Constraining the Higgs boson width at the LHC with off-shell production

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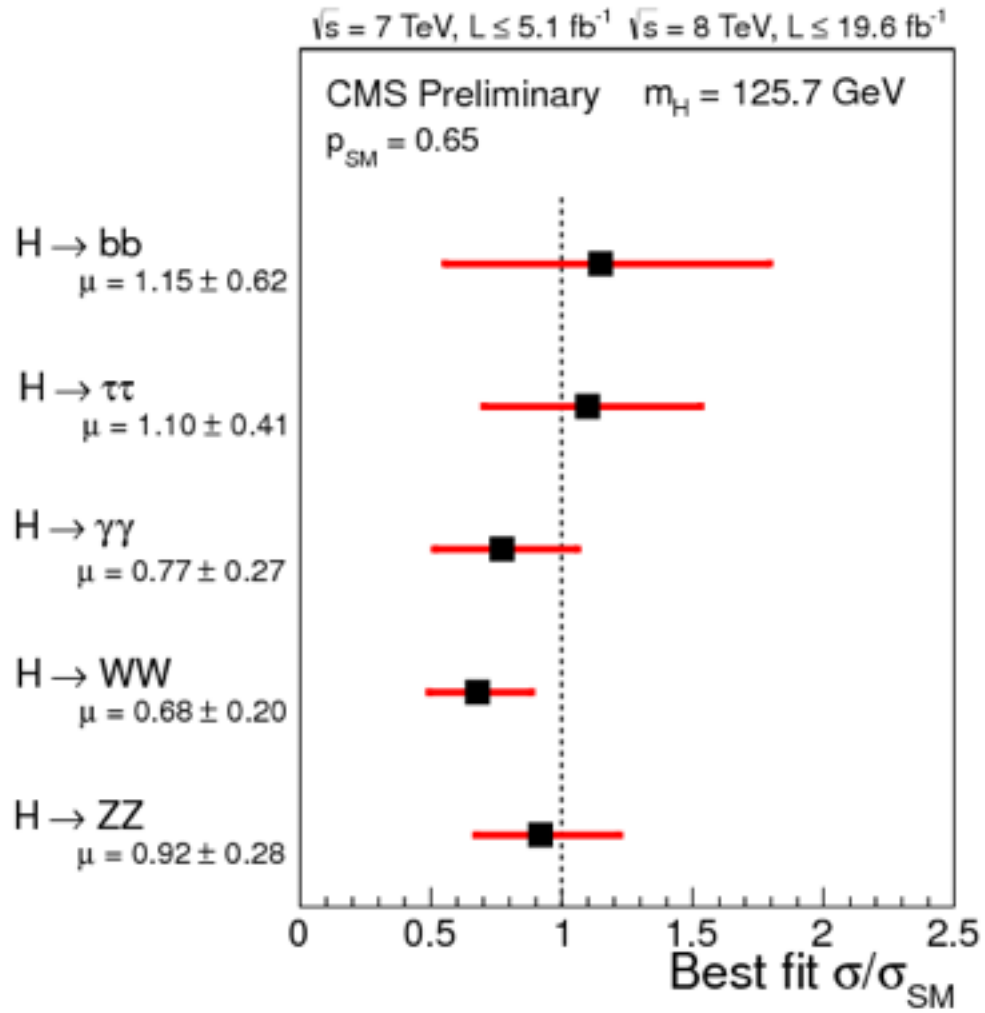
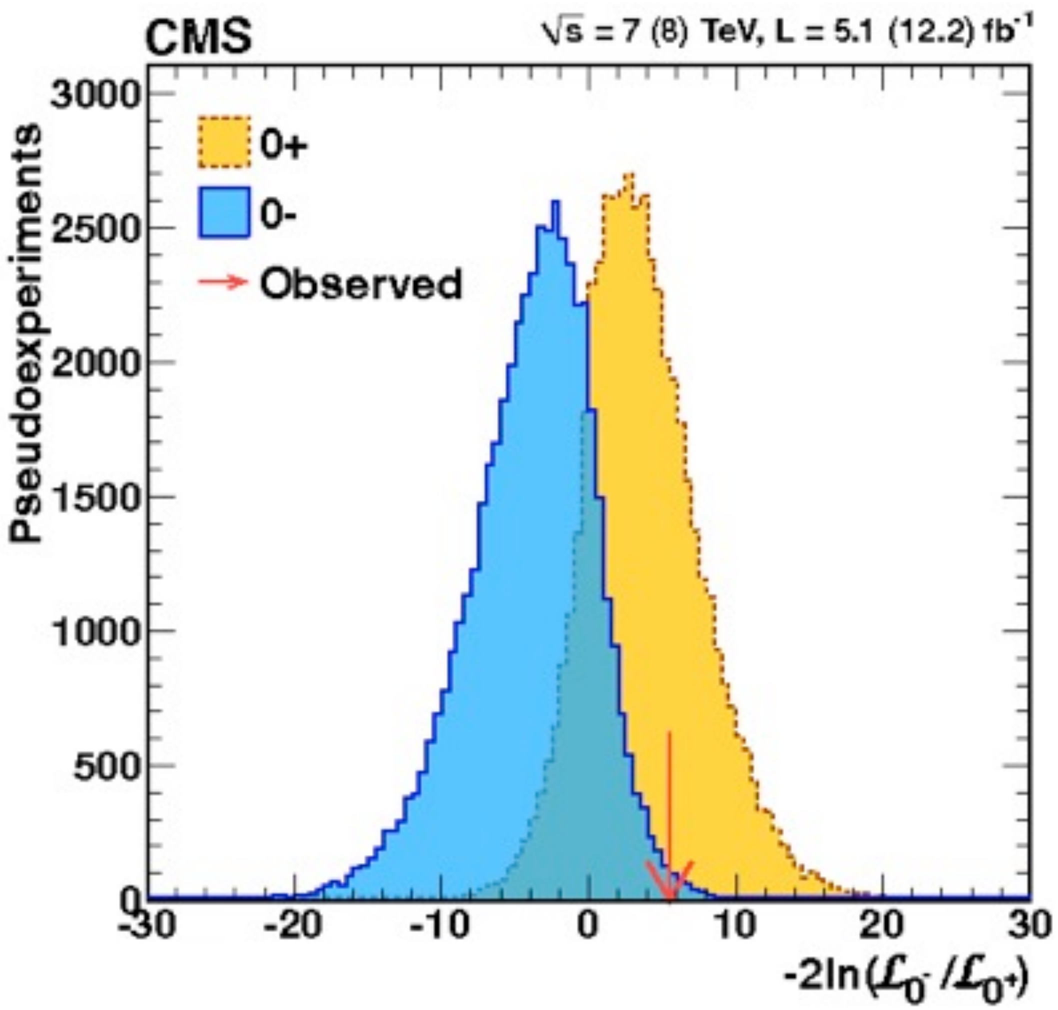
The discovery of the Higgs boson

The discovery of a new particle by CMS and ATLAS collaborations opened up a way to its detailed exploration. Such studies occurred quite rapidly and provided us with important information about its properties.

The Higgs boson properties

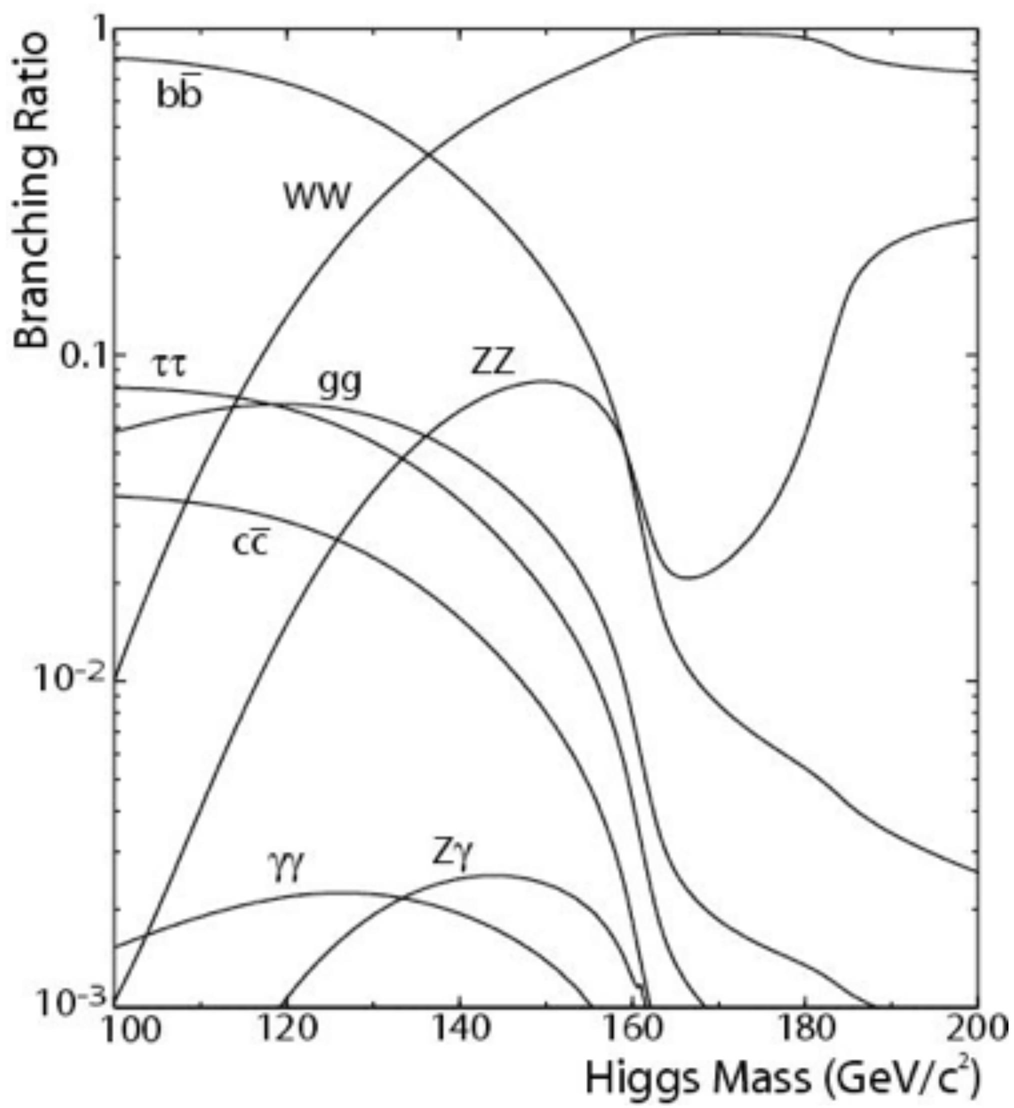
The new particle appears to be the Higgs boson of the Standard Model. Indeed, its production and decay rates, its spin and parity, as well as its mass, are consistent with the Standard Model expectations. Further studies of these quantities with higher precision are definitely warranted but there are a few ``big items'' in Higgs physics that, at the moment, we do not know much about. One such item is the Higgs width, the other one is the Higgs boson self-coupling and yet another one is the Higgs coupling to light fermions. The goal of this talk is to focus on one of these big items -- the Higgs boson width.

