to \gamma\gamma$: $J^P = 2^+_m$
  - $H \to WW^* \to l\nu l\nu$: $J^P = 2^+_m$
- Test statistic: ratio of profile likelihoods for the two alternative hypothesis 0+ and J^P_{alt}
  - Signal strength and NP profiled

$$q = \log \frac{\mathcal{L}(0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{alt}, \hat{\hat{\mu}}_{J^P_{alt}}, \hat{\hat{\theta}}_{J^P_{alt}})}$$

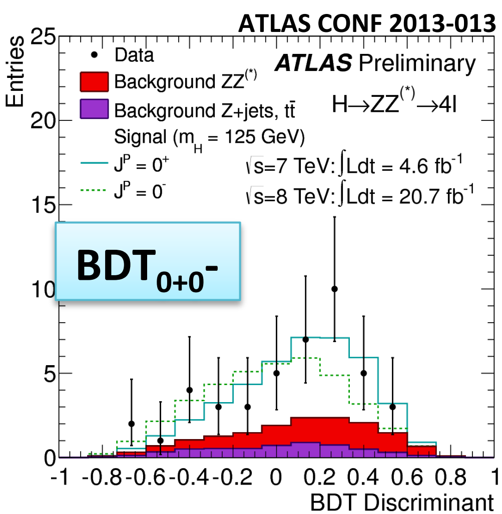
Spin parity measurement in H→ ZZ*→4l

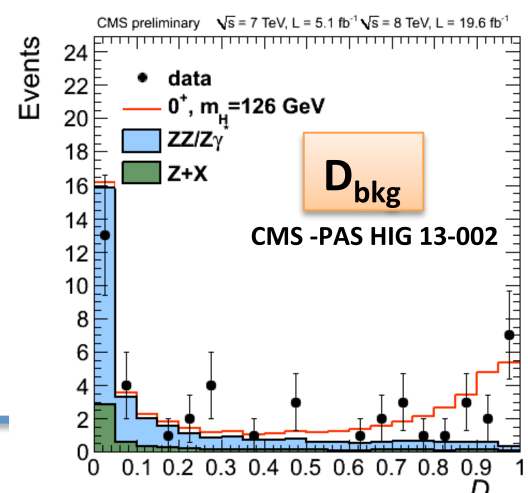


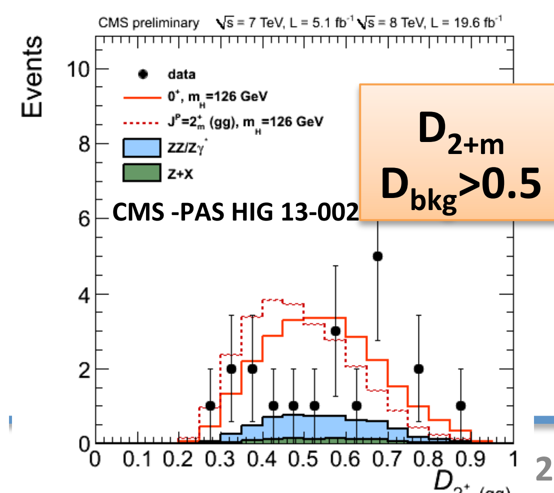
- Full final state reconstruction
  - Access to the spin and parity of the underlying resonance
- Discriminating variables:
  - m_Z, m_{Z^*}, 5 production and decay angles.
- Multivariate discriminant to separate different J^P used (MELA, BDT)

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

- $D_{bkg} = P_{sig}/(P_{sig}+P_{bkg})$ or m_{4l} used against ZZ background







Spin parity measurement in H→ ZZ*→4l

- **Observed exclusion for alternative hypotheses in favor of Standard Model $J^P=0^+$**

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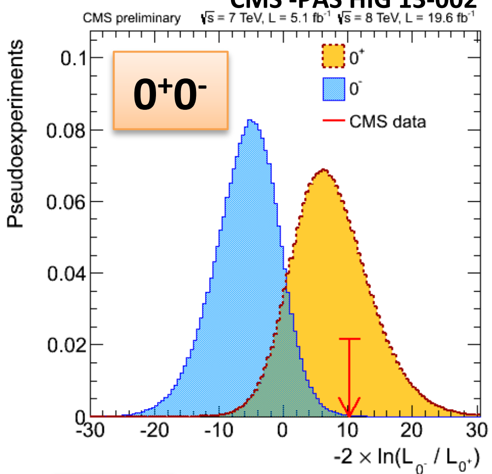

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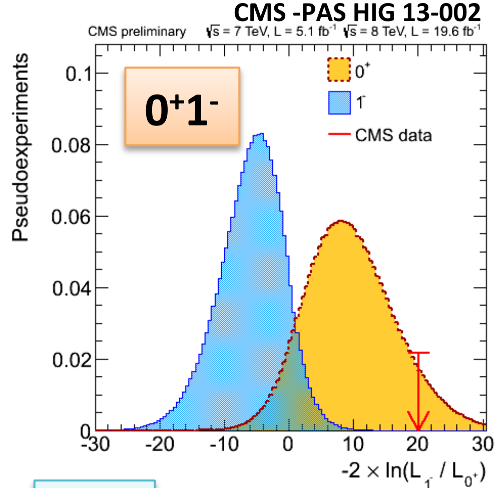

J^P	CL_s (CMS)	CL_s (ATLAS)
0^-	0.16%	0.4%
0^+_h	8.1%	-
2^+_{mgg}	1.5%	16.9%
2^+_{mqq}	<0.1%	11.5%
1^-	<0.1%	3.1%
1^+	<0.1%	0.2%

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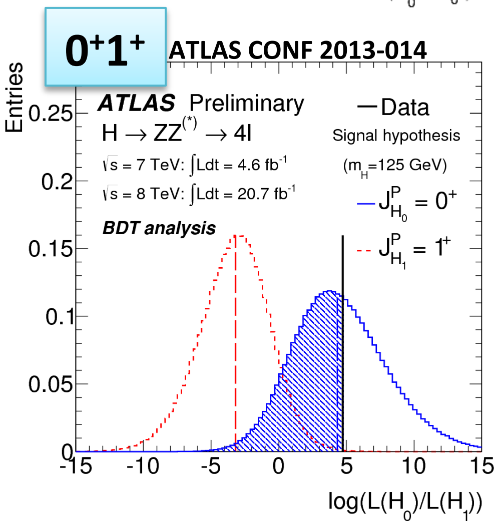

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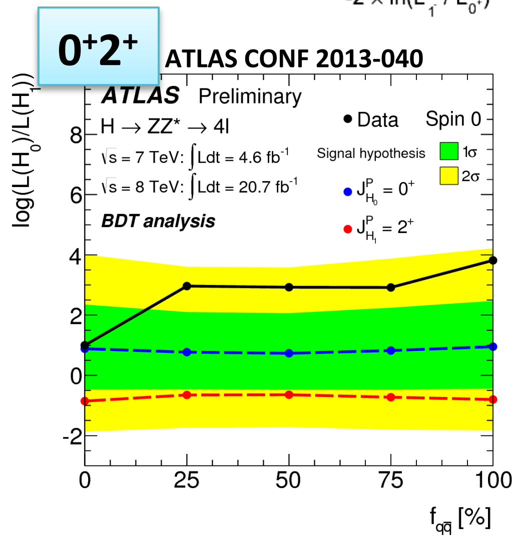

- **Data prefers $J^P=0^+$**
- **$J^P = 0^-, 1^+, 1^-, 2^+_{mgg}, 2^+_{mqq}$ excluded at >95% CL**

