University of Massachusetts Amherst

Off-shell Higgs boson production

Rafael Coelho Lopes de Sa

with inputs from Raoul Röntsch, Ennio Salvioni, and Savvas Kiriacou
(WG1 off-shell conveners)

The 20th Workshop of the LHC Higgs Working Group
November 14th, 2023

Introduction

The Higgs is a very narrow resonance, but several kinematical thresholds can increase the differential cross section in some decay channels [Kauer and Passarino, JHEP 08 (2012) 116]

Figure from J. M. Campbell, R. K. Ellis, and C. Williams, JHEP 04 (2014) 060

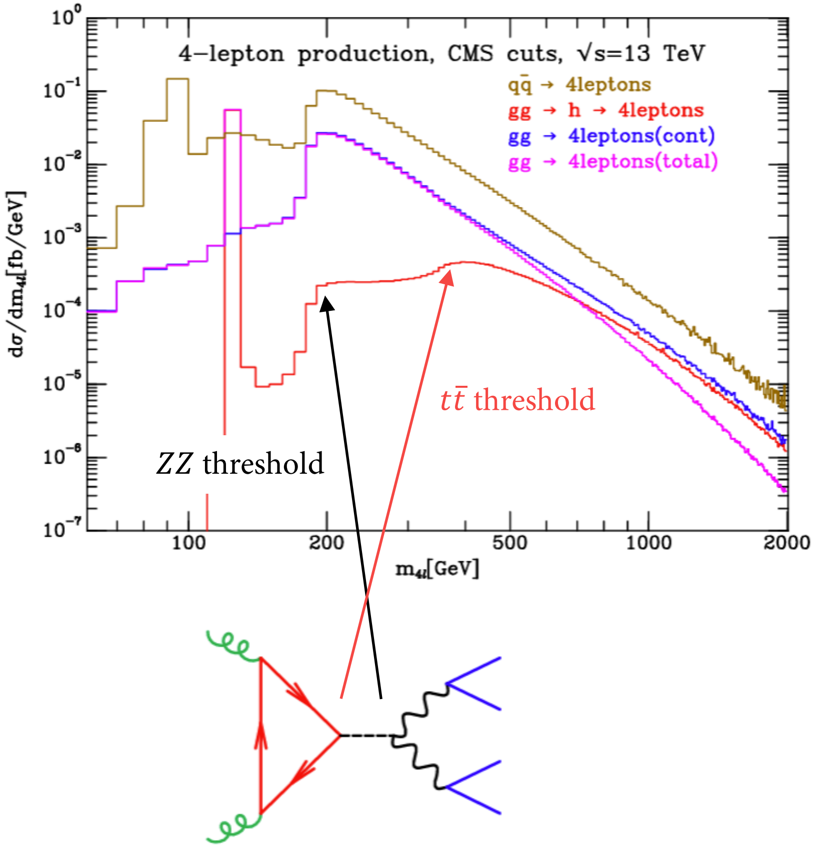


Table 1: Total cross-section in gg → H → ZZ and in gg → H → all; the part of the cross-section for $M_{ZZ} > 2\,M_Z$ is explicitly shown.

	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

Table from G. Passarino, Eur. Phys. J. C 74 (2014) 2866 (for $\sqrt{s} = 8$ TeV)

Since this initial observation, ATLAS and CMS have performed several measurements in the off-shell region. This talk reviews the most recent measurements and phenomenological studies of this region.

CMS: off-shell $H \to ZZ \to 4\ell$ with full Run 2 dataset

CMS has recently published a preliminary result with a measurement of the off-shell Higgs boson production in the $H \to ZZ \to 4\ell$ using with the full Run 2 dataset (PAS HIG-21-019)

It follows a similar strategy for observables and event categorization as previous CMS analyses

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

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

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

Discriminant calculated using LO matrix element squared from JHUGen and up to 13 reconstructed variables.

$m_{4\ell} > 220$ GeV

$$D^{\rm VBF}_{\rm 2jet} = \frac{\mathcal{P}_{\rm VBF}(H,{\rm 2jet})}{\mathcal{P}_{\rm VBF}(H,{\rm 2jet})+\mathcal{P}_{\rm ggF}(H,{\rm 2jet})} > 0.5$$

VBF-tagged

$$D^{VH}_{\rm 2jet} = \frac{\mathcal{P}_{\rm VH}(H,{\rm 2jet})}{\mathcal{P}_{\rm VH}(H,{\rm 2jet})+\mathcal{P}_{\rm ggF}(H,{\rm 2jet})}$$

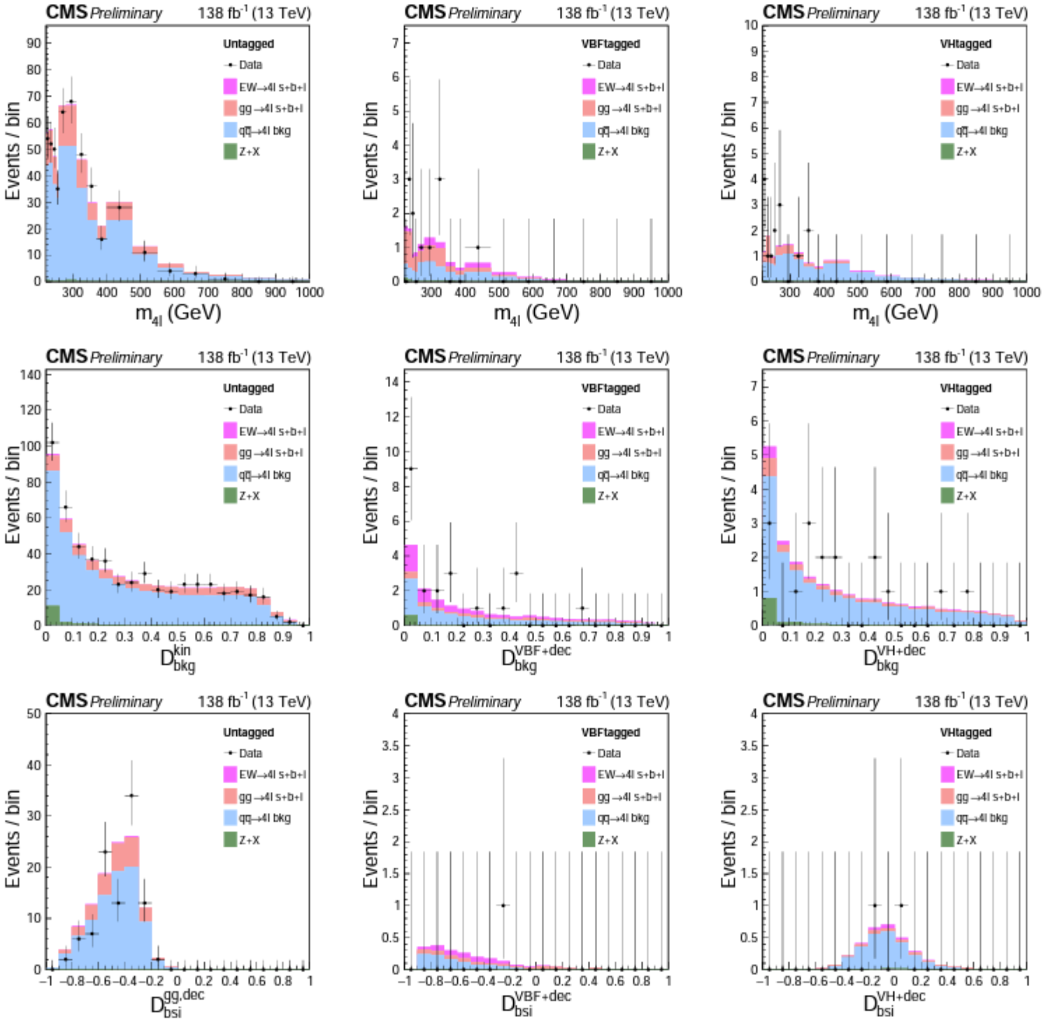
$$\max\left(\mathcal{D}^{ZH}_{\rm 2jet},\mathcal{D}^{WH}_{\rm 2jet}\right) > 0.5$$

VH-tagged

Rest of the events

untagged

CMS:off-shell $H \to ZZ \to 4\ell$ with full Run 2 dataset

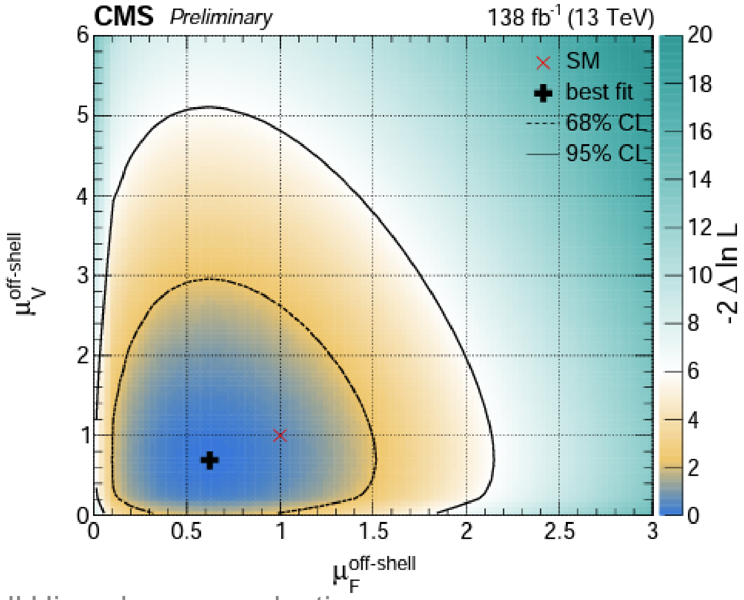


Analysis performed with 3D histograms in

$$\left\{ m_{4\ell}, \frac{\mathcal{P}_{\rm sig}}{\mathcal{P}_{\rm sig}+\mathcal{P}_{q\bar{q}ZZ}}, \frac{\mathcal{P}_{\rm int}}{2\sqrt{\mathcal{P}_{\rm sig}\mathcal{P}_{\rm bsi}}} \right\}$$