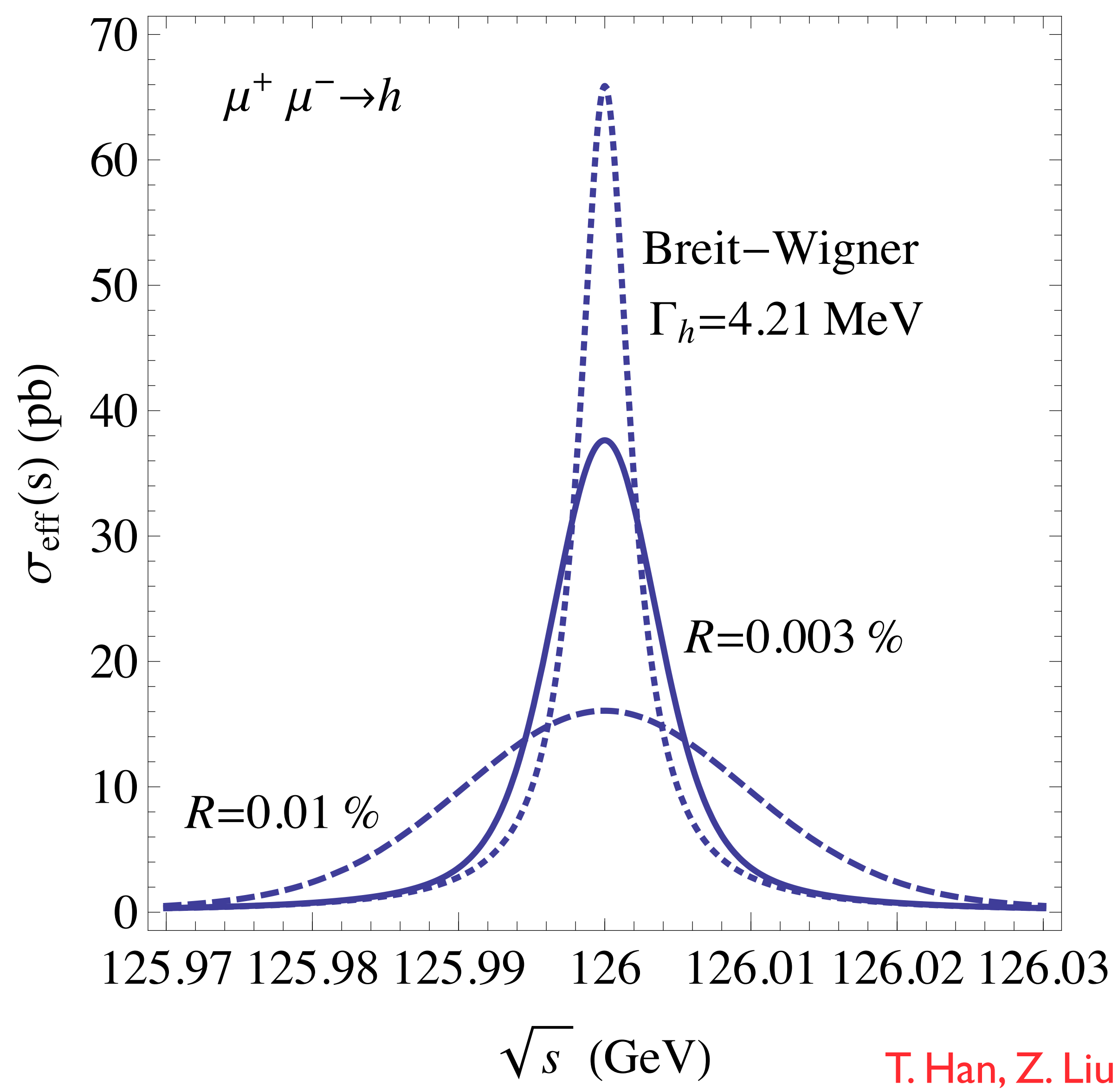




The Higgs boson width

In the Standard Model, the width of 126 GeV Higgs boson is extremely small, it is just 4.2 MeV. It is almost impossible to measure it directly at any collider, with the exception of the muon one. At hadron and electron colliders, one can measure Higgs branching to invisible final state in the Bjorken process and then infer the total width from there. At an e+e- and muon collider, a measurement of the Higgs width with a few percent precision can probably be achieved.



