Search for anomalous couplings affecting Higgs boson production and decay with the CMS experiment

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Motivations

- Precision measurements of the Higgs boson properties over the last 10 years after its discovery.
  - Higgs spin-parity quantum numbers $JCP=0^{++}$ are compatible with the SM.
- Constraints on Higgs couplings measurements:
  - Current precision allows for small anomalous CP-even and/or CP-odd couplings.
  - Anomalous couplings analyses test for deviation from SM expectations.
- General strategy
  - The kinematics of particles produced in the Higgs decay or in association with H boson production are sensitive to anomalous couplings of the H boson.

Higgs anomalous couplings in the HVV vertex

Generic spin-0 HVV scattering amplitude

$$A(\mathrm{HV_1V_2}) \sim \left[\boxed{a_1^{\mathrm{VV}}} + \boxed{\frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} \boxed{a_2^{\mathrm{VV}}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} \boxed{a_3^{\mathrm{VV}}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

SM **Higher-order SM loop or BSM contributions (anomalous couplings)**

Approach 1

- the SM and just one anomalous HVV coupling are considered
- $a_i^{ZZ} = a_i^{WW} \rightarrow$ 4 anomalous couplings individually analyzed

Approach 2

- Additional $SU(2) \times U(1)$ relationship enforced
- 3 anomalous couplings analyzed both individually and simultaneously

Convenient to use effective cross section ratios rather than the anomalous couplings themselves.

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \operatorname{sign}\left(\frac{a_i}{a_1}\right)$$

$$f_{a3}^{\mathrm{ggH}} = \frac{|a_3^{\mathrm{gg}}|^2 \sigma_3^{\mathrm{gg}}}{|a_2^{\mathrm{gg}}|^2 \sigma_2^{\mathrm{gg}} + |a_3^{\mathrm{gg}}|^2 \sigma_3^{\mathrm{gg}}} \operatorname{sign}\left(\frac{a_3^{\mathrm{gg}}}{a_2^{\mathrm{gg}}}\right)$$

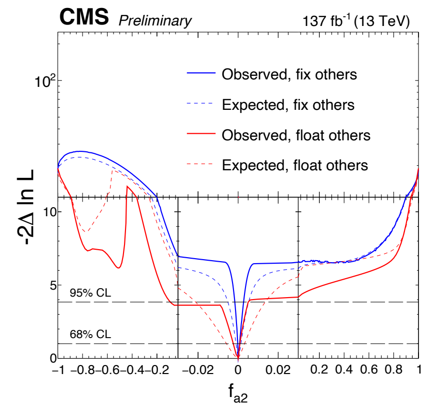
Higgs anomalous couplings @ CMS

July 2020

Higgs to 4 leptons → no AC detected

still limited by statistical precision

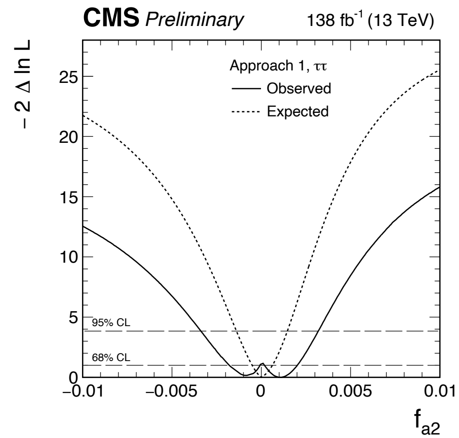
Phys. Rev. D 104 (2021) 052004



October 2021

Higgs to $\tau\tau$ → no AC detected

Phys. Rev. D 108 (2023) 032013



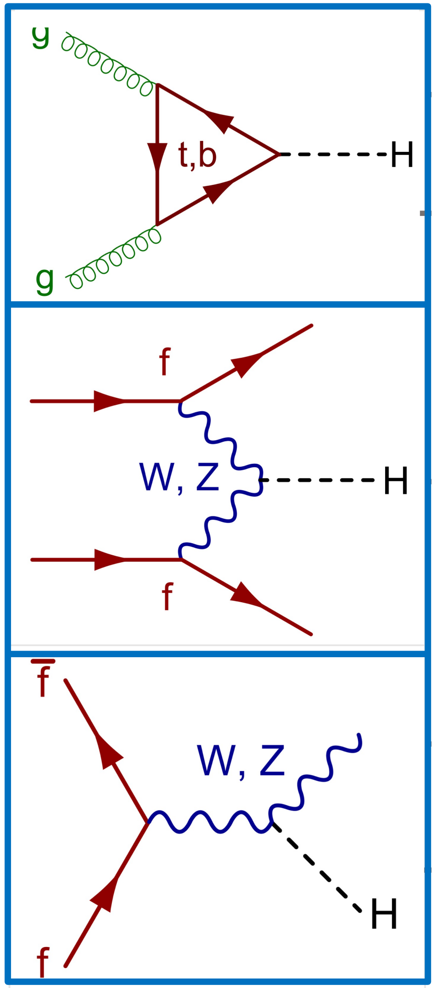
September 2023

Higgs to WW → This presentation

CMS-PAS-HIG-22-008

General Strategy: HWW channel

Higgs Production



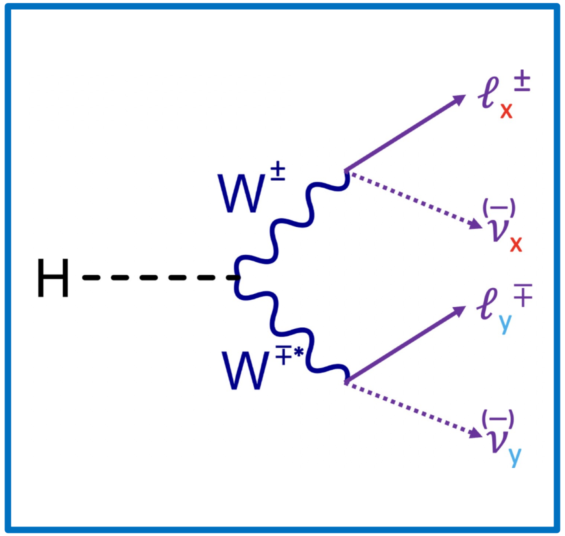
Several Categories

ggH-0J and ggH-1J
ggH-2J (VBF-like)

