Higgs boson precision measurements @ CMS and ATLAS

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Higgs Potential ‘22
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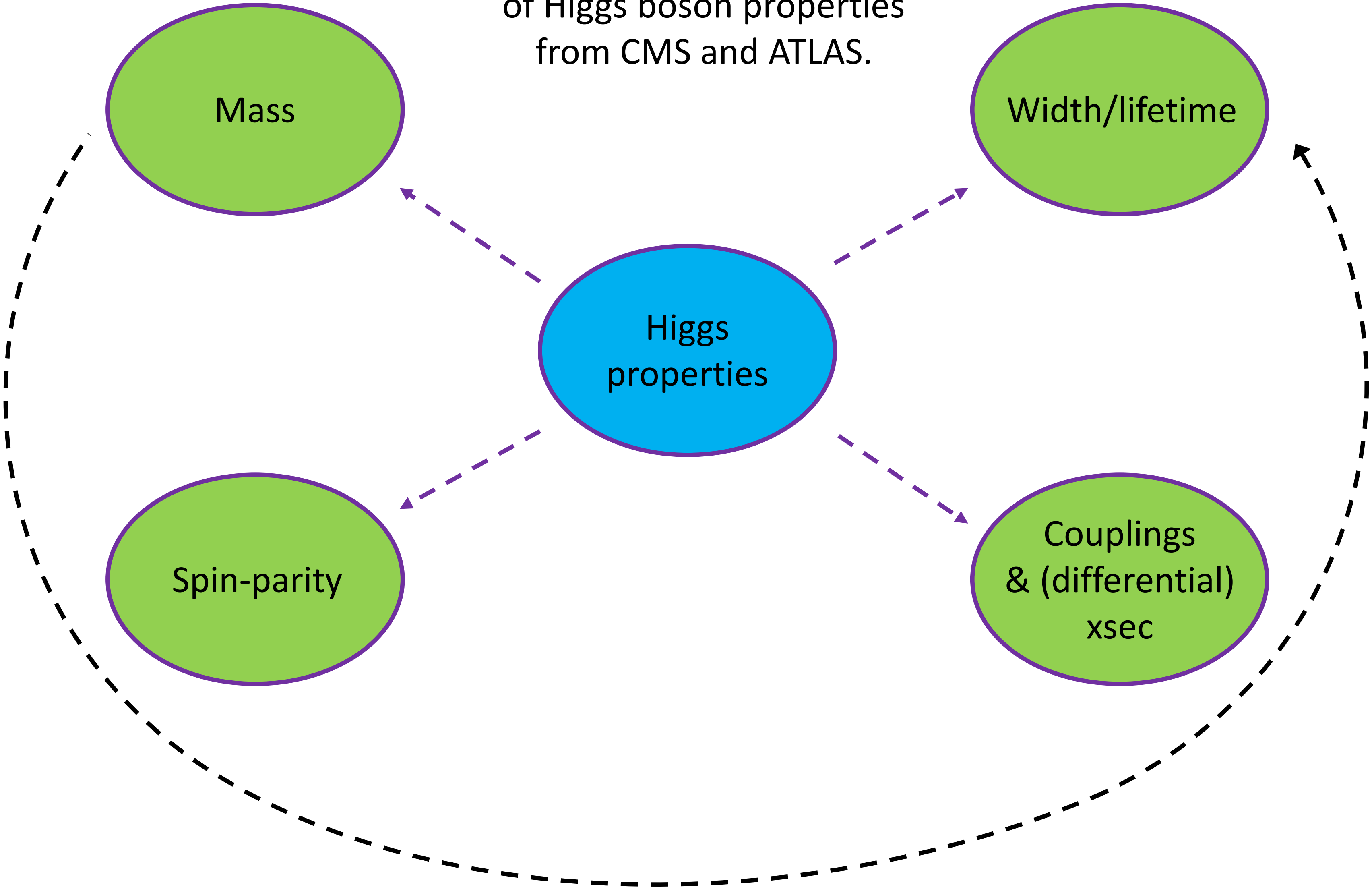
Introduction

We summarize precision measurements
of Higgs boson properties
from CMS and ATLAS.



Mass

Width/lifetime

Higgs properties

Spin-parity

Couplings & (differential) xsec

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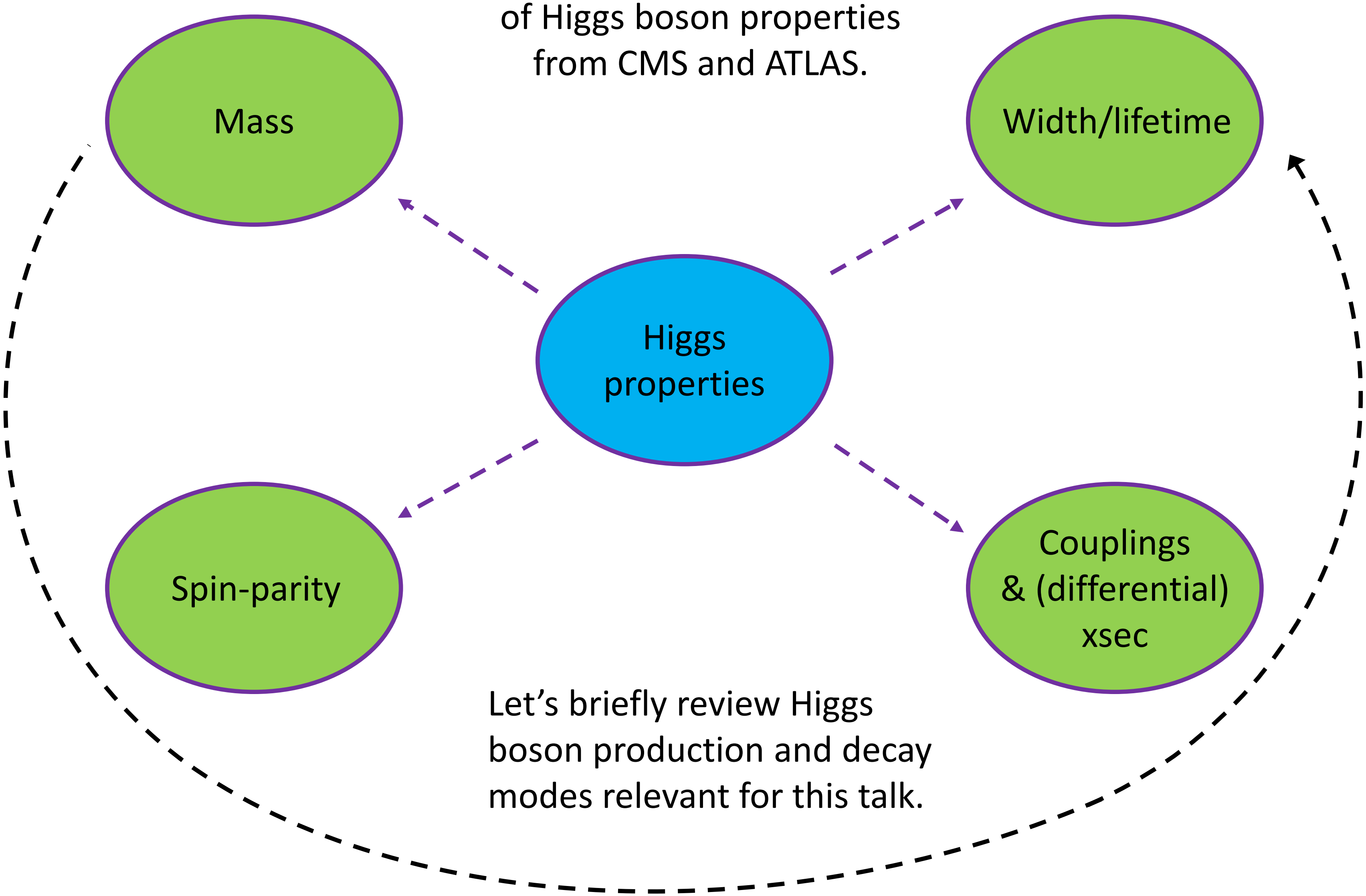


Higgs properties

Mass

Width/lifetime

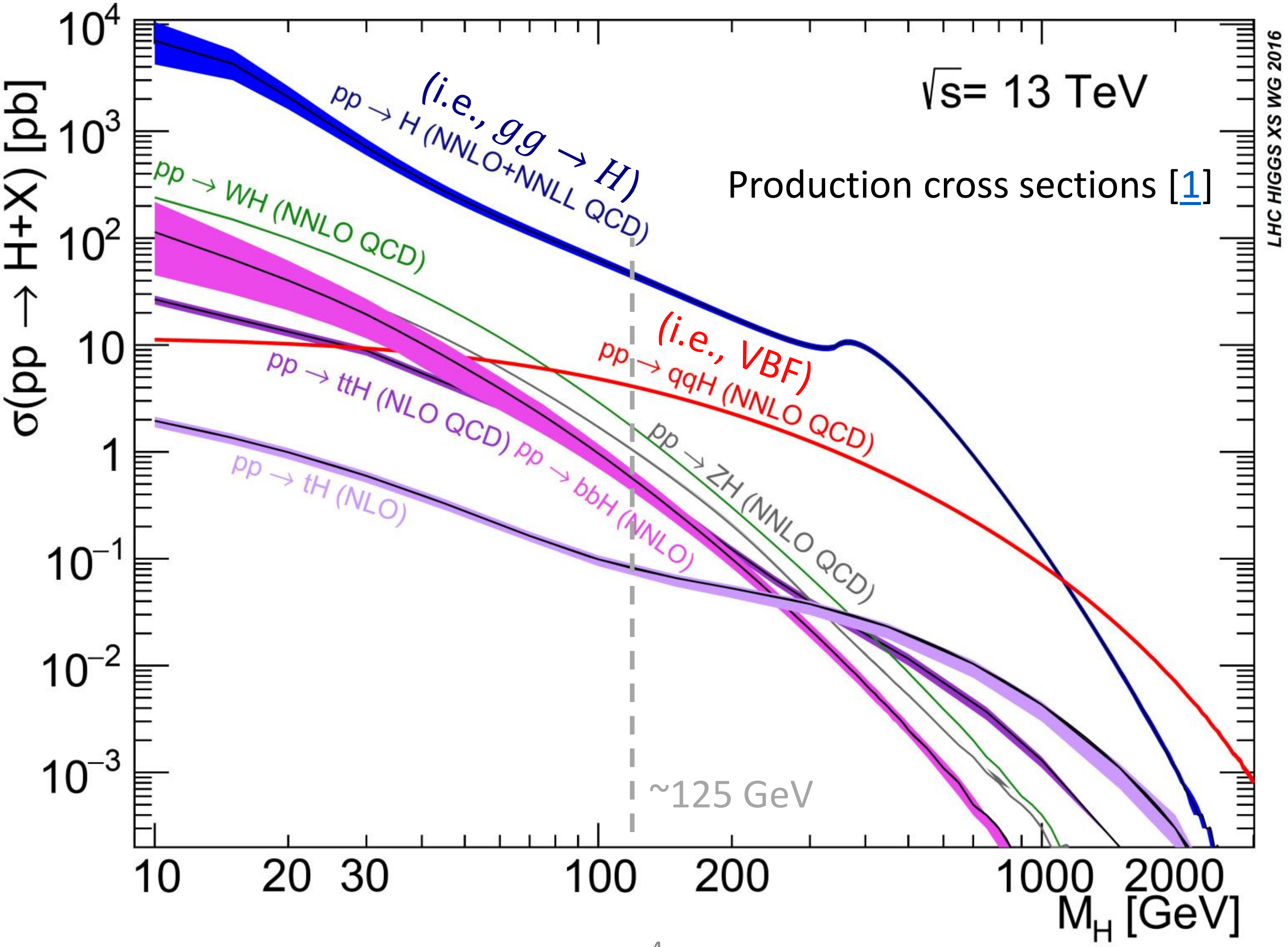
Spin-parity

Couplings & (differential) xsec

Let's briefly review Higgs
boson production and decay
modes relevant for this talk.

Higgs production and decay

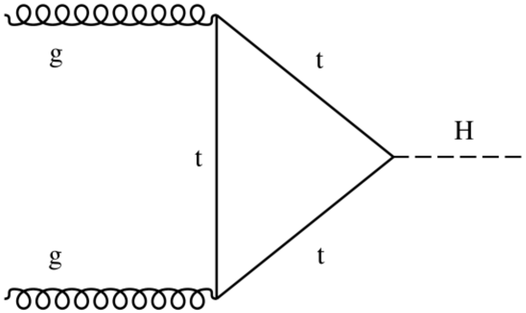
Common ways to produce a Higgs boson through pp collisions:



Production cross sections [1]

Higgs production

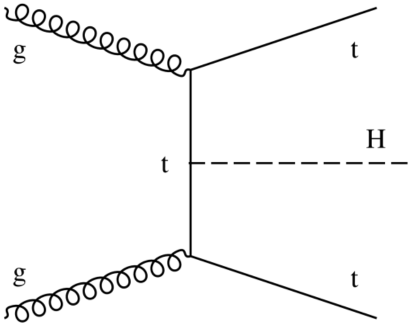
Most common production mechanisms:

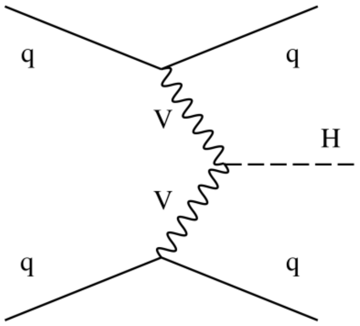


$gg \to H$

Can probe fermionic couplings of the Higgs

$t\bar{t}H$

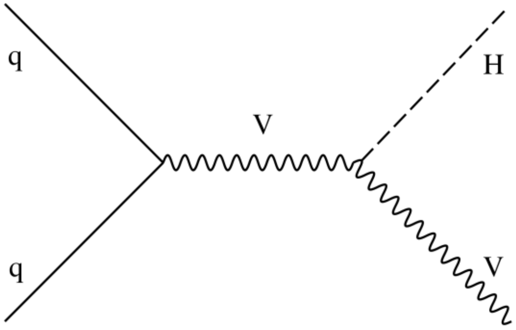




[Weak] Vector boson fusion (VBF)

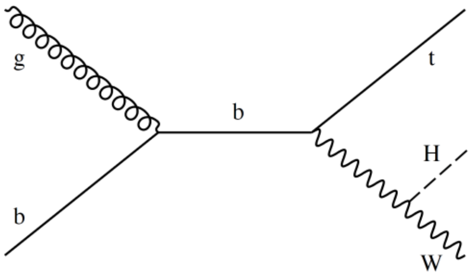
Can probe bosonic couplings of the Higgs

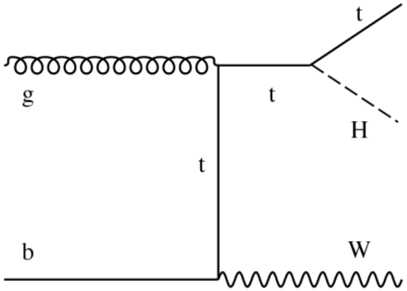
WH and ZH

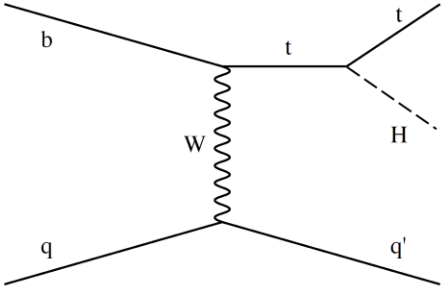


Higgs production

Less common ways:

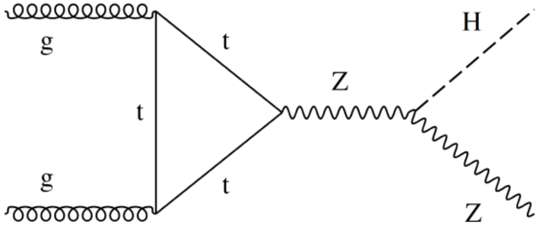


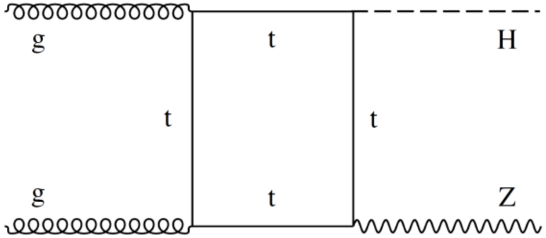




tH and tHW: Allows to resolve relative phase of Htt and HWW couplings

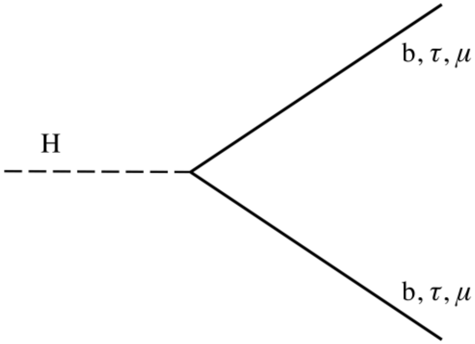
$gg \rightarrow ZH$: Allows to resolve relative phase of Htt and HZZ couplings



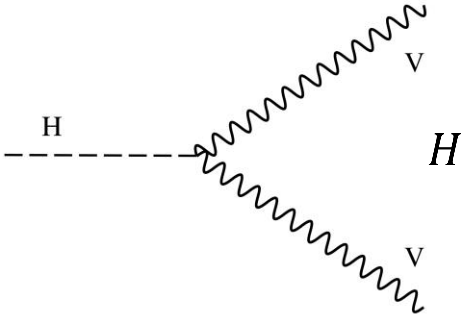


Higgs decay

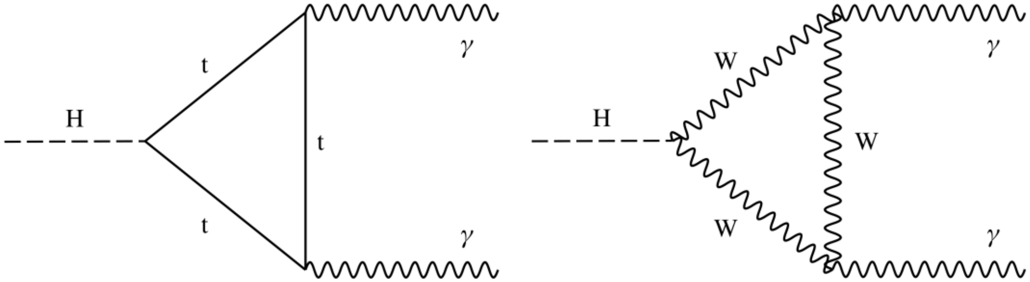
Higgs boson decay modes commonly used in analyses:



$H \rightarrow f\bar{f}$

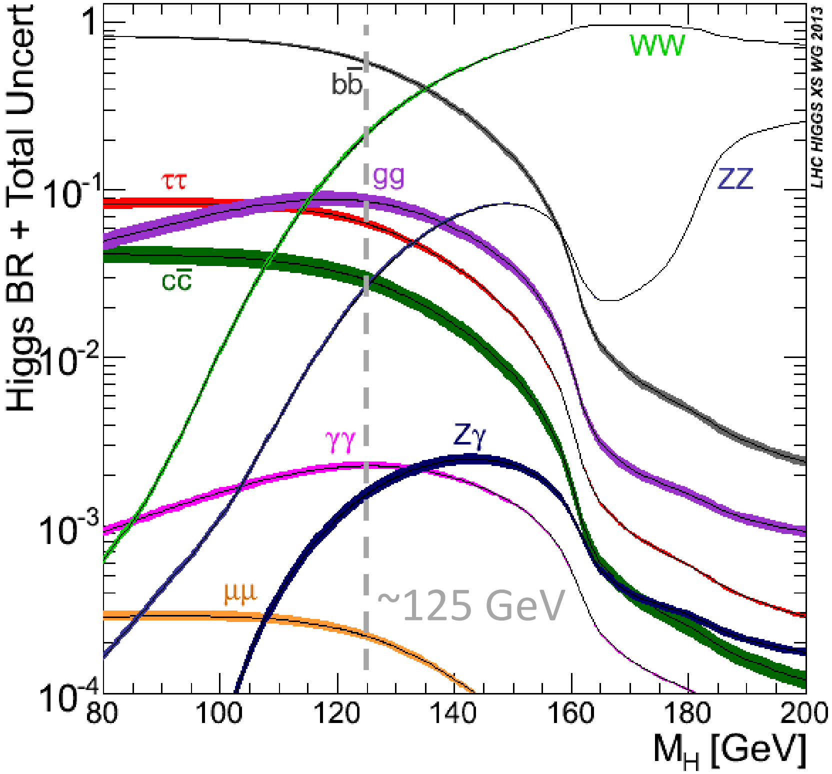


$H \rightarrow ZZ$ or WW



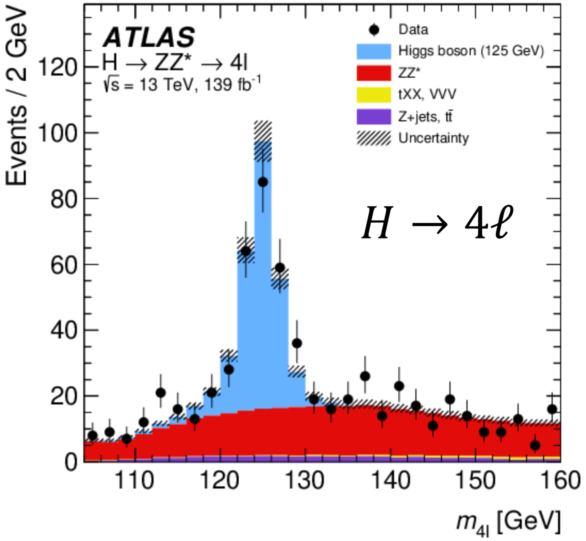
$H \rightarrow \gamma\gamma$

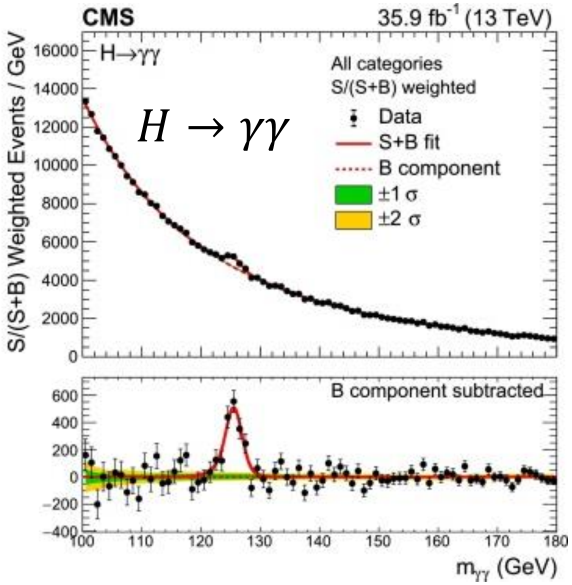
$\mathcal{B}$ for major decay modes [1]



Mass

Measure mass from the resonance mass line shape:





Doable from the 4ℓ and $\gamma\gamma$ final states to excellent precision (1-2% resolution)

Best measurements to date:

→ $4\ell + \gamma\gamma$ combined measurement of ATLAS and CMS using LHC Run 1 data [1]:

$$m_H = 125.09 \pm 0.21\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{GeV}$$

→ $4\ell + \gamma\gamma$ measurement of CMS using LHC Run 1 + Run 2 2016 data [2]:

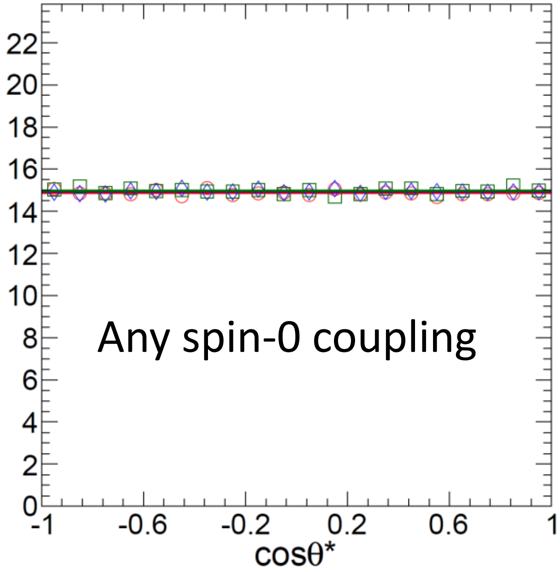
$$m_H = 125.38 \pm 0.11\ (\text{stat.}) \pm 0.08\ (\text{syst.})\ \text{GeV}$$

→ 4ℓ measurement of ATLAS using LHC Run 1 + Run 2 2016-2018 data [3]:

$$m_H = 124.94 \pm 0.17\ (\text{stat.}) \pm 0.03\ (\text{syst.})\ \text{GeV}$$

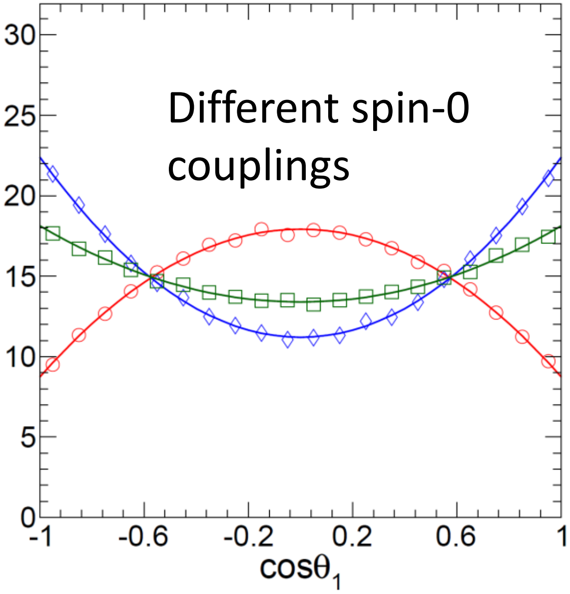
Spin-parity

Angular correlations change for different Higgs boson spin and parity scenarios.

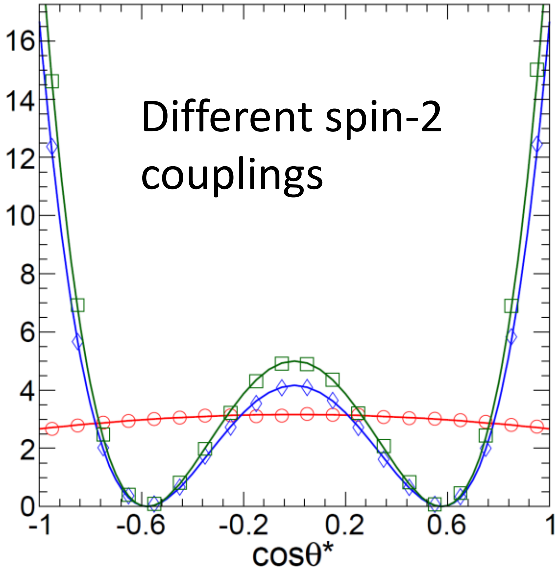


Any spin-0 coupling

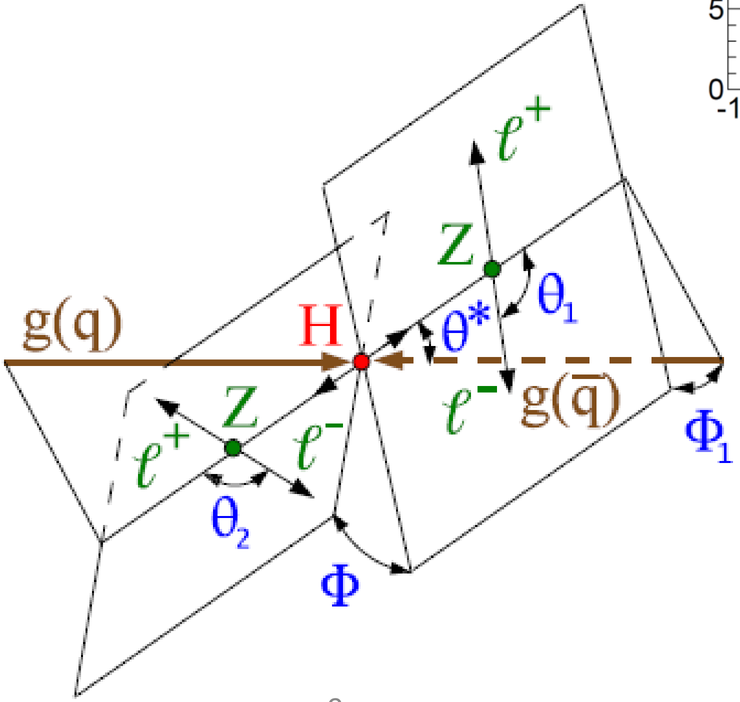
Can exploit such **information from** Higgs boson **production** (correlation between Higgs boson and associated particles) or decay (correlation between **decay** products) to measure the spin and parity of the Higgs boson



Different spin-0 couplings

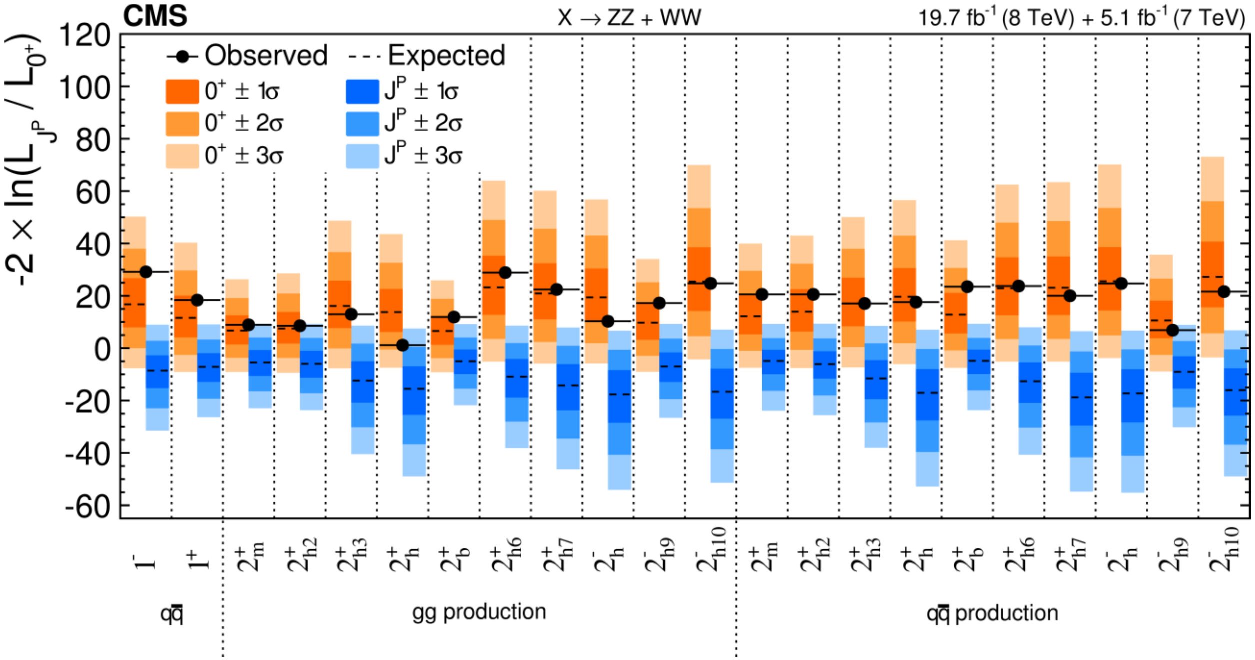


Different spin-2 couplings



Plots from Refs. [1,2].

Spin from diboson decays

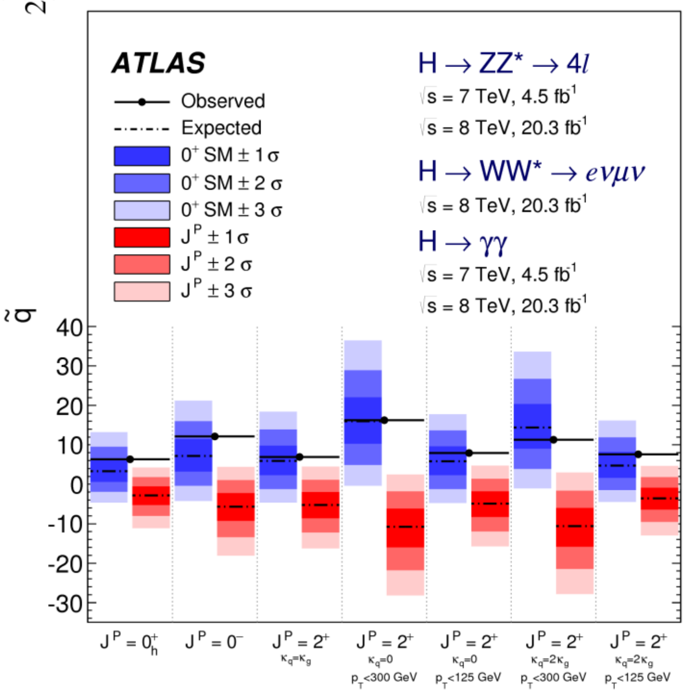


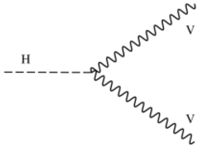
Extensive list of tests of spin-1 and -2 hypotheses from CMS and ATLAS using ZZ, WW and $\gamma\gamma$ decays [1,2]

The Higgs boson is consistent with spin 0.

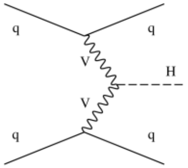
Spin-1 models excluded at >99.999% CL from CMS using $ZZ + WW$ decays.

Spin-2 models excluded at >99% CL from CMS using $ZZ + WW$ decays, or at 99.87% for minimal gravitons using $ZZ + WW + \gamma\gamma$ decays, >99.9% CL in the tested ATLAS models using $ZZ + WW + \gamma\gamma$ decays





Anomalous spin-0 couplings: HVV



$$A(HVV)\sim\left[\boldsymbol{a_1} - e^{i\phi_{\Lambda1}}\frac{(q_{V1}^2+q_{V2}^2)}{\Lambda_1^2} - e^{i\phi_{\Lambda1}^{Z\gamma}}\frac{q_\gamma^2}{\left(\Lambda_1^{Z\gamma}\right)^2}\dots\right] m_V^2\epsilon_{V1}^*\epsilon_{V2}^*$$

$$+\ |a_2|\, e^{i\phi_{a2}}\, f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + |a_3|\, e^{i\phi_{a3}}\, f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

HVV amplitude
∝ SM-like $\boldsymbol{a_1}$ term
+ other BSM CP-even
or -odd contributions

CMS $H \rightarrow ZZ + H \rightarrow \tau\tau$ measurements using Run 2 data [1]

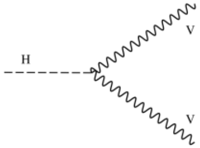
Results in terms of fractional xsec $f_{ai} = |a_i|^2\sigma_i/(|a_1|^2\sigma_1 + |a_i|^2\sigma_i)$ with $\phi_{ai} = 0$ or π.

→ Make use of HVV vertices in both Higgs decay and production.

Approach	Parameter	Observed / (10^{-3})		Expected / (10^{-3})	
		68% CL	95% CL	68% CL	95% CL
Approach 1 $(a_i^{WW} = a_i^{ZZ})$	f_{a3}	$0.20^{+0.26}_{-0.16}$	$[-0.01, 0.88]$	0.00 ± 0.05	$[-0.21, 0.21]$
	f_{a2}	$0.7^{+0.8}_{-0.6}$	$[-1.0, 2.5]$	$0.0^{+0.5}_{-0.4}$	$[-1.1, 1.2]$
	$f_{\Lambda1}$	$-0.04^{+0.04}_{-0.08}$	$[-0.22, 0.16]$	$0.00^{+0.11}_{-0.04}$	$[-0.11, 0.38]$
	$f_{\Lambda1}^{Z\gamma}$	$0.7^{+1.6}_{-1.3}$	$[-2.7, 4.1]$	$0.0^{+1.0}_{-1.0}$	$[-2.6, 2.5]$
Approach 2	f_{a3}	$0.28^{+0.39}_{-0.23}$	$[-0.01, 1.28]$	0.00 ± 0.08	$[-0.30, 0.30]$

$(a_3^{WW} = a_3^{ZZ} \cos^2\theta_W)$

→ HZZ channel results [2] alone (see table in backup) also provide constraints with other BSM couplings profiled.



Anomalous spin-0 couplings: HVV

$$A(HVV) \sim \boldsymbol{\kappa_{SM}} m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + \tilde{\kappa}_{HVV} \mathrm{f}_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \tilde{\kappa}_{AVV} \tan\alpha \, \mathrm{f}_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

HVV amplitude
∝ SM-like $\boldsymbol{\kappa_{SM}}$ term
+ CP-even $\tilde{\kappa}_{HVV}$
or -odd $\tilde{\kappa}_{AVV}$ contributions

ATLAS $H \to ZZ + WW$ measurements using Run 1 data [1]
→ In terms of coupling scale factor ratios:

Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
● $\tilde{\kappa}_{HVV}/\kappa_{\mathrm{SM}}$	-0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
● $(\tilde{\kappa}_{AVV}/\kappa_{\mathrm{SM}}) \cdot \tan\alpha$	-0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

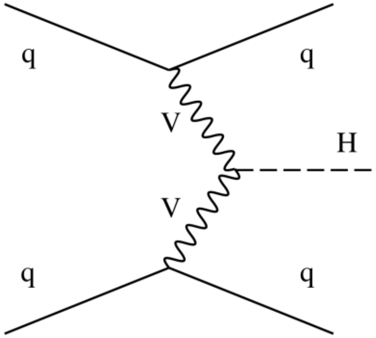
→ Comparable to Run 1 CMS results using the same final states [2]:

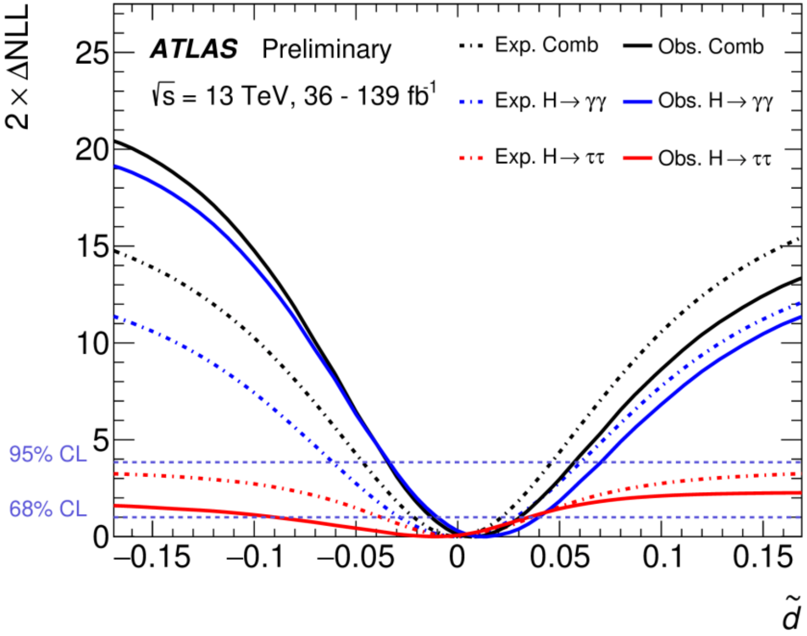
Parameter	Observed	Expected
$(\Lambda_1 \sqrt{\lvert a_1 \rvert}) \cos(\phi_{\Lambda_1})$	$[-\infty, -100\,\mathrm{GeV}] \cup [103\,\mathrm{GeV}, \infty]$	$[-\infty, 43\,\mathrm{GeV}] \cup [116\,\mathrm{GeV}, \infty]$
● a_2/a_1	$[-0.58, 0.76]$	$[-0.45, 1.67]$
● a_3/a_1	$[-1.54, 1.57]$	$[-2.65, 2.65]$

Anomalous spin-0 couplings: HVV

$$L_{eff} = \boldsymbol{L_{SM}} + \frac{g}{2m_W}\tilde{d}\left[HA_{\mu\nu}\tilde{A}^{\mu\nu} + HZ_{\mu\nu}\tilde{Z}^{\mu\nu} + 2\,HW^{+}_{\mu\nu}\widetilde{W}^{-\mu\nu}\right]$$

HVV amplitude
∝ SM-like term
+ CP-odd contribution

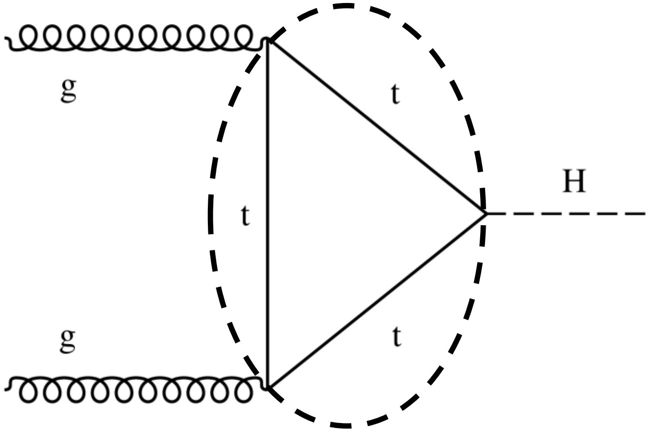


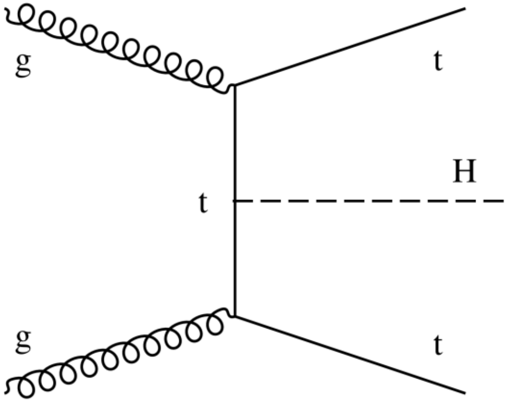


ATLAS $H \to \tau\tau$ (Run 2 2016) + $H \to \gamma\gamma$ (Run 2) through VBF production [1,2]

	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[-0.027, 0.027]	[-0.055, 0.055]	[-0.011, 0.036]	[-0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[-0.028, 0.028]	[-0.061, 0.060]	[-0.010, 0.040]	[-0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[-0.038, 0.036]	-	[-0.090, 0.035]	-
Combined $\tilde{d}$	[-0.022, 0.021]	[-0.046, 0.045]	[-0.012, 0.030]	[-0.034, 0.057]

Anomalous spin-0 couplings: Hgg/Htt





$$A(Hgg) \sim a_2^{gg} \mathrm{f}_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{gg} \mathrm{f}_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \quad A(Htt) = -\frac{m_t}{v} \bar{\psi}_t (\boldsymbol{\kappa_t} + i\tilde{\kappa}_t \gamma_5) \psi_t$$

With $m_H < 2m_t$, resolving loop structure from $gg \rightarrow H$ on-shell Higgs boson production statistically difficult.