Run 2 $H \to ZZ \to 4\ell$ results

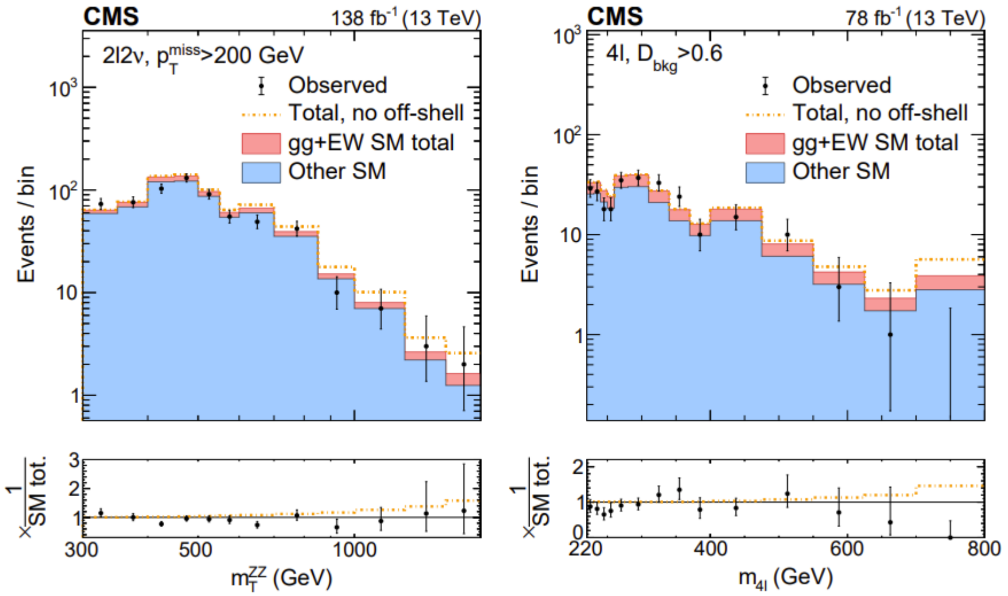
Parameter	Observed	Expected
$\mu^{\rm off\text{-}shell}$	$0.64^{+0.50}_{-0.37}$ [0.06, 1.69]	$1.00^{+0.99}_{-0.97}$ [0.00, 2.80]
$\mu_{\rm F}^{\rm off\text{-}shell}$	$0.62^{+0.57}_{-0.41}$ [0.03, 1.81]	$1.00^{+1.05}_{-1.00}$ [0.00, 2.93]
$\mu_{\rm V}^{\rm off\text{-}shell}$	$0.69^{+1.32}_{-0.63}$ [0.00, 3.91]	$1.00^{+3.34}_{-1.00}$ [0.00, 7.65]



CMS: $H \to ZZ \to 4\ell + H \to ZZ \to 2\ell 2\nu$

CMS combined result of full Run 2 dataset for $ZZ \to 2\ell 2\nu$ and partial Run 2 dataset for $ZZ \to 4\ell$

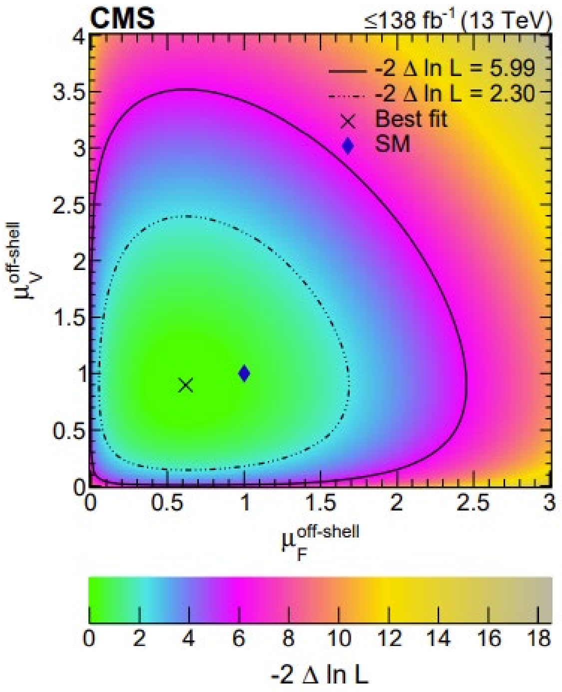
[Nat. Phys. 18 (2022) 1329]



Analysis in the $ZZ \to 2\ell 2\nu$ channel uses a similar categorization as the $ZZ \to 4\ell$ analysis using $\mathcal{D}_{2\mathrm{jet}}^{\mathrm{VBF}}$ for events with $m_T^{ZZ} > 300$ GeV

$$\left(m_{\mathrm{T}}^{ZZ}\right)^2 = \left[\sqrt{p_{\mathrm{T}}^{\ell\ell 2} + m_{\ell\ell}{}^2} + \sqrt{p_{\mathrm{T}}^{\mathrm{miss}2} + m_Z{}^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}\right|^2$$

Param.	Cond.	Observed 68% CL	Observed 95% CL	Expected 68% CL	Expected 95% CL
$\mu_F^{\text{off-shell}}$	$\mu_V^{\text{off-shell}}$ (u)	$0.62^{+0.68}_{-0.45}$	$^{+1.38}_{-0.614}$	$^{+1.1}_{-0.99998}$	< 3.0
$\mu_V^{\text{off-shell}}$	$\mu_F^{\text{off-shell}}$ (u)	$0.90^{+0.9}_{-0.59}$	$^{+2.0}_{-0.849}$	$^{+2.0}_{-0.89}$	< 4.5
$\mu^{\text{off-shell}}$	$R_{V,F}^{\text{off-shell}} = 1$	$0.74^{+0.56}_{-0.38}$	$^{+1.06}_{-0.61}$	$^{+1.0}_{-0.84}$	$^{+1.7}_{-0.9914}$
	$R_{V,F}^{\text{off-shell}}$ (u)	$0.62^{+0.68}_{-0.45}$	$^{+1.38}_{-0.6139}$	$^{+1.1}_{-0.99996}$	$^{+2.0}_{-0.99999}$



The "no off-shell production scenario" is excluded with 3.6σ significance.

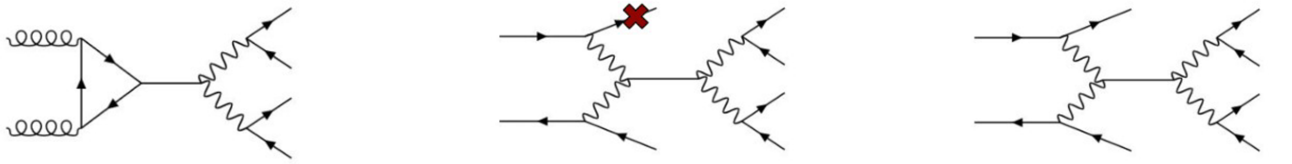
More details in Savvas' talk.

ATLAS: off-shell $H \to ZZ \to 4\ell + ZZ \to 2\ell 2\nu$

ATLAS has recently published their full Run 2 dataset analysis in the $ZZ \to 2\ell 2\nu$ and $ZZ \to 4\ell$ decay channels [Phys.Lett.B 846 (2023) 138223]

For the first time in ATLAS, this measurement uses an event categorization to be sensitive to gluon-fusion and electroweak off-shell Higgs boson production separately.

ggF Signal region | 1 jet mixed signal region | EW signal region



ggF Signal region:

