Off-shell production of the Higgs boson: measurement and interpretation

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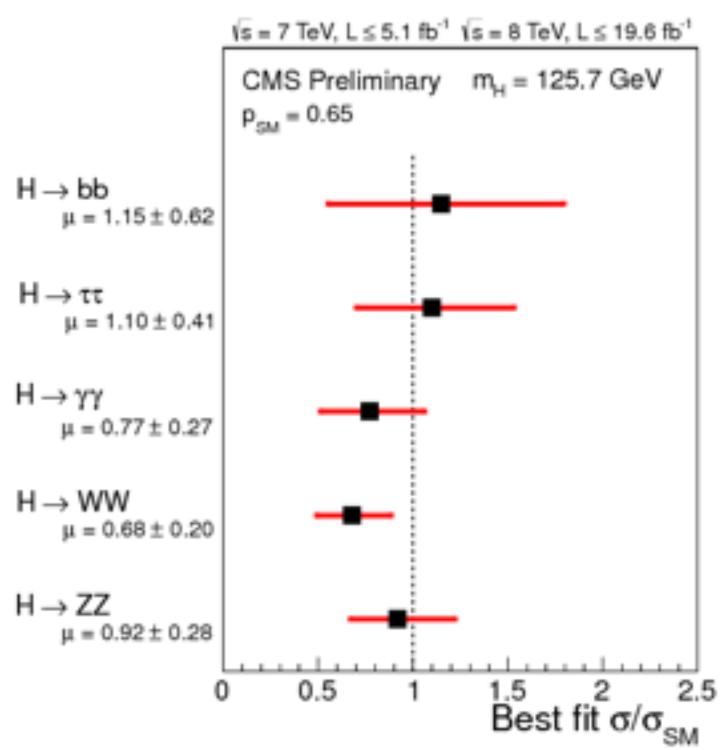
Based on collaboration with F. Caola

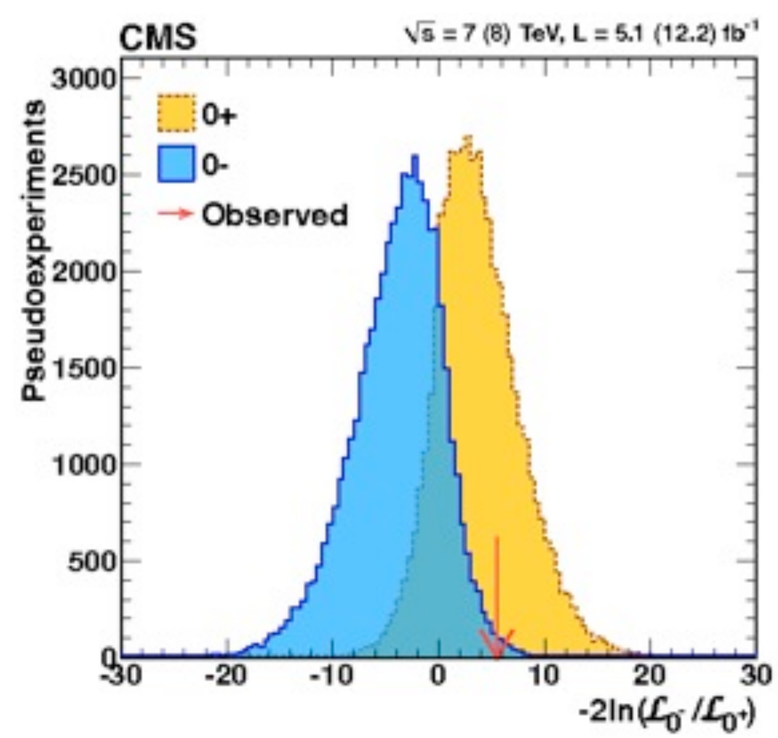
The Higgs boson

The new particle discovered at the LHC more than two years ago appears to be the Higgs boson of the Standard Model. This follows from its observed production and decay rates, its spin, its parity and its mass, that are all perfectly consistent with the Standard Model expectations. Further studies of these quantities with higher precision are important and will be performed during the Run 2.

Most of these studies involve production of the on-shell Higgs boson. This is because the on-shell production is the largest signal and, also, the cleanest one to interpret.

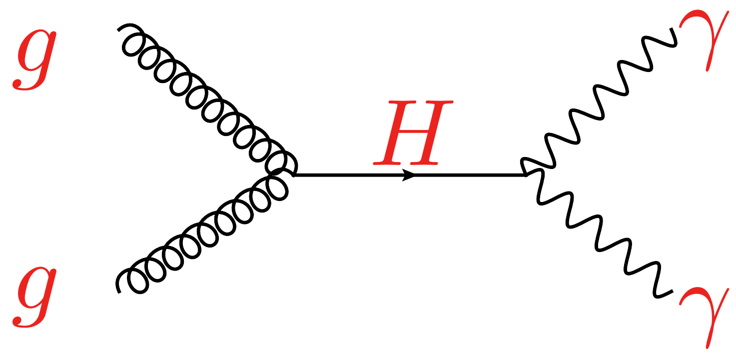
However, the off-shell production of the Higgs is also interesting. It allows us to constrain the width of the Higgs boson, look for internal structure of loop-induced Higgs boson couplings and check for higher-dimensional operators that may affect Higgs production and decay.





From rates to couplings: degeneracies

The original motivation to study the off-shell production came from an observation that interpretation of the Higgs boson production rates in terms of Higgs couplings suffers from an interesting ambiguity.



$$\sigma_{i \to H \to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

Indeed, starting from the measured on-shell cross-sections, it is impossible to determine the Higgs couplings and the Higgs width separately. This can be easily seen from the fact that any on-shell cross-section is invariant under a simultaneous re-scaling of the Higgs couplings and the Higgs width.

$$g \to \xi g, \quad \Gamma_H \to \xi^4 \Gamma_H \quad \Rightarrow \quad \sigma_H \to \sigma_H$$

Since the width of the Higgs boson used to be unconstrained, extraction of the Higgs couplings from production/decay rates suffered from significant ambiguity.

To resolve this ambiguity, we need to either measure the width of the Higgs boson or the Higgs couplings independently of each other.

