Off-shell H*(125) measurements: perspective from CMS and EFT strategy

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for CMS

with pheno input from LHCHXSWG YR4,
MCFM / JHUGen framework,
with thanks to Markus Schulze

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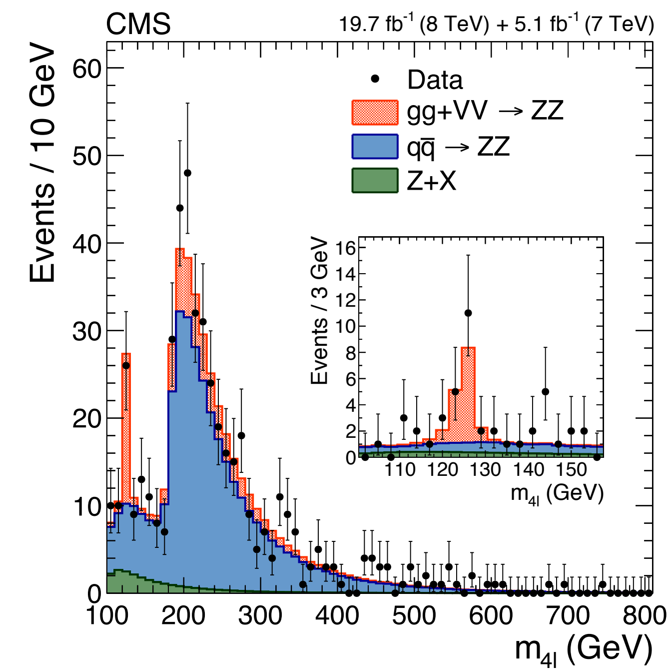
LHCHXSWG Offshell & Interference Meeting

Off-shell H*(125) measurements from CMS

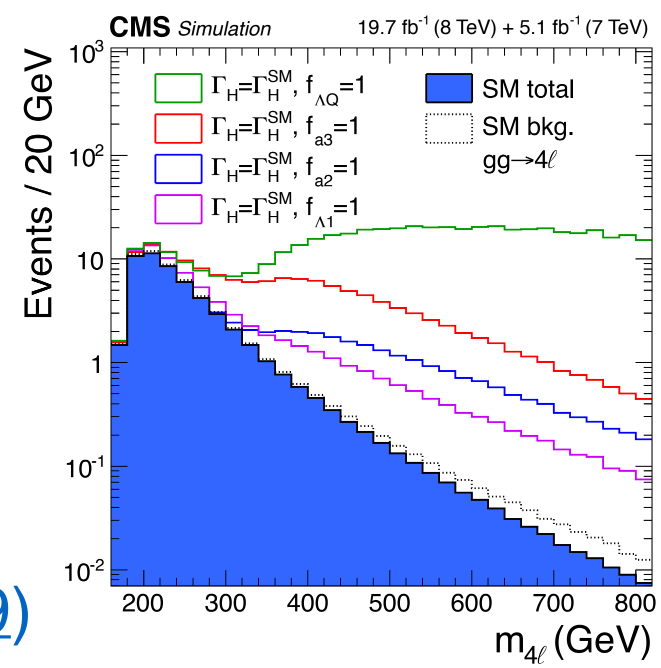
- Some history of off-shell width of H(125)
  - H→4ℓ,2ℓ2ν (arXiv:1405.3455)

    $\Gamma_H < 22\ \mathrm{MeV}$



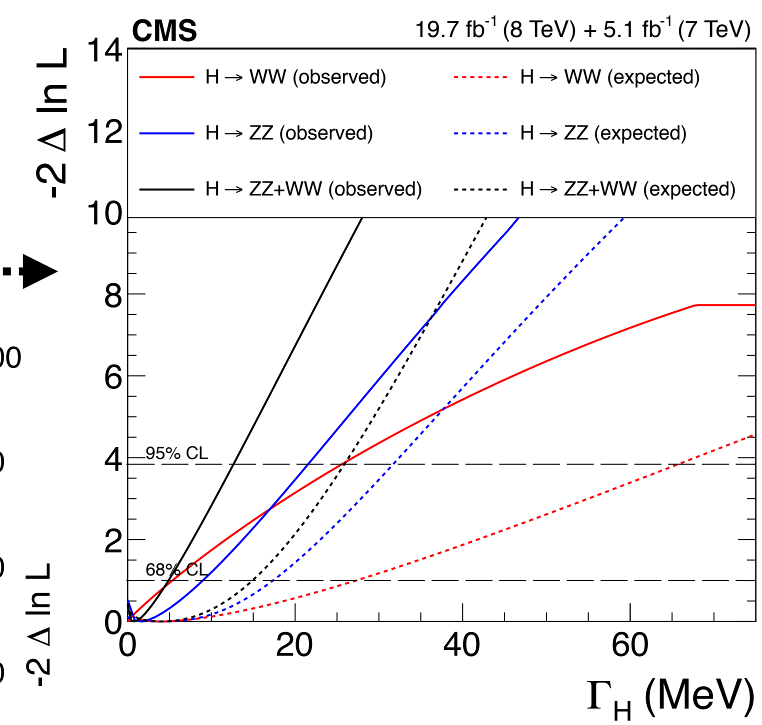
  - H→4ℓ (arXiv:1507.06656)

    τ_H, Γ_H and $f_{\Lambda Q}$



  - H→WW+ZZ (arXiv:1605.02329)

    $\Gamma_H < 13\ \mathrm{MeV}$

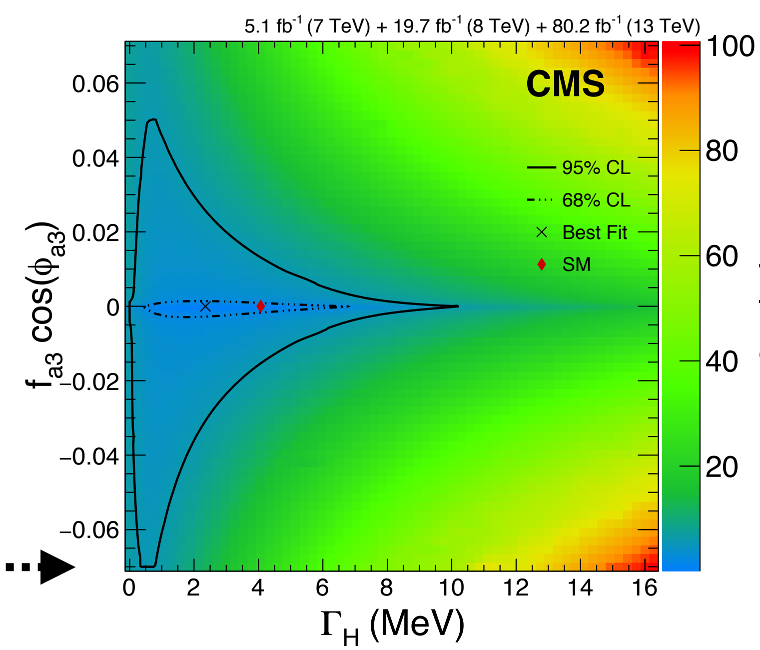


focus today

  - H→4ℓ (arXiv:1901.00174)

    $\Gamma_H = 3.2^{+2.8}_{-2.2}\ \mathrm{MeV}$ $\begin{matrix} < 9.16\ \mathrm{MeV} \\ > 0.08\ \mathrm{MeV} \end{matrix}$

    Γ_H and $f_{a3}, f_{a2}, f_{\Lambda 1}$



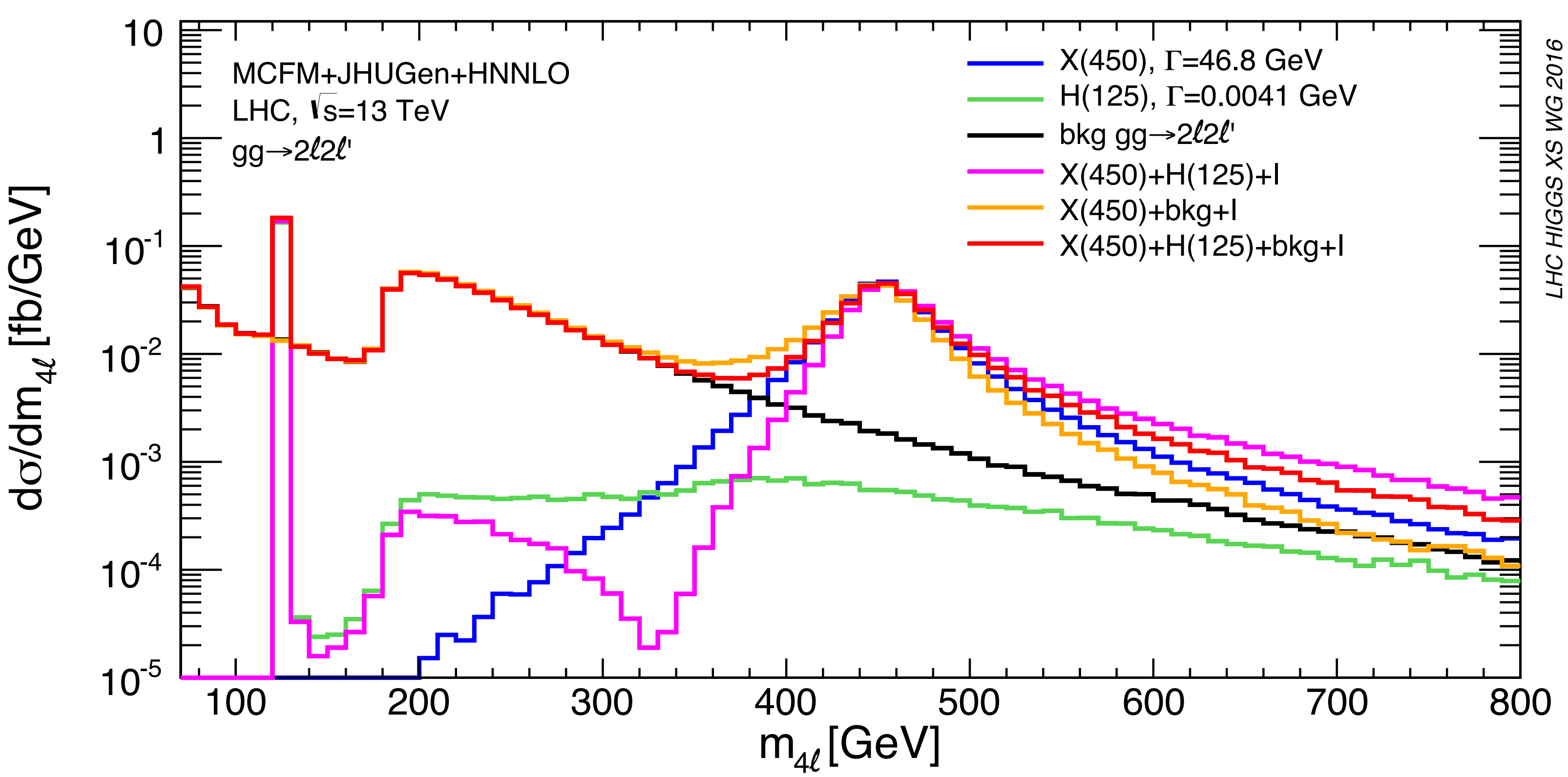
Off-shell gluon fusion and EW production