VBF-2J

VH-2J
VH-Boosted

Higgs Decay



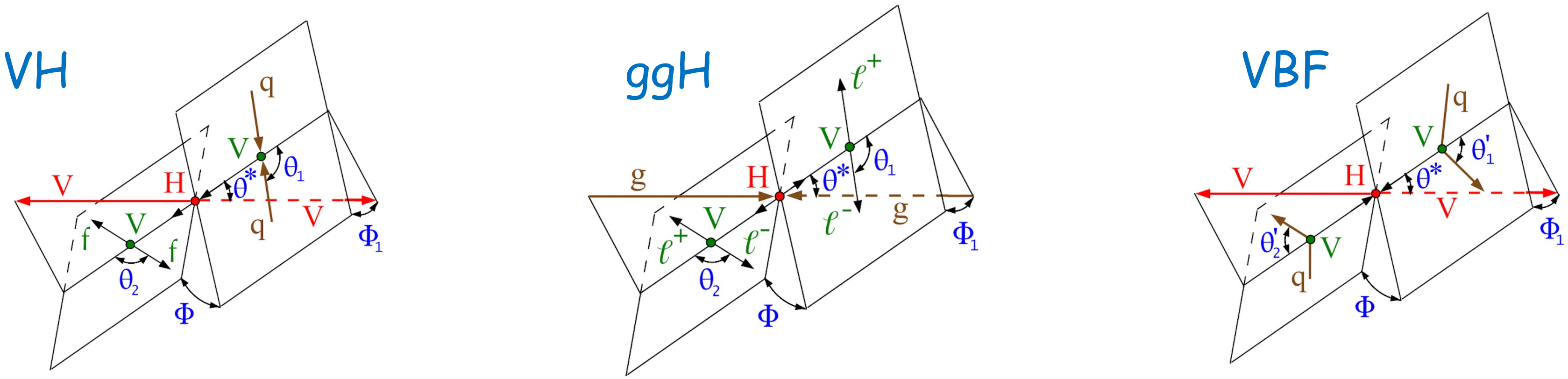
Different flavour final state: μ+e+MET

Dramatic reduction of background

Drives sensitivity of SM analysis

Observables and Kinematic discriminants

- **Kinematic discriminants**
  - the two quark jets from VBF and VH production (HVV coupling)
  - the H → WW decay products (HVV coupling)
  - the two quark jets from ggH + 2 jets production (Hgg coupling)
- **MELA discriminants** using associated jets from VH – ggH (+2jet) – VBF



- In general, 5 angles fully characterize the orientation of the production and decay chain, but HWW has 2 neutrinos in the final state → no Ws four-vectors available → not all 5 angles are available
- **Several discriminants** (cross-section ratio) defined to extract anomalous couplings (all discriminants depend on the 5 blue angles)

Observables and Kinematic discriminants

- For a spin-0 object, only 5 variables (3 angles and 2 four-momenta of the vector bosons) describe the EW production processes
- 3 class of discriminants are defined for the production process:

$$\mathcal{D}_{\rm sig} = \frac{\mathcal{P}_{\rm sig}(\vec{\Omega})}{\mathcal{P}_{\rm sig}(\vec{\Omega}) + \mathcal{P}_{\rm bkg}(\vec{\Omega})}$$ → ggH signal vs VBF/VH signal

$$\mathcal{D}_{\rm BSM} = \frac{\mathcal{P}_{\rm BSM}(\vec{\Omega})}{\mathcal{P}_{\rm BSM}(\vec{\Omega}) + \mathcal{P}_{\rm SM}(\vec{\Omega})}$$ → SM signal vs BSM signal

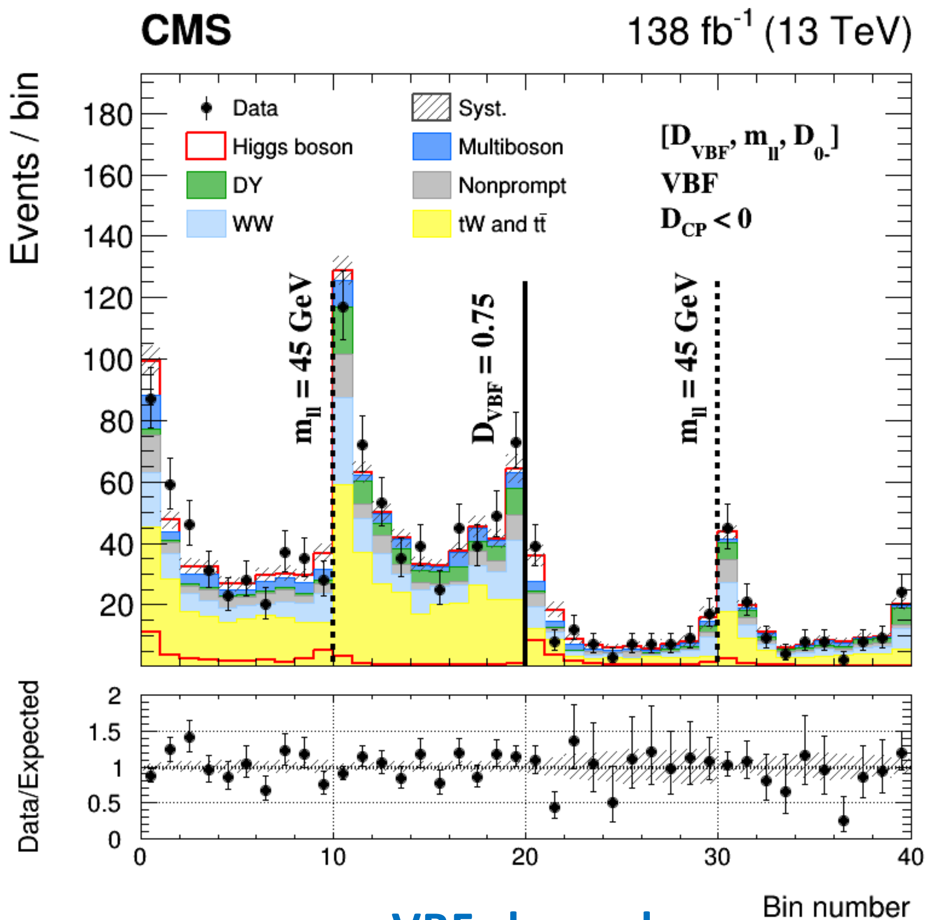
$$\mathcal{D}_{\rm int} = \frac{\mathcal{P}^{\rm int}_{\rm SM-BSM}(\vec{\Omega})}{\mathcal{P}_{\rm SM}(\vec{\Omega}) + \mathcal{P}_{\rm BSM}(\vec{\Omega})}$$ → Interference signal vs Pure SM/BSM signal