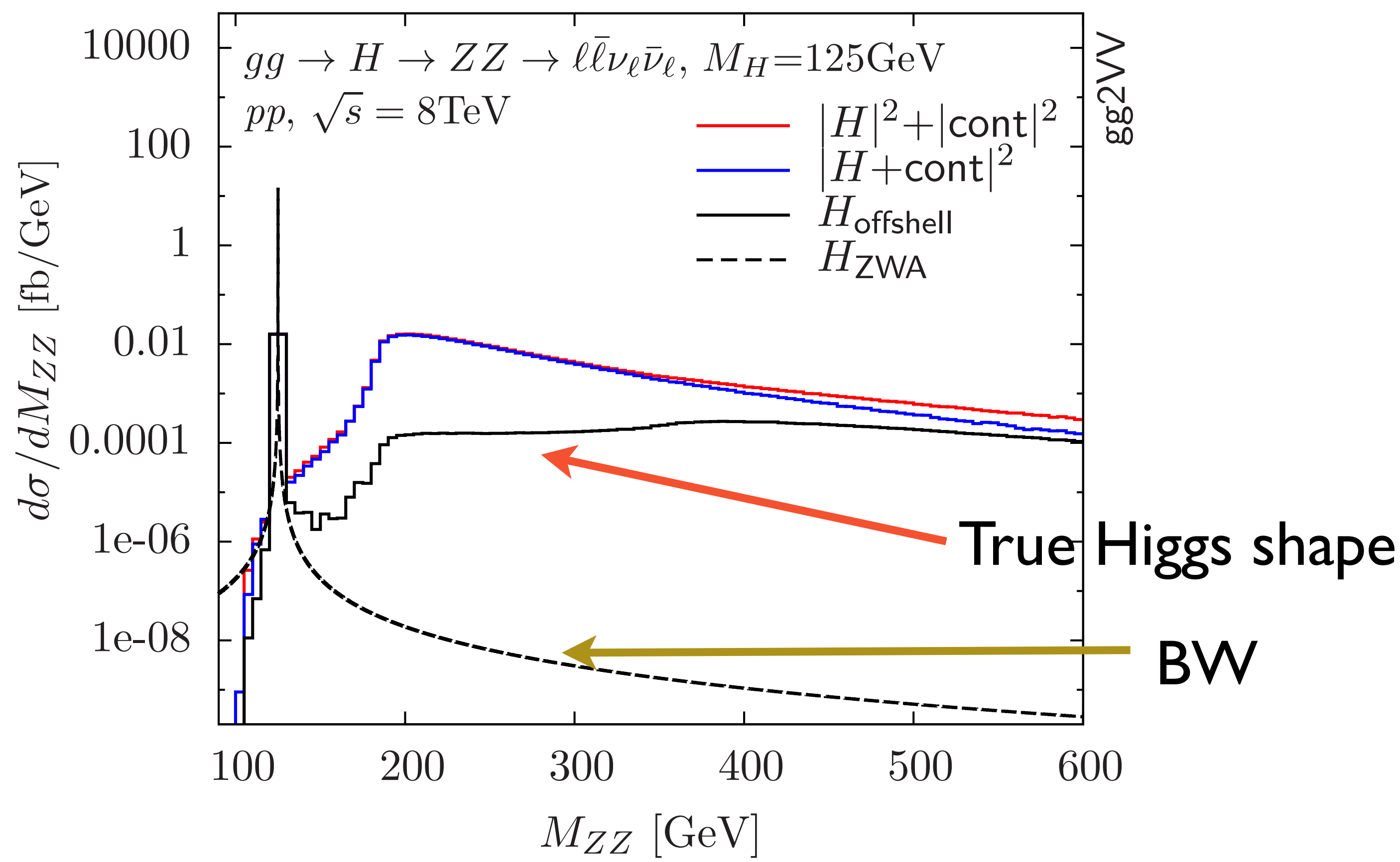
Couplings from off-shell production

One can try to measure the couplings of the Higgs boson when it is produced off-shell. The off-shell cross-section is proportional to Higgs couplings and is independent of the width; this resolves the width/couplings ambiguity.

$$\sigma_{i\to H\to f} \sim \int \frac{\mathrm{d}s \quad g_i^2 g_f^2}{(s-m_h)^2 + m_h^2\Gamma_h^2}\Big|_{s\gg m_h^2} \to \frac{g_i^2 g_f^2}{s}$$

The immediate problem with this idea is that off-shell contribution to Higgs boson production is expected to be extremely small.

However, Kauer and Passarino pointed out that a significant enhancement in the off-shell Higgs production rate exists, making the invariant mass distribution very different from the expected Breit-Wigner shape.



Kauer, Passarino

Higgs decays to ZZ

One can use this enhancement in the off-shell Higgs production to resolve the couplings/width degeneracy. The cleanest final state is ZZ (four leptons), so it is natural to look there.

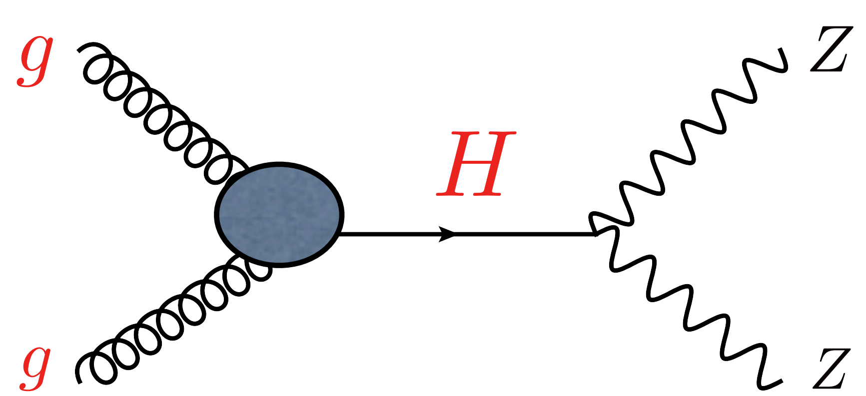
Caola, K.M.

In this case, the off-shell rate appears to be significant because decay to two on-shell Z bosons opens up and because the cross-section for producing two longitudinally polarized Z bosons in decays of (strongly) off-shell Higgs is large.

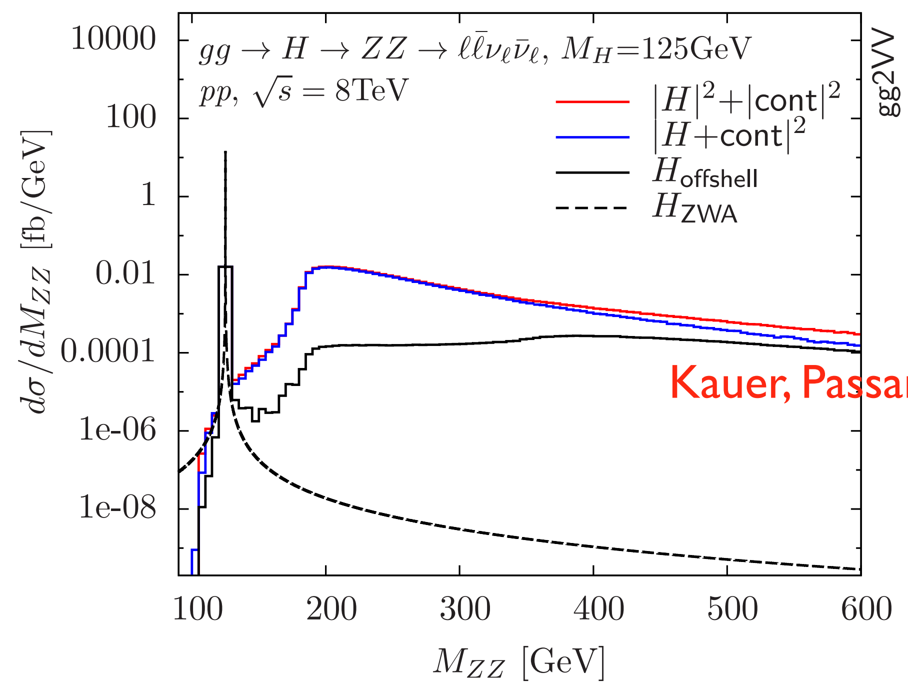
Kauer, Passarino

$$\mathcal{A}_{H^* \to Z_L Z_L} \sim \frac{s}{v} \qquad \frac{|\mathcal{A}_{H^* \to Z_L Z_L}|^2}{(s-m_h^2)^2 + m_h^2 \Gamma_h^2} \to \text{const}, \quad s \gg m_h^2$$

For large invariant masses of the Z boson pair, the amplitude divided by the Higgs propagator becomes independent of ZZ invariant mass, enhancing the off-shell production significantly. Numerically, the off-shell production cross section is really significant; it is close to ten percent of the resonance cross-section.



