CMS Higgs boson measurements: Highlights and prospects

Ulaşcan Sarıca
Univ. of California, Santa Barbara

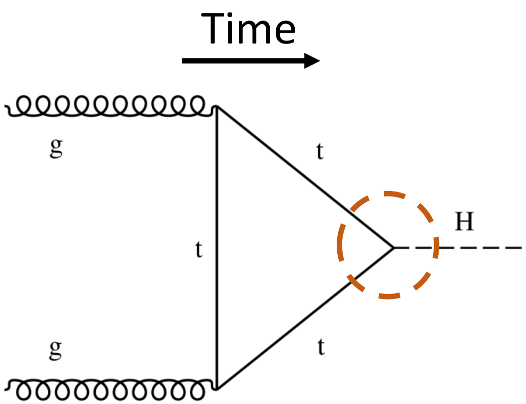
SLAC LCWS '23
May 16, 2023

Progress over a decade in measuring...

- Mass
- Spin/parity
- Couplings to particles
- Lifetime or width
- Self-couplings

...of the Higgs boson

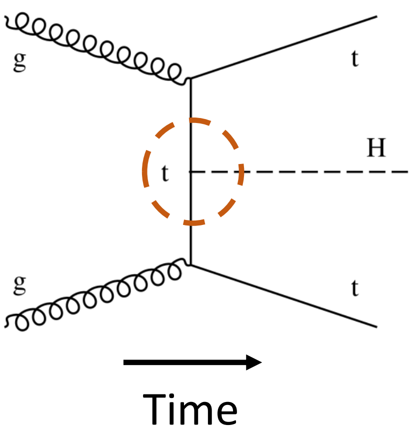
Common ways to produce a SM Higgs in pp collisions

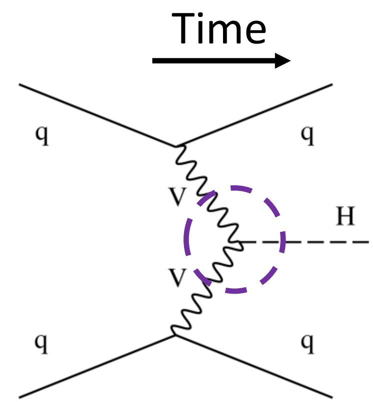


$gg \rightarrow H$ (87%)

Can probe fermionic couplings of the Higgs e.g., Htt, Hbb

$t\bar{t}H$ (1%)

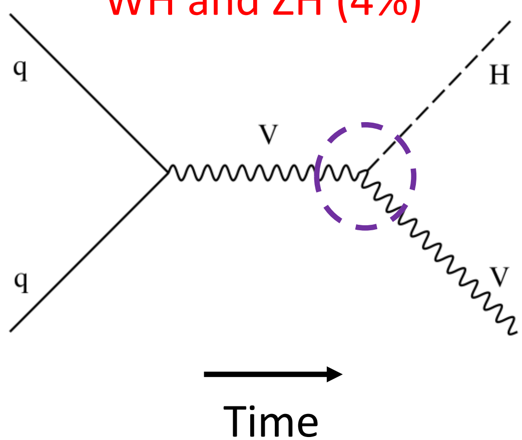




Can probe bosonic couplings of the Higgs e.g., HZZ, HWW

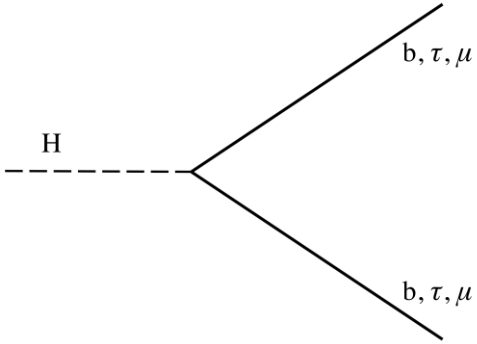
[Weak] Vector boson fusion (VBF) (7%)

WH and ZH (4%)

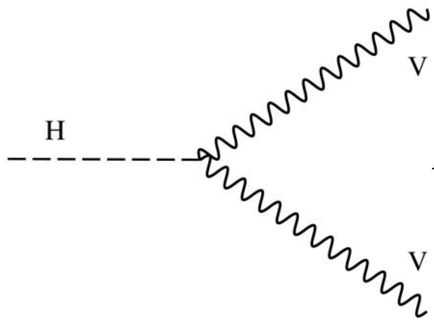


SM Higgs decays

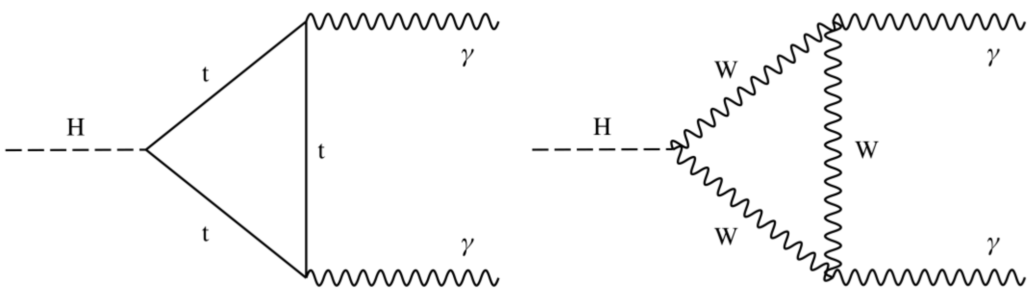
Time



$H \rightarrow$ fermions (primarily heavier quarks and leptons)



$H \rightarrow ZZ$ or WW



$H \rightarrow \gamma\gamma$

By far most dominant decay mode is $H \rightarrow b\bar{b}$ (58.2%)

→ Other $H \rightarrow$ fermions scale $\propto m_f^2$

→ Can also measure decay to $\tau\tau$ (6.3%) and $\mu\mu$ (0.02%)

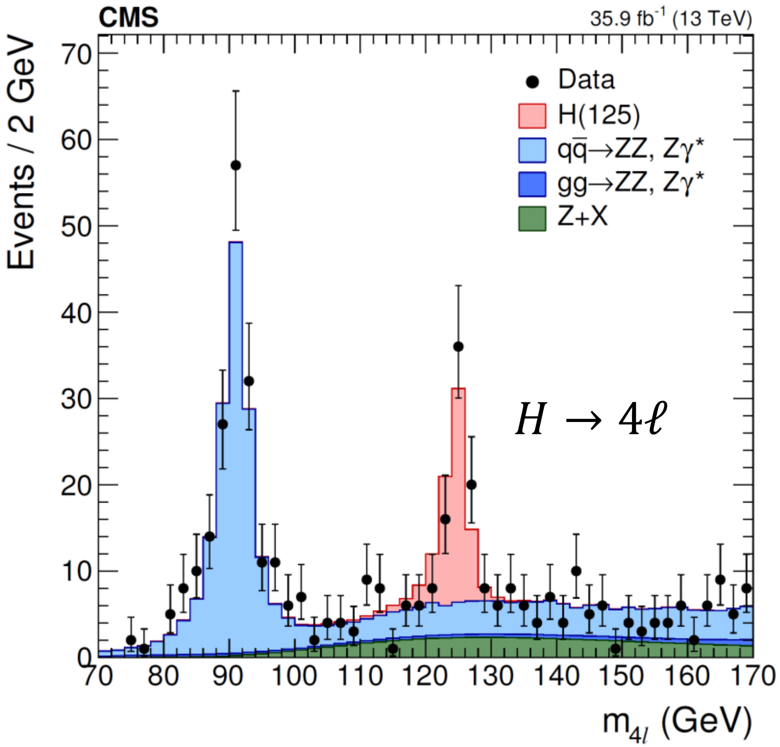
Cleanest decay modes are ZZ (2.6%), $\gamma\gamma$ (0.23%), and WW (21.4%).

Best mass resolution from $\gamma\gamma$ and ZZ.

What do we know about Higgs properties @ CMS today?

Mass & spin

Mass

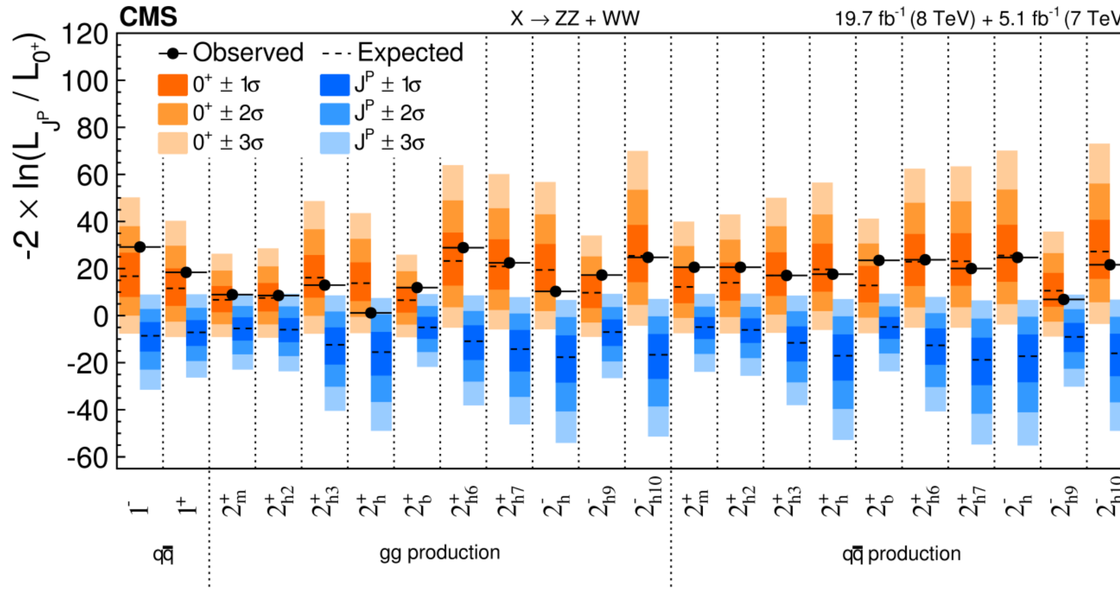


Measure from resonance line shape:
→ 1-2% resolution in 4ℓ and $\gamma\gamma$ decays

$4\ell + \gamma\gamma$ Run 1 + Run 2 2016 data [link]:

$$m_H = 125.38 \pm 0.14 \text{ GeV}$$

Spin



Extensive list of tests of spin-1 and -2 hypotheses using ZZ, WW and $\gamma\gamma$ decays [link]
→ Exploit angular correlations

The Higgs boson is consistent with spin 0.
→ Looser constraints on different spin-0 hypotheses
→ **Spin-1** excluded at >99.999% CL
→ **Spin-2** excluded at >99% CL (99.87% for min. graviton)

Anomalous spin-0 couplings: HVV

$$A(HVV) \sim \left[\boldsymbol{a_1} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2 + q_{V2}^2)}{\Lambda_1^2} - e^{i\phi_{\Lambda 1}^{Z\gamma}} \frac{q_\gamma^2}{\left(\Lambda_1^{Z\gamma}\right)^2} \cdots \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$
$$+ |a_2|\, e^{i\phi_{a2}}\, f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + |a_3|\, e^{i\phi_{a3}}\, f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

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

$H \to ZZ + H \to \tau\tau$ measurements using Run 2 data [link]

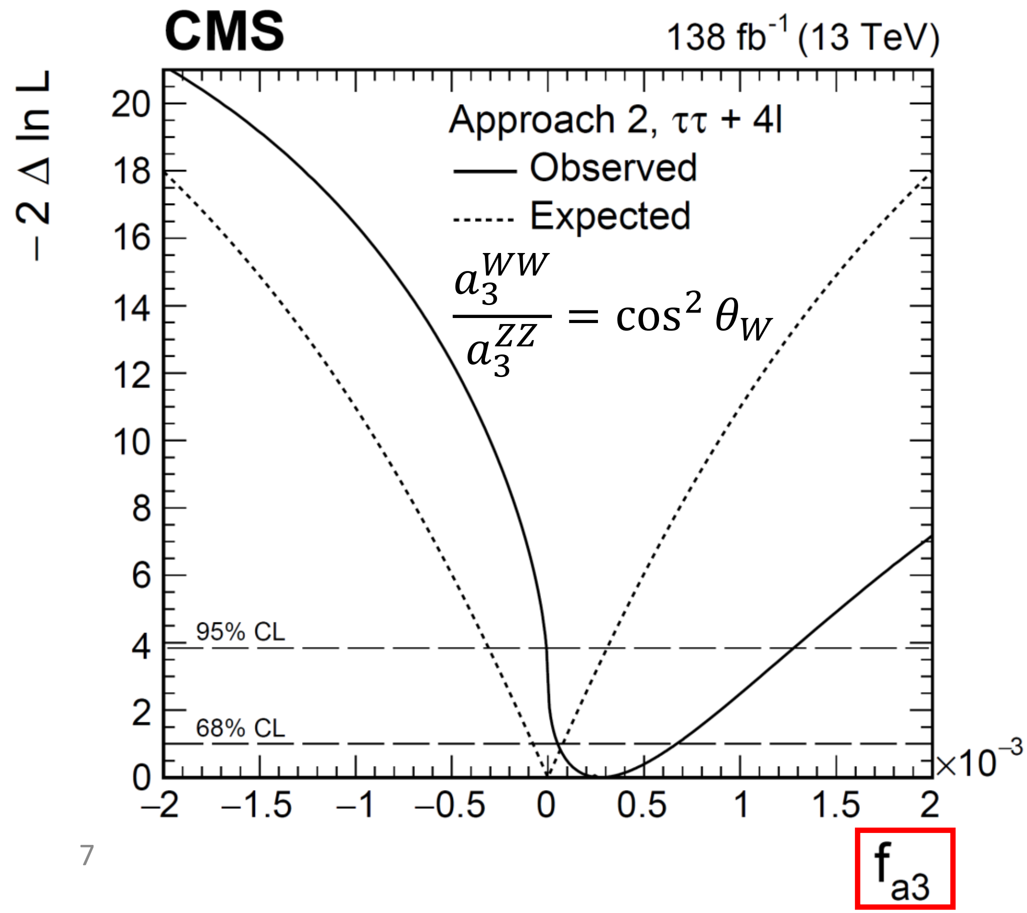
Results in terms of fractional xsec

$$f_{ai} = |a_i|^2\sigma_i / (|a_1|^2\sigma_1 + |a_i|^2\sigma_i)$$

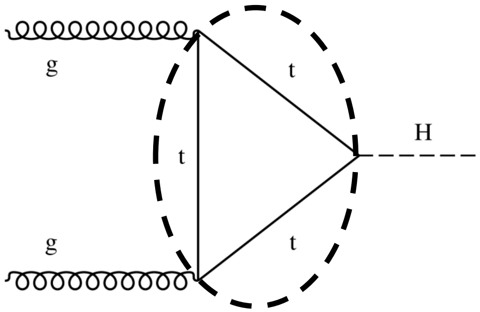
with $\phi_{ai} = 0$ or π.

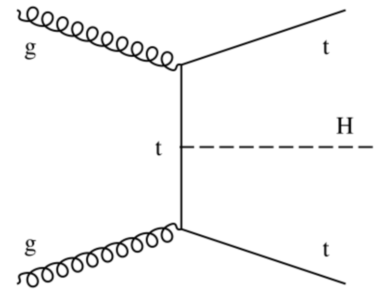
→ Make use of HVV vertices in both Higgs decay and production

→ HZZ channel results [link] alone also provide constraints with other BSM couplings profiled



Anomalous spin-0 couplings: Hgg/Htt





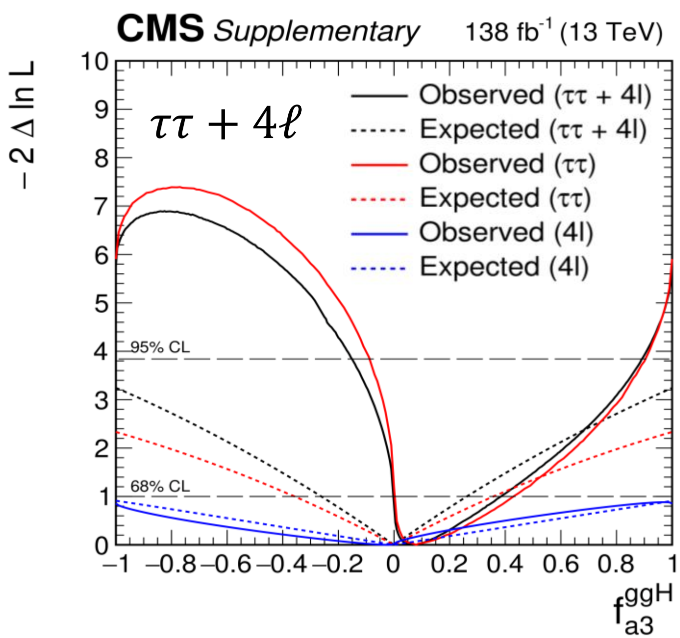
$$A(Hgg) \sim a_2^{gg} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{gg} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Can apply EFT treatment in $gg \rightarrow H$ when $m_H < 2m_t$

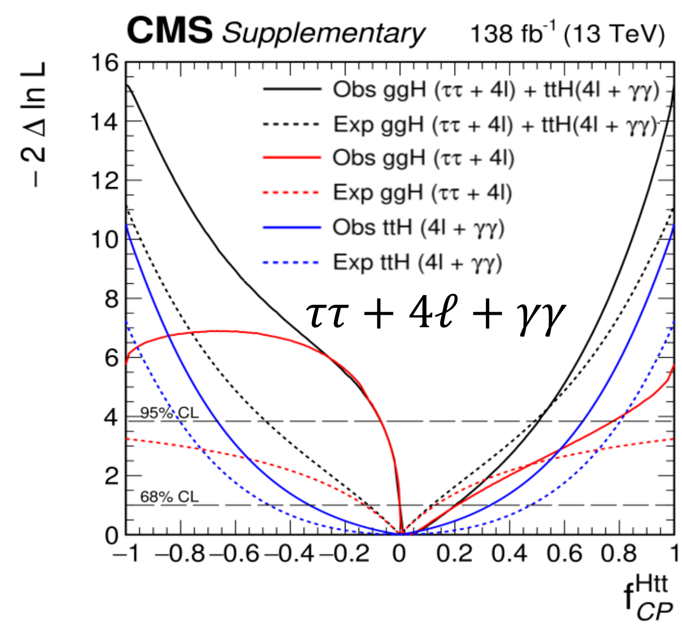
→ Can be translated to Htt couplings

$$A(Htt) = -\frac{m_t}{v} \bar{\psi}_t (\boldsymbol{\kappa_t} + i\boldsymbol{\tilde{\kappa}_t}\gamma_5)\psi_t$$

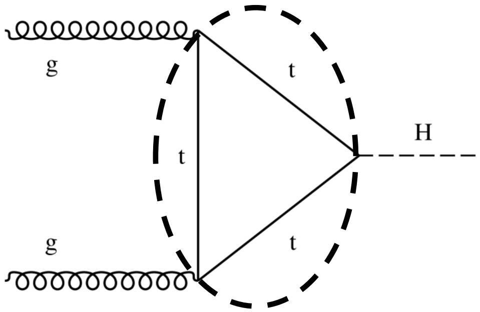
With discovery of $t\bar{t}H$ associated production [link], one can probe Htt couplings directly

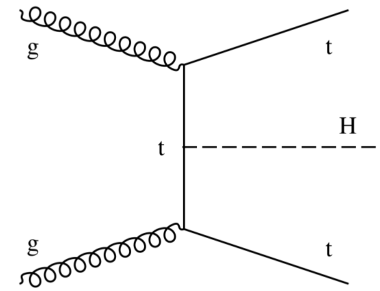


Link



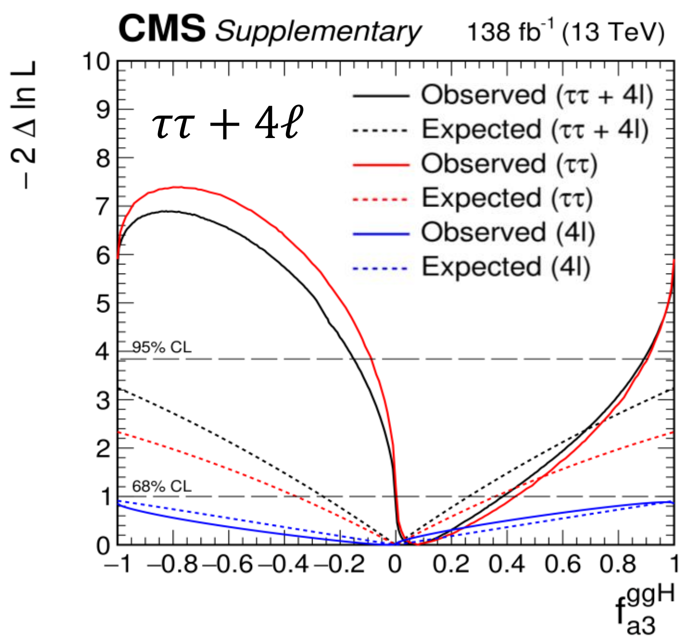
Anomalous spin-0 couplings: Hgg/Htt





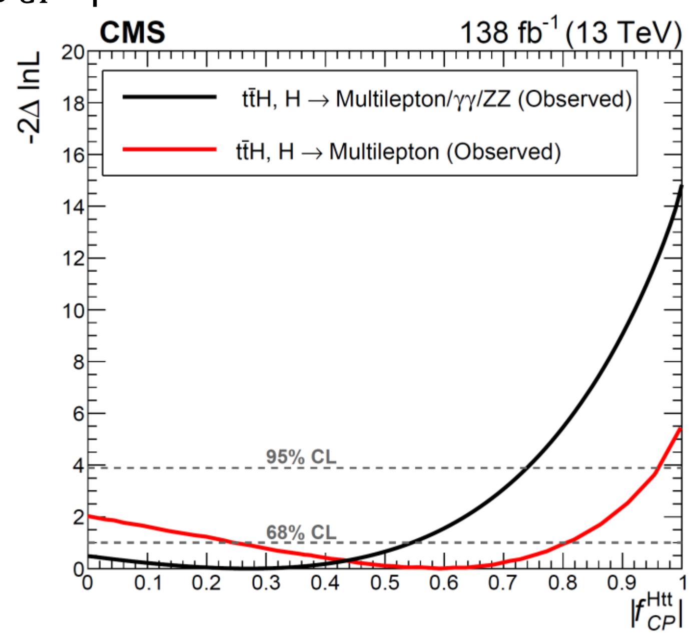
$$A(Hgg) \sim a_2^{gg} \mathrm{f}_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{gg} \mathrm{f}_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Can apply EFT treatment in $gg \to H$ when $m_H < 2m_t$
→ Can be translated to Htt couplings