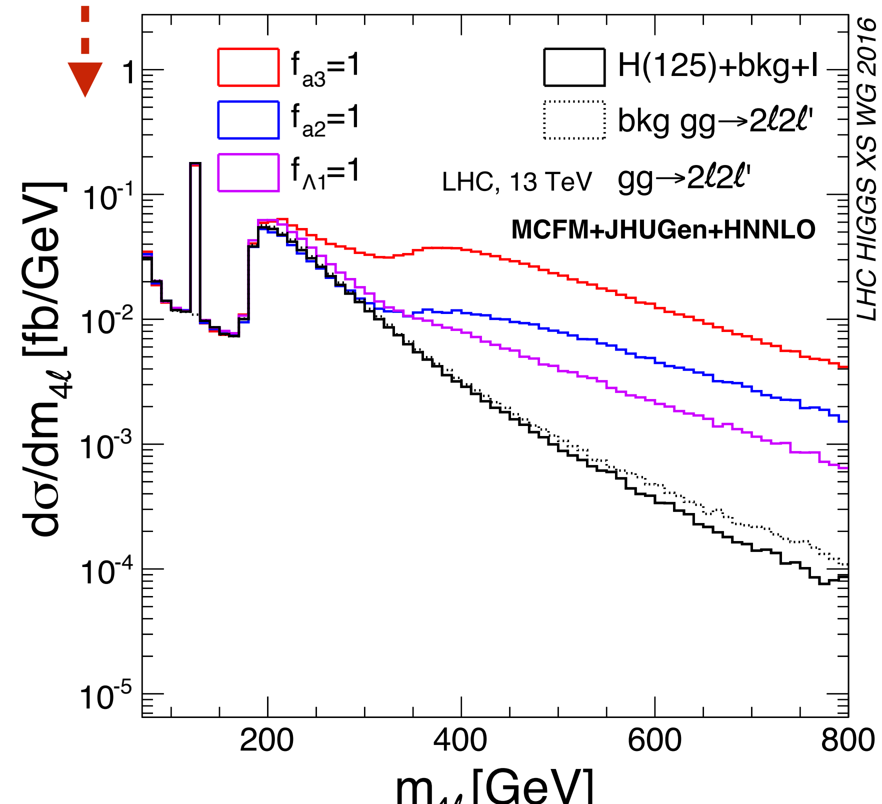
- Coherent framework to treat four effects in “off-shell”

(1) width Γ_H modification
(2) new resonance(s) X
(3) anomalous H couplings HVV and Hgg
(4) anomalous VBS

- Tools MCFM+JHUGen and MELA
H* + X + continuum + interference
include re-weighting and discriminants
cover both ggH and EW (VBF, VH)
integrated with POWHEG, MiNLO…

http://spin.pha.jhu.edu





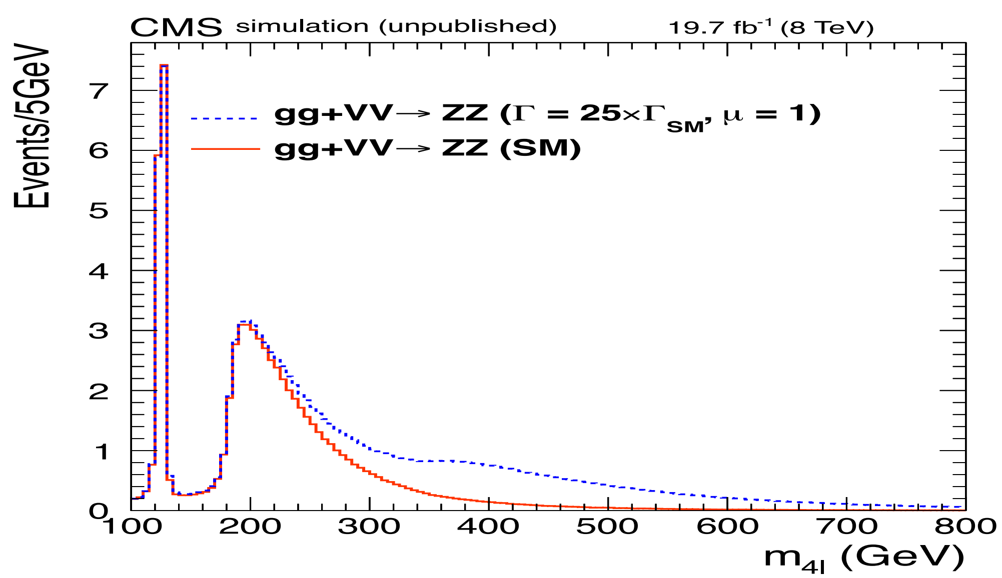
Some questions to discuss in this forum

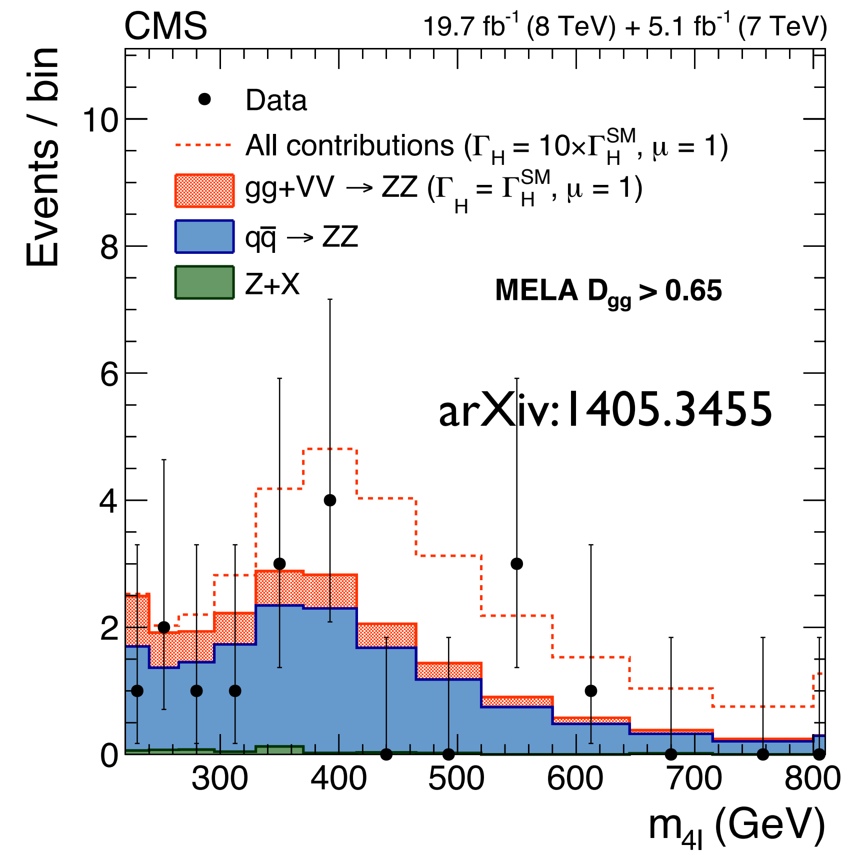
- How to explore (hep-ex → hep-ph) off-shell region?
  - — present as Γ_H
  - — present as off-shell signal strength μ, or σ
  - — present as some STXS-like signal strengths
  - — present as modification of (EFT) H couplings
  - — present as modification of (EFT) EW parameters
  - — present as search for new resonance(s)
  - — present as search for some other (exotic) model
  - — present as differential distribution
  - — present as in other ways …
- May become very complex, but we also should be practical:
  - — in hep-ex, we like to have a path to explore the data
  - — at present, we are not limited in having paths
  - — each option has pros and cons…

(1) width Γ_H modification

$$\frac{d\,\sigma_{gg\to H\to ZZ}}{d\,m^2_{ZZ}} \sim \frac{g^2_{\mathrm{ggH}}\,g^2_{\mathrm{HZZ}}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma_H{}^2}$$

hep-ph: arXiv:1206.4803, arXiv:1307.4935





PDG-2016

VALUE (GeV)		*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1.7		95	[1] KHACHATRY...15AM	CMS	pp, 7, 8 TeV
>3.5	$\times 10^{-12}$	95	[2] KHACHATRY...15BA	CMS	pp, 7, 8 TeV, flight distance
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.022		95	[7] KHACHATRY...14D	CMS	pp, 7, 8 TeV, $ZZ^{(*)}$