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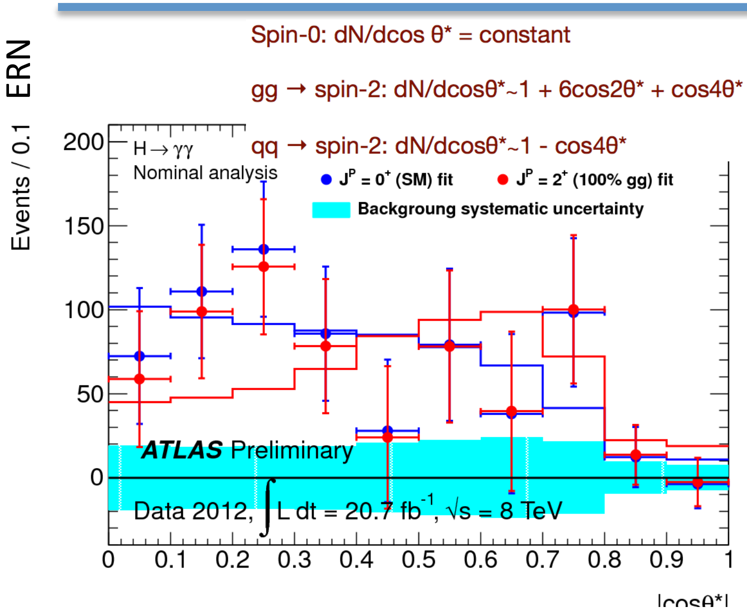
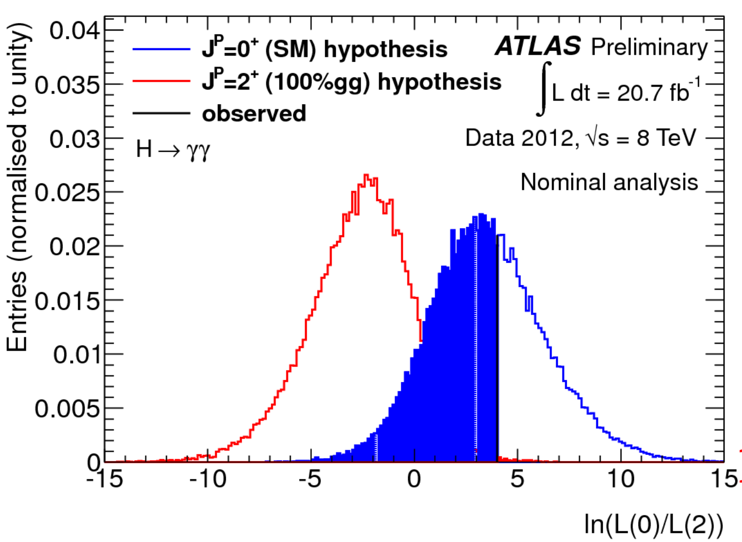
Spin measurement in H→ γ γ





- $|\cos(\theta^*)|$ used as discriminating variable
  - For spin 0 isotropic distribution before kinematic cuts

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2} .$$

- Signal region: 122 GeV<$m_{\gamma\gamma}$<130 GeV
- Background shape taken from data

	$f_{q\bar{q}}$ (%)	Spin hypothesis	p-values (%) expected	p-values (%) observed	$1-\mathrm{CL_S}(2^+)$ (%)
2^+_m	0	0^+ 2^+	1.2 0.5	58.8 0.3	99.3
	25	0^+ 2^+	5.2 3.9	60.9 2.1	94.6
	50	0^+ 2^+	19.8 18.7	70.8 7.6	74
	75	0^+ 2^+	31.9 30.5	90.2 3.3	66
	100	0^+ 2^+	14.8 13.5	79.8 2.5	88

Data exclude $J^P=2^+_m$ in favor of $J^P=0^+$ at 99.3% CL

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Spin measurement in H→ WW*→ lν lν

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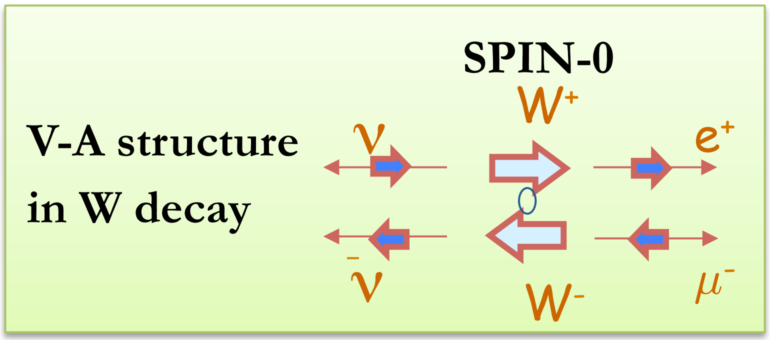
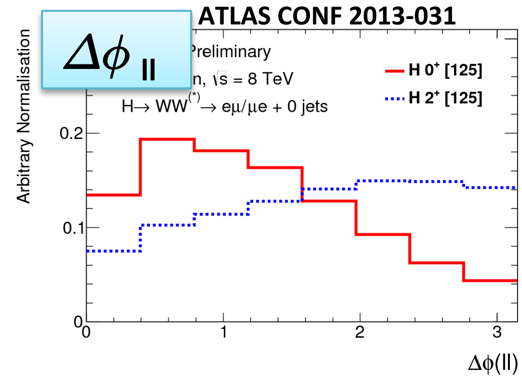
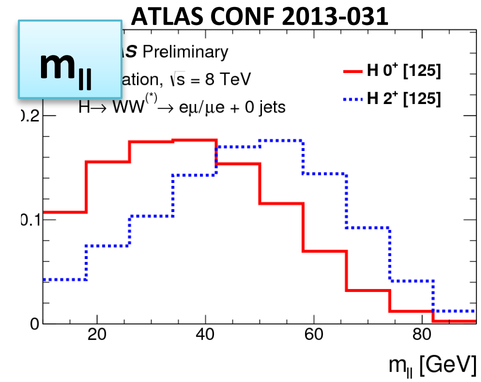
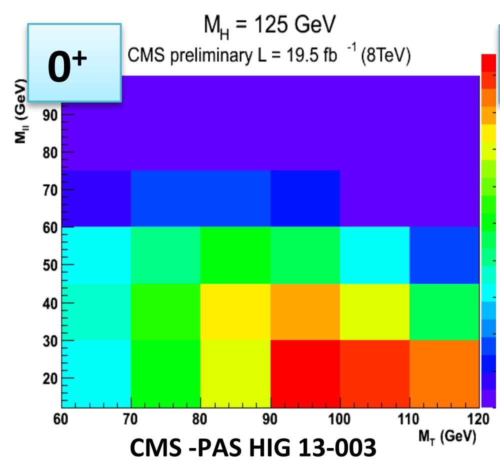
- **Discriminating variables:**
  - M_{ll}, $\Delta\phi_{ll}$, $p_{T,ll}$, $E^{miss}_{T,rel}$

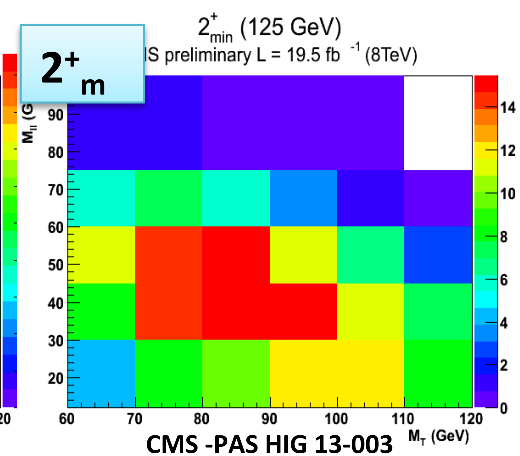


- e/μ final state used due to relative low background
- Analysis approaches with 2D template fit
  - CMS: (m_{ll}, m_T)
  - ATLAS: (BDT 0^+- bkg , BDT 2^+- bkg)









