CMS – Higgs coupling and spin studies

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for the CMS collaboration

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Higgs Hunting Orsay-France
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CMS Higgs Results

- Avalanche of CMS results in past month...
  - *"Constraints on anomalous HVV interactions using $H \to 4\ell$ decays"*
    (CMS-PAS-HIG-14-014, July 3, 2014)
  - *"Constraints on Anomalous HWW Interactions using Higgs boson decays to W+W- in the fully leptonic final state"*
    (CMS-PAS-HIG-14-012, July 3, 2014)
  - *"Precise determination of the mass of the Higgs boson and studies of the compatibility of its couplings with the standard model"*
    (CMS-PAS-HIG-14-009, July 3, 2014)
  - *"Observation of the diphoton decay of the Higgs boson and measurement of its properties"*
    submitted to EPJ C (arXiv:1407.0558, July 2, 2014)
  - *"Evidence for the direct decay of the 125GeV Higgs boson to fermions"*
    Nature Phys. 10 (doi:10.1038/nphys3005, June 22, 2014)

CMS Higgs Couplings

CMS Higgs searches

	Inclusive (ggH)	VBF tag	VH tag	$t\bar{t}H$ tag
$H \to b\bar{b}$		✓	✓	✓
$H \to \tau\tau$	✓	✓	✓	✓
$H \to WW$	✓	✓	✓	✓
$H \to ZZ$	✓	✓	✓	✓
$H \to \gamma\gamma$	✓	✓	✓	✓
$H \to Z\gamma$	✓	✓		
$H \to \mu\mu$	✓	✓		
$H \to$ invisible		✓	✓	

✓ Used in the current combination (CMS-PAS-HIG-14-009)

- 200+ categories, 2500+ nuisance parameters
- Tags are never 100% pure

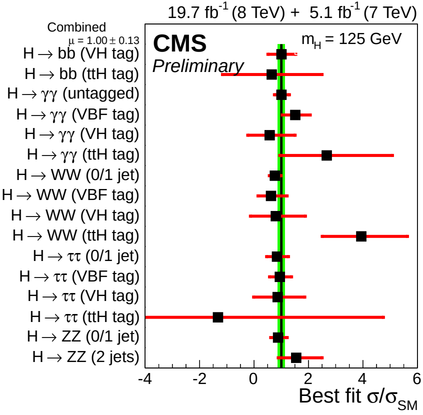
- Combination of $VH \to b\bar{b}$ and $H \to \tau\tau$ Nature Phys. 10 (doi:10.1038/nphys3005)

✓ Consistent with SM Yukawa coupling

at 125.0 GeV	Obs.	Exp.
$H \to ZZ$	6.5	6.3
$H \to \gamma\gamma$	5.6	5.3
$H \to WW$	4.7	5.4
$H \to \tau\tau$	3.8	3.9
$H \to b\bar{b}$	2.0	2.3
$H \to ff$	3.8	4.4

Global signal strength

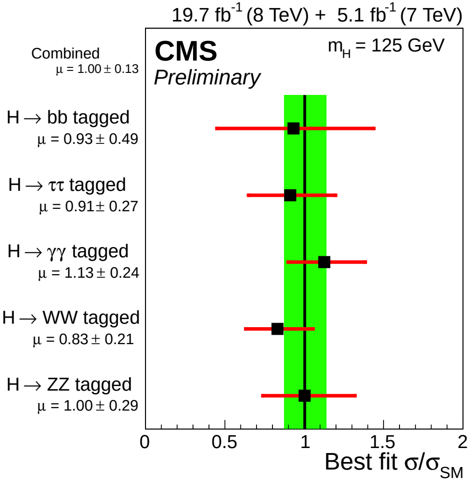
- Theoretical Uncertainties: QCD scales, PDF+α_S, UEPS, and BR
- Per production & decay tag:
  - $\chi^2/\text{d.o.f.} = 10.5/16$
  - p-value = 0.84 (asymptotic)



$$1.00 \pm 0.09(\text{stat.})\,^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})$$