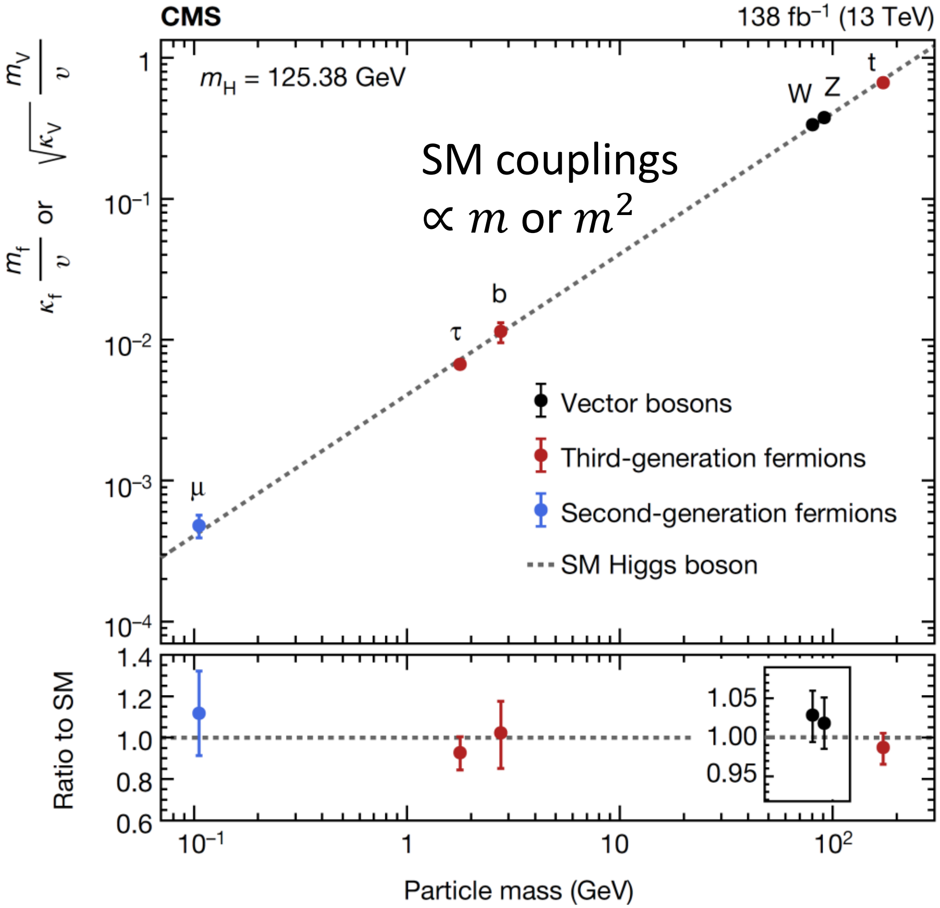
$$A(Htt) = -\frac{m_t}{v} \bar{\psi}_t (\boldsymbol{\kappa_t} + i\boldsymbol{\tilde{\kappa}_t}\gamma_5)\psi_t$$

See also multilepton $t\bar{t}H + tH$ combination [link] with 4ℓ and $\gamma\gamma$: $|f_{CP}^{Htt}| < 0.73$ @ 95% CL

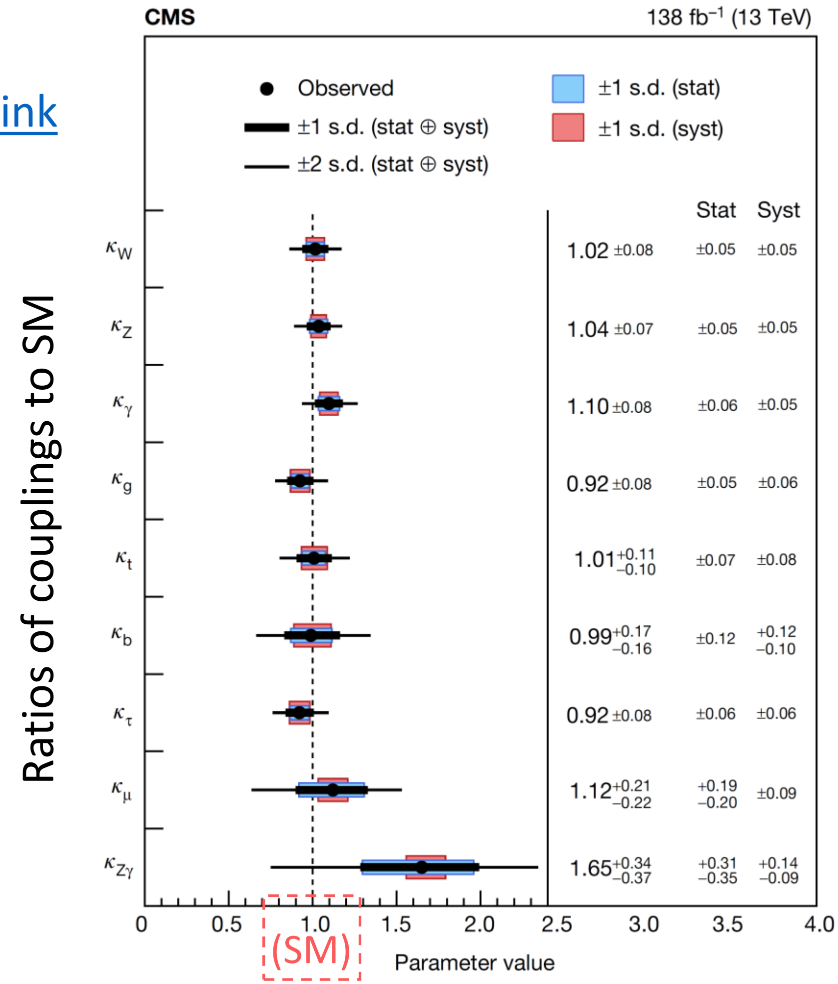


Higgs couplings to other particles

Measurements performed using a combination of multiple Higgs decays



Link



Couplings can be represented in different ways

→ O(**10%**) precision in most

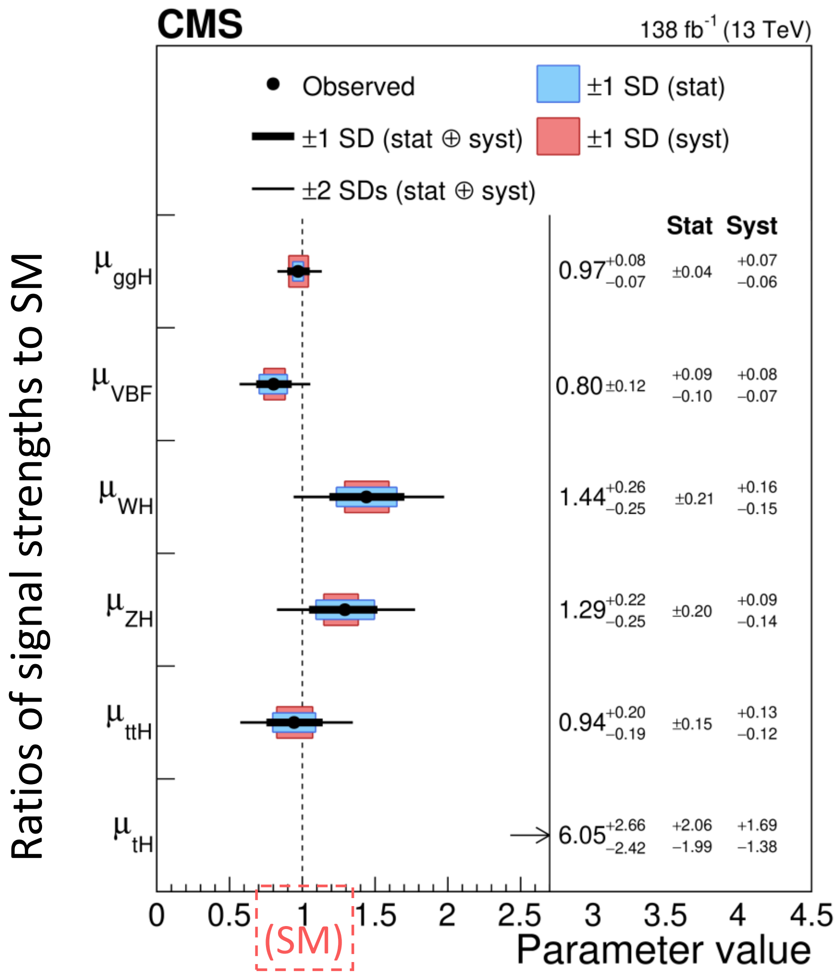
→ Also notable from $\boldsymbol{VH, H \to c\bar{c}}$ analysis (link):

$$1.1 < |\kappa_c| < 5.5 \text{ @ 95\% CL}$$

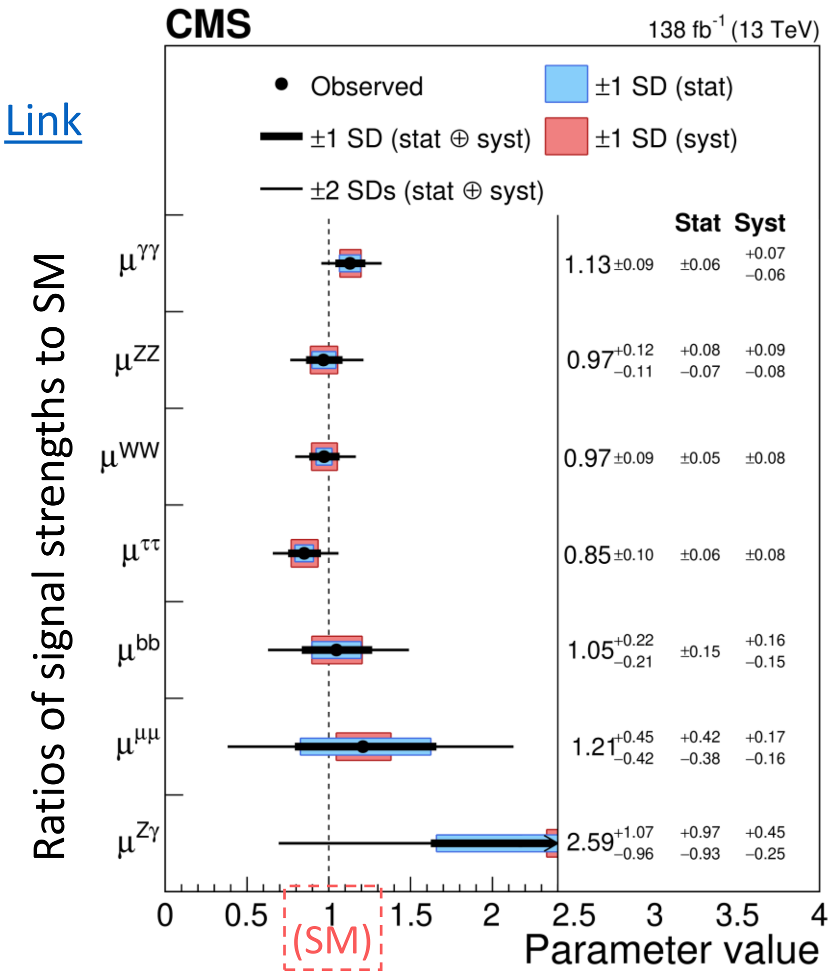
Limitations still statistical

→ Uncertainties $\sim 1/\sqrt{N}$.

Constraints on production and visible decays



[Link]



→ Measurements so far consistent with the SM

→ **Gluon fusion** within ∼**5%**, **VBF** within ∼**10%**

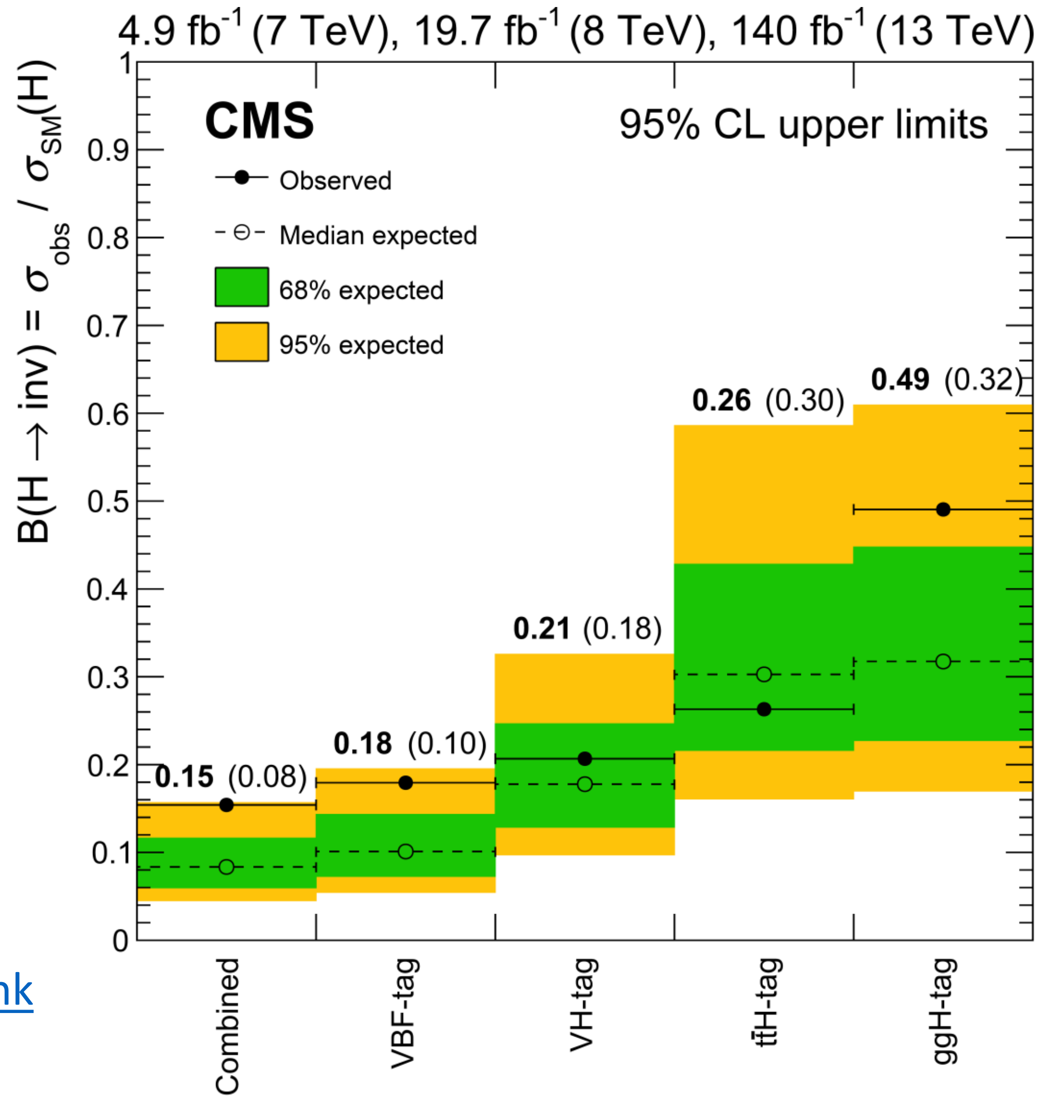
→ Consistent excess in tH, but large uncertainty due to small xsec and $t\bar{t}H$ contamination

→ Precision in $\boldsymbol{ZZ}, \boldsymbol{WW}, \boldsymbol{\gamma\gamma}$, and $\boldsymbol{\tau\tau}$ decays ∼**10%**

$H \rightarrow$ invisible limits

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

Combination with other analyses:
$\mathcal{B}_{inv} < 0.15$ @ 95% CL

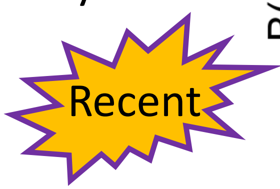


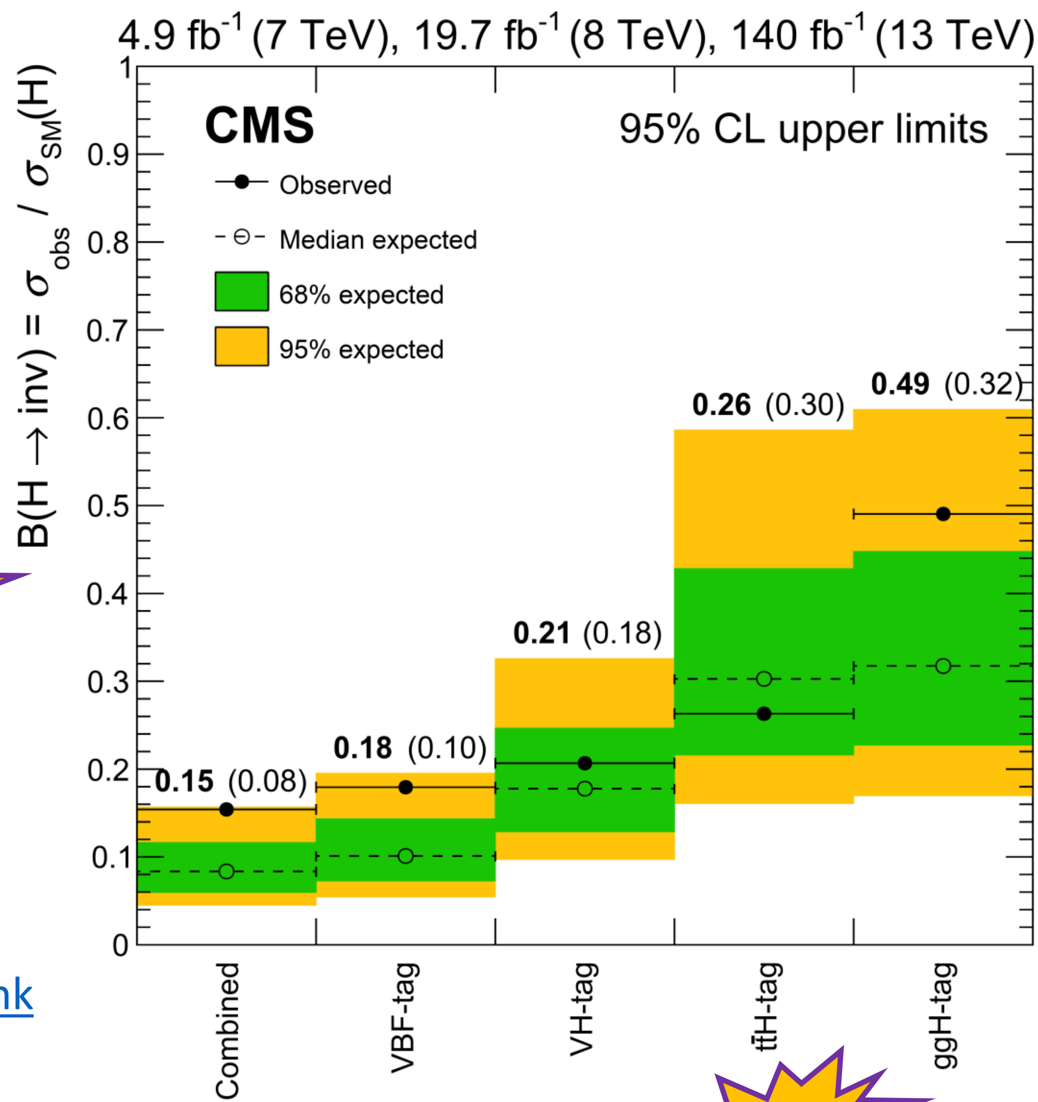
Link

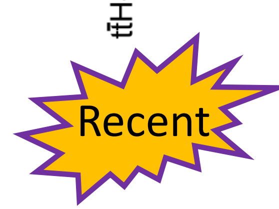
$H \rightarrow$ invisible limits

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

Combination with other analyses:
$\mathcal{B}_{inv} < 0.15$ @ 95% CL

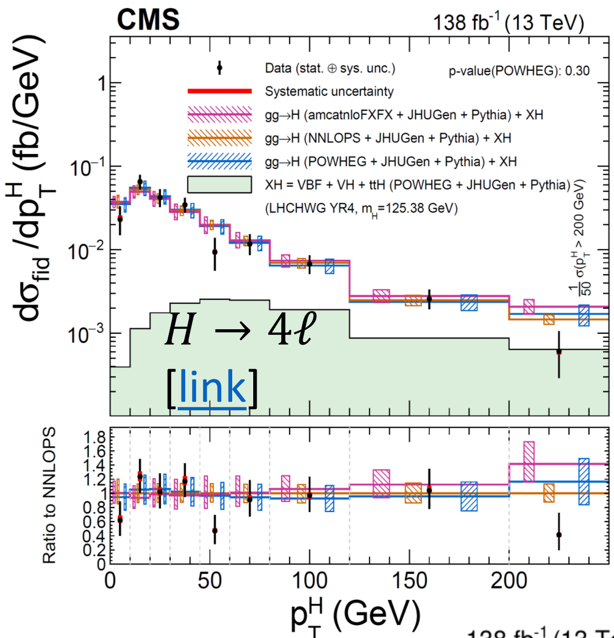






Link

Beyond couplings: Fiducial differential xsecs

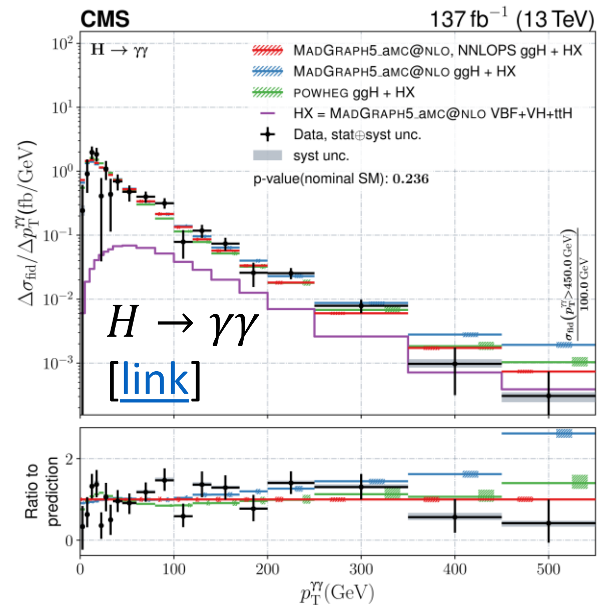


Can measure total Higgs xsec in bins of p_T^H, y_H or other variables within a fiducial selection volume