Spin measurement in $H \rightarrow WW^* \rightarrow l\nu \, l\nu$

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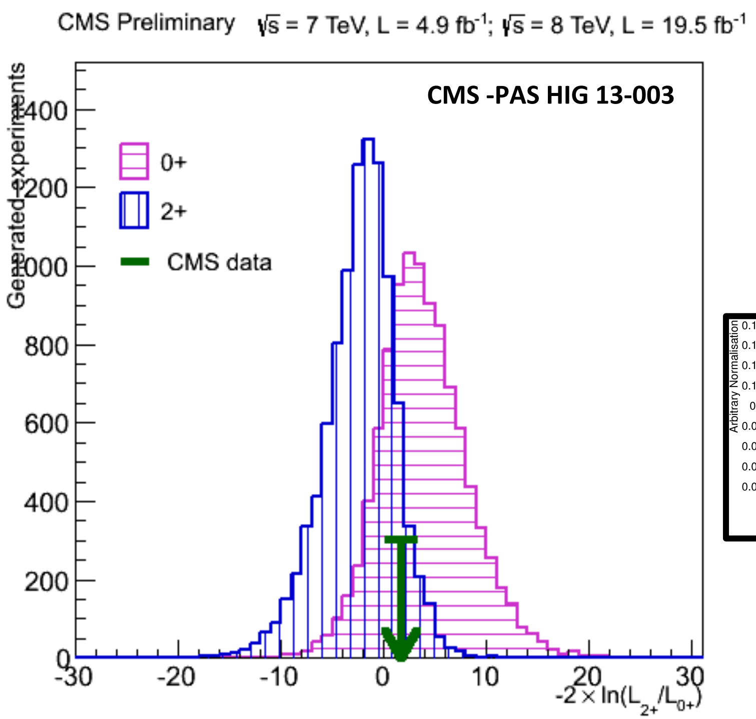
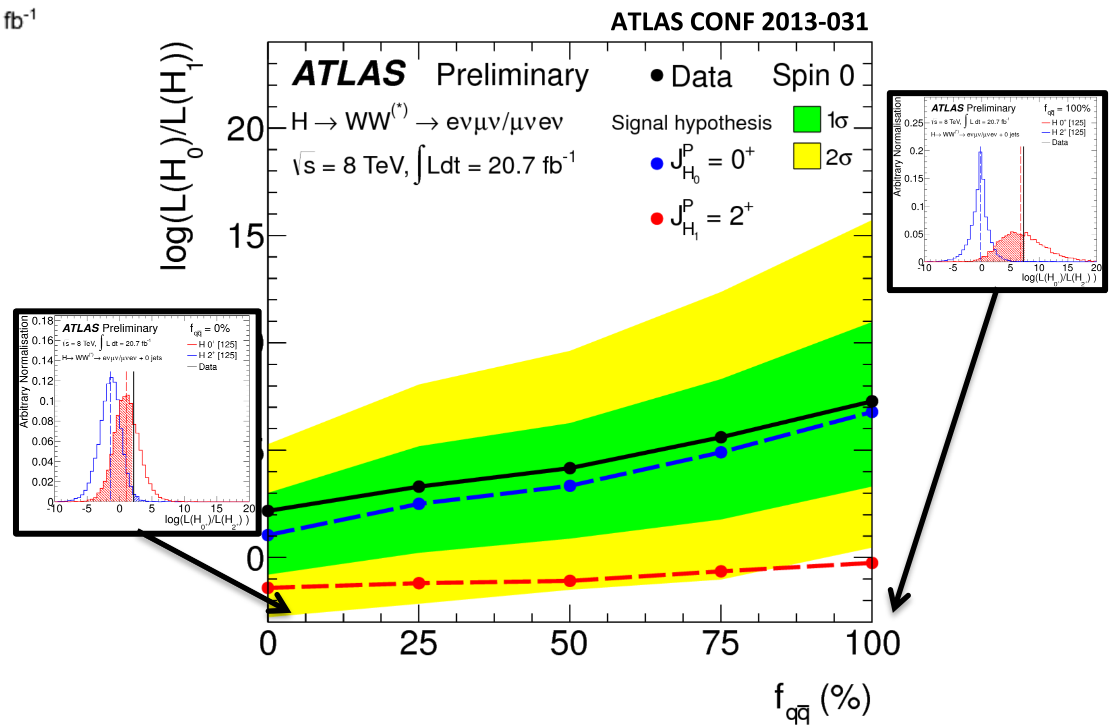
- Separation between Standard Model $J^P=0^+$ and $J^P=2^+$ increases with qq fraction





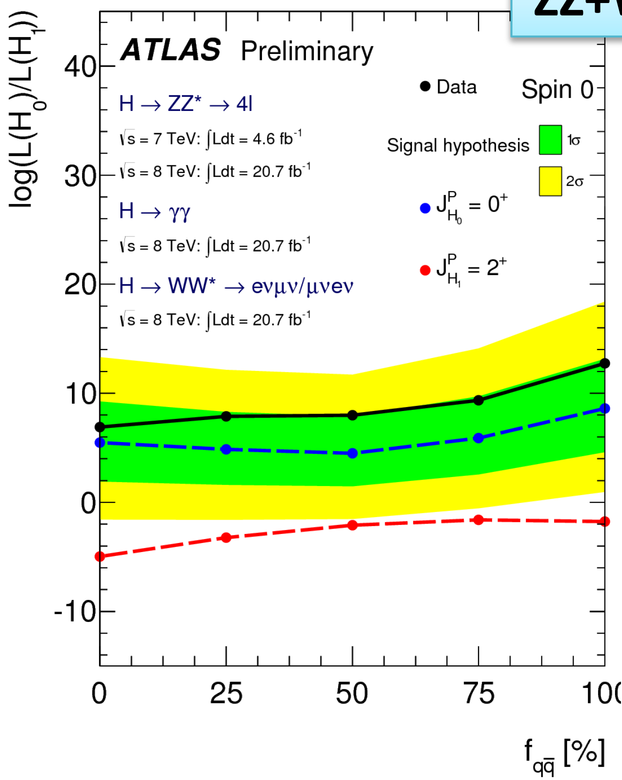
- Data prefers SM $J^P=0^+$ in the WW channel
- $J^P=2^+_m$ excluded in favor of $J^P=0^+$ at 94.7% CL