$\Rightarrow$

EFT treatment with point-like couplings

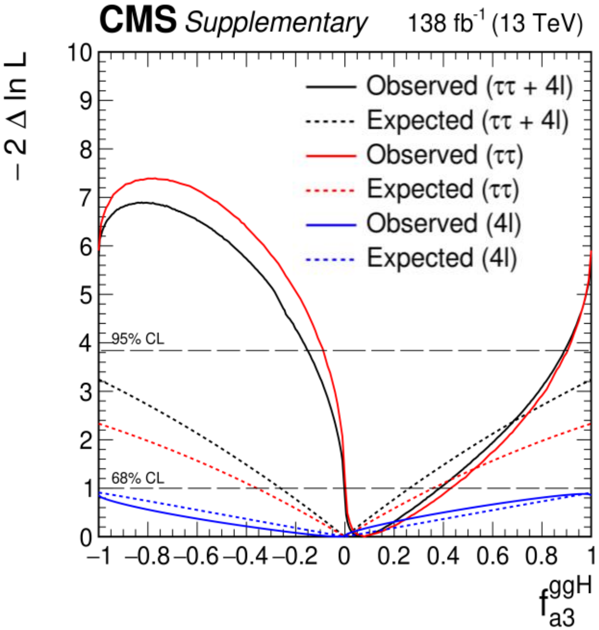
→ Can be translated to Htt couplings

With discovery of $t\bar{t}H$ associated production [1,2], one can probe Htt couplings directly

→ If $f_{a3}^{ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \operatorname{sgn}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$ and $f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \operatorname{sgn}\left(\frac{\tilde{\kappa}_t}{\kappa_t}\right)$,

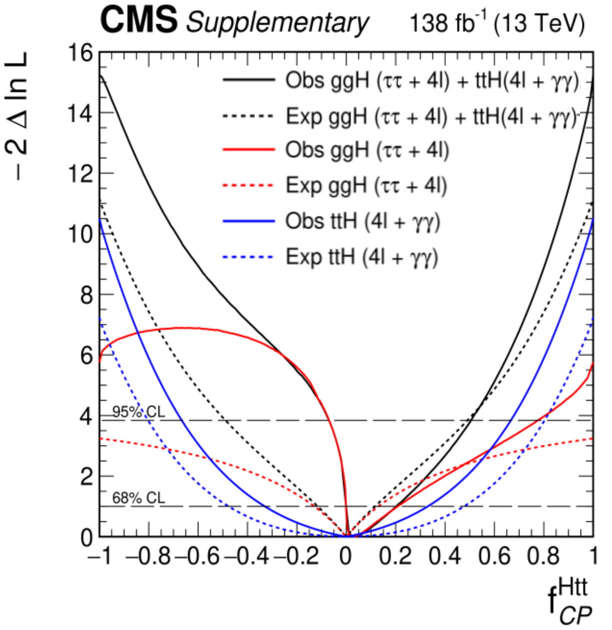
the two fractions are related as $\left|f_{CP}^{Htt}\right| = \left[1 + 2.38\left(\frac{1}{\left|f_{a3}^{ggH}\right|} - 1\right)\right]^{-1}$.

Anomalous spin-0 couplings: Hgg/Htt



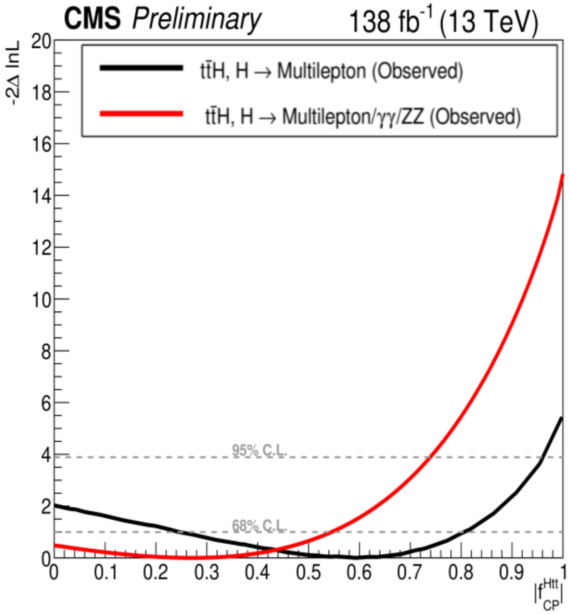
CMS constraints on CP-violating contributions in Higgs boson production via fermionic couplings

→ Using Run 2 $4\ell + \tau\tau$ data, also combining with recent $t\bar{t}H, H \to \gamma\gamma$ analysis [1,2].

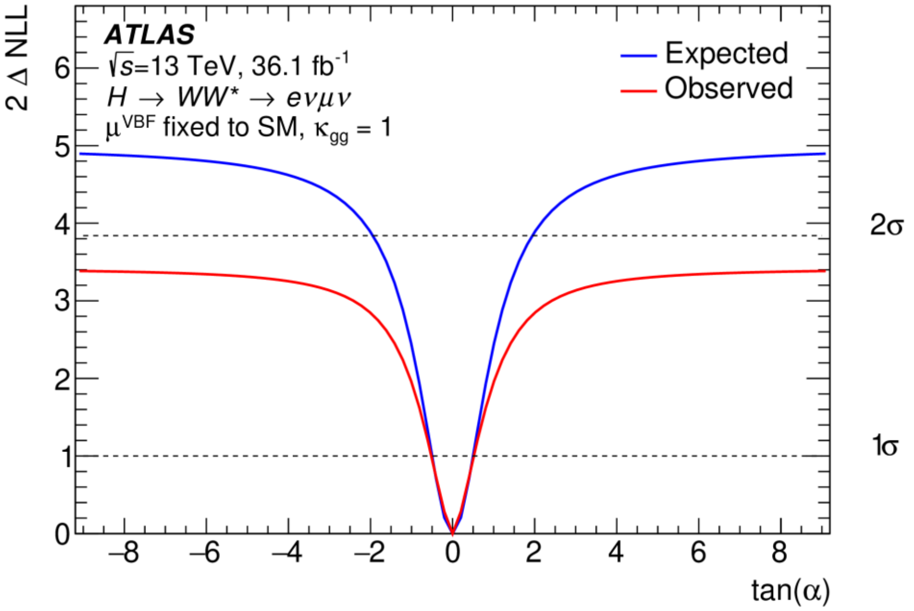


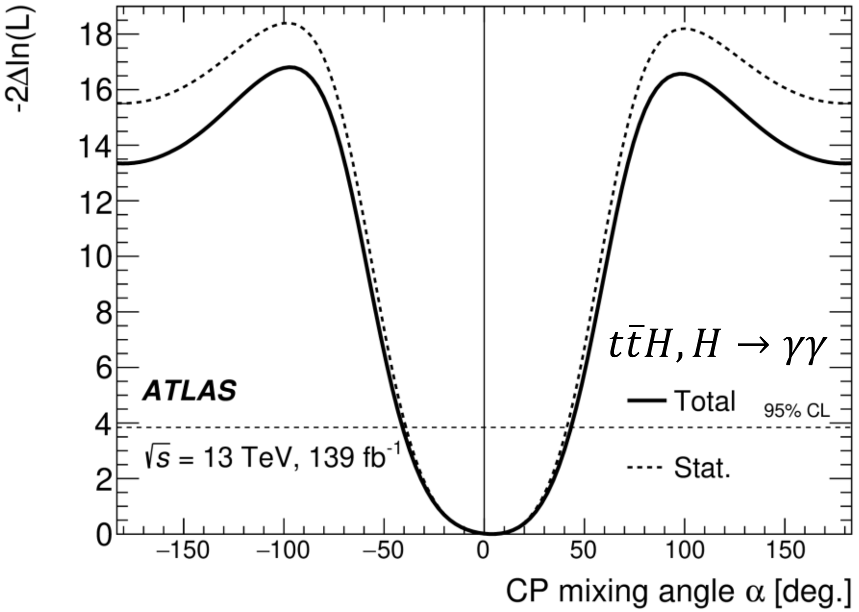
Parameter	Observed		Expected	
	68% CL	95% CL	68% CL	95% CL
f_{a3}^{ggH}	$0.07^{+0.32}_{-0.07}$	$[-0.15, 0.89]$	0.00 ± 0.26	—
f_{CP}^{Htt}	$0.03^{+0.17}_{-0.03}$	$[-0.07, 0.51]$	0.00 ± 0.12	$[-0.49, 0.49]$

→ Another CMS analysis of multilepton $t\bar{t}H + tH$ final states combines with the 4ℓ and $\gamma\gamma$ channels:
$|f_{CP}^{Htt}| < 0.73$ @ 95% CL [3]



Anomalous spin-0 couplings: Hgg/Htt



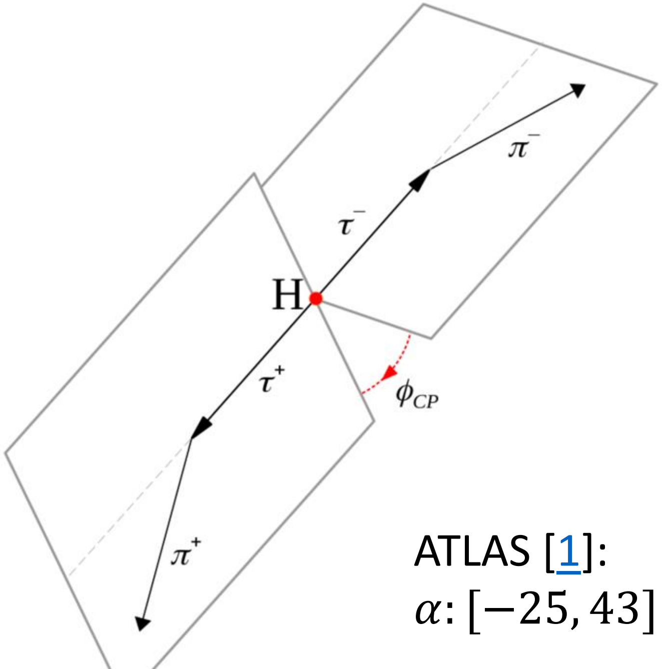


→ Hgg CP mixing angle: Run 2 2016 $WW \rightarrow e\nu_e\mu\nu_\mu$ data from ATLAS:
$|\tan\alpha| < 0.5$ @ 68% CL [1] ($|f_{CP}^{ggH}| < 0.2$ in CMS language)

→ Htt CP mixing angle Run 2 $t\bar{t}H, H \rightarrow \gamma\gamma$ data from ATLAS:
$|\alpha| < 43°$ @ 95% CL [2] ($|f_{CP}^{Htt}| < 0.47$ in CMS language)

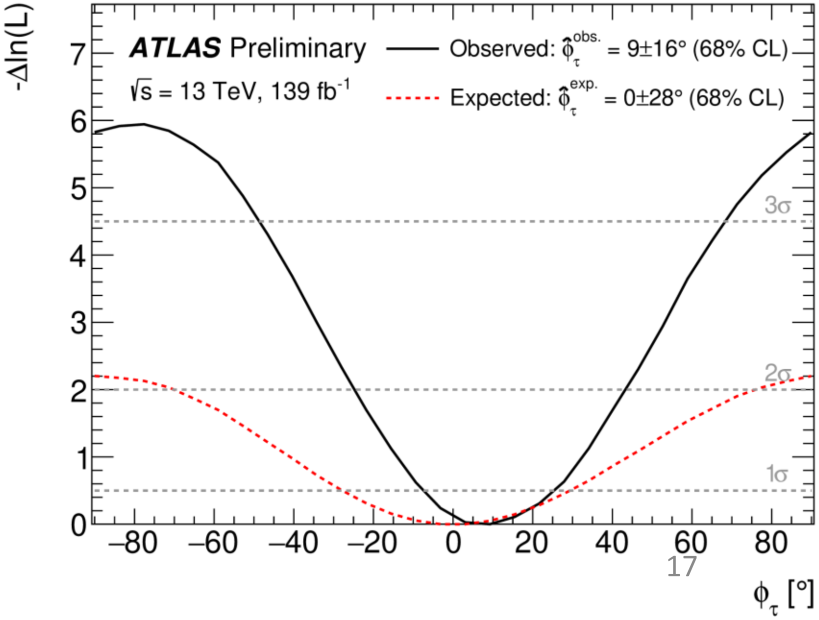
→ Also Run 2 $t\bar{t}H, H \rightarrow b\bar{b}$ data from ATLAS:
$|\alpha| < 66°$ @ 68% CL [3] ($|f_{CP}^{Htt}| < 0.83$ in CMS language)

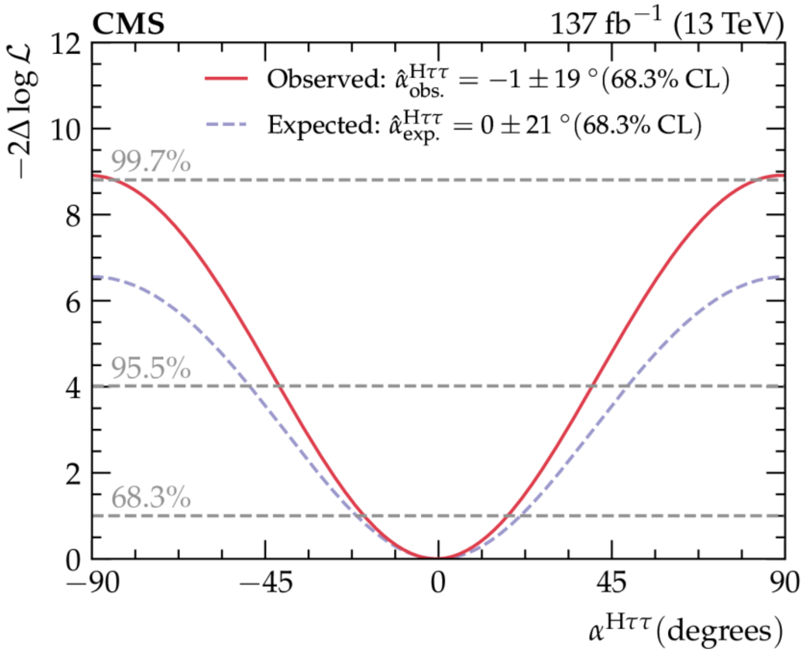
Anomalous spin-0 couplings: Hττ



Same amplitude/Lagrangian formalism as in Htt couplings to determine CP-violation in $H \rightarrow \tau\tau$ decays

ATLAS [1]:
α: $[-25, 43]$ @ 95.5% CL



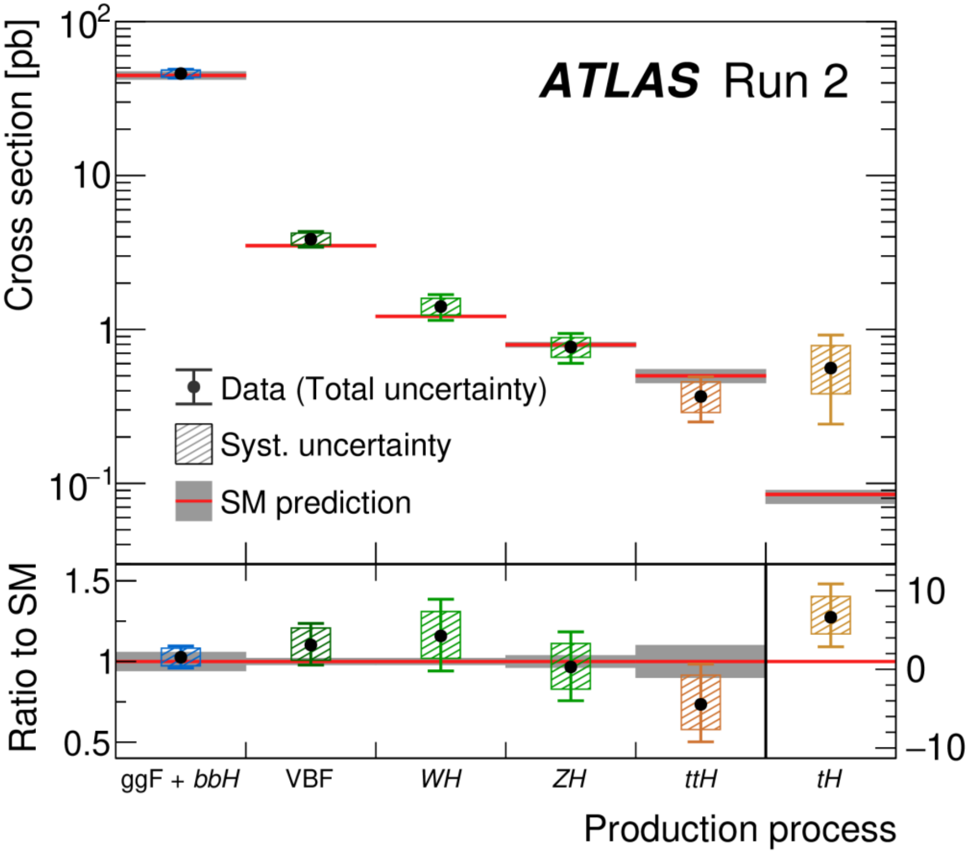


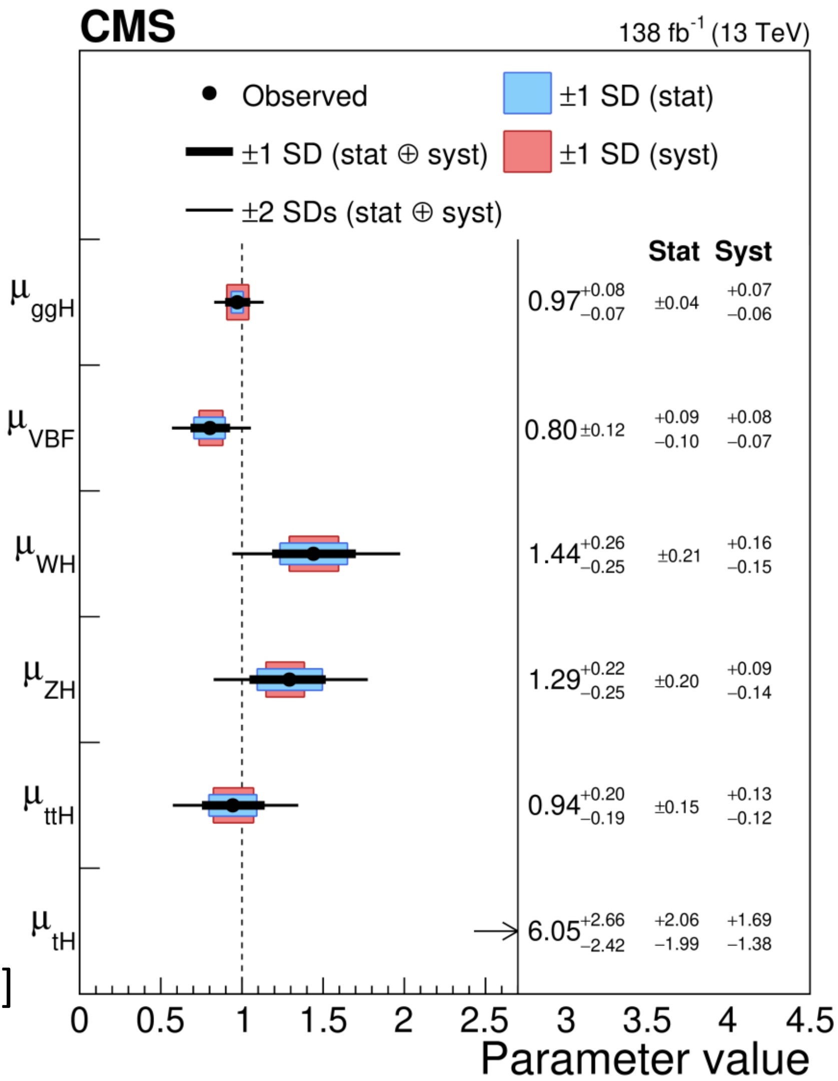
CMS [2]:
α: $[-42, 40]$ @ 95% CL

The Higgs boson is predominantly a CP-even spin-0 particle as prescribed in the SM.

