Higgs Mass - Width - CP

HIGGS 2021

Oct. 19 2021

Savvas Kyriacou (Johns Hopkins University)
On behalf of the
ATLAS and **CMS** collaborations

The Higgs properties

Mass

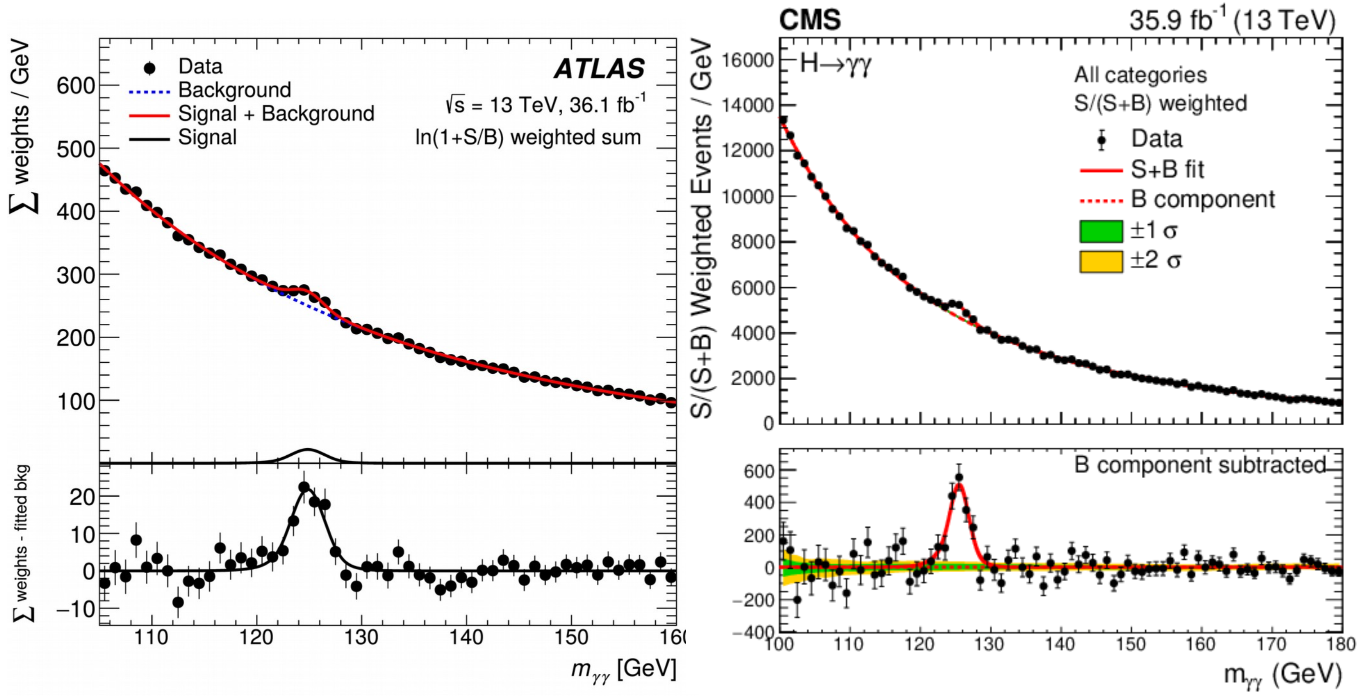
- Measurements in high resolution channels
  H→4l and H→γγ
- Multiple combinations between Run1 Run2 and channels

Width

- Onshell measurements
- Offshel measurements **(NEW RESULTS!!!)**

CP in Higgs couplings **(NEW RESULTS!!!)**

- HVV
- Yukawa (tt, ττ)
- Hgg



m_H measurements

Mass: H→2γ+H→4l,H→4l(ATLAS)

Phys. Lett. B 784 (2018) 345
ATLAS-CONF-2020-005

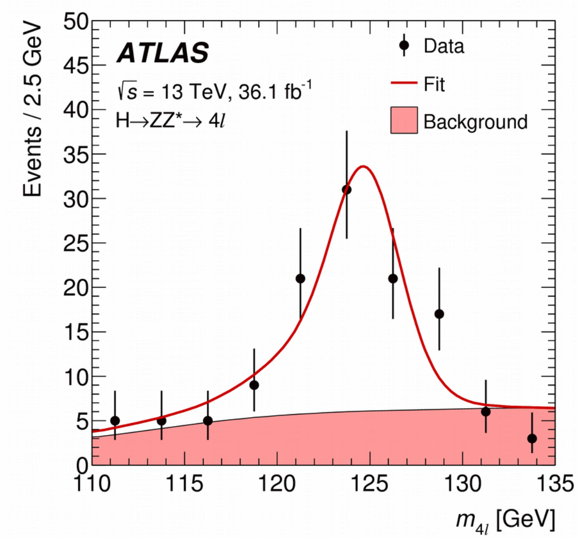
H→2γ + H→4l (partial Run2 '16)

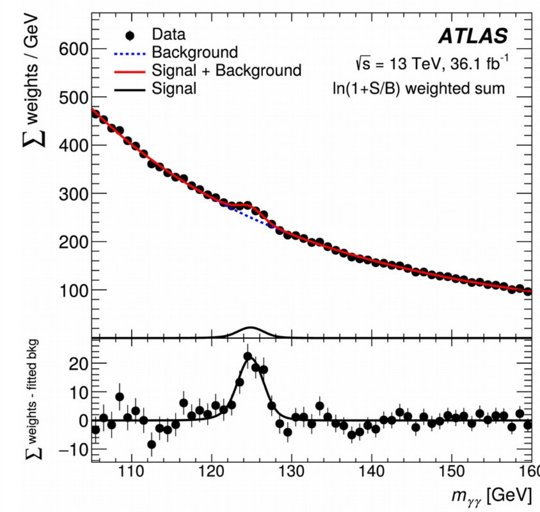
H→4l:

- Constrain m12 to mz to improve mH resolution
- BDT for sig. / backgr. separation

H→ γγ:

- Tight isolation req. for photons
- NN based diphoton vertex selection
- Per event resolution and signal to background categorization
- Photon energy uncertainty dominates in diphoton channel
- Combination with Run1 results

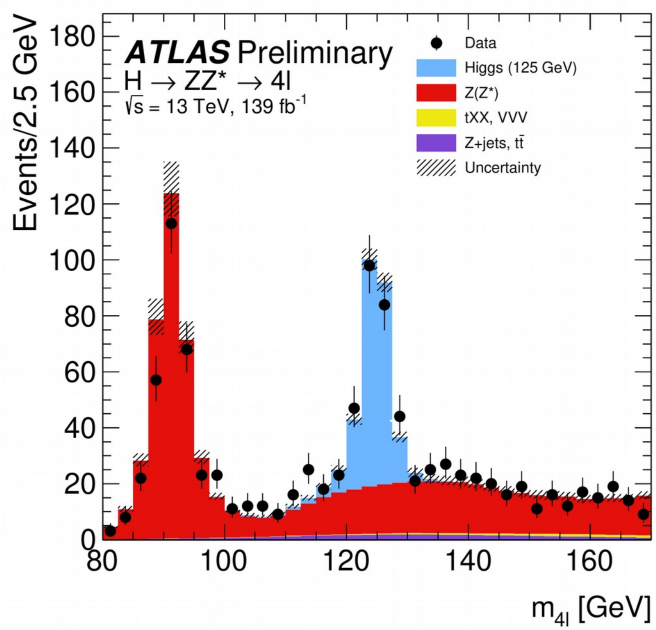


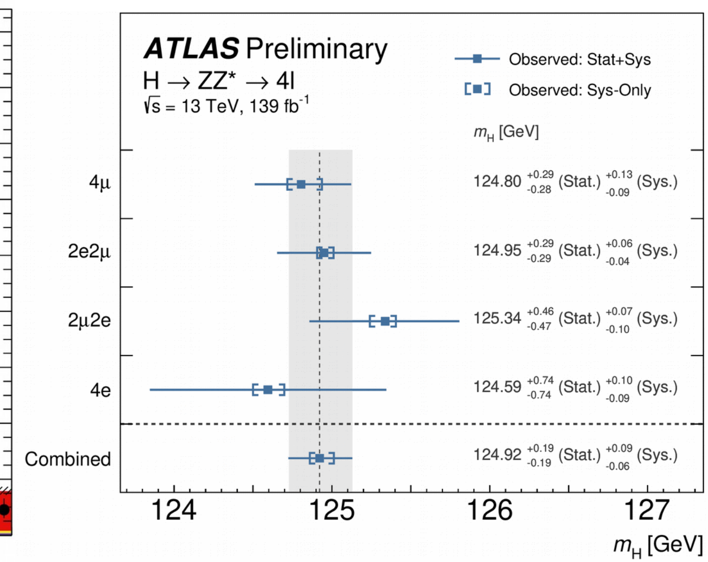


H→4l full Run2:

- J/ψ, Z used to improve μ pt resolution
- BDT for ZZ*/HZZ* separation with H pt, η and Matrix element based discriminant
- Per-event - NN based – resolution (σ_i) estimation
- DCB fit

First Full Run2 result!!!





$$m_H \quad 124.92 \pm 0.19(\text{stat.})^{+0.09}_{-0.06}(\text{syst.})\ \text{GeV}$$

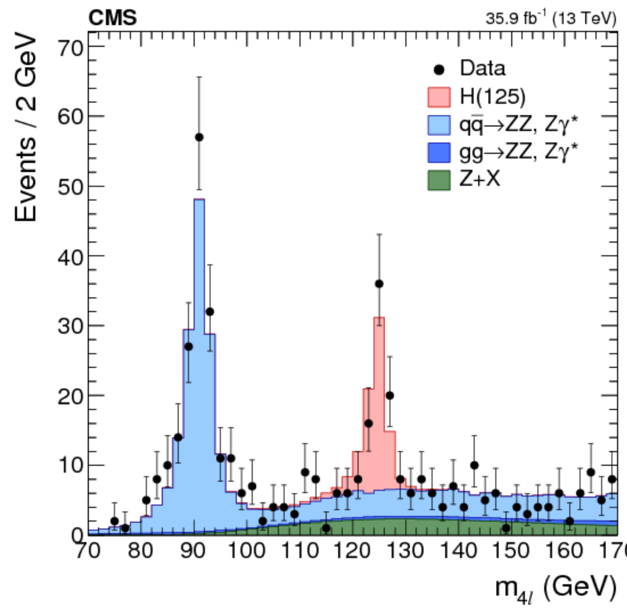
Mass: H→4l,H→2γ+H→4l (CMS)

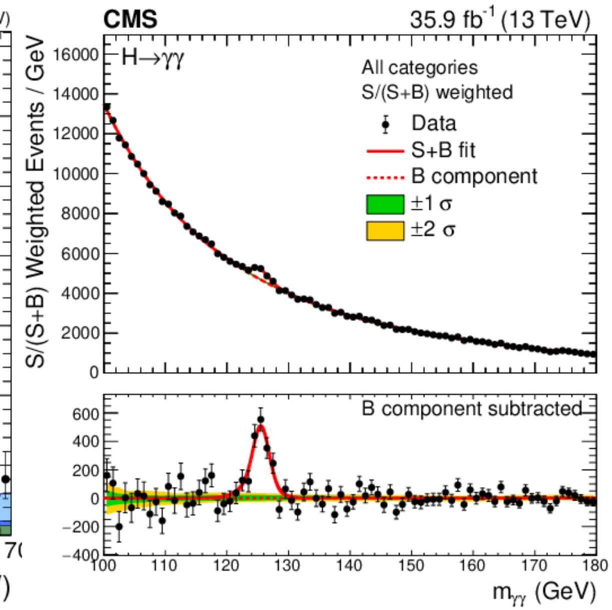
JHEP11 (2017) 047
Phys. Lett. B 805 (2020) 135425

H→4l (partial Run2 '16)

- MELA based discriminant for signal/background separation
- MZ1 constrainted
- 3 lepton channels (4e,4μ,2e2μ)
- Perform fit in an inclusive category
- 3D fit (D_{bkg} / m4l / σ_{m4l}| m4l)
- Most precise single channel measurement

$$m_{\mathrm{H}}\ (\mathrm{GeV})\ 125.26 \pm 0.21$$





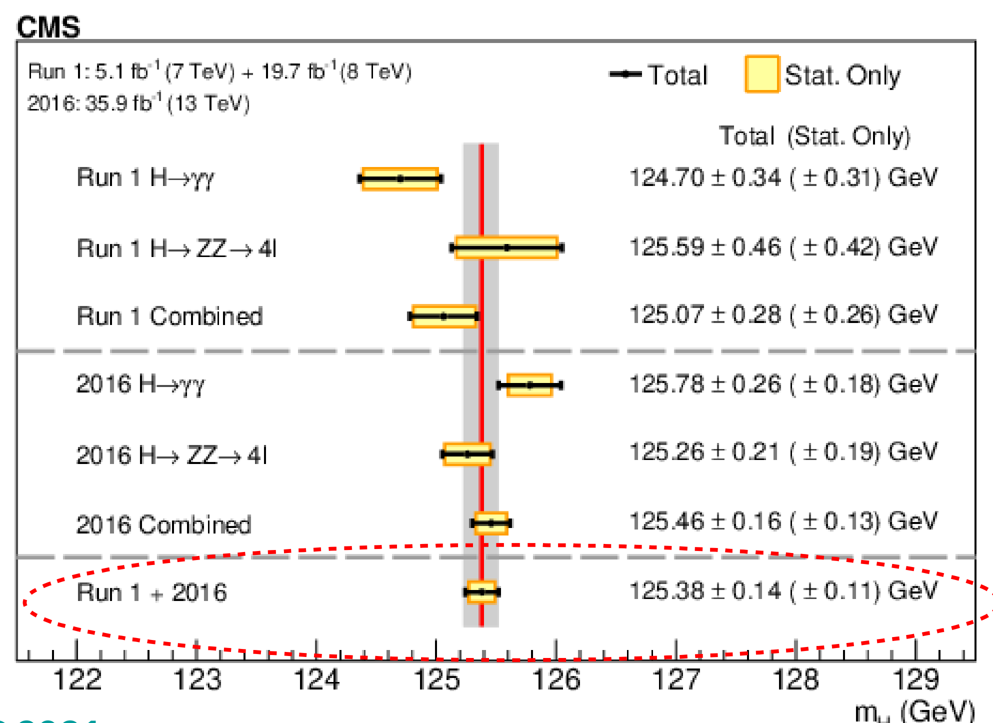
H→ γγ + H→4l (partial Run2 '16)

- BDT based diphoton vertex selection
- BDT photon ID selection
- Background extracted with discreet profiling method
- Improved detector calibration
- Use electrons to study energy scale uncertainties and propagate to photons

Combined with 4l '16 + RUN1

Most precise measurement to-date!

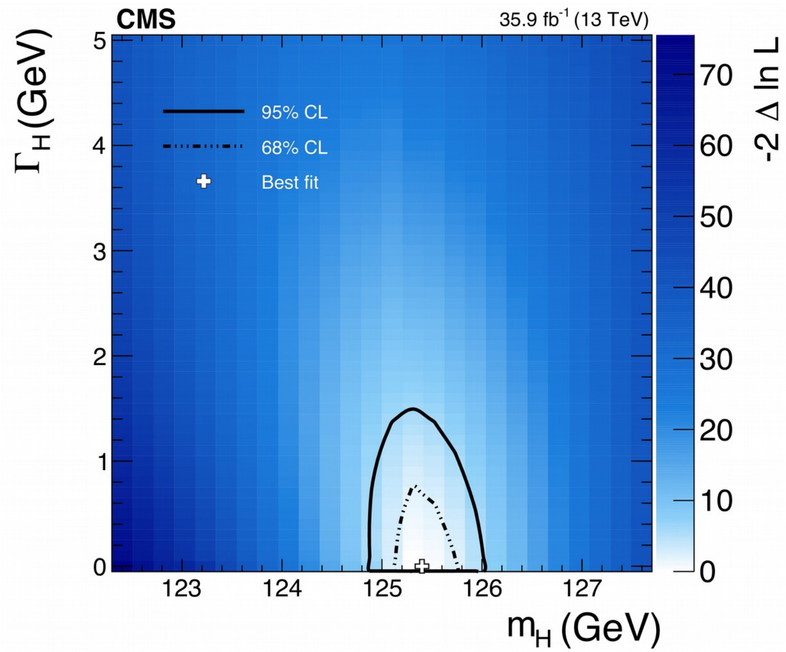
$$m_{\mathrm{H}} = 125.38 \pm 0.14\,\mathrm{GeV}$$

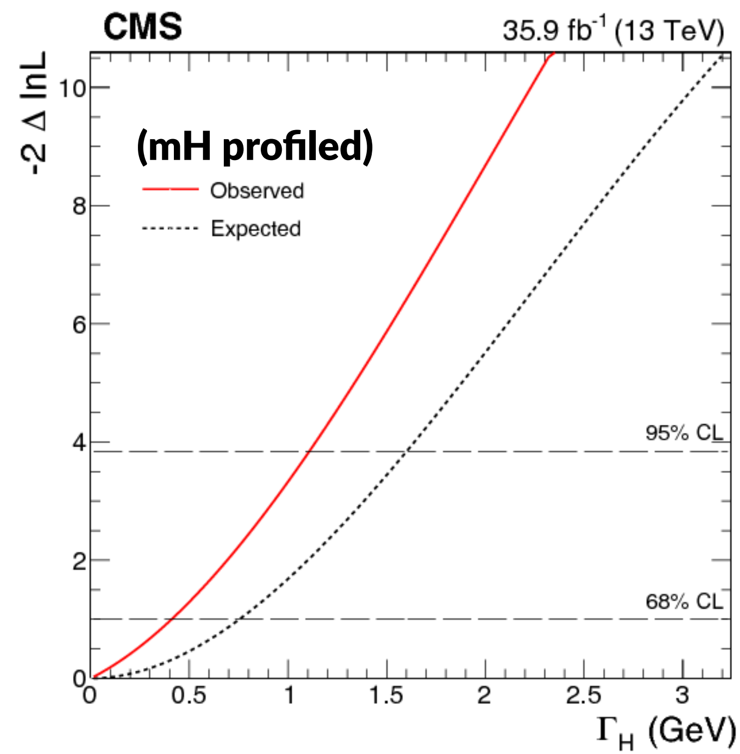


Γ_H measurements

Γ_H: H→4l Onshell (CMS)

JHEP11 (2017) 047



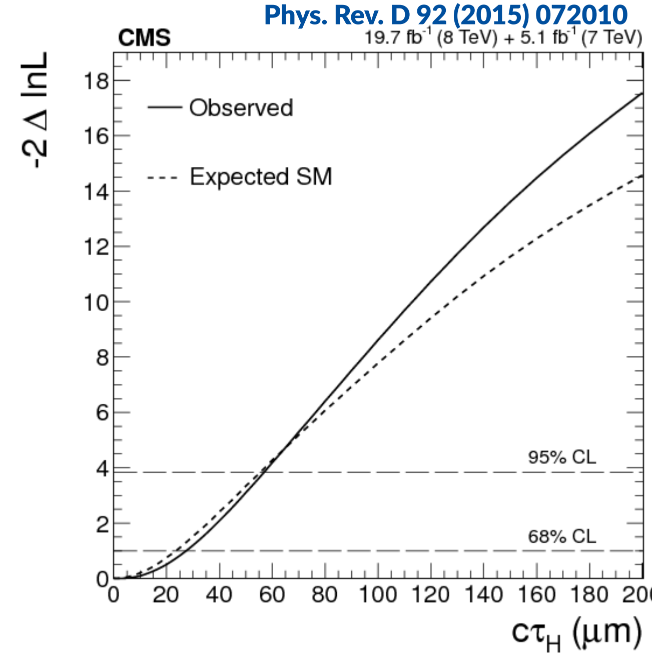


- Extract the width from the Breit-Wigner lineshape
- **Limited by detector resolution**

Γ_H < 1.1GeV at 95% CL

CMS also performed a Higgs lifetime measurement ct : $\Gamma_H > 3.5 \times 10^{-9}$ MeV

Phys. Rev. D 92 (2015) 072010

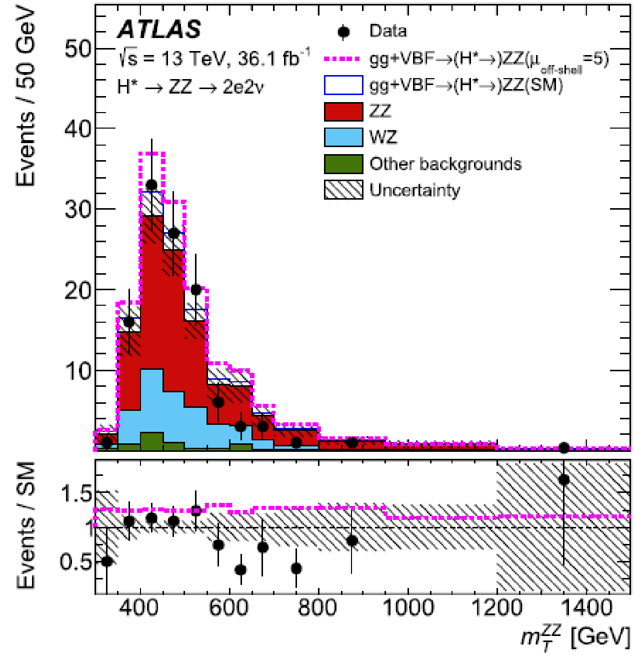


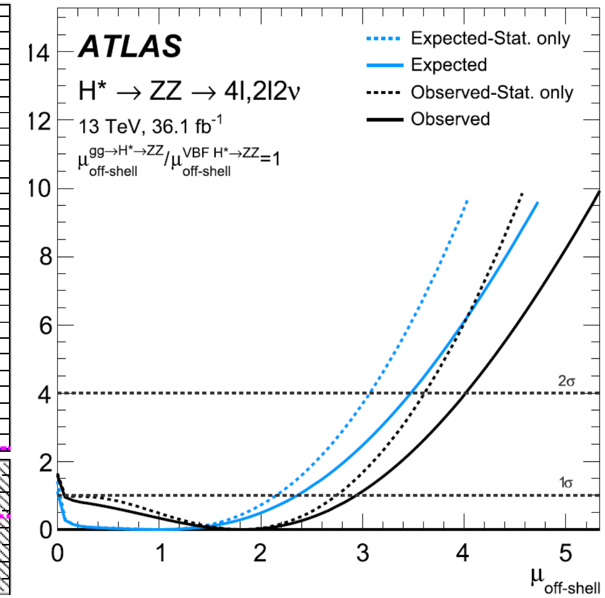
Γ_H: Offshell (ATLAS)

Phys. Lett. B 786 (2018) 223

$$\frac{\sigma^{\text{off-shell}}_{vv\to H\to 4\ell}}{\sigma^{\text{on-shell}}_{vv\to H\to 4\ell}} \propto \Gamma_H$$

- Measure ratio of onshell and offshell yields
- Background interferes destructively with signal in offshell!