PDG-2018

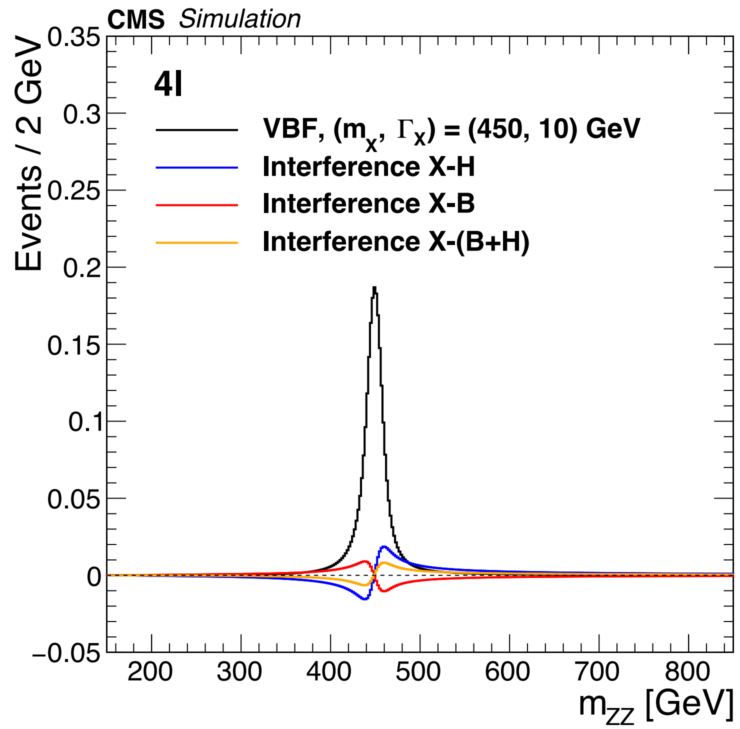
VALUE (GeV)		*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
<1.10		95	[1] SIRUNYAN 17AV	CMS	pp, 13 TeV, $ZZ^* \rightarrow 4\ell$
<0.013		95	[2] KHACHATRY...16BA	CMS	pp, 7, 8 TeV, $ZZ^{(*)}$, $WW^{(*)}$
<1.7		95	[3] KHACHATRY...15AM	CMS	pp, 7, 8 TeV
>3.5	$\times 10^{-12}$	95	[4] KHACHATRY...15BA	CMS	pp, 7, 8 TeV, flight distance
<5.0		95	[5] AAD 14W	ATLS	pp, 7, 8 TeV, $\gamma\gamma$
<2.6		95	[5] AAD 14W	ATLS	pp, 7, 8 TeV, $ZZ^* \rightarrow 4\ell$
• • • We do not use the following data for averages, fits, limits, etc. • • •					

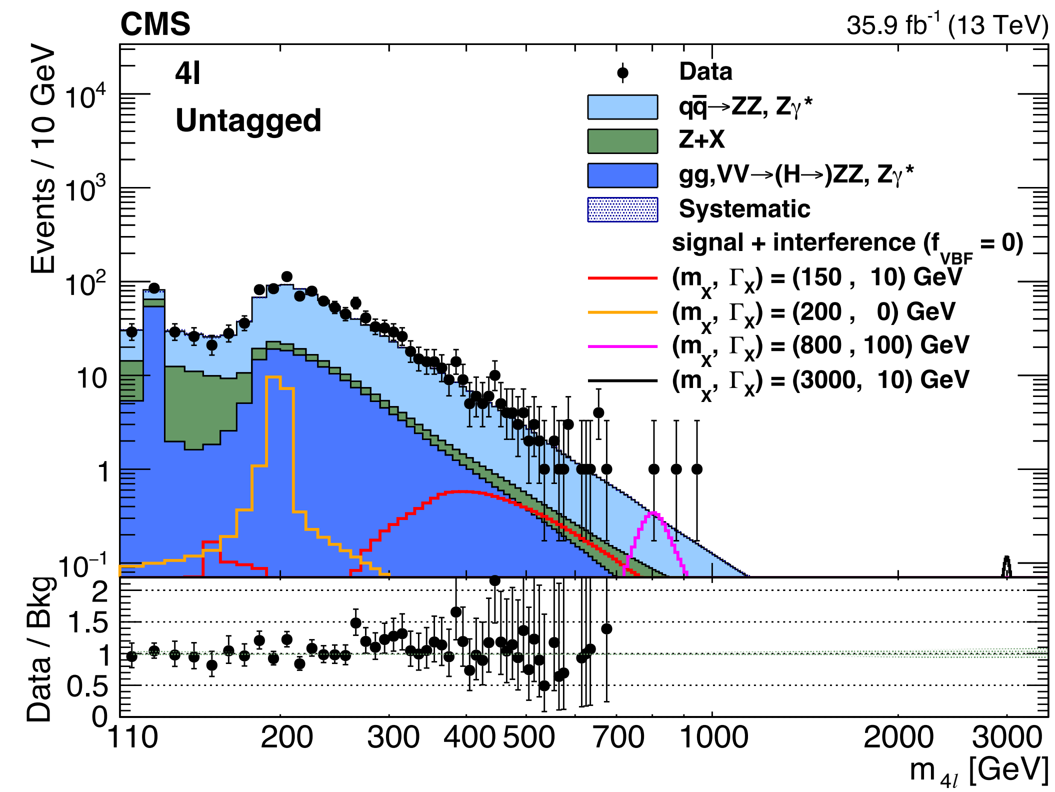
PDG-2020…

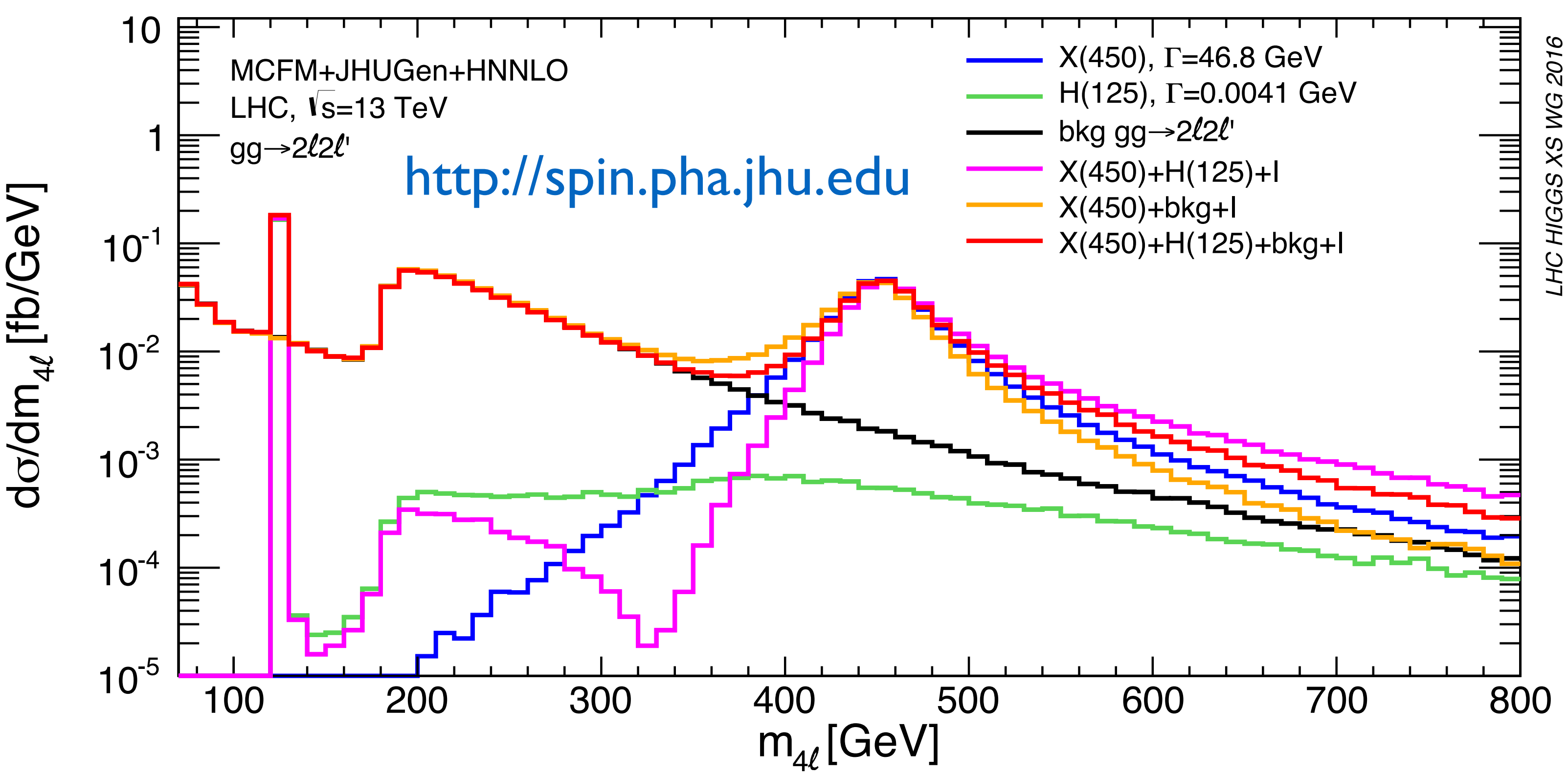
(2) new resonance(s) X

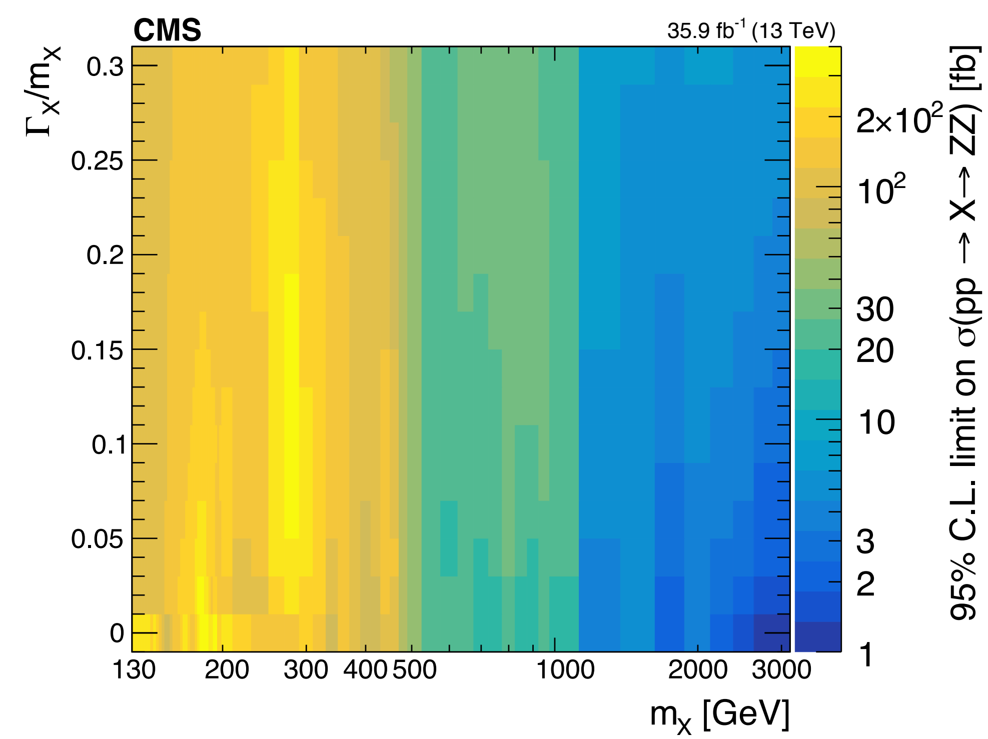
– H→4ℓ,2ℓ2q,2ℓ2ν (arXiv:1804.01939)