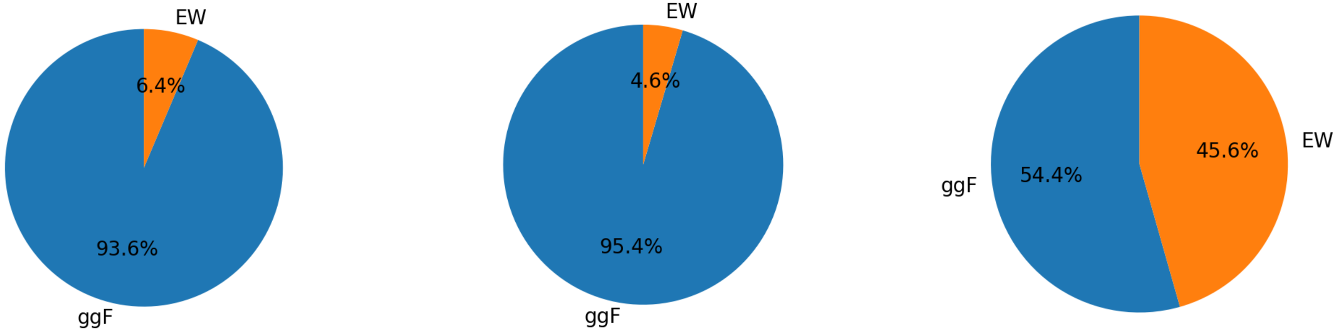
$n_{\text{jets}} = 0$

$n_{\text{jets}} = 1$ and $\eta_j < 2.2$

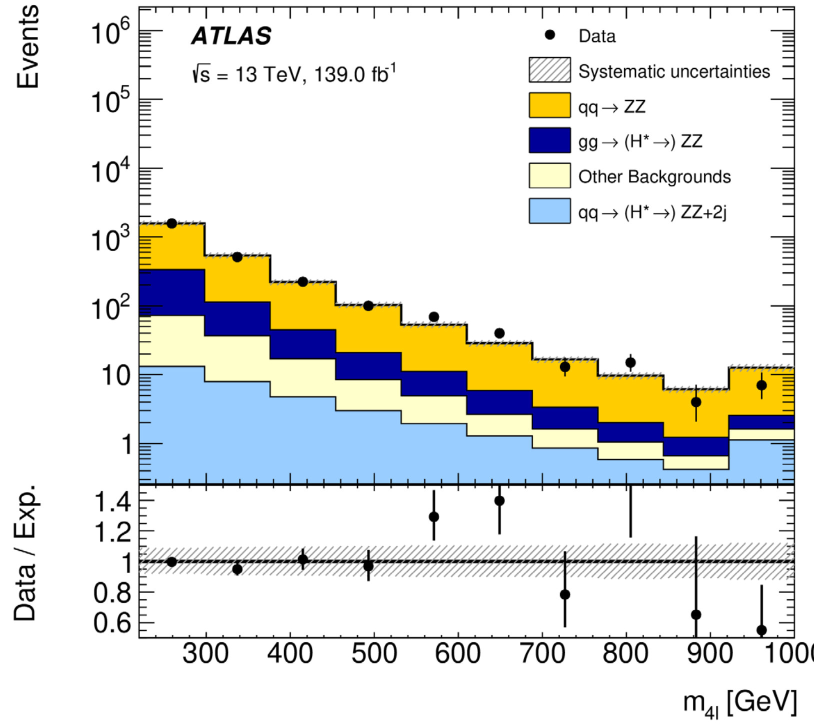
$n_{\text{jets}} \geq 2$ and $|\Delta\eta_{jj}| < 4.0$

1 jet mixed signal region: $n_{\text{jets}} = 1$ and $|\eta_j| \geq 2.2$

EW signal region: $n_{\text{jets}} \geq 2$ and $|\Delta\eta_{jj}| \geq 4.0$

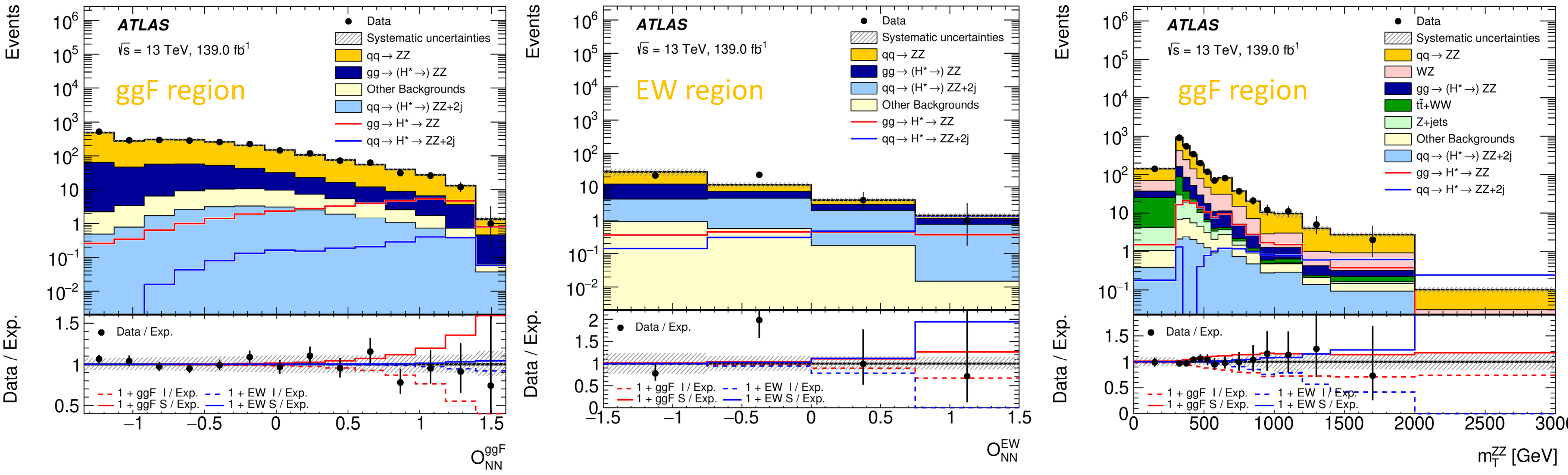


Fractions in 4ℓ channel

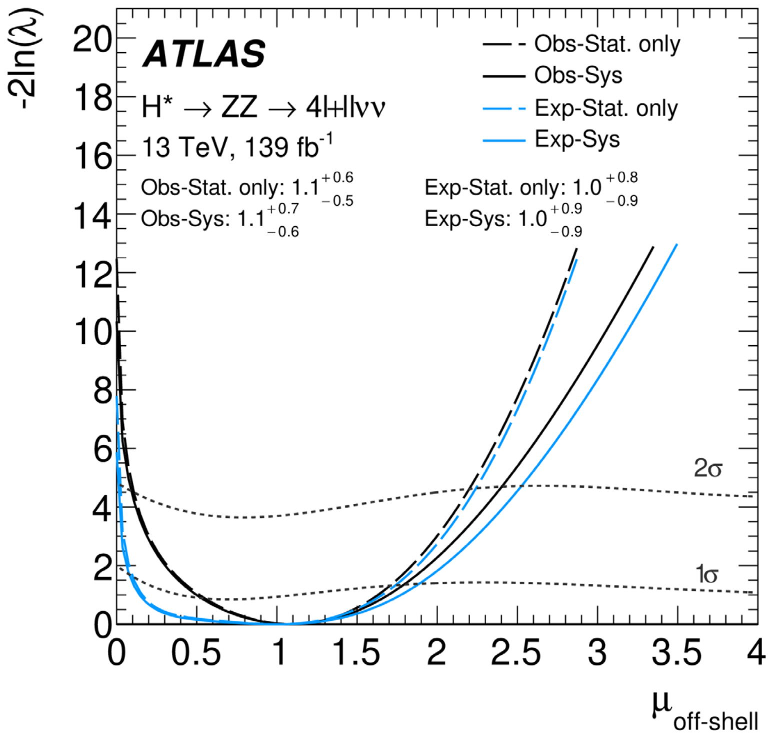


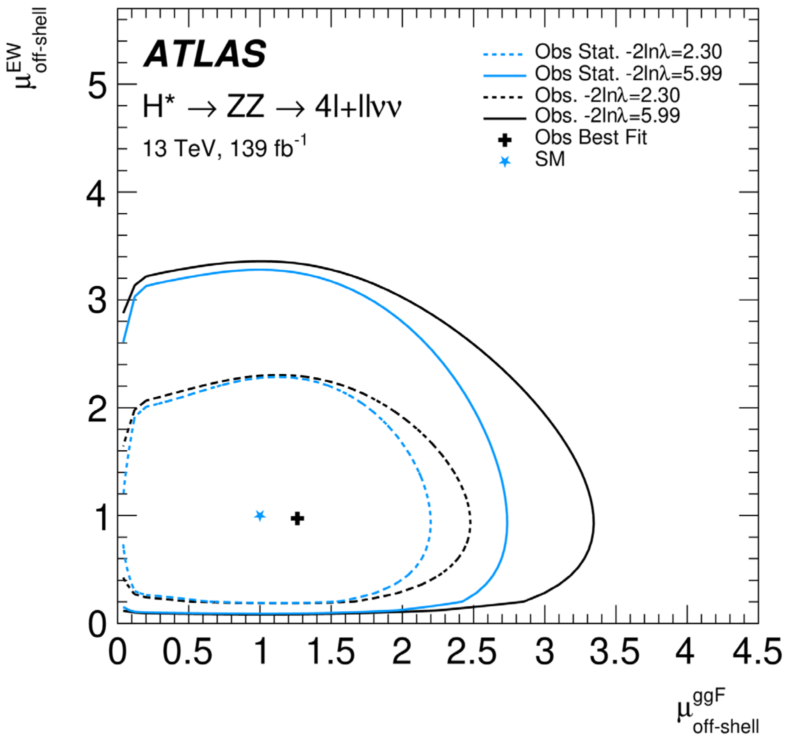
ATLAS: off-shell $H \to ZZ \to 4\ell + ZZ \to 2\ell 2\nu$

- NN-based probability ratios for the 4ℓ channel: $O_{\mathrm{NN}}^{\mathrm{ggF}} = \log\left(\frac{\mathcal{P}_S^{\mathrm{ggF}}}{\mathcal{P}_B^{\mathrm{ggF}} + \mathcal{P}_{q\bar{q}ZZ}}\right)$. Probability ratios estimated for $m_{4\ell} > 220\ \mathrm{GeV}$ as a function of production and decay kinematics.
- Region with $180 < m_{4\ell} < 220\ \mathrm{GeV}$ used as control region for $q\bar{q} \to ZZ$ normalization.
- m_T^{ZZ} variable used for $ZZ \to 2\ell 2\nu$ channel



ATLAS: off-shell $H \to ZZ \to 4\ell + ZZ \to 2\ell 2\nu$





The background-only hypothesis is rejected at an observed significance of 3.3σ (2.2σ expected).

The observed value is $\mu_{\text{off-shell}} = 1.1^{+0.7}_{-0.6}$ @ 68% CL.
The observed (expected) upper limit at 95% CL. is 2.2 (2.3).

More details in Michiel's talk.