Let’s examine its couplings closer for the SM-like tensor structure...

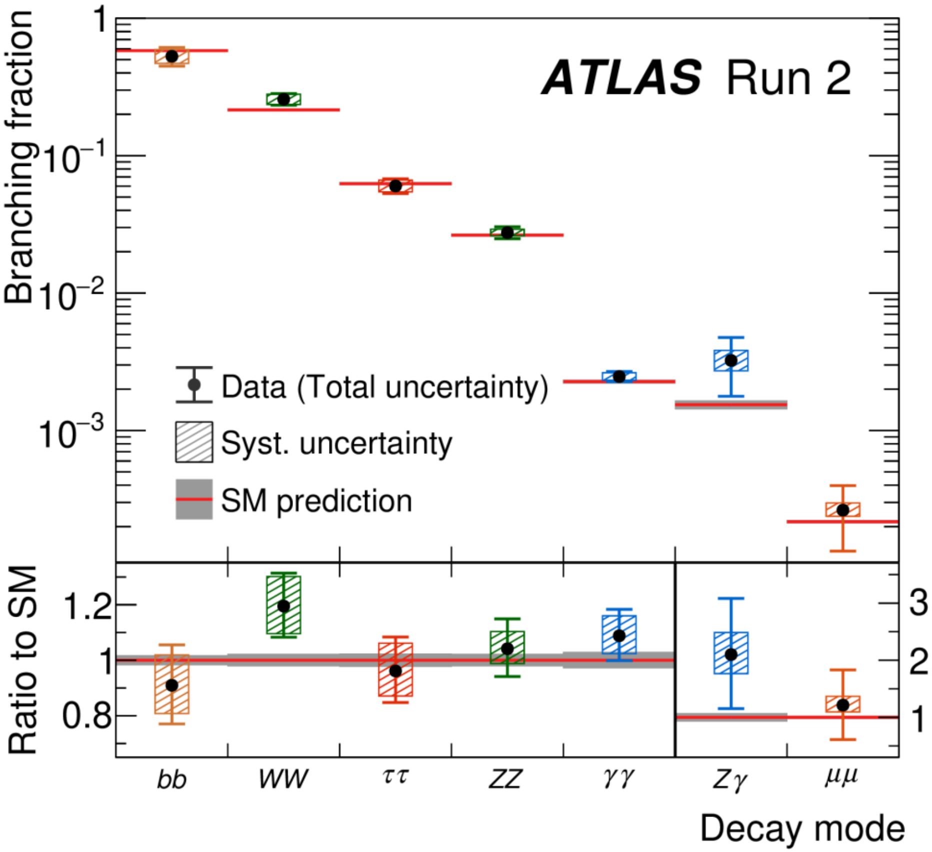
Constraints on production modes

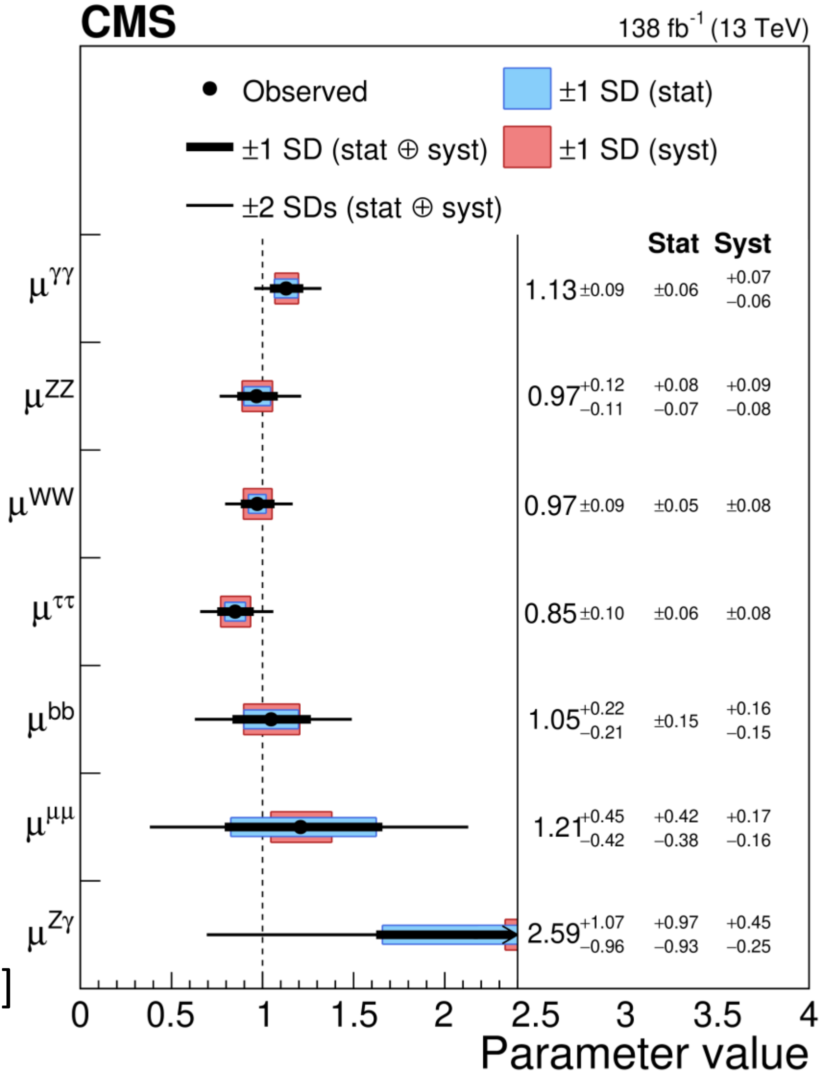




Combine results from all channels and interpret:
→ Measurements so far consistent with the SM [1,2]
→ Gluon fusion within ~5%, VBF within ~10%
→ Consistent excess in tH, but large uncertainty due to small xsec and $t\bar{t}H$ contamination

Constraints on visible decays

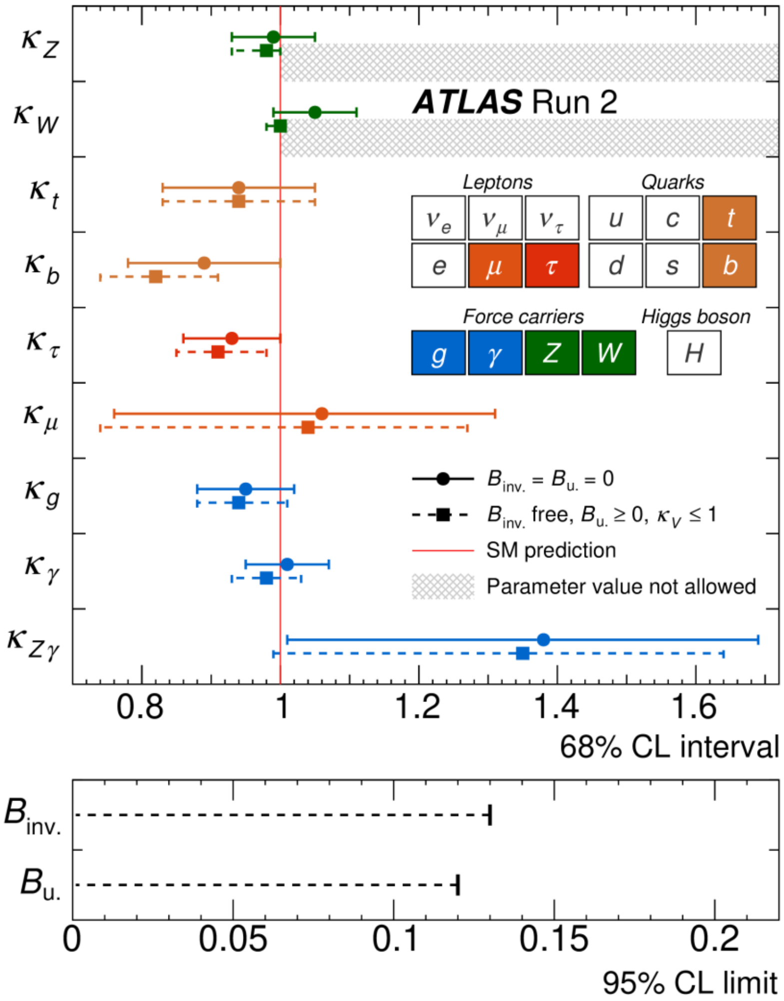




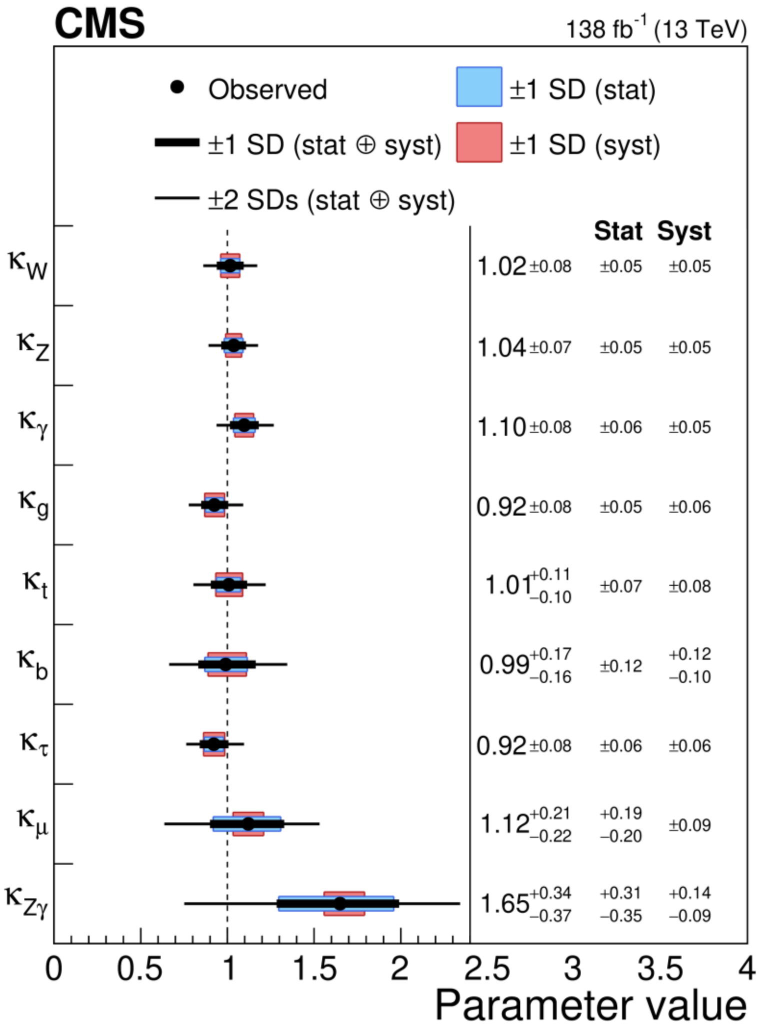
→ Measurements so far consistent with the SM [1,2]

→ $ZZ, WW, \gamma\gamma$, and $\tau\tau$ precision within 10%

Interpretation in terms of couplings



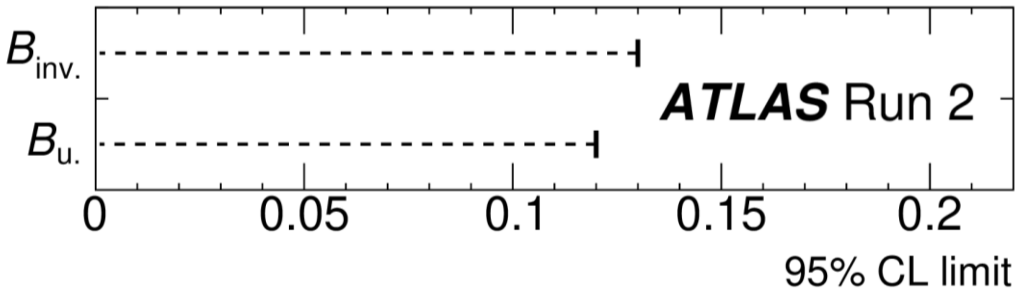
From [1,2]



→ $HZZ, HWW, H\tau\tau$, and effective coupling modifiers for $H\gamma\gamma, Hgg$ measured to 10%

→ ATLAS also presents constraints with invisible and undetected branching ratios.
(see comparison on next slide)

$H \rightarrow$ invisible limits

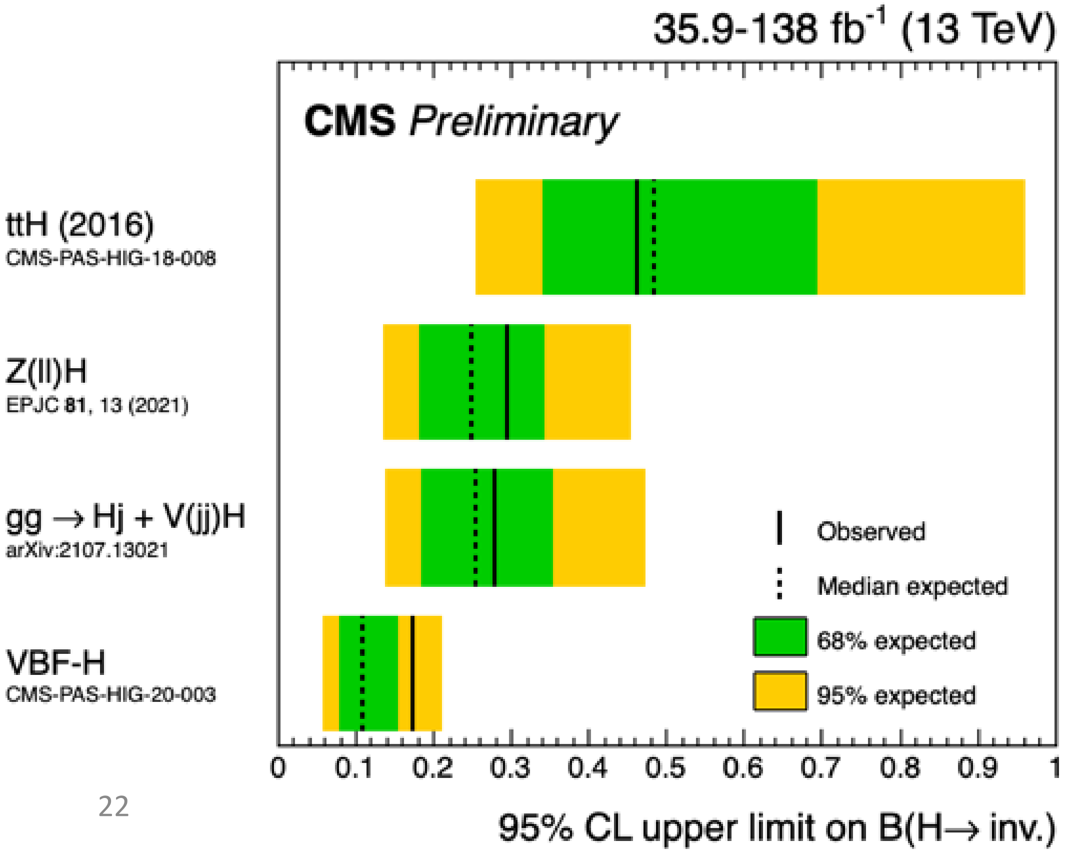


From Ref. [1], based on Run 2 $H \rightarrow$ inv. data:
$\mathcal{B}_{inv} < 0.15$ from VBF [2]
and
$\mathcal{B}_{inv} < 0.19$ from $Z(\rightarrow \ell\ell)H$ [3]

ATLAS invisible and undetected branching ratio result from combination of all channels:
$\mathcal{B}_{inv} < 0.13$ and $\mathcal{B}_u < 0.12$ at 95% CL
(assuming $\kappa_Z, \kappa_W \leq 0$)

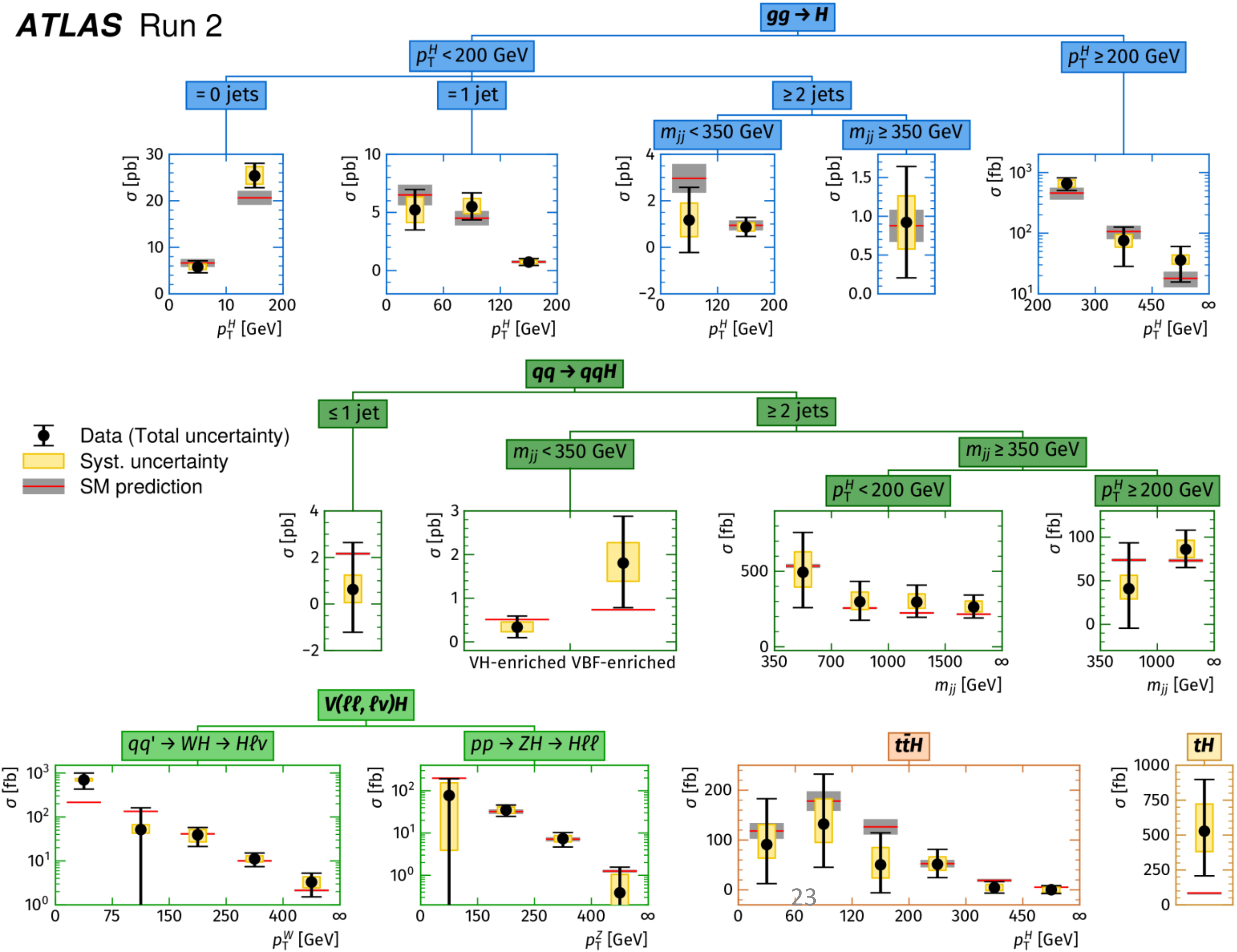
Most stringent CMS limit from Run 2 VBF [4]:
$\mathcal{B}_{inv} < 0.18$ @ 95% CL

Other CMS $H \rightarrow$ inv. interpretations:
$t\bar{t}H$ [5]: < 0.46
$Z(\rightarrow \ell\ell)H$ [6]: < 0.29
$gg \rightarrow Hj, V(\rightarrow jj)H$ [7]: < 0.28



Beyond couplings: STXS (1.2)

The idea is to split production modes finer in specific final states, p_T^H, or m_{jj} and measure the cross section for each 'production bin'.