Spin Measurement Combination

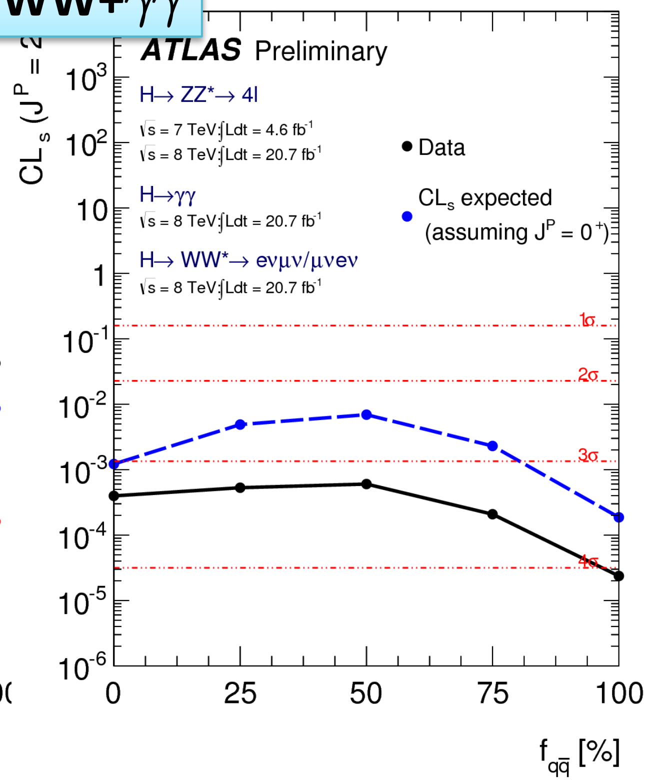
- Exclusion of $J^P=2^+$ in favor of the Standard Model $J^P=0^+$ for ATLAS and CMS

ZZ+WW+$\gamma\gamma$

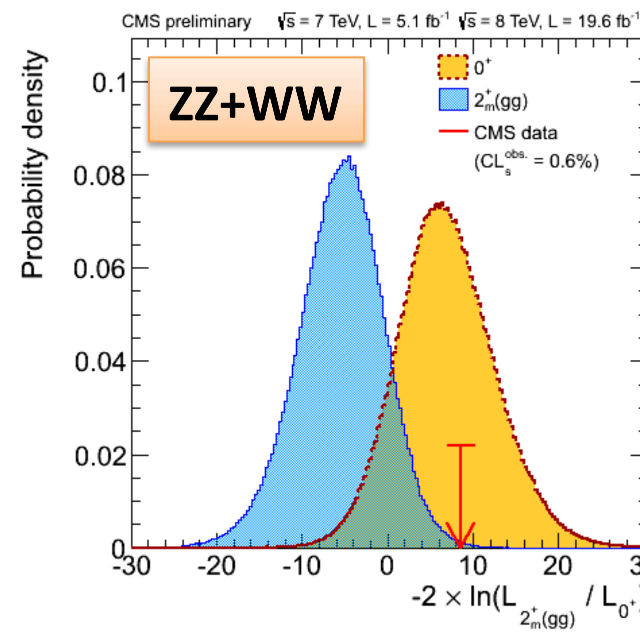
ATLAS CONF 2013-040



ATLAS CONF 2013-040



CMS -PAS HIG 13-002



- Combination of decay channel allow to exclude the $J^P=2^+$ hypothesis at >99.9 % CL (ATLAS:ZZ+WW+$\gamma\gamma$) and 99.4% CL (CMS:ZZ+WW)

CP violation in the Higgs sector

- **In several BSM theories anomalous contribution to Higgs sector and (or) CP violation predicted**
- **HZZ vertex well suited for CP violation study**
  - Same observables as for the spin parity measurement
- **Most general vertex for spin=0 boson coupling to 2 vector bosons**

$$A(X \rightarrow VV) \sim (a_1 M_X^2 g_{\mu\nu} + a_2 (q_1 + q_2)_\mu (q_1 + q_2)_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta) \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}$$

CP-even

CP-odd

- **$a_1=1$, $a_2=0$ $a_3=0$ → Standard Model**
- **CP violation with $a_3 \neq 0$ with $a_1 \neq 0$ and/or $a_2 \neq 0$**

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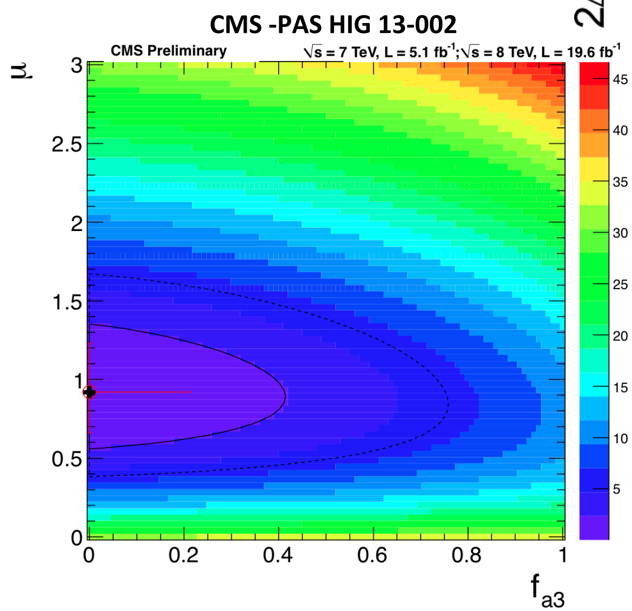
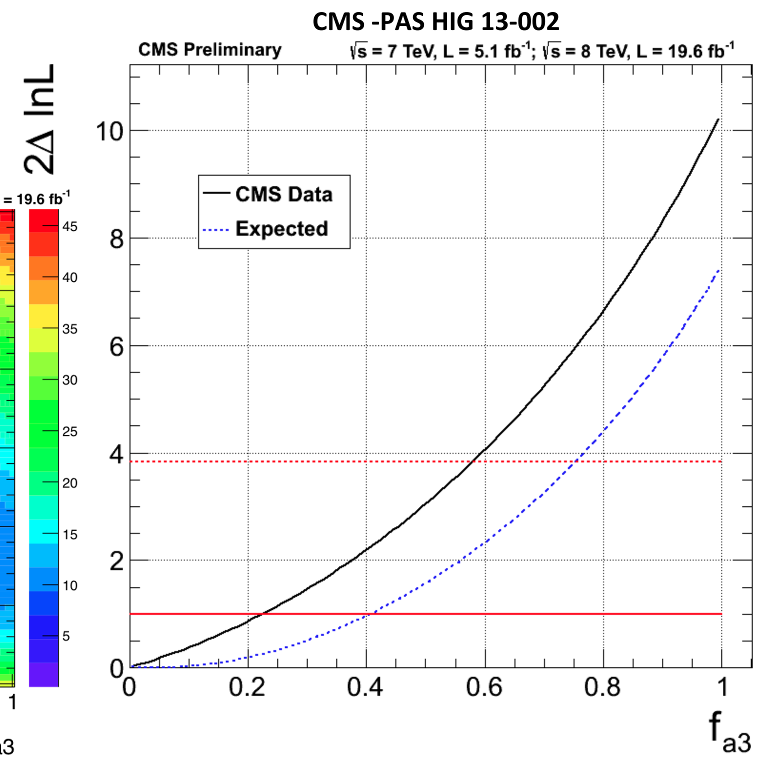
CP violation in HZZ vertex

- The amplitude A(X→VV) can be written in the form A(X→VV) $=A_1+A_2+A_3$
- The quantity f $f_{a3} = |A_3|^2/(|A_1|^2 + |A_3|^2)$ represents the fraction of the signal observed with a **CP-odd component**
  - Model independent quantity
  - $f_{a3}>0$ imply **CP violation** in HZZ vertex

Preliminary CMS limit:
$f_{a3} < 0.58$ at 95%CL





Conclusions and prospective

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- Nature of the new particle discovered consistent with the Standard Model Higgs boson
- Results from ATLAS and CMS shows that the dominant spin and parity of the new resonance is 0^+
- Preliminary limit on the CP-violation in the Higgs sector
  - Still low statistics → Only large anomalous contribution can be excluded
- Possible future investigation using VBF production mechanism