$$\sigma_H(m_{ZZ} > 160 \text{ GeV}) \approx 0.1\, \sigma_H$$

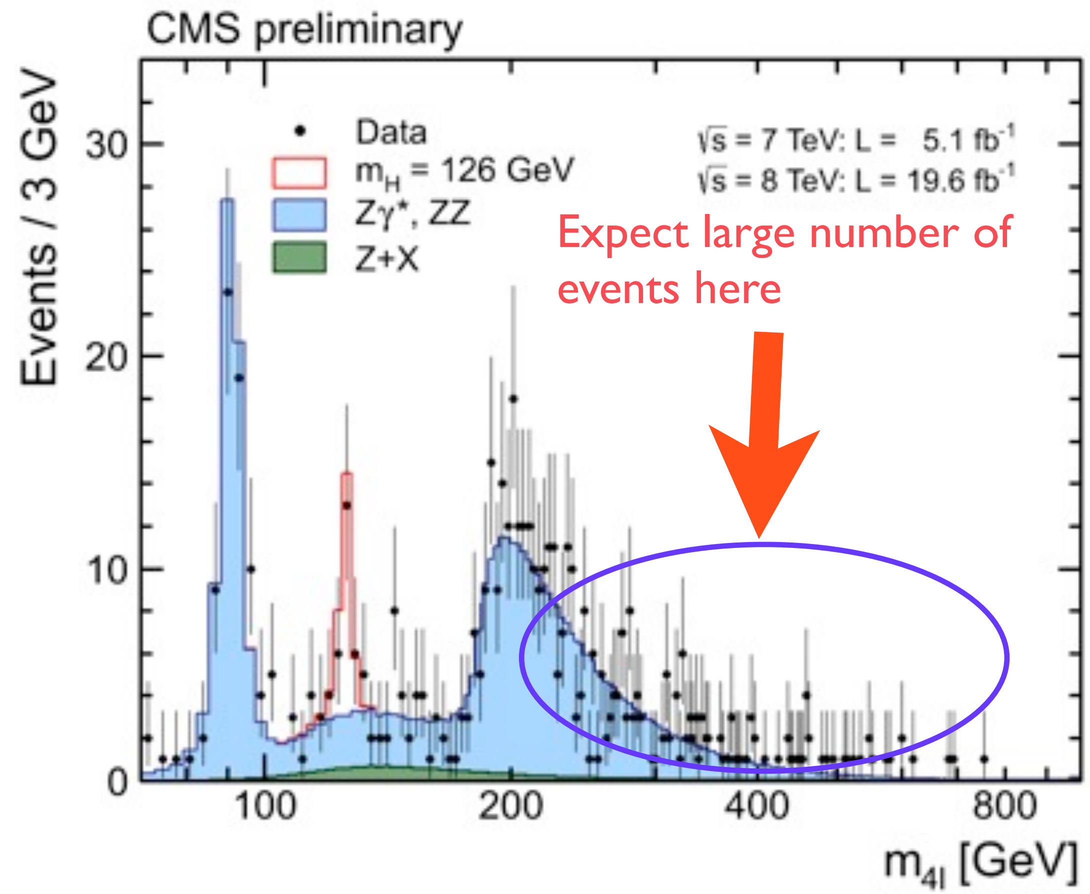


The Higgs width

The off-shell production cross-section does not depend on the Higgs width but does depend on the Higgs couplings to initial state particles (gluons) and final state particles (Z bosons). This implies that if we change both the width of the Higgs and its couplings to other particles in such a way that the resonance cross-section does not change, the off-shell production cross-section changes proportionally to the Higgs width.

$$\sigma_H \sim \frac{g^2_{H\to gg} g^2_{H\to ZZ}}{\Gamma_H}; \qquad \sigma_{\rm off} \sim g^2_{H\to gg} g^2_{H\to ZZ}. \qquad \sigma_H \sim \sigma_H^{\rm SM} \qquad \sigma_{\rm off} \sim \sigma_{\rm off}^{\rm SM} \frac{\Gamma_H}{\Gamma_H^{\rm SM}}$$

The current direct upper bound on the Higgs boson width is O(2) GeV. This is O(400) times larger than the Standard Model value. If the width were actually that large, the total number of events in the off shell region would be a factor of two larger than the total number of events that, the CMS collaboration has in ZZ channel ! Therefore, one can put quite meaningful bounds on the Higgs width using the current data on ZZ final states !

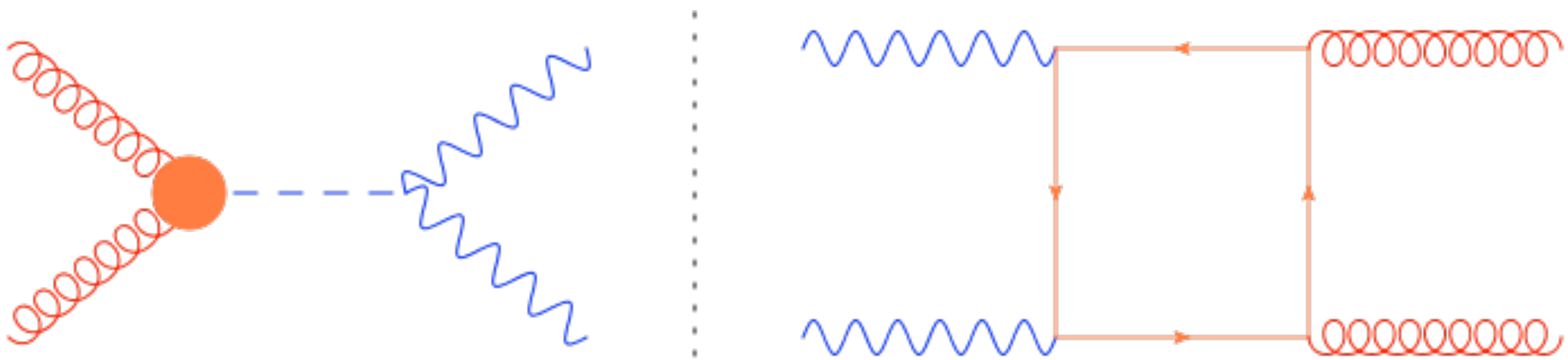


Caola, K.M.

Signal-background interference

An important caveat is the signal-background interference. Indeed, production of two Z bosons in collisions of two gluons can occur either directly or through the Higgs boson. The two amplitudes interfere destructively (essentially, unitarity cancellations in the Standard Model). The interference is negligible at the peak (narrow resonance) but it is significant (-50%) off the peak.

Kauer, Passarino; Ellis, Campbell, Williams



For our purposes, it is important that the scaling of the interference with the width differs from the scaling of the off-shell cross-section, since dependence of the interference on the Higgs boson couplings is weaker.

$$\sigma_{\rm int} \sim \mathcal{A}_{gg\to H^*\to ZZ} \sim g^2 \sim \sqrt{\Gamma_H}$$

Constraining the width

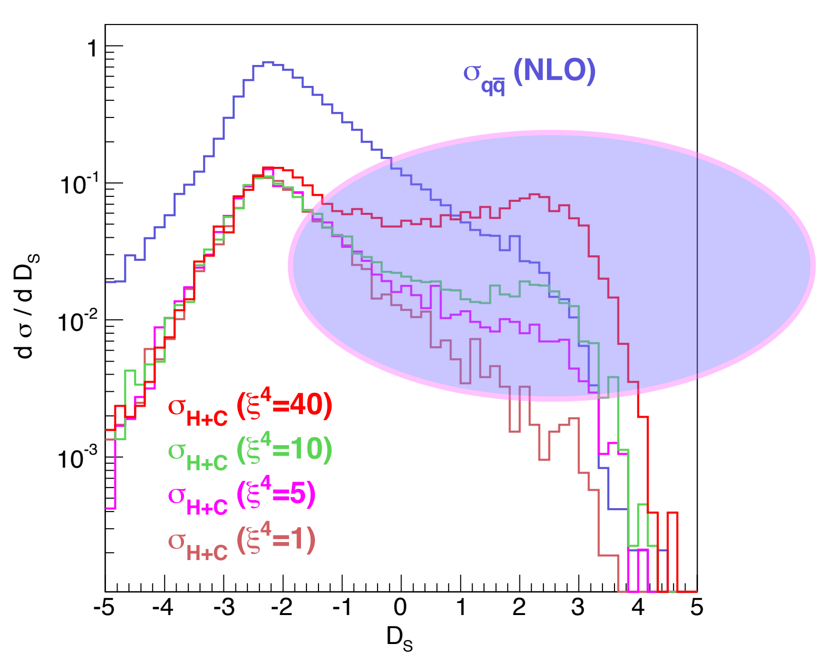
If we float the width of the Higgs boson keeping on-shell production rates fixed, the number of expected off-shell events changes; as we have seen, the off-shell Higgs production cross-section scales as the width and the interference scales as the square root of the width. Considering ZZ invariant mass range from 100 GeV to 800 GeV, we find a new estimate for the number of events

$$N_{\rm exp} = 432 + 2.78\frac{\Gamma_H}{\Gamma_H^{\rm SM}} - 5.95\sqrt{\frac{\Gamma_H}{\Gamma_{\rm H}^{\rm SM}}} \pm 31$$

$$|N_{\rm nobs} - \bar{N}_{\rm exp}| < 62$$

$$\Gamma_H < 43\ \Gamma_H^{\rm SM} = 181\ {\rm MeV}\ (95\%{\rm C.L})$$

The analysis can be improved in many different ways, e.g. by focusing on the region of high invariant mass of four leptons, by using angular distributions of two Z-bosons to select longitudinal polarizations and/or by using multivariate techniques in the analysis.