- Probabilities $\mathcal{P}$ calculated with MELA and depends on the 5 variables
- Generic BSM label is generally replaced by the specific anomalous coupling state targeted

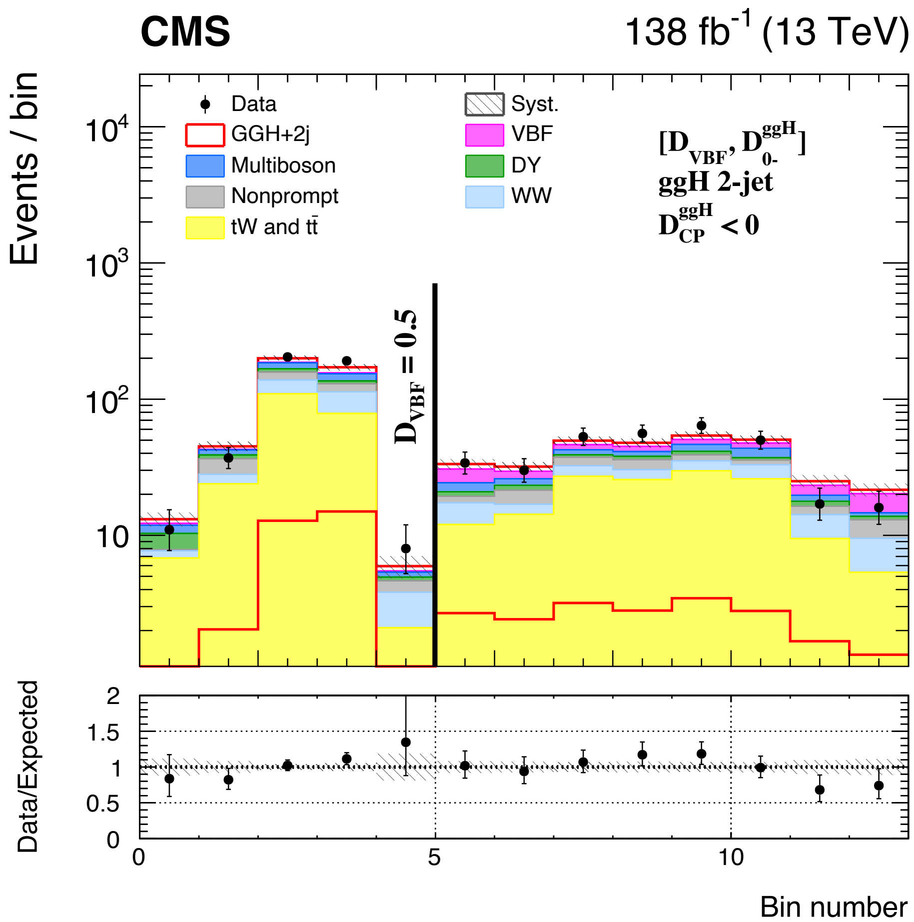
Final discriminants categorization

Analysis	Channel	Categorization	Final discriminant
HVV Approach 1	VBF (a_3)	$\mathcal{D}_{CP}$	$\boxed{[\mathcal{D}_{\mathrm{VBF}}, m_{\ell\ell}, \mathcal{D}_{0-}]}$
	VBF (a_2)	$\mathcal{D}_{\mathrm{int}}$	$[\mathcal{D}_{\mathrm{VBF}}, m_{\ell\ell}, \mathcal{D}_{0+}]$
	VBF ($\kappa_1 \Lambda_1$)	-	$[\mathcal{D}_{\mathrm{VBF}}, m_{\ell\ell}, \mathcal{D}_{\Lambda 1}]$
	VBF ($\kappa_2^{Z\gamma} \Lambda_1^{Z\gamma}$)	-	$[\mathcal{D}_{\mathrm{VBF}}, m_{\ell\ell}, \mathcal{D}_{\Lambda_1}^{Z\gamma}]$
	VH (a_3)	$\mathcal{D}_{CP}$	$[m_{\ell\ell}, \mathcal{D}_{0-}]$
	VH (a_2)	-	$[m_{\ell\ell}, \mathcal{D}_{0+}]$
	VH ($\kappa_1 \Lambda_1$)	-	$[m_{\ell\ell}, \mathcal{D}_{\Lambda 1}]$
	VH ($\kappa_2^{Z\gamma} \Lambda_1^{Z\gamma}$)	-	$[m_{\ell\ell}, \mathcal{D}_{\Lambda_1}^{Z\gamma}]$
	0- & 1-jet ggH	-	$[m_{\ell\ell}, m_{\mathrm{T}}]$
HVV Approach 2	VBF	$\mathcal{D}_{CP}, \mathcal{D}_{\mathrm{int}}$	$[\mathcal{D}_{\mathrm{VBF}}, m_{\ell\ell}, \mathcal{D}_{0-}, \mathcal{D}_{0+}]$
	VH	$\mathcal{D}_{CP}$	$[m_{\ell\ell}, \mathcal{D}_{0-}, \mathcal{D}_{0+}]$
	0- & 1-jet ggH	-	$[m_{\ell\ell}, m_{\mathrm{T}}]$
Hgg	2-jet ggH	$\mathcal{D}_{CP}^{\mathrm{ggH}}$	$\boxed{[\mathcal{D}_{\mathrm{VBF}}, \mathcal{D}_{0-}^{\mathrm{ggH}}]}$
	0- & 1-jet ggH	-	$[m_{\ell\ell}, m_{\mathrm{T}}]$