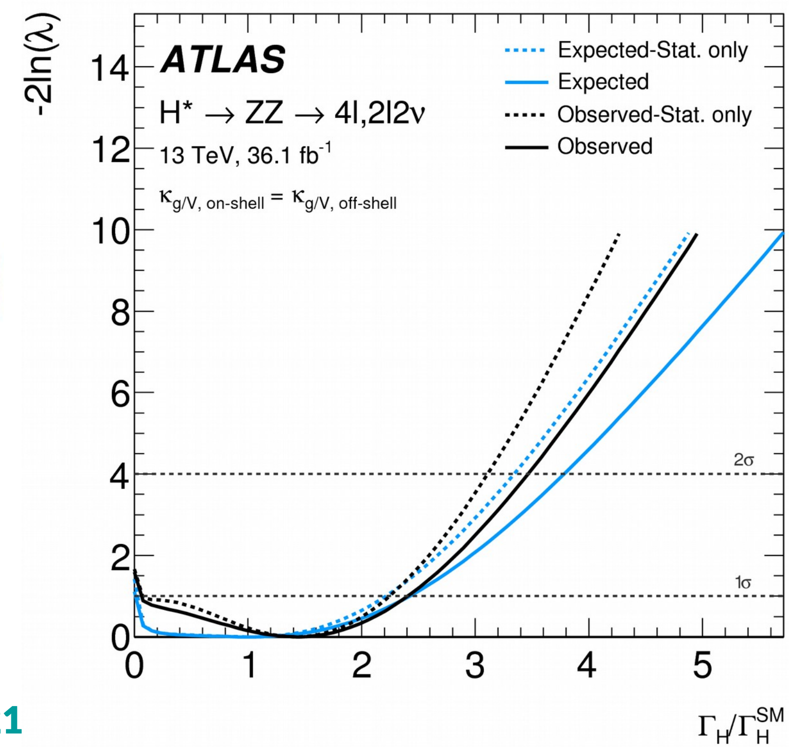




- H→4l + H→2l2ν combination
- 220GeV < m_{4l} < 2 TeV
- Fit: D_{ME} (4l) and M_T^{ZZ} (2l2ν)
- ‘15+‘16 data
- Upper bound set

$$D_{\text{ME}} = \log_{10}\left(\frac{P_H}{P_{gg} + c\cdot P_{q\bar{q}}}\right)$$

Γ_H < 14.4 MeV

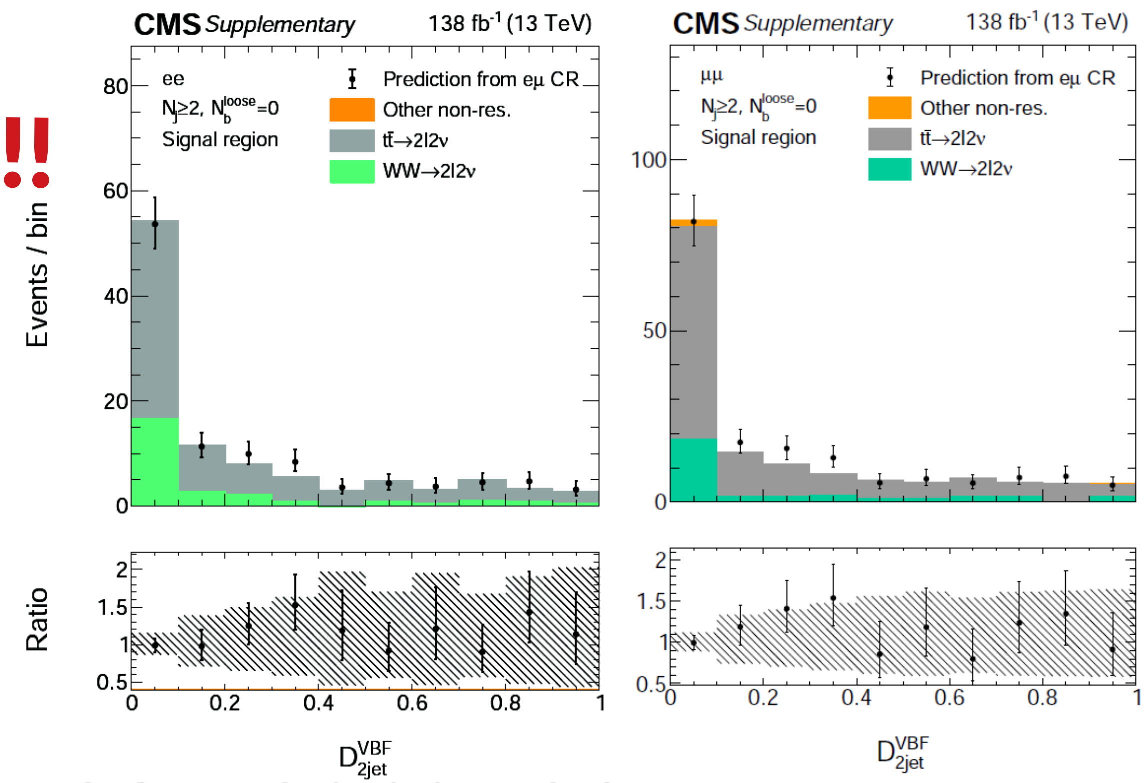


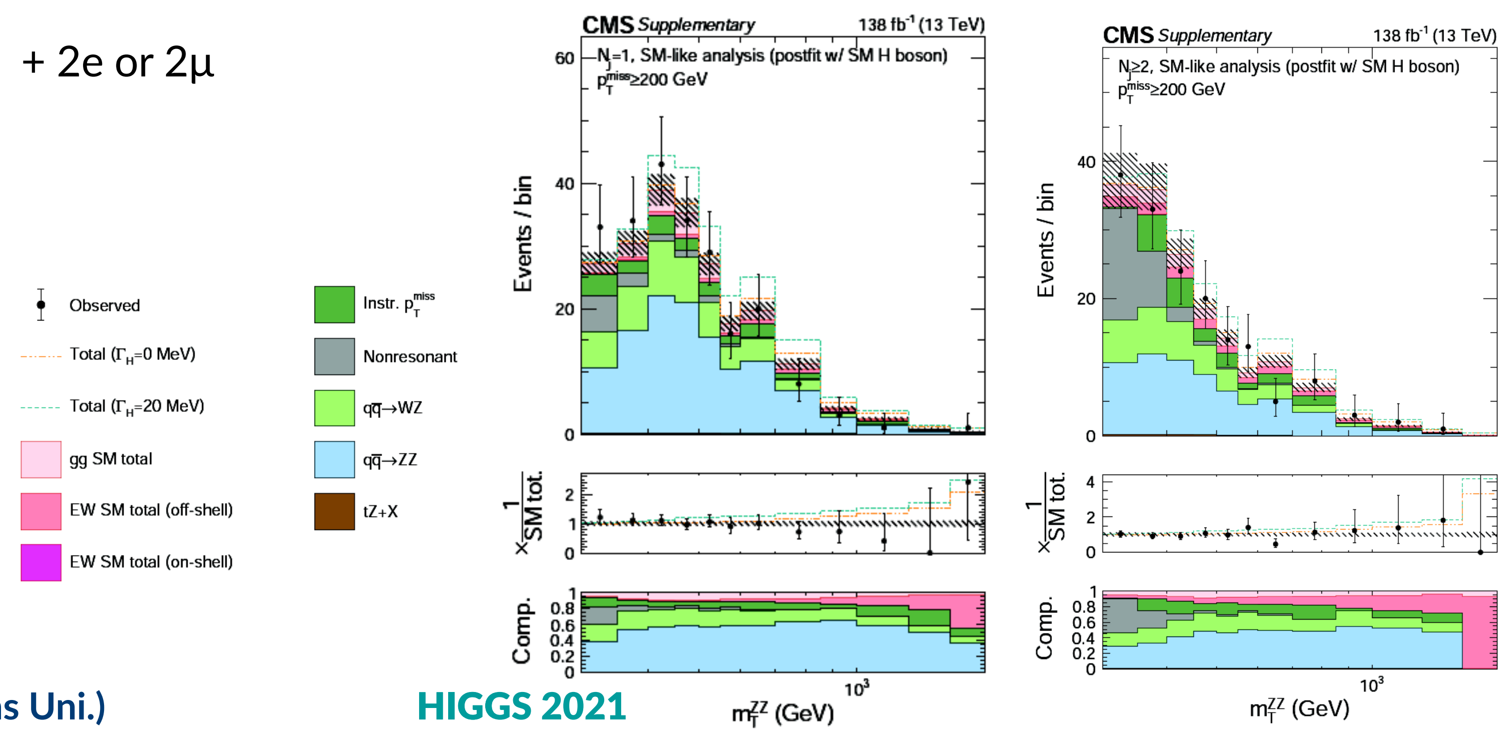
Γ_H: Offshell (CMS)

NEW!!!!

CMS-PAS-HIG-21-013

- **Analysis of offshell H→ 2l2v Full Run2**
- Multiple CR for background estimations
  - Reducible Z+jets background estimated from γ+jets CR
  - e/μ CR for WW/tt backgrounds
  - Trilepton CR for qq→ ZZ
- Other backgrounds estimated from simulation
- Events split in Nj categ. + 2e or 2μ





Γ_H: Offshell (CMS)

NEW!!!!

$$m_T^{ZZ^2} = \left[\sqrt{p_T^{\ell\ell^2} + m_{\ell\ell}{}^2} + \sqrt{p_T^{\text{miss}^2} + m_Z{}^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,\text{miss}}\right|^2$$

Fit :

$$m_T^{ZZ},\ p_T^{\text{miss}},\ \mathcal{D}_{2\text{jet}}^{\text{VBF}} \text{ and } \mathcal{D}_{2\text{jet}}^{\text{VBF},ai}$$

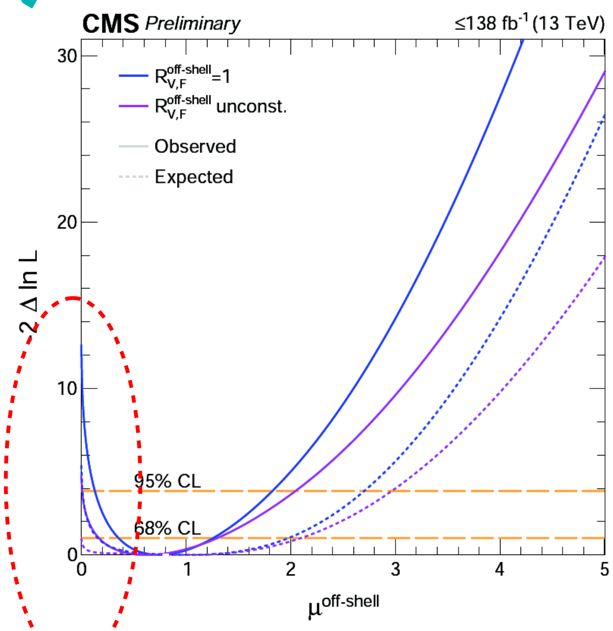
Fit Γ_H , μv ,μf offshel
+anomalous couplings (more later)

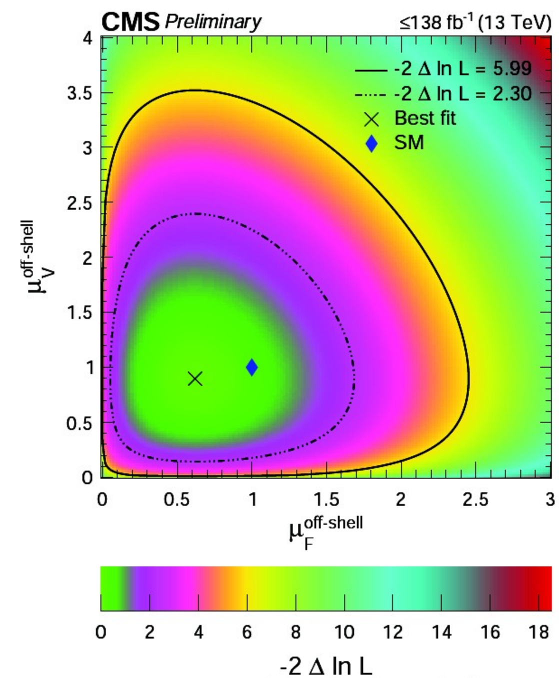
Combination of H→2l2ν (offshell Full Run2) + H→4l (onshell Full Run2 + offshell '15-'16-'17)

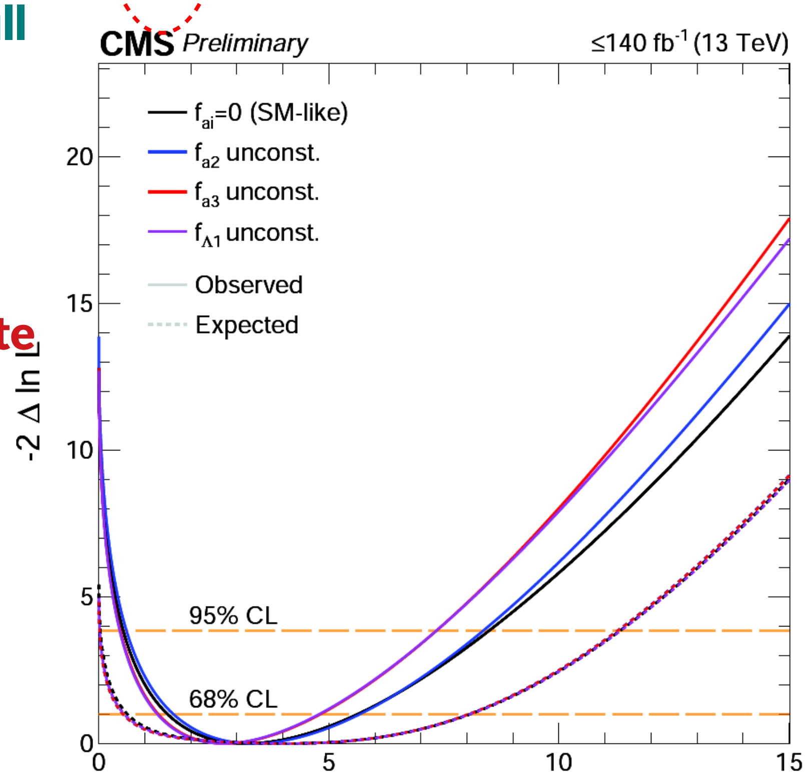
Evidence for offshell production at 3.6σ

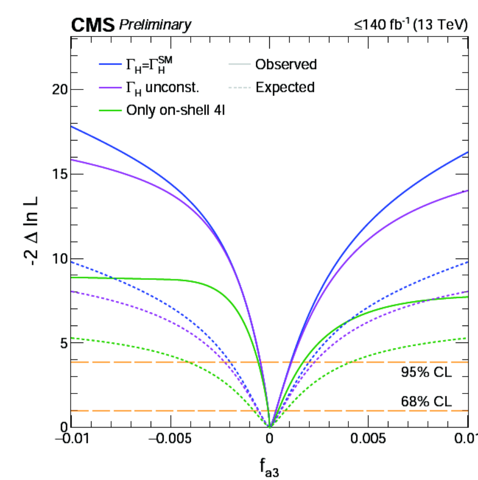
Most precise Γ_H measurement to-date

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

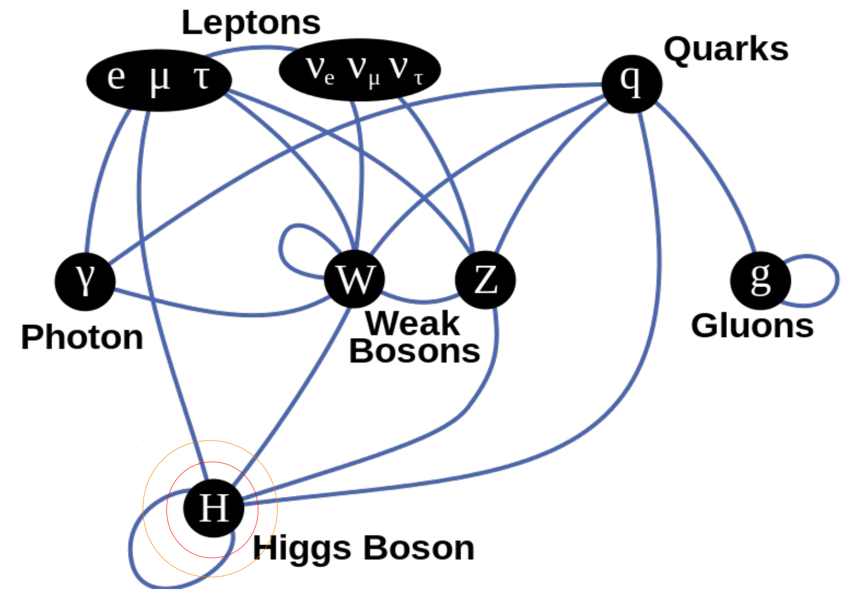




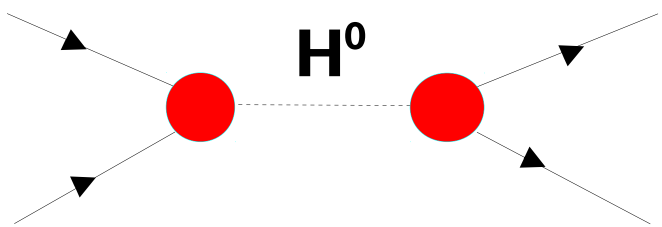




See also dedicated talk by Mostafa



CP measurements

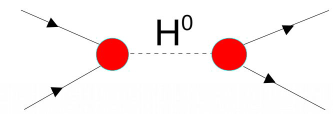


This talk focuses on measurements with
CP sensitive observables

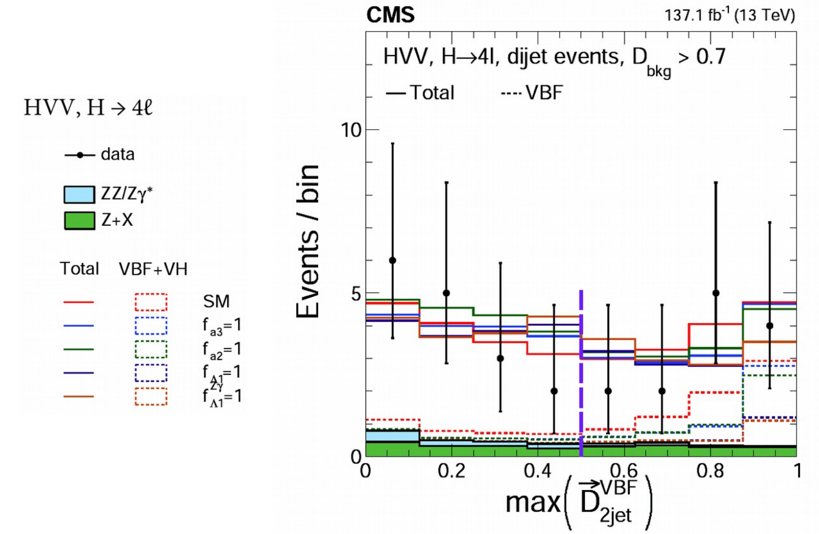
(and not general AC)

Phys. Rev D 104 (2021) 052004

CP: HVV in H→4l (CMS)



- MELA based discriminants (categorization + measurement)
- Categories:
  - Untagged, Boosted, VBF 1jet, VBF 2jet, VHHadr. , VHLept.
- **Production + Decay** information incorporated
- **Parametrization using mass eigenstate basis (Higgs basis)**



$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_{V1}+q_{V2})^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^*$$

$$+ \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

V = W,Z,g,γ

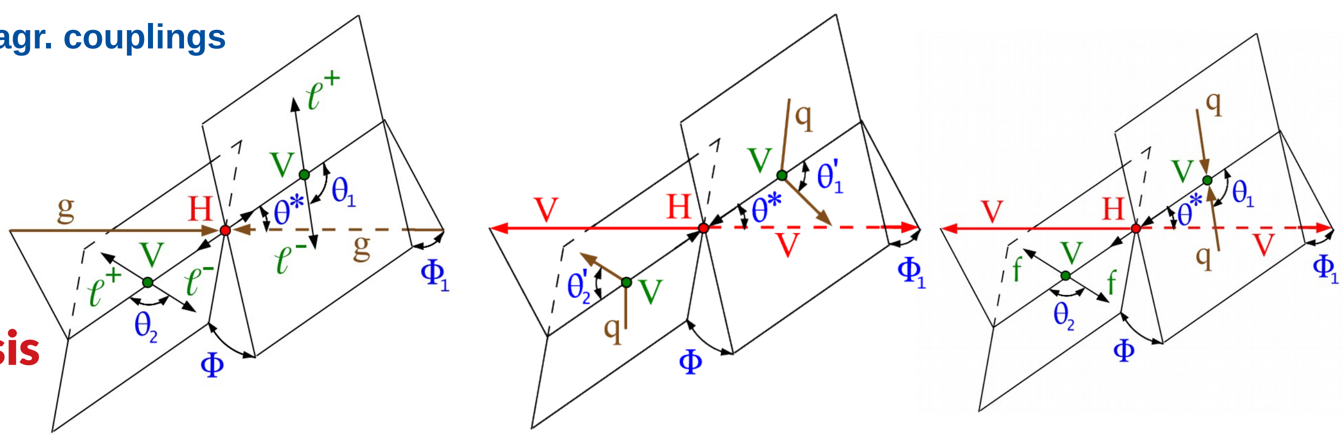
$$\mathcal{D}_{\mathrm{alt}}(\Omega) = \frac{\mathcal{P}_{\mathrm{sig}}(\Omega)}{\mathcal{P}_{\mathrm{sig}}(\Omega) + \mathcal{P}_{\mathrm{alt}}(\Omega)},$$

$$\mathcal{D}_{\mathrm{int}}(\Omega) = \frac{\mathcal{P}_{\mathrm{int}}(\Omega)}{2\sqrt{\mathcal{P}_{\mathrm{sig}}(\Omega)\ \mathcal{P}_{\mathrm{alt}}(\Omega)}},$$

See back-up slides for more info on EFT + Lagr. couplings

2 EFT schemes:
- SU(2)xU(1) not implemented (Aprr. 1)
- SU(2)xU(1) – SMEFT (Appr. 2)

Results translated to Warsaw basis



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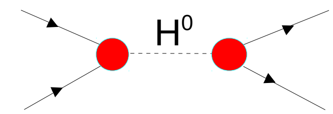

fai measurements:

Effective fractional xsec:

$$f_{ai}^{VV} = \frac{|a_i^{VV}|^2 \, \alpha_{ii}^{(dec)}}{\sum_j |a_j^{VV}|^2 \, \alpha_{jj}^{(dec)}} \operatorname{sign}\left(\frac{a_i^{VV}}{a_1}\right)$$