$$D_S = \log\left[\frac{P_H}{P_{gg} + P_{qq}}\right] \qquad P_i \sim |M_i|^2$$

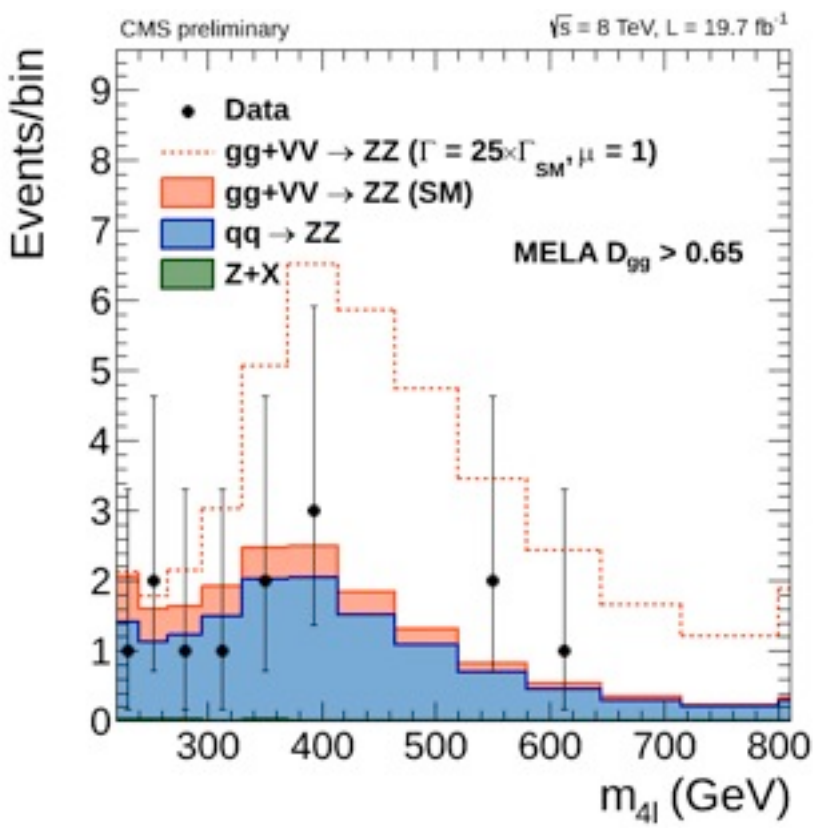
$$\Gamma_H < 15.7\Gamma_H^{\rm SM}\ (95\%{\rm C.L.})$$

Campbell, Ellis, Williams

But, regardless of what theorists were suggesting, CMS and ATLAS knew how to it better....

The Higgs width constraint: CMS

CMS collaboration measured the number of 4-lepton events in the off-shell region and used it to constrain the Higgs width. The measurement includes both ZZ and WW channels.



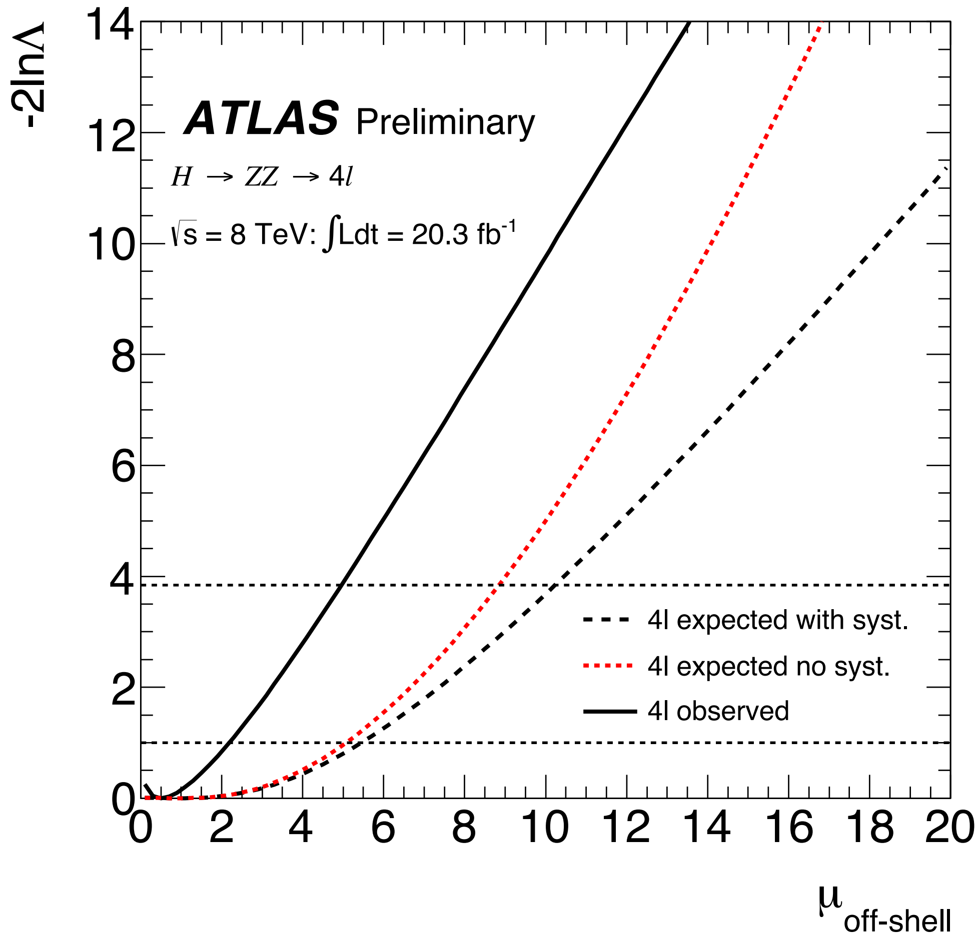
		4ℓ	$2\ell 2\nu$
(a)	total gg ($\Gamma_H = \Gamma_H^{SM}$)	1.8 ±0.3	9.6 ±1.5
	gg signal component ($\Gamma_H = \Gamma_H^{SM}$)	1.3 ±0.2	4.7 ±0.6
	gg background component	2.3 ±0.4	10.8 ±1.7
(b)	total gg ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	9.9 ±1.2	39.8 ±5.2
(c)	total VBF ($\Gamma_H = \Gamma_H^{SM}$)	0.23 ±0.01	0.90 ±0.05
	VBF signal component ($\Gamma_H = \Gamma_H^{SM}$)	0.11 ±0.01	0.32 ±0.02
	VBF background component	0.35±0.02	1.22 ±0.07
(d)	total VBF ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	0.77 ±0.04	2.40 ±0.14
(e)	$q\bar{q}$ background	9.3 ±0.7	47.6 ±4.0
(f)	other backgrounds	0.05 ±0.02	35.1 ±4.2
(a+c+e+f)	total expected ($\Gamma_H = \Gamma_H^{SM}$)	11.4 ±0.8	93.2 ±6.0
(b+d+e+f)	total expected ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	20.1 ±1.4	124.9 ±7.8
	observed	11	91

$$\Gamma_H < 5.4\ \Gamma_{H,SM} = 22\ \text{MeV @ 95CL}$$

A very impressive result -- almost two orders of magnitude improvement compared to the direct (on peak) bound of the width.

The Higgs width constraint: ATLAS

A similar measurement was performed by the ATLAS collaboration. Data is analyzed in ZZ and WW channels and then combined. ATLAS analysis emphasized the dependence of the final bound on the width on the (back then unknown) size of QCD corrections to gg->ZZ background process.



Process	220 GeV $< m_{4\ell} <$ 1000 GeV	400 GeV $< m_{4\ell} <$ 1000 GeV
$gg \to H^* \to ZZ$ (S)	2.2 ± 0.5	1.1 ± 0.3
$gg \to ZZ$ (B)	30.7 ± 7.0	2.7 ± 0.7
$gg \to (H^* \to) ZZ$	29.2 ± 6.7	2.3 ± 0.6
$gg \to (H^* \to) ZZ$ ($\mu_{\text{off-shell}} = 10$)	40.2 ± 9.2	9.0 ± 2.5
VBF $H^* \to ZZ$ (S)	0.2 ± 0.0	0.1 ± 0.0
VBF ZZ (B)	2.2 ± 0.1	0.7 ± 0.0
VBF $(H^* \to) ZZ$	2.0 ± 0.1	0.6 ± 0.0
VBF $(H^* \to) ZZ$ ($\mu_{\text{off-shell}} = 10$)	3.0 ± 0.2	1.4 ± 0.1
$q\bar{q} \to ZZ$	168 ± 13	21.3 ± 2.1
Reducible backgrounds	1.4 ± 0.1	0.1 ± 0.0
Total Expected (SM)	200 ± 15	24.3 ± 2.2
Observed	182	18

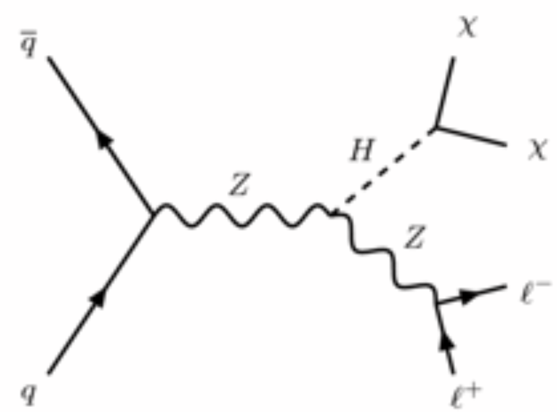
$$\Gamma_H < 4.8\text{-}7.7\ \Gamma_{H,SM} = 20\text{-}32 \text{ MeV @ 95CL}$$