- @ 125.0: See talk by S. Nourbakhsh

Signal strength

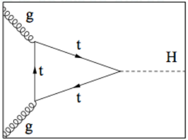


- Per decay tag:
  - $\chi^2/\text{d.o.f.} = 0.9/5$
  - p-value = 0.97 (asymptotic)

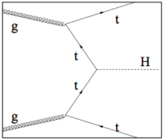
Production modes

Fermion Mediated

ggH

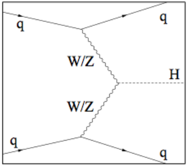


ttH

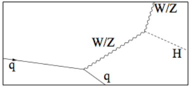


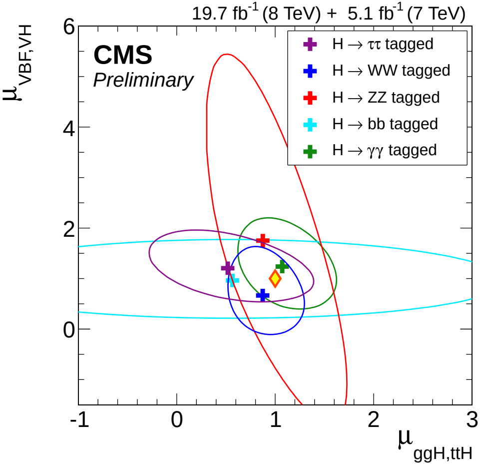
Boson Mediated

VBF

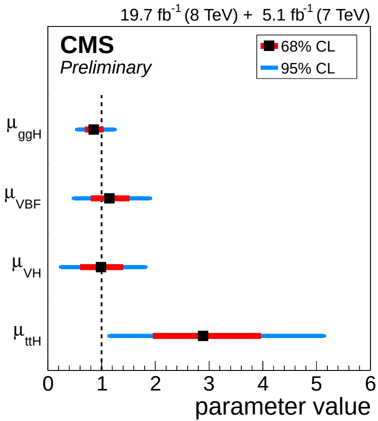


VH





Higgs production mode



- Simultaneous fit for 4 production modes
- Decay BR's are assumed to be the SM
- ttH production observes a 2σ deviation from SM

- Investigating μ_{ggH} uncertainty:
  - $0.85^{+0.11}_{-0.09}$(stat.)$^{+0.11}_{-0.08}$(theo.)$^{+0.10}_{-0.09}$(syst.)

Higgs Couplings Overview

- Following the LHCHXSWG (arXiv:1307.1347)
- Assume: single state, spin-0, and CP-even
- Narrow-width approx. $(\sigma \cdot \mathcal{B})(x \to H \to ff) = \frac{\sigma_x \cdot \Gamma_{ff}}{\Gamma_{tot}}$

Production modes

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

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

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

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

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

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

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

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

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

Currently undetectable decay modes

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

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

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

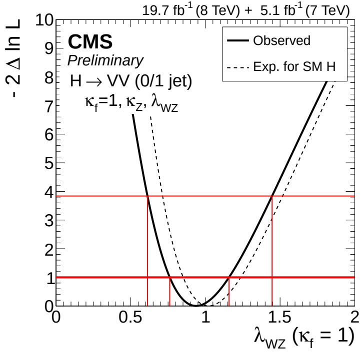
$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

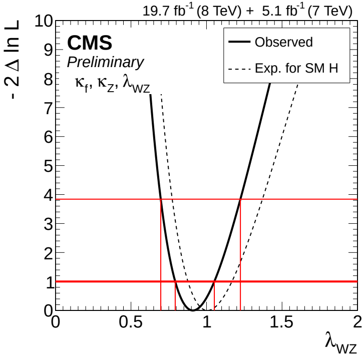
$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

Custodial symmetry?