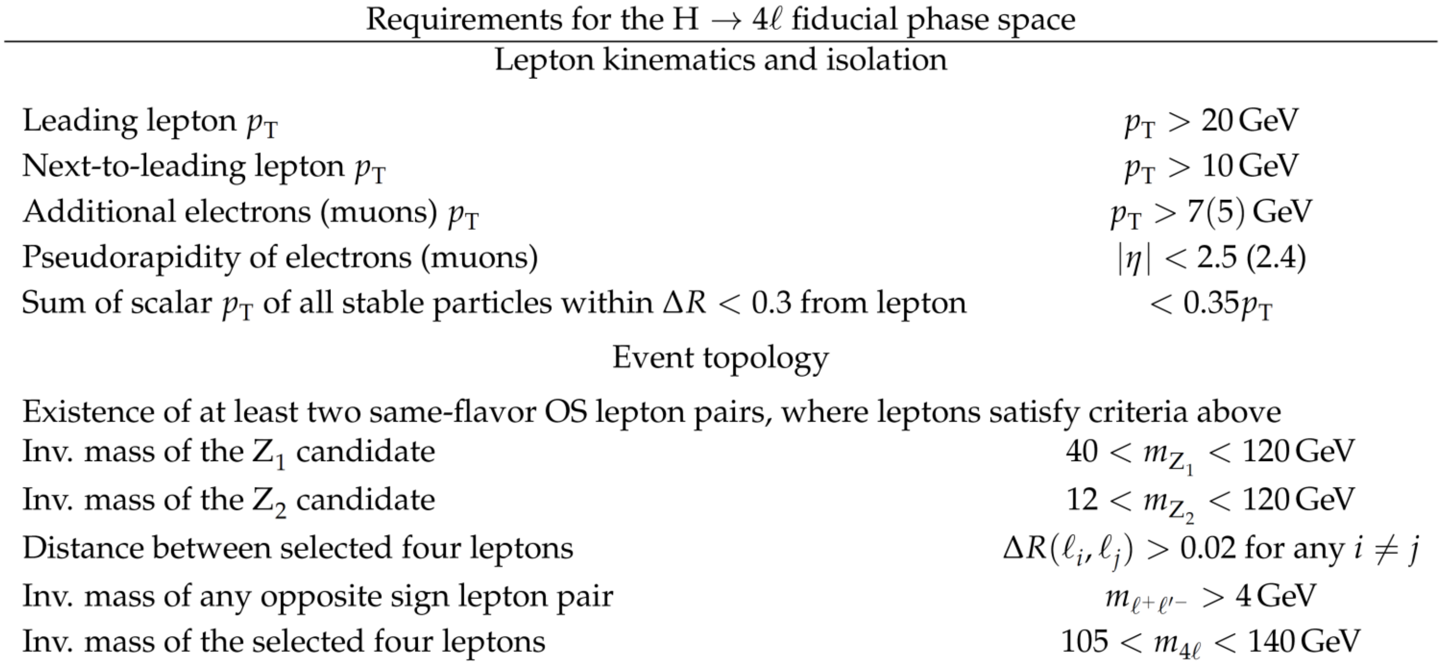
So far, ATLAS Run 2 results consistent with the SM [1]

Other CMS results from individual channels:
WW [2]
$\tau\tau$ [3]
$\gamma\gamma$ [4]
ZZ [5]

Beyond couplings: Fiducial differential xsecs

→ Another way to go beyond simple coupling constants is to measure the aggregate Higgs boson production xsec in bins of p_{T}^{H}, y_H or other kinematic variables within a fiducial selection volume.

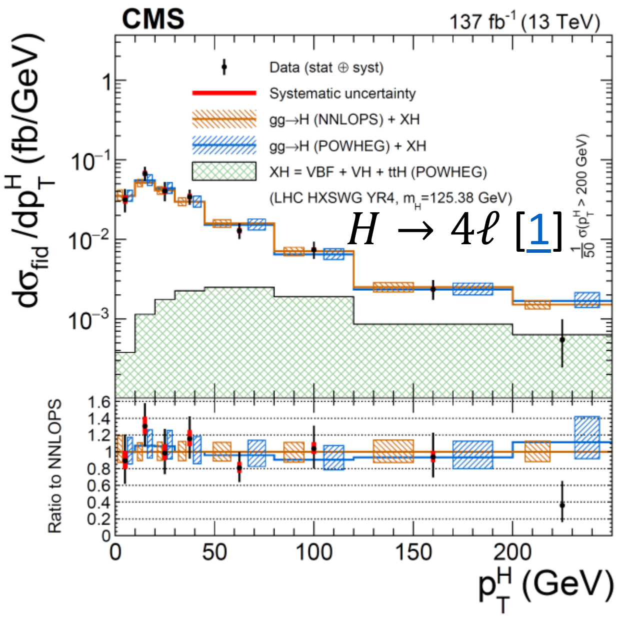
→ Example fiducial volume from CMS 4ℓ analysis:



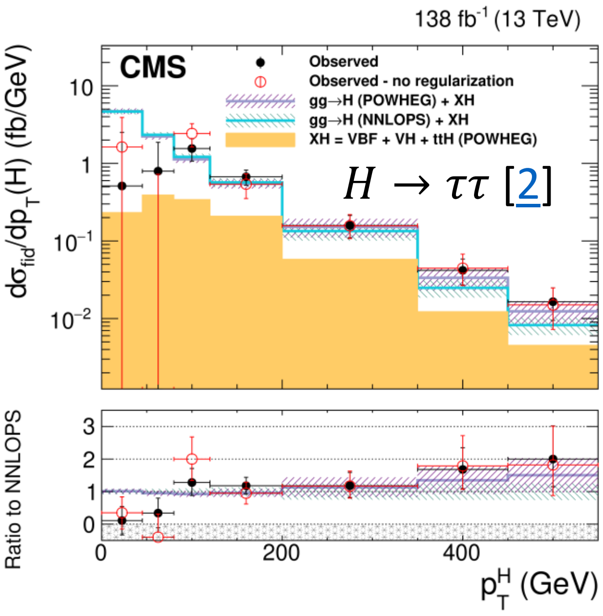
Requirements for the $\mathrm{H} \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_{T}	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$
Next-to-leading lepton p_{T}	$p_{\mathrm{T}} > 10\,\mathrm{GeV}$
Additional electrons (muons) p_{T}	$p_{\mathrm{T}} > 7(5)\,\mathrm{GeV}$
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5$ (2.4)
Sum of scalar p_{T} of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_{\mathrm{T}}$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{\mathrm{Z}_1} < 120\,\mathrm{GeV}$
Inv. mass of the Z_2 candidate	$12 < m_{\mathrm{Z}_2} < 120\,\mathrm{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\mathrm{GeV}$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140\,\mathrm{GeV}$

→ Higgs boson production outside of the fiducial volume is ‘background’.
→ Measure true cross section after unfolding, and efficiency and acceptance corrections.

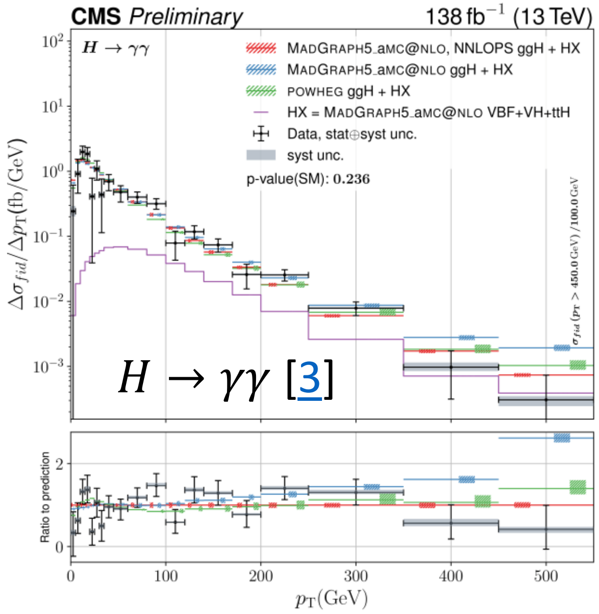
Example fid. xsecs differential in p_{T}^{H}



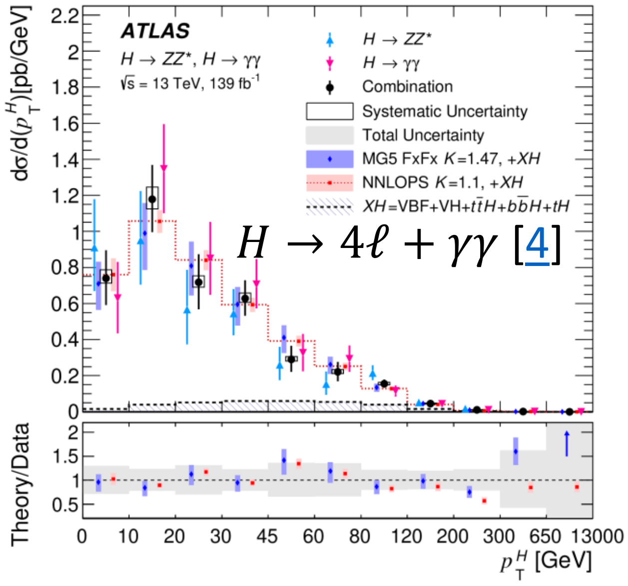
$H \to 4\ell$ [1]



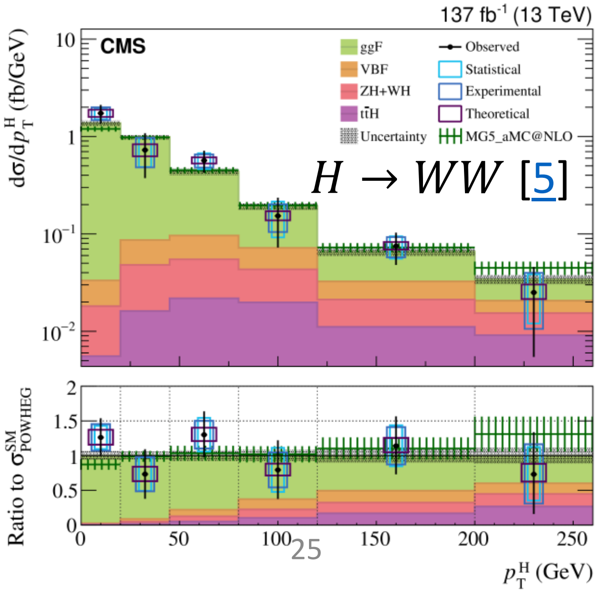
$H \to \tau\tau$ [2]



$H \to \gamma\gamma$ [3]



$H \to 4\ell + \gamma\gamma$ [4]

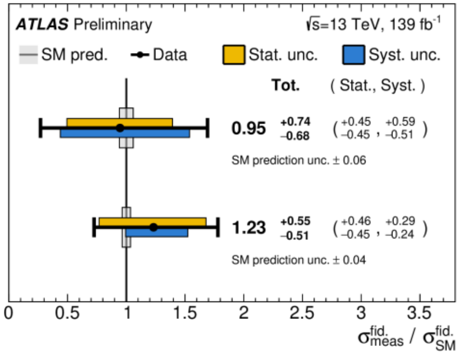


$H \to WW$ [5]

p_T^{miss}:

150-250 GeV

>250 GeV



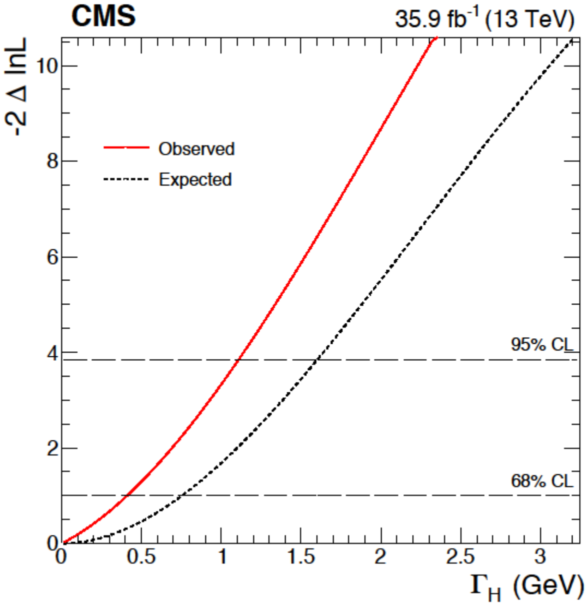
$VH, H \to b\bar{b}$ (0-ℓ) [6]

More observables measured in the linked references

All measurements of Higgs boson couplings in production and decay seem consistent with the SM for now.

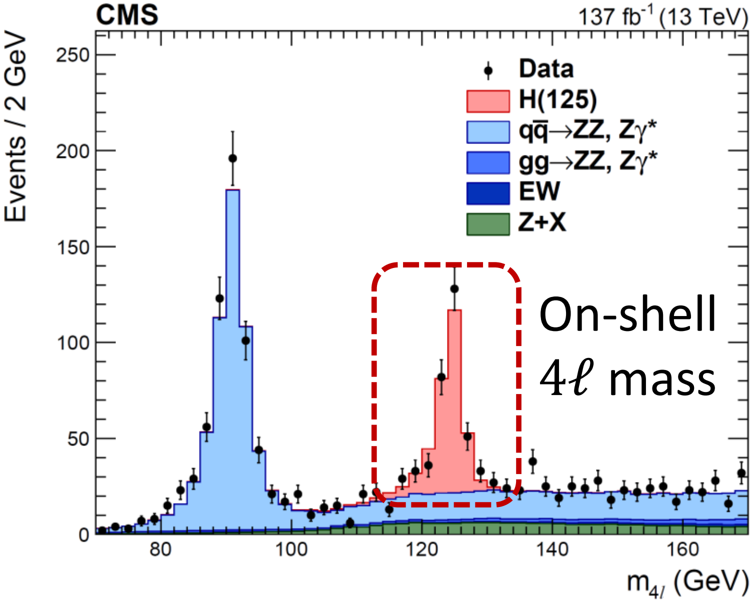
Let’s examine the last piece in our properties investigation, the lifetime of the Higgs boson...

Higgs boson width/lifetime

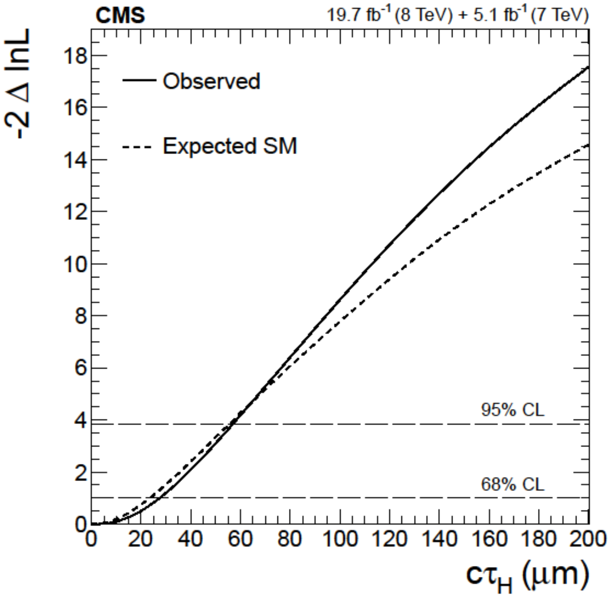


Best width upper bounds from on-shell mass spectra comes from CMS 4ℓ [1]:

$\Gamma_\mathrm{H} < 1.1$ GeV
($\tau_\mathrm{H} > 6.0 \times 10^{-25}$ s)



On-shell 4ℓ mass



Only lifetime upper bound comes from CMS on-shell 4ℓ displacement [2]:

$\tau_\mathrm{H} < 1.9 \times 10^{-13}$ s
($\Gamma_\mathrm{H} > 3.5 \times 10^{-12}$ GeV)

SM value:
$\tau_\mathrm{H} = 1.6 \times 10^{-22}$ s
$\Gamma_\mathrm{H} = 4.1$ MeV

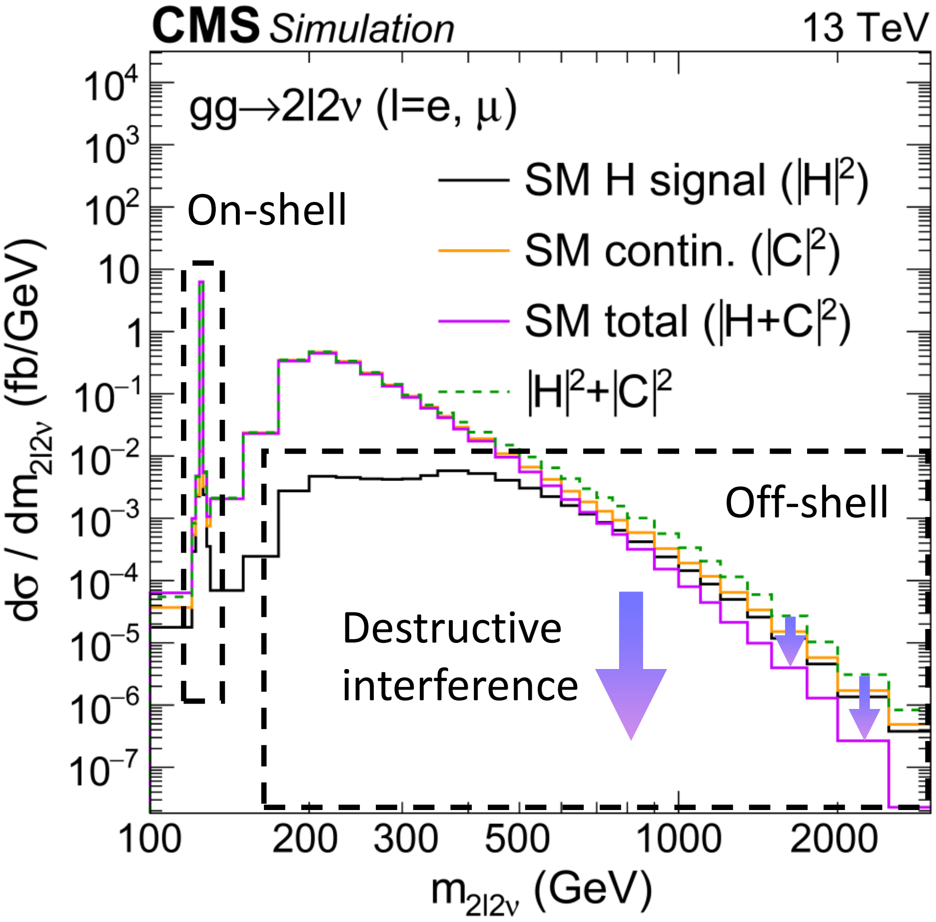
Out of reach of either method in precision!