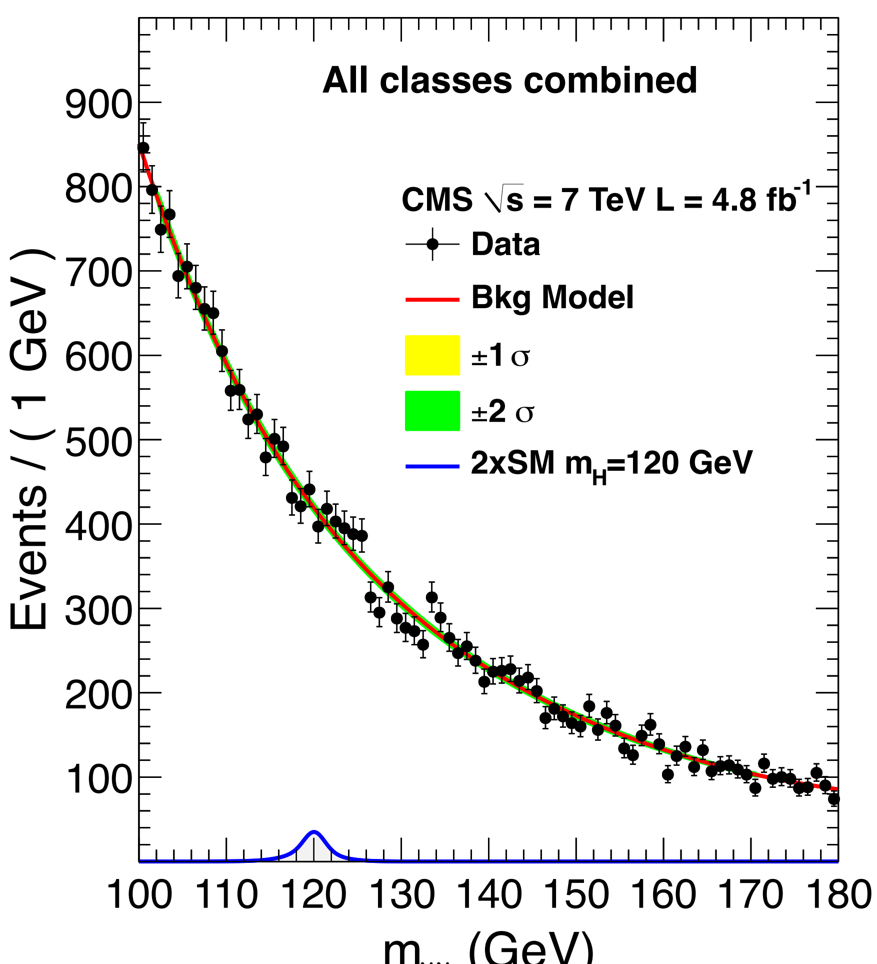


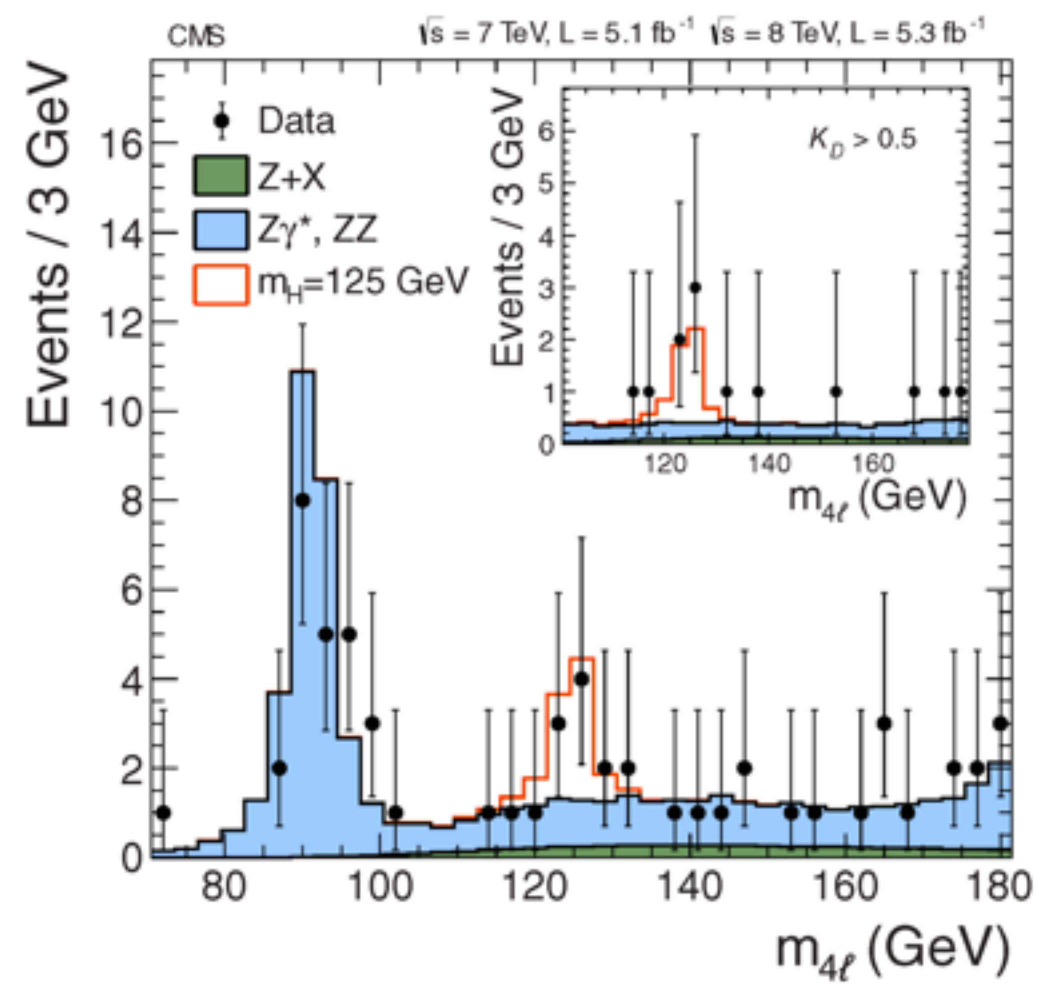
T. Han, Z. Liu

The Higgs boson width at the LHC

To measure the width directly, we typically study invariant mass distribution of the resonance decay products in the vicinity of a resonance and fit it to the Breit-Wigner formula. Unfortunately, since the invariant mass of the Higgs decay products can be reconstructed with (for these purposes) poor resolution, the LHC is only sensitive to the Higgs width if it is in a few GeV range. The current direct limit on the Higgs width by the CMS collaboration is $\Gamma_H < 3.4\ \mathrm{GeV}$. The ultimate reach is estimated to be between 1 and 3 GeV.

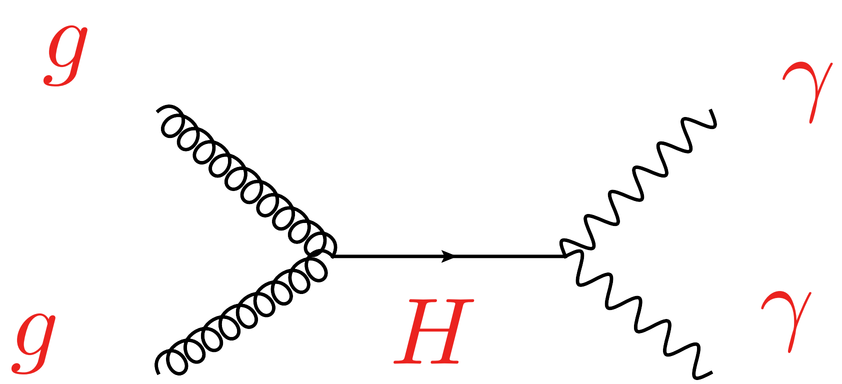
To get into an MeV range for the Higgs width measurement, we need to improve the sensitivity of our methods by a factor of a thousand ! Because of that, measuring the Higgs width at the LHC with any degree of precision was always considered an utopian endeavor.





From rates to couplings: degeneracies

Independent of the exact value of the Higgs boson width, we know that it is a narrow resonance; as such it is mainly produced on-shell. This feature leads to a relation between production rates, Higgs couplings and the width.



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

Unfortunately, such a relation makes it impossible to extract the couplings and the width separately, from the measured on-shell cross-sections. Indeed, 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 is practically unconstrained, extraction of the Higgs couplings from production/decay rates suffers from significant ambiguity.

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

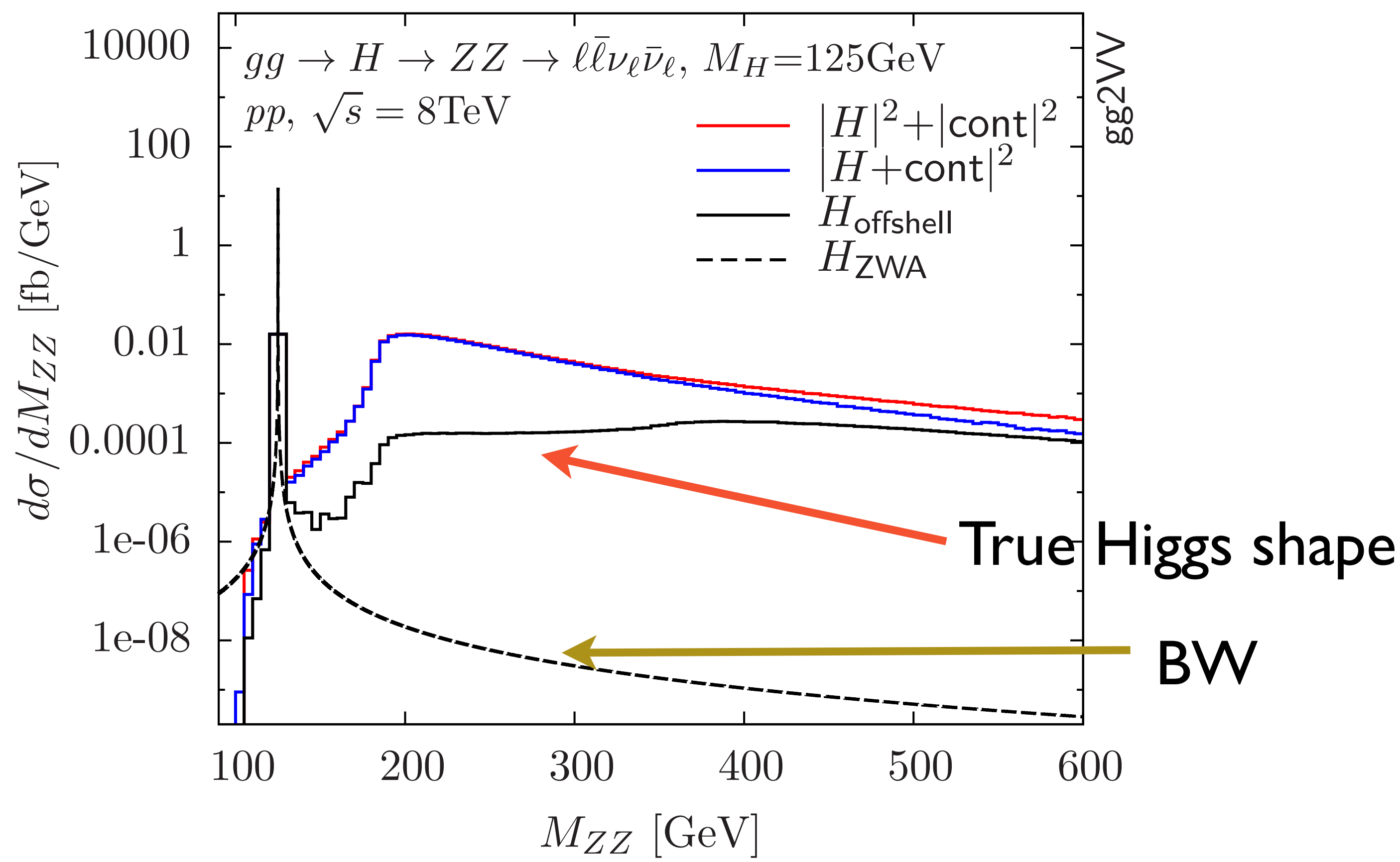
Couplings from off-shell production

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 couplings and is independent of the width, resolving 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 couplings/width degeneracy. The cleanest final state is ZZ (four leptons), so it is natural to look there.

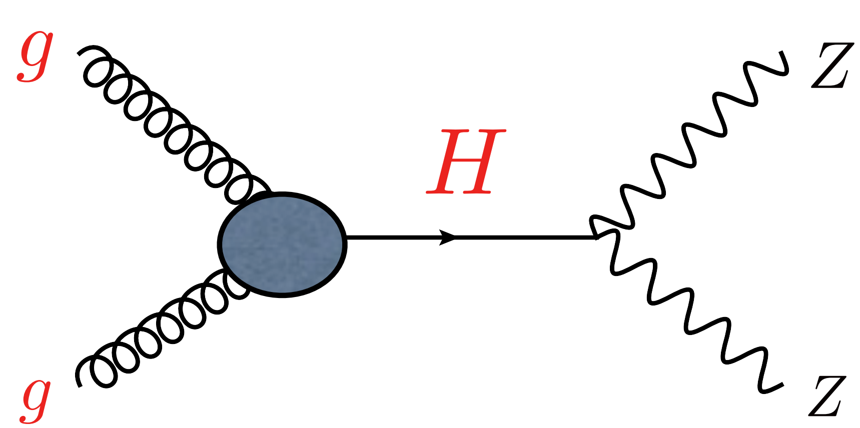
Caola, K.M.

In this case, the off-shell rate appears to be significant due to large cross-section for producing two longitudinally polarized Z bosons in decays of (strongly) off-shell Higgs.

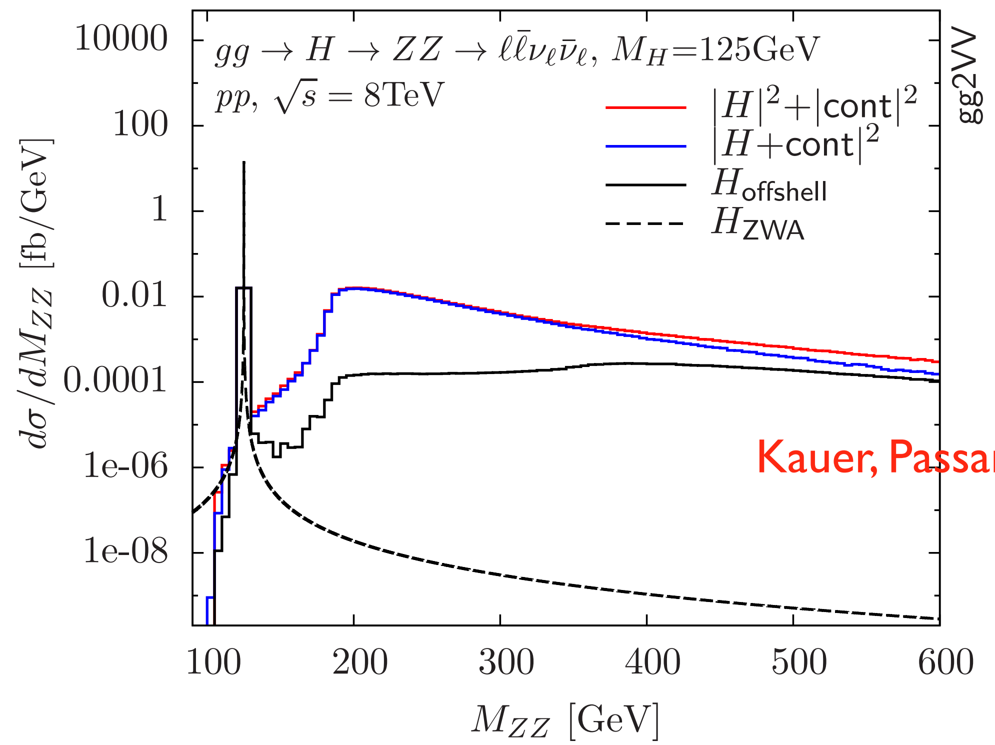
Kauer, Passarino

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

For large invariant masses of the Z boson pair, the amplitude squared becomes independent of ZZ invariant mass, enhancing the off-shell production significantly. Off-shell cross-section is large; it is close to ten percent of the resonance cross-section.