Coupling a_i^{VV}	Fraction f_{ai}^{VV}	Approach 1 α_{ii}/α_{11}	Approach 2 α_{ii}/α_{11}
a_3	f_{a3}	0.153	0.153
a_2	f_{a2}	0.361	6.376
κ_1	$f_{\Lambda 1}$	0.682	5.241
$\kappa_2^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$	1.746	N/A

direct couplings measurements:

Anomalous contributions modify the total width!

$$\sigma(i \to H \to f) \propto \frac{\left(\sum \alpha_{jk} g_j g_k\right)\left(\sum \alpha_{lm} g_l g_m\right)}{\Gamma_{tot}}$$

$$\Gamma_{tot} = \sum_f \Gamma_f = \Gamma_{tot}^{SM} \times \sum_f \left(\frac{\Gamma_f^{SM}}{\Gamma_{tot}^{SM}} \times \frac{\Gamma_f}{\Gamma_f^{SM}}\right) = \Gamma_{tot}^{SM} \times \sum_f \left(\mathcal{B}_f^{SM} \times R_f(\vec{g}_j)\right)$$

$$R_{ZZ/Z\gamma^*/\gamma^*\gamma^*} = \left(\frac{g_1^{ZZ}}{2}\right)^2 + 0.1695\left(\kappa_1^{ZZ}\right)^2 + 0.09076\left(g_2^{ZZ}\right)^2 + 0.03809\left(g_4^{ZZ}\right)$$
$$+ 0.8095\left(\frac{g_1^{ZZ}}{2}\right)\kappa_1^{ZZ} + 0.5046\left(\frac{g_1^{ZZ}}{2}\right)g_2^{ZZ} + 0.2092\kappa_1^{ZZ}g_2^{ZZ}$$
$$+ 0.1023\left(\kappa_2^{Z\gamma}\right)^2 + 0.1901\left(\frac{g_1^{ZZ}}{2}\right)\kappa_2^{Z\gamma} + 0.07429\kappa_1^{ZZ}\kappa_2^{Z\gamma} + 0.04710 g_2^{ZZ}\kappa_2^{Z\gamma}$$

$$\delta c_z = \frac{1}{2}a_1 - 1,$$
$$c_{z\Box} = \frac{m_Z^2 s_W^2}{4\pi\alpha}\frac{\kappa_1}{(\Lambda_1)^2}$$
$$c_{zz} = -\frac{s_W^2 c_W^2}{2\pi\alpha}a_2,$$
$$\tilde{c}_{zz} = -\frac{s_W^2 c_W^2}{2\pi\alpha}a_3.$$

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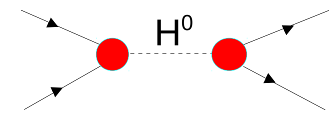
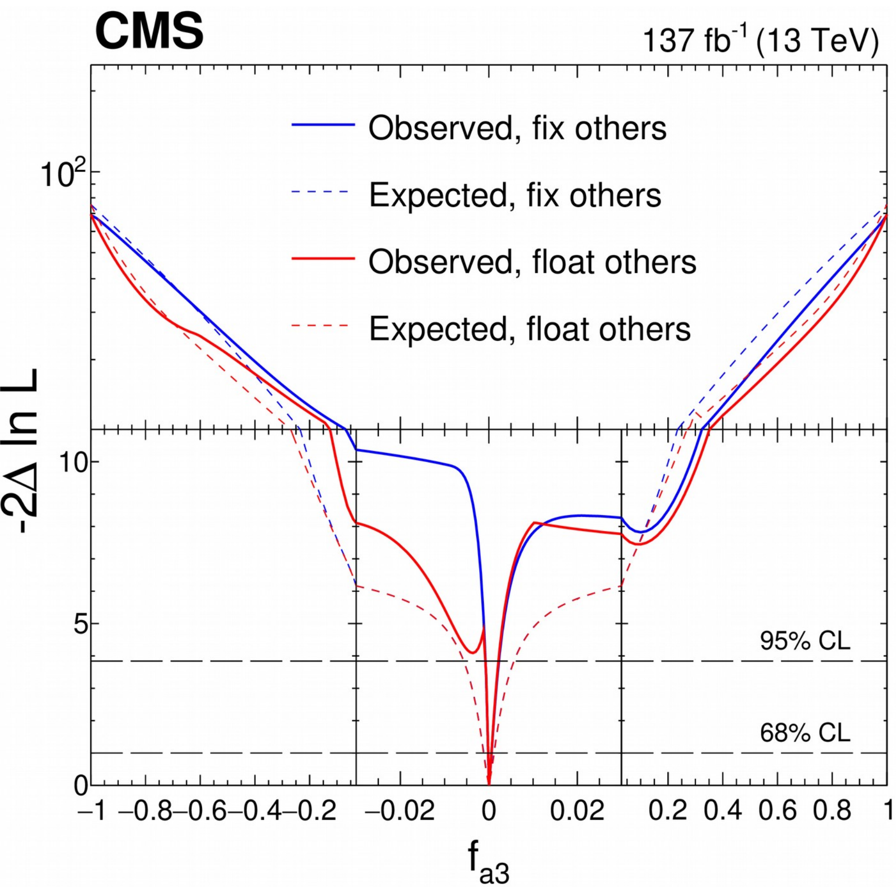
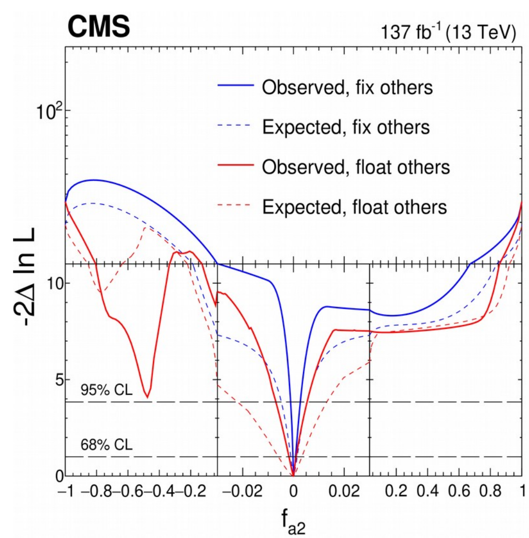
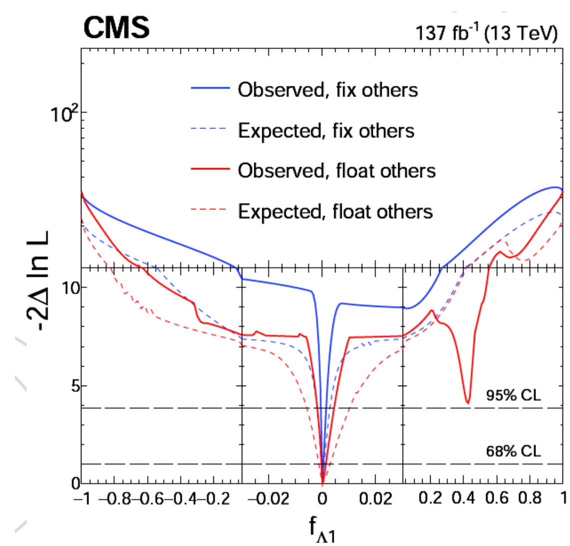
CP: HVV in H→4l (CMS)





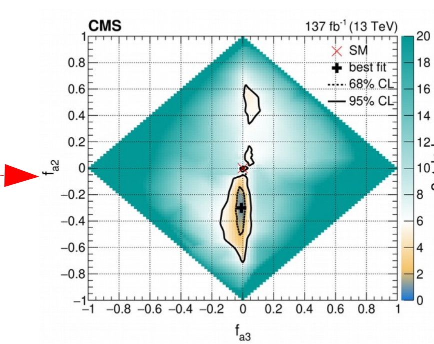
- SU(2)xU(1) sym. (SMEFT) with only 3 independent A.C.
- **Stringent constraints driven by production information**
- **Full Run2**
- **Minima consistent with SM**





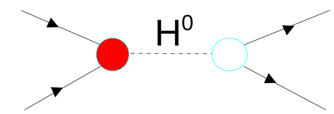
Parameter	Scenario		Observed	Expected
f_{a3}	Approach 1	best fit	0.00004	0.00000
	$f_{a2} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	68% CL	[−0.00007, 0.00044]	[−0.00081, 0.00081]
		95% CL	[−0.00055, 0.00168]	[−0.00412, 0.00412]
	Approach 1	best fit	−0.00805	0.00000
	float $f_{a2}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	68% CL	[−0.02656, 0.00034]	[−0.00086, 0.00086]
		95% CL	[−0.07191, 0.00990]	[−0.00423, 0.00422]
	Approach 2	best fit	0.00005	0.0000
	float $f_{a2}, f_{\Lambda 1}$	68% CL	[−0.00010, 0.00061]	[−0.0012, 0.0012]
		95% CL	[−0.00072, 0.00218]	[−0.0057, 0.0057]

Non SU(2)xU(1) results in back up:



CP: HVV in H→4l + H→2l2ν Offshell (CMS)

NEW!!!!



Full Run2

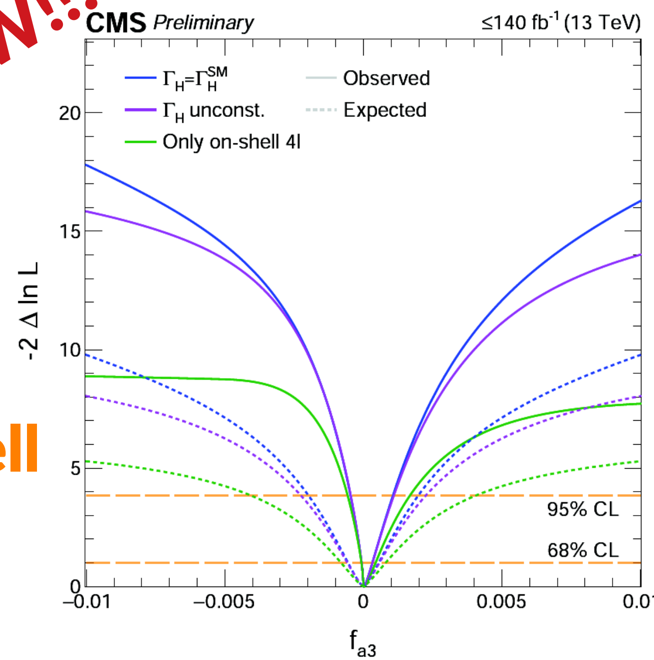
$$\mathcal{D}_{2jet}^{VBF,ai}$$

Combine **onshell** and **offshell**

H→4l + **H→2l2ν**

single A.C. scans

width constrained
and unconstrained



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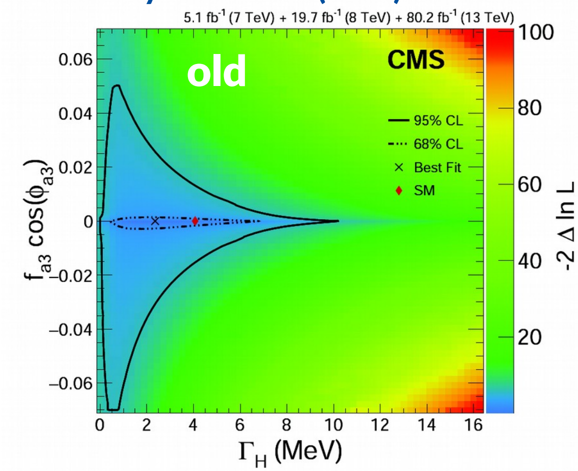
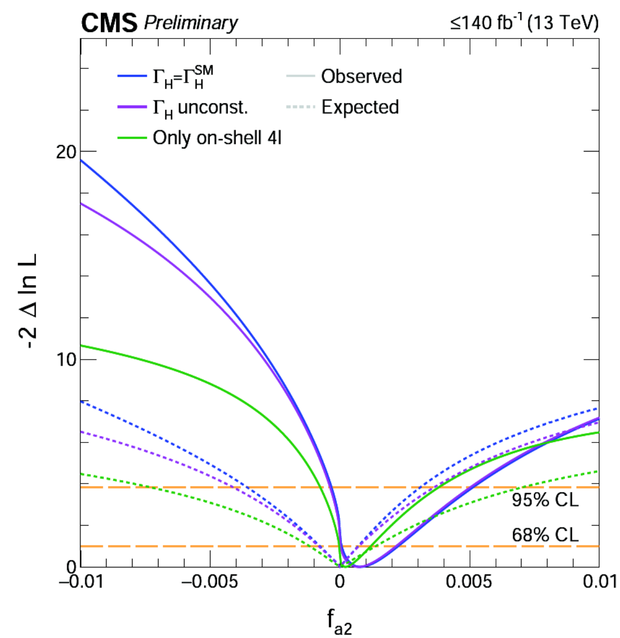
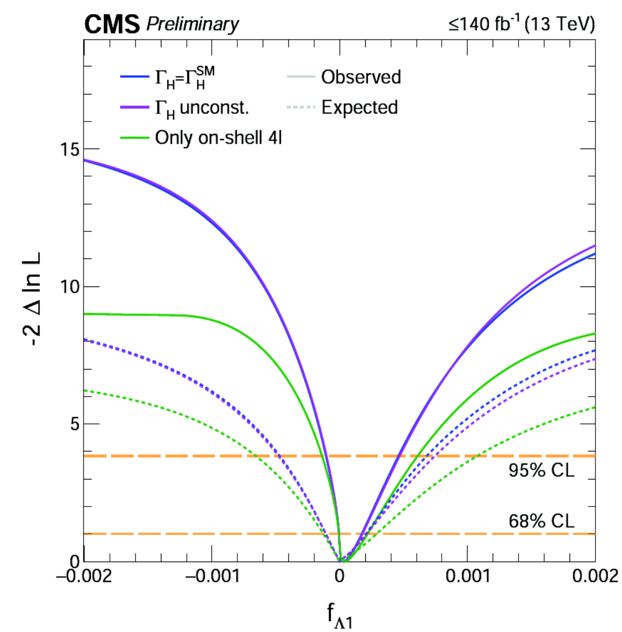


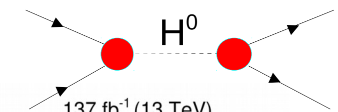


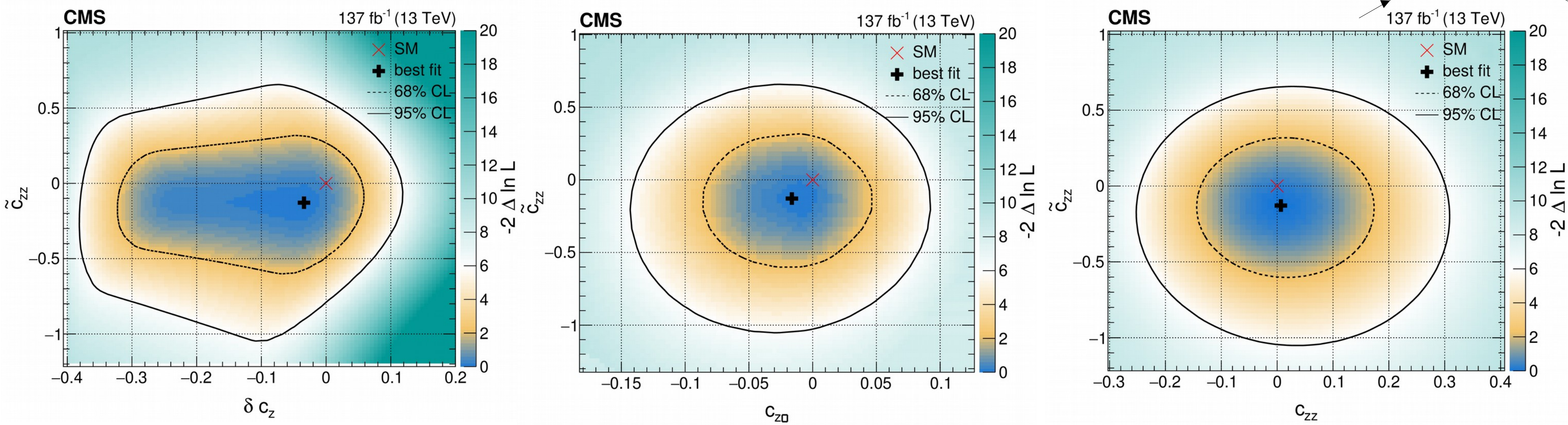


See also dedicated talk by Mostafa

Phys. Rev D 104 (2021) 052004

CP: HVV in H→4l (CMS)





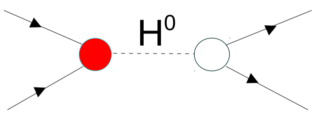
Constraints in Lagrangian coupling in Higgs basis

Channels	Coupling	Observed
VBF & VH & $H \to 4\ell$	δc_z	$-0.03^{+0.06}_{-0.25}$
	c_{zz}	$0.01^{+0.11}_{-0.10}$
	$c_{z\Box}$	$-0.02^{+0.04}_{-0.04}$
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$

Translated to Warsaw basis:

Channels	Coupling	Observed	Expected
VBF & VH & $H \to 4\ell$	$c_{H\Box}$	$0.04^{+0.43}_{-0.45}$	$0.00^{+0.75}_{-0.93}$
	c_{HD}	$-0.73^{+0.97}_{-4.21}$	$0.00^{+1.06}_{-4.60}$
	c_{HW}	$0.01^{+0.18}_{-0.17}$	$0.00^{+0.39}_{-0.28}$
	c_{HWB}	$0.01^{+0.20}_{-0.18}$	$0.00^{+0.42}_{-0.31}$
	c_{HB}	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.08}$
	$c_{H\tilde{W}}$	$-0.23^{+0.51}_{-0.52}$	$0.00^{+1.11}_{-1.11}$
	$c_{H\tilde{W}B}$	$-0.25^{+0.56}_{-0.57}$	$0.00^{+1.21}_{-1.21}$
	$c_{H\tilde{B}}$	$-0.06^{+0.15}_{-0.16}$	$0.00^{+0.33}_{-0.33}$

CP: HVV from H→ττ + H→4l (CMS)

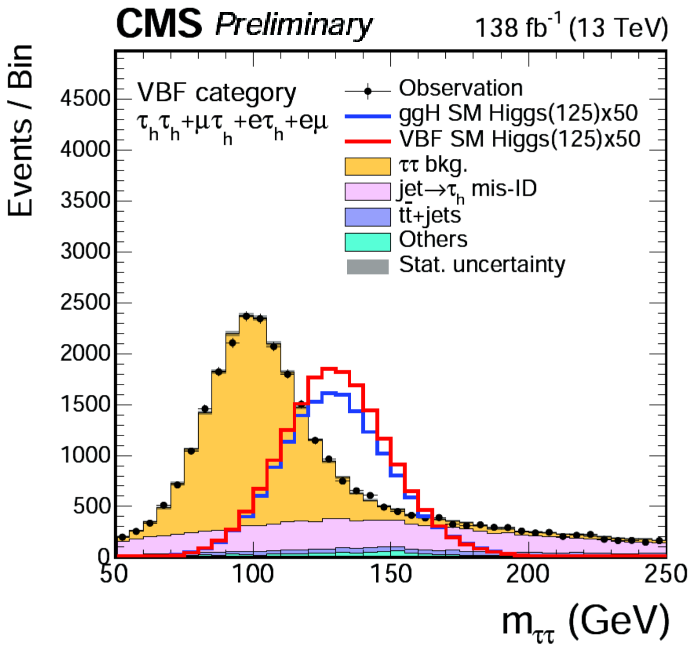


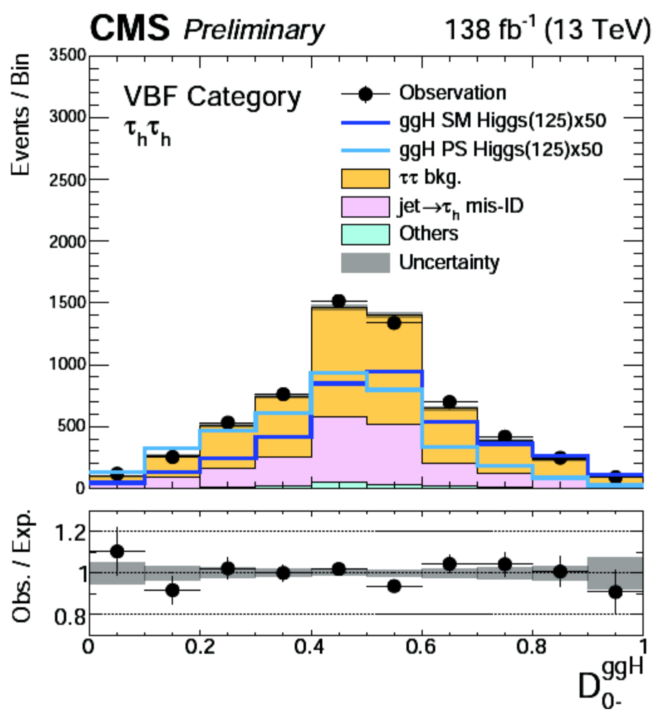
NEW!!!!

- **Full Run2 analysis**
- Parametrization of AC as in H→4l
- Dedicated **MELA** discriminants
- Information from **production**
- Single AC scans
- Results combined with H→4l

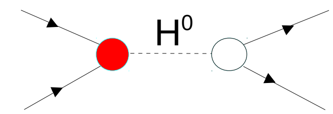
- Use 2 EFT approaches:
  - without SU(2)xU(1) (Appr 1.)
  - with (Appr. 2.)