- any mass
  any width
  any production
  (ggH or EW)
  full interference
  SM-like coupling
  (but can vary)









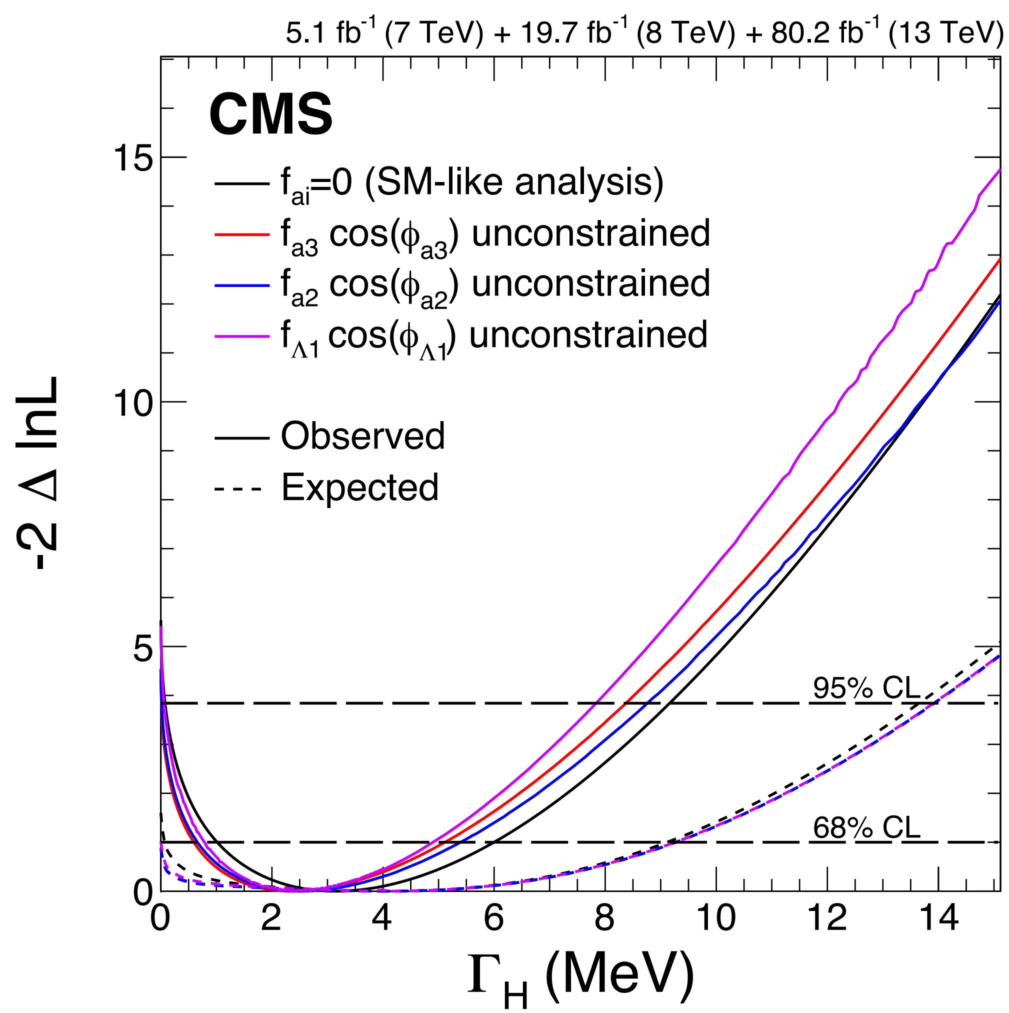
(3) anomalous HVV couplings (EFT)

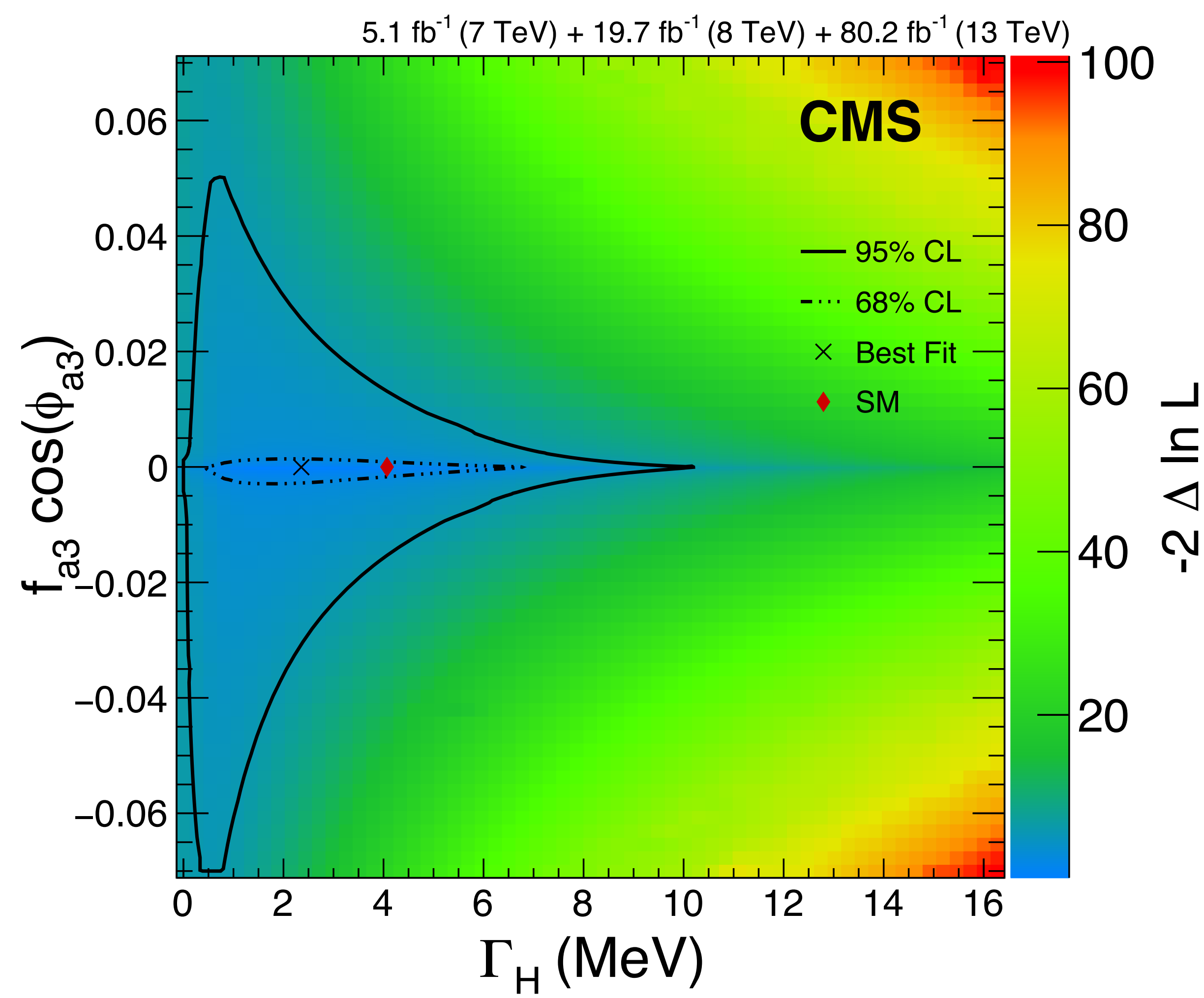
- tested anomalous HVV couplings (production and decay)

$$\frac{d\,\sigma_{gg\to H\to ZZ}}{d\,m_{ZZ}^2} \sim \frac{g_{\mathrm{ggH}}^2 g_{\mathrm{HZZ}}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H{}^2}$$

(1) not much effect on Γ_H

(2) constrain couplings given Γ_H or profile Γ_H





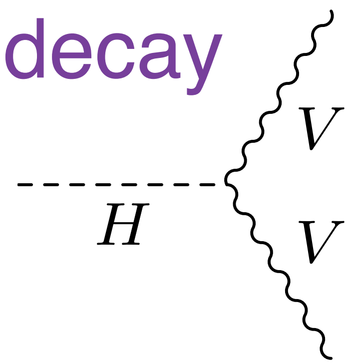
Consider HVV and Hgg couplings for $J_H=0$

- HVV: H→VV, VBF, VH, ggH — affect kinematics

$$A = \frac{1}{v}\left(\left[a_1 - e^{i\phi_{\Lambda Q}}\frac{(q_1+q_2)^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}}\frac{q_1^2+q_2^2}{(\Lambda_1)^2}\right] m_V^2\epsilon_1^*\epsilon_2^* + a_2 f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + a_3 f^{*(1)}_{\mu\nu}\tilde{f}^{*(2),\mu\nu}\right) \longleftarrow \left(\frac{q^2}{\Lambda^2}\right)^N$$