Higgs width interpretation

Interpretation of the off-shell Higgs production measurement as an indirect probe for Higgs width

[J. M. Campbell, R. K. Ellis, and C. Williams, JHEP 04 (2014) 060; F. Caola and K. Melnikov, Phys. Rev. D 88 (2013) 054024]

$$\frac{d\sigma^{pp\to H\to ZZ}}{dm_{ZZ}} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

on-shell:

$$\sigma_{\text{on-shell}}^{pp\to H\to ZZ} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H\Gamma_H}$$

off-shell:

$$\frac{d\sigma_{\text{off-shell}}^{pp\to H\to ZZ}}{dm_{ZZ}} \propto \frac{g_{Hgg}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2}$$

Interpretation assumes no new physics between on-shell and off-shell scales

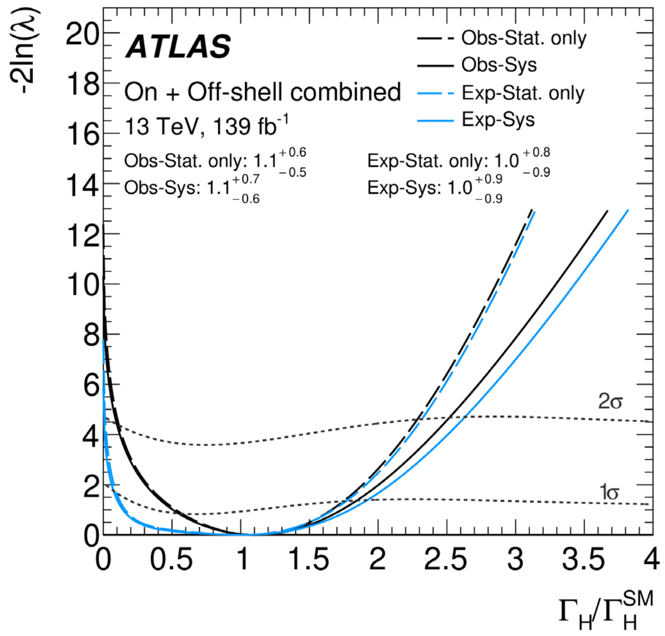
$$\mu_{\text{on-shell}} = \frac{\sigma_{\text{on-shell}}^{pp\to H\to ZZ}}{\sigma_{\text{on-shell,SM}}^{pp\to H\to ZZ}} = \frac{\kappa_{g,\text{on-shell}}^2 \kappa_{V,\text{on-shell}}^2}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

$$\mu_{\text{off-shell}} = \frac{\sigma_{\text{off-shell}}^{pp\to H\to ZZ}}{\sigma_{\text{off-shell,SM}}^{pp\to H\to ZZ}} = \kappa_{g,\text{off-shell}}^2 \kappa_{V,\text{off-shell}}^2$$

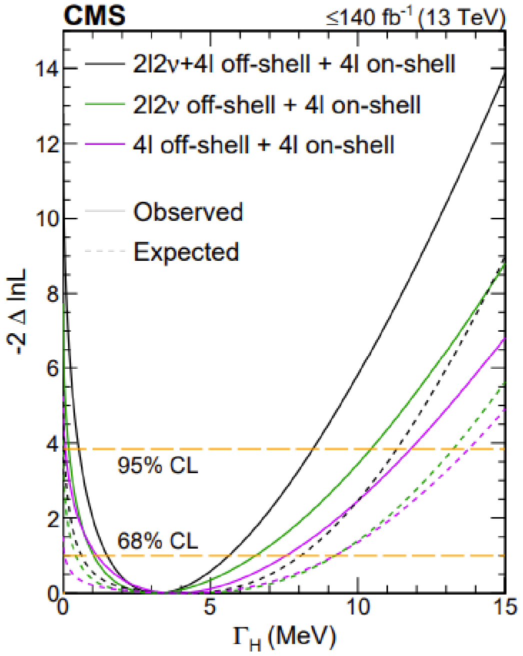
$$\rightarrow \quad \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}}$$

Higgs width: experimental results

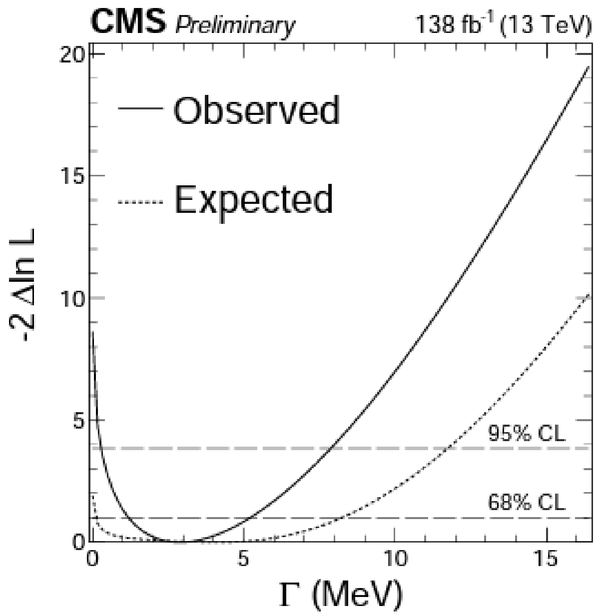
Both CMS and ATLAS combine their off-shell Higgs production measurement in the $H \to ZZ \to 4\ell$ and $H \to ZZ \to 2\ell 2\nu$ channels with on-shell $H \to ZZ \to 4\ell$ to provide indirect determinations of the Higgs total width



ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}\ MeV$ @ 68% CL.
[based on full Run 2 $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$]



CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}\ MeV$ @ 68% CL.
[based on partial Run 2 $ZZ \to 4\ell$ ($78\ \text{fb}^{-1}$) and full Run 2 $ZZ \to 2\ell 2\nu$]



CMS: $\Gamma_H = 2.9^{+2.3}_{-1.7}\ MeV$ @ 68% CL.
[based on full Run 2 $ZZ \to 4\ell$]

More details in Filippo's talk,
see also Federico's talk.

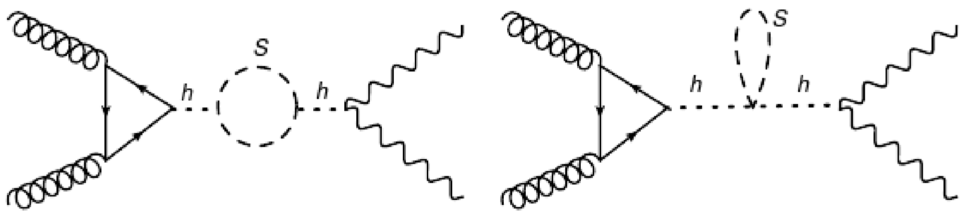
New low-mass states

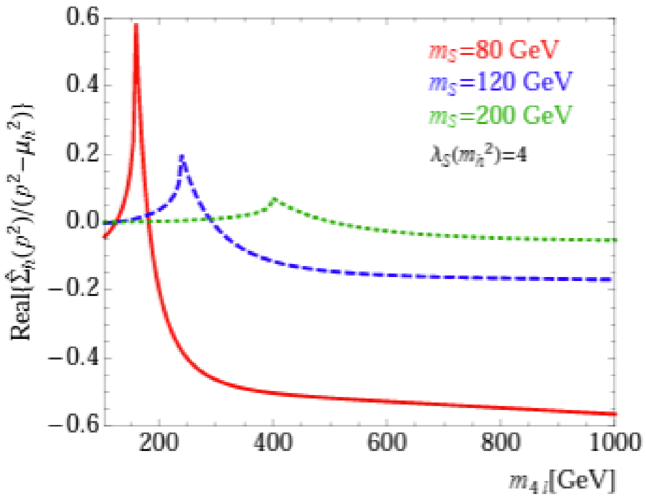
The presence of new light particles would break the assumptions used to perform the Higgs width interpretation.

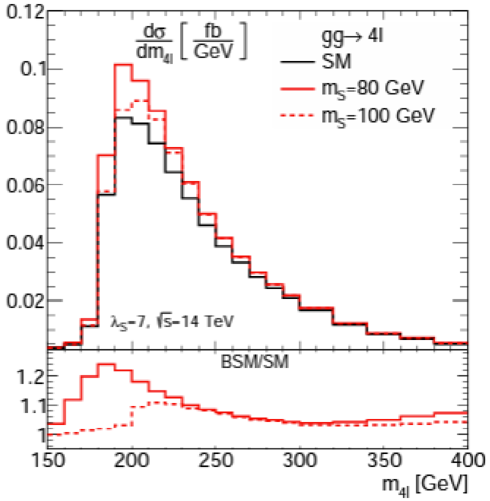
But the measurement of off-shell production could then be used as an indirect probe of these new states via new kinematic thresholds introduced at 1-loop.

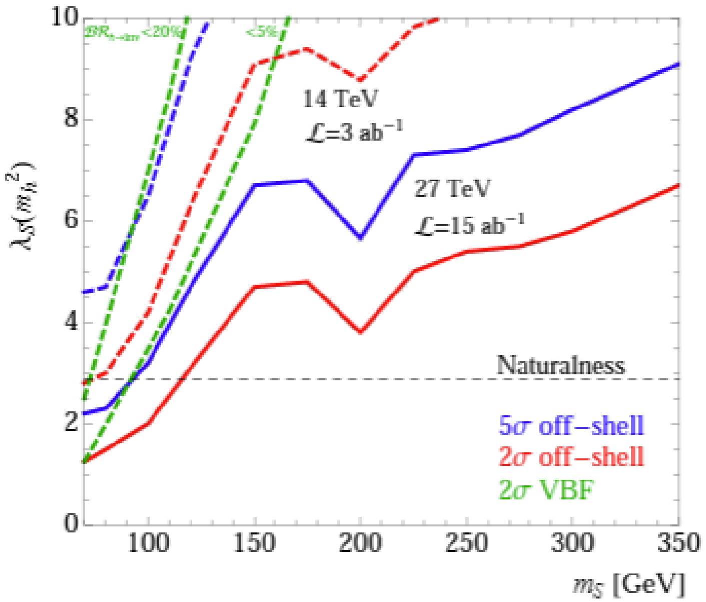
This method hasn't been explored experimentally yet, but is promising as more data is collected.