- Using only WW and ZZ 0/1 jet categories
- $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 0.94^{+0.22}_{-0.18}$



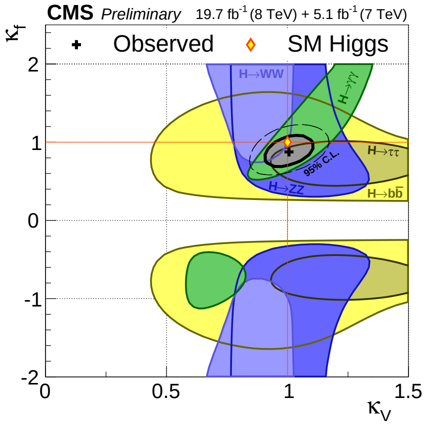
- Full combination
- $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 0.91^{+0.14}_{-0.12}$

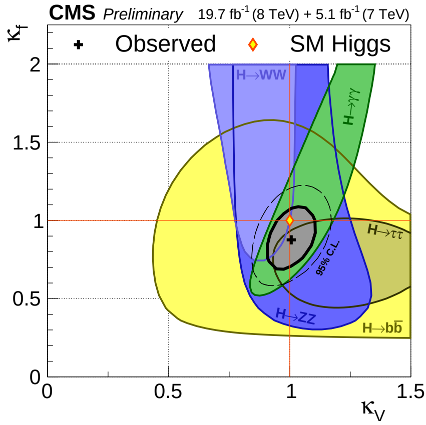


✓ Results justify treating W and Z as single coupling V

Couplings κ_V and κ_f

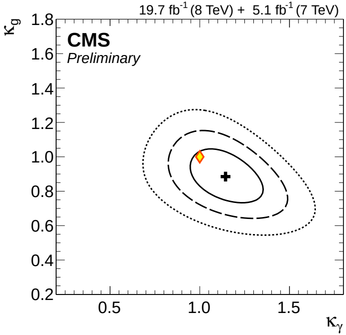
- Map vector-boson and fermion couplings to κ_V and κ_f
- two quadrant (left) and one quadrant (right)



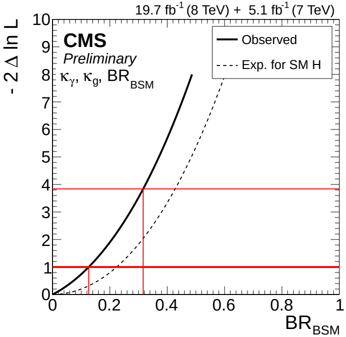


New Physics in Loops

- New particles can hide in loop mediated couplings
- Treat photons and gluons as effective couplings



- New particles can contribute to the total width
- Allow total width to scale as $1/(1 - BR_{BSM})$

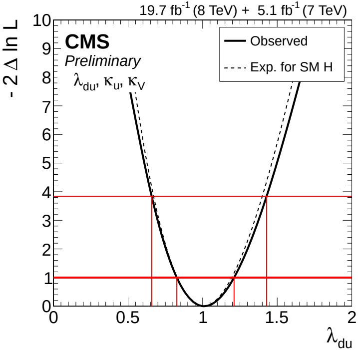


✓ Everything is consistent with SM, $BR_{BSM} < 0.32$ at 95% CL

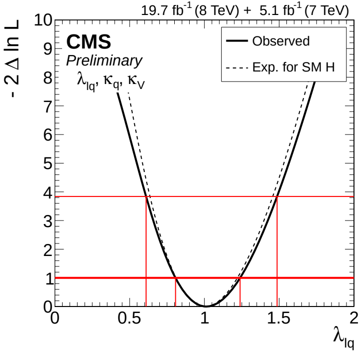
Fermion asymmetry?

- Some BSM models (e.g. 2HDM, SUSY) have altered relative couplings to fermions

- Up-type vs down-type
- $\lambda_{du} = \frac{\kappa_d}{\kappa_u} = 1.01^{+0.20}_{-0.19}$



- Leptons vs quarks
- $\lambda_{lq} = \frac{\kappa_l}{\kappa_q} = 1.02^{+0.22}_{-0.21}$