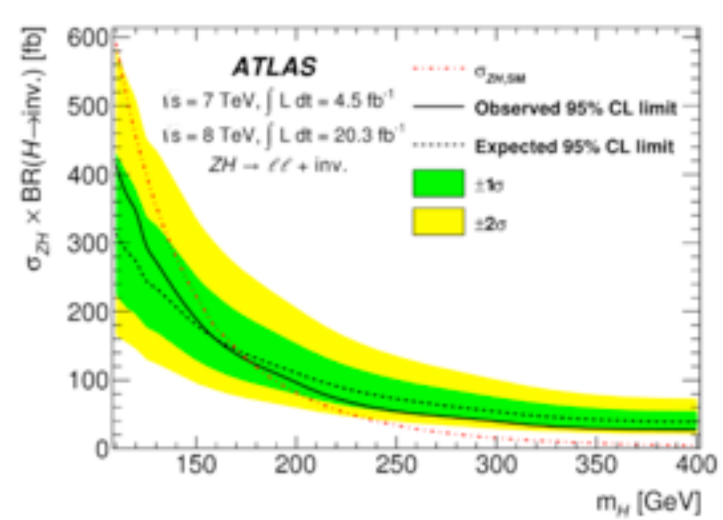
(depending on the assumed K-factor for gg->ZZ background)

Invisible branching and the Higgs width: ATLAS

Important information about the Higgs boson width can be obtained from experimental constraints on the branching ratio of Higgs decays to invisible final states, Br(H -> inv) < 0.75. Current constraints are obtained assuming the Standard Model production cross-section ratio for pp -> ZH but the re-scaling of couplings violates this assumption.

Azatov





$$\xi^2\, \mathrm{Br}_{\mathrm{inv}} < 0.75$$

Within the framework where all couplings and the width change coherently, the bound on the width from invisible branching needs to be reconsidered.

$$\mathrm{Br}_{\mathrm{inv}} = 1 - \xi^{-2}$$

$$\sqrt{\frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}} - 1 < 0.75$$

$$\Gamma_H \leq 3.1\, \Gamma_{H,\mathrm{SM}}$$

The constraint on the width from invisible branching ratio appears to be in the same ballpark but somewhat stronger than the constraint from the off-shell production that we just discussed.

General comments

1) A suggestion that the Higgs boson width can be constrained at the LHC appeared unexpectedly; it showed that it is possible to use subtle quantum mechanical effects (off-shell, interference) to get to interesting physics. Hopefully, we will see more examples of this in the future.

2) CMS/ATLAS measurements prove that it is possible in practice to use off-shell production of Z and W pairs to obtain interesting information about the Higgs boson.

3) By going off-shell, we measure couplings. No width enters the off-shell physics. We infer the information about the width from the on-shell cross-section once couplings are known, under the assumption that the difference between on-shell and off-shell couplings is can be neglected.

4) If we want to push these ideas/measurements further, precise theoretical predictions for the off-shell regime are important; compared to the on-shell case, precise predictions for off-shell regime require somewhat different ingredients.

If we see an off-shell enhancement, is it the width ?

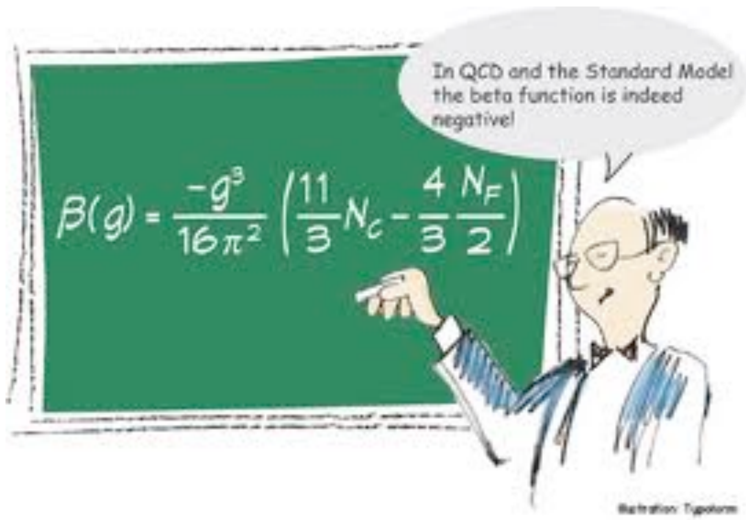
Enhancement at large ZZ invariant masses

If we see an enhancement at large ZZ invariant masses, it may be larger Higgs width or it may be something else.

Regardless of the interpretation, the main idea behind the Higgs width measurement method is that excessive events at high-invariant mass of Z-boson pairs are interesting and may be related to Higgs boson physics. Interpretation of such excesses (or lack of them) as limits on the Higgs boson width is possible, but requires care since it forces us to relate couplings measured at different invariant masses.

In any QFT couplings "run" (which is another way of saying that there are radiative corrections). Weak, logarithmic running is not important for constraints that we just discussed. However, the difference between on- and off-shell couplings may become significant if, e.g., the HZZ vertex contains anomalous couplings or the HGG vertex receives significant contributions from light degrees of freedom. In those cases the couplings may change so strongly, that it is incorrect to assume that they are equal on- and off-shell.

It was pointed out by various authors that these effects can tame or mimic the couplings/width enhancement. Luckily, it seems that many such effects can be constrained by other (on-shell) measurements, as I will discuss shortly.



Anomalous HZZ coupling

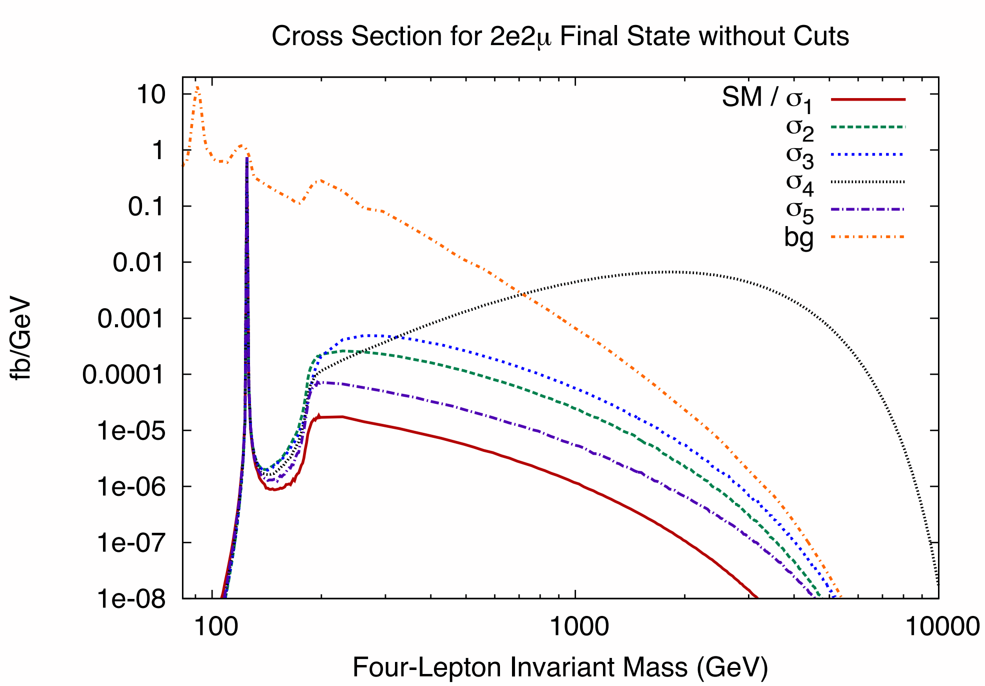
Anomalous HZZ couplings may lead to an increase in the number of events in the off-shell tail that, however, is independent of the “width” (i.e. effects of anomalous couplings on-shell are small).