More details in D. Goncalves, T. Han, and S. Mukhopadhyay, Off-Shell Higgs Probe of Naturalness, [Phys. Rev. Lett. 120 (2018) 111801]



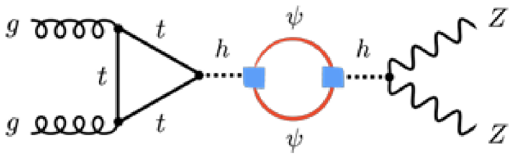


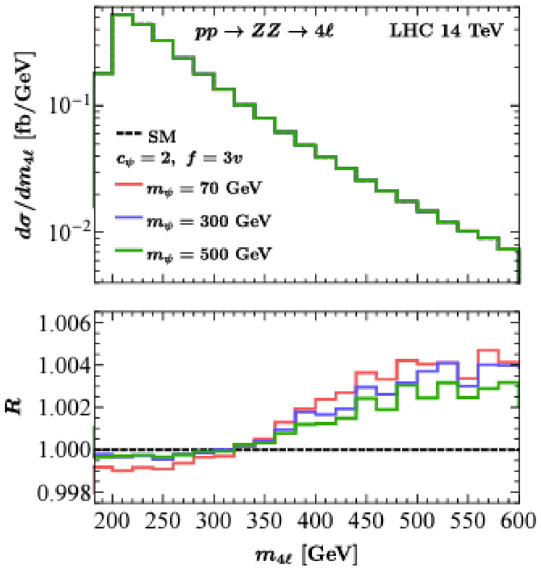


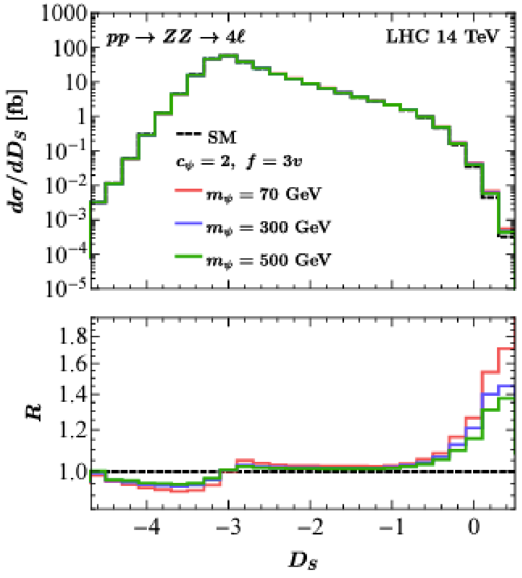


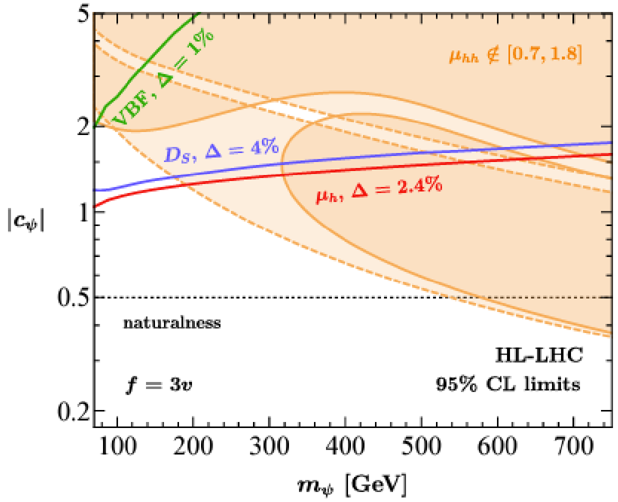
Fermionic Higgs portal

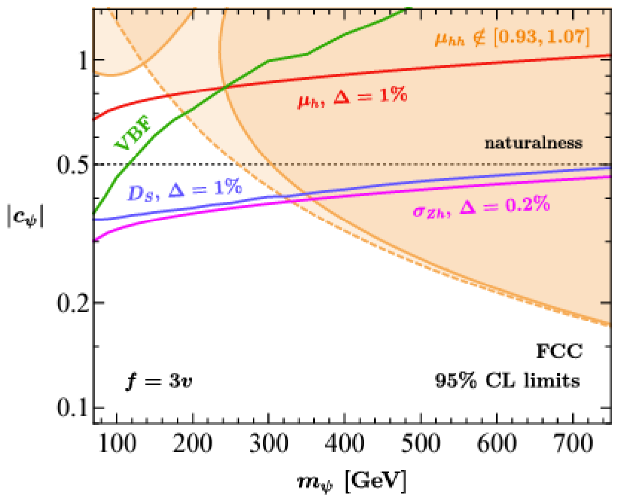
Recent application of the idea for fermionic Higgs portal by U. Haisch, M. Ruhdorfer, K. Schmid, A. Weiler [arXiv:2311.03995]











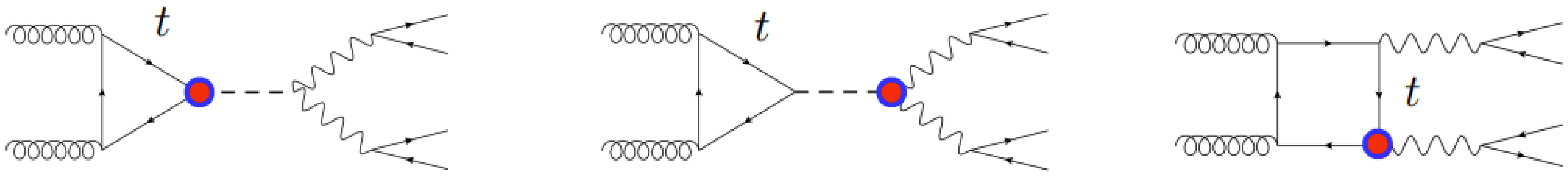
Loop effects in $gg \rightarrow ZZ$ can surpass direct production

Interesting ideas for HL-LHC and future colliders

Off-shell Higgs and EFT

Subset of SMEFT operators relevant for $gg \to ZZ$ (CP-even, CP-odd)

$$\Delta\mathcal{L} = \frac{h}{v}\Big(c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^{\mu\nu\,a} - m_t[\delta y_u]_{33}\bar{t}_L t_R + \text{h.c.} + \delta c_z\frac{g_Z^2 v^2}{4}Z_\mu Z^\mu + c_{zz}\frac{g_Z^2}{4}Z_{\mu\nu}Z^{\mu\nu} + c_{z\Box}g_L^2 Z_\mu\partial_\nu Z^{\mu\nu}$$
$$+\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\widetilde{G}^a_{\mu\nu} + \tilde{c}_{zz}\frac{g_Z^2}{4}Z_{\mu\nu}\widetilde{Z}_{\mu\nu}\Big) - g_Z(\delta g_L^{Zu})_{33}Z_\mu\bar{t}_L\gamma^\mu t_L - g_Z(\delta g_R^{Zu})_{33}Z_\mu\bar{t}_R\gamma^\mu t_R$$
$$-\frac{m_t}{4v^2}\Big(1+\frac{h}{v}\Big)\Big(g_s\bar{t}_R\sigma^{\mu\nu}T^a[d_{Gu}]_{33}t_L G^a_{\mu\nu} + g_Z\bar{t}_R\sigma^{\mu\nu}T^a[d_{Zu}]_{33}t_L Z_{\mu\nu}\Big) + \text{h.c.}$$



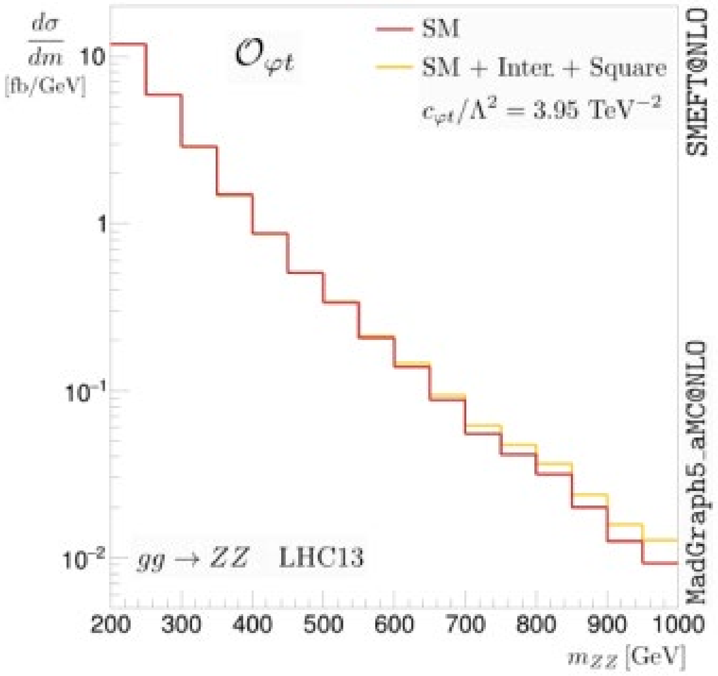
No real "signal" vs "background" distinction:

motivated new physics can appear in Higgs diagrams, box diagrams, or both

Goal: for each SMEFT operator that can in principle contribute to off-shell region, assess impact after accounting for constraints from other measurements systematically

Identify EFT directions where off-shell has most competitive sensitivity

EFT interpretation: a work in progress



Strategy: first step at simplified level [ongoing for CP-even operators]

$\mathcal{O}_i$
single operator → determine max size of coefficient allowed by global fit to current data

↓

generate $d\sigma/dm_{ZZ}$
(SMEFT@NLO / JHUGen+MCFM)
and evaluate max deviation from SM