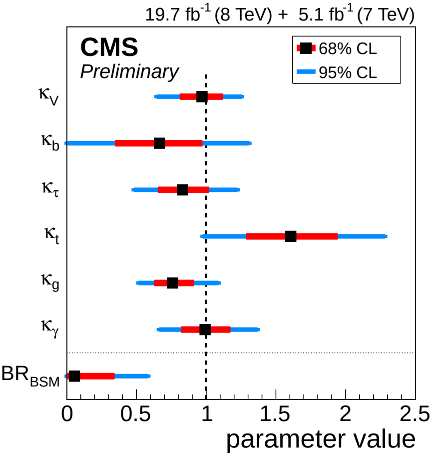


✓ No asymmetry seen

Six-parameter model

- Fit Tree-level couplings
  - Effective coupling for gluon and photon
  - Couplings to W and Z scaled by common factor
  - Couplings to third generation fermions are scaled independently
  - Partial width Γ_{BSM} is zero

- Additionally, lift last restriction but restrict $\kappa_V \leq 1$ to test BR_{BSM}



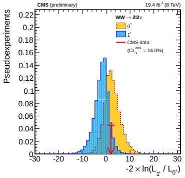
✓ Everything is consistent with SM, $BR_{BSM} < 0.58$ at 95% CL

CMS Higgs Spin-parity

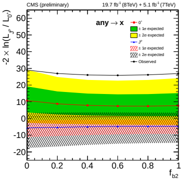
Spin-1 & 2 Results

Spin-1

WW $q\bar{q} \rightarrow 1^+$

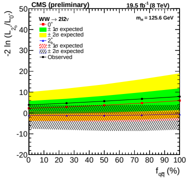


ZZ $any \rightarrow 1$

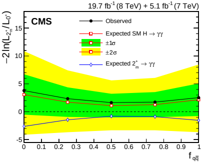


Spin-2

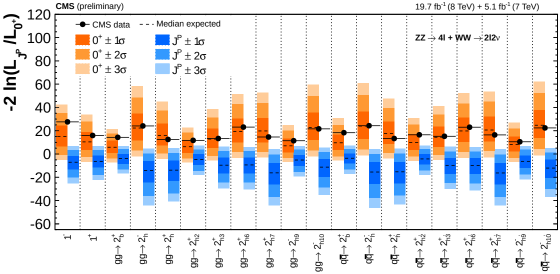
WW 2^+_b



$\gamma\gamma$ 2^+_m



✓ ZZ+WW combination: alt. models excluded at 99.9%CL



Anomalous HVV couplings

- Spin-0 Amplitude
  - Expression to the order of q^2
  - Interpretation only clear for small BSM contributions
  - Include ZZ, WW, $Z\gamma^*$, and $\gamma^*\gamma^*$ terms

$$A(X_{J=0} \to V_1 V_2) \sim v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q^2_{V_1} + q^2_{V_2}}{(\Lambda_1)^2} \right] m_V^2 \epsilon^*_{V_1} \epsilon^*_{V_2} + a_2 f^{*(V_1)}_{\mu\nu} f^{*(V_2),\mu\nu} + a_3 f^{*(V_1)}_{\mu\nu} \tilde{f}^{*(V_2),\mu\nu} \right)$$

  - In the SM only the a_1 term is sizable for ZZ and WW ($a_1 = 2$)
  - Λ_1 is scale of new physics affecting the tree level coupling
  - a_2 is a CP-even scalar ($10^{-2} - 10^{-3}$ in SM)
  - a_3 is a CP-odd pseudo-scalar (three-loop level in SM)
- a_2, a_3, Λ_1 (ZZ terms) would contribute to $H \to 4\ell$
- $a_2^{Z\gamma}$, $a_3^{Z\gamma}$, $a_2^{\gamma\gamma}$, $a_3^{\gamma\gamma}$ would contribute to $H \to 4\ell$
- a_2^{WW}, a_3^{WW}, Λ_1^{WW} would contribute to $H \to WW \to \ell\nu\ell\nu$

Spin-0 Measurables

- To measure HVV anomalous couplings in spin-0, we report effective cross section fractions
  - Invariant under coupling notation and allows for full coverage

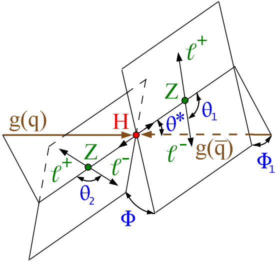
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/\left(\Lambda_1\right)^4} \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