See also dedicated talk by Daniel



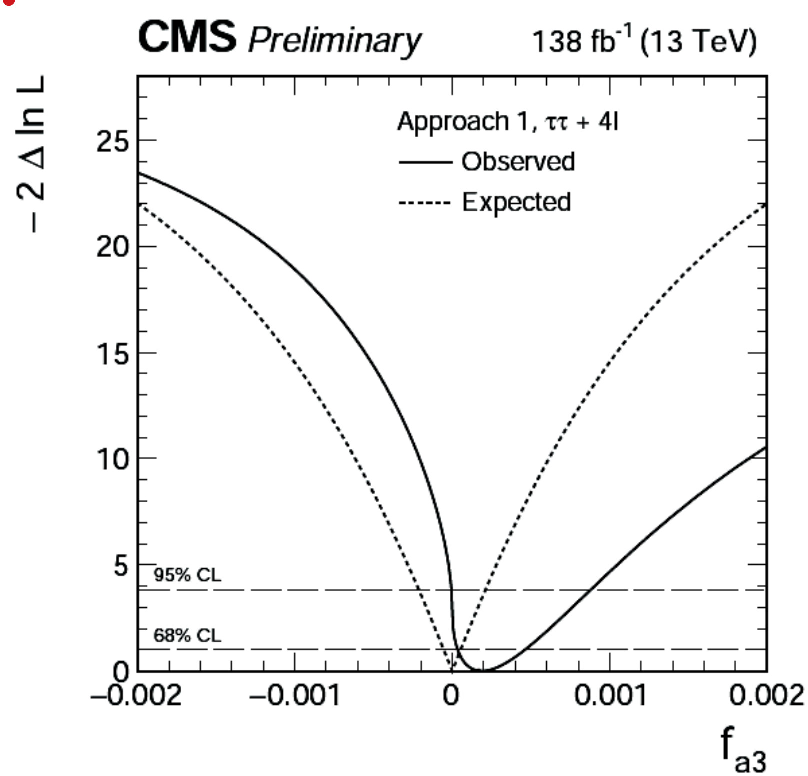


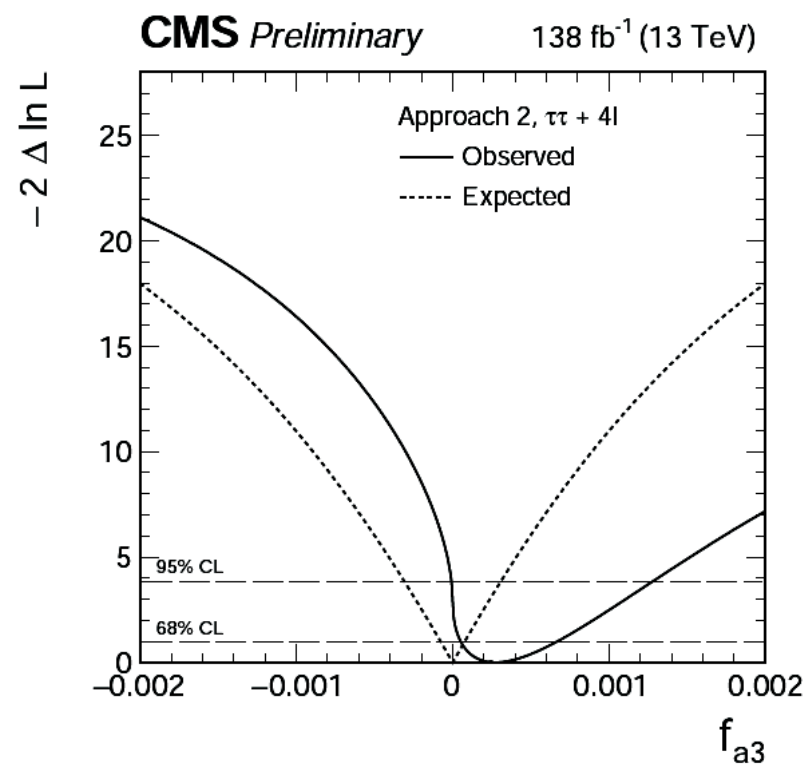
HIG-17-034



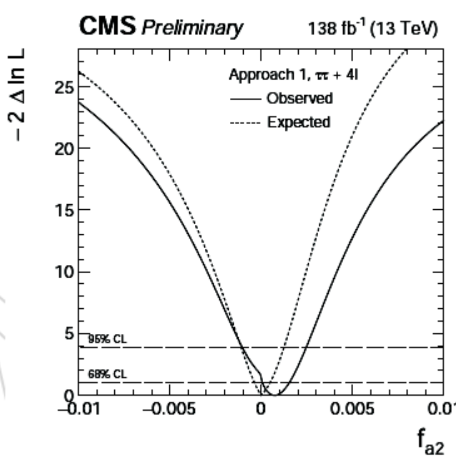
CP: HVV from H→ττ + H→4l (CMS)

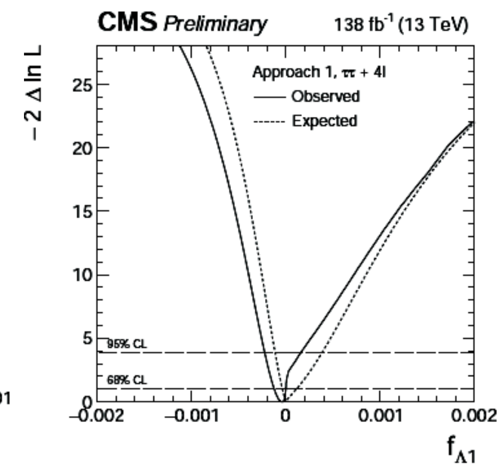
NEW!!!!

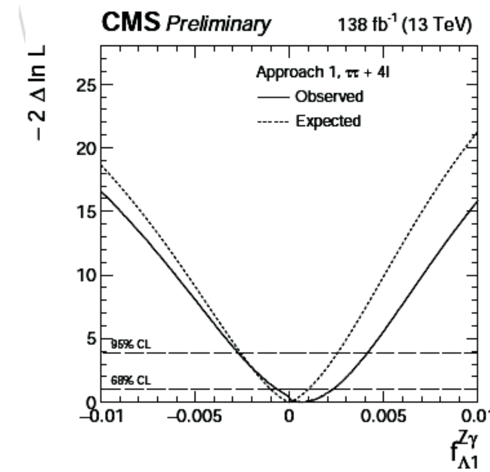




Tight constraints on CP odd and other anomalous couplings

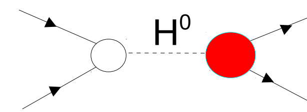






See also dedicated talk by Daniel

CP: Yukawa ττH from H→ττ (CMS)



NEW!!!!

$$\frac{d\Gamma}{d\phi_{CP}}(H \to \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

$$\mathcal{L}_Y = -\frac{m_\tau}{v}H(\kappa_\tau\bar{\tau}\tau + \tilde{\kappa}_\tau\bar{\tau}i\gamma_5\tau)$$

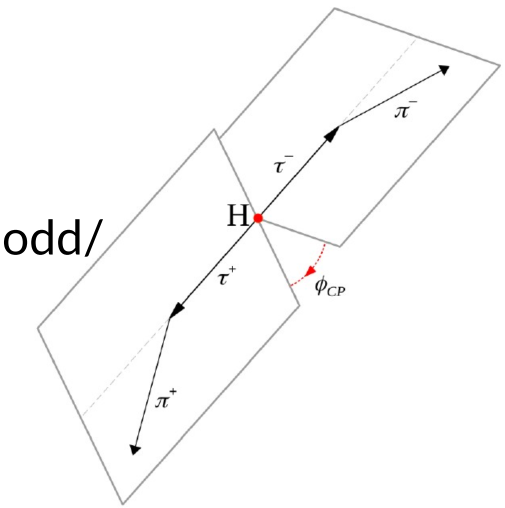
Full Run2 data

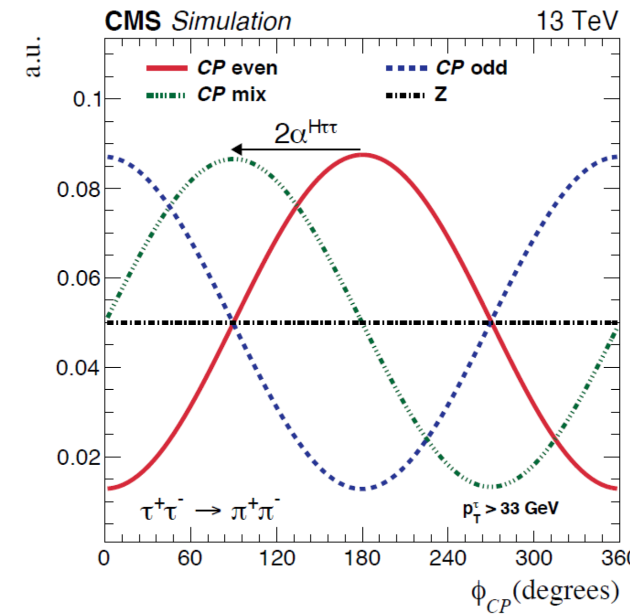
Decay vertex probed

Use decays to ττ pair to measure CP odd/even mixing in Hττ

Use ~70% of τ BR:

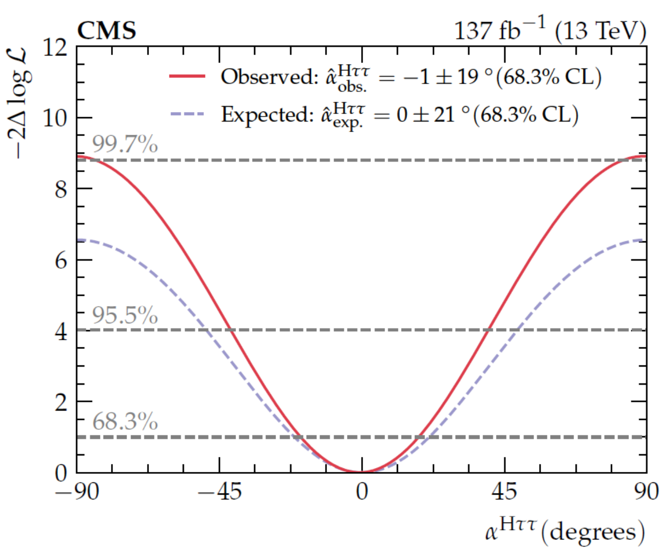
$$\tau_h\tau_h,\ \tau_\mu\tau_h,\ \tau_e\tau_h$$

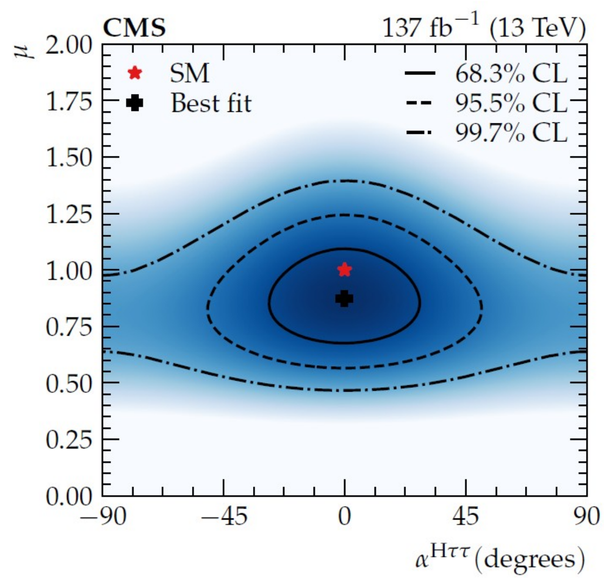


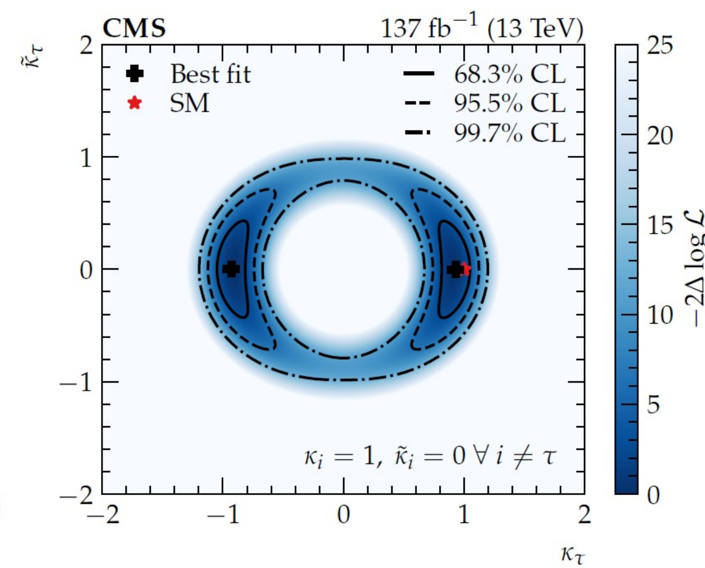


4 reconstruction methods of ϕ_{CP}

Pure CP odd excluded at 3σ







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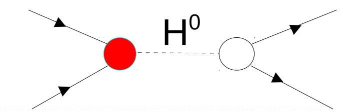
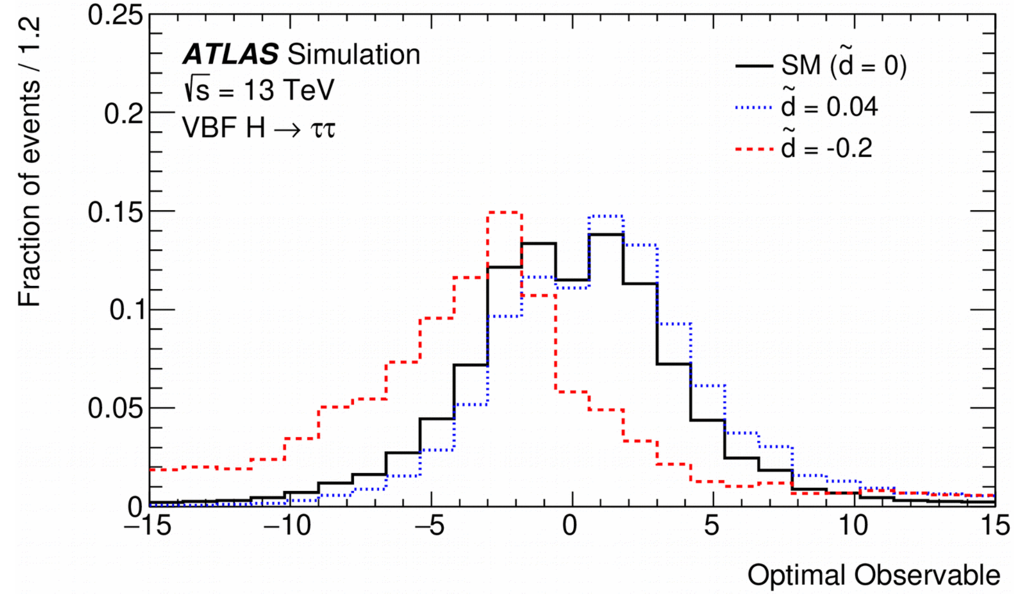
CP: HVV from H→ττ (ATLAS)





Study CP in **production**

2J events

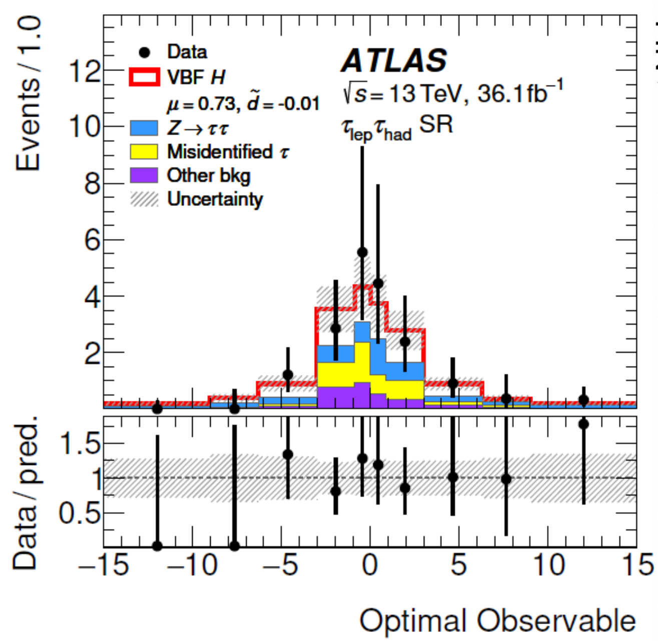
event selection using BDTs in 4 signal categories (based on τ decay)

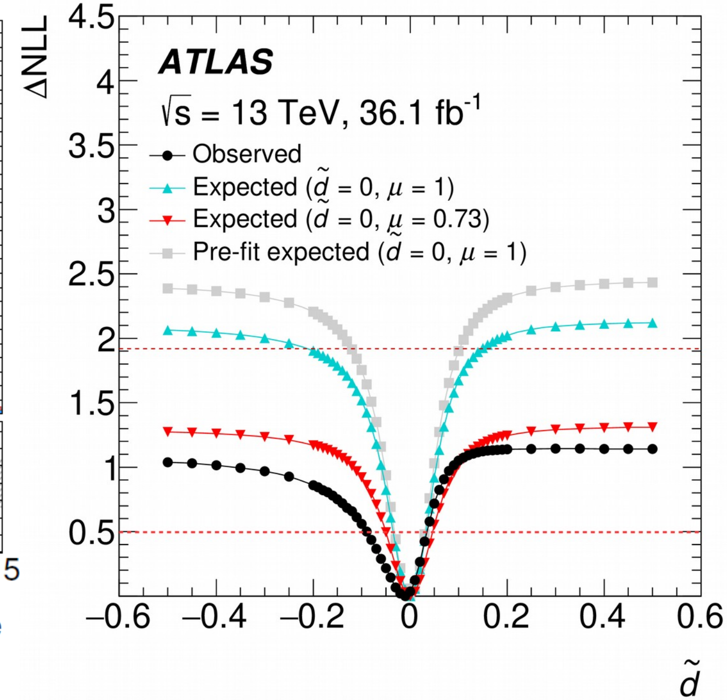
Implement :

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$$ (as in HAWK)

$$O_{\text{opt}} = \frac{2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$

Fit Optimal Observable + mττ





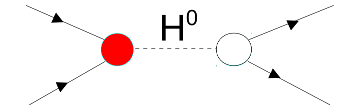
Observed:

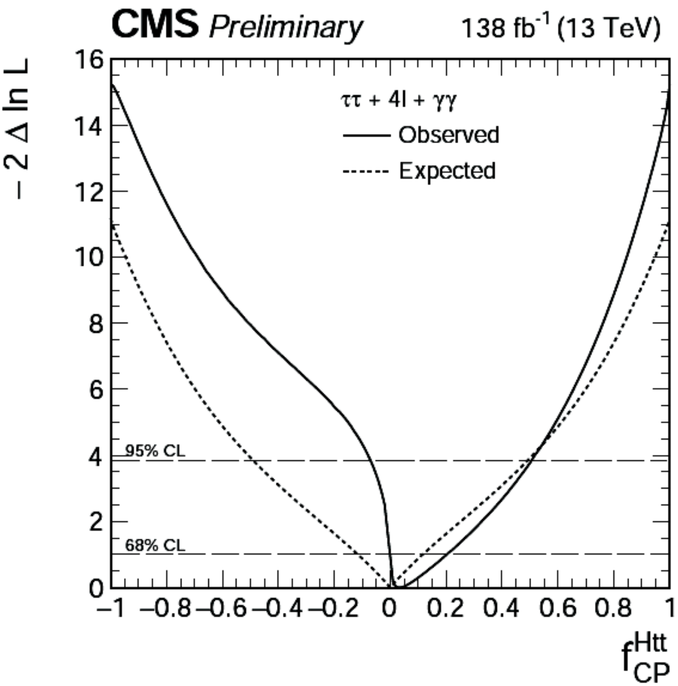
$$\tilde{d} \in [-0.090, 0.035]$$
68% CL

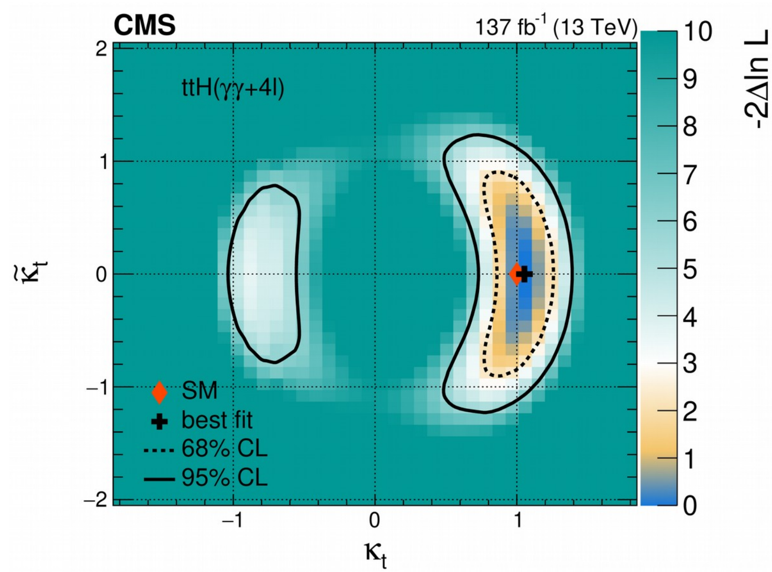
See also dedicated talk by Chiara

Phys. Rev D 104 (2021) 052004
CMS-PAS-HIG-20-007

CP: Yukawa ttH with ttH, ggH, H→4l/γγ/ττ (CMS) NEW!!!!