Discriminants events distributions



VBF channel



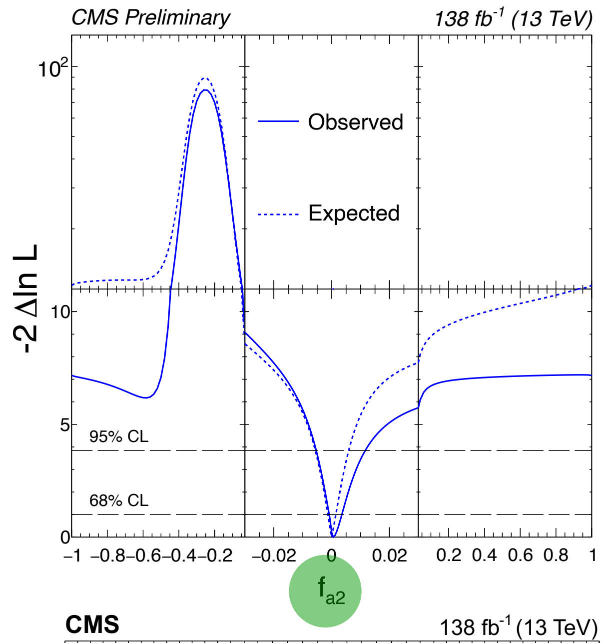
2-jets ggH channel

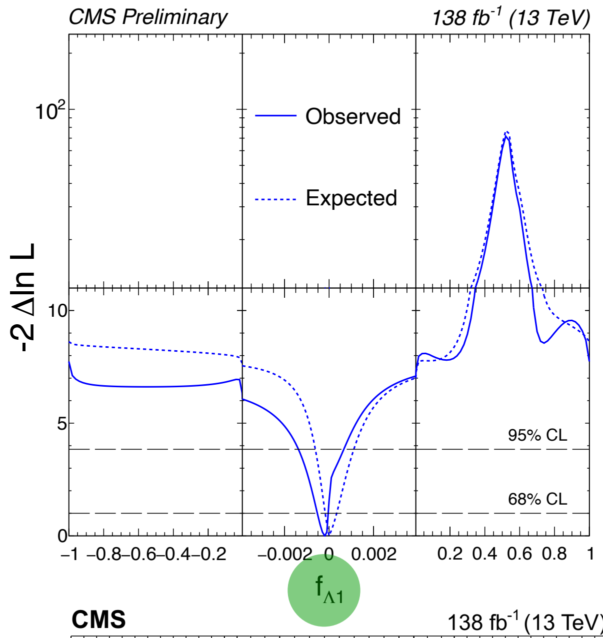
multidimensional discriminants are statistically optimized

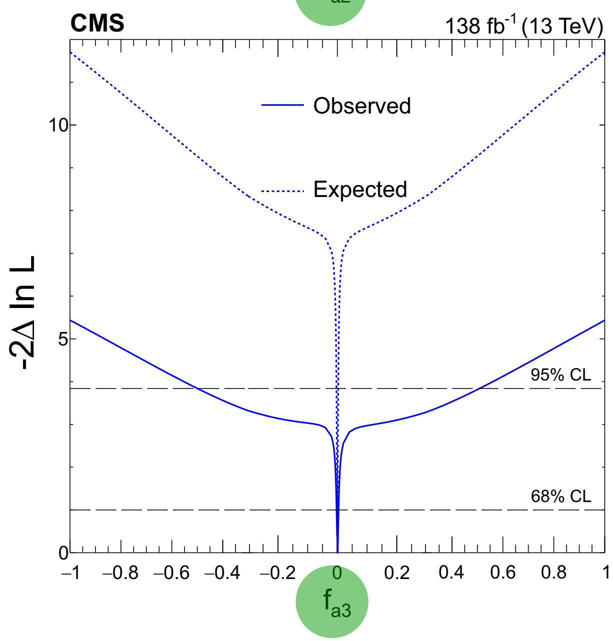
Systematic uncertainties

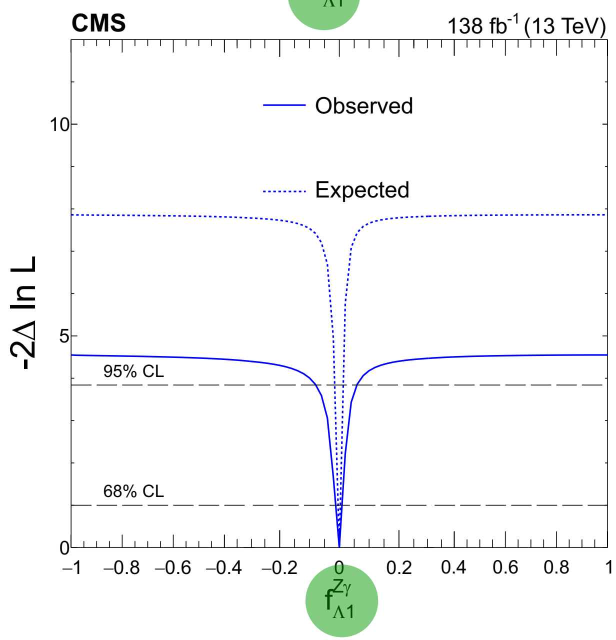
- Signal extraction is performed using binned templates
- Systematic uncertainties that change the normalization or shape of the templates are taken into account
- All the uncertainties are modelled as nuisance parameters that are profiled in the **final maximum likelihood fit**
- Main experimental uncertainties are related to luminosity, trigger efficiency, lepton and *b*-jet identification, lepton momentum and jet energy scale, E_T^{mis} scale, pile-up effect and estimation of the nonprompt background
- Main theoretical uncertainties are related to PDF choice, higher order cross section contribution, pile-up and parton shower modelling and underlying events tune.