Off-shell Higgs boson production

In $H \to VV$ ($V = Z, W$), $m_V < m_{\mathrm{H}} < 2m_V$:
→ Either H is on-shell and one V is off-shell, or H is off-shell and both Vs are on-shell

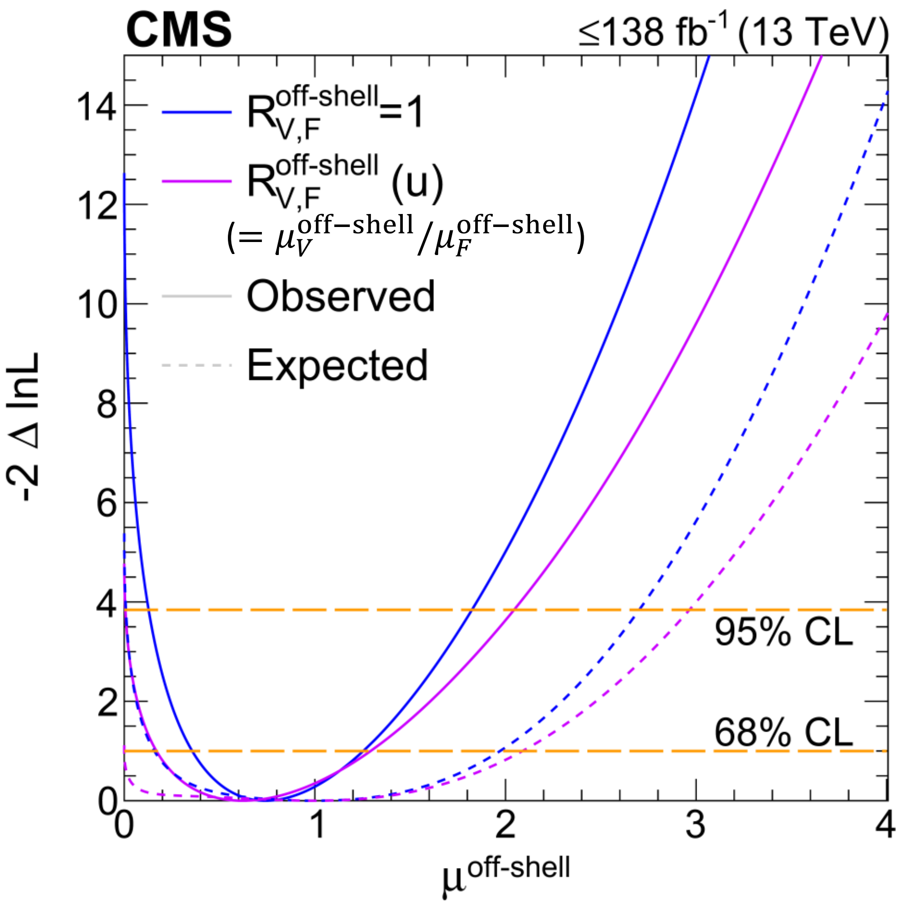
→ Both Vs going on-shell allows $\sim$10% of events in the SM to produce an off-shell Higgs boson [1]

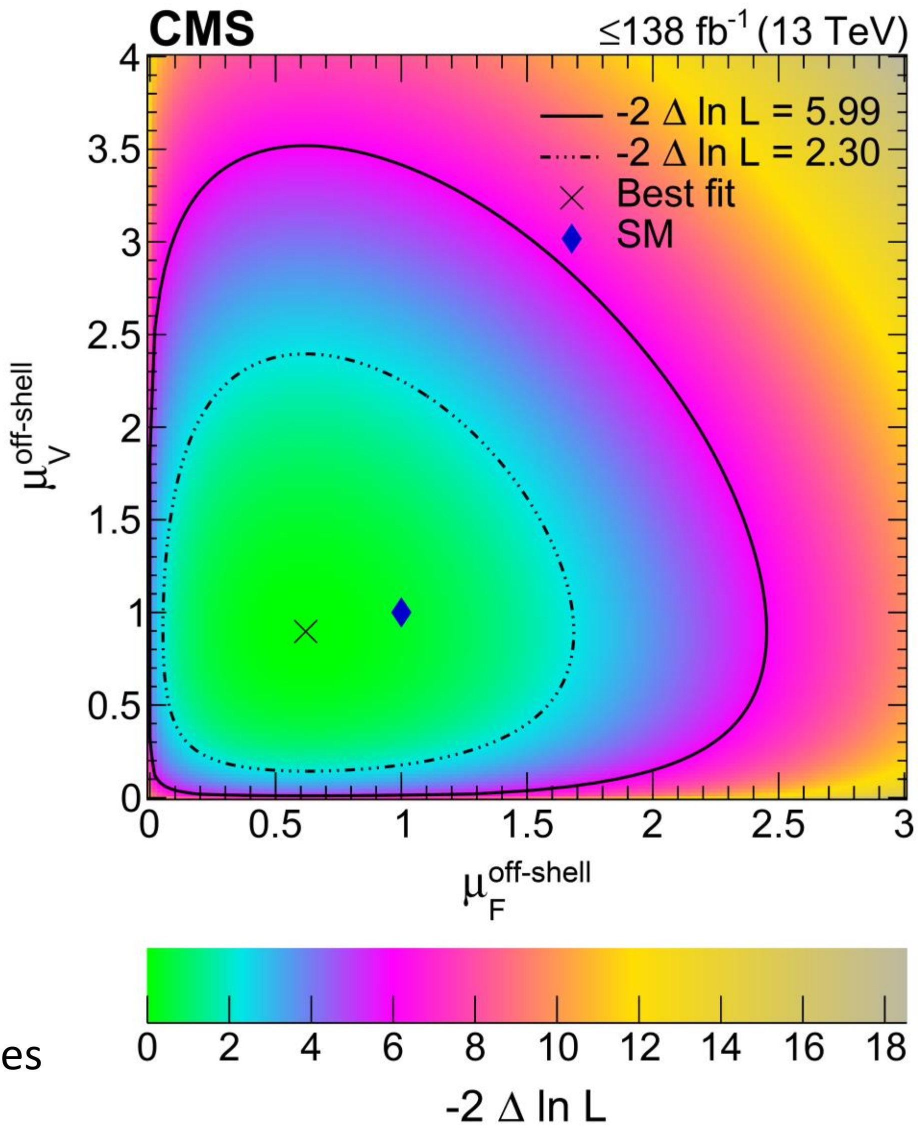
Possible to measure two off-shell production mechanisms:
- $\mu_F^{\text{off-shell}}$ (gg)
- $\mu_V^{\text{off-shell}}$ (EW $H + 2$ jets)
- Can also measure overall $\mu^{\text{off-shell}}$



Higgs-mediated diagrams interfere destructively with continuum VV production:
→ Large in magnitude
→ $\sim$Twice the size of the Higgs signal
→ Necessary in the SM to ensure unitarity

Off-shell Higgs boson production





CMS finds evidence for off-shell Higgs boson contributions in $ZZ \to 4\ell + 2\ell 2\nu$ and measures $\mu_F^{\text{off-shell}}$ and $\mu_V^{\text{off-shell}}$ [1].

Higgs boson width from off-shell

Combine with on-shell signal strength measurement to extract Γ_{H} [1]:

$$\sigma = \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_{\mathrm{H}}^2)^2 + m_{\mathrm{H}}^2 \Gamma_{\mathrm{H}}^2} \dots dm^2$$

On-shell

Off-shell

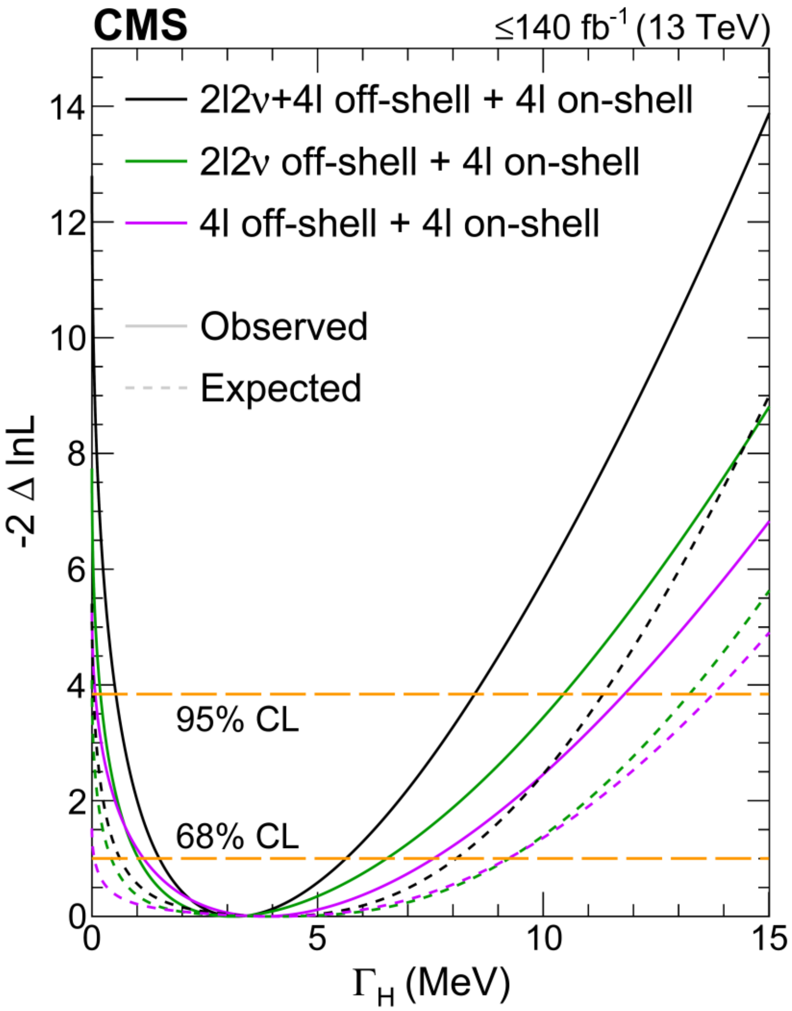
$$\sigma \propto \frac{g_{prod}^2 g_{dec}^2}{\Gamma_{\mathrm{H}}} \propto \mu_{\mathrm{prod}}$$

$$\sigma \sim \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_{\mathrm{H}}^2)^2} \dots dm^2 \propto \underbrace{\mu_{\mathrm{prod}} \cdot \Gamma_{\mathrm{H}}}_{\mu_{\mathrm{prod}}^{\mathrm{off-shell}}}$$

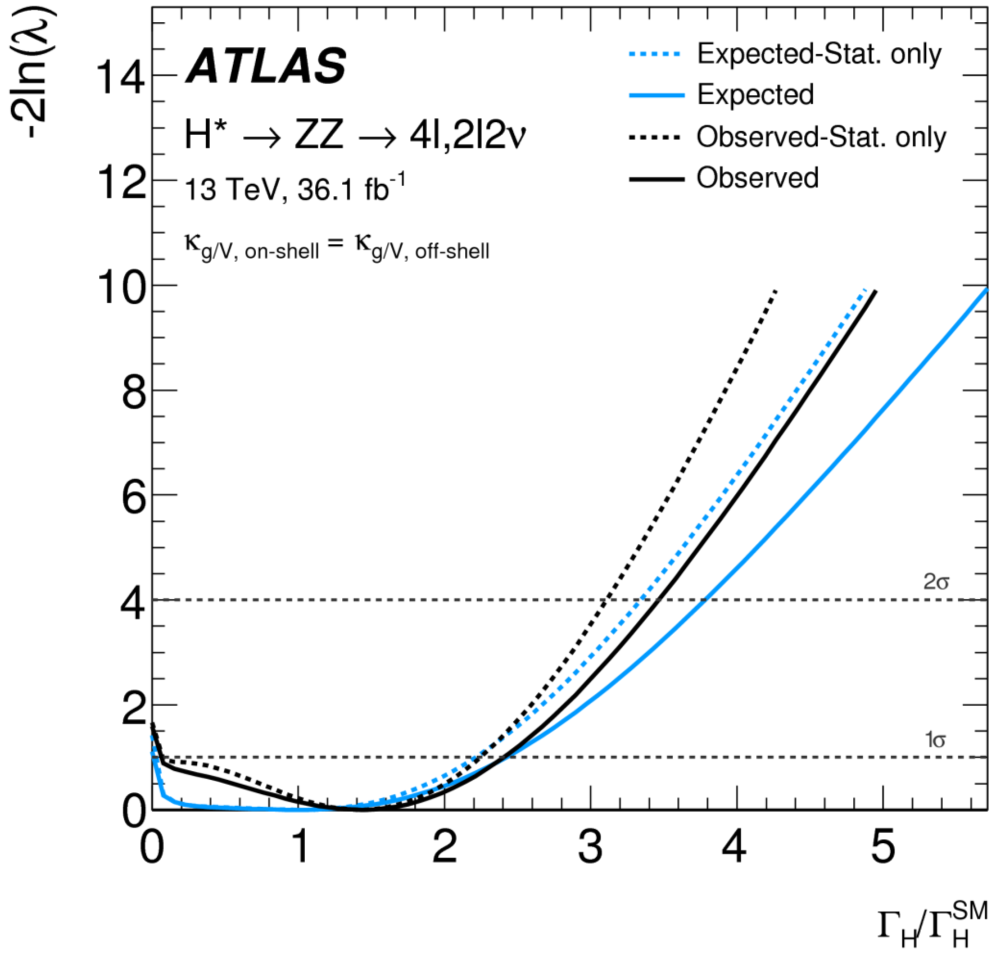
Measure on-shell signal strength from final states ZZ or WW

Ratio of off-shell to on-shell signal strengths for each production mode gives Γ_{H}

Higgs boson width from off-shell

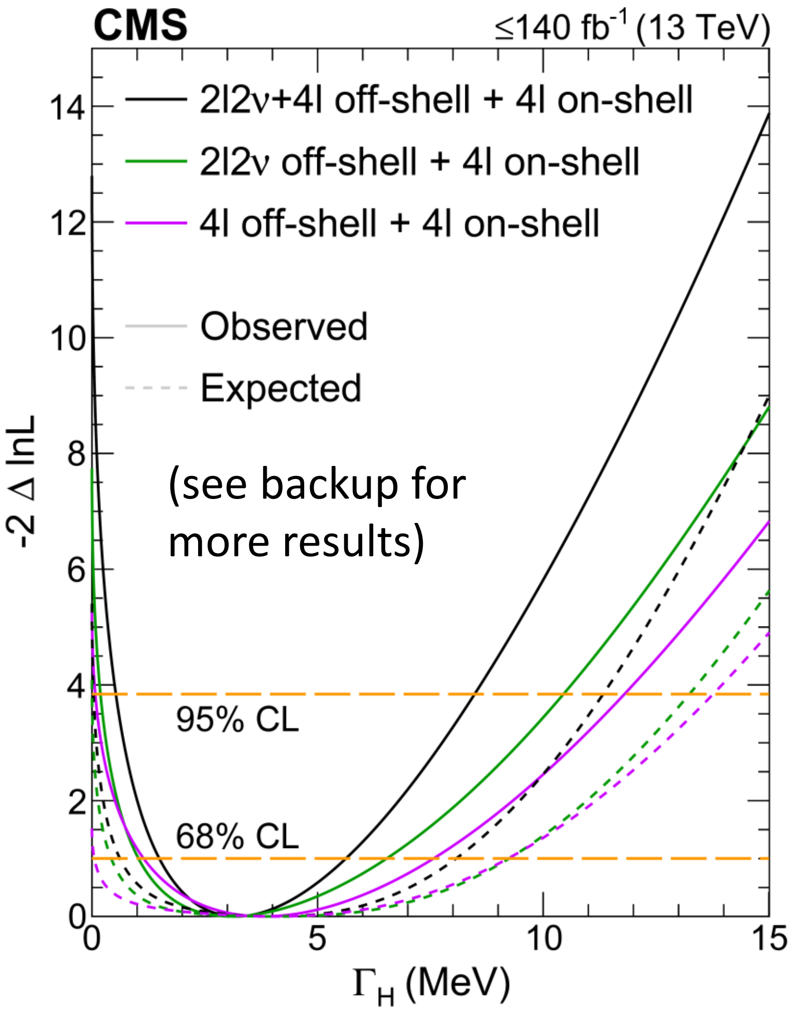


CMS Run 2 $4\ell + 2\ell 2\nu$ [1]:
$\Gamma_{\mathrm{H}} = 3.2^{+2.4}_{-1.7}$ MeV
[0.5, 8.5] MeV @ 95% CL
($7.7\ 10^{-23} < \tau_H < 1.3\ 10^{-21}$s)

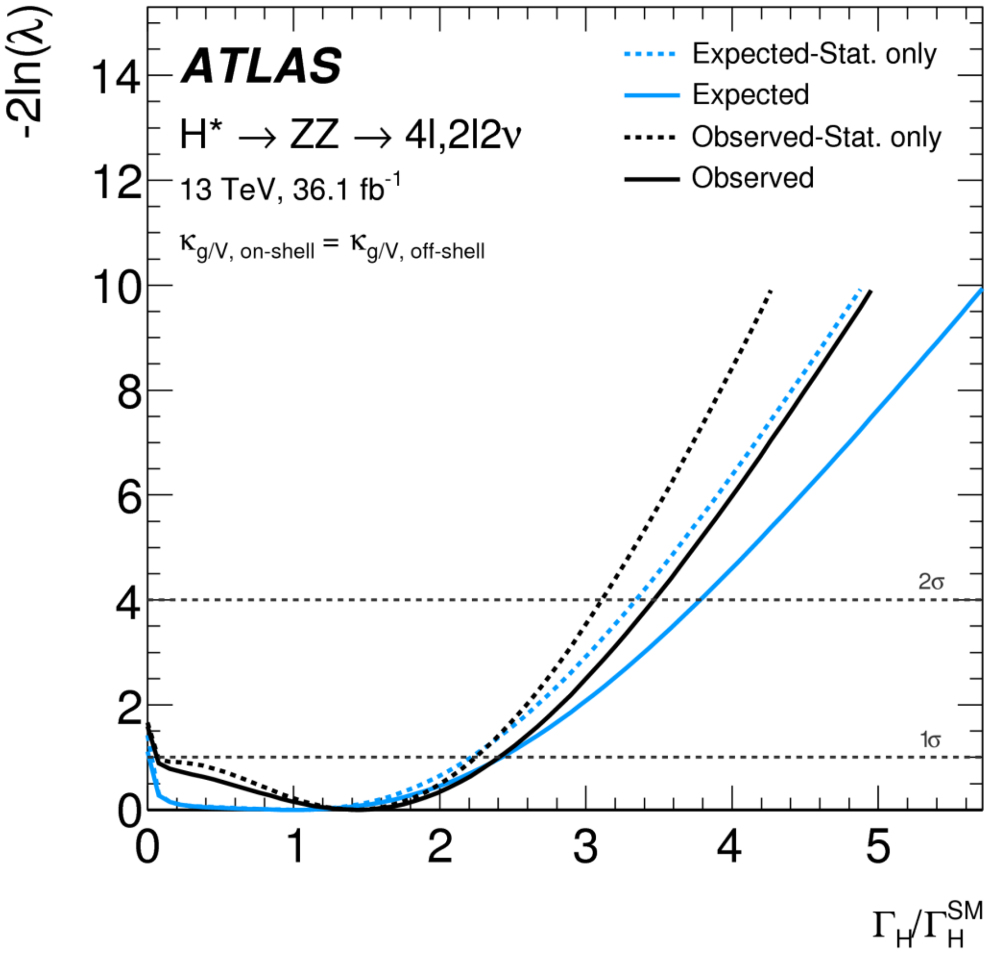


ATLAS Run 2 '16 $4\ell + 2\ell 2\nu$ [2]:
$\Gamma_{\mathrm{H}} < 14.4$ MeV @ 95% CL

Higgs boson width from off-shell



(see backup for more results)



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ATLAS Run 2 '16 $4\ell + 2\ell 2\nu$ [2]:
$\Gamma_\mathrm{H} < 14.4$ MeV @ 95% CL

Many exciting results from ATLAS and CMS to understand Higgs boson properties.

Excellent progress in exploiting kinematic information, more progress in the horizon.

No new physics yet, but great precision already being achieved.

Stay tuned for more exciting results as we enter the LHC Run 3 era!