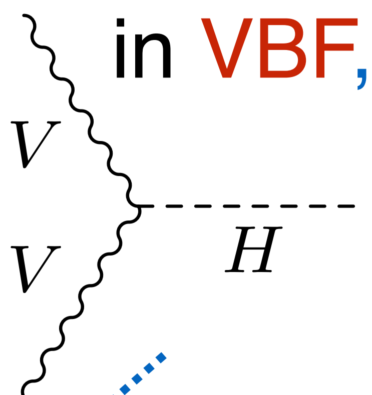
$N = 0,1\ldots$

in decay

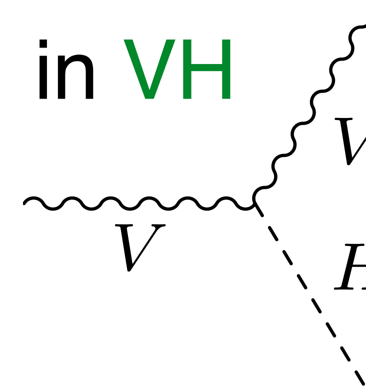


V=W,Z,γ,g

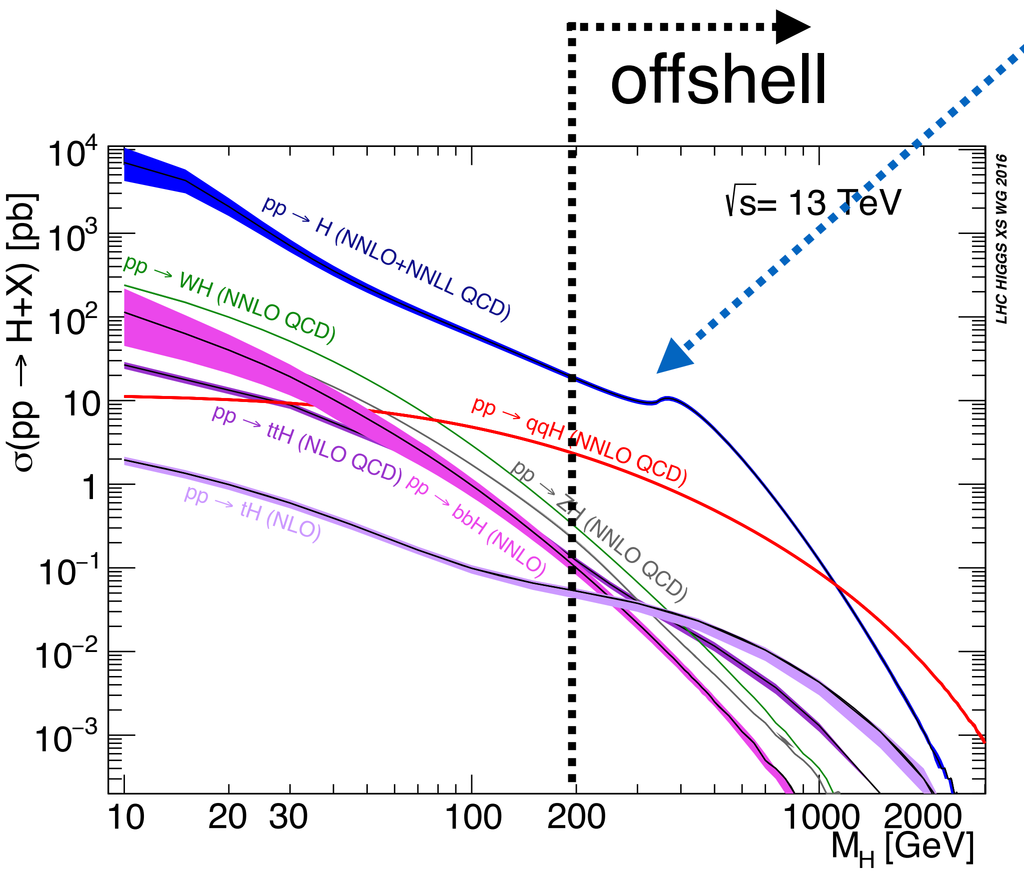
in VBF, ggH

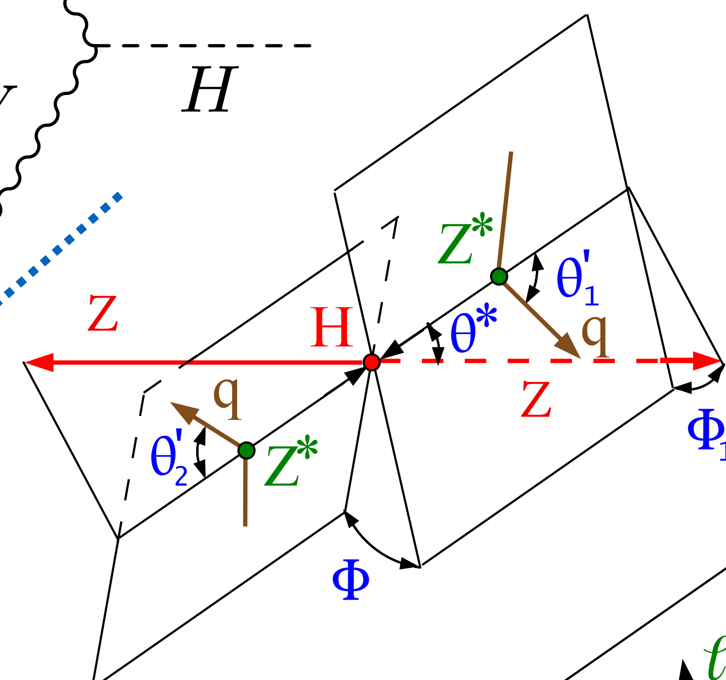


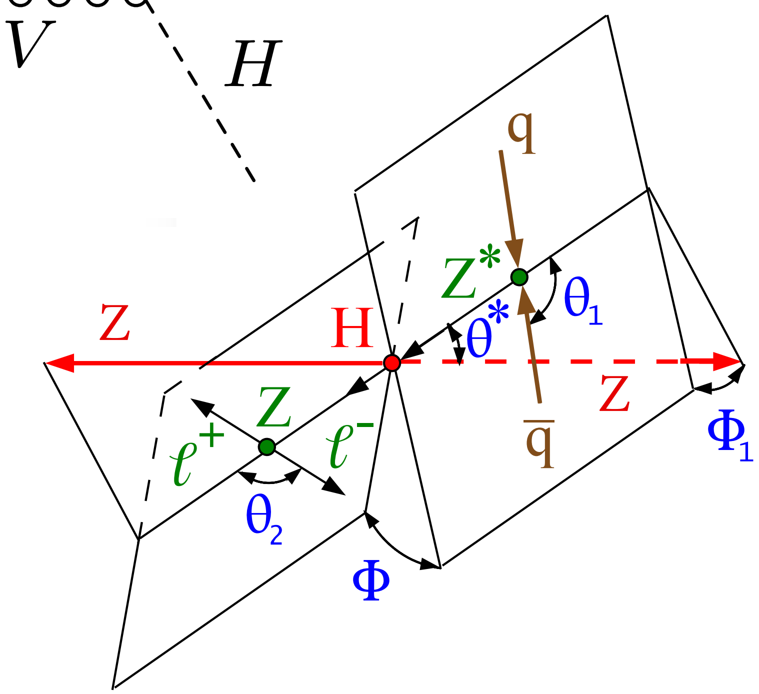
in VH

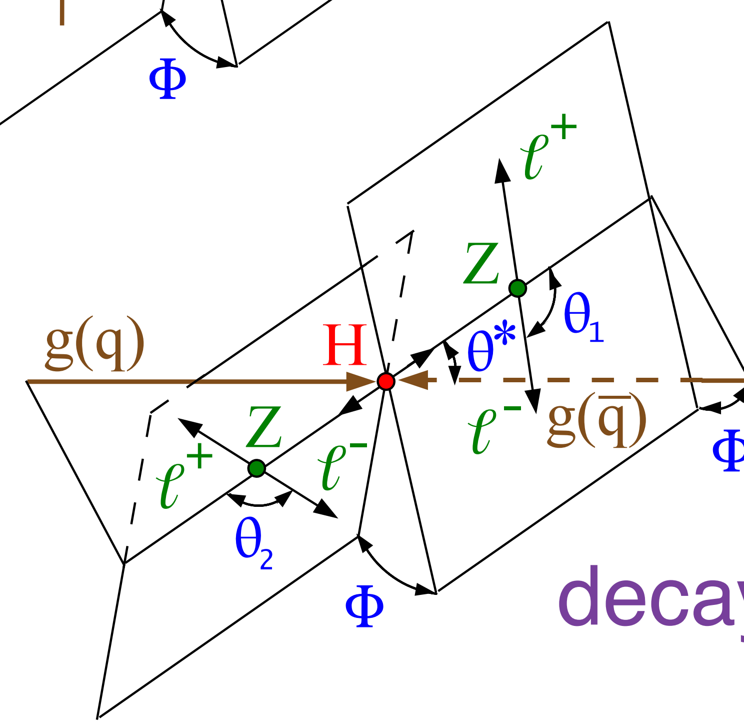


offshell









decay

Effective Lagrangian and EFT

- Effective Lagrangian (up to dim.6) $\in$ Amplitude (last slide)

$$L(HVV) \sim \boxed{a_1 \frac{m_Z^2}{2} H Z^\mu Z_\mu - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 H Z^\mu \Box Z_\mu - \frac{\kappa_3}{2(\Lambda_Q)^2} m_Z^2 \Box H Z^\mu Z_\mu - \frac{1}{2} a_2 H Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 H Z^{\mu\nu} \tilde{Z}_{\mu\nu}}$$

ZZ

$$+ a_1^{WW} m_W^2 H W^{+\mu} W_\mu^- - \frac{1}{(\Lambda_1^{WW})^2} m_W^2 H \left(\kappa_1^{WW} W_\mu^- \Box W^{+\mu} + \kappa_2^{WW} W_\mu^+ \Box W^{-\mu} \right)$$
$$- \frac{\kappa_3^{WW}}{\left(\Lambda_Q^{WW}\right)^2} m_W^2 \Box H W^{+\mu} W_\mu^- - a_2^{WW} H W^{+\mu\nu} W_{\mu\nu}^- - a_3^{WW} H W^{+\mu\nu} \tilde{W}_{\mu\nu}^-$$