Result: approach 1 - f_{ai} scans

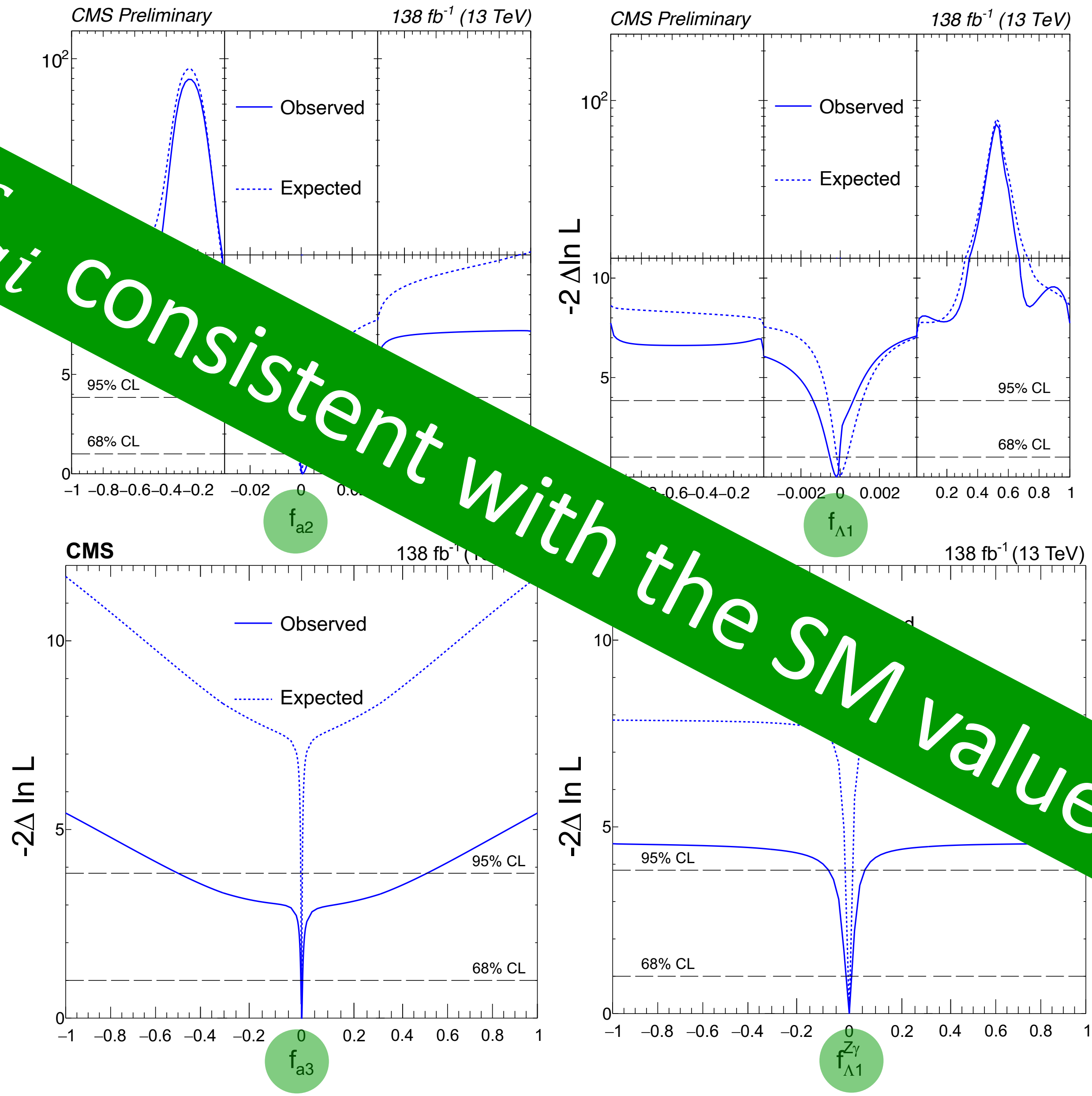






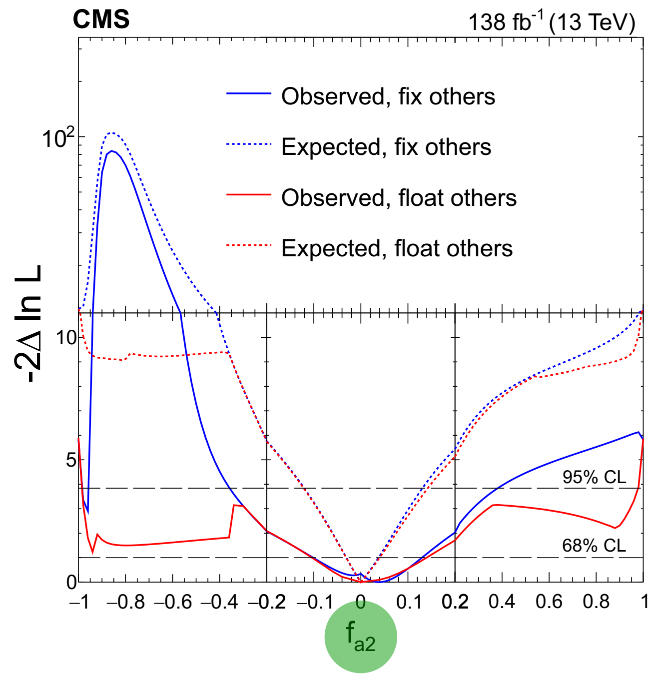


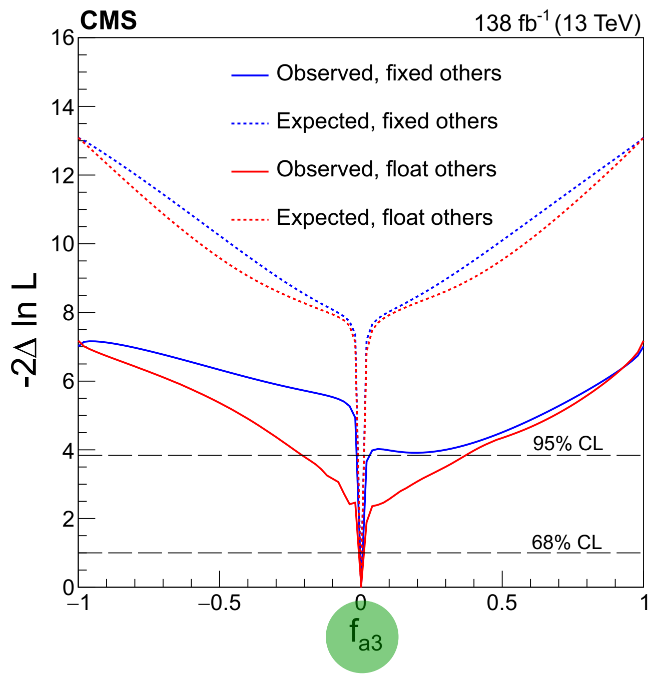