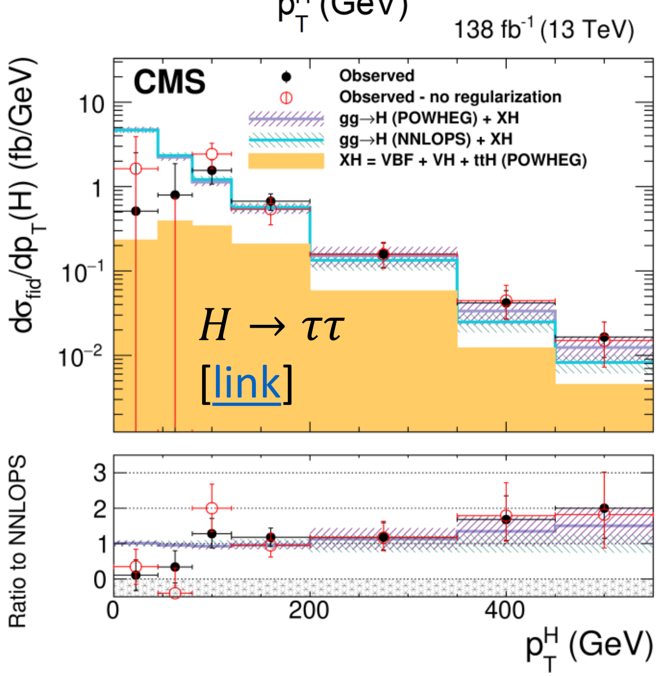
→ Examples for p_T^H

→ More observables in the linked references

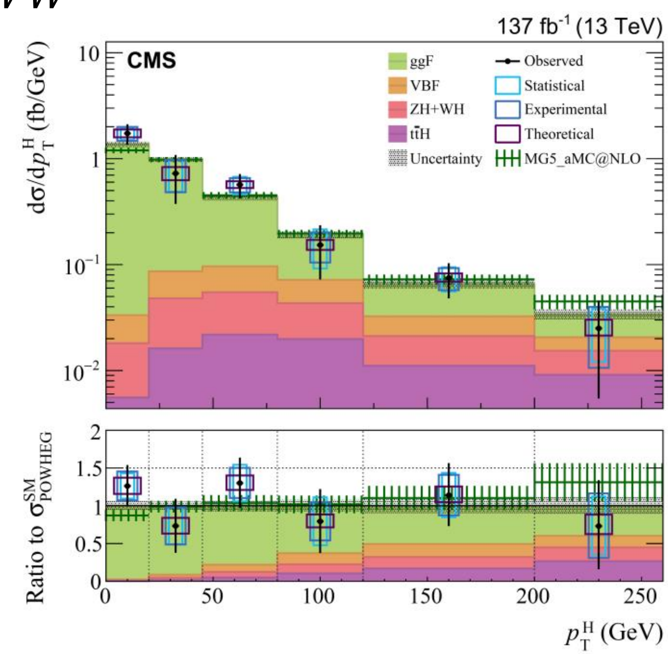
→ See also backup for simplified template xsec results



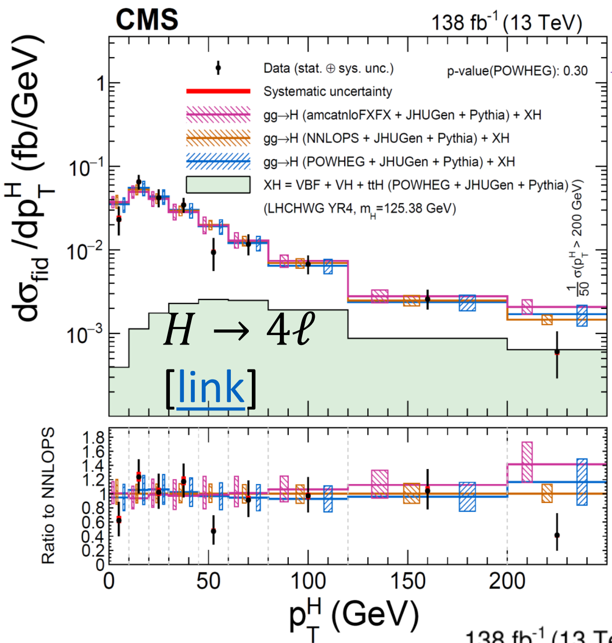
$H \to WW$
[link]



Data consistent with SM simulation so far



Beyond couplings: Fiducial differential xsecs



$H \rightarrow 4\ell$

[link]

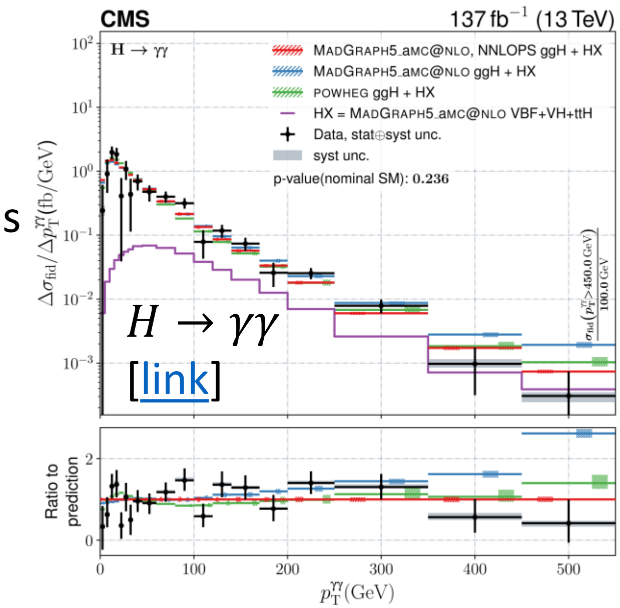
Recent

Can measure total Higgs xsec in bins of p_T^H, y_H or other variables within a fiducial selection volume

→ Examples for p_T^H

→ More observables in the linked references

→ See also backup for simplified template xsec results

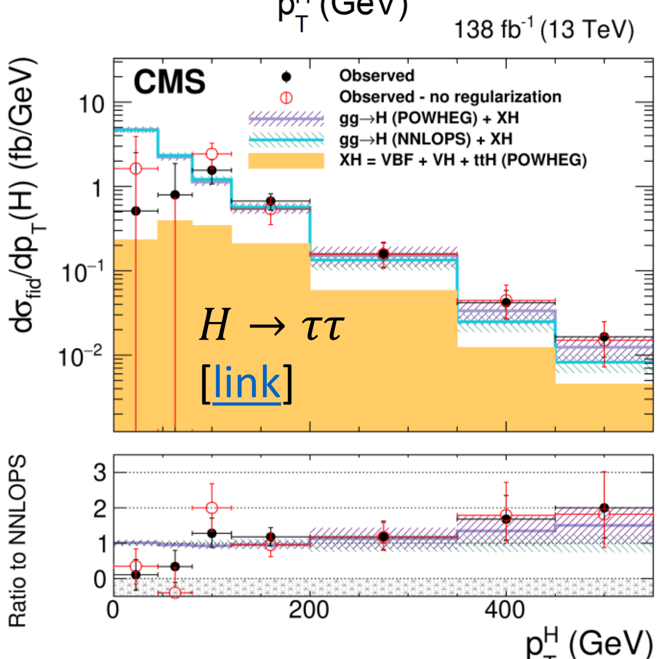


$H \rightarrow \gamma\gamma$

[link]

$H \rightarrow WW$

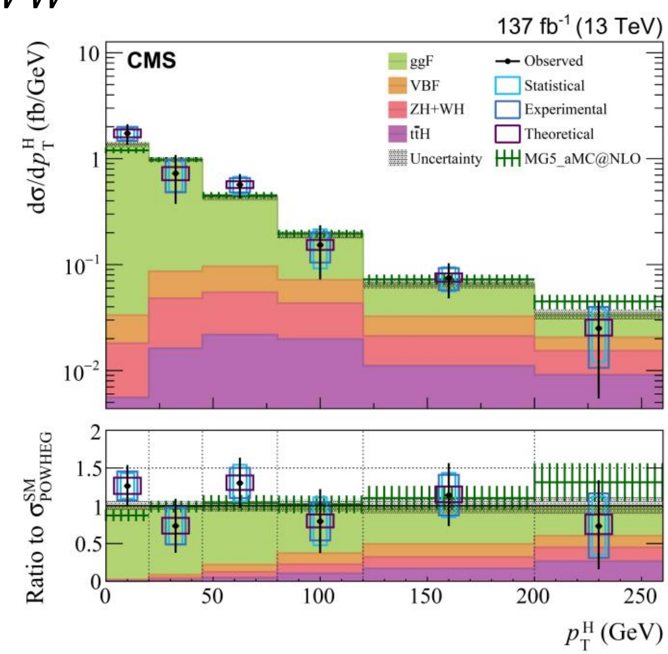
[link]



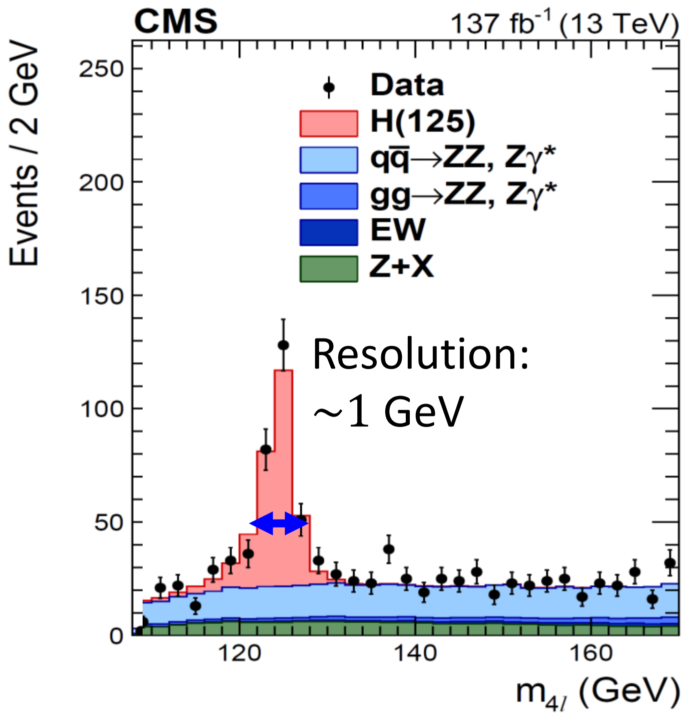
$H \rightarrow \tau\tau$

[link]

Data consistent with SM simulation so far

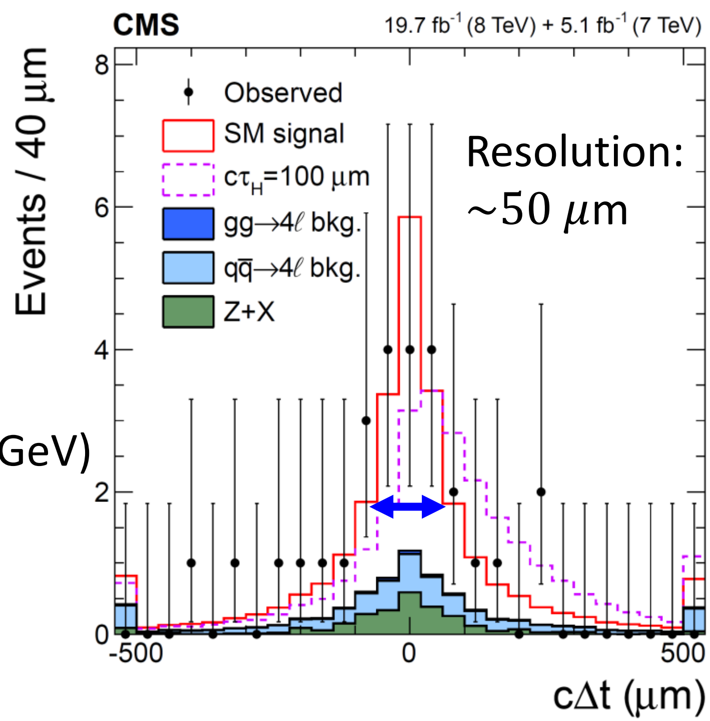


Higgs boson width/lifetime



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

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



SM $\Gamma_H = 0.0041$ GeV, $c\tau_H = 4.8 \times 10^{-8}\ \mu m$
→ Mass resolution: ~1 GeV
→ 4ℓ vertex resolution: ~ 50 μm

Γ_H and τ_H too small to be measured directly

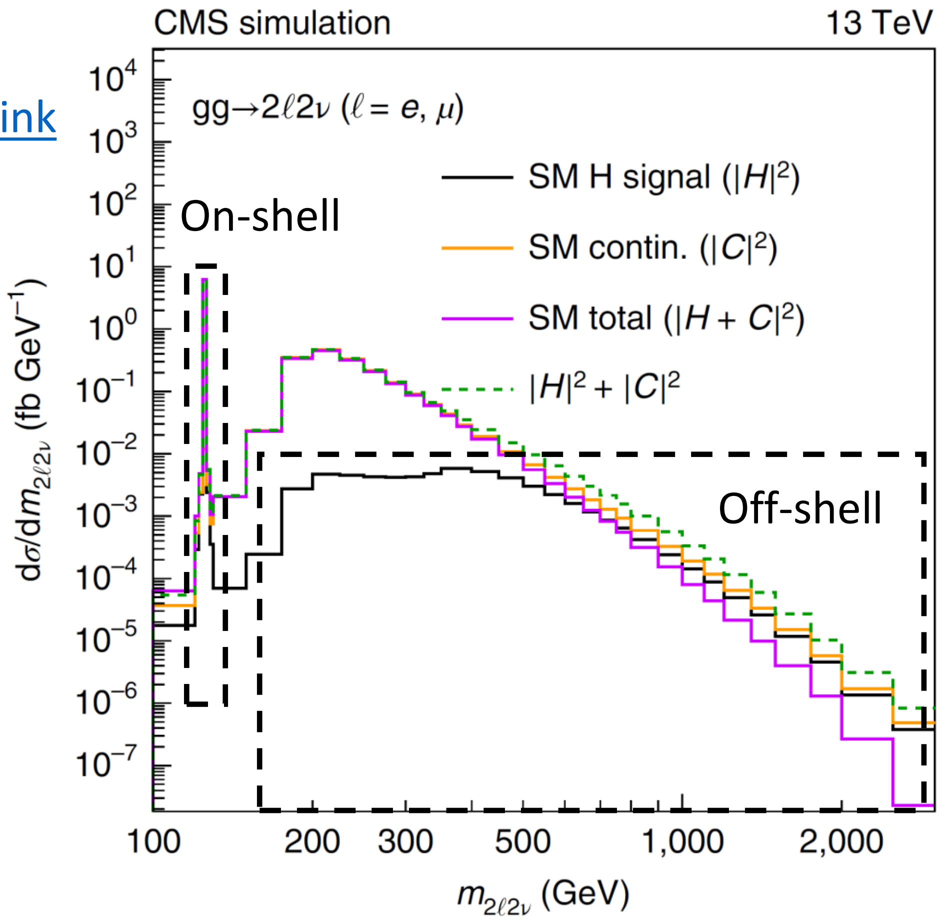
Off-shell Higgs boson production

In $H \rightarrow VV$ ($V = Z, W$), $m_V < m_{\mathrm{H}} < 2m_V$:
→ 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 [link]

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 $\mu^{\text{off-shell}}$

Link



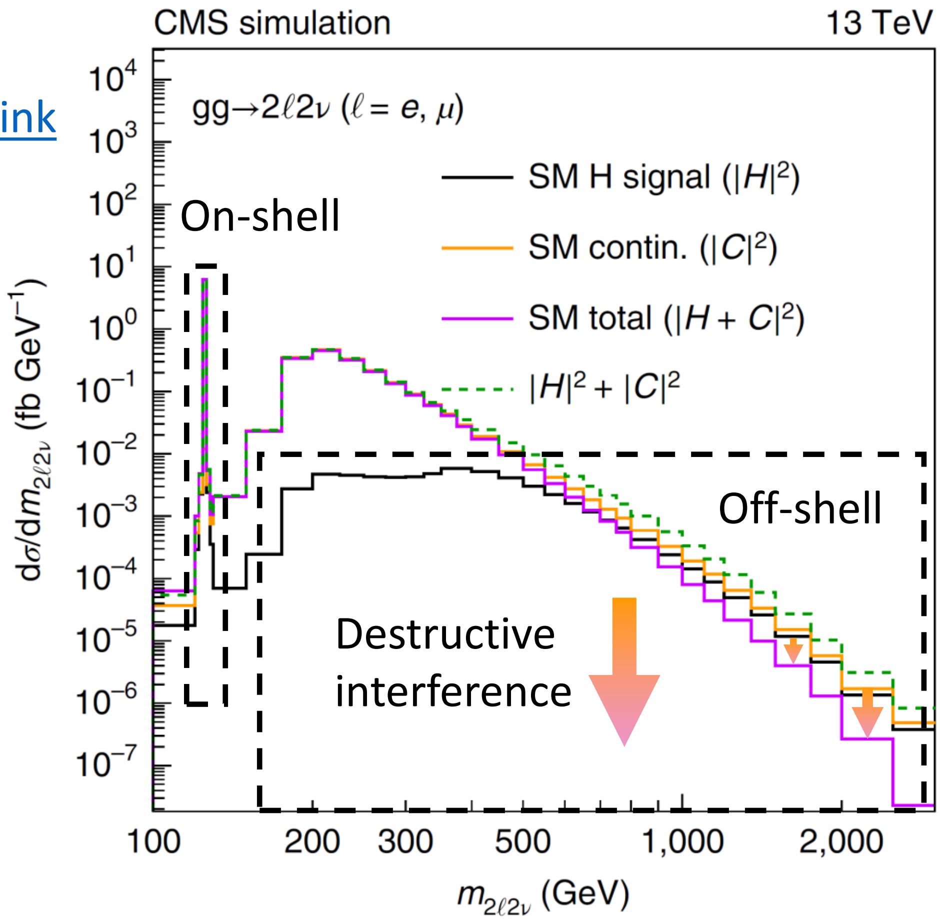
Off-shell Higgs boson production

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 [link]

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 $\mu^{\text{off-shell}}$

Link



Challenging measurement in multiple ways:
→ Sizeable, negative interference with continuum ZZ background
→ $\sim$Twice the size of the Higgs signal
→ Necessary in the SM to ensure unitarity

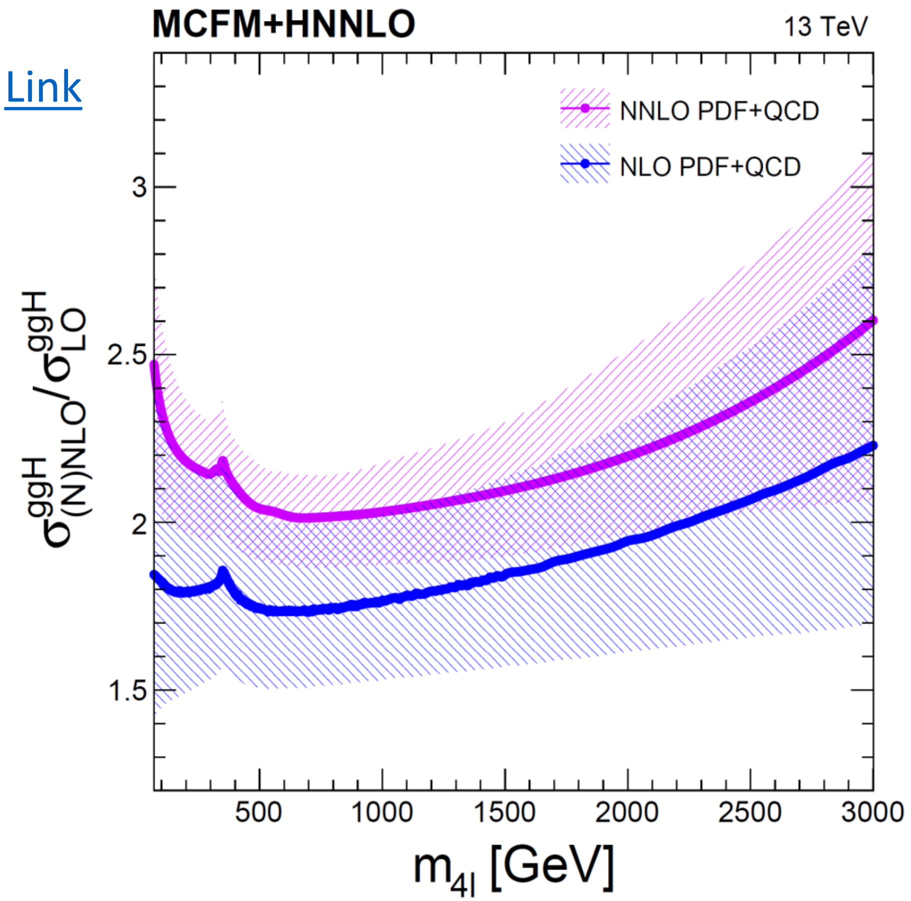
Off-shell Higgs boson production

In $H \rightarrow VV$ ($V = Z, W$), $m_V < m_{\rm H} < 2m_V$:
→ 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 [link]

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

Link



Challenging measurement in multiple ways:
→ Large perturbative corrections in gluon fusion
→ Requires consistent simulation and corrections