Backup

$H \rightarrow \gamma\gamma$

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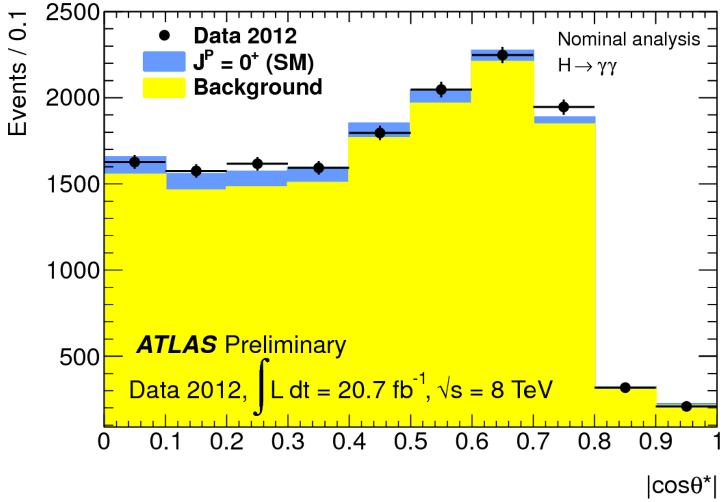

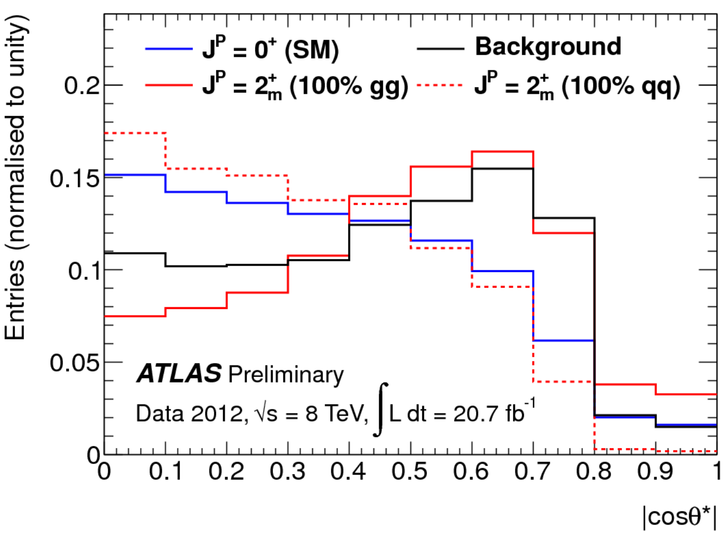

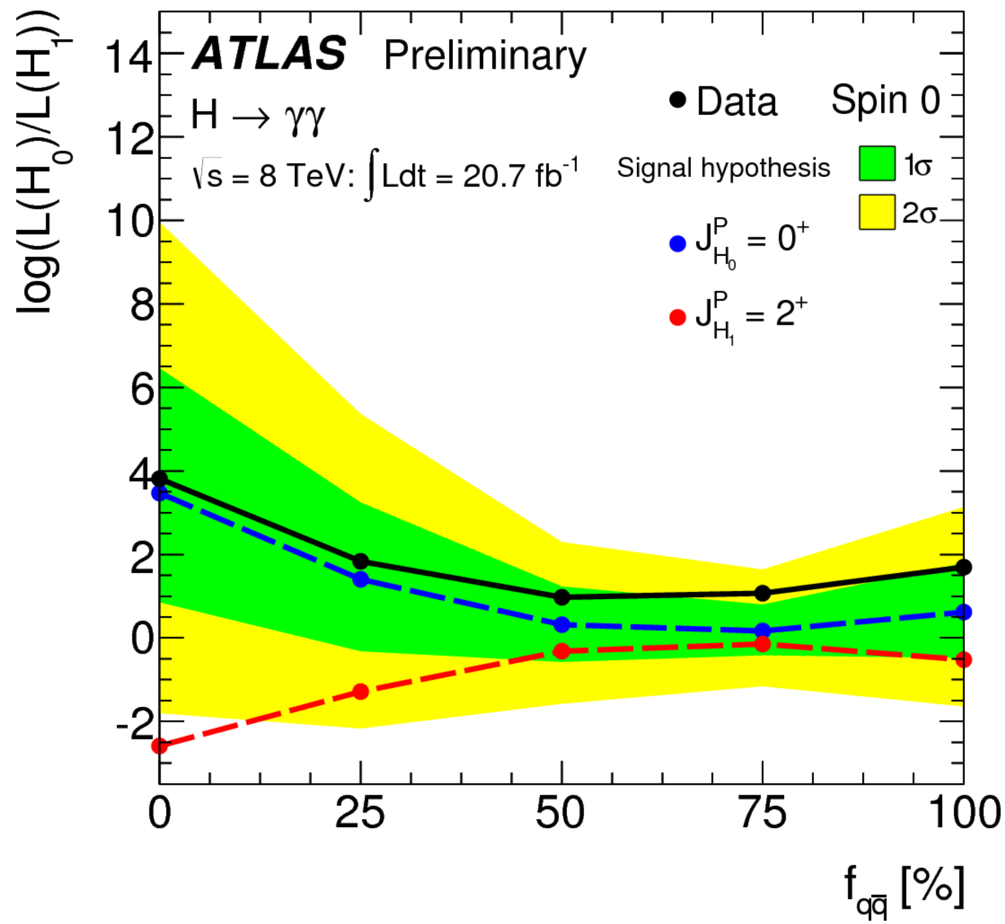

ATLAS CONF 2013-029