WW

$$+ \frac{\kappa_2^{Z\gamma}}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 H Z_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} H F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} H F^{\mu\nu} \tilde{Z}_{\mu\nu}$$

Zγ

$$- \frac{1}{2} a_2^{\gamma\gamma} H F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} H F^{\mu\nu} \tilde{F}_{\mu\nu}$$

γγ

$$- \frac{1}{2} a_2^{gg} H G_a^{\mu\nu} G_{\mu\nu}^a - \frac{1}{2} a_3^{gg} H G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a,$$

gg

- used on CMS since 2012

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

- Higgs basis
  Eq.(II.2.20) of YR4
  arXiv:1610.07922

Effective Lagrangian and EFT

- One can relate coefficients (see JHUGen manual http://spin.pha.jhu.edu)

$$\delta c_z = \frac{1}{2} g_1^{ZZ} - 1, \qquad c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} g_2^{ZZ}, \qquad c_{z\Box} = \frac{M_Z^2 s_w^2}{e^2} \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}, \qquad \tilde{c}_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} g_4^{ZZ},$$

$$\delta c_w = \frac{1}{2} g_1^{WW} - 1, \qquad c_{ww} = -\frac{2 s_w^2}{e^2} g_2^{WW}, \qquad c_{w\Box} = \frac{M_W^2 s_w^2}{e^2} \frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}, \qquad \tilde{c}_{ww} = -\frac{2 s_w^2}{e^2} g_4^{WW},$$

$$c_{z\gamma} = -\frac{2 s_w c_w}{e^2} g_2^{Z\gamma}, \qquad \tilde{c}_{z\gamma} = -\frac{2 s_w c_w}{e^2} g_4^{Z\gamma}, \qquad c_{\gamma\Box} = \frac{s_w c_w}{e^2} \frac{M_Z^2}{(\Lambda_1^{Z\gamma})^2} \kappa_2^{Z\gamma},$$

$$c_{\gamma\gamma} = -\frac{2}{e^2} g_2^{\gamma\gamma}, \qquad \tilde{c}_{\gamma\gamma} = -\frac{2}{e^2} g_4^{\gamma\gamma}, \qquad c_{gg} = -\frac{2}{g_s^2} g_2^{gg}, \qquad \tilde{c}_{gg} = -\frac{2}{g_s^2} g_4^{gg}.$$

- SU(2)xU(1) symmetry reduces the number of independent coefficients

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

Count the number of EFT parameters in the Higgs basis

- Start with 13 HVV and 2 Hgg:

$$\delta c_z = \frac{1}{2} g_1^{ZZ} - 1, \quad c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} g_2^{ZZ}, \quad c_{z\Box} = \frac{M_Z^2 s_w^2}{e^2} \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}, \quad \tilde{c}_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} g_4^{ZZ},$$

$$\delta c_w = \frac{1}{2} g_1^{WW} - 1, \quad c_{ww} = -\frac{2 s_w^2}{e^2} g_2^{WW}, \quad c_{w\Box} = \frac{M_W^2 s_w^2}{e^2} \frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}, \quad \tilde{c}_{ww} = -\frac{2 s_w^2}{e^2} g_4^{WW},$$

$$c_{z\gamma} = -\frac{2 s_w c_w}{e^2} g_2^{Z\gamma}, \quad \tilde{c}_{z\gamma} = -\frac{2 s_w c_w}{e^2} g_4^{Z\gamma}, \quad c_{\gamma\Box} = \frac{s_w c_w}{e^2} \frac{M_Z^2}{(\Lambda_1^{Z\gamma})^2} \kappa_2^{Z\gamma},$$

$$c_{\gamma\gamma} = -\frac{2}{e^2} g_2^{\gamma\gamma}, \quad \tilde{c}_{\gamma\gamma} = -\frac{2}{e^2} g_4^{\gamma\gamma}, \quad c_{gg} = -\frac{2}{g_s^2} \boxed{g_2^{gg}}, \quad \tilde{c}_{gg} = -\frac{2}{g_s^2} \boxed{g_4^{gg}}.$$

- Reduce to 8 HVV and 2 Hgg:

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

also appear
in H→Zγ,γγ

no on-shell vs
off-shell interplay

Connection to the Warsaw basis

- Higgs basis (see II.2.1.d of YR4) is more intuitive experimentally

  use mass eigenstates

- Warsaw basis
  is simply a rotation
  from Z,γ,W to B,W⁰,W →

$$\boxed{g_4^{ZZ}} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 w_{\phi\tilde{B}} + c_w^2 w_{\phi\tilde{W}} + s_w c_w w_{\phi B\tilde{W}}\right),$$

$$\boxed{g_4^{\gamma\gamma}} = -2\frac{v^2}{\Lambda^2}\left(c_w^2 w_{\phi\tilde{B}} + s_w^2 w_{\phi\tilde{W}} - s_w c_w w_{\phi B\tilde{W}}\right),$$

$$\boxed{g_4^{Z\gamma}} = -2\frac{v^2}{\Lambda^2}\left(s_w c_w (w_{\phi\tilde{W}} - w_{\phi\tilde{B}}) + \frac{1}{2}(s_w^2 - c_w^2) w_{\phi B\tilde{W}}\right),$$

$$\boxed{g_4^{gg}} = -2\frac{v^2}{\Lambda^2} w_{\phi\tilde{G}}.$$

Higgs basis

3 HZZ couplings

SM

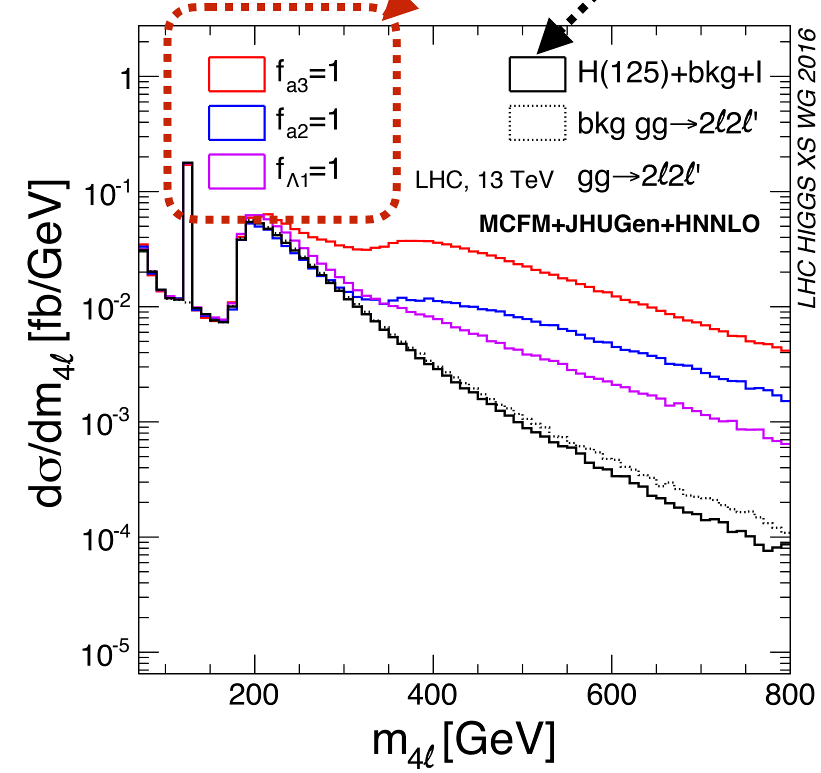
- Warsaw HVV basis complicates exp. parameterization:

— mixes physical states Z,γ,W to B,W⁰,W

— off-shell effect interplay of
H→ZZ* (or WW*) vs H*→ZZ (or WW)

— off-shell effect does not work with H→Vγ*

— mixing H→Zγ*, γ*γ*, ZZ*
need to code ~3 times more parameters



Count the number of EFT parameters in the Higgs basis

- Higgs HVV basis is ideal for off-shell studies
  - — does not mix physical states Z,γ,W to non-physical B,W⁰,W
  - — off-shell effect is interplay of Z* (or W*) vs H*
  - — it is always possible to rotate the basis in the end
- Reduce to 4 HVV and 2 Hgg EFT couplings

  on CMS also set $g_i^{WW} = g_i^{ZZ}$ $(\Leftrightarrow c_w = 1$ in EFT relationship)

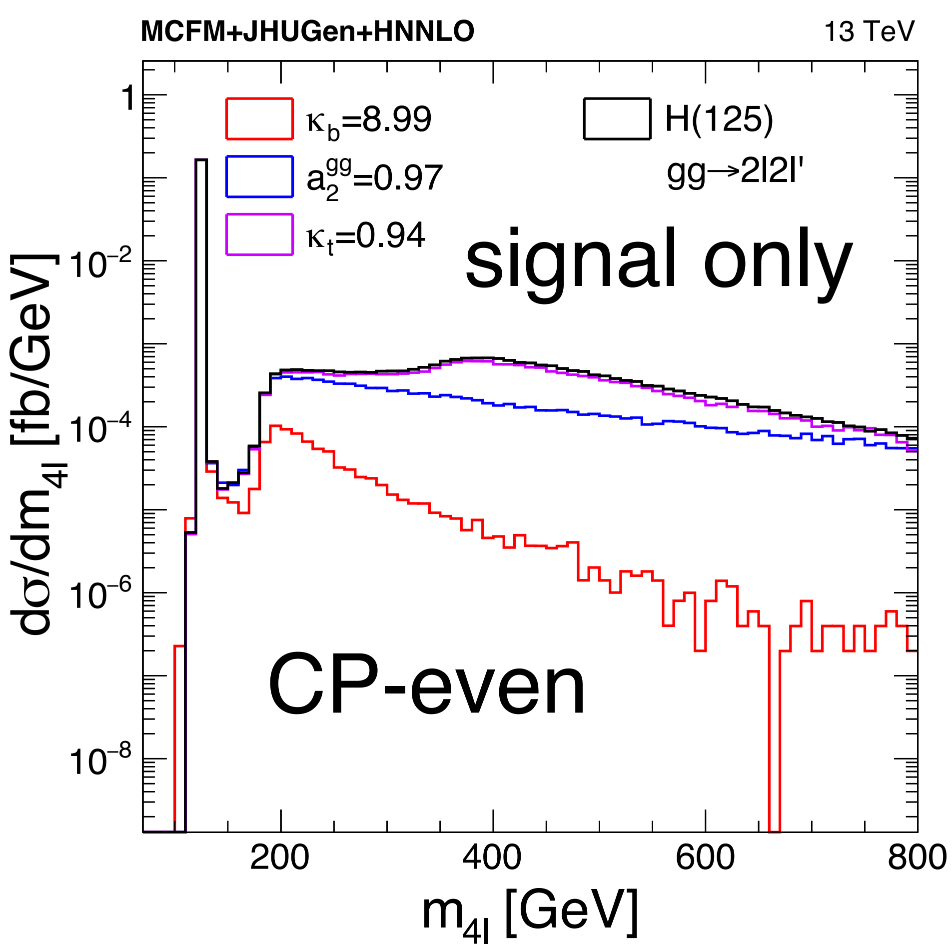
$$
\begin{aligned}
g_1^{WW} &= \boxed{g_1^{ZZ}}, \\
g_2^{WW} &= c_w^2 \boxed{g_2^{ZZ}} + \cancel{s_w^2} \boxed{g_2^{\gamma\gamma}} + 2\cancel{s_w} c_w \boxed{g_2^{Z\gamma}}, \\
g_4^{WW} &= c_w^2 \boxed{g_4^{ZZ}} + \cancel{s_w^2} \boxed{g_4^{\gamma\gamma}} + 2\cancel{s_w} c_w \boxed{g_4^{Z\gamma}}, \\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