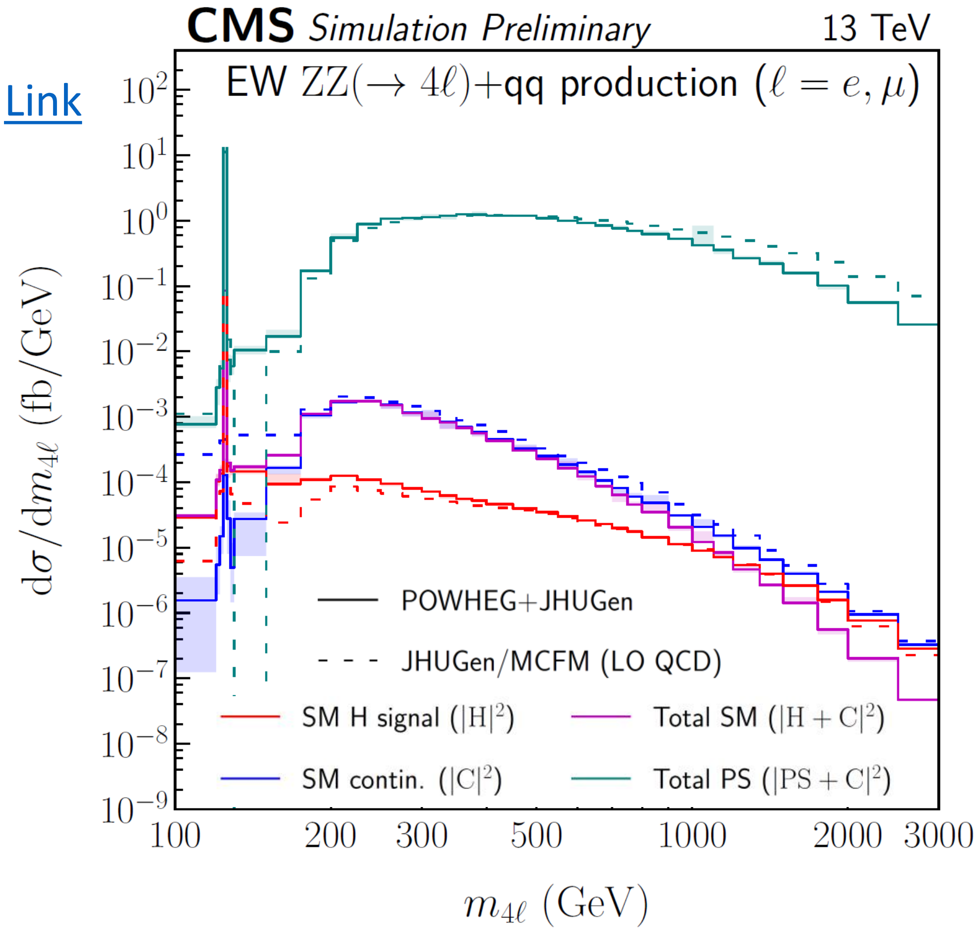
Off-shell Higgs boson production

In $H \rightarrow VV$ ($V = Z, W$), $m_V < m_{\mathrm{H}} < 2m_V$:
→ 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 ~10% of events in the SM to produce an off-shell Higgs boson [link]

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 $\mu^{\text{off-shell}}$

Link



Challenging measurement in multiple ways:
→ Simulated event generation computationally very intensive
→ Challenging integration of perturbative corrections

Higgs boson width from off-shell

Combine with on-shell signal strength measurement to extract Γ_H [link]:

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

On-shell

Off-shell

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

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

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

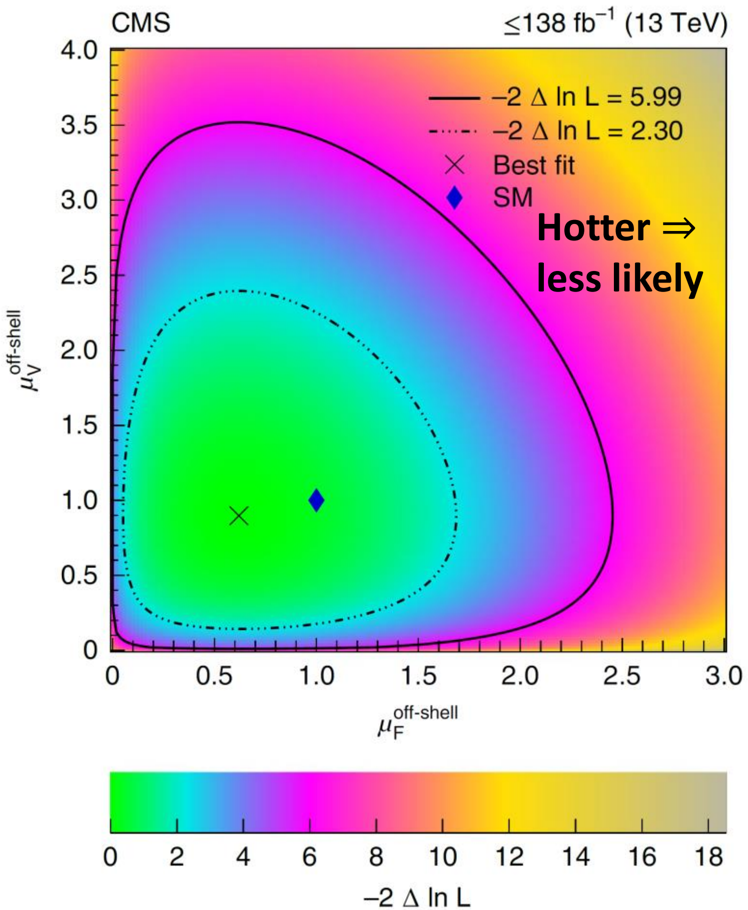
Ratio of off-shell to on-shell signal strengths for each production mode gives Γ_H

Higgs boson width from off-shell

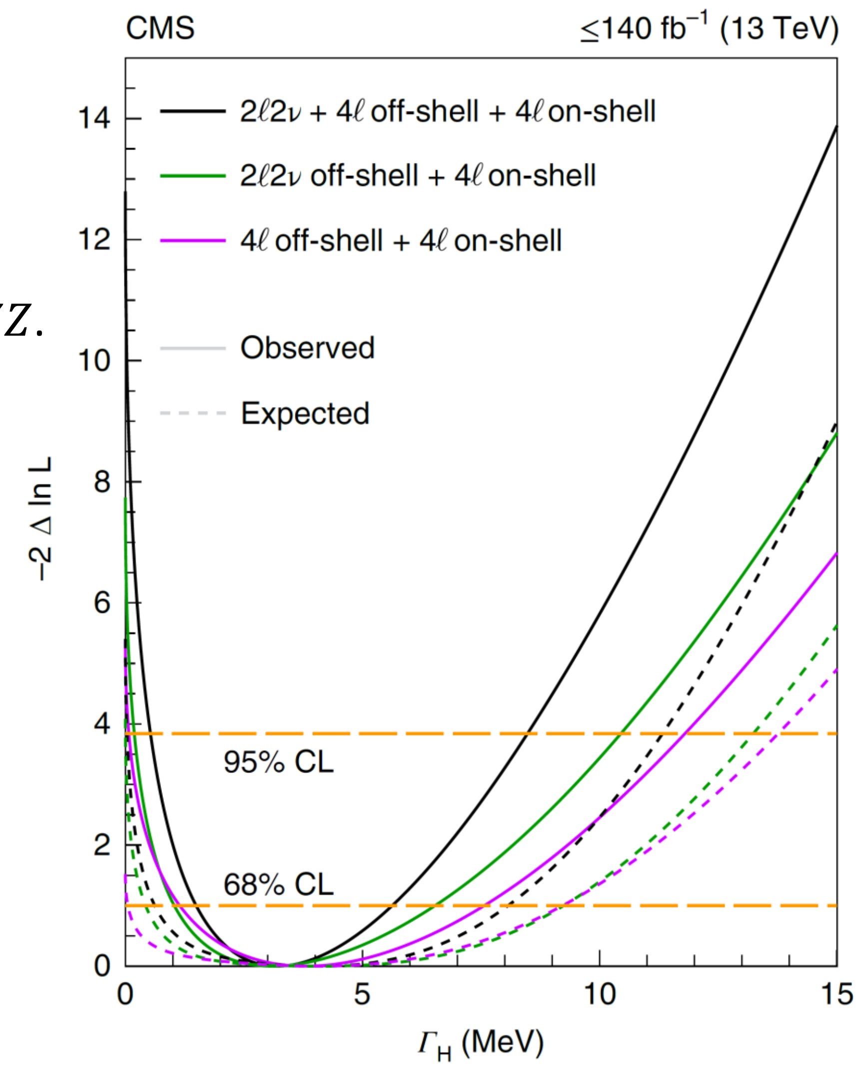
Using the off-shell method, we measure

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV, or}$$
$$7.7 \times 10^{-23}\ \text{s} < \tau_H < 1.3 \times 10^{-21}\ \text{s}$$

and find evidence for off-shell Higgs prod. in $H \to ZZ$.



Link

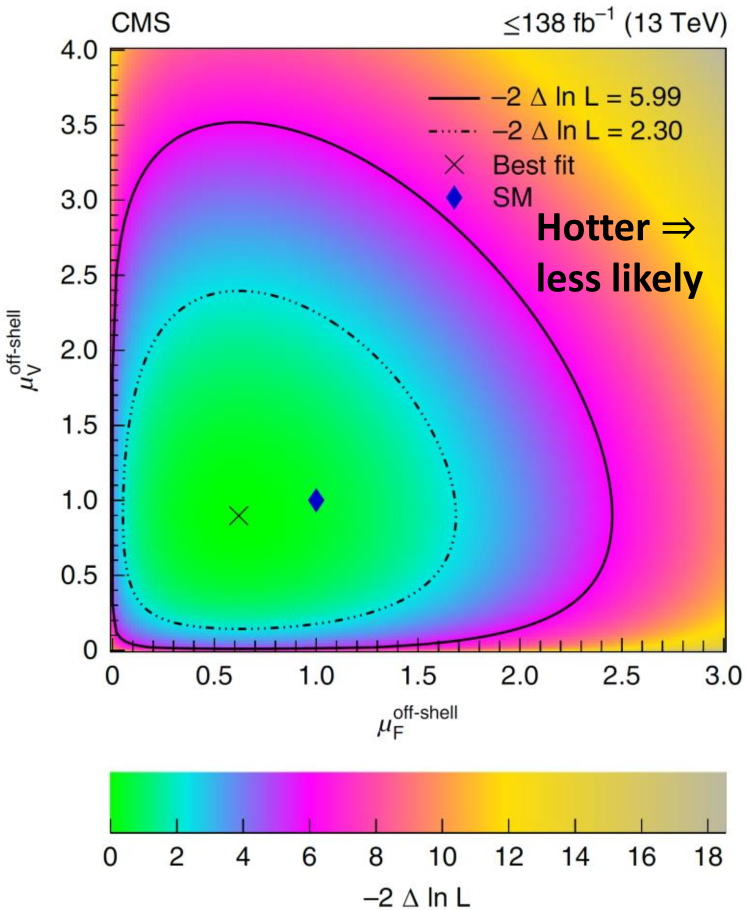


Higgs boson width from off-shell

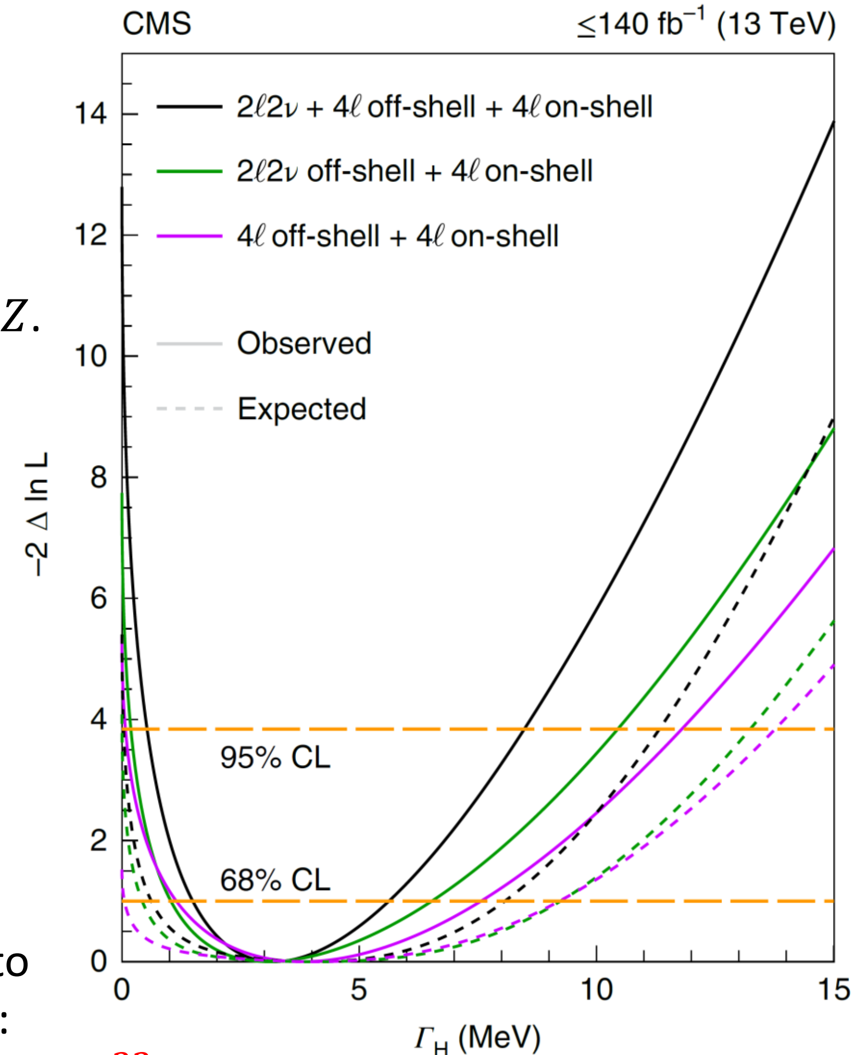
Using the off-shell method, we measure

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV, or}$$
$$7.7 \times 10^{-23}\ \text{s} < \tau_H < 1.3 \times 10^{-21}\ \text{s}$$

and find evidence for off-shell Higgs prod. in $H \to ZZ$.



Link

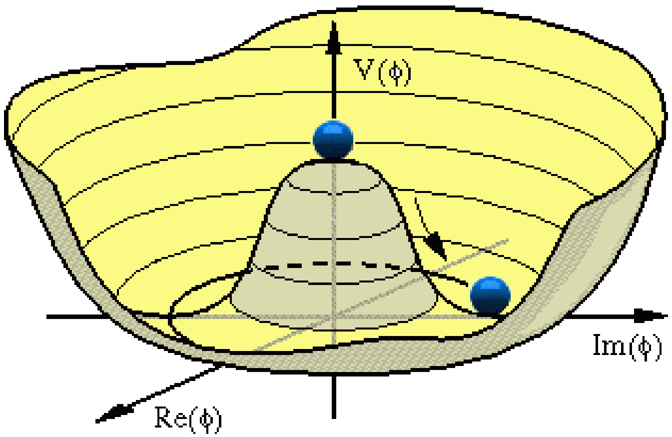


Compare to SM values:

$\tau_H = 1.6 \times 10^{-22}$ s

$\Gamma_H = 4.1$ MeV

Higgs self-couplings: Di-Higgs final states



SM Higgs potential:

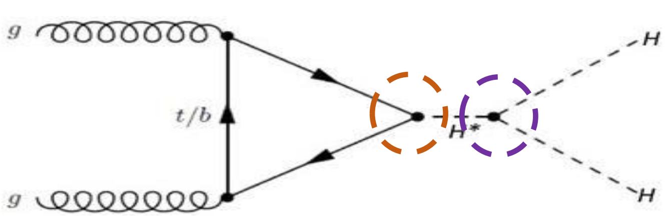
$$V(\phi) = 1/2\, \mu^2 \phi^\dagger \phi + 1/4\, \lambda \left(\phi^\dagger \phi\right)^2$$

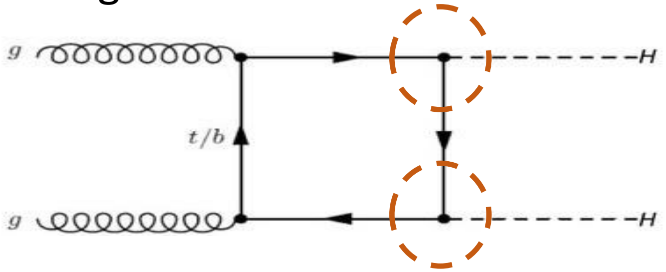
→ After gauge rotations and using the vacuum expectation v:

$$V(H) = V_0 + \lambda v^2 H^2 + \lambda v H^3 + 1/4 H^4$$

→ Allows triple and quartic Higgs couplings
→ Di-Higgs final state @ LHC

SM features interference of two diagrams:





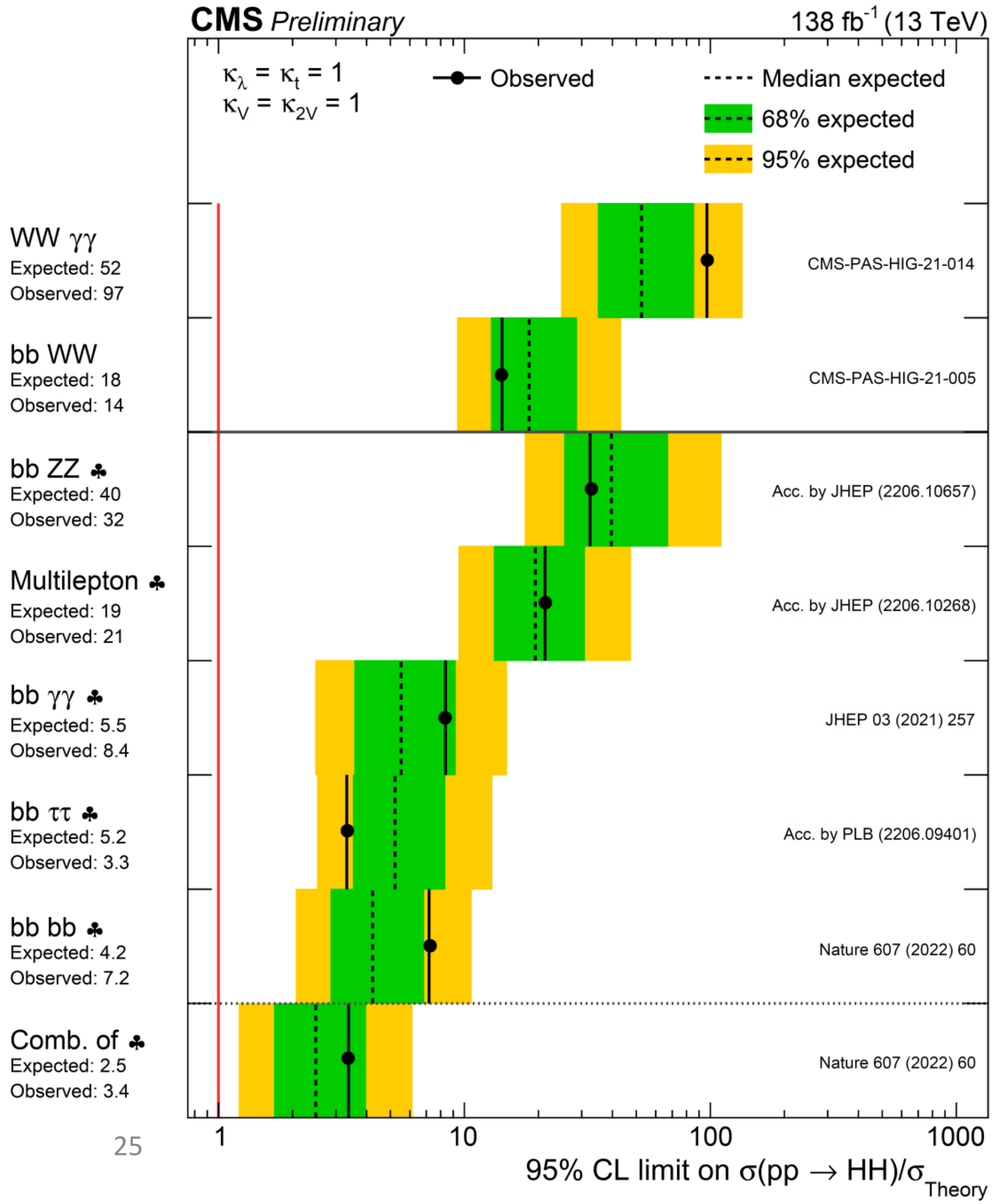
Left diagram sensitive to the triple-Higgs coupling through λ
→ Both sensitive to different powers of Htt & Hbb couplings
→ Different ways new physics could change this interaction

Higgs self-couplings: Di-Higgs final states

Di-Higgs measurements done using events with a larger multiplicity of particles and/or jets

Different final states either dirtier but with larger Higgs decay probability (e.g., $HH \to 4b$), or cleaner in bkgs. with smaller decay rates ($HH \to b\bar{b}\gamma\gamma$).

Uncertainties statistically dominated, but some channels will only barely reach an observation threshold by the end of HL-LHC.



Higgs self-couplings: Di-Higgs final states

Di-Higgs measurements done using events with a larger multiplicity of particles and/or jets

Different final states either dirtier but with larger Higgs decay probability (e.g., $HH \to 4b$), or cleaner in bkgs. with smaller decay rates ($HH \to b\bar{b}\gamma\gamma$).