↓

"Drop" operators falling below sensitivity threshold

Second step: detailed analysis for remaining subset of operators

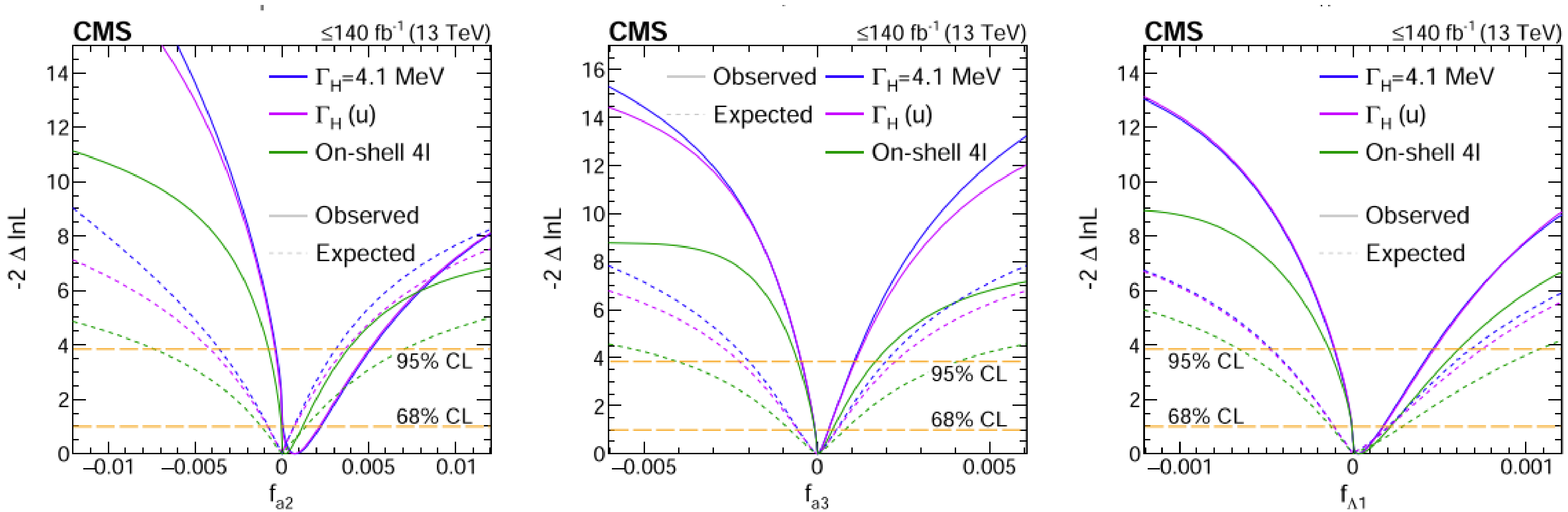
More details in Off-shell Interpretations Task Force report [arXiv:2203.02418]

CMS: off-shell EFT interpretation

Example: complementary between EFT limits using off-shell and on-shell $H \to ZZ$ measurements [Nat. Phys. 18 (2022) 1329].

Mesurément of EFT modifications of the $H \to VV$ decay. Analysis sses dedicated MELA discriminants.

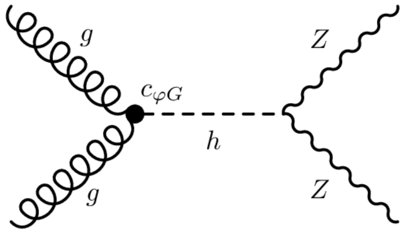
$$A \sim \left[a_1^{VV} - \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} - \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\,\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\,\mu\nu}.$$

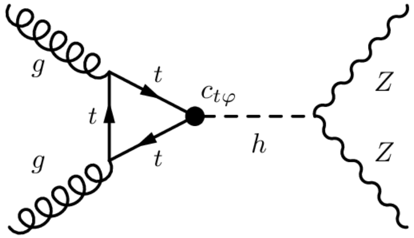


Some results stronger than on-shell analysis.

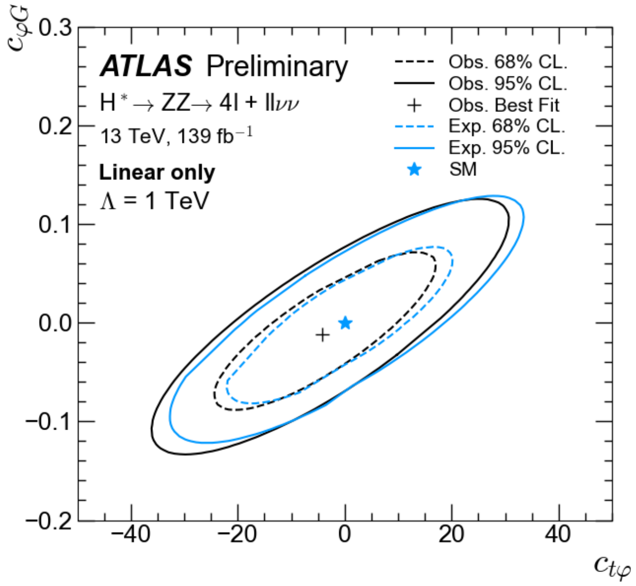
ATLAS: off-shell EFT interpretation

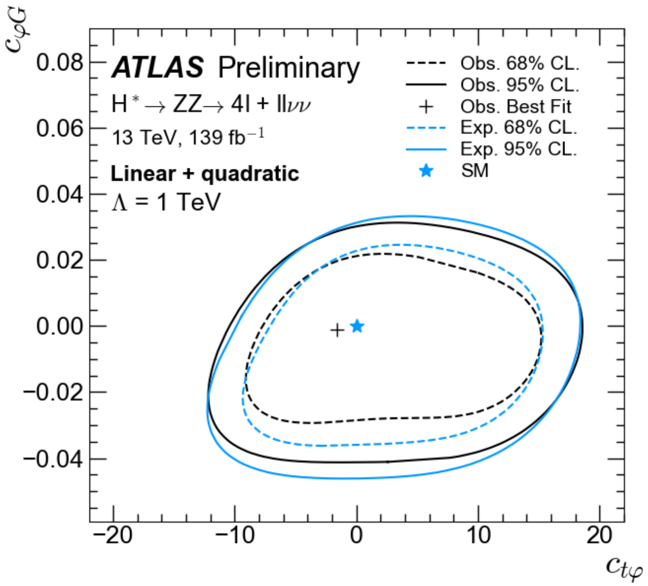
Example: off-shell breaks degeneracy between the top Yukawa and Higgs-gluon interaction which exists for on-shell Higgs production [ATL-PHYS-PUB-2023-012].





Operator	Coefficient (Λ^{-2})	Definition
$\mathcal{O}_{\varphi G}$	$c_{\varphi G}$	$(\varphi^\dagger\varphi - \frac{v^2}{2})G_A^{\mu\nu}G_{\mu\nu}^A$
$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$(\varphi^\dagger\varphi - \frac{v^2}{2})\bar{Q}_L\tilde{\varphi}t_R + \text{h.c.}$





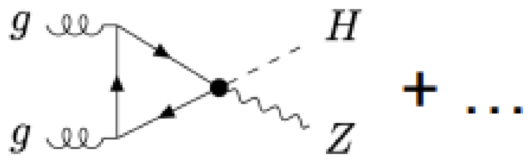
Large differences between linear and linear+quadratic limits.

May indicate that expansion is not within EFT validity regime.

More data is required! Run 3 will be essential.

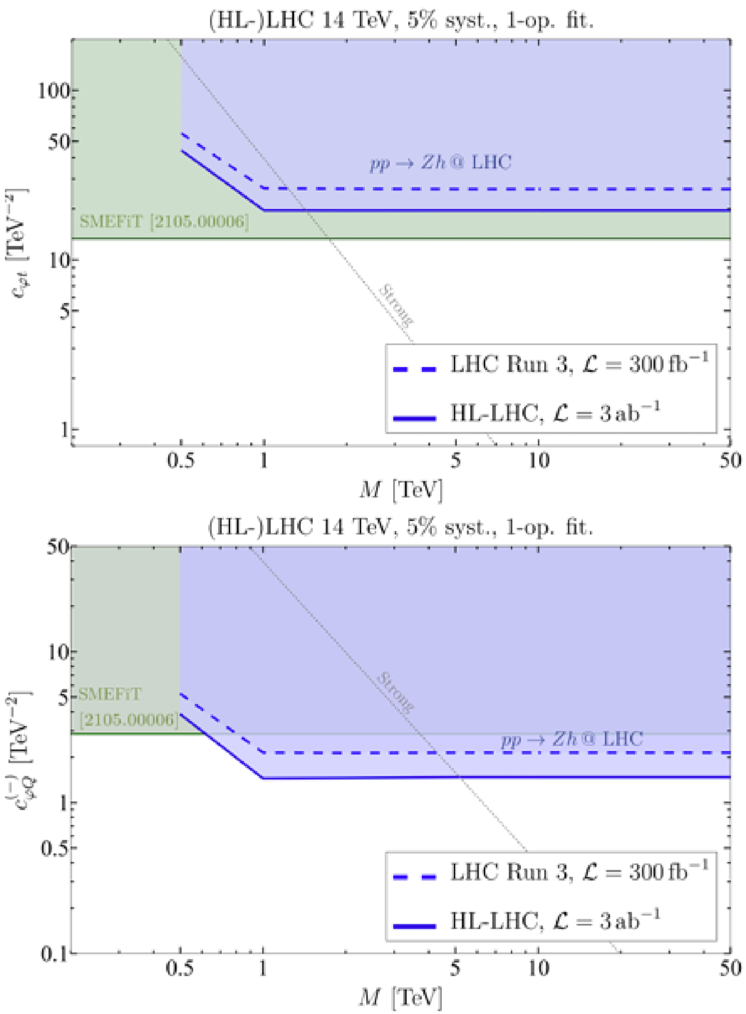
Scrutinizing EFT contribution

- For EFT studies it is important to understand contributions from different channels
- Recent extended analysis of $gg \to \mathrm{diboson}$ in SMEFT (ZZ, ZH, WW, HH)
  [Rossia, Thomas, Vryonidou. arXiv:2306.09963]
- Scrutinizes connection between Higgs & top sectors



- In some cases, $gg \to \mathrm{diboson}$ can provide competitive limits to precision measurements (such as $t\bar{t}X$ in this case).