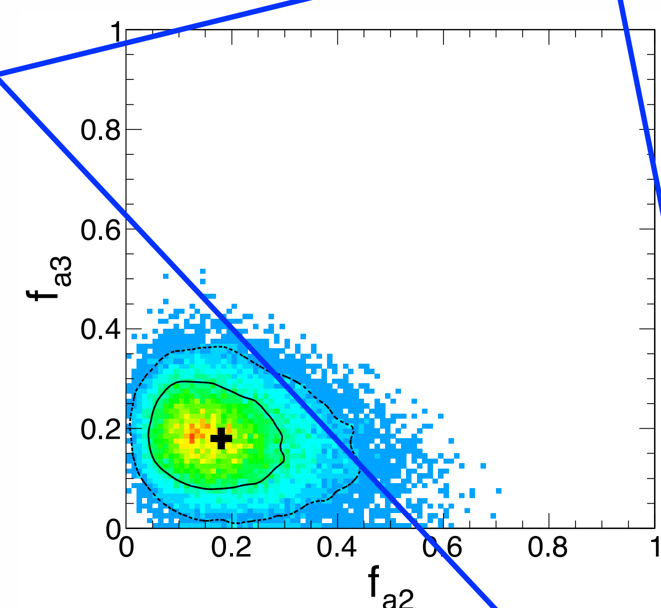
Gainer, Lykken et al (2013)

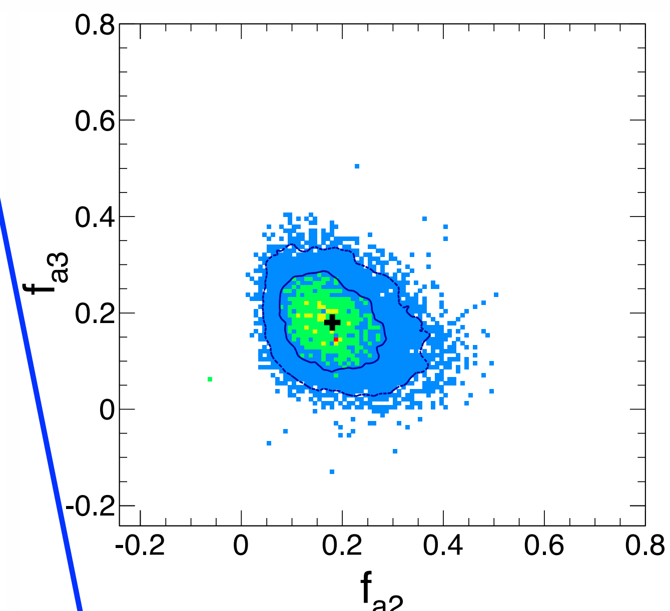
$$\mathcal{O}_1 = -\frac{M_Z^2}{v} H Z_\mu Z^\mu, \quad \mathcal{O}_2 = -\frac{1}{2v} H Z_{\mu\nu} Z^{\mu\nu} \qquad \mathcal{O}_3 = -\frac{1}{2v} H Z_{\mu\nu} \tilde{Z}^{\mu\nu}, \quad \mathcal{O}_4 = \frac{2}{v} H Z_\mu \partial^2 Z^\mu$$

$$\mathcal{O}_6 = -\frac{M_Z^2}{M_H^2 v} Z_\mu Z^\mu \partial^2 H$$

Strong modification of the m_{4l} shape







Modification of lepton angular distributions can be detected with 300 fb^{-1}

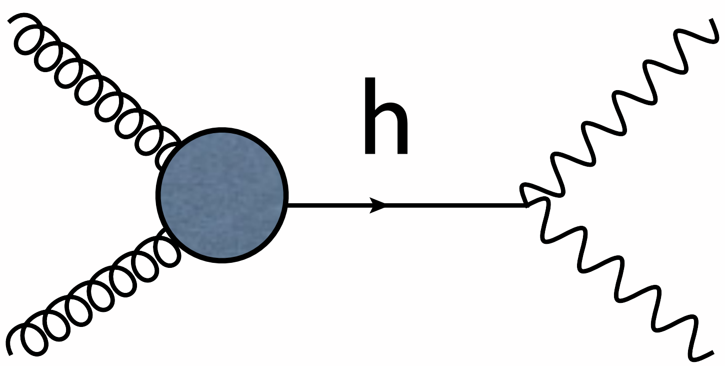
Note that O_6 can be re-written as a contact ZZGG operator that may have nothing to do with the Higgs boson, a’priori.

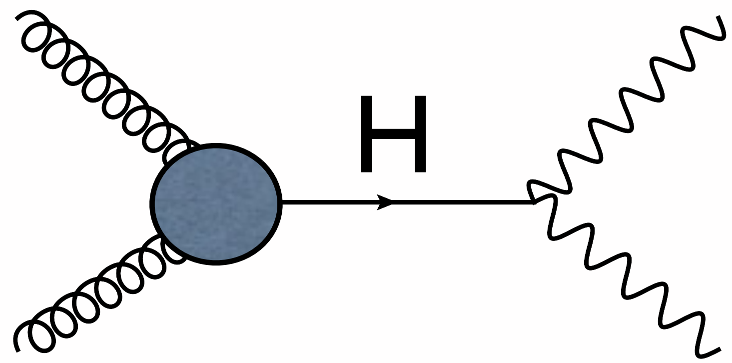
Anderson et al. (2013)]

Hiding the off-shell enhancement with additional Higgs bosons

A possible physics illustration of the previous operator analysis is provided by a model with two Higgs bosons; the role of the second (heavier) Higgs boson is to restore violations of unitarity that occur if couplings of the discovered Higgs boson to top quarks and Z-bosons are changed.

Logan et al (2014)



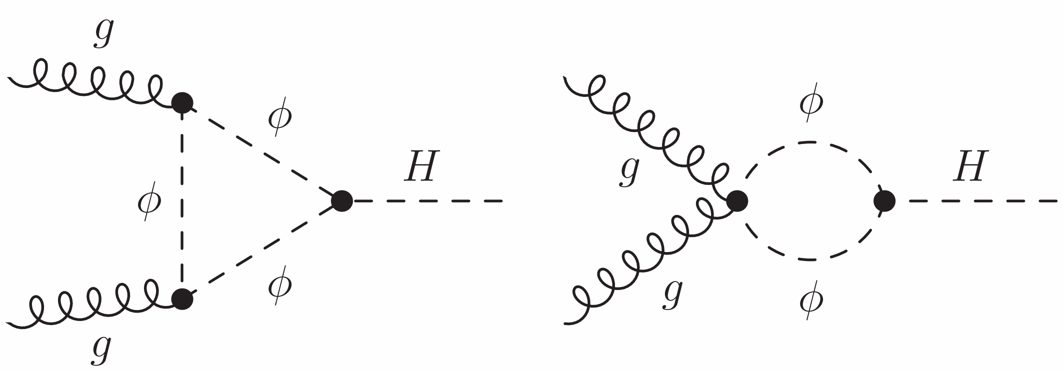


$$\mathcal{M} = \mathcal{M}_{SM} \left(1 + \Delta - \Delta \frac{p^2 - m_h^2}{p^2 - M_H^2} \right)$$

At low invariant masses, the coupling of the lighter Higgs to Z's is enhanced, requiring modification of the Higgs boson width. However, the gg->ZZ amplitude becomes equal to the SM one for invariant masses higher than masses of both Higgs bosons, so the enhancement disappears.