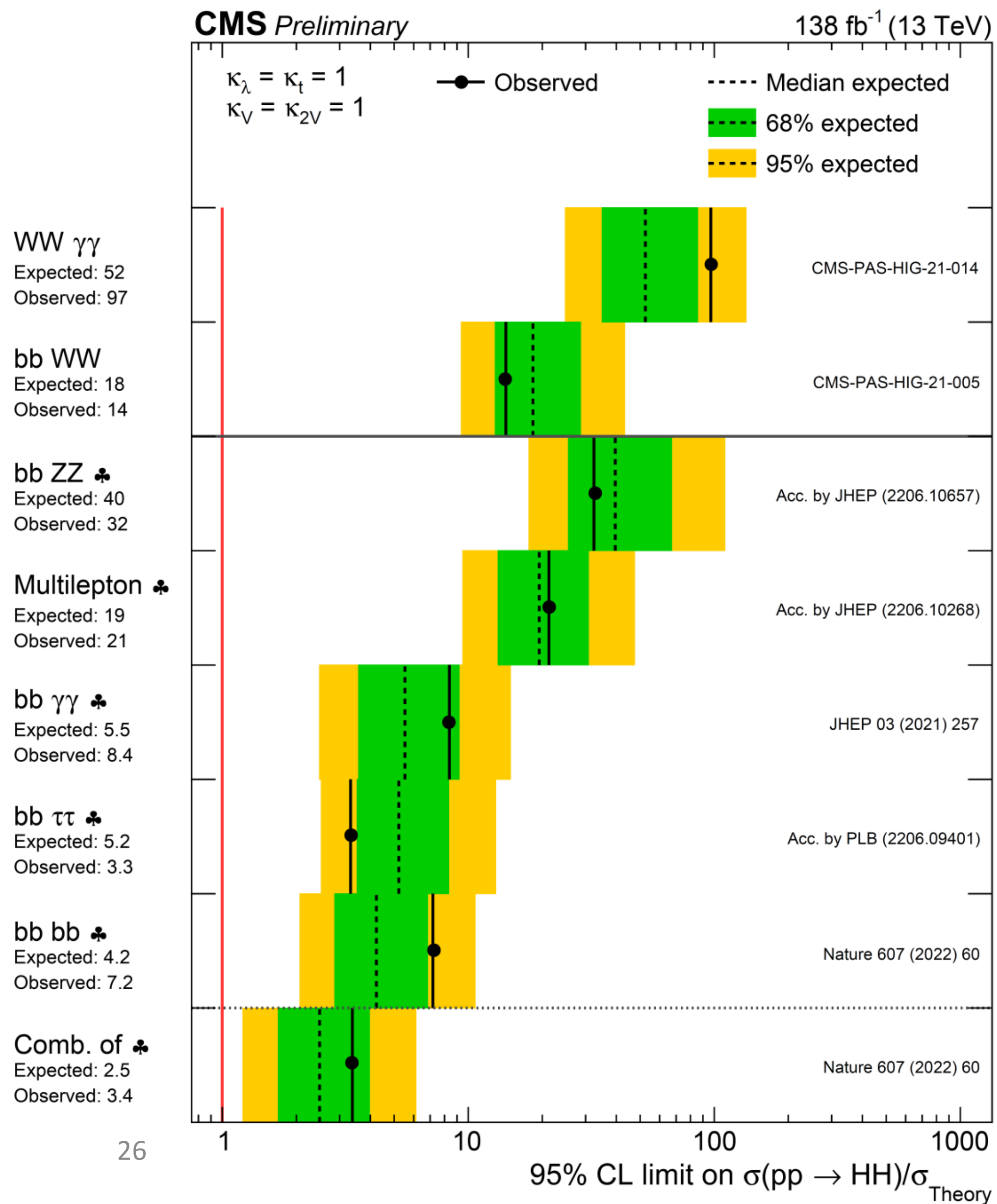
Uncertainties statistically dominated, but some channels will only barely reach an observation threshold by the end of HL-LHC.

Interaction rate is tiny, so we can only place limits.

→ Take $HH \to 4b$:

Max. ~ 1450 events / 10^{16} pp interactions

→ Rates enhances in BSM cases

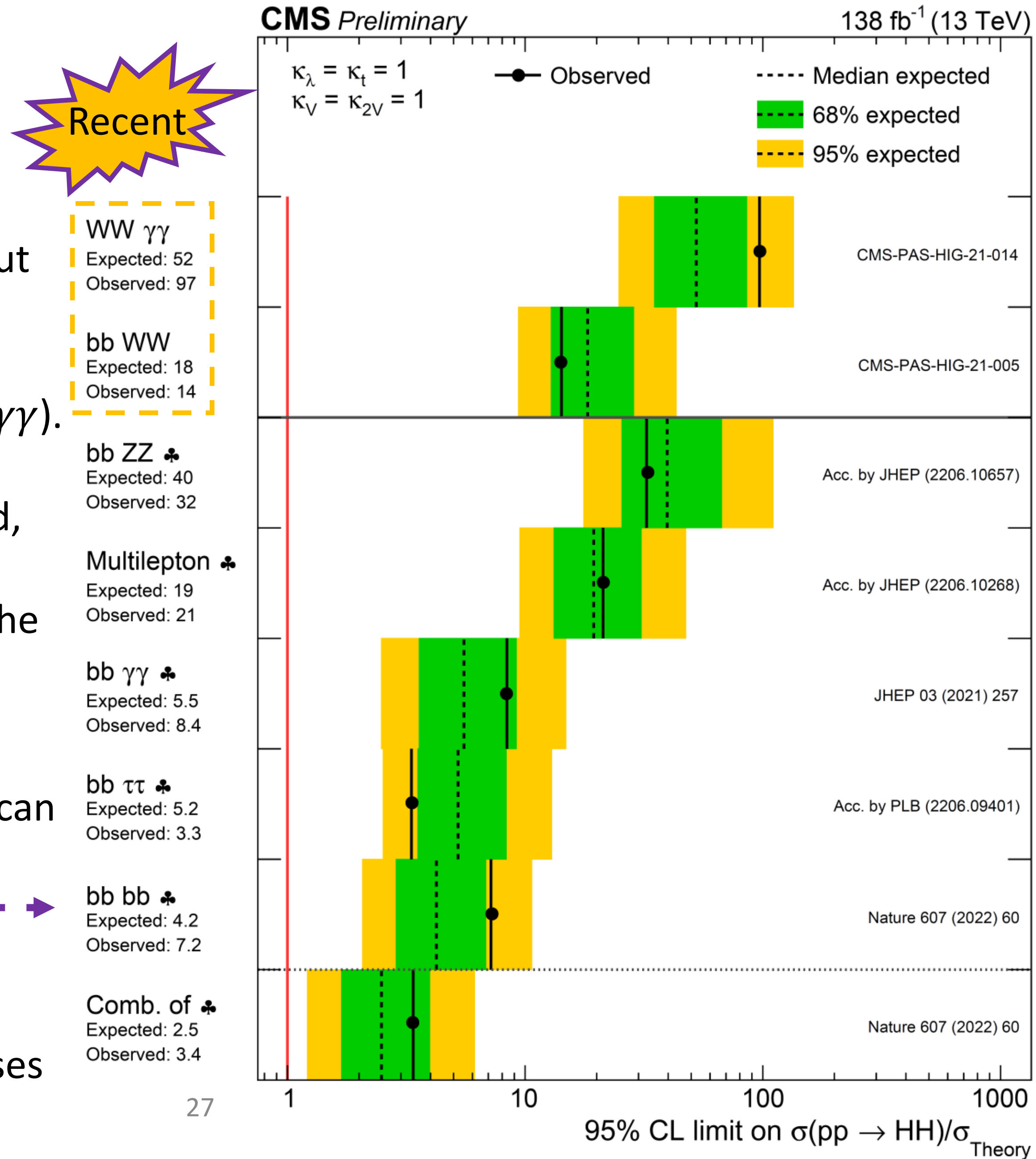


Higgs self-couplings: Di-Higgs final states

Di-Higgs measurements done using events with a larger multiplicity of particles and/or jets

Different final states either dirtier but with larger Higgs decay probability (e.g., $HH \to 4b$), or cleaner in bkgs. with smaller decay rates ($HH \to b\bar{b}\gamma\gamma$).

Uncertainties statistically dominated, but some channels will only barely reach an observation threshold by the end of HL-LHC.

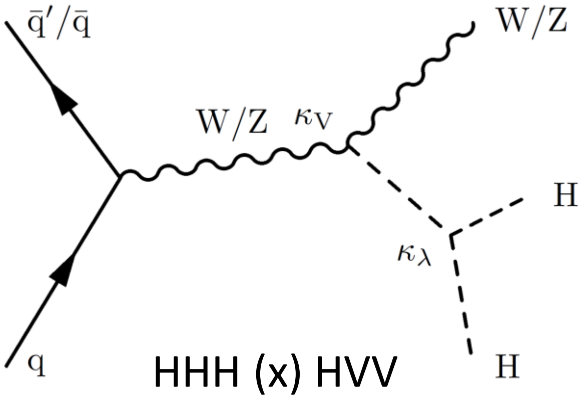


Interaction rate is tiny, so we can only place limits.

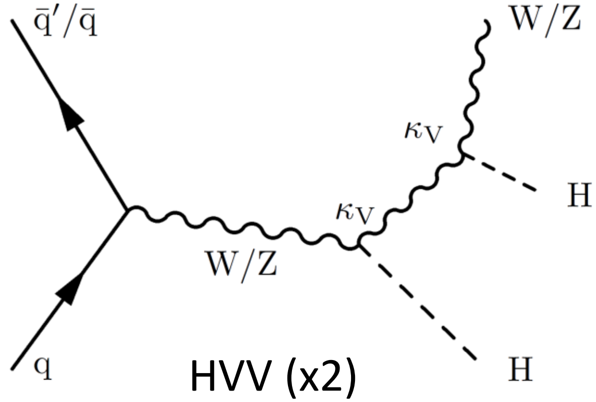
→ Take $HH \to 4b$:
Max. ~ 1450 events / 10^{16} pp interactions

→ Rates enhances in BSM cases

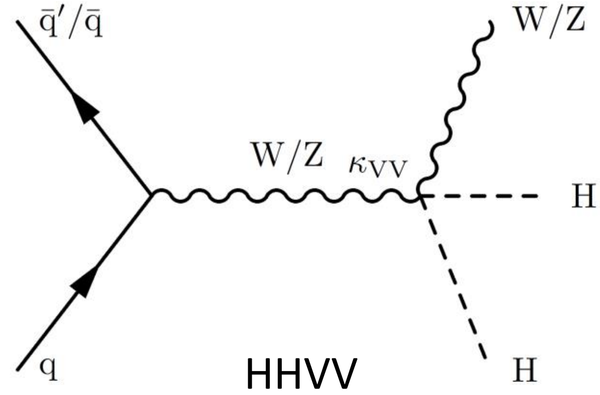
Higgs self-couplings: Di-Higgs in VHH



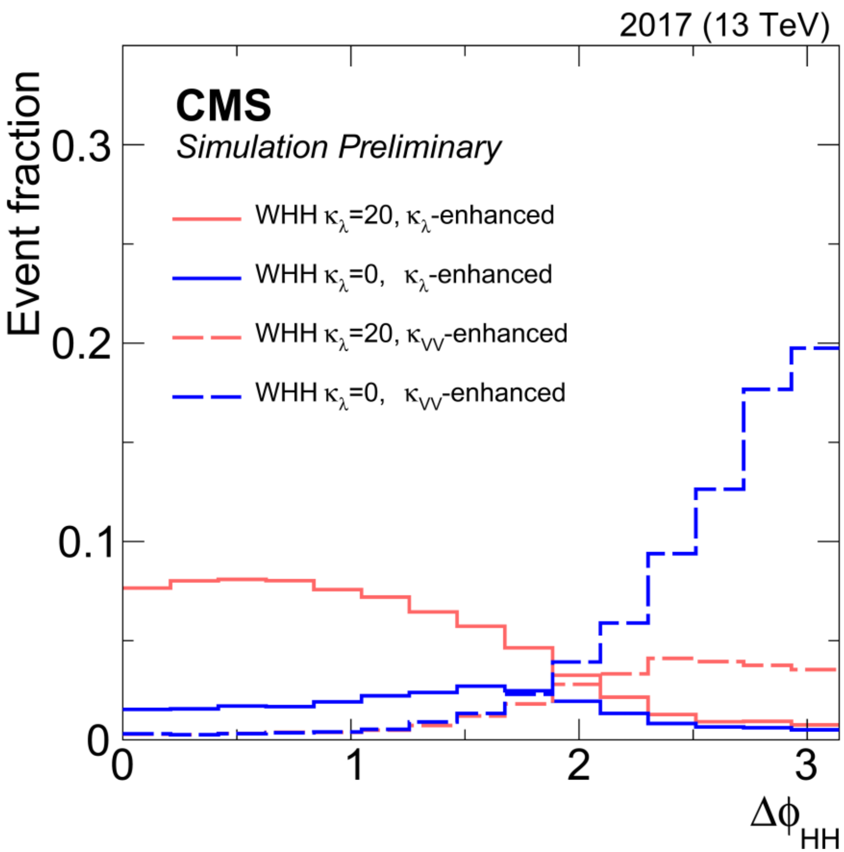
HHH (x) HVV



HVV (x2)



HHVV

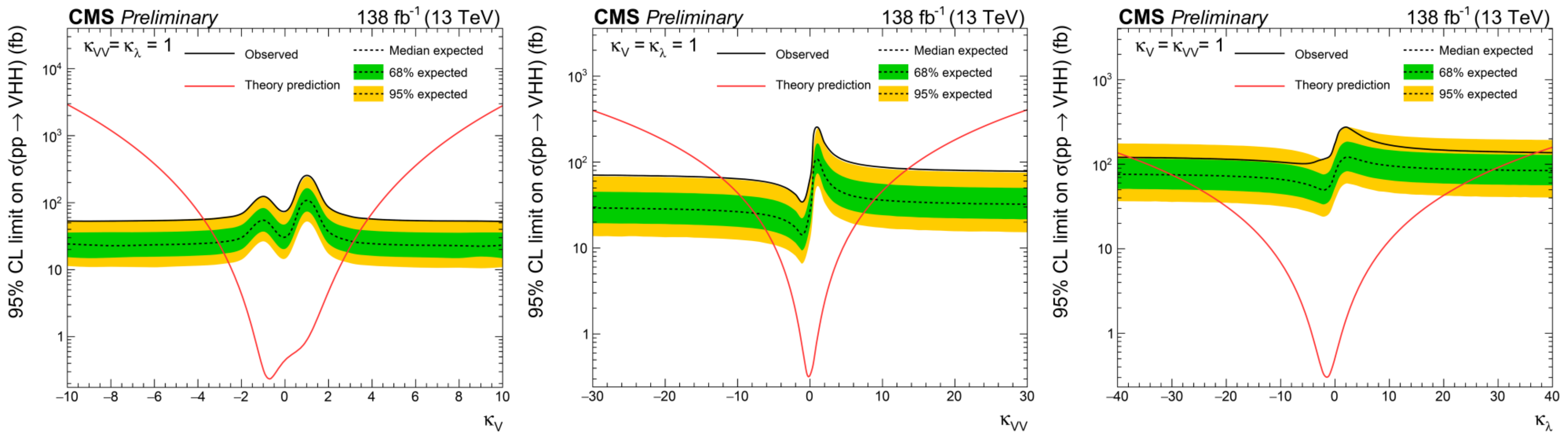


[Link](#)

Can have proportions of
HHH (x) HVV, HVV (x2), and HHVV diagrams different from the SM
→ Differences reflect on kinematic quantities
→ Can be utilized to constraint new physics contributions

Recent

Higgs self-couplings: Di-Higgs in VHH



κ_V κ_{VV} κ_λ

Link

Recent

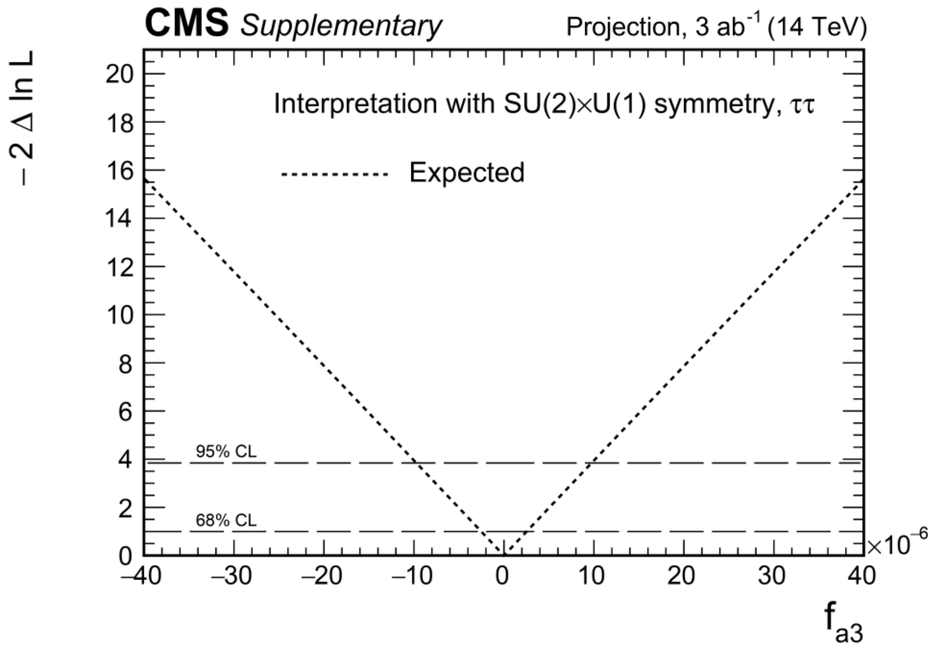
Results obtained by keeping the parameters not shown fixed to SM

→ Complementary to HH final state results

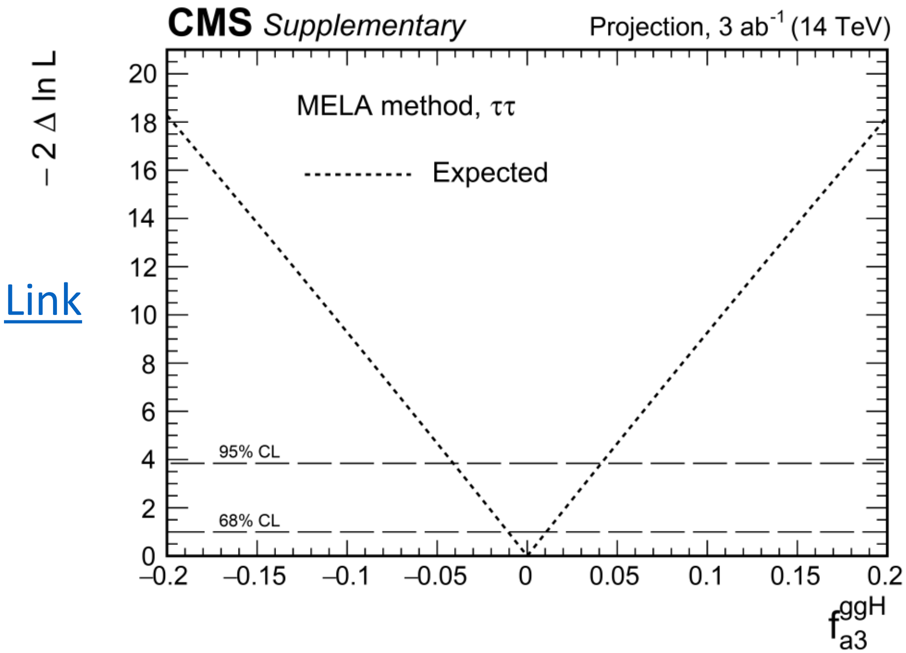
→ Independent of κ_t and modelling of loops

CMS prospects @ HL-LHC

Anomalous spin-0 HVV & Hgg couplings

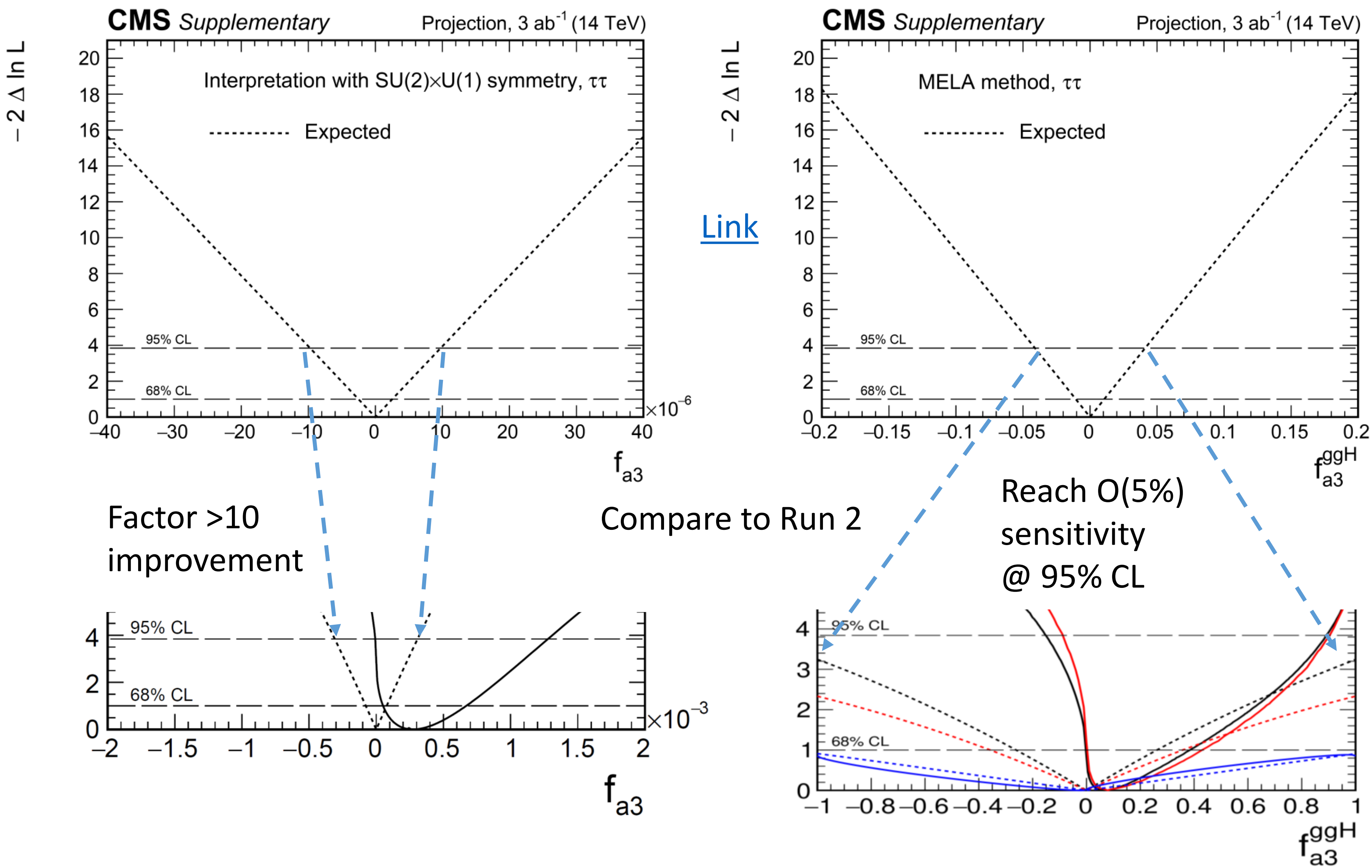


Link



Projections obtained from $\tau\tau$ channel alone
→ Could expect even further improvements after combination with other decay modes