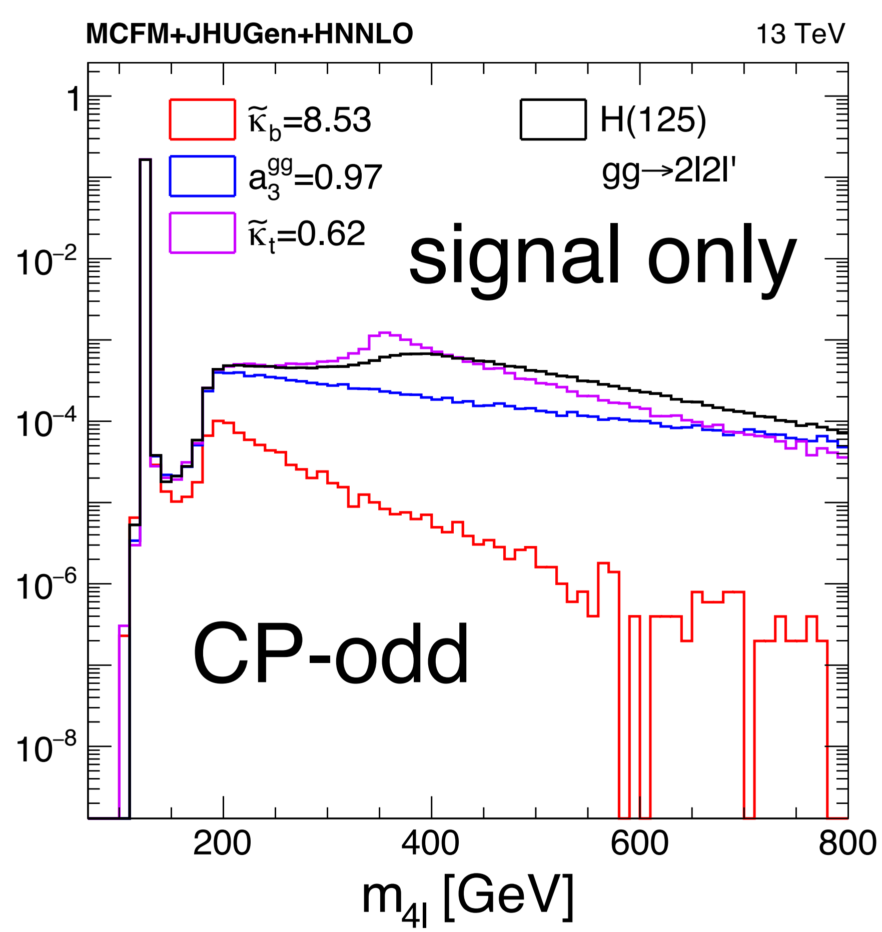
do not consider in off-shell

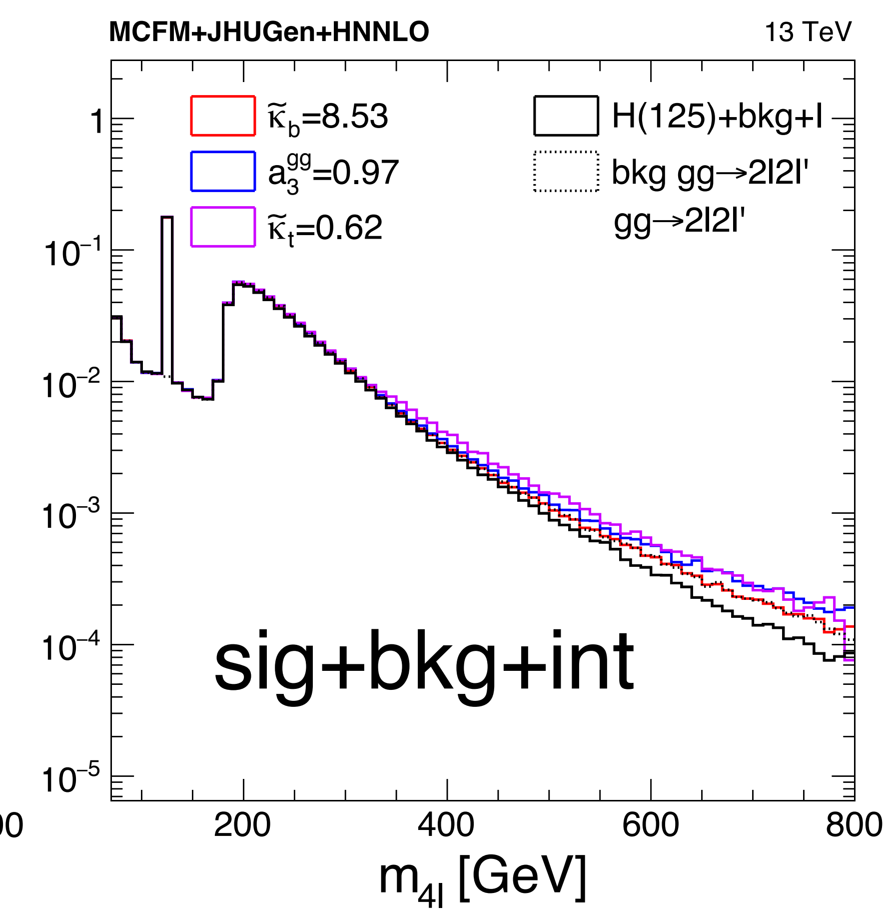
(3) anomalous Hgg couplings

- Hgg basis is much simpler, only CP-odd and CP-even, but
  - — resolve the loop with the top and bottom
  - — assume heavy particles in the loop (point-like)
  - — any combination of the above, any CP mixture
- Not explored yet on CMS, but published tools and distributions:

Springer ISBN 978-3-030-25474-2 also CERN-THESIS-2018-189







(4) anomalous VBS (EW)

- Example of quartic-gauge couplings / VBS:

$$\mathcal{L}_{\rm qgc} = e^2(W^+_\mu A_\mu W^-_\nu A_\nu - W^+_\mu W^-_\mu A_\nu A_\nu) + \frac{e^2}{2s^2_w}(1+2c^2_w \boxed{\delta g_{1,z}})(W^+_\mu W^+_\mu W^-_\nu W^-_\nu - W^+_\mu W^-_\mu W^+_\nu W^-_\nu)$$
$$+ e^2 \frac{c^2_w}{s^2_w}(1+2\boxed{\delta g_{1,z}})(W^+_\mu Z_\mu W^-_\nu Z_\nu - W^+_\mu W^-_\mu Z_\nu Z_\nu)$$
$$+ e^2 \frac{c_w}{s_w}(1+\boxed{\delta g_{1,z}})(W^+_\mu Z_\mu W^-_\nu A_\nu + W^+_\mu A_\mu W^-_\nu Z_\nu - 2W^+_\mu W^-_\mu Z_\nu A_\nu) + \ldots$$

0 in SM

- Relate HIG and EW thru EFT:

$$\boxed{\delta g_{1,z}} = \frac{1}{2}\left(\frac{s^2_w}{c^2_w} d^{ZZWW} - 1\right) = \frac{s_w}{c_w} d^{Z\gamma WW} - 1$$

$$d^{ZZWW} = \frac{c^2_w}{s^2_w}\left(2d^Z_2 - 1\right)$$

CP-even HVV couplings

$$d^Z_2 = d^Z_3 = 1 - \frac{s^2_w}{c^2_w - s^2_w}(\boxed{g_2^{\gamma\gamma}} - \boxed{g_2^{ZZ}}) - \frac{s_w}{c_w}\boxed{g_2^{Z\gamma}} - \frac{M^2_Z}{2(c^2_w - s^2_w)}\boxed{\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}} + \ldots$$

- So far off-shell H analysis does not change VBS for EFT have the option to change HVV and QGC/TGC coherently…

Likelihood fit analysis

- MC-driven: fill templates of observables [arXiv:1901.00174]

(1) very large number of observables (13 for production + decay) translates to a very large number of bins in histograms

solution: MELA discriminants guaranteed full information

$$\mathcal{D}_{\rm alt}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\rm sig}(\mathbf{\Omega})}{\mathcal{P}_{\rm sig}(\mathbf{\Omega}) + \mathcal{P}_{\rm alt}(\mathbf{\Omega})} \qquad \mathcal{D}_{\rm int}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\rm int}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{\rm sig}(\mathbf{\Omega})\ \mathcal{P}_{\rm alt}(\mathbf{\Omega})}}$$