- Measure f^{Htt}_{CP} in production
- Combine
  - H→ 4l
  - H→ττ
  - H→γγ

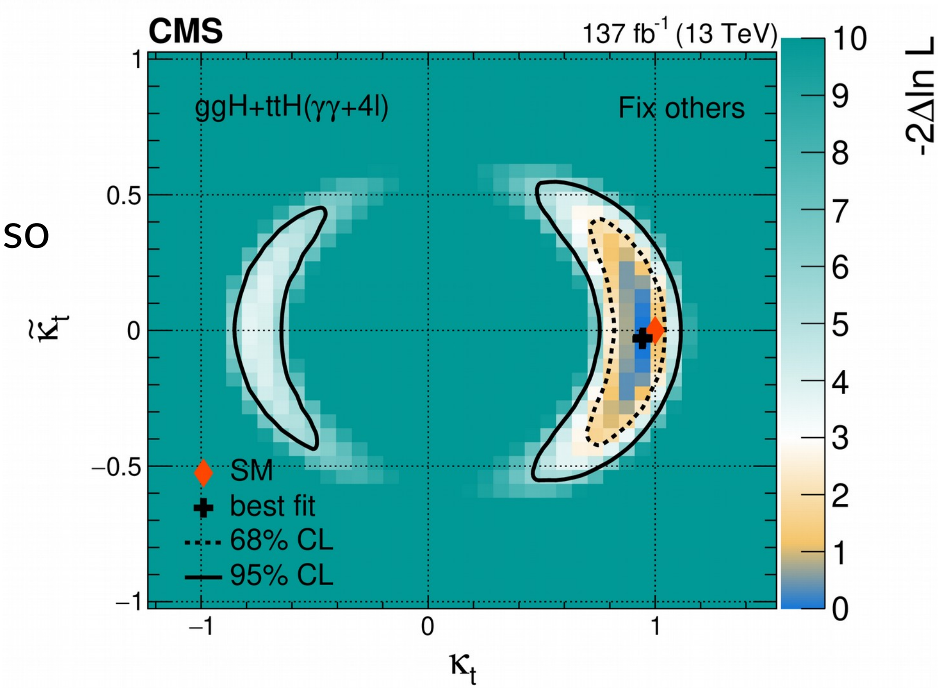
- Combine measurements with uncorrelated μs
- Interpret as top couplings

Constrain Htt from ggH and ttH:

Assume top dominance in the ggH loop:

assume $\kappa_b = \kappa_t$ and for CP odd contributions also

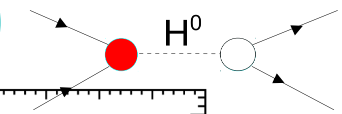
Combine H→4l result and H→γγ



See dedicated talk on Yukawa ttH by Sergio

Phys, Rev. Lett. 125 (2020) 061802

CP: Yukawa ttH with ttH,H→γγ (ATLAS)



Analysis targets **CP mixing angle and kt**

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t\kappa_t[\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$

Classify ttH events in **hadronic** and **leptonic**

- lept: require at least single isolated lepton
- had: at least 2 jets

Use **production information**

Dedicated signal-background BDT

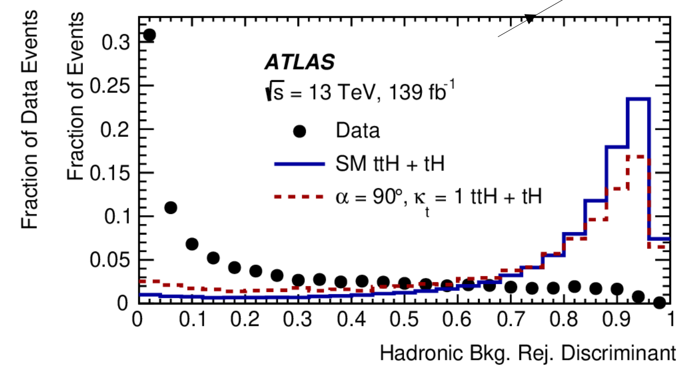
BDT CP: use top and diphoton system kinematics

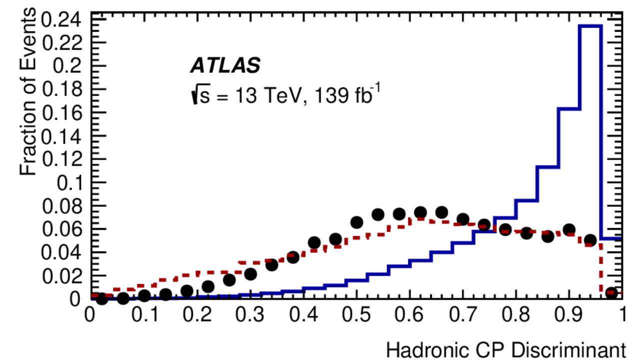
Fit mγγ in overall 20 categories (12Had + 8Lept)

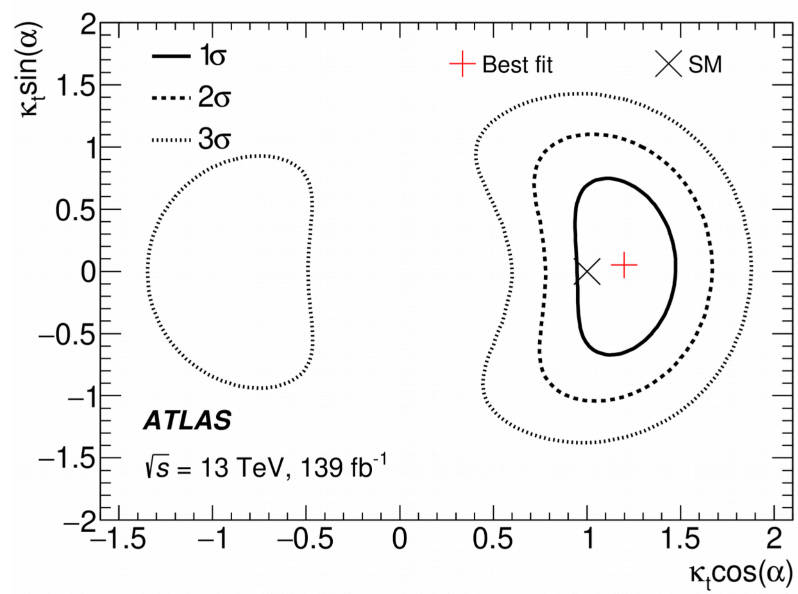
Tightly constrain pure CP odd ttH coupling

Full Run 2

See also dedicated talk by Chiara

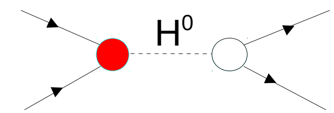






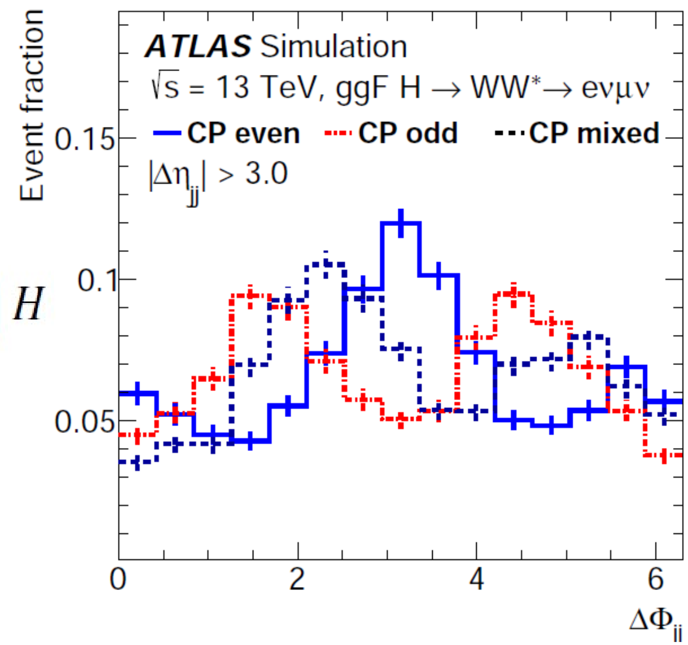
CP: Hgg in H→WW*→ eνμν+jj (ATLAS)

NEW!!!!

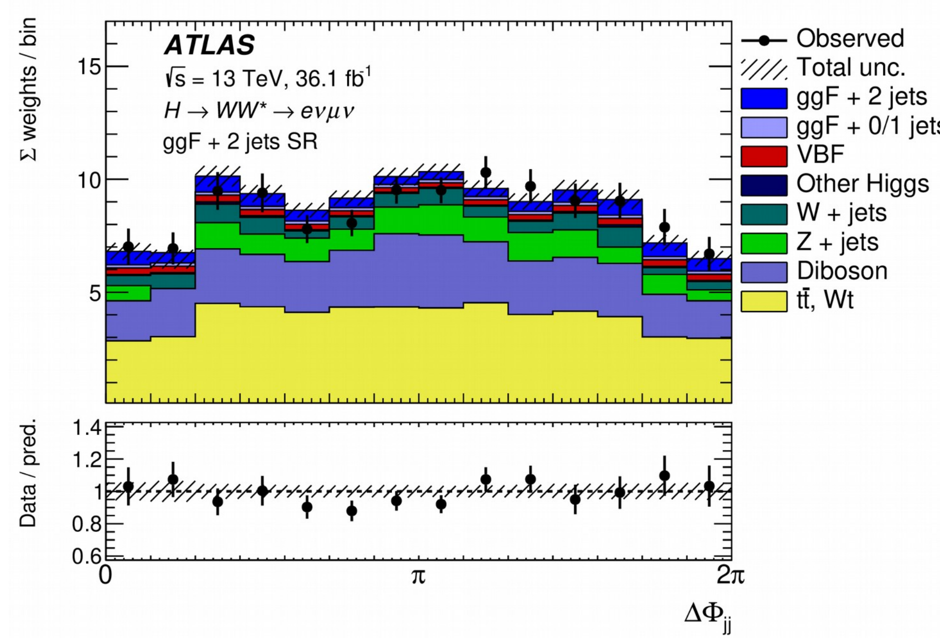


- Parameterization in terms of mixing angle and κ

$$\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg}\cos(\alpha)G^a_{\mu\nu}G^{a,\mu\nu} + \kappa_{gg}\sin(\alpha)G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H$$



- Use **production information**
- Assume HVV -SM like
- BDT to separate signal and background
- 12 categories – BDT and Δηjj
  - CP odd/even separation in ΔΦjj enhanced in high Δηjj

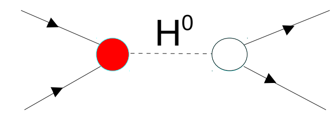


- Backgrounds constrained in CR

See also dedicated talk by Chiara

CP: Hgg in H→WW*→ eνμν+jj (ATLAS)

NEW!!!!



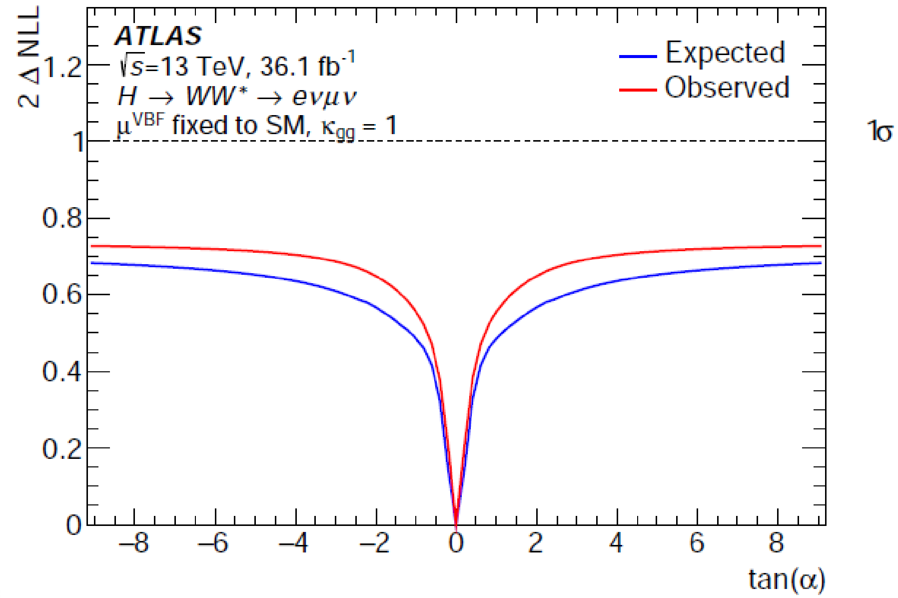
use BDT and ΔΦjj distributions for fitting

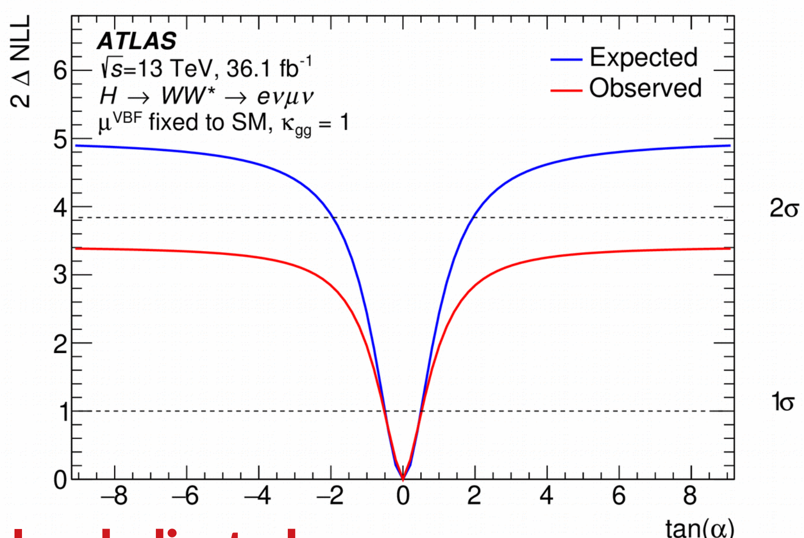
Fit Δφjj in SR: 3 BDT X 4 |Δηjj| regions

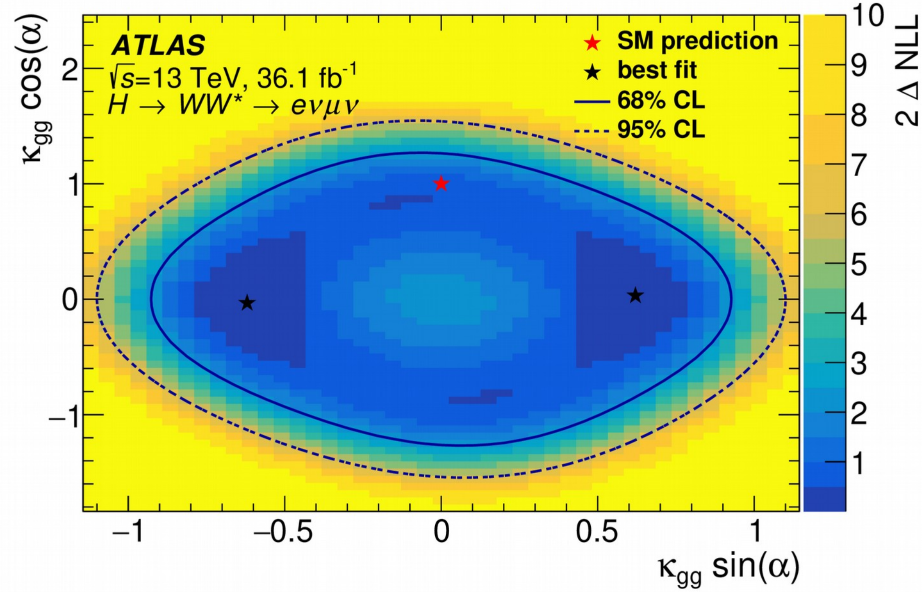
2 likelihood fits:

- Shape only considered scan (BSM rate floated)
- Shape + fix rate to BSM scenario

1σ constraints on CP mixing angle



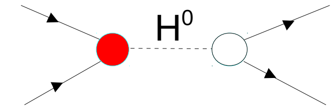


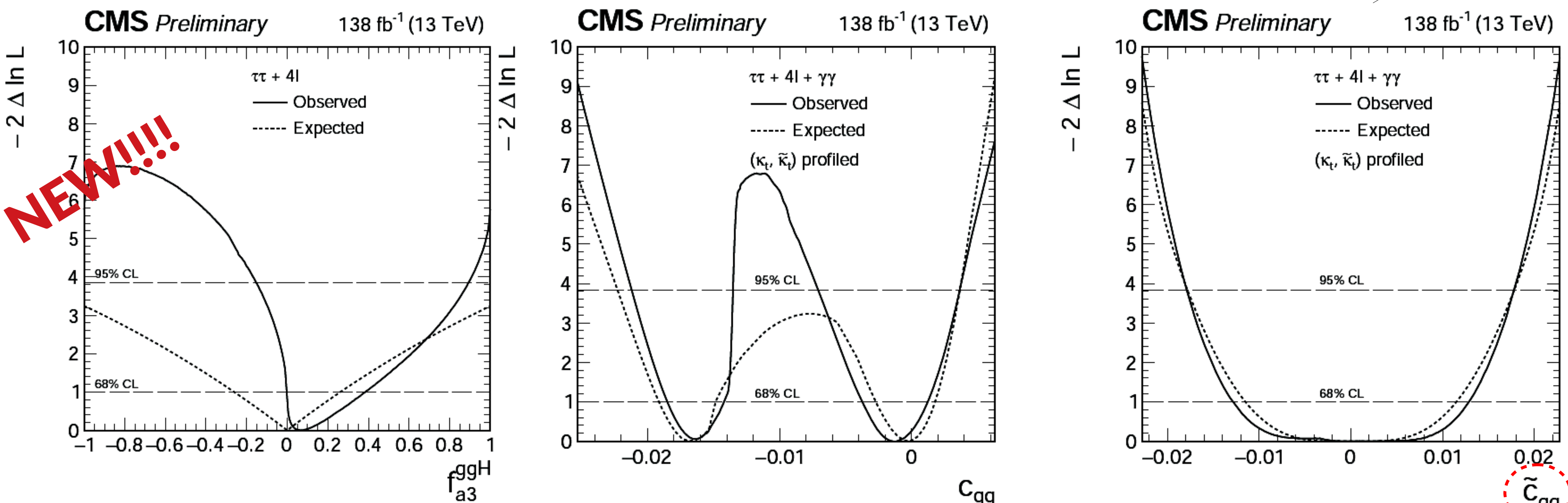


See also dedicated talk by Chiara

Phys. Rev D 104 (2021) 052004
CMS-PAS-HIG-20-007

CP: Hgg in H→4l+H→ ττ+H→ γγ (CMS)





Combination of H→4l, H→ττ, H→γγ

FULL RUN2

Measure CP sensitive fa3^{ggH} and μ_{ggH}

Use events in VBF2J to study ggH category

4 couplings fit simultaneously:

Consider ktop measured from the tH,ttH process and study cgg

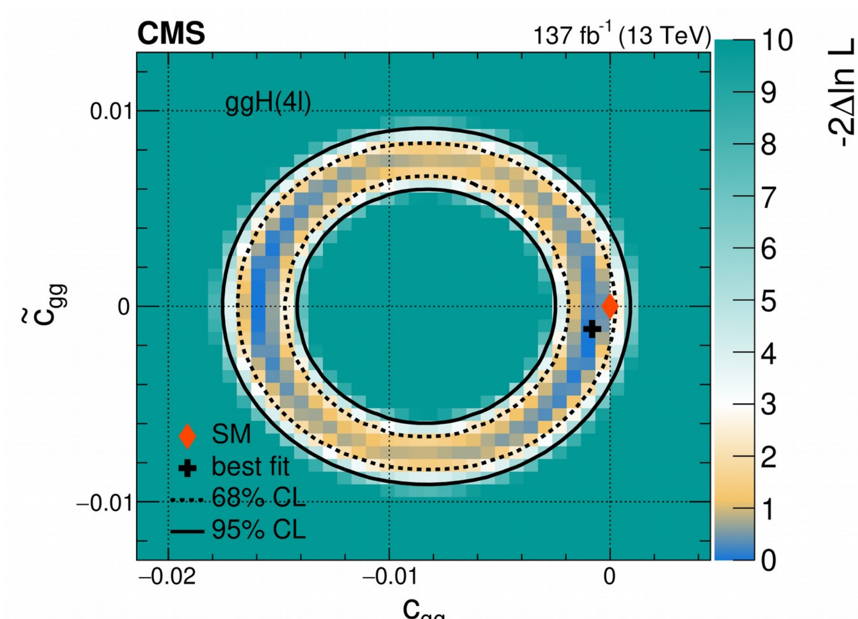
$$c_{gg} = -\frac{1}{2\pi\alpha_S} a_2^{gg}$$

$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S} a_3^{gg}$$

Channels	Coupling	Observed
tH & t$\bar{t}$H & ggH	c_{gg}	$-0.0012^{+0.0022}_{-0.0174}$
	$\tilde{c}_{gg}$	$-0.0017^{+0.0160}_{-0.0130}$
	κ_t	$1.05^{+0.25}_{-0.20}$
	$\tilde{\kappa}_t$	$-0.01^{+0.69}_{-0.67}$

More in back-up

from: H→4l and H→γγ



Summary

Mass:

- **CMS most precise measurement with Run1 + partial Run2**
- **ATLAS first Full Run2 in H→4l**

Width:

- **Offshell 2l2v + 4l using full Run2 2l2v by CMS** NEW!!!
- **Γ_H= 3.2 +2.4/-1.7 MeV**

CP :

- **Multiple Full Run2 results**
- Combinations from dif. decay modes
- EFT interpretations

- **HVV CP odd couplings well constrained**

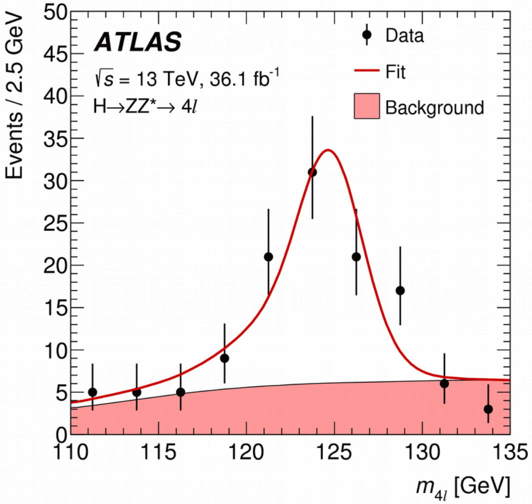
- **Full Run2 constraints on HVV by CMS**
- **Full Run2 Combination in H4l and Hττ by CMS** **NEW!!!**
- **Full Run2 on ttH by ATLAS and CMS**
- **Full Run2 Yukawa ττH couplings by CMS** **New!!!**

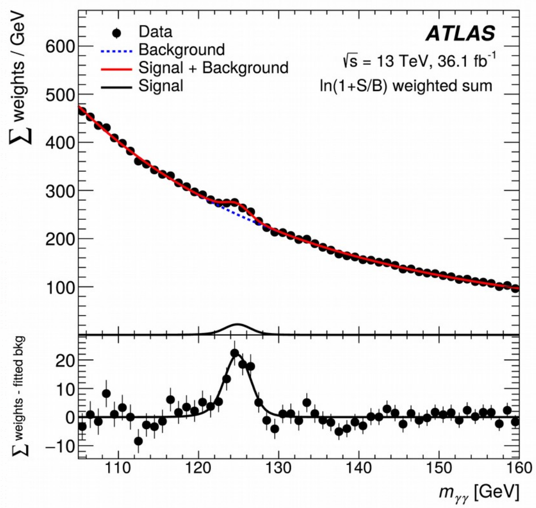
- **CMS first full Run2 ggH CP analysis** **New!!!**

Additional Material

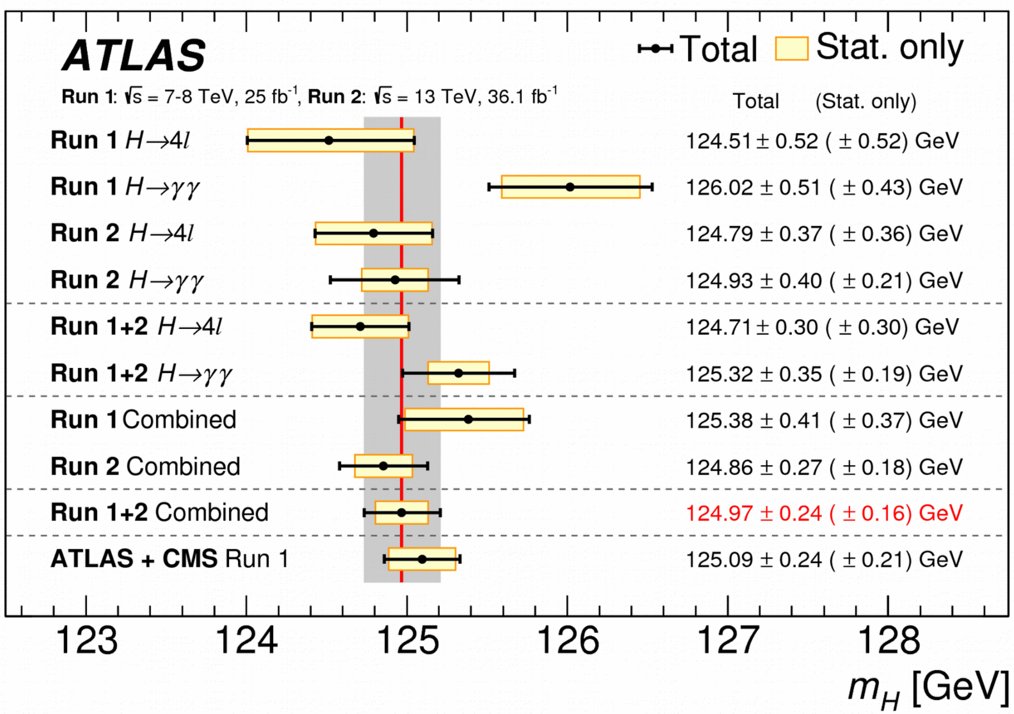
Phys. Lett. B 784 (2018) 345

Mass: H→4l + H→γγ(ATLAS)





Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20
$H \to \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10



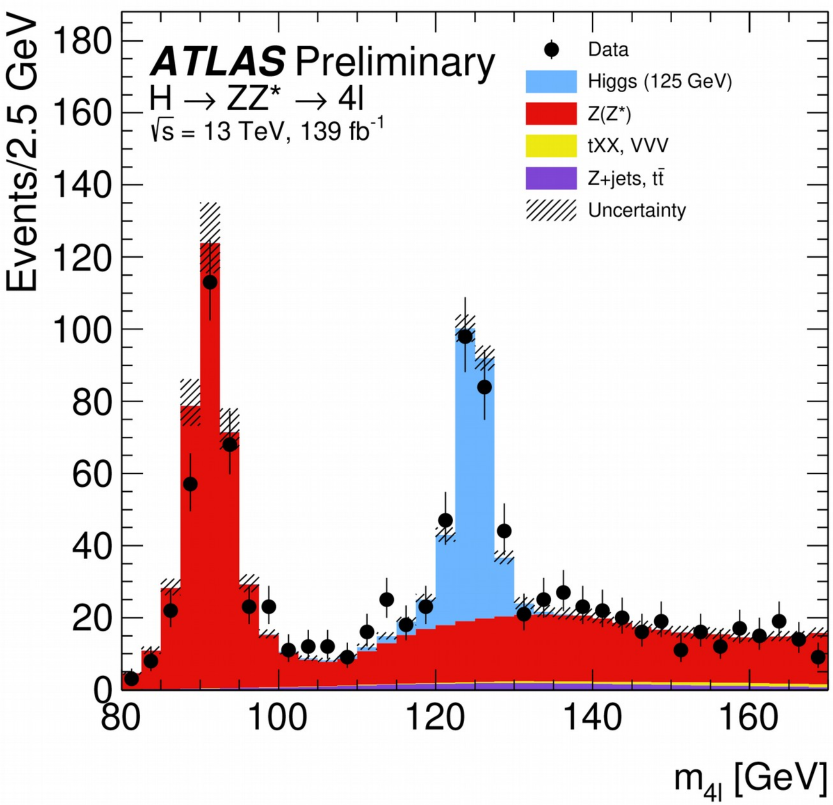
H→4l:

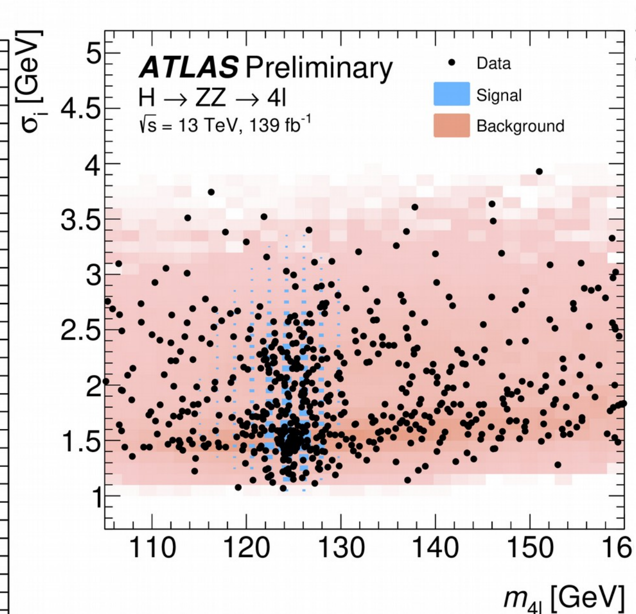
- Constrain m12 to mz to improve mH resolution
- BDT for sig. / backgr. separation

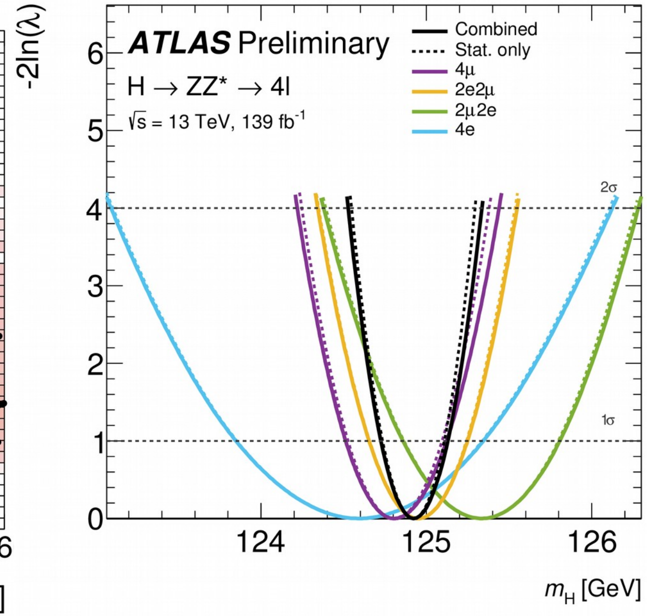
H→ γγ:

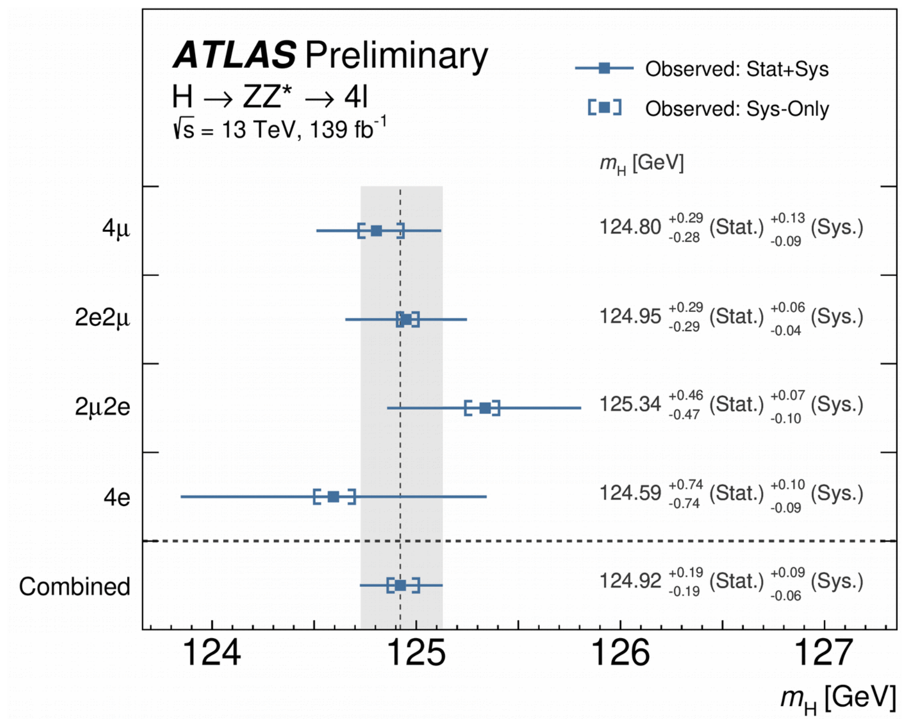
- Tight isolation req. for photons
- NN based diphoton vertex selection
- Per event resolution and signal to background categorization
- Photon energy uncertainty dominates in diphoton channel
- Results compatible with LHC Run1 combination

Mass: H→4l (ATLAS)





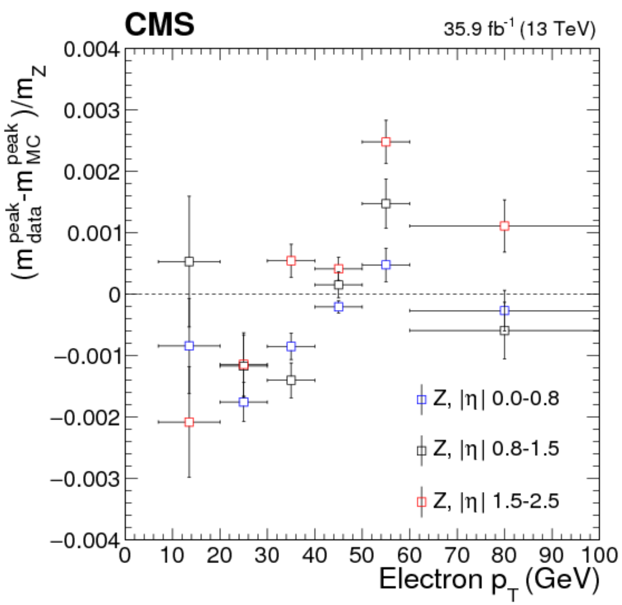


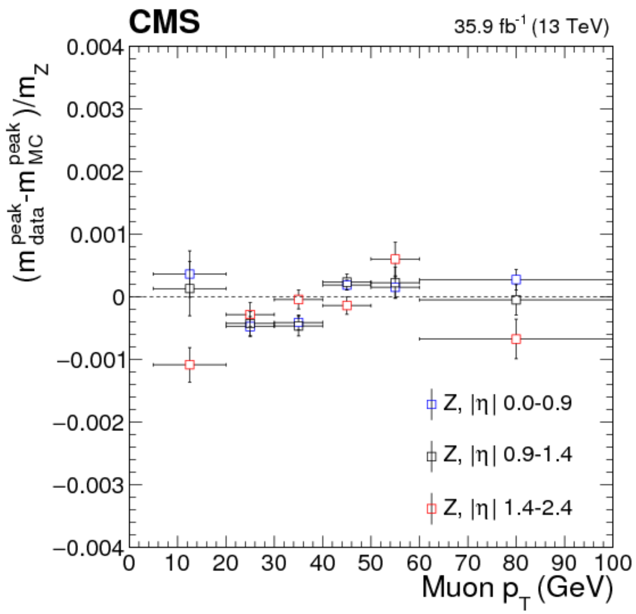


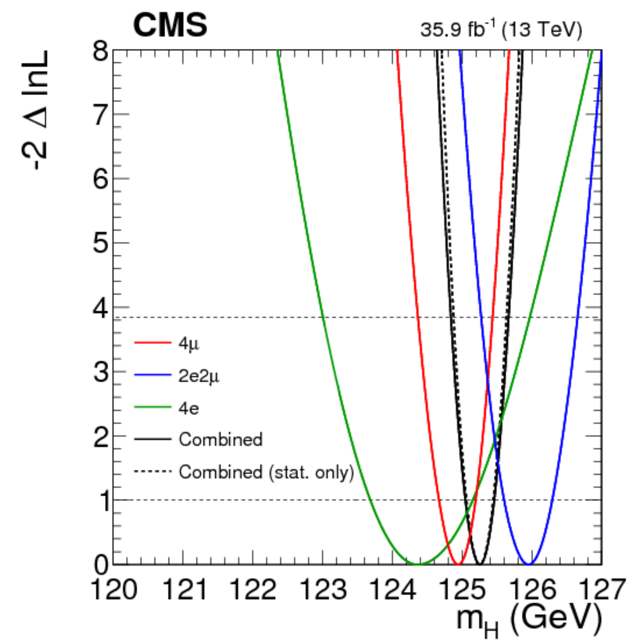
- J/ψ, Z used to improve μ pt resolution
- Per-event - NN based – resolution (σ_i) estimation
- BDT for ZZ*/HZZ* separation :
  - H pt, η
  - Matrix element based discriminant
- DCB fit
- **Full Run 2 measurement**

JHEP11 (2017) 047

Mass: H→ 4l(CMS)

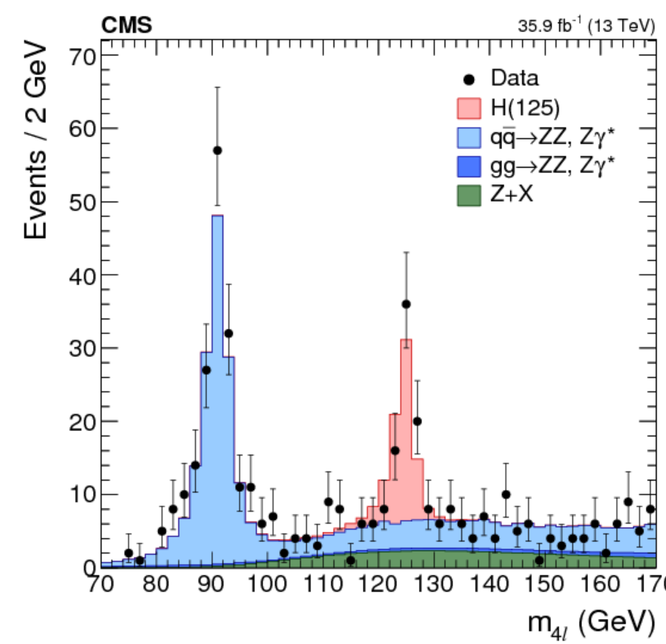






- MELA based discriminant for signal/background separation
- MZ1 constrained
- 3 lepton channels (4e,4μ,2e2μ)
- Perform fit in an inclusive category
- 3D fit (D^{kin}_{bkg} / m4l / σ_{m4l}| m4l)
- Most sensitive single channel measurement

$$m_{\rm H}\ (\text{GeV})\ 125.26 \pm 0.21$$



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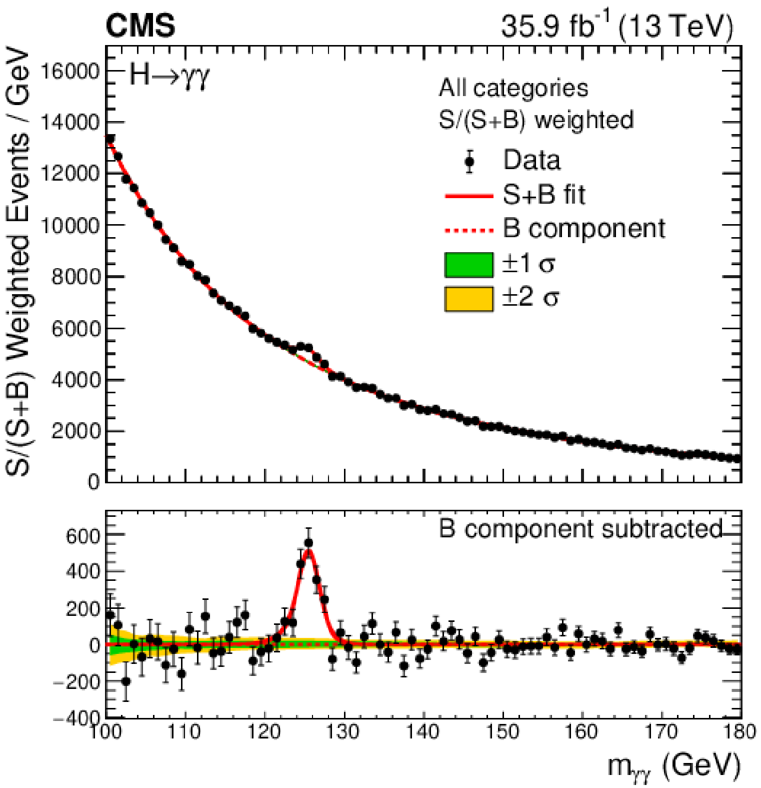
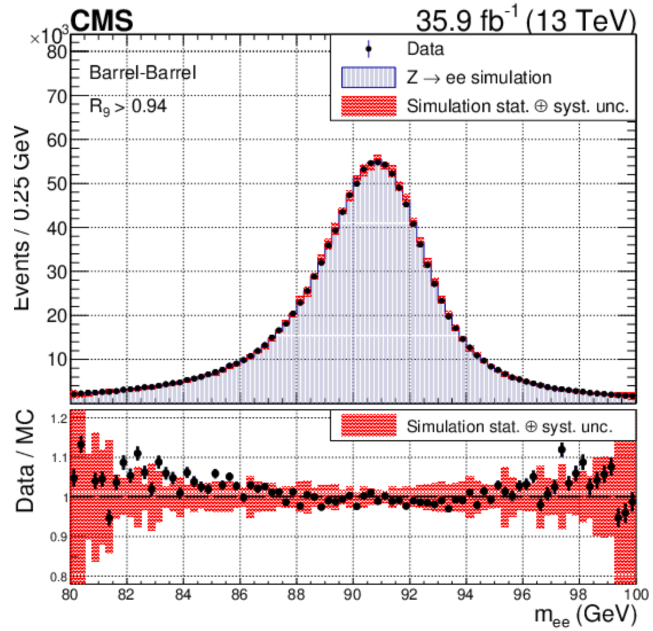
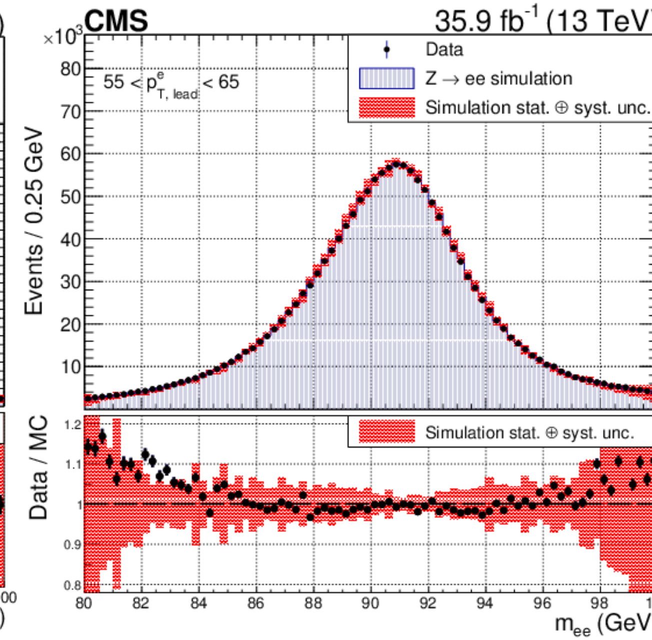
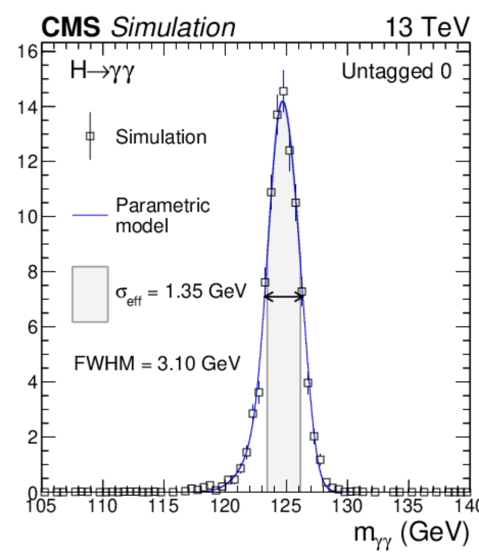
Mass: H→γγ(CMS)

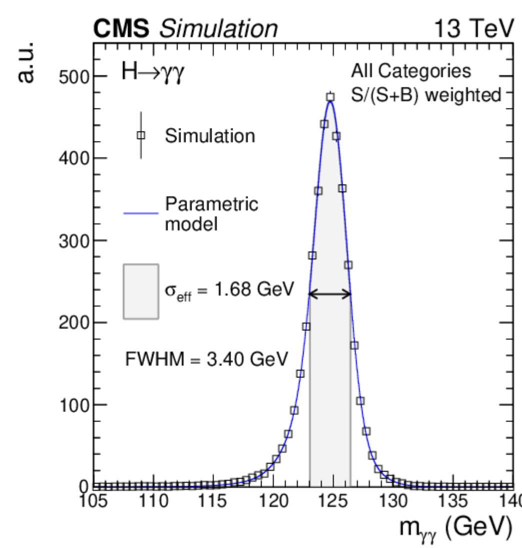






- BDT based diphoton vertex selection
- BDT photon ID selection
- Background extracted with discreet profiling method
- Improved detector calibration
- Use electrons to study energy scale uncertainties and propagate to photons
- Include uncertainties for e-γ diferences





Simulation smeared to match data resolution

Mass: H→ 4l + H→ γγ (CMS)