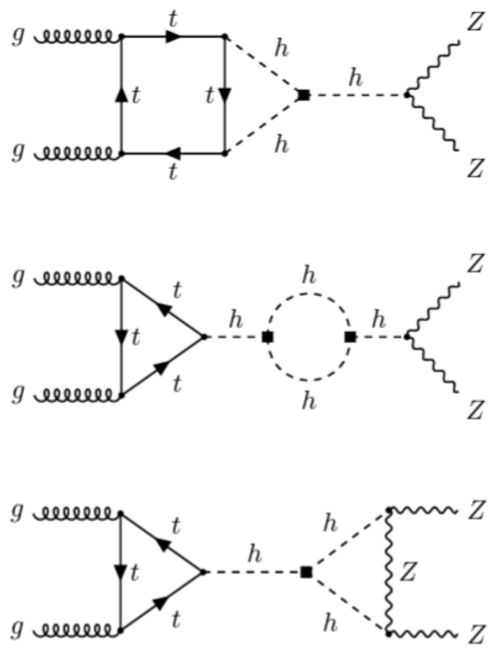
More details in Marion's talk



Higgs trilinear coupling

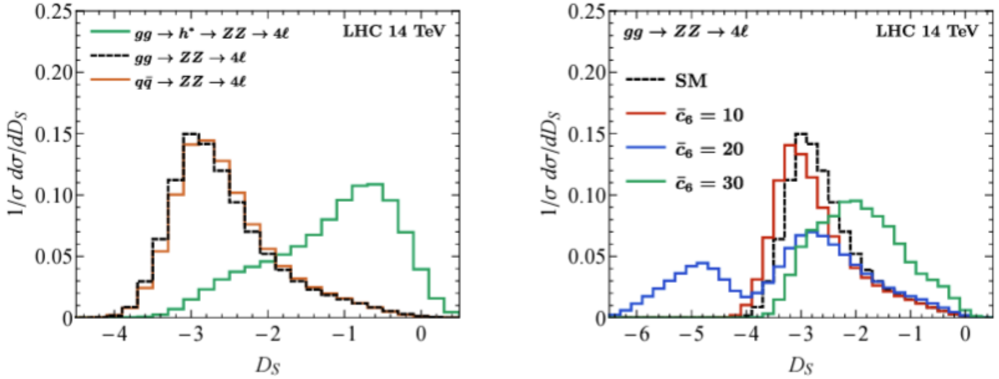
New off-shell effects can also be induced by modifications in the Higgs trilinear coupling

(from Ulrich Haisch, Gabriël Koole. JHEP 02 (2022) 030)

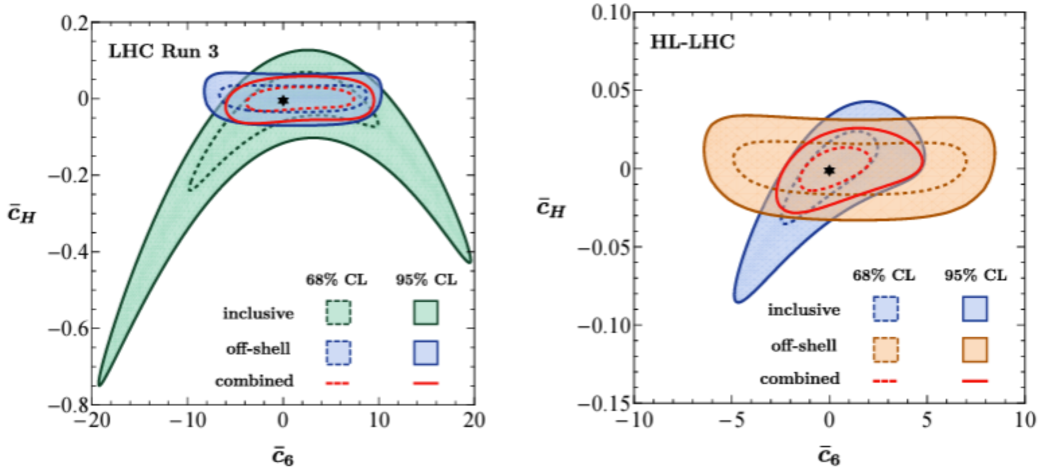


$$\mathcal{O}_6 = -\lambda |H|^6 \,, \qquad \mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

$$c_3 = 1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H$$



$$D_S = \log_{10}\left(\frac{P_h}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$



Study performed with methods similar to the ATLAS and CMS off-shell analyses.

Provides complementary information to single-Higgs inclusive constraints.

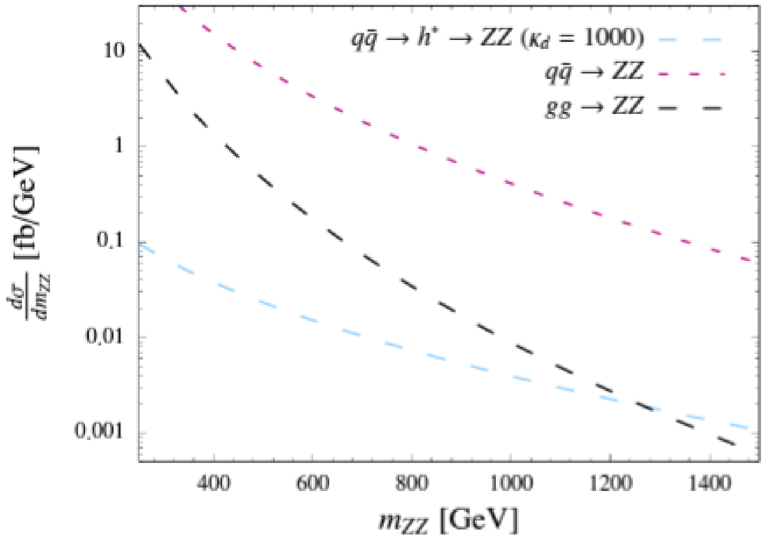
Not explored by experimental collaborations yet, but attractive analysis with Run 3 data!

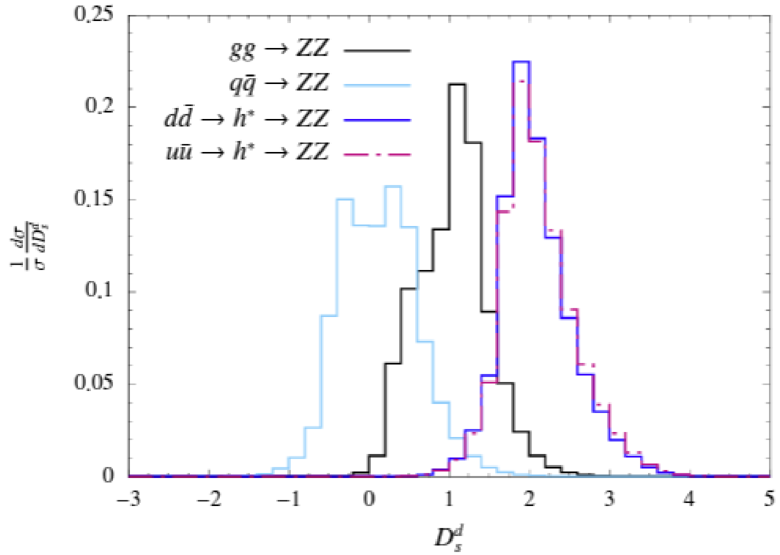
BSM Yukawa couplings to light quarks

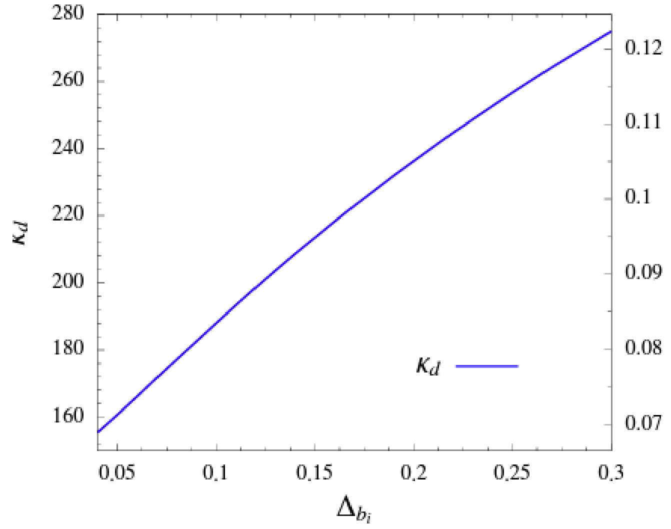
Off-shell Higgs production can be used to probe BSM Yukawa couplings to light quarks [arXiv:2304.09772].