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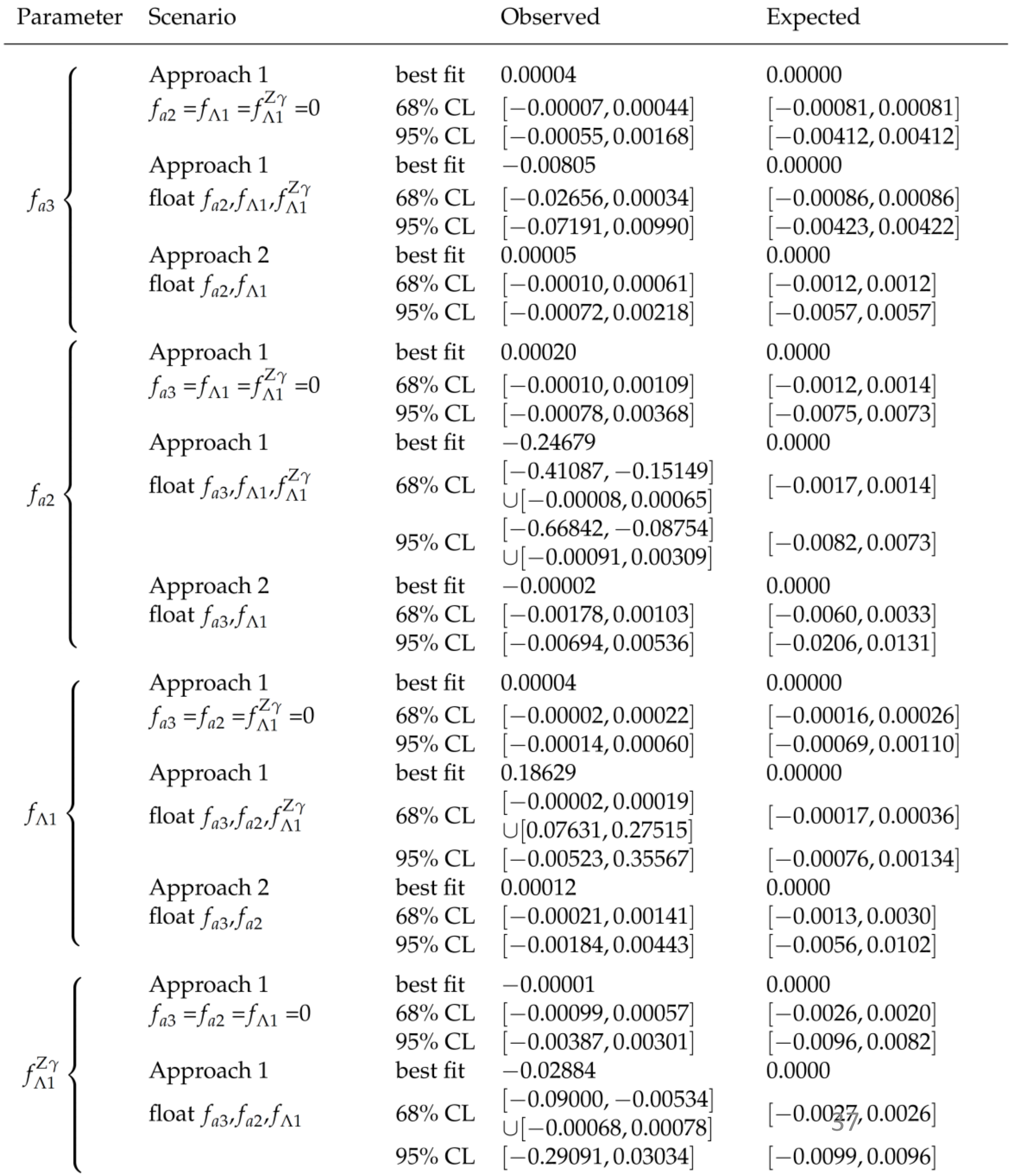
Back-up

Anomalous HVV couplings from on-shell 4ℓ



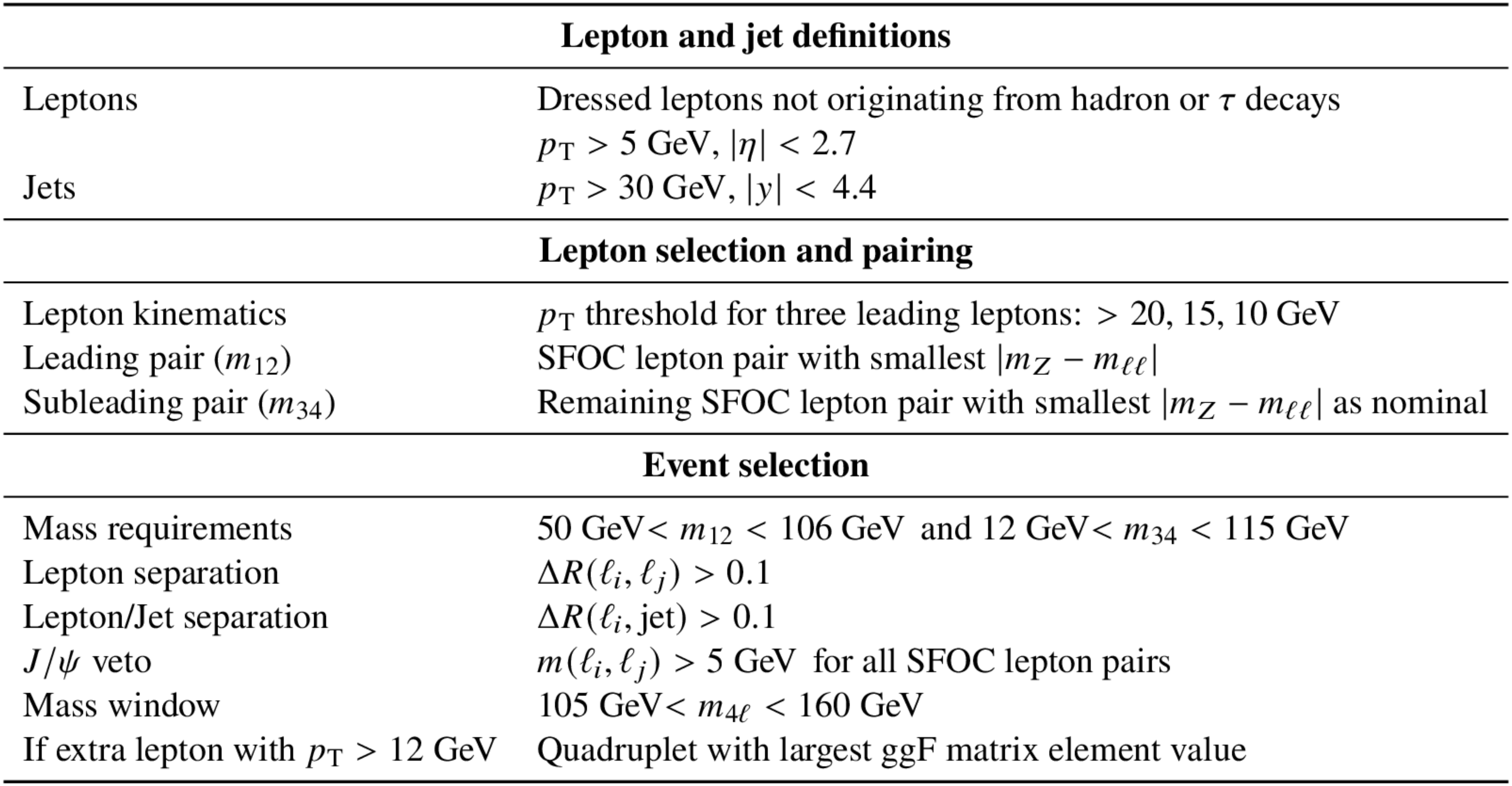
Parameter	Scenario		Observed	Expected
f_{a3}	Approach 1	best fit	0.00004	0.00000
	$f_{a2} = f_{\Lambda1} = f_{\Lambda1}^{Z\gamma} = 0$	68% CL	$[-0.00007, 0.00044]$	$[-0.00081, 0.00081]$
		95% CL	$[-0.00055, 0.00168]$	$[-0.00412, 0.00412]$
	Approach 1	best fit	-0.00805	0.00000
	float $f_{a2}, f_{\Lambda1}, f_{\Lambda1}^{Z\gamma}$	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 $f_{a2}, f_{\Lambda1}$	68% CL	$[-0.00010, 0.00061]$	$[-0.0012, 0.0012]$
		95% CL	$[-0.00072, 0.00218]$	$[-0.0057, 0.0057]$
f_{a2}	Approach 1	best fit	0.00020	0.0000
	$f_{a3} = f_{\Lambda1} = f_{\Lambda1}^{Z\gamma} = 0$	68% CL	$[-0.00010, 0.00109]$	$[-0.0012, 0.0014]$
		95% CL	$[-0.00078, 0.00368]$	$[-0.0075, 0.0073]$
	Approach 1	best fit	-0.24679	0.0000
	float $f_{a3}, f_{\Lambda1}, f_{\Lambda1}^{Z\gamma}$	68% CL	$[-0.41087, -0.15149]$ $\cup[-0.00008, 0.00065]$	$[-0.0017, 0.0014]$
		95% CL	$[-0.66842, -0.08754]$ $\cup[-0.00091, 0.00309]$	$[-0.0082, 0.0073]$
	Approach 2	best fit	-0.00002	0.0000
	float $f_{a3}, f_{\Lambda1}$	68% CL	$[-0.00178, 0.00103]$	$[-0.0060, 0.0033]$
		95% CL	$[-0.00694, 0.00536]$	$[-0.0206, 0.0131]$
$f_{\Lambda1}$	Approach 1	best fit	0.00004	0.00000
	$f_{a3} = f_{a2} = f_{\Lambda1}^{Z\gamma} = 0$	68% CL	$[-0.00002, 0.00022]$	$[-0.00016, 0.00026]$
		95% CL	$[-0.00014, 0.00060]$	$[-0.00069, 0.00110]$
	Approach 1	best fit	0.18629	0.00000
	float $f_{a3}, f_{a2}, f_{\Lambda1}^{Z\gamma}$	68% CL	$[-0.00002, 0.00019]$ $\cup[0.07631, 0.27515]$	$[-0.00017, 0.00036]$
		95% CL	$[-0.00523, 0.35567]$	$[-0.00076, 0.00134]$
	Approach 2	best fit	0.00012	0.0000
	float f_{a3}, f_{a2}	68% CL	$[-0.00021, 0.00141]$	$[-0.0013, 0.0030]$
		95% CL	$[-0.00184, 0.00443]$	$[-0.0056, 0.0102]$
$f_{\Lambda1}^{Z\gamma}$	Approach 1	best fit	-0.00001	0.0000
	$f_{a3} = f_{a2} = f_{\Lambda1} = 0$	68% CL	$[-0.00099, 0.00057]$	$[-0.0026, 0.0020]$
		95% CL	$[-0.00387, 0.00301]$	$[-0.0096, 0.0082]$
	Approach 1	best fit	-0.02884	0.0000
	float $f_{a3}, f_{a2}, f_{\Lambda1}$	68% CL	$[-0.09000, -0.00534]$ $\cup[-0.00068, 0.00078]$	$[-0.0027, 0.0026]$
		95% CL	$[-0.29091, 0.03034]$	$[-0.0099, 0.0096]$

→ Results from [1]

→ Approach 1 fixes or unconstrains couplings without assuming any relationship between each other.

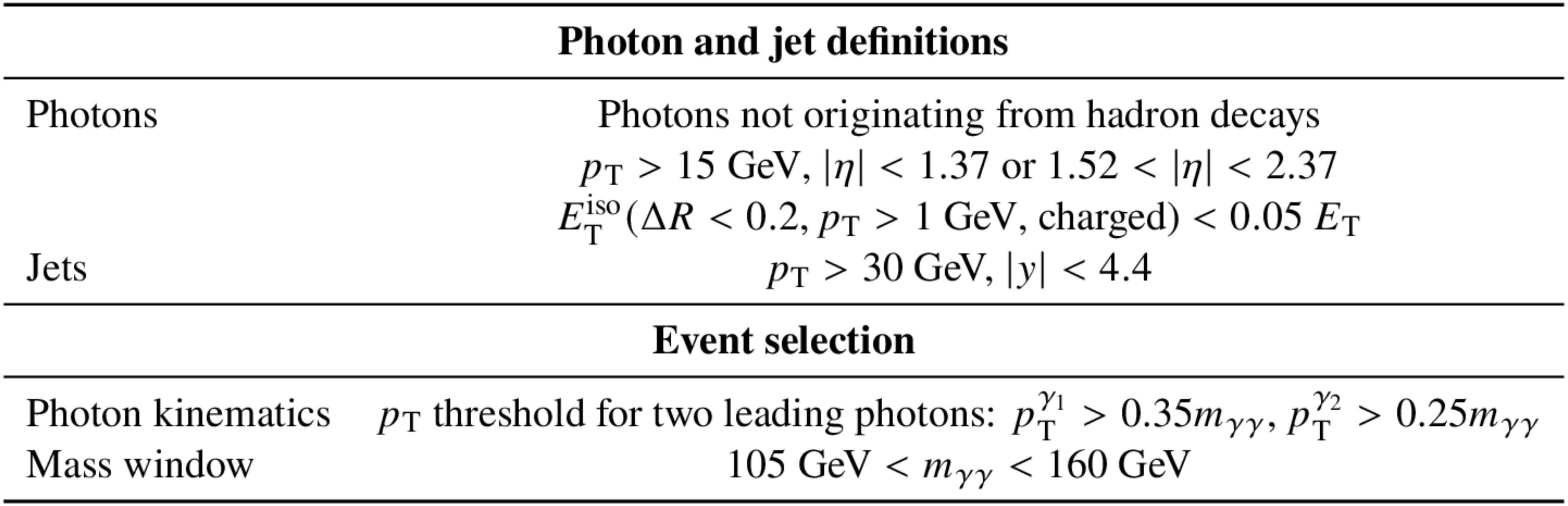
→ Approach 2 assumes Λ_1 and $\Lambda_1^{Z\gamma}$ couplings are determined by the combination of a_1 and a_2 couplings according to SMEFT relations.

Fiducial volume in ATLAS 4ℓ



Lepton and jet definitions	
Leptons	Dressed leptons not originating from hadron or τ decays $p_T > 5$ GeV, $\vert\eta\vert < 2.7$
Jets	$p_T > 30$ GeV, $\vert y\vert < 4.4$
Lepton selection and pairing	
Lepton kinematics	p_T threshold for three leading leptons: $> 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\vert m_Z - m_{\ell\ell}\vert$
Subleading pair (m_{34})	Remaining SFOC lepton pair with smallest $\vert m_Z - m_{\ell\ell}\vert$ as nominal
Event selection	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV$< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \text{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV$< m_{4\ell} <$ 160 GeV
If extra lepton with $p_T > 12$ GeV	Quadruplet with largest ggF matrix element value

Fiducial volume in ATLAS $\gamma\gamma$

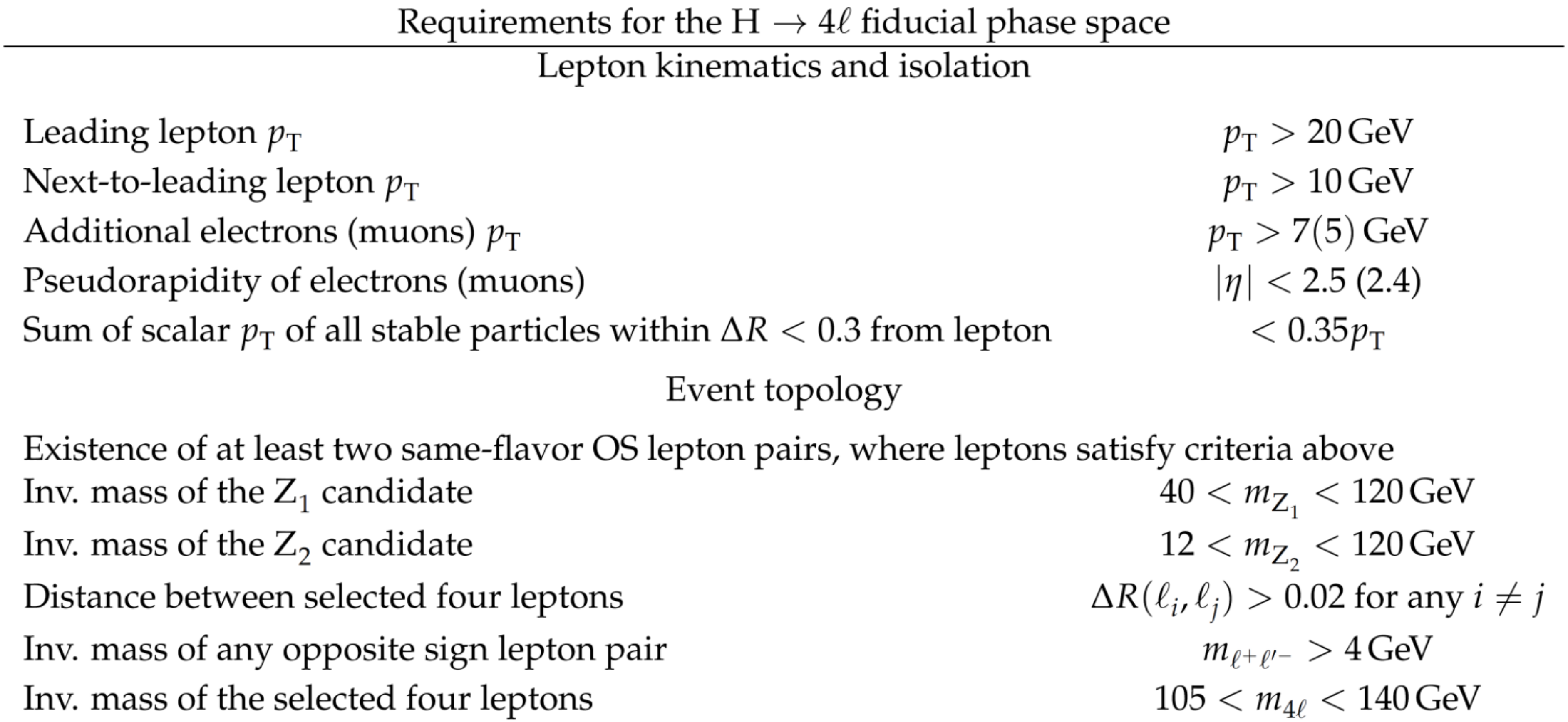


Photon and jet definitions	
Photons	Photons not originating from hadron decays $p_{\mathrm{T}} > 15$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$ $E_{\mathrm{T}}^{\mathrm{iso}}(\Delta R < 0.2, p_{\mathrm{T}} > 1$ GeV, charged$) < 0.05\ E_{\mathrm{T}}$
Jets	$p_{\mathrm{T}} > 30$ GeV, $\lvert y\rvert < 4.4$
Event selection	
Photon kinematics	p_{T} threshold for two leading photons: $p_{\mathrm{T}}^{\gamma_1} > 0.35 m_{\gamma\gamma}$, $p_{\mathrm{T}}^{\gamma_2} > 0.25 m_{\gamma\gamma}$
Mass window	105 GeV $< m_{\gamma\gamma} < 160$ GeV

Fiducial volume in ATLAS $b\bar{b}$

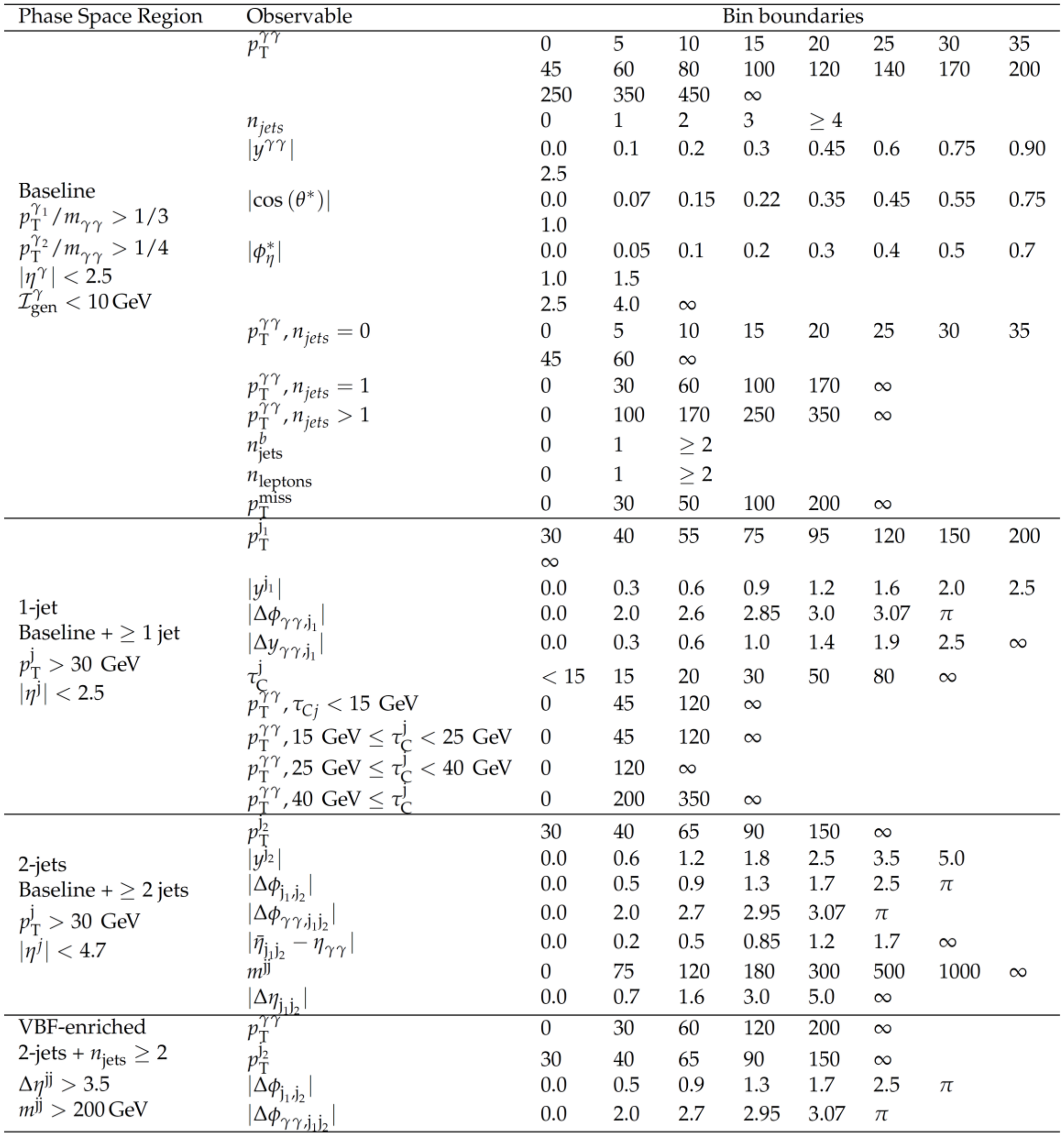
Selection	Detector-level	Particle-level
Leptons	No electrons or muons $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ Electrons Muons $\lvert\eta\rvert < 2.47$ $\lvert\eta\rvert < 2.7$ LooseLH Loose $\lvert d_0/\sigma_{d_0}\rvert < 5$ $\lvert d_0/\sigma_{d_0}\rvert < 3$ $\lvert z_0 \sin\theta\rvert < 0.5\,\mathrm{mm}$ $\lvert z_0 \sin\theta\rvert < 0.5\,\mathrm{mm}$ Loose track-isolation	No electrons or muons $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ Electrons Muons $\lvert\eta\rvert < 2.47$ $\lvert\eta\rvert < 2.7$
Hadronic τ	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$ $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.5$ Medium	τ-labelled central jets
Anti-k_t $R = 0.4$ Jets	From topological clusters ≥ 2 central jets Central Forward $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ $\lvert\eta\rvert < 2.5$ $2.5 < \lvert\eta\rvert < 4.5$	From collider-stable particles ≥ 2 central jets Central Forward $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ $\lvert\eta\rvert < 2.5$ $2.5 < \lvert\eta\rvert < 4.5$
b-jets	2 b-tagged central jets, MV2 (70% efficiency) At least one b-jet with $p_{\mathrm{T}} > 45\,\mathrm{GeV}$	2 b-labelled central jets At least one b-labelled jet with $p_{\mathrm{T}} > 45\,\mathrm{GeV}$
Jet categories	Two, with exactly 2 and 3 jets	One, with 2 or 3 jets
Overlap removal	Between e, μ, τ and jets	Remove e/μ within $\Delta R = 0.4$ of a jet, remove τ-labelled jets
$E_{\mathrm{T}}^{\mathrm{miss}}$	Negative vectorial sum of p_{T} of jets, leptons, taus and photons plus a track-based soft term $> 150\,\mathrm{GeV}$	Negative vectorial sum of p_{T} of all stable interacting particles with $\lvert\eta\rvert < 5$, including muons with $p_{\mathrm{T}} > 6\,\mathrm{GeV}$ $> 150\,\mathrm{GeV}$
H_{T}	$> 120\,\mathrm{GeV}$ (2 jets), $> 150\,\mathrm{GeV}$ (3 jets)	$> 120\,\mathrm{GeV}$ (2 jets), $> 150\,\mathrm{GeV}$ (3 jets)
$\min \Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{j})$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{b}_1 + \vec{b}_2)$	$> 120^\circ$	$> 120^\circ$
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$	$< 140^\circ$
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^\circ$	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ regions	$150\,\mathrm{GeV} \leq E_{\mathrm{T}}^{\mathrm{miss}} < 250\,\mathrm{GeV}$ $E_{\mathrm{T}}^{\mathrm{miss}} \geq 250\,\mathrm{GeV}$	$150\,\mathrm{GeV} \leq E_{\mathrm{T}}^{\mathrm{miss}} < 250\,\mathrm{GeV}$ $E_{\mathrm{T}}^{\mathrm{miss}} \geq 250\,\mathrm{GeV}$