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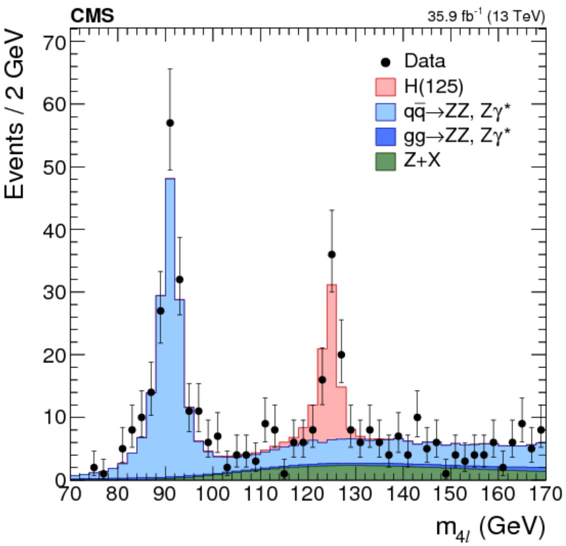
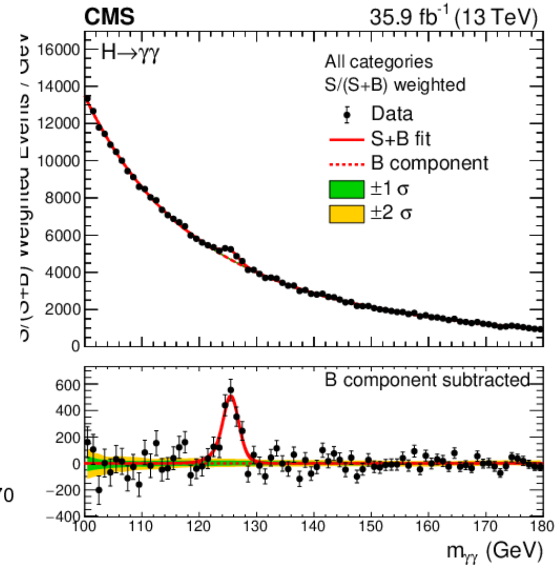
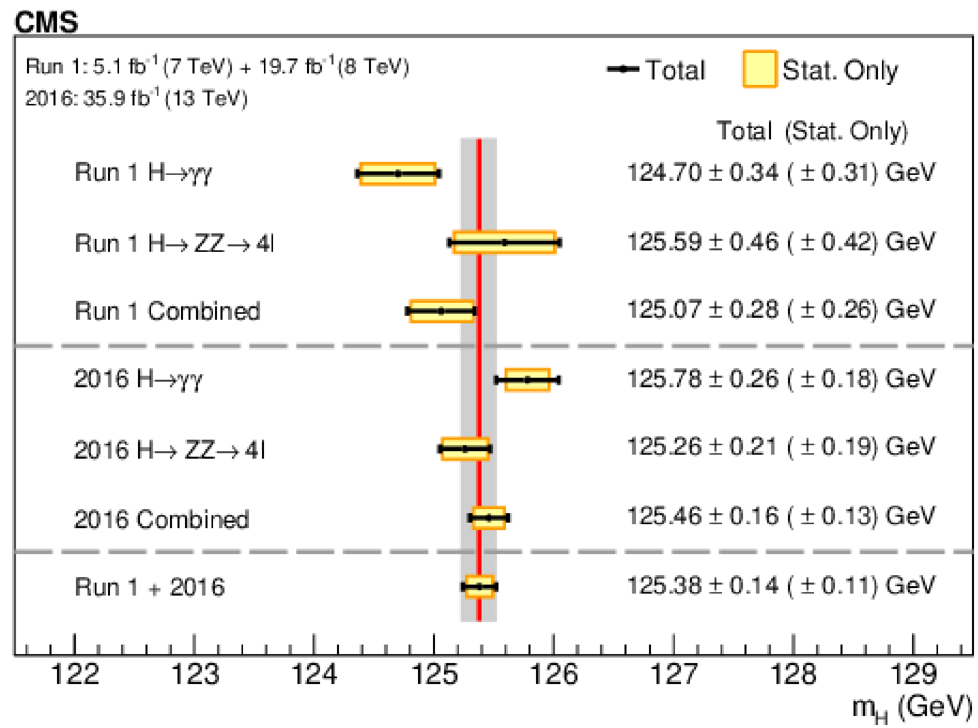
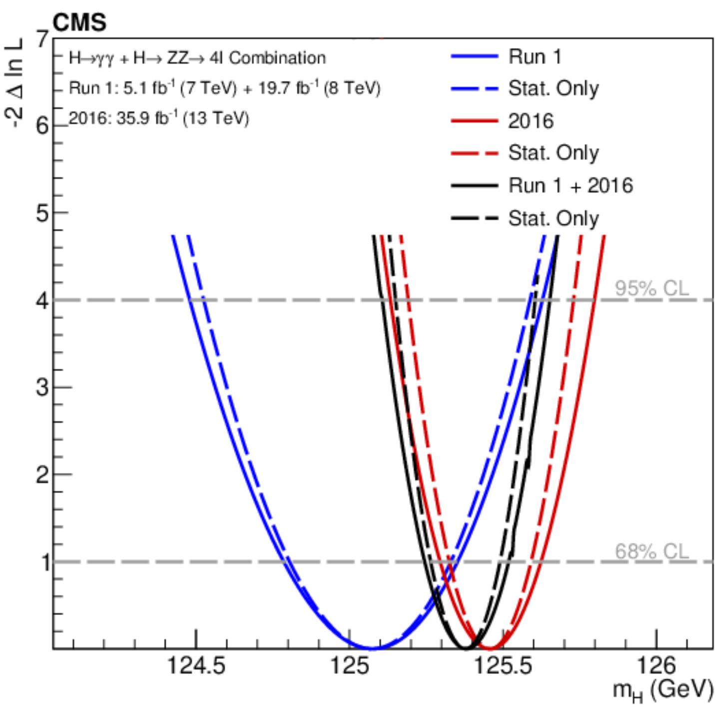




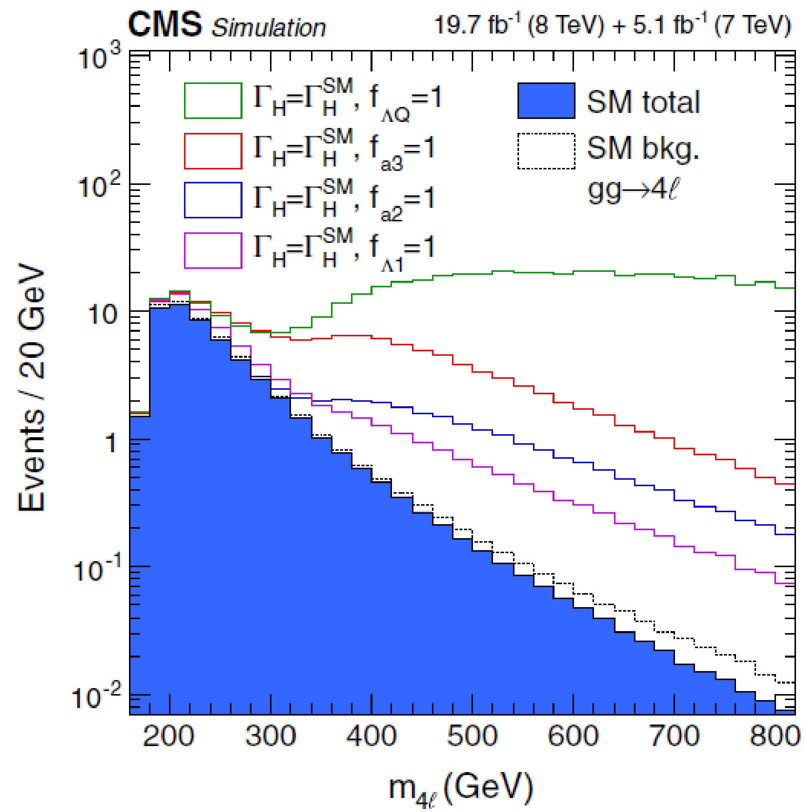




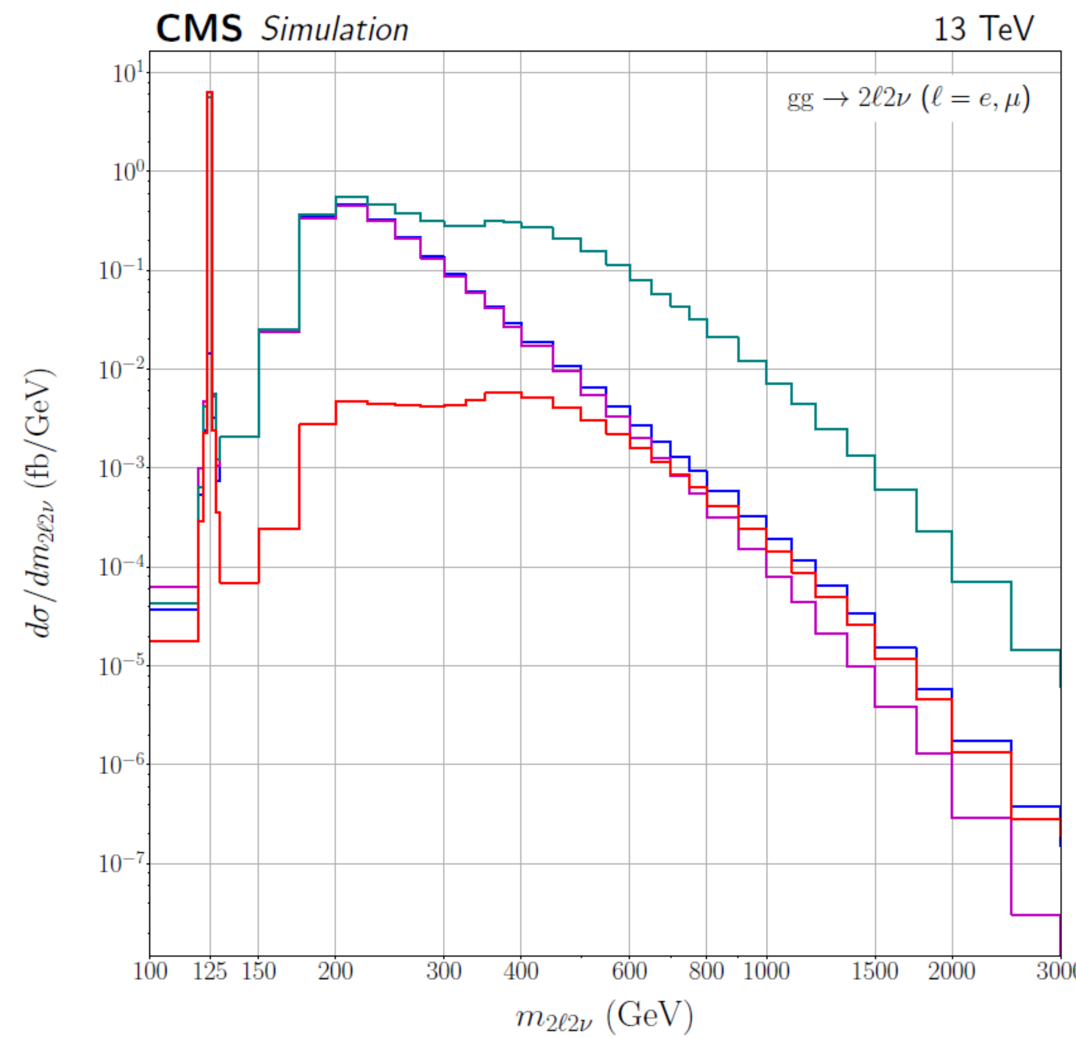
- Combination in H→4l + H→γγ
- Combination of Run1 + 2016 data
- **Most precise measurement to date ~0.12%**

Higgs Width – lifetime + ac

$$\langle \Delta t \rangle = \tau_H = \frac{\hbar}{\Gamma_H}$$



Width CMS 2l2nu



Phenomenology and EFT

Parametrize H couplings in the mass eingestate base:

$$A(\mathrm{Hff}) = -\frac{m_\mathrm{f}}{v}\bar{\psi}_\mathrm{f}\left(\kappa_\mathrm{f} + \mathrm{i}\,\tilde{\kappa}_\mathrm{f}\gamma_5\right)\psi_\mathrm{f}$$

$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}}(q_{\mathrm{V1}}+q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Notation:

$a_i^{VV} = g_i^{VV}$ for i = 1,2 $\quad a_3^{VV} = g_4^{VV}$

$$g_{\Lambda 1}^{ZZ,WW} = \frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2} \quad \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}$$

$$g_{\Lambda 1}^{Z\gamma} = \frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}$$

a1 SM
a2 CP even AC
a3 CP odd AC

Amplitude Related to a fundamental Lagrangian density
→ couplings related to the Lagrangian coefficients

$$\begin{aligned}\mathcal{L}_{\rm hvv} = \; & \frac{h}{v}\Big[(1+\delta c_z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu + c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} + c_{z\Box}g^2 Z_\mu\partial_\nu Z_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu} \\ & + (1+\delta c_w)\frac{g^2v^2}{2}W_\mu^+W_\mu^- + c_{ww}\frac{g^2}{2}W_{\mu\nu}^+W_{\mu\nu}^- + c_{w\Box}g^2\left(W_\mu^-\partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) + \tilde{c}_{ww}\frac{g^2}{2}W_{\mu\nu}^+\tilde{W}_{\mu\nu}^- \\ & + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu} \\ & + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^aG_{\mu\nu}^a + \tilde{c}_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a\tilde{G}_{\mu\nu}^a\Big],\end{aligned}$$

→

$$\delta c_z = \frac{1}{2}a_1 - 1$$

$$c_{z\Box} = \frac{m_Z^2 s_w^2}{e^2}\frac{\kappa_1}{(\Lambda_1)^2}$$

$$c_{zz} = -\frac{2s_w^2c_w^2}{e^2}a_2$$

$$\tilde{c}_{zz} = -\frac{2s_w^2c_w^2}{e^2}a_3$$

$$c_{gg} = -\frac{1}{2\pi\alpha_s}a_2^{gg}$$

$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_s}a_3^{gg}$$

Symmetries and more…

- Onshell Zγ and γγ couplings well constrained
- **Custodial symmetry**
- **Consider $g^{WW} = g^{ZZ}$**

$$\begin{aligned} g_1^{WW} &= g_1^{ZZ} \\ g_2^{WW} &= c_w^2 g_2^{ZZ} + s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma}, \\ g_4^{WW} &= c_w^2 g_4^{ZZ} + s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma}, \\ \frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) &= \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} + 2 \frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}, \\ \frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) &= 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} \right) + 2(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2} \end{aligned}$$

5 independent HVV couplings

Or…

- **Consider SU(2)xU(1)** → enforces relations between couplings:

$$\begin{aligned} g_1^{WW} &= g_1^{ZZ} \\ g_2^{WW} &= c_w^2 g_2^{ZZ} + s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma}, \\ g_4^{WW} &= c_w^2 g_4^{ZZ} + s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma}, \\ \frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) &= \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} + 2 \frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}, \\ \frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) &= 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} \right) + 2(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2} \end{aligned}$$

4 independent HVV couplings

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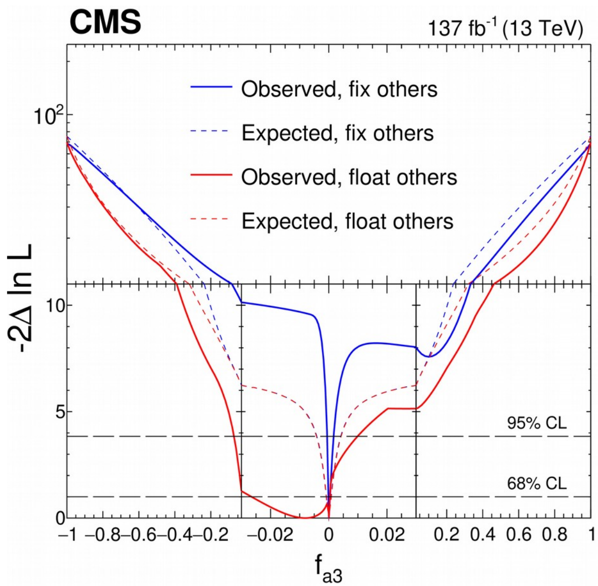
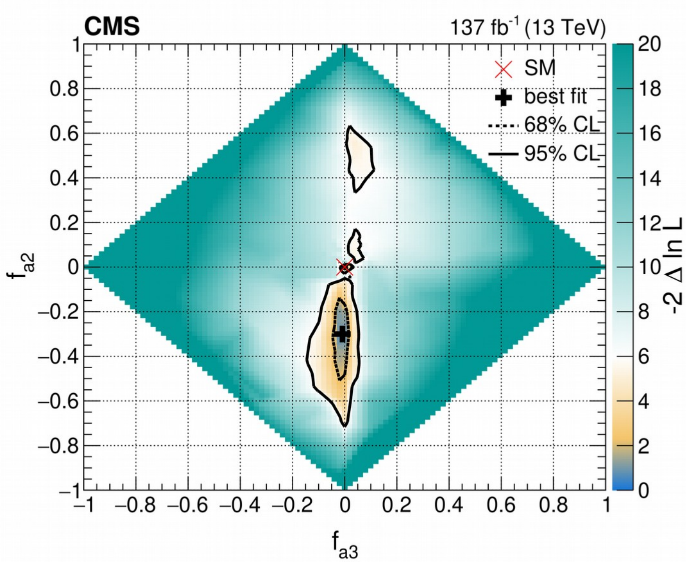
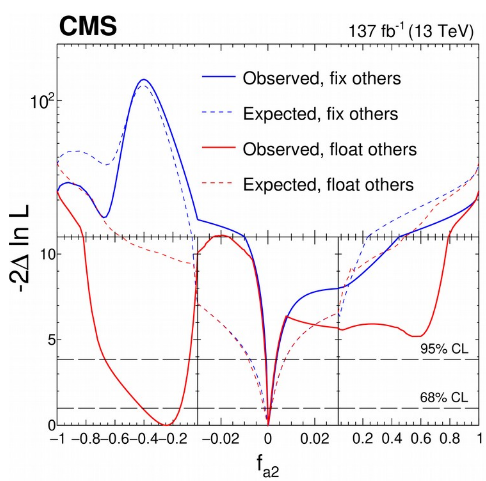
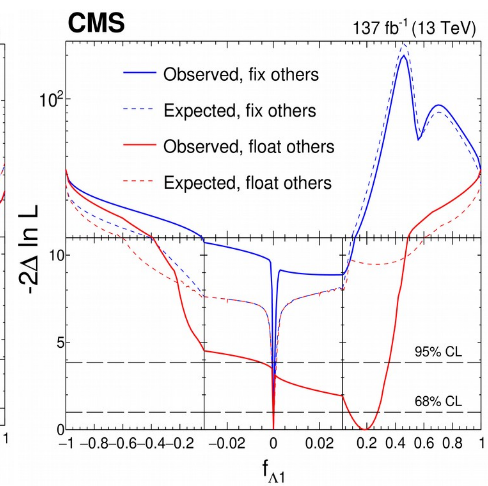
CP: HVV in H→4l (CMS)

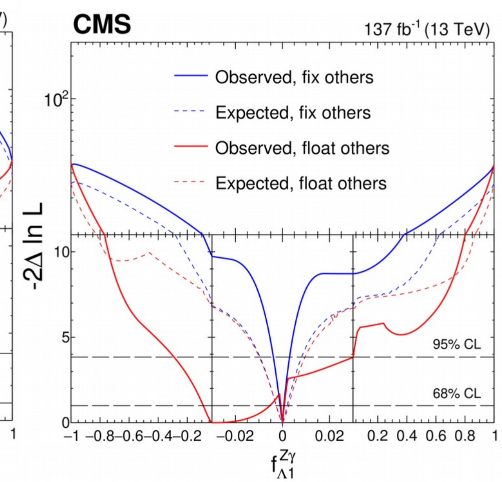
- Non-SMEFT with 4 independent A.C.
- Simultaneous scan of all AC considered
- Non-zero minima
- **SM consistent**











Summary of HVV/Hff results

HIG-19-009

Parameter	Scenario		Observed	Expected
f_{a3}	Approach 1	best fit	0.00000	0.00000
	$f_{a2}=f_{\Lambda1}=f_{\Lambda1}^{Z\gamma}=0$	68% CL	$[-0.00017, 0.00017]$	$[-0.00081, 0.00081]$
		95% CL	$[-0.0010, 0.0038] \cup [0.01, 0.24]$	$[-0.0056, 0.0056]$
	Approach 1	best fit	±0.010	0.00000
	float $f_{a2}, f_{\Lambda1}, f_{\Lambda1}^{Z\gamma}$	68% CL	$[-0.042, 0.034]$	$[-0.00088, 0.00088]$
		95% CL	$[-0.20, 0.20]$	$[-0.0057, 0.0057]$
	Approach 2	best fit	0.00005	0.0000
	float $f_{a2}, f_{\Lambda1}$	68% CL	$[-0.00013, 0.00066]$	$[-0.0012, 0.0012]$
		95% CL	$[-0.0010, 0.0028] \cup [0.024, 0.092]$	$[-0.0074, 0.0074]$
f_{a2}	Approach 1	best fit	0.00000	0.0000
	$f_{a3}=f_{\Lambda1}=f_{\Lambda1}^{Z\gamma}=0$	68% CL	$[-0.00031, 0.00098]$	$[-0.0012, 0.0013]$
		95% CL	$[-0.0033, 0.0039]$	$[-0.0095, 0.0081]$
	Approach 1	best fit	-0.29	0.0000
	float $f_{a3}, f_{\Lambda1}, f_{\Lambda1}^{Z\gamma}$	68% CL	$[-0.50, -0.18] \cup [-0.00024, 0.00052]$	$[-0.0018, +0.0013]$
		95% CL	$[-0.68, -0.05] \cup [-0.027, 0.185] \cup [0.38, 0.55]$	$[-0.0106, 0.0081]$
	Approach 2	best fit	-0.0001	0.0000
	float $f_{a3}, f_{\Lambda1}$	68% CL	$[-0.0024, 0.0008]$	$[-0.0053, 0.0033]$
		95% CL	$[-0.0209, 0.0133]$	$[-0.0869, 0.0055]$
$f_{\Lambda1}$	Approach 1	best fit	0.00000	0.00000
	$f_{a3}=f_{a2}=f_{\Lambda1}^{Z\gamma}=0$	68% CL	$[-0.00009, 0.00022]$	$[-0.00016, 0.00025]$
		95% CL	$[-0.00036, 0.00110] \cup [0.002, 0.135]$	$[-0.00081, 0.00112]$
	Approach 1	best fit	0.13	0.00000
	float $f_{a3}, f_{a2}, f_{\Lambda1}^{Z\gamma}$	68% CL	$[-0.00012, 0.00015] \cup [0.02, 0.24]$	$[-0.00017, 0.00036]$
		95% CL	$[-0.16, -0.01] \cup [-0.0056, 0.3423]$	$[-0.00089, 0.00144]$
	Approach 2	best fit	0.00019	0.0000
	float f_{a3}, f_{a2}	68% CL	$[-0.00017, 0.00168]$	$[-0.0012, 0.0029]$
		95% CL	$[-0.0019, 0.0055] \cup [0.10, 0.29]$	$[-0.0060, 0.0103]$
$f_{\Lambda1}^{Z\gamma}$	Approach 1	best fit	-0.0004	0.0000
	$f_{a3}=f_{a2}=f_{\Lambda1}=0$	68% CL	$[-0.0010, 0.0014]$	$[-0.0026, 0.0020]$
		95% CL	$[-0.0063, 0.0060] \cup [0.05, 0.21]$	$[-0.0102, 0.0091]$
	Approach 1	best fit	-0.06	0.0000
	float $f_{a3}, f_{a2}, f_{\Lambda1}$	68% CL	$[-0.18, -0.02] \cup [-0.00049, 0.00058]$	$[-0.0026, 0.0025]$
		95% CL	$[-0.53, 0.52]$	$[-0.011, 0.011]$