More details in Ramona's talk

$q\bar{q} \to H \to ZZ$ starts to win over $gg \to H \to ZZ$ due to the different behavior of the quark and gluon PDF.







$$\Delta\mathcal{L}_y = \frac{\phi^\dagger\phi}{\Lambda^2}\left((C_{u\phi})_{ij}\overline{Q}_L^i\tilde{\phi}u_R^j + (C_{d\phi})_{ij}\overline{Q}_L^i\phi d_R^j + \text{ h.c. }\right)$$

$$g_{hq_i\bar{q}_j} = \frac{m_q}{v}\delta_{ij} - \frac{1}{\sqrt{2}}\frac{v^2}{\Lambda^2}(\tilde{C}_{q\phi})_{ij} \qquad g_{hq\bar{q}} = \kappa_q\frac{m_q}{v}$$

$$D_s^d = \log_{10}\left(\frac{P_{d\bar{d}}^{sig}}{P_{q\bar{q}}^{back} + P_{gg}^{back}}\right)$$

Sensitivity studies using similar methods as the ATLAS and CMS analyses show constraints $O(200)$ with HL-LHC dataset.

Theoretical modeling in experimental analyses

Both CMS and ATLAS analyses are dominated by theoretical modeling uncertainties.

ATLAS uses LO SHERPA with 0+1 jets merged

m_{ZZ}-dependent NLO/LO k-factor applied based on fixed-order calculations [F. Caola, K. Melnikov, R. Röntsch, and L. Tancredi. Phys. Rev. D 92 (2015) 18,377]

Additional NNLO and approximate N3LO correction based on signal-only calculation

Large uncertainties due to jet merging and soft-gluon resummation

CMS generates signal samples at NLO with POWHEG at different masses

Samples are reweighted using the MELA matrix element package, which interfaces with JHUGEN and MCFM.

m_{ZZ}-dependent NNLO correction based on signal-only calculation applied to all components

Approximate N3LO correction based on signal-only calculation.

NNLO calculation currently out of reach for interference.
NNLO corrections are important for experimental results.
How good is the signal-only extrapolation?

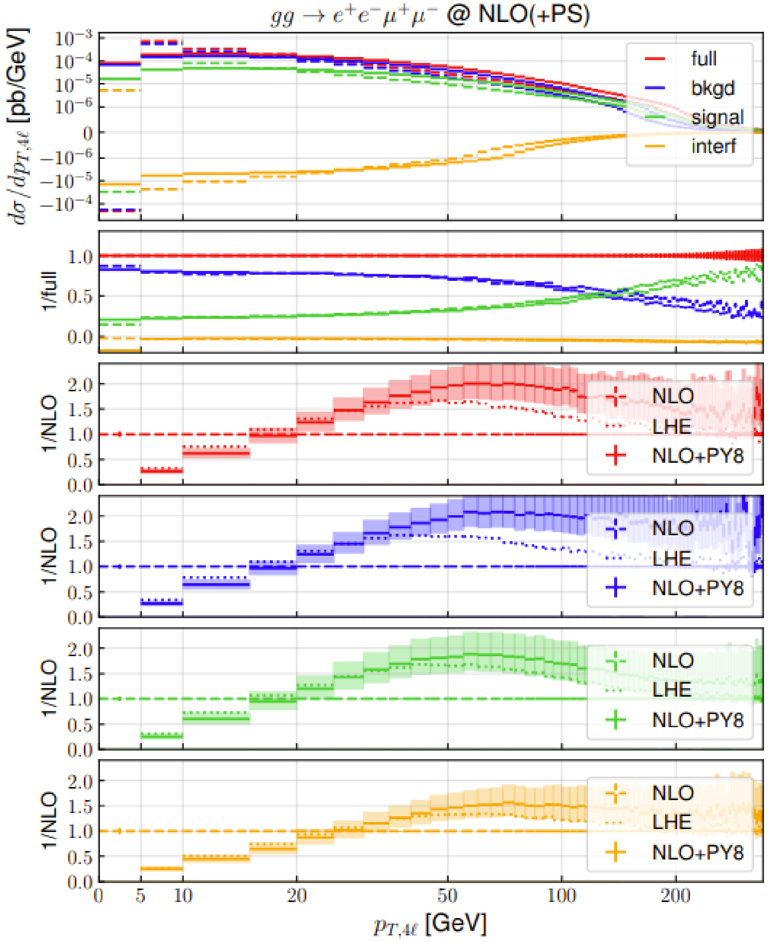
NLO calculation matched to parton shower

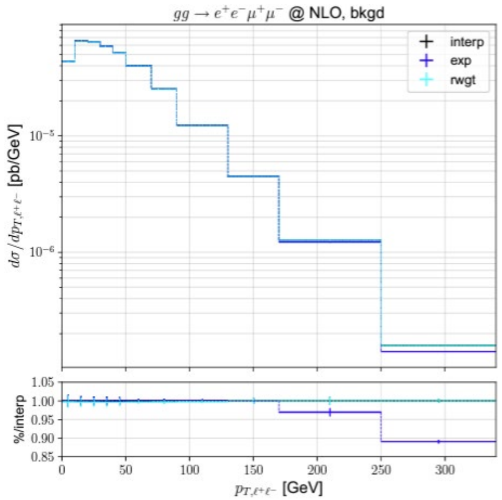
NLO simulation matched to parton shower has recently become available in POWHEG

[Simone Alioli, Silvia Ferrario Ravasio, Jonas M. Lindert, Raoul Röntsch. Eur.Phys.J.C 81 (2021) 8, 687]

Provides simulation at NLO without need of reweighting and can make the $gg \to ZZ \to 4\ell$ description more uniform across experiments.

The simulation was recently used by the ATLAS experiment for the on-shell $H \to ZZ \to 4\ell$ fiducial cross section measurement at $\sqrt{s} = 13.6$ TeV.





Different methods to estimate heavy-quark contribution to 2-loop calculation: m_t expansion (expected to be accurate until $m_{ZZ} \simeq 2m_t$), and via ad-hoc reweighting

$$\mathcal{A}^{(2),ZZ}_{\text{bkgd}} \approx \mathcal{A}^{(2),ZZ}_{\text{bkgd}}(d,u,s,c,b) \times \frac{\mathcal{A}^{(1),ZZ}_{\text{bkgd}}(d,u,s,c,b,\mathbf{t})}{\mathcal{A}^{(1),ZZ}_{\text{bkgd}}(d,u,s,c,b)}$$

Ongoing work: full theory uncertainty model needs to be built for use in future off-shell measurements.

New ways to explore the off-shell region

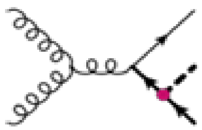
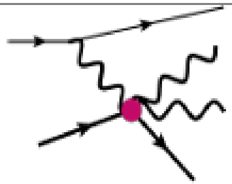
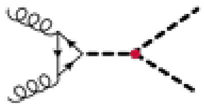
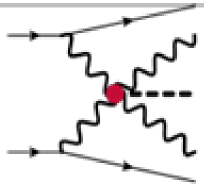
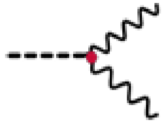
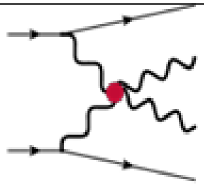
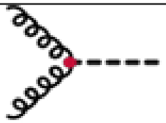
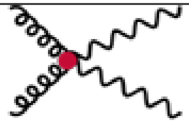
The off-shell Higgs phase space can be explored by different observables, complementary to the off-shell Higgs signal strength.

Polarization has been proposed as a powerful observable for SMEFT effects in the off-shell region

[Brian Henning, Davide Lombardo, Marc Riembau, Francesco Riva. Phys.Rev.Lett. 123 (2019) 18, 181801].

Ongoing work: polarization fractions at high mass can provide an observable to determine SMEFT limits without having to rely on dedicated analyses

$$
\begin{aligned}
&\kappa_t : pp \to jt + V_L V_L' \\
&\quad (e^+e^- \to ll + \{tbW_L, tbZ_L, ttW_L, ttZ_L\}) \\
&\kappa_\lambda : pp \to jjh + V_L V_L',\ (e^+e^- \to llhV_L V_L') \\
&\quad pp \to jj + 4V_L,\ (e^+e^- \to ll\,4V_L) \\
&\kappa_{\gamma\gamma,Z\gamma} : pp \to jj + V'V,\ \ (e^+e^- \to llV'V) \\
&\kappa_V : pp \to jj + V_L V_L',\ \ (e^+e^- \to llV_L V_L') \\
&\kappa_g : pp \to W_L^+ W_L^-, Z_L Z_L,\ \ (e^+e^- \to lljj)
\end{aligned}
$$

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

$$
\begin{aligned}
\mathcal{O}_r &= |H|^2 \partial_\mu H^\dagger \partial^\mu H \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R \\
\mathcal{O}_{BB} &= g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu} \\
\mathcal{O}_{GG} &= g_s^2 |H|^2 G^a_{\mu\nu} G^{a\,\mu\nu} \qquad \mathcal{O}_6 = |H|^6 \qquad (1)
\end{aligned}
$$

Future perspectives

- The evidence-level measurement of the off-shell Higgs boson production achieved by ATLAS and CMS in the $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow ZZ \rightarrow 2\ell 2\nu$ channels has been an important milestone.
- But this is only the beginning of the exploration of the off-shell Higgs phase-space.
- Experimental collaborations should measure off-shell production in all accessible decay channels. These measurements will provide complimentary information. One example is the $H \rightarrow WW \rightarrow 2\ell 2\nu$ which was done in Run 1.
- New machine learning techniques are starting to become more popular and showing their power for the off-shell Higgs production measurement.
- A more comprehensive exploration of new physics searches using off-shell Higgs production (EFT, new light states, Higgs trilinear coupling, Higgs coupling to light quarks, …) is already possible and will become more interesting with the Run 3 dataset.
- New observables can be explored to provide a complementary perspective of the off-shell Higgs boson phase-space.
- NLO simulation of off-shell Higgs processes matched to parton shower can provide a unified description of the processes and their uncertainties.