Fiducial volume in CMS 4ℓ



Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20\,\mathrm{GeV}$
Next-to-leading lepton p_T	$p_T > 10\,\mathrm{GeV}$
Additional electrons (muons) p_T	$p_T > 7(5)\,\mathrm{GeV}$
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5\ (2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120\,\mathrm{GeV}$
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120\,\mathrm{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\mathrm{GeV}$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140\,\mathrm{GeV}$

Fiducial volume and obs. in CMS $\gamma\gamma$



Phase Space Region	Observable	Bin boundaries							
Baseline $p_{\mathrm{T}}^{\gamma_1}/m_{\gamma\gamma} > 1/3$ $p_{\mathrm{T}}^{\gamma_2}/m_{\gamma\gamma} > 1/4$ $\lvert\eta^{\gamma}\rvert < 2.5$ $\mathcal{I}_{\mathrm{gen}}^{\gamma} < 10\,\mathrm{GeV}$	$p_{\mathrm{T}}^{\gamma\gamma}$	0	5	10	15	20	25	30	35
		45	60	80	100	120	140	170	200
		250	350	450	∞				
	n_{jets}	0	1	2	3	≥ 4			
	$\lvert y^{\gamma\gamma}\rvert$	0.0	0.1	0.2	0.3	0.45	0.6	0.75	0.90
		2.5							
	$\lvert\cos(\theta^*)\rvert$	0.0	0.07	0.15	0.22	0.35	0.45	0.55	0.75
		1.0							
	$\lvert\phi_{\eta}^{*}\rvert$	0.0	0.05	0.1	0.2	0.3	0.4	0.5	0.7
		1.0	1.5						
		2.5	4.0	∞					
	$p_{\mathrm{T}}^{\gamma\gamma}, n_{jets} = 0$	0	5	10	15	20	25	30	35
		45	60	∞					
	$p_{\mathrm{T}}^{\gamma\gamma}, n_{jets} = 1$	0	30	60	100	170	∞		
	$p_{\mathrm{T}}^{\gamma\gamma}, n_{jets} > 1$	0	100	170	250	350	∞		
	n_{jets}^{b}	0	1	≥ 2					
	n_{leptons}	0	1	≥ 2					
	$p_{\mathrm{T}}^{\mathrm{miss}}$	0	30	50	100	200	∞		
1-jet Baseline + $\geq$ 1 jet $p_{\mathrm{T}}^{\mathrm{j}} > 30$ GeV $\lvert\eta^{\mathrm{j}}\rvert < 2.5$	$p_{\mathrm{T}}^{\mathrm{j}_1}$	30	40	55	75	95	120	150	200
		∞							
	$\lvert y^{\mathrm{j}_1}\rvert$	0.0	0.3	0.6	0.9	1.2	1.6	2.0	2.5
	$\lvert\Delta\phi_{\gamma\gamma,\mathrm{j}_1}\rvert$	0.0	2.0	2.6	2.85	3.0	3.07	π	
	$\lvert\Delta y_{\gamma\gamma,\mathrm{j}_1}\rvert$	0.0	0.3	0.6	1.0	1.4	1.9	2.5	∞
	$\tau_{\mathrm{C}}^{\mathrm{j}}$	< 15	15	20	30	50	80	∞	
	$p_{\mathrm{T}}^{\gamma\gamma}, \tau_{Cj} < 15$ GeV	0	45	120	∞				
	$p_{\mathrm{T}}^{\gamma\gamma}$, 15 GeV $\leq \tau_{\mathrm{C}}^{\mathrm{j}} <$ 25 GeV	0	45	120	∞				
	$p_{\mathrm{T}}^{\gamma\gamma}$, 25 GeV $\leq \tau_{\mathrm{C}}^{\mathrm{j}} <$ 40 GeV	0	120	∞					
	$p_{\mathrm{T}}^{\gamma\gamma}$, 40 GeV $\leq \tau_{\mathrm{C}}^{\mathrm{j}}$	0	200	350	∞				
2-jets Baseline + $\geq$ 2 jets $p_{\mathrm{T}}^{\mathrm{j}} > 30$ GeV $\lvert\eta^{j}\rvert < 4.7$	$p_{\mathrm{T}}^{\mathrm{j}_2}$	30	40	65	90	150	∞		
	$\lvert y^{\mathrm{j}_2}\rvert$	0.0	0.6	1.2	1.8	2.5	3.5	5.0	
	$\lvert\Delta\phi_{\mathrm{j}_1,\mathrm{j}_2}\rvert$	0.0	0.5	0.9	1.3	1.7	2.5	π	
	$\lvert\Delta\phi_{\gamma\gamma,\mathrm{j}_1\mathrm{j}_2}\rvert$	0.0	2.0	2.7	2.95	3.07	π		
	$\lvert\bar{\eta}_{\mathrm{j}_1\mathrm{j}_2} - \eta_{\gamma\gamma}\rvert$	0.0	0.2	0.5	0.85	1.2	1.7	∞	
	m^{jj}	0	75	120	180	300	500	1000	∞
	$\lvert\Delta\eta_{\mathrm{j}_1,\mathrm{j}_2}\rvert$	0.0	0.7	1.6	3.0	5.0	∞		
VBF-enriched 2-jets + $n_{\mathrm{jets}} \geq 2$ $\Delta\eta^{\mathrm{jj}} > 3.5$ $m^{\mathrm{jj}} > 200\,\mathrm{GeV}$	$p_{\mathrm{T}}^{\gamma\gamma}$	0	30	60	120	200	∞		
	$p_{\mathrm{T}}^{\mathrm{j}_2}$	30	40	65	90	150	∞		
	$\lvert\Delta\phi_{\mathrm{j}_1,\mathrm{j}_2}\rvert$	0.0	0.5	0.9	1.3	1.7	2.5	π	
	$\lvert\Delta\phi_{\gamma\gamma,\mathrm{j}_1\mathrm{j}_2}\rvert$	0.0	2.0	2.7	2.95	3.07	π		

Fiducial volume and obs. in CMS WW

Observable	Condition
Lepton origin	Direct decay of $\mathrm{H} \to \mathrm{W}^{+}\mathrm{W}^{-}$
Lepton flavors; lepton charge	eμ(not from τdecay); opposite
Leading lepton p_{T}	$p_{\mathrm{T}}^{l_1} > 25\,\mathrm{GeV}$
Trailing lepton p_{T}	$p_{\mathrm{T}}^{l_2} > 13\,\mathrm{GeV}$
$\lvert\eta\rvert$ of leptons	$\lvert\eta\rvert < 2.5$
Dilepton mass	$m^{ll} > 12\,\mathrm{GeV}$
p_{T} of the dilepton system	$p_{\mathrm{T}}^{ll} > 30\,\mathrm{GeV}$
Transverse mass using trailing lepton	$m_{\mathrm{T}}^{l_2} > 30\,\mathrm{GeV}$
Higgs boson transverse mass	$m_{\mathrm{T}}^{\mathrm{H}} > 60\,\mathrm{GeV}$

Jet counting: All jets clustered with the anti-k_{T} algo. with $p_{\mathrm{T}} > 30$ GeV

Fiducial volume in CMS $\tau\tau$

Fiducial region definition:

→ Leptons include FSR within $\Delta R < 0.1$

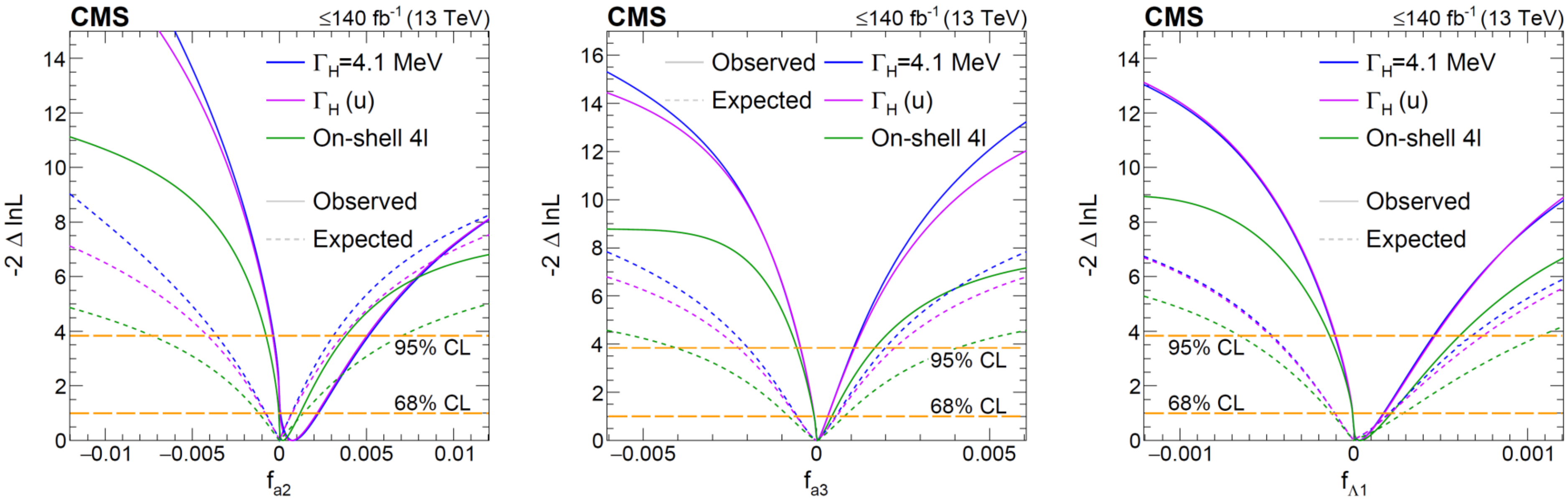
→ $\mu\tau_h$: $p_T^{\mu} > 20$ GeV, $|\eta^{\mu}| < 2.1$, $p_T^{\tau_h} > 30$ GeV, $|\eta^{\tau_h}| < 2.3$, $m_T^{\ell} < 50$ GeV

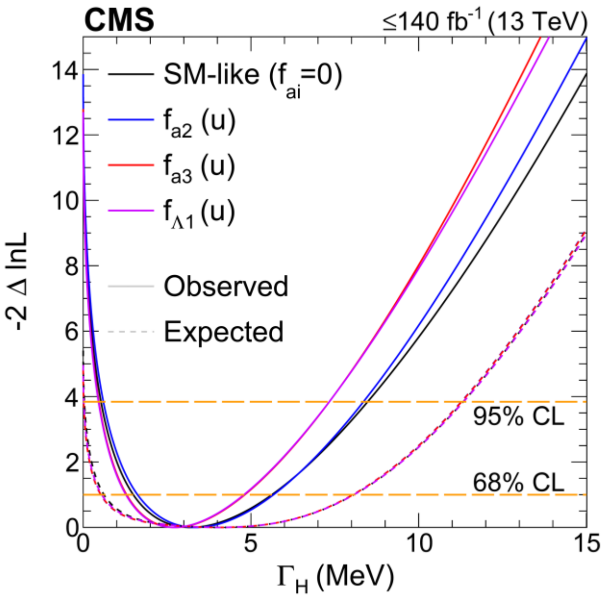
→ $e\tau_h$: $p_T^{e} > 25$ GeV, $|\eta^{\mu}| < 2.1$, $p_T^{\tau_h} > 30$ GeV, $|\eta^{\tau_h}| < 2.3$, $m_T^{\ell} < 50$ GeV

→ $e\mu$: $p_T^{\ell_1\,(\ell_2)} > 24\ (15)$ GeV, $\left|\eta^{\ell}\right| < 2.4$, $\mathrm{m}_T^{\ell\ell} < 60$ GeV, $p_T^{miss} < 60$ GeV

→ $\tau_h\tau_h$: $p_T^{\tau_h} > 40$ GeV, $|\eta^{\tau_h}| < 2.1$, should have at least one jet with $p_T > 30$ GeV

Anomalous spin-0 HVV couplings & off-shell

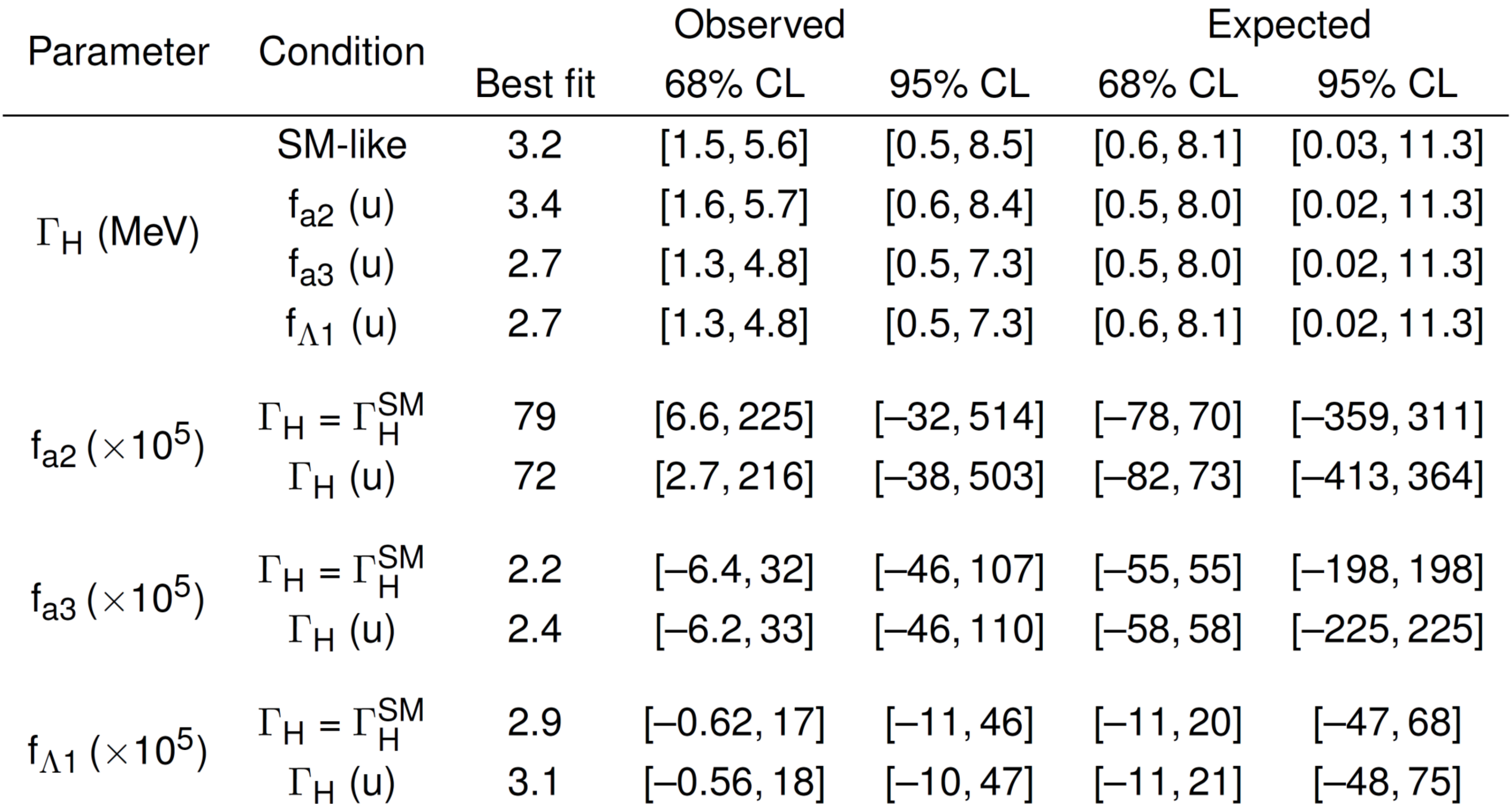




→ Measurement [1] relatively stable if anomalous HVV couplings considered

→ Can use off-shell to further constrain these couplings

Anomalous spin-0 HVV couplings & off-shell



Parameter	Condition		Observed		Expected	
		Best fit	68% CL	95% CL	68% CL	95% CL
Γ_H (MeV)	SM-like	3.2	[1.5, 5.6]	[0.5, 8.5]	[0.6, 8.1]	[0.03, 11.3]
	f_{a2} (u)	3.4	[1.6, 5.7]	[0.6, 8.4]	[0.5, 8.0]	[0.02, 11.3]
	f_{a3} (u)	2.7	[1.3, 4.8]	[0.5, 7.3]	[0.5, 8.0]	[0.02, 11.3]
	$f_{\Lambda 1}$ (u)	2.7	[1.3, 4.8]	[0.5, 7.3]	[0.6, 8.1]	[0.02, 11.3]
f_{a2} ($\times 10^5$)	$\Gamma_H = \Gamma_H^{SM}$	79	[6.6, 225]	[−32, 514]	[−78, 70]	[−359, 311]
	Γ_H (u)	72	[2.7, 216]	[−38, 503]	[−82, 73]	[−413, 364]
f_{a3} ($\times 10^5$)	$\Gamma_H = \Gamma_H^{SM}$	2.2	[−6.4, 32]	[−46, 107]	[−55, 55]	[−198, 198]
	Γ_H (u)	2.4	[−6.2, 33]	[−46, 110]	[−58, 58]	[−225, 225]
$f_{\Lambda 1}$ ($\times 10^5$)	$\Gamma_H = \Gamma_H^{SM}$	2.9	[−0.62, 17]	[−11, 46]	[−11, 20]	[−47, 68]
	Γ_H (u)	3.1	[−0.56, 18]	[−10, 47]	[−11, 21]	[−48, 75]

Width and anomalous HVV coupling constraints using off-shell information [1]