Anomalous spin-0 HVV & Hgg couplings

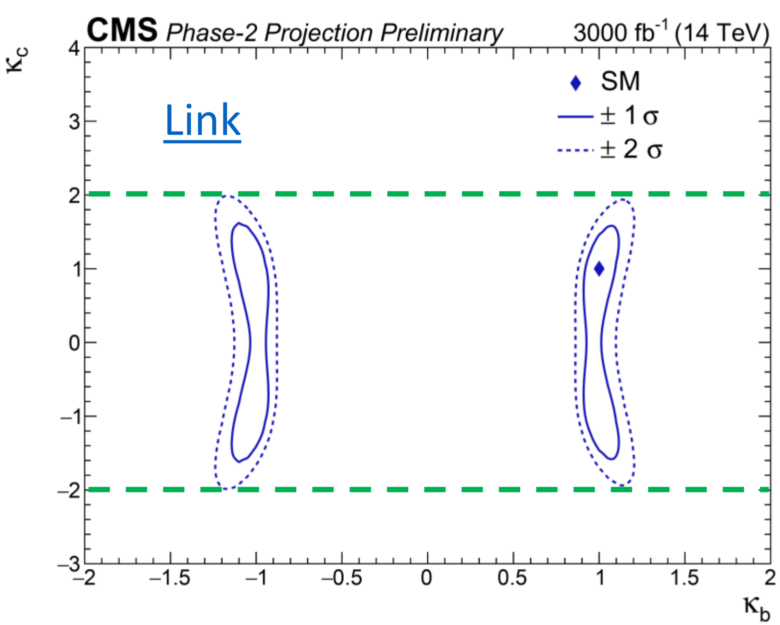


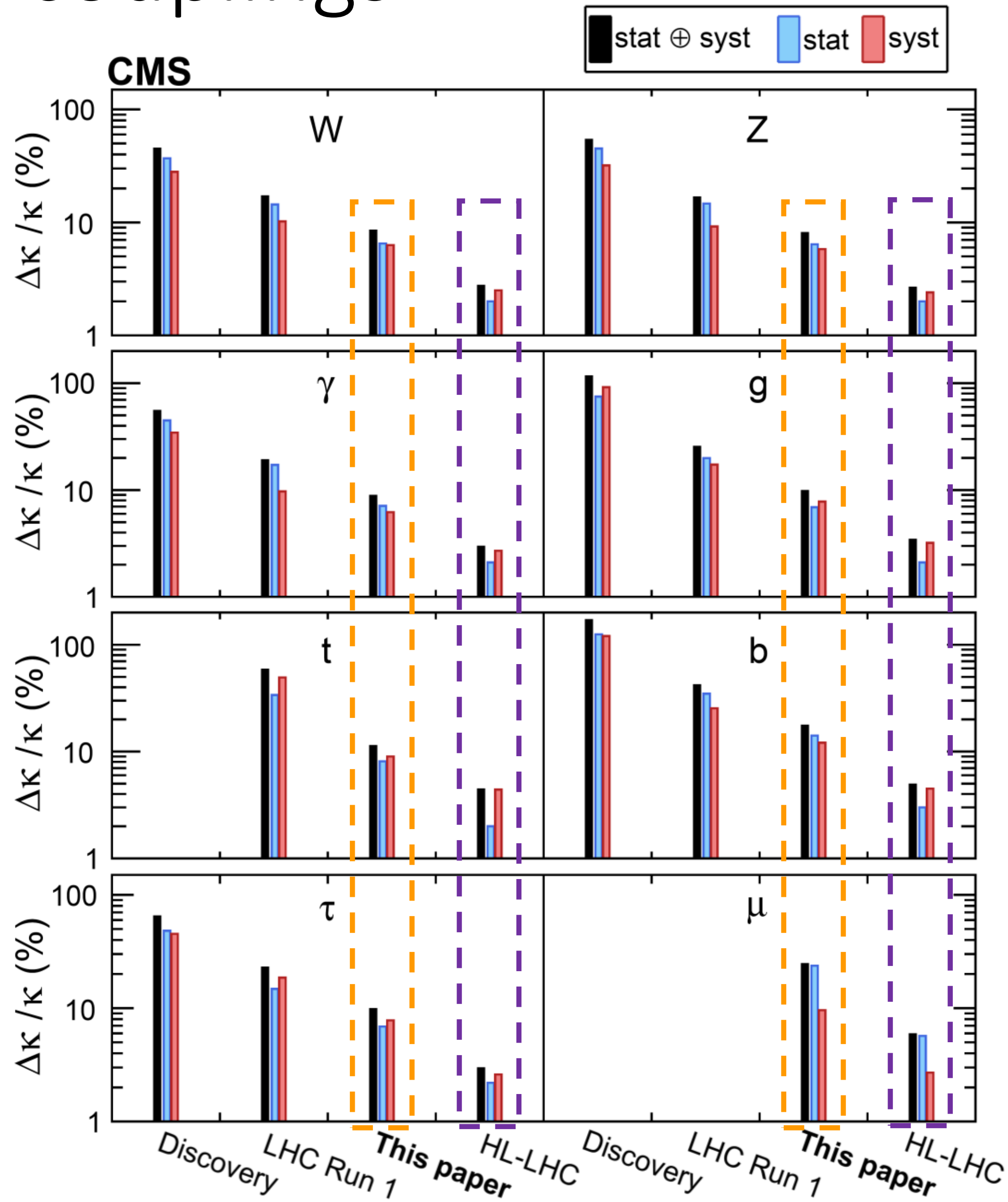
Higgs couplings

Link

Improve sensitivity by × ~3
→ Not × ~4.7 expected from lumi. increase alone
→ Expect systematics to begin to dominate in almost all couplings
→ $H\mu\mu$ reaches <10% @ HL-LHC

Note also that sensitivity to Yukawa charm coupling also reaches O(2) @ HL-LHC:





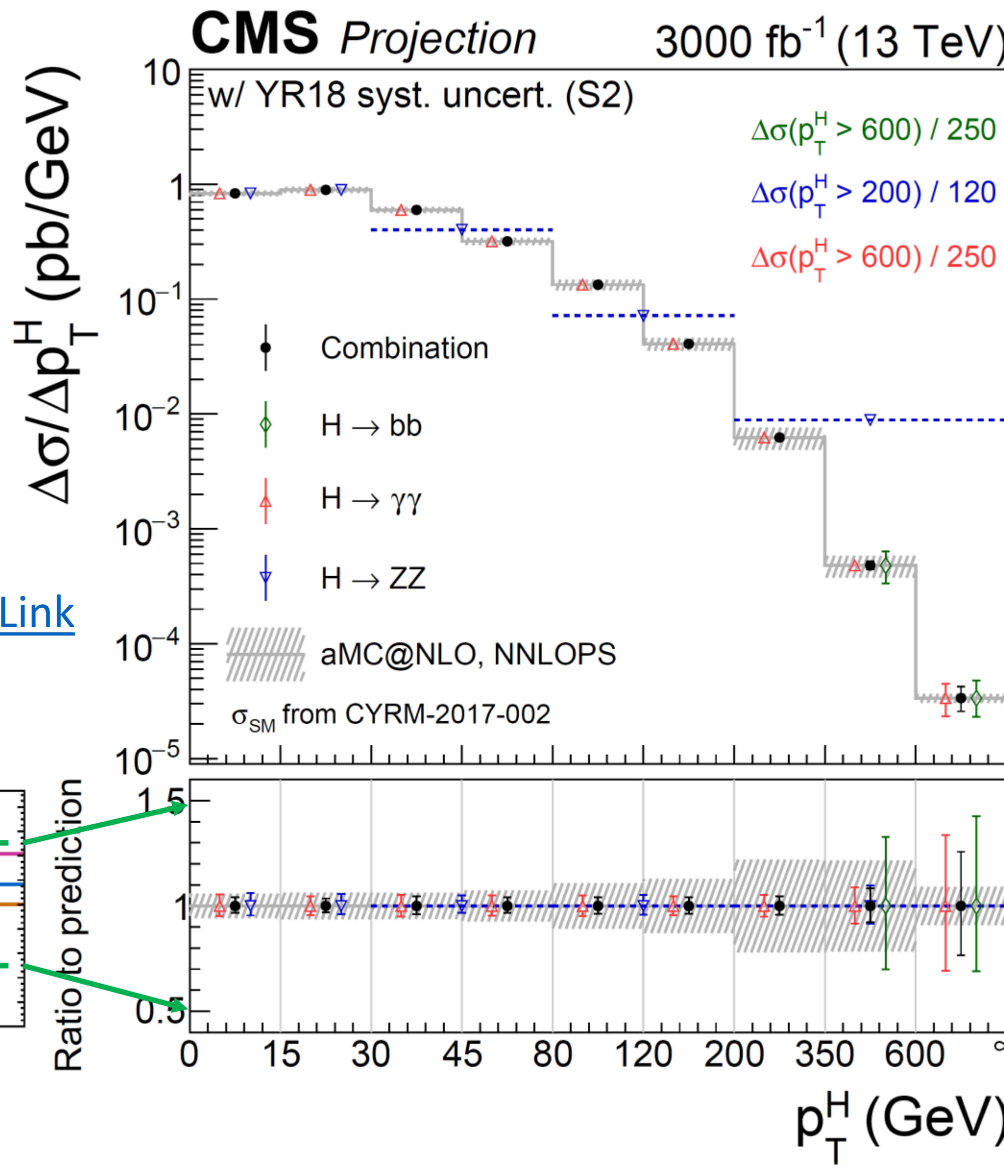
Differential cross sections

Differential xsec measurements are statistically dominated

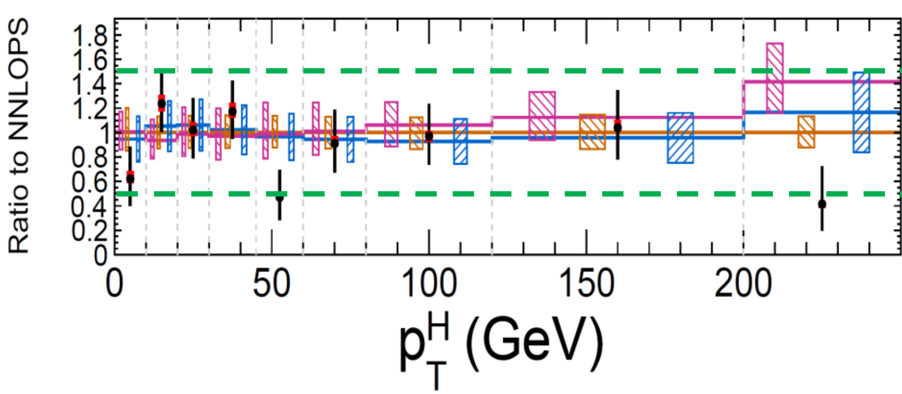
→ Expect to improve stat. scatter by factor ~4.7

→ Can reach higher in p_T^H, N_j, or other observables

Link



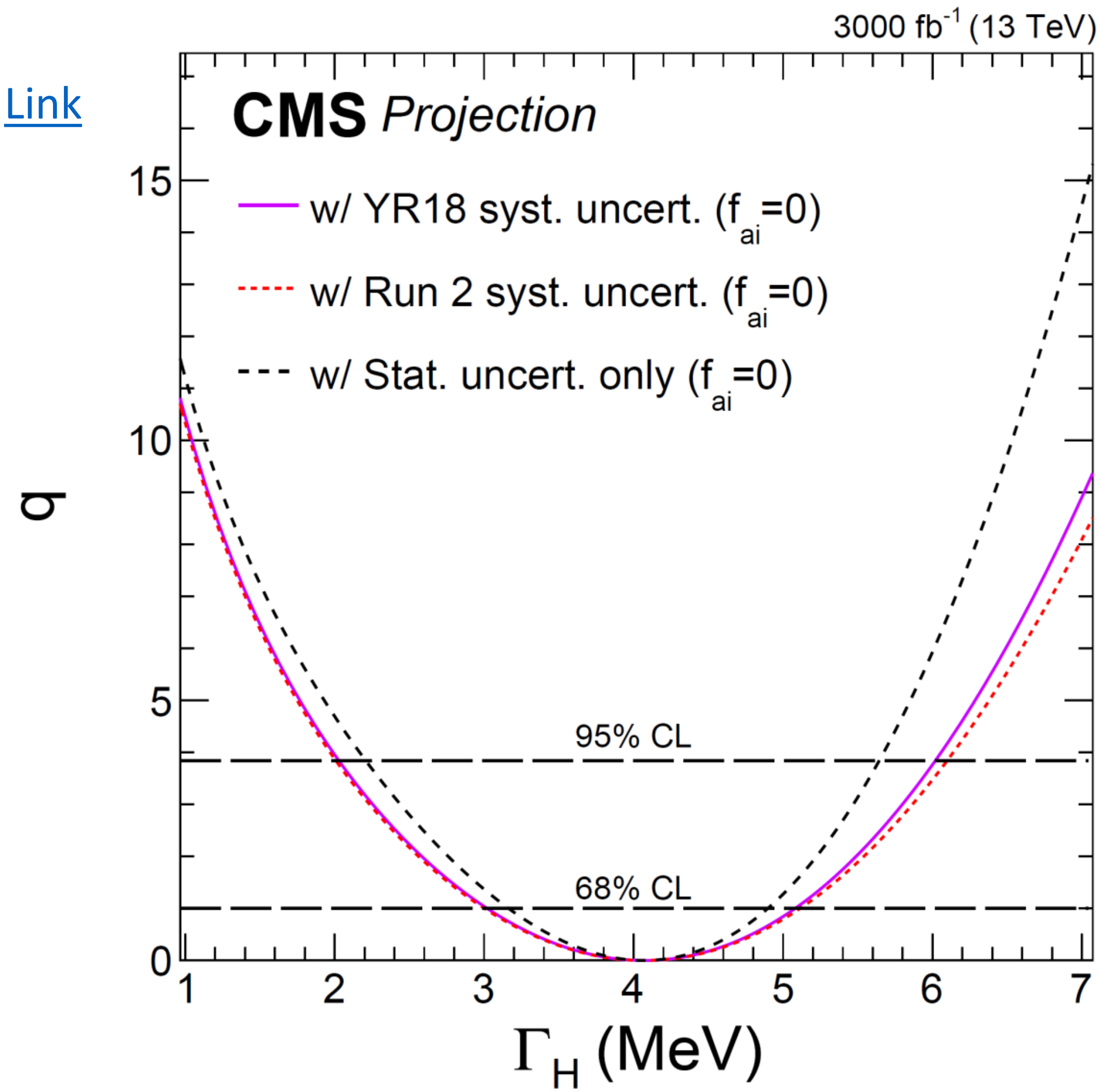
Current Run 2 4ℓ:



Higgs width

Link

Estimated from 4ℓ alone,
but expect $\sim\sqrt{2}$ better in stat.
component of unc. when
combined with $ZZ \to 2\ell 2\nu$

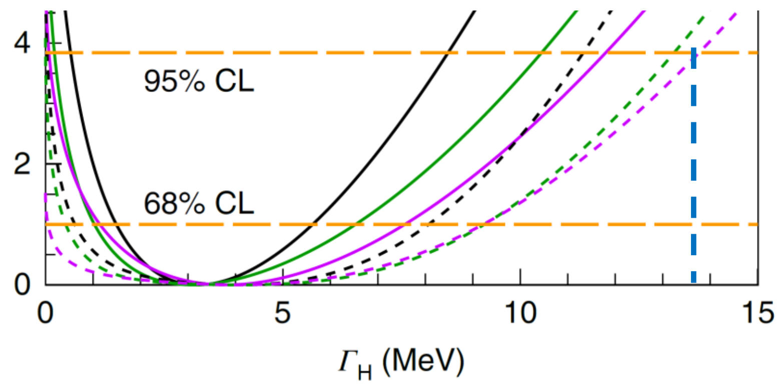


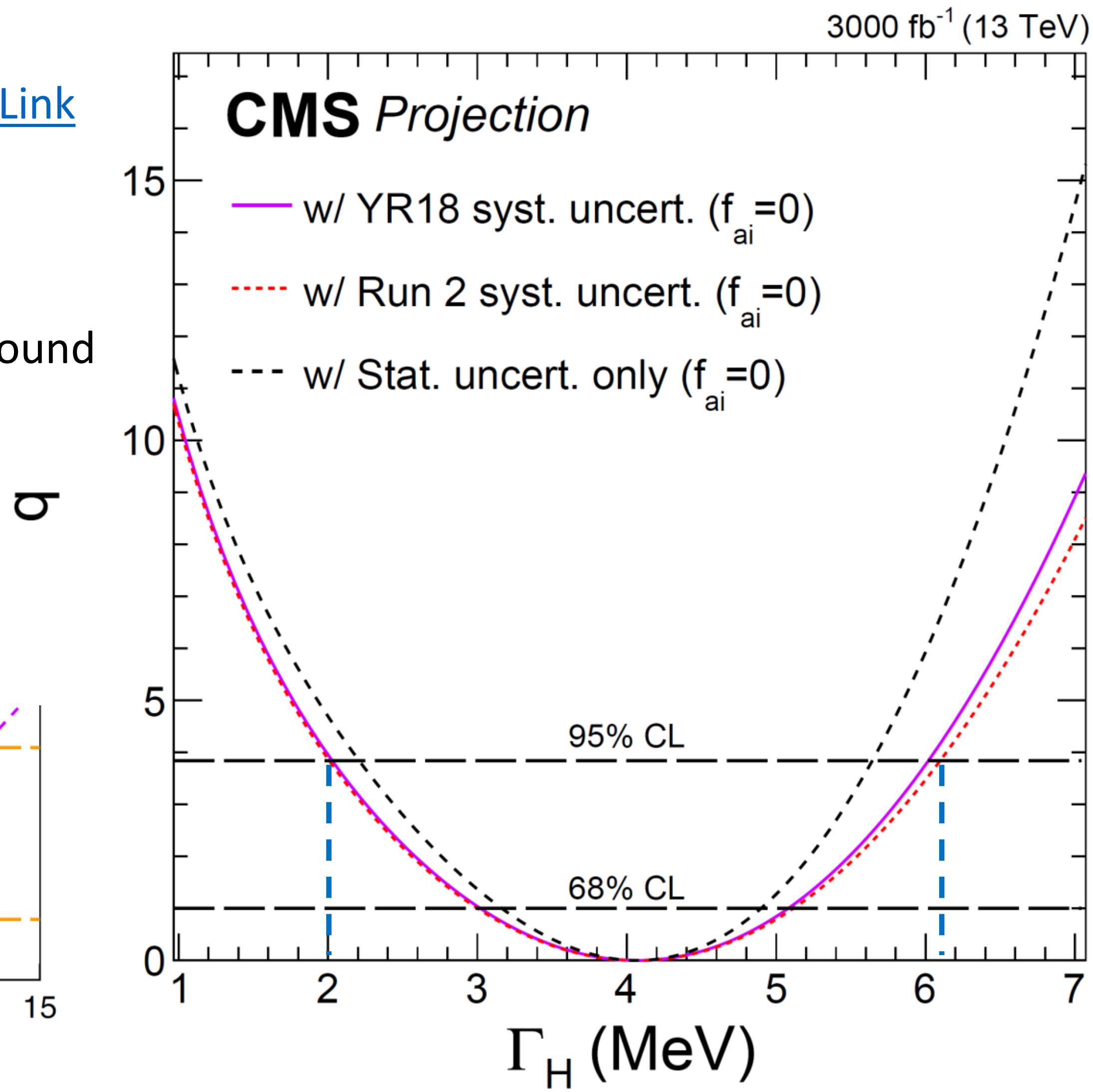
Higgs width

Link

Run 2 measurements stat.-driven
→ Upper bound sees more noticeable effect from systematic uncs. @ HL-LHC
→ Lower bound catches up to upper bound

From latest Run 2 analysis:

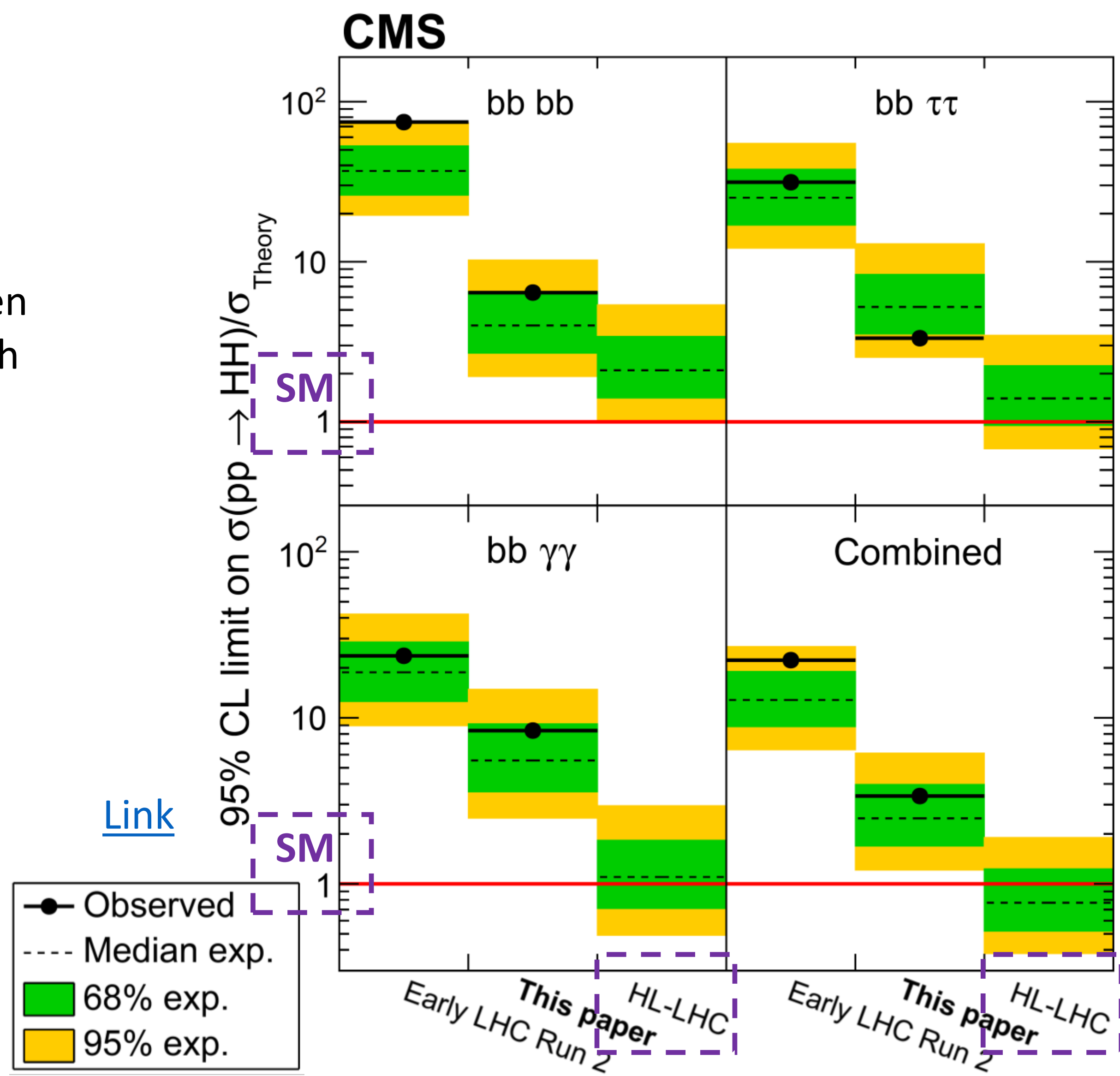




Di-Higgs couplings

Run 2 analyses statistically-driven
→ Most sensitive channels reach within O(1) of the SM
→ Combination of different channels remains crucial
→ Persistence is key.