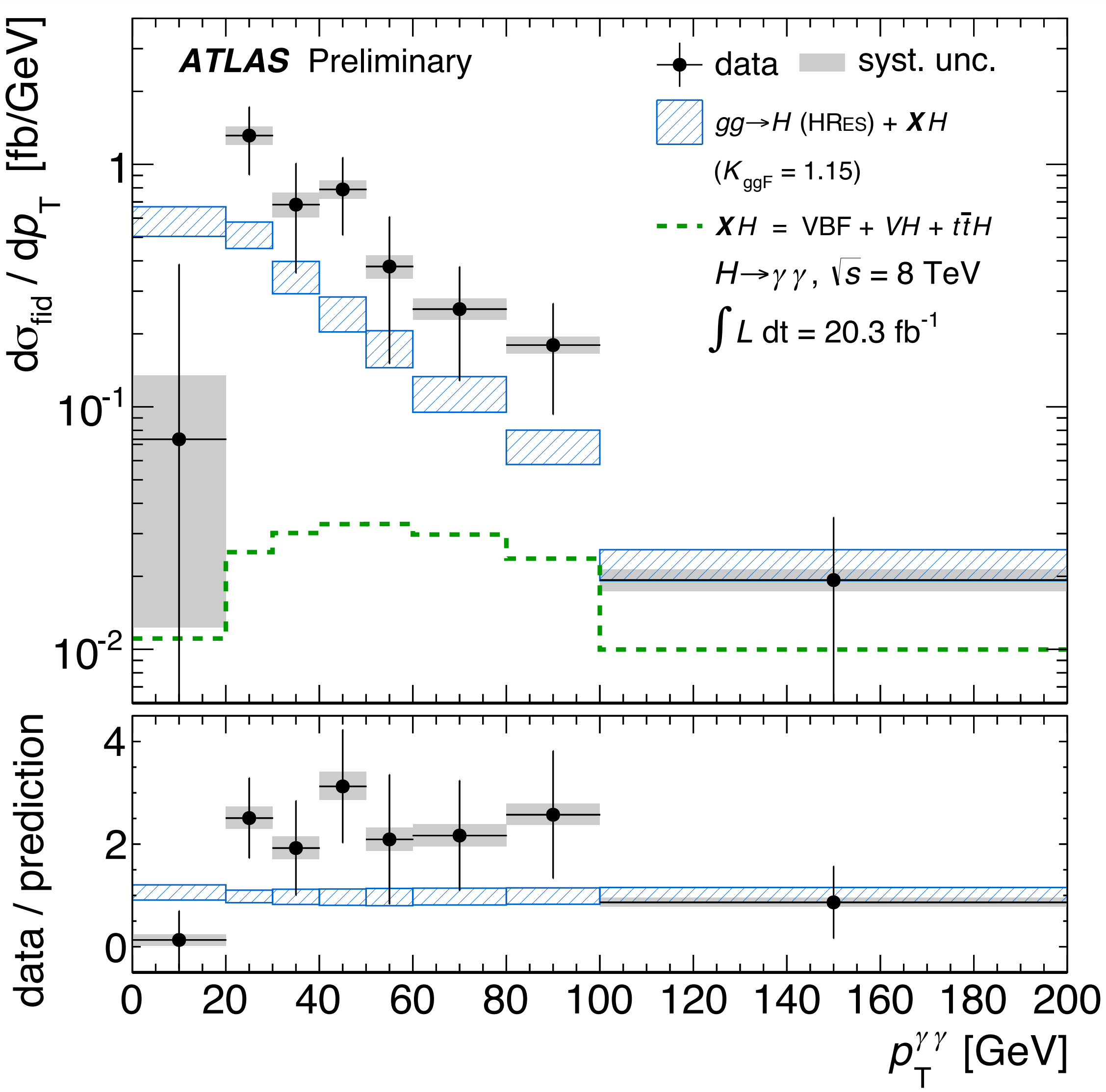
While this example shows that it is possible to hide the Higgs width enhancement from the off-shell measurements, it is done at the expense of introducing even more exciting physics -- another Higgs boson -- that is detectable in the high-energy tail!

Light colored singlets in the HGG vertex



Englert, Spannowsky (2014)

Light particles in the HGG vertex induce power-like running of the coupling constant and, therefore, can change the relation between on- and off-shell couplings.



m_ϕ	μ (h peak)	Γ_h/Γ_h^{SM}	$\overline{\sigma}/\overline{\sigma}^{SM}$ [$m(4\ell) \geq 330$ GeV][a]
70 GeV	$\simeq 1.0$	$\simeq 5$	-2%
170 GeV	$\simeq 1.0$	$\simeq 4.7$	$+80\%$
170 GeV	$\simeq 1.0$	$\simeq 1.7$	$+6\%$

[a] We impose the cut set used by CMS [18] without the MELA cut [35].

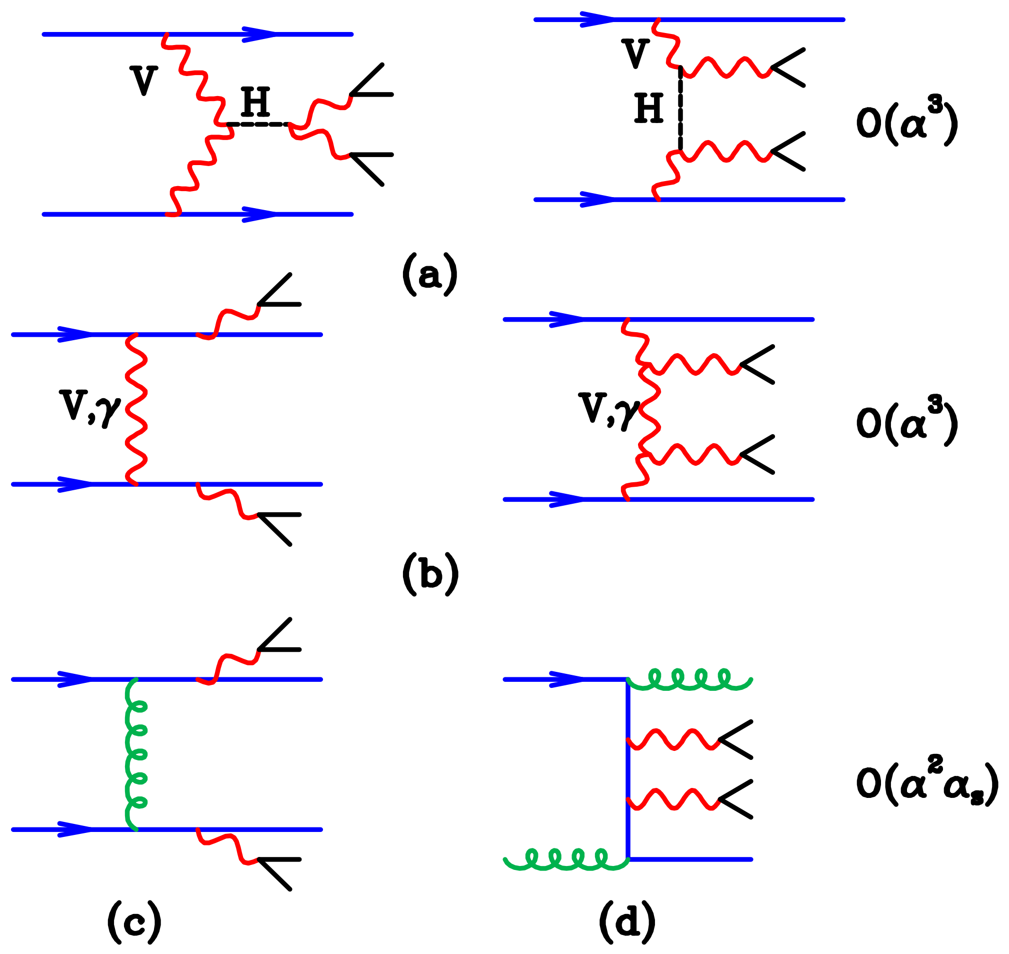
However, these light particles can be detected by by studying the Higgs p_T distribution (probably, need theoretical improvement, full m_t dependence) where the off-shell probe will be the gluon and not the Higgs.

Prospects

New channels: weak boson fusion

It is possible to apply a similar analysis to other production channels of the Higgs boson, most notably to the production of the Higgs boson in weak boson fusion.

A recent analysis suggests that the most promising channel to look for off-shell events is the equal sign W-boson production because of tiny backgrounds. The Higgs boson in this case appears in the t-channel and it is never on-shell.



Standard VBF cuts are applied; 4-lepton invariant (or transverse) mass is required to be smaller than 300 GeV.

Results from Run I constrain the width to be smaller than 60 times its Standard Model values (O(1) event observed by ATLAS)

Number of events with 100 inverse fb for realistic selection cuts

$$l^+l^+\nu\nu: \quad N_{\rm off} = 38.8 - 18.3\kappa_V^2 + 8.3\kappa_V^4$$

$$l^-l^-\bar\nu\bar\nu: \quad N_{\rm off} = 11.5 - 4.1\kappa_V^2 + 1.8\kappa_V^4$$

Limits expected from future LHC runs

$$\Gamma_H < 4.4 \times \Gamma_H^{SM} \qquad (100\ {\rm fb}^{-1}\ {\rm data})\ ,$$

$$\Gamma_H < 3.2 \times \Gamma_H^{SM} \qquad (300\ {\rm fb}^{-1}\ {\rm data})\ .$$

Ellis and Campbell

Higgs loop effects

In principle, any appearance of the Higgs boson in loop diagrams provides us with potentially observable effects that depend on Higgs couplings and not on the width. Several suggestions were made in that context.

1) Limits on the Yukawa coupling from electroweak corrections to top pair production at the LHC where some sensitivity exists in the threshold region. Defining the threshold region as up to 50 GeV away from top pair threshold, I estimate that there should be already O(1000) events (all channels) at the 8 TeV LHC in that region. For SM Yukawa, the EW corrections in this region are tiny. For the Yukawa re-scaled from its SM value by a factor of two -- the EW corrections in this region are O(10%). Such an effect should, in principle, be observable already with the current data.