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



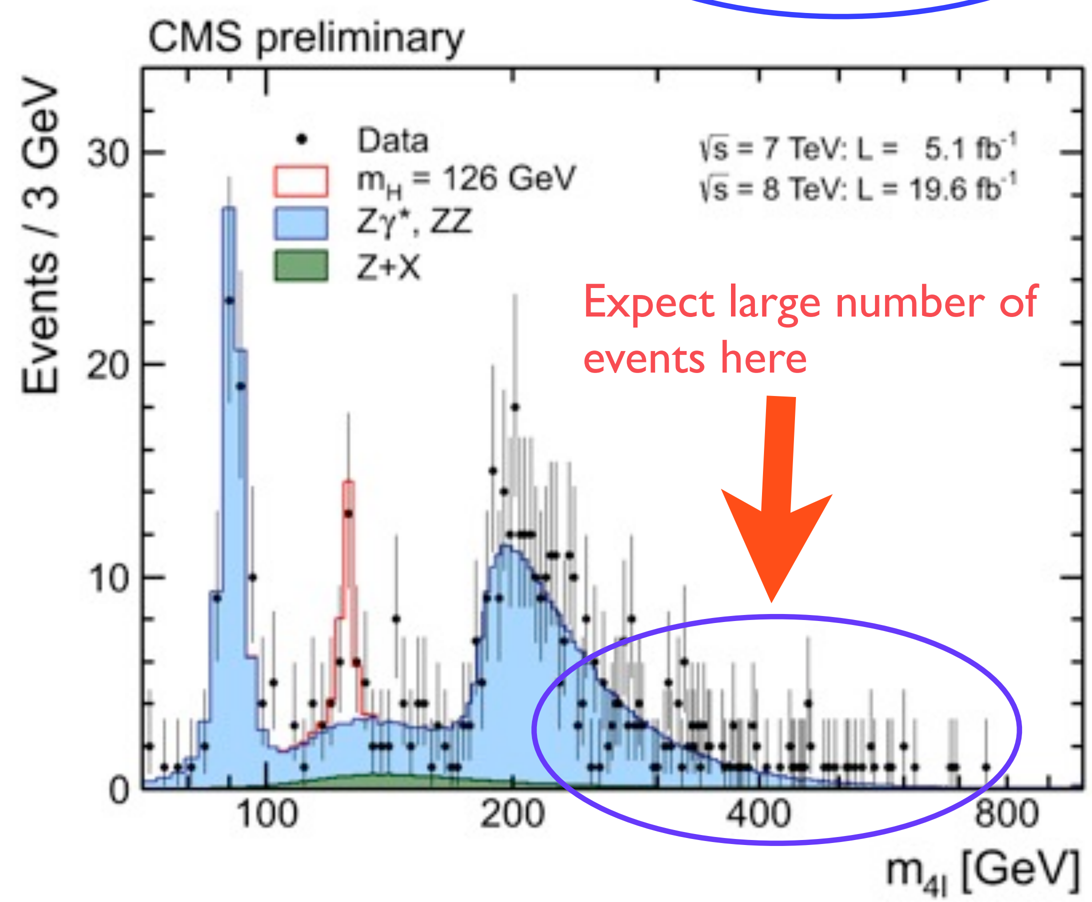
Kauer, Passarino

Higgs decay to ZZ

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 width is 3.4 GeV (CMS) which is 820 times larger than the Standard Model value. If the width were actually that large, Higgs couplings to gluons and ZZ should be different from their SM values to ensure agreement of the on-shell cross-section. However, once couplings are modified, one should expect a very large number of additional off-shell events that exceed by almost a factor four the total number of ZZ events observed by the CMS!



$$N_{\rm off} \approx 0.1 \times N_{\rm peak} \times 820 \sim 1600 \gg N_{4l}^{\rm total}$$

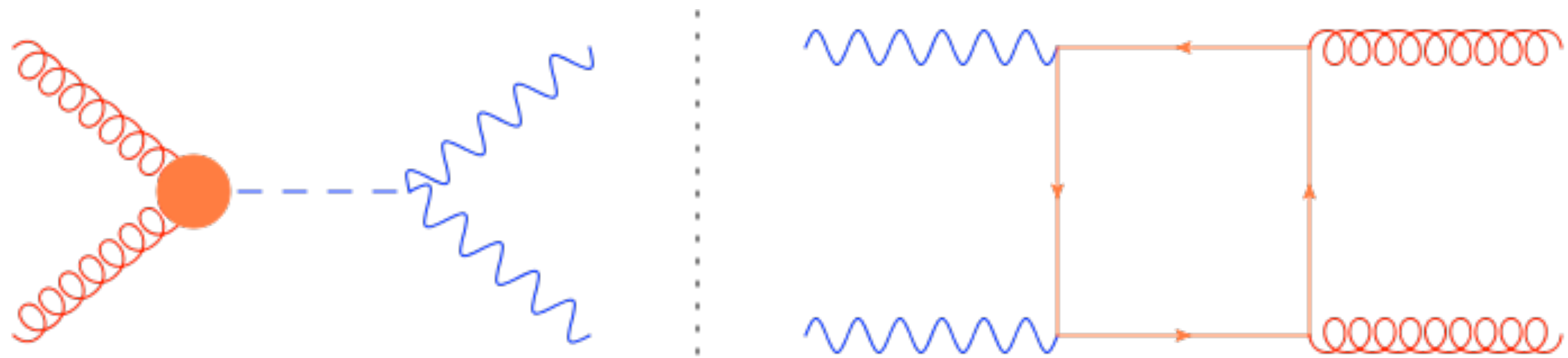
Therefore, one can already put meaningful bounds on the Higgs width using current data on ZZ final states !

Caola, K.M.

Complication: signal-background interference

Production of two Z bosons in collisions of two gluons can occur either directly or through the Higgs boson. The two amplitudes interfere destructively. 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 couplings is weaker.

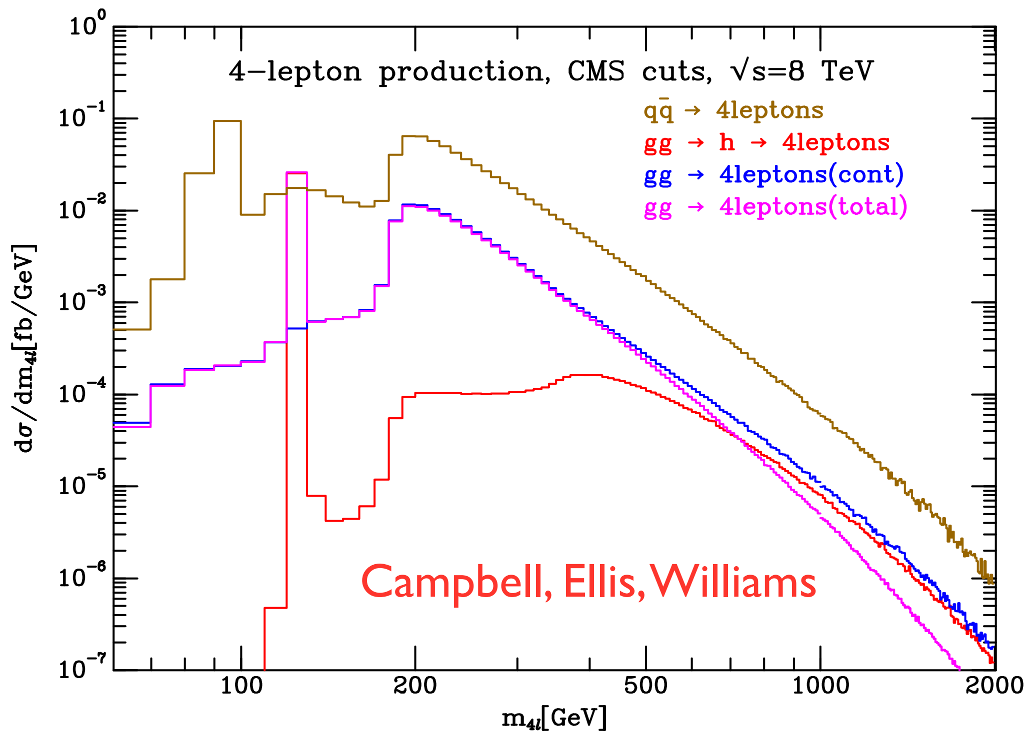
$$\sigma_{\rm int} \sim \mathcal{A}_{gg\to H^*\to ZZ} \sim g^2 \sim \sqrt{\Gamma_H}$$

Magnitude of various contributions

How large is the total sample of events we have now and how large are different contributions to pp -> ZZ for realistic selection cuts?

Consider CMS 4-lepton events as an example. CMS observes 451 ZZ (4l) events in the invariant mass range between 100 and 800 GeV; while 432(30) ZZ events were expected.