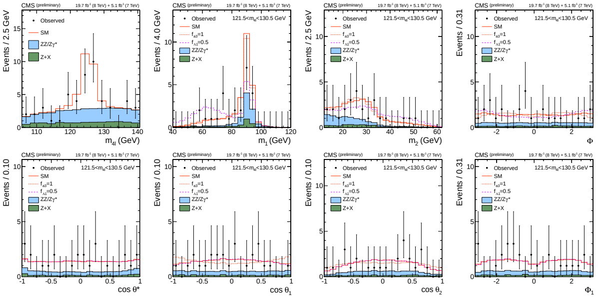
- ZZ, $Z\gamma^*$, $\gamma^*\gamma^*$, and WW are tested when amplitude ratio is real ($\phi_{ai} = 0$ or π) (e.g. $\phi_{ai} = 0$ is SM)
- $H \to 4\ell$ measures ZZ couplings by profiling the phase as well
- When combining ZZ+WW we define r_{ai} and R_{ai}

$$r_{ai} = \frac{a_i^{WW}/a_1^{WW}}{a_i^{ZZ}/a_1^{ZZ}} \qquad R_{ai} = \frac{r_{ai}|r_{ai}|}{1 + r_{ai}^2}$$

Observables in $ZZ \to 4\ell$

- Eight independent d.o.f. describe the kinematics in center of mass frame
  - $m_{4\ell}, m_{Z1}, m_{Z2}, \theta^*, \Phi_1, \theta_1, \theta_2, \Phi$
  - Can use all 8 simultaneously or combine in optimal discriminants

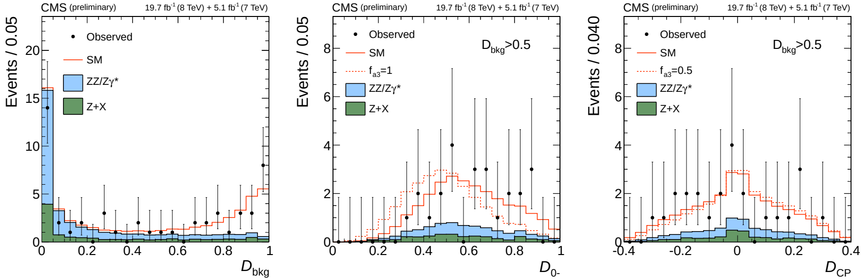




- Spin-0 signals: NLO (POWHEG + JHUGen) $\{ZZ, WW, \gamma\gamma\}$
- Spin-1 & Spin-2 signals: LO (JHUGen) $\{ZZ, WW, \gamma\gamma\}$
- $q\bar{q} \to ZZ$ NLO (POWHEG)
- $gg \to ZZ$: LO (GG2VV & MCFM) with $m_{4\ell}$ dependent K-factor