H→ ZZ→ 4l

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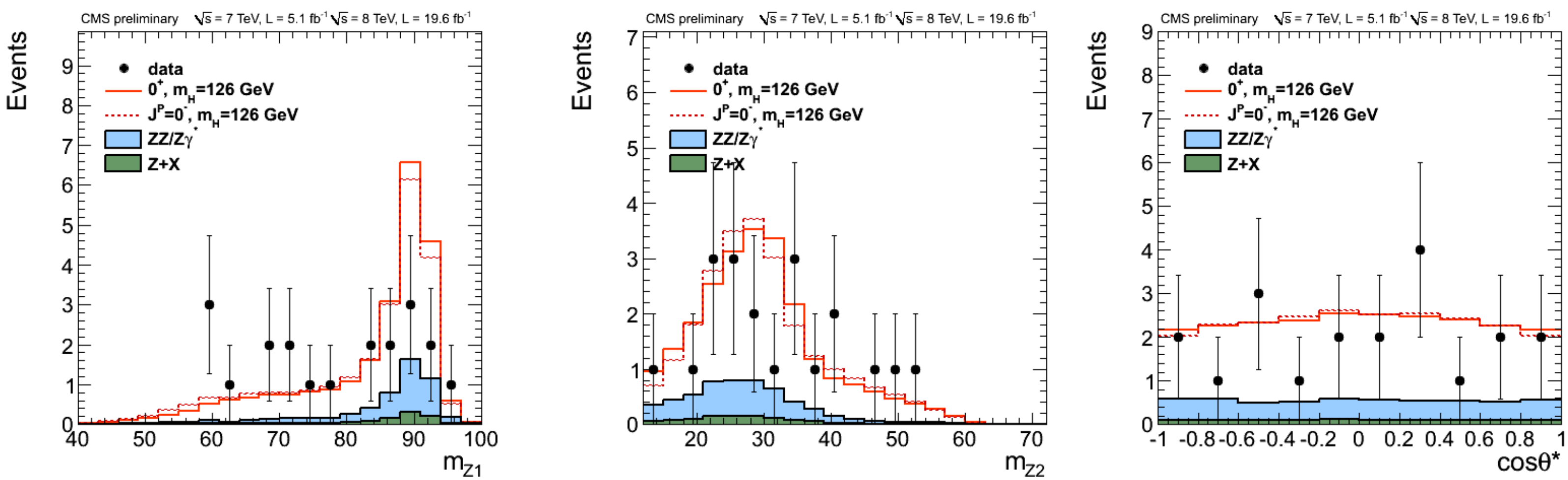
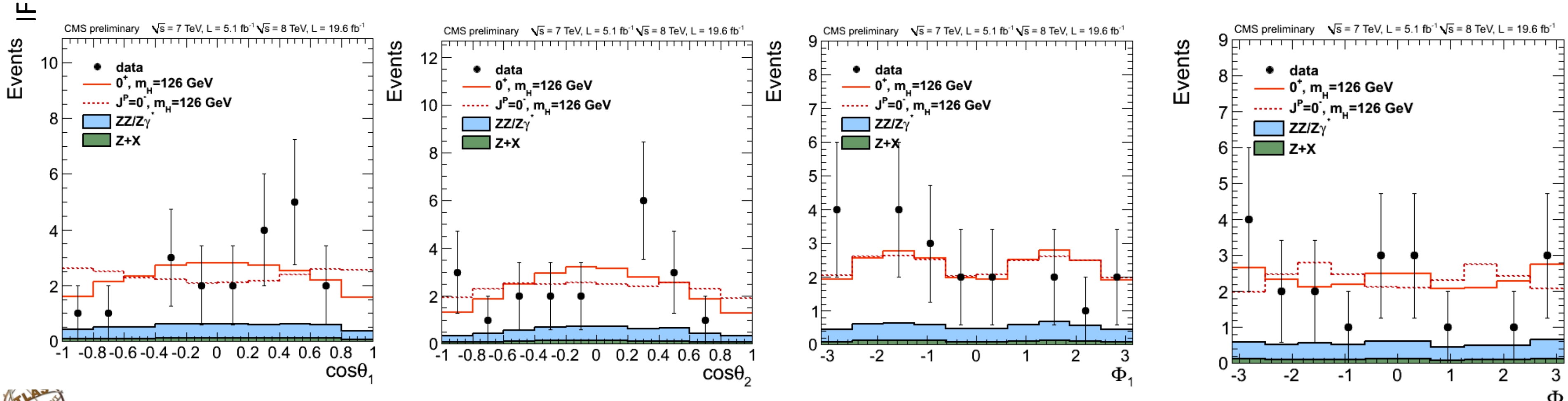
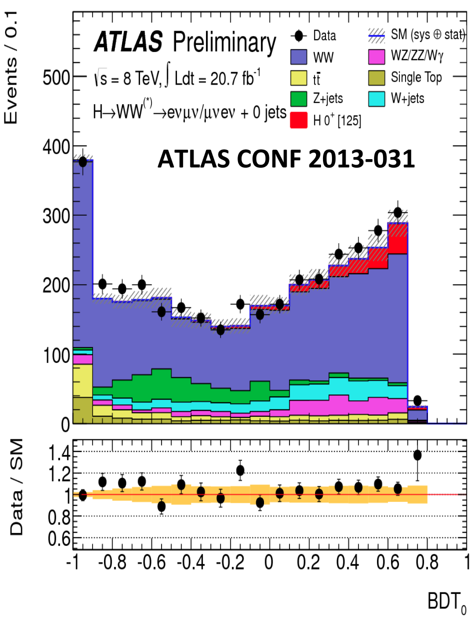
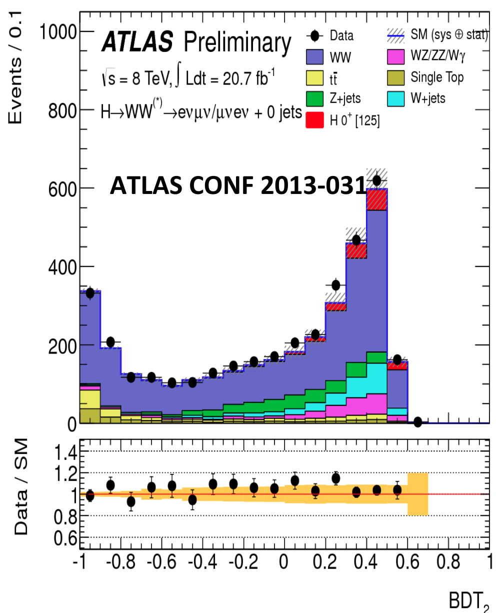