Result: approach 1 - f_{ai} scans

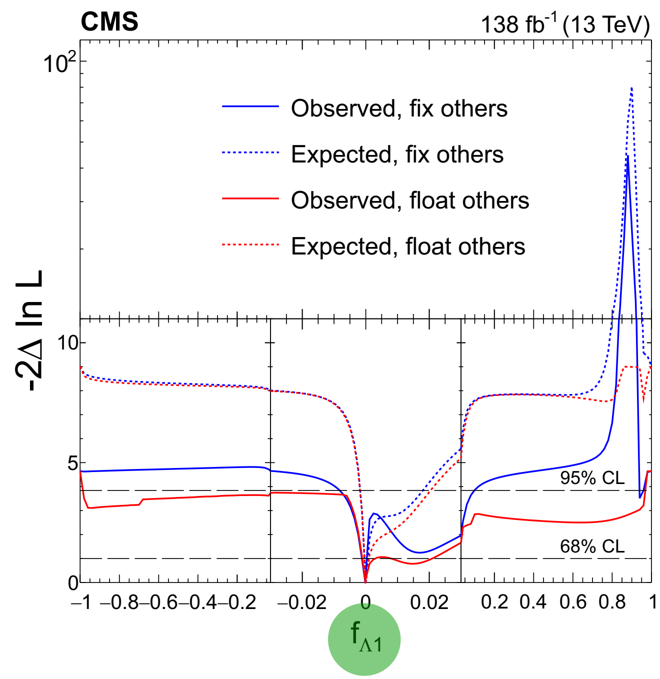


All f_{ai} consistent with the SM value of 0

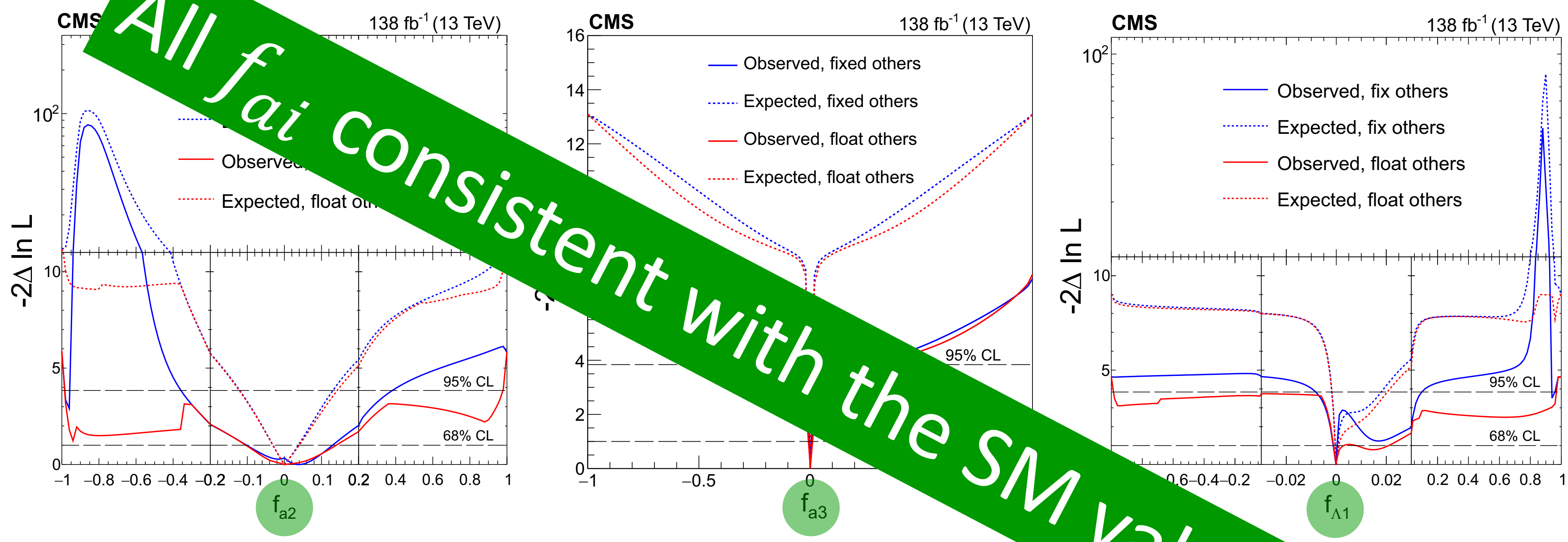
Result: approach 2 - f_{ai} scans