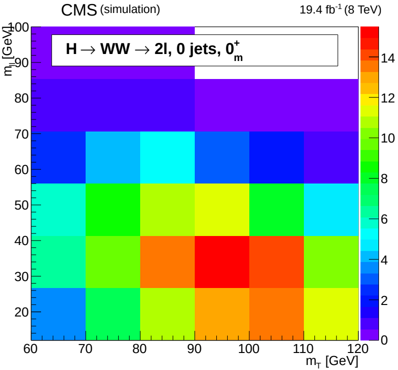
$ZZ \to 4\ell$ Discriminants

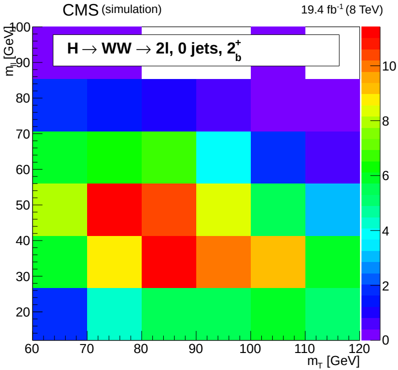
- Transform into Discriminants sensitive to specific pieces of amplitude using MELA method
  - $\mathcal{D}_{\rm bkg} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM}+\mathcal{P}_{\rm bkg}}$: Signal from Background
  - $\mathcal{D}^{\rm kin}_{J^P} = \frac{\mathcal{P}^{\rm kin}_{\rm SM}}{\mathcal{P}^{\rm kin}_{\rm SM}+\mathcal{P}^{\rm kin}_{J^P}}$: SM from pure J^P state
  - $\mathcal{D}_{\rm Interf} = \frac{\left(\mathcal{P}^{\rm kin}_{\rm SM+JP}-\mathcal{P}^{\rm kin}_{\rm JP}-\mathcal{P}^{\rm kin}_{\rm SM}\right)}{\mathcal{P}^{\rm kin}_{\rm SM}+\mathcal{P}^{\rm kin}_{J^P}}$: Pure states (SM, J^P) from interference



Observables in WW

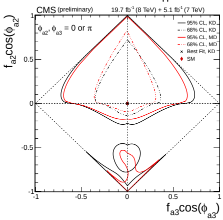
- $H \to WW \to \ell\nu\ell\nu$ kinematics described by lepton momenta and MET
  - Build 2D p.d.f. of $[M_T, m_{\ell\ell}]$
  - Fit spin-0 HVV anomalous couplings
  - Hypothesis testing for pure spin-1 & as a function of $q\bar{q}$ for spin-2





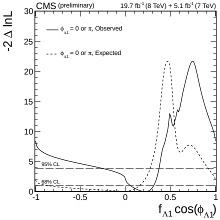
Spin-0 HVV Constraints

$H \to ZZ_{MELA||MD}$



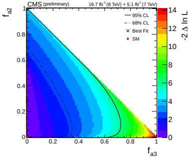
interaction	parameter ($\phi_{ai}^{VV} = 0$ or π)	observed allowed at 95% CL	expected allowed at 95% CL
template method			
HZZ	$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$[-0.25, 0.37]$	$[-1.00, 0.27] \cup [0.92, 1.00]$
	$f_{a2}\cos(\phi_{a2})$	$[-0.66, -0.57] \cup [-0.15, 1.00]$	$[-0.18, 1.00]$
	$f_{a3}\cos(\phi_{a3})$	$[-0.40, 0.43]$	$[-0.70, 0.70]$
HWW	$f_{\Lambda 1}^{WW}\cos(\phi_{\Lambda 1}^{WW})$	$[-1.00, 0.44] \cup [0.49, 1.00]$	$[-1.00, 0.43] \cup [0.48, 1.00]$
	$f_{a2}^{WW}\cos(\phi_{a2}^{WW})$	$[-1.00, -0.58] \cup [-0.25, 1.00]$	$[-1.00, -0.56] \cup [-0.24, 1.00]$
	$f_{a3}^{WW}\cos(\phi_{a3}^{WW})$	$[-1.00, 1.00]$	$[-1.00, 1.00]$
$HZ\gamma$	$f_{a2}^{Z\gamma}\cos(\phi_{a2}^{Z\gamma})$	$[-0.49, 0.46]$	$[-0.78, 0.79]$
	$f_{a3}^{Z\gamma}\cos(\phi_{a3}^{Z\gamma})$	$[-0.40, 0.51]$	$[-0.75, 0.75]$
$H\gamma\gamma$	$f_{a2}^{\gamma\gamma}\cos(\phi_{a2}^{\gamma\gamma})$	$[-0.51, 0.04]$	$[-0.34, 0.32]$
	$f_{a3}^{\gamma\gamma}\cos(\phi_{a3}^{\gamma\gamma})$	$[-0.32, 0.35]$	$[-0.40, 0.37]$
multidimensional distribution method			
HZZ	$f_{a2}\cos(\phi_{a2})$	$[-0.14, 1.00]$	$[-0.18, 0.97]$
	$f_{a3}\cos(\phi_{a3})$	$[-0.44, 0.40]$	$[-0.67, 0.67]$