Most of these events come from quark-antiquark and gluon annihilation to Z-pairs; the third largest contribution is the resonance Higgs production. Off-shell production of the Higgs and its interference with gg -> ZZ production were not even included in early CMS analysis because they are small in the Standard Model and because they do not affect properties of the Higgs resonance (off-shell effects, no impact on the Higgs properties extracted from peak cross-sections).



$$N_{qq\to ZZ} \approx N_{\rm tot}$$

$$N_{gg} \sim 10^{-1} \times N_{\rm tot}$$

$$N_H \sim 5\times 10^{-2} \times N_{\rm tot}$$

$$N_{\rm off} \sim 10^{-2} N_{\rm tot}$$

$$N_{\rm int} \sim -2\times 10^{-2} N_{\rm tot}$$

Constraining the width

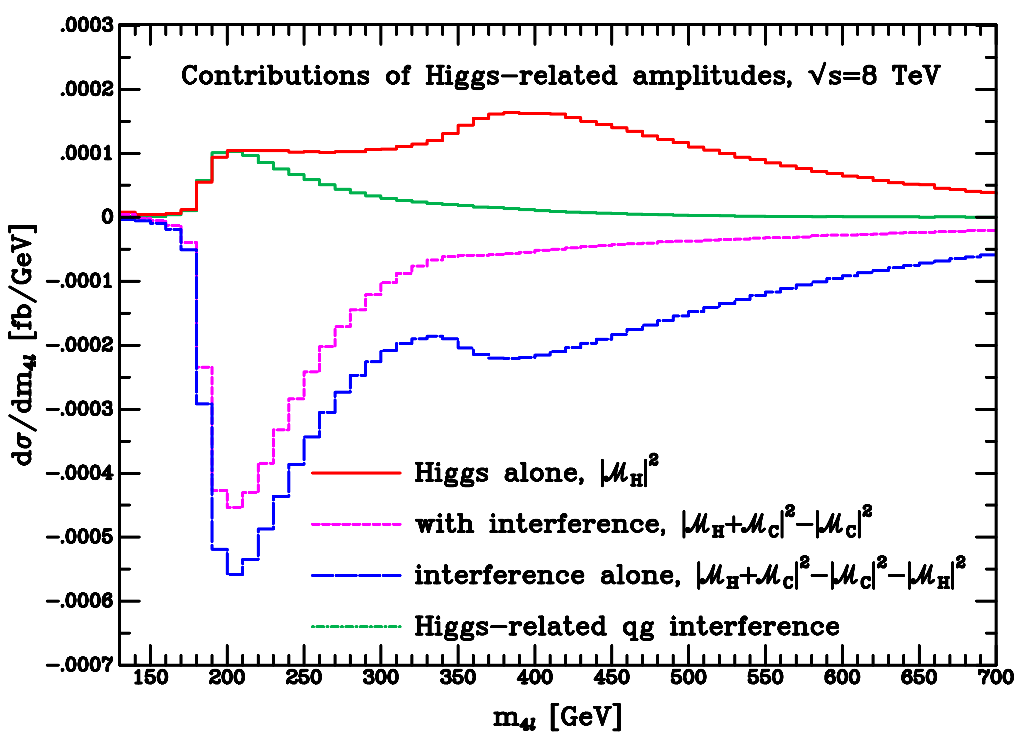
However, if we float the width of the Higgs boson, the number of expected events changes; as we have seen, the off-shell Higgs production cross-section scales as the width and the interference scales as the square root of the width. Considering the ZZ invariant mass range from 100 GeV to 800 GeV, we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

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

Requiring that observed (451) and expected number of events do not differ by more than two standard deviations, we derive an upper bound on the Higgs boson width

$$|N_{\rm nobs} - \bar{N}_{\rm exp}| < 62 \qquad \Gamma_H < 43\ \Gamma_H^{\rm SM} = 181\ {\rm MeV}\ (95\%{\rm C.L})$$

Caola, K.M.; Campbell, Ellis, Williams



Campbell, Ellis, Williams

The analysis can be improved by focusing on the region of higher invariant masses. This is because the off-shell Higgs production is significant beyond 200 GeV while there is large negative interference below 200 GeV; removing contribution of that region, improves the constraint. For example, selecting events with 4-lepton invariant mass higher than 300 GeV, we find $\Gamma_H < 25.2\ \Gamma_H^{\rm SM} < 105\ {\rm MeV}(95\%{\rm C.L.})$

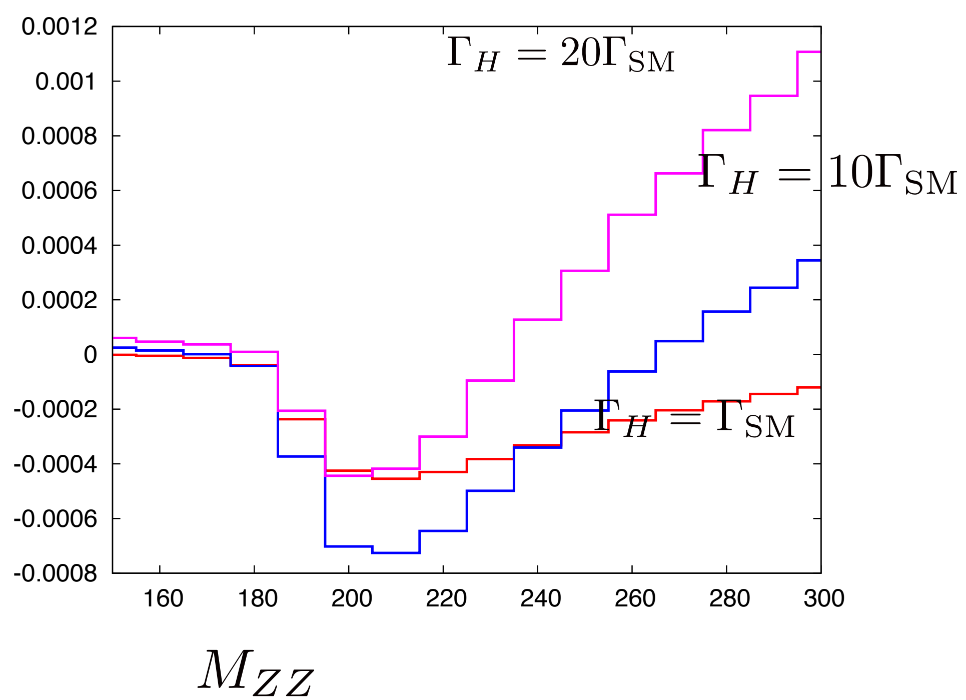
Caola, K.M.; Campbell, Ellis, Williams

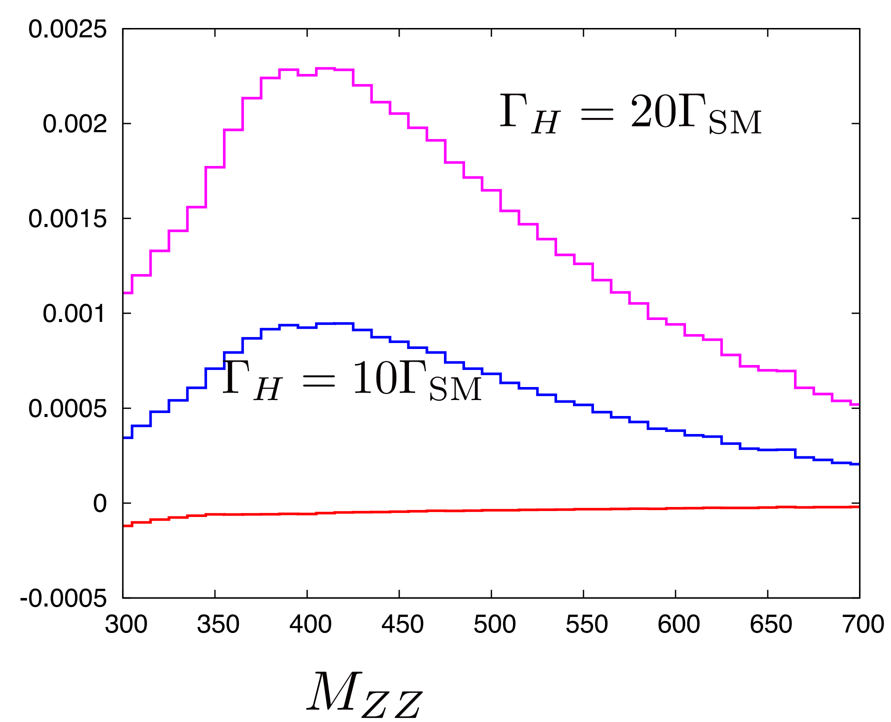
Further improvements in the analysis

In principle, one can imagine further steps to improve the analyses by accounting for the shape of 4l invariant mass distribution and the angular distributions of leptons.

Indeed, as one can see from the plots below, shapes of the invariant mass distribution (gg ->ZZ only) change for different values of the width. This is particular clear at small(ish) invariant masses where interference is large; at higher invariant masses, the invariant mass distribution develops a bump whose position is not sensitive to the width.

Angular distributions of leptons may be helpful to select events with longitudinally-polarized Z's -- these are the Higgs-related events in the off-shell tail of 4l-invariant mass distribution. The qq -> ZZ background should have higher fraction of transversely polarized Z-bosons, so focusing on longitudinal polarization may help to effectively reduce qq->ZZ background (MELA cut in CMS).