Category	VBF-tagged	VH-tagged	Untagged
Selection	$\mathcal{D}_{\rm 2jet}^{\rm VBF}$ or $\mathcal{D}_{\rm 2jet}^{\rm VBF,BSM} > 0.5$	$\mathcal{D}_{\rm 2jet}^{\rm WH}$ or $\mathcal{D}_{\rm 2jet}^{\rm WH,BSM}$, or $\mathcal{D}_{\rm 2jet}^{\rm ZH}$ or $\mathcal{D}_{\rm 2jet}^{\rm ZH,BSM} > 0.5$	Rest of events
SM obs.	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm VBF+dec}$, $\mathcal{D}_{\rm bsi}^{\rm VBF+dec}$	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm VH+dec}$, $\mathcal{D}_{\rm bsi}^{\rm VH+dec}$	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm kin}$, $\mathcal{D}_{\rm bsi}^{\rm gg,dec}$
a_3 obs.	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm VBF+dec}$, $\mathcal{D}_{0-}^{\rm VBF+dec}$	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm VH+dec}$, $\mathcal{D}_{0-}^{\rm VH+dec}$	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm kin}$, $\mathcal{D}_{0-}^{\rm dec}$
a_2 obs.	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm VBF+dec}$, $\mathcal{D}_{0h+}^{\rm VBF+dec}$	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm VH+dec}$, $\mathcal{D}_{0h+}^{\rm VH+dec}$	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm kin}$, $\mathcal{D}_{0h+}^{\rm dec}$
Λ_1 obs.	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm VBF+dec}$, $\mathcal{D}_{\Lambda1}^{\rm VBF+dec}$	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm VH+dec}$, $\mathcal{D}_{\Lambda1}^{\rm VH+dec}$	$m_{4\ell}$, $\mathcal{D}_{\rm bkg}^{\rm kin}$, $\mathcal{D}_{\Lambda1}^{\rm dec}$

Likelihood fit analysis

- MC-driven: fill templates of observables — arXiv:1901.00174

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translates to a very large number of bins in histograms

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(2) large number of cross-terms in $|(A_1 + A_2 + \ldots)(B_1 + B_2 + \ldots)|^2$
translates to a large number of histograms

solution: limit number of couplings: $\Gamma_H, \mu_{EW}, \mu_{ggH}, f_{ai} = \frac{|a_i|^2\sigma_i}{\Sigma|a_j|^2\sigma_j}$

joint fit with on-shell

$$\mathcal{P}_{jk}(\vec{x};\vec{\xi}_{jk},\vec{\zeta}) = \frac{\mu_j\Gamma_{\rm H}}{\Gamma_0}\mathcal{P}^{\rm sig}_{jk}\left(\vec{x};\vec{\xi}_{jk},f_{ai},\phi_{ai}\right) + \sqrt{\frac{\mu_j\Gamma_{\rm H}}{\Gamma_0}}\mathcal{P}^{\rm int}_{jk}\left(\vec{x};\vec{\xi}_{jk},f_{ai},\phi_{ai}\right) + \mathcal{P}^{\rm bkg}_{jk}\left(\vec{x};\vec{\xi}_{jk}\right)$$

$$\mathcal{P}^{\rm sig/int}_{jk}\left(\vec{x};\vec{\xi}_{jk},f_{ai},\phi_{ai}\right) = \sum_{m=0}^{M}\mathcal{P}^{\rm sig/int}_{jk,m}\left(\vec{x};\vec{\xi}_{jk}\right) f_{ai}^{\frac{m}{2}}\left(1-f_{ai}\right)^{\frac{M-m}{2}}\cos^m(\phi_{ai}).$$

M=4 in VBF: VV→H→VV
M=2 in VBF/bkg int or ggH
M=1 in ggH/bkg int

Presentation of off-shell results on CMS

(1) Γ_H with SM-like couplings:

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

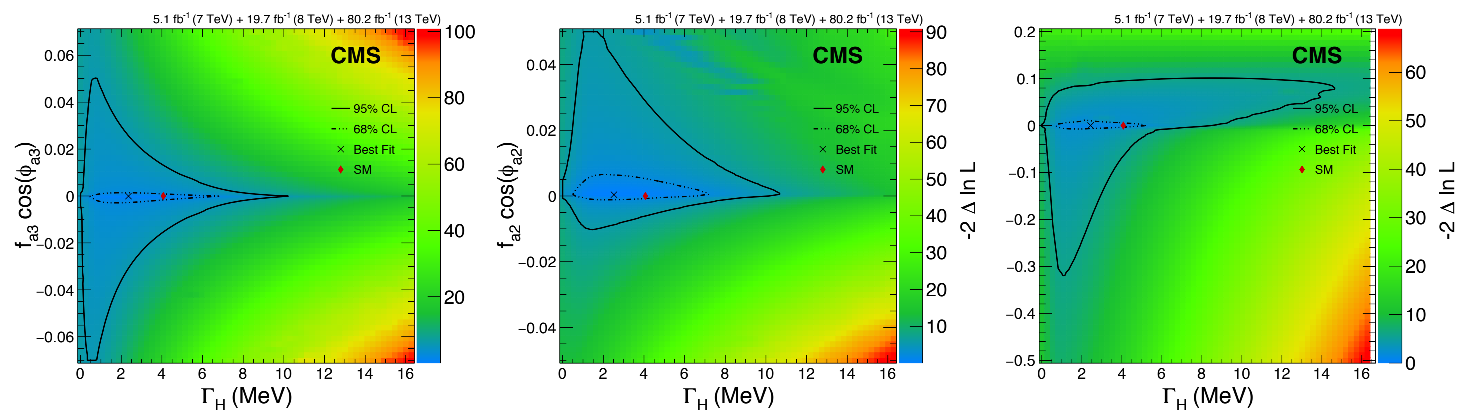
(2) Γ_H with EFT param. profiled:

Parameter	Unconstrained parameter	Observed	Expected
Γ_H (MeV)	$f_{a3}\cos(\phi_{a3})$	$2.4^{+2.7}_{-1.8}$ [0.02, 8.38]	$4.1^{+5.2}_{-4.1}$ [0.0, 13.9]
Γ_H (MeV)	$f_{a2}\cos(\phi_{a2})$	$2.5^{+2.9}_{-1.8}$ [0.02, 8.76]	$4.1^{+5.2}_{-4.1}$ [0.0, 13.9]
Γ_H (MeV)	$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$2.4^{+2.5}_{-1.6}$ [0.06, 7.84]	$4.1^{+5.2}_{-4.1}$ [0.0, 13.9]

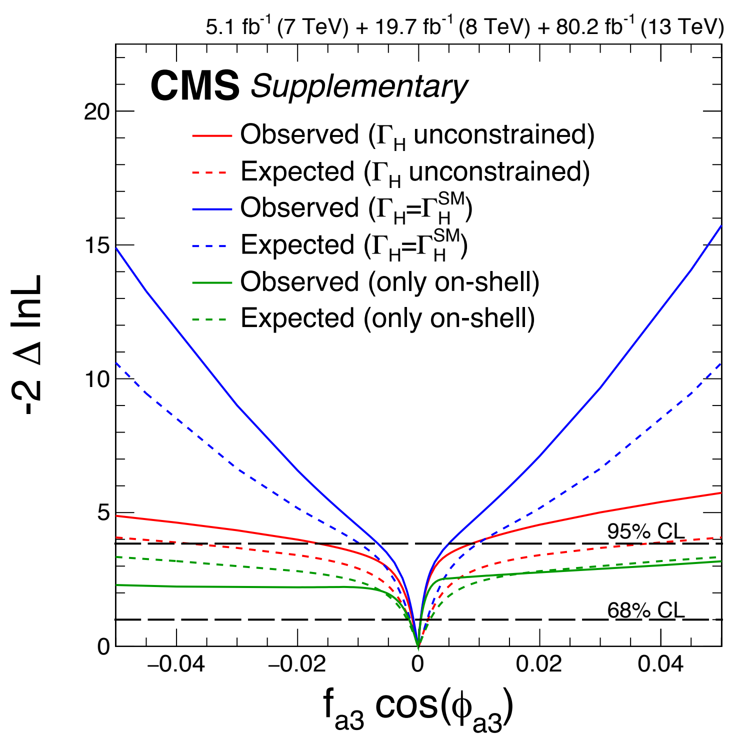
(3) off-shell cross section (μ) with SM-like couplings:

Parameter	Observed	Expected
$\mu^{\text{off-shell}}$	$0.78^{+0.72}_{-0.53}$ [0.02, 2.28]	$1.00^{+1.20}_{-0.99}$ [0.0, 3.2]
$\mu_F^{\text{off-shell}}$	$0.86^{+0.92}_{-0.68}$ [0.0, 2.7]	$1.0^{+1.3}_{-1.0}$ [0.0, 3.5]
$\mu_V^{\text{off-shell}}$	$0.67^{+1.26}_{-0.61}$ [0.0, 3.6]	$1.0^{+3.8}_{-1.0}$ [0.0, 8.4]

(4) 2D scan of Γ_H vs EFT param.



(5) EFT param.



arXiv:1901.00174

Presentation of off-sell results

Pros and cons, going down the list:

- straightforward: Γ_H, signal strength μ, or σ with SM-like couplings
- Γ_H and modification of (EFT) H couplings
  — already done, but growing complexity with multiple couplings
- Γ_H and modification of (EFT) EW parameters
  — next step after the above
- STXS-like signal strengths
  — attractive, but limited to SM-like couplings only (SM full sim.)
  — not necessarily optimal for further analysis
- differential distribution
  — should be done, but signal ~2σ only even before binning
  — reduced information in 1D bins
- exotic (resonance) searches
  — should be done, but outside the focus of this group

Summary

- Our goal to measure H coupling strengths, structures, width
  — in an optimal and correct way
- Measure through H kinematics in
  — in off-shell and on-shell production, and decay
  — in interference with (EW) background
- Developing tools takes most of the time
  — full simulation of all H+bkg+I production and decay processes
  — re-weighting to increase statistics and cover all models
  — observables to be optimal to full kinematics
  — fitting tools to pull it all together
- Presentation of H* off-shell results
  — growing complexity Γ_H, signal strength (μ), (EFT) H couplings
  — often limited by the tools
  — reduced information in differential or template-like cross sections