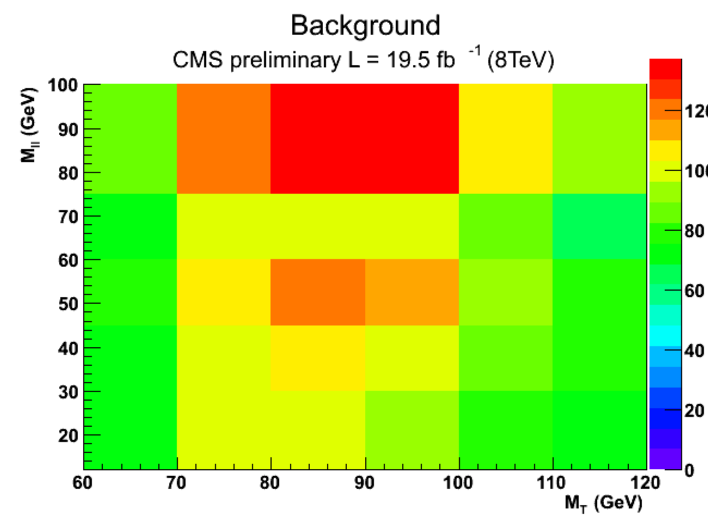


H→ WW

- **Main bkg:**
  - Z->tt, W+jet, tt, WW





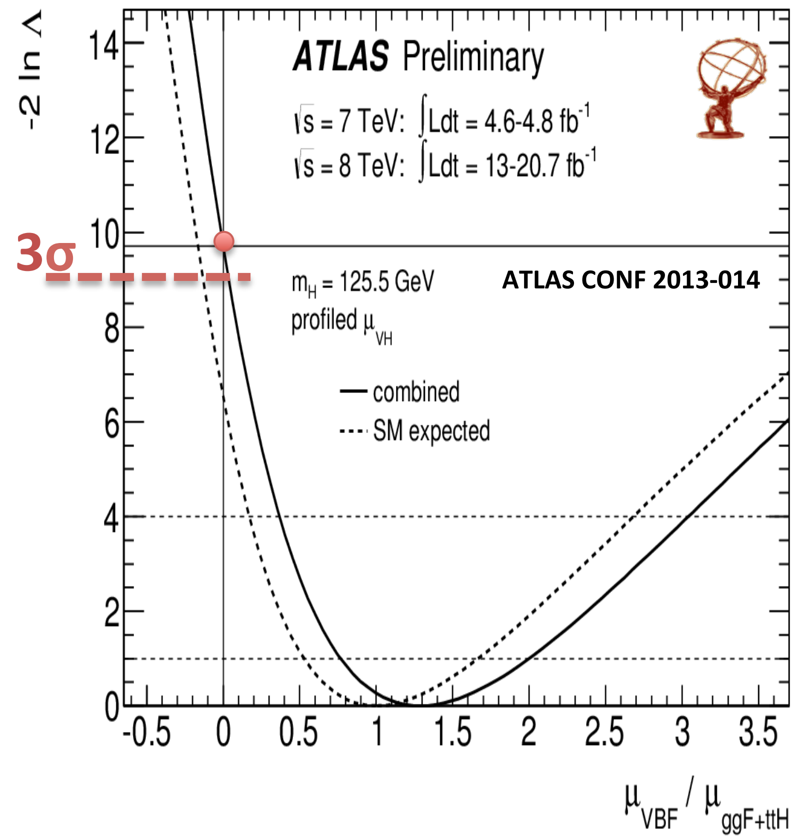


CMS -PAS HIG 13-003

Backup

Testing production modes: ratios

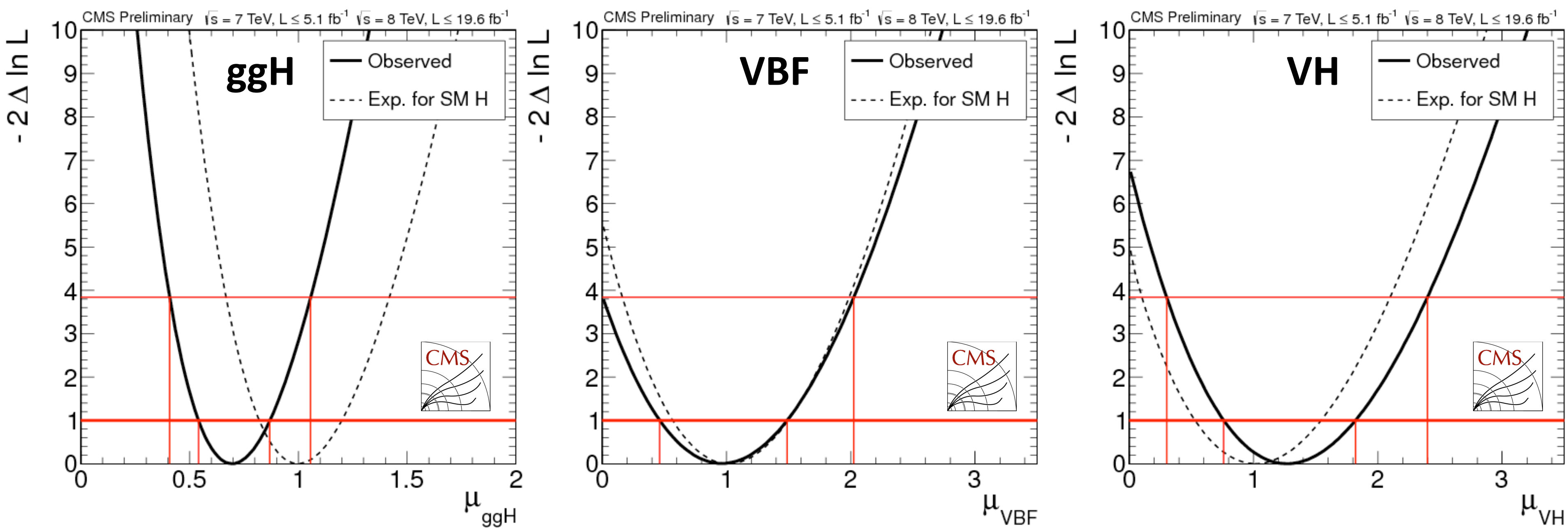
- ATLAS: fit for μ(VBF)/μ(ggH+ttH) ratio while leaving μ(VH) floating.
- **3.1σ evidence for VBF production.**



Testing production modes: fits

- CMS: simultaneous fit with one signal strength per production mode, assuming BR's to be as predicted for the SM Higgs.

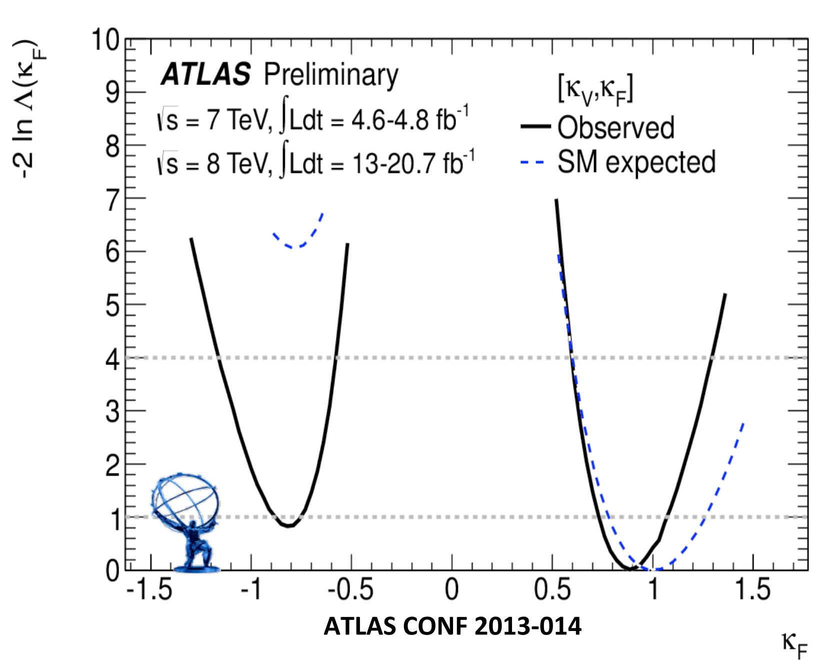
CMS -PAS HIG 13-005



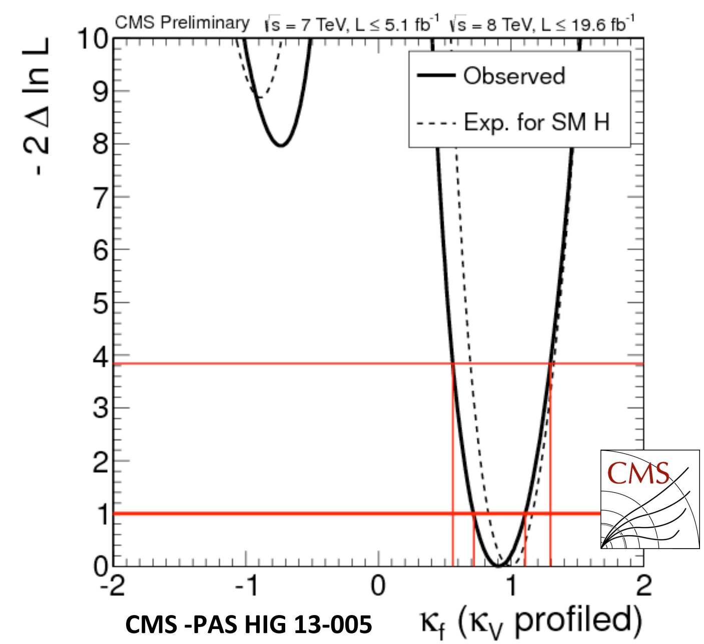
(Still pretty far from SM sensitivity in ttH alone, so no plot for that)

Interference and disfermiophylia

- The $\kappa_f < 0$ region has been under the spotlight, initially favoured by Hγγ excesses, now less so (disfavoured at 2.7σ by CMS, 1σ by ATLAS).
- Interference being chased also in tH prod., where effect is larger, but no experimental result yet.