$H \to ZZ_{MELA}$



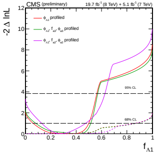
- ✓ When coupling ratio's are real results are consistent with SM
  - ▸ $Z\gamma^*$ and $\gamma^*\gamma^*$ much less sensitive than on-shell CMS results

$H \to ZZ_{MELA}$



Observed (expected) allowed 95% CL intervals				
Kinematic discriminants method				
Parameter	ϕ_{ai} profiled	$\phi_{ai}, f_{\Lambda 1}, \phi_{\Lambda 1}$ profiled	$\phi_{ai}, f_{a2}, \phi_{a2}$ profiled	$\phi_{ai}, f_{a3}, \phi_{a3}$ profiled
$f_{\Lambda 1}$	$[0.00, 0.56(-)]$	———	$[0.00, 0.57(-)]$	$[0.00, 0.63(-)]$
f_{a2}	$-(-)$	$[0.00, 0.65(-)]$	———	$[0.00, 0.97(-)]$
f_{a3}	$[0.00, 0.47(0.74)]$	$[0.00, 0.21(0.85)]$	$[0.00, 0.54(0.81)]$	———

$H \to ZZ_{MELA}$

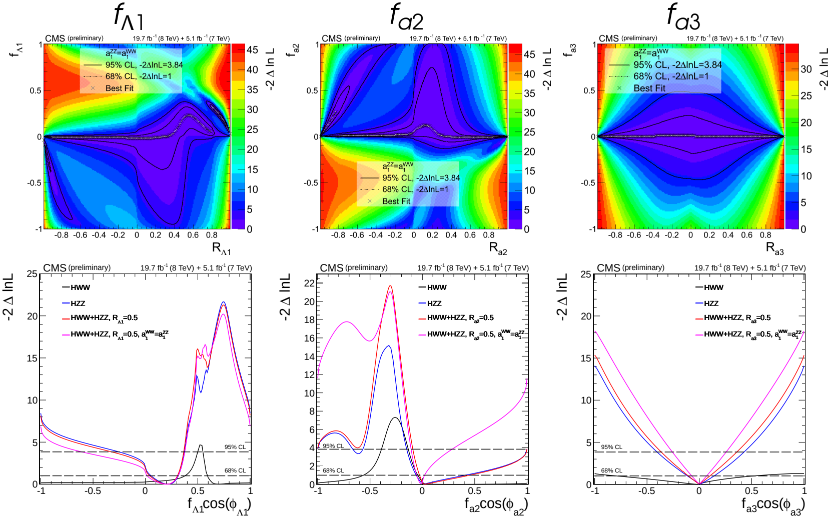


- ✓ When phases/amplitudes are profiled → consistent with SM

Spin-0 Constraints (ZZ+WW)

Custodial Symmetry →

$(a_1^{ZZ} = a_1^{WW})$



Summary: CMS Higgs

- Extensive study of 125 GeV boson over the past 2-years
  - ✓ Main analyses have published/submitted Run-1 results
  - ✓ Preliminary combination investigated couplings
  - ✓ Intensive study of spin-parity properties in diboson channels
- Extensive set of measurements
  - ✓ Full combination → SM expected couplings
    - Custodial symmetry, No fermion asymmetry, evidence for SM Yukawa couplings, BR_{BSM} constraints
  - ✓ Diboson analysis of spin-parity properties
    - Hypothesis Testing for spin-1 & 2, coupling fits in spin-0