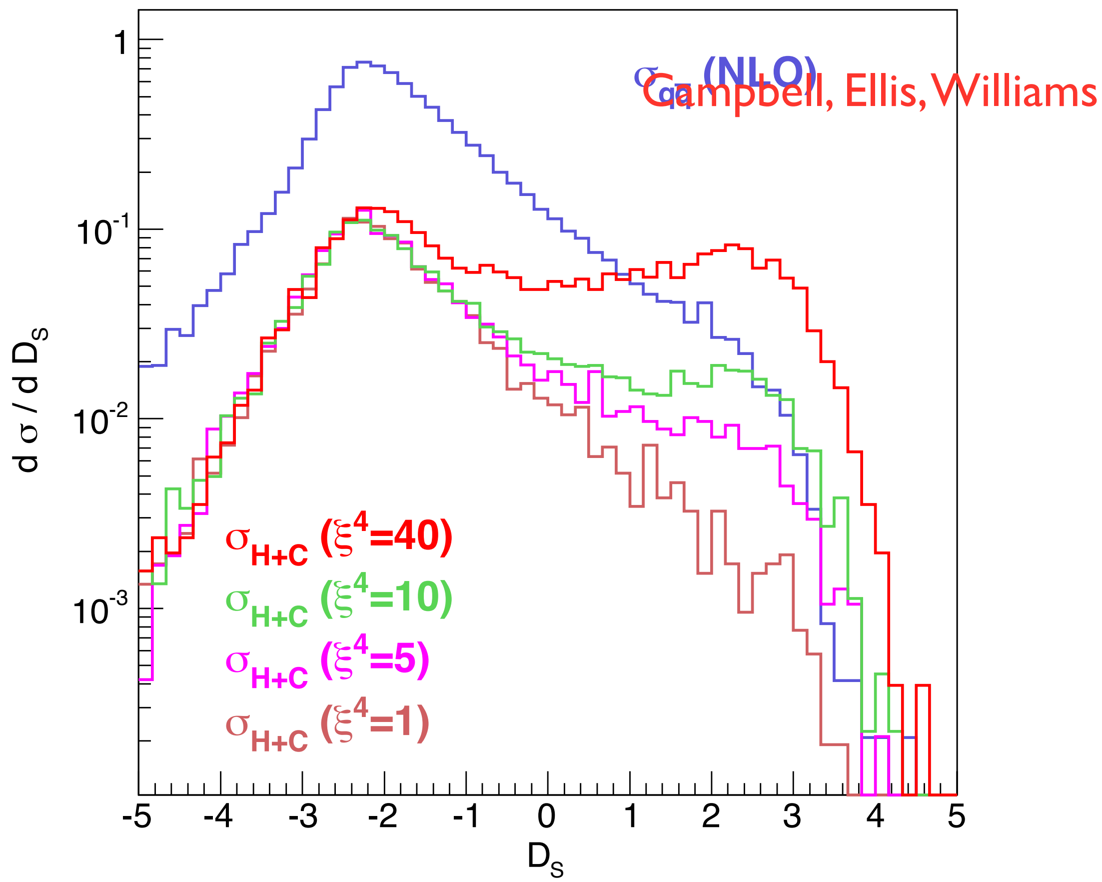


Using discriminant to constrain the width

A standard way to pick up the essential differences in the kinematics of interesting (signal) and uninteresting (background) events is to use kinematic discriminants. Kinematic discriminants are functions of matrix elements of signals and backgrounds that become large for events where signal is large and background is small; this allows us to find relevant places in multi-particle phase-space to look at, to optimize signal/background separation.

A discriminant for this problem was suggested by Campbell, Ellis and Williams. Events with large width develop a feature at large values of discriminant.

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



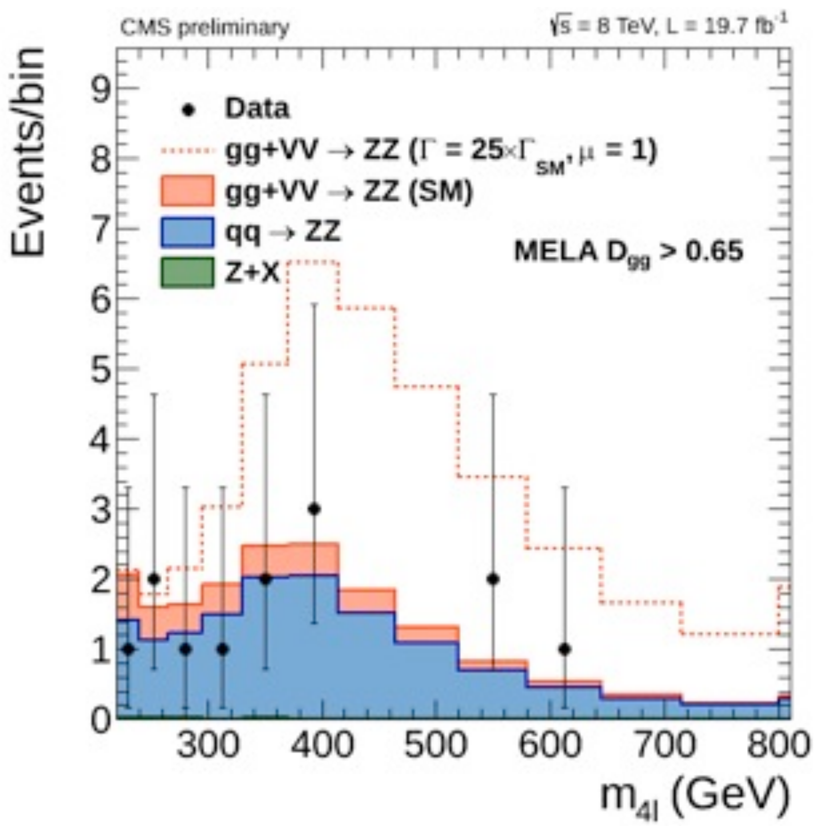
By selecting events with Ds>1, one can improve bounds on the width by a factor 1.6, compared to an analysis with 300 GeV cut on ZZ invariant mass. Campbell et al find that

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

can be reached. Further improvements should be possible by fitting Ds distribution, rather than simply cutting on it.

Recent CMS measurement

CMS collaboration has presented results of the actual width measurement using off-shell ZZ production at the Moriond conferences, earlier this year. Very recently the preprint appeared (arXiv/1405.3455) .



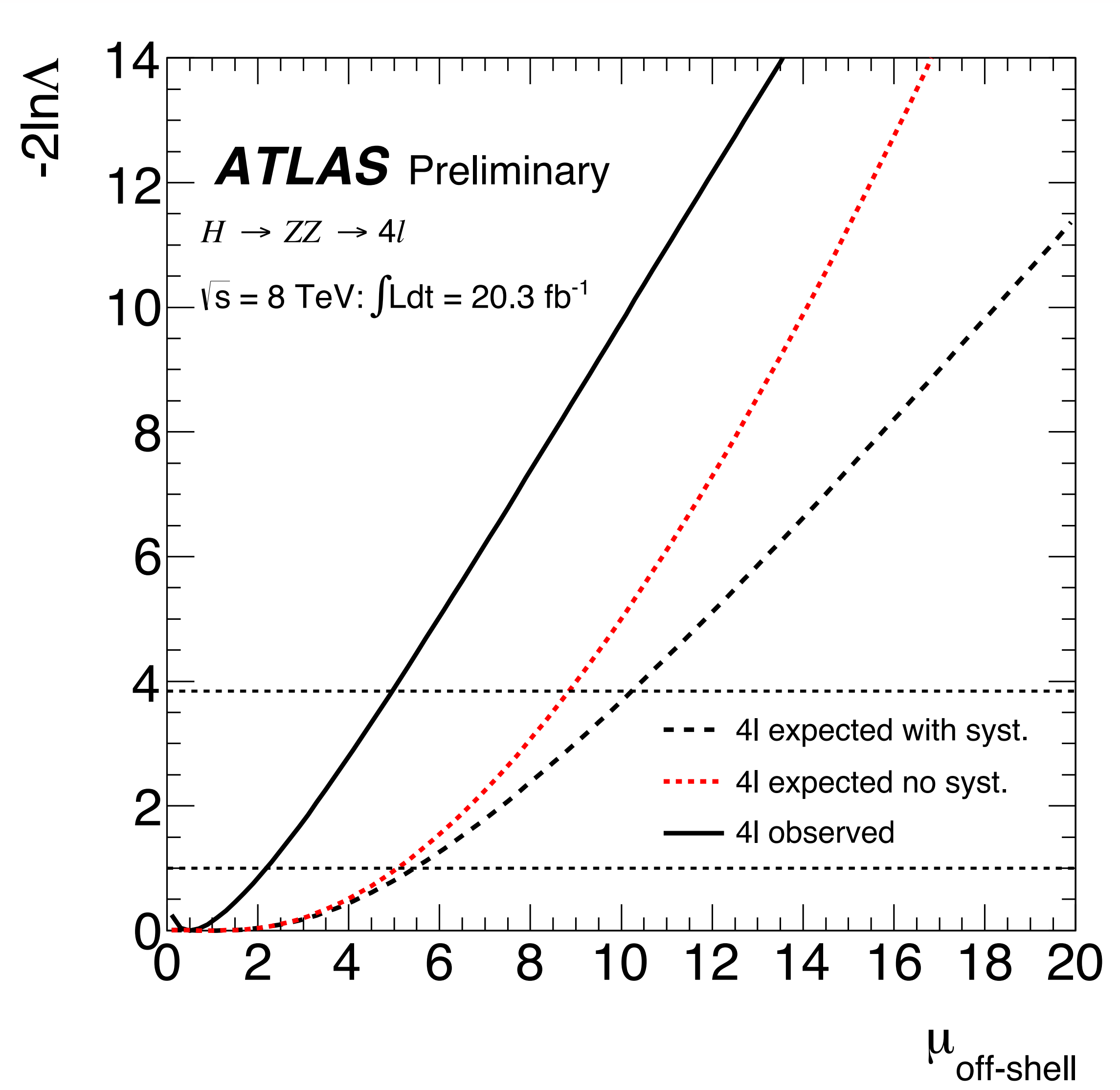
		4ℓ	$2\ell 2\nu$
(a)	total gg ($\Gamma_H = \Gamma_H^{SM}$)	1.8 ±0.3	9.6 ±1.5
	gg signal component ($\Gamma_H = \Gamma_H^{SM}$)	1.3 ±0.2	4.7 ±0.6
	gg background component	2.3 ±0.4	10.8 ±1.7
(b)	total gg ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	9.9 ±1.2	39.8 ±5.2
(c)	total VBF ($\Gamma_H = \Gamma_H^{SM}$)	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; more than two orders of magnitude improvement compared to direct (on peak) bound of the width.

Experimental results: ATLAS

[ATLAS-CONF-2014-042]



Analysis in the 4l and 2l2ν channels combined

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

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

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

General comments

1) CMS/ATLAS measurements prove that it is possible -- in practice -- to constrain the Higgs boson width using off-shell production of Z and W pairs.

1) It is important to get the logic of the measurement correctly: by going off-shell, we measure couplings. No width enters the off-shell physics. We infer the information about the width from the off-shell cross-section once couplings are known.

2) Even with all statistical tricks (likelihood etc.), at its core, this is a counting experiment that requires understanding of yields rather than shapes. Proper theoretical predictions for signal, background and interferences are therefore very important.