Link



Many exciting results from CMS to understand Higgs boson properties.

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

Sadly, no new physics yet ☹, but we have just started looking ☺.

Entering *precision* era in Higgs properties as we proceed toward Run 3 & HL-LHC.

Stay tuned for more exciting results in the future!

CMS references

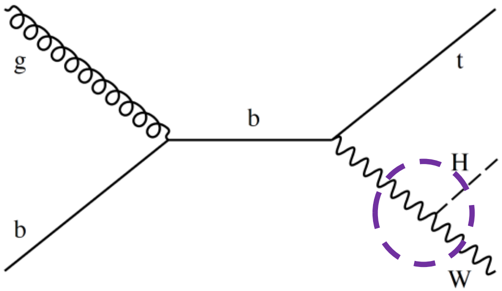
CMS LHC Run 1 + Run 2 '16 $4\ell + \gamma\gamma$ mass: https://doi.org/10.1016/j.physletb.2020.135425
CMS LHC Run 1 spin-parity: https://doi.org/10.1103/PhysRevD.92.012004
CMS LHC Run 2 $4\ell + \tau\tau$ anomalous HVV couplings: https://arxiv.org/abs/2205.05120
CMS LHC Run 2 4ℓ anomalous HVV couplings: https://doi.org/10.1103/PhysRevD.104.052004
CMS LHC Run 1 + Run 2 2016 $t\bar{t}H$ observation: https://doi.org/10.1103/PhysRevLett.120.231801
CMS LHC Run 2 $t\bar{t}H$ production and CP: https://doi.org/10.1103/PhysRevLett.125.061801
CMS LHC Run 2 $t\bar{t}H + tH$ multilepton production and CP: https://arxiv.org/abs/2208.02686
CMS LHC Run 2 $\tau\tau$ CP: https://doi.org/10.1007/JHEP06(2022)012
CMS LHC Run 2 couplings combination: https://doi.org/10.1038/s41586-022-04892-x
CMS LHC Run 2 $VH, H \to c\bar{c}$: http://arxiv.org/abs/2205.05550
CMS LHC Run 2 VBF $H \to$ invisible: https://doi.org/10.1103/PhysRevD.105.092007
CMS LHC Run 2 $t\bar{t}H \to$ invisible: https://arxiv.org/abs/2303.01214
CMS LHC Run 2 $Z(\to \ell\ell)H \to$ invisible: https://doi.org/10.1140/epjc/s10052-020-08739-5
CMS LHC Run 2 $gg \to Hj, V(\to jj)H, H \to$ invisible: https://doi.org/10.1007/JHEP11(2021)153
CMS LHC Run 2 WW cross sections: https://cds.cern.ch/record/2812784
CMS LHC Run 2 $\tau\tau$ cross sections: https://arxiv.org/abs/2204.12957
CMS LHC Run 2 $\gamma\gamma$ cross sections: https://doi.org/10.1007/JHEP07(2021)027
CMS LHC Run 2 2016 4ℓ cross sections and mass: https://doi.org/10.1007/JHEP11(2017)047
CMS LHC Run 2 4ℓ cross sections: https://doi.org/10.1140/epjc/s10052-021-09200-x
CMS LHC Run 2 $\tau\tau$ fiducial cross sections: https://doi.org/10.1103/PhysRevLett.128.081805
CMS LHC Run 2 $\gamma\gamma$ fiducial cross sections: https://arxiv.org/abs/2208.12279
CMS LHC Run 2 WW fiducial cross sections: https://doi.org/10.1007/JHEP03(2021)003
CMS LHC Run 2 4ℓ fiducial cross sections: https://cds.cern.ch/record/2858768
CMS LHC Run 1 4ℓ lifetime: https://doi.org/10.1103/PhysRevD.92.072010
CMS LHC Run 2 $ZZ \to 4\ell + 2\ell 2\nu$ off-shell analysis: https://doi.org/10.1038/s41567-022-01682-0
CMS off-shell simulation study: https://cds.cern.ch/record/2826782
CMS LHC Run 2 di-Higgs $bbWW$: https://cds.cern.ch/record/2853597
CMS LHC Run 2 di-Higgs $WW\gamma\gamma$: https://cds.cern.ch/record/2840773
CMS LHC Run 2 VHH: https://cds.cern.ch/record/2853338
CMS HL-LHC sensitivity projections: https://cds.cern.ch/record/2647699

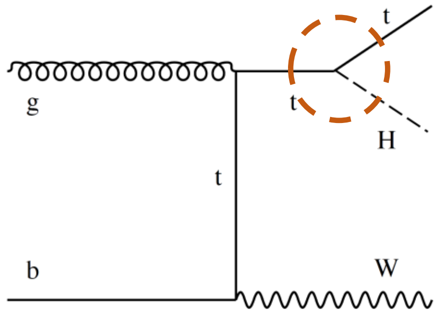
Other references

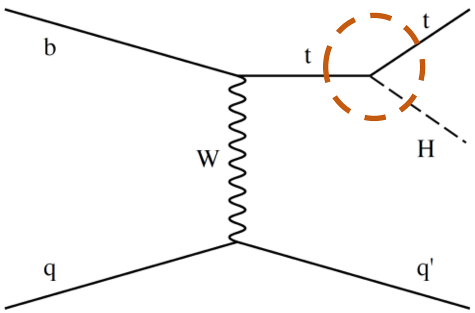
N Kauer and G. Passarino, “Inadequacy of zero-width approximation for a light Higgs boson signal”: https://doi.org/10.1007/JHEP08(2012)116
CERN Yellow Report 3: http://cds.cern.ch/record/1559921
CERN Yellow Report 4: https://cds.cern.ch/record/2227475
Study of QCD K-factors for ggH production: https://doi.org/10.1007/978-3-030-25474-2

Back-up

(Less) common ways to produce a SM Higgs in pp collisions

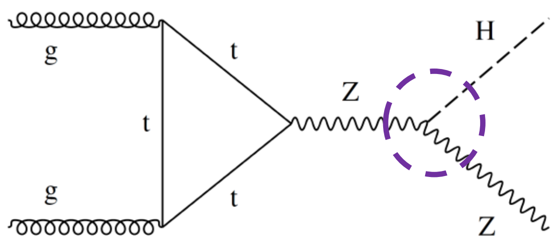


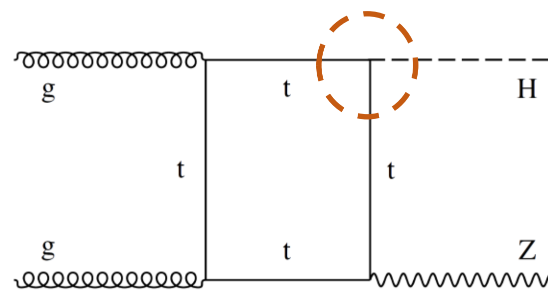




tH and tHW: Allows to resolve relative phase of Htt and HWW couplings

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



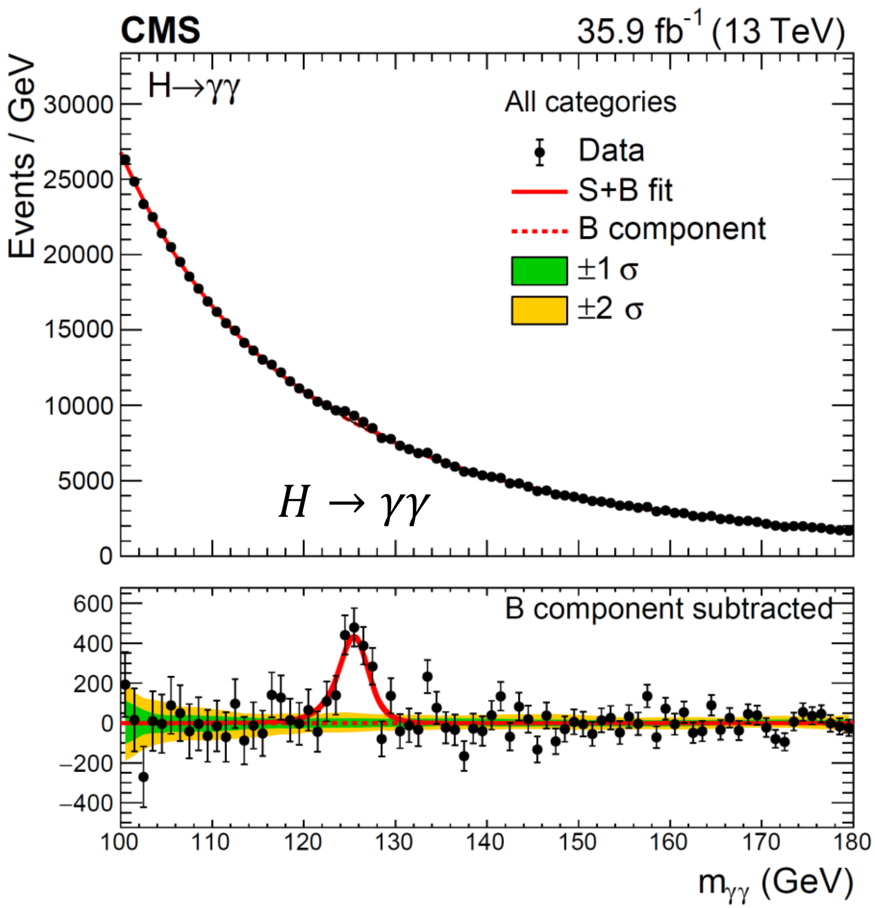


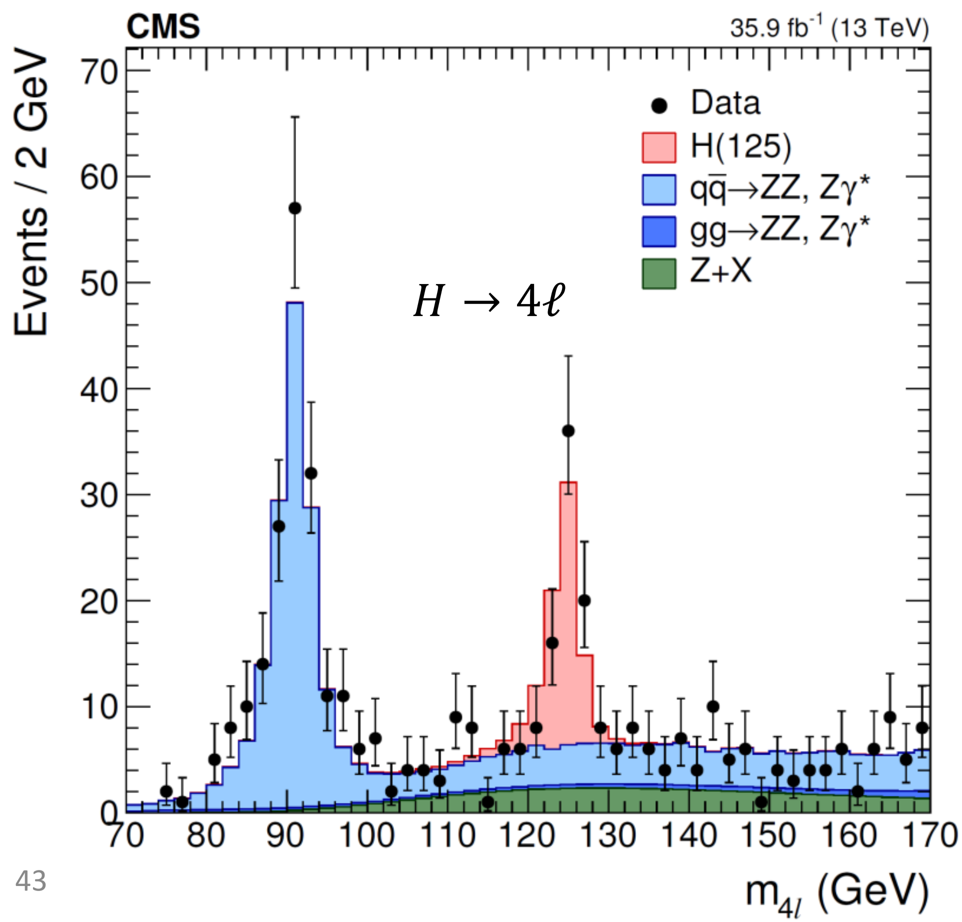
Mass

Measure mass from the resonance line shape:
→ Doable from the 4ℓ and $\gamma\gamma$ final states to excellent precision (1-2% resolution)

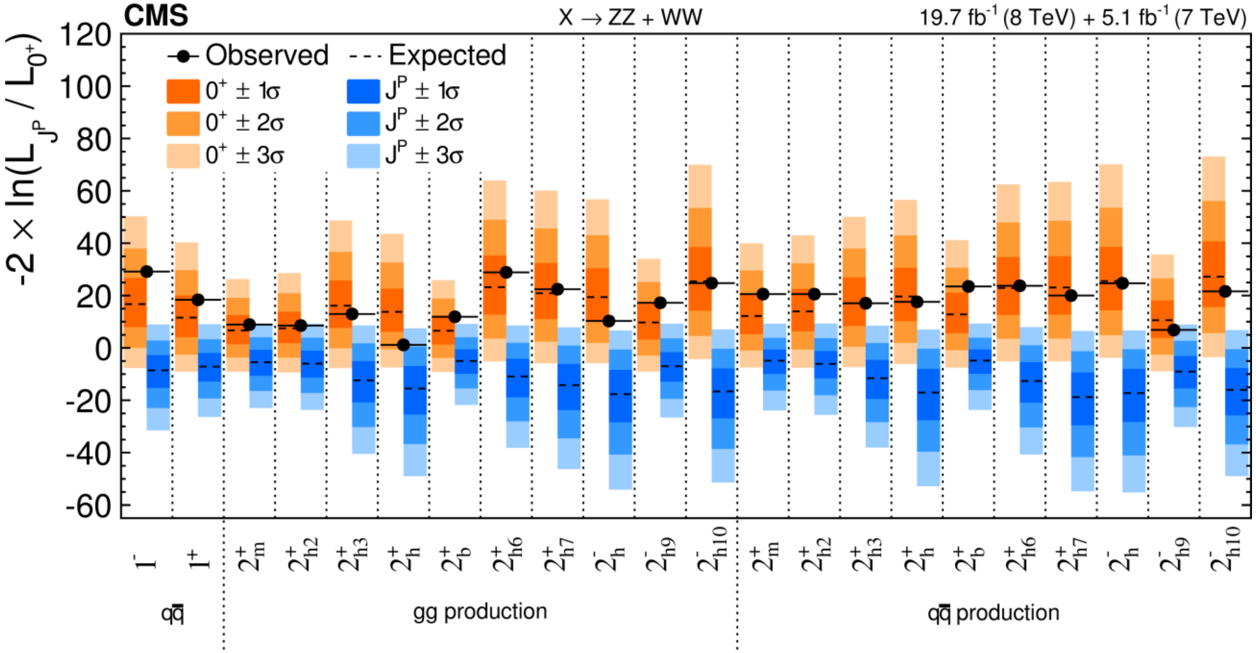
Best measurement to date from CMS alone using $4\ell + \gamma\gamma$ Run 1 + Run 2 2016 data [link]:

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





Spin from diboson decays



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

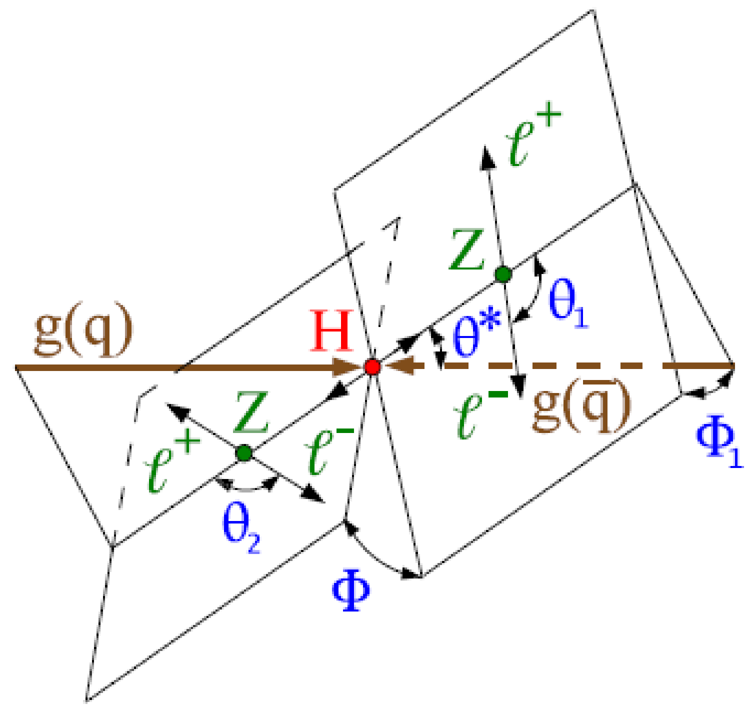
→ Exploit angular correlations

The Higgs boson is consistent with spin 0.

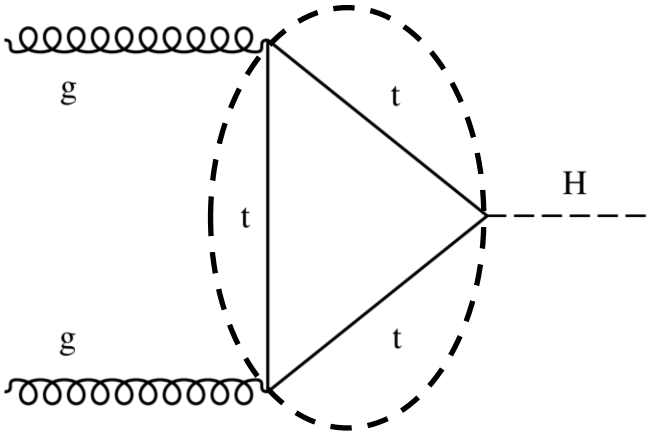
→ Looser constraints on different spin-0 hypotheses

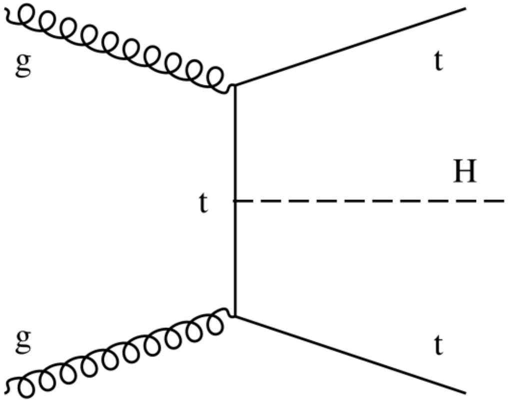
Spin-1 models excluded at >99.999% CL from CMS using $ZZ + WW$ decays

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



Anomalous spin-0 couplings: Hgg/Htt





$$A(Hgg) \sim a_2^{gg} \mathrm{f}_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{gg} \mathrm{f}_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

$$A(Htt) = -\frac{m_t}{v} \bar{\psi}_t (\boldsymbol{\kappa_t} + i\tilde{\boldsymbol{\kappa}}_t \gamma_5) \psi_t$$

Can apply EFT treatment in $gg \to H$ when $m_H < 2m_t$
→ Can be translated to Htt couplings

With discovery of $t\bar{t}H$ associated production [link], 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 HVV couplings from on-shell 4ℓ

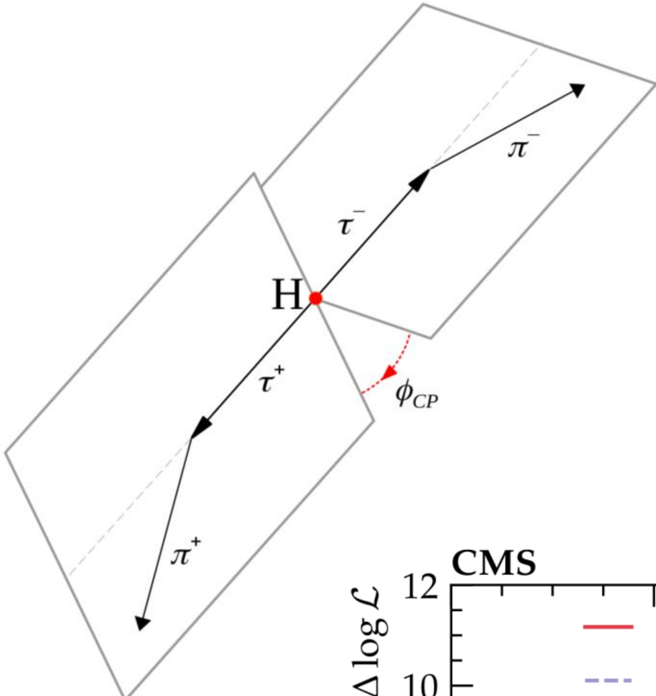
Parameter	Scenario		Observed	Expected
f_{a3}	Approach 1	best fit	0.00004	0.00000
	$f_{a2} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	68% CL	$[-0.00007, 0.00044]$	$[-0.00081, 0.00081]$
		95% CL	$[-0.00055, 0.00168]$	$[-0.00412, 0.00412]$
	Approach 1	best fit	-0.00805	0.00000
	float $f_{a2}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	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	$[-0.00072, 0.00218]$	$[-0.0057, 0.0057]$
f_{a2}	Approach 1	best fit	0.00020	0.0000
	$f_{a3} = f_{\Lambda 1} = f_{\Lambda 1}^{Z\gamma} = 0$	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 $f_{a3}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$	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 $f_{a3}, f_{\Lambda 1}$	68% CL	$[-0.00178, 0.00103]$	$[-0.0060, 0.0033]$
		95% CL	$[-0.00694, 0.00536]$	$[-0.0206, 0.0131]$
$f_{\Lambda 1}$	Approach 1	best fit	0.00004	0.00000
	$f_{a3} = f_{a2} = f_{\Lambda 1}^{Z\gamma} = 0$	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 $f_{a3}, f_{a2}, f_{\Lambda 1}^{Z\gamma}$	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	$[-0.00184, 0.00443]$	$[-0.0056, 0.0102]$
$f_{\Lambda 1}^{Z\gamma}$	Approach 1	best fit	-0.00001	0.0000
	$f_{a3} = f_{a2} = f_{\Lambda 1} = 0$	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 $f_{a3}, f_{a2}, f_{\Lambda 1}$	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 [link]

→ 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.