ATLAS CONF 2013-014



CMS -PAS HIG 13-005

Testing decay mode: ratios

- ATLAS: fit for ratio of branching fractions for two decay modes, relaxing assumptions on the production (ie profiling $\mu_{VBF,VH}/\mu_{ggH,ttH}$)

ATLAS CONF 2013-014

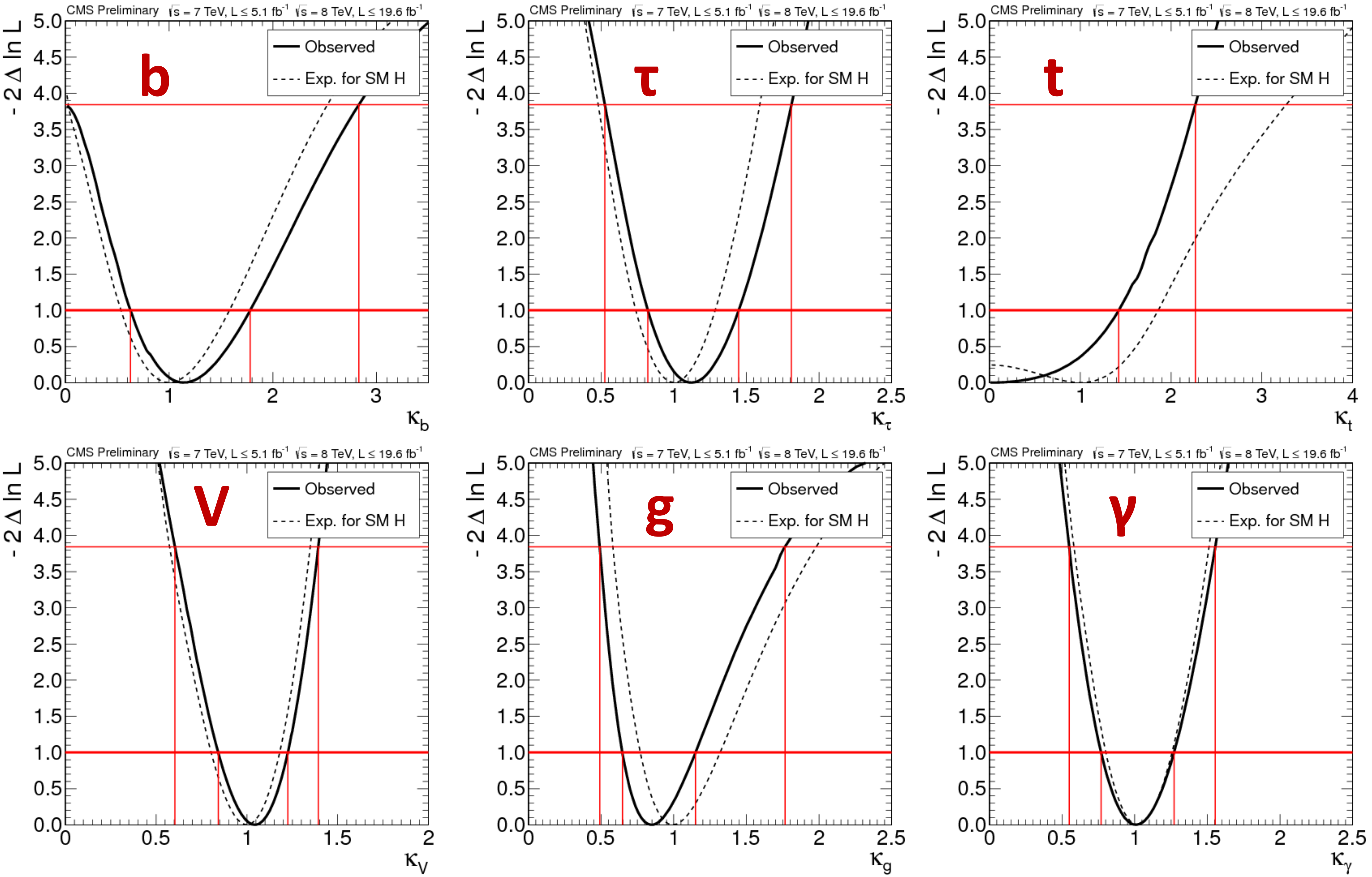
$$\rho_{\gamma\gamma/ZZ} = 1.1^{+0.4}_{-0.3}$$

$$\rho_{\gamma\gamma/WW} = 1.7^{+0.7}_{-0.5}$$

$$\rho_{ZZ/WW} = 1.6^{+0.8}_{-0.5}$$

Fit all couplings at once

CMS -PAS HIG 13-005



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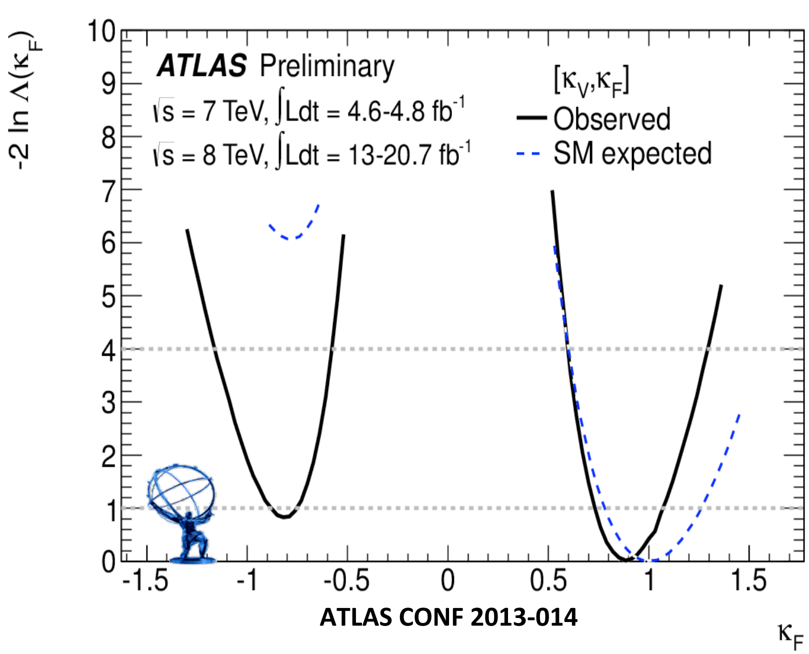
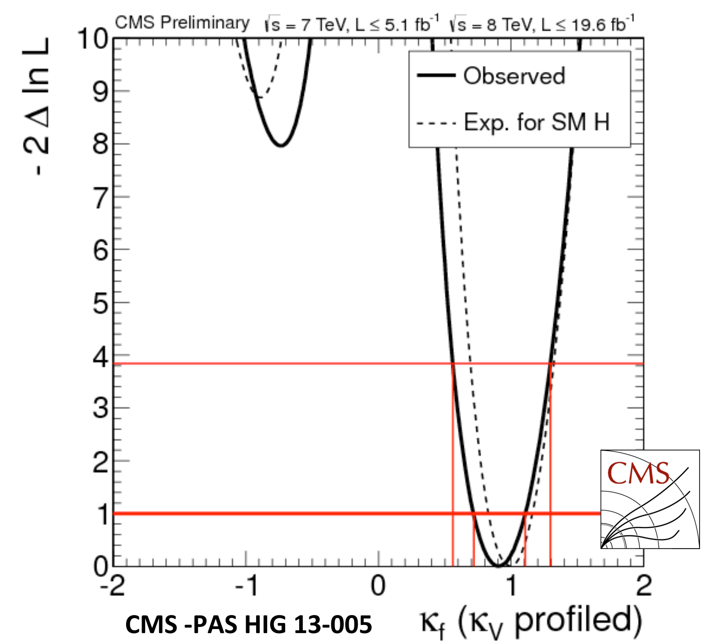


ATLAS CONF 2013-014



CMS -PAS HIG 13-005