3) The main idea of the method is that excessive events at high-invariant mass of Z-boson pairs are interesting and may be related to Higgs physics. Interpretation of such excesses in terms of limits on the Higgs boson width is possible, as we have seen, but may require some care since it forces us to relate couplings measured at different invariant masses.

4) In general, a relation between on- and off-shell couplings may become less straightforward if the HZZ vertex contains anomalous couplings and the HGG vertex receives significant contributions from light degrees of freedom. Luckily, such effects can be constrained from various on-shell measurements, as I will discuss shortly.

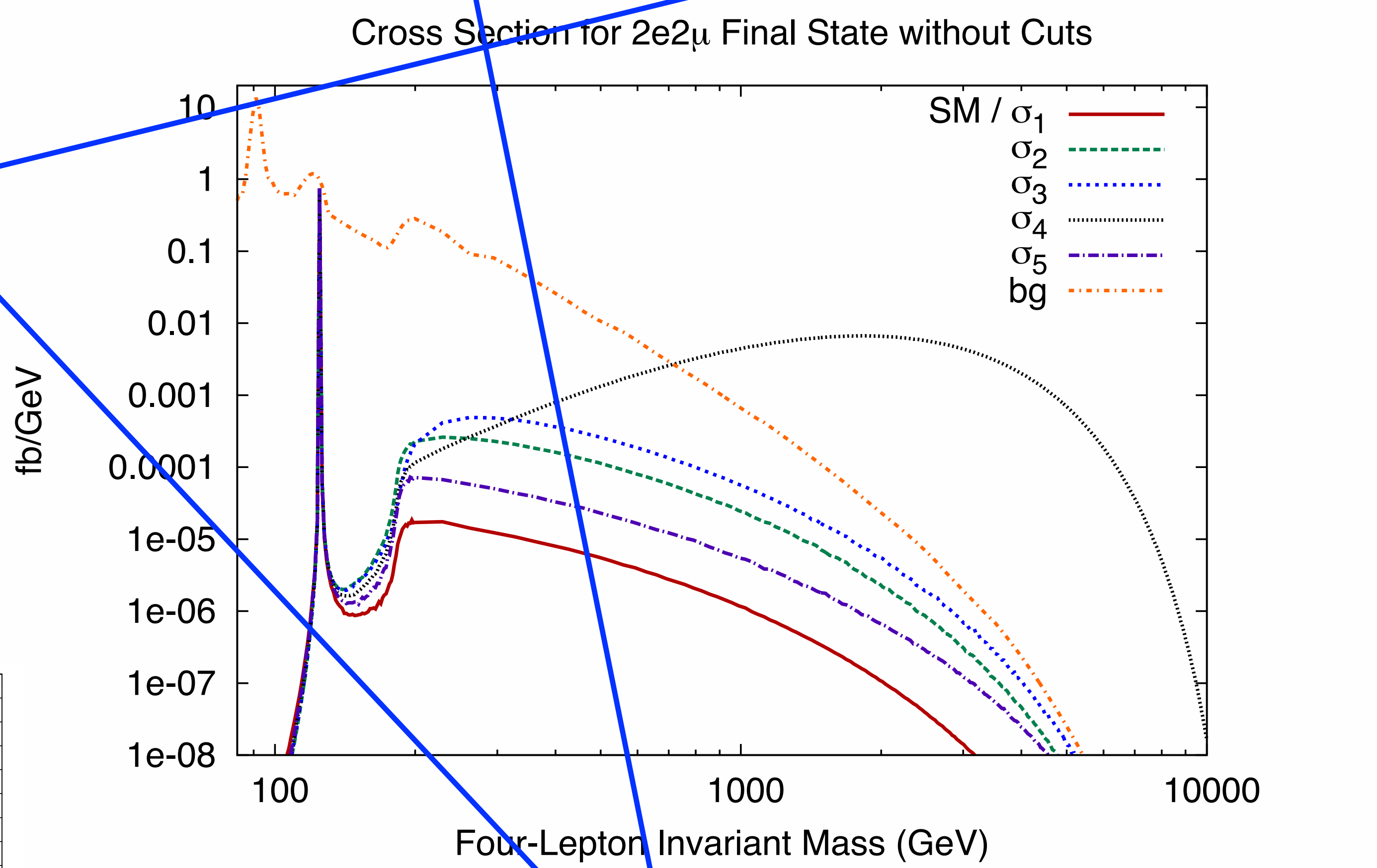
Example: anomalous HZZ coupling

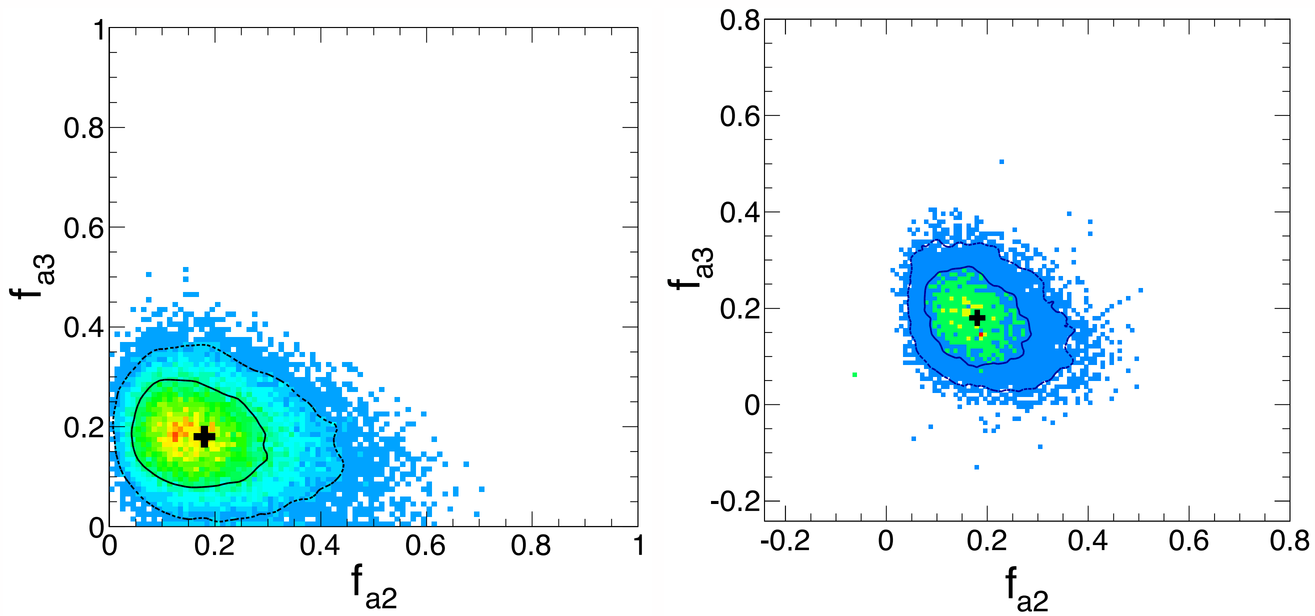
Basis of HZZ operators [Gainer, Lykken et al (2013)]

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

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

Strong modification of the m_{4l} shape



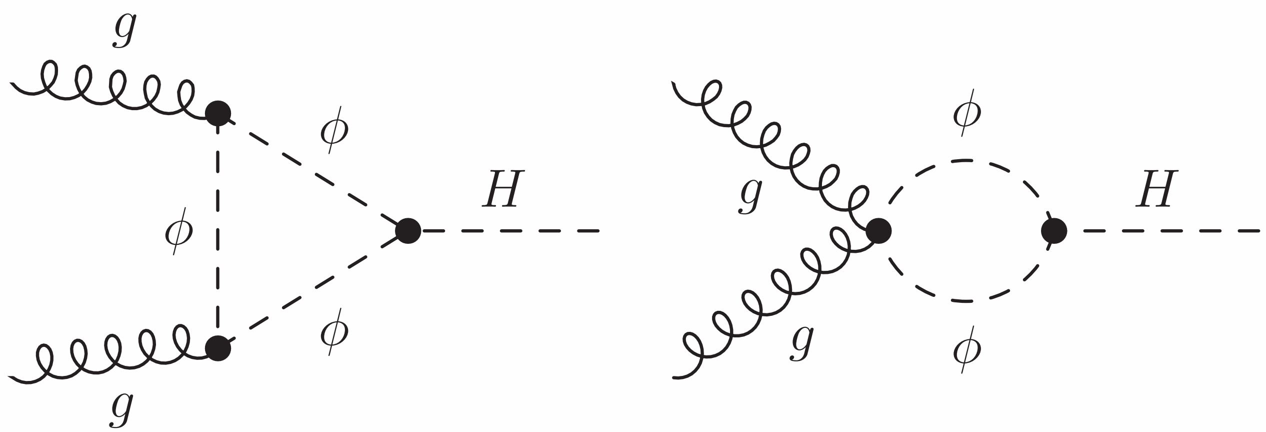


[Anderson et al. (2013)]