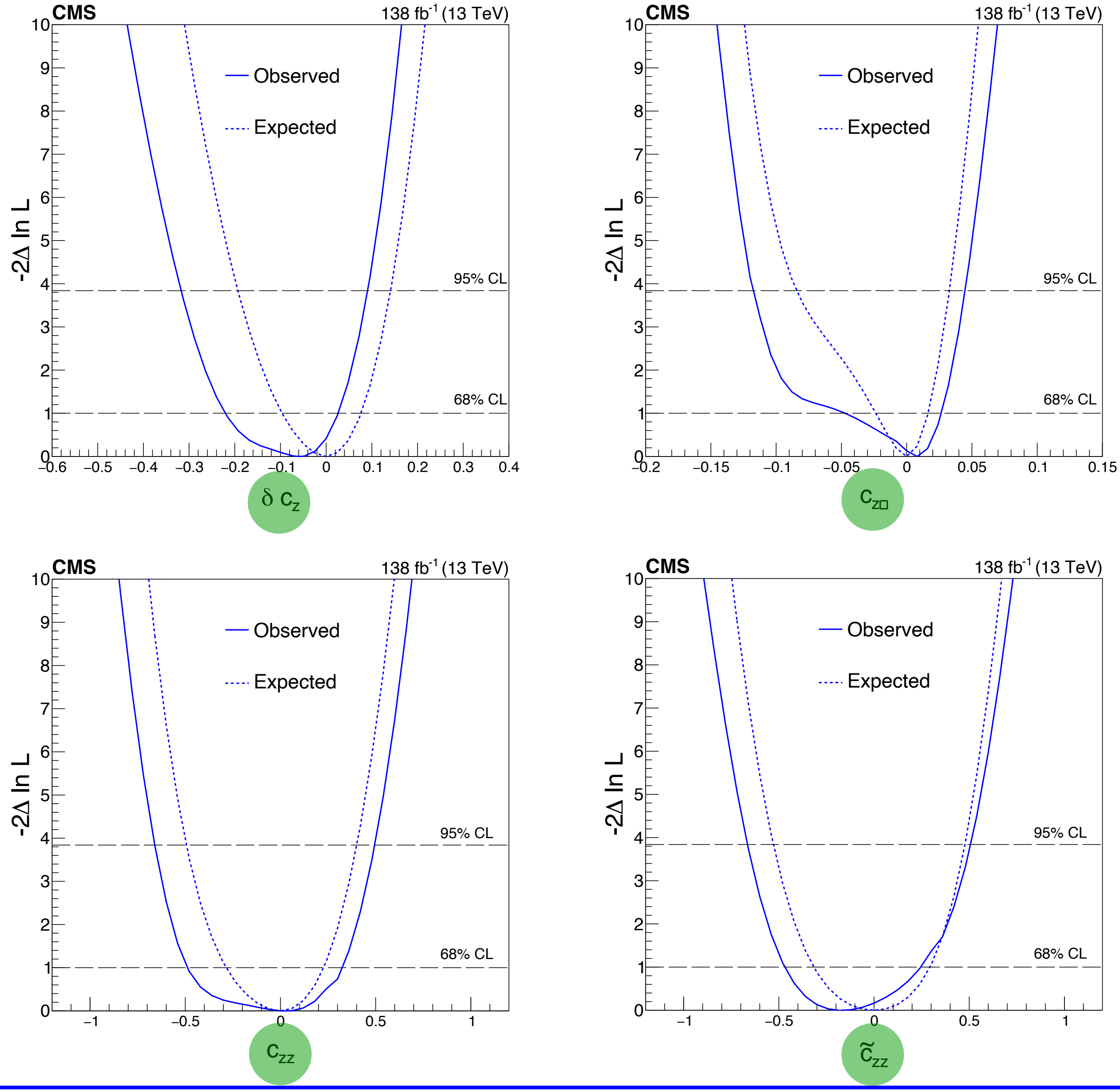
Result: approach 2 - f_{ai} scans



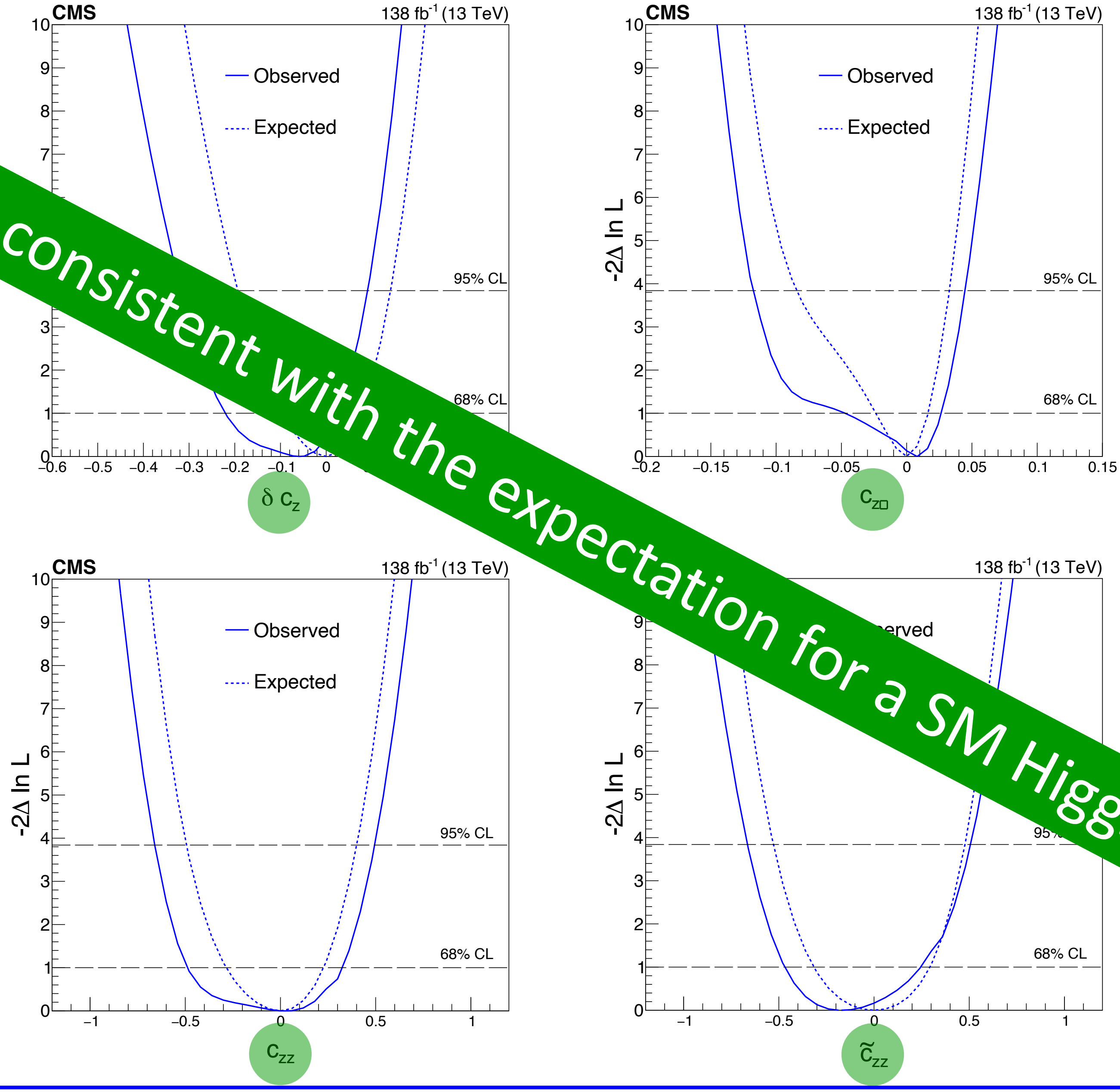
All f_{ai} consistent with the SM value of 0