Couplings constraints from H→4l

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

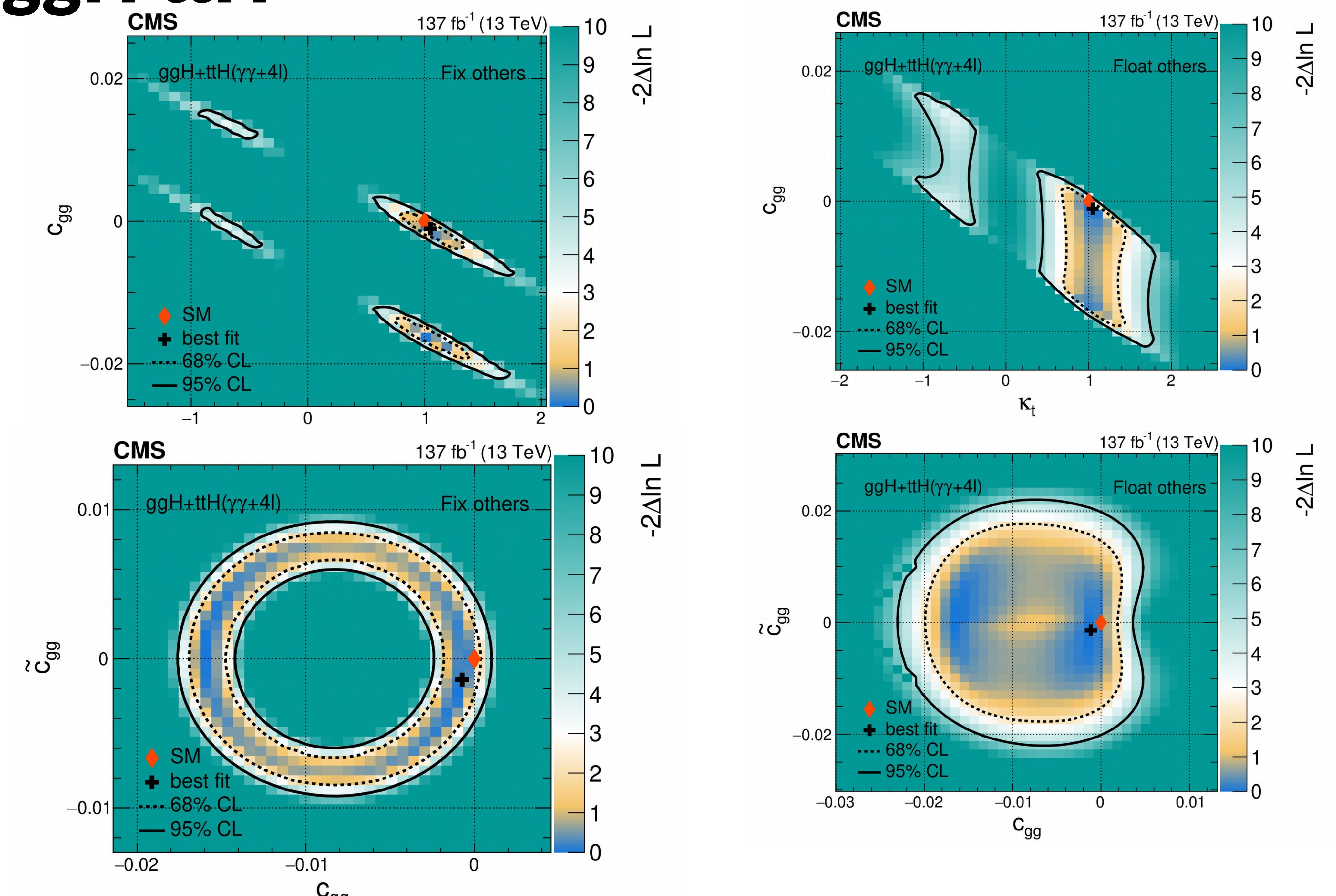
$$f_{CP}^{\mathrm{Hff}} = \frac{|\tilde{\kappa}_{\mathrm{f}}|^2}{|\kappa_{\mathrm{f}}|^2 + |\tilde{\kappa}_{\mathrm{f}}|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_{\mathrm{f}}}{\kappa_{\mathrm{f}}}\right)$$

Assuming only top/b in ggH :

$$|f_{CP}^{\mathrm{Hff}}| = \left(1 + 2.38\left[\frac{1}{|f_{a3}^{\mathrm{ggH}}|} - 1\right]\right)^{-1} = \sin^2\alpha^{\mathrm{Hff}}$$

Channels	Coupling	Observed	Expected	Observed correlation			
				c_{gg}	$\tilde{c}_{gg}$	κ_t	$\tilde{\kappa}_t$
tH & $\mathrm{t\bar{t}H}$ & ggH	c_{gg}	$-0.0012^{+0.0022}_{-0.0174}$	$0.0000^{+0.0019}_{-0.0196}$	1	−0.050	−0.941	+0.029
	$\tilde{c}_{gg}$	$-0.0017^{+0.0160}_{-0.0130}$	$0.0000^{+0.0138}_{-0.0138}$		1	+0.046	−0.568
	κ_t	$1.05^{+0.25}_{-0.20}$	$1.00^{+0.34}_{-0.26}$			1	+0.168
	$\tilde{\kappa}_t$	$-0.01^{+0.69}_{-0.67}$	$0.00^{+0.71}_{-0.71}$				1
				δc_z	c_{zz}	$c_{z\Box}$	$\tilde{c}_{zz}$
VBF & VH & $H \to 4\ell$	δc_z	$-0.03^{+0.06}_{-0.25}$	$0.00^{+0.07}_{-0.27}$	1	+0.241	−0.060	−0.009
	c_{zz}	$0.01^{+0.11}_{-0.10}$	$0.00^{+0.22}_{-0.16}$		1	−0.884	+0.058
	$c_{z\Box}$	$-0.02^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$			1	+0.020
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$				1

ggH ttH


CMS
137 fb^{-1} (13 TeV)
ggH+ttH(γγ+4l)
Fix others
SM
best fit
68% CL
95% CL
c_{gg}
$-2\Delta\ln L$
CMS
137 fb^{-1} (13 TeV)
ggH+ttH(γγ+4l)
Float others
SM
best fit
68% CL
95% CL
κ_t
c_{gg}
$-2\Delta\ln L$
CMS
137 fb^{-1} (13 TeV)
ggH+ttH(γγ+4l)
Fix others
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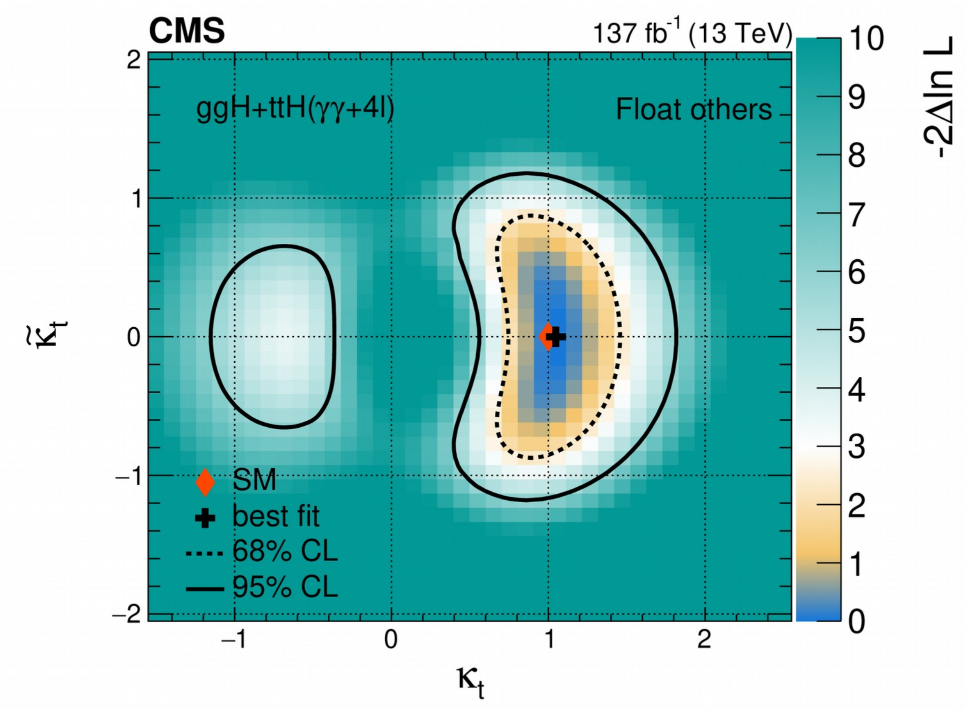
$-2\Delta\ln L$

ggH ttH


CMS
137 fb^{-1} (13 TeV)
ggH+ttH(γγ+4l)
Float others
SM
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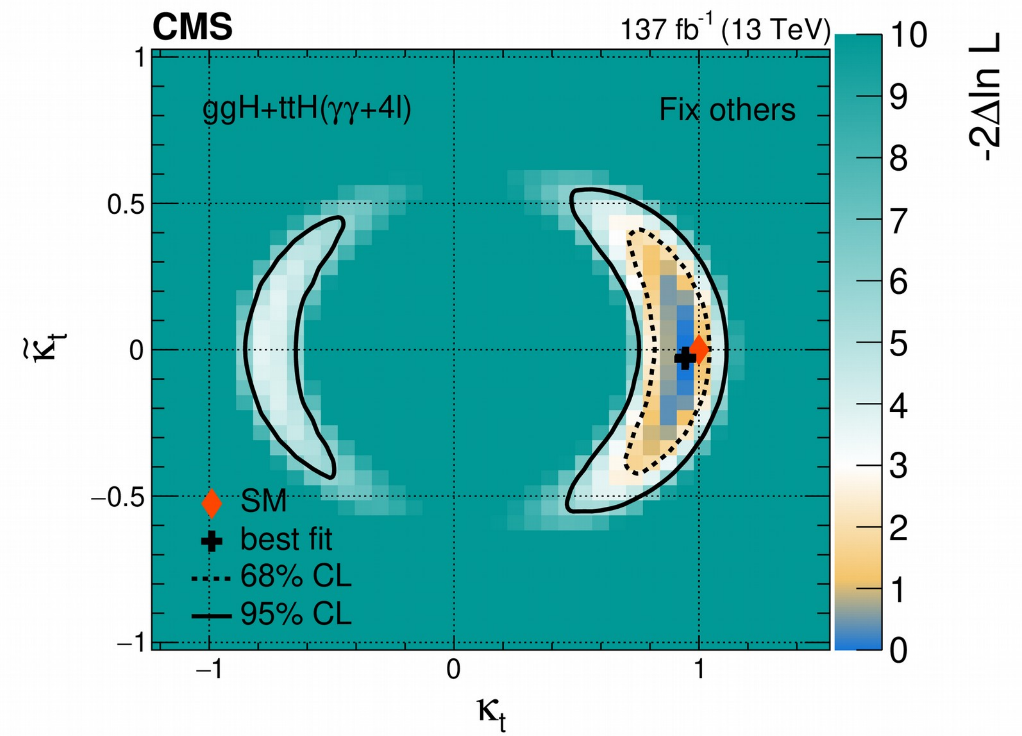
κ_t
$\tilde{\kappa}_t$
-2Δln L


CMS
137 fb^{-1} (13 TeV)
ggH+ttH(γγ+4l)
Fix others
SM
best fit
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95% CL
κ_t
$\tilde{\kappa}_t$
-2Δln L

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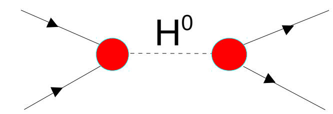
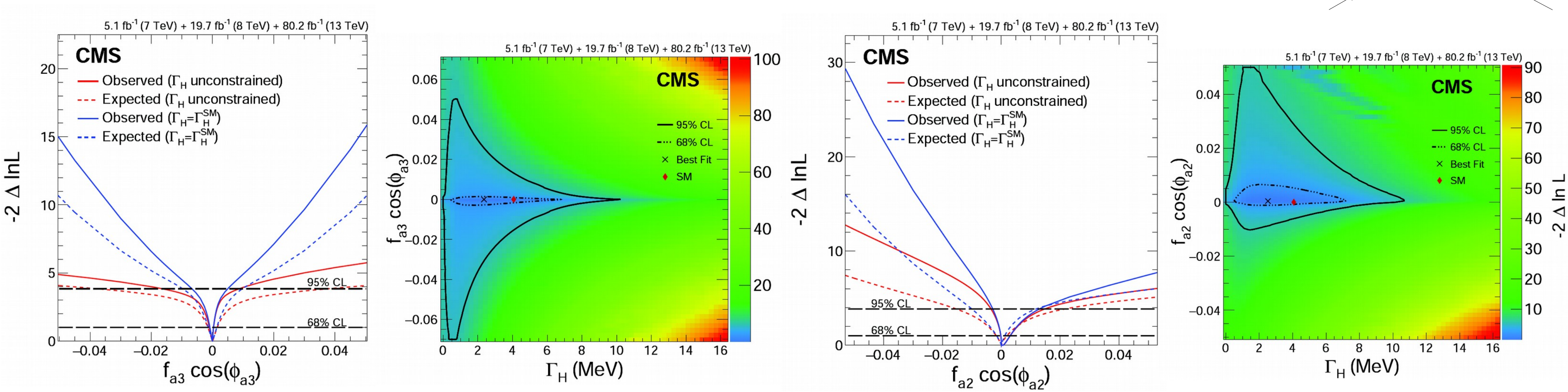
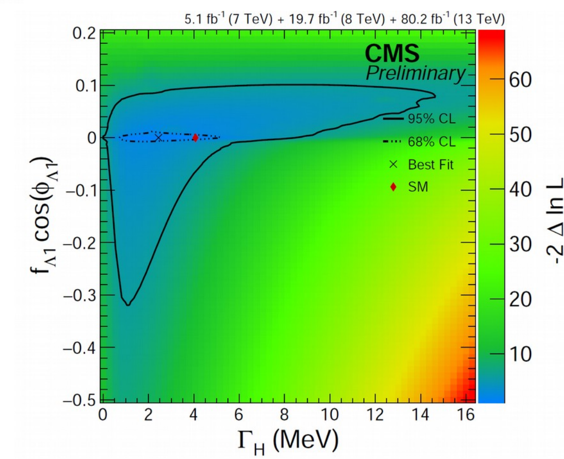
CP: HVV in H→4l offshell (CMS)

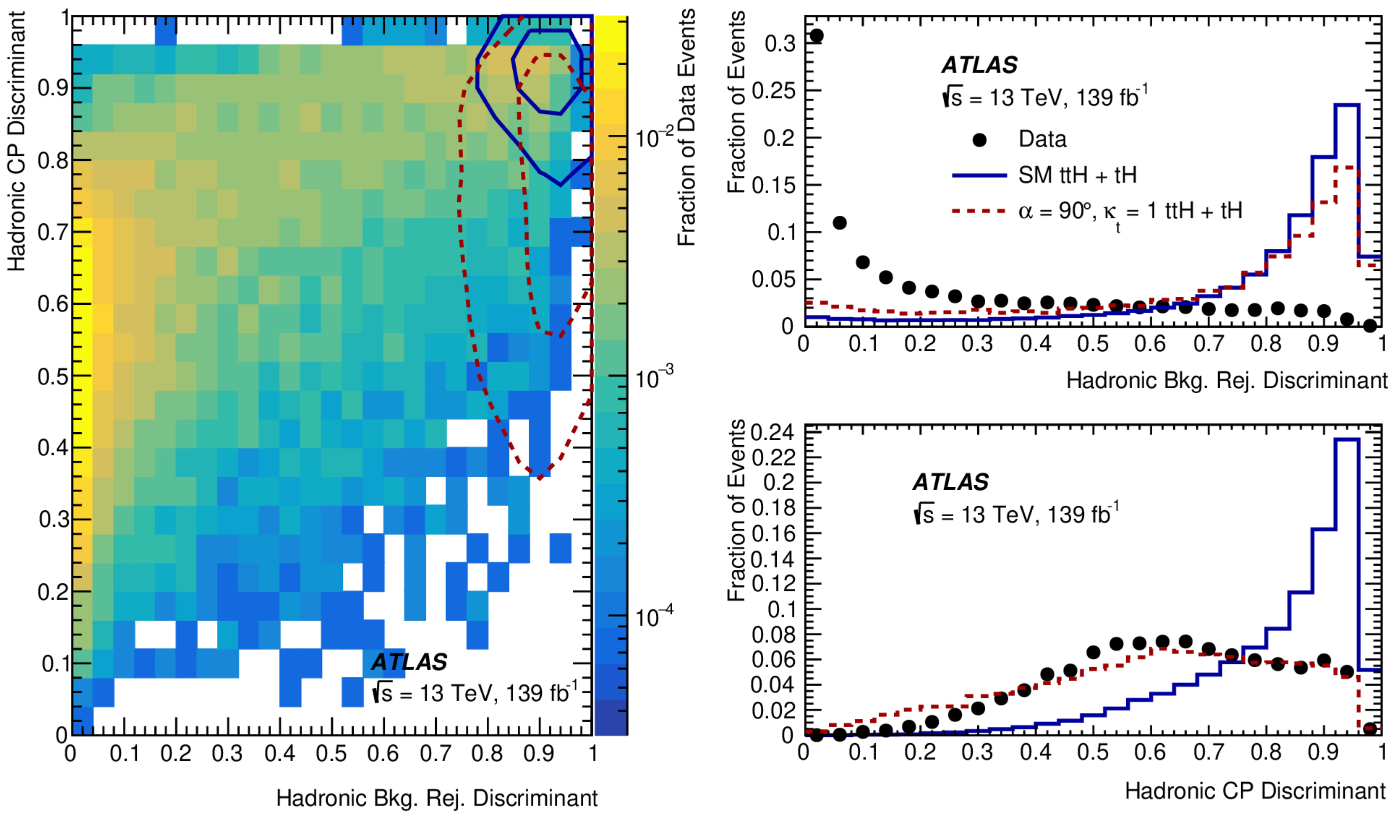




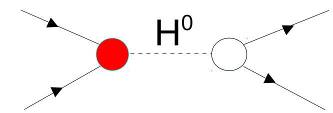
- AC parametrization and analysis strategy as in HVV, H→4l onshell
- AC greatly affect offshell H production
- Background interferes with signal → more challenging analysis
- AC, Γ_H simultaneous measurement
- Individual AC scanned
- First Offshell AC measurement



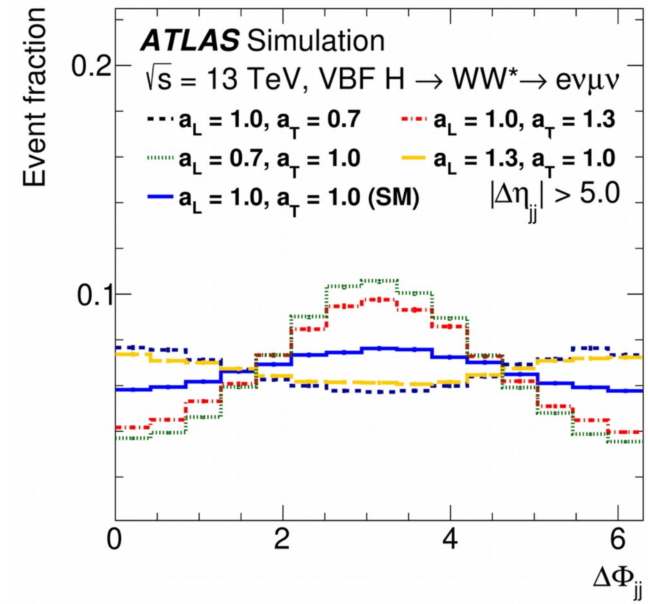
Yukawa ttH , Hγγ ATLAS



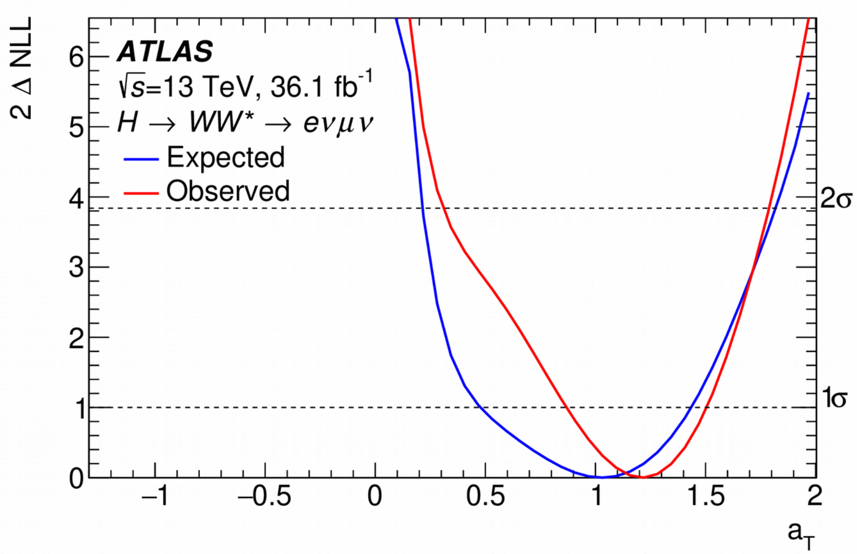
HVV in H→WW*→ eνμν+jj (ATLAS)

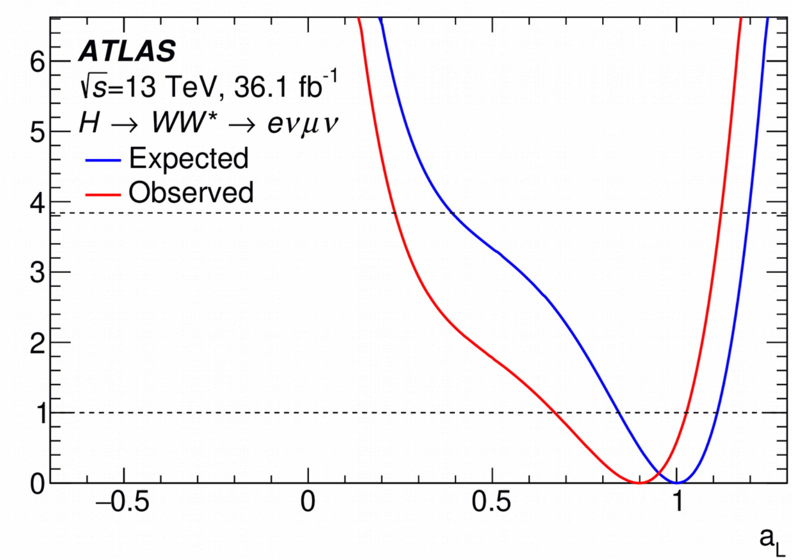


- Parametrize anomalous contributions in terms of V polarization contributions
- approximate mapping done to constrain pseudo-observables
- Utilize BDT and ΔΦjj
- Categorize events with BDT +cuts
- Dominant top quark and Z+jets backgrounds constrained by CRs
- Results consistent with SM



$$a_{\mathrm{L}} = \frac{g_{HV_{\mathrm{L}}V_{\mathrm{L}}}}{g_{HVV}}, \; a_{\mathrm{T}} = \frac{g_{HV_{\mathrm{T}}V_{\mathrm{T}}}}{g_{HVV}}$$





H→4l off-shell

HIG-18-002

anomalous couplings :
→ increase the number of off-shell events