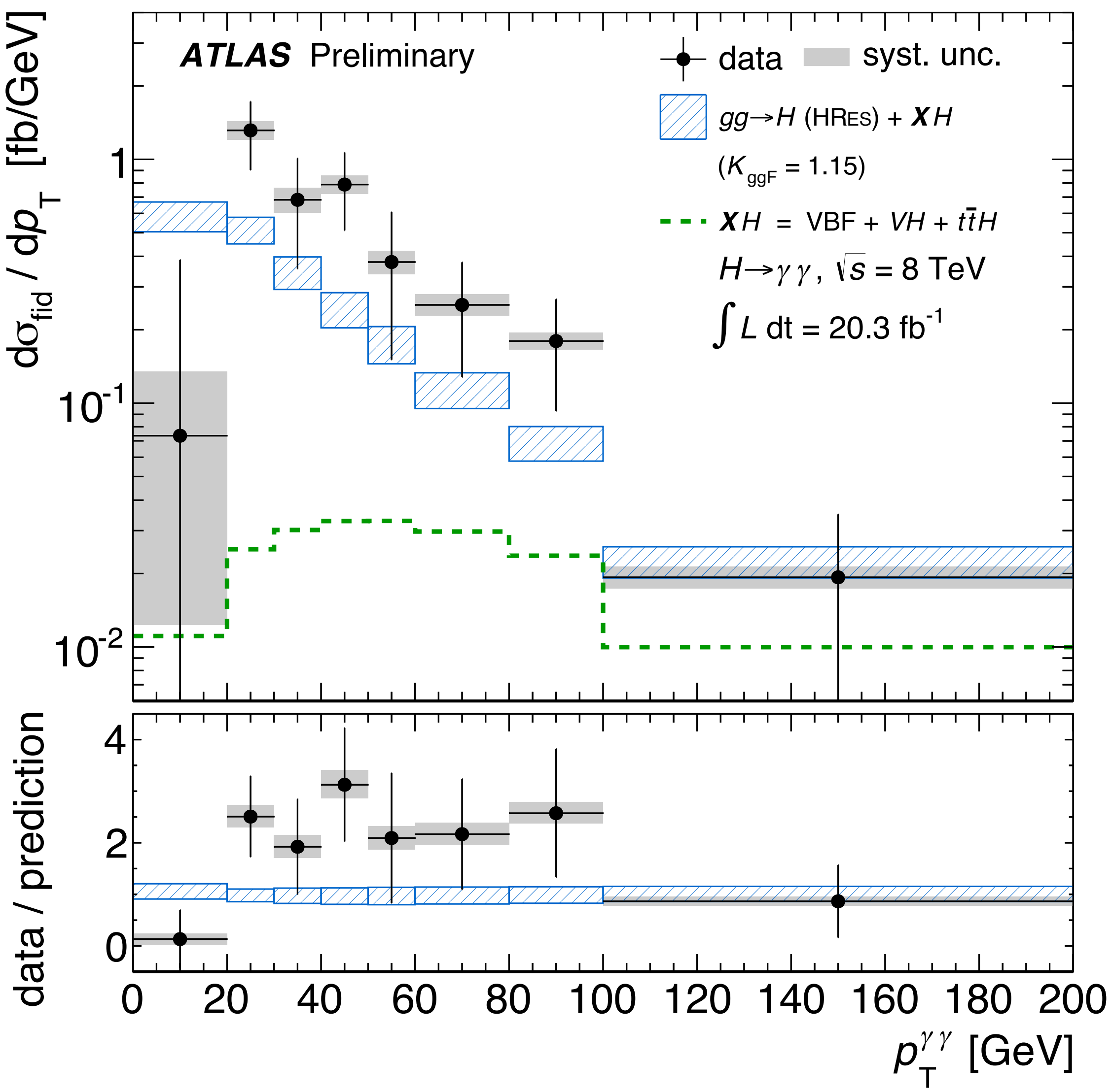
Modification of lepton angular distributions -> good control with 300 fb^{-1}

Example: light colored singlets in the loop

[Englert, Spannowsky (2014)]



Light d.o.f. can qualitatively change the analysis



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].

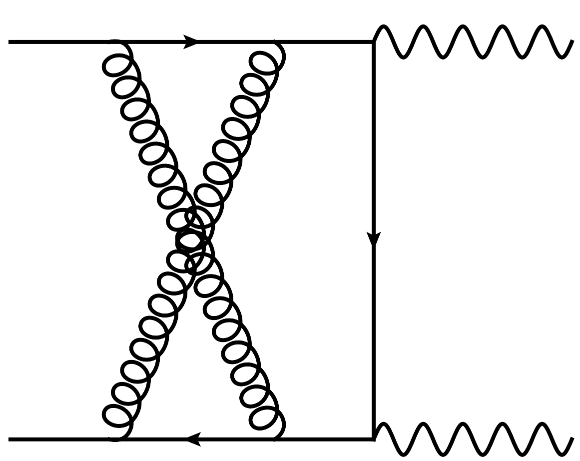
Can be detected by studying the Higgs p_T distribution (need theoretical improvement, full m_t dependence)

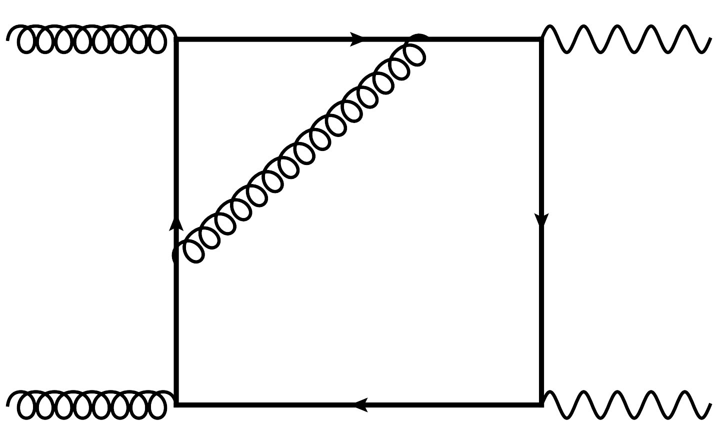
The ultimate reach of the width measurement

The ultimate reach of this method to constrain the width is determined by how well the number of ZZ events at high invariant mass can be predicted in the Standard Model. This requires NNLO computations for qq->ZZ, two-loop NLO QCD computations for gg -> ZZ and the signal-background interference. Electroweak corrections may be also sizable, at high invariant mass.

Two-loop computations are not easy. However, recently there appeared to be a breakthrough with two groups completing the necessary scalar integrals. These results where already used to construct the NNLO QCD predictions for ZZ production cross-section (Grazzini et al.). It was found that the corrections are at the level of 12 to 14 percent depending on the center-of-mass energy with the residual scale dependence at the level of three percent.

Further down the road are computations of NLO QCD corrections to gg -> ZZ and to the interference. When everything is completed, the quality of the Standard Model prediction for the off-shell ZZ production will be extremely high. A residual theoretical uncertainty for pp -> ZZ at the level of just a few percent can probably be reached within a year or two.





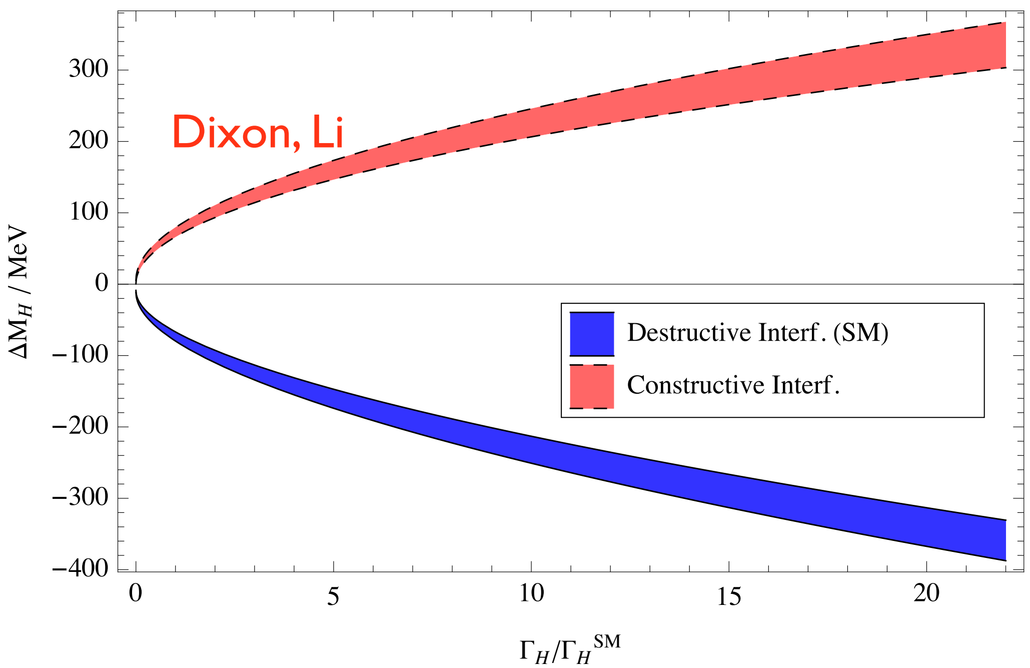
top quark

Bounding the Higgs boson width with di-photons

An alternative way to measure the Higgs width relies on the fact that signal-background interference in di-photon channel leads to an apparent difference between Higgs ``masses" measured in di-photon and four-lepton final states. The mass difference is proportional to square root of the width.

Dixon, Li

$$\delta m_h = \frac{2I\delta}{\sigma_0} \sim \frac{A_B}{A_s}\Gamma_H \qquad \sigma_0 \sim \frac{A_s^2}{\Gamma_H} \qquad A_s \sim \sqrt{\Gamma_H} \quad \Rightarrow \quad \delta m_H \sim 100 \text{ MeV} \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{\rm SM}}}$$



What can be said about the Higgs width using existing mass measurement? Unfortunately, CMS and ATLAS have quite different results on the Higgs mass in ZZ and di-photon channels.

$$m_H^{\gamma\gamma} - m_H^{ZZ} = 1.48 \pm 0.7 \text{ GeV} \quad \text{(ATLAS)}$$

$$m_H^{\gamma\gamma} - m_H^{ZZ} = -0.9 \pm 0.7 \text{ GeV} \quad \text{(CMS)}$$

Given the current data, the results are inconclusive. However, the important feature of this (di-photon) method is that, in variance with ZZ, much less off-shell extrapolation is required. From this point of view, di-photons offer an important alternative way to constrain the Higgs boson width.

Conclusions

Interesting effects in Higgs physics can come from subtle phenomena, such as off-shell production and interference of scattering amplitudes.

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's and is independent 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, we can argue that the Higgs width can not exceed O(15-20) times the SM value and significant improvements in this result are very likely. In fact, the very recent CMS measurement suggests $\Gamma < 5.4\,\Gamma_{\rm SM}$. ATLAS arrives at similar results.

Further advances in constraining the Higgs width using this method will require very precise theoretical predictions for ZZ production in proton collisions (the recent progress with multi-loop computations makes this well within reach), detailed studies of on-shell couplings to Z's and gluons as well as detailed exploration of four-lepton invariant mass shape, to constrain possible effects of higher dimensional operators.

Difference of Higgs masses measured in di-photon and four-lepton channels provides an alternative observable to constrain the Higgs boson width at the LHC.

Altogether, this is a rich research program that requires strong cooperation between theory and experiment and will, hopefully, lead to interesting insights into Higgs physics during the LHC Run II.