The approach 2 compatibility with the SM is found to be 91%

Coupling interpretation in the Higgs basis

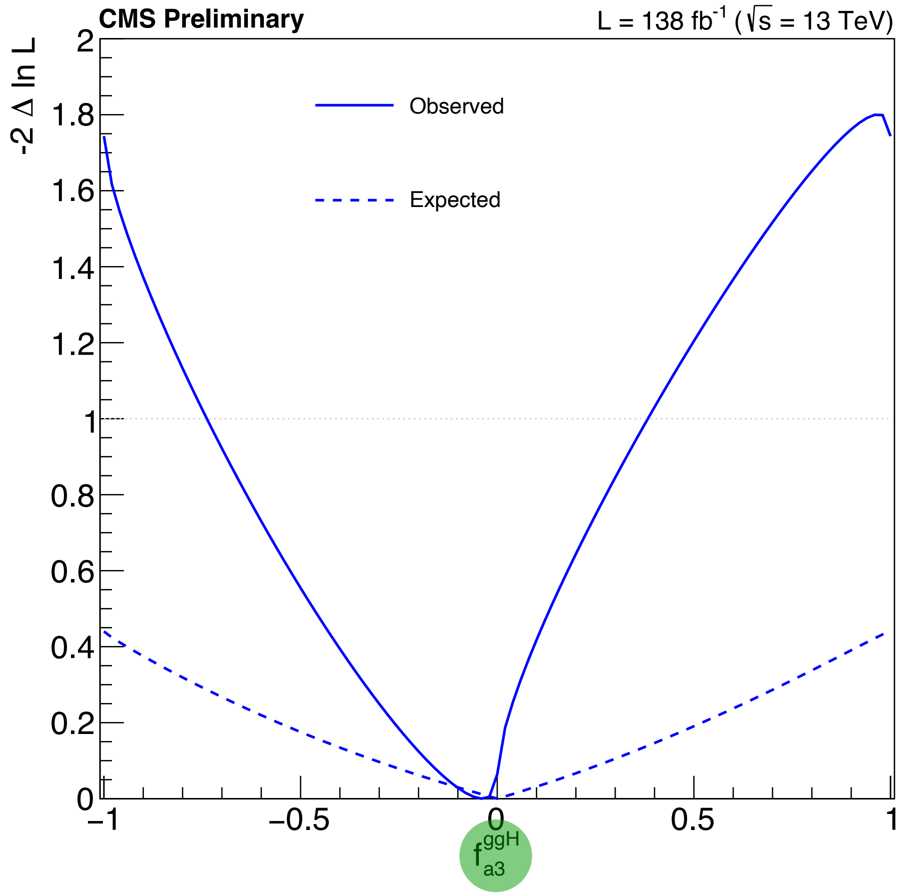


Coupling interpretation in the Higgs basis



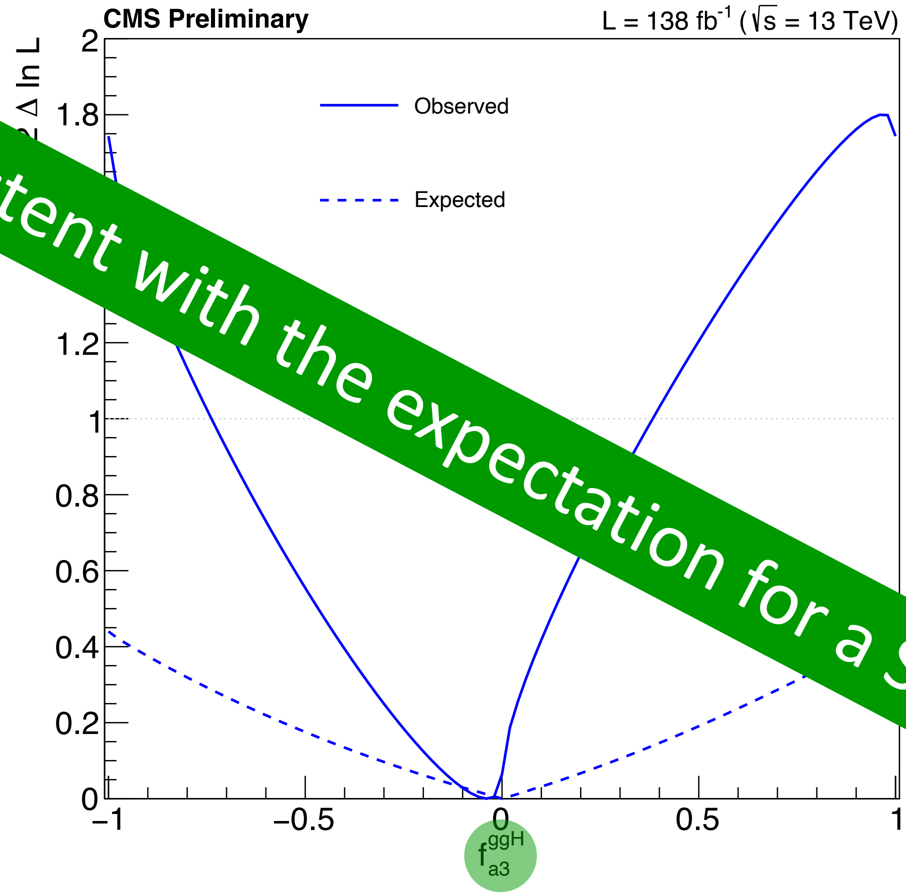
result consistent with the expectation for a SM Higgs boson

f_{a3}^{ggH} scan



CMS Preliminary
L = 138 fb^{-1} ($\sqrt{s}$ = 13 TeV)
-2 Δ ln L
Observed
Expected
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−1
−0.5
0
0.5
1
f_{a3}^{ggH}

f_{a3}^{ggH} scan



result consistent with the expectation for a SM Higgs boson

Conclusions

The Run 2 anomalous coupling analysis in the HWW channel is another step for better understanding the nature of the Higgs boson

all measurements are so far

in agreement with a SM Higgs boson

BACKUP

Data sets and simulations

- **Chosen final state topology is $e + \mu + E_T^{mis}$**
- DATA SAMPLE
  - Data recorded by CMS in 2016, 2017 and 2018
  - Total analyzed luminosity 138 fb^{-1}
  - Trigger: logic OR between the main $e\mu$ filter and single-lepton filters
- SIMULATED SAMPLE
  - 4 independent sets of simulated events, corresponding to the four era of data taking (2 eras in 2016 and 1 each for 2017 and 2018)
  - Signal and Background processes produced with state-of-art generators (POWHEGv2, MINLO, MADGRAPH5_aMC@NLO, PYTHIA, JHUGEN, MCFM) and simulated with GEANT
  - Additional pp interactions (pileup) in the simulation is adjusted to match that observed in data
  - Trigger efficiency evaluated in data and applied to simulated events

Event reconstruction

base selection

2 leptons (eμ) of opposite charge
$p_T^{\ell 1} > 25\,\mathrm{GeV}$
$p_T^{\ell 2} > 13\,\mathrm{GeV}$ (10 GeV in 2016)
No additional lepton with $p_T > 10\,\mathrm{GeV}$
$12 < m_{\ell\ell} < 76.2$ or $m_{\ell\ell} > 106.2\,\mathrm{GeV}$
$p_T^{\ell\ell} > 30\,\mathrm{GeV}$
$p_T^{miss} > 20\,\mathrm{GeV}$
$m_T^{\ell 2} > 30\,\mathrm{GeV}$
$60 < m_T^H < 125\,\mathrm{GeV}$
b jet veto

control regions

Variable	DY$\tau\tau$	top quark	WW
$m_{\ell\ell}$	40–80 GeV	$> 50\,\mathrm{GeV}$	$> 106.2\,\mathrm{GeV}$
m_T^H	$< 60\,\mathrm{GeV}$	–	60–125 GeV
$m_T^{\ell 2}$	–	$> 30\,\mathrm{GeV}$	$> 30\,\mathrm{GeV}$
b jet veto	yes	no	yes
Inverse b jet veto	no	yes	no

HVV vertex

Variable	ggH	VBF	Resolved VH	Boosted VH
N_{jet} (V jets)	0	0	0	> 0
N_{jet} (AK4 jets)	0&1	2	2	–
m_{jj}	–	$> 120\,\mathrm{GeV}$	60–120 GeV	–

Hgg vertex

Variable	ggH	2-jet ggH
N_{jet} (AK4 jets)	0&1	2
m_{jj}	-	$> 120\,\mathrm{GeV}$
$m_{\ell\ell}$	-	$< 55\,\mathrm{GeV}$