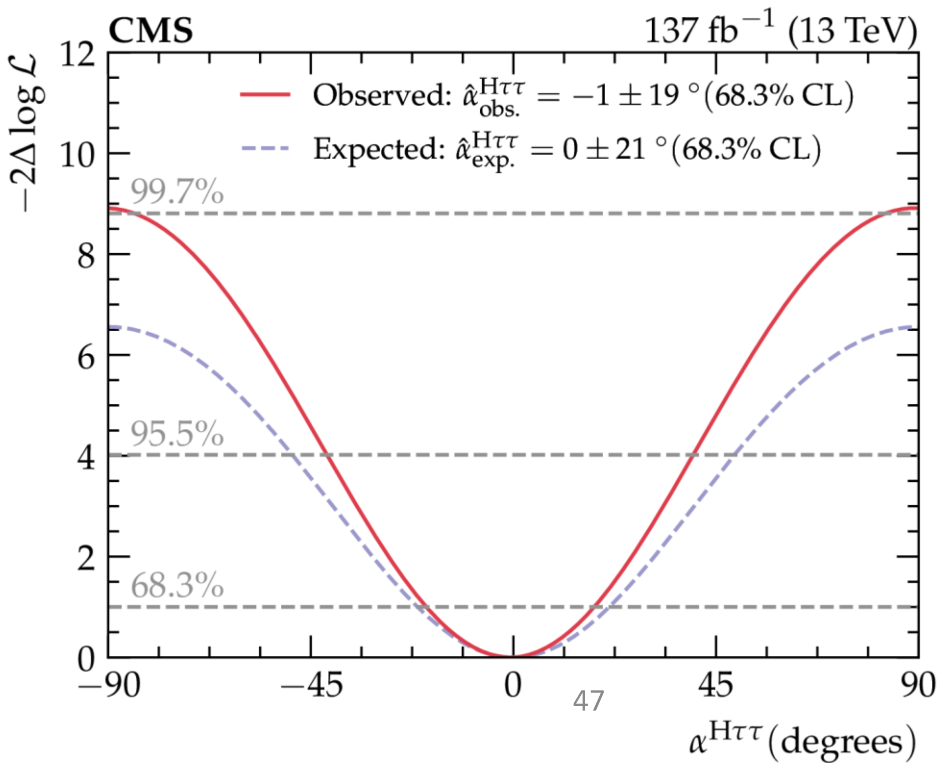
Anomalous spin-0 couplings: Hττ



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

$$A(H\tau\tau) = -\frac{m_\tau}{v}\bar{\psi}_\tau(\boldsymbol{\kappa_\tau} + i\boldsymbol{\tilde{\kappa}_\tau}\gamma_5)\psi_\tau$$

$$\alpha = \tan^{-1}\frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$



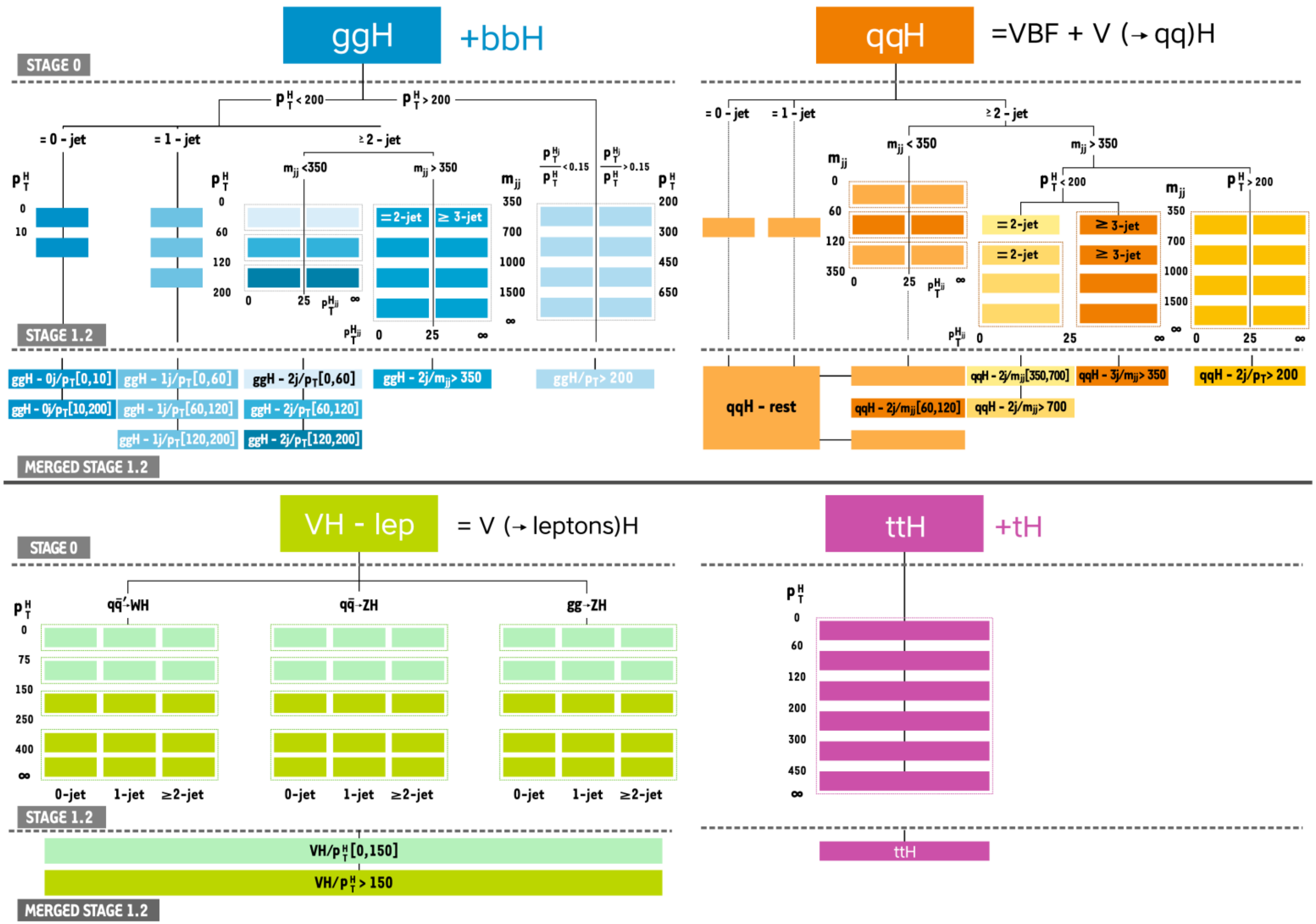
Link

α: [−42, 40] @ 95% CL

Beyond couplings: STXS (1.2)

Split production modes finer in specific final states, p_T^H, or m_{jj}

Measure the cross section for each 'production bin'



Results from individual channels:

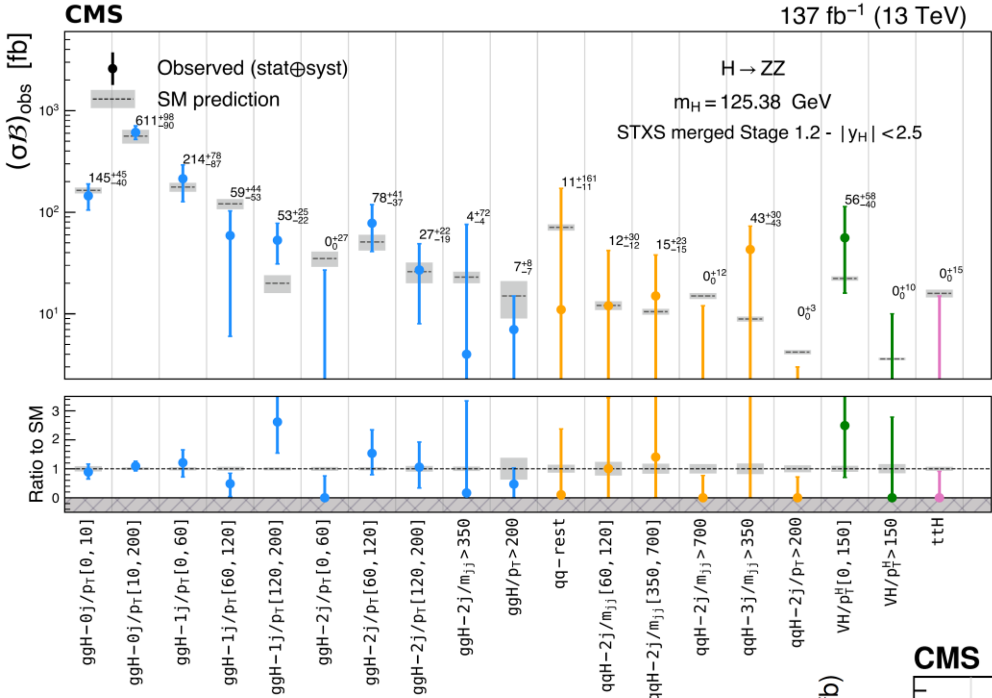
ZZ [link]

WW [link]

$\tau\tau$ [link]

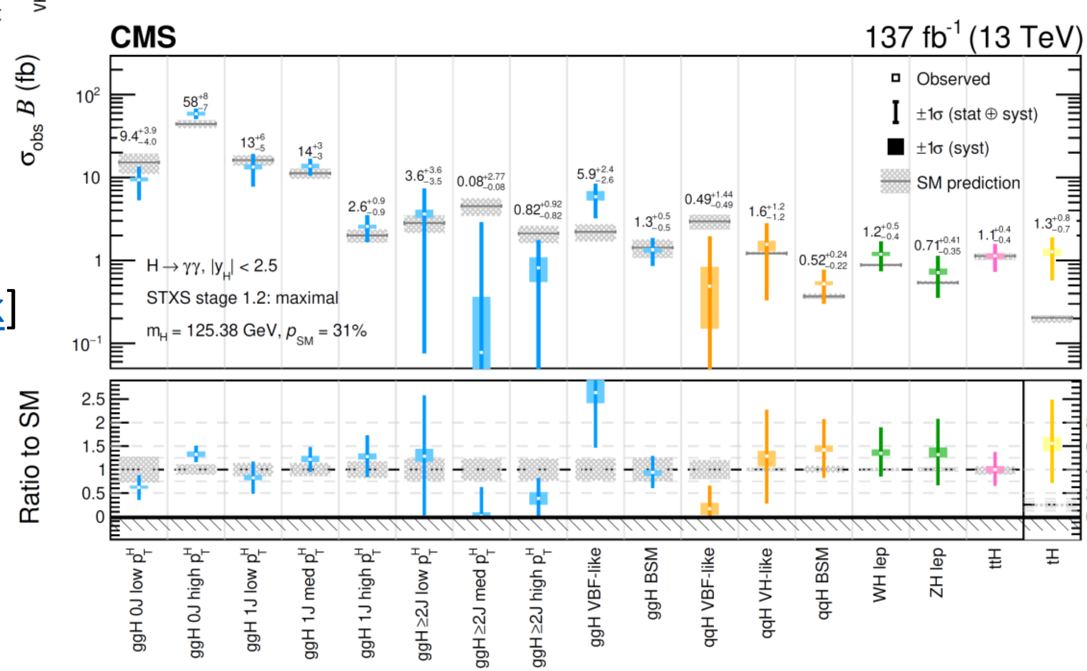
$\gamma\gamma$ [link]

Beyond couplings: STXS (1.2)



ZZ [link]

Examples from ZZ and $\gamma\gamma$ analyses
→ Slightly different bin merging schemes, but results consistent with the SM predictions so far



$\gamma\gamma$ [link]

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 (also in next slide):

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)	$\|\eta\| < 2.5\ (2.4)$
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.

Fiducial volume in CMS 4ℓ

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20\,\text{GeV}$
Next-to-leading lepton p_T	$p_T > 10\,\text{GeV}$
Additional electrons (muons) p_T	$p_T > 7(5)\,\text{GeV}$
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5\ (2.4)$
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	$40 < m_{Z_1} < 120\,\text{GeV}$
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120\,\text{GeV}$
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	$m_{\ell^+\ell'^-} > 4\,\text{GeV}$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140\,\text{GeV}$

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

Phase Space Region	Observable	Bin boundaries							
Baseline $p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$ $p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$ $\lvert\eta^{\gamma}\rvert < 2.5$ $\mathcal{I}_{gen}^{\gamma} < 10\,\text{GeV}$	$p_T^{\gamma\gamma}$	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	∞					
	$p_T^{\gamma\gamma}, n_{jets} = 0$	0	5	10	15	20	25	30	35
		45	60	∞					
	$p_T^{\gamma\gamma}, n_{jets} = 1$	0	30	60	100	170	∞		
	$p_T^{\gamma\gamma}, n_{jets} > 1$	0	100	170	250	350	∞		
	n_{jets}^{b}	0	1	≥ 2					
	$n_{leptons}$	0	1	≥ 2					
	p_T^{miss}	0	30	50	100	200	∞		
1-jet Baseline + ≥ 1 jet $p_T^{j} > 30$ GeV $\lvert\eta^{j}\rvert < 2.5$	$p_T^{j_1}$	30	40	55	75	95	120	150	200
		∞							
	$\lvert y^{j_1}\rvert$	0.0	0.3	0.6	0.9	1.2	1.6	2.0	2.5
	$\lvert\Delta\phi_{\gamma\gamma,j_1}\rvert$	0.0	2.0	2.6	2.85	3.0	3.07	π	
	$\lvert\Delta y_{\gamma\gamma,j_1}\rvert$	0.0	0.3	0.6	1.0	1.4	1.9	2.5	∞
	τ_C^{j}	< 15	15	20	30	50	80	∞	
	$p_T^{\gamma\gamma}, \tau_{Cj} < 15$ GeV	0	45	120	∞				
	$p_T^{\gamma\gamma}, 15\text{ GeV} \leq \tau_C^{j} < 25$ GeV	0	45	120	∞				
	$p_T^{\gamma\gamma}, 25\text{ GeV} \leq \tau_C^{j} < 40$ GeV	0	120	∞					
	$p_T^{\gamma\gamma}, 40\text{ GeV} \leq \tau_C^{j}$	0	200	350	∞				
2-jets Baseline + ≥ 2 jets $p_T^{j} > 30$ GeV $\lvert\eta^{j}\rvert < 4.7$	$p_T^{j_2}$	30	40	65	90	150	∞		
	$\lvert y^{j_2}\rvert$	0.0	0.6	1.2	1.8	2.5	3.5	5.0	
	$\lvert\Delta\phi_{j_1,j_2}\rvert$	0.0	0.5	0.9	1.3	1.7	2.5	π	
	$\lvert\Delta\phi_{\gamma\gamma,j_1j_2}\rvert$	0.0	2.0	2.7	2.95	3.07	π		
	$\lvert\bar{\eta}_{j_1j_2} - \eta_{\gamma\gamma}\rvert$	0.0	0.2	0.5	0.85	1.2	1.7	∞	
	m^{jj}	0	75	120	180	300	500	1000	∞
	$\lvert\Delta\eta_{j_1,j_2}\rvert$	0.0	0.7	1.6	3.0	5.0	∞		
VBF-enriched 2-jets + $n_{jets} \geq 2$ $\Delta\eta^{jj} > 3.5$ $m^{jj} > 200\,\text{GeV}$	$p_T^{\gamma\gamma}$	0	30	60	120	200	∞		
	$p_T^{j_2}$	30	40	65	90	150	∞		
	$\lvert\Delta\phi_{j_1,j_2}\rvert$	0.0	0.5	0.9	1.3	1.7	2.5	π	
	$\lvert\Delta\phi_{\gamma\gamma,j_1j_2}\rvert$	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	$\mathrm{e}\mu$(not from τdecay); opposite
Leading lepton p_{T}	$p_{\mathrm{T}}^{l_1} > 25\,\mathrm{GeV}$
Trailing lepton p_{T}	$p_{\mathrm{T}}^{l_2} > 13\,\mathrm{GeV}$
$\|\eta\|$ of leptons	$\|\eta\| < 2.5$
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 $\Delta R < 0.1$

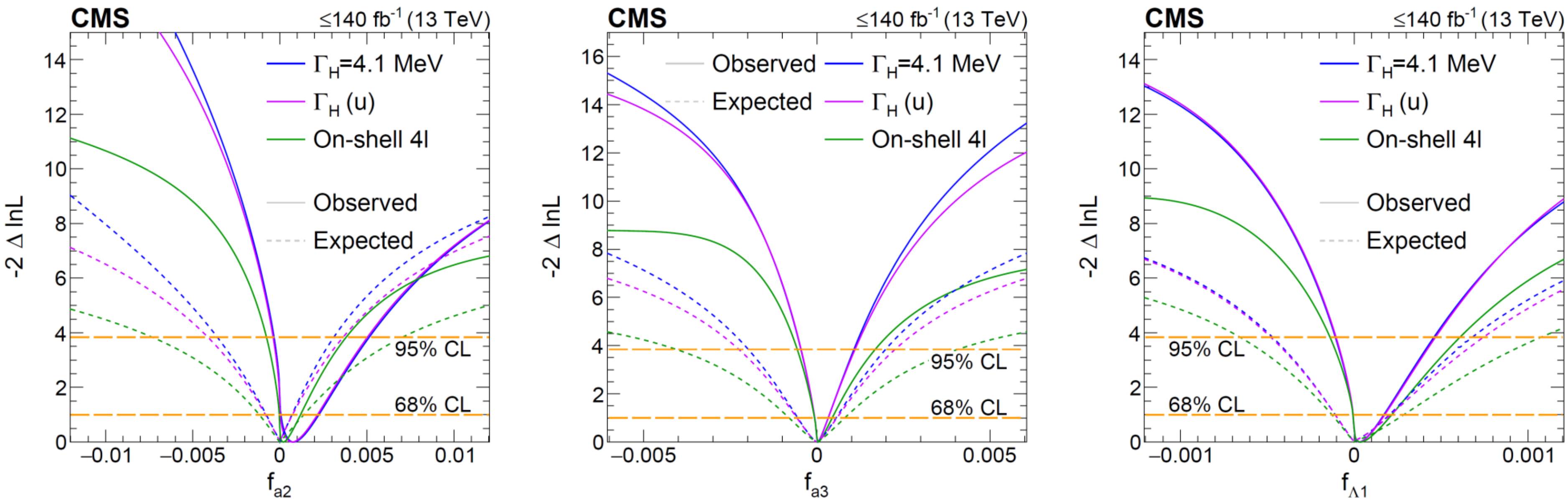
→ $\mu\tau_h$: $p_T^{\mu} > 20$ GeV, $|\eta^{\mu}| < 2.1$, $p_T^{\tau_h} > 30$ GeV, $|\eta^{\tau_h}| < 2.3$, $m_T^{\ell} < 50$ GeV

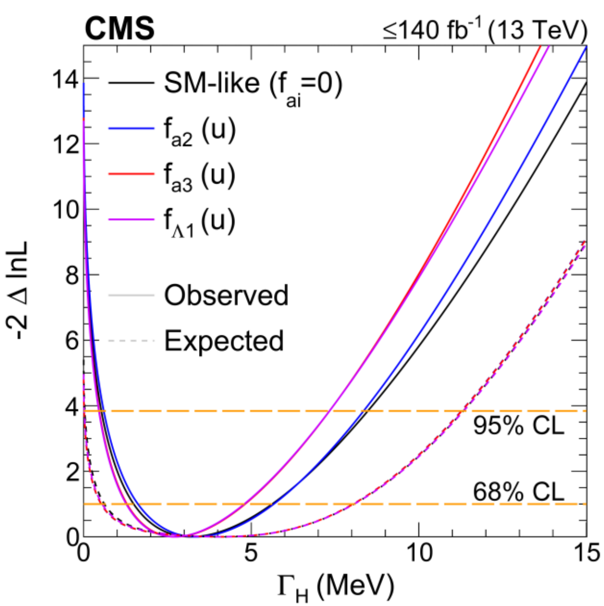
→ $e\tau_h$: $p_T^{e} > 25$ GeV, $|\eta^{\mu}| < 2.1$, $p_T^{\tau_h} > 30$ GeV, $|\eta^{\tau_h}| < 2.3$, $m_T^{\ell} < 50$ GeV

→ $e\mu$: $p_T^{\ell_1\,(\ell_2)} > 24\ (15)$ 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 [link] 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	Best fit	Observed 68% CL	Observed 95% CL	Expected 68% CL	Expected 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 [link]