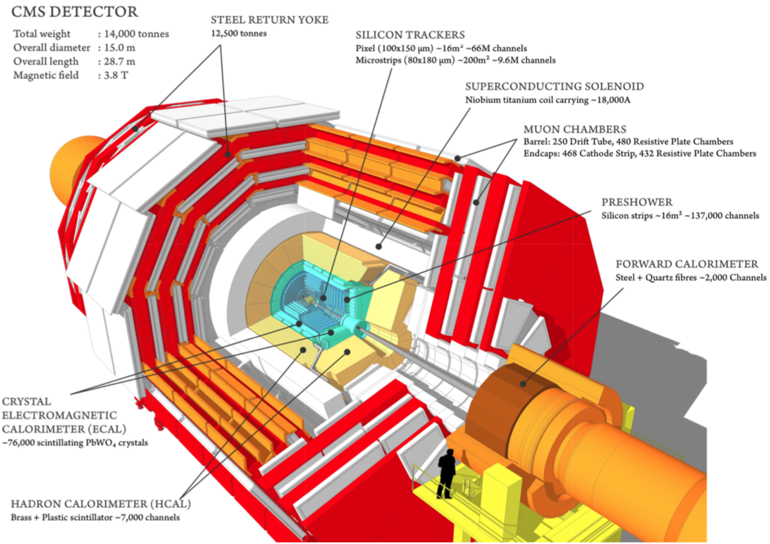
! Results are quickly approaching theo. uncertainties (*ggH*)
→ Need help form theory community

- Many results are stat. limited → promising for Run-2 & beyond

? Questions for Run-2 & beyond
  - ? Is this **THE** Higgs boson?
  - ? Can this Higgs provide a hint of BSM physics?

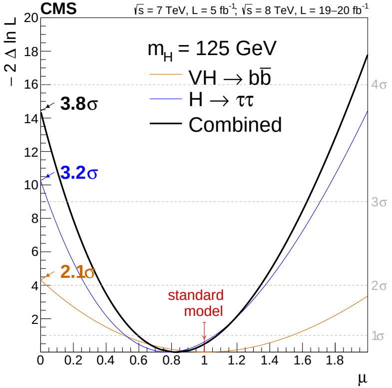
Backup

The CMS Detector



Evidence for fermion decay

- Combination of $VH \to b\bar{b}$ and $H \to \tau\tau$ published in Nature Phys. (doi:10.1038/nphys3005)



✓ Everything is consistent with Yukawa SM coupling

Alternative spin-1 & 2 Boson

- Spin-1 Amplitude

$$A(X_{J=1} \to V_1 V_2) \sim b_1 \left[\left(\epsilon^*_{V_1} q\right) \left(\epsilon^*_{V_2} \epsilon_X\right) + \left(\epsilon^*_{V_2} q\right) \left(\epsilon^*_{V_1} \epsilon_X\right) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon^{\alpha}_{X} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} \tilde{q}^{\beta}$$

  - ZZ tests if boson is any fraction of vector(b_1) & pseudo-vector(b_2) for $q\bar{q}$ production and prod. indep.
  - WW tests pure states with $q\bar{q}$ production

- Spin-2 Amplitude

$$\begin{aligned} A(X_{J=2} \to V_1 V_2) \sim \Lambda^{-1} \Big[& 2c_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \\ & + c_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + c_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\ & + m_V^2 \left(2c_5 t_{\mu\nu} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} + 2c_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon^{*\nu}_{V_1} \epsilon^{*\alpha}_{V_2} - \epsilon^{*\alpha}_{V_1} \epsilon^{*\nu}_{V_2} \right) + c_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^*_{V_1} \epsilon^*_{V_2} \right) \\ & + c_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu}_{V_1} \epsilon^{*\rho}_{V_2} q^\sigma \\ & + \frac{c_{10} t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon^{*\nu}_{V_1} (q\epsilon^*_{V_2}) + \epsilon^{*\nu}_{V_2} (q\epsilon^*_{V_1}) \right) \Big] \end{aligned}$$

  - ZZ, WW tested terms in Run-1 Papers (arXiv:1312.5353, arXiv:1312.1129) have completed/combined in new results
    - ZZ tests three production modes (gg, $q\bar{q}$, prod. indep.)
    - WW tests as a function of $q\bar{q}$ contribution
  - $H \to \gamma\gamma$ tests 2^+_m ($c_1 = c_5$) as a function of $q\bar{q}$ contribution

Observables in $\gamma\gamma$

- $H \rightarrow \gamma\gamma$ binned fit signal strength in $|\cos(\theta^*_{CS})|$ before acceptance & efficiency
  - Hypothesis testing as a function of $q\bar{q}$ for 2^+_m
  - Correct for accep. $\times$ eff. of 2^+_m boson