Kuehn, Scharf, Uwer

2) Precision electroweak (LEP) data allows to constrain HZZ and HWW couplings under the assumption that re-scaled HZZ and HWW couplings are the only BSM effects. This is interesting since this line of reasoning is independent of HGG or Higgs-Yukawa. Possible to combine with WBF constraints on Higgs boson couplings from the LHC off-shell measurements; ultimate reach with 3000/fb collected luminosity seems to be $\Gamma_H < \mathcal{O}(2) \times \Gamma_H^{\rm SM}$

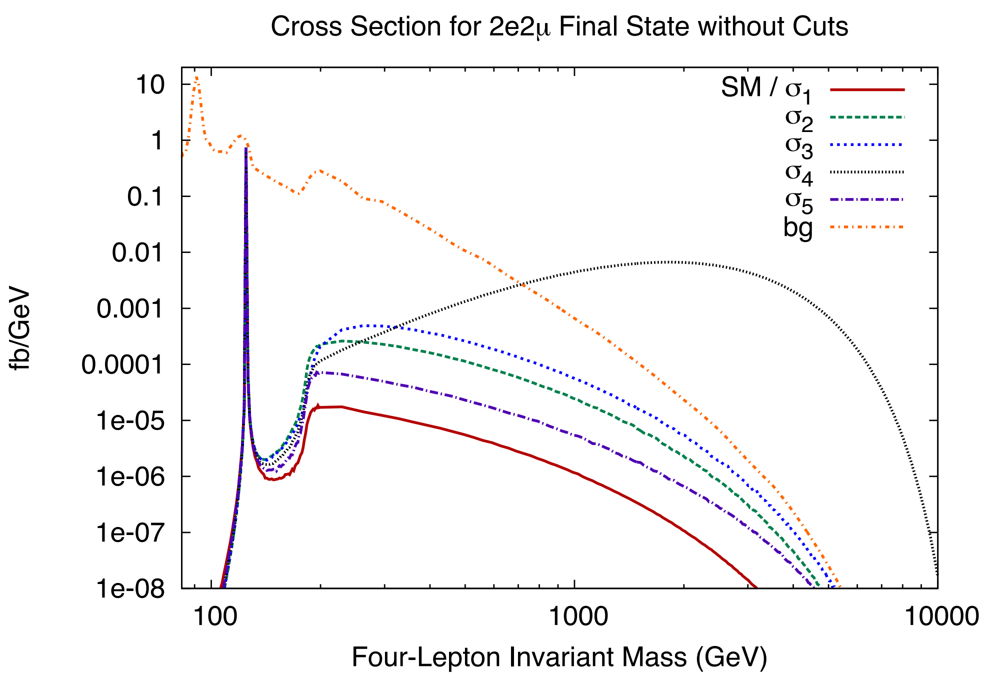
Englert, McCullough, Spannowsky

New predictions for background processes

To verify the consistency of the off-shell production regime with the Standard Model nature of the Higgs boson as precisely as possible, we need to predict the number of four-lepton events at high ZZ-invariant mass accurately.

To understand what precision is needed, it is instructive to keep in mind that in the current (8 TeV) 4-lepton analysis, CMS expects 11 off-shell events in the SM and that 1 event, out of these 11, is caused by the off-shell Higgs boson, 2 event are caused by gg -> ZZ and -1 event by the interference. The rest is qqb -> ZZ.

This implies that if we want to constrain the couplings to O(20%) (and the width within a factor of two), O(10%) prediction for qq->ZZ and O(50%) prediction for gg ->ZZ is required. This was an important challenge but we have almost reached it !



		4ℓ	$2\ell 2\nu$
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(a+c+e+f)	total expected ($\Gamma_H = \Gamma_H^{SM}$)	11.4 ±0.8	93.2 ±6.0
(b+d+e+f)	total expected ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	20.1 ±1.4	124.9 ±7.8
	observed	11	91

New predictions for background processes

Indeed, a recent progress towards this goal is quite impressive. The NNLO QCD prediction for pp -> ZZ production cross-section recently appeared; the residual uncertainty is estimated at 3 percent.

T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhoefer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi

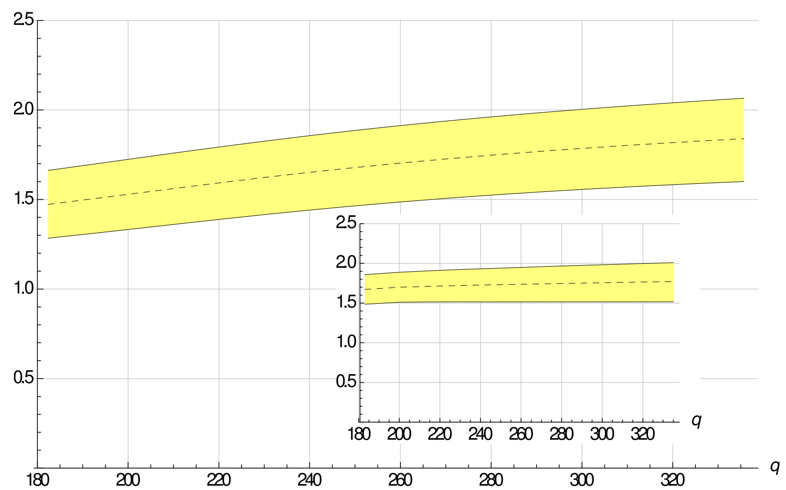
The NLO QCD corrections to gg -> ZZ production through massless quark loops were computed as well; large K-factor (1.7-1.9) was found and the residual uncertainty was estimated to be close to 10 percent.

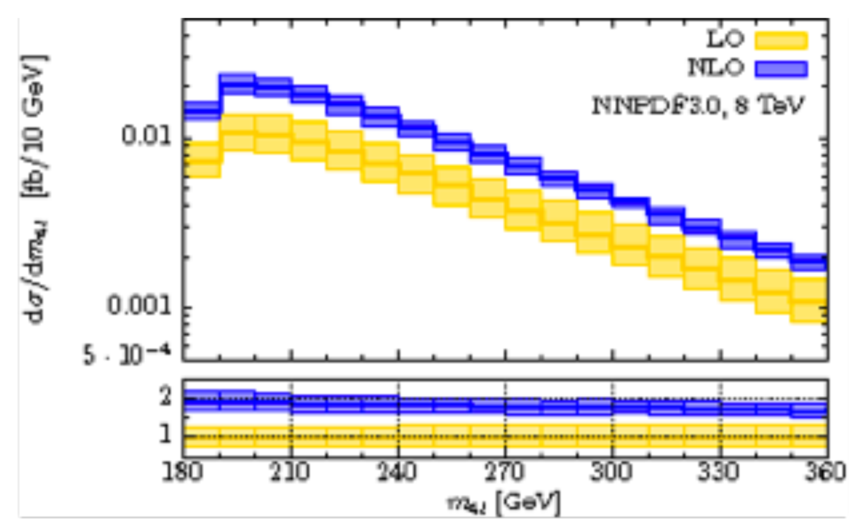
F. Caola, K. Melnikov, R. Rontsch, L. Tancredi

Top quark loops perhaps are not important for the cross-section but are likely to be relevant for the interference with the Higgs. Recent results for gg ->ZZ cross-section in the approximation of the infinitely heavy top quark indicate large (1.8) K-factor.

Dowling, Melnikov

Overall, it appears that the K-factors for gg->ZZ are large and similar to gg -> H -> ZZ; the interference effects at NLO are not yet known but all information that we have suggests that the current approach by the CMS collaboration, that assumes that K-factors for the signal and the interference are similar, is quite reliable.





Conclusions

Interesting effects in Higgs physics come from subtle phenomena such as off-shell production and the interferences.

In the four-lepton channel, large effects are caused by the decay of an ''off-shell Higgs'' to longitudinal Z bosons at large invariant masses. This leads to a plateau of Higgs-induced events. Measuring the number of events at the high-invariant mass region probes Higgs couplings to gluons and Z bosons, independently of the Higgs width. The measured value of the Higgs on-shell production cross-section is then used to infer the value of the Higgs width. Already with the current data, constraints on the Higgs width from the off-shell production are impressive; the very recent CMS/ATLAS measurements suggest $\Gamma_H < \mathcal{O}(7)\ \Gamma_H^{\rm SM}$.

Further advances in constraining the Higgs width and other physics accessible in the off-shell regime require precise theoretical predictions for ZZ production in proton collisions; the recent progress in describing qq -> ZZ and gg -> ZZ provides the required theoretical results.

It is useful to explore the off-shell physics in H+jet and H+2 jet channels, study weak boson fusion and explore width constraints that follow from di-photon final states.

Campbell, Ellis, Furlan, Rontsch; Buschman, Goncalves, Kuttimalai, Schonherr, Krauss, Plehn; Dixon and Li

Altogether, off-shell measurements define rich research program that requires strong collaboration between theory and experiment that, hopefully, will lead to further important insights into Higgs boson physics during the Run II of the LHC.